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Beyond Iron peak: focus trasversale sulle sorgenti di neutroni $^{13}C(\alpha,n)$ e $^{22}Ne(\alpha,n)$, e sulla $^{12}C+^{12}C$

Cristian Massimi

Dipartimento di Fisica e Astronomia

Outline:

- $^{13}C(\alpha,n)$
- $^{22}Ne(\alpha,n)$
- $^{12}C + ^{12}C$

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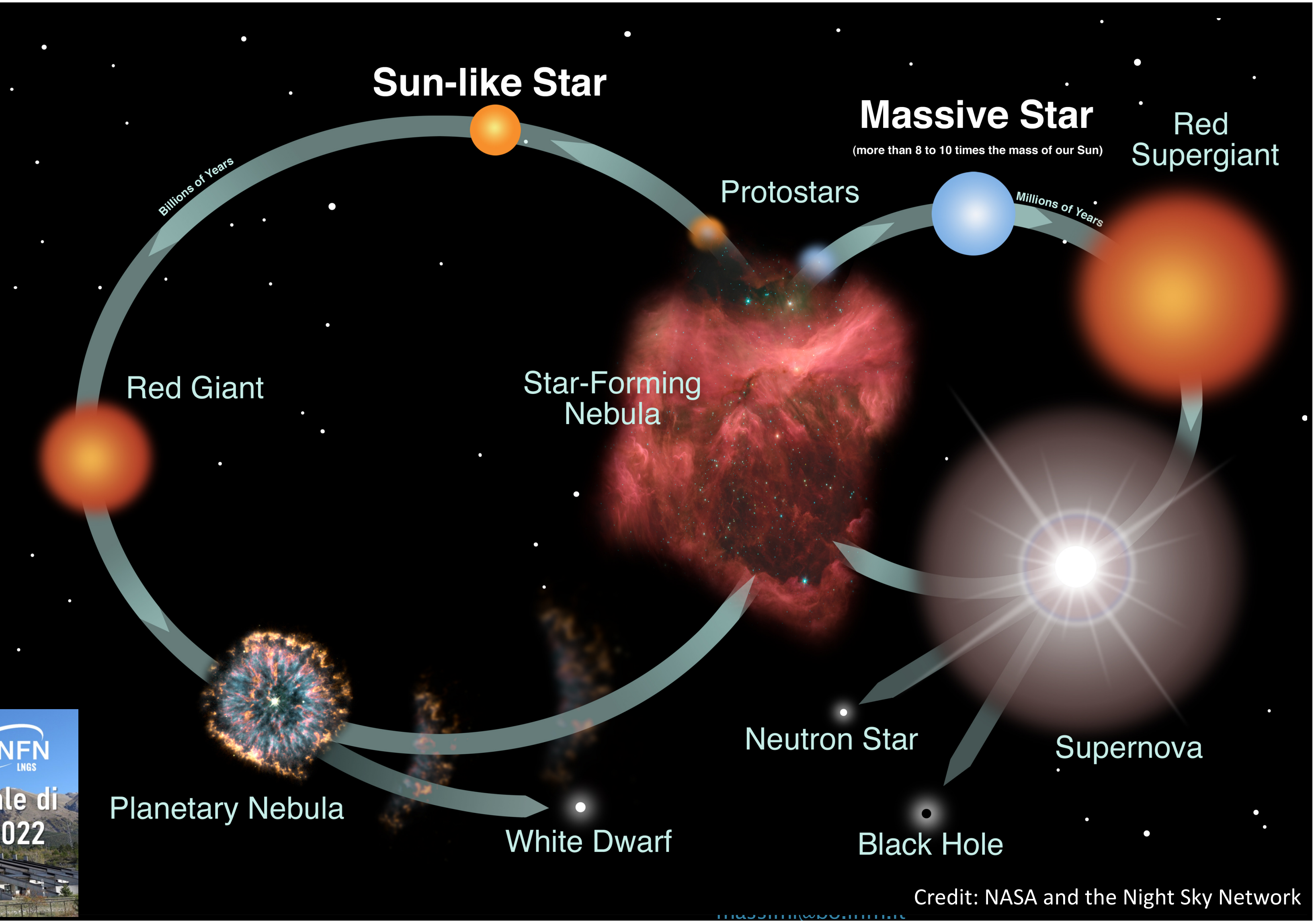
In the cosmos,



Credit: NASA and the Night Sky Network

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Quinto Incontro Nazionale di Fisica Nucleare INFN 2022

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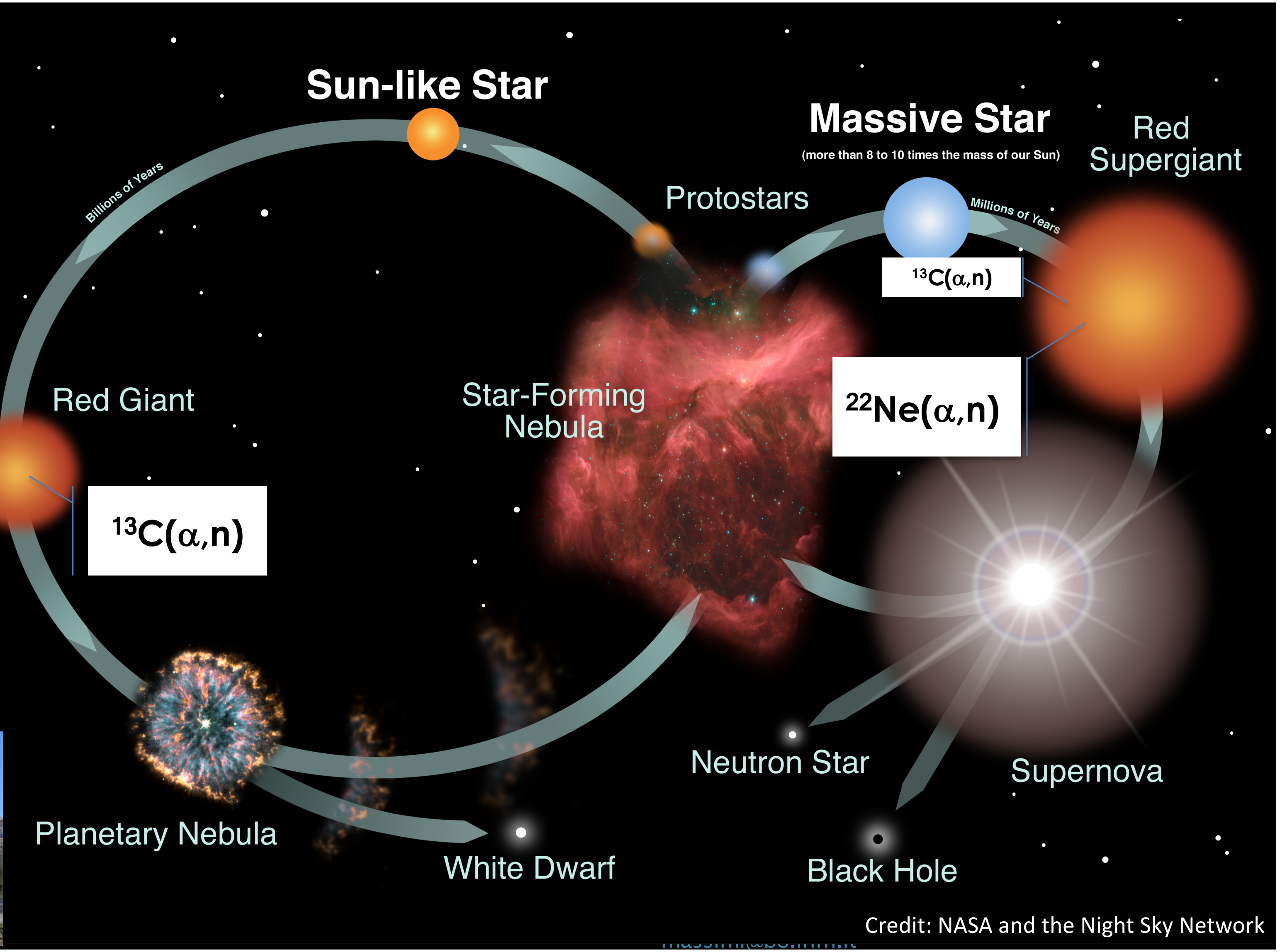

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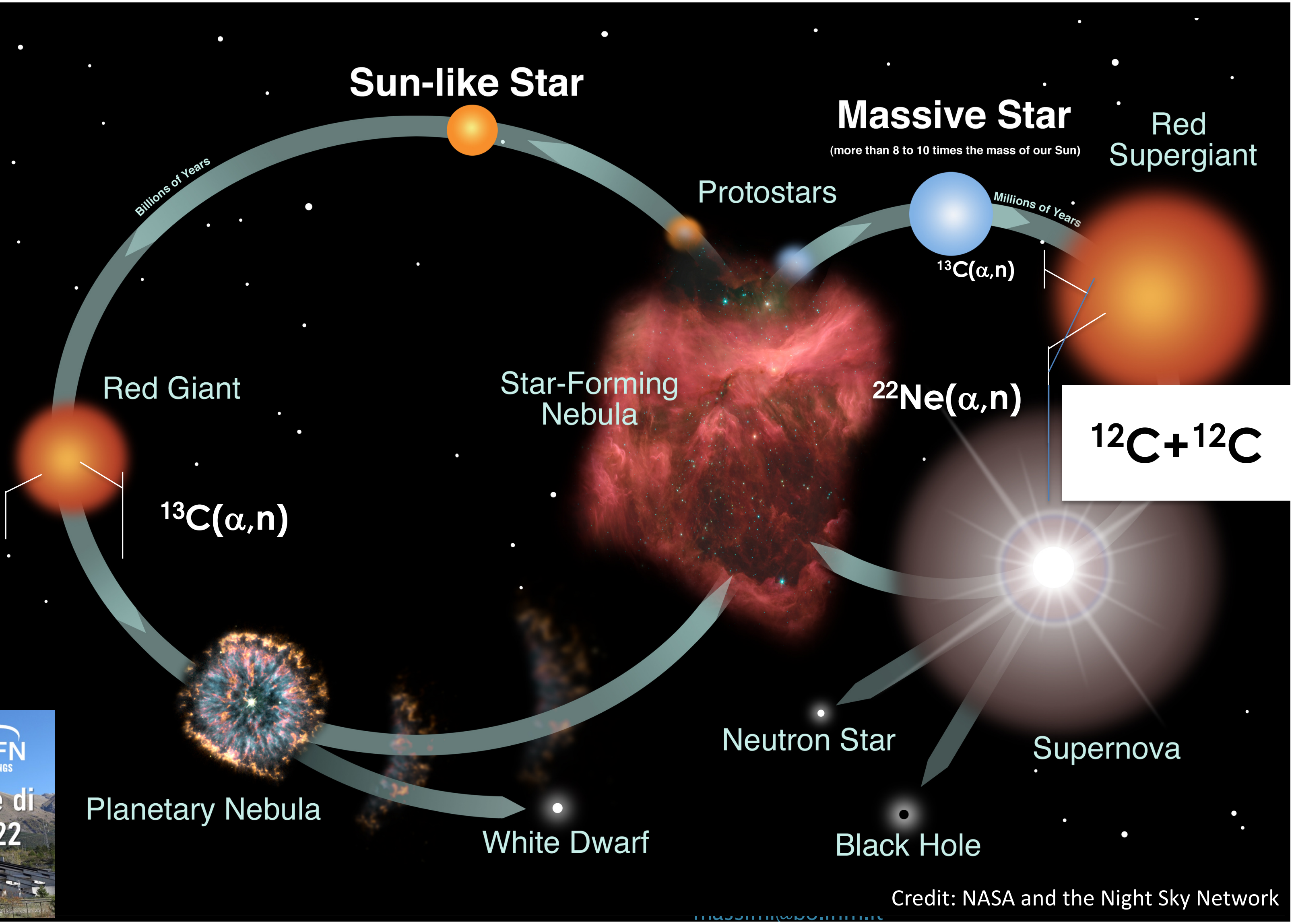

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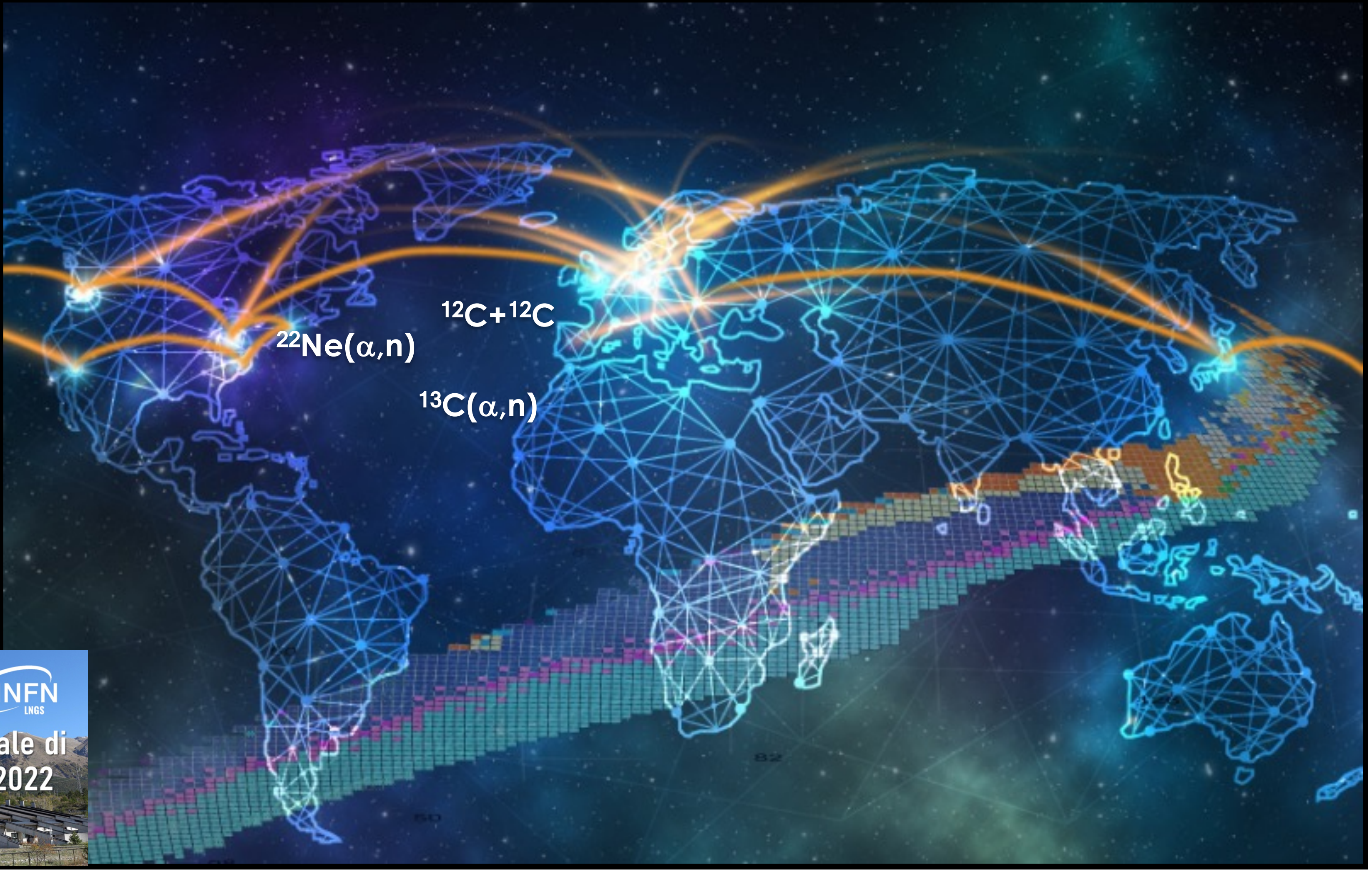
In the cosmos,
On Earth (labs),



Credit: Facility for Rare Isotope Beams

Outline:

- $^{13}C(\alpha,n)$
- $^{22}Ne(\alpha,n)$
- $^{12}C + ^{12}C$

In the cosmos,
On Earth (labs),
@ INFN

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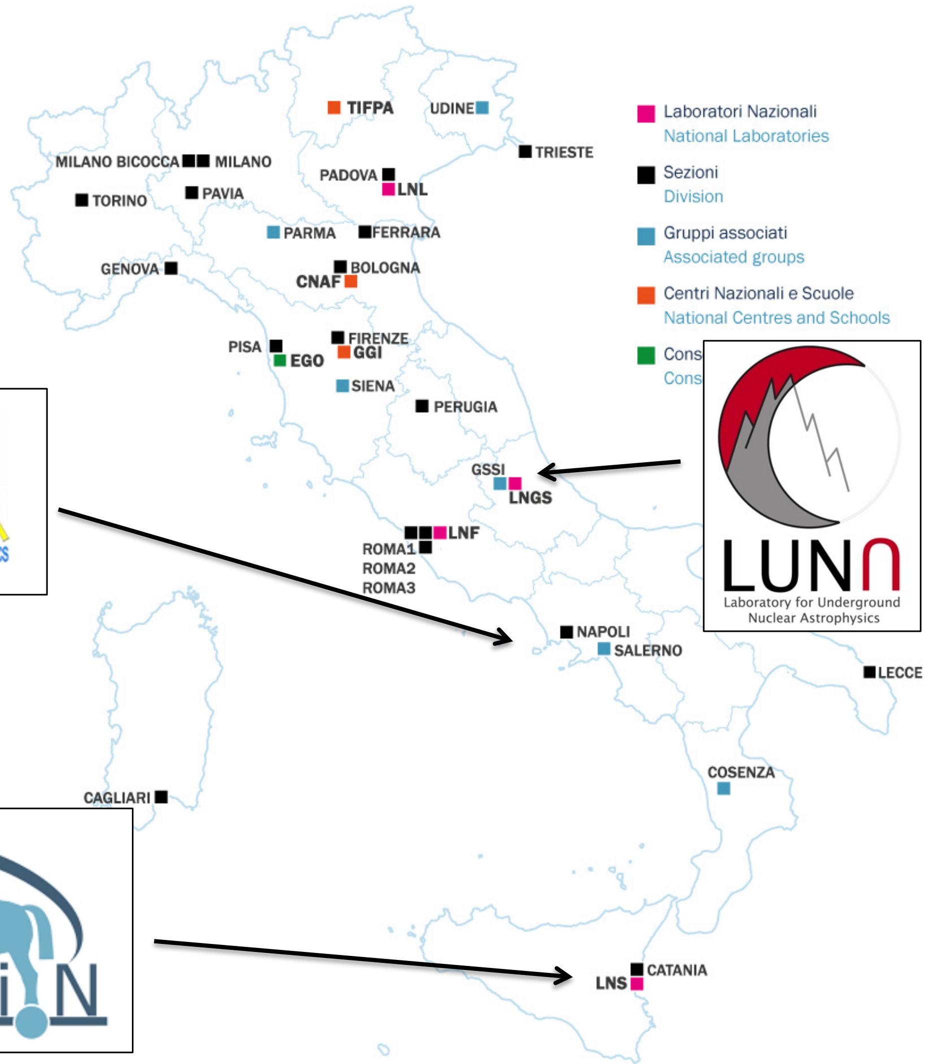
CERN

nTOF

ERNA
European Recoil separator for Nuclear Astrophysics

AsFiN

LUNA
Laboratory for Underground Nuclear Astrophysics



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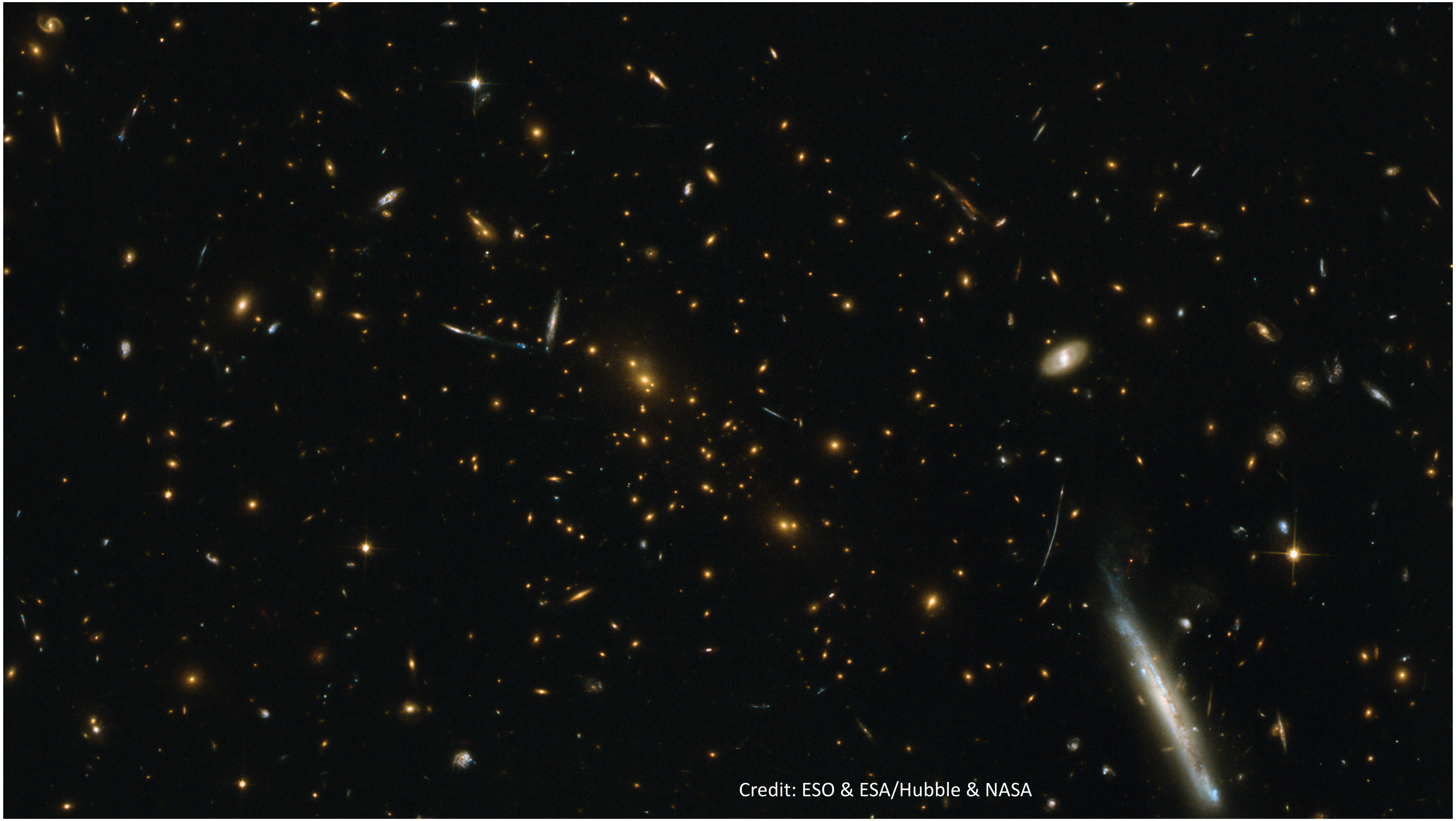


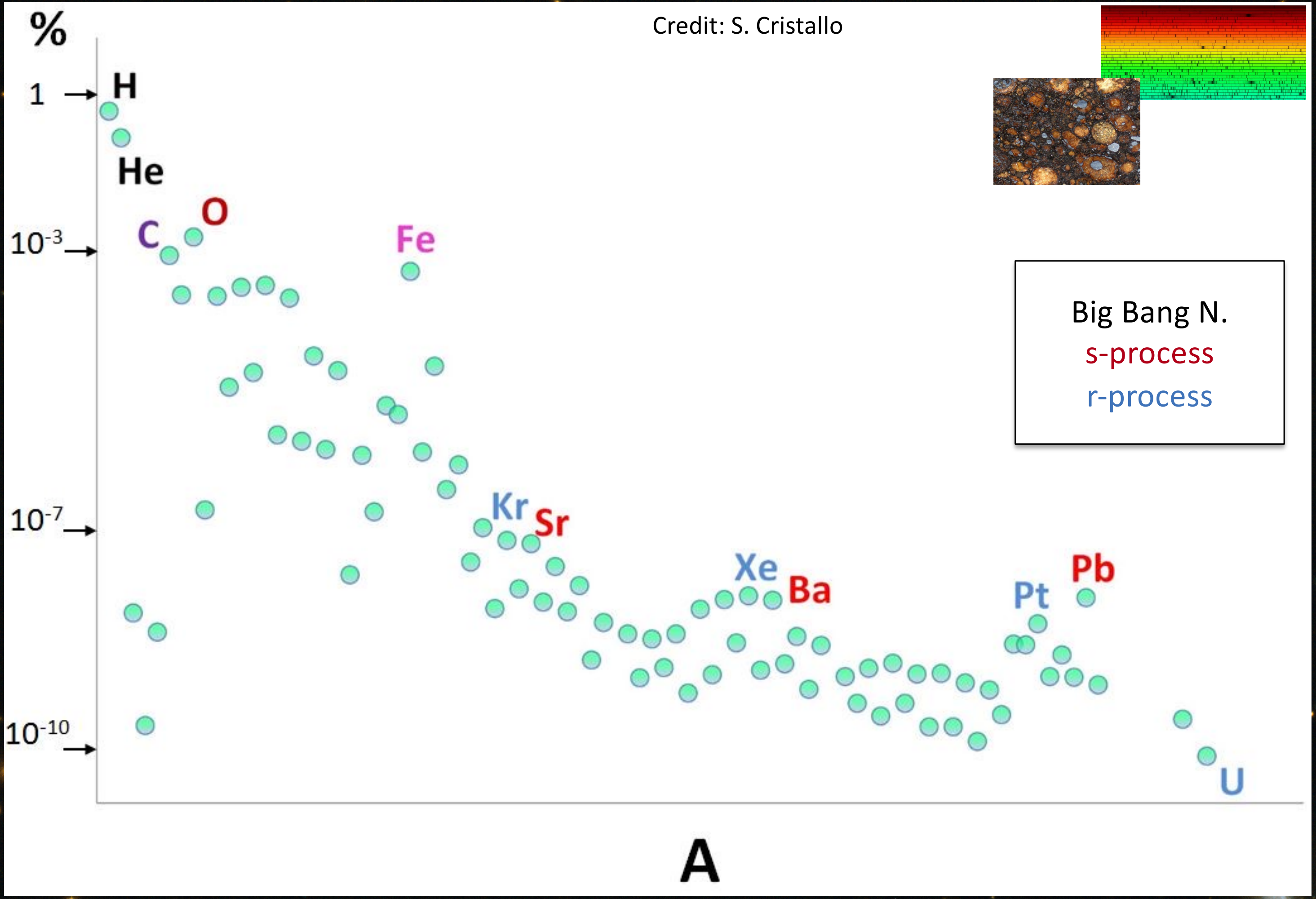
Credit: ESO & ESA/Hubble & NASA

All visible objects in the night sky are powered by nuclear reactions

Nuclear physics governs the evolution of stars from birth to their final fate

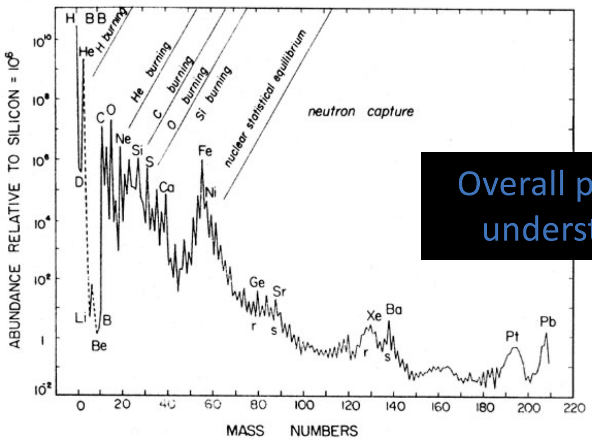
Nuclear reactions in the Big Bang, in stars and in stellar explosions have created every single chemical element found in nature today

Credit: ESO & ESA/Hubble & NASA

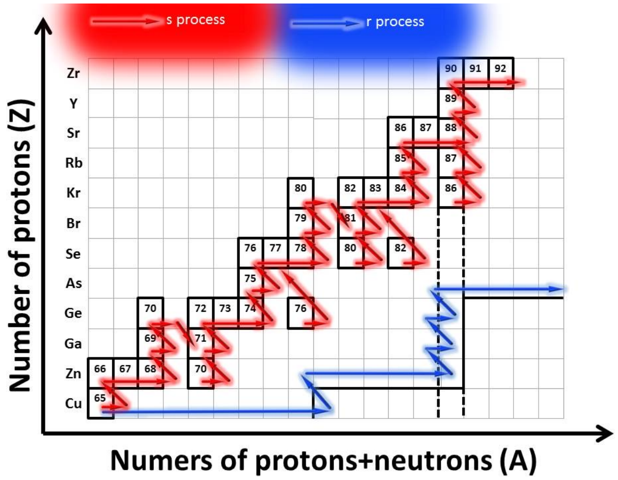


Credit: S. Cristallo

Credit: ESO & ESA/Hubble & NASA



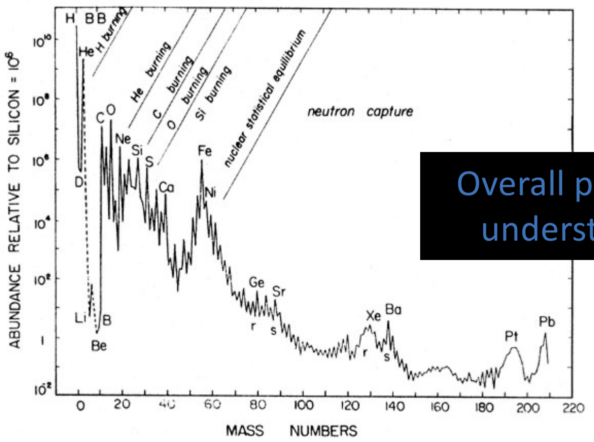
Overall picture understood



massimi@bo.infn.it

(Some) open questions

- ^{7}**Li** produced in Big Bang Nucleosynthesis
- Elements in the **Sun** beyond He (**metallicity**)
- **r process** (Main & Weak ?)
- **r process site** (Supernovae or Neutron Star mergers, …)
- Stellar explosion (basic mechanism)
- X-ray bursts
- …



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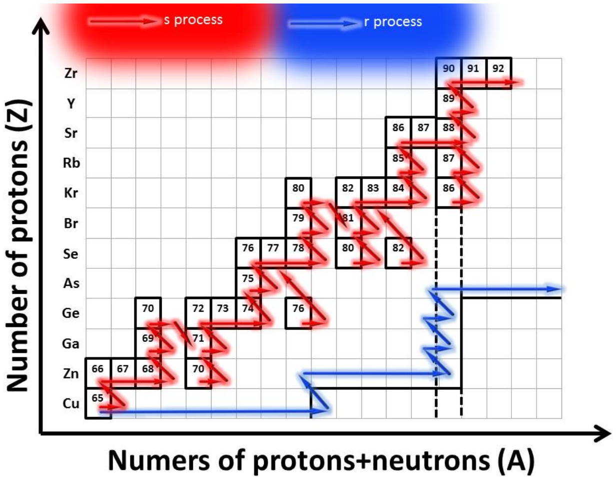

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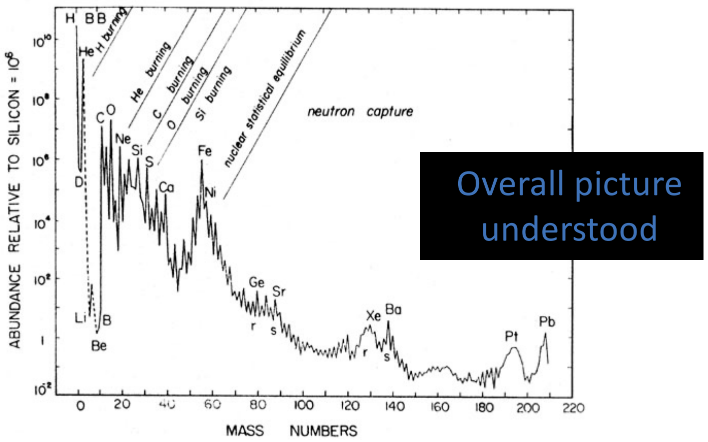
- ❖ …

3 main **drivers pushing the frontiers**:

- **Multi-messenger observations** force rethinking our paradigms (e.g. detection of surprisingly massive neutron stars)
- **Multi-facility nuclear experiments** and advances in nuclear theory
- Expansion of **computational capabilities** enables 3D simulations of stellar interiors



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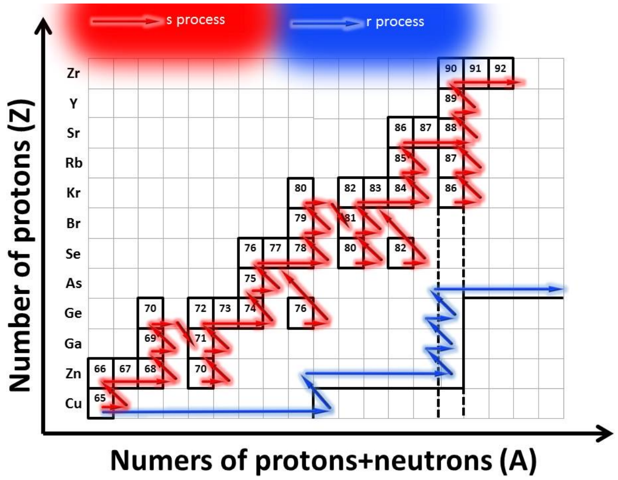
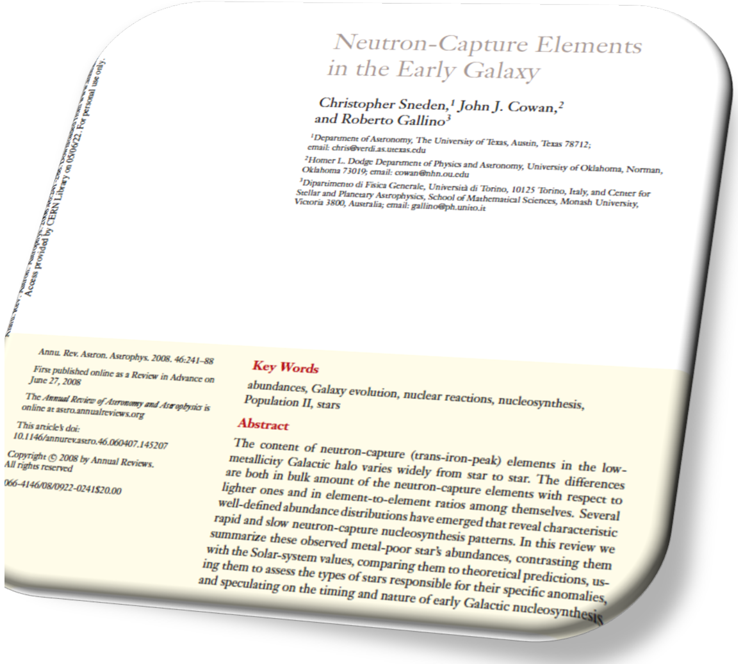


The role of s-process, an example



Annu. Rev. Astron. Astrophys. 2008.46:241-288. Downloaded from www.annualreviews.org
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Neutron-Capture Elements in the Early Galaxy

Christopher Sneden,[1] John J. Cowan,[2] and Roberto Gallino[3]

[1]Department of Astronomy, The University of Texas, Austin, Texas 78712; email: chris@verdi.as.utexas.edu

[2]Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma 73019; email: cowan@nhn.ou.edu

[3]Dipartimento di Fisica Generale, Università di Torino, 10125 Torino, Italy, and Center for Stellar and Planetary Astrophysics, School of Mathematical Sciences, Monash University, Victoria 3800, Australia; email: gallino@ph.unito.it

Annu. Rev. Astron. Astrophys. 2008. 46:241–88

The *Annual Review of Astronomy and Astrophysics* is online at astro.annualreviews.org

This article's doi:
10.1146/annurev.astro.46.060407.145207

066-4146/08/0922-0241$20.00

Key Words

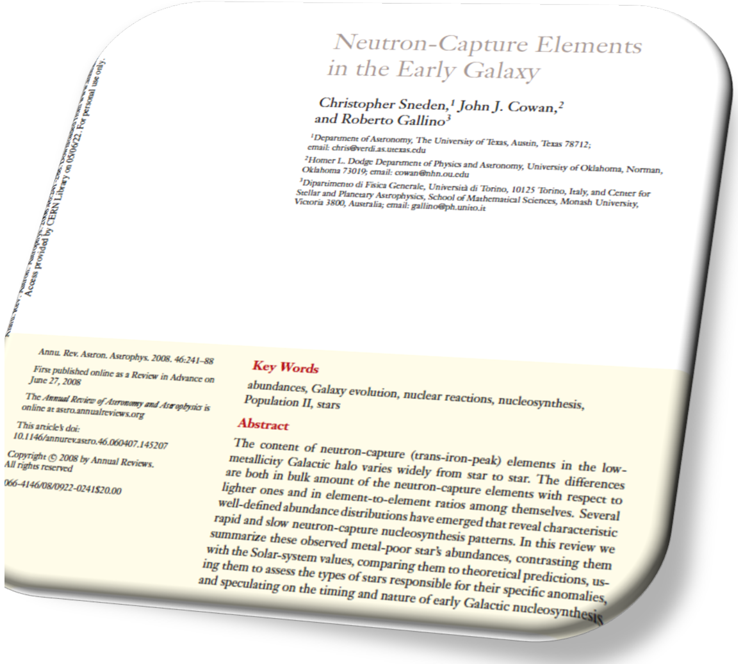
abundances, Galaxy evolution, nuclear reactions, nucleosynthesis, Population II, stars

Abstract

The content of neutron-capture (trans-iron-peak) elements in the low-metallicity Galactic halo varies widely from star to star. The differences are both in bulk amount of the neutron-capture elements with respect to lighter ones and in element-to-element ratios among themselves. Several well-defined abundance distributions have emerged that reveal characteristic rapid and slow neutron-capture nucleosynthesis patterns. In this review we summarize these observed metal-poor star's abundances, contrasting them with the Solar-system values, comparing them to theoretical predictions, using them to assess the types of stars responsible for their specific anomalies, and speculating on the timing and nature of early Galactic nucleosynthesis

$$r = \underset{\substack{\nearrow \\ \text{Solar}}}{1} - s$$

The role of s-process, an example



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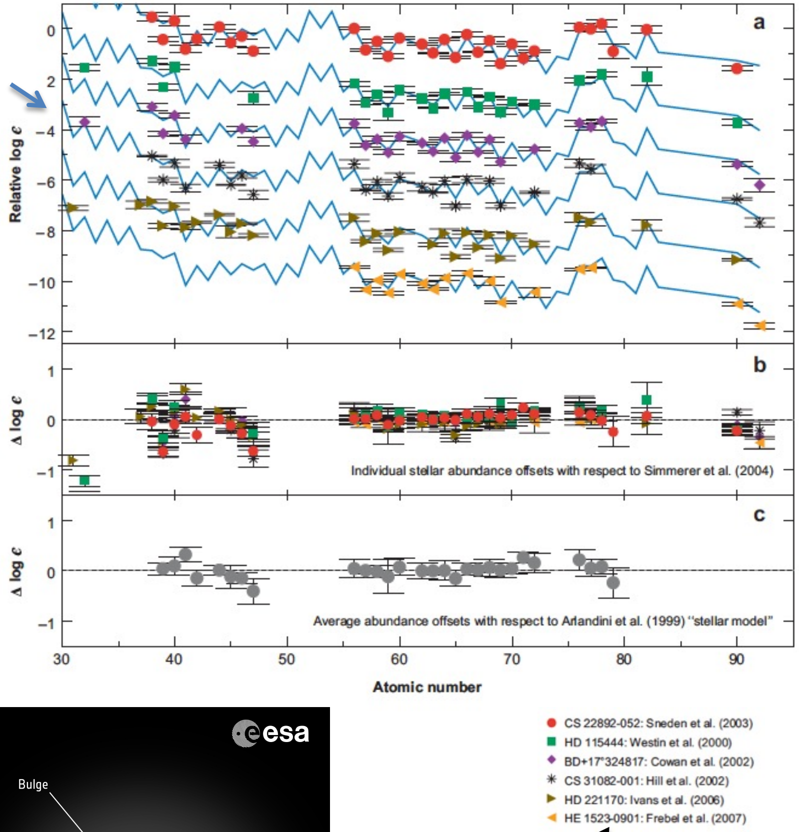
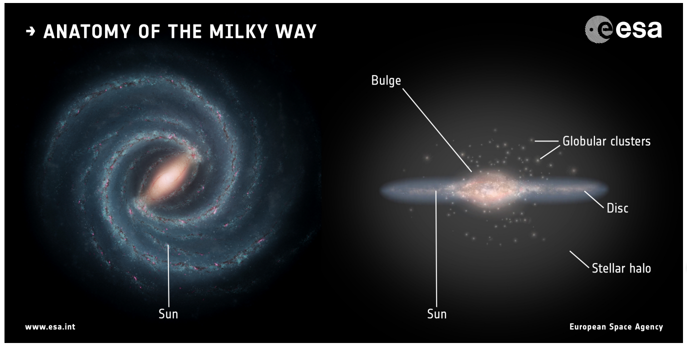
$$r = 1 - s$$

Solar

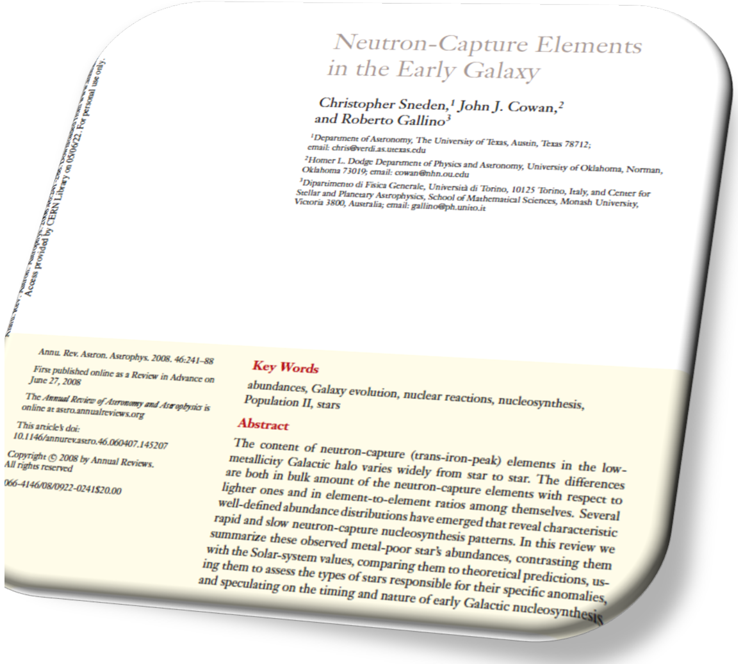
Solar-system **r-only** abundance distribution





r-process rich
Galactic halo stars

The role of s-process, an example



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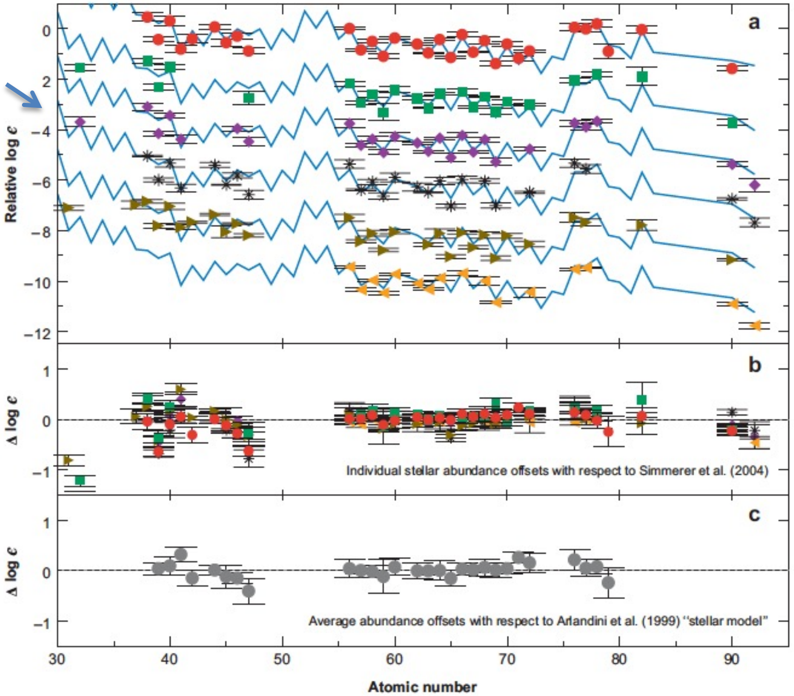
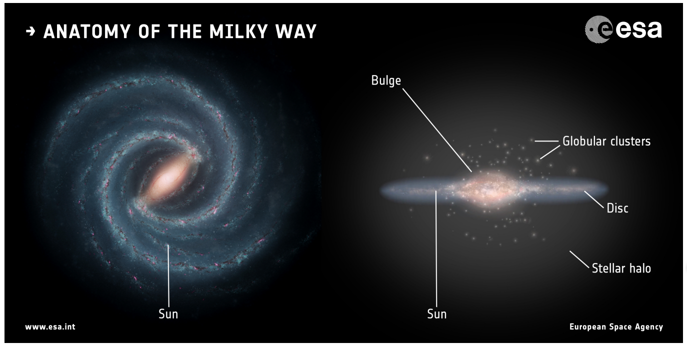
Solar-system **r-only** abundance distribution

Detailed knowledge of the s-process nucleosynthesis is the prerequisite for the study of the chemical evolution of the Galaxy



● CS 22892-052: Sneden et al. (2003)
■ HD 115444: Westin et al. (2000)
◆ BD+17°324817: Cowan et al. (2002)
✳ CS 31082-001: Hill et al. (2002)
▶ HD 221170: Ivans et al. (2006)
◀ HE 1523-0901: Frebel et al. (2007)

r-process rich Galactic halo stars



$r = 1 - s$

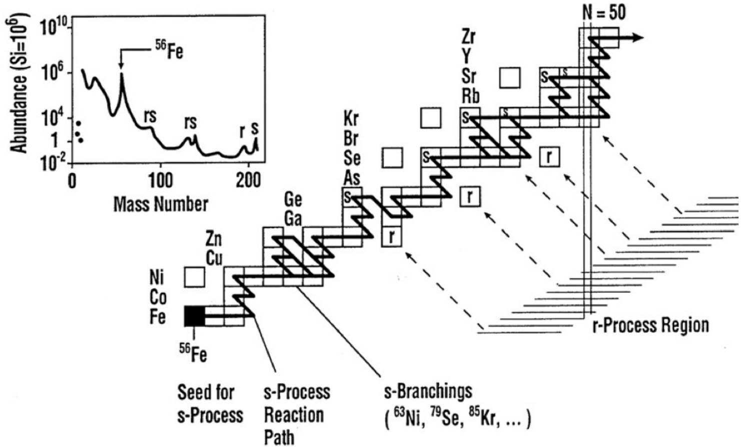
Solar

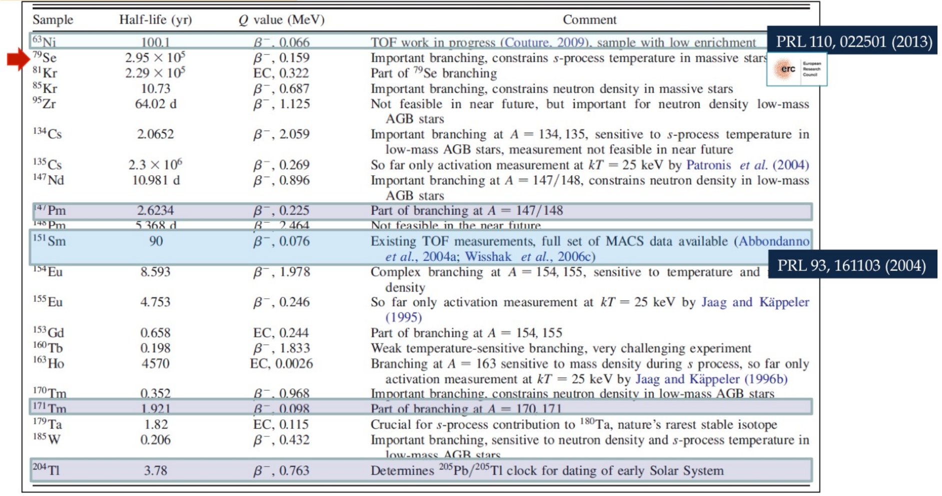
INFN2022, 9–11 May 2022, LNGS

massimi@bo.infn.it

s process, what matters?

- Reaction rate of the two main neutron sources **$^{13}C(\alpha,n)^{16}O$** and **$^{22}Ne(\alpha,n)^{25}Mg$**
- (n,γ) cross sections with small (5%) uncertainty
- (n,γ) cross sections of branching-point isotopes and β-decay rates
- Stellar models
- Stellar enhancement factors





REVIEWS OF MODERN PHYSICS The s process: Nuclear physics, stellar models, and observations, Vol. 83, 2011

Sample	Half-life (yr)	Q value (MeV)	Comment
^{63}Ni	100.1	β^-, 0.066	TOF work in progress (Couture, 2009), sample with low enrichment
^{79}Se	2.95×10^5	β^-, 0.159	Important branching, constrains *s*-process temperature in massive stars
^{81}Kr	2.29×10^5	EC, 0.322	Part of ^{79}Se branching
^{85}Kr	10.73	β^-, 0.687	Important branching, constrains neutron density in massive stars
^{95}Zr	64.02 d	β^-, 1.125	Not feasible in near future, but important for neutron density low-mass AGB stars
^{134}Cs	2.0652	β^-, 2.059	Important branching at $A = 134, 135$, sensitive to *s*-process temperature in low-mass AGB stars, measurement not feasible in near future
^{135}Cs	2.3×10^6	β^-, 0.269	So far only activation measurement at $kT = 25$ keV by Patronis *et al.* (2004)
^{147}Nd	10.981 d	β^-, 0.896	Important branching at $A = 147/148$, constrains neutron density in low-mass AGB stars
^{147}Pm	2.6234	β^-, 0.225	Part of branching at $A = 147/148$
^{148}Pm	5.368 d	β^-, 2.464	Not feasible in the near future
^{151}Sm	90	β^-, 0.076	Existing TOF measurements, full set of MACS data available (Abbondanno *et al.*, 2004a; Wisshak *et al.*, 2006c)
^{154}Eu	8.593	β^-, 1.978	Complex branching at $A = 154, 155$, sensitive to temperature and density
^{155}Eu	4.753	β^-, 0.246	So far only activation measurement at $kT = 25$ keV by Jaag and Käppeler (1995)
^{153}Gd	0.658	EC, 0.244	Part of branching at $A = 154, 155$
^{160}Tb	0.198	β^-, 1.833	Weak temperature-sensitive branching, very challenging experiment
^{163}Ho	4570	EC, 0.0026	Branching at $A = 163$ sensitive to mass density during *s* process, so far only activation measurement at $kT = 25$ keV by Jaag and Käppeler (1996b)
^{170}Tm	0.352	β^-, 0.968	Important branching, constrains neutron density in low-mass AGB stars
^{171}Tm	1.921	β^-, 0.098	Part of branching at $A = 170, 171$
^{179}Ta	1.82	EC, 0.115	Crucial for *s*-process contribution to ^{180}Ta, nature's rarest stable isotope
^{185}W	0.206	β^-, 0.432	Important branching, sensitive to neutron density and *s*-process temperature in low-mass AGB stars
^{204}Tl	3.78	β^-, 0.763	Determines ^{205}Pb/^{205}Tl clock for dating of early Solar System

PRL 110, 022501 (2013)

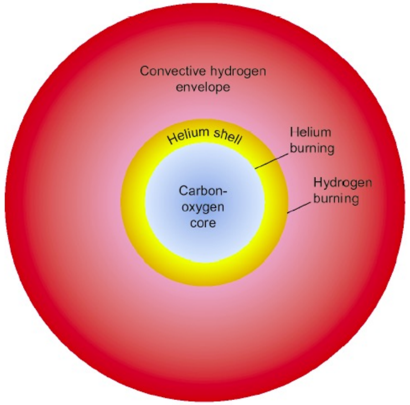
PRL 93, 161103 (2004)

massimi@bo.infn.it

$^{13}C(\alpha,n)^{16}O$

$^{13}C(\alpha,n)^{16}O$

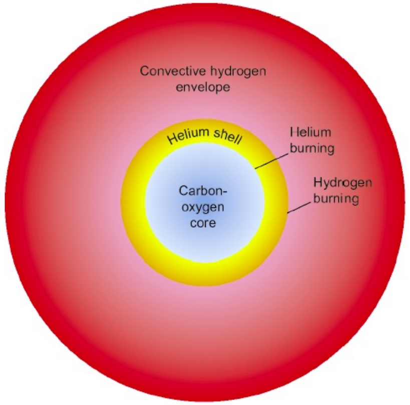
- Main neutron source in low-mass AGB stars at temperature ~ 90-100 MK



- Gamow window ~ 150 -230 keV

$^{13}C(\alpha,n)^{16}O$

- ❖ Main neutron source in low-mass AGB stars at temperature ~ 90-100 MK
- ❖ Gamow window ~ 150 -230 keV



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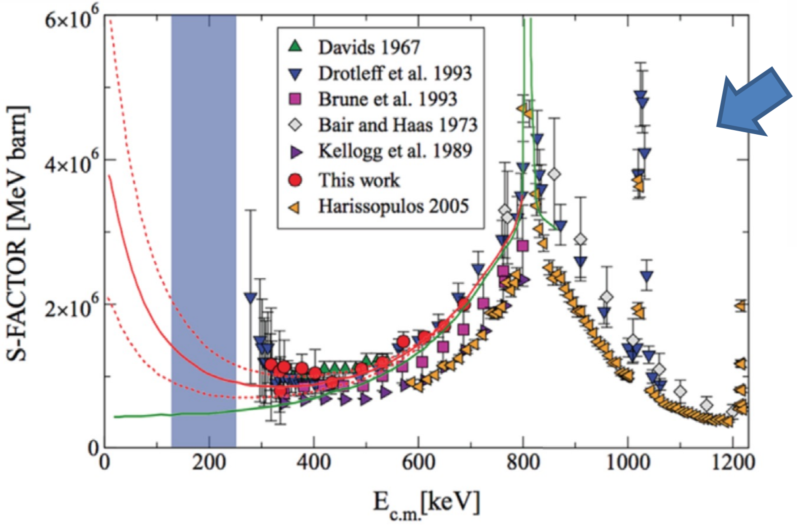
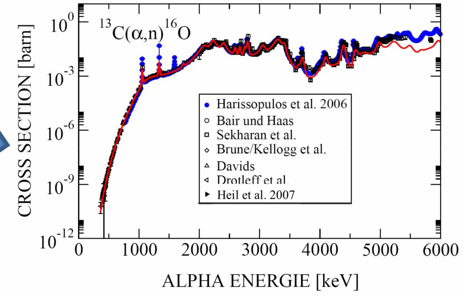
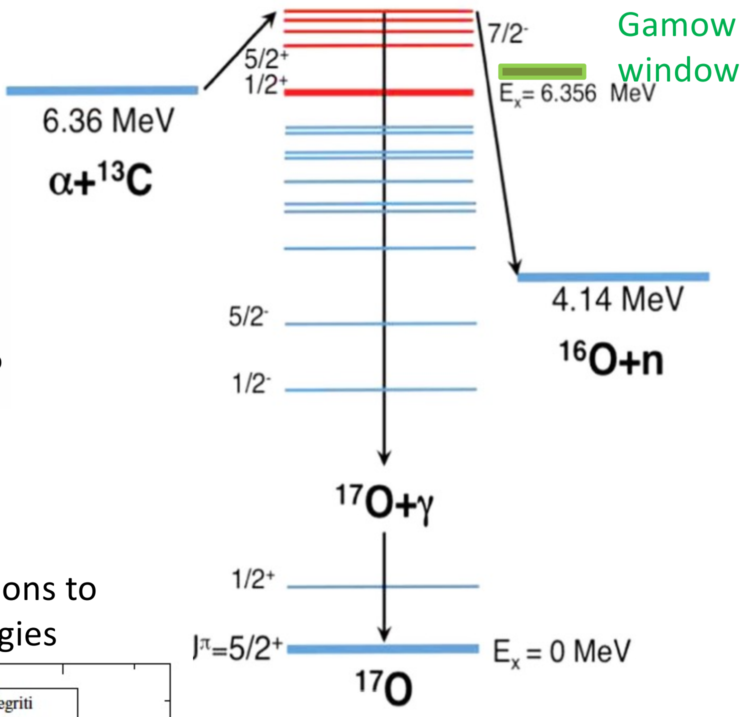
^{13}C(α,n)^{16}O "BEFORE"

S-Factor



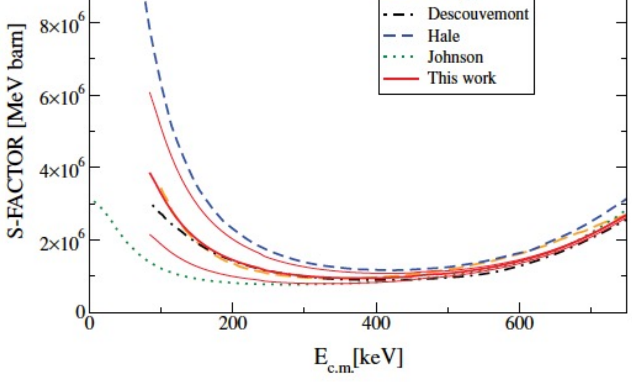
Cross section





The broad ½+ state at 6.356 keV plays a major role

Tentative extrapolations to Astrophysics energies



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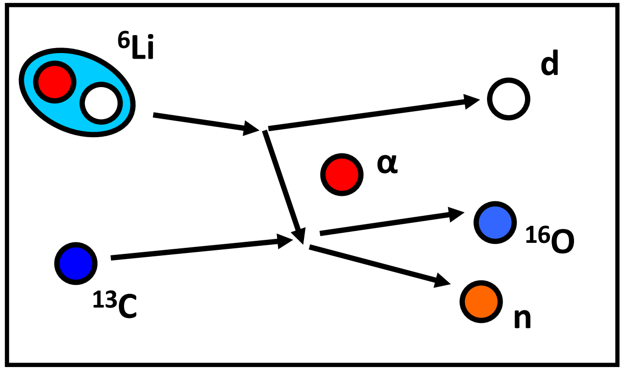
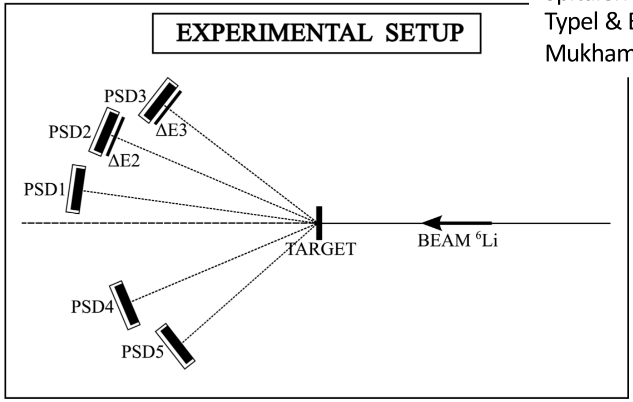
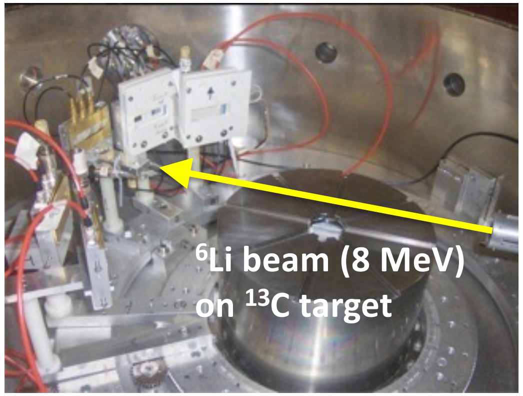
$^{13}C(\alpha,n)^{16}O$





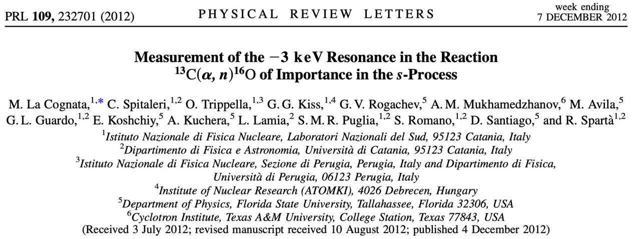
Baur PLB 178 (1986) 135
Spitaleri, in *Problems of Fundamental Modern Physics II,* World Sci. (1991) 21
Spitaleri et al., PAN 74 (2011) 1763
Typel & Baur, Ann. Phys. 305 (2003) 228
Mukhamedzhanov et al., JPG 35 (2008) 014016


^{6}Li beam (8 MeV) on ^{13}C target

Measurement of the the sub-Coulomb $^{13}C(\alpha,n)^{16}O$ reaction through the $^{13}C(^{6}Li,n^{16}O)d$ reaction in the quasi-free kinematics regime @ Florida State University.

Charged particle detection (instead of neutron)
Measurement at ~ 10 – 60 MeV kinetic energy (>> Coulomb barrier)
No electron screening

Model dependent (from indirect to direct)
Normalization needed

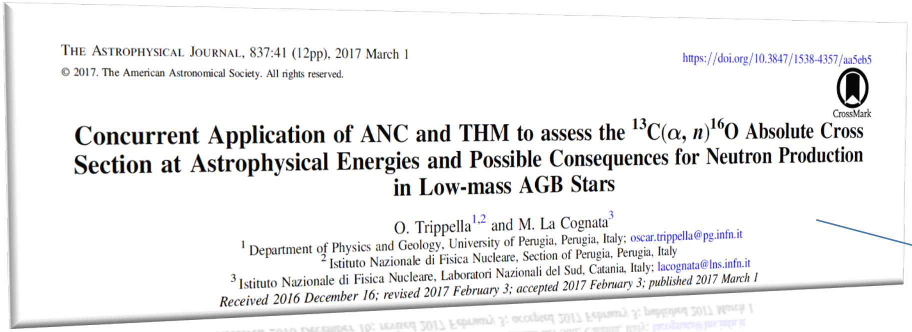


PRL **109,** 232701 (2012) PHYSICAL REVIEW LETTERS week ending 7 DECEMBER 2012

Measurement of the −3 keV Resonance in the Reaction
$^{13}C(\alpha, n)^{16}O$ of Importance in the *s*-Process

M. La Cognata,[1,*] C. Spitaleri,[1,2] O. Trippella,[1,3] G. G. Kiss,[1,4] G. V. Rogachev,[5] A. M. Mukhamedzhanov,[6] M. Avila,[5] G. L. Guardo,[1,2] E. Koshchiy,[5] A. Kuchera,[5] L. Lamia,[2] S. M. R. Puglia,[1,2] S. Romano,[1,2] D. Santiago,[5] and R. Spartà[1,2]
[1]*Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud, 95123 Catania, Italy*
[2]*Dipartimento di Fisica e Astronomia, Università di Catania, 95123 Catania, Italy*
[3]*Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, Perugia, Italy and Dipartimento di Fisica, Università di Perugia, 06123 Perugia, Italy*
[4]*Institute of Nuclear Research (ATOMKI), 4026 Debrecen, Hungary*
[5]*Department of Physics, Florida State University, Tallahassee, Florida 32306, USA*
[6]*Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*
(Received 3 July 2012; revised manuscript received 10 August 2012; published 4 December 2012)

$^{13}C(\alpha,n)^{16}O$



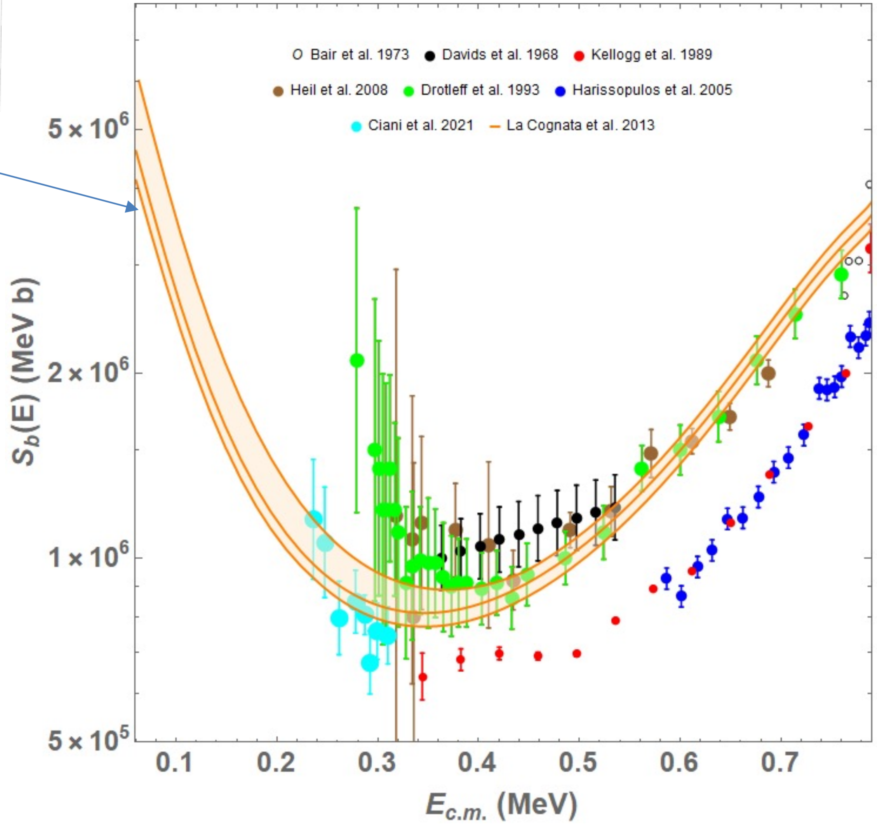
The Astrophysical Journal, 837:41 (12pp), 2017 March 1

https://doi.org/10.3847/1538-4357/aa5eb5

Concurrent Application of ANC and THM to assess the $^{13}C(\alpha, n)^{16}O$ Absolute Cross Section at Astrophysical Energies and Possible Consequences for Neutron Production in Low-mass AGB Stars

O. Trippella[1,2] and M. La Cognata[3]
[1] Department of Physics and Geology, University of Perugia, Perugia, Italy; oscar.trippella@pg.infn.it
[2] Istituto Nazionale di Fisica Nucleare, Section of Perugia, Perugia, Italy
[3] Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud, Catania, Italy; lacognata@lns.infn.it

Received 2016 December 16; revised 2017 February 3; accepted 2017 February 3; published 2017 March 1



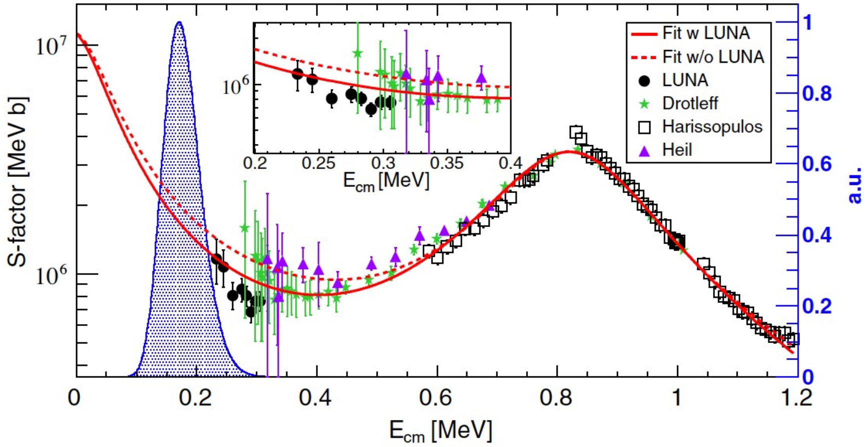
Good agreement with direct data from the LUNA collaboration (and some previous extrapolations).

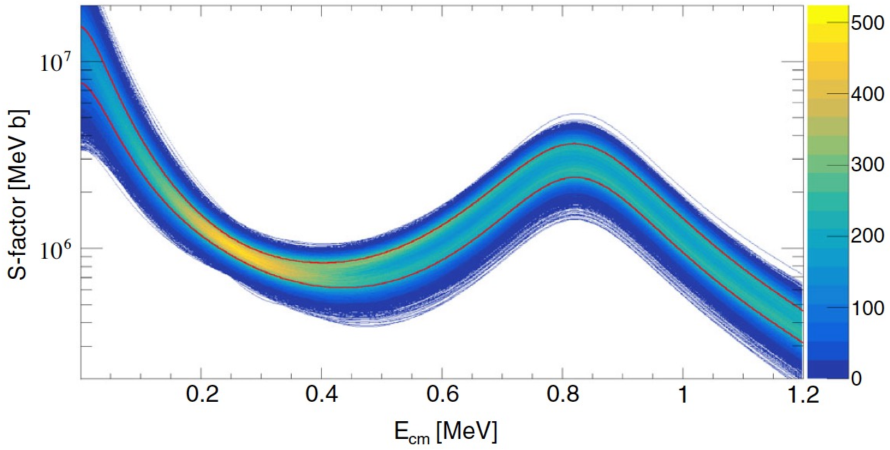
Towards a concordance scenario for the **$^{13}C(\alpha,n)^{16}O$ S(E)**

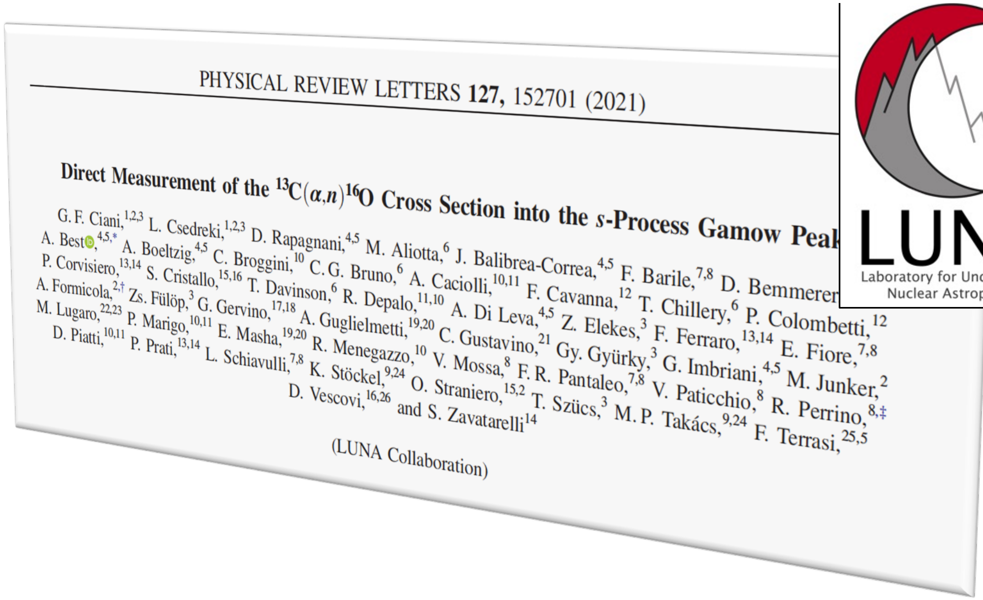
massimi@bo.infn.it

$^{13}C(\alpha,n)^{16}O$

$^{13}C(\alpha,n)^{16}O$






PHYSICAL REVIEW LETTERS **127,** 152701 (2021)

Direct Measurement of the $^{13}C(\alpha,n)^{16}O$ Cross Section into the *s*-Process Gamow Peak

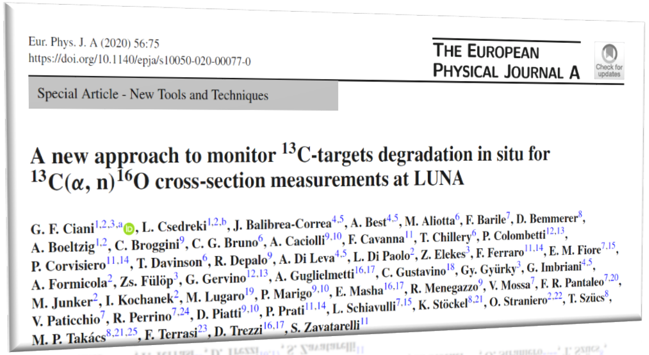
G. F. Ciani,[1,2,3] L. Csedreki,[1,2,3] D. Rapagnani,[4,5] M. Aliotta,[6] J. Balibrea-Correa,[4,5] F. Barile,[7,8] D. Bemmerer
A. Best,[4,5,*] A. Boeltzig,[4,5] C. Broggini,[10] C. G. Bruno,[6] A. Caciolli,[10,11] F. Cavanna,[12] T. Chillery,[6] P. Colombetti,[12]
P. Corvisiero,[13,14] S. Cristallo,[15,16] T. Davinson,[6] R. Depalo,[11,10] A. Di Leva,[4,5] Z. Elekes,[3] F. Ferraro,[13,14] E. Fiore,[7,8]
A. Formicola,[2,†] Zs. Fülöp,[3] G. Gervino,[17,18] A. Guglielmetti,[19,20] C. Gustavino,[21] Gy. Gyürky,[3] G. Imbriani,[4,5] M. Junker,[2]
M. Lugaro,[22,23] P. Marigo,[10,11] E. Masha,[19,20] R. Menegazzo,[10] V. Mossa,[8] F. R. Pantaleo,[7,8] V. Paticchio,[8] R. Perrino,[8,‡]
D. Piatti,[10,11] P. Prati,[13,14] L. Schiavulli,[7,8] K. Stöckel,[9,24] O. Straniero,[15,2] T. Szücs,[3] M. P. Takács,[9,24] F. Terrasi,[25,5]
D. Vescovi,[16,26] and S. Zavatarelli[14]

(LUNA Collaboration)

- ❖ Deep-underground measurement
- ❖ Energy range 230 –300 keV
- ❖ Drastically reduced uncertainties
- ❖ First time providing data directly inside the s-process Gamow peak

massimi@bo.infn.it

$^{13}C(\alpha,n)^{16}O$



Eur. Phys. J. A (2020) 56:75
https://doi.org/10.1140/epja/s10050-020-00077-0

THE EUROPEAN PHYSICAL JOURNAL A

Special Article - New Tools and Techniques

A new approach to monitor ^{13}C-targets degradation in situ for $^{13}C(\alpha, n)^{16}O$ cross-section measurements at LUNA

G. F. Ciani[1,2,3,a], L. Csedreki[1,2,b], J. Balibrea-Correa[4,5], A. Best[4,5], M. Aliotta[6], F. Barile[7], D. Bemmerer[8], A. Boeltzig[1,2], C. Broggini[9], C. G. Bruno[6], A. Caciolli[9,10], F. Cavanna[11], T. Chillery[6], P. Colombetti[12,13], P. Corvisiero[11,14], T. Davinson[6], R. Depalo[9], A. Di Leva[4,5], L. Di Paolo[2], Z. Elekes[3], F. Ferraro[11,14], E. M. Fiore[7,15], A. Formicola[2], Zs. Fülöp[3], G. Gervino[12,13], A. Guglielmetti[16,17], C. Gustavino[18], Gy. Gyürky[3], G. Imbriani[4,5], M. Junker[2], I. Kochanek[2], M. Lugaro[19], P. Marigo[9,10], E. Masha[16,17], R. Menegazzo[9], V. Mossa[7], F. R. Pantaleo[7,20], V. Paticchio[7], R. Perrino[7,24], D. Piatti[9,10], P. Prati[11,14], L. Schiavulli[7,15], K. Stöckel[8,21], O. Straniero[2,22], T. Szücs[8], M. P. Takács[8,21,25], F. Terrasi[23], D. Trezzi[16,17], S. Zavatarelli[11]

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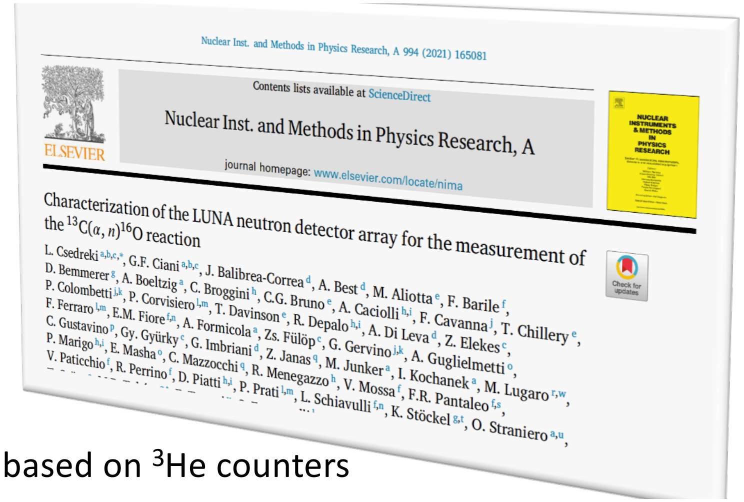


Nuclear Inst. and Methods in Physics Research, A 994 (2021) 165081

Contents lists available at ScienceDirect

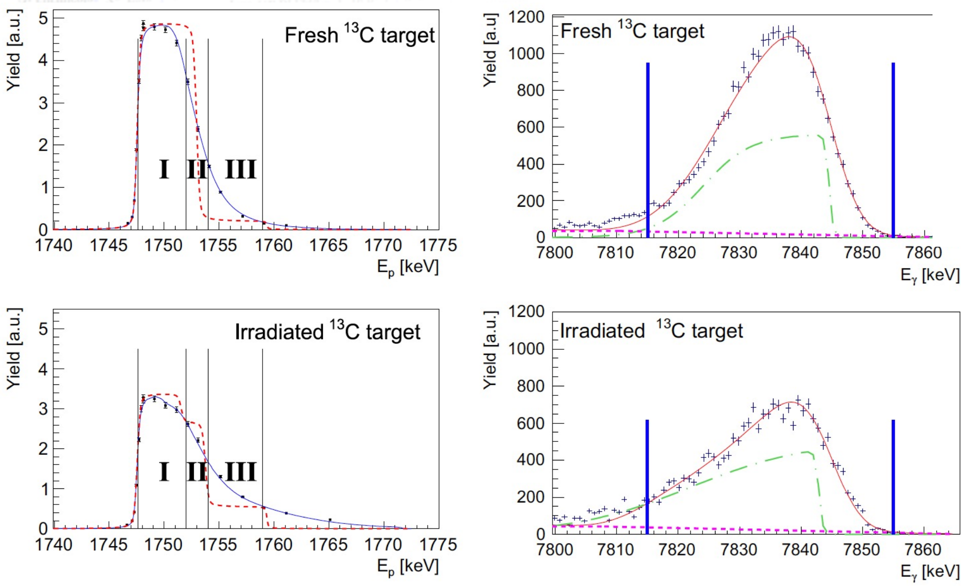
Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

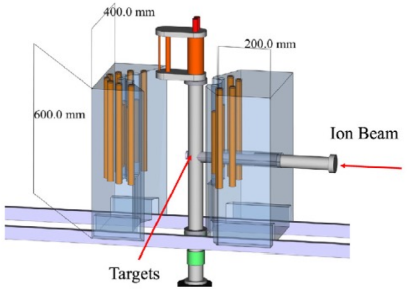
Characterization of the LUNA neutron detector array for the measurement of the $^{13}C(\alpha, n)^{16}O$ reaction

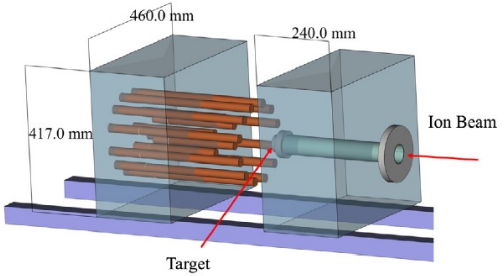
L. Csedreki[a,b,c,*], G.F. Ciani[a,b,c], J. Balibrea-Correa[d], A. Best[d], M. Aliotta[e], F. Barile[f], D. Bemmerer[g], A. Boeltzig[a], C. Broggini[h], C.G. Bruno[e], A. Caciolli[h,i], F. Cavanna[j], T. Chillery[e], P. Colombetti[j,k], P. Corvisiero[l,m], T. Davinson[e], R. Depalo[h,i], A. Di Leva[d], Z. Elekes[c], F. Ferraro[l,m], E.M. Fiore[f,n], A. Formicola[a], Zs. Fülöp[c], G. Gervino[j,k], A. Guglielmetti[o], C. Gustavino[p], Gy. Gyürky[c], G. Imbriani[d], Z. Janas[q], M. Junker[a], I. Kochanek[a], M. Lugaro[r,w], P. Marigo[h,i], E. Masha[o], C. Mazzocchi[q], R. Menegazzo[h], V. Mossa[f], F.R. Pantaleo[f,s], V. Paticchio[f], R. Perrino[f], D. Piatti[h,i], P. Prati[l,m], L. Schiavulli[f,n], K. Stöckel[g,t], O. Straniero[a,u],

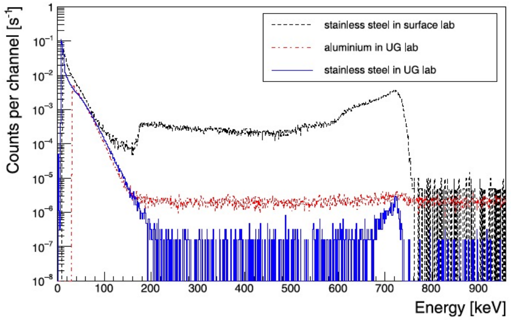
Collaboration with Atomki & HZDR



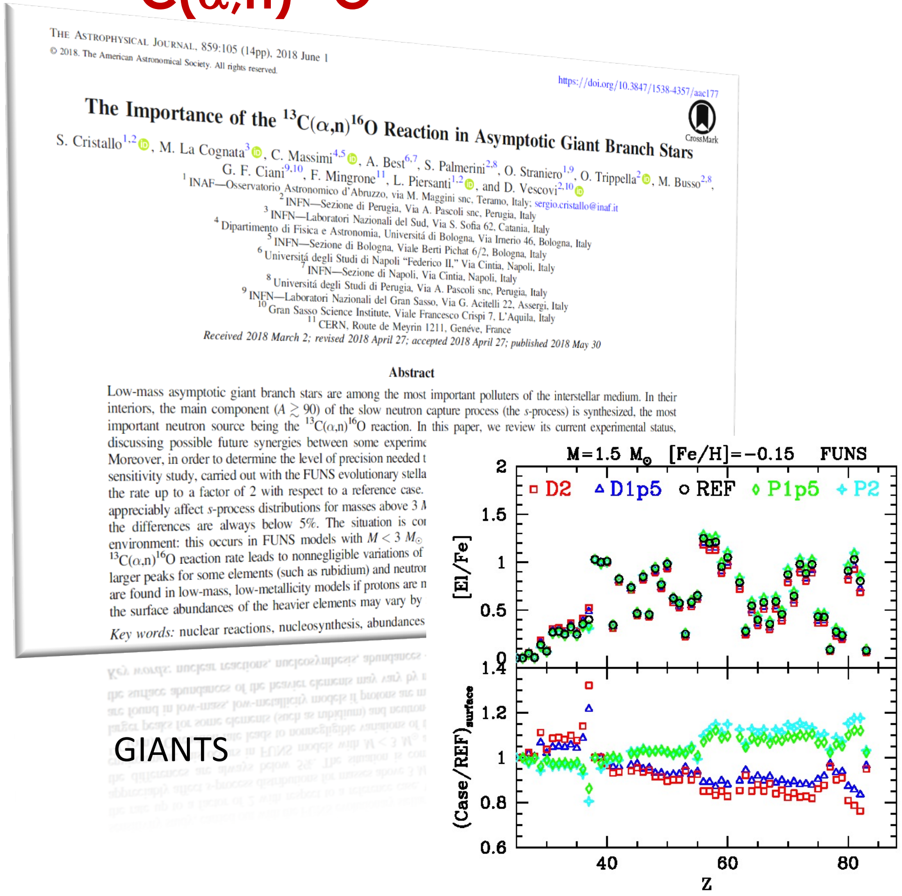
Neutron detector based on ^{3}He counters







$^{13}C(\alpha,n)^{16}O$



THE ASTROPHYSICAL JOURNAL, 859:105 (14pp), 2018 June 1

https://doi.org/10.3847/1538-4357/aac177

The Importance of the $^{13}C(\alpha,n)^{16}O$ Reaction in Asymptotic Giant Branch Stars

S. Cristallo[1,2], M. La Cognata[3], C. Massimi[4,5], A. Best[6,7], S. Palmerini[2,8], O. Straniero[1,9], O. Trippella[2], M. Busso[2,8], G. F. Ciani[9,10], F. Mingrone[11], L. Piersanti[1,2], and D. Vescovi[2,10]
[1] INAF—Osservatorio Astronomico d'Abruzzo, via M. Maggini snc, Teramo, Italy; sergio.cristallo@inaf.it
[2] INFN—Sezione di Perugia, Via A. Pascoli snc, Perugia, Italy
[3] INFN—Laboratori Nazionali del Sud, Via S. Sofia 62, Catania, Italy
[4] Dipartimento di Fisica e Astronomia, Universitá di Bologna, Via Imerio 46, Bologna, Italy
[5] INFN—Sezione di Bologna, Viale Berti Pichat 6/2, Bologna, Italy
[6] Universitá degli Studi di Napoli "Federico II," Via Cintia, Napoli, Italy
[7] INFN—Sezione di Napoli, Via Cintia, Napoli, Italy
[8] Universitá degli Studi di Perugia, Via A. Pascoli snc, Perugia, Italy
[9] INFN—Laboratori Nazionali del Gran Sasso, Via G. Acitelli 22, Assergi, Italy
[10] Gran Sasso Science Institute, Viale Francesco Crispi 7, L'Aquila, Italy
[11] CERN, Route de Meyrin 1211, Genéve, France

Received 2018 March 2; revised 2018 April 27; accepted 2018 April 27; published 2018 May 30

Abstract

Low-mass asymptotic giant branch stars are among the most important polluters of the interstellar medium. In their interiors, the main component ($A \gtrsim 90$) of the slow neutron capture process (the *s*-process) is synthesized, the most important neutron source being the $^{13}C(\alpha,n)^{16}O$ reaction. In this paper, we review its current experimental status, discussing possible future synergies between some experime
Moreover, in order to determine the level of precision needed t
sensitivity study, carried out with the FUNS evolutionary stella
the rate up to a factor of 2 with respect to a reference case.
appreciably affect *s*-process distributions for masses above 3
the differences are always below 5%. The situation is co
environment: this occurs in FUNS models with $M < 3\ M_\odot$
$^{13}C(\alpha,n)^{16}O$ reaction rate leads to nonnegligible variations of
larger peaks for some elements (such as rubidium) and neutro
are found in low-mass, low-metallicity models if protons are
the surface abundances of the heavier elements may vary by

Key words: nuclear reactions, nucleosynthesis, abundances

GIANTS

nTOF

There is some interest in measuring the inverse reaction at n_TOF (a first attempt with gas detector failed, and a new setup is being developed).

By using the detailed balance (i.e., time-reversal invariance theorem) the reaction cross section of $^{13}C(\alpha,n)^{16}O$ is deduced from the measurement in the reverse direction $^{16}O(n,\alpha)^{13}C$.

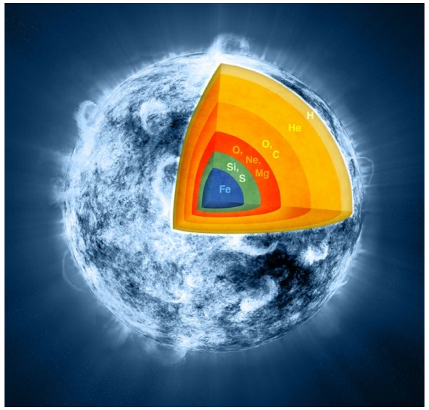
A single measurement could provide data in a large energy region.

$^{22}Ne(\alpha,n)^{25}Mg$

massimi@bo.infn.it

$^{22}Ne(\alpha,n)^{25}Mg$

- Main neutron source in massive stars
- Gamow window: threshold ~ 300 keV



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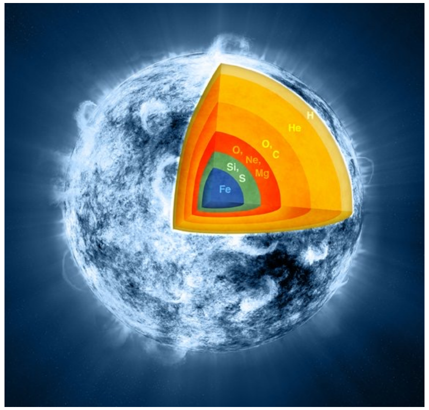
n_TOF

AsFiN

^{22}Ne(α,n)^{25}Mg

- ❖ Main neutron source in massive star
- ❖ Gamow window: threshold ~ 300 keV



Istituto Nazionale di Fisica Nucleare

INFN2022, 9–11 May 2022, LNGS

massimi@bo.infn.it

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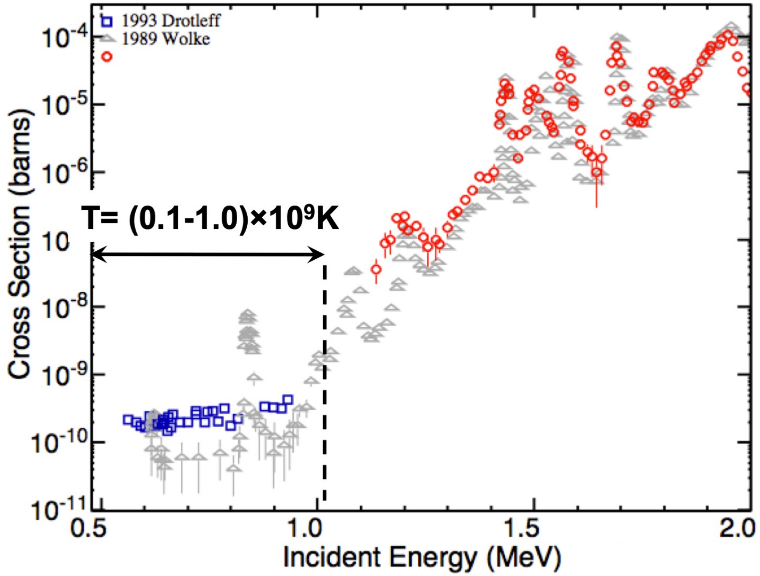
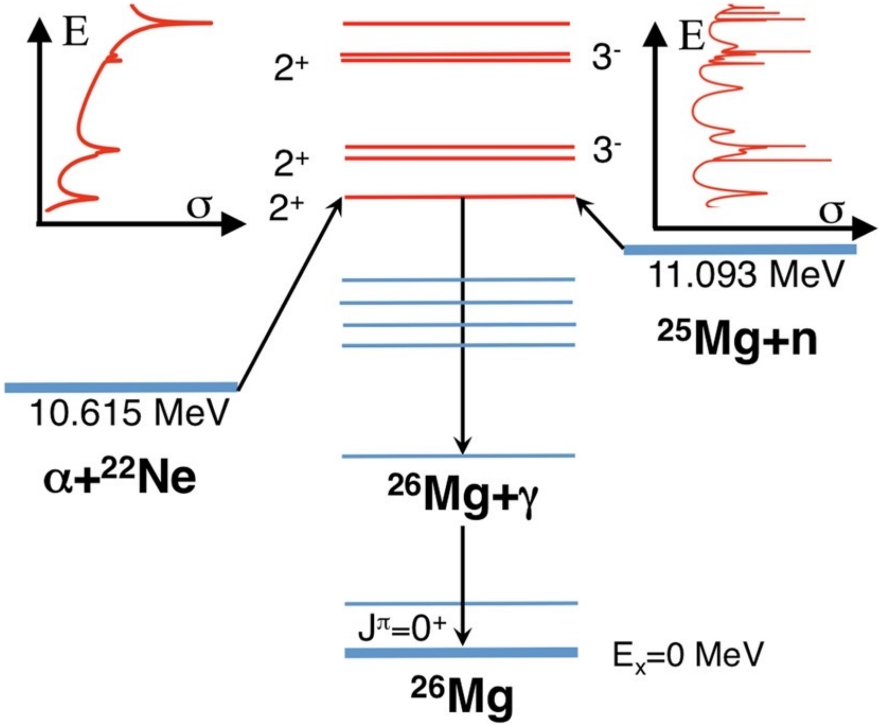
UNIVERSITÀ DI BOLOGNA

^{22}Ne(α,n)^{25}Mg

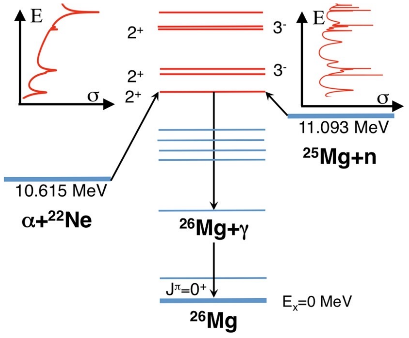




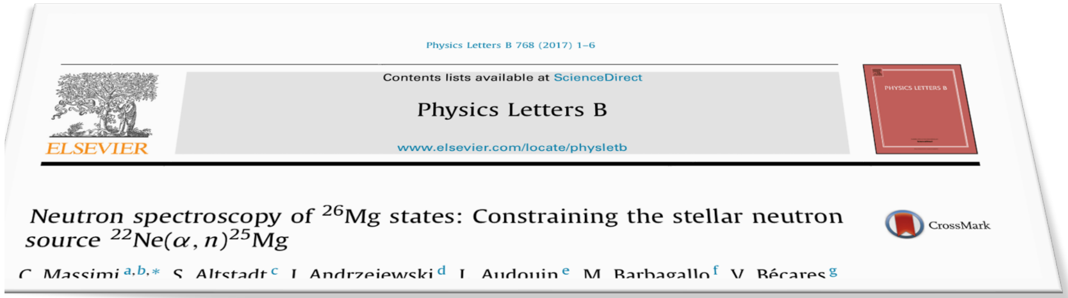
- Possible presence of resonances in the Gamow window (unmeasured)
- Large uncertainty in extrapolations at low energy
- Background on surface labs. too high (only upper limit in Gamow window)
- Non negligible ^{22}Ne(α,γ) branch

massimi@bo.infn.it

$^{22}Ne(\alpha,n)^{25}Mg$



$^{22}Ne(\alpha,n)^{25}Mg$



Physics Letters B 768 (2017) 1–6

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Physics Letters B

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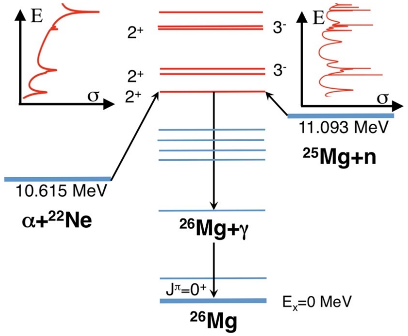
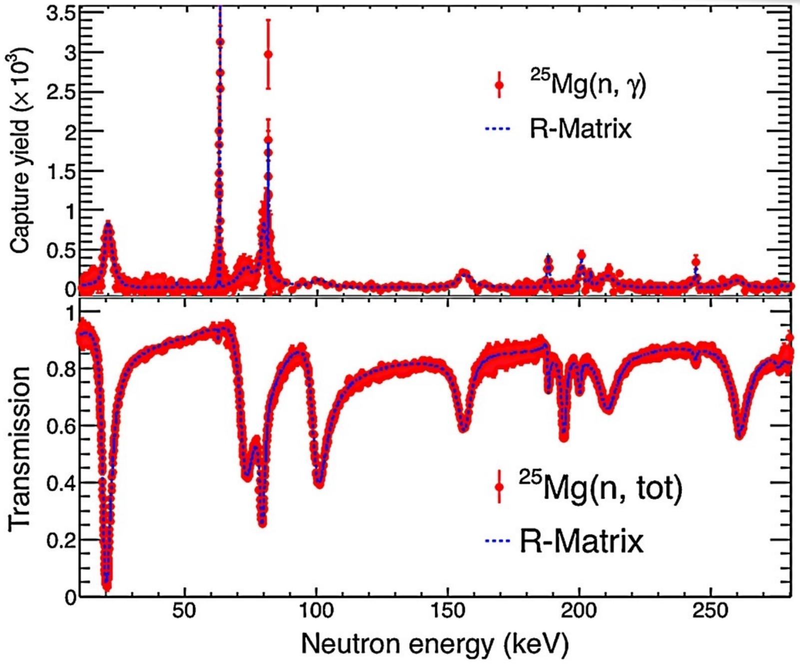
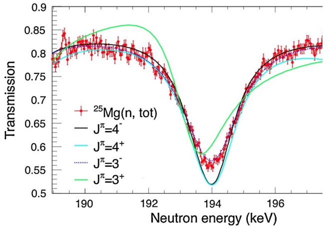
Neutron spectroscopy of ^{26}Mg states: Constraining the stellar neutron source $^{22}Ne(\alpha,n)^{25}Mg$

C. Massimi [a,b,*], S. Altstadt [c], J. Andrzejewski [d], L. Audouin [e], M. Barbagallo [f], V. Bécares [g]

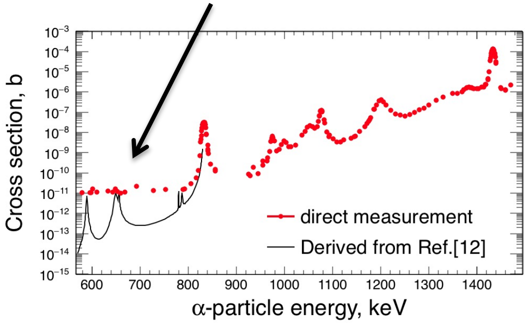




- Indirect approach, resonances above *n*-threshold
- R-Matrix parametrization (E_R, Γ_γ,Γ_n J^π)
- Deduced ^{26}Mg states with natural parity



- No experimental Γ_α



^{22}Ne(α,n)^{25}Mg

international effort

ChETEC

n+^{25}Mg
^{26}Mg(α,α')^{26}Mg, ^{26}Mg(p,p')^{26}Mg, ^{26}Mg(d,d')^{26}Mg
^{22}Ne(^{6}Li,d)^{26}Mg
^{11}B(^{16}O,p)^{26}Mg

PHYSICAL REVIEW C **103**, 015805 (2021)

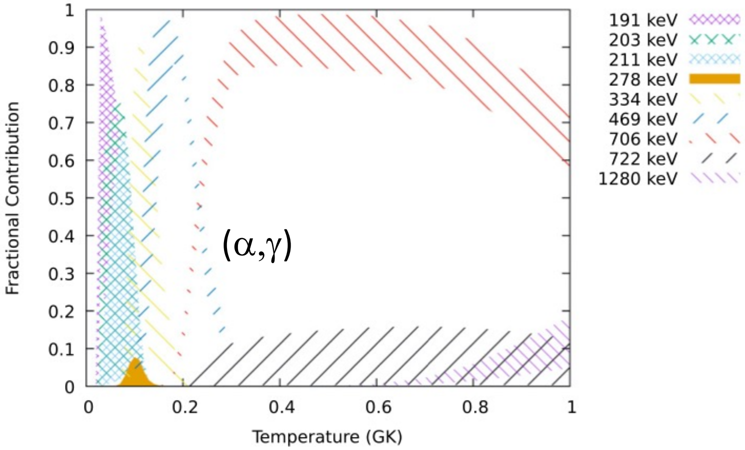
Reevaluation of the ^{22}Ne(α, γ)^{26}Mg and ^{22}Ne(α, n)^{25}Mg reaction rates

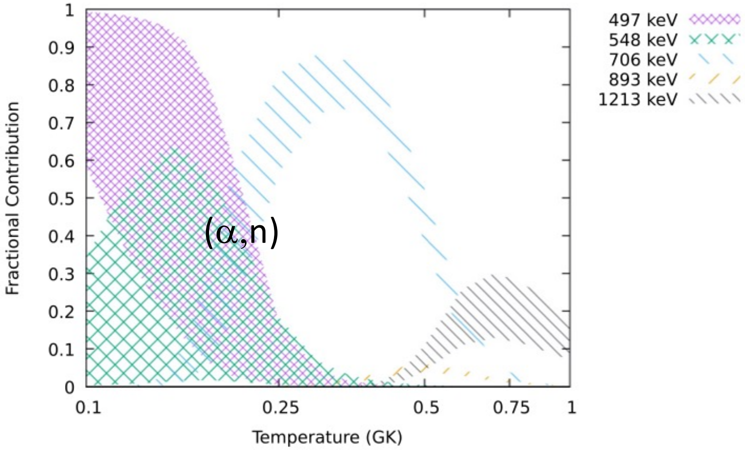
Philip Adsley,[1,2,3,*] Umberto Battino,[4,†] Andreas Best,[5,6] Antonio Caciolli,[7,8] Alessandra Guglielmetti,[9] Gianluca Imbriani,[5,6] Heshani Jayatissa,[10] Marco La Cognata,[11] Livio Lamia,[12,11,13] Eliana Masha,[9] Cristian Massimi,[14,15] Sara Palmerini,[16,17] Ashley Tattersall,[4,†] and Raphael Hirschi[18,19,†]

E_x (MeV)	E_r^{CM} (keV)	J^π	$\omega\gamma_{(\alpha,\gamma)}$ (eV)	$\omega\gamma_{(\alpha,n)}$ (eV)	Γ_α (eV)	Γ_γ (eV)	Γ_n (eV)	Integrate resonance?
10.6963(4)	81.6(4)	4^+			$3.5(18) \times 10^{-46}$	3.0(15)	0	No
11.084(1)	469(1)	2^+			$5.7(1.5) \times 10^{-11}$	3.0(15)	0	No
11.321(1)	706(1)[a]	$0^+/1^-$	$3.7(4) \times 10^{-5}$	$4.2(11) \times 10^{-5}$				No
11.44120(4)	826.46(5)	3^-		$3.9(10) \times 10^{-5}$	$5.50(14) \times 10^{-6}$	3.0(15)	$1.47(8) \times 10^{3}$	Yes
11.46574(6)	851.00(6)	3^-		$5.5(17) \times 10^{-5}$	$7.9(2.4) \times 10^{-6}$	3.0(15)	$6.55(9) \times 10^{3}$	Yes
11.5080(9)	893.3(9)	1^-		$3.5(6) \times 10^{-4}$	$1.2(4) \times 10^{-4}$	3.0(15)	$1.27(25) \times 10^{3}$	Yes
11.5260(15)	911.3(15)	1^-		$1.3(4) \times 10^{-3}$	$4.3(11) \times 10^{-4}$	3.0(15)	$1.80(25) \times 10^{3}$	Yes
11.630(1)	1015.3(14)	1^-		$7.1(15) \times 10^{-3}$	$2.4(5) \times 10^{-3}$	3.0(15)	$13.5(17) \times 10^{3}$	Yes
11.749(5)	1133(6)	1^-		$5.9(8) \times 10^{-2}$	$2.0(3) \times 10^{-2}$	3.0(15)	$64(9) \times 10^{3}$	Yes
11.787(3)	1172(3)	1^-		$2.5(9) \times 10^{-2}$	$8(3) \times 10^{-3}$	3.0(15)	$24.5(24) \times 10^{3}$	Yes
11.828(1)	1213(1)	2^+		$2.5(3) \times 10^{-4}$	$1.8(1) \times 10^{-1}$	3.0(15)	$1.10(25) \times 10^{3}$	Yes
11.863(3)	1248(3)	1^-			$1.5(10) \times 10^{-2}$	3.0(15)	$2.45(34) \times 10^{4}$	Yes
11.880(3)	1265(3)	1^-		$1.9(19) \times 10^{-1}$	$6.30(63) \times 10^{-2}$	3.0(15)	$3.0(15) \times 10^{3}$	No
11.895(4)	1280(4)	1^-	$2.0(2) \times 10^{-3}$	$4.1(4) \times 10^{-1}$				No
11.911(1)	1297(3)	1^-	$3.4(4) \times 10^{-3}$	1.4(1)	1.9(9.8)	3.0(15)	$5(2) \times 10^{3}$	Yes
11.953(3)	1338(3)	2^+	$3.4(4) \times 10^{-3}$	1.60(13)	$3.2(1.7) \times 10^{-1}$	3.0(15)	$2(1) \times 10^{3}$	Yes
12.050(1)	1436(3)	2^+	$6.0(7) \times 10^{-3}$	4.7(3)	$1.1(3) \times 10^{-1}$	3.0(15)	$4(1) \times 10^{3}$	Yes
12.141(1)	1526(3)	1^-	$1.0(2) \times 10^{-3}$	2.4(2)	1.7(5)	3.0(15)	$1.5(2) \times 10^{4}$	Yes
12.184(5)	1569(7)	0^+	$1.1(2) \times 10^{-3}$	$1.21(29) \times 10^{1}$	0.90(11)	3.0(15)	$3.3(5) \times 10^{4}$	Yes
12.270(5)	1658(7)	0^+	$8.9(1) \times 10^{-3}$	$2.1(2) \times 10^{1}$	$2.2(4) \times 10^{2}$	3.0(15)	$7.3(9) \times 10^{4}$	Yes
12.344(2)	1728(4)	0^+	$5.4(7) \times 10^{-2}$	$1.57(10) \times 10^{2}$	$6.30(12) \times 10^{2}$	3.0(15)	$3.5(5) \times 10^{4}$	Yes

[a] Resonance energy is taken using the state observed in Ref. [17] and assuming a single resonance.

Only natural-parity states in ^{26}Mg contribute





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$^{22}Ne(\alpha,n)^{25}Mg$

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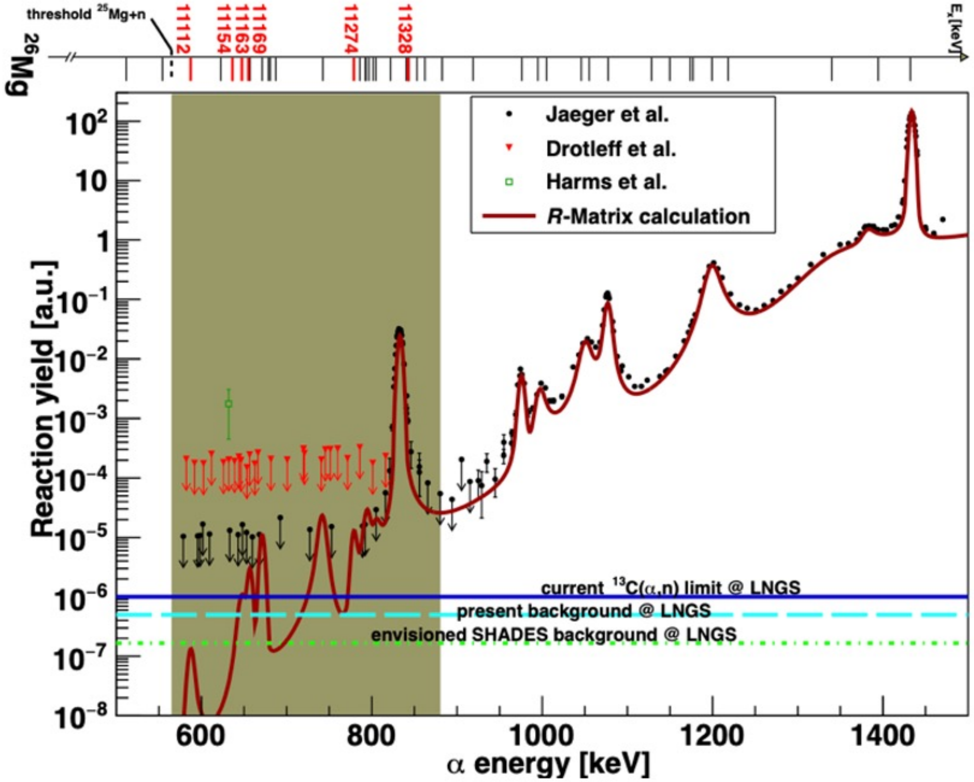
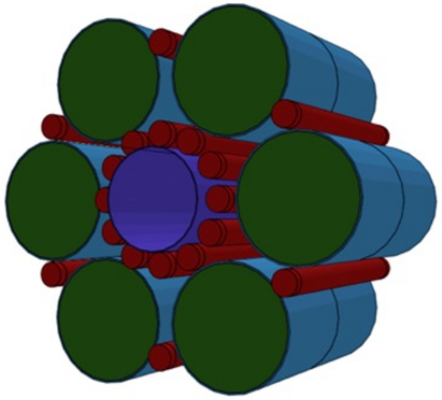
Laboratory for Underground Nuclear Astrophysics

- LUNA-MV scientific proposal: **started in 2020, first measurements in 2022**
- Novel high-efficiency, energy sensitive detector array (^{3}He + liquid scintillator)





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$^{22}Ne(\alpha,n)^{25}Mg$

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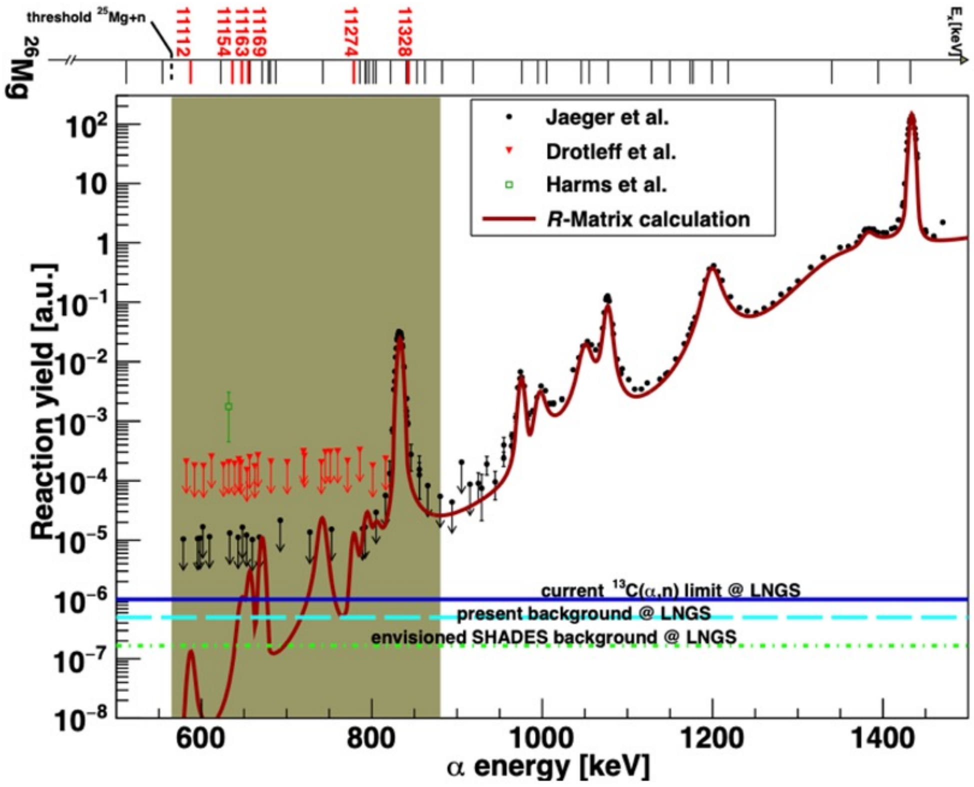
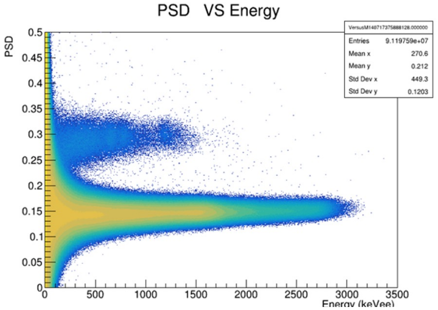
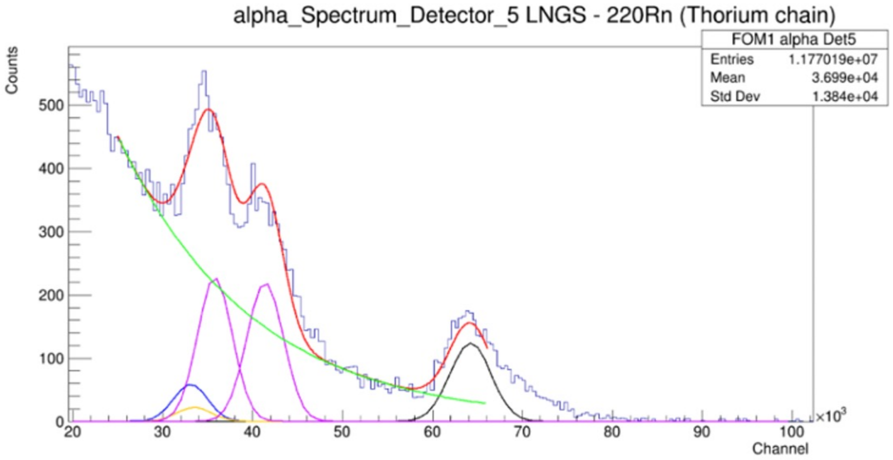
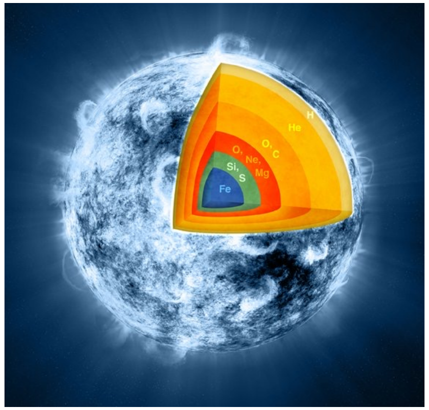
- Novel high-efficiency, energy sensitive detector array (^{3}He + liquid scintillator)





Characterization of detectors and gas target ongoing





$^{22}Ne(\alpha,n)^{25}Mg$

ASFIN aims at measuring the inverse reaction $^{25}Mg(n,\alpha)^{22}Ne$ with an indirect method based on Trojan Horse Method (feasibility studies ongoing)

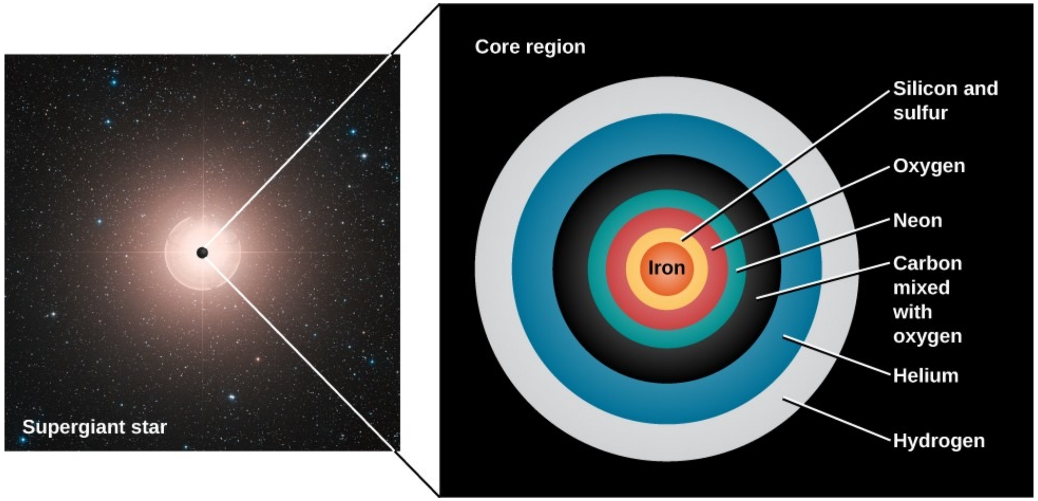
INFN2022, 9–11 May 2022, LNGS

massimi@bo.infn.it

$^{12}C + ^{12}C$

massimi@bo.infn.it

Explosive burning (massive stars)



Quiescent ^{4}He and heavy Ion burnings result in massive stars with convective shells at different densities: onion structure

Quiescent and explosive nucleosynthesis in massive stars are constrained by a few nuclear reactions:

$^{12}C(\alpha,n)$

$^{12}C(^{12}C,p)^{23}Na$

$^{12}C(^{12}C,\alpha)^{20}Ne$

$^{12}C + ^{16}O$

… and others

Type Ia Supernovae

ERNA

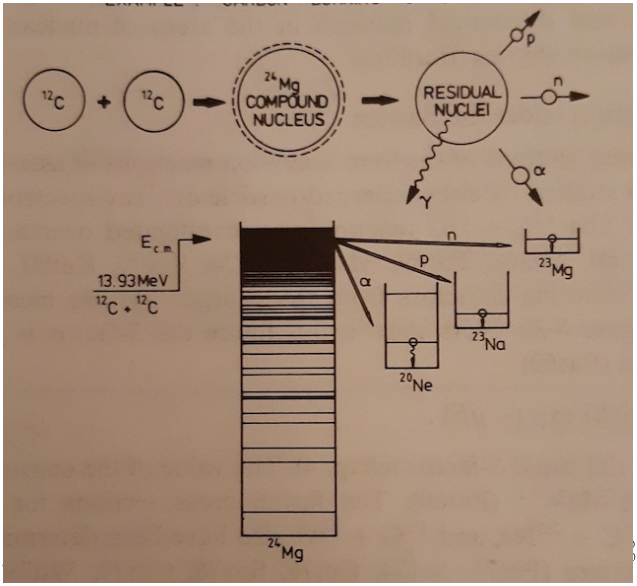
European Recoil separator for Nuclear Astrophysics

AsFiN

LUNA

Laboratory for Underground Nuclear Astrophysics

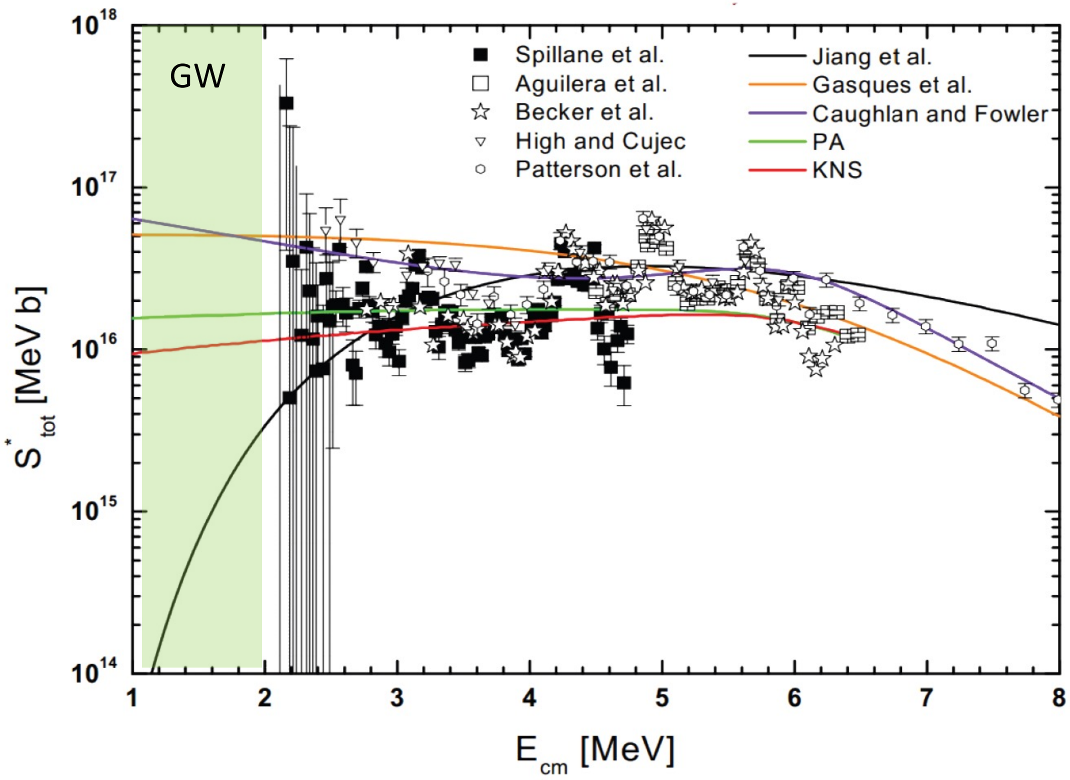
$^{12}C + ^{12}C$



❖ Reaction rate determines the late phase of stellar evolution

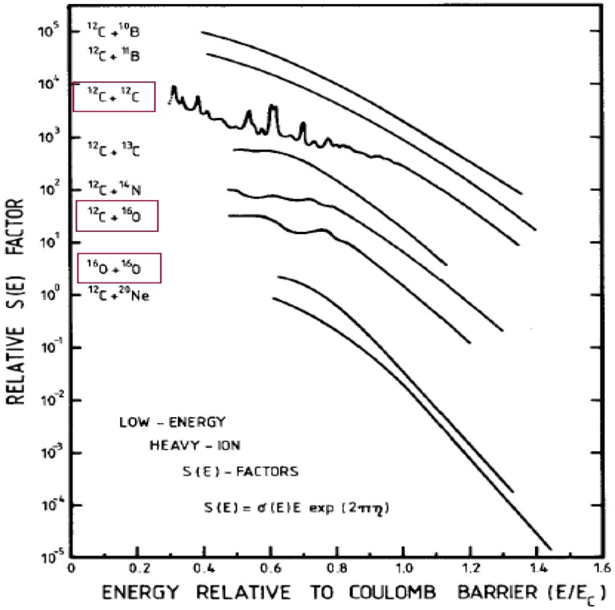
❖ Gamow window below Coulomb barrier ~ 1- 2 MeV

$^{12}C+^{12}C$ "BEFORE"



Measurements based on γ-ray or particle spectroscopy

- Presence of resonances in the Gamow window (unmeasured)
- Large uncertainty in extrapolations at low energy
- Microscopic model?
- Impact of the background

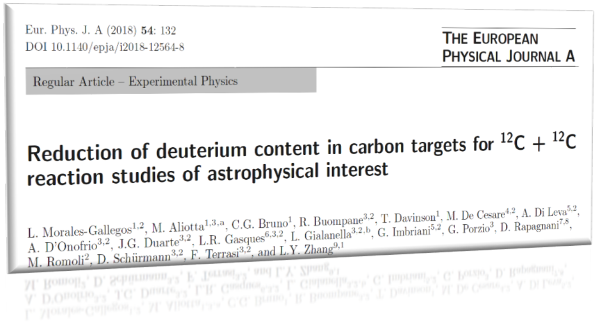


R. Stokstad et al., Phys.Rev.Lett. 37 (1976)

$^{12}C+^{12}C$

massimi@bo.infn.it

^{12}C+^{12}C


Eur. Phys. J. A (2018) **54**: 132
DOI 10.1140/epja/i2018-12564-8

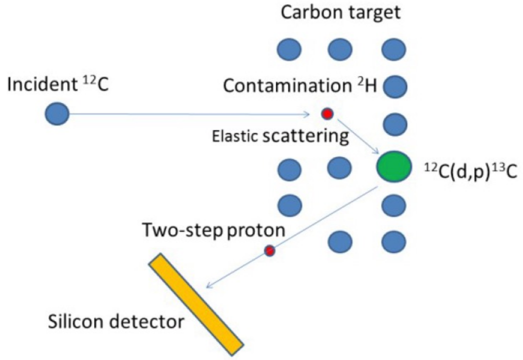
THE EUROPEAN PHYSICAL JOURNAL A

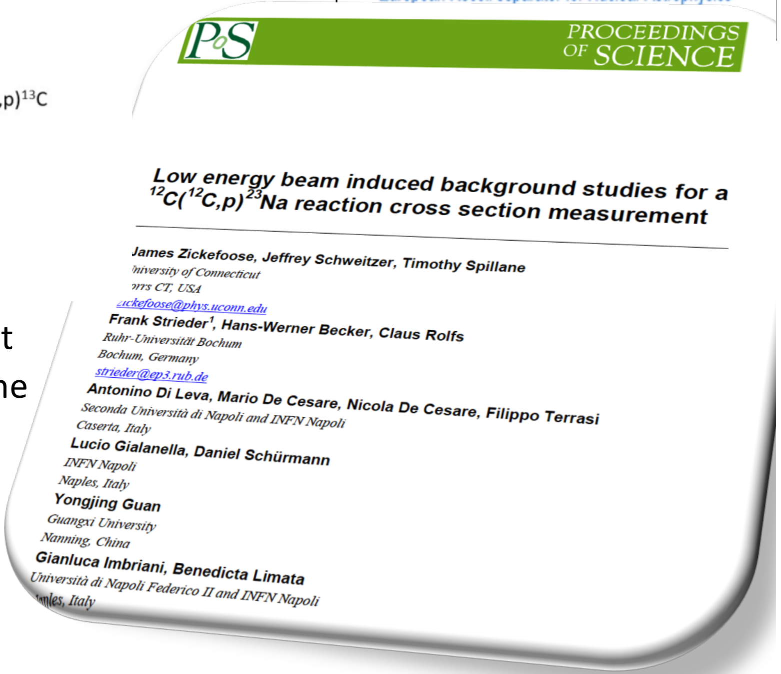
Regular Article – Experimental Physics

Reduction of deuterium content in carbon targets for ^{12}C + ^{12}C reaction studies of astrophysical interest

L. Morales-Gallegos[1,2], M. Aliotta[1,3,a], C.G. Bruno[1], R. Buompane[3,2], T. Davinson[1], M. De Cesare[4,2], A. Di Leva[5,2], A. D'Onofrio[3,2], J.G. Duarte[3,2], L.R. Gasques[6,3,2], L. Gialanella[3,2,b], G. Imbriani[5,2], G. Porzio[3], D. Rapagnani[7,8], M. Romoli[2], D. Schürmann[3,2], F. Terrasi[3,2], and L.Y. Zhang[9,1]

Beam-induced background background




PROCEEDINGS OF SCIENCE

Low energy beam induced background studies for a ^{12}C(^{12}C,p)^{23}Na reaction cross section measurement

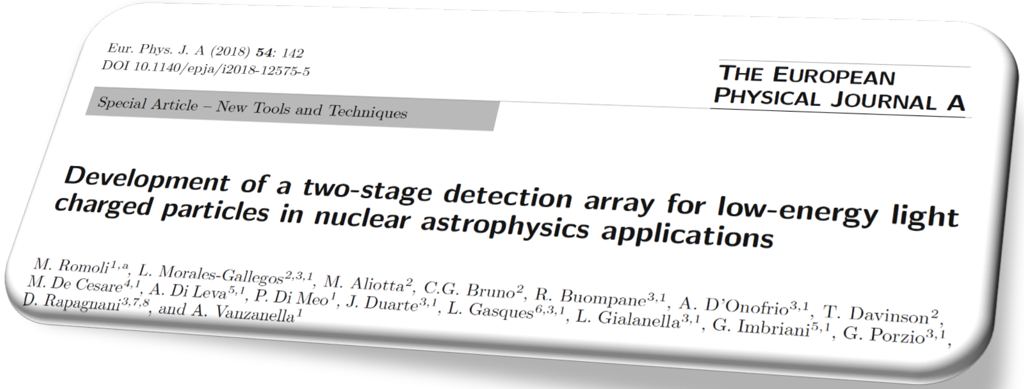
James Zickefoose, Jeffrey Schweitzer, Timothy Spillane
niversity of Connecticut
rrs CT, USA
ckefoose@phys.uconn.edu
Frank Strieder[1], Hans-Werner Becker, Claus Rolfs
Ruhr-Universität Bochum
Bochum, Germany
strieder@ep3.rub.de
Antonino Di Leva, Mario De Cesare, Nicola De Cesare, Filippo Terrasi
Seconda Università di Napoli and INFN Napoli
Caserta, Italy
Lucio Gialanella, Daniel Schürmann
INFN Napoli
Naples, Italy
Yongjing Guan
Guangxi University
Nanning, China
Gianluca Imbriani, Benedicta Limata
Università di Napoli Federico II and INFN Napoli
ples, Italy

Using thick ^{12}C target methods (Taking the difference of two measurements at different energies) experimental evidences are protons and α particle from the reactions **^{12}C(^{12}C,p)^{23}Na** & **^{12}C(^{12}C,α)^{20}Ne**

- ❖ Detailed study of the background
- ❖ Study of suitable ^{12}C carbon targets → Morales-Gallegos et al 2015 J. Phys.: Conf. Ser. 578 012002

massimi@bo.infn.it

$^{12}C+^{12}C$



Eur. Phys. J. A (2018) **54**: 142
DOI 10.1140/epja/i2018-12575-5

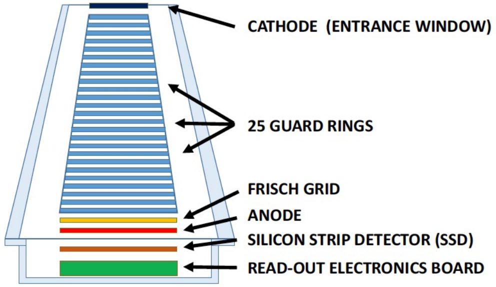
THE EUROPEAN PHYSICAL JOURNAL A

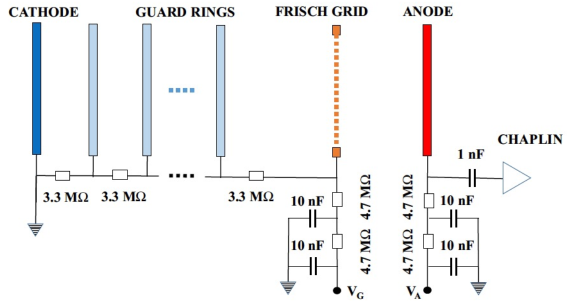
Special Article – New Tools and Techniques

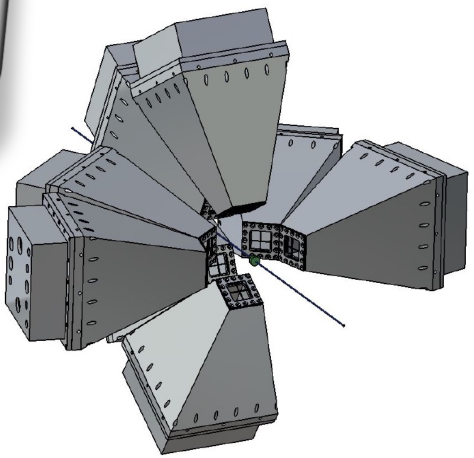
Development of a two-stage detection array for low-energy light charged particles in nuclear astrophysics applications

M. Romoli[1,a], L. Morales-Gallegos[2,3,1], M. Aliotta[2], C.G. Bruno[2], R. Buompane[3,1], A. D'Onofrio[3,1], T. Davinson[2], M. De Cesare[4,1], A. Di Leva[5,1], P. Di Meo[1], J. Duarte[3,1], L. Gasques[6,3,1], L. Gialanella[3,1], G. Imbriani[5,1], G. Porzio[3,1], D. Rapagnani[3,7,8], and A. Vanzanella[1]

ERNA
European Recoil separator for Nuclear Astrophysics







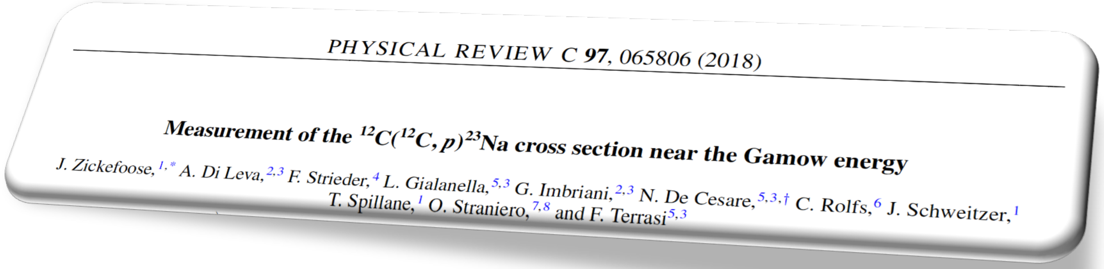
Gastly -> particle spectroscopy

- ❖ Detailed study of the background
- ❖ Study of suitable ^{12}C carbon targets → Morales-Gallegos et al 2015 J. Phys.: Conf. Ser. 578 012002
- ❖ Development of detection setup for p and α

^{12}C+^{12}C

@ CIRCE
$2<E_{CM}<4$ MeV

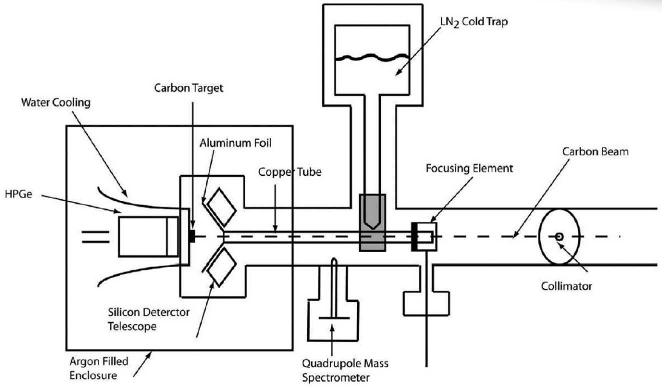
ERNA
European Recoil separator for Nuclear Astrophysics

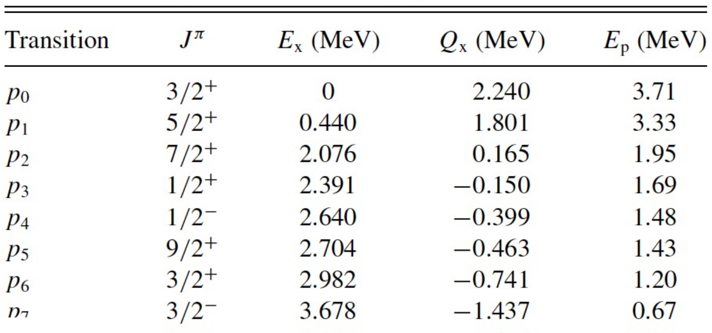


PHYSICAL REVIEW C **97**, 065806 (2018)

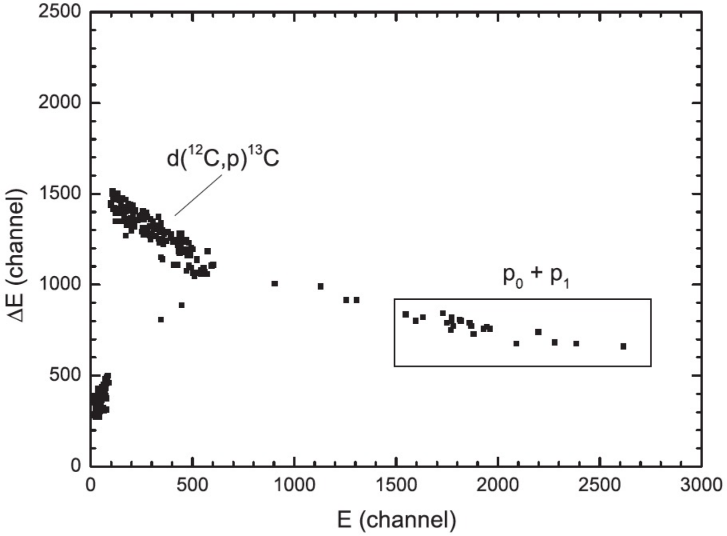
Measurement of the ^{12}C(^{12}C, p)^{23}Na cross section near the Gamow energy

J. Zickefoose,[1,*] A. Di Leva,[2,3] F. Strieder,[4] L. Gialanella,[5,3] G. Imbriani,[2,3] N. De Cesare,[5,3,†] C. Rolfs,[6] J. Schweitzer,[1] T. Spillane,[1] O. Straniero,[7,8] and F. Terrasi[5,3]





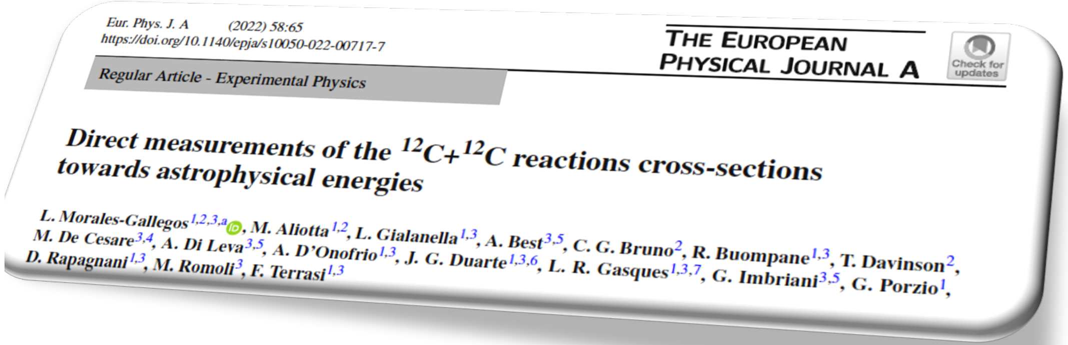
Transition	J^π	E_x (MeV)	Q_x (MeV)	E_p (MeV)
p_0	$3/2^+$	0	2.240	3.71
p_1	$5/2^+$	0.440	1.801	3.33
p_2	$7/2^+$	2.076	0.165	1.95
p_3	$1/2^+$	2.391	−0.150	1.69
p_4	$1/2^-$	2.640	−0.399	1.48
p_5	$9/2^+$	2.704	−0.463	1.43
p_6	$3/2^+$	2.982	−0.741	1.20
p_7	$3/2^-$	3.678	−1.437	0.67
	$5/2^-$	3.848	−1.607	0.53
	$5/2^+$	3.914	−1.673	0.48
	$1/2^+$	4.430	−2.189	0.13



Istituto Nazionale di Fisica Nucleare

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

^{12}C+^{12}C



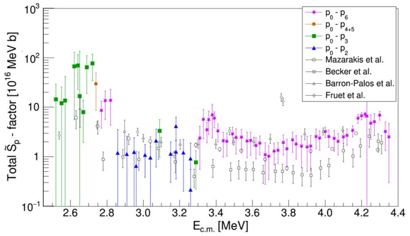
Eur. Phys. J. A (2022) 58:65
https://doi.org/10.1140/epja/s10050-022-00717-7

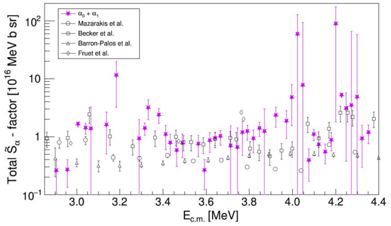
THE EUROPEAN PHYSICAL JOURNAL A

Regular Article - Experimental Physics

Direct measurements of the ^{12}C+^{12}C reactions cross-sections towards astrophysical energies

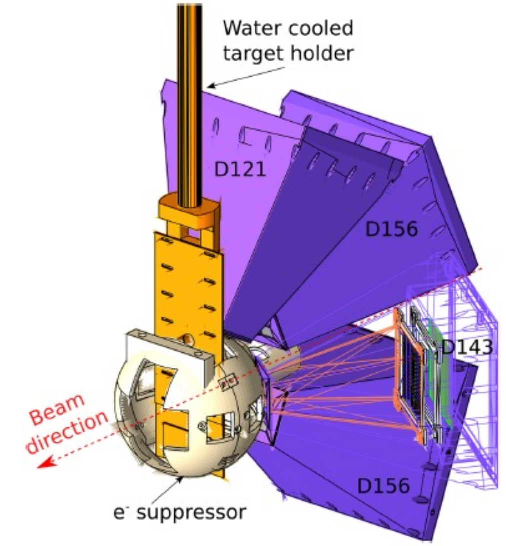
L. Morales-Gallegos[1,2,3,a], M. Aliotta[1,2], L. Gialanella[1,3], A. Best[3,5], C. G. Bruno[2], R. Buompane[1,3], T. Davinson[2], M. De Cesare[3,4], A. Di Leva[3,5], A. D'Onofrio[1,3], J. G. Duarte[1,3,6], L. R. Gasques[1,3,7], G. Imbriani[3,5], G. Porzio[1], D. Rapagnani[1,3], M. Romoli[3], F. Terrasi[1,3]

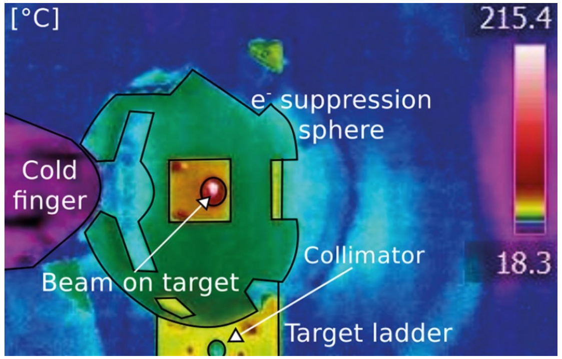




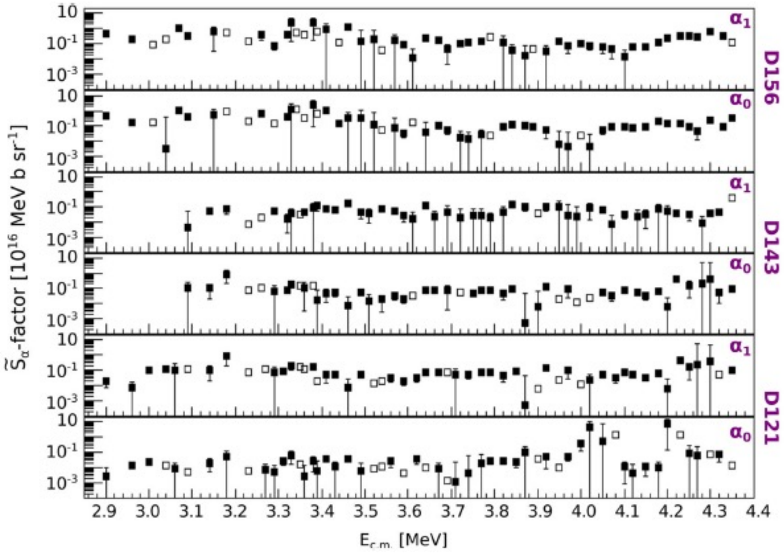
ERNA
European Recoil separator for Nuclear Astrophysics

To be completed …
data analysis ongoing



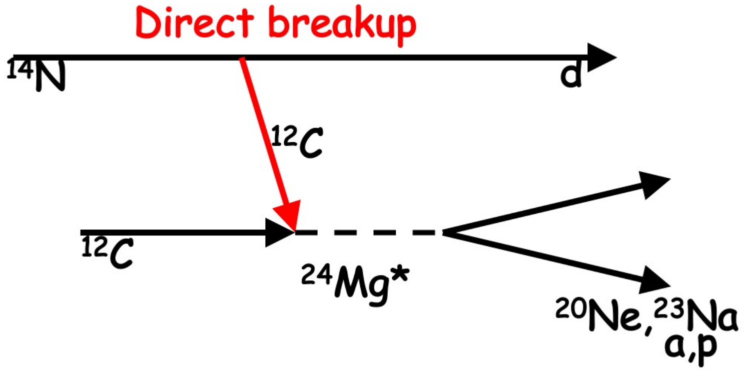


Temperature monitor



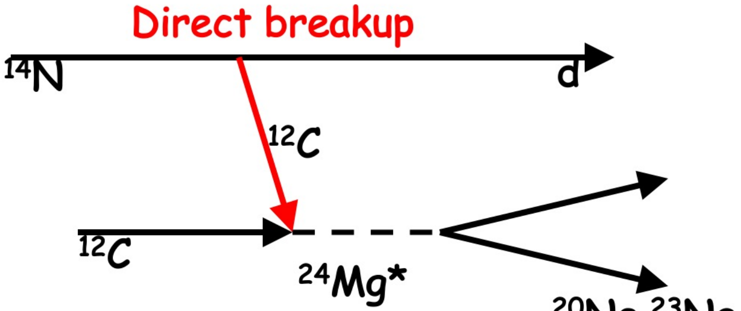
$^{12}C+^{12}C$

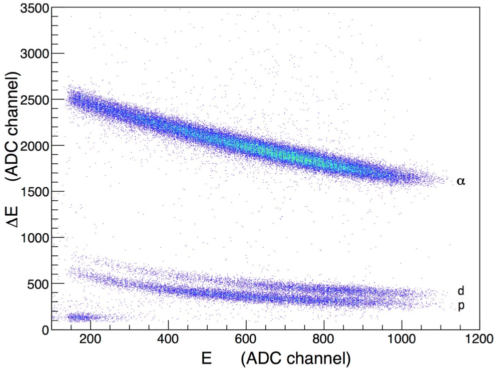
$^{12}C(^{12}C,\alpha)^{20}Ne$
$^{12}C(^{12}C,p)^{23}Na$
via the Trojan Horse Method applied to
$^{12}C(^{14}N,\alpha^{20}Ne)^{2}H$
$^{12}C(^{14}N,p^{23}Na)^{2}H$
three-body processes



$^{12}C+^{12}C$

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





- Normalization to direct data
- Model to extract direct cross section

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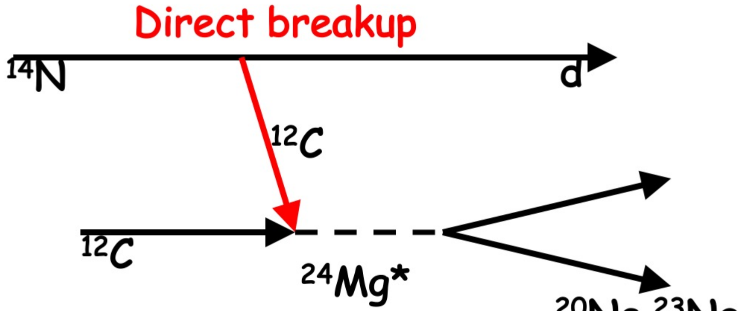
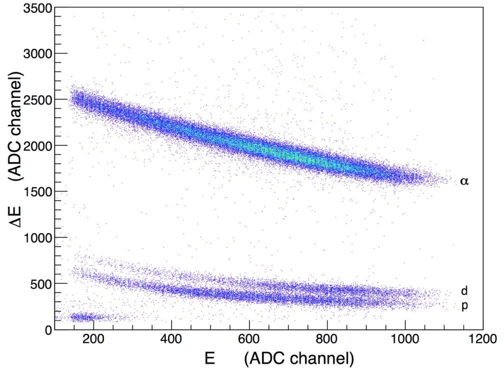
UNIVERSITÀ DI BOLOGNA

^{12}C+^{12}C

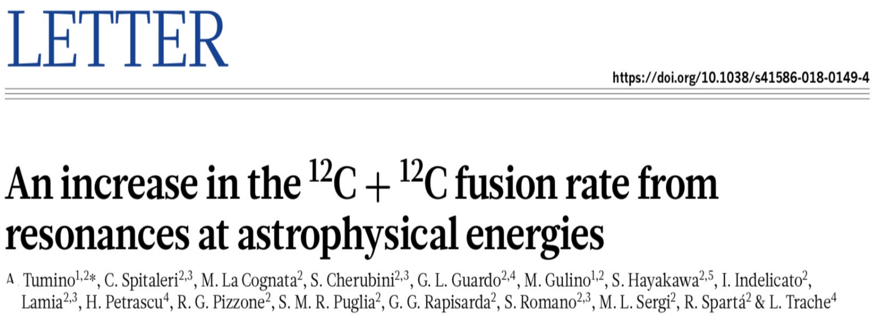
^{12}C(^{12}C,α)^{20}Ne
^{12}C(^{12}C,p)^{23}Na
via the Trojan Horse Method applied to
^{12}C(^{14}N,α^{20}Ne)^{2}H
^{12}C(^{14}N,p^{23}Na)^{2}H
three-body processes





- ❖ Normalization to direct data
- ❖ Model to extract direct cross section

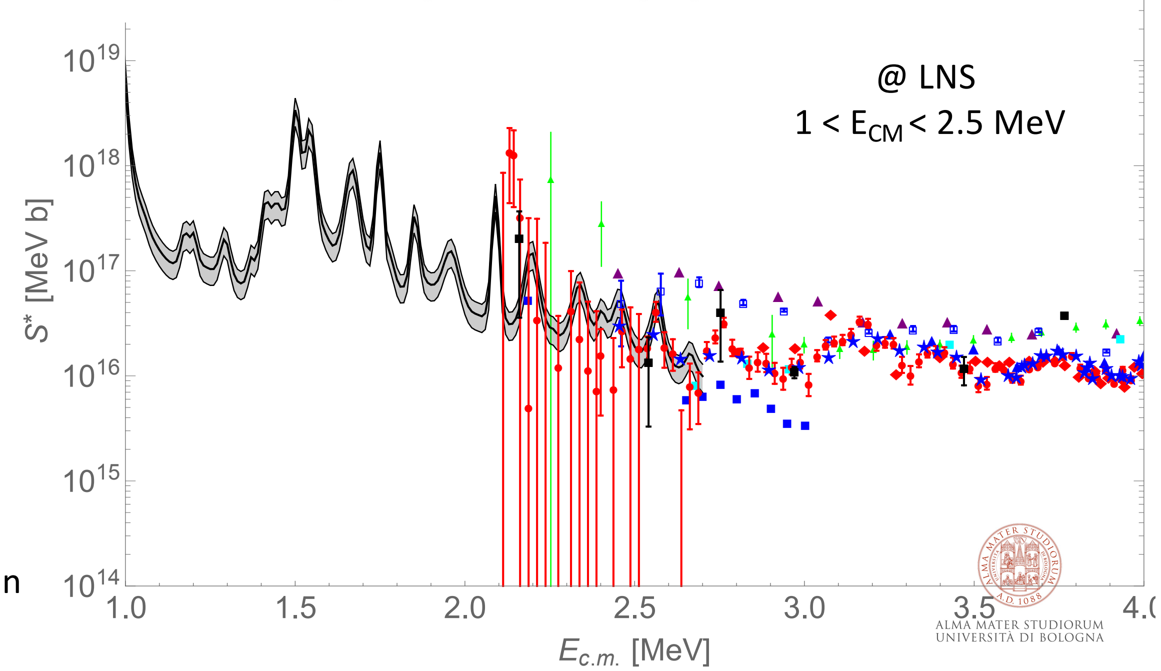
Nature volume 557, pages687–690 (2018) Published: 23 May 2018


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], 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]

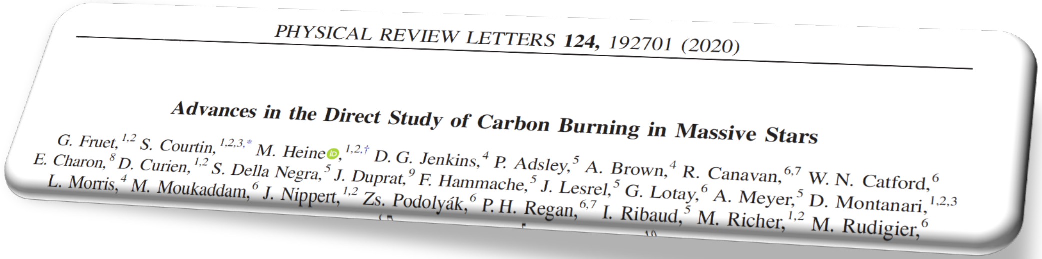


@ LNS
1 < E_{CM} < 2.5 MeV

$^{12}C+^{12}C$ **international effort** $\left\{ \begin{array}{l} \text{STELLA @ IPN ORSAY} \\ \text{NOTRE DAME Univ.} \end{array} \right.$

^{12}C+^{12}C international effort

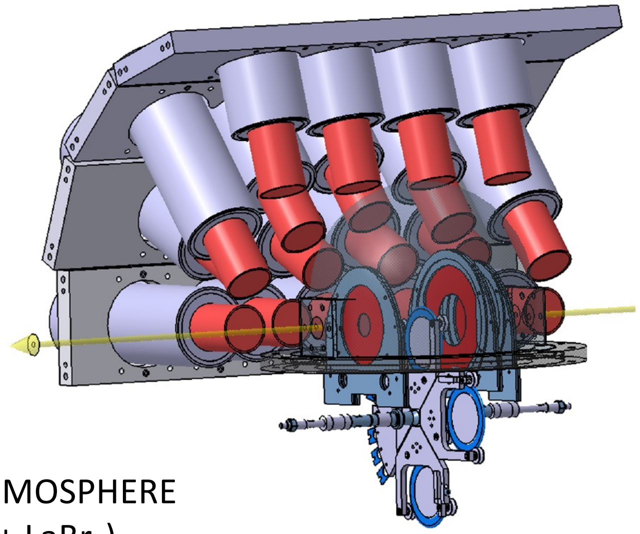
STELLA @ IPN ORSAY
NOTRE DAME Univ.



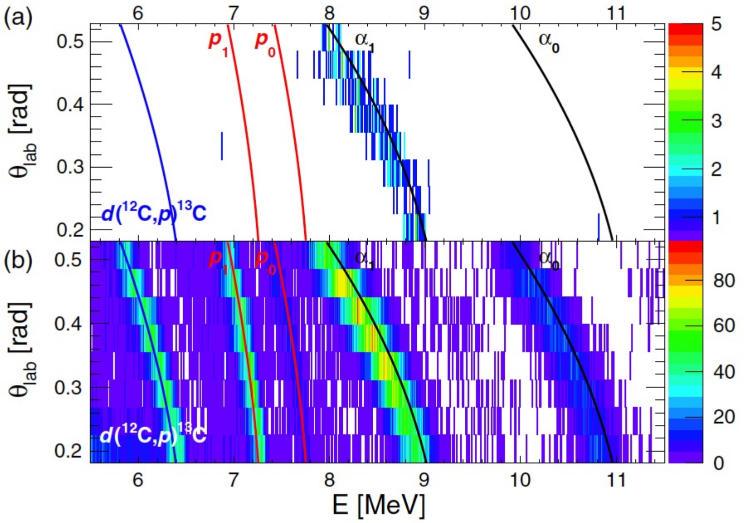
PHYSICAL REVIEW LETTERS **124,** 192701 (2020)

Advances in the Direct Study of Carbon Burning in Massive Stars

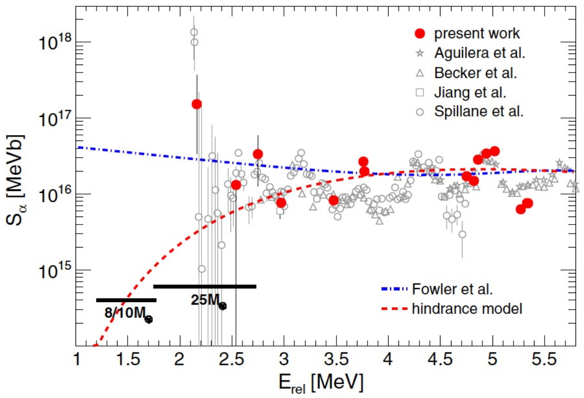
G. Fruet,[1,2] S. Courtin,[1,2,3,*] M. Heine,[1,2,†] D. G. Jenkins,[4] P. Adsley,[5] A. Brown,[4] R. Canavan,[6,7] W. N. Catford,[6] E. Charon,[8] D. Curien,[1,2] S. Della Negra,[5] J. Duprat,[9] F. Hammache,[5] J. Lesrel,[5] G. Lotay,[6] A. Meyer,[5] D. Montanari,[1,2,3] L. Morris,[4] M. Moukaddam,[6]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

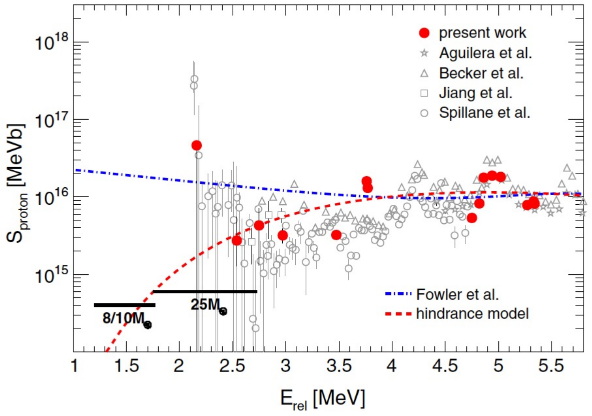


Measurements based on
γ-ray + particle spectroscopy
In coincidence



STELLA + GAMMOSPHERE
(Anular Si + LaBr$_3$)

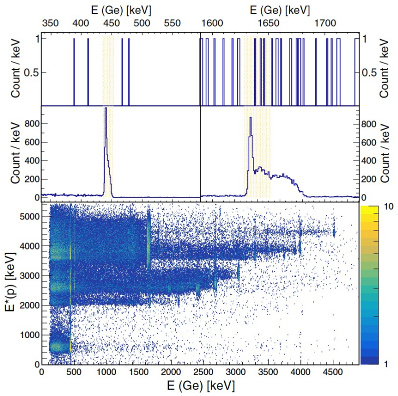


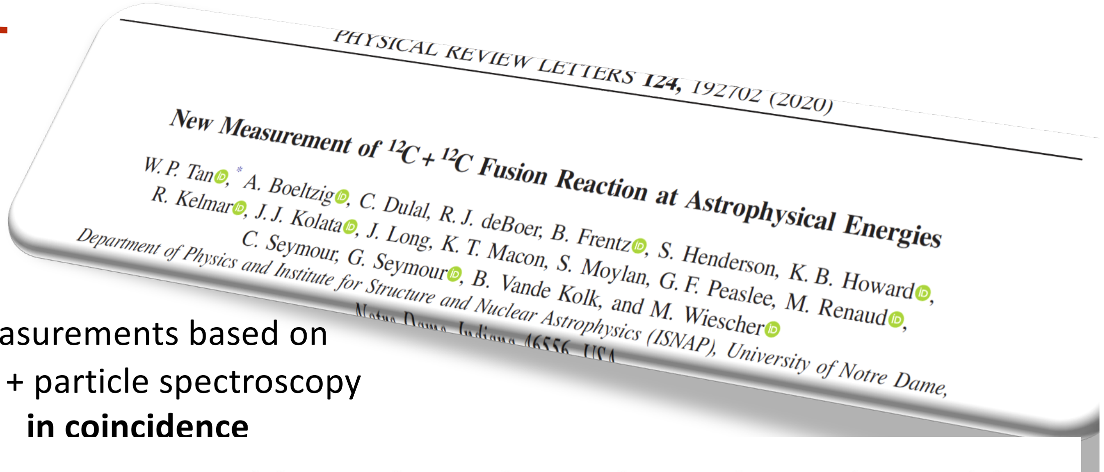


^{12}C+^{12}C international effort

STELLA @ IPN ORSAY
NOTRE DAME Univ.

Silicon detector array + HPGe



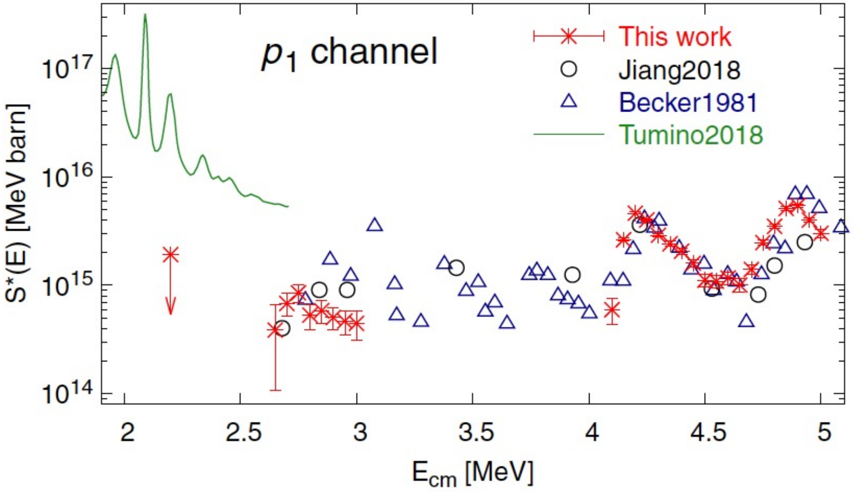

PHYSICAL REVIEW LETTERS 124, 192702 (2020)

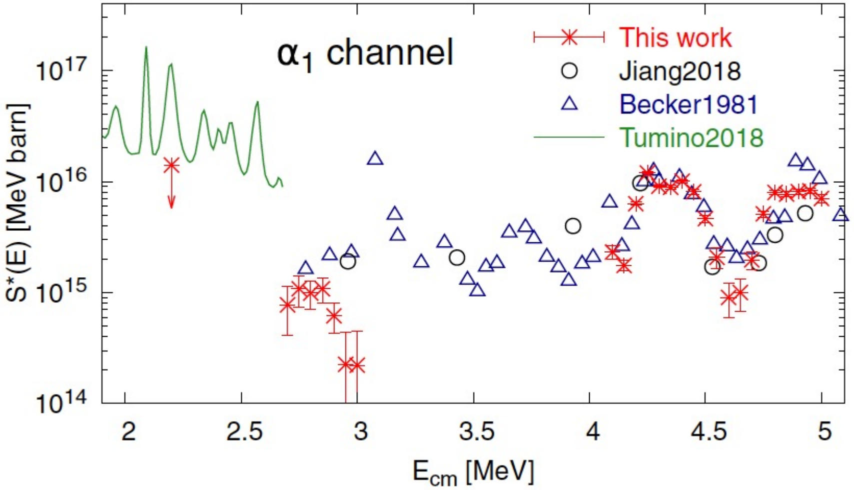
New Measurement of ^{12}C + ^{12}C Fusion Reaction at Astrophysical Energies

W. P. Tan,* A. Boeltzig, C. Dulal, R. J. deBoer, B. Frentz, S. Henderson, K. B. Howard, R. Kelmar, J. J. Kolata, J. Long, K. T. Macon, S. Moylan, G. F. Peaslee, M. Renaud, C. Seymour, G. Seymour, B. Vande Kolk, and M. Wiescher

Department of Physics and Institute for Structure and Nuclear Astrophysics (ISNAP), University of Notre Dame, Notre Dame, Indiana 46556, USA

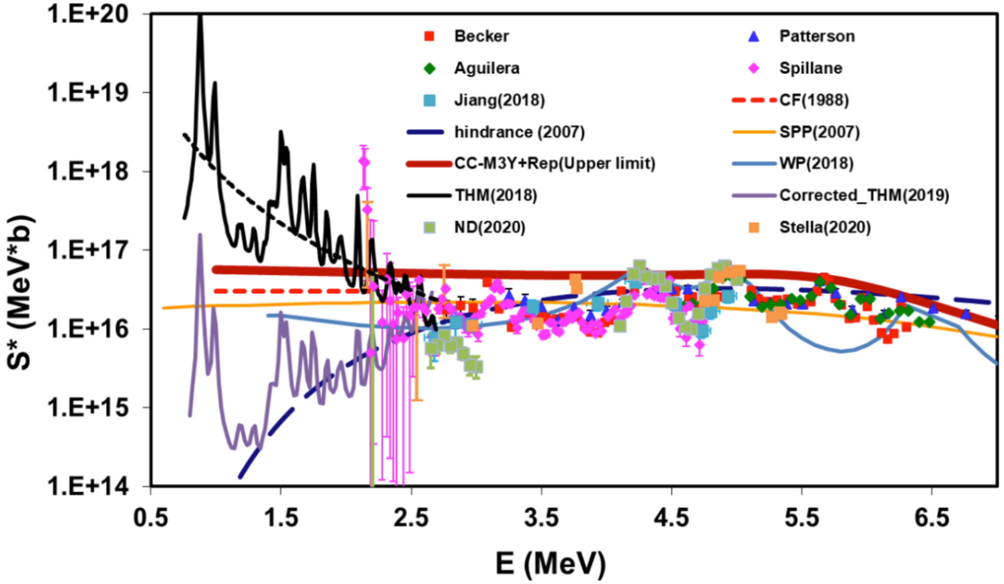
Measurements based on
γ-ray + particle spectroscopy
in coincidence





^{12}C+^{12}C

Present situation unclear



Measuremetn to be included in the LUNA-MV scientific program

$^{12}C+^{12}C$

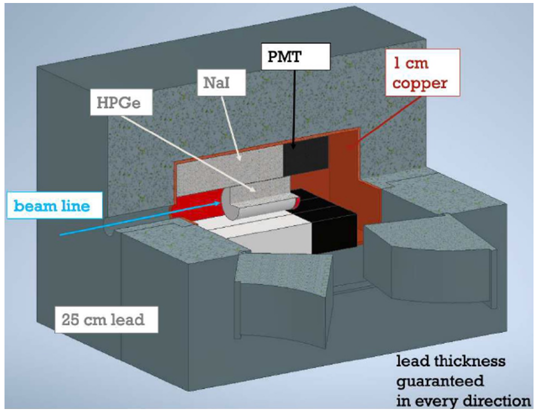
LUNA aims at measuring down to E=1500 keV through detection of de-excitation γ-rays of residual nuclei (^{20}Ne or ^{23}Na) and/or detection of emitted particles (GASTLY ?)

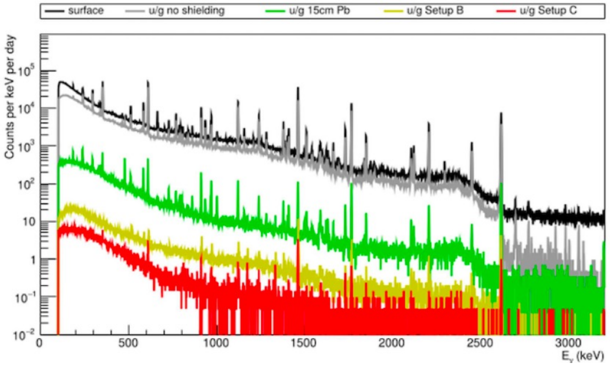
Several tasks are being afforded:

1) ^{12}C target production and characterization, with particular emphasis on the strategy to reduce and quantify residual H and D impurities that cause beam induced background

2) Setup for gamma measurement: a new ultra pure HPGe with 158% efficiency is being tested at LNGS

2-a) A proper shielding is being developed and the use of ancillary NaI detectors is under evaluation





Conslusions

Many **intriguing open questions** in Nuclear Astrophysics.
Common international effort required to address some of these puzzles.

Neutron source in Red Giant Stars:

^{13}**C(α,n) well characterised, possible** some future activities @ n_TOF & perhaps LUNA)
^{22}**Ne(α,n)** fair knowledge, ongoing activities (ASFIN & **LUNA**)

Heavy-Ion burning in Red SUpergiants stars:

^{12}**C + ^{12}C** still far from being accurately constrained, ongoing activities (ERNA, **LUNA**).
After Normalization to LUNA data, ASFIN data will provide S(E) in the whole Gamow window

massimi@bo.infn.it

Acknowledgments

Thank you for your attention

Thanks to the organizers

Many Thanks to
L. Lamia & G. Pizzone (RL ASFIN)
A. Di Leva (RN ERNA)
G. Imbriani (RN LUNA)

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Cristian Massimi

Dipartimento di Fisica e Astronomia

cristian.massimi@unibo.it

Backup

massimi@bo.infn.it

Backup ^{13}C(α,n)

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **77**, 042801(R) (2008)

Indirect study of the ^{13}C(α, n)^{16}O reaction via the ^{13}C(^{7}Li,t)^{17}O transfer reaction

M. G. Pellegriti,[1,*] F. Hammache,[1,†] P. Roussel,[1] L. Audouin,[1] D. Beaumel,[1] P. Descouvemont,[2] S. Fortier,[1] L. Gaudefroy,[3]
J. Kiener,[4] A. Lefebvre-Schuhl,[4] M. Stanoiu,[5] V. Tatischeff,[4] and M. Vilmay[1]
[1] *IPN-Orsay, IN2P3-CNRS, Université Paris XI, F-91406 Orsay, France*
[2] *Physique Nucléaire Théorique et Physique Mathématique, ULB CP229, B-1050 Brussels, Belgium*
[3] *GANIL, IN2P3-CNRS, Caen, France*
[4] *CSNSM, IN2P3-CNRS, Université Paris XI, F-91405 Orsay, France*
[5] *GSI, Postfach 110552, D-64220 Darmstadt, Germany*

(Received 31 May 2007; revised manuscript received 21 December 2007; published 22 April 2008)

The ^{13}C(α, n)^{16}O reaction is considered the main neutron source for the s process in low mass asymptotic giant branch (AGB) stars. In the Gamow peak, the cross section sensitively depends on the $1/2^+$ subthreshold state of ^{17}O ($E_x = 6.356$ MeV). In this work, we determined the astrophysical S factor through an evaluation of the α spectroscopic factor and the corresponding asymptotic normalization factor (ANC) of the 6.356 MeV state using the transfer reaction ^{13}C(^{7}Li,t)^{17}O at two different incident energies. Our result confirms that the contribution of the $1/2^+$ state is dominant at astrophysical energies. Our reaction rate at $T = 0.09$ GK is slightly lower than the value adopted in the Nuclear Astrophysics Compilation of REaction rates (NACRE), but two times larger than the one obtained in a recent ANC measurement.

DOI: 10.1103/PhysRevC.77.042801 PACS number(s): 25.70.Hi, 25.55.Hp, 26.20.−f, 27.20.+n

Nearly half of the heavy elements observed in the universe are produced by a sequence of slow neutron capture reactions, the so-called s-process nucleosynthesis. In AGB stars of 1–3 solar masses at low temperatures, the description of this process critically depends on the neutron flux from the ^{13}C(α, n)^{16}O reaction [1].

Direct measurements of the ^{13}C(α, n)^{16}O cross section have been performed down to 270 keV [2], whereas in asymptotic giant branch(AGB) stars at temperatures around 10^8 K, the Gamow peak is at $E_{\rm cm} \sim 190$ keV. R-matrix extrapolations [3] of the cross sections measured at higher energies then have to be performed and have to include the contribution of the $1/2^+$ state of ^{17}O which lies at 6.356 MeV (3 keV below the $\alpha +^{13}$ C threshold). This contribution strongly depends on the α-spectroscopic factor S_α of this state. With values $S_\alpha \sim 0.3$–0.7 deduced from a nuclear model [4] and considered in the s-process modeling, a rise of the astrophysical S factor is expected when the energy decreases. This rise is compatible with the experimental data of Drotleff *et al*. [2] but their error bars are too large to derive definite conclusions.

From the analyses of the experimental results of Kubono *et al*. [5] on the ^{13}C(^{6}Li,d)^{17}O transfer reaction, performed at the incident energy of 60 MeV, two different results are deduced: one by Kubono *et al*. [5], $S_\alpha \sim 0.011$, and the other one by Keeley *et al*. [6], $S_\alpha \sim 0.4$, which lies within the theoretical values [4]. In addition to these controversial analyses, the new study of the contribution of the $1/2^+$ state to the total ^{13}C(α, n)^{16}O reaction rate by a ^{6}Li(^{13}C,d)^{17}O asymptotic normalization factor (ANC) measurement [7] led to an astrophysical S factor at the energy of 190 keV ten times smaller than the value adopted in the Nuclear Astrophysics Compilation of REaction rates (NACRE) [8] but five times larger than the value deduced by Kubono *et al*. Consequently, it appeared highly desirable to perform a new determination of this S_α factor.

In this article, we report on a study of the 6.356 MeV state and of three other excited states at 3.055 MeV($1/2^-$), 4.553 MeV ($3/2^-$), and 7.380 MeV ($5/2^-$) by means of the α transfer reaction ^{13}C(^{7}Li,t)^{17}O. Two incident energies, 28 and 34 MeV, were used to check the direct mechanism character of our transfer reaction. The use of ^{7}Li instead of ^{6}Li reduces possible multistep effects [9] and the transfer cross sections to low spin states are enhanced because of the nonzero α angular momentum in ^{7}Li as observed when comparing the transfer reactions (^{6}Li,d) and (^{7}Li,t) on ^{12}C [10,11]. Moreover, an estimate of the systematic errors associated with the DWBA analysis can be evaluated from the comparison of the results of different reactions involving different angular momenta and performed at different energies.

The experiment was performed with a ^{7}Li^{3+} beam at the Orsay TANDEM. Two self-supporting enriched ^{13}C targets, with 72(4) and 133(7) μg/cm^2 of ^{13}C and an initial purity of 90%, were used. A ^{12}C target of 80(4) μg/cm^2 was also used for calibration and background subtraction. Despite a rather low gas pressure in the reaction chamber ($\leqslant 10^{-5}$ mb), a ^{12}C buildup was observed during the whole experiment ending with an amount of ^{12}C in the enriched ^{13}C target about twice its initial value. This building up was of least consequence as shown in the analysis described below and was however duly monitored. Note that a more enriched target would not have brought a big improvement.

The absolute (and constant) amount of ^{13}C and the final amount of ^{12}C in the ^{13}C targets were deduced from α energy loss measurements on all targets and by comparing the ratio between 28 MeV elastically scattered ^{7}Li particles at 21° from the ^{12}C nuclei in ^{12}C and ^{13}C targets [see Figs. 1(a) and 1(b)] measured in a run at the end of the experiment.

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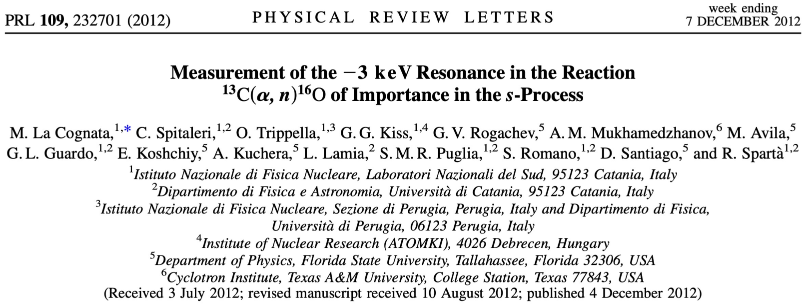
[*] Present address: Dipartimento di Fisica e Astronomia, Universitá di Catania and Laboratori Nazionali del Sud - INFN, Catania, Italy.

[†] Corresponding author: hammache@ipno.in2p3.fr

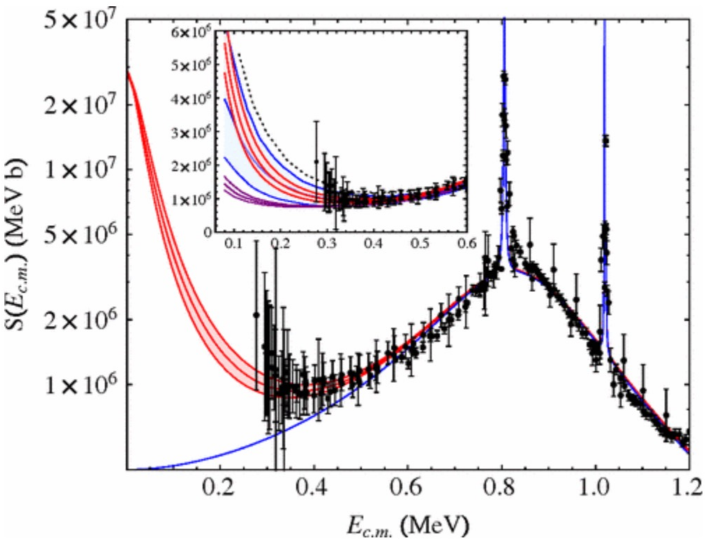


PRL **109,** 232701 (2012) PHYSICAL REVIEW LETTERS week ending
7 DECEMBER 2012

Measurement of the −3 keV Resonance in the Reaction ^{13}C(α, n)^{16}O of Importance in the s-Process

M. La Cognata,[1,*] C. Spitaleri,[1,2] O. Trippella,[1,3] G. G. Kiss,[1,4] G. V. Rogachev,[5] A. M. Mukhamedzhanov,[6] M. Avila,[5]
G. L. Guardo,[1,2] E. Koshchiy,[5] A. Kuchera,[5] L. Lamia,[2] S. M. R. Puglia,[1,2] S. Romano,[1,2] D. Santiago,[5] and R. Spartà[1,2]
[1] *Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud, 95123 Catania, Italy*
[2] *Dipartimento di Fisica e Astronomia, Università di Catania, 95123 Catania, Italy*
[3] *Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, Perugia, Italy and Dipartimento di Fisica,*
Università di Perugia, 06123 Perugia, Italy
[4] *Institute of Nuclear Research (ATOMKI), 4026 Debrecen, Hungary*
[5] *Department of Physics, Florida State University, Tallahassee, Florida 32306, USA*
[6] *Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*

(Received 3 July 2012; revised manuscript received 10 August 2012; published 4 December 2012)



Backup $^{12}C+^{12}C$

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

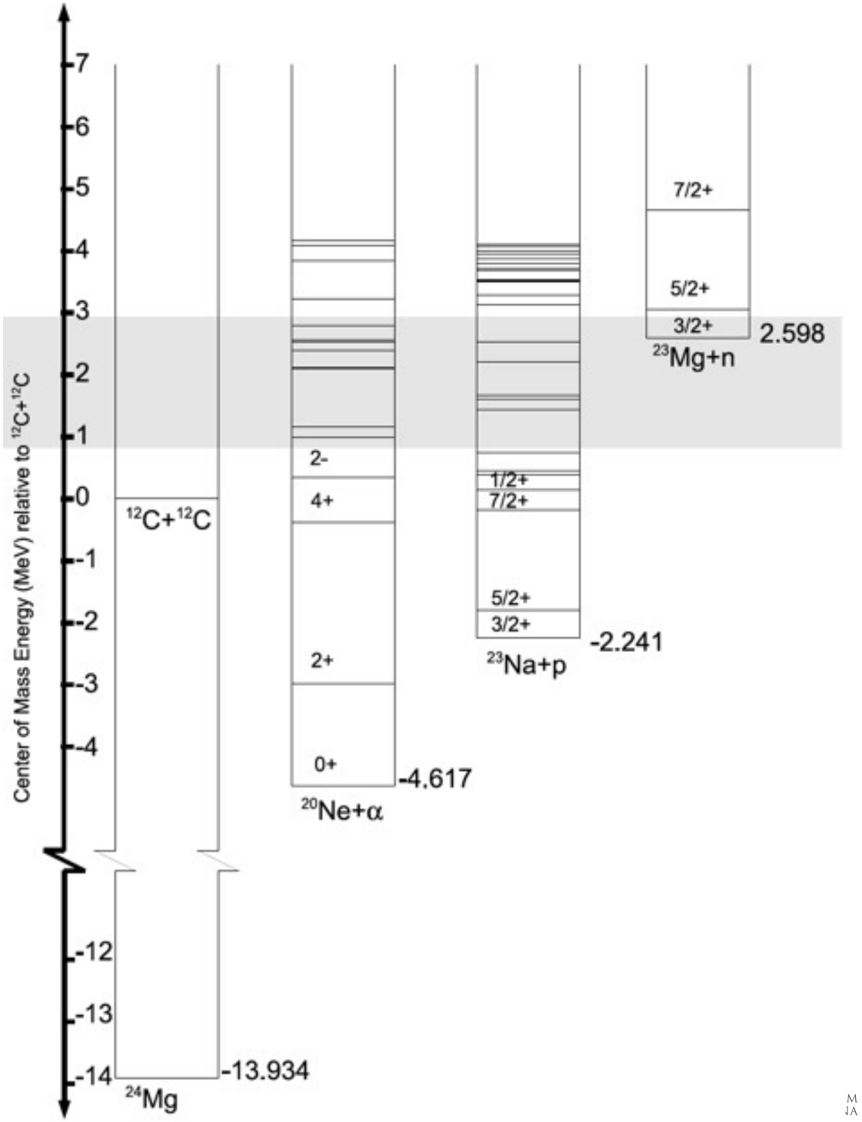
$^{12}C+^{12}C \rightarrow {}^{23}Na + p$ Q = 2.24 MeV

$^{12}C+^{12}C \rightarrow {}^{24}Mg + \gamma$ Q = 13.93 MeV

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

$^{12}C+^{12}C \rightarrow {}^{16}O + 2\alpha$ Q = -0.12 MeV

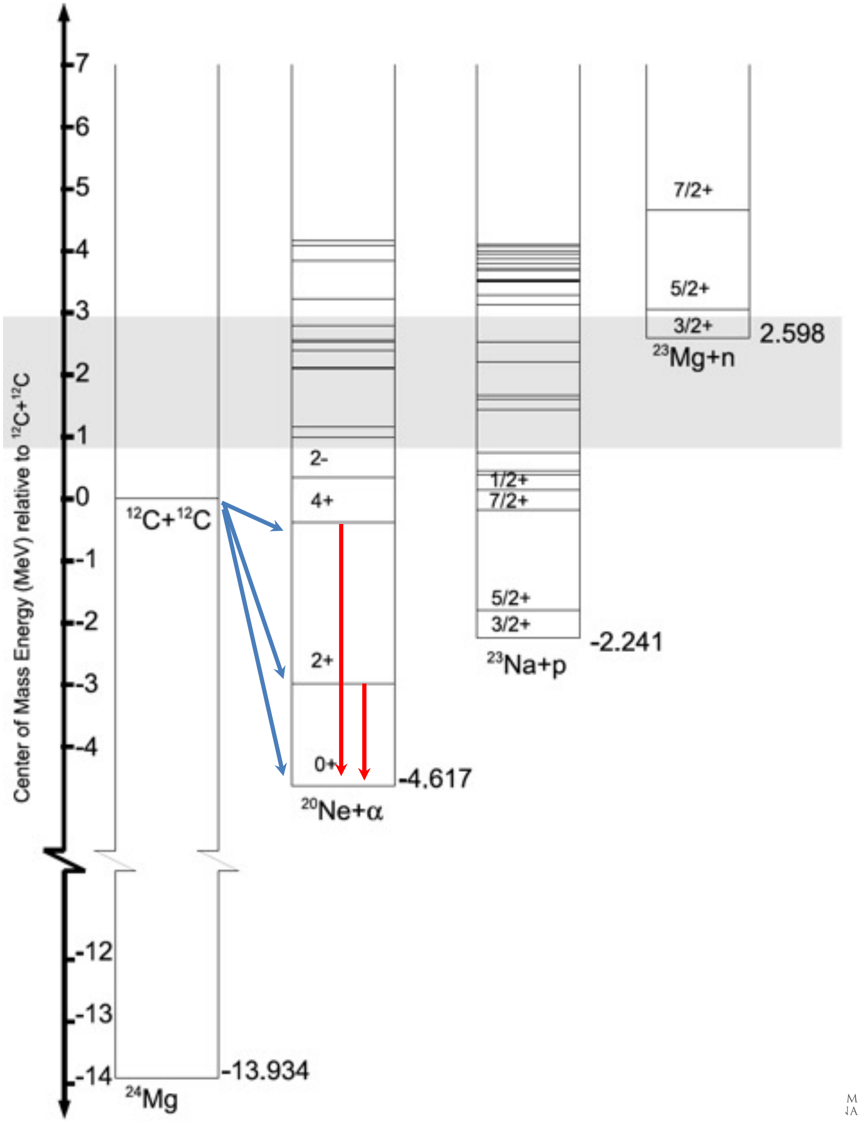
$^{12}C+^{12}C \rightarrow {}^{16}O + {}^{8}Be$ Q= -0.21 MeV



Backup $^{12}C+^{12}C$

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

γ-rays and α particles energies for excited states for $^{12}C(^{12}C, \alpha)^{20}Ne$ (Q = 4.617 MeV)					
E_X (MeV)	**J^p**	**Main γ transitions (MeV)**		**ID**	**$E_{\alpha-max}$ (MeV) (E^{CM} = 2 MeV)**
0.0	0^+			α_0	8.6
1.63	2^+	*1.63 → 0* **1.63**		α_1	6.8
4.24	4^+	*4.24 → 1.63* **2.61**		α_2	3.9
4.96	2^-	*4.96 → 1.63* **3.33**		α_3	3.1
5.62	3^-	*5.62 → 1.63* **3.98**		α_4	2.2
5.78	1^-	*5.78 → 1.63* **4.15**	*5.78 → 0* **5.78**	α_5	2.0

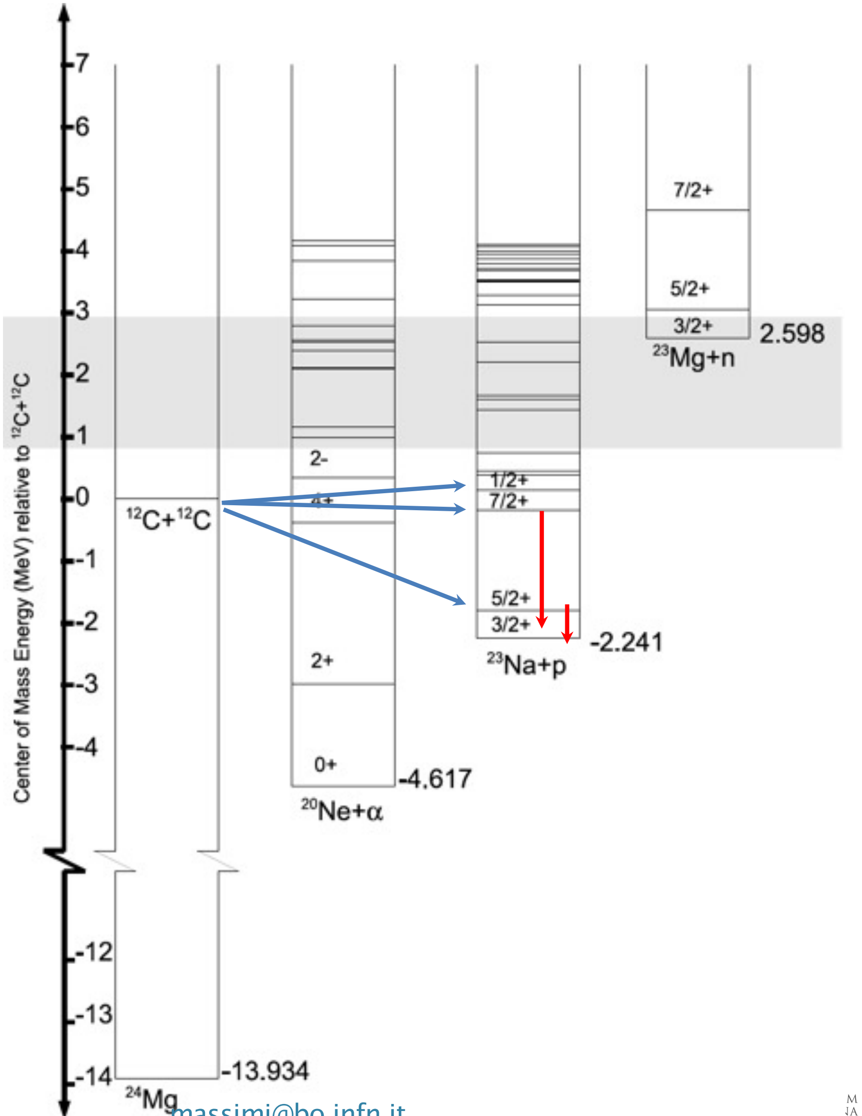


Backup $^{12}C+^{12}C$

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

γ-rays and p particles energies for excited states for $^{12}C(^{12}C, p)^{23}Na$ (Q = 2.241 MeV)

E_X (MeV)	J^p	Main γ transitions (MeV)		ID	$E_{p\text{-max}}$ (MeV) (E^{CM} = 2 MeV)
0.0	3/2⁺			p_0	5.3
0.44	5/2⁺	0.44 → 0 **0.44**		p_1	4.8
2.07	7/2⁺	2.07 → 0.44 **1.63**		p_2	3
2.39	1/2⁺	2.39 → 0.44 **1.95**	2.39 → 0 **2.39**	p_3	2.6
2.64	1/2⁻	2.64 → 0 **2.64**		p_4	2.3
2.70	9/2⁺	2.70 → 2.07 **0.62**	2.70 → 0.44 **2.26**	p_5	2.3
2.98	3/2⁺	2.98 → 0.44 **2.54**	2.98 → 0 **2.98**	p_6	1.9



massimi@bo.infn.it

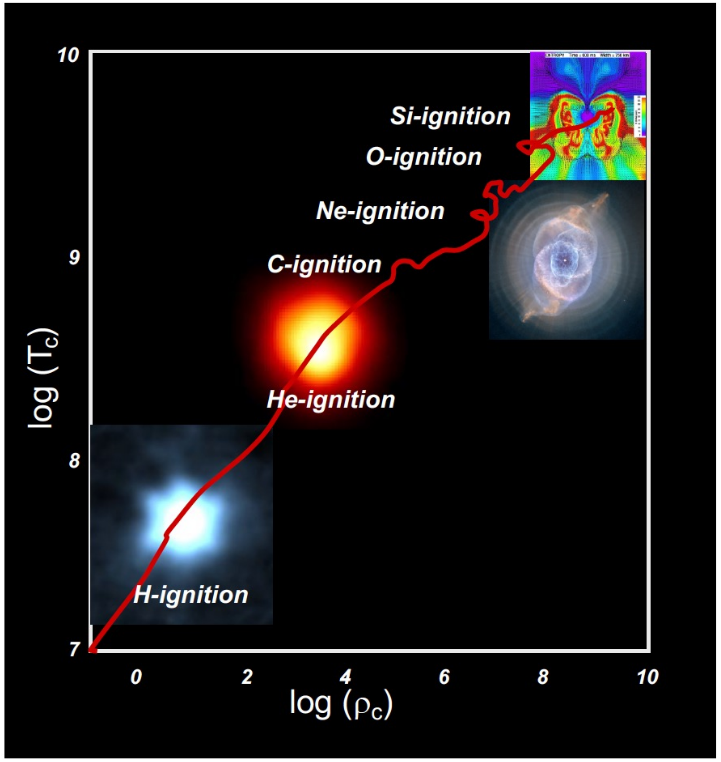
Backup $^{12}C+^{12}C$

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

↓

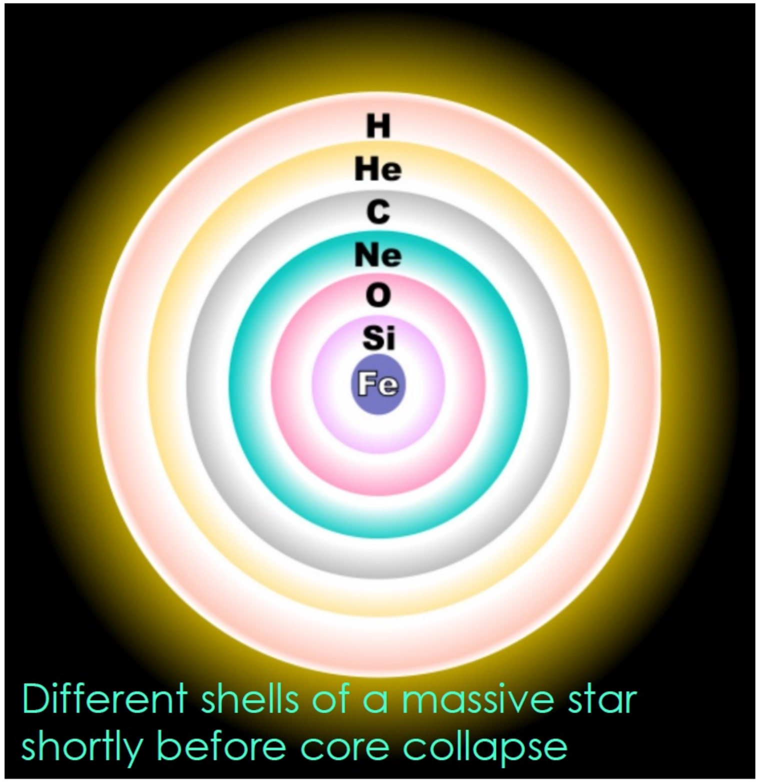
each burning phase is controlled by different nuclear reactions, which govern the:

- energy production
- time scale
- nucleosynthesis



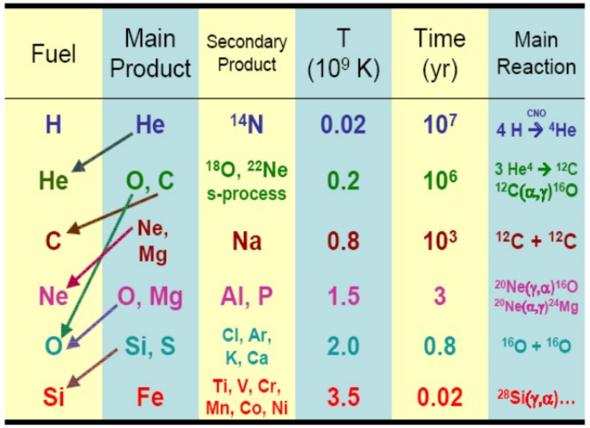
massimi@bo.infn.it

Backup $^{12}C+^{12}C$



Different shells of a massive star shortly before core collapse

- key reactions at each stage of stellar burning



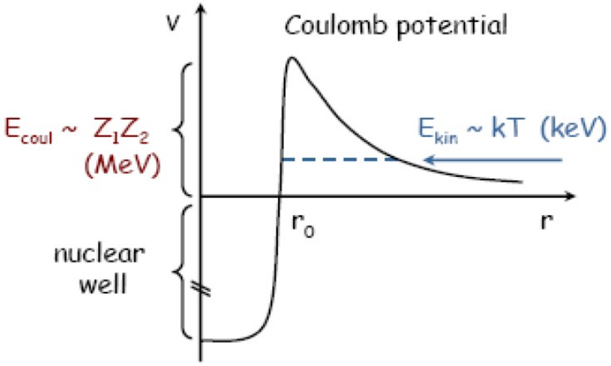
Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,H \xrightarrow{CNO} {}^4He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\,He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$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

Backup

charged particles ➡ Coulomb barrier

energy available: from thermal motion

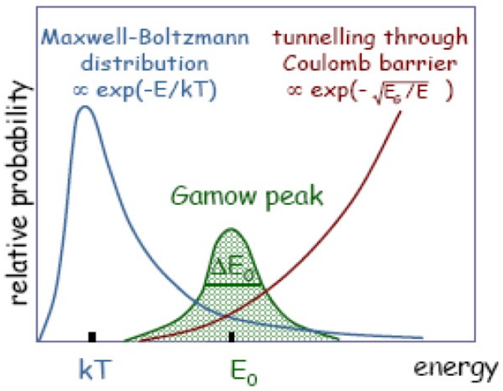


$T \sim 15\times10^6$ K (e.g. our Sun) $\Rightarrow$ $kT \sim 1$ keV

during <u>static burnings</u>: $kT \ll E_{coul}$

reactions occur through <u>TUNNEL EFFECT</u>

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



$$\boxed{\sigma(E) = \underbrace{\frac{1}{E}\exp(-2\pi\eta)}_{\substack{\text{non-nuclear origin}\\ \text{STRONG energy}\\ \text{dependence}}}\ \underbrace{S(E)}_{\substack{\text{nuclear origin}\\ \text{WEAK energy}\\ \text{dependence}}}}$$

ASTROPHYSICAL S(E)-FACTOR