The origin of CEMP-i stars

Results from a comprehensive multi-method simulations approach

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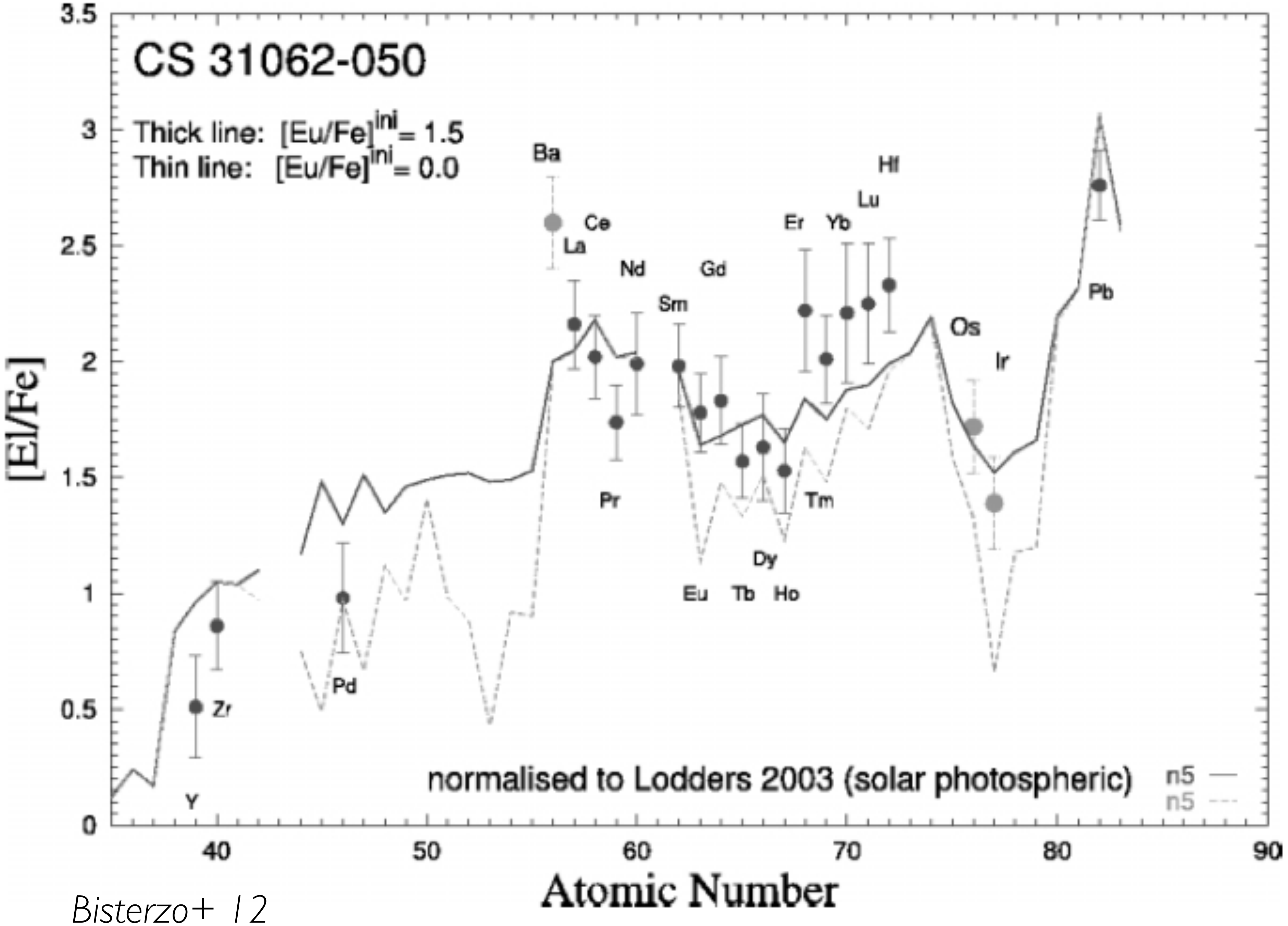
How to explain CEMP-r/s stars?

- C-enhanced metal-poor stars, there are different flavors: -s, -r, -r/s and -no depending on the amount and kind of heavy elements they have, -r/s have both Ba and Eu
- previously best model assumes superposition of “known” r- and s-process sources
- binary forms in r-process pre-enriched cloud
- primary evolves into AGB star that produces s-process elements and transfers them to secondary
- we are now observing the secondary
- there are several problems with this scenario …..
- there is about a dozen other scenarios or variants thereof, none has really been convincing

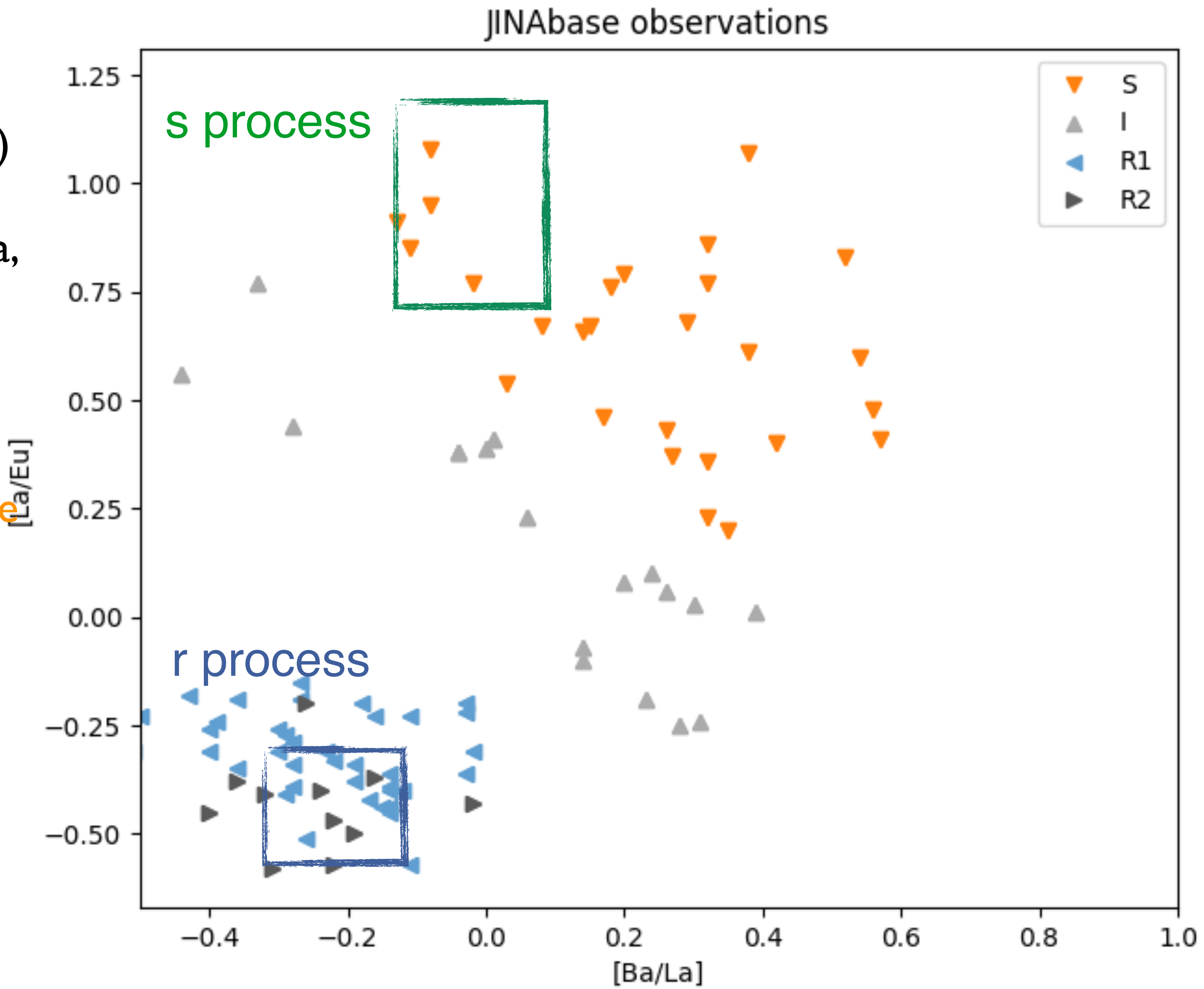
Is there a more plausible explanation?



Bisterzo+ 12

The challenge:
Observed abundances in CEMP stars

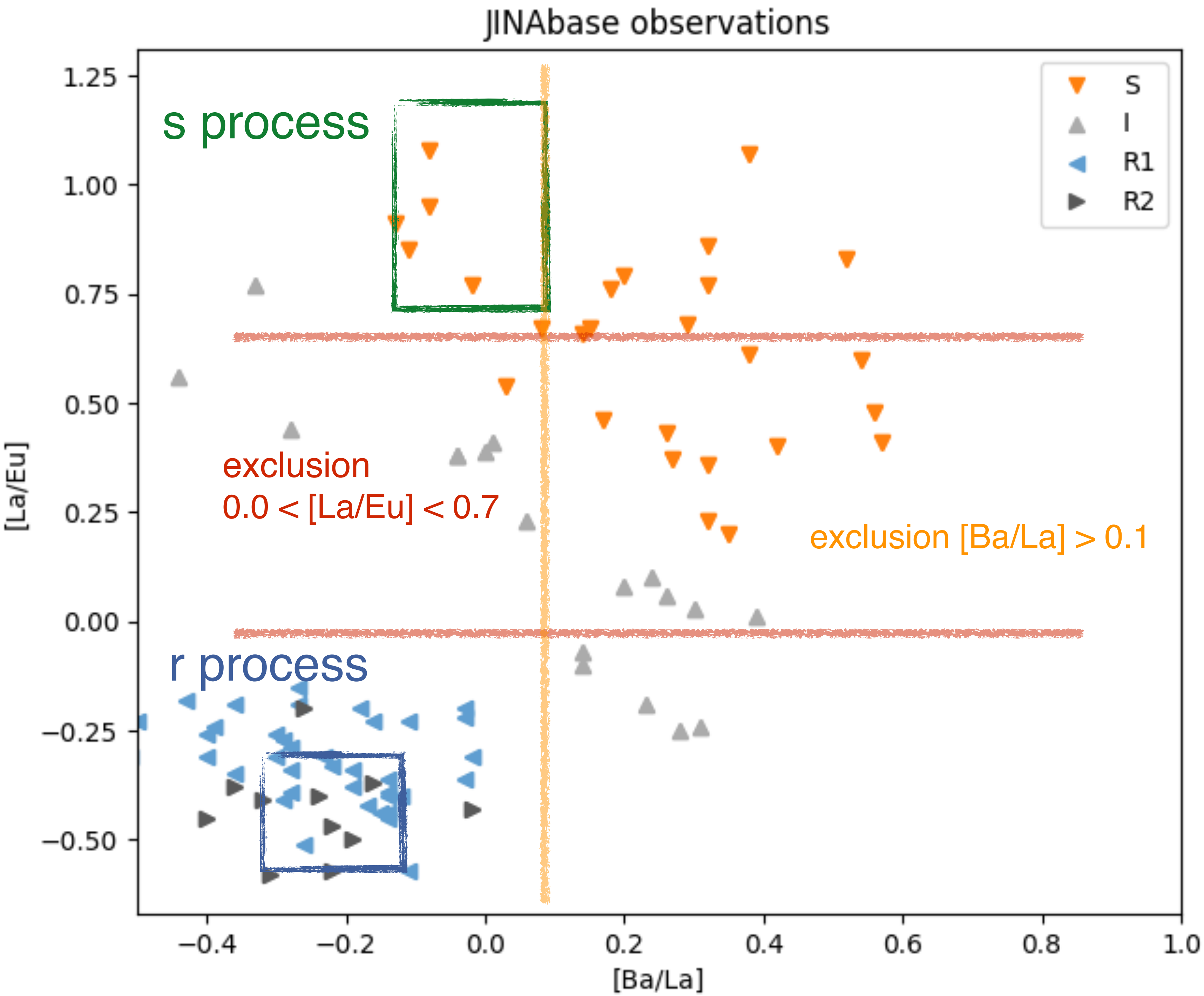
- CEMP stars have (sometimes) very large enhancements of heavy elements, such as La, Ba, Eu
- C-enhanced metal poor (CEMP) stars carry the nucleosynthesis signature of the rise of the elements in the early universe
- CEMP-s, -r, -r/s stars: [Ba/La] and [La/Eu] elemental ratios very different for known s process and r process nucleosynthesis



Observations JINAbase (Abohalima & Frebel, 2018, http://jinabase.pythonanywhere.com)

The challenge: Observed abundances in CEMP stars

- Neither s nor r can make 0.0 < [La/Eu] < 0.7.
- With a superposition of just s and r it is impossible to make [Ba/La] > 0.1.
- But many CEMP stars have element ratios in both exclusion zones?!?!?



Observations JINAbase (Abohalima & Frebel, 2018, http://jinabase.pythonanywhere.com)

The solar system abundance distribution

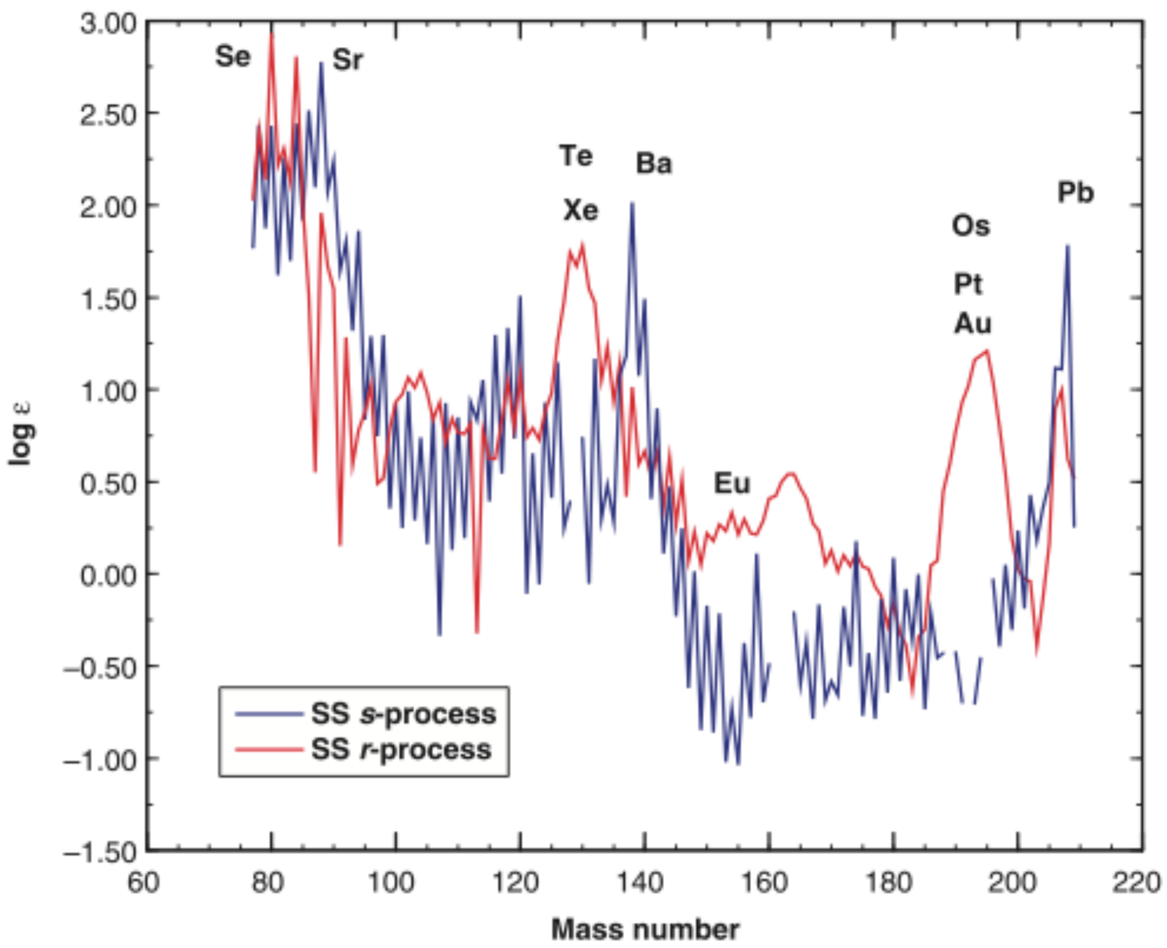


Fig. 3. The breakdown of solar system (meteoritic) n-capture isotopic abundances into r- and s-process components [adapted from (6)]. The approximate mass numbers corresponding to some prominent elements are noted.

Sneden & Cowan 2003

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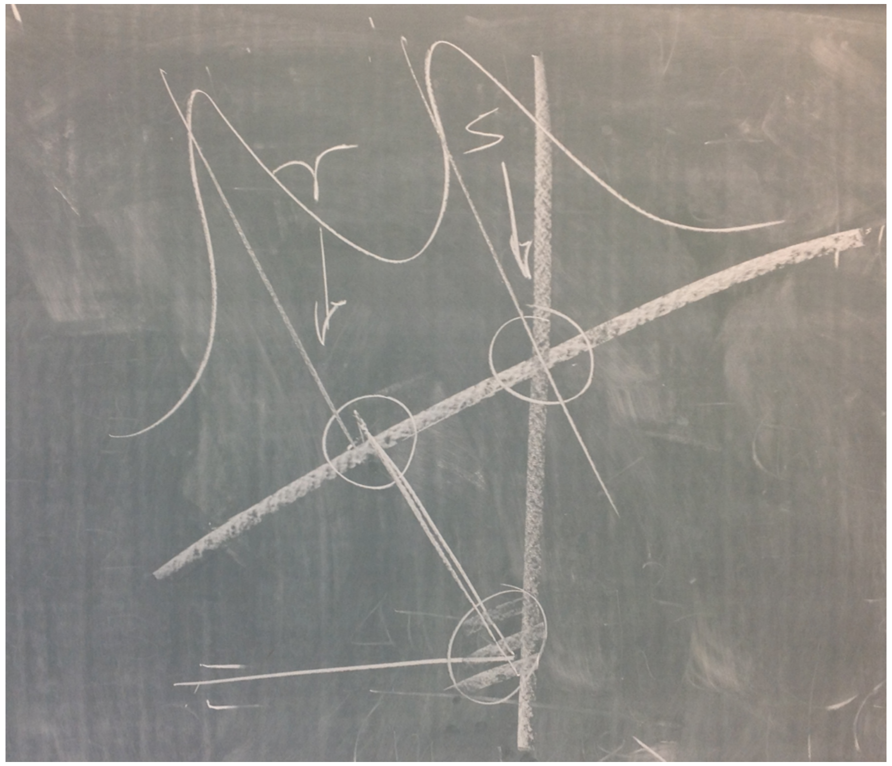
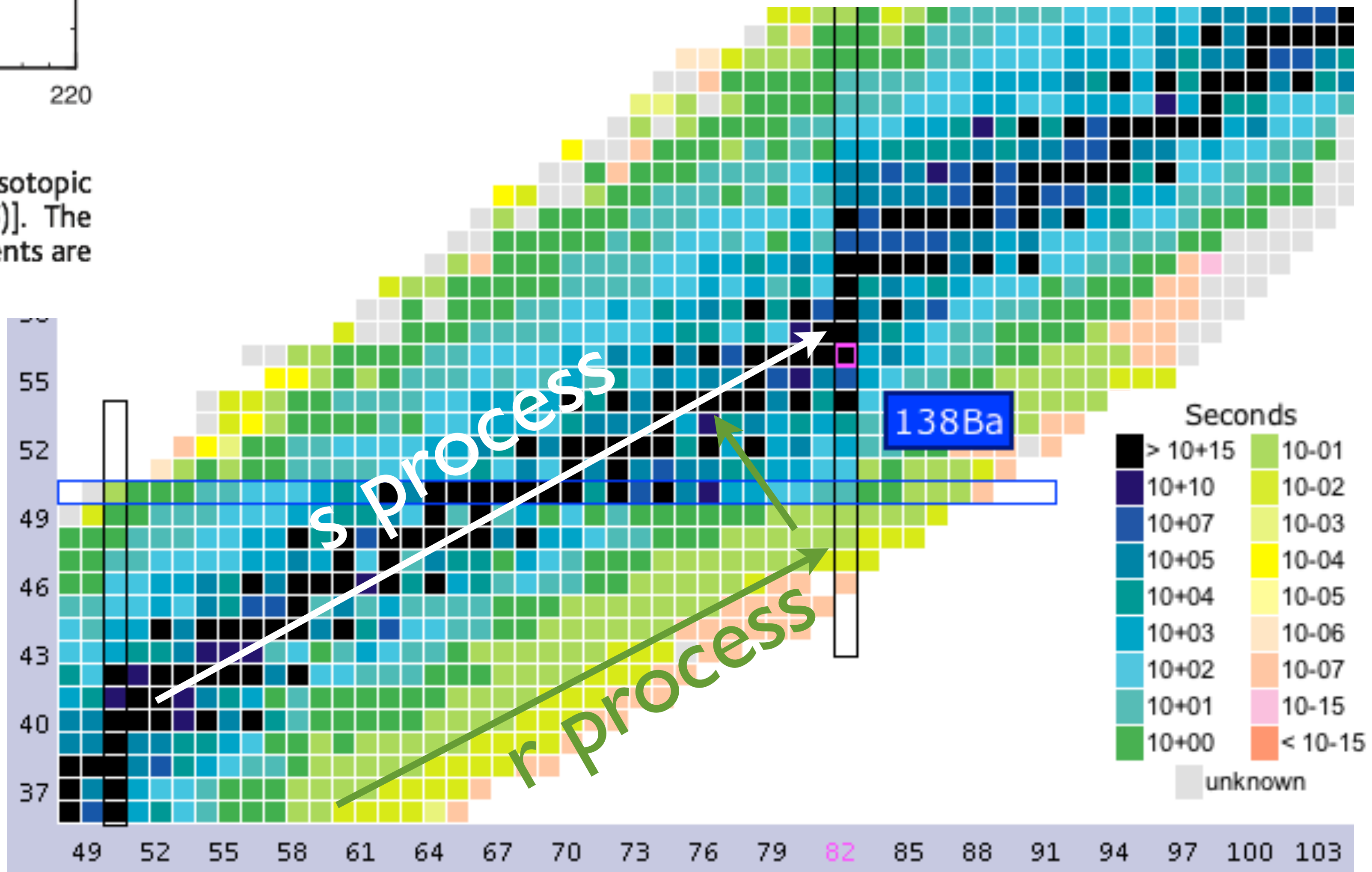
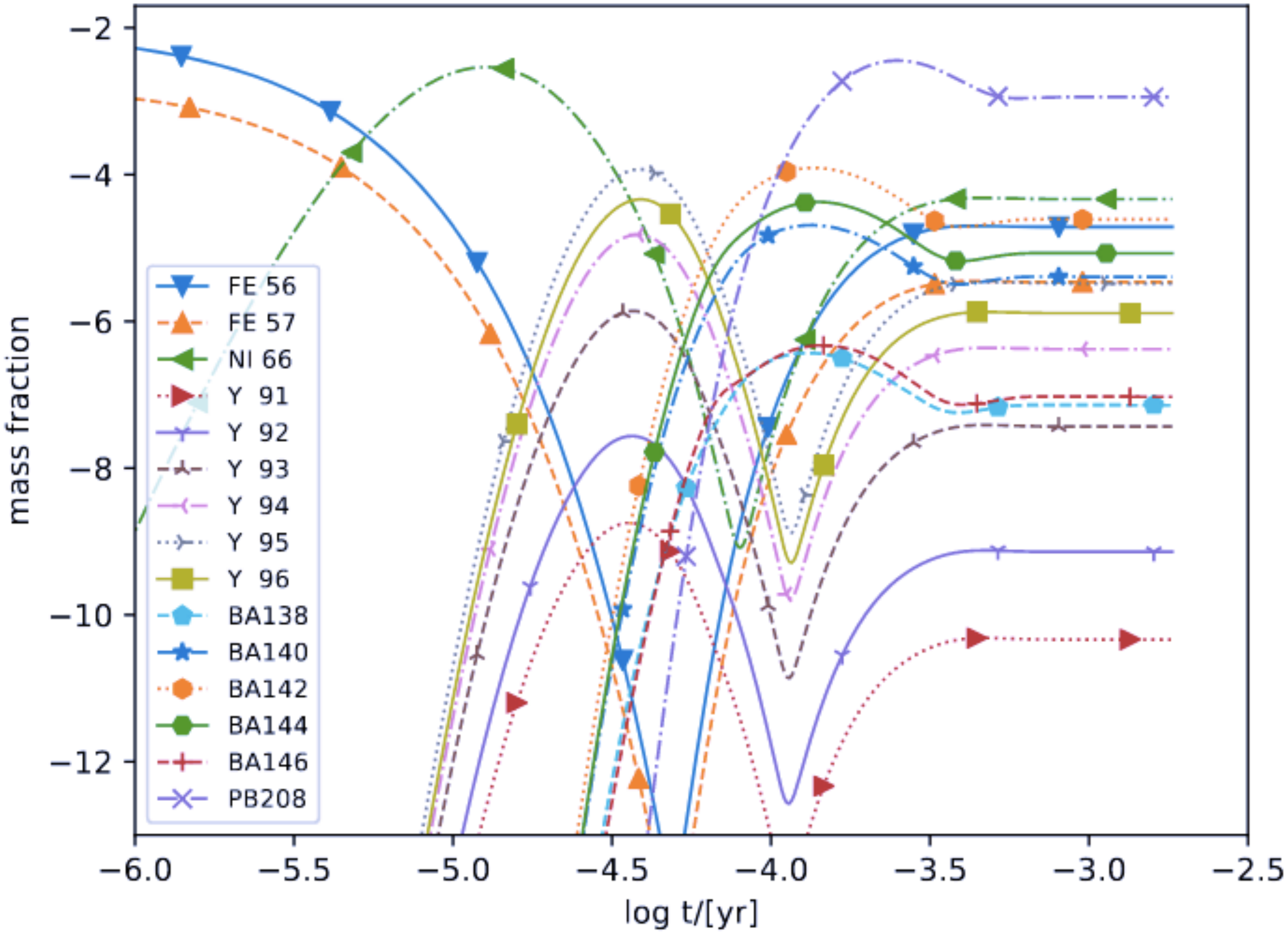


Rapid vs. slow neutron capture process



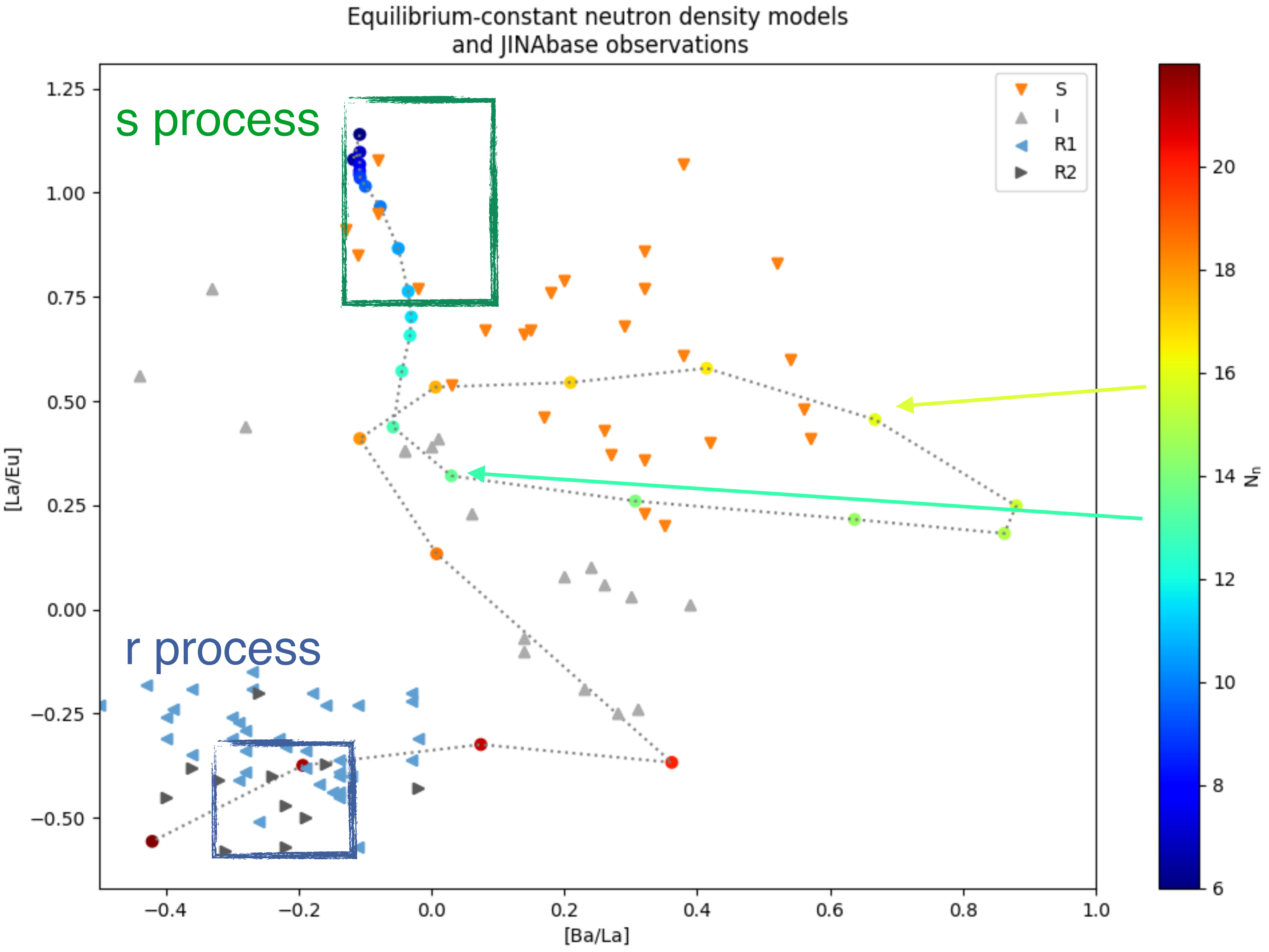
Constant neutron density one-zone nucleosynthesis network calculations

- Neutron density N_n is input, feed network endpoint ^{209}Bi back to ^{56}Fe seed
- This is the method used in the past for the classical s process
- Once equilibrium is reached we decay, and the result is a single elemental abundance distribution for the given value of N_n
- Has no neutron exposure, thus no information on ratio of elements in different peaks, e.g. no Ba/Sr
- Instead astrophysics-independent (pure nuclear physics) predictions for nearby elemental ratios, such as Ba/La
- Potentially a power-full new method for nuclear physics-based classification



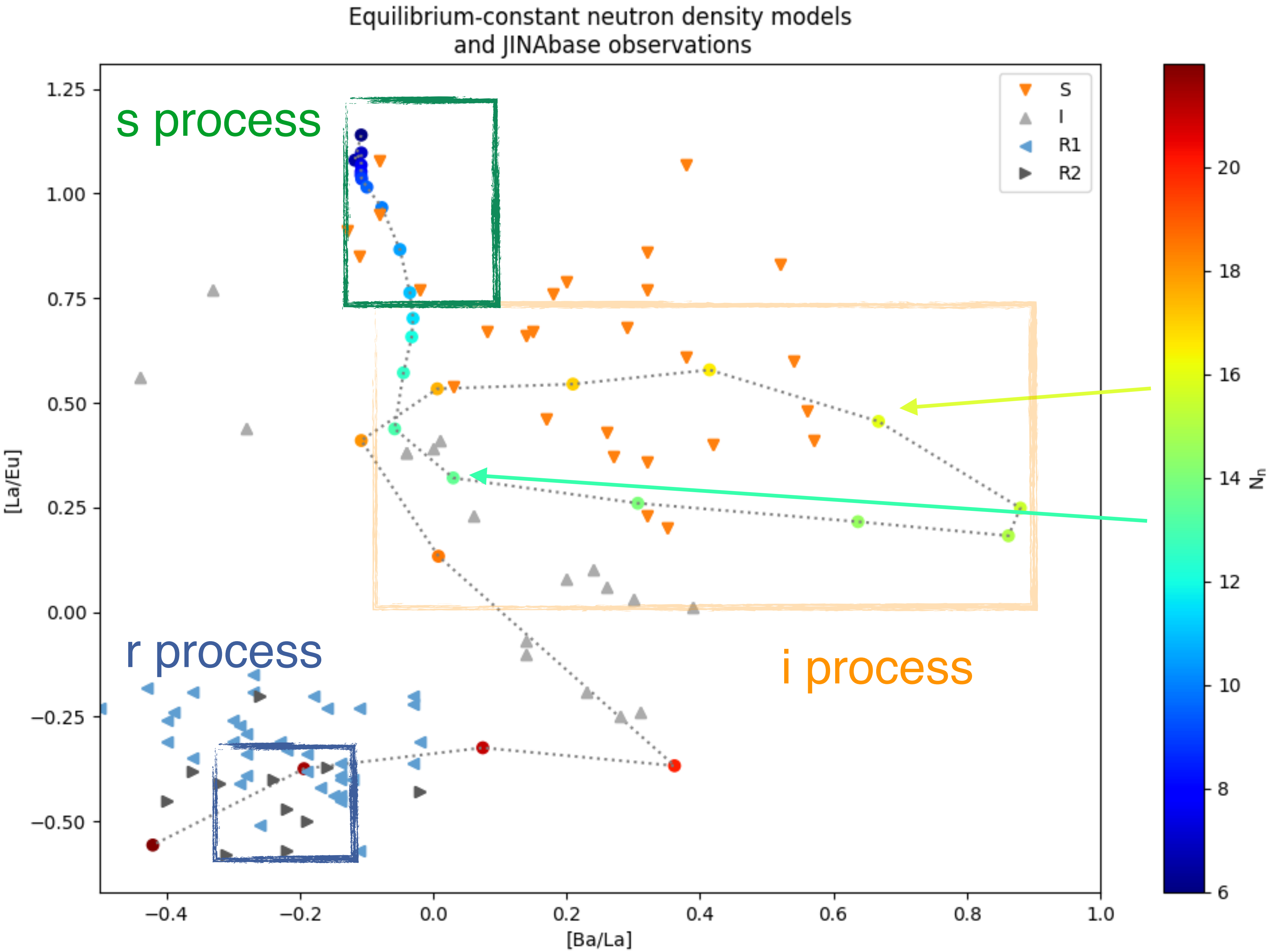
The i-process covers many observations that can't be explained by s and r process alone

- Characterize different neutron capture regimes with constant neutron density equilibrium models. Depend *only* on nuclear physics.

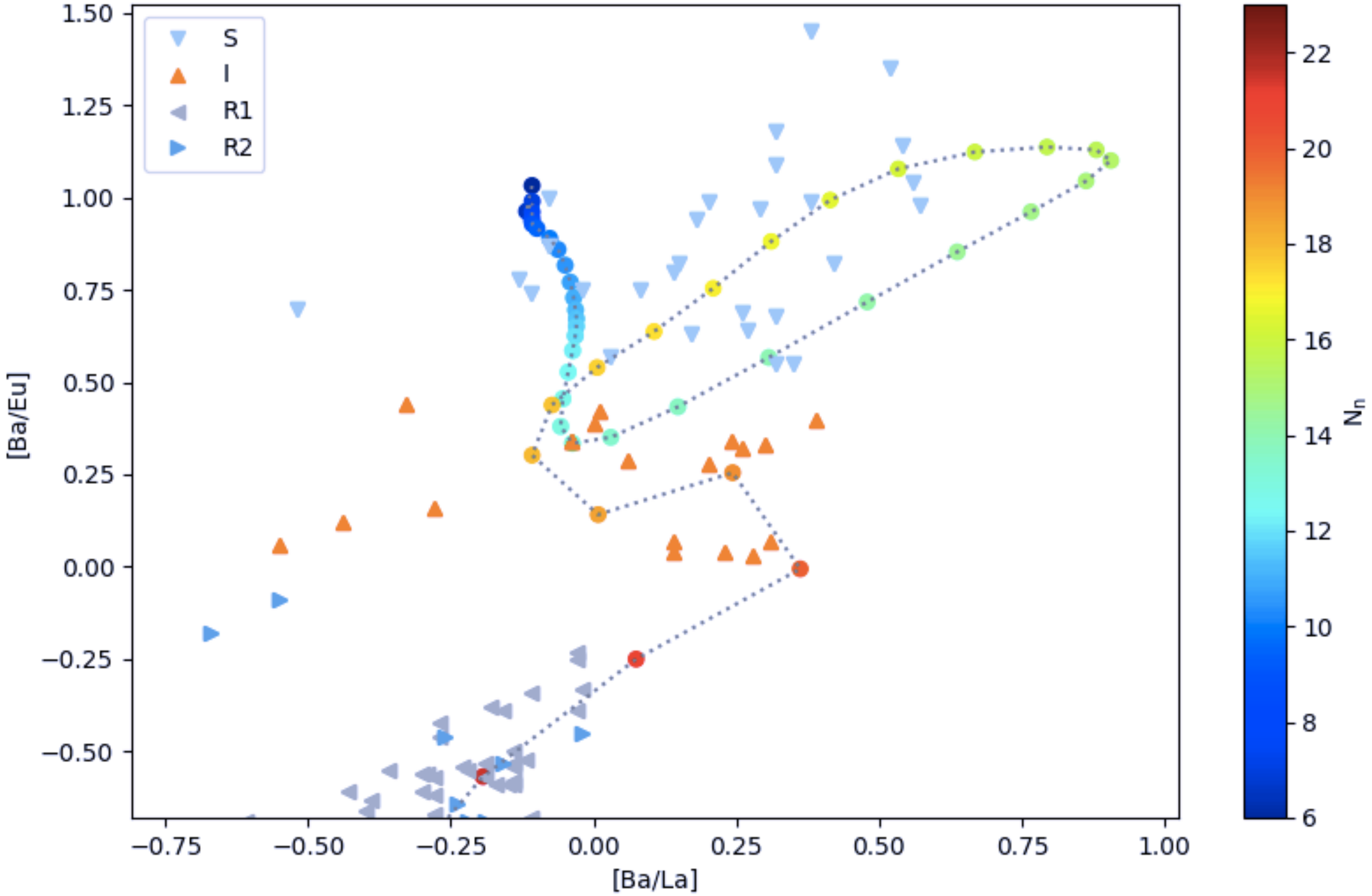


The i-process covers many observations that can't be explained by s and r process alone

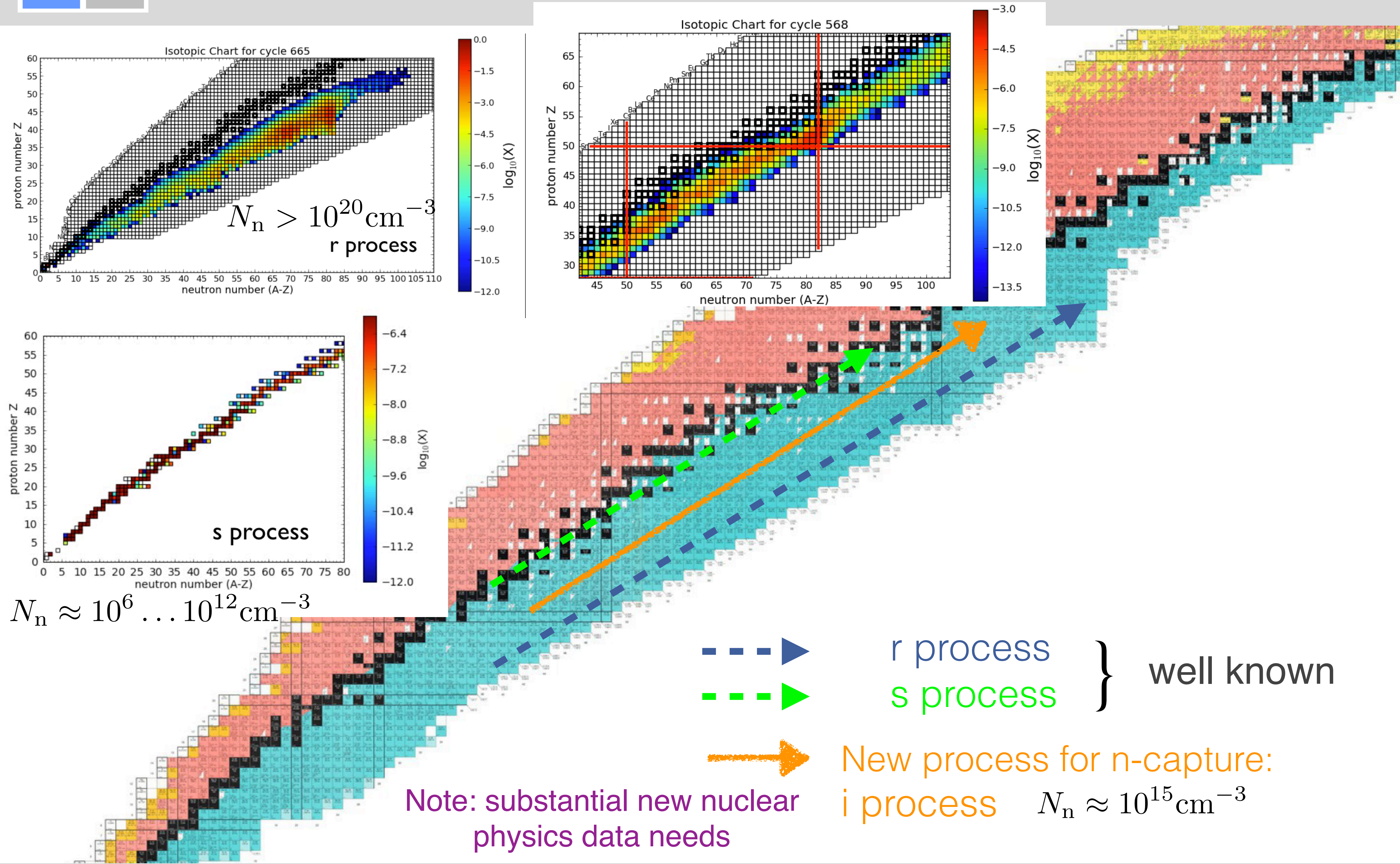
- Characterize different neutron capture regimes with constant neutron density equilibrium models. Depend *only* on nuclear physics.
- The intermediate or i process at neutron densities higher than for s and lower than for r allows us to explain many of the CEMP stars with n-capture enhancements.
- Now - figure out how to make intermediate neutron densities, and where could it happen.



Why is [Ba/Eu] degenerate in classifying CEMP-i stars?



Neutron-capture: slow, rapid and intermediate!



$N_n > 10^{20}\mathrm{cm}^{-3}$

r process

s process

$N_n \approx 10^6 \ldots 10^{12}\mathrm{cm}^{-3}$

r process
s process
} well known

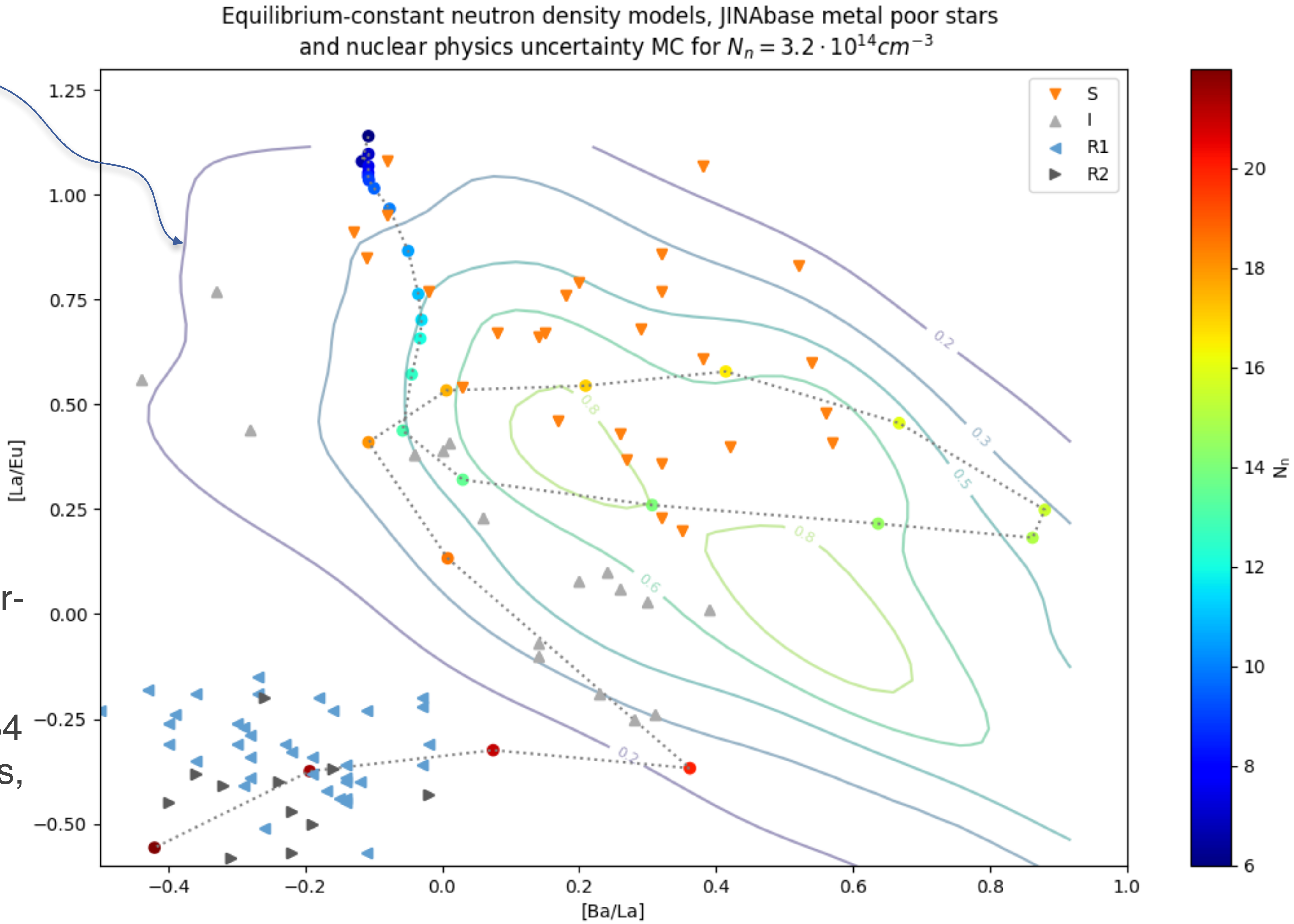
New process for n-capture:
i process $N_n \approx 10^{15}\mathrm{cm}^{-3}$

Note: substantial new nuclear physics data needs

Second-peak nuclear physics impact study

Contour lines: probability density nuclear physics uncertainties according to Monte-Carlo nuclear physics impact study.

10,000 simulations involving Hauser-Feshbach uncertainty estimates for 164 unstable species, for just one neutron density.



Denissenkov P, Perdikakis G, Herwig F, et al. 2018. Journal of Physics G Nuclear Physics. 45(5):055203

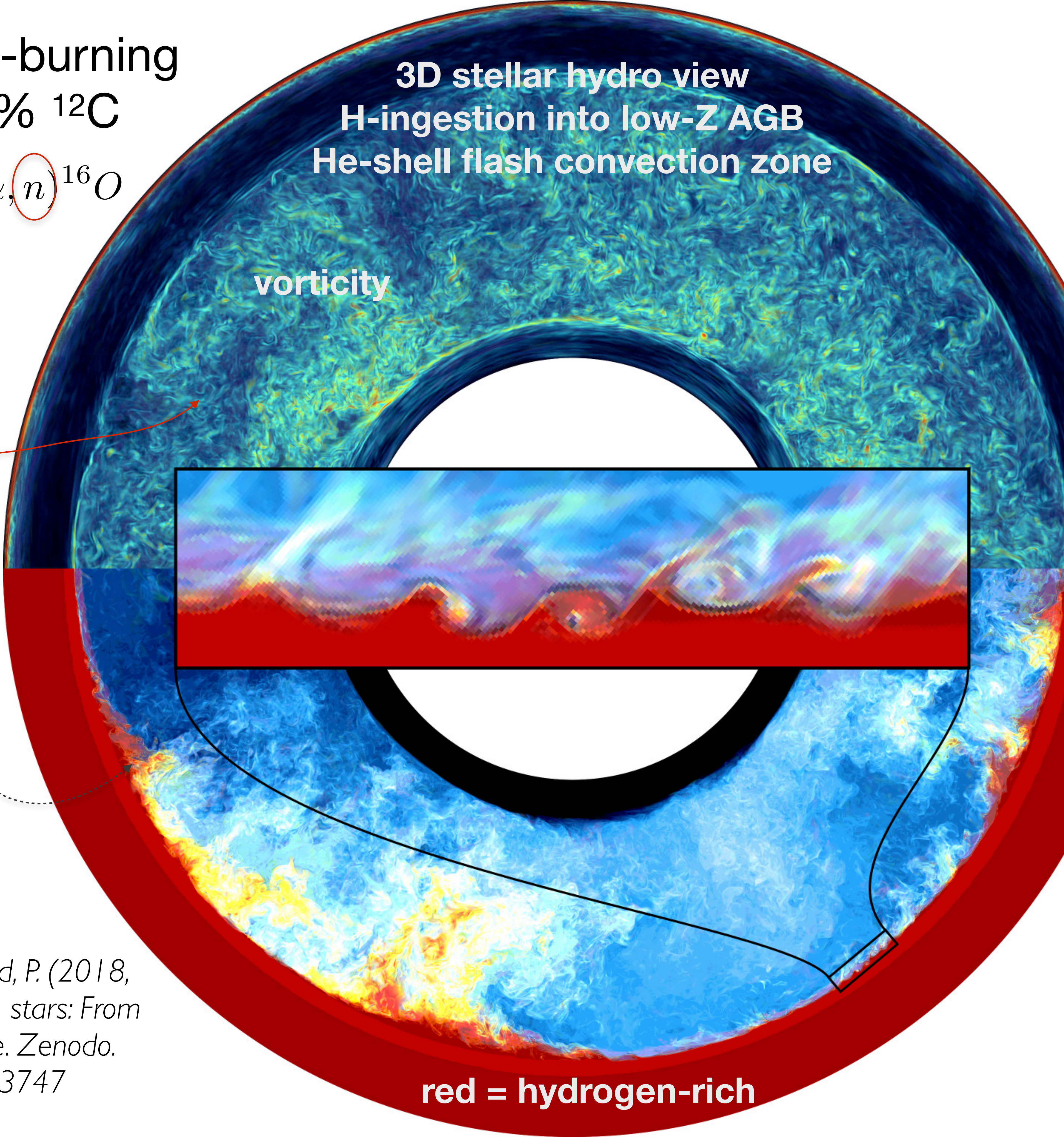
The convective He-burning shell contains ~40% ^{12}C

$$^{12}C(p,\gamma)^{13}N(\beta^{+}\nu)^{13}C(\alpha,\boxed{n})^{16}O$$

$$\tau_{\frac{1}{2}} = 9.6\mathrm{m}$$

$$\tau_{\mathrm{conv}} \sim 15\mathrm{m}$$

entrainment/ ingestion of H in the He-shell convection



Andrassy, R., Herwig, F., & Woodward, P. (2018, October). 3D convection in massive stars: From the main sequence to core collapse. Zenodo. http://doi.org/10.5281/zenodo.1473747

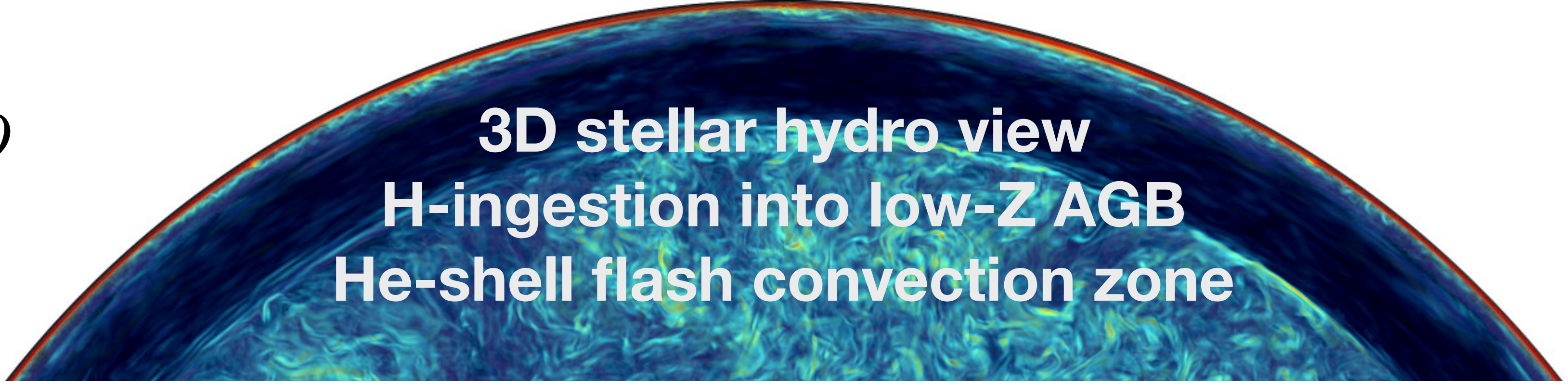
$$^{12}C(p,\gamma)^{13}N(\beta^+\nu)^{13}C(\alpha,n)^{16}O$$

$$\tau_{\rm conv} \sim 15{\rm m} \longleftrightarrow \tau_{\frac{1}{2}} = 9.6{\rm m}$$

Nuclear and hydrodynamic timescales are the same order → convective-reactive nucleosynthesis.

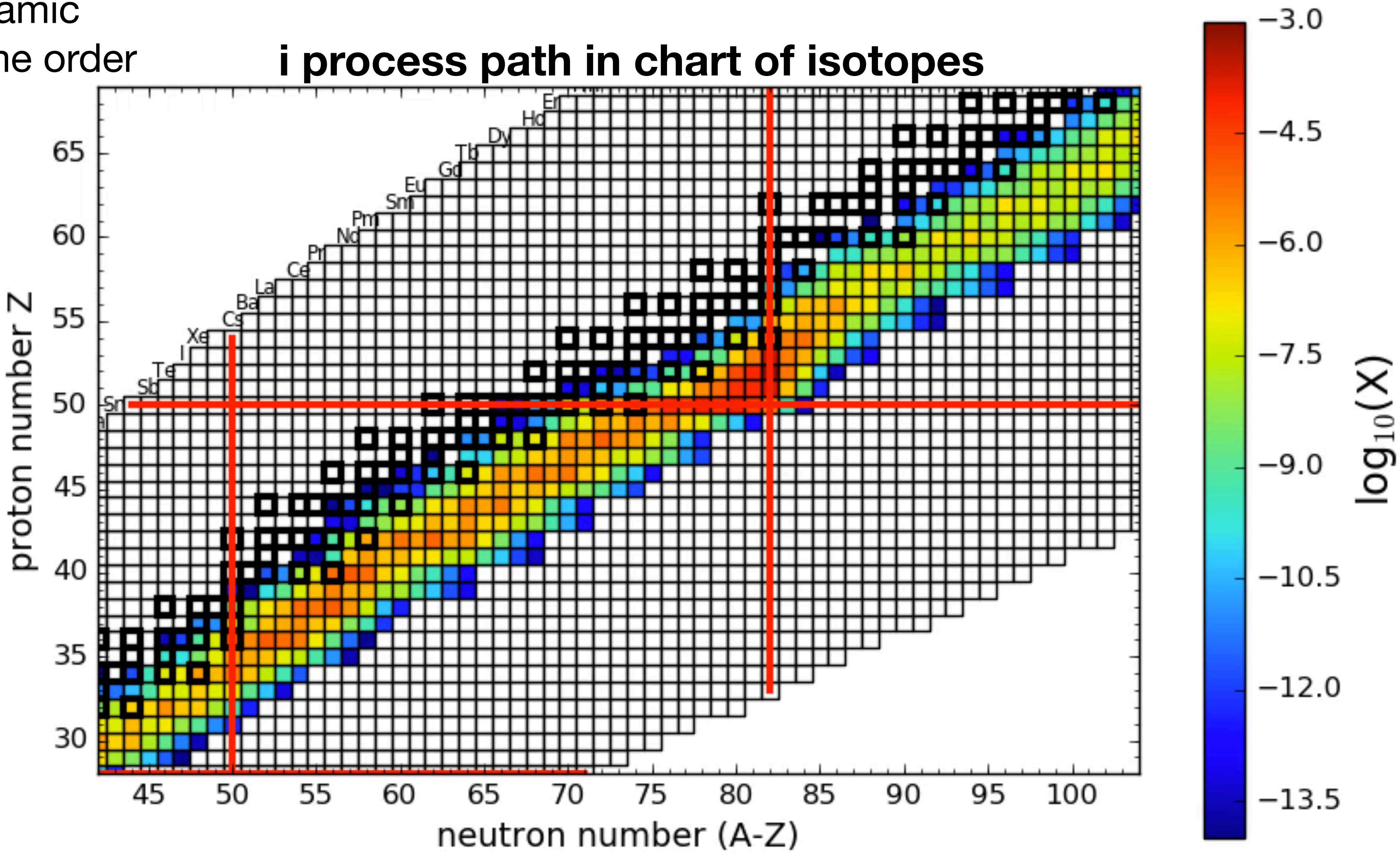
Neutrons released with intermediate neutron density → i process element production.

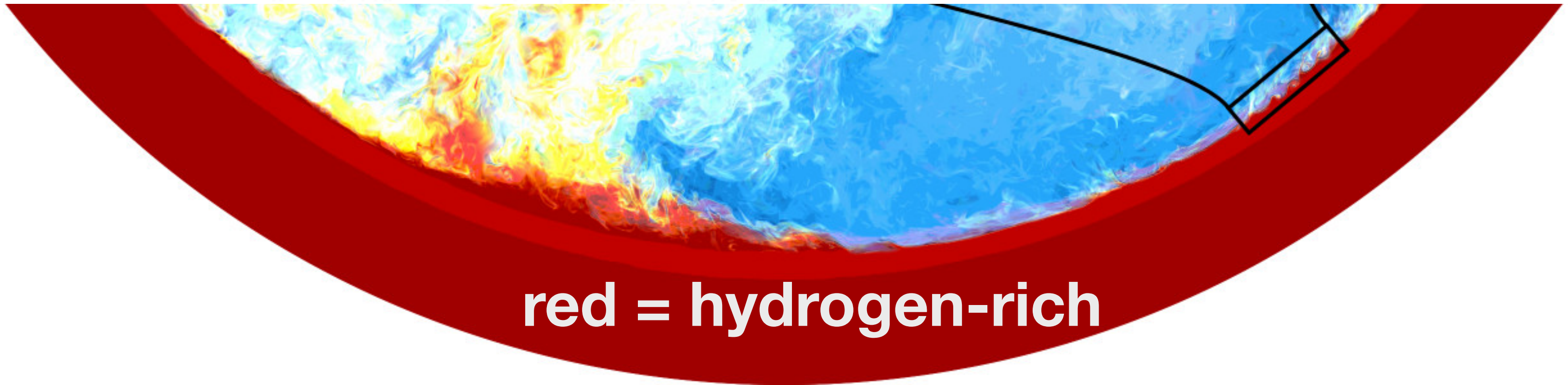
Need multi-physics, multi-method approach. How to combine detailed 3D hydro with detailed n-rich nucleosynthesis involving thousands of species?



3D stellar hydro view
H-ingestion into low-Z AGB
He-shell flash convection zone

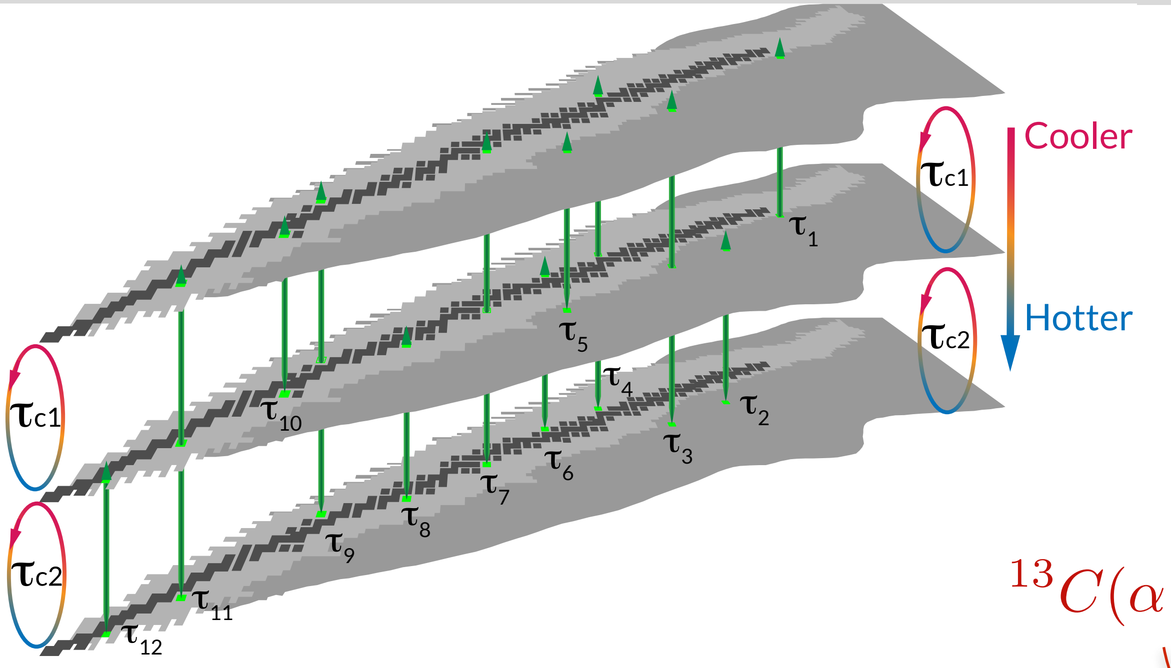
i process path in chart of isotopes



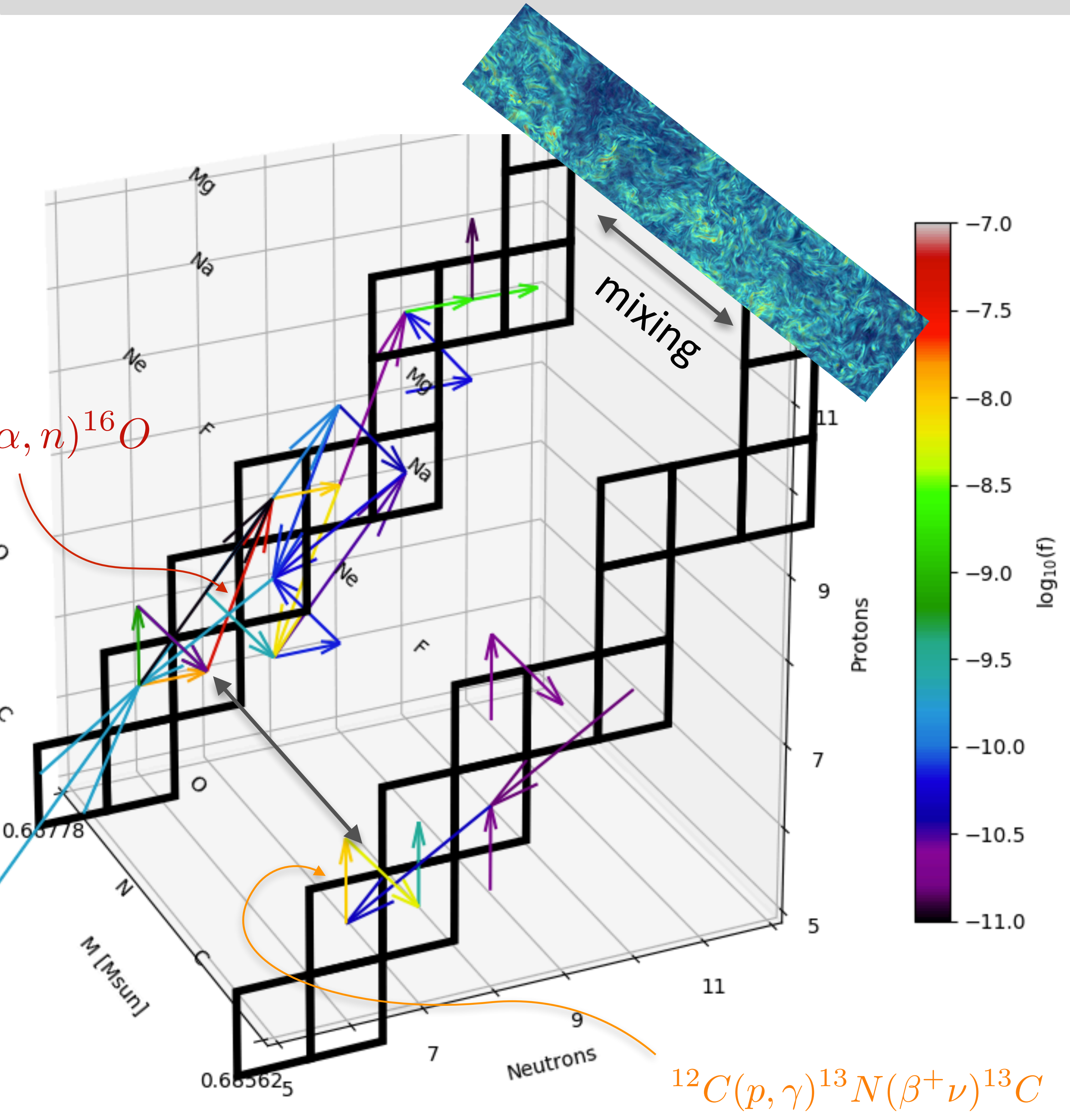


red = hydrogen-rich

Convective-reactive i-process nucleosynthesis



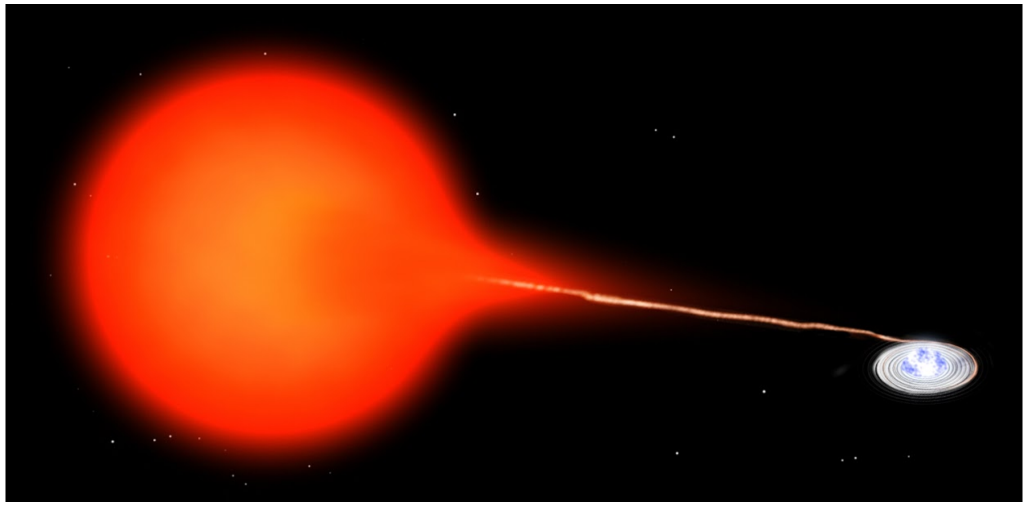
$^{13}C(\alpha,n)^{16}O$



$^{12}C(p,\gamma)^{13}N(\beta^{+}\nu)^{13}C$

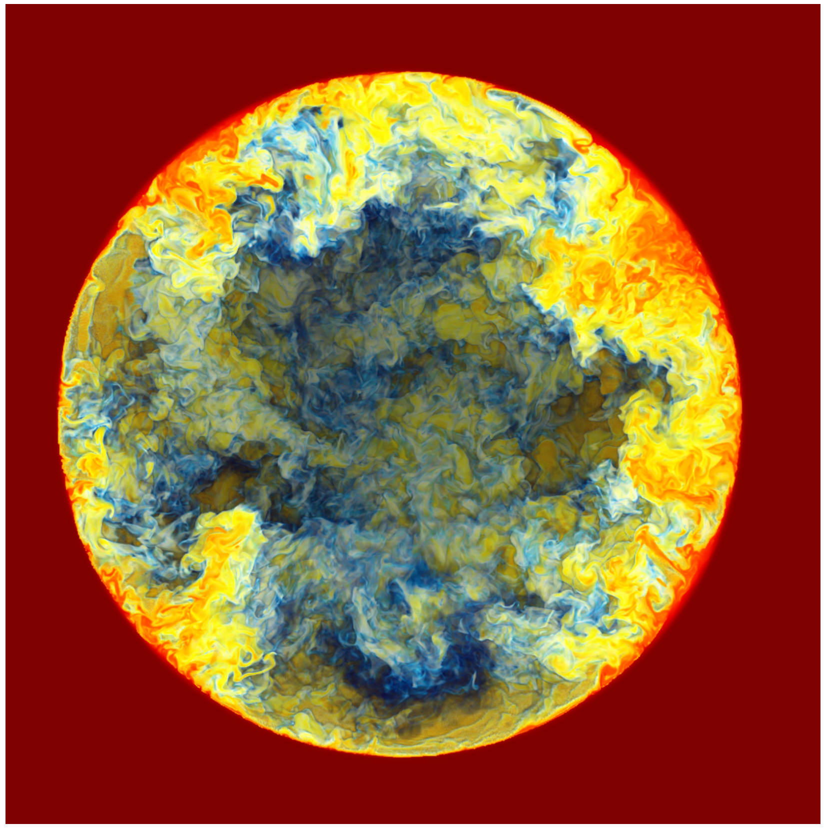
Rapid production of neutrons requires convective mixing connection of two different T regimes for $^{12}C(p,\gamma)$ and $^{13}C(\alpha,n)$ to operate on same time scale

Where does it happen?
Most promising option: i process in rapidly accreting white dwarfs

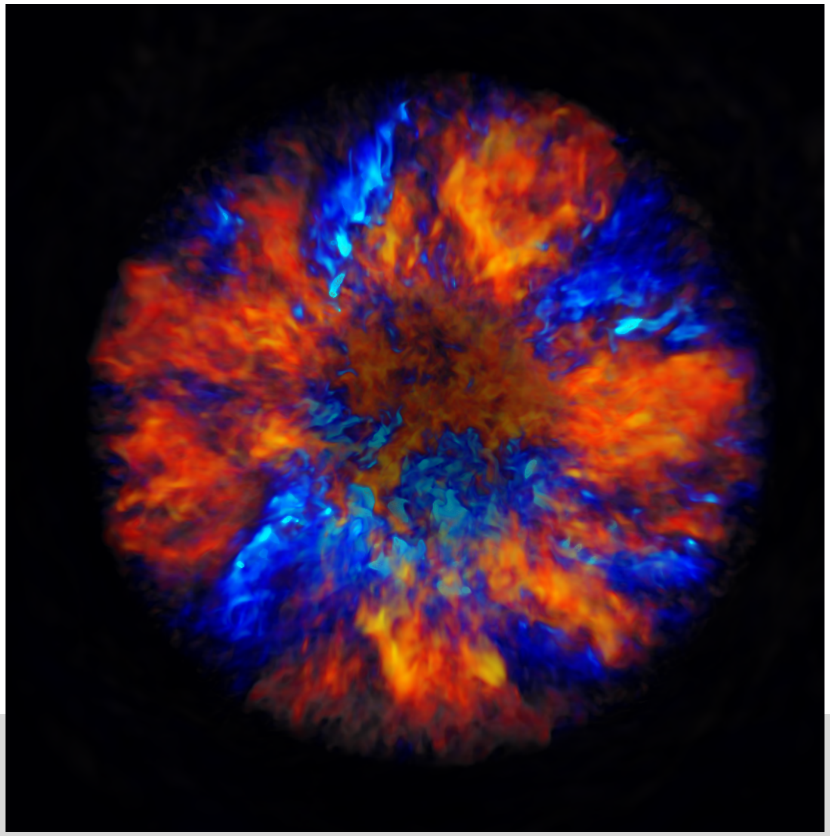


- Artist impression of accreting white dwarf, like novae!
- But unlike nova here accretion rates are high and allow stable H burning!
- However, these accreting WDs then experience He-shell flashes! (Cassisi+ 98)
- In these convective He-shell flashes: H-entrainment, convective reactive i process!

Denissenkov+ 17, ApJ Letters



Concentration of entrained material

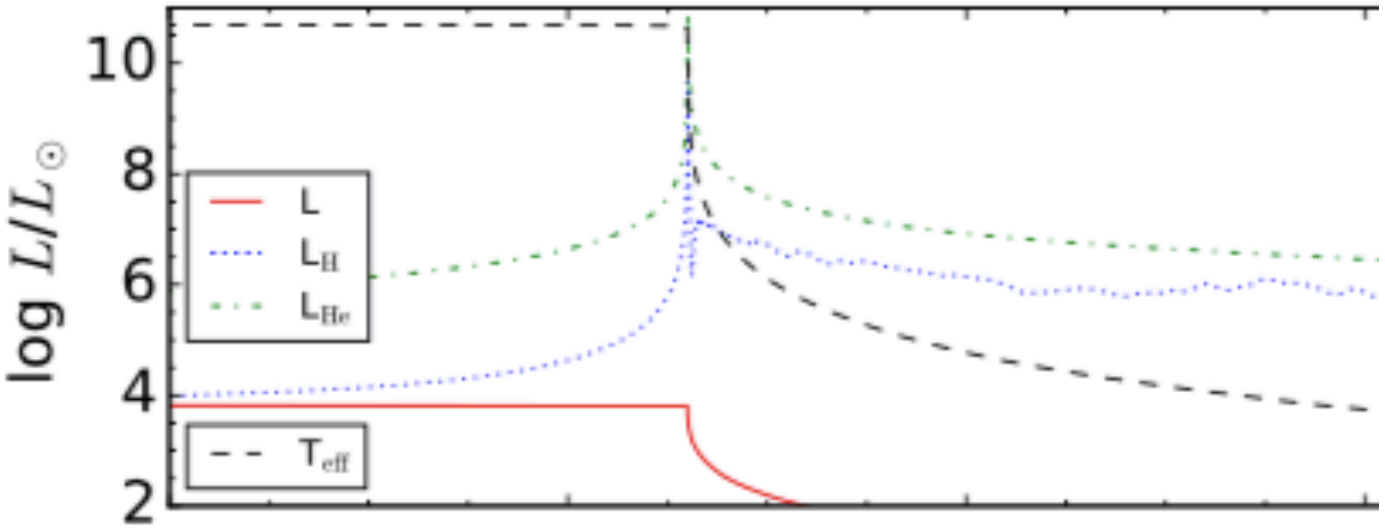


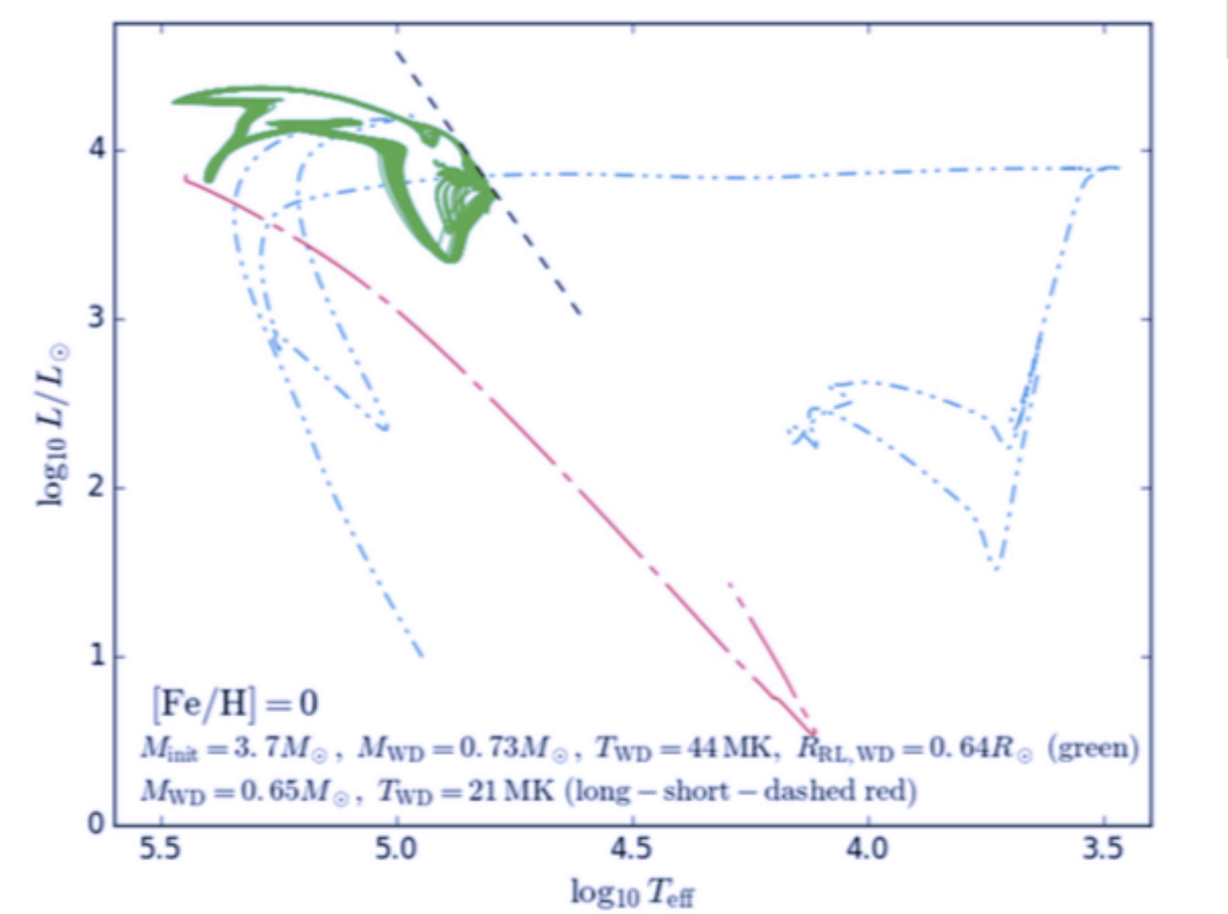
Radial velocity component

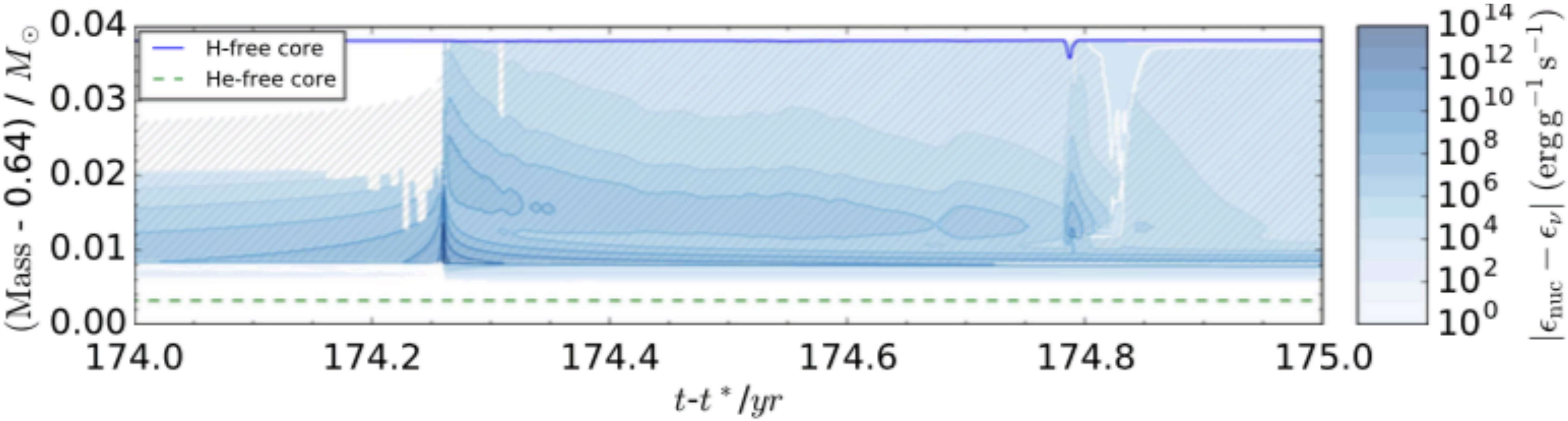
3D hydrodynamic simulations of H ingestion into He-shell flash convection on rapidly accreting white dwarfs

Multi-cycle Evolution of Rapidly Accreting White Dwarfs

1D stellar evolution view







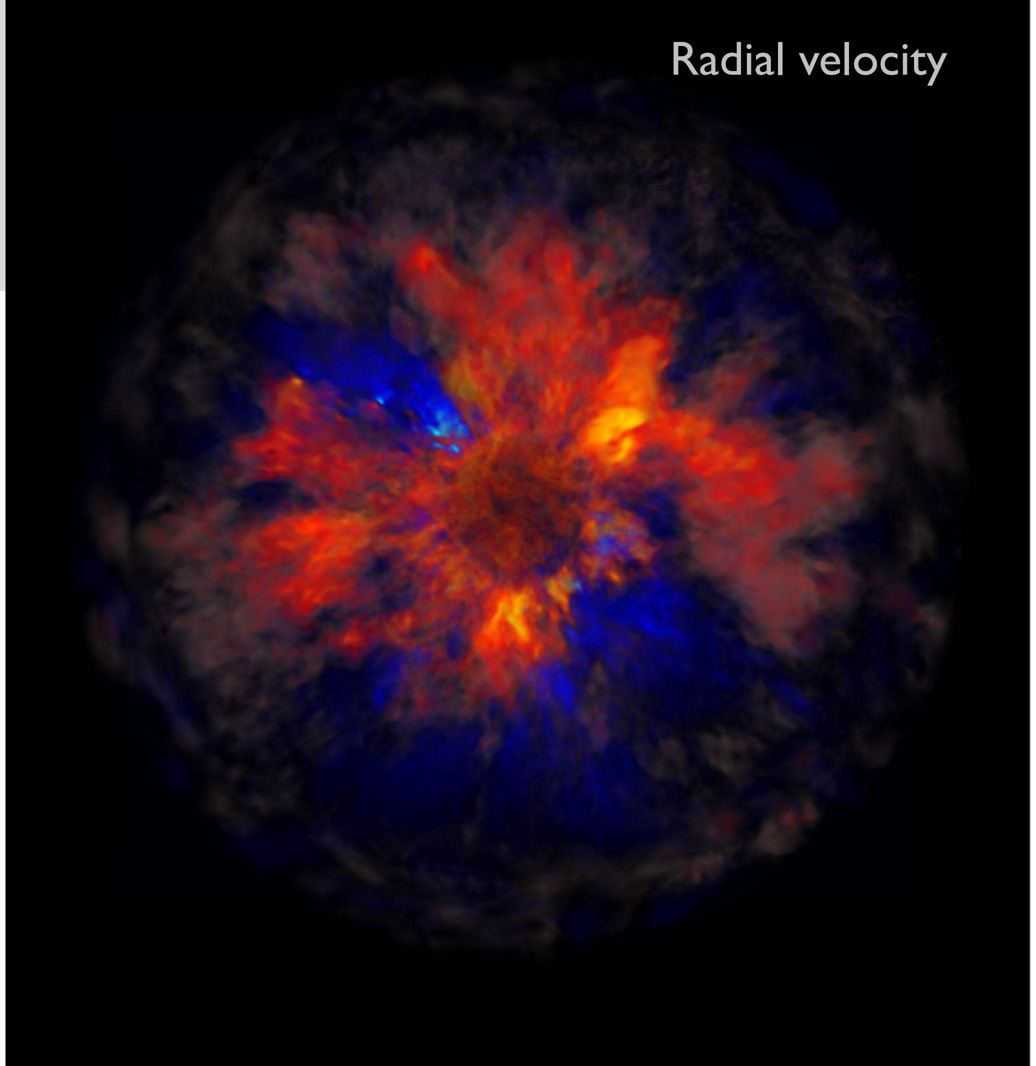
Denissenkov+ 17, ApJ Letters

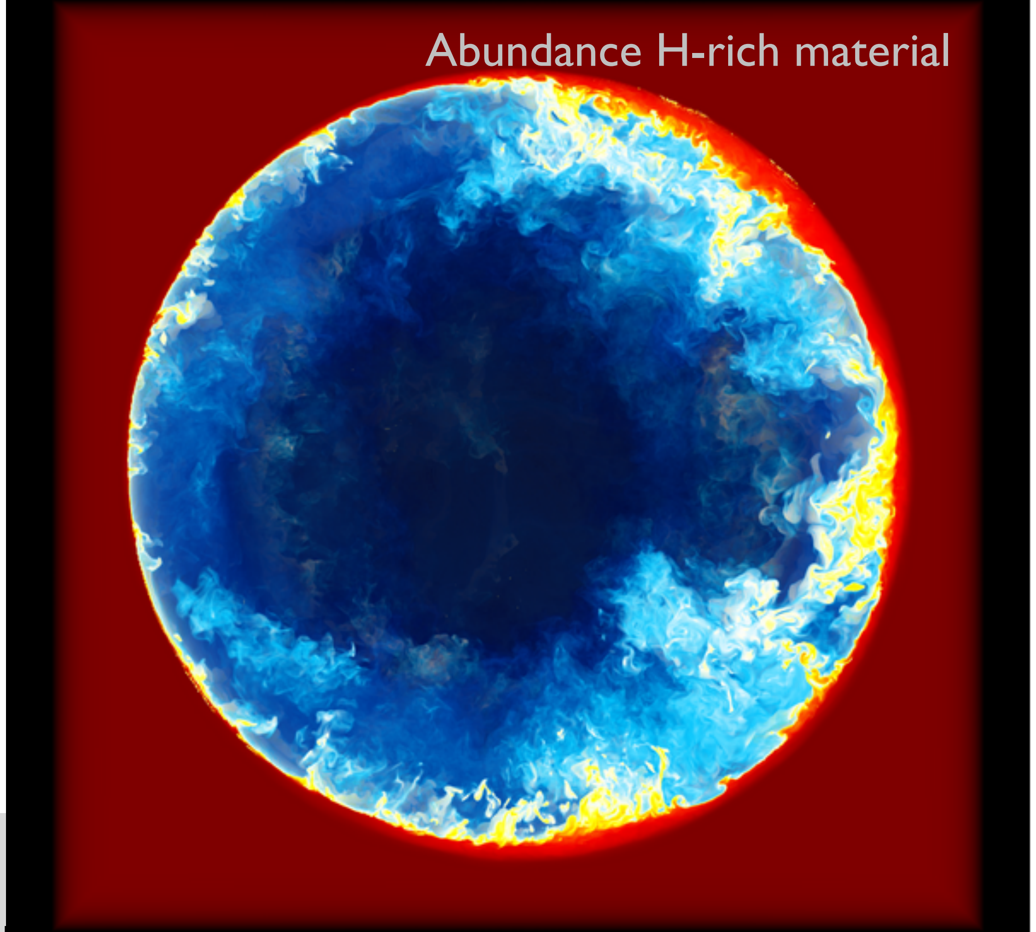
3D1D hydro-nucleosynthesis simulations of iRAWD

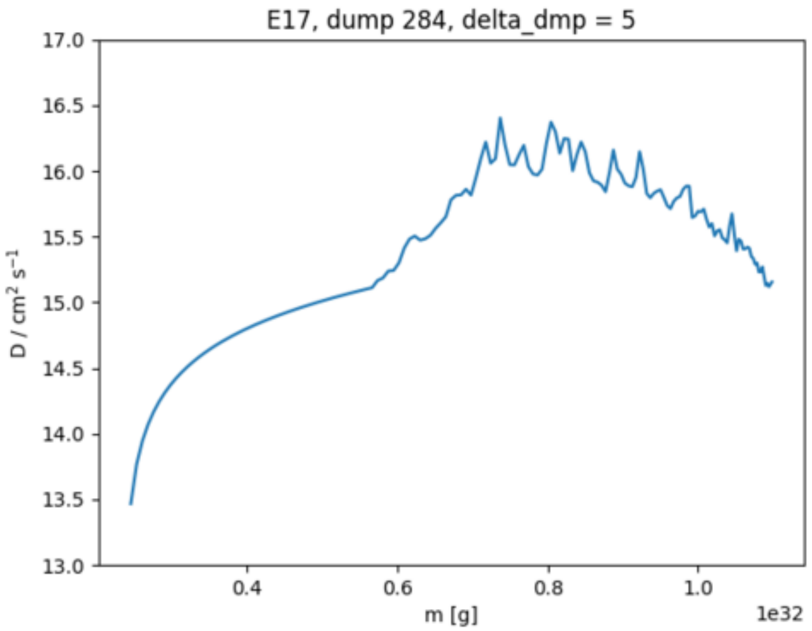
Left panels: 768^3-grid simulation of H-ingestion in RAWD

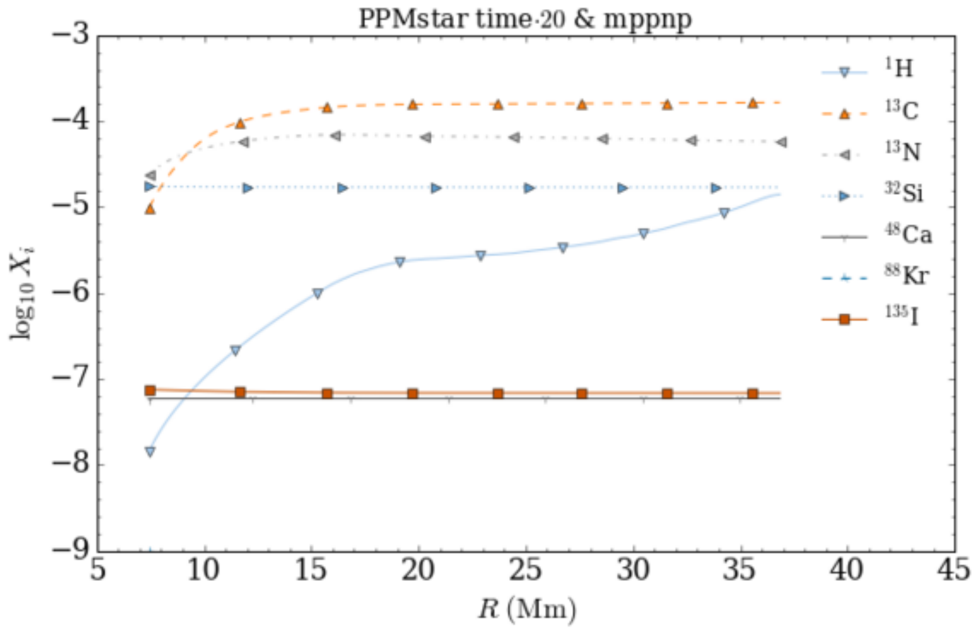
Right (top to bottom):

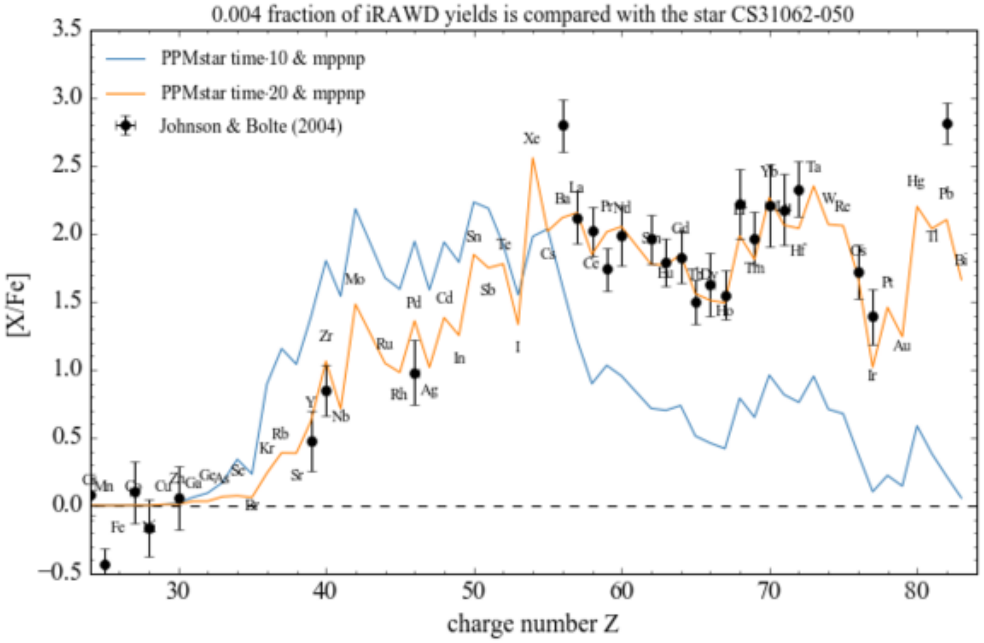
- 1D diffusion coefficient determined from spherical averaged abundance profile from 3D simulations
- abundance profiles of H, 13C and unstable i-process isotopes from multi-zone 1D post-processing of evolving hydro stratification
- abundance distribution compared to CEMP-i star observation
- [time stretched in post-process to compensate for shorter hydro simulation]











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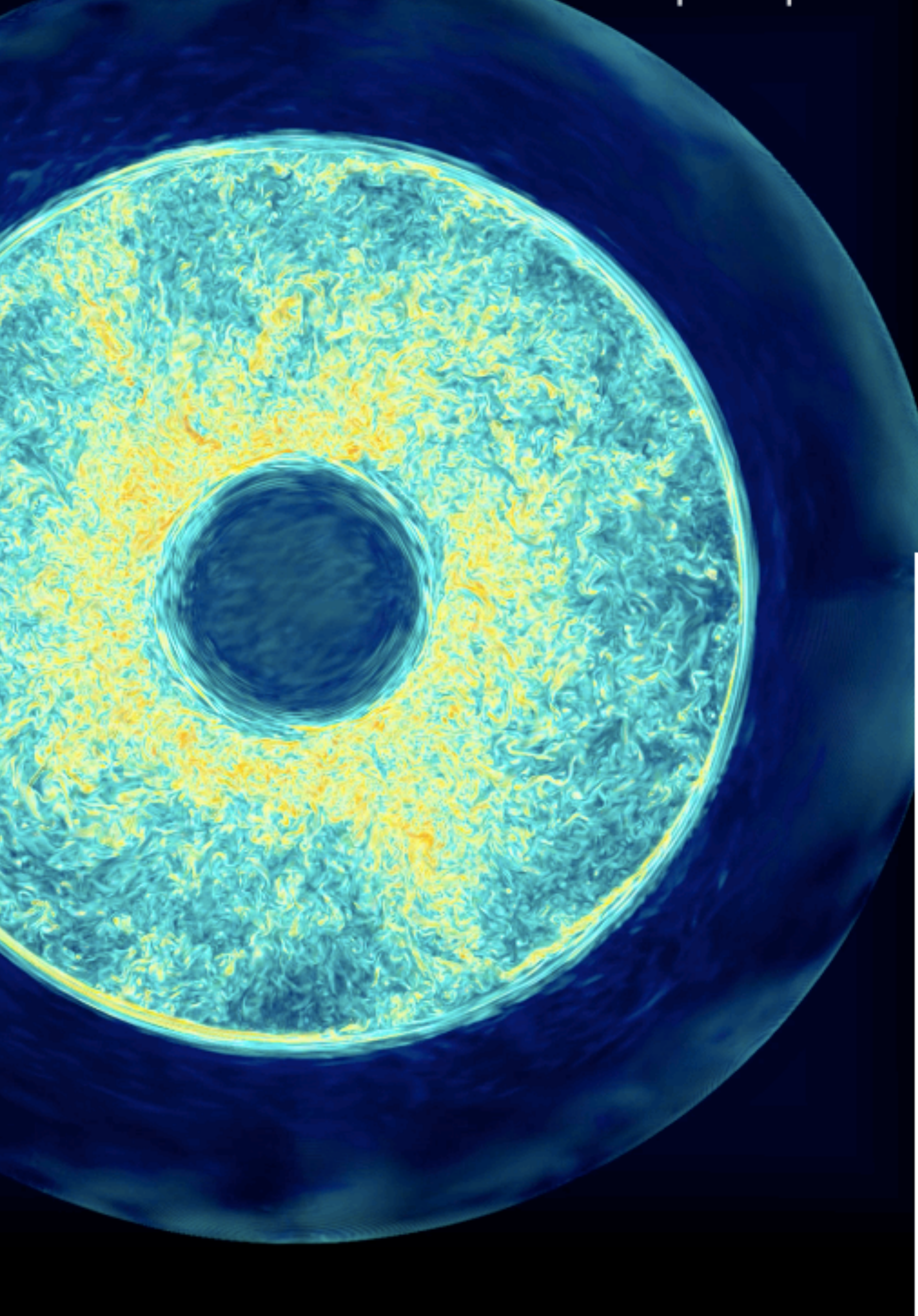
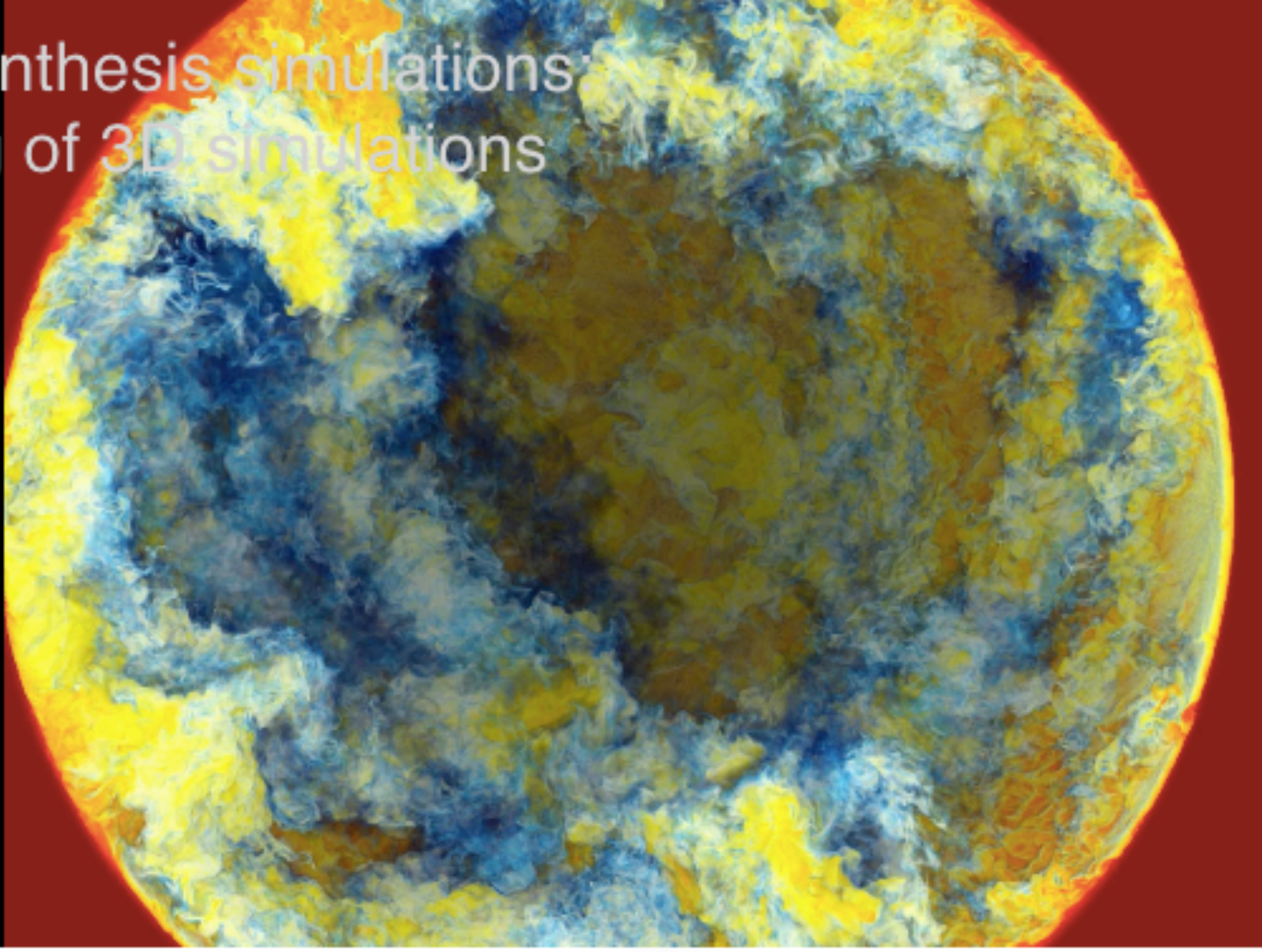
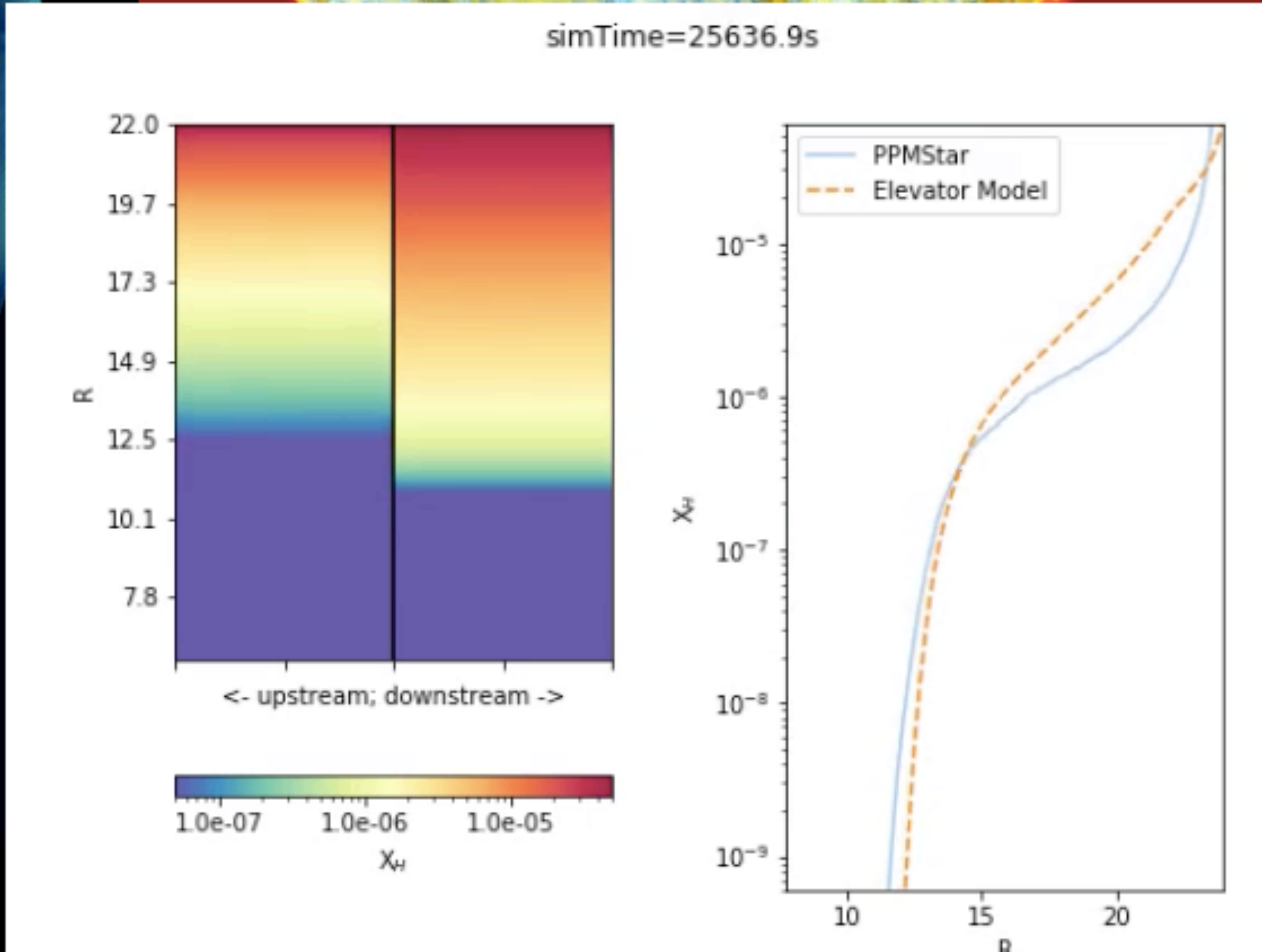
The next generation 3D1D nucleosynthesis simulations: advective-reactive post-processing of 3D simulations

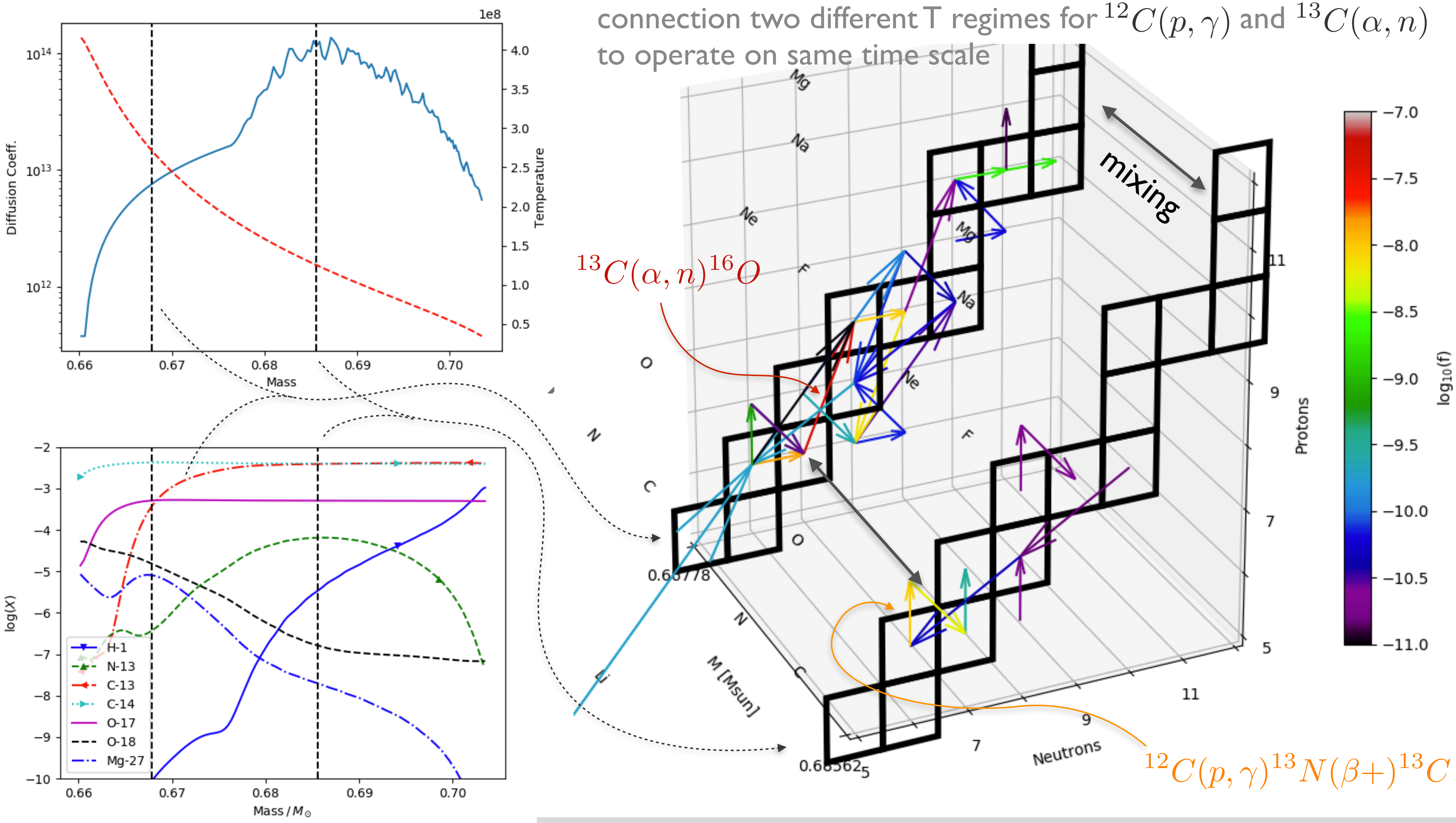






Network flux of convective-reactive i-process nucleosynthesis

Rapid production of neutrons requires convective mixing connection two different T regimes for $^{12}C(p,\gamma)$ and $^{13}C(\alpha,n)$ to operate on same time scale



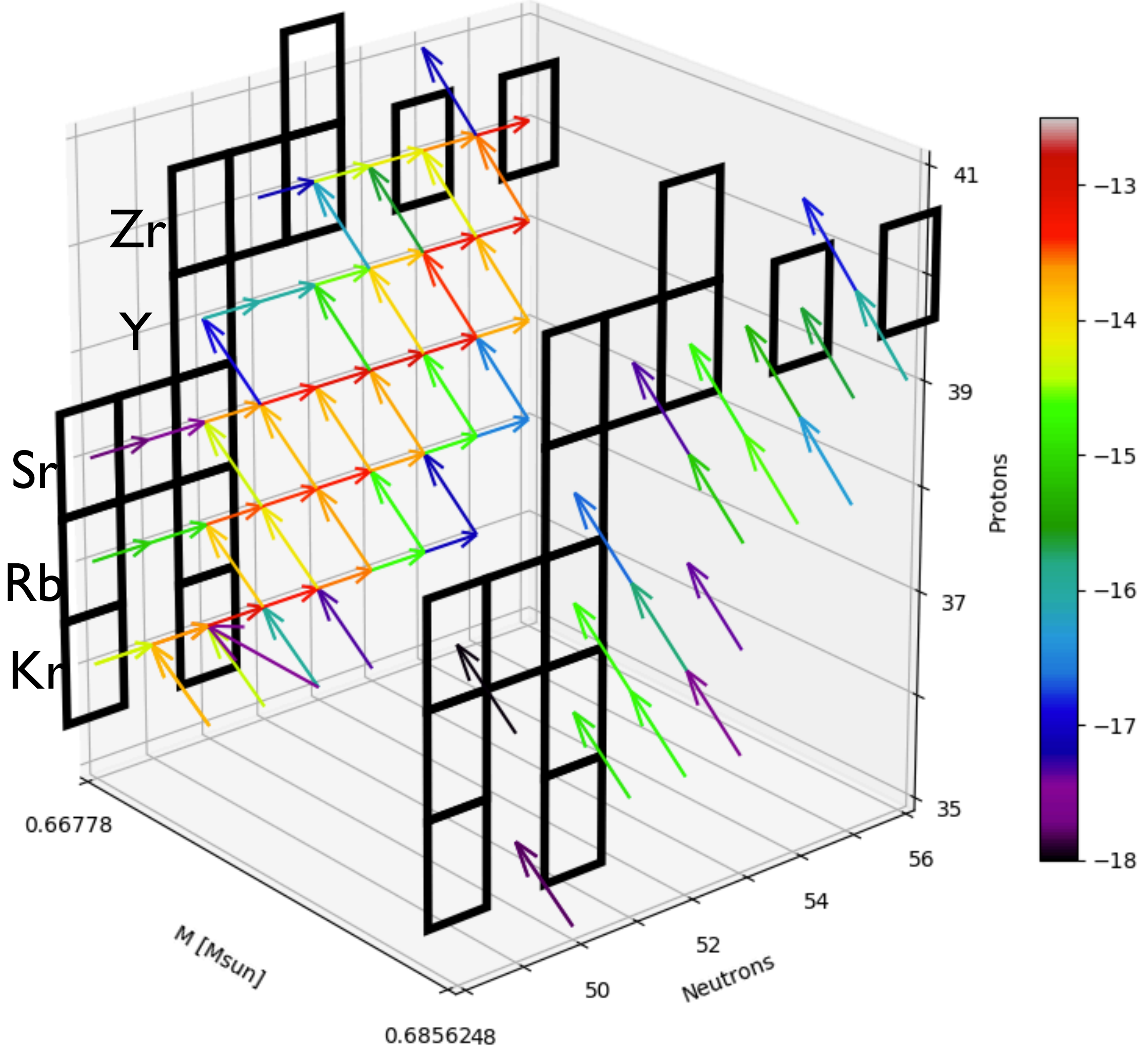
$^{13}C(\alpha,n)^{16}O$

mixing

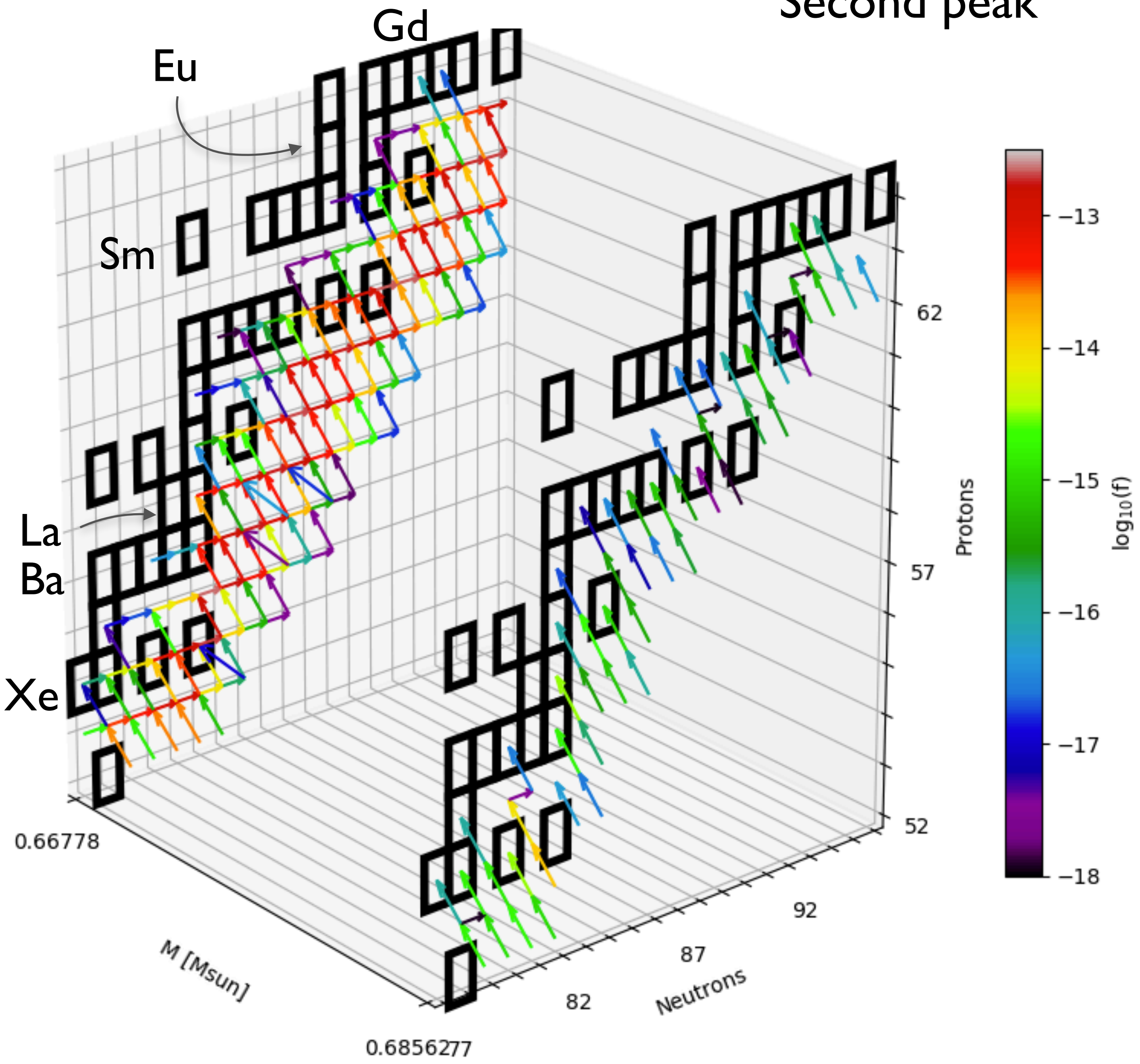
$^{12}C(p,\gamma)^{13}N(\beta+)^{13}C$

Flux plots of convective-reactive nucleosynthesis

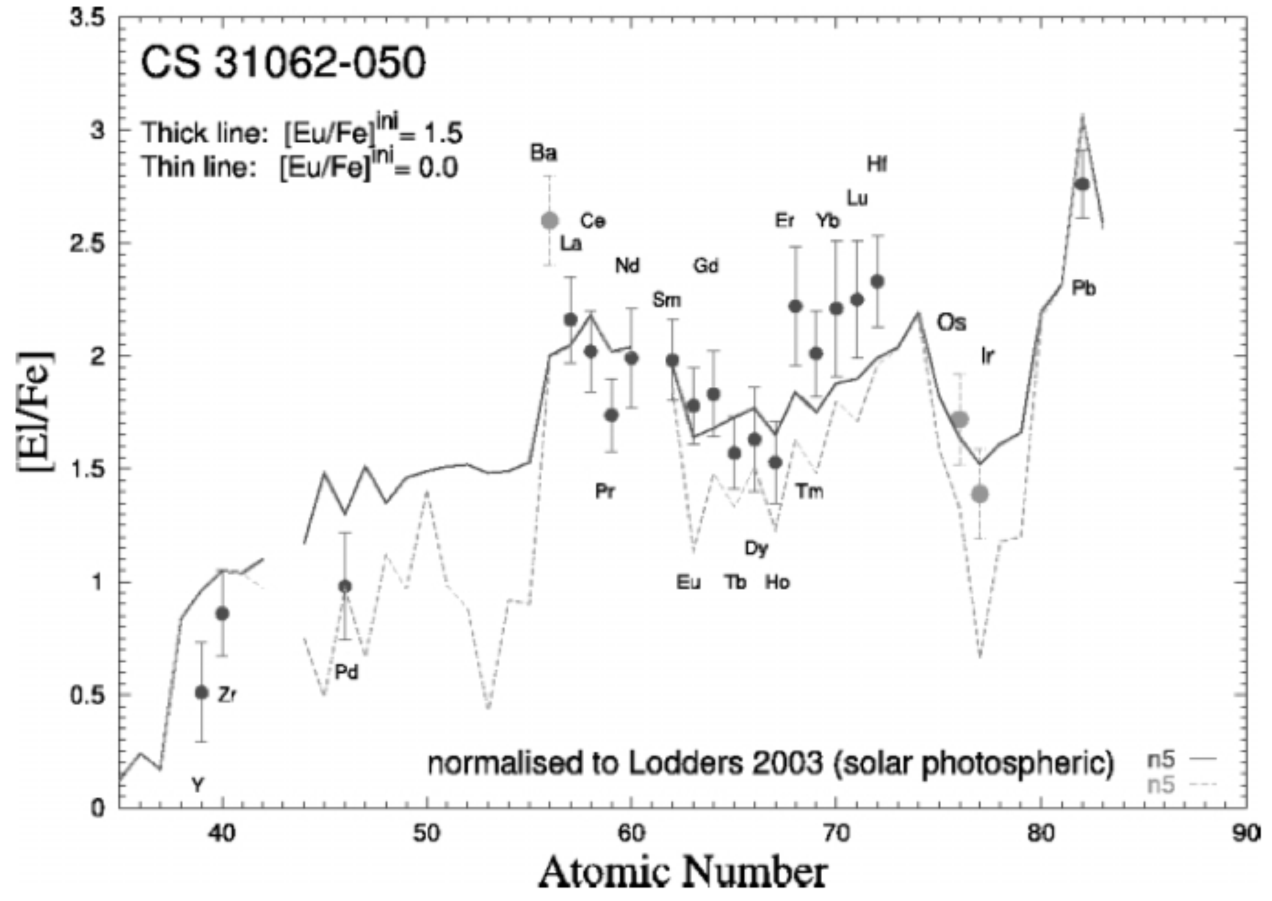
First peak



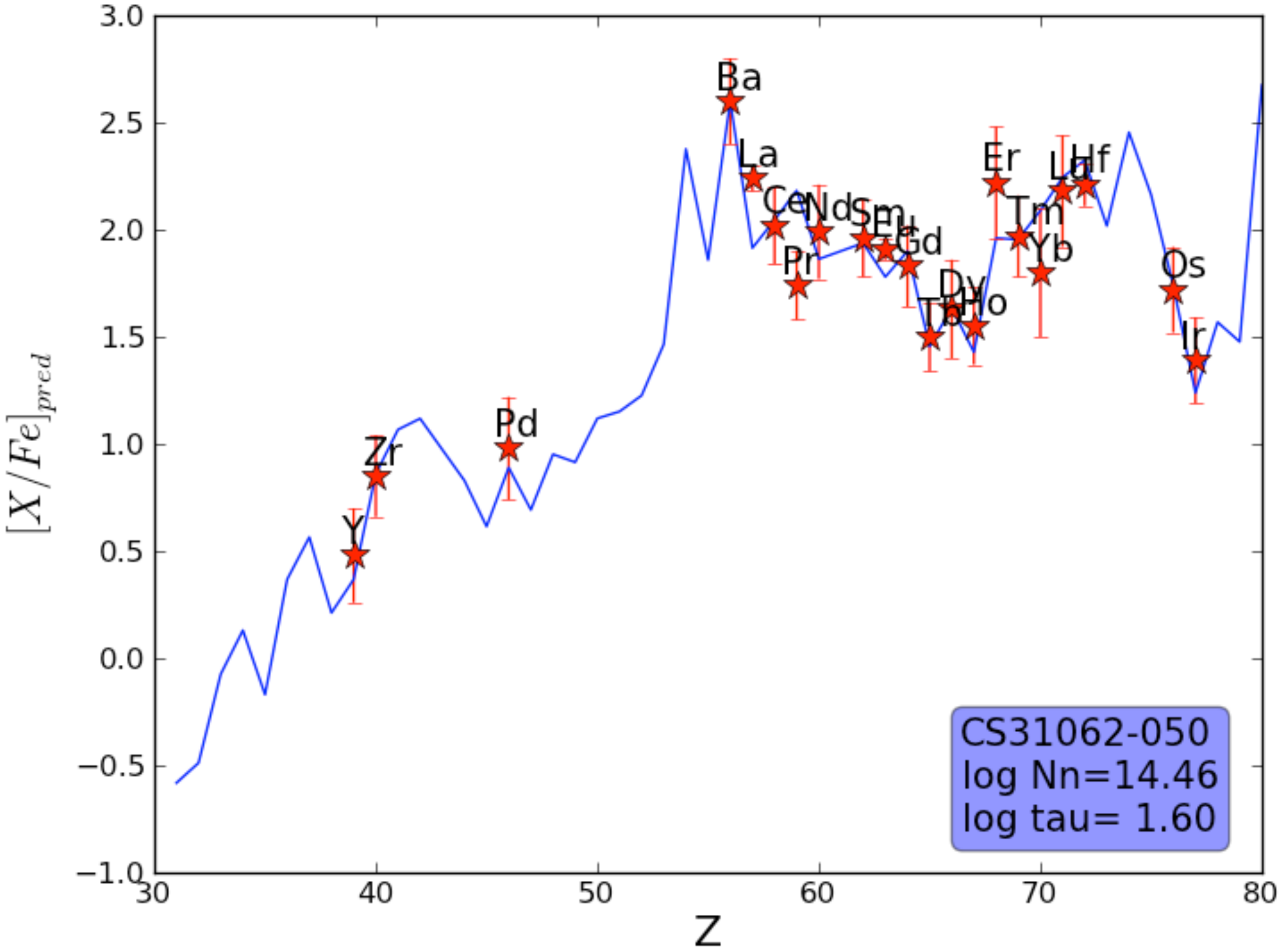
Second peak

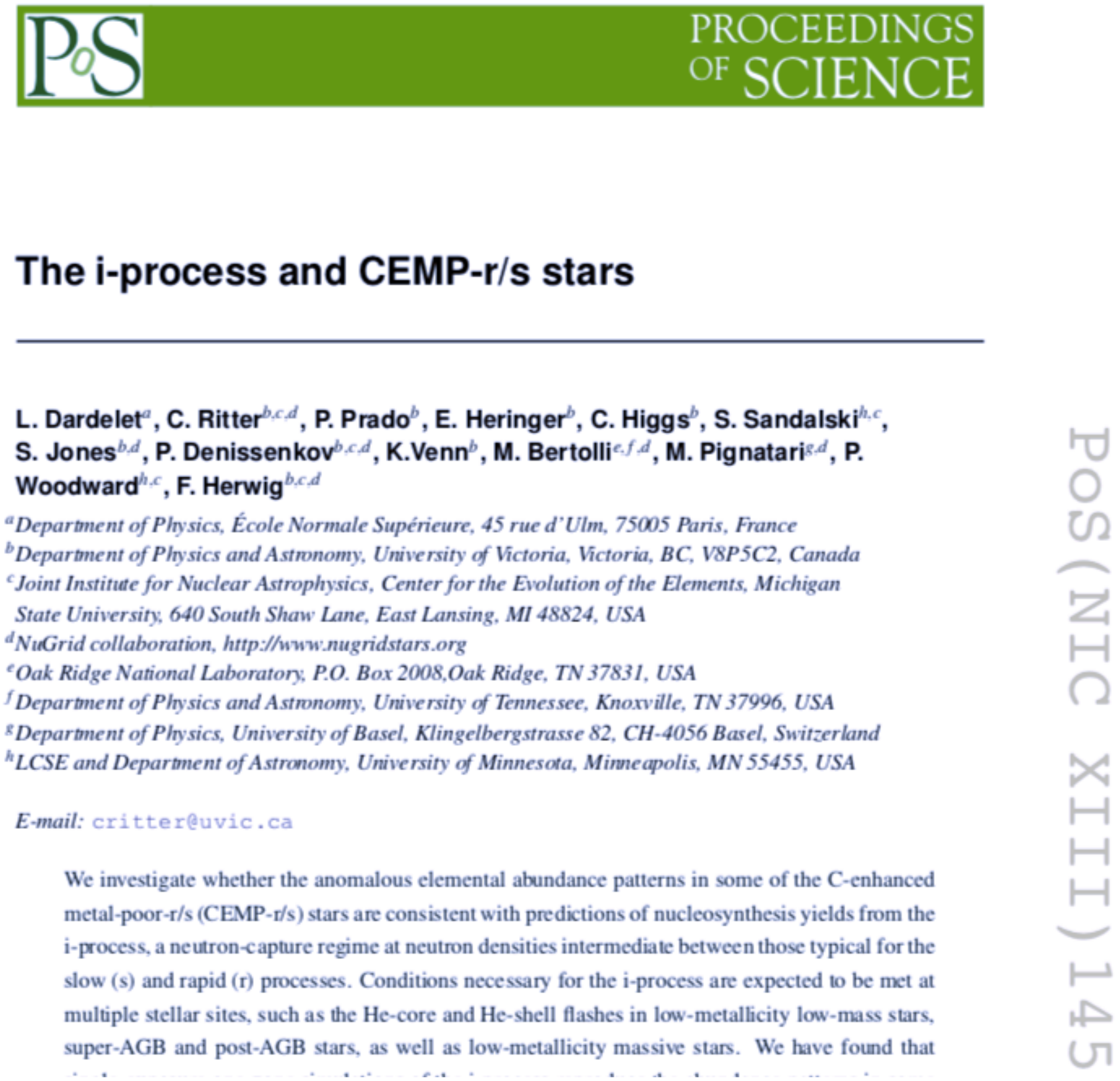


- CEMP-r/s stars
  - anomalous metal-poor star
  - present best model assumes superposition of "known" r- and s-process fingerprint (Bisterzo+ 12)



- instead CEMP-i stars
  - typical neutron density for i process: $N_n \sim 10^{15} cm^{-3}$
  - very good match to reproduction of observed abundance pattern of this CEMP-r/s star → CEMP-i star! (Dardalet+ 14, Proceedings of XIII Nuclei in the Cosmos (NIC XIII). 7-11 July, 2014. 2014nic..confE.145D)
  - see also Hampel+ 16, 2016ApJ…831..171H
  - simple, single-zone i-process network calculation





PROCEEDINGS OF SCIENCE

The i-process and CEMP-r/s stars

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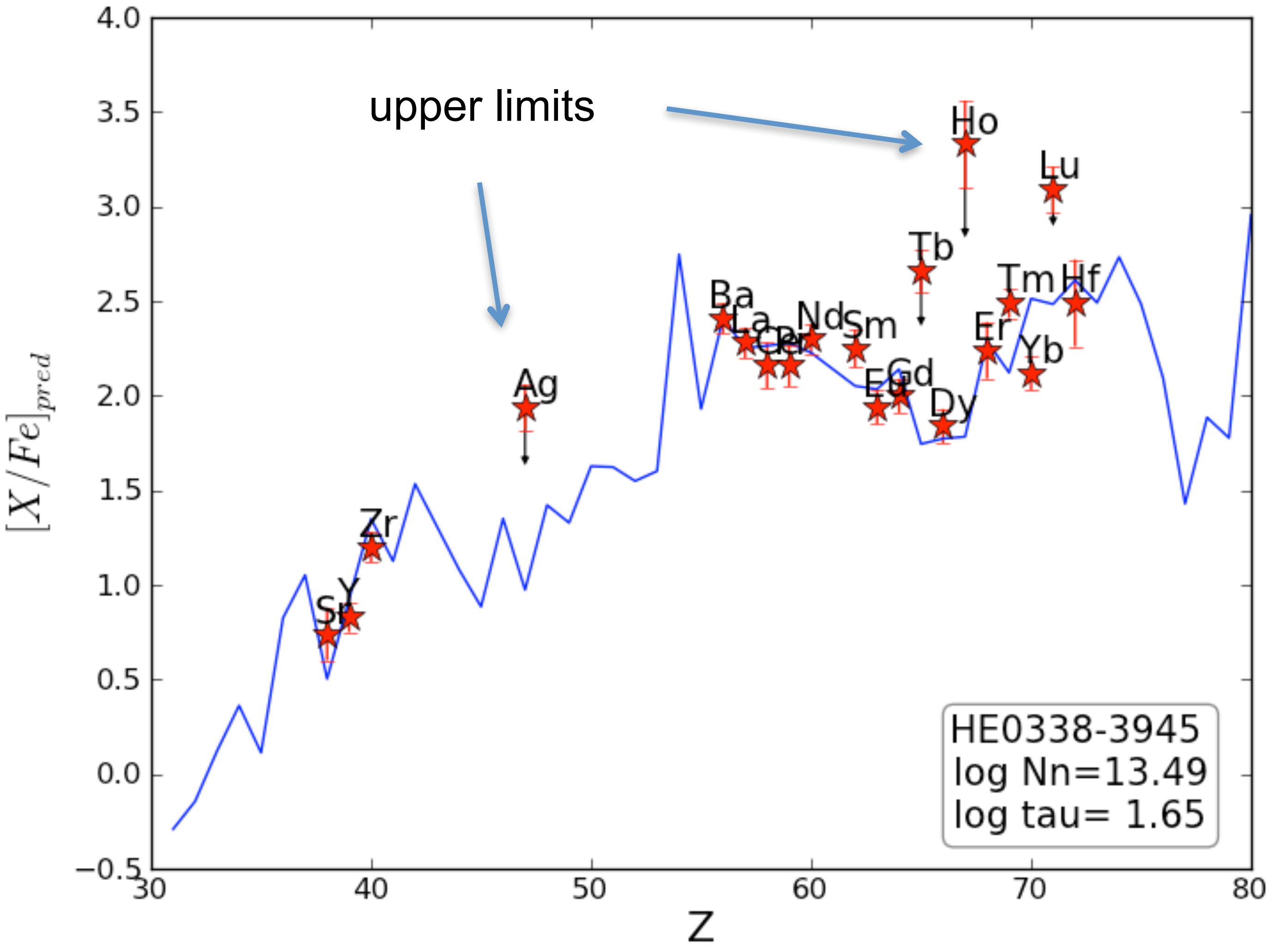
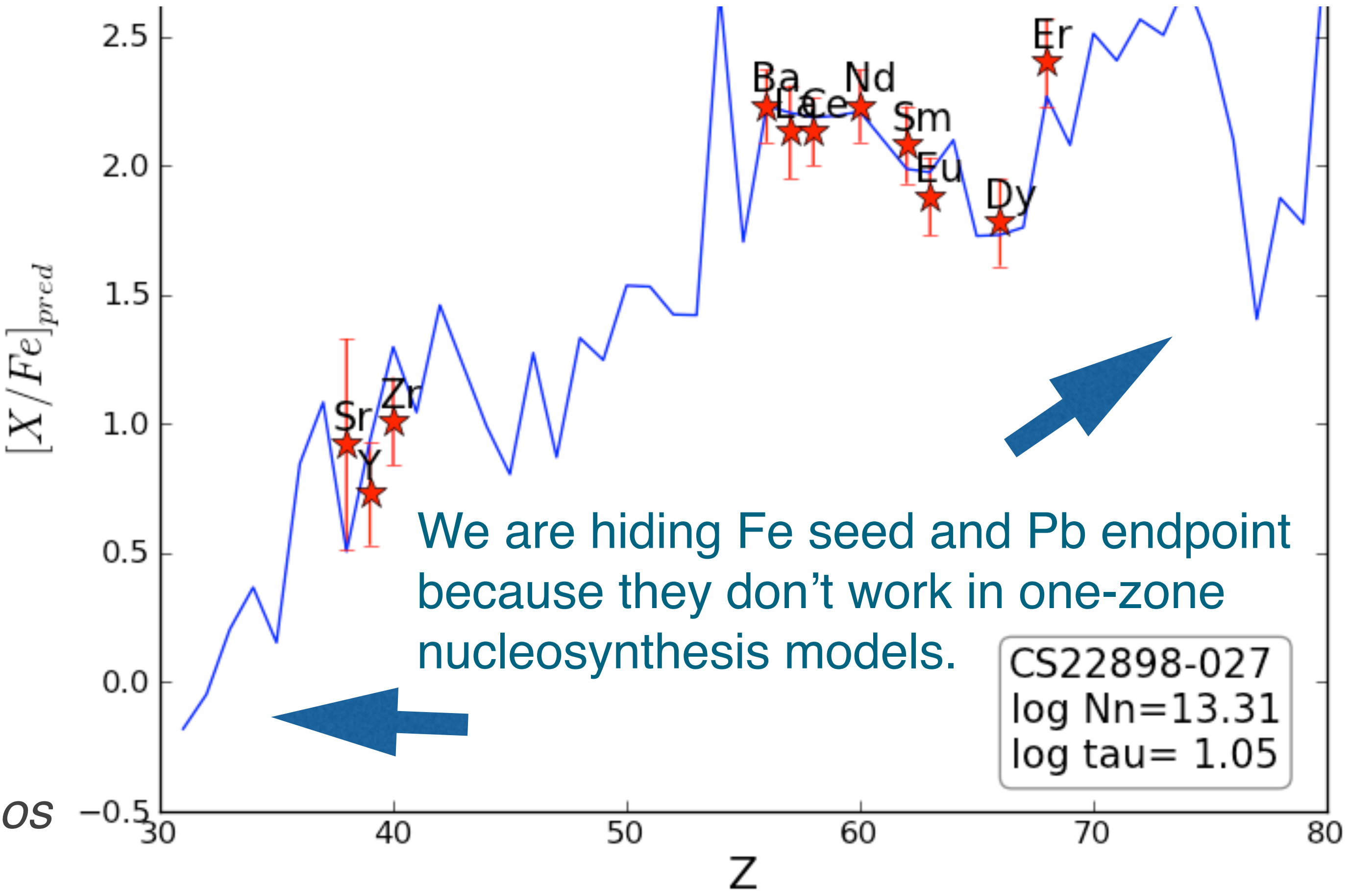
We investigate whether the anomalous elemental abundance patterns in some of the C-enhanced metal-poor-r/s (CEMP-r/s) stars are consistent with predictions of nucleosynthesis yields from the i-process, a neutron-capture regime at neutron densities intermediate between those typical for the slow (s) and rapid (r) processes. Conditions necessary for the i-process are expected to be met at multiple stellar sites, such as the He-core and He-shell flashes in low-metallicity low-mass stars, super-AGB and post-AGB stars, as well as low-metallicity massive stars. We have found that

PoS(NIC XIII)145





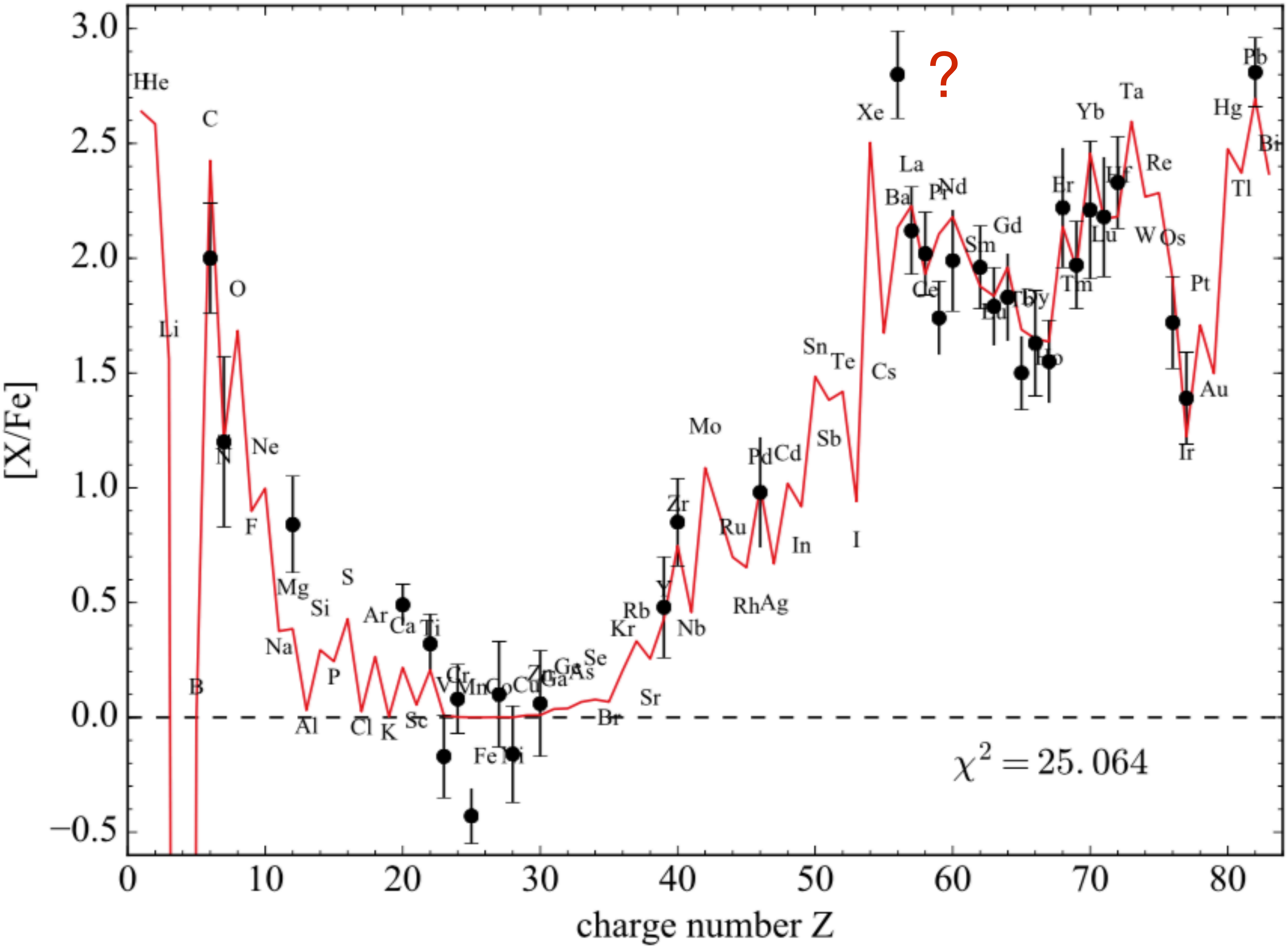
We are hiding Fe seed and Pb endpoint because they don't work in one-zone nucleosynthesis models.

- out of an initial sample (23):
    - 5 category A
    - 13 category B
- ongoing project, what stars to add to analysis

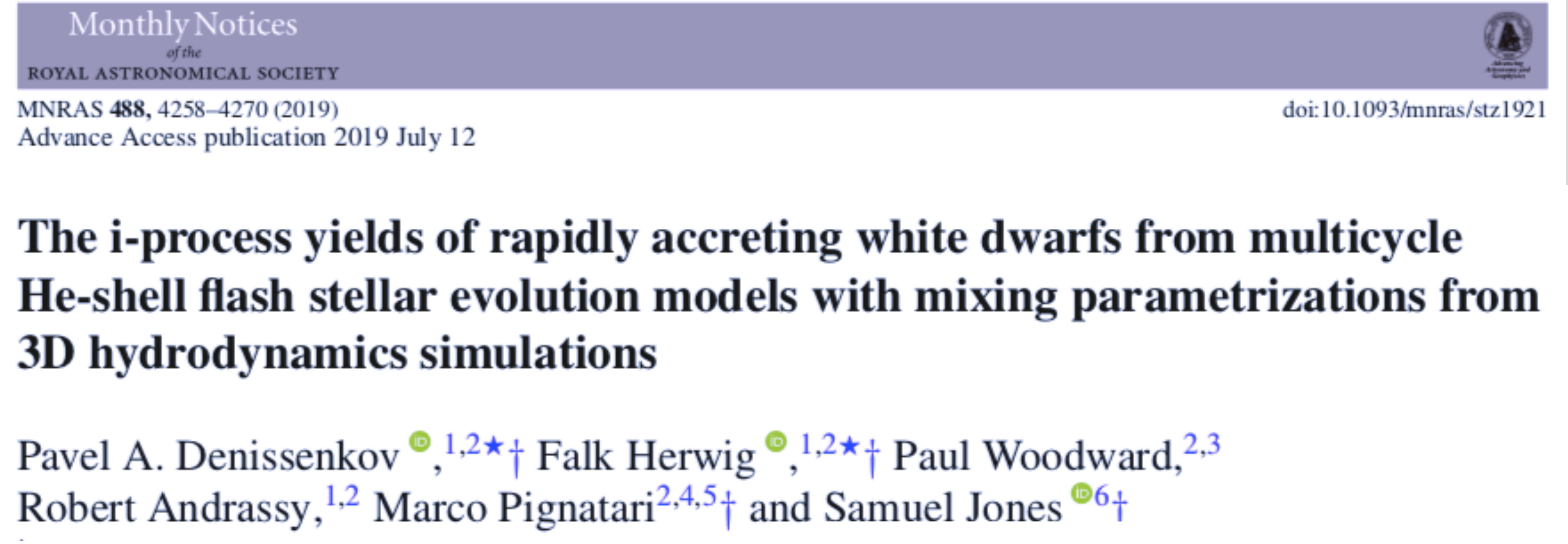
- *Bertolli+ 13, arXiv:1310.4578*
- *Dardelet+ 14, Proceedings of XIII Nuclei in the Cosmos (NIC XIII). 7-11 July, 2014. 2014nic..confE.145D*
- *Hampel+ 2016 (ApJ)*

i process in low-Z RAWD - origin of CEMP-i stars

- Rapidly Accreting White Dwarf model G from D19.
- These i-process simulations are essentially parameter free.
- These new models can for the first time explain these CEMP star abundances within a realistic astrophysical site.



Denissenkov+ 19 (MNRAS); observations Aoki+ 02 & Johnson & Bolte 04



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MNRAS **488**, 4258–4270 (2019)
Advance Access publication 2019 July 12

doi:10.1093/mnras/stz1921

The i-process yields of rapidly accreting white dwarfs from multicycle He-shell flash stellar evolution models with mixing parametrizations from 3D hydrodynamics simulations

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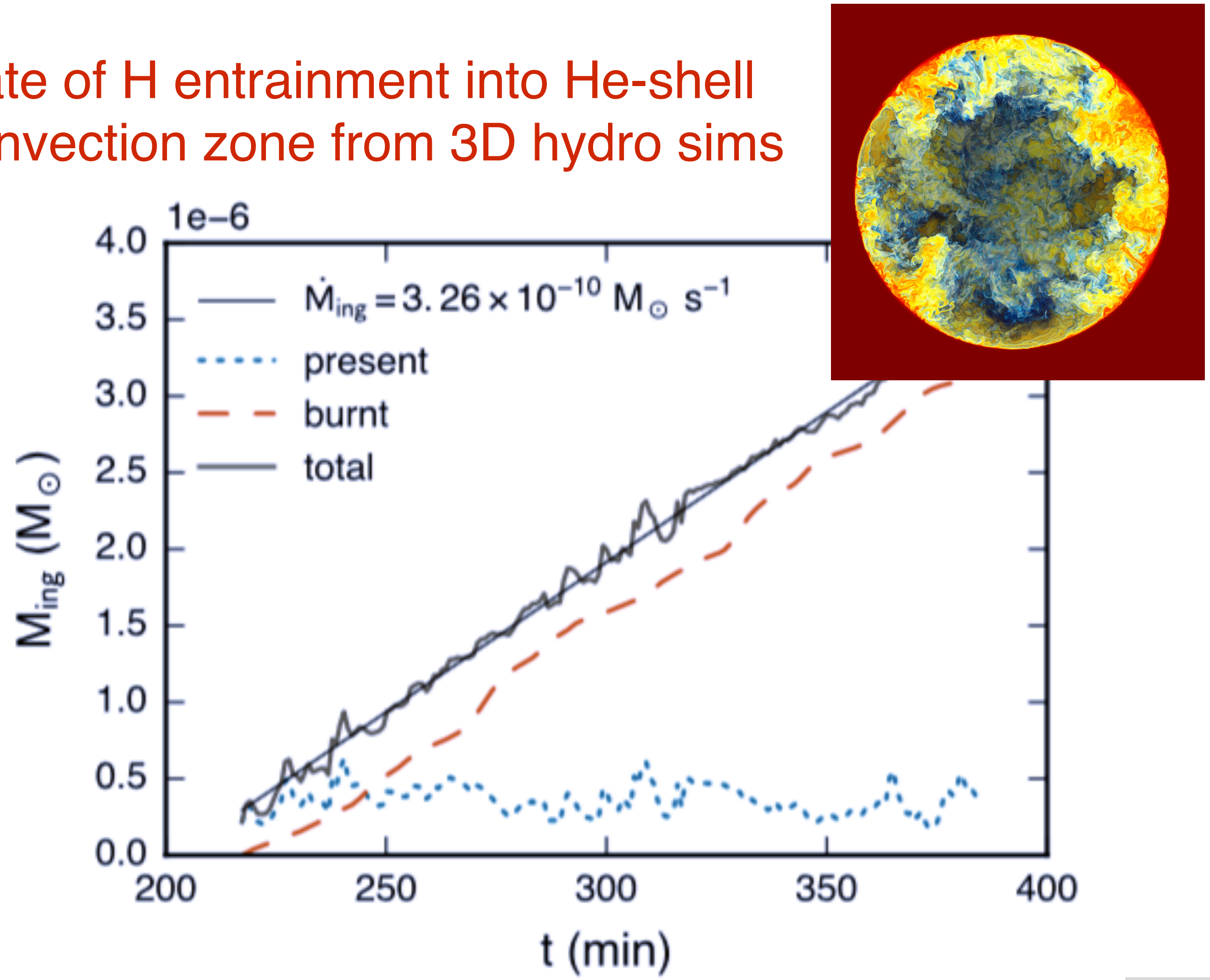
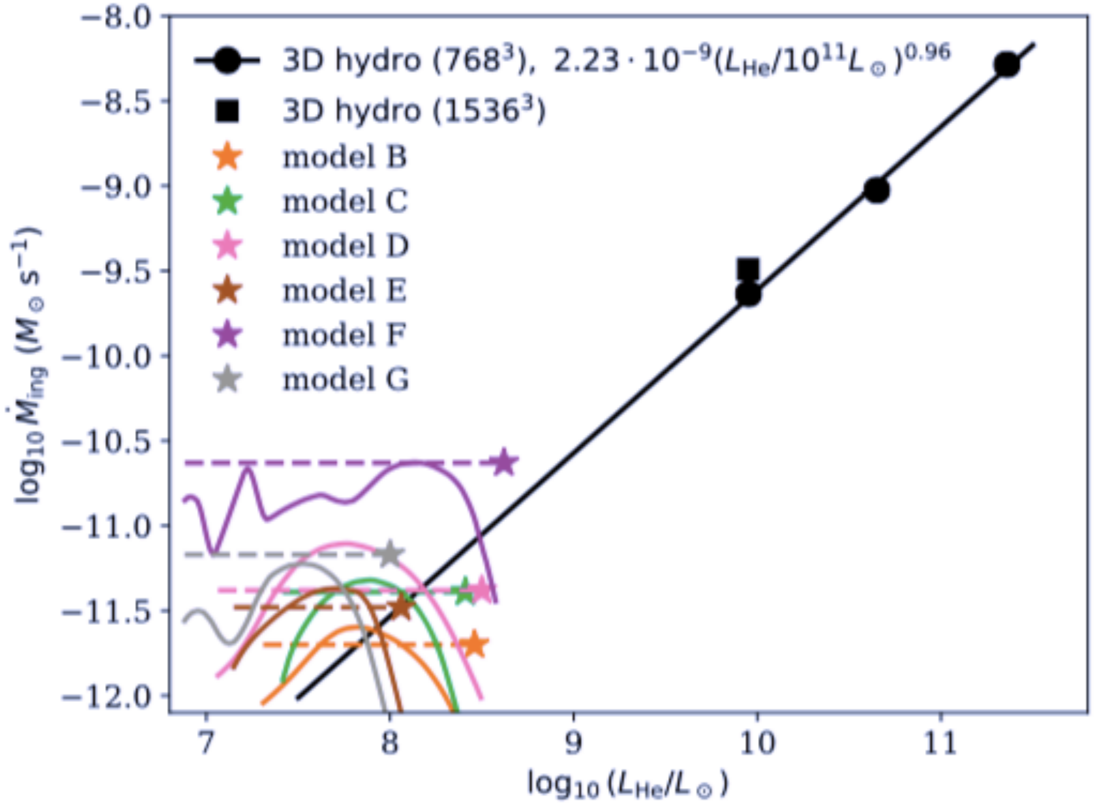
Robert Andrassy,[1,2] Marco Pignatari[2,4,5†] and Samuel Jones[6†]

Rate of H entrainment into He-shell convection zone from 3D hydro sims





Rate of H entrainment as a function of driving luminosity.

Higher WD mass → higher L_{He} → higher entrainment rate → higher N_n → higher [Ba/La]

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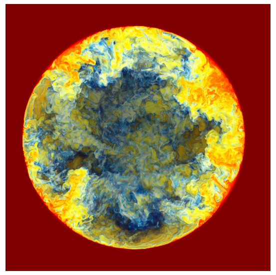


The i-process yields of rapidly accreting white dwarfs from multicycle He-shell flash stellar evolution models with mixing parametrizations from 3D hydrodynamics simulations

Determination of 1D convective diffusion coefficient from 3D hydro sims (cf. Jones+ 17 for 3D hydro simulations in O-shell convection in a massive star) and fitting of convective boundary mixing parameter f.

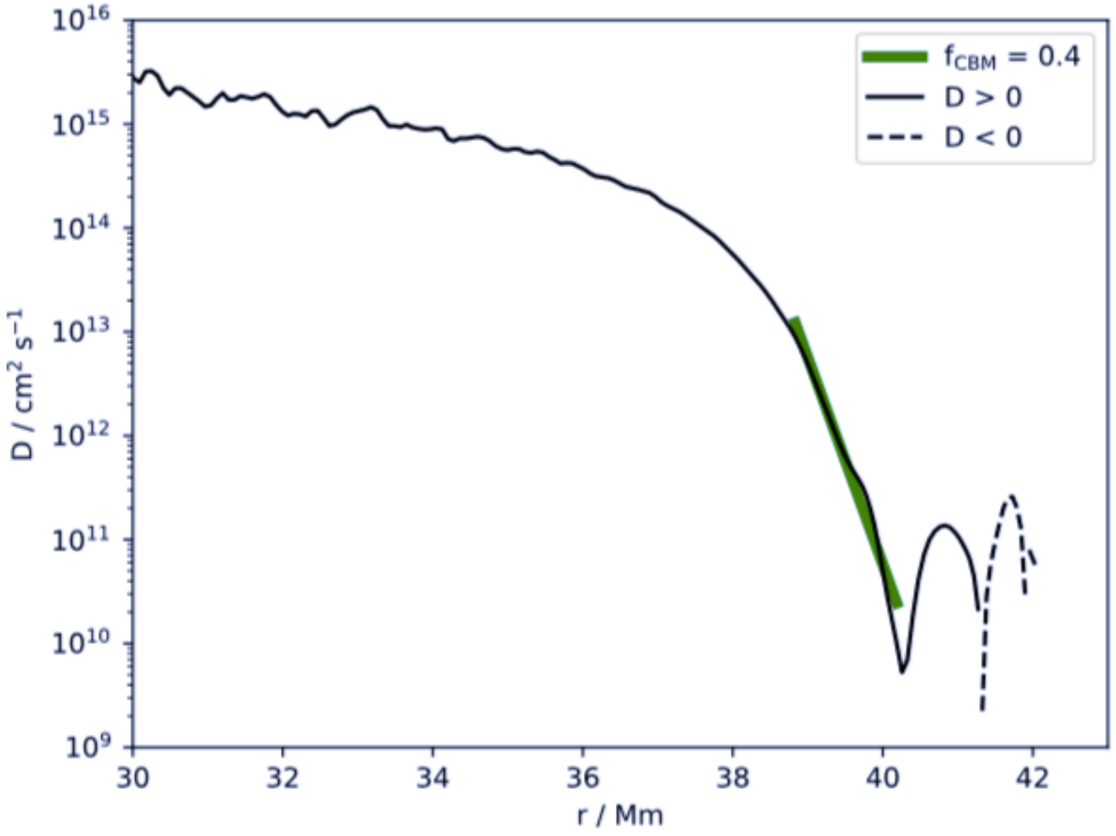


Figure 6. Determination of the f_{top} mixing parameter from the high-grid-resolution 3D hydrodynamics simulation E10.

Extrapolate RAWD hydro f to nominal heating of stellar evolution model using f-scaling relation → $f_{top} = 0.08$ → apply in stellar evolution

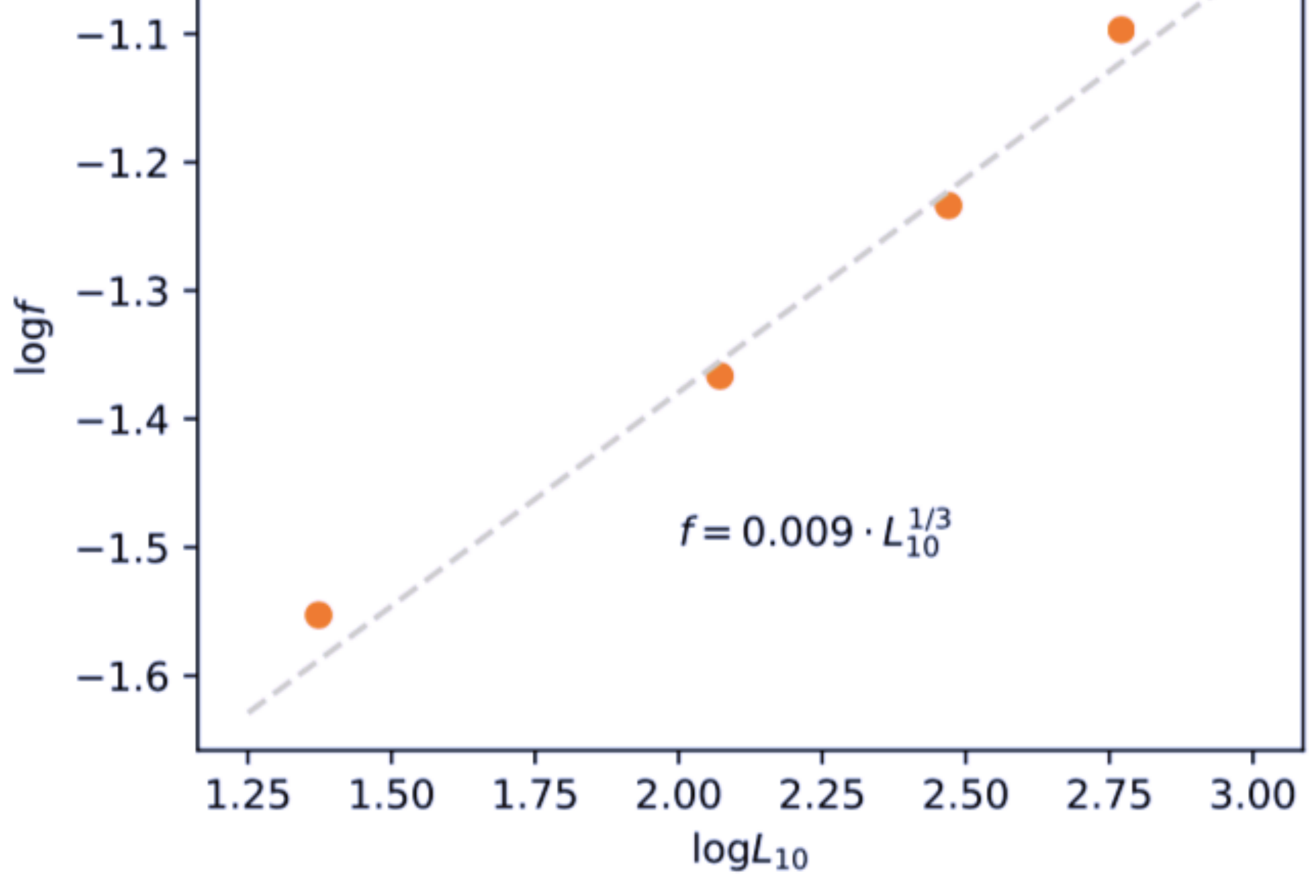


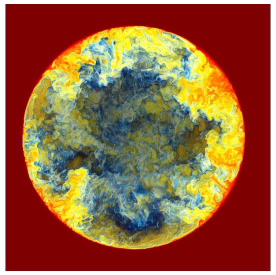
Figure 7. Scaling relation of the convective boundary mixing parameter f_{top} versus the driving luminosity based on a series of 1536-grid simulations of O-shell convection with the same setup as in Jones et al. (2017).

Andrassy+ 19, in preparation

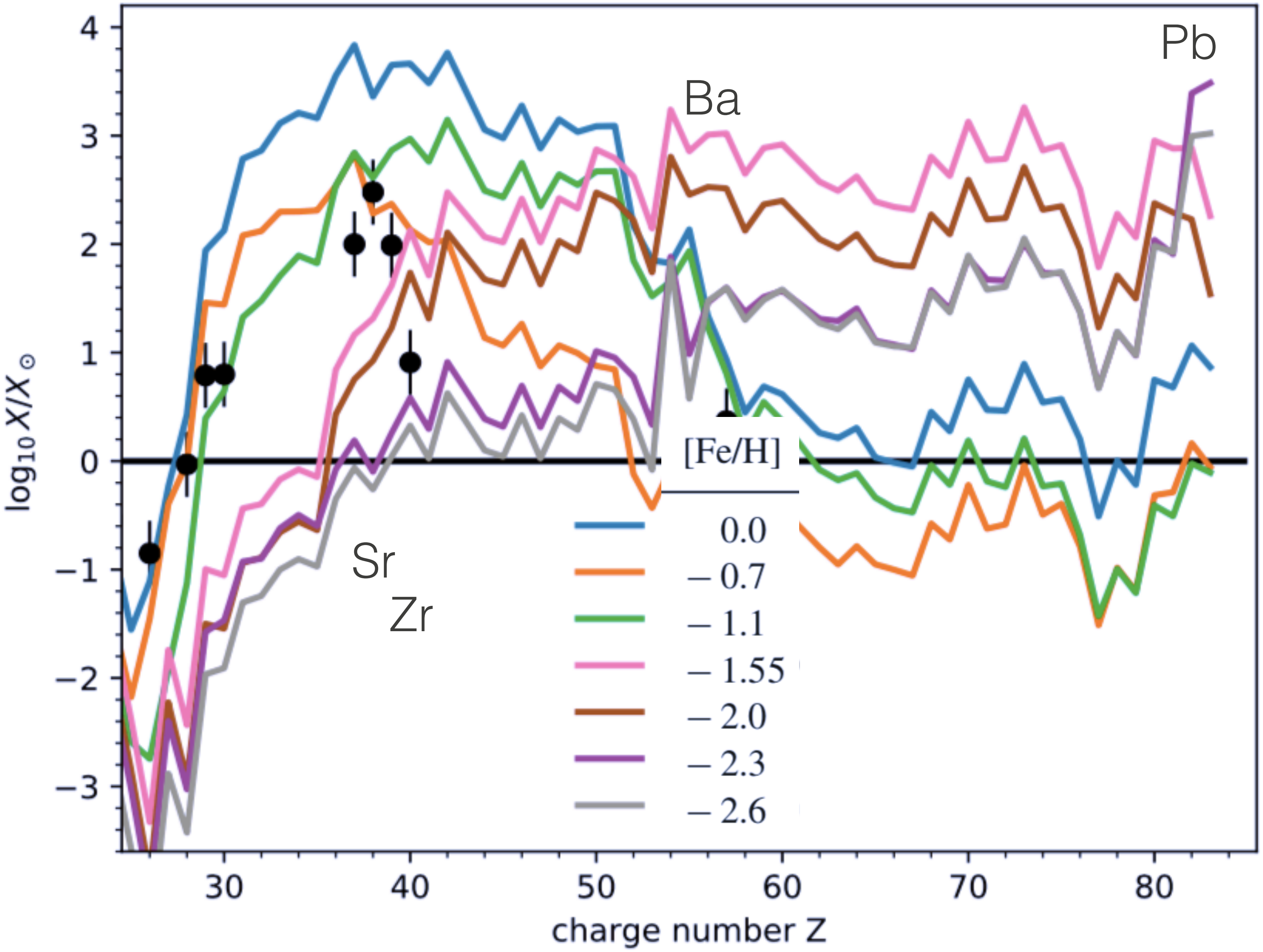
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **488**, 4258–4270 (2019)
Advance Access publication 2019 July 12

doi:10.1093/mnras/stz1921



The i-process yields of rapidly accreting white dwarfs from multicycle He-shell flash stellar evolution models with mixing parametrizations from 3D hydrodynamics simulations



The Astrophysical Journal, 854:105 (14pp), 2018 February 20 https://doi.org/10.3847/1538-4357/aaae8

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i-process Contribution of Rapidly Accreting White Dwarfs to the Solar Composition of First-peak Neutron-capture Elements

Benoit Côté[1,2,3,10], Pavel Denissenkov[1,3,10], Falk Herwig[1,3,10], Ashley J. Ruiter[4,5,6], Christian Ritter[1,3,7,10], Marco Pignatari[3,8,10], and Krzysztof Belczynski[9]

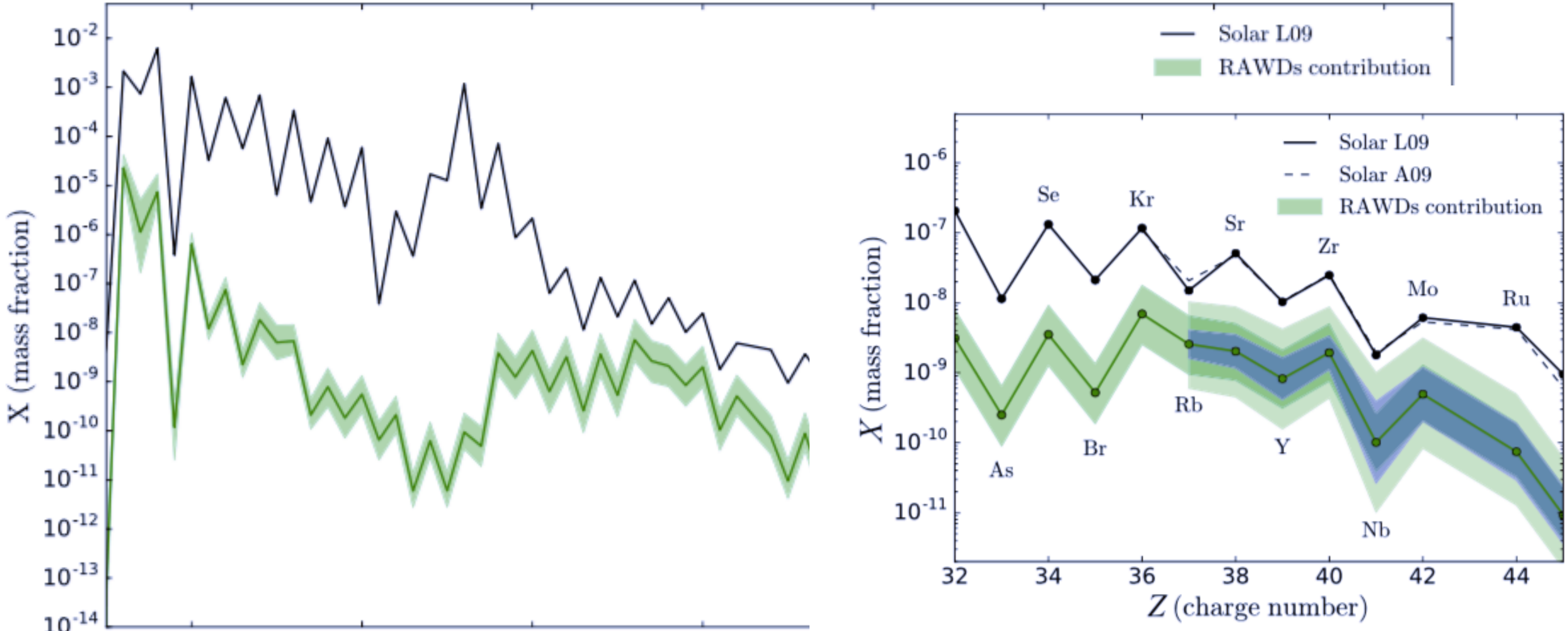


Figure 8. Predicted contribution of rapidly accreting white dwarfs (green, RAWDs) to th fiducial model while the green shaded area shows the range of solutions generated by un different early chemical evolution paths (see Figure 6). The solar composition was taken

Figure 9. Same as in Figure 8, but zoomed on first-peak elements. The dashed black line shows the solar composition of Asplund et al. (2009, A09). The blue shaded area shows the uncertainties generated by nuclear reaction rates (see Section 6.4). The larger lighter-green shaded area shows the combined uncertainties generated by different chemical evolution paths, different ejecta masses for each RAWD, and by nuclear reaction rate uncertainties.

A new paradigm for nucleosynthesis: Convective-reactive nucleosynthesis

New mode of nucleosynthesis when nuclear reaction time scale equals stellar mixing time scale.

This is the convective-reactive, dynamic nucleosynthesis.

The i process is one of several newly identified convective/ advective - reactive cases.

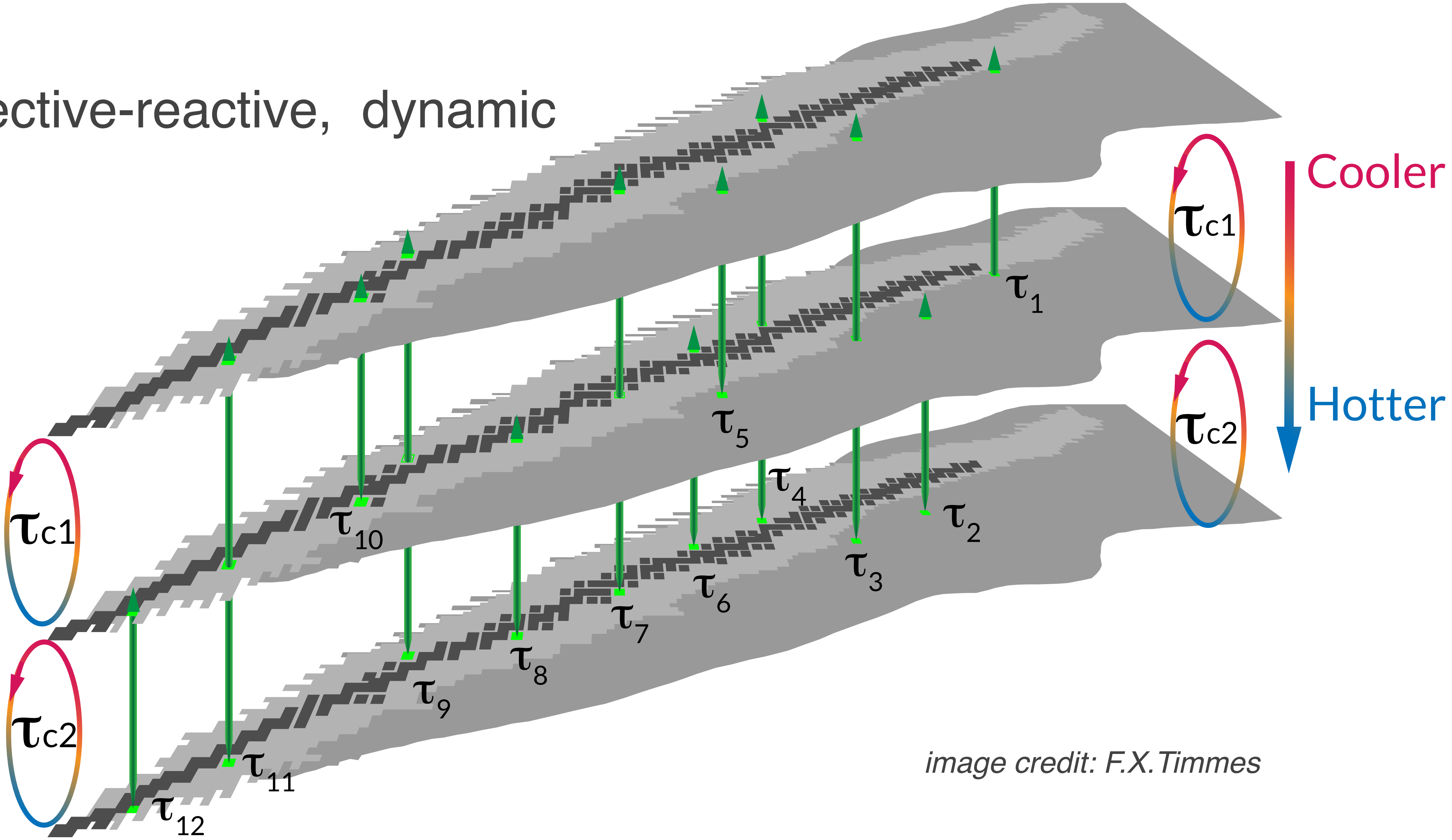


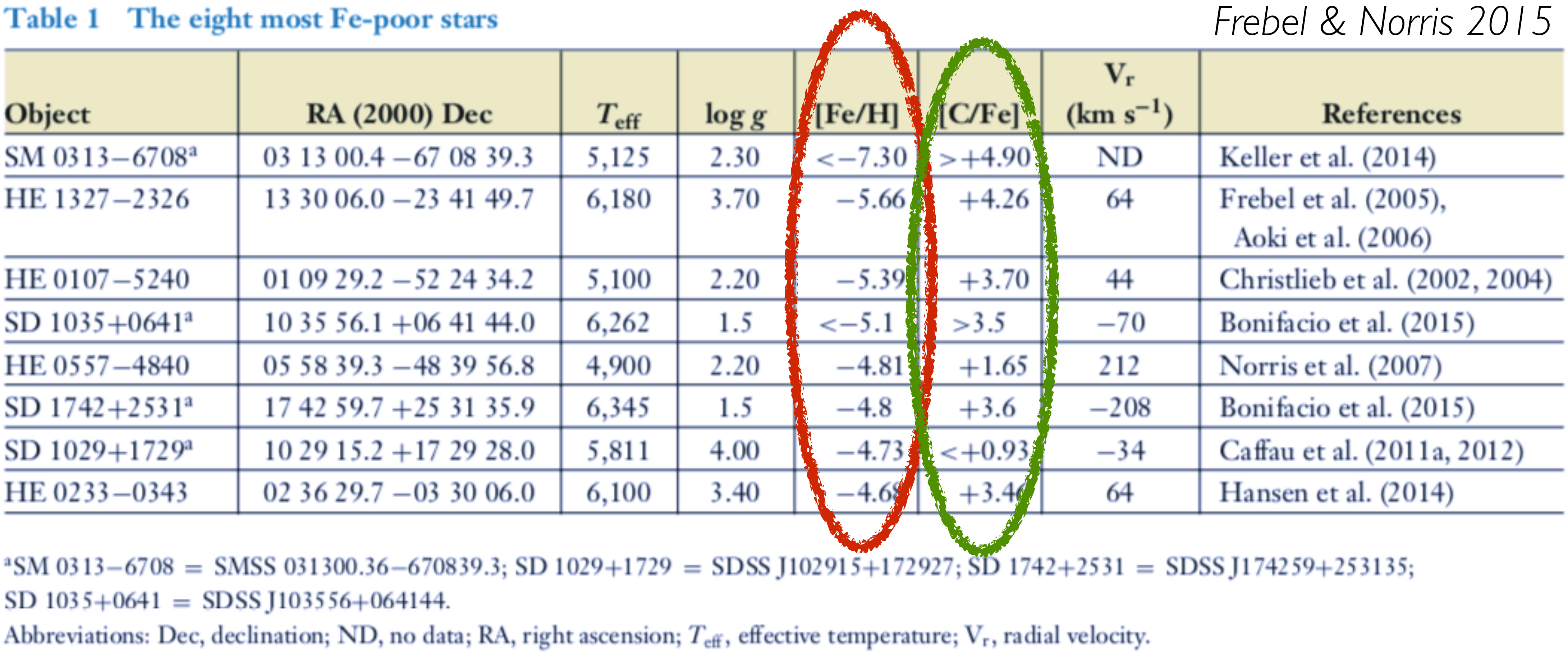
image credit: F.X.Timmes

Convective-reactive nucleosynthesis

Family of nucleosynthetic sites in which nucleosynthesis is coupled with mixing, makes predominantly odd-Z elements.

- H-ingestion in He-shell flashes RAWDs, Sakurai's object, low-Z AGB: Li, i process
  - i-process Nucleosynthesis and Mass Retention Efficiency in He-shell Flash Evolution of Rapidly Accreting White Dwarfs. Denissenkov PA, Herwig F, et al. 2017. *ApJ Lett.* 834(2):L10
  - i-Process yields from multi-cycle evolution of rapidly-accreting white dwarfs for a range of metallicities. Denissenkov P, Herwig F, etal 2019 (MNRAS).
  - i-process Contribution of Rapidly Accreting White Dwarfs to the Solar Composition of First-peak Neutron-capture Elements. Côté B, Denissenkov P, Herwig F, et al. 2018. *ApJ*. 854(2):105
- O-C shell mergers in massive stars: P, Cl, K, Sc
  - Convective-reactive nucleosynthesis of K, Sc, Cl and p-process isotopes in O-C shell mergers. Ritter C, Andrássy R, Côté B, Herwig F et al. 2018. *MNRAS*. 474(1):L1–L6.
- H-He shell mergers in Pop III massive stars: Na, Al, Ca
  - Pop III i-process nucleosynthesis and the elemental abundances of SMSS J0313-6708 and the most iron-poor stars. Clarkson O, Herwig F, Pignatari M. 2018/2019. *MNRAS*.
- Slow mixing and burning in post-He+CO WD merger pre-RCB: F, s-process
  - Abundances in RCB stars. Post-double degenerate merger models - constraints on merger and post-merger simulations and physics processes. Menon A, Herwig F, et al. 2013. *ApJ*. 772(1):59
- Hot-bottom burning in massive AGB stars: N, Li
  - Ritter C, Herwig F, et al. 2018. *MNRAS*. 480(1):538–71

The most Fe-poor stars are C enhanced (CEMP-no)



Frebel & Norris 2015

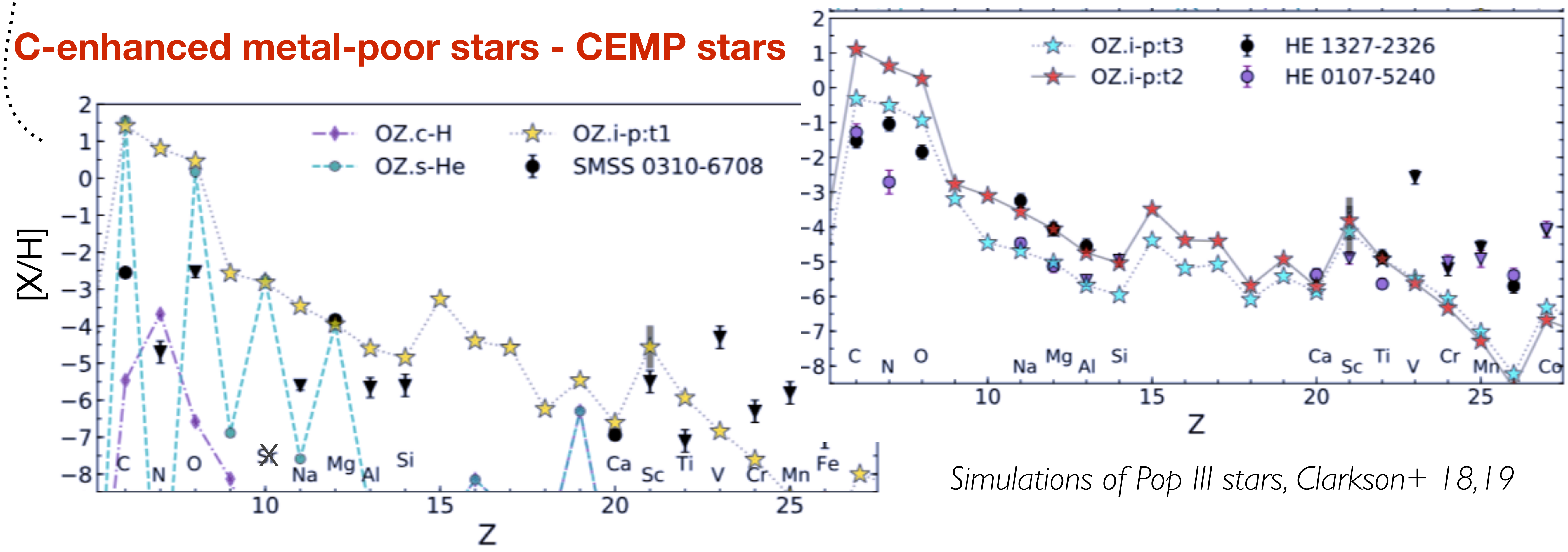
Table 1 The eight most Fe-poor stars

Object	RA (2000) Dec	$T_{\rm eff}$	log g	[Fe/H]	[C/Fe]	V_r (km s^{-1})	References
SM 0313−6708[a]	03 13 00.4 −67 08 39.3	5,125	2.30	<−7.30	>+4.90	ND	Keller et al. (2014)
HE 1327−2326	13 30 06.0 −23 41 49.7	6,180	3.70	−5.66	+4.26	64	Frebel et al. (2005), Aoki et al. (2006)
HE 0107−5240	01 09 29.2 −52 24 34.2	5,100	2.20	−5.39	+3.70	44	Christlieb et al. (2002, 2004)
SD 1035+0641[a]	10 35 56.1 +06 41 44.0	6,262	1.5	<−5.1	>3.5	−70	Bonifacio et al. (2015)
HE 0557−4840	05 58 39.3 −48 39 56.8	4,900	2.20	−4.81	+1.65	212	Norris et al. (2007)
SD 1742+2531[a]	17 42 59.7 +25 31 35.9	6,345	1.5	−4.8	+3.6	−208	Bonifacio et al. (2015)
SD 1029+1729[a]	10 29 15.2 +17 29 28.0	5,811	4.00	−4.73	<+0.93	−34	Caffau et al. (2011a, 2012)
HE 0233−0343	02 36 29.7 −03 30 06.0	6,100	3.40	−4.68	+3.46	64	Hansen et al. (2014)

[a] SM 0313−6708 = SMSS 031300.36−670839.3; SD 1029+1729 = SDSS J102915+172927; SD 1742+2531 = SDSS J174259+253135; SD 1035+0641 = SDSS J103556+064144.

Abbreviations: Dec, declination; ND, no data; RA, right ascension; $T_{\rm eff}$, effective temperature; V_r, radial velocity.

C-enhanced metal-poor stars - CEMP stars



Simulations of Pop III stars, Clarkson+ 18,19

Summary

- i process is a unique neutron-capture process induced by convective H mixing into He-shell convection
- i process generates neutron densities in-between s and r process and unique local abundance signatures
- In order to reproduce the large 2nd-peak enhancements observed in CEMP-i stars a sustained H ingestion is needed.
- Rapidly accreting white dwarfs naturally produce these conditions in complete, self-consistent stellar evolution models
- Our models include calibrations of convective parameters (CBM) from 3D hydro simulations
- The detailed 3D1D convective-reactive nucleosynthesis predictions are in excellent agreement to observations all the way from C to Pb

Epilog

Questions I did not answer but have good answers to:

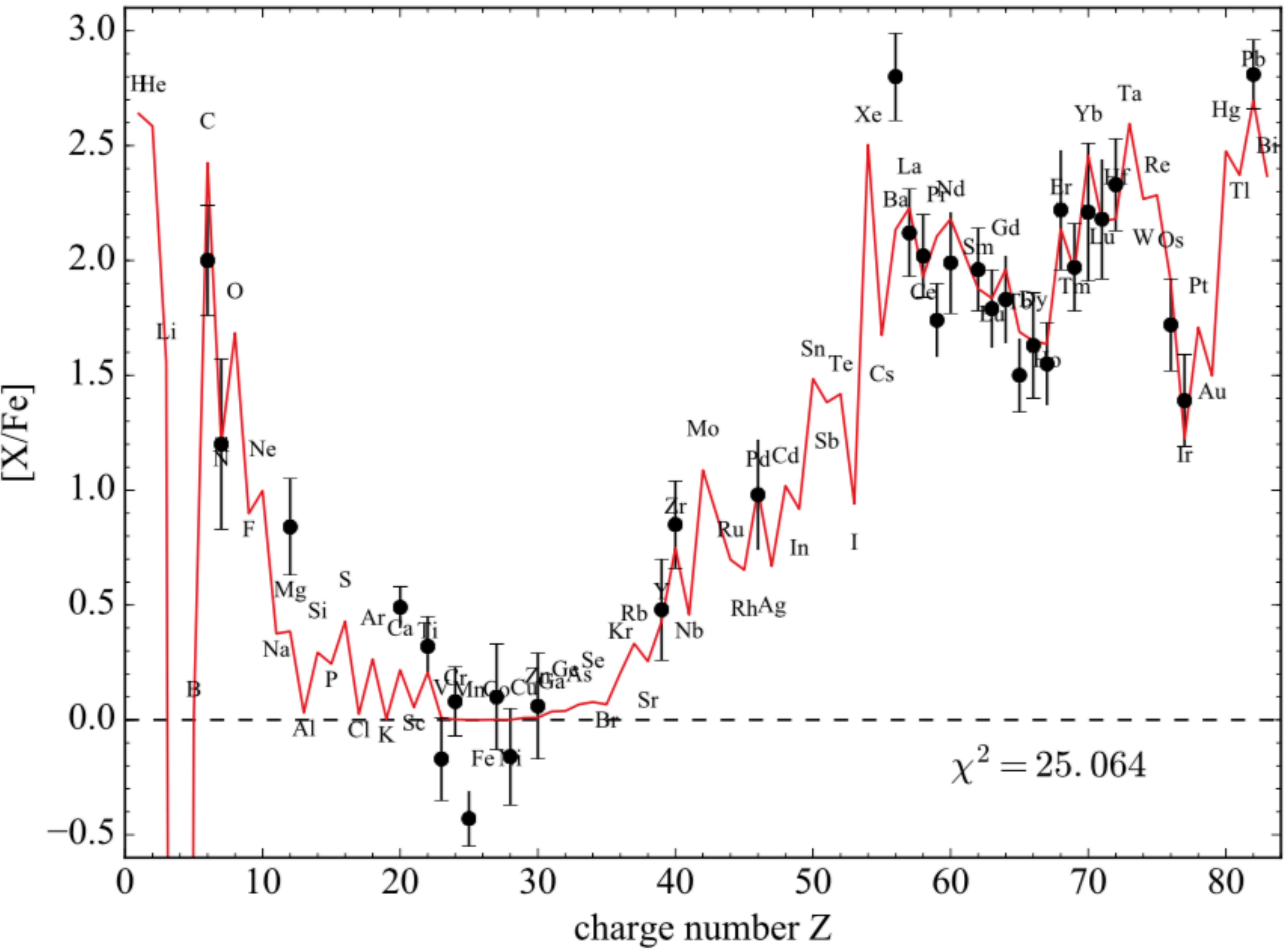
- You say the i process can explain CEMP-r/s star abundance pattern. Can the i process explain anything else?
- You talk about the RAWDs as a likely site for CEMP-i star formation. Are there other sites and what is possibly wrong about them?
- You propose the RAWDs as a site, but they have short periods. Many CEMP-i stars are in binaries and have long periods, and some have no detected binarity. How can we understand this?
- Are all CEMP-r/s stars CEMP-i stars?

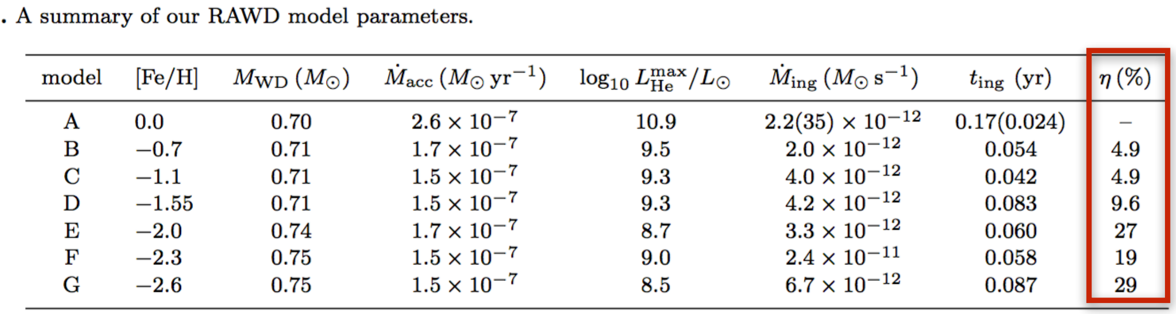
Bibliography i process theory:

- **Cowan** JJ, Rose WK. 1977. *ApJ*. 212:149 *first introduced the term i process and the concept for AGB star H-ingestion He-shell flashes*
- **Malaney** RA. 1986. *MNRAS*. 223(4):683–707, **Herwig** F et al. 2011. *ApJ*. 727(2):89 *investigate i-process nucleosynthesis in post-AGB stars*
- **Campbell** SW, Lugaro M, Karakas AI. 2010. *A&A*. 522:L6, **Cruz** MA, Serenelli A, Weiss A. 2013. *A&A*. 559:A4 *present models of i process in H-ingestion into He-core flash*
- **Bertolli** MG, Herwig F, Pignatari M, Kawano T. 2013. *Phys Rev C submitted, arXiv:1310.4578,* ***Dardelet*** *L, Ritter C, Prado P, Heringer E, Higgs C, et al. 2014. I process and CEMP-s+r stars,* **Hampel** M, Stancliffe RJ, Lugaro M, Meyer BS. 2016. *ApJ*. 831(2):171 *first make the connection of i-process with CEMP-r/s stars → CEMP-i*
- **Côté** B, Denissenkov P, Herwig F et al. 2018. *ApJ*. 854(2):105 *GCE simulations to demonstrate iRAWD contribution to solar system*
- **Clarkson** O, Herwig F, Pignatari M. 2018. *MNRAS*. 474(1):L37–L41; Clarkson+ 19 *propose Pop III i process for CEMP-no stars;* **Banerjee** P, etal 2018. *ApJ*. 865(2):120 *considers metal-poor stars in more general*
- *Large body of literature on H-ingestion flashes (HIF orPIE) in AGB stars (Iben, Schönberner, Fujimoto, Sudo, Iwamoto, Campbell, Schlattel ….*

i process in low-Z RAWD - origin of CEMP-i stars

Low-Z iRAWD multi-zone simulation





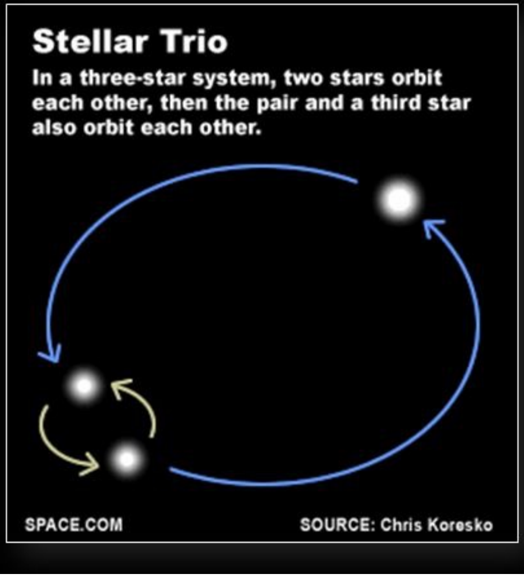
. A summary of our RAWD model parameters.

model	[Fe/H]	$M_{\rm WD}$ ($M_\odot$)	$\dot{M}_{\rm acc}$ ($M_\odot$ yr^{-1})	$\log_{10} L_{\rm He}^{\rm max}/L_\odot$	$\dot{M}_{\rm ing}$ ($M_\odot$ s^{-1})	$t_{\rm ing}$ (yr)	η (%)
A	0.0	0.70	2.6×10^{-7}	10.9	$2.2(35) \times 10^{-12}$	0.17(0.024)	–
B	−0.7	0.71	1.7×10^{-7}	9.5	2.0×10^{-12}	0.054	4.9
C	−1.1	0.71	1.5×10^{-7}	9.3	4.0×10^{-12}	0.042	4.9
D	−1.55	0.71	1.5×10^{-7}	9.3	4.2×10^{-12}	0.083	9.6
E	−2.0	0.74	1.7×10^{-7}	8.7	3.3×10^{-12}	0.060	27
F	−2.3	0.75	1.5×10^{-7}	9.0	2.4×10^{-11}	0.058	19
G	−2.6	0.75	1.5×10^{-7}	8.5	6.7×10^{-12}	0.087	29

At low [Fe/H] maybe path to SN Ia?!

The i-process nucleosynthesis can explain the abundances of heavy elements observed in the CEMP-i star CS31062-050 if in the past it had been a distant companion of a close binary system with a RAWD. RAWD may or may not have exploded as SN Ia. CEMP-i stars may or may not now be in wide binary.

Some stars are a part of a triple or quadruple star system. Triple systems appear to be binary stars that have trapped a single star into their orbit.



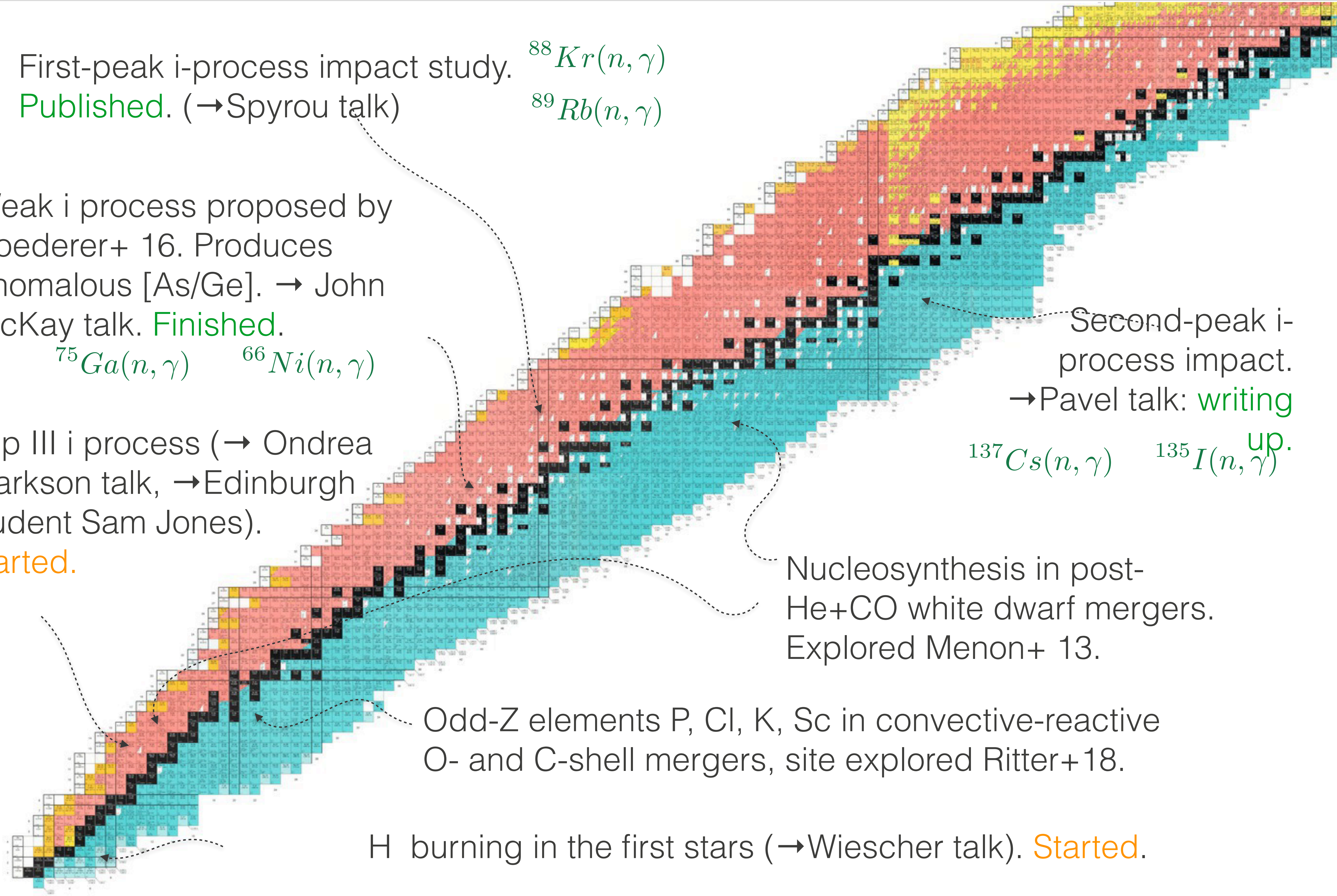
Stellar Trio

In a three-star system, two stars orbit each other, then the pair and a third star also orbit each other.

The triple star system 40 Eridani.

Denissenkov+ 18, observations Aoki+ 02 Johnson & Bolte 04

Nuclear physics impact studies for i process and convective-reactive regimes



First-peak i-process impact study. Published. (→Spyrou talk)

$^{88}Kr(n,\gamma)$

$^{89}Rb(n,\gamma)$

Weak i process proposed by Roederer+ 16. Produces anomalous [As/Ge]. → John McKay talk. Finished.

$^{75}Ga(n,\gamma)$ $^{66}Ni(n,\gamma)$

Second-peak i-process impact. →Pavel talk: writing up.

$^{137}Cs(n,\gamma)$ $^{135}I(n,\gamma)$

Pop III i process (→ Ondrea Clarkson talk, →Edinburgh student Sam Jones). Started.

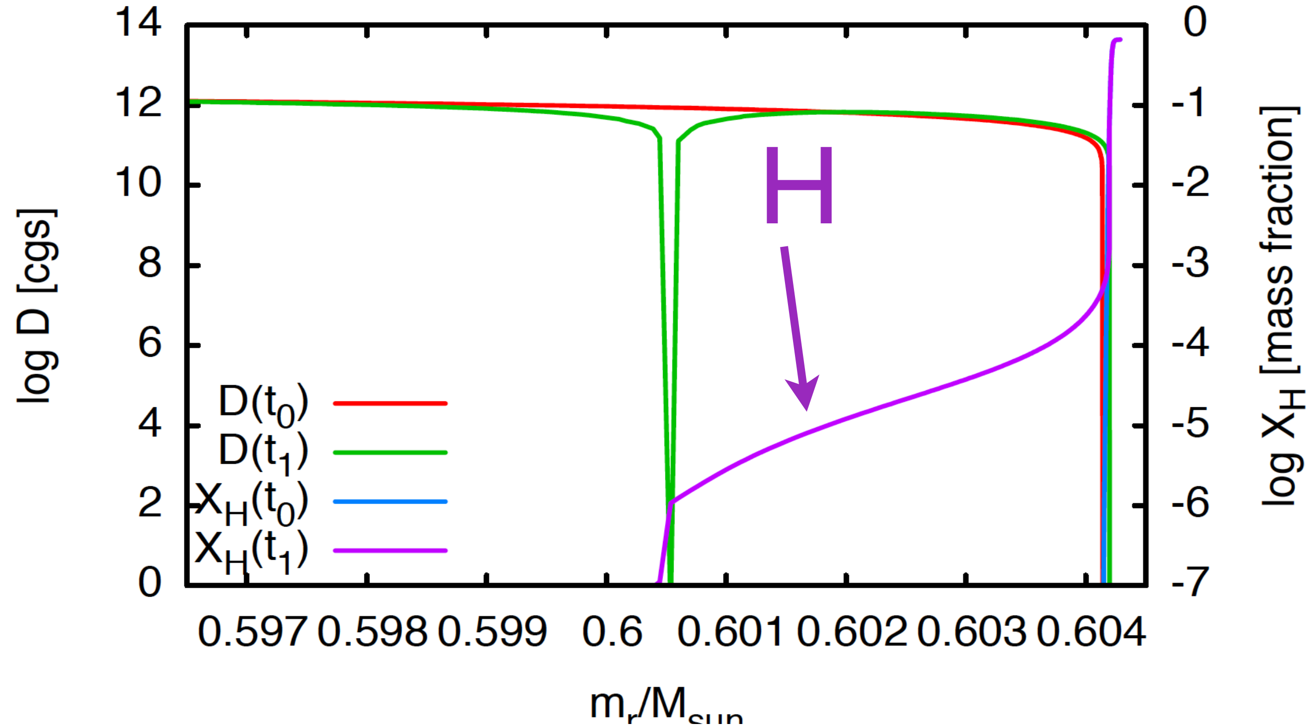
Nucleosynthesis in post-He+CO white dwarf mergers. Explored Menon+ 13.

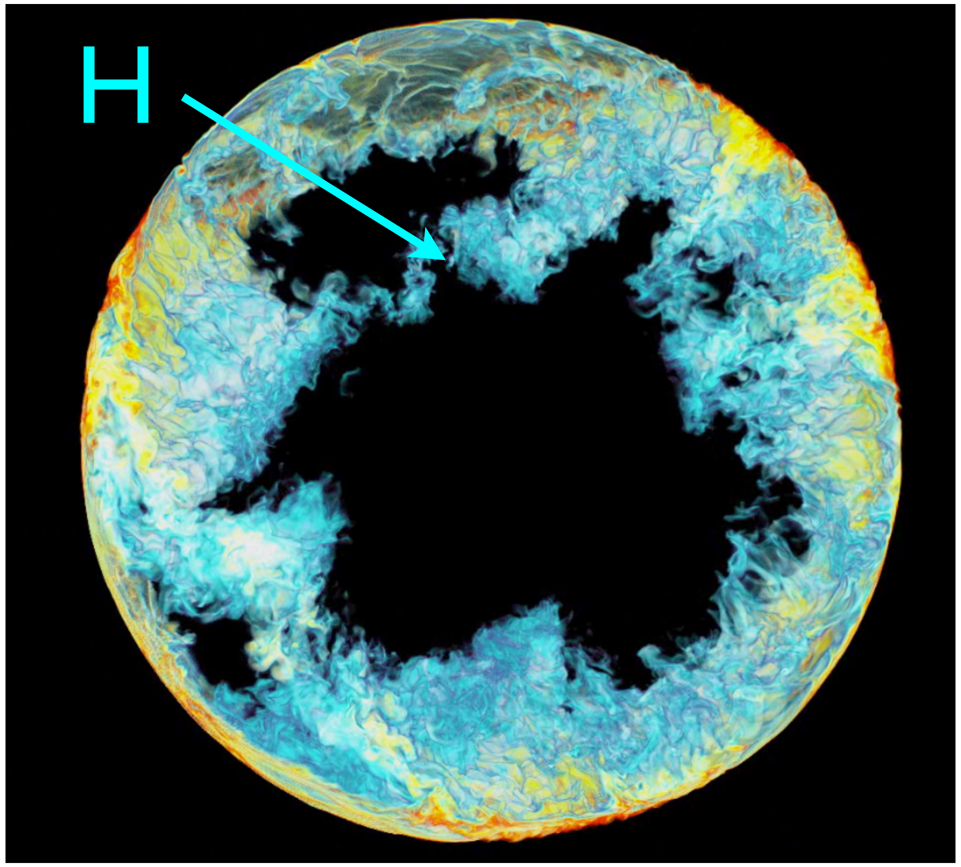
Odd-Z elements P, Cl, K, Sc in convective-reactive O- and C-shell mergers, site explored Ritter+18.

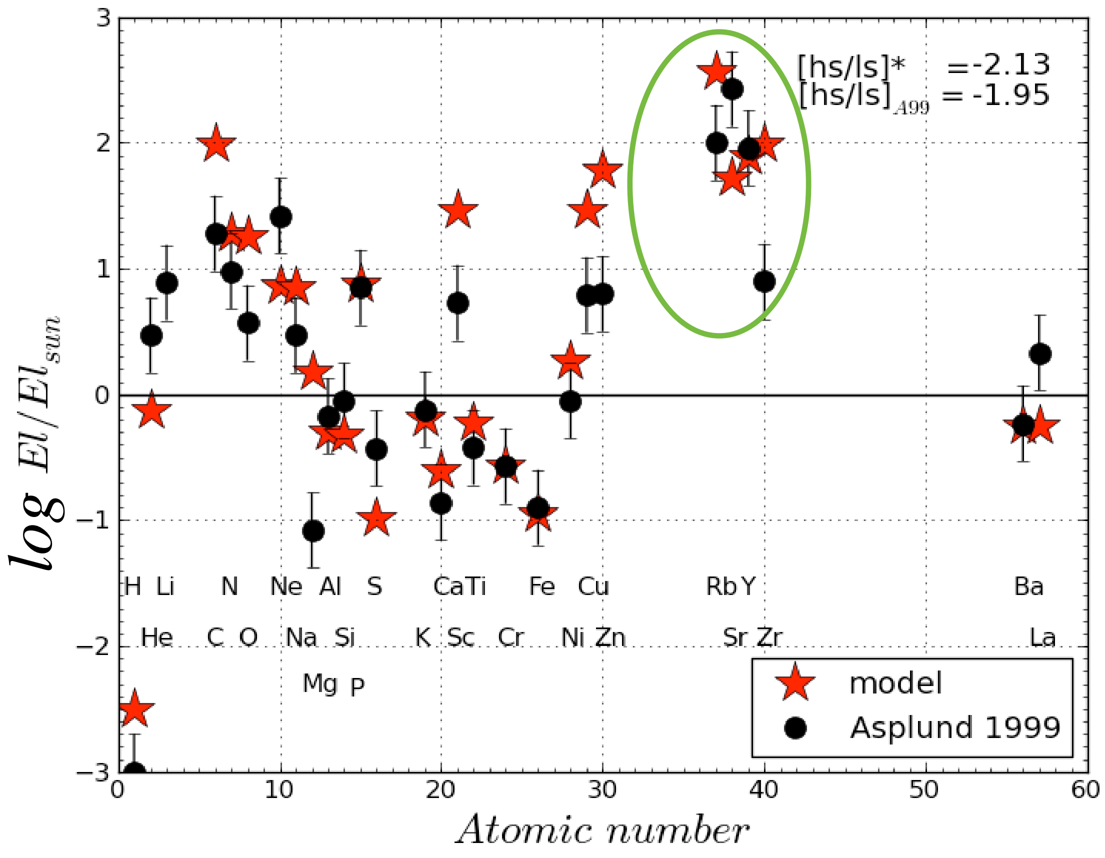
H burning in the first stars (→Wiescher talk). Started.

Simultaneous mixing and nucleosynthesis is required to explain the observed abundances

- highly anomalous heavy-element signature, not know from “normal” s process in post-AGB star Sakurai’s object
- unmodified stellar evolution models fail to account for this fingerprint of H-ingestion flash



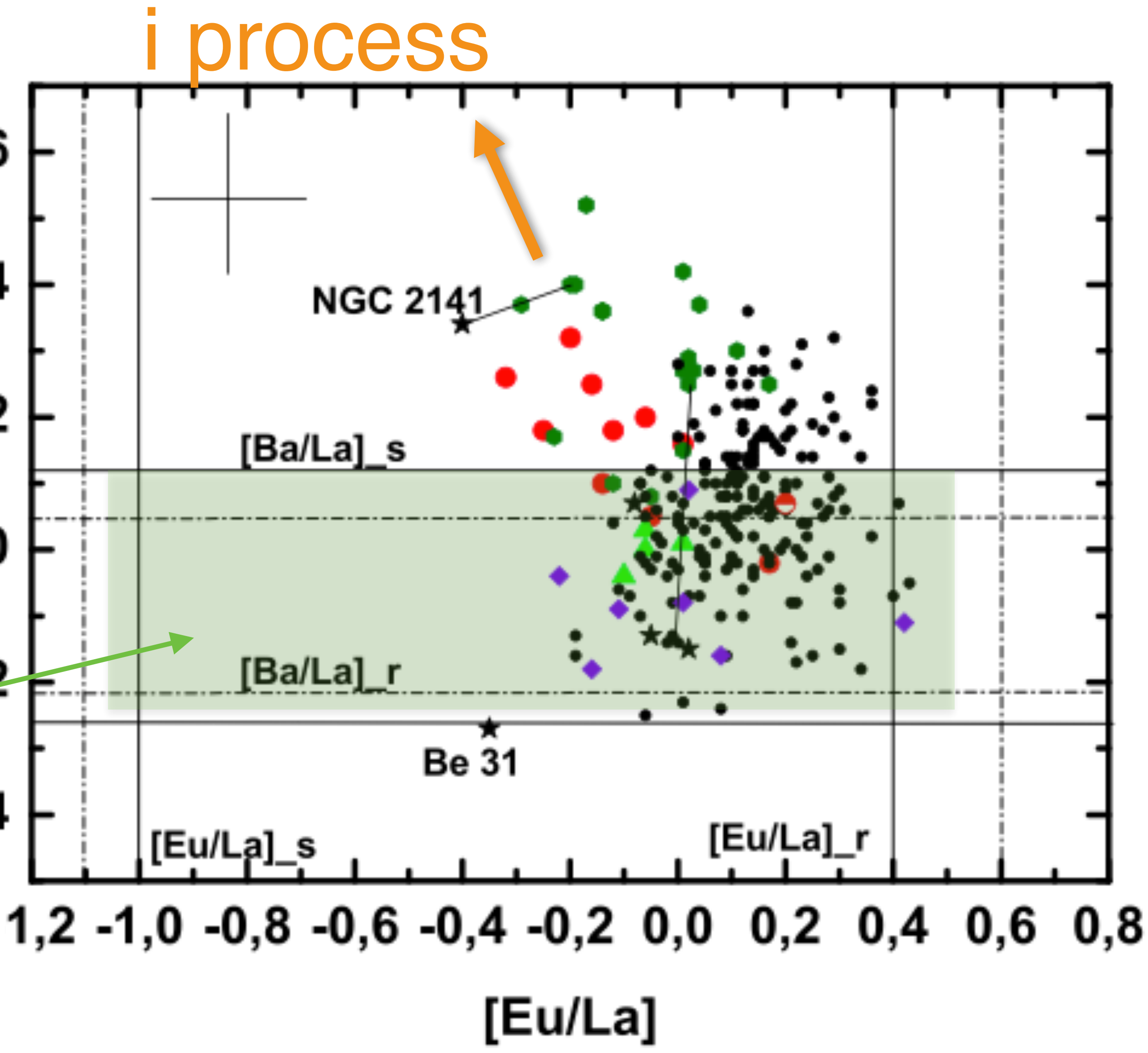




Herwig+ ’11

i process in open clusters

- i-process fingerprint in stellar populations
  - larger symbols: open clusters
  - black dots: thin disk stars
- no star can fall out of box if only s and r process exist



all possible mixtures of s and r process

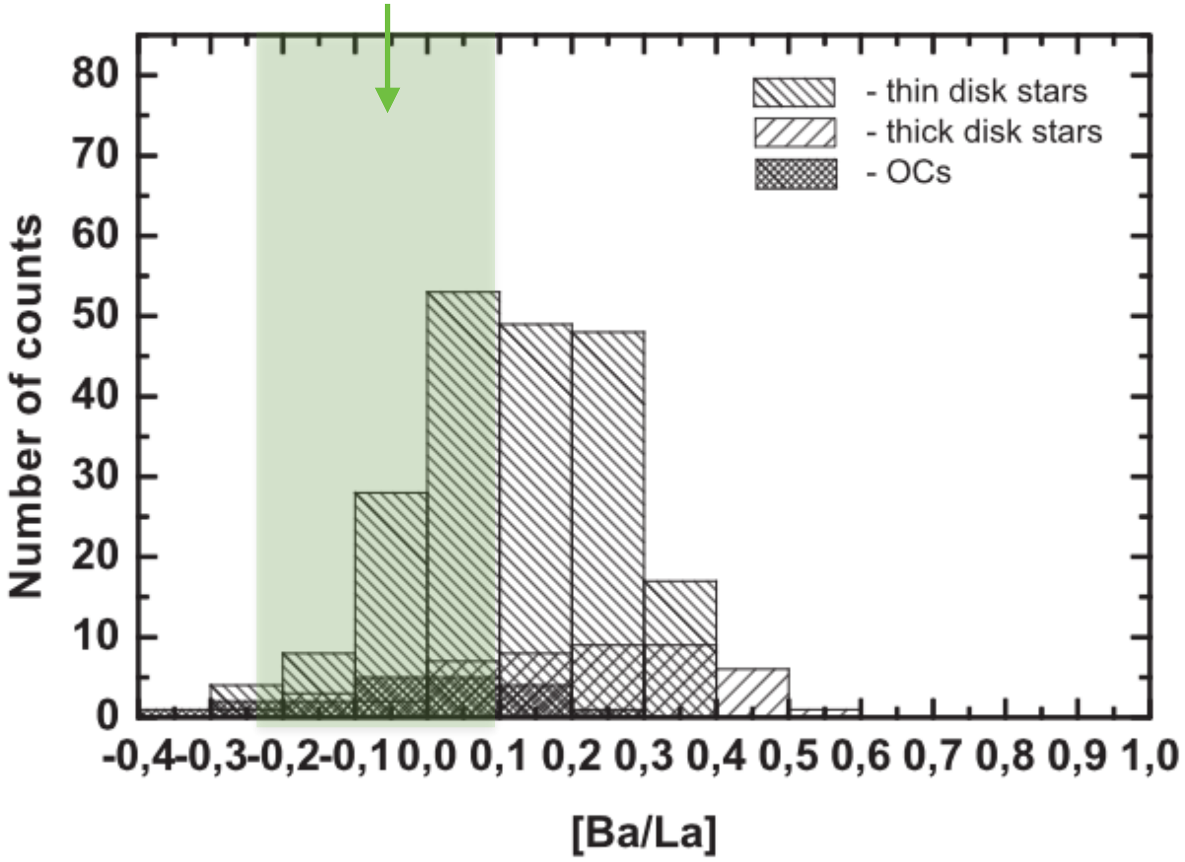


Figure 7. The distribution of the [Ba/Fe], [La/Fe], and [Ba/La] ratio for OCs is shown compared to the thin disc stars and thick disc stars in Mishenina et al. (2013b).

- i-process in GCE?

Mishenina+ '15

Pre-solar grains from born-again giants

Anomalous ^{32}S in SiC grains of type A+B

THE ASTROPHYSICAL JOURNAL LETTERS, 776:L29 (6pp), 2013 October 20

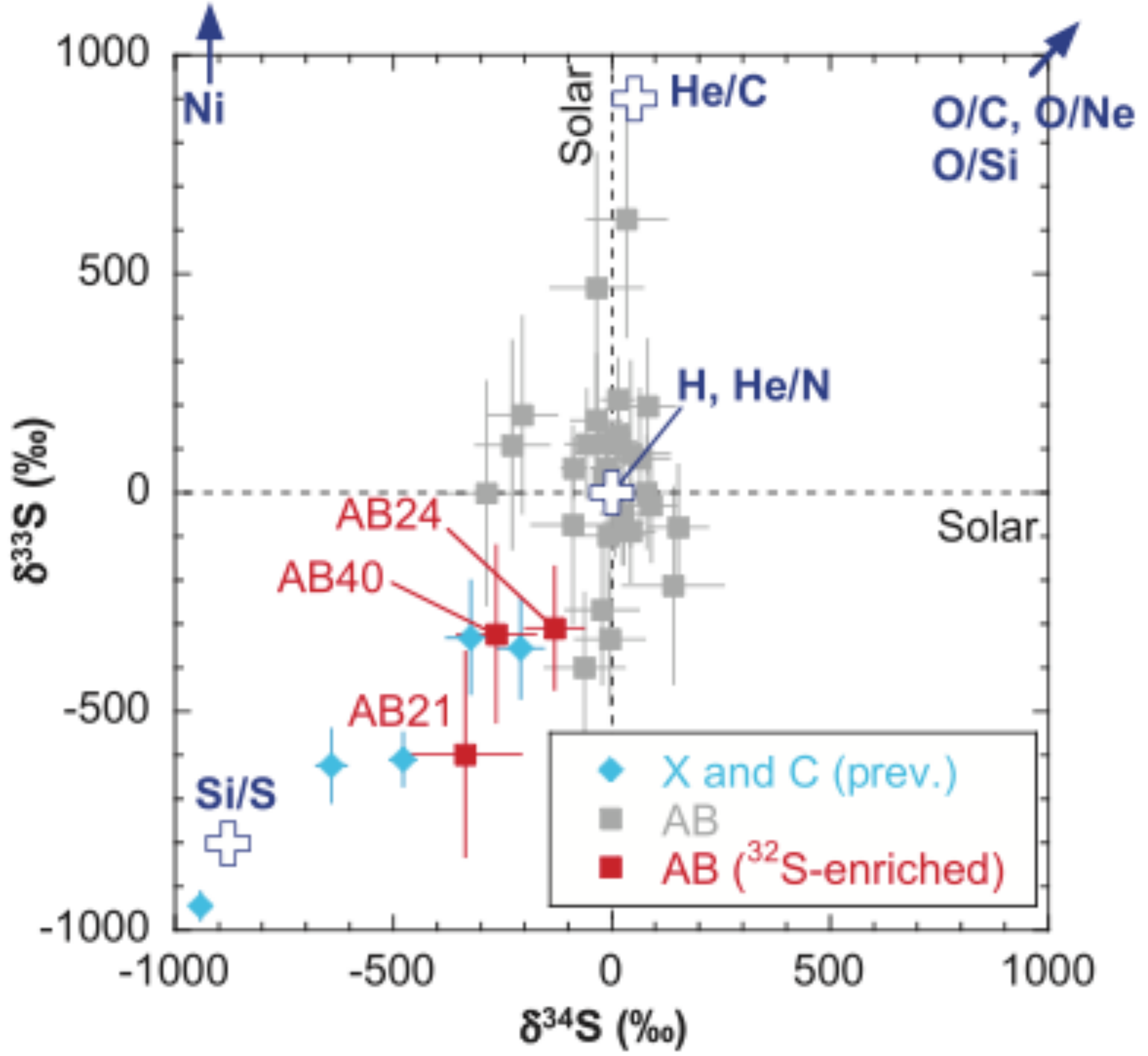


Figure 2. Sulfur-isotopic compositions of 34 SiC AB grains. Three grains (AB21, 24 and 40) show large ^{32}S excesses of >100‰. Also shown are X and C grains with significant S isotope anomalies from previous studies (Gyngard et al. 2010a; Hoppe et al. 2012; Xu et al. 2012). The predicted S-isotopic compositions of the different zones in a 15 $M_{\odot}$ SN II (Rauscher et al. 2002) are shown by crosses and arrows for comparison.

Fujiya+ '13 (ApJ Letter)

i process signature in AB SiC grains

SiC grains of type AB

THE ASTROPHYSICAL JOURNAL LETTERS, 776:L29 (6pp), 2013 October 20

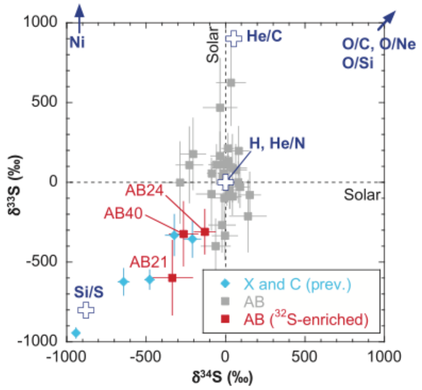
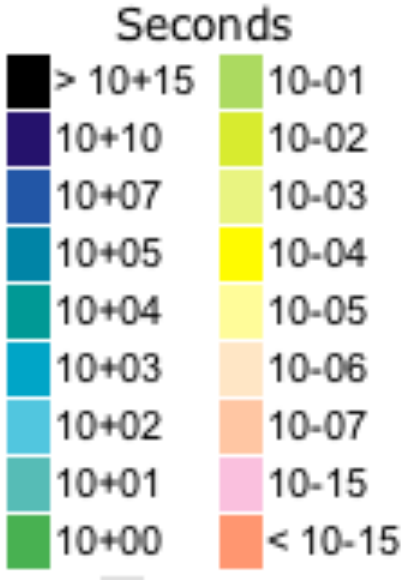
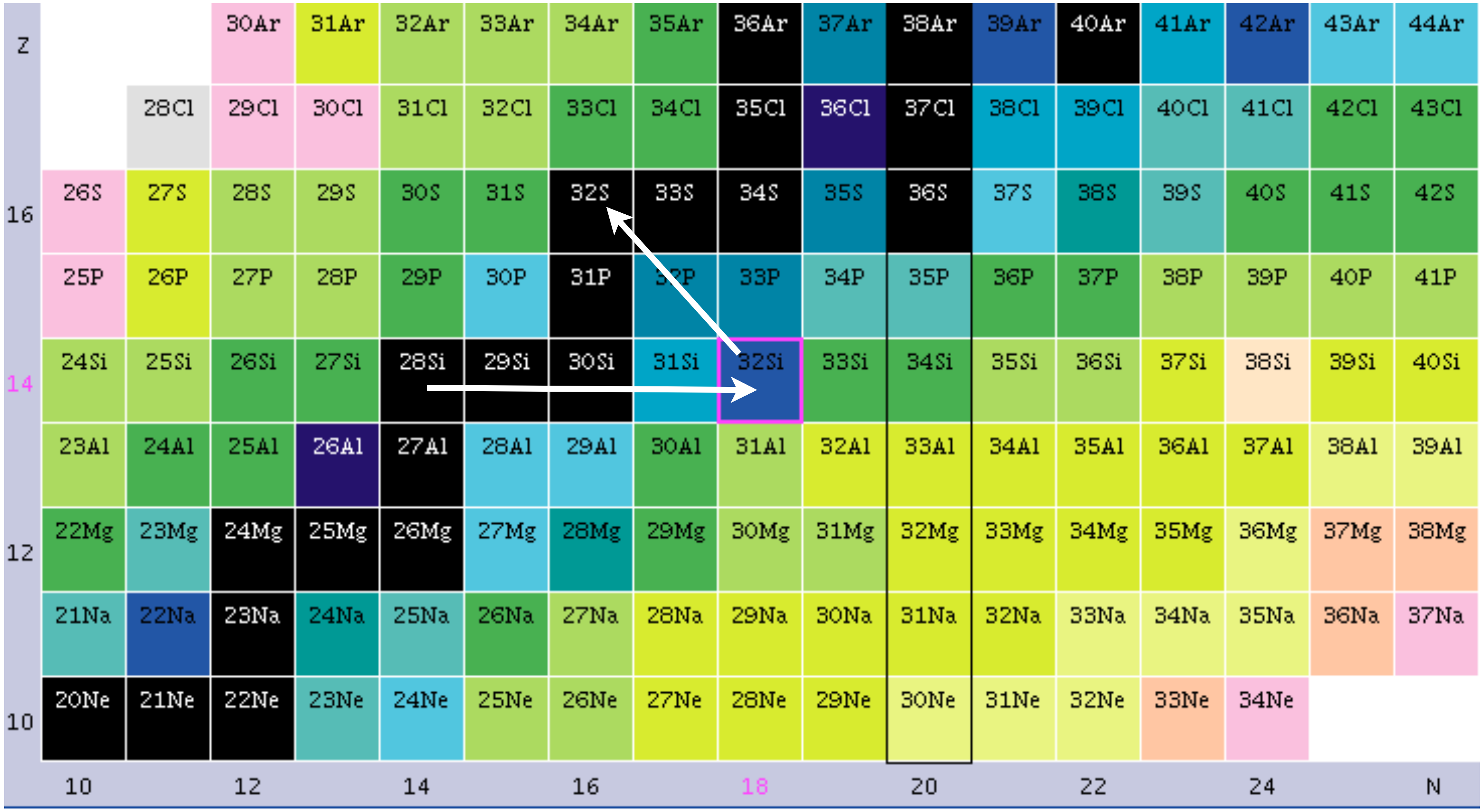


Figure 2. Sulfur-isotopic compositions of 34 SiC AB grains. Three grains (AB21, 24 and 40) show large ^{32}S excesses of >100‰. Also shown are X and C grains with significant S isotope anomalies from previous studies (Gyngard et al. 2010a; Hoppe et al. 2012; Xu et al. 2012). The predicted S-isotopic compositions of the different zones in a 15 $M_\odot$ SN II (Rauscher et al. 2002) are shown by crosses and arrows for comparison.

Nuclear network flux at i process neutron densities of $N_n \sim 10^{15} cm^{-3}$





Z																	
			30Ar	31Ar	32Ar	33Ar	34Ar	35Ar	36Ar	37Ar	38Ar	39Ar	40Ar	41Ar	42Ar	43Ar	44Ar
		28Cl	29Cl	30Cl	31Cl	32Cl	33Cl	34Cl	35Cl	36Cl	37Cl	38Cl	39Cl	40Cl	41Cl	42Cl	43Cl
16	26S	27S	28S	29S	30S	31S	32S	33S	34S	35S	36S	37S	38S	39S	40S	41S	42S
	25P	26P	27P	28P	29P	30P	31P	32P	33P	34P	35P	36P	37P	38P	39P	40P	41P
14	24Si	25Si	26Si	27Si	28Si	29Si	30Si	31Si	32Si	33Si	34Si	35Si	36Si	37Si	38Si	39Si	40Si
	23Al	24Al	25Al	26Al	27Al	28Al	29Al	30Al	31Al	32Al	33Al	34Al	35Al	36Al	37Al	38Al	39Al
12	22Mg	23Mg	24Mg	25Mg	26Mg	27Mg	28Mg	29Mg	30Mg	31Mg	32Mg	33Mg	34Mg	35Mg	36Mg	37Mg	38Mg
	21Na	22Na	23Na	24Na	25Na	26Na	27Na	28Na	29Na	30Na	31Na	32Na	33Na	34Na	35Na	36Na	37Na
10	20Ne	21Ne	22Ne	23Ne	24Ne	25Ne	26Ne	27Ne	28Ne	29Ne	30Ne	31Ne	32Ne	33Ne	34Ne		
	10		12		14		16		18		20		22		24		N

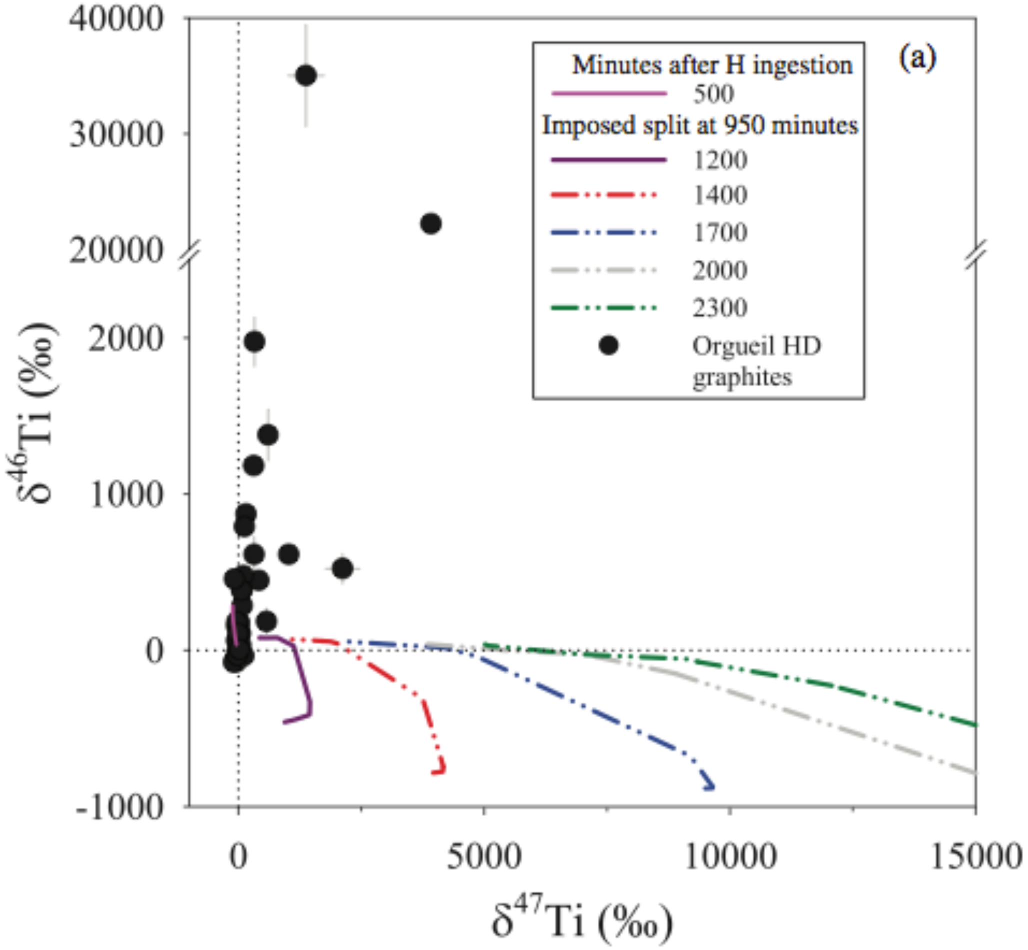
Ground and isomeric state information for $^{32}_{14}$Si

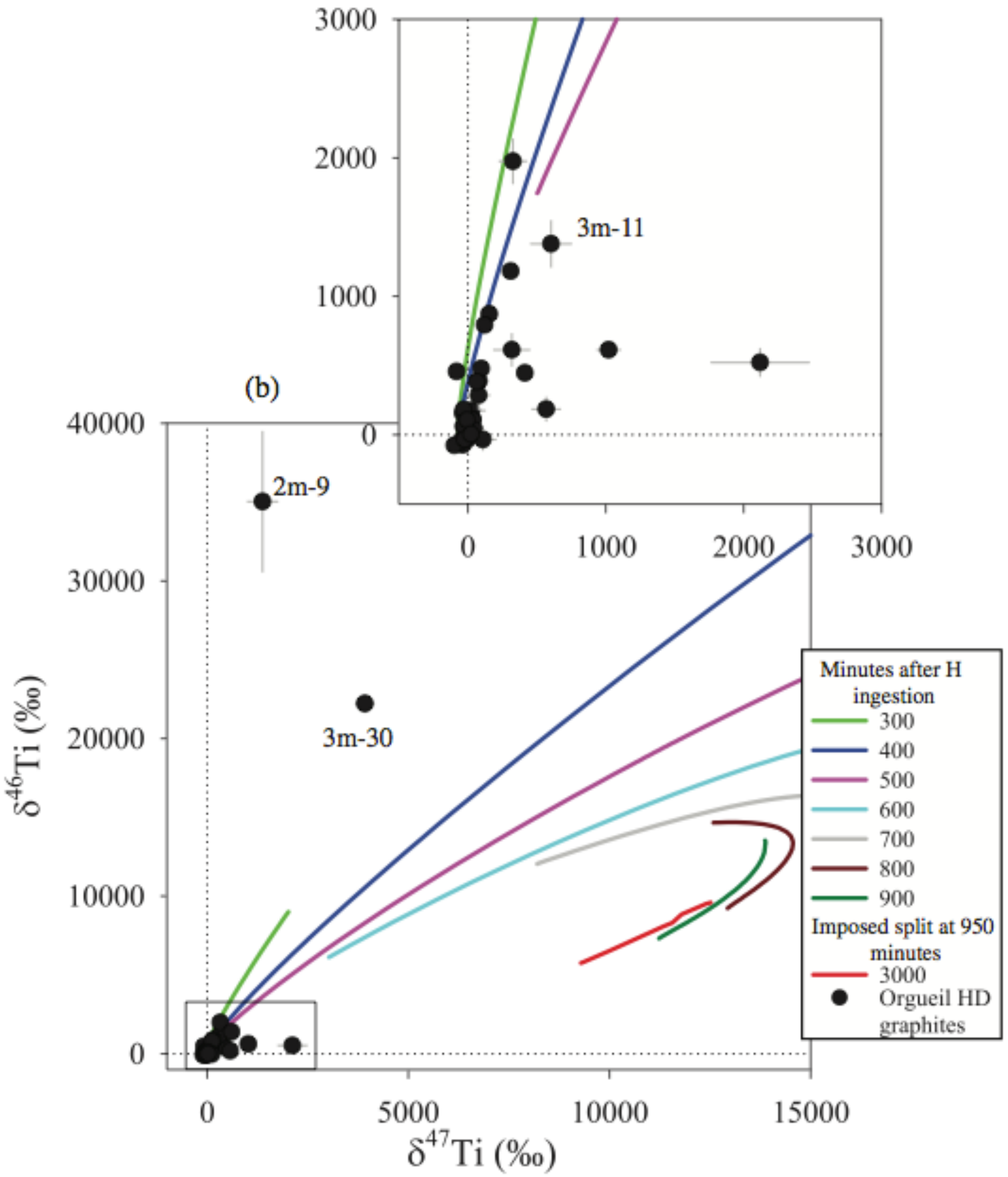
E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Decay Modes
0.0	0+	-24.0776	153 y *19*	β- : 100.00 %

^{46}Ti in HD pre-solar graphite grains

comparison with Ti + Ca isotopes from model added

comparison with Ti model prediction





Jadhav+ ’13 (ApJ Letter)

i process signature in pre-solar grains

- isobaric interference explains Ti anomalies in A+B Sic grains (Jadhav+ 13)
- i process source of ^{48}Ca in the universe?

Z				45Fe	46Fe	47Fe	48Fe	49Fe	50Fe	51Fe	52Fe	53Fe	54Fe	55Fe	56Fe	57Fe	58Fe
				44Mn	45Mn	46Mn	47Mn	48Mn	49Mn	50Mn	51Mn	52Mn	53Mn	54Mn	55Mn	56Mn	57Mn
24			42Cr	43Cr	44Cr	45Cr	46Cr	47Cr	48Cr	49Cr	50Cr	51Cr	52Cr	53Cr	54Cr	55Cr	56Cr
		40V	41V	42V	43V	44V	45V	46V	47V	48V	49V	50V	51V	52V	53V	54V	55V
22	38Ti	39Ti	40Ti	41Ti	42Ti	43Ti	44Ti	45Ti	46Ti	47Ti	48Ti	49Ti	50Ti	51Ti	52Ti	53Ti	54Ti
	37Sc	38Sc	39Sc	40Sc	41Sc	42Sc	43Sc	44Sc	45Sc	46Sc	47Sc	48Sc	49Sc	50Sc	51Sc	52Sc	53Sc
20	36Ca	37Ca	38Ca	39Ca	40Ca	41Ca	42Ca	43Ca	44Ca	45Ca	46Ca	47Ca	48Ca	49Ca	50Ca	51Ca	52Ca
	35K	36K	37K	38K	39K	40K	41K	42K	43K	44K	45K	46K	47K	48K	49K	50K	51K
18	34Ar	35Ar	36Ar	37Ar	38Ar	39Ar	40Ar	41Ar	42Ar	43Ar	44Ar	45Ar	46Ar	47Ar	48Ar	49Ar	50Ar
	16		18		20		22		24		26		28		30		N

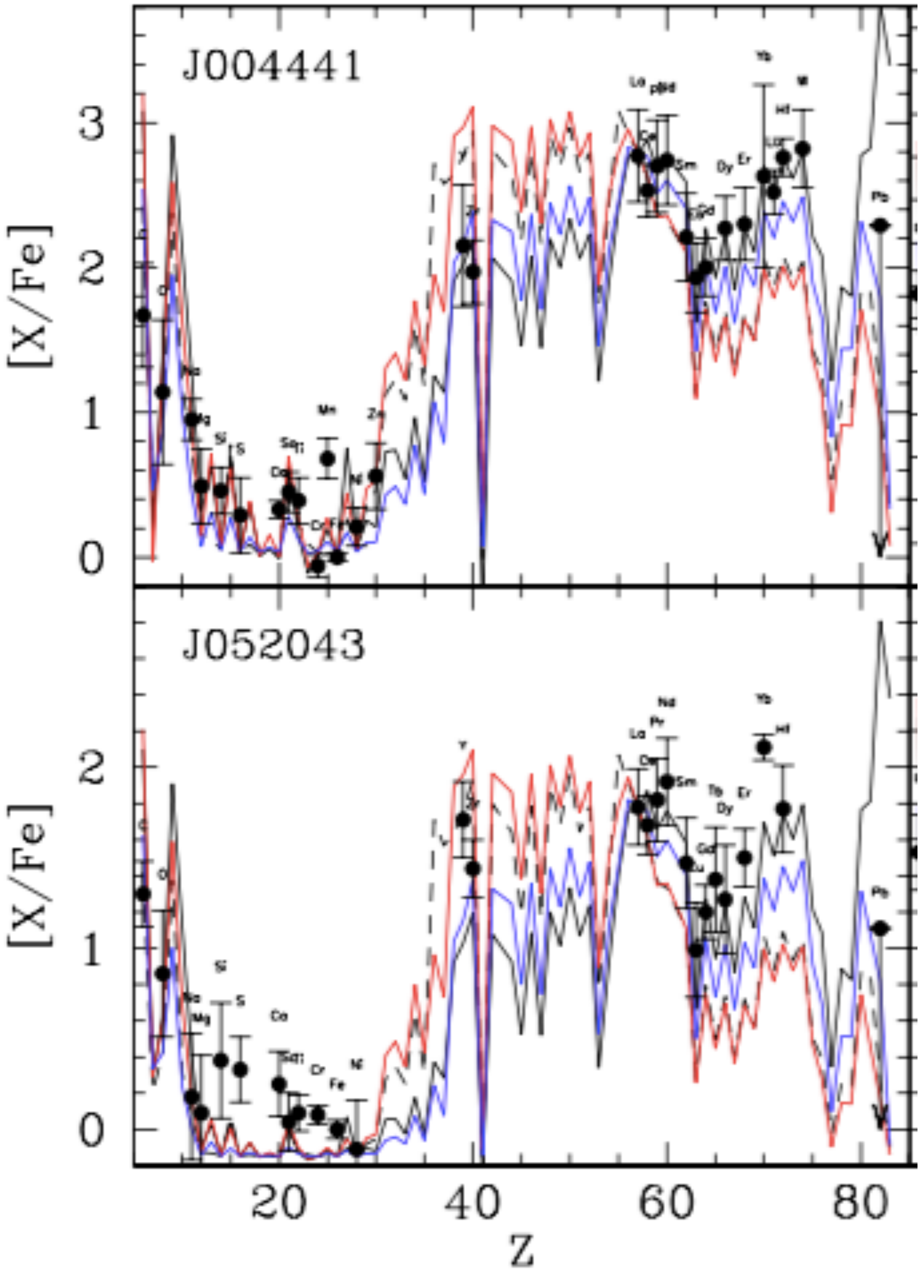
Seconds

> 10+15	10-01
10+10	10-02
10+07	10-03
10+05	10-04
10+04	10-05
10+03	10-06
10+02	10-07
10+01	10-15
10+00	< 10-15

i process in pAGB stars

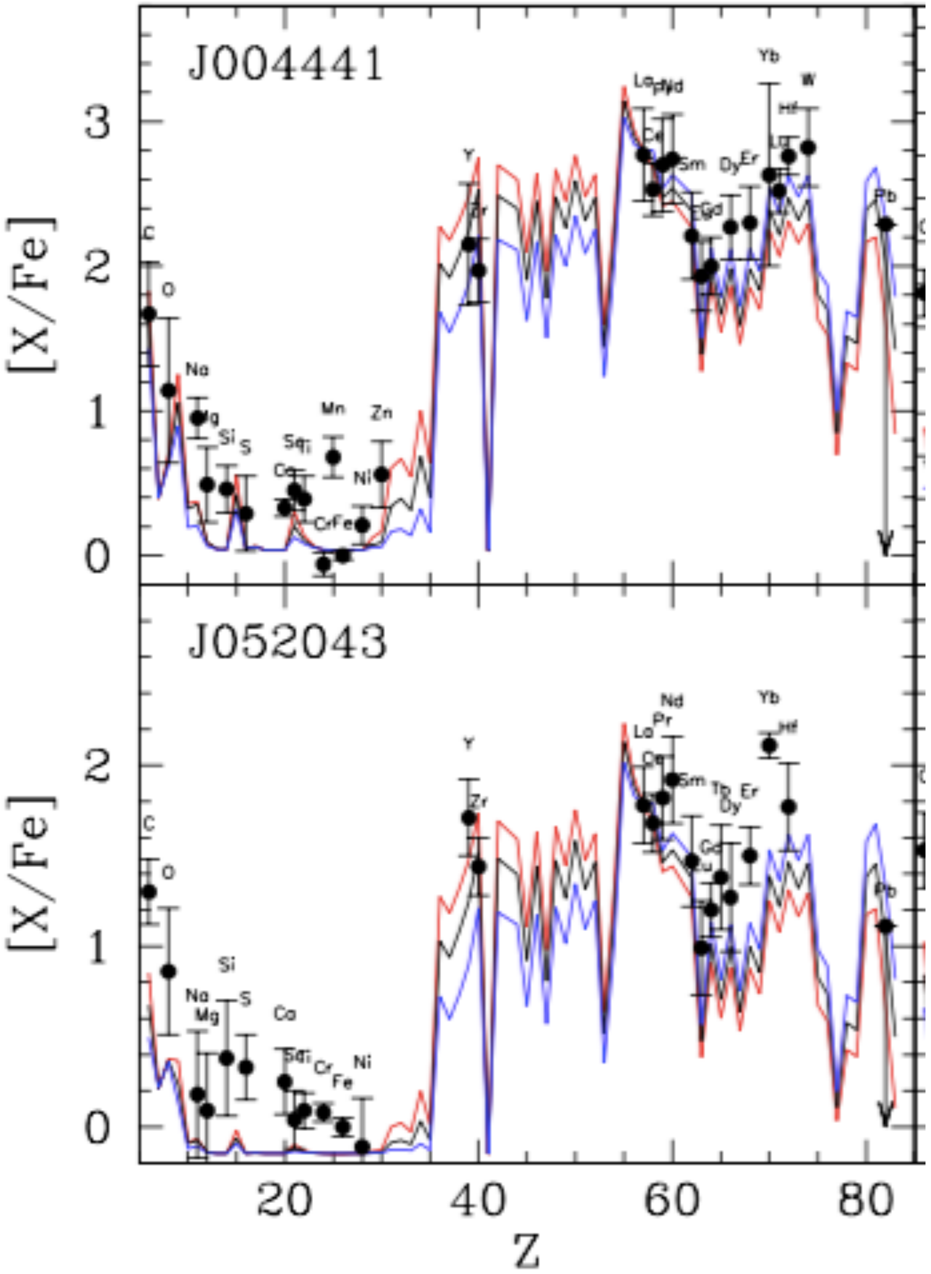
- pAGB stars in MC
  - s process predicts too much Pb
  - only high n-density exposure (i process) can marginally match data
  - i process common in low-mass AGB stars for [Fe/H]

s-process models



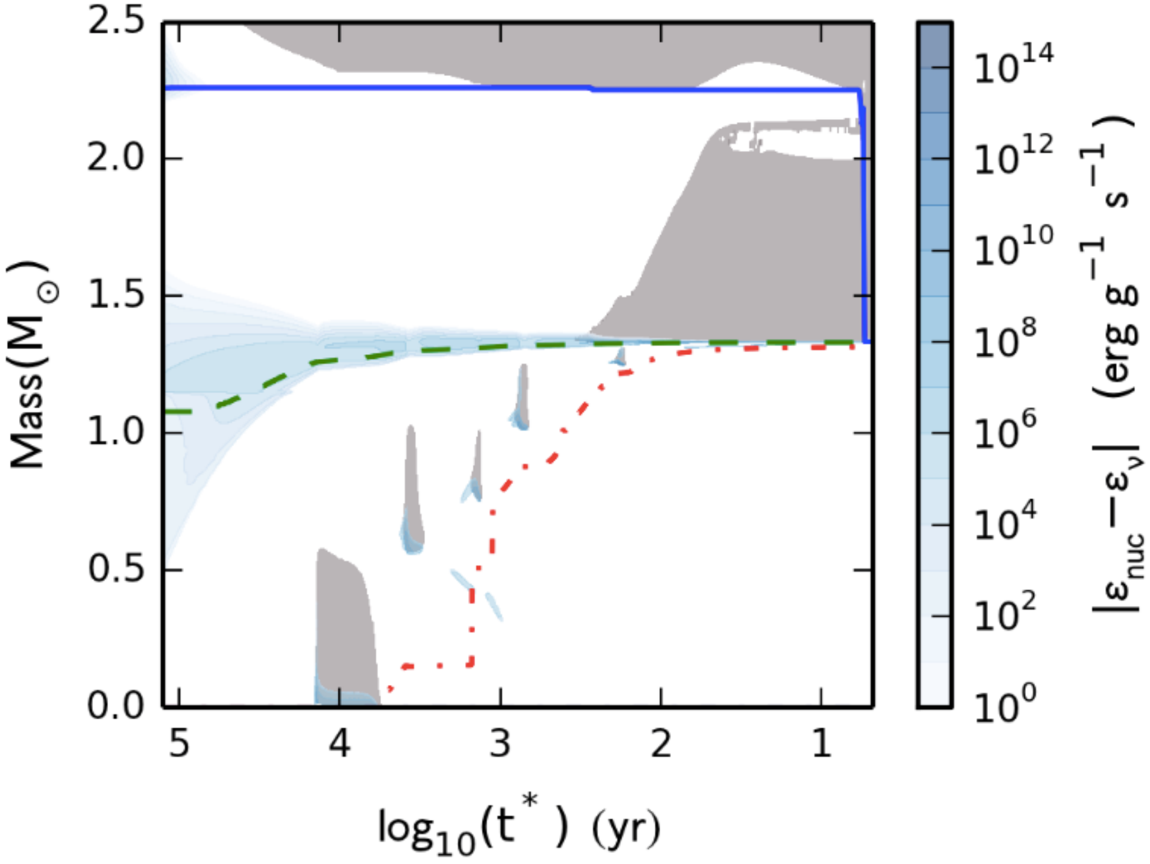
Lugaro+ '15

s- + i-process models



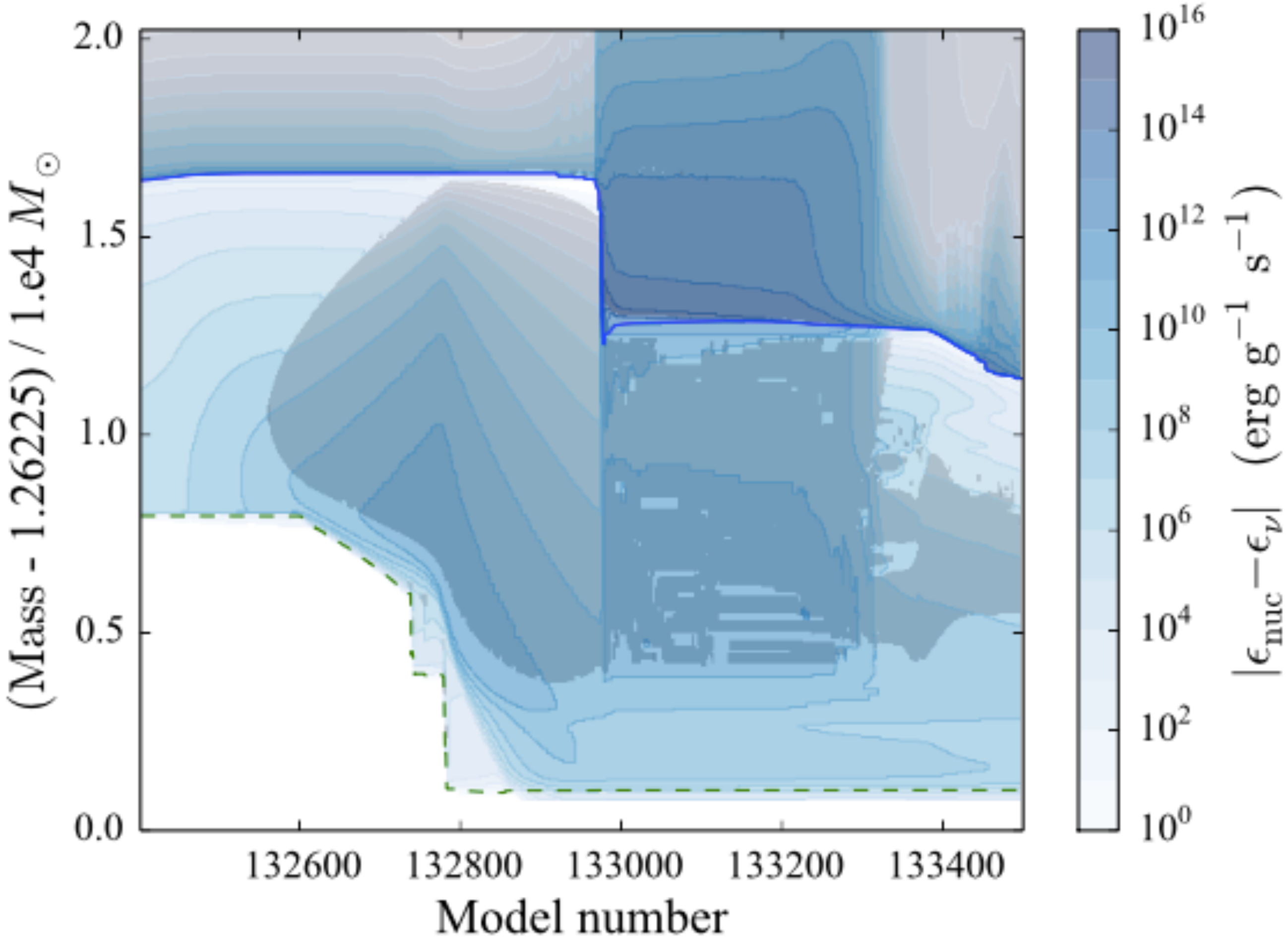
Other possible i-process sites:
H-ingestion in low-Z super-AGB star models

“dredge-out” before thermal pulse phase



$7.5\ M_{sun}$ Z=0.001

hot dredge-up with H-mixing into still live He-shell flash convection zone



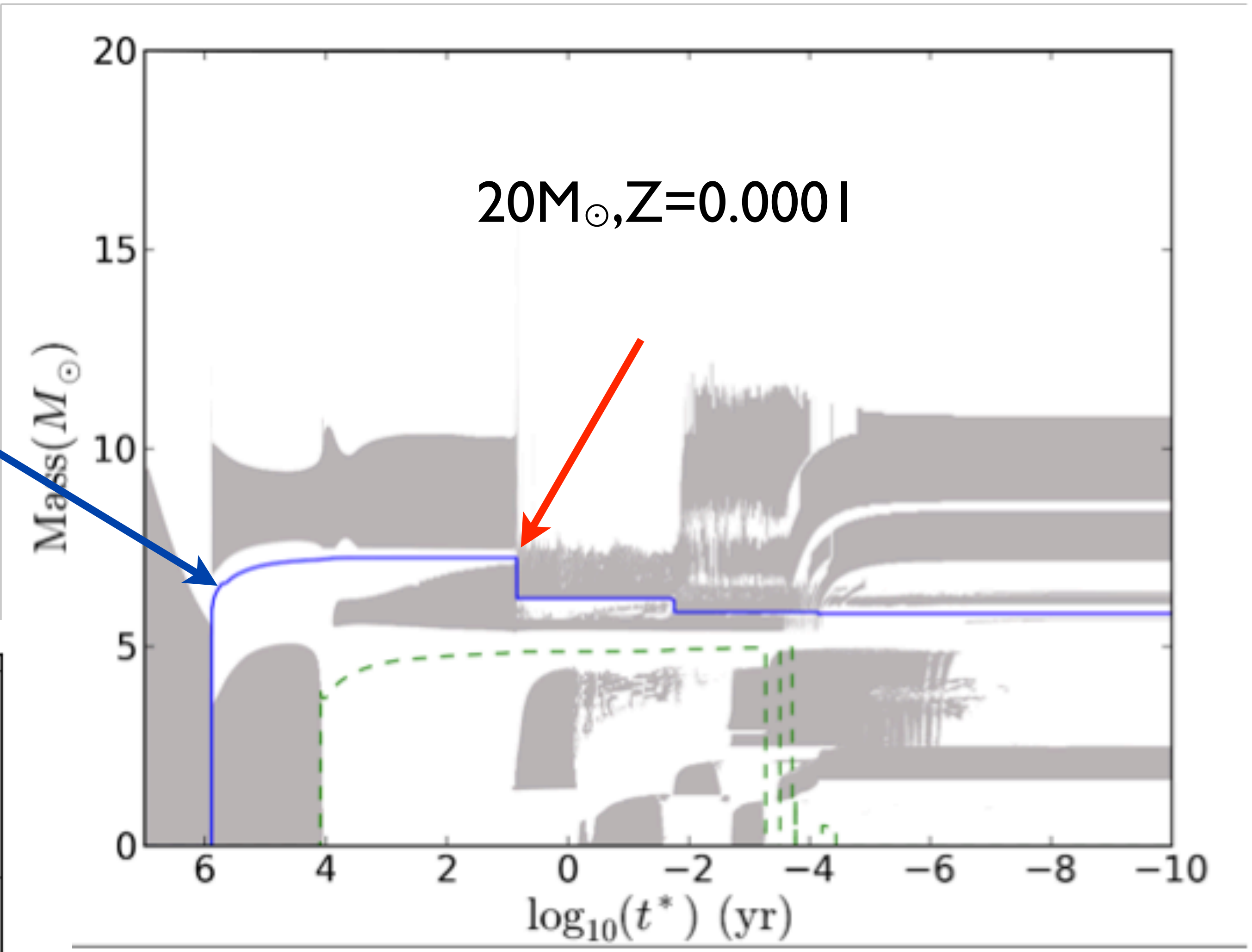
$7\ M_{sun}$, metallicity $Z = 10^{-4}$
$f_{env} = 0.014$ and $f_{PDCZ} = 0.014$

- depends on convective boundary mixing efficiency
- $\varepsilon_{nuc} \times t_{conv} / E_{int} \sim 1$
- hydro needed

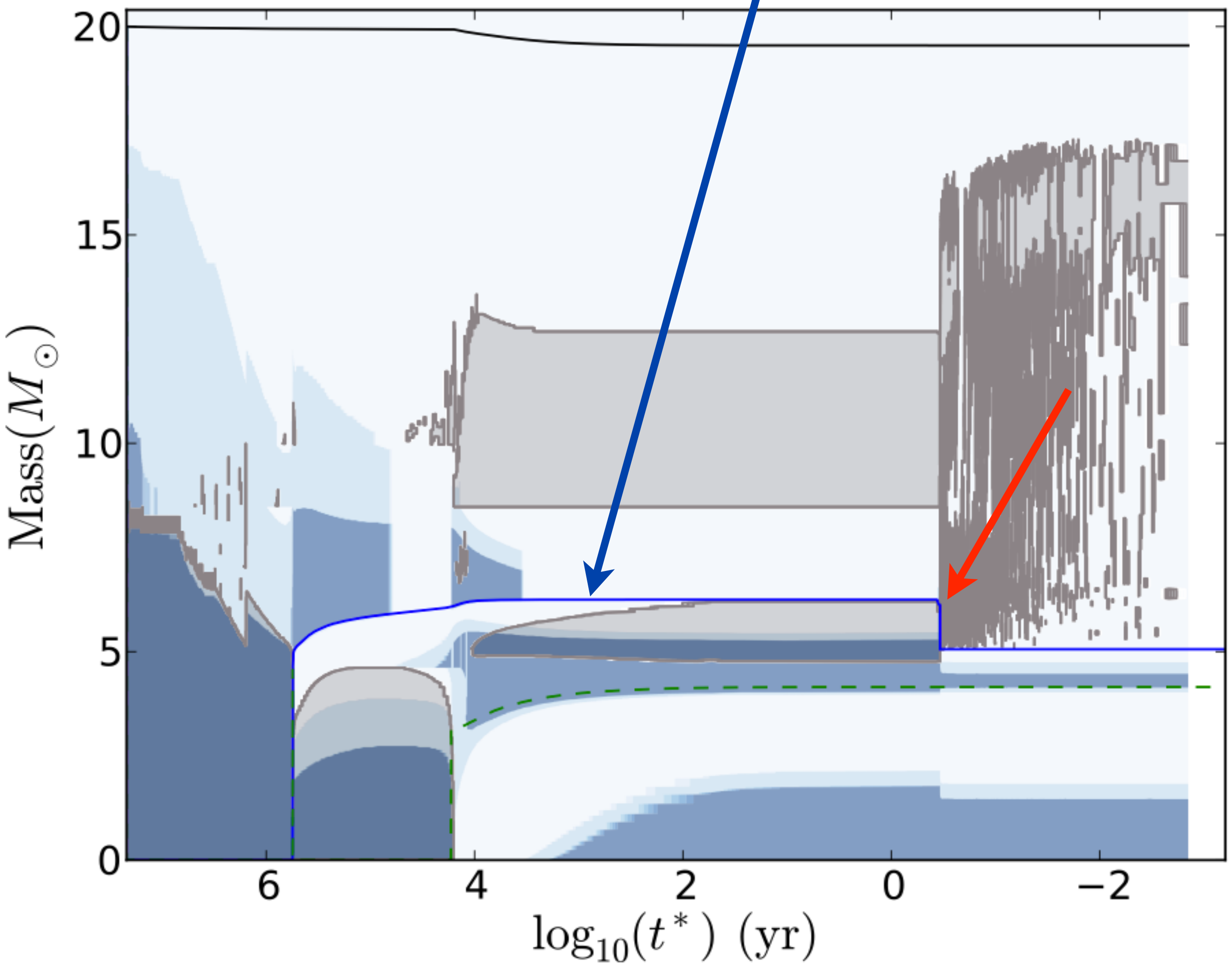
Jones+ 16, MNRAS

Convective-reactive H-combustion phases in massive stars

H-free boundary



20M⊙,Z=0.0



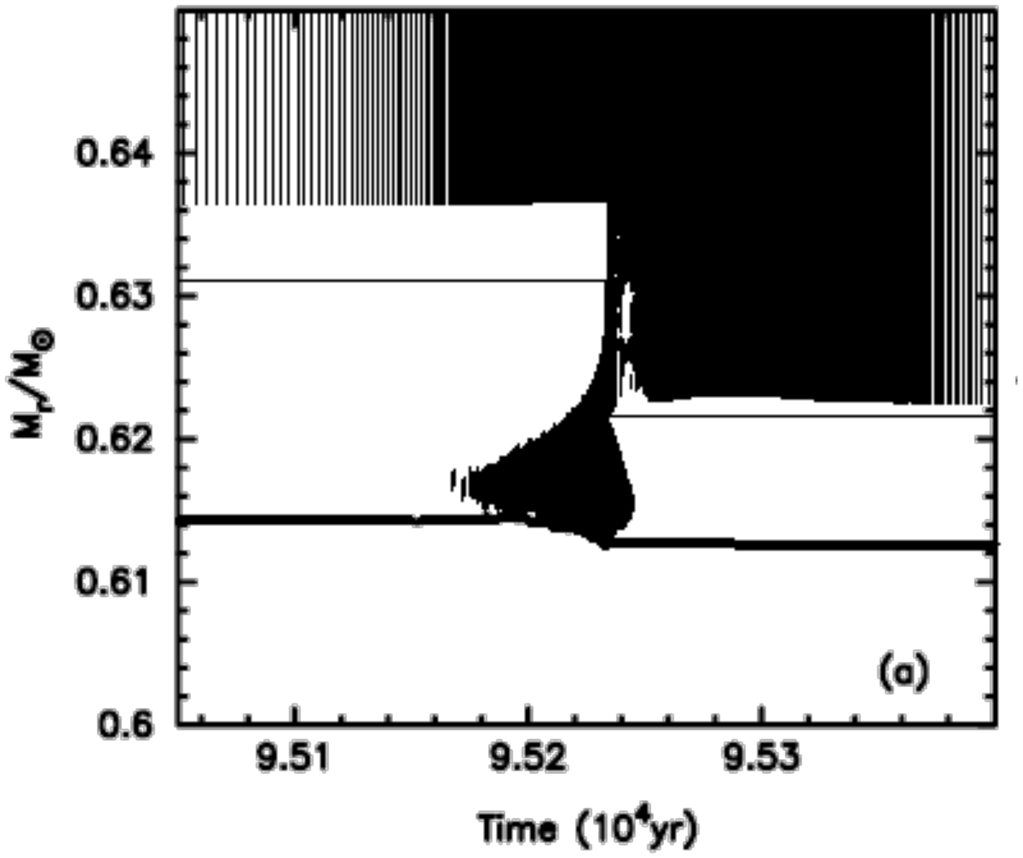
Ritter+ 17
Banerjee+ 18

Low-mass AGB stars

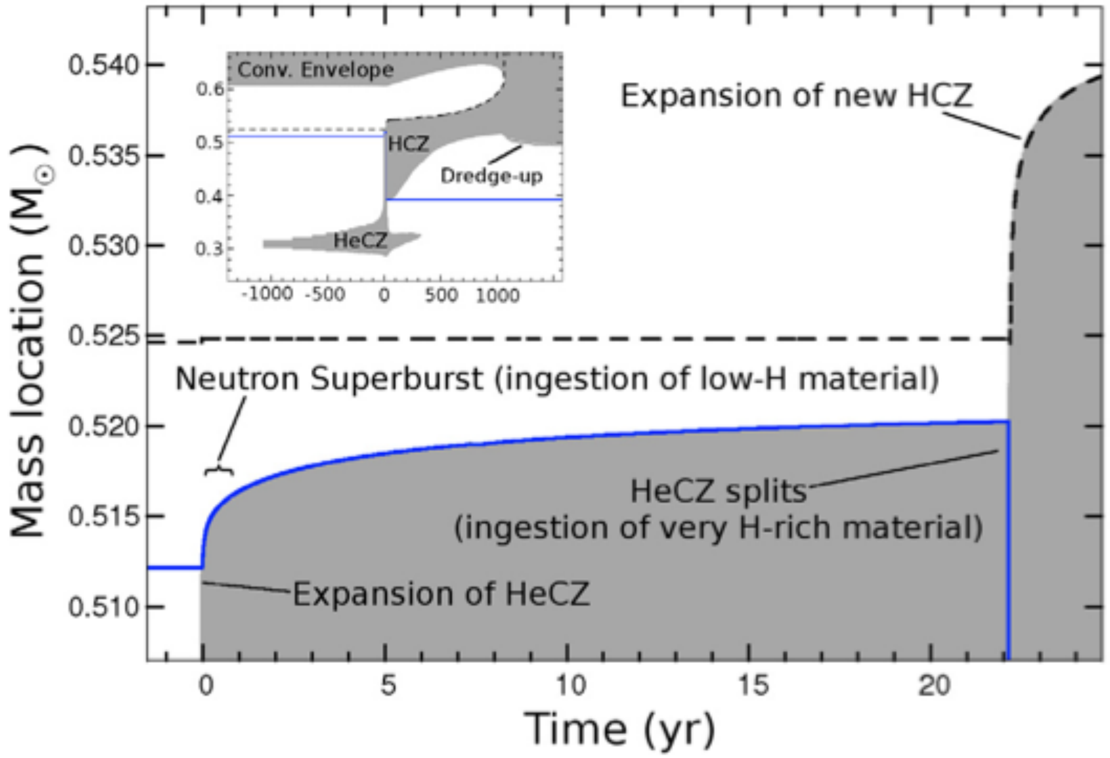
- Convective-reactive H-ingestion has been studied for a long time in 1D stellar evolution

Fujimoto etal. (1990), Hollowell etal. (1990), Iwamoto etal (2004), Fujimoto etal (2000), Herwig (2002), Chieffi etal (2001), Weiss etal. (2004), Schlattl etal (2001), Picardie etal (2004), Suda etal (2004) … Campbell etal. Lau etal., Cruz etal. (2013)

Iwamoto etal (2004):



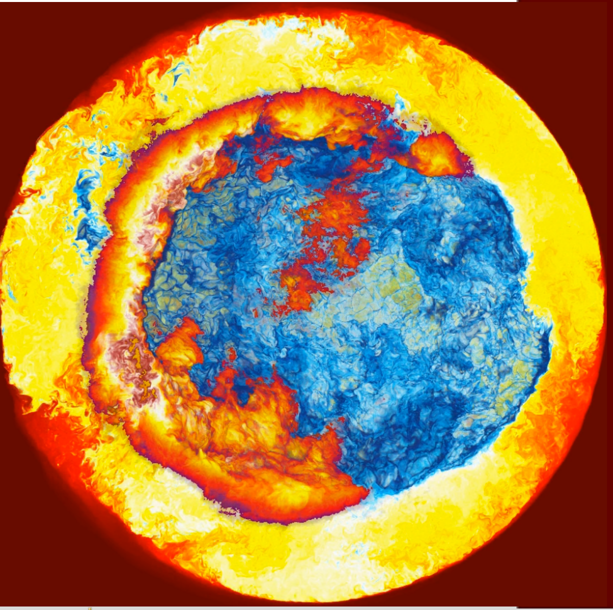
Campbell, Lugaro & Karakas (2013)



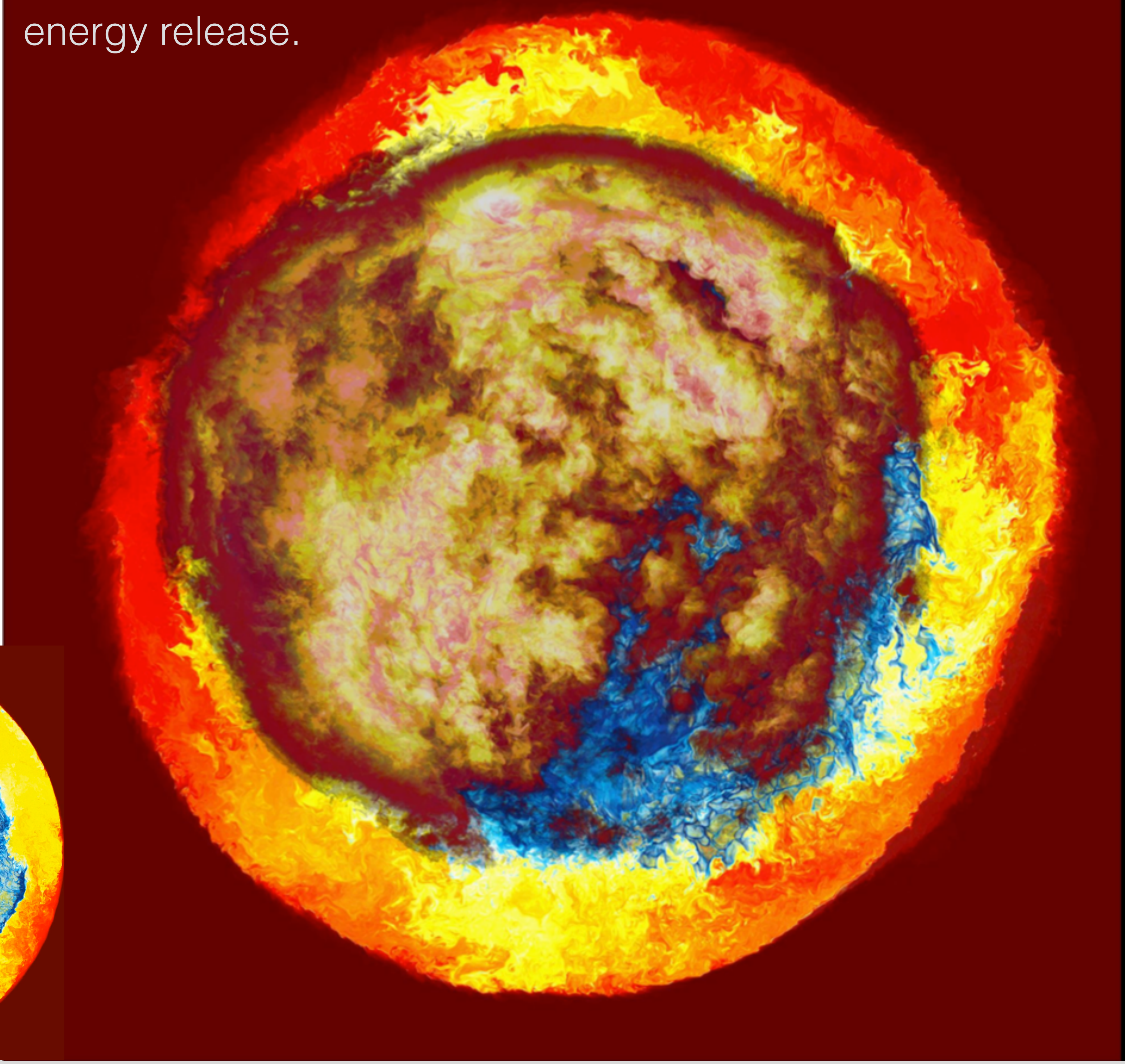
Low-Z AGB H-ingestion into He-shell flash

H-ingestion events in low-Z stars can trigger Global Oscillations (GOSH) - one site of the i process?!

Ondrea Clarkson on H-ingestion in Pop III star and Keller star.



Two different color scales show entrained fluid and nuclear energy release.



2 M_{sun}, Z = 10^{-5}
AGB star
H-ingestion
simulation on Blue
Waters machine
on a
grid of 1536^3 cells.

The GOSH is indeed <u>global</u>. This flow has a 1-D average, but it is by no means a 1-D phenomenon. Blue Waters makes it possible to see the GOSH in its full 3-D complexity.

t = 2703.7 min.

Paul Woodward
NSF BlueWaters