The production of ^{19}F in AGB stars: observational and theoretical problems

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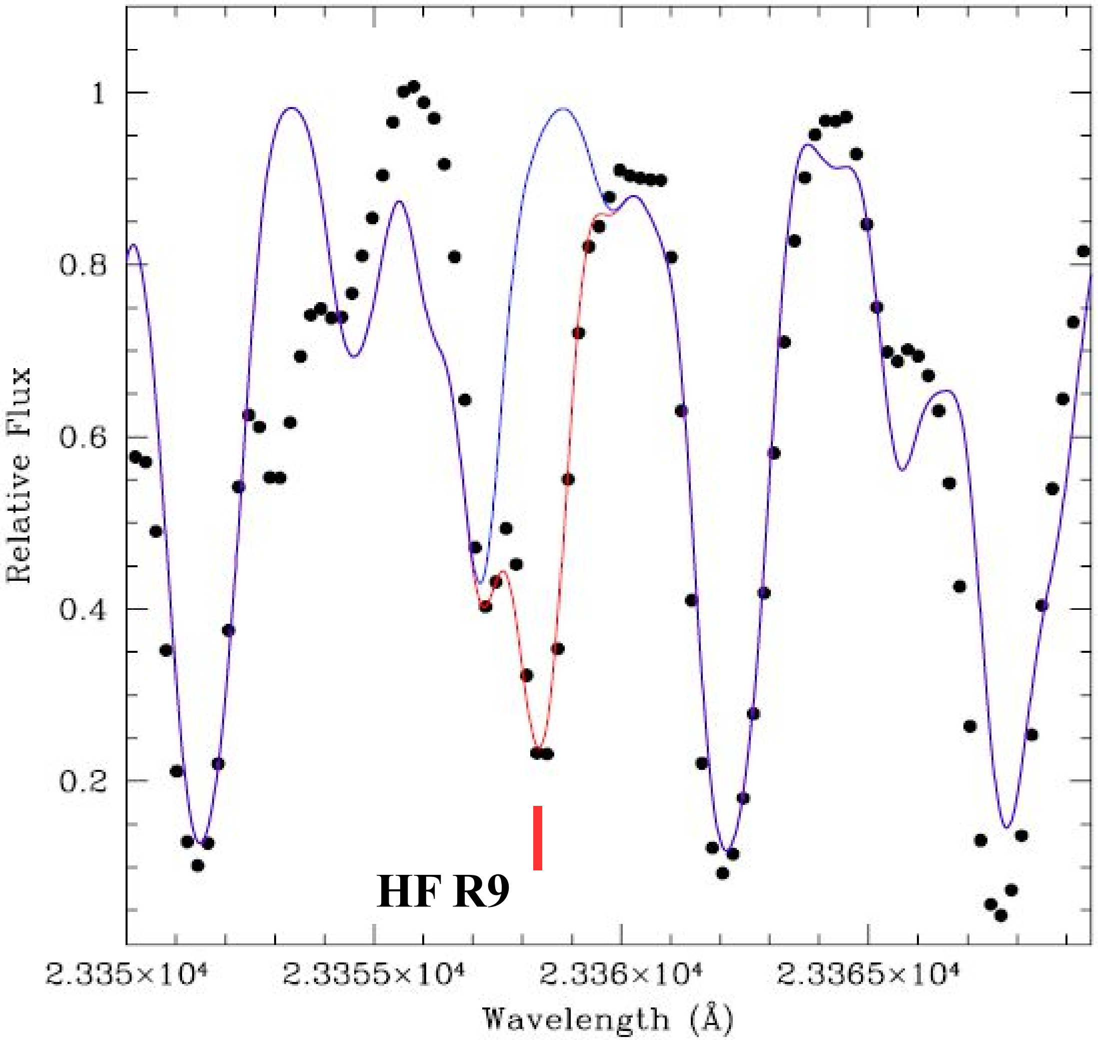
➢ ^{19}F is a fragile element easily destroyed by p & α captures and difficult to observe in astronomical objects

Origin not very well known...

1. ν-induced spallation in **SN II** (Woosley et al. 1990)
2. **AGB** stars (Forestini et al. 1992)
3. Hydrostatic **He-burning** in heavy mass-losing **WR** (Meynet & Arnould 2000)
4. He + CO **WD** mergers (Longland et al. 2011)

→ Sources 1 & 4 seem to be discarded as significant ^{19}F contributors

...Only AGB stars show observational evidence of F production, (Jorissen et al. 1992) **confirmed by observations in post-AGB stars and planetary nebulae** (Werner et al. 2009; Zhang & Liu 2005; Pandey et al. 2008; Otsuka et al. 2011)

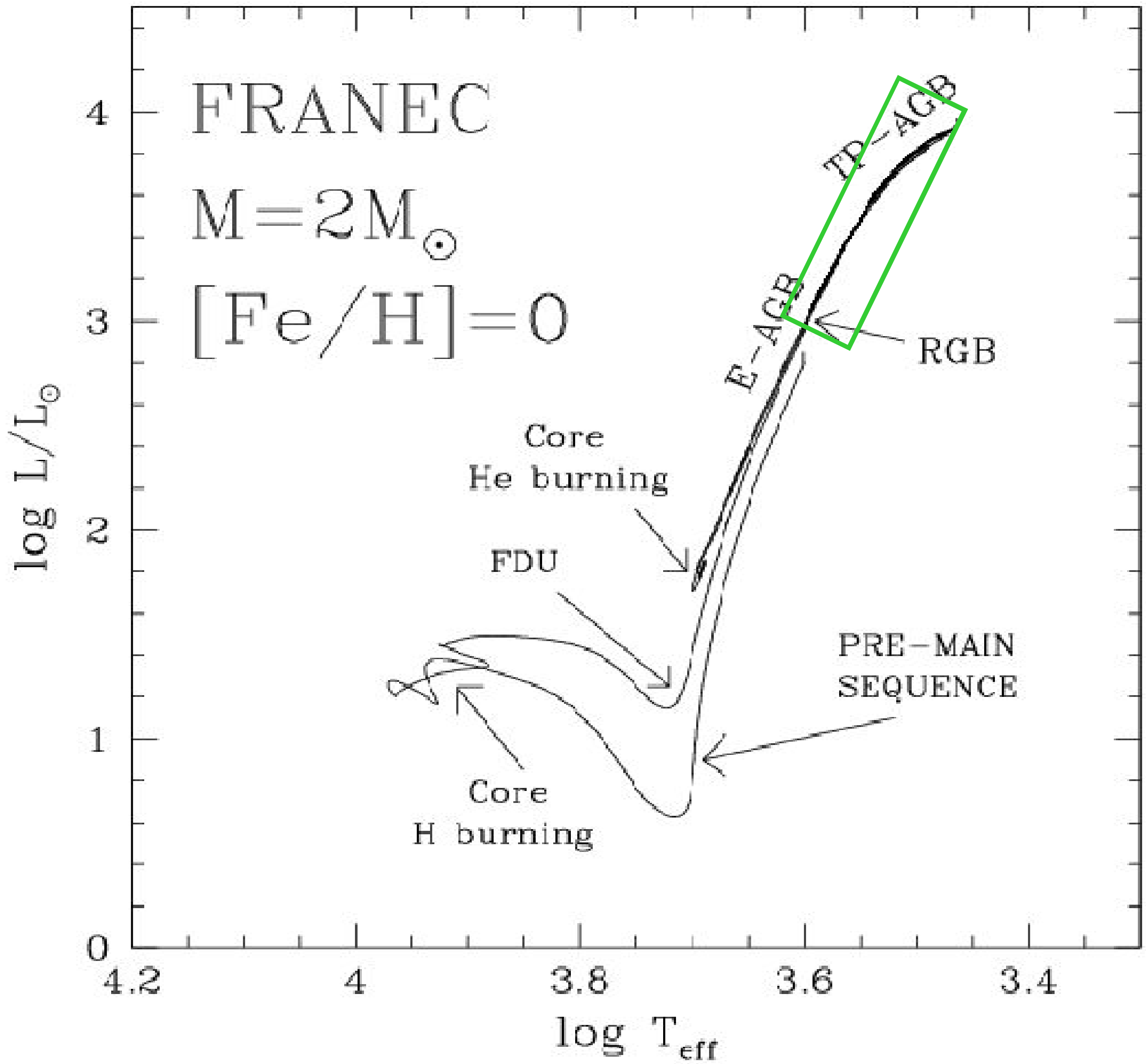


WZ Cas: a typical AGB carbon star

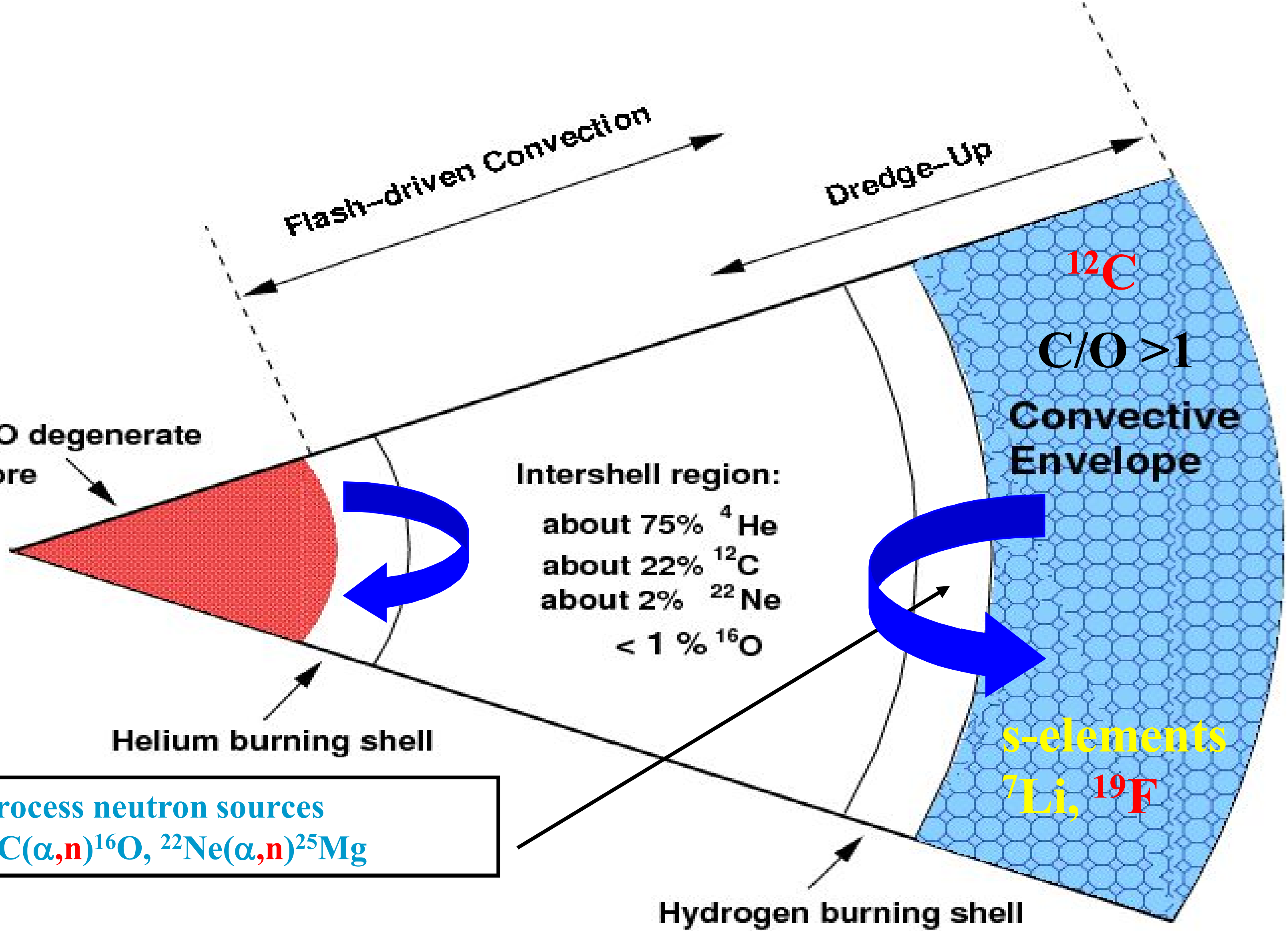
T_{eff} = 2800 K, [Fe/H] = 0.0
C/O = 1.01

[F/Fe] = +0.95 ± 0.18

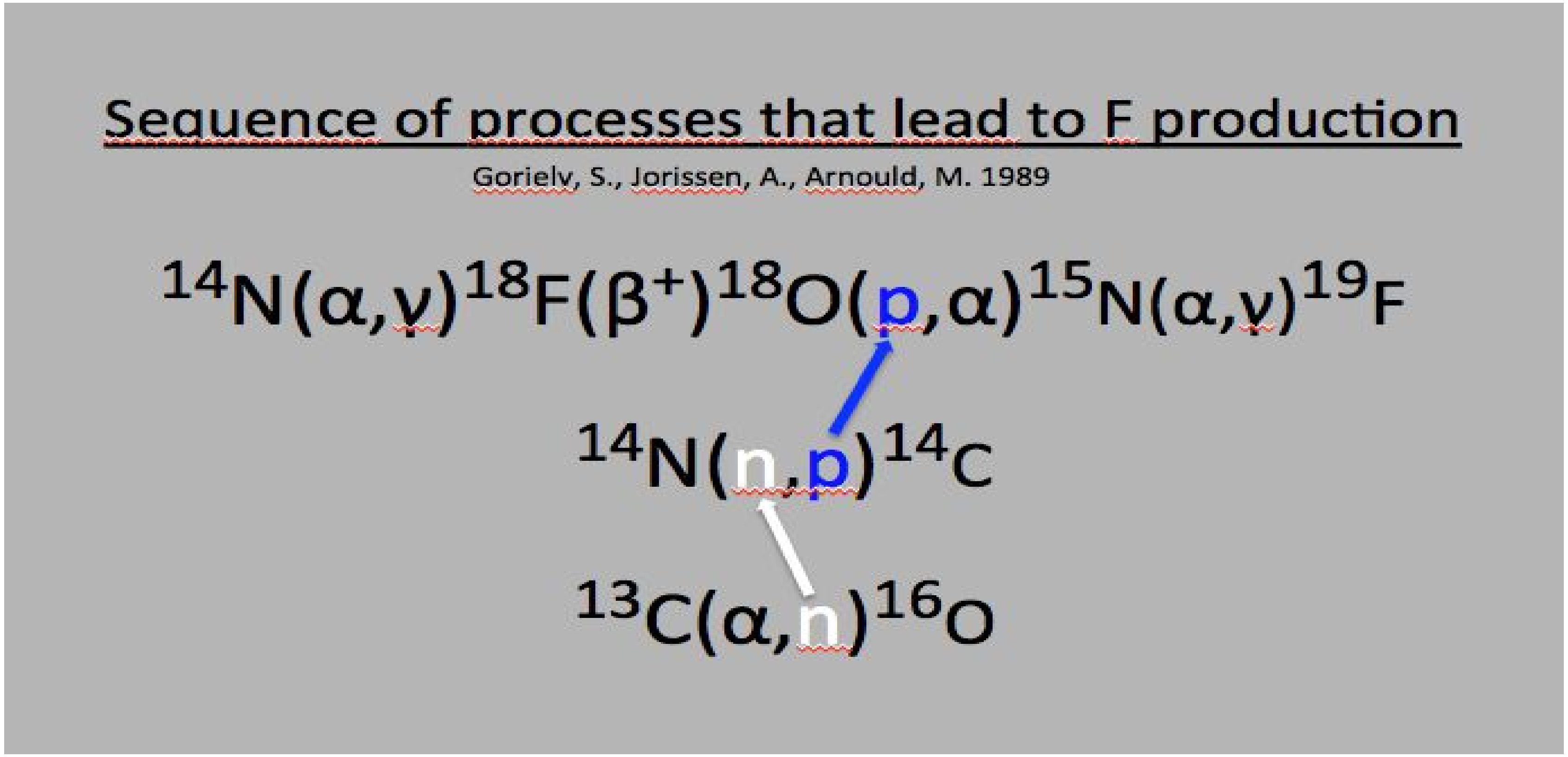
AGB stars: “*the laboratory for nucleosynthesis*”



AGB stars: "*the laboratory for nucleosynthesis*" *(not a scale)*



s-process neutron sources
$^{13}C(\alpha,n)^{16}O$, $^{22}Ne(\alpha,n)^{25}Mg$

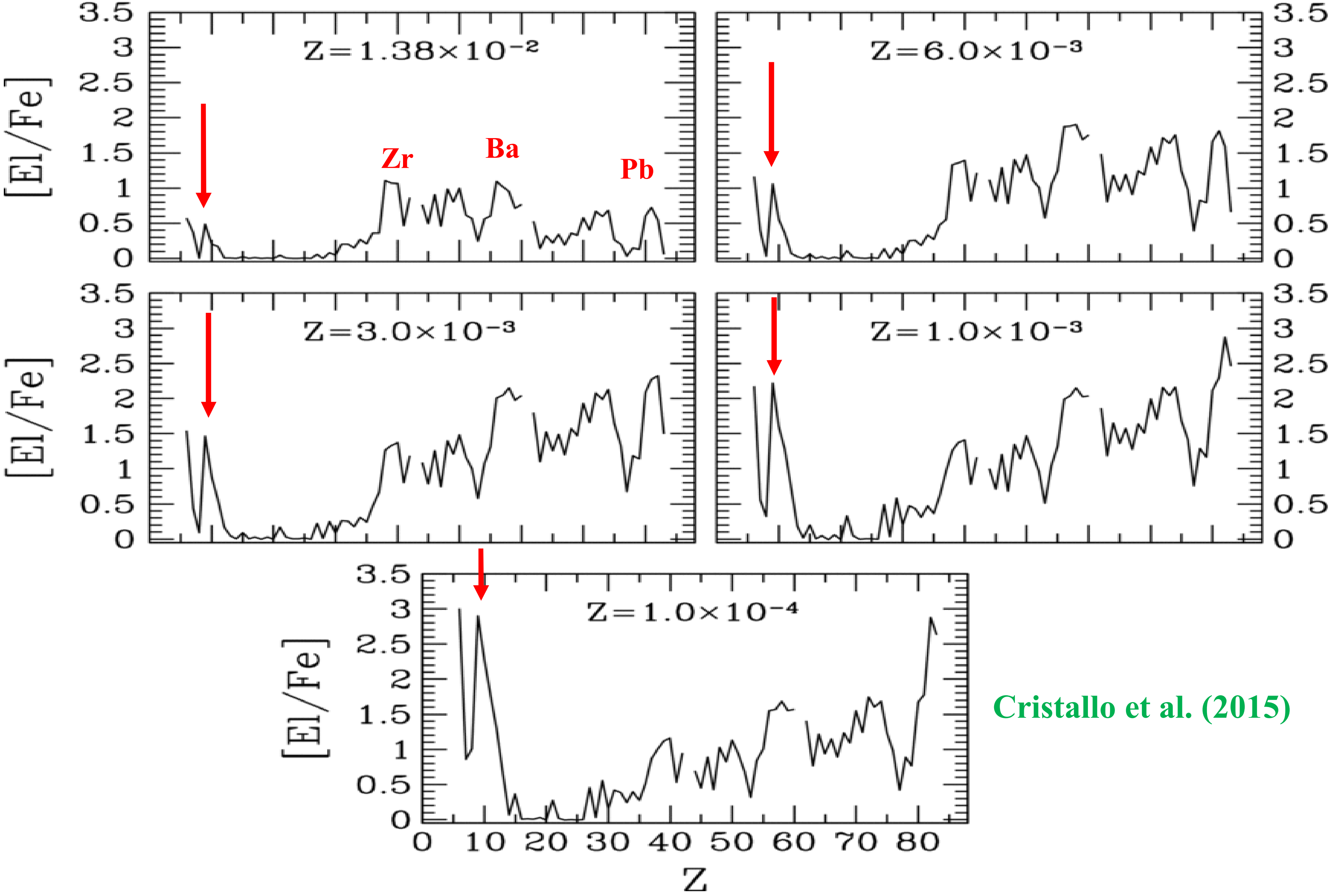


1. F & s-elements are produced simultaneously

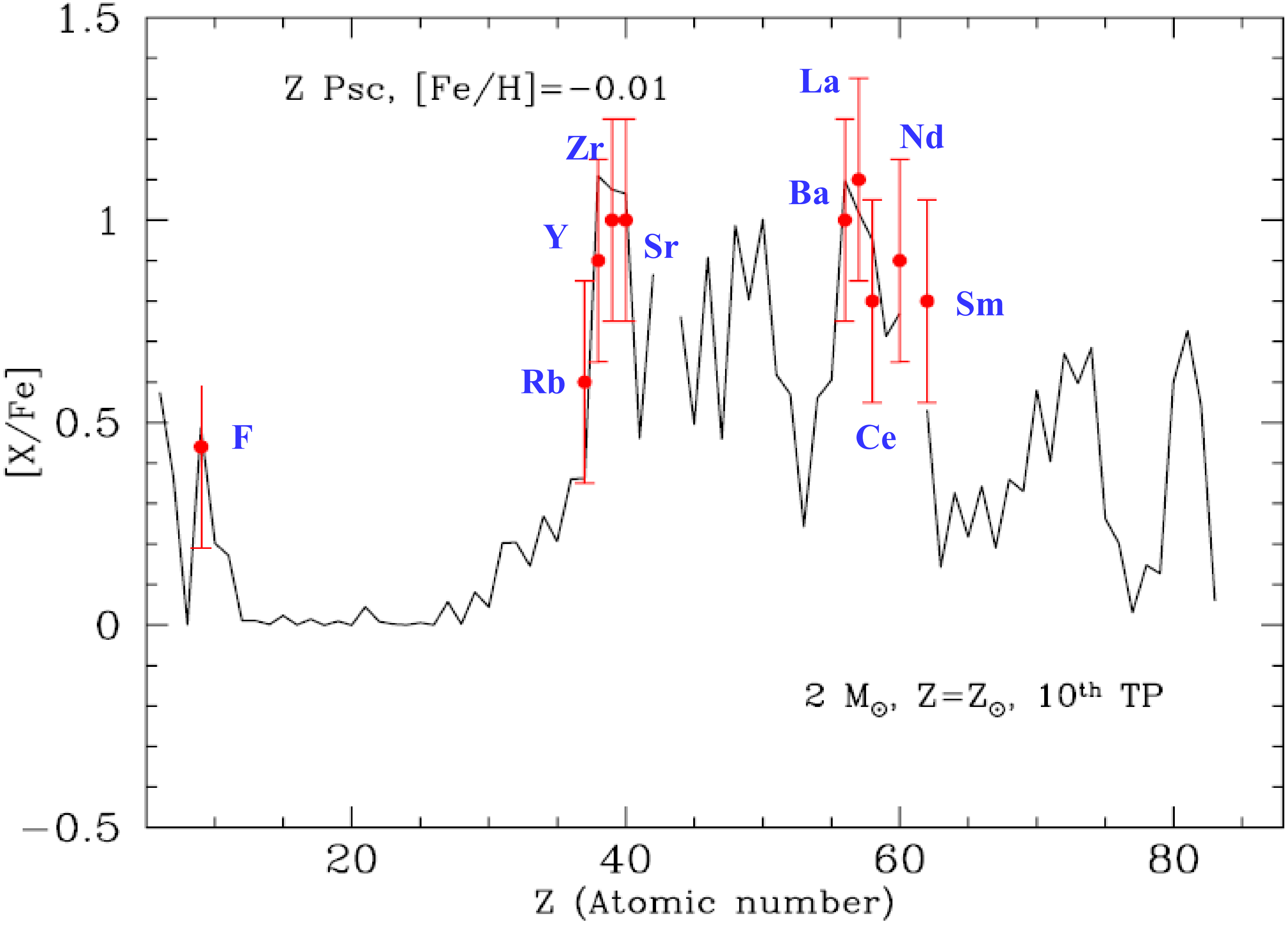
- **secondary: ^{13}C produced in the H-burning shell**
- **primary: ^{13}C produced in the He-intershell**

2. Large [F/Fe] are predicted in metal deficient AGBs

Expected ^{19}F & s-elements enhancements for different Z

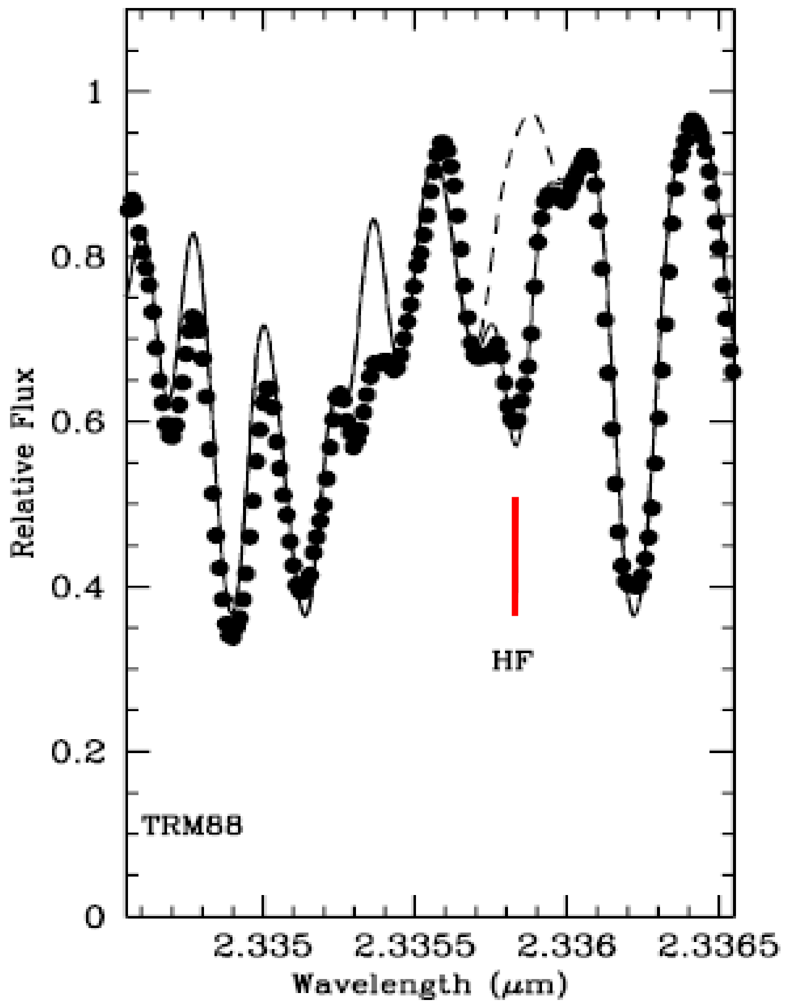


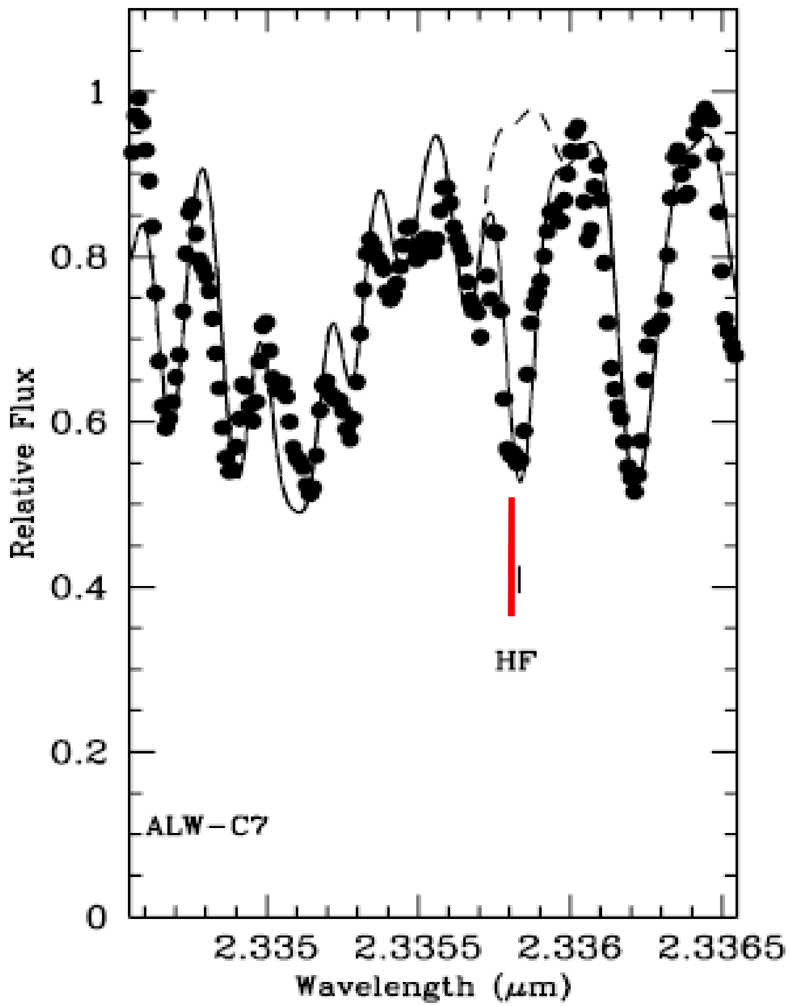
Cristallo et al. (2015)



Z Psc, [Fe/H]=−0.01
2 M⊙, Z=Z⊙, 10th TP
[X/Fe]
Z (Atomic number)
1.5
1
0.5
0
−0.5
20
40
60
80
F
Rb
Y
Zr
Sr
La
Ba
Nd
Ce
Sm

Fluorine in metal deficient AGB C-stars

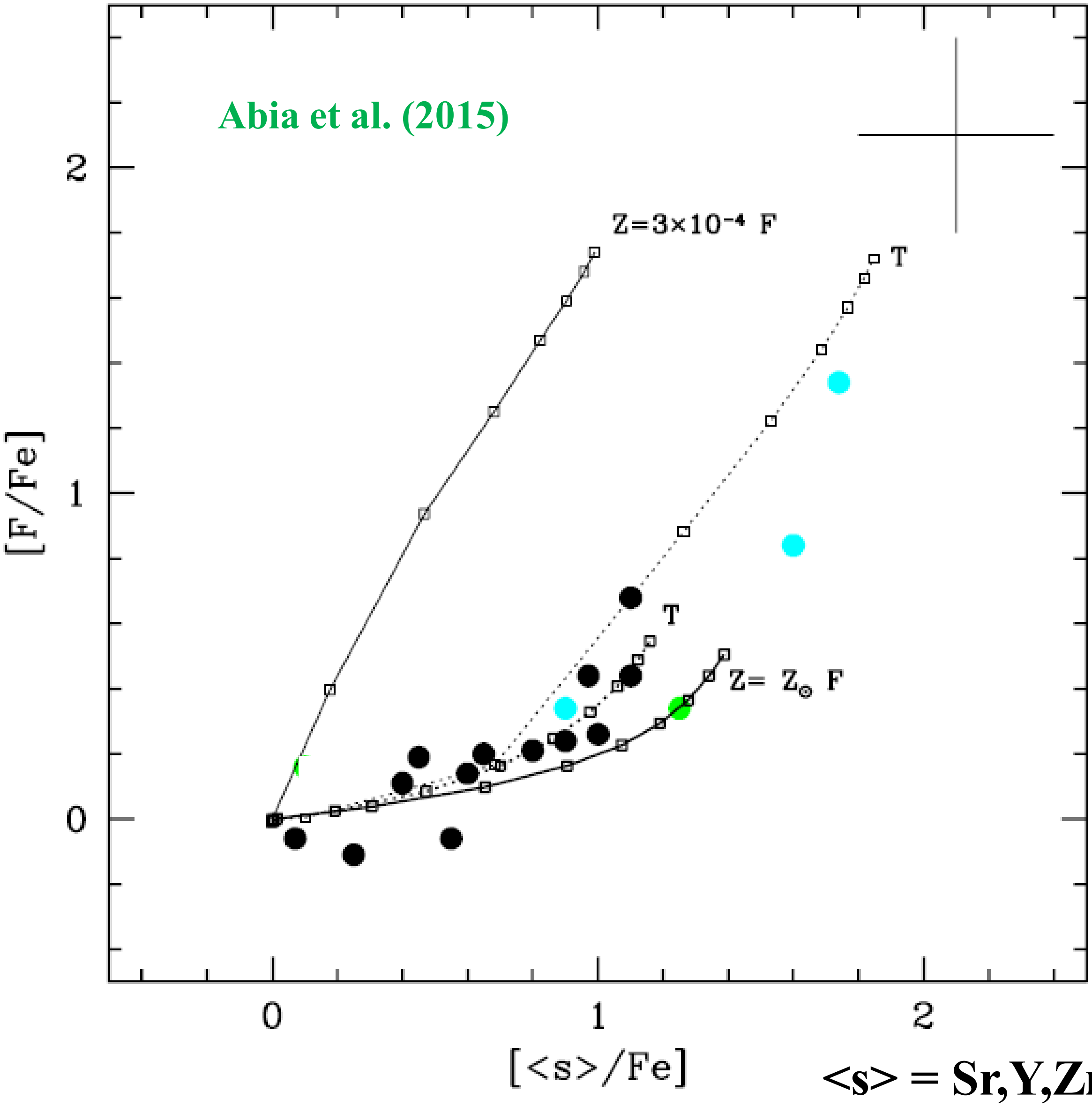




[Fe/H]= -0.6 [F/Fe]= +0.74

[Fe/H]= -1.9 [F/Fe]= +1.34

The problem: too much ^{19}F at low metallicities



2 $M_\odot$ TP-AGB

● Normal C-stars $Z \sim Z_\odot$

● Metal-poor C-stars $Z \sim 10^{-4}$

<s> = Sr,Y,Zr,Ba,La,Nd,Sm

Possible solutions:

- ✓ Systematic errors in the observational analysis
- ✓ Chemical evolution: initial F abundance
- ✓ Models of AGB stars
- ✓ Nuclear reaction rate uncertainties
- ✓ ....

Cristallo et al. (2014)
A&A 570, A46

Table 1. Sources of the reaction rates relevant for fluorine nucleosynthesis.

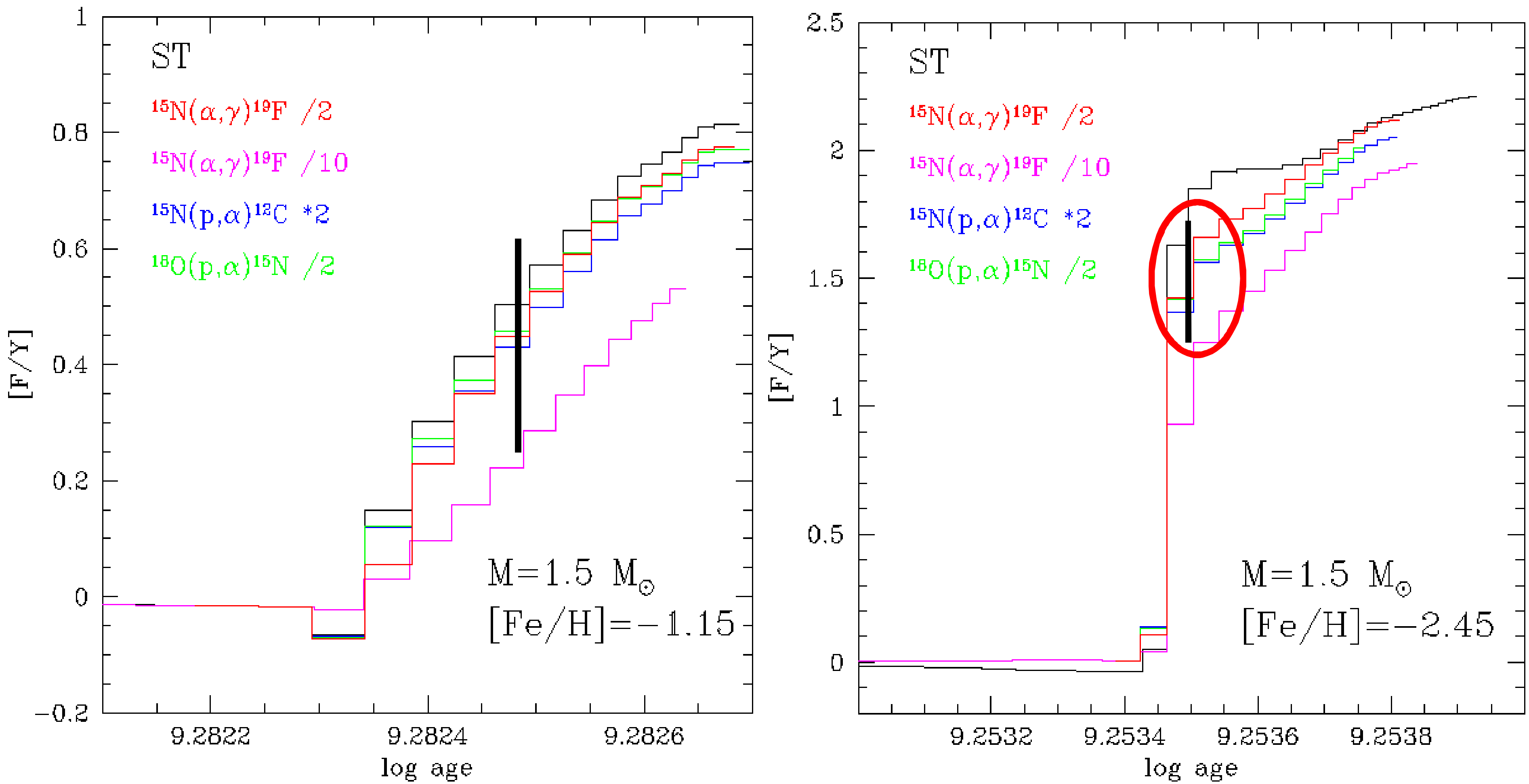
	Reaction rate	Old source	New source
	1 Proton captures		
10%	$^{14}N(p,\gamma)^{15}O$	Formicola et al. (2004)	Adelberger et al. (2011)
10%	$^{15}N(p,\gamma)^{16}O$	Angulo et al. (1999)	Leblanc et al. (2010)
15%	$^{17}O(p,\gamma)^{18}F$	Angulo et al. (1999)	Scott et al. (2012)
10%	$^{18}O(p,\gamma)^{19}F$	Angulo et al. (1999)	Iliadis et al. (2010)
10%	$^{15}N(p,\alpha)^{12}C$	Angulo et al. (1999)	Angulo et al. (1999)
20%	$^{17}O(p,\alpha)^{14}N$	Angulo et al. (1999)	Iliadis et al. (2010)
30%	$^{18}O(p,\alpha)^{15}N$	Angulo et al. (1999)	Iliadis et al. (2010)
30%	$^{19}F(p,\alpha)^{16}O$	Angulo et al. (1999)	La Cognata et al. (2011)
	α captures		
50%	$^{14}C(\alpha,\gamma)^{18}O$	Caughlan & Fowler (1988)	Lugaro et al. (2004)
50%	$^{14}N(\alpha,\gamma)^{18}F$	Görres et al. (2000)	Iliadis et al. (2010)
20%	$^{15}N(\alpha,\gamma)^{19}F$	Angulo et al. (1999)	Iliadis et al. (2010)
50%	$^{18}O(\alpha,\gamma)^{22}Ne$	Giesen et al. (1994)	Iliadis et al. (2010)
50%	$^{19}F(\alpha,p)^{22}Ne$	Ugalde (2005)	Ugalde et al. (2008)
50%	$^{13}C(\alpha,n)^{16}O$	Drotleff et al. (1993)	Heil et al. (2008)

2σ percentage cross section upper & lower uncertainties at different T and corresponding % fluorine ratio variations

Reaction rate	2σ (T_8 = 1)		2σ (T_8 = 2.5)		Δ [F/Fe] (% var.)		Δ [F/⟨s⟩] (% var.)	
	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
$^{14}N(p,\gamma)^{15}O$	10	10	8	8	−3	+5	−3	+3
$^{15}N(p,\gamma)^{16}O$	15	15	15	15	−1	−2	−3	−2
$^{17}O(p,\gamma)^{18}F$	15	15	20	20	0	−2	−3	0
$^{18}O(p,\gamma)^{19}F$	30	30	30	30	−2	−3	−1	−3
$^{15}N(p,\alpha)^{12}C$	20	20	15	15	−3	+1	−3	−3
$^{17}O(p,\alpha)^{14}C$	15	15	6	6	−2	−2	−1	0
$^{18}O(p,\alpha)^{15}N$	8	8	8	8	+1	−2	+3	−1
$^{19}F(p,\alpha)^{16}O$	35	35	35	35	0	−1	−4	−4
$^{14}C(\alpha,\gamma)^{18}O$	100	84	100	62	−2	0	−3	−2
$^{14}N(\alpha,\gamma)^{18}F$	20	20	10	10	−1	−1	+3	−1
$^{15}N(\alpha,\gamma)^{19}F$	100	50	15	15	−3	−2	0	+5
$^{18}O(\alpha,\gamma)^{22}Ne$	70	50	70	50	−3	+1	−4	−5
$^{19}F(\alpha,p)^{22}Ne$	100	100	50	50	−5	+2	−2	+4
$^{13}C(\alpha,n)^{16}O$	25	25	25	25	−3	+7	−1	+3

Cristallo et al. (2014)

Changes in the main reaction rates (within uncertainties) affecting F are not enough : $^{15}N(\alpha,\gamma)^{19}F$ is the most sensitive



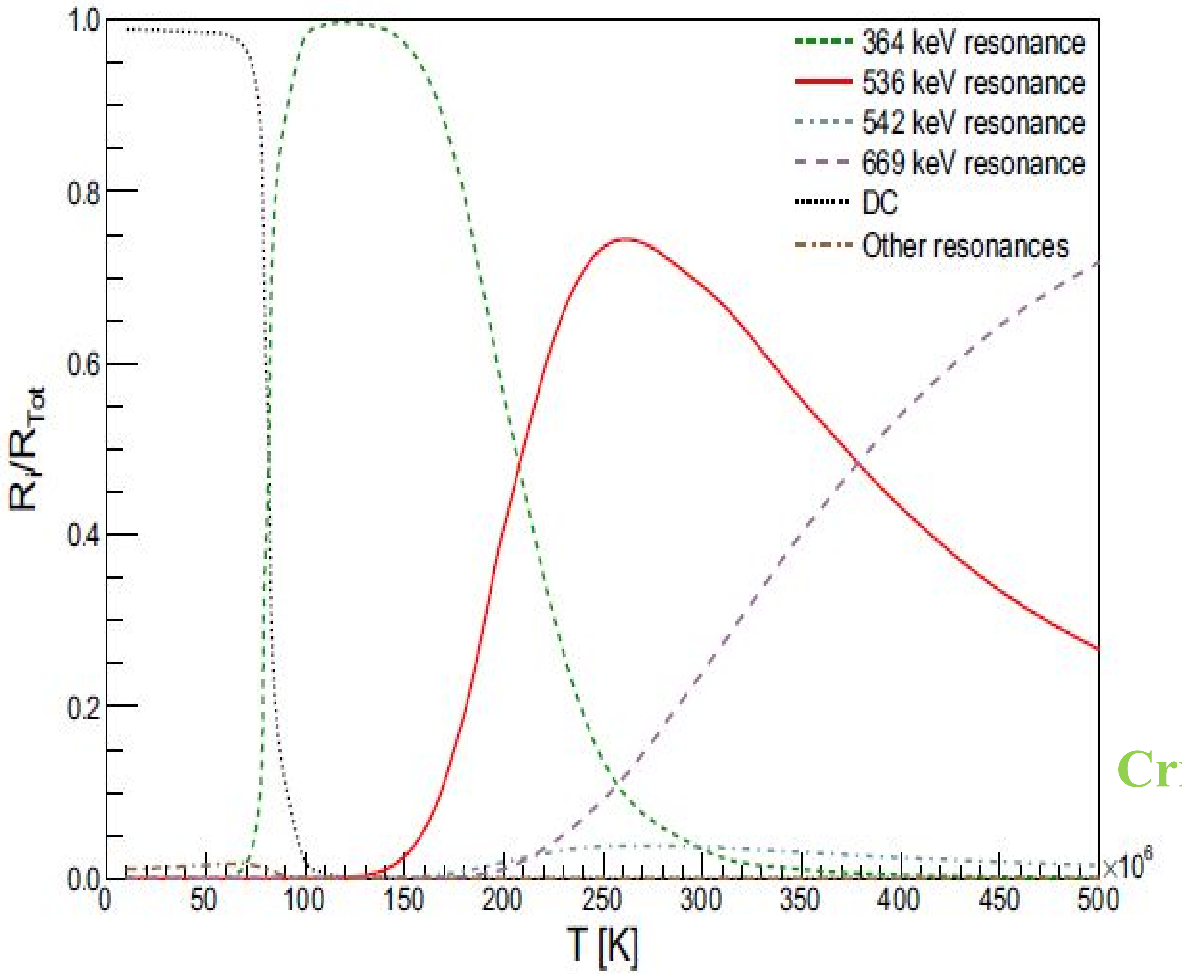
Tests above current experimental uncertainties

Table 3. Scaling factors sf of the computed tests with the corresponding ^{19}F and F/⟨s⟩ surface ratios with respect to the reference case.

Reaction rate	sf	$R(^{19}F)$	$R(F/\langle s\rangle)$
$^{13}C(\alpha,n)^{16}O$	0.01	4.70	2.80
$^{13}C(\alpha,n)^{16}O$	100	0.62	0.67
$^{14}C(\alpha,\gamma)^{18}O$	0.01	1.03	1.59
$^{14}C(\alpha,\gamma)^{18}O$	100	1.04	1.61
$^{14}N(\alpha,\gamma)^{18}F$	0.01	3.03	5.14
$^{14}N(\alpha,\gamma)^{18}F$	100	0.64	1.10
$^{15}N(\alpha,\gamma)^{19}F$	0.01	0.11	0.12
$^{15}N(\alpha,\gamma)^{19}F$	100	0.96	1.50
$^{18}O(\alpha,\gamma)^{22}Ne$	0.01	2.21	2.01
$^{18}O(\alpha,\gamma)^{22}Ne$	100	0.52	0.52
$^{19}F(\alpha,p)^{22}Ne$	0.01	1.05	1.19
$^{19}F(\alpha,p)^{22}Ne$	100	0.08	0.14

Models with a strongly reduced $^{15}N(\alpha,\gamma)^{19}F$ matches the observations at low metallicity BUT then models and observations disagree a solar metallicities

Fractional contribution of the different resonances and DC to the $^{15}N(\alpha,\gamma)^{19}F$



Cristallo et al. (2014)

The only other reaction able to significantly change the F abundances is the $^{19}F(\alpha,p)^{22}Ne$, but it is expected to work efficiently in stars $M > 4\ M_\odot$

Summary

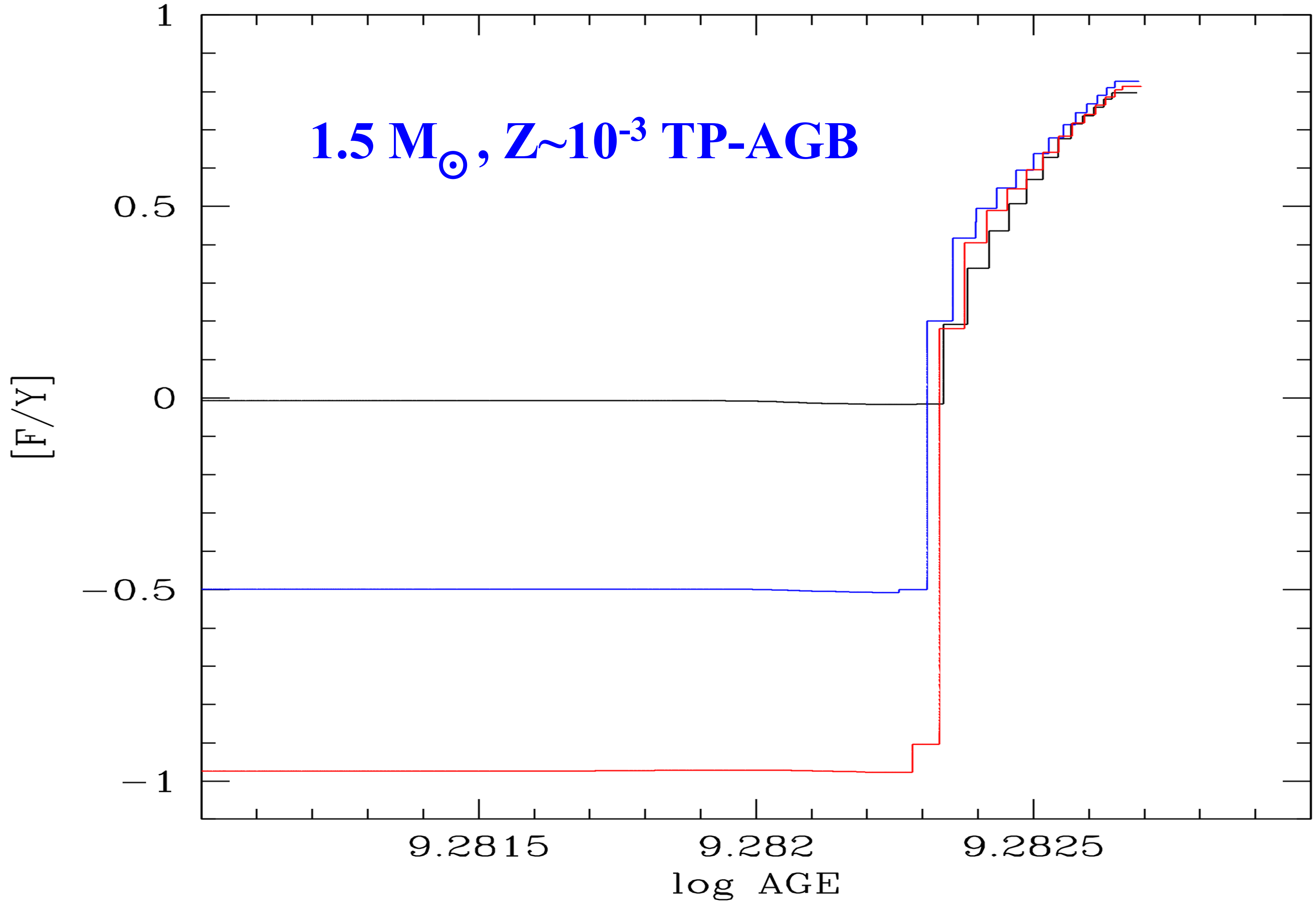
- Abundance measurements of ^{19}F in metal deficient low mass AGB stars disagree with theoretical models.

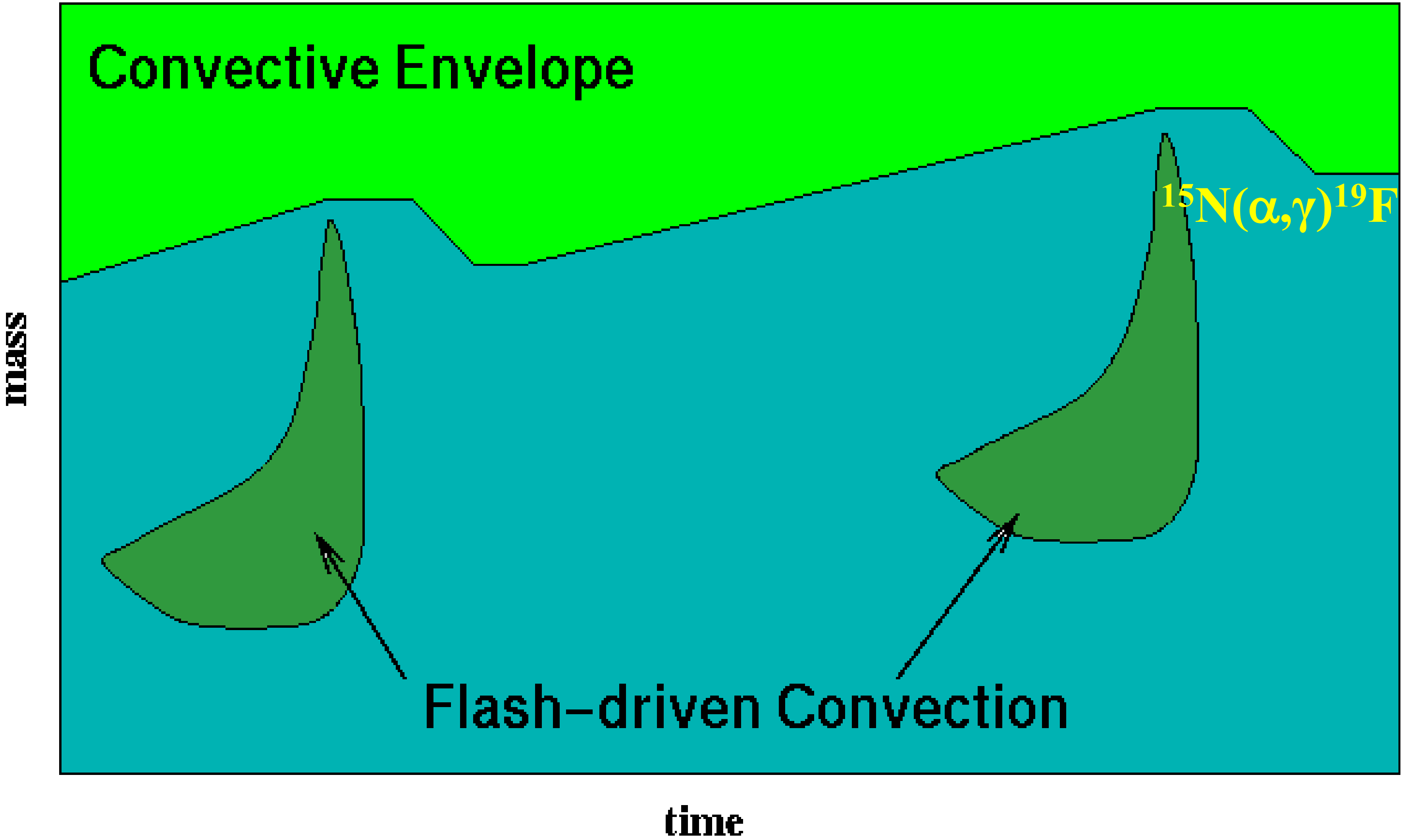
- Varying current nuclear rates within 2σ standard deviations, the surface ^{19}F abundances change less than 10% .

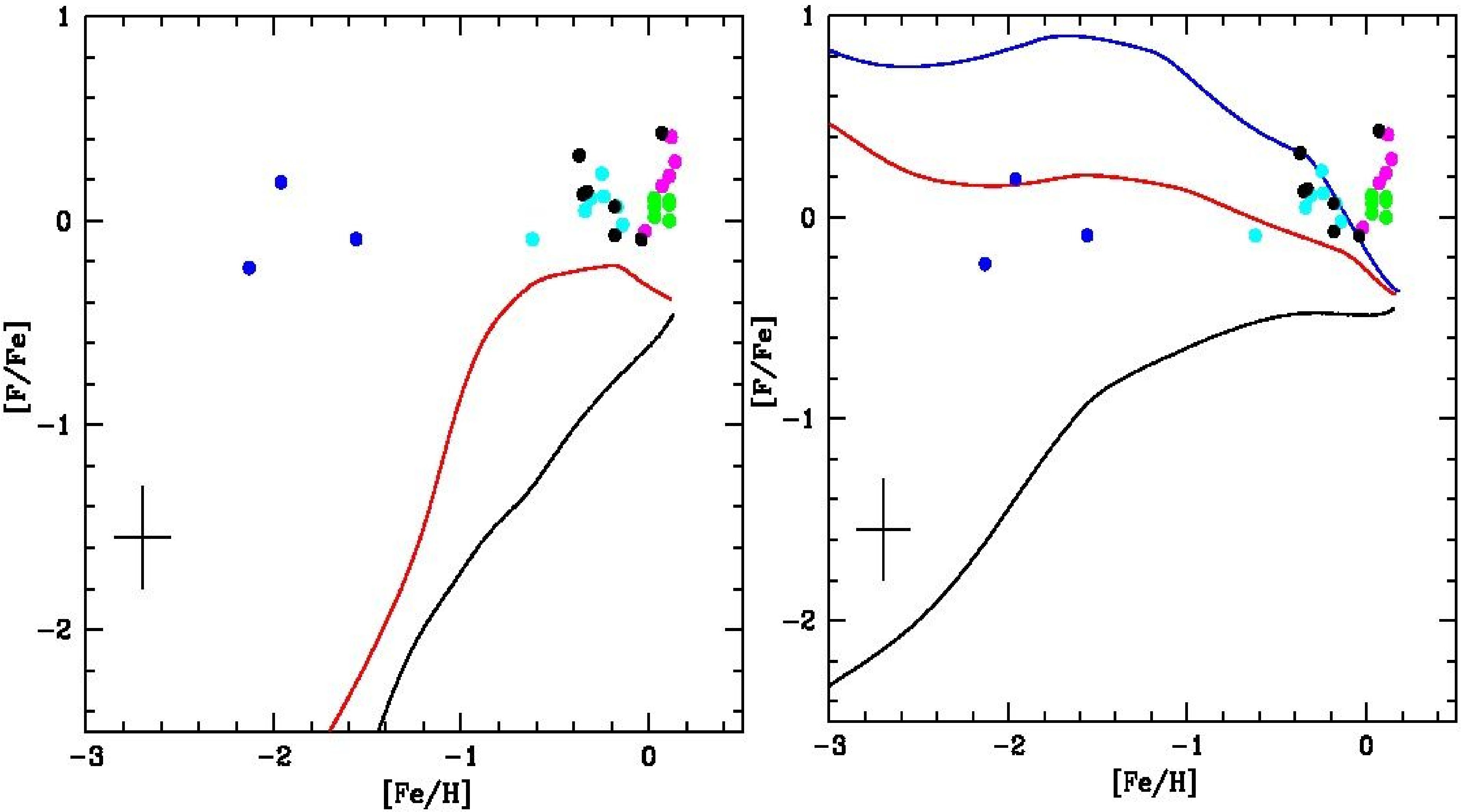
- Reducing the $^{15}N(\alpha,\gamma)^{19}F$ rate or increasing the $^{19}F(\alpha,p)^{22}Ne$ rate by a large amount has the largest impact on the ^{19}F abundance. Experimental measurements at stellar energies of these rates are desirable (ERNA, CUNA?).

- Current models for ^{19}F production in AGB stars have to be revised

The abundance ratio [F/Fe] is almost insensitive during the C-rich AGB phase to the initial F abundance




Convective Envelope
15N(α,γ)19F
Flash-driven Convection
mass
time



[F/Fe]
[Fe/H]
1
0
−1
−2
−3
−2
−1
0
[F/Fe]
[Fe/H]
1
0
−1
−2
−3
−2
−1
0