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Between the s and r Process: Nuclear Data Needs of Radioactive Species to Understand Stellar Abundances from the Early Universe

Falk Herwig, Pavel Denissenkov
Dept Physic & Astronomy
University of Victoria

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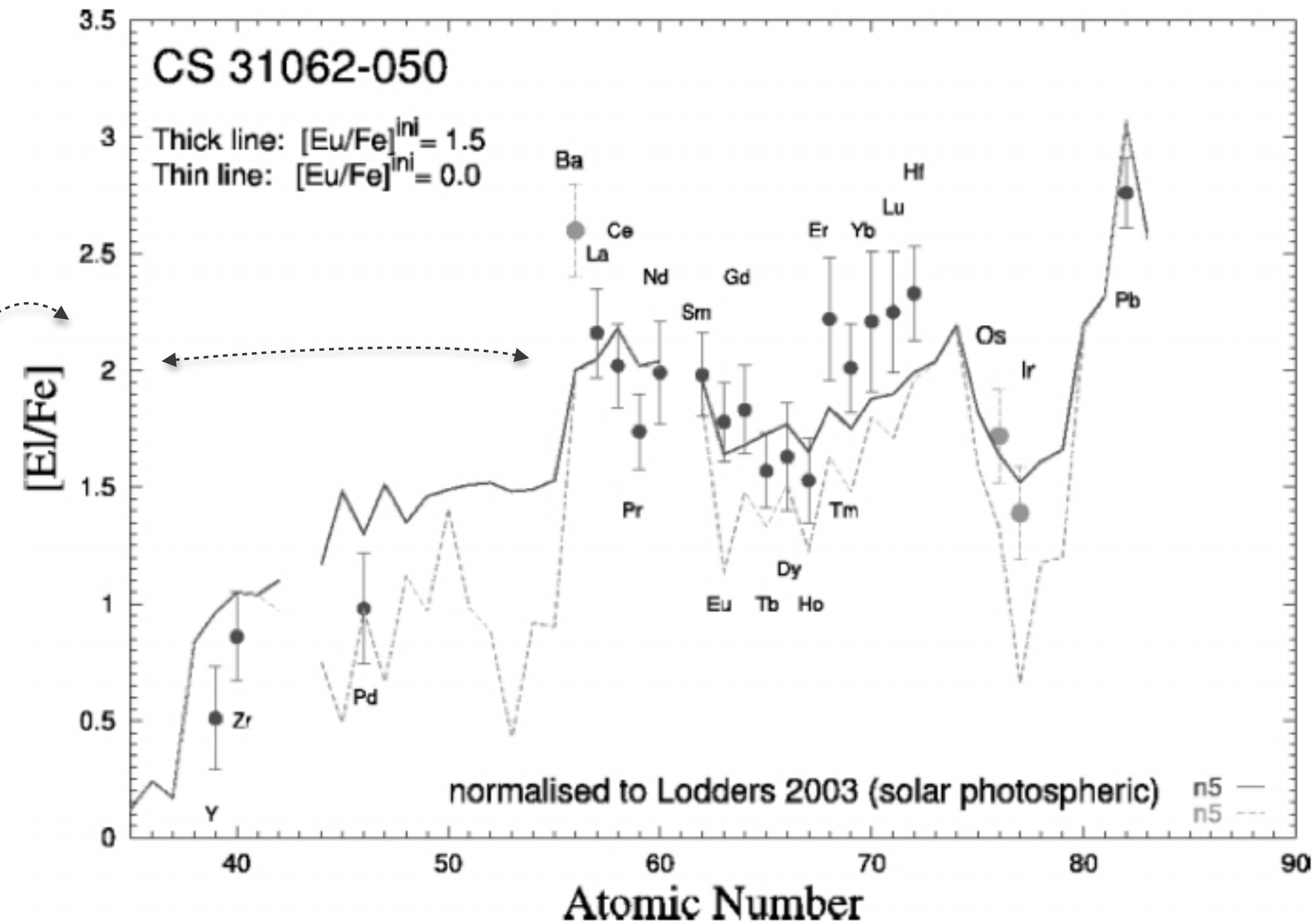
C-enhanced Metal-poor Stars: Messengers from the Early Universe

- CEMP-r/s stars have both Ba and Eu (Beers & Christlieb 05 ARAA)
- previously best model assumes superposition of "known" r- and s-process sources
- requires a cloud pre-enriched with r-process material where then an AGB-star binary forms and mass-transfers s-process to a companion
- Quite unlikely, and the resulting match is not very good

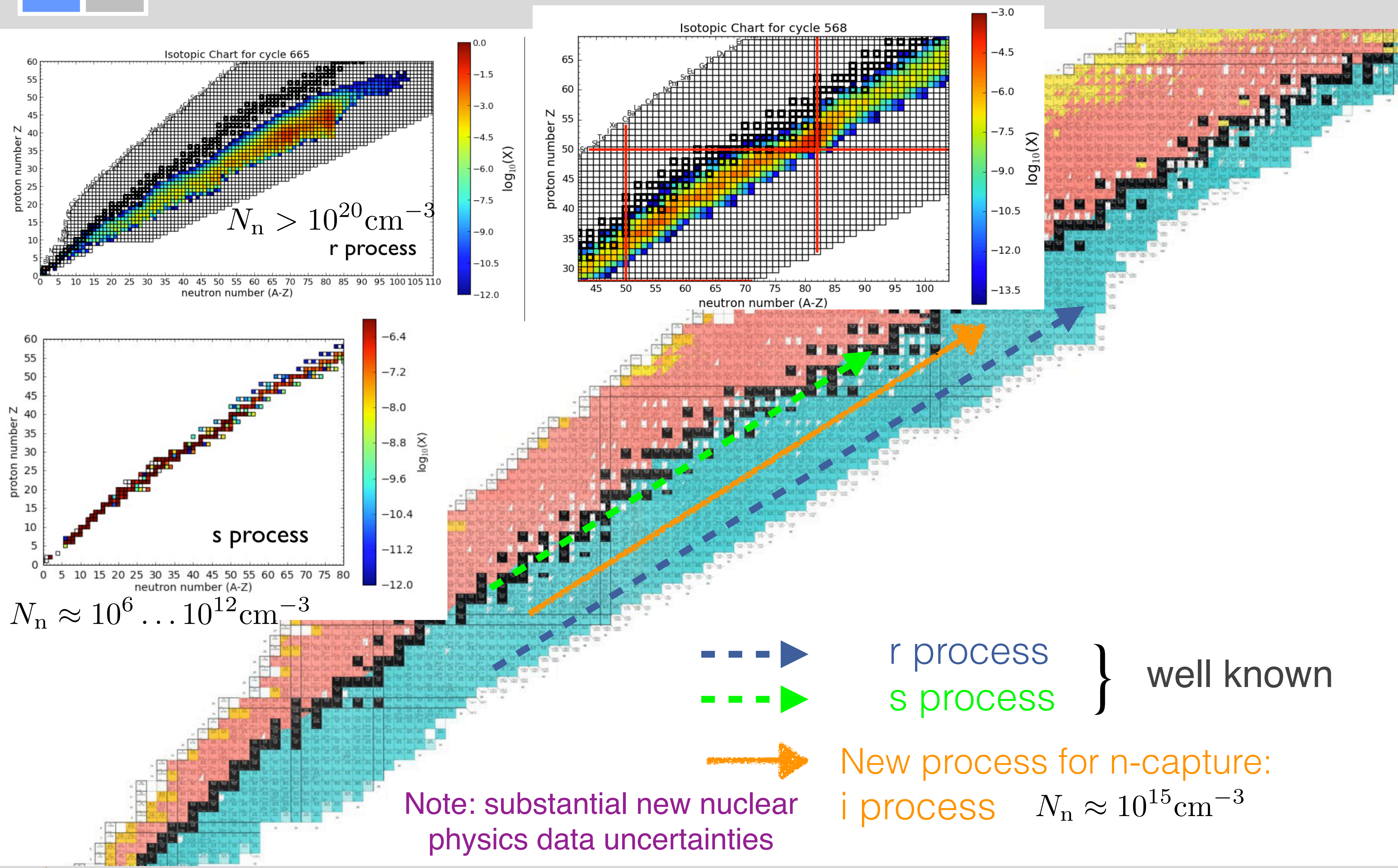


Note that the heavy elements are enhanced by 2 to 2.5 dex compared to solar. This means ~300 time the amount of Ba wrt Fe compared to that ratio in the sun. That is huge!

Is there a more plausible explanation?

Bisterzo+ 12 observations Aoki+ 02 & Johnson & Bolte 04

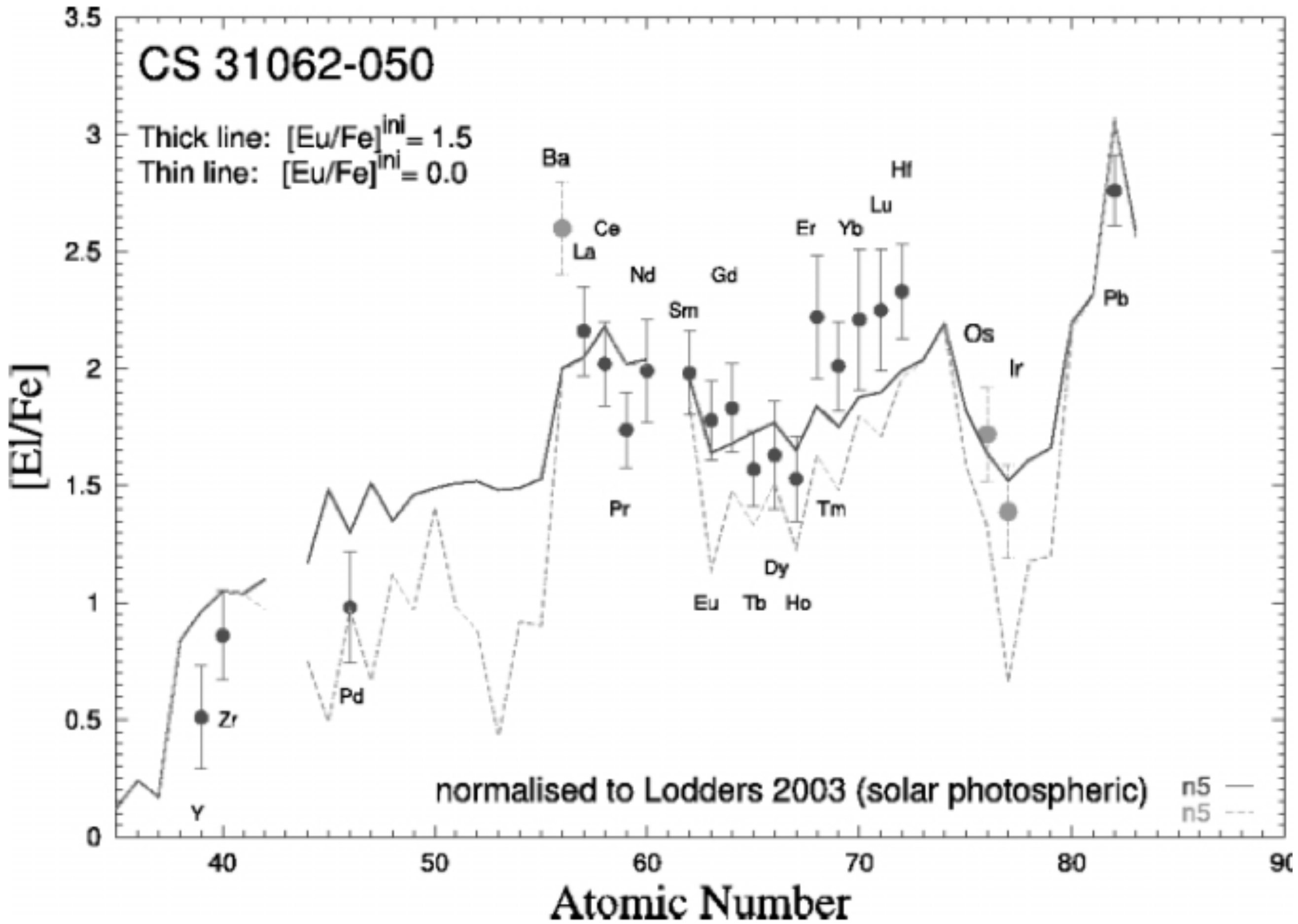
Neutron-capture: slow, rapid and intermediate!



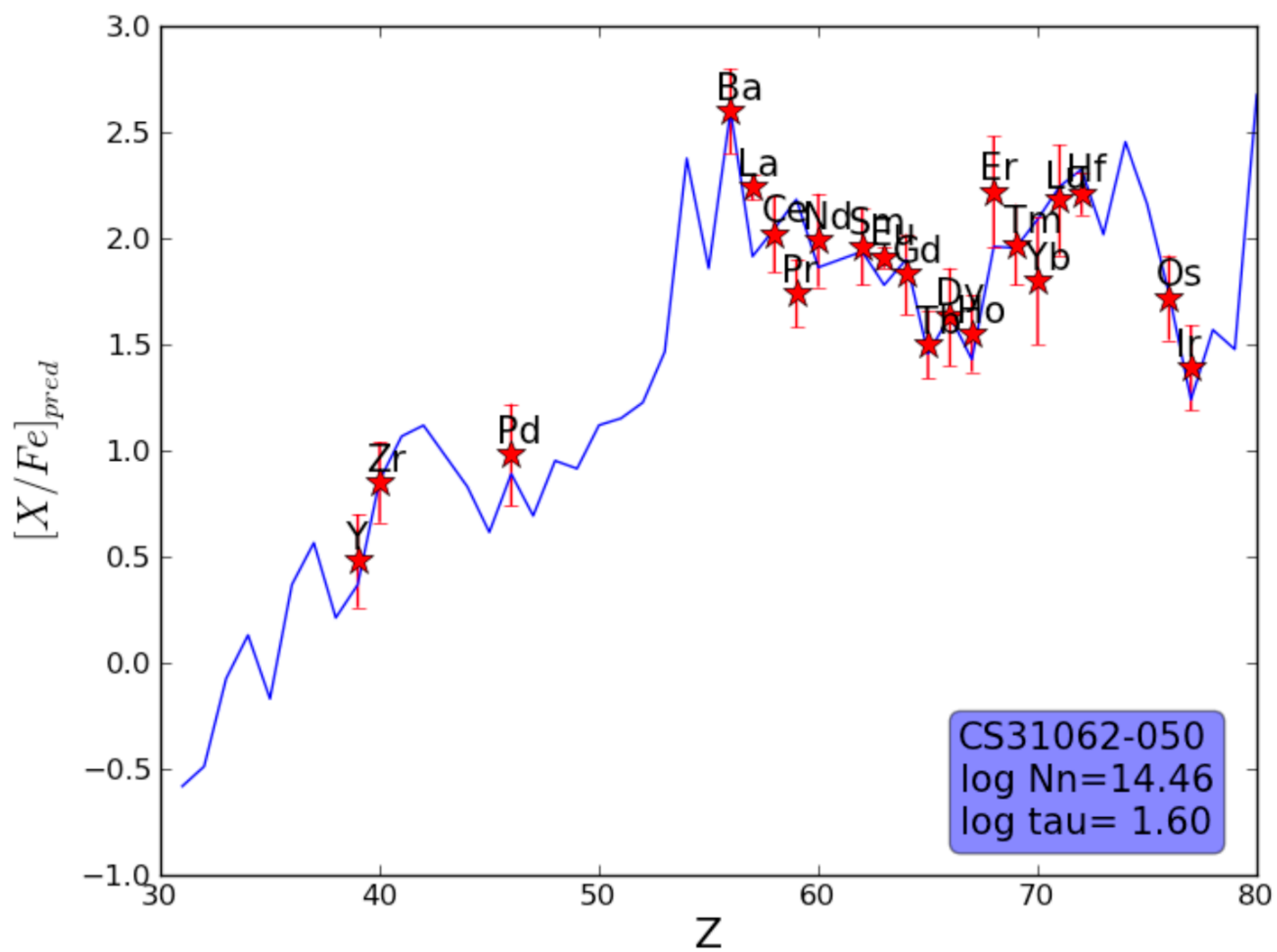
CEMP-i stars

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) based on simplistic one-zone models

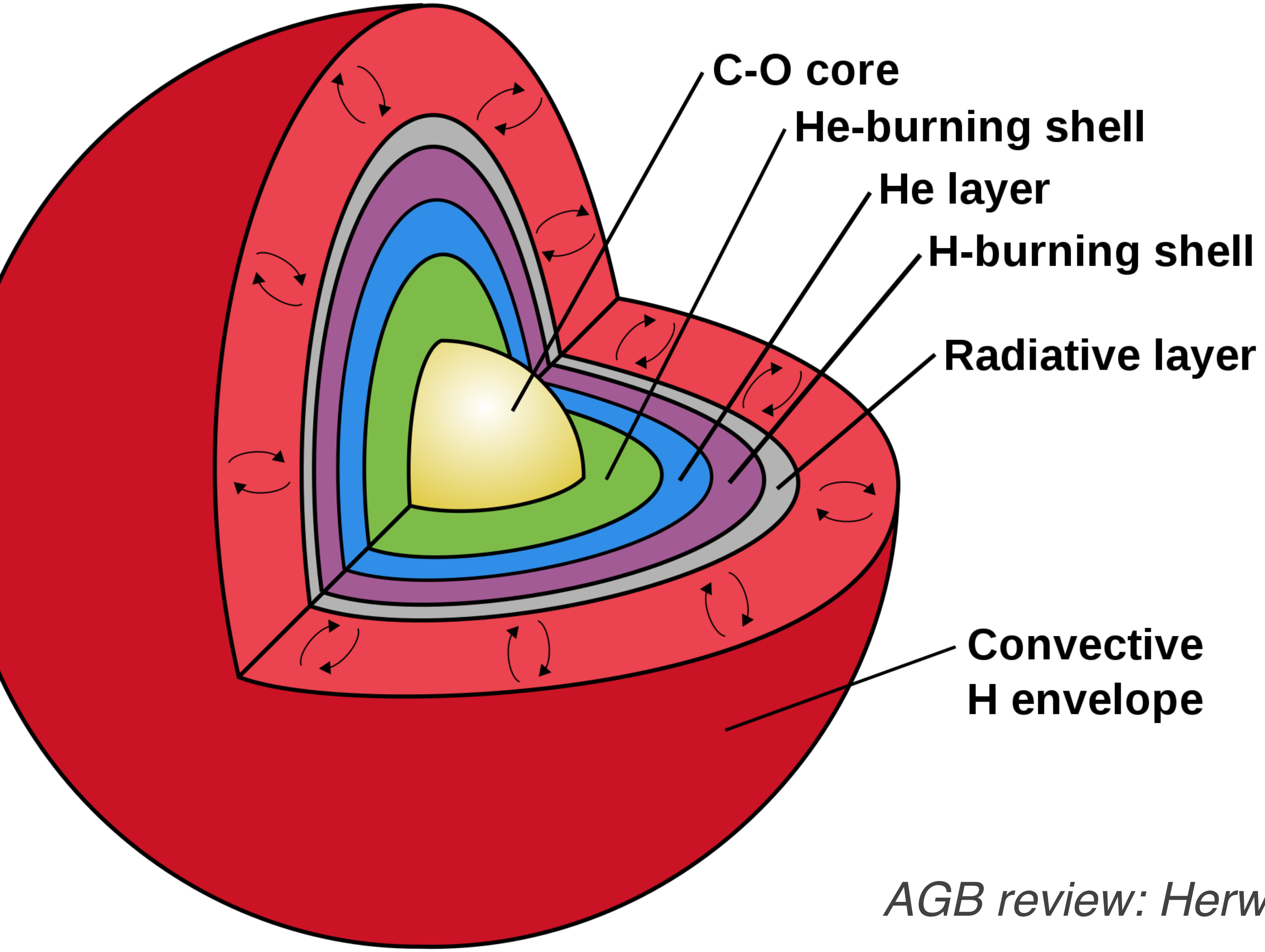


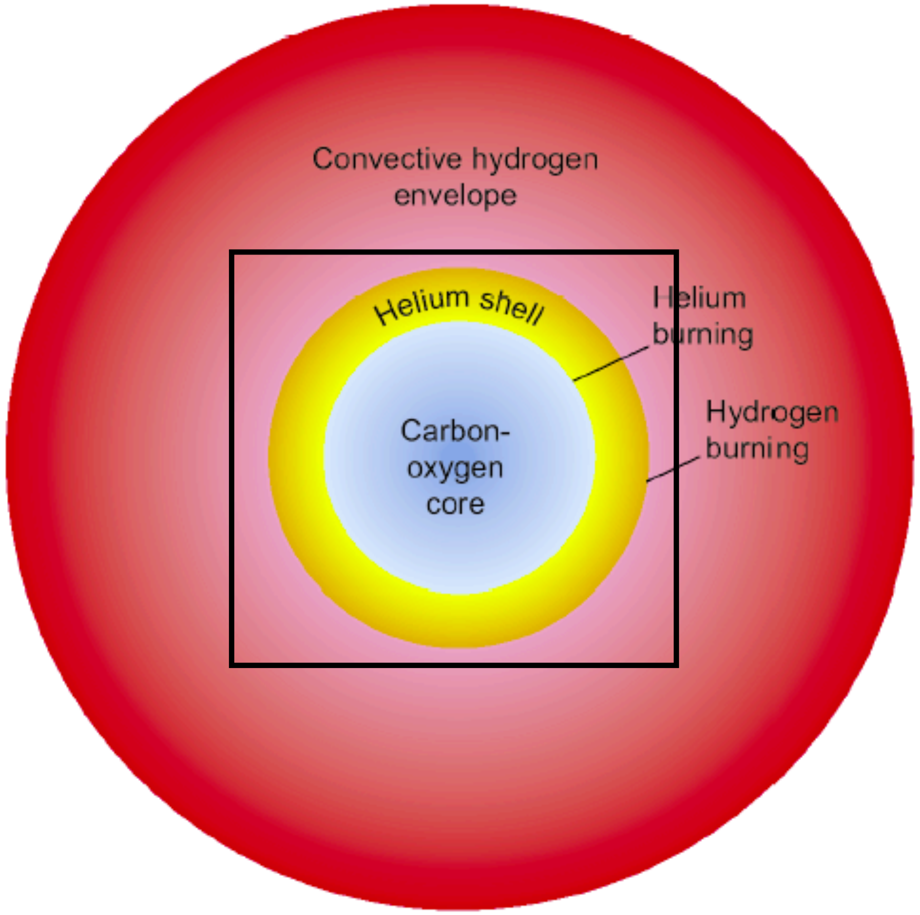
He-shell flash in low-mass stars

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

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

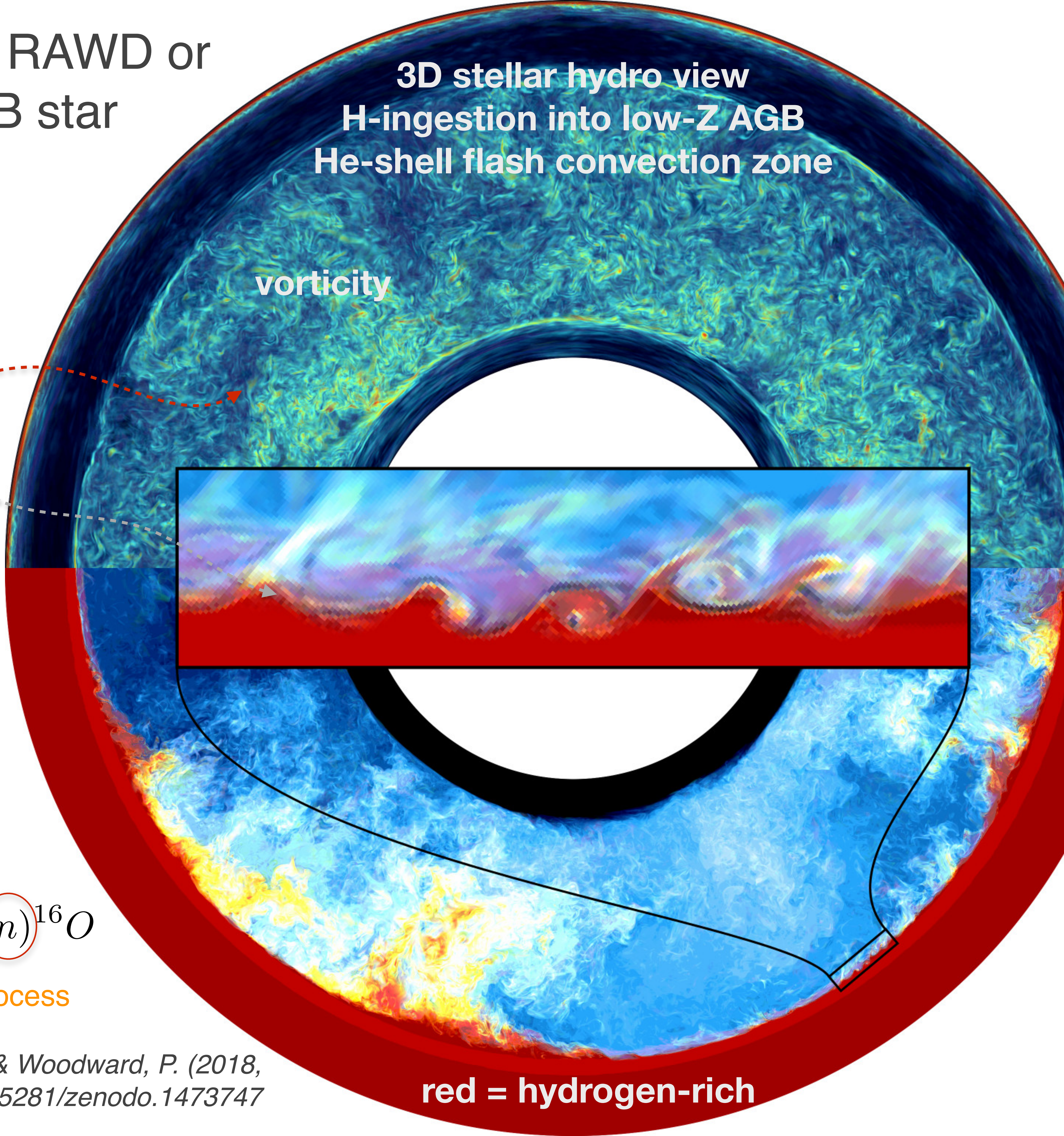
Damköhler number

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

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

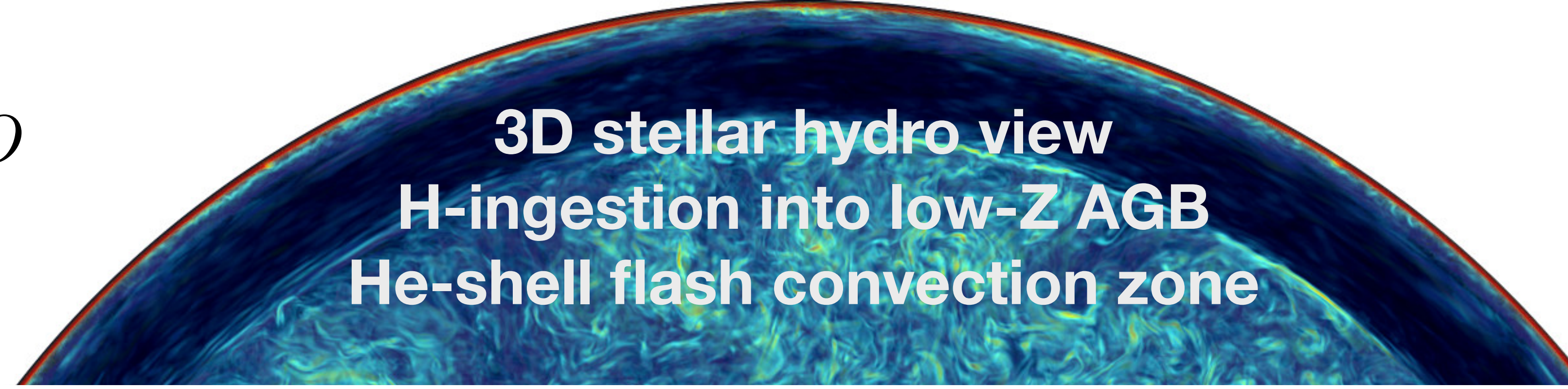
$$^{12}C(p,\gamma)^{13}N(\beta^{+}\nu)^{13}C(\alpha,n)^{16}O$$

Fast neutron source: i process



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

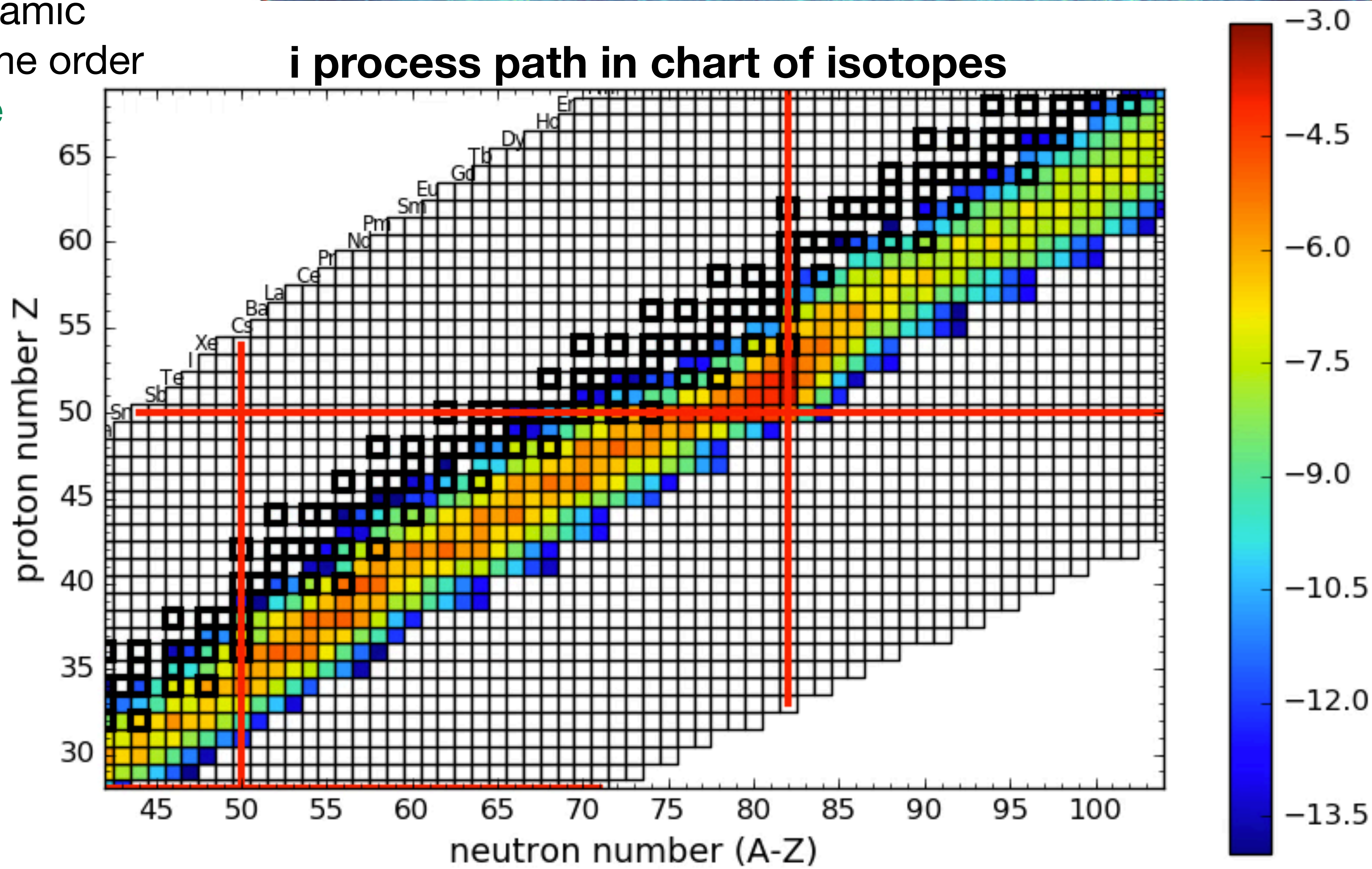
$^{12}C(p,\gamma)^{13}N(\beta^+\nu)^{13}C(\alpha,n)^{16}O$



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

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

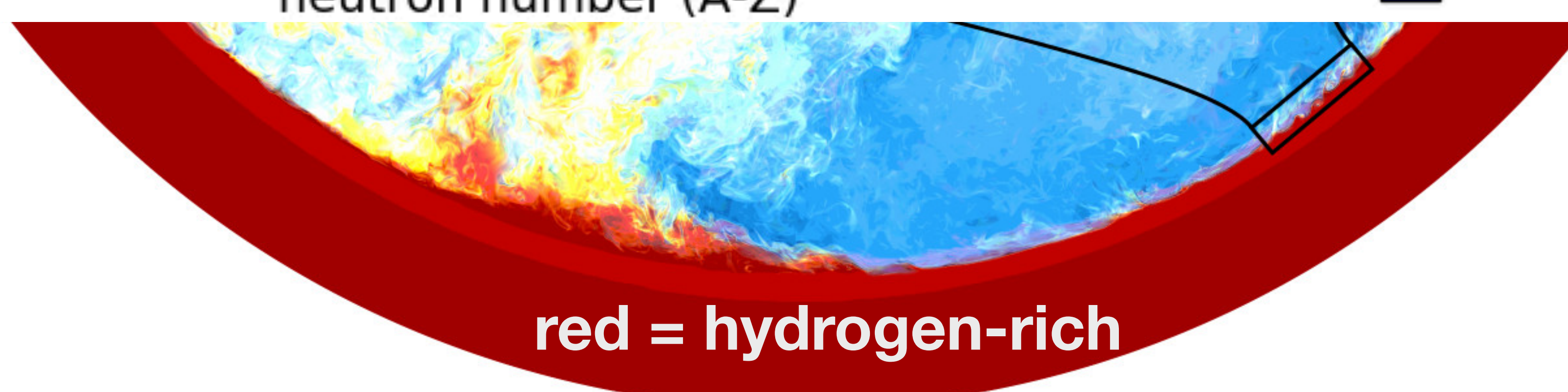
i process path in chart of isotopes



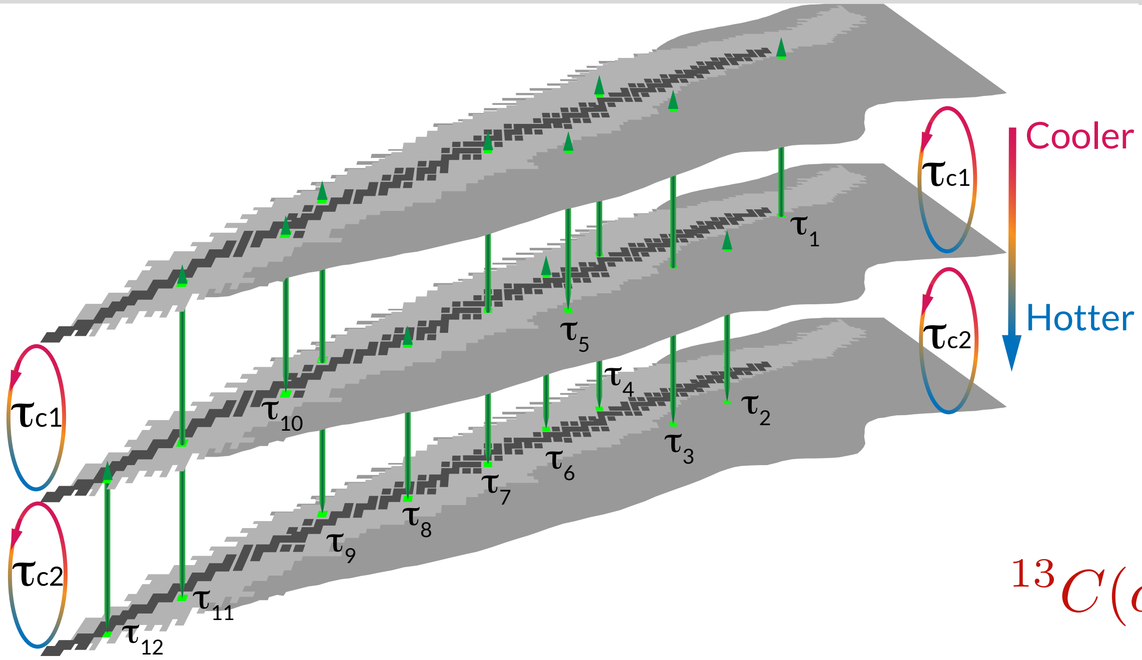
Neutrons released with intermediate neutron density → i process element production.

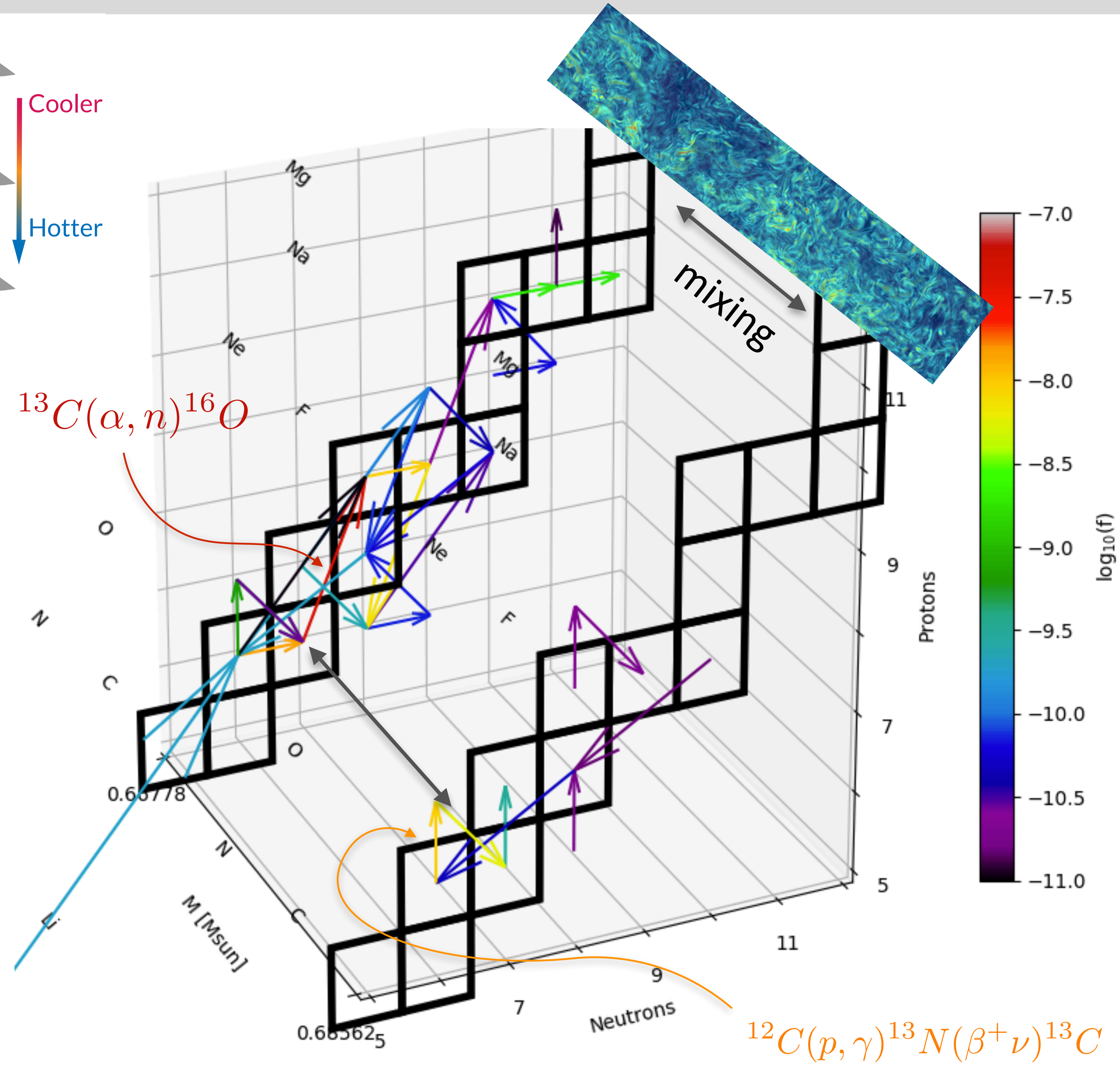
Multi-physics, multi-method approach:

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



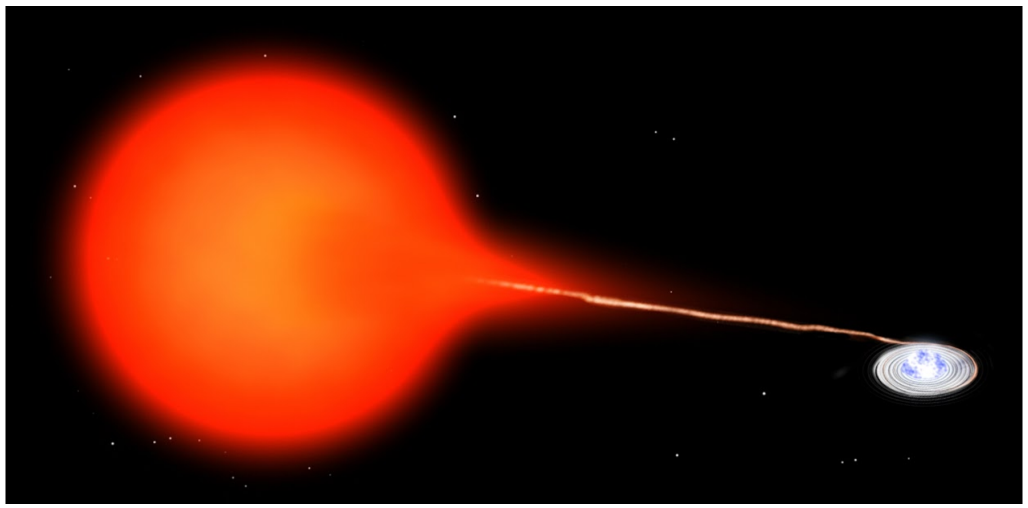
Convective-reactive i-process nucleosynthesis





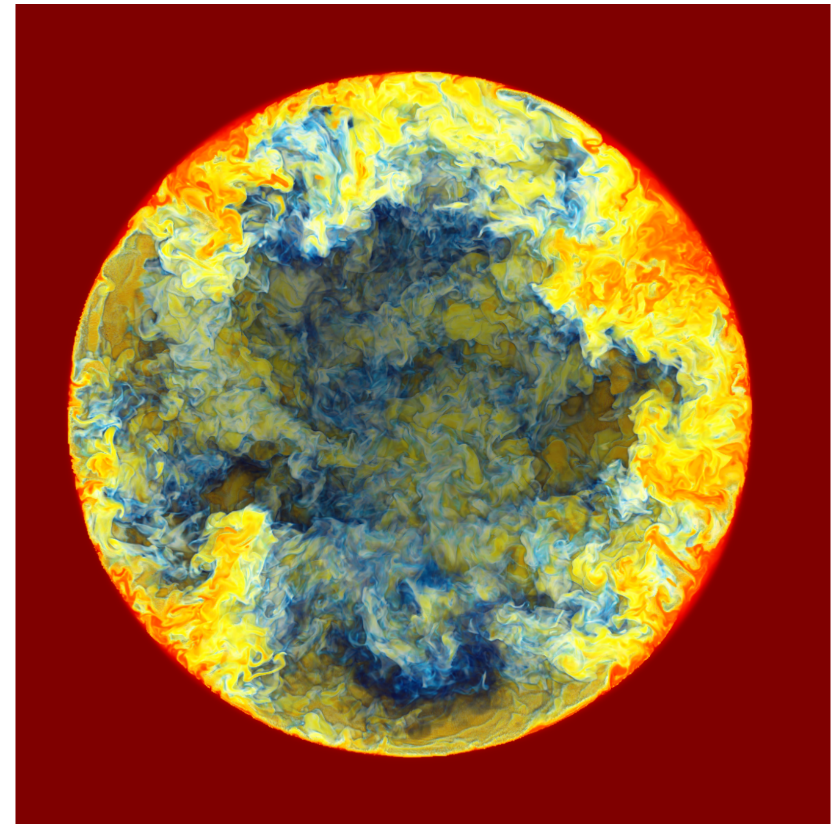
Rapid production of neutrons requires convective mixing connection of two different T regimes for $^{12}C(p,\gamma)$ and $^{13}C(\alpha,n)$ to operate on same time scale

Where does it happen?
One promising option for CEMP-i stars: Rapidly Accreting White Dwarfs



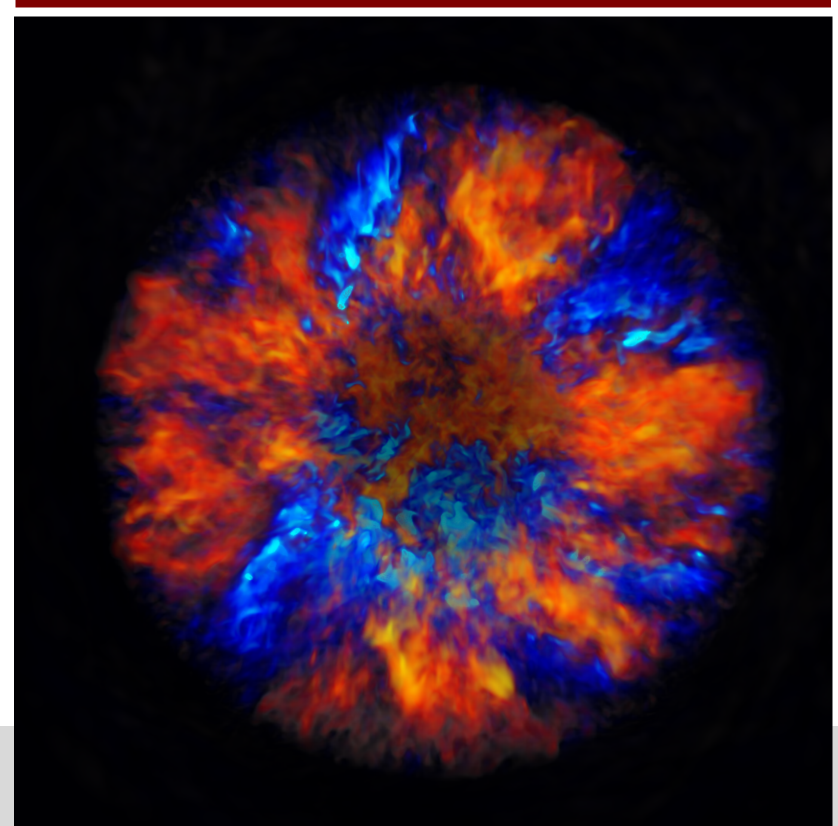
- Artist impression of accreting white dwarf, like novae!
- But unlike nova here accretion rates are high and allow stable H burning!
- However, these accreting WDs then experience He-shell flashes! (Cassisi+ 98)
- In these convective He-shell flashes: H-entrainment, convective reactive i process!

Denissenkov+ 17, ApJ Letters



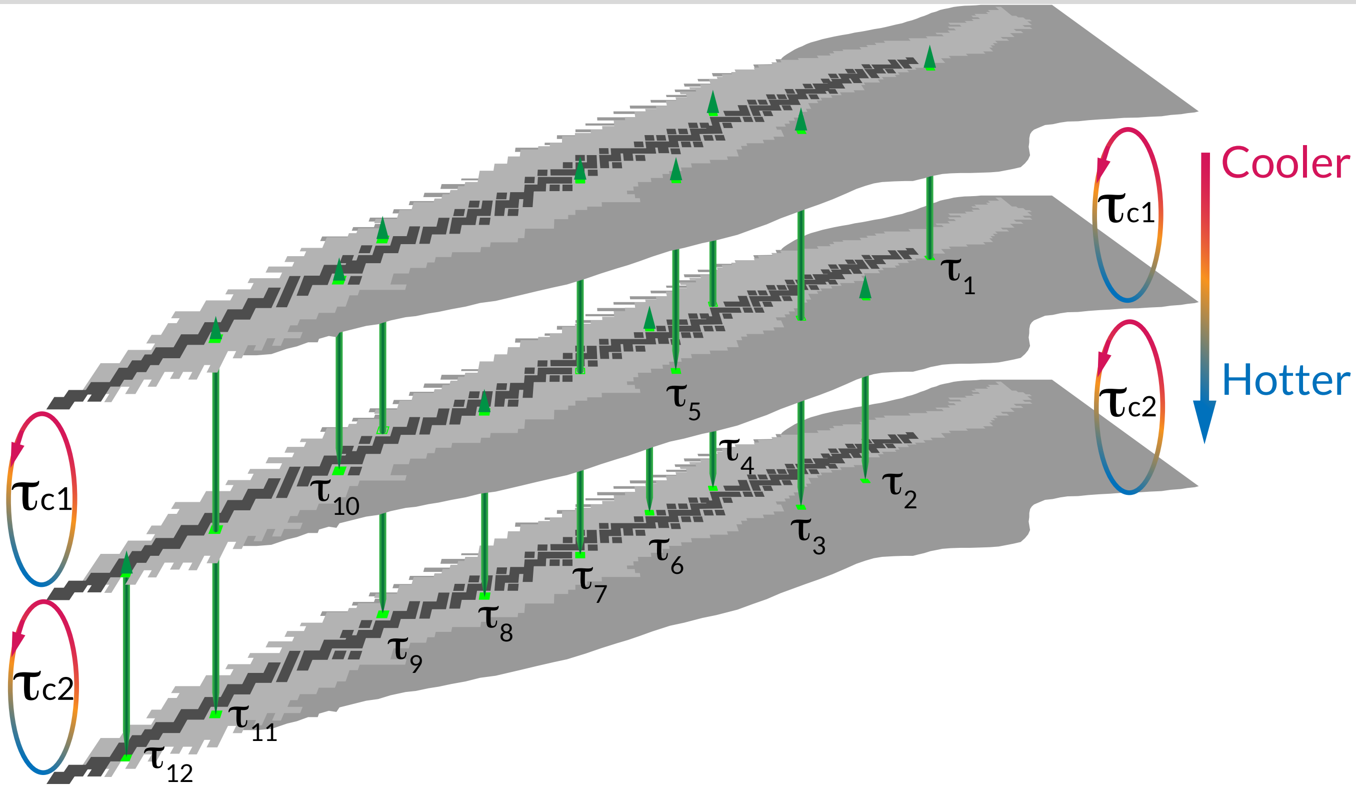
Concentration of entrained material

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



Radial velocity component

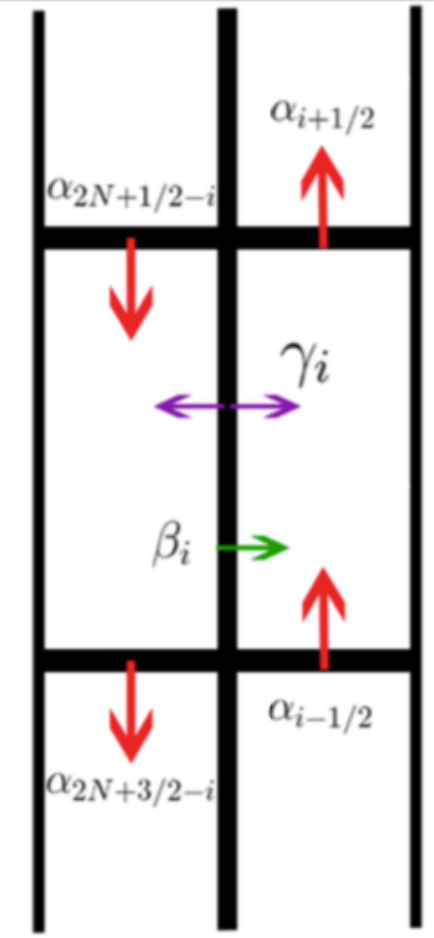
Advective Two-Stream post-processing of 3D Hydro Simulations for Convective-reactive Nucleosynthesis

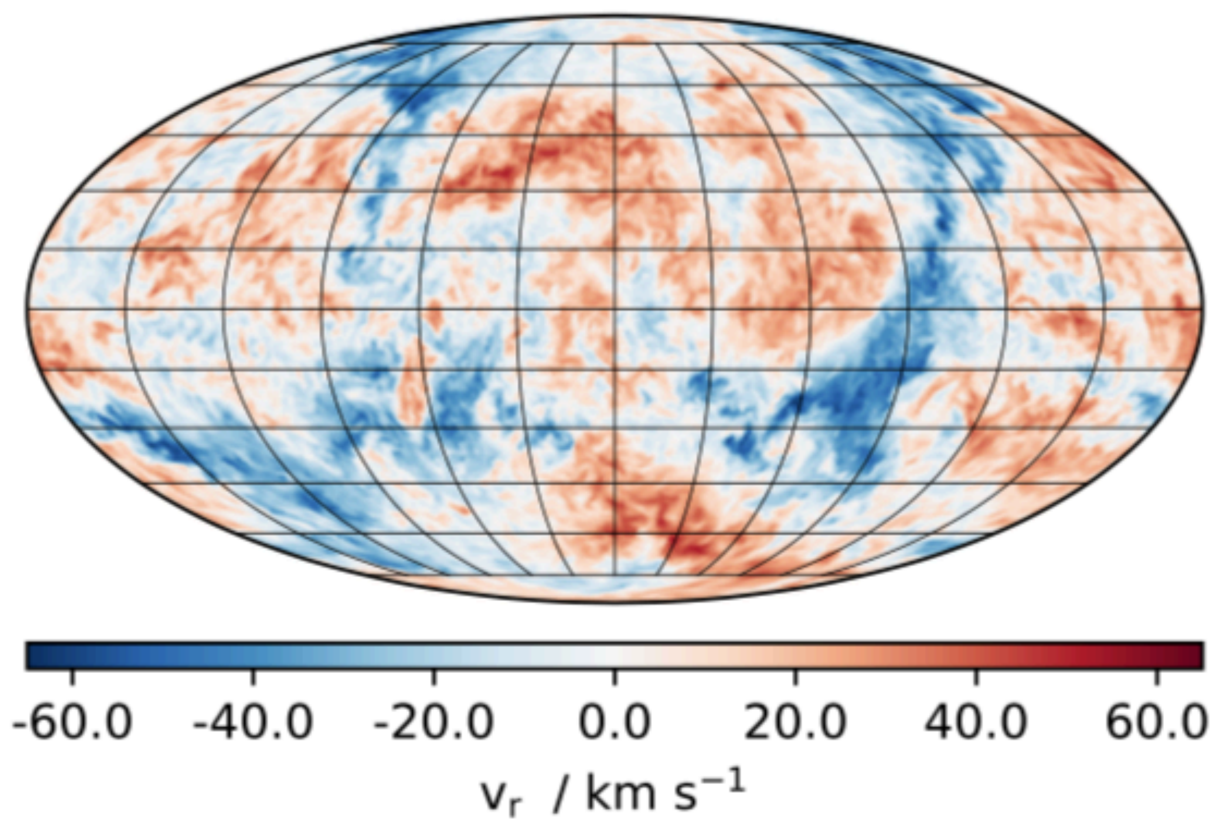


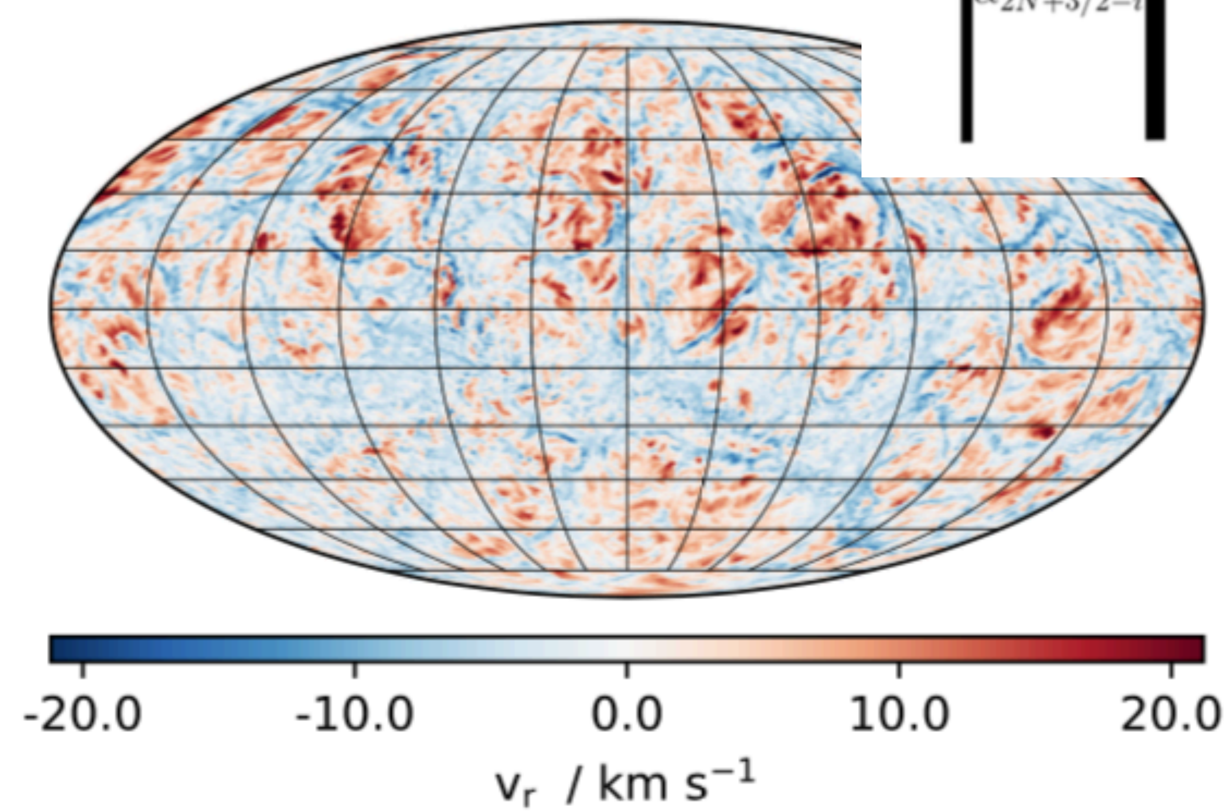
Convective-reactive nucleosynthesis happens by nature on the convective time scale, which is

- 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



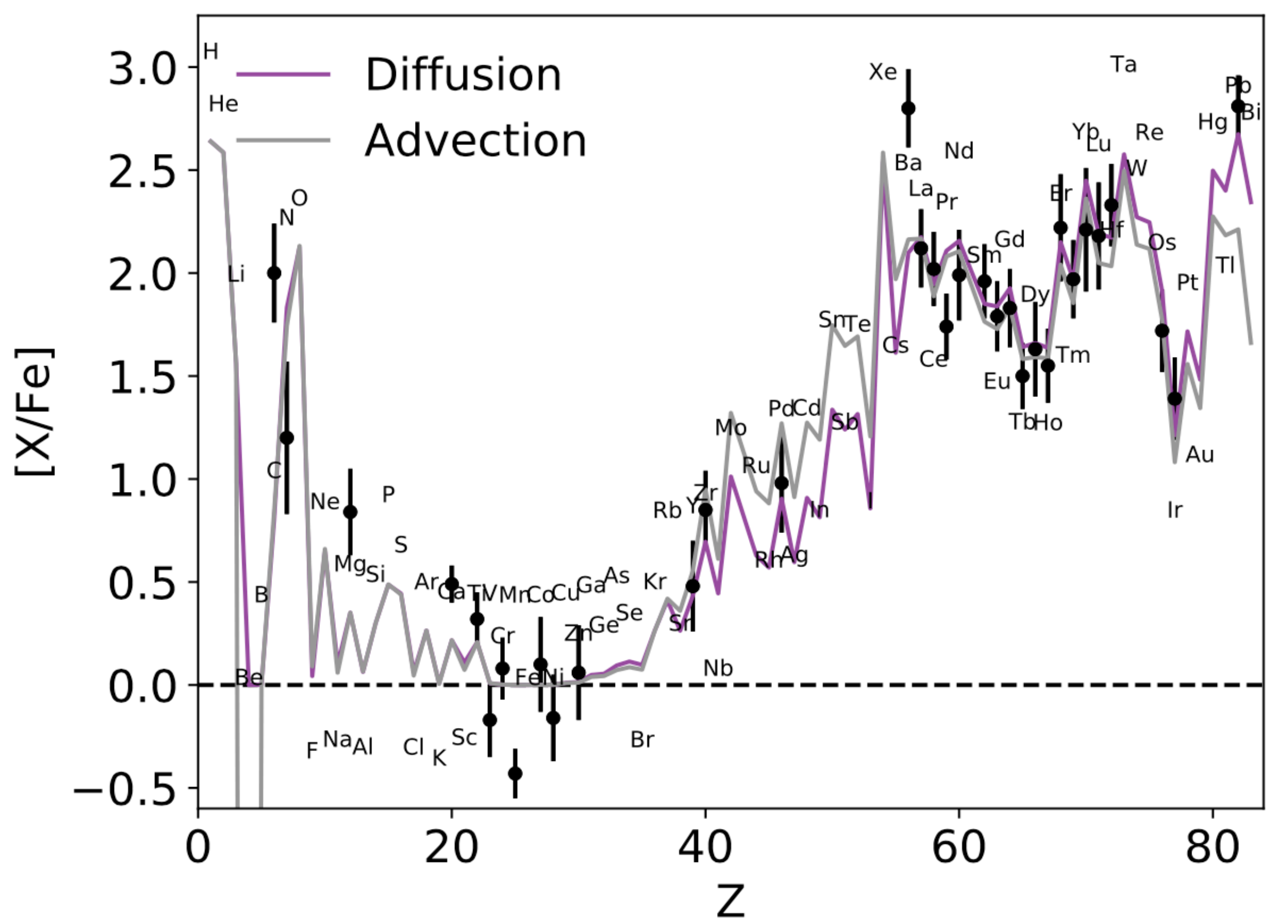




Stephens+ 20, MNRAS

CEMP-i star observations & simulations and nuclear physics uncertainty impact

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



Impact of nuclear physics uncertainties (Denissenkov+ 21)

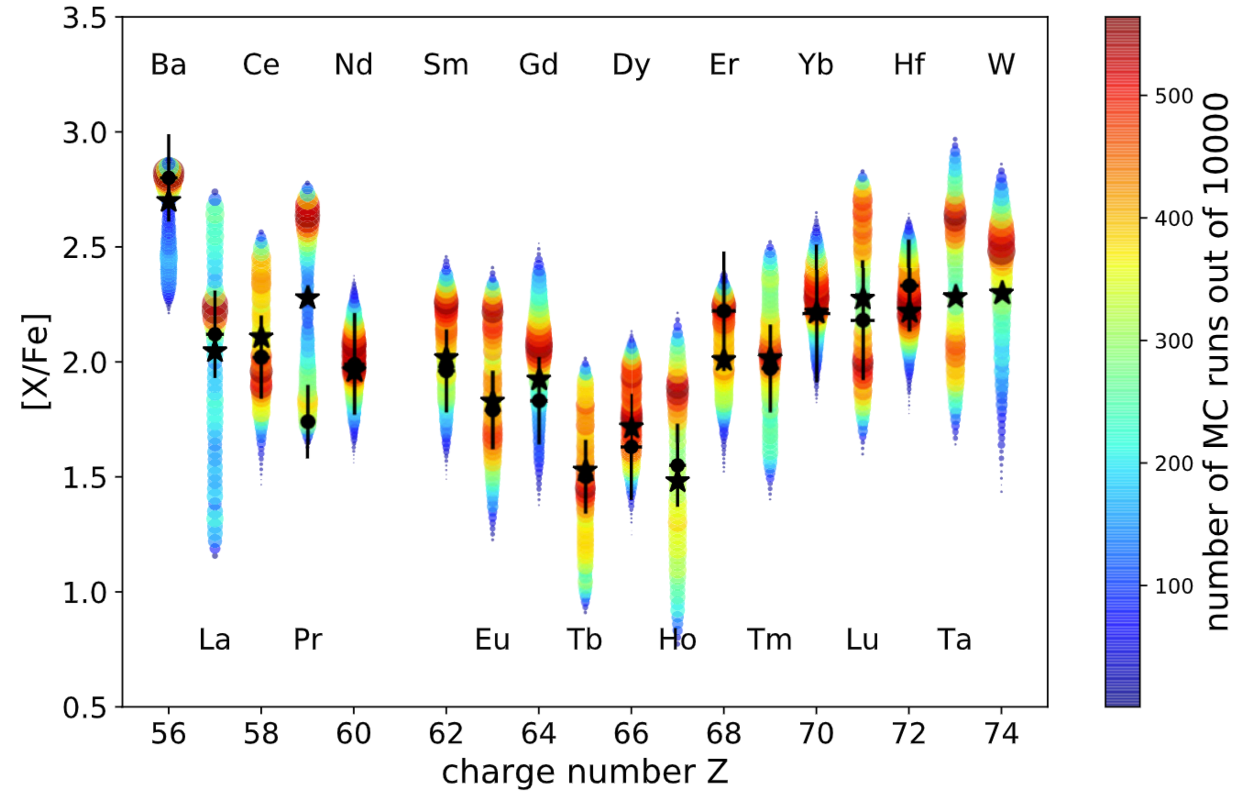
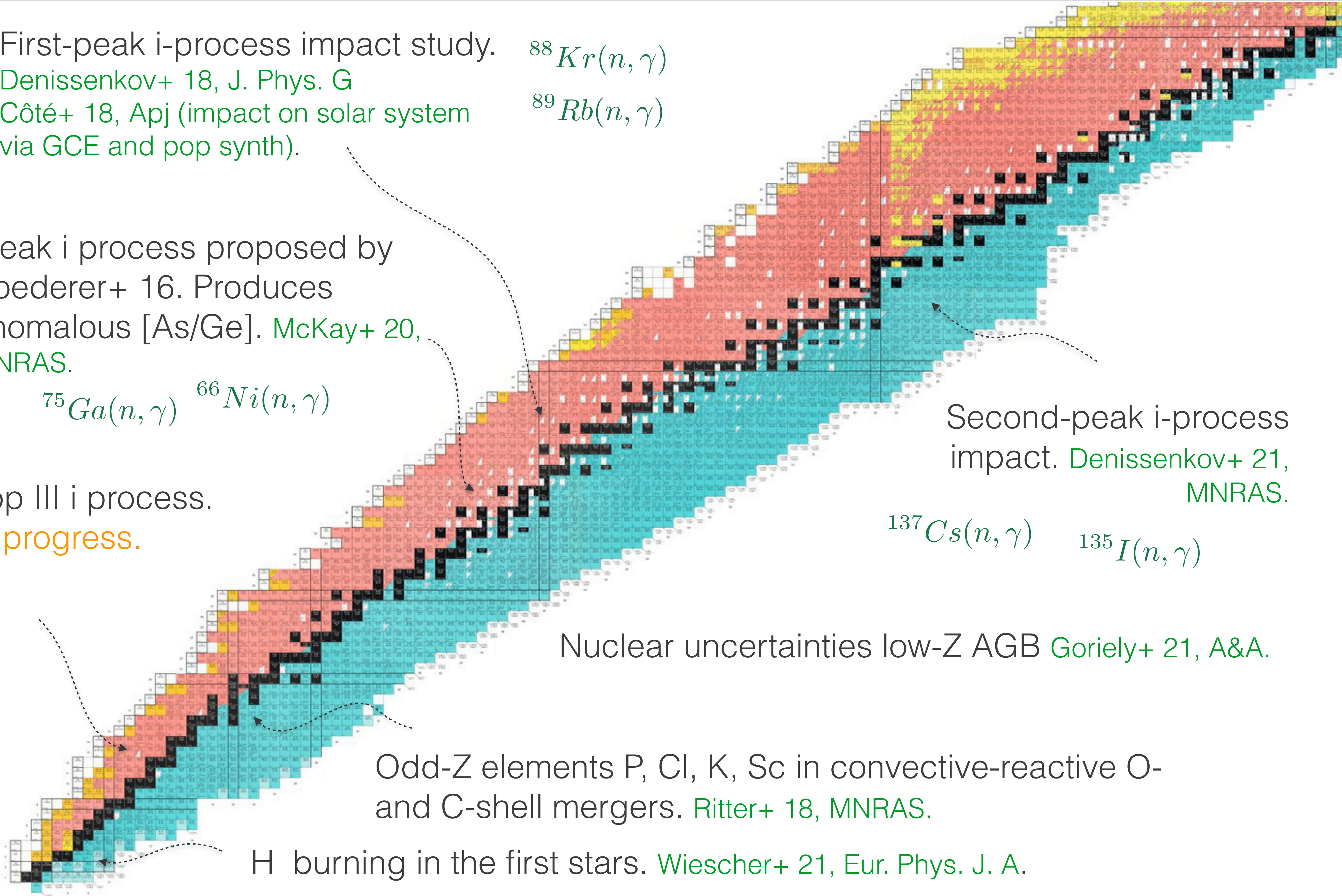


Figure 7. The circle colour- and size-coded distributions of the abundances in the selected element range observed in the CEMP-i star CS 31062−050 (black circles with error bars) predicted in the MC simulation based on the one-zone benchmark model with the constant $N_\mathrm{n} = 3.16 \times 10^{14}\ \mathrm{cm}^{-3}$. Only (n,$\gamma$) rates of the 164 unstable isotopes from Fig. 6 have been varied. Black star symbols represent the abundances from the benchmark model.

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

Denissenkov, P. A., Herwig, F., Perdikakis, G. & Schatz, H. *The impact of (n,γ) reaction rate uncertainties of unstable isotopes on the i-process nucleosynthesis of the elements from Ba to W*. MNRAS **503**, 3913–3925 (2021).

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, A&A.

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.

CaNPAN

Canadian Nuclear Physics for Astrophysics Network

- A new network involving McMaster, Saint Mary’s, TRIUMF, UBC, UVic, Guelph
- Bring nuclear astrophysics modelling and nuclear physics experiments together through research and training involving graduate students https://www.canpan.ca
- Member of the International Research Network for Nuclear Astrophysics IReNA (https://www.irenaweb.org)

Summary

- C-enhanced metal-poor (CEMP) stars - messengers from the early Universe that have an anomalous signature of heavy element abundances
- Intermediate neutron-capture process (i process): a **convective-reactive nucleosynthesis** process that can explain the anomalous CEMP(-r/s) star abundances
- **New nuclear data** needed from radioactive-beam facilities
- New Canadian network launched in 2021 **CaNPAN** Canadian Nuclear Physics for Astrophysics Network canpan.ca