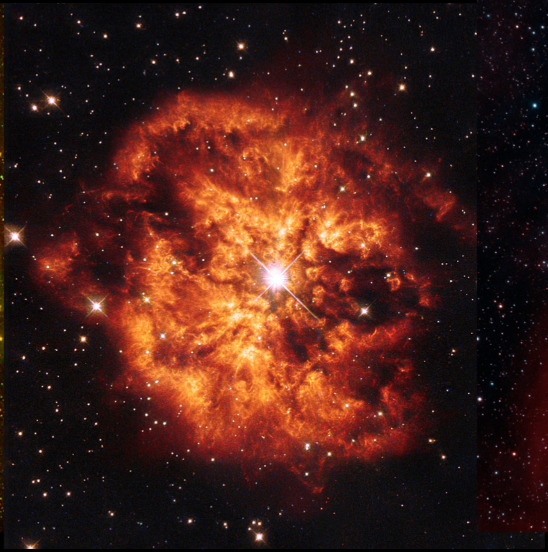
CONTRIBUTION OF MASSIVE STAR STELLAR WINDS TO FLUORINE 19

An element for which stellar winds may play a role

- Georges Meynet, Sylvia Ekström, Cyril Georgy (UNIGE)
- Stéphane Goriely, Marcel Arnould, Sophie Van Eck and Alain Jorissen (ULB)
- Hannah Brinkmann and Maria Lugaro (Konkoly Observatory, Budapest)

Stellar winds can save them from destruction!



- Enriched layers have to be removed at the right moment
- Other elements share this property → He, ^{12}C, ^{13}C, ^{22}Ne, ^{26}Al

Why is this element interesting?

Comparisons with observations – Tests of stellar physics and nucleosynthesis

^{19}F in AGB stars

Jorissen+,1992
Uttenthaler+,2008
Abbia+,2009,10,15,19

^{19}F in red giants

Jönsson+2017

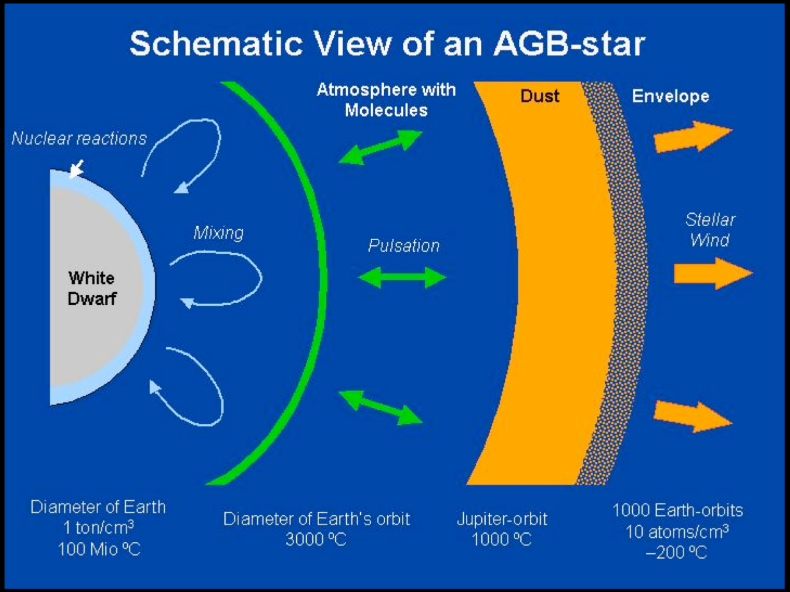
^{19}F in normal G and K stars in the thin disk

Pilachowski & pace +2015

^{19}F in dwarf stars

Recio-Blanco+2012

Physics of AGB stars



Help keeping white teeth in the MW

Which are the potential sources of ^{19}F ?

AGB stars

Karakas 2010
Cristallo + 2014

Massive stars

Meynet & Arnould 2000
Palacios + 2005
Prantzos+ 2018

ν–process

Woosley & Haxton 2002

Novae

José & Hernanz 1998

Synthesis in He-burning Regions

Both intermediate and massive stars

Explosive processes can contribute to both

THE NUCLEOSYNTHETIC PATH

PRODUCED AT VERY BEGIINNING OF THE He-BURNING CORE

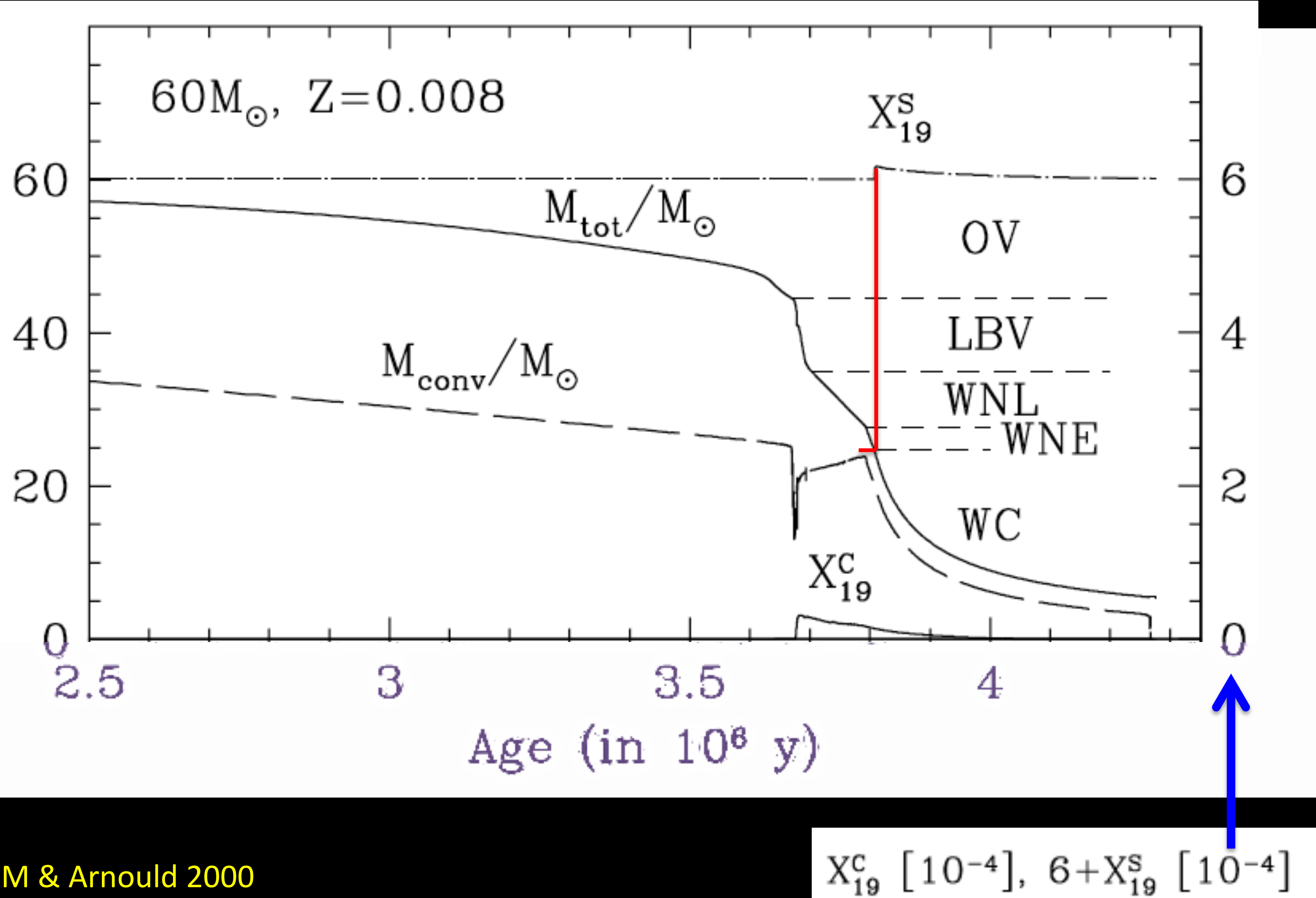
$$
\begin{array}{ccccc}
 & & (\beta^{+})^{18}\mathrm{O}(p,\alpha)^{15}\mathrm{N}(\alpha,\gamma)^{19}\mathrm{F} & & \\
 & \nearrow & & \searrow & \\
{}^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F} & \rightarrow & (n,p)^{18}\mathrm{O}(p,\alpha)^{15}\mathrm{N}(\alpha,\gamma)^{19}\mathrm{F}(\alpha,p) & & {}^{22}\mathrm{Ne}. \\
 & \searrow & & \nearrow & \\
 & & (n,\alpha)^{15}\mathrm{N}(\alpha,\gamma)^{19}\mathrm{F} & &
\end{array}
$$

$^{13}\mathrm{C}\,(\alpha\,,n)\,^{16}\mathrm{O}$ and $^{14}\mathrm{N}\,(n\,,p)\,^{14}\mathrm{C}$

Goriely et al. (1989)

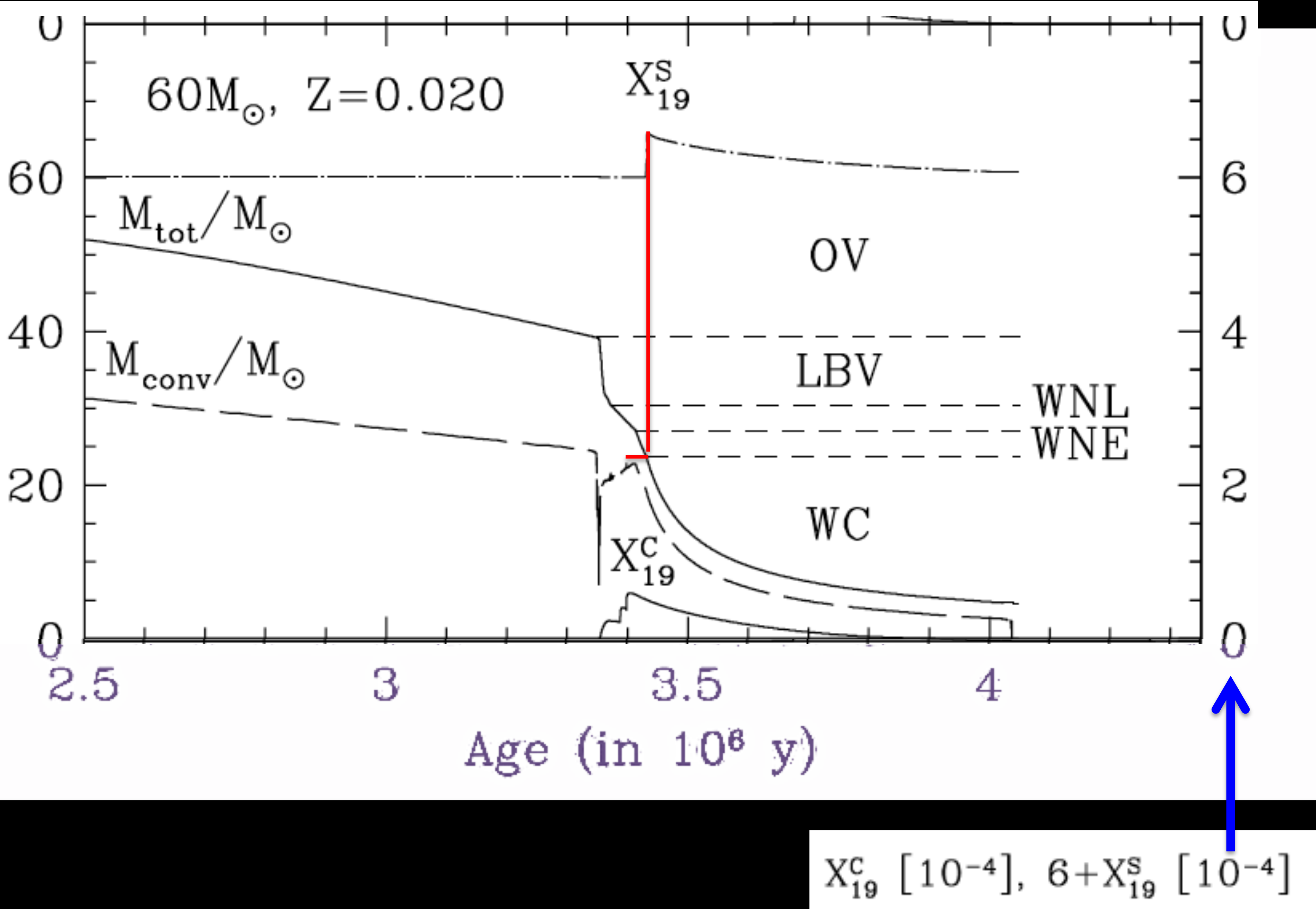
EJECTED WHEN He-CORE IS UNCOVERED AT AN EARLY STAGE OF CORE He-BURNING

WEAK MASS LOSSES → He-core uncovered late when 19F already in part destroyed

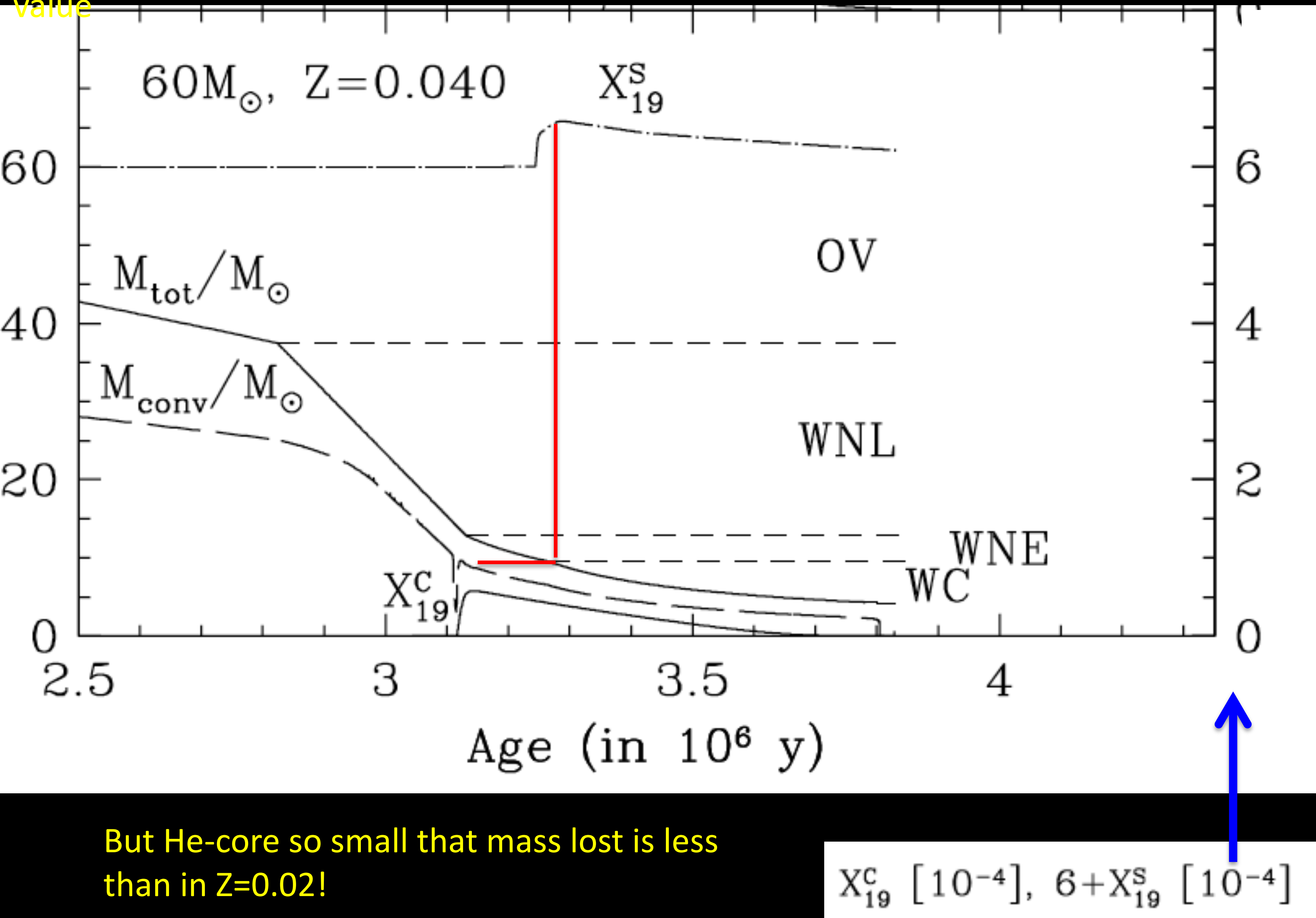


GM & Arnould 2000

STRONGER MASS LOSSES → He-core uncovered early when ^{19}F has reached max. value

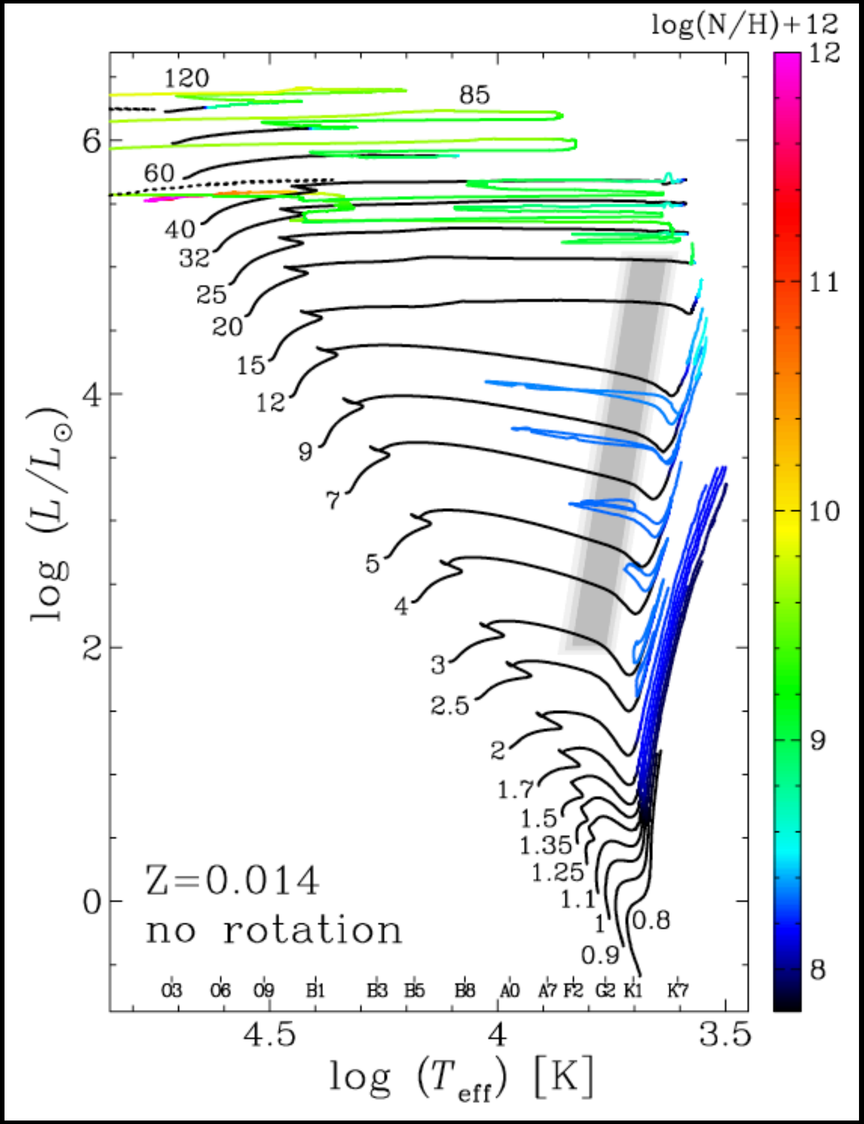


STILL STRONGER MASS LOSSES → He-core uncovered early when ^{19}F has reached max. value



But He-core so small that mass lost is less than in Z=0.02!

More recent computations with GENEC



Ekström + 2012 Z=0.014

Georgy+ 2013 Z=0.002

Groh+ 2019 Z=0.0004

In preparation Z=0.006

Z=0.000

Z=0.020

With respect to GM & Arnould 2000

Mass loss different (reduced)

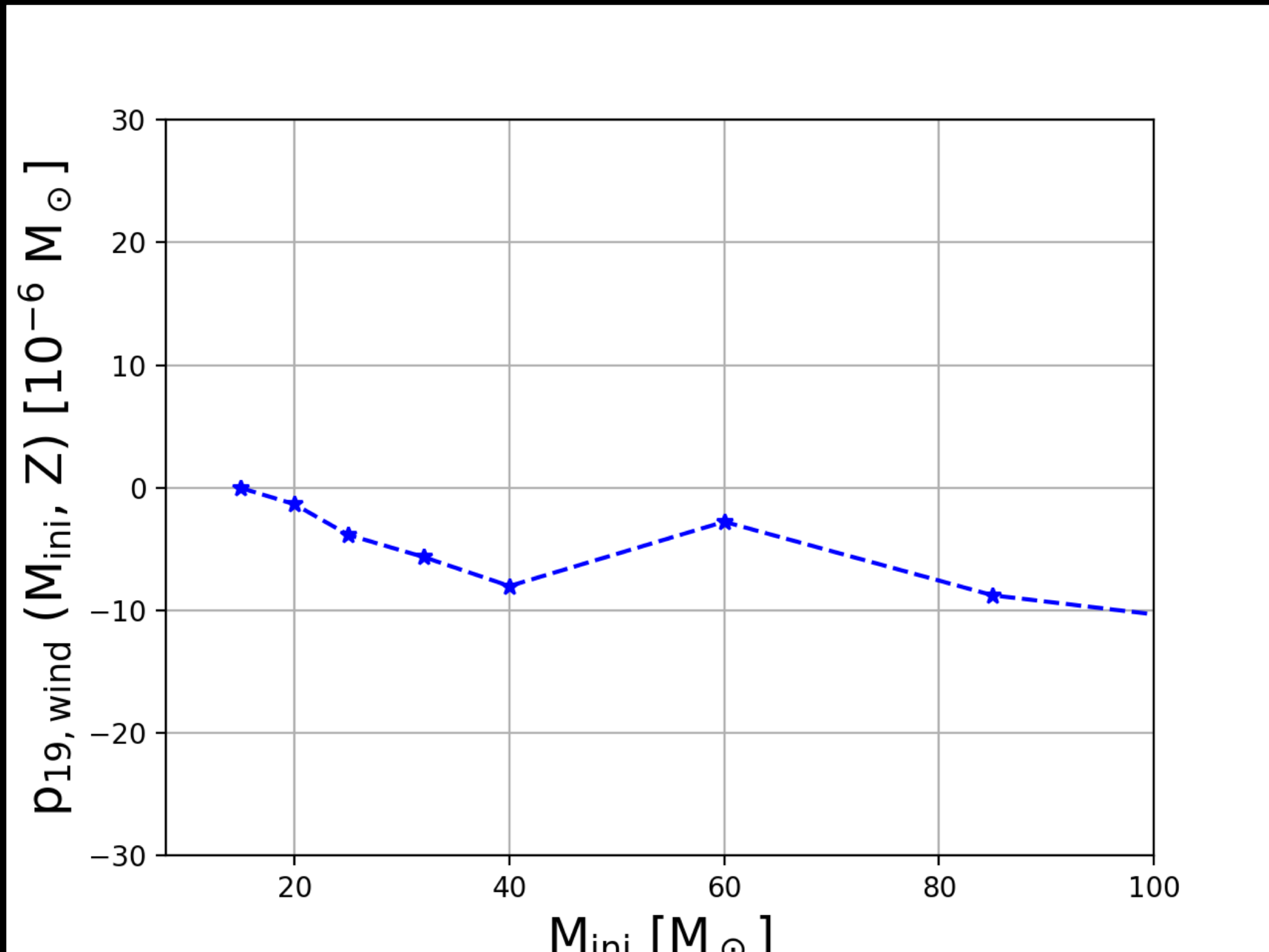
Nuclear reaction rates CF88-Nacre

Initial abundances Z=0.014

Rotational mixing effect included

Negative stellar yields : the H-rich layers are depleted in ^{19}F and overcome the effect ofnthe ejection of ^{19}F rich layers

Non-rotating

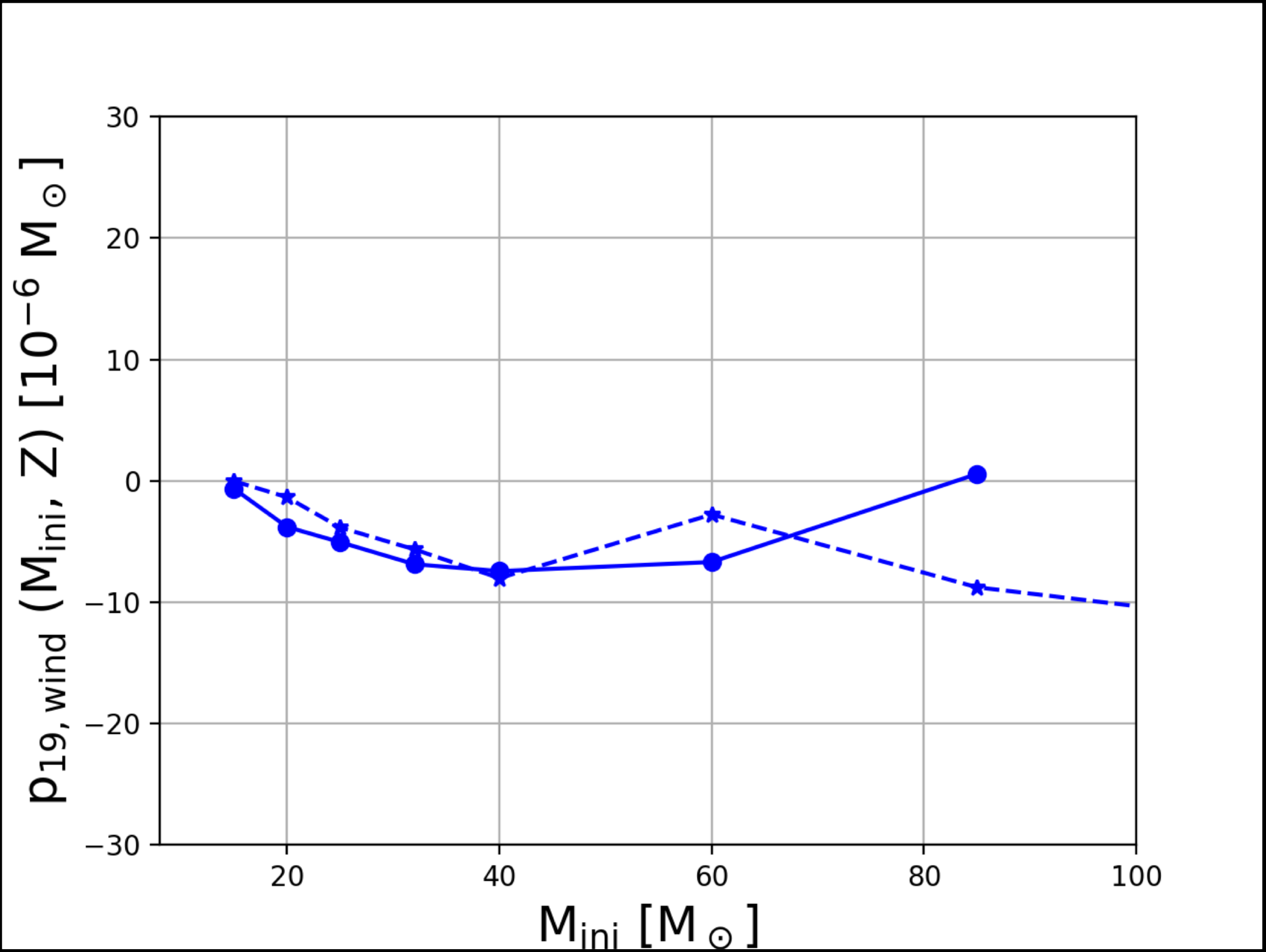


$$p_{19}^{\mathrm{wind}}(M_{\mathrm{i}}, Z) = \int_0^{\tau(M_{\mathrm{i}},Z)} [X_{19,\mathrm{S}}(M_{\mathrm{i}}, Z, t) - X_{19,\mathrm{S}}(Z, 0)]\dot{M}(M_{\mathrm{i}}, Z, t)\mathrm{d}t.$$

Models by Ekström+2012 No Rot Z=0.014

Rotation has small effects

Non-rotating
+
Rotating



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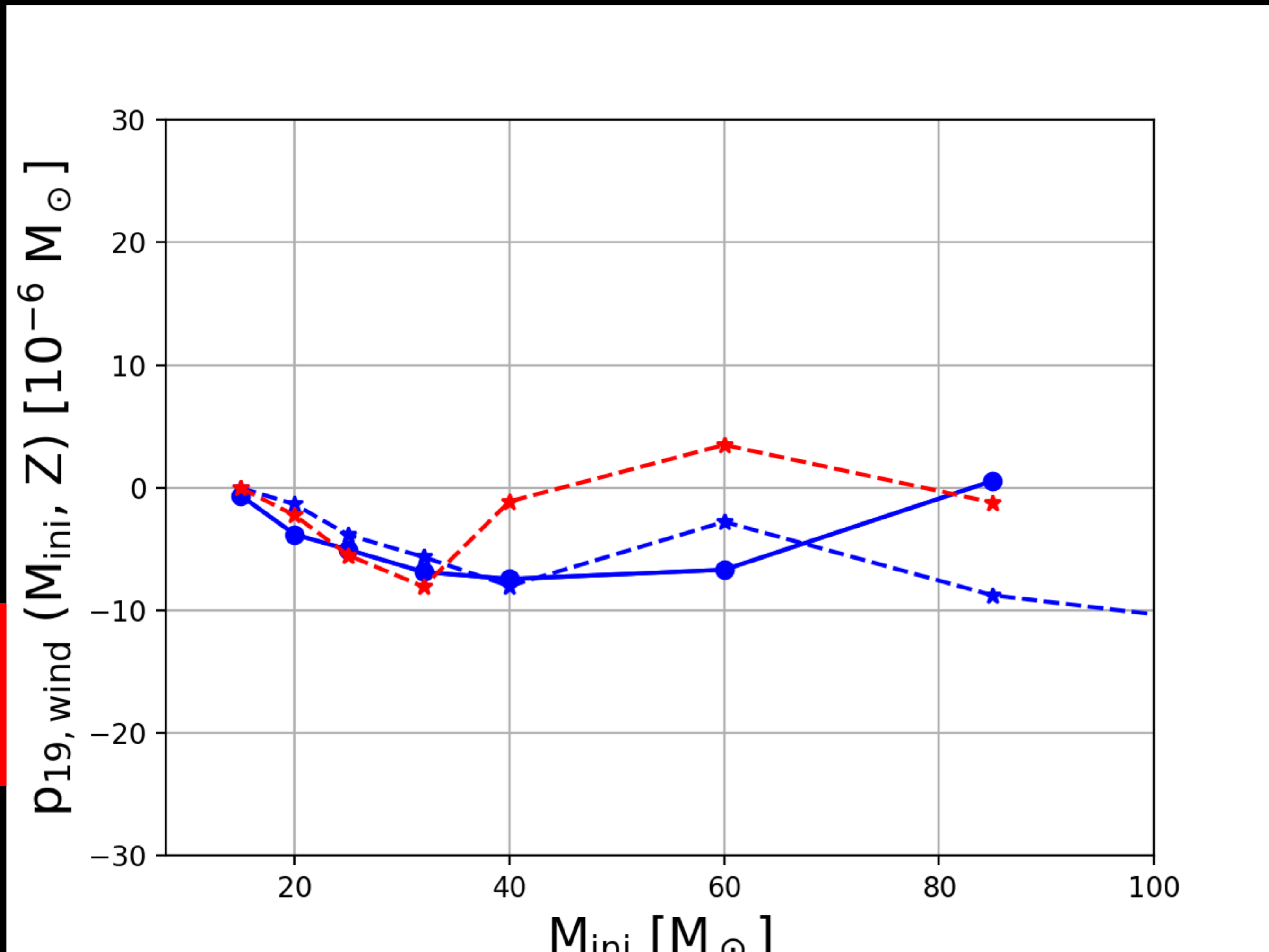
Models by Ekström+2012 No Rot Z=0.014

Change of initial composition, but same physics as Ekstöm+ 2012

Non-rotating
+
Rotating

Non-rotating
0.020
Yusof+In pre



Non-rotating
Z=0.020
Palacios+
2005

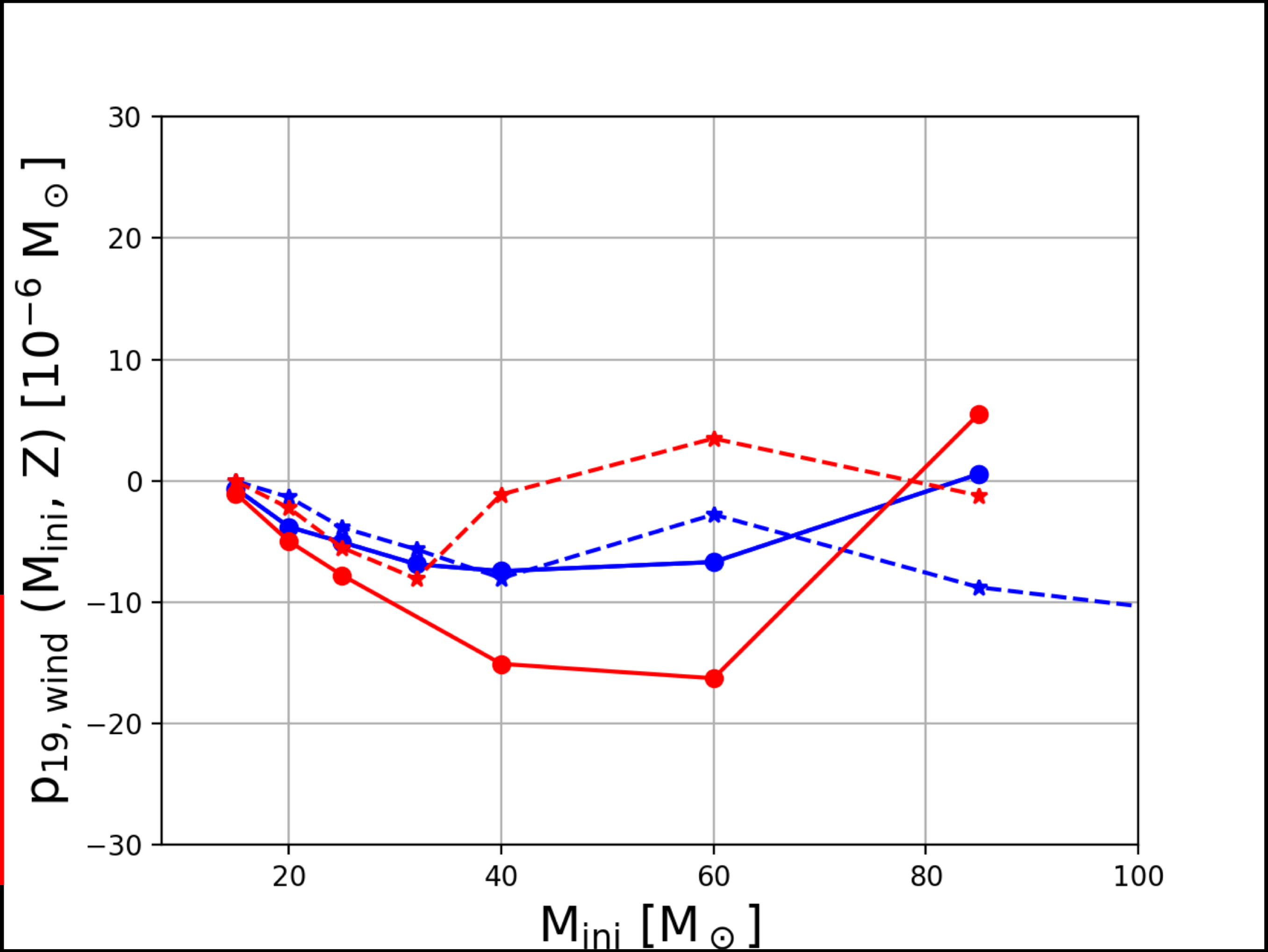
$$p_{19}^{\mathrm{wind}}(M_{\mathrm{i}}, Z) = \int_0^{\tau(M_{\mathrm{i}},Z)} [X_{19,\mathrm{S}}(M_{\mathrm{i}}, Z, t) - X_{19,\mathrm{S}}(Z, 0)]\dot{M}(M_{\mathrm{i}}, Z, t)\mathrm{d}t.$$

Models by Ekström+2012 No Rot Z=0.014

Change of initial composition+rotation, but same physics as Ekstöm+ 2012

Non-rotating
+
Rotating

Non-rotating
+
rotating
0.020
Yusof+In pre



Non-rotating
Z=0.020
Palacios+
2005

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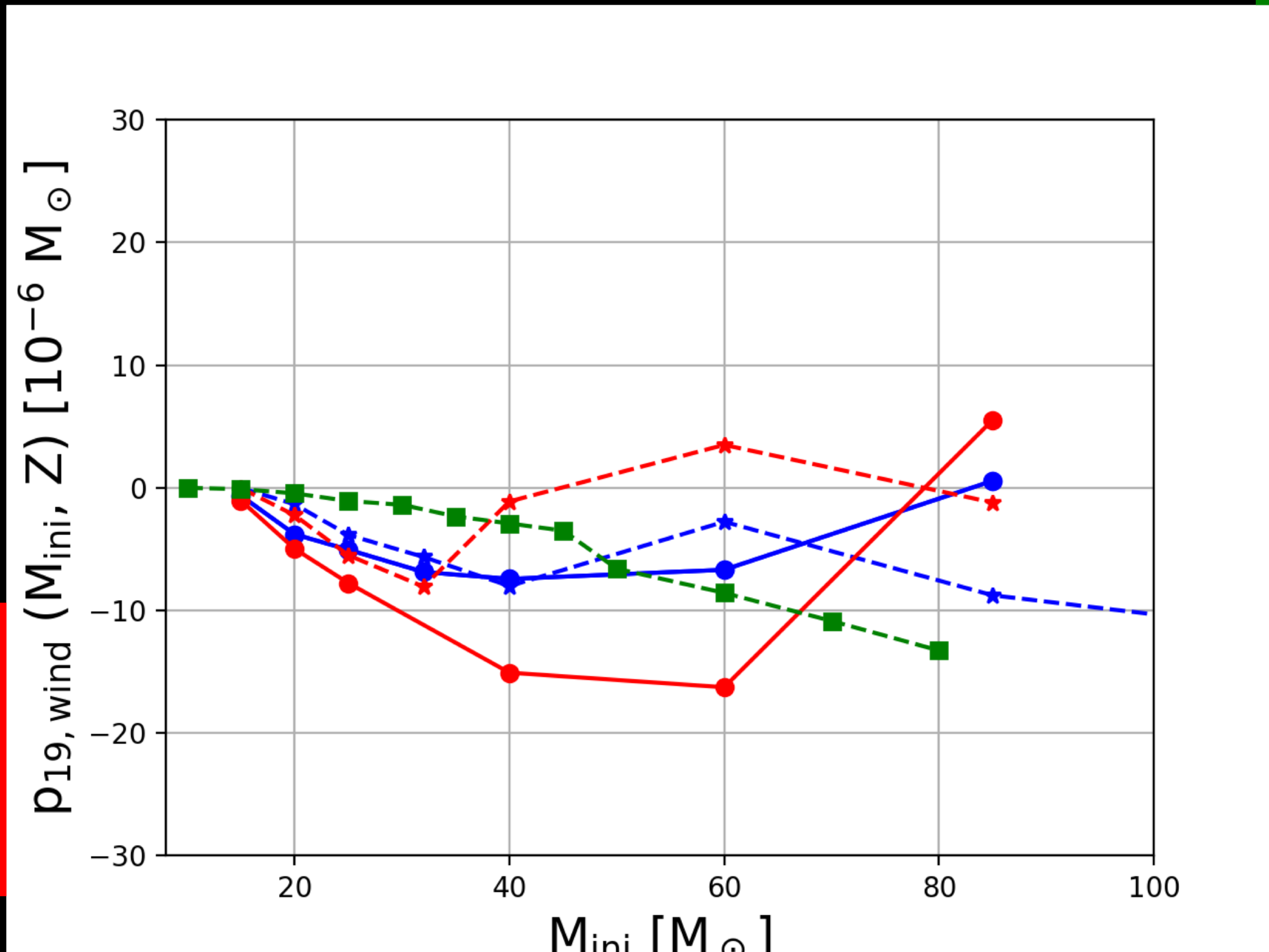
Models by Ekström+2012 No Rot Z=0.014

MESA models

Non-rotating
Z=0.014
MESA
Brinkmann
Private com

Non-rotating
+
Rotating

Non-rotating
+
rotating
0.020
Yusof+In pre



Non-rotating
Z=0.020
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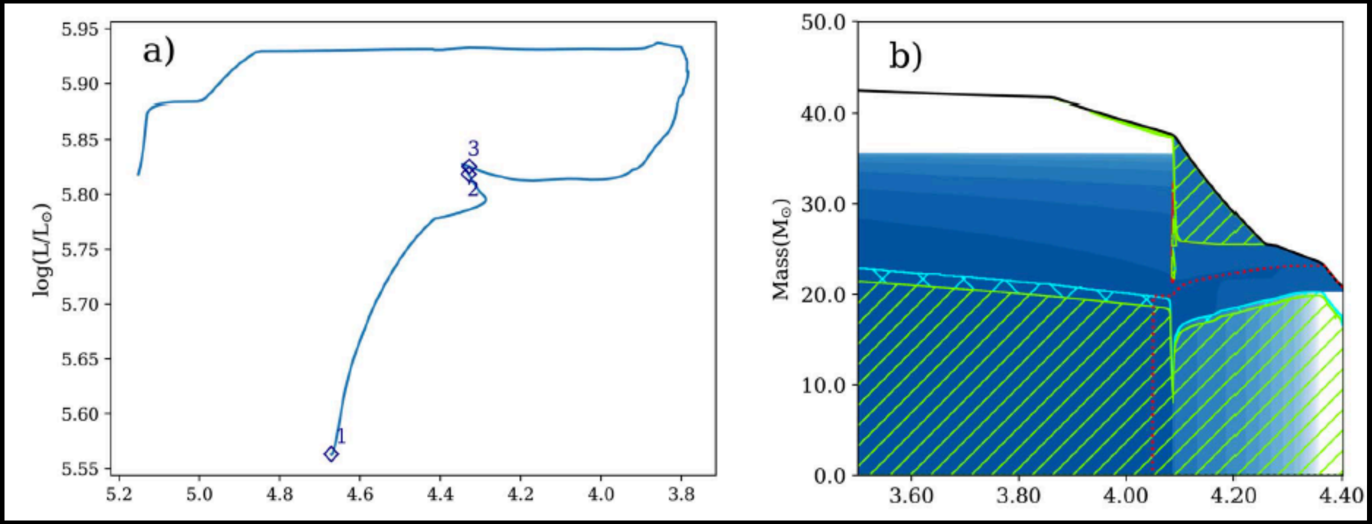
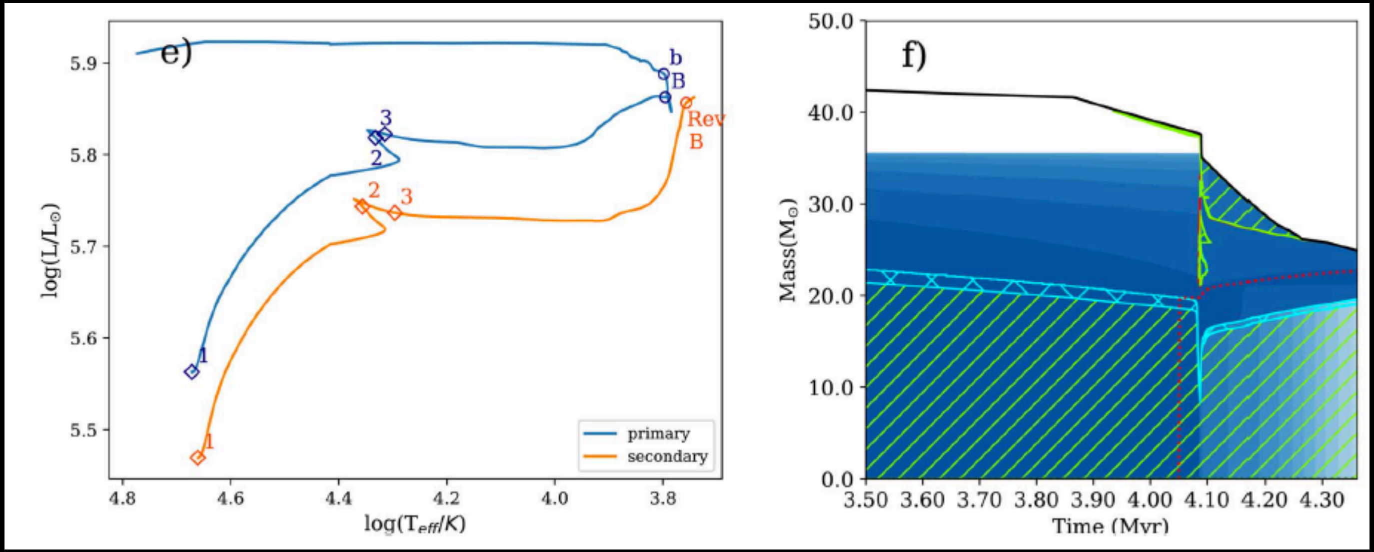
Models by Ekström+2012 No Rot Z=0.014

Close binaries

50 M_{sol}



50 M_{sol}+45M_{sol}, P_{ini}=72.3 day

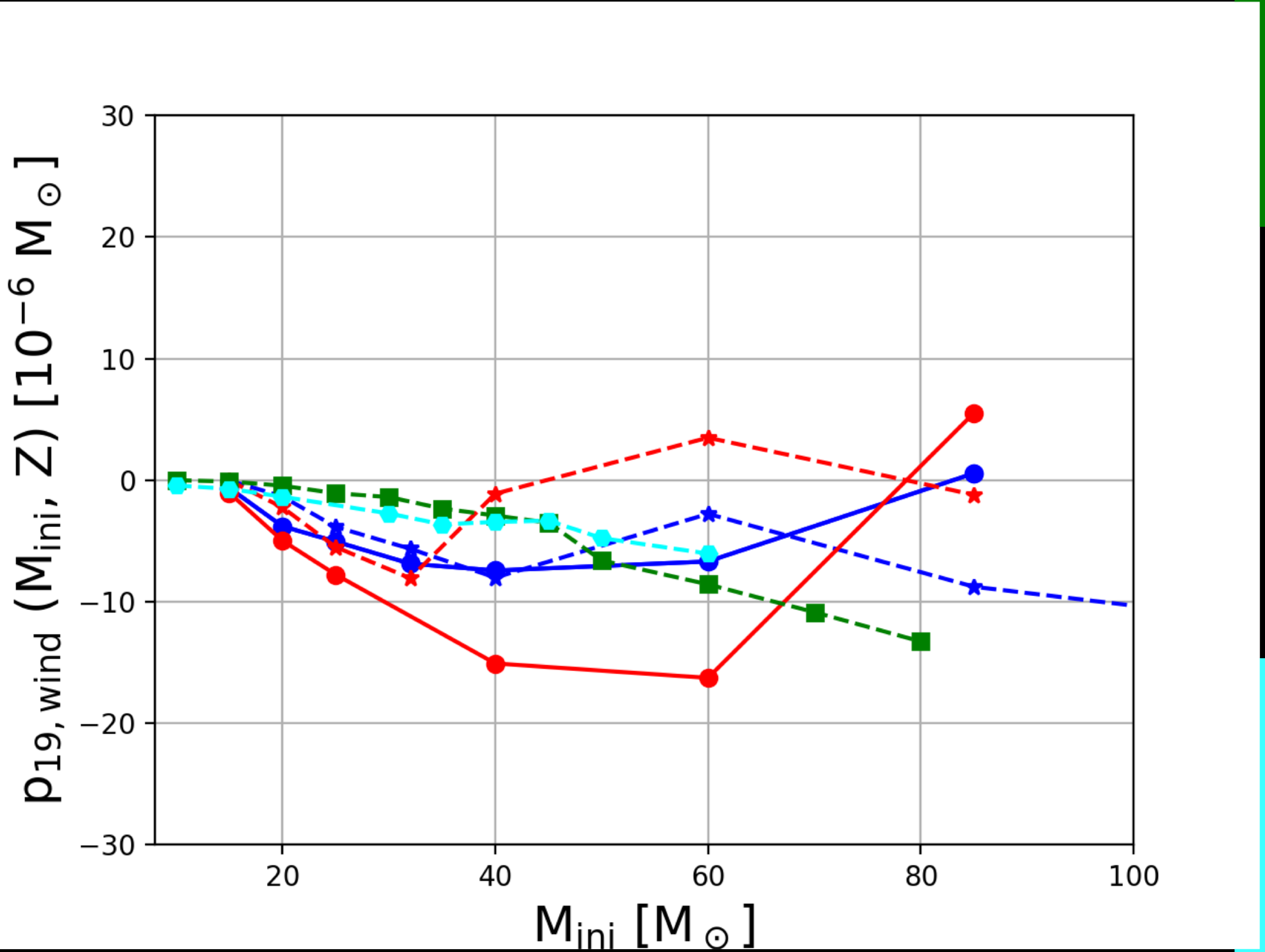


Brinkman+ 2019

CLOSE BINARIES

Non-rotating
Z=0.014
MESA
Brinkmann
Private com

Non-rotating
+
Rotating



Non-rotating
Z=0.020
Palacios+
2005

Non-rotating
+
rotating
0.020
Yusof+In pre

Non-rotating
binaries
Z=0.014
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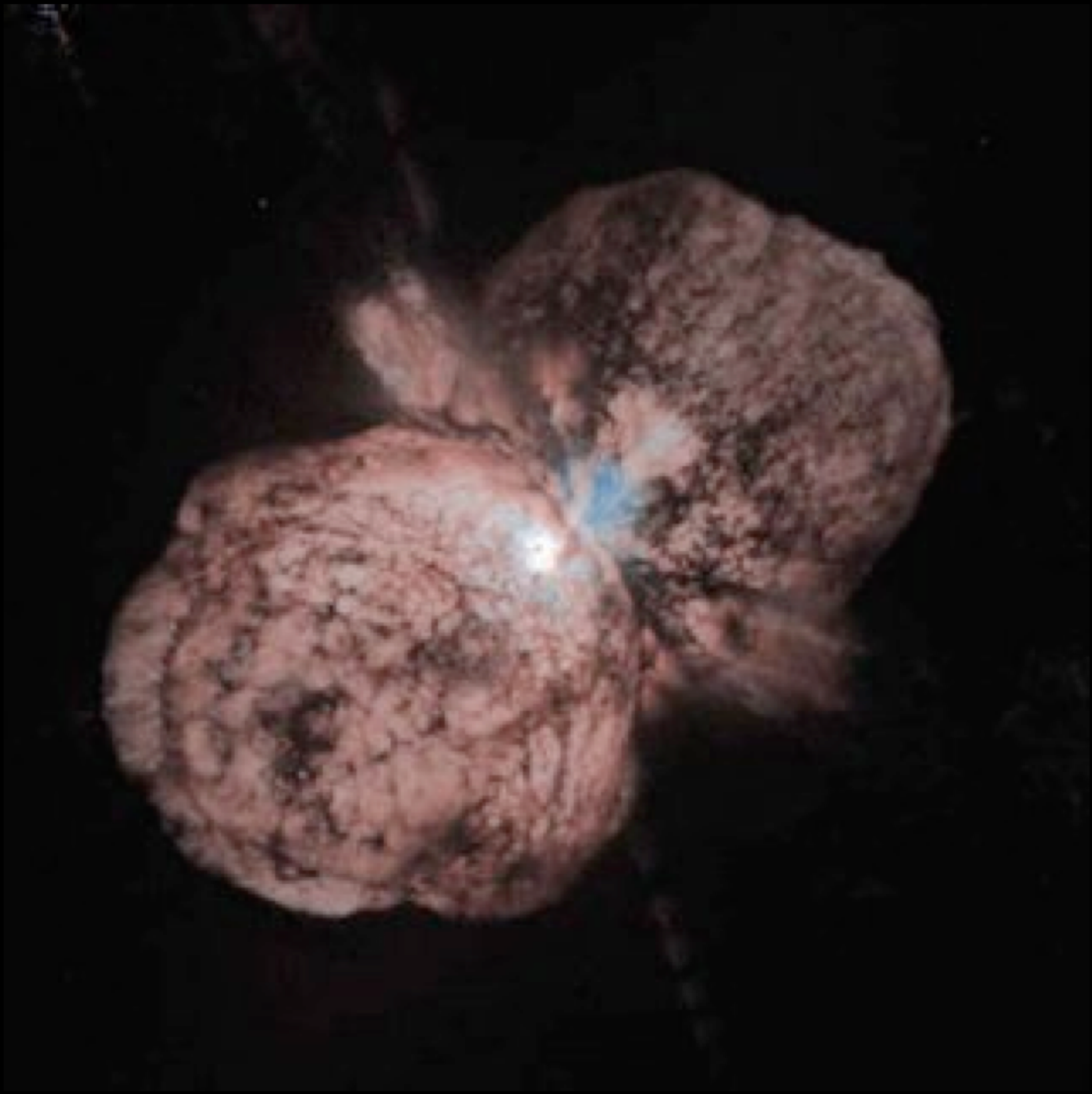
$$p_{19}^{\mathrm{wind}}(M_{\mathrm{i}}, Z) = \int_0^{\tau(M_{\mathrm{i}},Z)} [X_{19,\mathrm{S}}(M_{\mathrm{i}}, Z, t) - X_{19,\mathrm{S}}(Z, 0)]\dot{M}(M_{\mathrm{i}}, Z, t)\mathrm{d}t.$$

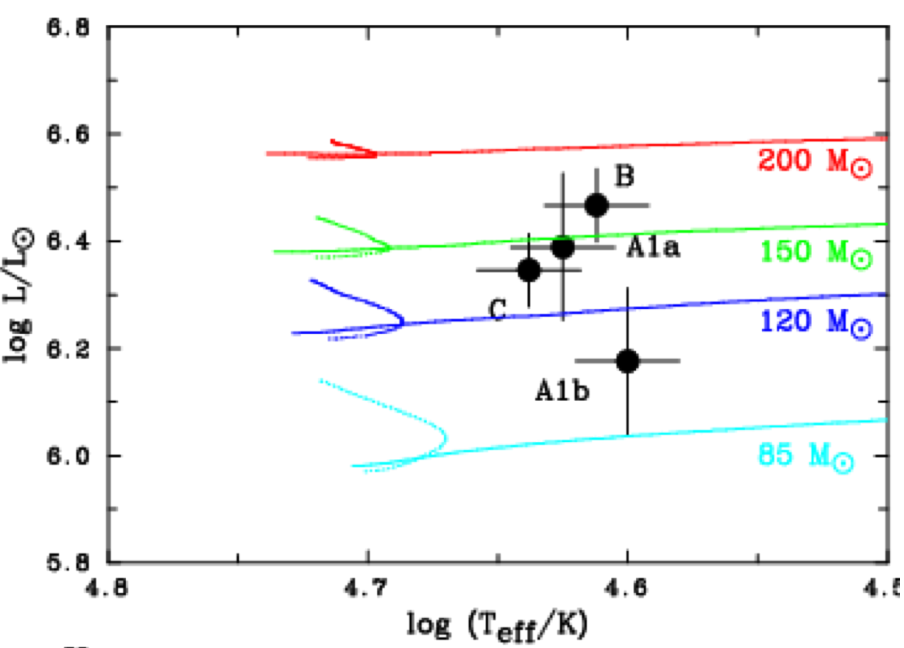
Models by Ekström+2012 No Rot Z=0.014

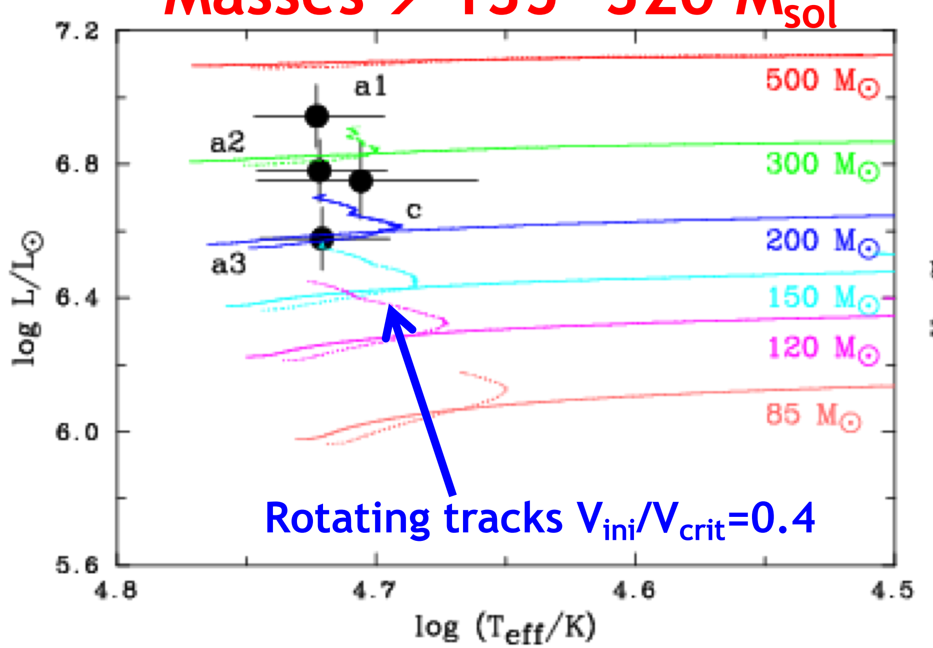
Very massive stars > 120 M_{sol}



Milky way, NGC 3603 :
10^4 M_{sol}, , age ~1.5 Myr
Masses→ 83 - 180 M_{sol}

LMC, R136 :
5 10^4 M_{sol}, , age ~1.7 Myr
Masses→ 135- 320 M_{sol}

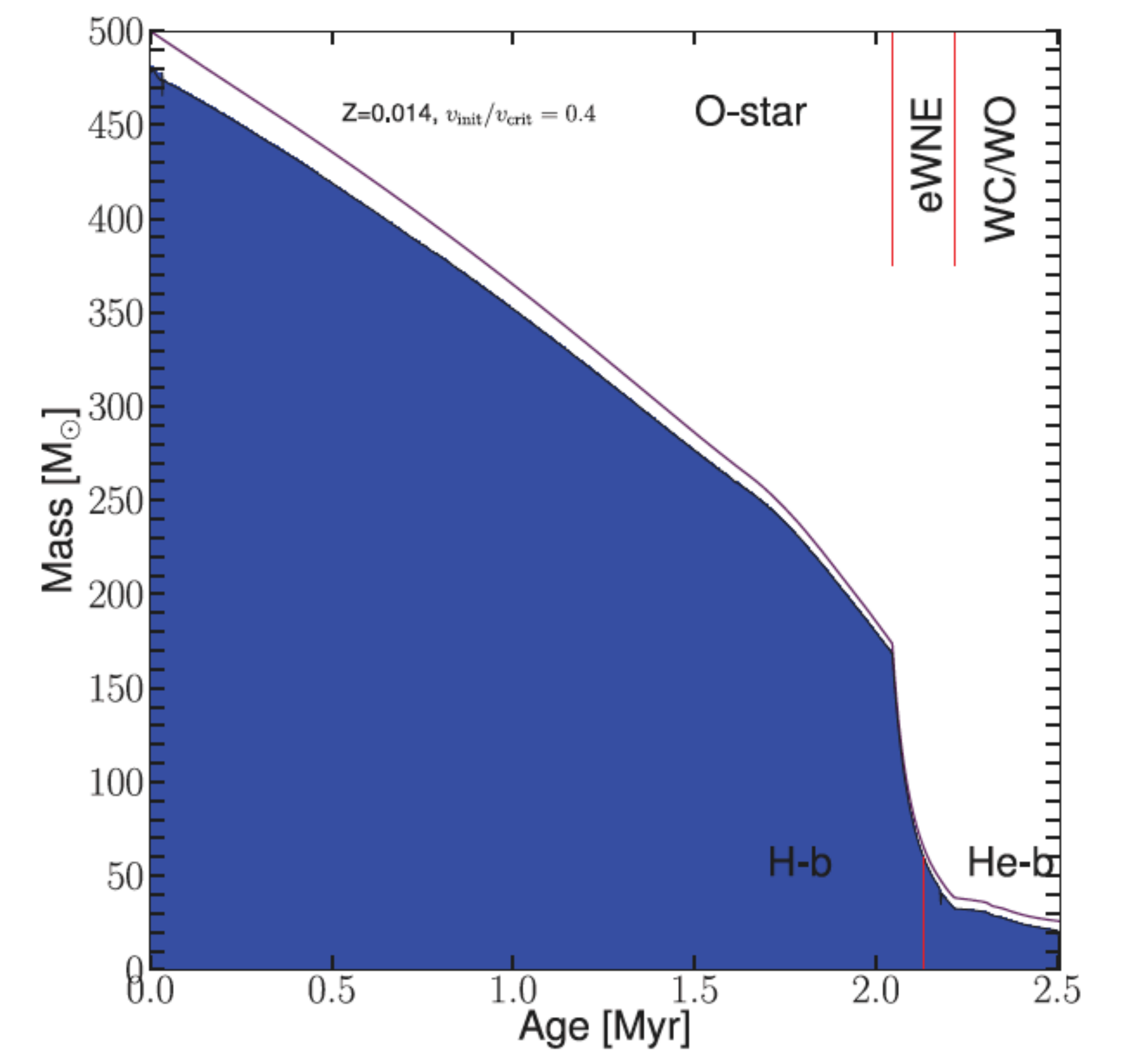




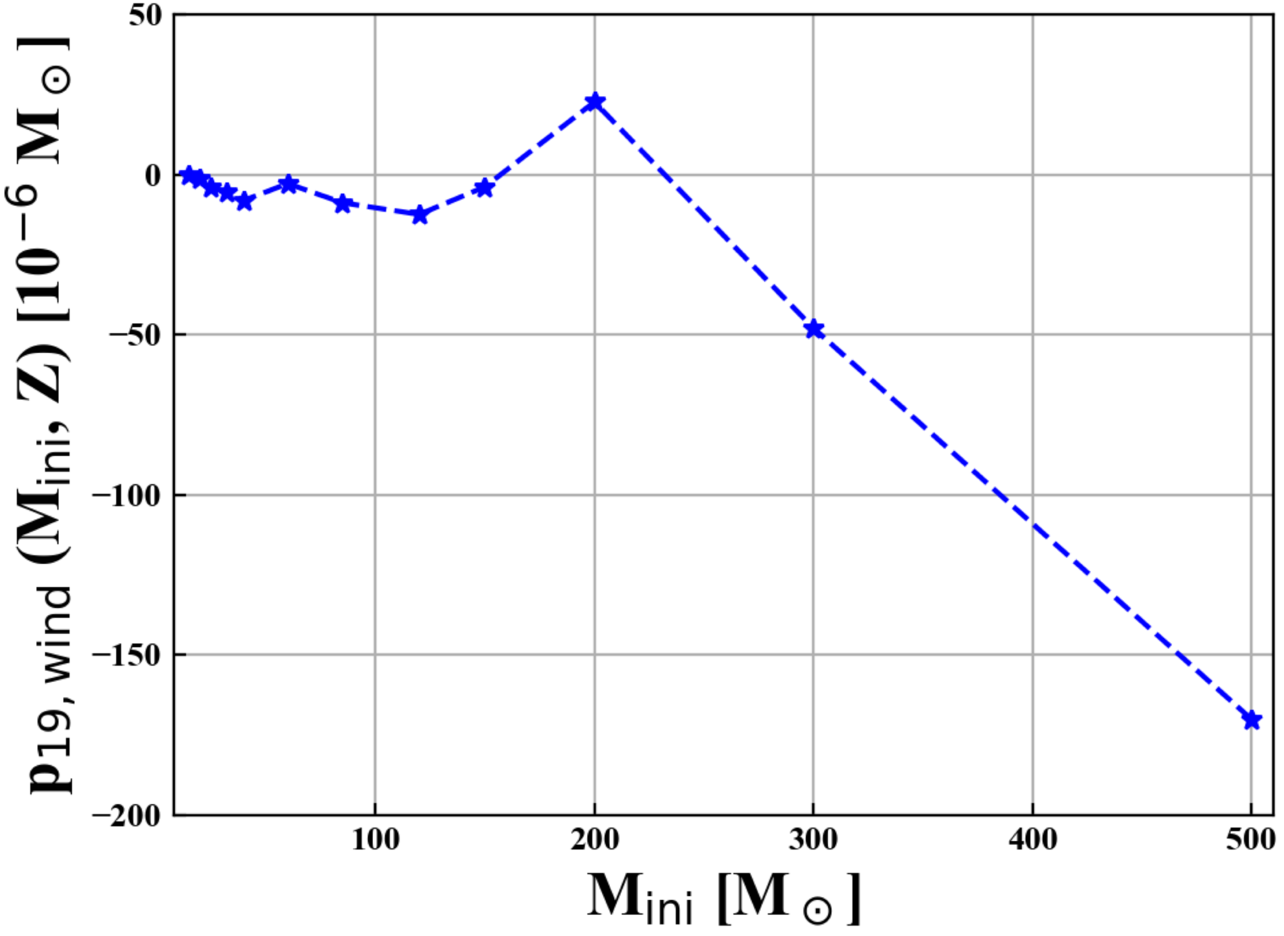
Crowther, Schnurr, Hirschi, Yusof, Parker, Goodwin, Abu Kassim, 2010

STARS WITH MASSES ABOVE 150 M_{sol}

$N(120\text{-}500M_{sol})$
$\sim$
$1./44\ N(8\text{-}120M_{sol})$



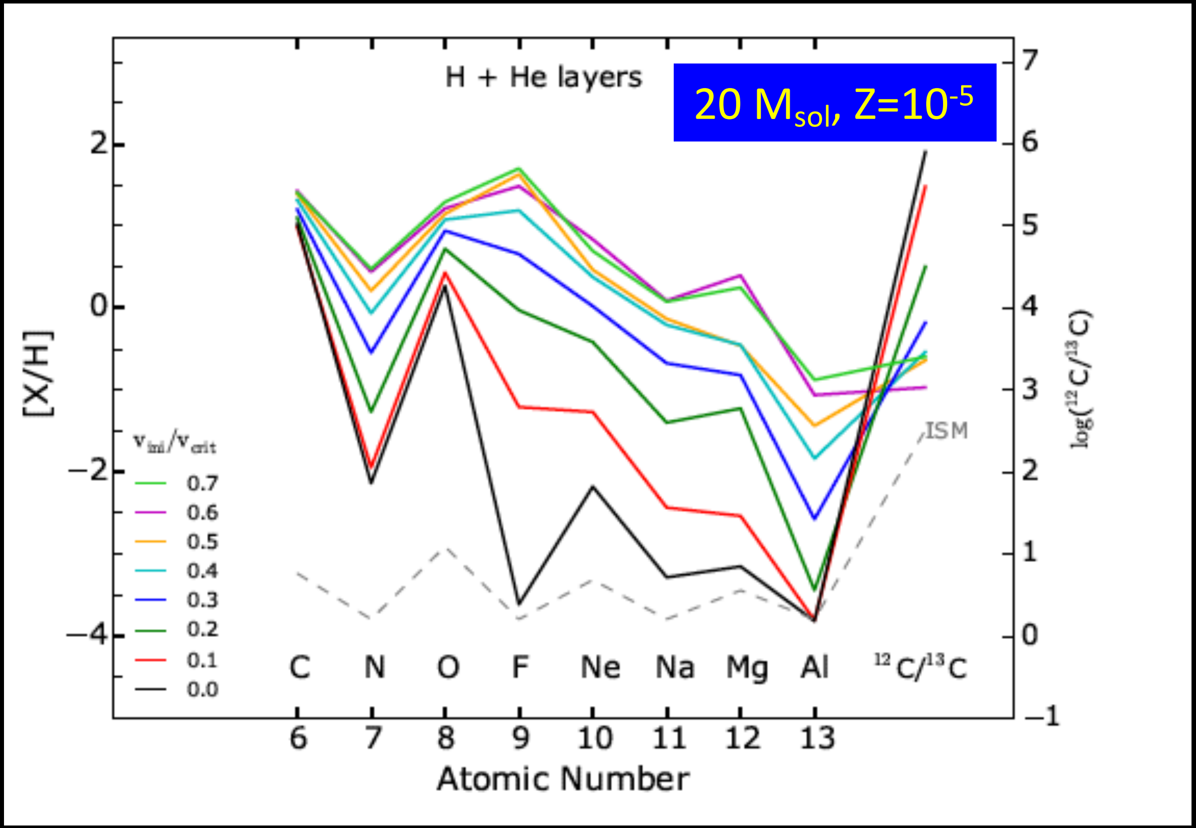
Yusof+ 2013



Very long phase during which material depleted in fluorine is ejected
Little mass removed when He-core uncorvered

Spinstars: metal-poor fast rotating massive stars

At low metallicity, rotational mixing is boosted
Mixing between the H-burning shell and the He-burning core enhance
^{13}C, ^{14}N, ^{19}F, ^{22}Ne, s-process elements



Choplin+ 2019

Application: origin of the Carbon enhanced metal poor stars

STRONG STELLAR WINDS AT THE RIGHT MOMENT

He-core has to be uncovered at the right moment: very early in the core He-burning phase and when this occurs, a lot of mass has to be wind ejected.

NO FREQUENT OCCURRENCE

These circumstances do not appear to occur frequently according to present day stellar models (GENEC-MESA) for single and binary stars, for very mass stars too.

ROLE OF MASSIVE STAR STELLAR WINDS

With the present day reduced mass losses from massive stars, Models predict that stellar winds cannot contribute to the ^{19}F enrichment of the ISM

SPINSTARS AND ^{19}F

Strong production of ^{19}F expected.
A prediction of Spinstar's model for CEMP stars.
What is the impact at the level of the MW?

And the ^{26}Al?
What is the importance of stellar winds?

Situation is much more favorable

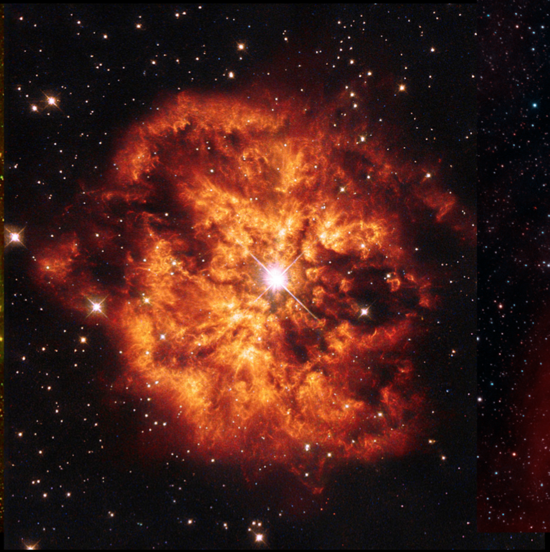
^{19}F and ^{26}Al share a common property

Built in stars at some stage and destroyed if kept locked in the star

^{26}Al → core H-burning phase
^{19}F → core He-burning phase

Stellar winds can save them from destruction!






- Enriched layers have to be removed at the right moment
- Other elements share this property → He, ^{12}C, ^{13}C, ^{22}Ne

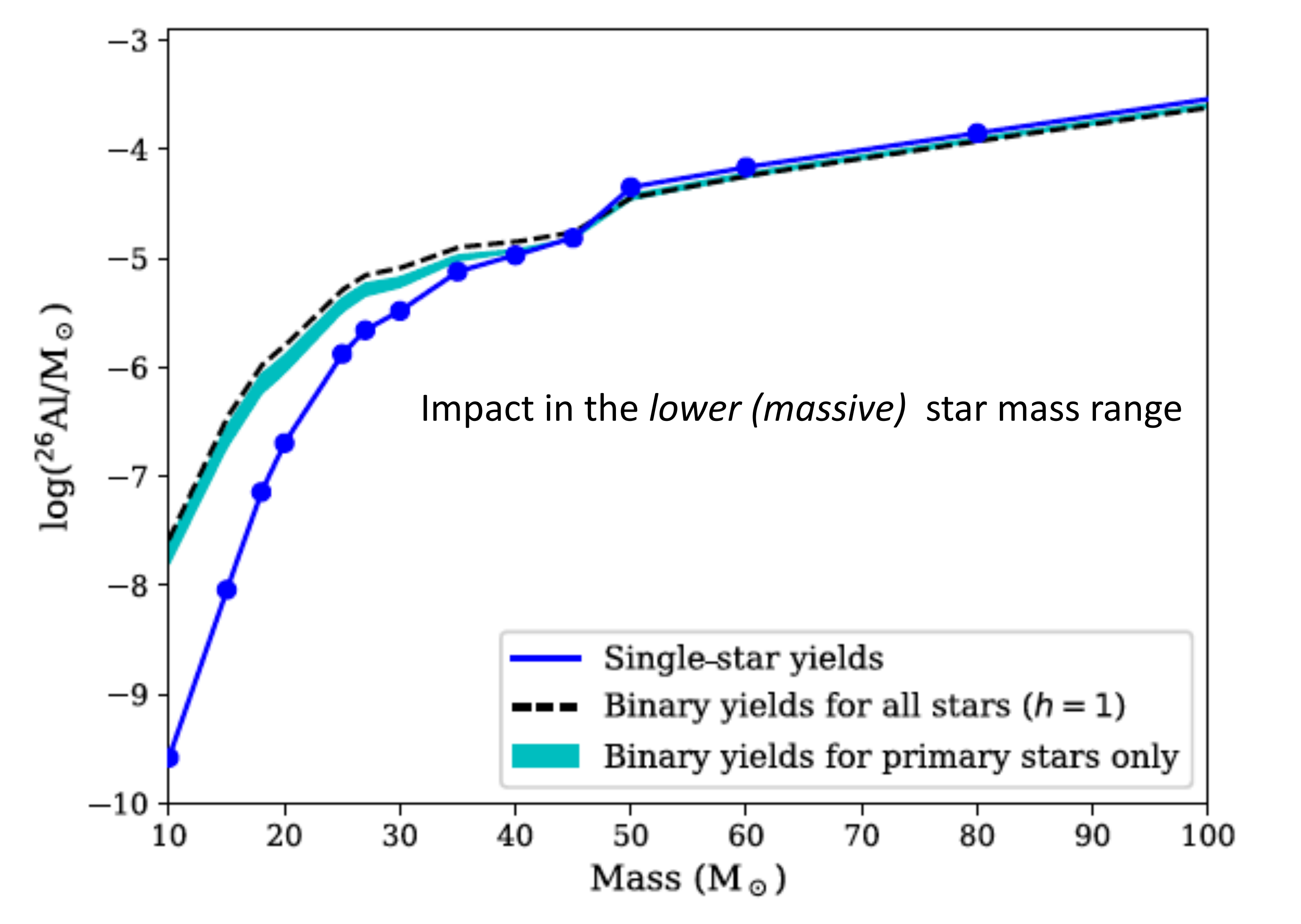
Comparison of stellar winds impacts on ^{19}F and ^{26}Al

FLUORINE 19	ALUMINIUM 26
Produced at the beginning of the core He-burning phase In the He-burning core	Produced during the core H-burning phase in the H-burning core
He-core needs be uncovered at early time and star still have Kept sufficient mass for strong mass losses	H-rich stellar winds during the Main-Sequence phase and the Phases before any WC phase
Rotation has little impact Very massive stars have little impact, close binaries have some effects	Rotation has an impact, Very massive stars have an impact, Close binaries have some effects

The Astrophysical Journal, 884:38 (19pp), 2019 October 10 https://doi.org/10.3847/1538-4357/ab40ae

Aluminium-26 from Massive Binary Stars. I. Nonrotating Models*

H. E. Brinkman[1,2], C. L. Doherty[1,3], O. R. Pols[4], E. T. Li[5], B. Côté[1,6], and M. Lugaro[1,3]



VERY MASSIVE STARS

Z	v_{ini}	M_{ini} [M$_\odot$]							
		40	60	85	120	150	200	300	500
0,002	0		0,060	0,157	0,651				
	40 %(v_{critique})		0,057	0,284	0,311				
0,014	0		0,718	1,680	3,714	6,217	11,94	32,58	76,11
	40 %(v_{critique})	0,422	1,100	2,643	7,289				

$$\int_0^R 2\pi r\sigma(r)\,\mathrm{d}r \int_{M_\star=8}^{120} \Phi(M_\star)\,\mathrm{d}M_\star = 2\times 10^4\ \mathrm{Ma}^{-1}.$$

Number of core-collapse SNe in the last 1 Myr (2 per century)

$$P_{26} = \int_0^R 2\pi r\sigma(r) \int_{M_\star=M_{\min}}^{M_{\max}} \Phi(M_\star)\cdot M_{^{26}\mathrm{Al}}^{\mathrm{totale}}(M_\star)|_{v_\star,Z_\star}\,\mathrm{d}M_\star\,\mathrm{d}r.$$

Mass of 26Al produced per unit time in the MW

$$M_{26}(t) = \tau\cdot P_{26} \equiv M_{26}^{\mathrm{gal}}.$$

Mass present in the MW now, assuming steady state, $\tau\sim 1$ Myr

	vitesse [%(v_{critique})]	$M_{^{26}\mathrm{Al}}$ [M$_\odot$]	$M_\star\ \in$	méthode
Z=0.014	0	0,141	[0,1 ; 120] M$_\odot$	calculé
	0	$\boxed{0,931}$	$\boxed{[0,1\ ;\ 500]\ \mathrm{M}_\odot}$	calculé
	40	0,560	[0,1 ; 120] M$_\odot$	calculé
	$\boxed{40}$	$\boxed{3,698}$	[0,1 ; 500] M$_\odot$	$\boxed{\text{extrapolé}}$

SOLAR METALLICITY MASSIVE STARS

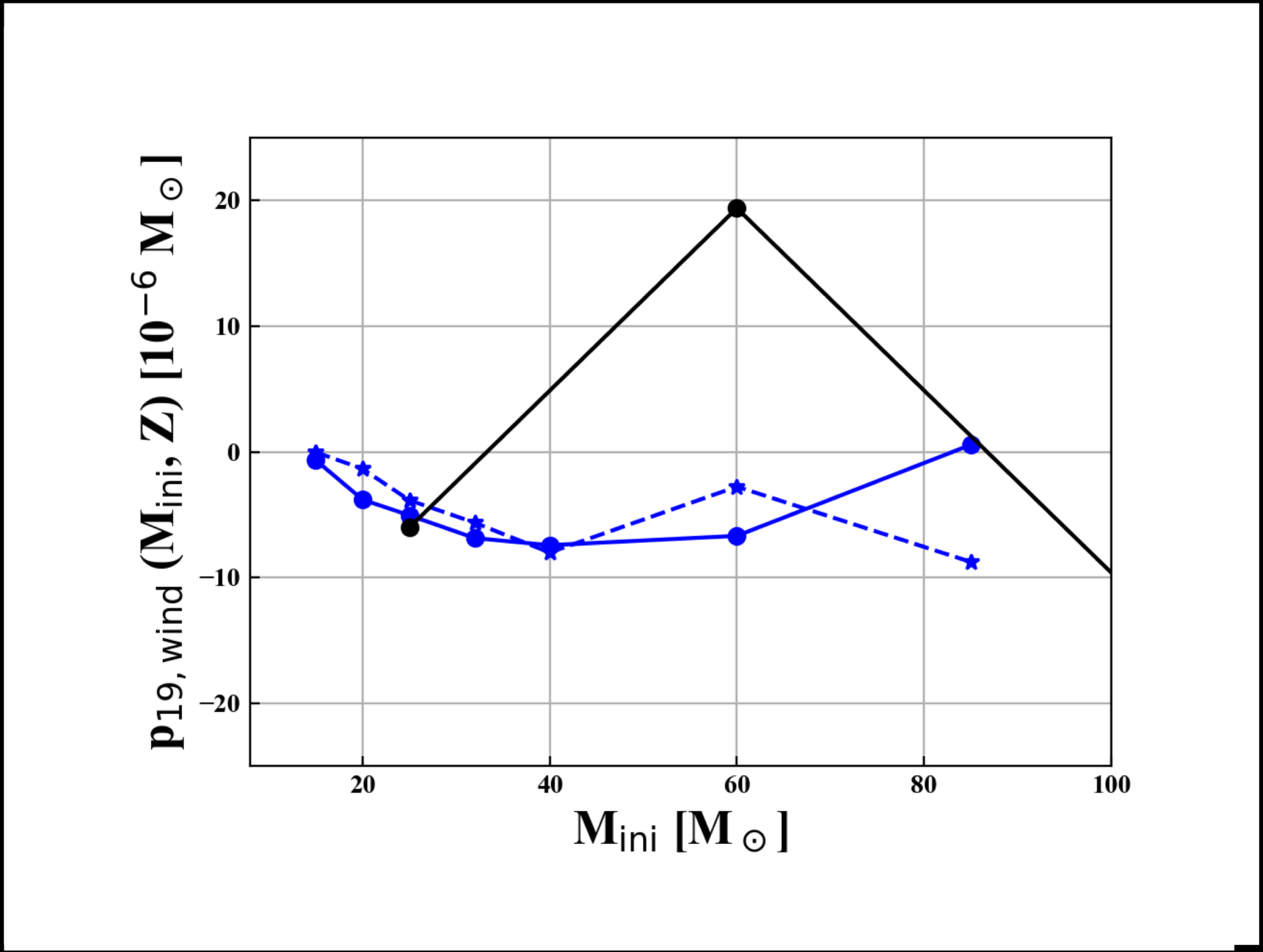
Models by Ekström + 2012 → ~0.5 M_{sol} of ^{26}Al from stellar winds in the MW

SOLAR METALLICITY VERY MASSIVE STARS

May enhance significantly the ^{26}Al production by massive stellar winds**, up to 1 to 4 M_{sol}**

Change of initial composition→ 0.020→ 0.014 tends to lower the yields

Non-rotating + Rotating



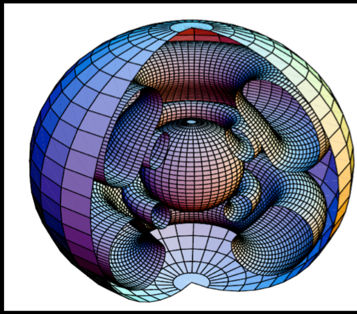
Non-rotating Z=0.020 Palacios+ 2005

$$p_{19}^{\rm wind}(M_{\rm i},Z) = \int_0^{\tau(M_{\rm i},Z)} [X_{19,\rm S}(M_{\rm i},Z,t) - X_{19,\rm S}(Z,0)]\dot{M}(M_{\rm i},Z,t){\rm d}t.$$

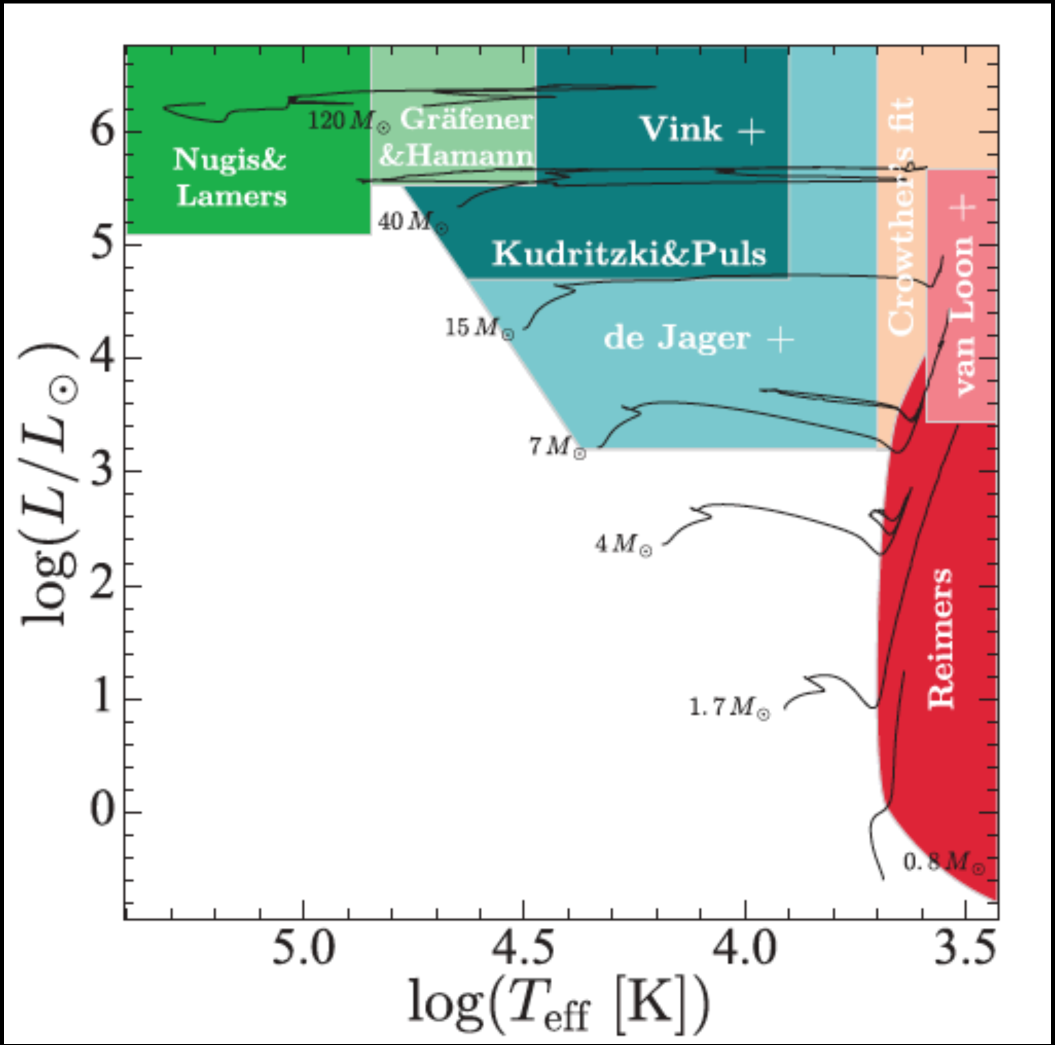
Models by Ekström+2012 No Rot Z=0.014

Effect of rotation?

<u>Phase when Fluorine is abundant in the core is too short for allowing rotational mixing to play a big role (at solar Z)</u>



Rotation changes the tracks in the HRD, modifies the impact of mass loss by stellar winds



Solar abundances revisited

logarithmic scale with H defined to have 12.00

Element	Anders & Grevesse (1989)	Asplund et al. (2005)	Mass fractions Decreased
Carbon	8.56+/-0.06	8.39+/-0.05	-32%
Nitrogen	8.05+/-0.04	7.80+/-0.05	-44%
Oxygen	8.93+/-0.03	8.66+/-0.05	-54%
	C+N+O→ 0.015	C+N+O→ 0.080	

3D hydrodynamical solar model atmosphere

- Non-LTE line formation when necessary
- Atomic and molecular lines with improved data

Nuclear reactions

Effects of nuclear cross sections on ^{19}F nucleosynthesis at low metallicities
(Research Note)

S. Cristallo[1,2], A. Di Leva[3,2], G. Imbriani[3,2], L. Piersanti[1,2], C. Abia[4], L. Gialanella[5,2], and O. Straniero[1,2]

Reaction rate	Old source	New source
1 Proton captures		
^{14}N(p,γ)^{15}O	Formicola et al. (2004)	Adelberger et al. (2011)
^{15}N(p,γ)^{16}O	Angulo et al. (1999)	Leblanc et al. (2010)
^{17}O(p,γ)^{18}F	Angulo et al. (1999)	Scott et al. (2012)
^{18}O(p,γ)^{19}F	Angulo et al. (1999)	Iliadis et al. (2010)
^{15}N(p,α)^{12}C	Angulo et al. (1999)	Angulo et al. (1999)
^{17}O(p,α)^{14}N	Angulo et al. (1999)	Iliadis et al. (2010)
^{18}O(p,α)^{15}N	Angulo et al. (1999)	Iliadis et al. (2010)
^{19}F(p,α)^{16}O	Angulo et al. (1999)	La Cognata et al. (2011)
α captures		
^{14}C(α,γ)^{18}O	Caughlan & Fowler (1988)	Lugaro et al. (2004)
^{14}N(α,γ)^{18}F	Görres et al. (2000)	Iliadis et al. (2010)
^{15}N(α,γ)^{19}F	Angulo et al. (1999)	Iliadis et al. (2010)
^{18}O(α,γ)^{22}Ne	Giesen et al. (1994)	Iliadis et al. (2010)
^{19}F(α,p)^{22}Ne	Ugalde (2005)	Ugalde et al. (2008)
^{13}C(α,n)^{16}O	Drotleff et al. (1993)	Heil et al. (2008)

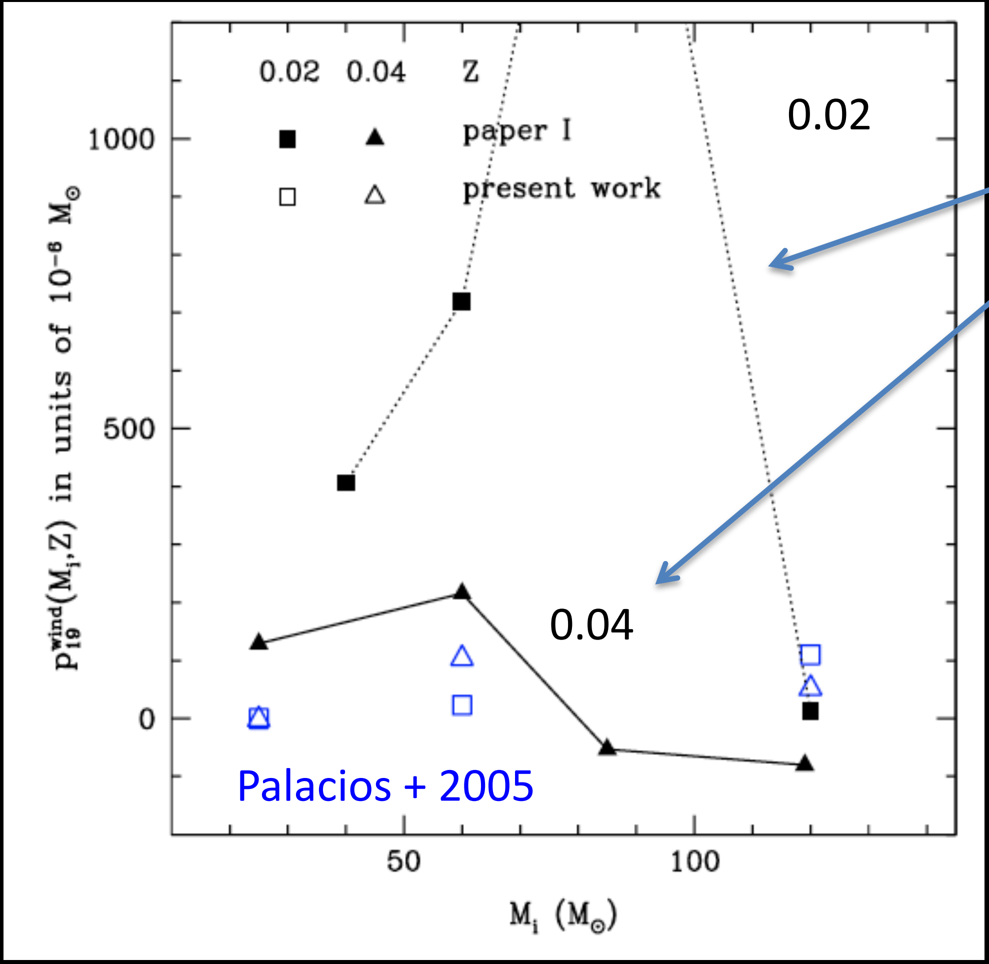
→ Minor effects

^{15}N(α,γ)^{19}F and the ^{19}F(α,p)^{22}Ne

The thermonuclear production of ^{19}F by Wolf-Rayet stars revisited

A. Palacios[1], M. Arnould[1], and G. Meynet[2]

A&A 443, 243–250 (2005)



Meynet & Arnould 2000

Effect of rotation small

These models → WR would not be important contributors