CaNPAN

McMaster University

UNIVERSITY OF ALBERTA

UNIVERSITY of GUELPH

Saint Mary's University

TRIUMF

CaNPAN

Goals, Activities, Accomplishments and Future Plans

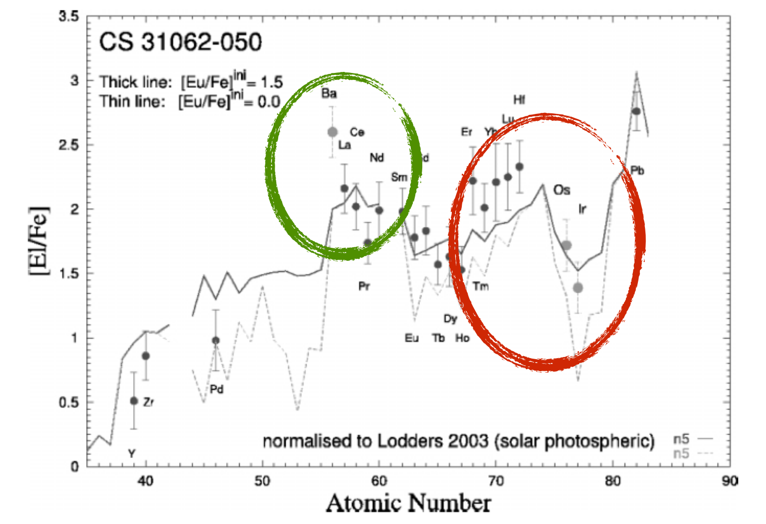
University of Victoria

Falk Herwig, May 1, 2024

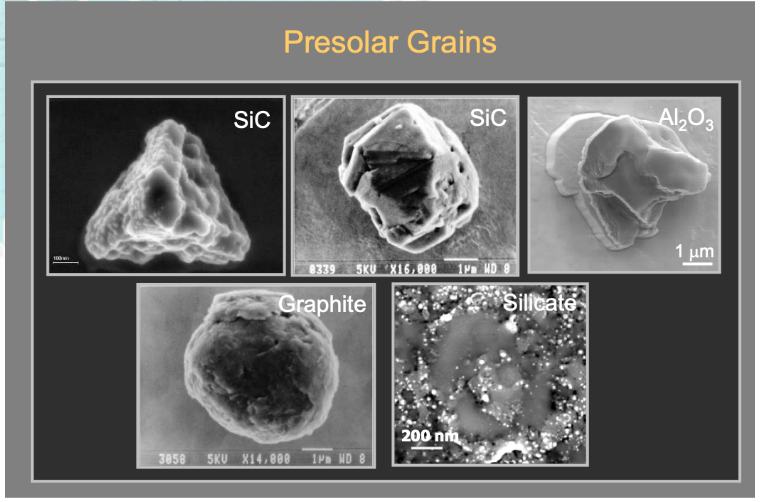
CaNPAN

Canadian Nuclear Physics for Astrophysics Network

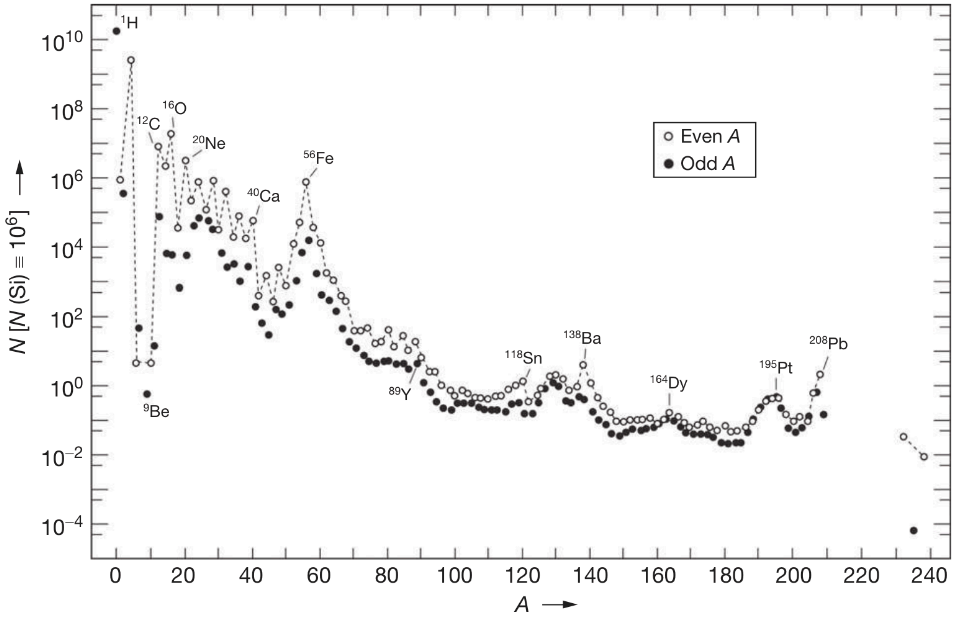
- What's in a name
- Nuclear Astrophysics: What is the origin of the elements?
    - What is the origin of anomalous abundance patterns observed in stars?
    - How did material with anomalous isotopic abundance ratios in pre-solar grains form that reflect the nuclear production in individual stellar production sites?
    - What are the processes that contributed in which way to assemble the solar system abundance composition?



Bisterzo+ 12



Zinner 98



Palme+ 03

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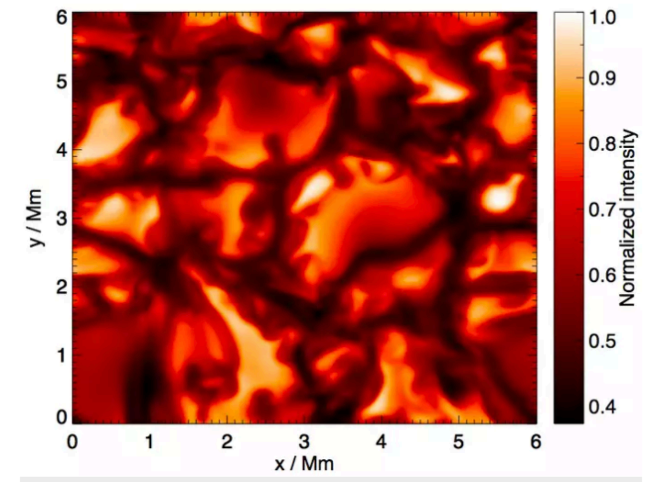
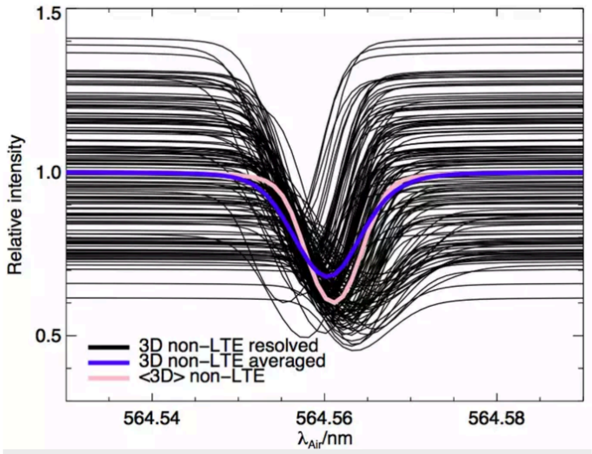
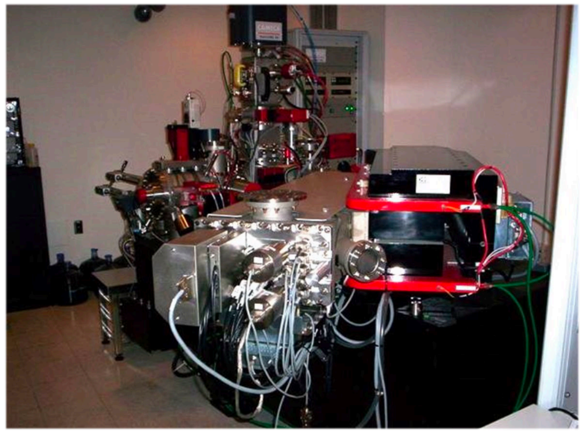
Canadian Nuclear Physics for Astrophysics Network

- To answer these questions we need a multidisciplinary team
  - Observations and measurements of the elements, pre-solar grains: telescopes, spectrographs, model atmospheres, nano-SIMS etc
  - Stellar models, astrophysics simulations of stars and stellar mixing





K Lind, MPI



NanoSIMS ion probe @ NASA JSC

Nguyen

Stars: multi-physics systems

… that's what makes them so interesting!

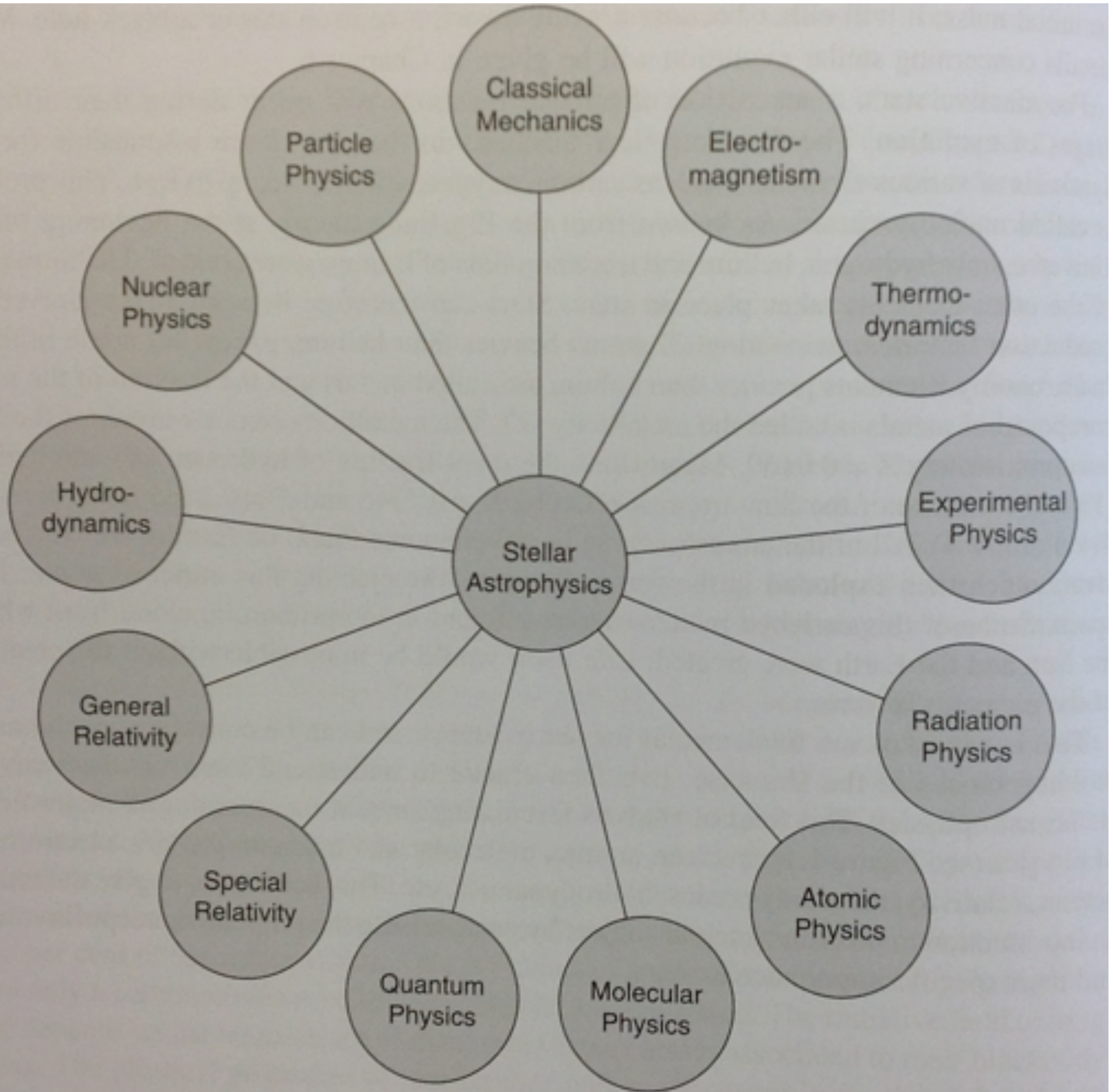


Figure 1.1 Figure illustrating the various fields of physics that intervene in stars.

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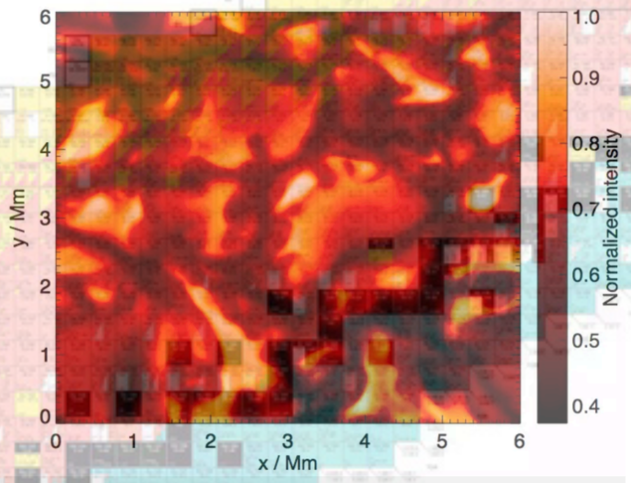
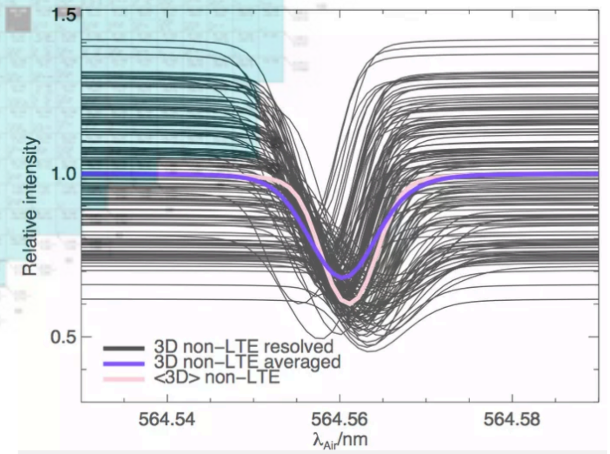
Canadian Nuclear Physics for Astrophysics Network

- To answer these questions we need a multidisciplinary team
    - Observations and measurements of the elements, pre-solar grains: telescopes, spectrographs, model atmospheres, nano-SIMS etc
    - Stellar models, astrophysics simulations of stars and stellar mixing
    - Nuclear physics input: reaction rates, masses, beta decays etc





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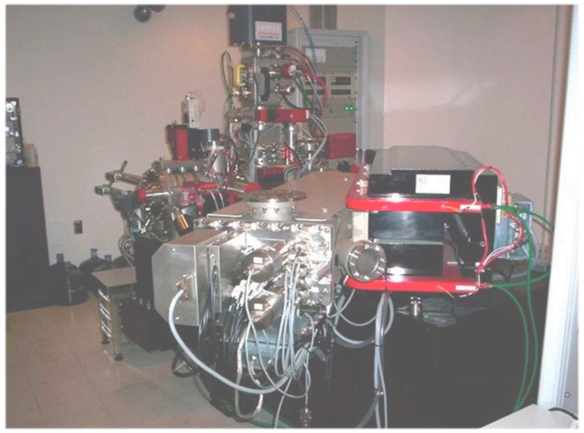

NanoSIMS ion probe @ NASA JSC

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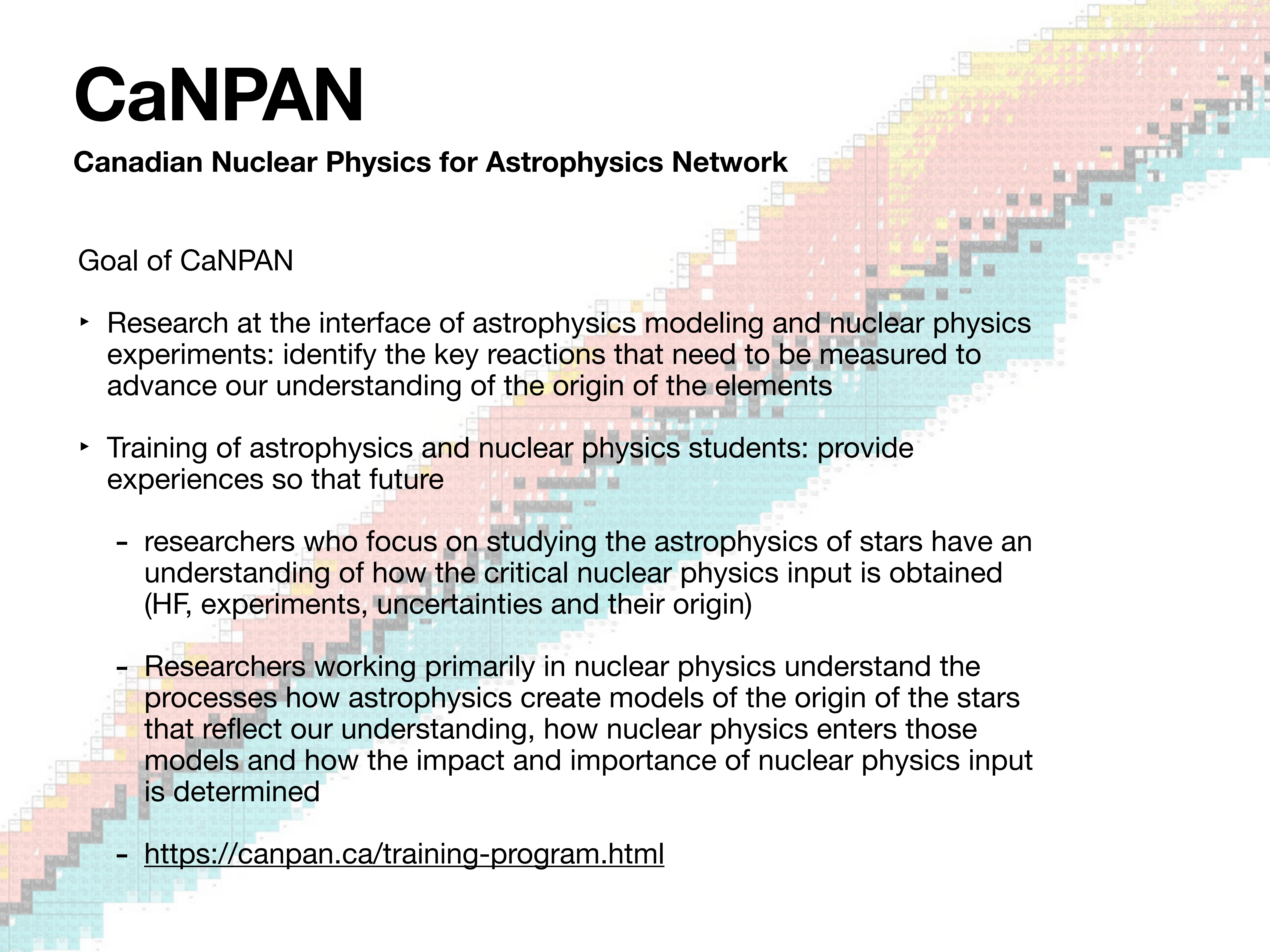

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Canadian Nuclear Physics for Astrophysics Network

Goal of CaNPAN

- Research at the interface of astrophysics modeling and nuclear physics experiments: identify the key reactions that need to be measured to advance our understanding of the origin of the elements
- Training of astrophysics and nuclear physics students: provide experiences so that future
  - researchers who focus on studying the astrophysics of stars have an understanding of how the critical nuclear physics input is obtained (HF, experiments, uncertainties and their origin)
  - Researchers working primarily in nuclear physics understand the processes how astrophysics create models of the origin of the stars that reflect our understanding, how nuclear physics enters those models and how the impact and importance of nuclear physics input is determined
  - https://canpan.ca/training-program.html

CaNPAN

Current work

https://www.canpan.ca


CaNPAN Home Team Training Program Projects Results & Publications Experiments Contact

- Current project: Nuclear Physics of the Dynamic Origin of the Elements
- Multi-disciplinary **training** at the intersection of nuclear physics theory and experiment on one side and astrophysics and astronomical observables on the other
- Since 2021 25 mostly graduate students from Canada, the USA, Croatia, India, France and Chile have participated in the program
- **Future plans at TRIUMF**: storage ring with neutron source to measure (n.g) in inverse kinematics directly, potentially own to half-lives of minutes

Nuclear physics impact studies:

Denissenkov et al. 2021. 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.

Denissenkov et al. 2018. 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. J. of Phys. G. 45:055203.

McKay J. E. et al. 2020. The impact of (n,γ) reaction rate uncertainties on the predicted abundances of I-process elements with 32 ≤ Z ≤ 48 in the metal-poor star HD94028. MNRAS. 491:5179.

Proposal Number	PI	Title	Isotope(s) measured (n,g)
ANL-1734	Ann-Cecilie Larsen	The rare-earth r-process peak: 156-159Sm(n,γ) reaction rates constrained with the beta-Oslo method	
ANL-1742	Artemis Spyrou	Constraints on neutron-capture reactions around N=82	
ANL-1755	Sean Liddick	Neutron-capture cross section constraints in neutron-rich Sn and Sb isotopes	
ANL-1799	Stephanie Lyons	Constraining neutron-capture cross sections for the i-process	
ANL-1807	Mallory Smith	Investigating gamma-ray strength functions and nuclear level densities in neutron-rich Zr isotopes	
ANL-1928	Hannah Berg	Constraining neutron-capture cross section for the i-process around A=150	
ANL-1929	Andrea Richard	Neutron-capture constraints for the astrophysical i-process	
ANL-2018	Andrea Richard	Constraining i-Process Nucleosynthesis in the Nb-Ru Region	
ANL-e1928	Andrea Richard	Neutron-capture constraints for the Astrophysical i-process	140Ba, 144Ce, 146Ce
ANL-e1929	Hannah Berg	Constraining neutron-capture cross sections for the i-process around A=150	151-153Nd
ANL-e2018	Andrea Richard	Constraining i-Process Nucleosynthesis in the Nb-Ru Region	99-101Mo
ANL-submitted	Adriana Sweet	Neutron-capture cross sections for heavy-mass fission fragments constrained with the β-Oslo method	
ANL-submitted	Erin Good	Astrophysical i-process constraints via the β-Oslo method	
FRIB-23084	Steve Pain	Informing the i process: constraining the As/Ge abundance ratio in a metal poor star via 75Ga(d,pg)76Ga	75Ga
FRIB-e23004	Eleanor Ronning	The Last Piece of the Generalized Brink Axel Hypothesis	69Zn 96Zr
FRIB-e23056	Andrea Richard	Indirect 99Nb(n,g)100Nb Constraint for the Astrophysical i-process	99Nb
NSCL-15136	N. Scielzo	Determination of the 92Sr(n,g) cross section and fission product burn up	
NSCL-e16033	Artemis Spyrou	Study of Kr isotopes for astrophysical applications	
NSCL-e17014	Sean Liddick	Photon strength function following the decay of 70Cu	
TRIUMF-S1944	Denis Mücher	Constraining neutron capture rates for the astrophysical i process	
TRIUMF-S2303	Matthew Williams	Can an i-process explain high (As/Ge) ratios seen in metal-poor stars?	75Ga

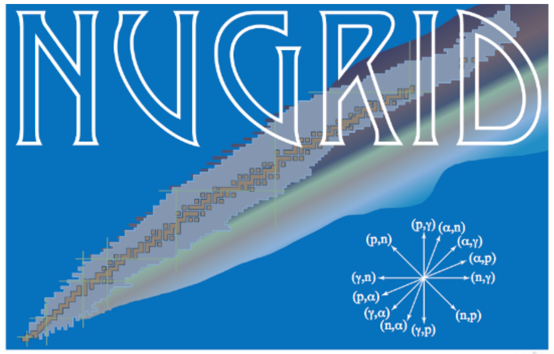
CaNPAN

CaNPAN in the network of networks

IReNA

International Research Network for Nuclear Astrophysics

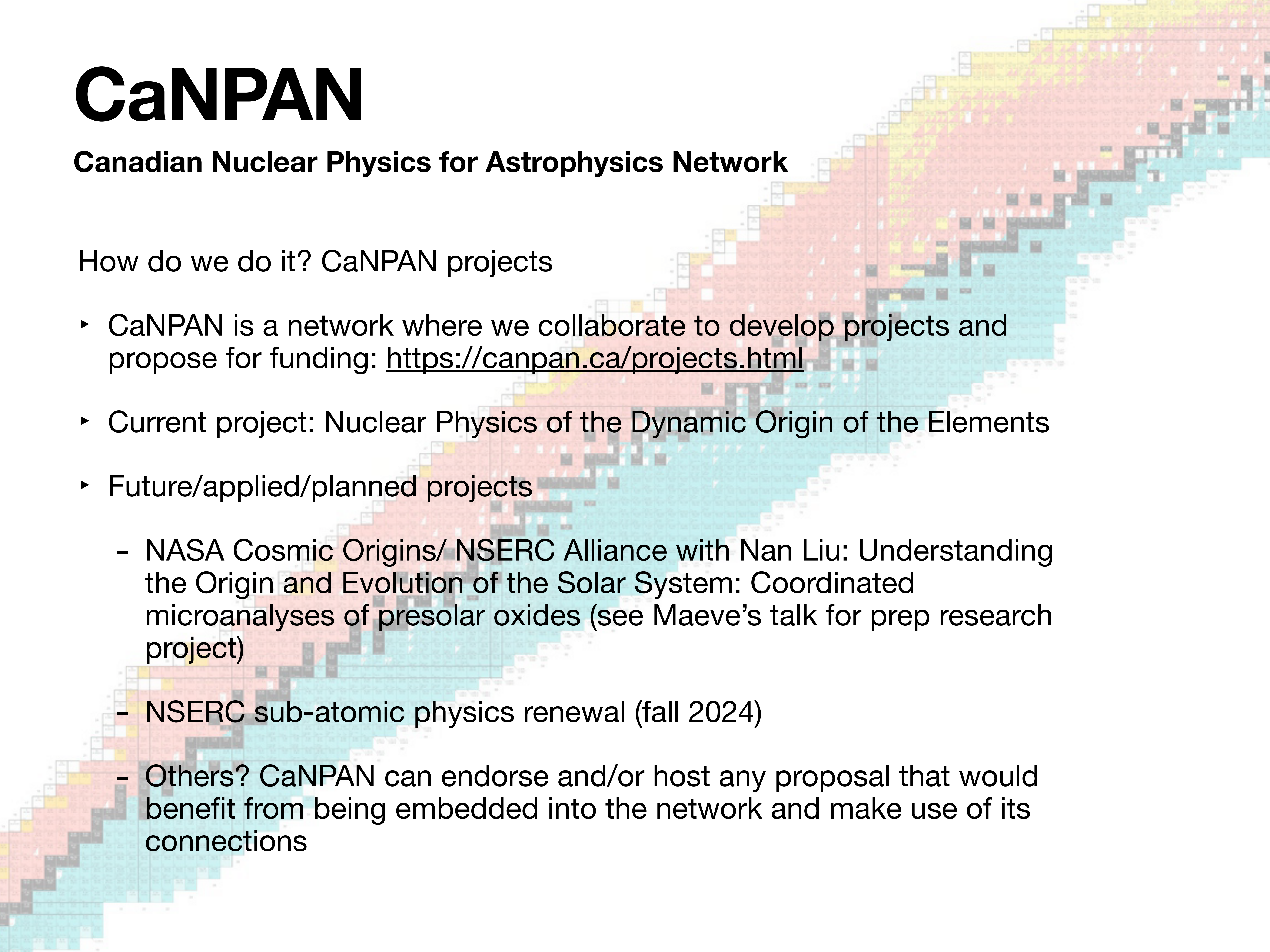
https://www.irenaweb.org/



https://www.nugridstars.org/

ARC

https://www.uvic.ca/arc



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Canadian Nuclear Physics for Astrophysics Network

How do we do it? CaNPAN projects

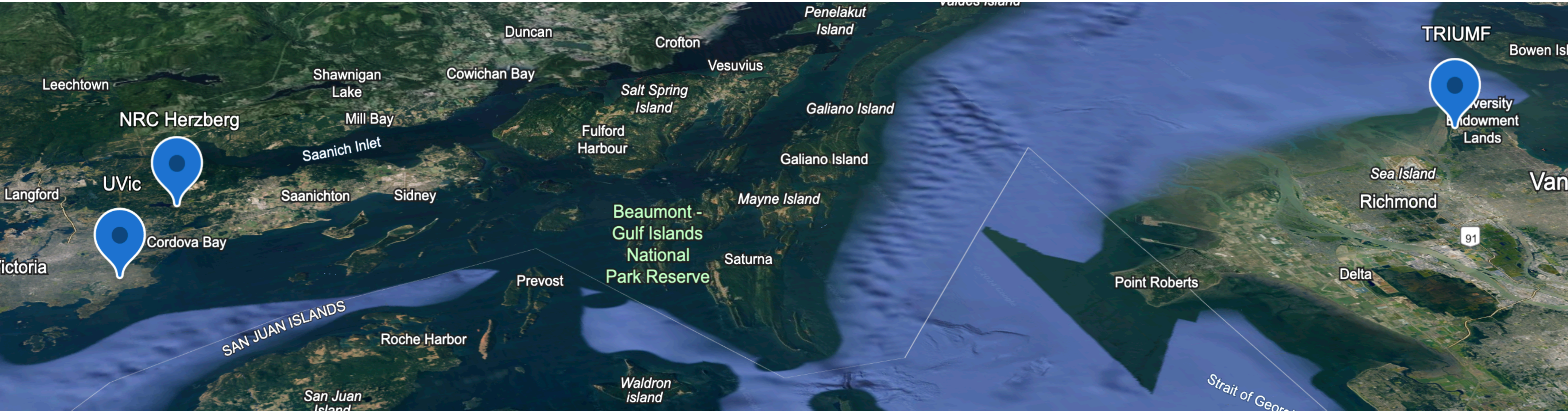
- CaNPAN is a network where we collaborate to develop projects and propose for funding: https://canpan.ca/projects.html
- Current project: Nuclear Physics of the Dynamic Origin of the Elements
- Future/applied/planned projects
  - NASA Cosmic Origins/ NSERC Alliance with Nan Liu: Understanding the Origin and Evolution of the Solar System: Coordinated microanalyses of presolar oxides (see Maeve's talk for prep research project)
  - NSERC sub-atomic physics renewal (fall 2024)
  - Others? CaNPAN can endorse and/or host any proposal that would benefit from being embedded into the network and make use of its connections

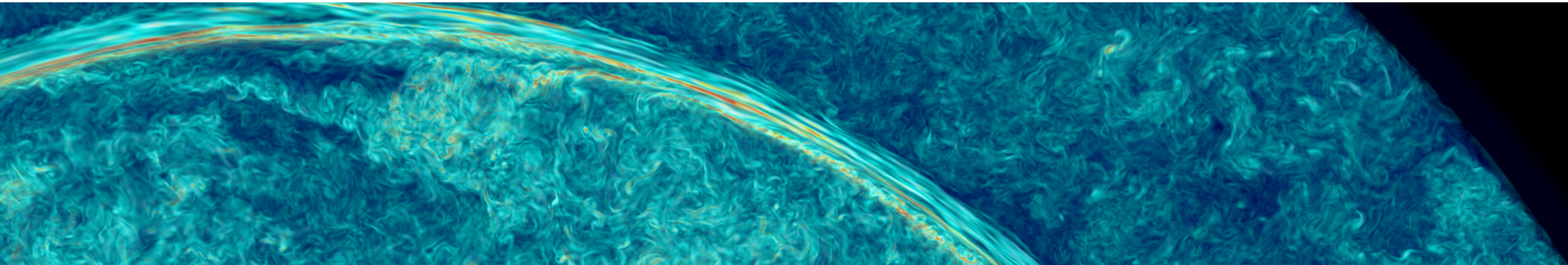
Herzberg Astronomy and
Astrophysics Research Centre

University
of Victoria

ARC

TRIUMF

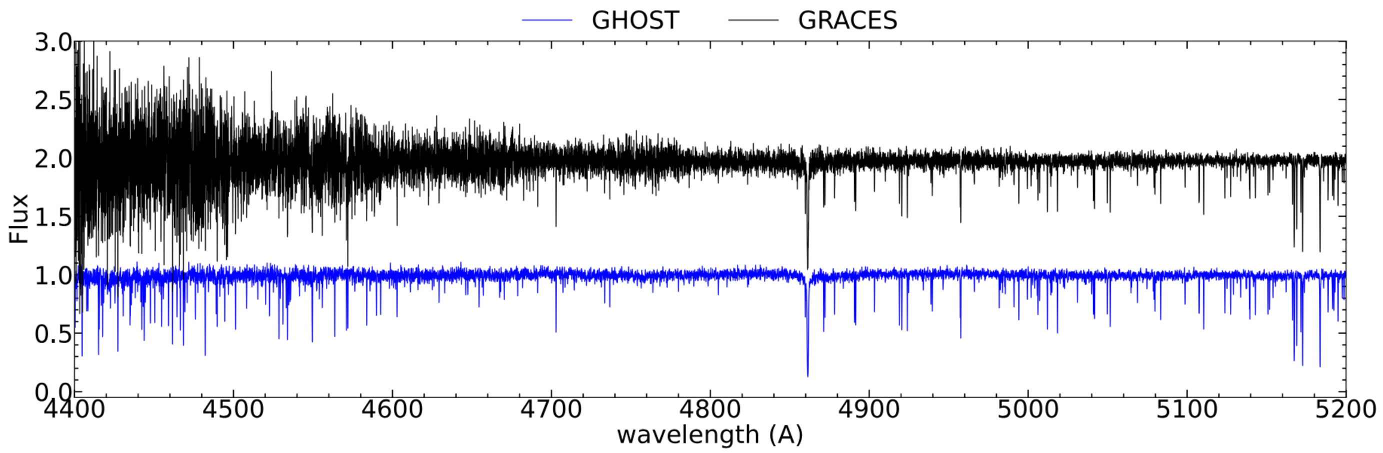


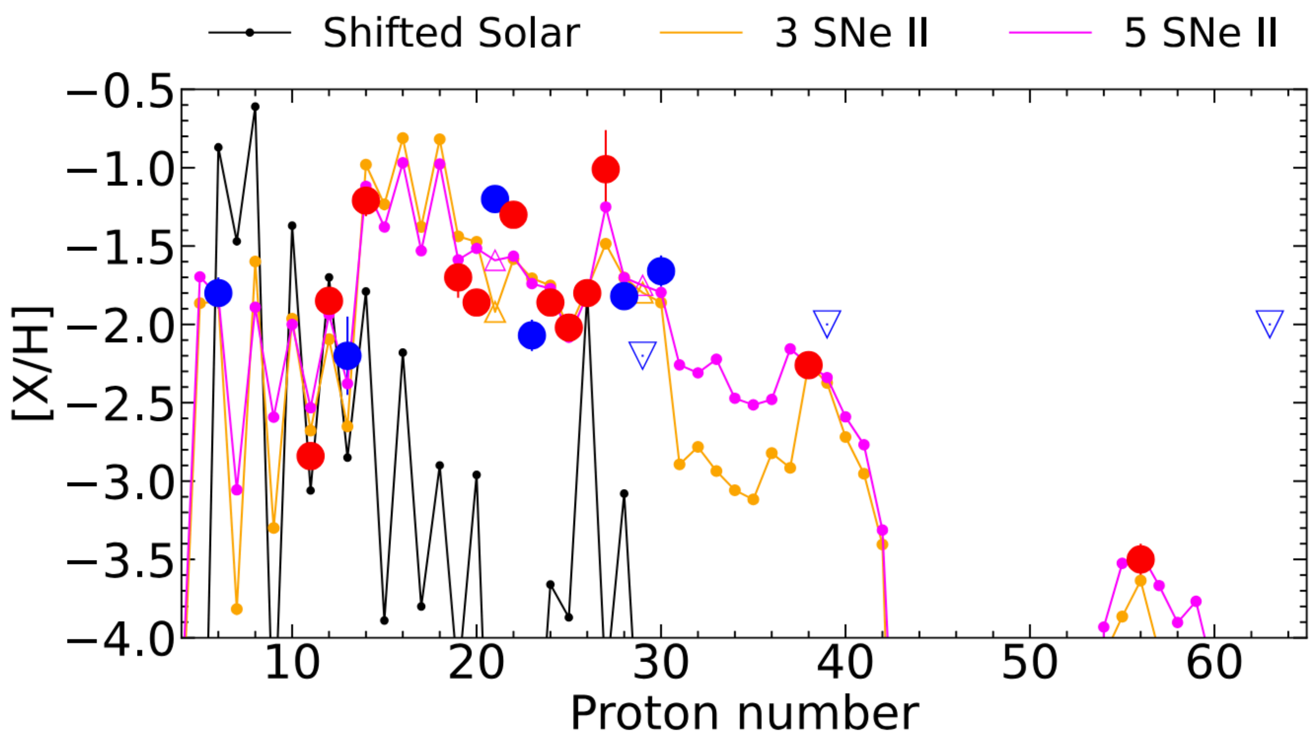


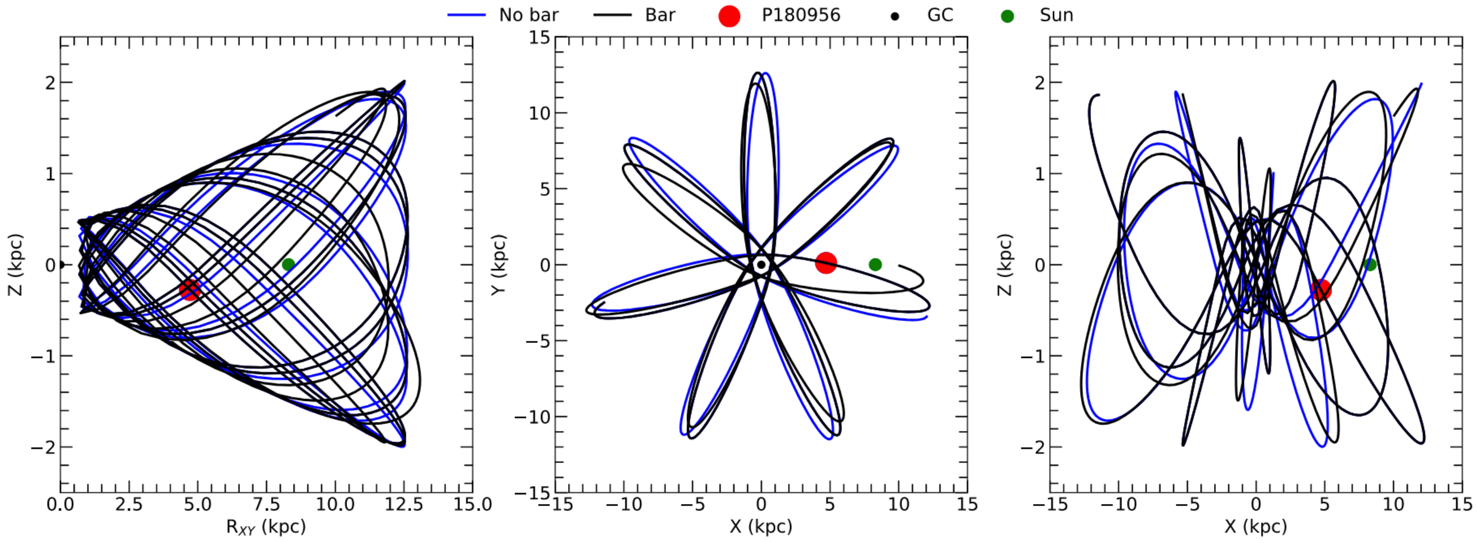
ARC - Science

GHOST instrumentation — origin of the elements — early galactic assembly

- ARC collaboration Venn/Navarro/McConnachie
- GHOST Gemini High-resolution Optical SpecTrograph, very high efficiency and wide spectral coverage (3700–11 000 Å), especially high efficiency in the blue spectral region (3700–4800 Å) enables the detection of elemental tracers of early supernovae (e.g. Al, Mn, Sr, and Eu).
- Instrument scientist: Dr. Alan McConnachie at NRC
- GHOST commissioning science results – II: a very metal-poor star witnessing the early galactic assembly (**Sestito+ 2024**)
- P180956 formed in a system similar to a UFD galaxy as part of a building block of the proto-Galaxy
- Orange purple lines model predictions of first star nucleosynthesis based on 1D stellar evolution and Hyper-super-nova explosion approximations, not taking into account …
- … nuclear physics uncertainties and 3D hydrodynamics effects of the progenitor and the supernova explosion - the dynamic origin of the elements.



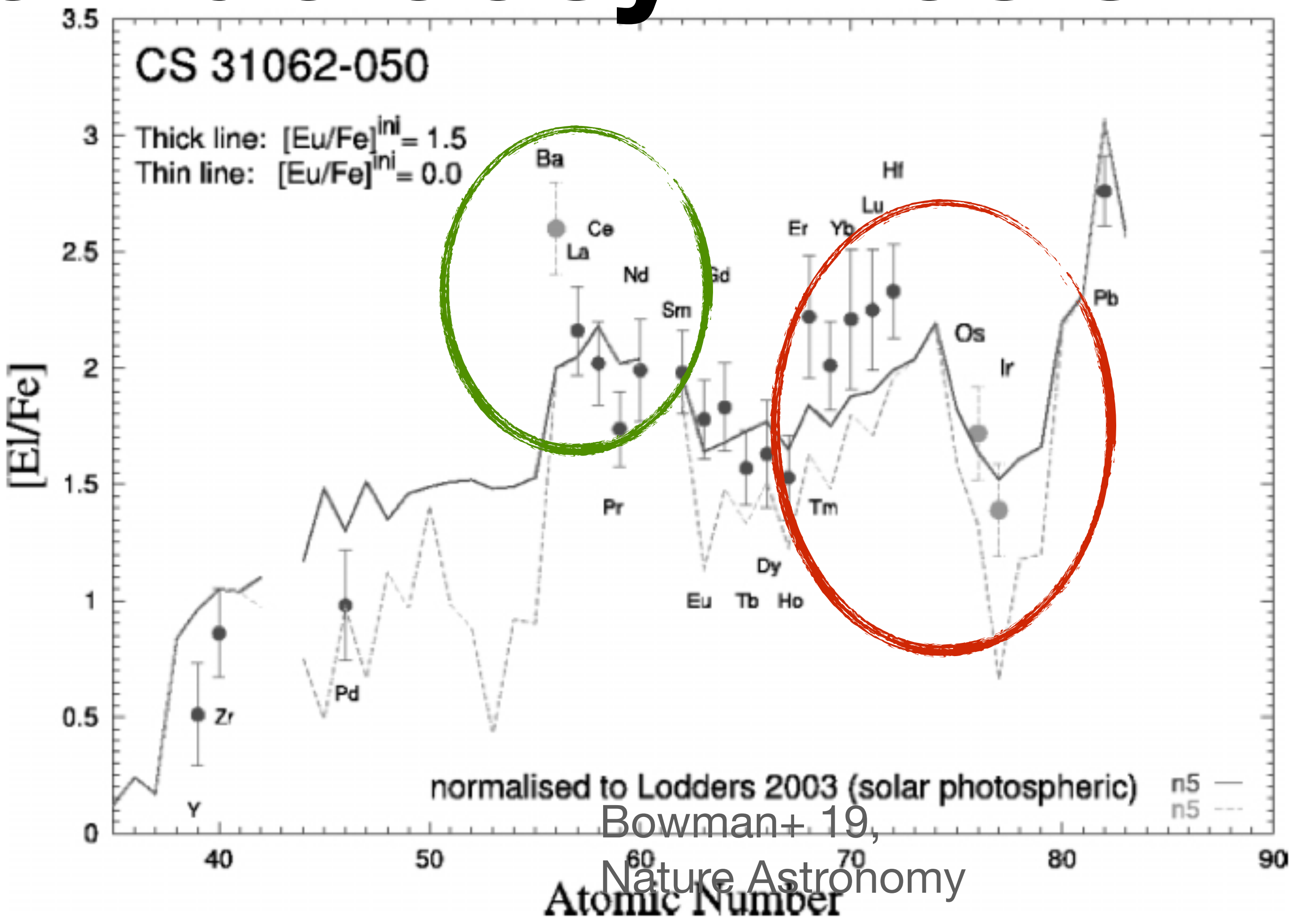




CaNPAN Dynamic Nucleosynthesis

Observations — Simulations — Experiments

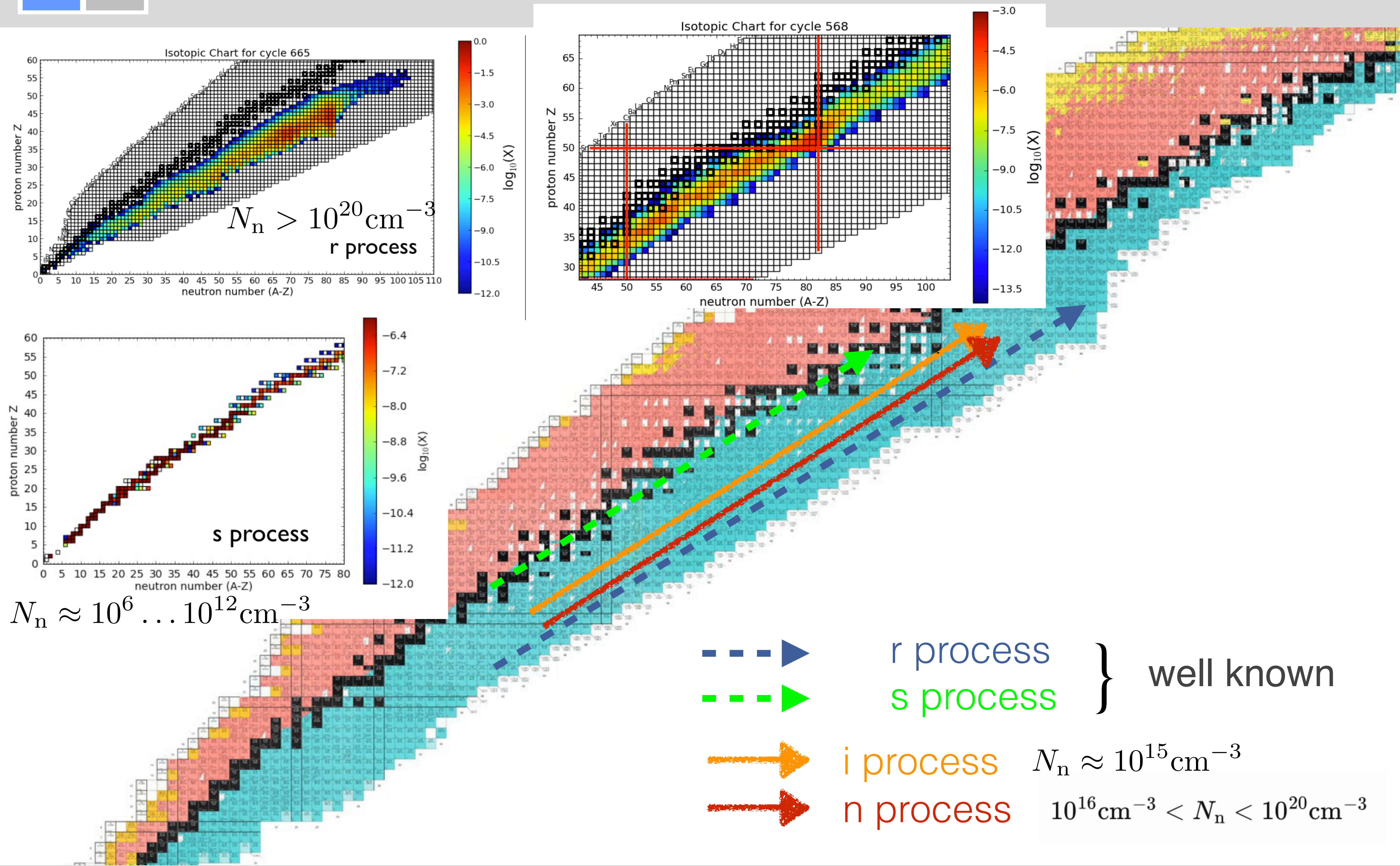
- C-enhanced Metal-Poor Stars: CEMP-r/s stars: anomalous metal-poor stars, superposition of “known” r- and s-process fingerprint (Bisterzo+ 12)??



Bowman+ 19,
Nature Astronomy

Observed main-sequence O-star HD46150.

Neutron-capture: slow, intermediate, n and rapid



- - ▶ r process
- - ▶ s process
} well known

→ i process $N_\mathrm{n} \approx 10^{15}\mathrm{cm}^{-3}$

→ n process $10^{16}\mathrm{cm}^{-3} < N_\mathrm{n} < 10^{20}\mathrm{cm}^{-3}$

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

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

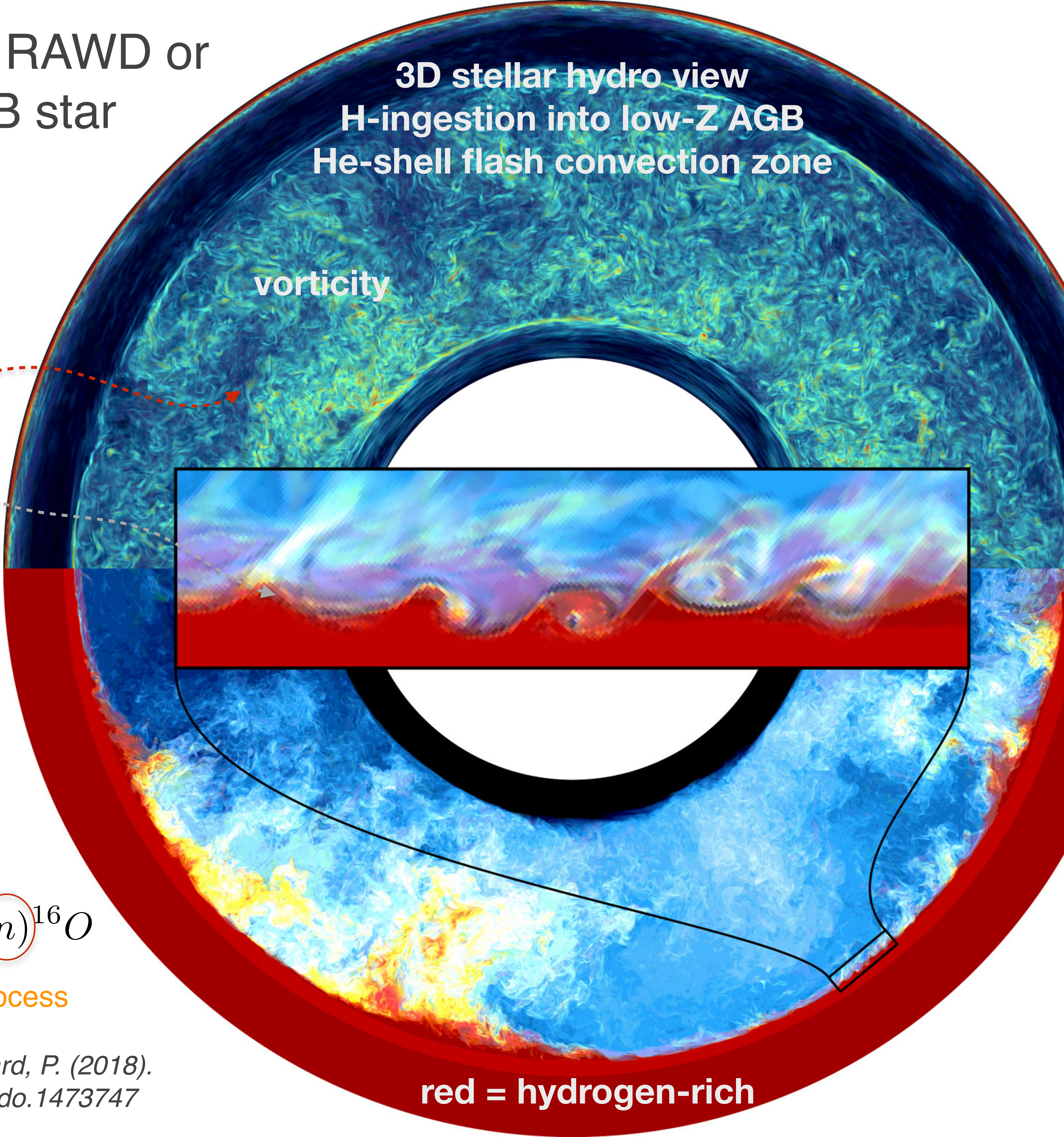
Damköhler number

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

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

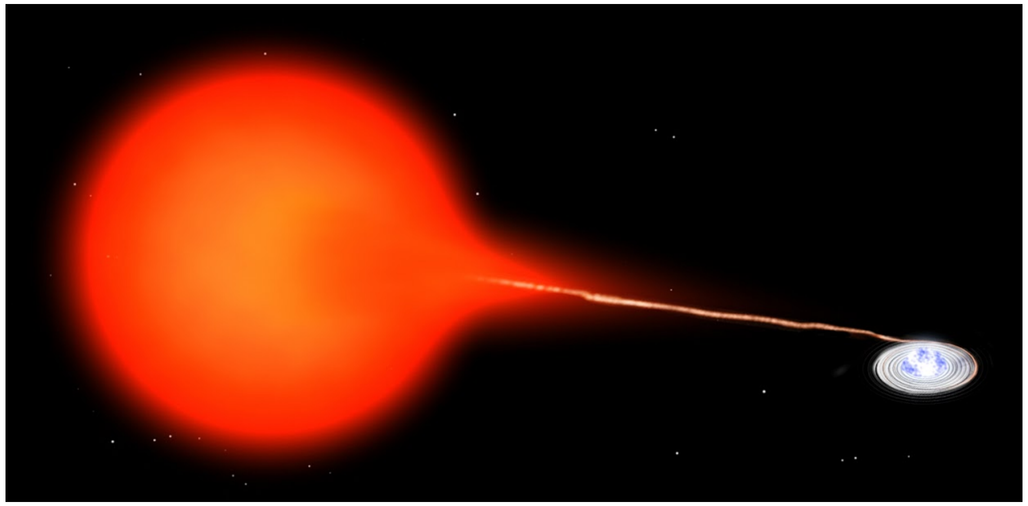
$$^{12}C(p,\gamma)^{13}N(\beta^{+}\nu)^{13}C(\alpha,n)^{16}O$$

Fast neutron source: i process



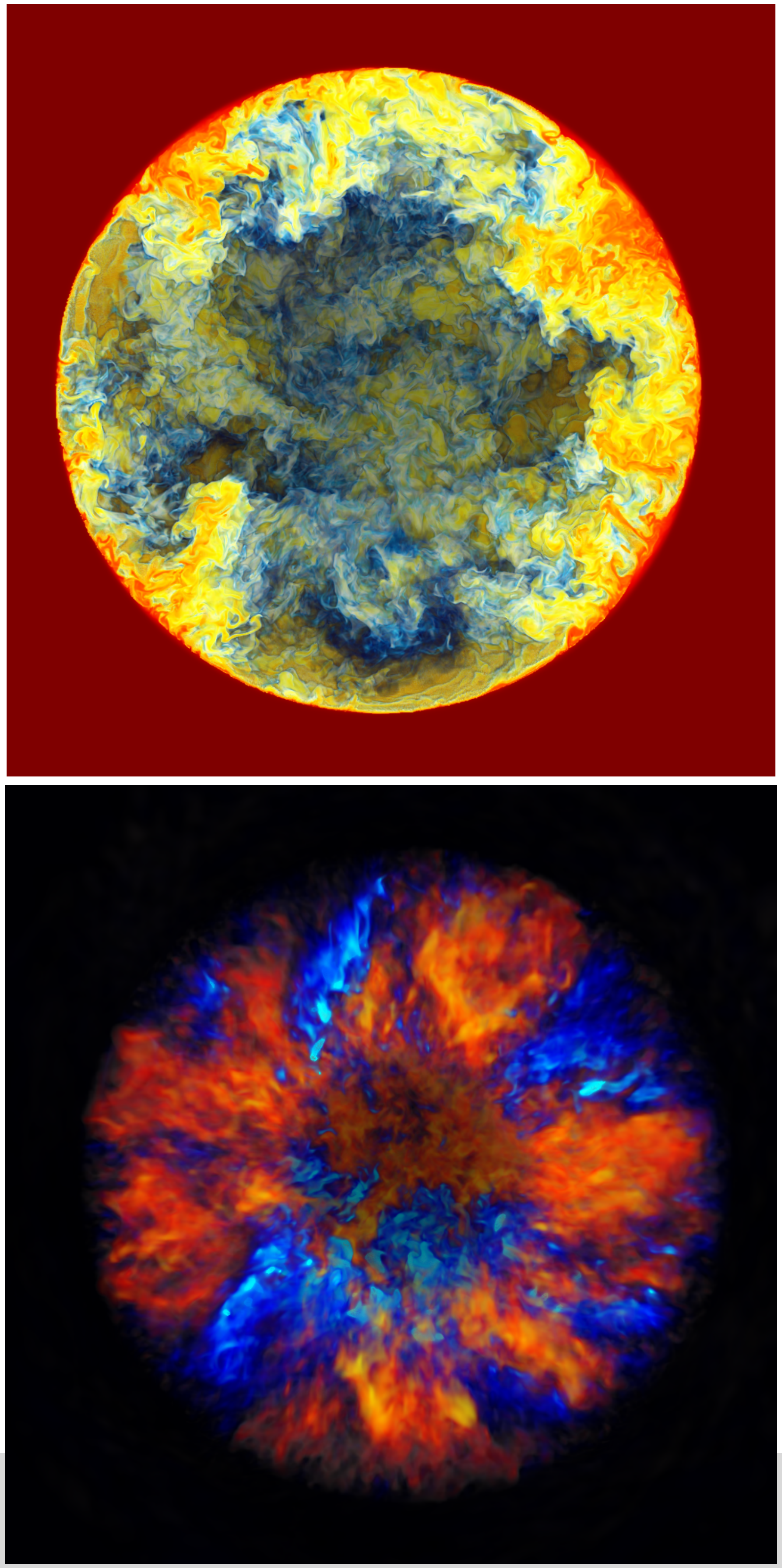
Andrassy, R., Herwig, F., & Woodward, P. (2018). Zenodo. http://doi.org/10.5281/zenodo.1473747

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

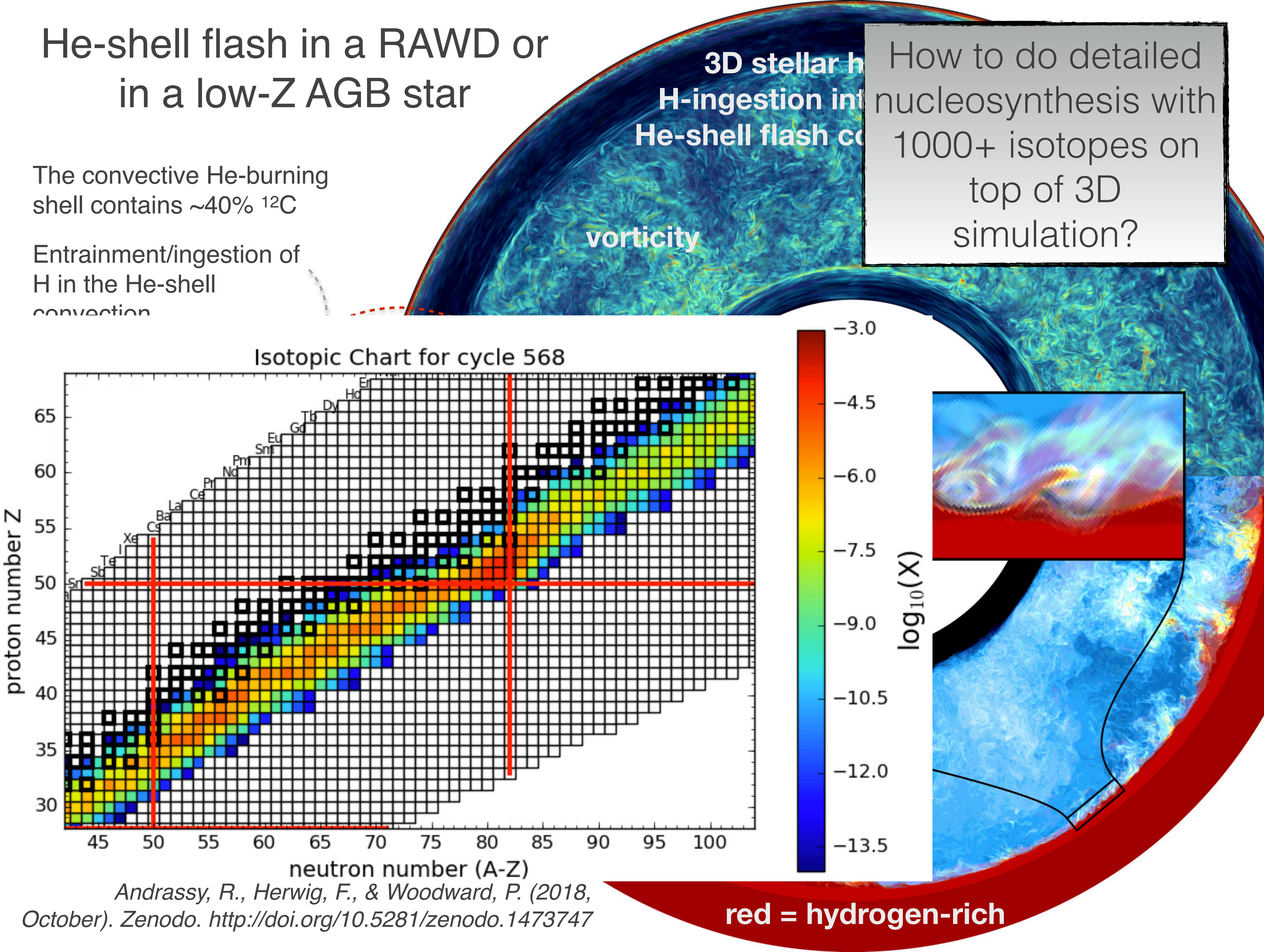
3D hydrodynamic simulations of H ingestion into He-shell flash convection on rapidly accreting white dwarfs

Radial velocity component

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

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

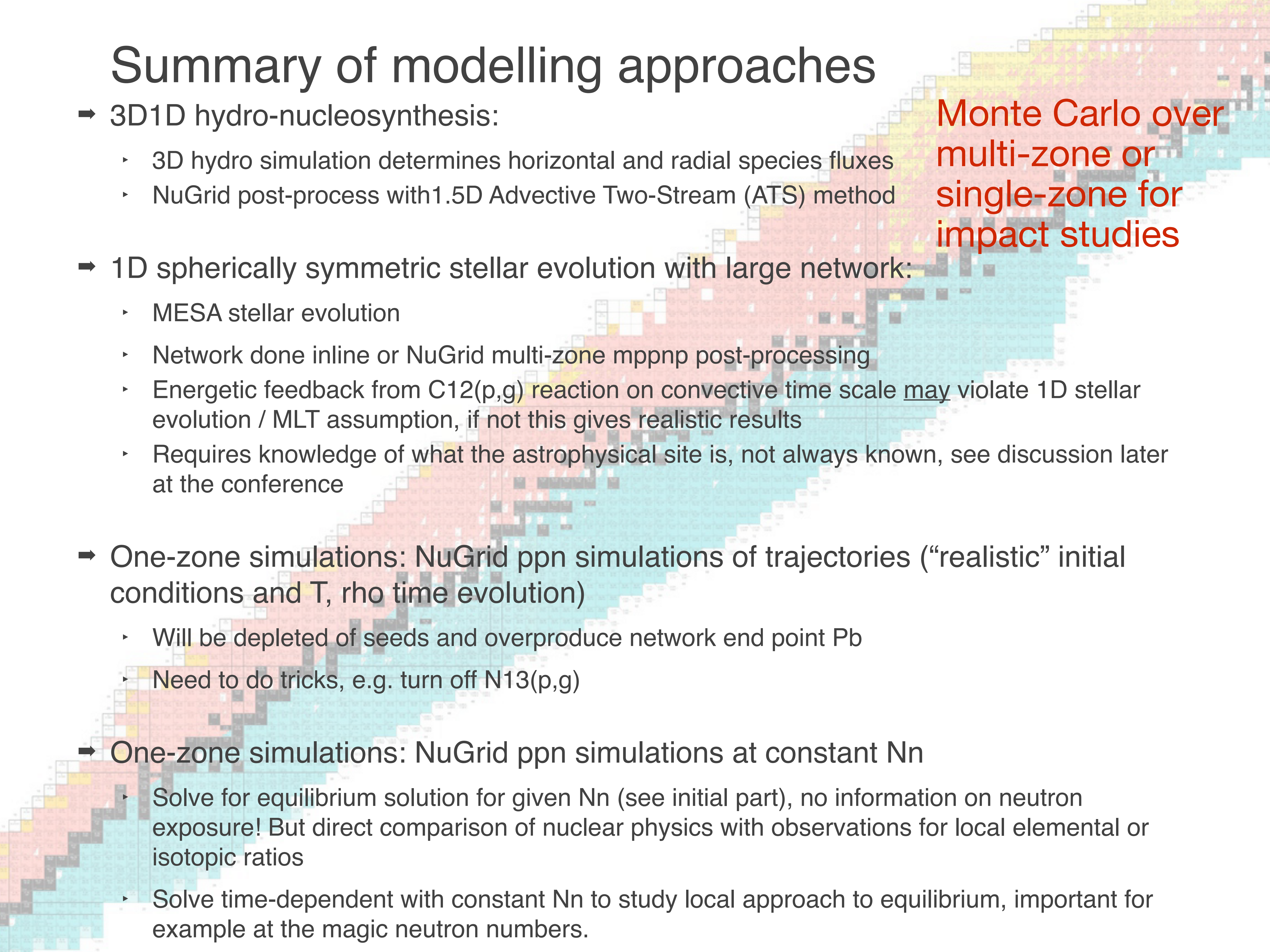
Entrainment/ingestion of H in the He-shell convection



How to do detailed nucleosynthesis with 1000+ isotopes on top of 3D simulation?

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

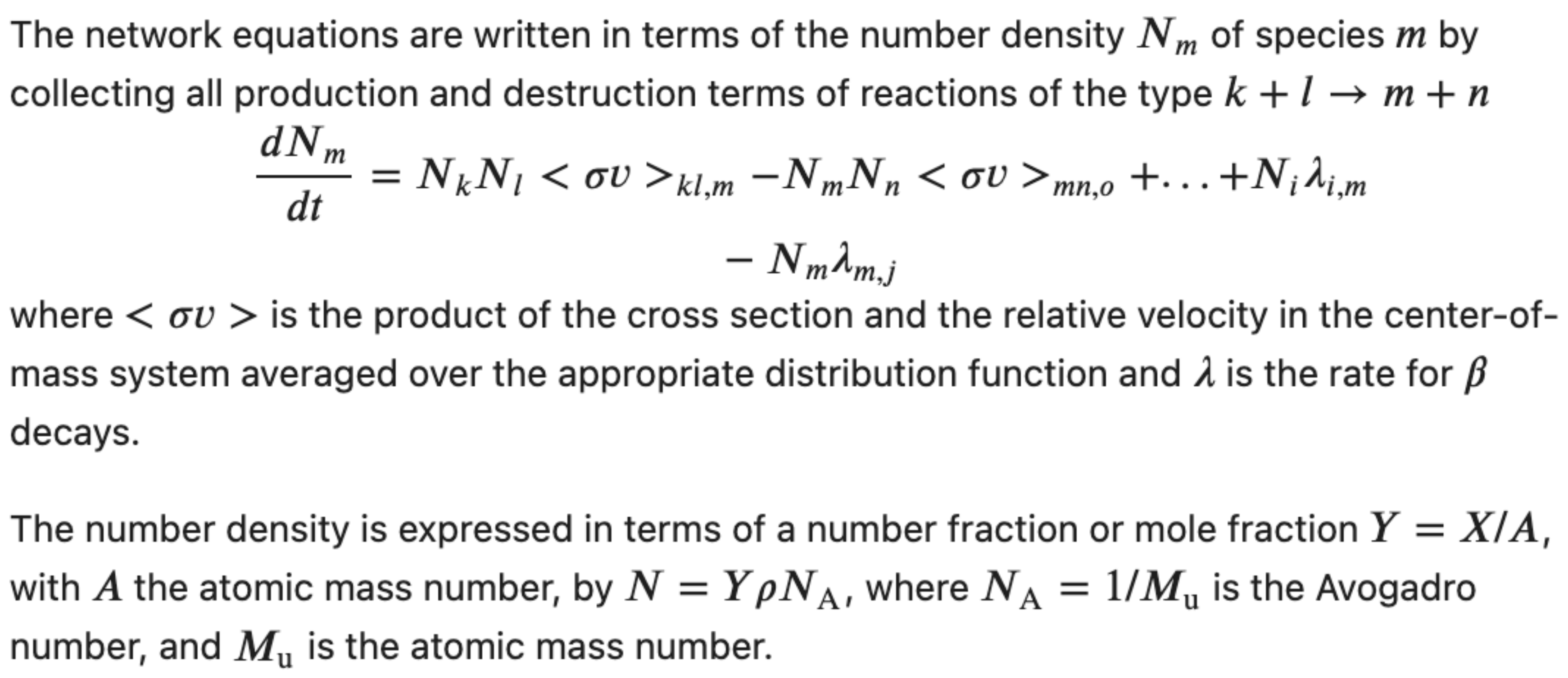
Summary of modelling approaches



Monte Carlo over multi-zone or single-zone for impact studies

- 3D1D hydro-nucleosynthesis:
  - 3D hydro simulation determines horizontal and radial species fluxes
  - NuGrid post-process with1.5D Advective Two-Stream (ATS) method
- 1D spherically symmetric stellar evolution with large network:
  - MESA stellar evolution
  - Network done inline or NuGrid multi-zone mppnp post-processing
  - Energetic feedback from C12(p,g) reaction on convective time scale may violate 1D stellar evolution / MLT assumption, if not this gives realistic results
  - Requires knowledge of what the astrophysical site is, not always known, see discussion later at the conference
- One-zone simulations: NuGrid ppn simulations of trajectories (“realistic” initial conditions and T, rho time evolution)
  - Will be depleted of seeds and overproduce network end point Pb
  - Need to do tricks, e.g. turn off N13(p,g)
- One-zone simulations: NuGrid ppn simulations at constant Nn
  - Solve for equilibrium solution for given Nn (see initial part), no information on neutron exposure! But direct comparison of nuclear physics with observations for local elemental or isotopic ratios
  - Solve time-dependent with constant Nn to study local approach to equilibrium, important for example at the magic neutron numbers.

Time-dependent versus equilibrium solutions

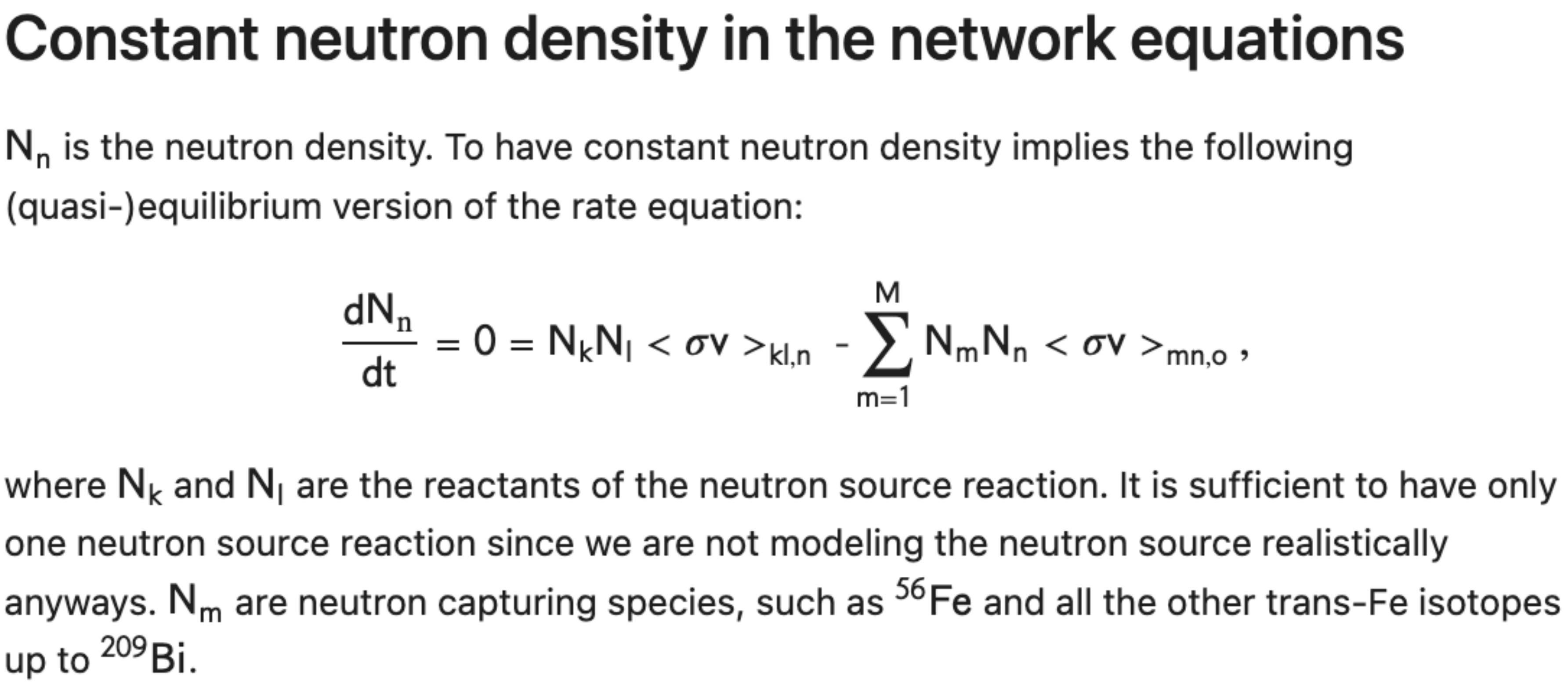


The network equations are written in terms of the number density N_m of species m by collecting all production and destruction terms of reactions of the type $k + l \rightarrow m + n$

$$\frac{dN_m}{dt} = N_k N_l < \sigma v >_{kl,m} - N_m N_n < \sigma v >_{mn,o} + \ldots + N_i \lambda_{i,m} - N_m \lambda_{m,j}$$

where $< \sigma v >$ is the product of the cross section and the relative velocity in the center-of-mass system averaged over the appropriate distribution function and λ is the rate for β decays.

The number density is expressed in terms of a number fraction or mole fraction $Y = X/A$, with A the atomic mass number, by $N = Y \rho N_\mathrm{A}$, where $N_\mathrm{A} = 1/M_\mathrm{u}$ is the Avogadro number, and M_u is the atomic mass number.



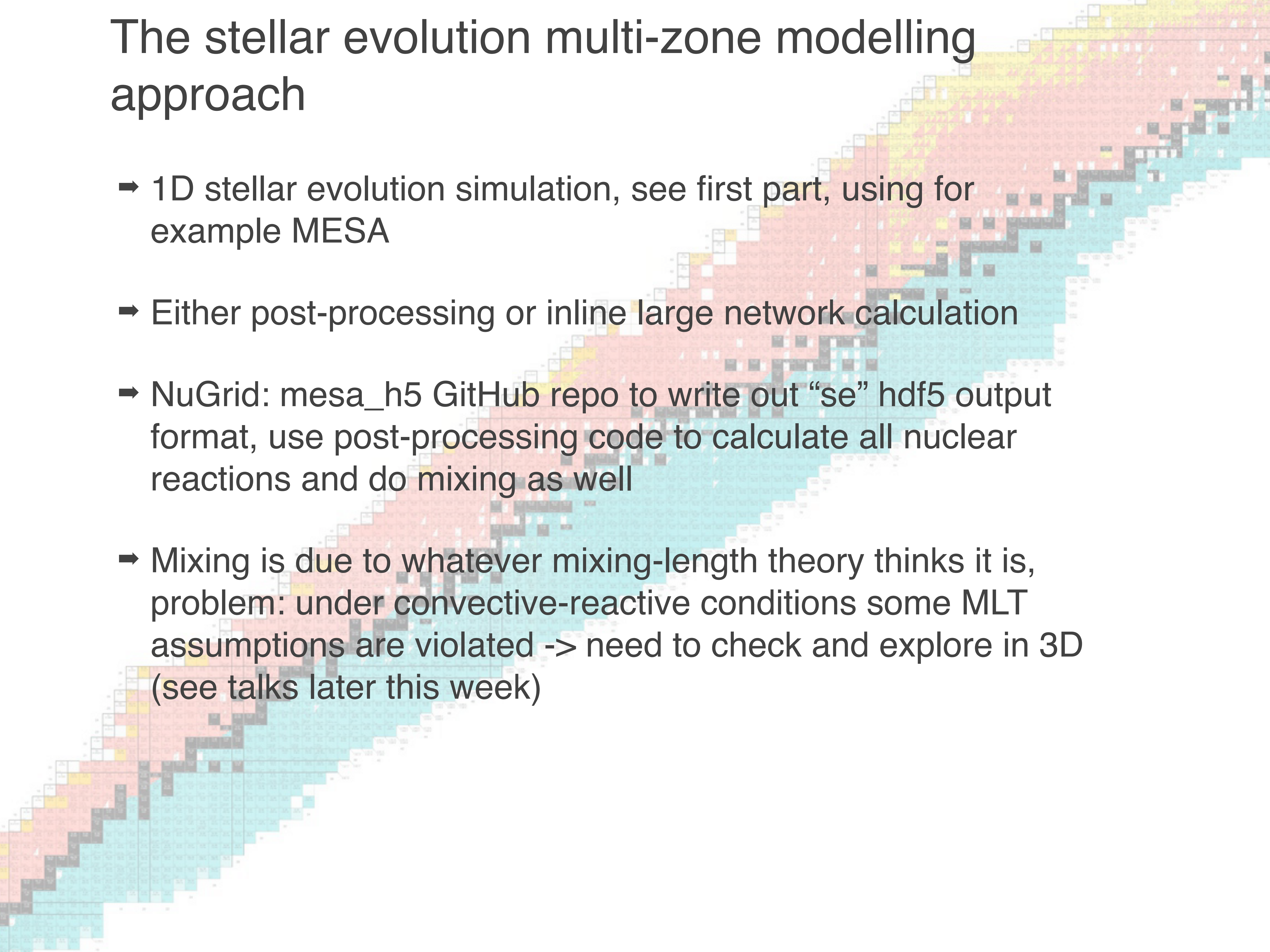
Constant neutron density in the network equations

N_n is the neutron density. To have constant neutron density implies the following (quasi-)equilibrium version of the rate equation:

$$\frac{dN_n}{dt} = 0 = N_k N_l < \sigma v >_{kl,n} - \sum_{m=1}^{M} N_m N_n < \sigma v >_{mn,o} ,$$

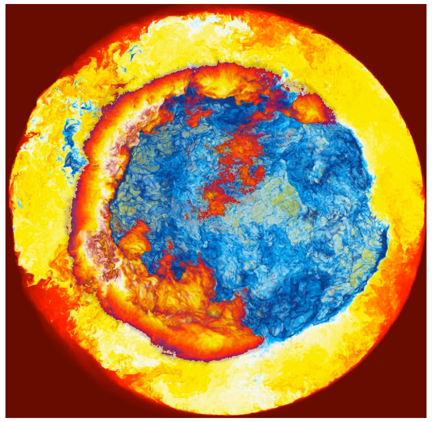
where N_k and N_l are the reactants of the neutron source reaction. It is sufficient to have only one neutron source reaction since we are not modeling the neutron source realistically anyways. N_m are neutron capturing species, such as ^{56}Fe and all the other trans-Fe isotopes up to ^{209}Bi.

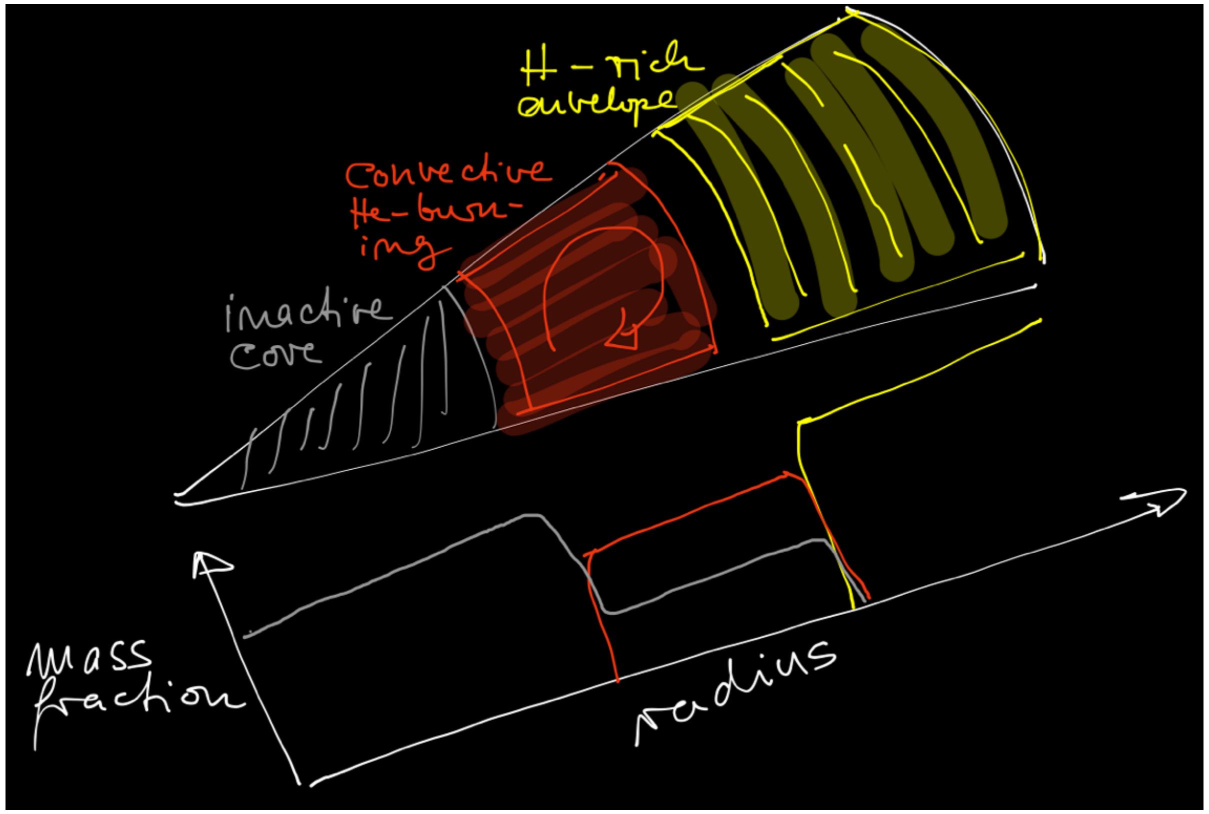
The stellar evolution multi-zone modelling approach



- 1D stellar evolution simulation, see first part, using for example MESA
- Either post-processing or inline large network calculation
- NuGrid: mesa_h5 GitHub repo to write out “se” hdf5 output format, use post-processing code to calculate all nuclear reactions and do mixing as well
- Mixing is due to whatever mixing-length theory thinks it is, problem: under convective-reactive conditions some MLT assumptions are violated -> need to check and explore in 3D (see talks later this week)

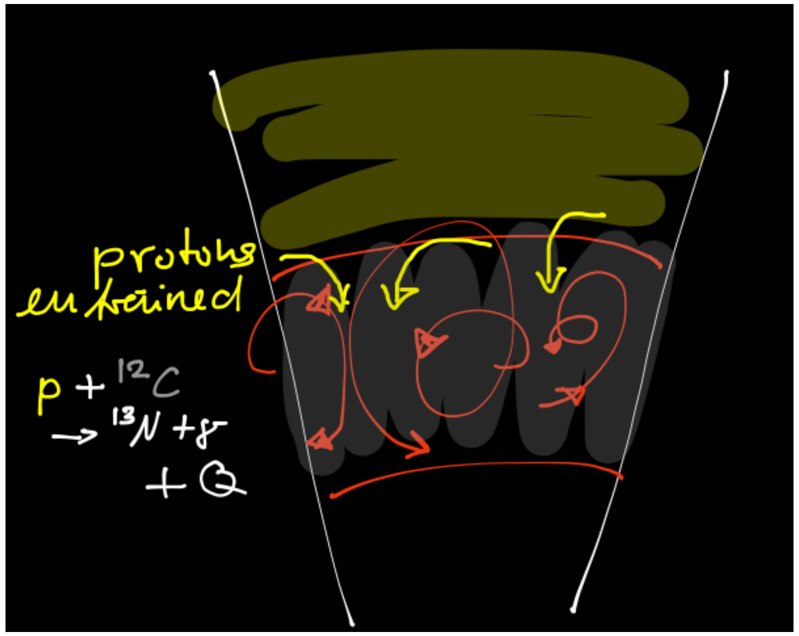
The principle of convective-reactive nucleosynthesis
Neutron production for i process

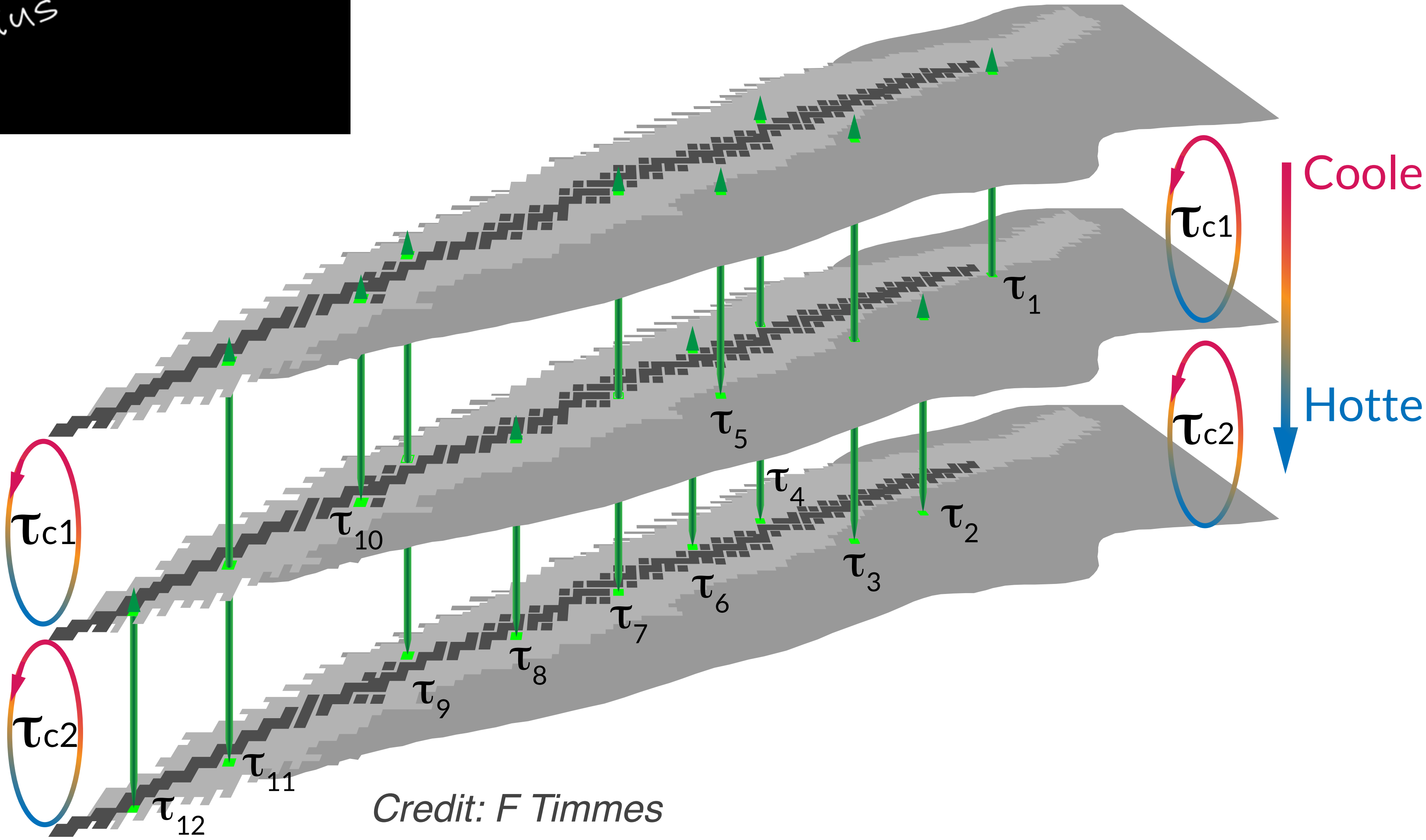




Key concept:

- simultaneous convective advection and nuclear reaction rates
- multi-physics: the two operators have the same time scale
- the two physics processes are coupling

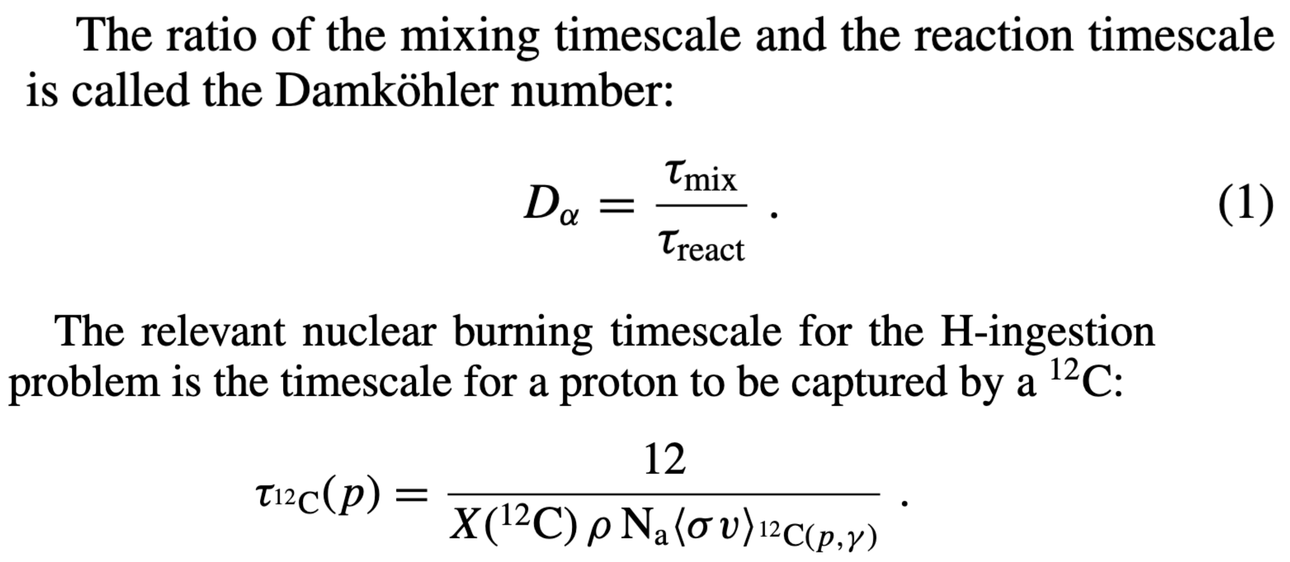




Credit: F Timmes

Nature of convective-reactive nucleosynthesis: the Damköhler number

Herwig+ 2011 ApJ, Dimotakis 2005 ARFM



The ratio of the mixing timescale and the reaction timescale is called the Damköhler number:

$$D_\alpha = \frac{\tau_{\rm mix}}{\tau_{\rm react}} \ . \qquad (1)$$

The relevant nuclear burning timescale for the H-ingestion problem is the timescale for a proton to be captured by a ^{12}C:

$$\tau_{^{12}\rm C}(p) = \frac{12}{X(^{12}{\rm C})\,\rho\,{\rm N_a}\langle\sigma v\rangle_{^{12}{\rm C}(p,\gamma)}} \ .$$

Mixing time scale $\tau_{\rm MLT} = l^2_{\rm MLT}/D_{\rm MLT}$

For Da ~ 1 we HAVE to consider the simultaneous action of nuclear reactions and mixing. Operator split NOT OK

For Da>>1 trajectories are fine. Operator split OK

For Da<<1 instantaneous mixing is fine Operator split OK

The Astrophysical Journal, 727:89 (15pp), 2011 February 1

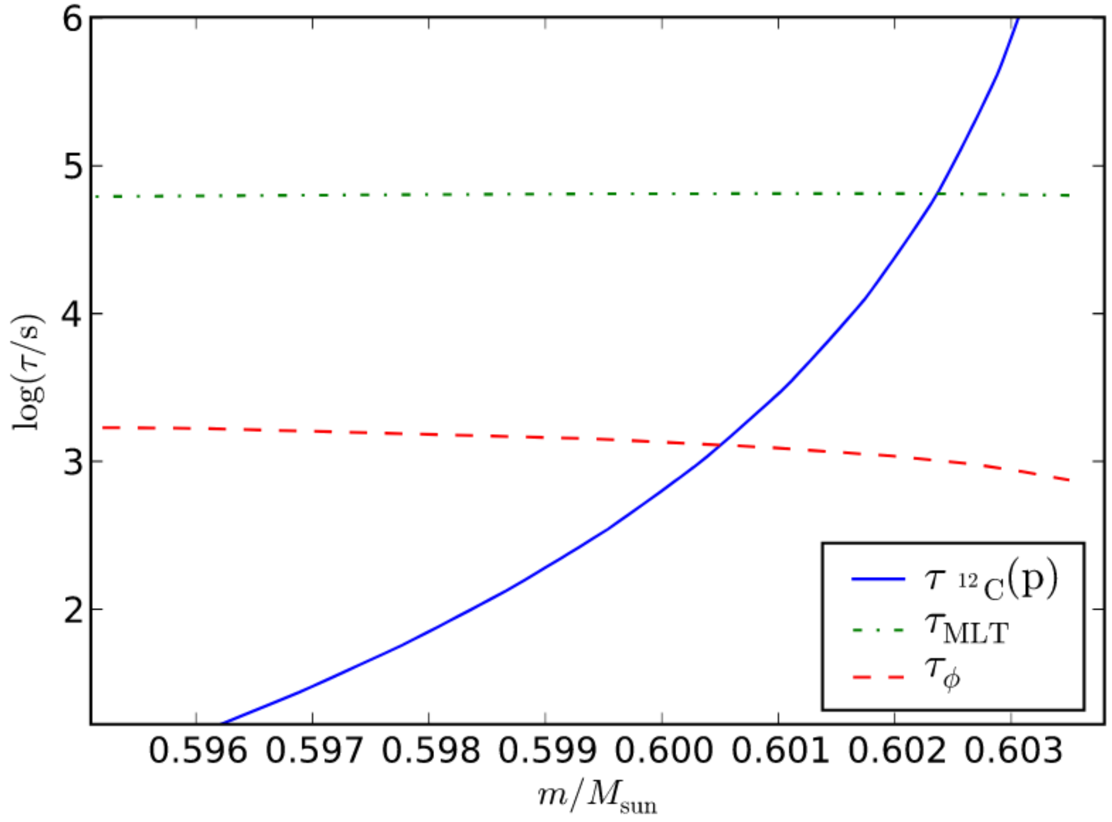
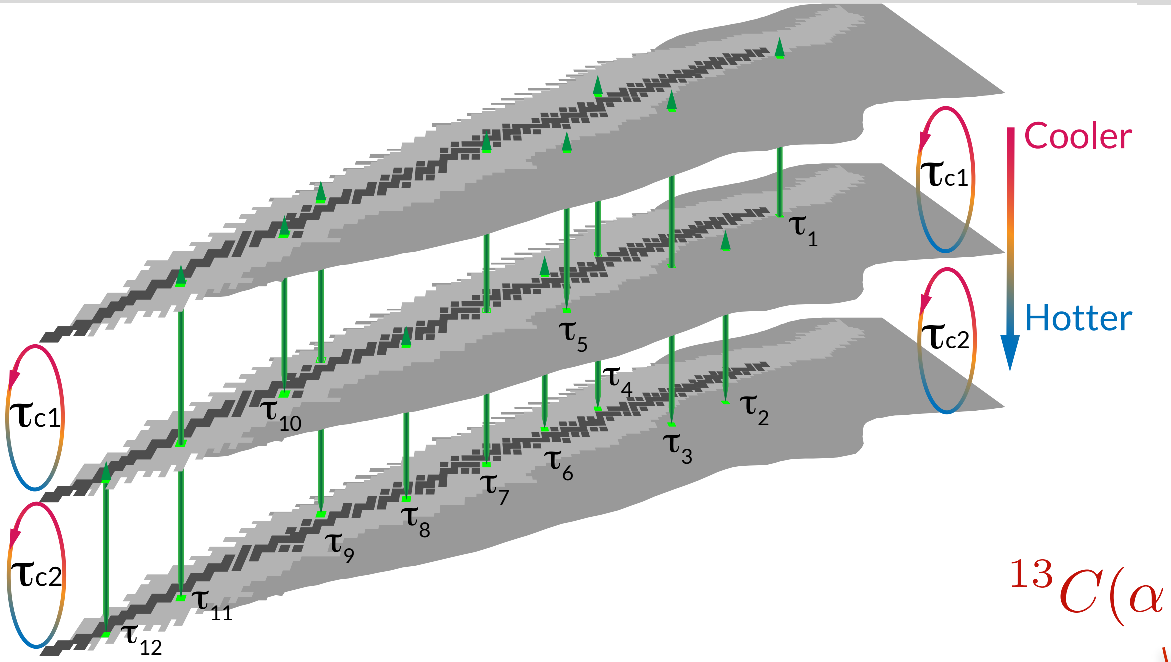
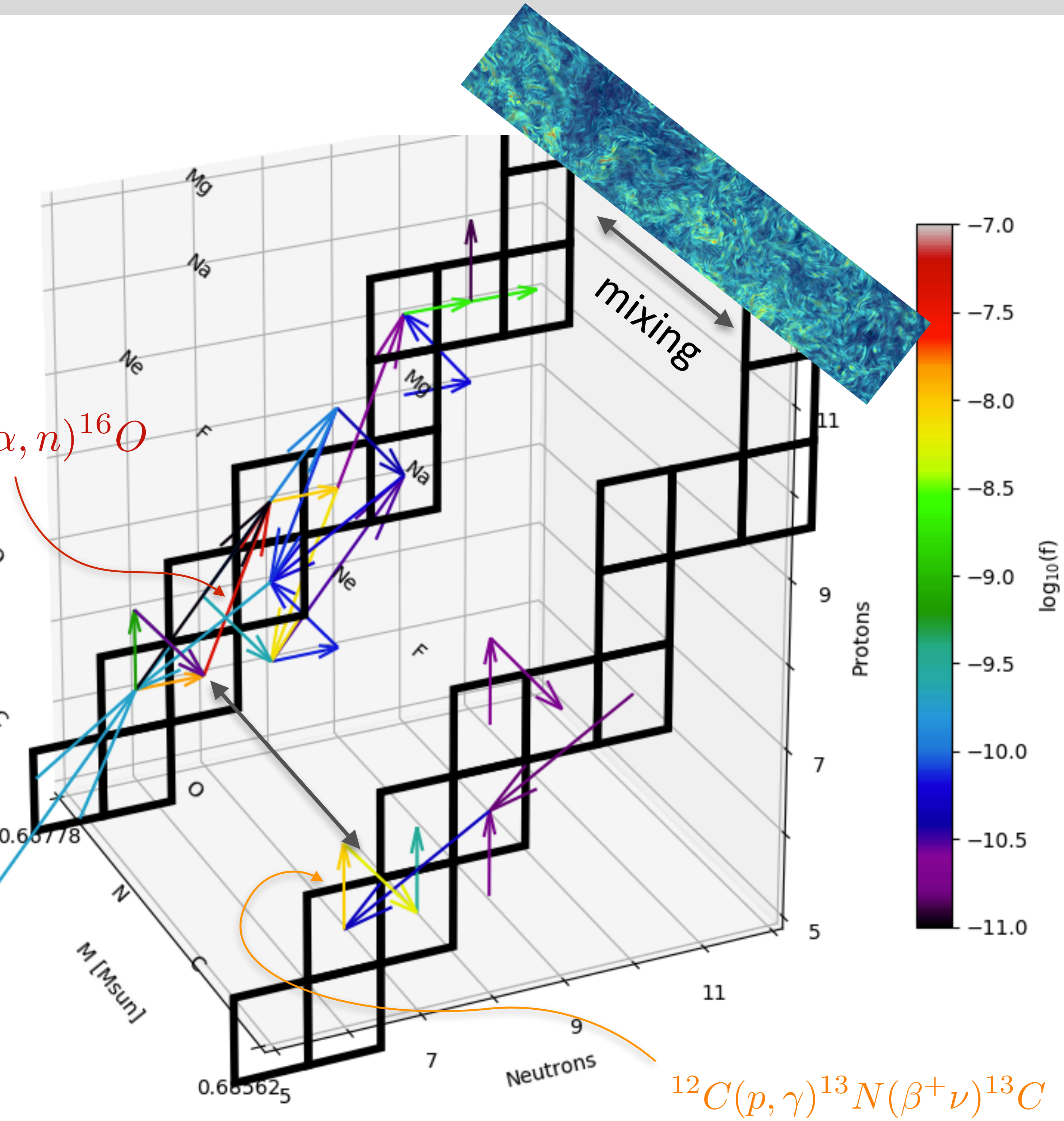


Figure 13. Timescales as a function of the mass coordinate in the convection zone, for proton capture by ^{12}C (blue solid line), as well as the MLT mixing timescale (green dash-dot) and the rate of reaction mixing timescale (red dashed; see the text for details). For this figure the tabulated reaction rate from Angulo et al. (1999) was used.

Herwig+ 11, appendix

Convective-reactive i-process nucleosynthesis





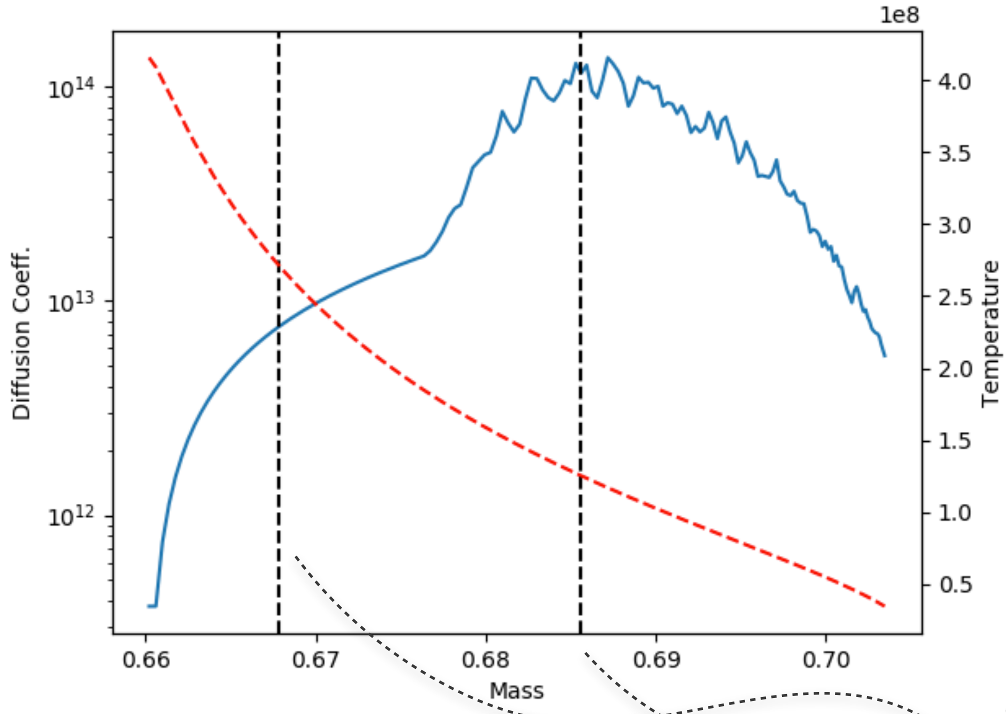
$^{13}C(\alpha,n)^{16}O$

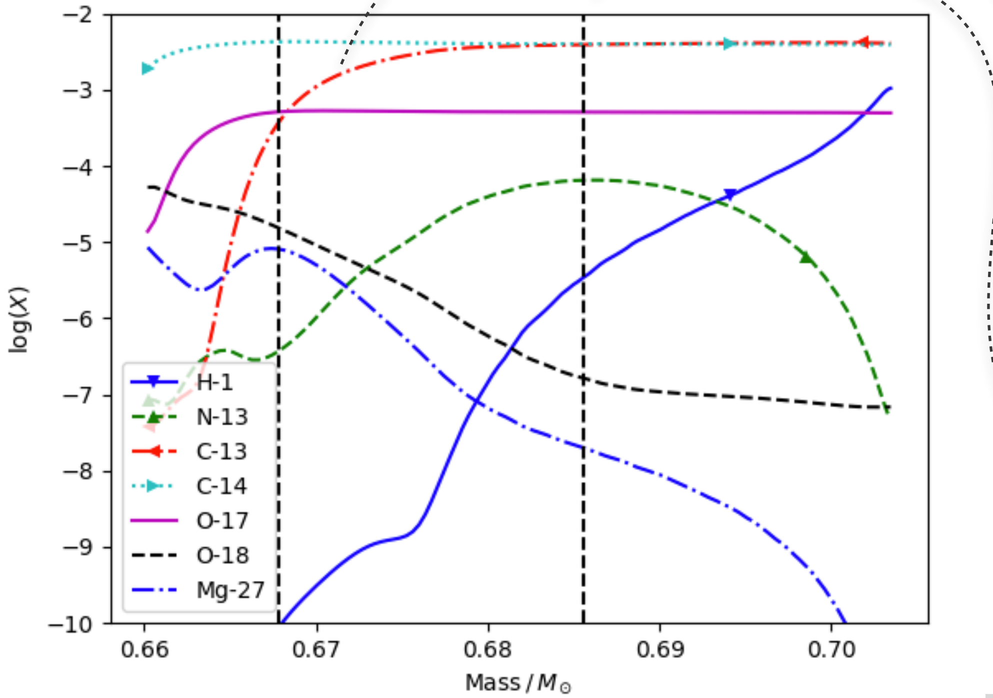
$^{12}C(p,\gamma)^{13}N(\beta^{+}\nu)^{13}C$

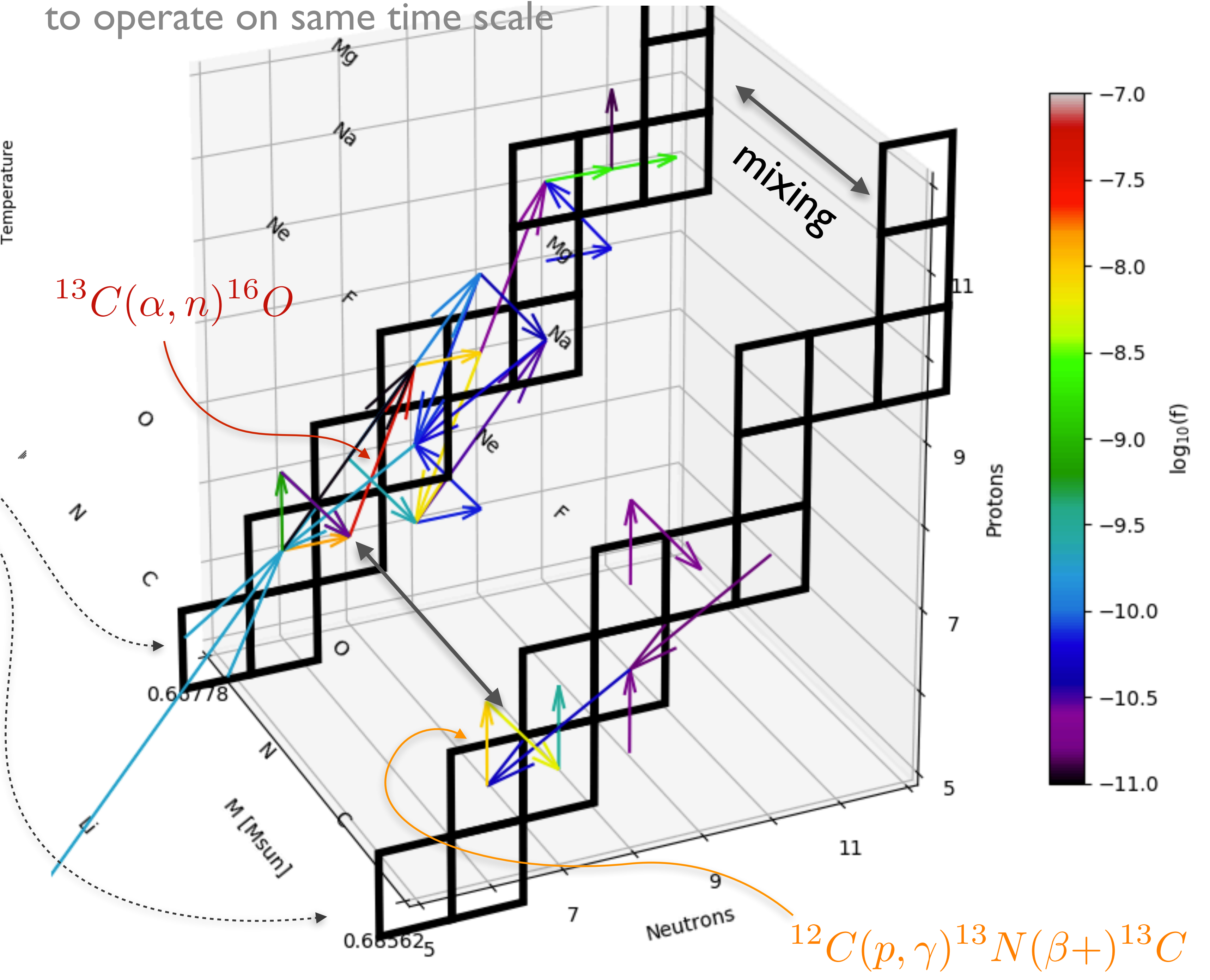
Rapid production of neutrons requires convective mixing connection of two different T regimes for $^{12}C(p,\gamma)$ and $^{13}C(\alpha,n)$ to operate on same time scale

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







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

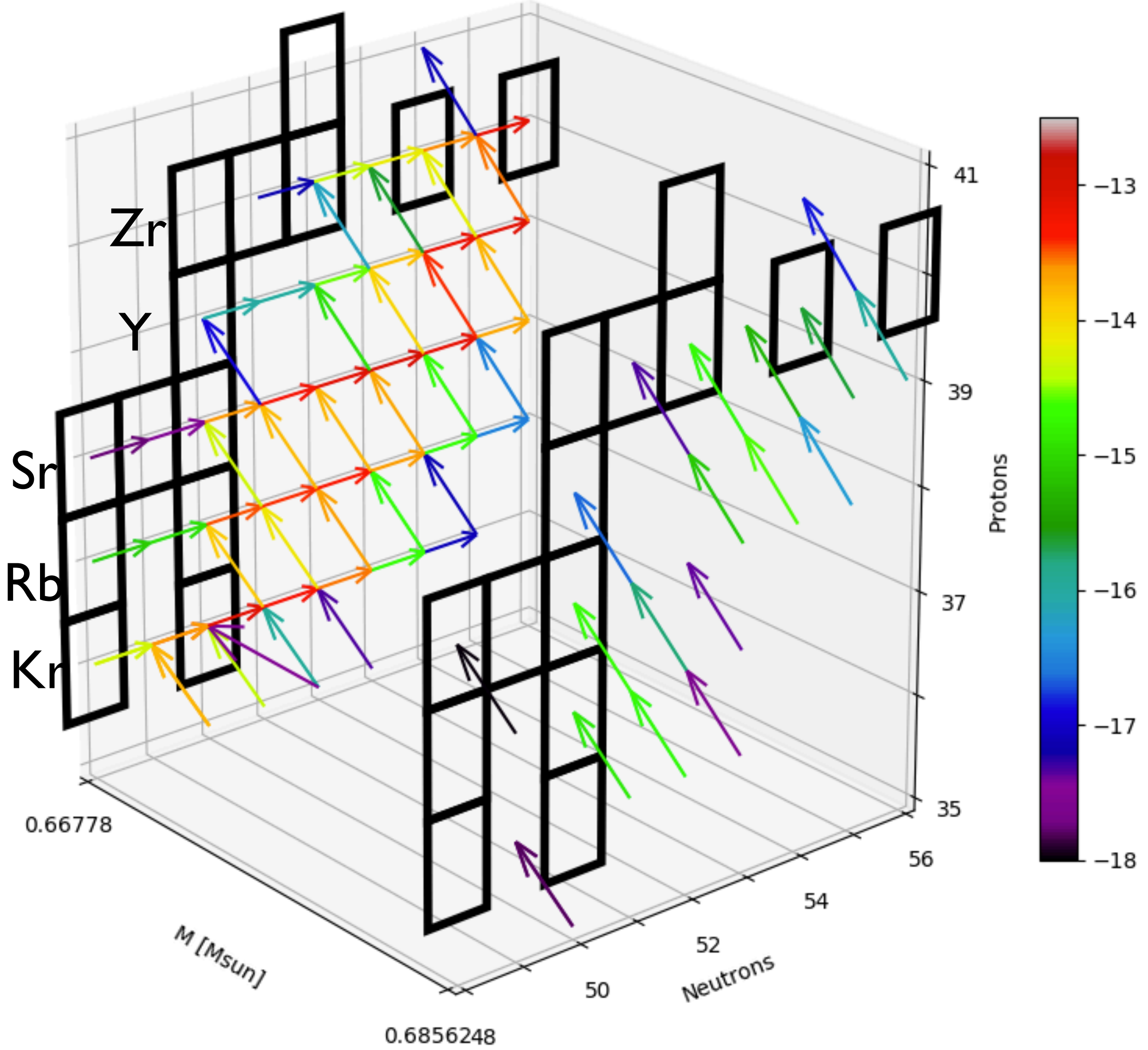
$^{12}C(p,\gamma)^{13}N(\beta+)^{13}C$

JINA-CEE

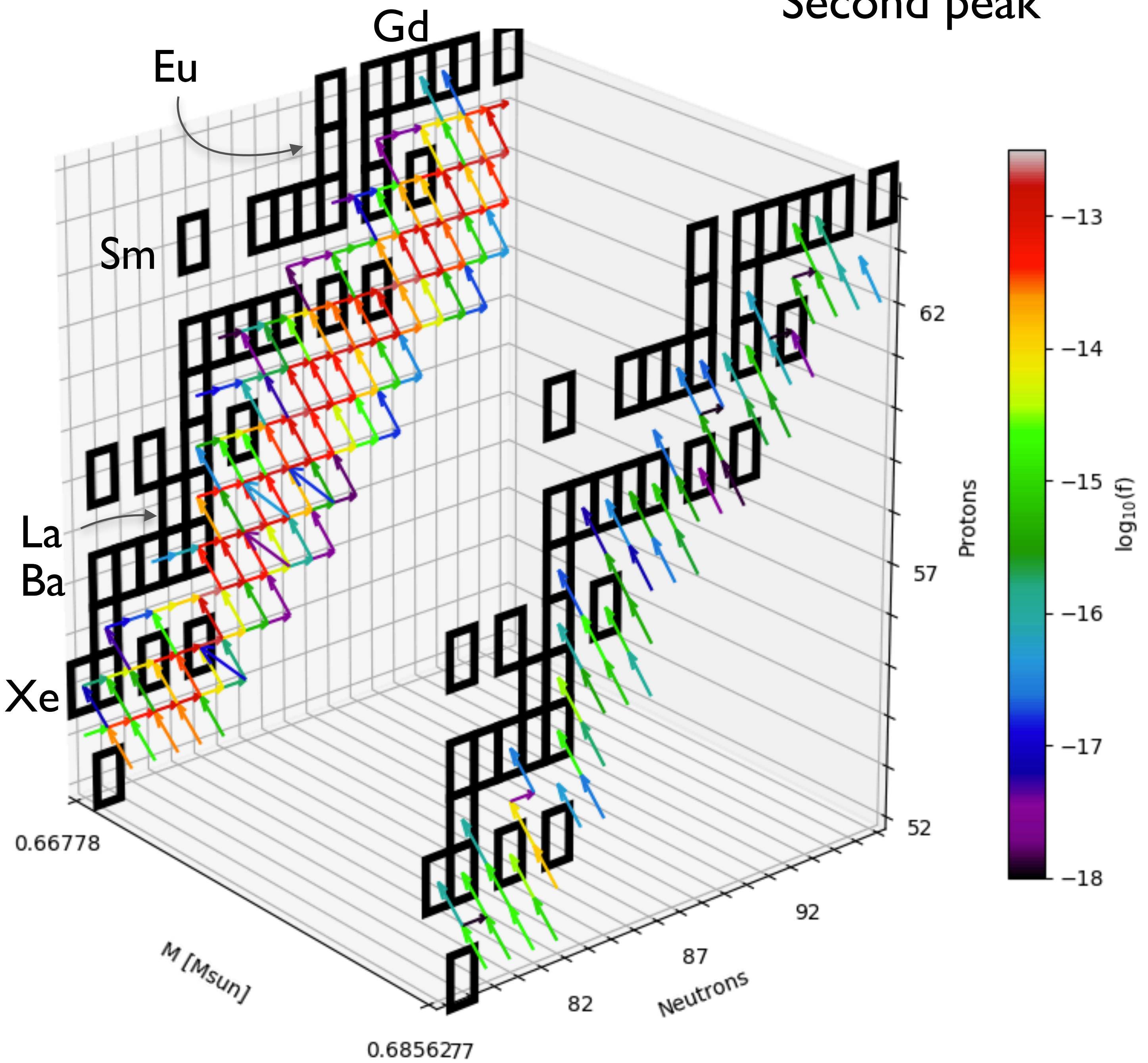
NSF Physics Frontiers Center

Flux plots of convective-reactive nucleosynthesis

First peak



Second peak



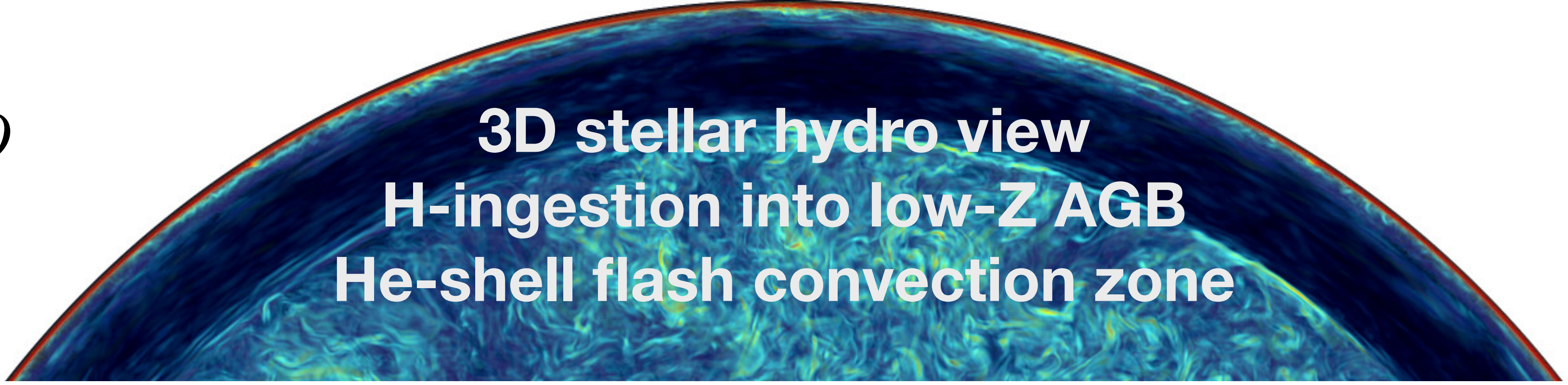
$$^{12}C(p,\gamma)^{13}N(\beta^+\nu)^{13}C(\alpha,n)^{16}O$$

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

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

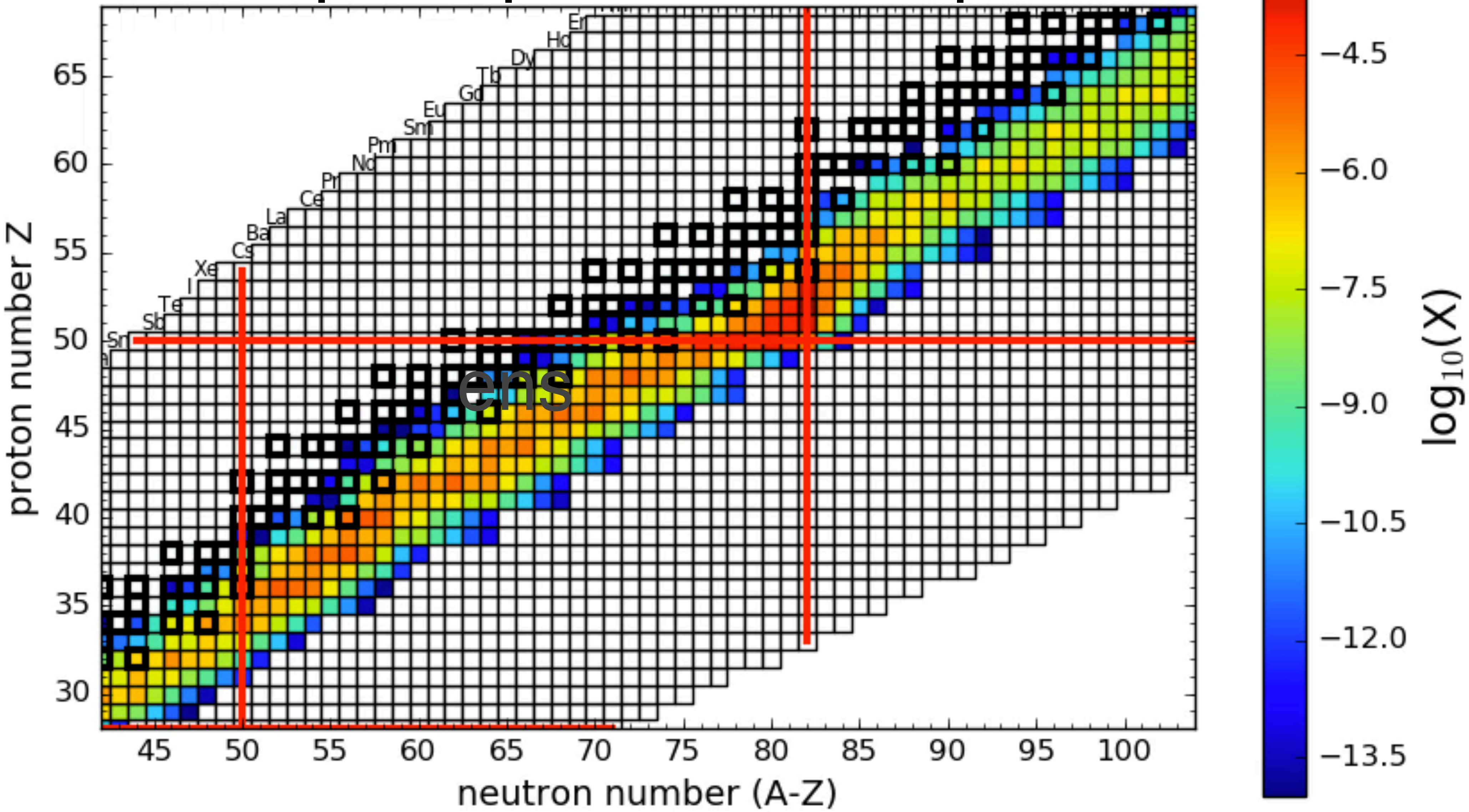
Neutrons released with intermediate neutron density → i process element production.

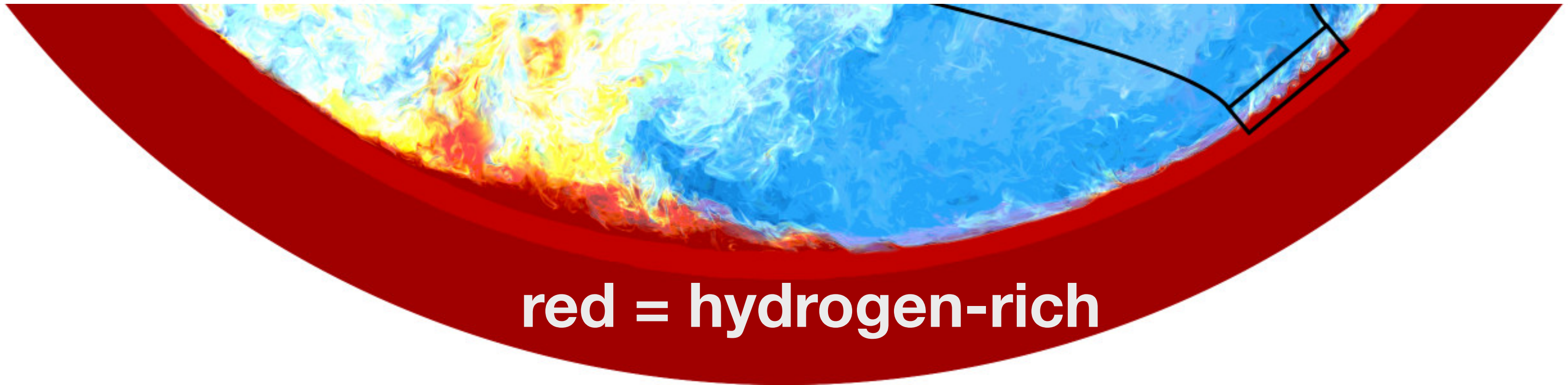
Need multi-physics, multi-method approach. How to combine detailed 3D hydro with detailed n-rich nucleosynthesis involving thousands of species?



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

i process path in chart of isotopes



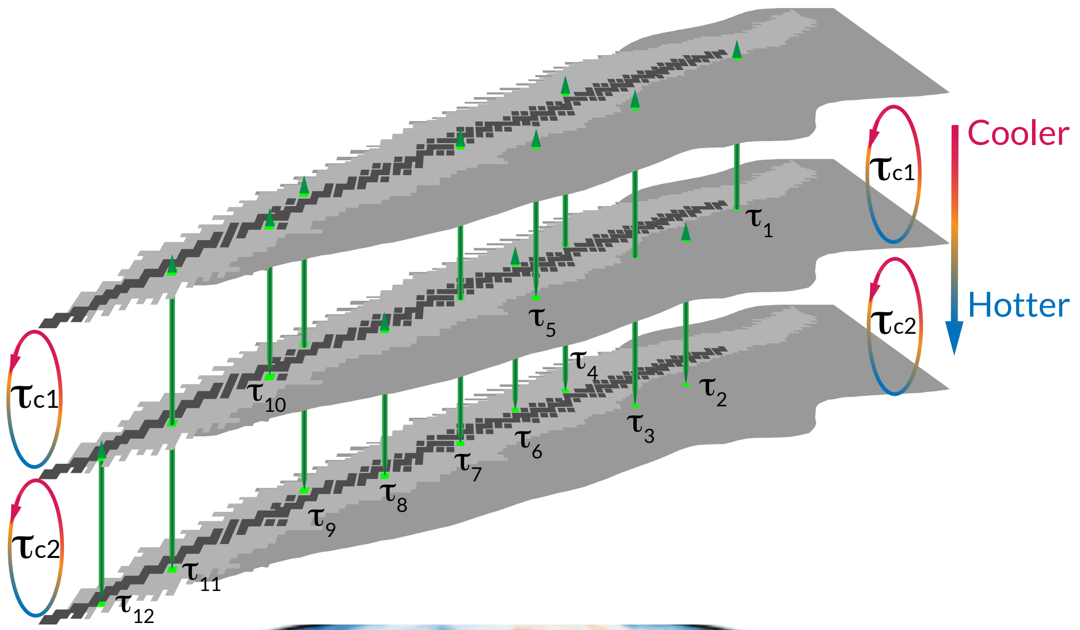


red = hydrogen-rich

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **504,** 744–760 (2021) doi:10.1093/mnras/stab500
Advance Access publication 2021 February 20

3D1D hydro-nucleosynthesis simulations – I. Advective–reactive post-processing method and its application to H ingestion into He-shell flash convection in rapidly accreting white dwarfs

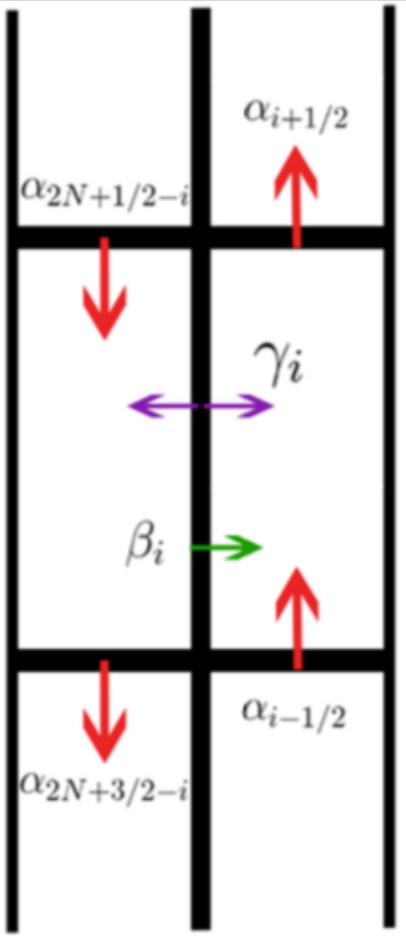
David Stephens,[1] Falk Herwig,[1,2★†] Paul Woodward,[2,3] Pavel Denissenkov,[1,2★†] Robert Andrassy[1,4] and Huaqing Mao[3]

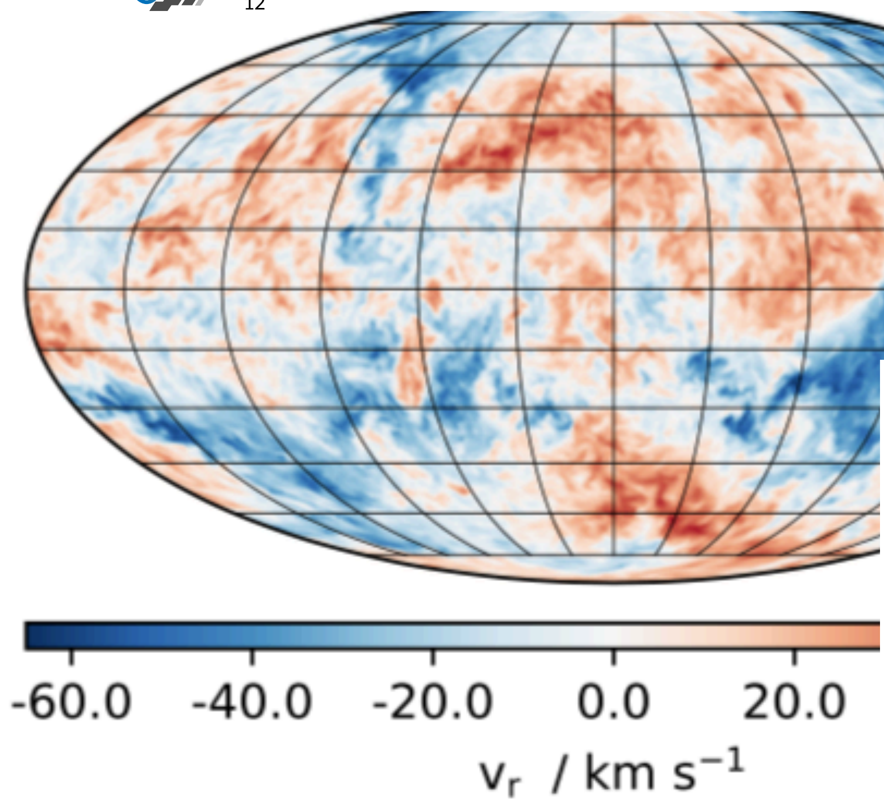


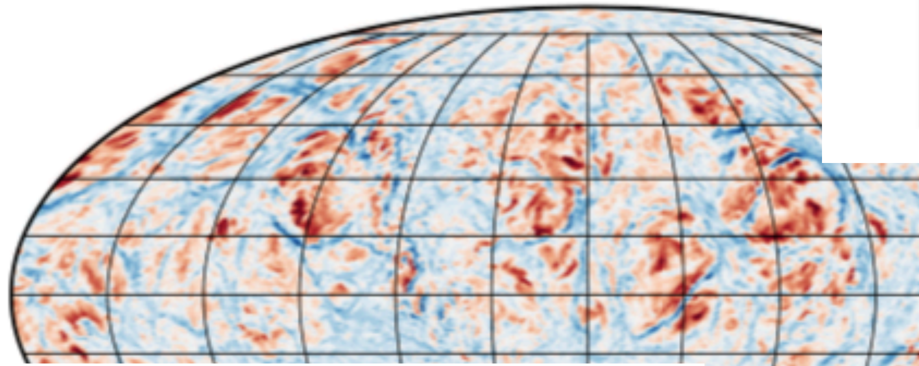
Convective-reactive nucleosynthesis happens by nature on the convective time scale, which is

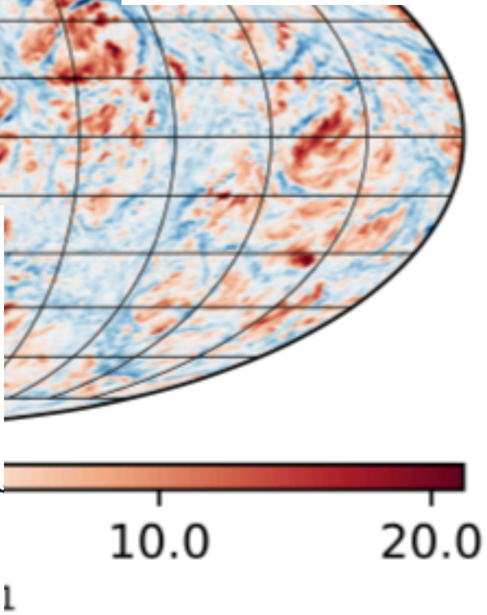
- minutes for O-shell
- 1/2 hour for He-shell

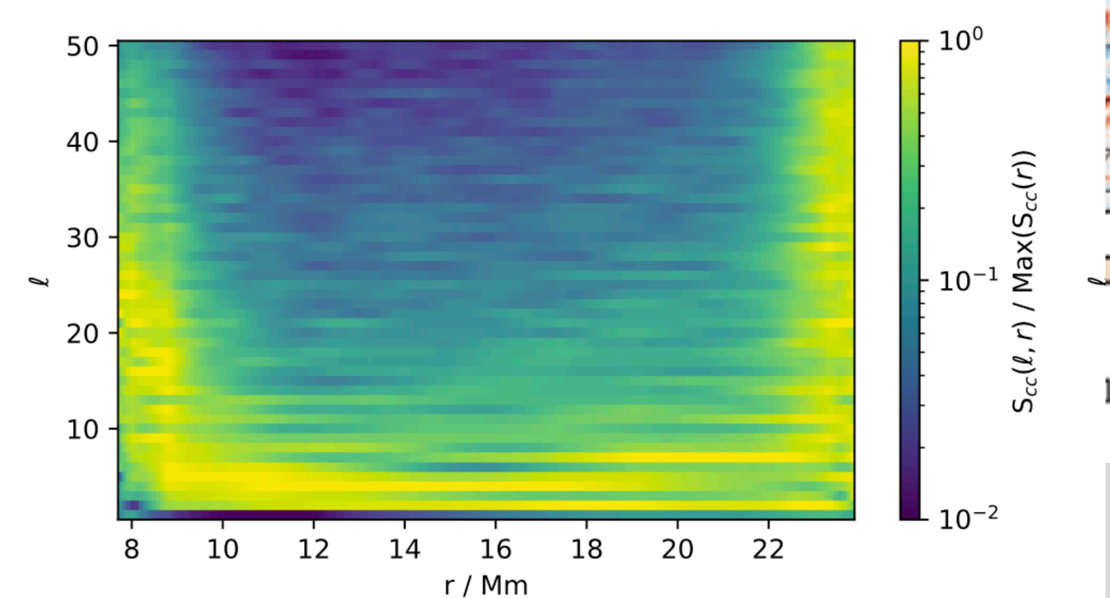
From this it follows: Species with half lives in this range can mix and participate in unique conv-reac nucleosynthesis



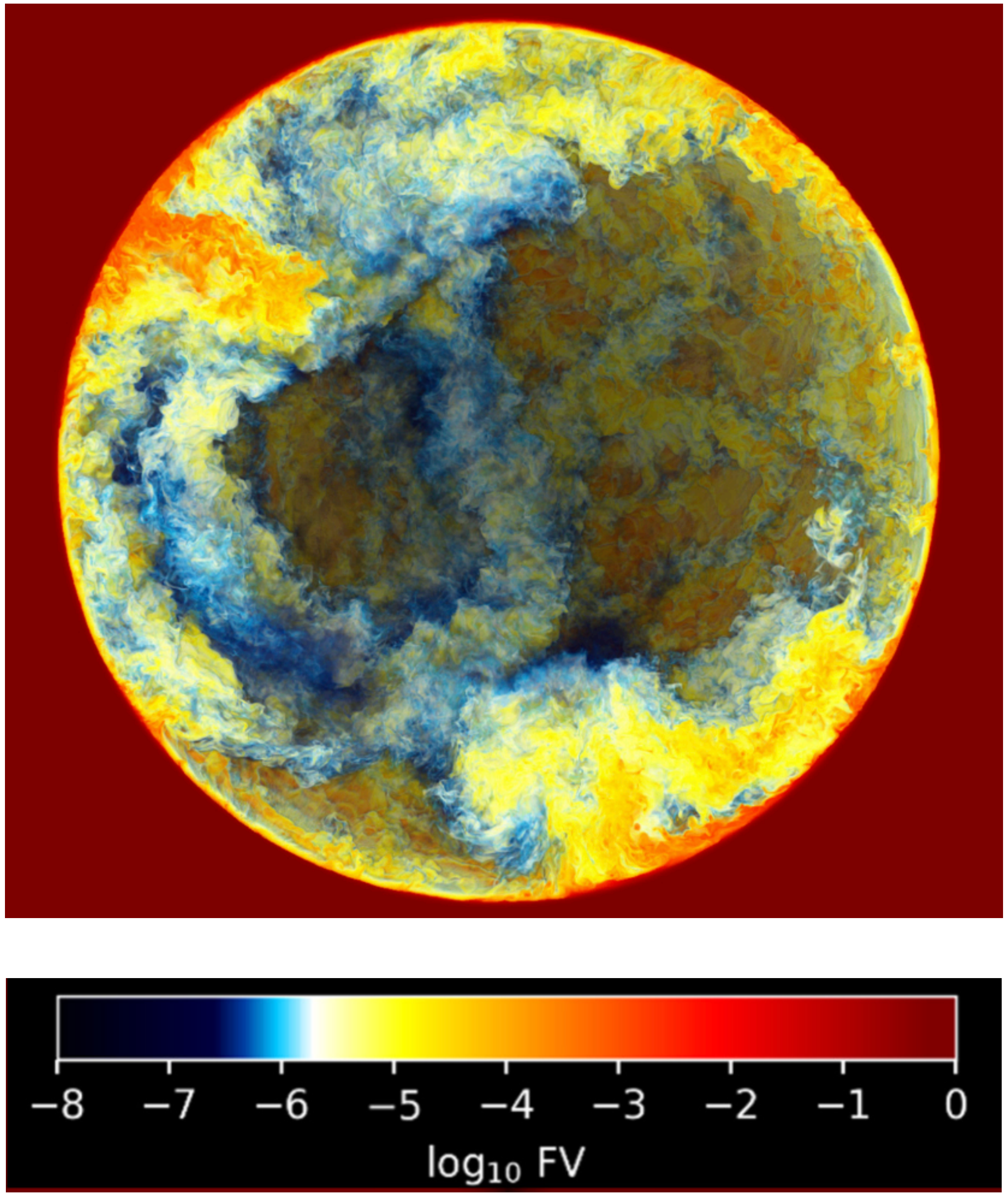


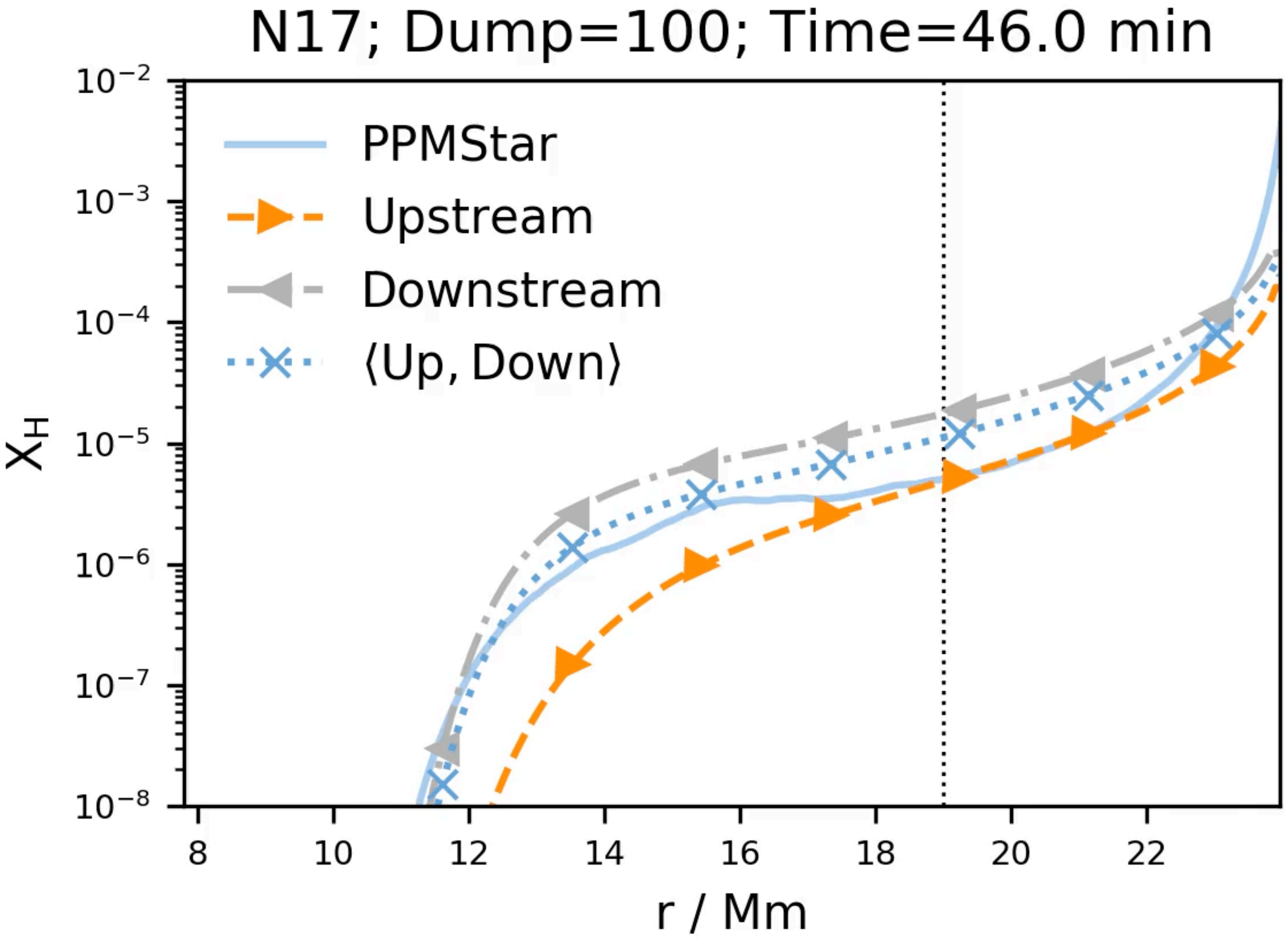






Advective-two-stream post-processing of 3D simulations

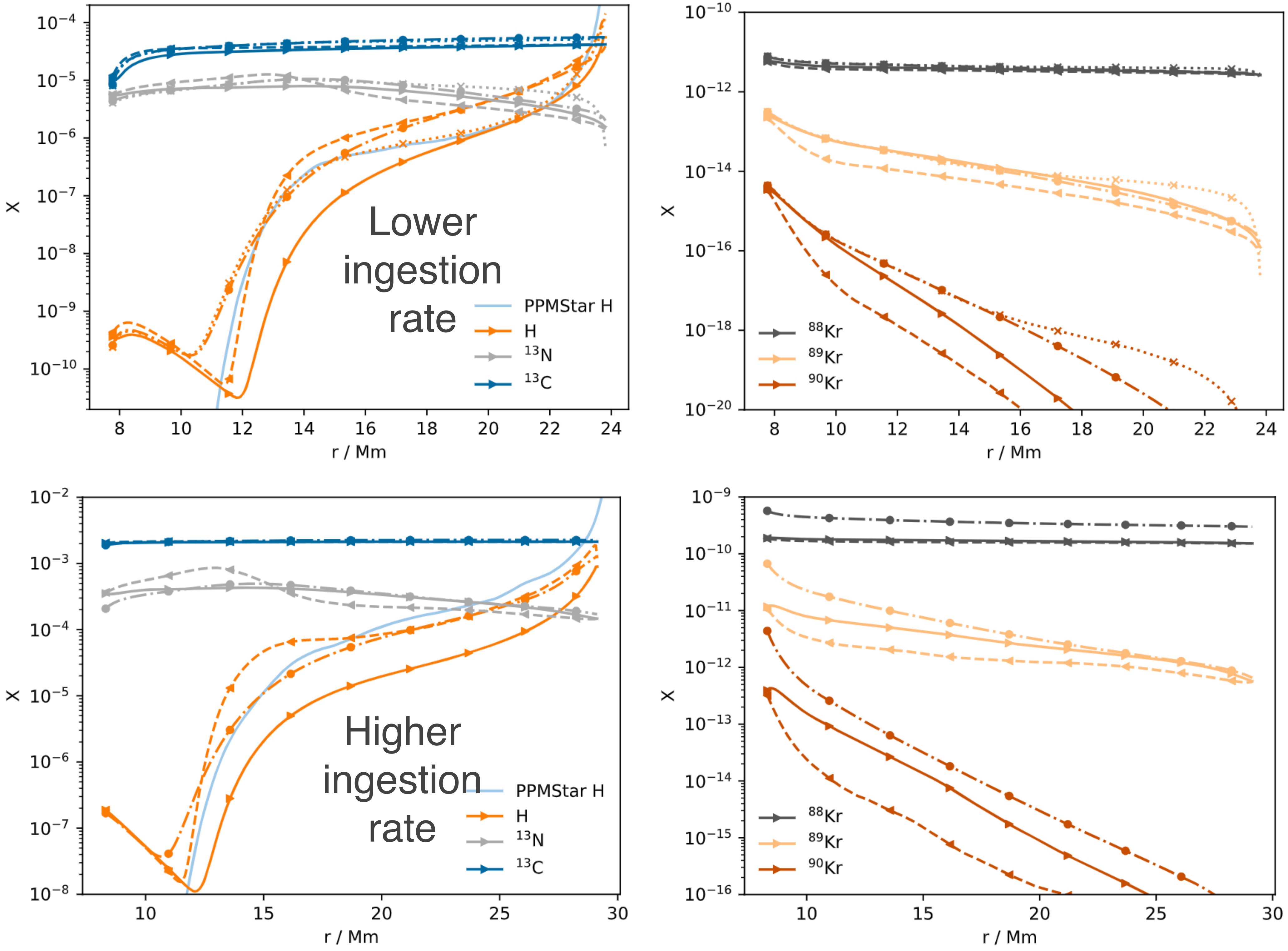




Stephens+ 21, MNRAS

Advective-two-stream post-processing of 3D simulations

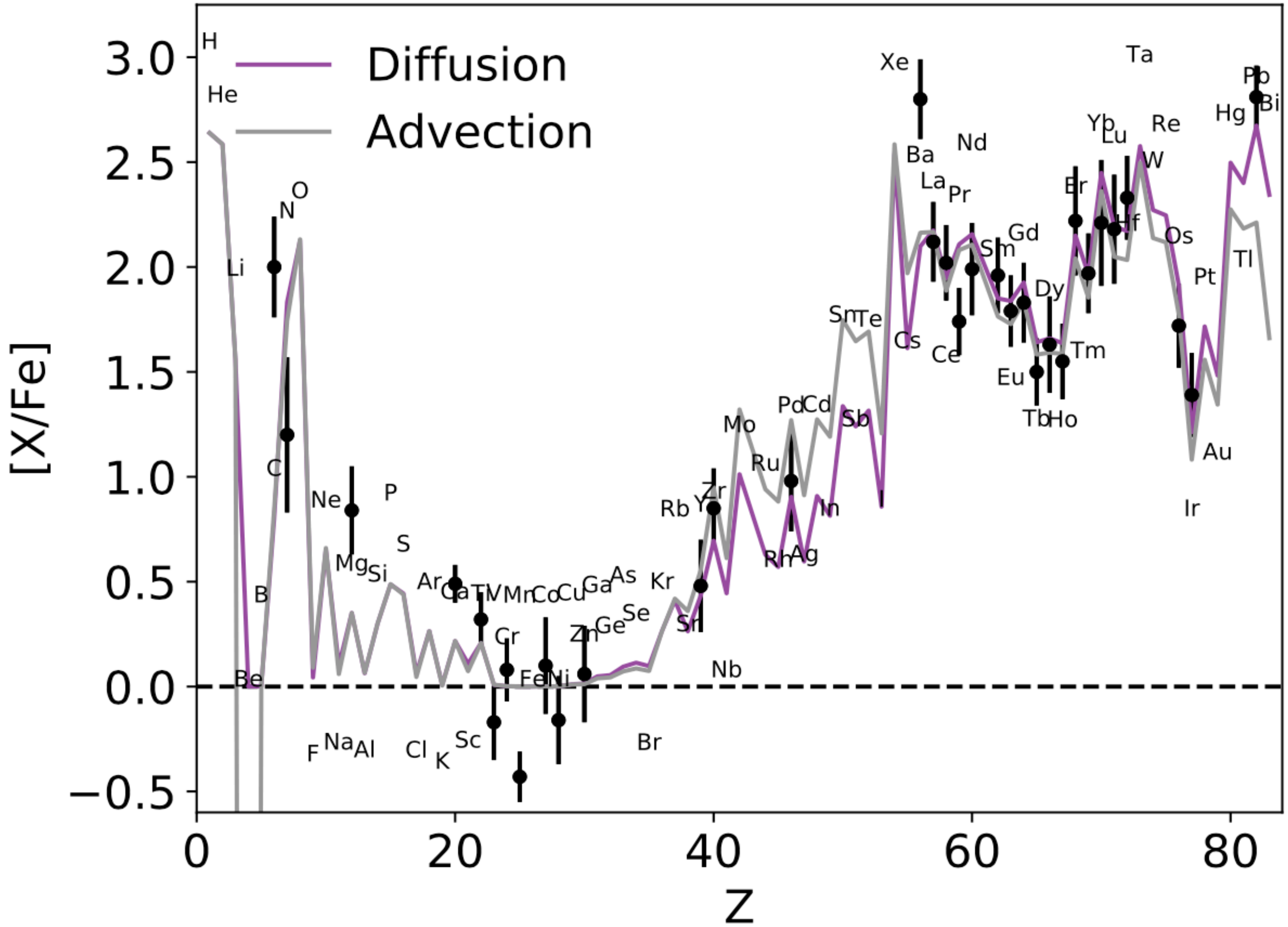
Comparing diffusive and ATS post-processing of 3D hydro simulations



Stephens+ 21, MNRAS

1D multi-zone diffusive mixing of 1D stellar evolution models vs 3D1D ATS

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

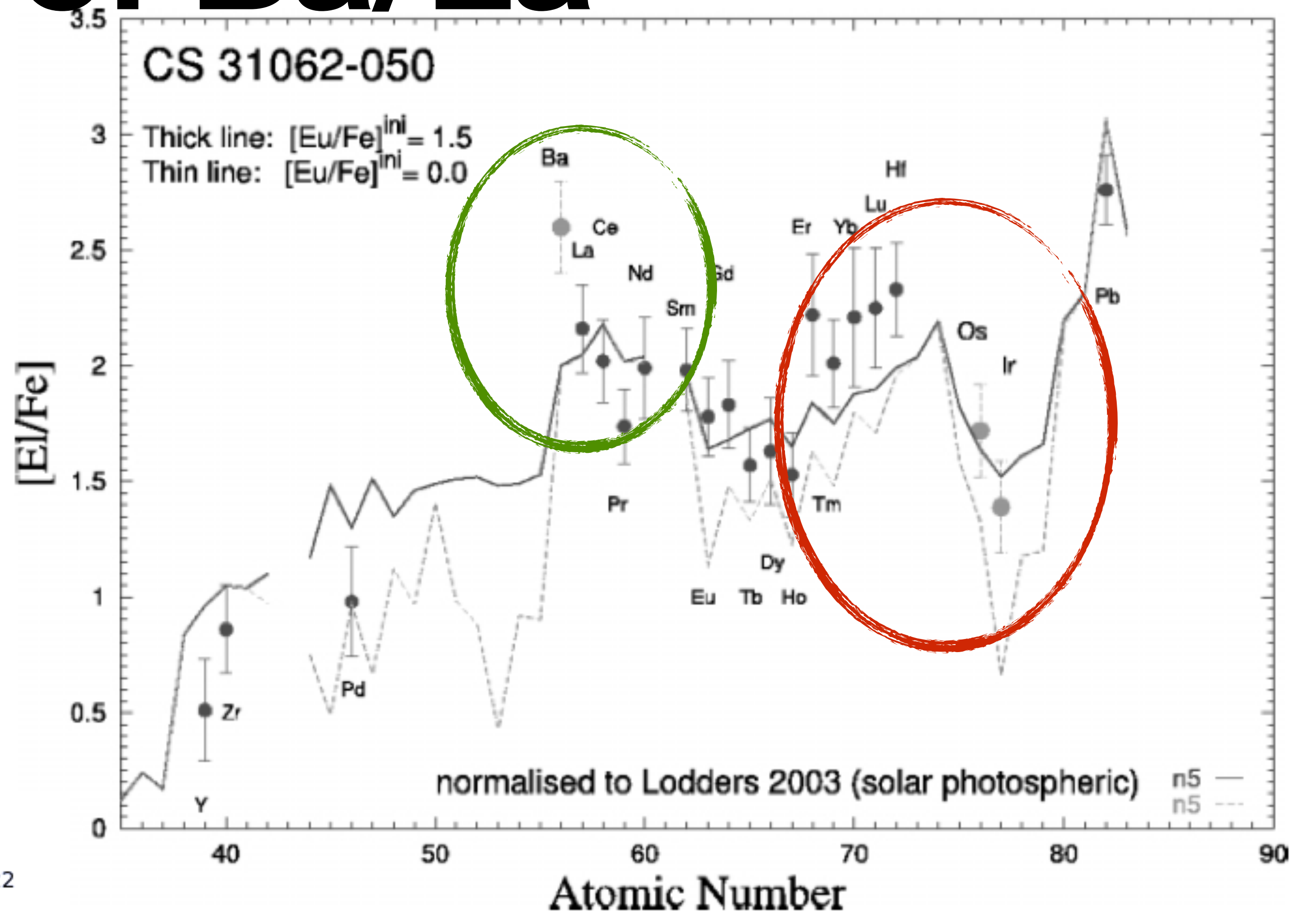


CS31062-050; observation: Aoki+ 02, Johnson & Bolte 04

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).

The special role of Ba/La

- C-enhanced Metal-Poor Stars: CEMP-r/s stars: anomalous metal-poor stars, superposition of “known” r- and s-process fingerprint (Bisterzo+ 12)??
- Systematic problem in [Ba/La] too large than predicted



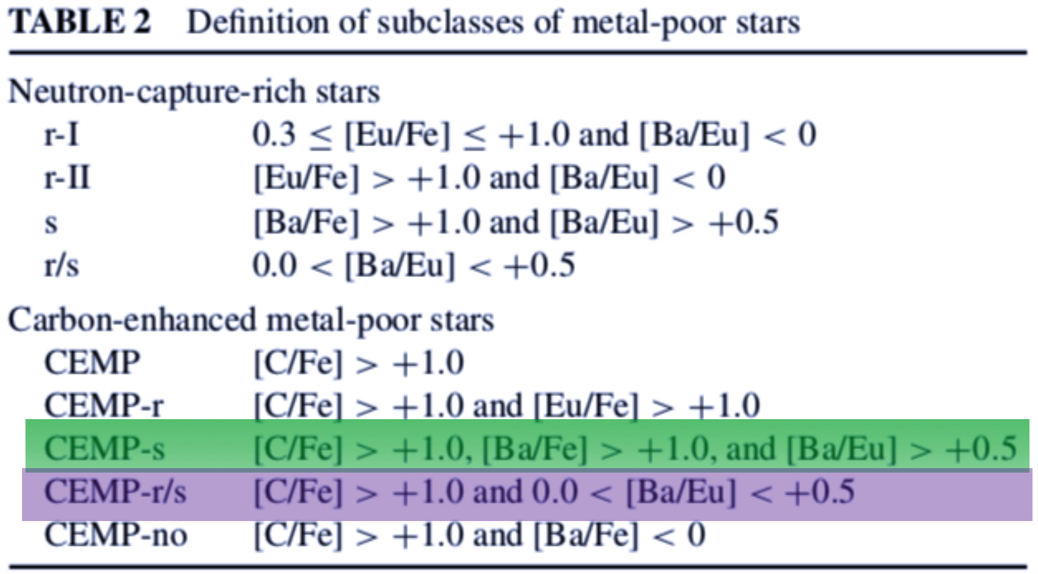
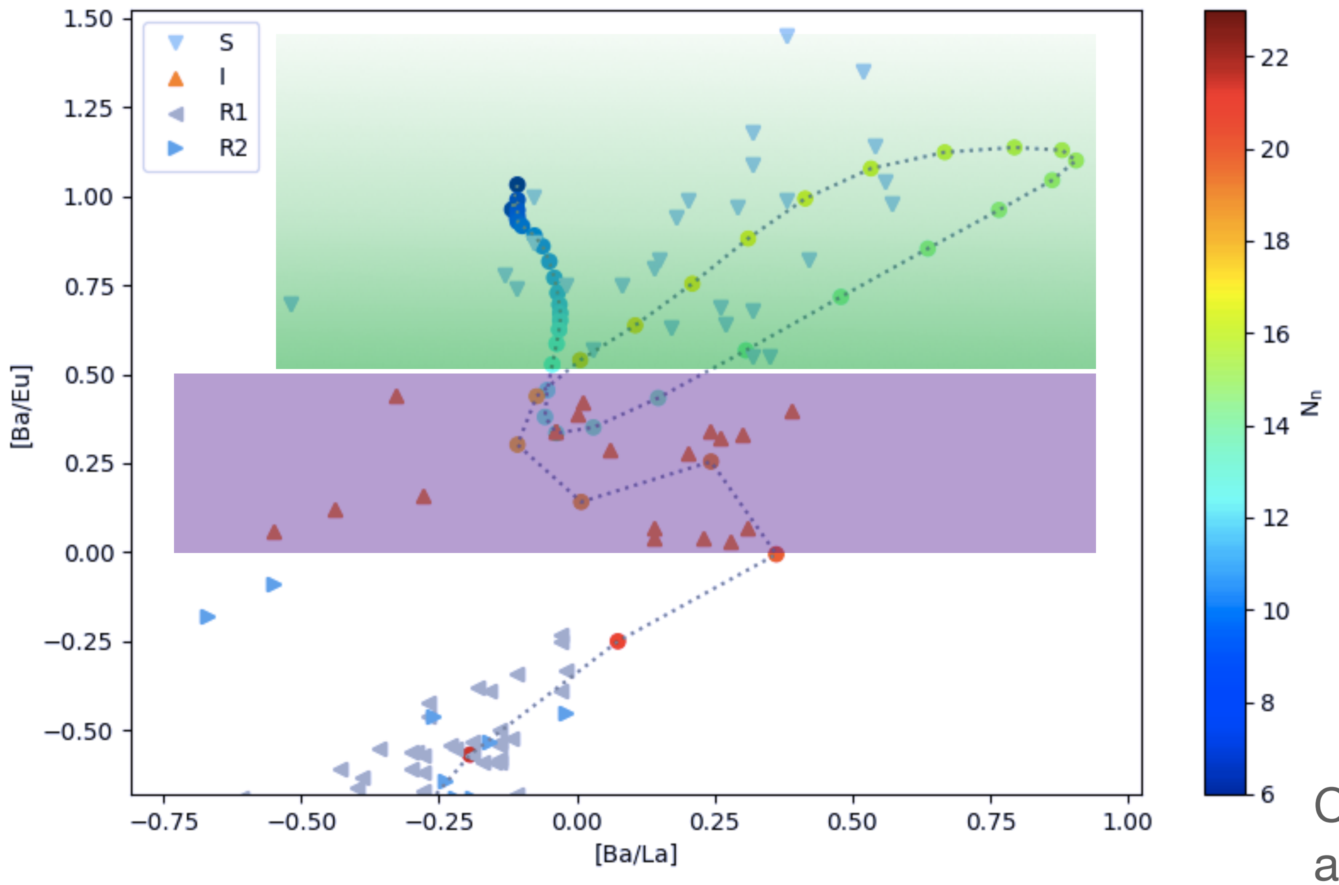


TABLE 2 Definition of subclasses of metal-poor stars

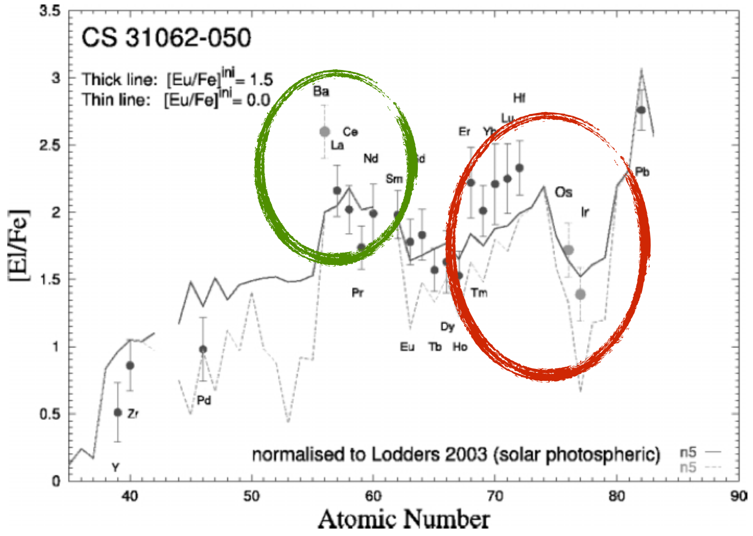
Neutron-capture-rich stars	
r-I	$0.3 \leq [Eu/Fe] \leq +1.0$ and $[Ba/Eu] < 0$
r-II	$[Eu/Fe] > +1.0$ and $[Ba/Eu] < 0$
s	$[Ba/Fe] > +1.0$ and $[Ba/Eu] > +0.5$
r/s	$0.0 < [Ba/Eu] < +0.5$
Carbon-enhanced metal-poor stars	
CEMP	$[C/Fe] > +1.0$
CEMP-r	$[C/Fe] > +1.0$ and $[Eu/Fe] > +1.0$
CEMP-s	$[C/Fe] >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



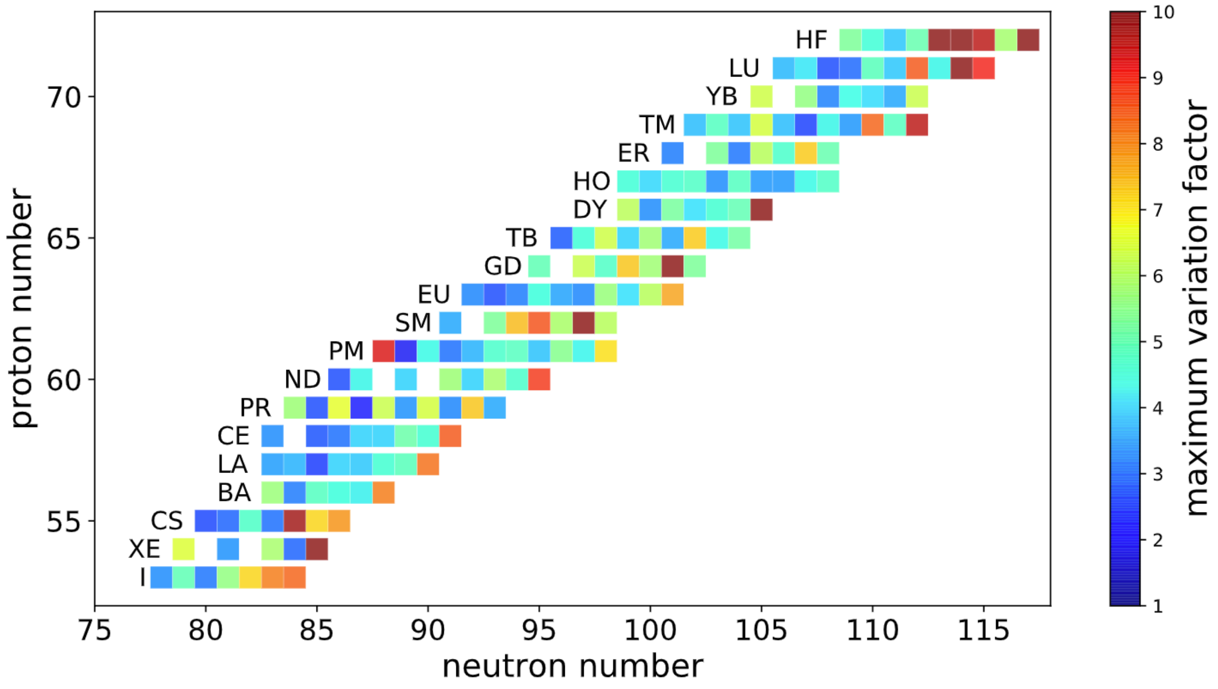
Constant neutron density network calculations and observed abundance ratios CEMP stars (JINAbase, Frebel+ 2017)

CaNPAN/NuGrid impact study

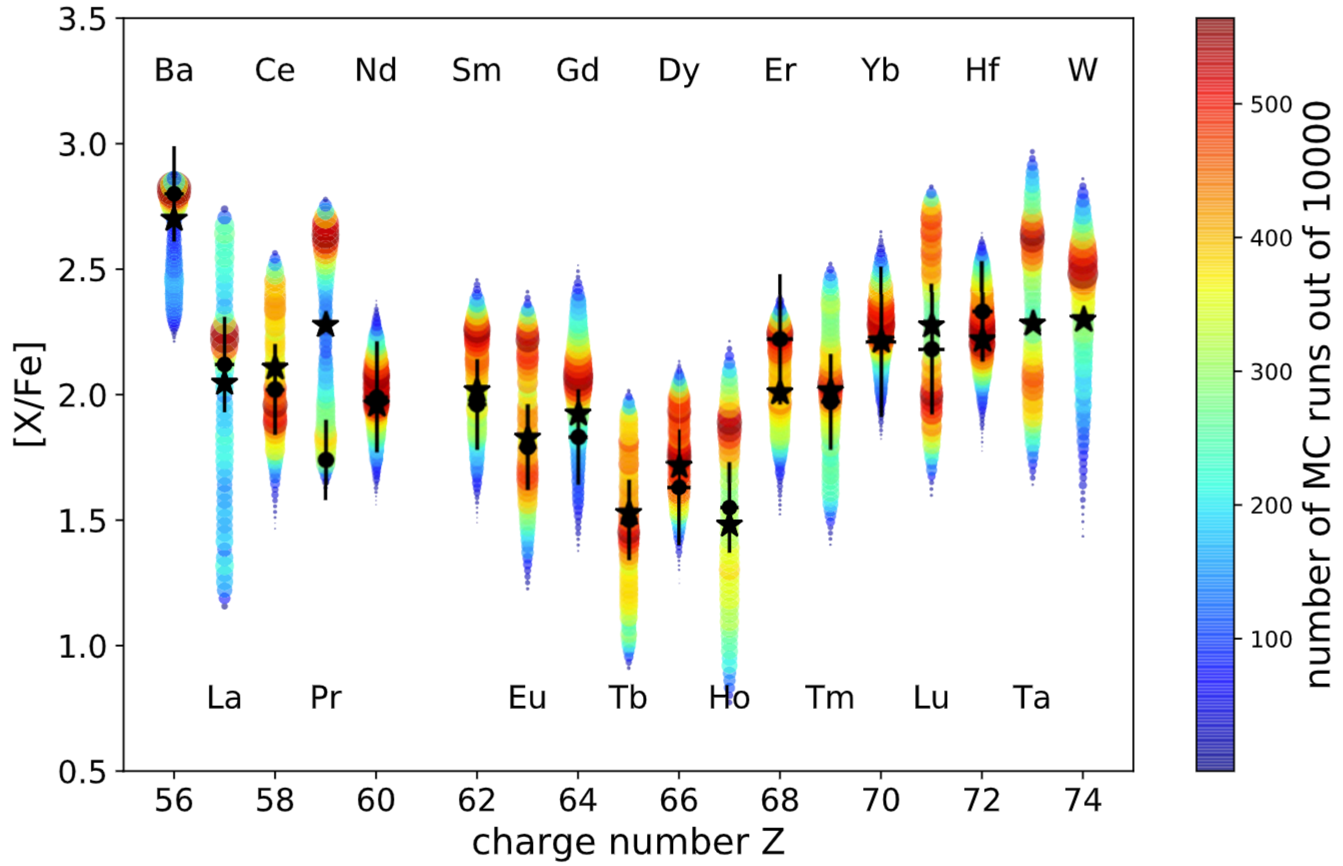
- Impact of nuclear physics uncertainties
- Monte-Carlo simulations over Hauser-Feshbach nuclear physics model-dependent reaction rate variations of unstable species



HF theoretical nuclear reaction rate variation factors

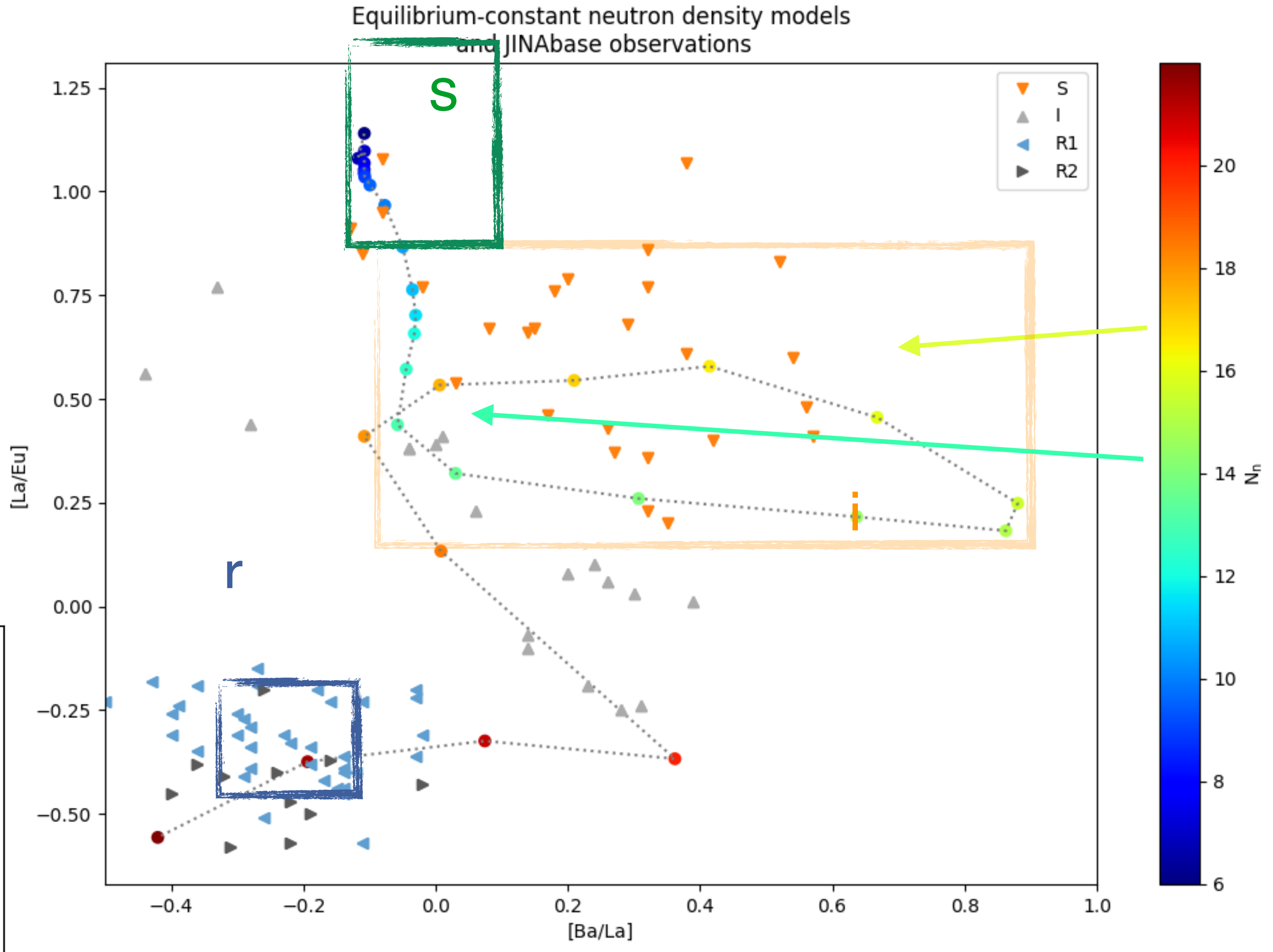


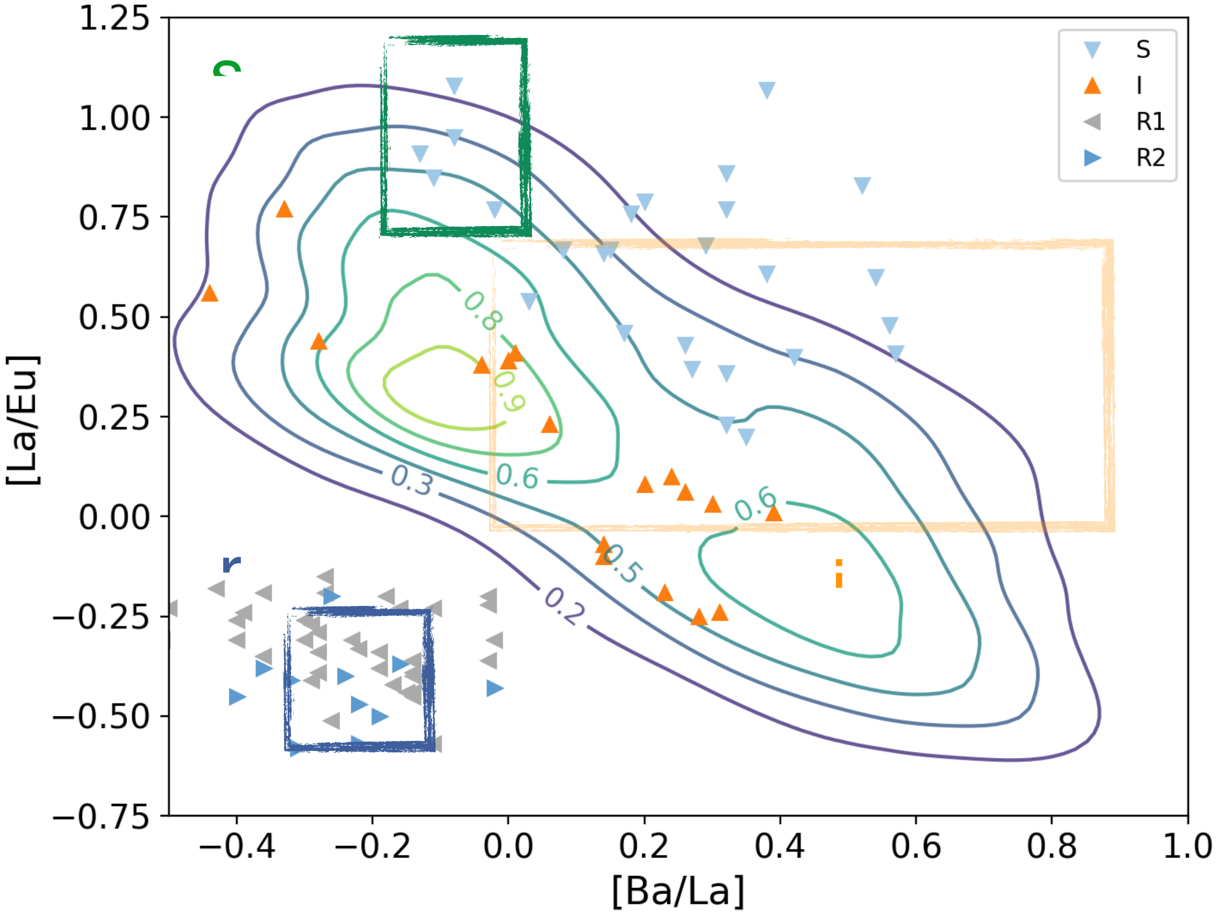
Predicted abundance distribution with MC nuclear physics impact propagation compared to observed for CS 31062-050. Denissenkov+ 21



Nuclear physics uncertainties prevent us from solving the puzzle of the origin of the CEMP stars

- CEMP stars in the La/Eu vs Ba/La plane
- Nuclear physics uncertainties is key obstacle to interpret observational data in terms of dynamic origin of the elements simulations.



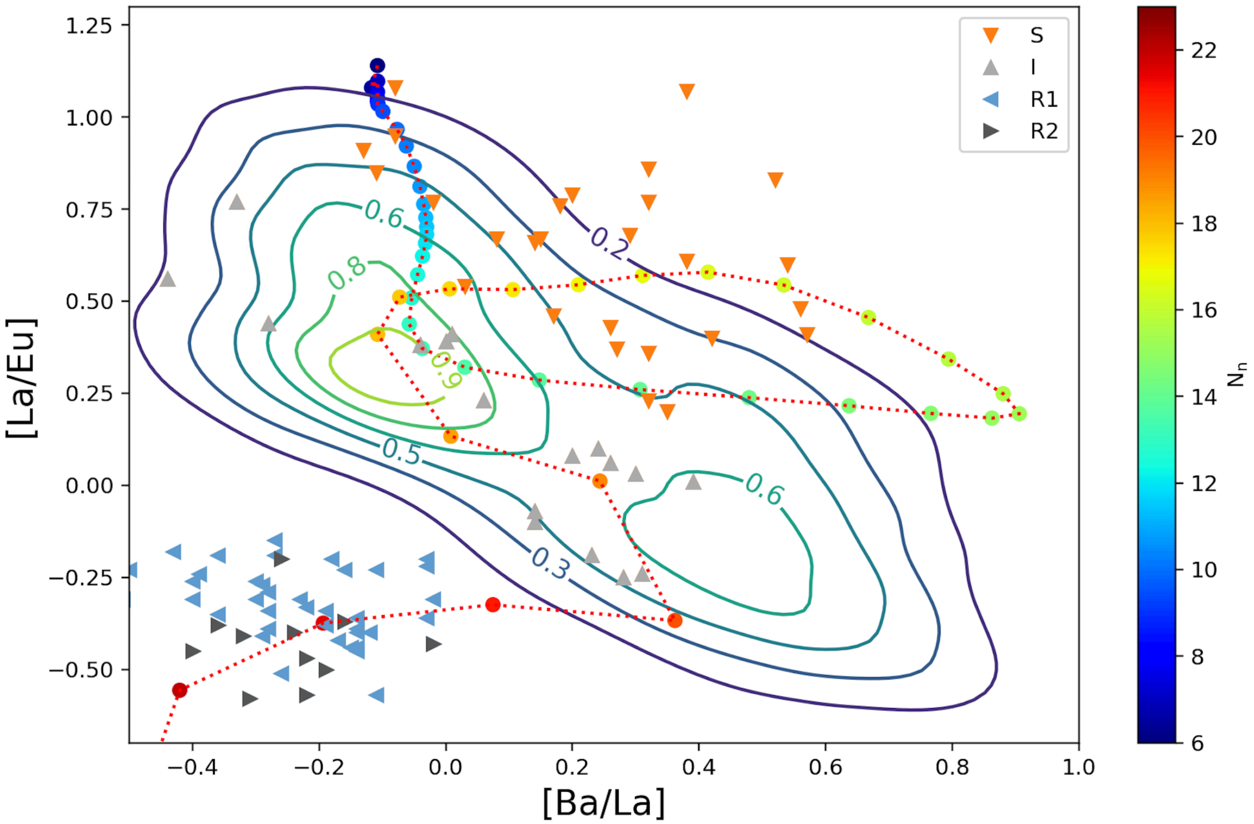


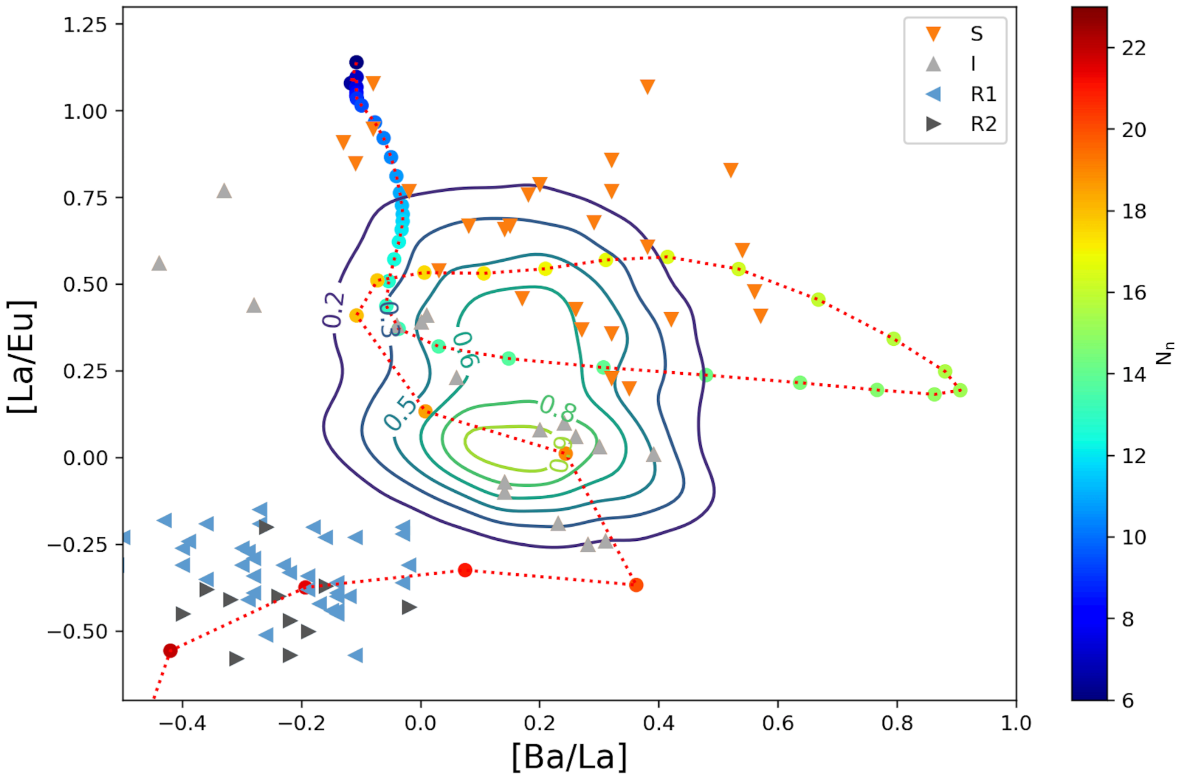
PDF of **one** N_n dot (3e13cm^{-3}) from plot above

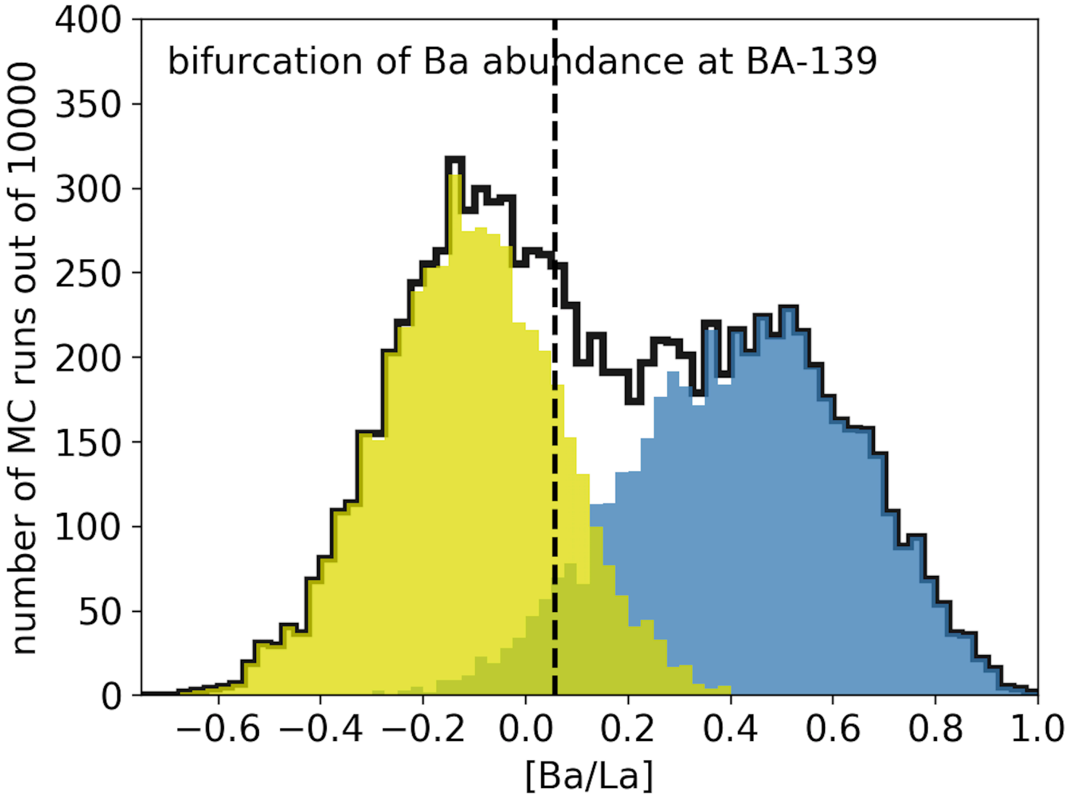
Reducing uncertainties of elemental abundance ratios predicted for i-process nucleosynthesis

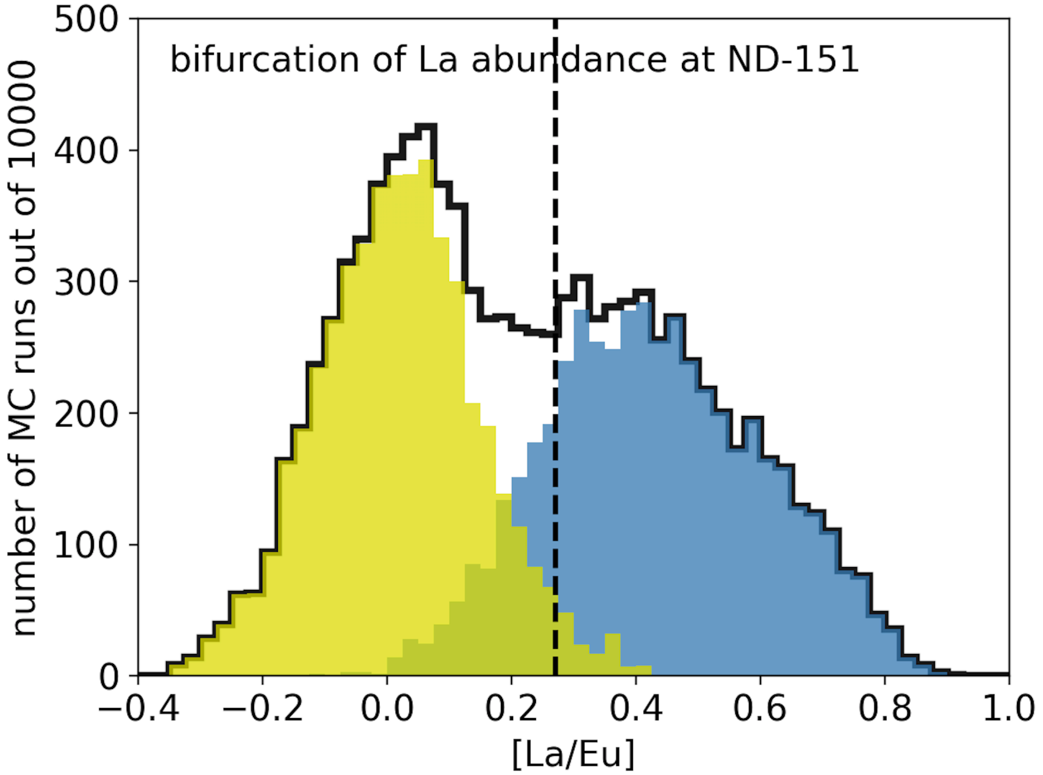
For neutron density $N_{\mathrm{n}} = 3.2 \times 10^{13}\,\mathrm{cm}^{-3}$

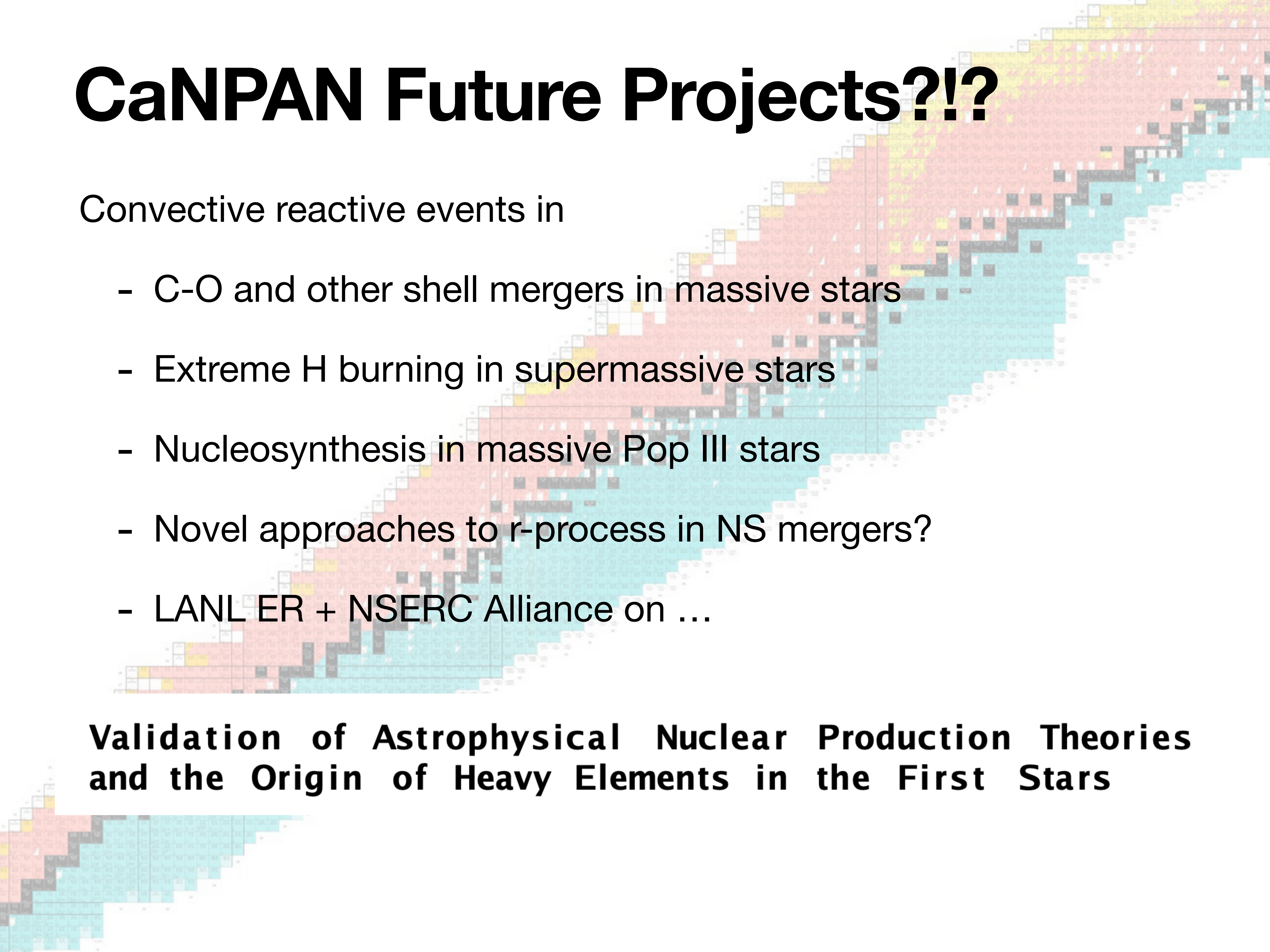
Spyrou+ 24, Rhys Rev Letters











CaNPAN Future Projects?!?

Convective reactive events in

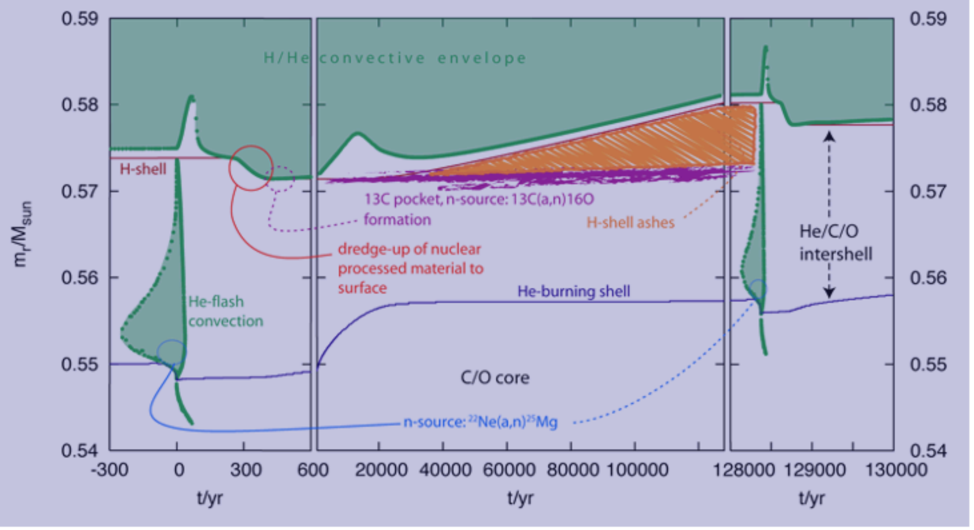
- C-O and other shell mergers in massive stars
- Extreme H burning in supermassive stars
- Nucleosynthesis in massive Pop III stars
- Novel approaches to r-process in NS mergers?
- LANL ER + NSERC Alliance on …

Validation of Astrophysical Nuclear Production Theories and the Origin of Heavy Elements in the First Stars

Sm-Eu-Gd: a collaborative multi-physics, multi-institutional project

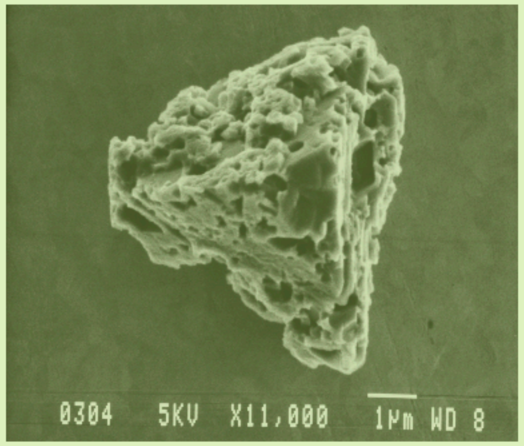
LANL

Astrophysics modeling: Provide theory and simulation to link from nuclear experiment to astrophysical observables -> improve predictive power of models (LANL/T-6).



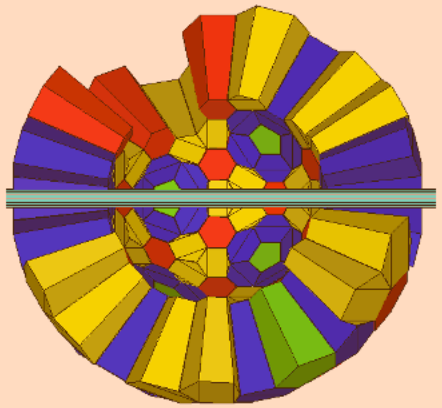
Pre-solar grains: First *individual grain* isotopic measurements for multiple elements - Sm-Eu-Gd - with new experimental technology (CHARISMA) at Argonne National Lab, collaboration request letter received.

External



Nuclear Physics Experiments with DANCE:

- (n,γ) measurements of radioactive samples with 4π BaF_2 array, that can not be performed anywhere else
- First complete experimental data coverage for an entire branching region
- LANL/LANSCE, T-16



Observations: Systematic campaign Eu hyper-fine line splitting to determine Eu isotopic ratios in extremely metal poor stars, sample will be obtained in part from SEGUE/SDSS-II candidates (JINA/MSU).