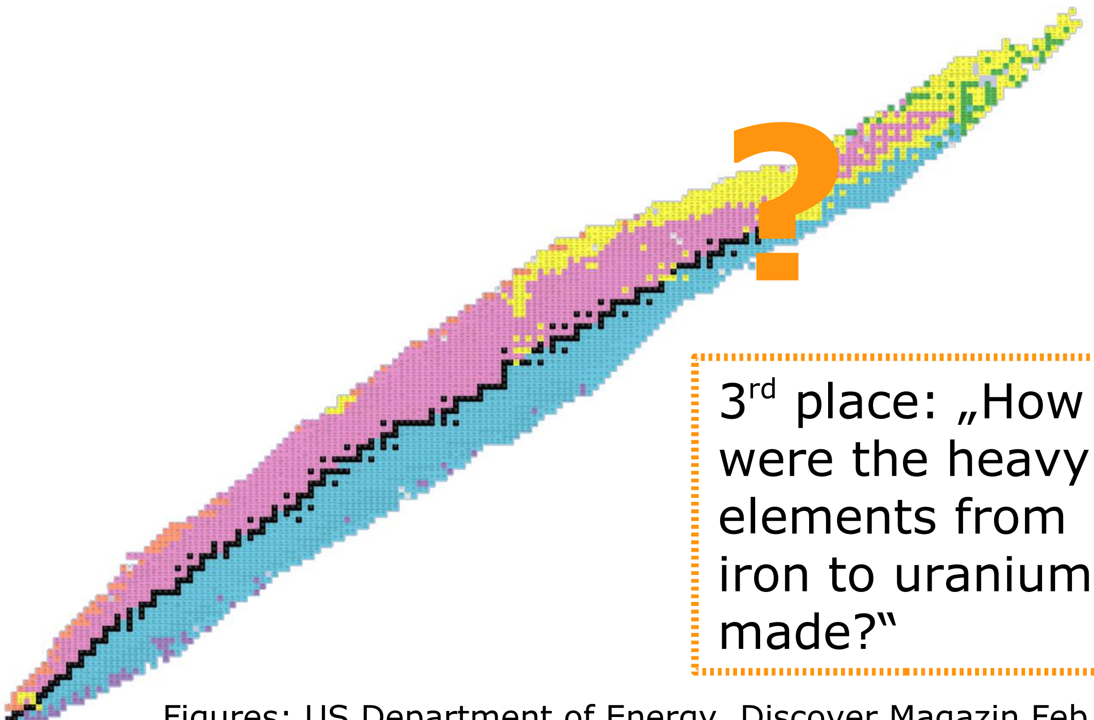
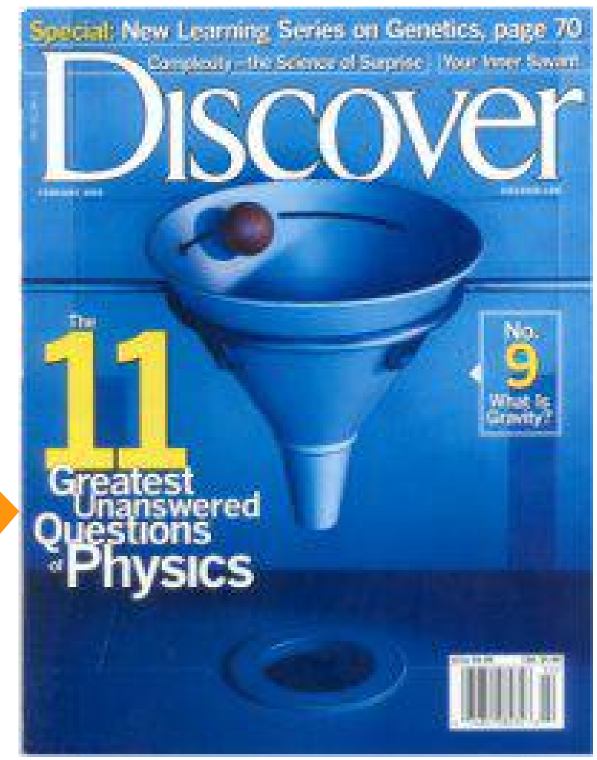
# Neutron capture:
# The r- and s-process

Seminar talk of Alexander Blecher



3rd place: „How were the heavy elements from iron to uranium made?"




Figures: US Department of Energy, Discover Magazin Feb. 2002

# Content of seminar talk

- Motivation: How are heavy isotopes made?
- Review: Nuclear chart and stability of isotopes
- Overview: r- and s-process
- Details of r-process
- Details of s-process
- Outlook for nuclear physics and astrophysics
- Summary of seminar talk

# Motivation: How are heavy isotopes made?

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- Creation of trans-iron isotopes (A>60) an exothermic reaction.

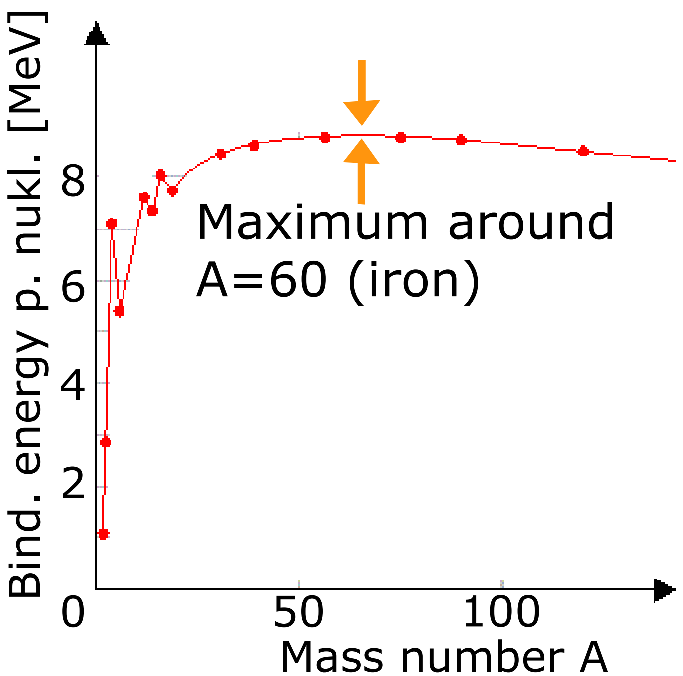
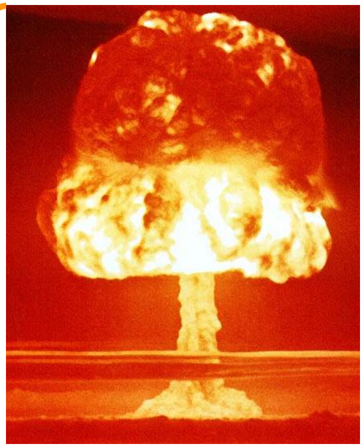


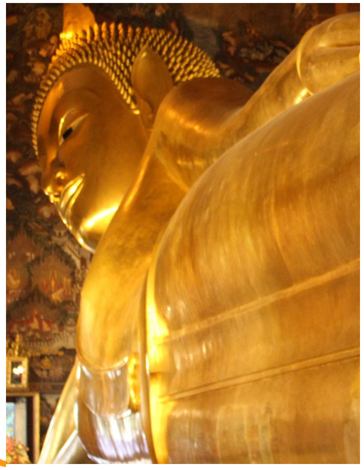

Figure: Leifi Physik, http://www.leifiphysik.de/kern-teilchenphysik/kernreaktionen

?

~~Nuclear fusion~~

Figure: NASA

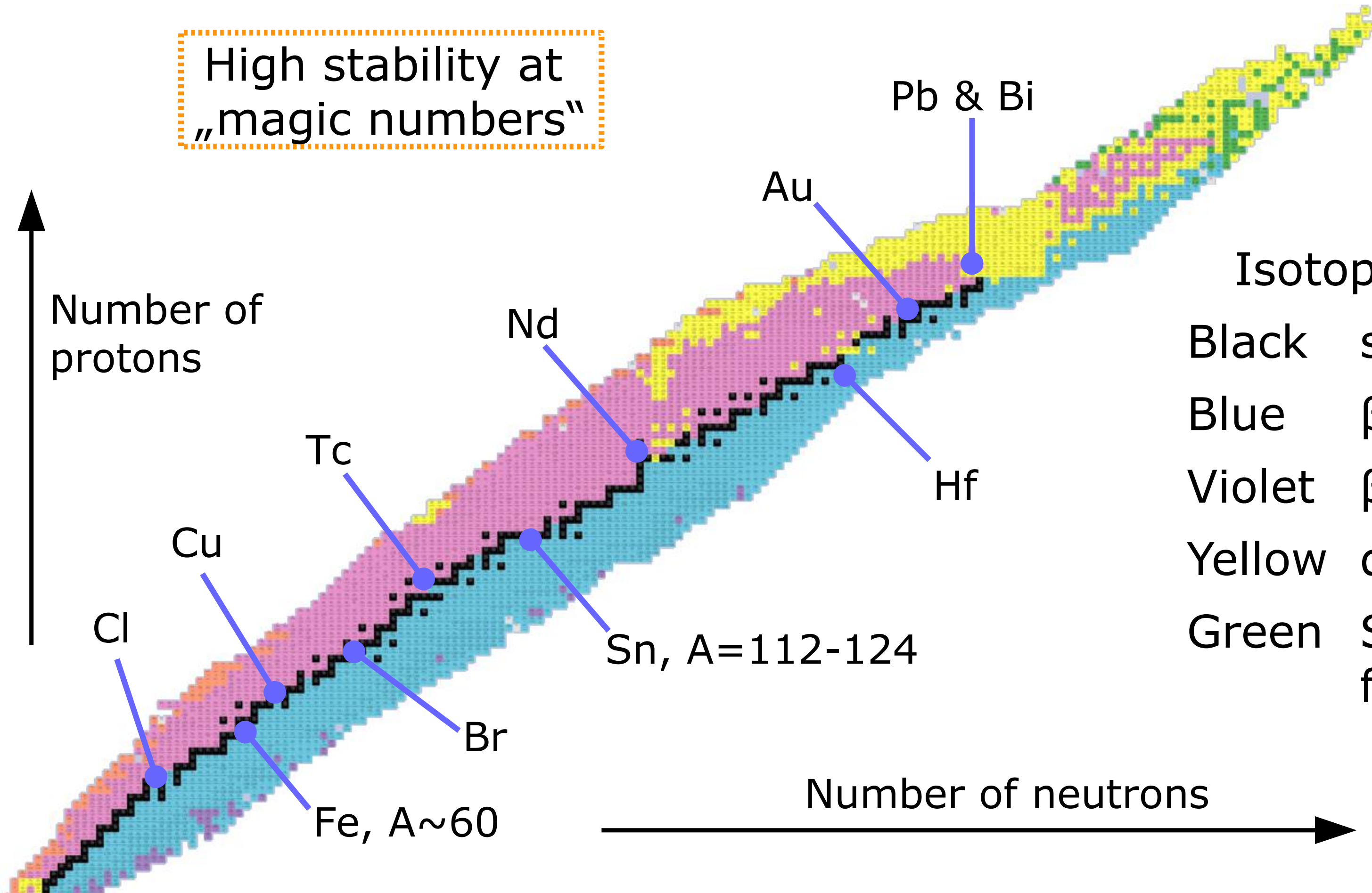




Illustrative pictures for Uranium (Z=92) and Gold (Z=79).

Figures, above: Operation Castle, event Romeo, US Department of Energy; bottom: Wat Pho, Thailand, Alexander Blecher.

# Review: Nuclear chart and stability of isotopes




Isotopes in chart

| | |
|---|---|
| Black | stable |
| Blue | $\beta^-$ decay |
| Violet | $\beta^+$ decay |
| Yellow | α decay |
| Green | Spontaneous fission |

Figure: Map of nuclides, National Nuclear Data Center, from Nudat2-Database, US Department of Energy

# Overview: r- and s-process

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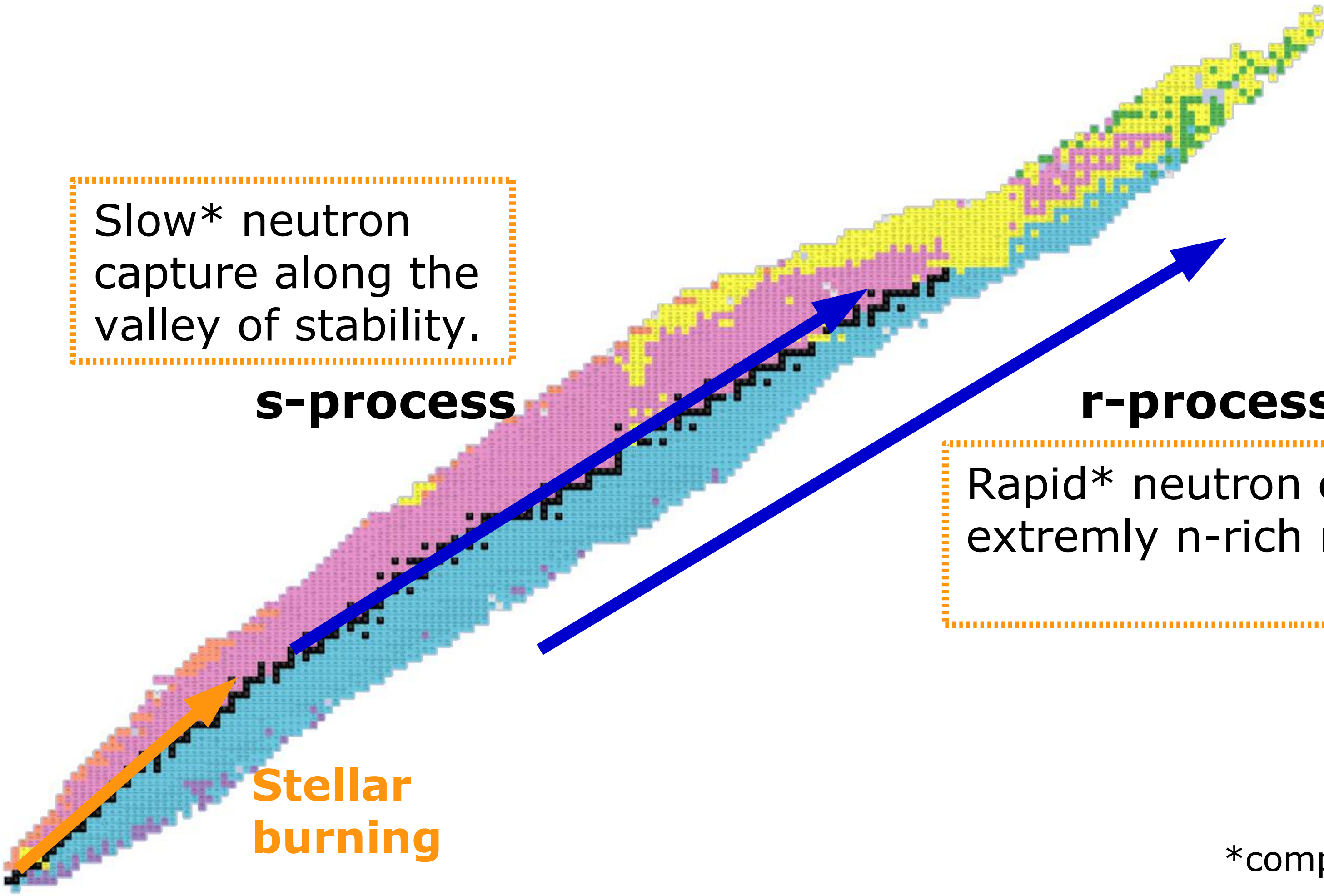


*compared to $\beta^-$ decay

# Overview: r- and s-process

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| | **R**apid process | **S**low process |
|---|---|---|
| Process overview | Given on the slide before | |
| Characteristic | $\tau_\beta \ll \tau_{(n,\gamma)}$ | $\tau_\beta \gg \tau_{(n,\gamma)}$ |
| Conditions | High neutron density, fast expansion<br>T~1-2 GK and neutron density $N_n \sim 10^{20}$-$10^{28}$ cm$^{-3}$ | Low but steady neutron flow<br>T~0.30 GK and neutron density $N_n \sim 10^{7}$ cm$^{-3}$ |
| Astrosite | Supernovae and mergers of neutron stars? | Typical: AGB star with ~2 solar masses |

# End of life cycle: AGB stars

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- End of life cycle: Star's core hydrogen is depleted; there: He burning.
- Star is extending into a red giant („asymptotic giant branch“, AGB).
- Now: Free neutrons of e.g. „C-13 pocket“: $^{13}C + {}^{4}He \rightarrow {}^{16}O + n$

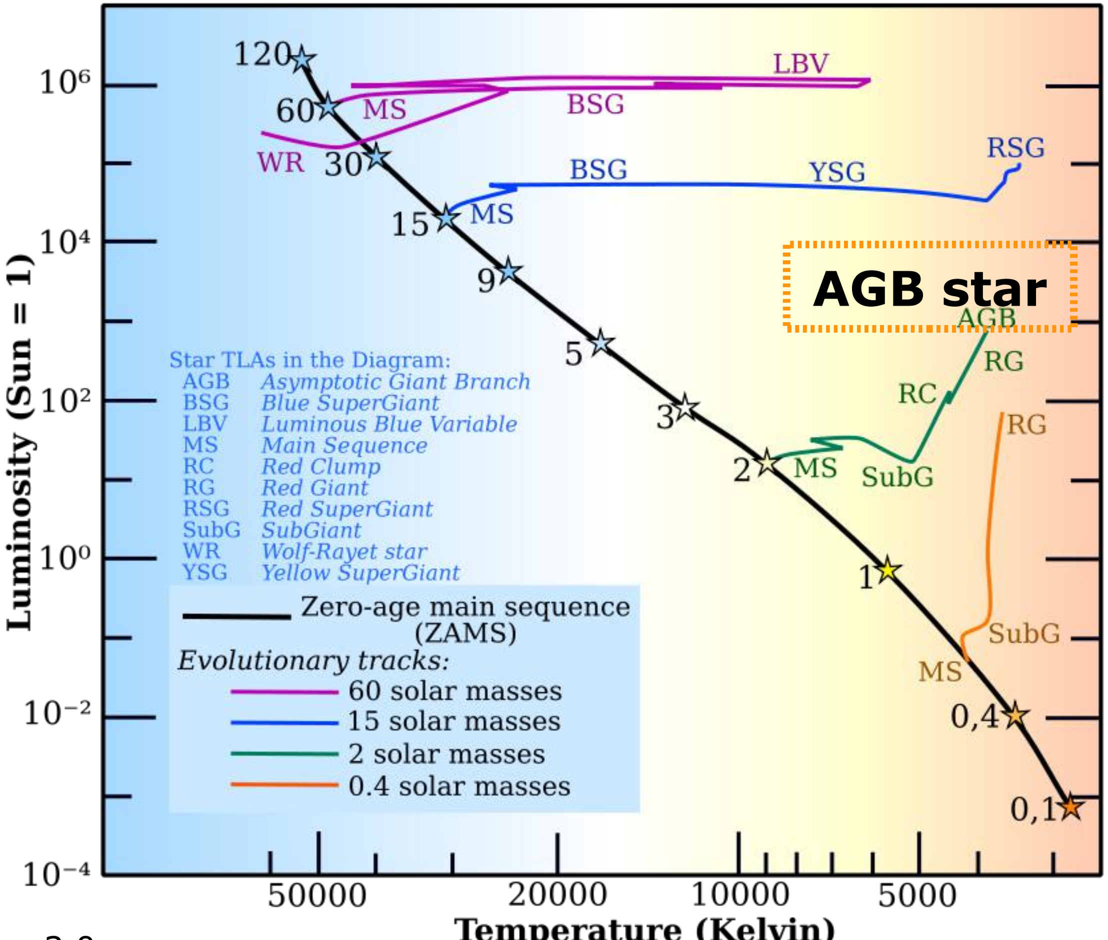


Figure: Sample stellar evolutionary tracks,
User: Rursus, Wikimedia Commons, CC-by-sa 3.0

# Neutron capture reaction: s-process

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- Additional neutron is captured → $\beta^-$ decay.
- This neutron capture process takes thousands of years.
- Abundance ~1/σ(n,γ); heavy isotopes are rare.
- „Branchings": either $\beta^-$ decay or another capture; subject of research.

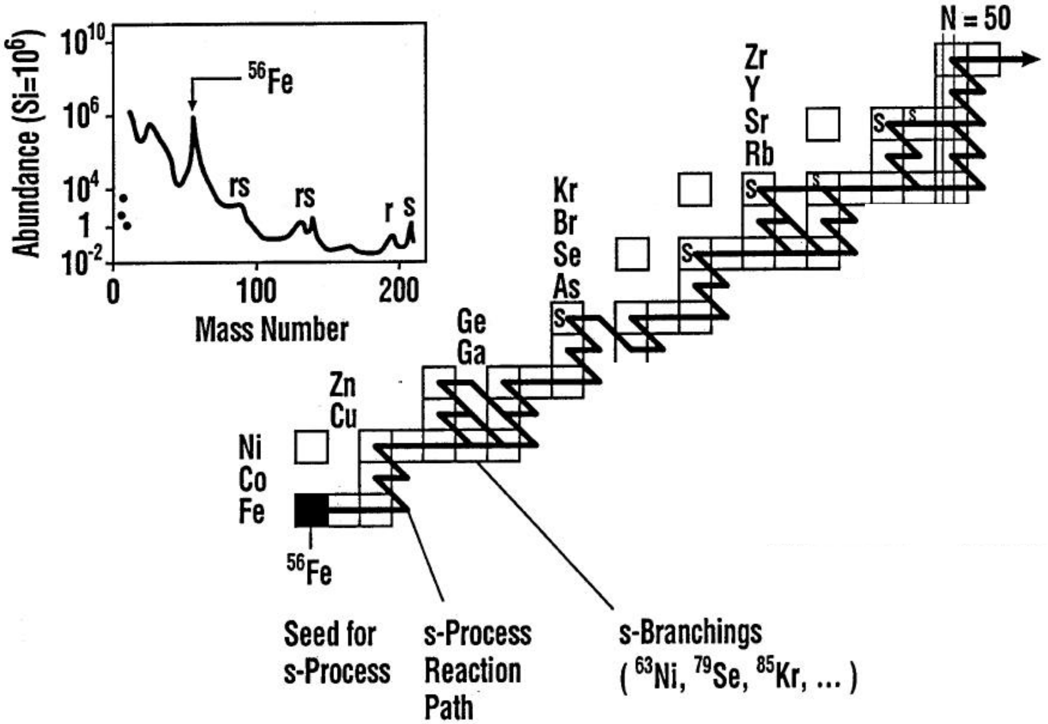


Figure: F. Käppeler et al., The s process: Nuclear physics, stellar models, and observations, Rev. Mod. Phys., Vol. 83, No. 1, 158—186 (2011), DOI: 10.1103/RevModPhys.83.157

# Evidence of s-process

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- Through internal convection of star the trans-iron isotopes are visible for spectroscopy.
- First evidence: Technetium ($t_{½}$~$10^6$ a) was observed in red giants in 1952 by P. Merrill; proof for neutron capture process.

Original article

SPECTROSCOPIC OBSERVATIONS OF STARS OF CLASS S


PAUL W. MERRILL
MOUNT WILSON AND PALOMAR OBSERVATORIES
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CALIFORNIA INSTITUTE OF TECHNOLOGY



*Received February 27, 1952*


ABSTRACT


This paper presents a brief survey of S-type spectra based largely on spectrograms with dispersion 9 A/mm of eight stars obtained by I. S. Bowen with the 200-inch telescope. The intensities of several groups of absorption lines and bands and of the more important emission lines are compared in various stars. Radial velocities from both bright and dark lines and a supplementary list of absorption lines identified in the green region are included. The remarkable behavior of certain bright lines of *V* I and of *Cr* I in the spectrum of R Cygni is described.



Published in Astrophys. J., 116, 21 (1952), doi:10.1086/145589

# „End“ of s-process

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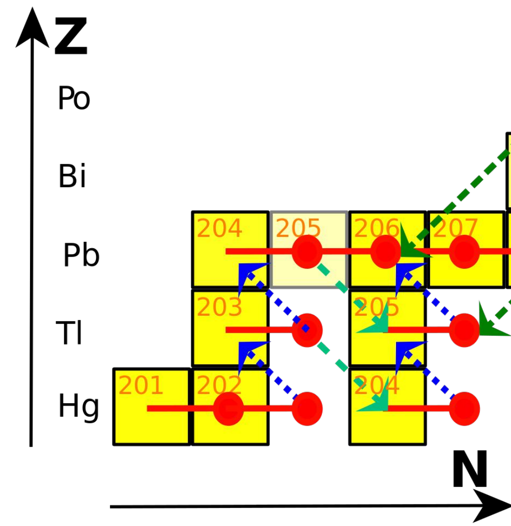
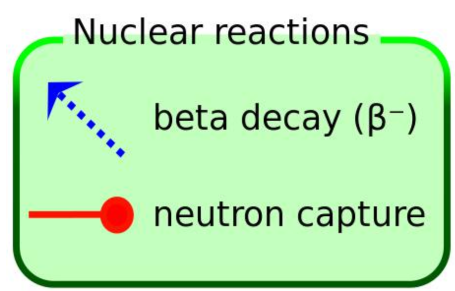
- s-process ends at A=210 with a α decay.
- Polonium is heaviest isotopes by s-process.

| | | | |
|---|---|---|---|
| $^{209}Bi + n$ | → | $^{210}Bi + \gamma$ | (neutron capture) |
| $^{210}Bi$ | → | $^{210}Po + e^-$ | ($\beta^-$ decay) |
| $^{210}Po$ | → | $^{206}Pb + {}^{4}He$ | (α decay) |
| $^{206}Pb + n$ | → | $^{207}Pb + \gamma$ | (neutron capt., #1) |
| $^{207}Pb + n$ | → | $^{208}Pb + \gamma$ | (neutron capt., #2) |
| $^{208}Pb + n$ | → | $^{209}Pb + \gamma$ | (neutron capt., #3) |
| $^{209}Pb$ | → | $^{209}Bi + e^-$ | ($\beta^-$ decay) |




Figures: (top right) S-R-processes-atomic-mass-201-to-210.svg, User: R8R Gtrs, Wikimedia Commons, public domain, (bottom right) S-process-elem-Ag-to-Sb.svg, User: Rursus, Wikimedia Commons, CC-by-sa 3.0

# s-process not the only process for trans-iron isotopes (1/3)

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1.) s-process cannot create elements like Uranium.

2.) Some observed peaks do not agree with mass spectrum.

3.) Some oberserved neutron rich isotopes cannot be created by this process.

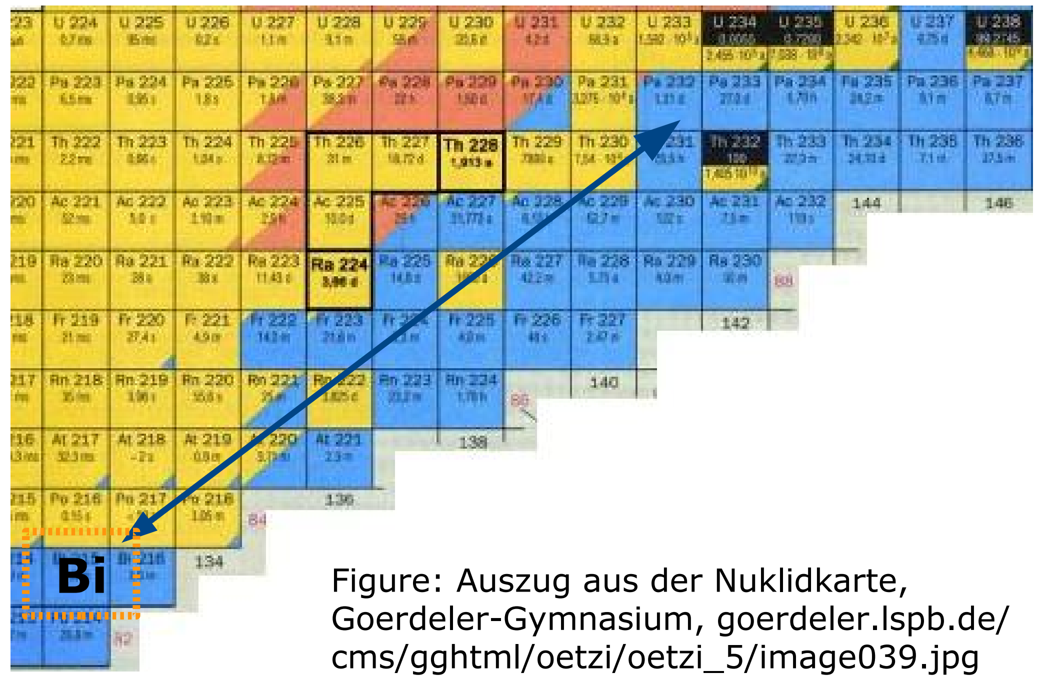


Figure: Auszug aus der Nuklidkarte, Goerdeler-Gymnasium, goerdeler.lspb.de/cms/gghtml/oetzi/oetzi_5/image039.jpg

# s-process not the only process for trans-iron isotopes (2/3)

1.) s-process cannot create elements like Uranium.
2.) Some observed peaks do not agree with mass spectrum.
3.) Some oberserved neutron rich isotopes cannot be created by this process.

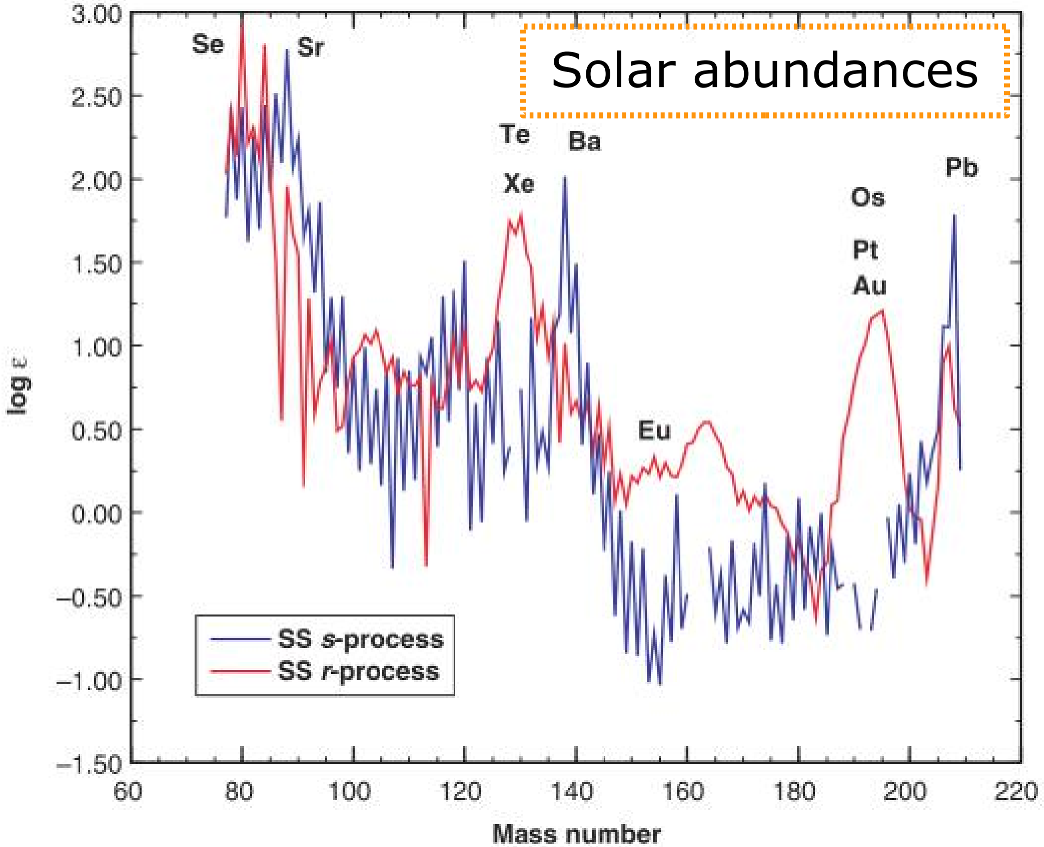


Figure: The breakdown of sun's n-capture isotopic abundances into r- and s-process components; from: C. Sneden & J.J. Cowan, doi: 10.1126/science.1077506

# s-process not the only process for trans-iron isotopes (3/3)

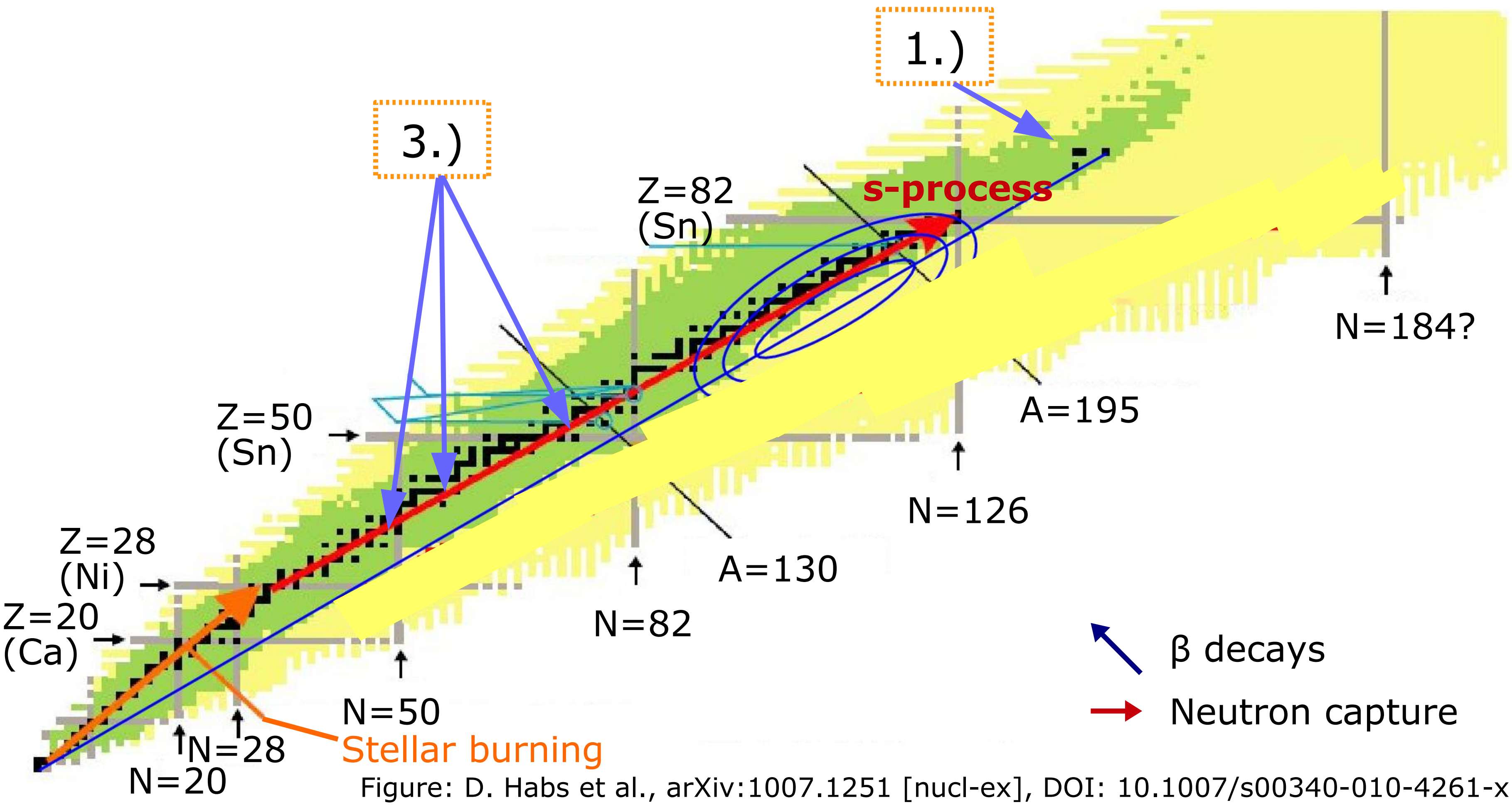


Figure: D. Habs et al., arXiv:1007.1251 [nucl-ex], DOI: 10.1007/s00340-010-4261-x

# Introduction: Rapid neutron capture

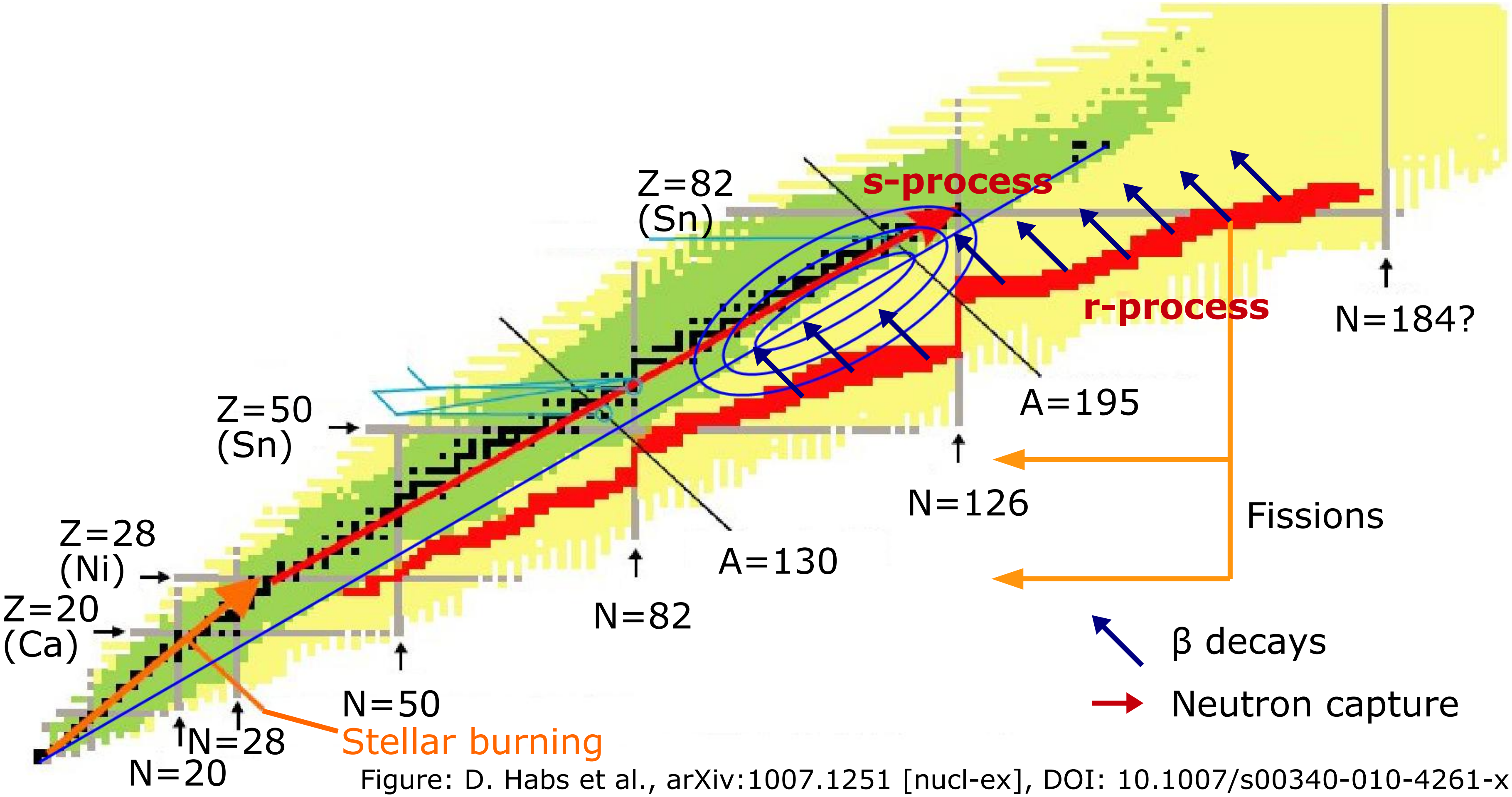


Figure: D. Habs et al., arXiv:1007.1251 [nucl-ex], DOI: 10.1007/s00340-010-4261-x

# Physical limits of r-process

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The process is limited by the physical circumstances:

- Limit where Q value of new neutrons is zero. Then: Not possible to add neutron to nuclei (→ neutron drip line).
- With increasing mass number, spontaneous or neutron induced fissions becomes more likely. It is assumed that this happens around A=260 (Cu/Rf).

Q value
$$Q = (m_{Initial} - m_{Final})c^2$$

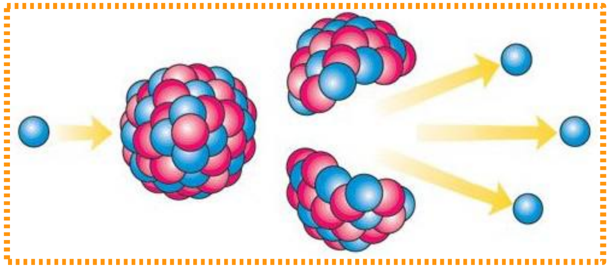

Figure: US Department of Energy, retrieved via e-education.psu.edu/eme444/node/264

# Where r-process occurs

- Basically: Necessary conditions known; place in universe is subject of research.
- Two most likely occurrences – indicated by simulations:
- In core-collapse supernovae.
- Mergers of two neutron stars or a neutron star with a black hole.

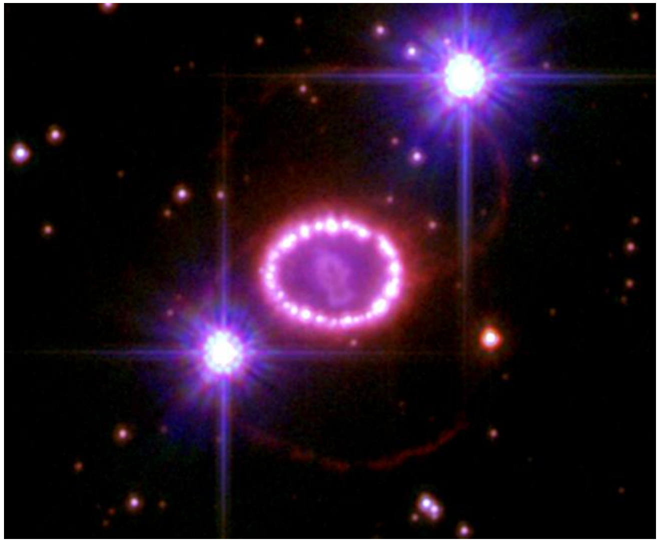

Figure: Supernovaeu, SN 1987A, NASA

Detection through gravitional waves?

# Overview: Creation of isotopes by neutron capture process

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- Isotopes can be created by r- or s-process or both processes.
- Identification of an isotope indicates creation by e.g. r- or s-process.

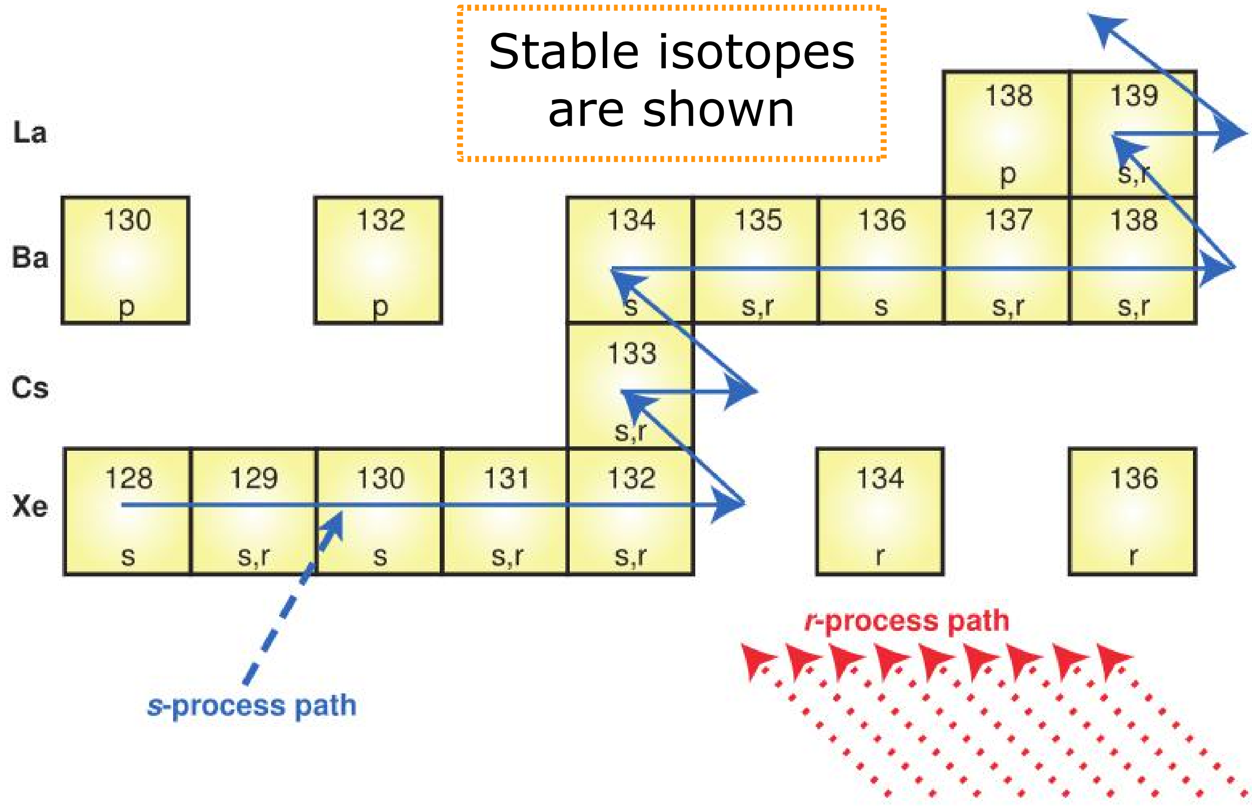


Figure: Isotopes built by r- and s-process; only the stable isotopes are shown; from: C. Sneden & J.J. Cowan, doi: 10.1126/science.1077506

# Outlook for nuclear physics & astrophysics

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Challenges in modern research – especially for r-process:

**Nuclear physics**

- More physical knowledge for better simulations, e.g.: $\sigma(n)$, $\tau_\beta$, masses, Q value.
- Improvement of mass modells and reducing of their uncertainties.

**Astrophysics**

- Observation and simulation of supernovae, mergers and abundances.
- „Chemical evolution" and metallicity of old stars.

# Outlook for nuclear physics & astrophysics: Unkown neutron-rich isotopes

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Huge gap between experimental known isotopes (dark green) and r-process path (purple path).

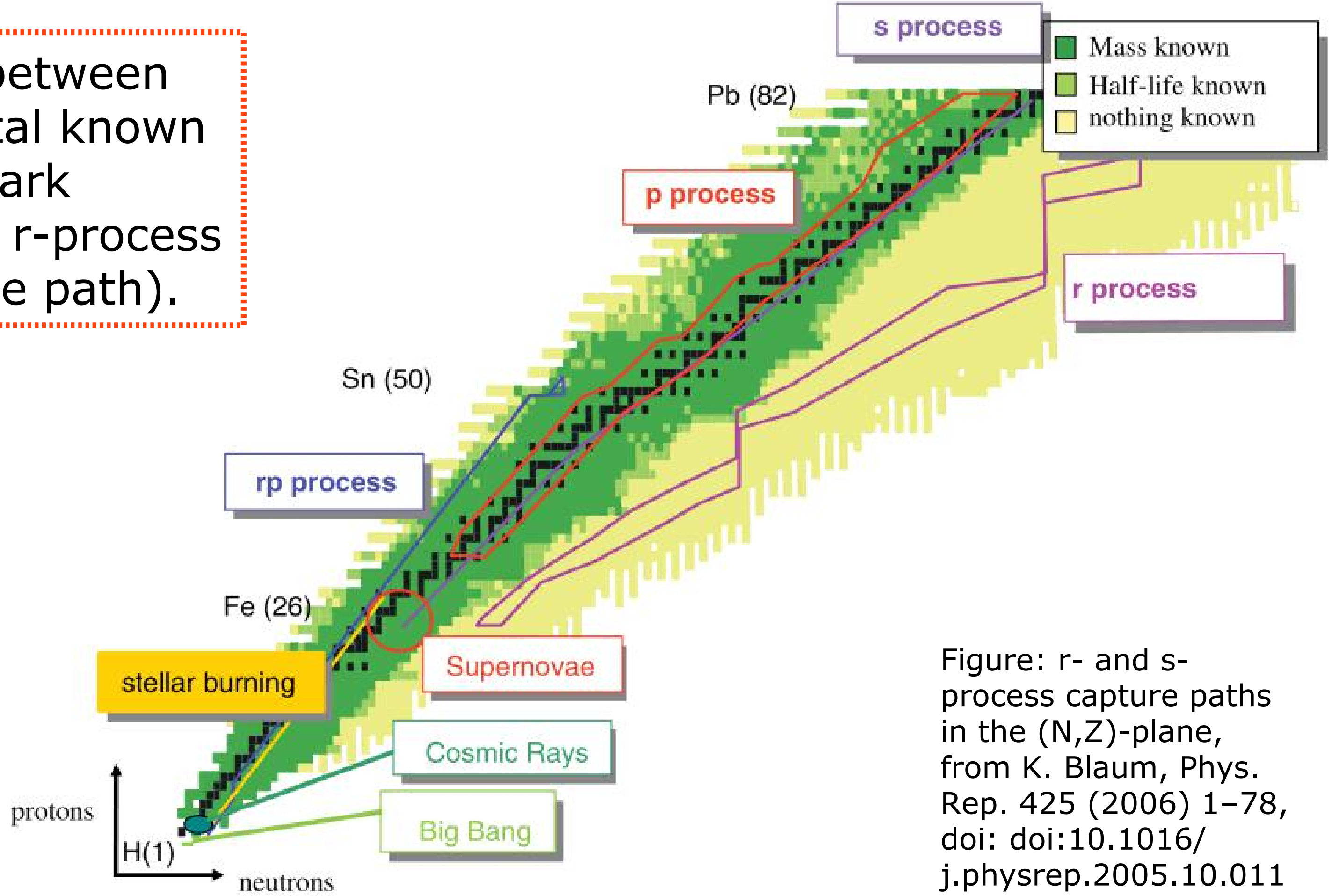


Figure: r- and s-process capture paths in the (N,Z)-plane, from K. Blaum, Phys. Rep. 425 (2006) 1–78, doi: doi:10.1016/ j.physrep.2005.10.011

# Outlook for nuclear physics & astrophysics: Consequences for simulations

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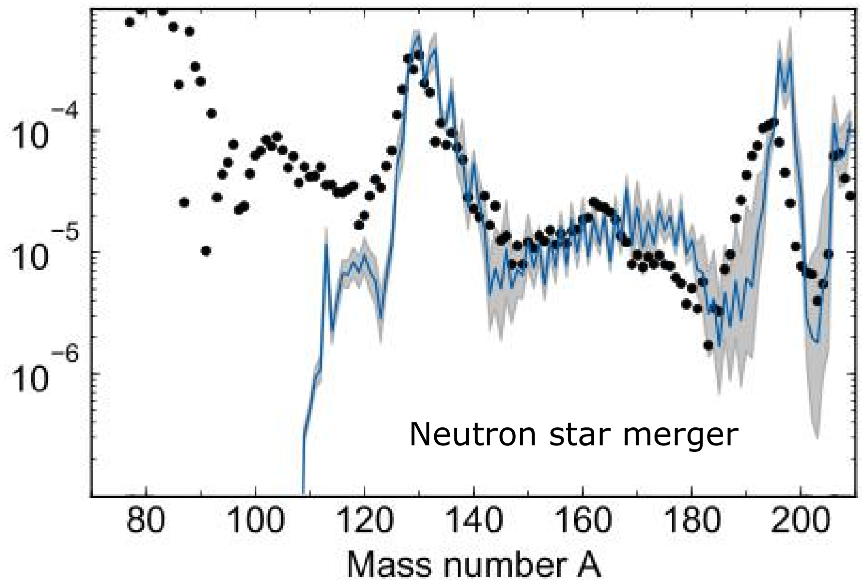
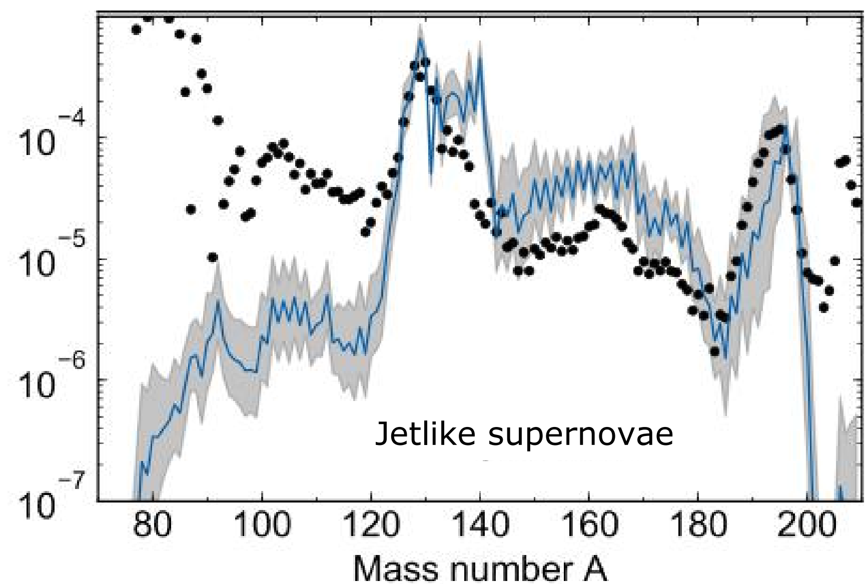
- Black dots: Solar system's r-process abundances;
- Gray bands: Uncertainties from the mass model; huge uncertainties → imprecise extrapolation for neutron rich nuclei;
- Blue solid line: Mean predicted abundances.




Figures: Impact of nuclear mass uncertainties on the r-process; D. Martin, A. Arcones, et al., in arXiv:1512.03158v2 [nucl-th] (2015), doi: 10.1103/PhysRevLett.116.121101

# Outlook for nuclear physics & astrophysics: Very old stars like Cayrel's star

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- Age determination by relative abundance of Th and U (see Fig.).
- Neutron star merger is unlikely due to timescale.
- Missing information about „progenitor“ stars.

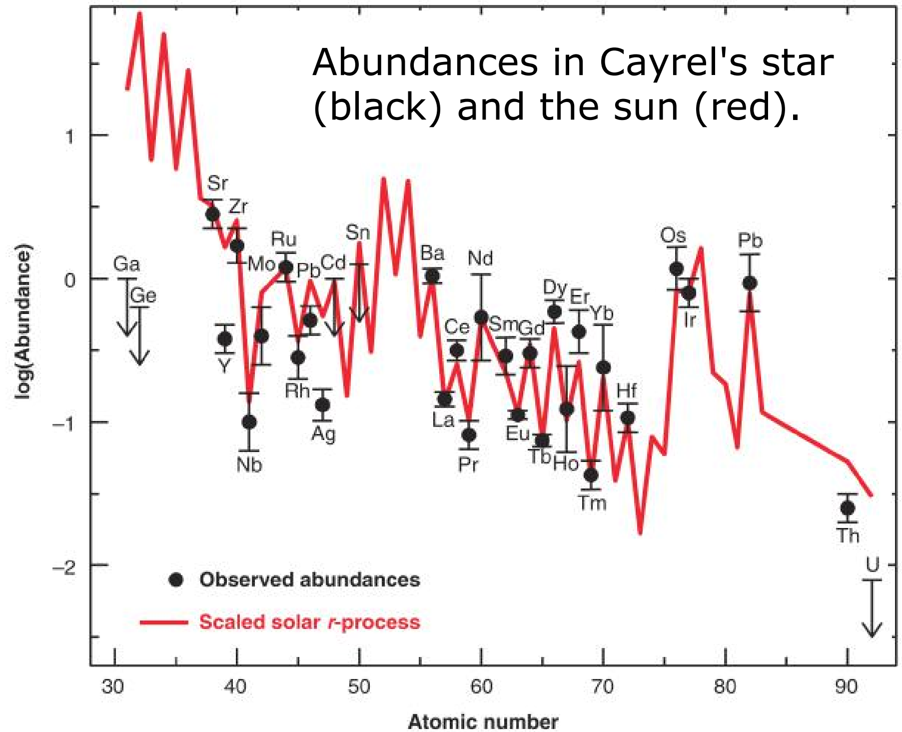
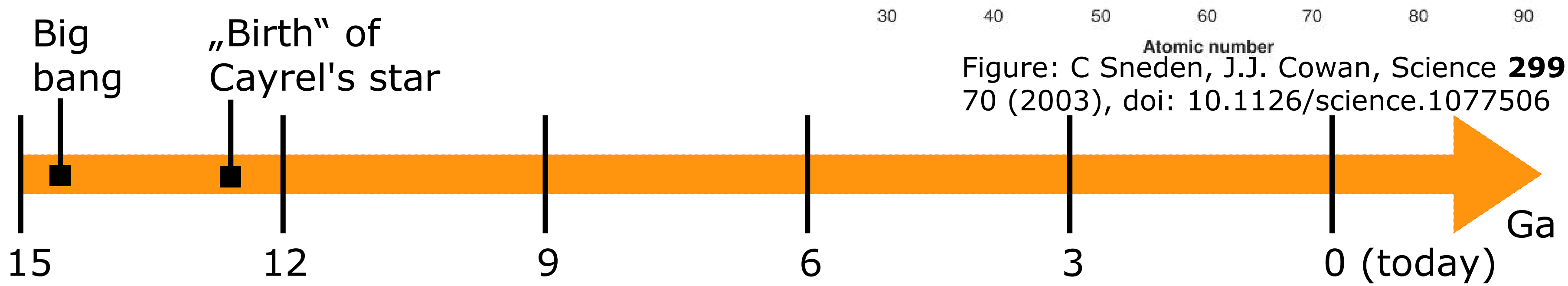



Figure: C Sneden, J.J. Cowan, Science **299** 70 (2003), doi: 10.1126/science.1077506

**Timescale of CS31082-0001**



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# Summary of talk

- Motivation for talk: Creation of trans-iron isotopes.
- Review of relevant nuclear physics.
- Overview and details of r- and s-process.
- State-of-the-art & outlook for nuclear physics and astrophysics.

# Thank you for your attention!
# Do you have question?

References:


- F. Käppeler, R. Gallino, S. Bisterzo, Wako Aoki: The *s* process: Nuclear physic, stellar models, and observations, Rev.Mod.Phys., 83 **157** (2011), doi: 10.1103/RevModPhys83.157
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- European Southern Observatory: How Old is the Universe?, eso.org/public/news/eso0106/, published in: Nature **409** 691—692 (2001)