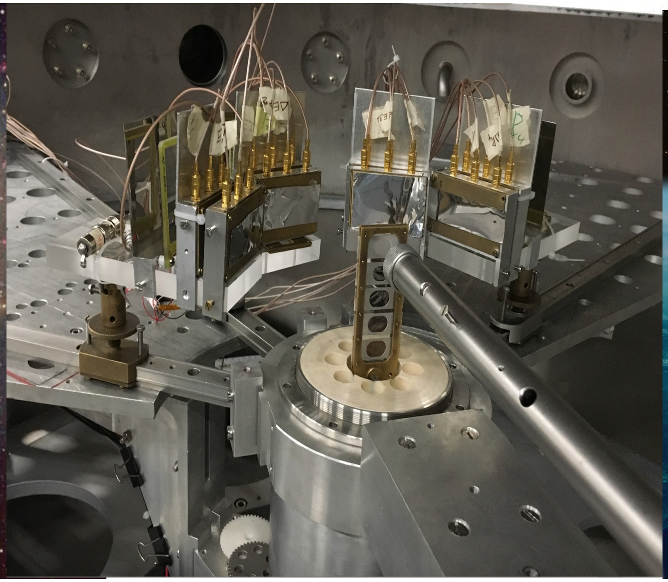
17th Rußbach School on Nuclear Astrophysics

March, 13-19 2022

Resonant 12C+12C fusion at astrophysical energies



UNIVERSITAS HENNAE STUDIORUM — LIBERA UNIVERSITÀ KORE ENNA

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Aurora Tumino

Outline

C-burning: astrophysical scenarios and status of measurements

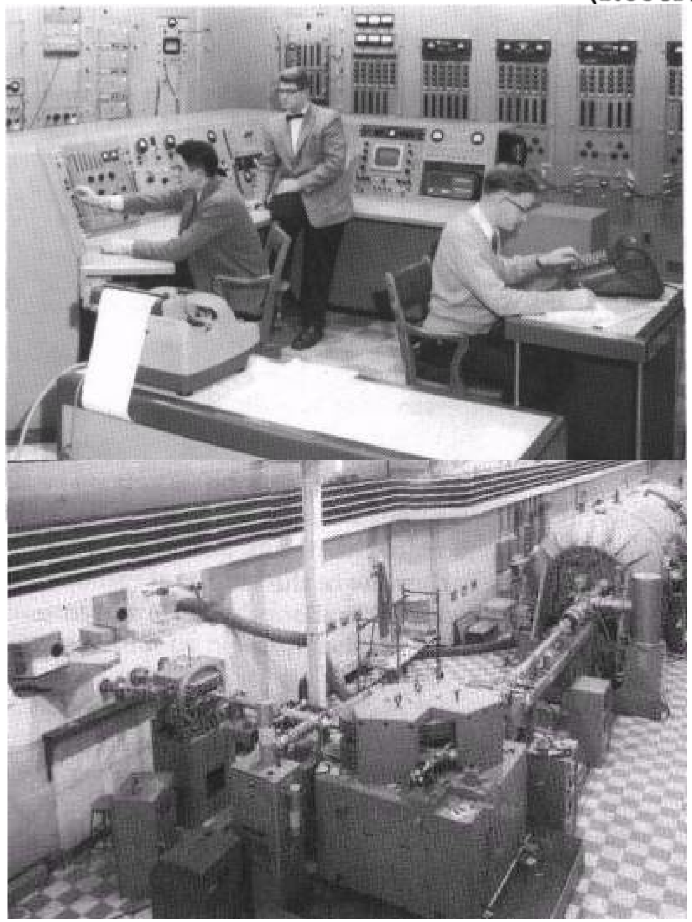
The THM $^{12}C(^{12}C,\alpha)^{20}Ne$ and $^{12}C(^{12}C,p)^{23}Na$ experiment

Results and implications

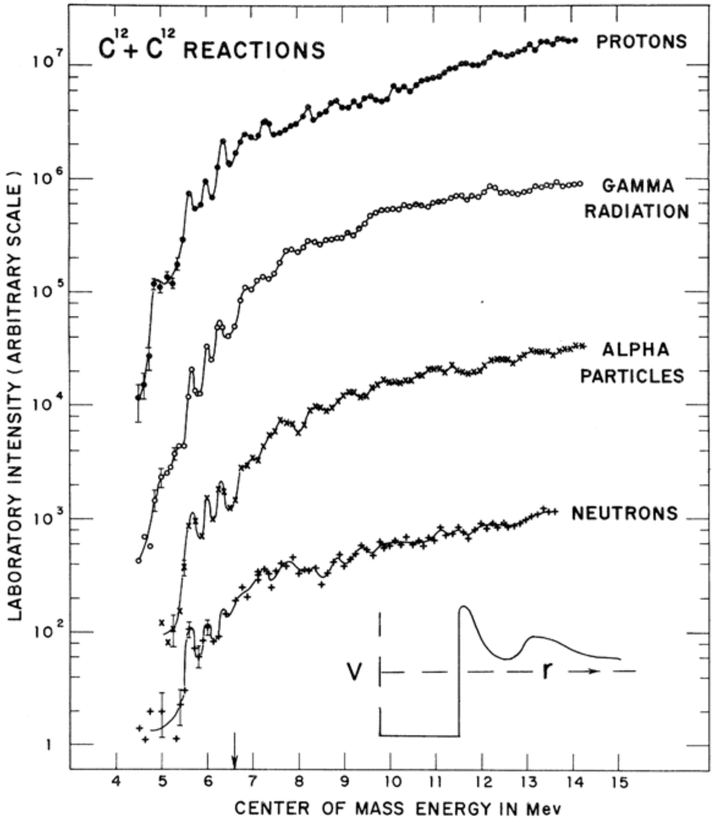
VOLUME 4, NUMBER 10 PHYSICAL REVIEW LETTERS MAY 1

RESONANCES IN C^{12} ON CARBON REACTIONS

E. Almqvist, D. A. Bromley, and J. A. Kuehner
Atomic Energy of Canada Limited, Chalk River Laboratories, Chalk River, Ontario, Canada
(Received March 28, 1960)



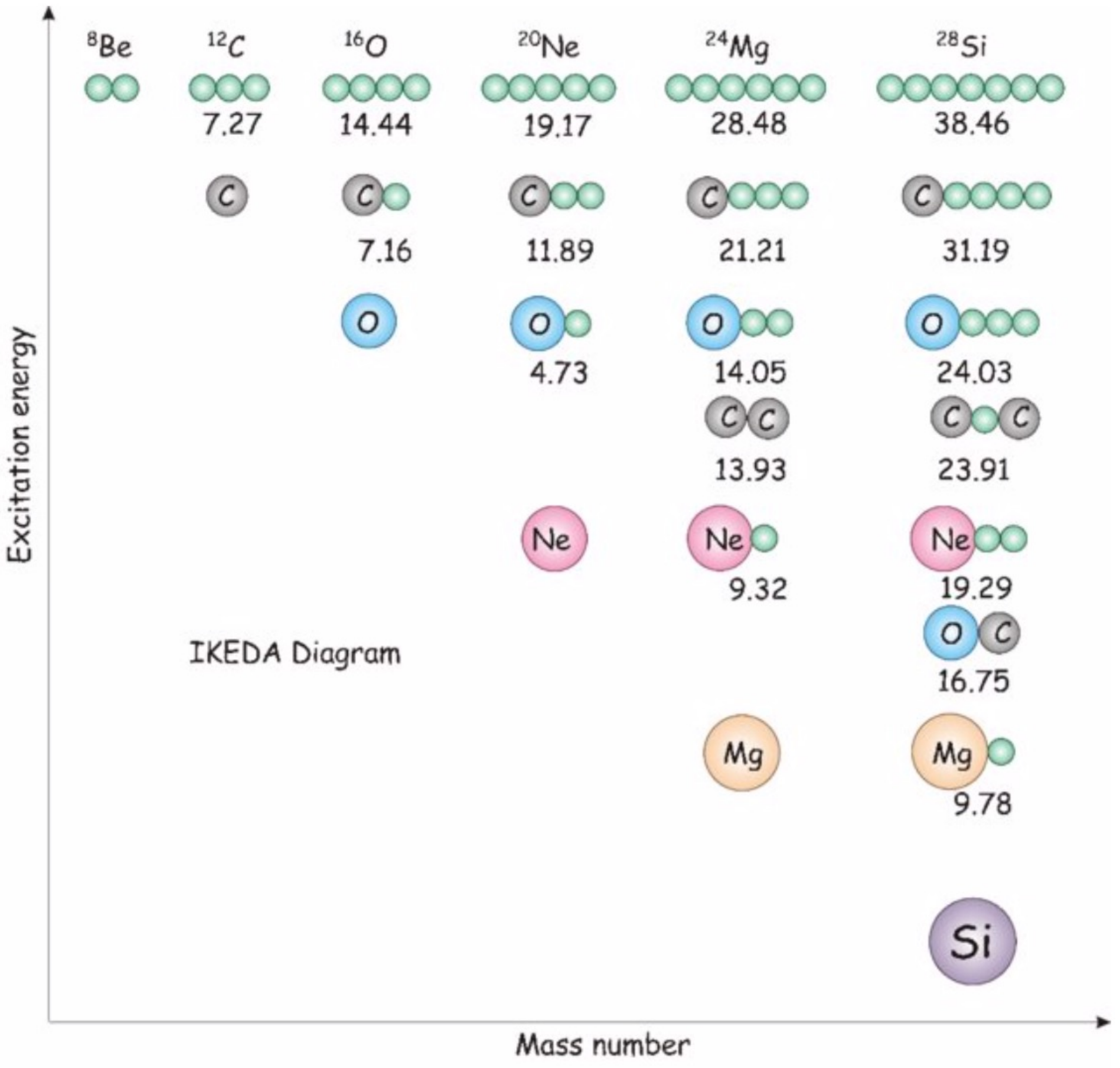
The world's first tandem accelerator
Installed at Chalk River in 1959



Molecular resonances in the $^{12}C+^{12}C$ fusion reaction

Ikeda diagram

The threshold energies for each configuration are given in MeV. The smallest, unlabelled clusters are alpha particles. Increasing excitation energy is required to form evermore complex cluster structures.



M. Ohkubo,K. Kato, H. Tanaka, Progr. of Theor. Phys. 67, 207 (1982)

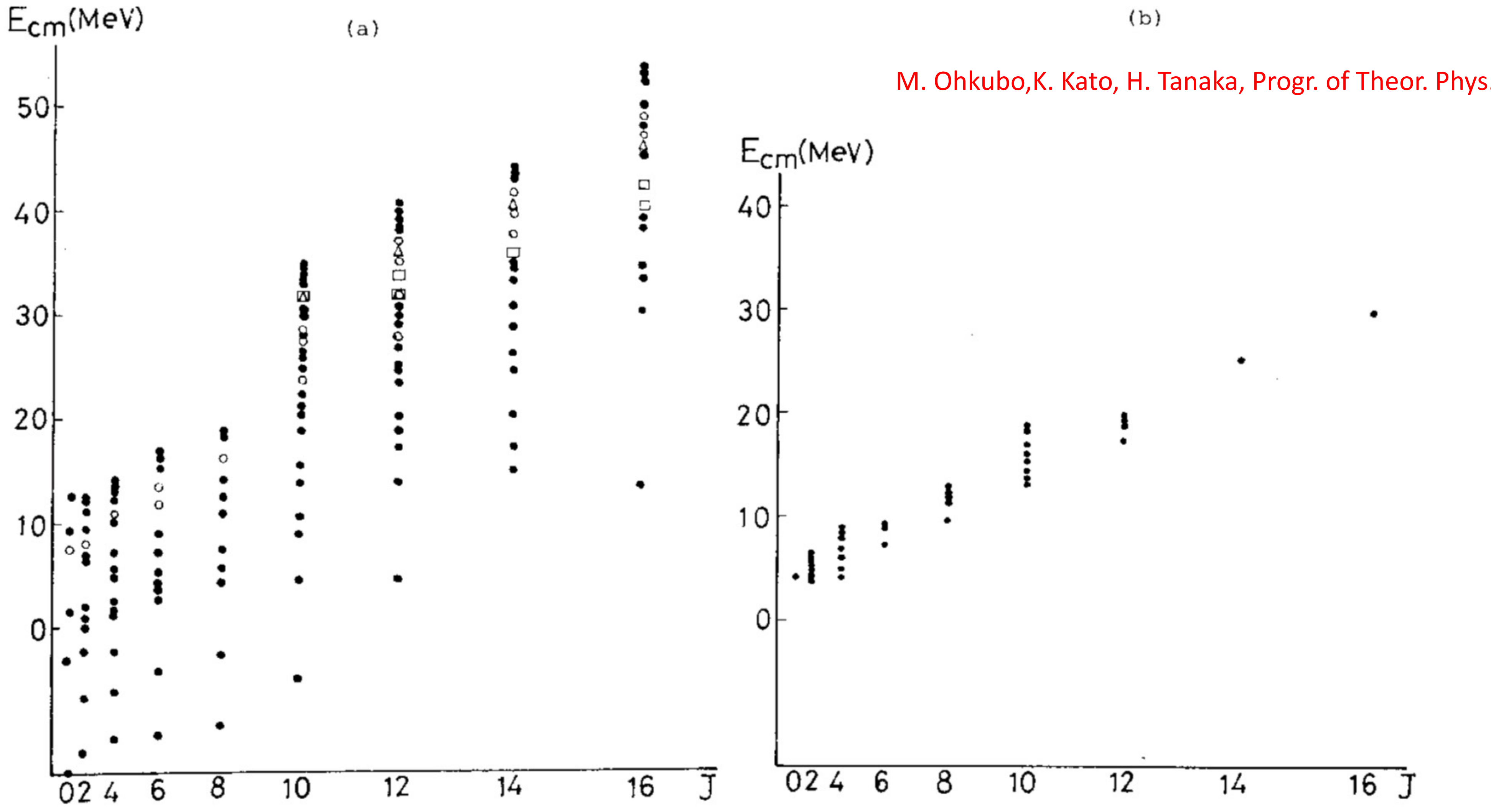
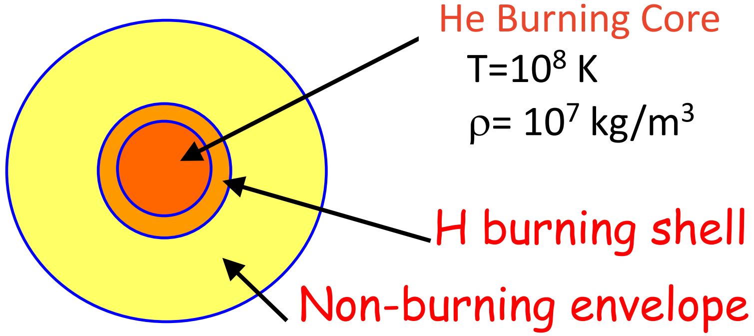


Fig. 2. (a) Calculated energy levels and (b) experimental resonance energies[1),2a)~2c)] of the $^{12}C+^{12}C$ system. Marked states with open circle, triangle and square have larger spectroscopic factors than 0.1 for elastic ($^{12}C(0^+)+^{12}C(0^+)$), aligned single excited ($^{12}C(2^+)+^{12}C(0^+)$) and aligned mutual excited ($^{12}C(2^+)+^{12}C(2^+)$) channels, respectively. The Coulomb interaction is switched off and N_{max} is taken to be 26.

C-burning

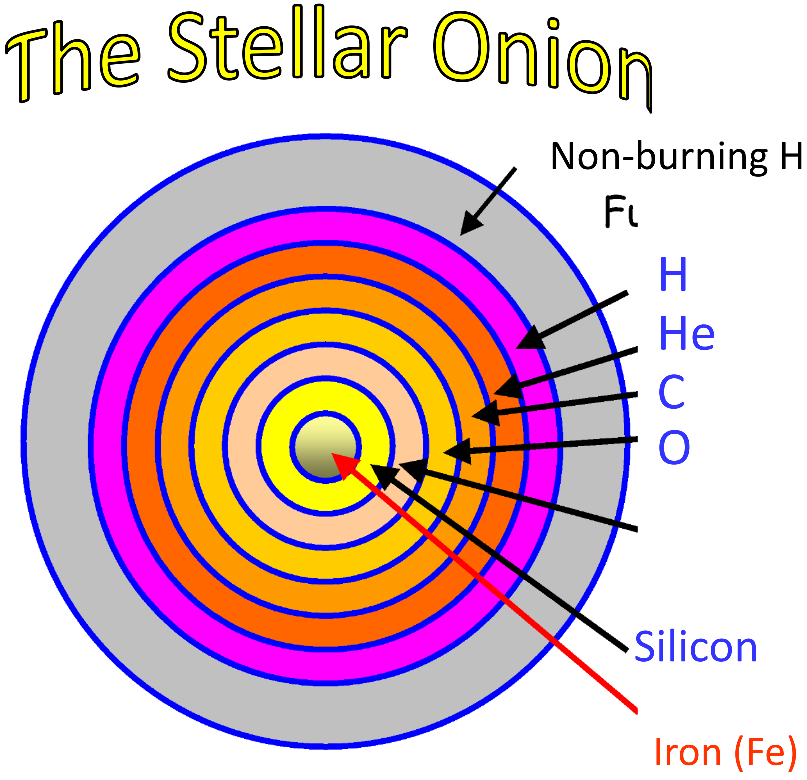
-Carbon burning: third most important phase in the evolution and nucleosynthesis of massive stars (> 8 $M_{\odot}$).

Starts like the sun:



But now, when He is exhausted in the core and the core collapses, it does get hot enough to burn carbon and oxygen.

The successive stages in the core are H $\rightarrow$ He, gravity, He $\rightarrow$ C,O, gravity, $\rightarrow$ C,O $\rightarrow$ Mg, Si, gravity, Si $\rightarrow$Fe.



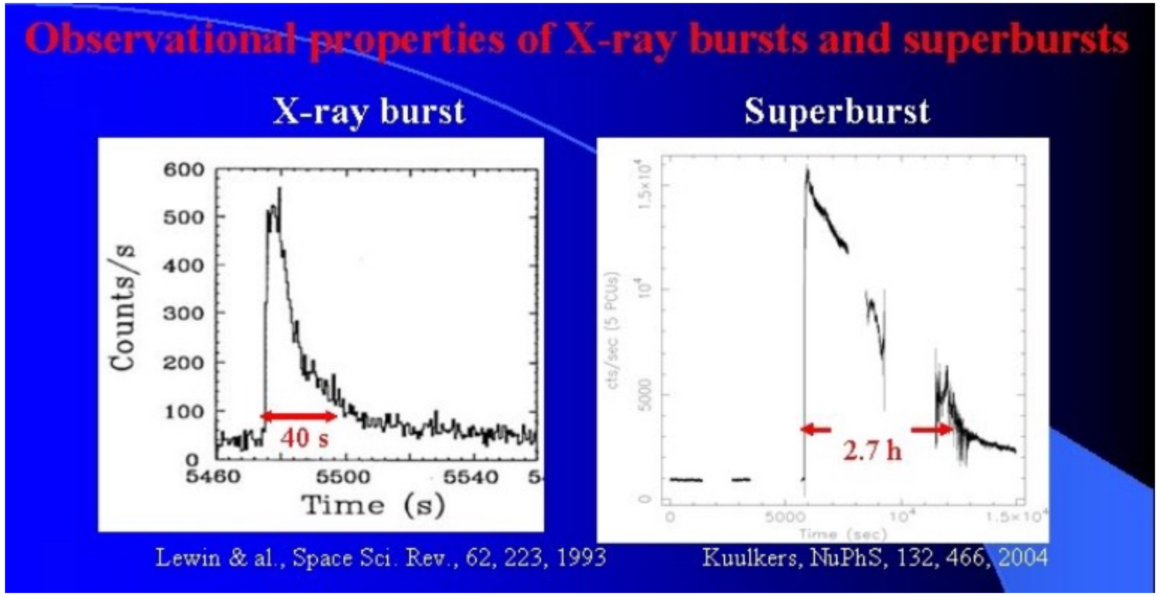
Carbon burning:
Relevant temperatures T ~ 0.6-1.2 GK and densities > 3 10^9 kg/m^3
More massive stars burn their nuclear fuel more quickly, since they have to offset greater gravitational forces to stay in (approximate) hydrostatic equilibrium. For example, a star of 25 solar masses burns hydrogen in the core for 10^7 years, helium for 10^6 years and carbon for only 10^3 years.

Carbon burning influences M_{up} minimum stellar mass required for hydrostatic carbon burning to occur. M_{up} is fundamental also for the evolution of supernova progenitors and the white dwarf luminosity functions.

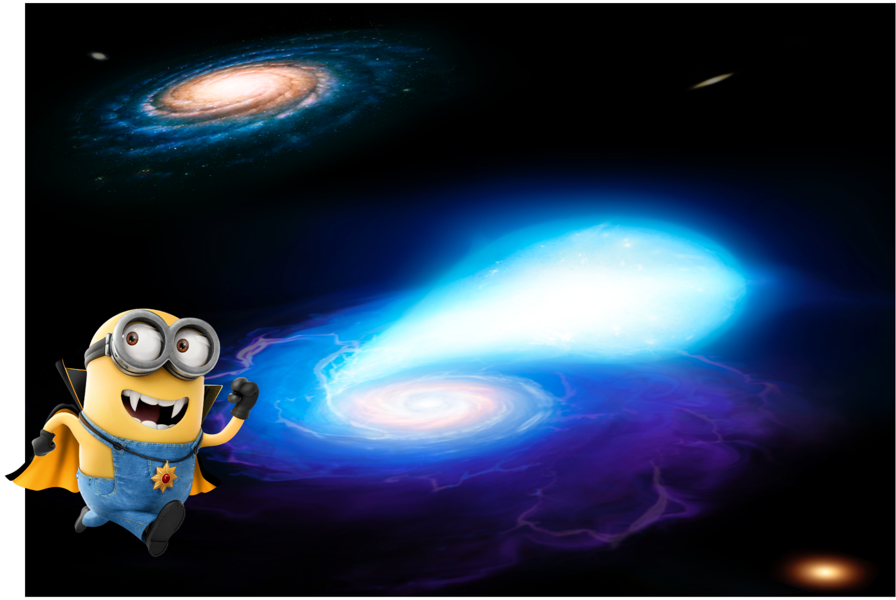
C-burning

- Engine for superbursts from accreting neutron stars

Relevant temperatures T ~ 0.4-0.7 GK



X-ray burst	Superburst
$L_{max} \cong 10^{38}$ ergs s^{-1}	$L_{max} \cong 10^{38}$ ergs s^{-1}
$E_{tot} \cong 10^{39}$ ergs	$E_{tot} \cong 10^{42}$ ergs
$t_{burst} \cong$ 10s – several min	$t_{burst} \cong$ several min – several hours
$t_{rec} \cong$ 5min - days	$t_{rec} \cong$ years



Source of superbursts: carbon burning in the outer crust ?

Key problem: with the standard 12C+12C rate from CF88, the crust temperature is too low to ignite the carbon fuel → need to have resonances …

C-burning

- ignition conditions of Type Ia supernovae

They are thought to be thermonuclear explosion of white dwarfs (WD)
Their progenitors are not well understood, but their fates depend on the rate of $^{12}C+^{12}C$ reaction. Indeed, they are interpreted as the consequence of explosive carbon burning ignited near the core of the white dwarf star in a binary system

Relevant numbers: (0.15-0.7 GK and $\rho \sim (2-5)\ 10^9$ g/cm^3):
the C/O ratio influences the nucleosynthesis and, in turn, the resulting light curve

12C+12C fusion

Carbon burning mainly through $^{12}C+^{12}C$ fusion at E_{cm} from 1 to 3 MeV

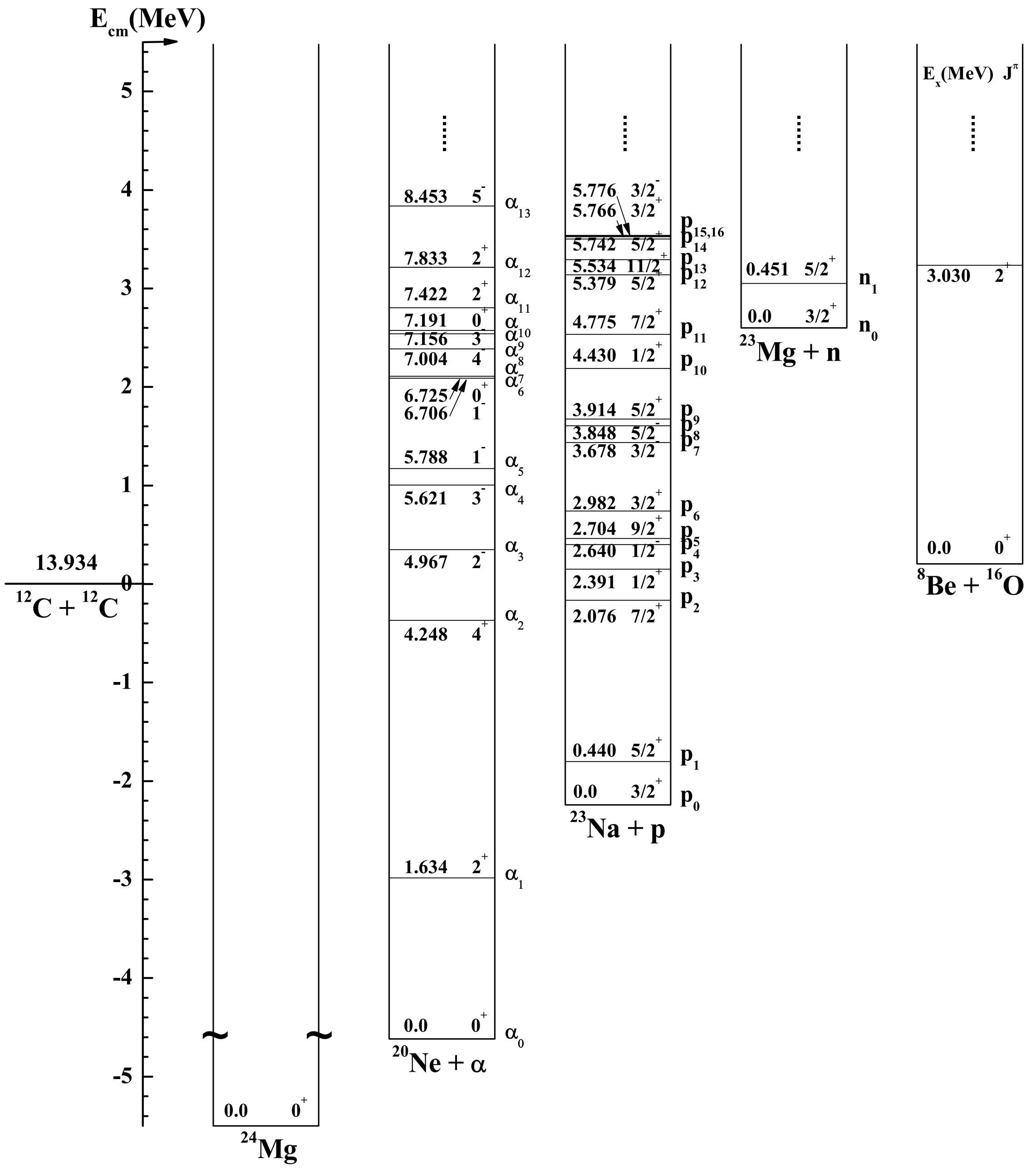
Principal reactions:

$^{12}C(^{12}C,\alpha)^{20}Ne$	+ 4.617 MeV	The most frequent results of the interaction
$^{12}C(^{12}C,p)^{23}Na$	+ 2.241 MeV	
$^{12}C(^{12}C,n)^{23}Mg$	- 2.599 MeV	
$^{12}C(^{12}C,\gamma)^{24}Mg$	+13.933 MeV	
$^{12}C(^{12}C,2\alpha)^{16}O$	-0.20 MeV	

Considerable efforts to measure the $^{12}C+^{12}C$ cross section at astrophysical energies

M.G. Mazarakis & W.E. Stephensen, Phys. Rev. C 7 1280 (1973)
K. U. Kettner *et al.*, Phys. Rev. Lett. 38, 337 (1977)

H.W. Becker et al., Z. Phys. A 303, 305 (1981)
L. Barron-Palos et al., Nucl. Phys. A 779, 318 (2006)
E.F. Aguleira et al.,Phys. Rev. C 73, 064601 (2006)
T. Spillane et al., Phys. Rev. C 73, 064601 (2006)
T. Spillane et al., Phys. Rev. Lett. 98, 122501 (2007)
B. Bucher et al., Phys. Rev. Lett. 114, 251102 (2015)
C.L. Jiang et al., Phys. Rev. C 97 012801 (2018)
J. Zickefoose et al., Phys. Rev. C 97, 065806 (2018)
A. Tumino et al., Nature (2018)
G. Fruet et al. PRL, 124 192701 (2020)
W.P. Tan et al. PRL, 124 192702 (2020)



12C+12C: Status before 2010

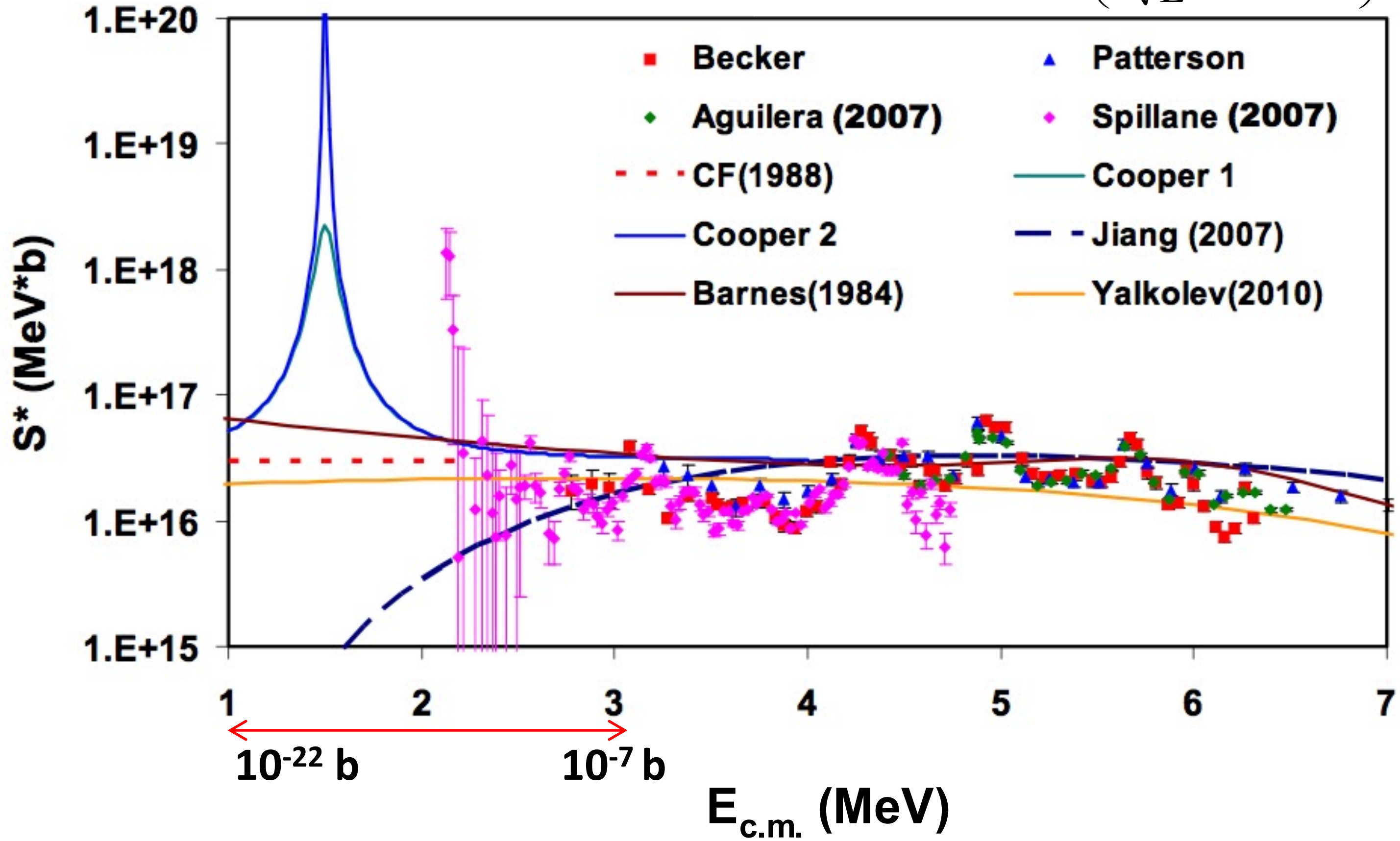
Measurements: Detection of either light charged particles (Patterson, Mazarakis, Becker) or characteristic γ-rays (Aguilera, Kettner, Spillane). With γ-rays no access to the ground states

Most of these measurements within the range $E_{cm} > 2.7$ MeV, limited by the target purity and beam-induced/cosmic rays backgrounds
Spillane: down to $E_{cm} = 2.14$ MeV, with a plastic veto detector, removing the target impurities and with a high intensity beam current.
Huge resonance at $E_{cm} = 2.14$ MeV.

$$S^*(E) = \sigma(E) E \exp\left(\frac{87.21}{\sqrt{E}} + 0.46E\right)$$

Extrapolations below 2 MeV:
-without resonances, the reference one is CF88
-Hindrance (incompressibility of nuclear matter)
-with isolated resonances (Cooper …)

difference by more
3 orders of magnitude



→ large uncertainties in astrophysical models of stellar evolution and nucleosynthesis

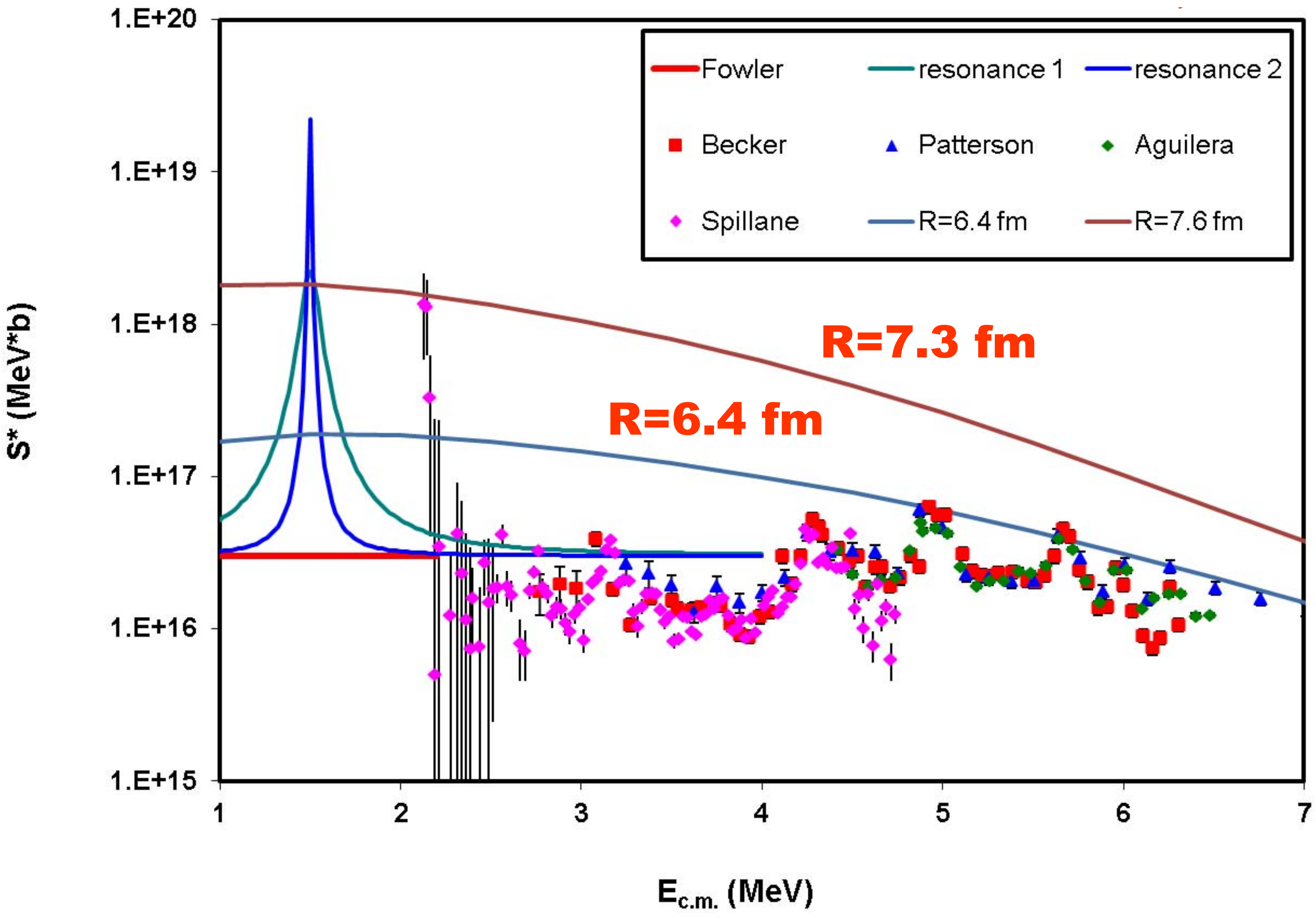
Other side studies for 12C+12C fusion

Upper limit for the $^{12}C+^{12}C$ fusion cross section comparing the cross sections for the three carbon isotope systems, $^{12}C+^{12}C$, $^{12}C+^{13}C$, and $^{13}C+^{13}C$, (M. Notani et al. PRC 85 (2012) 014607) A simple pattern for complicated resonances

Resonant structure smeared in the $^{12}C+^{13}C$ and $^{13}C+^{13}C$ systems, due to the much higher level density in their compound nuclei.

With the lowest energy point different upper limit (change in fusion barrier parameters)

No definite conclusion!



$^{12}C+^{12}C$: recent experiments

Jiang et al. 2018: down to $E_{c.m.}$ = 2.84 MeV and 2.96 MeV for the p and α channels, respectively, using a sphere array of 100 Compton-suppressed Ge detectors in coincidence with silicon detectors.

Fruet et al. 2020: down to $E_{c.m.}$=2.16 MeV using the particle-γ coincidence technique and thin C-target. Charged particles were detected using annular silicon strip detectors, while γ-ray detection was accomplished with an array of LaBr3(Ce) scintillators. Only the p_1 and α_1 channels. Total S* factor reconstructed taking not observed branchings from the literature

Tan et al. 2020: down to $E_{c.m.}$=2.2 MeV using the particle-γ coincidence technique and thick target. In particular, p and αs were detected using a silicon detector array, and γ-rays with HPGe detectors. Only the p_1 and α_1 channels. Total S* factor reconstructed taking not observed branchings from the literature.

Tumino et al. 2018: THM measurement down to 0.8 MeV for the $p_{0,1}$ and $\alpha_{0,1}$ channels. Coincidence experiment using the $^{14}N+^{12}C$ reaction at 30 MeV of beam energy.

All direct measurements: particle-γ concidence technique to further suppress the cosmic-ray background and some beam-induced background but no access to the ground state transitions

ground state transitions are crucial, as these channels contribute significantly at stellar energies

Indirect Methods for Nuclear Astrophysics

- to measure cross sections at never reached energies (no Coulomb suppression), where the signal is below current detection sensitivity
- to get independent information on U_e
- to overcome difficulties in producing the beam or the target (Radioactive ions, neutrons..)

Quite straightforward experiment, no Coulomb suppression, no electron screening but …

Entrance channel
A+a

→

Several reaction mechanisms link the two channels

→

Reaction products
C+c+…

The reaction theory is needed to select only one reaction mechanism. However, nowadays powerful techniques and observables for careful data analysis and theoretical investigation.

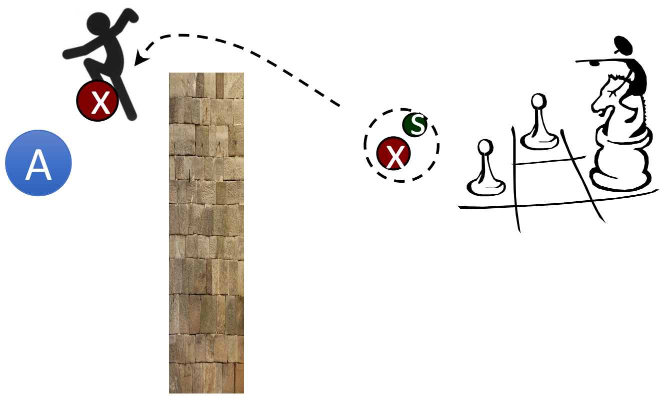
THM in short

Talk by Marco La Cognata this afternoon

Basic principle: relevant low-energy two-body σ from quasi-free contribution of an appropriate three-body reaction in quasi free kinematics

$$A + a \to b + B + s \quad \rightarrow\rightarrow\rightarrow \quad A + x \to b + B$$

a: x ⊕ s clusters



Repulsion wall

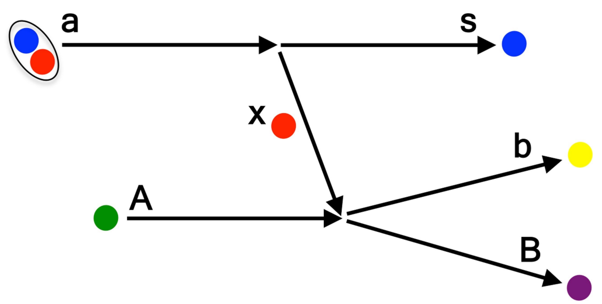
Quasi free mechanism

- ✓ only *x* - A interaction
- ✓ *s* = spectator (p_s~0)

$E_A > E_{Coul} \Rightarrow$

NO Coulomb suppression

NO electron screening



$$\frac{d^3\sigma}{d\Omega_c d\Omega_C dE_c} \propto KF \cdot |\Phi(p_s)|^2 \frac{d\sigma^{off}}{d\Omega}$$

need to normalize the two-body σ to direct data

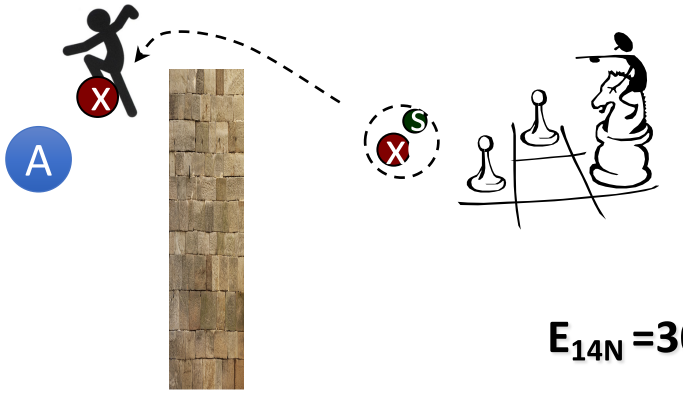
THM applied so far to more than 30 reactions, such as ^{6}Li(p,α)^{3}He, ^{7}Li(p,α)α, ^{2}H(d,p)^{3}H, ^{2}H(d, n)^{3}He, ^{10}B(p,α)^{7}Be,^{11}B(p,α)^{8}Be, ^{17,18}O(p,α)^{14,15}N, ^{13}C(α, n)^{16}O, ^{7}Be(n,α)^{4}He, ^{18}F(p,α)^{15}O, ^{19}F(p,α)^{16}O, ^{10}B(p,α)^{7}Be, ^{11}B(p,α)^{8}Be, ^{12}C(^{12}C,α)^{20}Ne, ^{12}C(^{12}C,p)^{23}Na …

Our Experiment with theTHM

$^{12}C(^{12}C,\alpha)^{20}Ne$ and **$^{12}C(^{12}C,p)^{23}Na$** reactions via the Trojan Horse Method applied to the **$^{12}C(^{14}N,\alpha^{20}Ne)^{2}H$** and **$^{12}C(^{14}N,p^{23}Na)^{2}H$** three-body processes

^{2}H from the ^{14}N as spectator s

Observation of ^{12}C cluster transfer in the $^{12}C(^{14}N,d)^{24}Mg^{*}$ reaction (R.H. Zurmûhle et al. PRC 49(1994) 5)

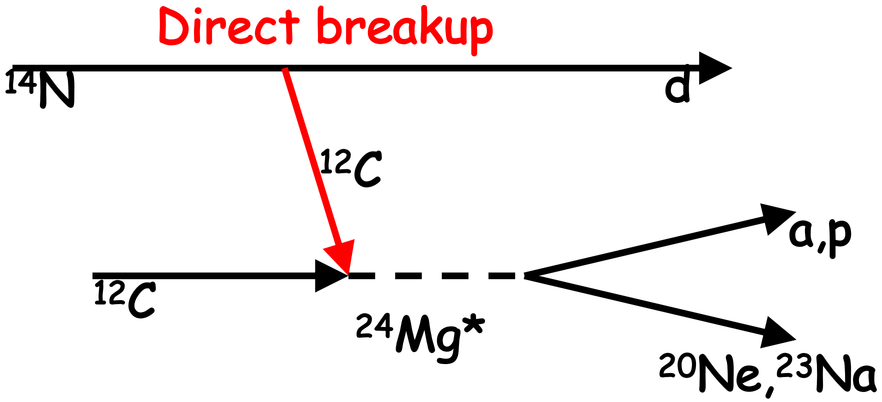


Repulsion wall

QUASI-FREE MECHANISM

✓ only ^{12}C - ^{12}C interaction

✓ d = spectator



E_{14N} =30 MeV> E_{Coul}

⇒ **NO Coulomb barrier in the entrance channel**

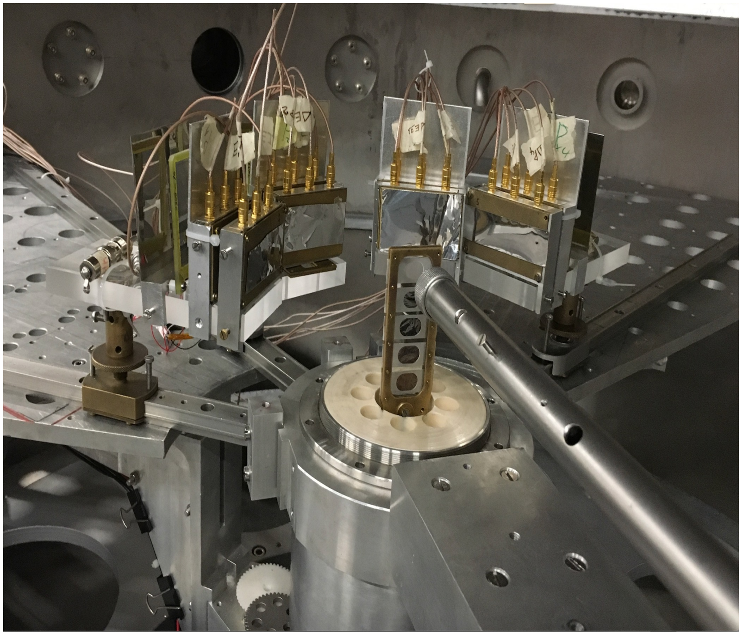
NO electron screening

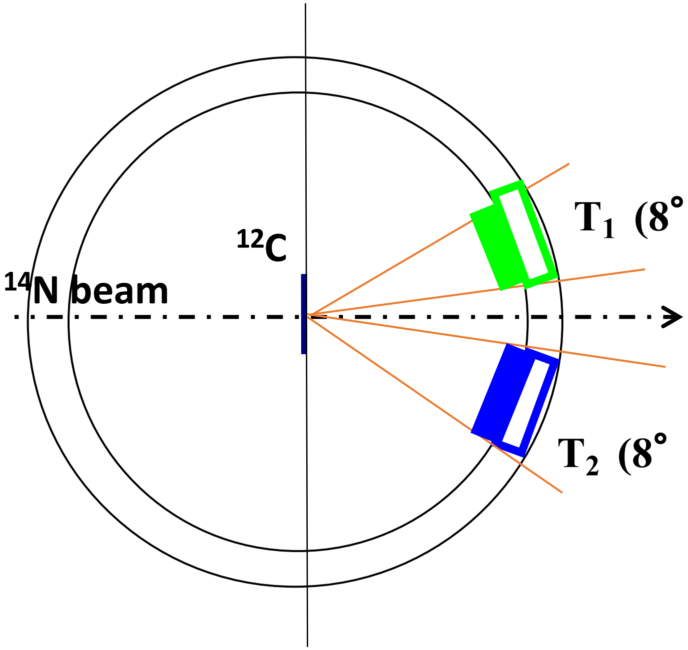
$$E_{QF} = E_{14N}\,\frac{m_{^{12}C}}{m_{^{14}N}}\cdot\frac{m_{^{12}C}}{m_{^{12}C}+m_{^{12}C}}\;-10.27\ \text{MeV}$$

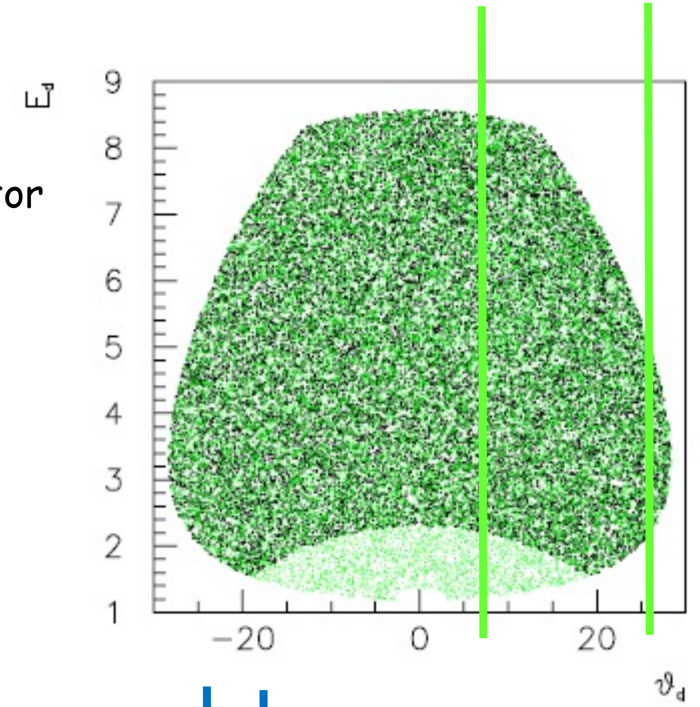
The 14N+12C experiment at LNS

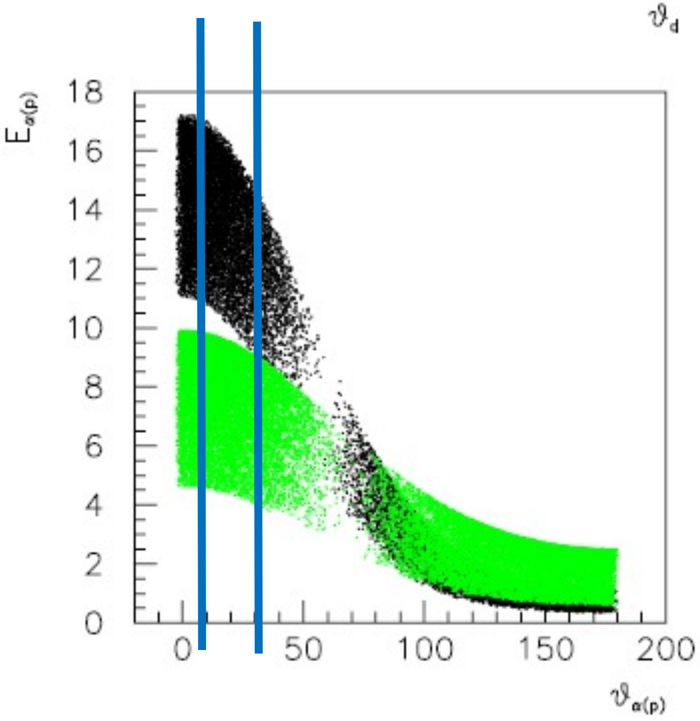
E_{14N}=30 MeV

Particle identification supplied by silicon telescopes: 38 μm silicon detector as ΔE- and 1000 μm Position Sensitive Detector (PSD) as E-detector





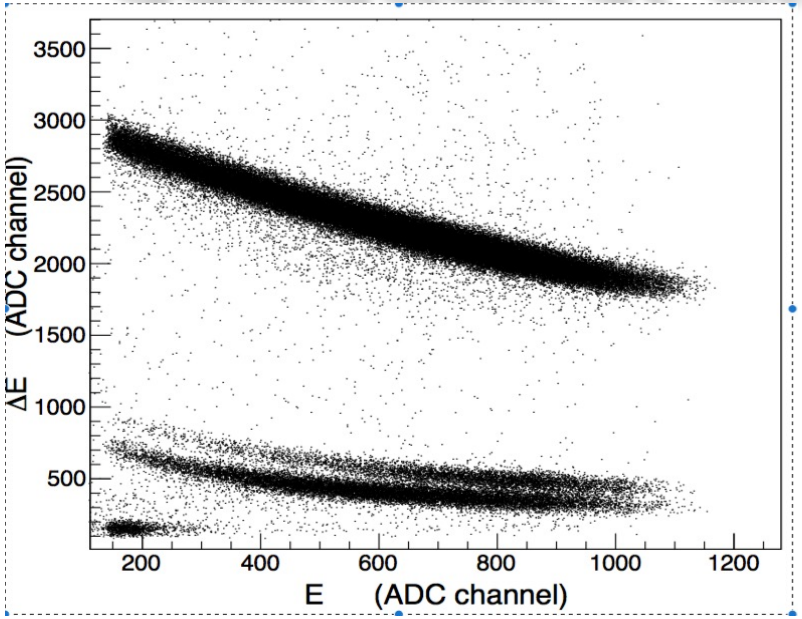


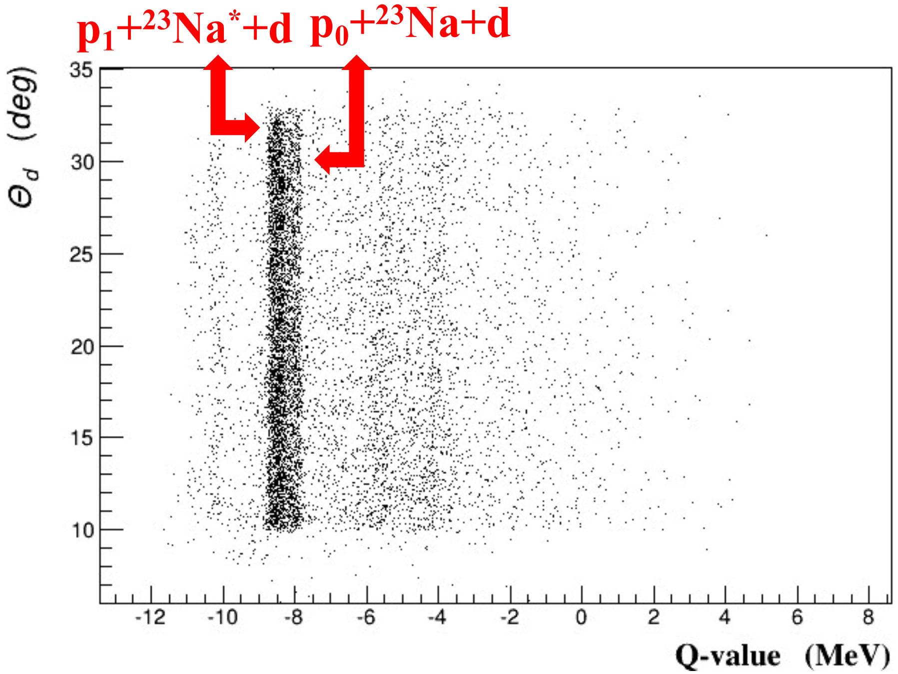


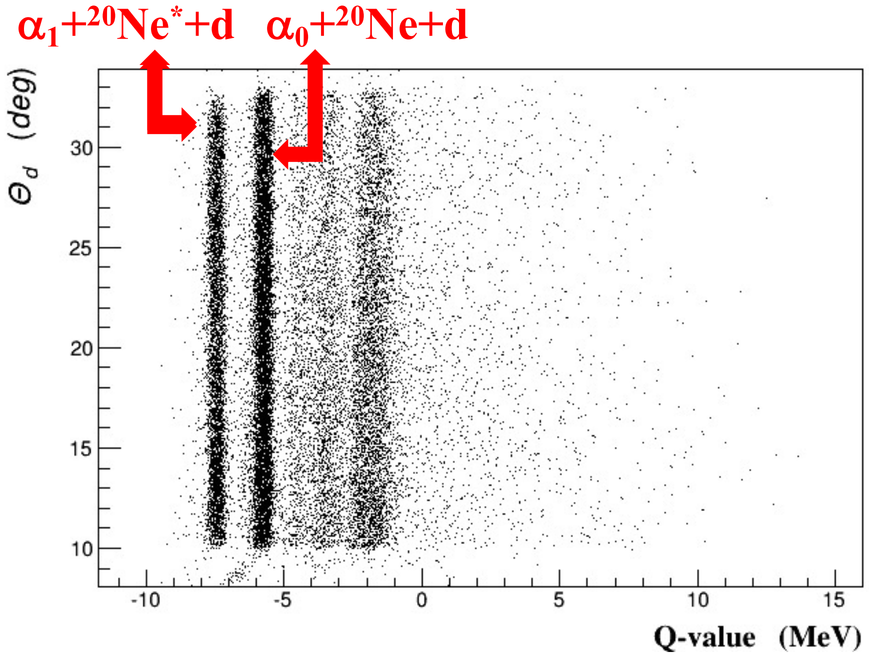
^{20}Ne+α+d and ^{23}Na+p+d reaction channels reconstructed when detecting the ejectile of the two-body reactions (either α (black dots) or p (green dots)) in coincidence with the spectator d particle.

No detection of ^{20}Ne or ^{23}Na quite low energy → too high detection threshold

Selection of the 3-body channels







PWIA approach to the THM

In the restricted phase space region where the quasi free kinematics holds true

$$\frac{d^3\sigma}{d\Omega_B d\Omega_b dE_B} \propto KF \left|\Phi(p_{xs})\right|^2 \left[\frac{d^2\sigma_{xA\to bB}}{dE_{xA} d\Omega}\right]^{HOES}$$

kinematical factor

momentum distribution of *s* inside *a*

Nuclear cross section for the A+x→C+c reaction

$$\frac{d^2\sigma_{xA\to c'}}{dE_{xA} d\Omega_s} = NF \sum_i (2J_i+1) \left| \sqrt{\frac{k_{c'}}{\mu_{c'}}} \frac{\sqrt{2P_{c'}} M_i(p_{xA} R_{xA}) \gamma^i_{xA} \gamma^i_{c'}}{D_i(E_{xA})} \right|^2$$

From the modified R-matrix approach assuming non-interfering resonances

R-matrix fits on all channels at the same time in the full energy range of interest

$^{12}C+^{12}C \to \alpha_0+^{20}Ne$

$^{12}C+^{12}C \to \alpha_1+^{20}Ne^*$

$^{12}C+^{12}C \to p_0+^{23}Na$

$^{12}C+^{12}C \to p_1+^{23}Na^*$

Important: the same reduced widths appear in the THM and in the on-energy-shell cross-sections, so the ones extracted from THM data can be used to determine the direct *S*(*E*) factor, without HOES effects.

but No absolute value of the cross section → normalization to direct data available at higher energies

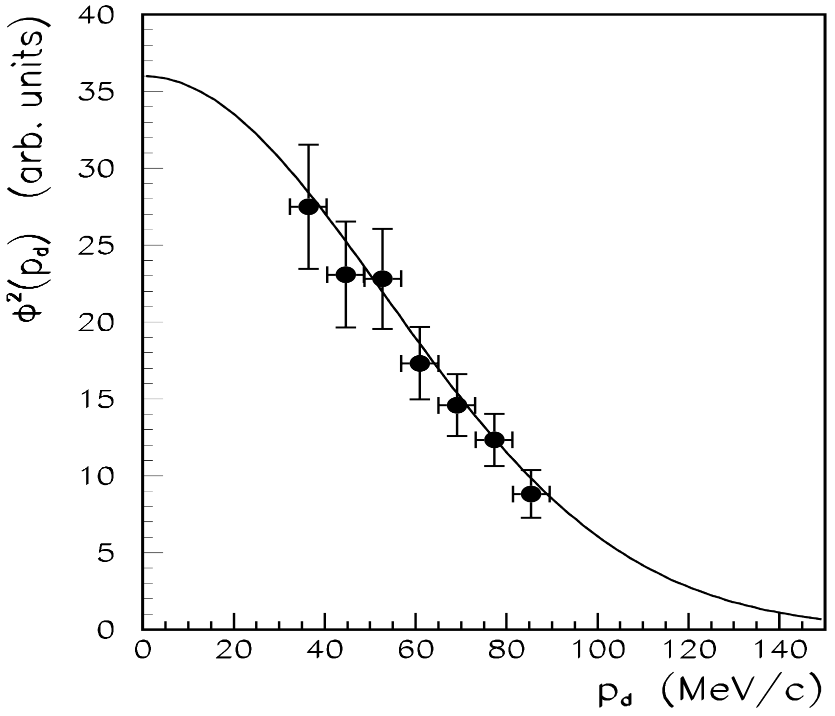
Selection of the quasi-free mechanism

Comparison between the experimental momentum distribution and the theoretical one

$$|\Phi(\overrightarrow{p_d})|^2 \propto \frac{\dfrac{d^3\sigma}{d\Omega_d d\Omega_{p,\alpha} dE_d}}{(KF)\left(\dfrac{d\sigma_{12C12C}}{d\Omega}\right)^N}$$

On-the-energy-shell bound state wave number ((see I.S. Shapiro, Soviet Physics Uspekhi Vol. 10, n. 4 (1968) and earlier works): $(2\mu_{d12C}B_{d12C})^{1/2}$=181 MeV/c.
Staying within this value is the condition for the QF mechanism to be dominant

Solid line: momentum distribution of d inside ^{14}N from the Wood-Saxon ^{12}C-d bound state potential with standard geometrical parameters r_0=1.25 fm, a=0.65 fm and V_0=54.427 MeV



Plane Waves reliable also because:

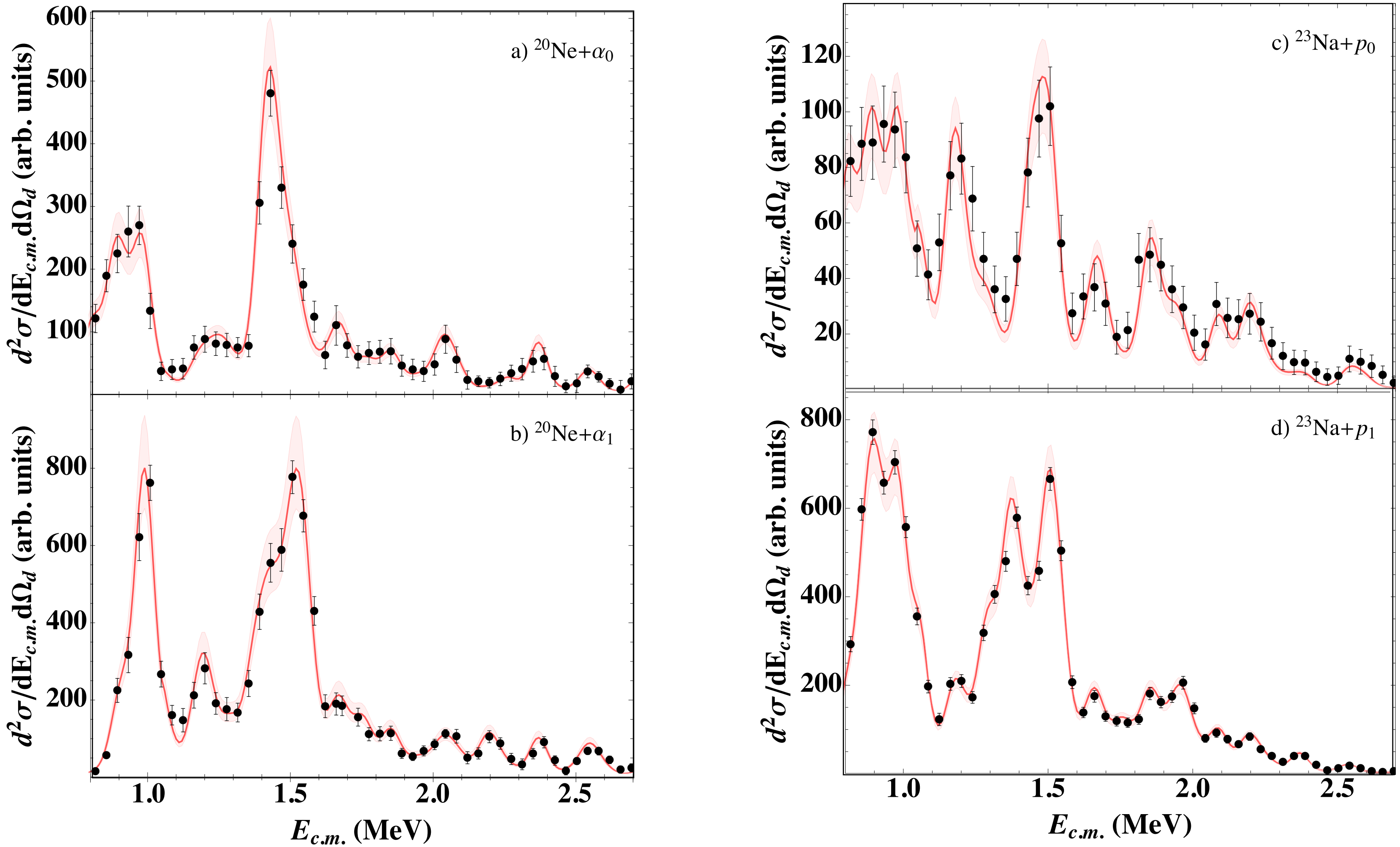
- $p_d < (2\mu_{d12C}B_{d12C})^{1/2}$=181 MeV/c → Proved that the shape of the momentum distribution is insensitive to the theoretical framework used for its derivation (agreement between PWA and DWBA)

- the ^{14}N beam energy of 30 MeV corresponds to a quite high momentum transfer q_t=500 MeV/c giving an associate de Broglie wavelenght of 0.4 fm (< 3 fm=^{12}C+d)

Extraction of the two-body cross section

$$\frac{d\sigma_3}{dE} = KF|\varphi(p_s)|^2 \frac{d\sigma}{dE}$$

A. Tumino et al., Nature 557, 687 (2018)



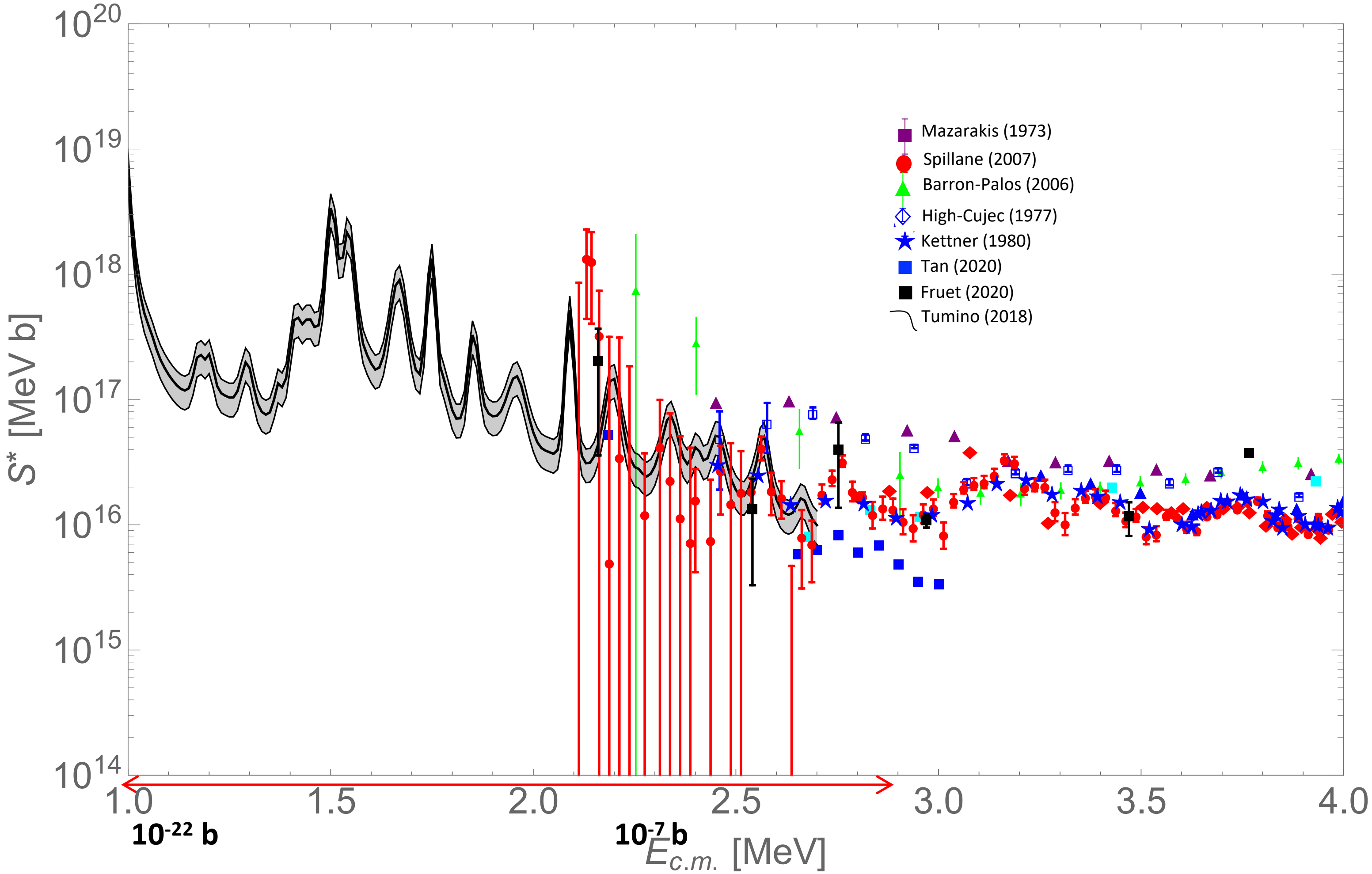
Red lines and bands: R-matrix fits for all channels at the same time

Reduced widths for known levels are used as free parameters to reproduce their total and partial widths as in Abegg & Davis, PRC 1991 → → →

12C+12C comprehensive figure

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

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



Next step:

- direct data below 2 MeV (LUNA MV, Stella collaboration …)
- improve the normalization of THM data to direct ones with larger overlap

Nature volume 557, pages687–690 (2018) Published: 23 May 2018

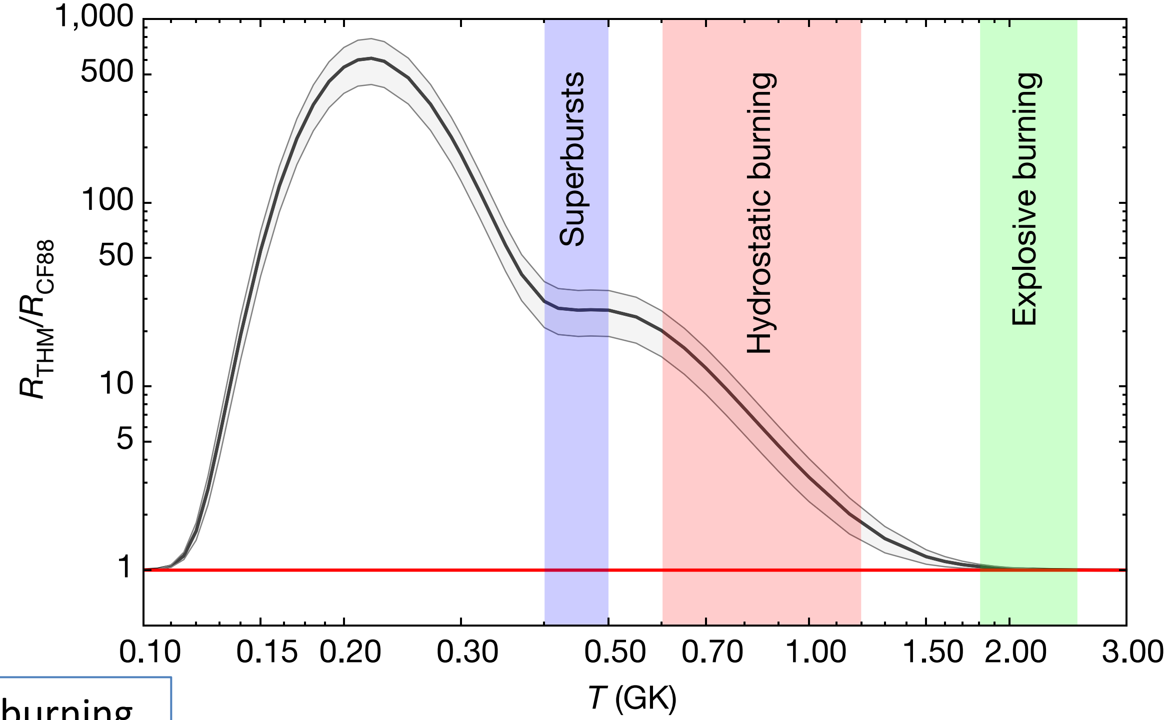
LETTER

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]

12C+12C Reaction Rate



Color shadings mark typical regions for C-burning

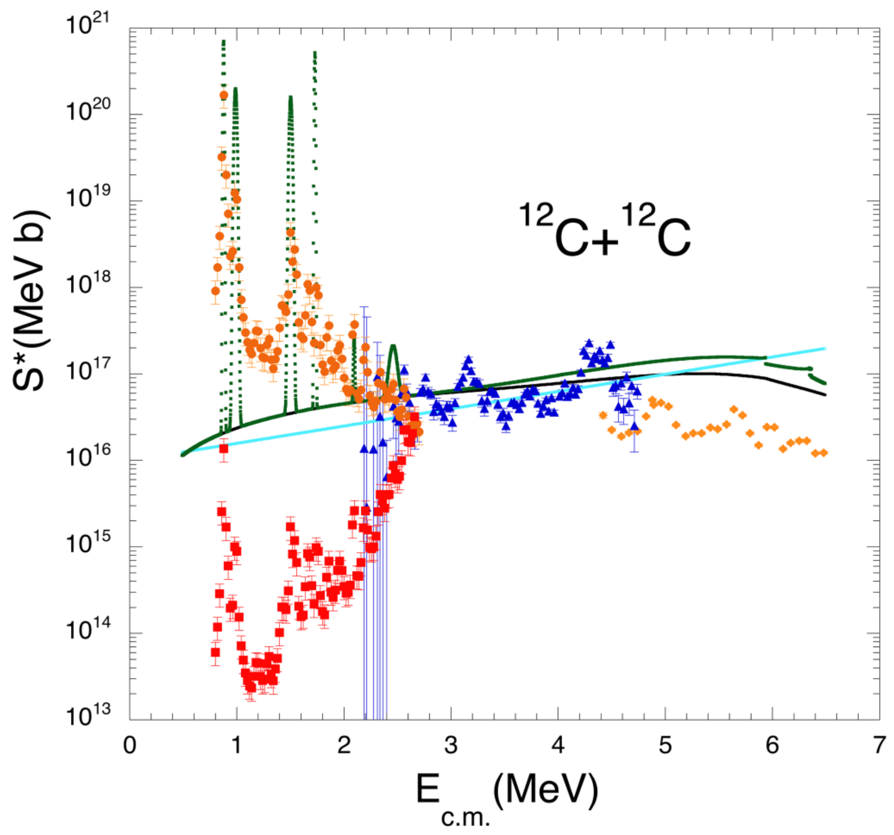
Compared to CF88, the present rate increases from a factor of 1.18 at 1.2 GK to a factor of more than 25 at 0.5 GK

Recent theoretical developements to investigate the $^{12}C+^{12}C$ fusion:

Debate around THM results:

theory calculations based on DWBA (Mukhamedzhanov et al., PRC 2019): large corrections (red squares) to the initially reported S-factors. However, several points are obscure, such as:

-the numerical stability of the calculations involving a transfer to the continuum is not guaranteed and needs a more critical examination.
-12C+12C unusual potential parameters: extremely large diffuseness and radius, bin functions to reproduce resonances with an unphysically large number of nodes …



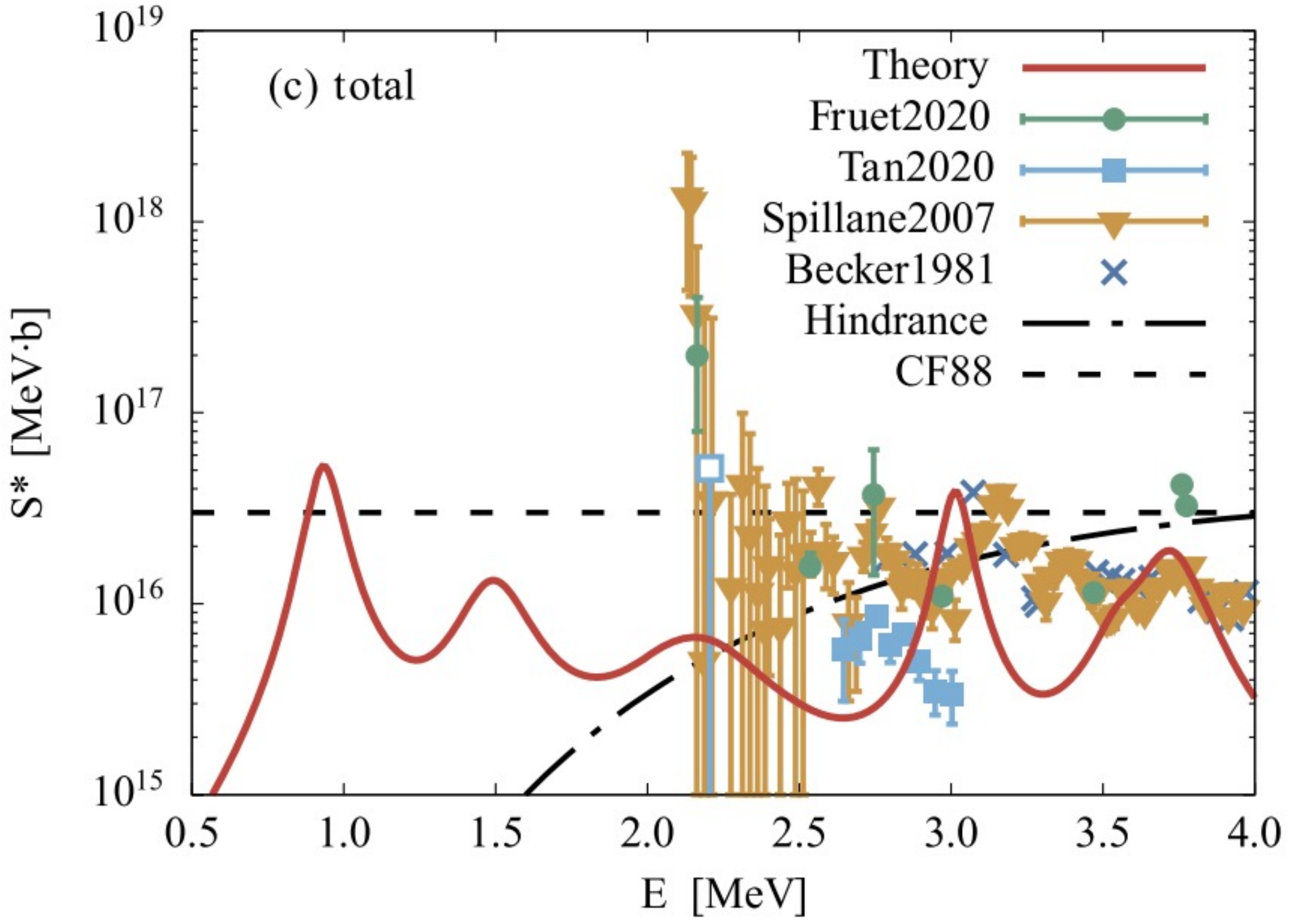
theory calculations using the Feynman path-integral method (Bonasera and Natowitz PRC(R) 2020) and including some l=0 resonances, lead to S-factor values (green color) in agreement with results from the THM experiment (orange circles), highlighting the role of resonances

New DWBA calculations to be published soon
Possible experiment with $^{13}C+^{12}C$, but ^{13}C not an easy TH nucleus (l=1 intercluster motion)

Recently, the AMD provided a a quantitative description of the low-energy resonances by handling the channel coupling and nuclear rotation without adjustable parameters.
It successfully described the gross structure of the main observed resonances above and below the Gamow window.

The calculation suggested
no low-energy suppression of the S*-factor

Y. Taniguchi & M. Kimura, PLB 823 136790 (2021)



Comparison between THM rate and recent assumptions exploring how even a single low-lying resonance can dramatically impact the evolution and nucleosynthesis of massive stars. Rates normalized to CF88:

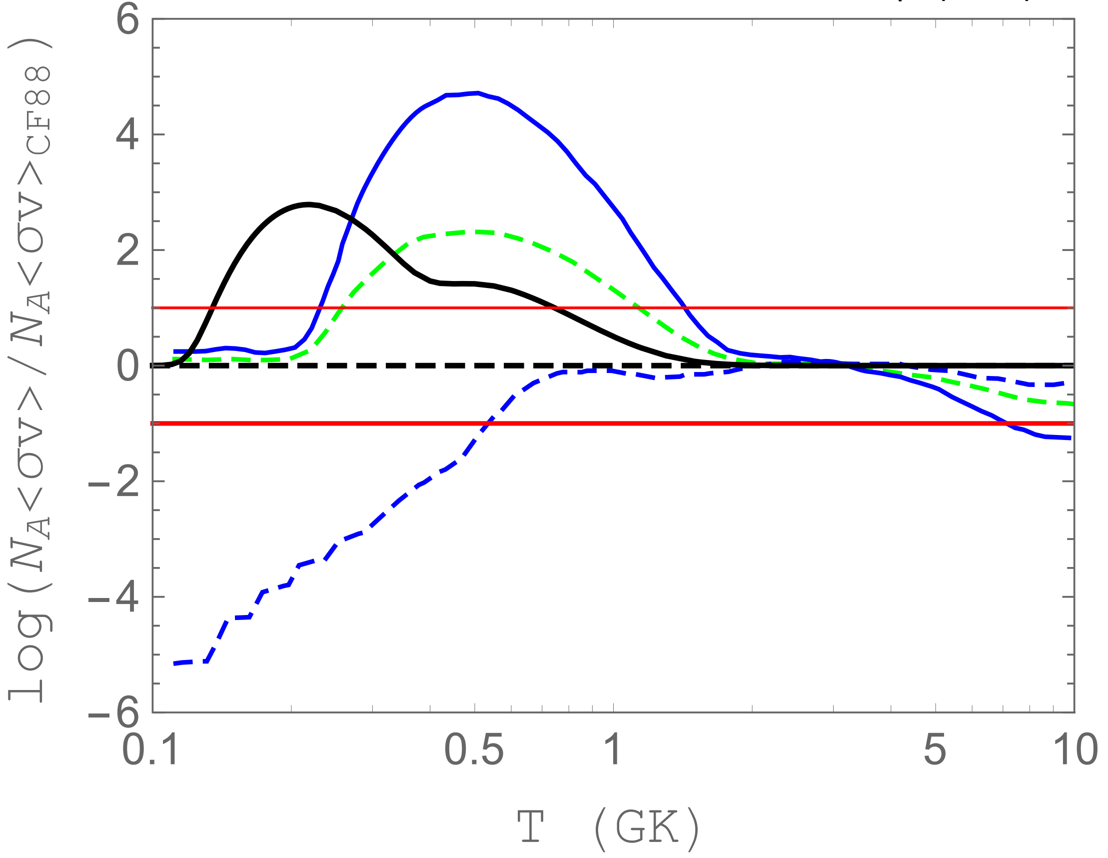
- THM $^{12}C + ^{12}C$ reaction rate from Tumino et al. (2018) (black solid line)

-CU rate (blue solid line) from Bennett et al. (2012) and Pignatari et al. ApJ (2013), 50,000 times higher than CF88 at 0.5 GK

- CI rate (green dashed line) from Bennett et al. ApJ (2012), representing the geometric mean of CF88 and CU
- CL rate (blue dashed line) from Pignatari et al. (2013), 20 times lower than CF88 at 0.5 GK

CF88t10 and CF88d10 rates (red thinner and thicker lines) from Pignatari et al. (2013), a factor of 10 (CF88T10) and 0.1 (CF88d10) with respect to CF88

Chieffi et al. ApJ (2021)



None of the explorations are confirmed by the THM rate that experiences a smoother increase than CU and CI, crossing CF88T10 around 0.75 GK, while reaching a much lower value than CU around 0.5 GK. Below 0.4 GK the THM rate shows a further increase by up to a factor of ~800 owing to the lowest-energy resonances occurring at center-of-mass energies around 1 MeV. Within a comparison with CF88, in the temperature range of interest for the current calculations, the increasing factor of the THM rate varies between ~25 at T=0.5GK and ~3 at T=1GK.

Some recent implications from the new 12C+12C rate

- Impacts of the New Carbon Fusion Cross Sections on Type Ia Supernovae (K. Mori et al. MNRAS 2018)

Partial solution of the Neutron star birthrate problem:

The NS birthrate has been estimated to be $10.8^{+7.0}_{-5.0}$ NSs/century, while the CCSN rate is estimated to be 1.9±1.1 SNe/century from measurements of γ-ray from ^{26}Al (Diehl et al. 2006; Keane & Kramer 2008), suggesting that the origin of NSs is supplemented by the so called Accretion Induced Collapse path of the WD mergers.

The enhanced reaction rate results in a lower ignition temperature, leading to a higher probability of finding WD-WD mergers reaching theAccretion Induced Collapse. This could increase the birthrate of the Galactic Neutron stars making the fraction of the WD mergers in the progenitors of type Ia SNe smaller.

To be continued … need to investigate the contribution of the DD scenario to SNe Ia, still largely subject to observational errors.

Some recent implications from the new 12C+12C rate

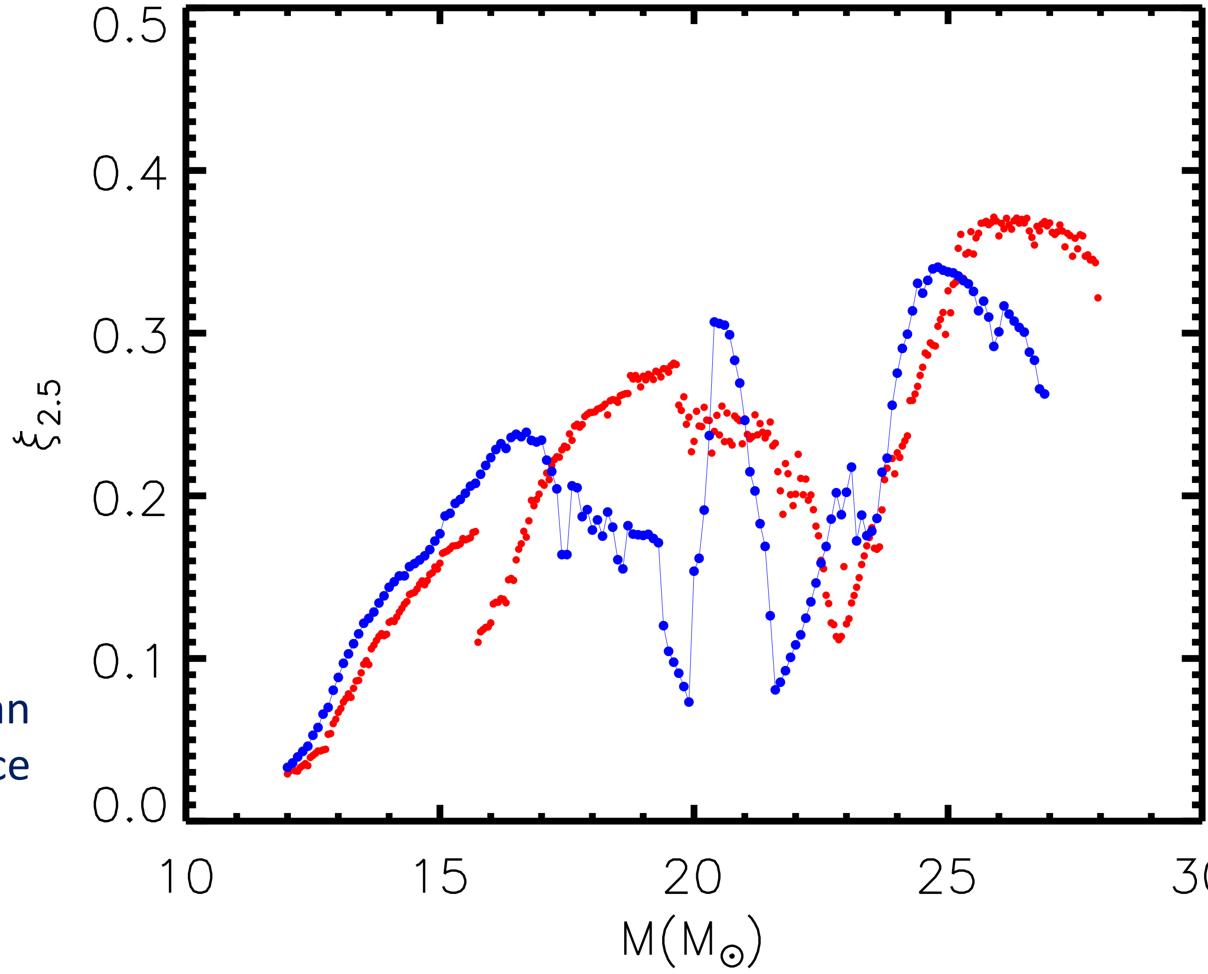
New investigation of the dependence of the compactness on the initial mass:

(A. Chieffi et al. ApJ 2021)

Compactness parameter ξ

(O' Connor & Ott 2011, ApJ 730,70)

$$\xi_i = \frac{M_i(M_\odot)}{R_i(10^3\ km)}$$ Best value → i=2.5 $M_\odot$



Scaling of the compactness of a star with the initial mass for two diffferent choices of the $^{12}C+^{12}C$ nuclear cross section:

red dots → CF88
blue dots →THM

It is quite evident that the adopted nuclear cross section plays an important role in determing the final compacness of a star and hence its final fate: explosion or collapse.

Remarkable lower compactness in some mass intervals, like between 17 and 20 $M_\odot$, and 21 and 23$M_\odot$, and above 25$M_\odot$. It would be interesting to follow with a 3D code what happens to the explosion …

To be continued … a lot of experimental and theoretical activity in the field

Thank you!