Stellar Modeling for Nuclear Astrophysics: Constraining the astrophysical origin of the p-nuclei

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NuGrid Collaboration

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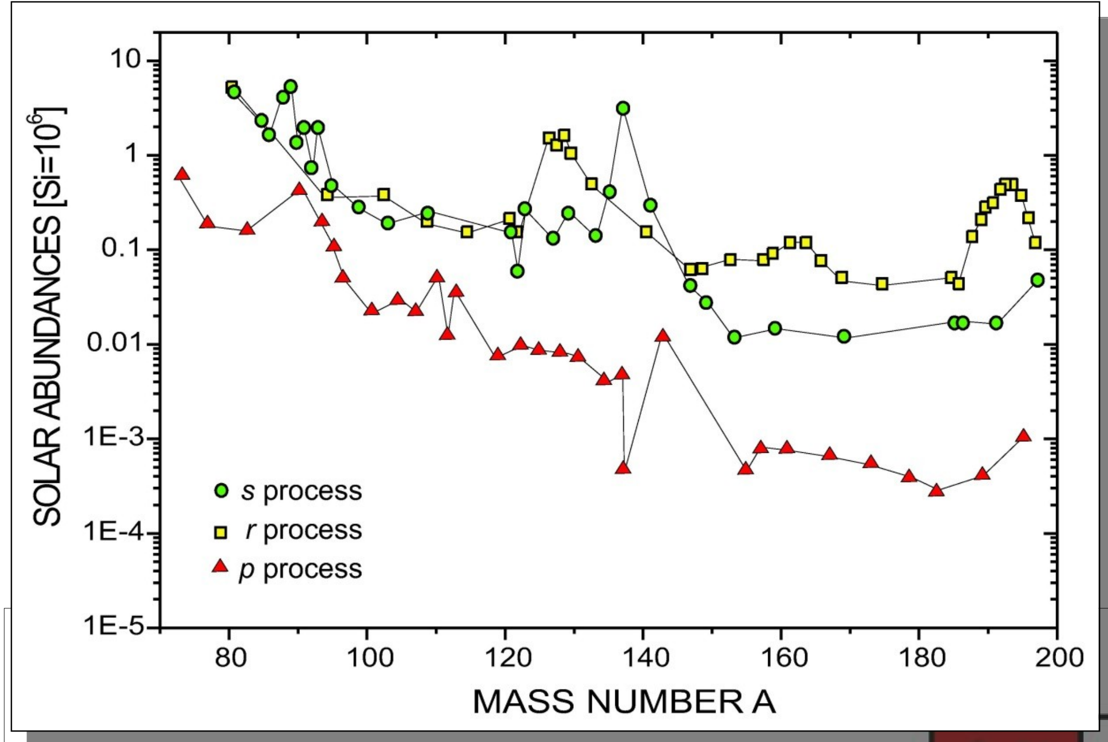
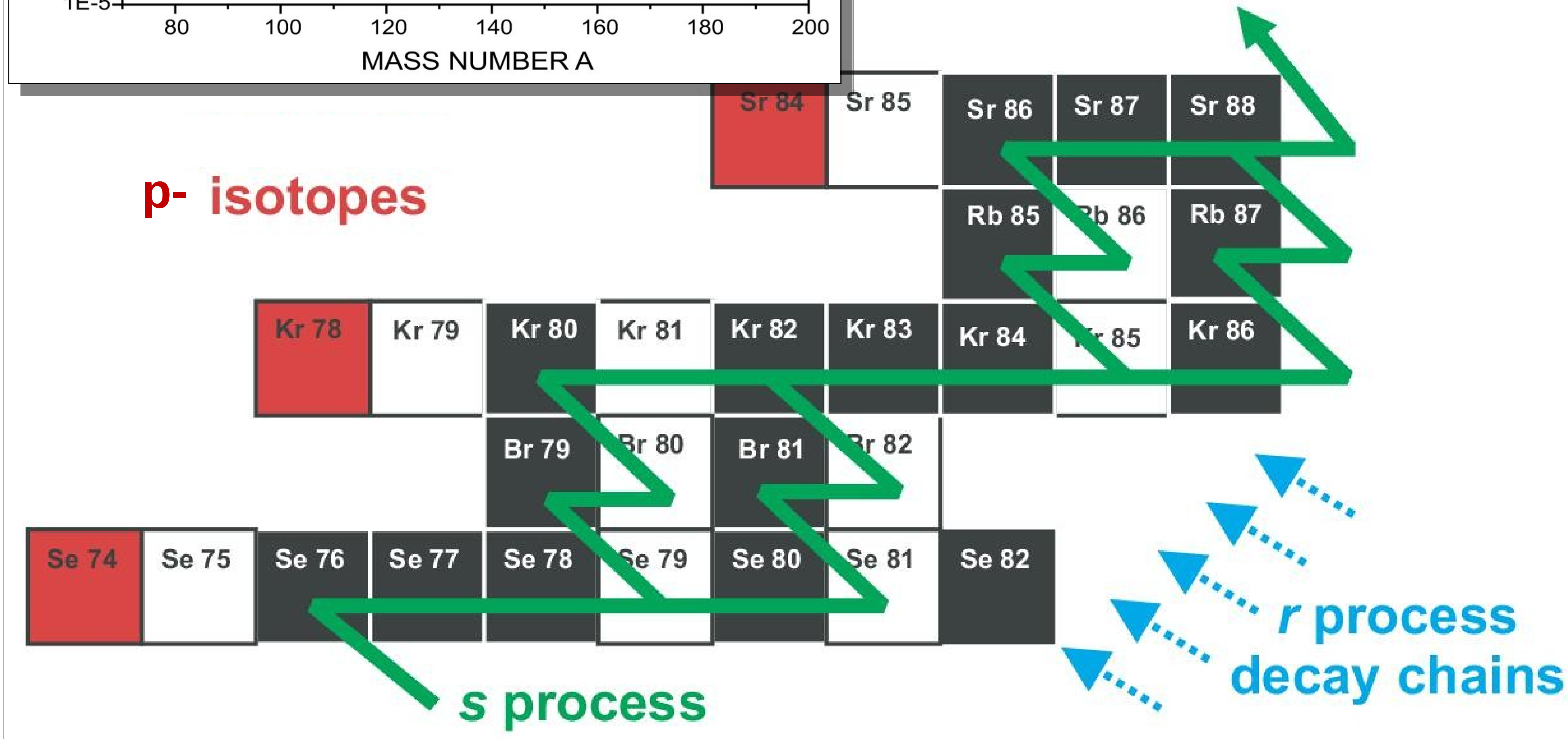
EUNPC Conference, 2-7 September 2018, Bologna

p-Nuclei



Def.: “What is not made by s- and r-process”; (Tommy Rauscher)



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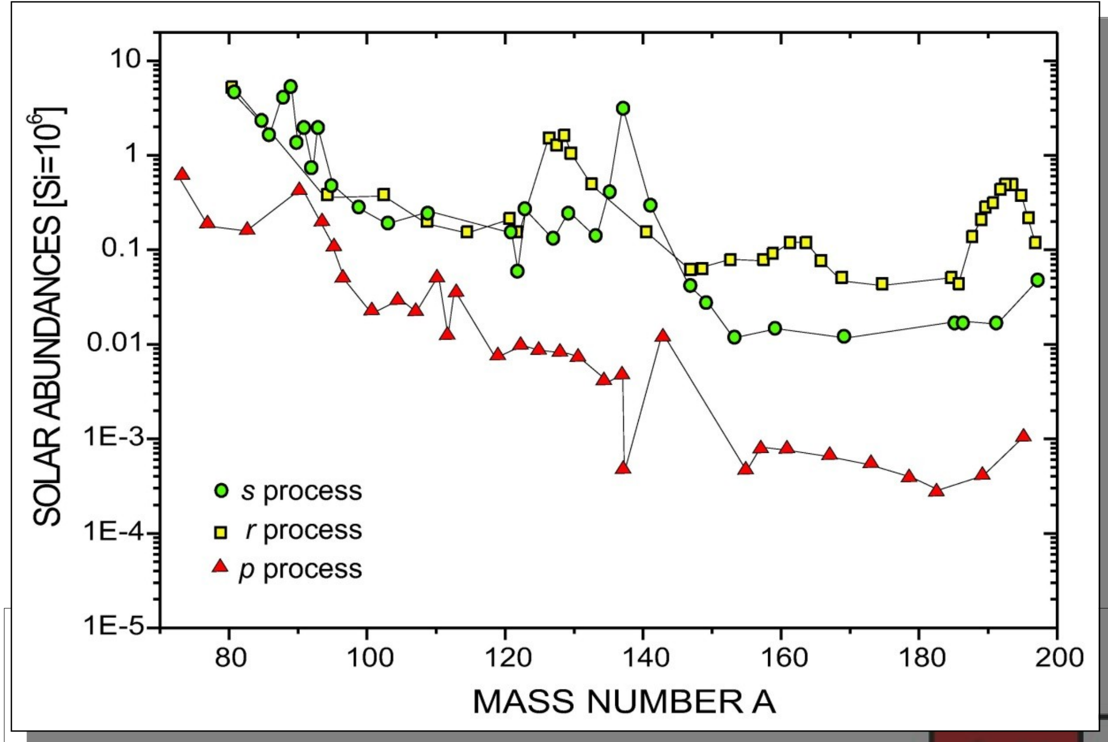

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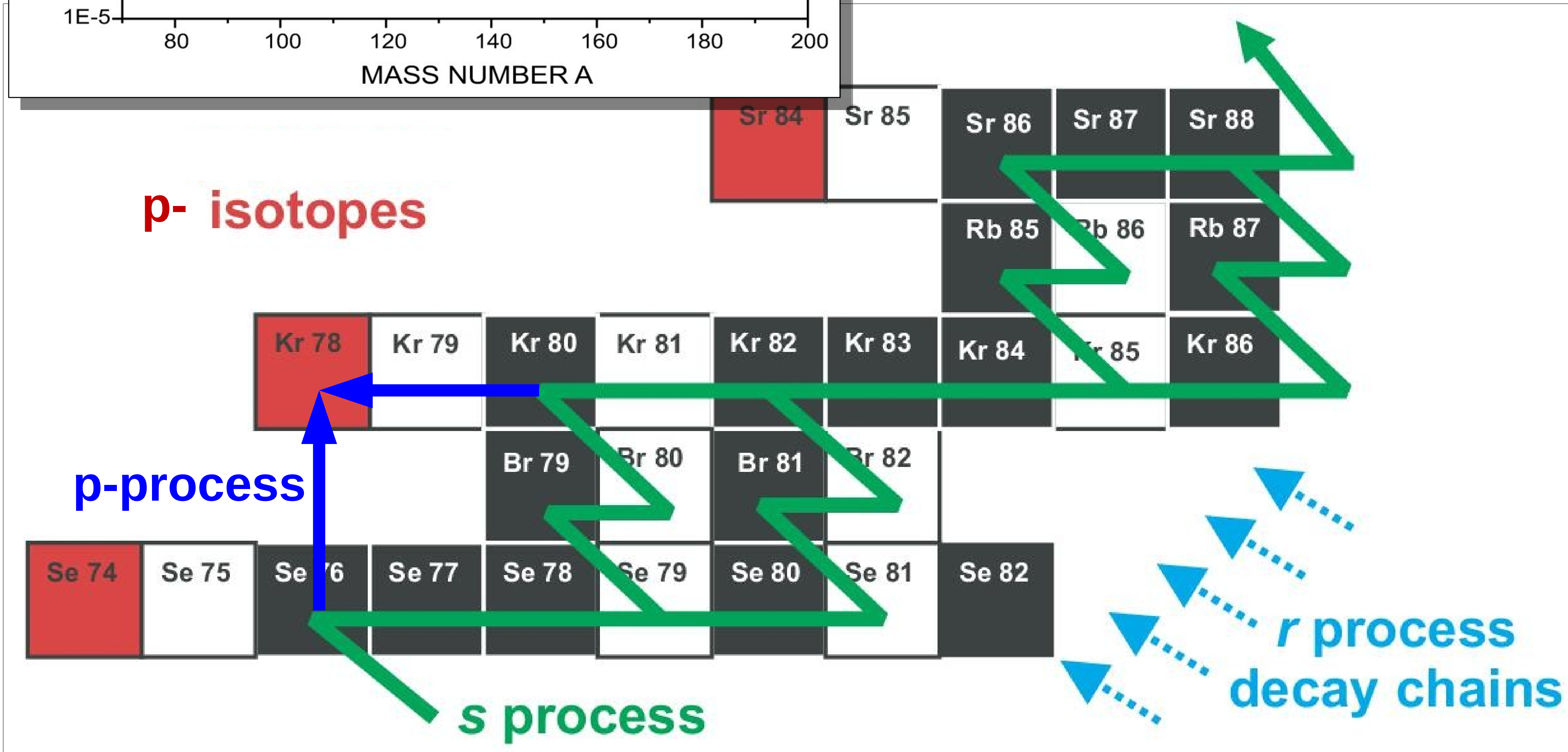
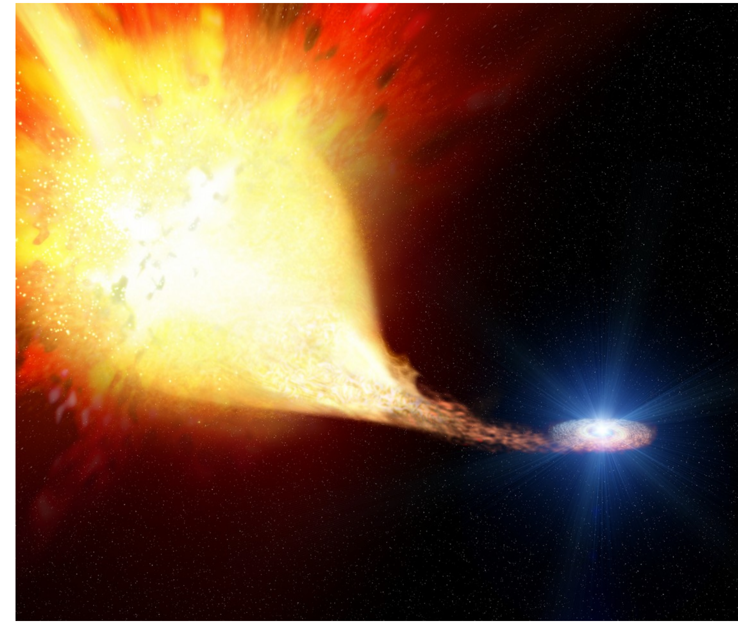


Type Ia Supernovae

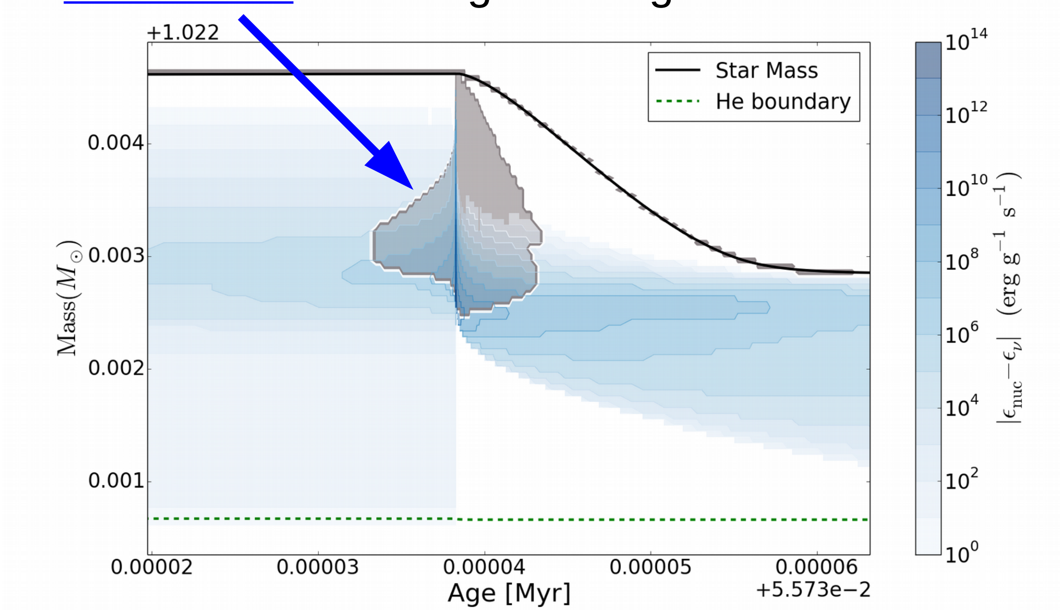
- Type Ia supernovae (SNIa) are luminous stellar explosions which marks the fatal destruction of accreting white dwarfs in binary systems.

- The two scenatios to make SNIa explosions are **Single-Degenerate** (SD, here considered; Whelan & Iben 1972) and Double Degenerate (DD; Iben et al. 1984).

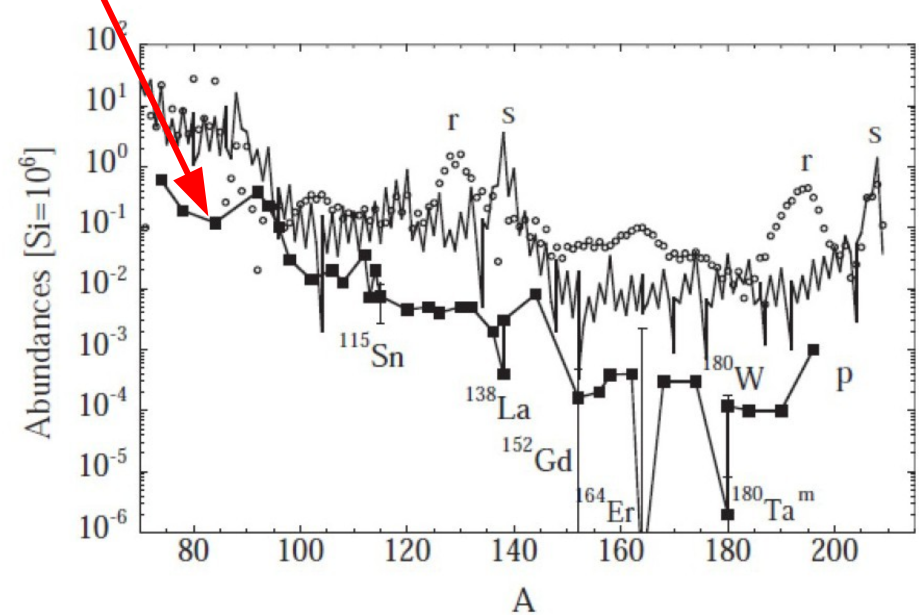
- Travaglio et al. 2011 showed how SNIa could be a relevant source for the ***p*-process isotopes** made by (γ,n), (γ,p) and (γ,α) photo-disintegrations reactions on **ASSUMED** **pre-existing heavy-element seeds distribution** formed from the neutrons released during the **He-flashes** occurring all along the accretion.



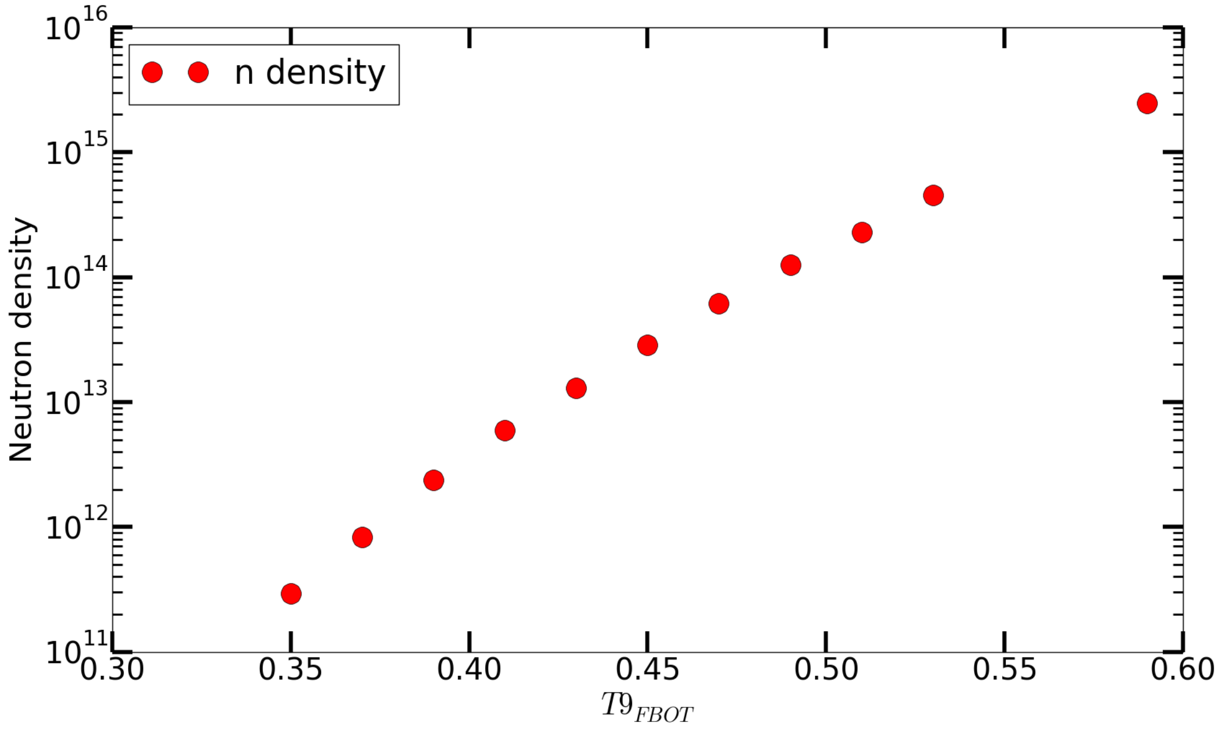
SD scenario artist's impression (from Wikipedia)



M. Arnould, S. Goriely / Physics Reports 384 (2003) 1–84



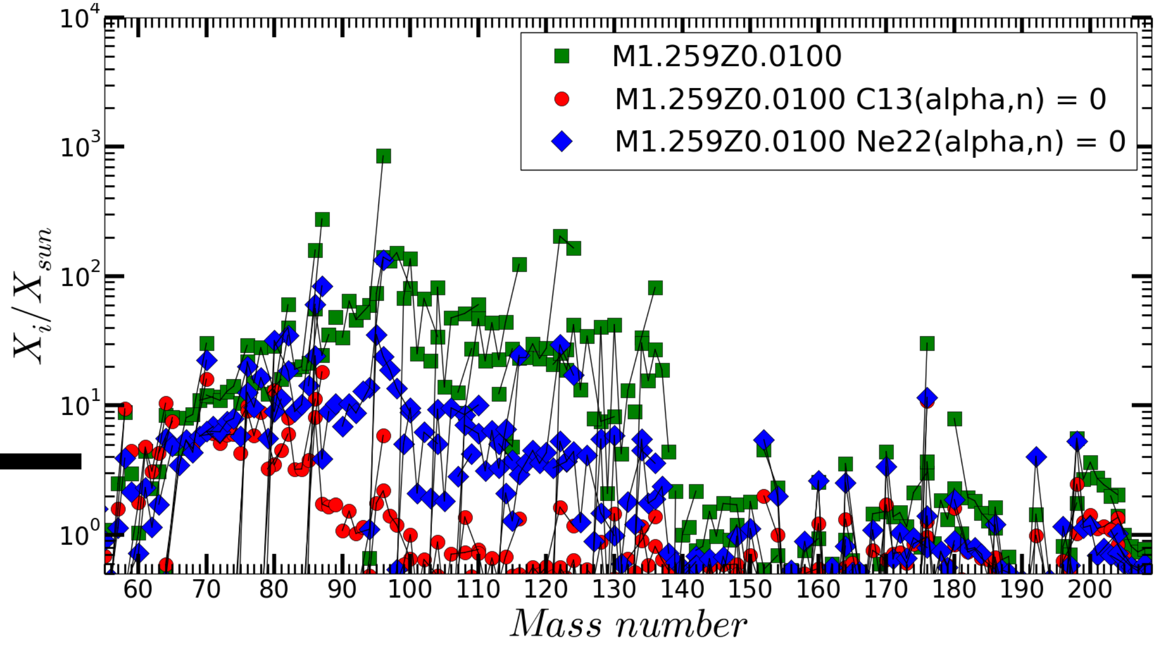
Nuclear rates tests: what is the main neutron source?



T at the bottom of the TP ranging from 0.35GK (M=0.85 Msun) to ~ 0.58 GK (M=1.376 Msun)

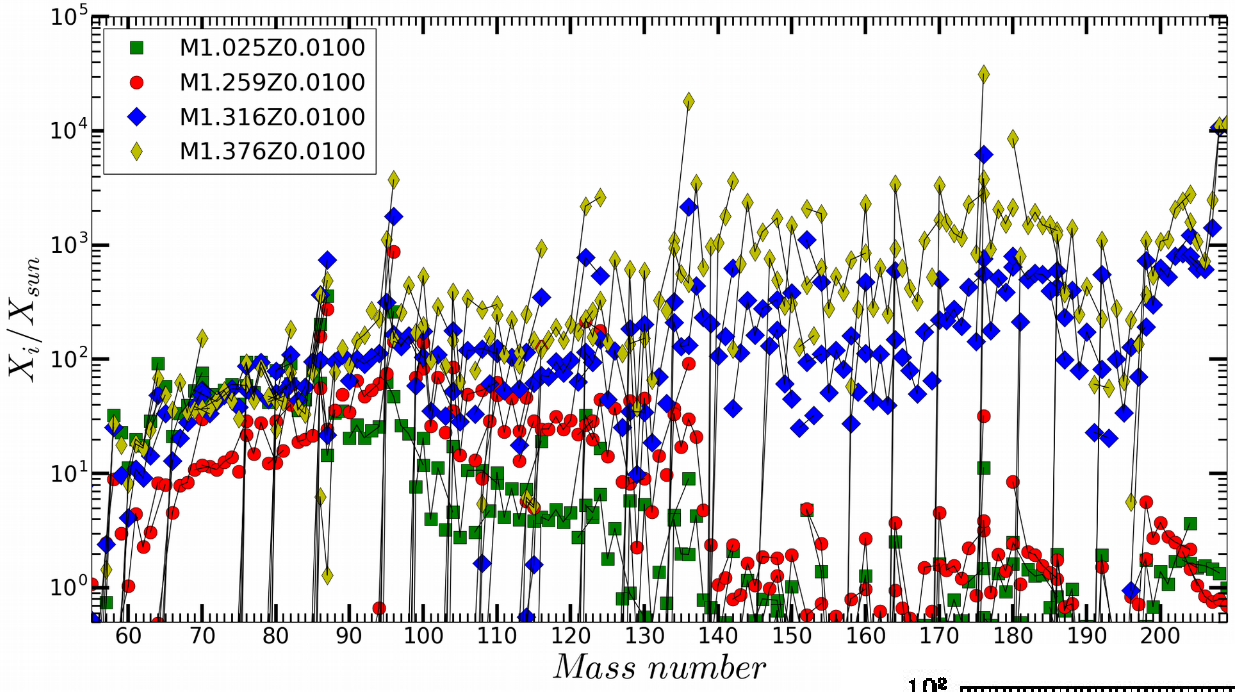
Neutron densities reaching 10^{15} n cm^{-3}

Many branching-points activated (Rb and Zr in particular)



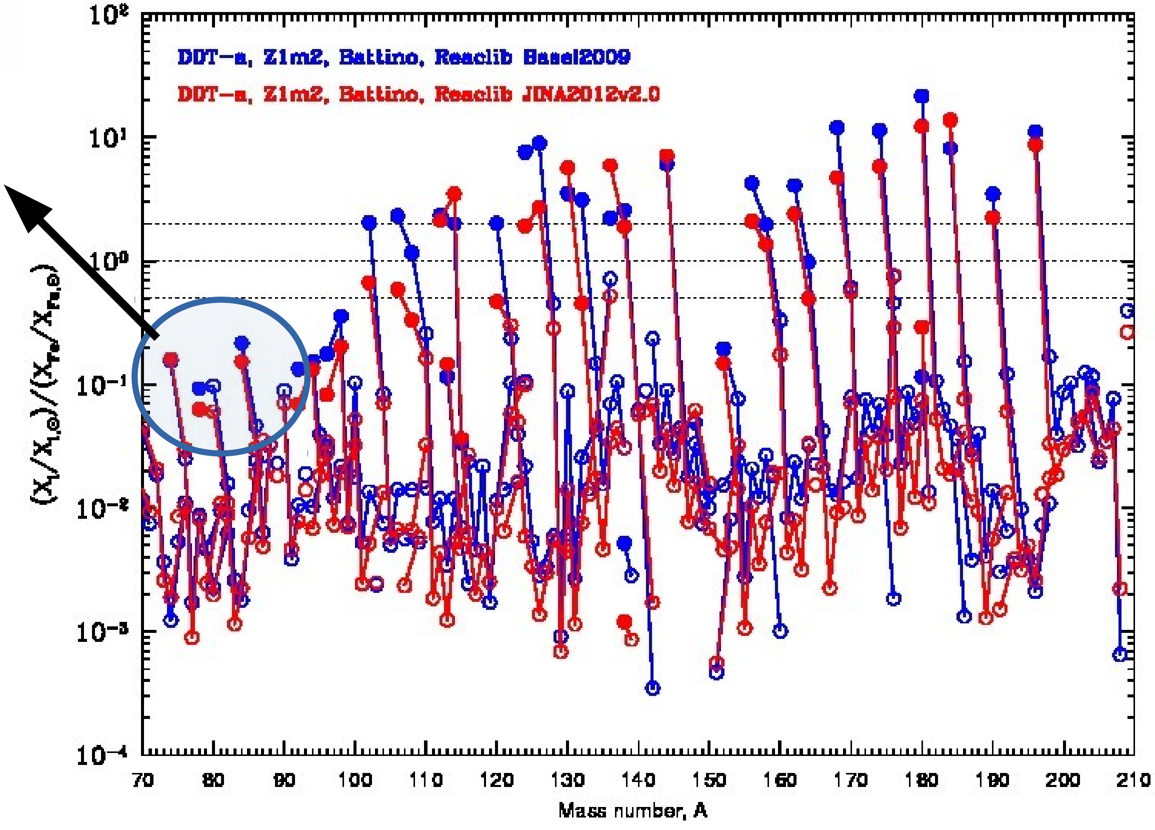
Production on the 1.26Msun and higher masses model is impacted by C13(alpha,n)O16 <u>(C13 coming from HIF events!)</u>

Results



Contribution from Type II Sne (Travaglio, Rauscher et al 2018; Rauscher et al 2018)

***^{14}N(n,p)^{14}C** may have a big impact on the seeds production, possibly favoring lighter elements and hence explosive nucleosynthesis of **^{94}Mo**???*
Tests are under way ;)



Battino et al 2018; in prep.

...about Type II Sne… **Reaction rates uncertainties impact:**

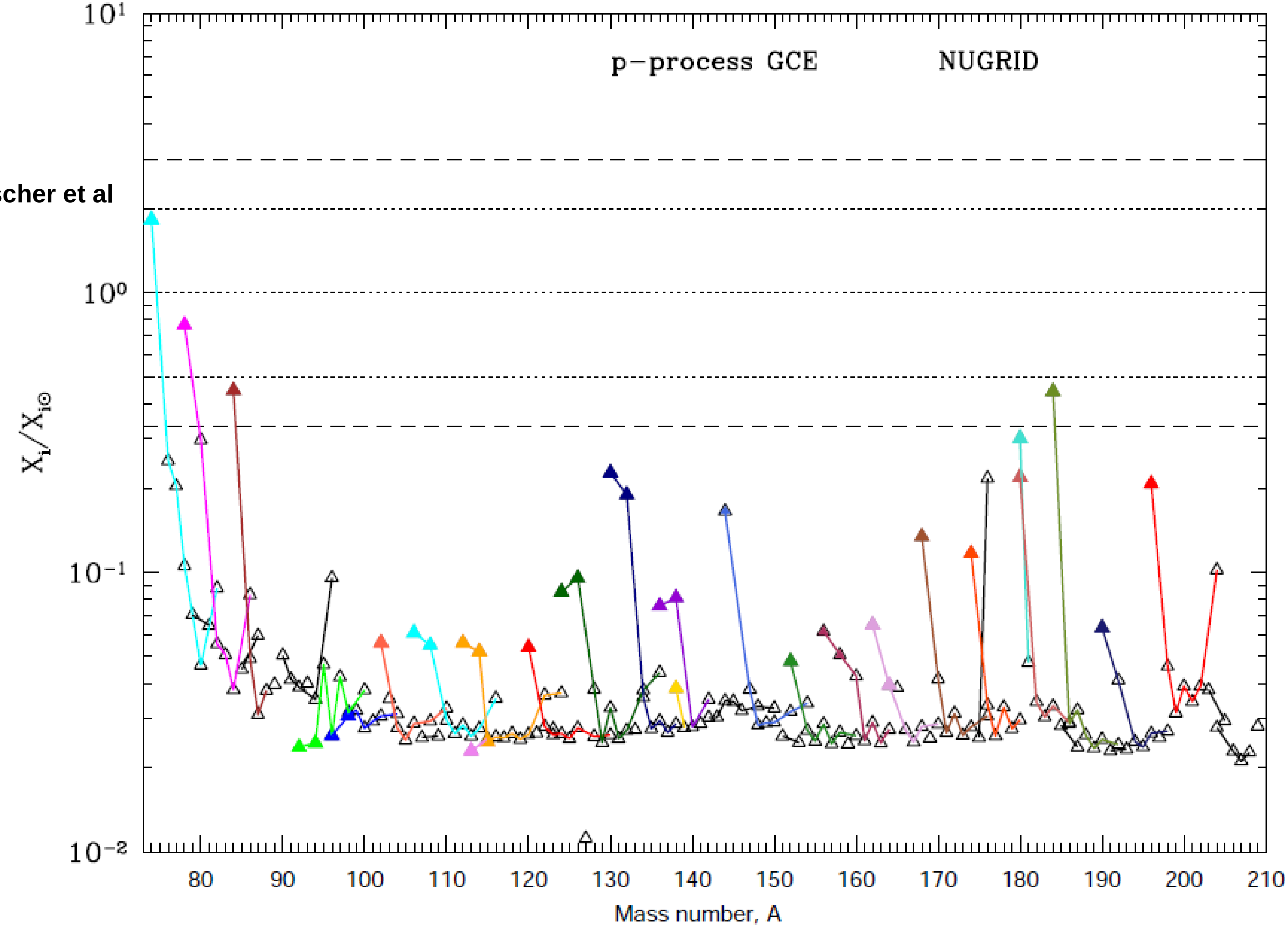
Results from Monte Carlo variations

Nuclide	$r_{\mathrm{corr},0}$	$r_{\mathrm{corr},1}$	$r_{\mathrm{corr},2}$	Key rate Level 1	Key rate Level 2	Key rate Level 3	X_0 (2 GK) capture	X_0 (3 GK) capture
^{78}Kr	−0.84			$^{77}\mathrm{Br}+\mathrm{p}\leftrightarrow\gamma+{}^{78}\mathrm{Kr}$			9.63×10^{-2}	4.44×10^{-2}
	0.34	0.87			$^{79}\mathrm{Kr}+\mathrm{n}\leftrightarrow\gamma+{}^{80}\mathrm{Kr}$		1.28×10^{-1}	7.94×10^{-2}
^{92}Mo	−0.74			$^{91}\mathrm{Nb}+\mathrm{p}\leftrightarrow\gamma+{}^{92}\mathrm{Mo}$			8.88×10^{-1}	8.24×10^{-1}
^{96}Ru	−0.73			$^{92}\mathrm{Mo}+\alpha\leftrightarrow\gamma+{}^{96}\mathrm{Ru}$			1.00	9.86×10^{-1}
	−0.43	−0.69			$^{95}\mathrm{Tc}+\mathrm{p}\leftrightarrow\gamma+{}^{96}\mathrm{Ru}$		7.64×10^{-1}	6.60×10^{-1}
^{102}Pd	−0.87			$^{101}\mathrm{Pd}+\mathrm{n}\leftrightarrow\gamma+{}^{102}\mathrm{Pd}$			5.62×10^{-1}	3.97×10^{-1}
^{112}Sn	−0.88			$^{111}\mathrm{Sn}+\mathrm{n}\leftrightarrow\gamma+{}^{112}\mathrm{Sn}$			7.79×10^{-1}	6.73×10^{-1}
^{114}Sn	−0.77			$^{113}\mathrm{Sn}+\mathrm{n}\leftrightarrow\gamma+{}^{114}\mathrm{Sn}$			1.82×10^{-1}	1.28×10^{-1}
^{120}Te	−0.64	−0.66			$^{119}\mathrm{Te}+\mathrm{n}\leftrightarrow\gamma+{}^{120}\mathrm{Te}$		2.43×10^{-1}	1.77×10^{-1}
^{124}Xe	−0.74			$^{123}\mathrm{Xe}+\mathrm{n}\leftrightarrow\gamma+{}^{124}\mathrm{Xe}$			8.25×10^{-2}	4.38×10^{-2}
^{126}Xe	−0.75			$^{125}\mathrm{Cs}+\mathrm{p}\leftrightarrow\gamma+{}^{126}\mathrm{Ba}$			1.17×10^{-1}	7.41×10^{-2}
	0.30	0.64	0.65			$^{127}\mathrm{Ba}+\mathrm{n}\leftrightarrow\gamma+{}^{128}\mathrm{Ba}$	5.78×10^{-2}	3.59×10^{-2}
^{130}Ba	−0.66			$^{129}\mathrm{Ba}+\mathrm{n}\leftrightarrow\gamma+{}^{130}\mathrm{Ba}$			5.77×10^{-2}	3.55×10^{-2}
^{132}Ba	−0.77			$^{131}\mathrm{Ba}+\mathrm{n}\leftrightarrow\gamma+{}^{132}\mathrm{Ba}$			1.07×10^{-1}	5.85×10^{-2}
^{136}Ce	−0.69			$^{135}\mathrm{Ce}+\mathrm{n}\leftrightarrow\gamma+{}^{136}\mathrm{Ce}$			1.86×10^{-1}	8.94×10^{-2}
	0.31	0.72			$^{139}\mathrm{Ce}+\mathrm{n}\leftrightarrow\gamma+{}^{140}\mathrm{Ce}$		8.56×10^{-1}	6.09×10^{-1}
^{138}Ce	−0.66			$^{137}\mathrm{Ce}+\mathrm{n}\leftrightarrow\gamma+{}^{138}\mathrm{Ce}$			4.16×10^{-1}	2.54×10^{-1}
	−0.16	−0.19	−0.66			$^{136}\mathrm{Ce}+\mathrm{n}\leftrightarrow\gamma+{}^{137}\mathrm{Ce}$	7.57×10^{-1}	4.70×10^{-1}
^{144}Sm	0.70			$^{145}\mathrm{Eu}+\mathrm{p}\leftrightarrow\gamma+{}^{146}\mathrm{Gd}$			8.06×10^{-1}	6.02×10^{-1}
^{152}Gd	−0.74			$^{151}\mathrm{Gd}+\mathrm{n}\leftrightarrow\gamma+{}^{152}\mathrm{Gd}$			6.18×10^{-1}	3.87×10^{-1}
	0.43	0.76			$^{153}\mathrm{Gd}+\mathrm{n}\leftrightarrow\gamma+{}^{154}\mathrm{Gd}$		5.38×10^{-2}	2.78×10^{-2}
	−0.14	−0.26	−0.73			$^{148}\mathrm{Sm}+\alpha\leftrightarrow\gamma+{}^{152}\mathrm{Gd}$	8.14×10^{-1}	5.22×10^{-1}
^{164}Er	−0.78			$^{160}\mathrm{Er}+\alpha\leftrightarrow\gamma+{}^{164}\mathrm{Yb}$			2.13×10^{-1}	1.24×10^{-1}
^{180}W	−0.83			$^{176}\mathrm{W}+\alpha\leftrightarrow\gamma+{}^{180}\mathrm{Os}$			1.83×10^{-1}	1.04×10^{-1}
	−0.19	−0.60	−0.68			$^{179}\mathrm{Os}+\mathrm{n}\leftrightarrow\gamma+{}^{180}\mathrm{Os}$	4.89×10^{-2}	2.49×10^{-2}
^{196}Hg	−0.83			$^{195}\mathrm{Pb}+\mathrm{n}\leftrightarrow\gamma+{}^{196}\mathrm{Pb}$			2.97×10^{-1}	1.89×10^{-1}
	0.31	0.70			$^{197}\mathrm{Pb}+\mathrm{n}\leftrightarrow\gamma+{}^{198}\mathrm{Pb}$		3.28×10^{-1}	2.39×10^{-1}
	0.17	0.35	0.67			$^{199}\mathrm{Pb}+\mathrm{n}\leftrightarrow\gamma+{}^{200}\mathrm{Pb}$	6.37×10^{-1}	3.47×10^{-1}
^{92}Nb	0.76			$^{90}\mathrm{Zr}+\mathrm{p}\leftrightarrow\gamma+{}^{91}\mathrm{Nb}$			1.00	9.95×10^{-1}
^{146}Sm	−0.57	−0.75			$^{144}\mathrm{Sm}+\alpha\leftrightarrow\gamma+{}^{148}\mathrm{Gd}$		9.99×10^{-1}	9.65×10^{-1}
	0.34	0.44	0.79			$^{147}\mathrm{Gd}+\mathrm{n}\leftrightarrow\gamma+{}^{148}\mathrm{Gd}$	9.92×10^{-1}	9.28×10^{-1}

Rauscher et al 2016

...but here’s what happens with GCE!!

Travaglio, Rauscher et al
2018



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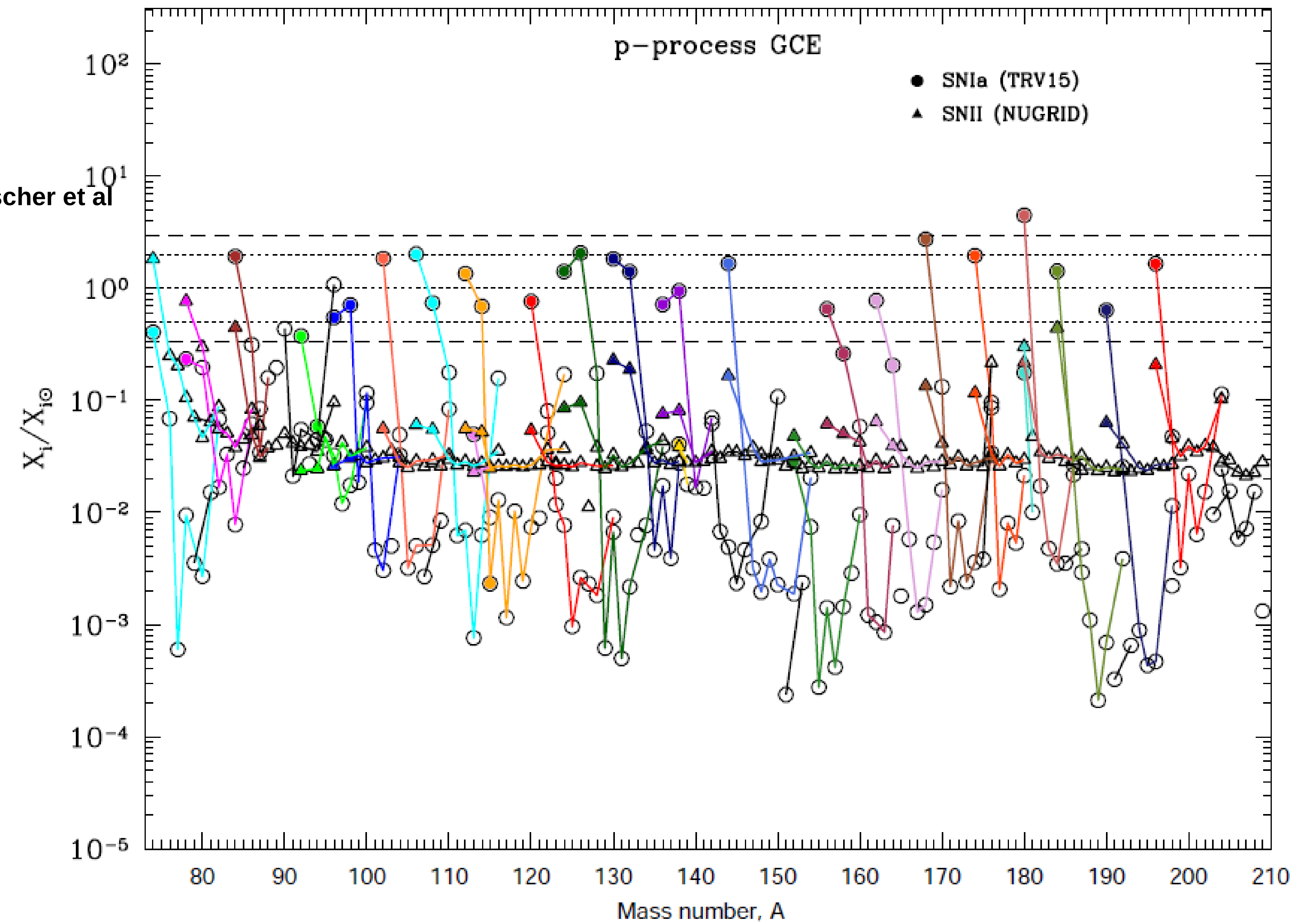


Conclusions and take-home messages...

- The production of the p-isotopes that we observe today in the solar system is still uncertain.
- Two main sites: Type II and Type Ia supernovae. **The first can only contribute to the A<92 region (Results from GCE)**
- KEEP THIS IN MIND WHEN MOTIVATING/TESTING A REACTION-RATE MEASUREMENT!! ;)
- I presented for the first time a heavy-element distribution calculated from realistic simulations of WD-accretion phase (**Battino et al 2018; in prep.**), this and GCE confirm that Type Ia SN are still essential to explain the production of p-nuclei in the whole mass range. **Main assumption: single-degenerate scenario actually works!!!**

Grazie mille per la vostra attenzione!!!

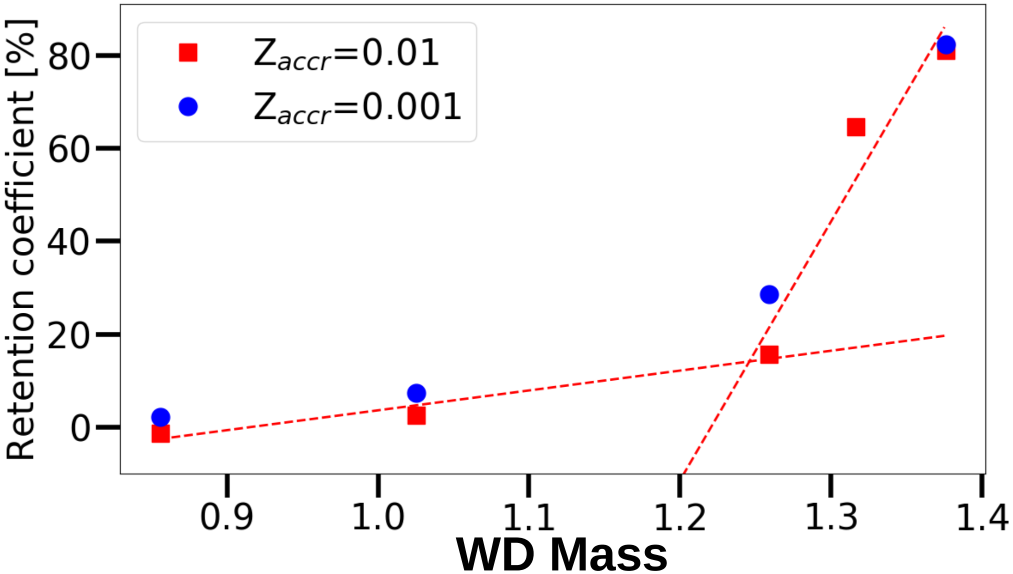
Mersì per la vostr atensiun!!!

Thank you so much for your kind attention!!!

Vielen Dank für Ihre Aufmerksamkeit!!!

Gratias vobis ago!!!

Can we reach the Chandrasekhar mass?



- The maximum CO-core mass in NON-rotating AGB stars cannot exceed **~1.1 Msun**… this fact and the lack of He II lines detection from elliptical galaxies seems to indicate that the SD-channel for SNe is highly unlikely (Woods+ 2013, Denissenkov+ 2017)

- Low retention-coefficient values for Mwd < 1 Msun in agreement with Denissenkov et al. 2017, the resulting minimum WD mass required to reach the Chandrasekhar is **1.2 Msun** at <u>solar metallicity</u> (p-process seeds are <u>secondary</u>!!!). A similar and very interesting work on He-accreting WDs has been done by Piersanti et al. 2014.

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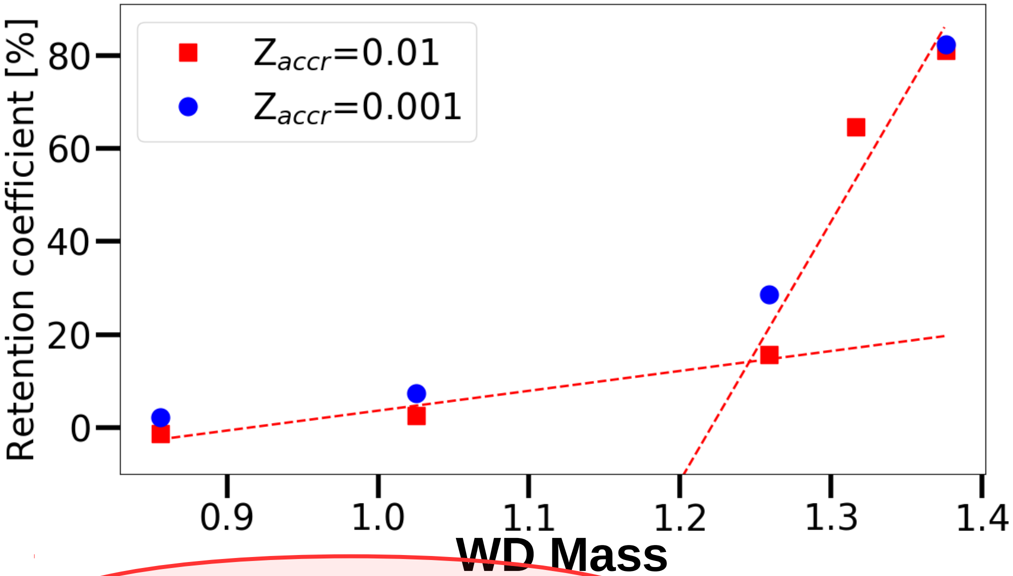

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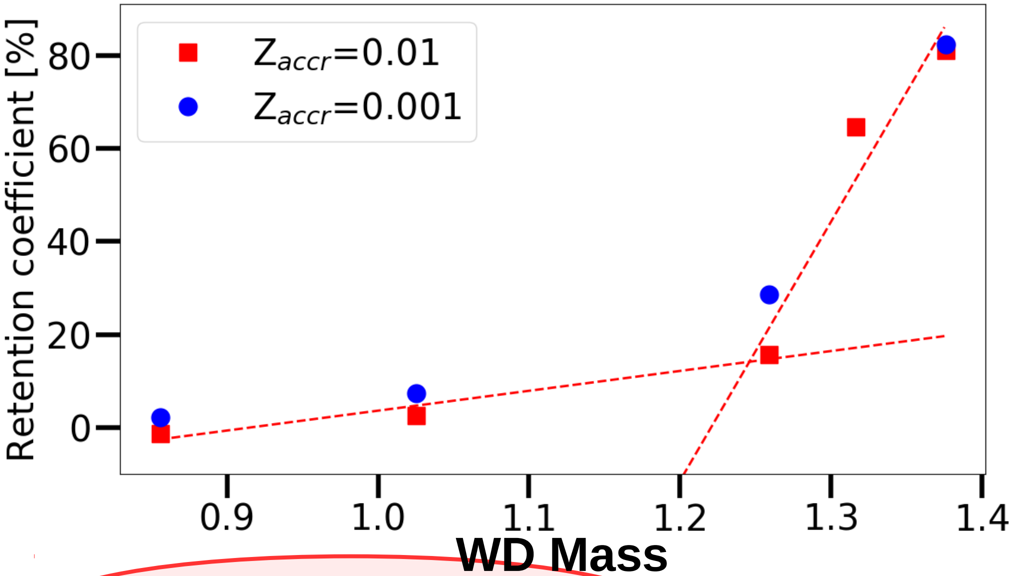

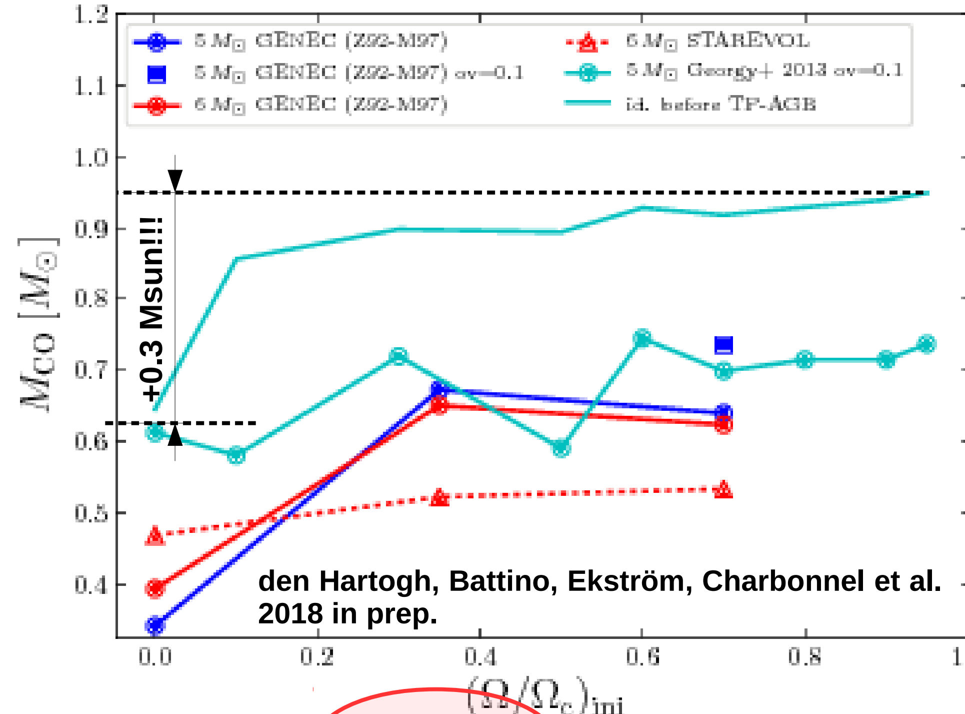

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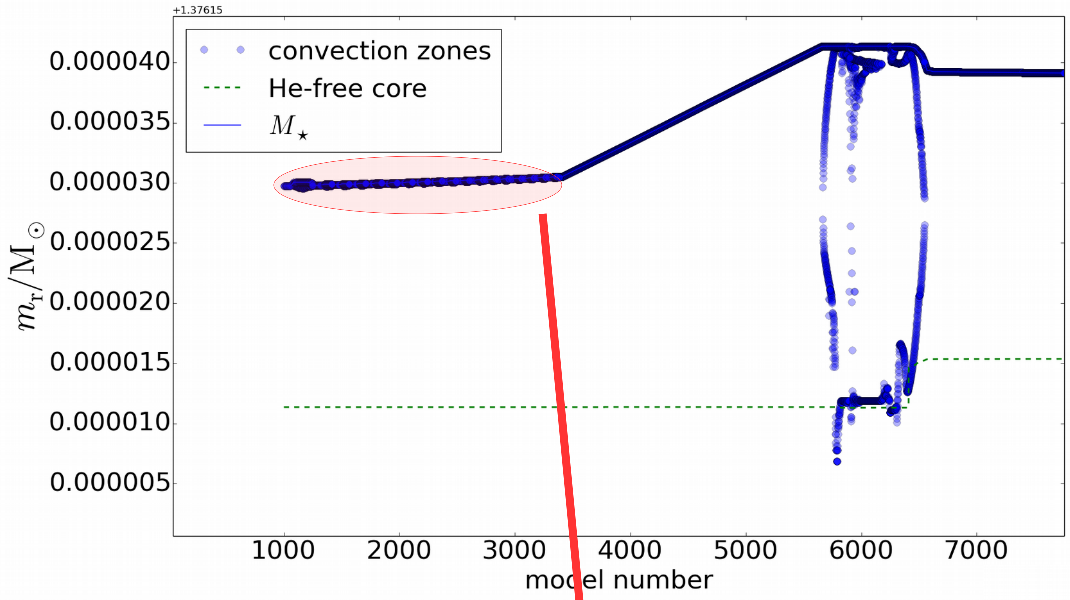
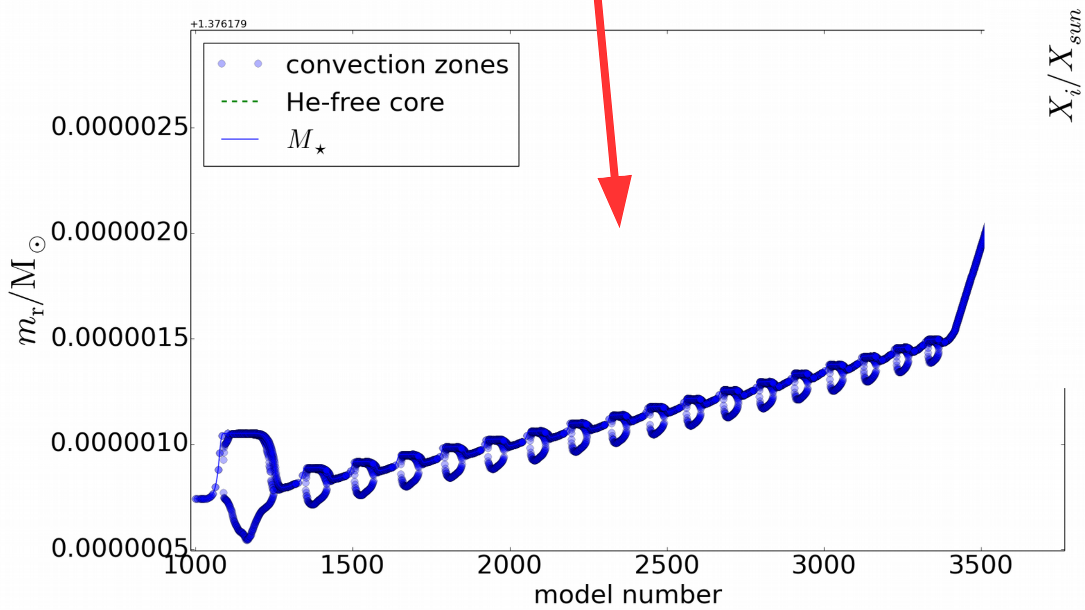
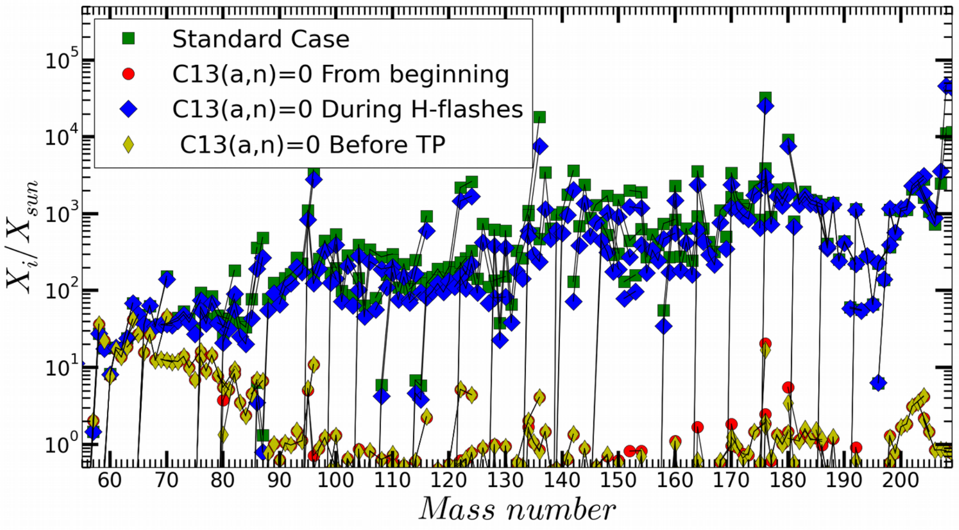
- **!!!** On the other hand, Dominguez et al. 1996 showed that in rotating massive AGB stars the final CO-core mass is markedly increased (**in the range 1.1-1.4 Msun!!**). Stellar models with MESA, GENEC and STAREVOL stellar codes including self-consistent treatment of stellar rotation are under analysis: preliminary results seems to confirm Dominguez et al. results!! (den Hartogh, Battino, Ekström, Charbonnel et al. 2018 in prep.)**!!!**

1.38 Msun Model: A peculiar case



- H-flashes temperature = 3 T8
- Interpulse temperature= 1.15 T8
- Everything happens in 10^-7 Msun





Popular Scenarios

- γ-process in O/Ne shell of massive stars

  combination of p-captures and γ-process

  additional ν-process for ^{138}La and ^{180}Ta

- Explosion of mass-accreting white dwarf

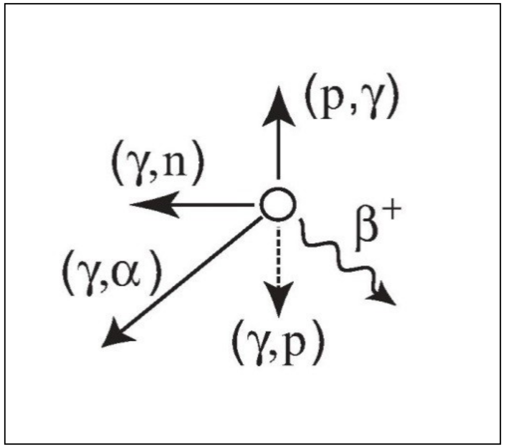
  "regular" SN Ia and/or sub-Chandrasekhar WD

  combination of p-captures and γ-process (and np-process)

- Extremely p-rich scenarios: rp-process, νp-process

  problem: detailed modelling, ejection, Nb/Mo ratio in meteorites puts tight constraint

"p-Process"



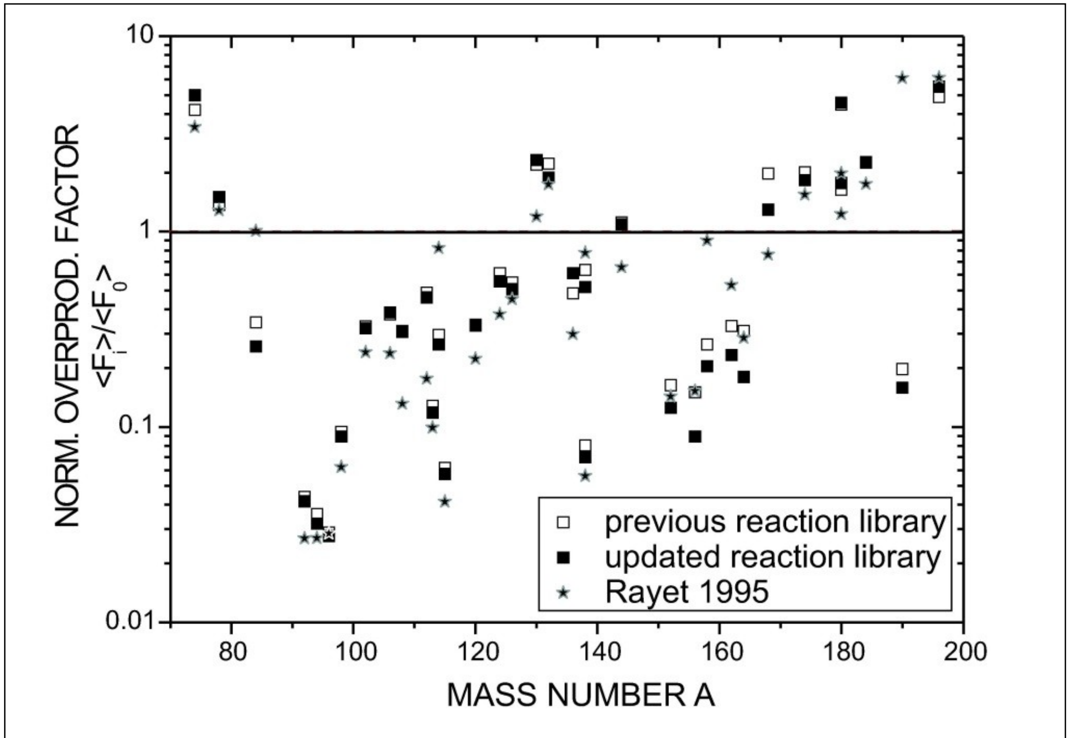
- Def.: "What makes the p-Nuclei"
  - One or several "manifestations"?

- Possibilities to get to the proton-rich side:
  - From "below": proton captures
    - hindered by Coulomb barrier, competition with photodisintegration
    - high proton densities required
  - From "above": (γ,p), (γ,α), decay
  - From neutron-richer nuclei: (γ,n)
    - favored in photodisintegration of near-stable nuclei

- What can be varied?
  - Proton abundance/density
  - Explosive conditions (temperature-density history)
  - Seed nuclei! (secondary process)

p-Production in Massive Stars

- Site: Explosive O-shell burning in core collapse SN
- Seed: s- and r-nuclides, either already existing when star formed or produced (weak s-process) during stellar life
- Underproduction of Mo-Ru region always found (no sufficient seed abundance to disintegrate)



Dillmann, Rauscher et al 2008
KADONIS v0.2