Galactic chemical evolution contributions to first-peak elements (Z=34-42) from i process in rapidly accreting white dwarfs

Benoit Côté (MSU/UVic)
Pavel Denisenkov (UVic)
Christian Ritter (Keele/UVic)
Robert Andrassy (UVic)
Paul Woodward (LCSE, Minnesota)

Falk Herwig
University of Victoria

UVic 2016

Pavel Denissenkov
i process uncertainty, RAWDs,
globular cluster stars

Austin Davis
hydro, massive stars

Robert Andrassy
1D3D, hydro sims

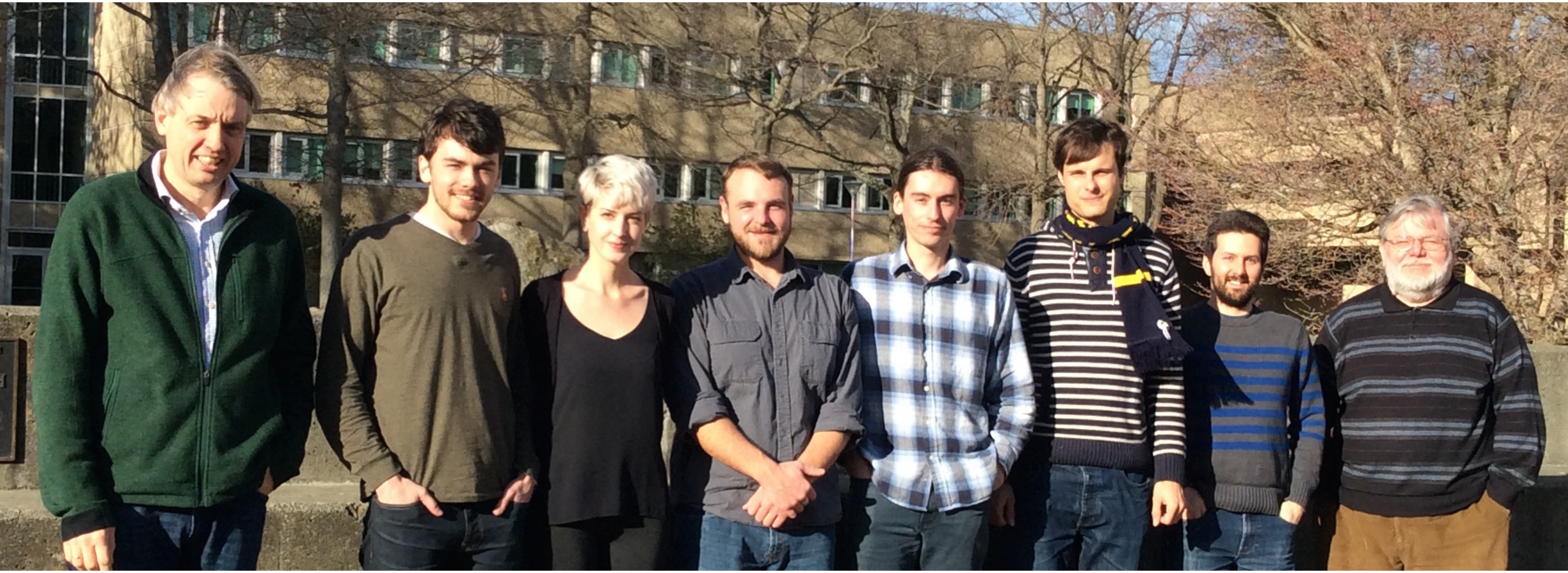
Benoit Côté
w/ O'Shea, MSU
NuPyCEE

Adam Paul
r process in NuPyCEE

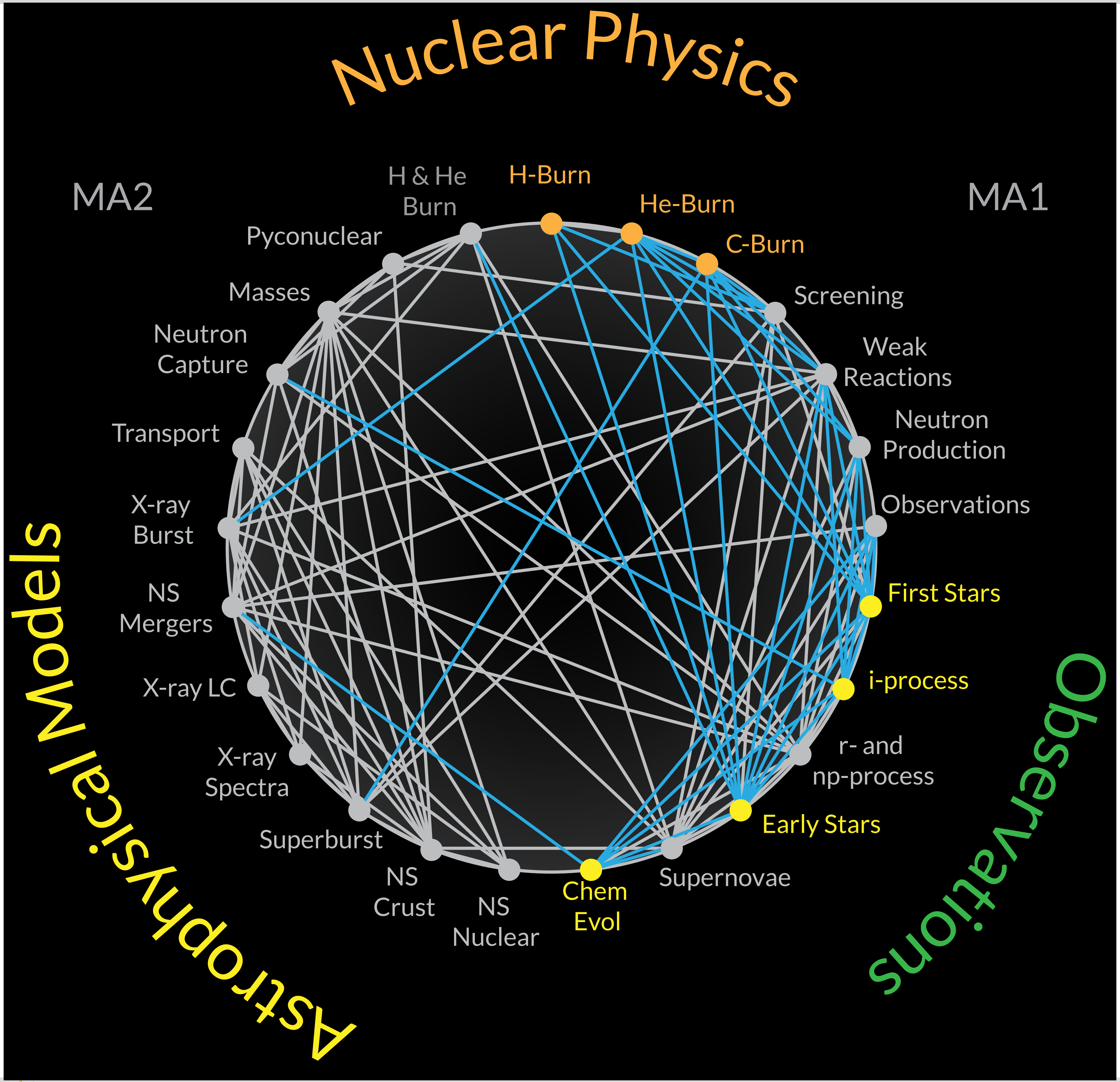
Christian Ritter
NuGrid yields, NuPyCEE
3D post-processing

Ondrea Clarkson
Pop III nucleosynthesis

Falk Herwig



Forging connections in the JINA-CEE Physics Frontier Center



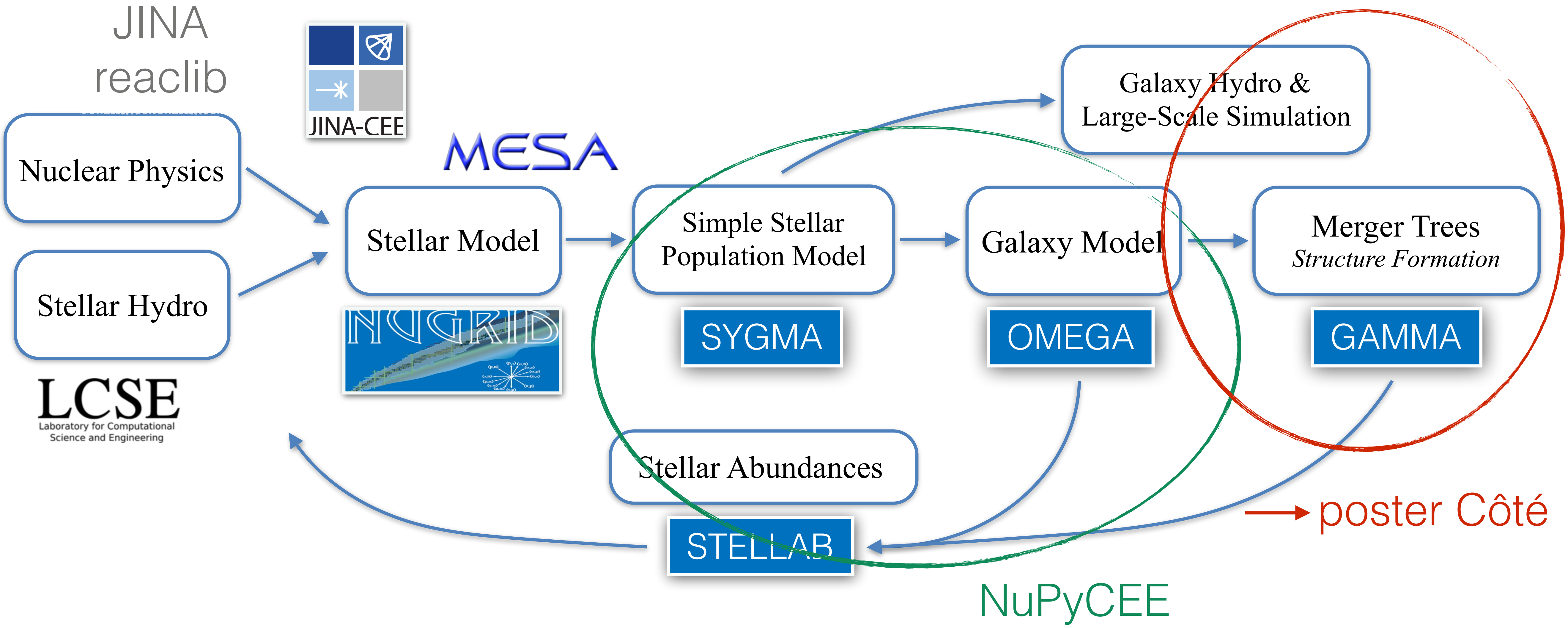
Joint Institute for Nuclear Astrophysics - Center for the Evolution of the Elements

- rise of the elements in the early universe
- nucleosynthesis in dynamically mixed stellar environments
- stellar hydrodynamics - macro physics for stellar models
- nuclear physics impact - microphysics for stellar models
- nuclear production in stars and stellar explosions
- galactic chemical evolution and associated observables

Forging connections between fundamental nuclear and stellar physics - and cosmological chemical evolution

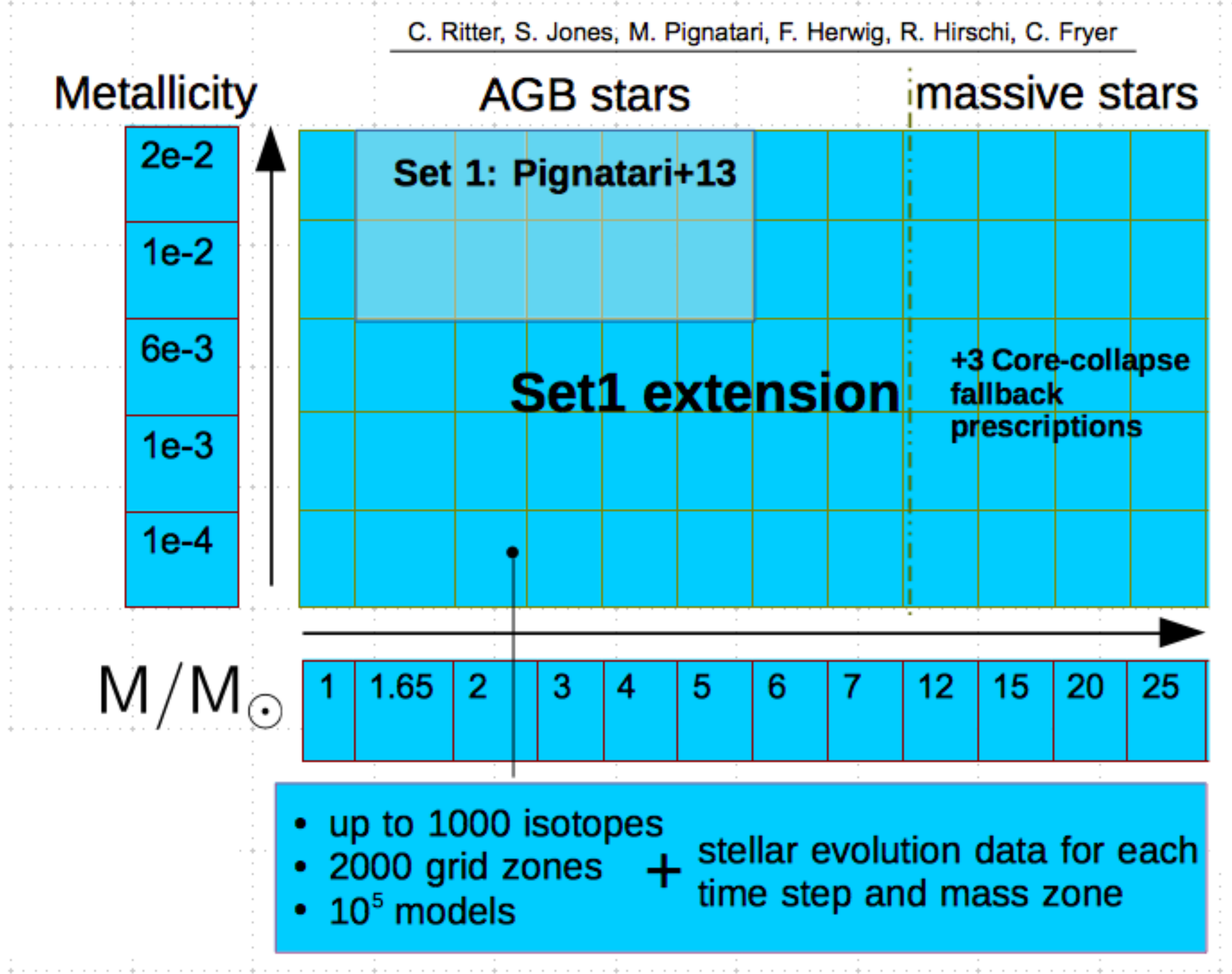
- JINA-CEE is about connecting a diverse set of islands of expertise

Create“pipelines” - this is one of them …



- tools, platforms, frameworks to establish persistent links/bridges between these islands → the JINA-CEE archipelago

NuGrid/JINA stellar models and yield data



C. Ritter, S. Jones, M. Pignatari, F. Herwig, R. Hirschi, C. Fryer

Metallicity

2e-2

1e-2

6e-3

1e-3

1e-4

AGB stars

massive stars

Set 1: Pignatari+13

Set1 extension

+3 Core-collapse fallback prescriptions

$M/M_\odot$

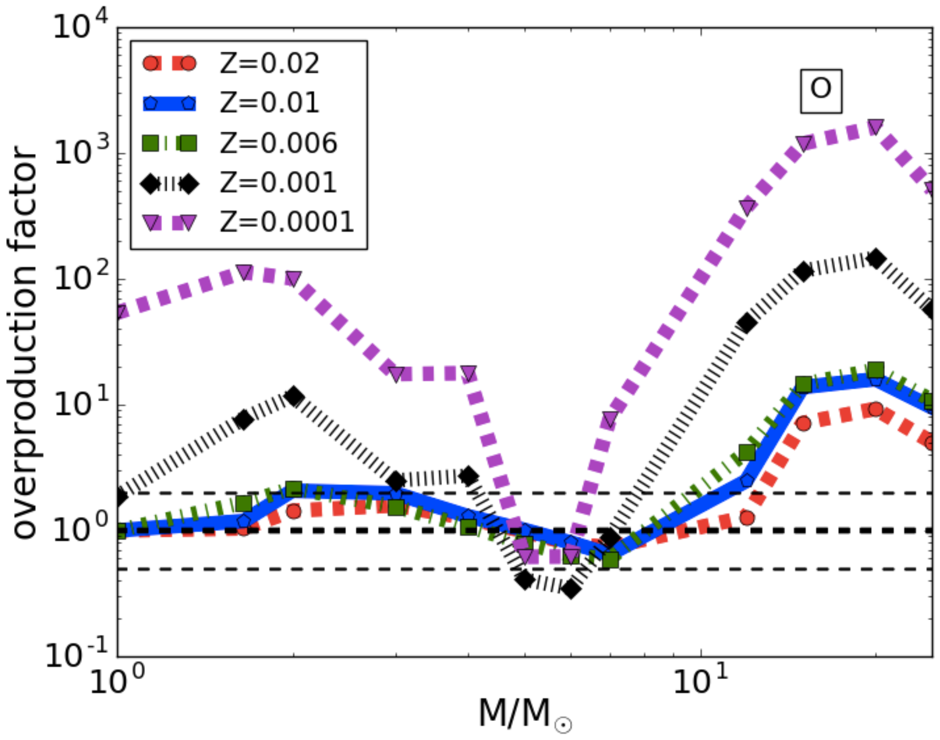
1	1.65	2	3	4	5	6	7	12	15	20	25

- up to 1000 isotopes
- 2000 grid zones
- 10^5 models

\+ stellar evolution data for each time step and mass zone

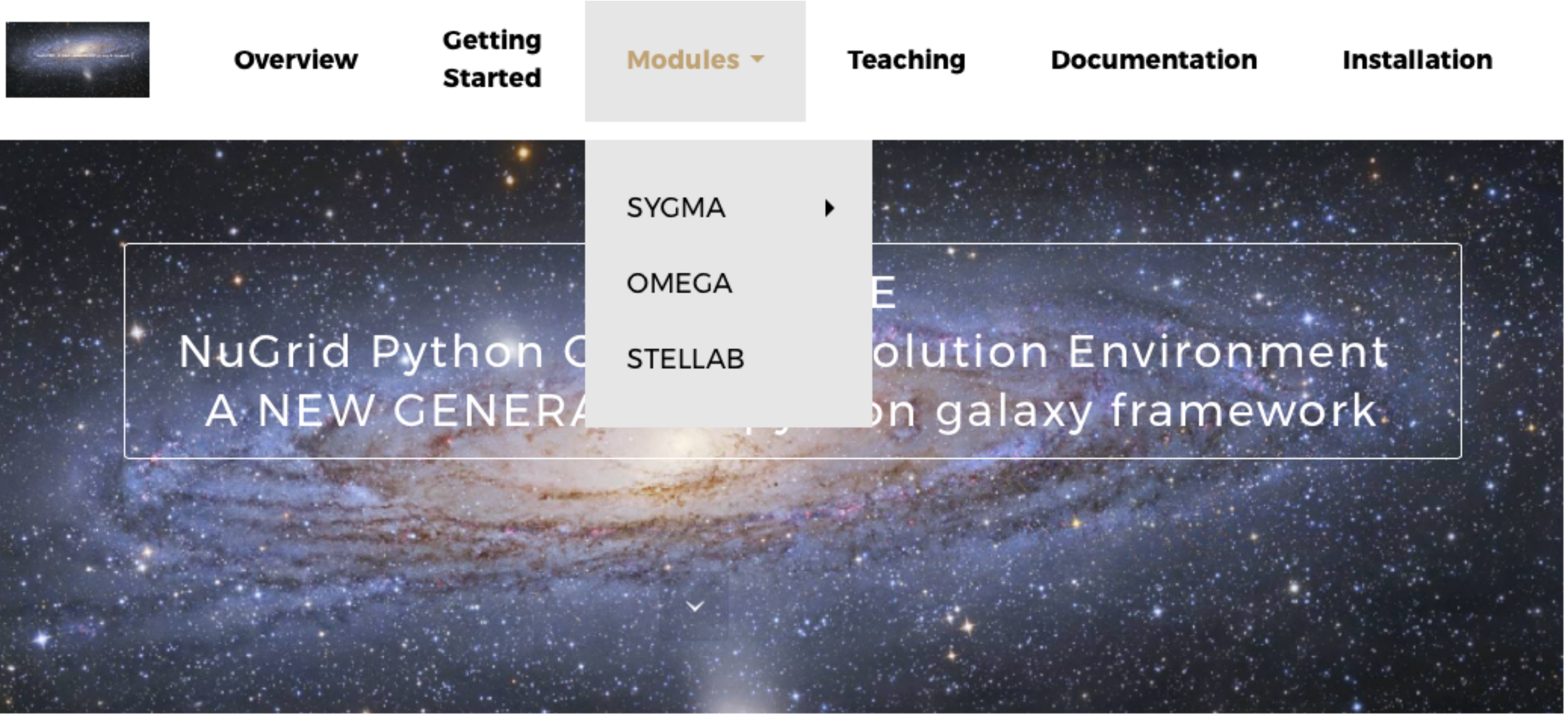
Ritter+ 17, submitted?

- ➤ Yields
- ➤ complete abundance profiles for all isotopes every 20 time steps
- ➤ SYGMA: Stellar Yields for Galactic Modeling Applications
- ➤ OMEGA: One-Zone Model for the Evolution of Galaxies
- ➤ WENDI: online jupyterhub based platform to access, explore, share and analyse NuGrid data (https://astrohub.uvic.ca - still evolving, subject to change)



A JINA NuGrid project:
NuGrid Python Chemical Evolution Environment

http://nugrid.github.io/NuPyCEE



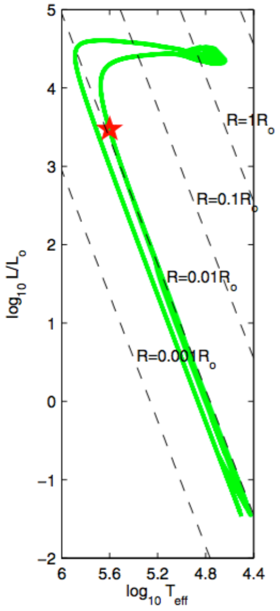
University of Victoria

JINA–CEE

Benoit Côté *poster*
Christian Ritter *poster*

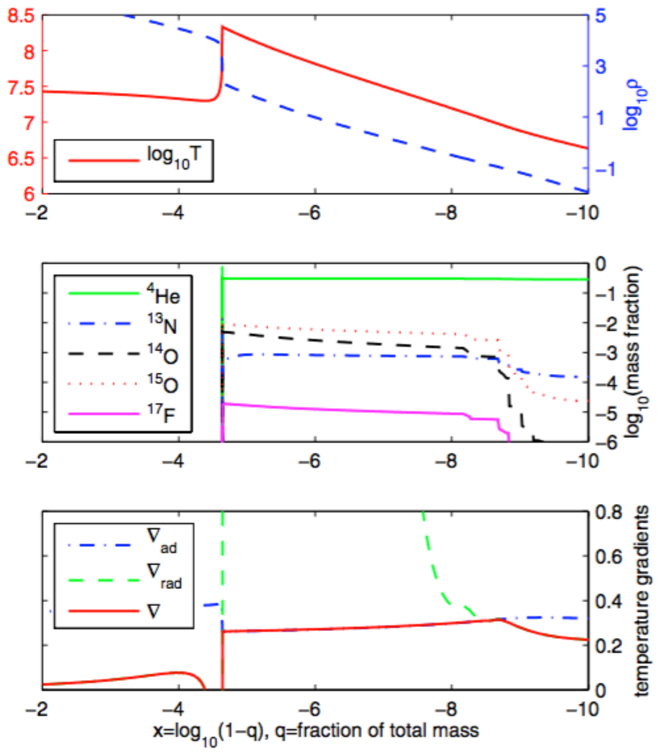
Côté+ 17 NIC XIV, doi: 10.7566/JPSCP.14.020203

With this network and tools - study new nuclear and stellar astrophysics and address astronomy challenges

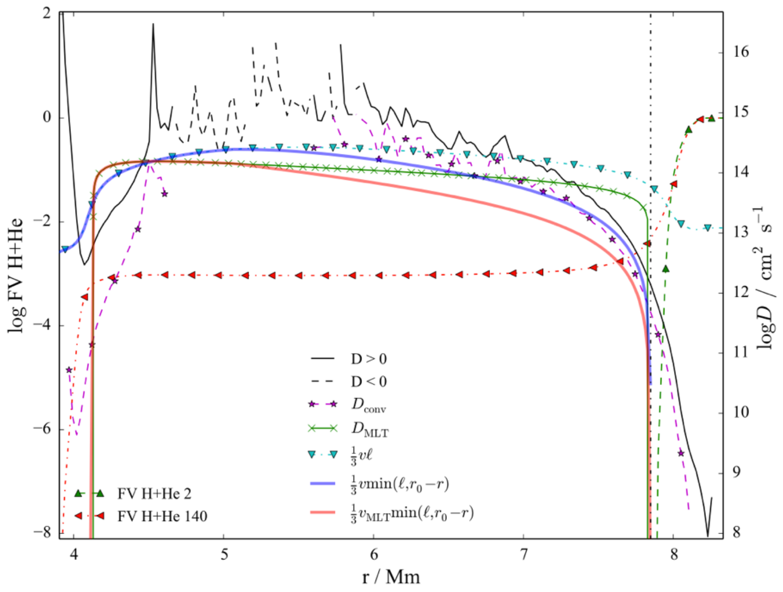


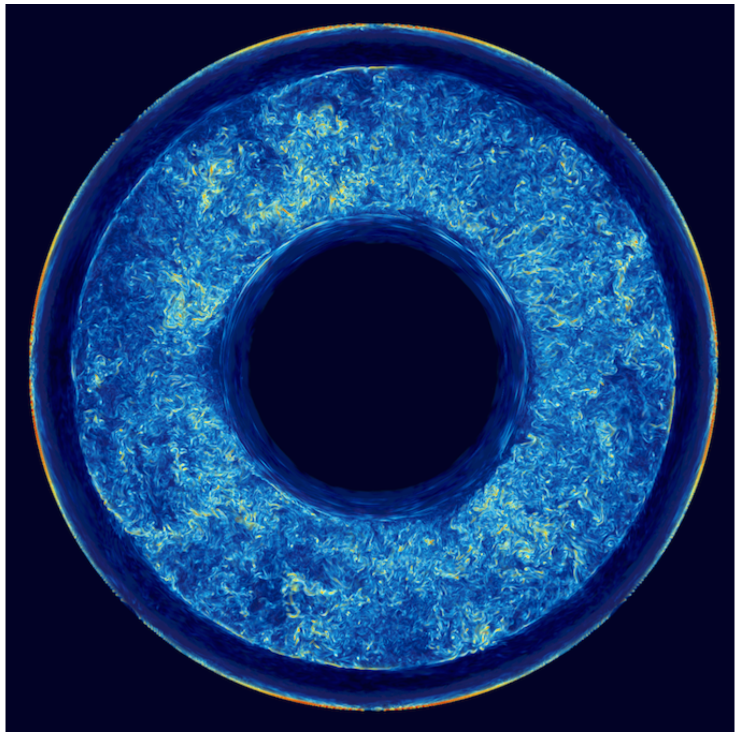
JINA **nova** framework project (Denissenkov+ 12, +13, with UCSB, TRIUMF and Chicago):

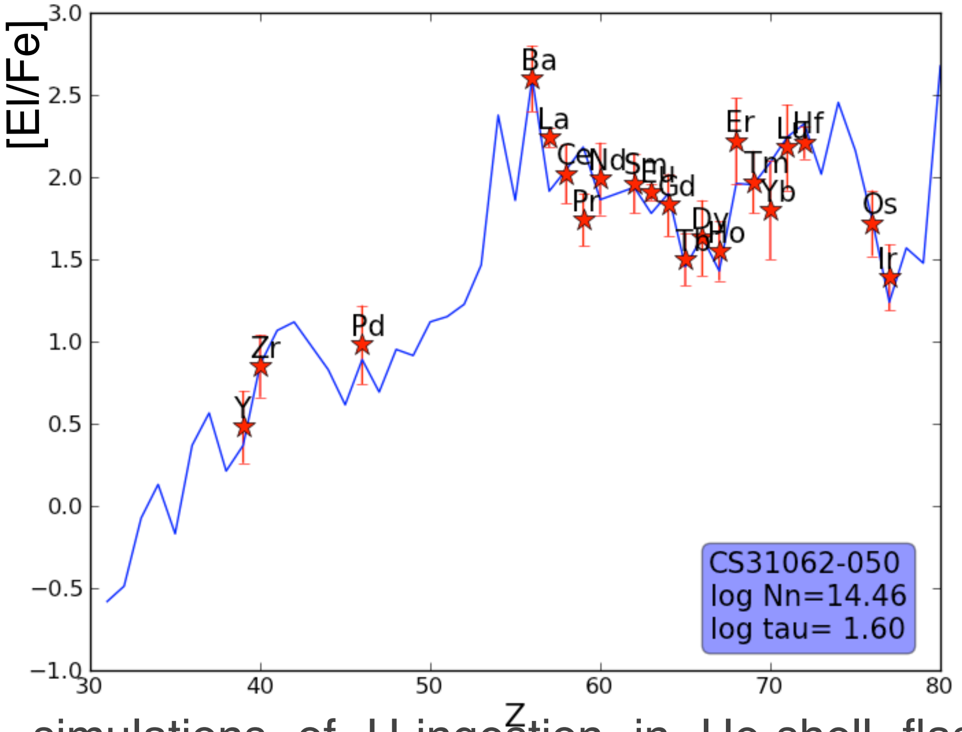
- recurrent H-shell flashes in accreting white dwarfs
- demonstrate (again) importance of convective boundary mixing



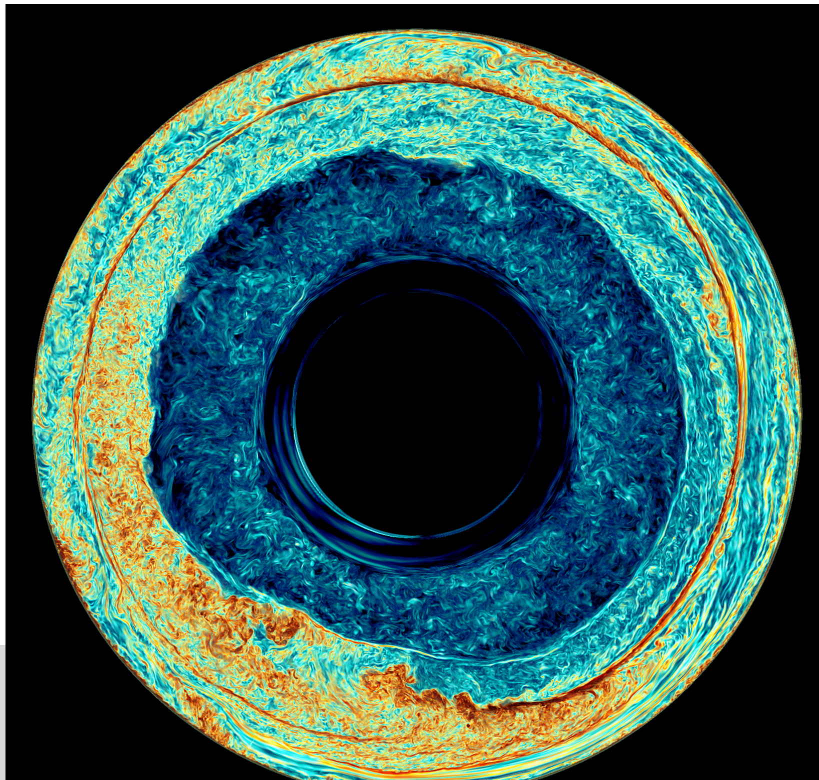
3D simulations of O-shell convection in **massive stars** and calibration of 1D mixing models for stellar evolution (Jones+ 17).



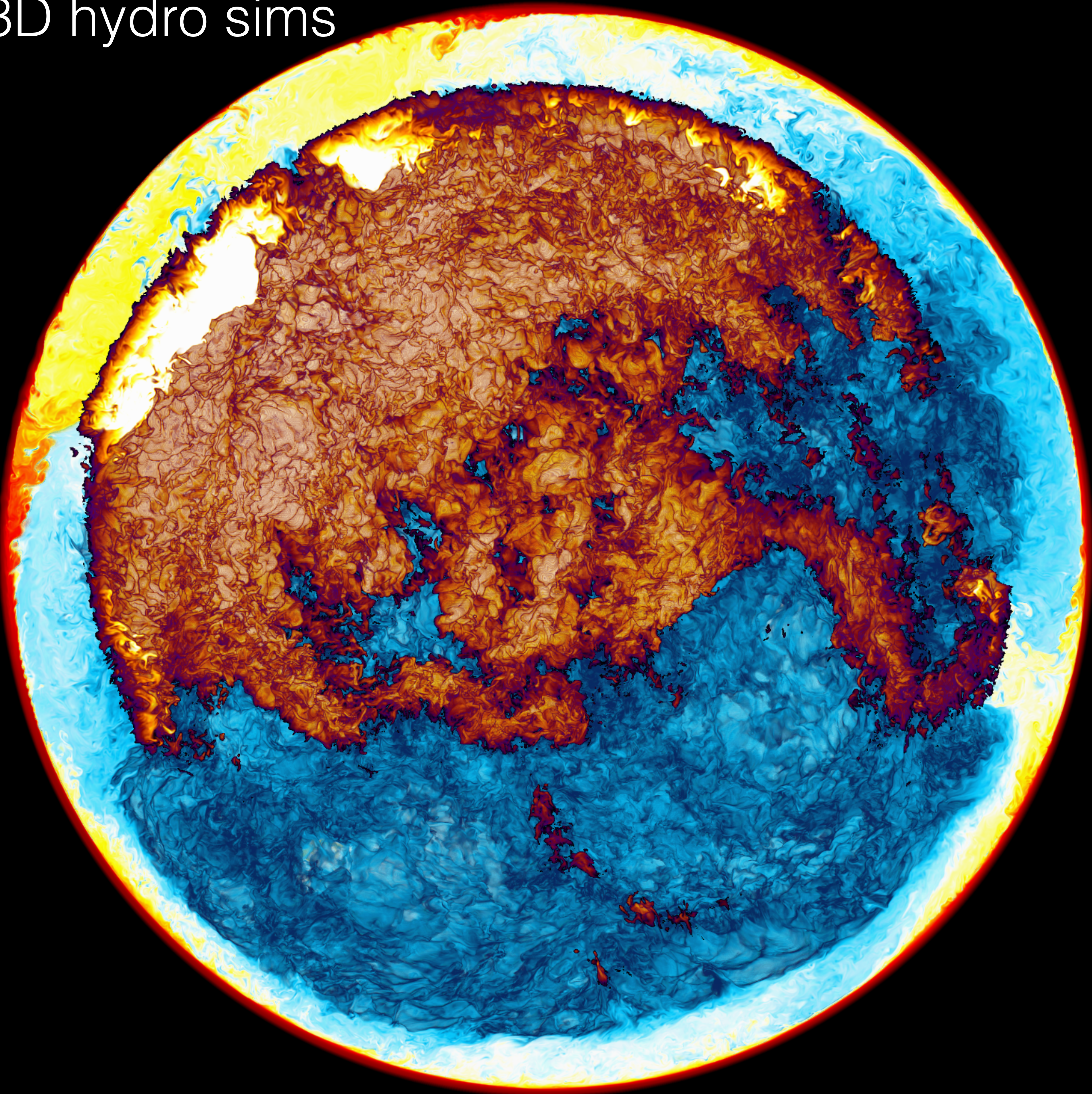




3D simulations of H-ingestion in He-shell flash convection in **low-mass stars** - **G**lobal **O**scillations of **S**hell **H**-ingestion and i-process nucleosynthesis (Herwig+14, Dardelet+14, Woodward+15)



3D hydro sims



Sakurai's Object H-ingestion simulation on Blue Waters machine in Jan., 2014, on a grid of 1536^3 cells.

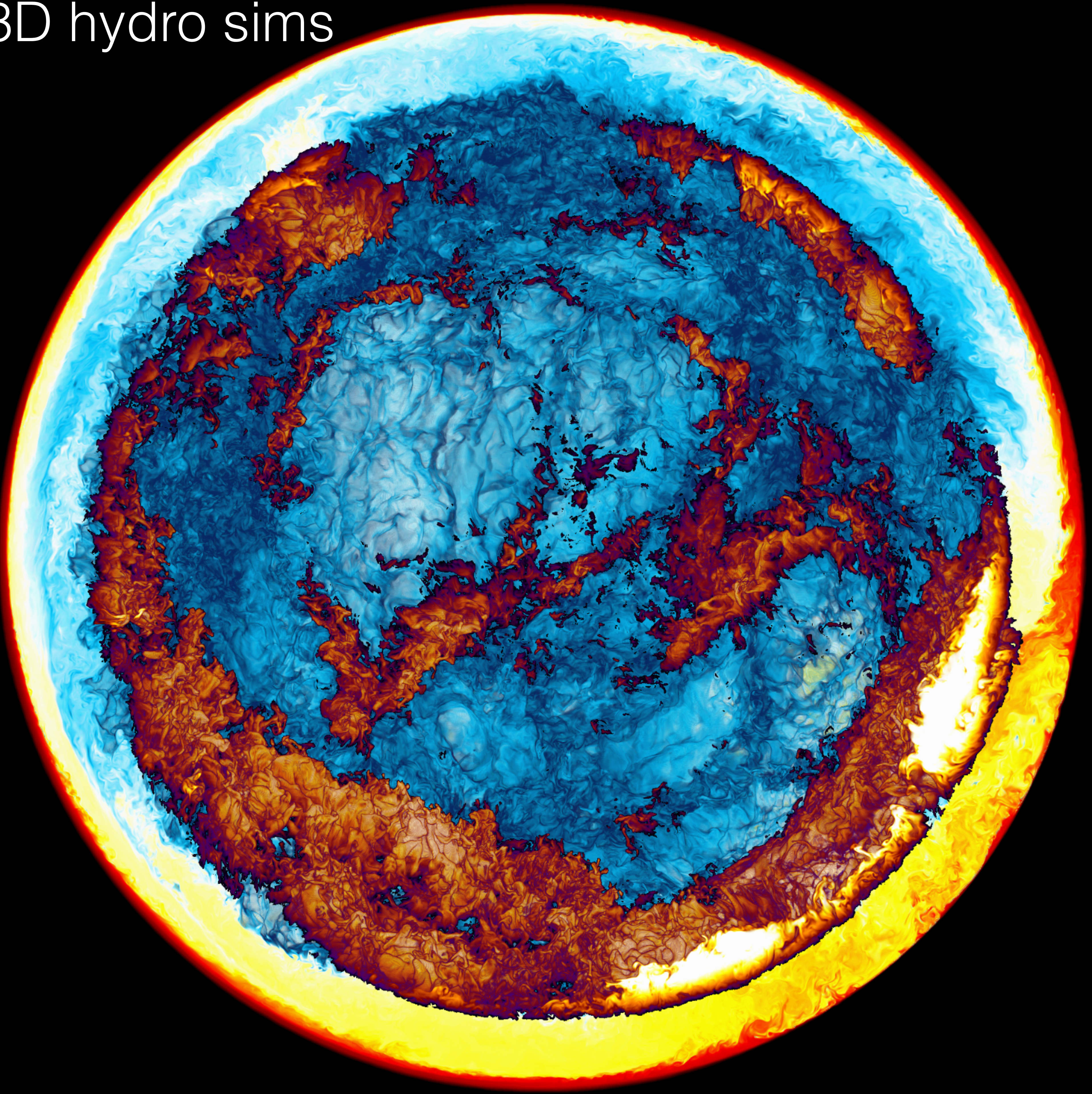
The burning front has now reached the antipode, where violent,
localized energy release drives the oscillation back
to its original site.

t = frame 1188

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

Slide from Paul Woodward

3D hydro sims



Sakurai's Object H-ingestion simulation on Blue Waters machine in Jan., 2014, on a grid of 1536^3 cells.

Once the GOSH quiets down, after about a day in the life of this star, we can be well justified in carrying our description of the star forward with a 1-D stellar evolution code, suitably modified.

t = frame 1212

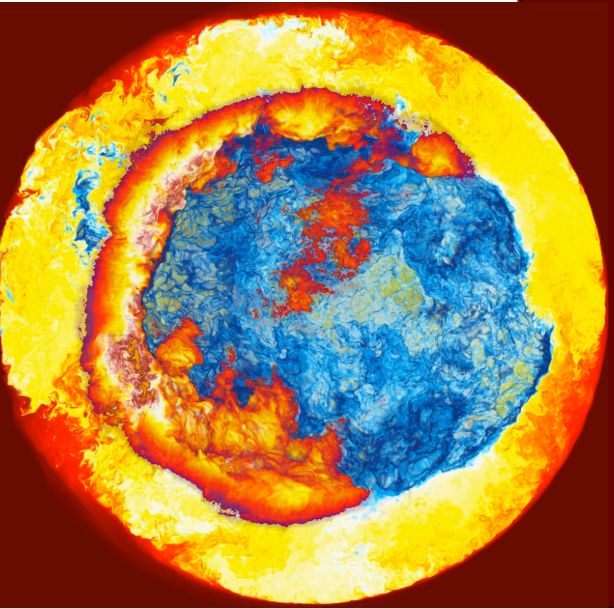
Two different color scales show entrained fluid and nuclear energy release.

Slide from Paul Woodward

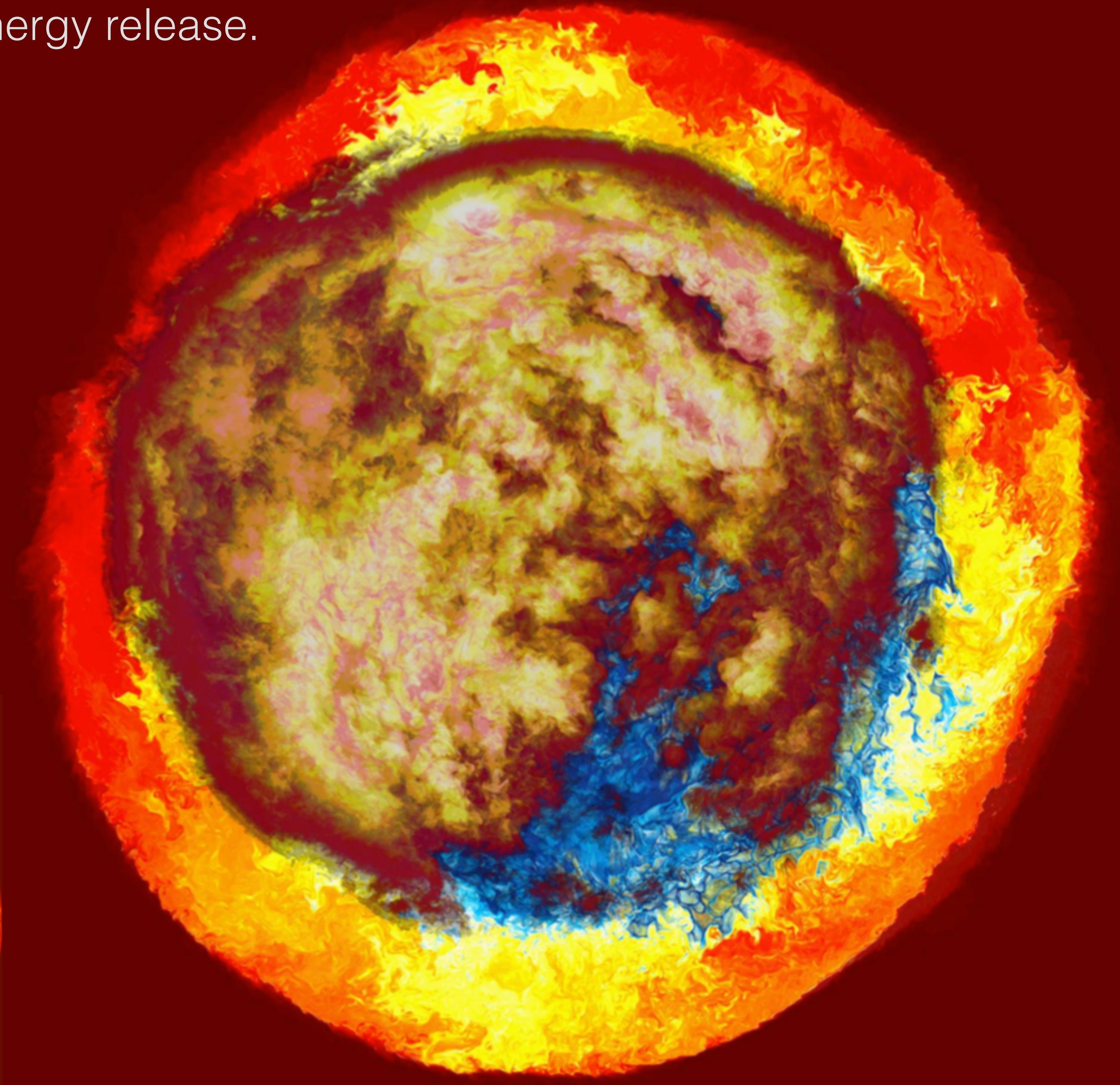
Low-Z AGB H-ingestion into He-shell flash

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

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



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



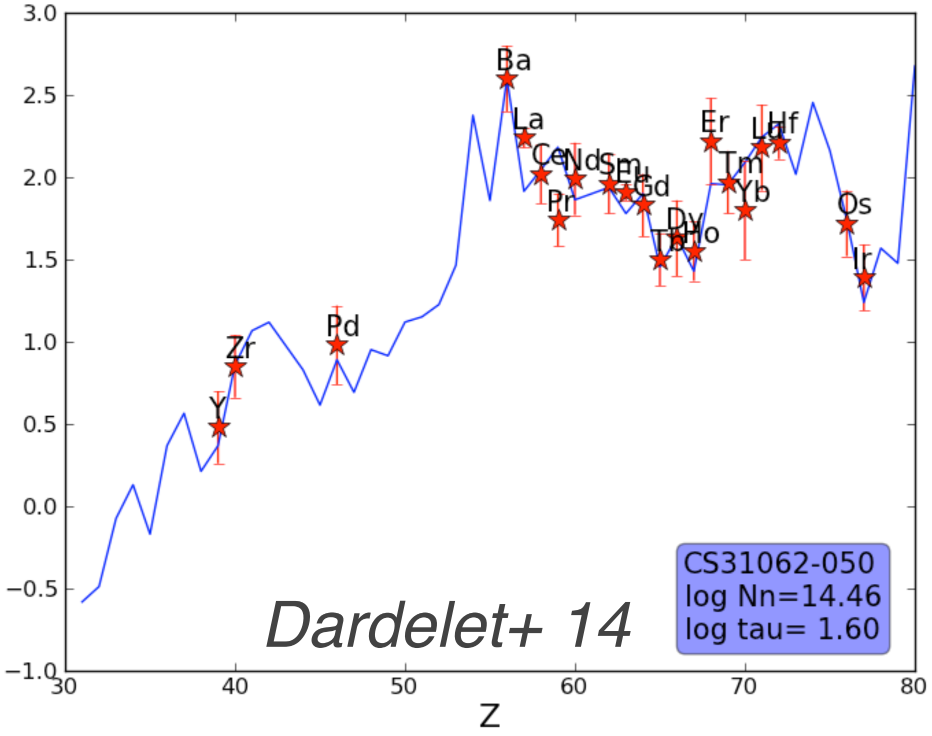
$2\ M_{sun}$, $Z = 10^{-5}$
AGB star
H-ingestion
simulation on Blue
Waters machine
on a
grid of 1536^3 cells.

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.

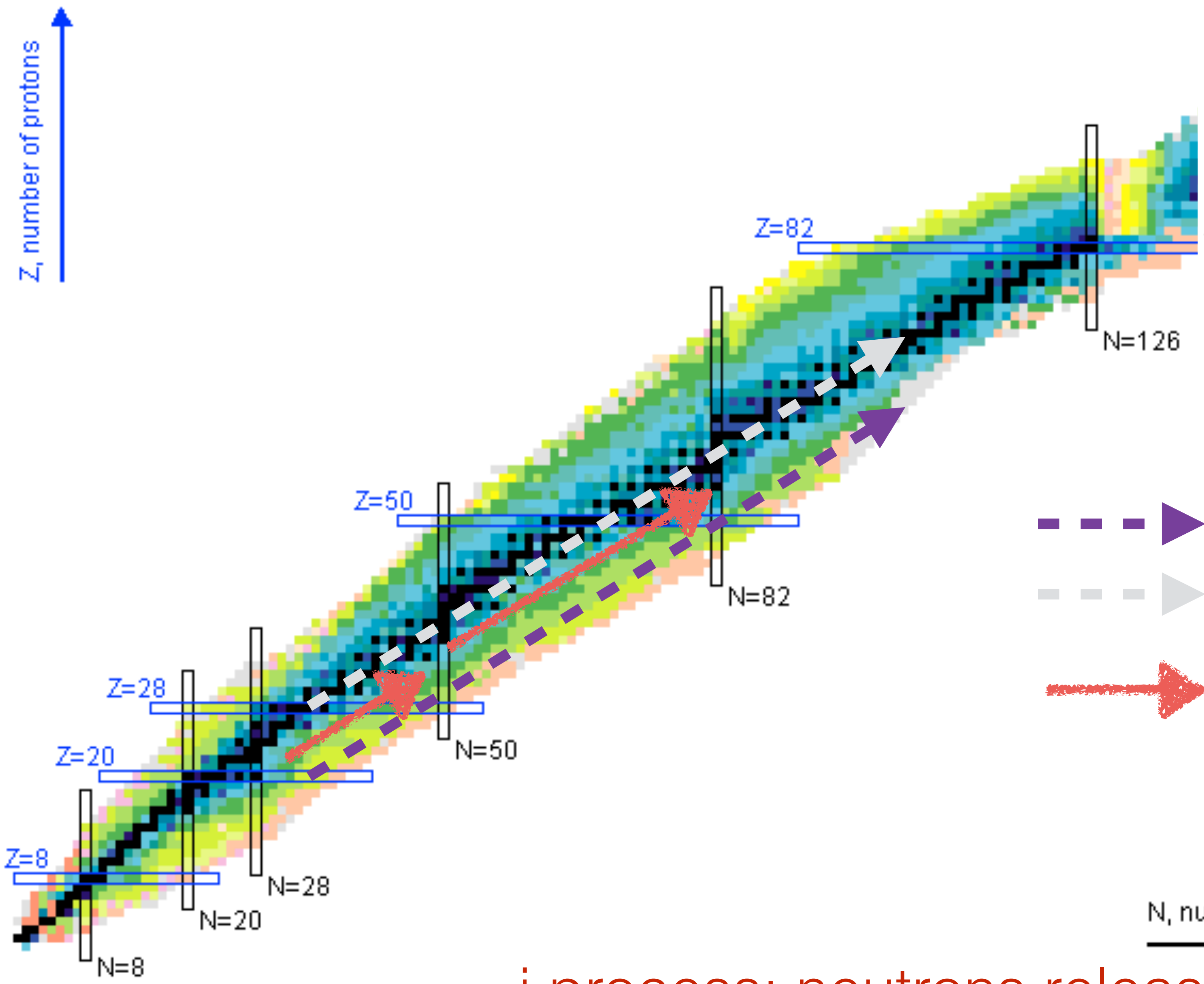
t = 2703.7 min.

Paul Woodward
NSF BlueWaters

Neutron capture processes



see also Hampel+ 16



}

standard model
(s and r process)

new: i process

i process: neutrons released on dynamical time scale of H ingestion into convective He burning

→ convective-reactive nucleosynthesis

http://www.nndc.bnl.gov

i process in rapidly accreting white dwarfs

- **building on previous JINA nova expertise:** first multi-cycle He-shell flash simulations of rapidly accreting white dwarfs (using MESA)

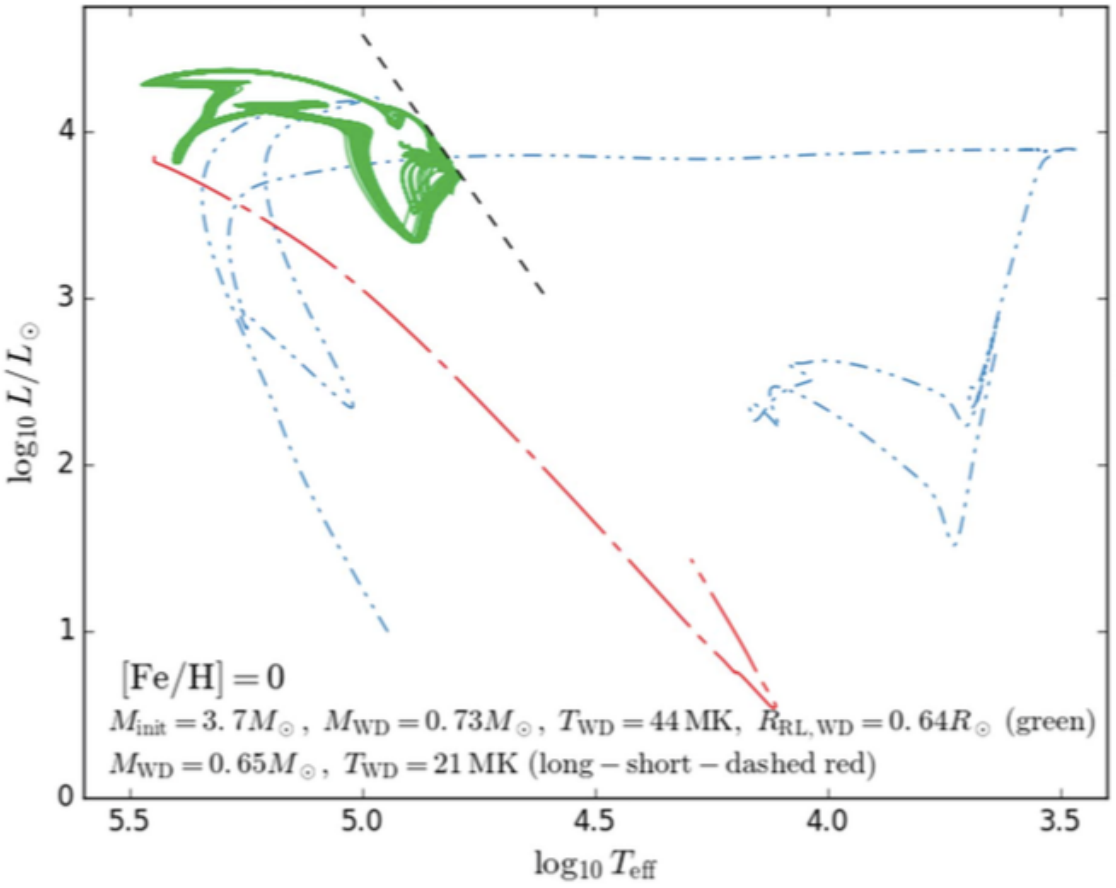


Figure 1. Tracks of progenitor and post-AGB evolution of 0.73 $M_\odot$ WD (double-dot–short-dashed blue line; see text for details) and multiple He-shell flashes with H-ingestion cycles in model B (green line). The flash causes the star to expand to the WD Roche-lobe radius (dashed black line) and lose the accreted material via the Roche-lobe overflow. The short–long-dashed red curve is a fragment of the track of model A during its second He-shell flash.

Denissenkov+ 17, ApJ 834, L10

- **Important result 1:** He-mass accretion is very small or even negative (depending on convective boundary mixing parameter)
- makes single-degenerate evolutionary pathway to SN Ia very unlikely!

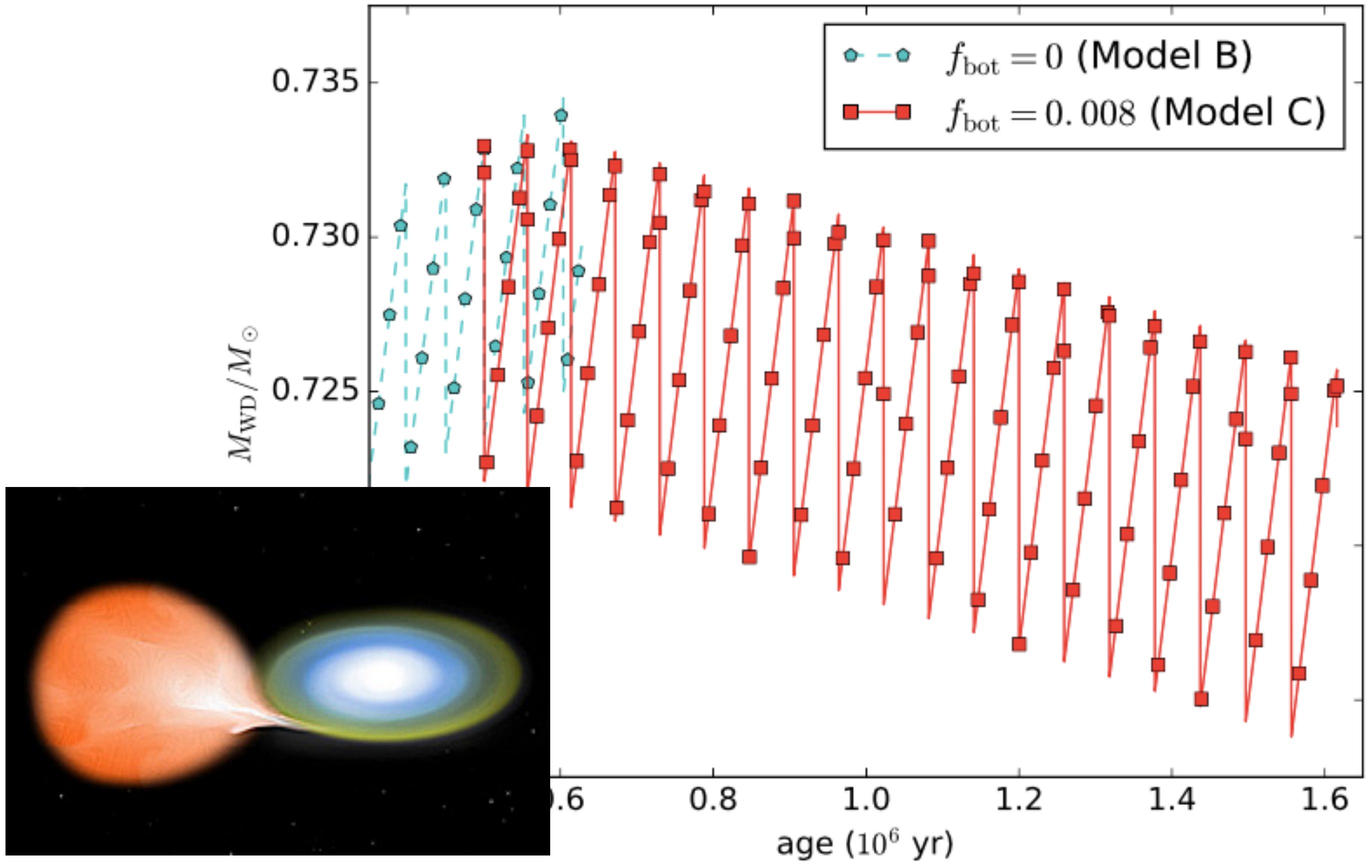


Figure 2. Evolution of the total mass of the 0.73 $M_\odot$ RAWD model B without CBM ($f_{\rm bot}=0$) and model C with CBM ($f_{\rm bot}=0.008$). Each of the saw-tooth-shaped features represents the mass increase during the accretion phase followed by mass ejection in Roche-lobe overflow (model B) or Eddington-luminosity mass loss (model C) triggered by the He-shell flash.

i process in rapidly accreting white dwarfs

Important result 2:

- He-shell flashes feature **H-ingestion** (hydro sims show no global oscillation in this case)
- these launch neutron-capture nucleosynthesis, just as in our previous work on post-AGB star Sakurai's object, with large (2-3 dex) production of first-peak elements at near-solar metallicity

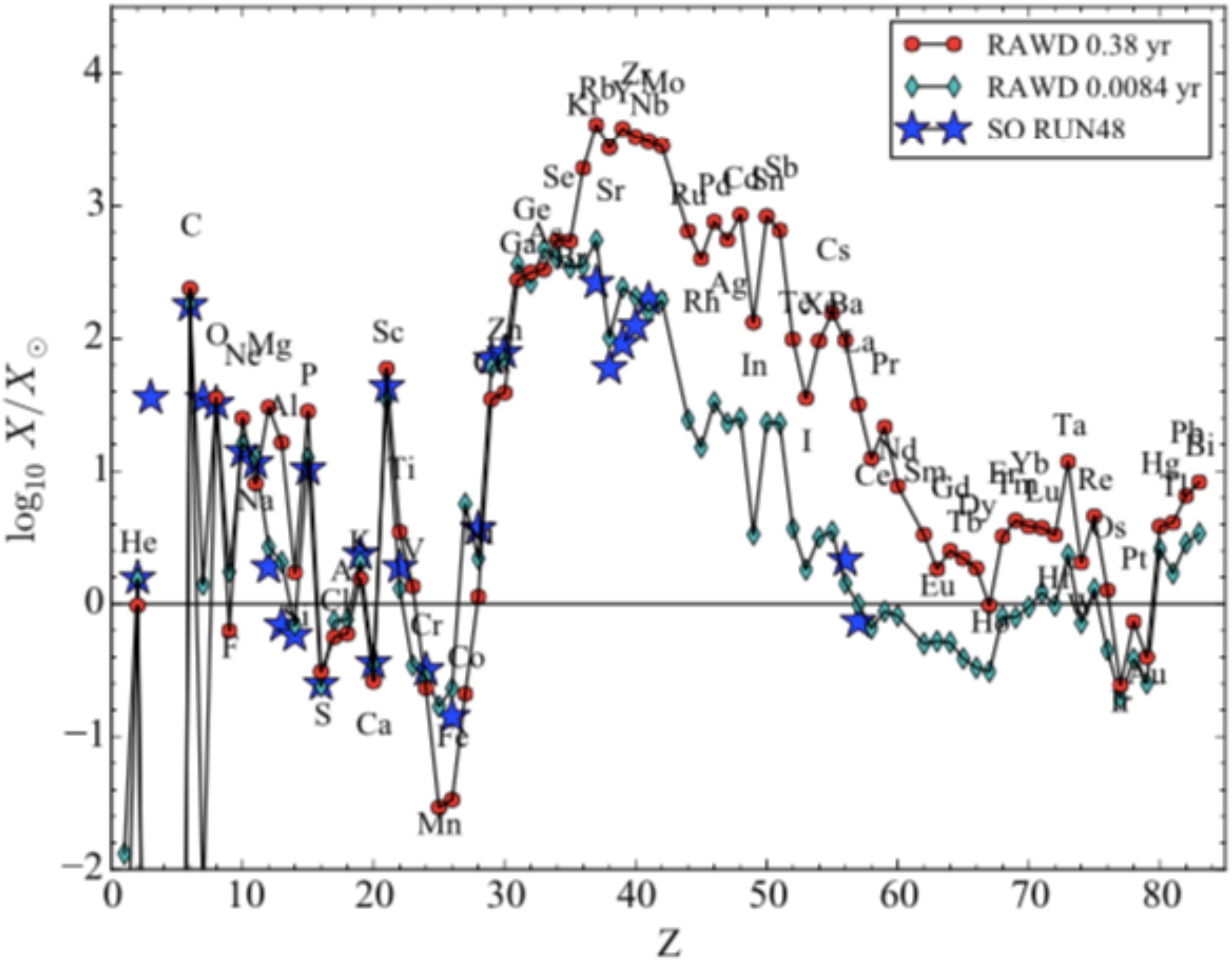
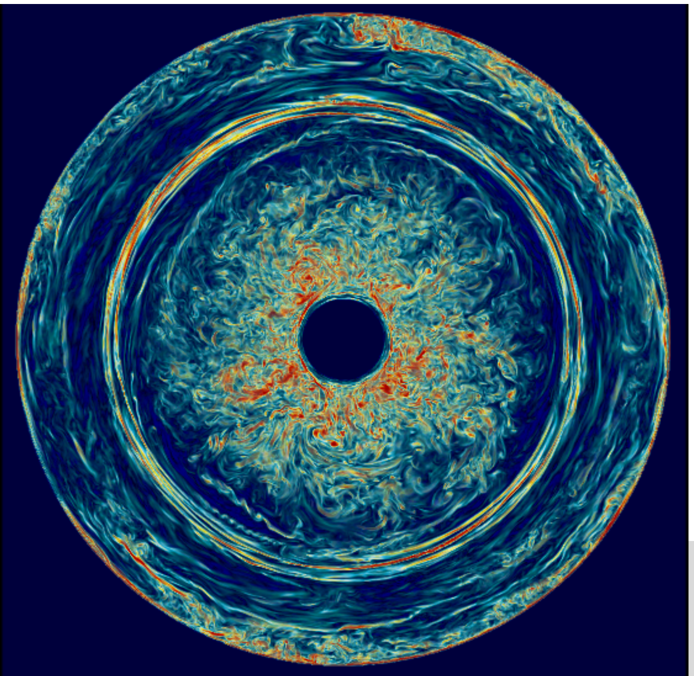


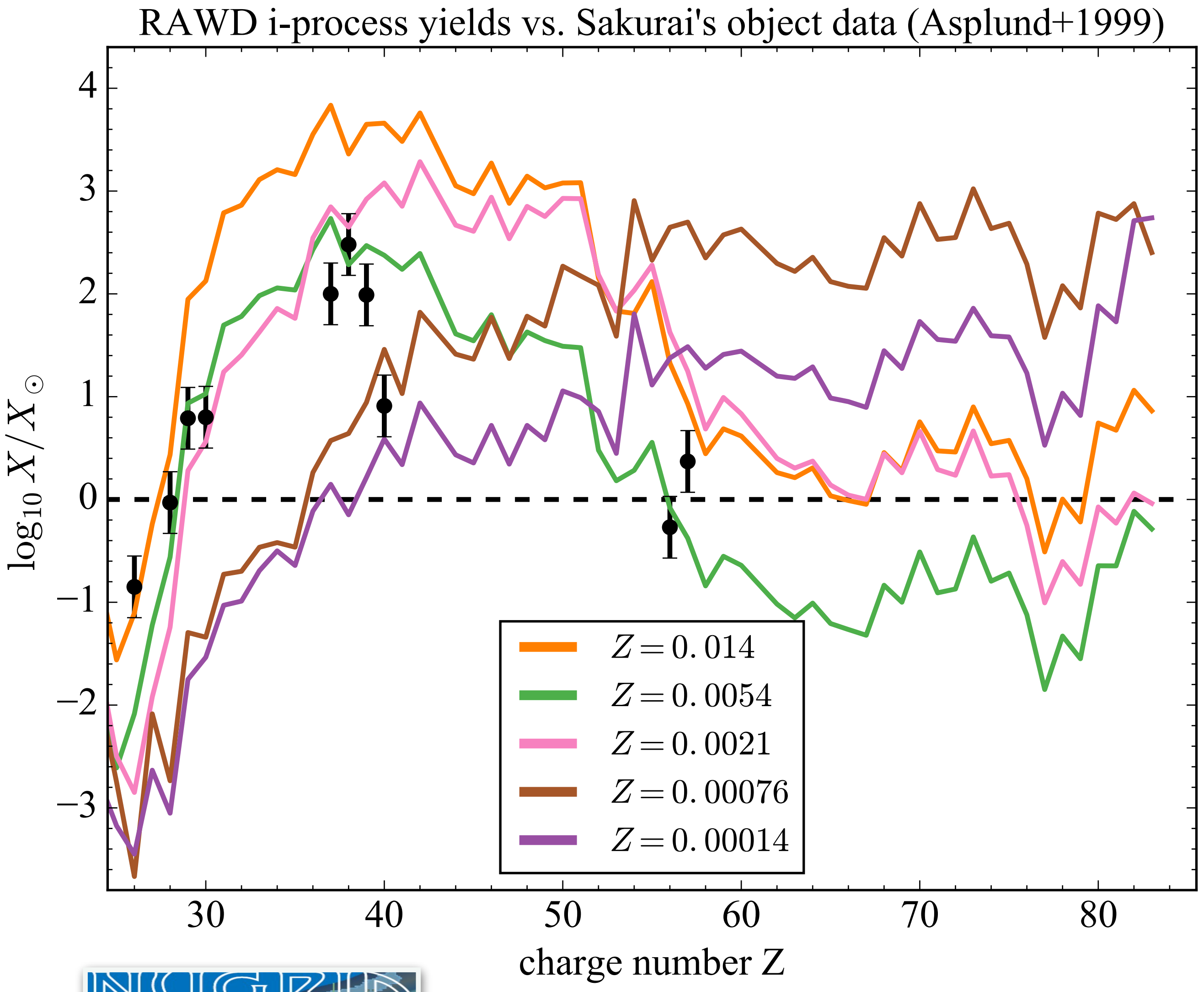
Figure 4. Abundance distributions in the RAWD model A, after the second He flash, with $M_{\mathrm{WD}} = 0.65\,M_\odot$ and $T_{\mathrm{WD}} = 21$ MK (teal diamonds, solid lines), and for comparison the model RUN48 (blue stars) from Herwig et al. (2011) that matches the observed abundances of Sakurai's object.

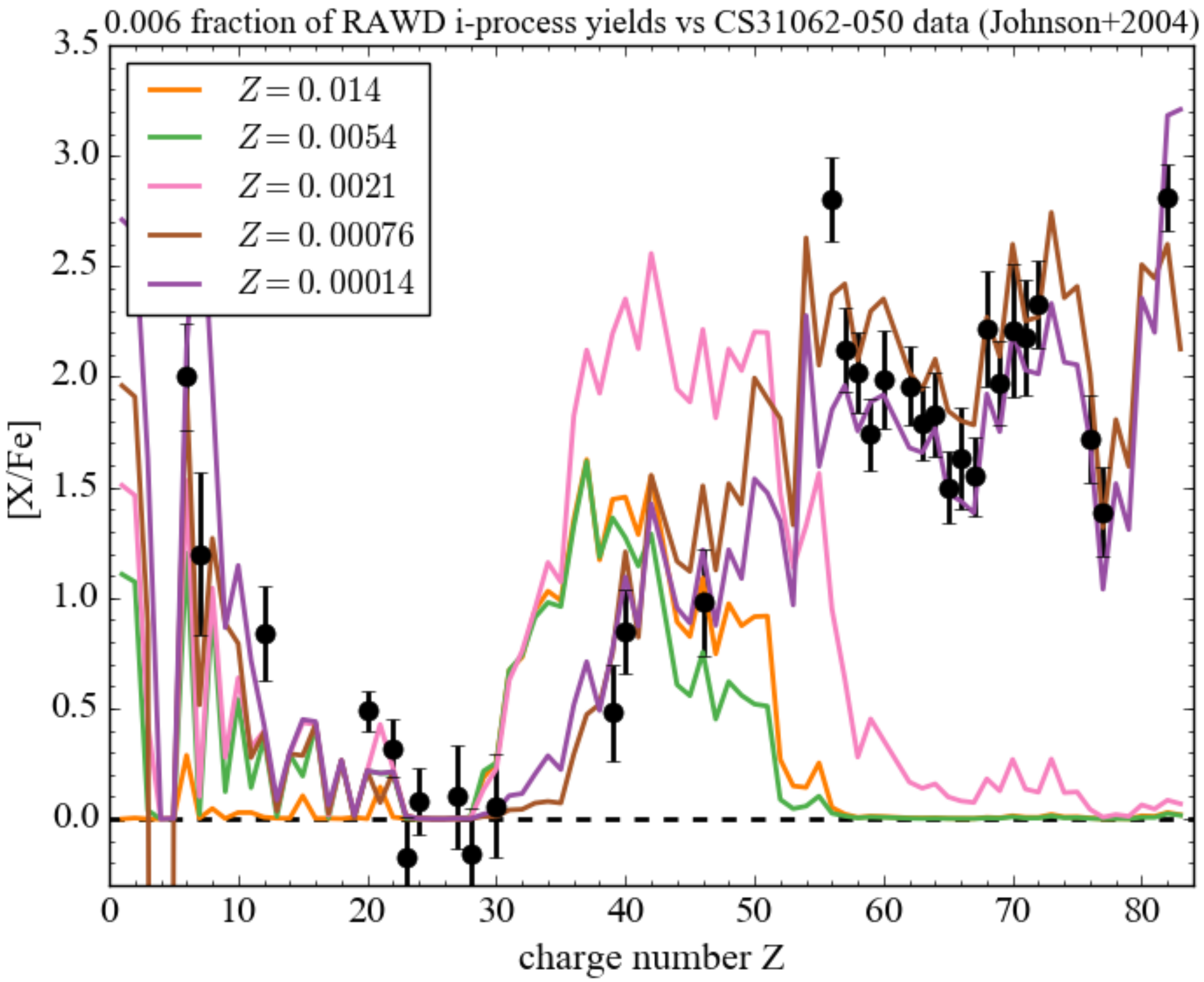


The first i-process yields for GCE from RAWDs

First i-process/s-process yields from metallicty (Z) grid of rapidly accreting white dwarfs

Hypothesis: CEMP-i stars are triple-star companion to iRAWDs at low Z

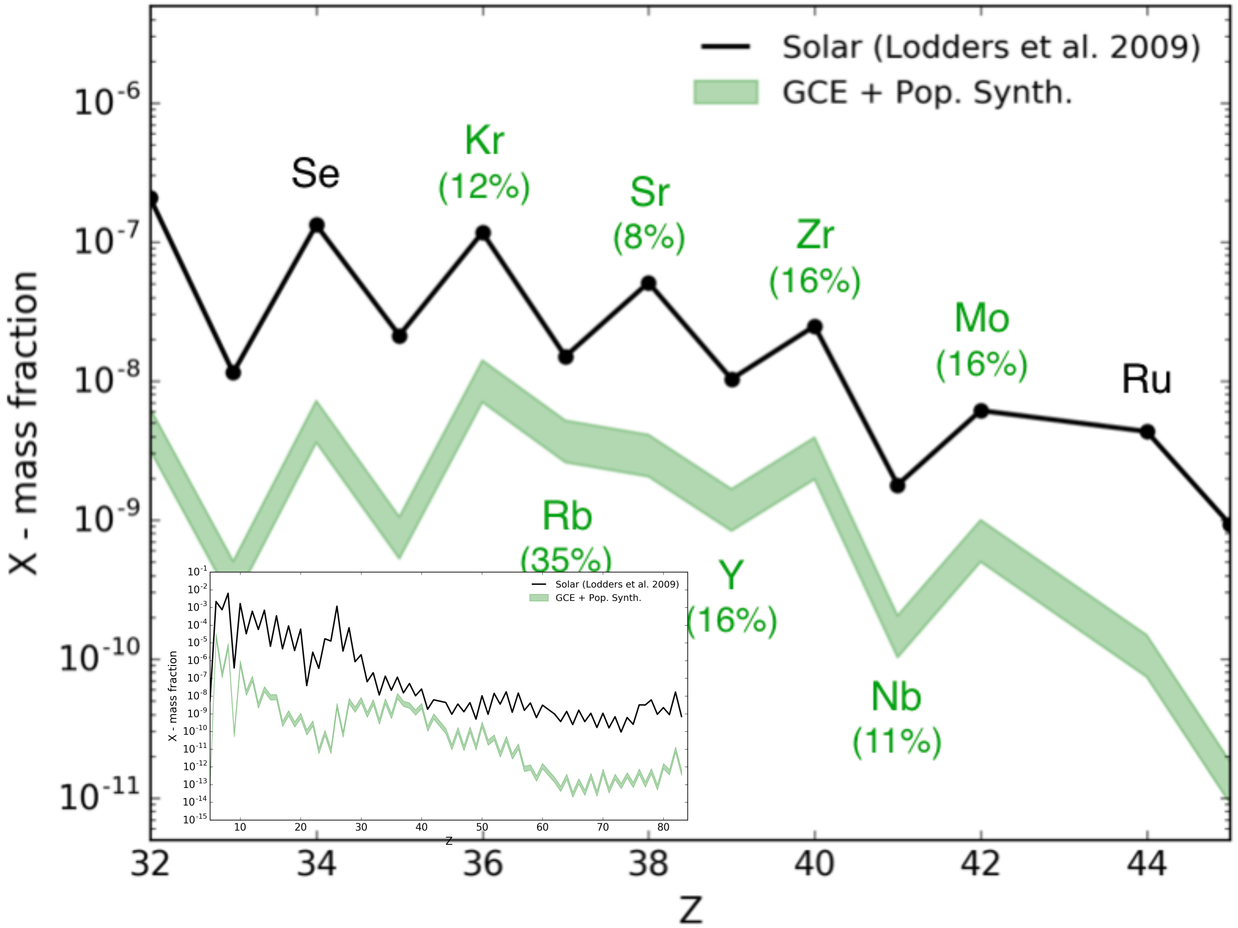




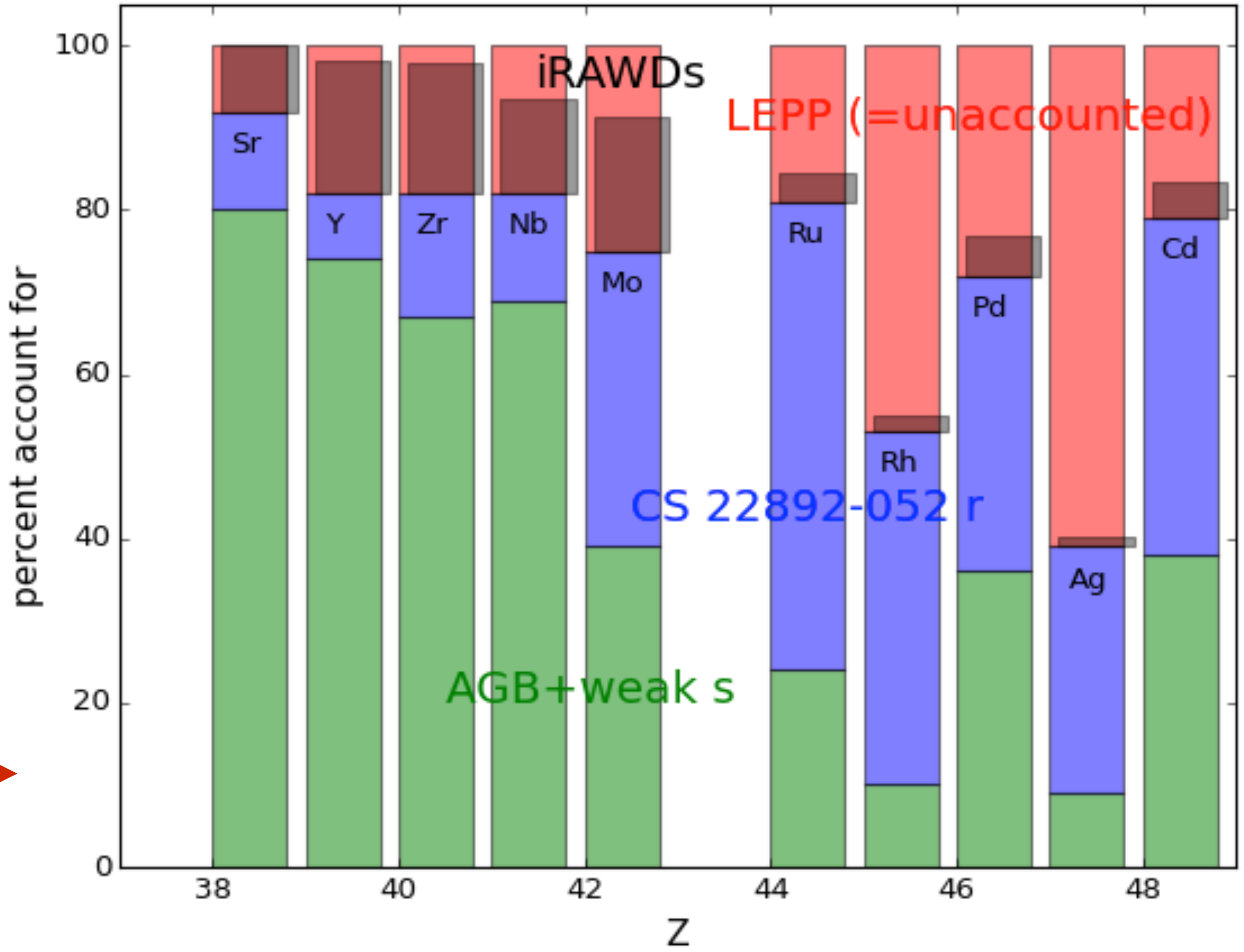
Denissenkov+ in prep

i process from RAWDs in solar system?

Côté+ 17, in prep



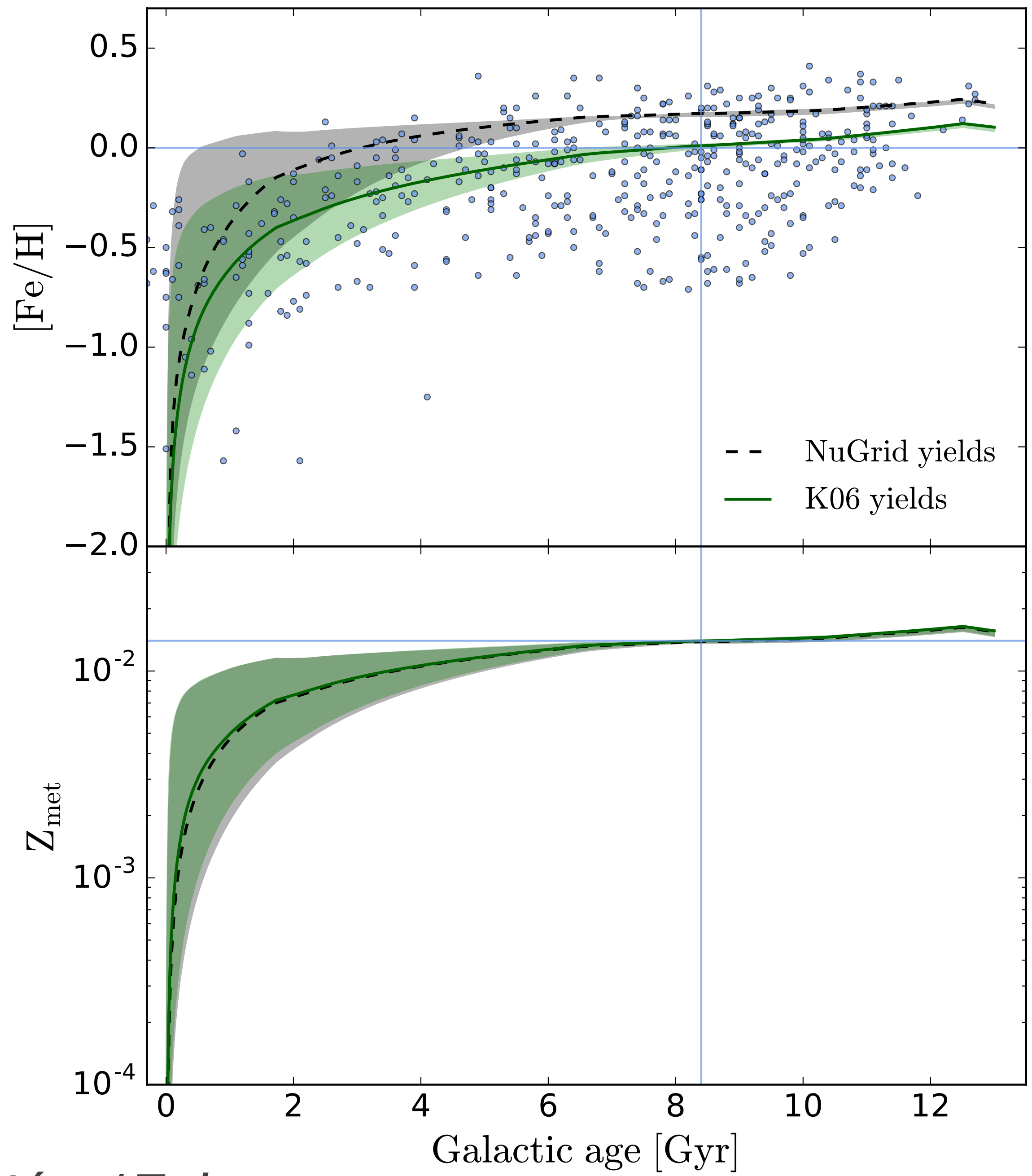
iRAWD contribution to first-peak elements in Milky-Way GCE OMEGA model with new iRAWD yields and iRAWD rates from population synthesis (Ruiter)



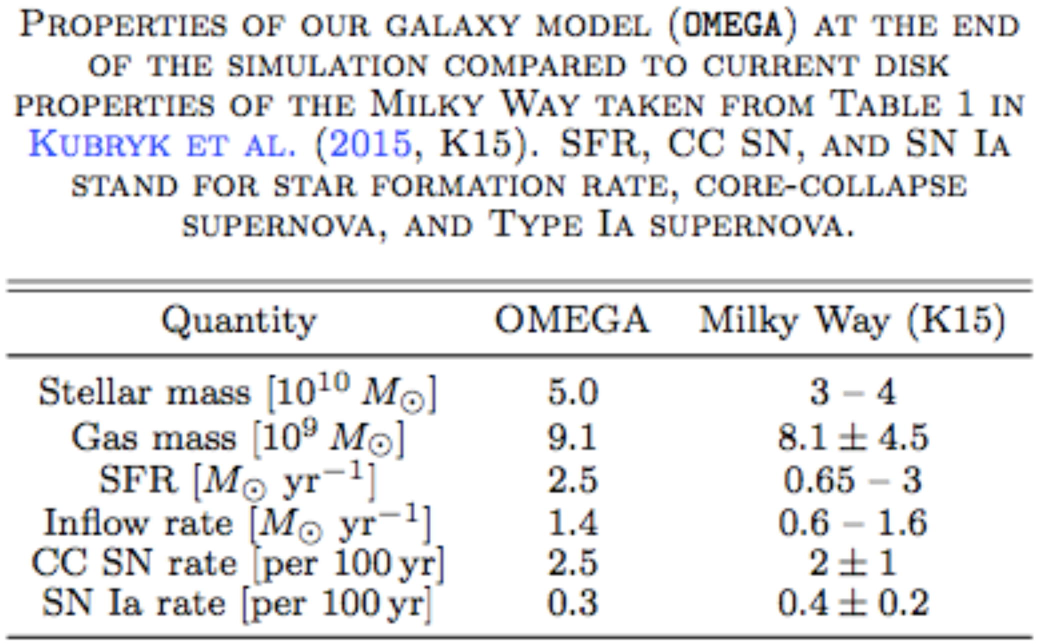
Unaccounted Lighter-Element Primary Process contribution (Travaglio+ 04) to first-peak elements and iRAWD contributions

Errors/uncertainties in (these) GCE predictions

Different chemical evolution paths at early times accounted for in OMEGA.

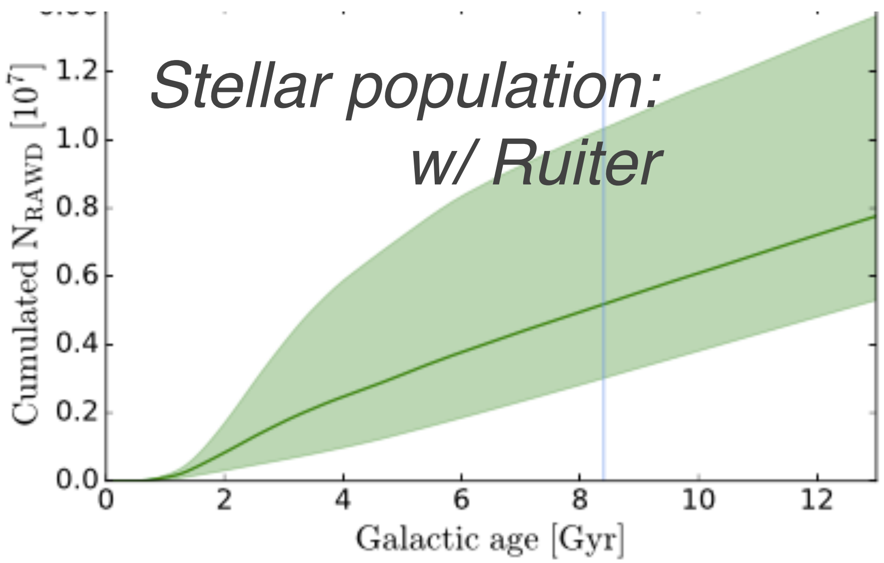


Côté+ 17, in prep



PROPERTIES OF OUR GALAXY MODEL (`OMEGA`) AT THE END OF THE SIMULATION COMPARED TO CURRENT DISK PROPERTIES OF THE MILKY WAY TAKEN FROM TABLE 1 IN KUBRYK ET AL. (2015, K15). SFR, CC SN, AND SN IA STAND FOR STAR FORMATION RATE, CORE-COLLAPSE SUPERNOVA, AND TYPE IA SUPERNOVA.

Quantity	OMEGA	Milky Way (K15)
Stellar mass [$10^{10}\,M_\odot$]	5.0	3 – 4
Gas mass [$10^{9}\,M_\odot$]	9.1	8.1 ± 4.5
SFR [$M_\odot$ yr^{-1}]	2.5	0.65 – 3
Inflow rate [$M_\odot$ yr^{-1}]	1.4	0.6 – 1.6
CC SN rate [per 100 yr]	2.5	2 ± 1
SN Ia rate [per 100 yr]	0.3	0.4 ± 0.2

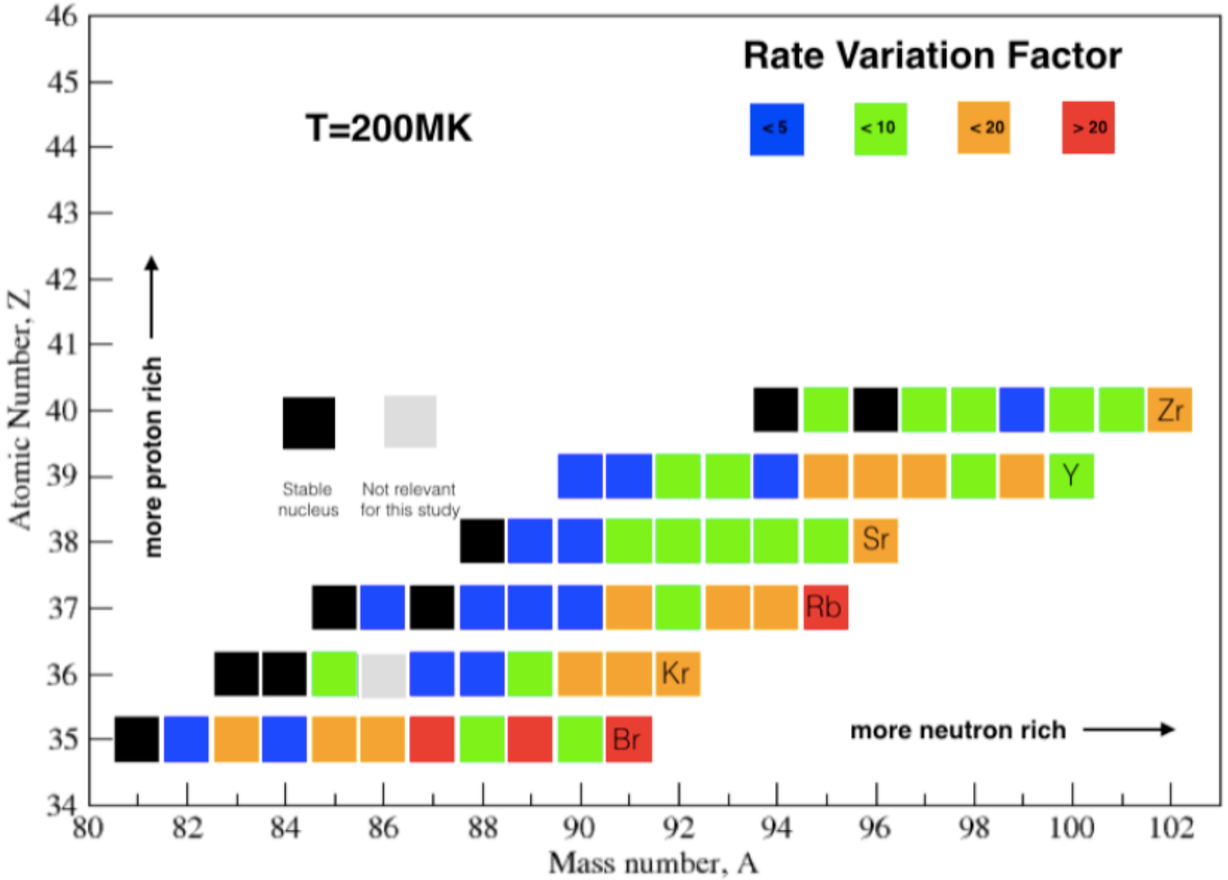


Stellar population: w/ Ruiter

FIG. 7.— Predicted rate (upper) and cumulated number (bottom) of rapidly accreting white dwarfs (RAWDs) as a function of Galactic age. The green solid lines represent our fiducial model while the green shaded areas show the uncertainties generated by different early chemical evolution paths (see Figure 6).

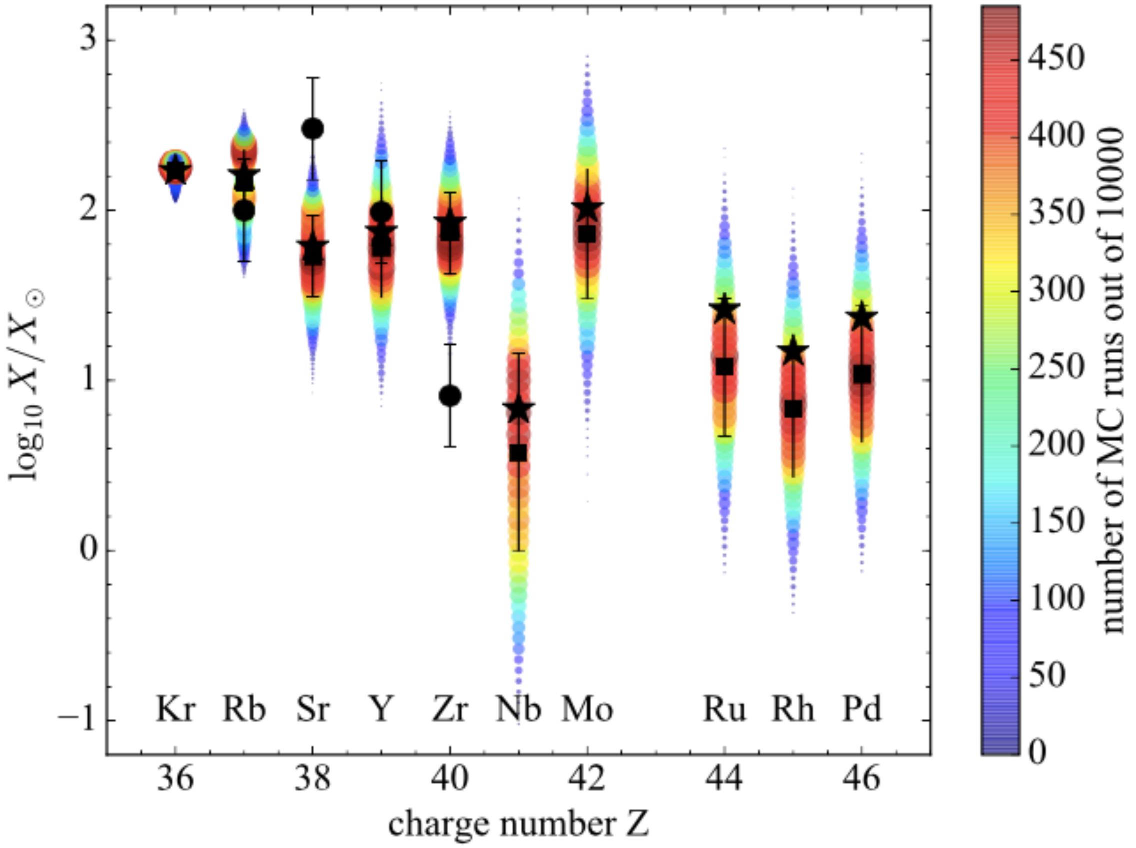
range of mass accreted by each RAWD: 0.5 - 1.0Msun

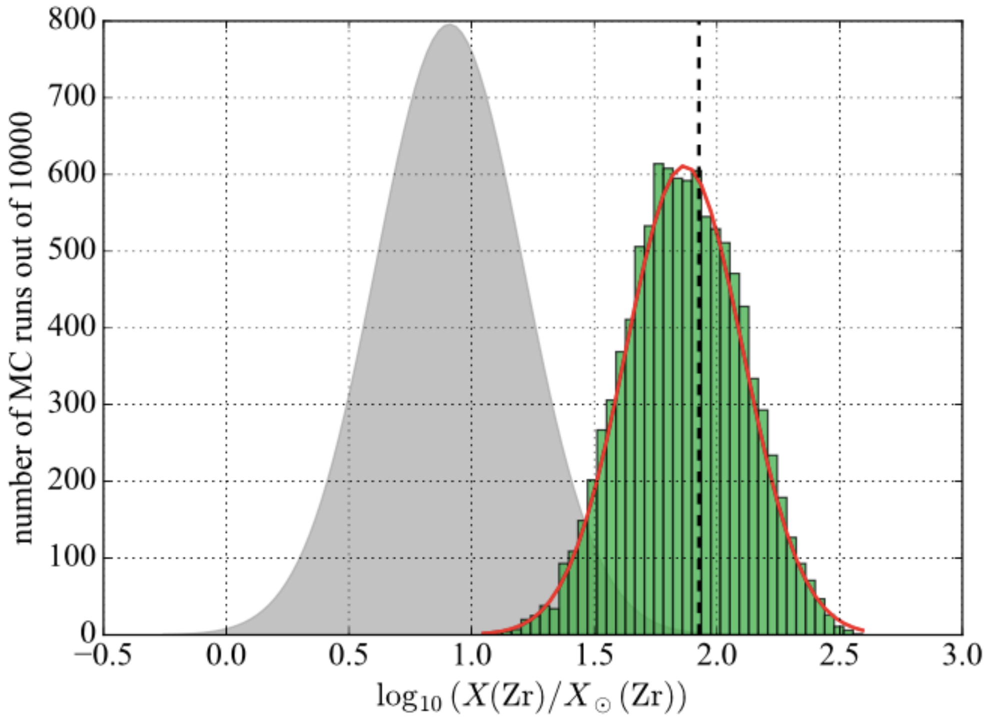
Nuclear physics uncertainty (JINA-CEE project)



Maximum variation factors for the (n,γ) cross sections of unstable isotopes near N=50 constrained by Hauser-Feshbach calculations with different physics input data and model assumptions.

Denissenkov+ arXiv:1611.01121
revision in prep, poster





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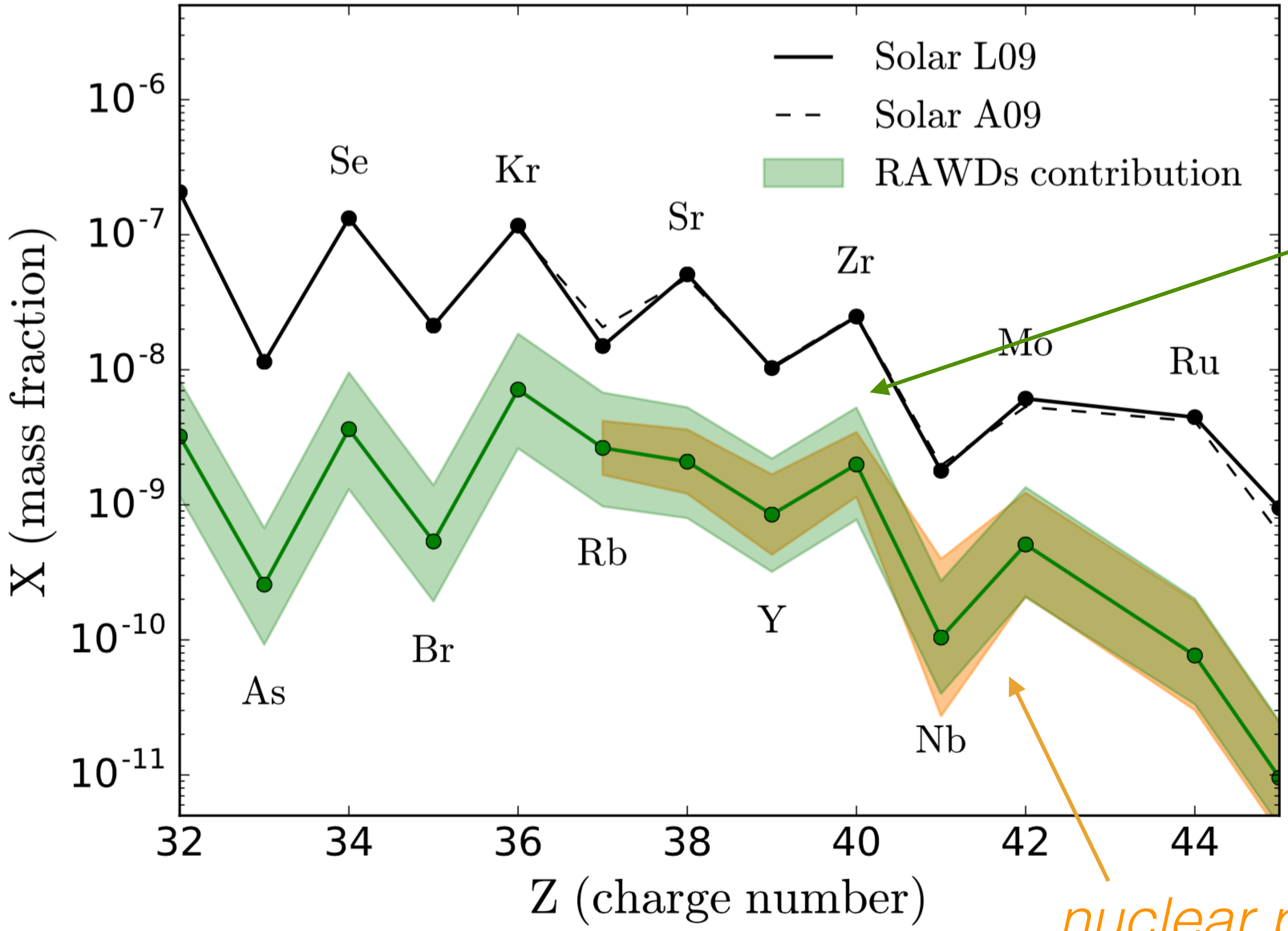
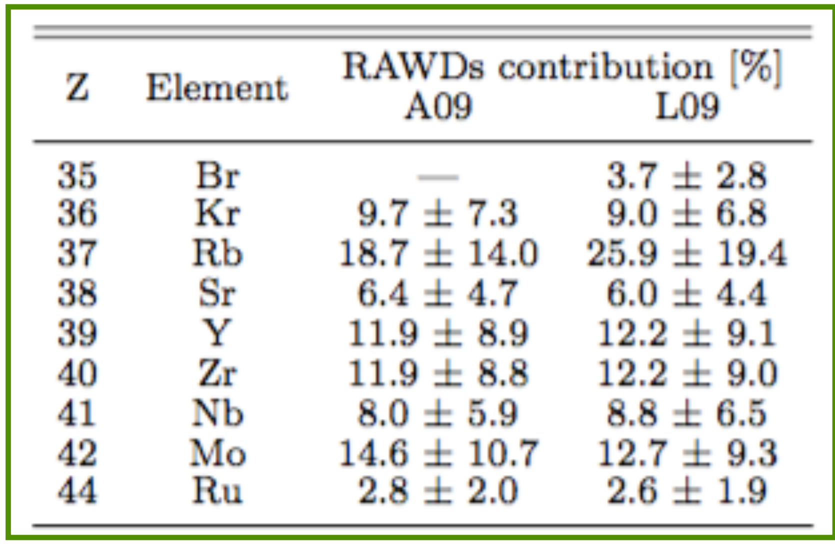
GCE prediction with uncertainties



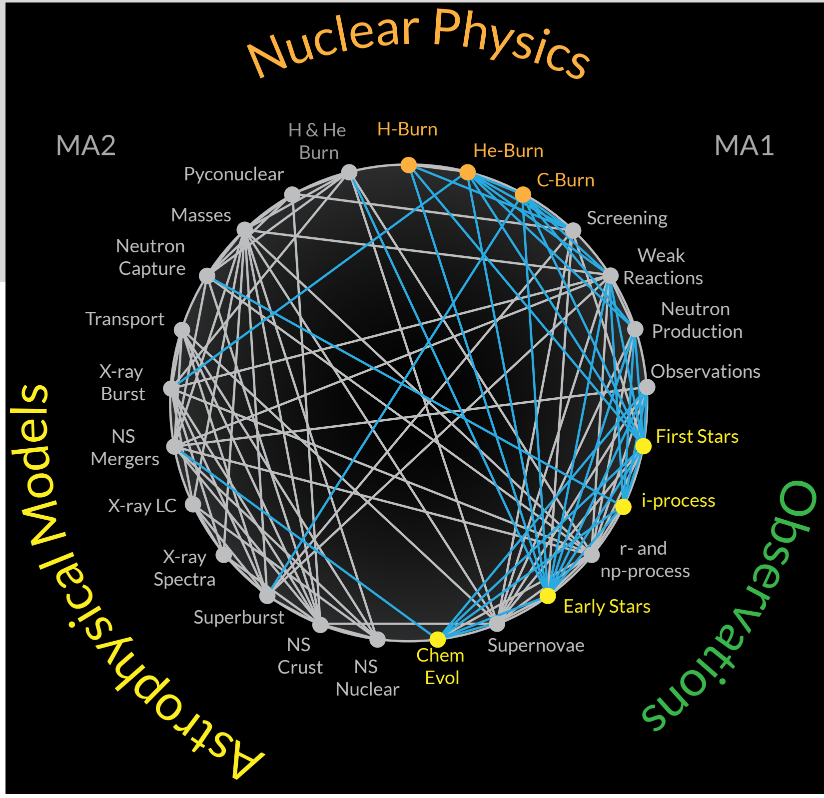
astrophysics uncertainty: early galaxy formation pathway and RAWD mass ejection



Z	Element	RAWDs contribution [%] A09	 L09
35	Br	—	3.7 ± 2.8
36	Kr	9.7 ± 7.3	9.0 ± 6.8
37	Rb	18.7 ± 14.0	25.9 ± 19.4
38	Sr	6.4 ± 4.7	6.0 ± 4.4
39	Y	11.9 ± 8.9	12.2 ± 9.1
40	Zr	11.9 ± 8.8	12.2 ± 9.0
41	Nb	8.0 ± 5.9	8.8 ± 6.5
42	Mo	14.6 ± 10.7	12.7 ± 9.3
44	Ru	2.8 ± 2.0	2.6 ± 1.9

*nuclear physics uncertainties, (n,**γ**) only*

This motivated nuclear physics experiments

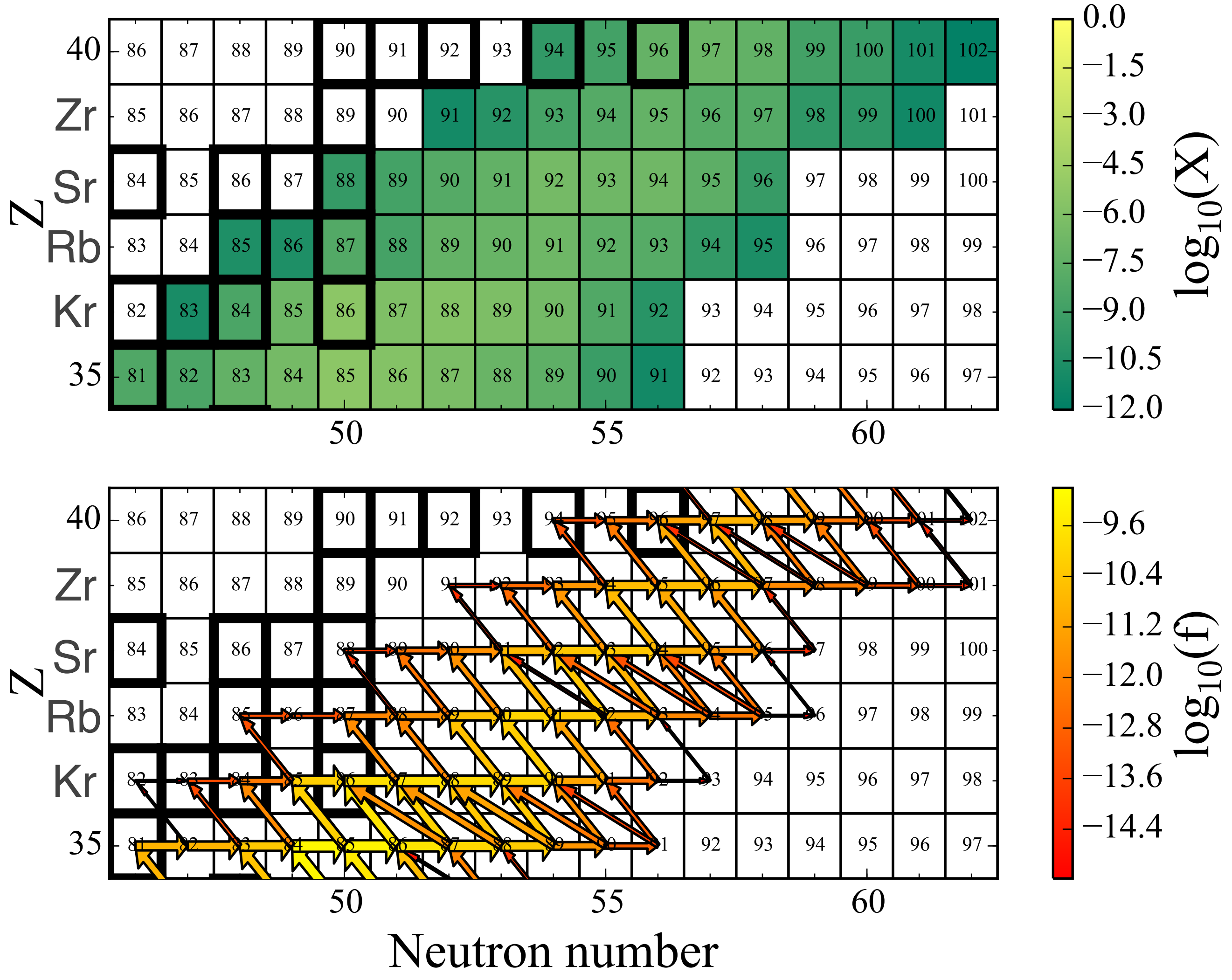


i-process uncertainty study with MSU/ UVic team⟶ identified ^{88}Kr(n,γ) as important nuclear physics input

Denissenkov+ arXiv:1611.01121

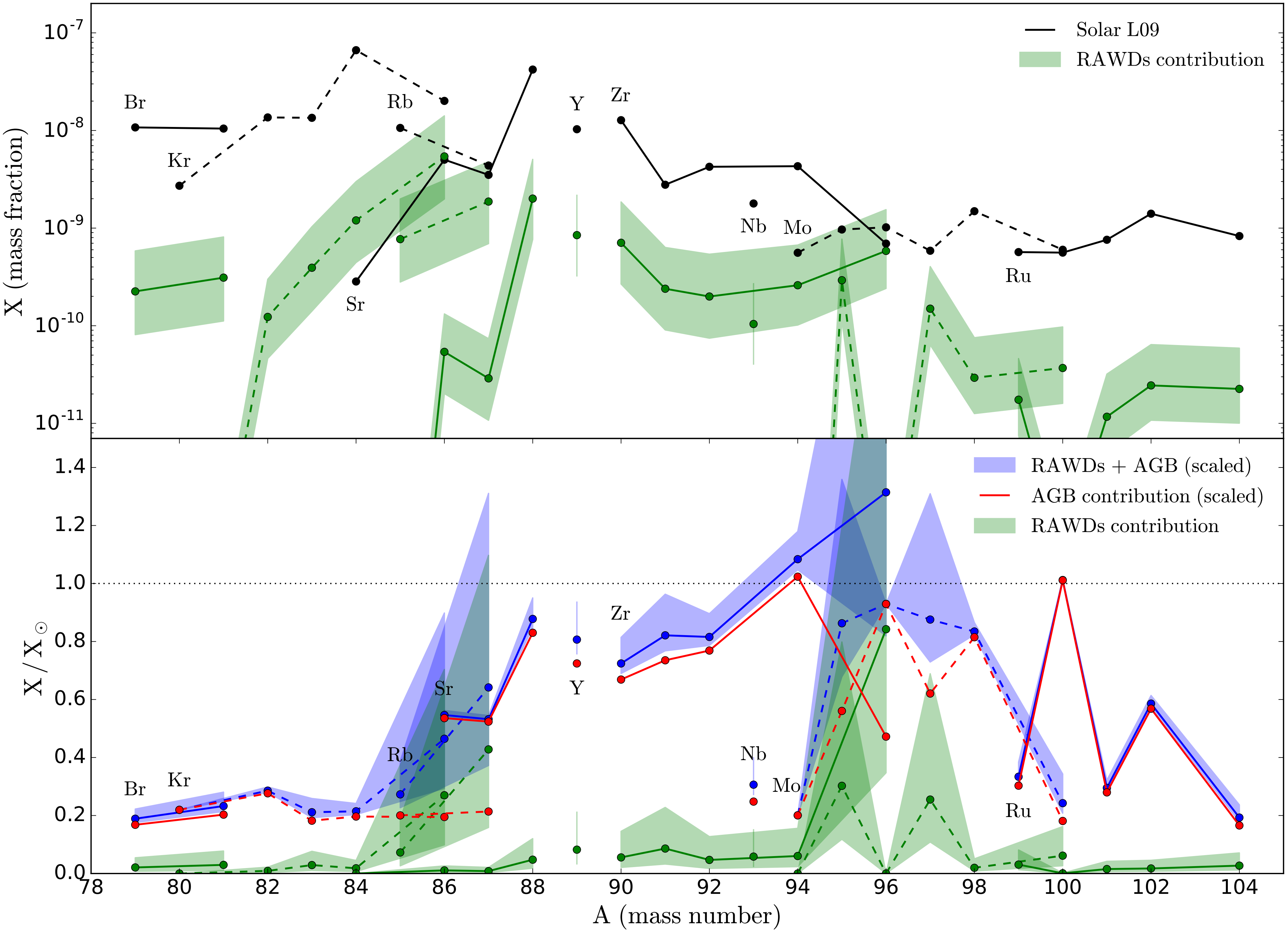
Experiments:

- MSU, Artemis Spyrou: approved proposal on ^{88}Kr(n,g)
- TRIUMF: ^{135}I(n,g) via ^{135}I(d,p)^{136}I in 2018, TRIUMF EEC proposal planned for June/July
- GSI/Fair, Rene Reifarth: submitted pre-proposal on ^{135}I(n,g), full proposal due 05/31, experiment will take advantage off existing facilities



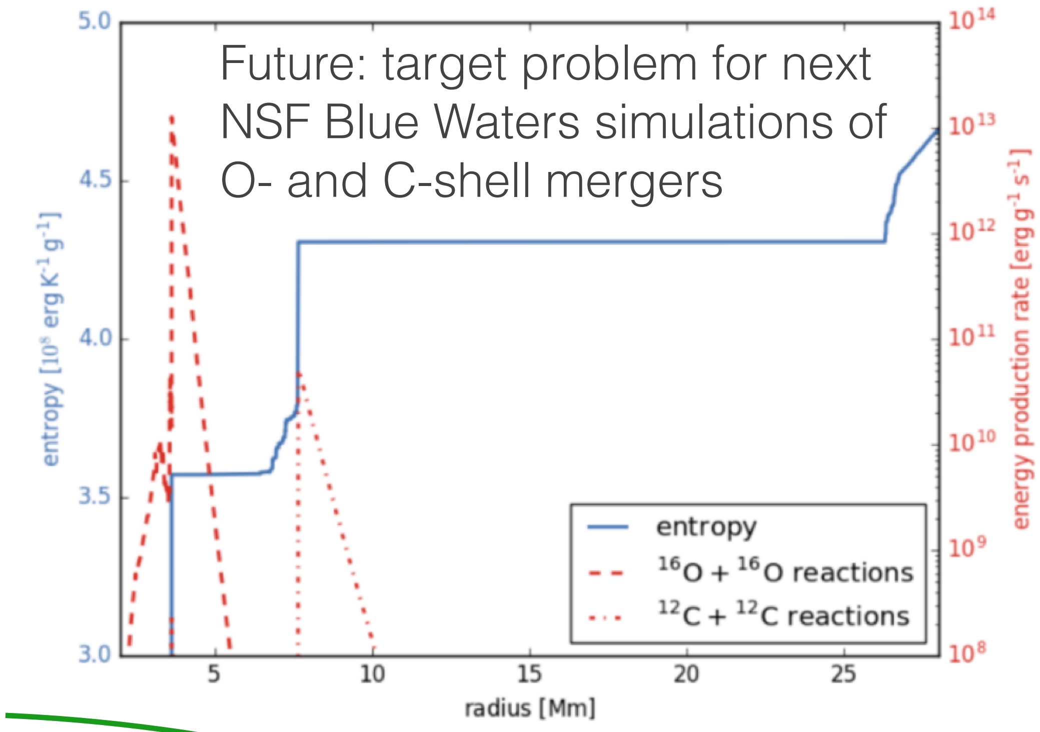
The isotopes keep us honest … (Don Clayton?)

GCE with (all) isotopes in NuPyCEE



Convective O- and C-shell mergers

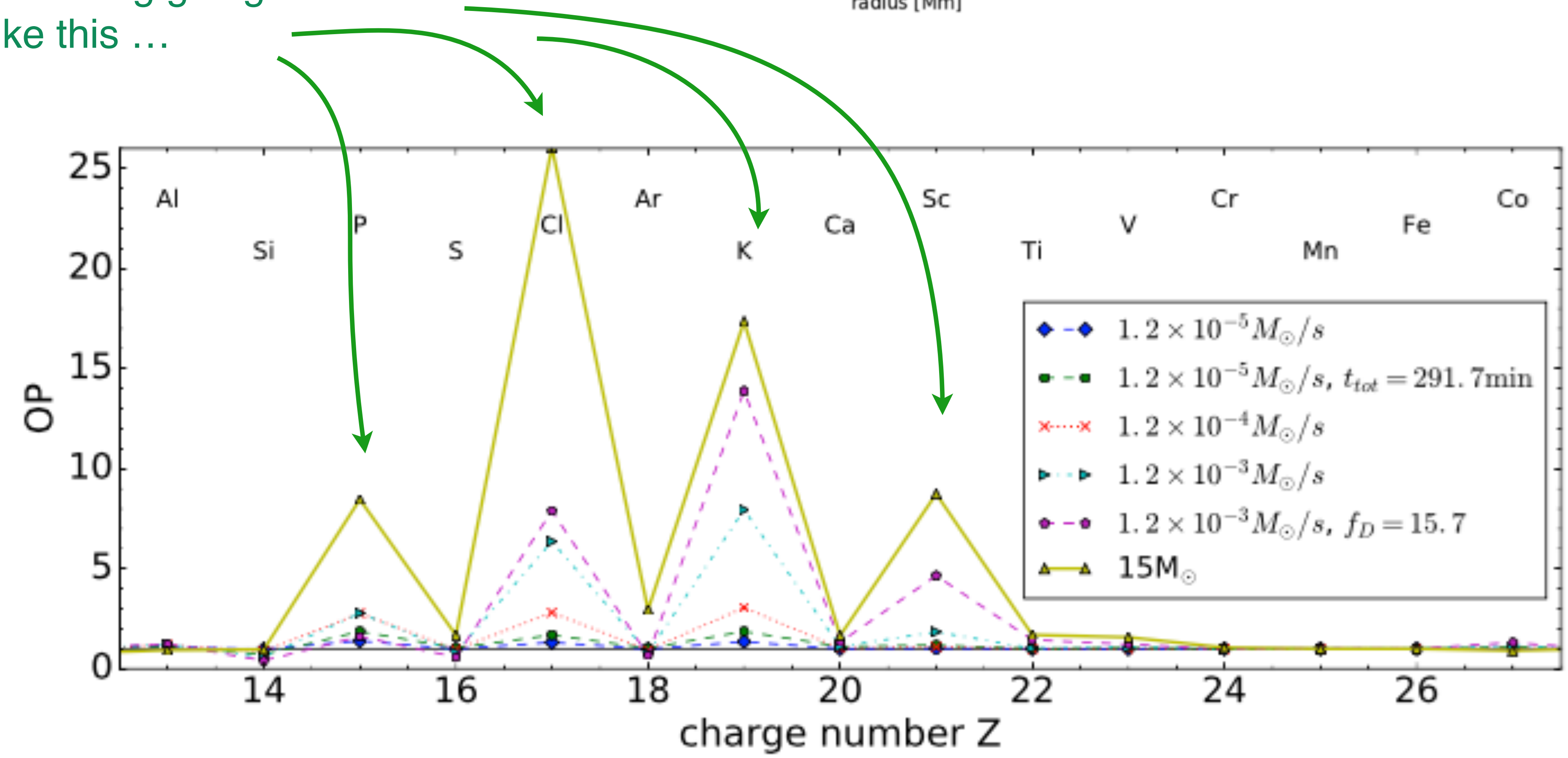
On the quest for a new stellar hydro setup for our collaboration with Woodward@Minnesota: searching through the NuGrid/JINA stellar model and yield data library, JINA-CEE graduate student Christian Ritter found eventually something promising … in terms of planned mesh-refinement features in the hydro code …



Future: target problem for next NSF Blue Waters simulations of O- and C-shell mergers

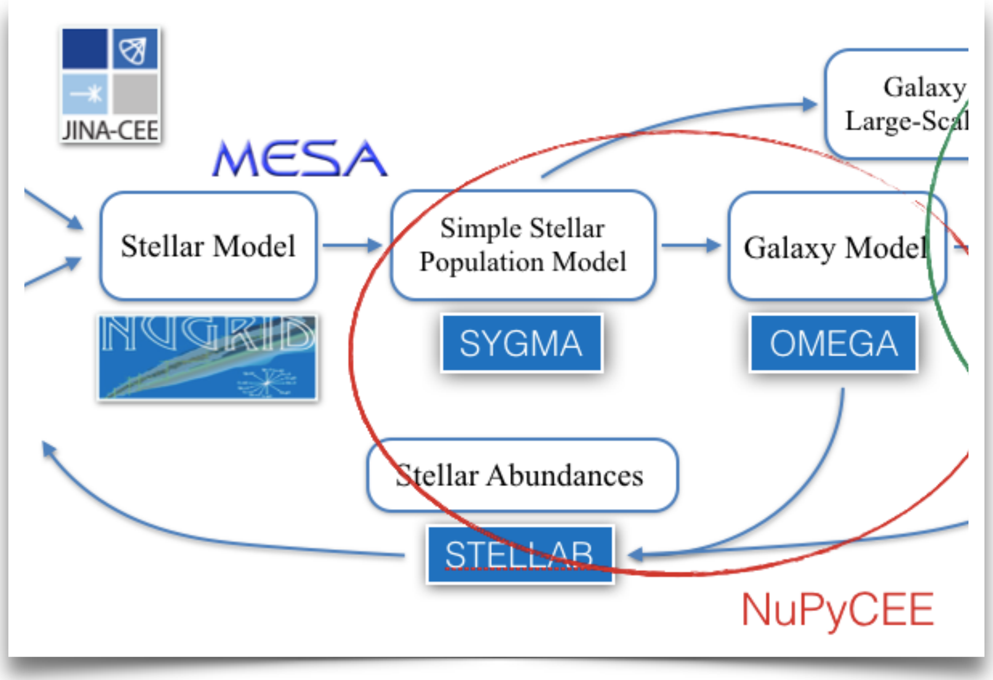
… but what we also serendipitously found was an abundance feature as a result of something going on in the O-shell that looked like this …

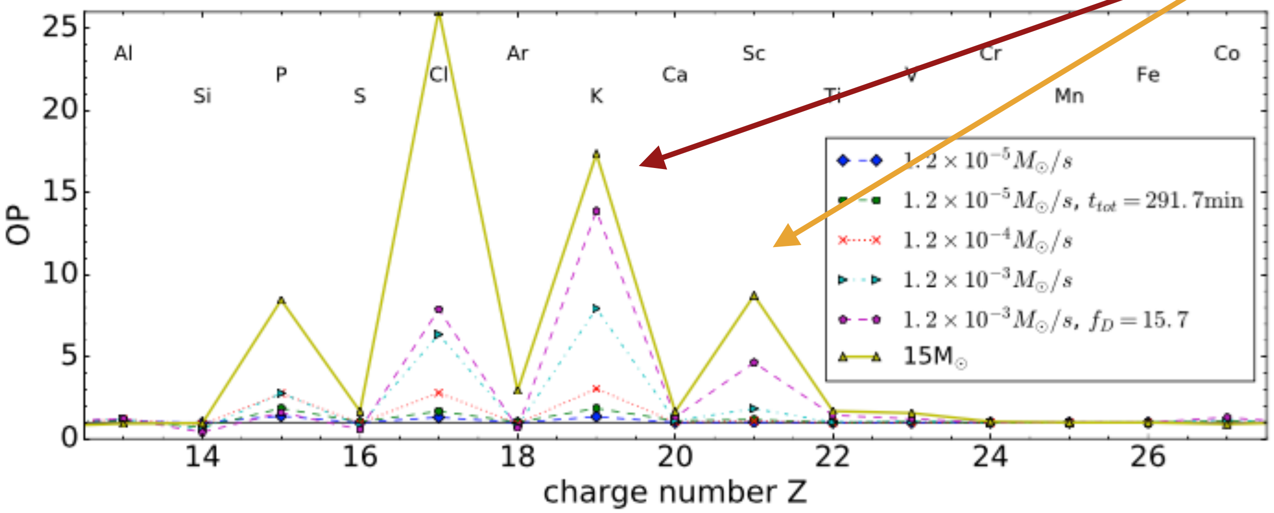
This is of course a prominent feature that one would immediately relate to the persistent inability of models to produce enough odd-Z elements compared to even-Z elements. We would have possibly missed it … except …



Ritter+ 17, submitted, astro-ph

Odd-Z elements from convective-reactive O- and C-shell mergers in massive pre-SN stars





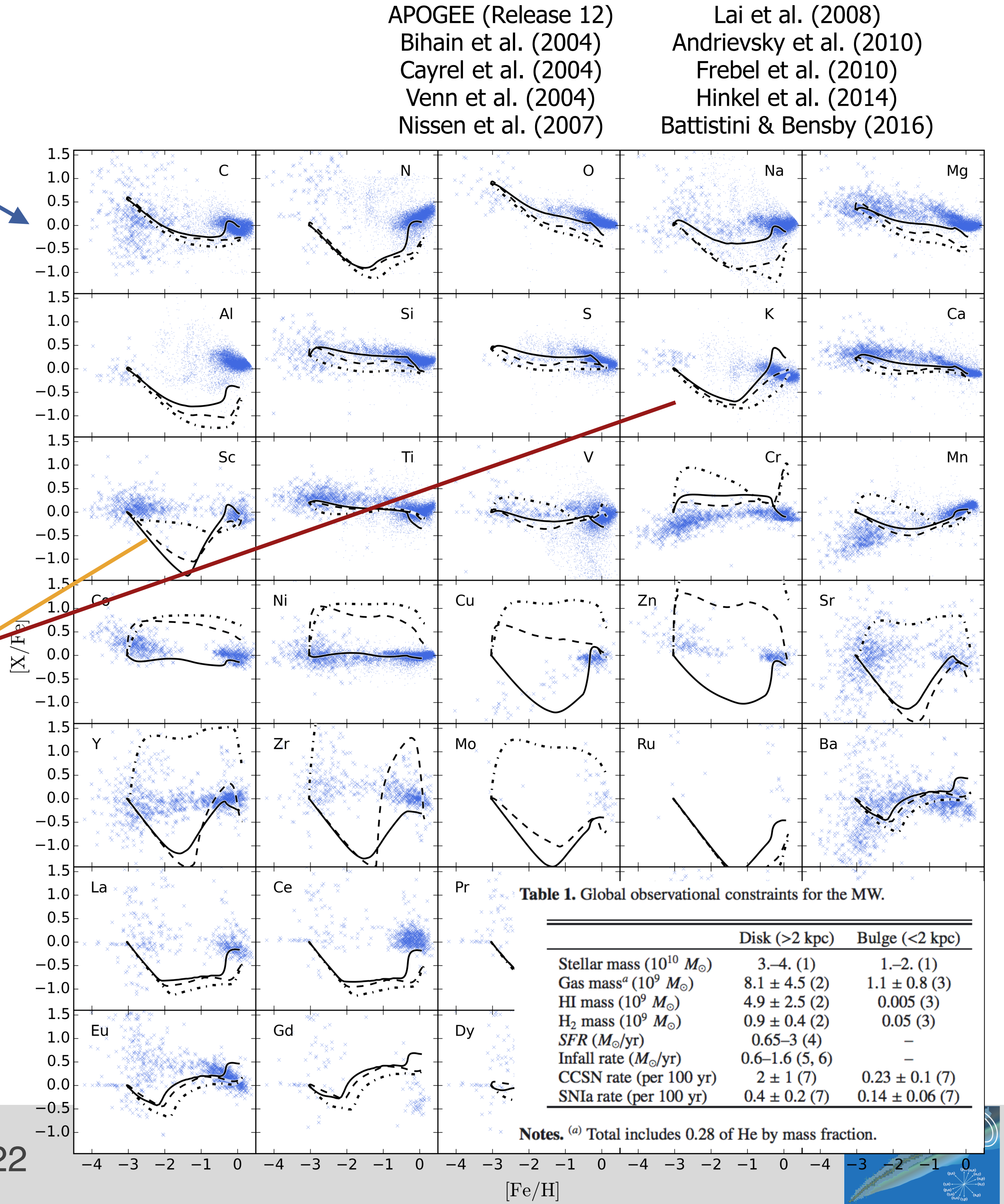
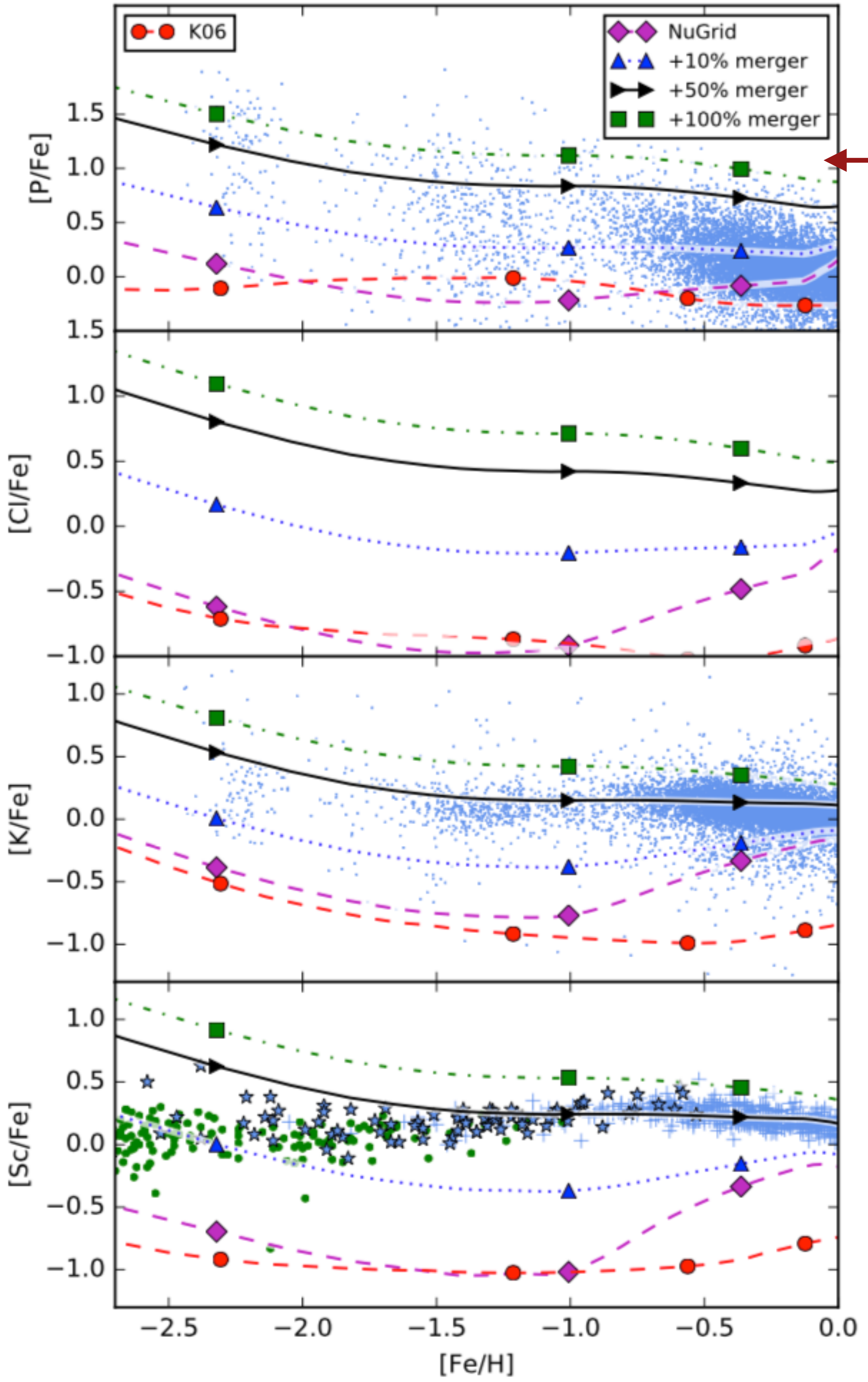


Table 1. Global observational constraints for the MW.

	Disk (>2 kpc)	Bulge (<2 kpc)
Stellar mass ($10^{10}\ M_\odot$)	3.–4. (1)	1.–2. (1)
Gas mass[a] ($10^9\ M_\odot$)	8.1 ± 4.5 (2)	1.1 ± 0.8 (3)
HI mass ($10^9\ M_\odot$)	4.9 ± 2.5 (2)	0.005 (3)
H_2 mass ($10^9\ M_\odot$)	0.9 ± 0.4 (2)	0.05 (3)
SFR ($M_\odot$/yr)	0.65–3 (4)	–
Infall rate ($M_\odot$/yr)	0.6–1.6 (5, 6)	–
CCSN rate (per 100 yr)	2 ± 1 (7)	0.23 ± 0.1 (7)
SNIa rate (per 100 yr)	0.4 ± 0.2 (7)	0.14 ± 0.06 (7)

Notes. (a) Total includes 0.28 of He by mass fraction.

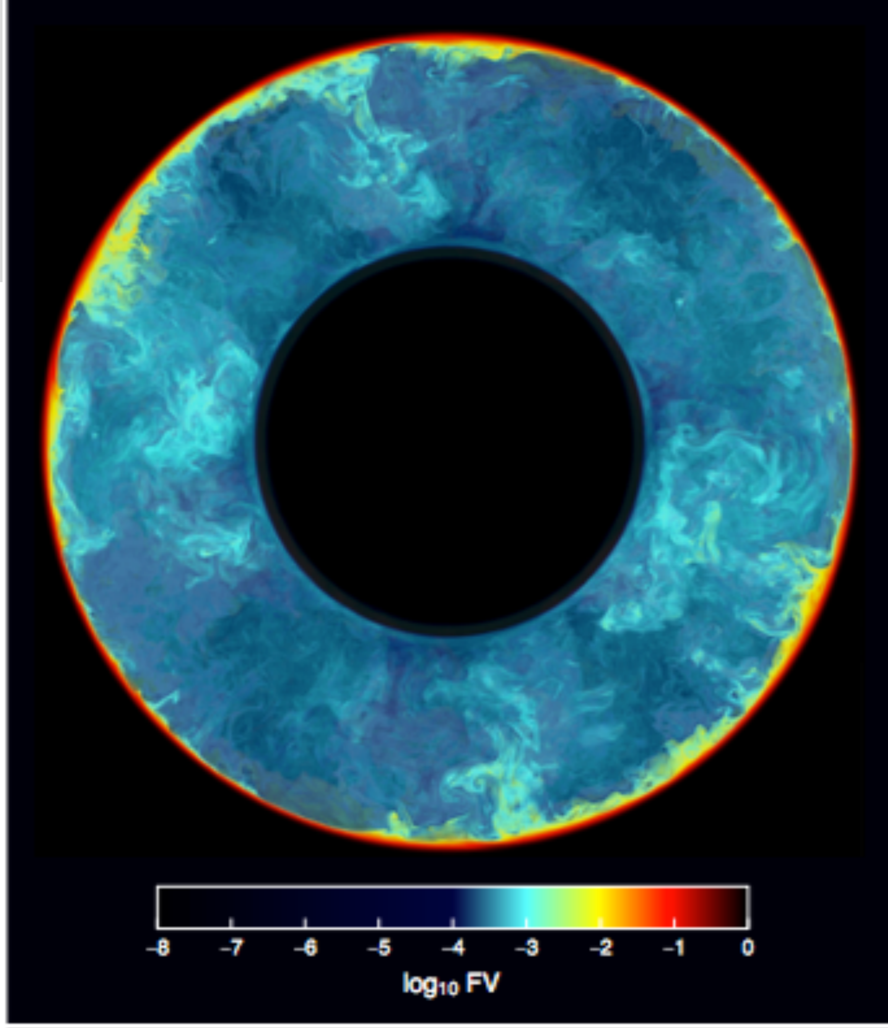
Stellar hydrodynamics of O-C shell mergers and impact on GCE

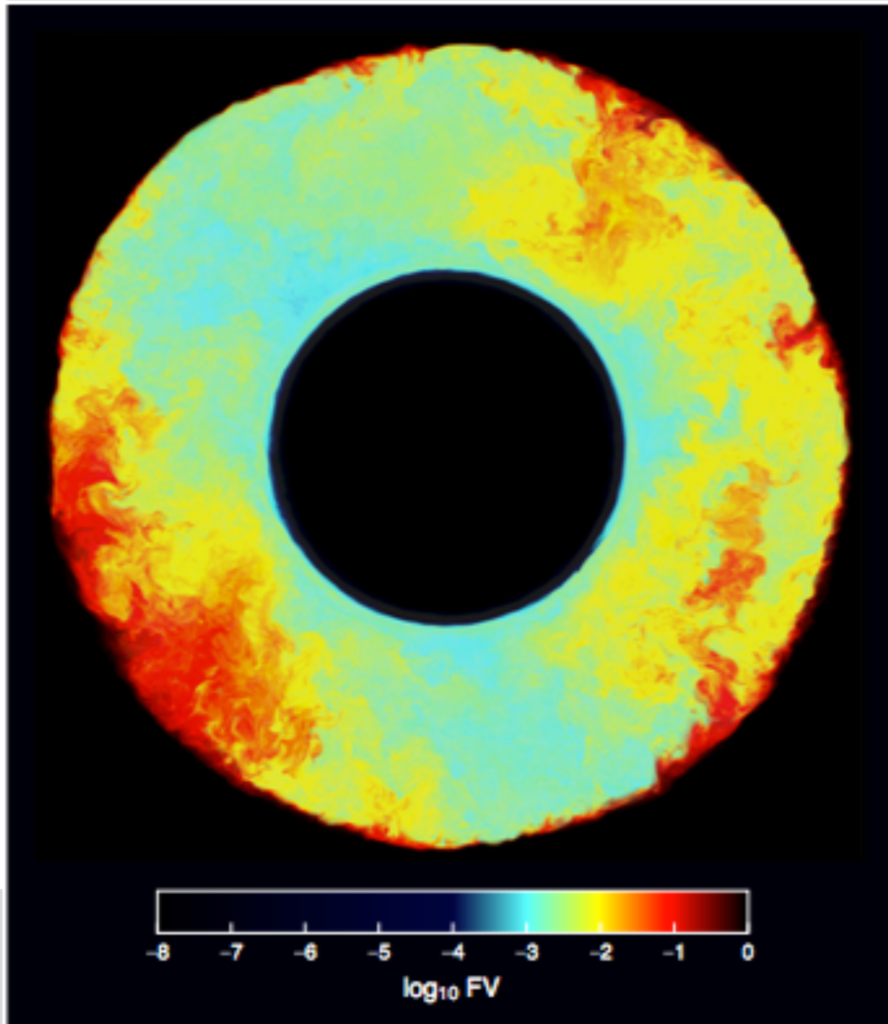


Assuming 50% O-C shell merger fraction accounts for odd-Z elements in MW GCE

C-ingestion with burn feedback to explore transition from mostly spherically symmetric to non-spherical regime expected in full-blown merger of convection zones … **see talk by Andrassy tomorrow**

most important reaction for energy feedback: $^{16}O+^{12}C$ … see Wiescher's talk





Ritter+ 17, submitted, astro-ph

Convective-reactive nucleosynthesis - a new dimension

Convective-reactive nucleosynthesis

- i process
- odd-Z elements in O-C shell mergers
- Cameron-Fowler transport mechanism, Li in hot-bottom burning in massive AGB stars

- emerging new insight: nucleosynthesis with an additional *dimension*: mixing

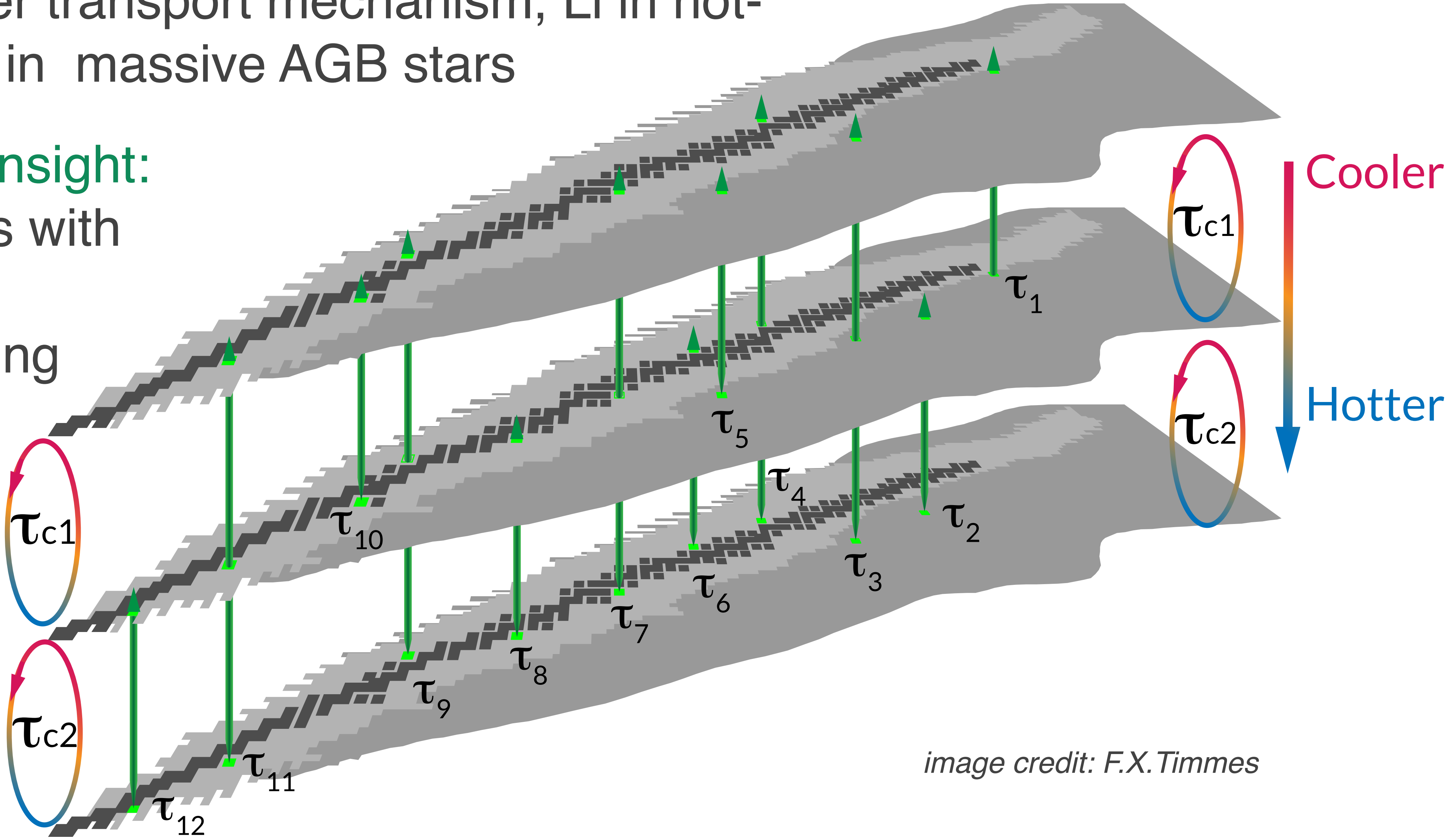


image credit: F.X.Timmes

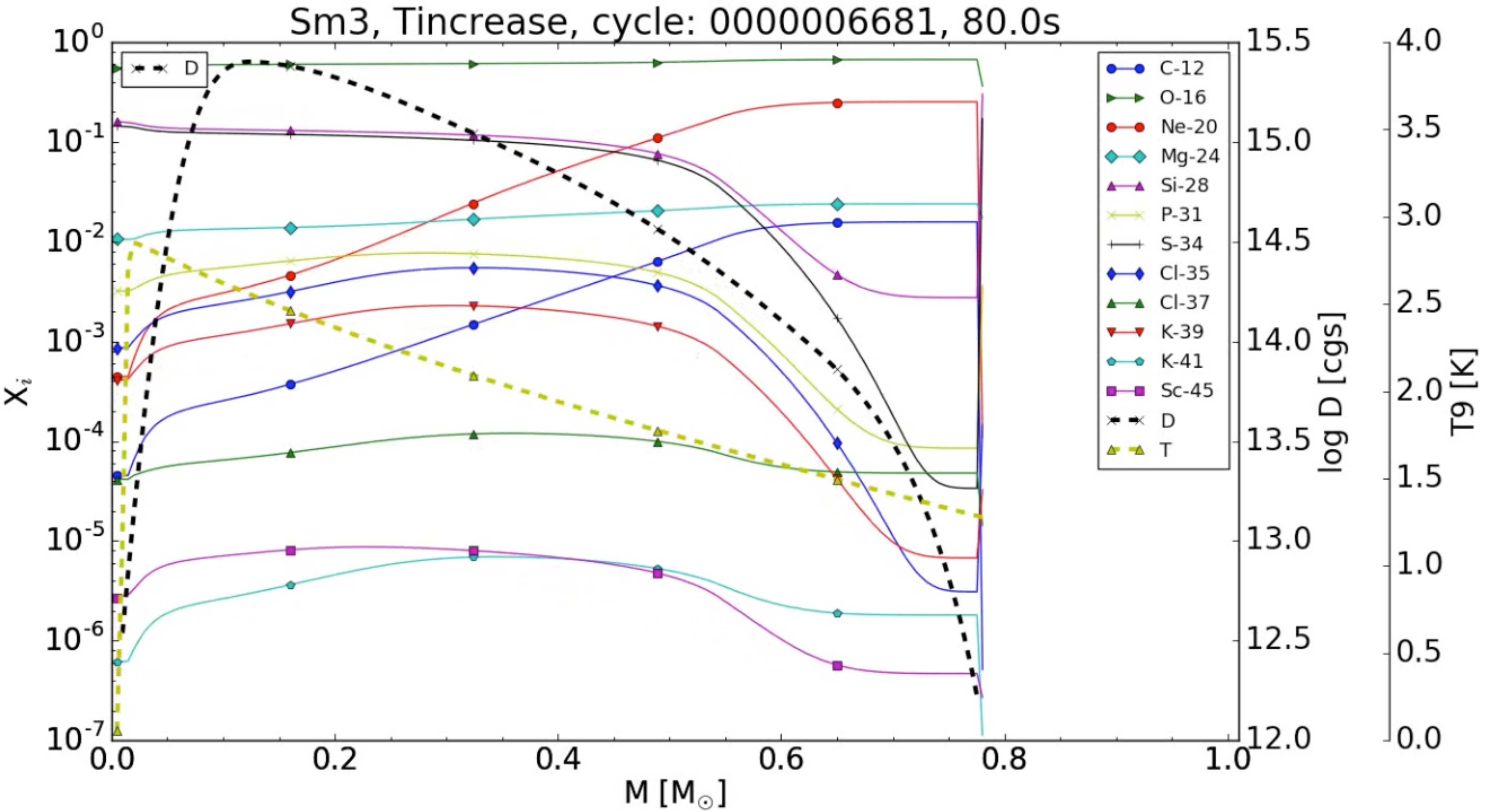
Conclusions

- JINA, NuGrid aim to combine nuclear astrophysics expertise across all relevant nuclear production sites
- Provide comprehensive yield, stellar evolution and explosion data, interfaces to GCE community and easy-to-use tools to explore
- Forging connections between micro- / macro-physics of stars with cosmological evolution of the elements
- new nuclear astrophysics sources: convective-reactive nucleosynthesis (such as iRAWDs, OC shell mergers)

Backup slides

Convective-reactive nucleosynthesis in O-C shell merger conditions

snapshot of movie in live presentation



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GCE scenario

- frequency of O-C shell mergers can not be reliably predicted by 1D stellar evolution simulations → conditions for merger need to be determined through 3D hydro simulations
- here: assume that O-C shell merger like the one in the 15Msun, Z=0.02 event happens with a certain frequency in all massive stars at all metallicities
- with about 50% *merger rate* observed levels of P, K and Sc in GCE can be accounted for
- scatter? observational uncertainty → address with observers (Beers, Frebel, Roederer)

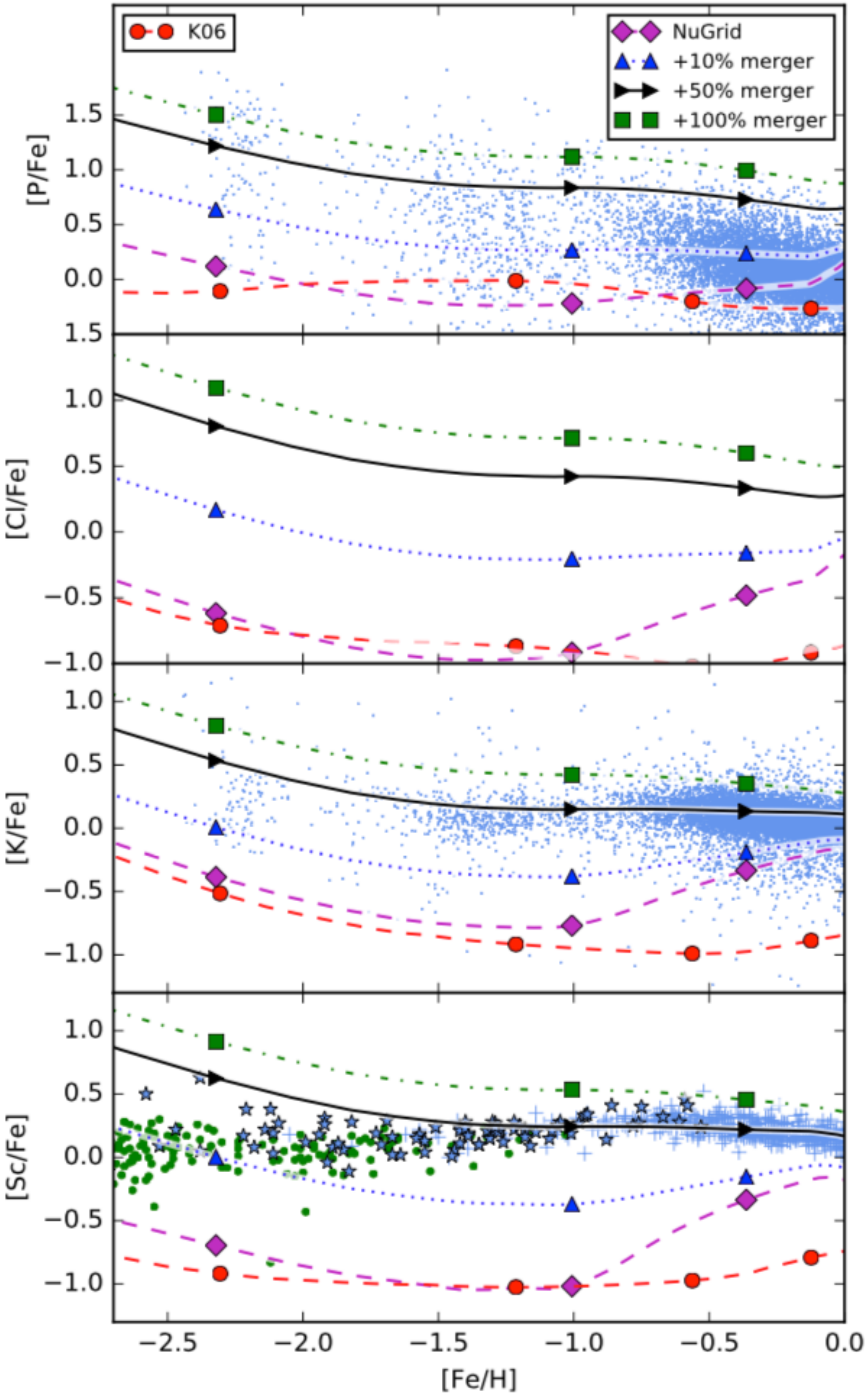

Figure 6. Comparison of the predictions of P, Cl, K and Sc of our Milky Way model with observational data (if available). Predictions with 10%, 50% and 100% addition of material produced in the O-C shell merger of the stellar model M15Z0.02 to all massive stars without O-C shell merger. For comparison, we show GCE predictions based on yields from K06. P and 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).

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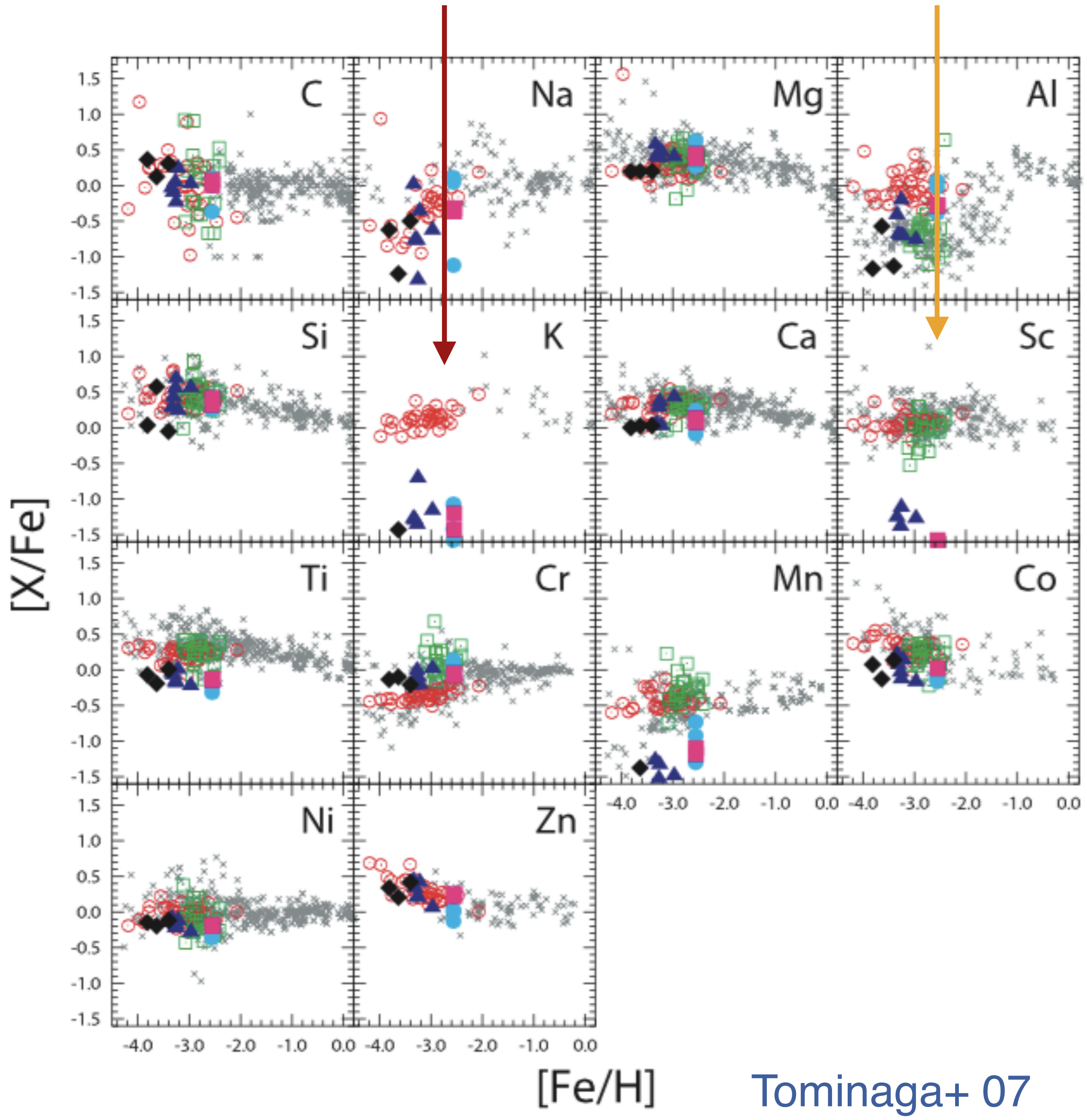
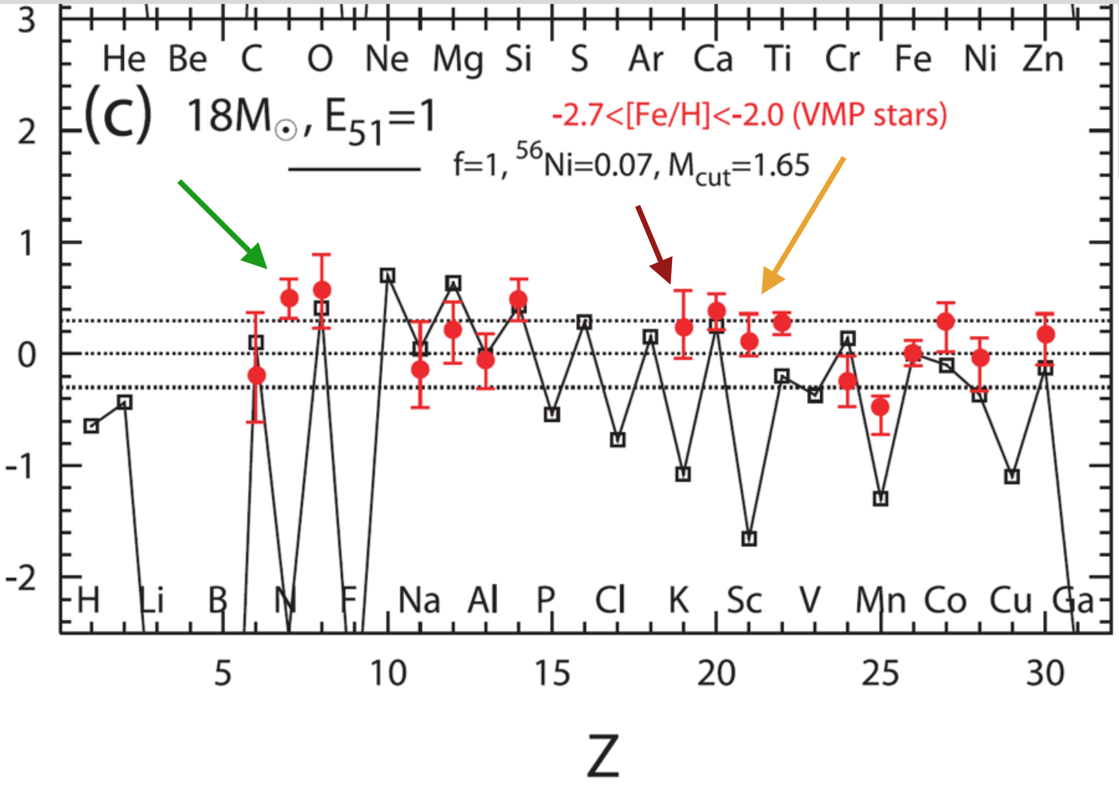
K, Sc in metal-poor stars

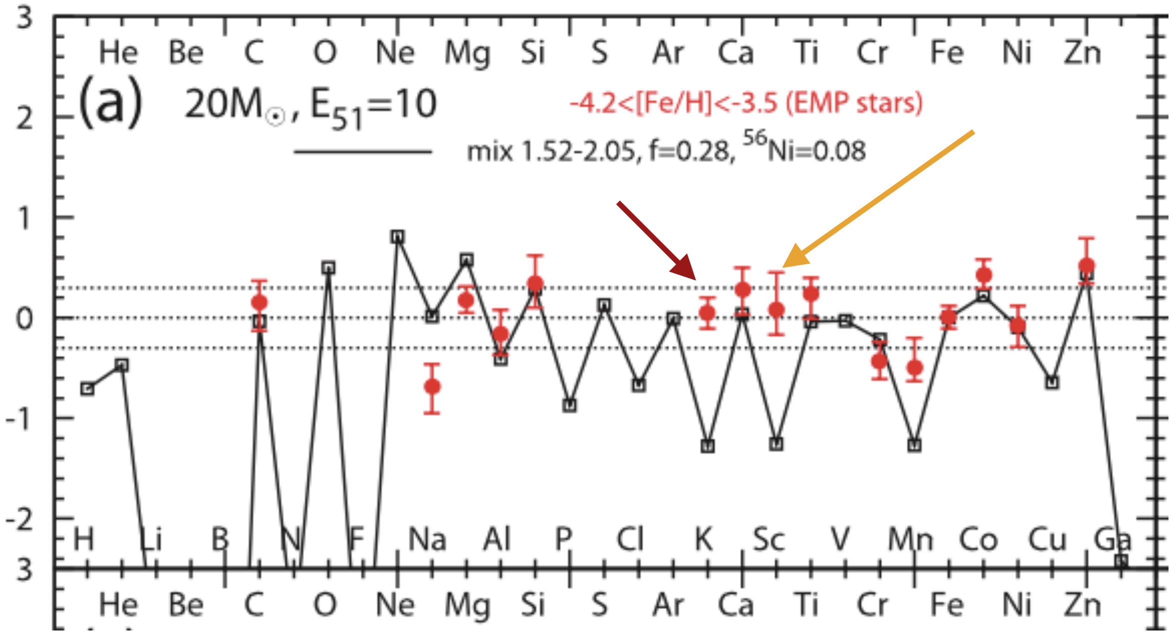
… of course this problem is well known in the literature …



Tominaga+ 07

Fig. 6.—Comparison between the [X/Fe] trends of observed stars (*crosses*: the previous studies [e.g., Gratton & Sneden 1991; Sneden et al. 1991; Edvardsson et al. 1993; McWilliam et al. 1995a, 1995b; Ryan et al. 1996; McWilliam 1997; Carretta et al. 2000; Primas et al. 2000; Gratton et al. 2003; Bensby et al. 2003]; *open circles*: CA04; *open squares*: HO04) and those of individual stars models (*filled circles*: normal SNe; *filled triangles*: HNe with case A; *filled rhombus*: HNe with case B) and IMF integration (*filled squares*). The parameters are shown in Table 1.





Observational data: Cayrel+ 04
SN models: Tominaga+ 07

Stellar evolution model of H-ingestion in rapidly accreting white dwarfs - site for the i process

- Like some single post-AGB stars or low-mass AGB stars rapidly accreting white dwarfs experience H-ingestion during the He-shell flashes.

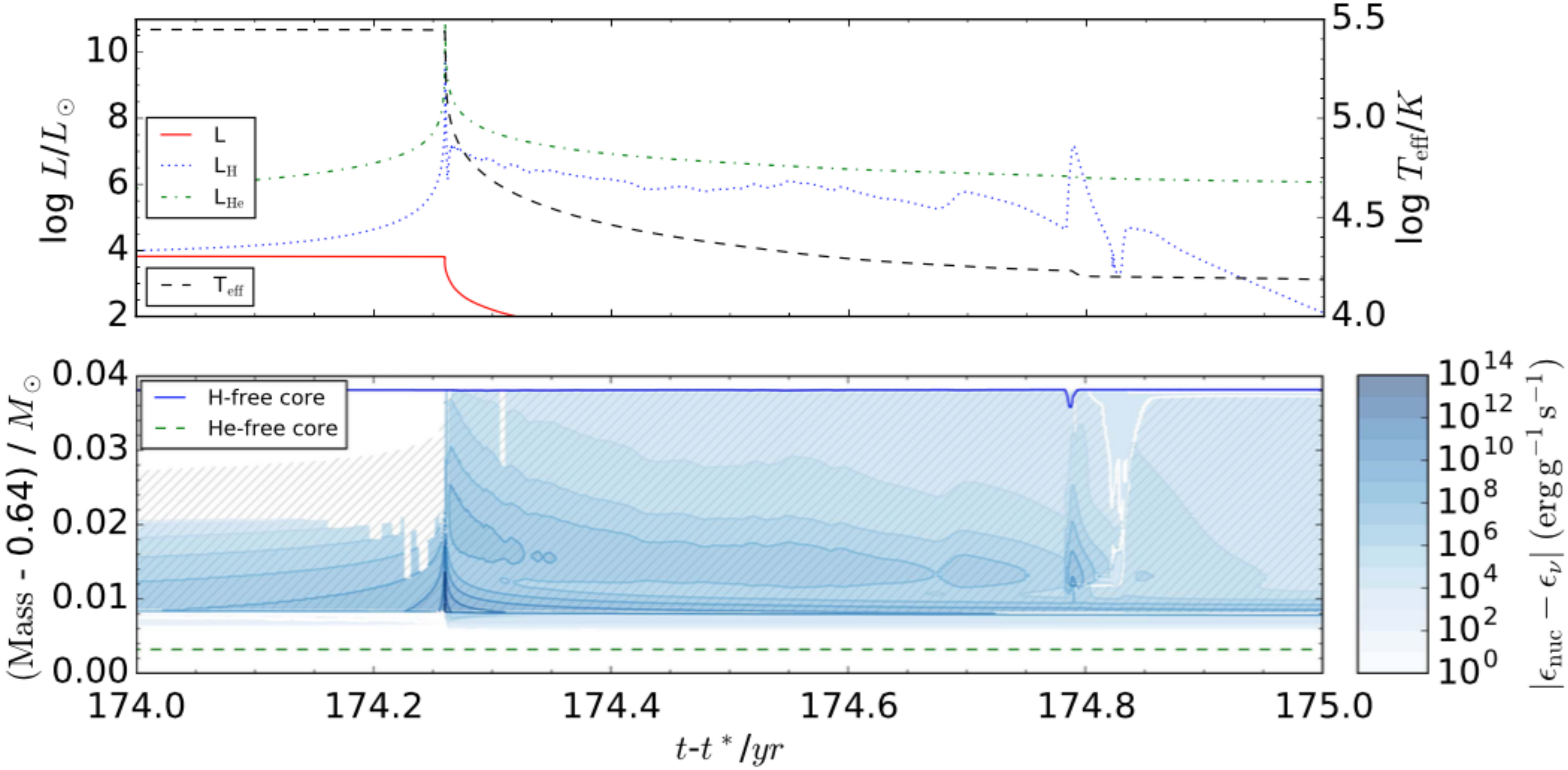
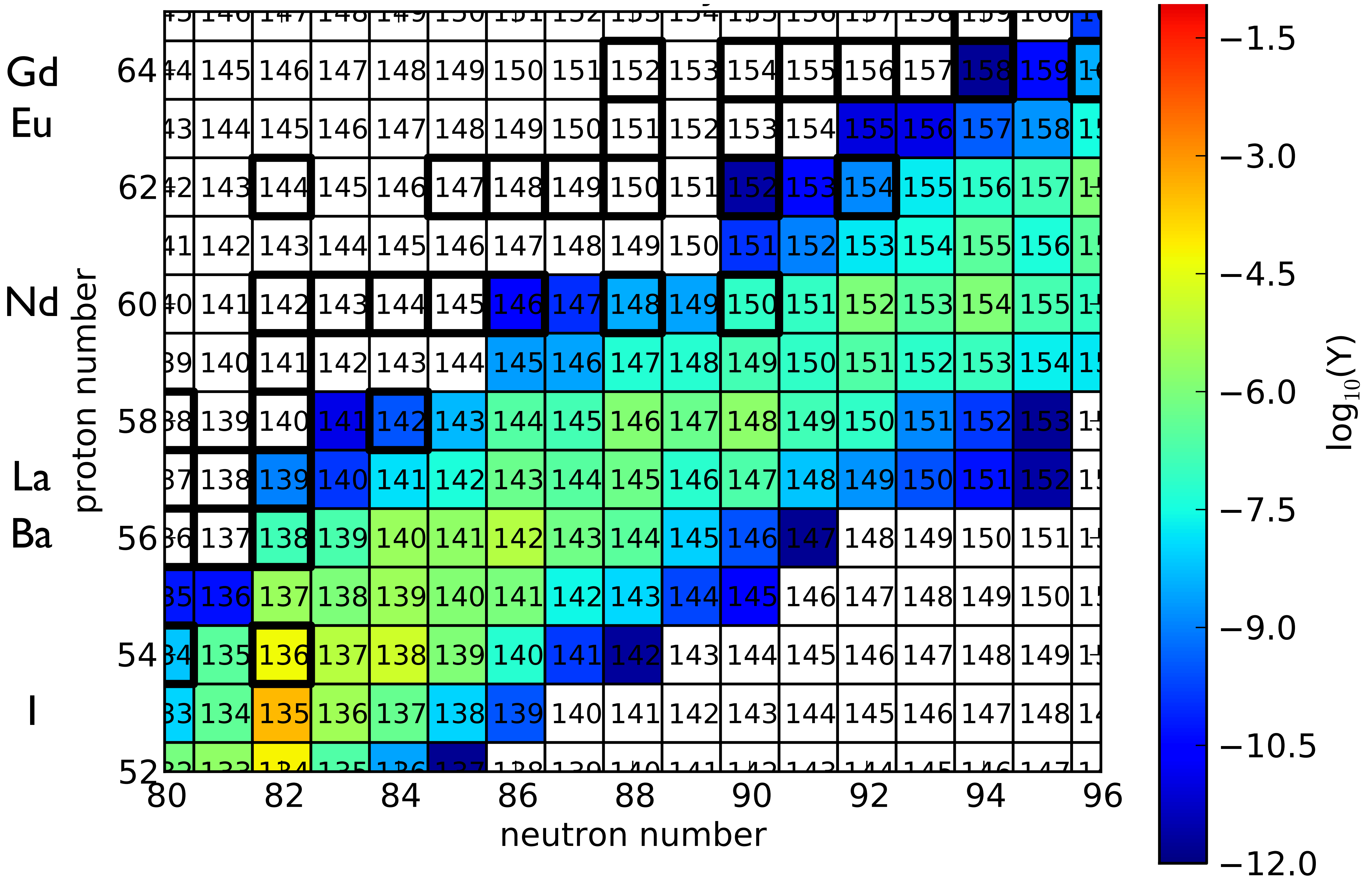


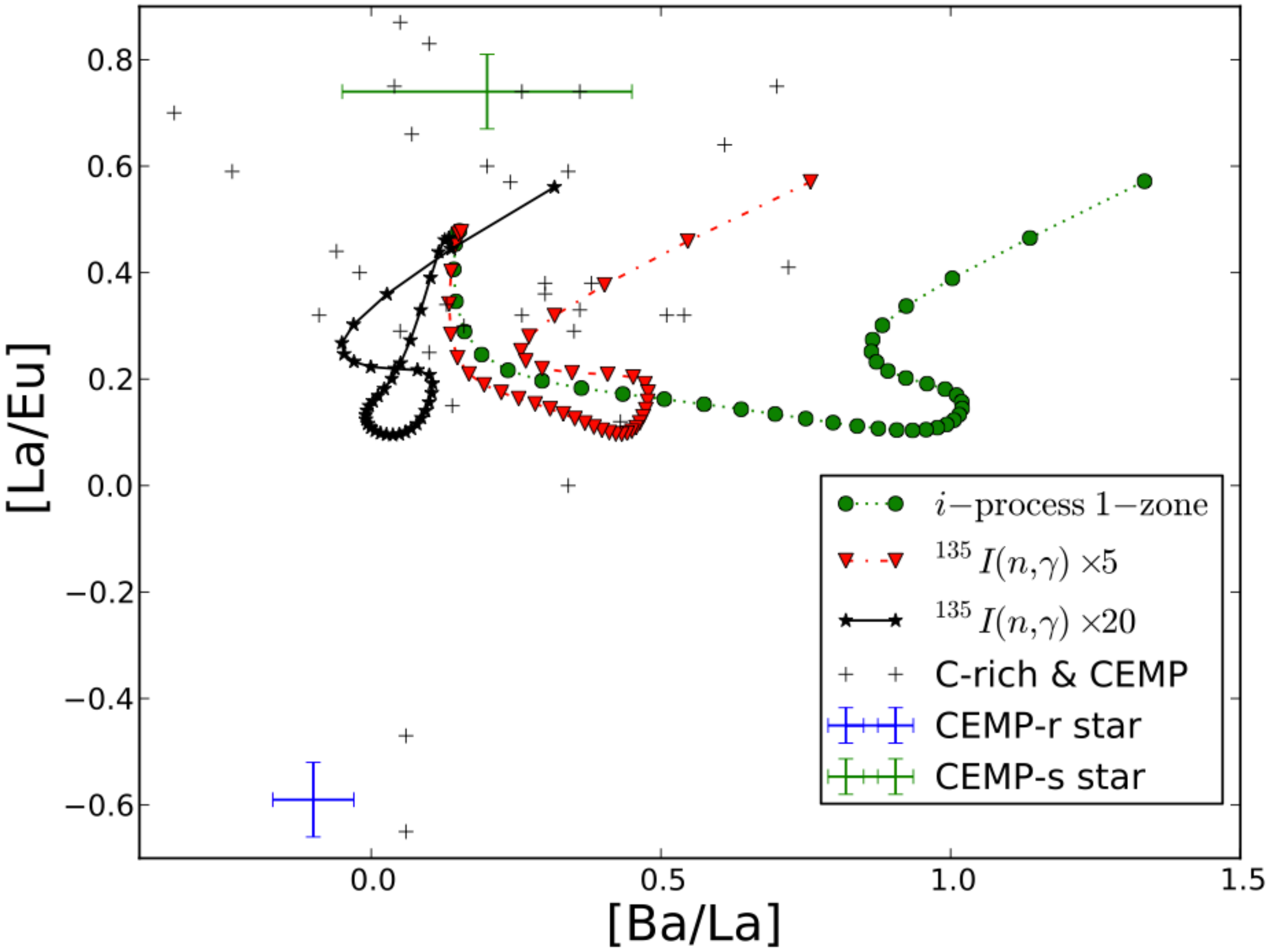
Figure 3. Top panel: $T_{\rm eff}$ and luminosity evolution (total, and due to H and He burning separately). Bottom panel: time evolution of convection zone (hatched area), energy generation (gray shades), and H- and He-free mass coordinates diagram of the He-shell flash in model A. t_* corresponds to the onset of the flash.

i process for N= 82 region: the ^{135}I bottleneck



		80		82		84		86		88		90		92		94	
Gd	64	44	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159
Eu		43	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158
	62	42	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157
		41	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156
Nd	60	40	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155
		39	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154
	58	38	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153
La		37	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152
Ba	56	36	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151
		35	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150
	54	34	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149
I		33	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148

^{135}I(n,γ) impact on Ba/La ratio



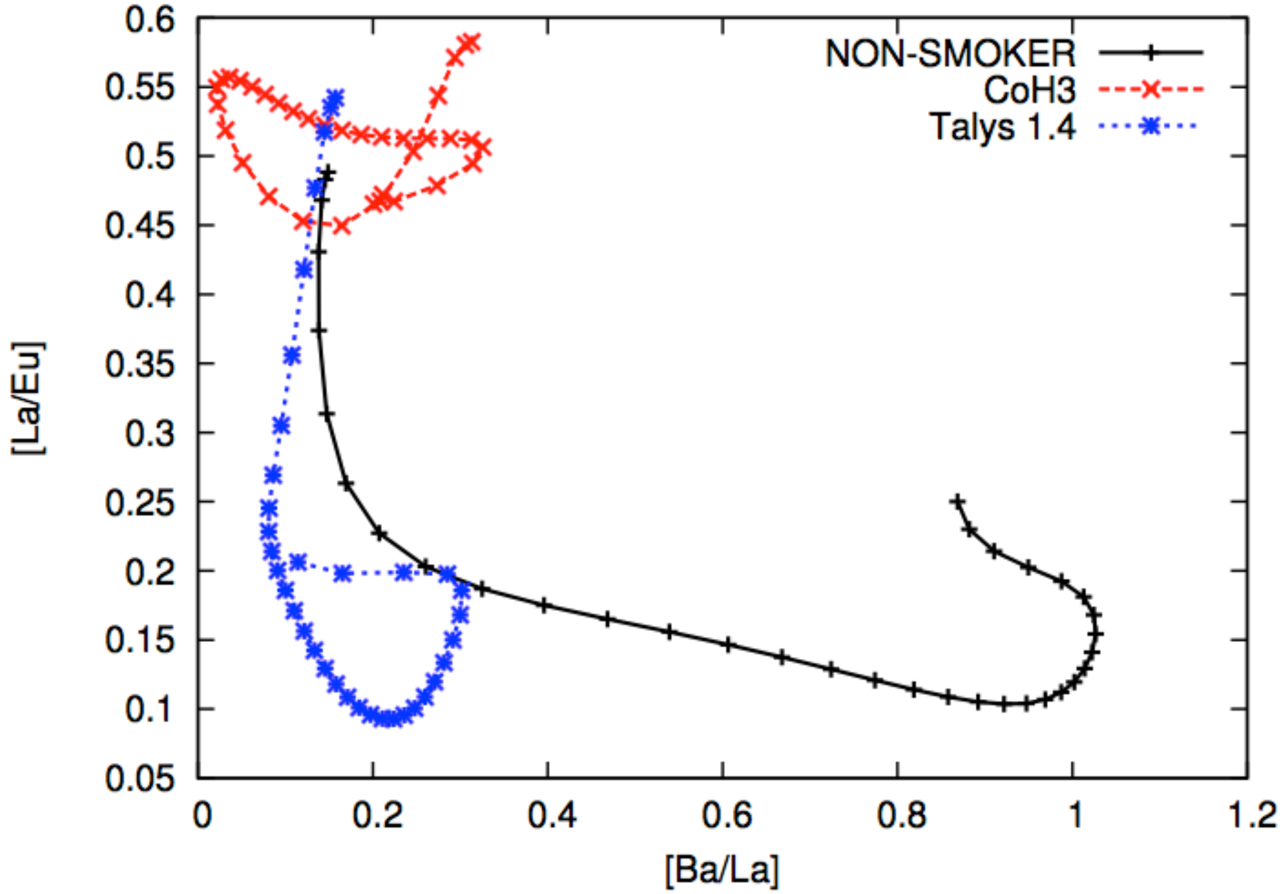
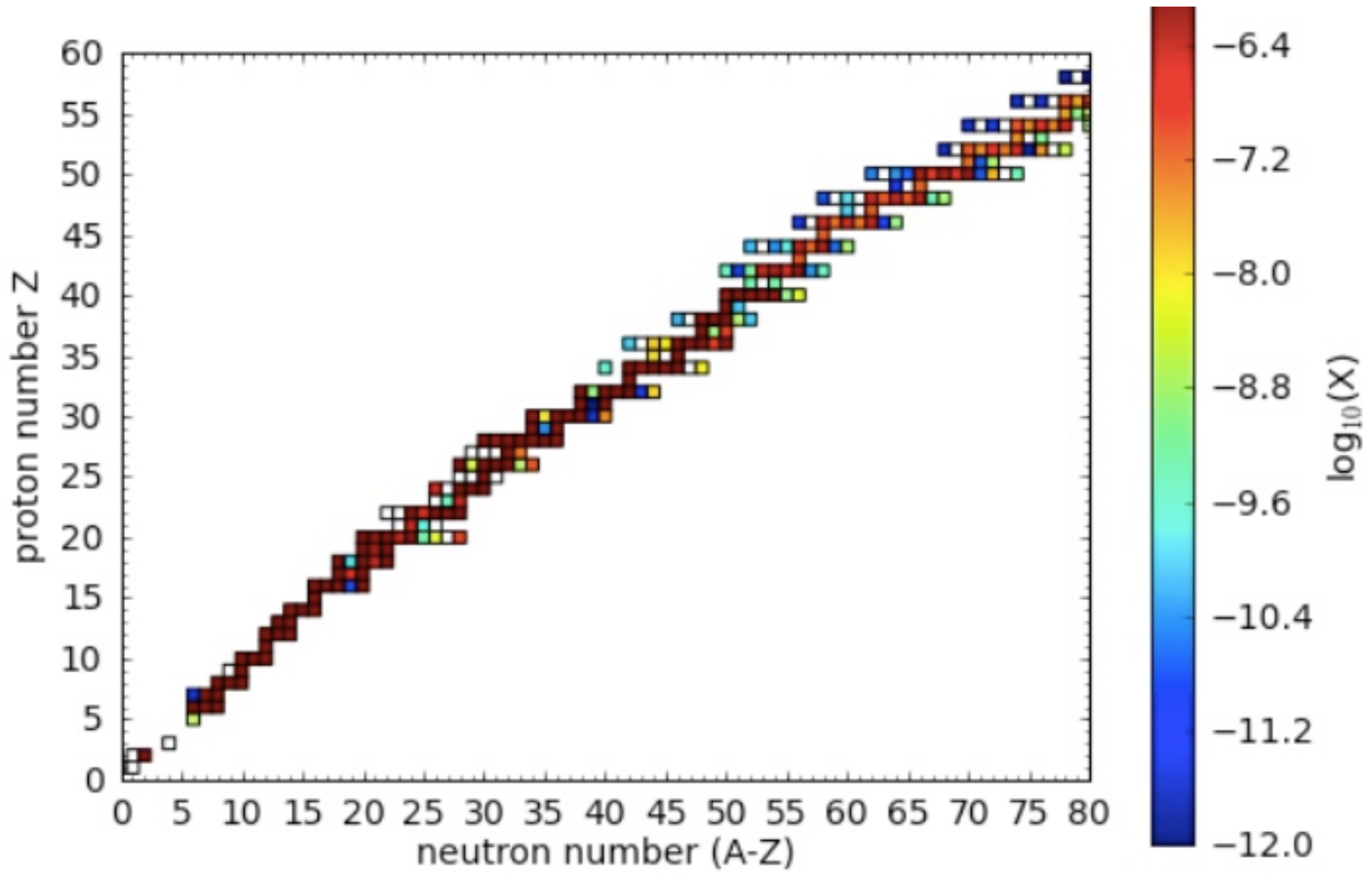


FIG. 6: (Colour online) Comparison of the [Ba/La] and [Eu/La] ratios over time when using the default **NON-SMOKER** (black), **CoH$_3$** (red) and **TALYS 1.4** (blue) models.

Bertolli+ 13, astro-ph

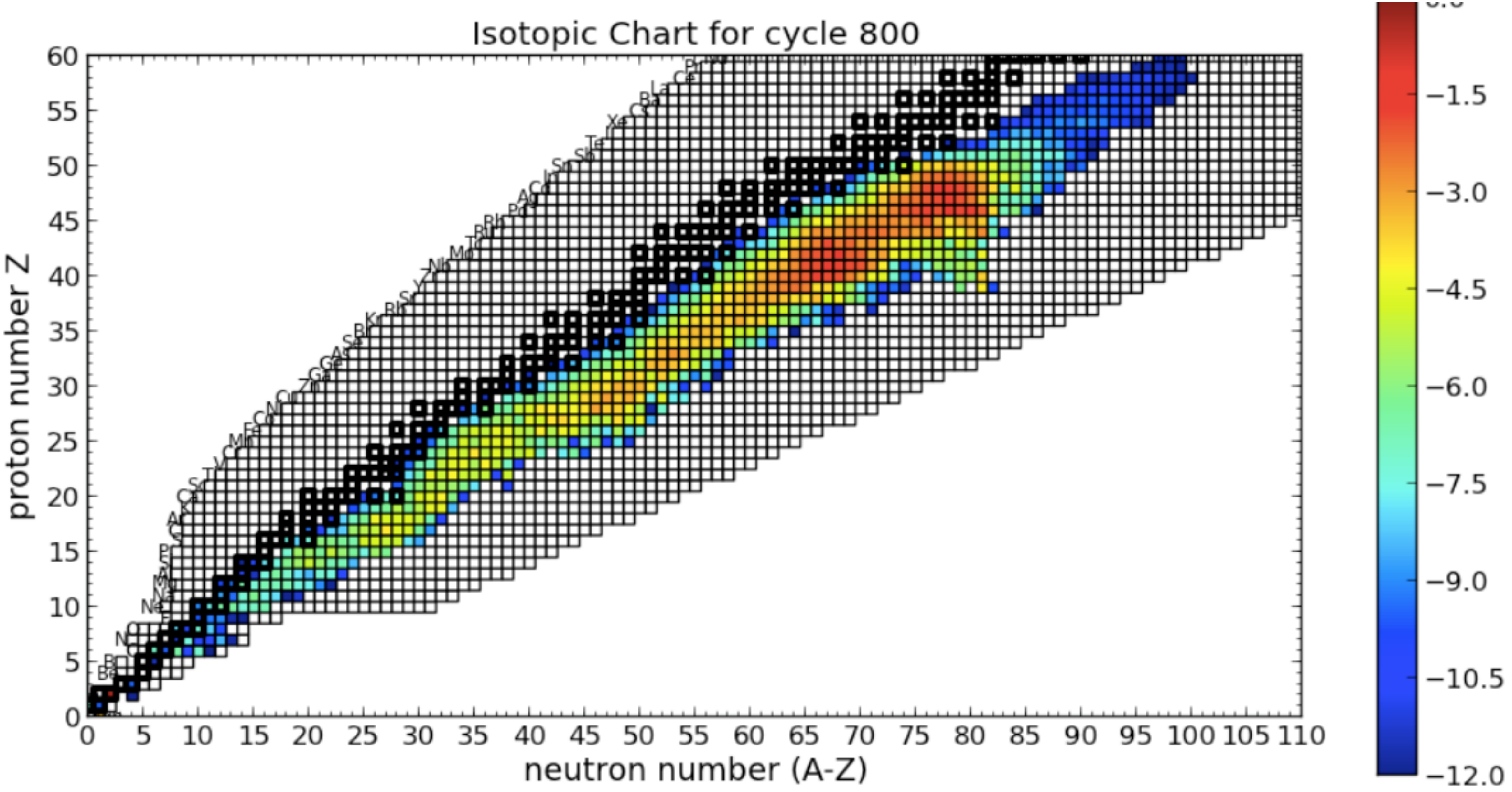
The s- process nucleosynthesis

- Network flux follows closely valley of stability
- this is associated with characteristic isotopic and elemental abundance signatures



The r- process nucleosynthesis

- Isotopic chart
- Neutrino-driven wind, S=150[1], Ye=0.4, adiabatic expansion



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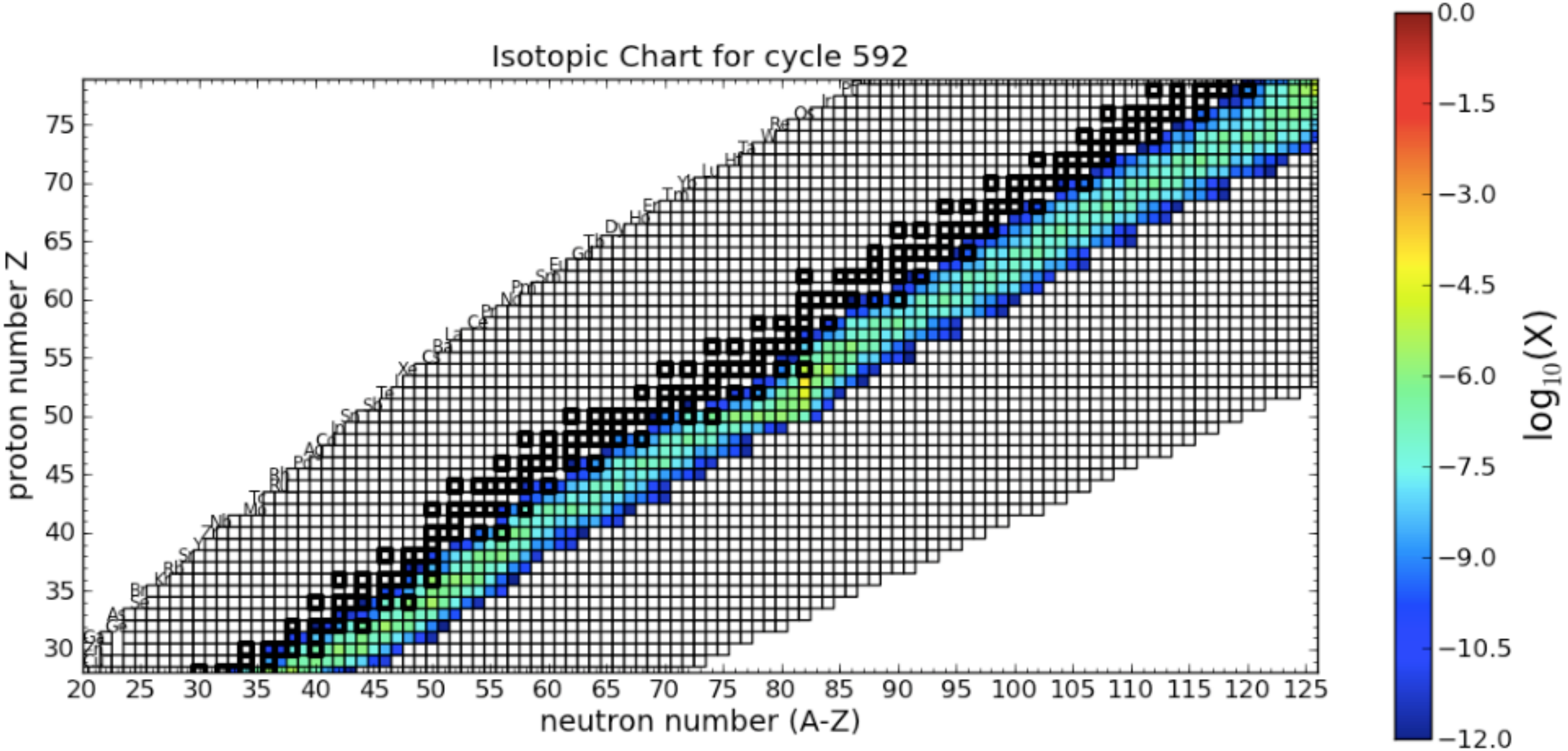
[1] in units of k_B/nucleon

1-zone i process nucleosynthesis simulation



- i-process is a multi-zone process, but can be approximated to some extent by 1-zone Network flux follows closely valley of stability
- this is associated with characteristic isotopic and elemental abundance signatures