Molecular resonances and their impact on nuclear astrophysics

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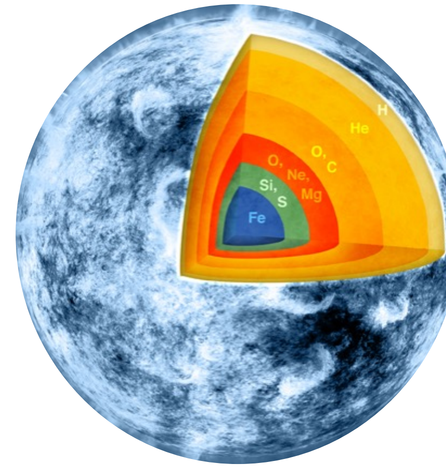

I. A tale of nuclear reactions & stars, example of the $^{12}C+^{12}C$ case

II. How to measure (possibly resonant) astrophysically relevant cross-sections - observables

III. New experimental results on the C burning

IV. Impact of resonances on stellar evolution and nucleosynthesis

III. Future

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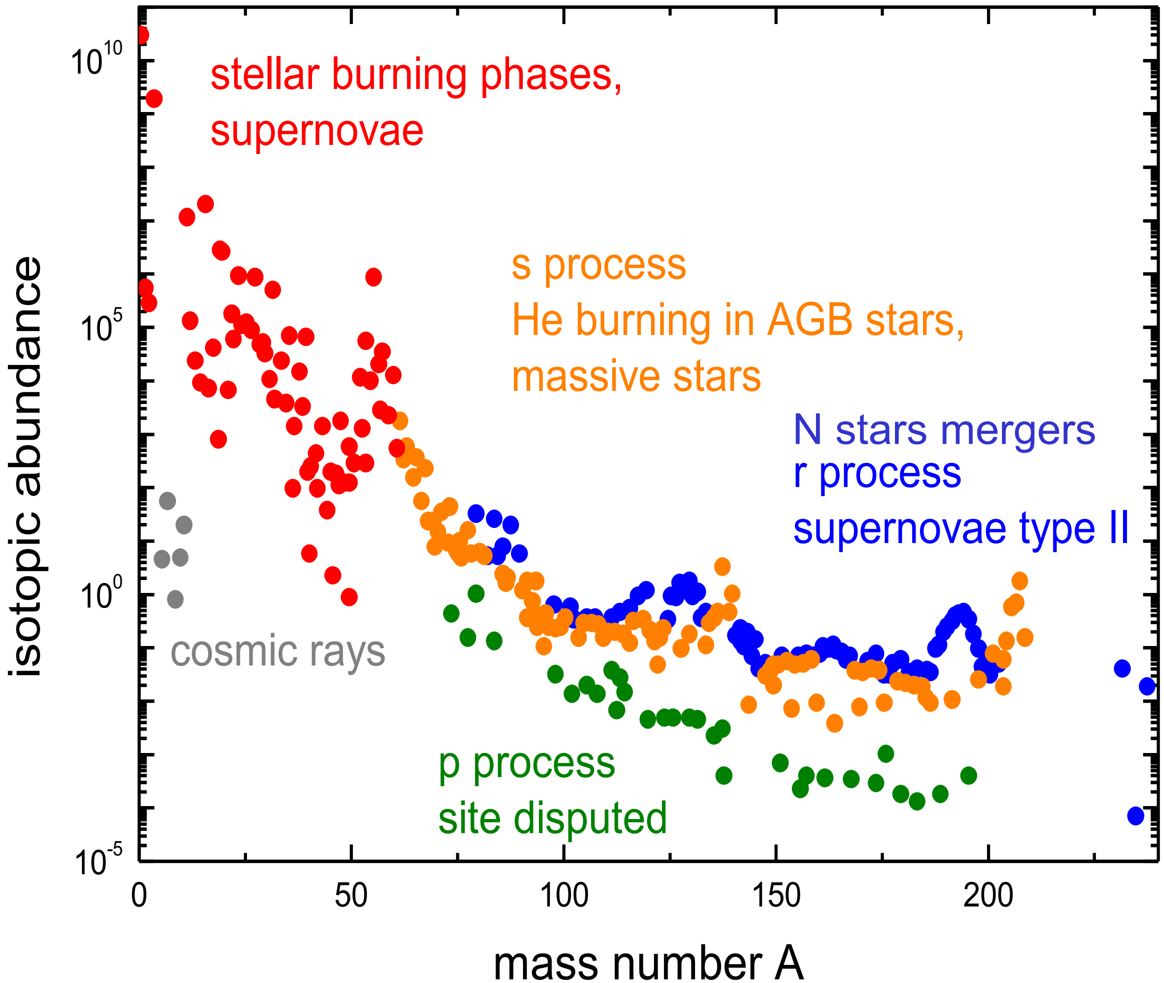
The $^{12}C+^{12}C$ (special) case



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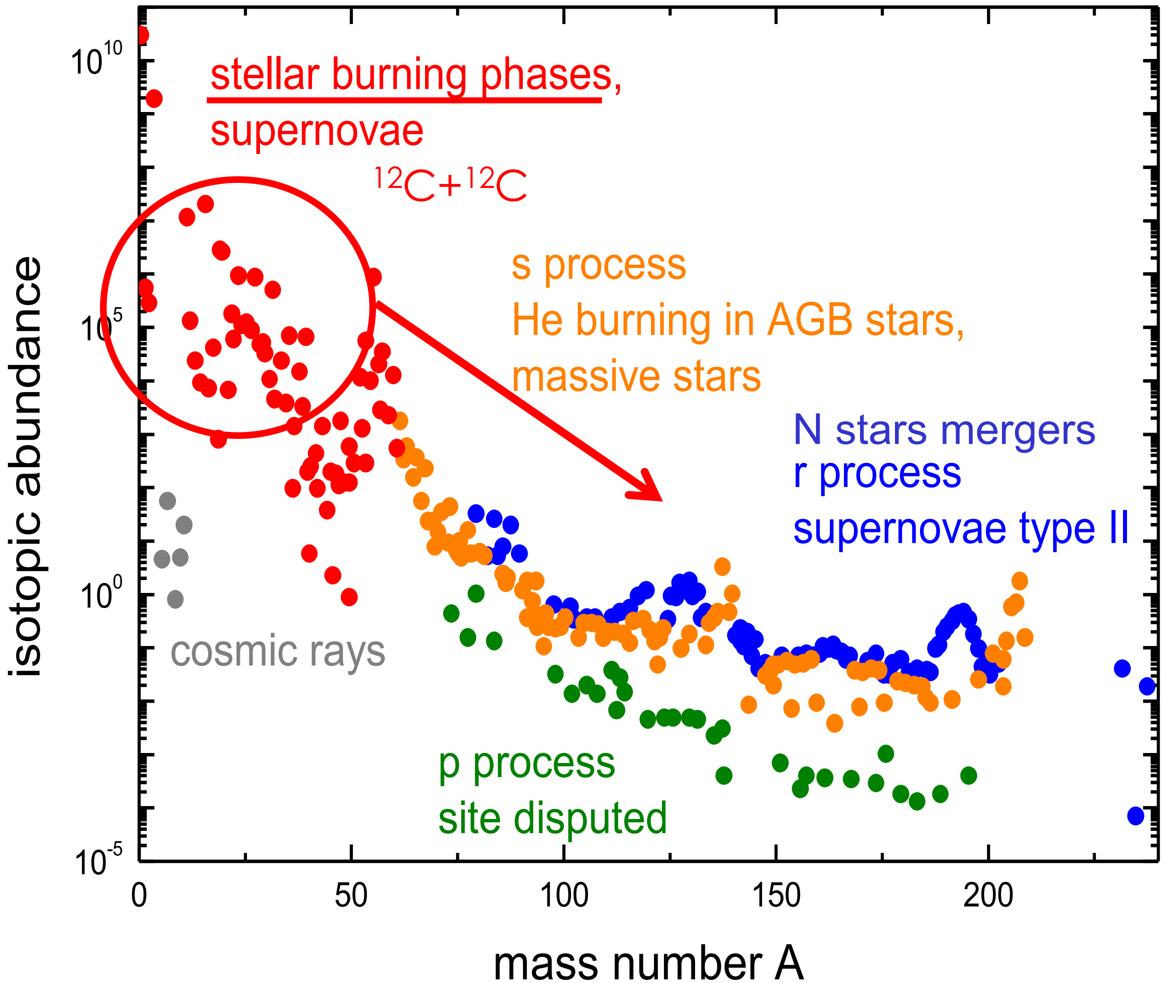

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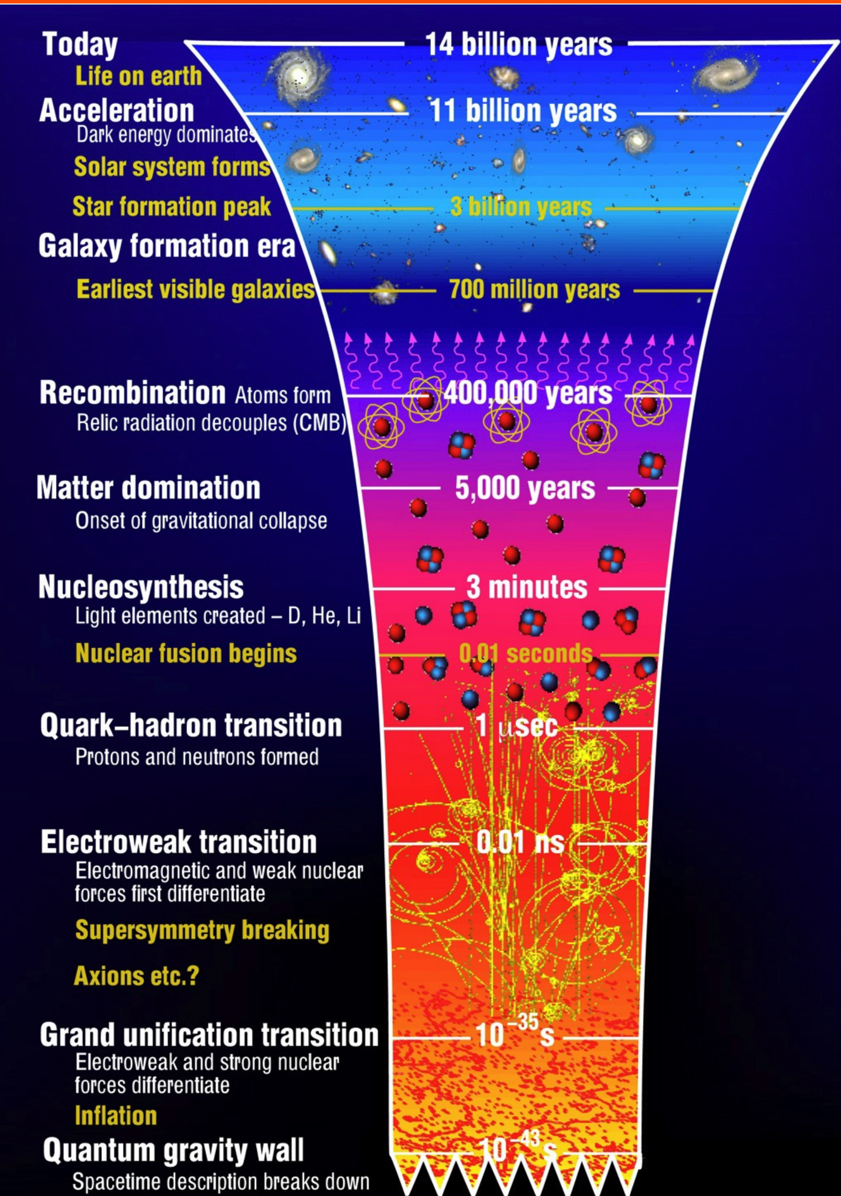
Nucleosynthesis : The $^{12}C+^{12}C$ (special) case

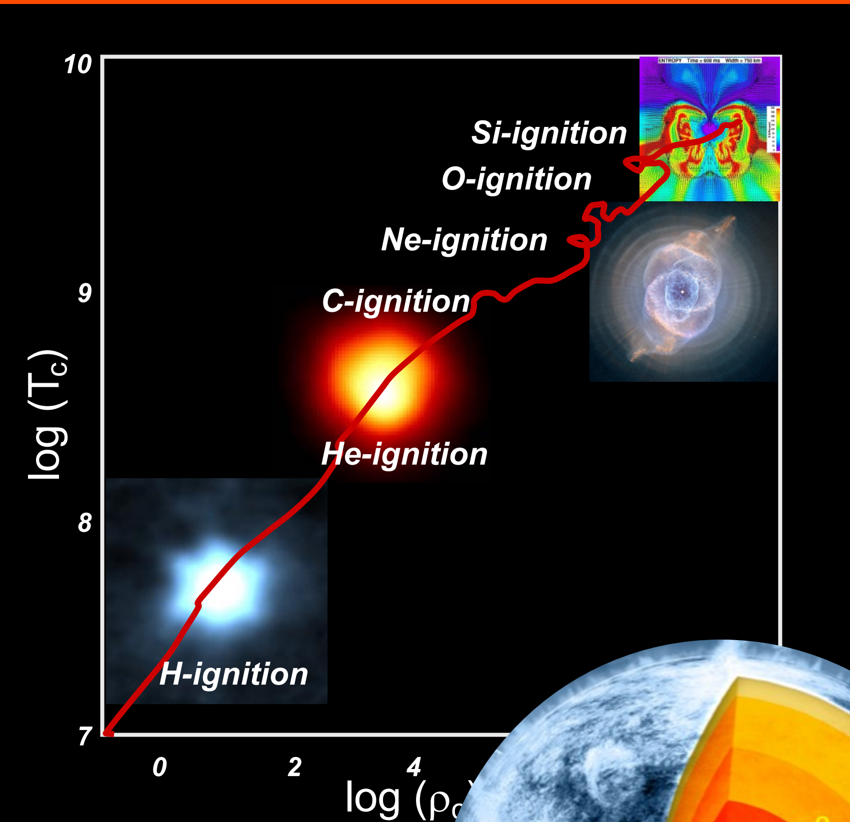


In a H-rich environment elements such as Li, Be, and B are easily destroyed at low temperatures (low Q_value), before fusion reactions start to play a role.

^{12,13}C the
1^{st} (p-shell) nuclei with sufficiently negative (p, α) Q_{values}.

$^{12}C+^{12}C$ the first fusion reaction that needs to be considered

Burning phases in massive stars

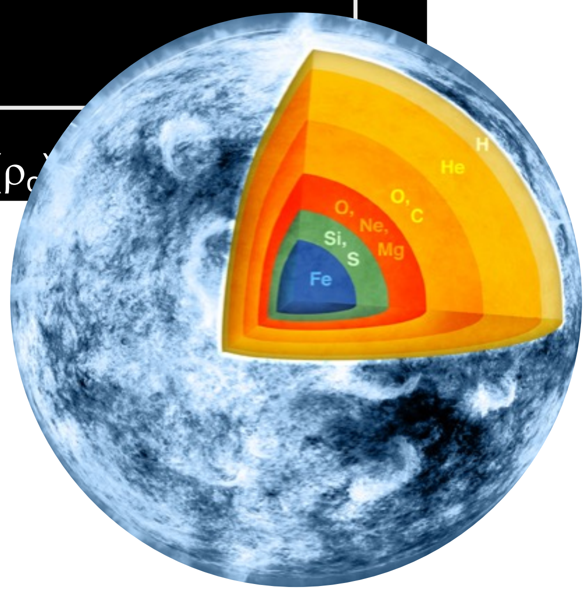


Different burning phases
In the evolution of a massive star

Each controled by different nuclear reactions which drive the:

- Energy production
- Time scale
- nucleosynthesis

Different shells of a massive star shortly before core collapse

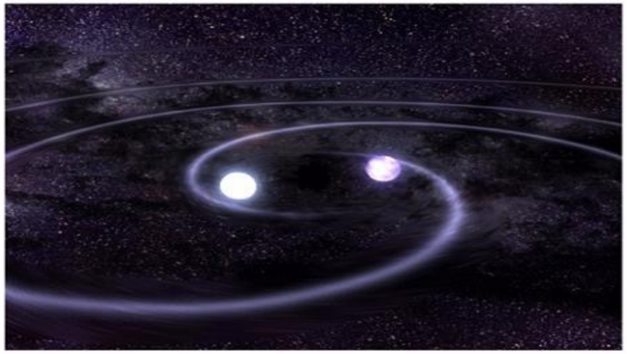
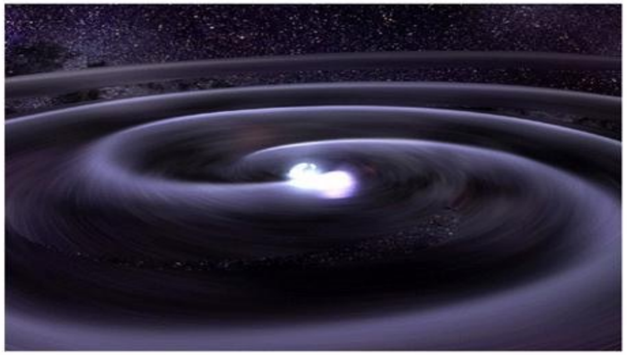
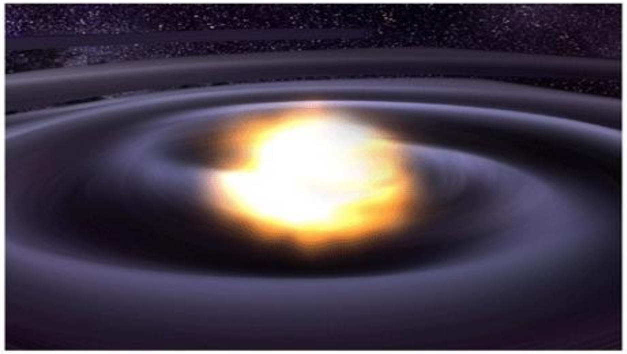


Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,H \xrightarrow{CNO} {}^4He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\,He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
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	$^{28}Si(\gamma,\alpha)$...

Nucleosynthesis : The $^{12}C+^{12}C$ (special) case

$^{12}C+^{12}C$ may impact different stages of stellar evolution

- Explosive scenarios / type Ia supernovae (standard candles)
- Quiescent C burning / contracting core of a massive star
- Superbursts of X-ray binary systems (possibly)

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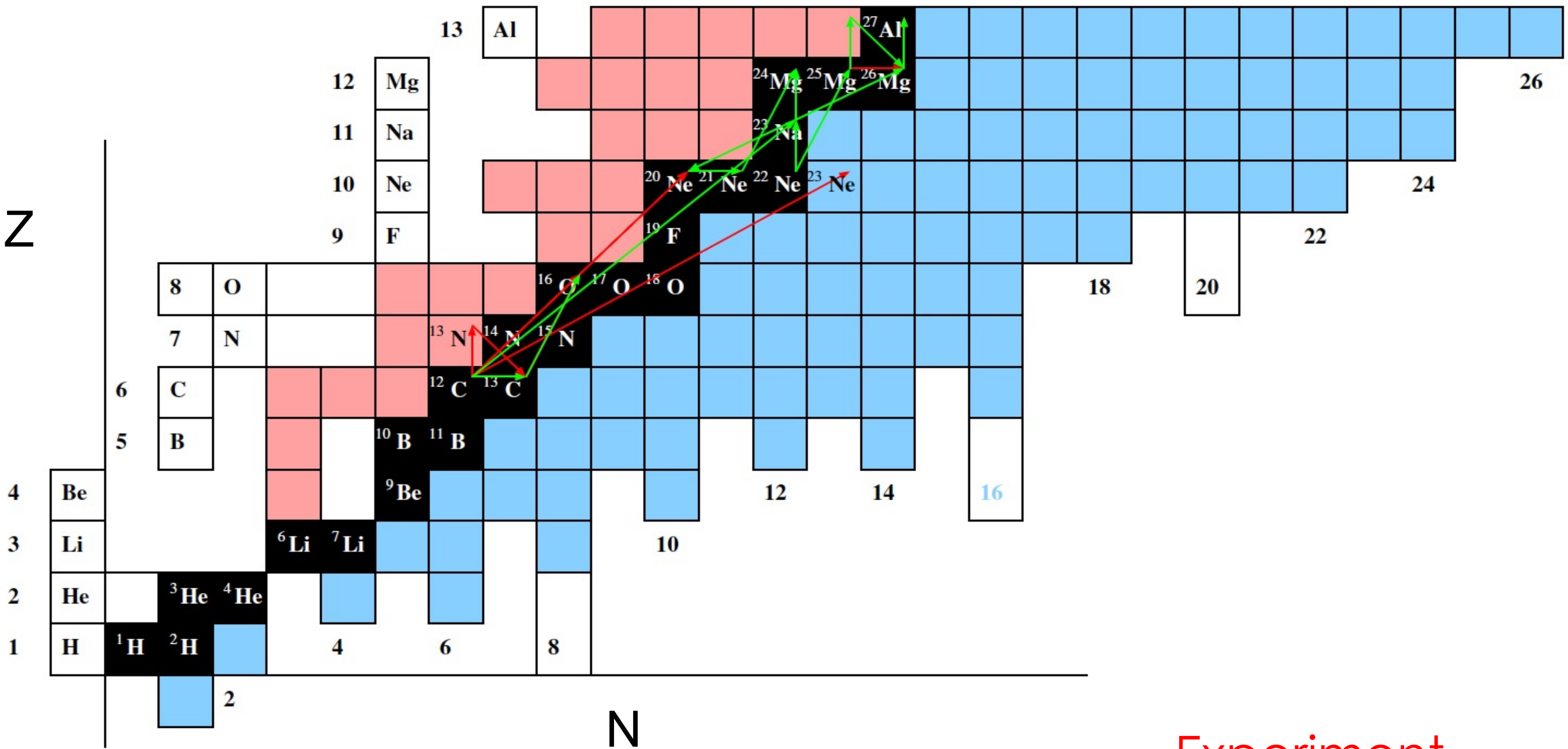
A key reaction: $^{12}C + ^{12}C$ (low Coulomb Barrier)

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



M. Heine, from A. Chieffi et al., APJ 502 (1998), 737

Reaction rates:

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

Experiment

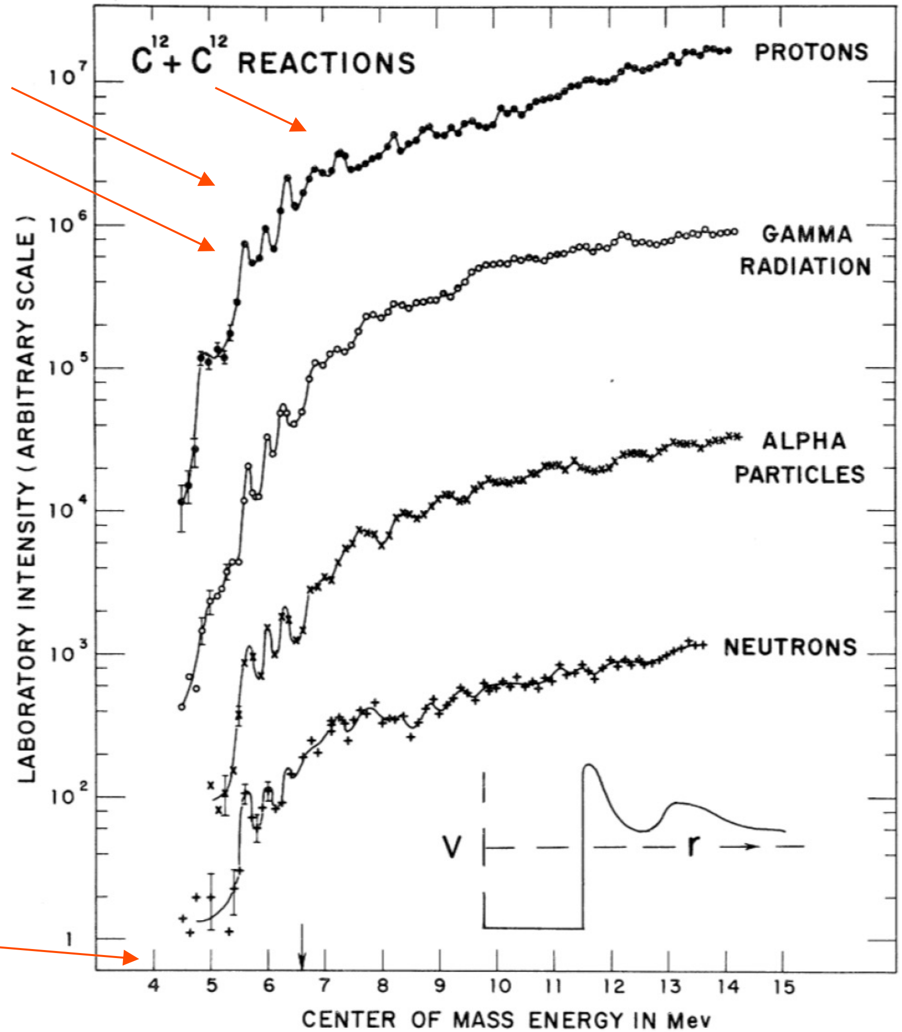
Extrapolations ?

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

Nuclear Structure / Resonances

Certainly an obstacle for extrapolations to stellar energies

?



E. Almqvist et al. Phys. Rev. Lett. 4, p. 515, (1960)

The incomplete (yet complex) story of ^{12}C fusion

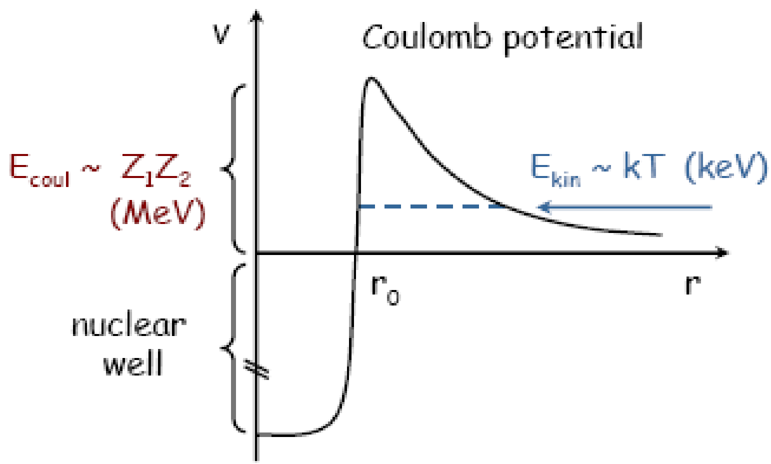
- ex D.A. Bromley *et al.*, **PRL** 4, 365, (1960)
- ex E. Almqvist *et al.*, **PRL** 4, 515, (1960)
- th B. IMANISHI *et al.*, **PLB** 27, 267, (1968)
- ex J.R. Patterson *et al.*, **APJ** 157, 367, (1969)
- th G.J. Michaud, E.W. Vogt, **PRC** 5, 350, (1972)
- ex M. Mazarakis, W. Stephens, **PRC** 7, 1280, (1973)
- th R.G. Stokstad *et al.*, **PRL** 37, 888, (1976)
- ex P.R. Christensen *et al.*, **NP A** 280, 189, (1977)
- ex W. Gaister *et al.*, **PRC** 15, 950, (1977)
- ex M.D. High, B. Čujec, **NIM A** 282, 181, (1977)
- ex K.-U. Kettner *et al.*, **PRL** 38, 377, (1977)
- ex S.K. Korotky *et al.*, **PRC** 20, 1014, (1979)
- ex K.A. Erb *et al.*, **PRC** 22, 507, (1980)
- th R.H. Lemmer *et al.*, **PRL** 44, 26, (1980)
- ex H.W. Becker *et al.*, **ZP A** 303, 305, (1981)
- th Y. Suzuki, K.T. Hecht, **NPA** 388, 102. (1982)
- ex B. Čujec *et al.*, **PRC** 39, 1326, (1989)
- ex P. Rosales *et al.*, **RMD** 49, 88, (2003)
- ex E.F. Aguilera *et al.*, **PRC** 73, 064601, (2006)
- ex R. Perez-Torres *et al.*, **PNCNP** 69, 1371, (2006)
- ex L. Barrón-Palos *et al*, **NP A** 779, 318, (2006)
- th L.R. Gasques *et al.*, **PRC** 76, 035802, (2007)
- ex D. Jenkins *et al.*, **PRC** 76, 044310, (2007)
- ex C.L. Jiang *et al.*, **PRC** 75, 015803, (2007)
- ex T. Spillane *et al.*, **PRL** 98, 122501, (2007)
- ex P.L. Marley *et al.*, **JMPE** 17, 2040, (2008)
- ex C.L. Jiang *et al.*, **NIM A** 682, 12, (2012)
- th H. Esbensen *et al.*, **PRC** 91, 064613, (2013)
- ex X. Fang *et al.*, **JP** 420, 012151, (2013)
- ex C.L. Jiang *et al.*, **PRL** 110, 072701, (2013)
- th A.A. Aziz *et al.*, **PRC** 91, 015811, (2015)
- ex B. Bucher *et al.*, **PRL** 114, 251102, (2015)
- ex J.M. Munson *et al.*, **PRC** 95, 015805, (2017)
- ex M. Heine *et al.*, **NIM** A 903, 1 (2018)
- ex C.L. Jiang *et al.*, **PRC** 97, 012801, (2018)
- th A. Torres, M. Wiescher, **PRC** 97, 055802, (2018)
- ex A. Tumino *et al.*, **Nature Letter** (23.05.2018)
- ex J. Zickefoose *et al.*, **PRC** 97, 065806 (2018)
- th K. Godbey *et al.*, **PRC** 100, 024619 (2019)
- ex A.M. Mukhamedzhanov *et al.*, **PRC** 99, 064618 (2019)
- ex C. Beck *et al.*, **EPJA** 56, 87 (2020)
- th A. Bonasera, J.B. Natowitz **PRC** 102, 061602, (2020)
- ex G. Fruet *et al.*, **PRL** 124, 192701 (2020)
- ex Y.J. Li *et al.*, **CPC** 44, 115001 (2020)
- ex W.P. Tan *et al.*, **PRL** 124, 192702 (2020)
- ex N.T. Zhang *et al.*, **PLB** 801, 135170 (2020)
- th Y. Taniguchi, M. Kimura, **arXiv**, 2106.04321v1 (2021) **PLB** (2021)

2022: Lee & Diaz-Torres Phys. Lett. B, Monpribat et al. A & A, Adsley et al. PRL …

Direct and indirect methods / Why ?

charged particles ➡ Coulomb barrier

energy available: from thermal motion

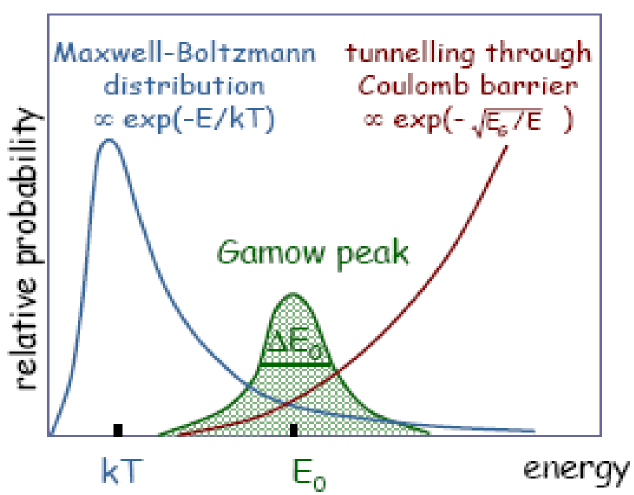


$T \sim 15 \times 10^6$ K (e.g. our Sun) $\Rightarrow$ $kT \sim 1$ keV

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

Trojan Horse Method

The X-section of a A(x,b)B reaction determined by selecting the quasi-free contribution of a A(a,b)B reaction,
where a = xs has a cluster structure.

Hypothesis: s, spectator / quasi free process, potential

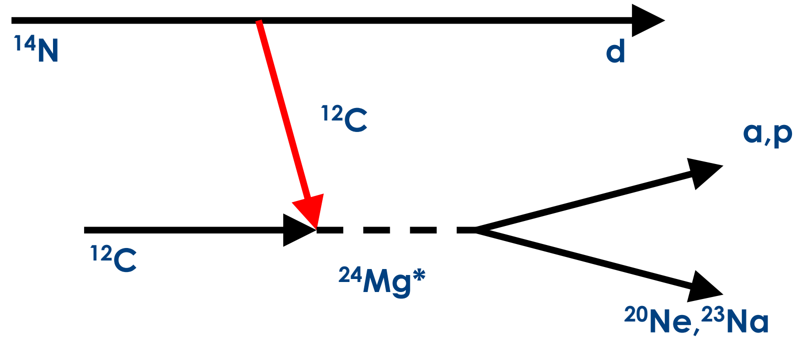
For $^{12}C+^{12}C$: $^{12}C(^{14}N, \alpha^{20}Ne)^{2}H$ and $^{12}C(^{14}N, p^{23}Na)^{2}H$
→ lots of resonances observed with corresponding spins 0^+, 2^+, 1^-, 3^-, 5^-
→ Normalization to direct data.

Direct :

$^{12}C+ ^{12}C \rightarrow ^{23}Na^* + p$

$^{12}C+ ^{12}C \rightarrow ^{20}Ne^* + \alpha$

Indirect :



A. Tumino et al. Nature 2018

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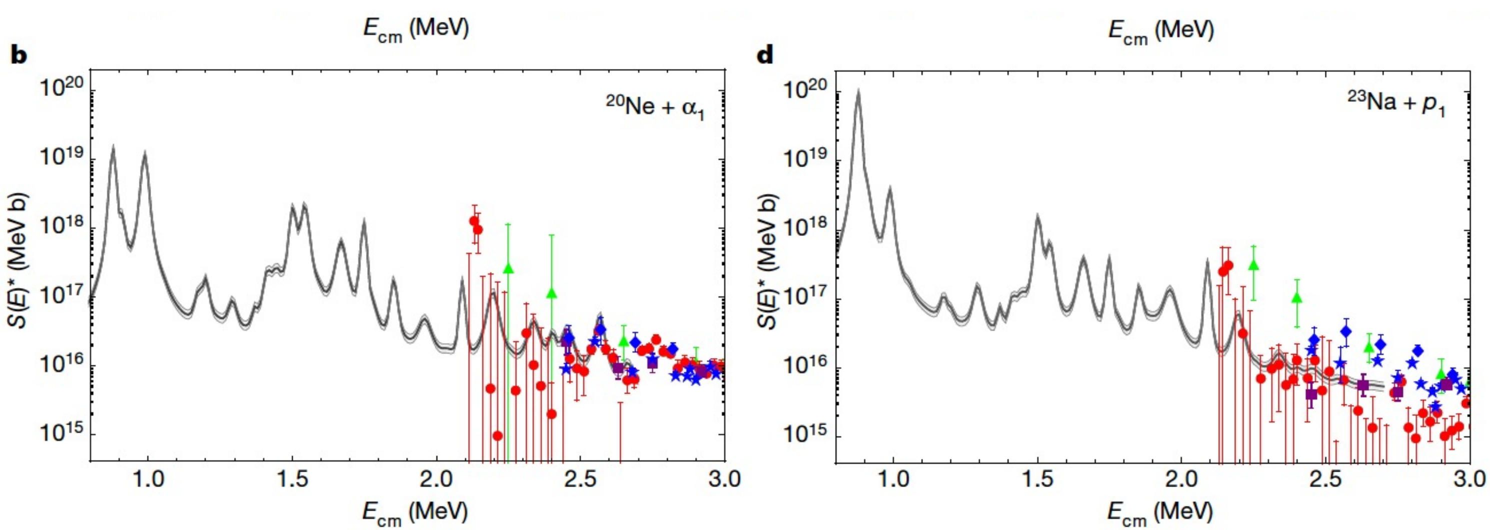
See also A. M. Mukhamedzhanov PRC 99 (2019), EPJA (2022)



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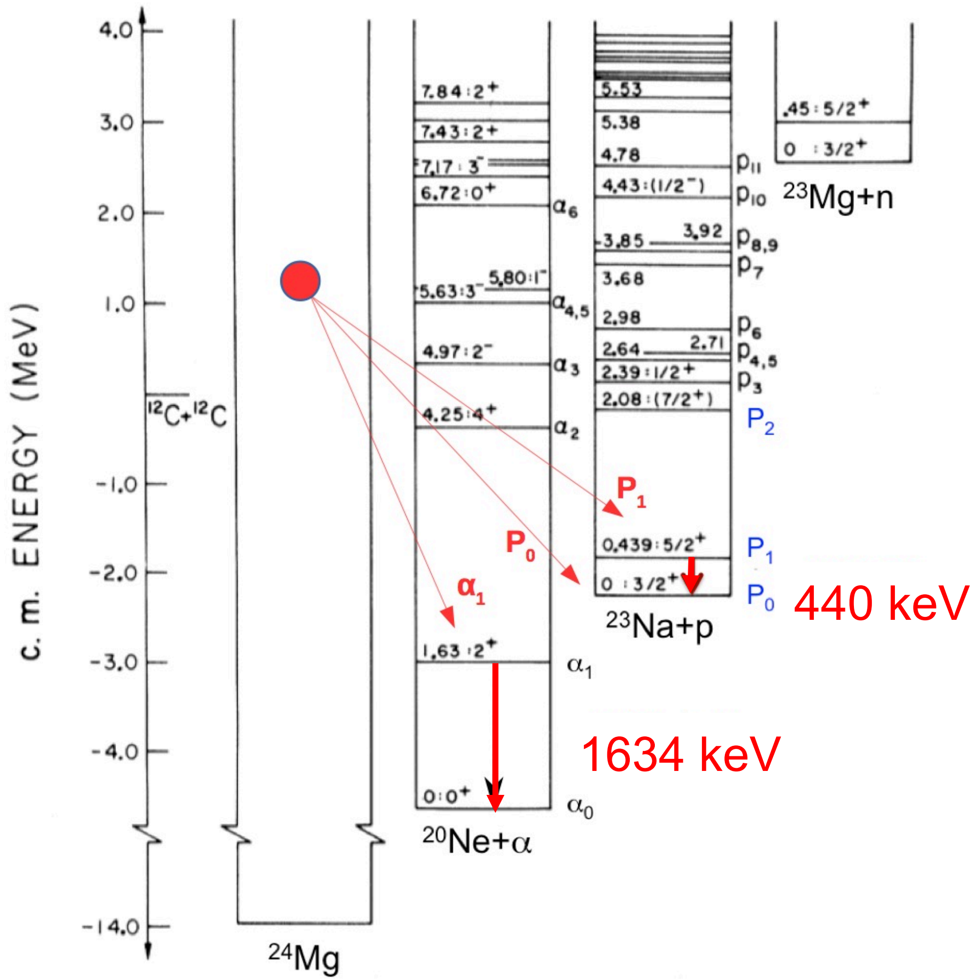

$^{12}C + ^{12}C \rightarrow ^{23}Na + p$, Q = 2.24 MeV

$^{12}C + ^{12}C \rightarrow ^{20}Ne + \alpha$, Q = 4.62 MeV

$^{12}C + ^{12}C \rightarrow ^{23}Mg + n$, Q = -2.62 MeV

Detection of γ-rays:

1st ex. state to g.s.

Detection of particles:

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

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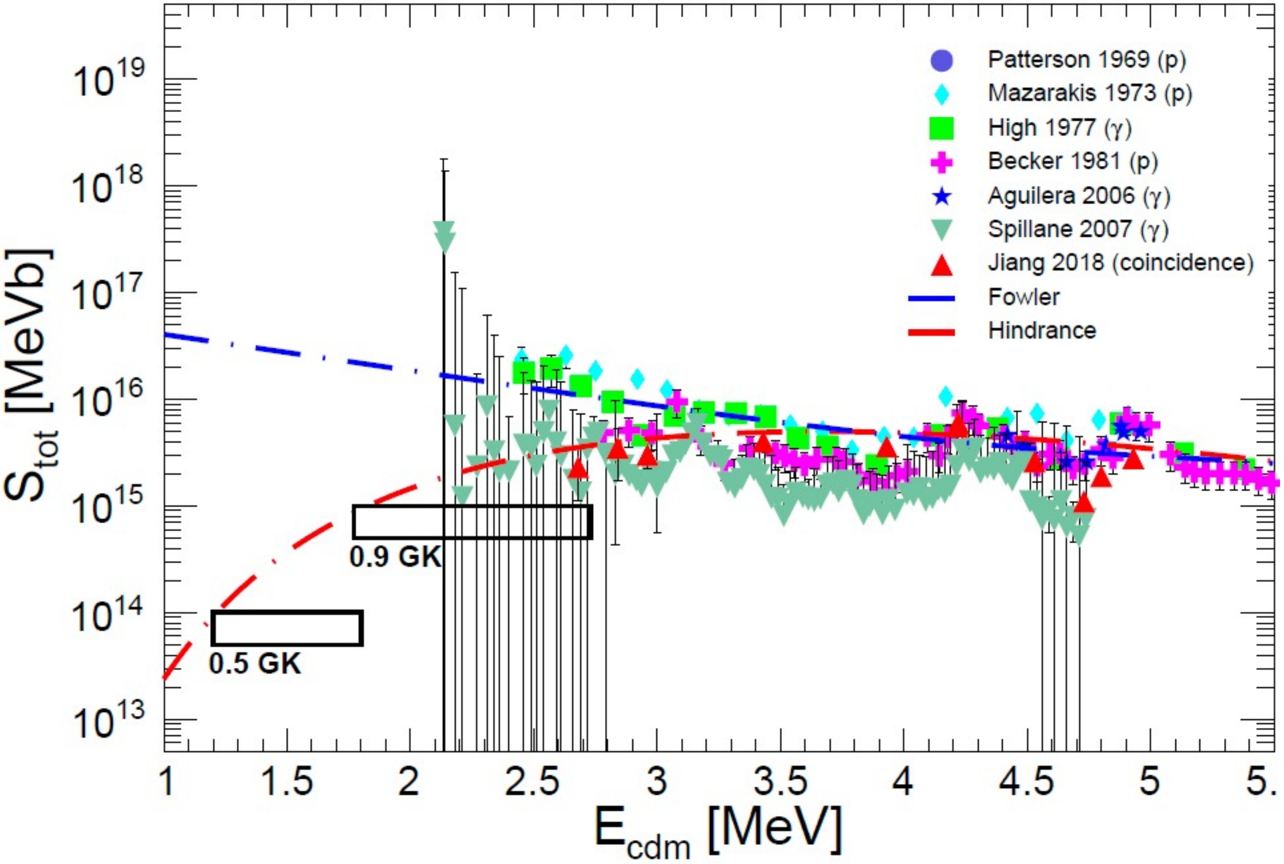
Carbon burning: $^{12}C + ^{12}C$, direct measurments
Situation in 2019



Mostly single particles or γ

Extremely sensitive to background

Extrapolations with very different trends

Role of resonances, impact on reaction rate

Challenges for sub-nb cross section $^{12}C+^{12}C$ direct measurements

Data taking – months, years, stability of the exp. setup

Beam intensity (~ 10 pμA)

Target system (thin vs thick)

Detection efficiency (Ge, $LaBr_3(Ce)$)

Background (H and D) reduction (subtraction, coincidences)

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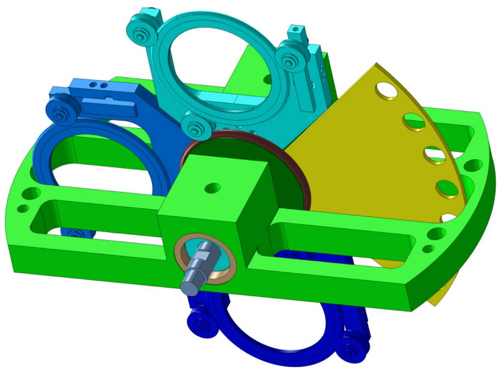
STELLA (Stellar Laboratory)

A toolbox for the measurement of fusion reactions of astrophysics interest



IPHC and GANIL collaboration

- Andromede facility, Orsay, France
  4 MV, ECR source, 10 pμA

Gamma detection

- 36 $LaBr_3$ detectors, UK FATIMA
  (P. Regan et al.)

Particle detection

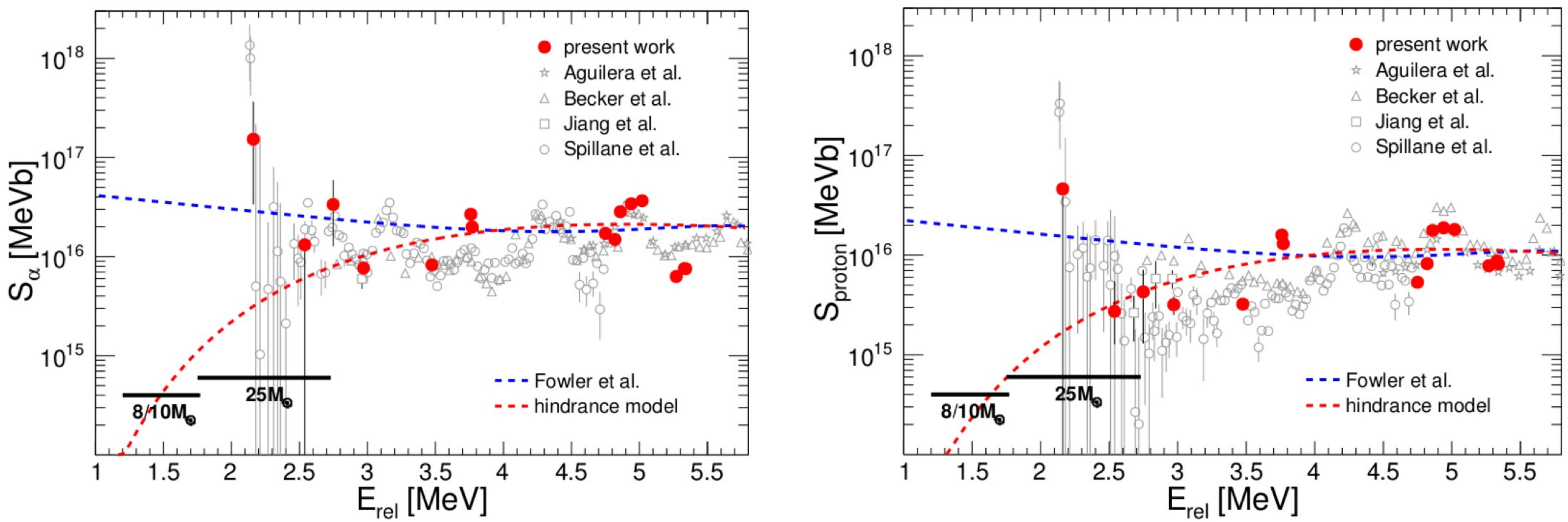
- Annular DSSD, MICRON chip
  IPHC & Univ. York (D. Jenkins et al)
  New PCB design / ceramics (IPHC)
  $\Delta\Omega$ ~ 24 % of 4π.

Target developments

- 1000 rpm, self-supporting, d = 5,2 cm
  150-200 nm (IPHC, GANIL)

M. Heine et al. NIM A 2018

Direct measurement of the STELLA collaboration



- Reliable excitation functions over 8 orders of magnitude, down to 2.1 MeV and the 100 pb range.
- Three regimes:
  i. Moderate sub-barrier E: validation of the experimental concept
  ii. Deep sub-barrier E: hindrance regime (observed in numerous other systems)
  iii. Gamow window - 25 M☉ E: another (resonant?) regime ?

G. Fruet, S.C., M. Heine et al, Phys. Rev. Lett. 124 (2020)

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Hindrance ?

- Incompressibility of the nuclear matter

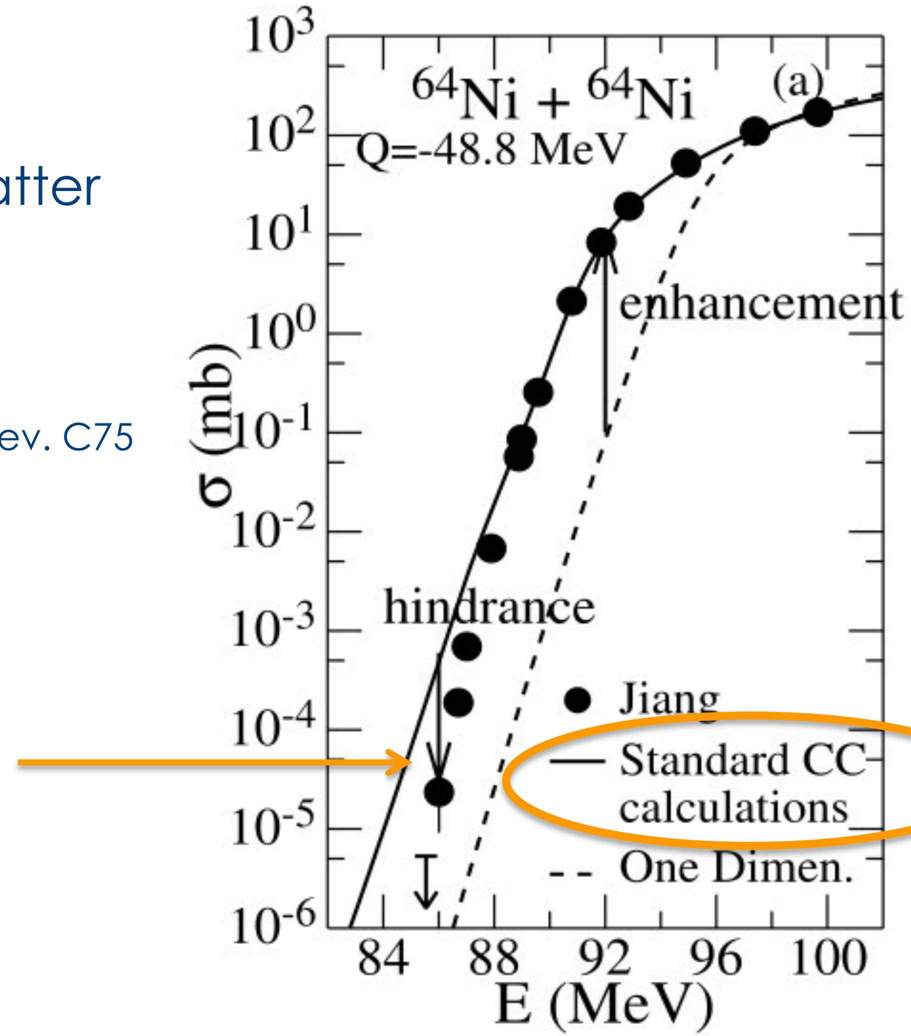
S. Mişicu, and H. Esbensen, Phys. Rev. Lett. 96 (2006).

- Neck formation

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

- Pauli repulsion

C. Simenel et al., Phys.Rev. C 95, 2017.
K. Godbey et al., Phys.Rev. C100, 2019.



C.L.Jiang et al., Phys.Rev. Lett.89 (2002); Phys.Rev.Lett.93 (2004)
For a review, see for ex. B. Back et al., Rev.Mod.Phys. 86 (2014)

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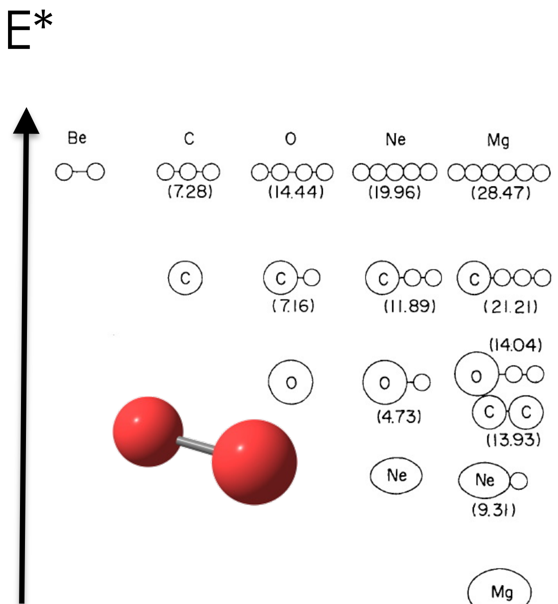
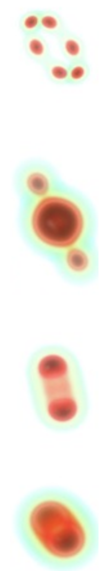
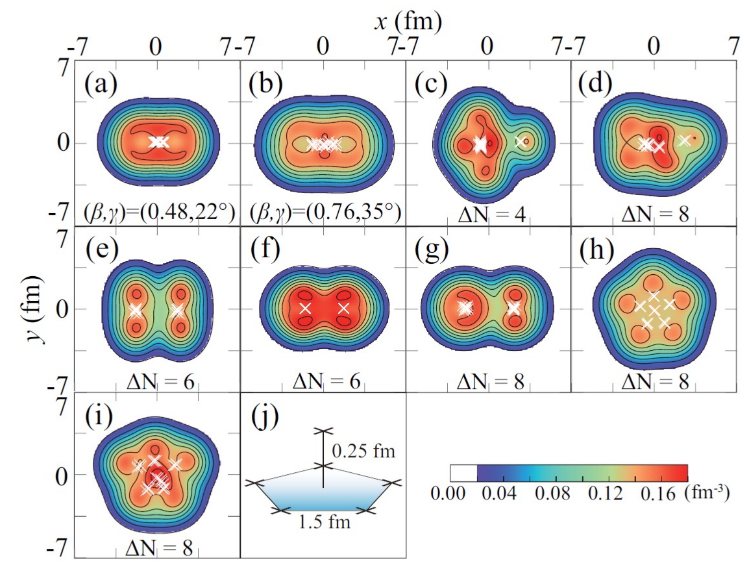
"We must still realise that the subsequent escape of α-rays necessitates a separate concentration process for the excess energy and that in particular we cannot draw any decisive conclusion from these phenomena about the presence of such particles in nuclei under normal conditions. » N. Bohr, Nature 137 (1936)







Ikeda diagram

Microscopic view

Ikeda et al., Prog.Theo.Phys.Suppl. E68 (1968) / J.-P. Ebran, E. Khan, T. Niksic, D. Vretenar PRC 90(2014); Nature 487(2012) / Y. Chiba & M. Kimura, PRC 91, R.

Molecular resonances ?

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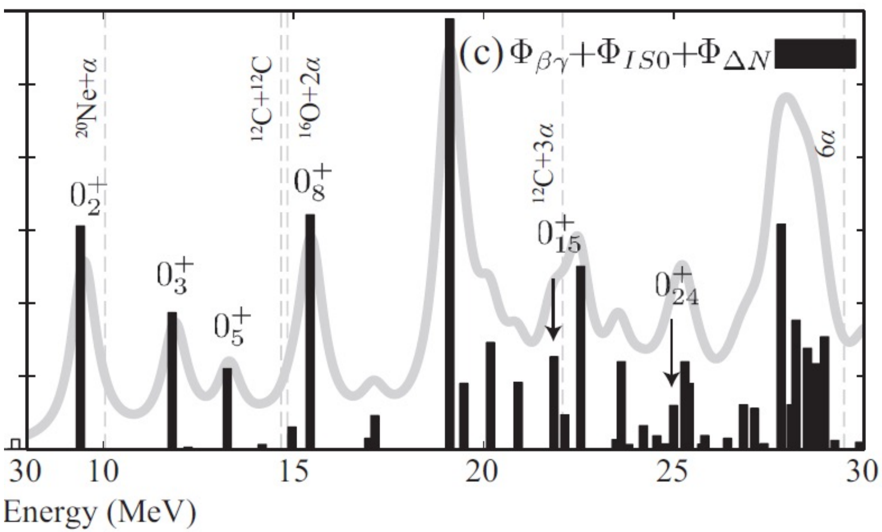
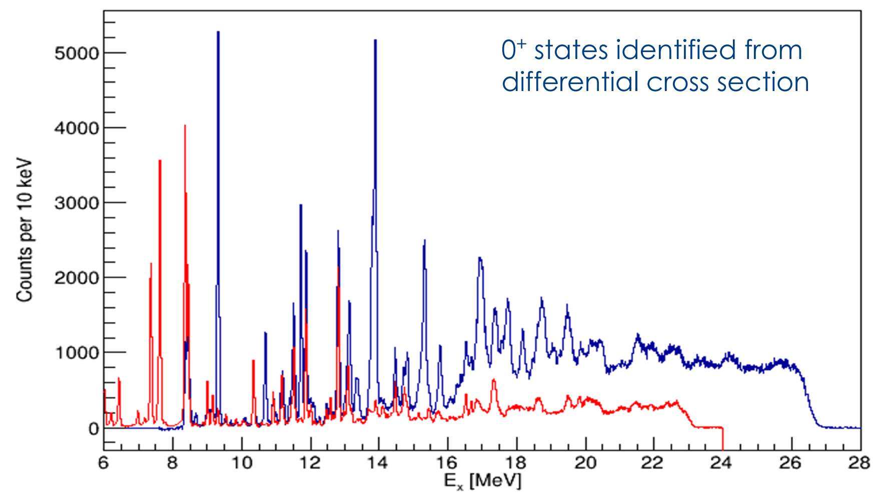




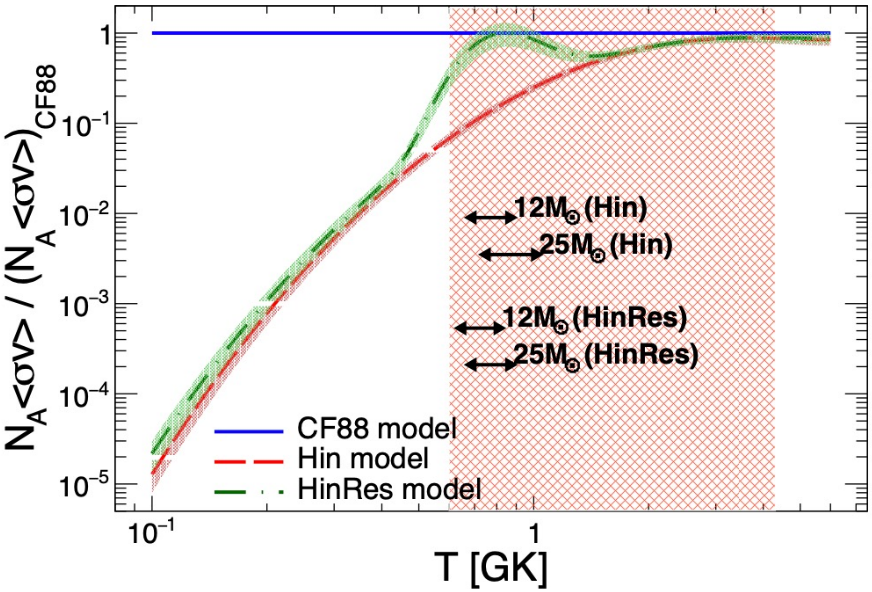
New experimental results

^{24}Mg(α,α') - look for candidate $J^{\pi}=0^+$ ^{12}C+^{12}C cluster configurations

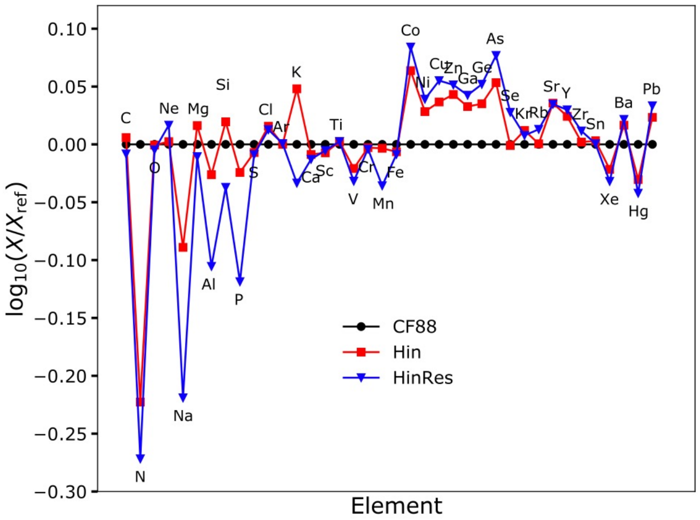
3 signatures: Energy, spin$^{\text{parity}}$, branching

Y. Chiba & M. Kimura, PRC 91, R / **P. Adsley, M. Heine, D. Jenkins, SC at al. Phys. Rev. Lett. 129 (2022)**

Impact of recent results on stellar evolution and nucleosynthesis GENEC code + one layer model



Normalized reaction rates



Abundances obtained at the end of C-burning phase

E. Monpribat, S. Martinet, S.C, M. Heine et al, A&A 660 (2022)

Thanks!

M. Heine, E. Monpribat, J. Nippert, D. Curien, T. Dumont et al, IPHC, Strasbourg, France

P.H. Regan, M. Rudigier, W. Catford et al., Univ. Surrey, UK and the FATIMA collaboration

D. Jenkins et al, Univ. York, UK

P. Adsley, Texas A&M, USA

G. Meynet, S. Martinet, S. Ekström, S. Tsiatsou Obs. and Univ. Geneva, Switzerland

A. Choplin, Université Libre de Bruxelles, Belgium

S. Della Negra, F. Hammache, N. de Séréville et al. IJCLab, Orsay, France

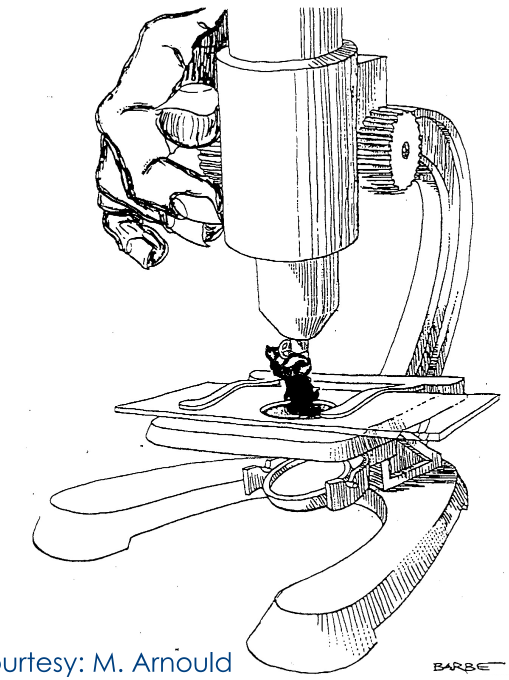
C. Stodel et al., GANIL, Caen, France

A. Tumino (INFN, LNS Catania, Italy)

W. Tan and M. Wiescher (Univ. Notre Dame, USA)

G. Imbriani, LUNA collaboration (INFN Napoli, Italy), LUNA

CL. Jiang, KH Rehm, Argonne National Laboratory, USA



Courtesy: M. Arnould