UNIVERSITY OF Hull

E.A. Milne Centre
for Astrophysics

Production of metals in the early universe

Marco Pignatari
E.A. Milne Center for Astrophysics
University of Hull (JINA-CEE associate)

www.nugridstars.org

NUGRID

JINA-CEE

NuGrid :

- www.nugridstars.org
- data.nugridstars.org
- wendi.nugridstars.org

Main research activities:

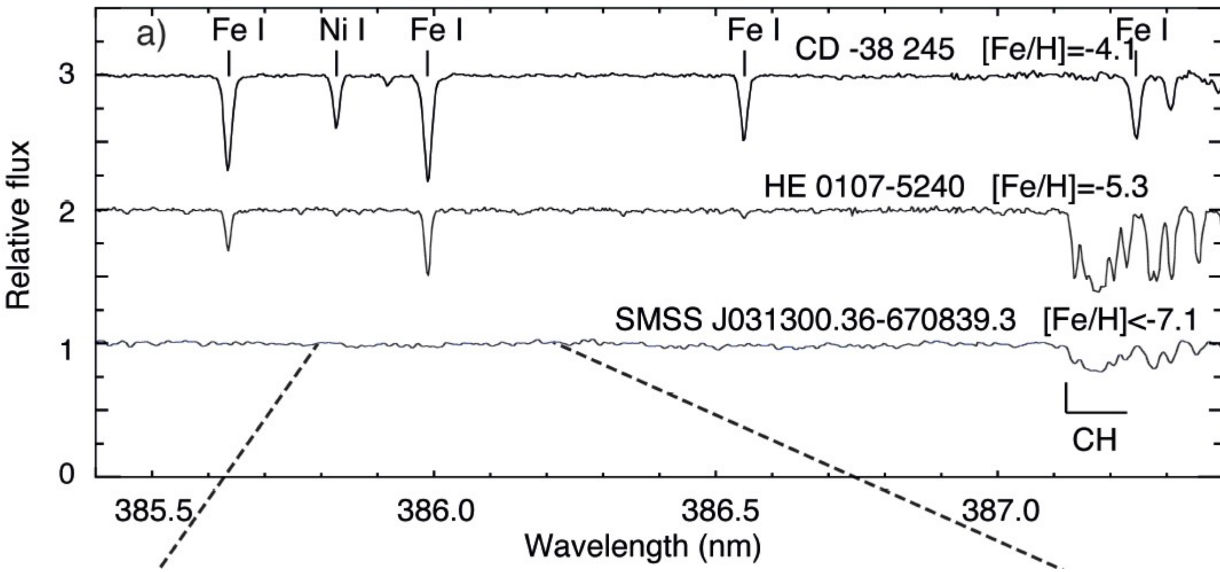
- production of stellar yields sets for GCE and data mining
- Nuclear and stellar uncertainties studies
- Comparison of stellar data with observations

Source: ADS Bumblebee

Production of Carbon (and Oxygen)

^{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-

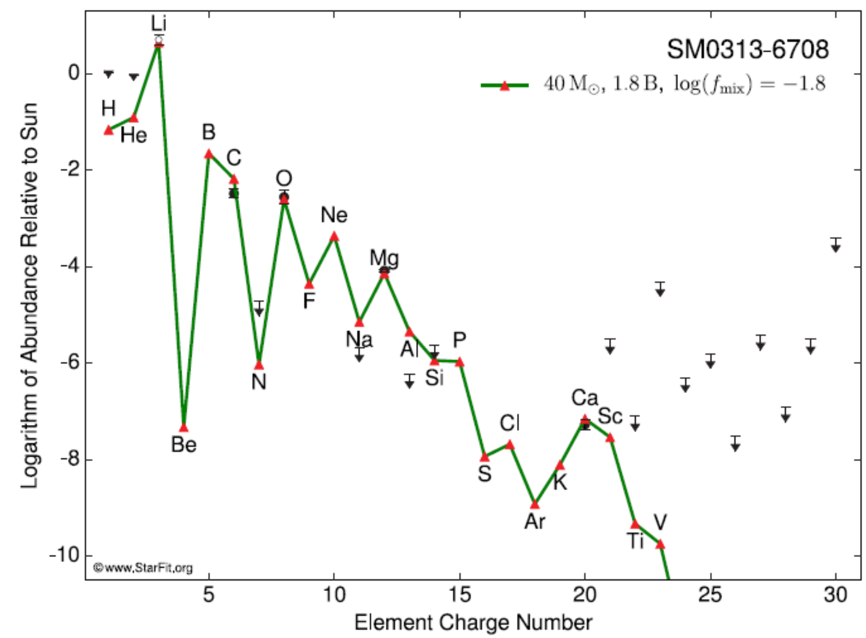
Z and [Fe/H]



Keller+2014, Nature

The Keller star (SM0313-6708):

- metal-poor
- [C/Fe] >> Sun

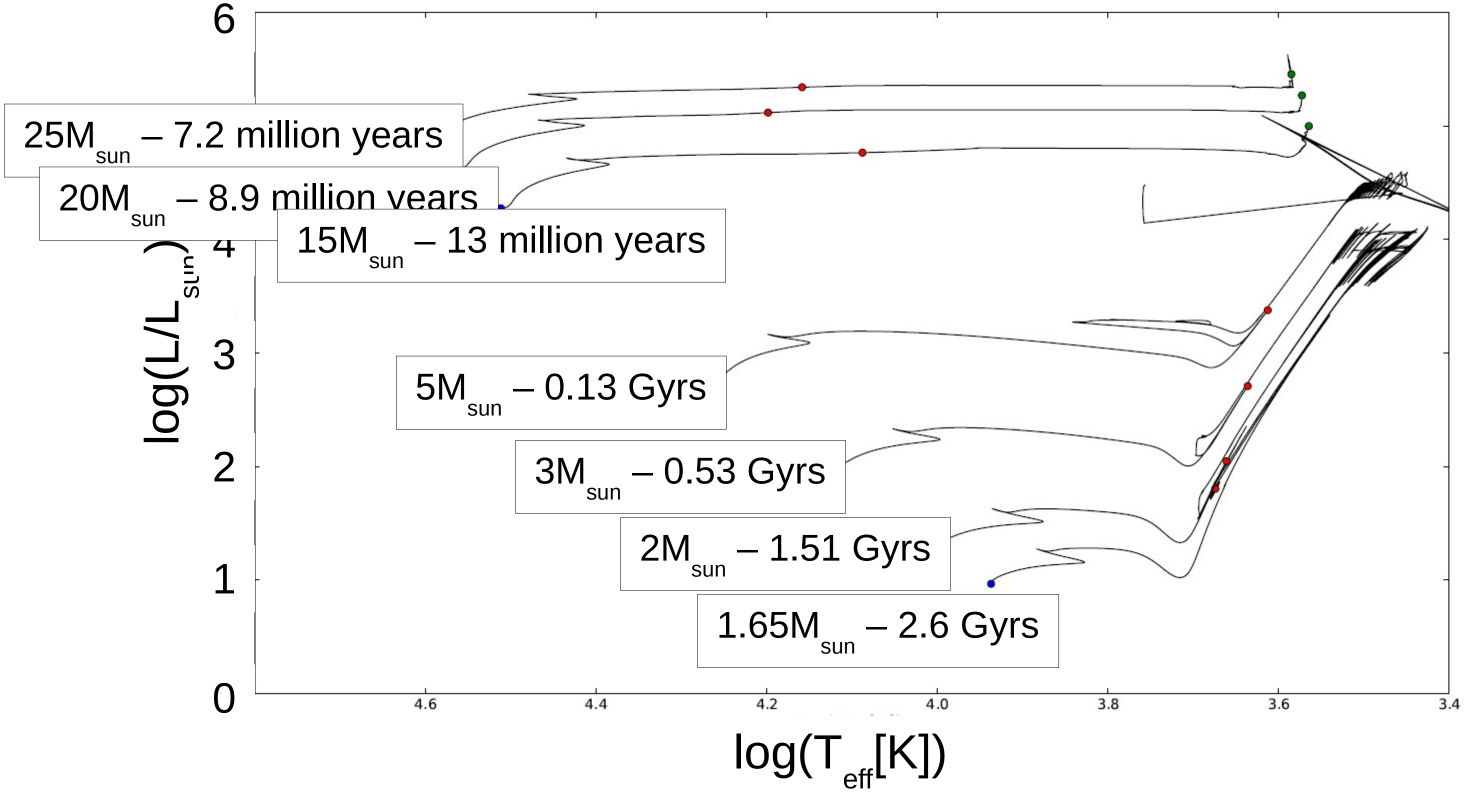


Bessel+2015, ApJ
Nordlander+2017, A&A

@Monday, I. Roederer

Massive stars and low-mass stars are both needed for galactic archaeology (e.g., CEMP stars)

HR diagram



CEMP stars = Carbon Enhanced Metal Poor stars

@Monday, A. Frebel

Low-mass stars
Intermediate-mass stars
High-mass stars

Nuclear burning stages

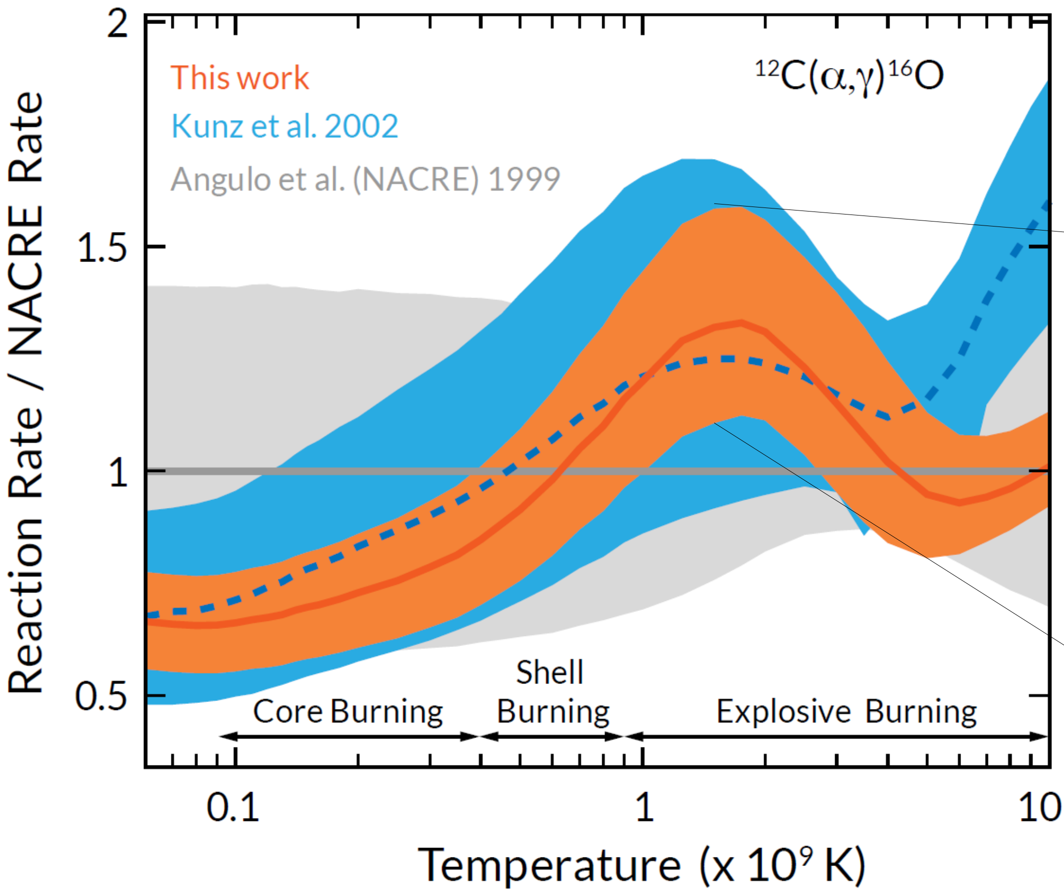
Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,H \xrightarrow{CNO} {}^4He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2–0.4	10^6	$3\,He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}O + {}^{16}O$
Si, S	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}Si(\gamma,\alpha)$…

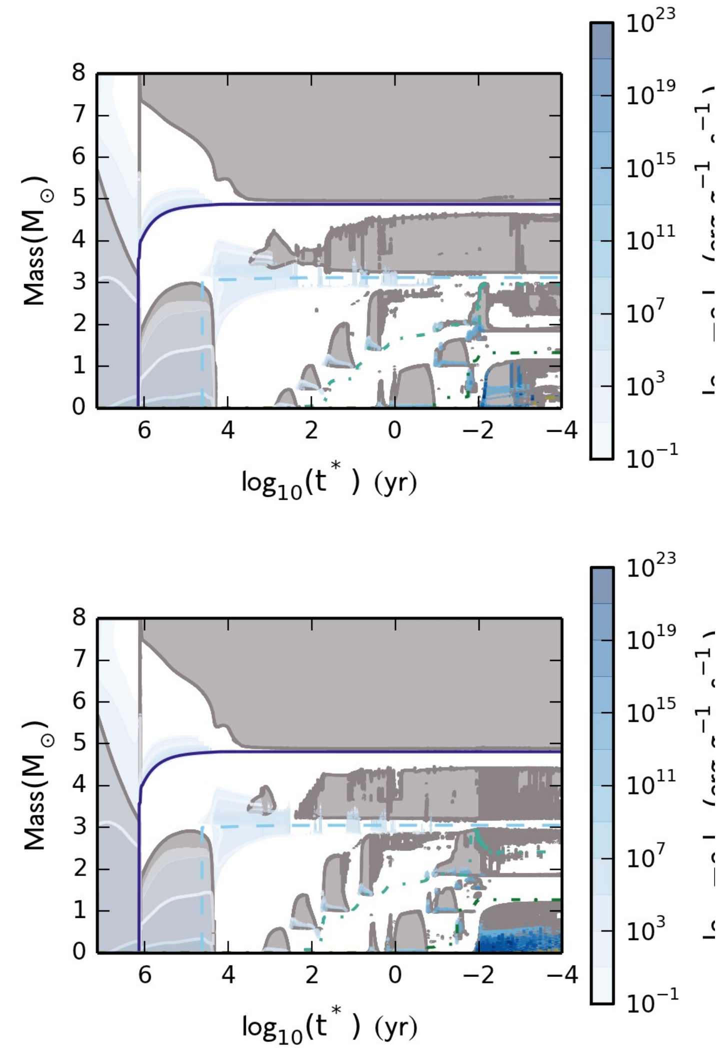
From: Alex Heger

See also Jones et al. 2013, ApJ

$^{12}C(\alpha,\gamma)^{16}O$ rate: deBoer et al. 2017, Rev.Mod.Phys

PreSN evolution of massive stars ($25M_{sun}$)

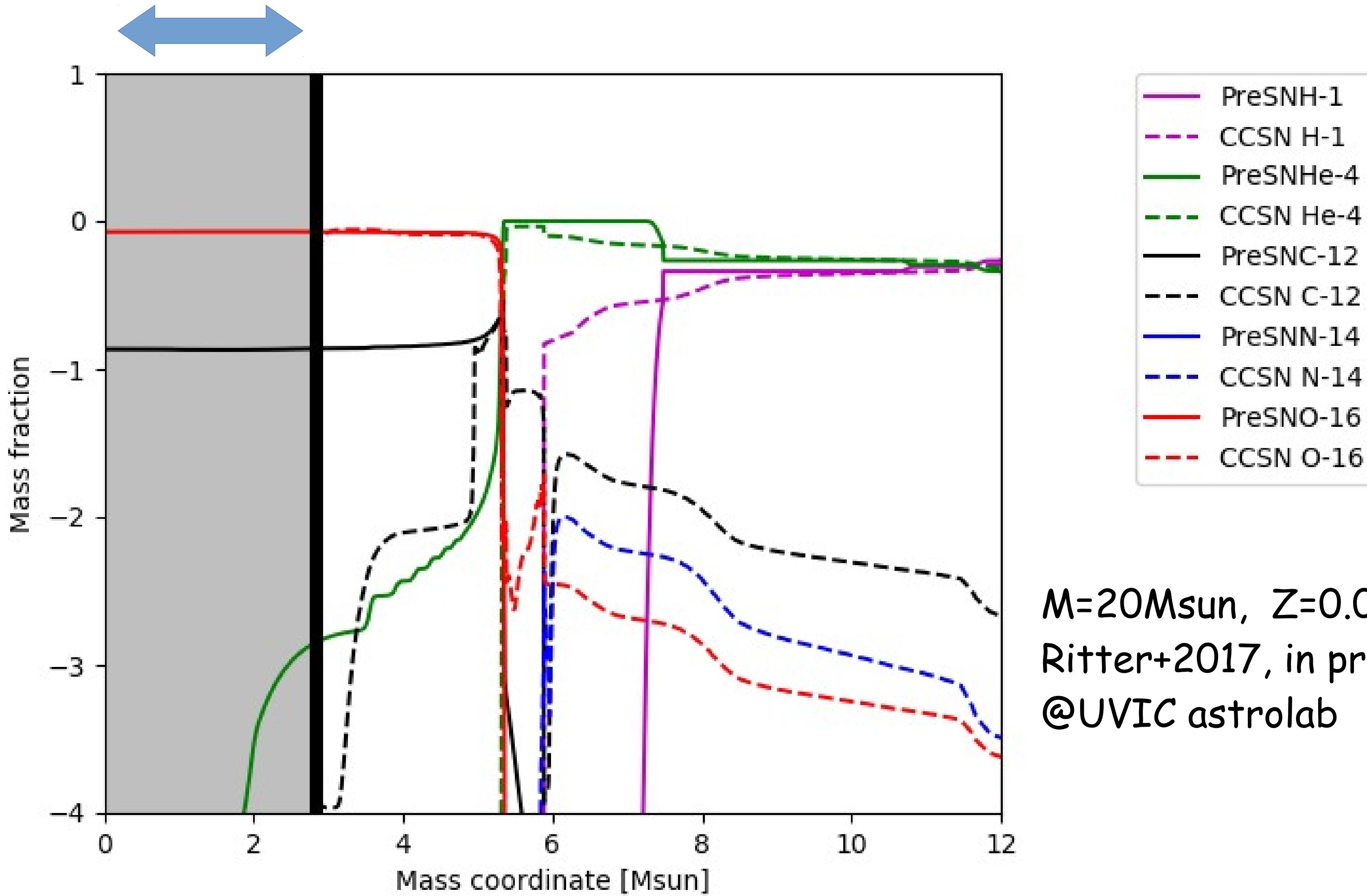




@Monday, M. Wiescher

@Monday, A. Heger

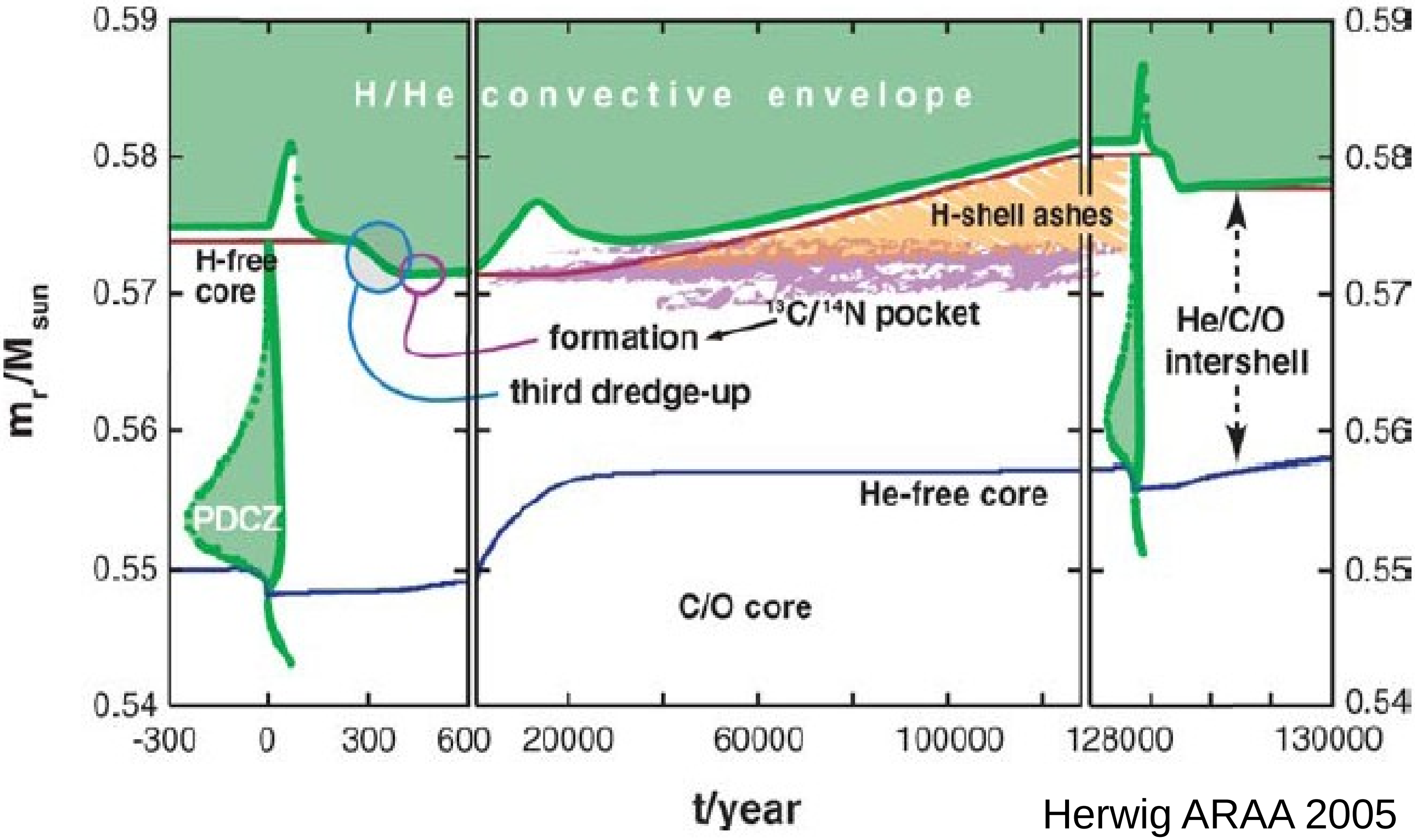
Not ejected - NS+fallback



M=20Msun, Z=0.0001
Ritter+2017, in prep.
@UVIC astrolab

In the plot:
abundances at the end of the core He-burning vs CCSN abundances

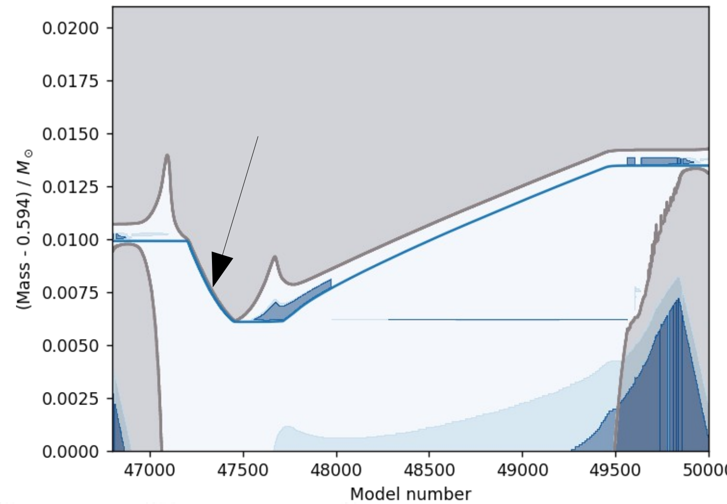
<u>AGB stars</u>: much weaker dependence on the $^{12}C(\alpha,\gamma)^{16}O$ rate. Strong dependence on the uncertainties on the convective-boundary mixing mechanisms (CBM).
E.g., Herwig et al. 2006, de Boer et al. 2017, RevModPhys



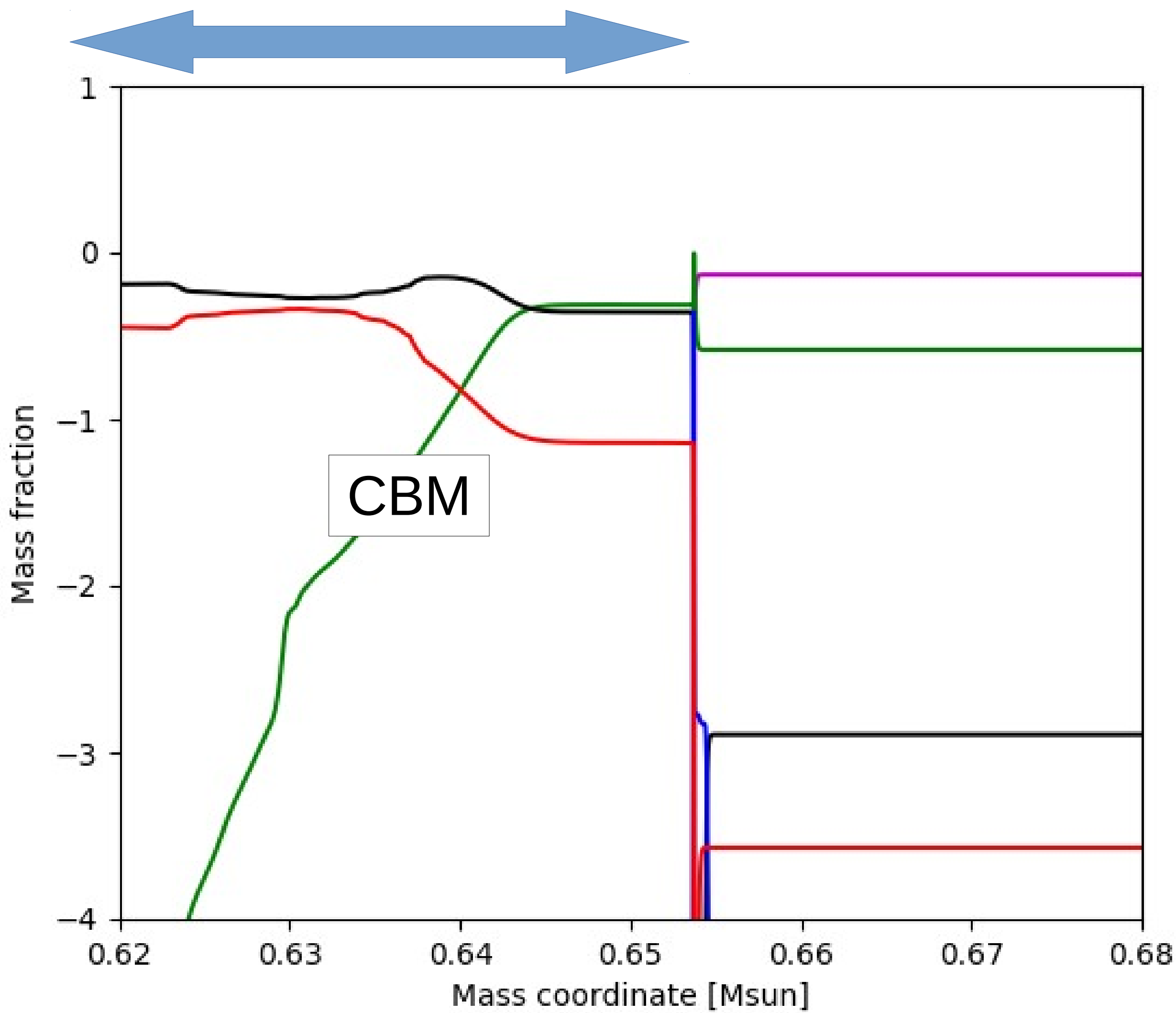
Herwig ARAA 2005

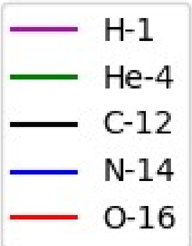
@Tuesday, A. Karakas

M=2Msun, TDU event
astrolab, @UVIC
Set1ext, Ritter+2017 in prep.
data.nugridstars.org



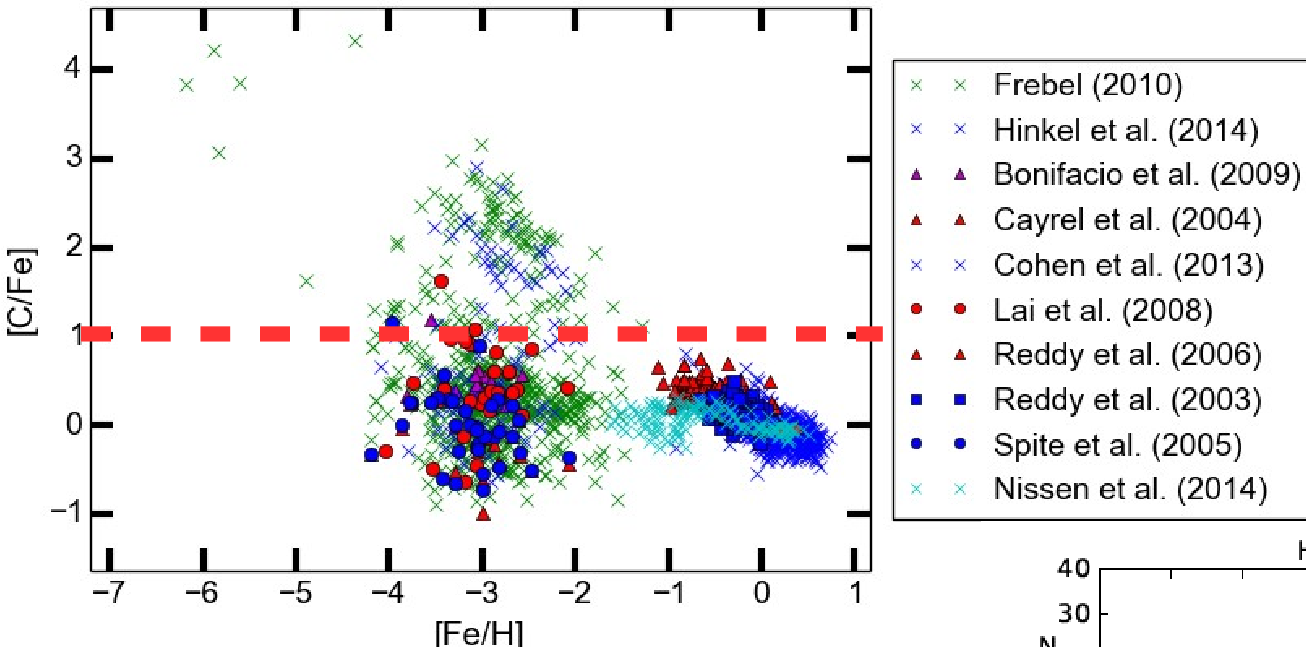
Not ejected - WD



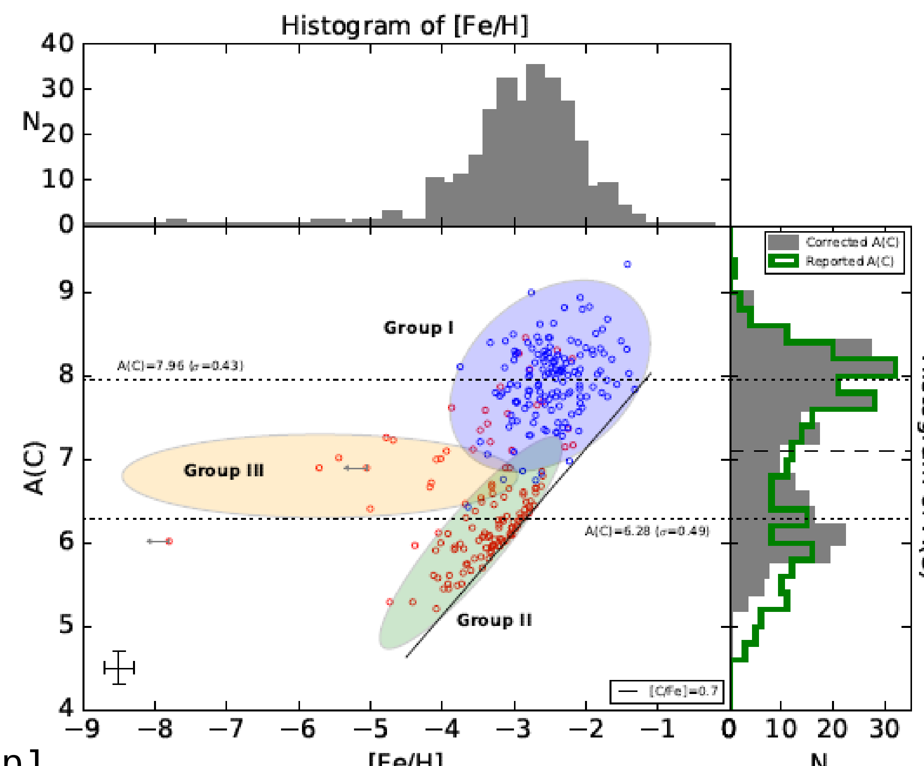


M=2Msun, Z=0.0001

CEMP stars family, with and without binary interaction



JINA-CEE/NuGrid NupyCEE



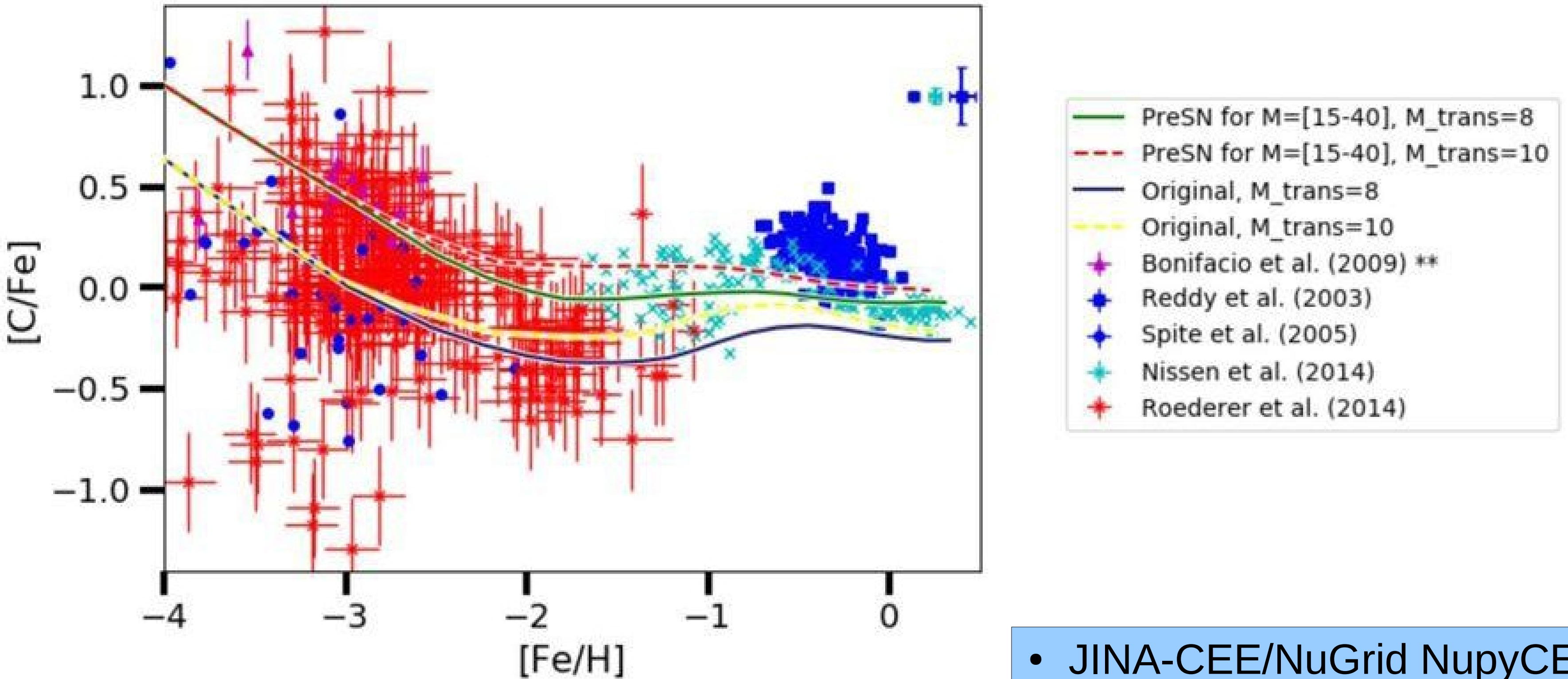
Yoon et al. 2016, ApJ

Highlights:

- There are CEMP-s, CEMP-r, CEMP-sr and CEMP-no stars.
- Bimodal C enrichment (e.g., Spite et al. 2013, Yoon et al. 2016)

What happens to carbon when it is ejected in the ISM?

- Nuclear physics is done, it is time for GCE



- JINA-CEE/NuGrid NupyCEE
- Jacob Brazier BSc project, @Hull Uni

What happens to carbon when it is ejected in the ISM?

- Nuclear physics is done, it is time for GCE
- Formation of molecules:
  - gas phase reactions
  - grain surface reactions
- The questions are:
  - What is the impact of the C12(α,γ)O16 and of CBM on the production of carbon in the early galaxy?
  - What is their impact on the astrochemistry in the early galaxy?
  - What is the impact on the formation of complex organic molecules?
  - What is the impact on dust formation?

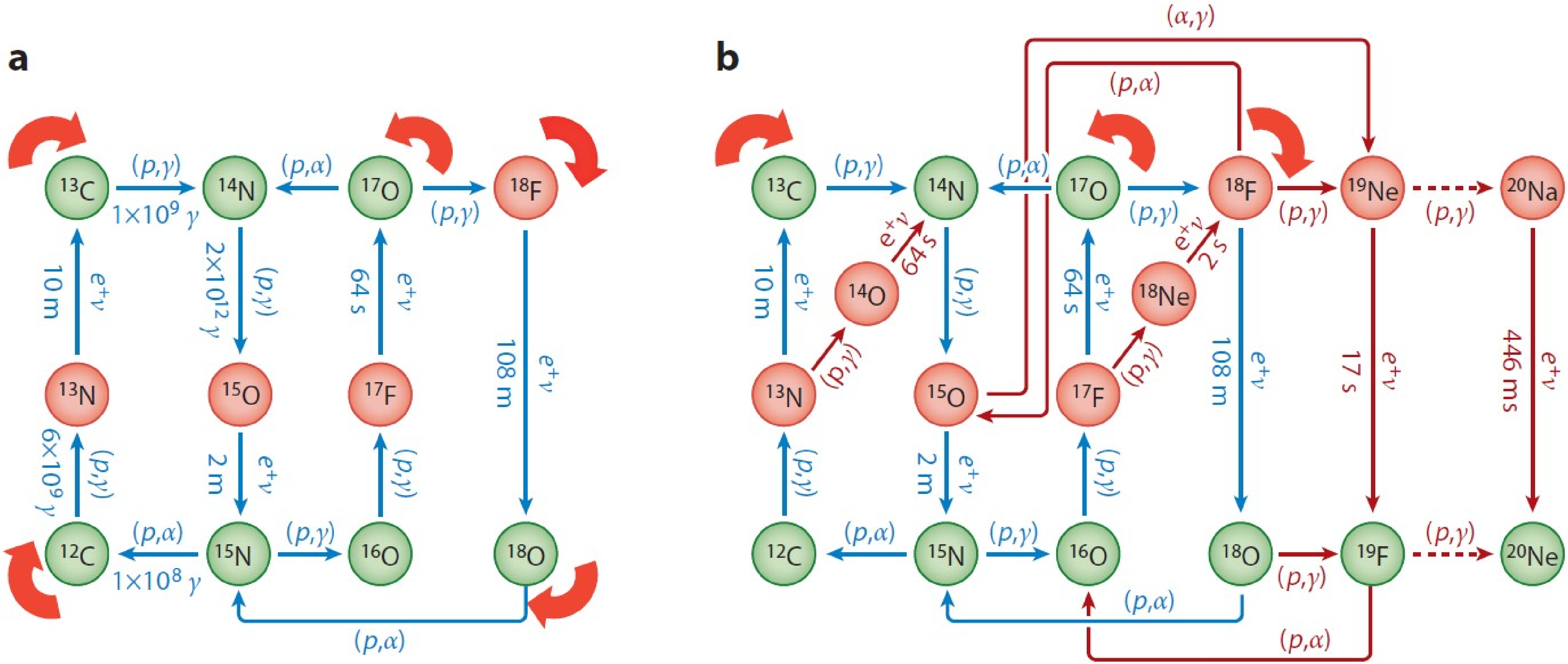
NUGRID + KROMEPACKAGE

http://kromepackage.org/

Nitrogen production

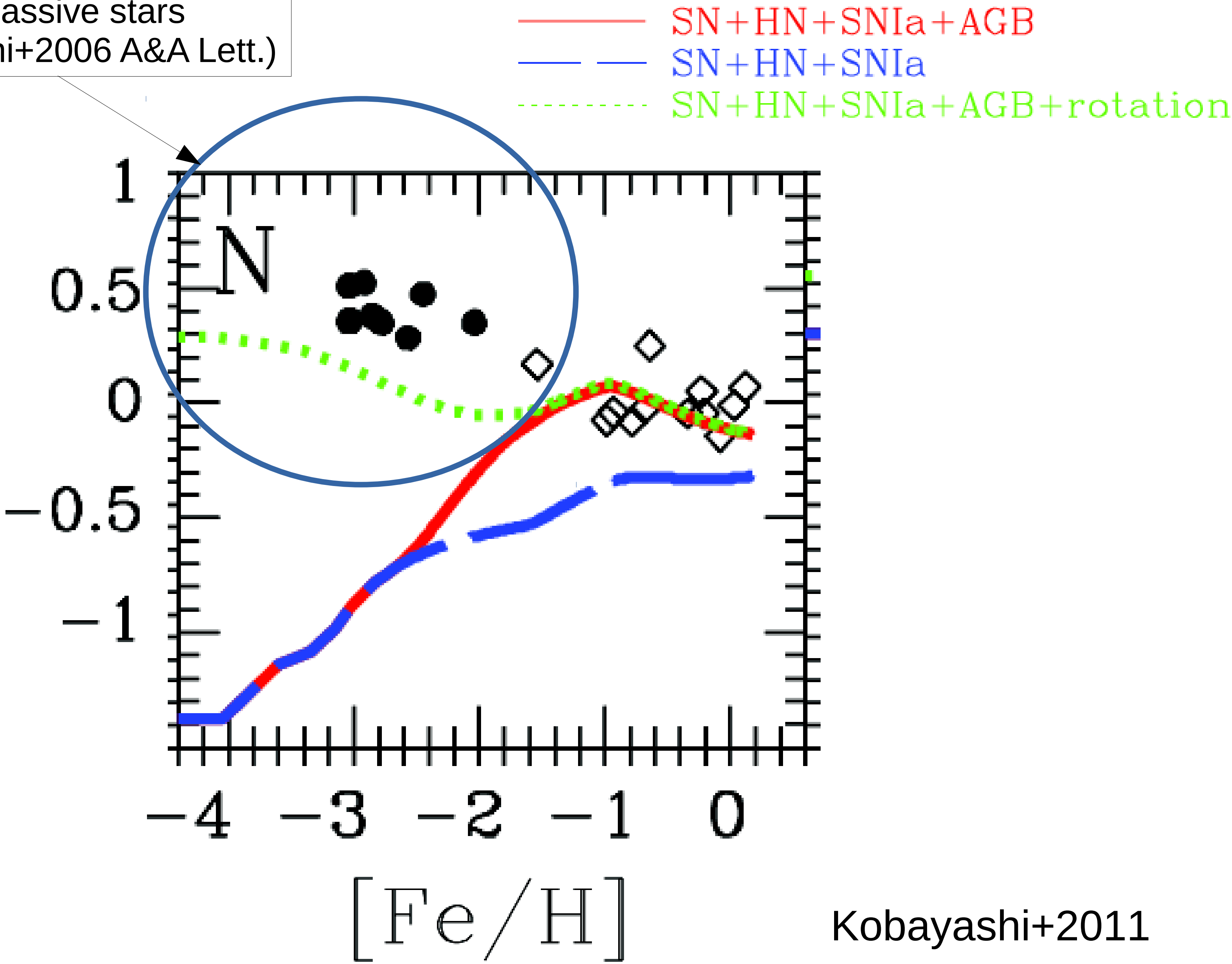
Cold CNO cycle

Hot CNO cycle



Wiescher et al. 2010, Annu. Rev. Nucl. Part. Sci.

Popular scenario: production of N in the Early Galaxy due to fast rotating massive stars (e.g., Chiappini+2006 A&A Lett.)



Kobayashi+2011

Can rotating models produce enough N15?

^{14}O 1.18 m β^+	^{15}O 2.04 m β^+	^{16}O 99.762 0.038 mb
^{13}N 9.96 m β^+	^{14}N 99.634 0.041 mb	^{15}N 0.366 0.0058 mb
^{12}C 98.89 0.0154 mb	^{13}C 1.11 0.021 mb	^{14}C 5.70 ka 0.00848 mb, β^-

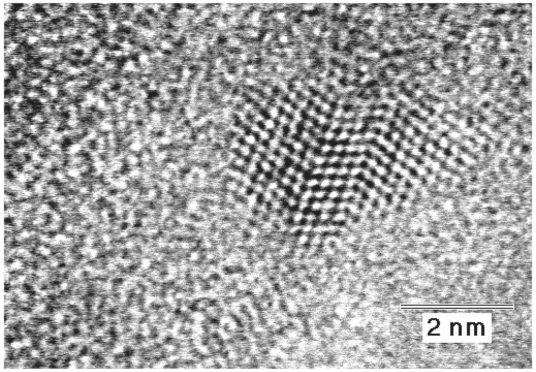
@ KADoNiS

Massive stars make N15:

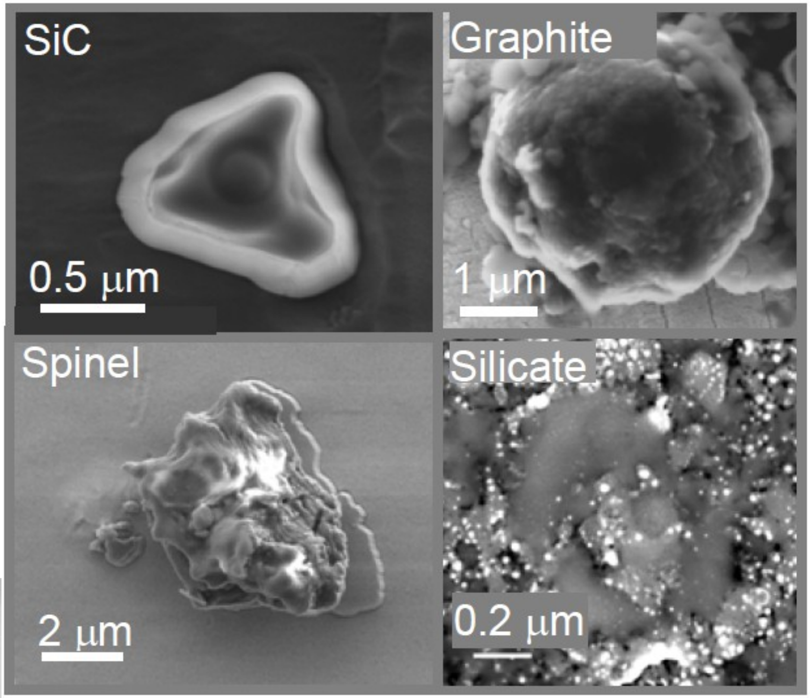
- Detections of extragalactic 15N as hydrogen cyanide isotope HC15N in the star-forming regions of the Large Magellanic Cloud (LMC) and the core of the (post-)starburst galaxy NGC 4945. 14N/15N ratio ~ 100 (Chin et al. 1999, ApJ 512).
- Isotopic ratios at z = 0.89: molecular line absorption in front of the quasar PKS 1830-211: low N14/N15 (Muller+2006 A&A)

Learning about N production in CCSNe with presolar grains

Nano-diamonds

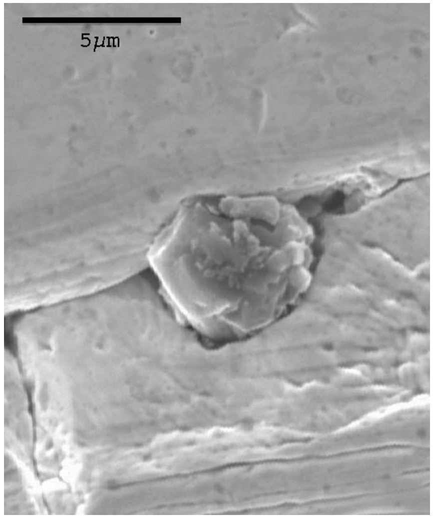


F. Banhart (MPI for Metal Research, Stuttgart)

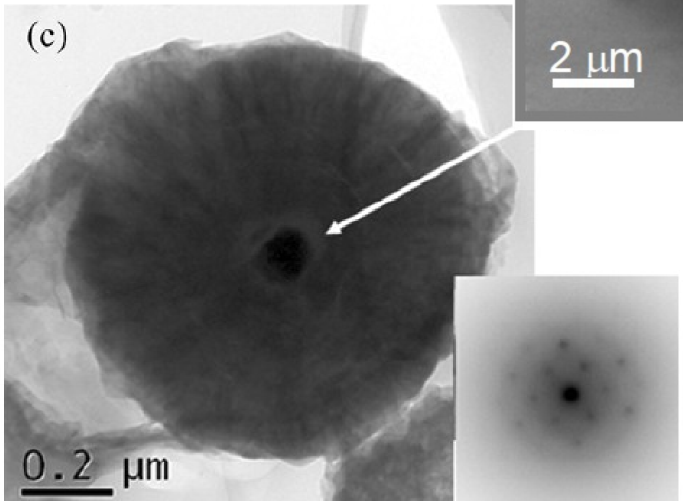


Hoppe 2010 PoS

SiC-X grain



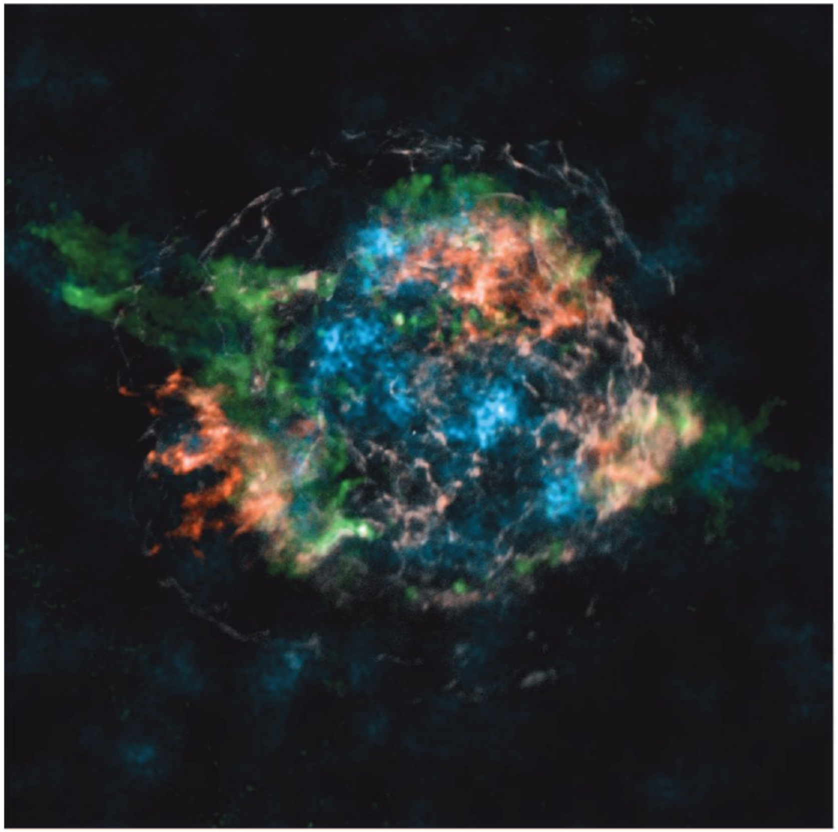
From Reto Trappitsch (Uni of Chicago)



Croat et al. 2010, AJ 139

Graphite (and a SiC in the center)

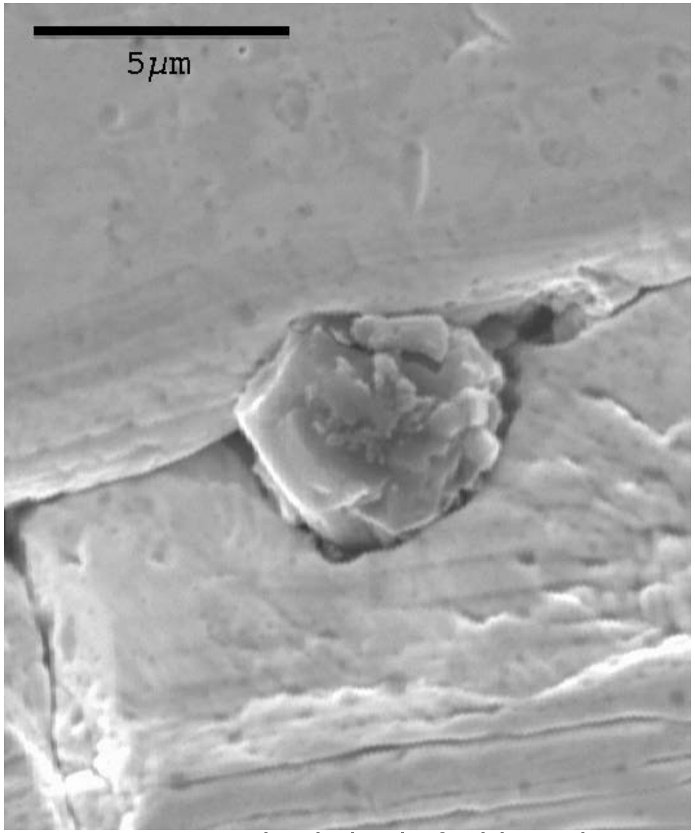
CCSN remnant



Cas A
11000 ly
~ 300 years ago

See Grefenstette et al. 2014, Nature
(NuSTAR data)

Presolar grain from an old CCSN



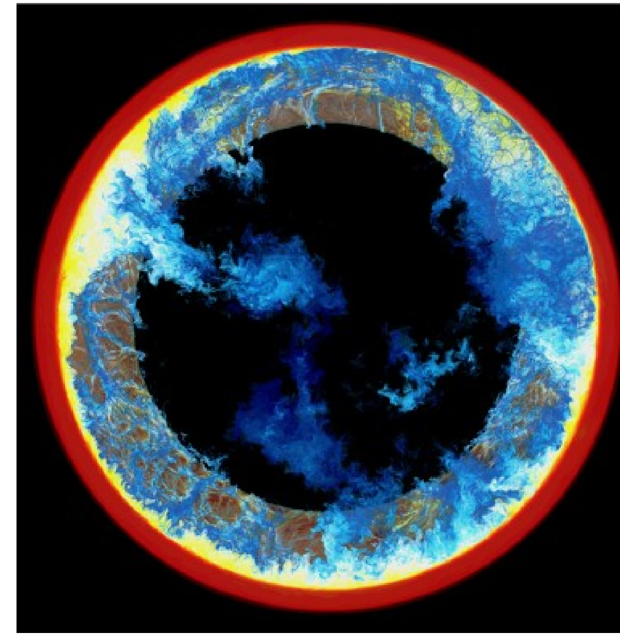
From Reto Trappitsch (Uni of Chicago)

unknown
? - (today in a lab)
~ 4.5-5 Gyrs ago

Zinner 2014, Tr. Geochem.

@Monday, C. Fryer

+ Herwig et al. 2014, ApJL 792
+ Woodward et al. 2015, ApJ 798



Highlights:

- Ingestion of H in hotter He-burning convective regions in massive stars;
- Alive H is found when the SN shock reaches He-burning layers

THE ASTROPHYSICAL JOURNAL LETTERS, 808:L43 (6pp), 2015 August 1 doi:10.1088/2041-8205/808/2/L43

CARBON-RICH PRESOLAR GRAINS FROM MASSIVE STARS: SUBSOLAR $^{12}C/^{13}C$ AND $^{14}N/^{15}N$ RATIOS AND THE MYSTERY OF ^{15}N

M. PIGNATARI[1,2,13], E. ZINNER[3], P. HOPPE[4], C. J. JORDAN[5,14], B. K. GIBSON[5,14], R. TRAPPITSCH[6,13], F. HERWIG[7,8,13], C. FRYER[9,13], R. HIRSCHI[10,11,13,14], AND F. X. TIMMES[8,12,13]

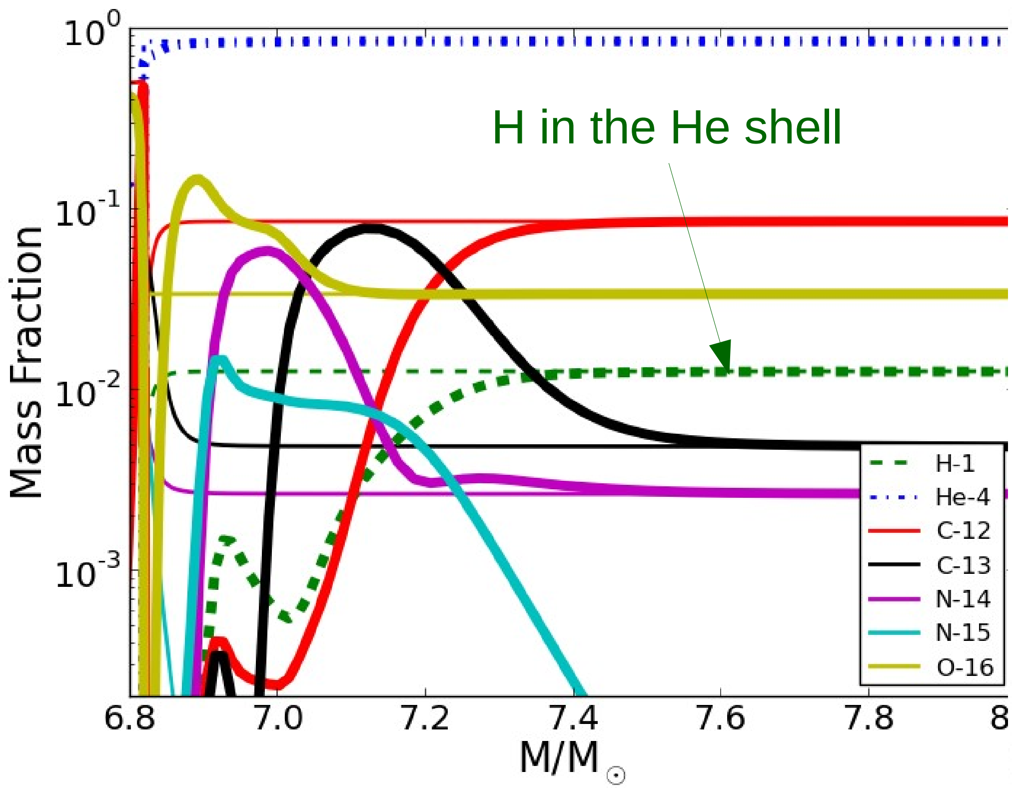
Presolar grains and H ingestion in CCSNe: results confirmed

Liu, ..., MP et al. 2016, 2017 – ApJ/ApJL

Model 25T

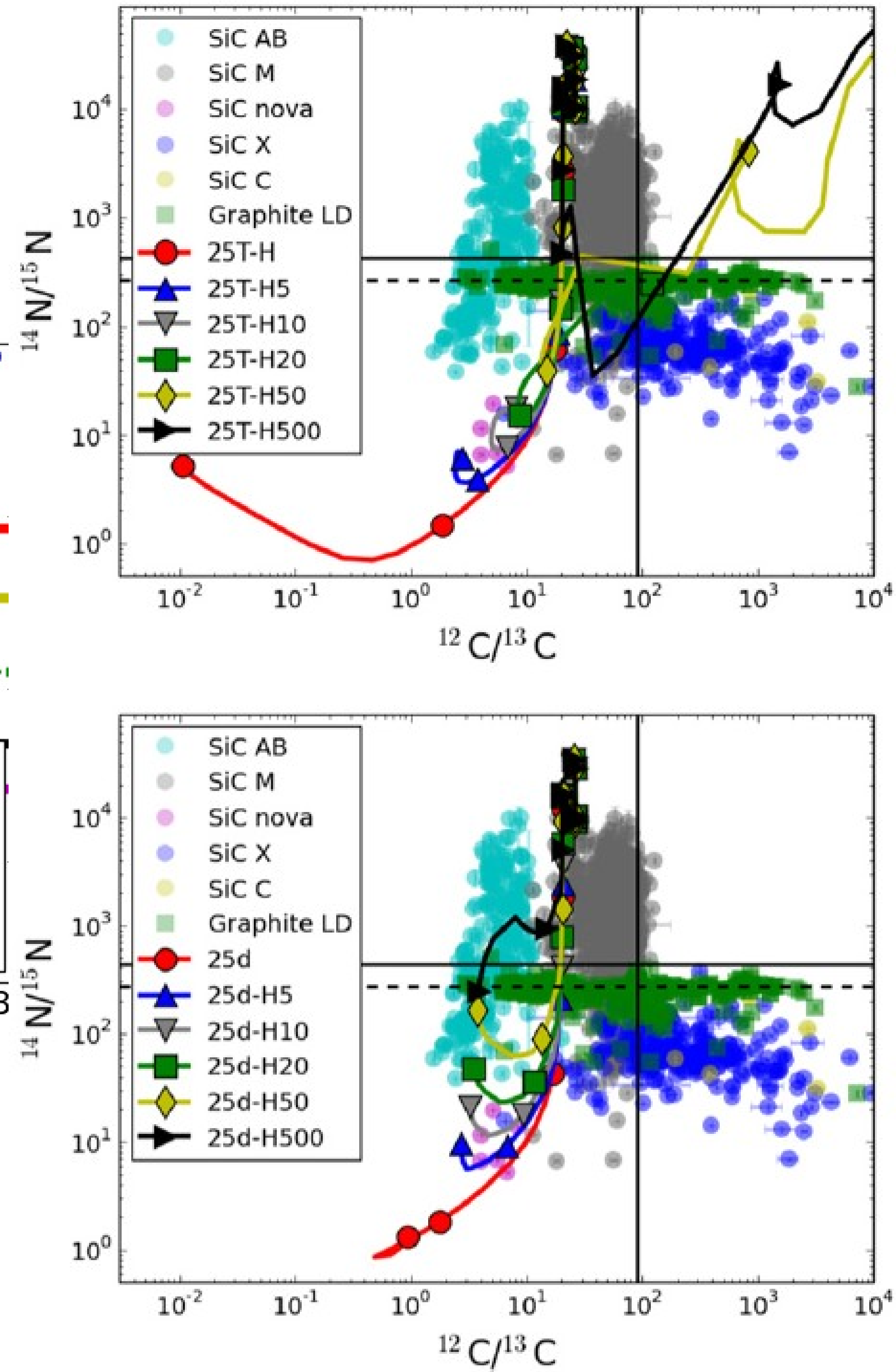
Metallicity = Z=0.02

Explosive He shell nucleosynthesis with H ingested still alive

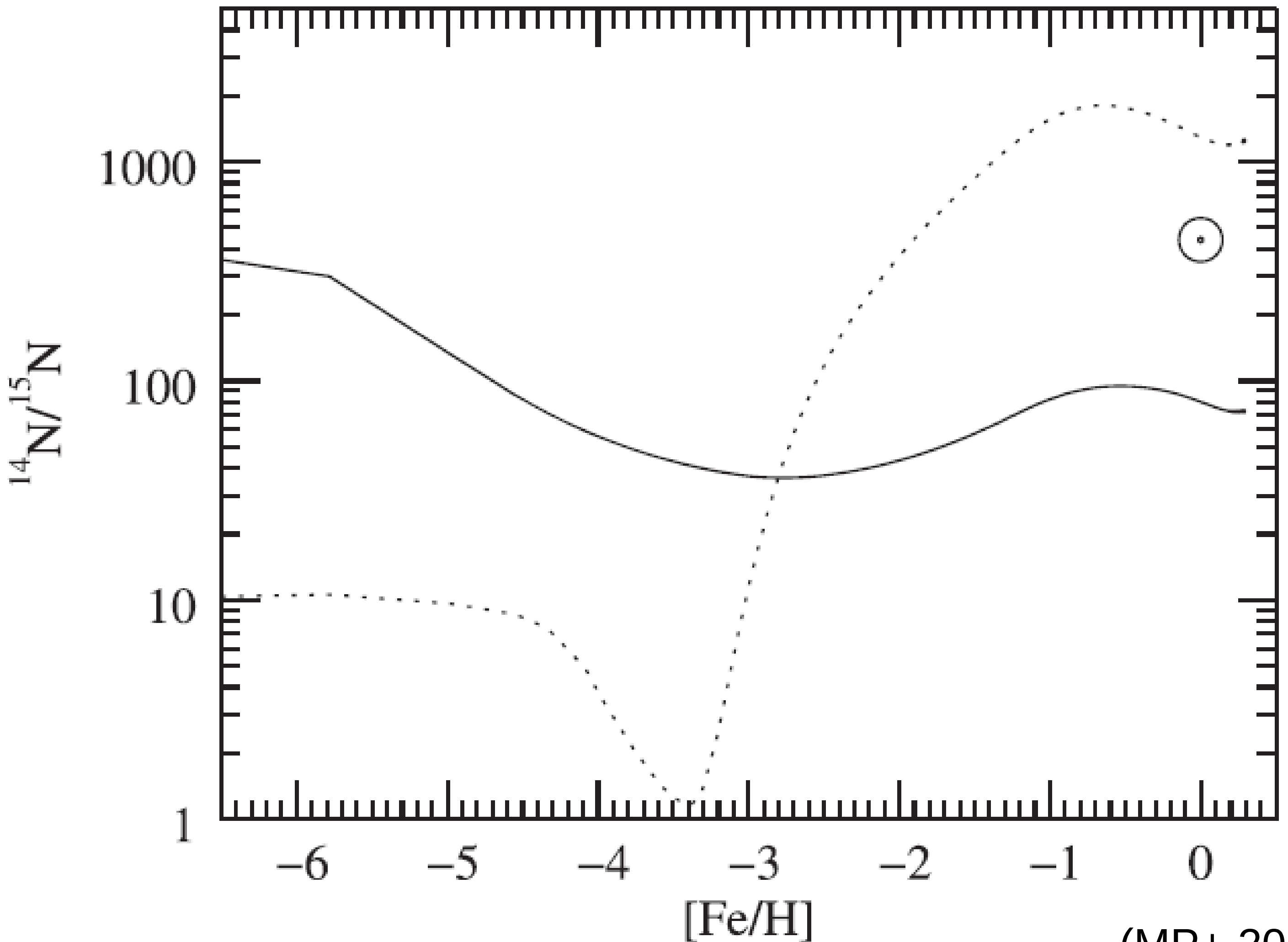


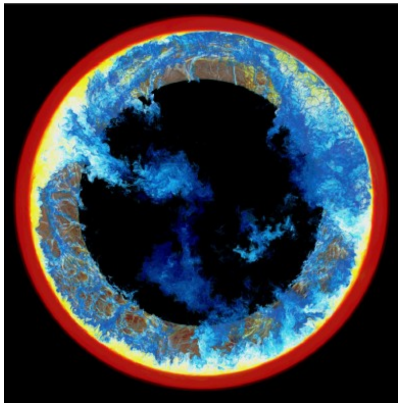
Centre of the star

He-shell layers



Impact on the CE of 14N/15N:





We need this !

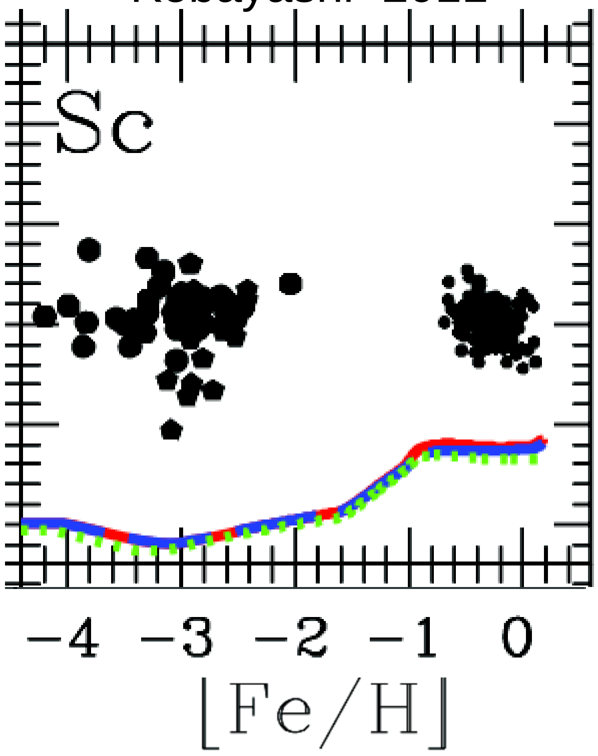
(MP+ 2015 ApJL)

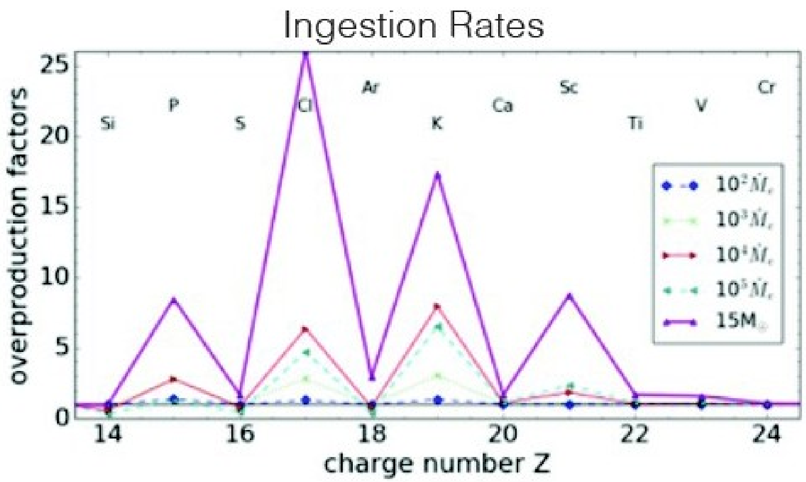
Production of intermediate-mass elements

Impact of CO-shell mergers on nucleosynthesis:

- An ideal case study for nuclear astrophysics
- Ritter+2017, arXiv:1704.05985
- @C.Ritter poster for GCE;
- @R. Andrassy talk, Thursday.

Kobayashi+2011





Uncertainty

Nucleosynthesis flows for C and O fusion

X_C12 = 0.0001

T9	c12c12	c12o16	o16o16
1.5	4.77e-15	1.55e-15	1.86e-16
2.0	2.41e-12	4.61e-12	3.73e-12
2.5	1.86e-10	1.27e-09	4.38e-09
3.0	4.79e-09	7.94e-08	8.54e-07

X_C12 = 0.001

T9	c12c12	c12o16	o16o16
1.5	4.77e-13	1.55e-14	1.86e-16
2.0	2.41e-10	4.61e-11	3.73e-12
2.5	1.86e-08	1.27e-08	4.38e-09
3.0	4.79e-07	7.94e-07	8.54e-07

X_C12 = 0.01

T9	c12c12	c12o16	o16o16
1.5	4.77e-11	1.55e-13	1.86e-16
2.0	2.41e-08	4.61e-10	3.73e-12
2.5	1.86e-06	1.27e-07	4.38e-09
3.0	4.79e-05	7.94e-06	8.54e-07

- Values: e.g., X_C12/12 * X_O16/16 * rate
- C12+C12, C12+O16 and O16+O16 all have three channels, with relative uncertainties.

@Monday, M. Wiescher

C12+C12:

2	C	12	+	0	00000	->	1	NA	23	+	1	PROT
2	C	12	+	0	00000	->	1	NE	20	+	1	HE 4
2	C	12	+	0	00000	->	1	MG	23	+	1	NEUT

C12+O16:

1	O	16	+	1	C	12	->	1	AL	27	+	1	PROT
1	O	16	+	1	C	12	->	1	MG	24	+	1	HE 4
1	O	16	+	1	C	12	->	1	SI	27	+	1	NEUT

O16+O16:

2	O	16	+	0	00000	->	1	P	31	+	1	PROT
2	O	16	+	0	00000	->	1	SI	28	+	1	HE 4
2	O	16	+	0	00000	->	1	S	31	+	1	NEUT

High uncertainty for nucleosynthesis, in particular for isotopic ratios

Summary

- Production of C, N and intermediate-mass elements in the early universe: comparing with the observations.
- Convective-reactive events in stars and nuclear astrophysics: the CO shell merger case
- Production of stellar yields for CE and astrochemistry. From nuclear astrophysics to a cosmochemistry framework?

www.nugridstars.org

JINA-CEE

Acknowledgements:

NuGrid acknowledges support from NSF grants PHY 02-16783 and PHY 08-22648 (Joint Institute for Nuclear Astrophysics, JINA), NSF grant PHY-1430152 (JINA Center for the Evolution of the Elements) and EU MIRG-CT-2006-046520. The continued work on codes and in disseminating data is made possible through funding from STFC (RH, UK), an NSERC Discovery grant (FH, Canada) and support from SNF (MP, Switzerland). NuGrid computations are performed at the Arizona State University's Fulton High-performance Computing Center (USA), the high-performance computer KHAOS at EPSAM Institute at Keele University (UK) as well as CFI (Canada) funded computing resources at the Department of Physics and Astronomy at the University of Victoria and through Computing Time Resource Allocation through the Compute Canada WestGrid consortium. We also acknowledge support by the STFC DiRAC High Performance Computing Facilities, and ongoing resource allocations on the University of Hulls High Performance Computing Facility viper. The collaboration uses services of the Canadian Advanced Network for Astronomy Research (CANFAR) which in turn is supported by CANARIE, Compute Canada, University of Victoria, the National Research Council of Canada, and the Canadian Space Agency.
RH acknowledges support from the World Premier International Research Center Initiative (WPI Initiative), MEXT, Japan and funding from the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement n. 306901.