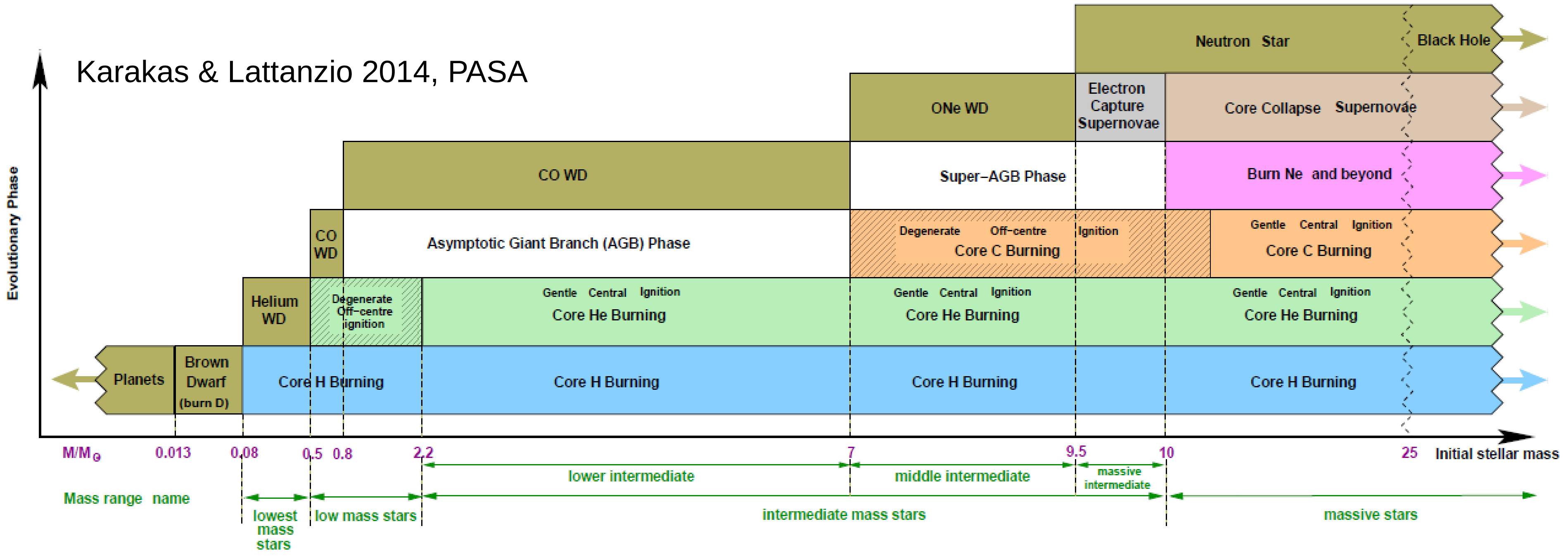
Explosive nucleosynthesis

Marco Pignatari

- @Konkoly Observatory, CSFK HUN-REN & MTA Centre of Excellence, Budapest, Hungary
- @BGI, Bayreuth University, Bayreuth, Germany

GIANTS2025, Catania, 3-4 July 2025

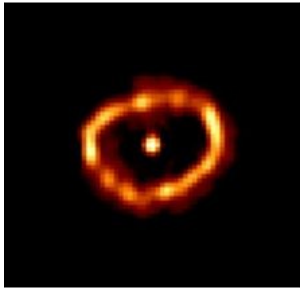
Stellar evolution: from low-mass star to massive stars



See Limongi's talk

Binary stars and else: another zoo

Novae

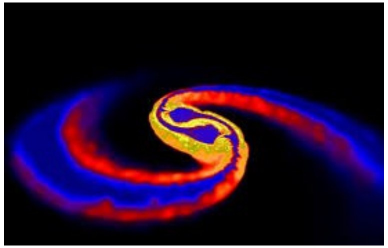


Nova Cygni 1992 (HST)

E ~ 10^{45} ergs
Mass ejected = 10^{-4} – 10^{-5} Msun
Nucl. contribution ~ C13, N15, O17

Jose & Hernanz 2007,
Casanova et al. 2011

NS-NS mergers

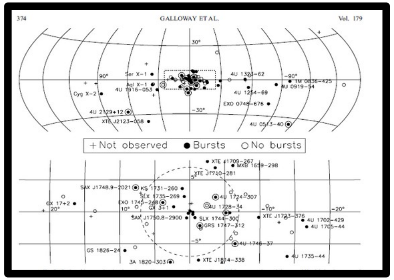


Neutron Star Mergers:
protons/neutrons ≤ 0.1

Source of gold?
Gravitational waves… LIGO

Cowan et al. 2021
Rev of Mod Phys

X-ray binaries



Galloway et al. 2008

X-ray bursts
E ~ 10^{39} ergs
Mass ejected = ?
Nucl. contribution ?
p nuclei ^{92,94}Mo and ^{96,98}Ru?

Schatz et al. 2001

… and many more… SNIa SD and DD scenario, R Crb stars, etc

See Cescutti's talk

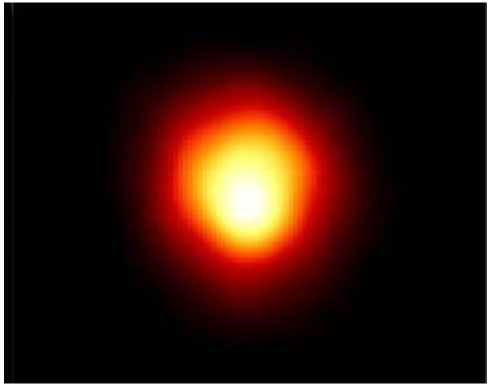
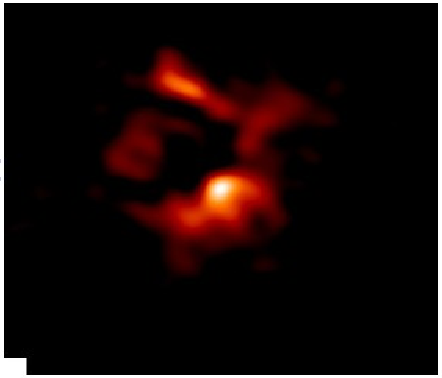


Image: A. Dupree/CFA/R. Gilliland/STScI/NASA/ESA

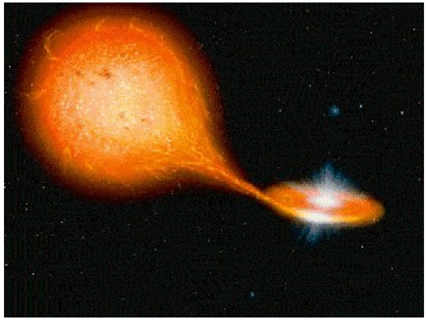
Betelgeuse (α-Ori):
~ *19* M_{sun}
~ *650 ly*
~ *1180* R_{sun}

.....

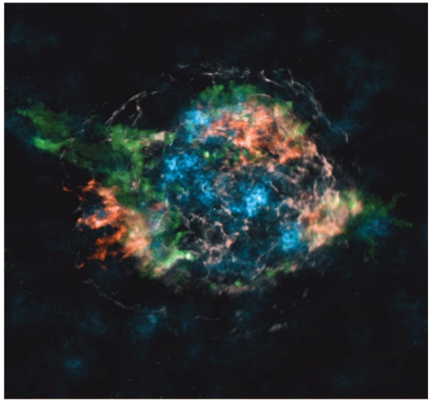
CWLeo
(IRC+10216)
~2-3 M_{sun}
~ 400 lyr
~ 250 R_{sun}



Tuthill et al. 2000, A&A, Keck Telescope

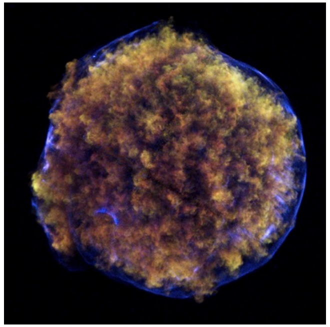


Artist conception of the WD and the binary system



Grefenstette et al. 2014, Nature (NuSTAR data)

CCSN: Cas A
~ 11000 lyr
~ 300 years ago



SNIa: Tycho's supernova (B Cas)
~ 9000 lyr
~ observed in 1572

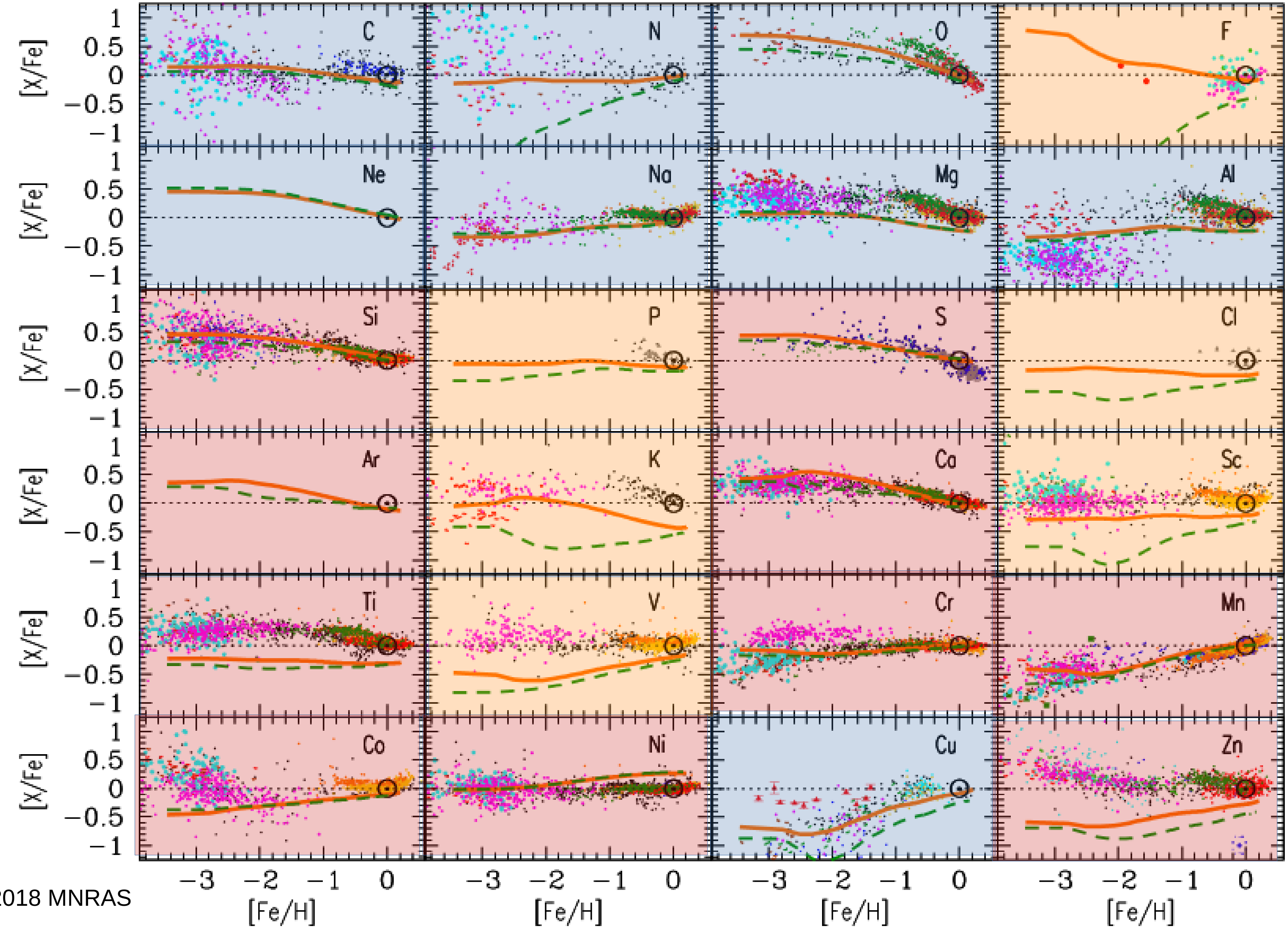
Chandra X-ray telescope +

Stellar Yields For GCE:

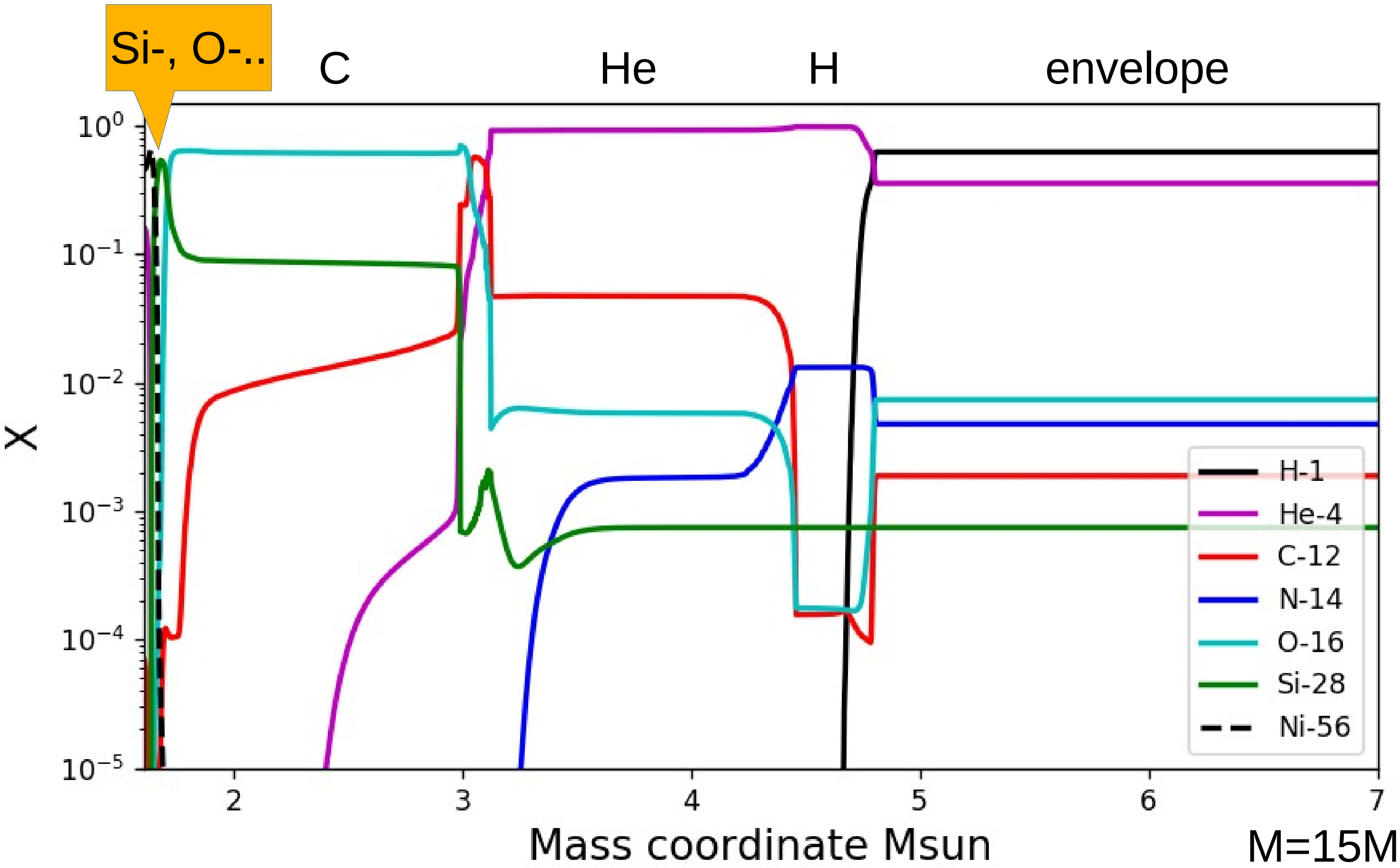
Production during explosion

Mixed or controversial

Mostly hydrostatic/ not explosive production



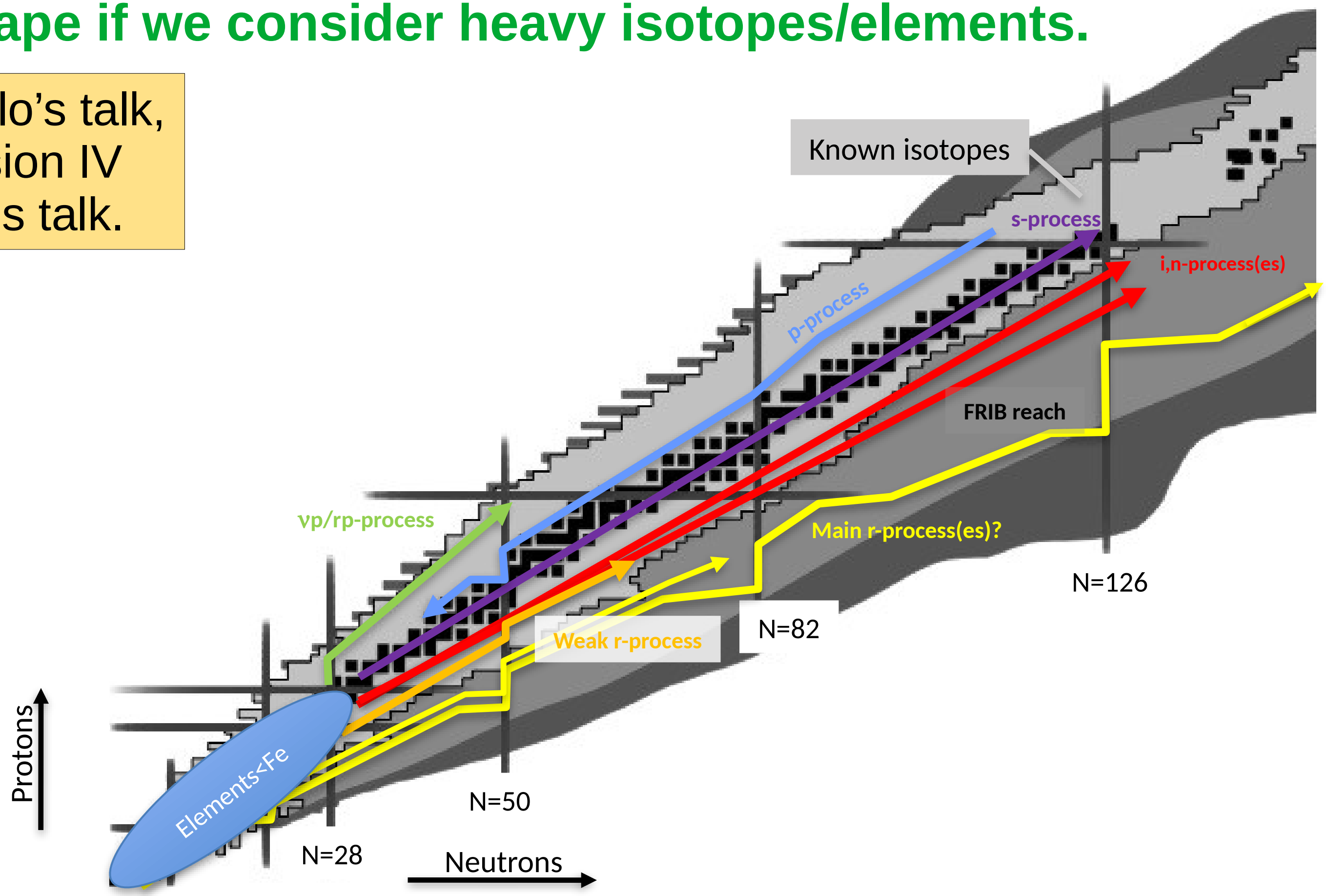
Prantzos+ 2018 MNRAS



M=15Msun, Z=0.02
Ritter+2018 MNRAS
MESA progenitor
Fryer+12 explosion

Landscape if we consider heavy isotopes/elements.

See Cristallo's talk, the all session IV and Spelta's talk.



Schematics from H. Schatz @ MSU

CCSNe vs SNIa contributions: context

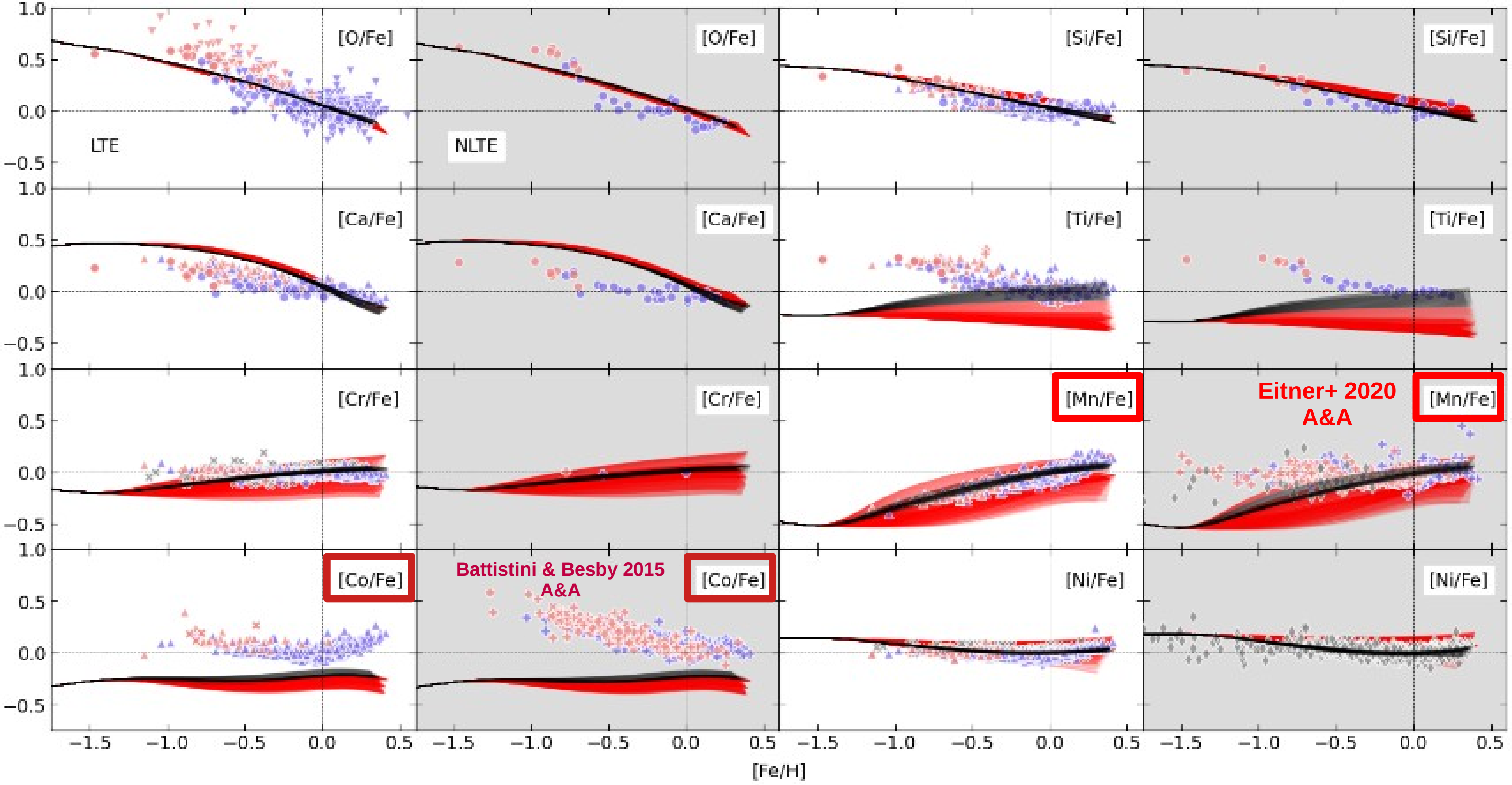
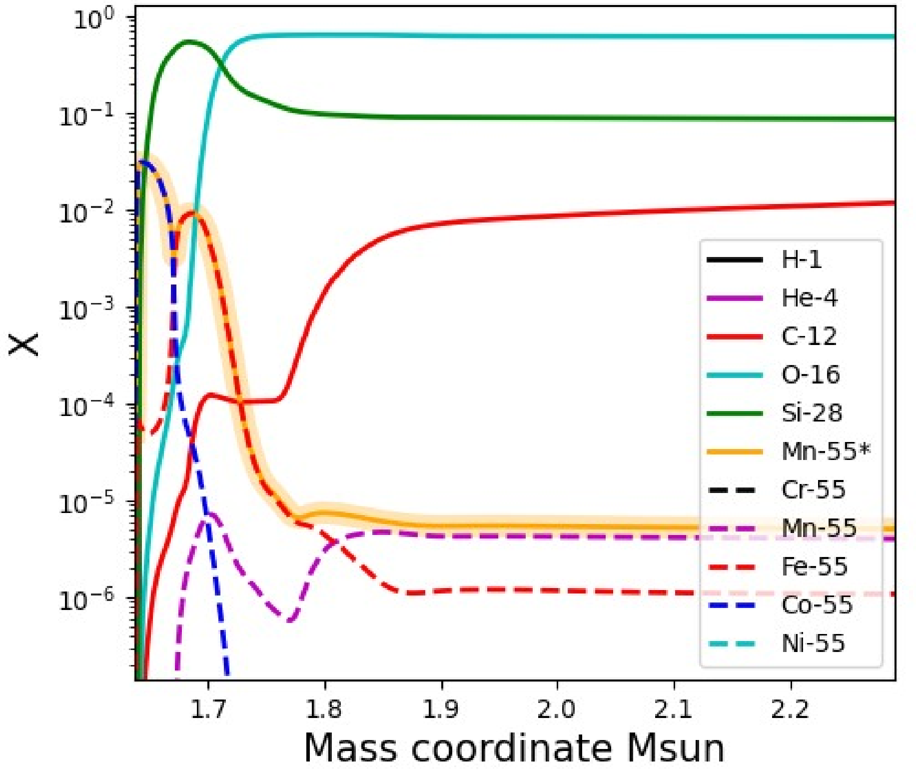


Fig. A.2. Same as Fig. A.1, but for LC18 CCSN yields.

Trueman+ 2025, A&A 696



M=15Msun, Z=0.02
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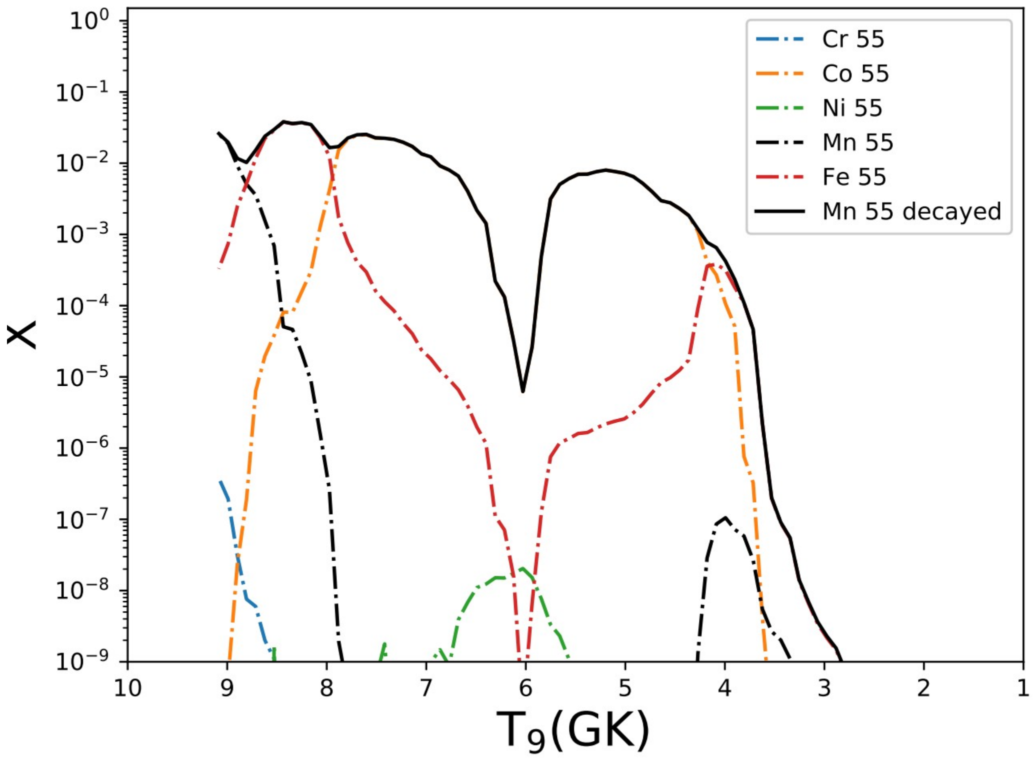
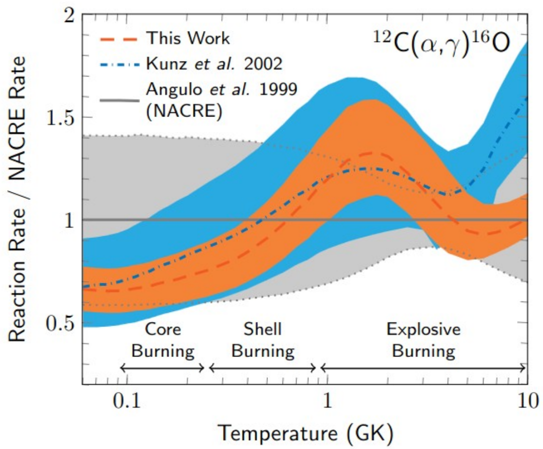


SNIa, Ch mass SD
Keegans+ 2023 ApJS 268
Townsley 2D explosion
Z=0.014

What do we need to know to have robust predictions for the abundance production in CCSNe?

Many talks today and tomorrow: C12+C12, Ne22+α, C12(α,γ), N14(p,γ)



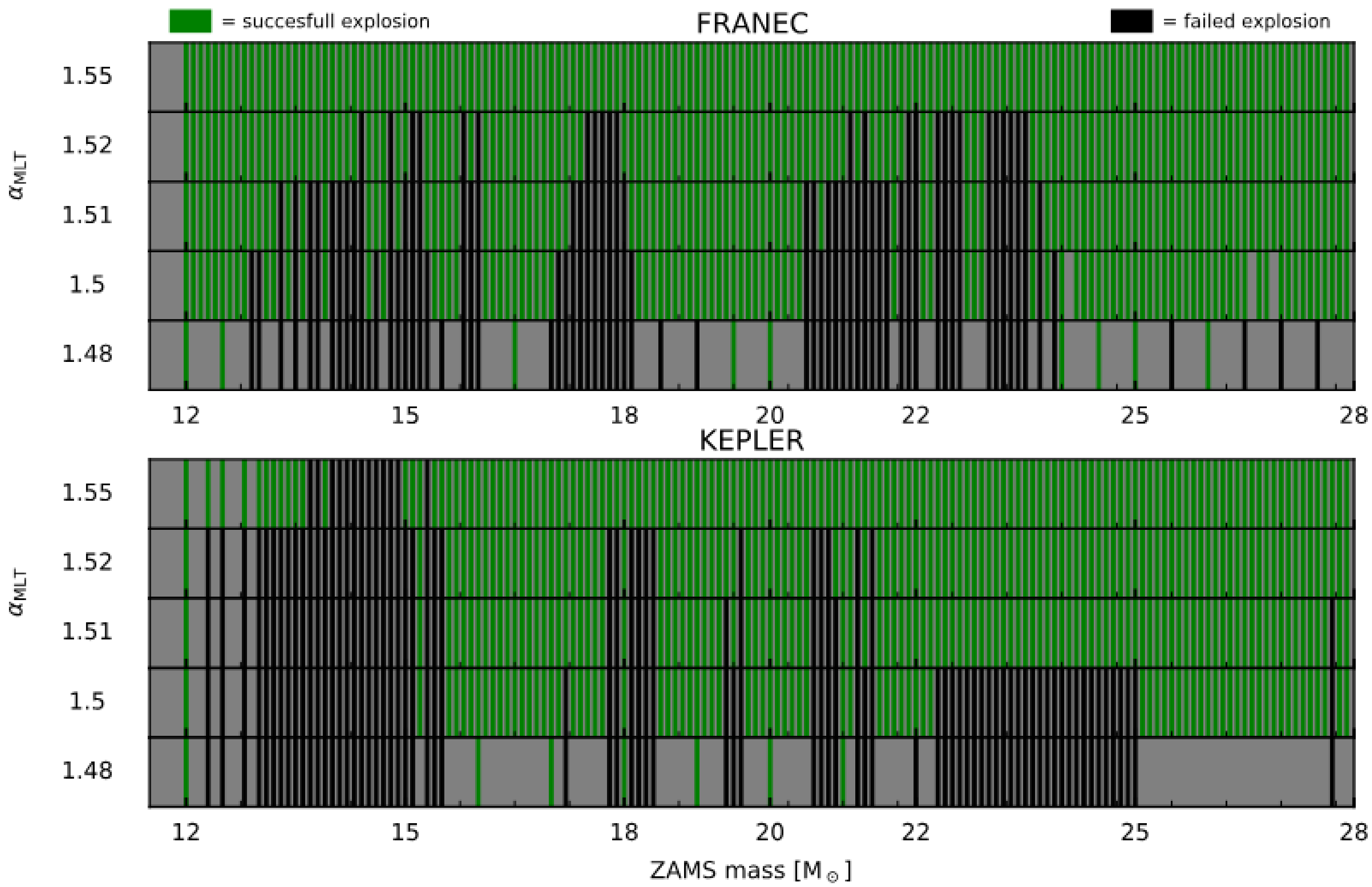
(1) Updated nuclear reaction rates
(e.g., deBoer et al. 2017 RvMP)

(2) stellar progenitor structure
(e.g., Andrassy et al. 2020 MNRAS)

(3) CCSN engine
(e.g., Burrows et al. 2021, Nature)

See Limongi and Roberti talks

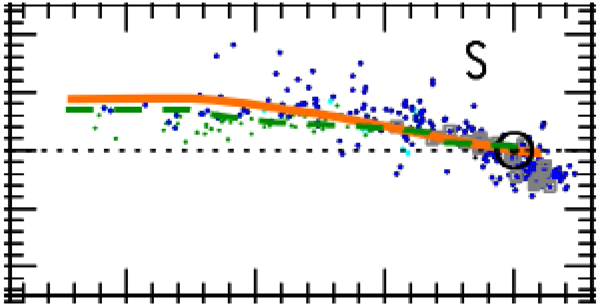
(4) SN shock propagation
(e.g.,Wongwathanarat et al. 2015 A&A)



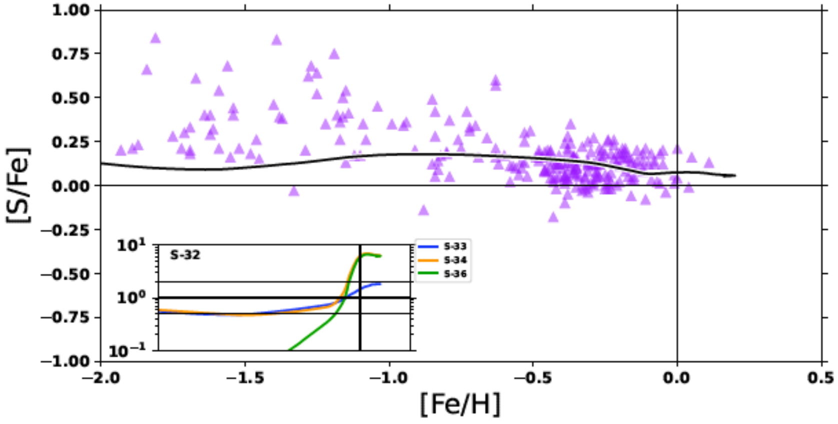
= succesfull explosion
FRANEC
= failed explosion
α_{MLT}
1.55
1.52
1.51
1.5
1.48
12
15
18
20
22
25
28
KEPLER
α_{MLT}
1.55
1.52
1.51
1.5
1.48
12
15
18
20
22
25
28
ZAMS mass [$M_\odot$]

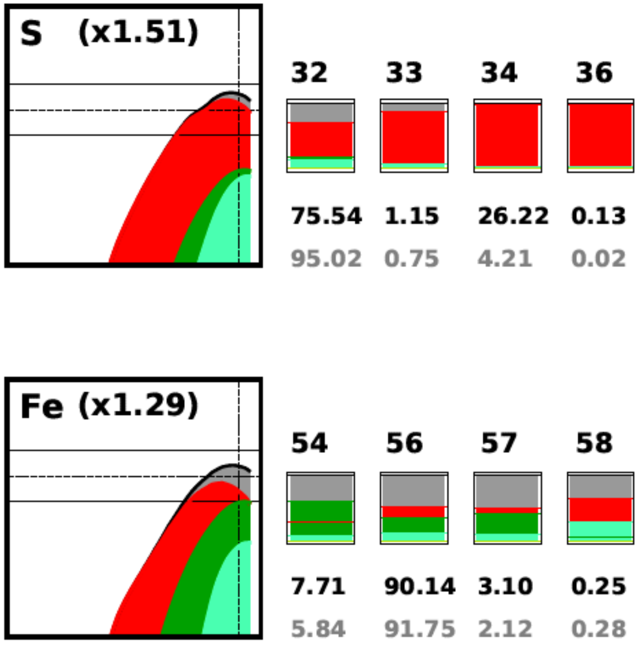
What about the isotopes?

^{14}O 1.18 m β^+	^{15}O 2.04 m β^+	^{16}O 99.762 0.038 mb	^{17}O 0.038	^{18}O 0.2 0.00886 mb
^{13}N 9.96 m β^+	^{14}N 99.634 0.041 mb	^{15}N 0.366 0.0058 mb	^{16}N 7.13 s β^-	^{17}N 4.17 s β^-
^{12}C 98.89 0.0154 mb	^{13}C 1.11 0.021 mb	^{14}C 5.70 ka 0.00848 mb, β^-	^{15}C 2.45 s β^-	^{16}C 747.00 ms β^-

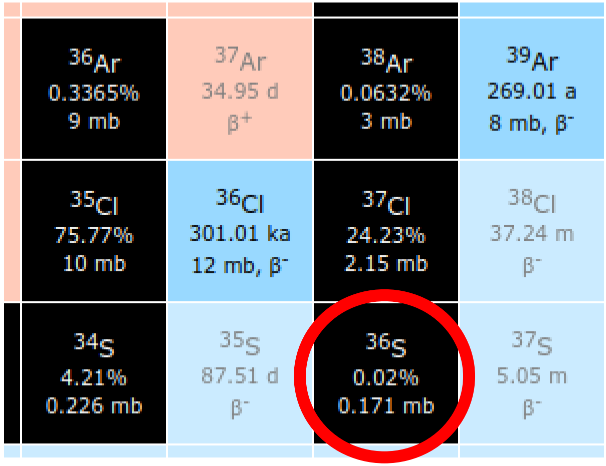


Prantzos+ 2018 MNRAS





Reifarth+ 2000 ApJ 528
The $^{34}S(n,\gamma)^{35}S$ rate made life really hard for ^{36}S.



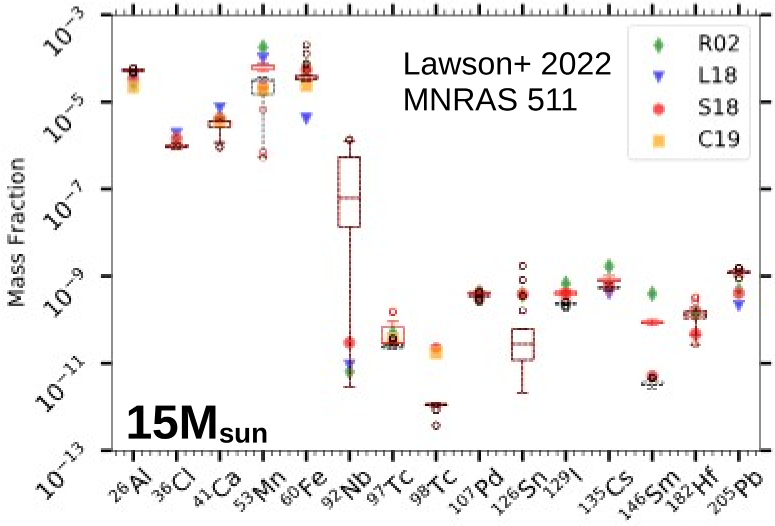
Preliminary: No statistics yet!

Short-lived-radioactive isotopes ($T_{1/2}$ ~ 0.1-100 million years) observed in the Early Solar System (Lugaro+ 2018 PrPNP 102)

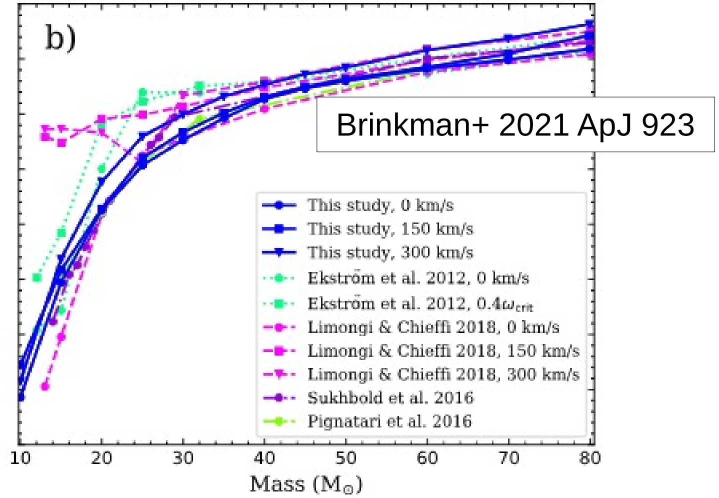
GCE contribution may be relevant for species with $T_{1/2} \geq 2$ Myr

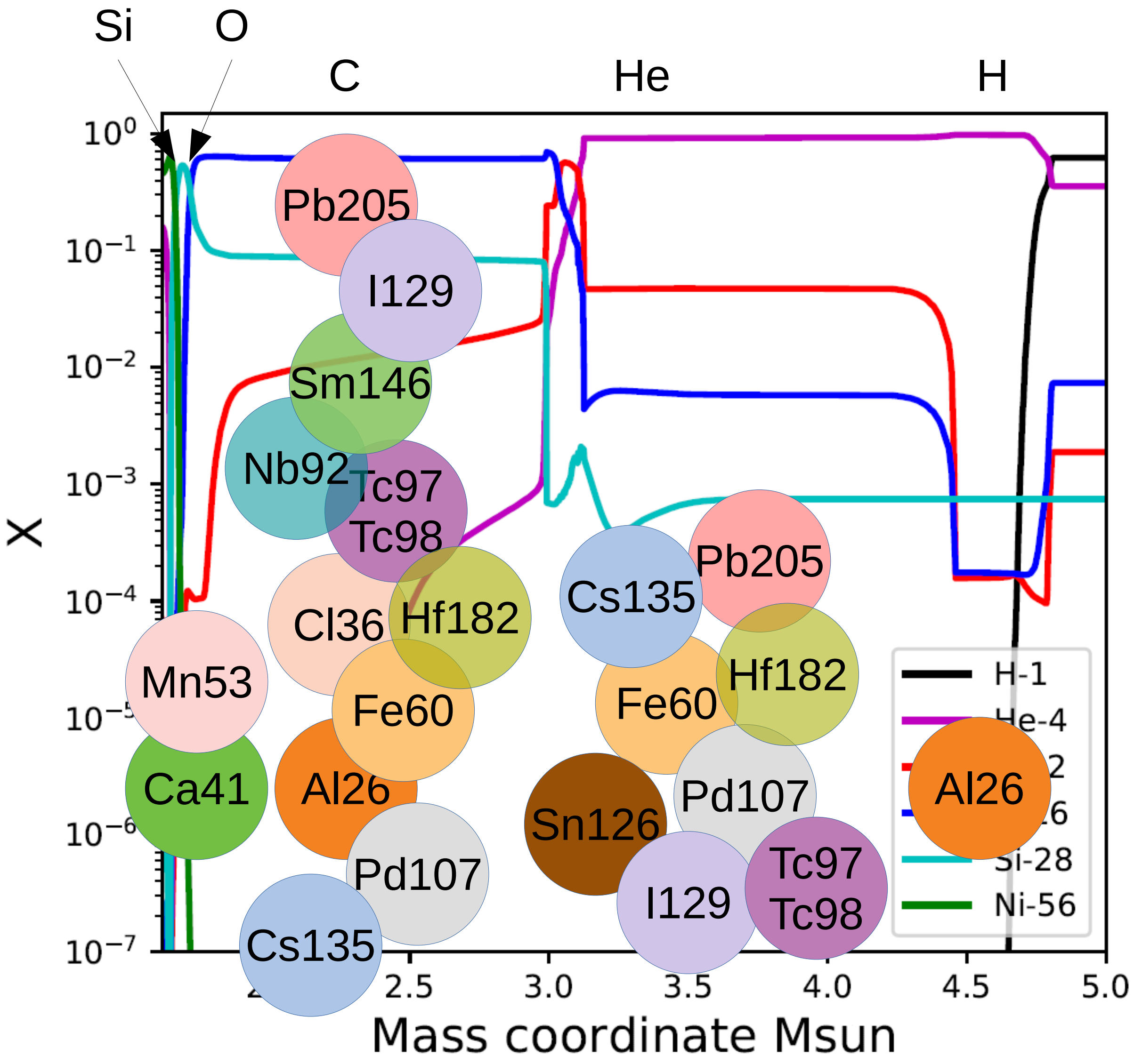
SLR	Daughter	Reference	$T_{1/2}$ (Myr)
^{26}Al	^{26}Mg	^{27}Al	0.72
^{36}Cl	^{36}S	^{35}Cl	0.30
^{41}Ca	^{41}K	^{40}Ca	0.099
^{53}Mn	^{53}Cr	^{55}Mn	3.7
^{60}Fe	^{60}Ni	^{56}Fe	2.6
^{92}Nb	^{92}Zr	^{92}Mo	34
^{97}Tc	^{97}Mo	^{98}Ru	4.2
^{98}Tc	^{98}Ru	^{98}Ru	4.2
^{107}Pd	^{107}Ag	^{108}Pd	6.5
^{126}Sn	^{126}Te	^{124}Sn	0.23
^{129}I	^{129}Xe	^{127}I	15
^{135}Cs	^{135}Ba	^{133}Cs	2.3
^{146}Sm	^{142}Nd	^{144}Sm	68
^{182}Hf	^{182}W	^{180}Hf	8.9
^{205}Pb	^{205}Tl	^{204}Pb	17

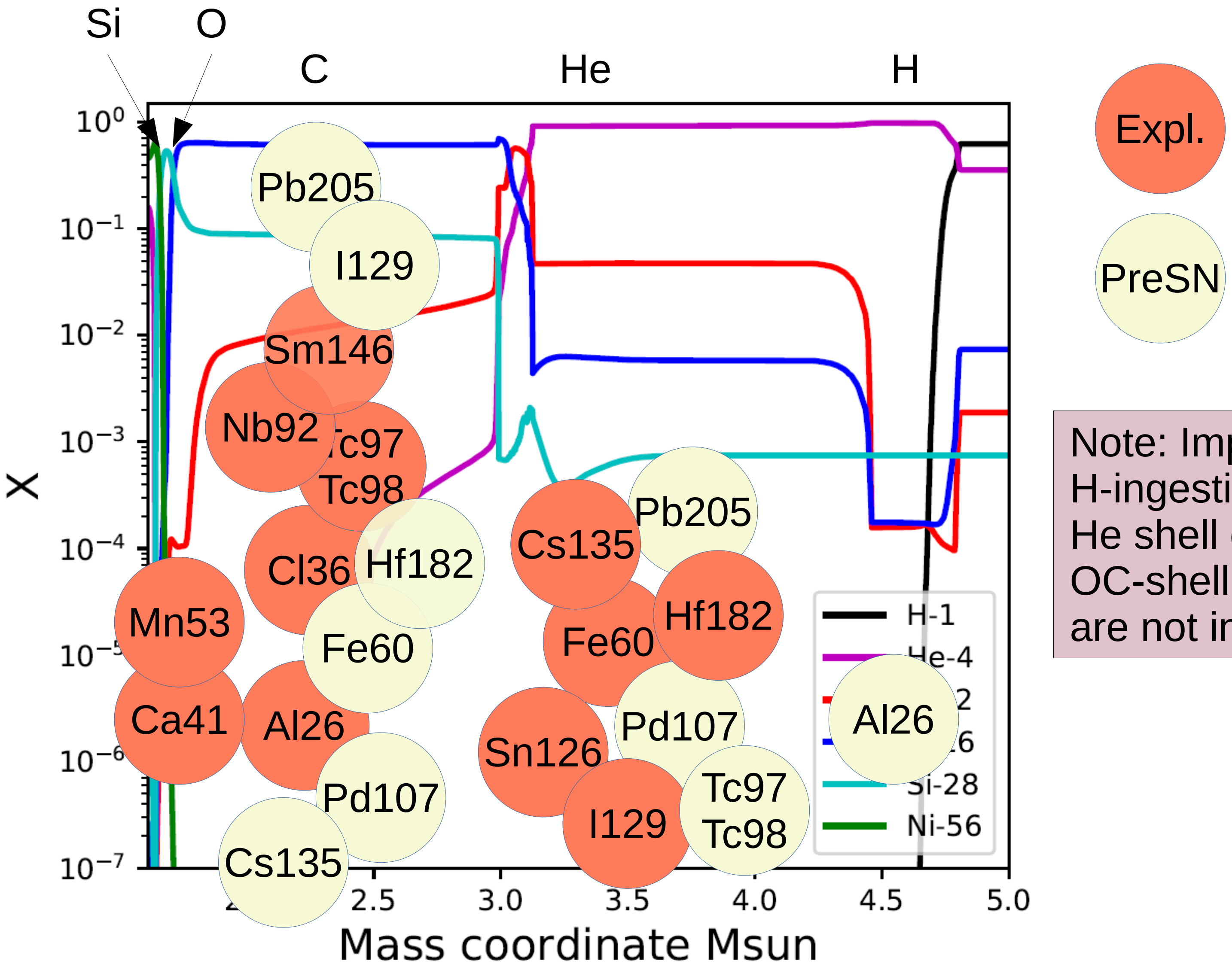
SLRs yields variation from CCSNe



SLR Al26 yields from massive star winds

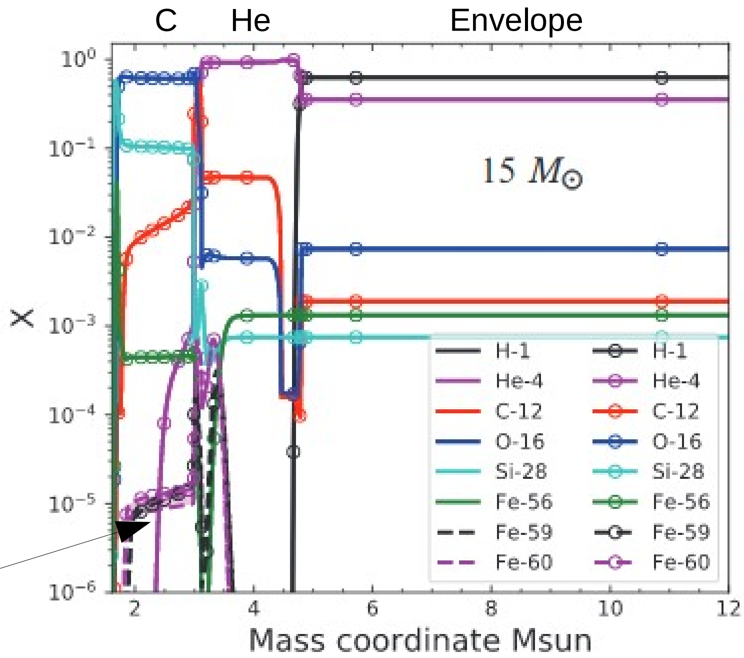



Si
O
C
He
H
X
Mass coordinate Msun
2.5
3.0
3.5
4.0
4.5
5.0
H-1
Ni-56
Pb205
I129
Sm146
Nb92
Tc97
Tc98
Cl36
Hf182
Mn53
Fe60
Ca41
Al26
Pd107
Cs135
Sn126



Note: Impact of H-ingestion in the He shell or OC-shell merger are not included!

Impact of the $^{59}Fe(n,\gamma)^{60}Fe$: Yan+ MP, ML, 2021 ApJ 919

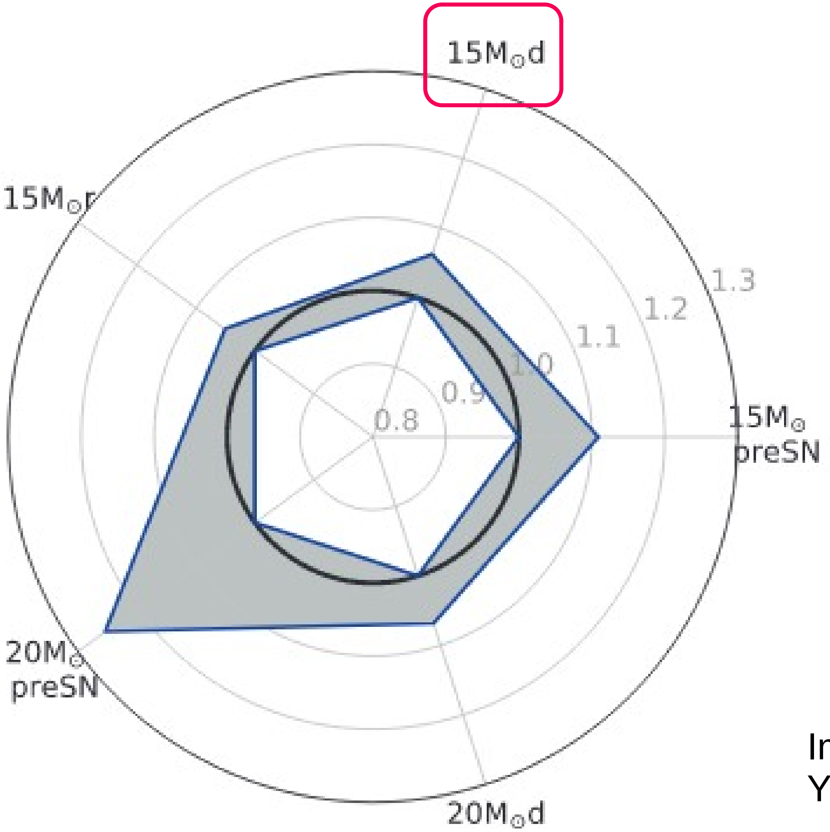


^{59}Ni 75.99 ka 87 mb, β+	^{60}Ni 26.223 30 mb	^{61}Ni 1.14 82 mb	^{62}Ni 3.634 22.3 mb	^{63}Ni 100.11 a 31 mb, β-
^{58}Co 70.86 d β+	^{59}Co 100 38 mb	^{60}Co 5.27 a β-	^{61}Co 1.65 h β-	^{62}Co 1.50 m β-
^{57}Fe 2.119 40 mb	^{58}Fe 0.282 12.1 mb	^{59}Fe 44.50 d β-	^{60}Fe 1.50 Ma β-	^{61}Fe 5.98 m β-
^{56}Mn 2.58 h β-	^{57}Mn 1.42 m β-	^{58}Mn 3.00 s β-	^{59}Mn 4.59 s β-	^{60}Mn 51.00 s β-
^{55}Cr 3.50 m β-	^{56}Cr 5.94 m β-	^{57}Cr 21.10 s β-	^{58}Cr 7.00 s β-	^{59}Cr 460.00 ms β-

2 supernova models shown here.
Total of 9 complete CCSN models made for the study

Fe60 in CCSNe:
e.g., Timmes+ 1995, Limongi+2006, Tur+ 2010, Jones+ 2019

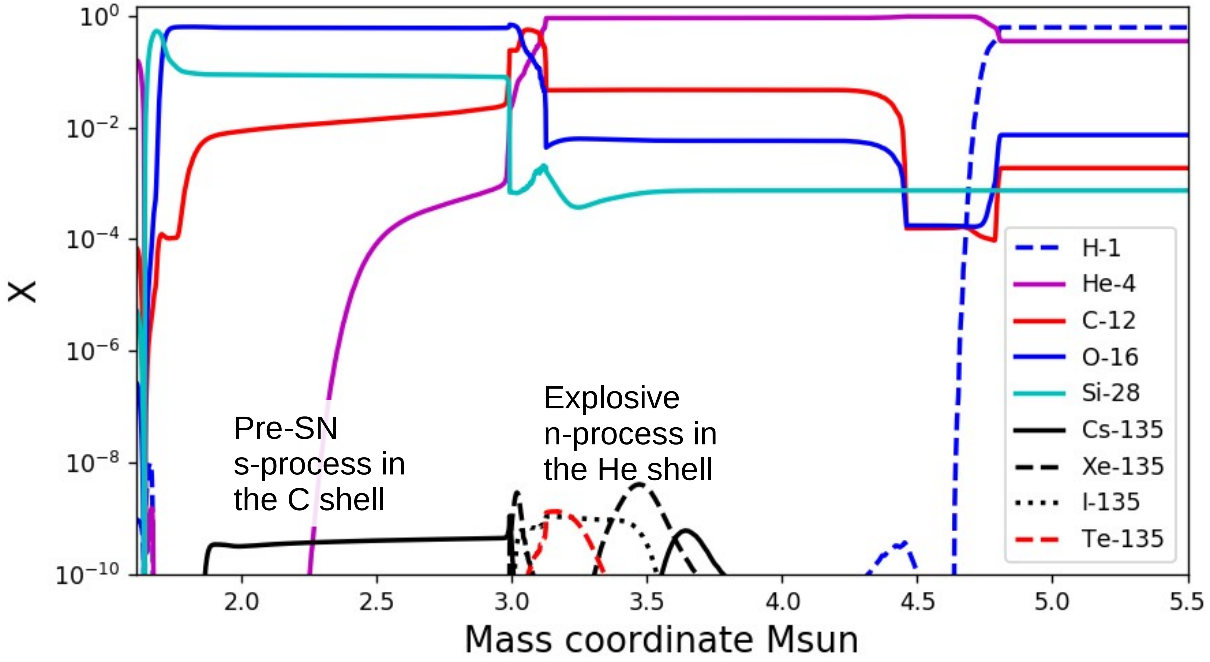
Variation of the ^{60}Fe produced, tested in 5 different models using 3 $^{59}Fe(n,\gamma)^{60}Fe$ rates.



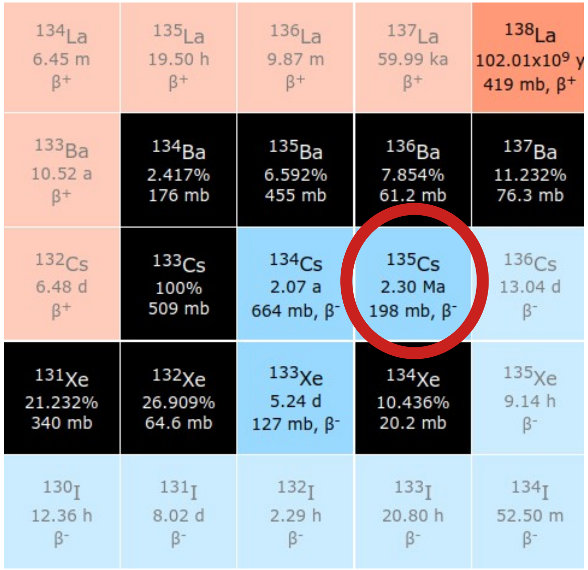
Impact of the new Fe59(n,γ)Fe60 on <u>Fe60 yields</u>:
Yan+ 2021, ApJ 919

See Spyrou+ 2024 NatCo 15 for a new Fe59(n,γ)Fe60 rate

Neutron burst driven by the $^{22}Ne(\alpha,n)$ in explosive He-burning: ^{135}Cs (r-process SLR?!)



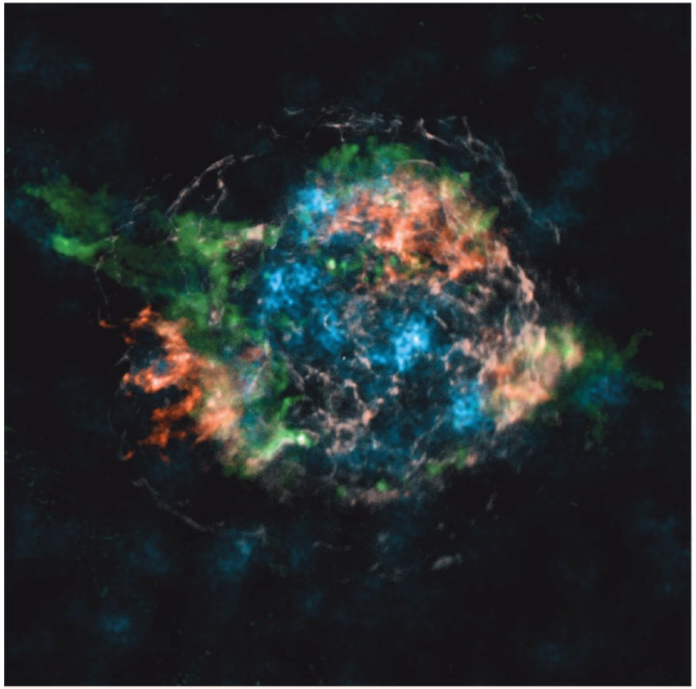
The n-process in CCSNe:
- Blake & Schramm 1976 ApJ
- Meyer+ 2000 ApJ
- Pignatari+ 2018 GeCoA



M=15Msun, Z=0.02
Ritter+2018 MNRAS
MESA progenitor
Fryer+12 explosion

Ti44 in CCSNe

CCSN remnant

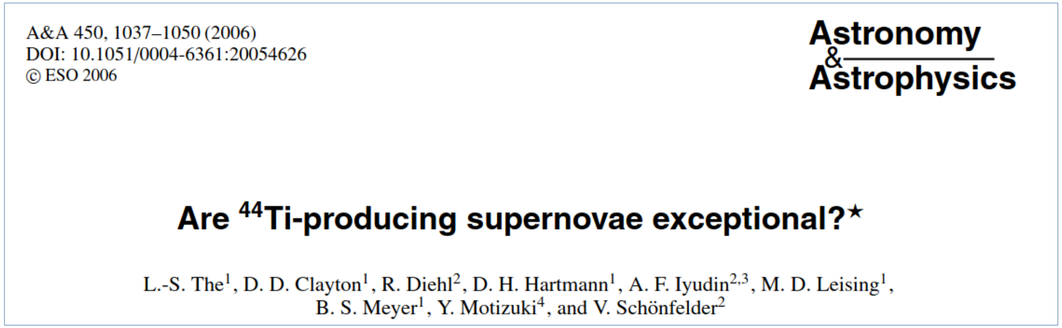


Grefenstette+ 2014, Nature
(NuSTAR data)

Cas A
11000 ly
~ 300 years ago

Red shows Fe
Blue is Ti
Green is Si

Ti44 production in CCSNe -
Some references:
Chieffi & Limongi 2017 ApJ
Wongwathanarat+ 2017 ApJ
Magkotsios+ 2010 ApJS



A&A 450, 1037–1050 (2006)
DOI: 10.1051/0004-6361:20054626
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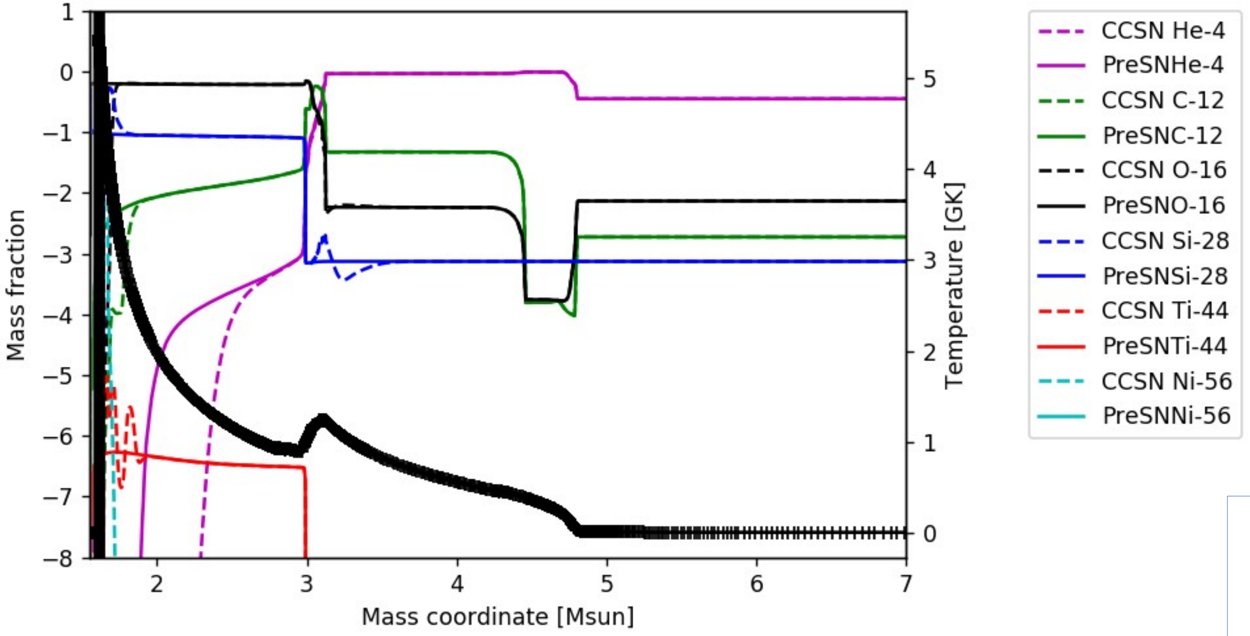
Astronomy & Astrophysics

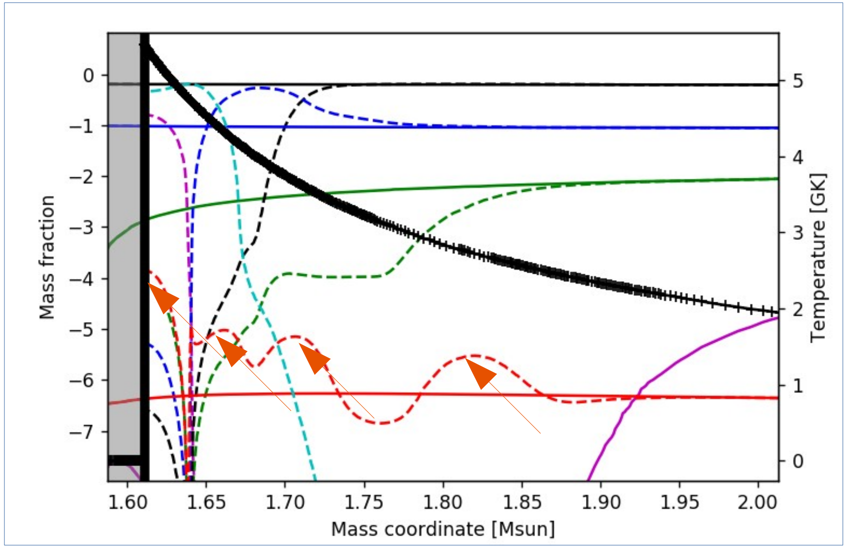
Are ^{44}Ti-producing supernovae exceptional?⋆

L.-S. The[1], D. D. Clayton[1], R. Diehl[2], D. H. Hartmann[1], A. F. Iyudin[2,3], M. D. Leising[1], B. S. Meyer[1], Y. Motizuki[4], and V. Schönfelder[2]

+ Impact from nuclear uncertainties:
e.g., Magkotsios+ 2010 ApJS

+ Multi-D vs 1D CCSN effects:
e.g., Sieverding et al. 2023 ApJL



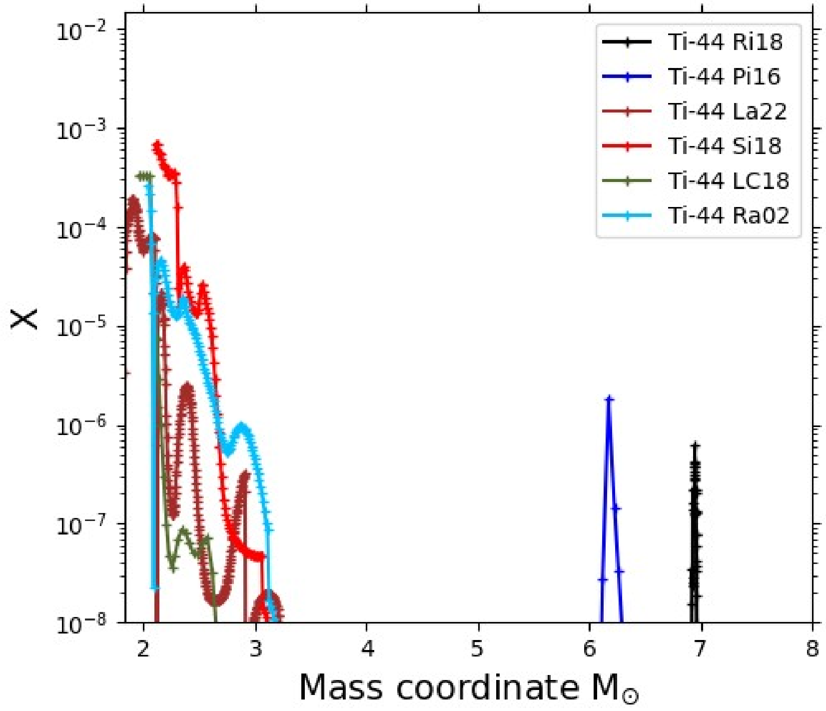


M=15Msun, Z=0.02
Ritter+ 2018 MNRAS

Stellar Interpretation of Meteoritic Data and PLotting for Everyone (SIMPLE): Isotope Mixing Lines for Six Sets of Core-Collapse Supernova Models

Marco Pignatari,[1,2,3] Mattias Ek,[4] Georgy V. Makhatadze,[5,6,1,2] Gábor G. Balázs,[1,2,7] Lorenzo Roberti,[1,2] Borbála Cseh,[8,2,7] Alessandro Chieffi,[9] Chris Fryer,[9] Falk Herwig,[9] Chiara Incollingo,[4] Thomas Lawson,[3] Marco Limongi,[9] Thomas Rauscher,[9] Maria Schönbächler,[4] Andre Sieverding,[9] Reto Trappitsch,[9] and Maria Lugaro[10,2,11,12]

SIMPLE tool (open source)
Pignatari+ 2025, in prep.



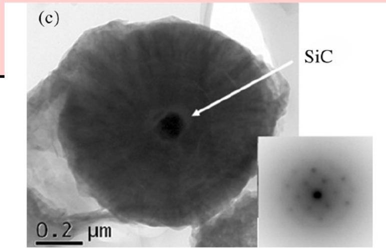
RI18: Ritter+ 2018; PI16: Pignatari+ 2016; LA22: Lawson+ 2022; SI18: Sieverdin+ 2018; LC18: Limongi&Chieffi 2018; RA02: Rauscher+ 2002.

ApJ submitted

Production of radioactive ^{22}Na in core-collapse supernovae: the Ne-E(L) component in presolar grains and its possible consequences on supernova observations

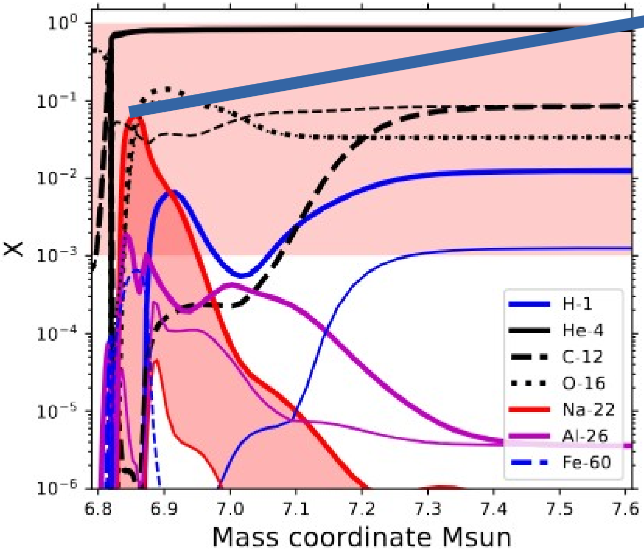
Marco Pignatari[1,2,3] Sachiko Amari[4] Peter Hoppe,[5] C. Fryer[6,7] S. Jones[8] A. Psaltis[9,10] A.M. Laird,[11] F. Herwig[12] L. Roberti[13,1,2,3] Thomas Siegert[14] and Maria Lugaro[1,2,15,16]

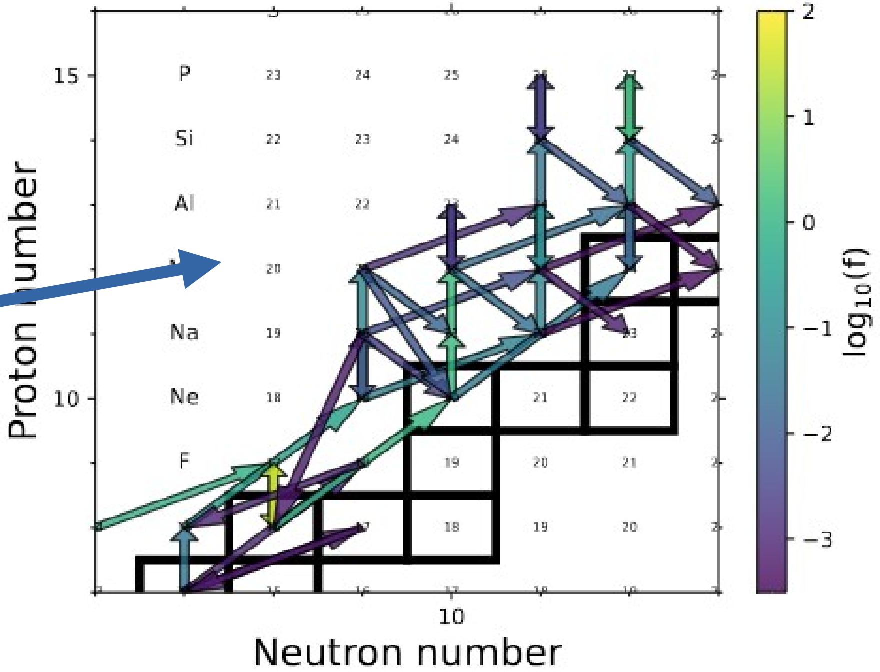
Ne-E(L) component in C-rich graphites LD grains (Amari+ 1990): A challenge for CCSNe models



Croat et al. 2010, AJ 139

^{22}Na
2.60 a
β^+



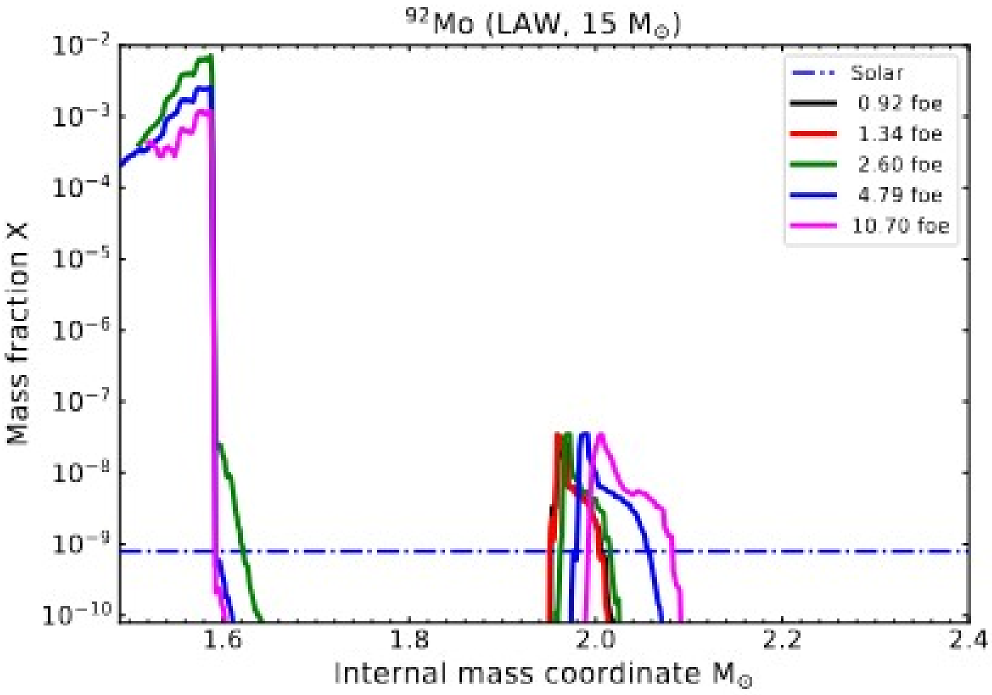


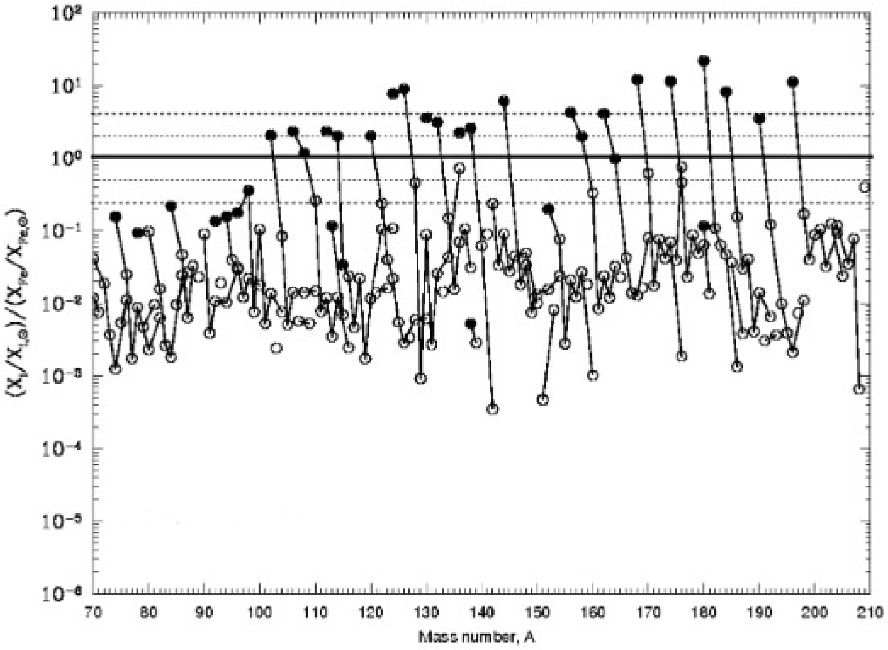
H-ingestion in the progenitor+CCSN

Pignatari+ 2015 ApJL

Impact on the SN light-curve, possibility to detect in gamma-ray emissions (1274.53 keV), etc

Activation of the γ-process in stars: CCSNe or SNIa?





Roberti+ 2023 A&AL
γ -process vs CCSNe setup

Battino+ 2020 MNRAS
γ -process in SD SNIa
(s+i-process seeds built in the accretion stage)

See Cristallo's talks

Conclusions

- Explosive nucleosynthesis does not make all elements and isotopes!
- CCSNe are the first sources of metals in the Galaxy. SNIa and other explosive sources are activated later, contributing to GCE
- Elements and isotopes: GCE of the isotopes is a powerful benchmark for models and nuclear physics
- The case of the SLRs in the Early Solar System (e.g., Fe60 and Cs135), of Ti44 and Na22.
- Beyond iron: the explosive γ-process.

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Advance Access publication 2023 July 21

The chemical evolution of the solar neighbourhood for planet-hosting stars

Marco Pignatari,[1,2,3,4,5★] Thomas C. L. Trueman,[1,3,4] Kate A. Womack,[3] Brad K. Gibson,[3,5] Benoit Côté,[1,4,5,6] Diego Turrini,[7,8,9] Christopher Sneden,[10] Stephen J. Mojzsis,[1,2,11] Richard J. Stancliffe,[4,12] Paul Fong,[3,4] Thomas V. Lawson,[3,4,13] James D. Keegans,[4,14] Kate Pilkington,[15] Jean-Claude Passy,[16] Timothy C. Beers[5,17] and Maria Lugaro[1,2,18,19]

- **16 authors**
- **5 PhD/young PDRA**

- **Target communities: nuclear astrophysics & planet formation/modeling**

Experimental Astronomy (2022) 53:225–278
https://doi.org/10.1007/s10686-021-09754-4

ORIGINAL ARTICLE

Exploring the link between star and planet formation with Ariel

Diego Turrini[1,2] · Claudio Codella[3] · Camilla Danielski[4] · Davide Fedele[2,3] · Sergio Fonte[1] · Antonio Garufi[3] · Mario Giuseppe Guarcello[5] · Ravit Helled[6] · Masahiro Ikoma[7] · Mihkel Kama[8,9] · Tadahiro Kimura[7] · J. M. Diederik Kruijssen[10] · Jesus Maldonado[5] · Yamila Miguel[11,12] · Sergio Molinari[1] · Athanasia Nikolaou[13,14] · Fabrizio Oliva[1] · Olja Panić[15] · Marco Pignatari[16,17,18] · Linda Podio[3] · Hans Rickman[19] · Eugenio Schisano[1] · Sho Shibata[7] · Allona Vazan[20] · Paulina Wolkenberg[1]

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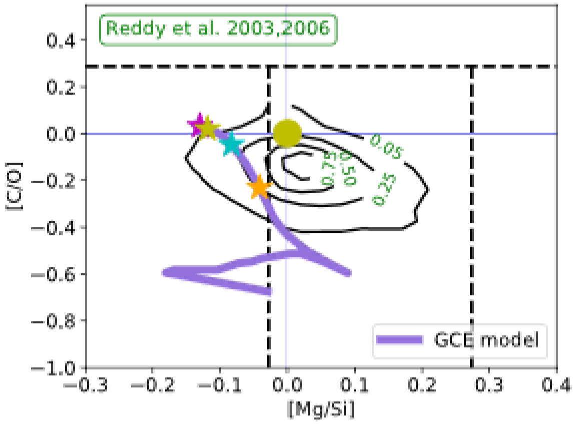
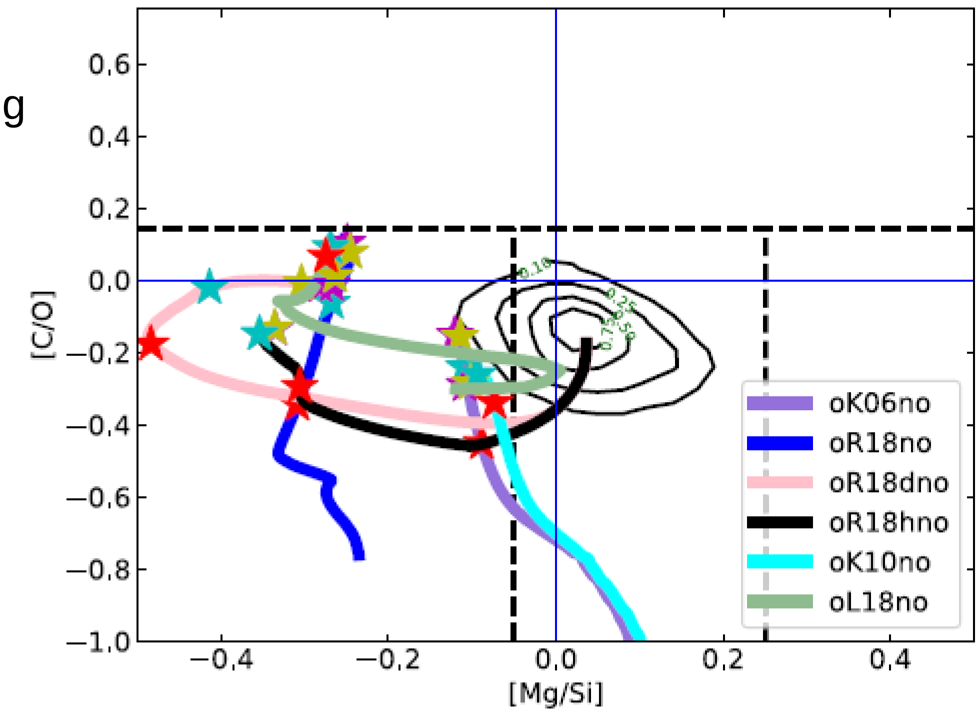


Effect of stellar yields & the Mg puzzle

- 6 stellar yield sets
- the solar [C/O] is obtained using 4 sets
- by using 2 other sets we get closer to the solar [Mg/Si], but none of them show enough Mg

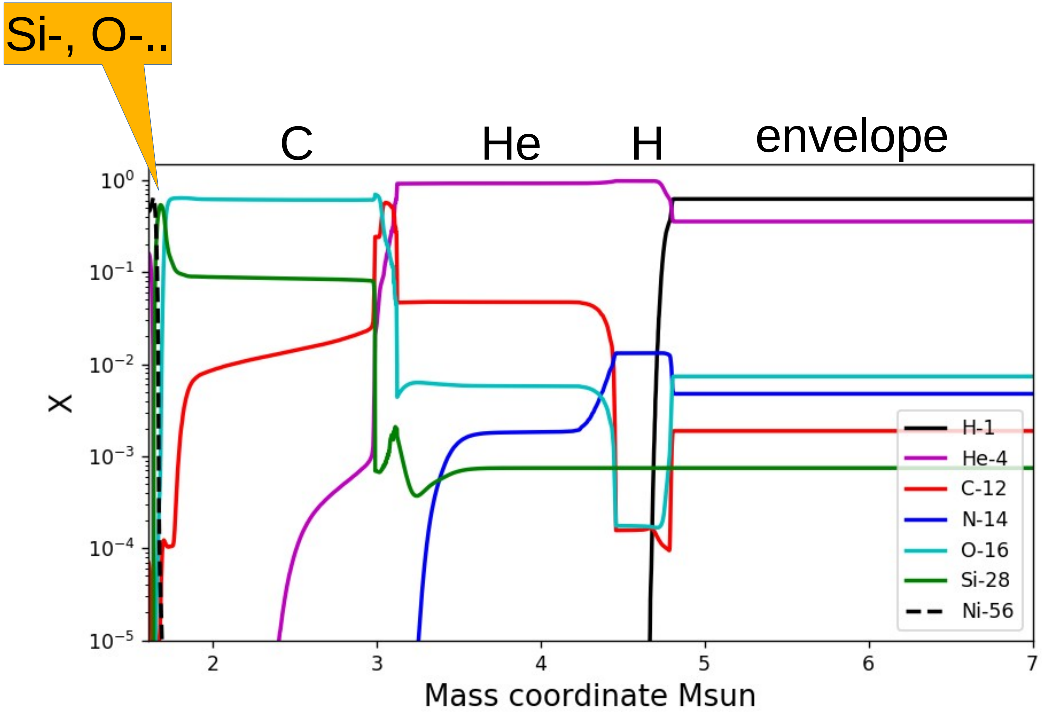
Mg puzzle!

Old problem, identified first from using WW95 CCSNe yields (e.g., Gibson+ 1997 MNRAS 290 and several works following)



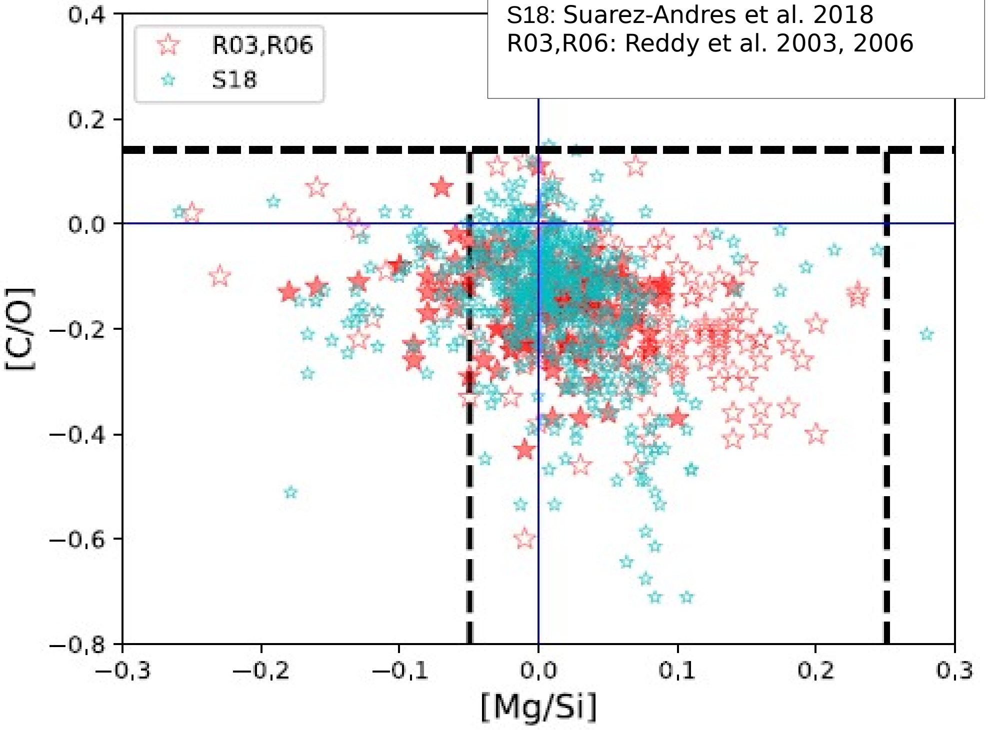
Nuclear astrophysics point of view: it should not be that difficult..

- **C**: product of 3α→ ^{12}C reaction (preSN partial He-burning)
- **O**: product of the $^{12}C(\alpha,\gamma)^{16}O$ reaction (preSN He-burning)
- **Mg**: product of the $^{20}Ne(\alpha,\gamma)^{24}Mg$ reaction (preSN C/Ne-burning)
- **Si**: product of $^{16}O+^{16}O$ (explosive O-burning)



M=15Msun, Z=0.02
Ritter+2018 MNRAS 480
MESA progenitor
Fryer+12 explosion

The zoo of solar normalizations



S18: Suarez-Andres et al. 2018
R03,R06: Reddy et al. 2003, 2006