Fusion in massive stars: Pushing the $^{12}C+^{12}C$ cross-section to the limits with the STELLA experiment at IPN Orsay

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Outline

I. C burning, where, why, which reactions ?

II. Experimental efforts to measure $^{12}C+^{12}C$ /new technique

III. The STELLA – FATIMA experiment

IV. Results on $^{12}C+^{12}C$ fusion rates

V. Conclusions

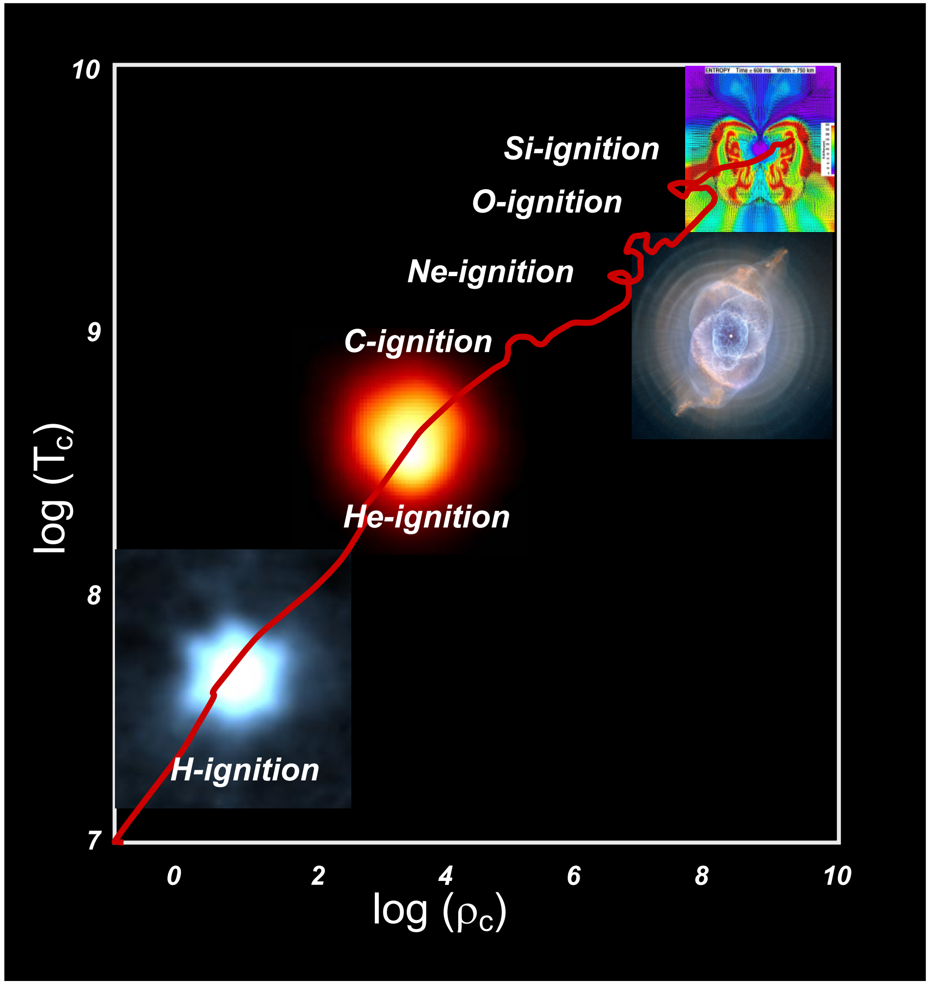
Burning phases in massive stars

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

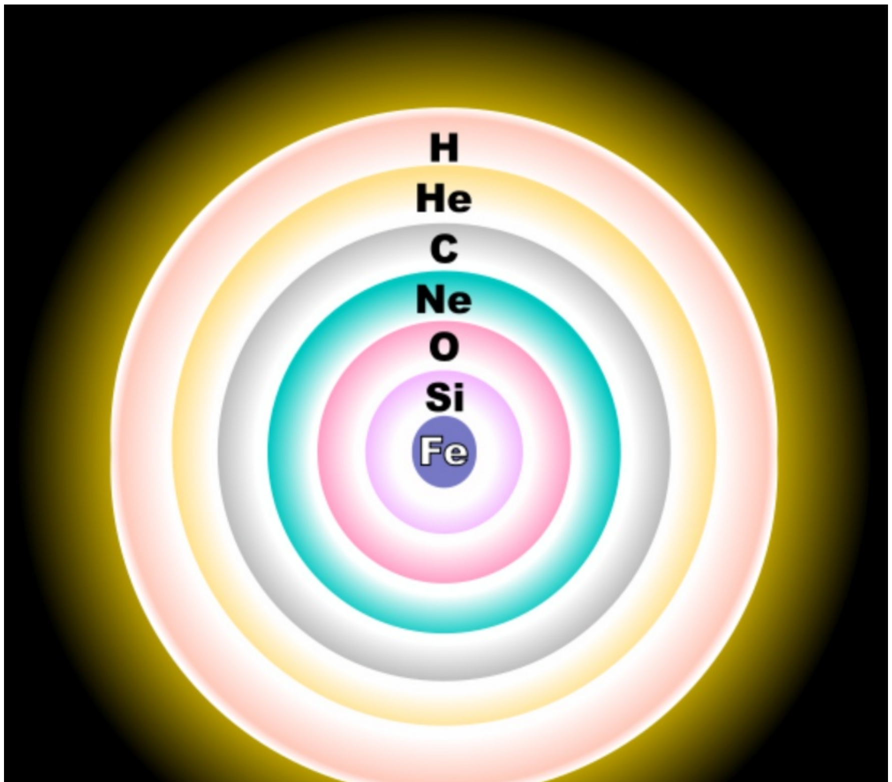
↓

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



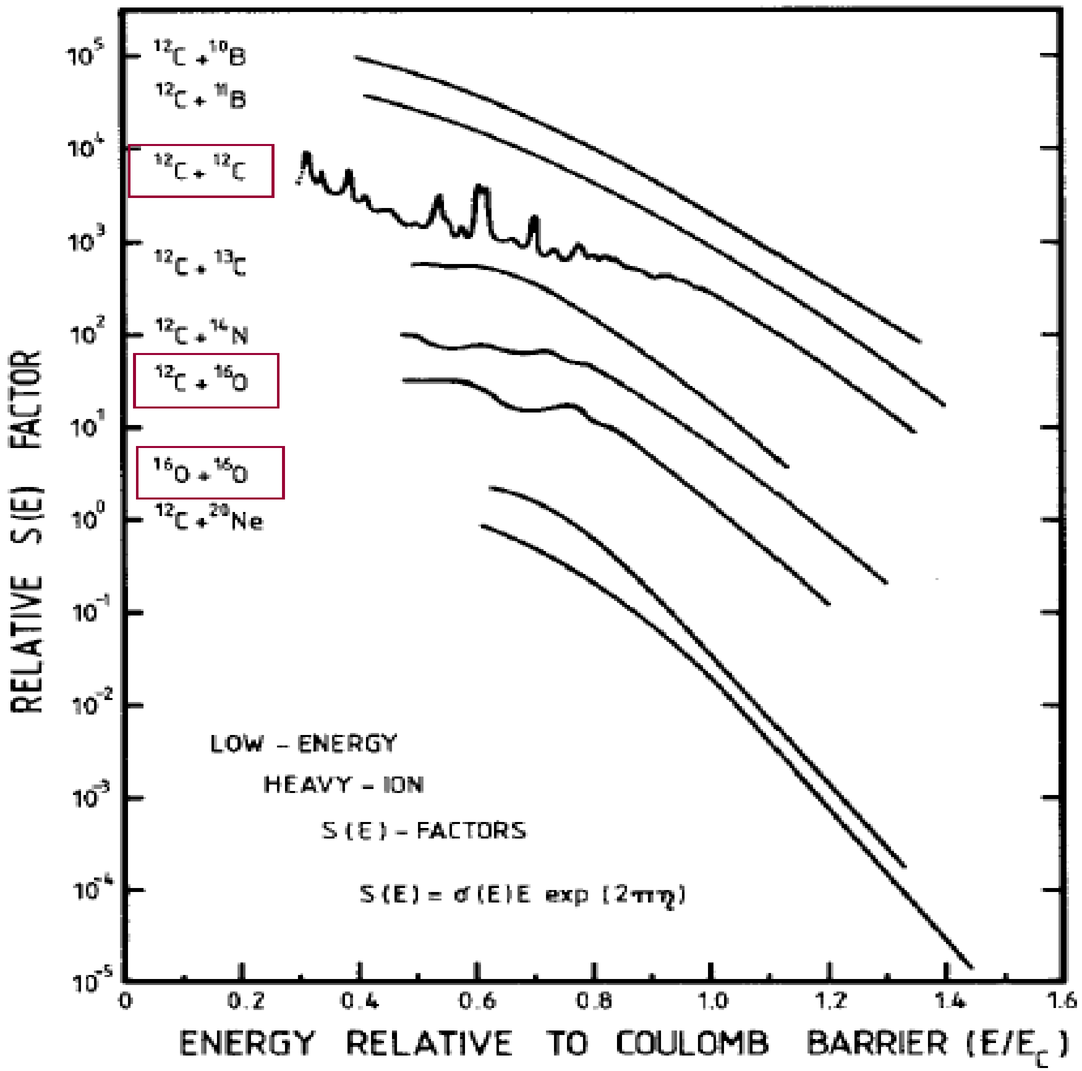
Different shells of a massive star shortly before core collapse

- 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	$^{28}Si(\gamma,\alpha)$…

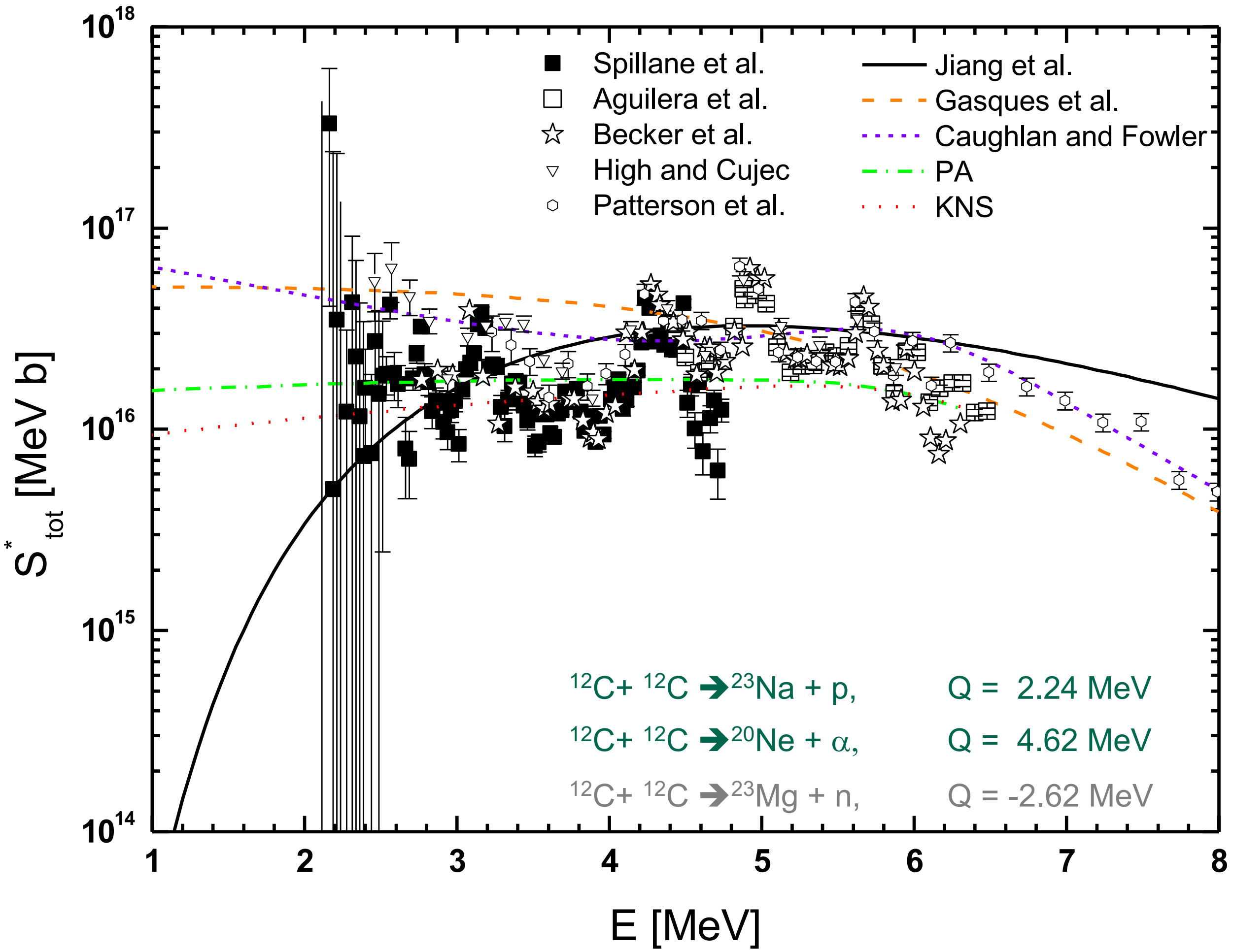
- In a star of 8-11 Solar masses, a carbon flash lasts just milliseconds.
- In a star of 25 Solar masses carbon burning lasts about 600 years.

Cross-sections for some light systems at subcoulomb energies



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

Carbon burning: $^{12}C + ^{12}C$, the main reaction



Experimental and theoretical efforts

- \+ J.R. Patterson *et al.*, APJ 157, 367, (1969)
- \- G.J. Michaud and E.W. Vogt, PRC 5, 350, (1972)
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- \+ J. Zickefoose, Ph.D. thesis, U. of Connecticut (2010)
- \+ C.L. Jiang *et al.*, NIM A 682, 12, (2012)
- \+ X. Fang *et al.*, Jour. Phys. 420, 012151, (2013)
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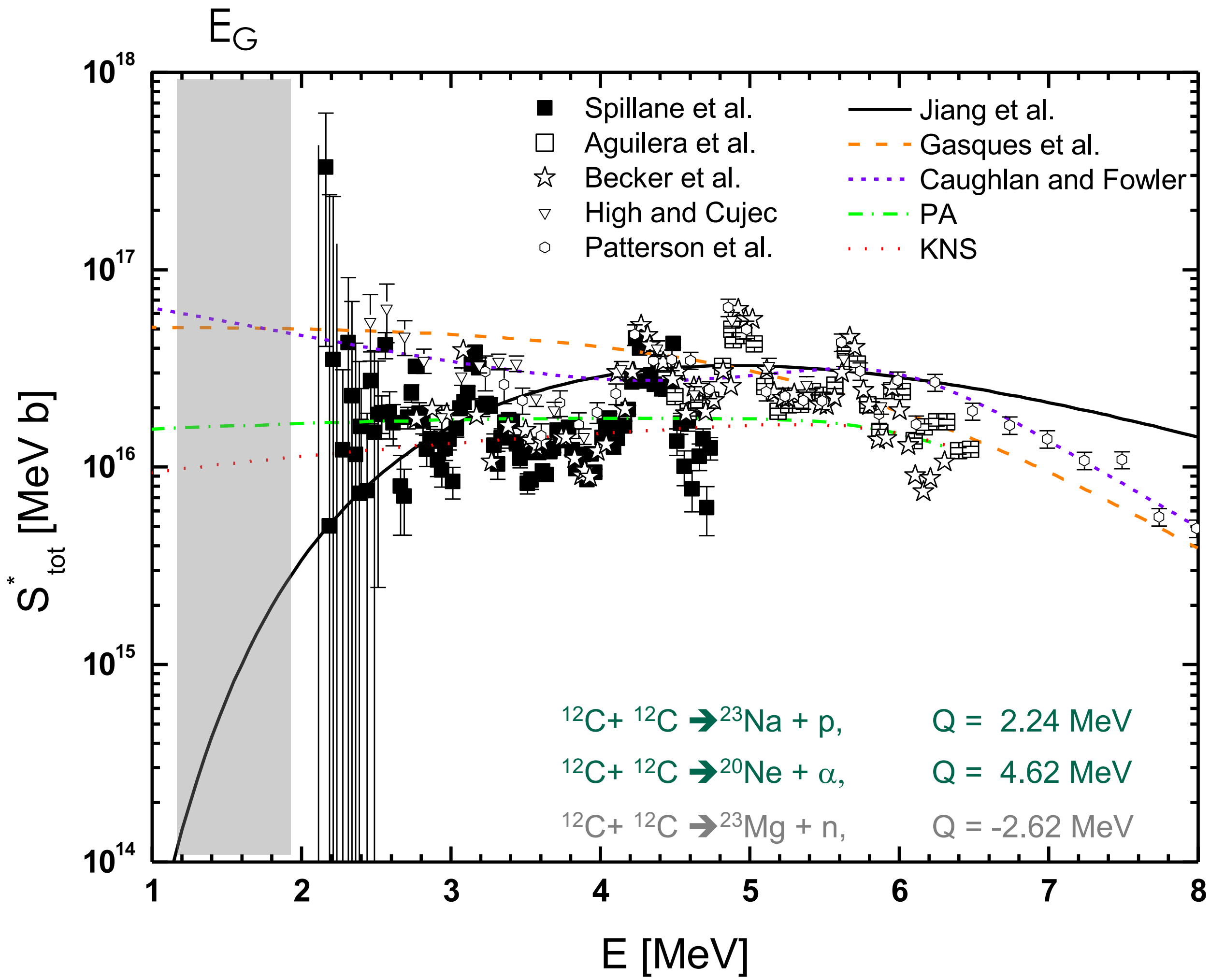
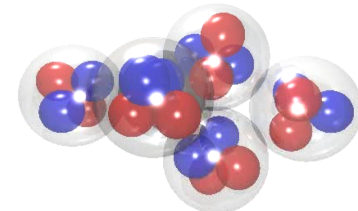
- \- A.A. Aziz *et al.*, PRC 91, 015811, (2015)
- \+ B. Bucher *et al.*, PRL 114, 251102, (2015)
- \+ A. Tumino *et al.*, EPJ Conf. 117, 09004, (2016)

Carbon burning: $^{12}C + ^{12}C$, the main reaction





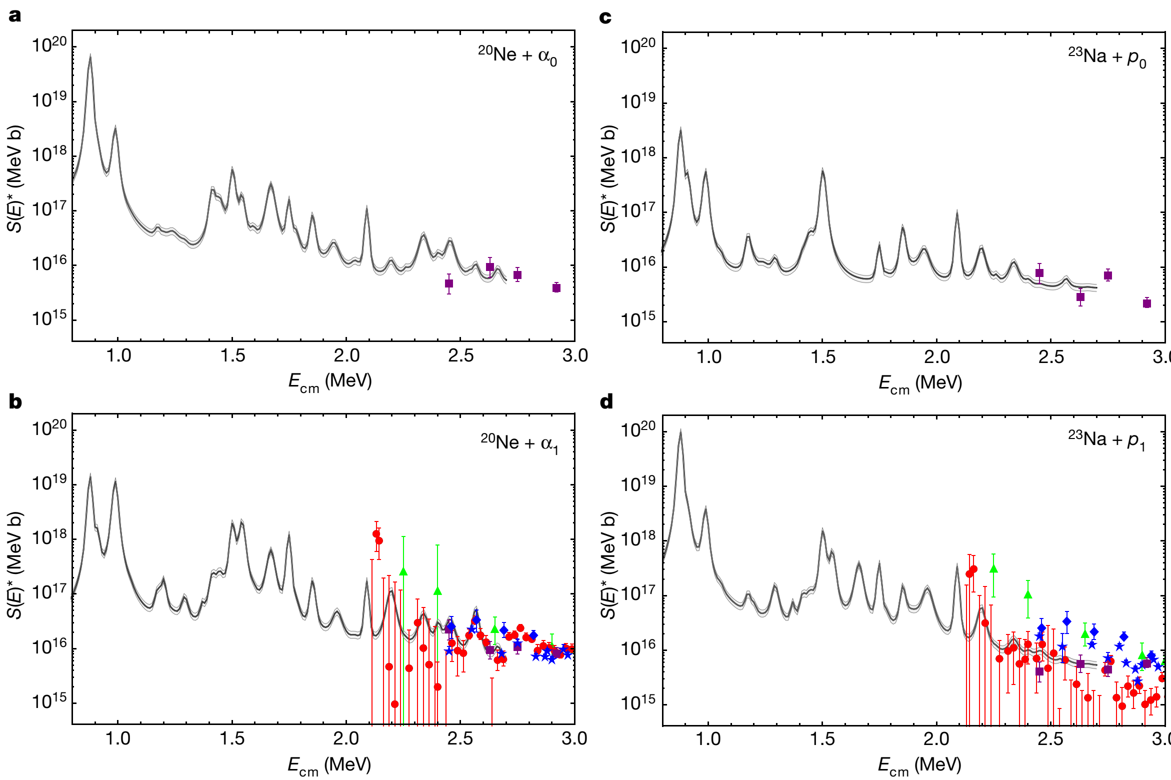
- Single particles or γ
- Extremely sensitive to background
- Extrapolations with very different trends
- Crucial role of resonances, impact on the reaction rate ?

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]



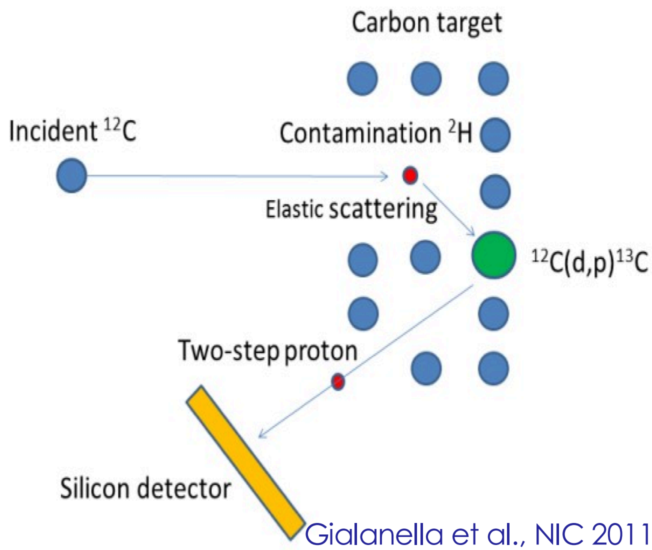
$^{12}C+^{12}C$ cross-sections , sources of uncertainties

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



Gialanella et al., NIC 2011

Detection of γ-rays:

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

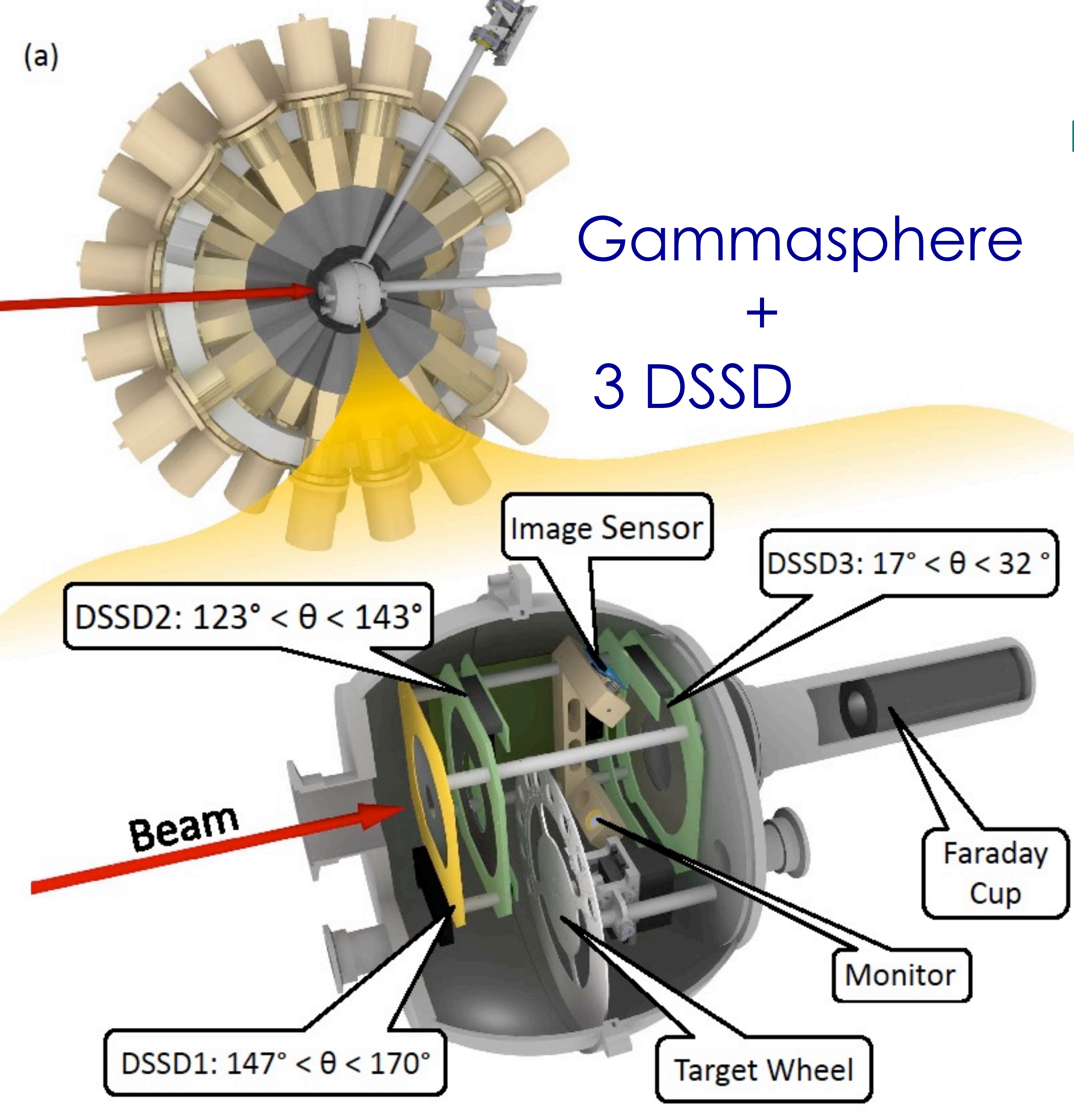
cosmic rays and room backgrounds

2) Thick targets measurements:

Taking the difference of two measurements at different energies.

New technique

Particle-γ coincidences

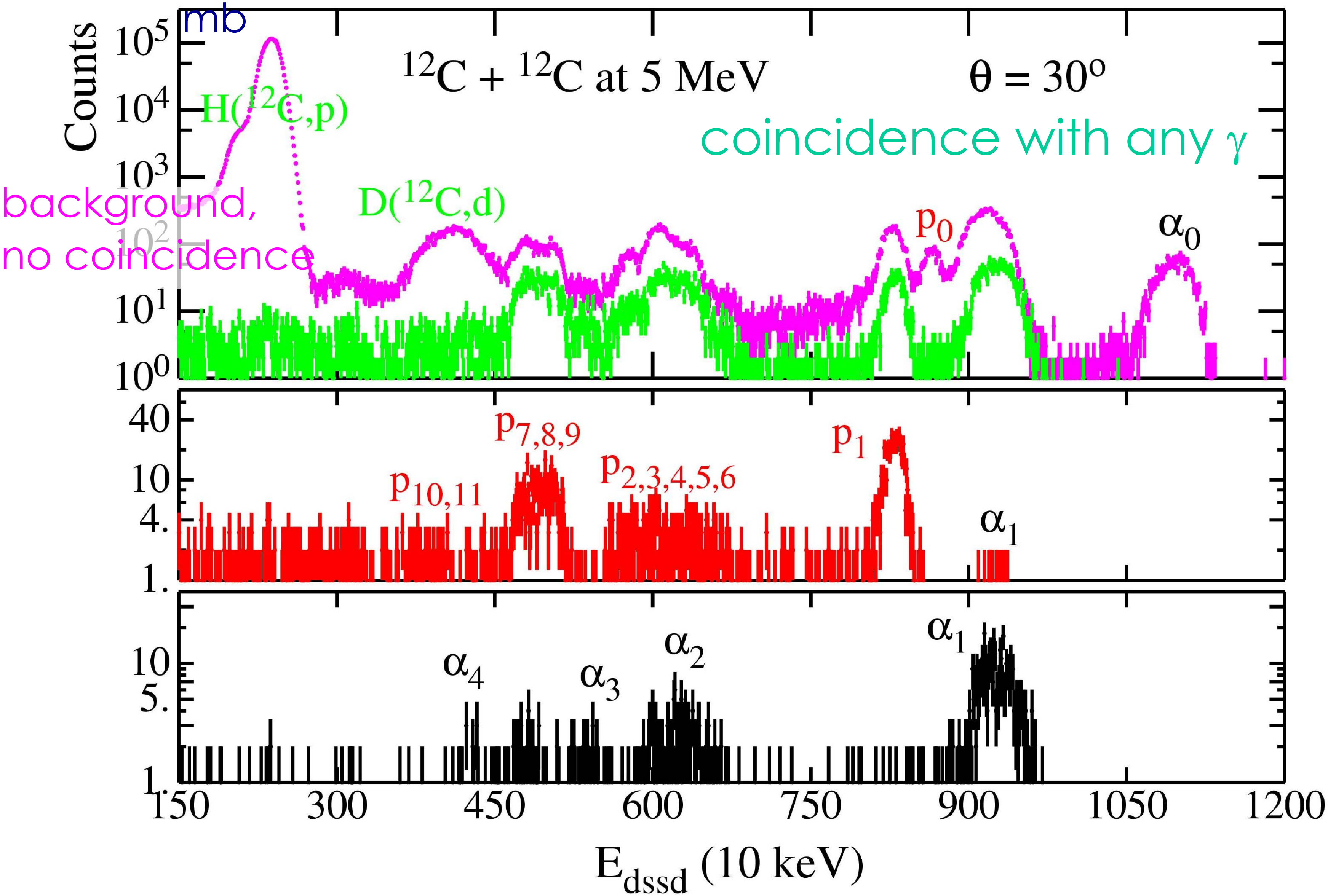


1) Reduction of the backgrounds
2) Using thin target

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

New technique

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



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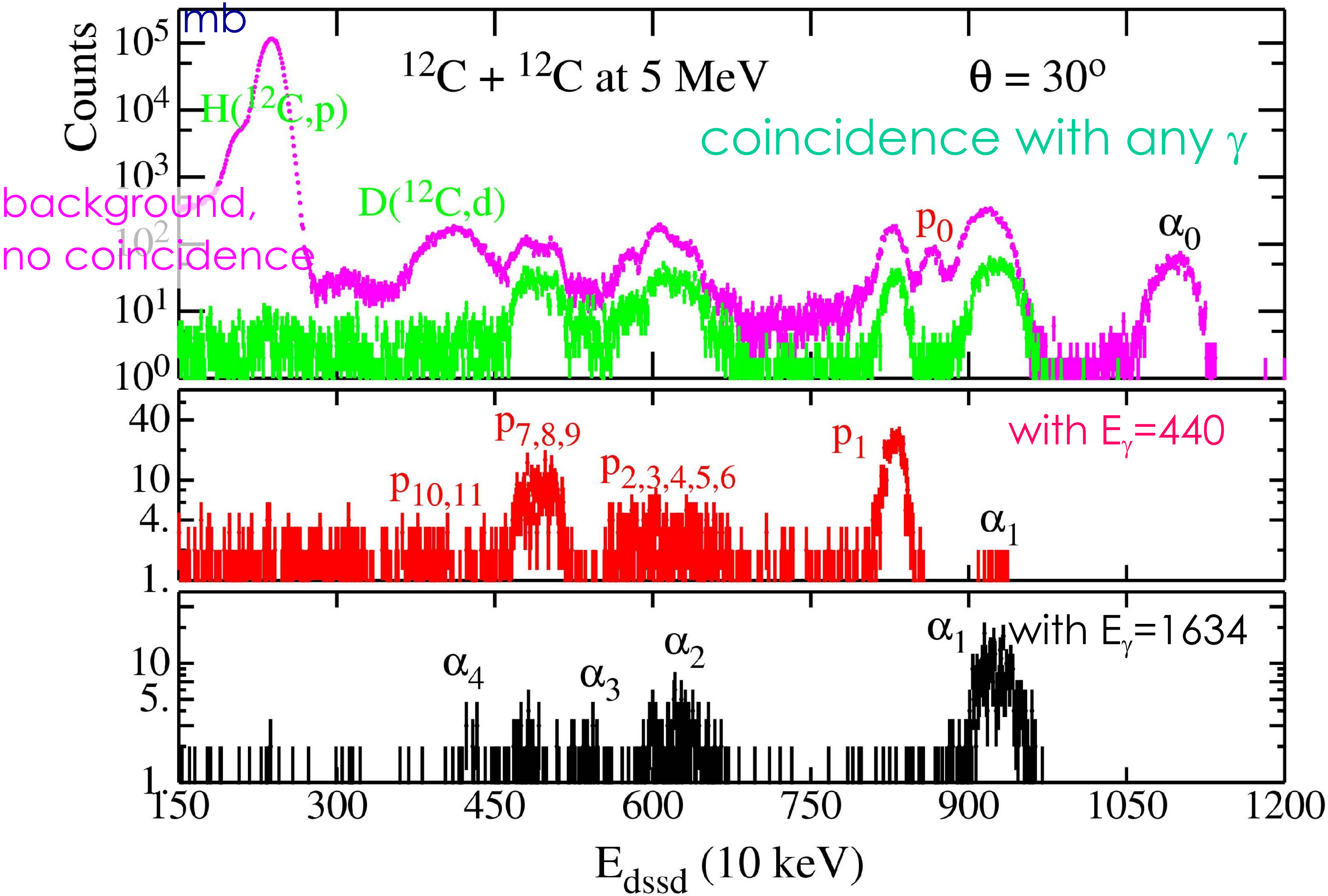
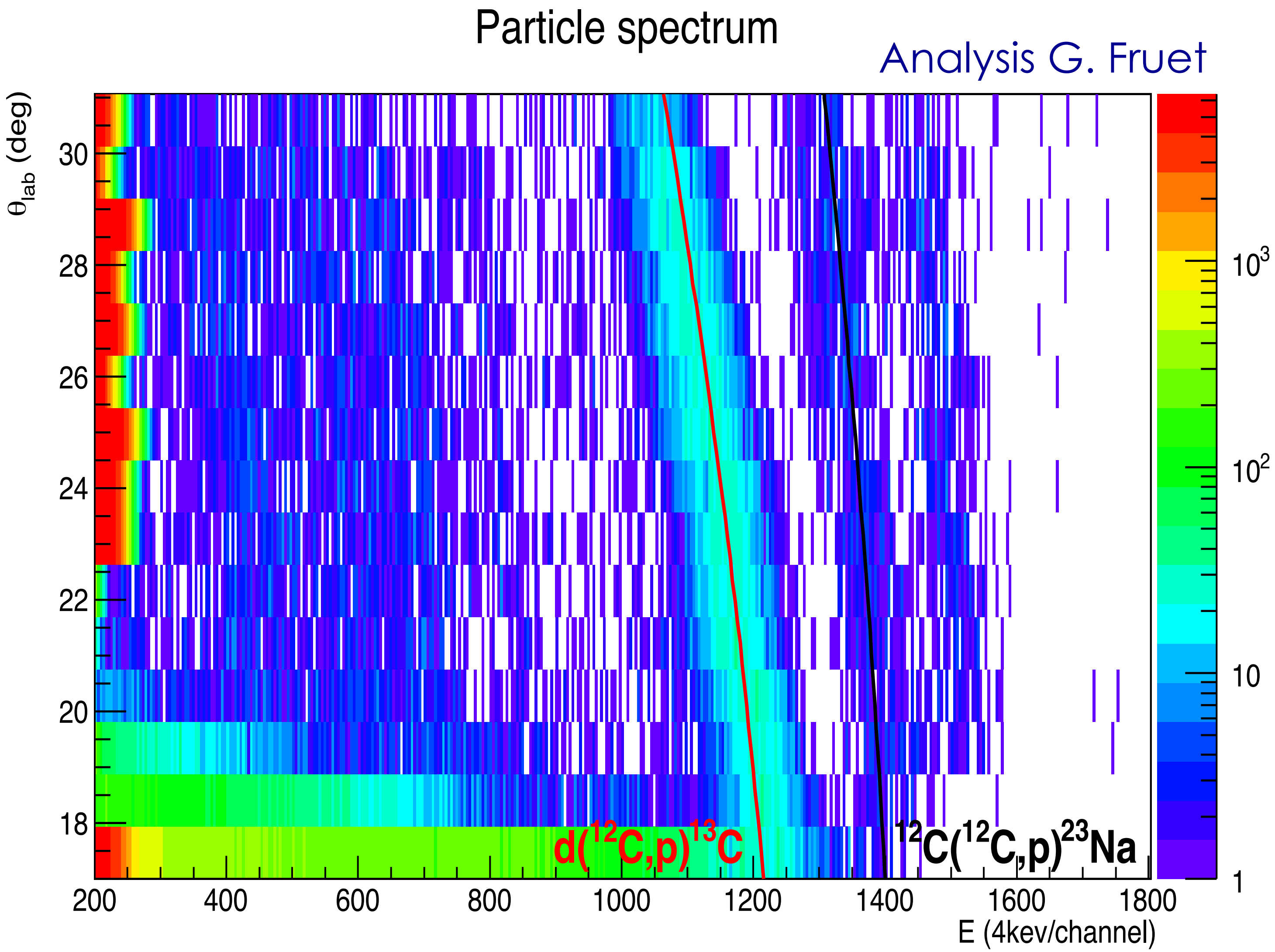
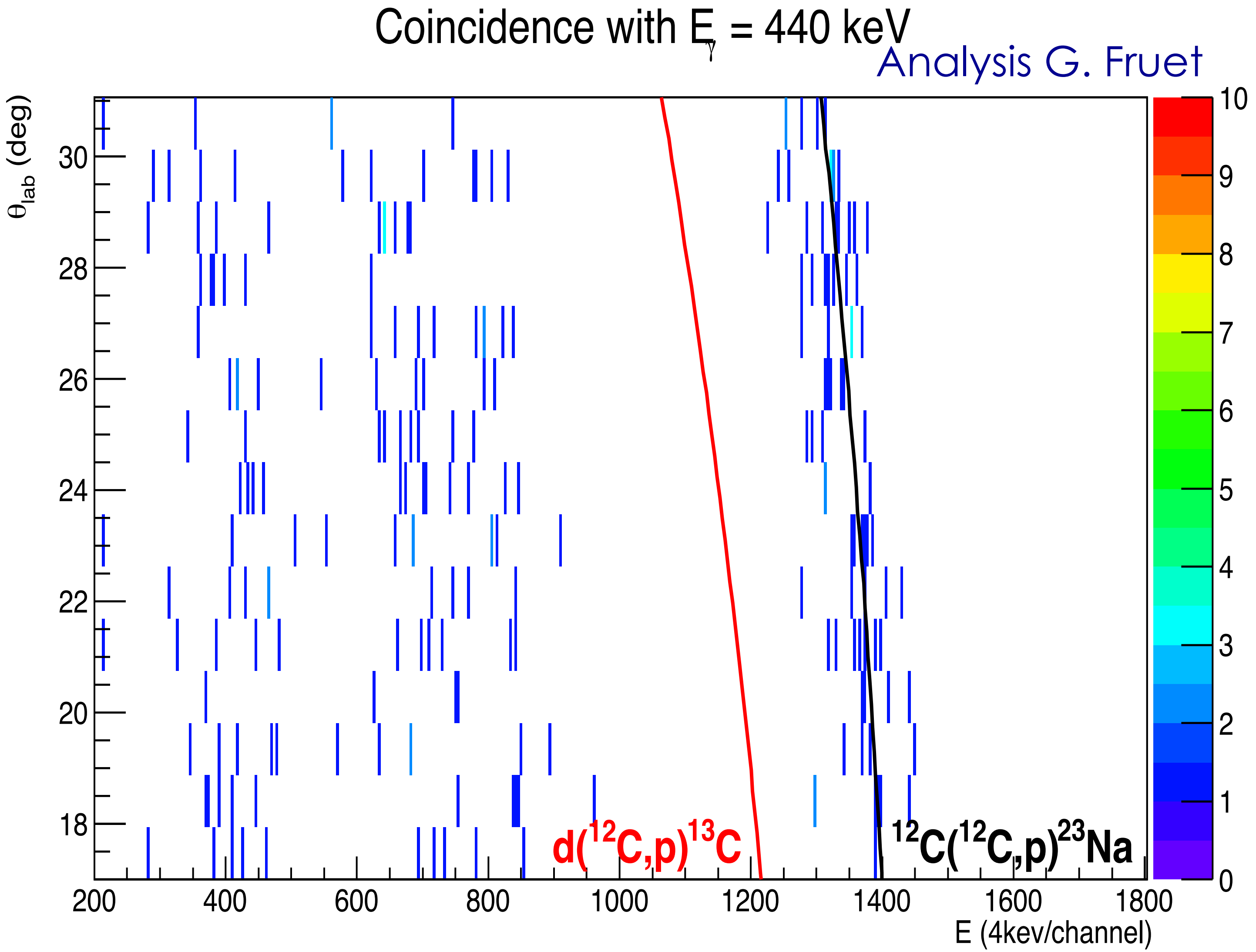


New technique

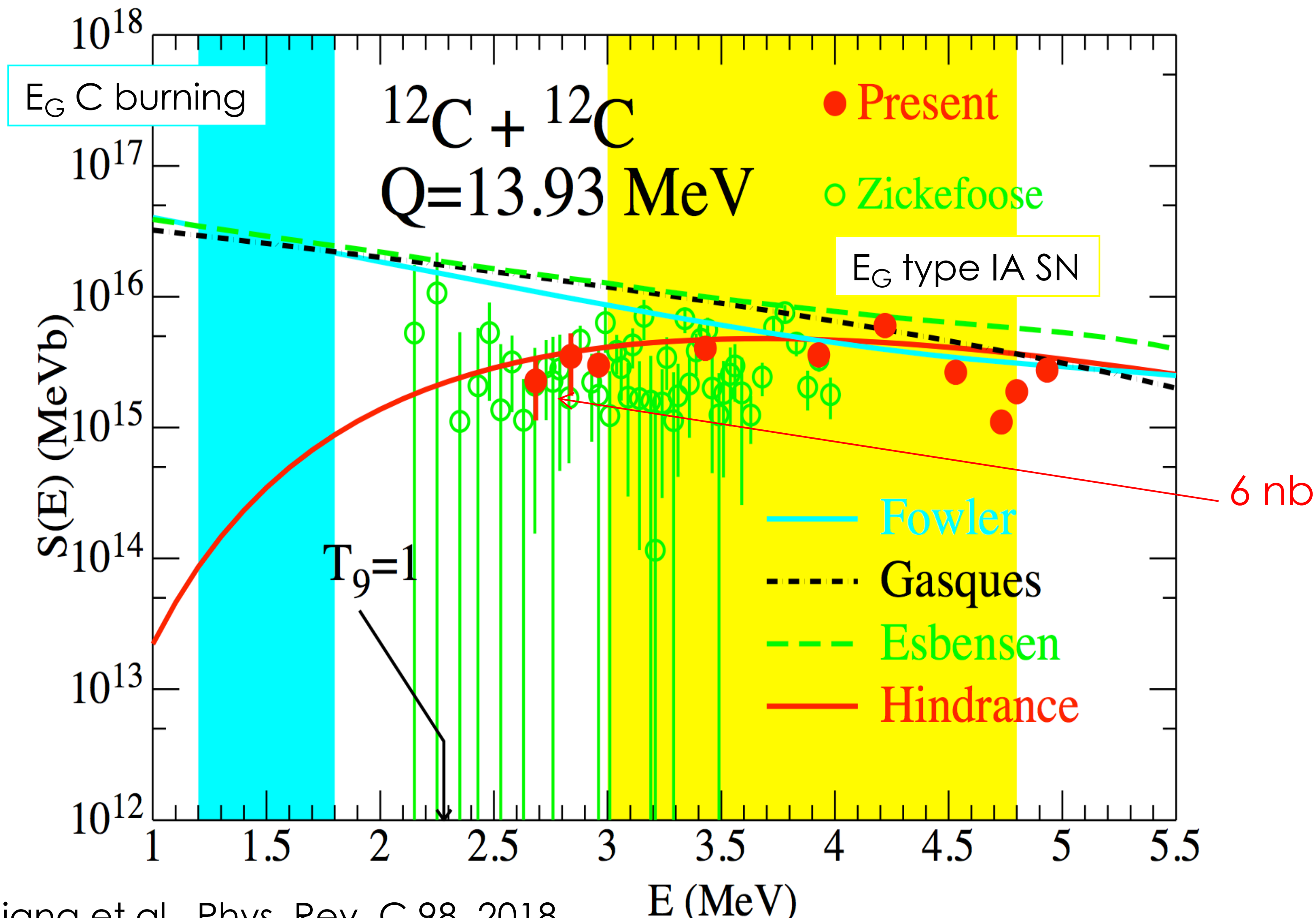


New technique



Results

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



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

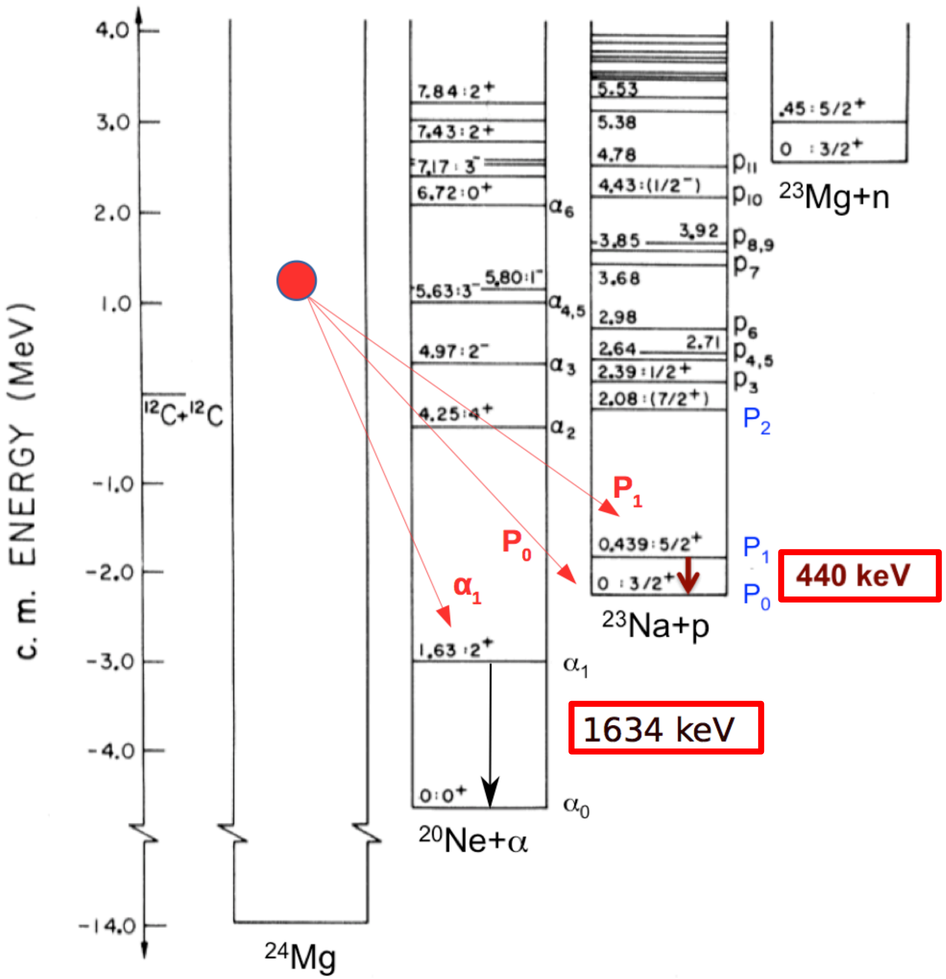
New challenges

Increase beam intensity

Adapt target system

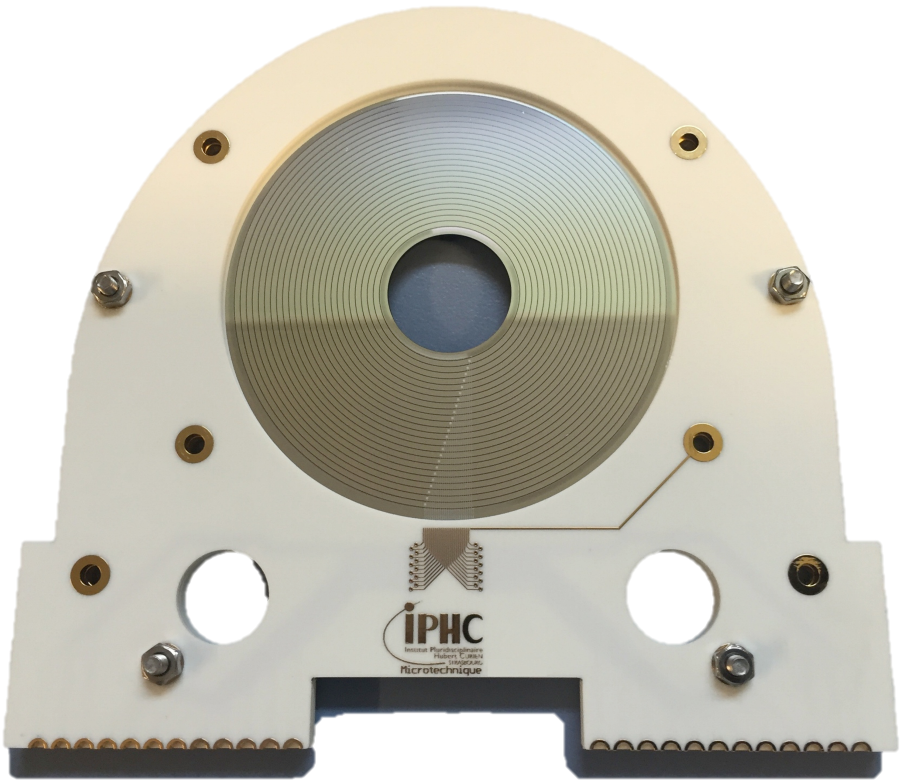
Use of the γ-particle coincidence technique with better gamma efficiency

Challenges for the STELLA + FATIMA project



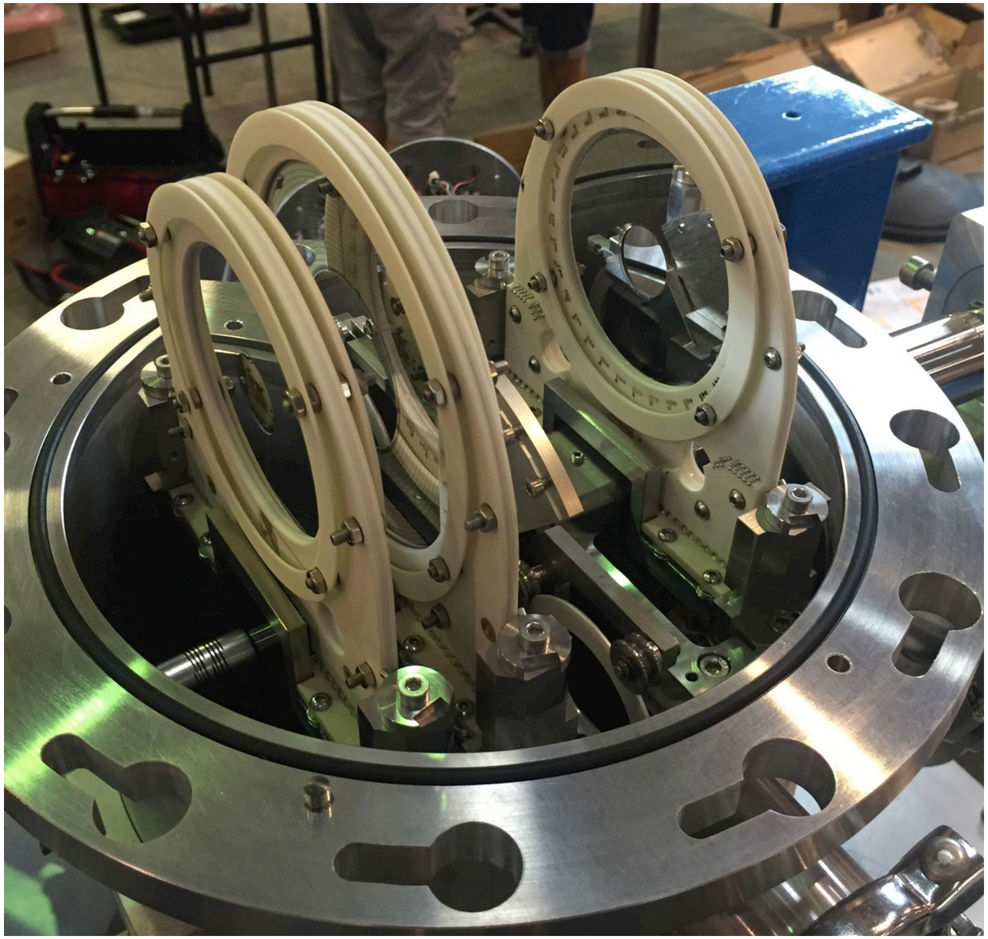
- γ-particle coincidences : Efficiency$_{Tot}$ = ε_γ x ε_{part}
- Contamination
- Carbon build-up
- Thin target under high intensity beam
- 'Long' beamtime

Particle detection



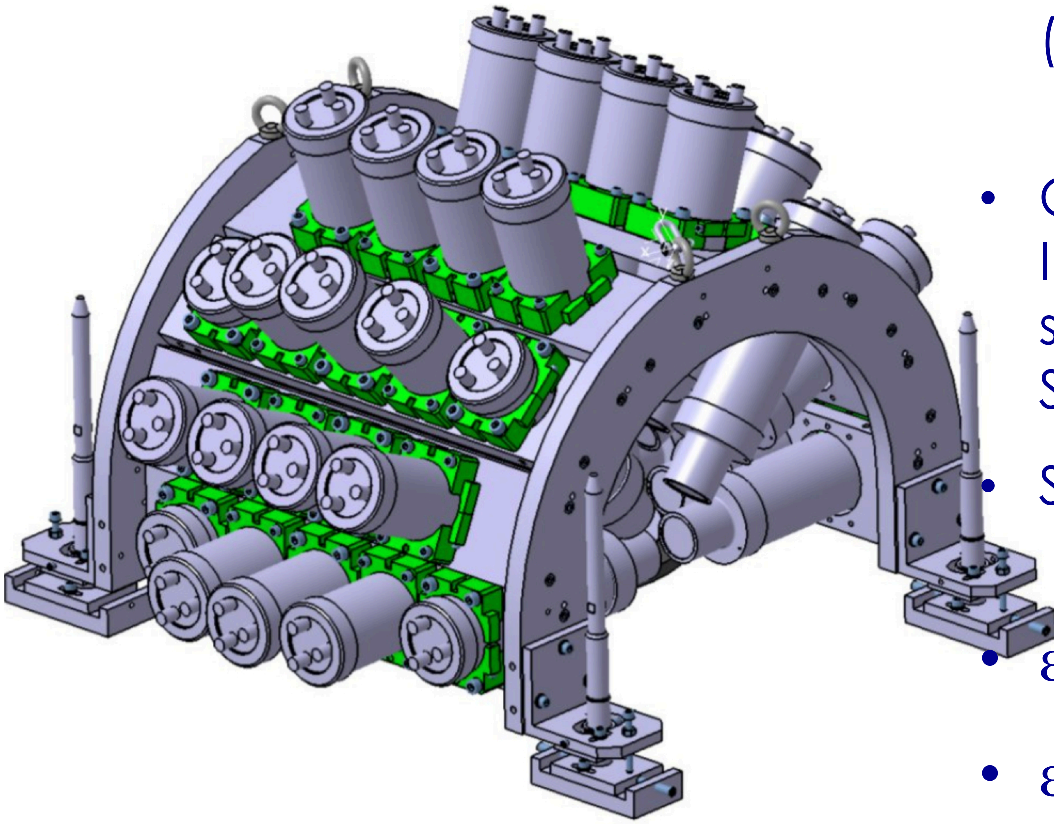
- Annular DSSD, MICRON chip Collab. York
- New PCB design / ceramics
- New pin connectors
- $\Delta\Omega$ ~ 24 % of 4π.

Particle detection



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

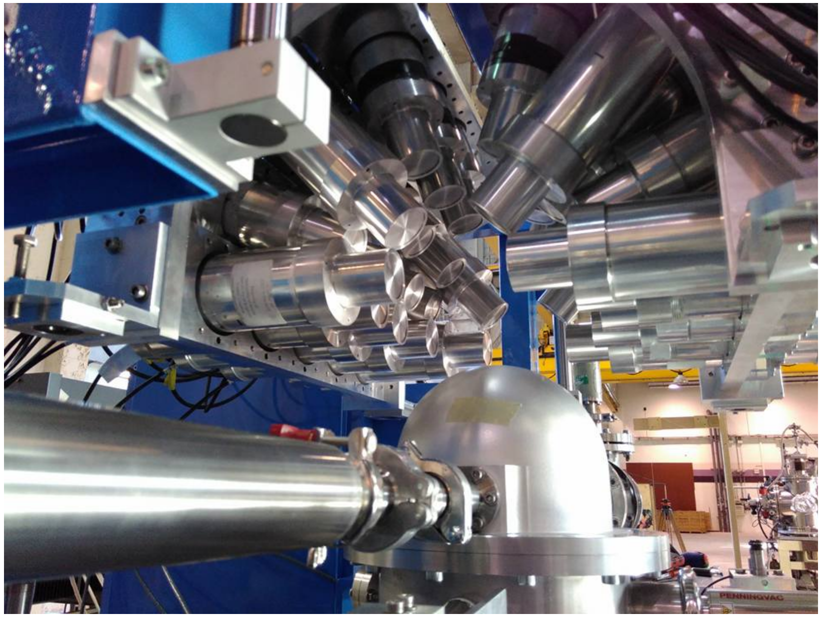
Gamma detection



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

Gamma detection



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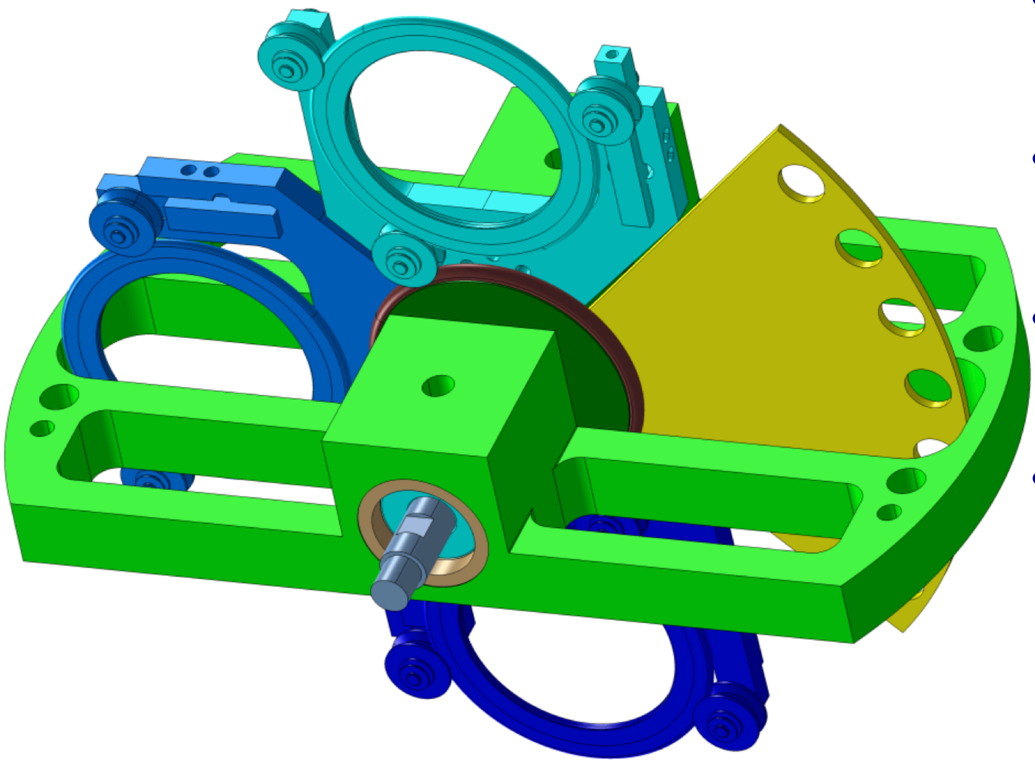
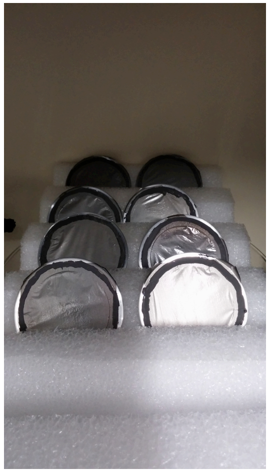
Targets



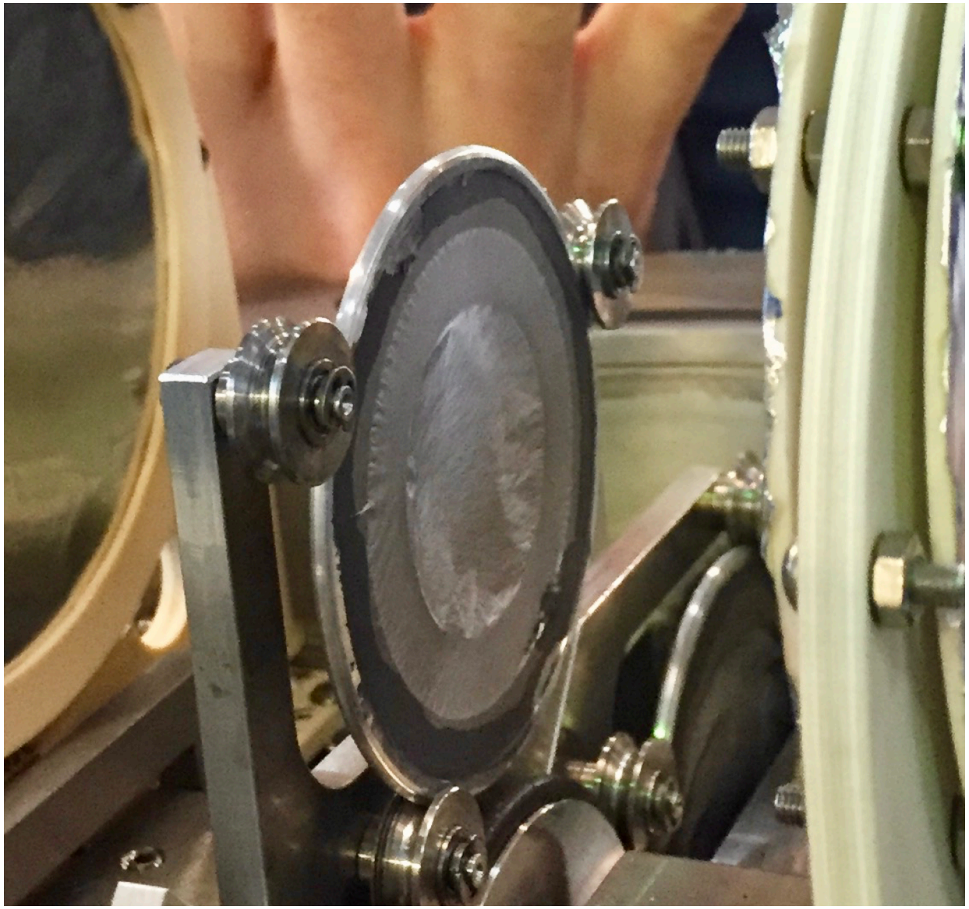
- Cryogenic pumping
- Fixed target system
- Rotating target (> 1000 rpm)
- I > 1 pμA

Collaboration : IPHC and GANIL



M. Heine et al., NIMA

Targets



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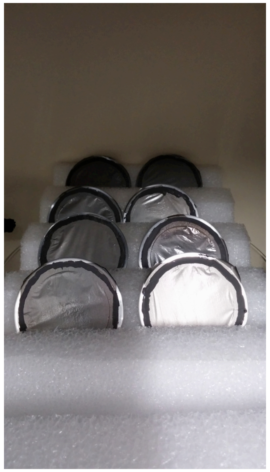
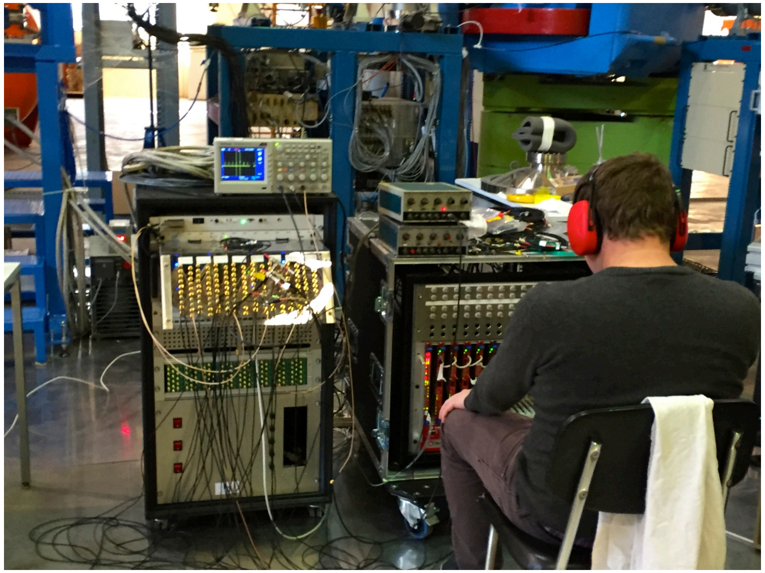
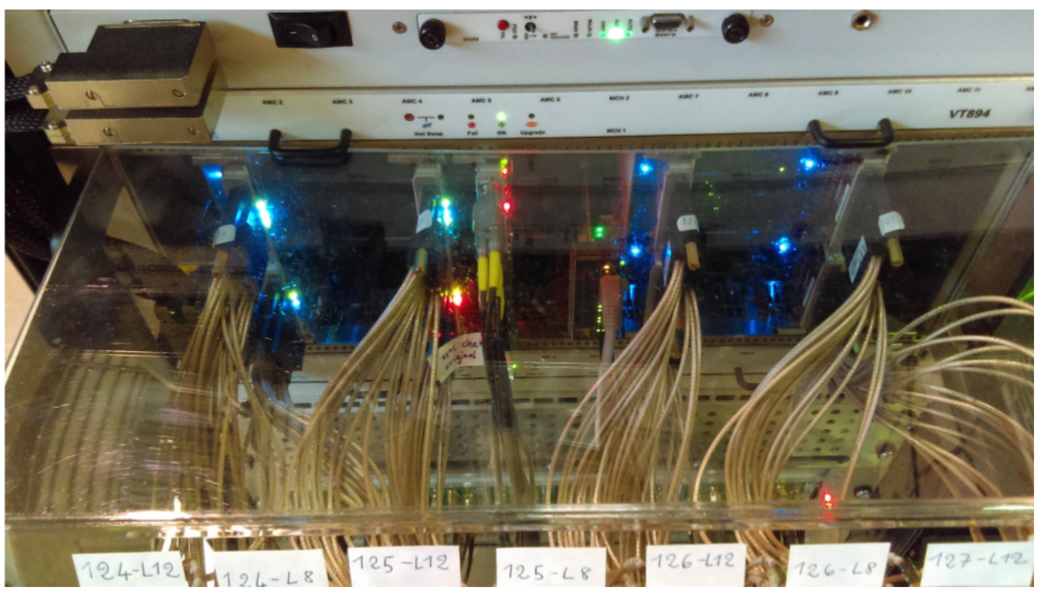


M. Heine et al., NIMA

DAQ





M. Heine, M. Rudigier

- μTCA system (CERN)
- 96 channels
- 125 MHz clock
- Synchronized with the FATIMA DAQ.

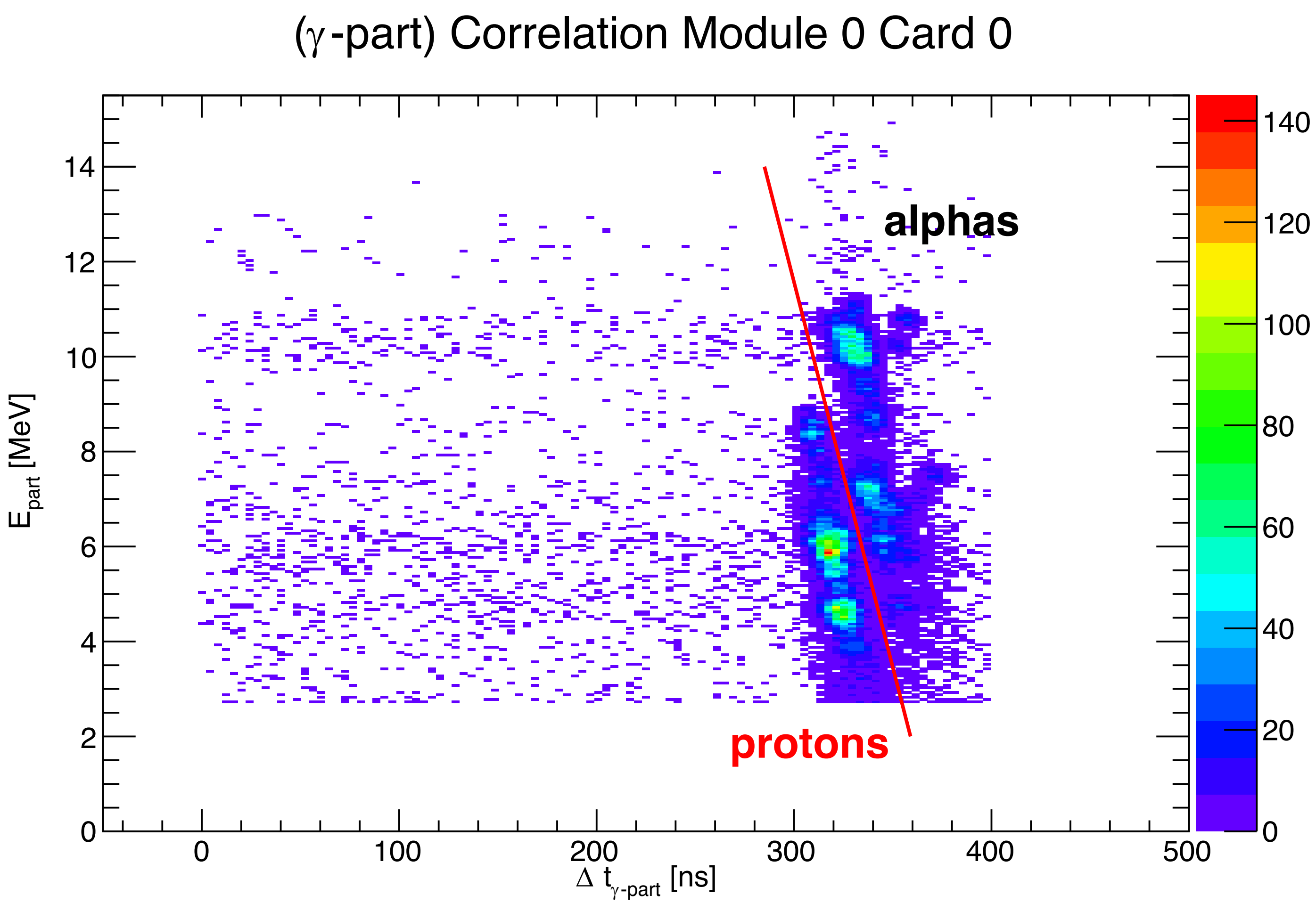
M. Heine et al., NIMA

Beam

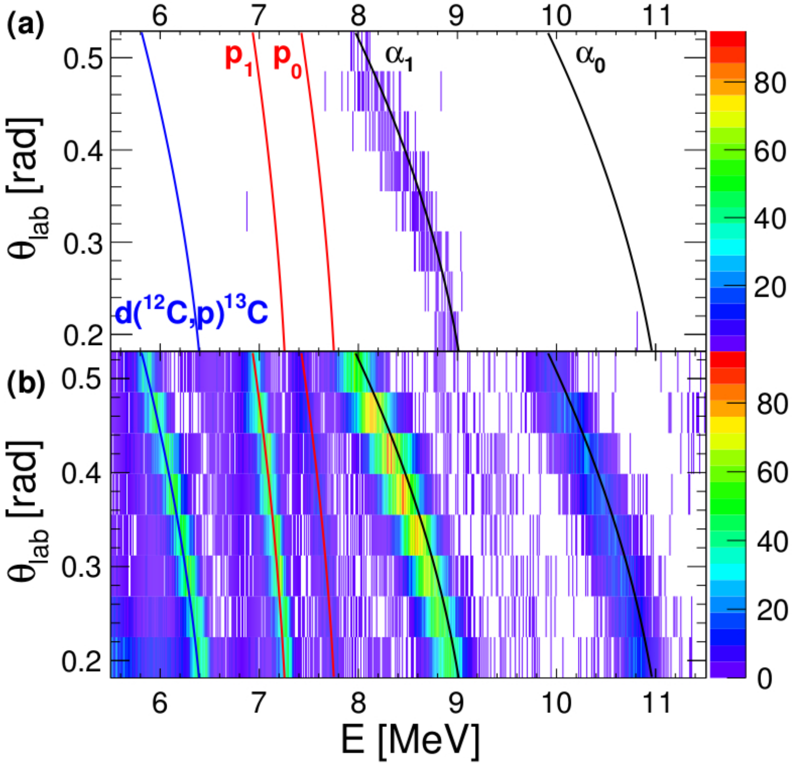
ANDROMEDE

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

Timing and background …

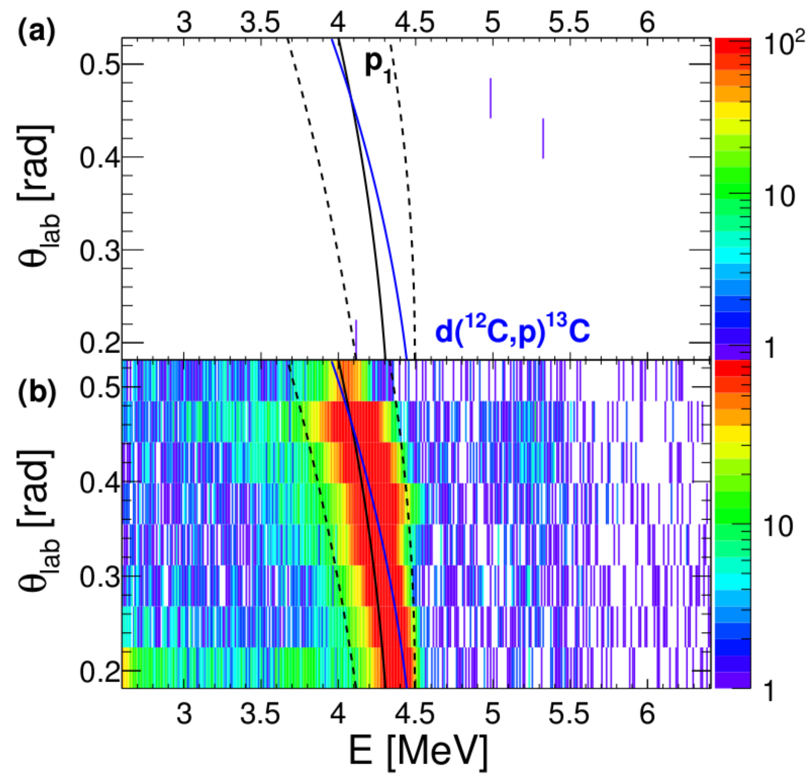


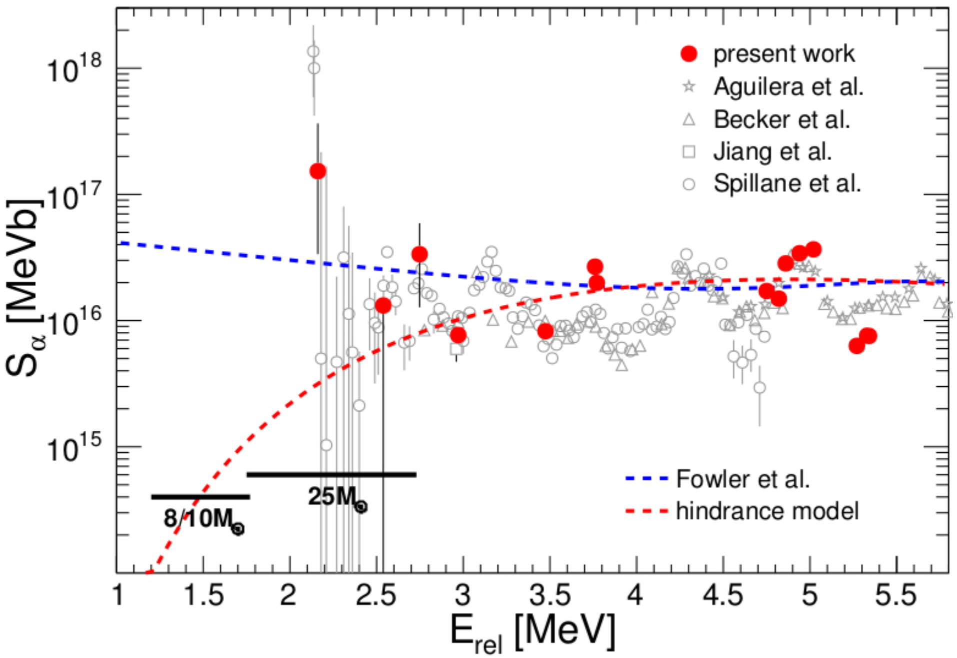
M. Heine et al., NIMA



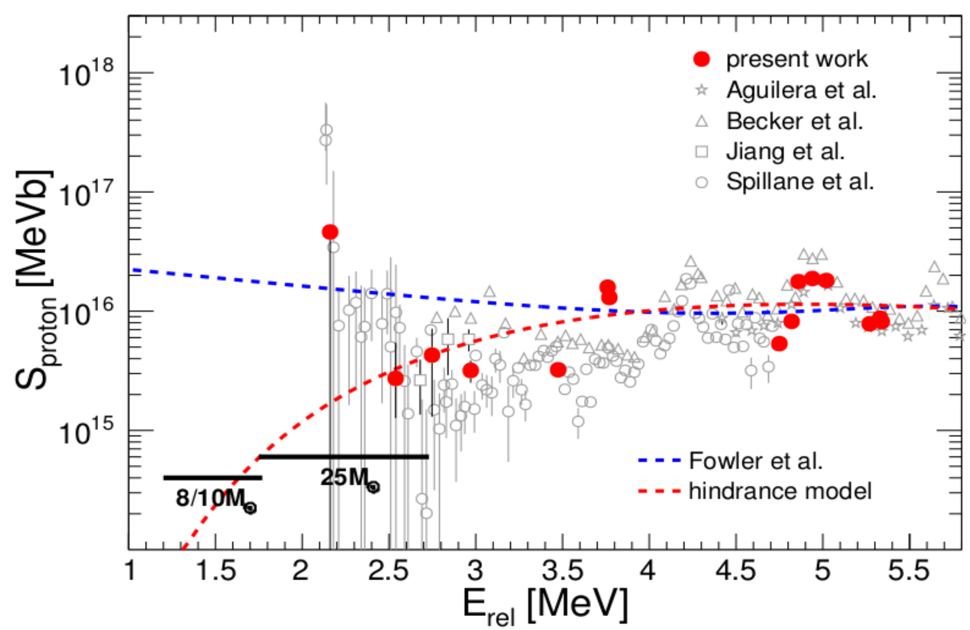
E$_{rel}$ = 3.77 MeV

E$_{rel}$ = 2.16 MeV





present work
Aguilera et al.
Becker et al.
Jiang et al.
Spillane et al.
Fowler et al.
hindrance model
8/10M⊙
25M⊙
S_α [MeVb]
E_{rel} [MeV]



present work
Aguilera et al.
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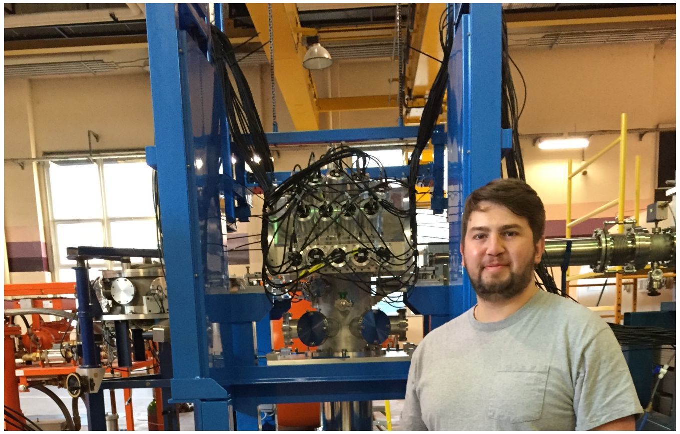
hindrance model
8/10M⊙
25M⊙
S_{proton} [MeVb]
E_{rel} [MeV]

Conclusions

- High sensitivity of the STELLA + FATIMA experiment
- 12 energy points explored E_{Lab} = 11 to 5.6 MeV consistent with previous work
- High intensity phase ($^{12}C+^{12}C$, I > 1 μA): Sept. – Dec. 2017
- Measurements well into Gamow window for 25 M_o stars
- Next measurements to focus on discrepancy with THM results

Thanks !



University of Strasbourg and IPHC (France):

S.C, G. Fruet, F.Haas, M.Heine et al.

University of York (UK): *D.Jenkins , L.Morris*

IPN Orsay *: S. Della Negra, F. Hammache, N. de Séreville, P. Adsley, A. Meyer et al.*

Argonne National Laboratory (USA):

C.L.Jiang, D.Santiago-Gonzalez, K.E.Rehm, B.B.Back et al.

University of Surrey (UK):

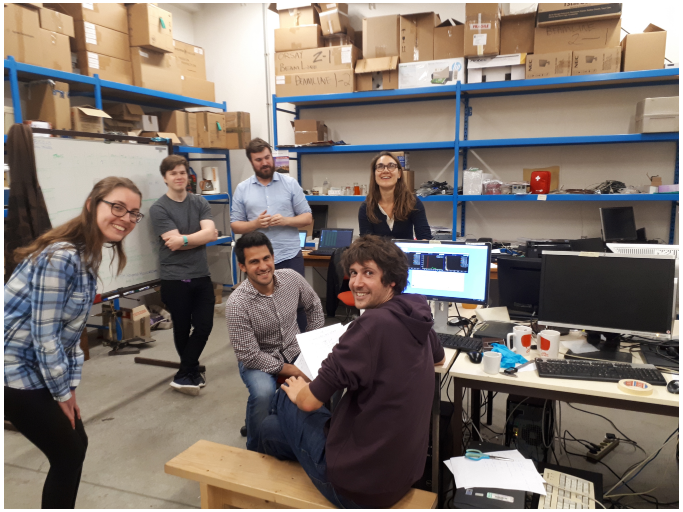
P.H. Regan, M. Rudigier

GANIL (Caen, France):

C. Stodel et al.

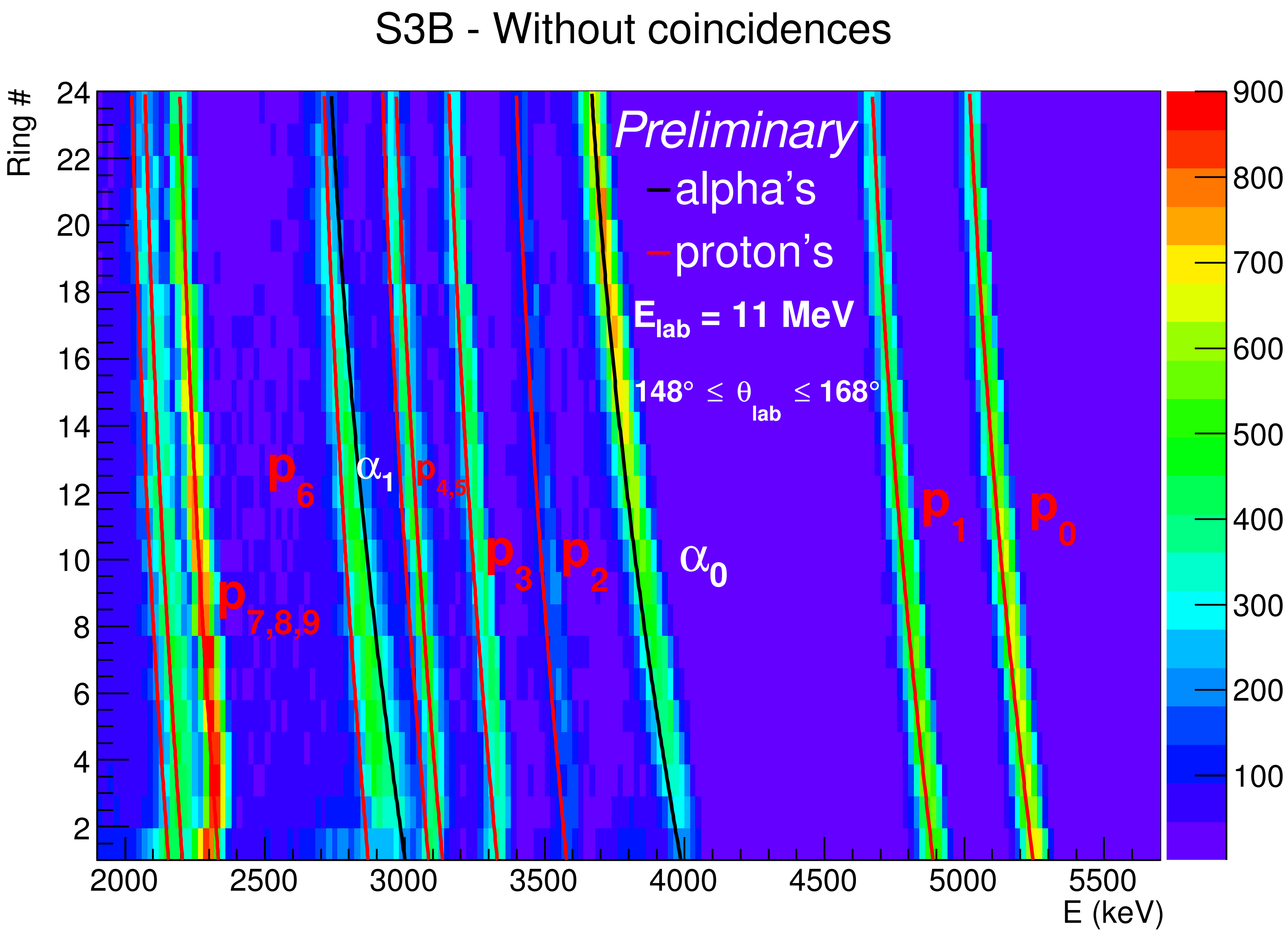
University of Aarhus (Denmark):

O. Kirsebom



Spare slides

Results of the 1st run



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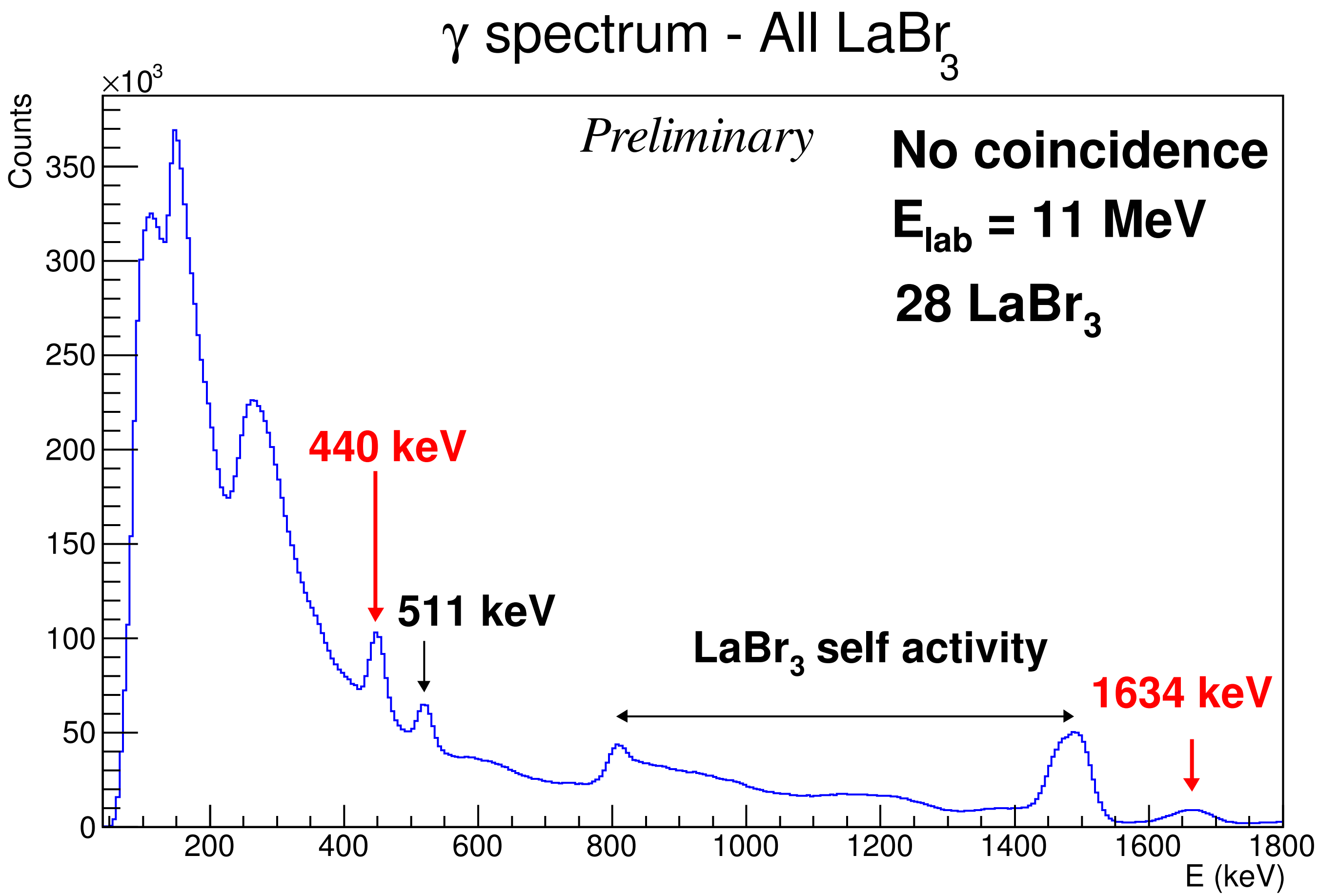
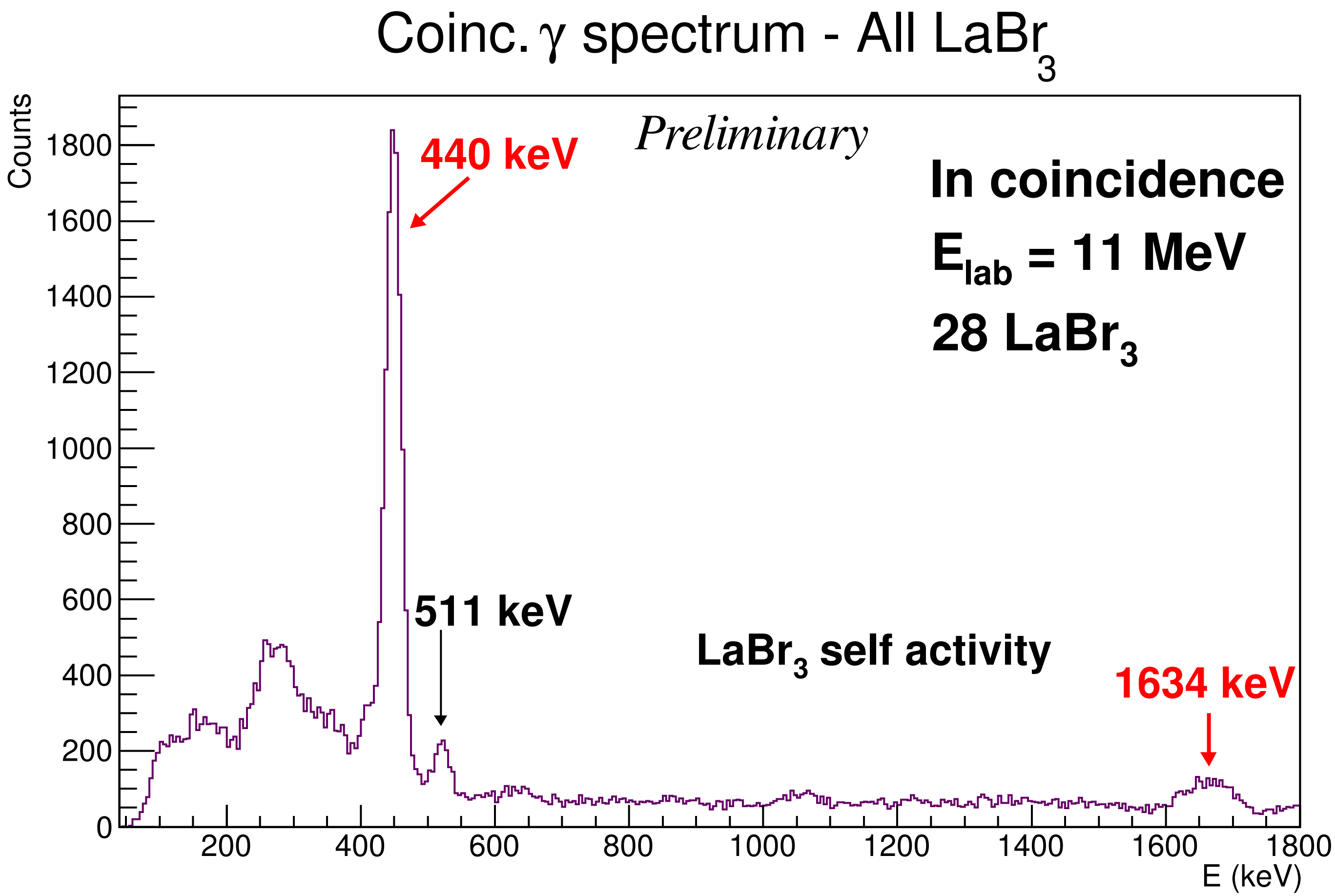


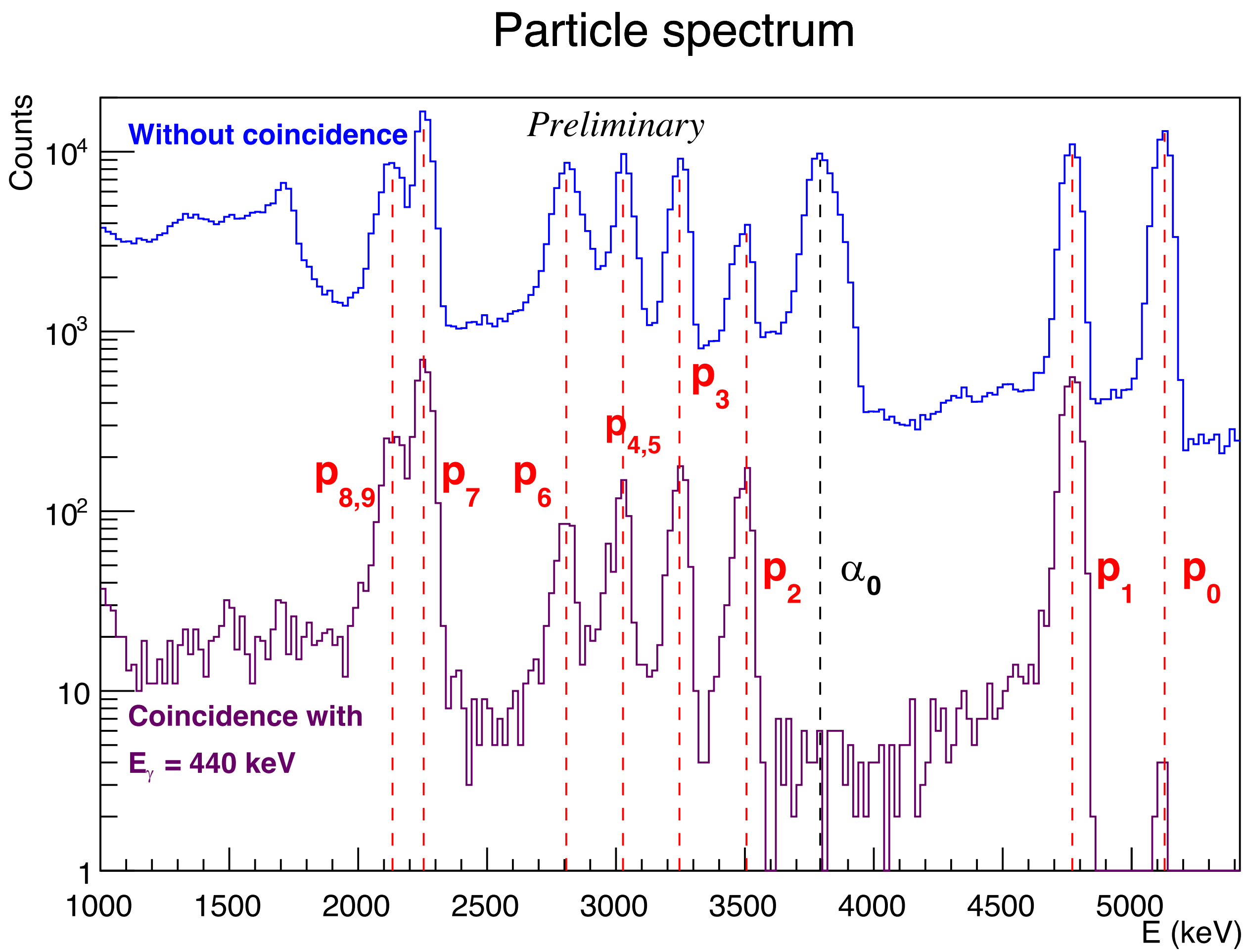
Self activity & γ of interest from $^{12}C+^{12}C$ fusion

Results of the 1st run



Coincidence with 1 particle : γ from fusion

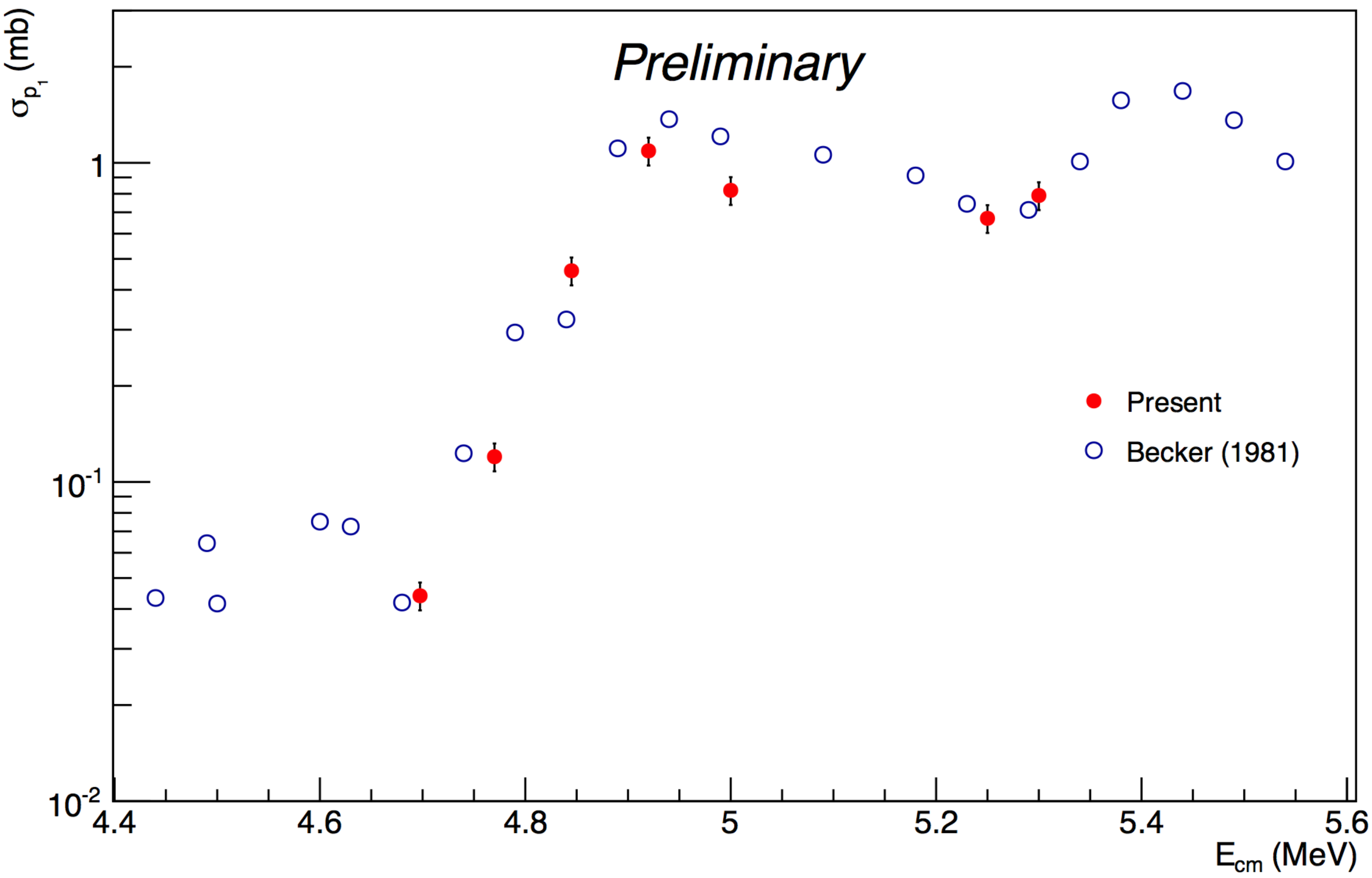
Results of the 1st run



Gate on E_γ = 440 keV

Suppression of α_0 and p_0 / $\varepsilon_{440\ keV}$ = 6%

Results of the 1st run

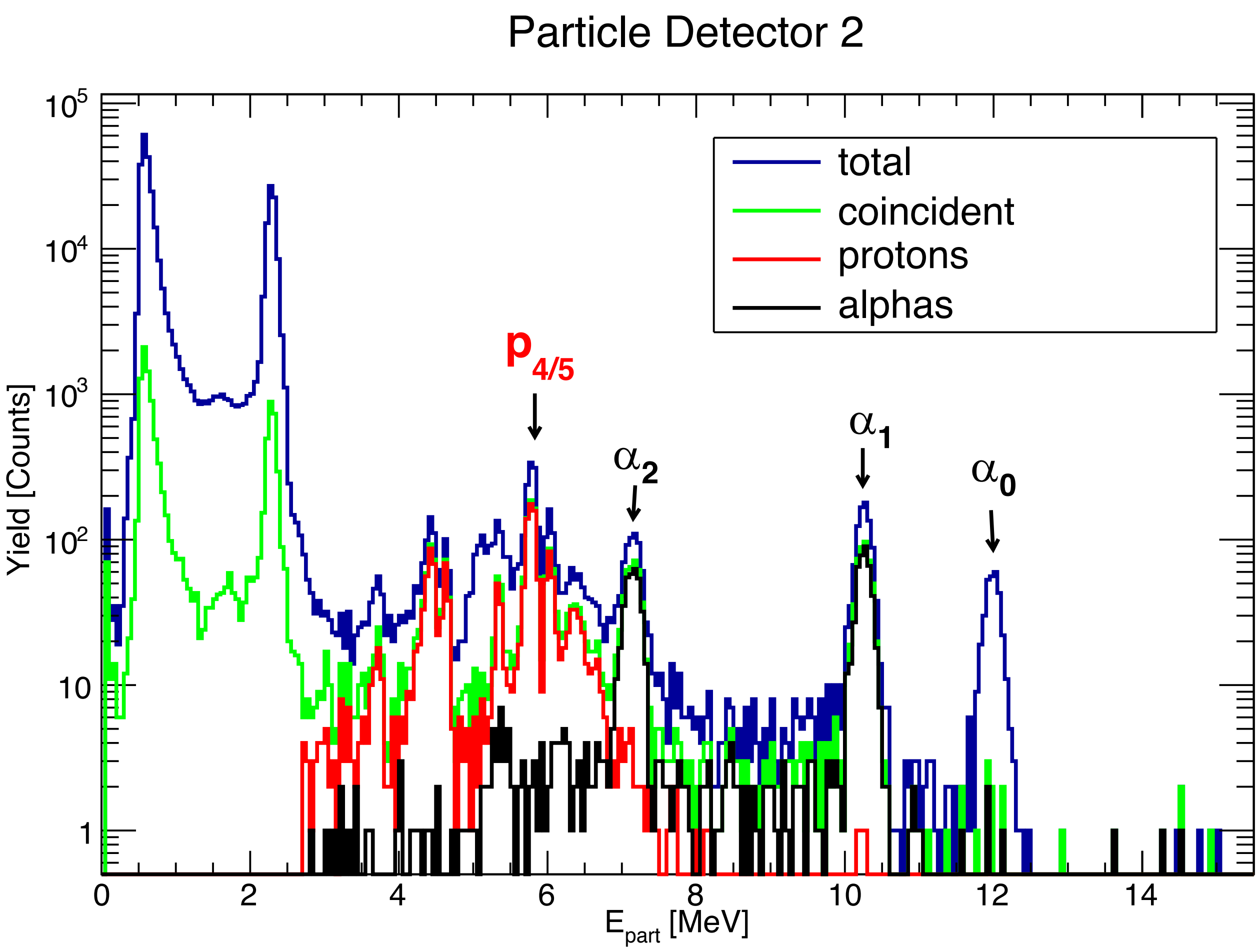


p_1 cross section vs center of mass energy

Cross section consistent with previous experiments

Analysis performed by G. Fruet and M. Heine

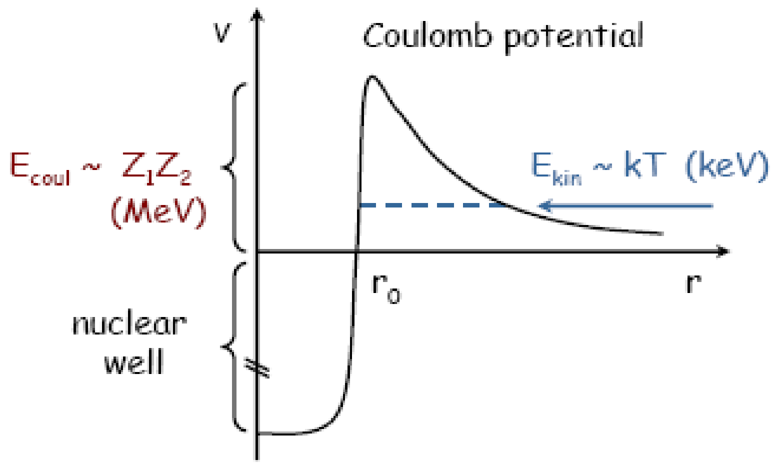
Timing and background ...



Fusion reactions at thermonuclear energies

charged particles ➡ Coulomb barrier

energy available: from thermal motion

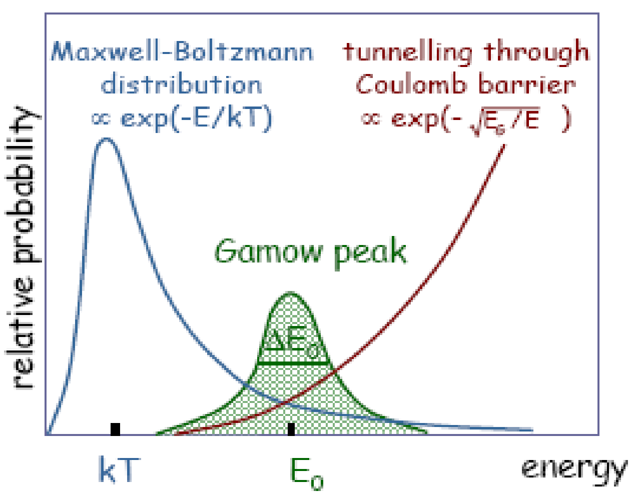


$T \sim 15\times10^6$ K (e.g. our Sun) $\Rightarrow$ $kT \sim 1$ keV

during static burnings: $kT \ll E_{coul}$

reactions occur through TUNNEL EFFECT

➡ tunneling probability $P \propto \exp(-2\pi\eta)$



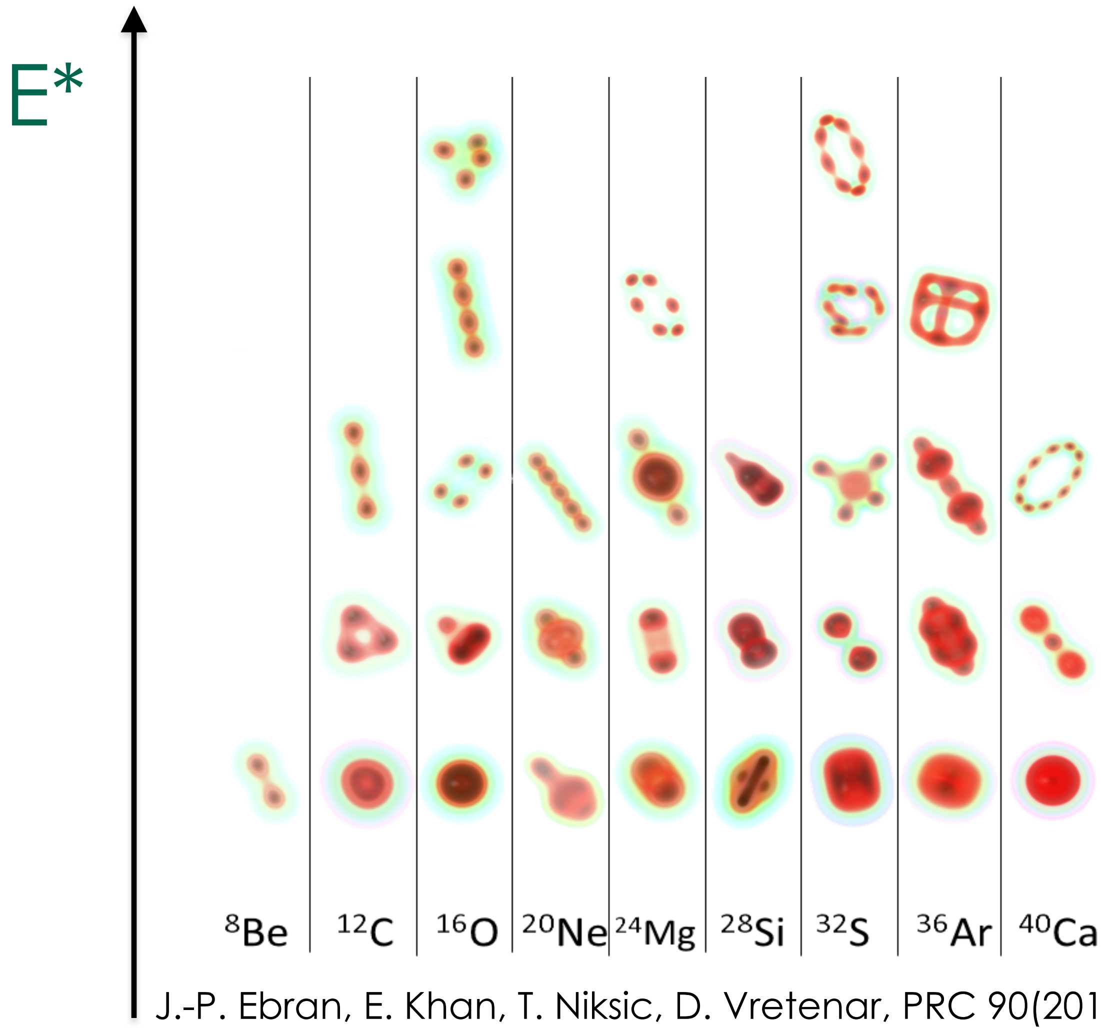
$$\sigma(E) = \frac{1}{E}\exp(-2\pi\eta)\,S(E)$$

non-nuclear origin
STRONG energy dependence

nuclear origin
WEAK energy dependence

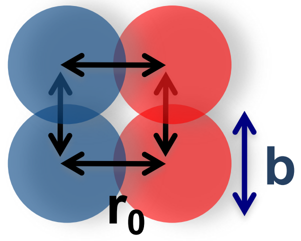
ASTROPHYSICAL S(E)-FACTOR

Ikeda diagram from microscopic calculations



Emergence of clusters

- $\alpha_{loc} = b/r_0$
- energy



J.-P. Ebran, E. Khan, T. Niksic, D. Vretenar, PRC 90(2014)054329, Nature 487(2012)341