i-process Review and Convective-Reactive Burning in Stars

Falk Herwig[1,6,7]

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Outline

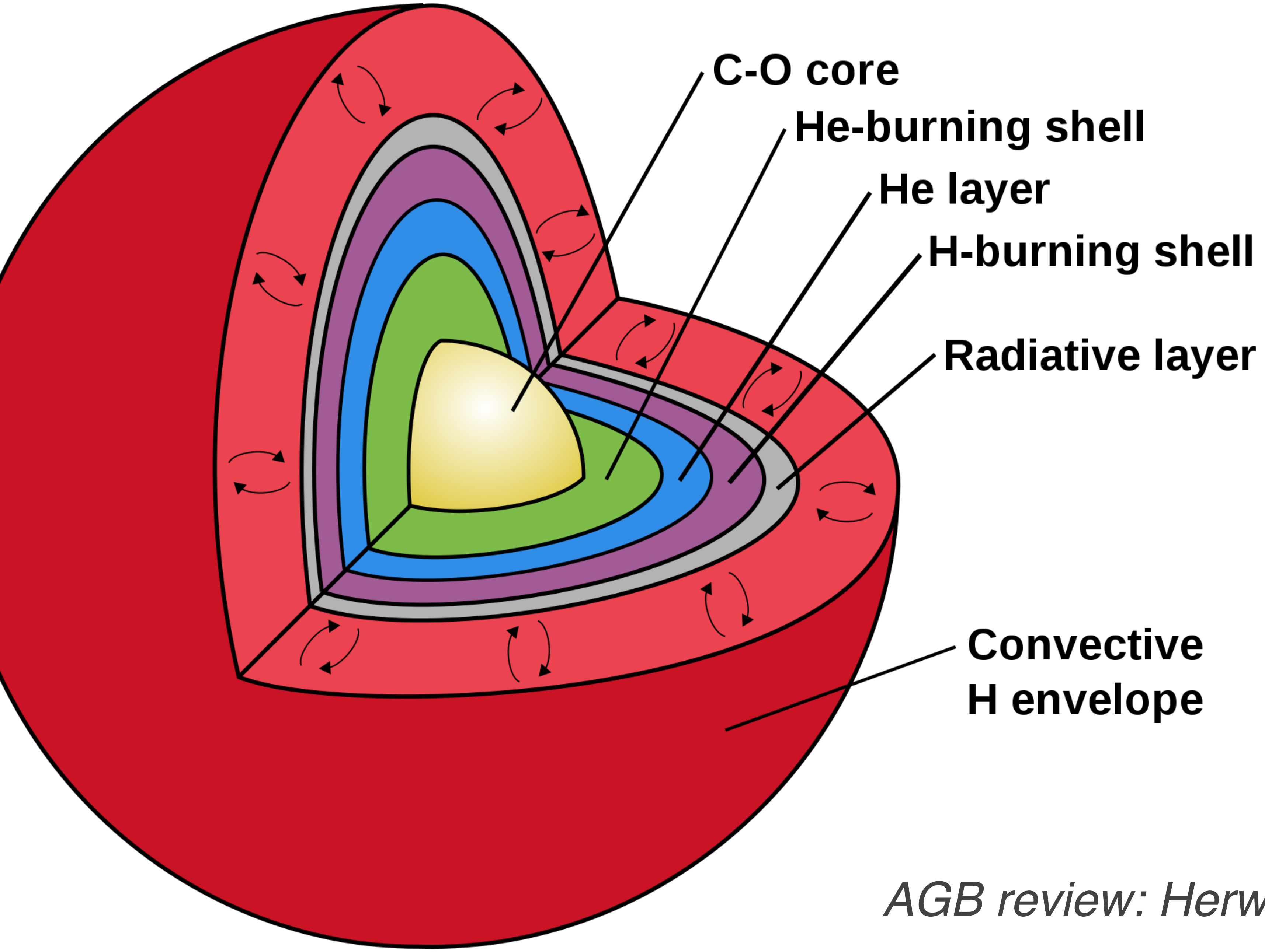
- Convective-reactive nucleosynthesis:
  - *How it works and why it requires new nuclear data*
- Two examples:
  - *C-O shell mergers in massive stars*
  - *Intermediate neutron-capture process (i process)*

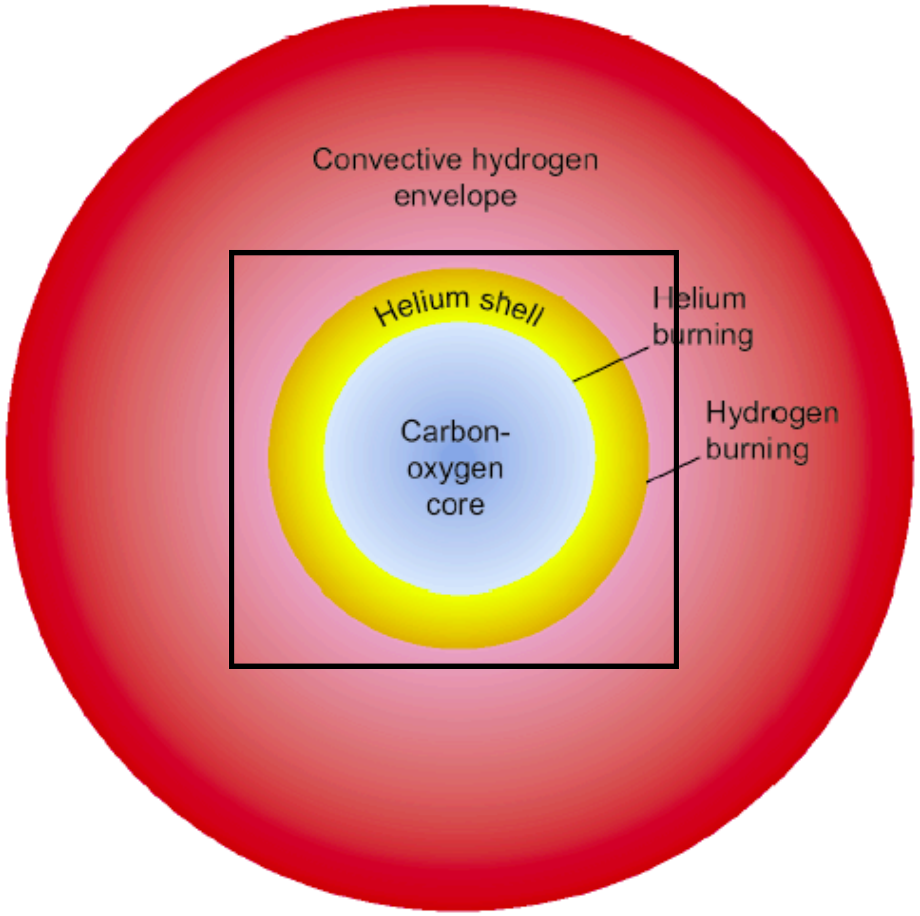
He-shell flash in low-mass stars

As an example to explain the workings of convective-reactive nucleosynthesis

Shell structure of stars

Shells may or may not be convectively unstable





- Rapidly accreting white dwarfs (Denissenkov+ 17, ApJ Letters)
- Low-Z AGB stars (Cristallo+ 16, Choplin+ 21, A&A)

AGB review: Herwig 2005 ARAA

He-shell flash in a RAWD or in a low-Z AGB star

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

Entrainment/ingestion of H in the He-shell convection

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

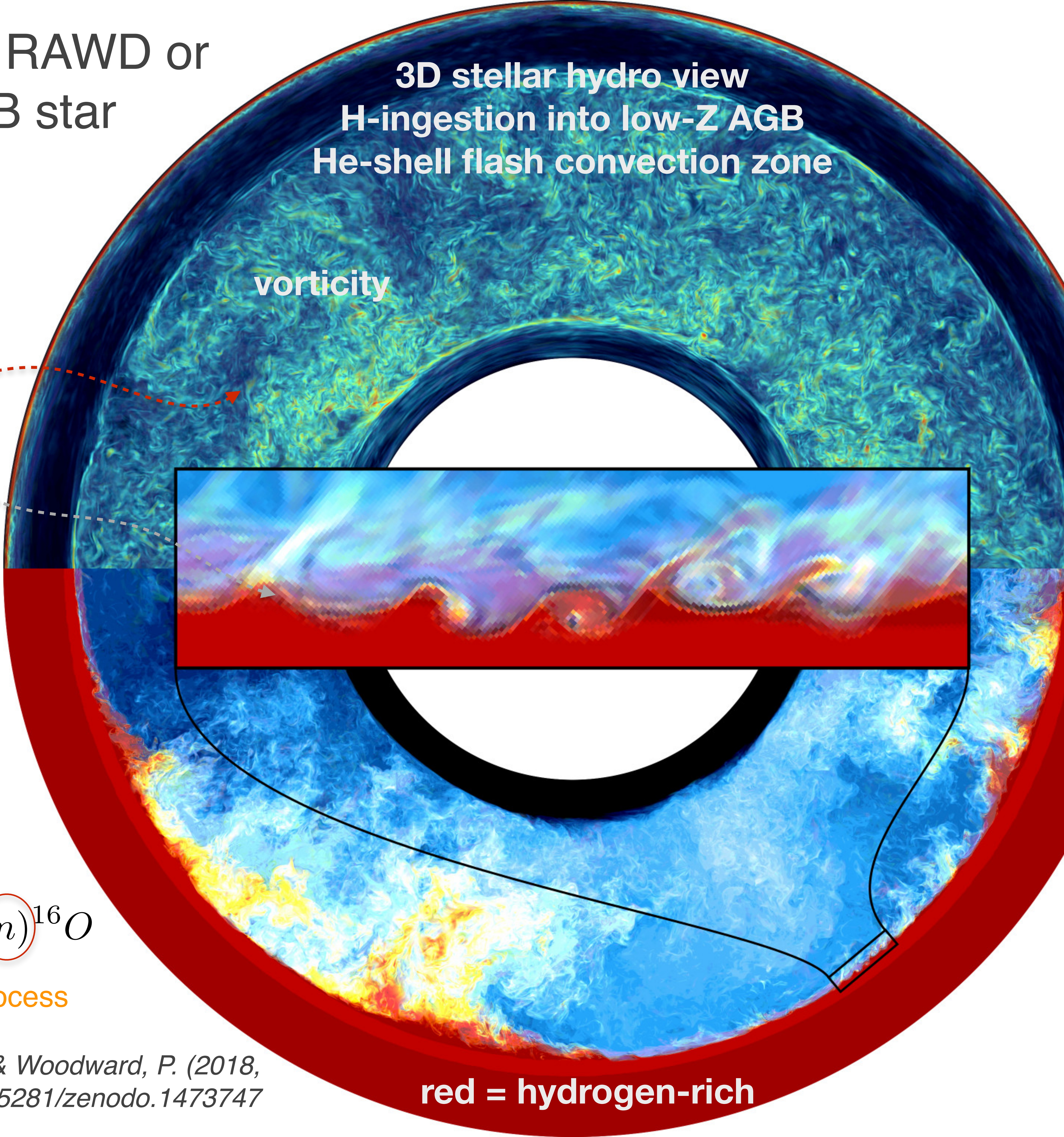
Damköhler number

$$Da = \frac{\tau_{\mathrm{conv}}}{\tau_{\mathrm{nuc}}} \approx 1$$

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

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

Fast neutron source: i process



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

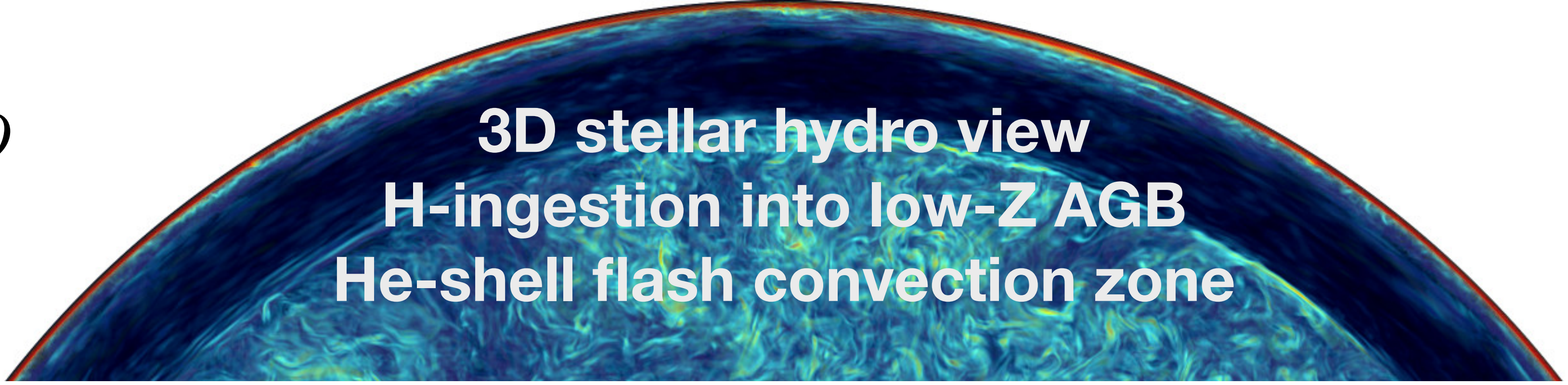
vorticity

red = hydrogen-rich

Andrassy, R., Herwig, F., & Woodward, P. (2018, October). Zenodo. http://doi.org/10.5281/zenodo.1473747

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

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



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

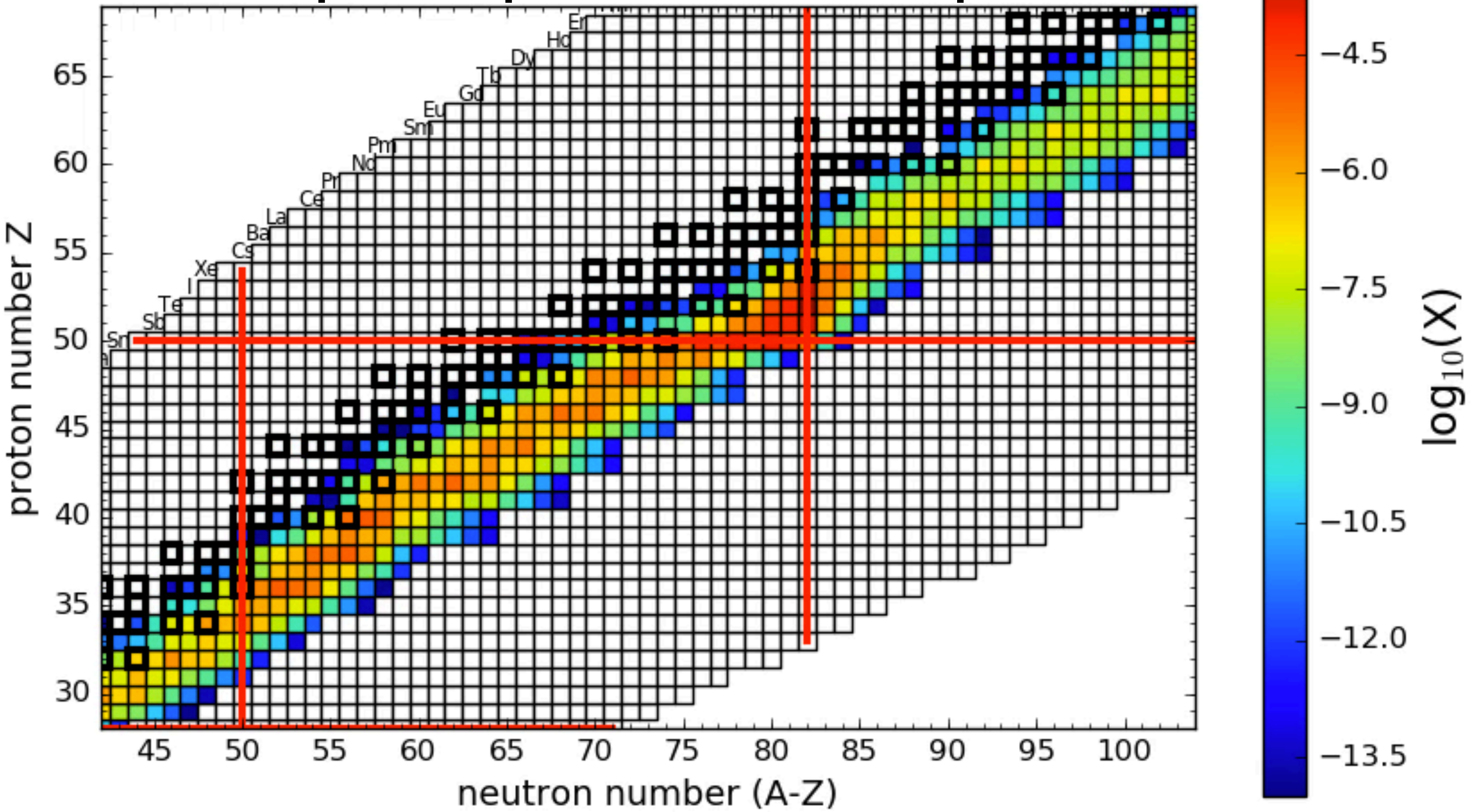
Nuclear and hydrodynamic timescales are the same order → convective-reactive nucleosynthesis.

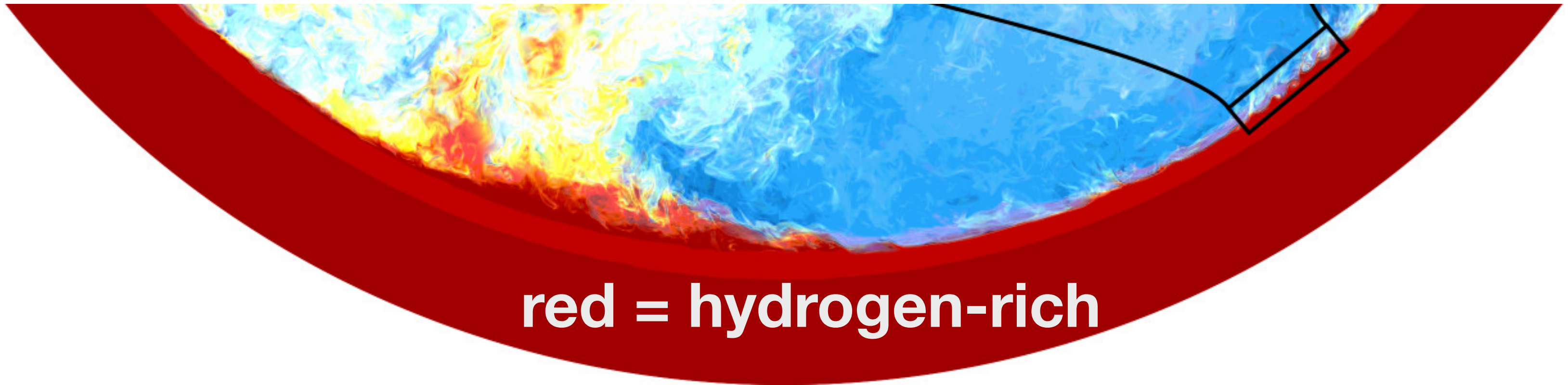
Neutrons released with intermediate neutron density → i process element production.

Multi-physics, multi-method approach:

- Nuclear physics data of unstable species
- Simulation approaches: combine detailed 3D hydro with detailed n-rich nucleosynthesis involving thousands of species?

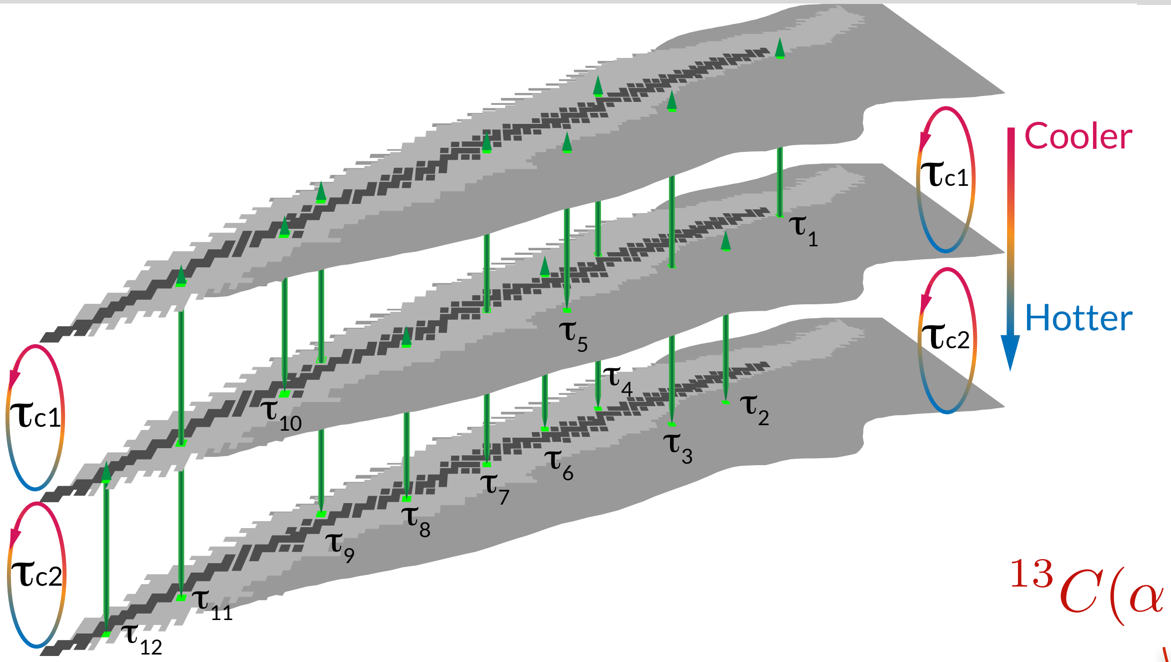
i process path in chart of isotopes

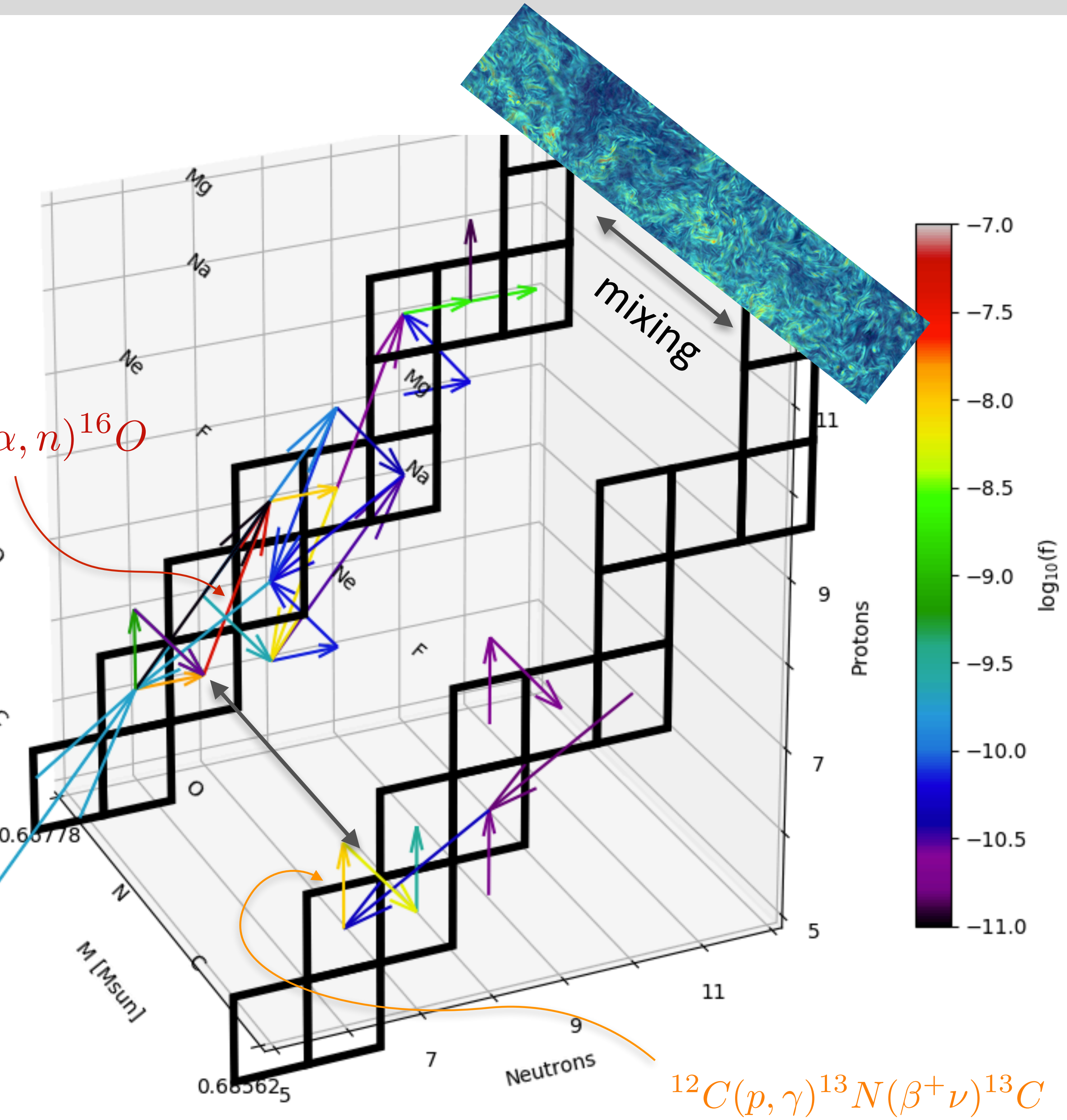




red = hydrogen-rich

Convective-reactive i-process nucleosynthesis



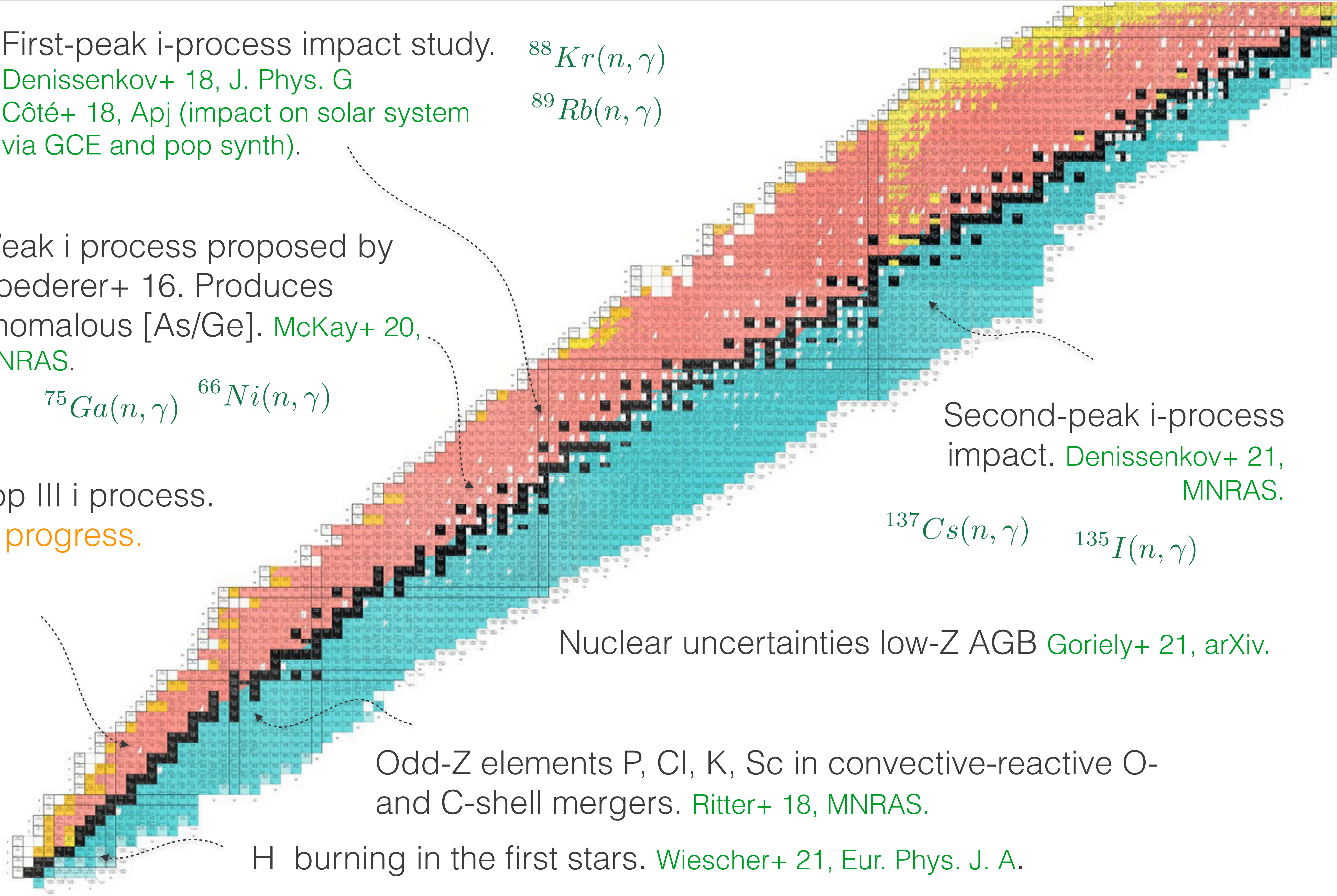


$^{13}C(\alpha,n)^{16}O$

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

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

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



First-peak i-process impact study. Denissenkov+ 18, J. Phys. G
Côté+ 18, Apj (impact on solar system via GCE and pop synth).

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

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

Weak i process proposed by Roederer+ 16. Produces anomalous [As/Ge]. McKay+ 20, MNRAS.

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

Pop III i process. In progress.

Second-peak i-process impact. Denissenkov+ 21, MNRAS.

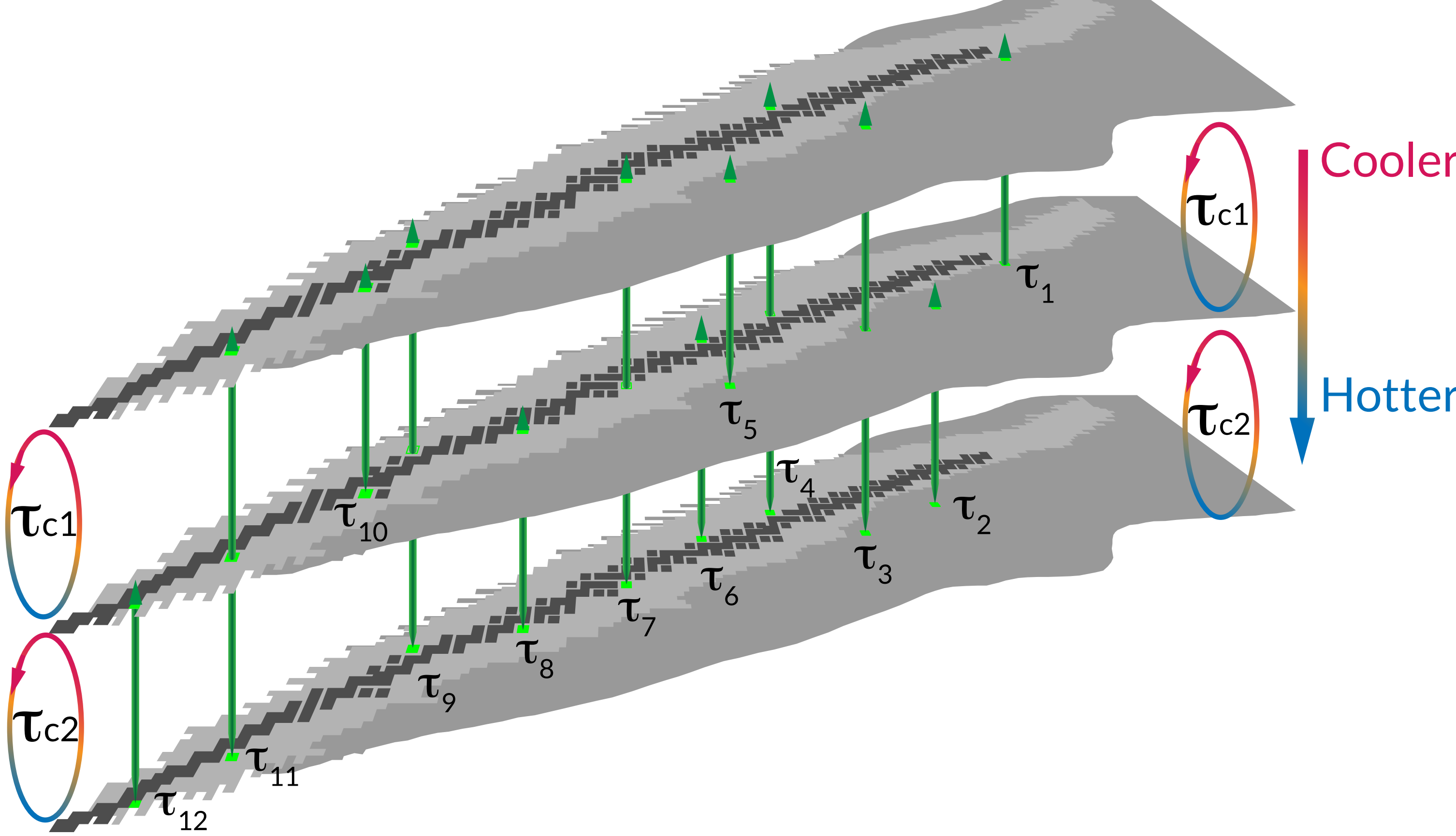
$^{137}Cs(n,\gamma)$ $^{135}I(n,\gamma)$

Nuclear uncertainties low-Z AGB Goriely+ 21, arXiv.

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

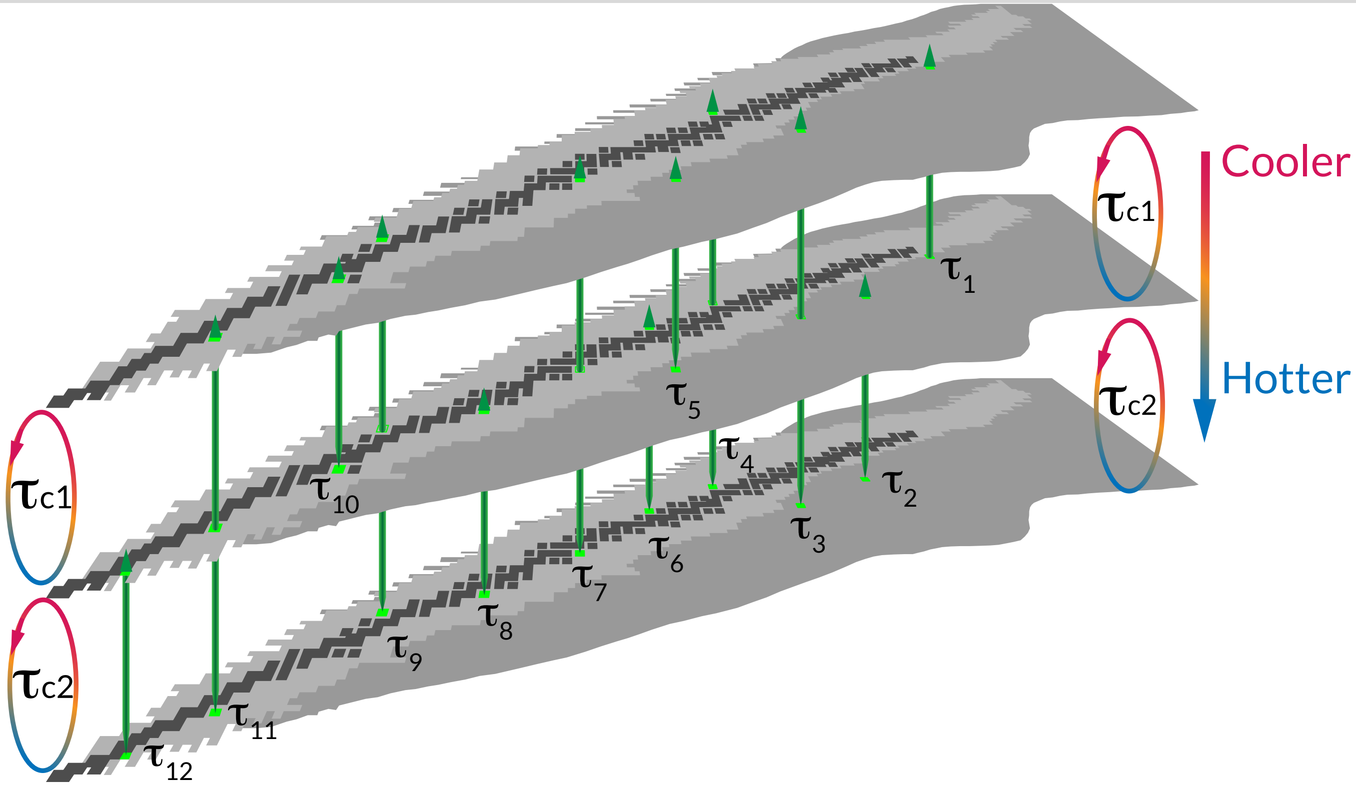
H burning in the first stars. Wiescher+ 21, Eur. Phys. J. A.

Simulation approaches



- 1-zone network calculation
  - ➡ Very limited as they do not capture the simultaneous addition and depletion of species due to mixing
  - ➡ Only useful to determine local ratios (Denissenkov+ 21, MNRAS)
- 1D multi-zone simulations
  - ➡ Can generally capture the simultaneous mixing and burning
  - ➡ Possibly significant simplification of mixing process may impact predictions
- Post-processing of 3D simulations
  - ➡ Most realistic
  - ➡ Can't use tracer particles as they do not mix (only appropriate for Da >> 1 as in explosions)
  - ➡ ATS method (Stephens+ 20, MNRAS)

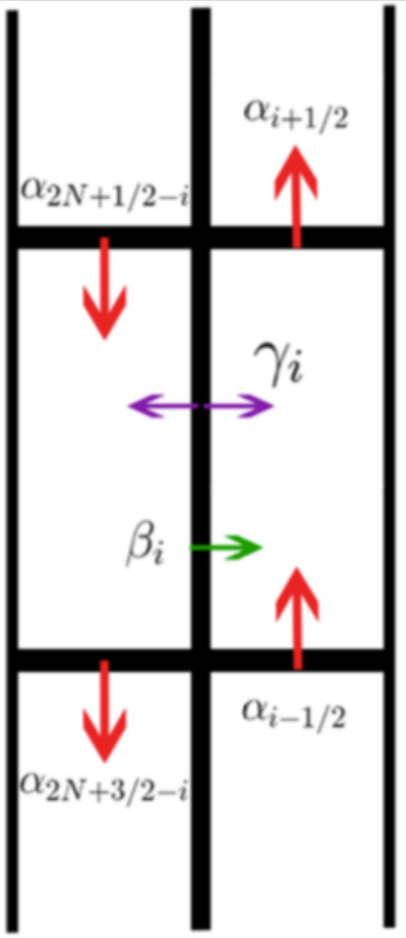
Advective Two-Stream post-processing of 3D Hydro Simulations for Convective-reactive Nucleosynthesis

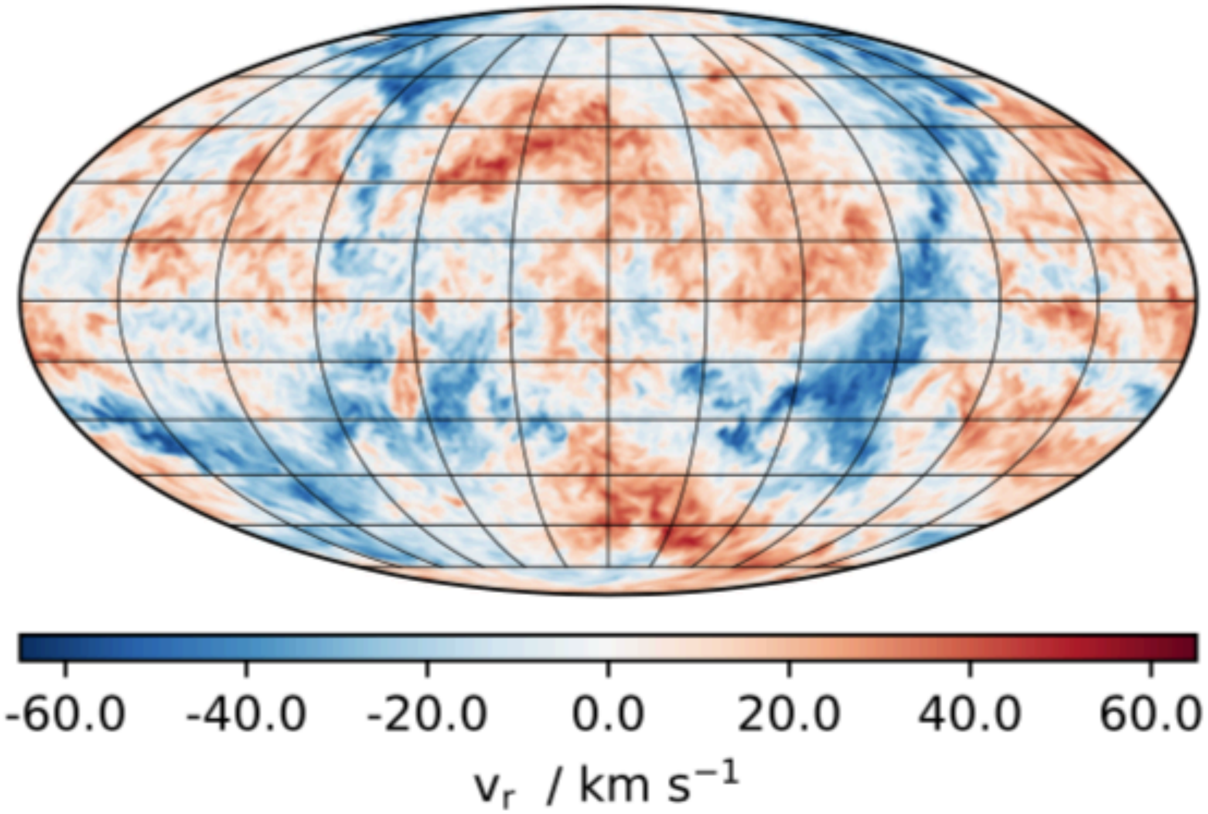


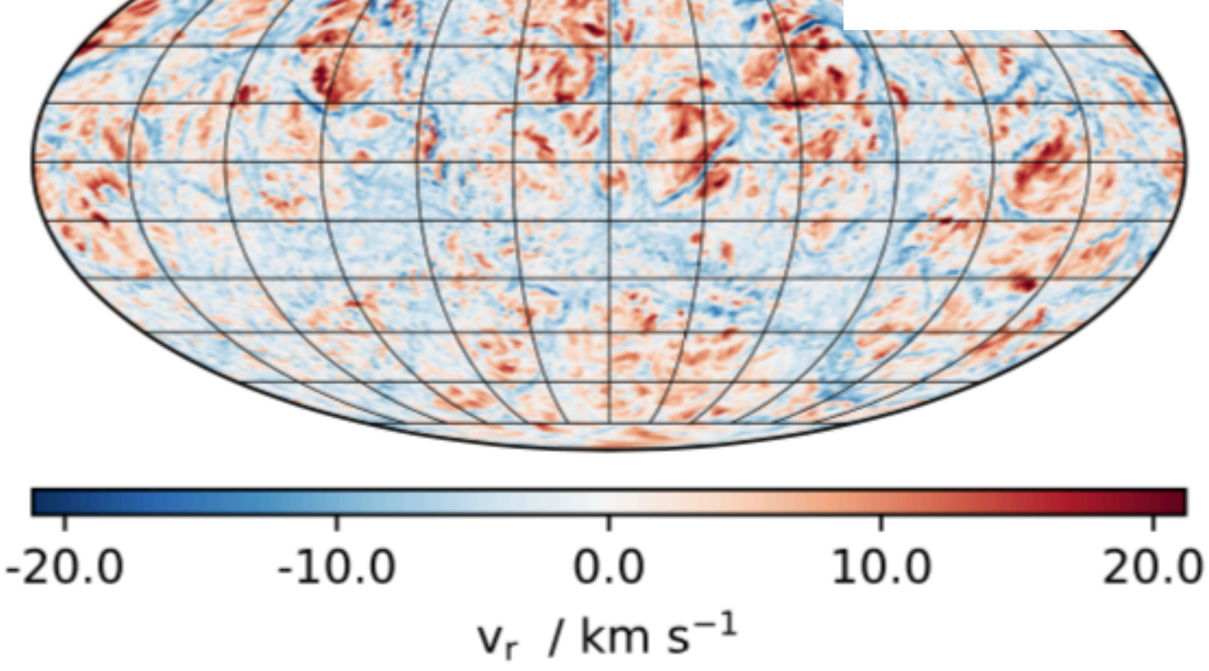
Convective-reactive nucleosynthesis happens by nature on the convective time scale, which is

- minutes for O-shell
- 1/2 hour for He-shell

From this it follows: Species with half lives in this range can mix and participate in unique conv-reac nucleosynthesis





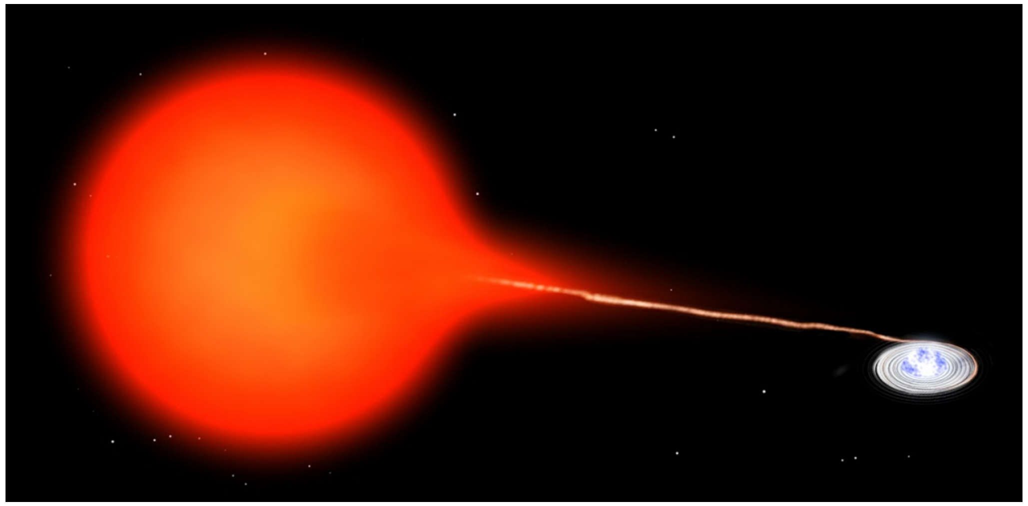


Stephens+ 20, MNRAS

Observations, predictions and open questions

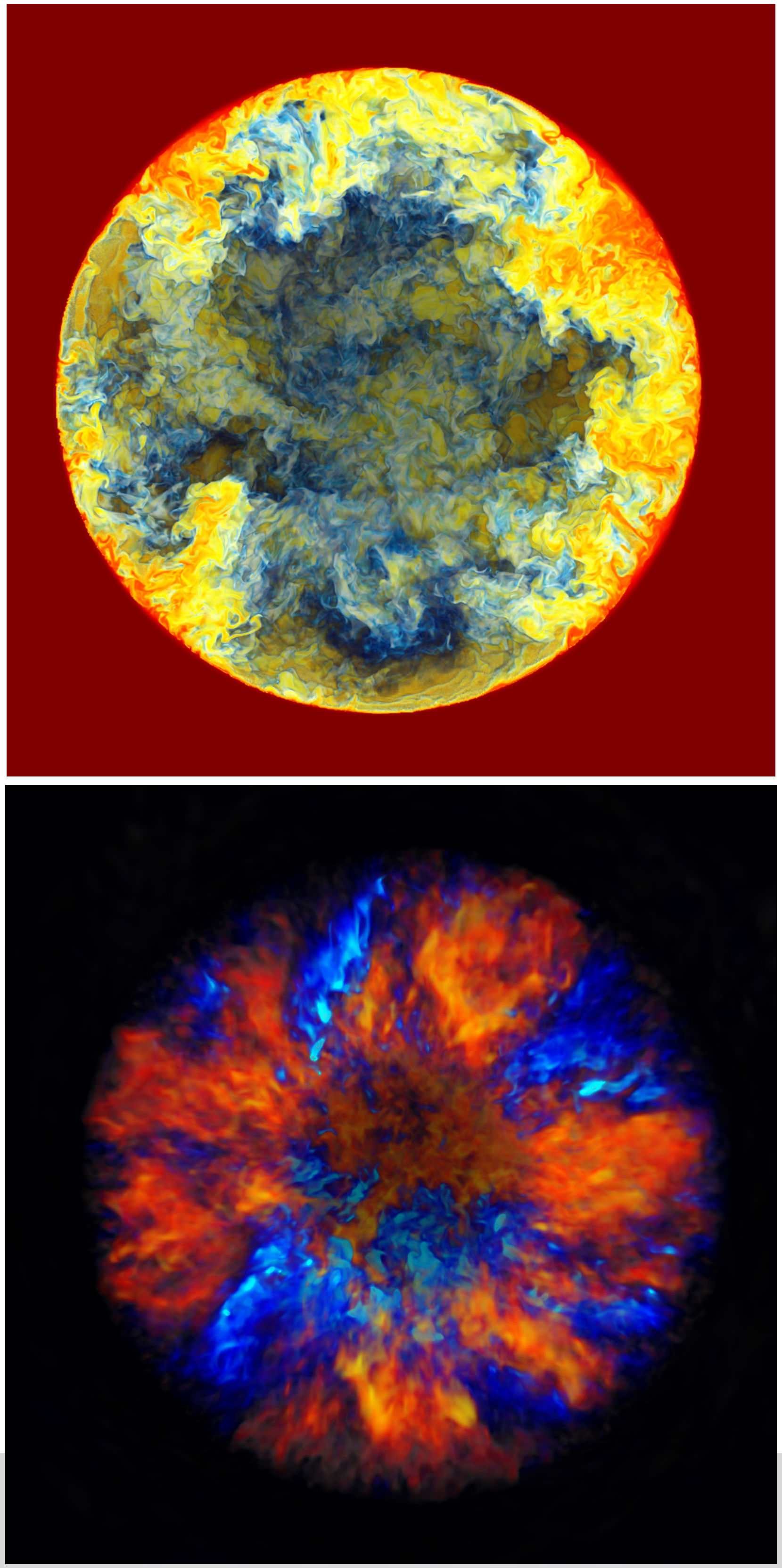
- What observations can the i process explain?
    - C-enhanced metal-poor stars
    - Open cluster stars
    - Pre-solar grains
- Where does the i process take place?
    - *Rapidly accreting white dwarfs*
    - *low-Z AGB stars? He-core flash? super-AGB stars?*
    - *He-shell burning in low-Z massive stars*

Where does it happen?
One promising option for CEMP-i stars: 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

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

Radial velocity component

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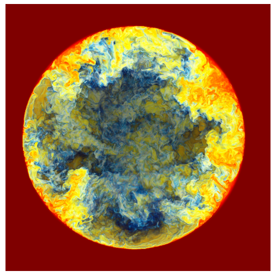
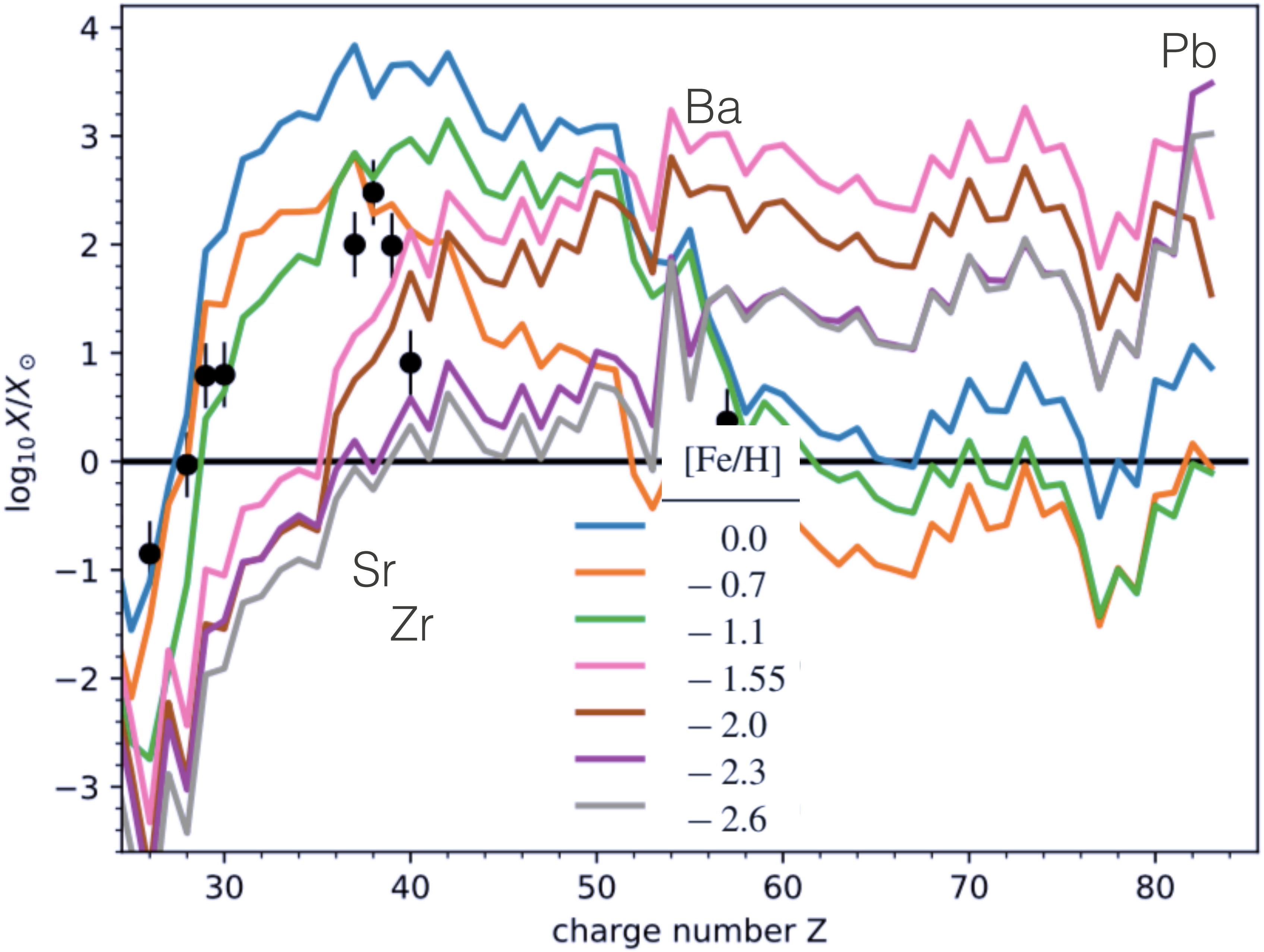
MNRAS **488,** 4258–4270 (2019)
Advance Access publication 2019 July 12

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



Just like in s and r process the I process comes with different neutron exposures depending on the site.

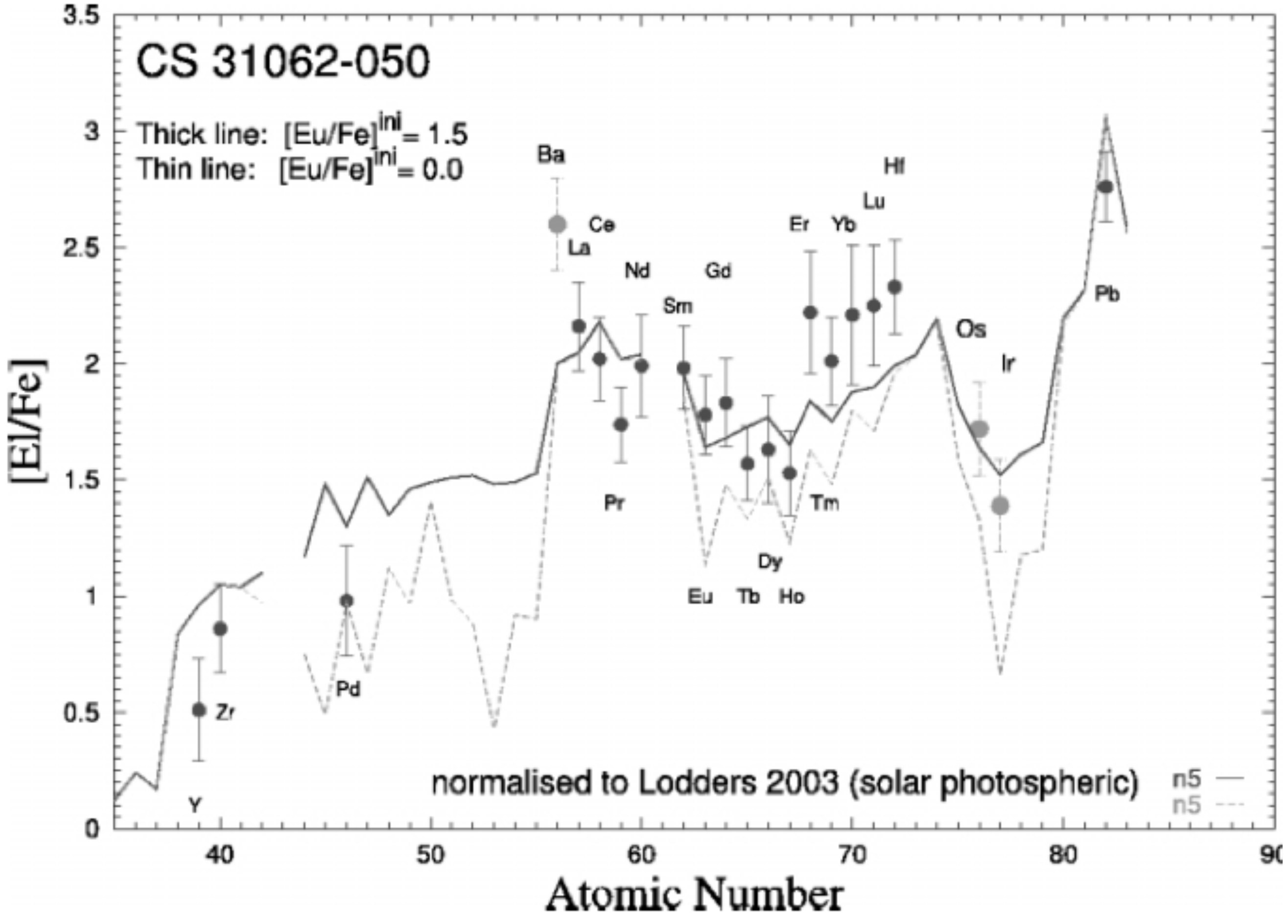
Elemental ratios of 1st and 2nd peak elements tell about neutron exposure not neutron density and are therefore not in itself a good I process diagnostic.

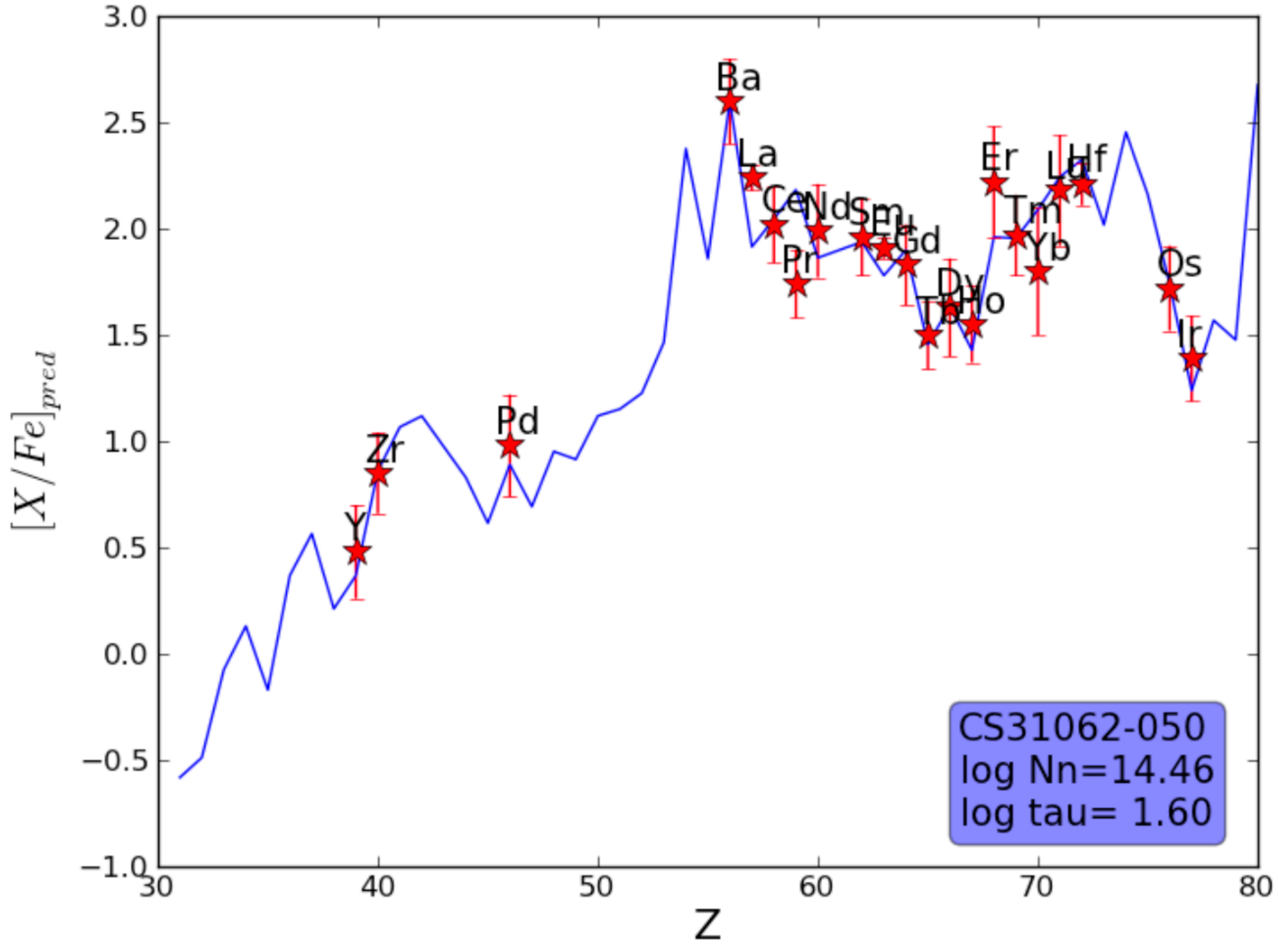
CEMP-i stars

The origin of the CEMP-r/s stars has been a conundrum since their discovery (Jonsell+ 06, Masseron+10, Lugaro+ 12, and others)

Bisterzo+ 12: Combination of r process and s process

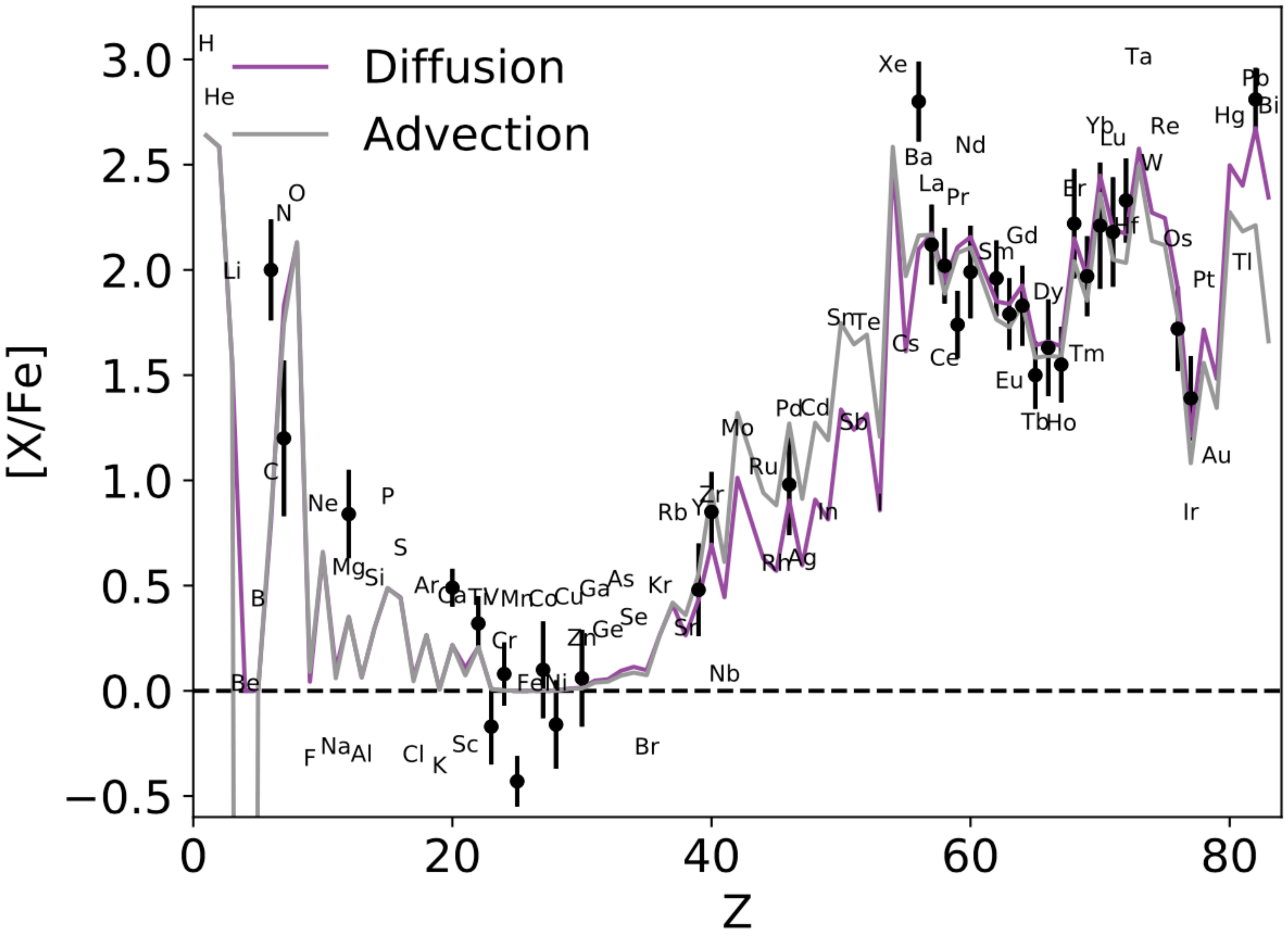
Victoria JINA/NuGrid group (Dardelet+ 14, PoS, NIC XIII): intermediate neutron density (confirmed by Hampel+ 16, 19)





CEMP-i stars

3D1D hydro-nucleosynthesis ATS post-processing (Stephens+ 20)



- 1D multi-zone and 3D ADS can reproduce entire abundance distribution from C to Pb
- Note here local ratio Ba/La does not fit
  - ➡ This is because the neutron density is in this particular model of an ~0.6Msun RAWD not high enough
  - ➡ Local elemental ratios probe neutron density!
  - ➡ In order to demonstrate that next slide show 1-zone constant neutron-density results

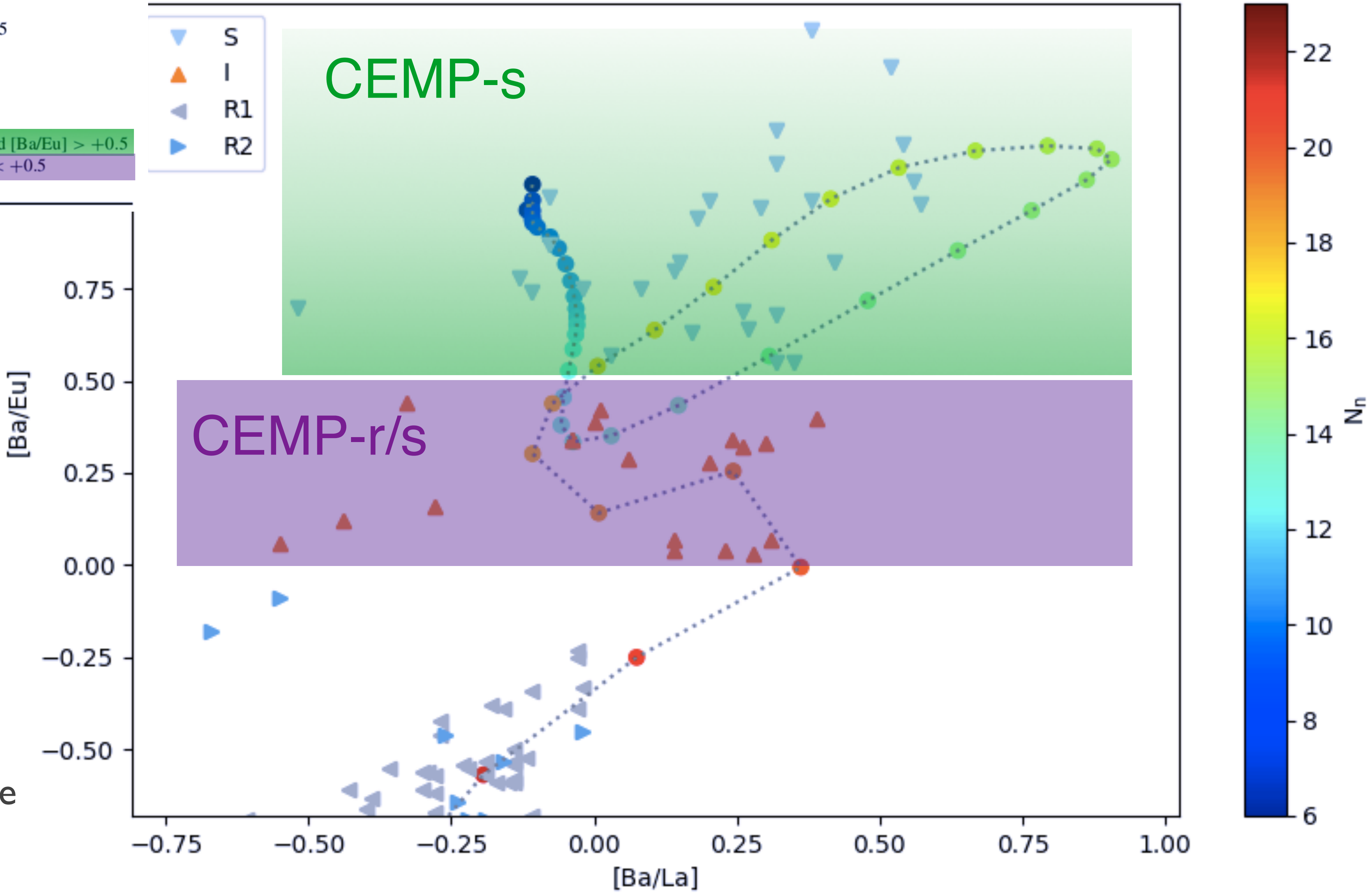
CS31062-050; observation: Aoki+ 02, Johnson & Bolte 04

[Ba/Eu] &CEMP star classification

TABLE 2 Definition of subclasses of metal-poor stars

Neutron-capture-rich stars	
r-I	$0.3 \leq$ [Eu/Fe] $\leq +1.0$ and [Ba/Eu] < 0
r-II	[Eu/Fe] $> +1.0$ and [Ba/Eu] < 0
s	[Ba/Fe] $> +1.0$ and [Ba/Eu] $> +0.5$
r/s	$0.0 <$ [Ba/Eu] $< +0.5$
Carbon-enhanced metal-poor stars	
CEMP	[C/Fe] $> +1.0$
CEMP-r	[C/Fe] $> +1.0$ and [Eu/Fe] $> +1.0$
CEMP-s	[C/Fe] $> +1.0$, [Ba/Fe] $> +1.0$, and [Ba/Eu] $> +0.5$
CEMP-r/s	[C/Fe] $> +1.0$ and $0.0 <$ [Ba/Eu] $< +0.5$
CEMP-no	[C/Fe] $> +1.0$ and [Ba/Fe] < 0

- According to present classification CEMP-r/s stars are indeed incompatible with s process.
- But many CEMP-s stars are also incompatible with an s-process signature because they have [Ba/La] > 0.1.
- →[Ba/Eu] alone insufficient to determine s-process nucleosynthesis origin



Herwig+ 19, https://doi.org/10.5281/zenodo.3429602

Observation compilation: JINA-base, Abohalima & Frebel

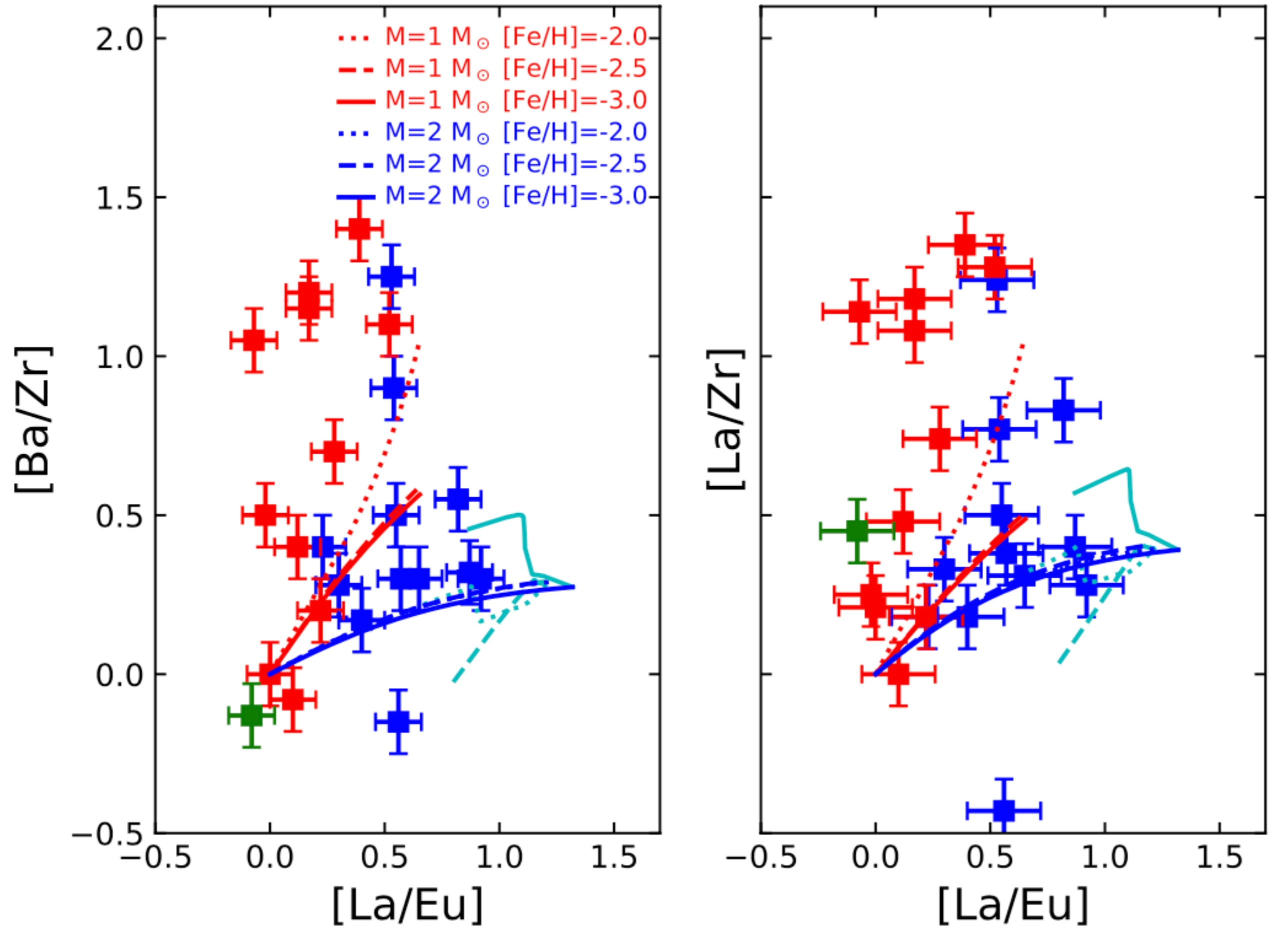
What is the site of i process for CEMP-i stars?

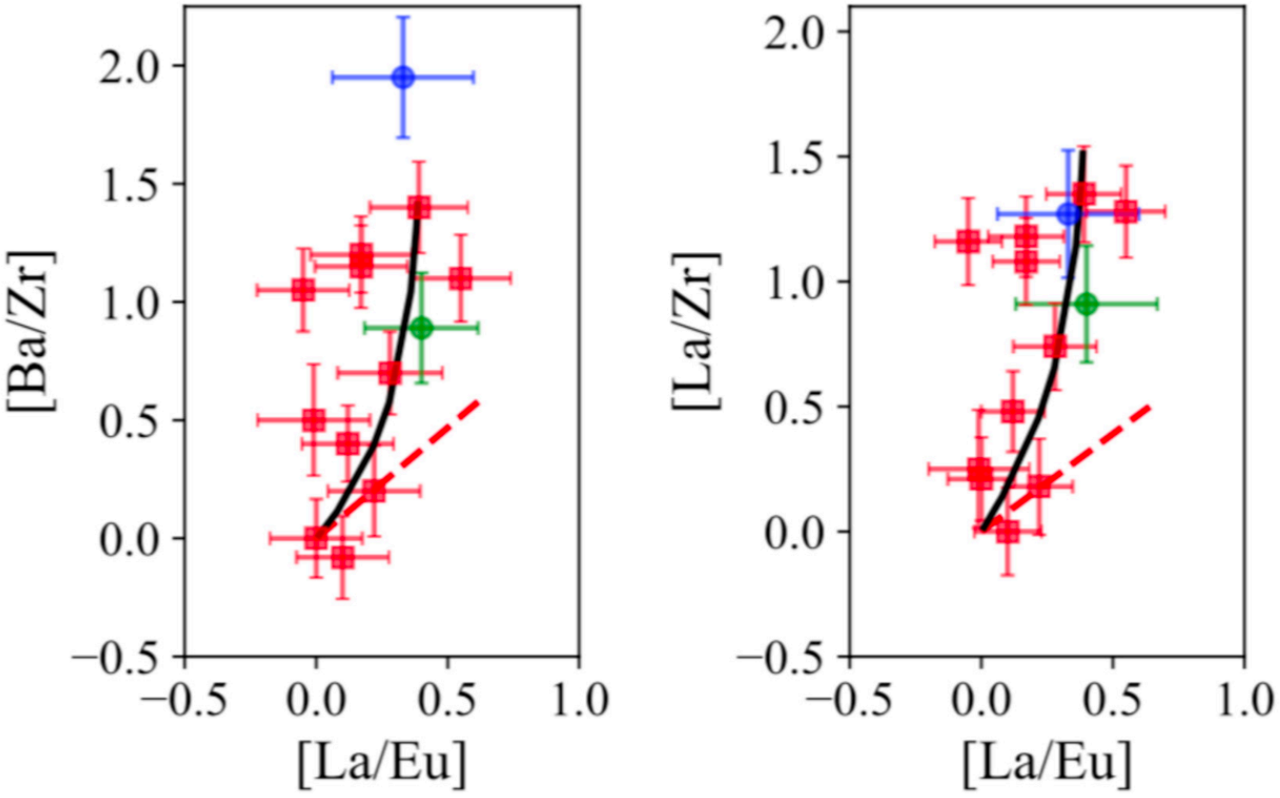
Low-Z AGB stars (Karinkuzhi+ 20, Choplin+ 21)

- ➡ AGB envelopes do not get enriched enough, requires unrealistic mixing ratio
- ➡ Simulations (1D and 3D) predict split of convection zone from feedback, need to make assumptions
- ➡ Neutron exposure not high enough to reach observed 1st to 2nd peak ratios

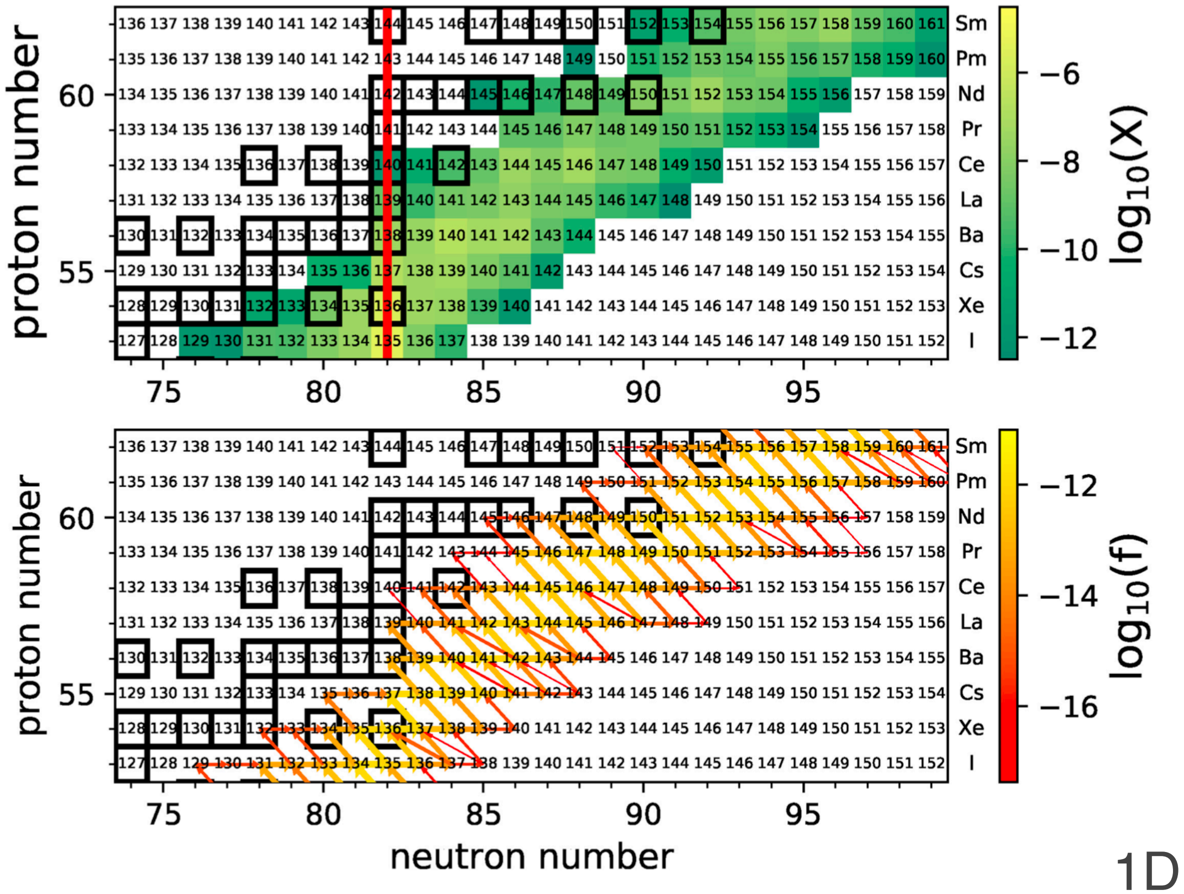
RAWD (Denissenkov+ 19, 21)

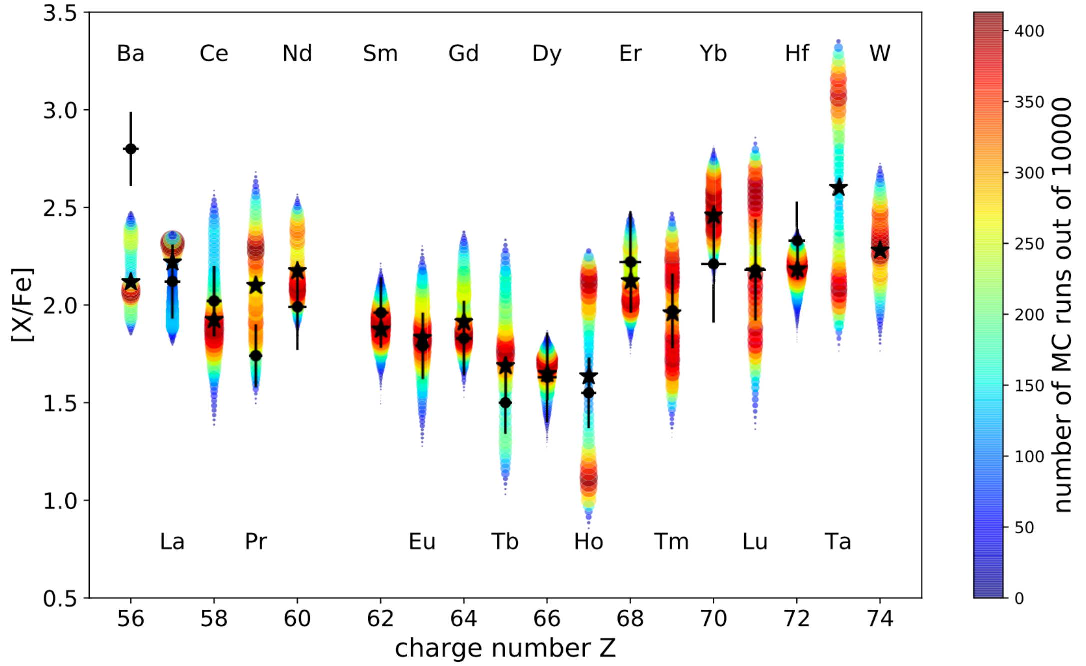
- ➡ RAWD ejecta strongly enriched, realistic mixing ratio (dilution factor)
- ➡ Simulations predict long convective-reactive episode, reach high neutron exposures
- ➡ Observed 1st to 2nd peak ratios naturally reproduced, no ad-hoc assumptions needed





Nuclear physics impact studies show:
There are branch points inside the i-process path!





1D multi-zone MC simulations

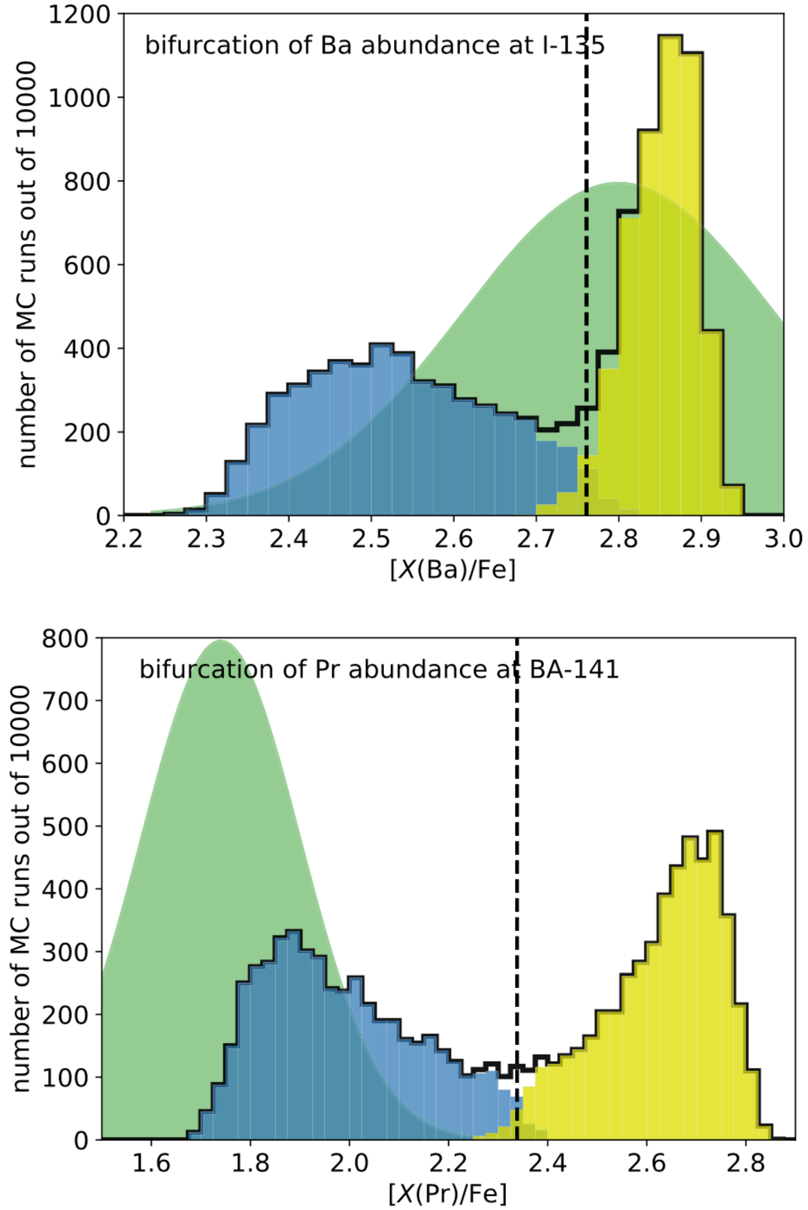


Figure 8. Comparison of the distributions of the Ba (top panel) and Pr (bottom panel) abundances obtained in the MC simulation (thick black line) based on the one-zone benchmark model with $N_\mathrm{n} = 3.16 \times 10^{14}\ \mathrm{cm}^{-3}$ (vertical dashed line) with the abundances of Ba and Pr reported for the star CS 31062−050 by Johnson & Bolte (2004) (green-shaded Gaussian curves). The single-peak distributions, blue and yellow histograms, correspond to rate multiplication factors $f_i > 1$ and $f_i < 1$ for the reactions $^{135}\mathrm{I}(\mathrm{n},\gamma)^{136}\mathrm{I}$ (top panel) and $^{141}\mathrm{Ba}(\mathrm{n},\gamma)^{142}\mathrm{Ba}$ (bottom panel), as identified by their strongest correlation coefficients in Table 1 for Ba and Pr, respectively.

Denissenkov+ 21, MNRAS

THE ASTROPHYSICAL JOURNAL, 854:105 (14pp), 2018 February 20
https://doi.org/10.3847/1538-4357/aaaae8

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]

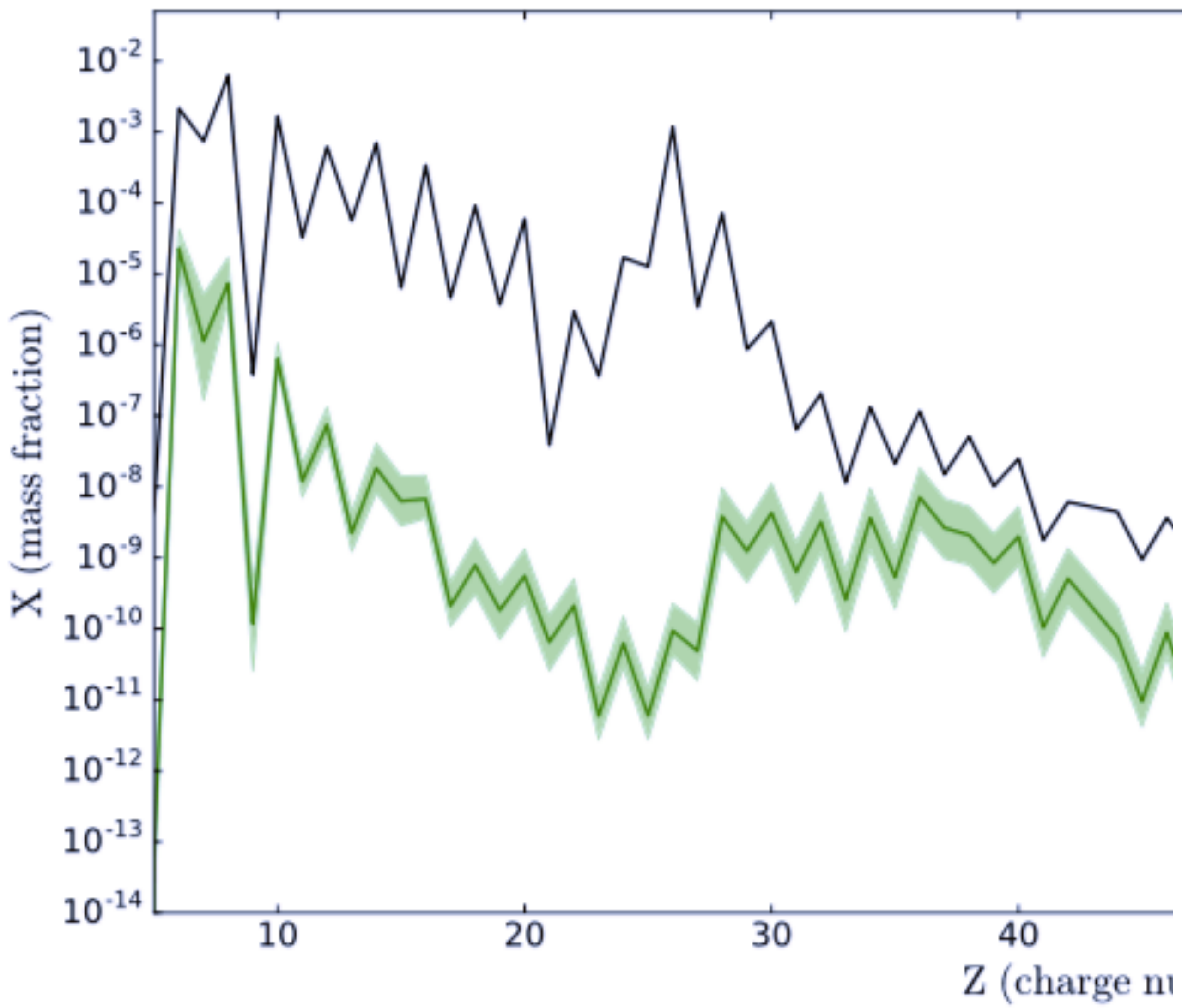


Figure 8. Predicted contribution of rapidly accreting white dwarfs (green, RAWDs) to th
fiducial model while the green shaded area shows the range of solutions generated by un
different early chemical evolution paths (see Figure 6). The solar composition was taken

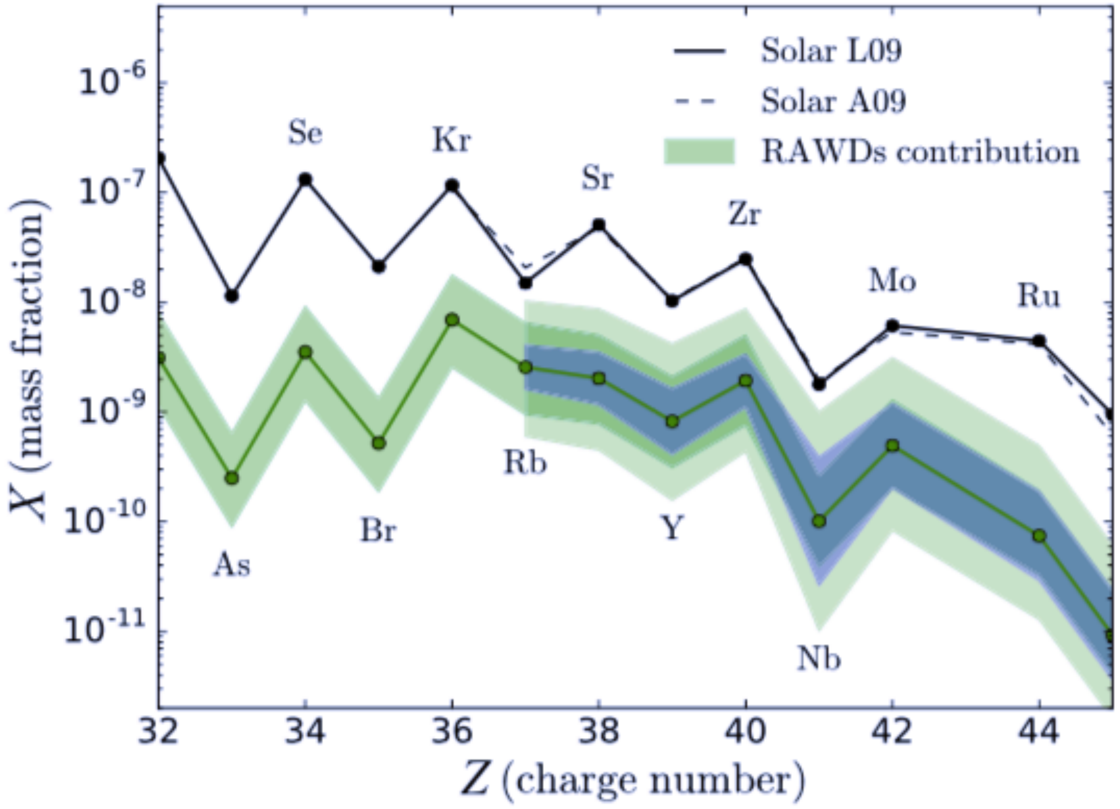
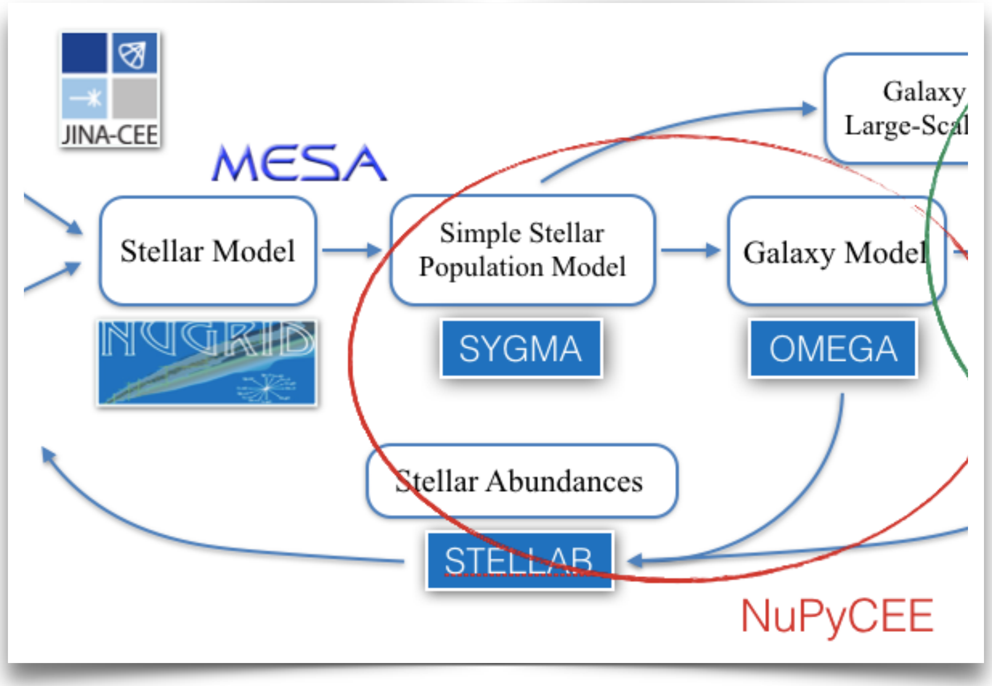


Figure 9. Same as in Figure 8, but zoomed on first-peak elements. The dashed black line shows the solar composition of Asplund et al. (2009, A09). The blue shaded area shows the uncertainties generated by nuclear reaction rates (see Section 6.4). The larger lighter-green shaded area shows the combined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

Open problem in GCE: odd-Z elements

Benoit Côté - **the JINA/NuGrid pipeline**



GCE OMEGA: models with NuGrid/JINA yields, Nomoto+ 13 and Kobayashi+ 06 yields.

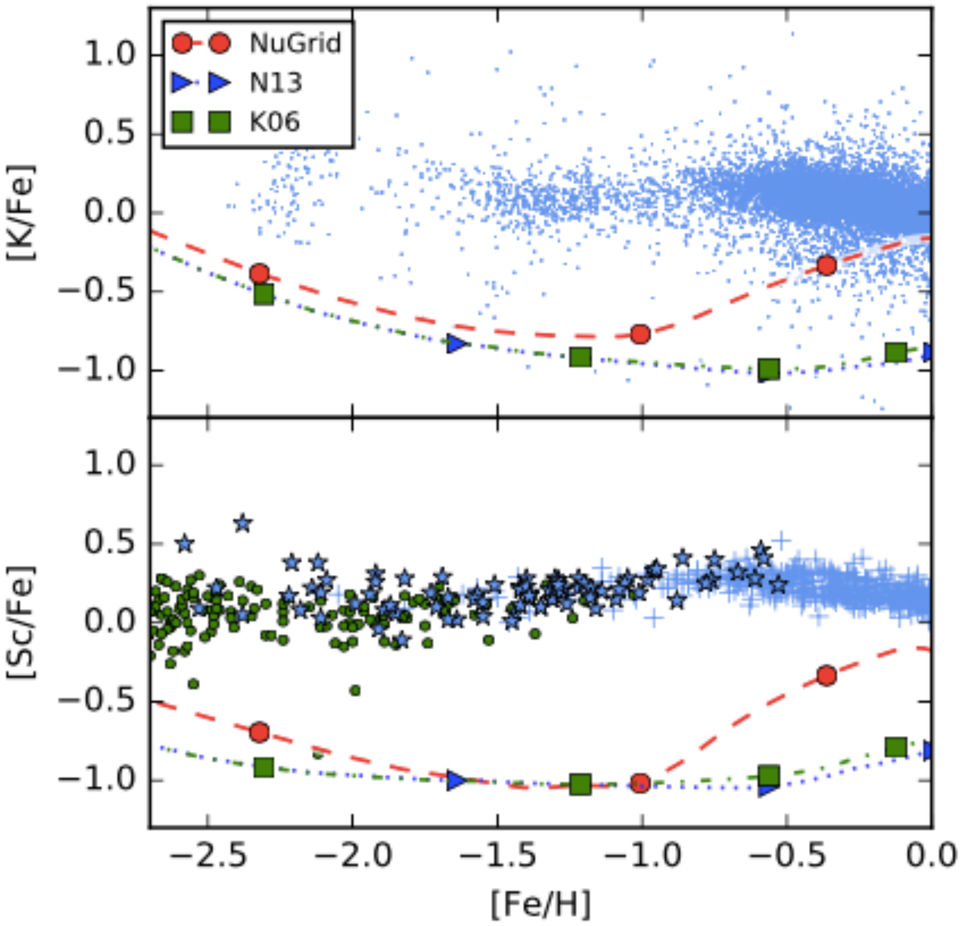
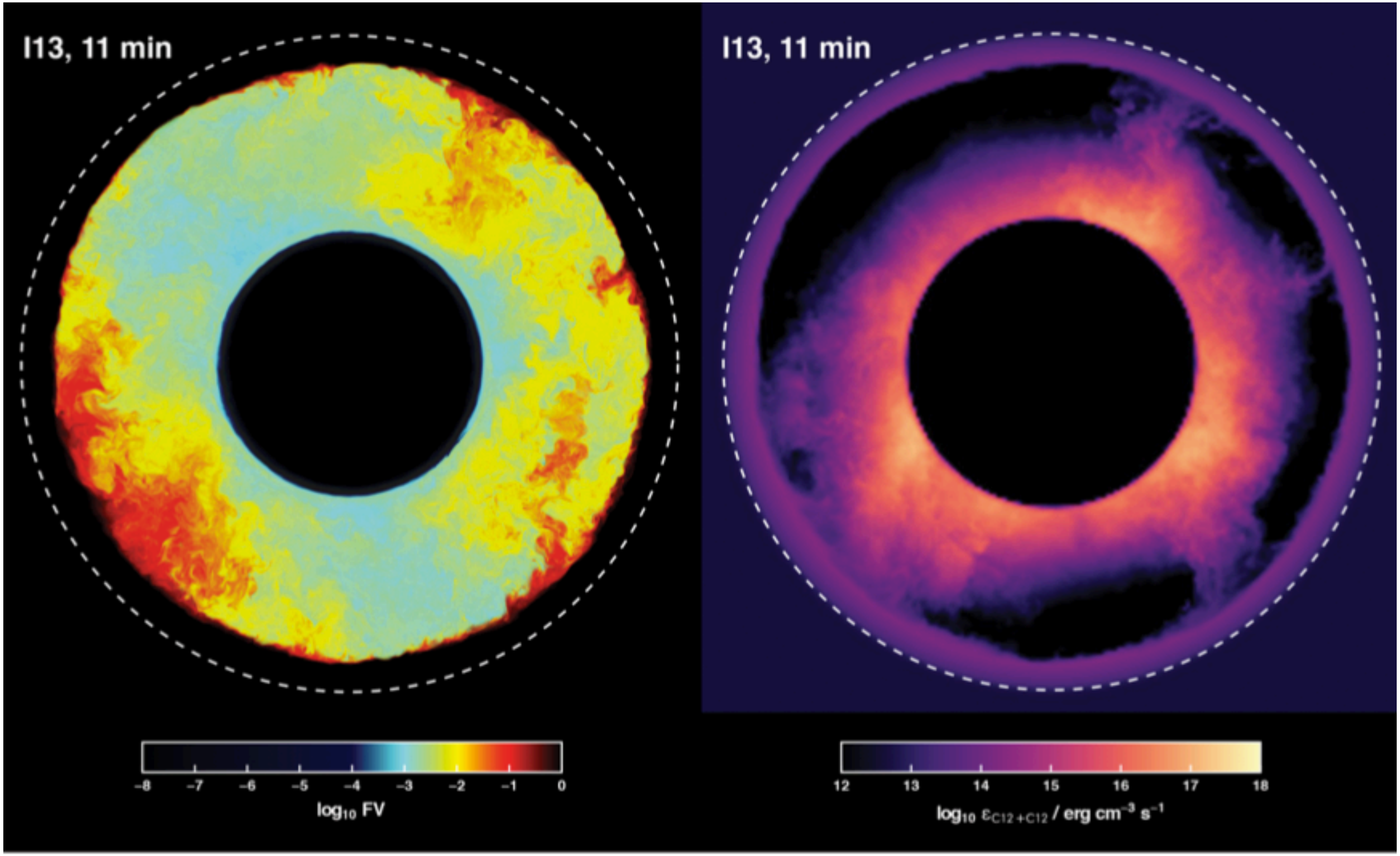


Figure 1. K and Sc predictions of our GCE model based on NuGrid yields (R17) in comparison with disk and halo stars of the Milky Way. For comparison, we show GCE predictions based on yields from K06 and N13. K data are from the APOGEE survey (Wilson et al. 2010; SDSS Collaboration et al. 2016), and Sc data from Ishigaki et al. (2012, 2013, crosses), Roederer et al. (2014, dots) and Battistini & Bensby (2015, stars).

Ritter+ 17, see also Rauscher, Kobayashi and others

3D Hydro simulations of C-ingestion into convective O-shell



Andrassy+ 19, MNRAS

3D Hydro simulations of C-O shell merger conditions

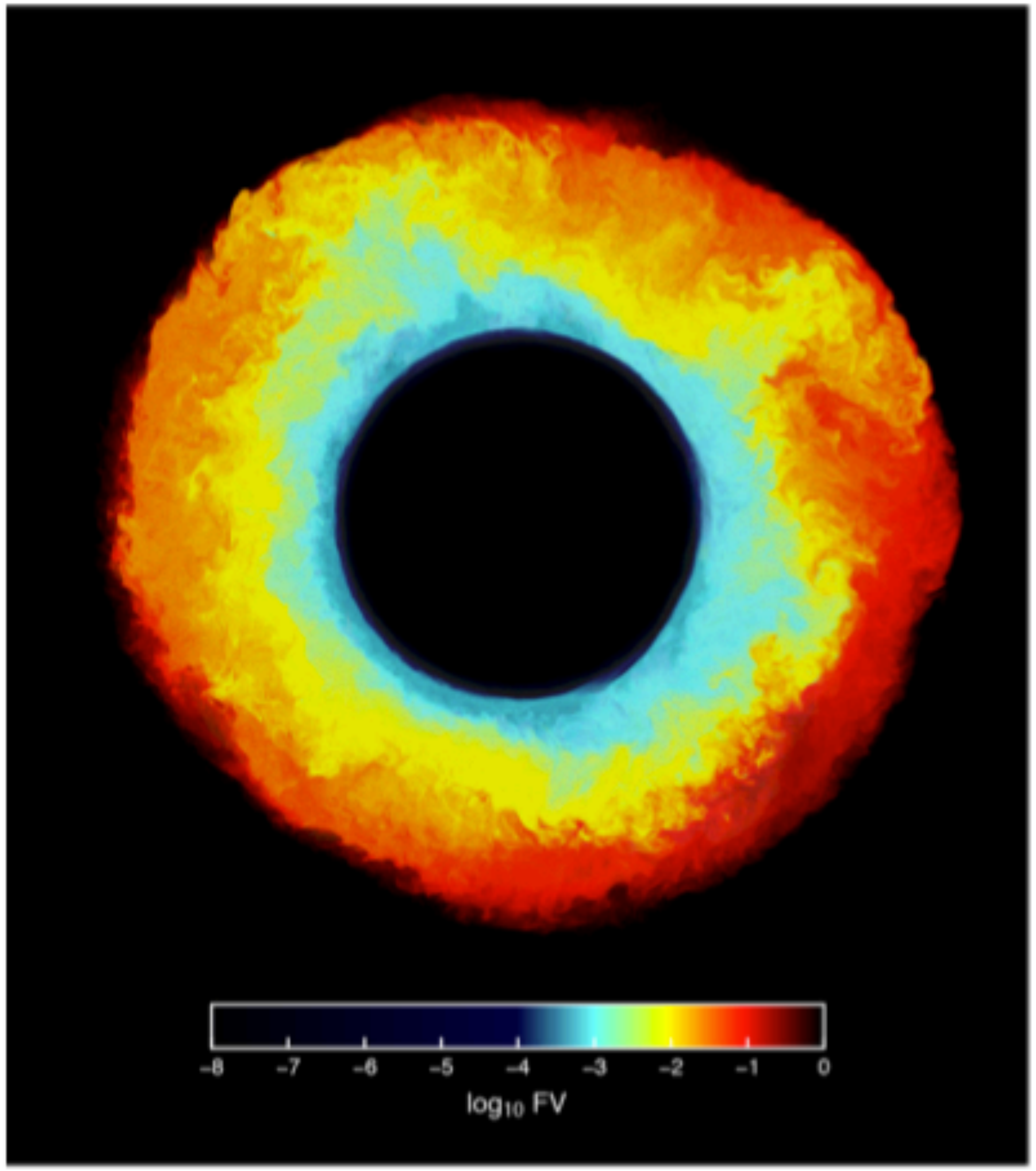
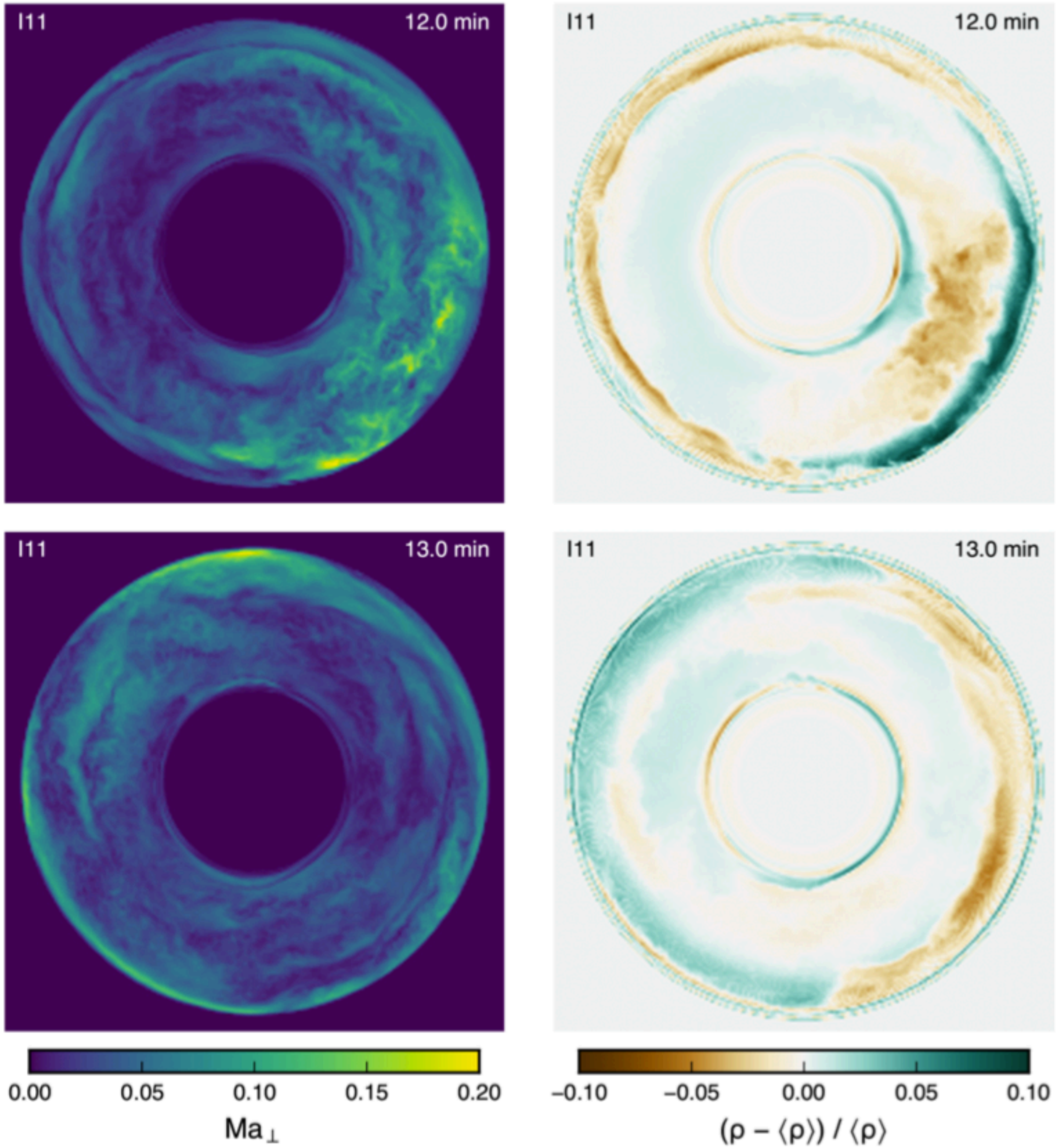


Figure 21. Rendering of the fractional volume of fluid $\mathcal{F}_C$ in a thin slice through the computational box at $t = 12.6$ min in run I11 ($f_{OO} = 13.5$, $f_{CC} = 10$).

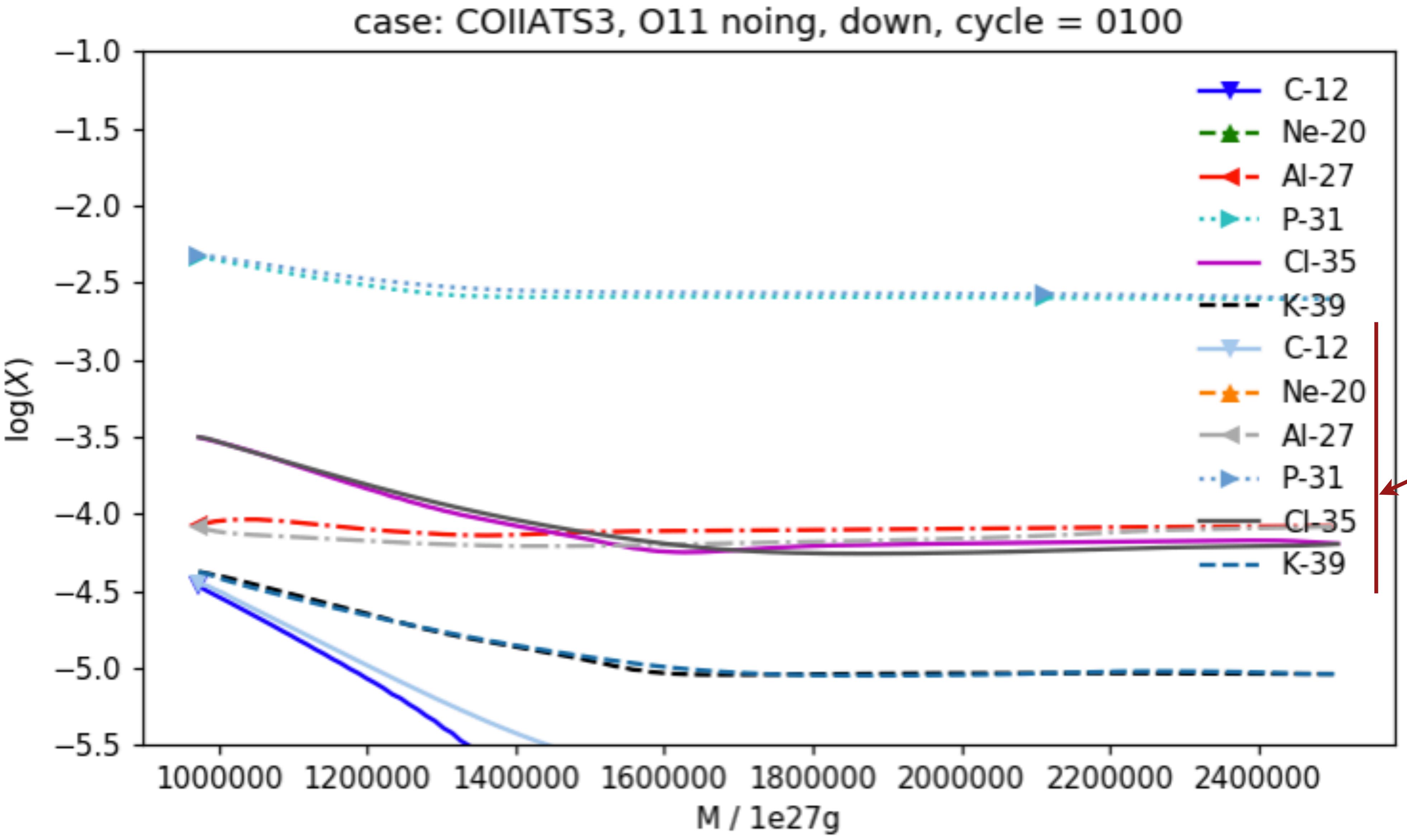


Andrassy+ 19, MNRAS

3D1D ATS post-processing

3D hydro feeds advection fluxes into 1.5D advective two-stream post-processing with complete network

O-shell without C-shell material ingestion

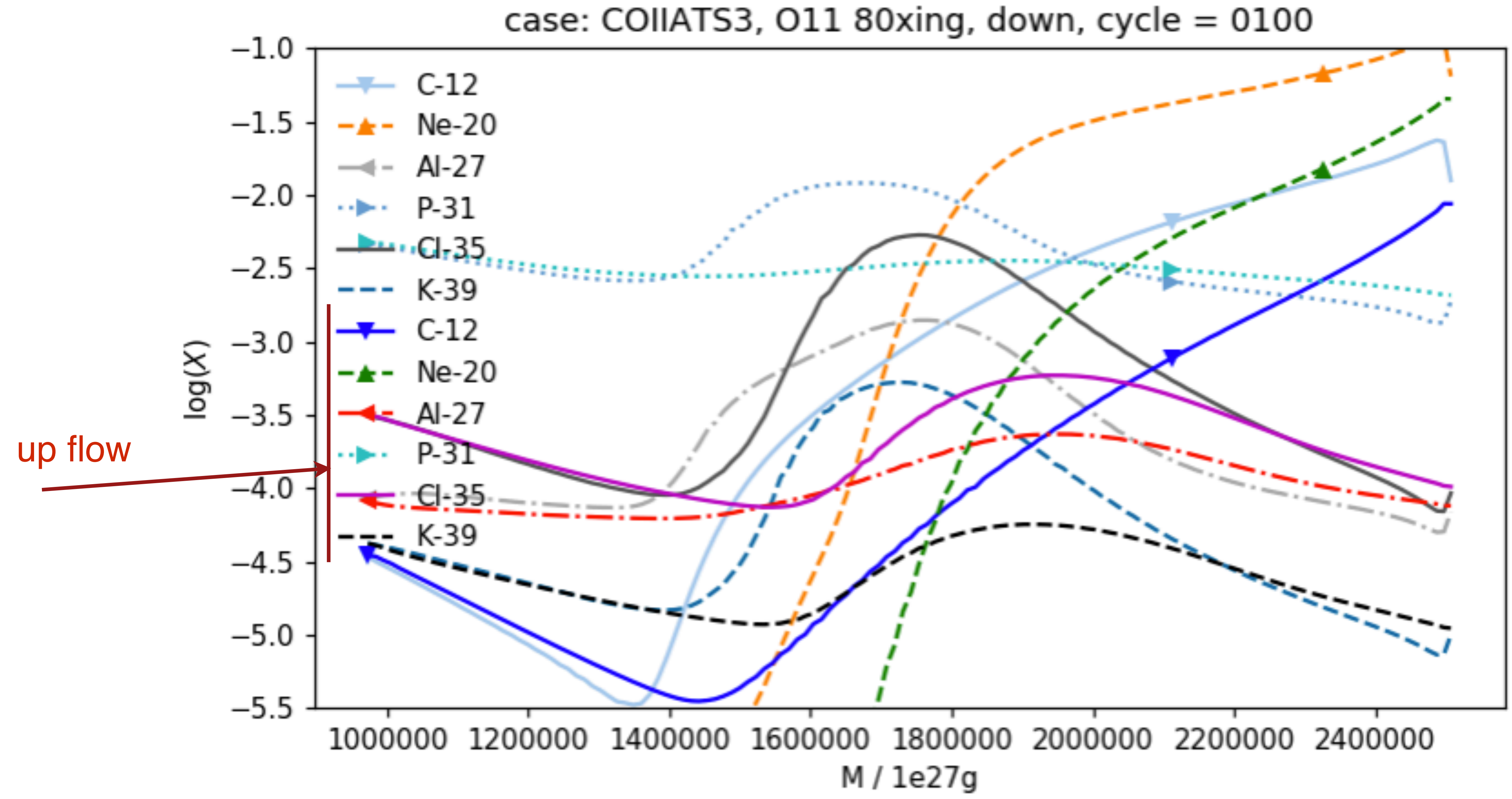


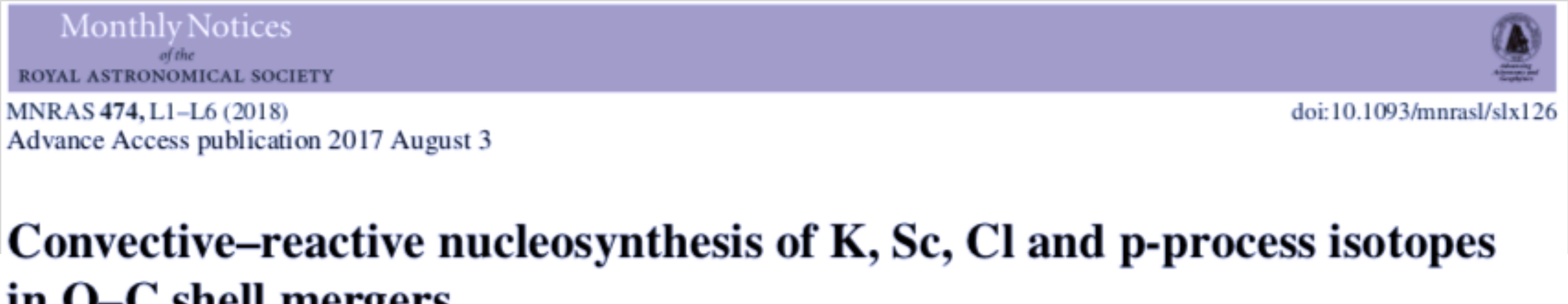
up flow

3D1D ATS post-processing

3D hydro feeds advection fluxes into 1.5D advective two-stream post-processing with complete network

O-shell with C-shell material ingestion





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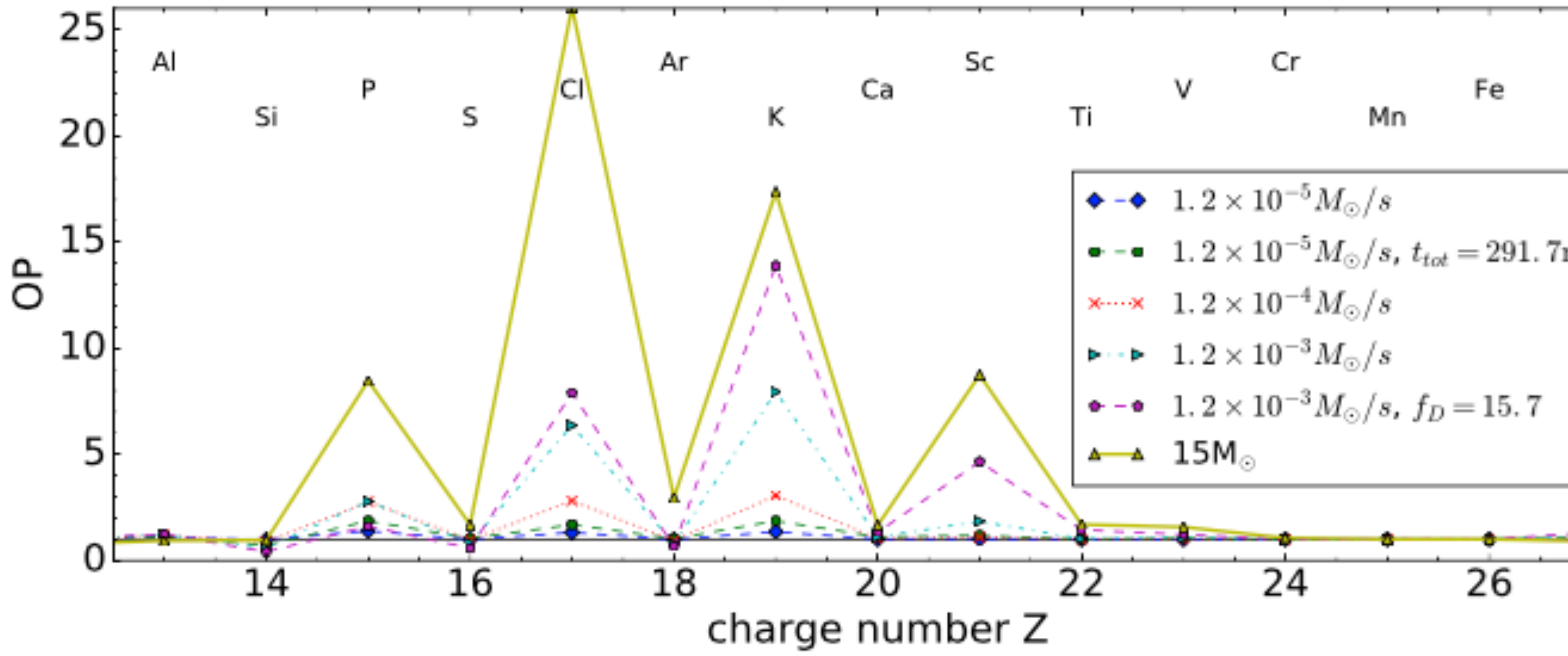
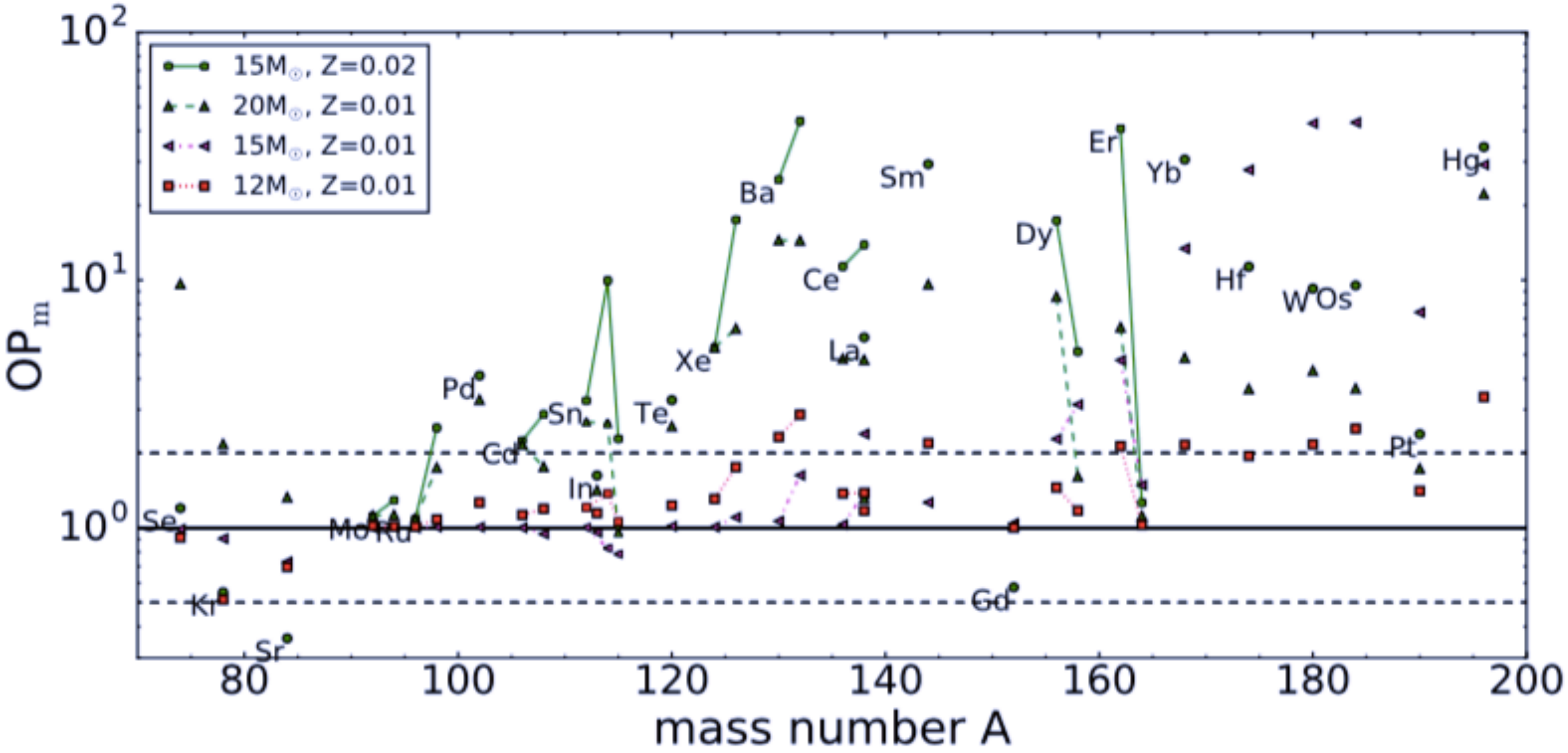
Convective–reactive nucleosynthesis of K, Sc, Cl and p-process isotopes in O–C shell mergers

C. Ritter,[1,2,3]★ R. Andrassy,[1,2]
M. Pignatari[3,6] and S. Jones[3,7]

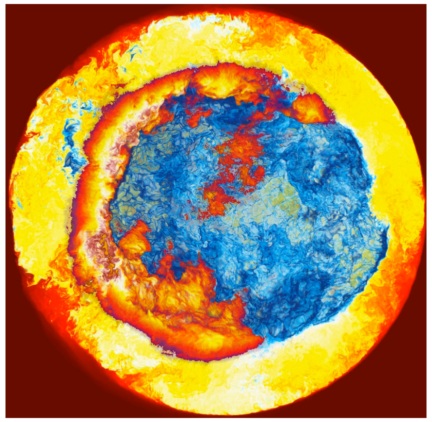


heavier odd-Z elements benefit more from faster mixing, (p,g)-(g,p)



p process benefits from C ingestion in O-C shell merger by adding fresh seed material

Convective-reactive nucleosynthesis



In common: production of odd-Z elements

Family of nucleosynthetic sites in which nucleosynthesis is coupled with mixing.

- Hot-bottom burning in massive AGB stars: N, Li
- H-ingestion in He-shell flashes RAWDs, Sakurai's object, low-Z AGB: Li, i process
- O-C shell mergers in massive stars: P, Cl, K, Sc
- H-He shell mergers in Pop III massive stars: Na, Al, Ca
- slow mixing and burning in post-He+CO WD merger pre-RCB: F, s-process

Involves many unstable species near valley of stability.

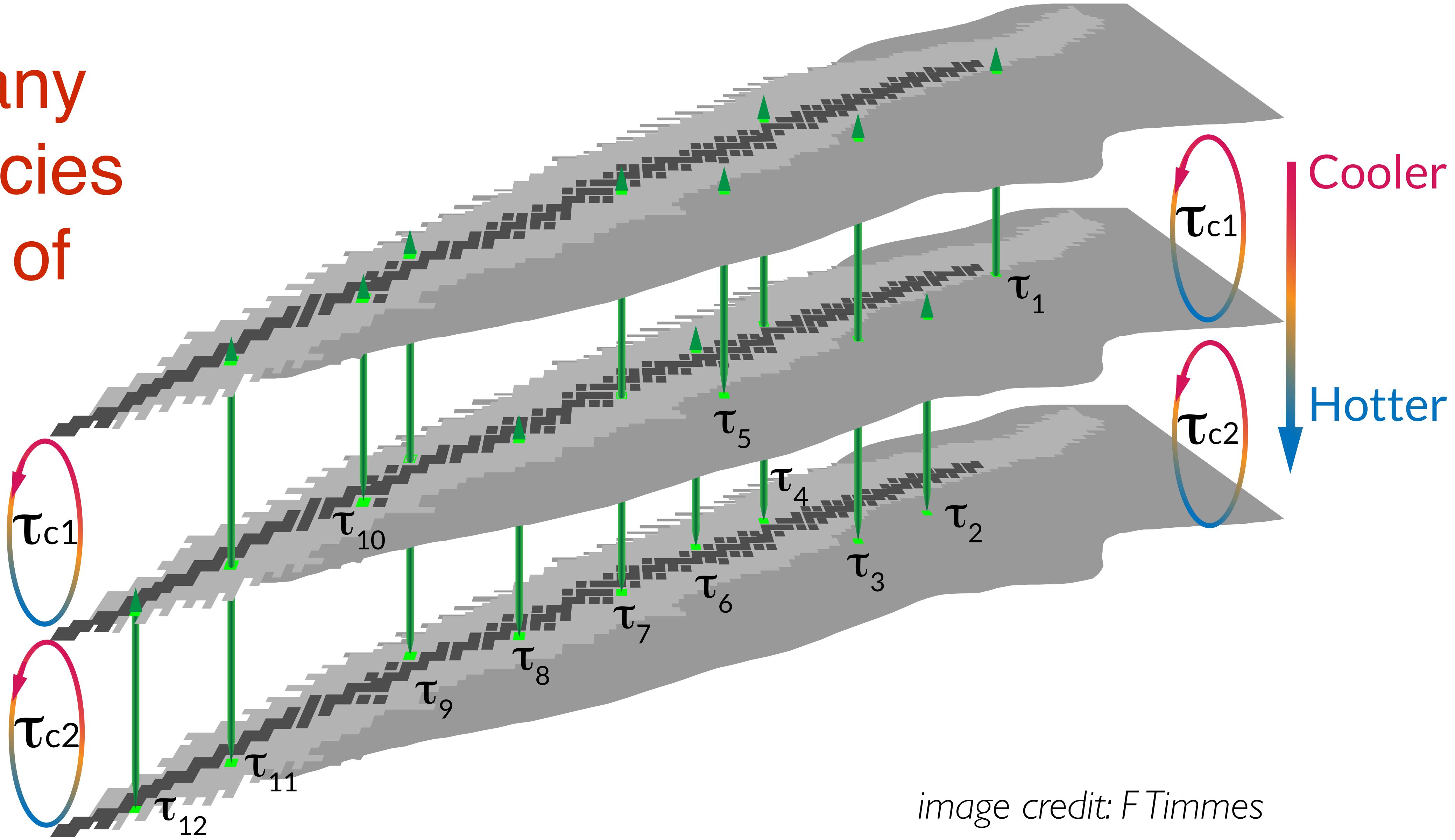


image credit: F Timmes

Summary

- Convective-reactive nucleosynthesis takes place when dynamic convective mixing processes interact with nuclear reactions on the same time scale and both processes are equally important in the particular situation
    - ➡ Simulations need to take into account mixing (best in 3D) and nucleosynthesis simultaneously
    - ➡ Nuclear reaction data away from stability is needed → radioactive beam facilities
- Key examples
    - ➡ i process: neutron-capture with neutron densities intermediate between s and r process, can uniquely explain a variety of observations, such as the CEMP-r/s stars
    - ➡ Mergers of convective O and C shell in massive stars: intermediate-mass odd-Z elements and p process

Convective-reactive nucleosynthesis

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

- Hot-bottom burning in massive AGB stars: N, Li
  - Ritter C, Herwig F, et al. 2018. *MNRAS*. 480(1):538–71
- 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