Lecture 1: An introduction to nuclear astrophysics

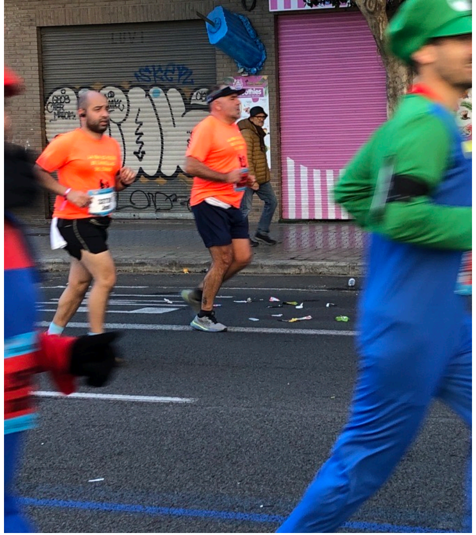
Photo credit: NASA

Thursday 15 Aug 2024

Ann-Cecilie Larsen, Department of Physics, University of Oslo, Norway

a.c.larsen@fys.uio.no

NUKLEÆRSENTERET



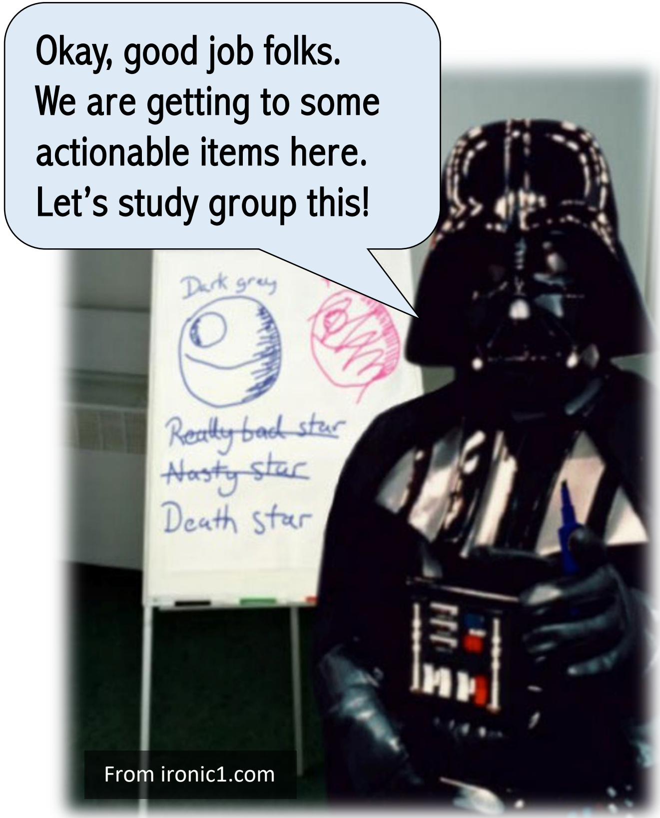
A little bit about me 🤗

- 44 years old
- Professor @ the University of Oslo
- Research field: experimental nuclear (astro)physics
- Two boys: Leo (15) and Georg (13) [photo from 2019 😅]
- Dog (Marco)
- Hobbies: running, reading books, movies & series (Star Wars , Dr Who, …), Nintendo, change tires on the car …

Overview of the lectures

- **Today**: A first introduction to nuclear astrophysics, with focus on heavy-element nucleosynthesis
- **Tomorrow**: (Some of the) Needed nuclear-physics input for heavy-element nucleosynthesis, brief intro to experimental methods to indirectly measure neutron-capture rates

How we’re gonna do this 🤓



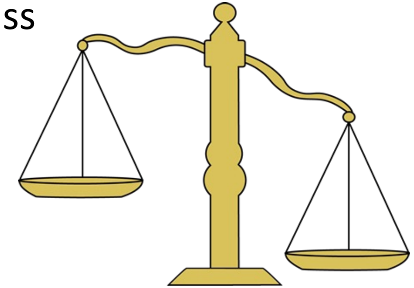
From ironic1.com

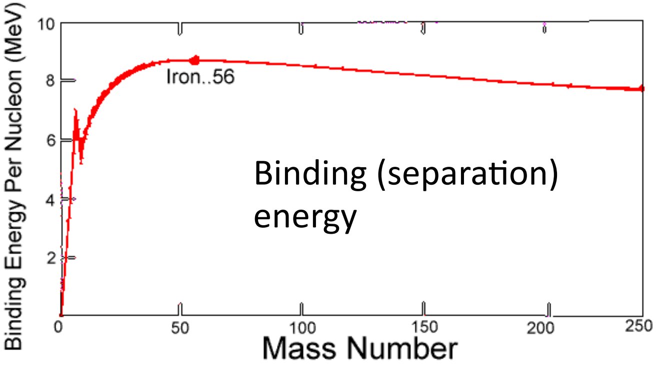
- Please raise your hand and ask questions during the lectures if you have any, don’t be shy!
- Slides will be available after the lectures
- Questions for discussion
- GOAL: you will learn something new each lecture and remember something (key points) afterwards 😅

Key nuclear properties and concepts

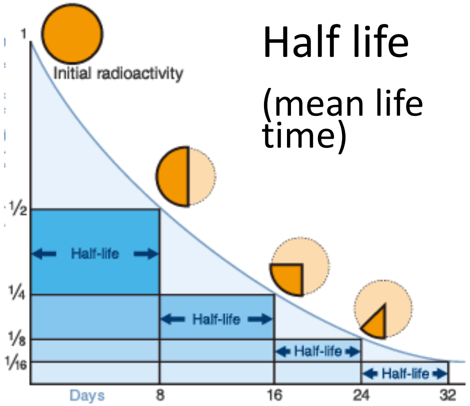
[Most of this is stolen from Artemis Spyrou]

Mass





Binding (separation) energy



Half life

(mean life time)

Reaction Q-value:

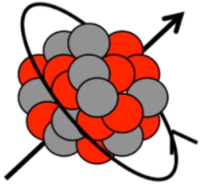
$Q = M_{initial} - M_{final}$

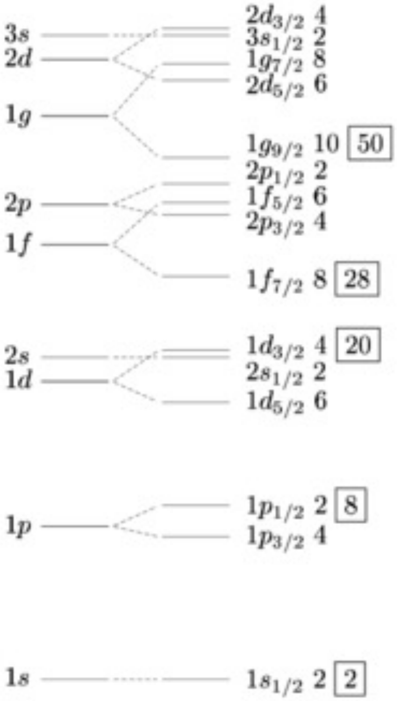
Q-value Calculator (QCalc)

Reaction Q-values for ^{134}Xe + ^{2}H

Reaction Products	Q-value (keV)	Threshold (keV)
^{135}Xe+^{1}H	4134.08 3.72	0.0 0.0

Angular momentum





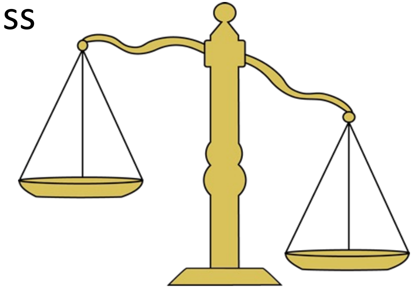
Single-particle levels & magic numbers

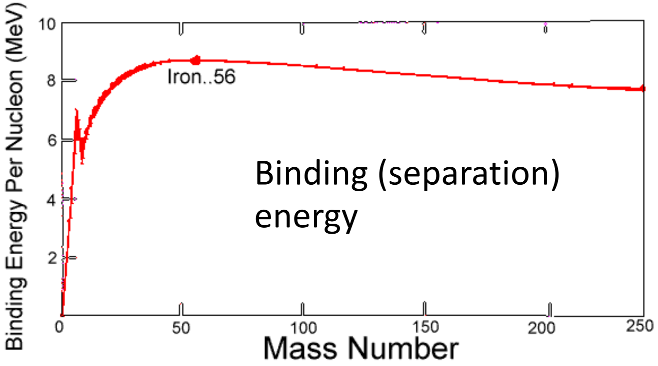
Compound-nucleus formation and decay

Key nuclear properties and concepts

[Most of this is stolen from Artemis Spyrou]

Mass





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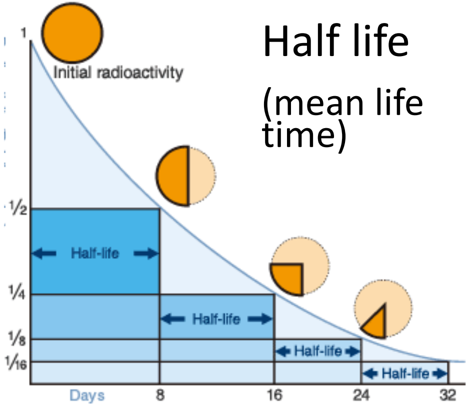

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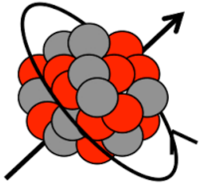


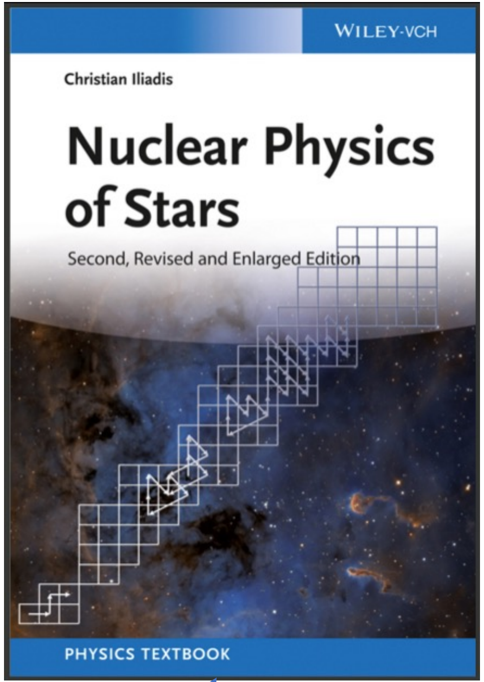
Maria Goeppert-Mayer
Photo: American Physical Society

Single-particle levels & magic numbers

Compound-nucleus formation and decay

Notation and terminology

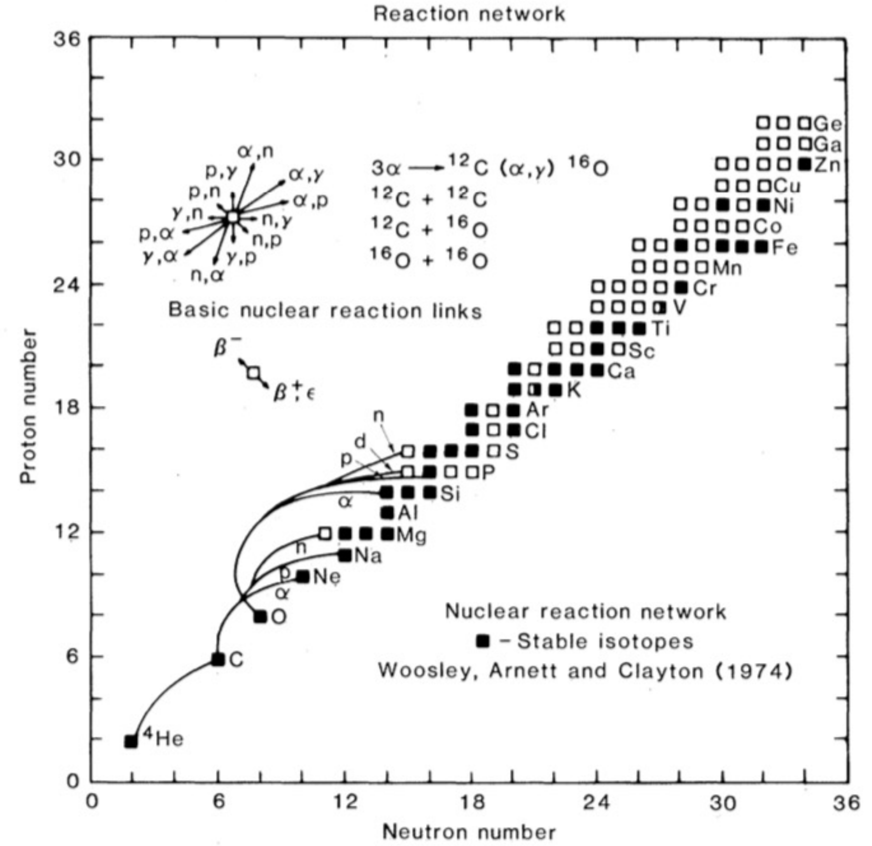
- **Radiative neutron capture reaction**: (n,γ) -> the "target" nucleus absorbs a neutron and emits γ rays to get rid of the excess energy (Z equal, A+1)
- **Radiative proton capture reaction**: (p,γ) -> the "target" nucleus absorbs a proton and emits γ rays (Z+1, A+1)
- **Beta decay**: either β^- (electron + anti neutrino emission, element Z+1, A equal) or β^+ (positron + neutrino emission, element Z-1, A equal)
- **Photodisintegration**: (γ,n), (γ,p), (γ,α) -> the inverse of radiative captures
- **Reaction network**: network including many different reactions connecting a set of nuclei, with the aim to reproduce observed elemental and isotopic abundances



Nice textbook!

Example, nuclear reaction network 

The **probability (reaction rate)** of a given reaction is essential

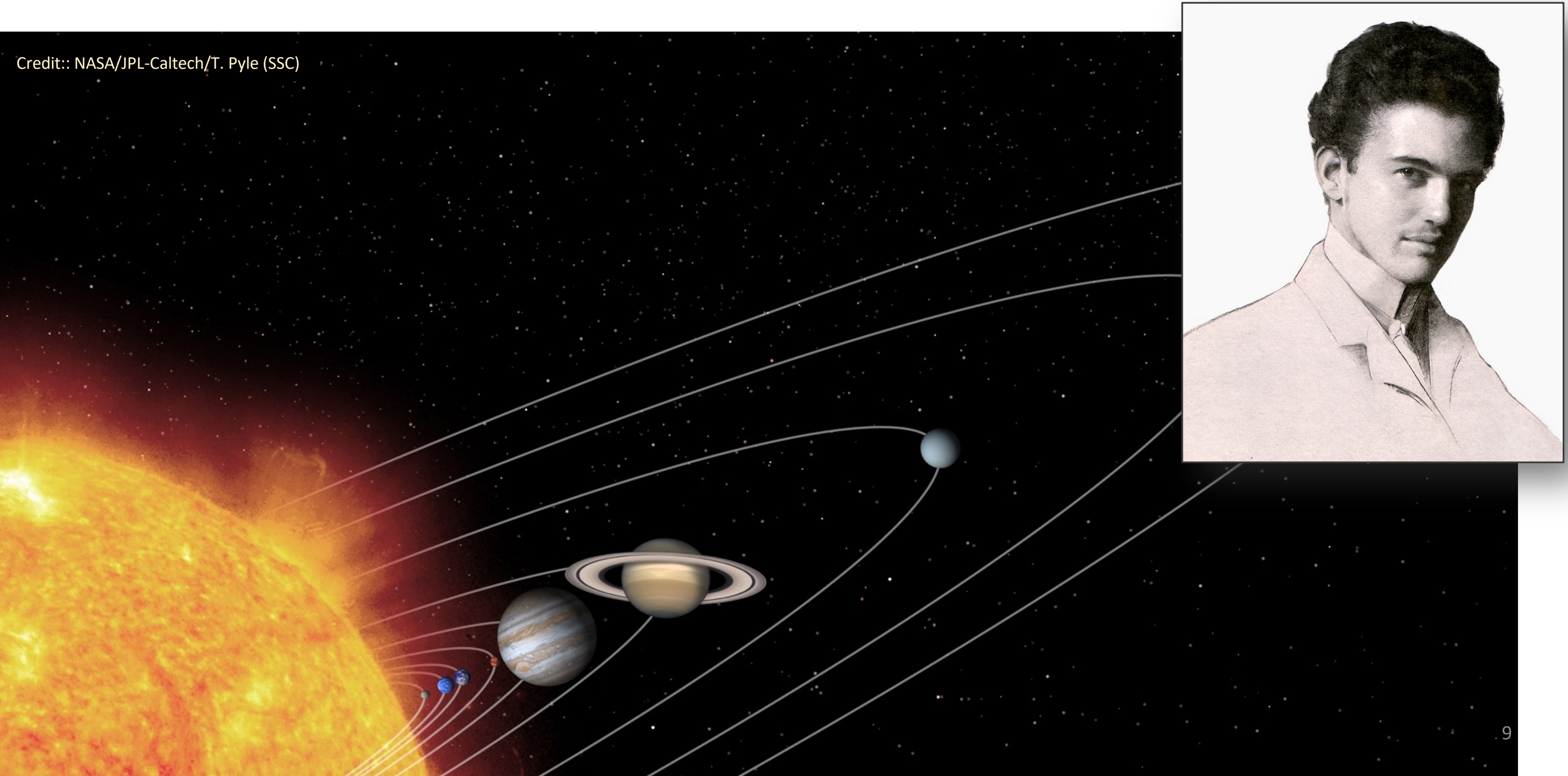


From William Fowler, Science (1984)

Fig. 3. Reaction network for nucleosynthesis involving the most important stable and radioactive nuclei with $N = 2$ to 34 and $Z = 2$ to 32. Stable nuclei are indicated by solid squares. Radioactive nuclei are indicated by open squares.

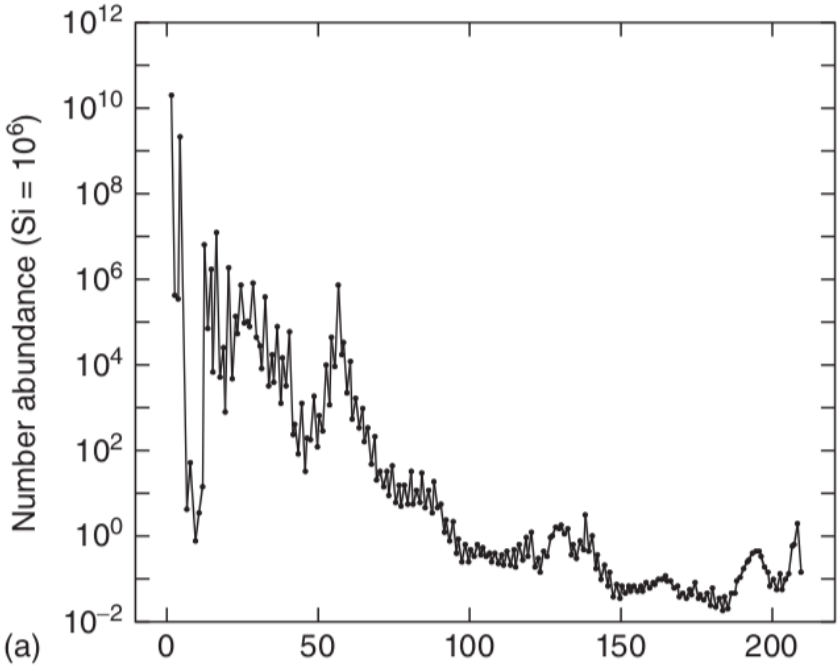
Our Solar system

Viktor M. Goldschmidt
Skrifter Norske Vitenskapsakad. Oslo. I.
Mat.-Naturv. Kl. (1937) No. 4.

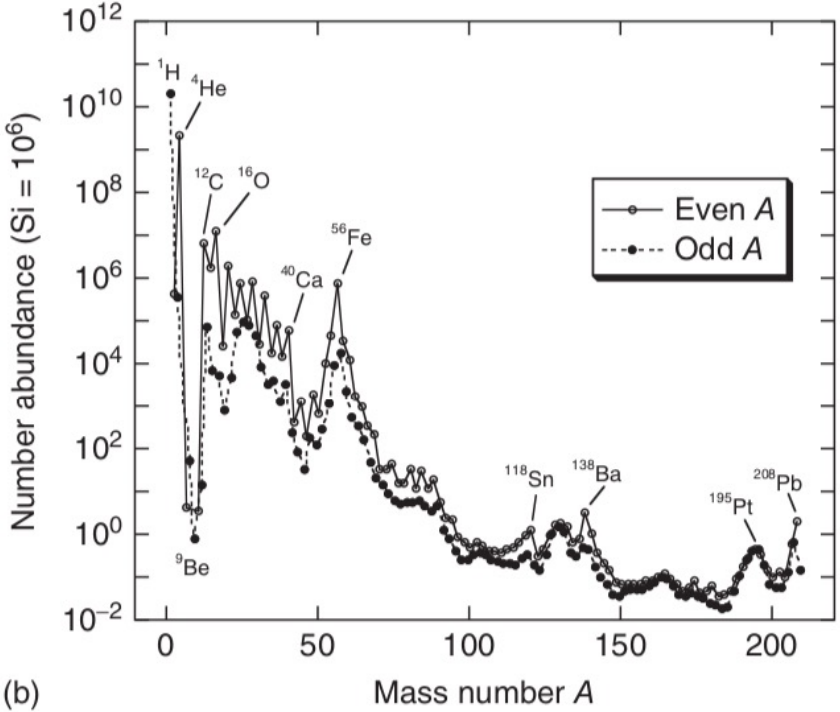


Element abundances in our solar system ☀️

Where do they come from? 🤔



Nucleosynthesis 🤩



[Figures from Iliadis' book "Nuclear Physics of Stars"]

From Big Bang until today

- Primordial (Big Bang) nucleosynthesis and atomic formation
- Stellar nucleosynthesis
- Explosive nucleosynthesis
- **Heavy-element nucleosynthesis**

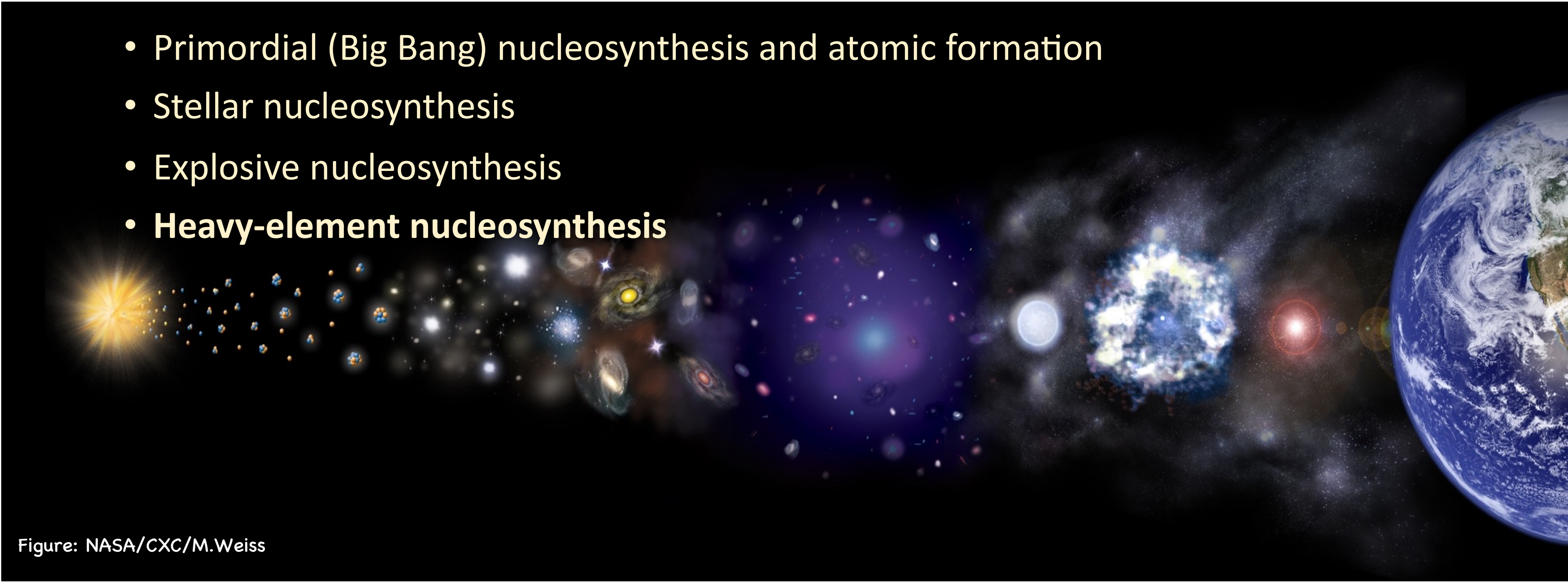


Figure: NASA/CXC/M.Weiss

“We are star-stuff” ✨

“The nitrogen in our DNA, the calcium in our teeth, the iron in our blood, the carbon in our apple pies were made in the interiors of collapsing stars.

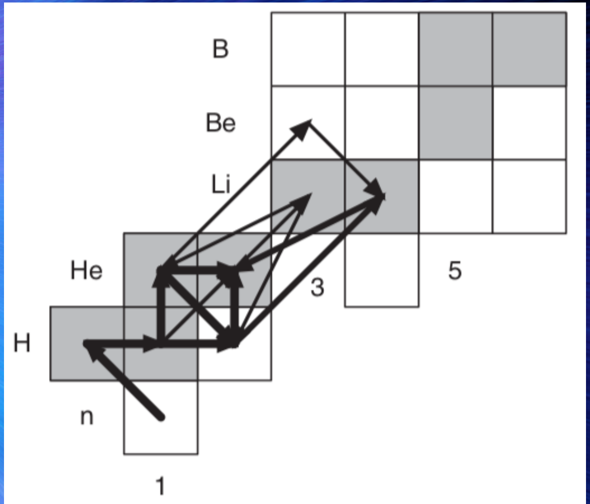
We are made of star-stuff.”

- Carl Sagan

Big Bang: hydrogen, helium, lithium
Stellar and explosive nucleosynthesis:
up to the iron group and (a little bit?) beyond

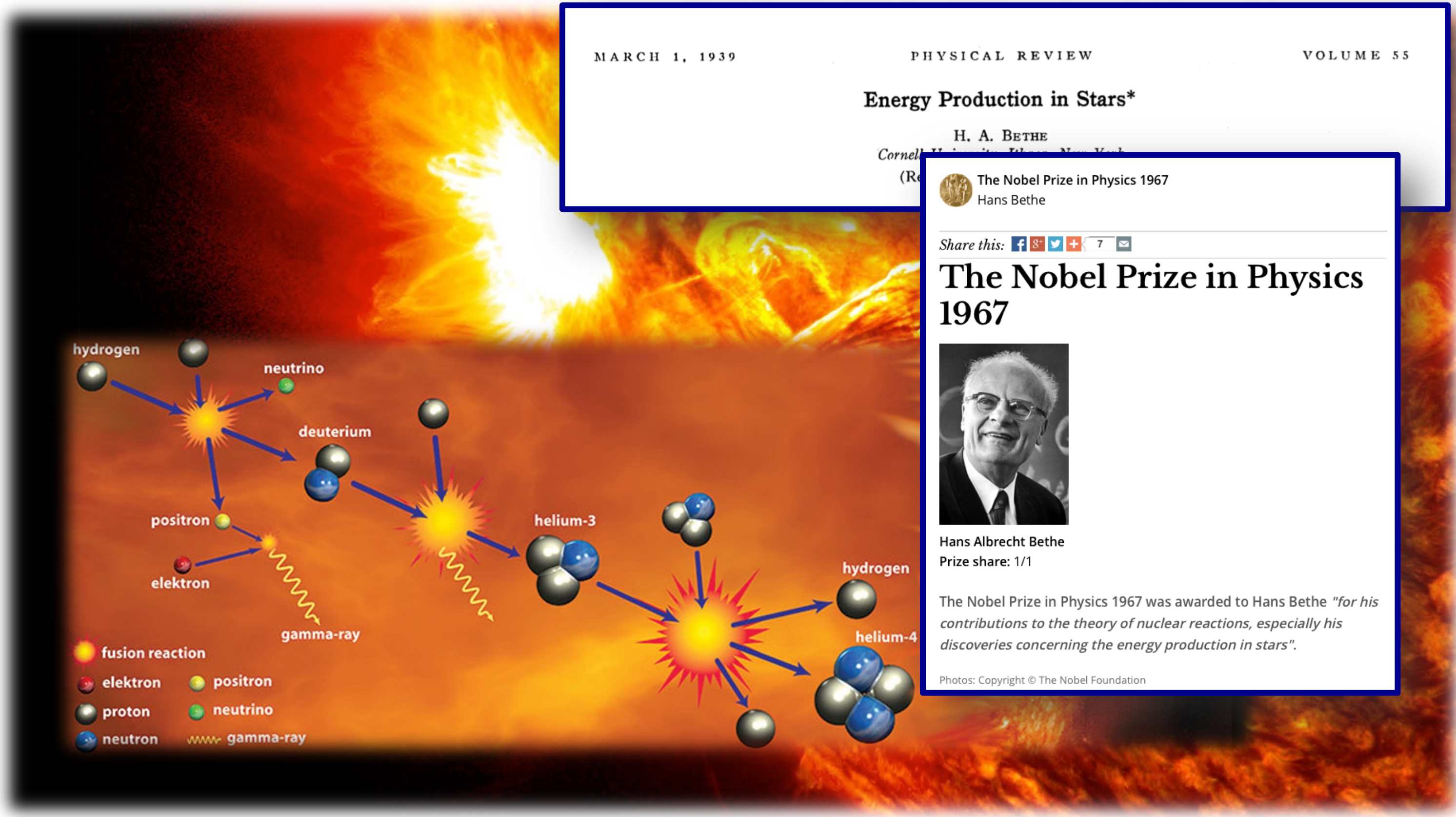
Primordial (Big Bang) nucleosynthesis

- Production of hydrogen and helium isotopes (and some traces of lithium, possibly some beryllium) ≈10 s–16 min after the Big Bang
- Initially, electron, neutrino and baryon gases in thermal equilibrium, and the fraction of neutrons to protons are $N_n/N_p = \exp[-Q/k_B T]$, where Q = 1293.3 keV is the neutron-proton mass difference
- At freeze-out, $N_n/N_p \approx 1/7$ and nuclear reactions can occur



[Figure from Iliadis' book "Nuclear Physics of Stars"]

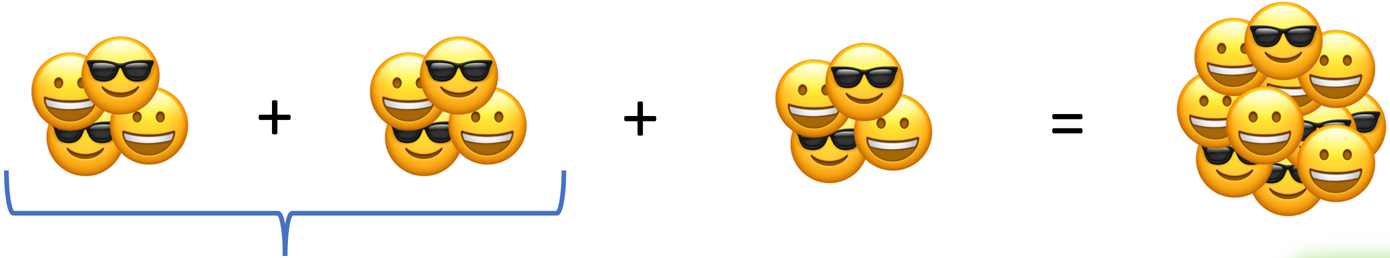
Nucleosynthesis in stars



Merging of protons to helium nuclei

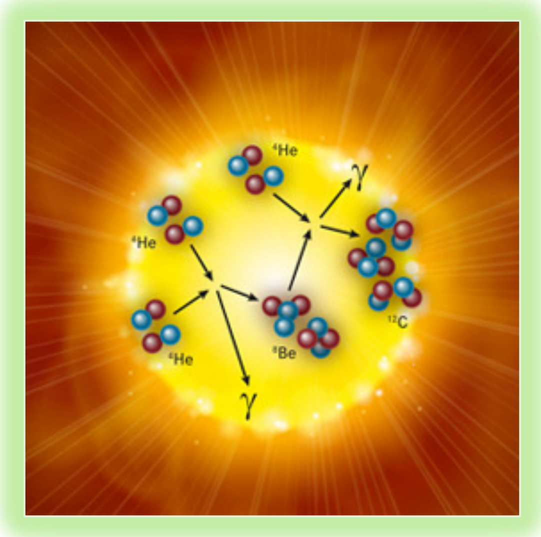
- pp chain (Sun-like stars)
- CNO cycle (massive stars)

The carbon bottleneck



Carbon-12
(6 protons, 6 neutrons)

Beryllium-8 disintegrates after ≈ 10^{-16} seconds

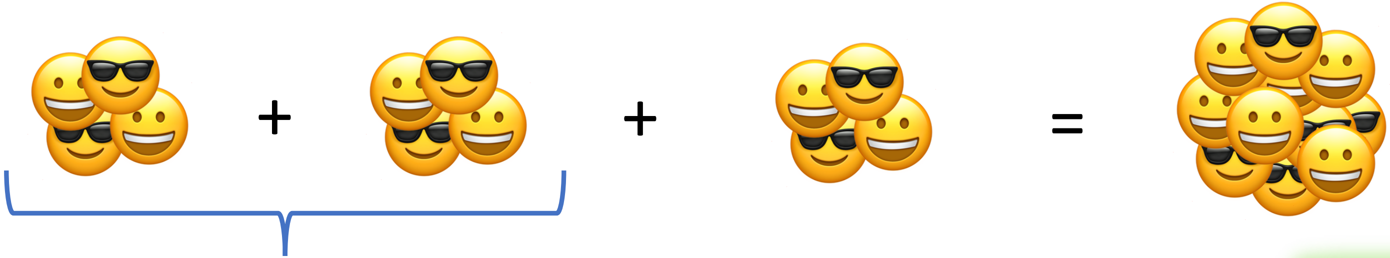


Fred Hoyle's suggestion:

There must exist a quantum state in ^{12}C so that the probability of ^{8}Be capturing an alpha particle increases significantly

≈ 1/2500 events, a ^{12}C nucleus is born

The carbon bottleneck 🍾



Carbon-12
(6 protons, 6 neutrons)

PHYSICAL REVIEW JOURNALS ARCHIVE
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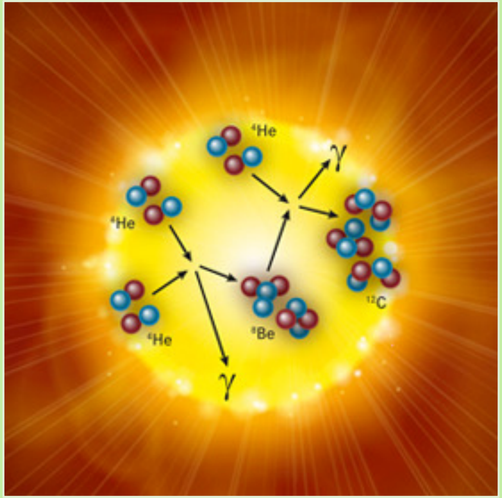
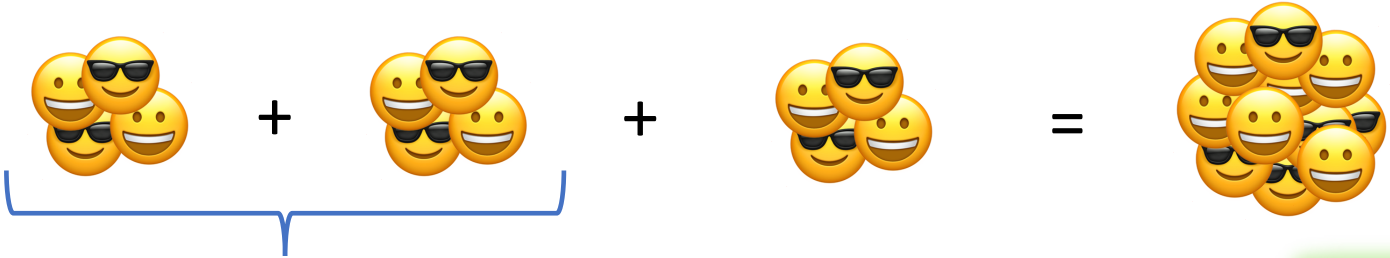
The 7.68-Mev State in C^{12}

D. N. F. Dunbar, R. E. Pixley, W. A. Wenzel, and W. Whaling
Phys. Rev. **92**, 649 – Published 1 November 1953



≈ 1/2500 events, a ^{12}C nucleus is born 👶

The carbon bottleneck



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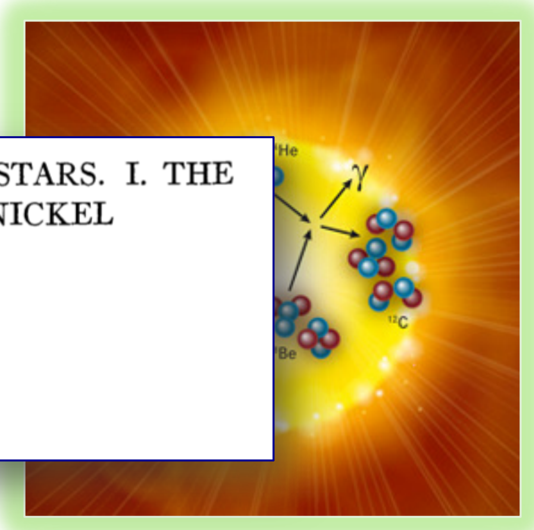
The 7.68-Me

D. N. F. Dunbar, R. E.
Phys. Rev. **92**, 649 –

ON NUCLEAR REACTIONS OCCURRING IN VERY HOT STARS. I. THE SYNTHESIS OF ELEMENTS FROM CARBON TO NICKEL

F. HOYLE*
MOUNT WILSON AND PALOMAR OBSERVATORIES
CARNEGIE INSTITUTION OF WASHINGTON
CALIFORNIA INSTITUTE OF TECHNOLOGY

Received December 22, 1953

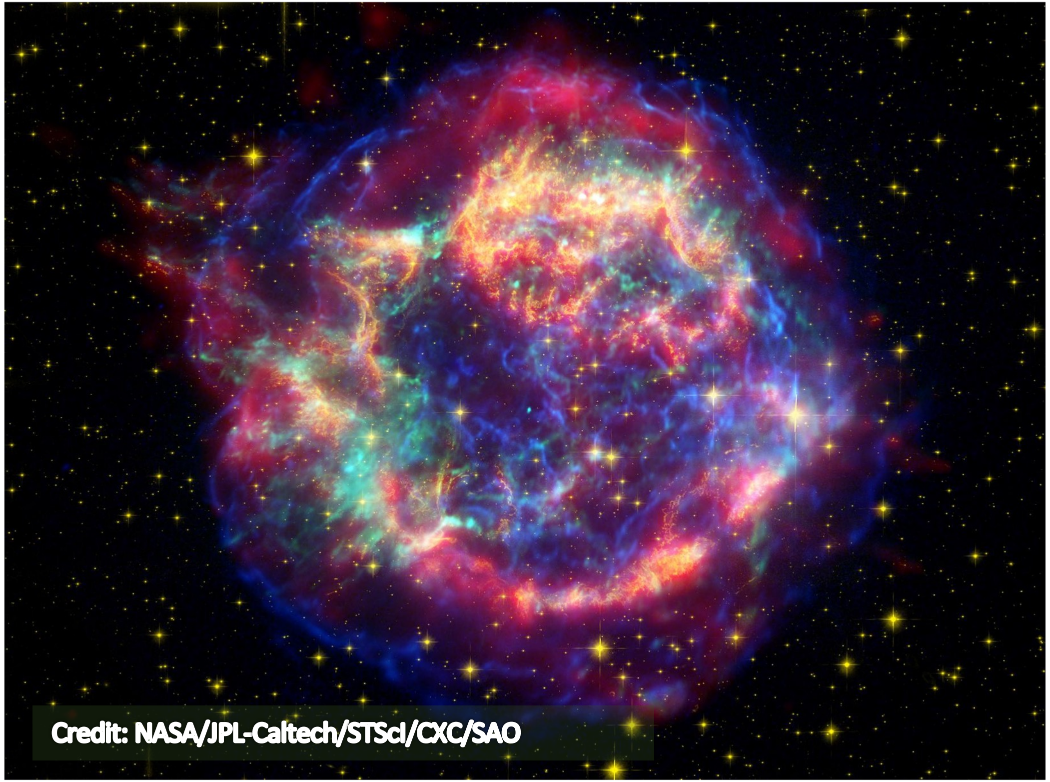


≈ 1/2500 events, a ^{12}C nucleus is born

Explosive nucleosynthesis

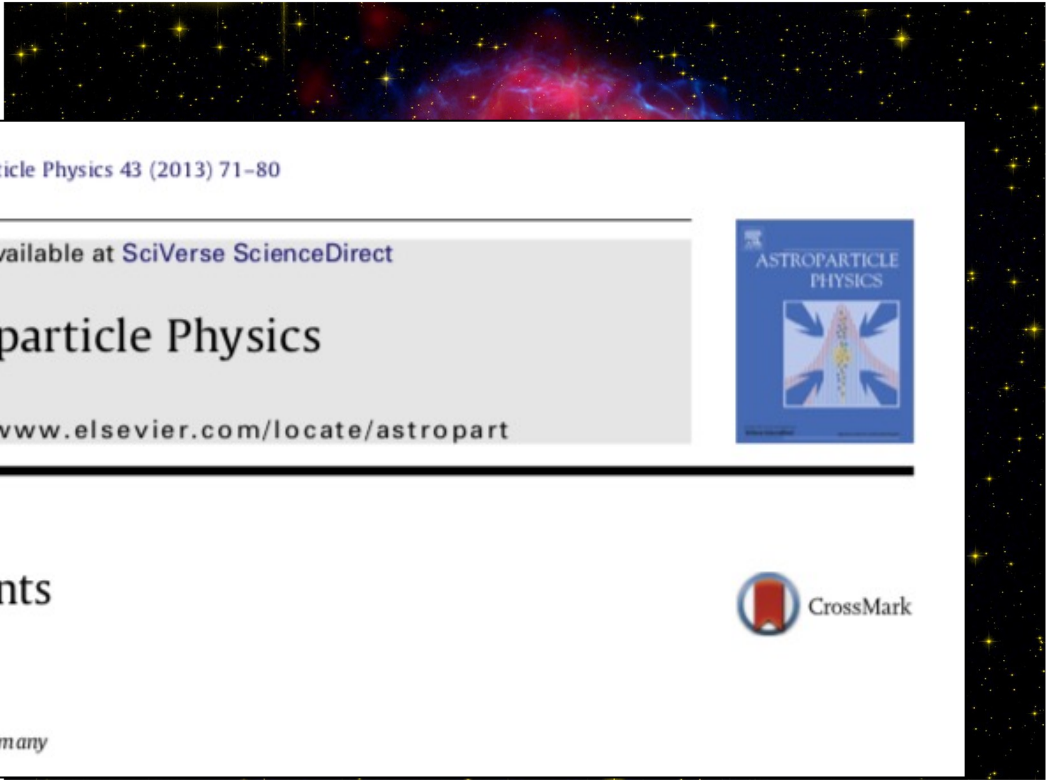
- Core-collapse supernovae
- Thermonuclear supernovae

Produce carbon,oxygen, phosphorus, aluminium, sulphur, titanium, potassium, calcium, …



Explosive nucleosynthesis

- Core-collapse supernovae



Astroparticle Physics 43 (2013) 71–80

Contents lists available at SciVerse ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropart

ELSEVIER

Gamma rays from supernova remnants

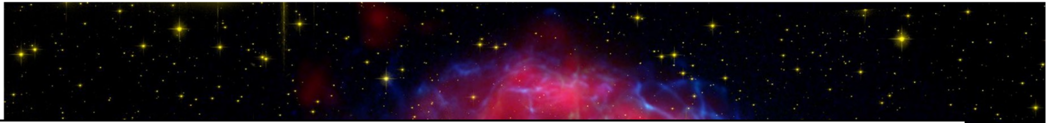
CrossMark

Felix A. Aharonian *

Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, Dublin 2, Ireland
Max Planck Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

Explosive nucleosynthesis

- Core-collapse supernovae



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ELSEVIER

Gamma rays from supernova

Felix A. Aharonian *

Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, D

Max Planck Institut für Kernphysik, Saupfercheckweg 1, 6911

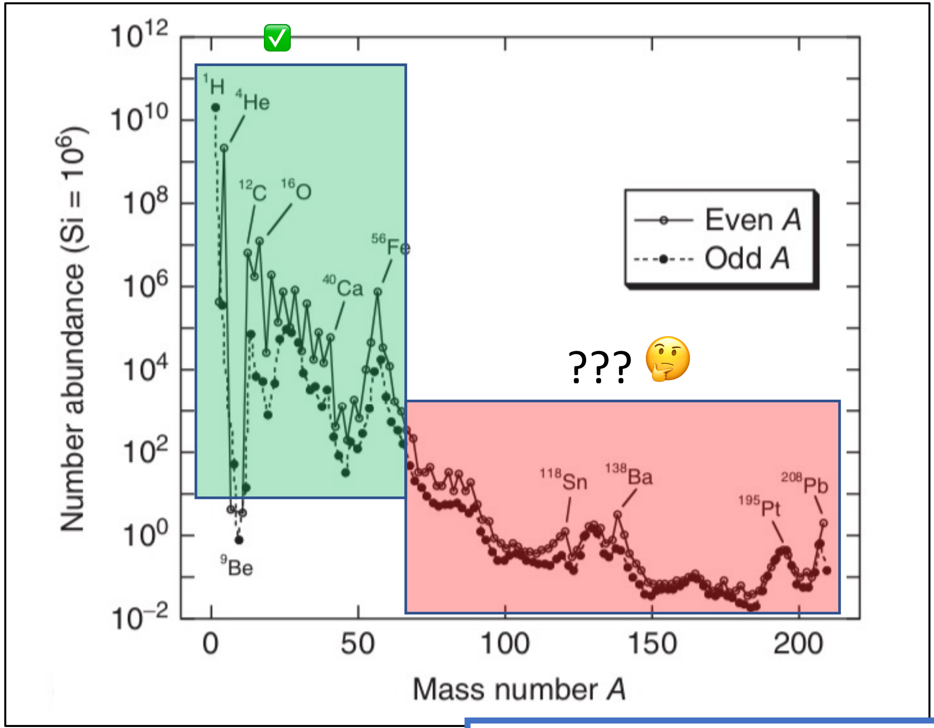
Another unique feature of this object is the reported γ-ray [64] and X-ray [65] emission lines which associate with ^{44}Ti. This radiation component provides direct information about the ejected mass of radioactive titanium, $M_{44\mathrm{Ti}} \approx 2 \times 10^{-4}\ \mathrm{M}_{\odot}$. The unusually high content of relativistic electrons in Cas A could have a link to the ejection of large amount of radioactive material, first of all ^{44}Ti and ^{56}Ni. The decay products of these nuclei provide a vast

«Revival» of white dwarves

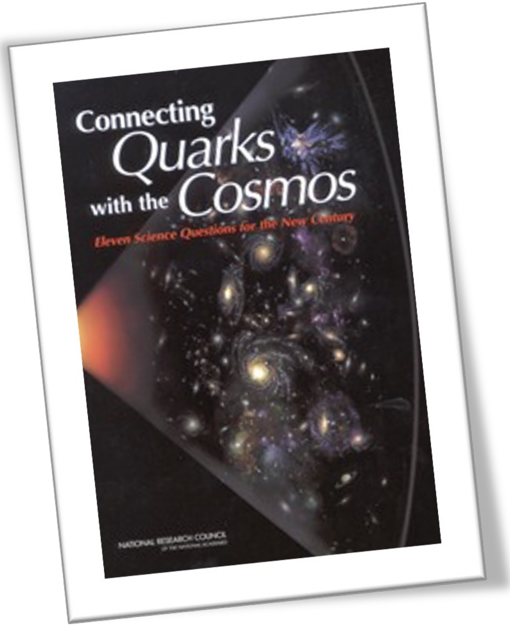
Silicon, sulphur, calcium, titanium, cromium, nickel, zink, …

Back to the element distribution

Figure from Iliadis’ book “Nuclear Physics of Stars”



Also thorium and uranium



“How Were the Elements from Iron to Uranium Made?”

[*Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*; US National Research Council (2003)]

Stars again ✨

REVIEWS OF

MODERN PHY

VOLUME 29, NUMBER 4

Synthesis of the Elements in

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER

Kellogg Radiation Laboratory, California Institute of Techno
Mount Wilson and Palomar Observatories, Carnegie Institution of
California Institute of Technology, Pasadena, Californ

"It is the stars, The stars above us, govern our condit
(*King Lear*, Act IV, Sc

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourse
(*Julius Caesar*, Act I, Sc

PUBLICATIONS OF THE
ASTRONOMICAL SOCIETY OF THE PACIFIC

Vol. 69 June 1957 No. 408

NUCLEAR REACTIONS IN STARS AND NUCLEOGENESIS*

A. G. W. CAMERON
Atomic Energy of Canada Limited
Chalk River, Ontario

INTRODUCTION

It was once thought that the stars and the interstellar matter had a uniform chemical composition except for some of the lighter elements, which were destroyed by thermonuclear reactions in stellar interiors. This view has caused astronomers and physicists to look for extreme physical conditions in which all the mat-

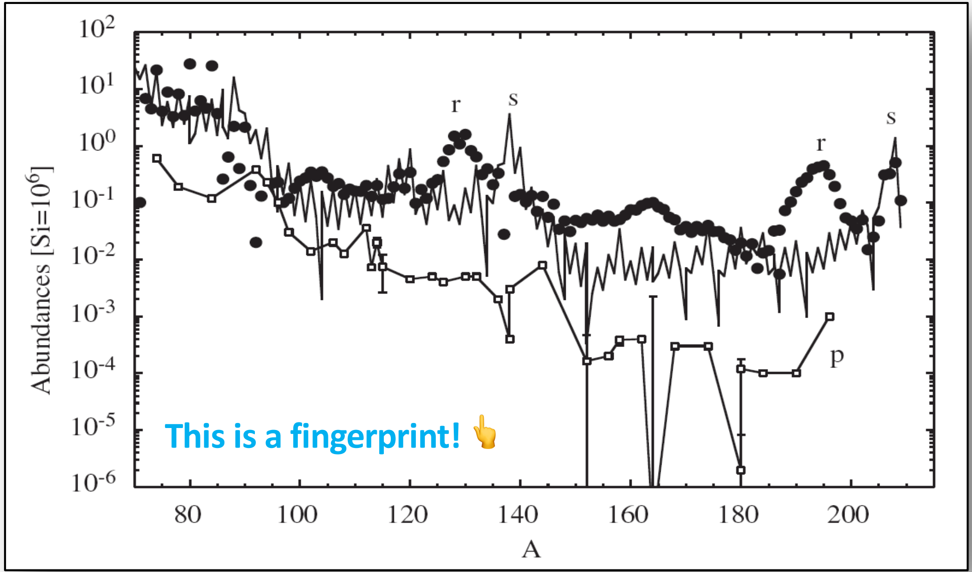
Photo credit: Annie Gracy

How to "cook" heavy elements 🍳

Slow neutron-capture (*s*) process (≈50%)

Rapid neutron-capture (*r*) process (≈50%)

p process: proton capture, photodisintegration, νp-process, … (~0.1-1%)



From *r*-process review: M. Arnould, S. Goriely, and K.Takahashi, Phys. Rep. **450**, 97 (2007)]

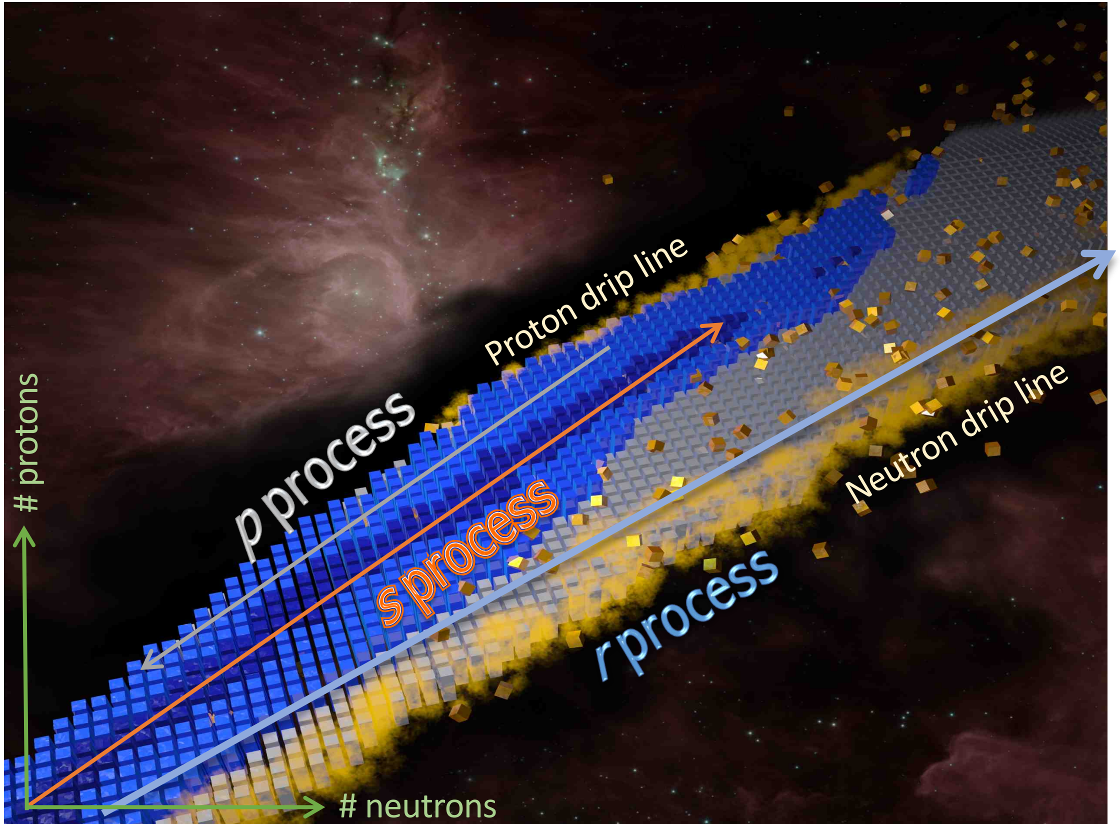
🤔 **Question:**

Why neutron capture?

Physics facts:

- No Coulomb barrier! 👍
- Cross sections (≈ probabilities) decrease with neutron energy, opposite to charged-particle reactions (👍 ?)
- Free neutrons are perishables ($T_{1/2}$≈ 10 minutes) 🍓 (👎?)

Heavy-element nucleosynthesis processes – schematic “paths” in the nuclear chart



In addition:

- *Rapid proton-capture process* (probably not contributing to the observed solar-system abundances)
- *Intermediate neutron-capture process* (?!)
- ++?

Figure: Andy Sproles, Oak Ridge National Lab

How to "cook" heavy elements 🍳

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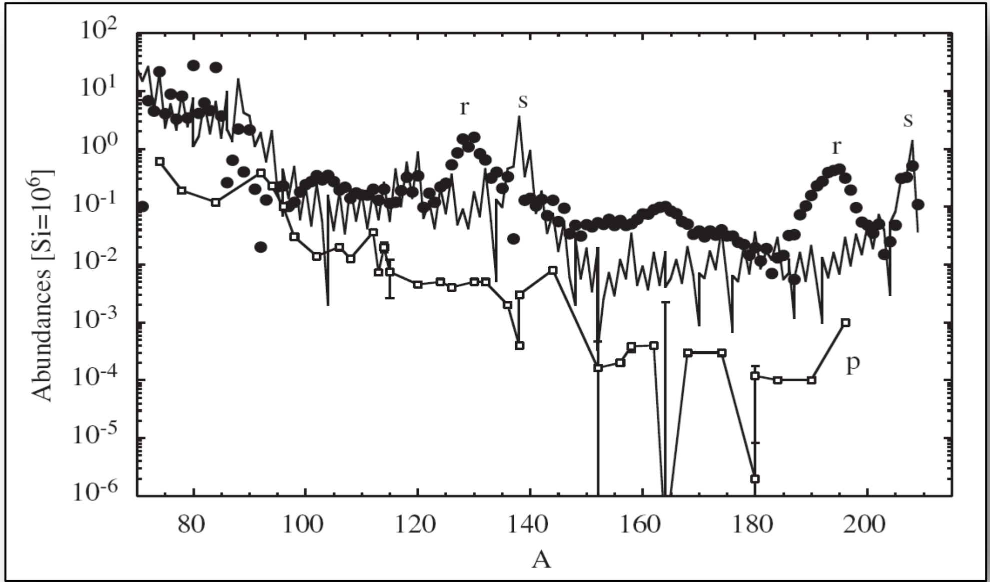


From *r*-process review: M. Arnould, S. Goriely, and K.Takahashi, Phys. Rep. **450**, 97 (2007)

🤔 **Question:**

Why are the *s*- and *r*-process peaks located where they are?

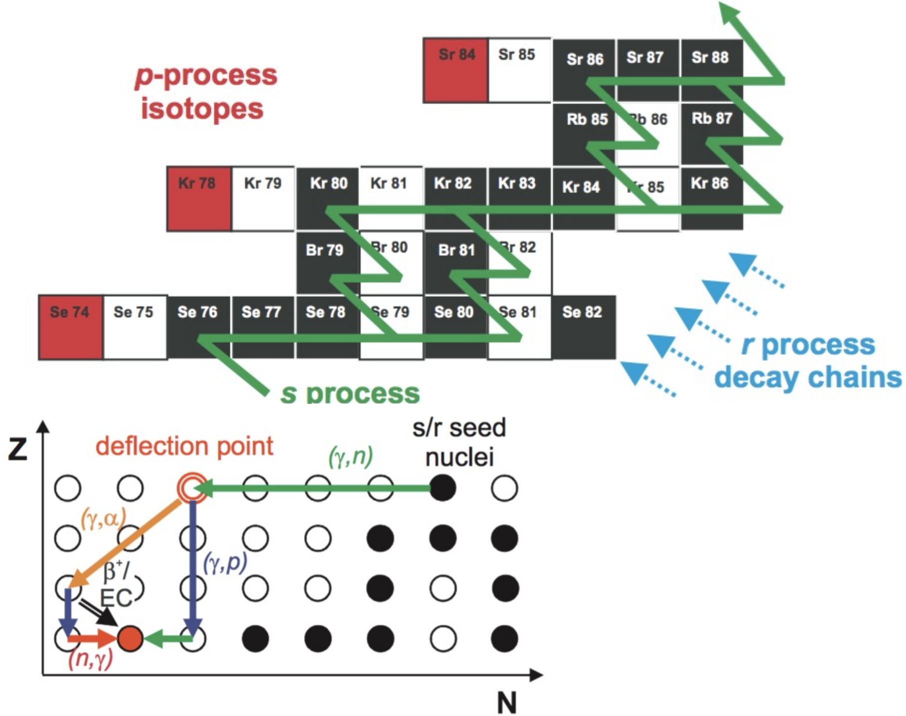
Physics facts:

- The nuclear shell model! 👍
- Signature of different neutron densities and timescales at the astrophysical sites 👍

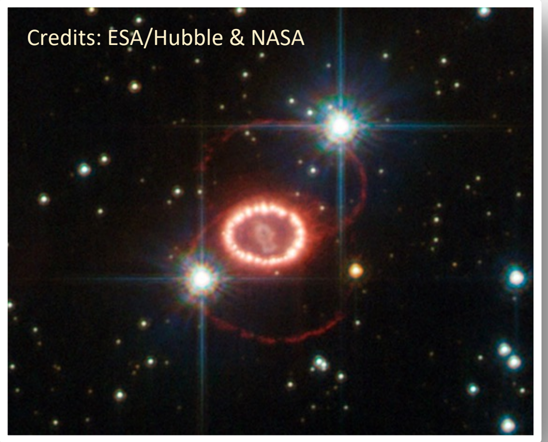
The *p* process

Review: Arnould & Goriely, Phys. Rep. **384**, 1 (2003)

[Rauscher et al., Rep. Prog. Phys. 76, 066201 (2013)]



Secondary process – "peeling off" neutrons on existing heavy nuclei



Favorable astrophysical sites:
Explosive O-Ne shell burning of type II supernovae, type Ia supernovae, …

But still may open questions! Mo and Ru anomaly, …

The *s* process

Direct evidence: spectral lines from technetium in red giant stars -> Tc has no stable isotopes, ^{99}Tc produced by β^- decay of ^{99}Mo
[P. W. Merrill, Science 116, 21 (1952)]

Relatively **low neutron density** (≈10^7-10^8 /cm^3), **low temperature** (0.1-0.4 x 10^9 K)


Cat's Eye nebula (credit:NASA)

AGB stars, massive stars (> 8 ☀️)

$$^{13}_{6}C + ^{4}_{2}He \rightarrow ^{16}_{8}O + n$$

$$^{22}_{10}Ne + ^{4}_{2}He \rightarrow ^{25}_{12}Mg + n$$

🐌 **Slow:**

One neutron capture per 1-1000 y, in total 100–100 000 y

Review: Käppeler et al., Rev. Mod. Phys. 83, 157 (2011)

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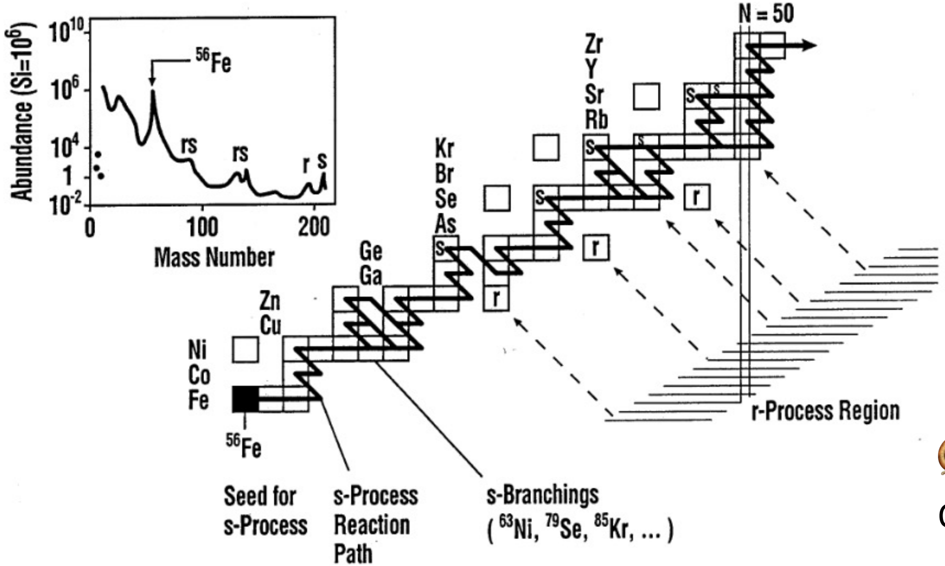

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The *r* process … WHERE???

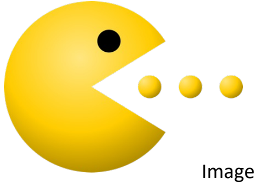
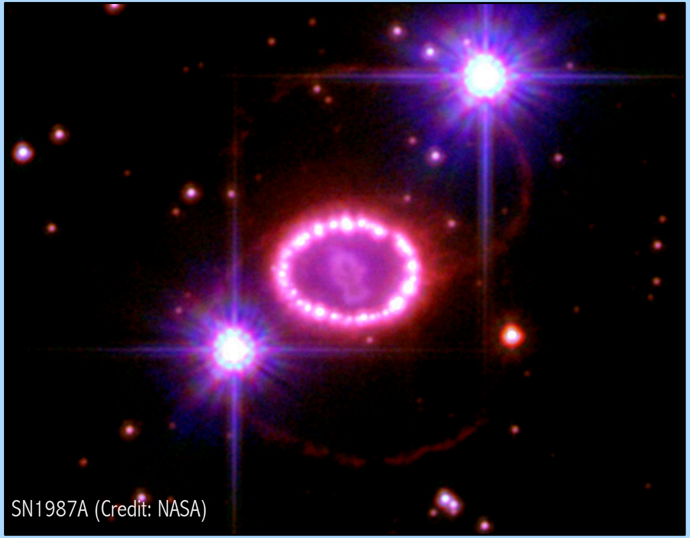


Image from pixabay.com

Extremely high neutron density (10^{20} /cm^3 or more), maybe (?) high temperature (1-5 x 10^9K), and **extremely** fast (≈ 1 second)



SN1987A (Credit: NASA)

For many years, supernovae were the favorite site

Astron. & Astrophys. 52, 63 – 68 (1976)

ASTRONOMY AND ASTROPHYSICS

… but more modern simulations gave too few neutrons…

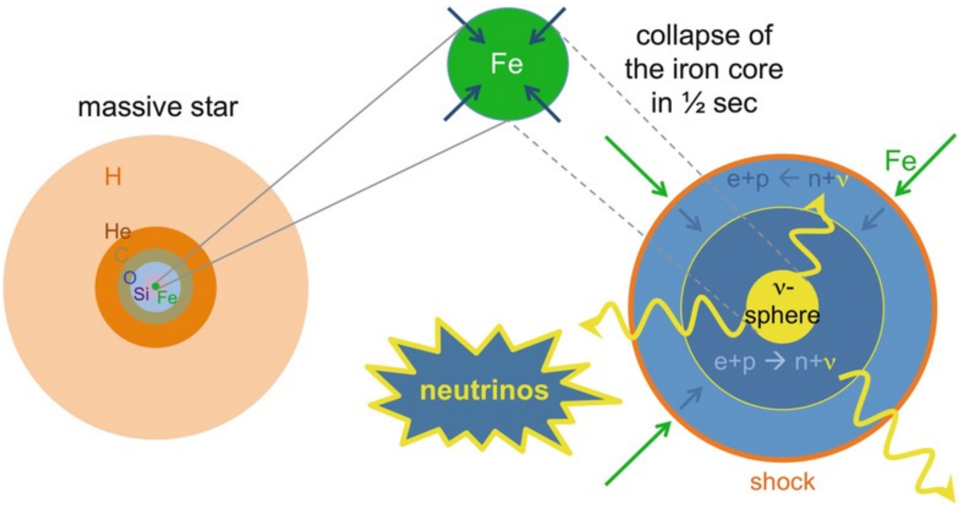
R-process Nucleosynthesis: A Dynamical Model*

W. Hillebrandt[1], K. Takahashi[1]** and T. Kodama[2]

[1] Institut für Kernphysik, Technische Hochschule Darmstadt, Schloßgartenstr. 9, D-6100 Darmstadt, Federal Republic of Germany
[2] Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brasil

Received March 15, 1976

A core-collapse supernova crash course 💥



Foglizzo T. (2017) Explosion Physics of Core-Collapse Supernovae; https://doi.org/10.1007/978-3-319-21846-5_52

- Thermonuclear fusion reactions stop when reaching the iron group (remember the nuclear binding-energy curve!)
- Gravity makes the massive star's core contract so much that the density gets extremely high (~2 x the nuclear density)
- All nuclei break down to their constituents and electrons are captured by protons, producing neutrons and neutrinos

The *r* process … WHERE???

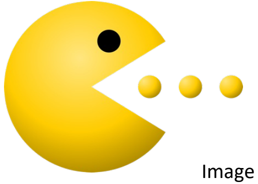


Image from pixabay.com

Extremely high neutron density (10^{20} /cm^3 or more), maybe (?) high temperature (1-5 x 10^9K), and **extremely** fast (≈ 1 second)

PRL **109,** 251104 (2012) PHYSICAL REVIEW LETTERS week ending 21 DECEMBER 2012

Charged-Current Weak Interaction Processes in Hot and Dense Matter and its Impact on the Spectra of Neutrinos Emitted from Protoneutron Star Cooling

G. Martínez-Pinedo,[1,2] T. Fischer,[2,1] A. Lohs,[1] and L. Huther[1]

[1]*Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstraße 2, 64289 Darmstadt, Germany*

[2]*GSI Helmholtzzentrum für Schwerioneneforschung, Planckstraße 1, 64291 Darmstadt, Germany*

(Received 12 May 2012; published 20 December 2012)

We perform three-flavor Boltzmann neutrino transport radiation hydrodynamics simulations covering a period of 3 s after the formation of a protoneutron star in a core-collapse supernova explosion. Our results show that a treatment of charged-current neutrino interactions in hot and dense matter as suggested by Reddy *et al.* [Phys. Rev. D **58**, 013009 (1998)] has a strong impact on the luminosities and spectra of the emitted neutrinos. When compared with simulations that neglect mean-field effects on the neutrino opacities, we find that the luminosities of all neutrino flavors are reduced while the spectral differences between electron neutrinos and antineutrinos are increased. Their magnitude depends on the equation of state and in particular on the symmetry energy at subnuclear densities. These modifications reduce the proton-to-nucleon ratio of the outflow, increasing slightly their entropy. They are expected to have a substantial impact on nucleosynthesis in neutrino-driven winds, even though they do not result in conditions that favor an *r* process. Contrary to previous findings, our results show that the spectra of

he favorite site

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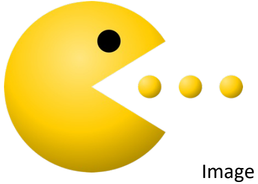
o few neutrons…

, Federal Republic of Germany

The *r* process … WHERE???



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"…does not yield heavy r-process nuclei…"

[A. Arcones and F. Montes, ApJ 731, 5 (2011)]

"…do not result in conditions that favor an *r* process…"

[G. Martínez-Pinedo et al, PRL **109**, 251104 (2012)]

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[H.-T. Janka, Annu. Rev. Nucl. Part. Sci. **62**, 407 (2012)]

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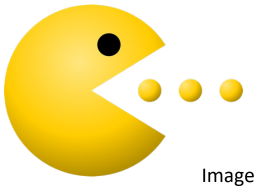

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ASTRONOMY AND ASTROPHYSICS

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Also, it was (and still is!) very difficult to actually make the star explode in the simulations!

"…does not yield heavy r-process nuclei…"
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Physics Reports 442 (2007) 237–268
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www.elsevier.com/locate/physrep

Where, oh where has the *r*-process gone?

Y.-Z. Qian[a,*], G.J. Wasserburg[b]

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[b] *The Lunatic Asylum, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA*

Available online 16 February 2007
editor: G.E. Brown

The appendix! 😂

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www.elsevier.com/locate/physrep

Where, oh where has the *r*-process gone?

Y.-Z. Qian[a,*], G.J. Wasserburg[b]

[a] Sch

[b] The Lunatic Asylum Di

Appendix A. The parable of the key: a story for Hans

Y.-Z.Q. was heavily involved with teaching in the fall of 2006. In trying to meet the deadline for this volume, G.J.W. traveled to Minneapolis to work on the manuscript. Bad weather conditions left him in Denver overnight. To get some rest, he went out to a more or less nearby Radisson Hotel and caught a few hours' sleep before returning to the Denver Airport early next morning for the remainder of the trip to Minneapolis. Y.-Z.Q. had arranged for him to stay at the Radisson Hotel near the University of Minnesota and met him at the hotel. Upon checking in and getting a card key, they went up to the seventh floor to find Room 729. They searched the seventh floor intensely but could not find a room with that number. G.J.W. was getting quite exhausted so they asked a chambermaid where the room was. She

Problems, unknown *r*-process site 🤔

- We don’t know the initial conditions (density, temperature, neutron flux, …)
- Because we don’t know the conditions, we don’t know exactly which nuclear-physics input is (most) relevant

In particular: **will there be an equilibrium between neutron capture (n,γ) and photodisintegration (γ,n) processes?**

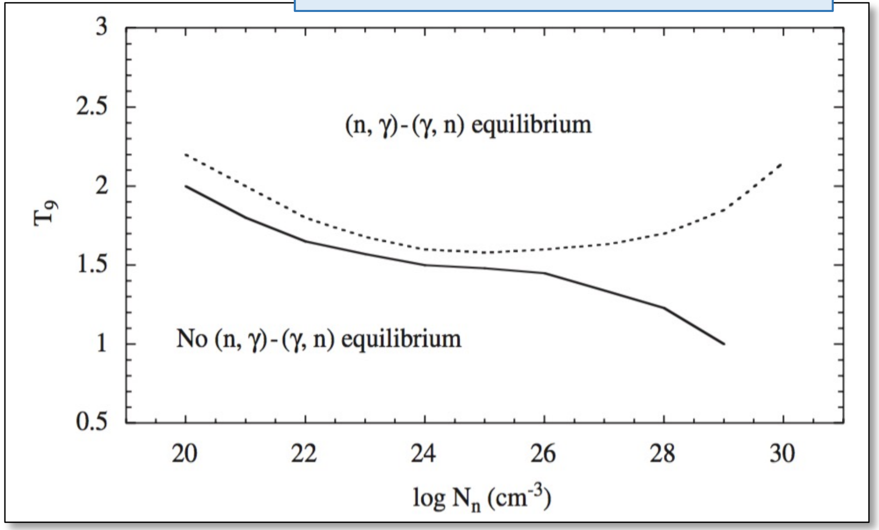
If ***yes***, masses (and hence neutron separation energies) and beta-decay rates are most important

If ***no***, neutron-capture rates (and fission rates) are also important => much more complicated reaction network!

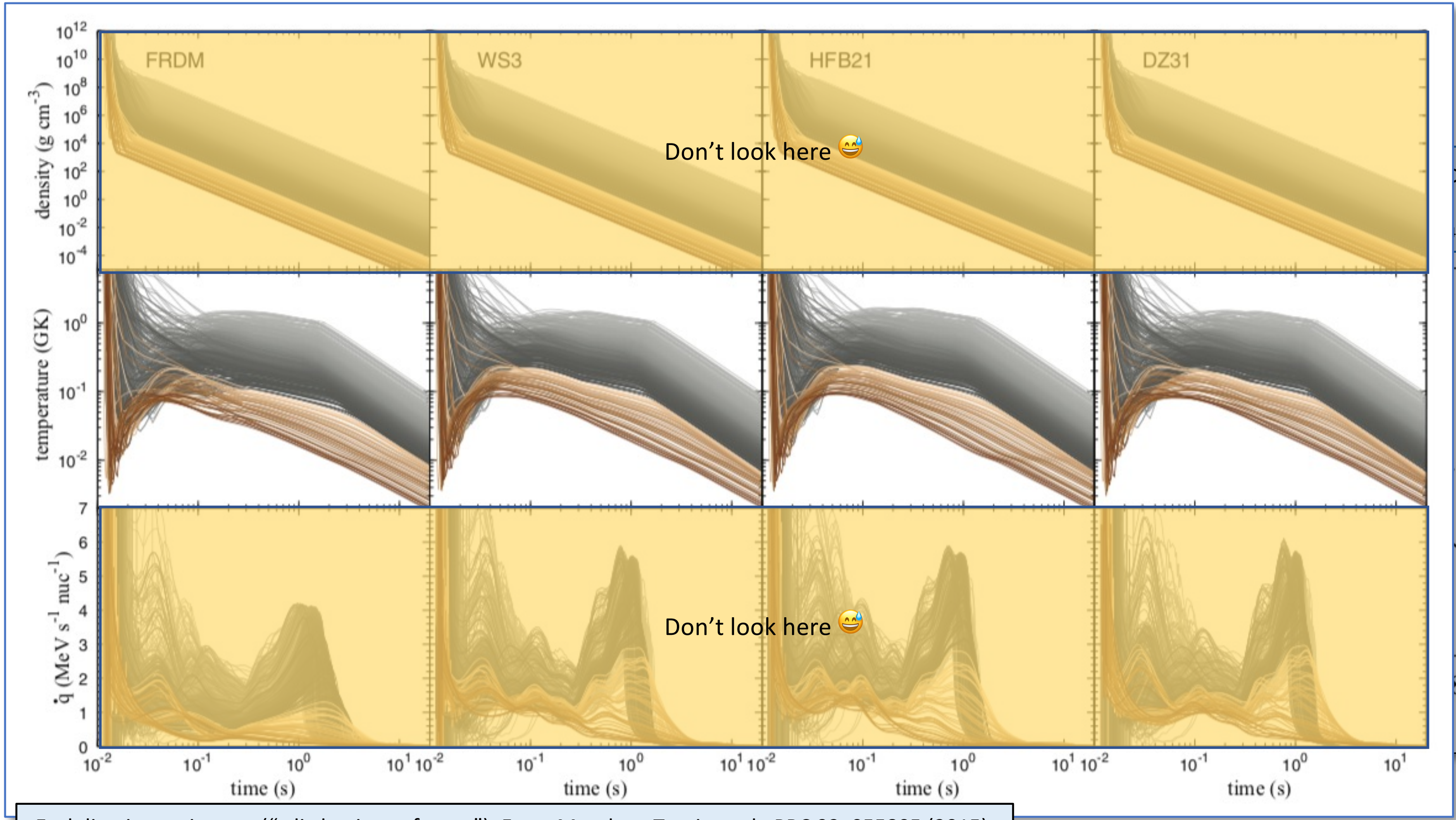
(n,γ)-(γ,n) equilibrium: to be or not to be ⚖️

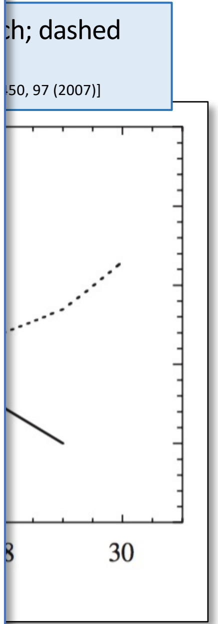
- Near and at the neutron drip line, the neutron separation energies are very low (~keV range)
- In the *r* process, both (n,γ) and (γ,n) are faster than β^- decay
- BUT: there is a strong interplay between temperature, neutron density, and nuclear-physics properties (capture cross sections!) that must be considered

Solid line: pure Hauser-Feshbach; dashed line: also **direct capture**
[M. Arnould, S. Goriely and K. Takahashi, Phys. Rep. 450, 97 (2007)]



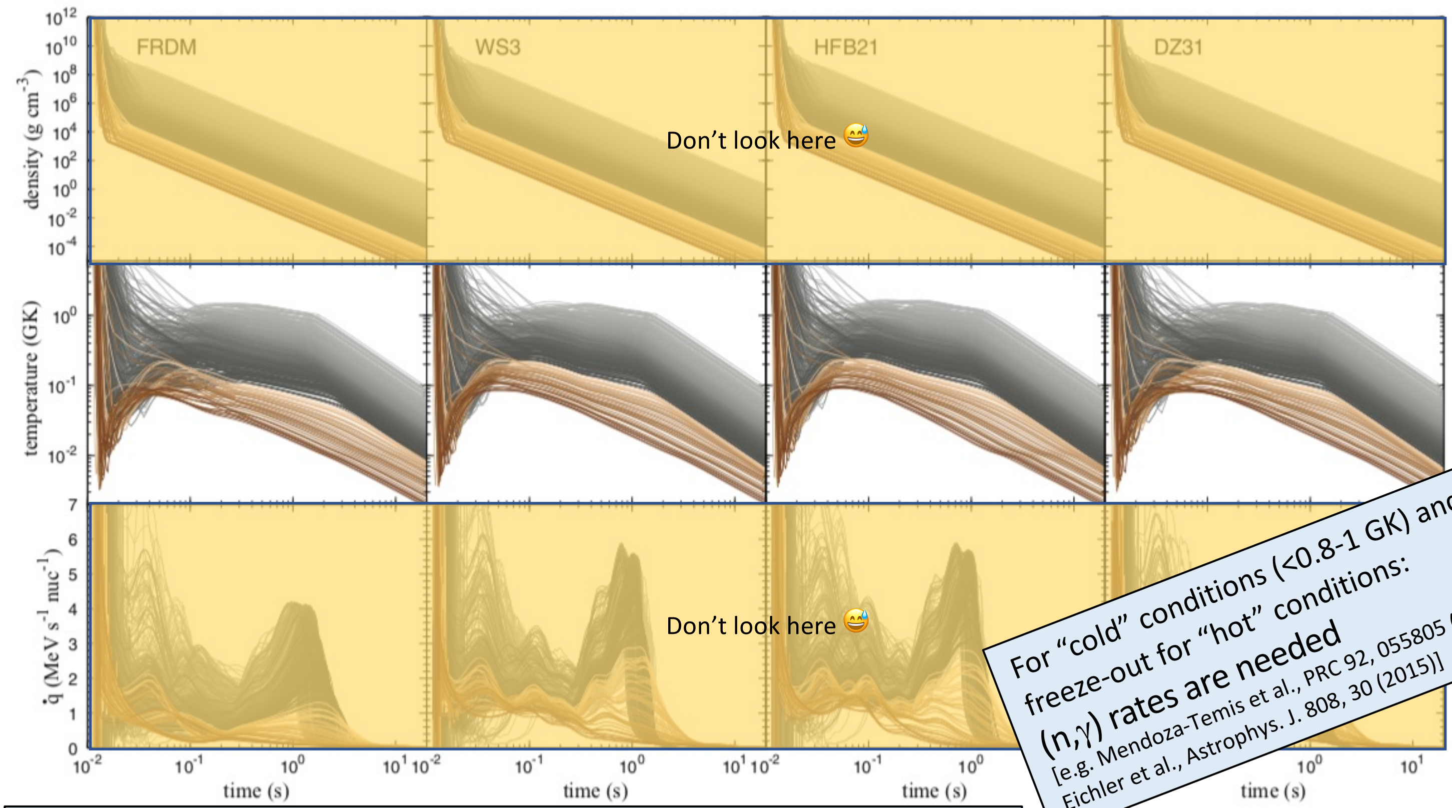
(n,γ)-(γ,n) equilibrium: to be or not to be ⚖️





Each line is a trajectory ("a little piece of mass"). From Mendoza-Temis et al., PRC 92, 055805 (2015)

(n,γ)-(γ,n) equilibrium: to be or not to be ⚖️



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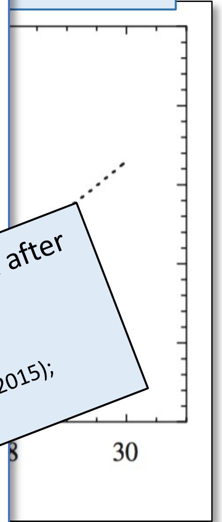


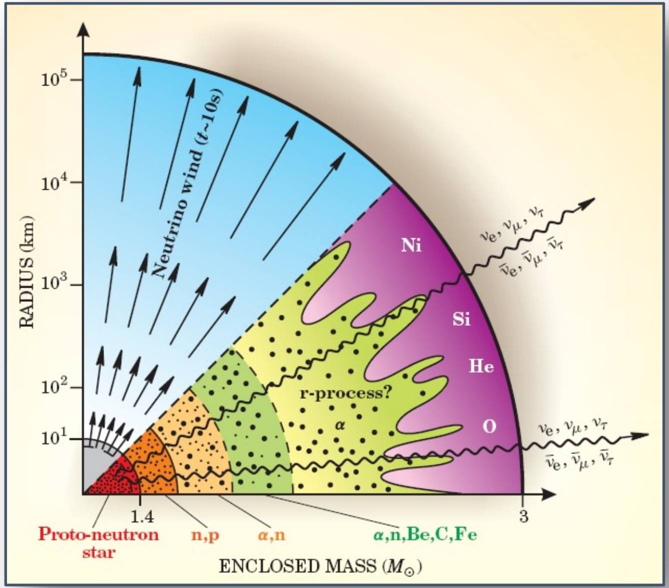
ch; dashed

50, 97 (2007)]

For "cold" conditions (<0.8-1 GK) and after freeze-out for "hot" conditions: (n,γ) rates are needed

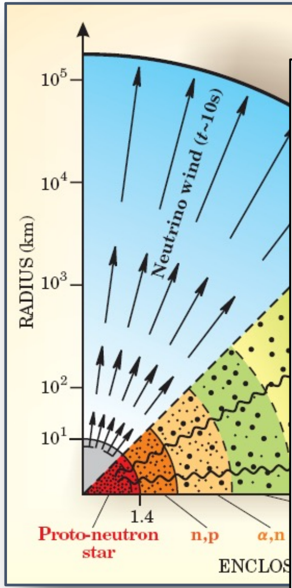
[e.g. Mendoza-Temis et al., PRC 92, 055805 (2015); Eichler et al., Astrophys. J. 808, 30 (2015)]

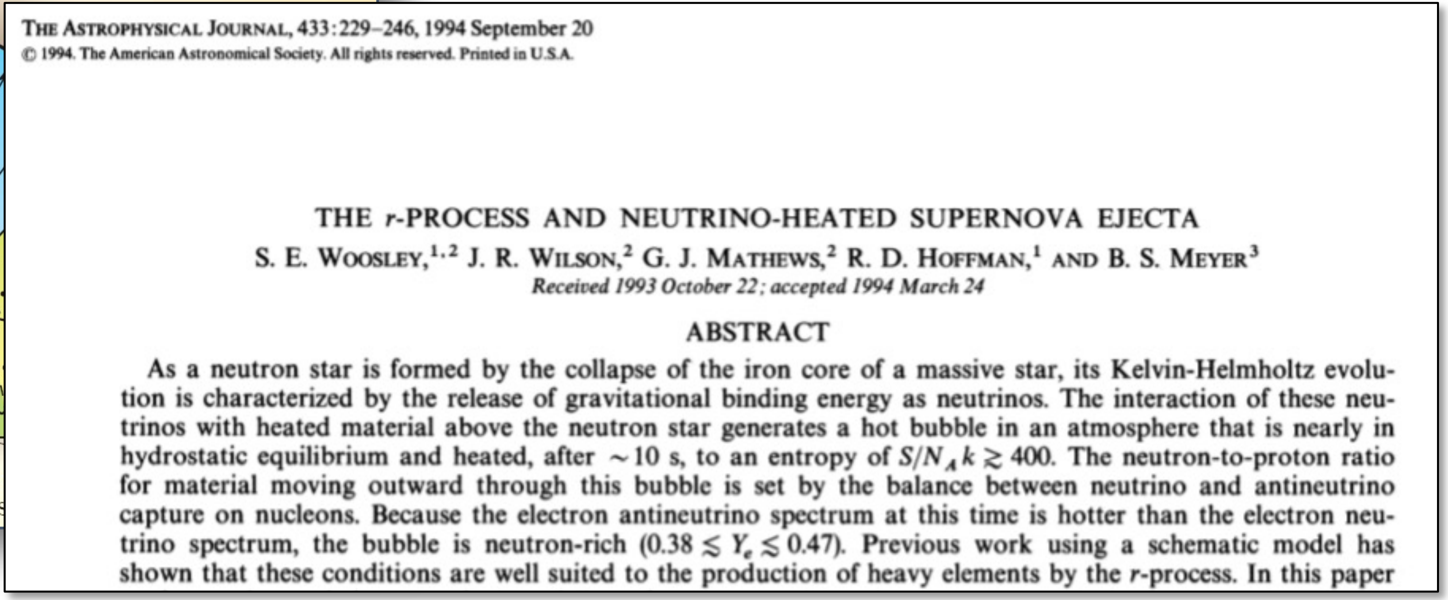
Alternative sites for the *r* process: neutrino-driven wind from a newborn neutron star



Equilibrium between (n,γ) and (γ,n) most of the time, only moderately neutron rich

Alternative sites for the *r* process: neutrino-driven wind from a newborn neutron star





THE ASTROPHYSICAL JOURNAL, 433:229–246, 1994 September 20

THE *r*-PROCESS AND NEUTRINO-HEATED SUPERNOVA EJECTA

S. E. WOOSLEY,[1,2] J. R. WILSON,[2] G. J. MATHEWS,[2] R. D. HOFFMAN,[1] AND B. S. MEYER[3]

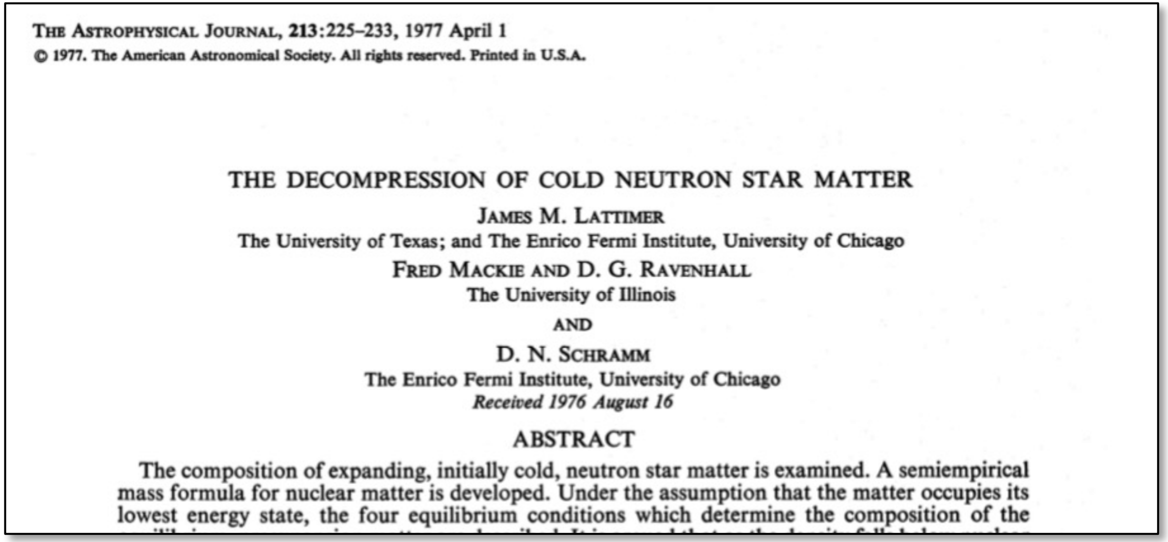
Received 1993 October 22; accepted 1994 March 24

ABSTRACT

As a neutron star is formed by the collapse of the iron core of a massive star, its Kelvin-Helmholtz evolution is characterized by the release of gravitational binding energy as neutrinos. The interaction of these neutrinos with heated material above the neutron star generates a hot bubble in an atmosphere that is nearly in hydrostatic equilibrium and heated, after ~10 s, to an entropy of $S/N_A k \gtrsim 400$. The neutron-to-proton ratio for material moving outward through this bubble is set by the balance between neutrino and antineutrino capture on nucleons. Because the electron antineutrino spectrum at this time is hotter than the electron neutrino spectrum, the bubble is neutron-rich ($0.38 \lesssim Y_e \lesssim 0.47$). Previous work using a schematic model has shown that these conditions are well suited to the production of heavy elements by the *r*-process. In this paper

Where can we find lots of neutrons?

Leftover after a supernova: black hole or **neutron star**

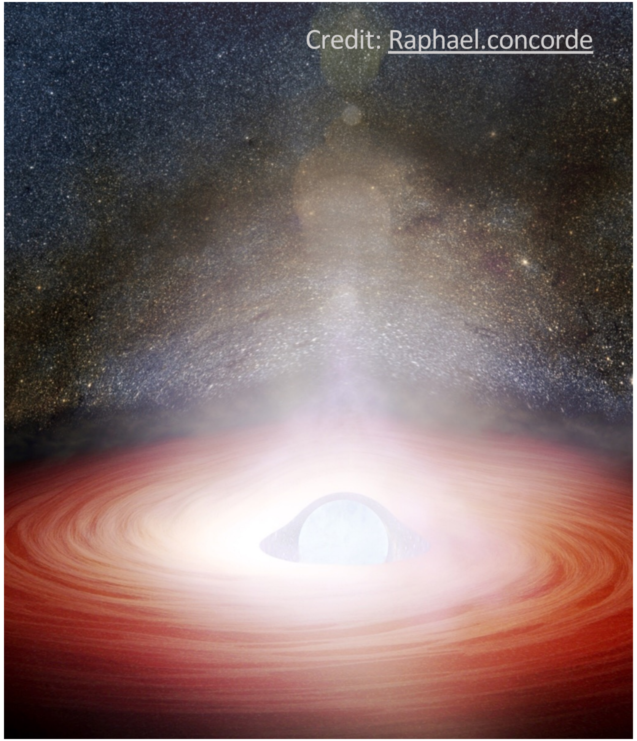

THE ASTROPHYSICAL JOURNAL, 213:225–233, 1977 April 1

THE DECOMPRESSION OF COLD NEUTRON STAR MATTER

JAMES M. LATTIMER
The University of Texas; and The Enrico Fermi Institute, University of Chicago
FRED MACKIE AND D. G. RAVENHALL
The University of Illinois
AND
D. N. SCHRAMM
The Enrico Fermi Institute, University of Chicago
Received 1976 August 16

ABSTRACT

The composition of expanding, initially cold, neutron star matter is examined. A semiempirical mass formula for nuclear matter is developed. Under the assumption that the matter occupies its lowest energy state, the four equilibrium conditions which determine the composition of the



First *live* observation of the *r* process in 2017 🥳🎉

Neutron-star merger observed live!

17 Aug 2017 by Adv. LIGO & Adv. Virgo

[Abbott et al., Phys. Rev. Lett. **119**, 161101 (2017)]

"Afterglow" consistent with *r*-process nucleosynthesis

[Kasen et al., Nature **551**, 80 (2017), E. Pian et al., Nature **551**, 67(2017) +++]

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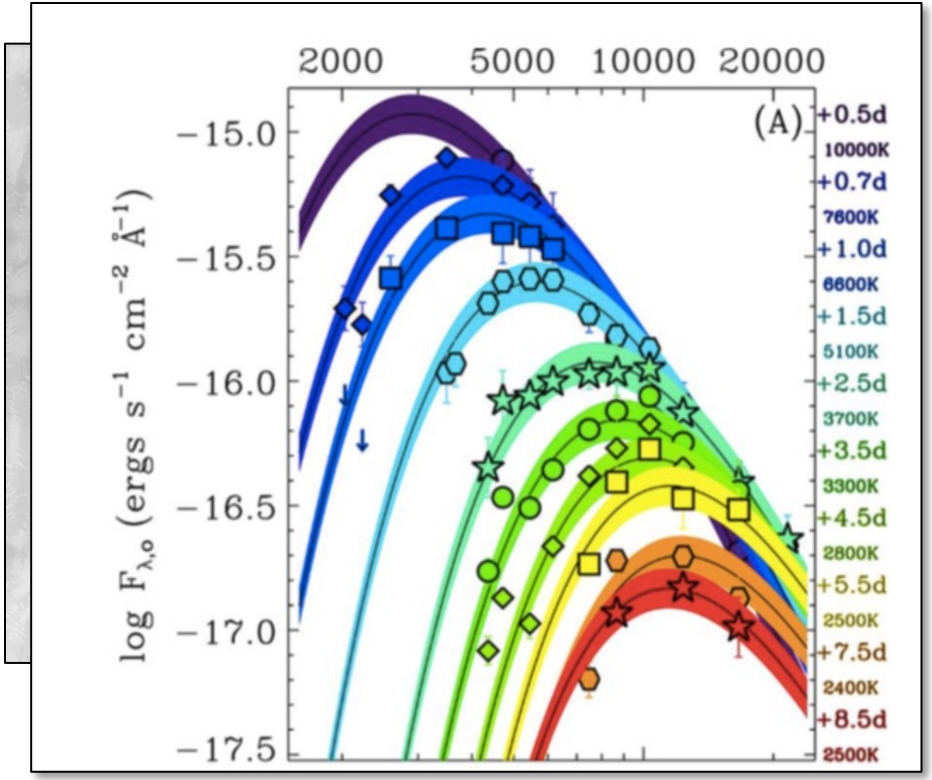

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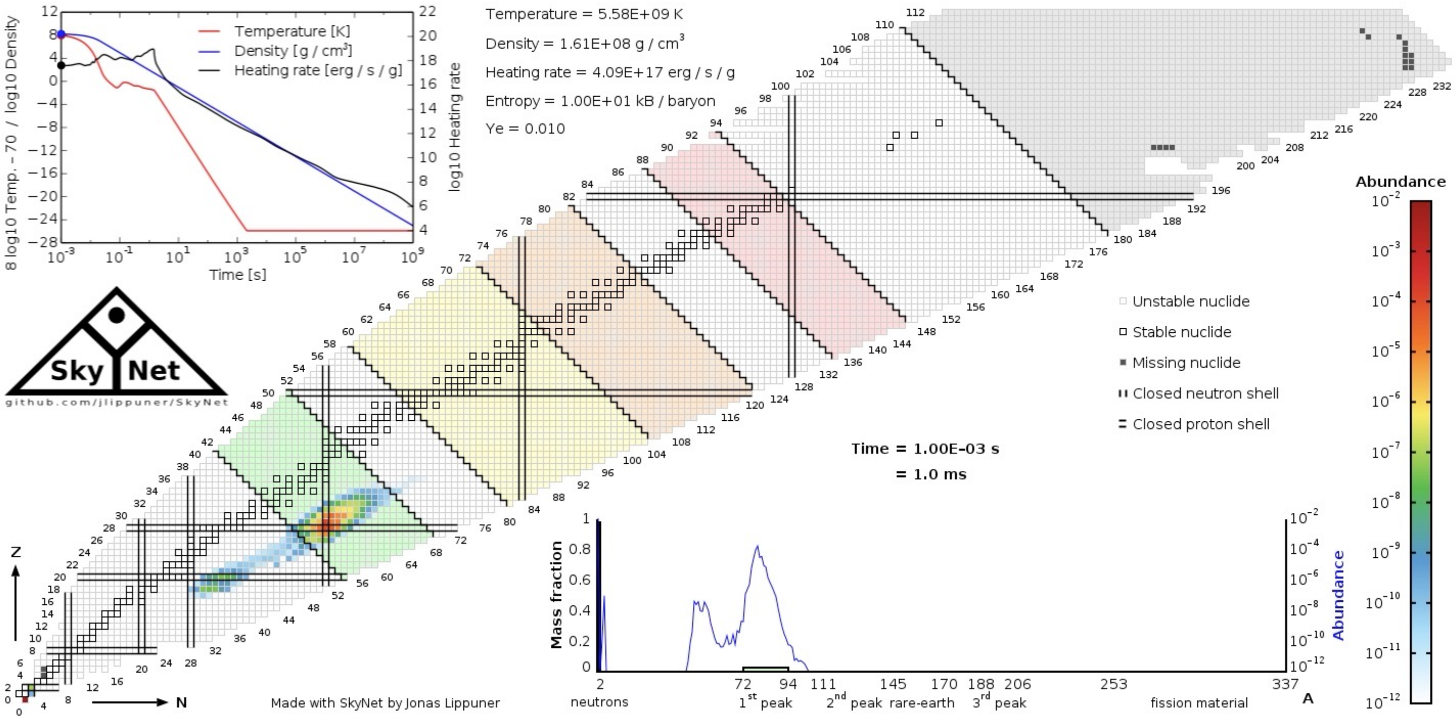
[Kasen et al., Nature **551**, 80 (2017), E. Pian et al., Nature **551**, 67(2017) +++]

M.R. Drout et al., Science **358**, 1570 (2017)

… So now we understand everything?

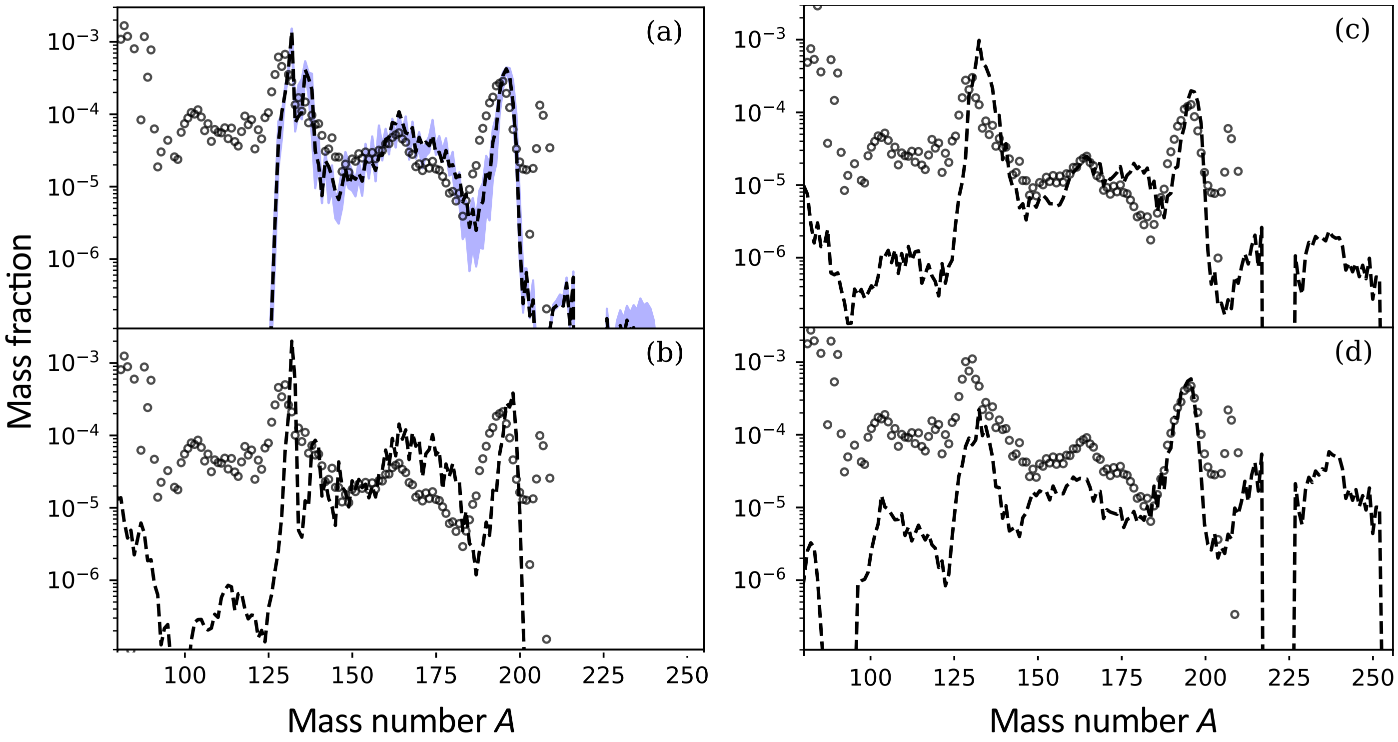


Jonas Lippuner, Skynet https://jonaslippuner.com/research/skynet/

Note: for *one* astrophysical trajectory

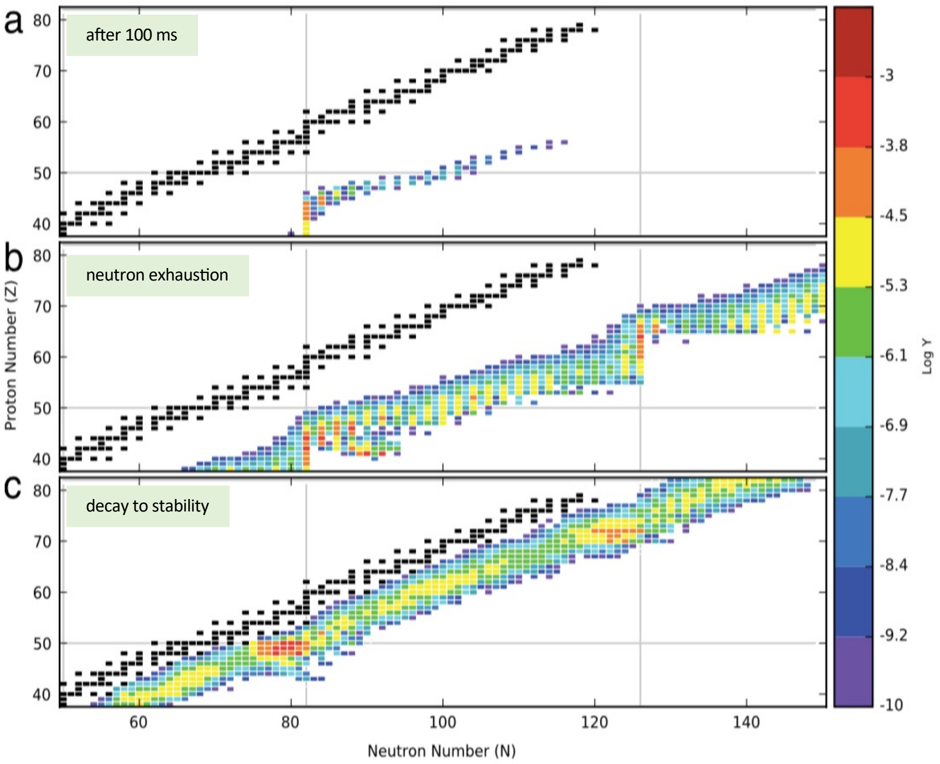
Maybe not...

Calculated *r*-process abundances for **four** different astrophysical conditions, **many** different nuclear-physics input models [level densities and gamma strength functions]. Note the log scale!



Calculations with "Skynet" 😊
[Pogliano & Larsen, Phys. Rev. C 108, 025807 (2023)]

Difficult stuff...



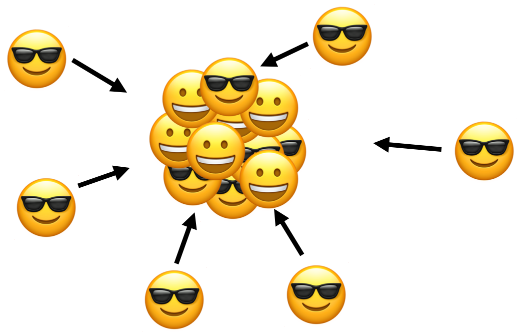
Snapshots , reaction network, neutron-star collision trajectory
Mumpower, Surman, McLaughlin, Aprahamian, Prog.Part. Nucl. Phys. 86, 86 (2016)

A big bunch of differential equations!!

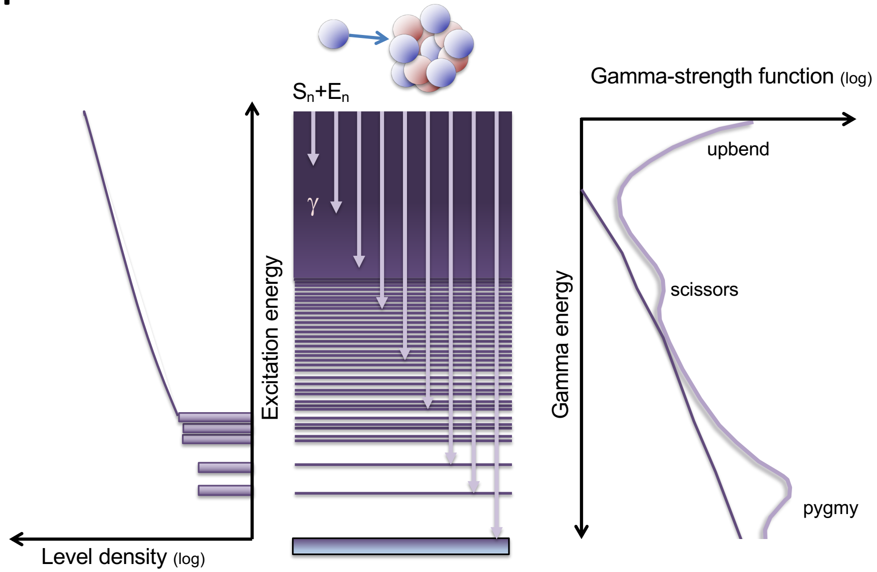
We need a reaction network of about 5000 nuclei and their possible (≈ 50 000) reactions – most of the nuclei are very short-lived! 😱

These nuclei are very hard to create in the lab...

Radiative neutron-capture reactions



(Wolfenstein-)Hauser-Feshbach theory
-> “compound nucleus” picture of Bohr
[W. Hauser and H. Feshbach, Phys. Rev. 87, 366 (1952)]



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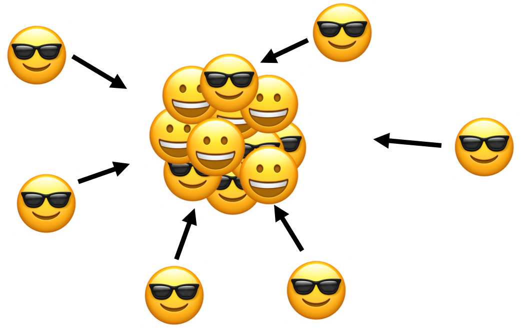

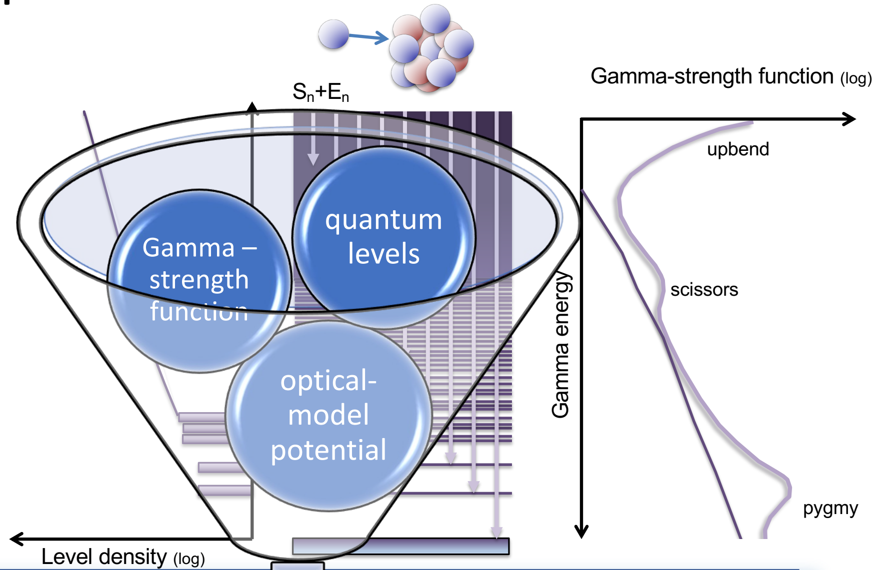

(Wolfenstein-)Hauser-Feshbach theory
-> “compound nucleus” picture of Bohr
[W. Hauser and H. Feshbach, Phys. Rev. 87, 366 (1952)]

Reaction rate (actually it’s reactivity):

$$N_A\langle\sigma v\rangle(T)=\left(\frac{8}{\pi m}\right)^{1/2}\frac{N_A}{(kT)^{3/2}G(T)}\int_0^\infty\sum_\mu\frac{(2I^\mu+1)}{(2I^0+1)}\sigma^\mu(E)E\exp\left[-\frac{(E+E_x^\mu)}{kT}\right]dE$$

$$G(T)=\sum_\mu(2I^\mu+1)/(2I^0+1)\exp(-E_x^\mu/kT)$$

Summary – key points 🗝️

- **Three main processes** for heavy-element nucleosynthesis: *s*, *r*, *p* process
- The ***p* process** is a secondary process; seed nuclei from the *s* and *r* processes; likely takes place in SN Ia and SN II (O-Ne shell)
- The ***s* process** deals with nuclei close to the valley of stability; astrophysical sites: AGB stars and massive stars (>8☀️)
- The ***r* process** involves highly neutron-rich nuclei; one astrophysical site (neutron-star mergers) has recently been confirmed
- To calculate **radiative-capture reaction rates** that cannot be measured directly, one needs an optical-model potential, the **nuclear level density**, and the **gamma-ray strength function**

To be continued tomorrow 😀