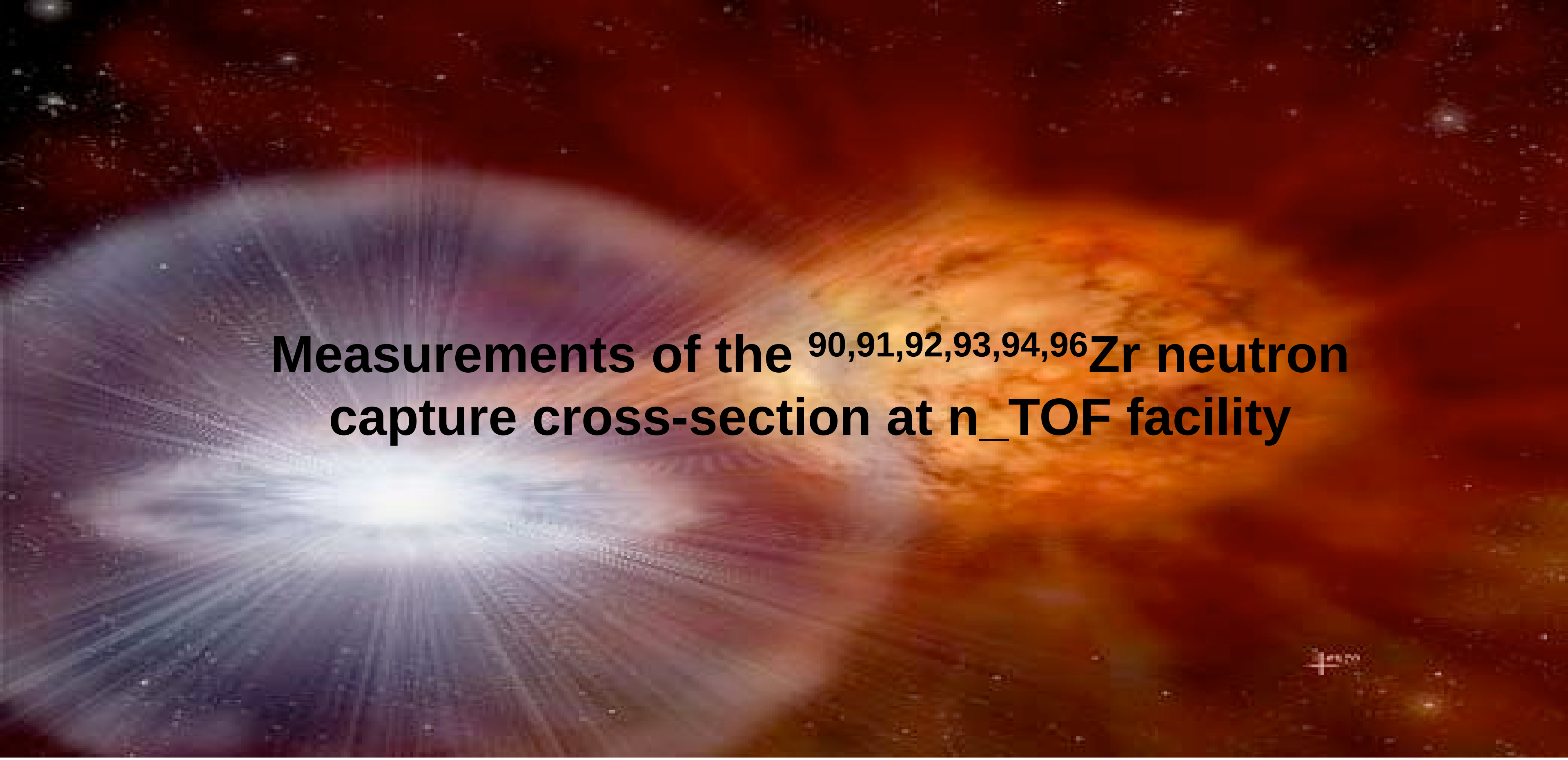


Measurements of the $^{90,91,92,93,94,96}Zr$ neutron capture cross-section at n_TOF facility

G.Tagliente
n_TOF collaboration

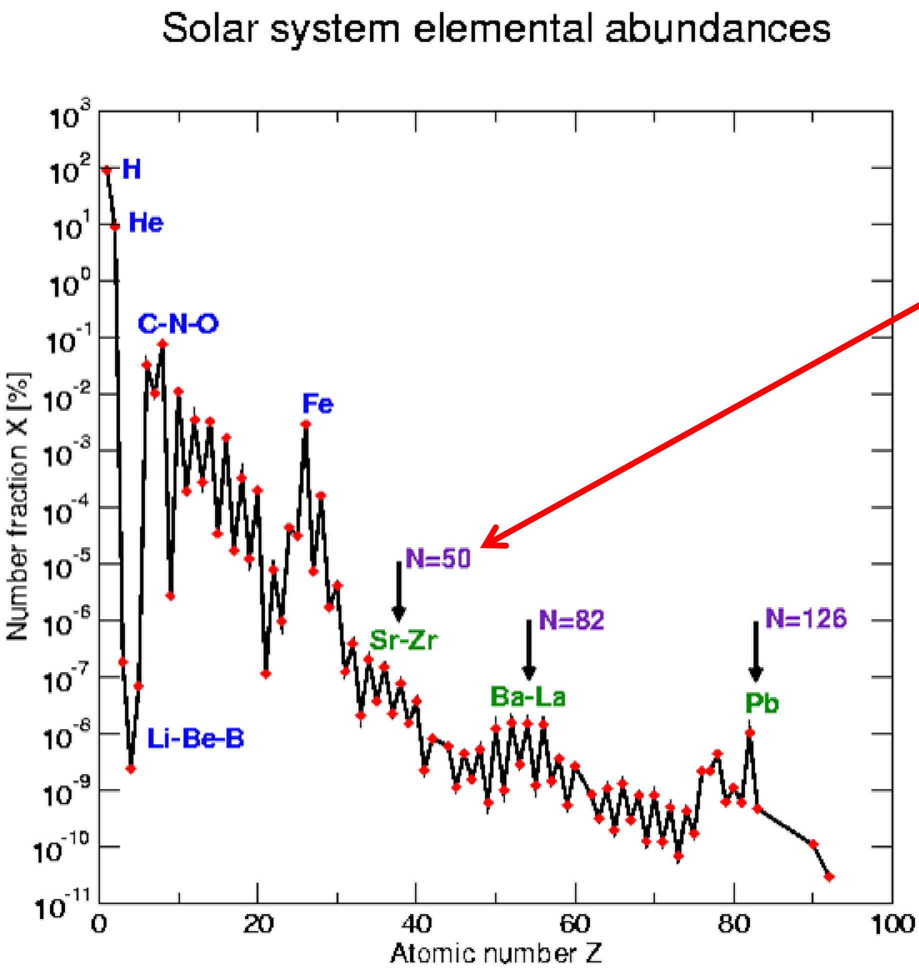
n_TOF Collaboration

U.Abbondanno[14], G.Aerts[7], H.Álvarez[24], F.Alvarez-Velarde[20], S.Andriamonje[7], J.Andrzejewski[33], P.Assimakopoulos[9], L.Audouin[5], G.Badurek[1], P.Baumann[6], F. Bečvář [31], J.Benlliure[24], E.Berthoumieux[7], F.Calviño[25],D.Cano-Ott[20],R.Capote[23],A.Carrillo de Albornoz[30],P.Cennini[4], V.Chepel1[7], E.Chiaveri[4], N.Colonna1[3], G.Cortes[25], D.Cortina[24], A.Couture[29], J.Cox[29], S.David[5], R.Dolfini[15], C.Domingo-Pardo[21], W.Dridi[7], I.Duran[24], M.Embid-Segura[20], L.Ferrant[5], A.Ferrari[4], R.Ferreira-Marques[17], L.Fitzpatrick[4], H.Frais-Koelbl[3], K.Fujii[13], W.Furman[18], C.Guerrero[20], I.Goncalves[30], R.Gallino[36], E.Gonzalez-Romero[20], A.Goverdovski[19], F.Gramegna[12], E.Griesmayer[3], F.Gunsing[7], B.Haas[32], R.Haight[27], M.Heil[8], A.Herrera-Martinez[4], M.Igashira[37], S.Isaev[5], E.Jericha[1], Y.Kadi[4], F.Käppeler[8], D.Karamanis[9], D.Karadimos[9], M.Kerveno[6], V.Ketlerov[19], P.Koehler[28], V.Konovalov[18], E.Kossionides[39], M.Krtička[31], C.Lamboudis[10], H.Leeb[1], A.Lindote[17], I.Lopes[17], M.Lozano[23], S.Lukic[6], J.Marganiec[33], L.Marques[30], S.Marrone[13], P.Mastinu[12], A.Mengoni[4], P.M.Milazzo[14], C.Moreau[14], M.Mosconi[8], F.Neves[17], H.Oberhummer[1], S.O'Brien[29], M.Oshima[38], J.Pancin[7], C.Papachristodoulou[9], C.Papadopoulos[40], C.Paradela[24], N.Patronis[9], A.Pavlik[2], P.Pavlopoulos[34], L.Perrot[7], R.Plag[8], A.Plompen[16], A.Plukis[7], A.Poch[25], C.Pretel[25], J.Quesada[23], T.Rauscher[26], R.Reifarth[27], M.Rosetti1[1], C.Rubbia[5], G.Rudolf[6], P.Rullhusen[16], J.Salgado[30], L.Sarchiapone[4], C.Stephan[5], G.Tagliente[13], J.L.Tain[21], L.Tassan-Got[5], L.Tavora[30], R.Terlizzi[13], G.Vannini[35], P.Vaz[30], A.Ventura[11], D.Villamarin[20], M.C.Vincente[20], V.Vlachoudis[4], R.Vlastou[40], F.Voss[8], H.Wendler[4], M.Wiescher[29], K.Wisshak[8]

40 Research Institutions

120 researchers

Scientific Motivations (n,γ) X-sections of Zr



Bottleneck in the s-process flow. N=50.

Small x-section

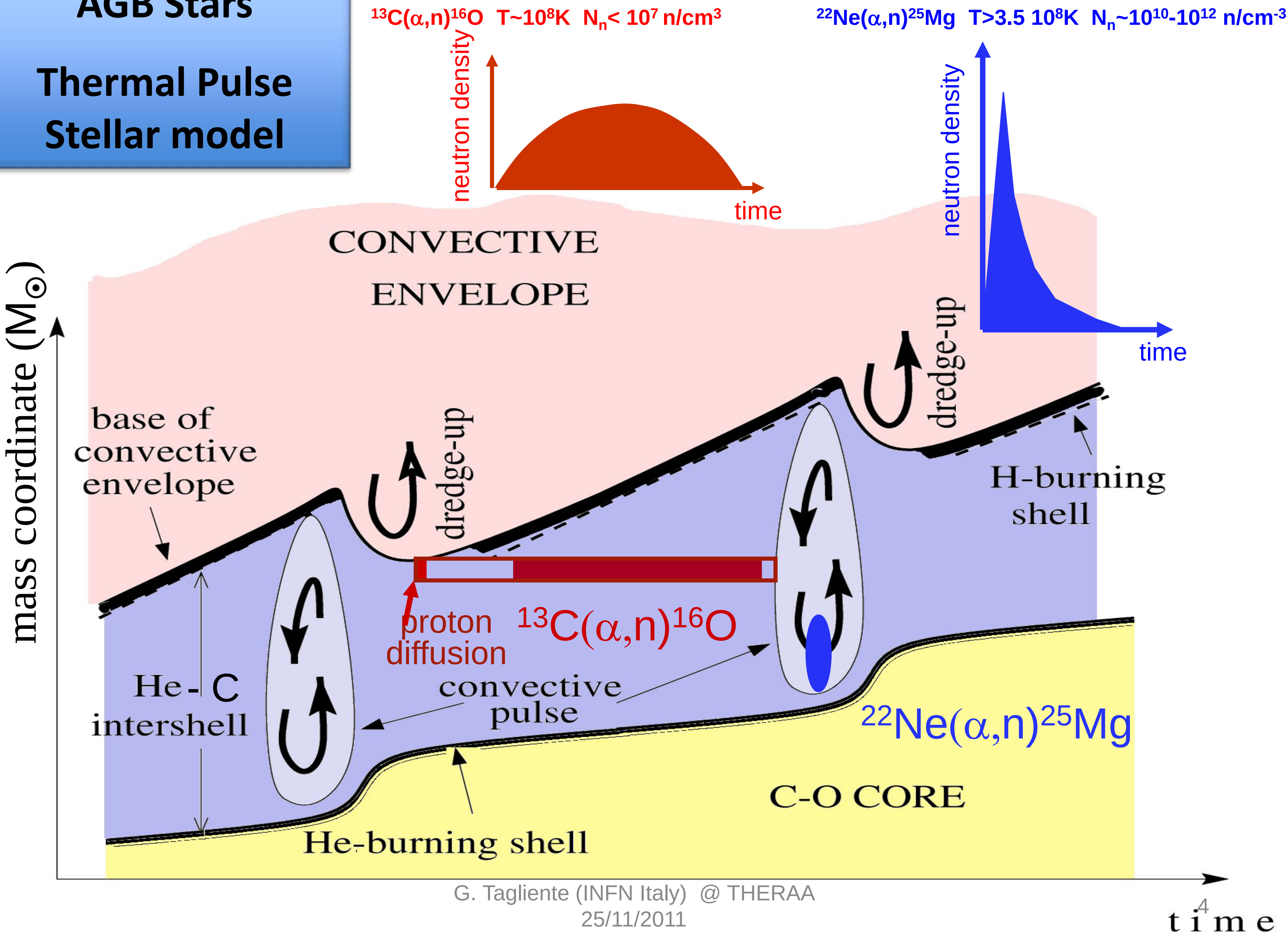
Can be used for normalization of s-process abundance

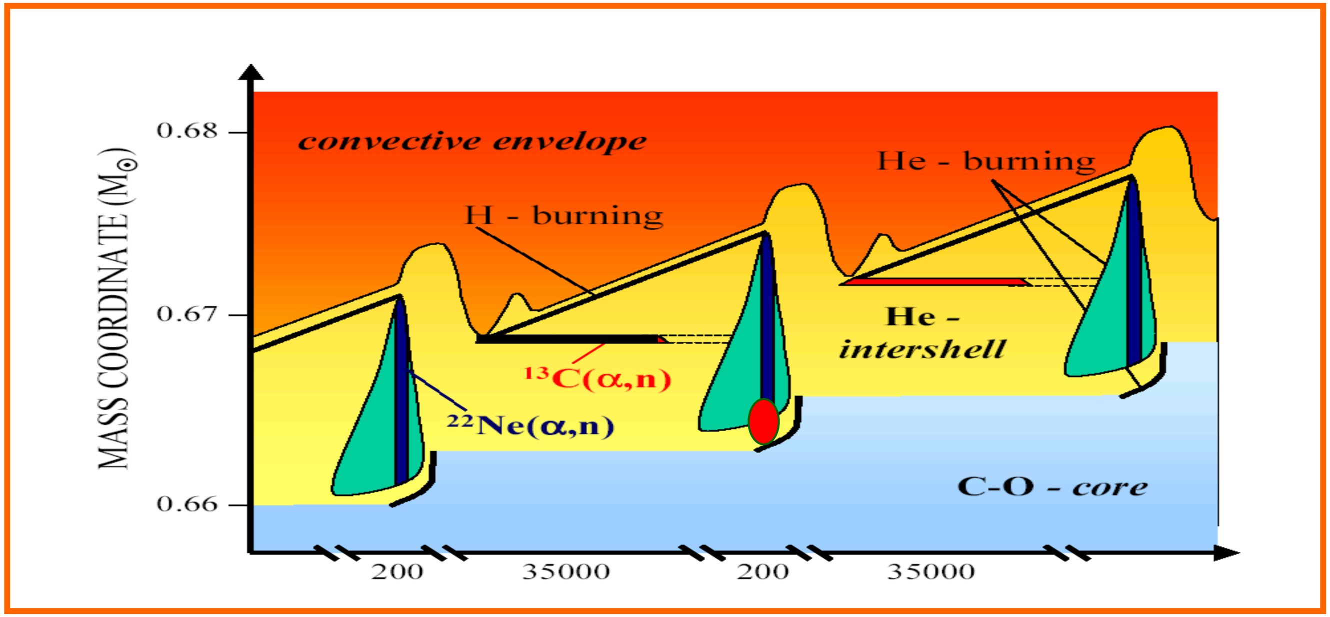
To solve the presolar grain problem

For modeling the stellar evolution of low mass AGB star

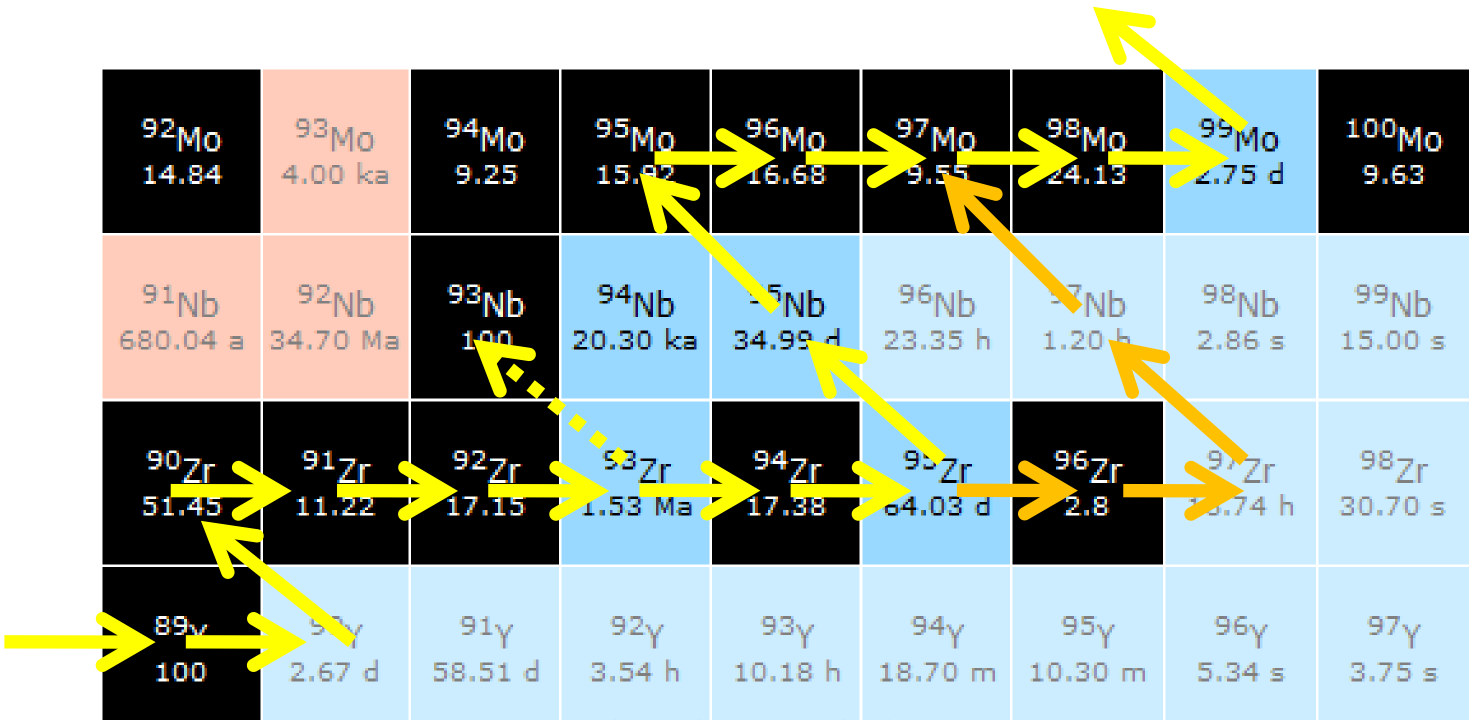
AGB Stars

Thermal Pulse Stellar model





MASS COORDINATE ($M_\odot$)
0.68
0.67
0.66
convective envelope
H - burning
He - burning
He - intershell
$^{13}C(\alpha,n)$
$^{22}Ne(\alpha,n)$
C-O - core
200
35000
200
35000



^{92}Mo 14.84
^{93}Mo 4.00 ka
^{94}Mo 9.25
^{95}Mo
^{96}Mo 16.68
^{97}Mo
^{98}Mo 24.13
^{100}Mo 9.63
^{91}Nb 680.04 a
^{92}Nb 34.70 Ma
^{93}Nb
^{94}Nb 20.30 ka
^{96}Nb 23.35 h
^{98}Nb 2.86 s
^{99}Nb 15.00 s
^{90}Zr 51.45
^{91}Zr 11.22
^{92}Zr 17.15
^{94}Zr 17.38
^{96}Zr 2.8
^{98}Zr 30.70 s
^{89}Y 100
2.67 d
^{91}Y 58.51 d
^{92}Y 3.54 h
^{93}Y 10.18 h
^{94}Y 18.70 m
^{95}Y 10.30 m
^{96}Y 5.34 s
^{97}Y 3.75 s

The Thermal Pulse Stellar model: the Zr case

There is some inconsistency using the TP stellar model to calculate the N_s abundances with values of the Zr cross sections before n_TOF.

Nucleus	$N_\odot$ Normalized to $N(Si)=10^6$ atoms	$N_s/N_\odot$
^{90}Zr	**5.546**	**0.789**
^{91}Zr	**1.21**	**1.066**
^{92}Zr	**1.848**	**1.052**
^{94}Zr	**1.873**	**1.217**
^{96}Zr	**0.302**	**0.842**

for low mass AGB star (1.5 - 3 $M_\odot$)

The uncertainty on the $N_\odot$ is 10%

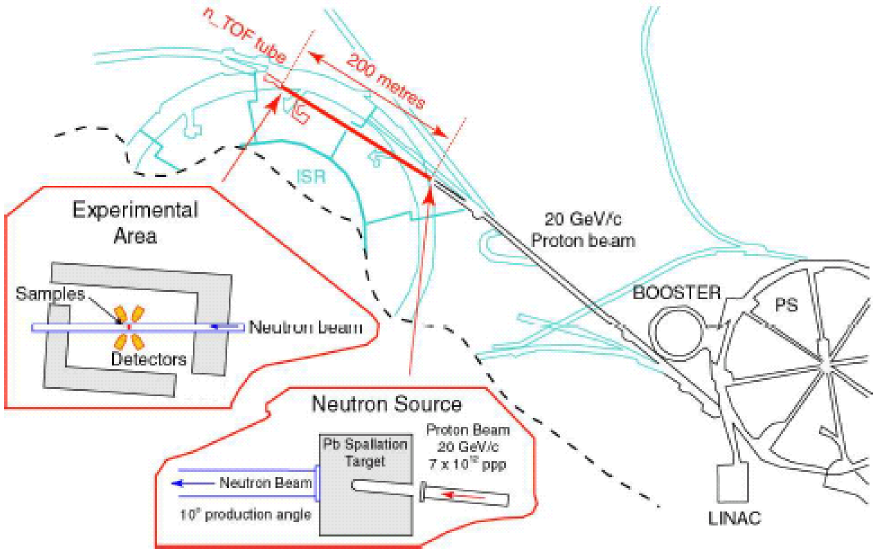
The uncertainty on Zr cross sections ranges from 5% to 20% (depending on the isotopes).

There are discrepancies up to 50% on the results of some measurements

New measurements with high accuracy needed !

The n_TOF facility at CERN

- Spallation of high-energy proton beam on a lead target (~360 neutrons/proton)
- 7x10^{12} protons/bunch @ 20 GeV/c from the PS accelerator (6 ns time resolution)
- 0.8 Hz maximum repetition rate

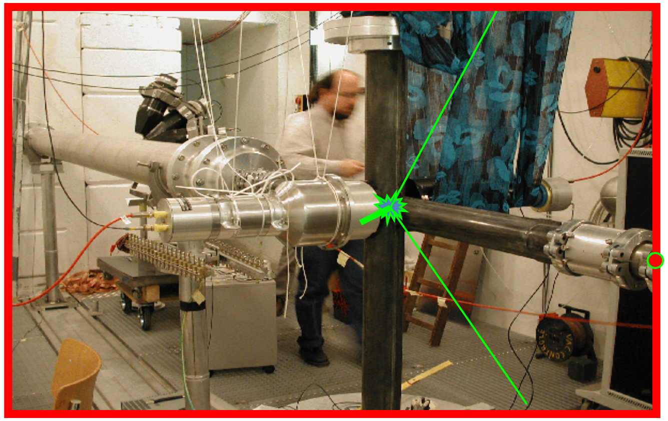


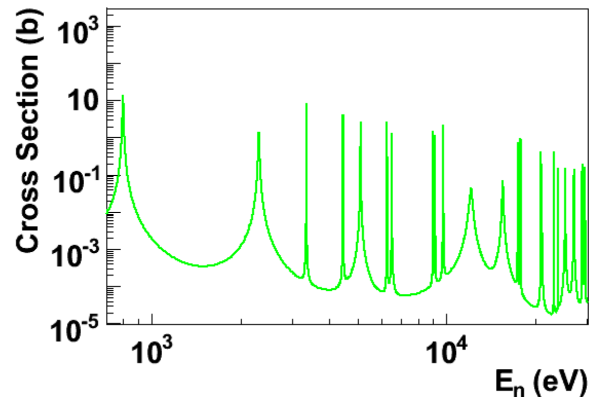
Very high instantaneous neutron flux
fundamental for studying small samples and radioactive isotopes

(n,γ) Total energy detection

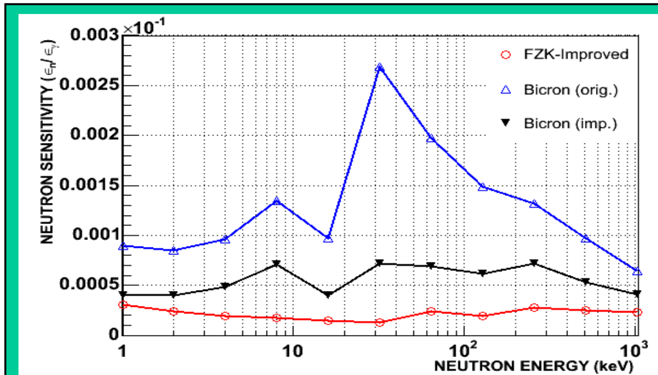
Improvements in the Experimental Setup & Data Analysis

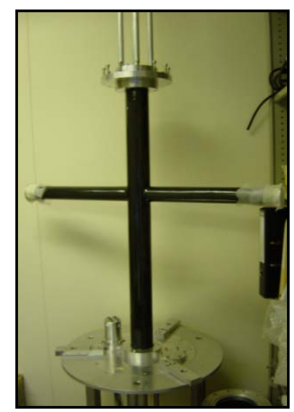
- Lowest neutron sensitivity ➡ No neutron background corrections !





(n,γ)

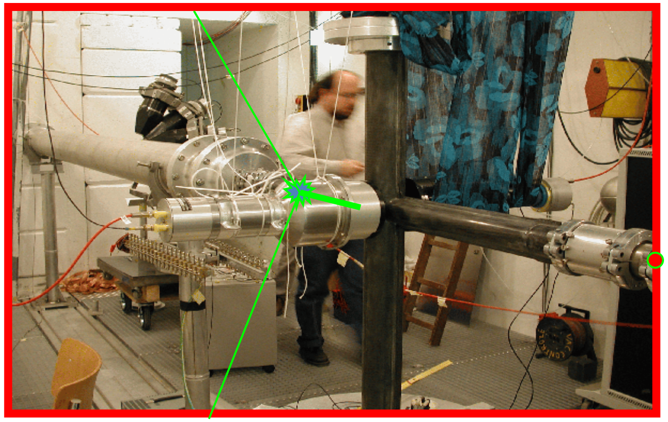


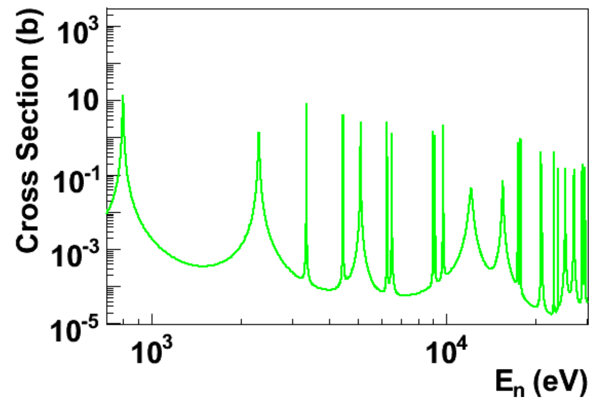


(n,γ) Total energy detection

Improvements in the ExperimentalSetup & Data Analysis

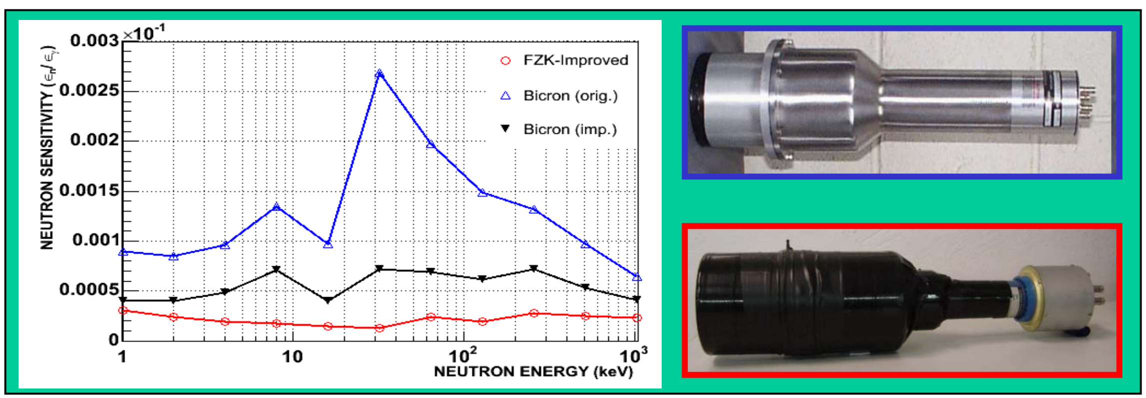
- Lowest neutron sensitivity ➡ No neutron background corrections !





(n,n)

(n,γ)



Zr measurements

Zr isotope samples

Sample	Isotopic content (%)					
	^{90}Zr	^{91}Zr	^{92}Zr	^{93}Zr	^{94}Zr	^{96}Zr
^{90}Zr	97.7	0.87	0.6	-	0.67	0.16
^{91}Zr	5.43	89.9	2.68	-	1.75	0.24
^{92}Zr	4.65	1.62	91.4	-	2.03	0.3
$^{93}Zr^*$	*1.5*	*19.0*	*20.0*	*20.0*	*20.0*	*19.0*
^{94}Zr	4.05	1.18	1.93	-	91.8	1.04
^{96}Zr	19.41	5.21	8.2	-	8.68	58.5

Admixture: Hf, Na, Mg, Al ...

* Radio isotope ($T_{1/2}$ =1.5x10^6 year)

Zr measurements @ n_TOF

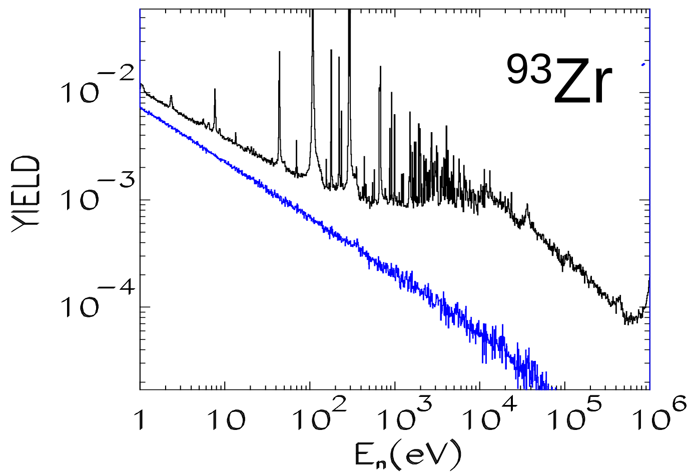
	^{90}Zr	^{91}Zr	^{92}Zr	^{93}Zr	^{94}Zr	^{96}Zr	^{197}Au	Pb
Mass (g)	2.717	1.404	1.349	4.88	2.015	3.398	1.871	3.895
Thickness (cm)	0,127	0,065	0,062	0,37	0,091	0,151	0.025	0.09
Chemical form	ZrO_2	ZrO_2	ZrO_2	ZrO_2	ZrO_2	ZrO_2	Metal	Metal
Enrichment (%)	97.7	89.9	91.4	*20.0*	91.8	58.5	100	Nat.

Samples 2.2 cm in diameter, 1 mm thick
Stable Zr isotopes encapsulated in 0.2 mm Al can
^{93}Zr isotope encapsulated in 0.2 mm Al + 0.2 mm Ti

Chemical form: ZrO_2

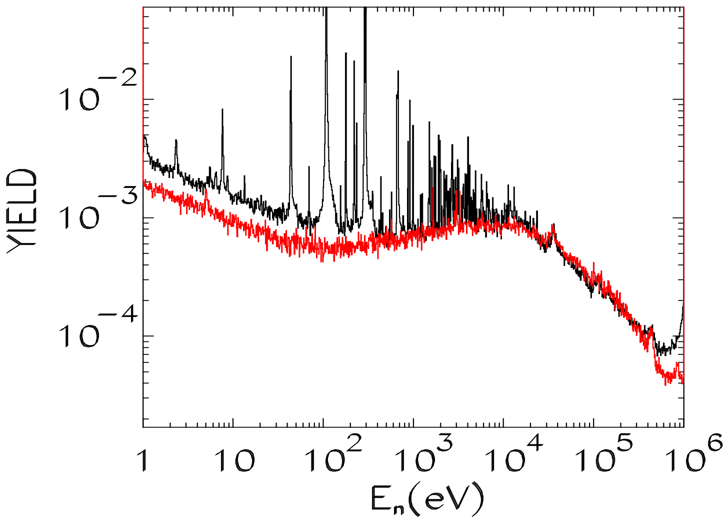
^{93}Zr isotope activity 92.5 MBq

Results - ^{93}Zr yield



raw Yield

Natural radioactivity of the sample

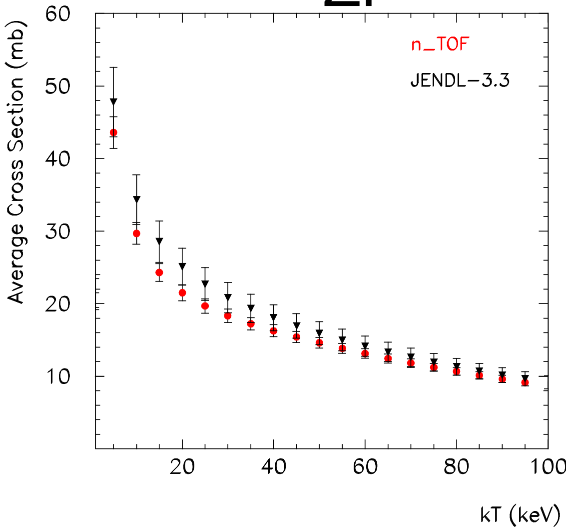


Yield – nat. radioactivity of the sample

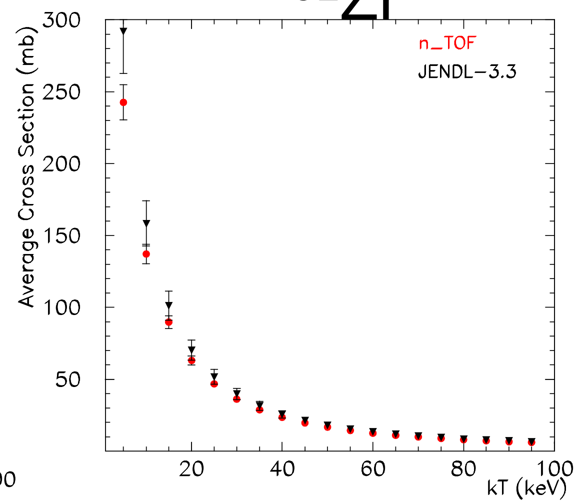
overall background

MACS: results

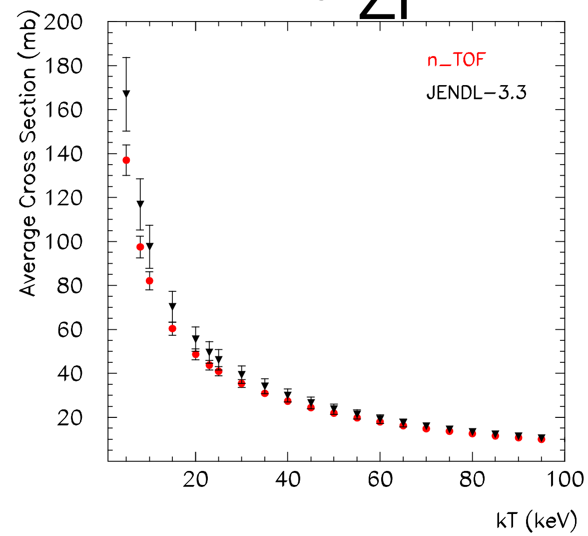
^{90}Zr



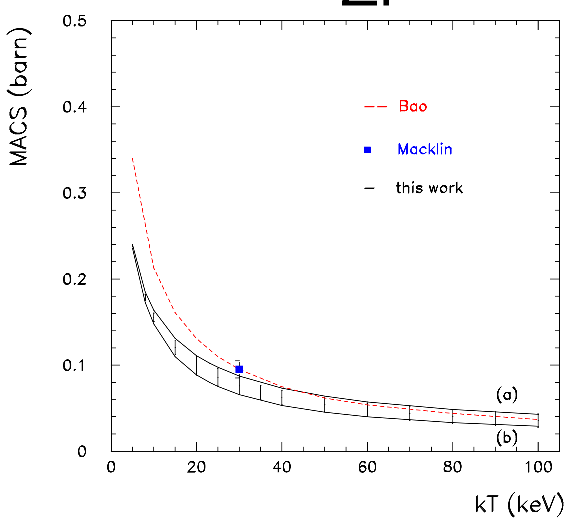
^{91}Zr



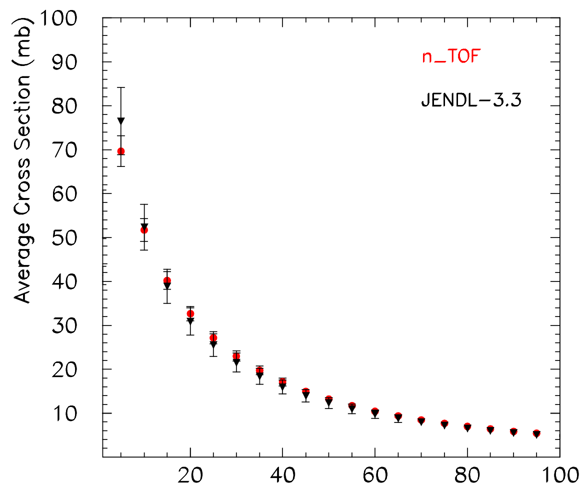
^{92}Zr



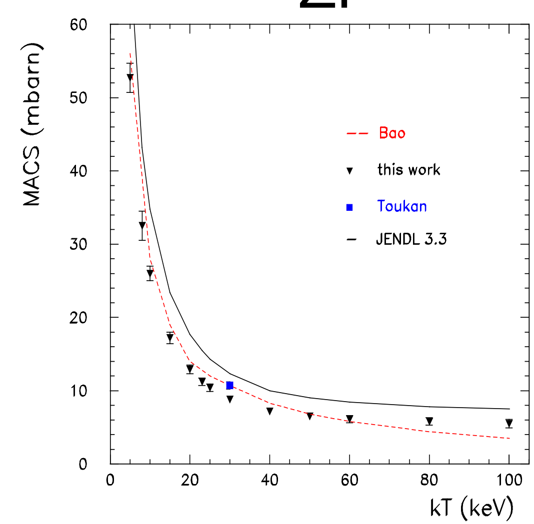
^{93}Zr



^{94}Zr



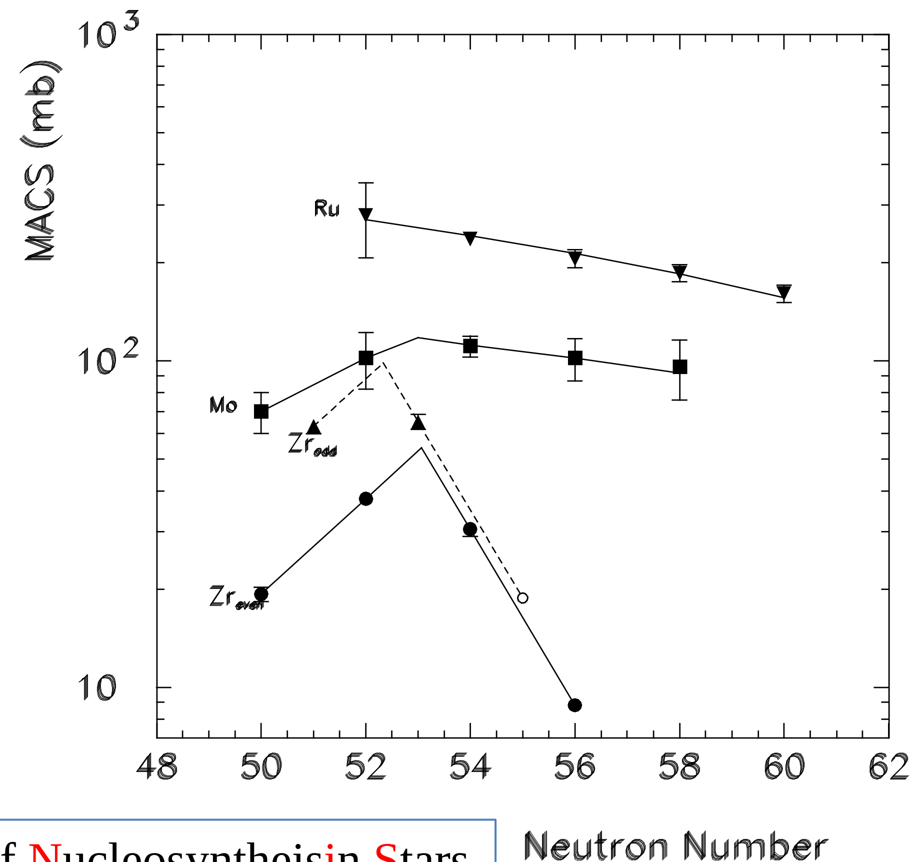
^{96}Zr



MACS:@ 30 keV

MACS in mbarn

Isotope	KADoNiS	n_TOF
^{90}Zr	21 ± 2	19.3 ± 0.9
^{91}Zr	60 ± 8	63 ± 4
^{92}Zr	34 ± 6	38 ± 3
^{93}Zr	95 ± 10	**65.1 ± 3**
^{94}Zr	26 ± 1	30.5 ± 2
^{95}Zr	79	**18.9**
^{96}Zr	10.7 ± 0.5	8.9 ± 0.5



KADoNIS: Karlsruhe Astrophysical Database of Nucleosyntheisin Stars

Astrophysical implication: Abundances

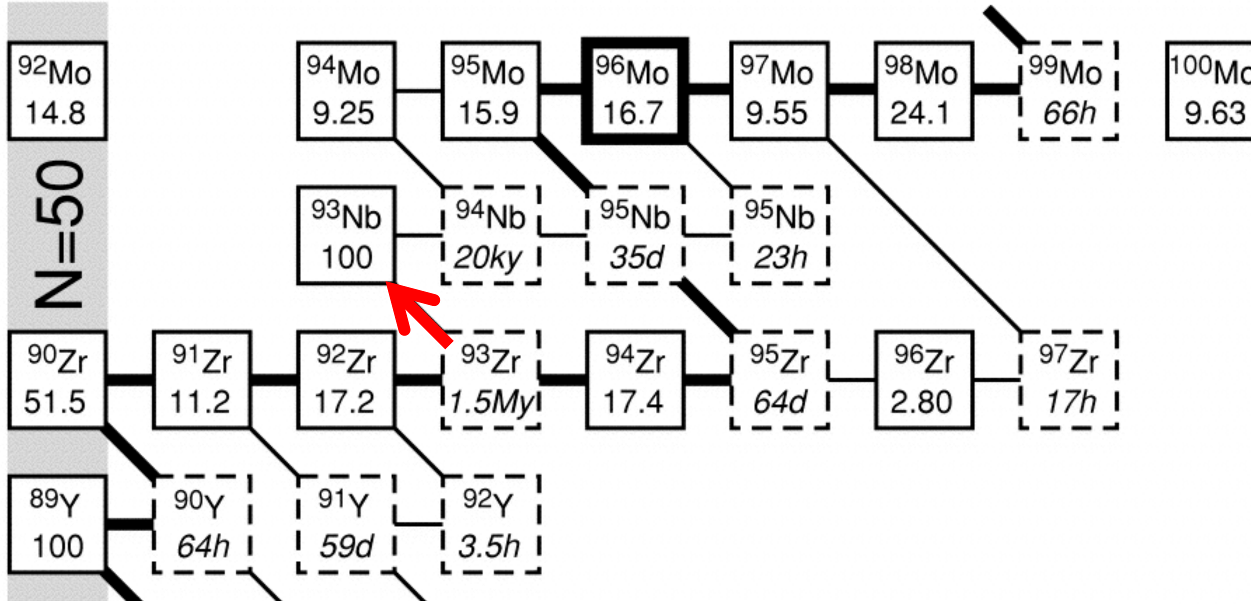
Curtsey of R. Gallino and S. Bisterzio

Nucleus	$N_\odot$ Normalized to $N(Si)=10^6$ atoms	$N_s/N_\odot$ % Old MACS	$N_s/N_\odot$ % n_TOF MACS
^{90}Zr	5.546	0.789	0.844
^{91}Zr	1.21	1.066	1.024
^{92}Zr	1.848	1.052	0.981
^{94}Zr	1.873	1.217	1.152
^{96}Zr	0.302	0.842	0.321

Solar abundances, $N_\odot$, from Lodders 2009, accuracy 10%

The s-abundances, N_s, are calculated using the TP stellar model for low mass AGB star (1.5 - 3 $M_\odot$).
Old MACS are from the KADoNiS data base 2008. Since 2009 the databases has been update at the new n_TOF data, as the new data are released.

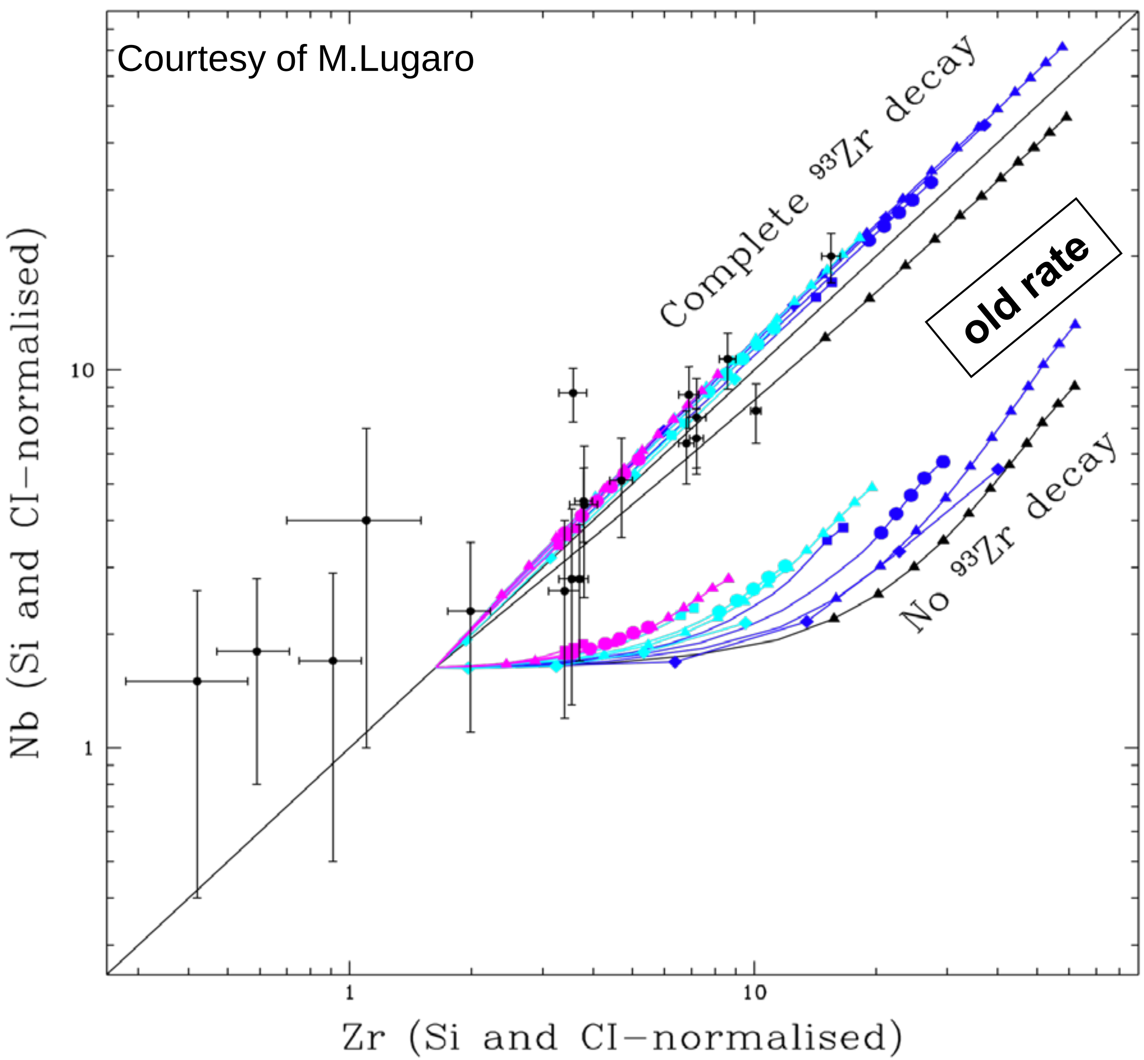
Astrophysical implication: Zr/Nb



A lower ^{93}Zr(n,γ) value means that more ^{93}Zr is produced. After radiogenic decay of ^{93}Zr more Nb will result.

The final result is ~50% more Nb!

Elemental Nb and Zr abundances in SiC



Mass, Metallicity

◇ 1.8, 0.01 ~ 0.7 $Z_\odot$

△ 3, 0.01 ~ 0.7 $Z_\odot$

○ 3, 0.02 ~ 1.5 $Z_\odot$

□ 3, 0.03 ~ 2 $Z_\odot$

$M_{mix}(M_\odot)$

0.002

0.0005

0.0002

With the new ^{93}Zr(n,γ) cross section the problem is solved.

Zr publications

Neutron capture cross section of ^{90}Zr: bottleneck in the s-process reaction flow: G. Tagliente et al., PRC 77(2008)

Study of the ^{91}Zr(n,γ) reaction up to 26 keV: G. Tagliente et al., PRC 78(2008)

The ^{92}Zr(n,γ) reaction and its implications on stellar nucleosynthesis: G. Tagliente et al., PRC 81(2010)

Neutron capture on ^{94}Zr: Resonance parameters and Maxwellian-averaged cross sections: G. Tagliente et al., PRC 84(2011)

^{96}Zr(n,) measurement at the n_TOF facility at CERN: G. Tagliente et al., PRC accepted

Conclusion

- New neutron capture measurements on $^{90,91,92,93,94,96}Zr$ were done at n_TOF facility
- MACS calculated from the new data for most of the Zr isotopes are lower than the previous MACS
- MACS uncertainty improved by a factor 2
- The new MACSs work much better when used in the TP stellar model to calculate the s-process abundances, proving the validity of the model

THANKS