

Forschung trifft Schule

Das Leben, das Universum & der ganze Rest

Eine Einführung in die nukleare Astrophysik

Steffen Turkat

27.09.2022



In Vorbereitung für das Seminar:

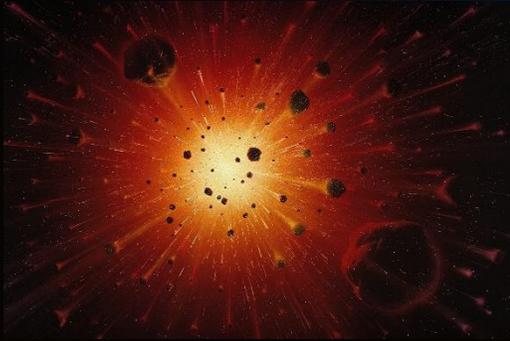
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INSTITUTE OF
NUCLEAR AND
PARTICLE PHYSICS



Konrad
Adenauer
Stiftung



Universum & Kosmologie

- Was ist in den letzten 14 Mrd. Jahren im Universum passiert?
- Wie sieht die Zukunft unseres Universums aus?



Nukleare Astrophysik

- Auf der Suche nach dem Ursprung aller Elemente



Kurzer Einblick in eigene Forschung

- Das Felsenkeller-Untertagelabor in Dresden
- Virtuelle Tour durch die Stollenanlage

Kern- und Teilchenphysik

Was die Welt im Innersten zusammenhält

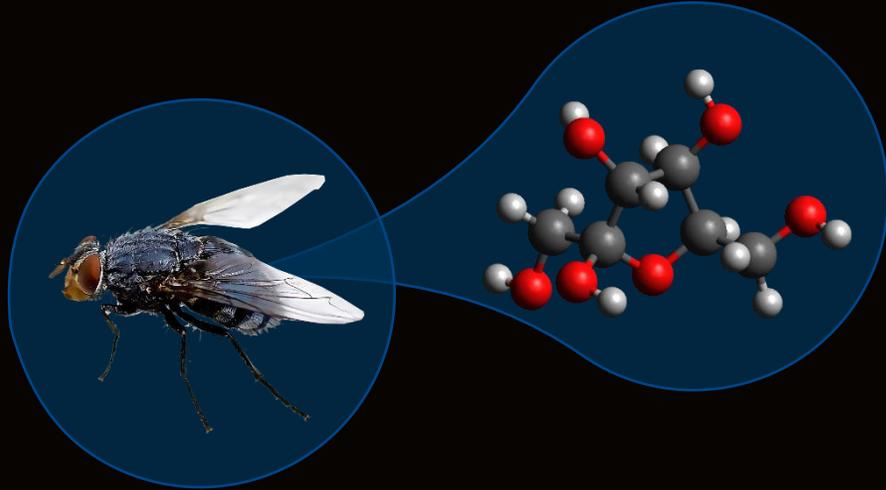
➤ Größenskalen im Universum



Biologie
~ 10^{-2} m

Was die Welt im Innersten zusammenhält

➤ Größenskalen im Universum



Biologie
~ 10^{-2} m

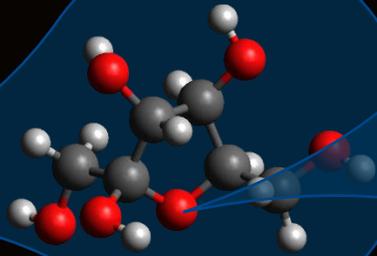
Chemie
~ 10^{-9} m

Was die Welt im Innersten zusammenhält

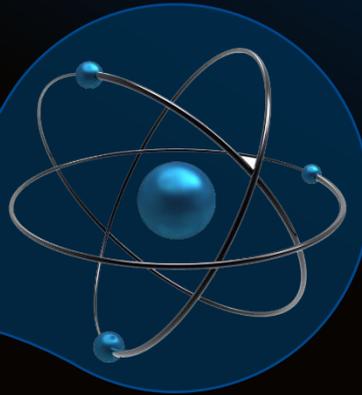
➤ Größenskalen im Universum



Biologie
 $\sim 10^{-2} \text{ m}$



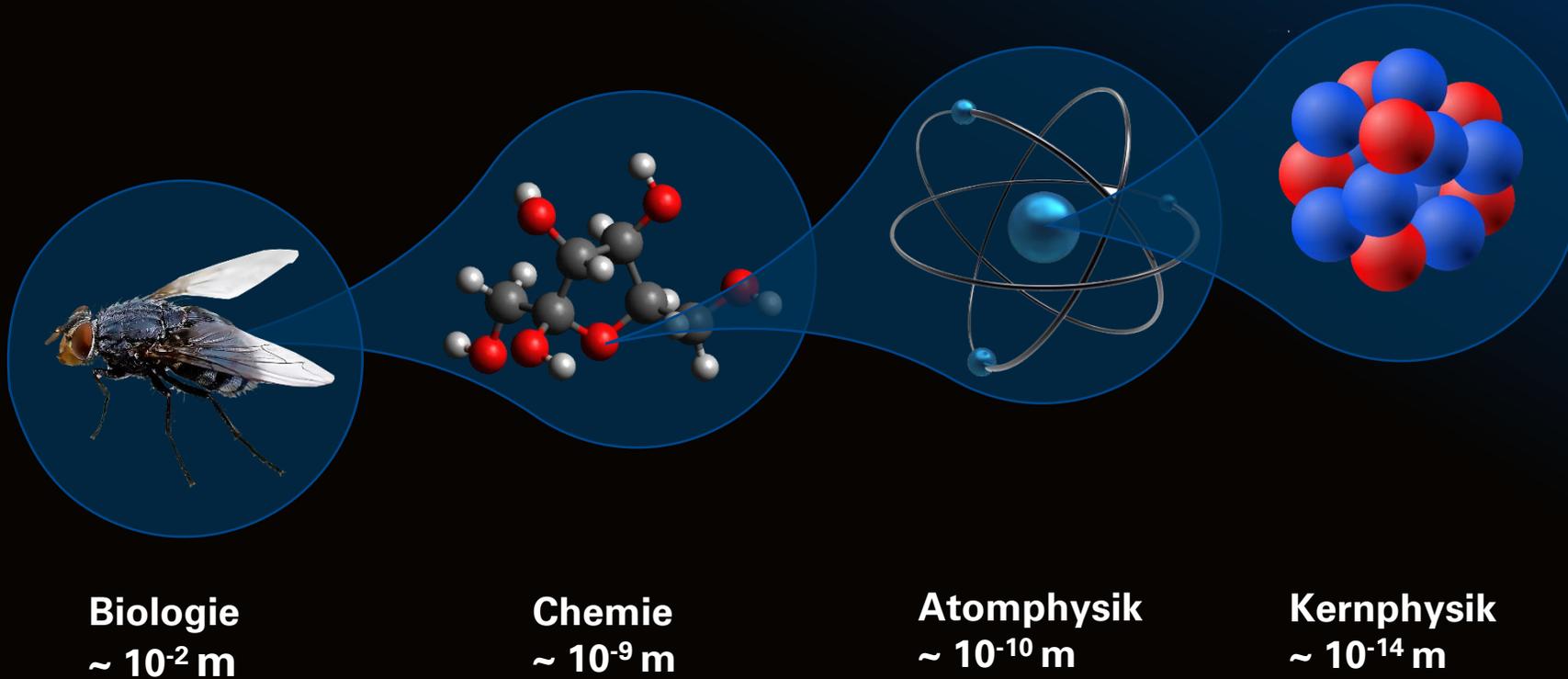
Chemie
 $\sim 10^{-9} \text{ m}$



Atomphysik
 $\sim 10^{-10} \text{ m}$

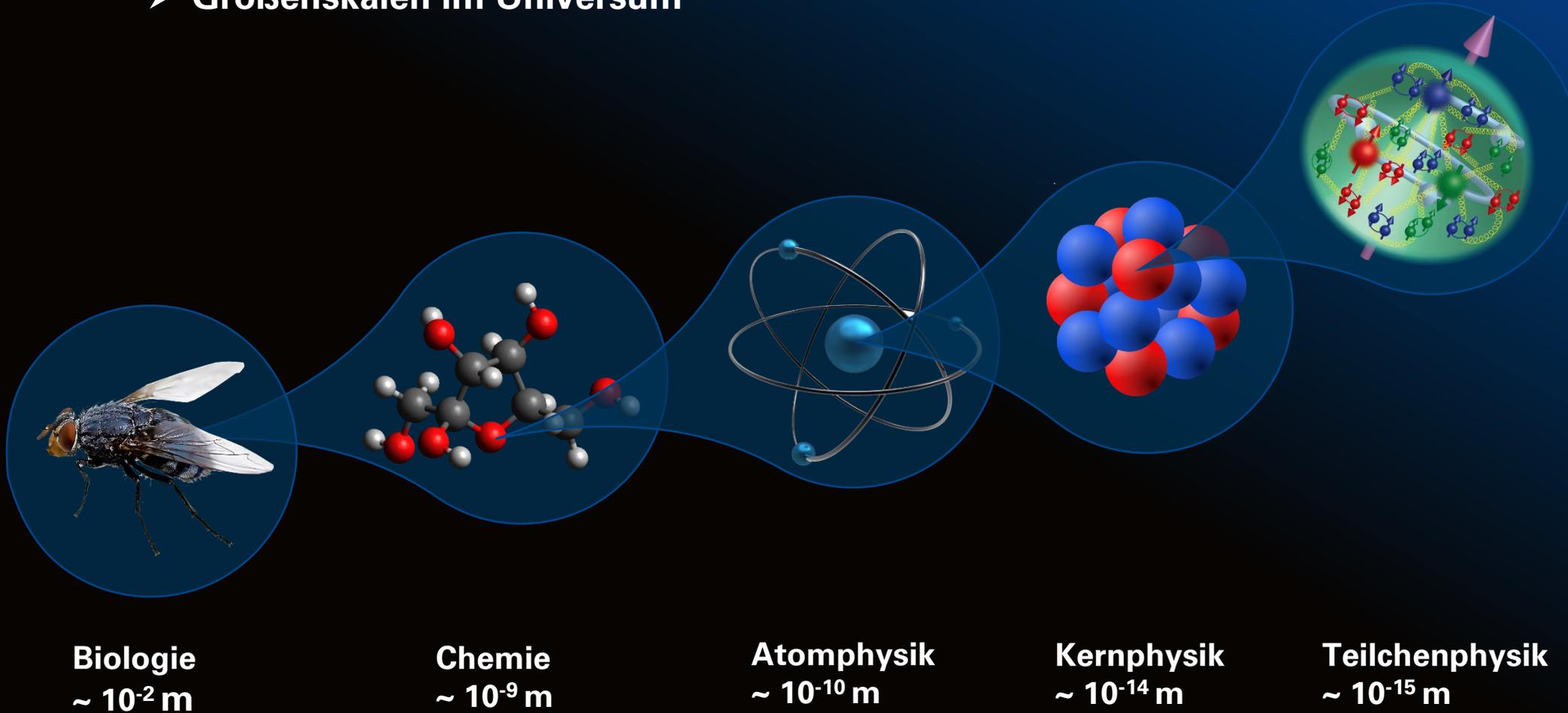
Was die Welt im Innersten zusammenhält

➤ Größenskalen im Universum



Was die Welt im Innersten zusammenhält

➤ Größenskalen im Universum

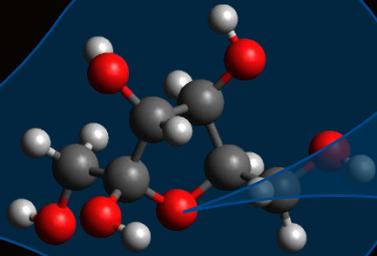


Was die Welt im Innersten zusammenhält

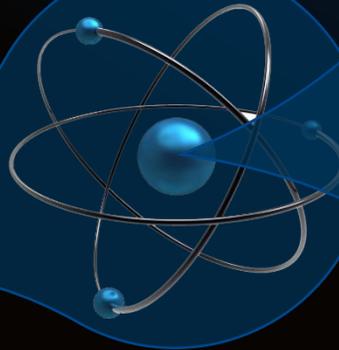
➤ Größenskalen im Universum



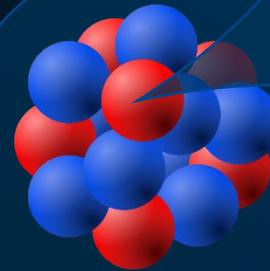
Biologie
~ 10^{-2} m



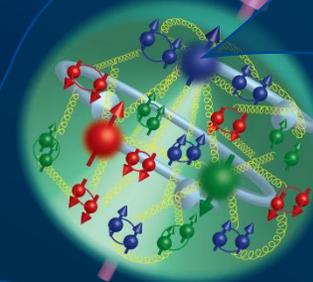
Chemie
~ 10^{-9} m



Atomphysik
~ 10^{-10} m



Kernphysik
~ 10^{-14} m



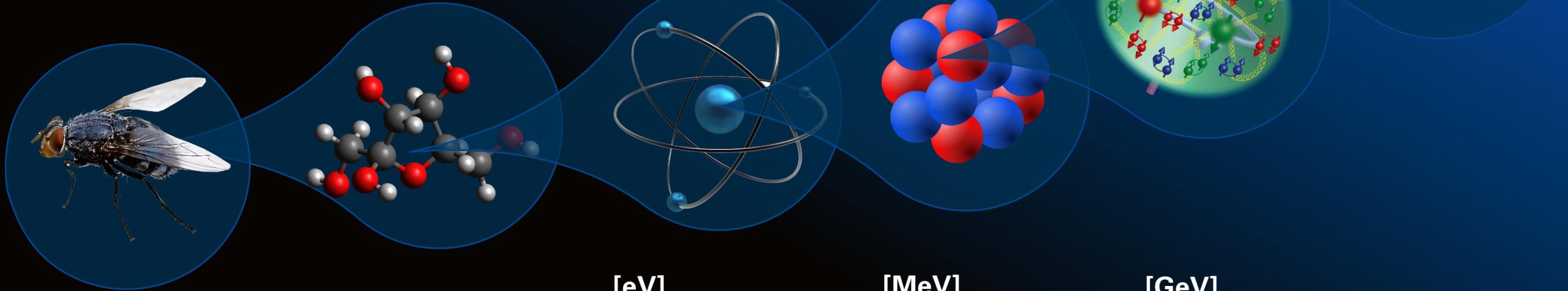
Teilchenphysik
~ 10^{-15} m



→ ???
< 10^{-18} m

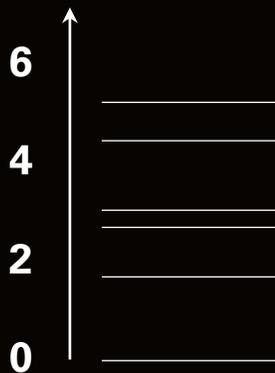
Was die Welt im Innersten zusammenhält

➤ Größenskalen im Universum

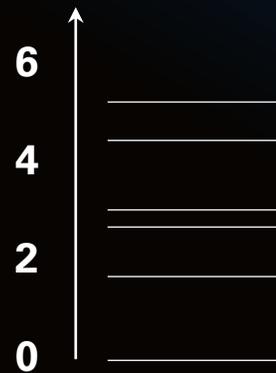


➤ Energieskalen im Universum

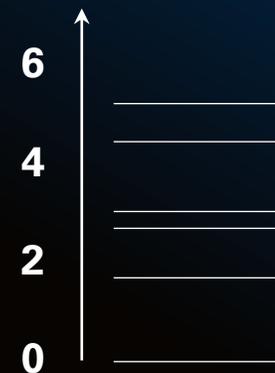
[eV]



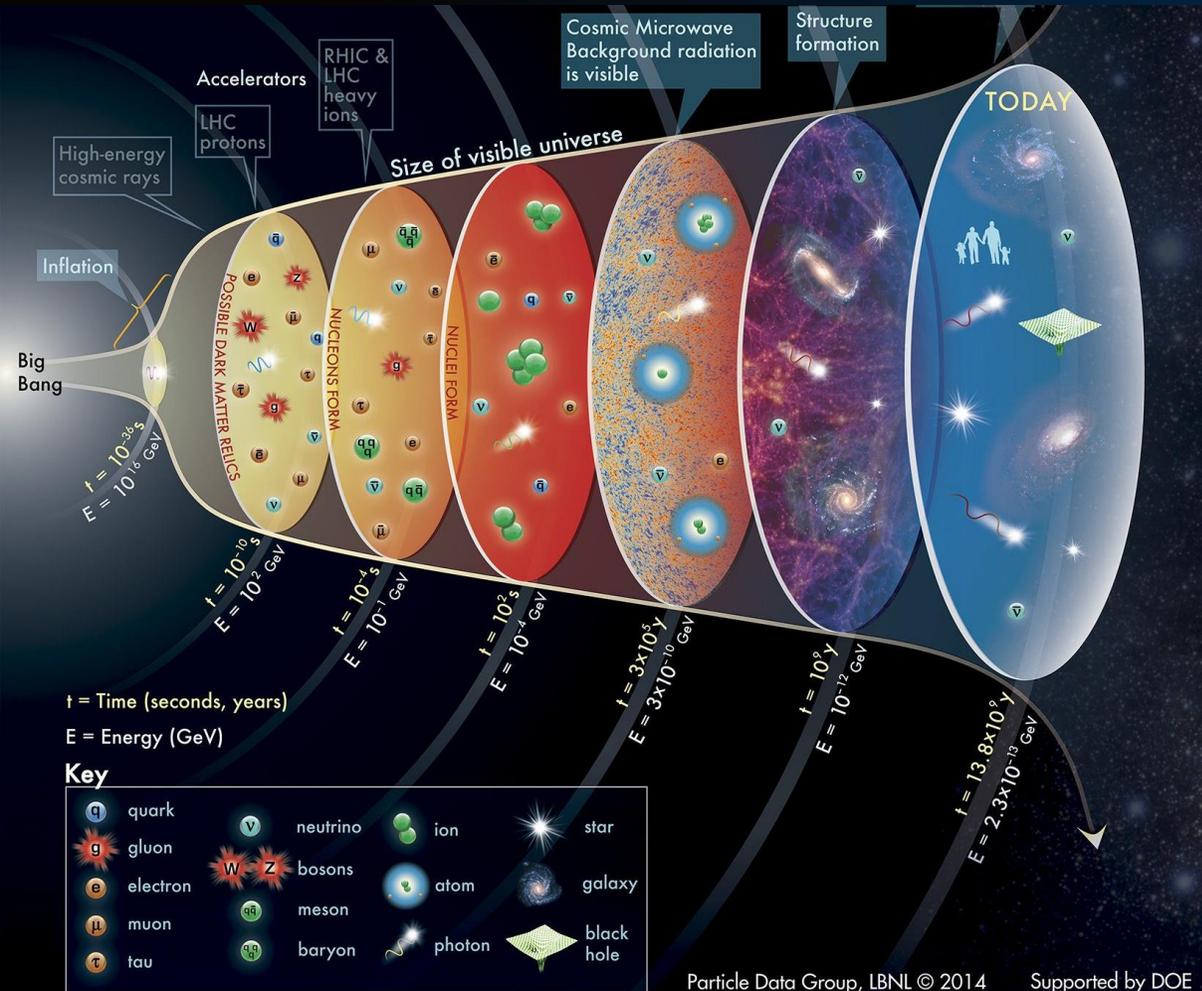
[MeV]



[GeV]

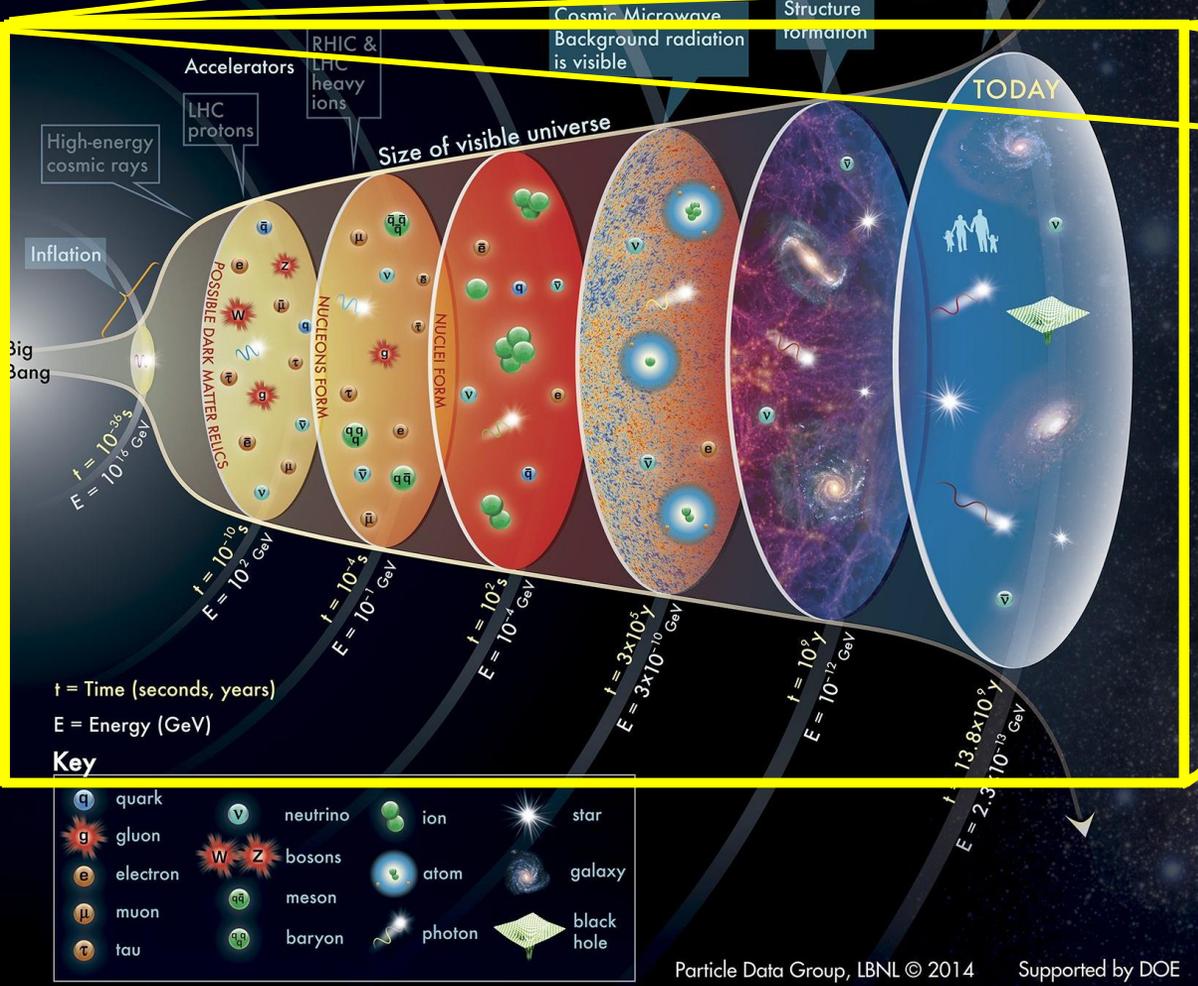
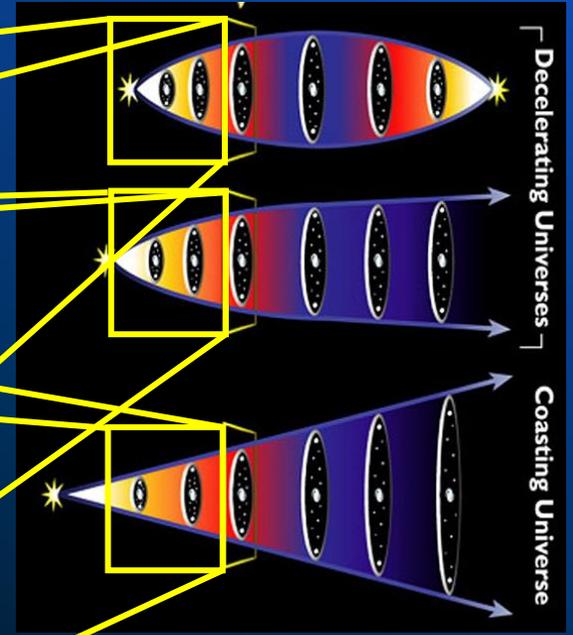


Was ist in den letzten 13.8 Milliarden Jahren so passiert?



- 0s Big Bang
- $10^{-44} s$ Planck-Zeit
- $10^{-32} s$ Inflation
- $10^{-6} s$ Bildungen von Proton & Neutron
- $10^0 s$ Urknall-Nukleosynthese
- 380000 y Mikrowellen-Hintergrundstrahlung
- $10^8 y$ Erste Sterne
- $1.38 \cdot 10^{10} y$ Heute

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- 0s **Big Bang**
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- 10^8 y **Erste Sterne**
- $1.38 \cdot 10^{10}$ y **Heute**

Nukleare Astrophysik

Chemische Zusammensetzung des Universums

➤ Wie, wann und in welchen Mengen wurden die Elemente unseres Universums gebildet?

Periodic Table of the Elements

1 IA 1A																	18 VIIIA 8A	
1 H Hydrogen 1.008	2 IIA 2A												3 IIIA 3A	4 IVA 4A	5 VA 5A	6 VIA 6A	7 VIIA 7A	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180	
11 Na Sodium 22.990	12 Mg Magnesium 24.305	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8		9	10	11 IB 1B	12 IIB 2B	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798	
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294	
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71		72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.222	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium 209	85 At Astatine 209	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103		104 Rf Rutherfordium 261	105 Db Dubnium 262	106 Sg Seaborgium 266	107 Bh Bohrium 264	108 Hs Hassium 269	109 Mt Meitnerium 268	110 Ds Darmstadtium 281	111 Rg Roentgenium 280	112 Cn Copernicium 285	113 Nh Nihonium 286	114 Fl Flerovium 289	115 Mc Moscovium 289	116 Lv Livermorium 293	117 Ts Tennessine 294	118 Og Oganesson 294
Lanthanide Series		57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.242	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967		
Actinide Series		89 Ac Actinium 227.038	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium 254	100 Fm Fermium 257.085	101 Md Mendelevium 258	102 No Nobelium 259	103 Lr Lawrencium 262		

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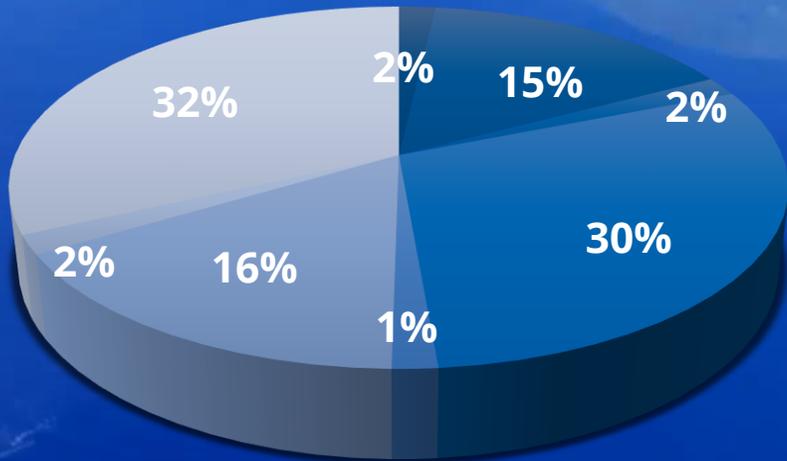
<https://sciencenotes.org/periodic-table-2017-edition-black-white/>

Chemische Zusammensetzung unserer Erde

Was sind die vier häufigsten Elemente unserer Erde?

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→ Alles einfach so lassen, der Rest erscheint automatisch

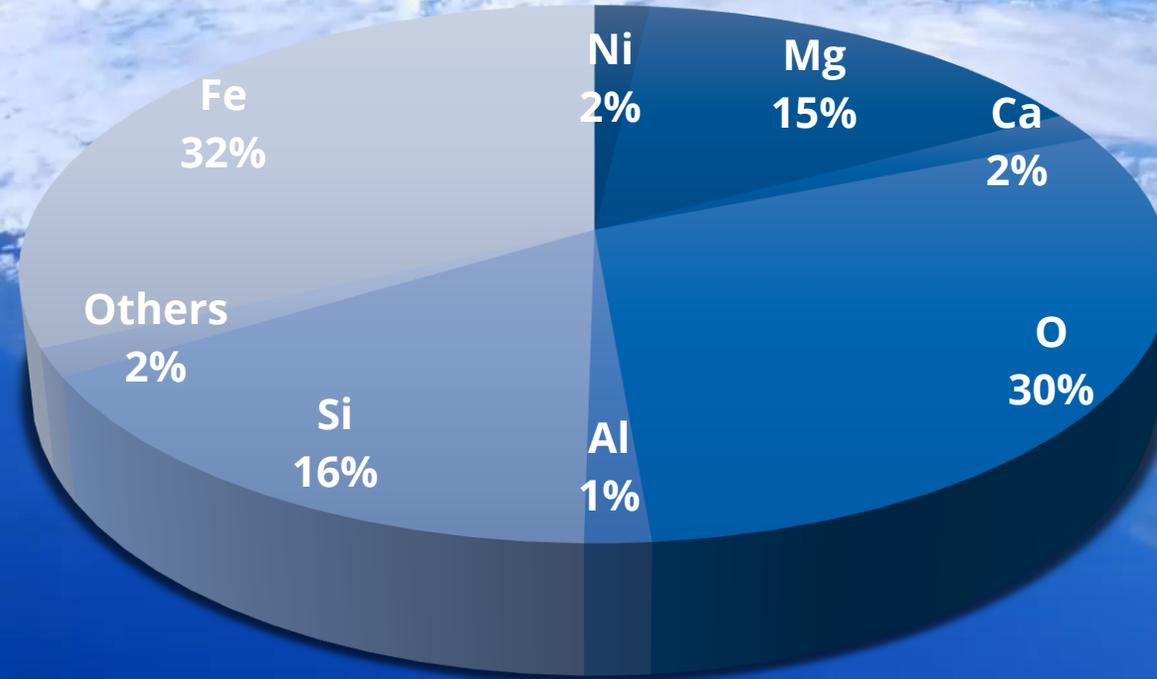


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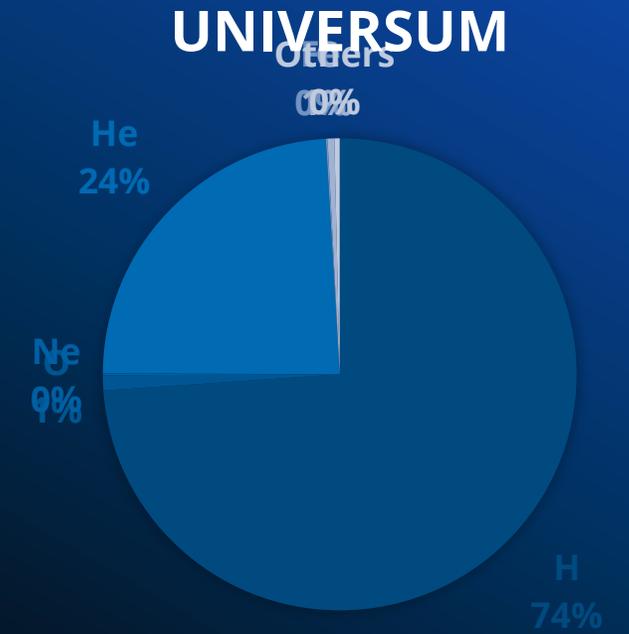
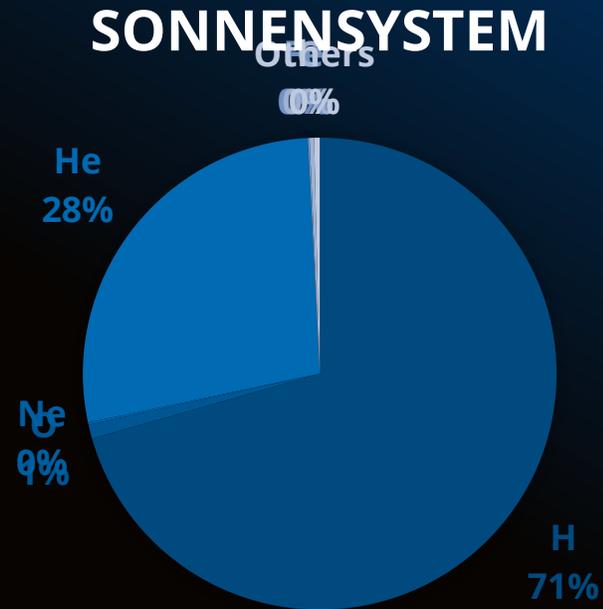
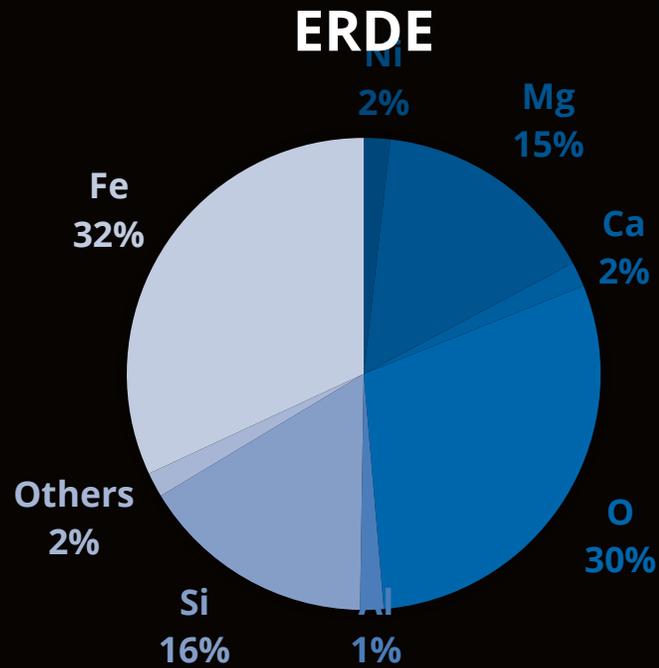
Was sind die vier häufigsten Elemente unserer Erde?

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Chemische Zusammensetzung unserer Erde



Die Zusammensetzung unserer Erde



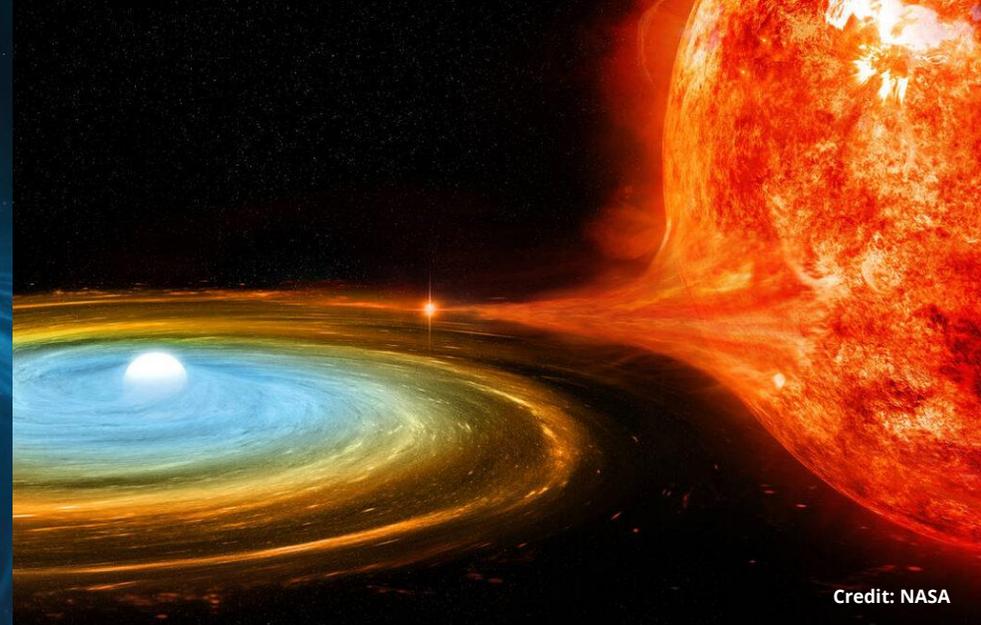
Die Geburtsstätten des Universums



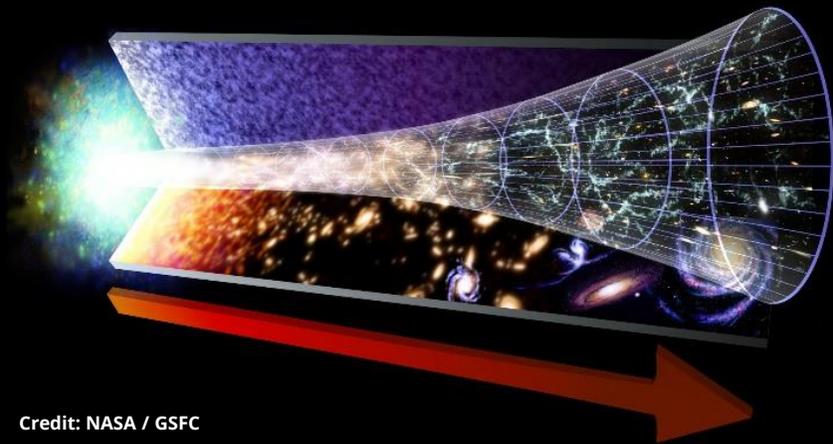
Credit: NASA



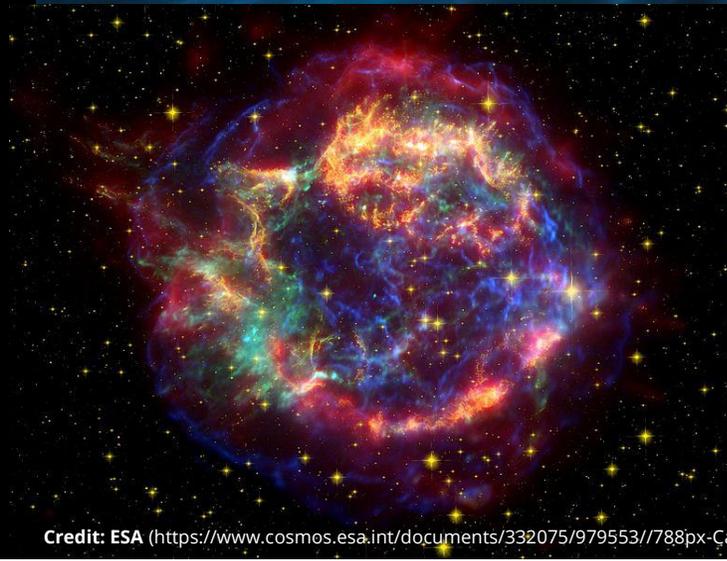
Credit: ESO/M.Kornmesser (<https://www.eso.org/public/germany/images/eso1229a/>)



Credit: NASA



Credit: NASA / GSFC

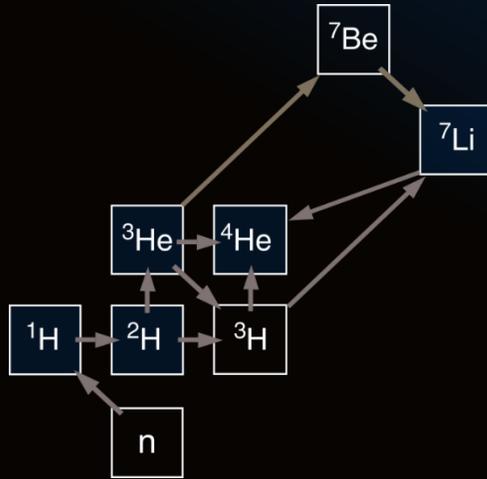


Credit: ESA (https://www.cosmos.esa.int/documents/332075/979553/788px-Cassiopeia_A_Spitzer_Crop.jpg)

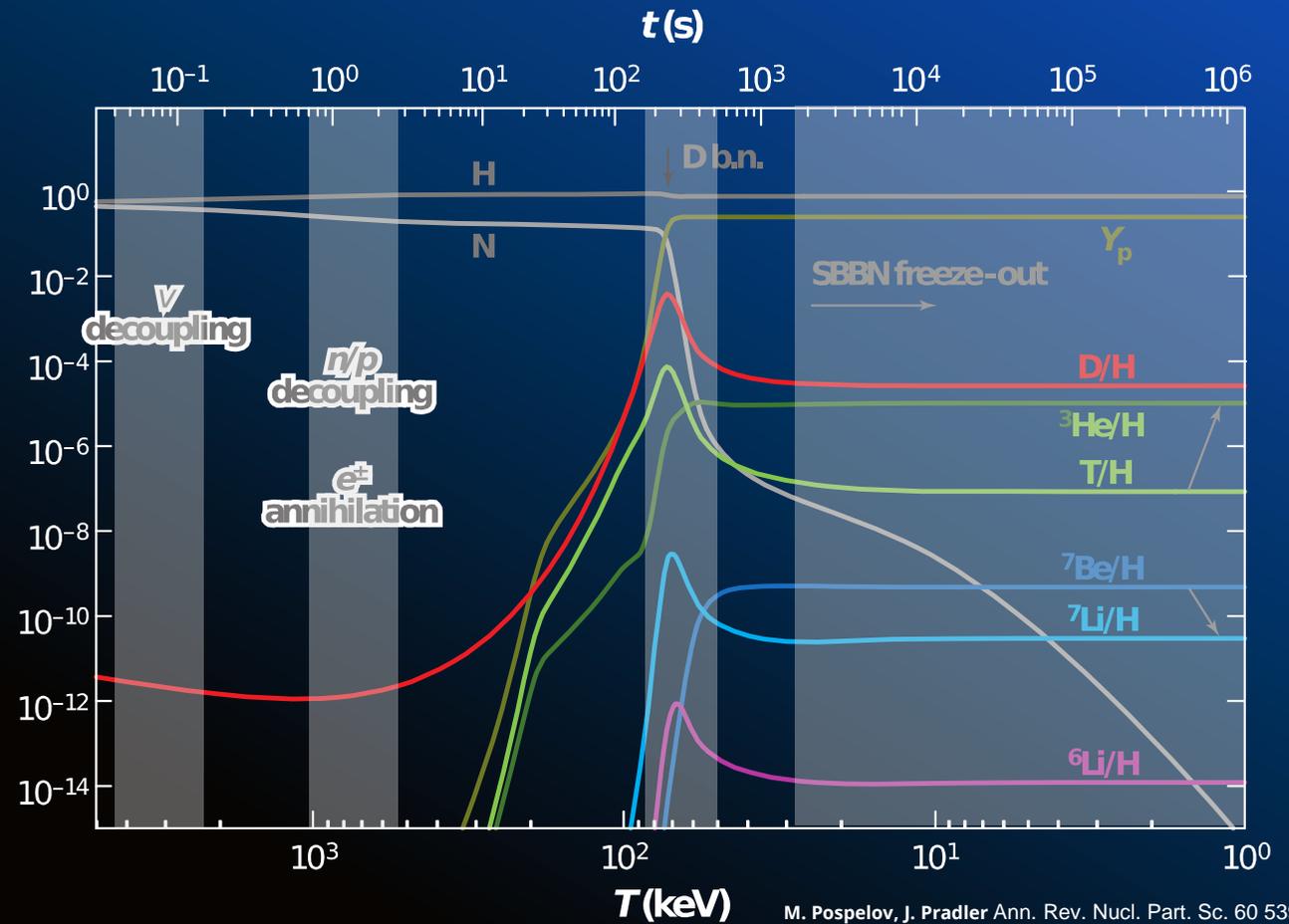
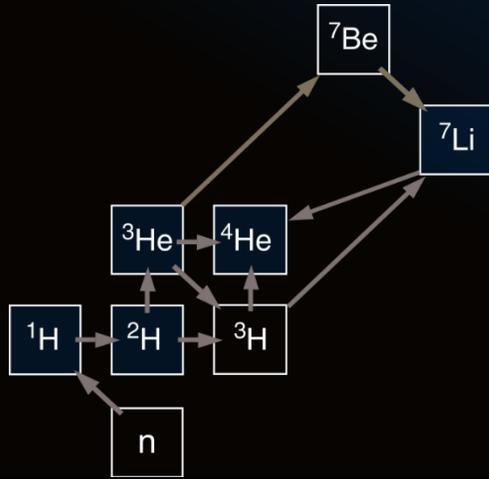


Credit: ESO (<https://www.eso.org/public/images/eso1733q/>)

Die Nuklidkarte

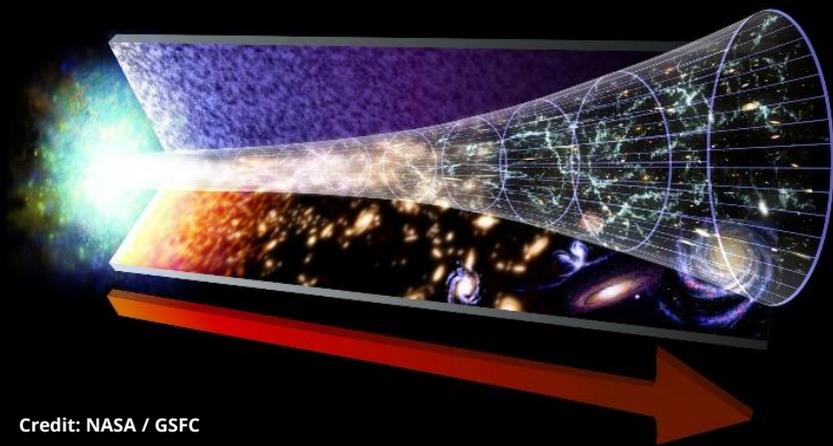


Die Urknall-Nukleosynthese



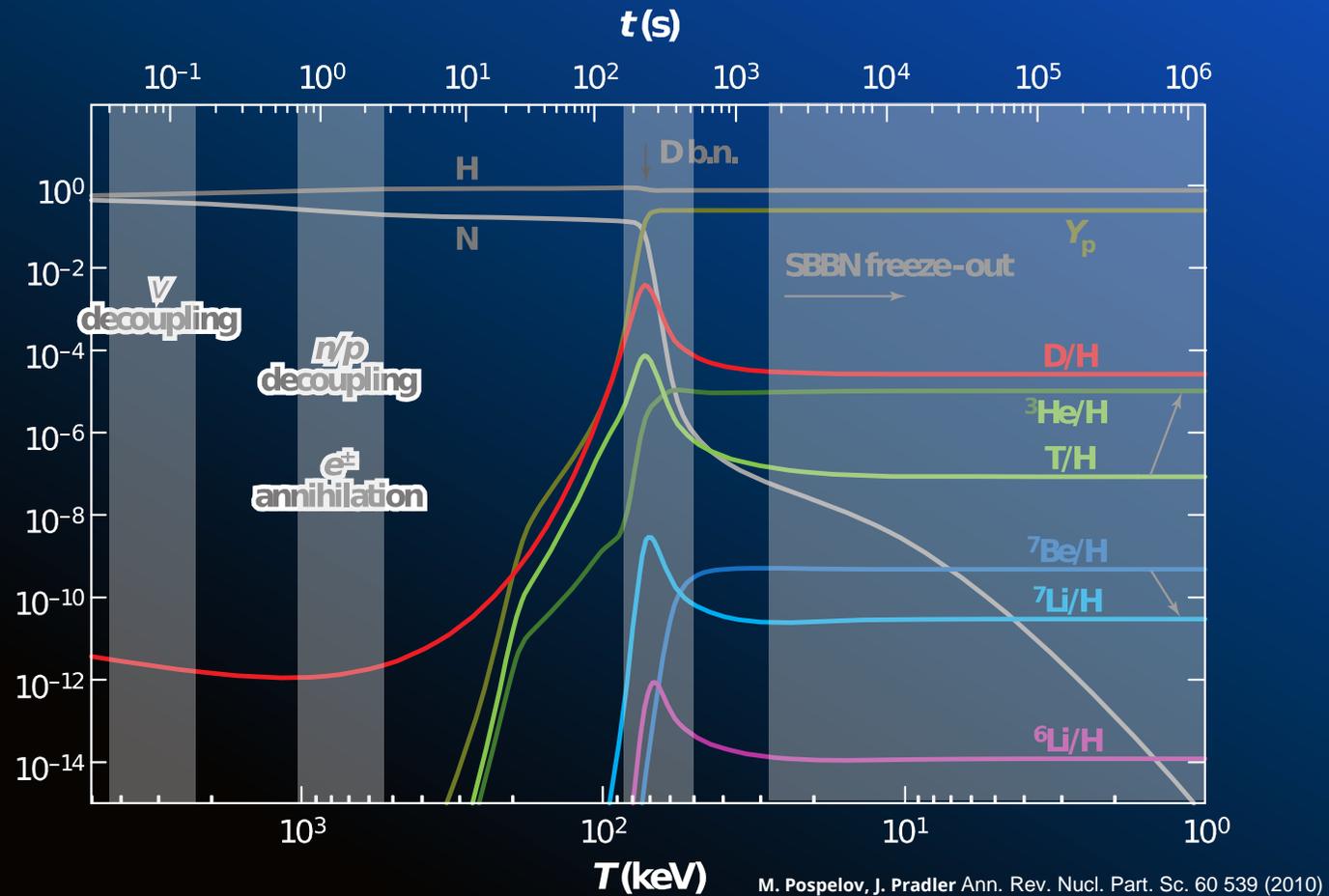
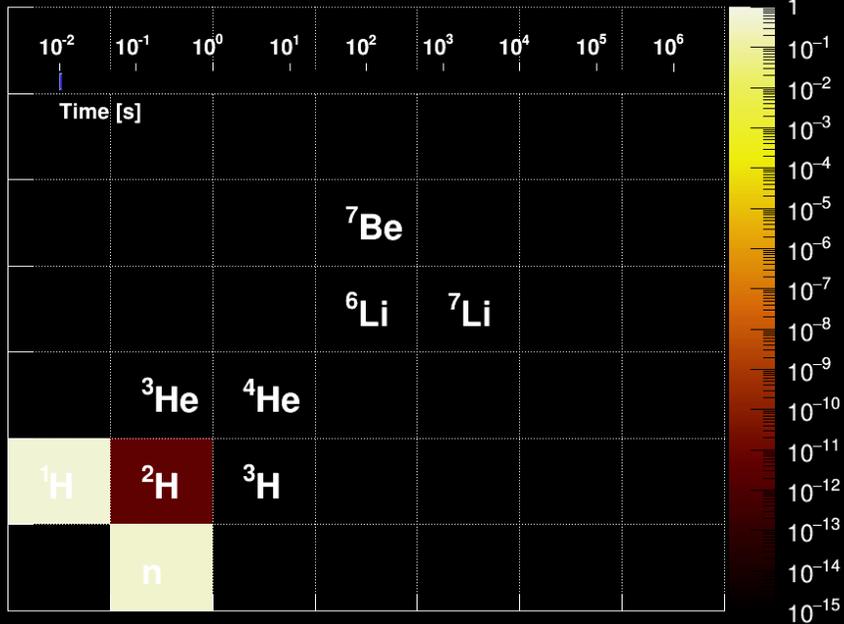
M. Pospelov, J. Pradler Ann. Rev. Nucl. Part. Sc. 60 539 (2010)

- **Chromodynamische Bindungsenergie p/n:** ~ 1 GeV
- **${}^2\text{H}$ Flaschenhals:** Das ganze Universums musste auf Deuterium warten



Credit: NASA / GSFC

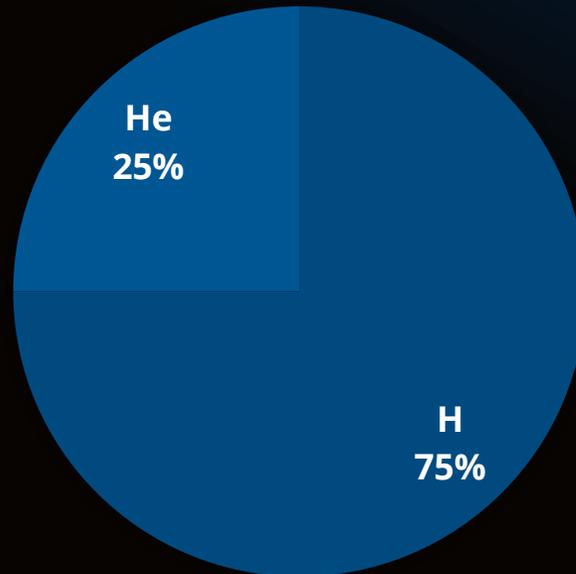
Die Urknall-Nukleosynthese



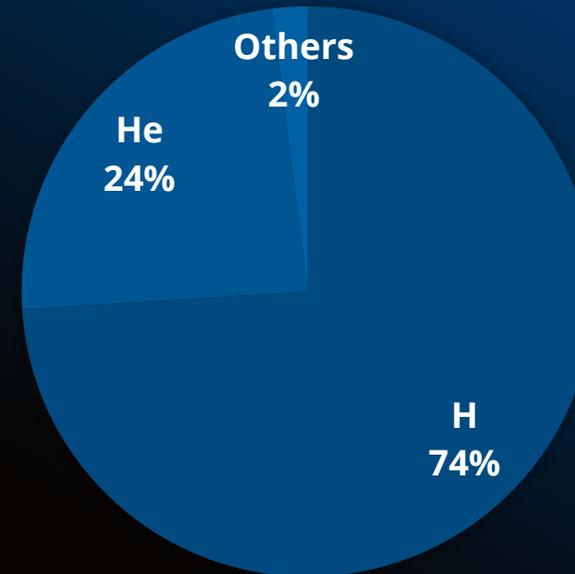
- **Chromodynamische Bindungsenergie p/n: ~1 GeV**
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Der Ursprung der Elemente

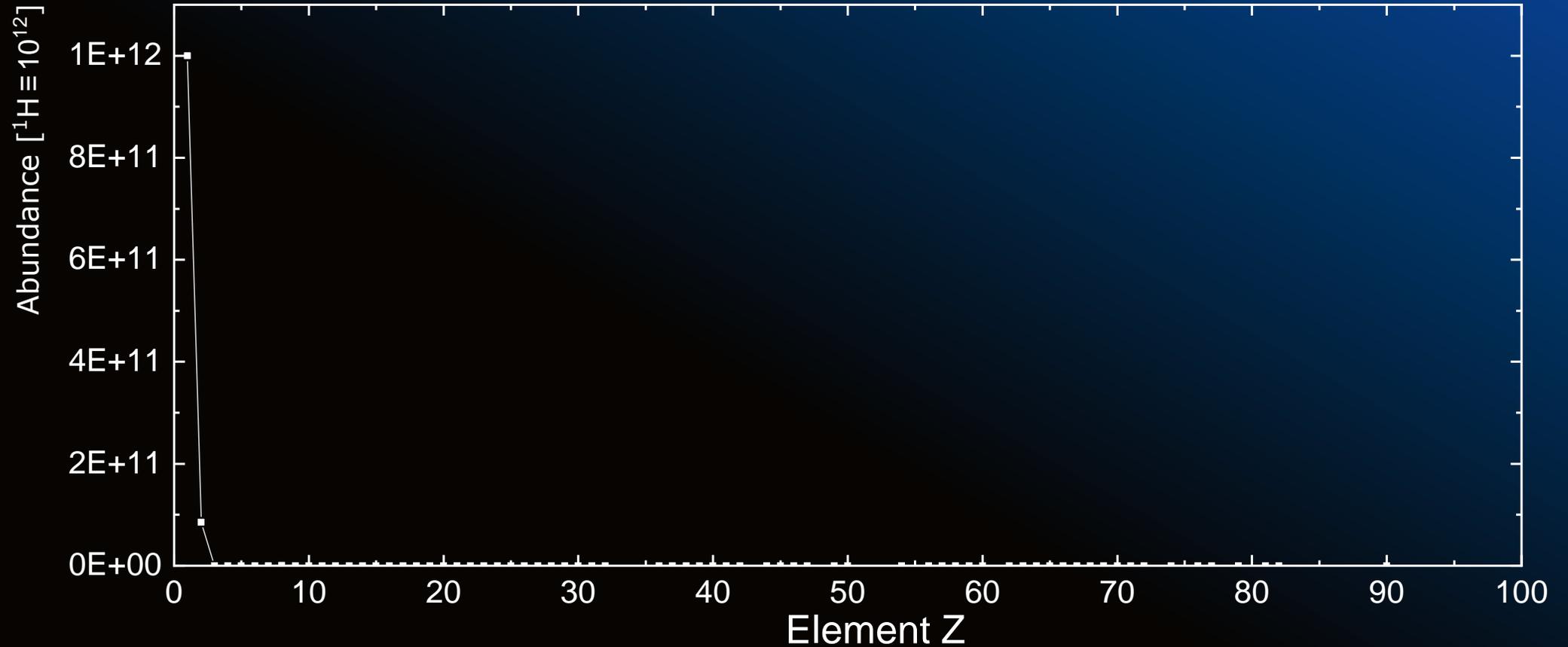
URKNALL-NUKLEOSYNTHESE



DERZEITIGES UNIVERSUM

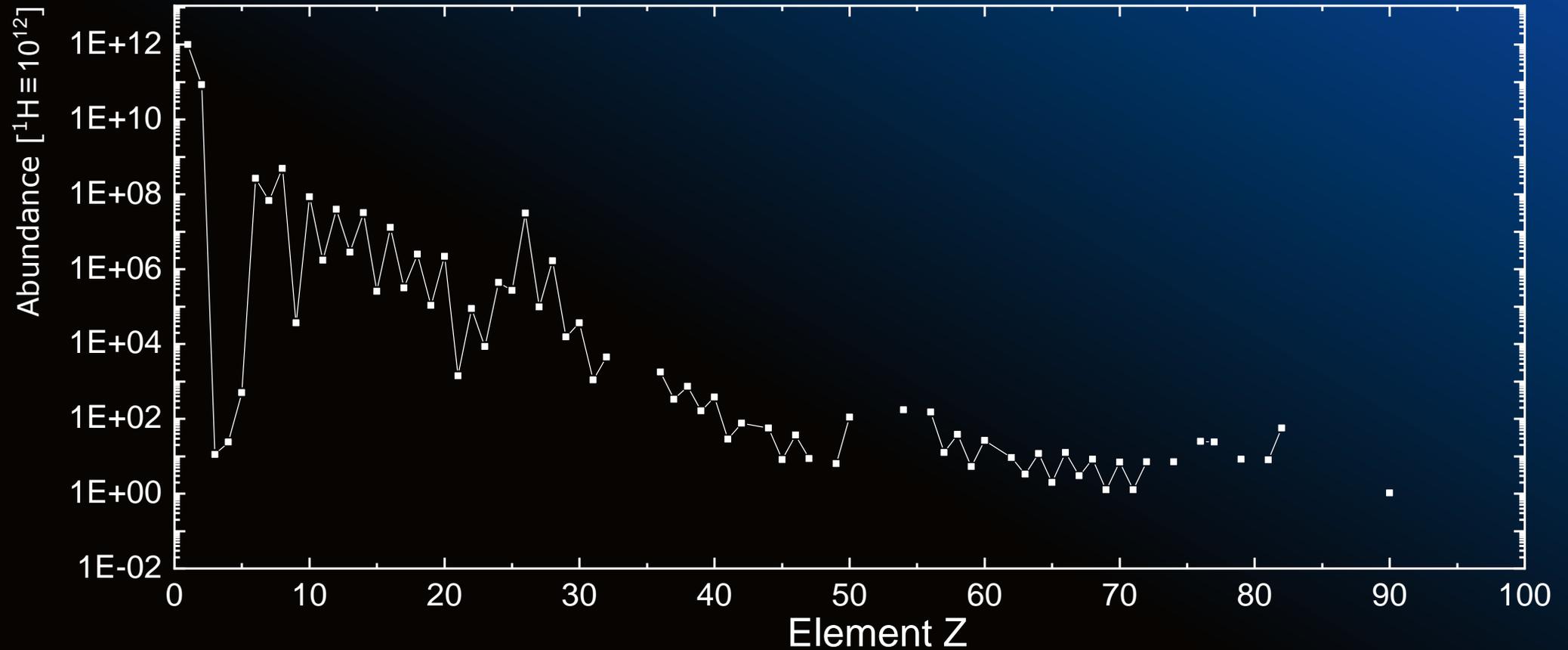


Chemische Zusammensetzung der solaren Photosphäre



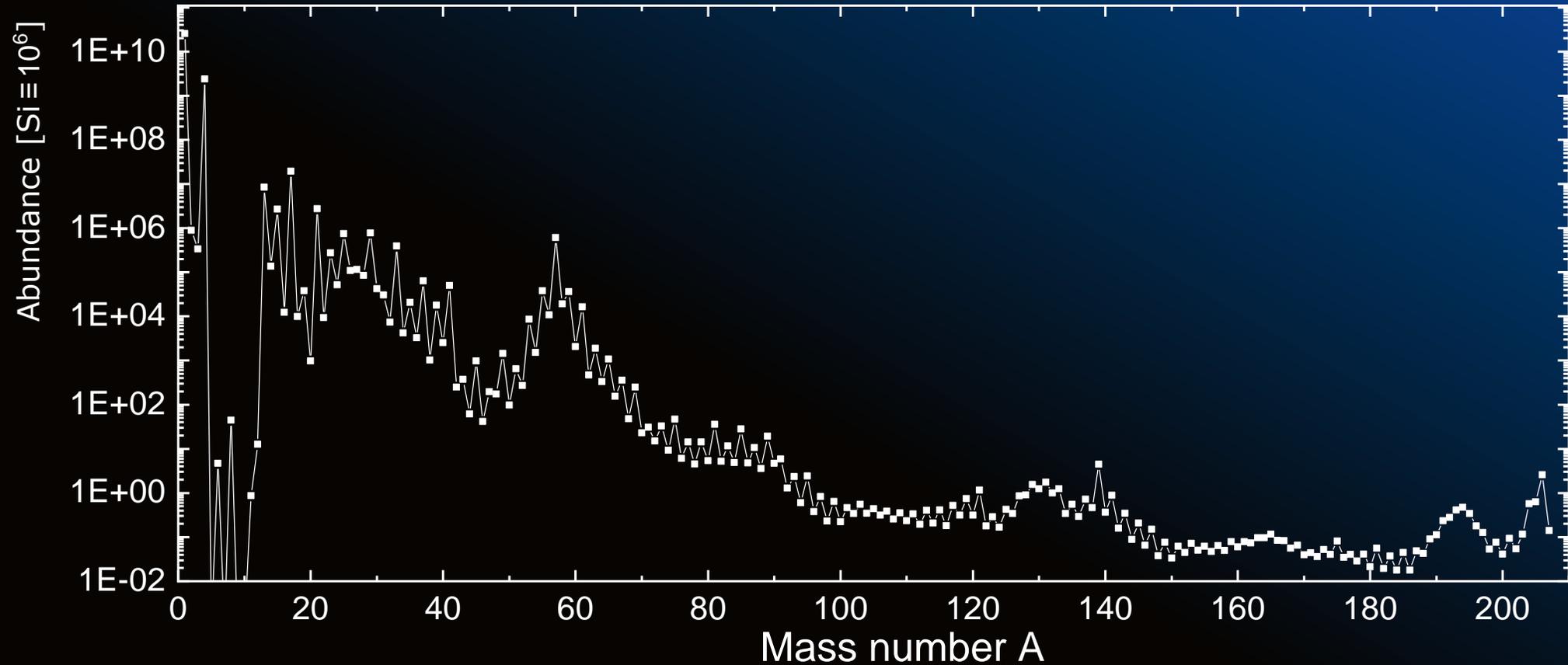
Data from: M. Asplund *et al.* Annual Reviews of Astronomy and Astrophysics, Vol. 47, 481 (2009)

Elemental abundance of the solar photosphere



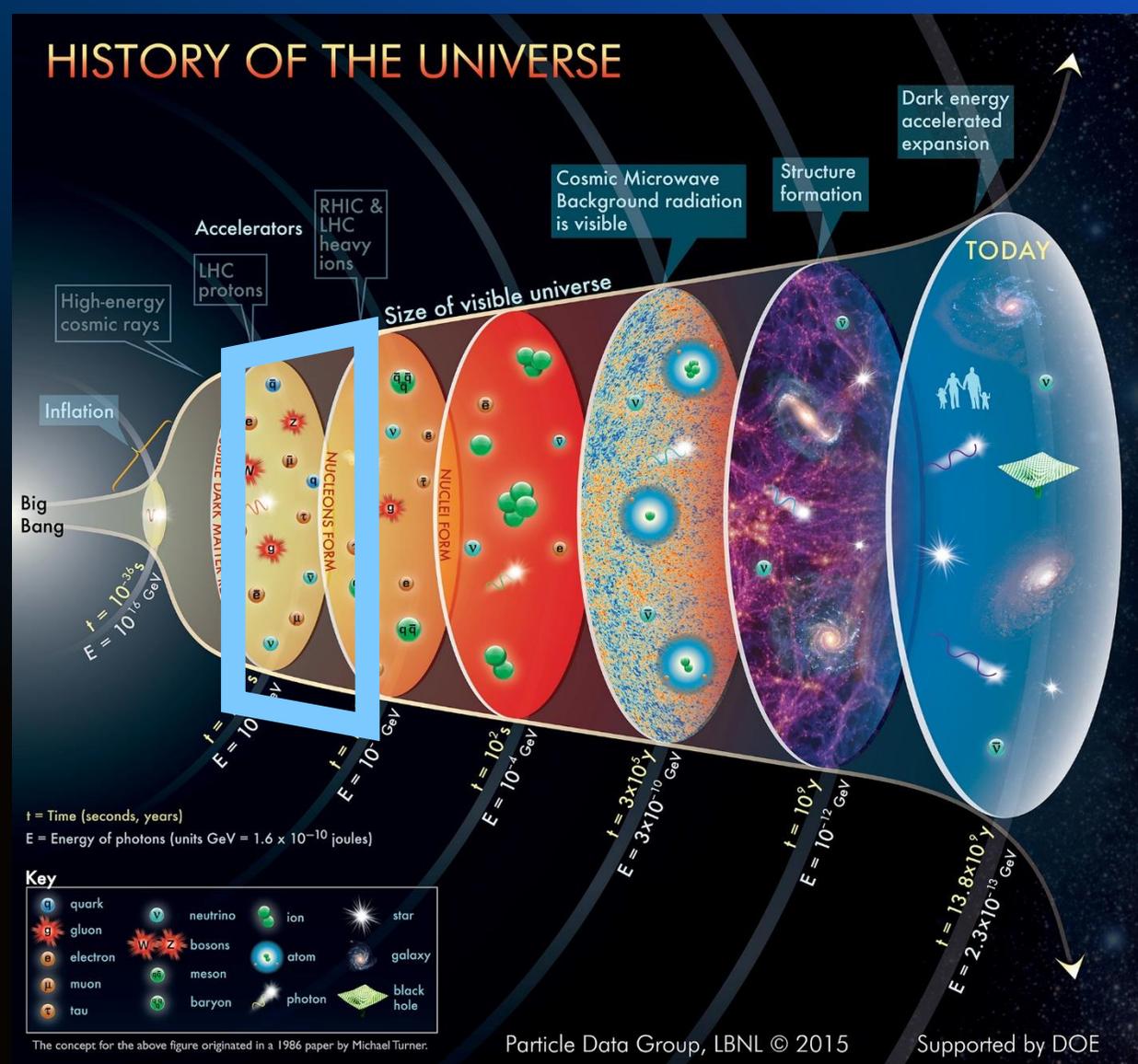
Data from: M. Asplund *et al.* Annual Reviews of Astronomy and Astrophysics, Vol. 47, 481 (2009)

Chemische Zusammensetzung der solaren Photosphäre



Data from: E. Anders & N. Grevesse, *Geochimica et Cosmochimica Acta*, Vol. 53, 197 (1989)

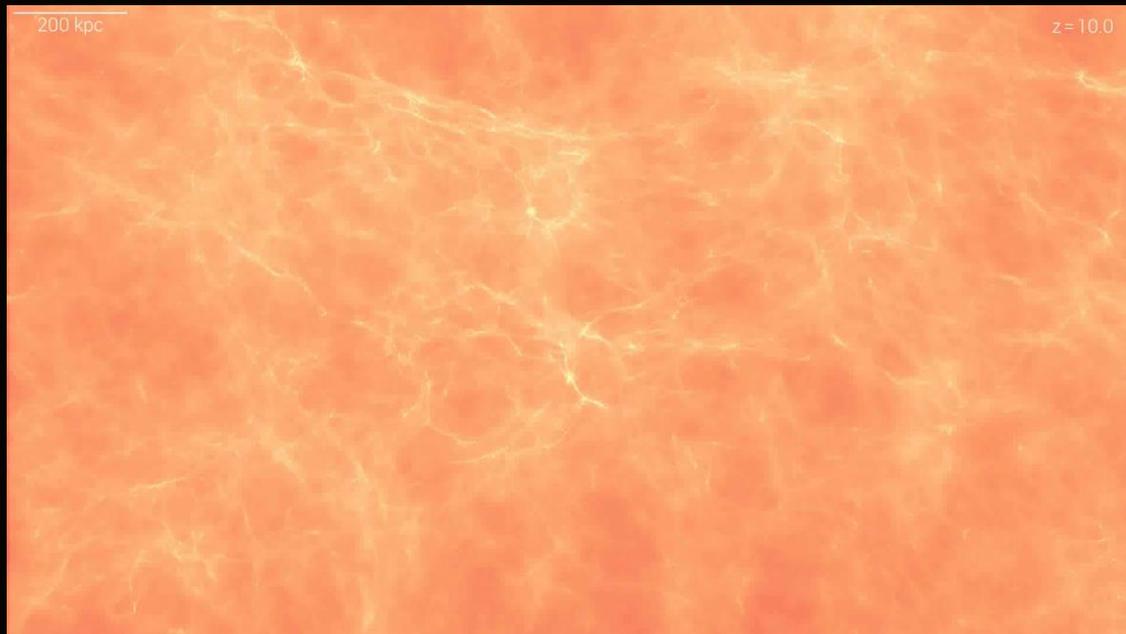
Während der letzten 13.6Mrd Jahre...



<https://particleadventure.org/images/history-of-the-universe-2015.jpg>

Widerherstellung von Nukleosynthese-Mileus

- Große Simulation $\sim \mathcal{O}(\text{Mpc})$
- Simulation von Galaxie-Superclustern



- Kleinskalige Simulation $\sim \mathcal{O}(\text{kpc})$
- Simulation einer einzelnen Galaxie



<https://en.wikipedia.org/wiki/Osmium>

- Osmium
- Dichte: $\sim 22 \text{ g/cm}^3$
- Dichtestes Material der Erde

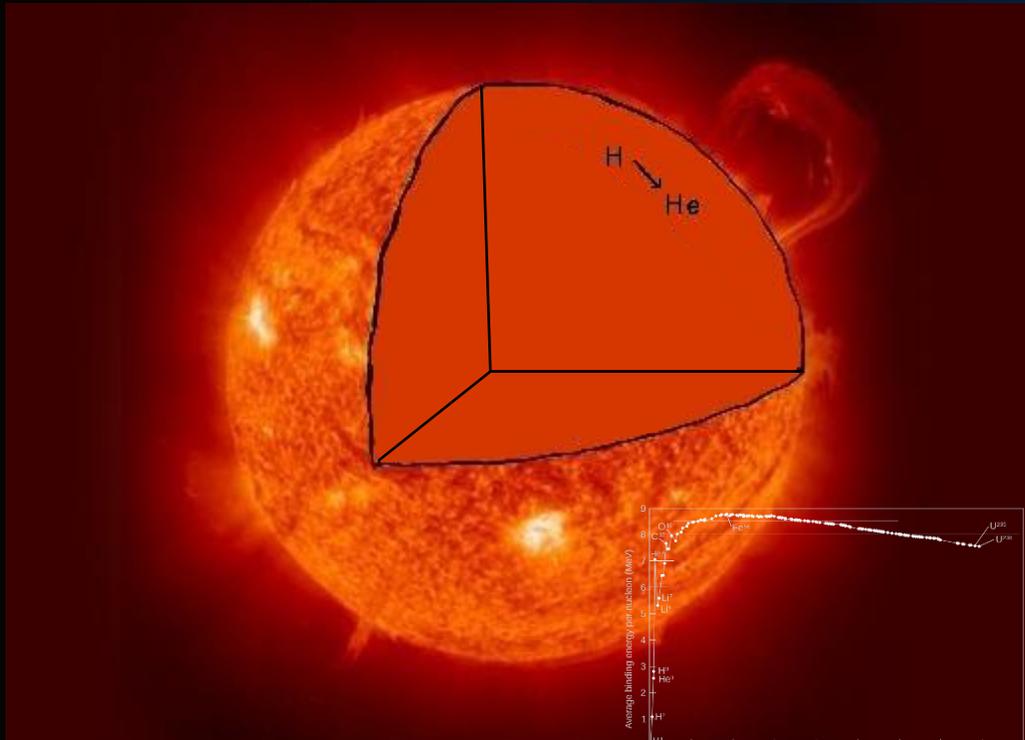
Credit: The TNG Project (<https://www.tng-project.org/media/>)

slido

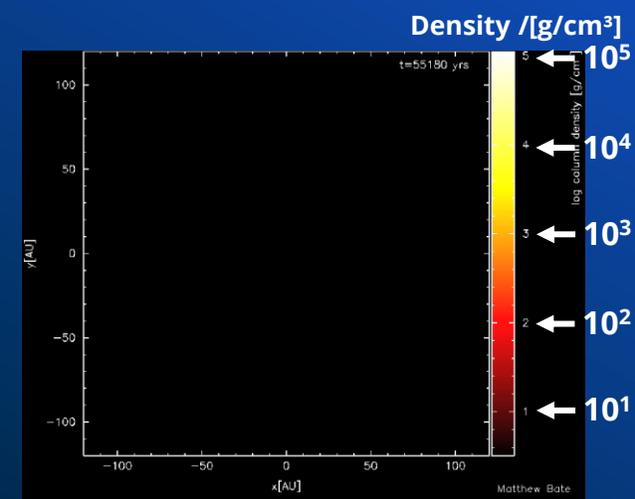
Wieviel dichter als Osmium muss das Zentrum eines Protostern sein, um wieder Kernfusion betreiben zu können?

 Start presenting to display the poll results on this slide.

Protostern-Formation + Stellare Nukleosynthese

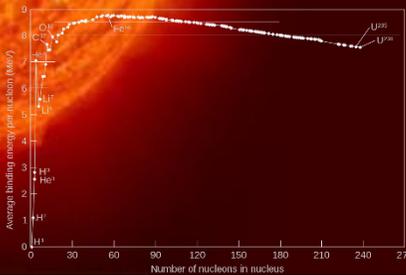


	T_{\min} [K]	ρ_{\min} [g/cm ³]
H → He	13 E+6	100 E+0
He → C,O	100 E+6	100 E+3
C → O, Ne, Mg, Na	500 E+6	200 E+3
Ne → O, Mg	1.2 E+9	4 E+6
O → Mg, Si, S, P	1.5 E+9	10 E+6
Si → Ti, Fe, Ni ...	~ 3.0 E+9	30 E+6



https://www.astro.ex.ac.uk/people/mbate/Animations/Beta0_01_RT_1M_DensSplash.mov

Credit: Blake Stacey, based on SOHO (ESA, NASA)

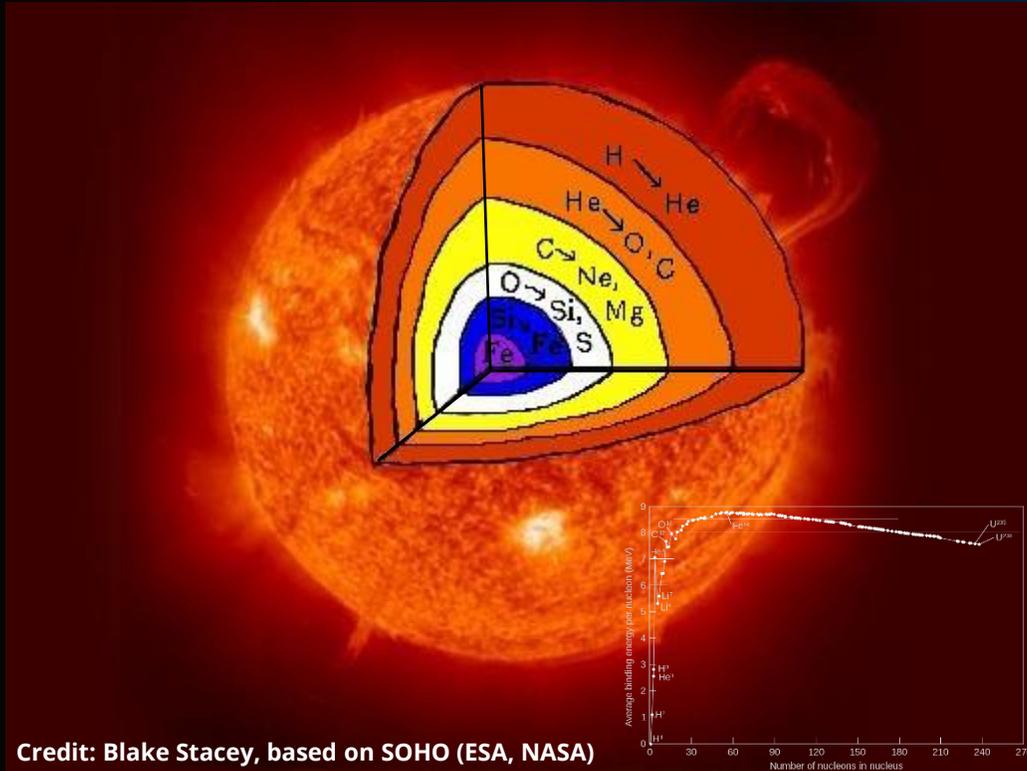


https://en.wikipedia.org/wiki/Nuclear_binding_energy



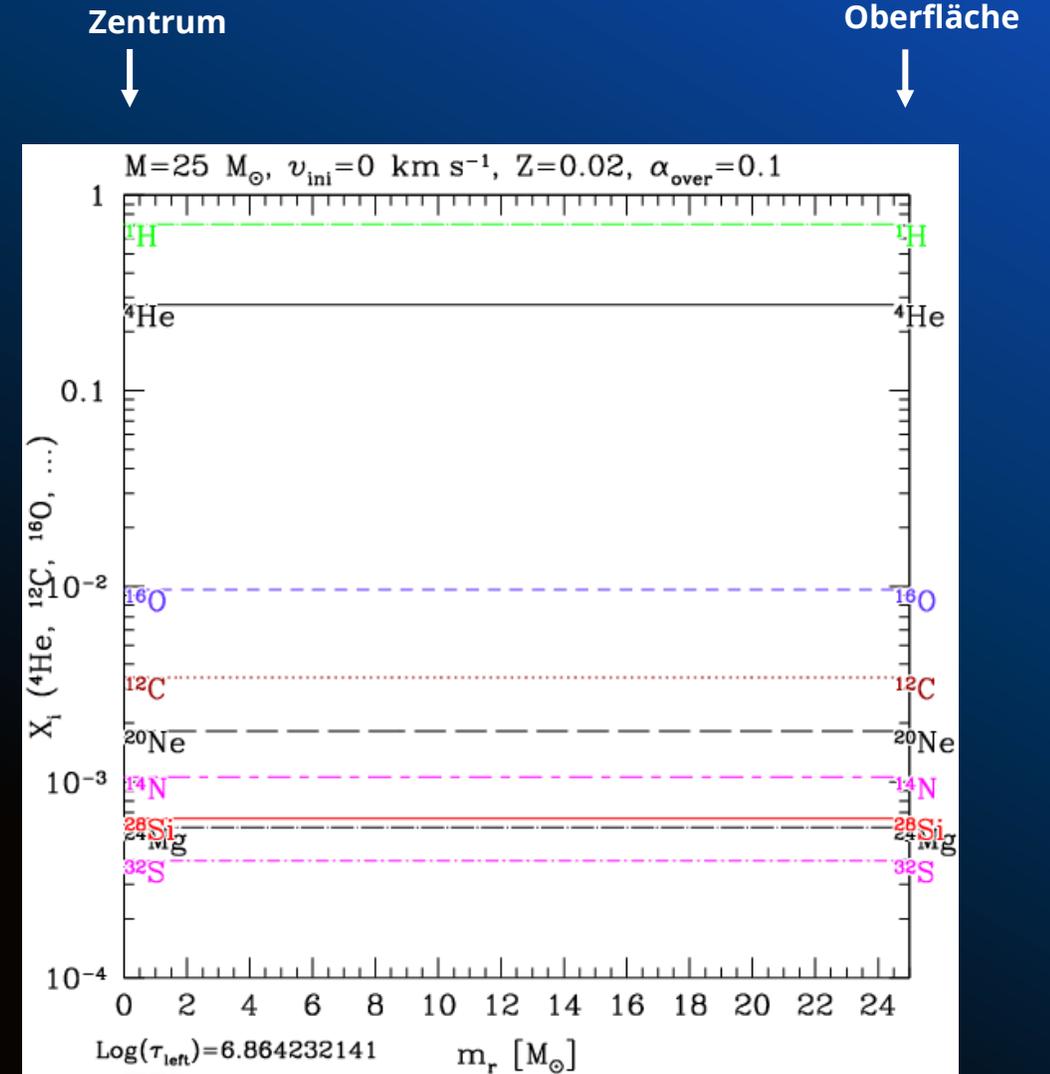
Courtesy: Matthew Bate (University of Exeter)

Stellare Nukleosynthese



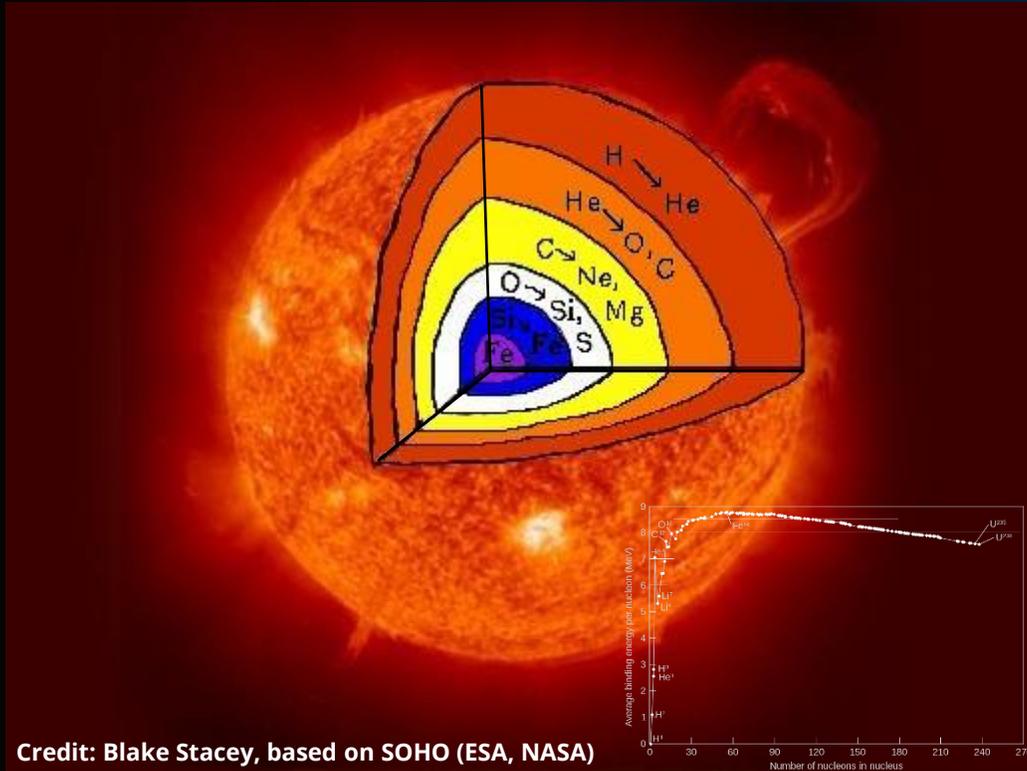
Credit: Blake Stacey, based on SOHO (ESA, NASA)

https://en.wikipedia.org/wiki/Nuclear_binding_energy



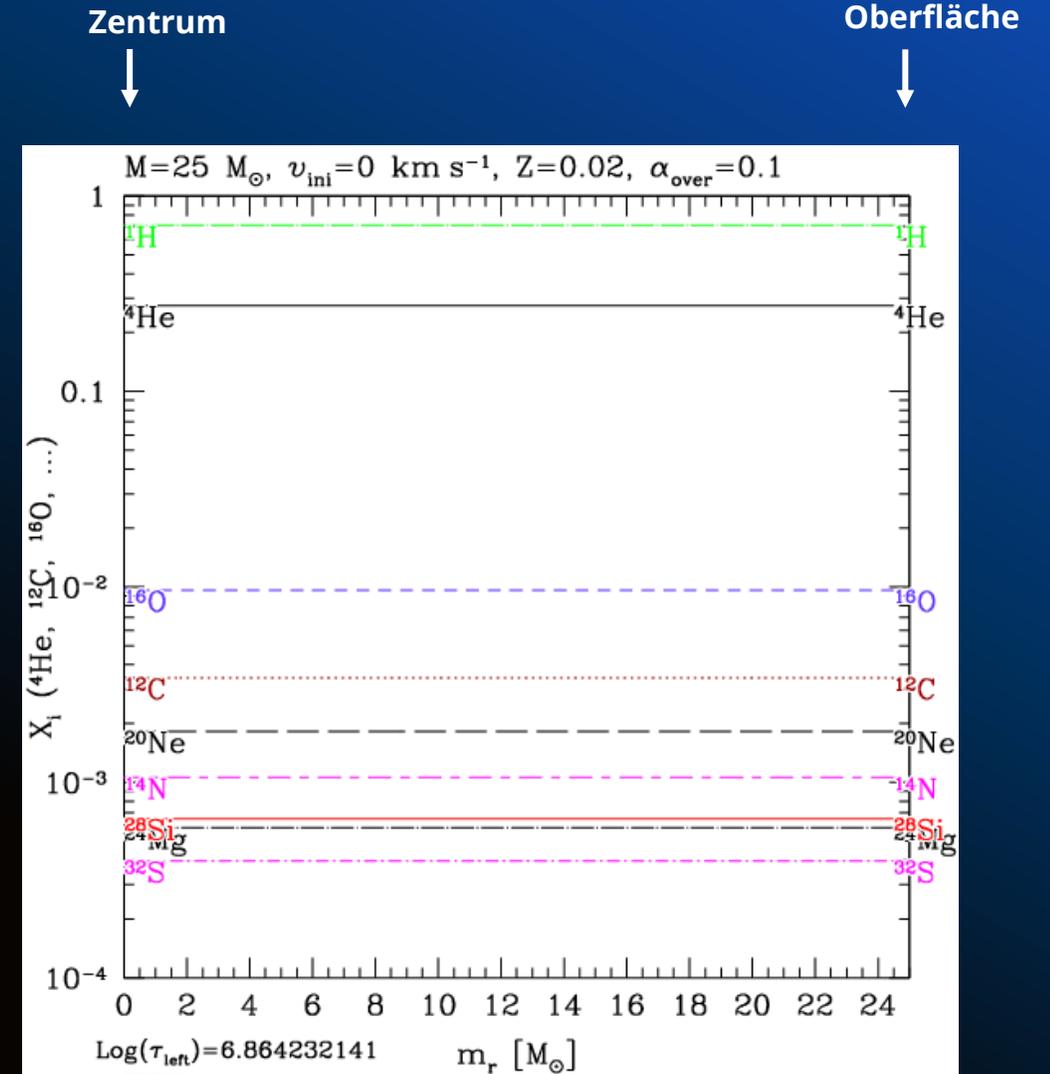
<https://www.astro.keele.ac.uk/~hirschi/animation/anim.html>

Stellare Nukleosynthese



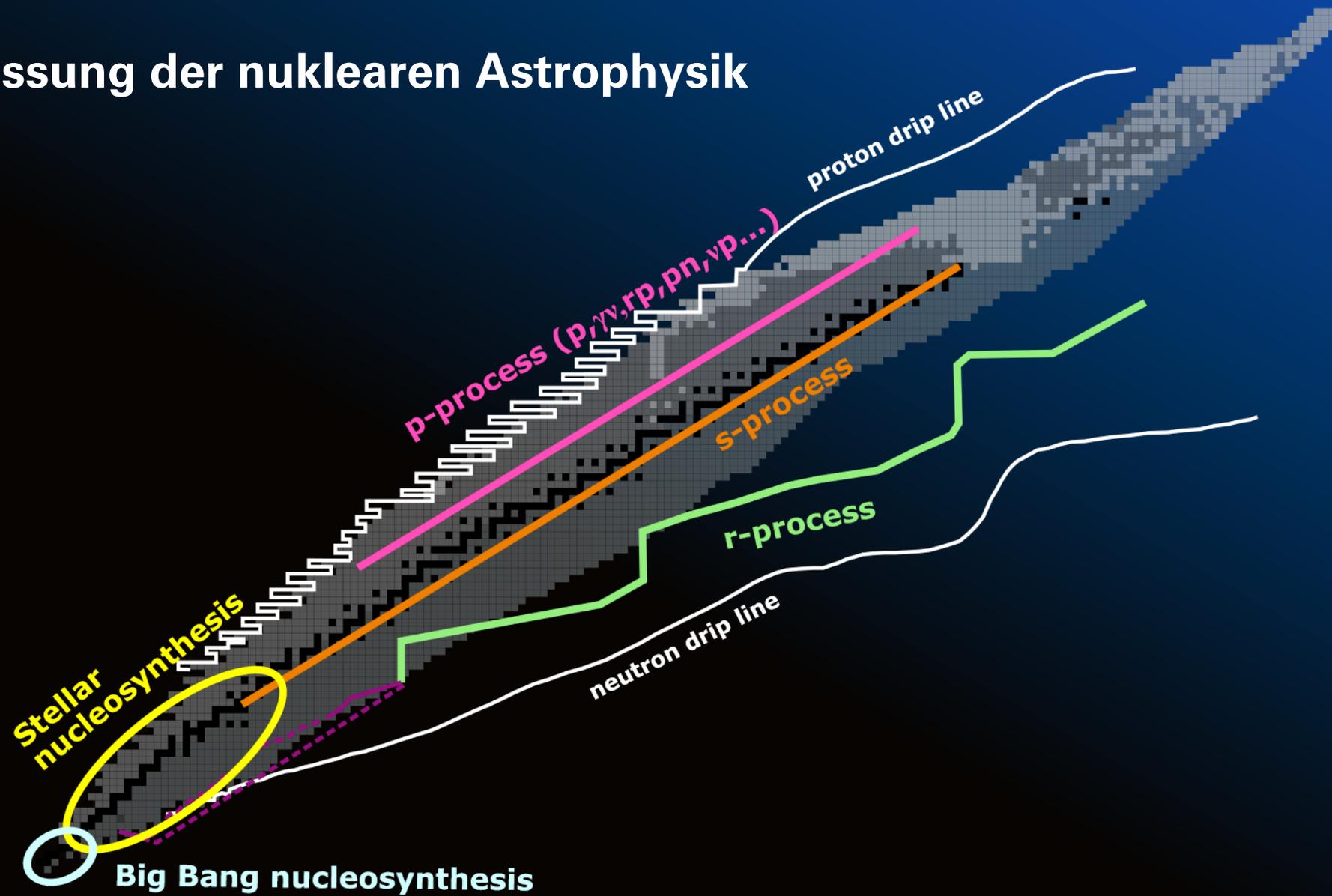
Credit: Blake Stacey, based on SOHO (ESA, NASA)

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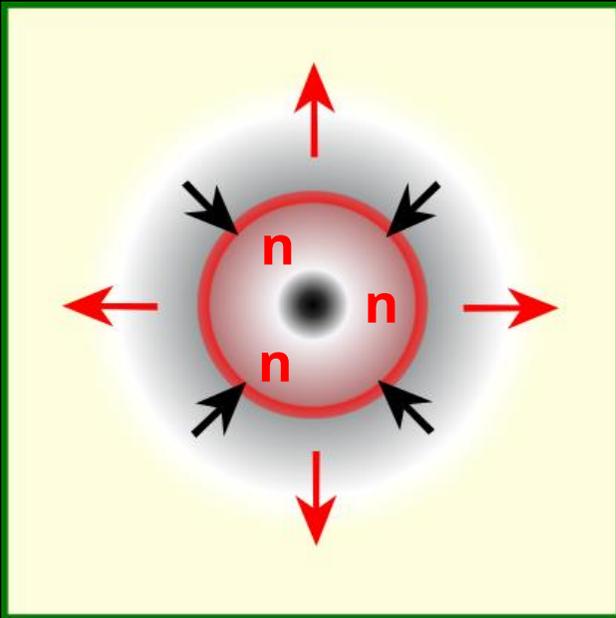


<https://www.astro.keele.ac.uk/~hirschi/animation/anim.html>

Zusammenfassung der nuklearen Astrophysik

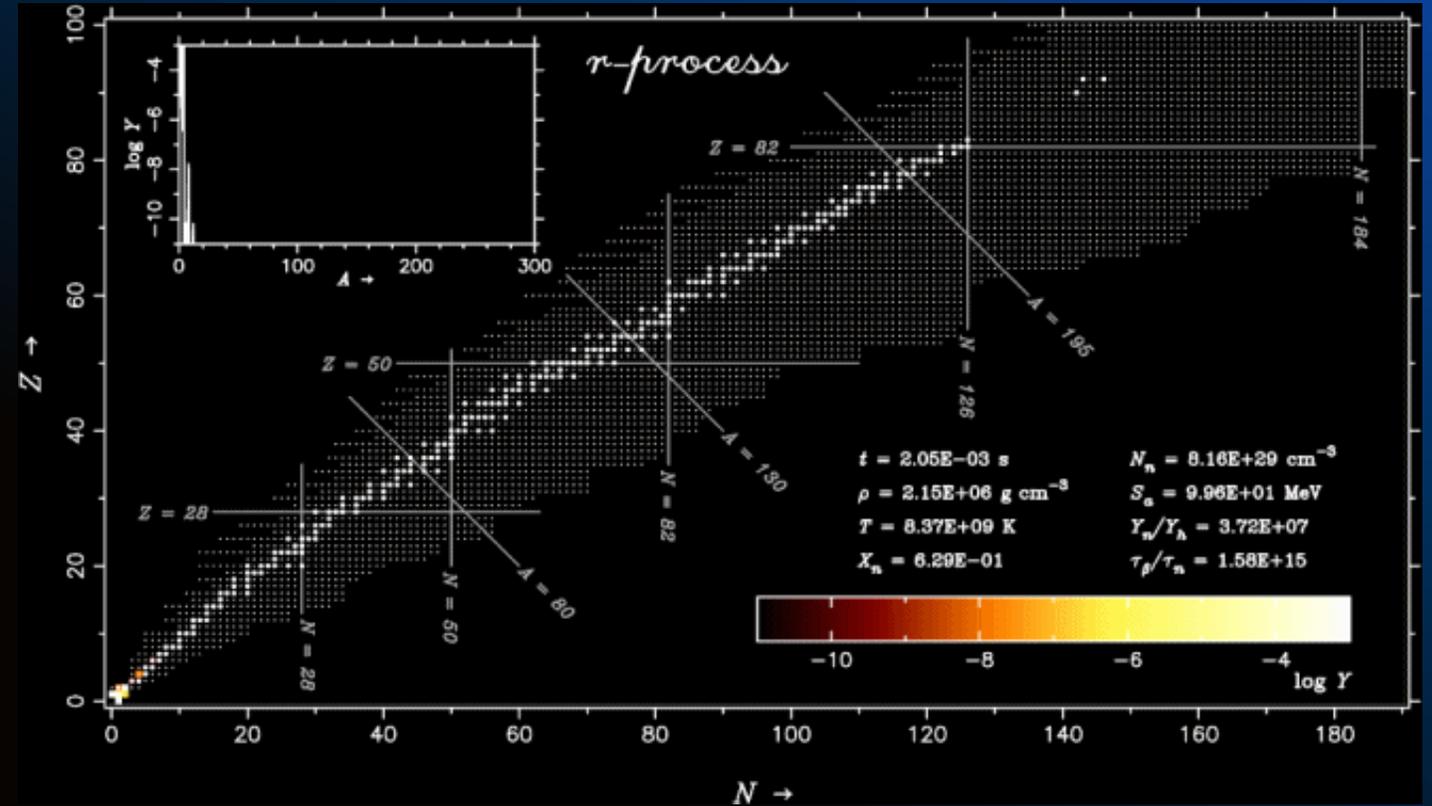
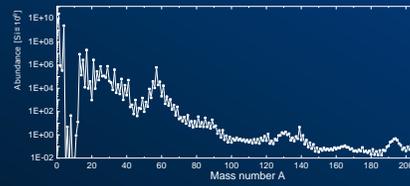


Explosive Nukleosynthese



https://en.wikipedia.org/wiki/Type_II_supernova#

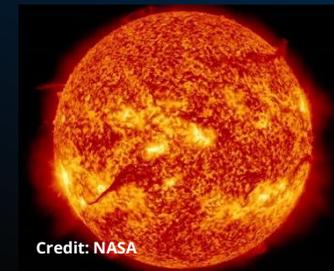
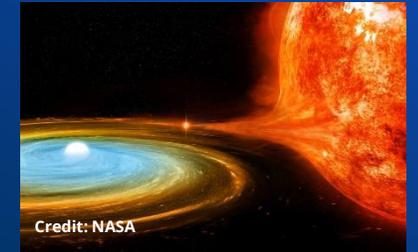
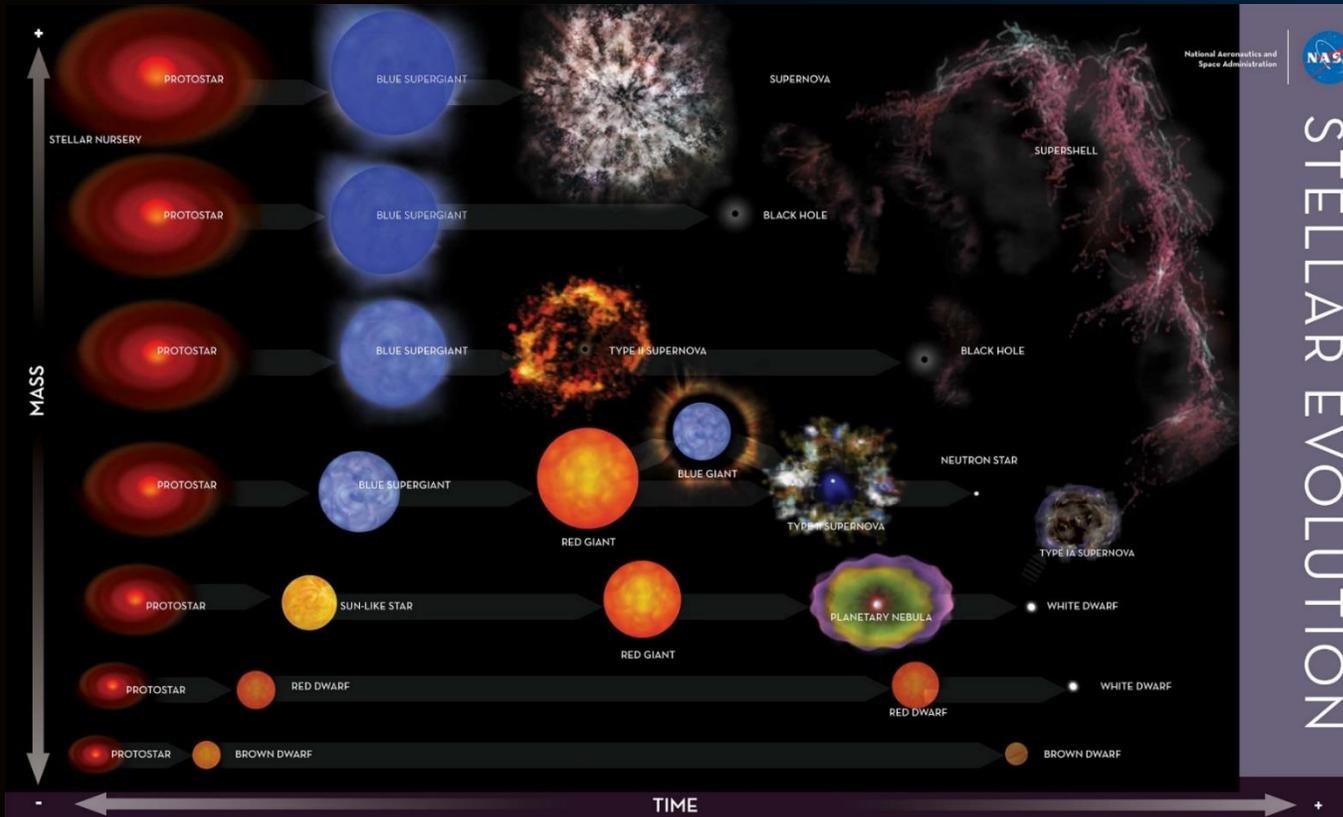
Explosive Nukleosynthese



<http://www.ph.sophia.ac.jp/~shinya/research/research.html>

Credit: ESA (https://www.esa.int/ESA_Multimedia/Images/2002/03/Spitzer_Star-forming_region) A_Spitzer_Crop.jpg

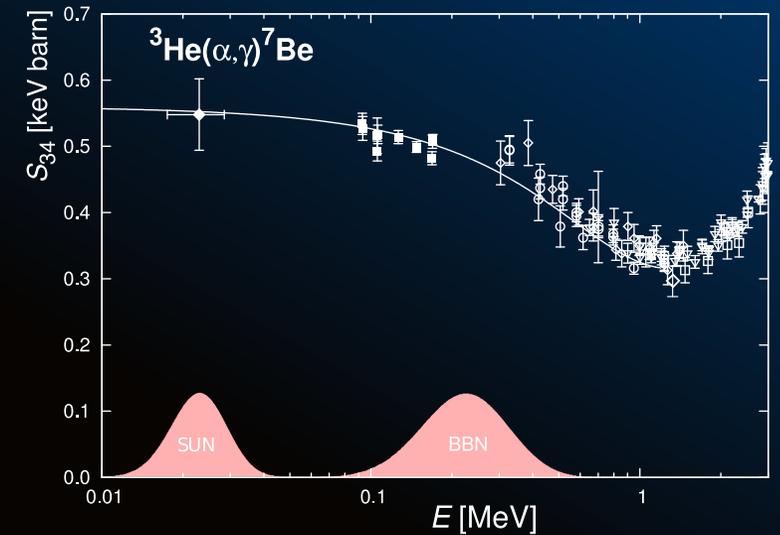
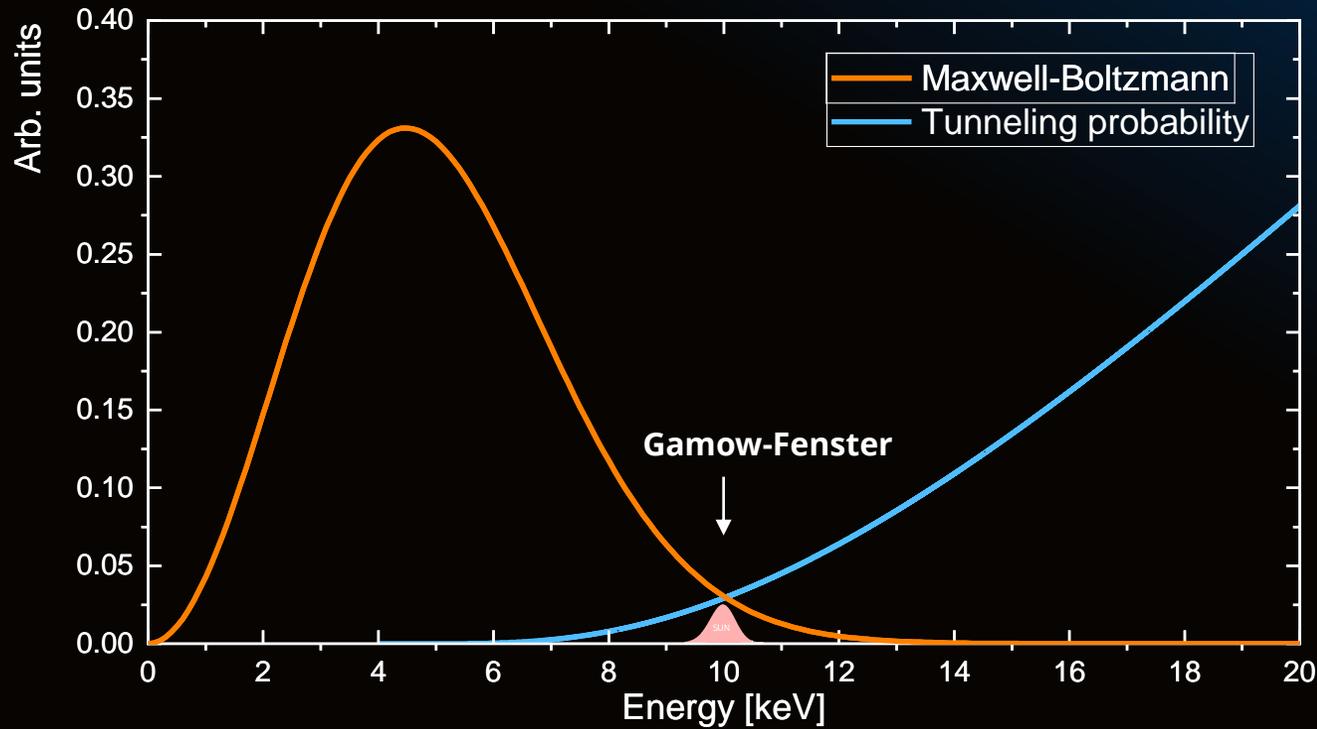
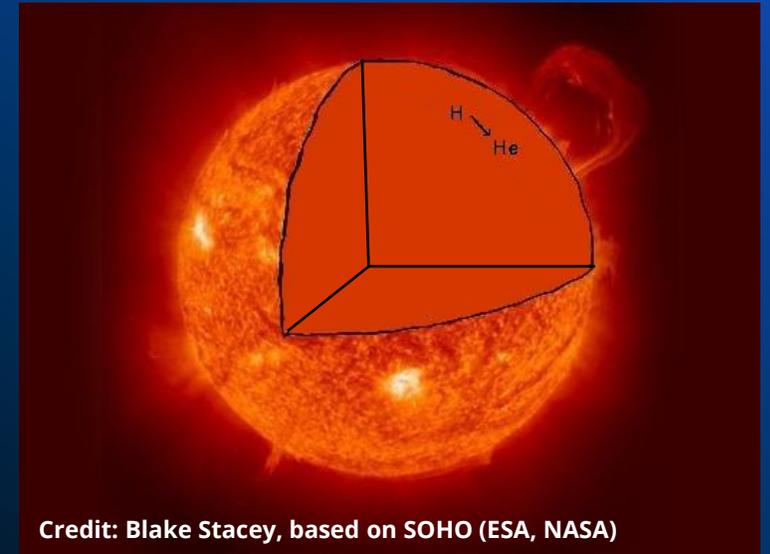
Nukleare Astrophysik in der Sternentwicklung



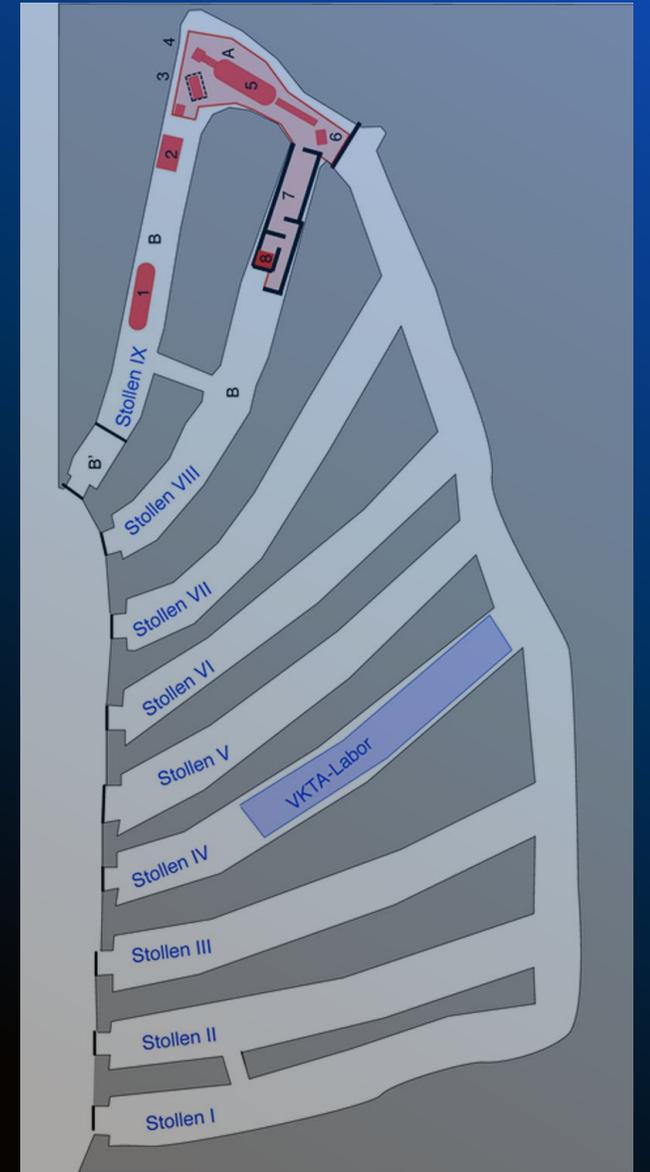
Credit: NASA (https://www.accessscience.com/media/EST/media/654000FG0010.jpg)

Das Felsenkeller-Untertagelabor

Vom Inneren der Sterne zum Inneren von Tunneln

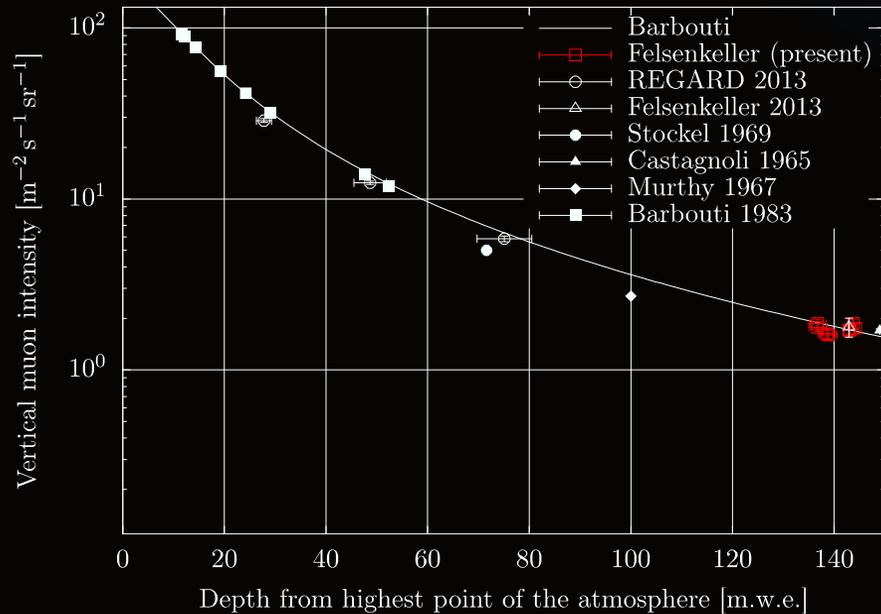


Das neue Felsenkeller-Labor

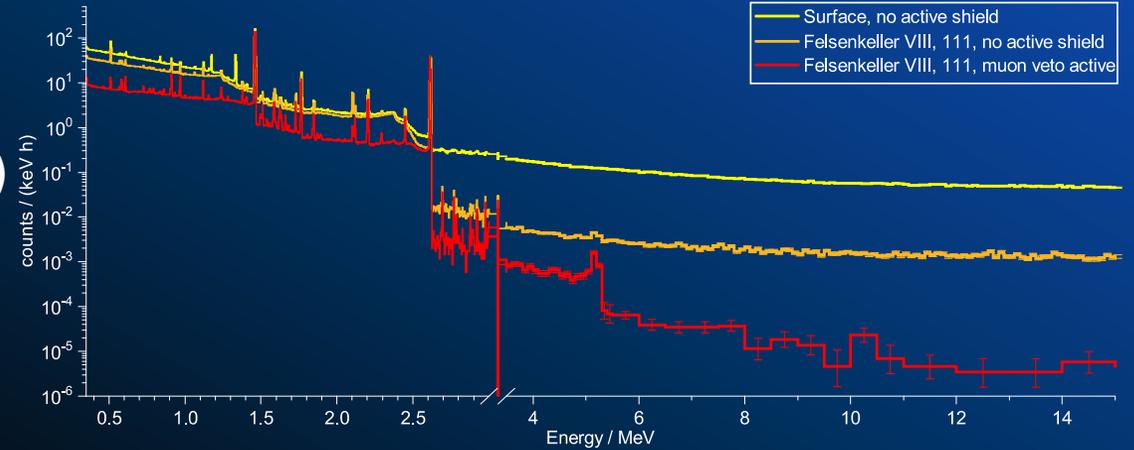


Warum untertage?

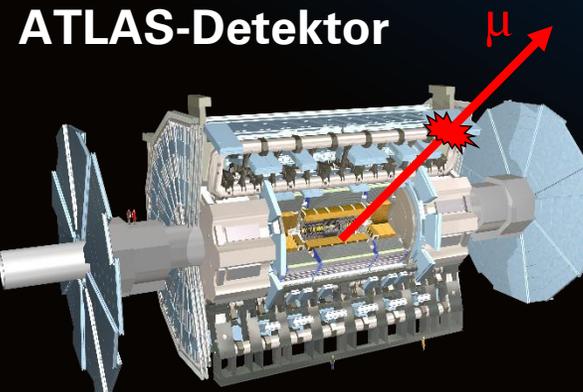
- Schutz vor kosmischen Myonen (Untergrund reduzieren)
- Erforschung sehr seltener Prozesse
 - Messungen im Bereich des Gamow-Fensters



F. Ludwig et al. Astroparticle Physics 112 (2019) 24-34



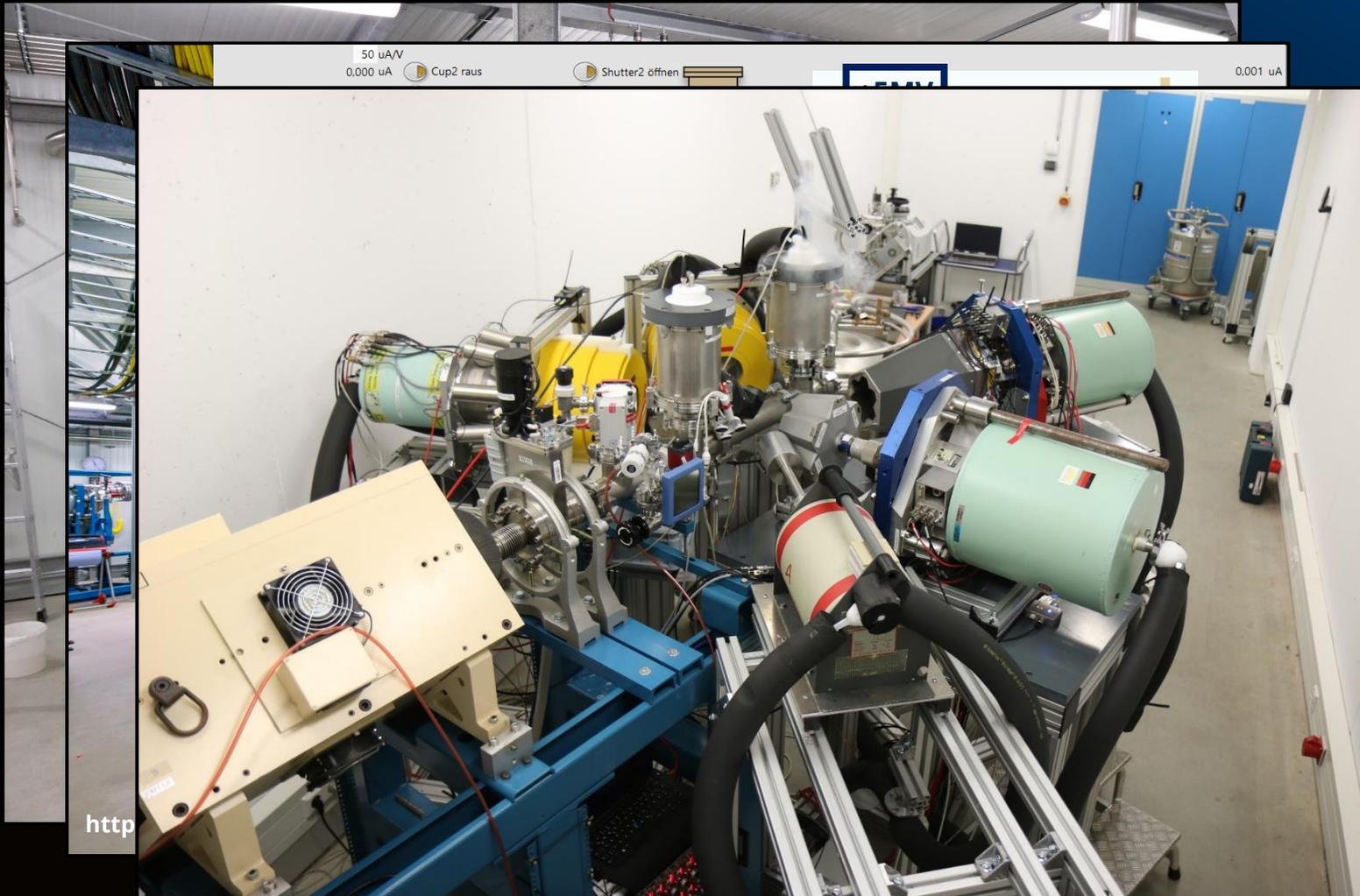
Adapted from: T. Szücs et al. European Physics Journal A 55, 174



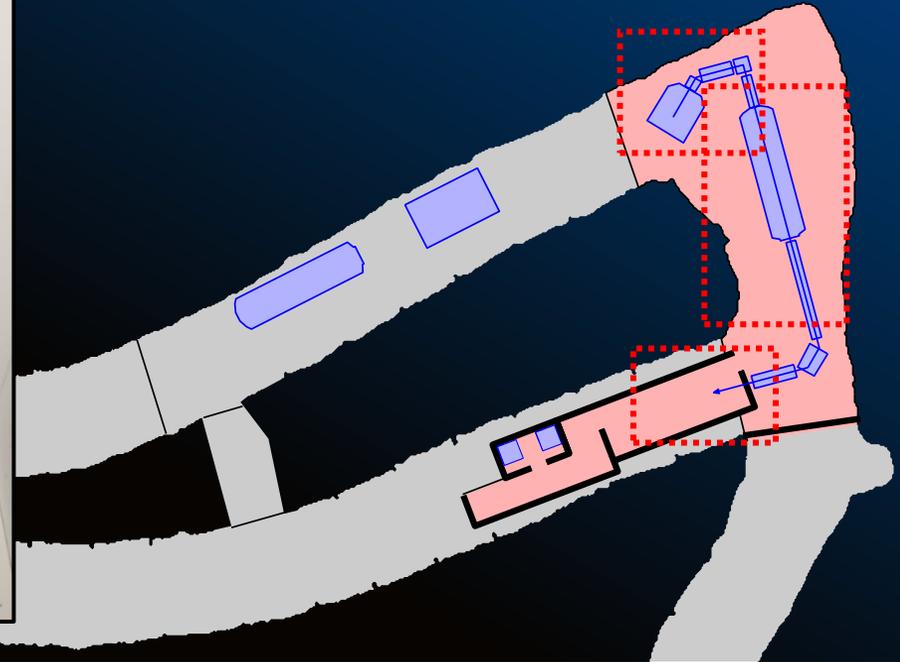
http://opendata.atlas.cern/books/current/get-started/_book/GLOSSARY.html



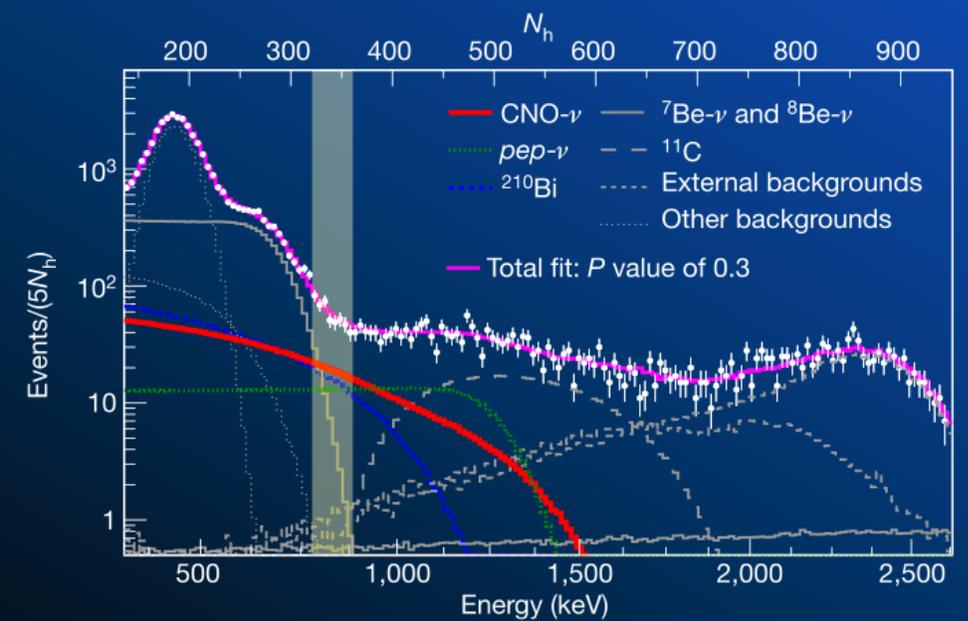
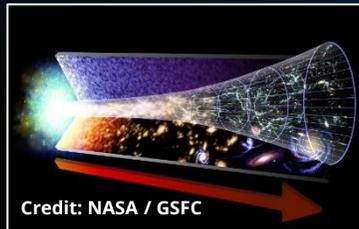
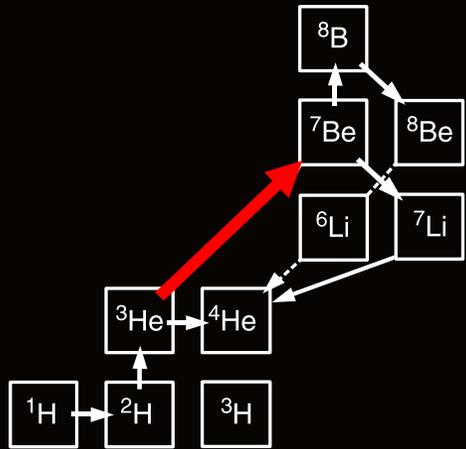
Das neue Felsenkeller Untertage-Labor



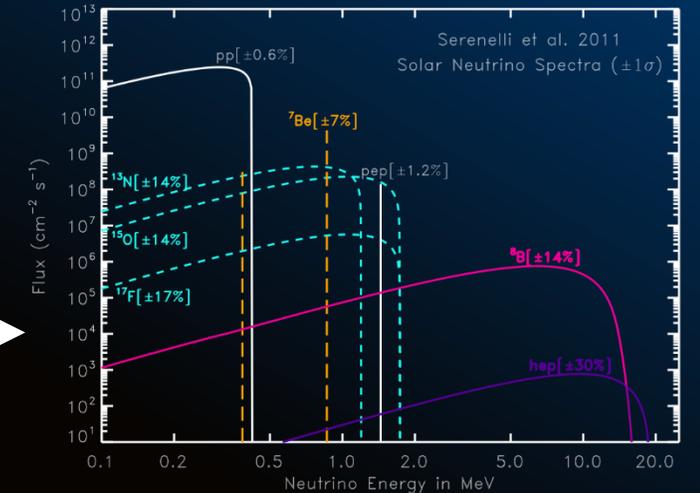
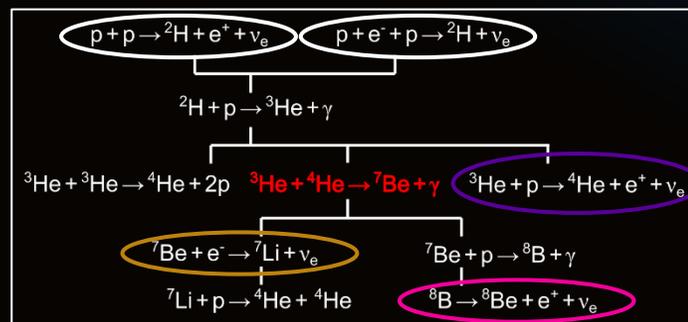
- Externe Ionenquelle
 - Kohlenstoffstrahl ($^{12}\text{C}^-$)
- 5MV Pelletron Beschleuniger
- Interne Ionenquelle
 - H & He-Strahl
- Derzeitiger Experimentier-Aufbau
 - $^3\text{He}(\alpha,\gamma)^7\text{Be}$ -Kampagne



Die ${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$ Reaktion



The Borexino collaboration, Nature volume 587, 577-582 (2020)



Haxton et al. Annu. Rev. Astron. Astrophys. 51 1 (2013)