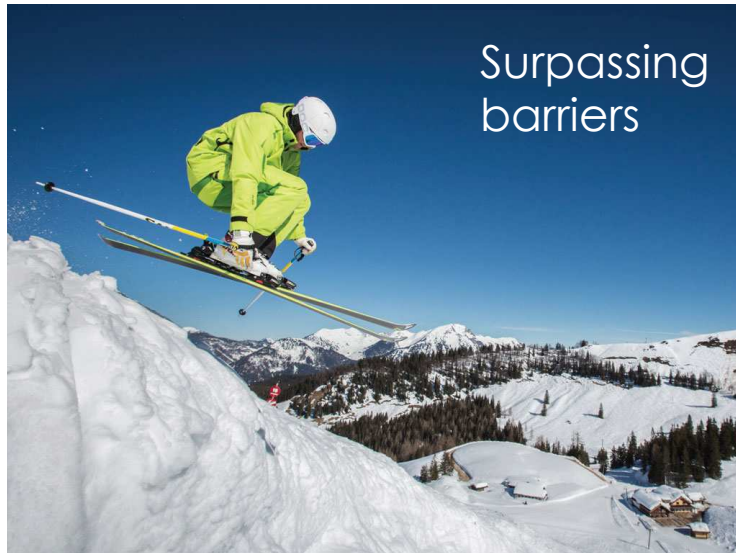
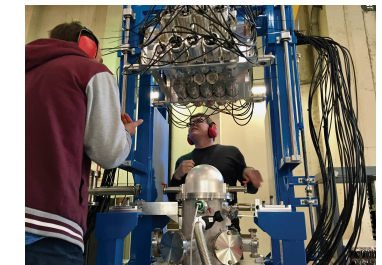
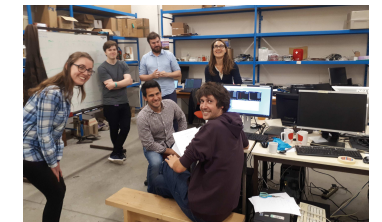
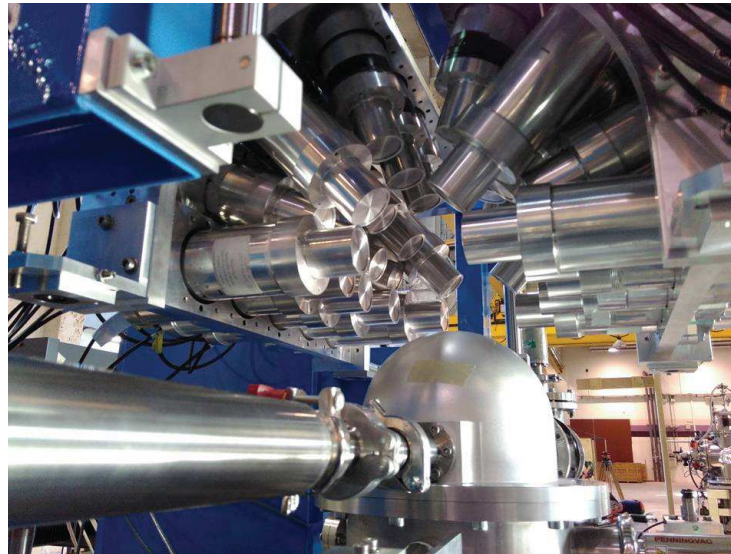


Sub-barrier fusion measurements of astrophysics interest



Surpassing
barriers

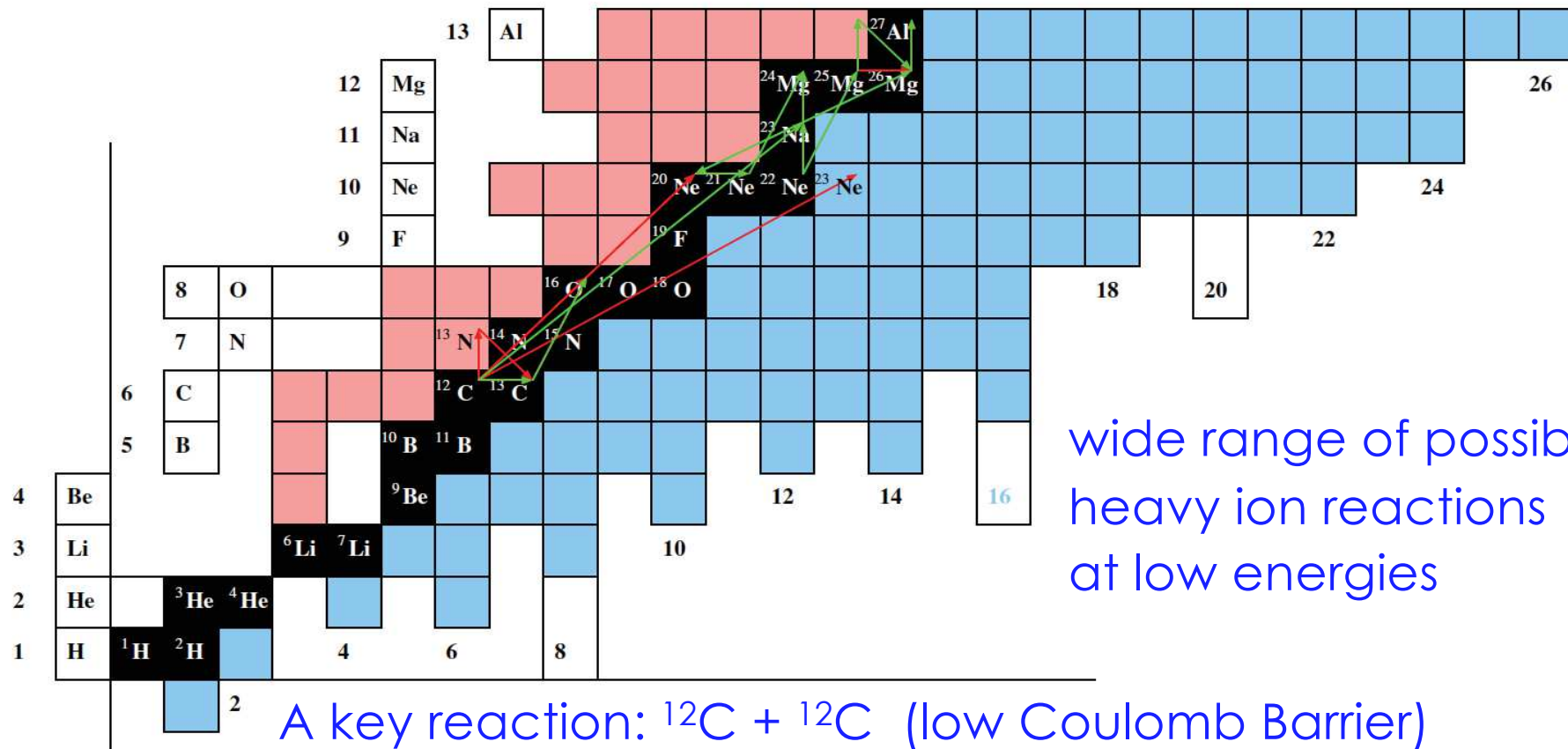


Sandrine Courtin
IPHC and University of Strasbourg, France
STELLA collaboration (France – UK – Switzerland)

- I. Why is it interesting to measure sub-barrier fusion cross section data?
- II. New techniques for $^{12}\text{C}+^{12}\text{C}$
A toolbox for sub-barrier fusion measurements
- III. New results on the $^{12}\text{C}+^{12}\text{C}$ fusion cross-sections
- IV. Impact on stellar evolution and nucleosynthesis

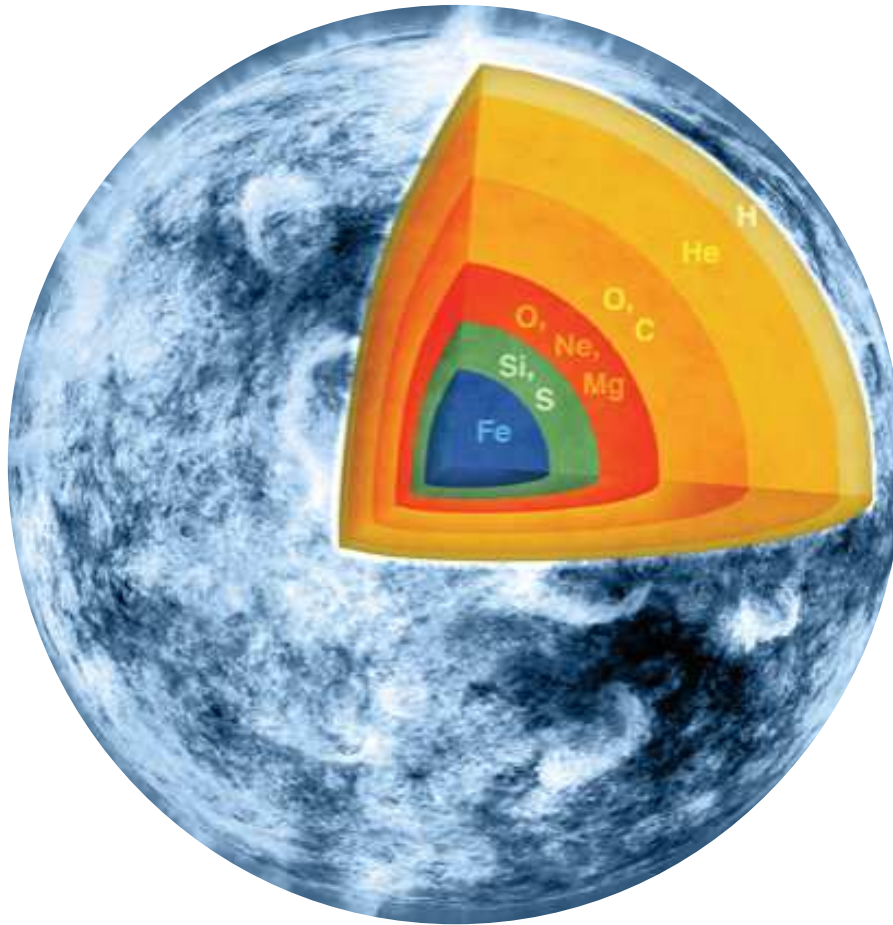
Carbon burning: an important phase in the stellar nucleosynthesis

The $^{12}\text{C}+^{12}\text{C}$ reaction - nucleosynthesis



$$E_G = 2.42 \times T_9^{2/3} \pm 0.75 \times T_9^{5/6} \rightarrow E_G = 1.5 \pm 0.3 \text{ MeV at } 5 \times 10^8 \text{ K}$$

Carbon burning: an important phase in the stellar nucleosynthesis



Different shells of a massive star before core collapse (source NASA)

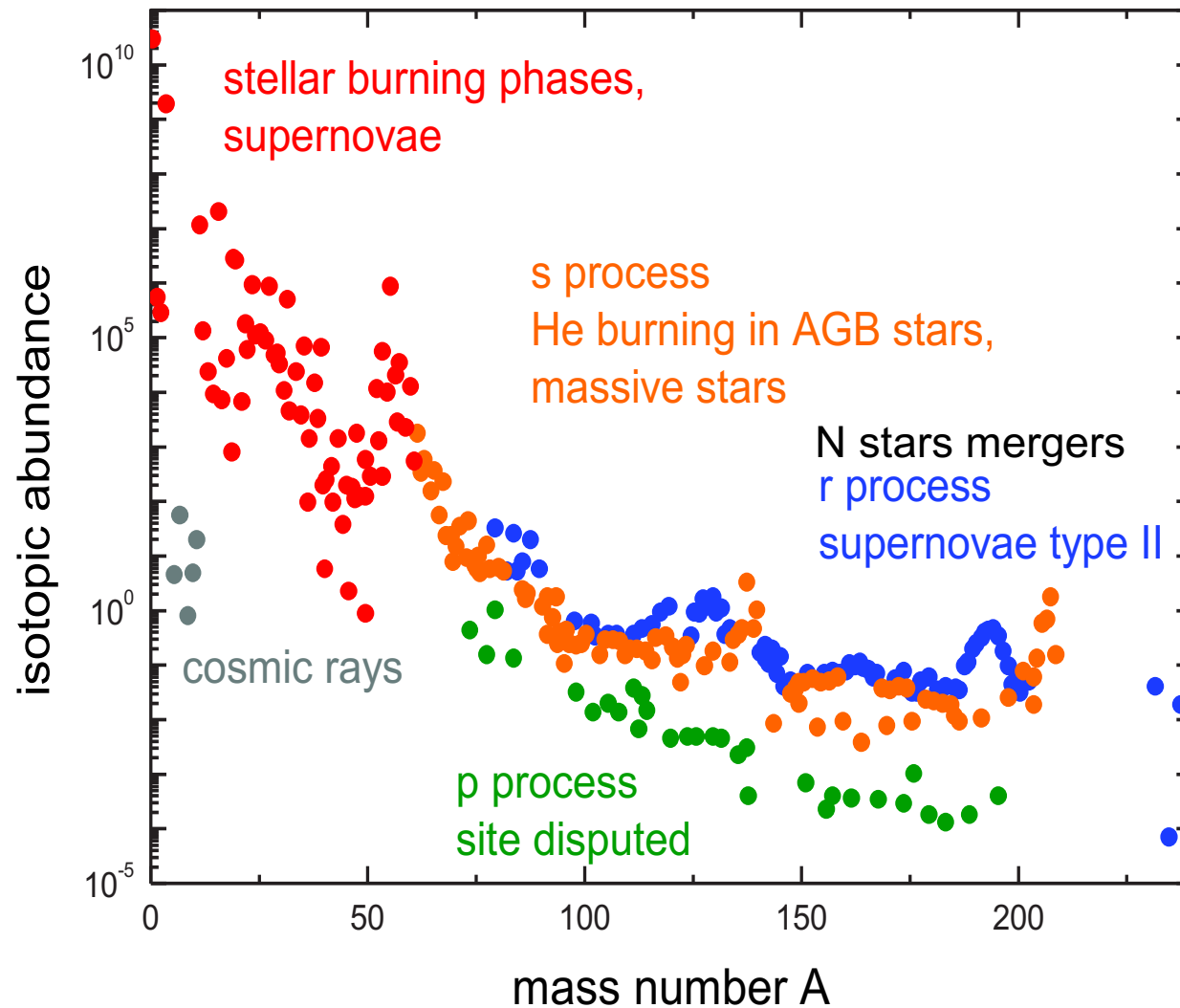
- key reactions at each stage of stellar burning

Fuel	Main Product	Secondary Product	T (10 ⁹ K)	Time (yr)	Main Reaction
H	He	¹⁴ N	0.02	10 ⁷	4 H $\xrightarrow{\text{CNO}}$ ⁴ He
He	O, C	¹⁸ O, ²² Ne s-process	0.2	10 ⁶	3 He ⁴ \rightarrow ¹² C ¹² C(α, γ) ¹⁶ O
C	Ne, Mg	Na	0.8	10 ³	¹² C + ¹² C
Ne	O, Mg	Al, P	1.5	3	²⁰ Ne(γ, α) ¹⁶ O ²⁰ Ne(α, γ) 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(γ, α)...

- 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.

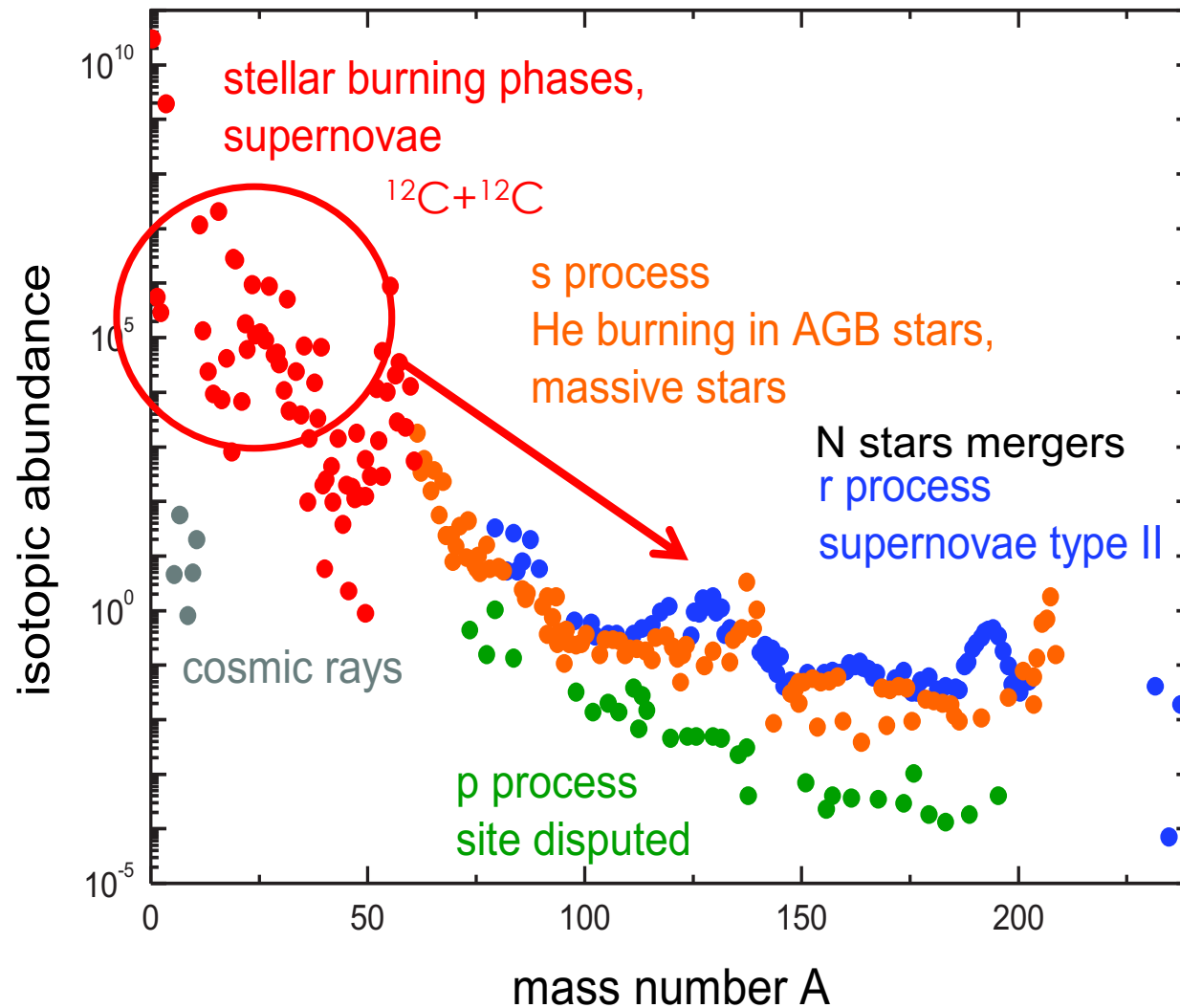
C burning and Abundances

Astrophysics



C burning and Abundances

Astrophysics



Burning phases in massive stars

Evolution of a star: mass
Several reactions / each phase
(time and energy release)

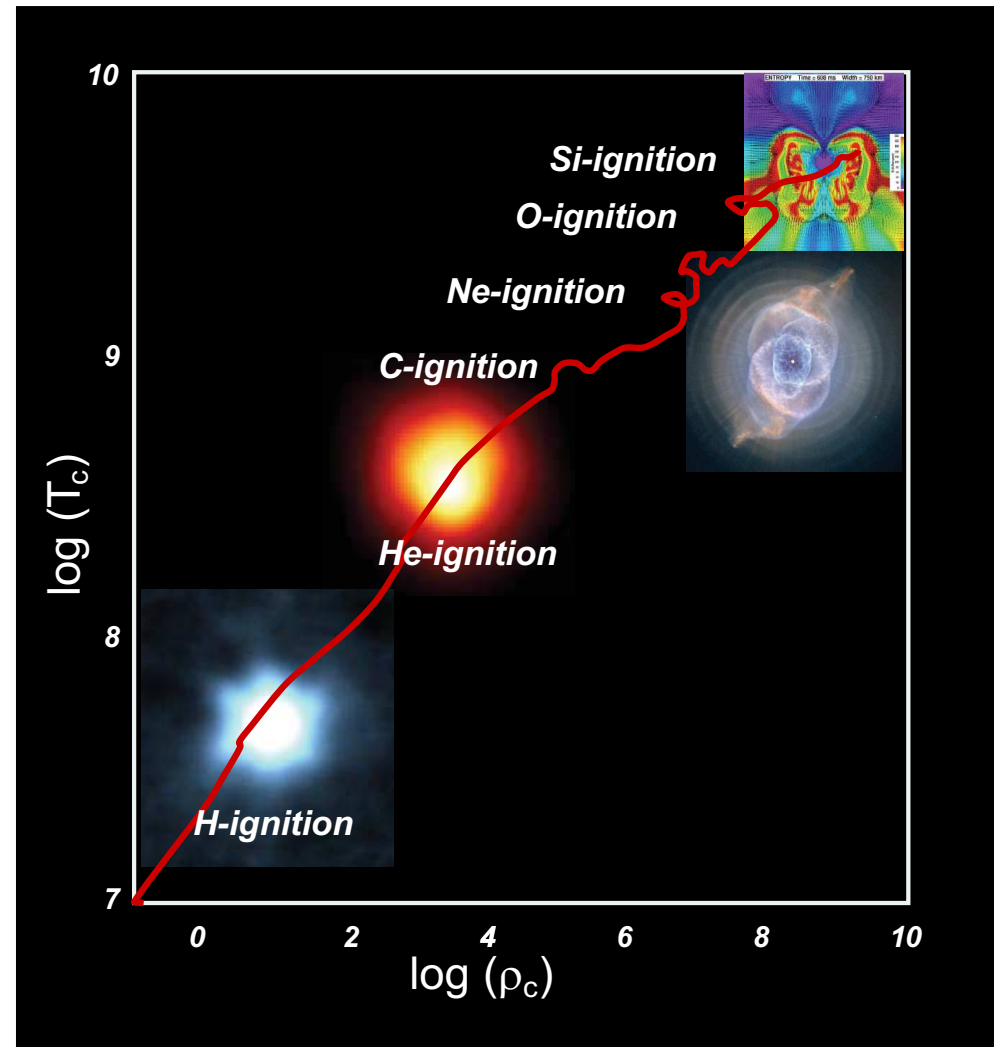
Synthesis of the chemical elements

Experiment
Extrapolations ?

Reaction rates:

$$r = N_x N_y \langle \sigma v \rangle (1 + \delta_{xy})^{-1}$$

$$\langle \sigma v \rangle = \left(\frac{8}{\pi \mu} \right)^{1/2} \left(\frac{1}{k_B T} \right)^{3/2} \int_0^\infty \sigma(E) E \exp\left(-\frac{E}{k_B T}\right) dE$$



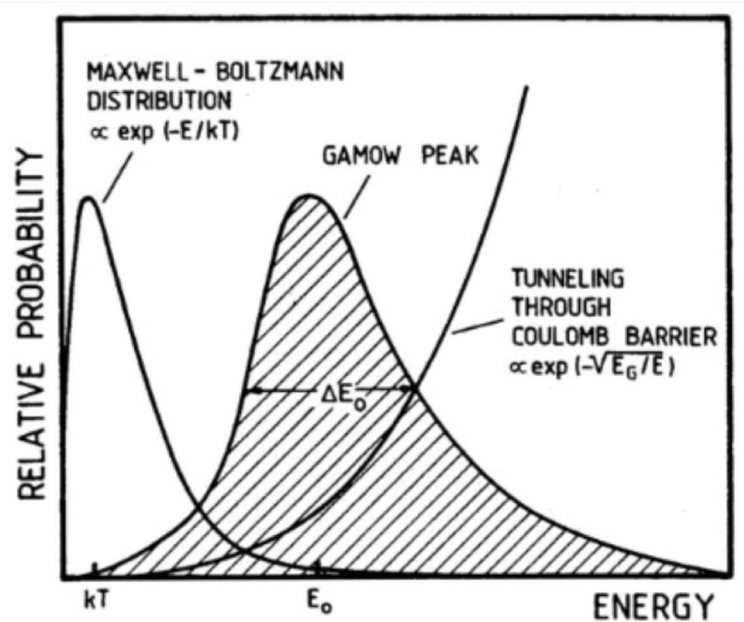
Courtesy : F. Strieder

Fusion reactions at thermonuclear energies

Nuclear potential:
Coulomb barrier $\sim Z_1 Z_2 \sim \text{MeV}$

Energy available in the stars:
 $kT \sim 1 \text{ keV}$ ($T_\odot = 1.5 \cdot 10^6 \text{ K}$)
Maxwell-Boltzmann

Tunneling : $P \approx e^{(-2\pi\eta)}$

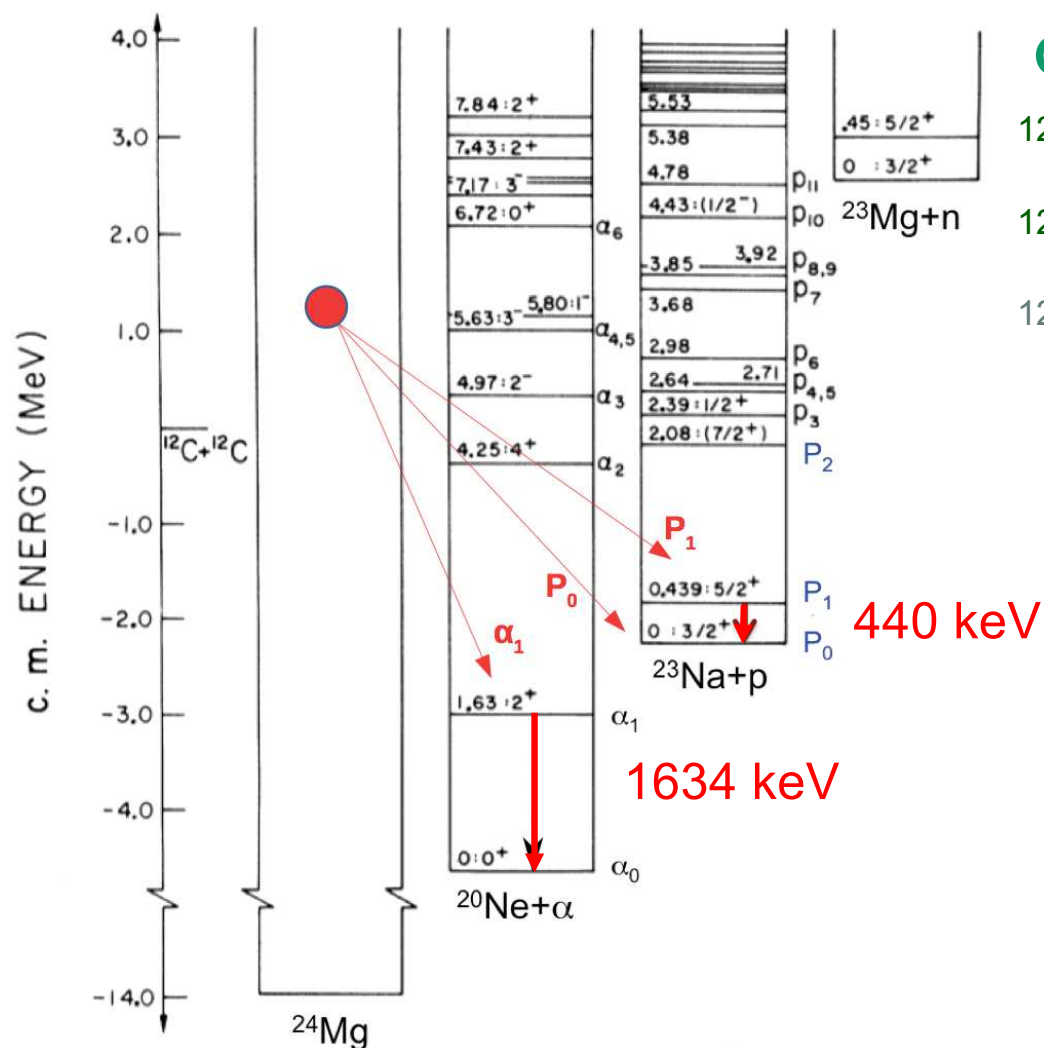


Gamow window

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

Cross section, measured,
Strong energy dependance,
Weak energy dependance,
S-factor – Burbidge 1957.

$^{12}\text{C}+^{12}\text{C}$ fusion cross section measurement



Channels



Cross section :

• Detection of γ -rays:

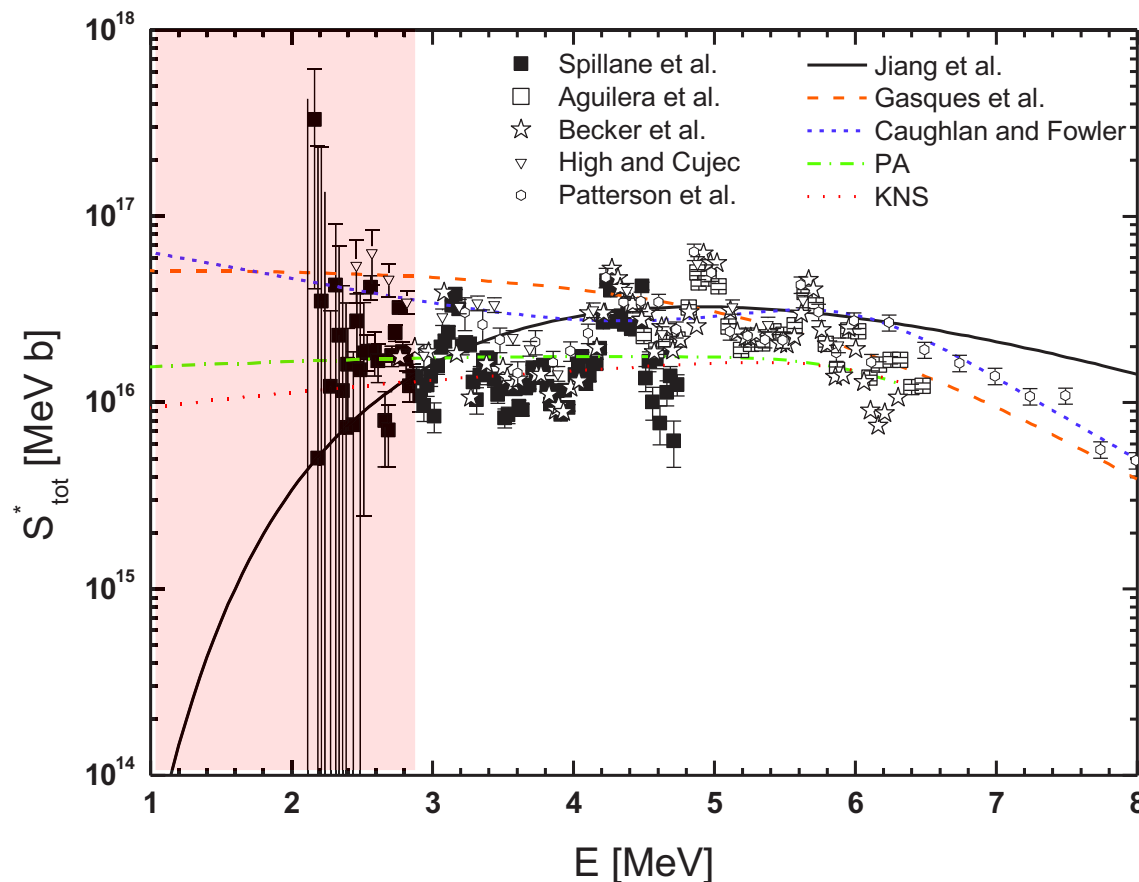
1st ex. state to g.s.

• Detection of particles:

$$\sigma_{p+\alpha} = \sum (\sigma_{pi} + \sigma_{\alpha i})$$

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

Direct measurements



- Single particles **or** γ
- Extrapolations with very different trends
- Crucial role of resonances, important from nuclear structure point of view
→ impact on the reaction rate ?
- Extremely sensitive to background
- Need for reliable direct data at low energies

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

nb to pb range

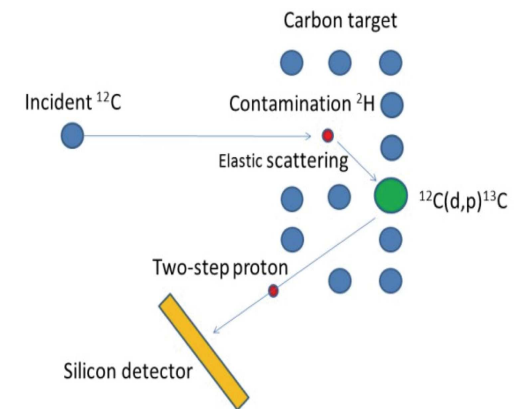
1) Backgrounds:

- Detection of charged particles:

p or d from collisions of C on H or D.

- Detection of γ -rays:

γ from collisions on H or D and from cosmics and from room background.



Gialanella et al., NIC 2011

2) Thin and thick targets measurements

3) Direct measurements: low statistics - long beamtime

Increase beam intensity (– and beamtime)

Adapt target system

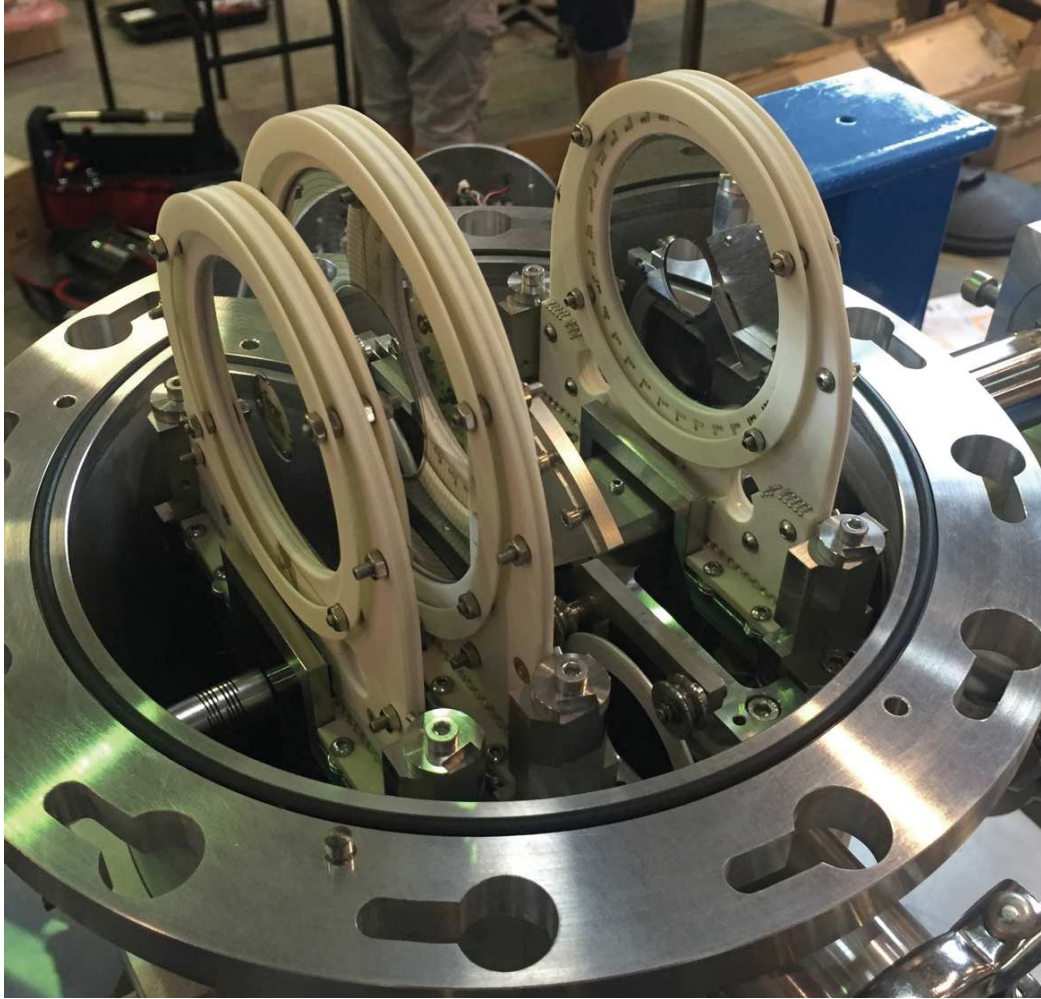
Use of the γ -particle coincidence technique with very good gamma efficiency and timing

Data analysis suited to low statistics

STELLA (Stellar Laboratory)

A toolbox for the measurement of fusion reactions of astrophysics interest

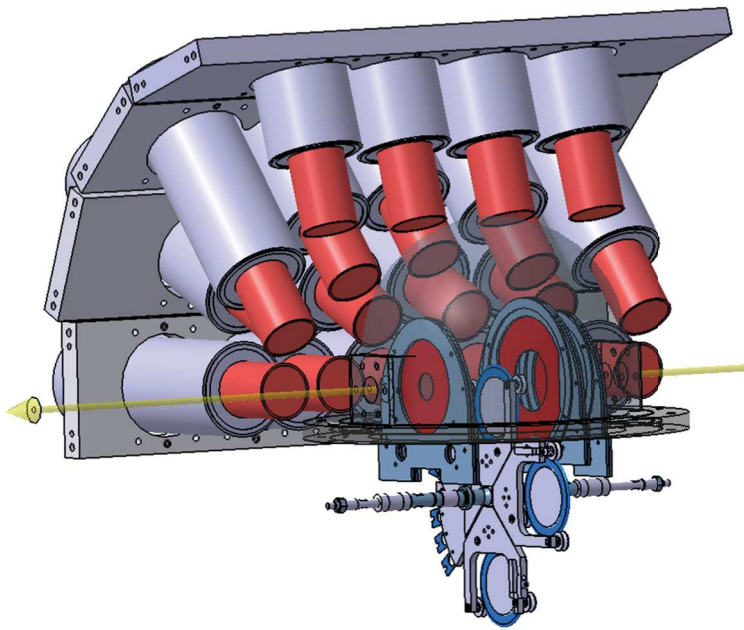
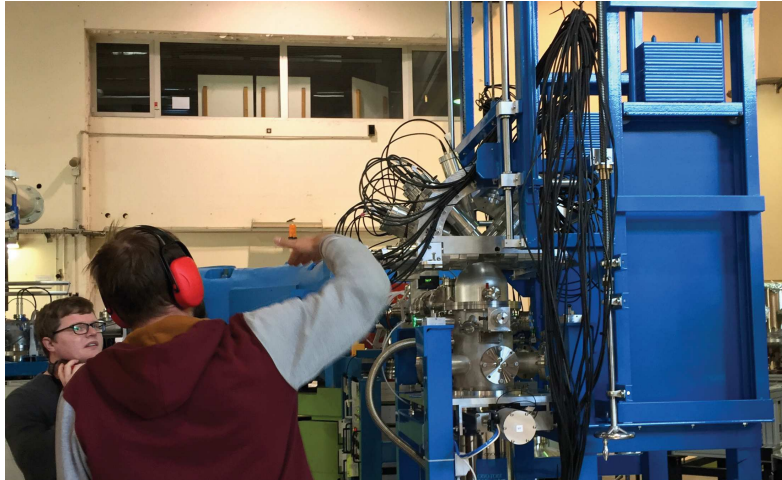
Particle detection



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

STELLA (Stellar Laboratory)

A toolbox for the measurement of fusion reactions of astrophysics interest



Design IPHC : G. Heitz / M. Heine

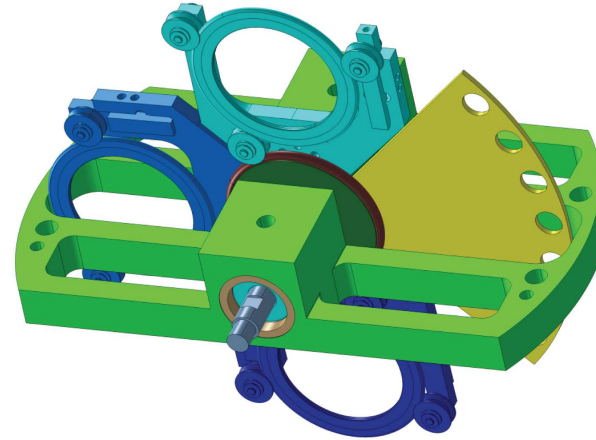
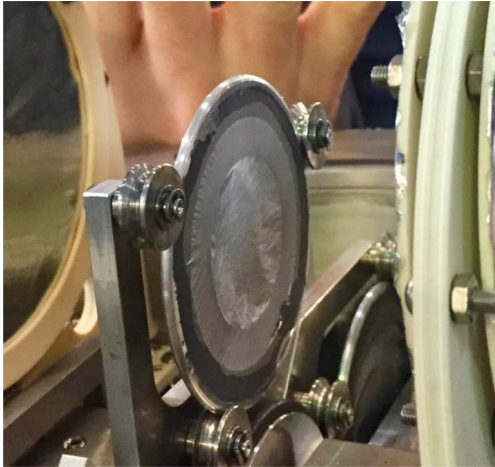
Gamma detection

- 36 LaBr_3 detectors
from the **FATIMA collaboration**
(P. Regan et al., Univ. Surrey, NPL UK)
- Cylindrical geometry
IPHC designed mechanical
support,
Strasbourg + York construction
- Self activity
- $\varepsilon = 6\%$ @ 440 keV
- $\varepsilon = 2\%$ @ 1634 keV

STELLA (Stellar Laboratory)

A toolbox for the measurement of fusion reactions of astrophysics interest

Target system

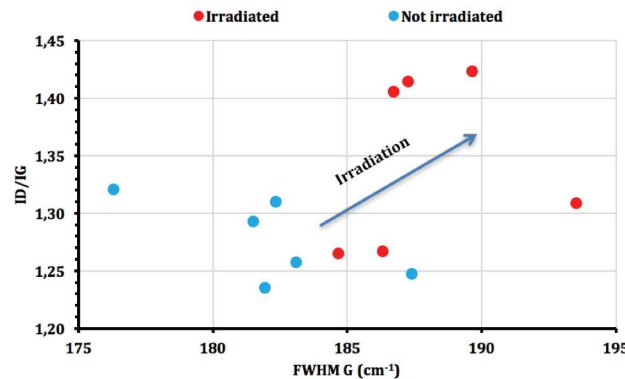
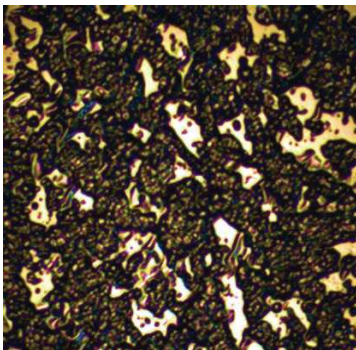


IPHC and GANIL collaboration

Cryogenic pumping, 20cm.

Thin target system (<200 nm)/
Thickness and homogeneity
monitored with a scanning setup

M. Heine, S. Courtin et al., NIM, A 903 (2018) 1–7



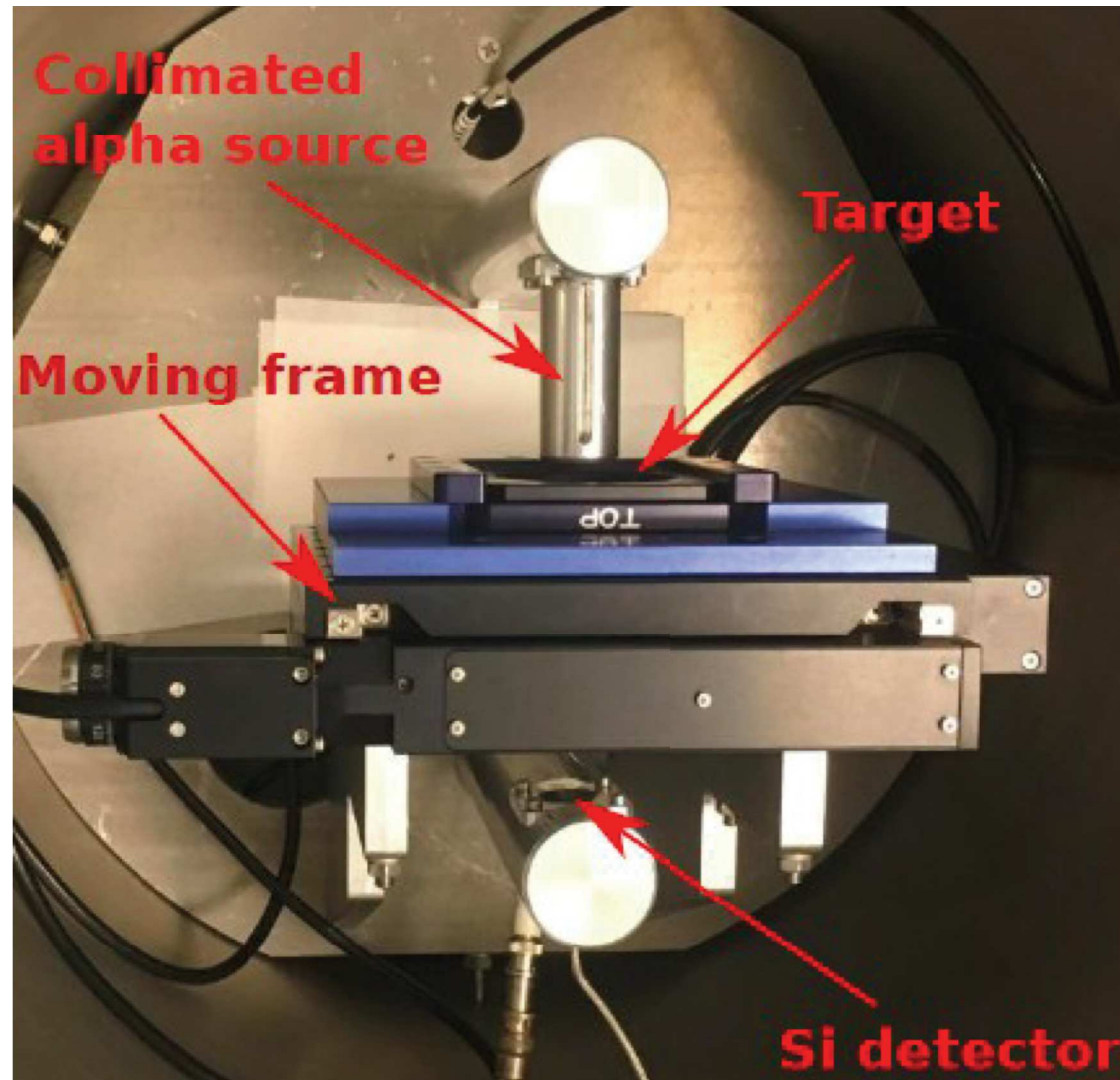
Raman analysis

-> no C build-up

Raman ->no structure change
(amorphous C)

- Rotating target (1000 rpm)

- ^{12}C beam: $I > 1 \text{ p}\mu\text{A}$



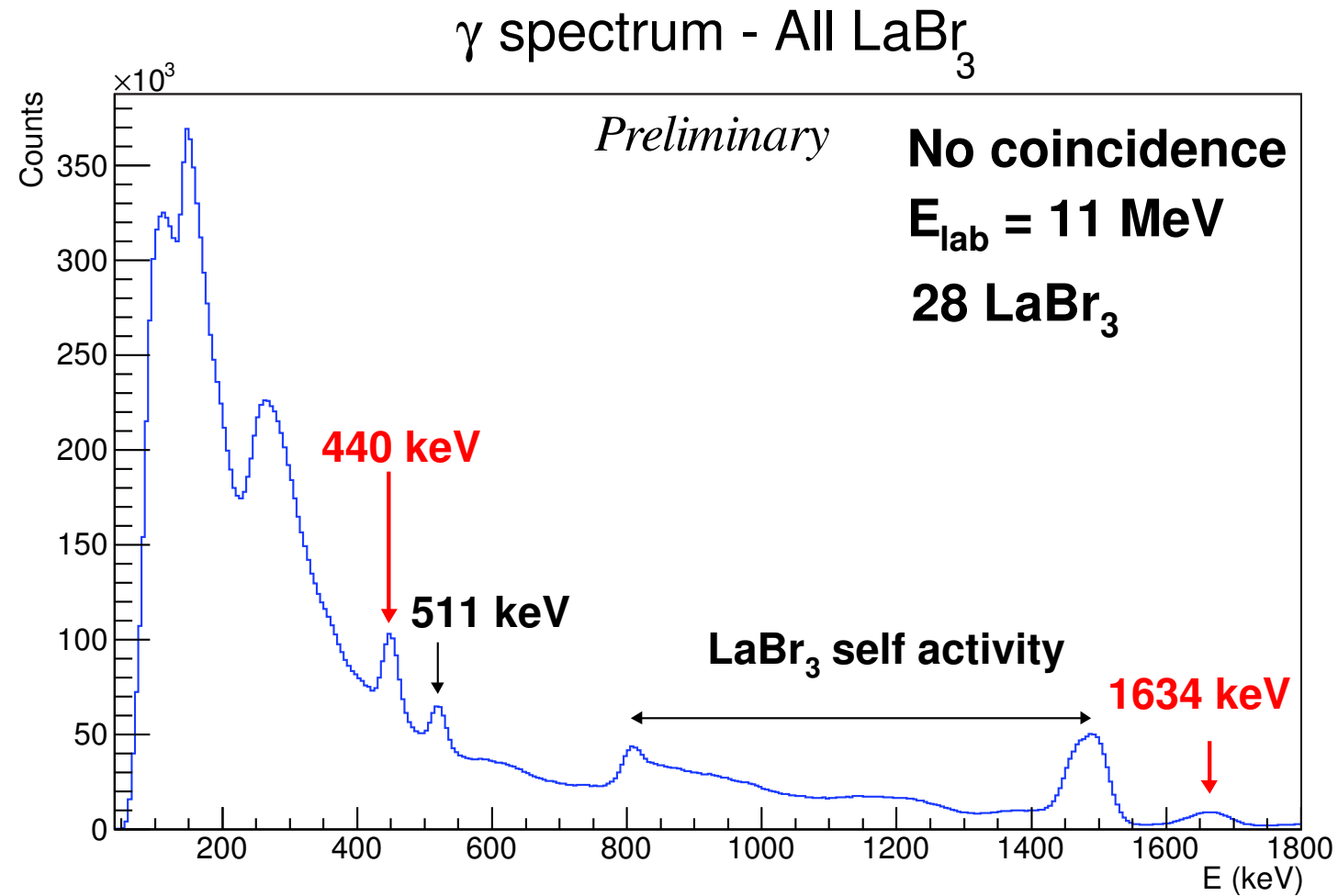
STELLA (Stellar Laboratory)

A toolbox for the measurement of fusion reactions of astrophysics interest

Beam

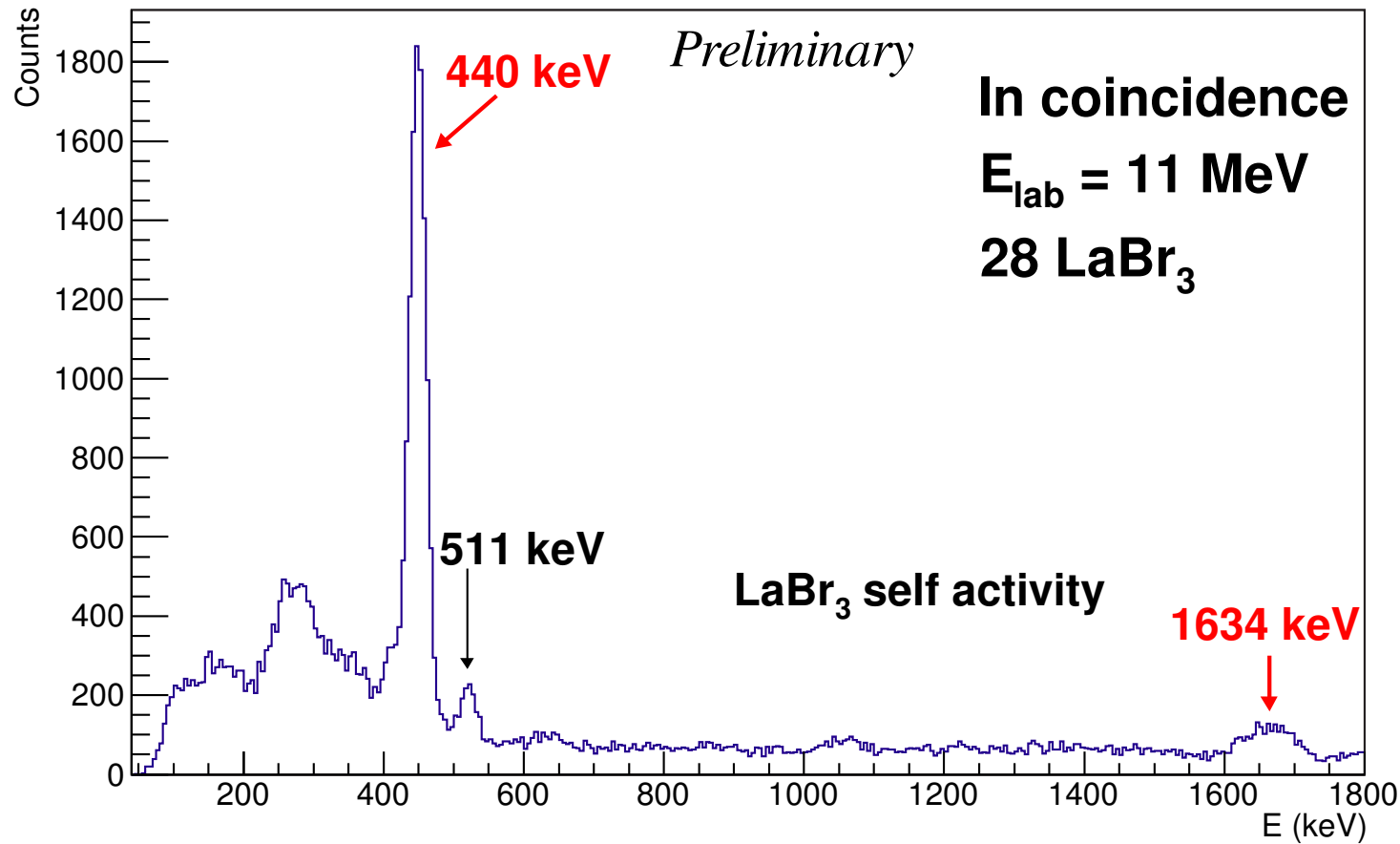


- Andromede facility, University of Paris-Sud – Orsay, 12 weeks
- 4 MV Pelletron
- ECR Source
- ^{12}C up to $10\ \mu\text{A}$



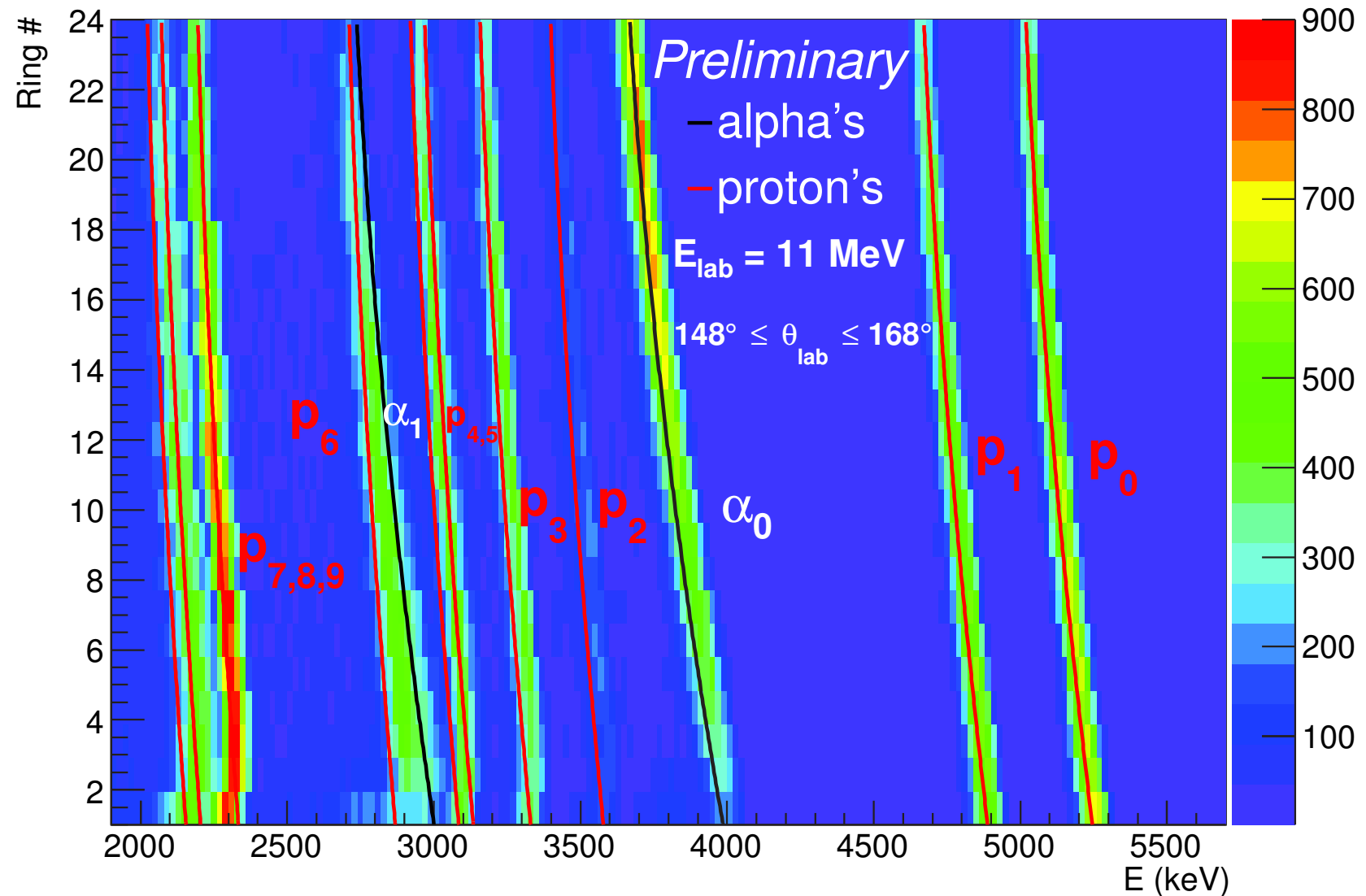
Self activity & γ of interest from $^{12}\text{C}+^{12}\text{C}$ fusion

Coinc. γ spectrum - All LaBr_3

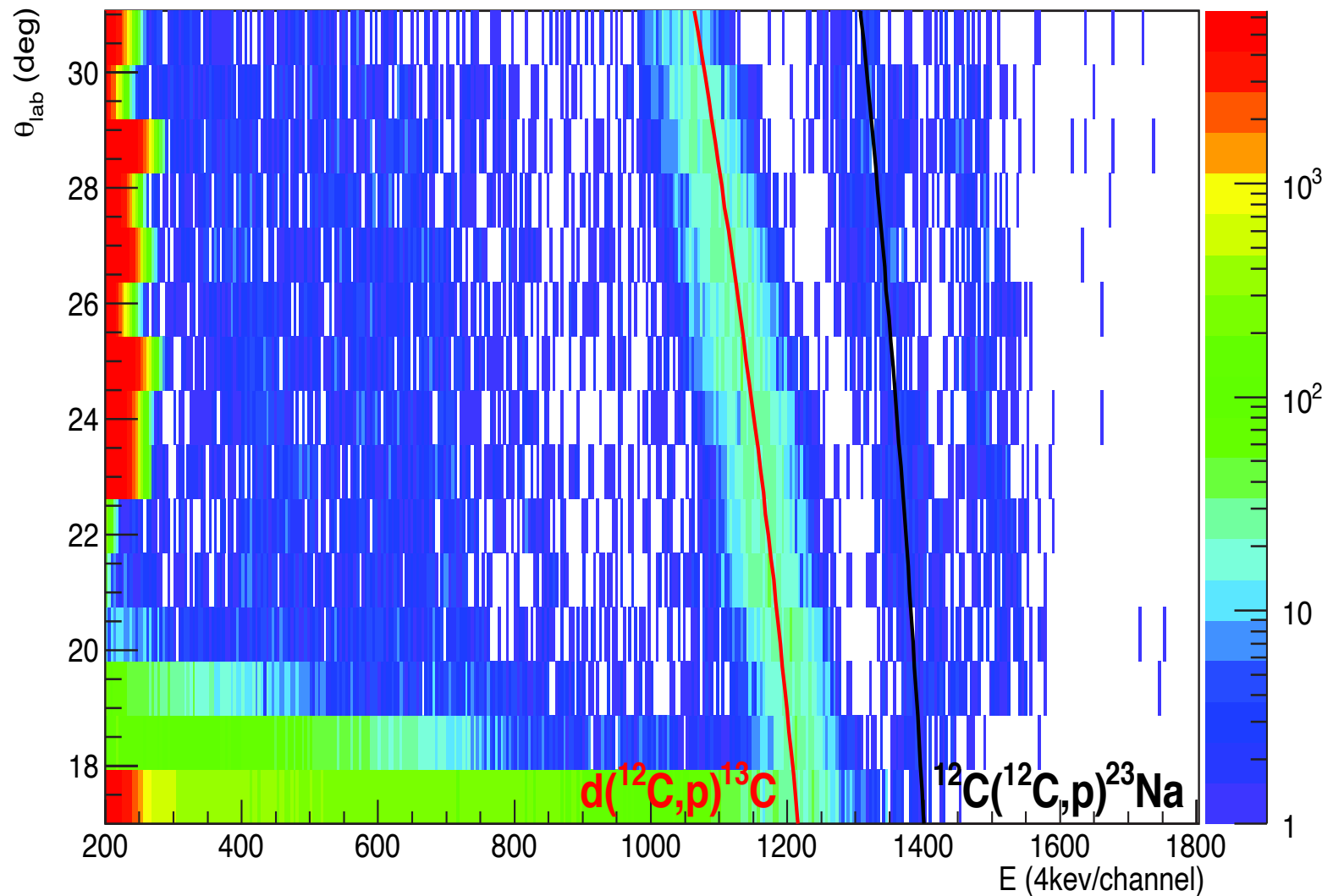


Coincidence with 1 particle : γ from fusion

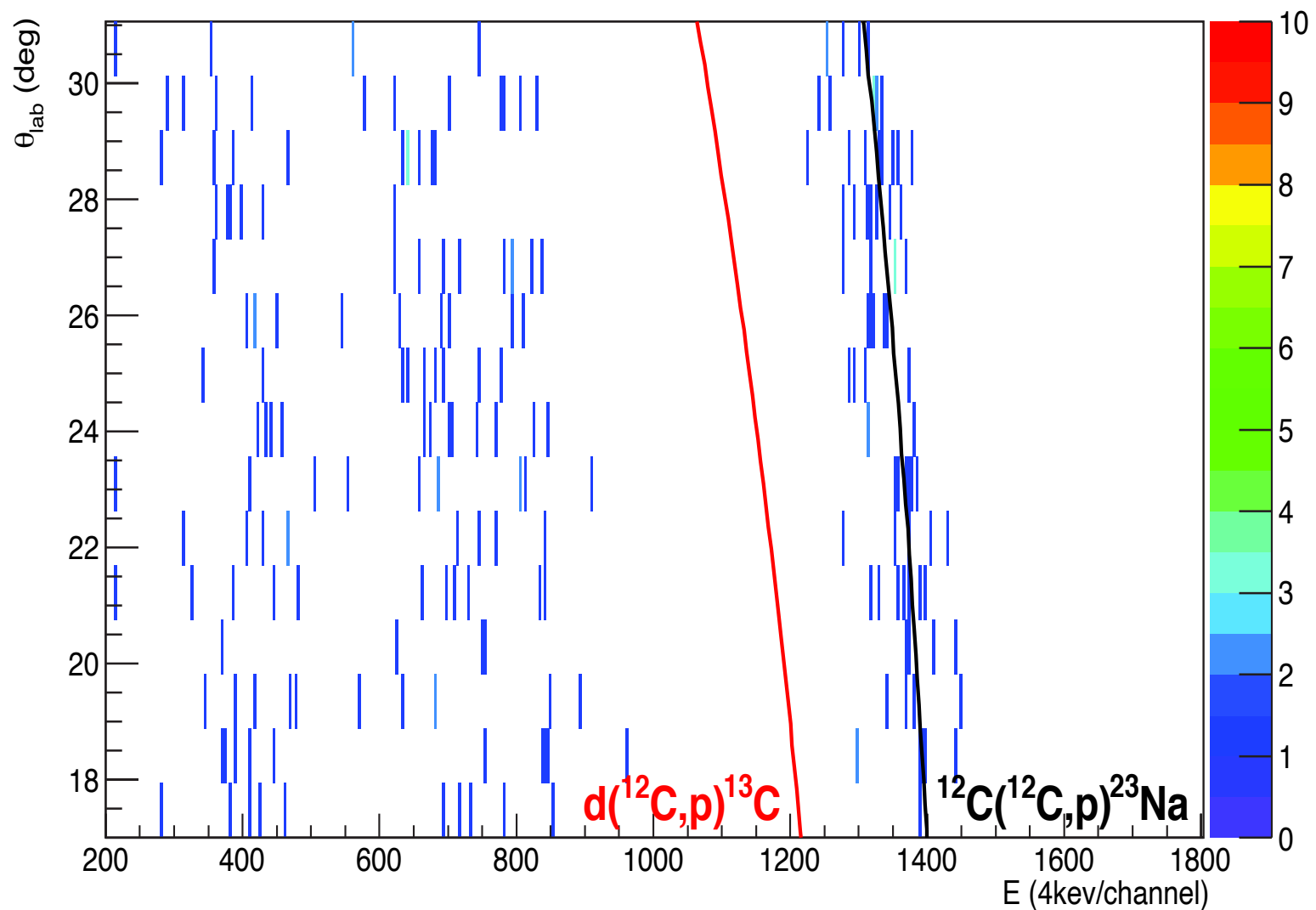
S3B - Without coincidences



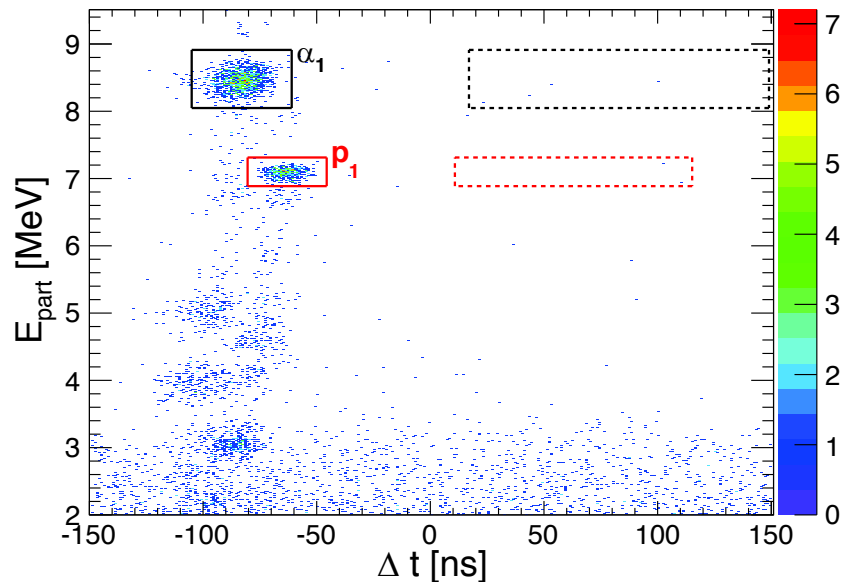
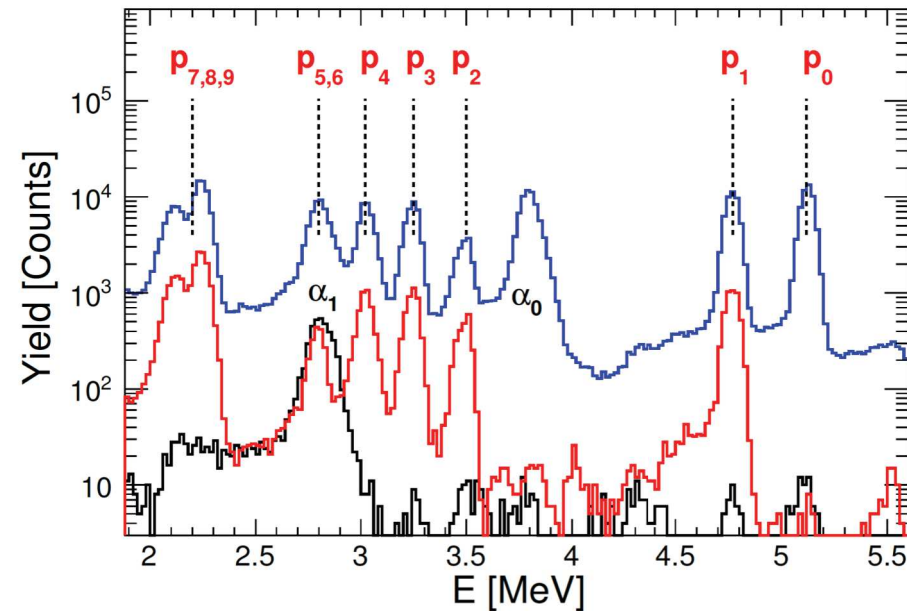
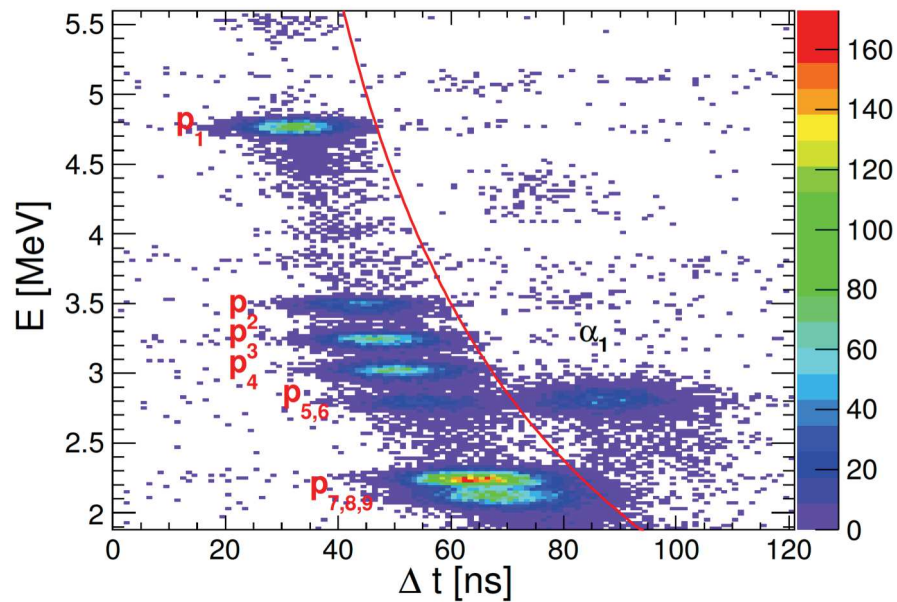
Particle spectrum



Coincidence with $E_\gamma = 440$ keV



Timing and background ...



Examples: $E = 5.33$ MeV and $E = 3.77$ MeV
Time-stamped data

Timing difference Δt , between gammas and charged particles vs. the particle Energy at $E = 3.77$ MeV.
The solid and dotted lines indicate 3σ intervals for the selection of the reaction channels and the background, respectively

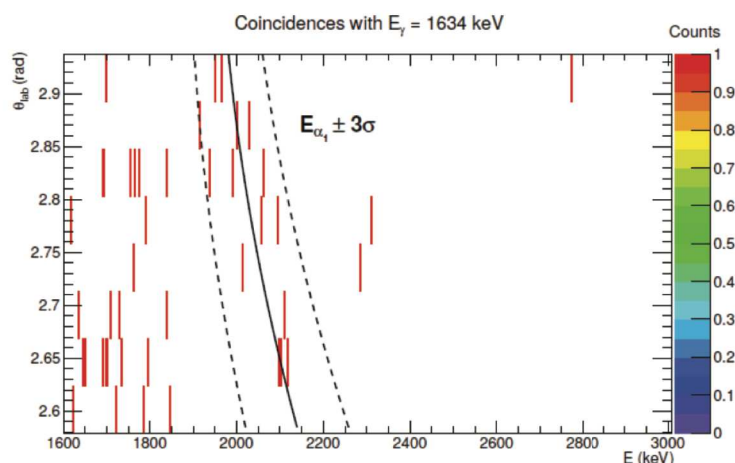
Low statistics analysis – confidence intervals

Simple case :

For 1 data observed with and estimated background 0

$$\mu = n - b = 1 + 1.755 - 0.63$$

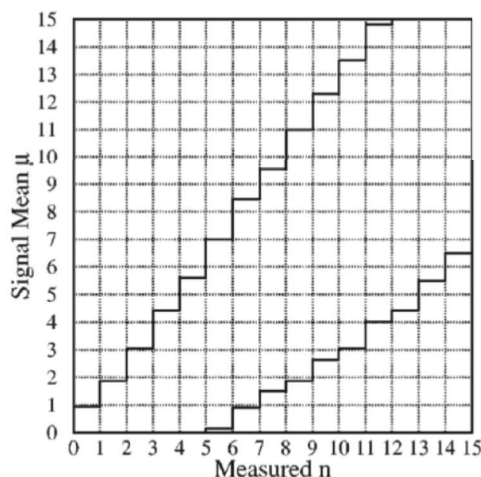
At 0.68 %CL the confidence interval is: [0.37, 2.755]



$$n = 15 \text{ (observed)}$$

$$b = R_\gamma \cdot R_\alpha \cdot t_{\text{coinc}} \cdot t_{\text{exp}} \\ = 12 \text{ (bkgr.)}$$

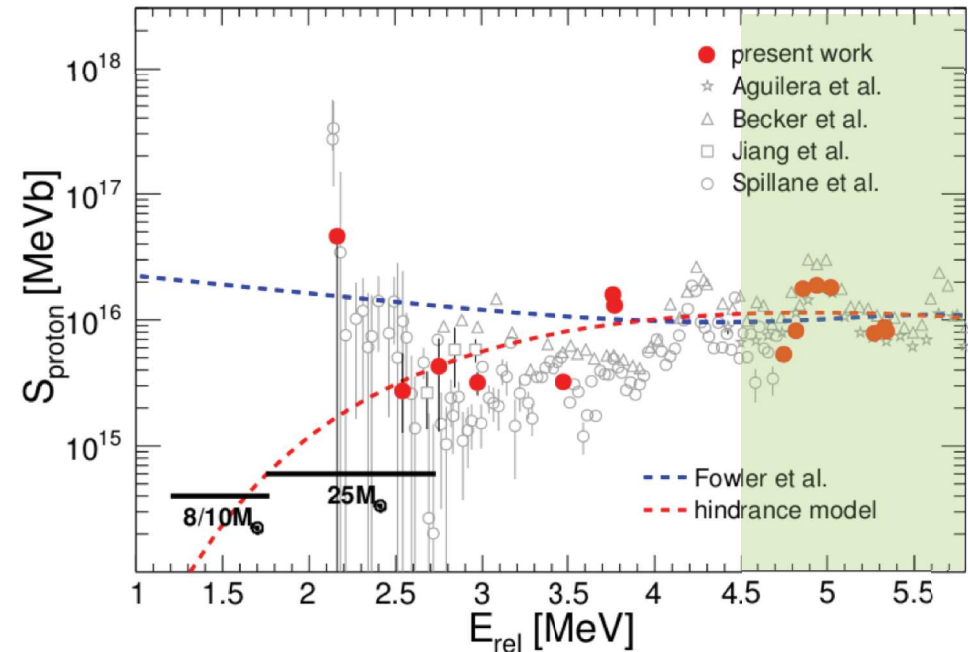
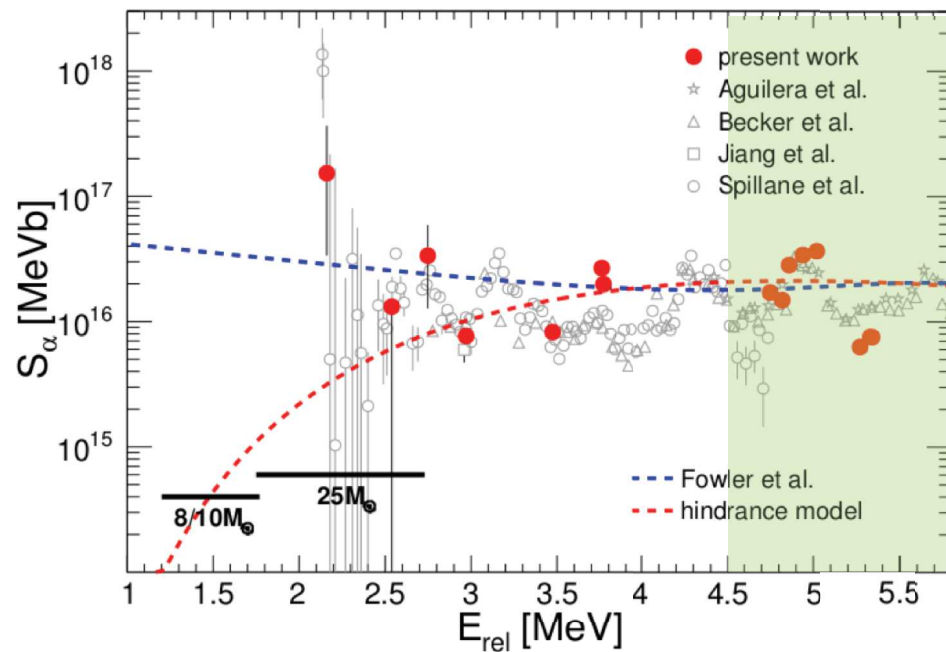
$$\mu = n - b = 3 \text{ (signal)}$$



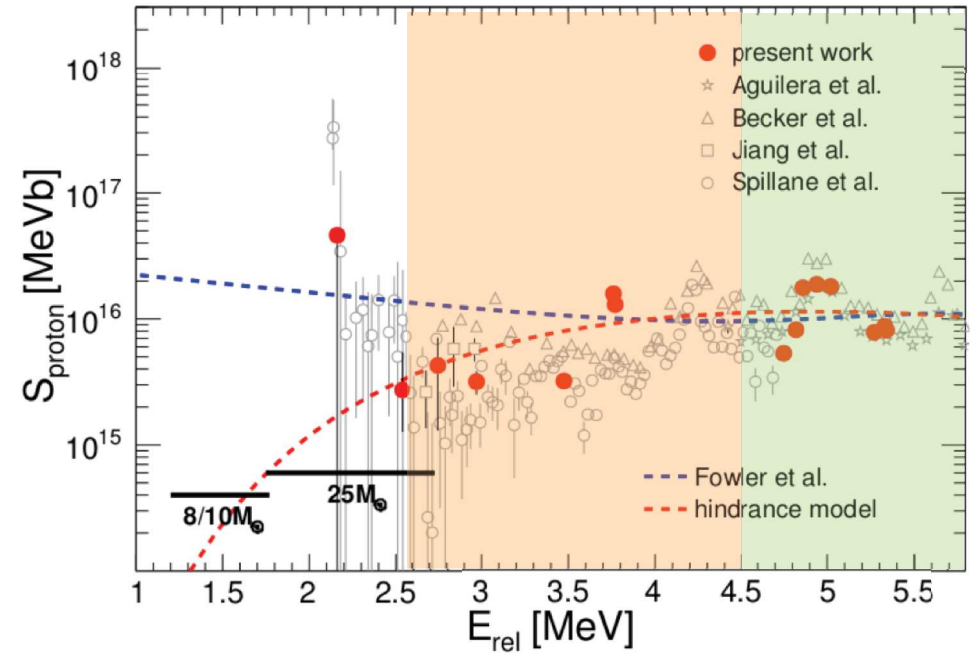
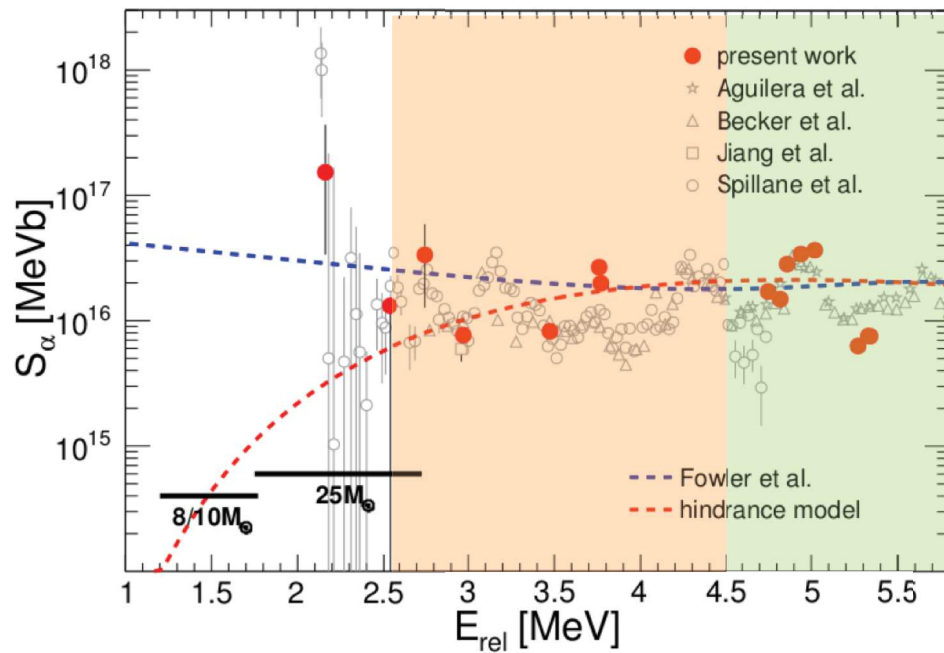
$$\frac{\Delta\mu}{\mu} = \sqrt{\left(\frac{\Delta n}{n}\right)^2 + \left(\frac{\Delta b}{b}\right)^2} \approx \frac{\Delta n}{n}$$

$$\rightarrow \mu = 3 \pm \sqrt{15} \text{ unphysical}$$

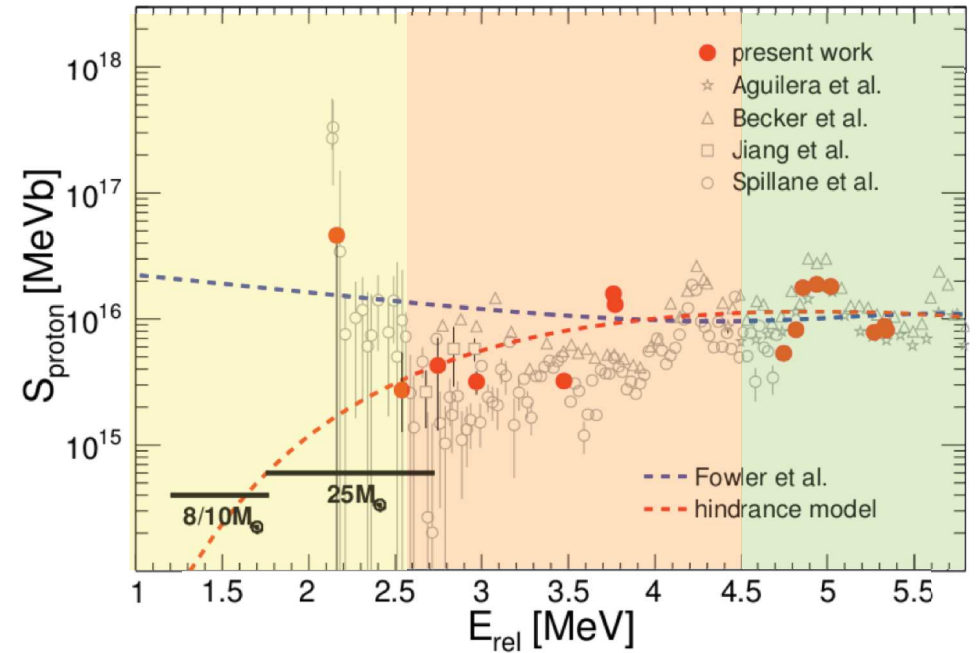
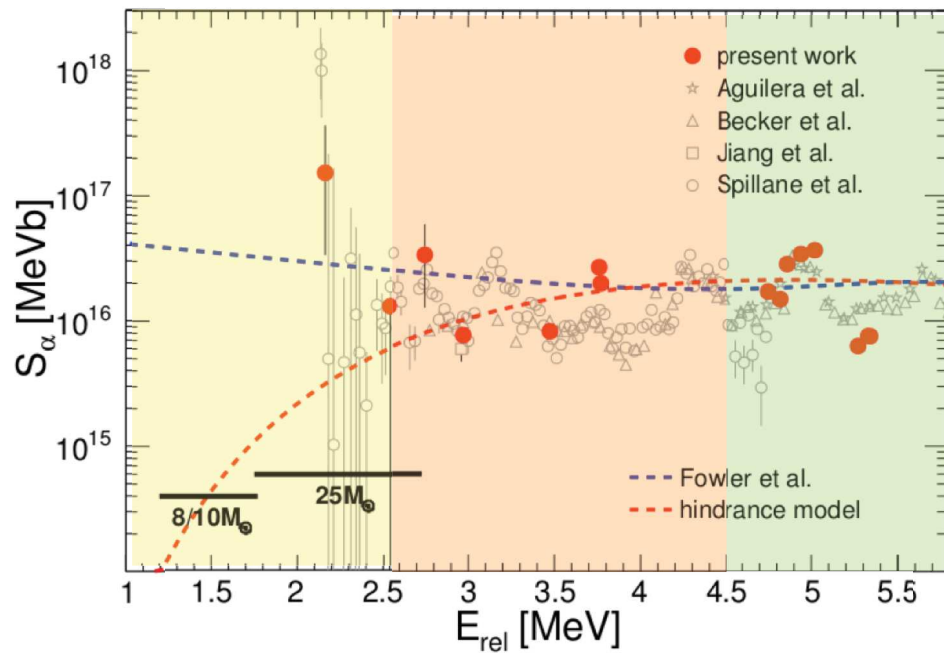
$$\Rightarrow \mu \in [0, 6.32]$$



- Reliable excitation functions over 8 orders of magnitude, down to 2.16 MeV
- Three regimes:
 - Moderate sub-barrier E: validation of the experimental concept**



- Reliable excitation functions over 8 orders of magnitude, down to 2.16 MeV
- Three regimes:
 - i. Moderate sub-barrier E: validation of the experimental concept
 - ii. Deep sub-barrier E: hindrance regime



- Reliable excitation functions over 8 orders of magnitude, down to 2.16 MeV
- Three regimes:
 - Moderate sub-barrier E: validation of the experimental concept**
 - Deep sub-barrier E: hindrance regime**
 - Gamow window - 25 M_{\odot} E: another regime ?**

Fusion hindrance and resonances

Origin ?

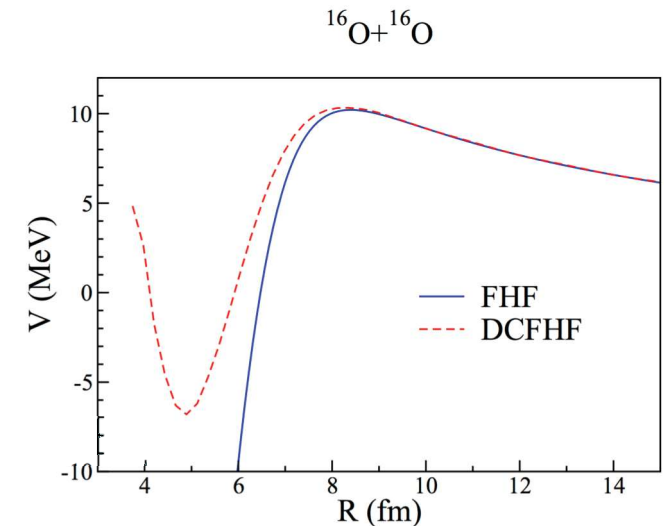
Hindrance:

- Adiabatic potential model (two steps model: capture in a 2 body potential pocket / penetration of one body potential -> compound nucleus state)

T.Ichikawa, K.Hagino and A.Iwamoto et al., Phys. Rev. C75 (2007), Phys. Rev. Lett. 103 (2009).

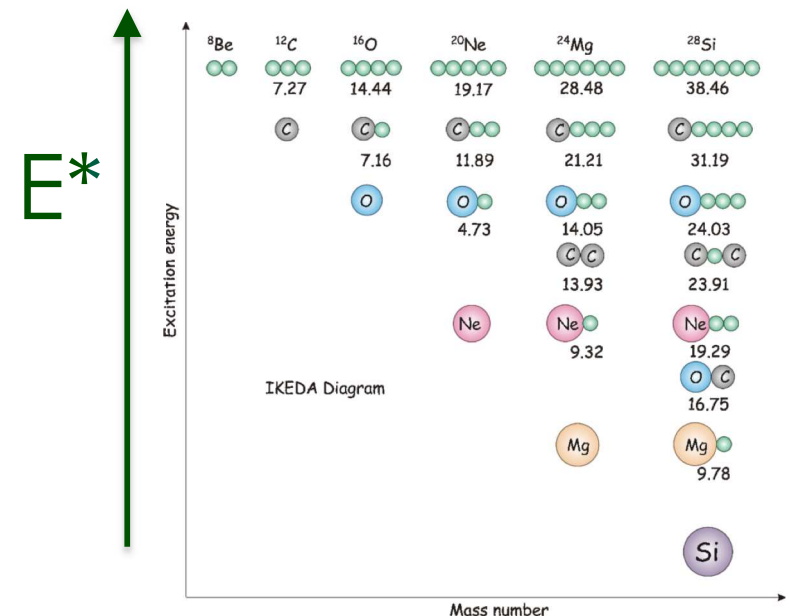
- Pauli principle

C. Simenel et al. Phys.Rev. C. 95 (2017), Phys. Rev. C 100



Resonances :

Ikeda



Ikeda, K; Tagikawa, N and Horiuchi, H (1968). The Ikeda Diagram. *Prog. Theo. Phys. Suppl.* extra number: 464.

Fusion hindrance and resonances

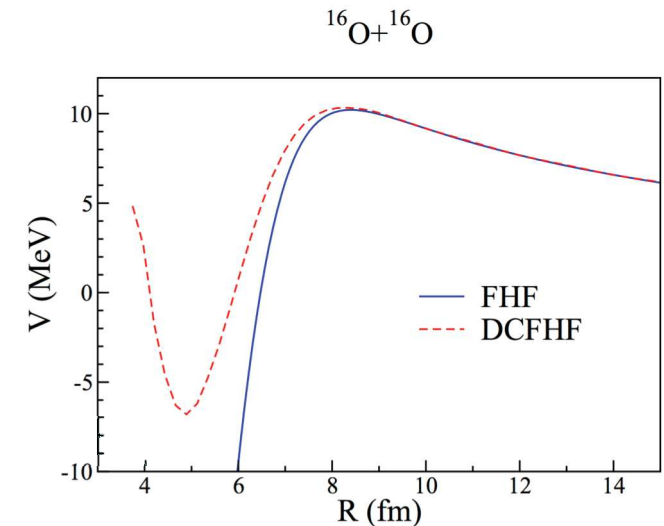
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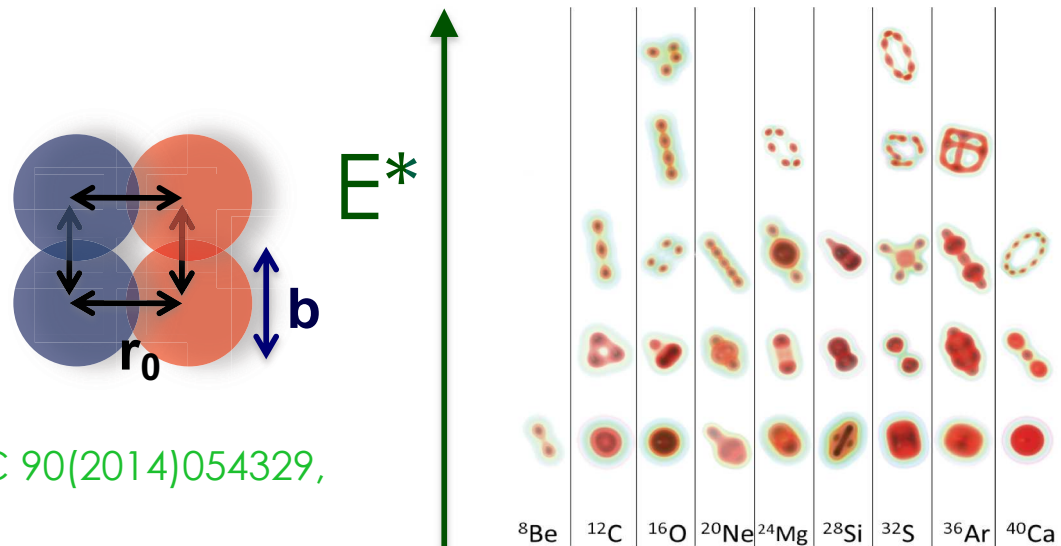


Resonances :

Ikeda

Emergence of clusters

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



J.-P. Ebran, E. Khan, T. Niksic, D. Vretenar, PRC 90(2014)054329,
Nature 487(2012)34

Fusion hindrance and resonances

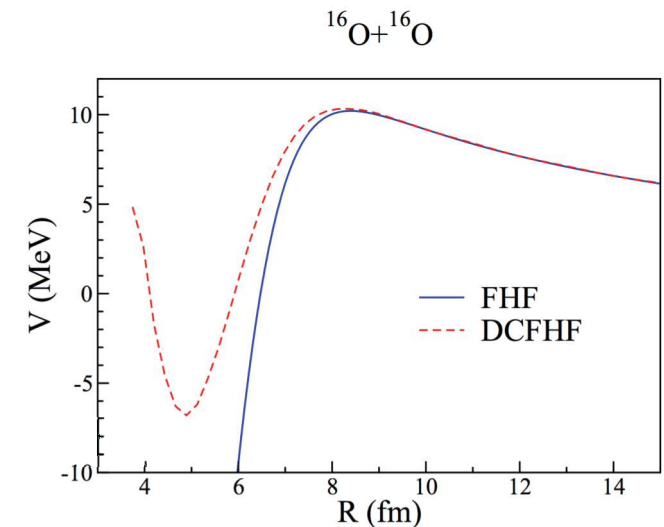
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T. Ichikawa, K. Hagino and A. Iwamoto et al., Phys. Rev. C75 (2007), Phys. Rev. Lett. 103 (2009).

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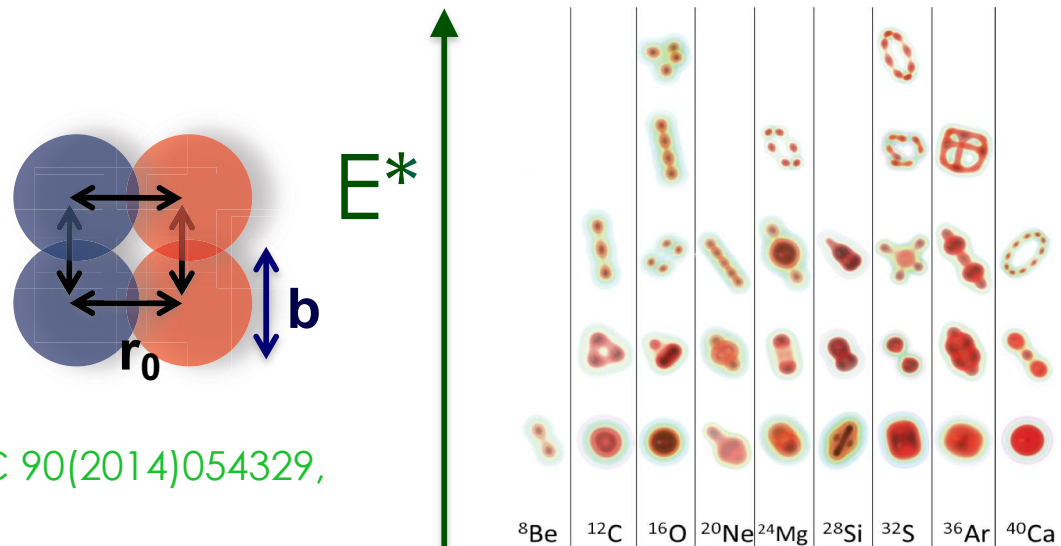
Resonances :

Ikeda

Emergence of clusters

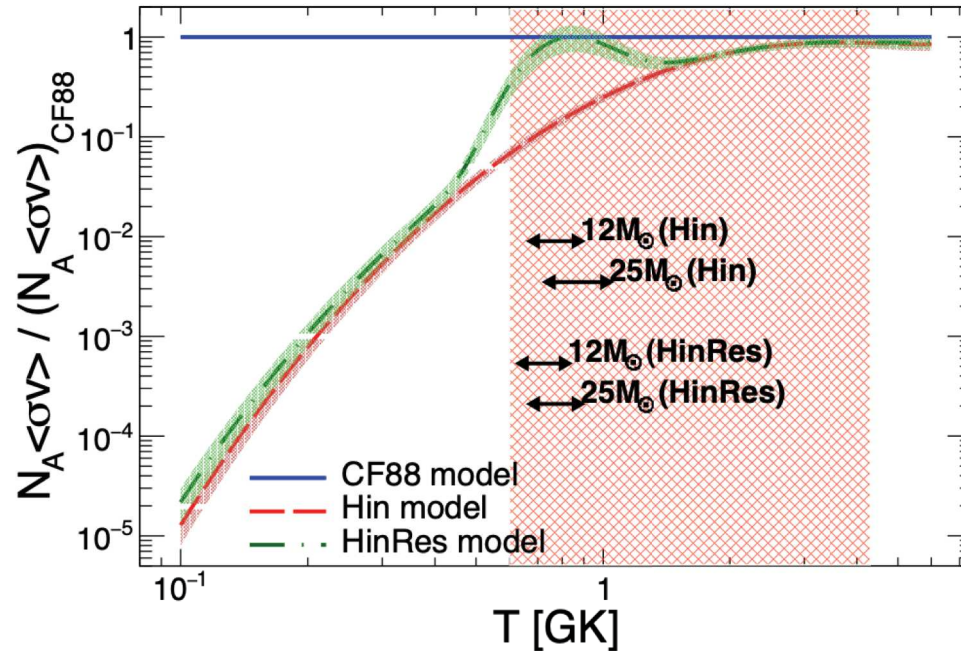
- $\alpha_{\text{loc}} = b/r_0$
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J.-P. Ebran, E. Khan, T. Niksic, D. Vretenar, PRC 90(2014)054329, Nature 487(2012)34



Density of states, Jiang et al, Phys. Rev. Lett. 110 (2013)

Impact on stellar evolution and nucleosynthesis



Normalized reaction rates

$$\langle \sigma v \rangle = \left(\frac{8}{\pi \mu} \right)^{1/2} \left(\frac{1}{k_B T} \right)^{3/2} \int_0^\infty \sigma(E) E \exp\left(-\frac{E}{k_B T}\right) dE$$

Collaboration with Observatory of Geneva & Université Libre de Bruxelles

- GENEC – Nucleosynthesis in a box –

E. Monpriat, S. Martinet, S. Courtin et al. A&A 660, A47 (2022)

Hindrance case:

C-burning phase found to occur at central temperatures 10% higher than with H and R
C-burning lifetime is reduced by a factor of 2.

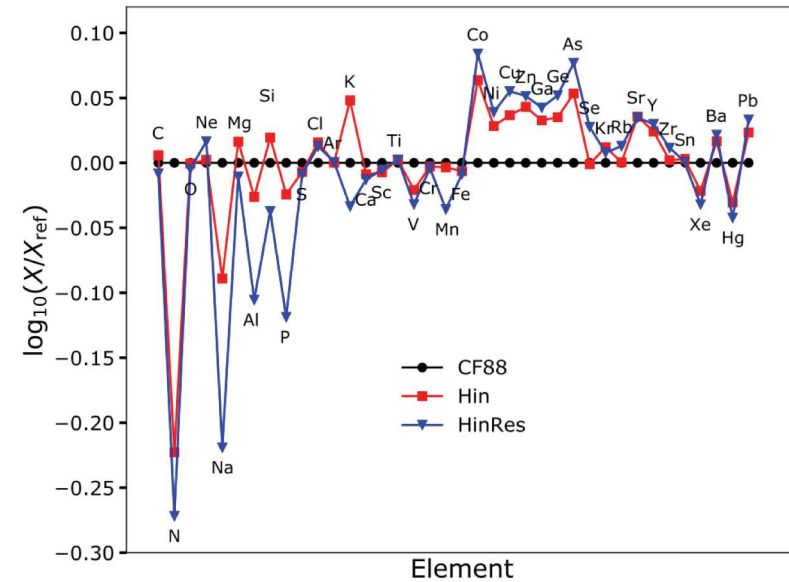


Fig. 9. Abundances obtained at the end of the C-burning phase normalised to the final abundances obtained using the CF88 rate. Only the elements with a mass fraction greater than 10^{-8} (in either the first or second model) are considered.

A&A 660, A47 (2022)
<https://doi.org/10.1051/0004-6361/202141858>
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**Astronomy
& Astrophysics**

A new $^{12}\text{C} + ^{12}\text{C}$ nuclear reaction rate: Impact on stellar evolution

E. Monpriat¹, S. Martinet², S. Courtin^{1,3}, M. Heine¹, S. Ekström², D. G. Jenkins^{3,4}, A. Choplin⁵, P. Adsley^{6,7}, D. Curien¹, M. Moukaddam¹, J. Nippert¹, S. Tsiatsiou², and G. Meynet²

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³ University of Strasbourg Institute of Advanced Studies (USIAS), Strasbourg, France

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⁶ Cyclotron Institute, Texas A&M University, College Station, TX 77843, USA

⁷ Department of Physics & Astronomy, Texas A&M University, College Station, TX 77843, USA

Received 23 July 2021 / Accepted 25 November 2021

- A new experimental setup for reactions of astrophysics interest
- $^{12}\text{C}+^{12}\text{C}$ deep sub-barrier fusion measured
Use of particle – γ coincidences (FATIMA array) is essential
almost background free technique
→ reliable data at astrophysics energies
→ 3 regimes identified
- Impact on stellar evolution – late phases
– see E. Monprieat et al. A&A 660, A47 (2022)
- New measurement 2022 (running !) with the PIXEL array (ang. Dist.)
- Massive stars and microscopic nuclear reactions

Thanks !

G. Fruet,^{1,2} S. Courtin,^{1,2,3,*} M. Heine^{1,2,†}, D. G. Jenkins,⁴ P. Adsley,⁵ A. Brown,⁴ R. Canavan,^{6,7} W. N. Catford,⁶
E. Charon,⁸ D. Curien,^{1,2} S. Della Negra,⁵ J. Duplaci,⁹ F. Hammache,⁵ J. Lesrel,⁵ G. Lotay,⁶ A. Meyer,⁵ D. Montanari,^{1,2,3}
L. Morris,⁴ M. Moukaddam,⁶ J. Nippert,^{1,2} Zs. Podolyák,⁶ P. H. Regan,^{6,7} I. Ribaud,⁵ M. Richer,^{1,2} M. Rudigier,⁶
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