Carbon burning in massive stars

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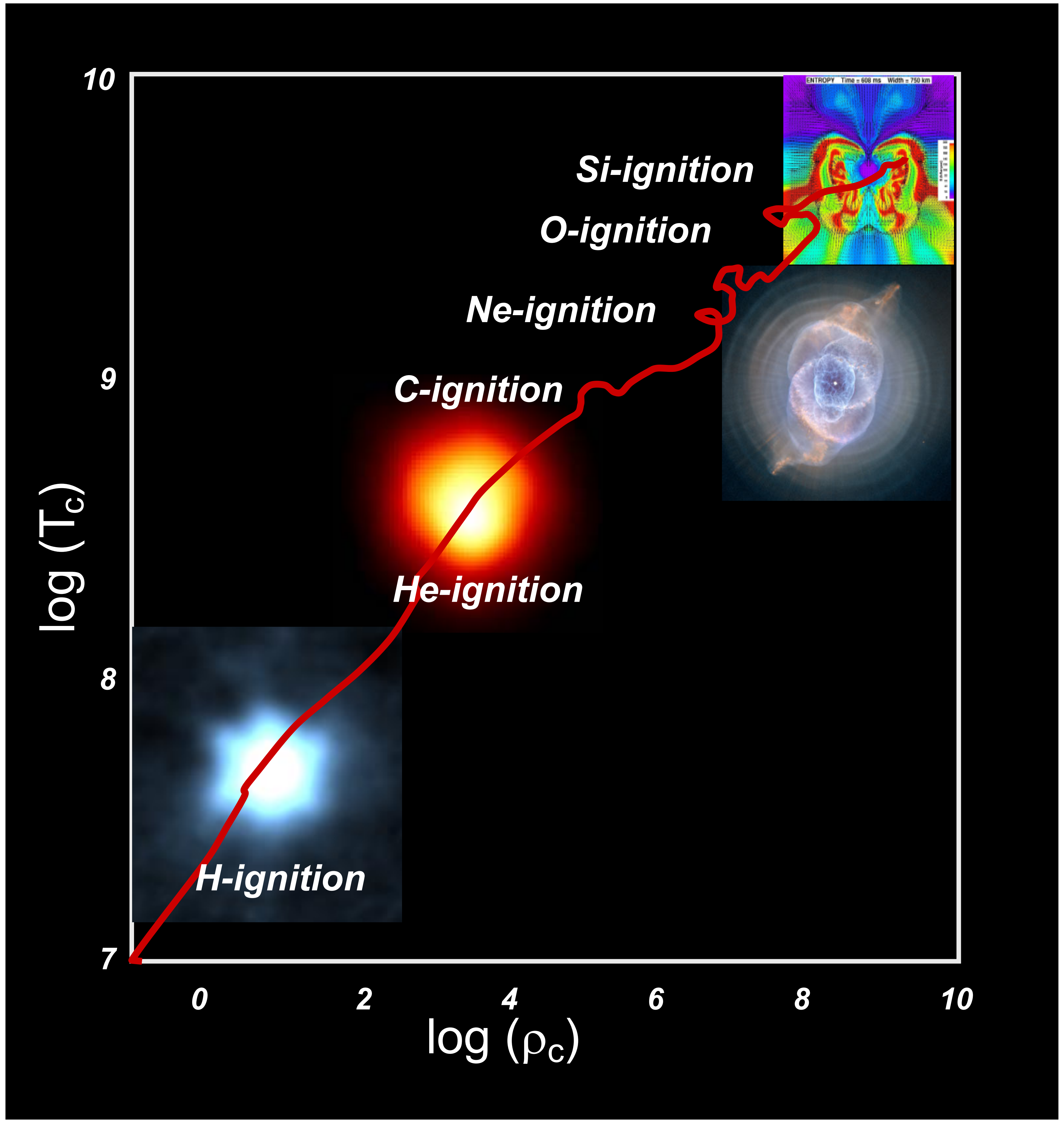
Burning phases in massive stars

different burning phases characterize the evolution of a „massive“ star

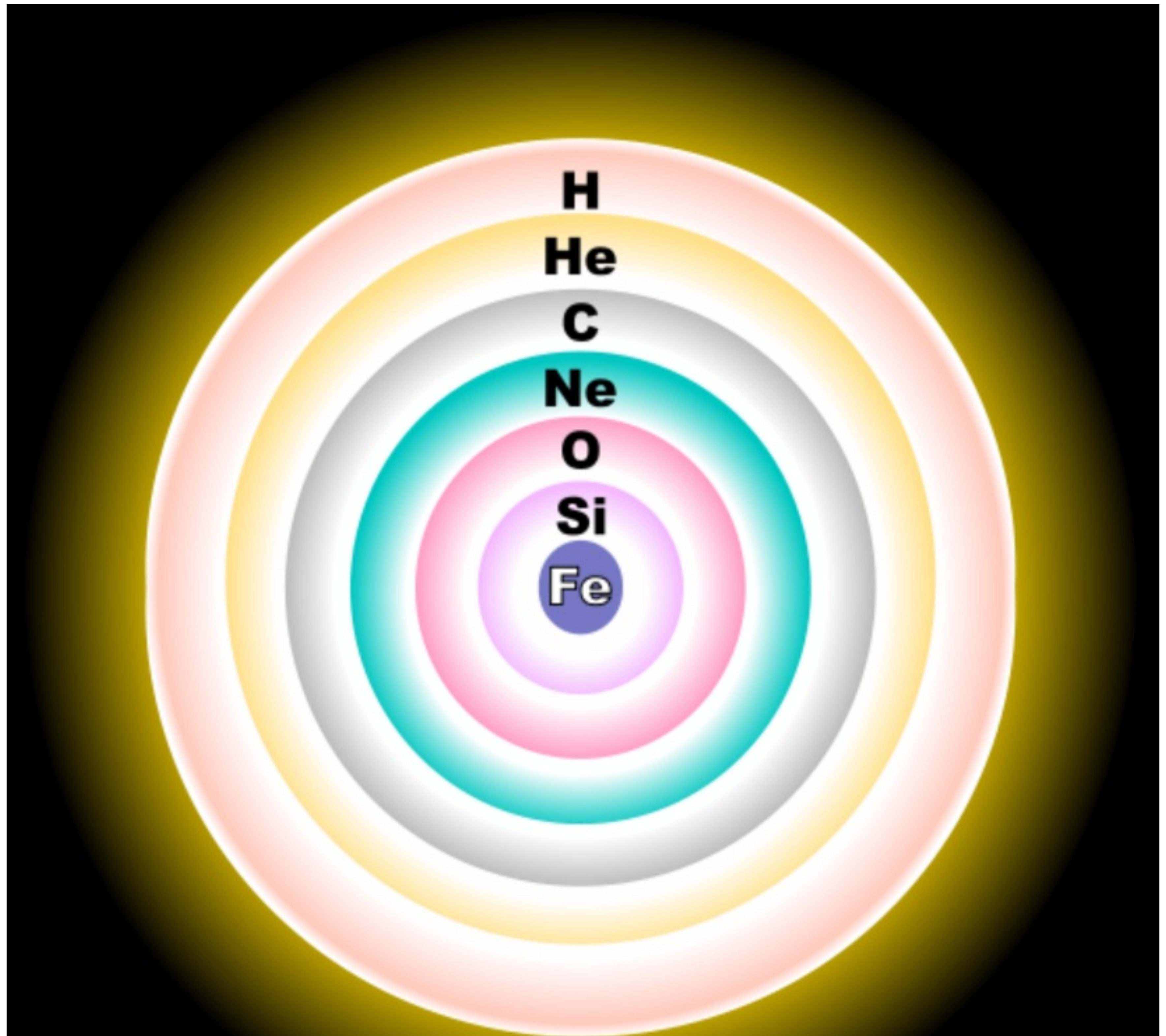
↓

each burning phase is controlled by different nuclear reactions, which govern the:

- energy production
- time scale
- nucleosynthesis



Carbon burning: a crucial phase in the stellar nucleosynthesis

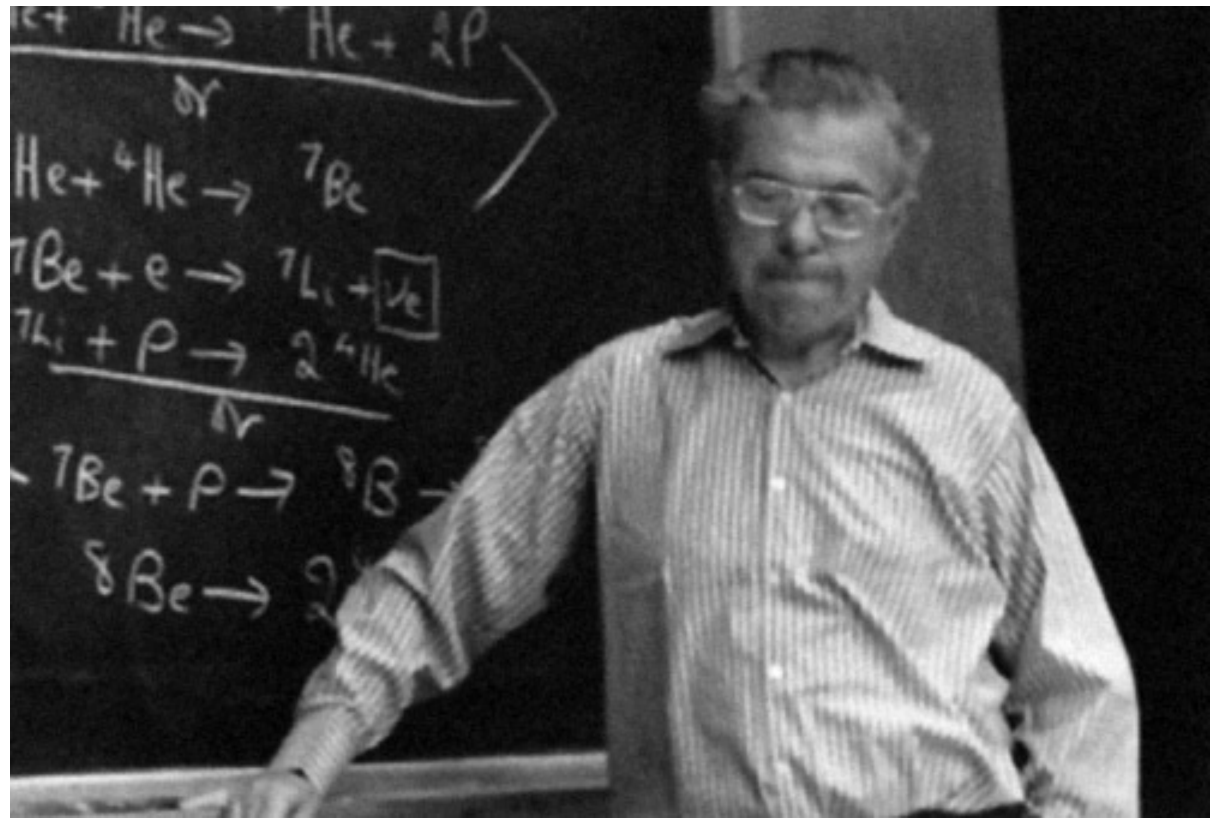


Different shells of a massive star shortly before core collapse

- key reactions at each stage of stellar burning

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,H \xrightarrow{CNO} {}^4He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\,He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}O + {}^{16}O$
Si	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}Si(\gamma,\alpha)$…

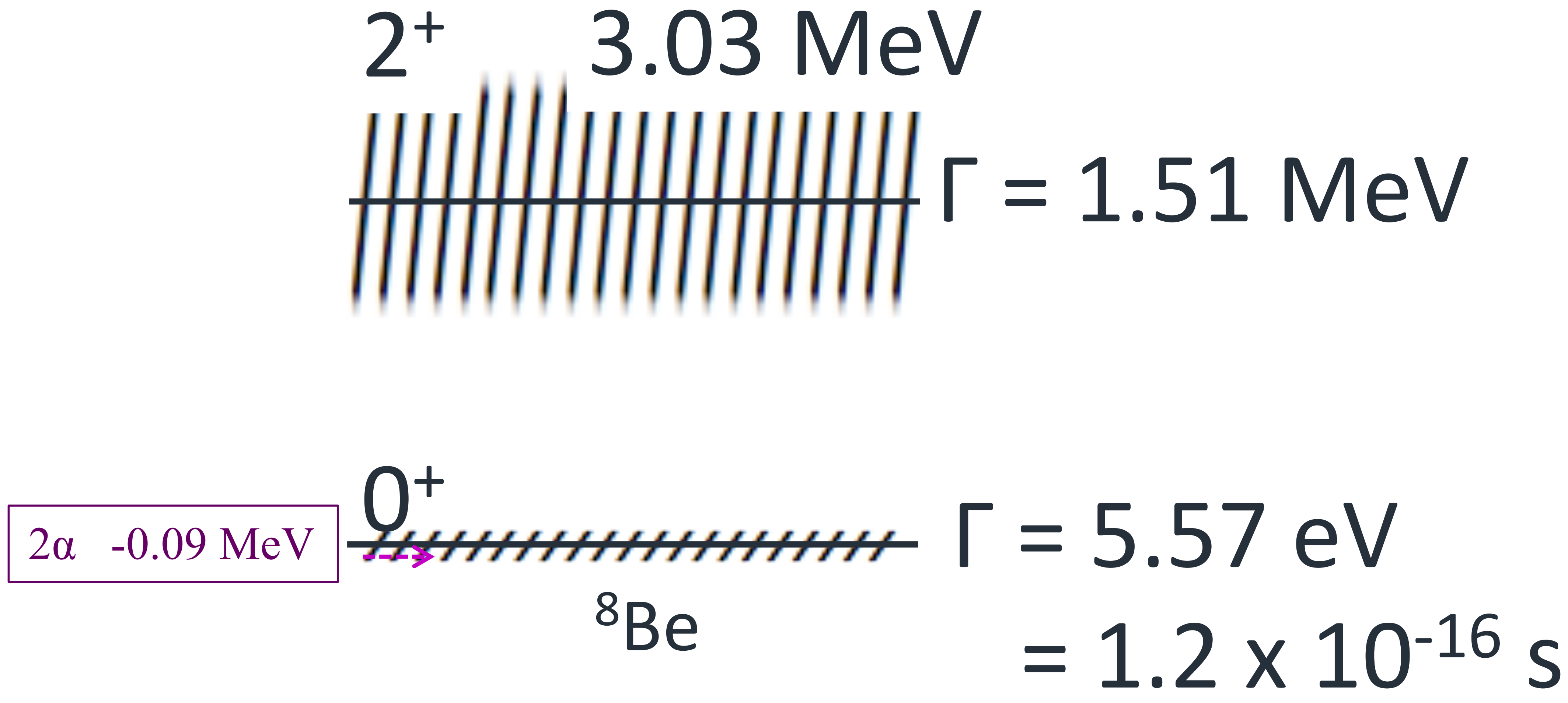
- In a star of 8-11 Solar masses, a carbon flash lasts just milliseconds.
- In a star of 25 Solar masses carbon burning lasts about 600 years.

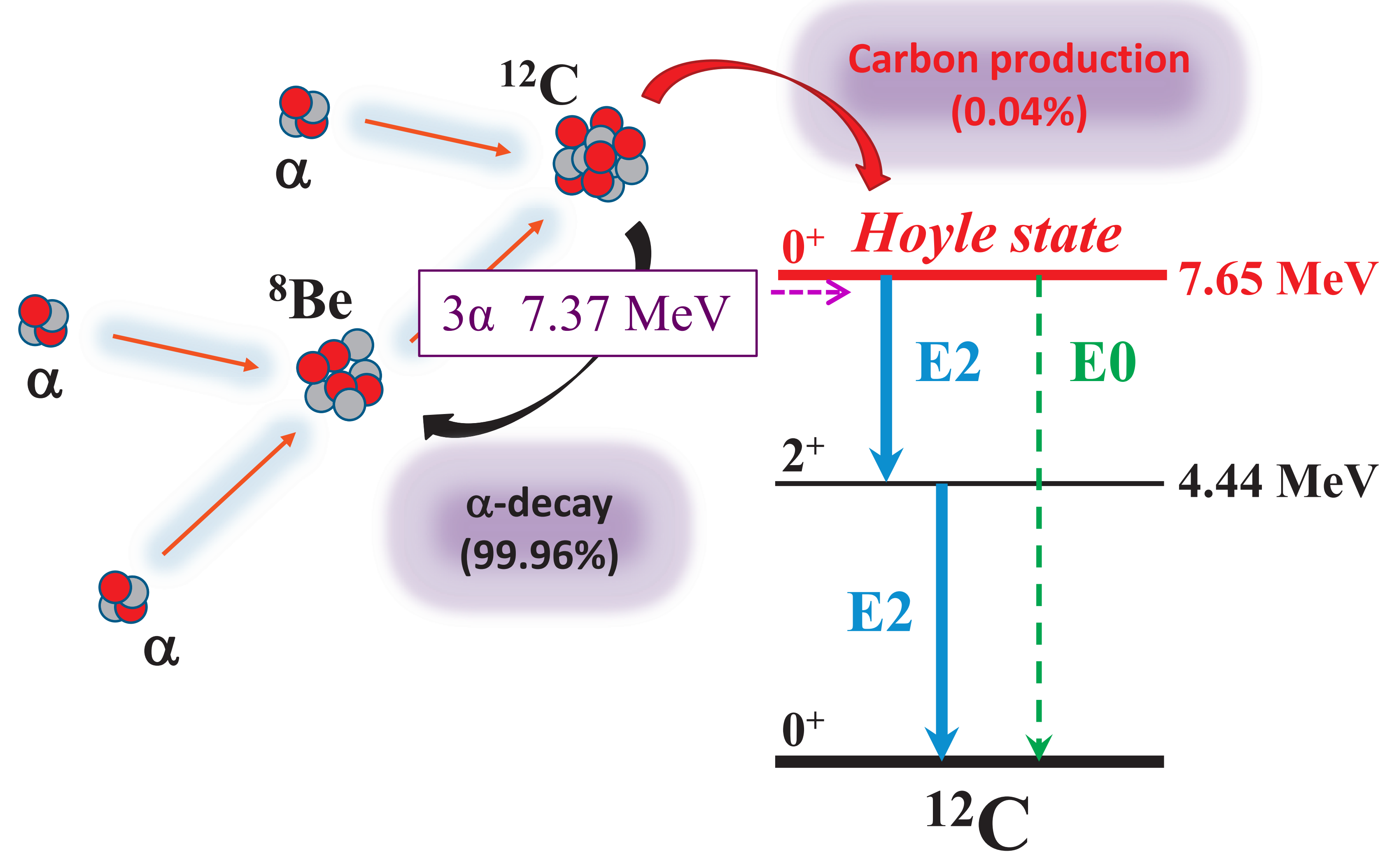


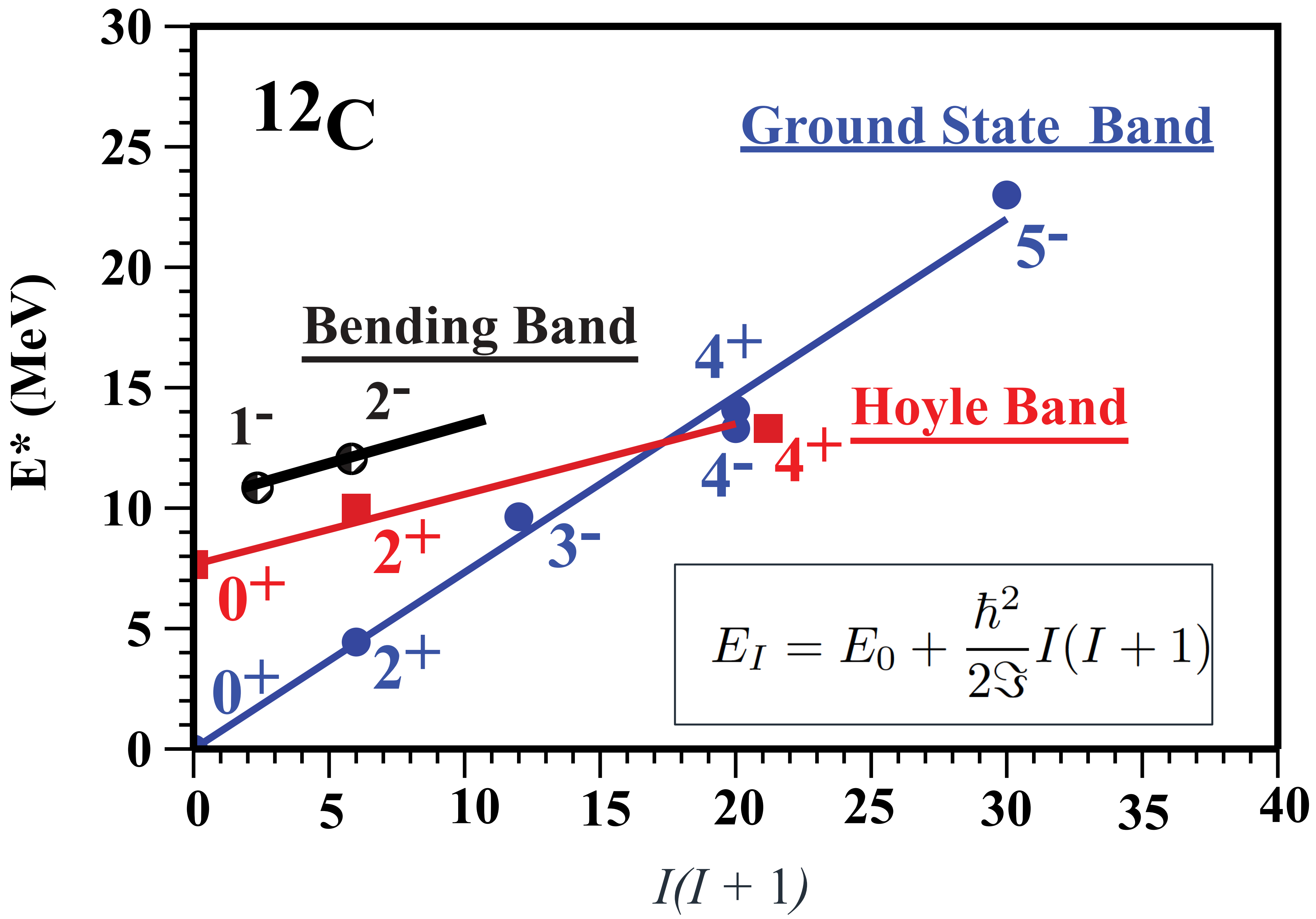
Sir Fred Hoyle (1915-2001)

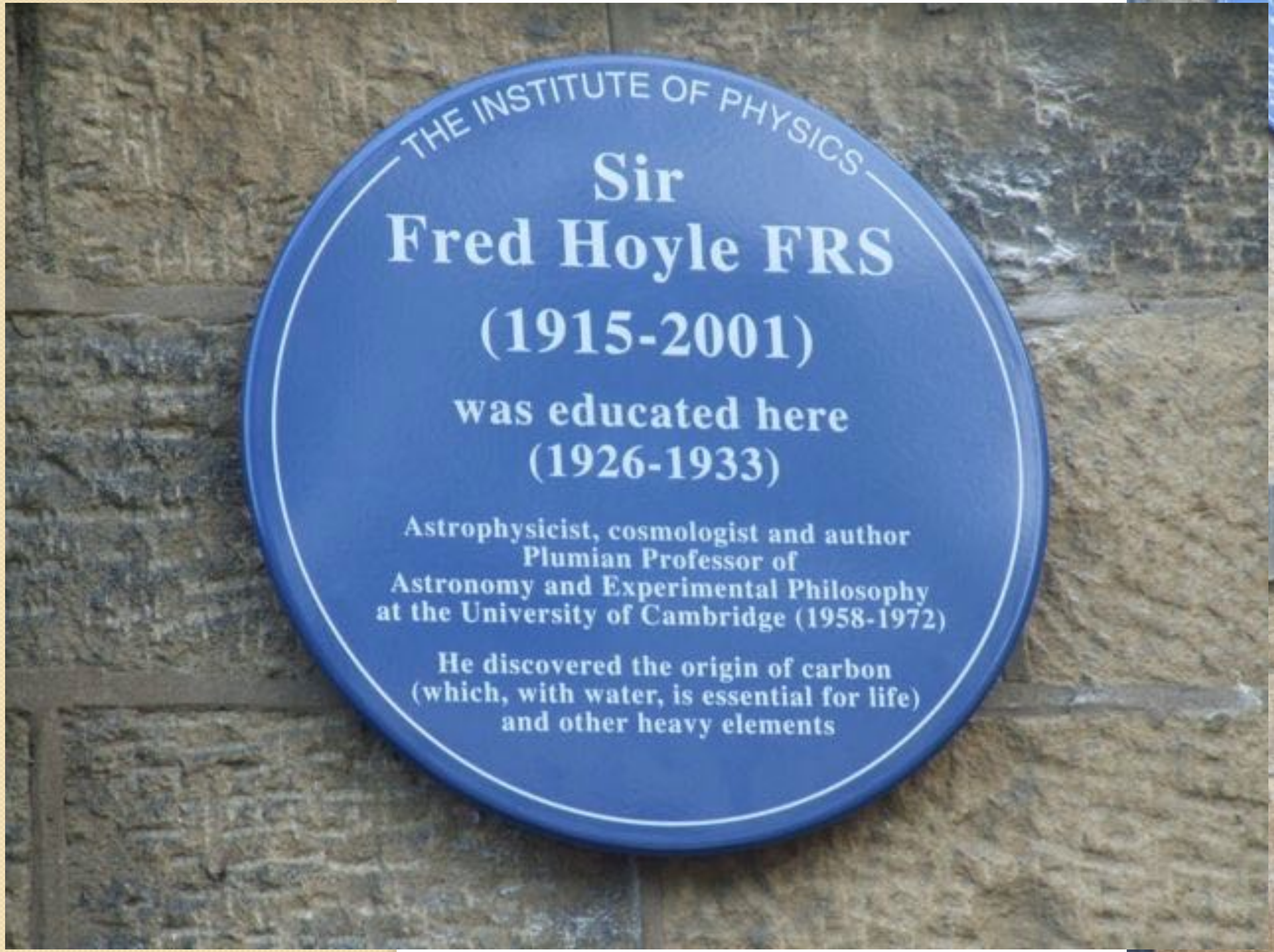
Helium fusion in stars

F. Hoyle, Astrophysical J. Suppl. Ser. **1** 121 1954



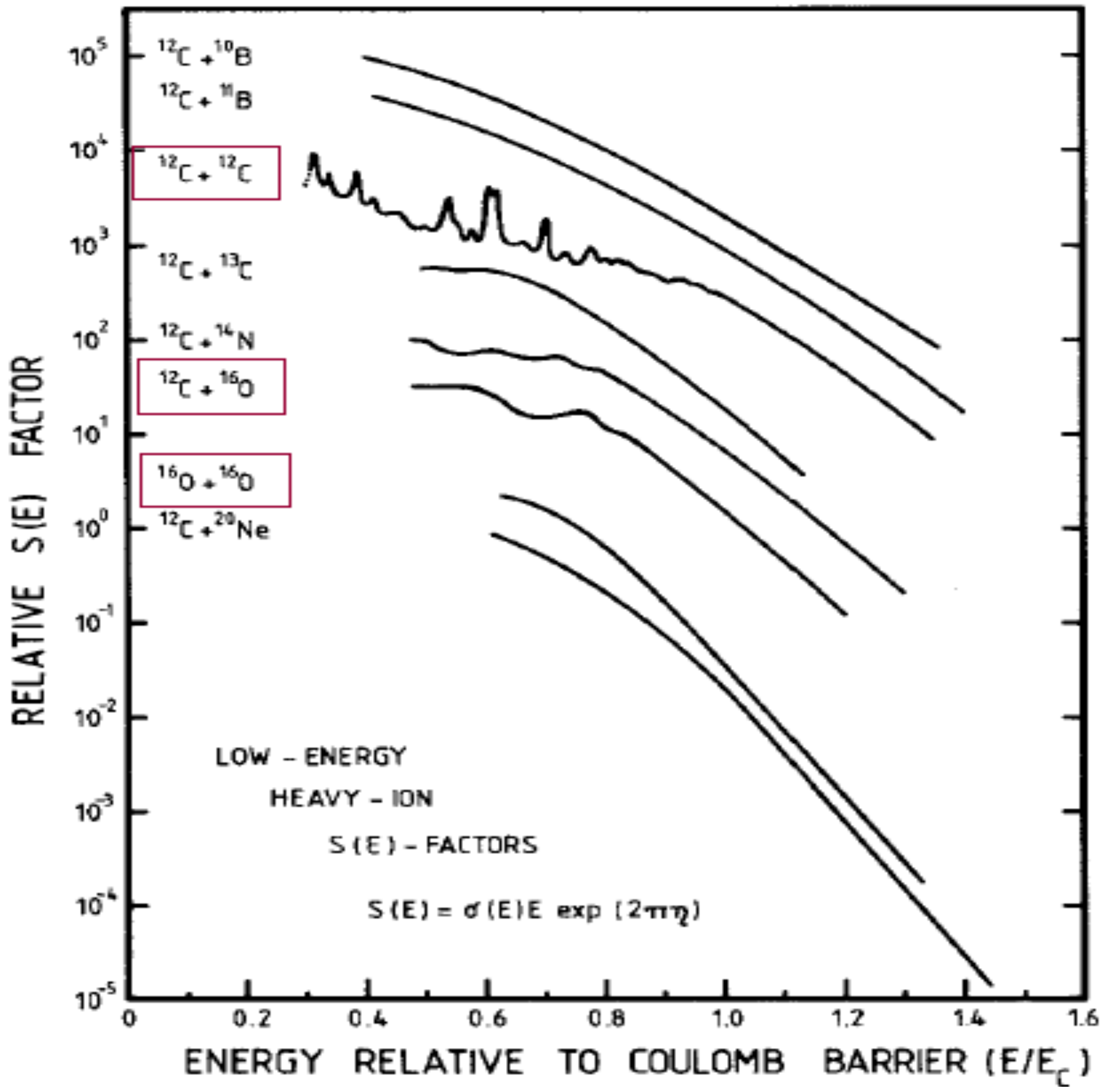




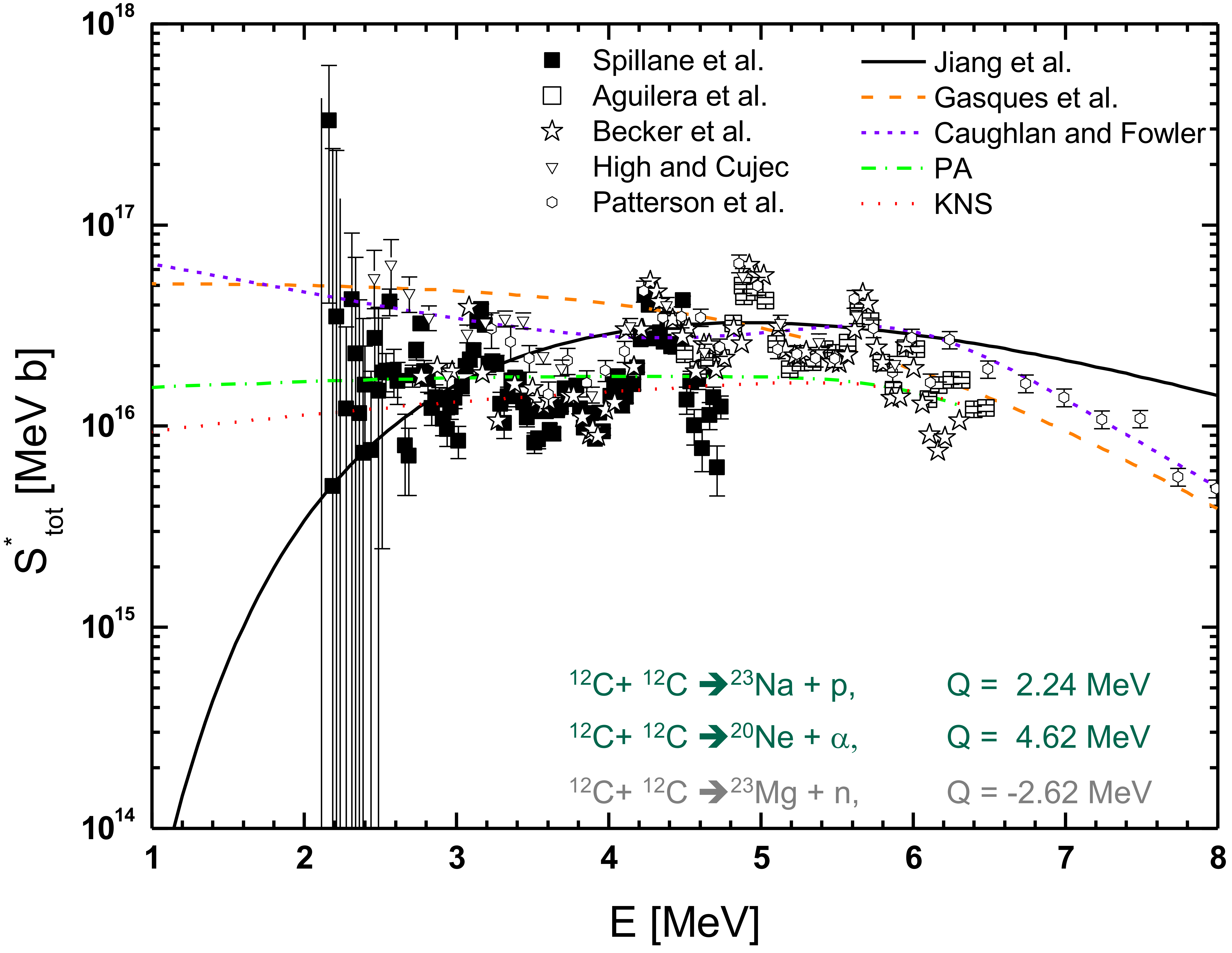

THE INSTITUTE OF PHYSICS
Sir
Fred Hoyle FRS
(1915-2001)
was educated here
(1926-1933)
Astrophysicist, cosmologist and author
Plumian Professor of
Astronomy and Experimental Philosophy
at the University of Cambridge (1958-1972)
He discovered the origin of carbon
(which, with water, is essential for life)
and other heavy elements

Ikeda Diagram

Cross-sections for some light systems at subcoulomb energies



R. Stokstad et al., Phys.Rev.Lett. 37 (1976)



Experimental and theoretical efforts

- \+ J.R. Patterson *et al.*, APJ 157, 367, (1969)
- \- G.J. Michaud and E.W. Vogt, PRC 5, 350, (1972)
- \+ M.G. Mazarakis and W.E. Stephens, PRC 7, 1280, (1973)
- \- R.G. Stokstad *et al.*, PRL 37, 888, (1976)
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- \+ M.D. High and B. Čujec, NIM A 282, 181, (1977)
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- \- Y. Suzuki and K.T. Hecht, Nucl. Phys. A 388, 102. (1982)
- \+ B. Čujec *et al.*, PRC 39, 1326, (1989)
- \- L.R. Gasques *et al.*, PRC 72, 025806, (2005)
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- \+ L. Barrón-Palos *et al*, Nucl. Phys. A 779, 318, (2006)
- \+ D. Jenkins *et al.*, PRC 76, 044310, (2007)
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- \+ X. Fang *et al.*, Jour. Phys. 420, 012151, (2013)
- \+ C.L. Jiang *et al.*, PRL 110, 072701, (2013)
- \- A.A. Aziz *et al.*, PRC 91, 015811, (2015)
- \+ B. Bucher *et al.*, PRL 114, 251102, (2015)
- \+ A. Tumino *et al.*, EPJ Conf. 117, 09004, (2016)

$^{12}C+^{12}C$ cross-sections , sources of uncertainties

nb to pb range

1) Backgrounds:

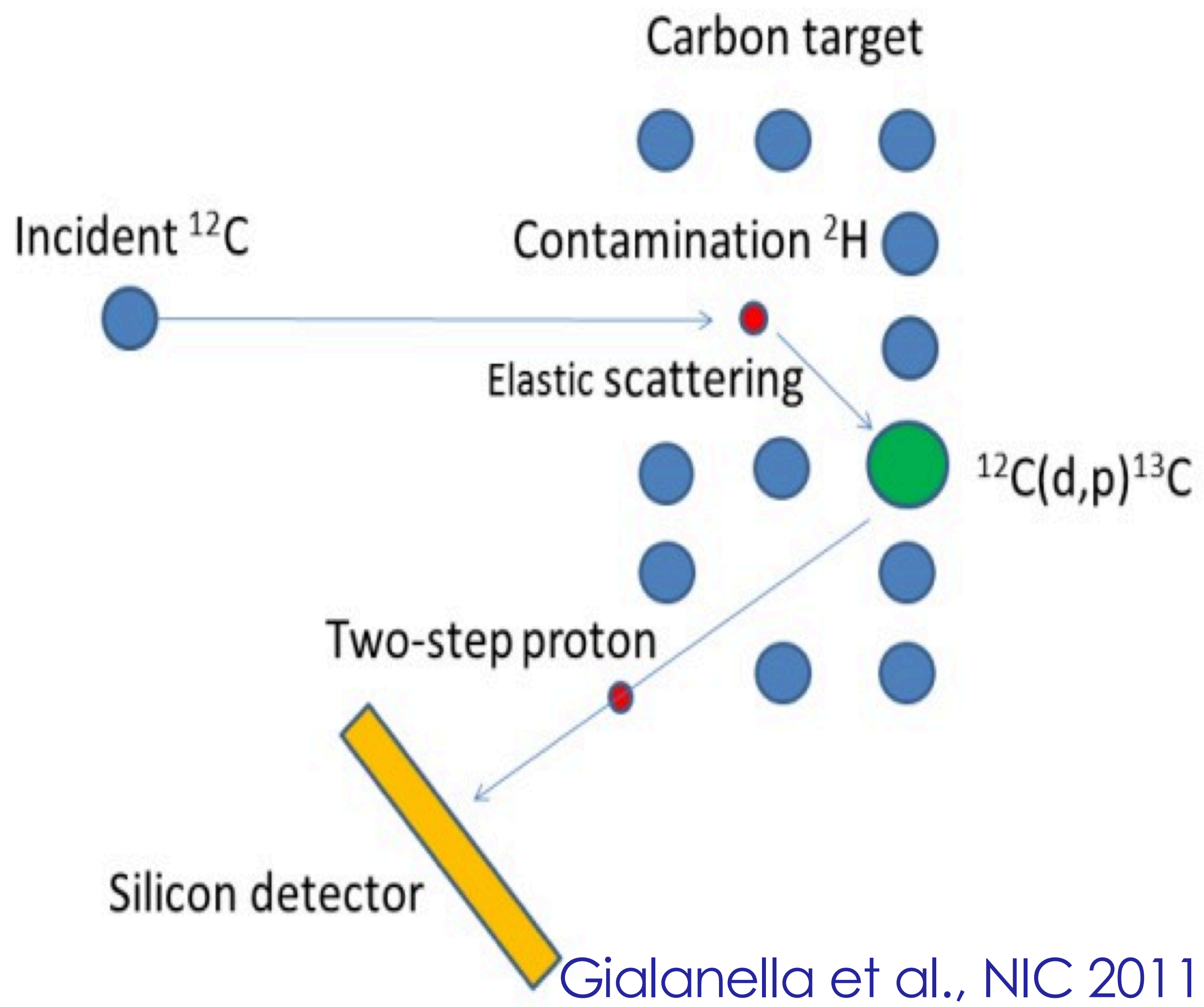
Detection of charged particles, p and α:

$^{12}C + H \longrightarrow p$ and $^{12}C + D \longrightarrow p$ or d

Detection of γ-rays:

$^{12}C + H \longrightarrow \gamma$ and $^{12}C + D \longrightarrow \gamma$;

cosmic rays and room backgrounds



Gialanella et al., NIC 2011

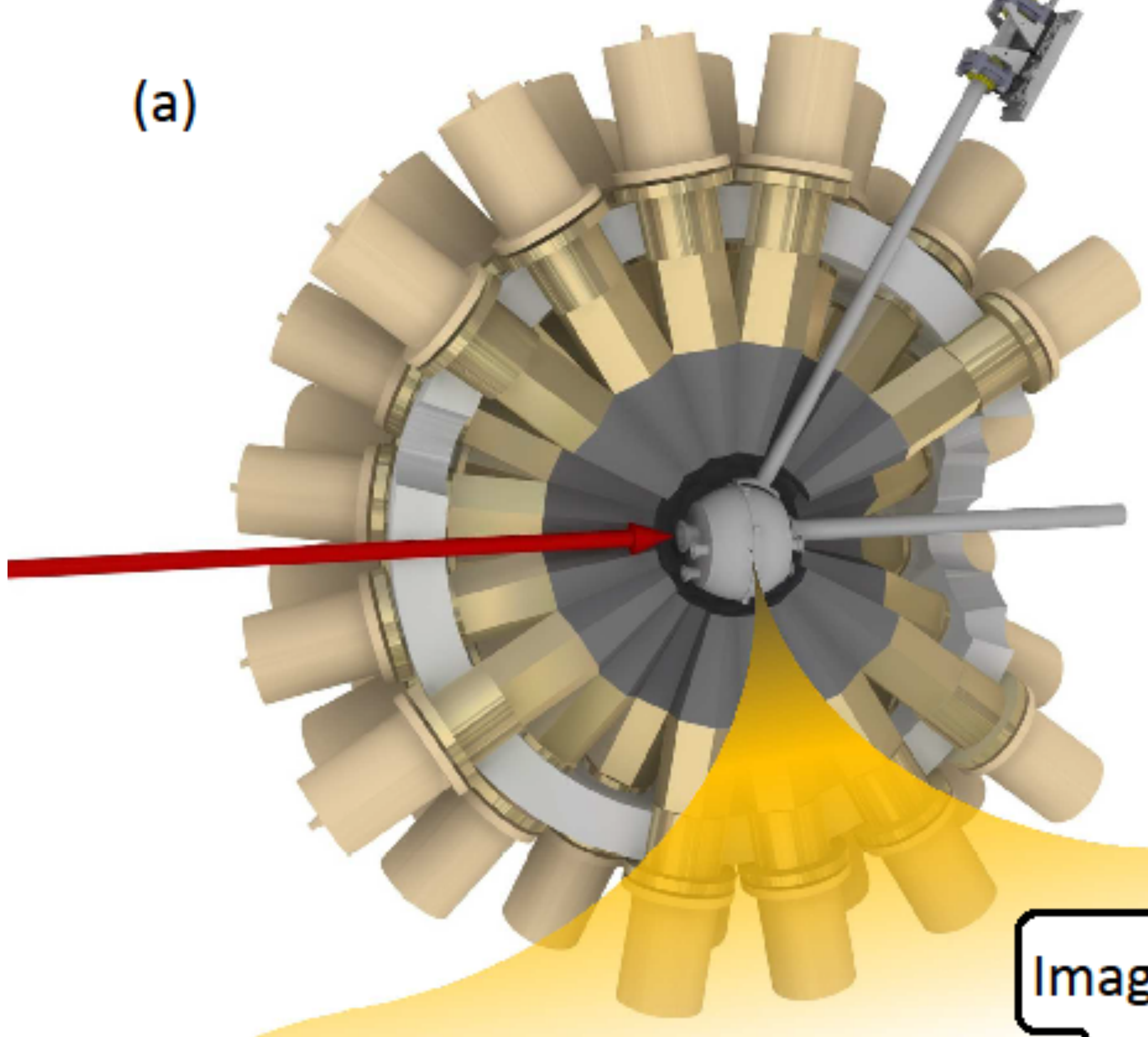
2) Thick targets measurements:

Taking the difference of two measurements at different energies.

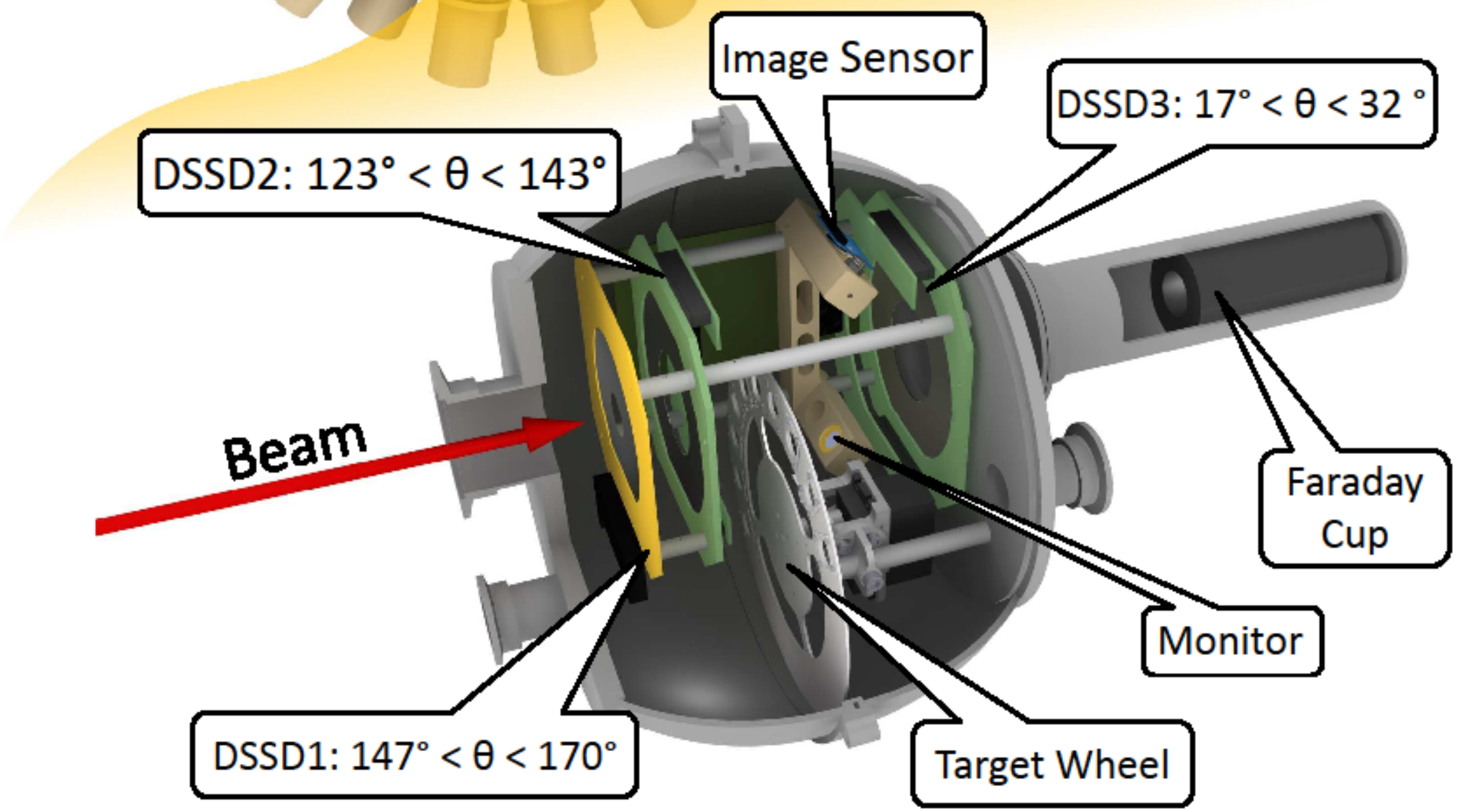
New technique

Particle-γ coincidences

(a)



Gammasphere
+
3 DSSD

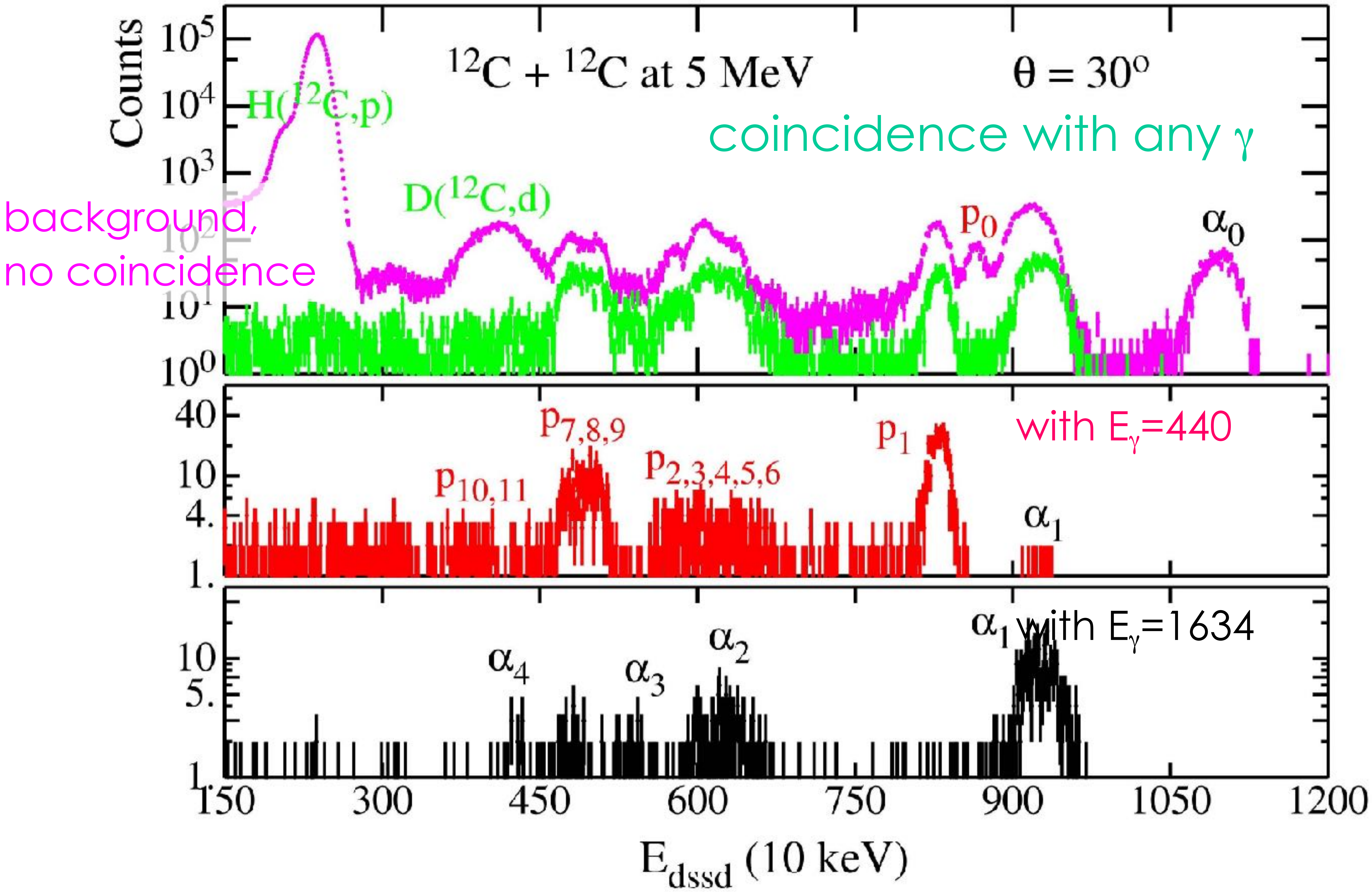


1) Reduction of the backgrounds
2) Using thin target

$I_{Max\text{-}12C}$ = 600 pnA

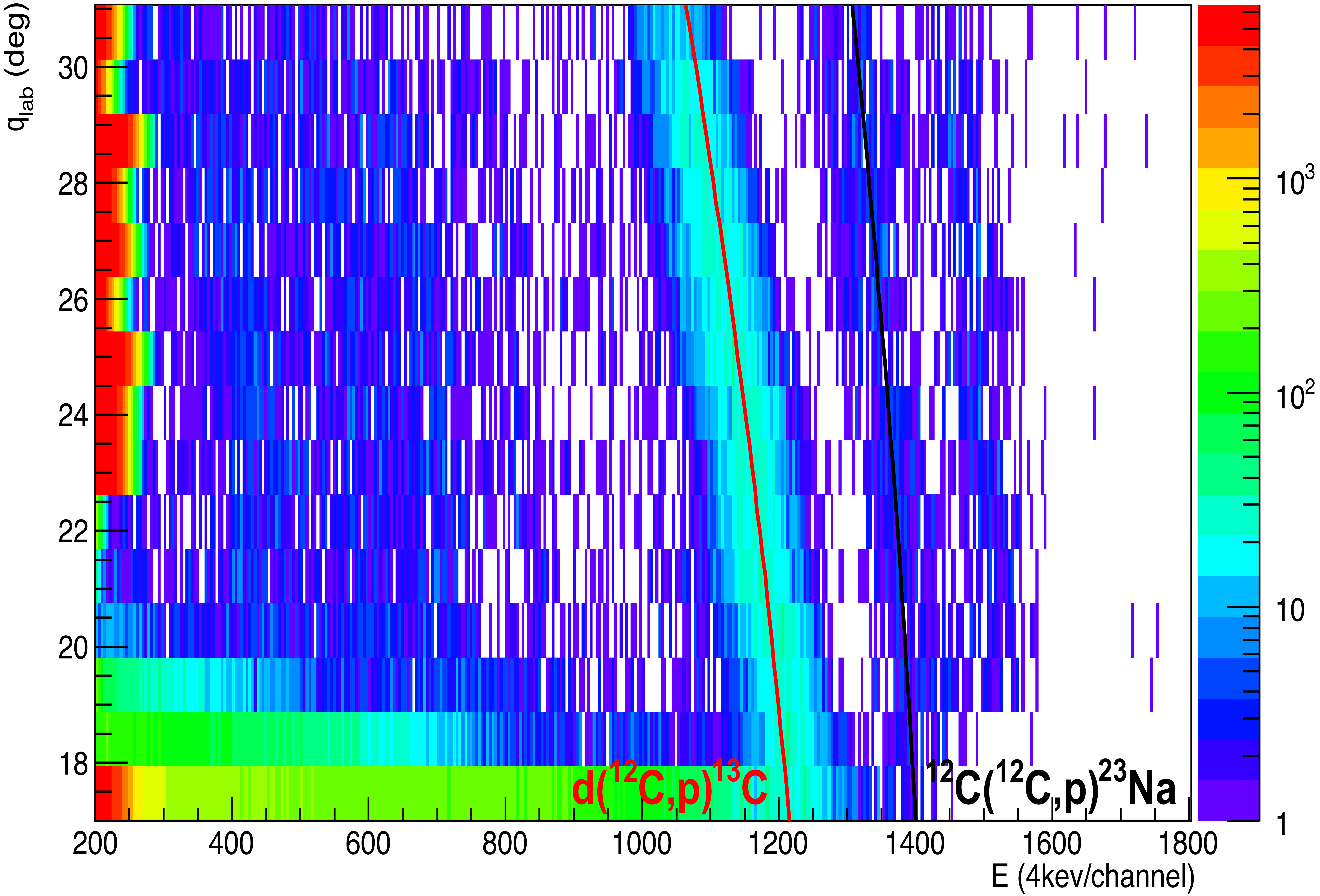
New technique

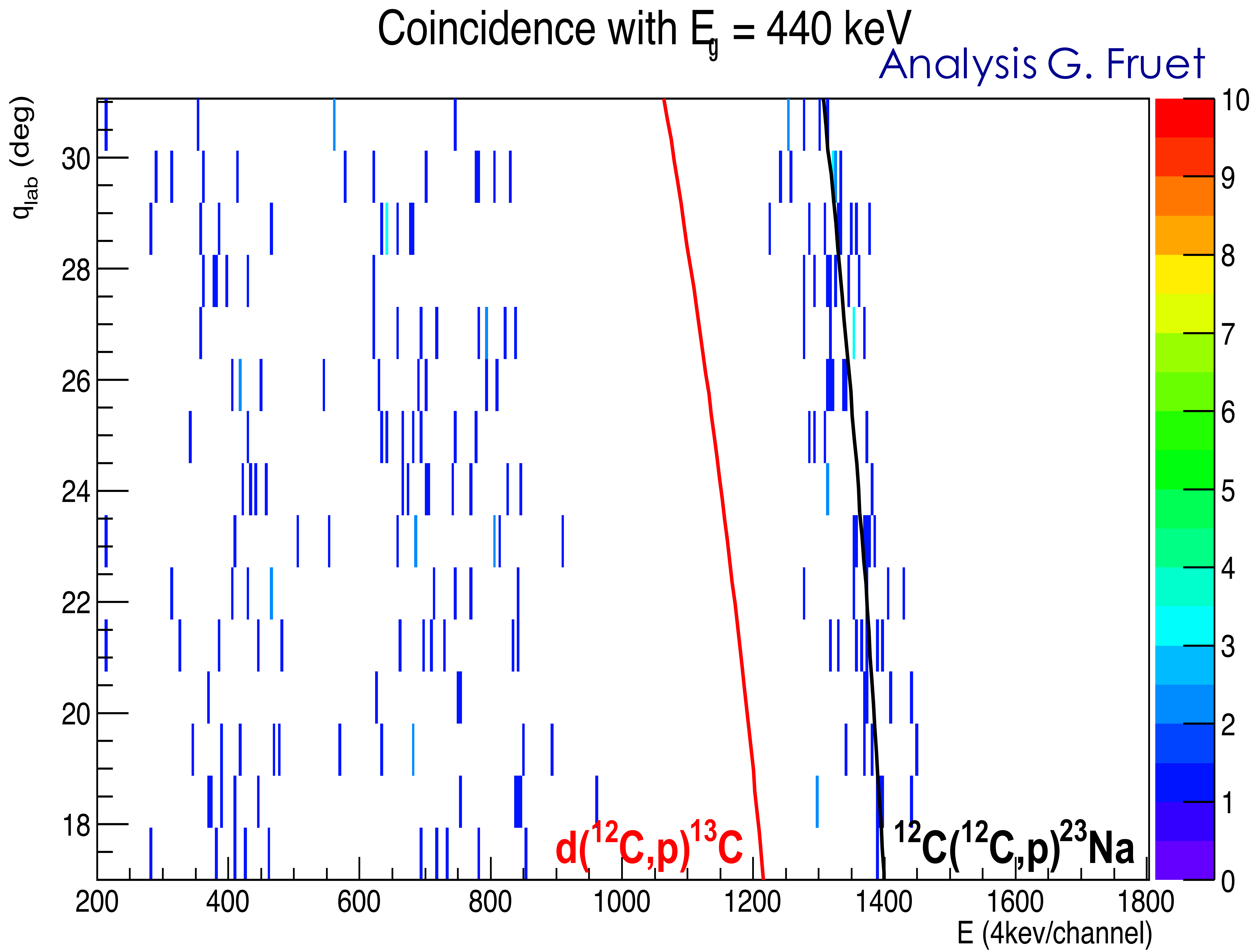
Particle spectra, E_{lab} = 10 MeV, σ ~5 mb



Particle spectrum

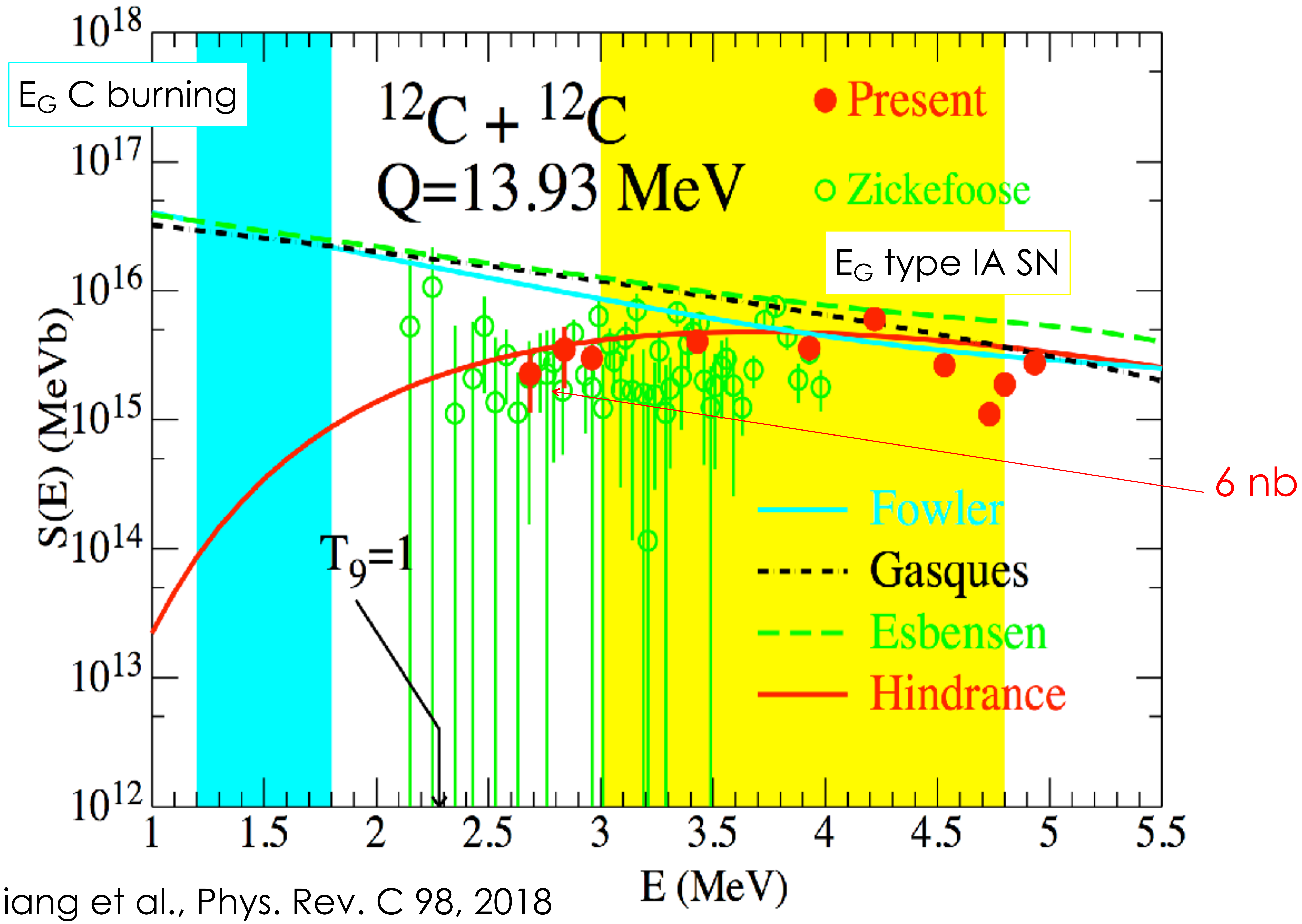
Analysis G. Fruet




Coincidence with E_g = 440 keV
Analysis G. Fruet
q_lab (deg)
30
28
26
24
22
20
18
200
400
600
800
1000
1200
1400
1600
1800
E (4kev/channel)
d(12C,p)13C
12C(12C,p)23Na
0
1
2
3
4
5
6
7
8
9
10

Results

Gammasphere runs E_{Lab} = 5.5 – 10 MeV, $I_{Max\text{-}12C}$ = 600 pnA



CL Jiang et al., Phys. Rev. C 98, 2018

New challenges

Increase beam intensity

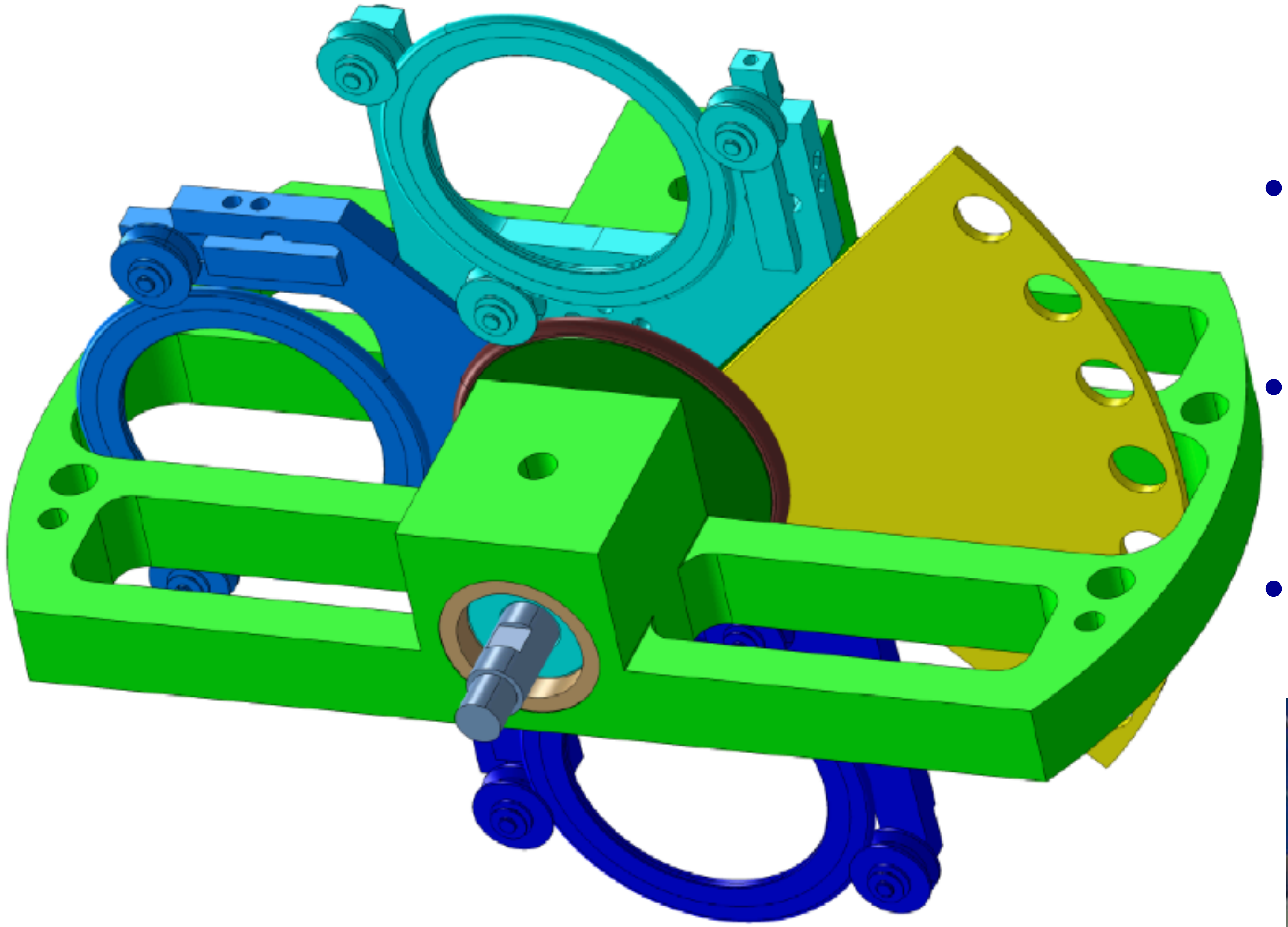
Adapt target system

Use of the γ-particle coincidence technique with better gamma efficiency

Beam

- Andromede facility, University of Paris-Sud - Orsay
- 4 MV Pelletron
- ECR Source
- ^{12}C up to 10 μA

Targets

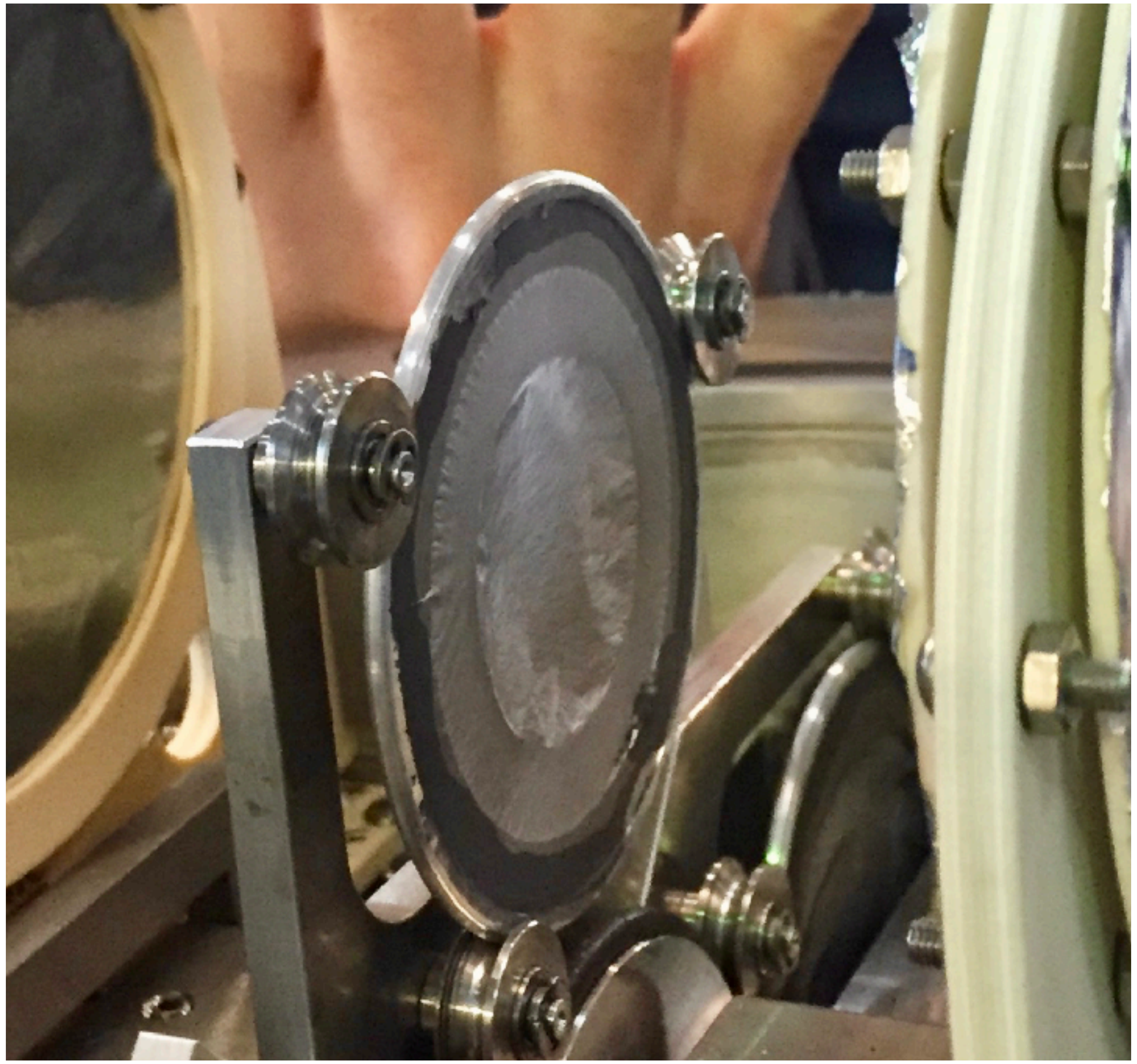


Collaboration : IPHC and GANIL

- Cryogenic pumping
- Fixed target system
- Rotating target (> 1000 rpm)
- I > 1 pμA

M. Heine et al., NIMA

Targets



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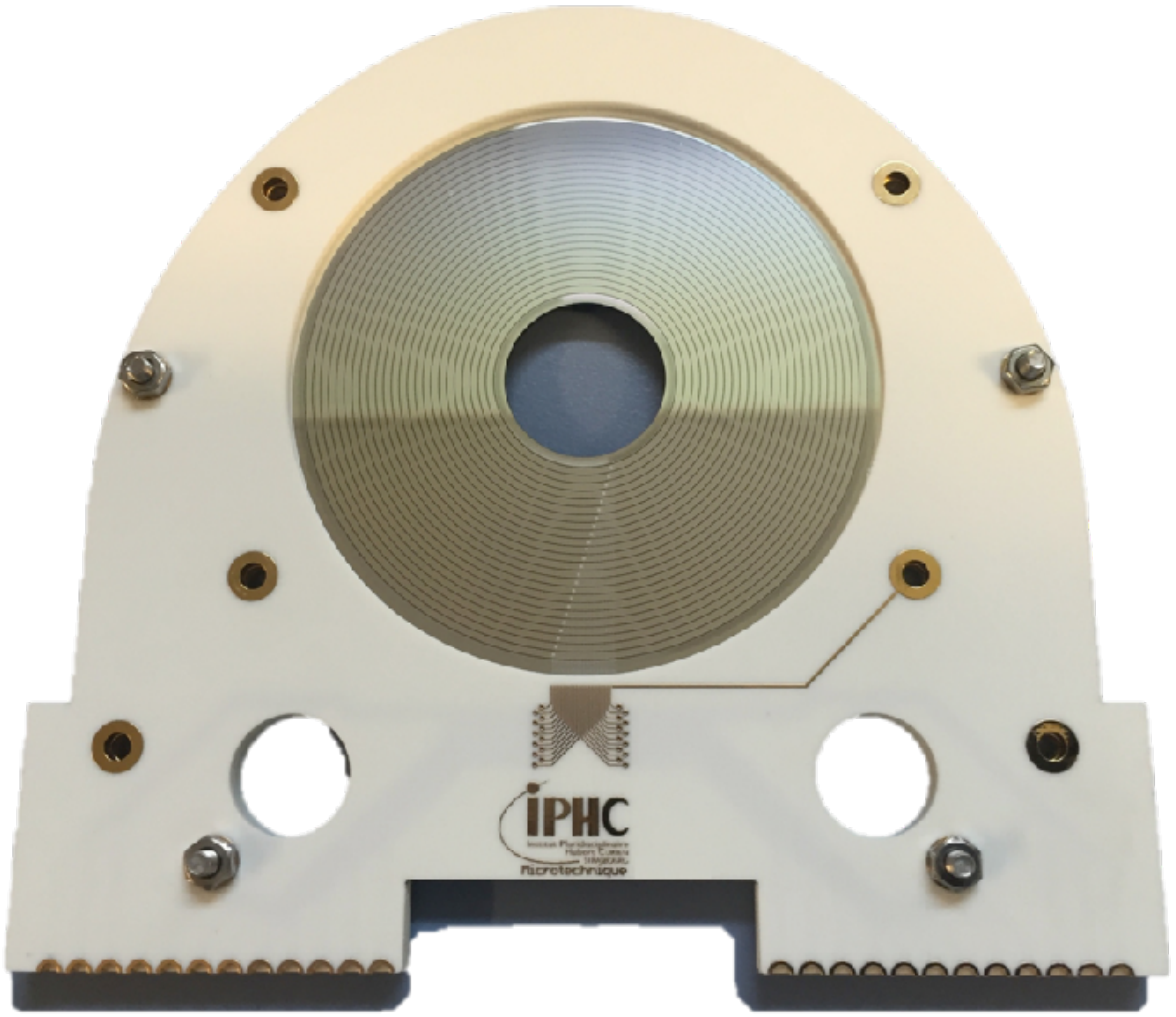
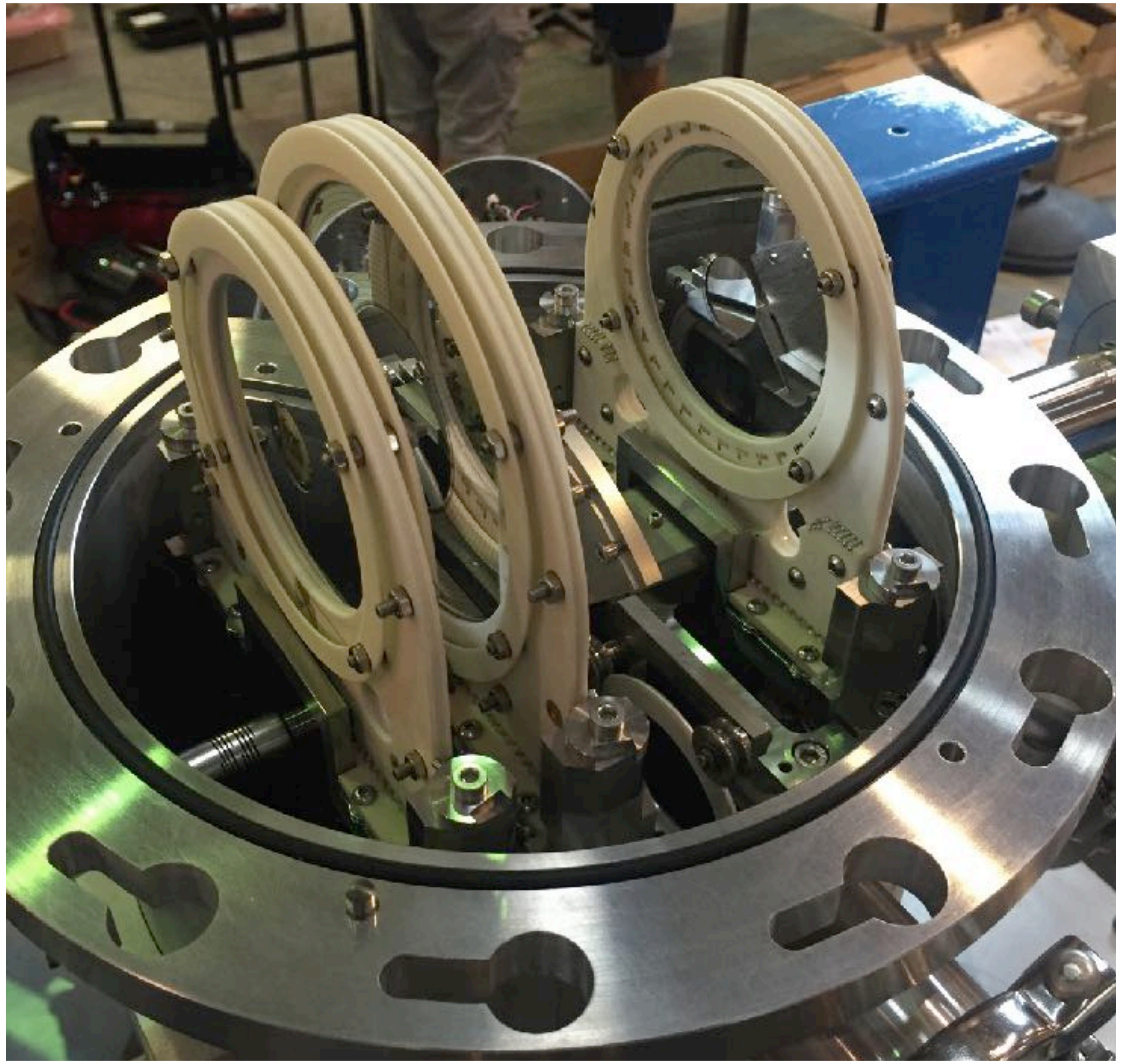
M. Heine et al., NIMA

Particle detection



- Annular DSSD, MICRON chip Collab. York
- New PCB design / ceramics
- New pin connectors
- $\Delta\Omega \sim 24\ \%$ of 4π.

Particle detection



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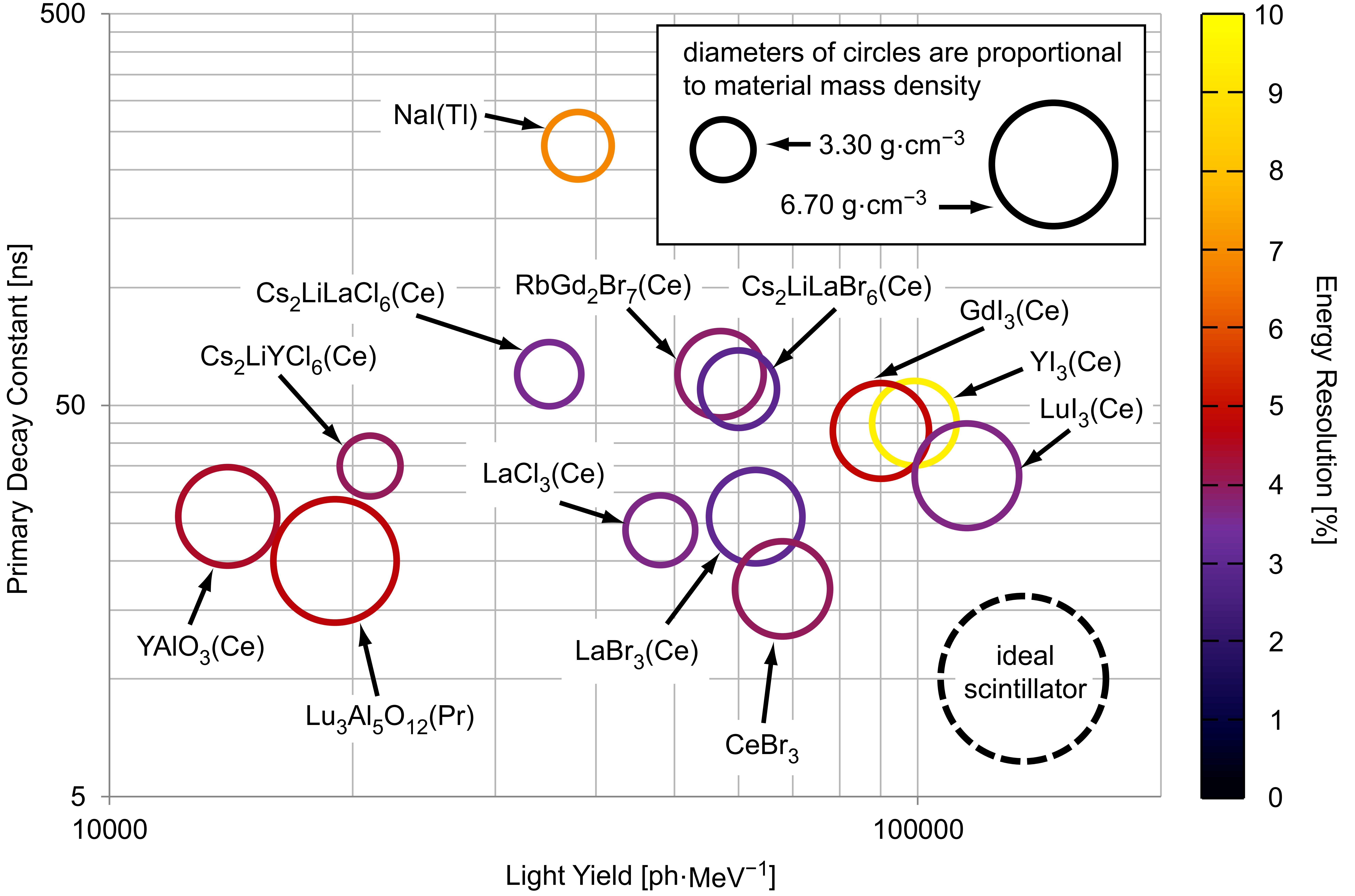
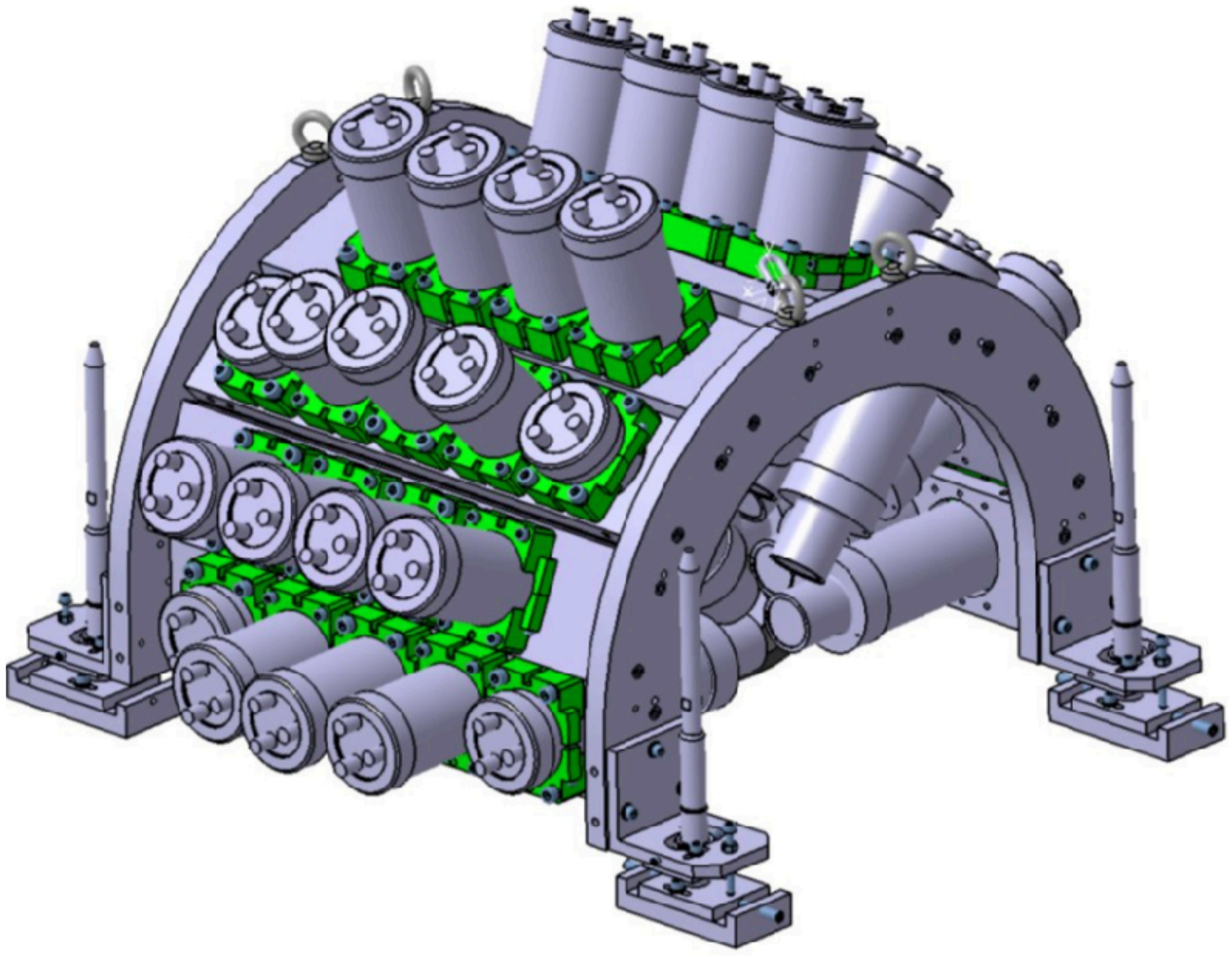


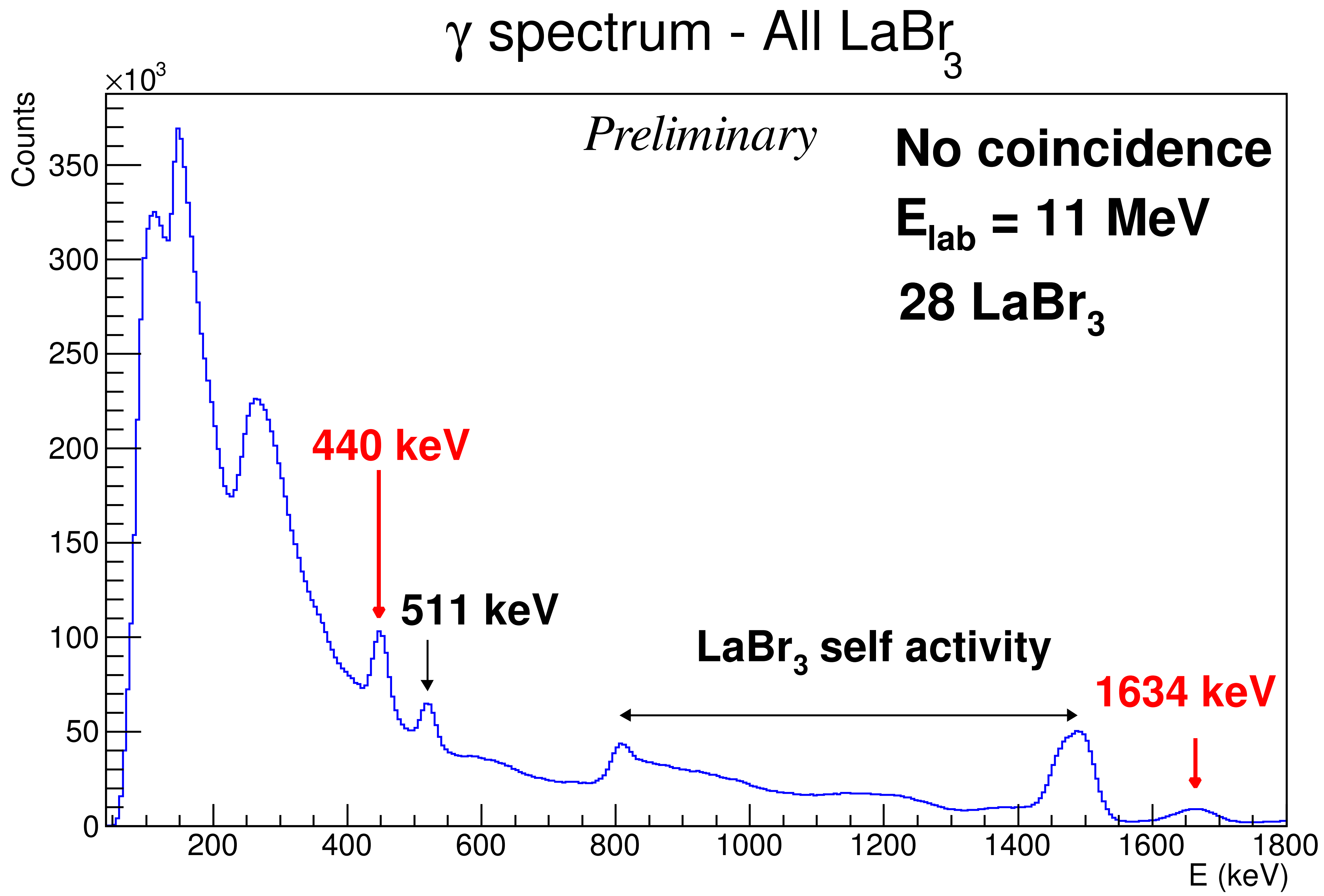
diameters of circles are proportional to material mass density
3.30 g·cm−3
6.70 g·cm−3
NaI(Tl)
Cs2LiLaCl6(Ce)
RbGd2Br7(Ce)
Cs2LiLaBr6(Ce)
GdI3(Ce)
YI3(Ce)
LuI3(Ce)
Cs2LiYCl6(Ce)
LaCl3(Ce)
YAlO3(Ce)
Lu3Al5O12(Pr)
LaBr3(Ce)
CeBr3
ideal scintillator
Primary Decay Constant [ns]
500
50
5
10000
100000
Light Yield [ph·MeV−1]
Energy Resolution [%]
0
1
2
3
4
5
6
7
8
9
10

Gamma detection

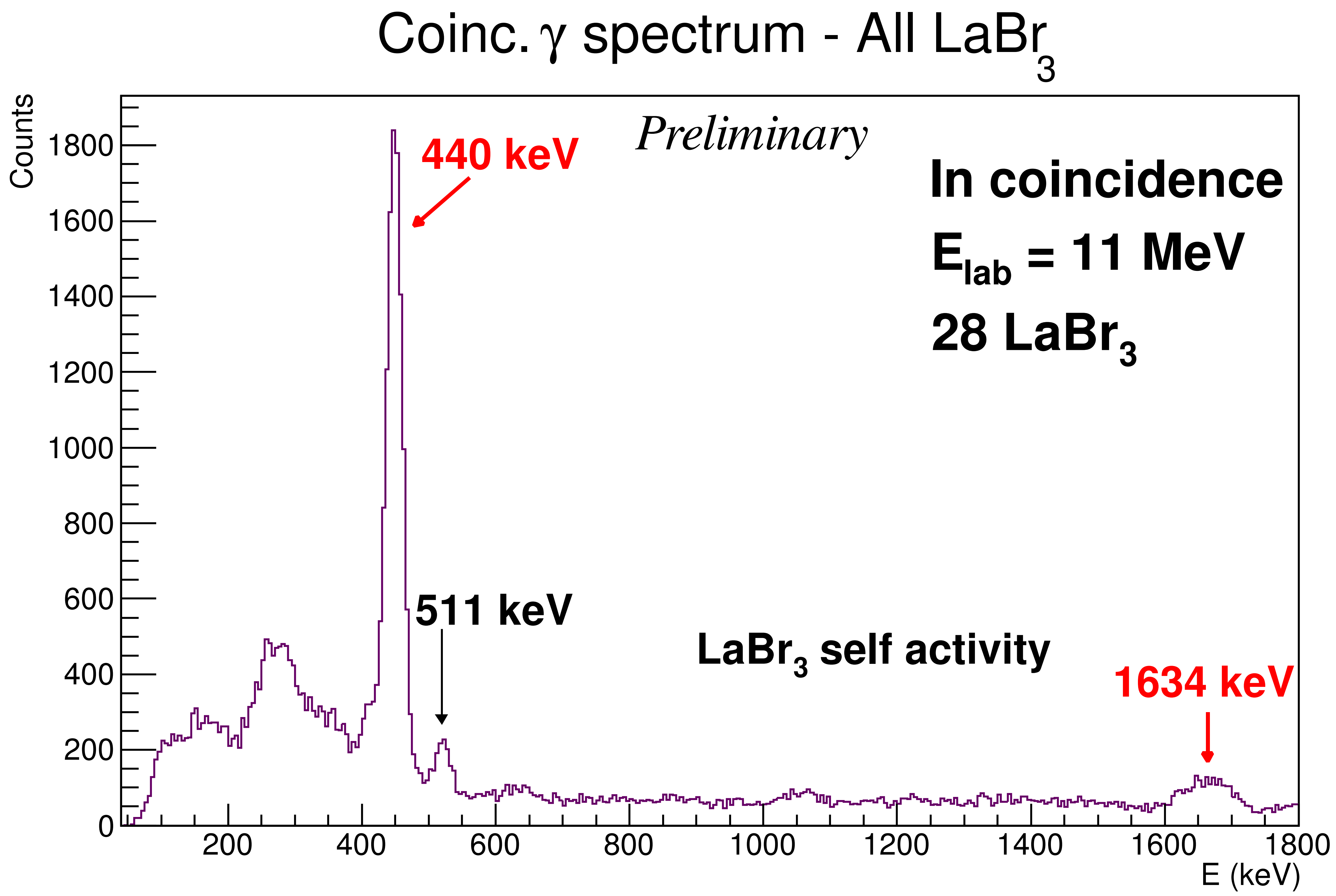


Design IPHC : G. Heitz / M. Heine

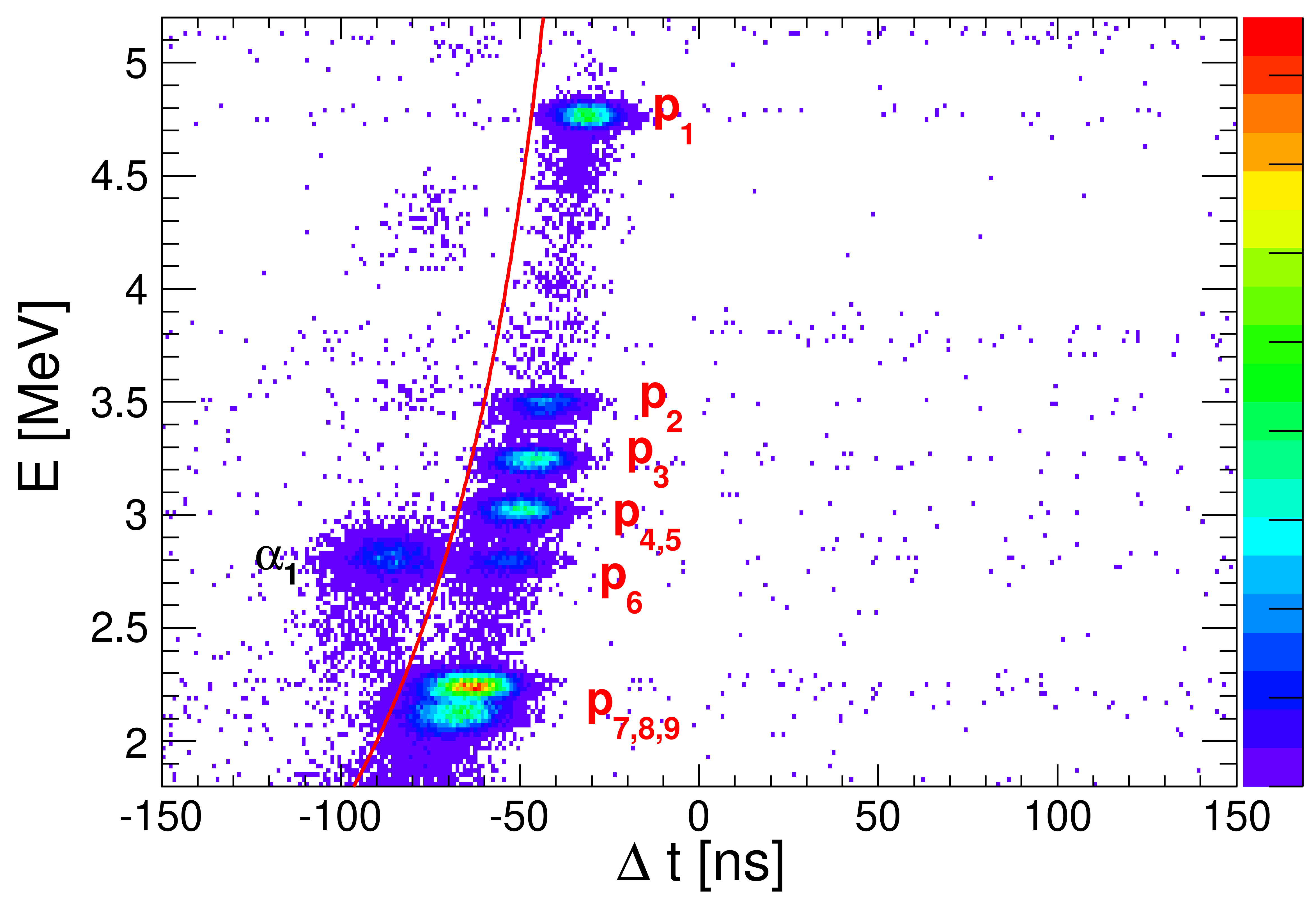
- Up to 36 $LaBr_3$ detectors from the FATIMA collaboration (P. Regan et al.)
- Cylindrical geometry IPHC designed mechanical support, Strabourg + York construction
- Self activity
- ε = 8% @ 440 keV
- ε = 5% @ 1634 keV



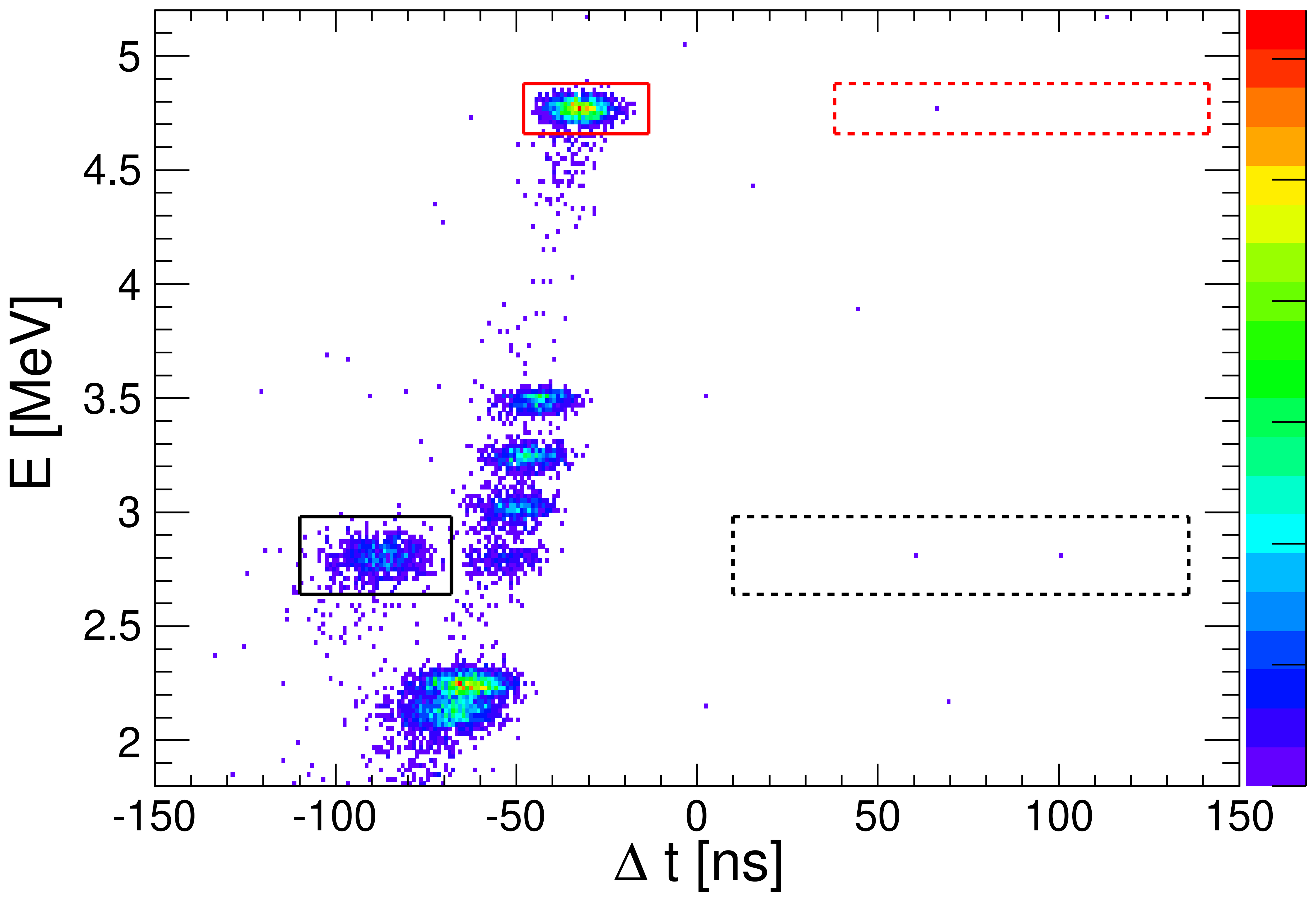
Self activity & γ of interest from $^{12}C+^{12}C$ fusion



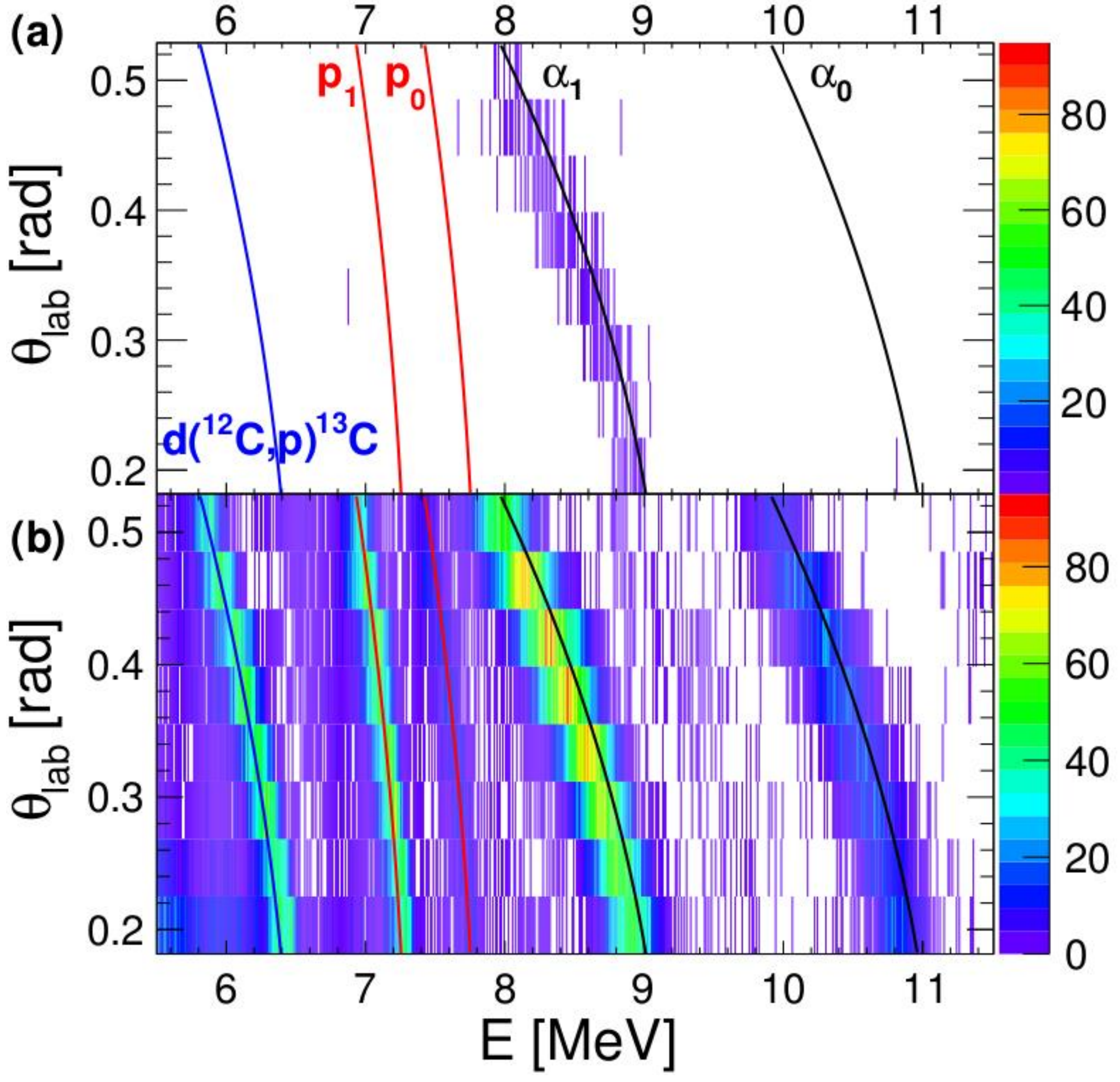
Coincidence with 1 particle : γ from fusion



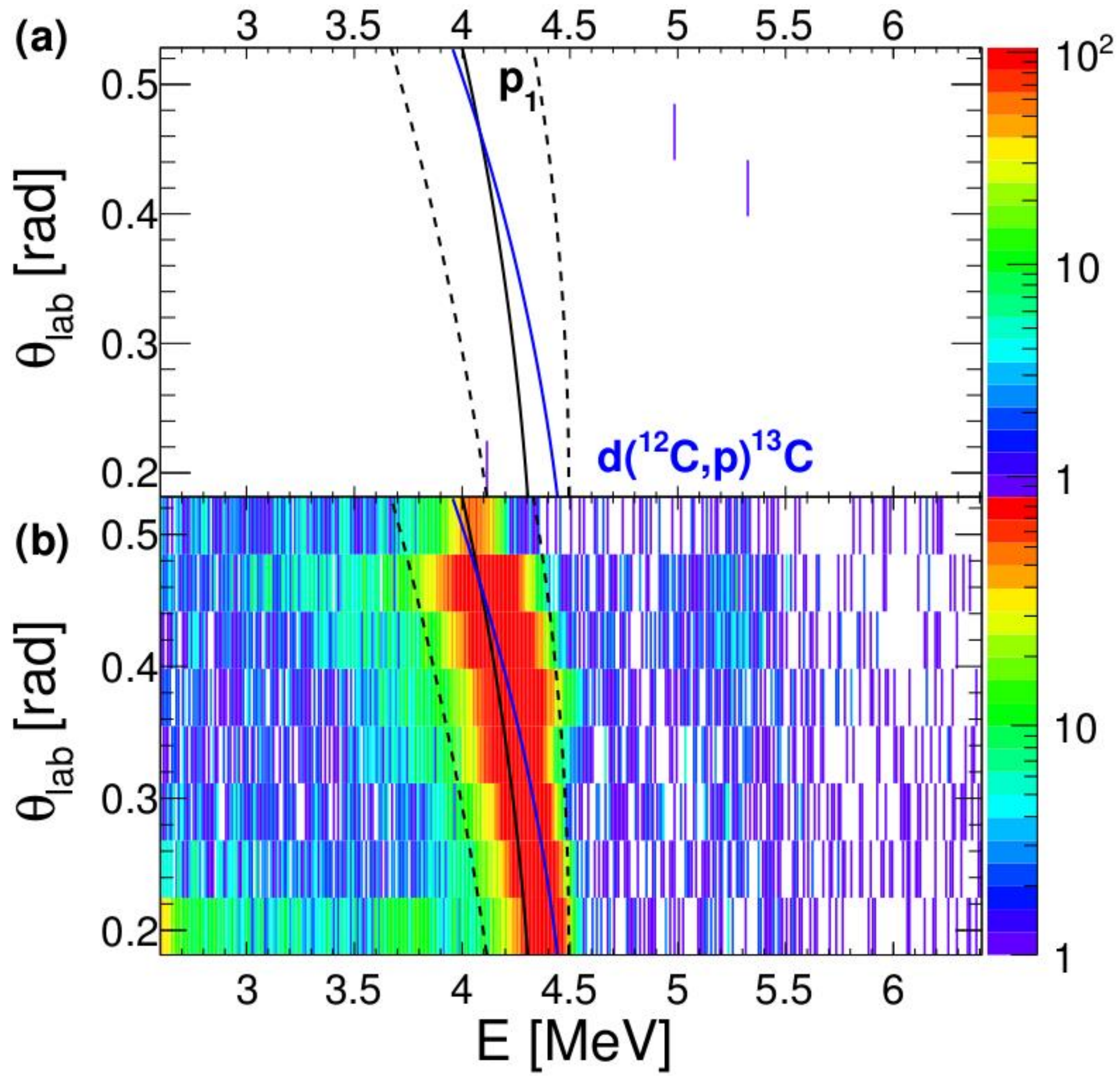
Without coincident gamma ray



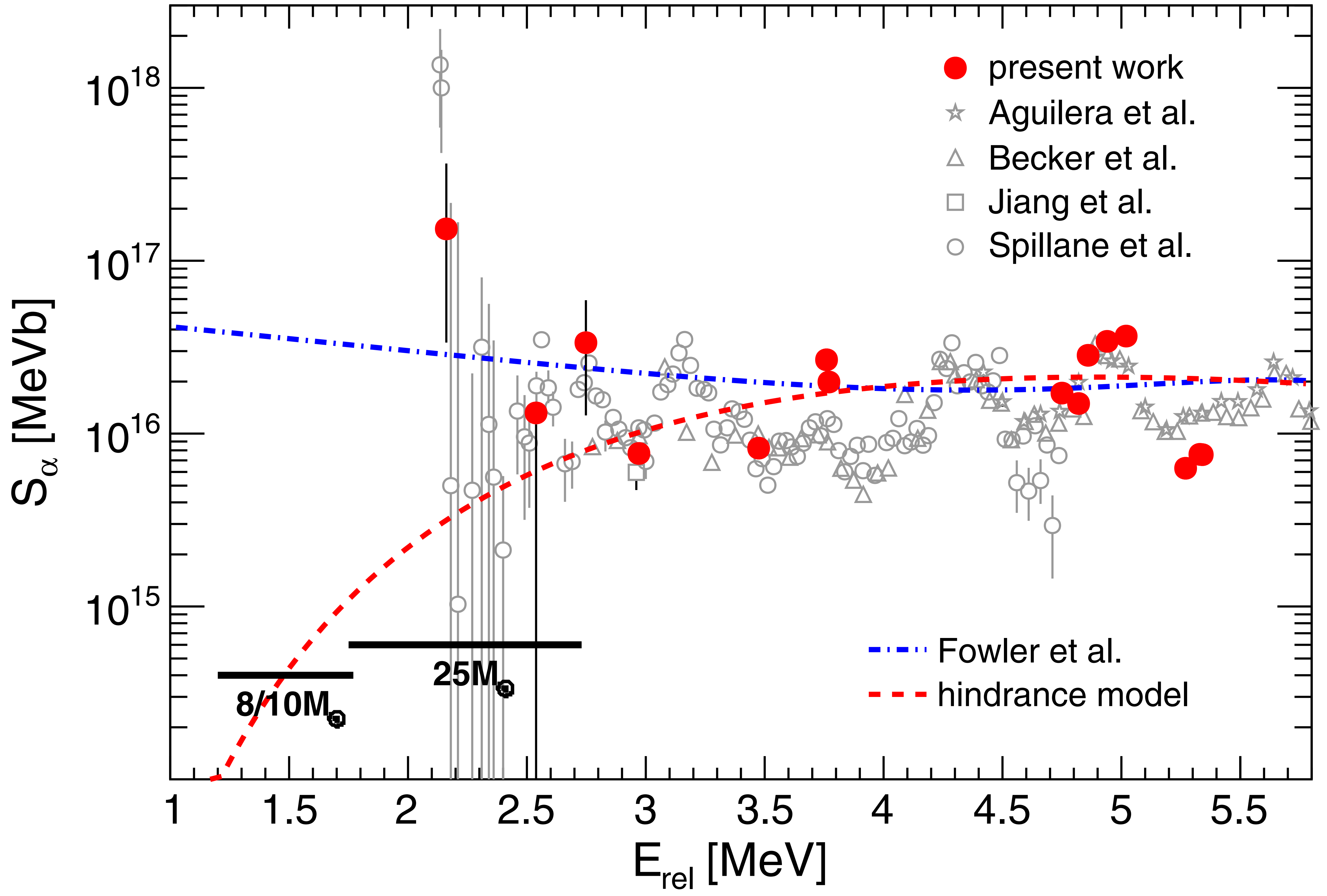
With coincident gamma ray

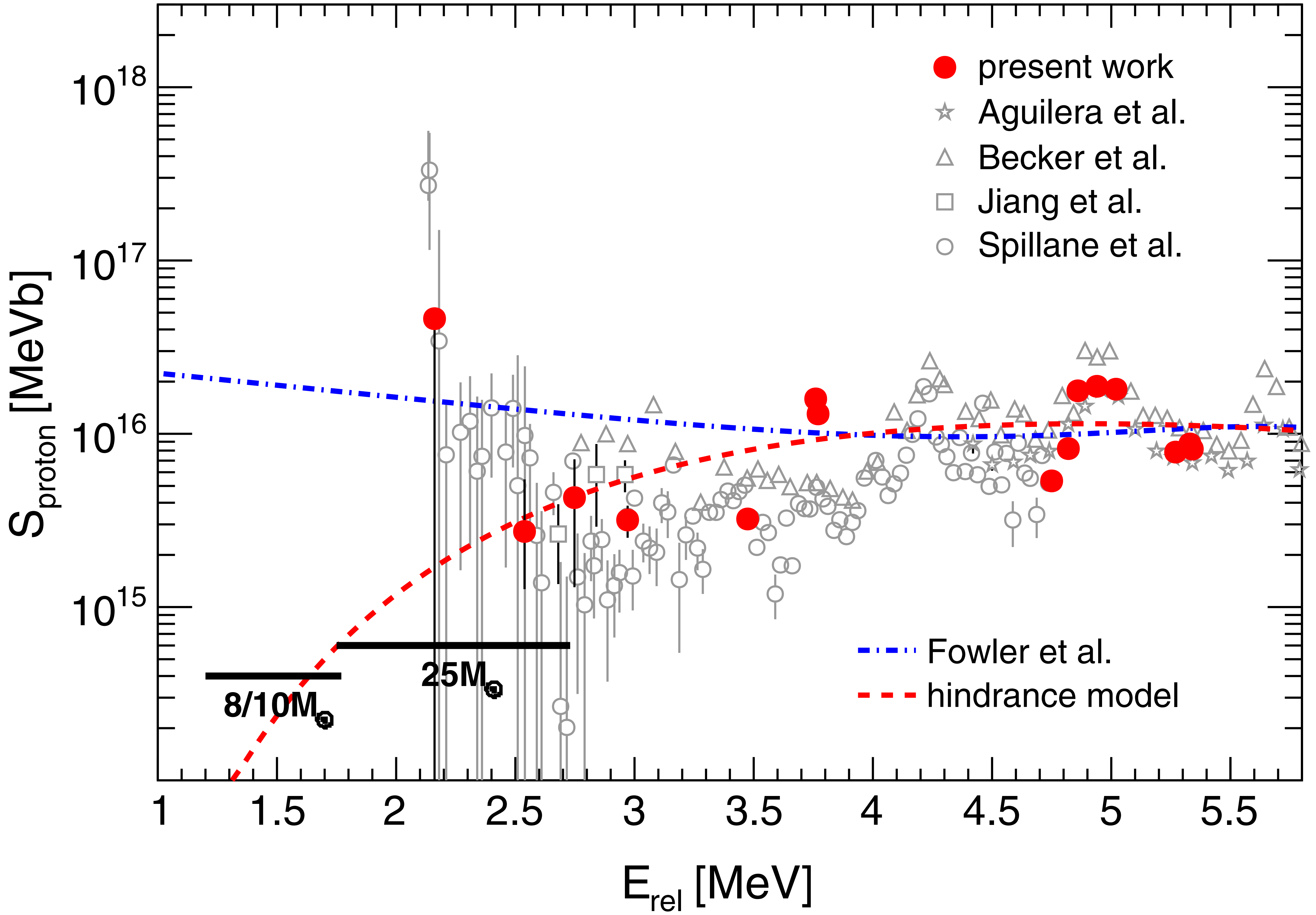


E_{rel} = 3.77 MeV



E_{rel} = 2.16 MeV





G. Fruet et al., Phys. Rev. Lett. 124, 192701 (2020)

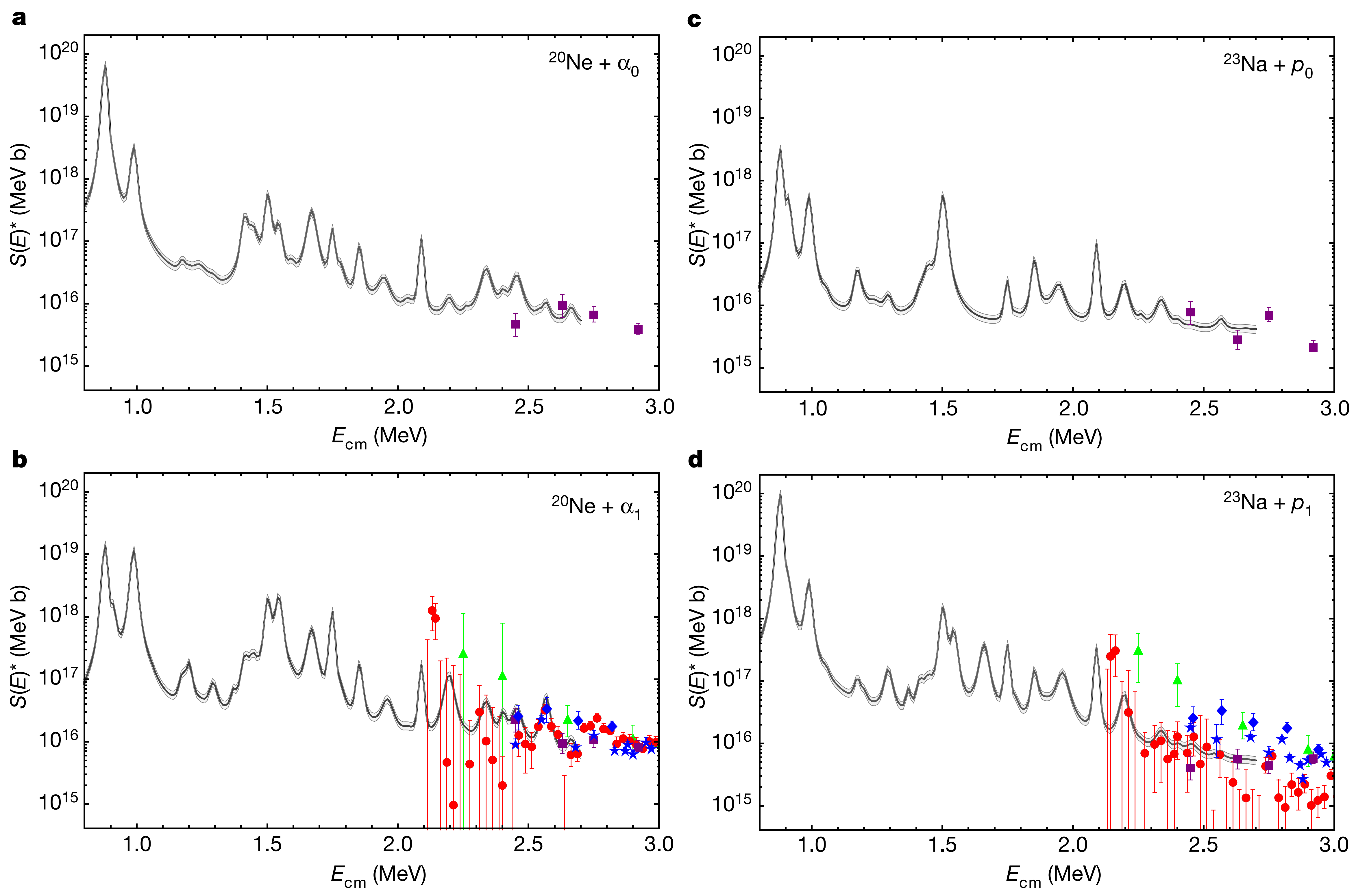
Indirect i.e. nuclear structure insights
are necessary to get further ….

LETTER

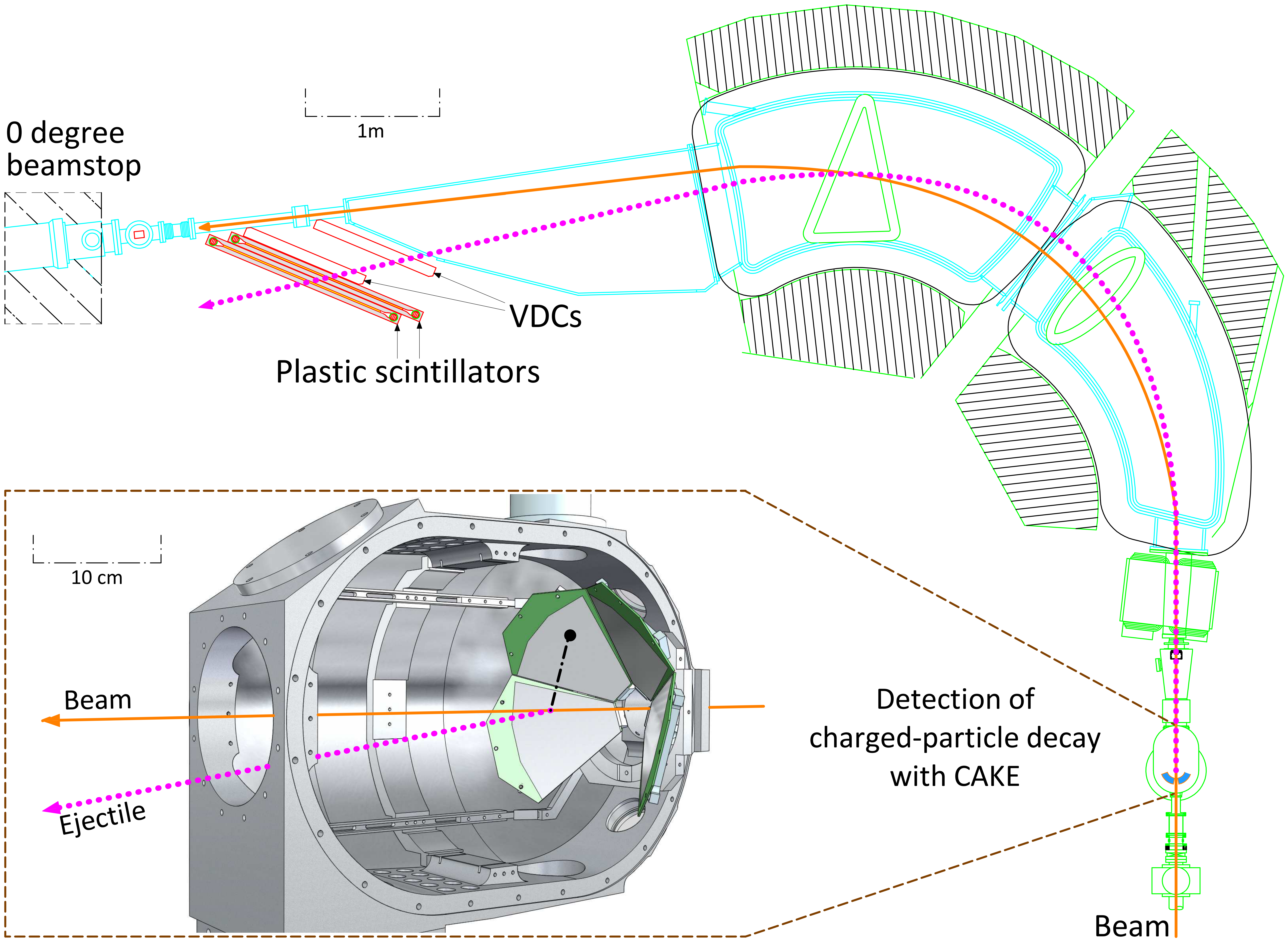
https://doi.org/10.1038/s41586-018-0149-4

An increase in the $^{12}C + ^{12}C$ fusion rate from resonances at astrophysical energies

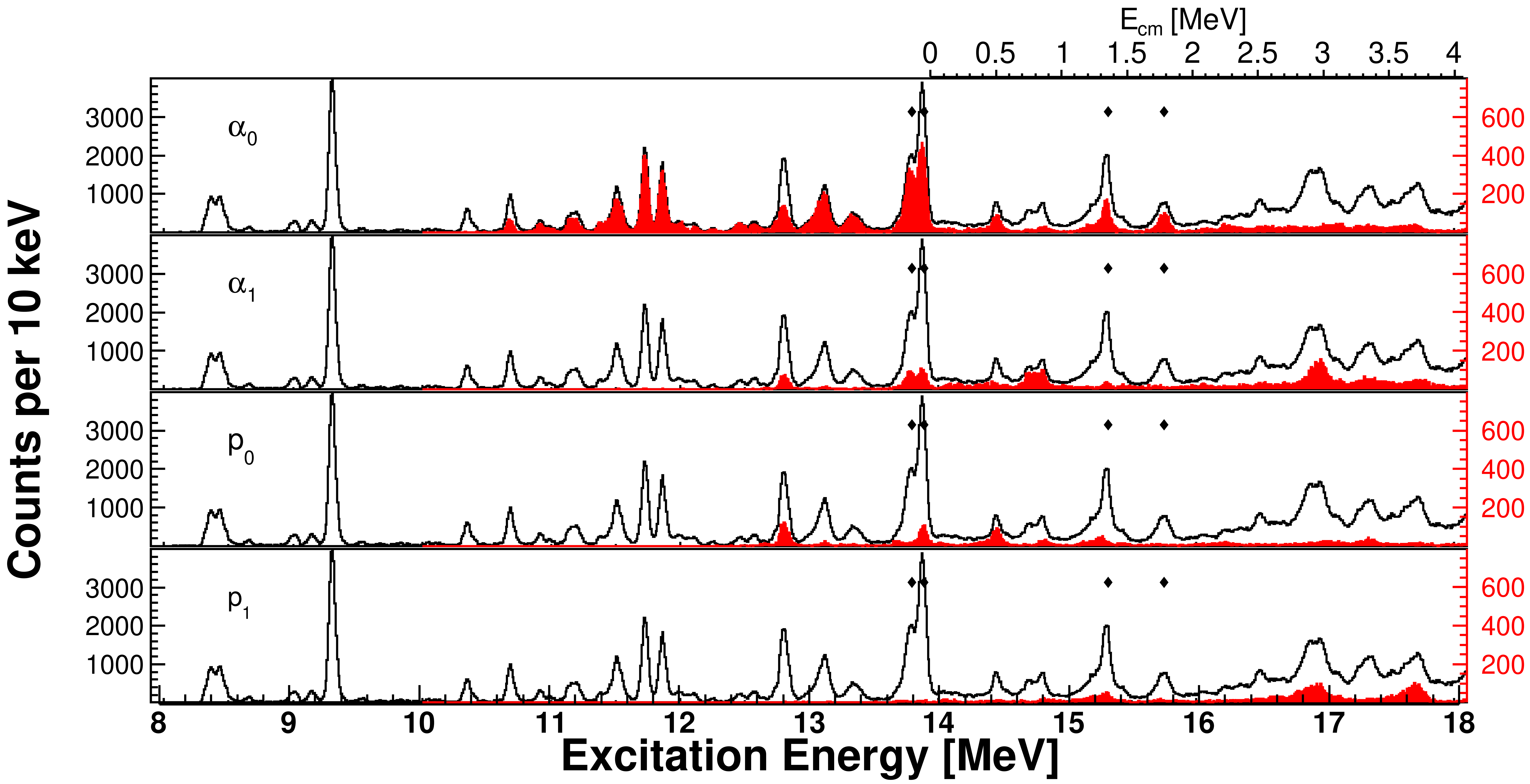
A. Tumino[1,2]*, C. Spitaleri[2,3], M. La Cognata[2], S. Cherubini[2,3], G. L. Guardo[2,4], M. Gulino[1,2], S. Hayakawa[2,5], I. Indelicato[2], L. Lamia[2,3], H. Petrascu[4], R. G. Pizzone[2], S. M. R. Puglia[2], G. G. Rapisarda[2], S. Romano[2,3], M. L. Sergi[2], R. Spartá[2] & L. Trache[4]



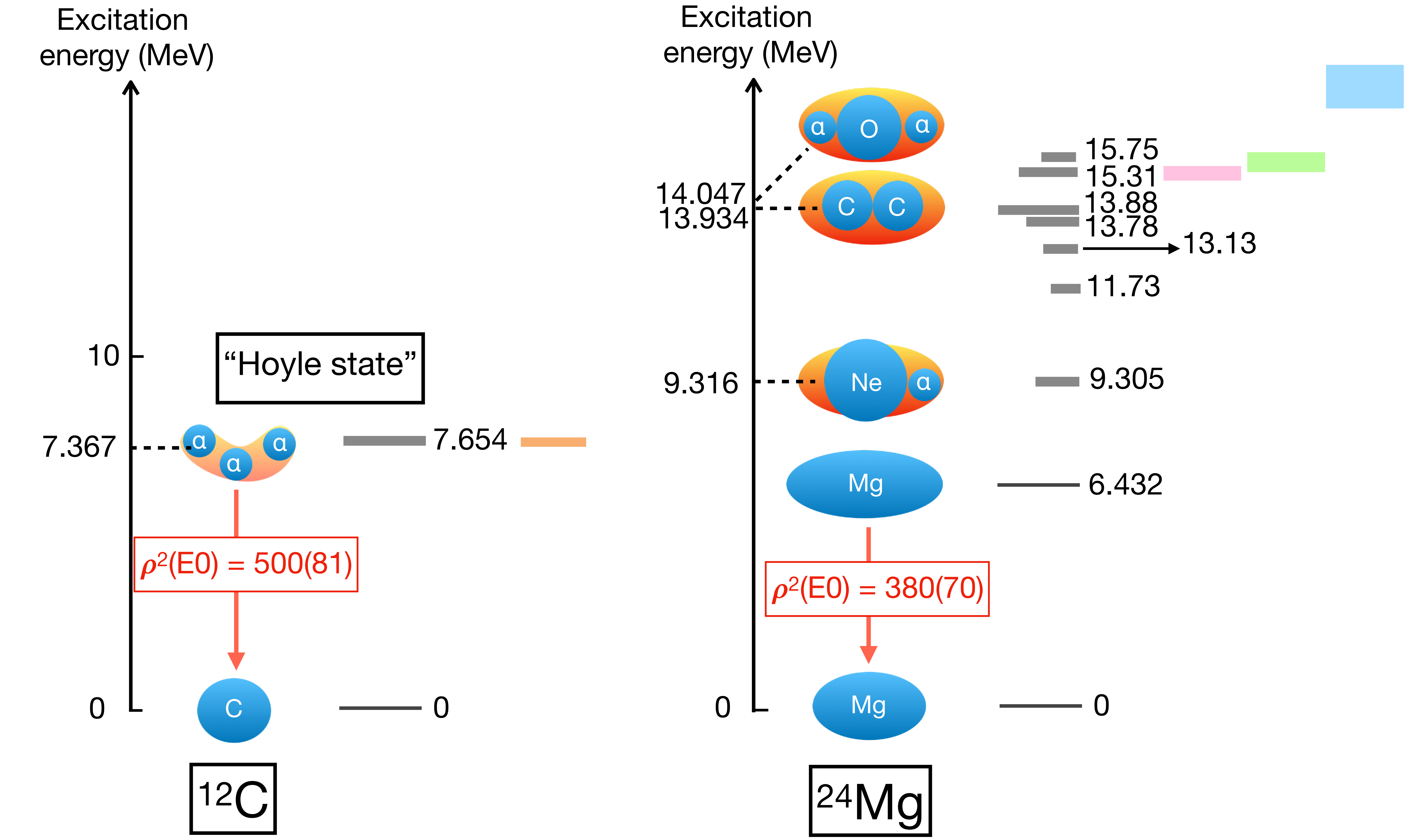
Tumino, A. et al., An increase in the $^{12}C+^{12}C$ fusion rate from resonances at astrophysical energies. Nature 557, 687 (2018).



P. Adsley, D.G. Jenkins et al., Phys. Rev. Lett. 129, 102701 (2022)

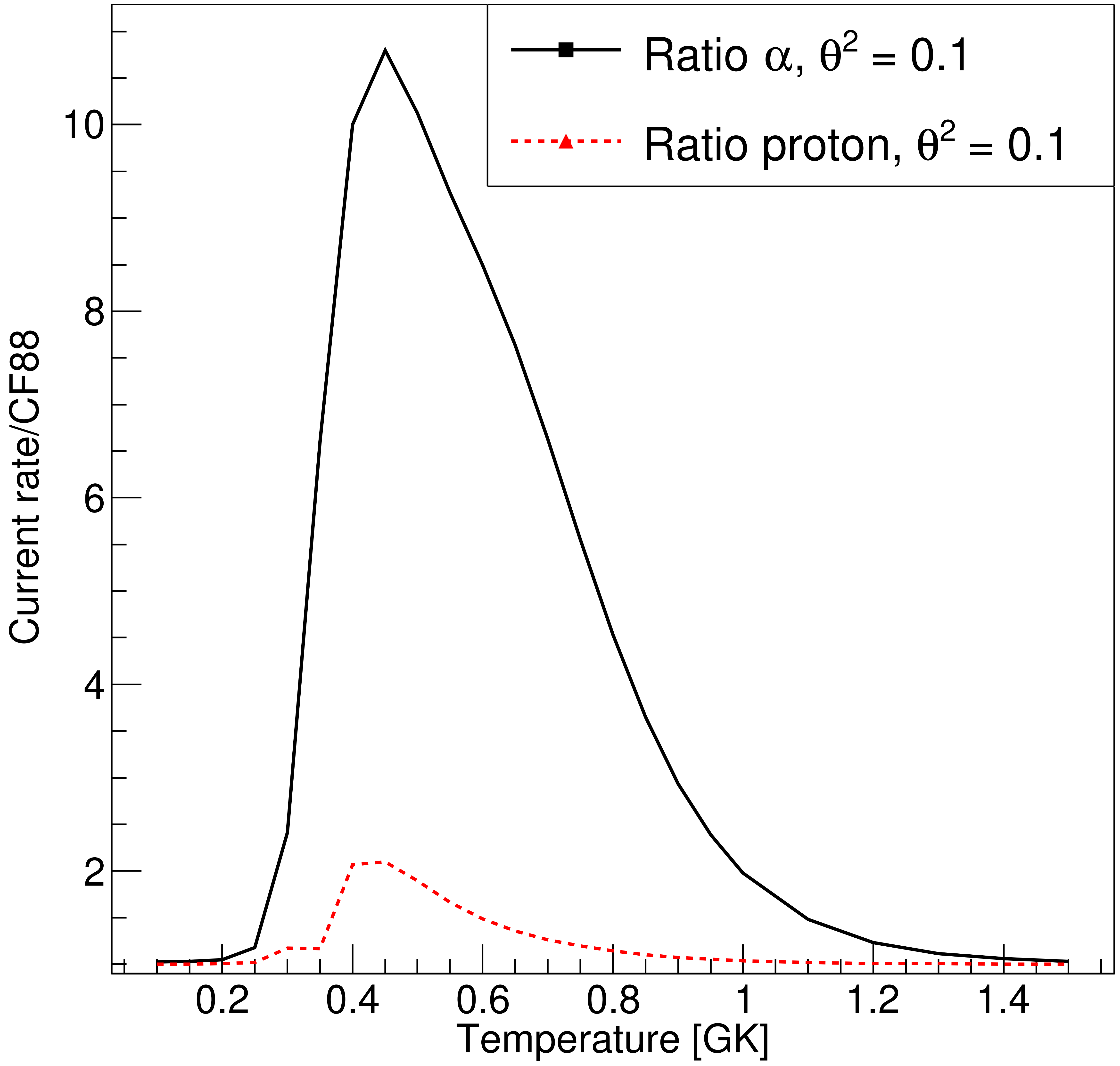


P. Adsley, D.G. Jenkins et al., Phys. Rev. Lett. 129, 102701 (2022)



Excitation energy (MeV)
10
7.367
0
“Hoyle state”
α
α
α
7.654
C
0
ρ^2(E0) = 500(81)
^{12}C
Excitation energy (MeV)
α
O
α
C
C
14.047
13.934
15.75
15.31
13.88
13.78
13.13
11.73
9.316
Ne
α
9.305
Mg
6.432
ρ^2(E0) = 380(70)
Mg
0
0
^{24}Mg

Implications for $^{12}C + ^{12}C$ burning



Note the favouritism for $^{20}Ne + \alpha$ vs. $^{23}Na + p$

P. Adsley,[1,2,*] M. Heine,[3,4] D. G. Jenkins,[5,6,7] S. Courtin,[3,4,6] R. Neveling,[2] J. W. Brümmer,[8]
L. M. Donaldson,[2] N. Y. Kheswa,[2] K. C. W. Li,[8] D. J. Marín-Lámbarri,[2,7,9] P. Z. Mabika,[7]
P. Papka,[2,8] L. Pellegri,[1,2] V. Pesudo,[2,7,10] B. Rebeiro,[7] F. D. Smit,[2] and W. Yahia-Cherif[11]

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Further details in P. Adsley, M. Heine, D.G. Jenkins et al., Phys. Rev. Lett. 129, 102701 (2022)

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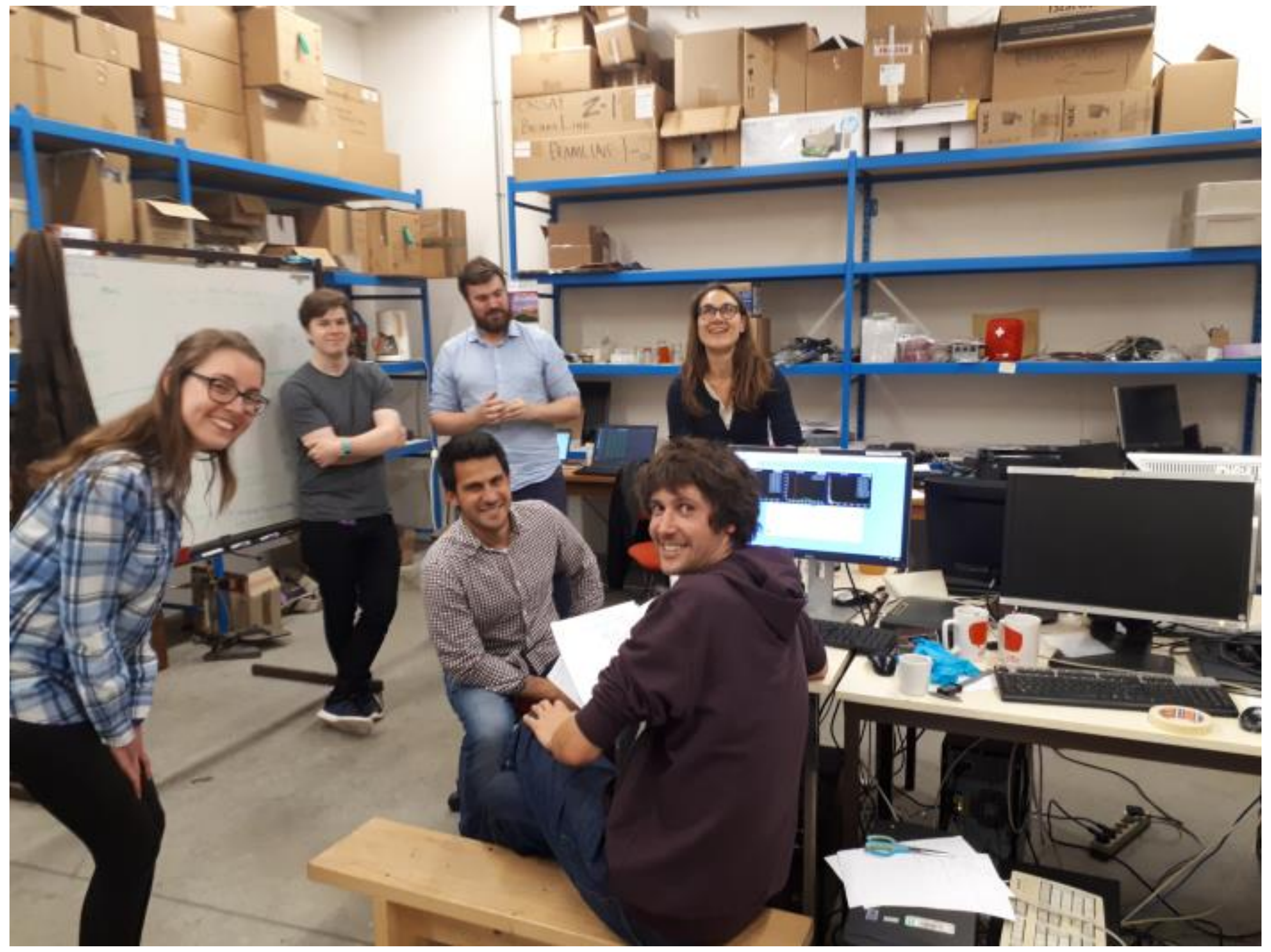
Argonne National Laboratory (USA):
C.L.Jiang, D.Santiago-Gonzalez, K.E.Rehm, B.B.Back et al.



University of Surrey (UK):
P.H. Regan, M. Rudigier

GANIL (Caen, France):
C. Stodel et al.

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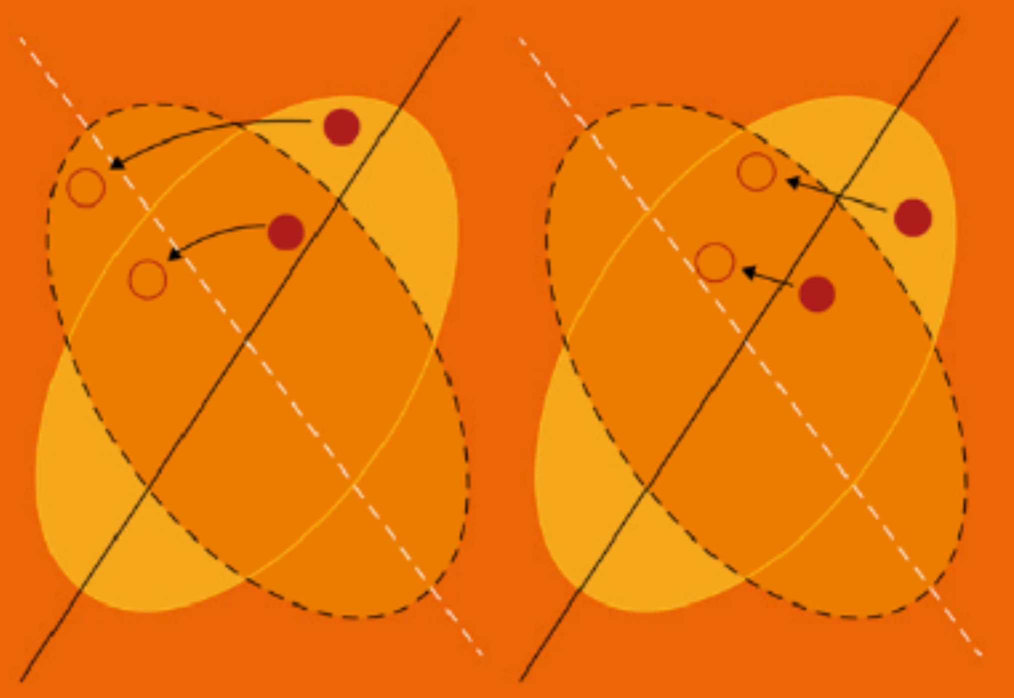
O. Kirsebom

IOP Series in Nuclear Spectroscopy and Nuclear Structure

Nuclear Data

A primer

David G Jenkins
John L Wood



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Nuclear Data

A collective motion view

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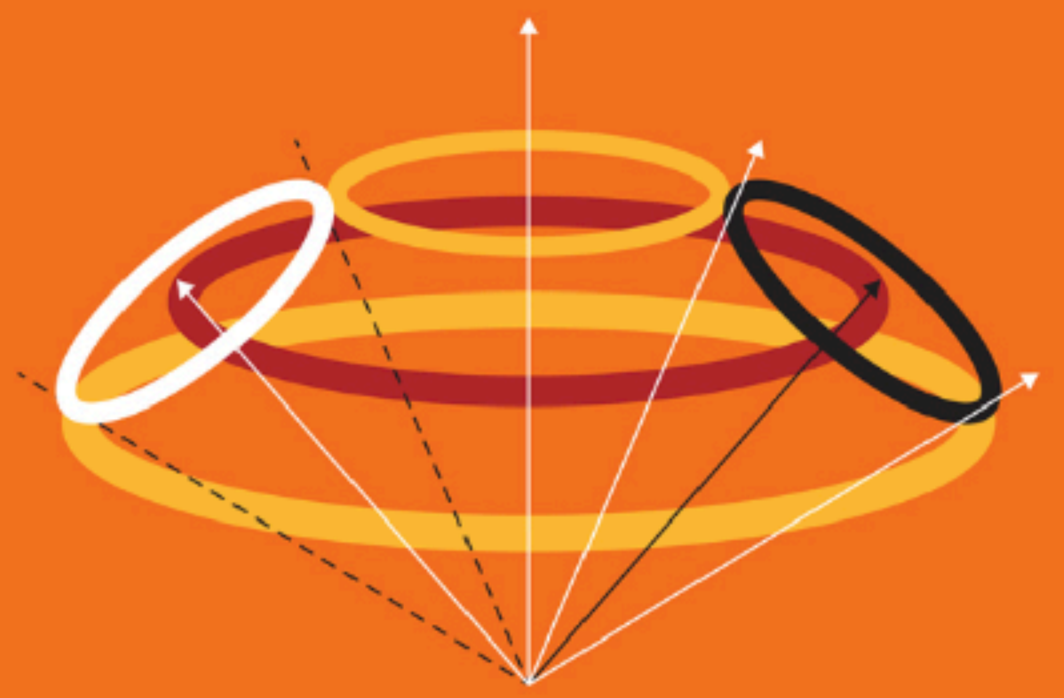

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Nuclear Data

An independent-particle motion view

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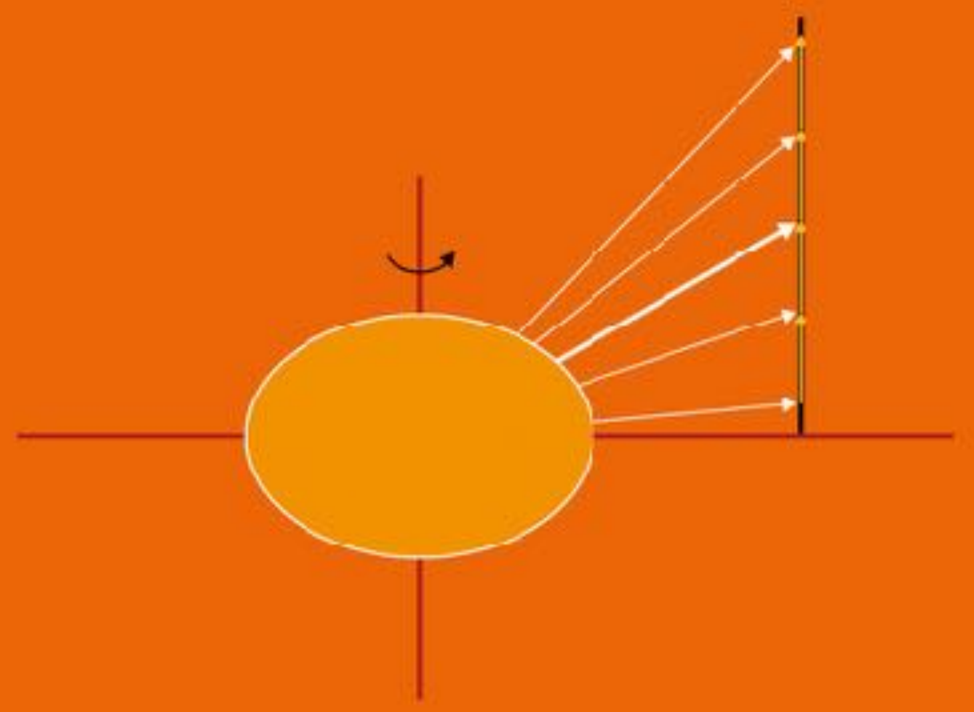

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