A classification of CEMP stars based on neutron density that reveals the important role of the i process and the need for better nuclear physics data

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JINA-CEE
NSF Physics Frontier Center

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University of Victoria

Outline

- C-enhanced metal poor stars: Classification with constant neutron-density models (nuclear physics only!) → the need for the i process
- Rapidly accreting white dwarfs as a likely site for the i process
- Nuclear physics impact studies

C-enhanced metal-poor stars

Classification of CEMP stars

TABLE 2 Definition of subclasses of metal-poor stars

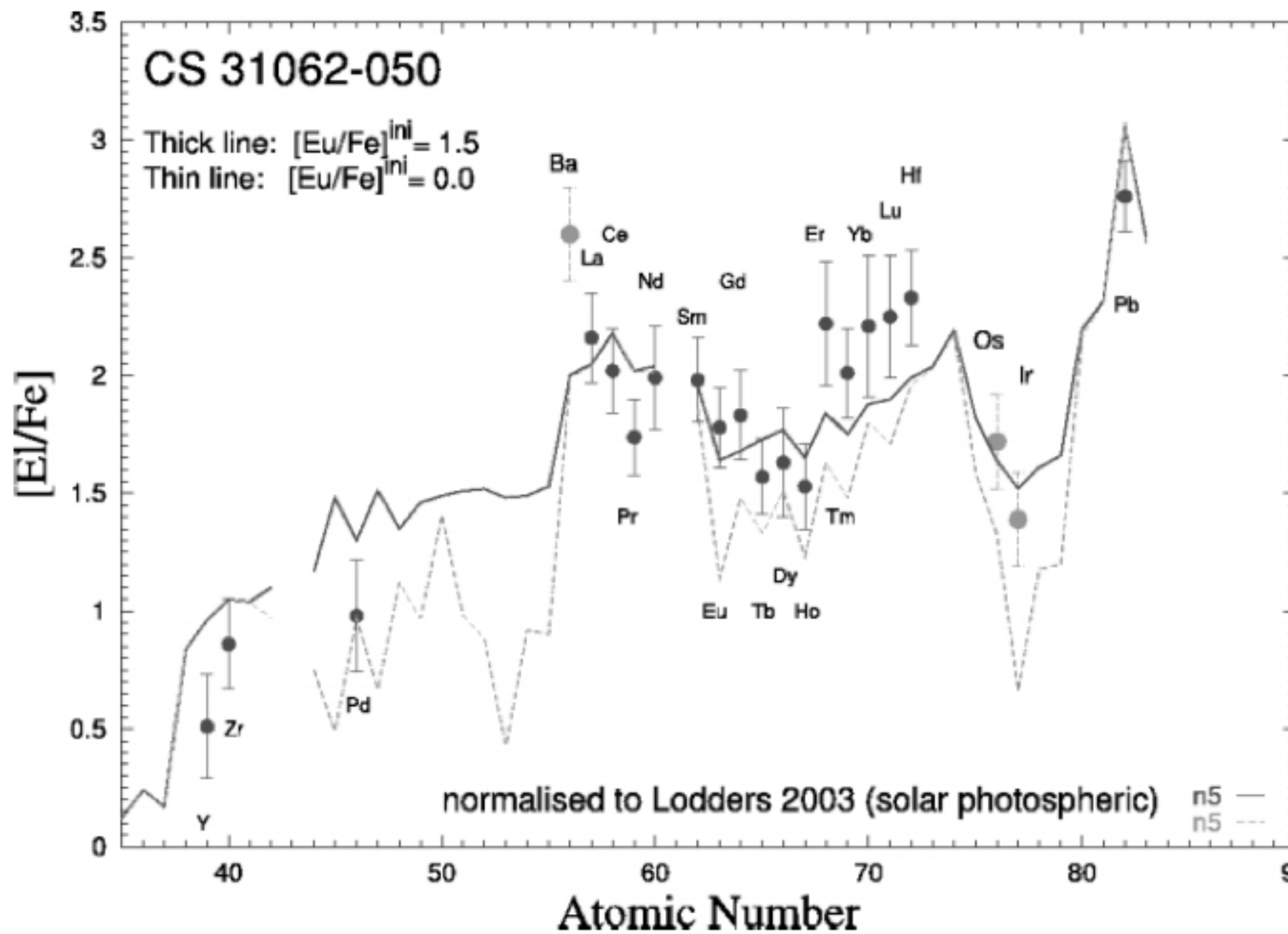
Neutron-capture-rich stars	
r-I	$0.3 \leq [Eu/Fe] \leq +1.0$ and $[Ba/Eu] < 0$
r-II	$[Eu/Fe] > +1.0$ and $[Ba/Eu] < 0$
s	$[Ba/Fe] > +1.0$ and $[Ba/Eu] > +0.5$
r/s	$0.0 < [Ba/Eu] < +0.5$
Carbon-enhanced metal-poor stars	
CEMP	$[C/Fe] > +1.0$
CEMP-r	$[C/Fe] > +1.0$ and $[Eu/Fe] > +1.0$
CEMP-s	$[C/Fe] > +1.0$, $[Ba/Fe] > +1.0$, 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 $[Ba/Fe] < 0$

- Classification-scheme based on Ba and Eu (which can be observed in many stars)

Beers & Christlieb 05 (ARAA)

- CEMP-r/s stars have both Ba and Eu
- previously best model assumes superposition of "known" r- and s-process sources

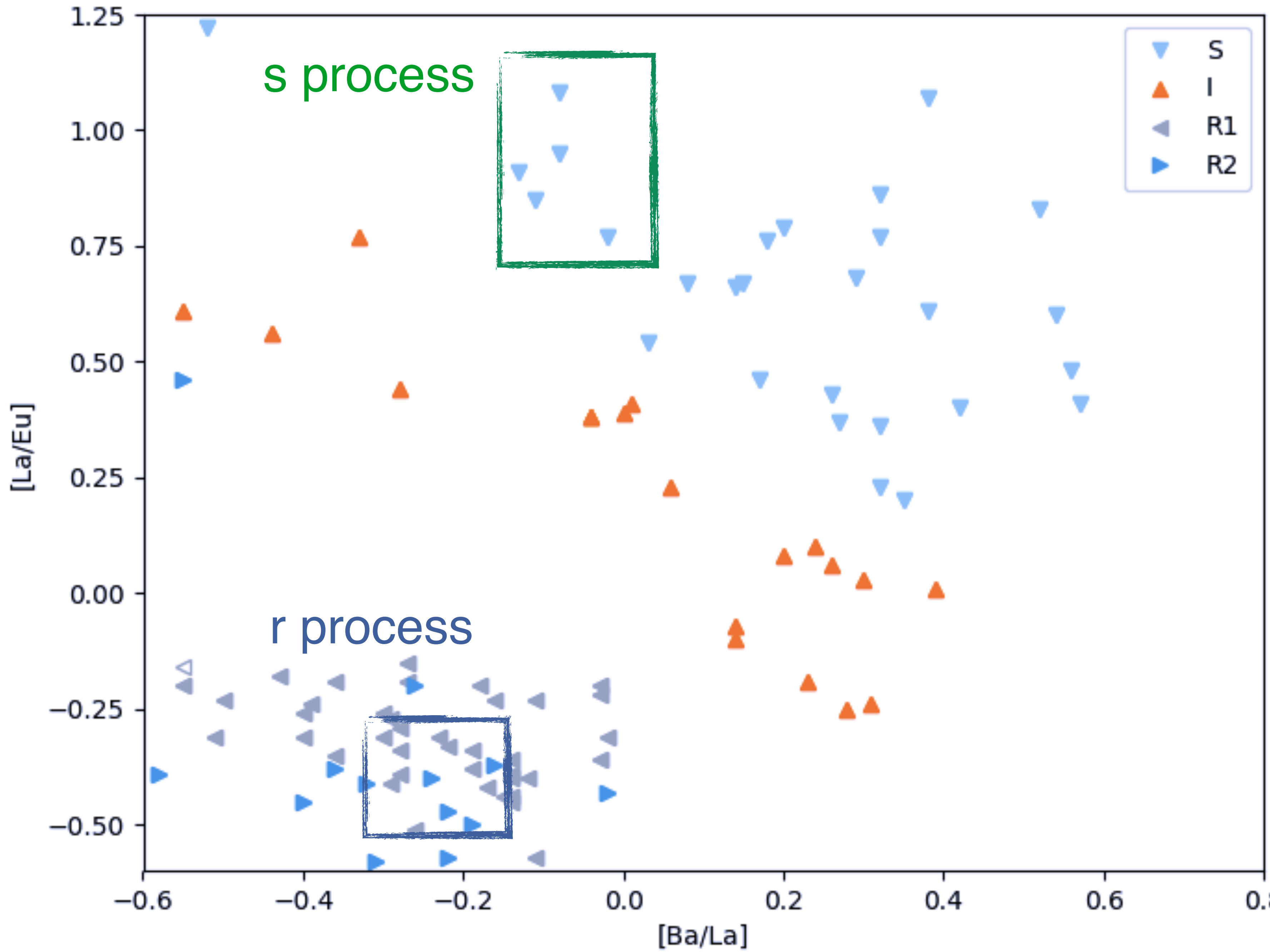
Is there a more plausible explanation?



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

Observed abundances in CEMP stars

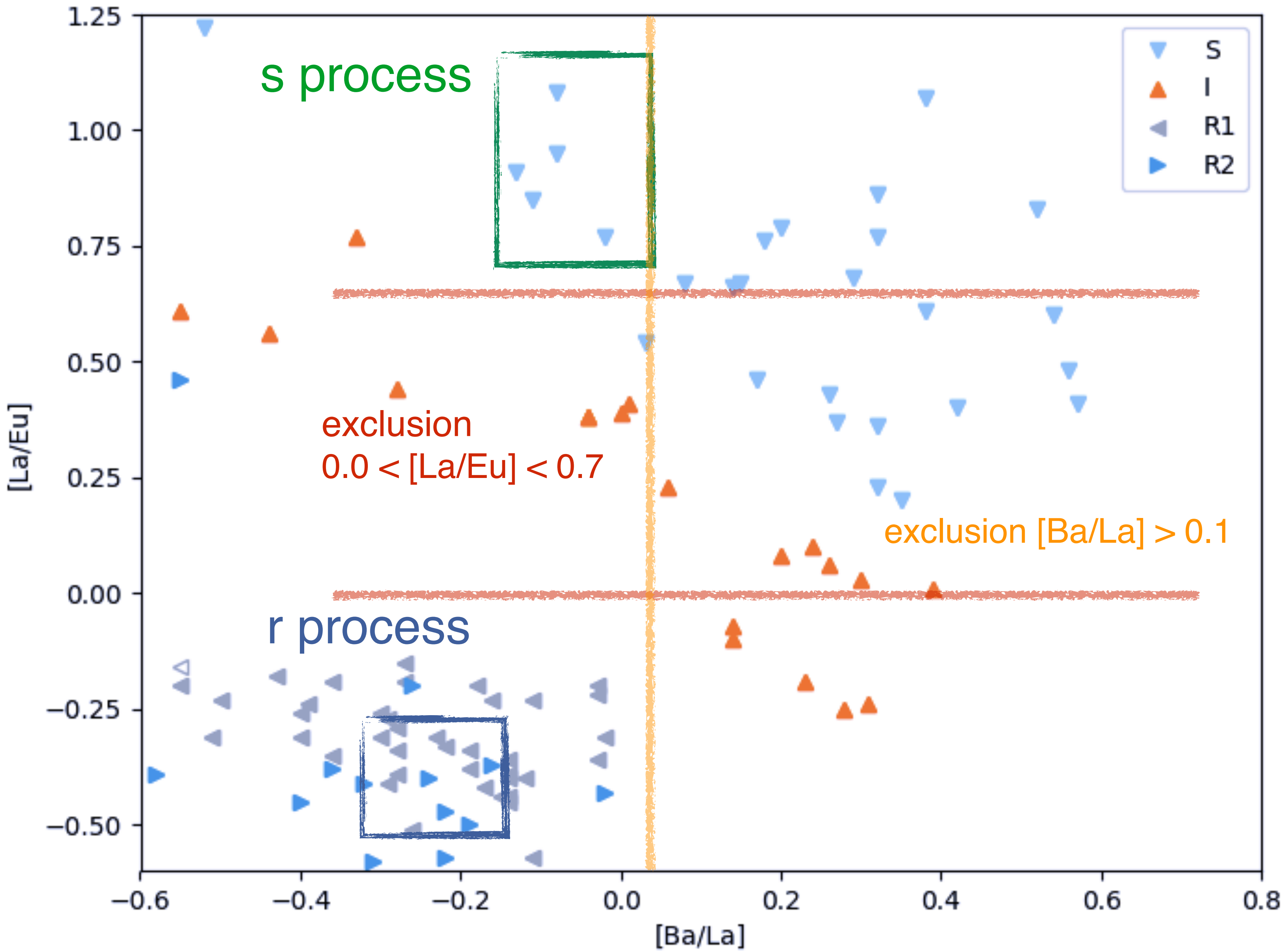
- The CEMP stars have (sometimes) very large enhancements of heavy elements, such as La, Ba, Eu
- C-enhanced metal poor (CEMP) stars carry the nucleosynthesis signature of the rise of the elements in the early universe
- CEMP-s, -r, -r/s stars: [Ba/La] and [La/Eu] elemental ratios very different for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



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

Observed abundances in CEMP stars

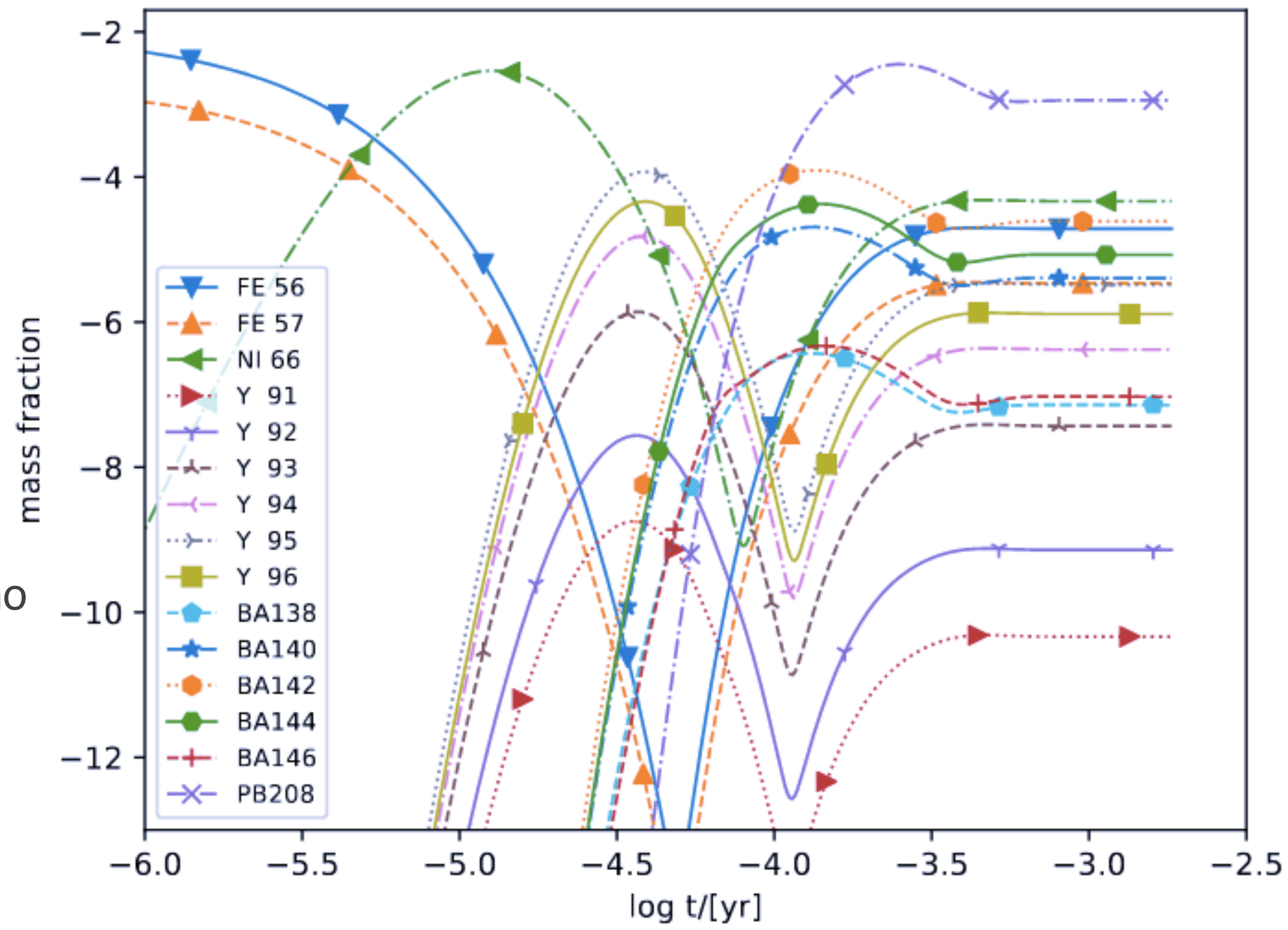
- Neither s nor r can make 0.0 < [La/Eu] < 0.7.
- With a superposition of just s and r it is impossible to make [Ba/La] > 0.1.
- But many CEMP stars have element ratios in exclusion zones?!?!?



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

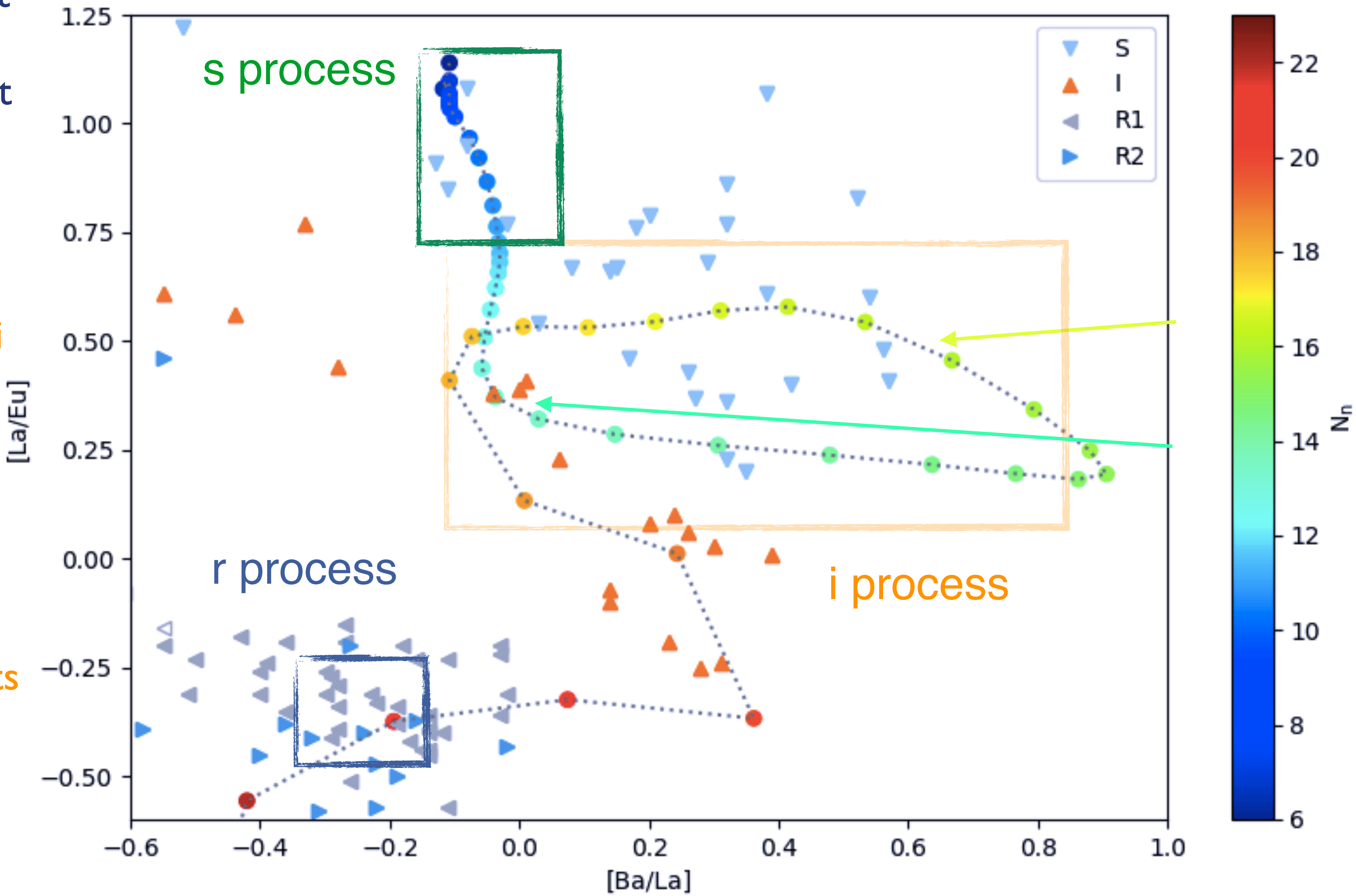
Constant neutron density one-zone nucleosynthesis network calculations

- 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
- Equilibrium models are independent of neutron exposure → no information on ratio of elements in different peaks, e.g. no Ba/Sr
- Instead astrophysics-independent (pure nuclear physics) predictions (only!) 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 → intermediate process

- 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



[Ba/Eu] &CEMP star classification & s-process origin

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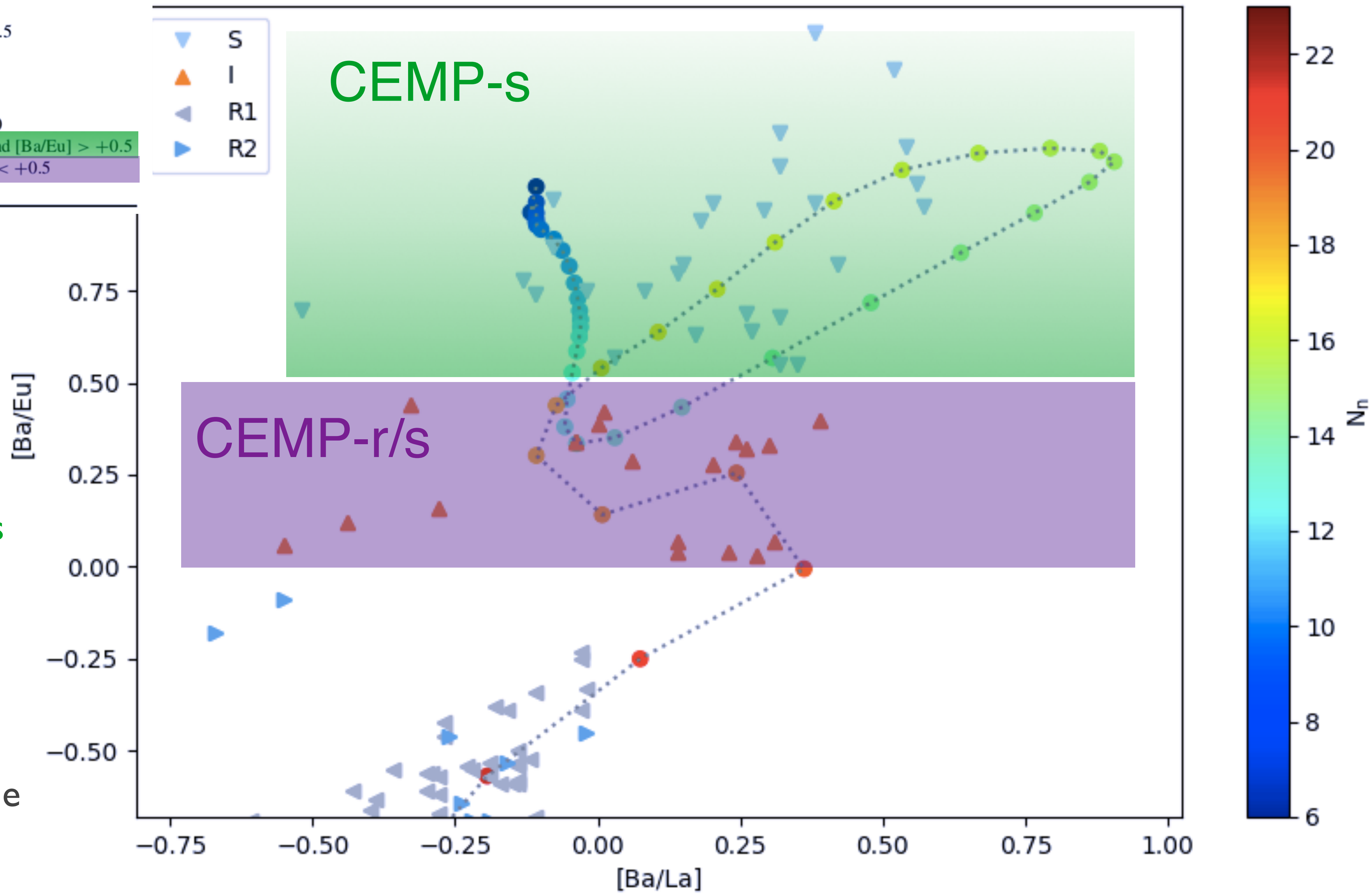
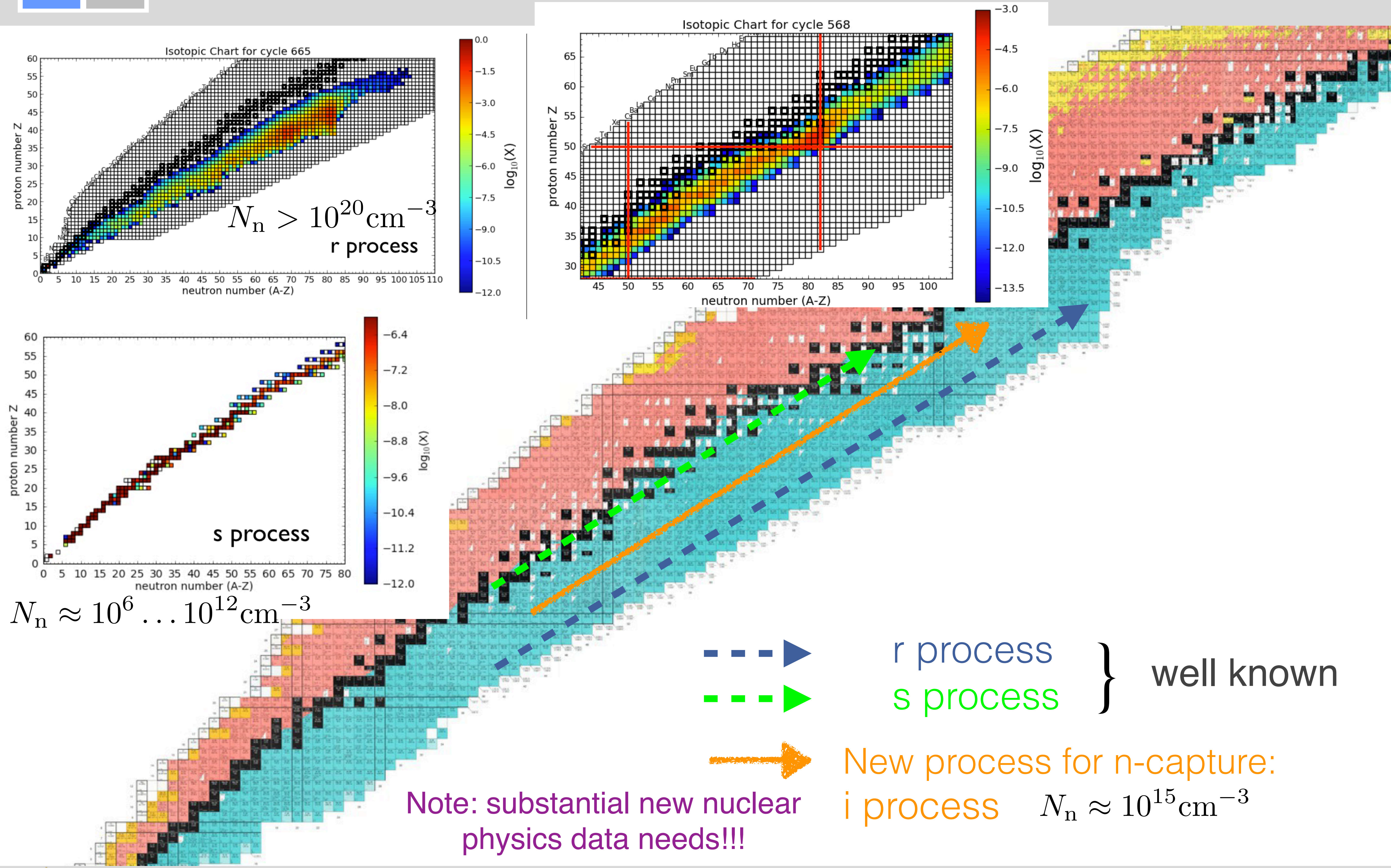
CEMP-r/s	[C/Fe] > +1.0 and 0.0 < [Ba/Eu] < +0.5
CEMP-no	[C/Fe] > +1.0 and [Ba/Fe] < 0

- 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



Neutron-capture: slow, rapid and intermediate!



r process
s process
} well known

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

Note: substantial new nuclear physics data needs!!!

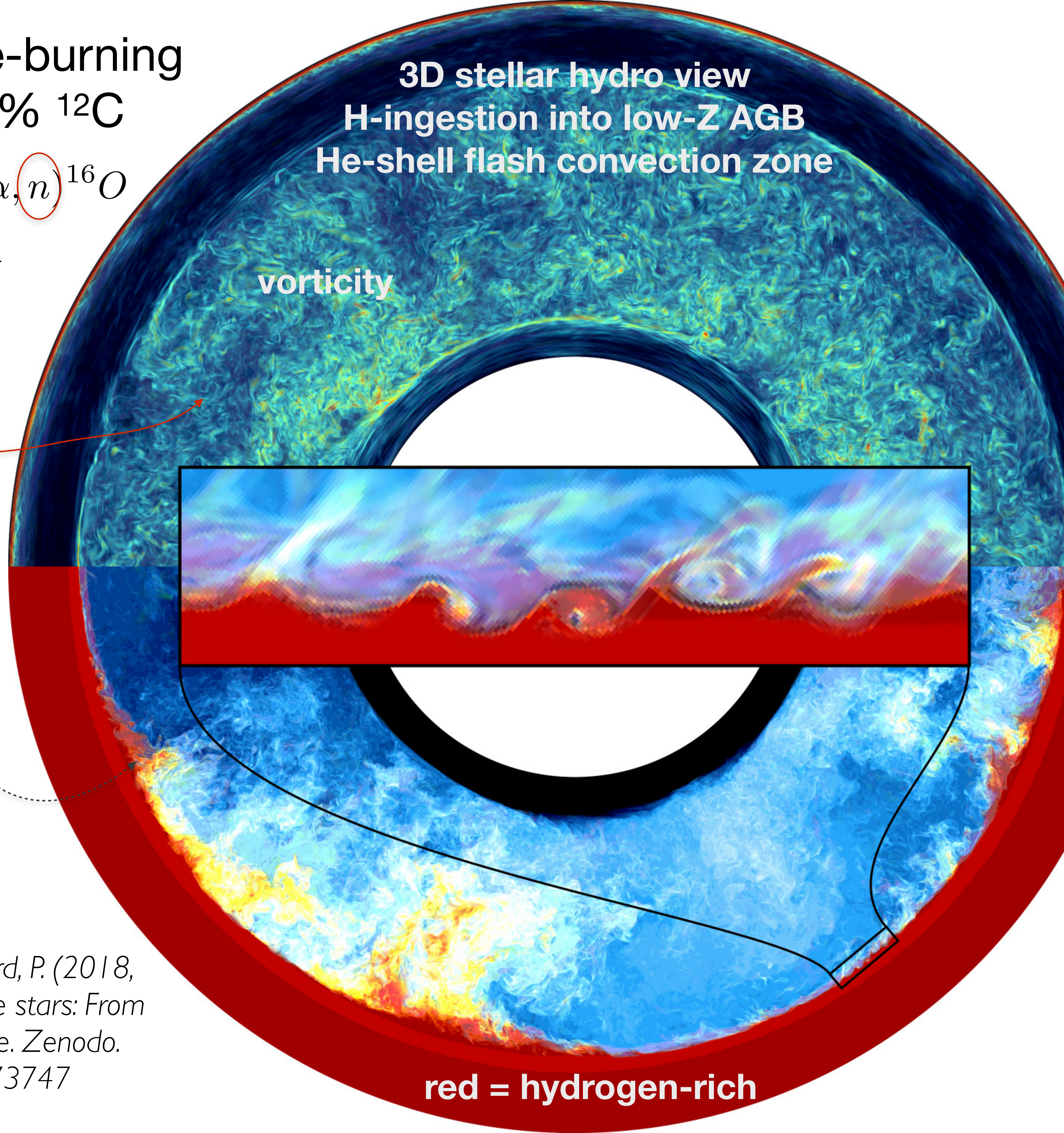
The convective He-burning shell contains ~40% ^{12}C

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

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

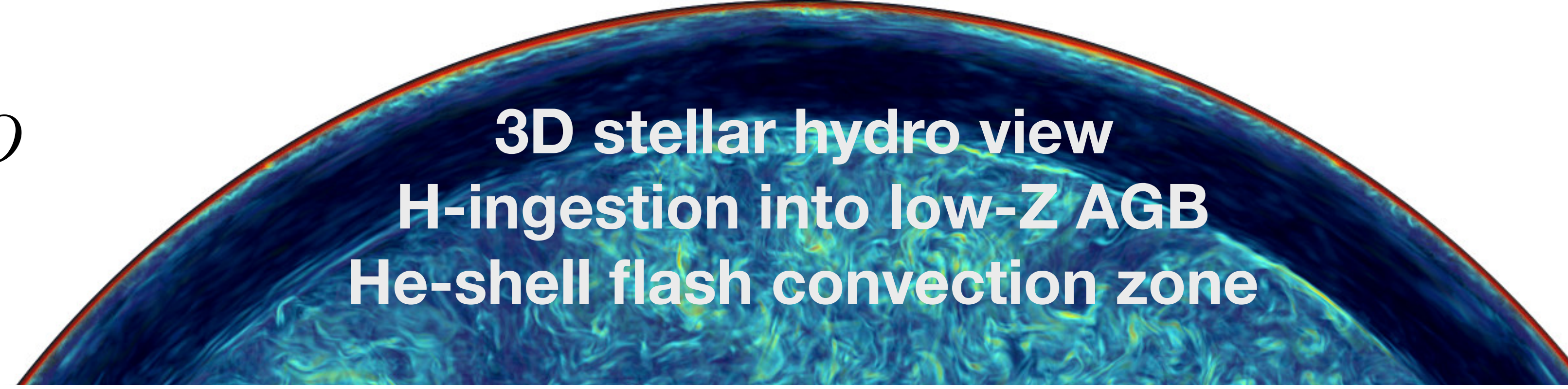
$$\tau_{\mathrm{conv}} \sim 15\mathrm{m}$$

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

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

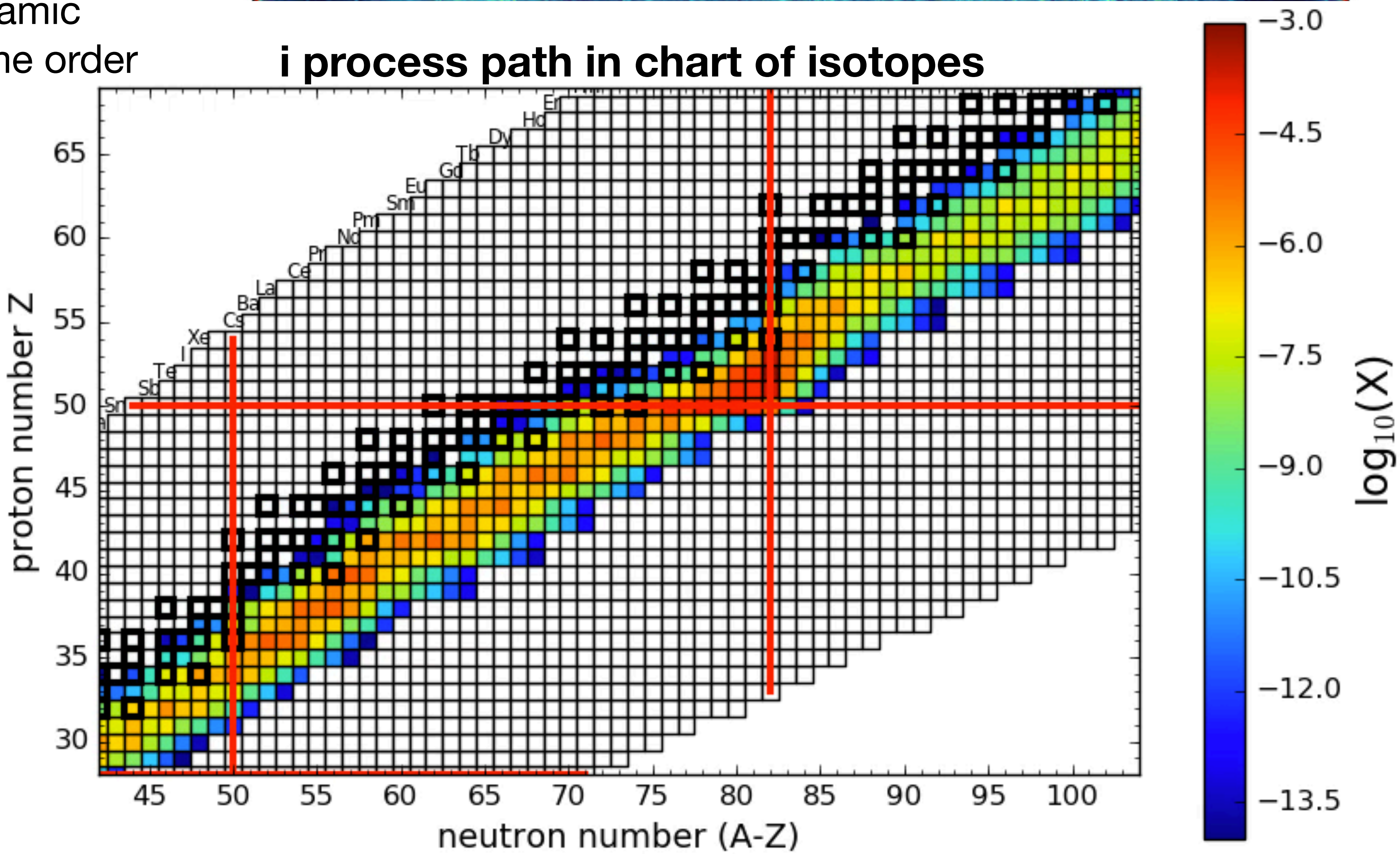


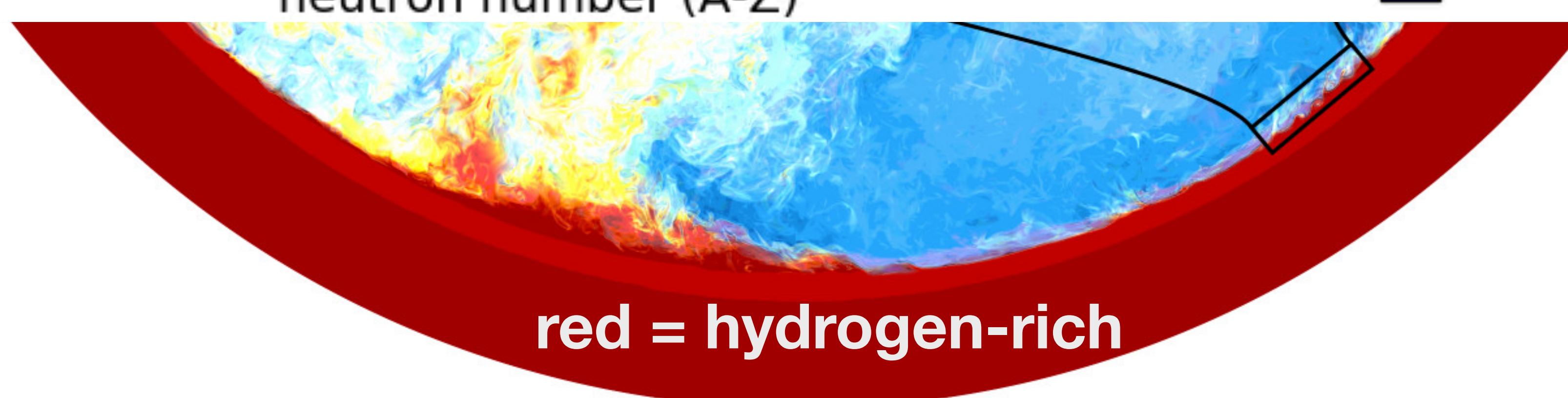
$\tau_{\mathrm{conv}} \sim 15\mathrm{m} \leftrightarrow \tau_{\frac{1}{2}} = 9.6\mathrm{m}$

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

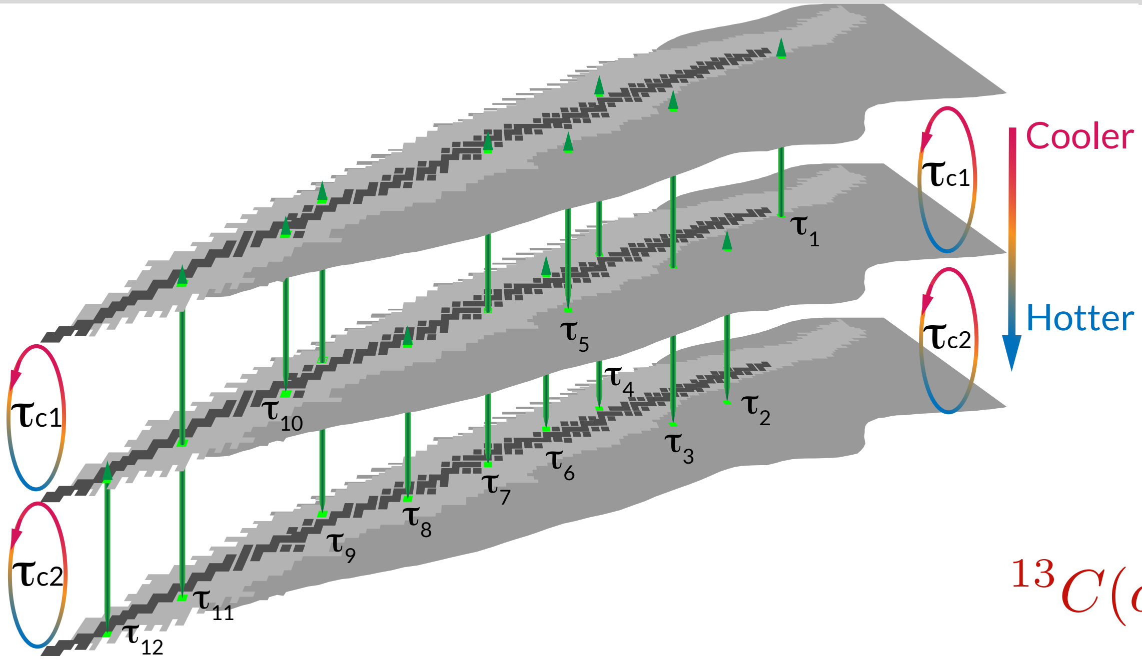
Neutrons released with intermediate neutron density → i process element production.

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

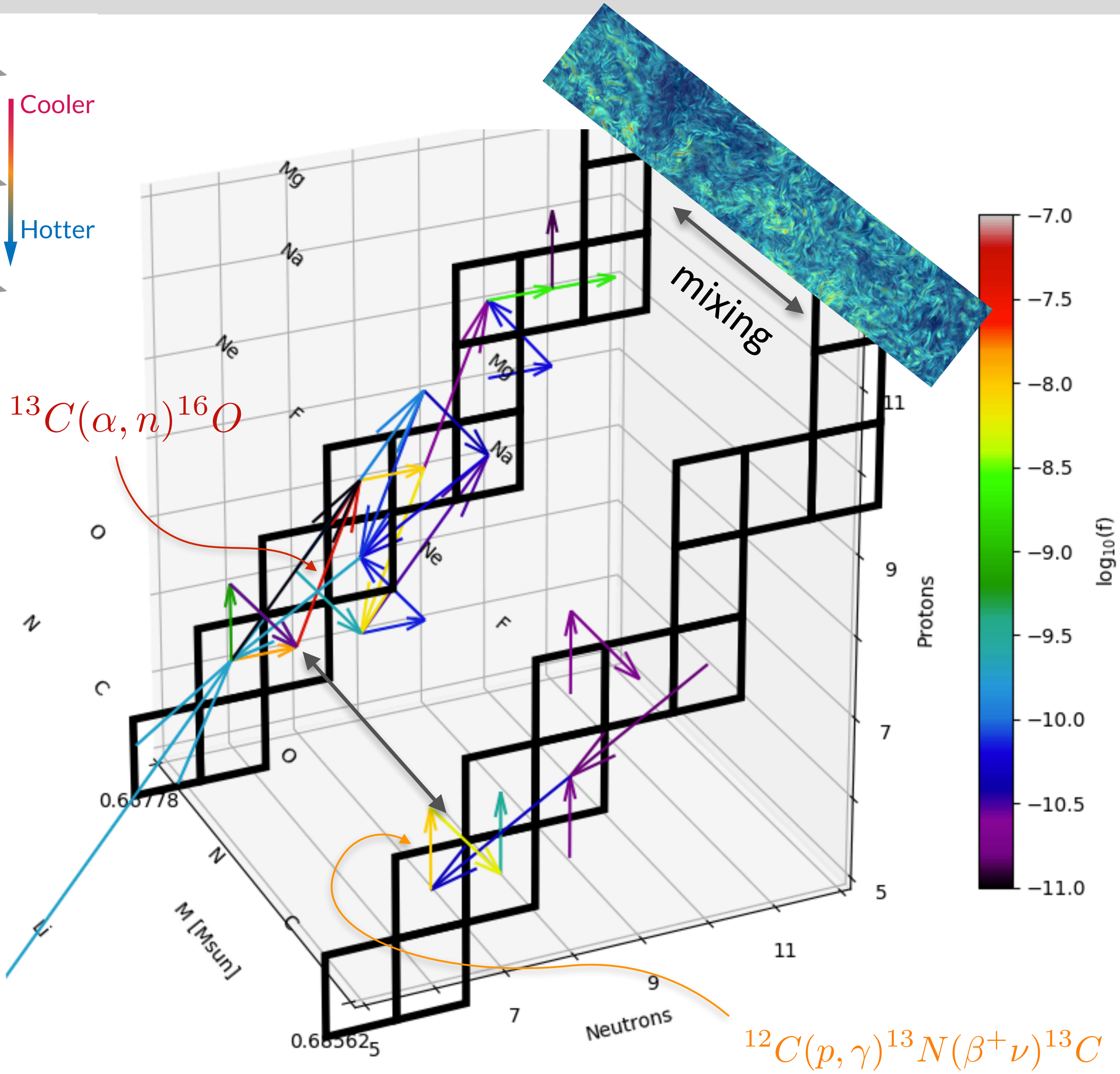




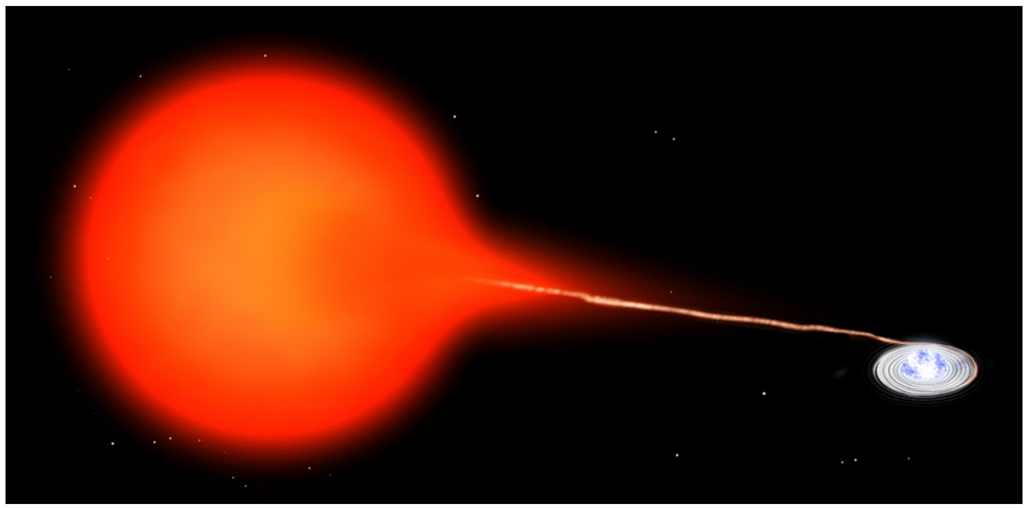
Convective-reactive i-process nucleosynthesis



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

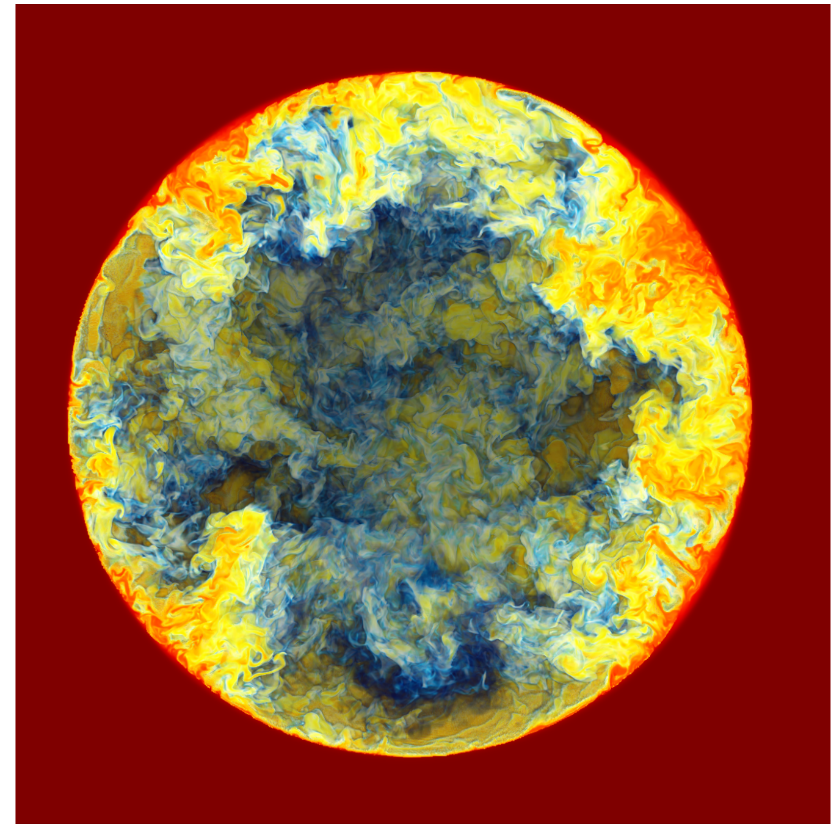


Where does it happen?
One promising option for CEMP-i stars: Rapidly Accreting White Dwarfs



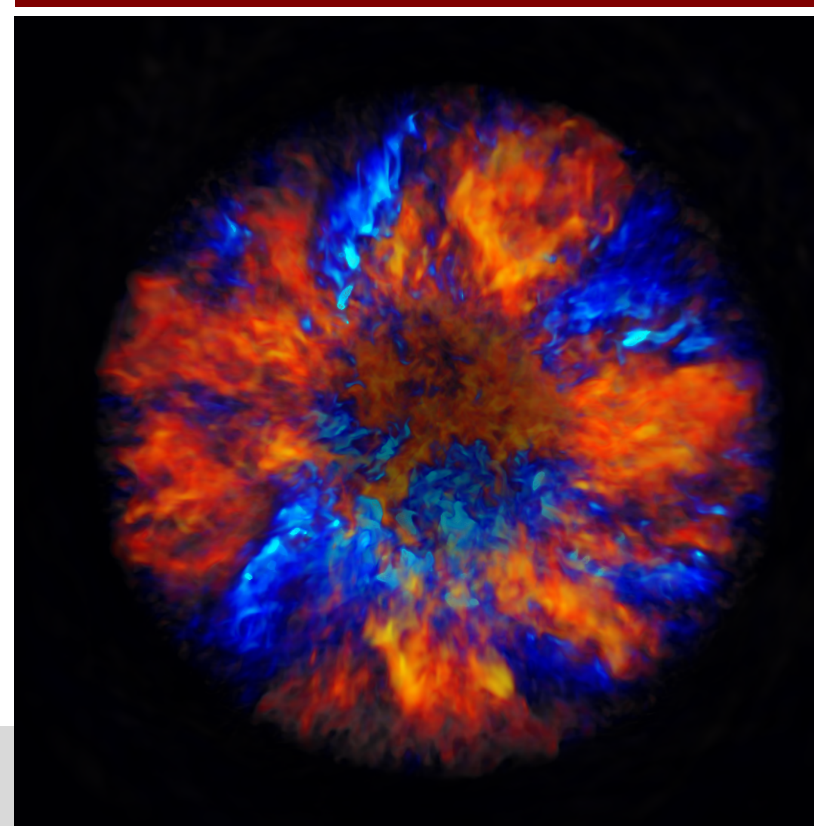
- Artist impression of accreting white dwarf, like novae!
- But unlike nova here accretion rates are high and allow stable H burning!
- However, these accreting WDs then experience He-shell flashes! (Cassisi+ 98)
- In these convective He-shell flashes: H-entrainment, convective reactive i process!

Denissenkov+ 17, ApJ Letters



Concentration of entrained material

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



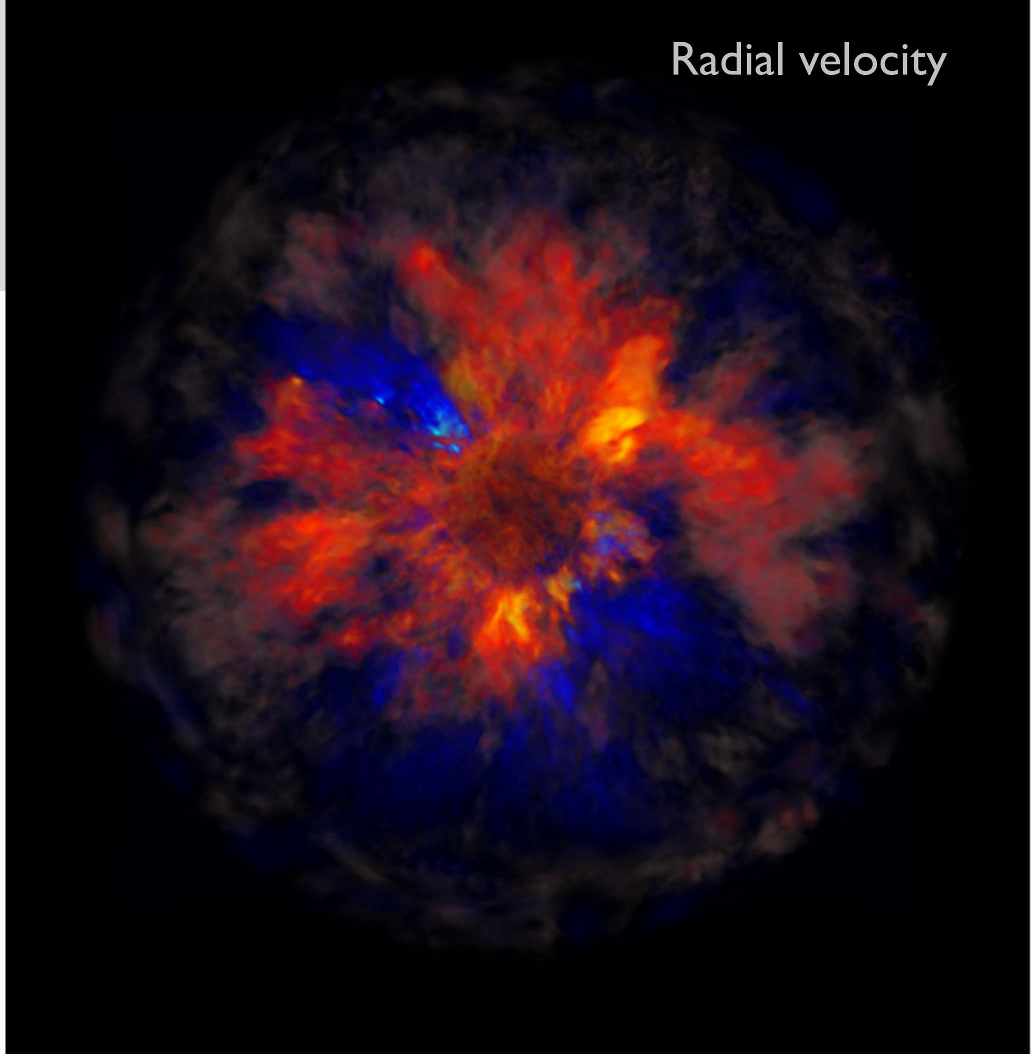
Radial velocity component

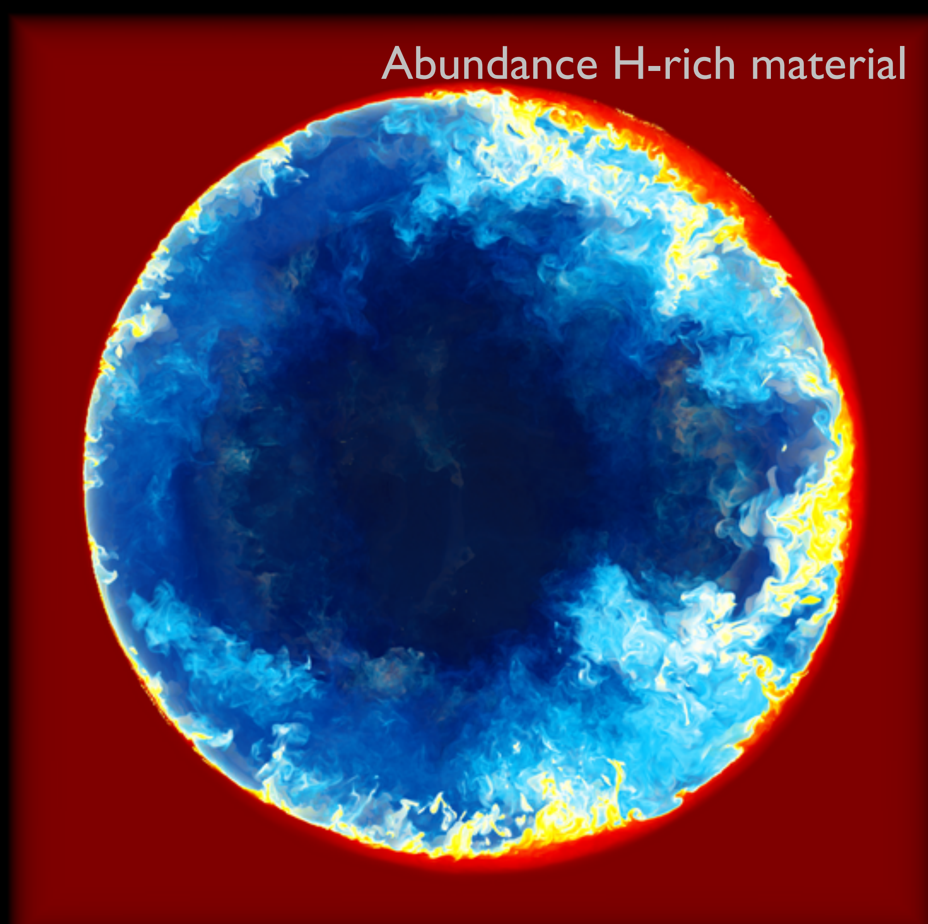
3D1D hydro-nucleosynthesis simulations of iRAWD

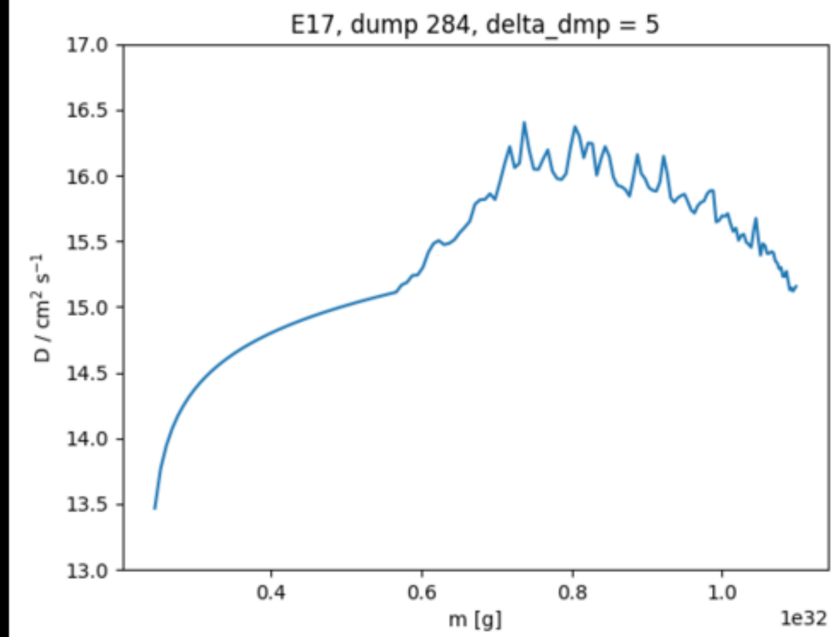
Left panels: 768^3-grid simulation of H-ingestion in RAWD

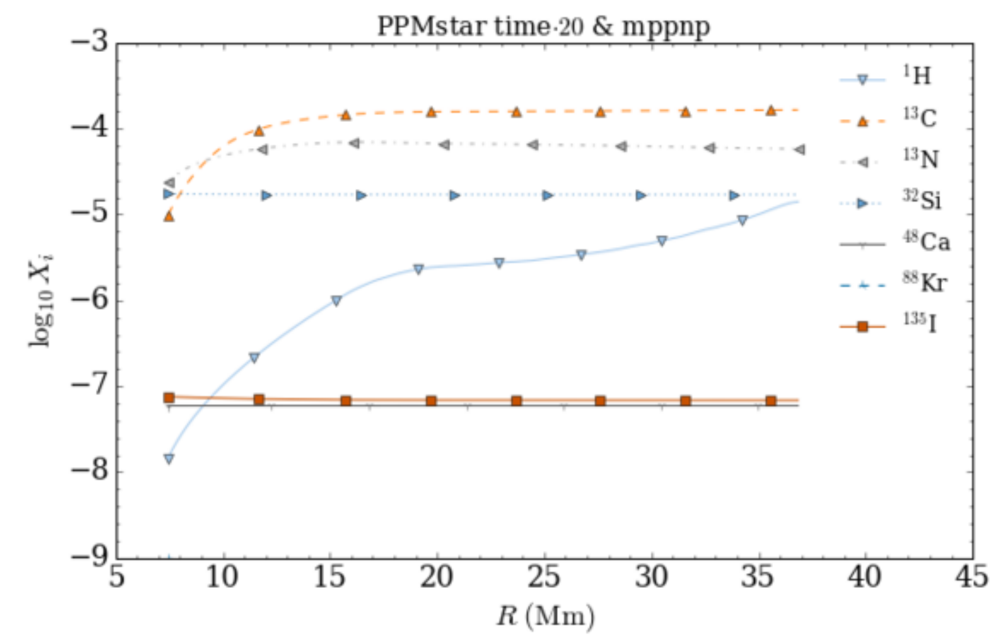
Right (top to bottom):

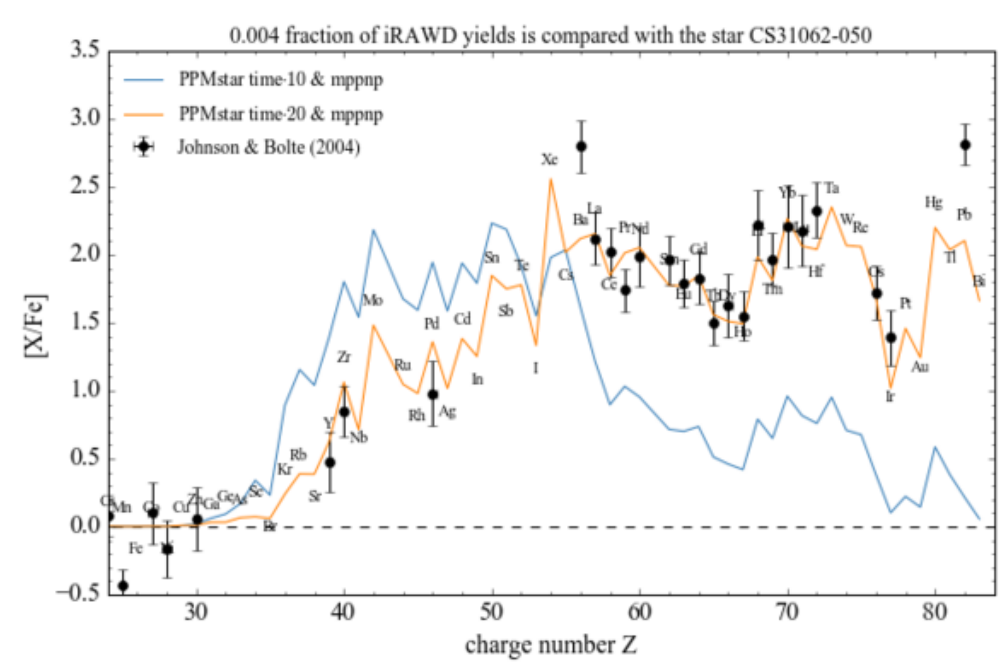
- 1D diffusion coefficient determined from spherical averaged abundance profile from 3D simulations
- abundance profiles of H, 13C and unstable i-process isotopes from multi-zone 1D post-processing of evolving hydro stratification
- abundance distribution compared to CEMP-i star observation
- [time stretched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



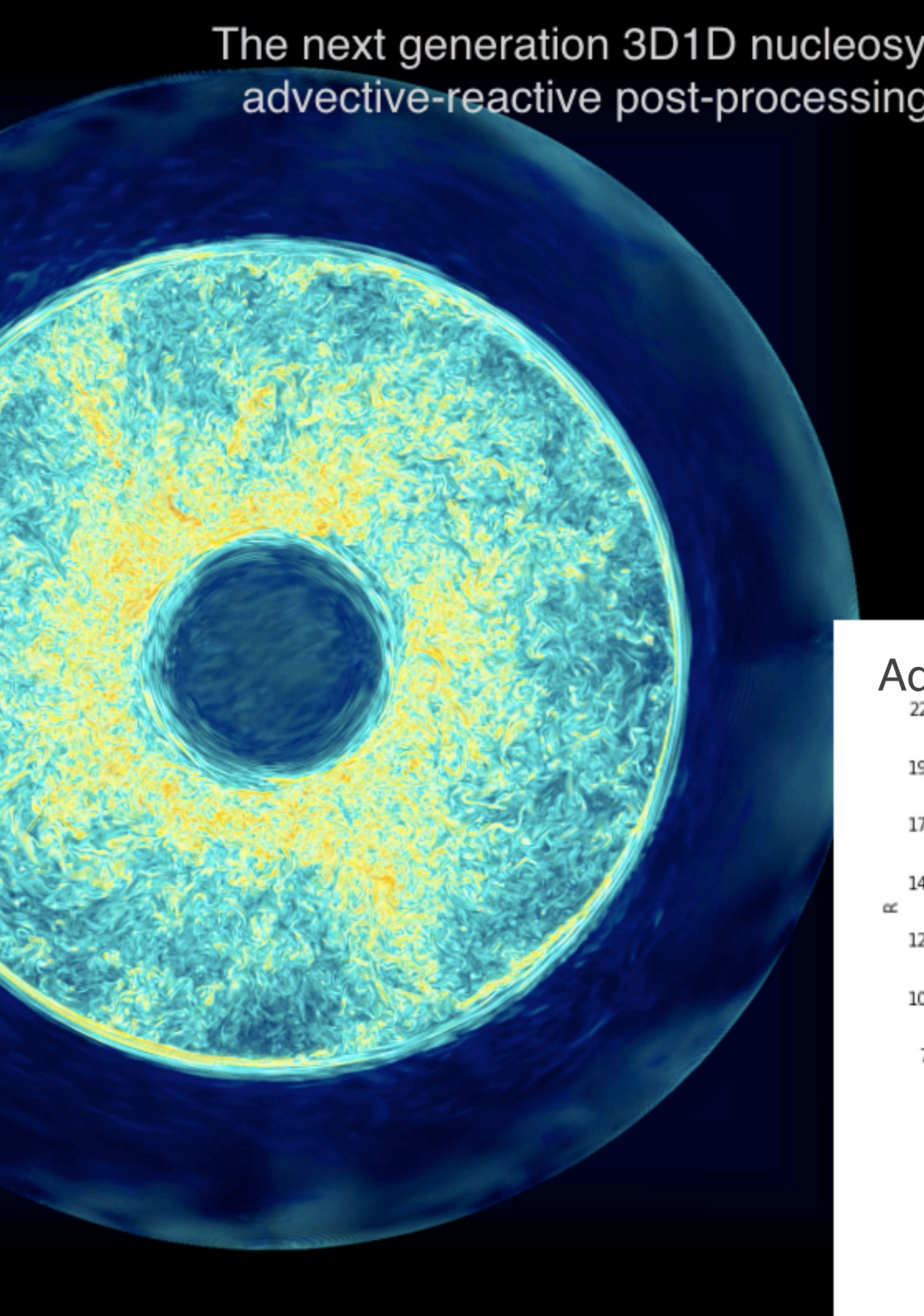


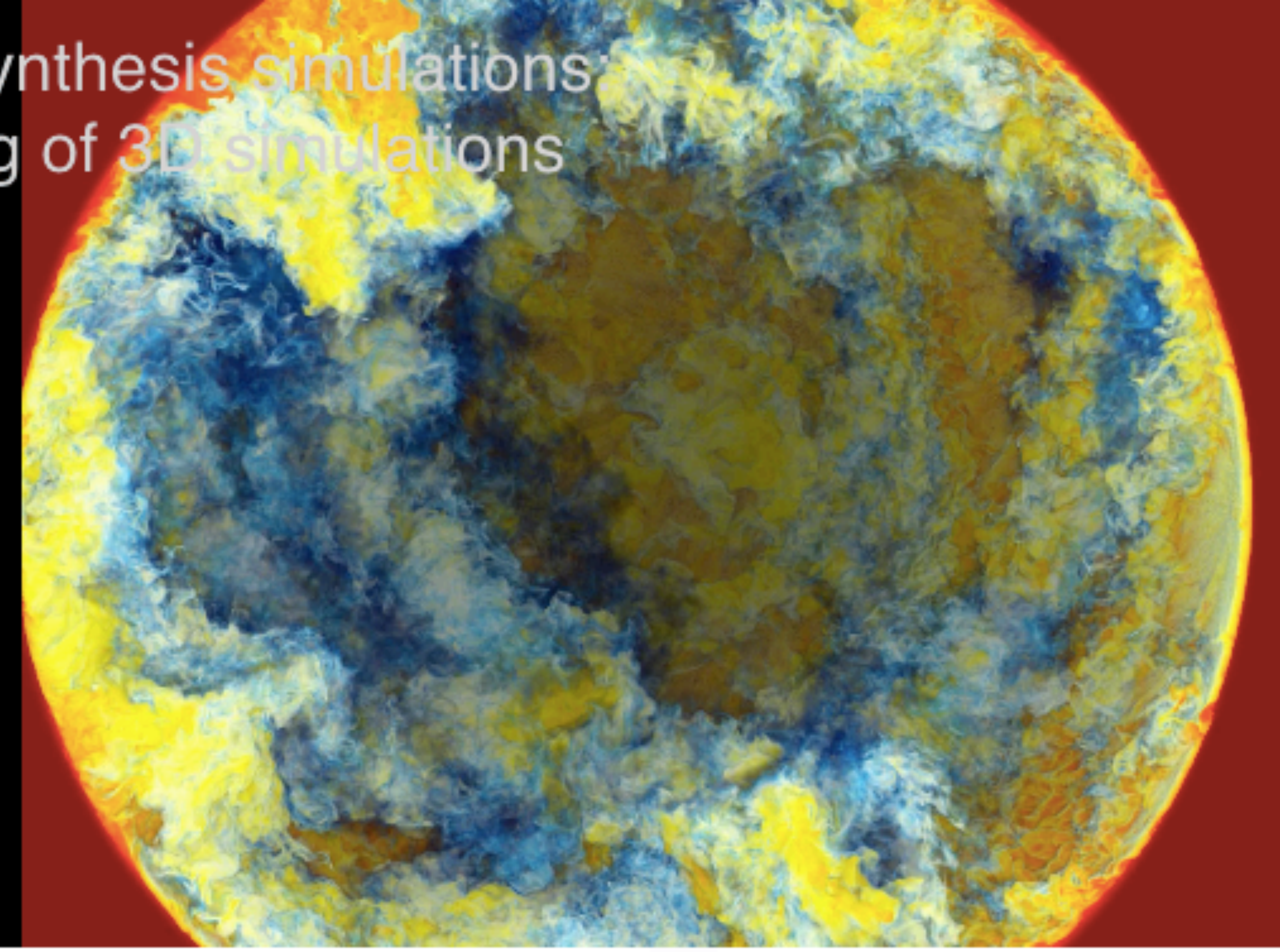




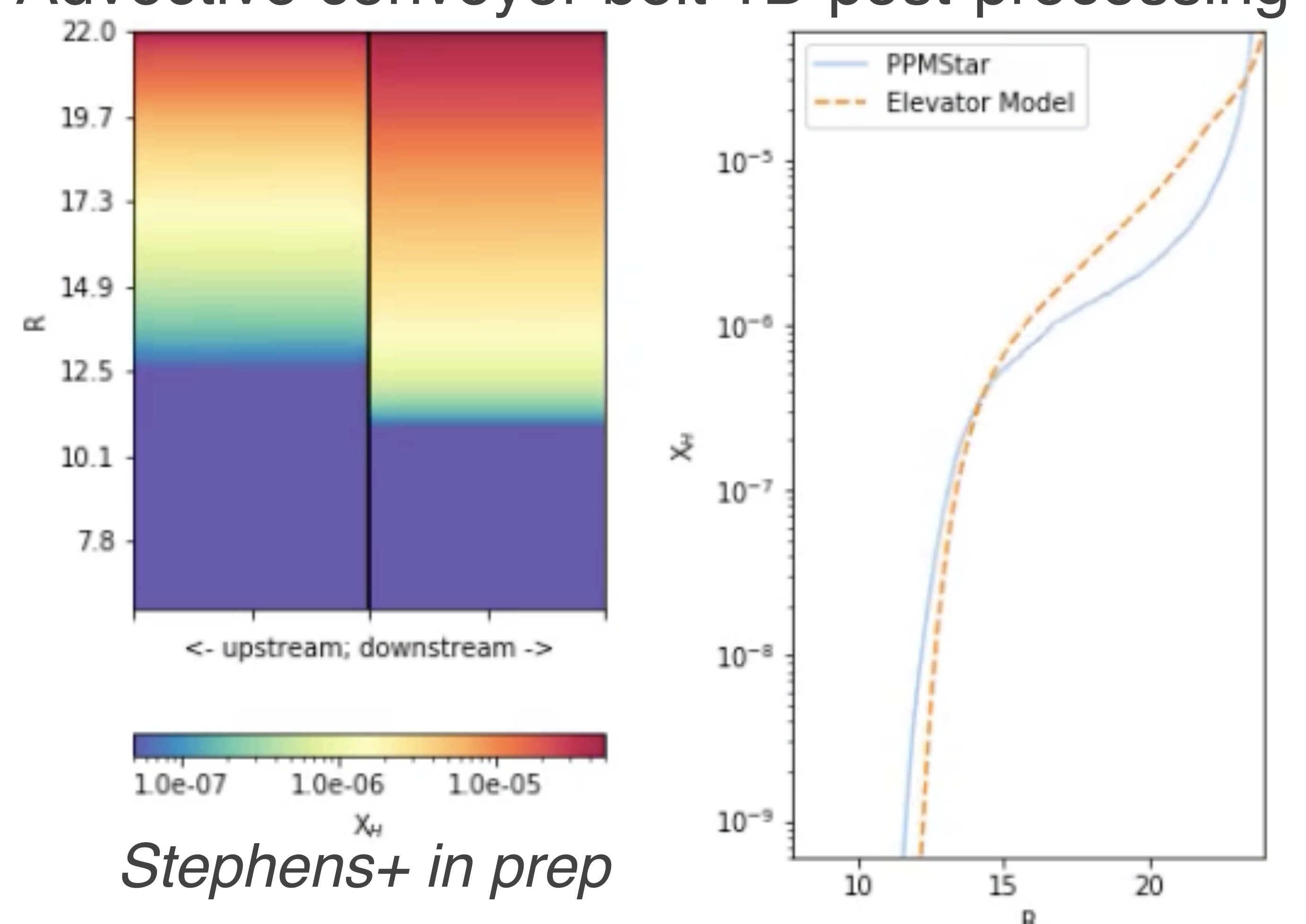


The next generation 3D1D nucleosynthesis simulations: advective-reactive post-processing of 3D simulations





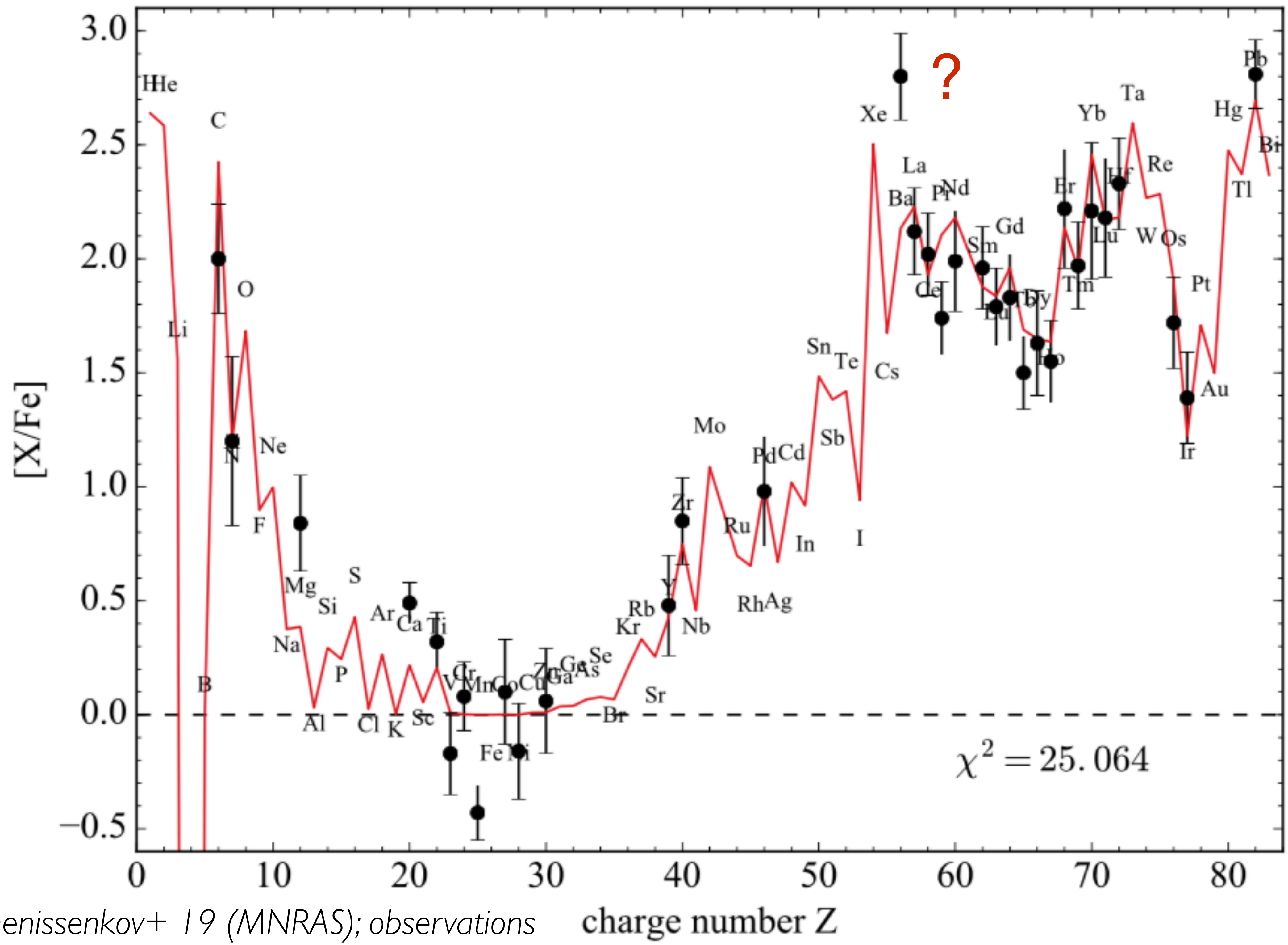
Advective conveyor belt 1D post-processing



Stephens+ in prep

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-r/s — or in fact CEMP-i — star abundances within a realistic astrophysical site.



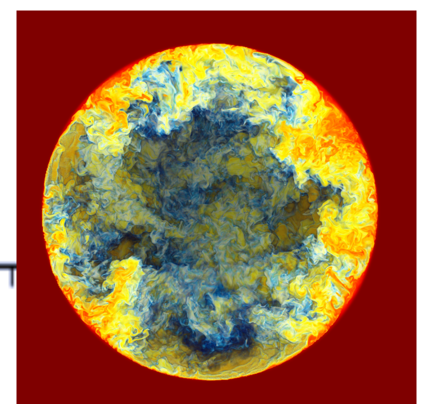
Denissenkov+ 19 (MNRAS); observations Aoki+ 02 & Johnson & Bolte 04

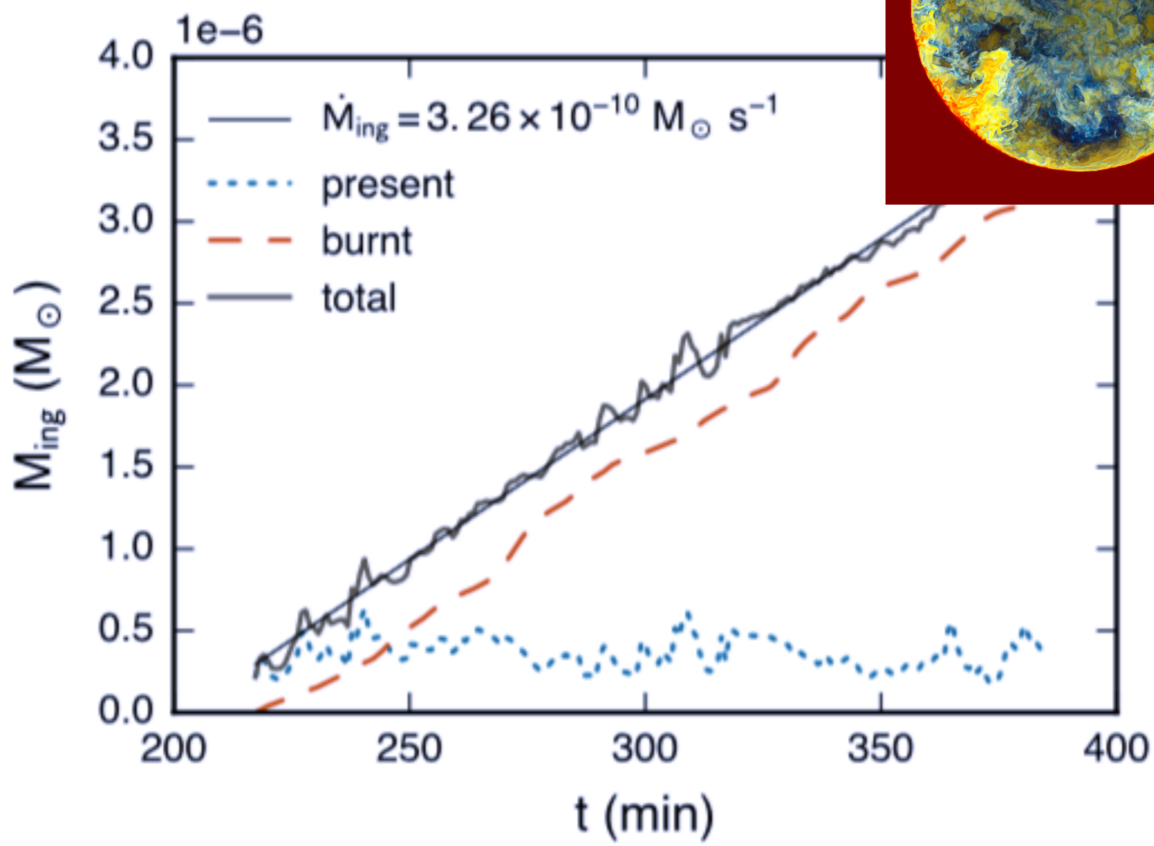
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 488, 4258–4270 (2019)
Advance Access publication 2019 July 12
doi:10.1093/mnras/stz1921

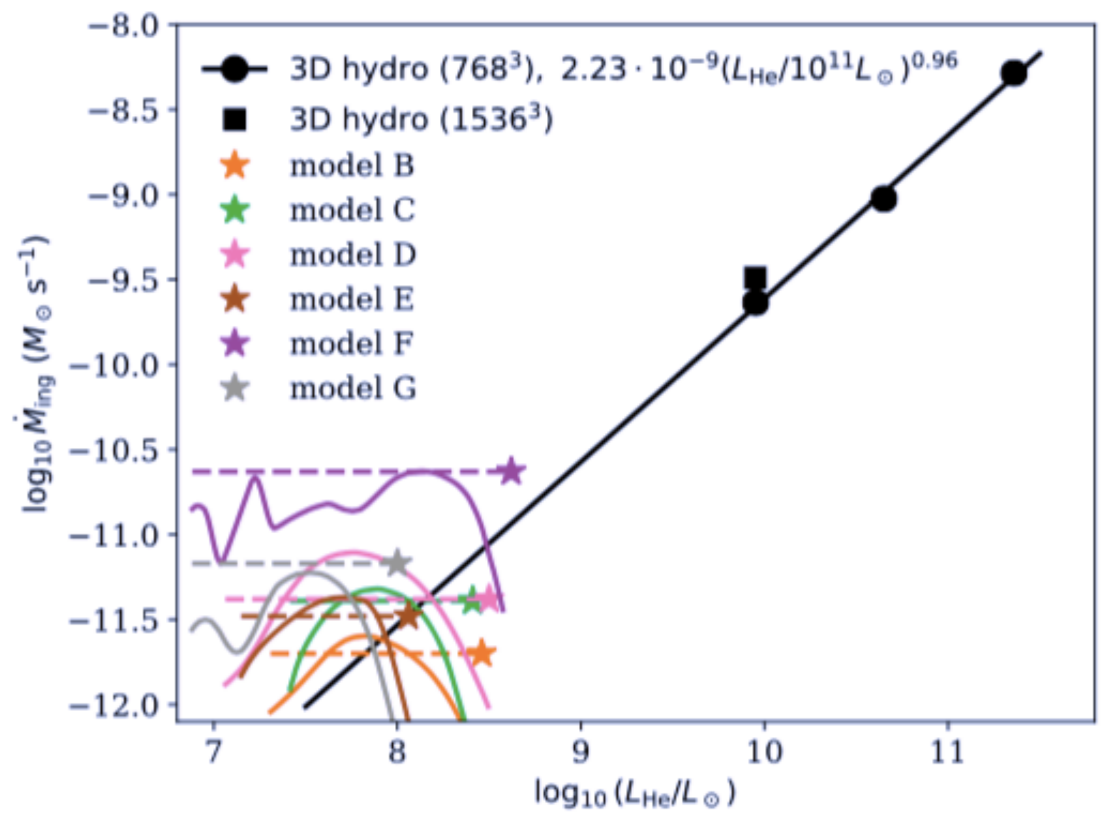
The i-process yields of rapidly accreting white dwarfs from multicycle He-shell flash stellar evolution models with mixing parametrizations from 3D hydrodynamics simulations

Pavel A. Denissenkov,[1,2★†] Falk Herwig,[1,2★†] Paul Woodward,[2,3] 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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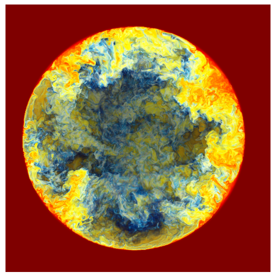

The i-process yields of rapidly accreting white dwarfs from multicycle He-shell flash stellar evolution models with mixing parametrizations from 3D hydrodynamics simulations

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.

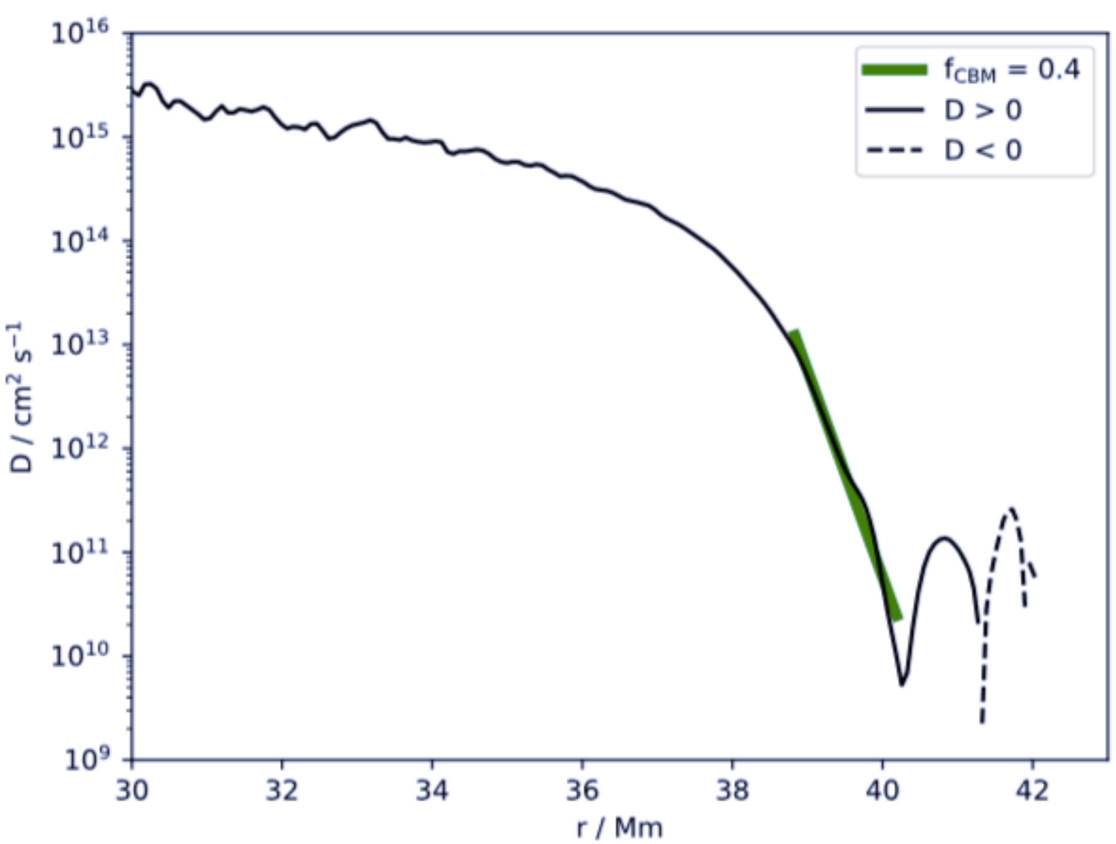

Figure 6. Determination of the f_{top} mixing parameter from the high-grid-resolution 3D hydrodynamics simulation E10.

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

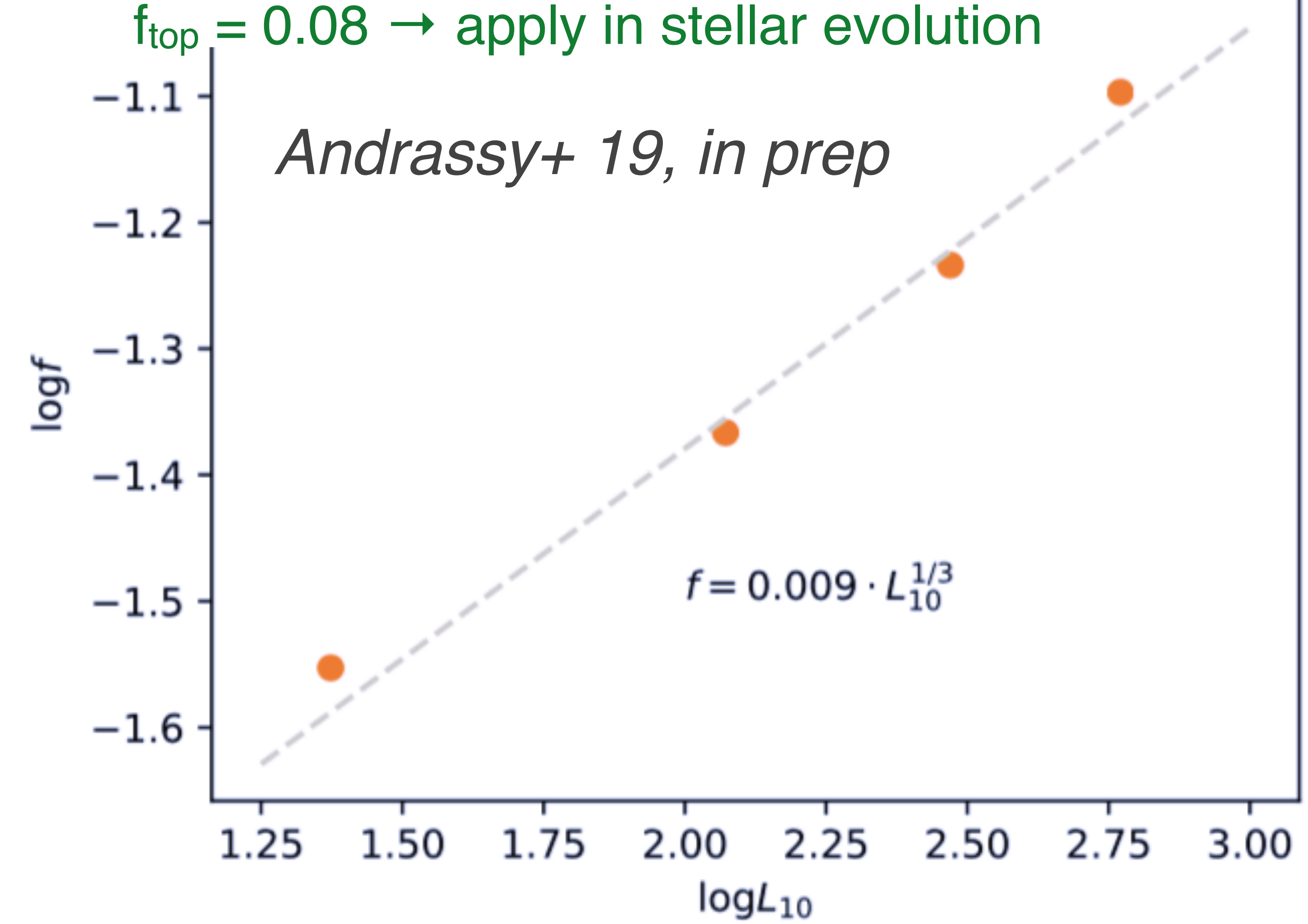

Figure 7. Scaling relation of the convective boundary mixing parameter f_{top} versus the driving luminosity based on a series of 1536-grid simulations of O-shell convection with the same setup as in Jones et al. (2017).

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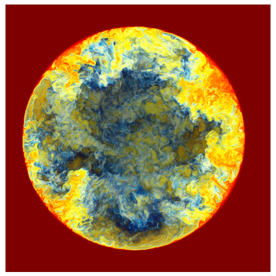

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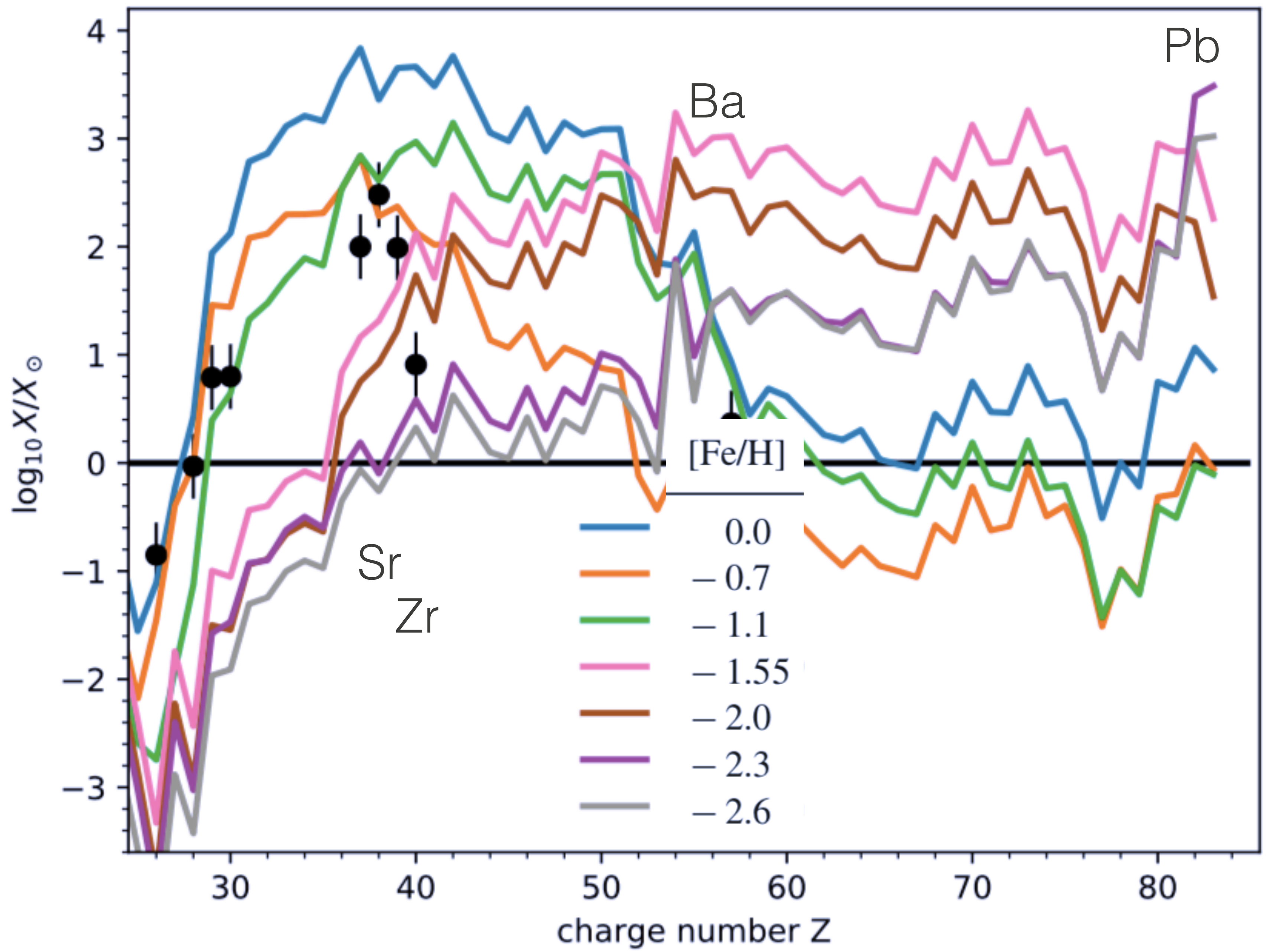


The Astrophysical Journal, 854:105 (14pp), 2018 February 20
https://doi.org/10.3847/1538-4357/aaaae8

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]

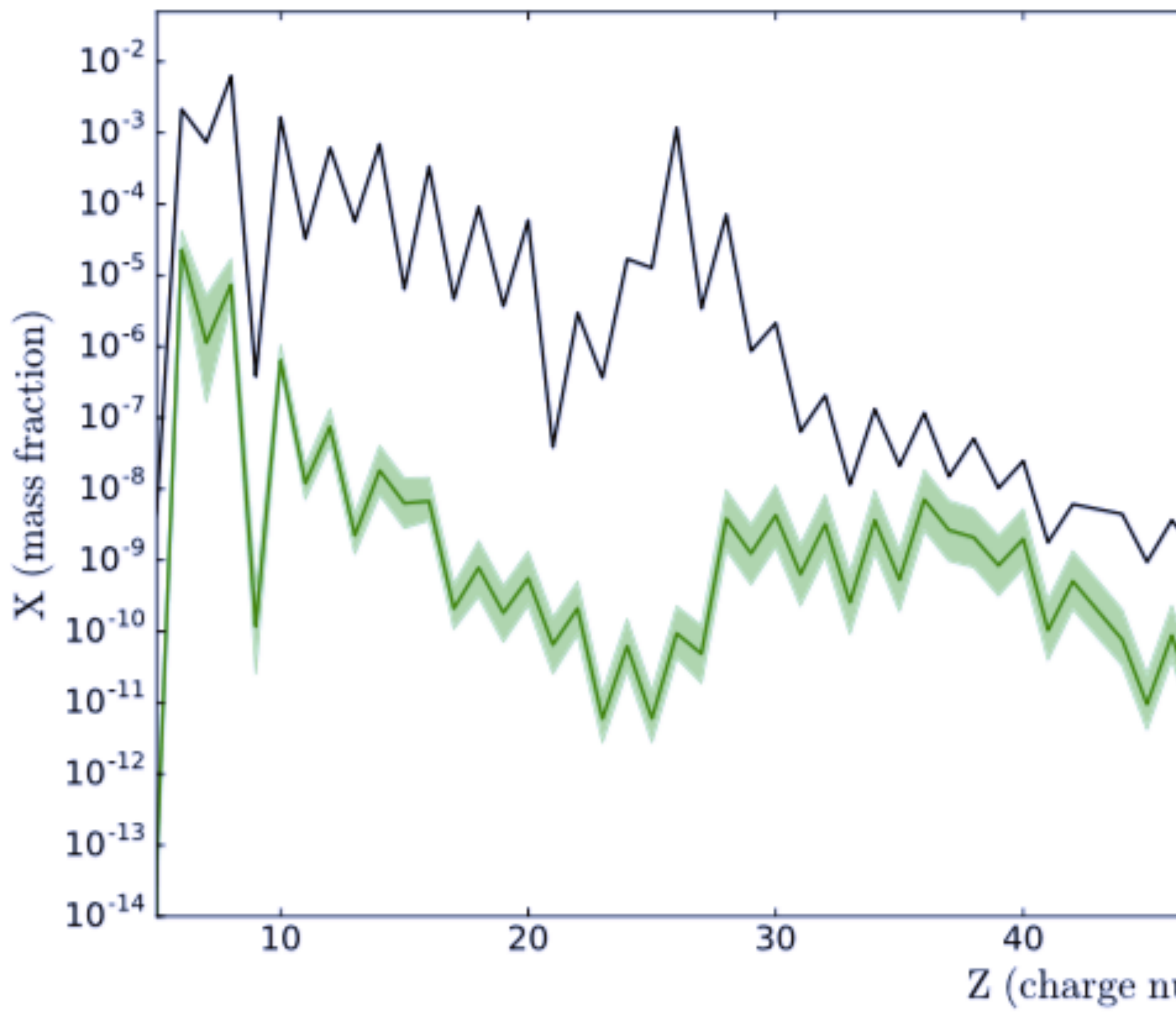


Figure 8. Predicted contribution of rapidly accreting white dwarfs (green, RAWDs) to th fiducial model while the green shaded area shows the range of solutions generated by un different early chemical evolution paths (see Figure 6). The solar composition was taken

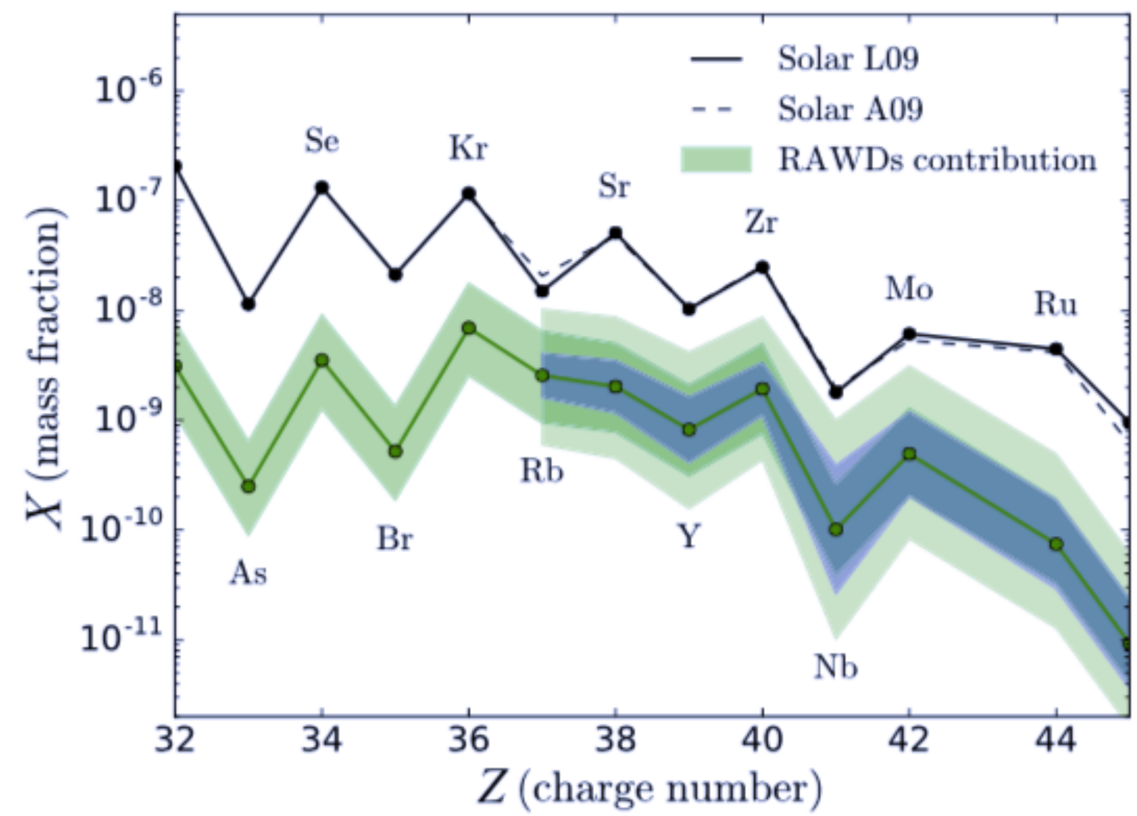


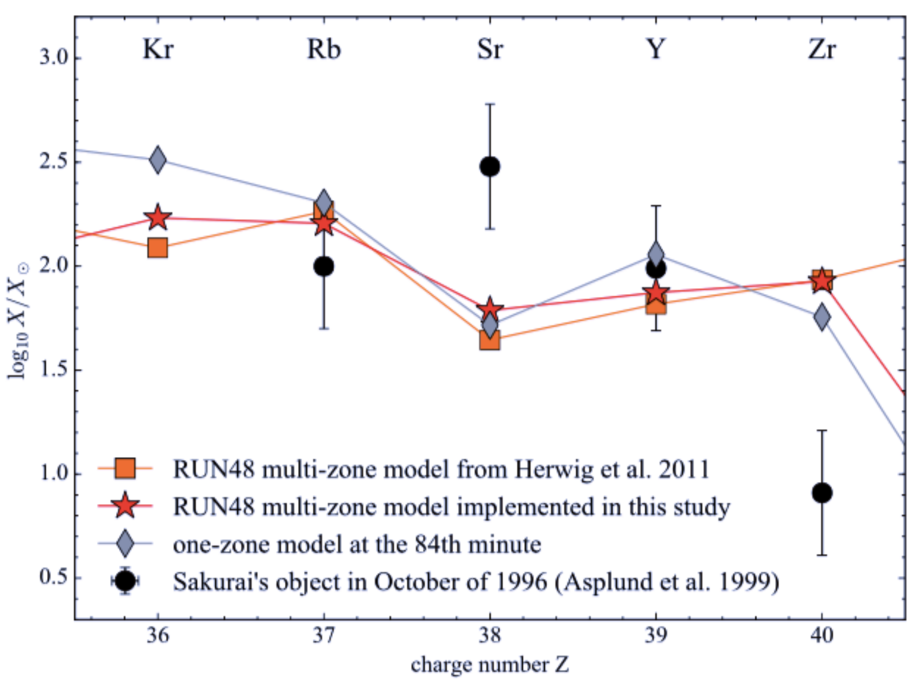
Figure 9. Same as in Figure 8, but zoomed on first-peak elements. The dashed black line shows the solar composition of Asplund et al. (2009, A09). The blue shaded area shows the uncertainties generated by nuclear reaction rates (see Section 6.4). The larger lighter-green shaded area shows the combined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

Nuclear-physics impact studies for i process

IOP Publishing   Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. **45** (2018) 055203 (23pp)   https://doi.org/10.1088/1361-6471/aabb6e

The impact of (n,γ) reaction rate uncertainties of unstable isotopes near $N = 50$ on the i-process nucleosynthesis in He-shell flash white dwarfs

Pavel Denissenkov[1,2,10], Georgios Perdikakis[2,3,4], Falk Herwig[1,2,10], Hendrik Schatz[2,4,5,10], Christian Ritter[1,2,10], Marco Pignatari[6,7,10], Samuel Jones[8,9,10], Stylianos Nikas[2,3] and Artemis Spyrou[2,4,5]



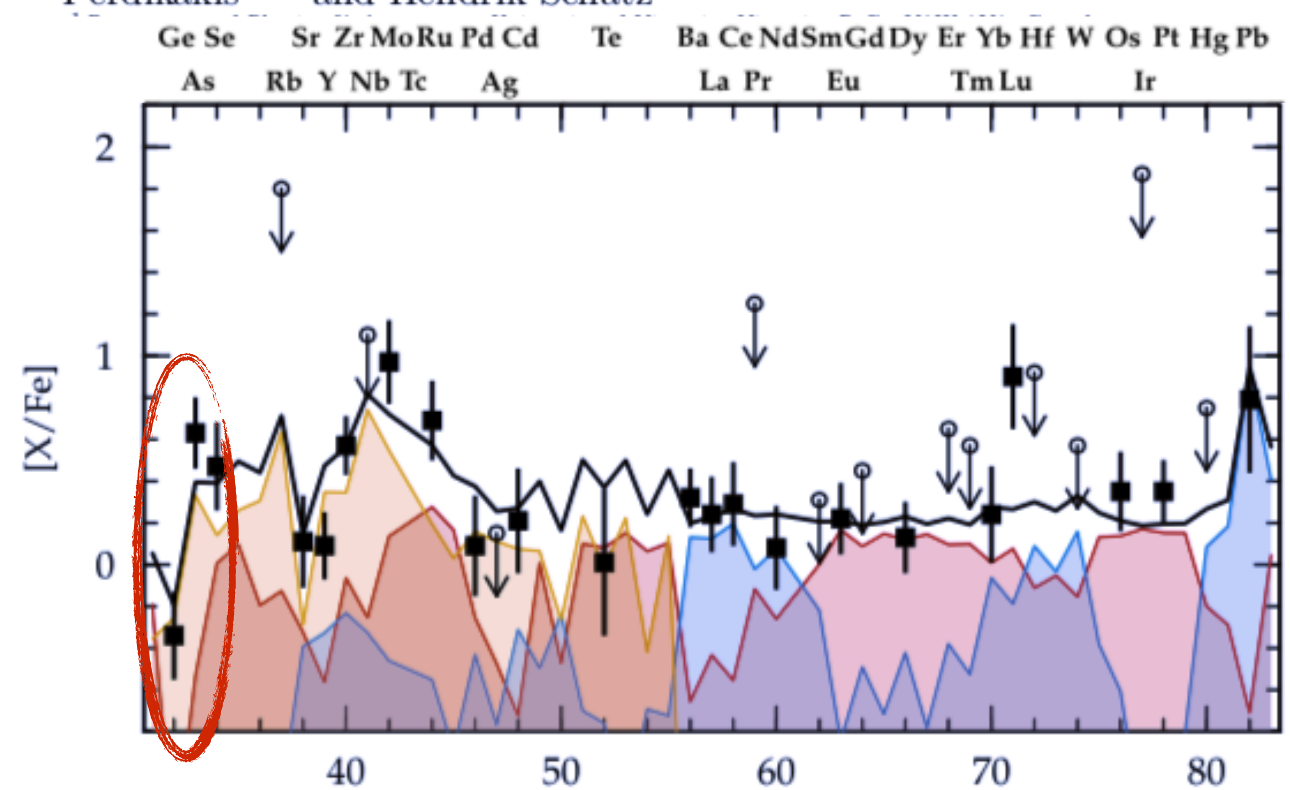
Step 1: observed abundance pattern and a nuclear network simulation (could be 1D multi-zone)

MNRAS submitted, arXiv:1909.07011

MNRAS **000**, 1–10 (2019)   Preprint 13 September 2019   Compiled using MNRAS LaTeX st

The impact of (n,γ) reaction rate uncertainties on the predicted abundances of i-process elements with $32 \leq Z \leq 48$ in the metal-poor star HD94028

John E. McKay[1,2,†], Pavel A. Denissenkov,[1,3,†⋆] Falk Herwig,[1,3,†], Georgios Perdikakis[3,4,5] and Hendrik Schatz[3,5,6,†]



Step 2: Determine nuclear physics uncertainties
Step 3: Perform Monte-Carlo simulations

- Determine variation factors from all relevant unstable (n,γ) cross section
- 20 combinations of HF model assumptions listed below
- 10,000 Monte-Carlo runs with randomly drawn factors for each of the included (n,γ) cross sections

Table 1. List of models used to describe the nuclear level density and the γ strength in the Hauser–Feshbach calculations. Calculations were performed with all 20 possible combinations of these models.

Nuclear level density (NLD) models used in this work
Constant temperature matched to the Fermi Gas (CT+BSFG) (Dilg *et al* 1973)
Back-shifted Fermi Gas (BSFG) (Dilg *et al* 1973, Gilbert and Cameron 1965)
Generalized super fluid (GSM) (Ignatyuk *et al* 1979, 1993)
Hartree–Fock using Skyrme force (HFS) (Goriely *et al* 2001)
Hartree–Fock–Bogoliubov + combinatorial (HFBS-C) (Goriely *et al* 2008)
γ ray strength function (γSF) models used in this work
Kopecky–Uhl generalized Lorentzian (KU) (Kopecky and Uhl 1990)
Hartree–Fock BCS + QRPA (HF-BCS+QRPA) (Goriely and Khan 2002)
Hartree–Fock–Bogolyubov + QRPA (HFB+QRPA) (Goriely *et al* 2004)
Modified Lorentzian (Gor-ML) (Goriely 1998)

J. Phys. G: Nucl. Part. Phys. **45** (2018) 055203

Case weak i process

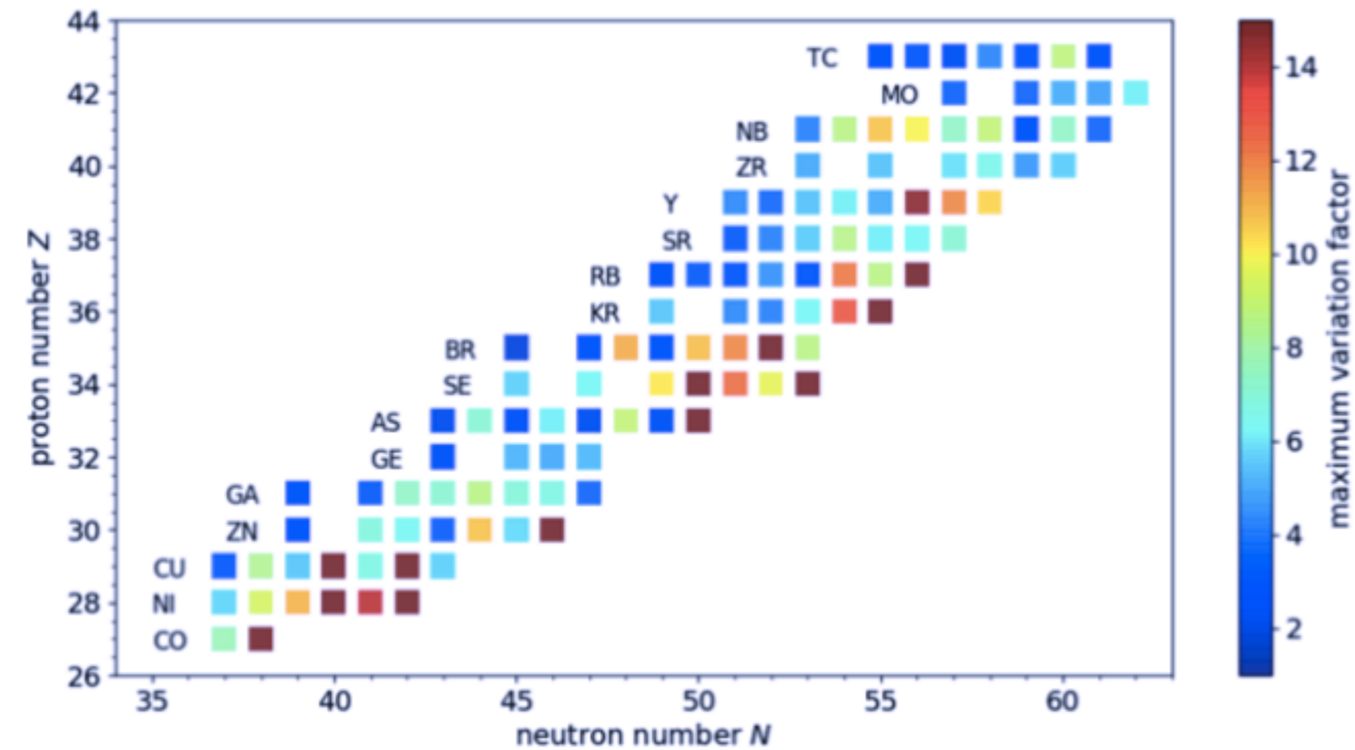


Figure 1. The unstable isotopes whose (n,γ) reaction rates were varied in this study and the maximum variation factors used for the rates. The maximum variation factors for ^{65}Co, ^{68}Ni, ^{70}Ni, ^{69}Cu, ^{71}Cu, ^{76}Zn, ^{83}As, ^{84}Se, ^{87}Se, ^{87}Br, ^{91}Kr, and ^{93}Rb exceed the maximum value of $v_i^{\max} = 15$ assigned to the color map.

Step 4: Analyse results (weak i process)

Network flux in abundance chart

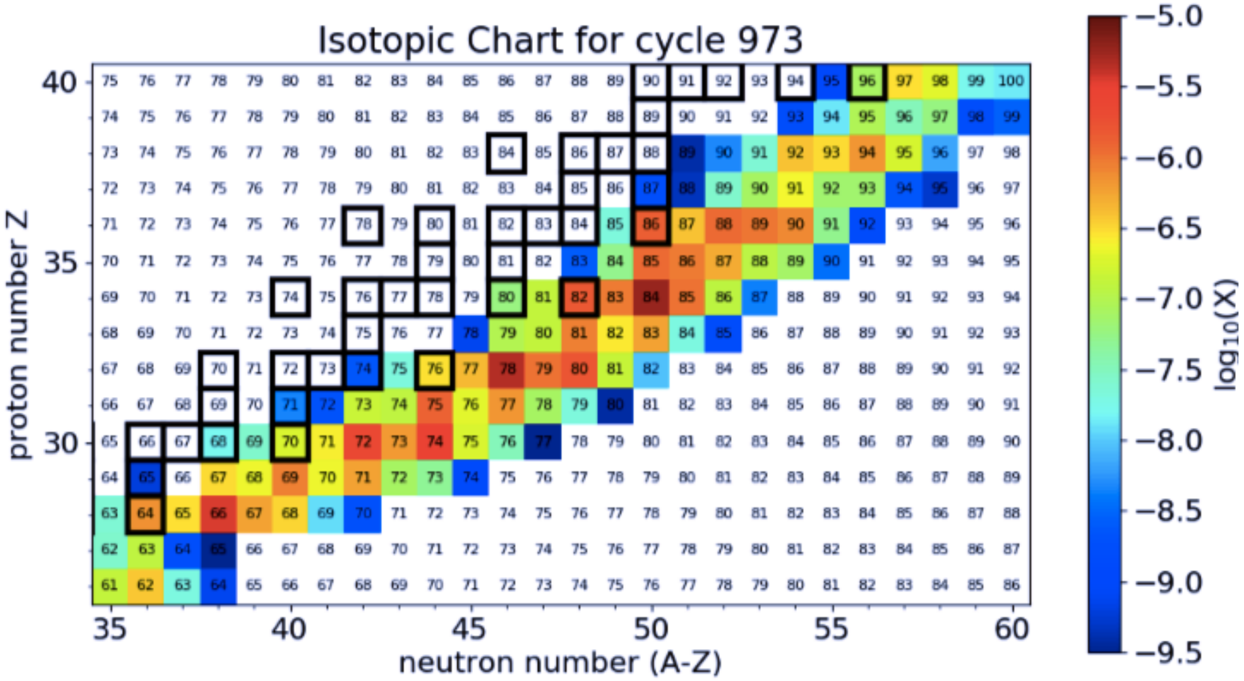


Figure 5. Undecayed isotopic abundances (mass fractions X) for the best-fit cycle 973 near the i-process nucleosynthesis peak.

Benchmark case and MC results

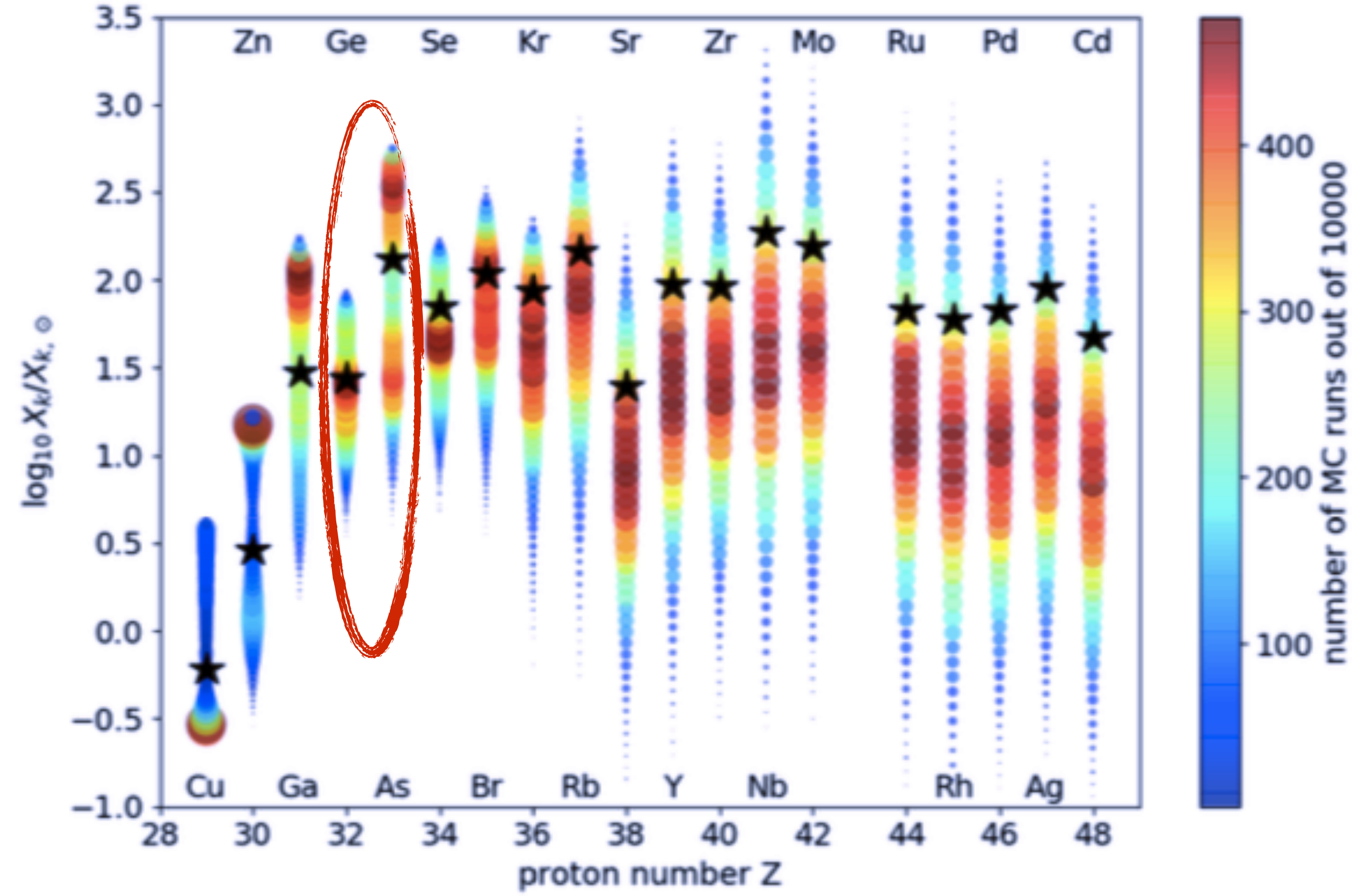
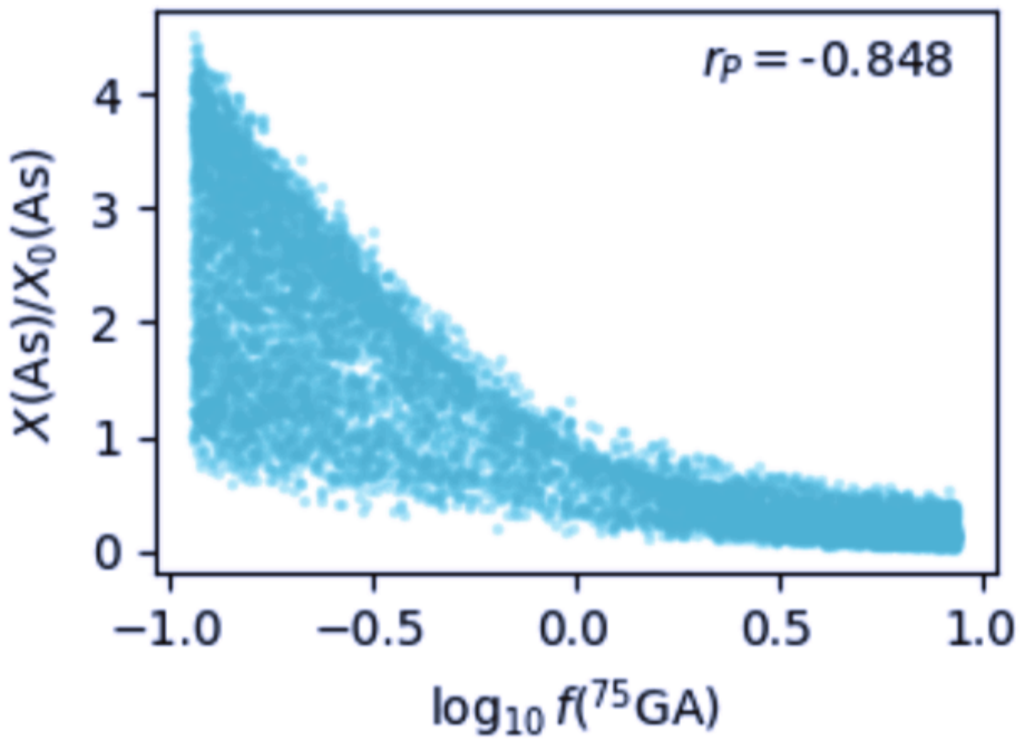


Figure 6. The distributions of the i-process elemental abundances generated in the Monte Carlo simulation by randomly varying (n,γ) reaction rates of the unstable isotopes that are displayed in Figure 1. The larger and redder circles correspond to a larger number of MC runs contributing to a given abundance. The black star symbols show the benchmark simulation abundances.

- In some cases, like here for As, the MC simulation yields a bimodal distribution corresponding to a specific branch point, in this case ^{75}Ga

Key importance of ^{75}Ga for As prediction

Correlation As abundance with ^{75}Ga cross section



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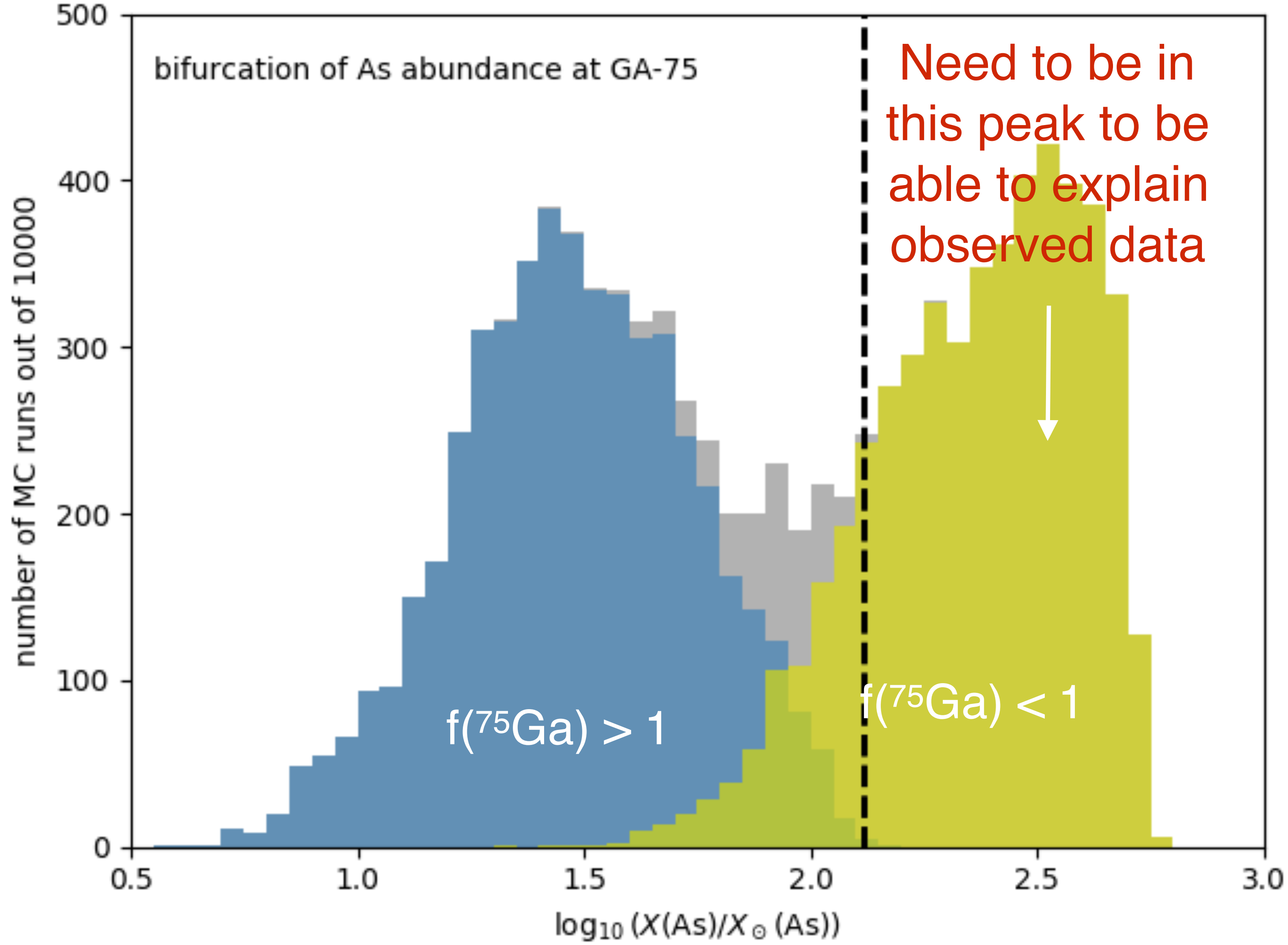
Benchmark case and MC results

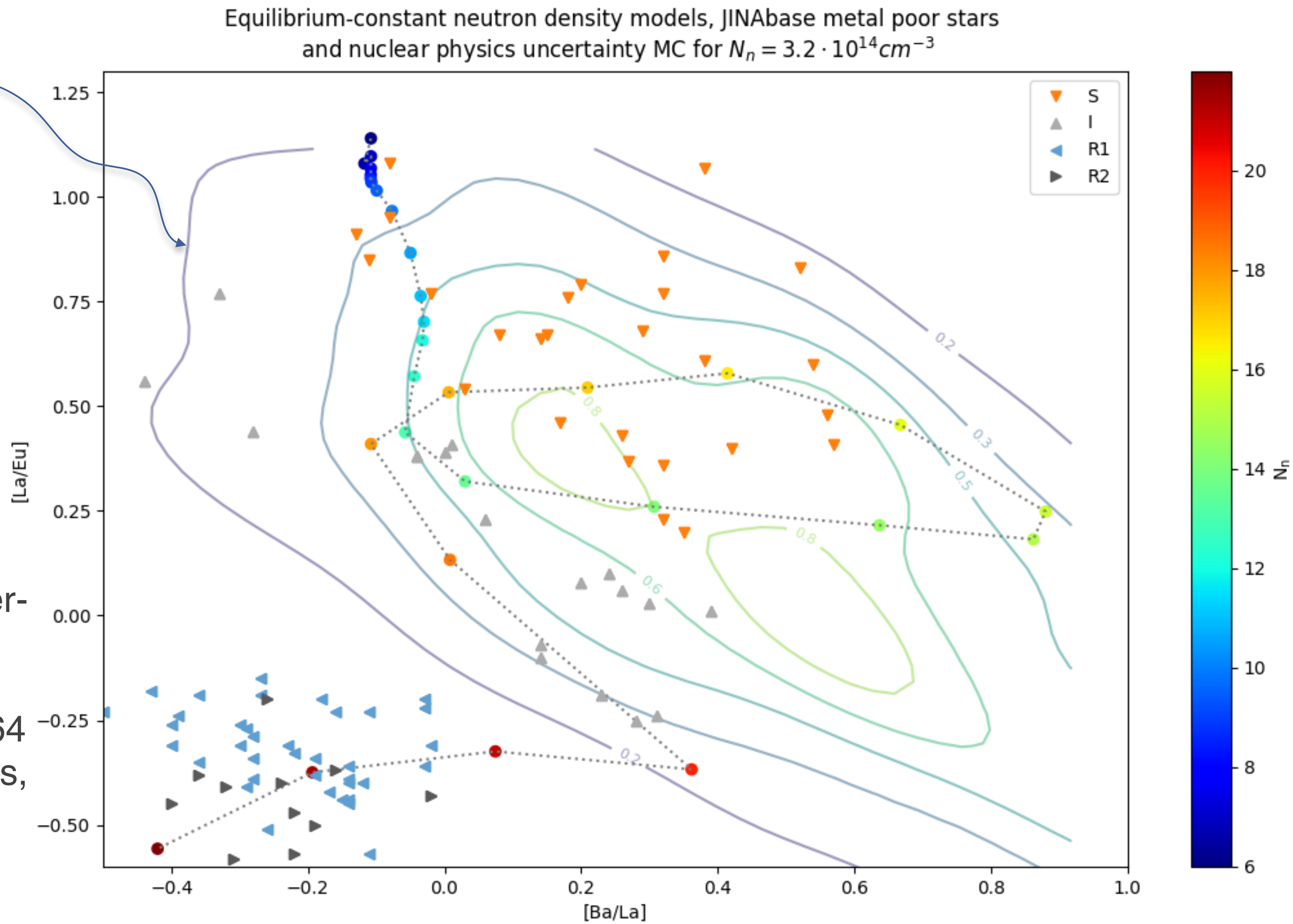


In order for i process to explain the observed [As/Ge] in HD94028 the ^{75}Ga(n,γ) cross section must be in lower part of range.

Second-peak nuclear physics impact study

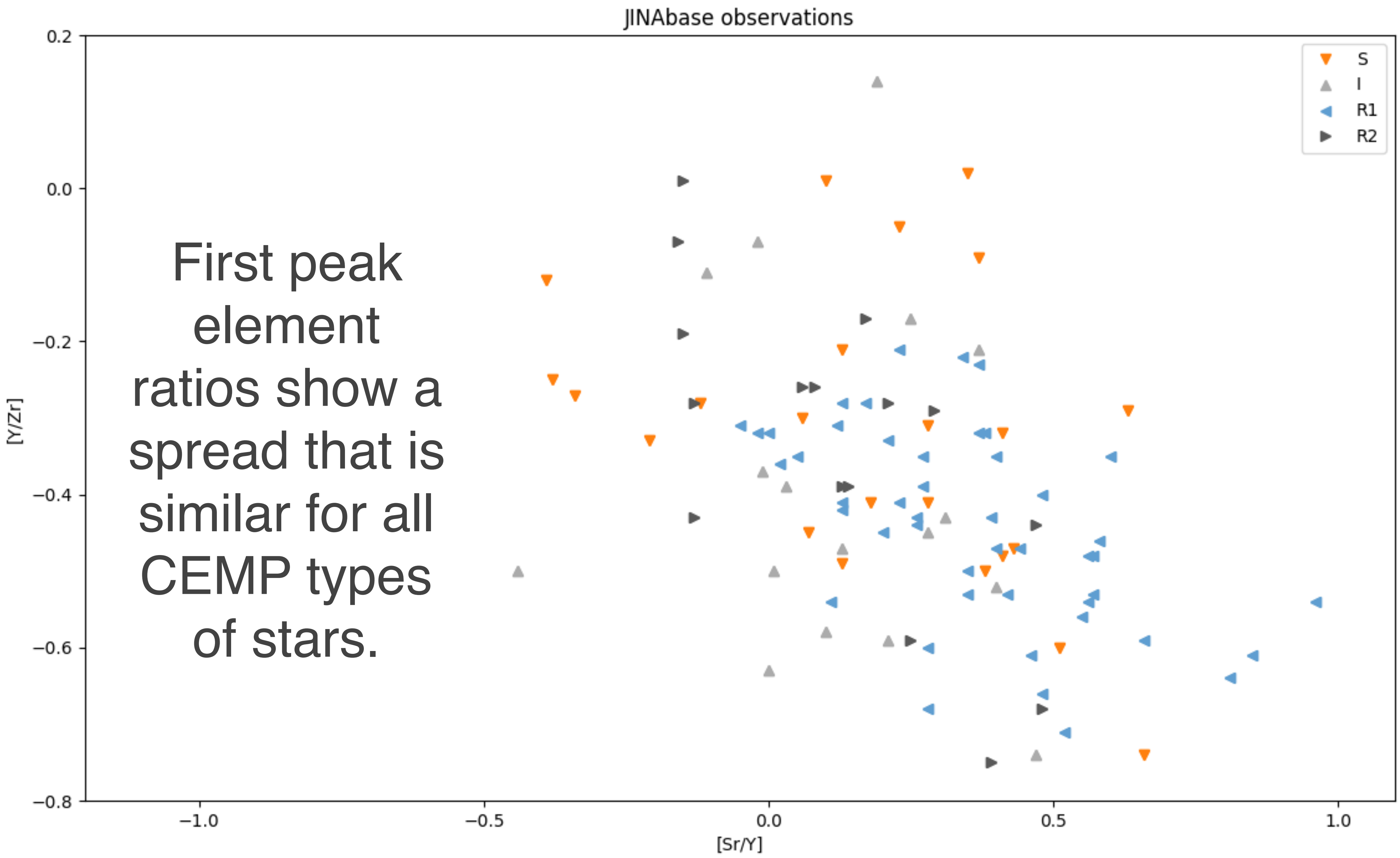
Contour lines: probability density nuclear physics uncertainties according to Monte-Carlo nuclear physics impact study.

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

First-peak elements metal-poor stars

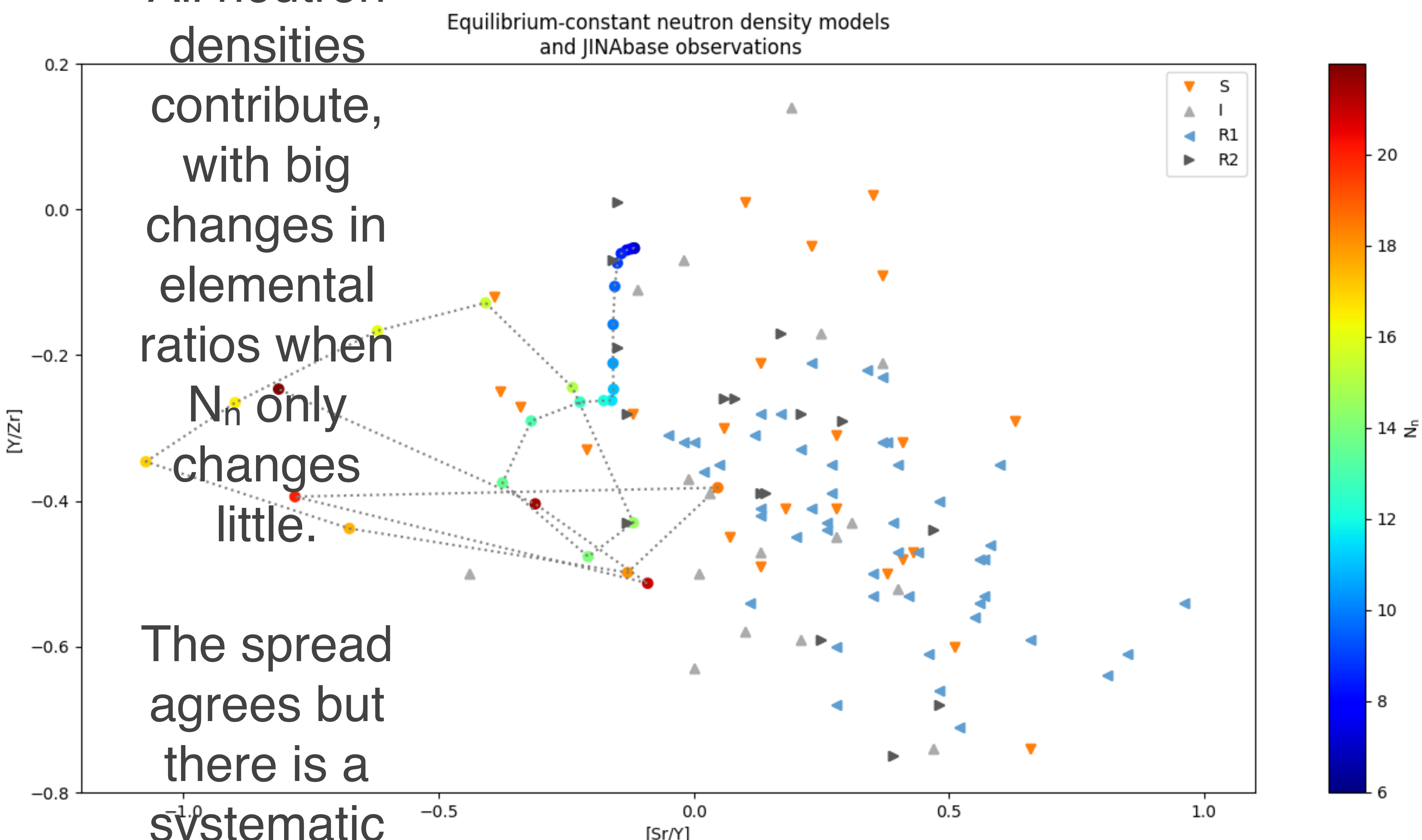


First peak element ratios show a spread that is similar for all CEMP types of stars.

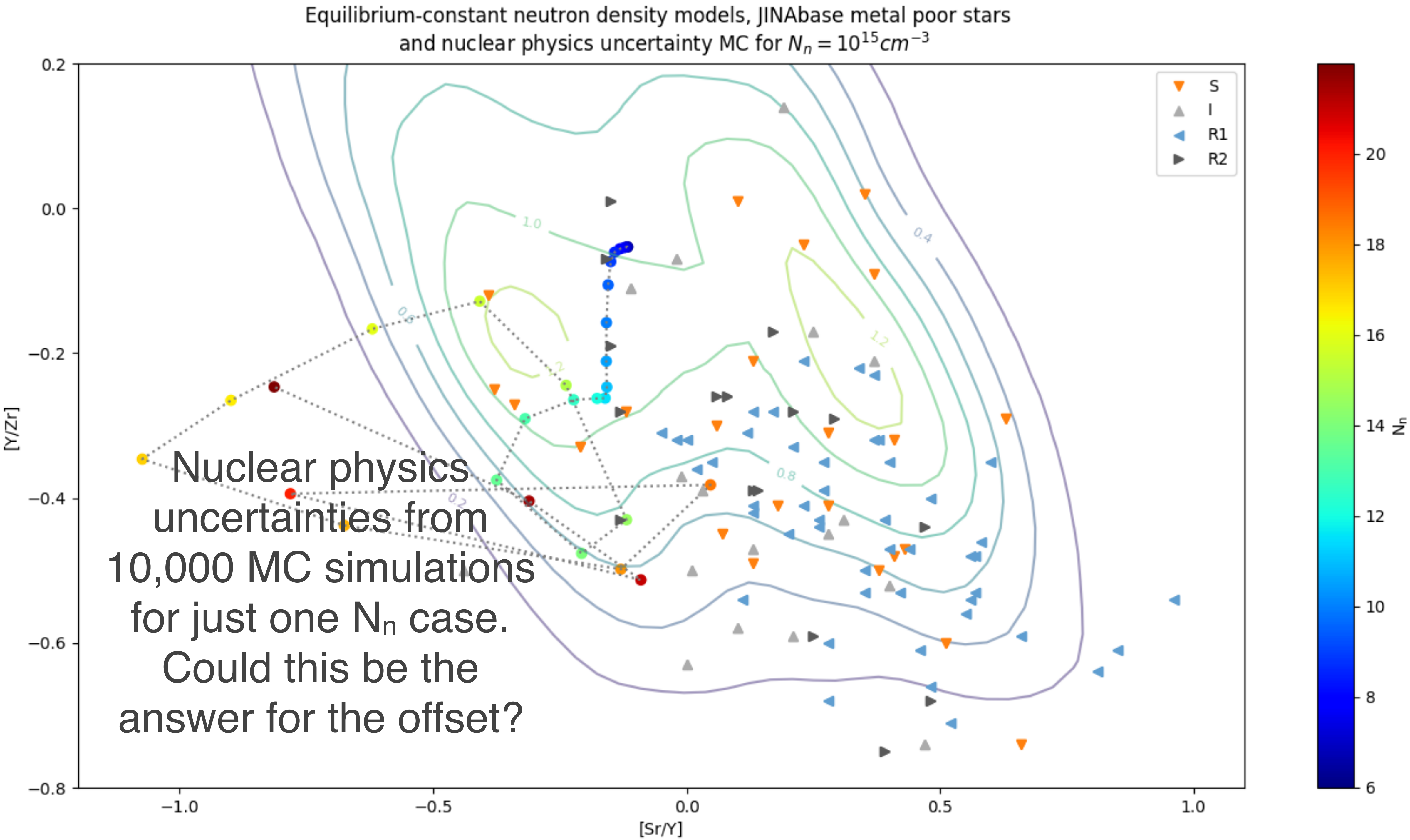
First-peak & constant neutron density models

All neutron densities contribute, with big changes in elemental ratios when N_n only changes little.

The spread agrees but there is a systematic offset.

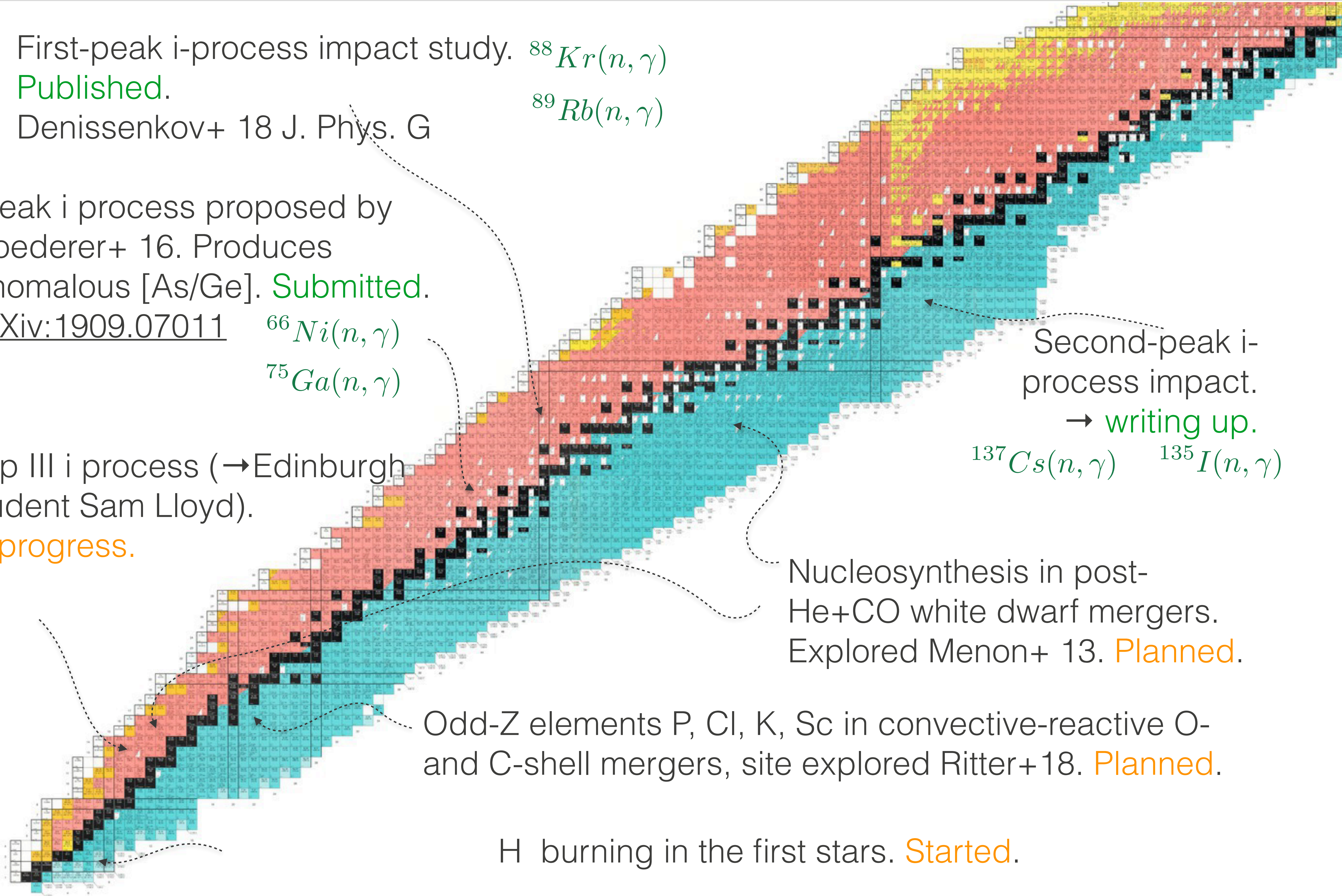


Nuclear physics impact



Nuclear physics uncertainties from 10,000 MC simulations for just one N_n case. Could this be the answer for the offset?

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



First-peak i-process impact study. Published.
Denissenkov+ 18 J. Phys. G
$^{88}Kr(n,\gamma)$
$^{89}Rb(n,\gamma)$

Weak i process proposed by Roederer+ 16. Produces anomalous [As/Ge]. Submitted.
arXiv:1909.07011
$^{66}Ni(n,\gamma)$
$^{75}Ga(n,\gamma)$

Pop III i process (→Edinburgh student Sam Lloyd). In progress.

Second-peak i-process impact. → writing up.
$^{137}Cs(n,\gamma)$ $^{135}I(n,\gamma)$

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

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

H burning in the first stars. Started.

Summary

- CEMP stars show the abundance signature of a wide range of neutron densities, including s and r, but also from intermediate neutron capture conditions
- i process is a unique neutron-capture process induced by convective H mixing into He-shell convection
- There are many potential i-process sites in massive and low-mass stars. Rapidly accreting white dwarfs naturally produce the right conditions, for example, for CEMP-r/s (CEMP-i) stars
- It is absolutely key to improve nuclear physics data for the i process, detailed impact studies are now available

Bibliography i process theory

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- **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 impact study: **Denissenkov** P, Perdikakis G, Herwig F, et al. 2018. (First peak elements) *Journal of Physics G Nuclear Physics*. 45(5):055203; **McKay** J, et al. 2019. (Weak i-process). *MNRAS*, submitted, astro-ph; **Denissenkov** et al. in prep. (Second-peak elements); **Lloyd** S, et al. in prep (Pop III light i process)