NuGrid Simulations
and
Explosive Events

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www.nugridstars.org

The NuGrid team

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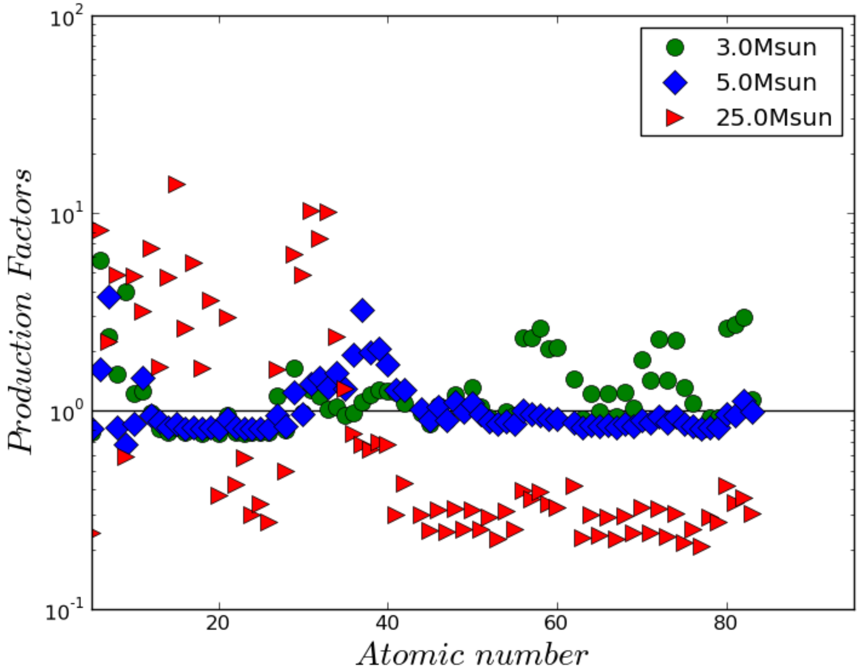
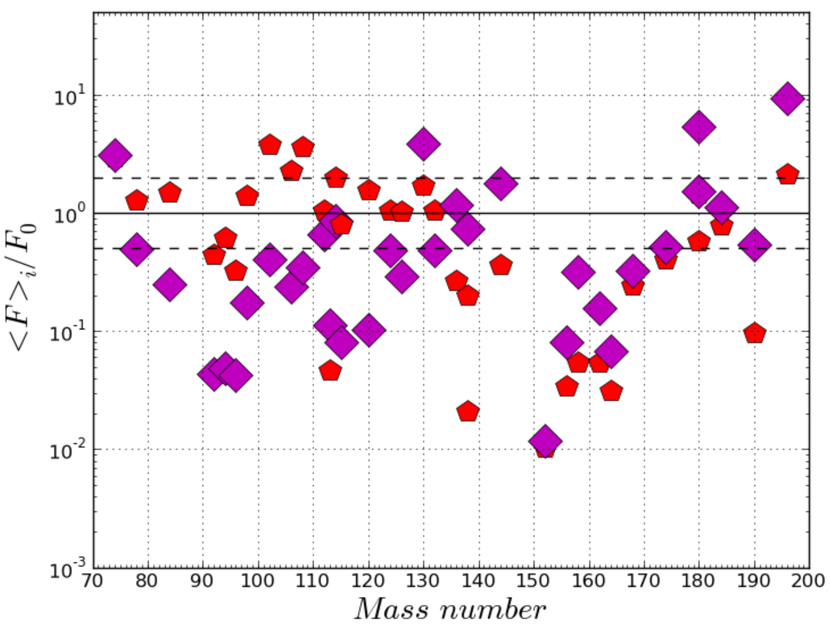
NuGrid :

- www.nugridstars.org
- comprehensive post-processing code suite for nucleosynthesis simulations

The Nucleosynthesis Grid (NuGrid) project develops and maintains tools for large scale post-processing nucleosynthesis simulations, and applies these to complete sets of quiescent and explosive nuclear production environments.

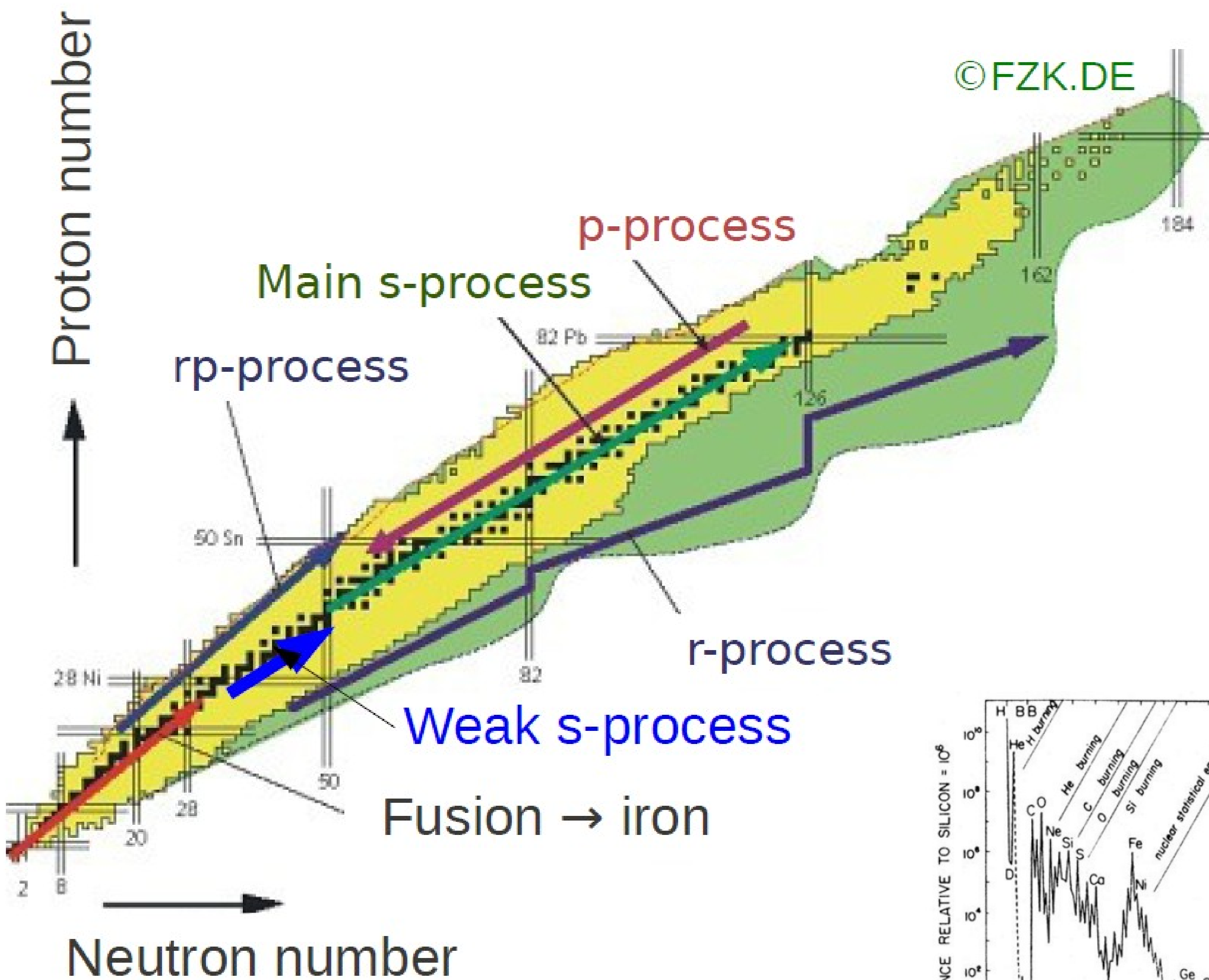


Final elemental production factors for a low mass AGB star (3 Msun), a massive AGB star (5 Msun), and a massive star (25 Msun).

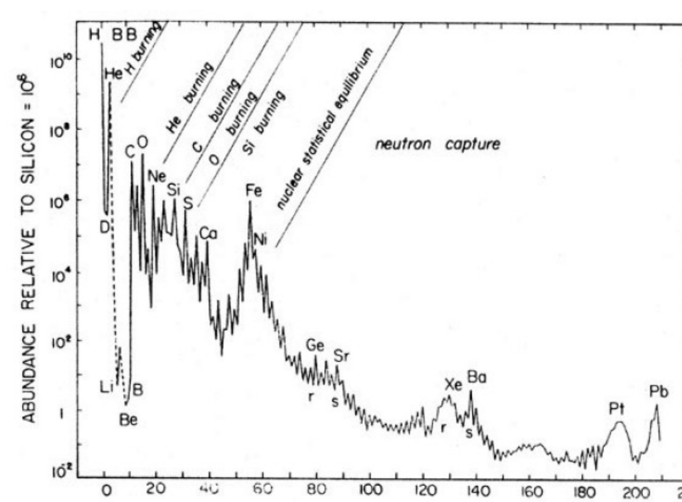


The final p-process yields for a 25 Msun star, Z = 0.02, and different C12+C12 rates.

What is the Origin of the Elements?



Cameron et al. 1982



The NuGrid framework

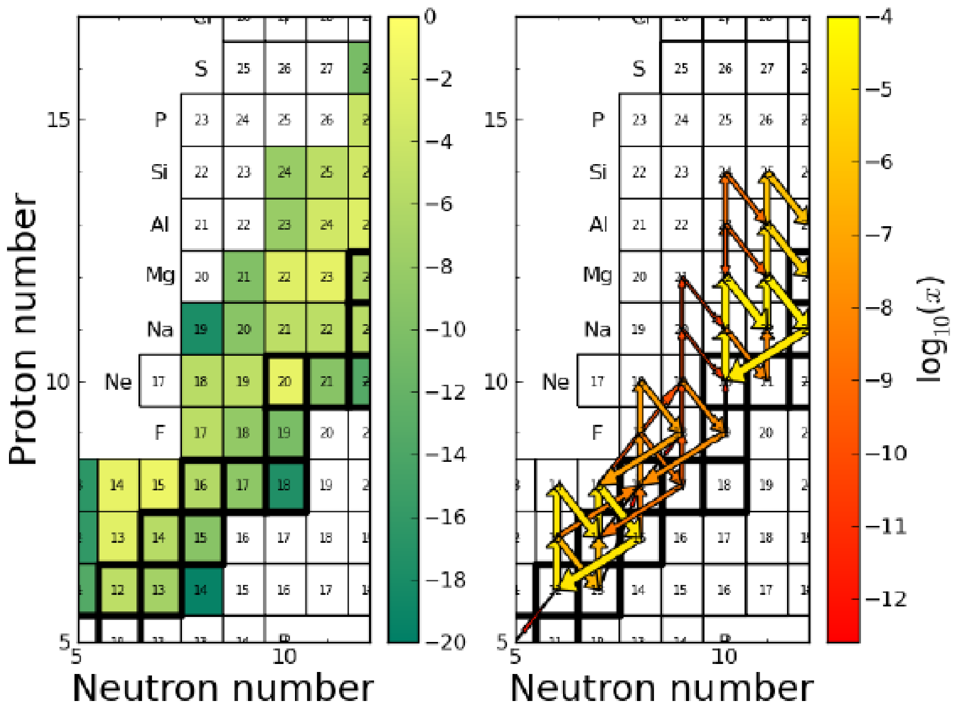
stellar evolution with minimal network for energy production

↓

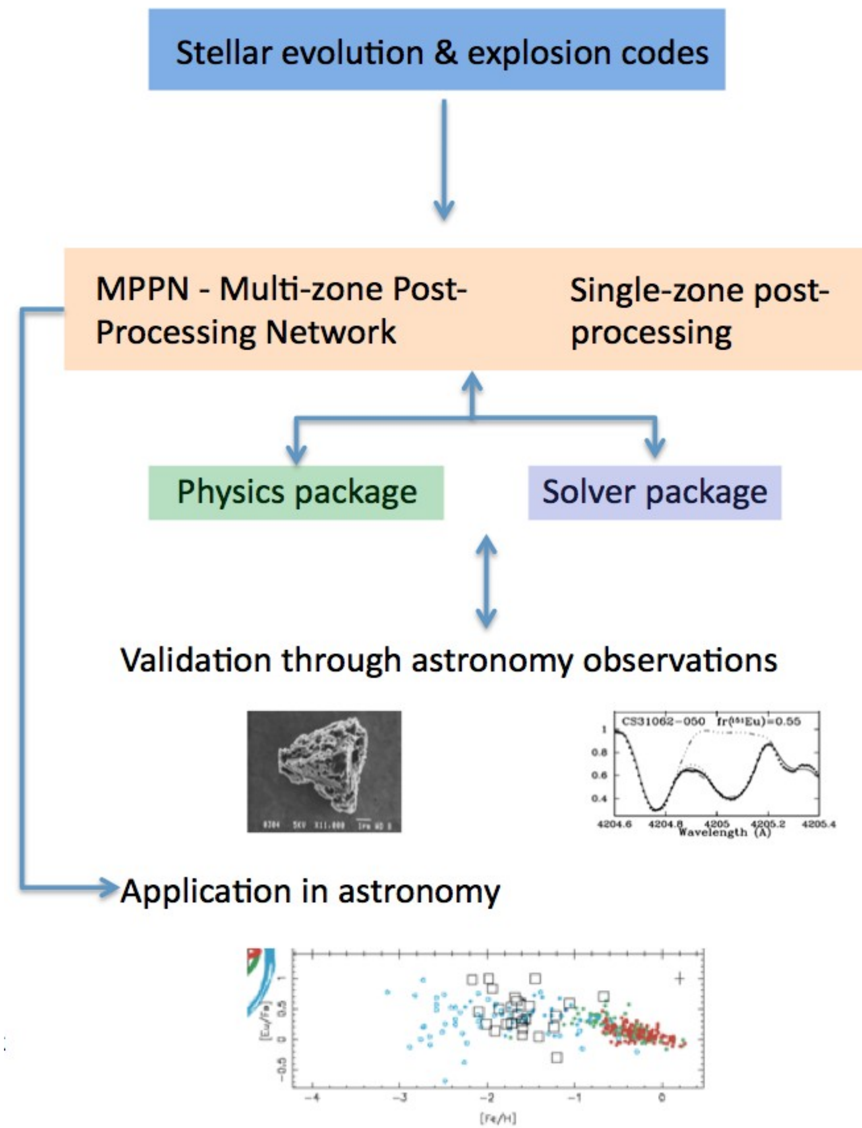
multi-zone nucleosynthesis post-processing and mixing with adaptive, complete network for all nucleosynthesis

↓

all abundance data at all times in all locations inside the star



Example of Nova nucleosynthesis simulations (Pignatari & Herwig 2013, NPN).



Physics package:

One physics package for all applications!

- **5100+ isotopes**
- **Reaction rate libraries:**

✓ JINA REACLIB 2008 revision, V1.0 (2011)
✓ Basel REACLIB revision 20090121
✓ KADoNIS (Dillmann et al. 2006)
✓ NACRE (Angulo et al. 1999)
✓ Iliadis et al. 2001
✓ Caughlan et al. 1988
✓ Weak interaction: Fuller et al. 1985, Oda et al. 1994, Goriely et al. 1999, Langanke & Martinez-Pinedo 2000

- **BRUSLIB Netgen interface** (Aikawa et al. 2005)
- **NSE:**

✓ T-dependent partition function & mass excess (REACLIB)
✓ Coulomb screening (Calder et al. 2007)
✓ Weak interaction feed-back considered

- **Isomeric state network**: Al26, Kr85, Cd115, Lu176, Ta180
- **Sandbox:** N14(p,g) from LUNA, 3a by Fynbo et al. 2005, C12(a,g)O16 by Kunz et al. 2002, etc.

Drivers:

SPPN:
⌘single zones, trajectories, analytic prescriptions
MPPNP (multi-zone PPN)
⌘MPI-parallel (typical runs on 100-200 procs)
⌘USEEPP (Unified Stellar Evolution and Explosion Post-processing) IO hdf5 library
⌘grid options:
✓Static
✓Input
✓(AMR)
⌘Flexible restart and re-grid options (batch queuing system enabled)
(TPPN (->BMPPN))

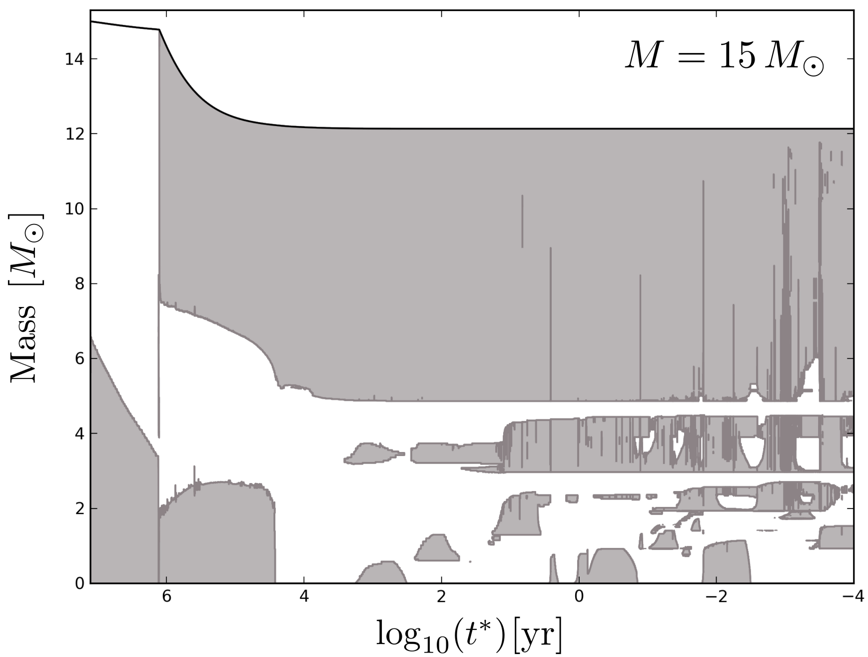
Solver package:

- Newton-Raphson, fully implicit
- Integrated dynamic network at iteration level
- (Adaptive, flux-guided time steps)
- Sparse solver

NuGrid research areas

- pre-supernova stellar evolution;
- **supernova explosions, explosive nucleosynthesis CCSN and SNIa**
- mixing processes and their implication for nucleosynthesis in stellar evolution
- properties of stellar populations, CMDs
- **nucleosynthesis in recurrent nova simulations**
- super-AGB star nucleosynthesis
- **nucleosynthesis in double-degenerate merging stars**
- impact of reaction rate uncertainties in stellar yields, including:
  - (n,p), (n,a) reactions
  - C12+C12
  - n-source reactions
  - n-capture and charged particle reactions
- s process and i process in stars
- evolution and nucleosynthesis of low- and intermediate mass stars
- **r process in SN fall-back and parametric conditions**
- **X-ray bursts**, Pop III stars, stellar rotation

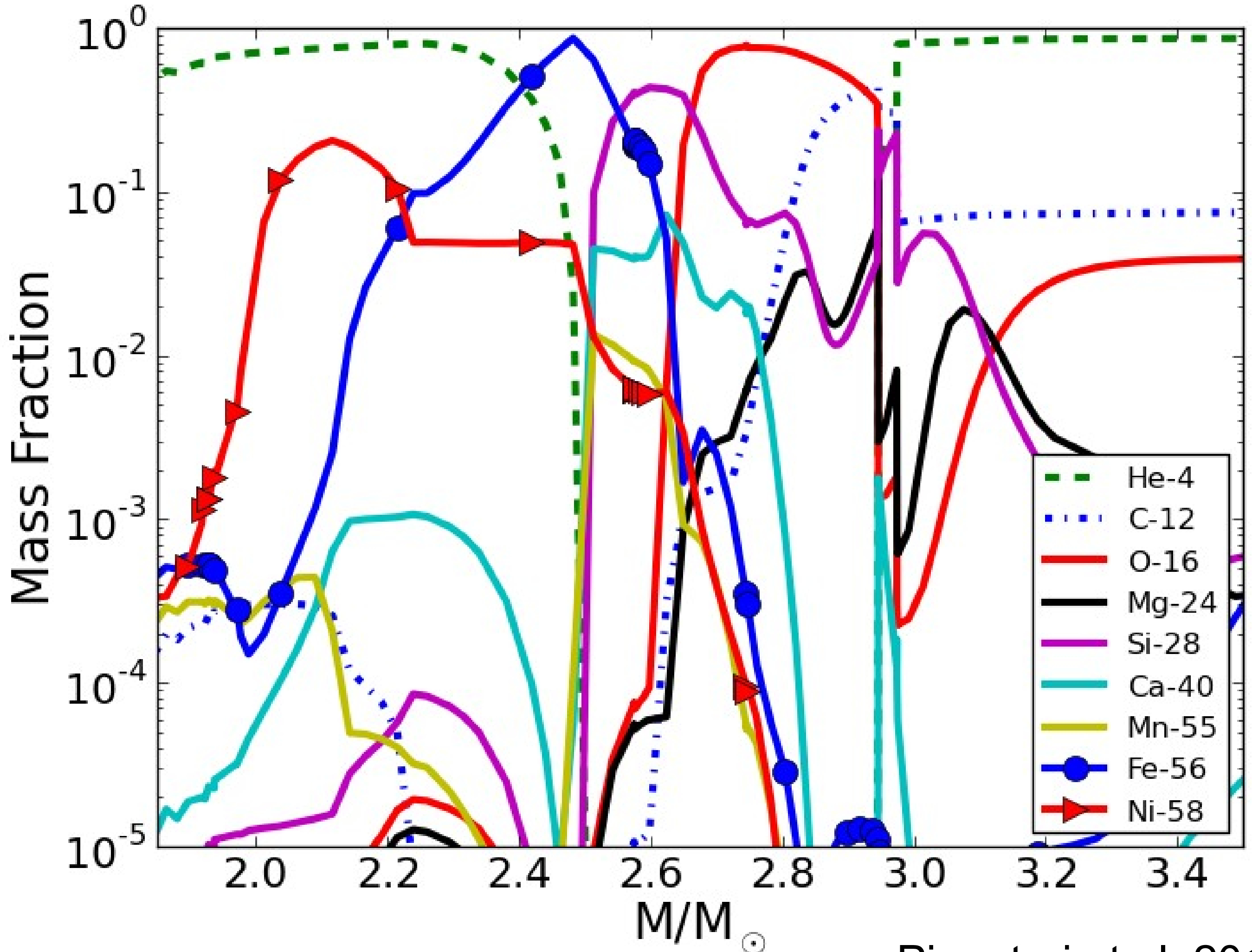
Explosive nucleosynthesis in Core Collapse Supernovae



- Element production from the nucleosynthesis in the pre-explosive evolution:
O, Na, Mg, s process (Cu, Ga, Ge)

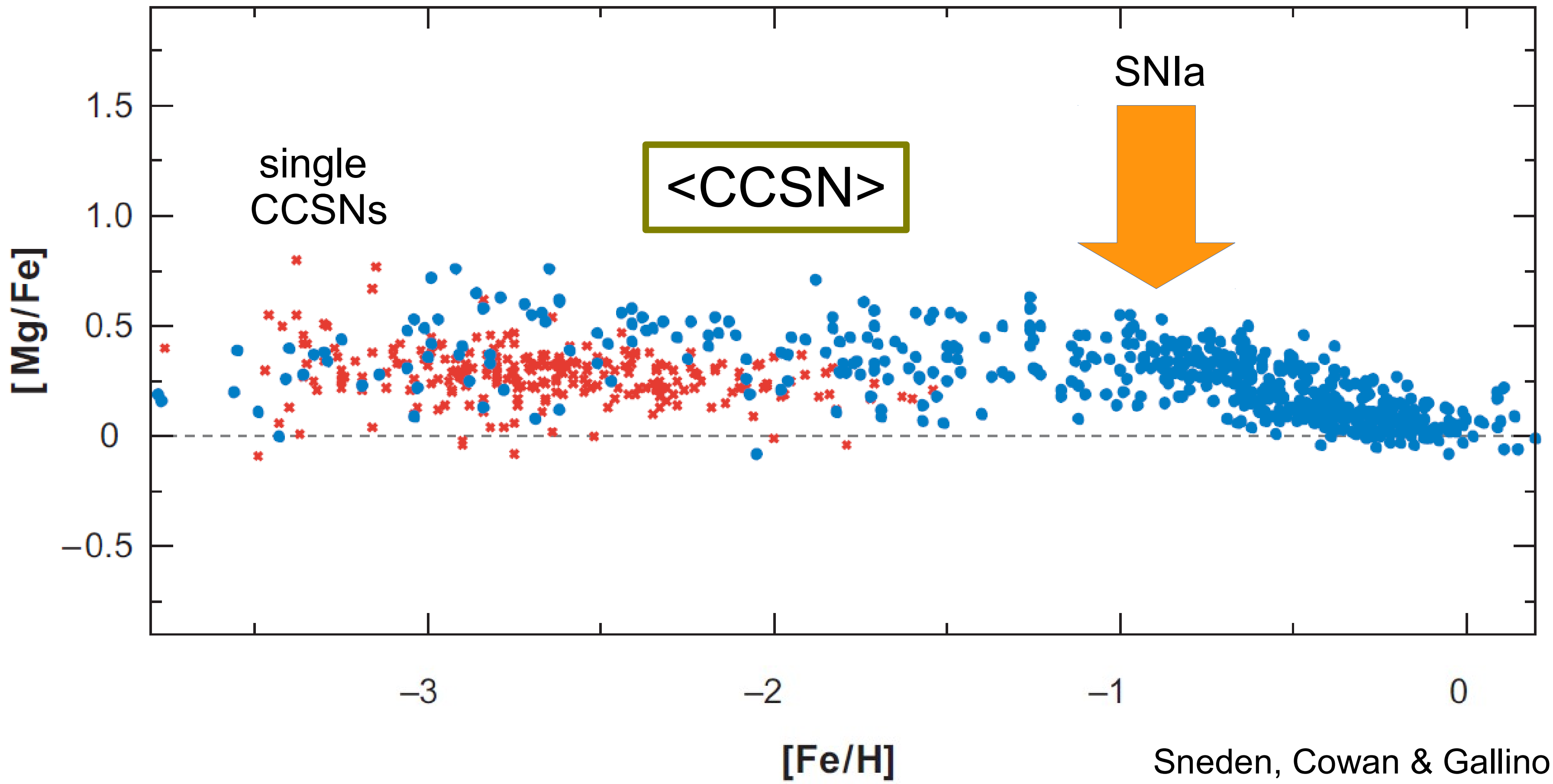
- Element production from the nucleosynthesis in the CCSN:
Si, Ca, S, Ti, **iron group**, p process (γp- and νp-), n process, α process, (r process?)

Ejecta of a 15 Msun star after the explosion



Pignatari et al. 2013, arXiv

GCE needs consistent yields from CCSN and SNIa to fit the chemical evolution of e.g., Mg/Fe.

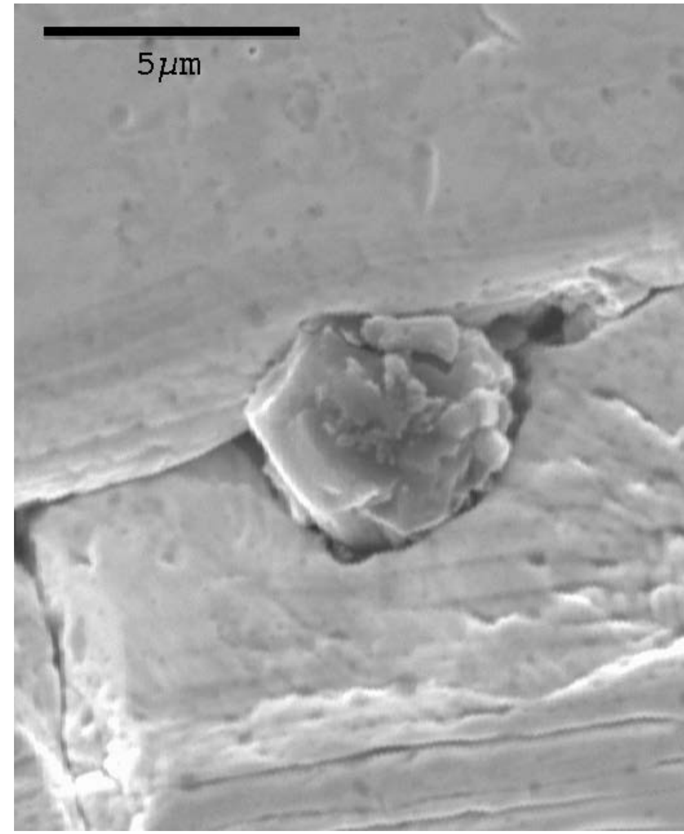


Sneden, Cowan & Gallino 2008

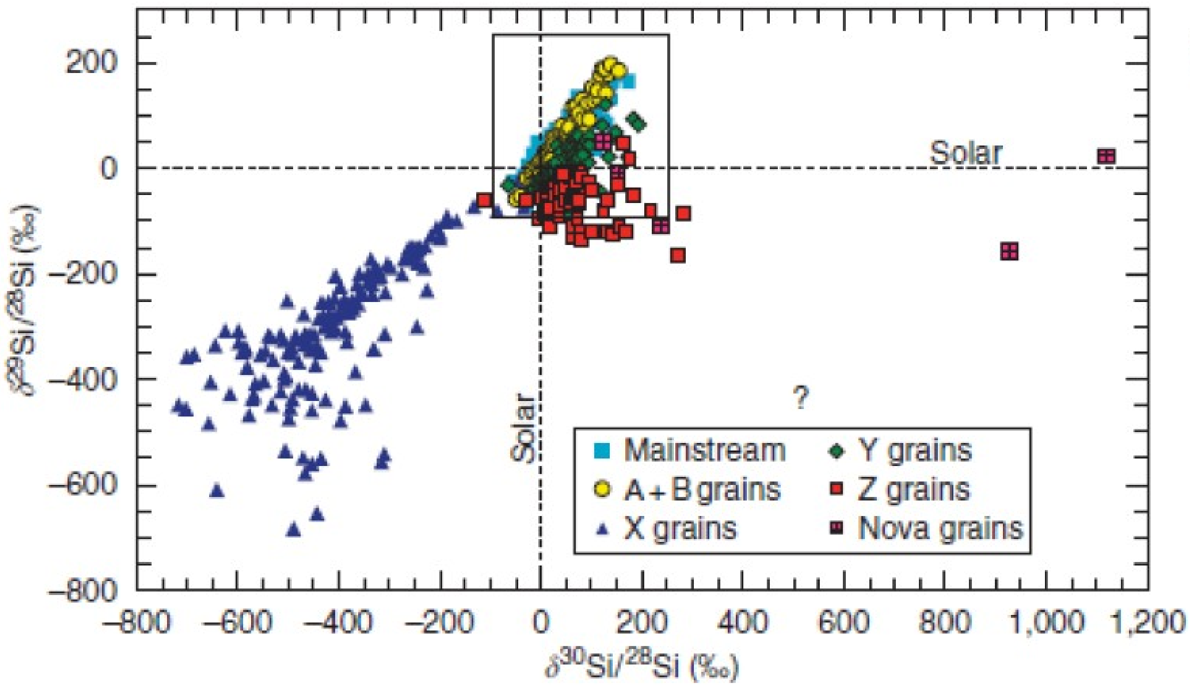
CCSN

Cas A
11000 ly
~ 300 years ago

Presolar grain from an old CCSN

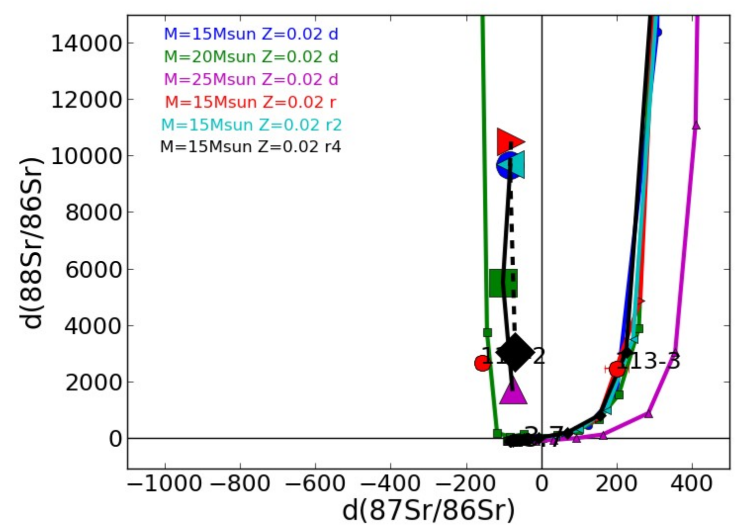


unknown
?
~ 4.5-5 Gy ago



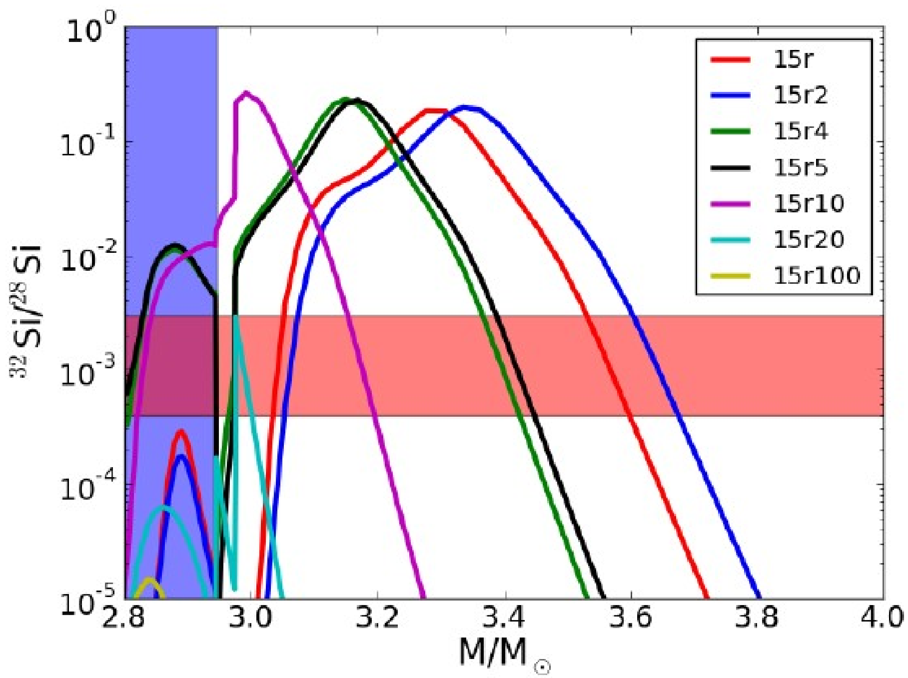
Zinner 2003

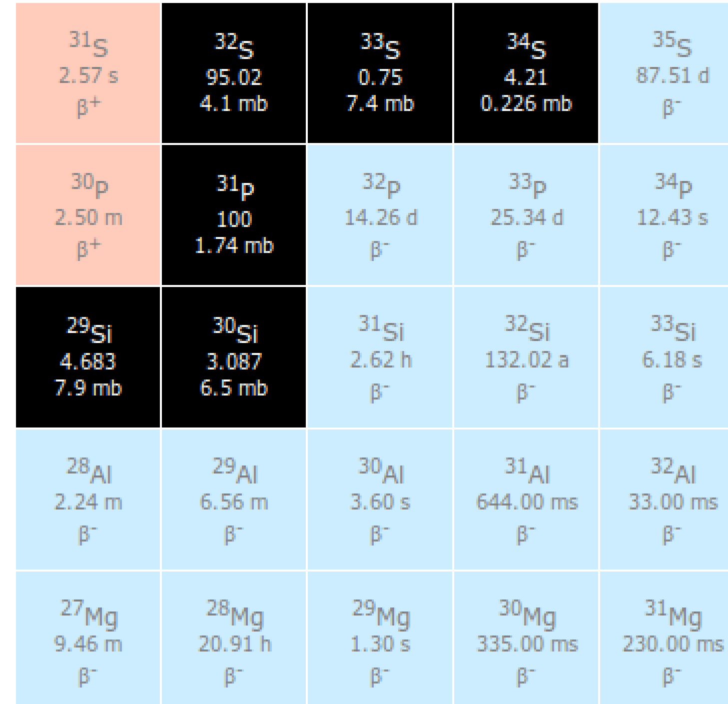
Isotopic ratios can be measured for different elements in single presolar grains, carrying The abundance signature imprinted from the progenitor CCSN event.

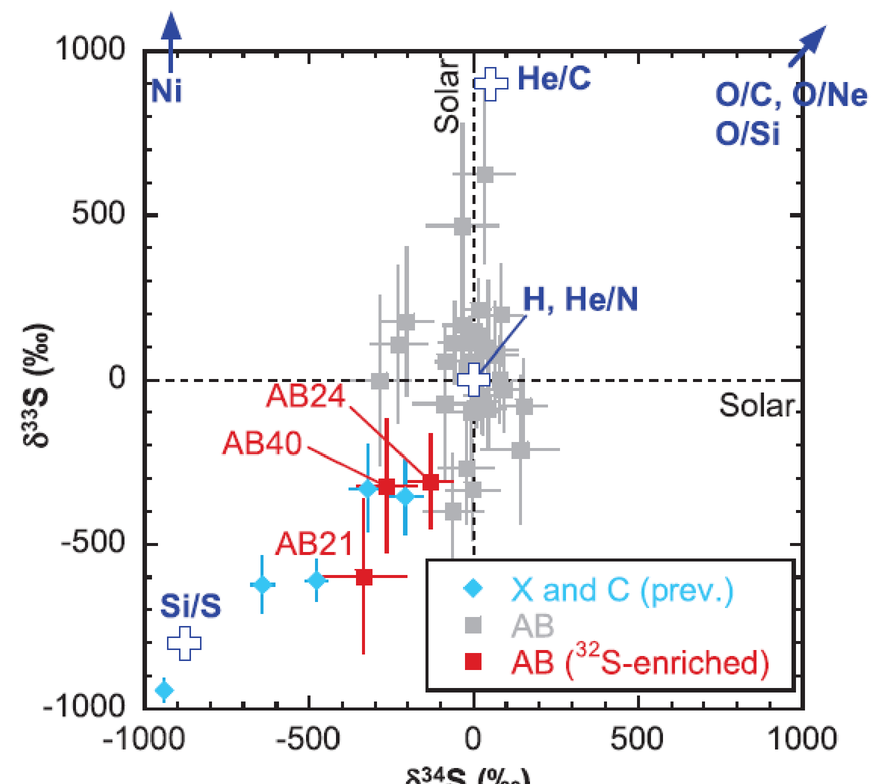


Pignatari et al. 2014, in prep.

Pignatari et al. 2013, ApJL
(SiC C presolar grains)



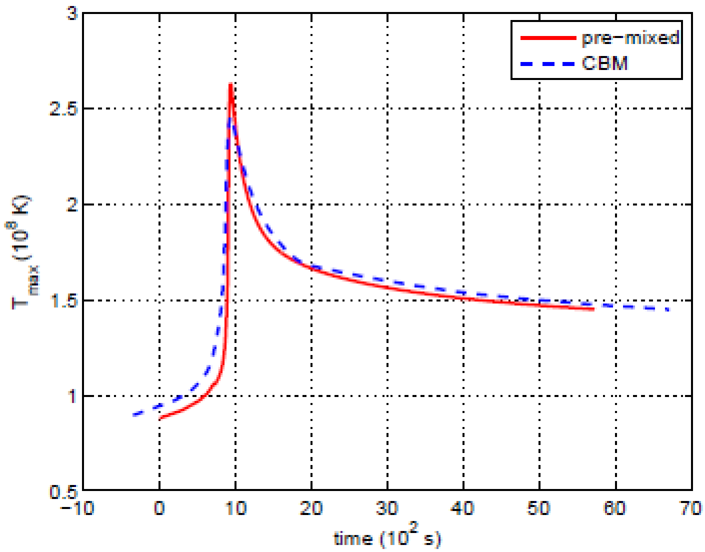


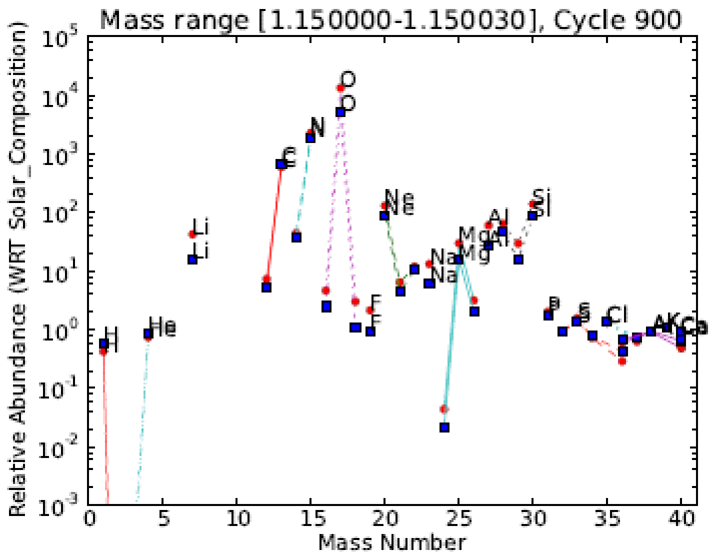


Signature of Si32 production found in presolar SiC C grains, constraining the explosive nucleosynthesis conditions in the C-rich He shell of the progenitor CCSN.

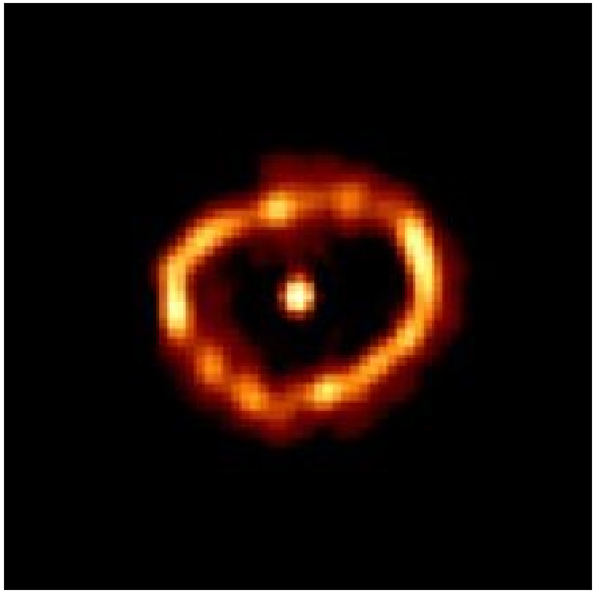
Nucleosynthesis in recurrent nova simulations

CBM = convective boundary mixing





Denissenkov et al. 2013, arXiv



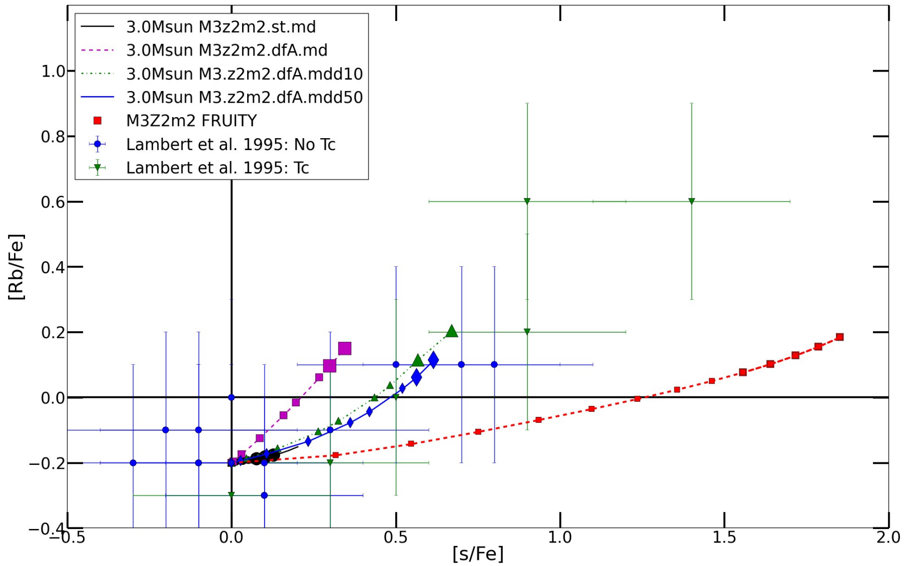
Nova Cygni 1992 (HST)

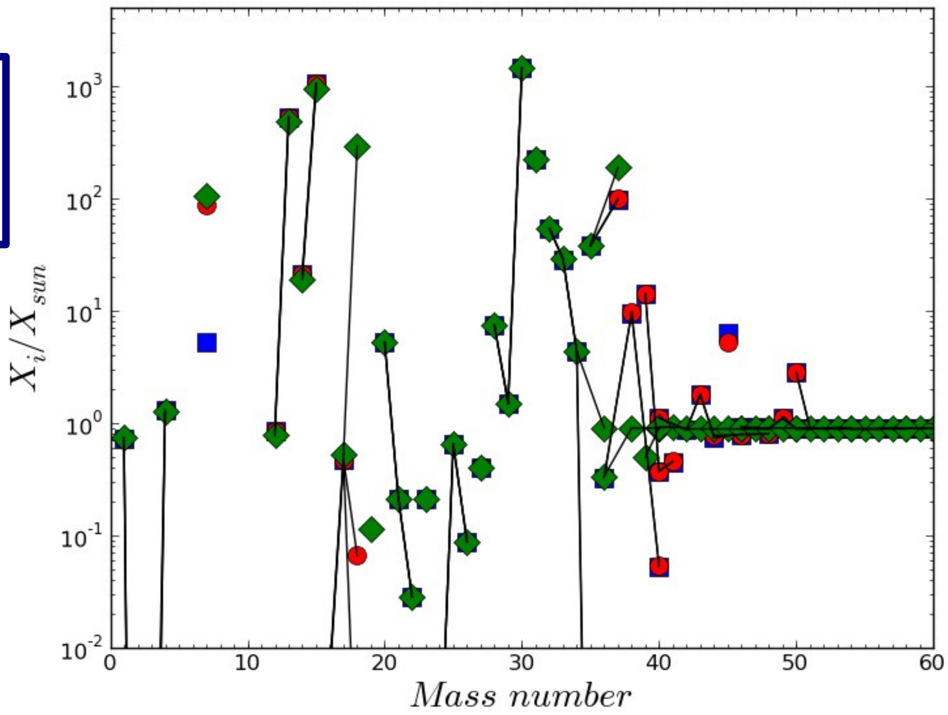
E ~ 10^{45} ergs
Mass ejected = 10^{-4} – 10^{-5} Msun
Nucl. contribution ~ C13, N15, O17

Jose & Hernanz 2007,
Casanova et al. 2011

With a good knowledge of the relevant nuclear reaction rates, it is possible to contrain the physics assumptions used in the stellar model.

Constrains about CBM conditions, similar to the CBM in the He intershell in AGB stars.

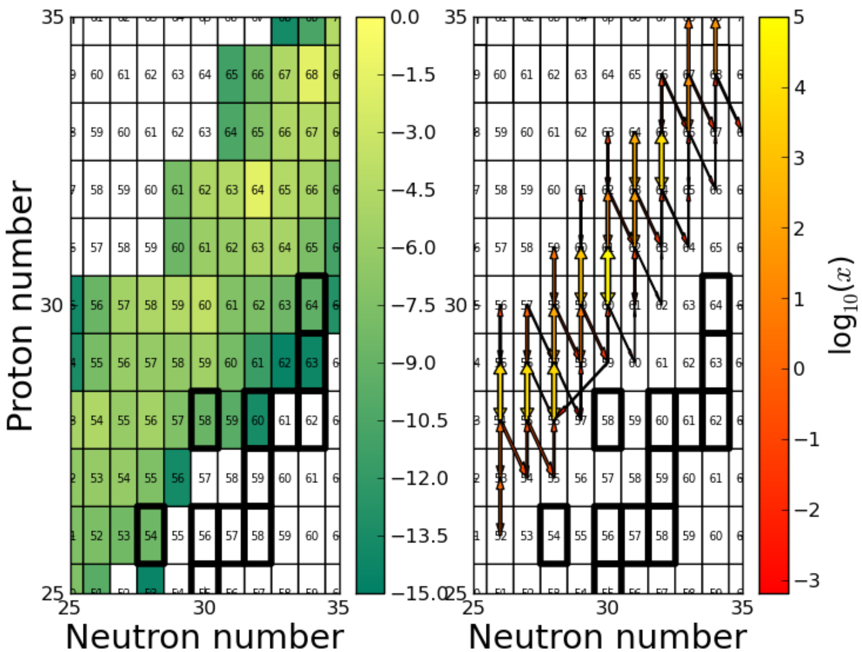


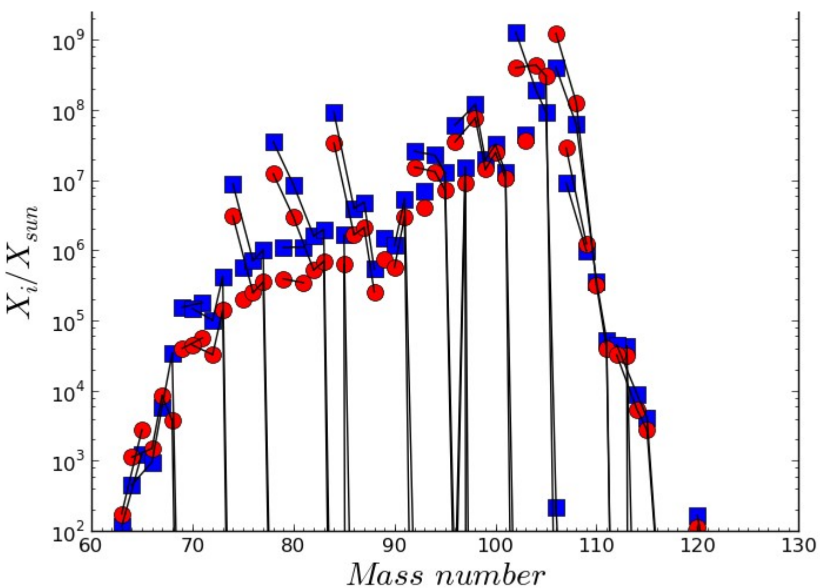


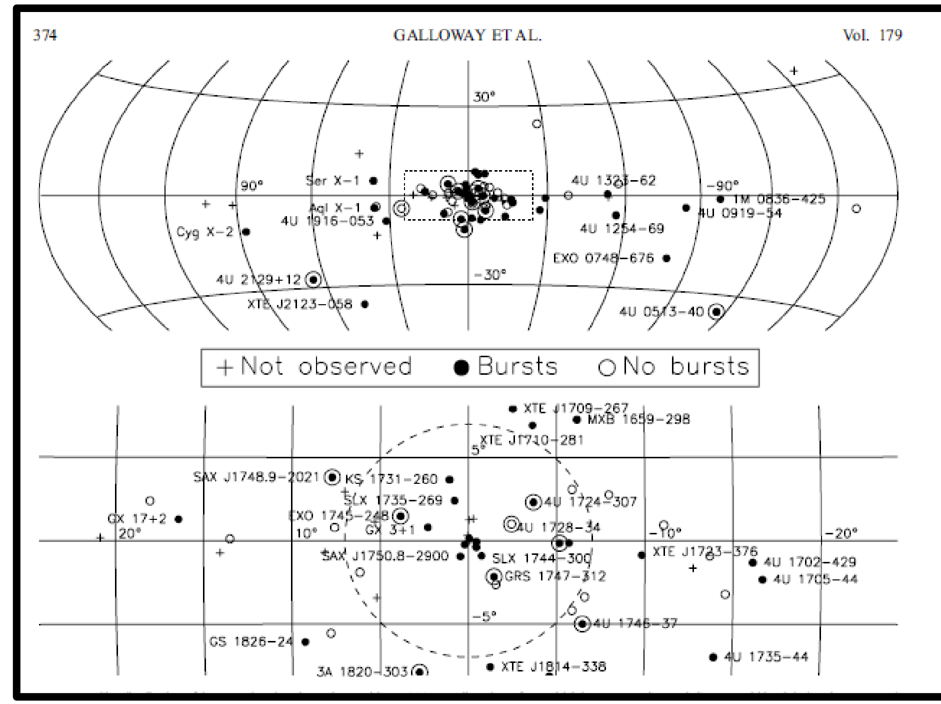
Example: Isotopic distributions for the same Nova simulation, but using different nuclear physics sets.

Battino et al. 2014, in prep.

X-ray bursts





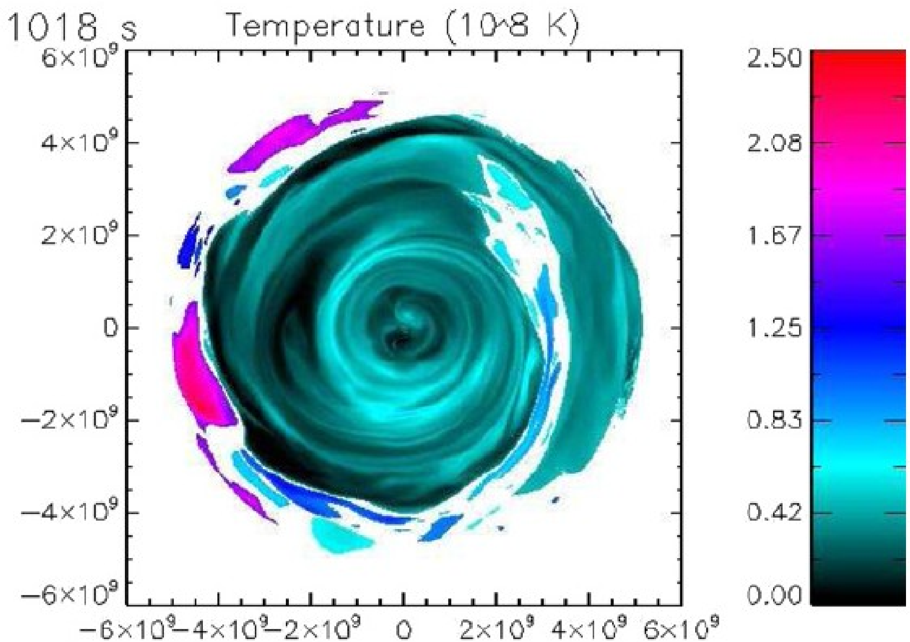


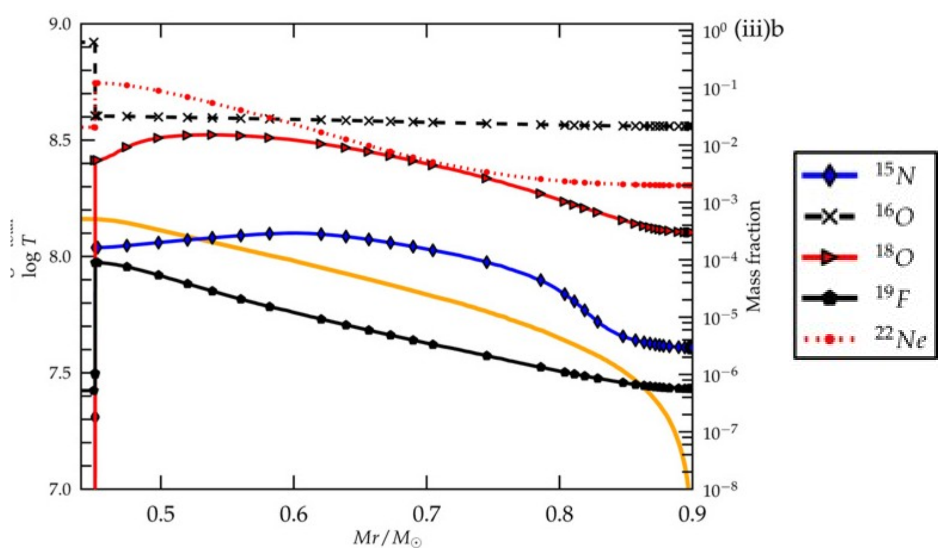
Galloway et al. 2008

E ~ 10^{39} ergs
Mass ejected = ?
Nucl. contribution ~ p nuclei ^{92,94}Mo and ^{96,98}Ru?

V&V and testing in progress:
Ben Shaw and Alison Laird (York), MP (Basel)

R Coronae Borealis





Merger of a CO WD and an He WD
Nucl. Production ~ O18, F19 (?)

Production of the stellar progenitors

Staff et al. 2012

Hydrodynamics simulations of the merger

Menon et al. 2013

Nucleosynthesis calculation for the merger
SOF

Roadmap 2014

- Validation of the network in X-ray bursts (York, Basel)
- Validation of the network in SNIa condition (Basel, UVIC, LANL, ASU)
- Validation of the network in r-process conditions (Basel, Keele, LANL, MSU, ASU)

Final message:
one of the main drivers of the NuGrid methodology is to introduce a higher level of consistency in stellar yields made from different types of stars.
This is fundamental for GCE, and to study the production of the solar abundances.

NuGrid stats:

15 institutions
16 senior investigators
25 postdocs and students

Acknowledgements:

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