

IKTP Institute seminar



From the interior of stars and tunnels

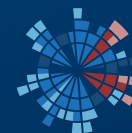
Nuclear astrophysics in a nutshell

Steffen Turkat

07.01.2021

In preparation for this talk:

Please visit [Slido.com](https://www.slido.com) (mobile phone) and enter with #1444
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INSTITUTE OF
NUCLEAR AND
PARTICLE PHYSICS





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Nuclear astrophysics

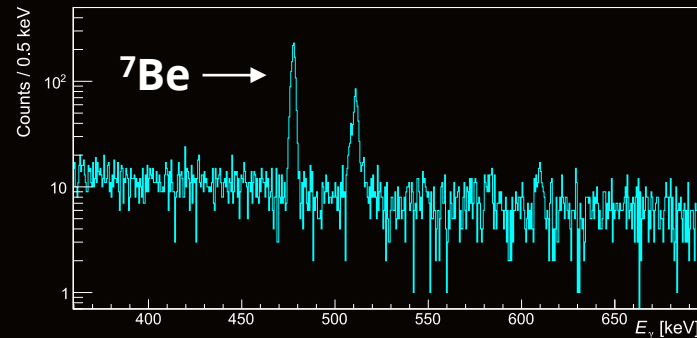
→ The origin of the elements



Copyright: André Wirsig (HZDR)

The new underground facility at Felsenkeller

→ How to study the universe from underground



Recent achievements and outlook

→ Experimental campaign on ${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$

Chemical evolution of the universe

➤ How, when & in which amounts were all the elements in our universe formed?

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	8 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 VIII 8	10 VIII 8	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 Lanthanide Series	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 (210)	86 Rn Radon (222)	
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103 Actinide Series	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (269)	109 Mt Meitnerium (278)	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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sciencenotes.org

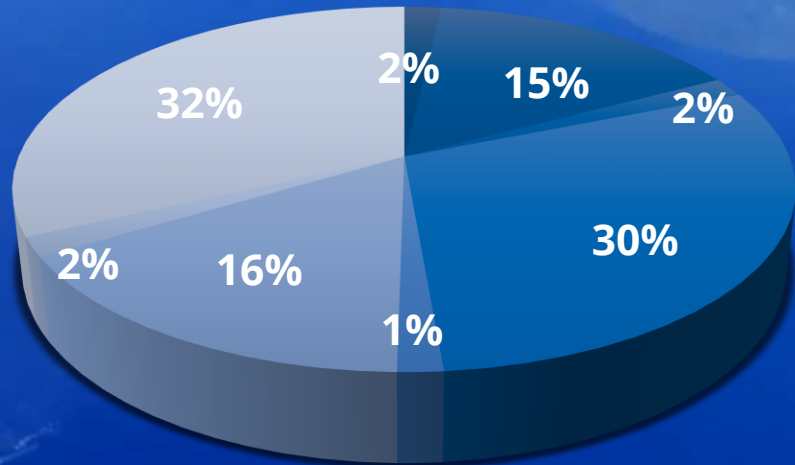
<https://sciencenotes.org/periodic-table-2017-edition-black-white/>

Elemental abundance of our earth

What are the four most abundant elements of our earth?

→ Please visit [Slido.com](https://www.slido.com) & enter **#1444**

→ Leave it like that, the rest will appear automatically





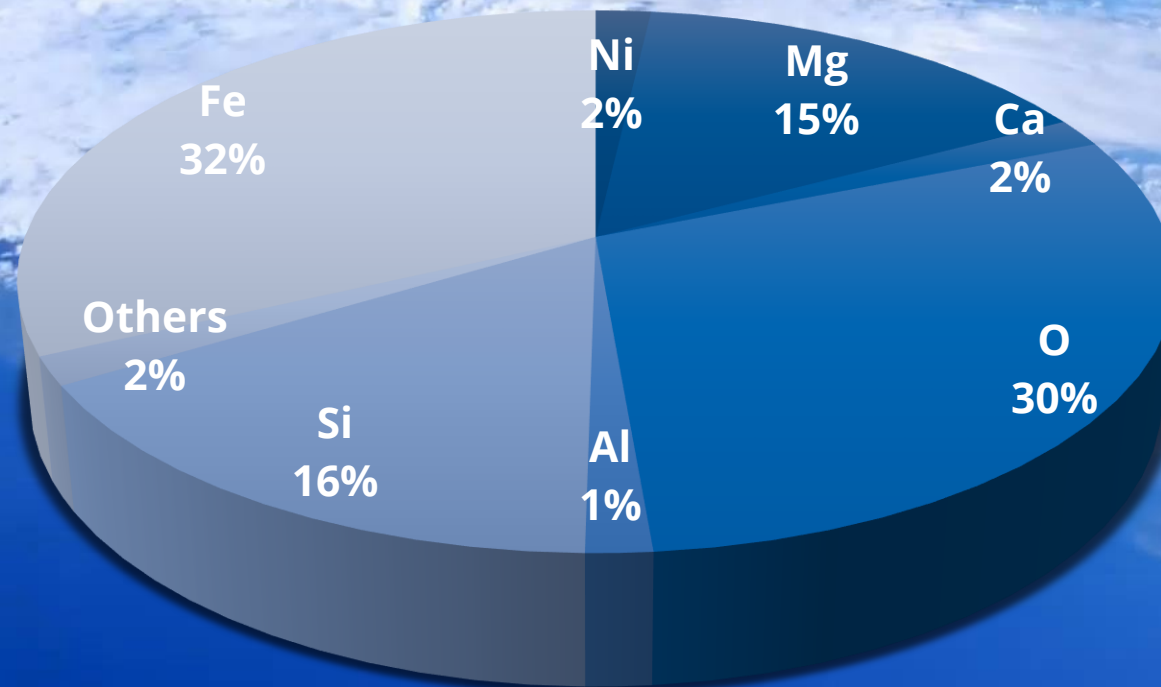
What are the four most abundant elements on our earth?

0 0 0

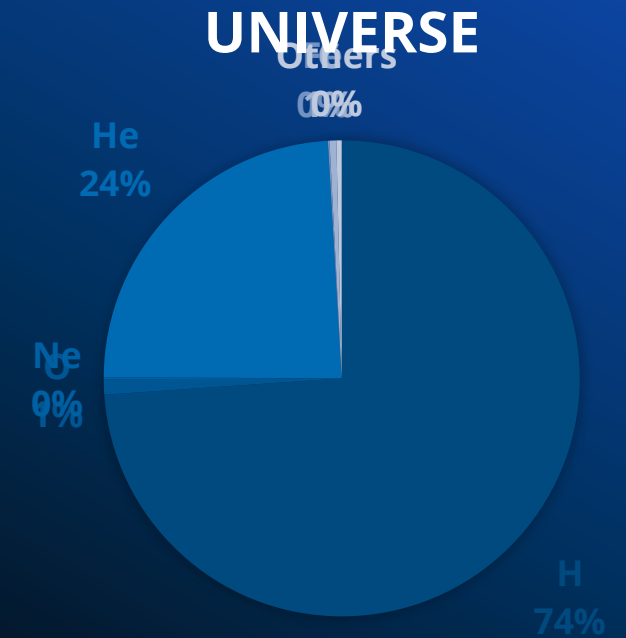
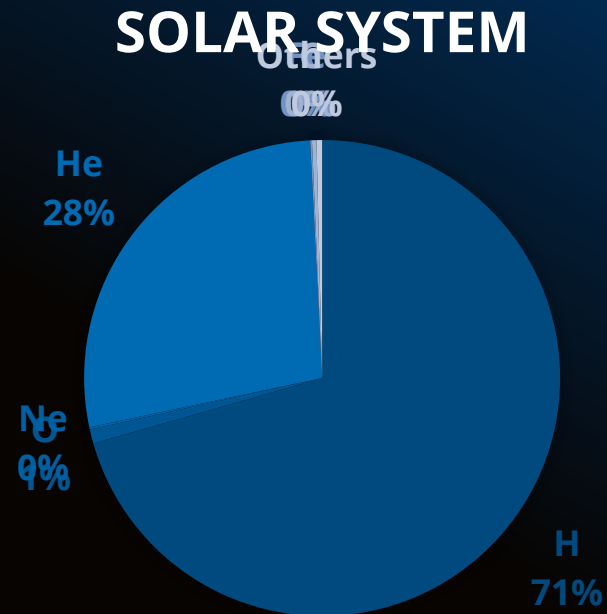
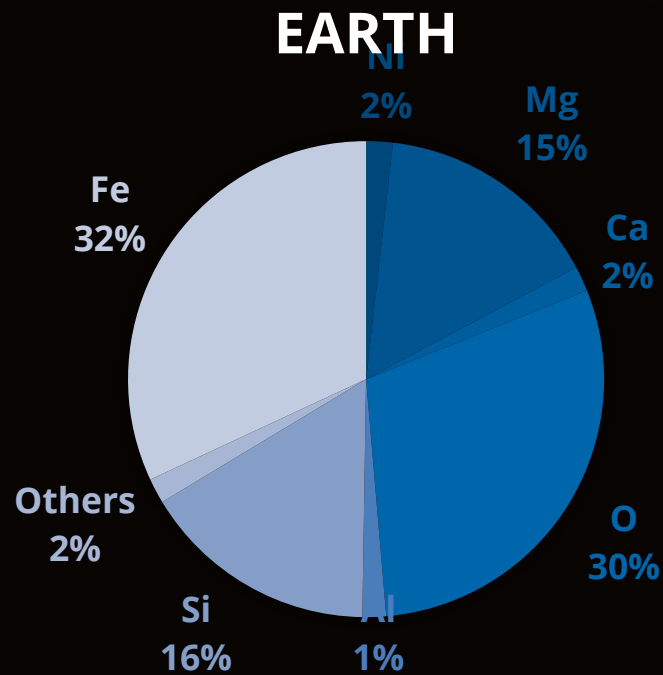
- H
- He
- C
- N
- O
- Na
- Mg
- Al
- Si
- K
- Ca

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Elemental abundance of our earth



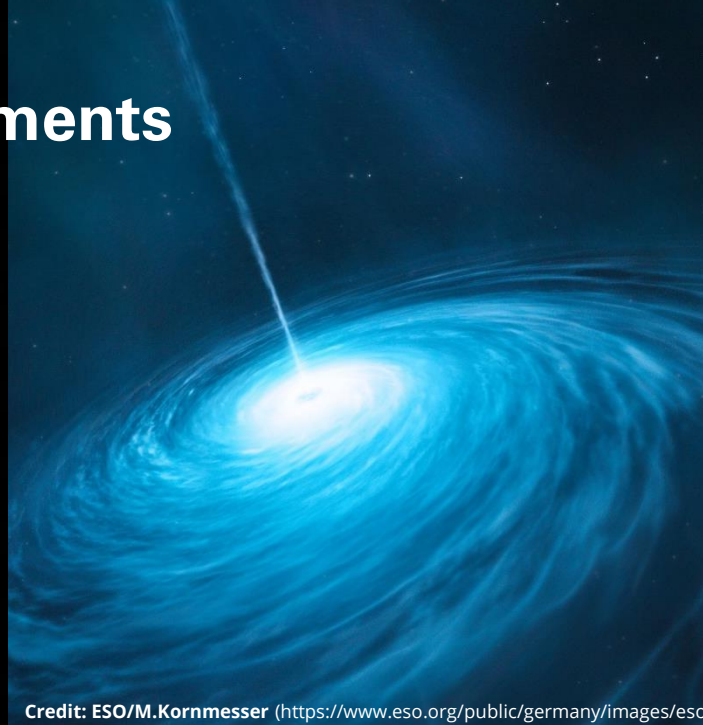
The composition of the universe



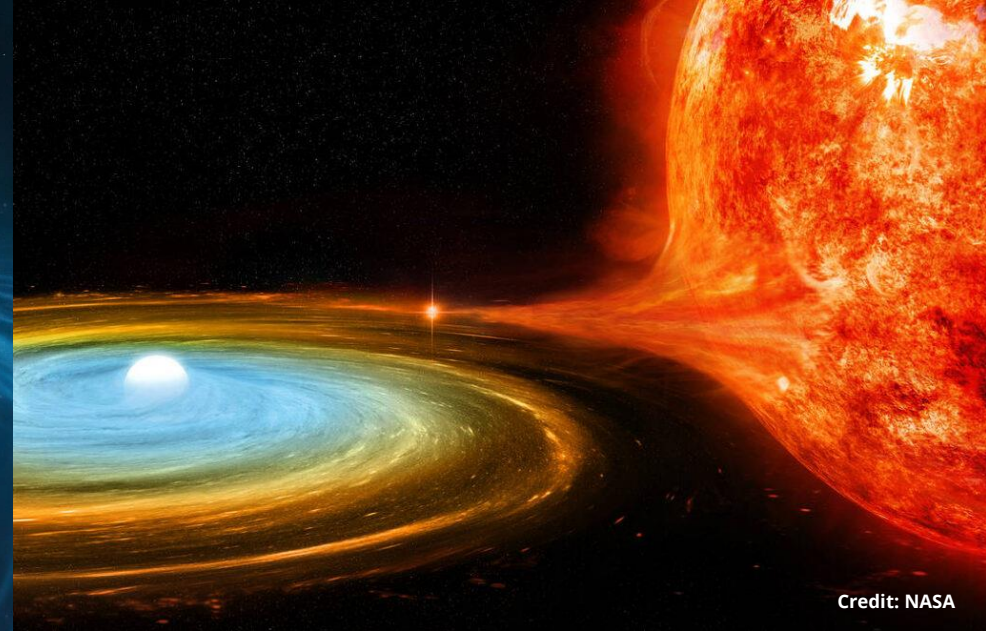
The birthplaces of the elements



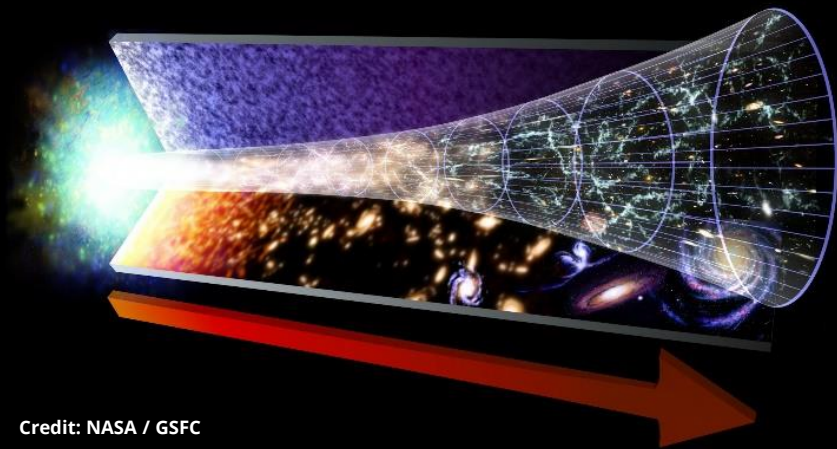
Credit: NASA



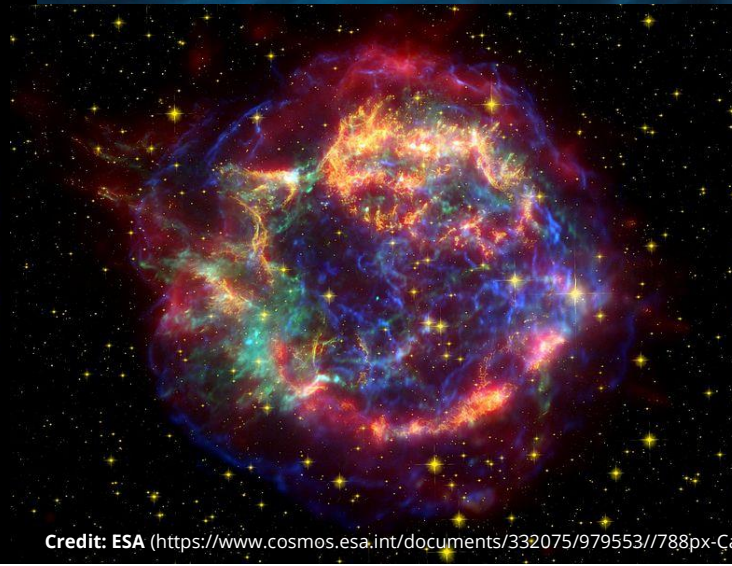
Credit: ESO/M.Kornmesser (<https://www.eso.org/public/germany/images/eso1229a/>)



Credit: NASA



Credit: NASA / GSCF

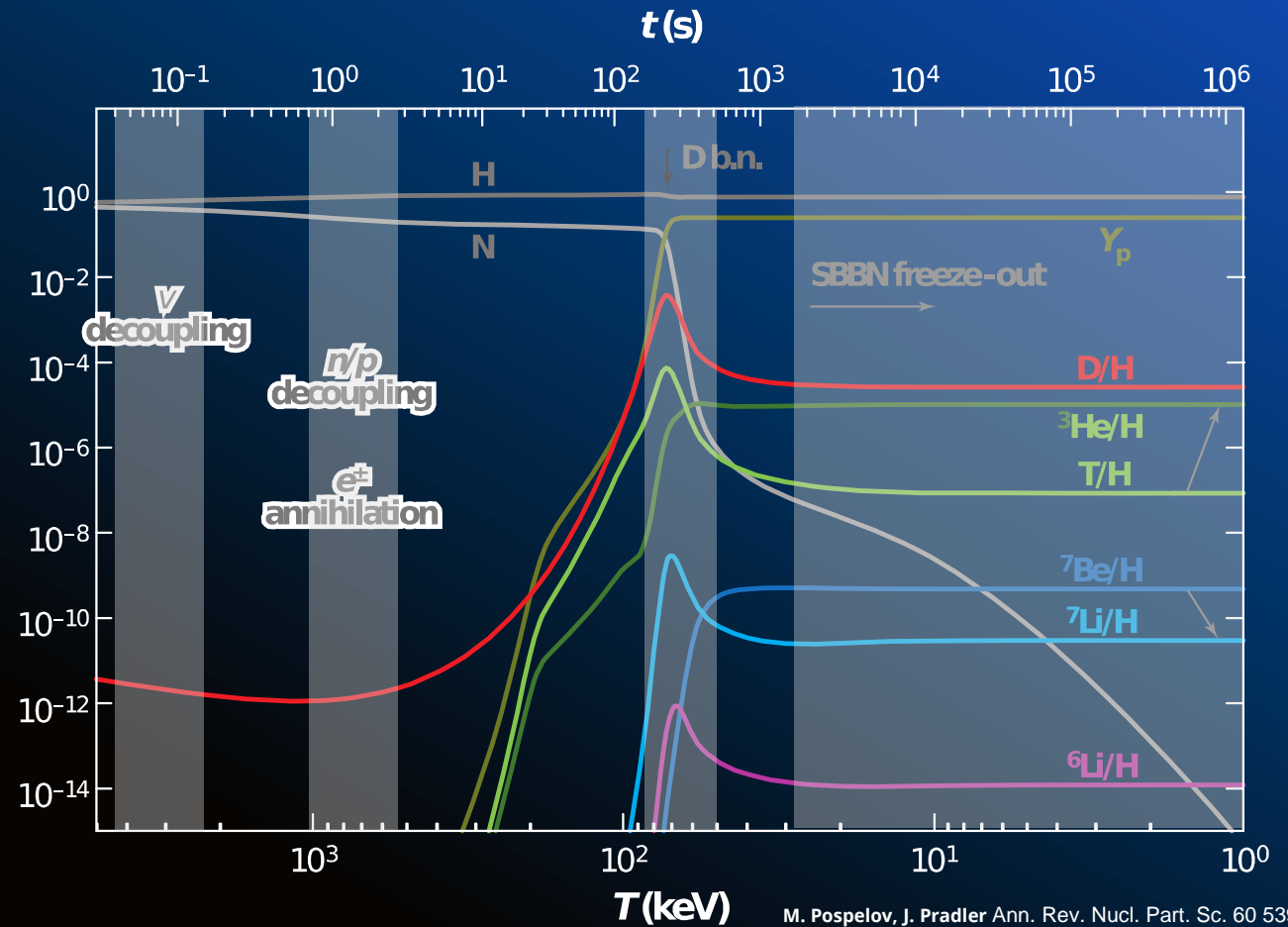
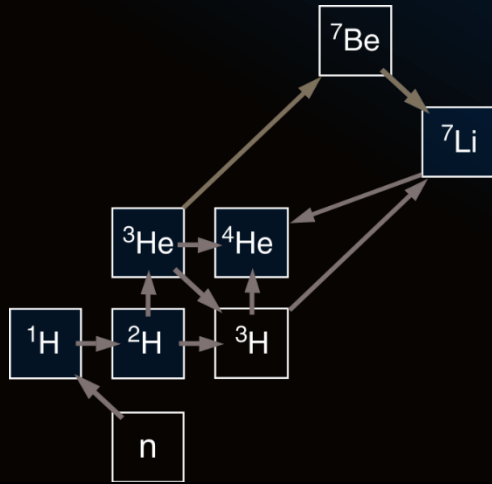


Credit: ESA (https://www.cosmos.esa.int/documents/332075/979553/788px-Cassiopeia_A_Spitzer_Crop.jpg)



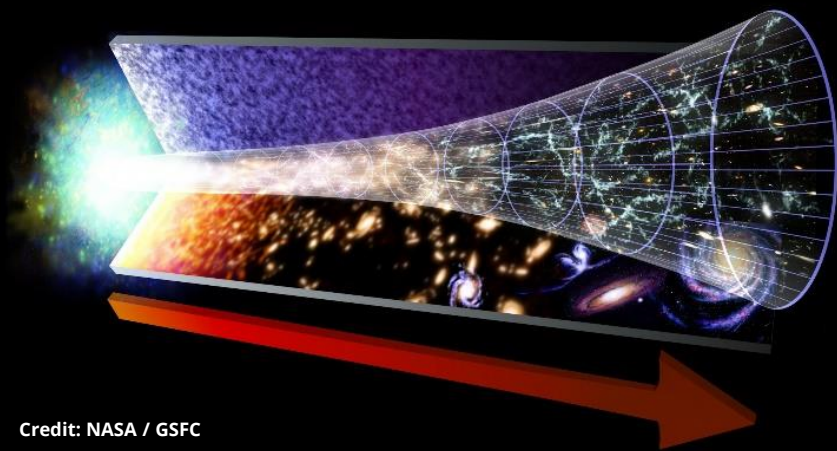
Credit: ESO (<https://www.eso.org/public/images/eso1733q/>)

The Big Bang Nucleosynthesis



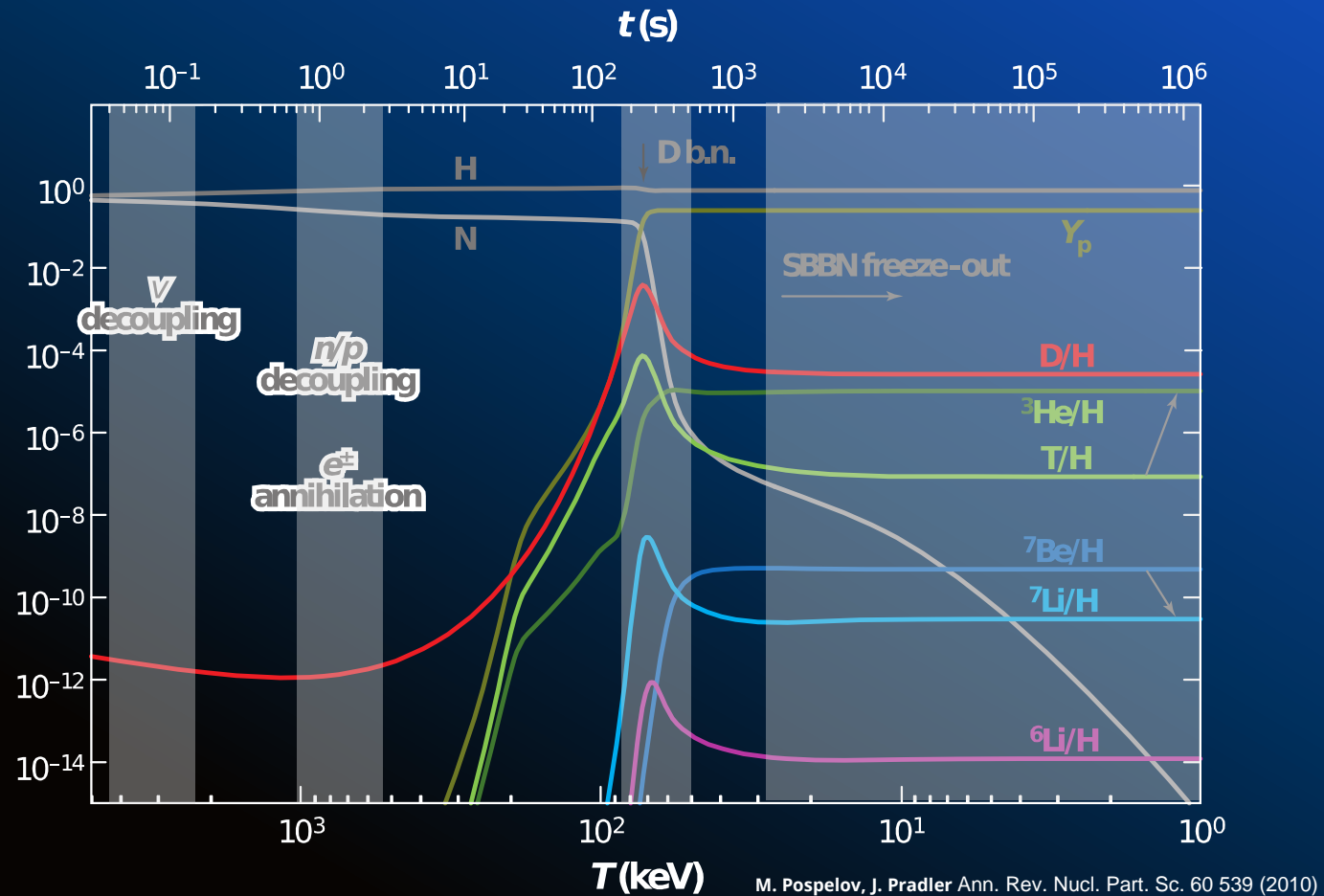
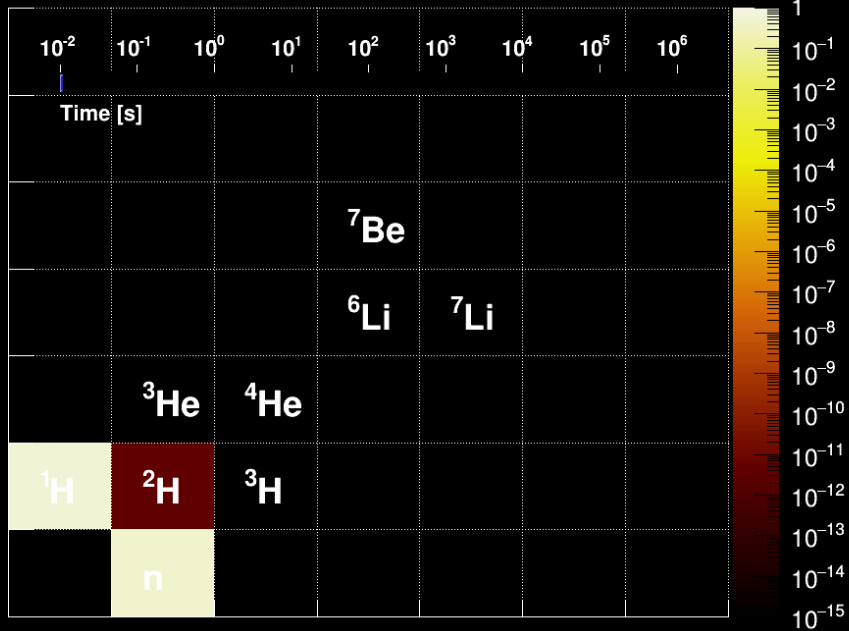
M. Pospelov, J. Pradler Ann. Rev. Nucl. Part. Sc. 60 539 (2010)

- **Chromodynamic binding energy p/n:** ~ 1 GeV
- **${}^2\text{H}$ bottle neck:** Literally the whole universe had to wait for ${}^2\text{H}$
- **Spoiler:** Upcoming paper on ${}^2\text{H}(p,\gamma){}^3\text{He}$ in Phys. Rev. C (Turkat et al.)



Credit: NASA / GSFC

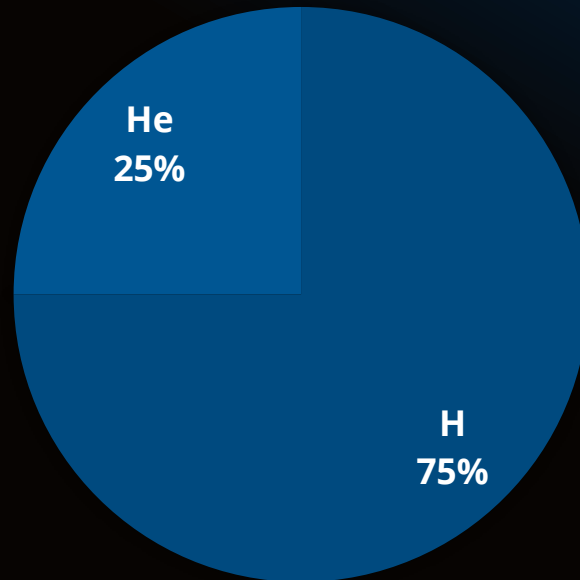
The Big Bang Nucleosynthesis



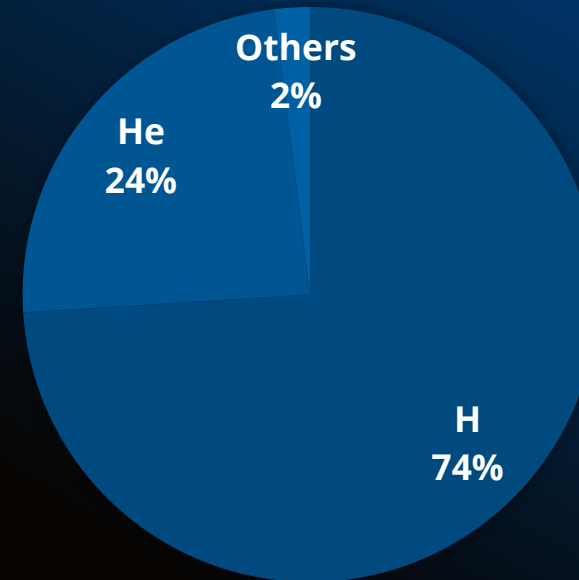
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The origin of the elements

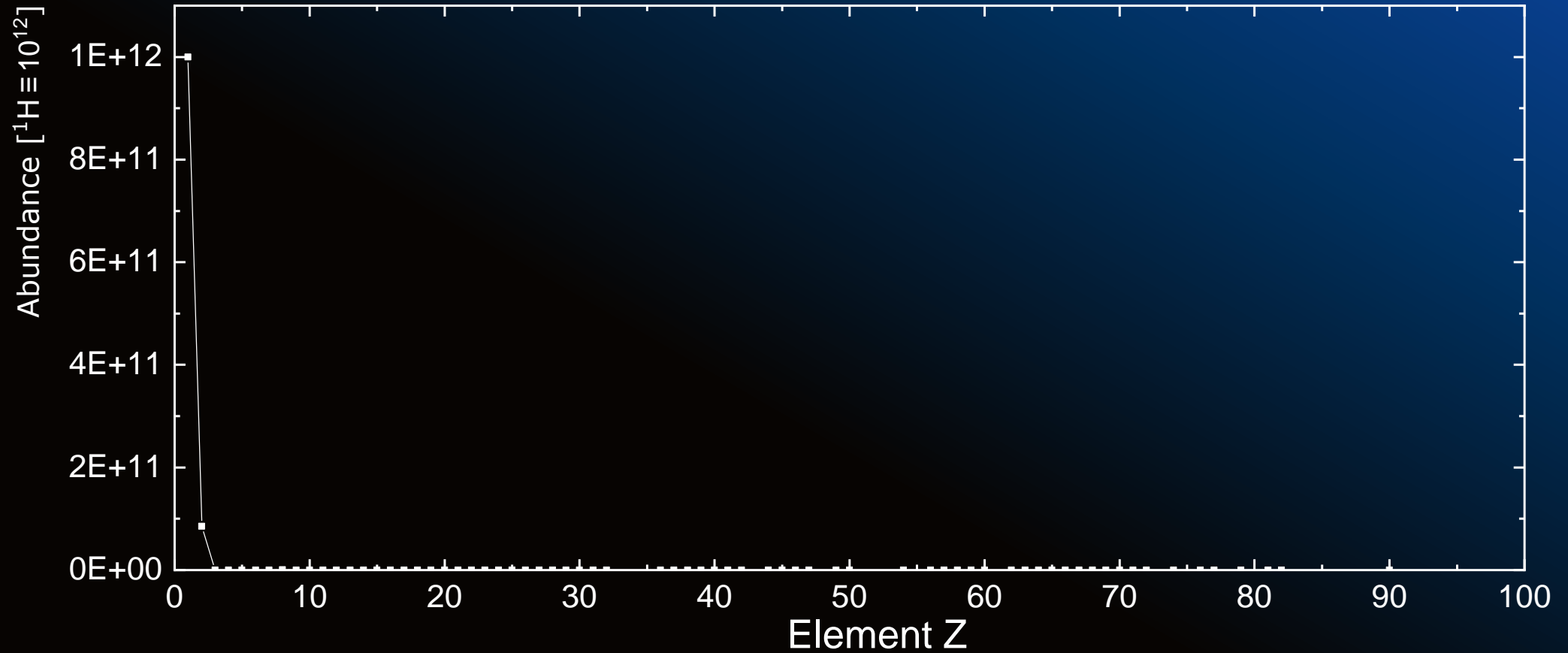
BIG BANG NUCLEOSYNTHESIS



CURRENT UNIVERSE

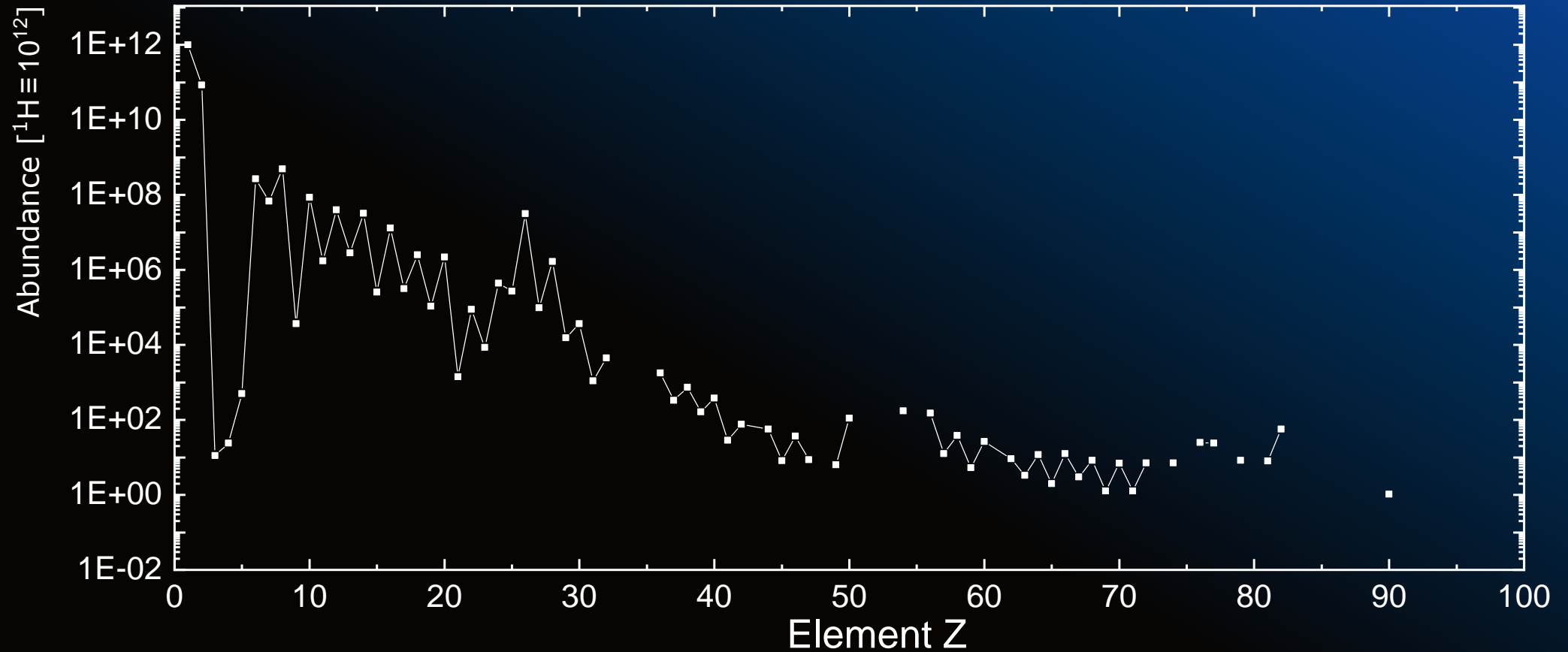


Elemental abundance of the solar photosphere



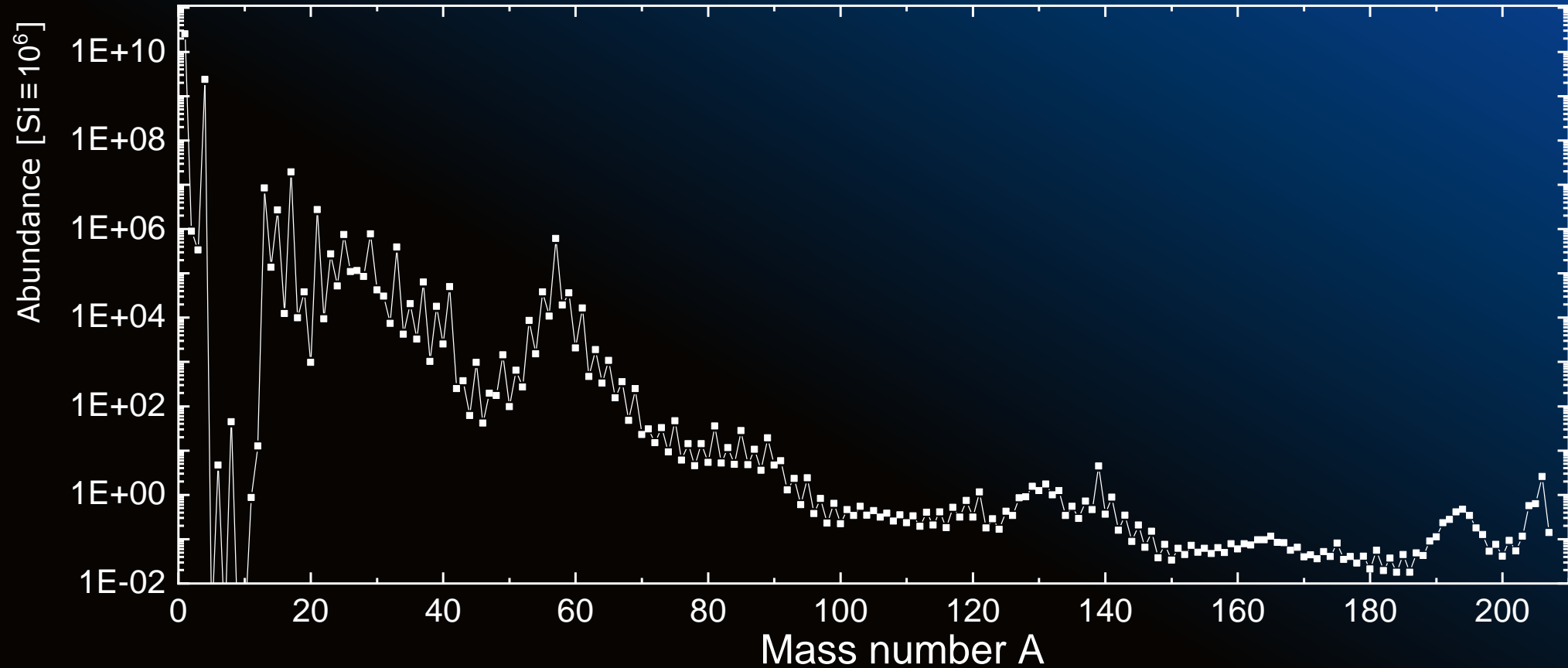
Data from: M. Asplund *et al.* Annual Reviews of Astronomy and Astrophysics, Vol. 47, 481 (2009)

Elemental abundance of the solar photosphere



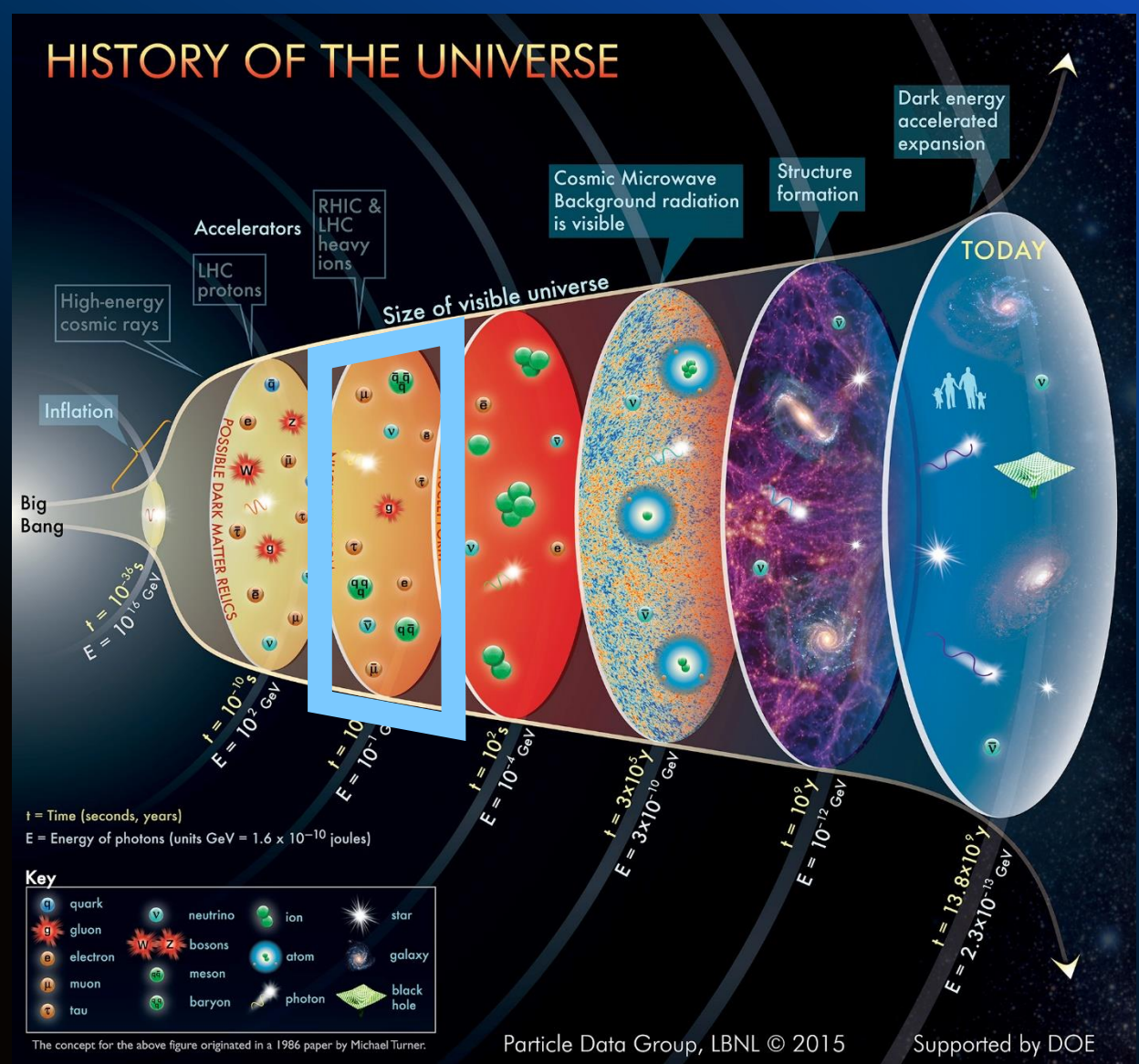
Data from: M. Asplund *et al.* Annual Reviews of Astronomy and Astrophysics, Vol. 47, 481 (2009)

Isobaric abundance of the solar system



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

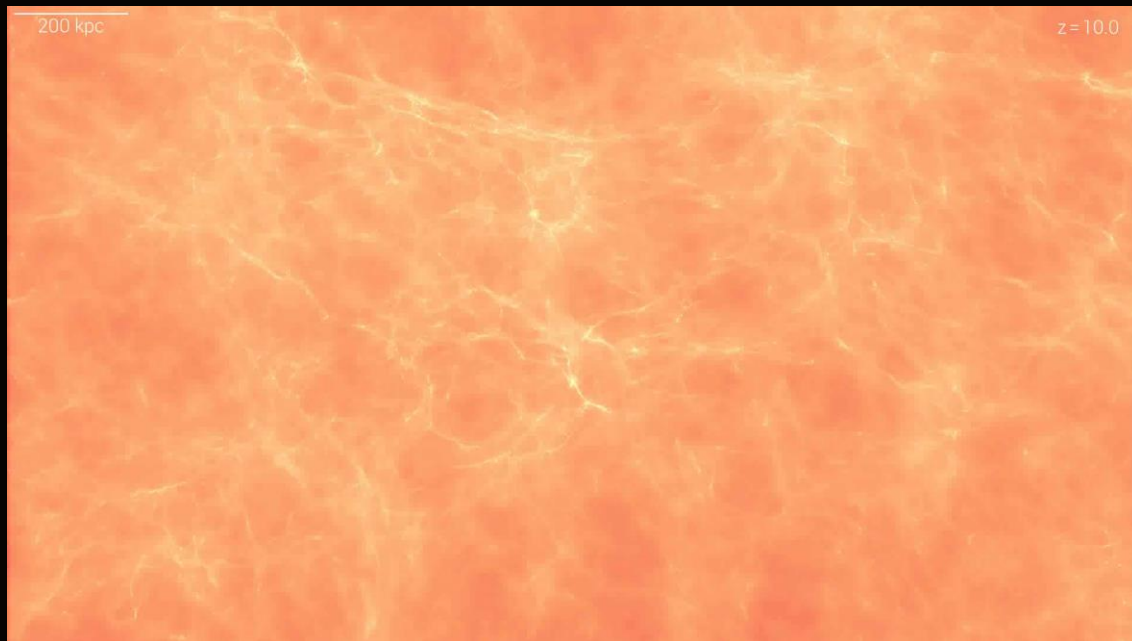
During the last 13.6Gyr...



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

Recreating nucleosynthesis environments

- Large scale simulation $\sim \mathcal{O}(\text{Mpc})$
- Simulation of galaxy supercluster



- "Small" scale simulation $\sim \mathcal{O}(\text{kpc})$
- Simulation of a single galaxy



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

- Osmium
- density: $\sim 22 \text{ g/cm}^3$
- densest material on earth

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



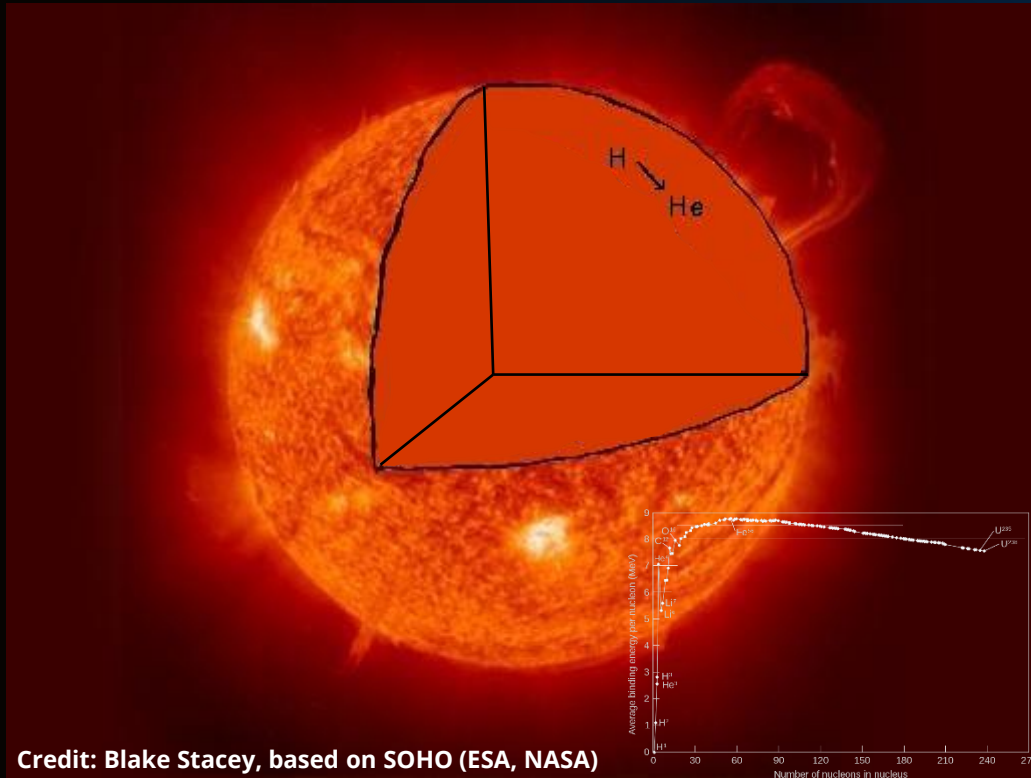
How much more dense does the center of a protostar need to get in order to finally start nucleosynthesis?

0 0 0

- 5 times more than Os
- 300 times more than Os
- 8000 times more than Os

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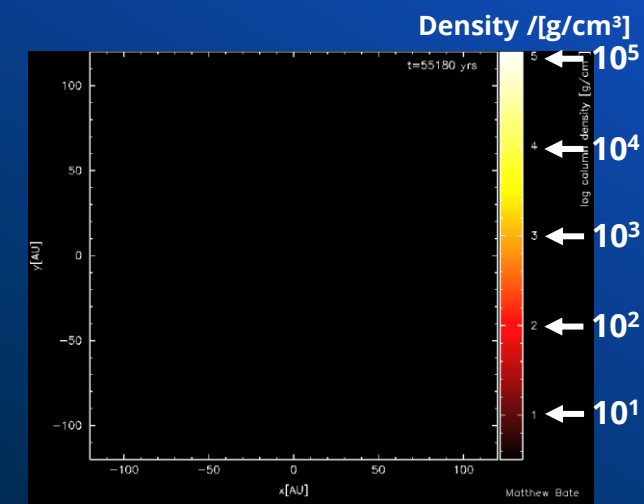
Protostar formation + stellar nucleosynthesis



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

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

	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

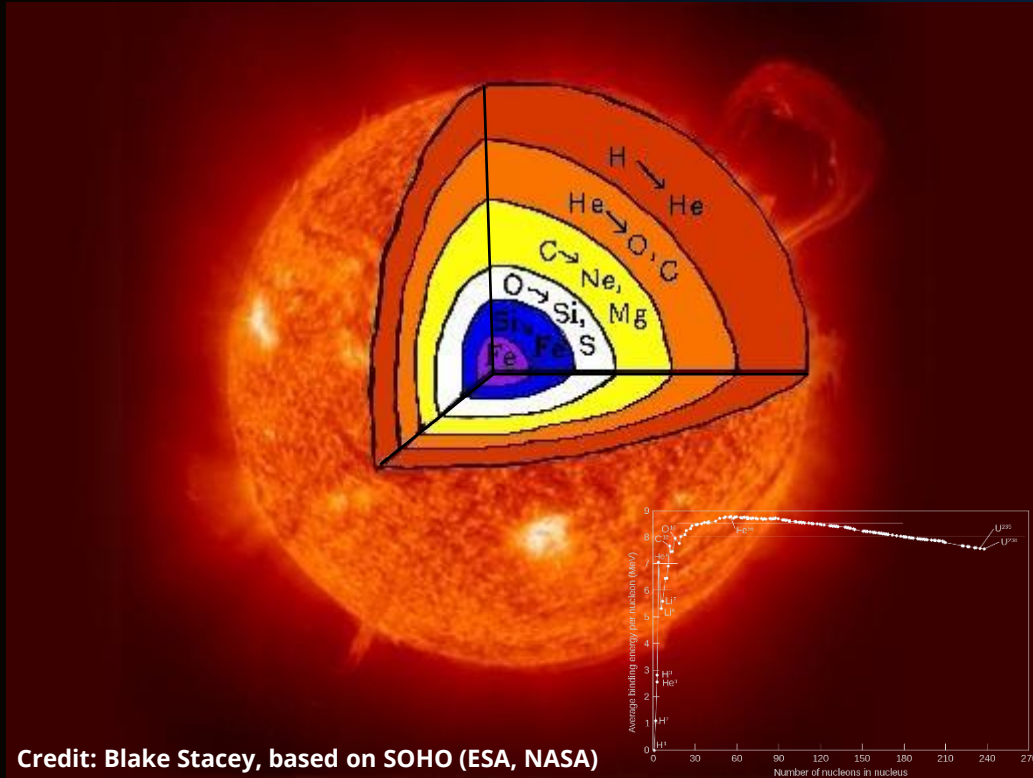


https://www.astro.ex.ac.uk/people/mbate/Animations/Beta0_01_RT_1M_DensSplash.mov

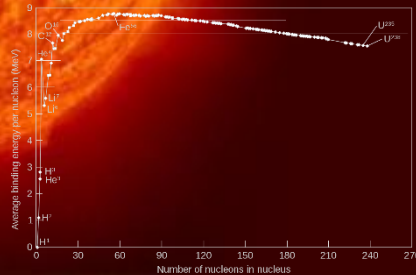


Courtesy: Matthew Bate (University of Exeter)

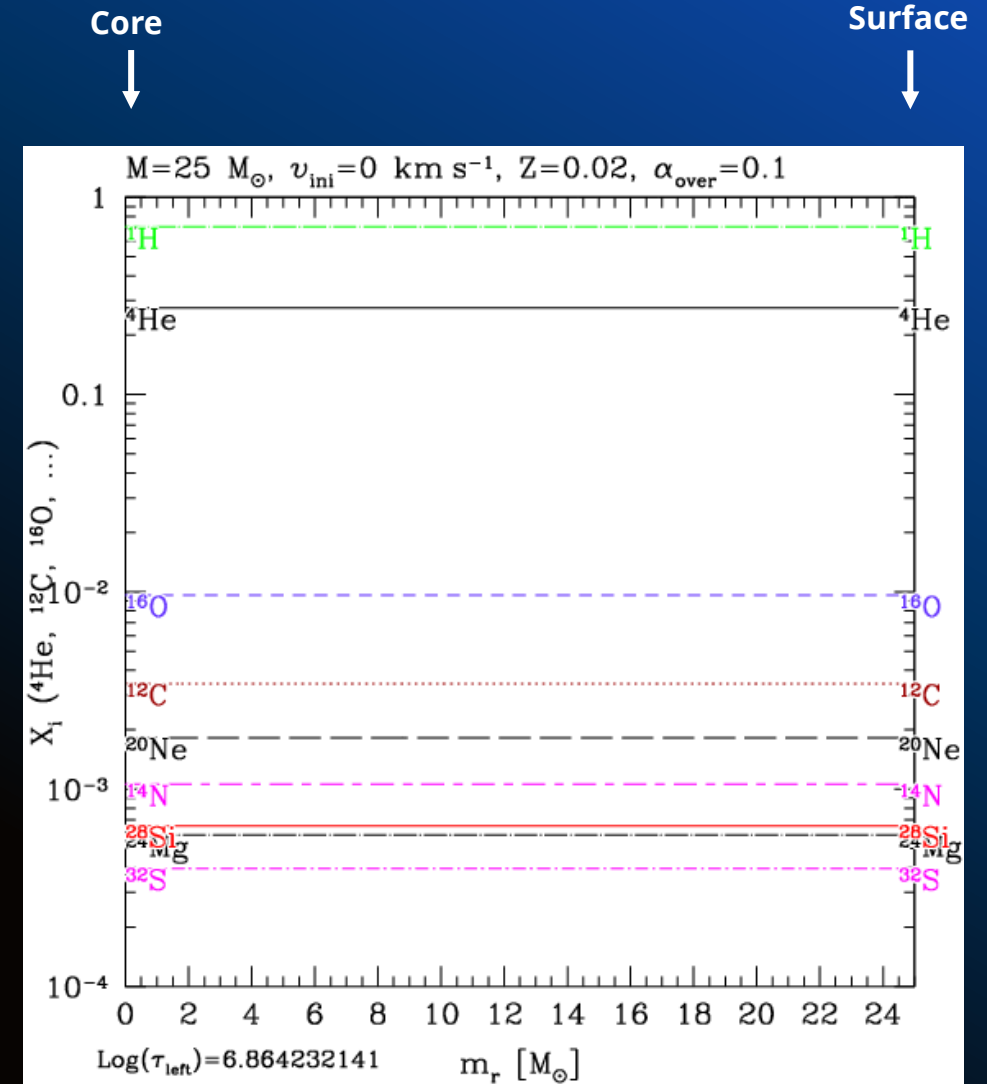
Stellar nucleosynthesis



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

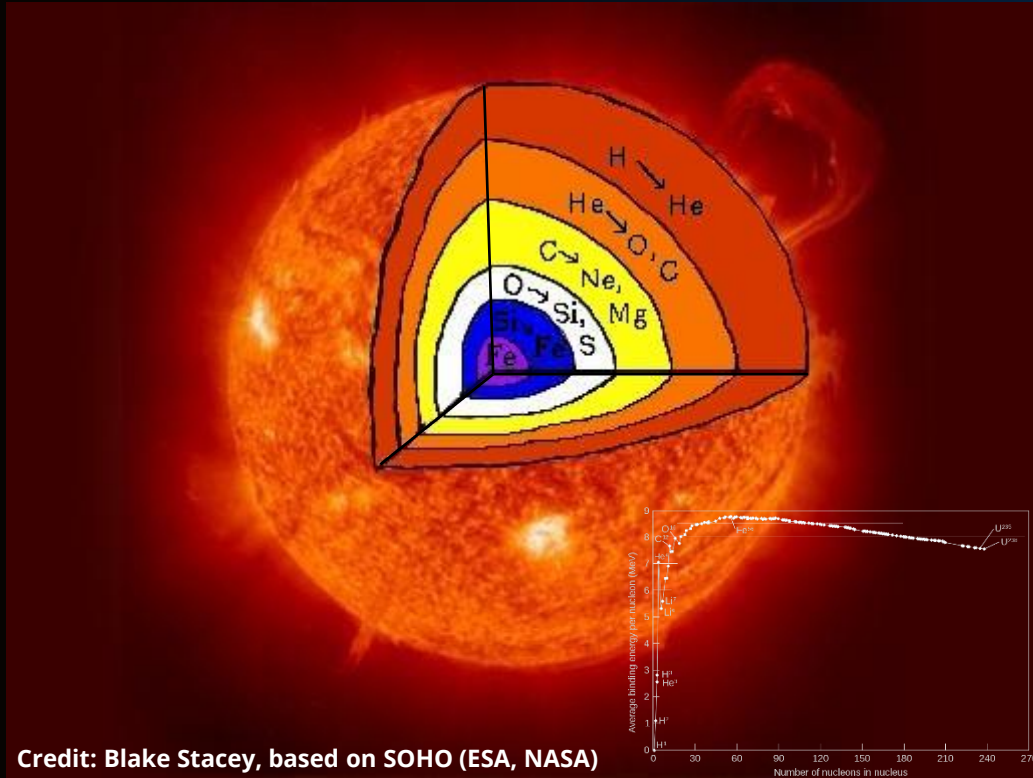


https://en.wikipedia.org/wiki/Nuclear_binding_energy

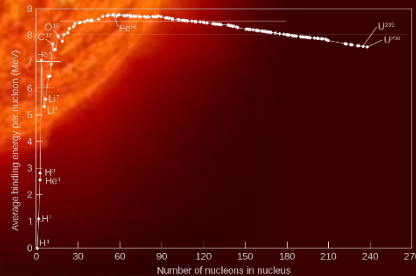


<https://www.astro.keele.ac.uk/~hirschi/animation/anim.html>

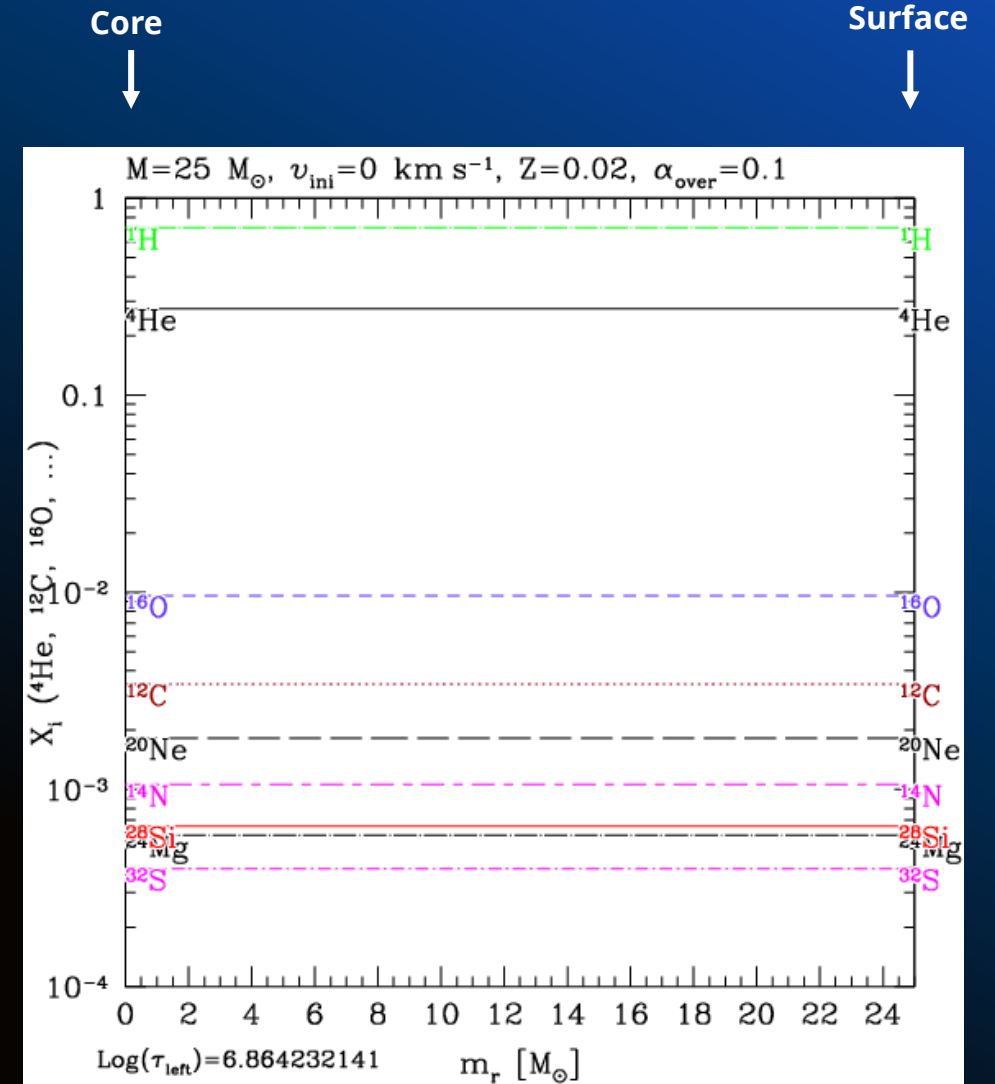
Stellar nucleosynthesis



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

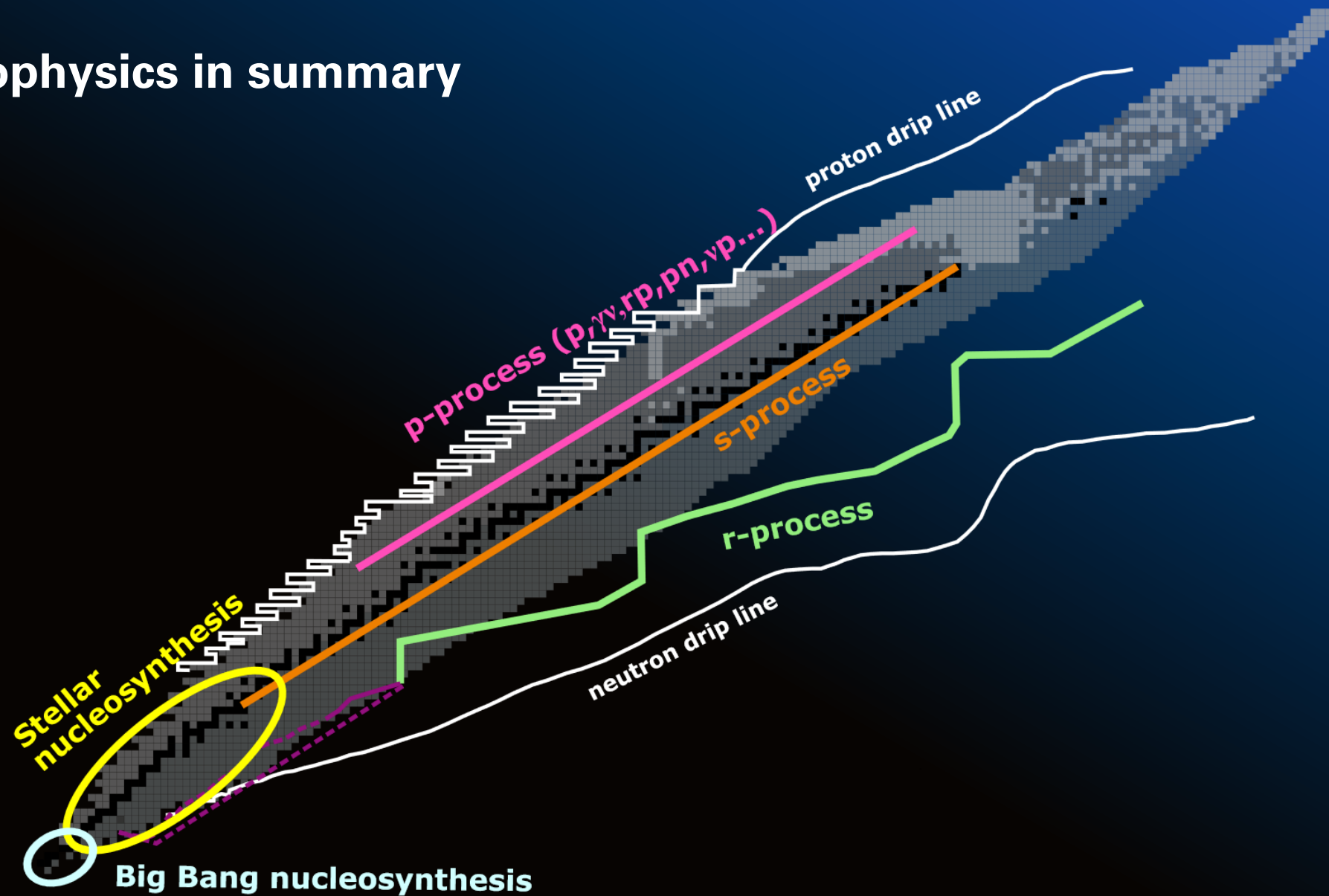


https://en.wikipedia.org/wiki/Nuclear_binding_energy

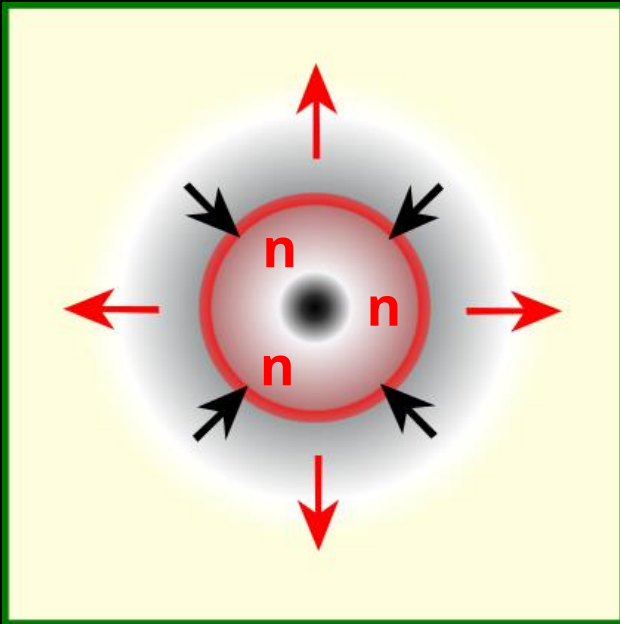


<https://www.astro.keele.ac.uk/~hirschi/animation/anim.html>

Nuclear astrophysics in summary

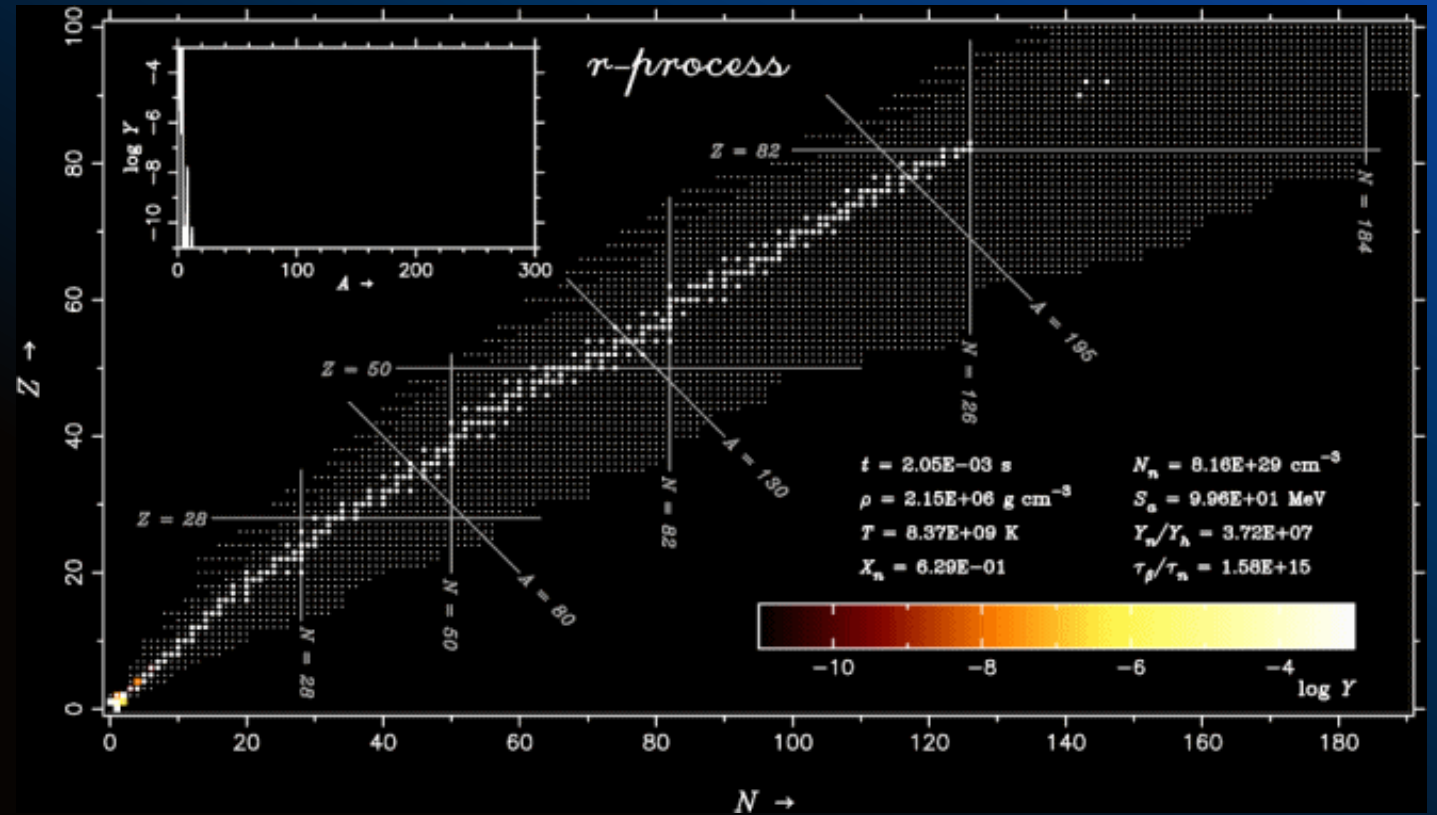


Explosive nucleosynthesis



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

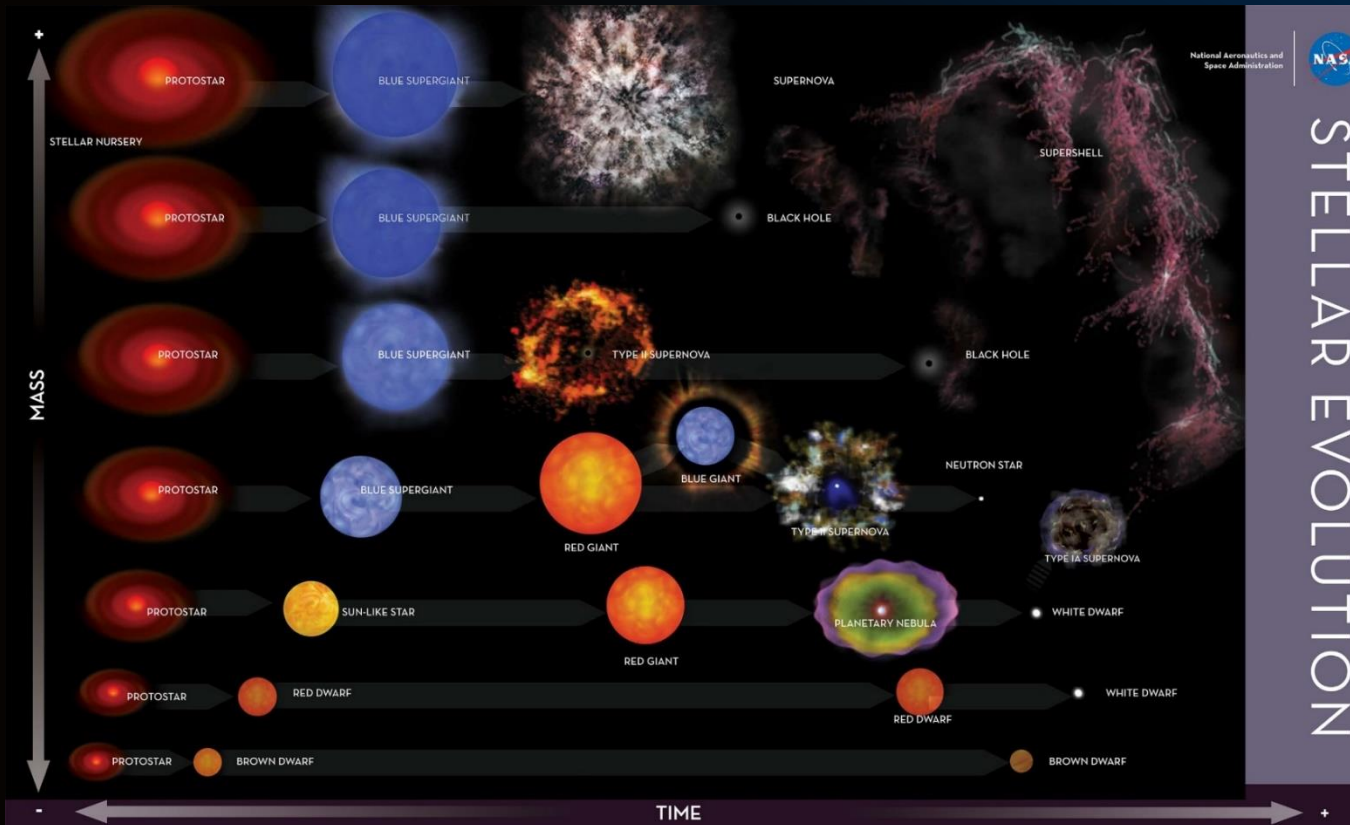
Explosive nucleosynthesis



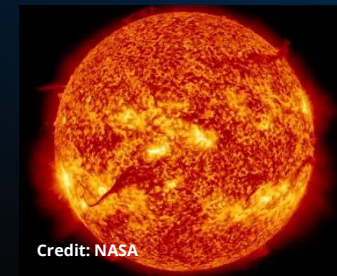
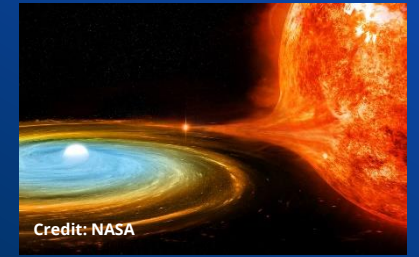
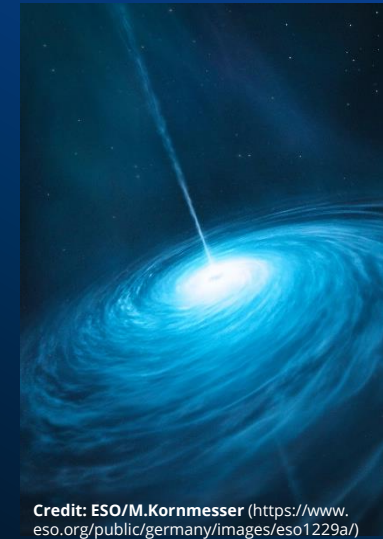
<http://www.ph.sophia.ac.jp/~shinya/research/research.html>

Credit: ESA (https://www.esa.int/ESA_Multimedia/Images/2003/07/Spitzer_Ultra-Deep_Field) A_Spitzer_Crop.jpg

Nuclear astrophysics during stellar evolution



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



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Nuclear astrophysics in a nutshell

Steffen Turkat
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INSTITUTE OF NUCLEAR AND PARTICLE PHYSICS



Konrad Adenauer Stiftung

Nuclear astrophysics
→ The origin of the elements

The new underground facility at Felsenkeller
→ How to study the universe from underground

Recent achievements and outlook
→ Experimental campaign about on ^{10}Be , ^{11}Be

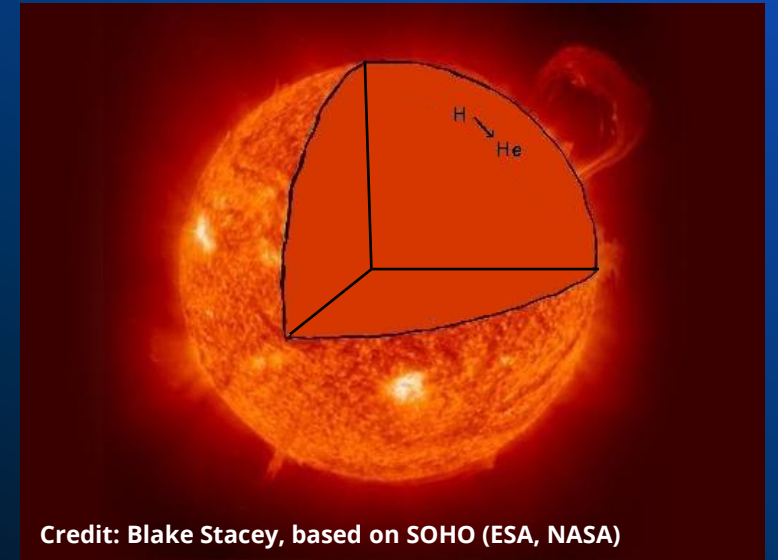
Chemical evolution of the universe

> How, when & in which amounts were all the elements in our universe formed?

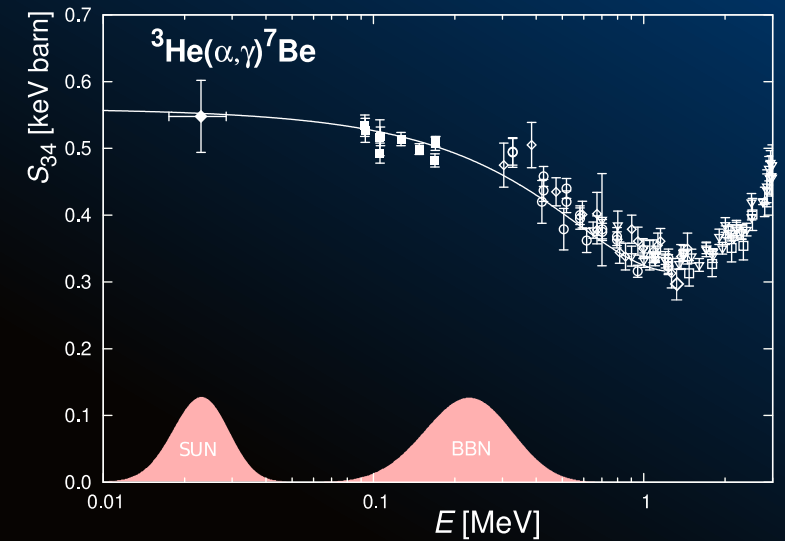
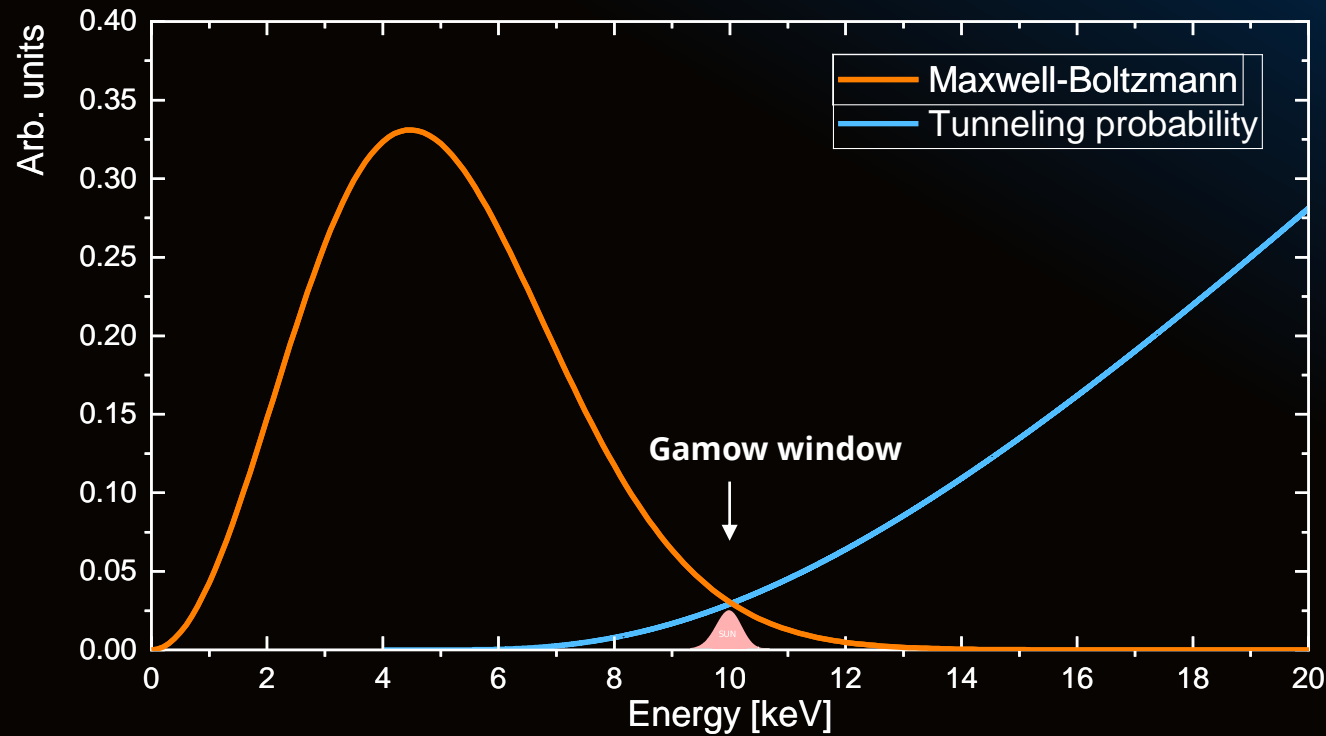
Nuclear Astrophysics
→ Our Earth

Q1: What are the four most abundant elements of our earth?
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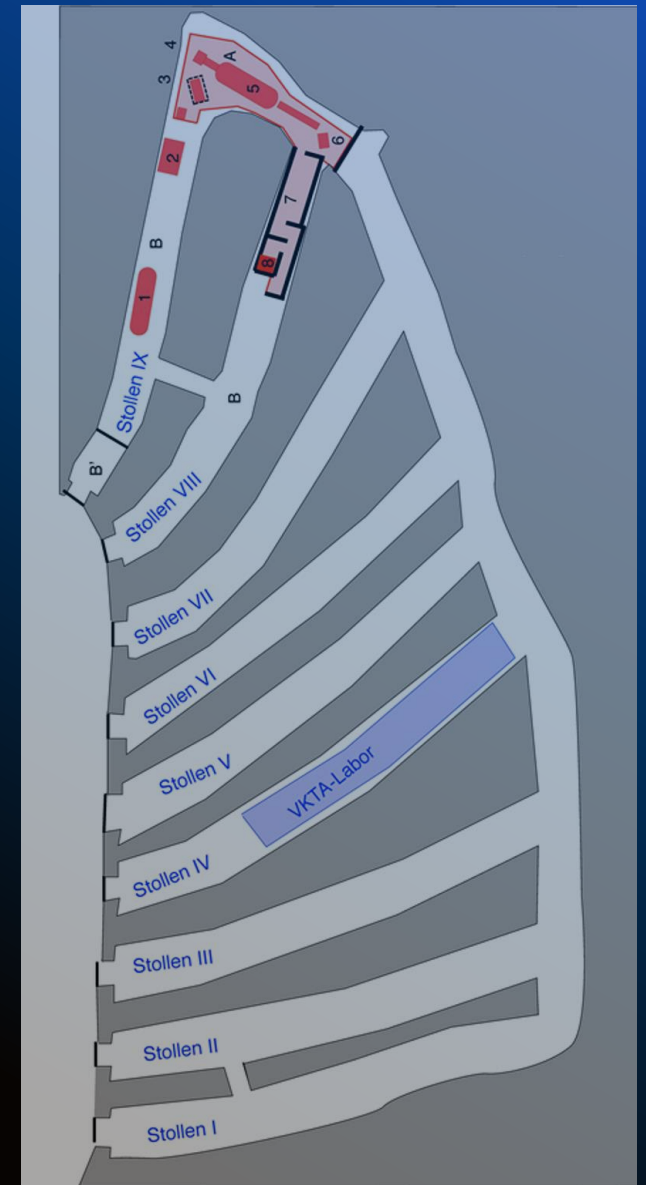
From the interior of stars to the interior of tunnels



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

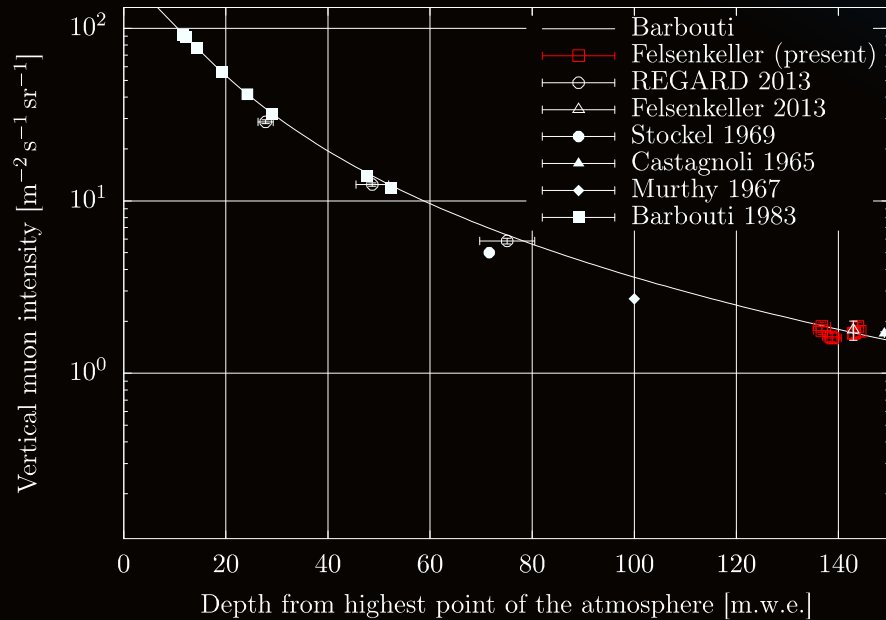


The new Felsenkeller laboratory

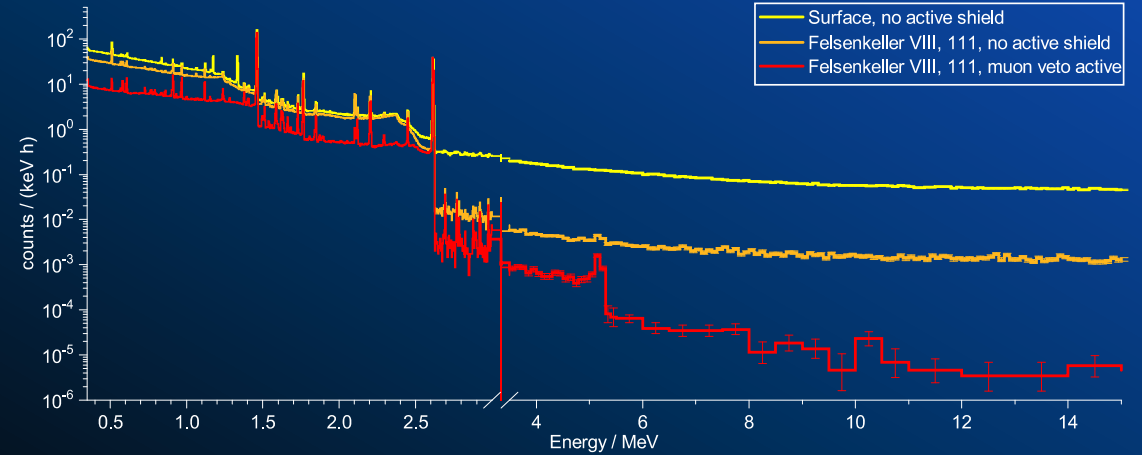


The benefit of going underground

- Protection from cosmic muons (reduce background)
- Investigate rare processes in nuclear astrophysics
 - Measure close to Gamow window

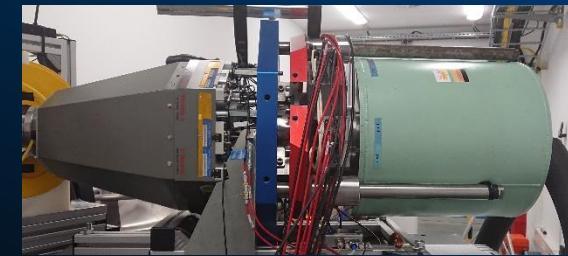
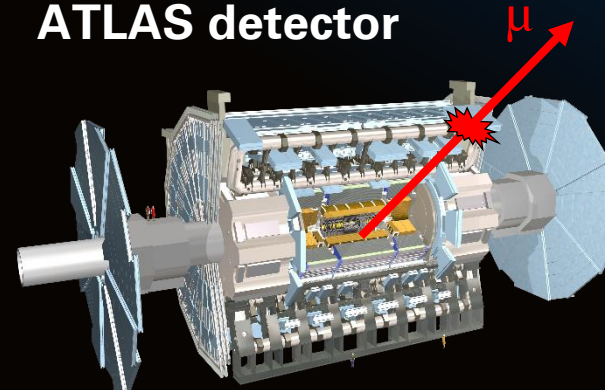


F. Ludwig et al. *Astroparticle Physics* 112 (2019) 24-34



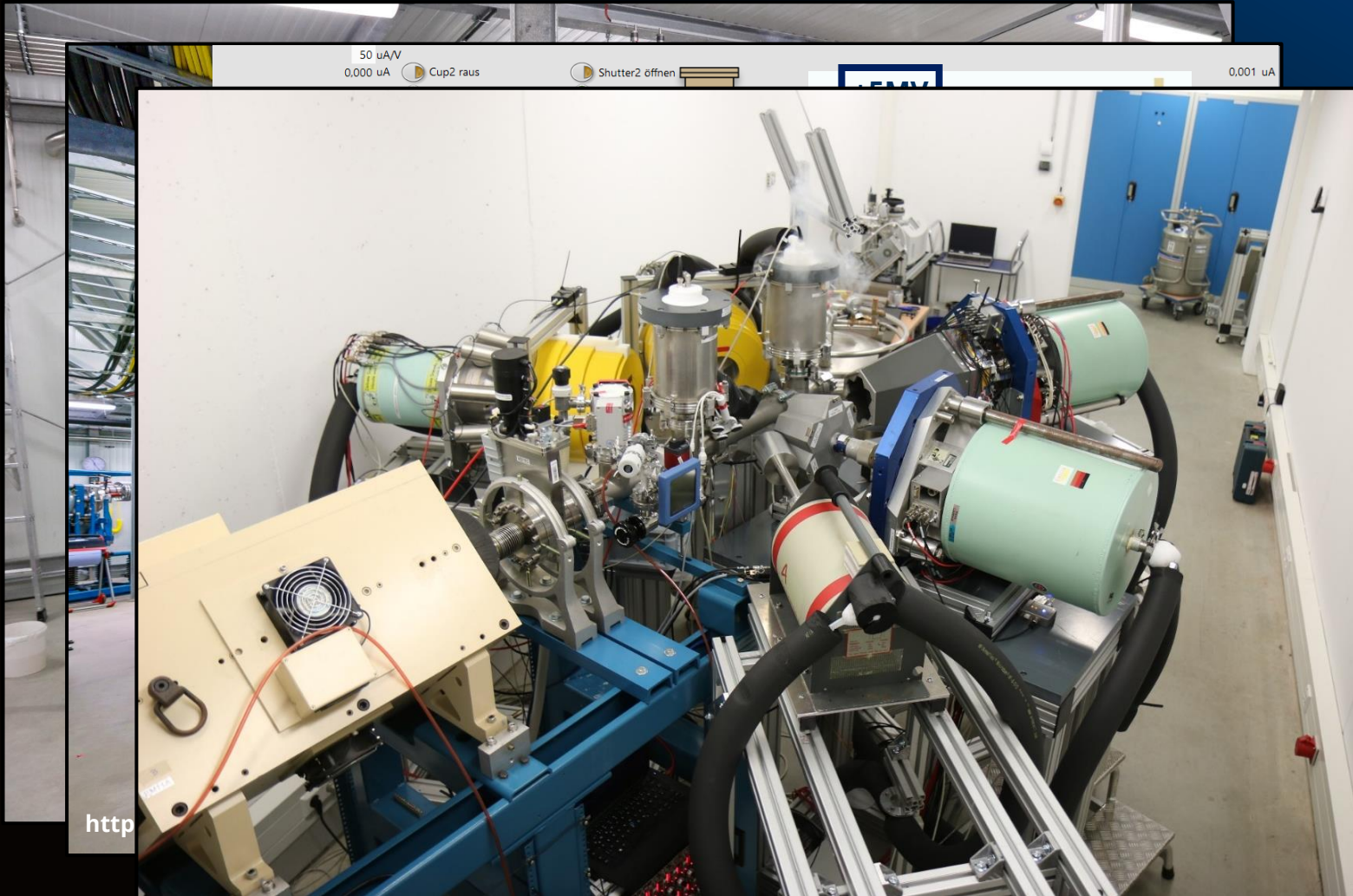
Adapted from: T. Szücs et al. *European Physics Journal A* 55, 174

ATLAS detector

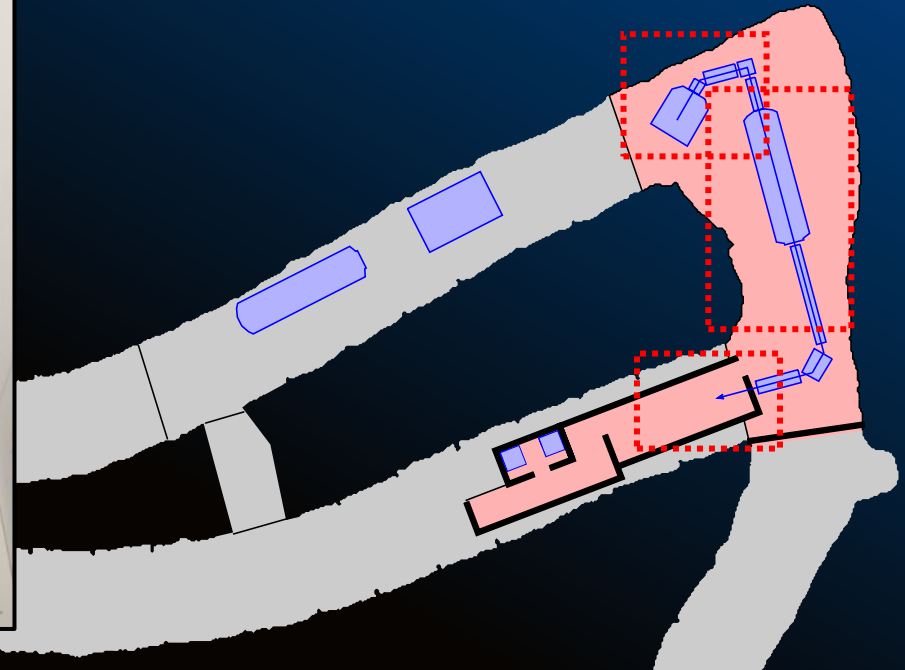


http://opendata.atlas.cern/books/current/get-started/_book/GLOSSARY.html

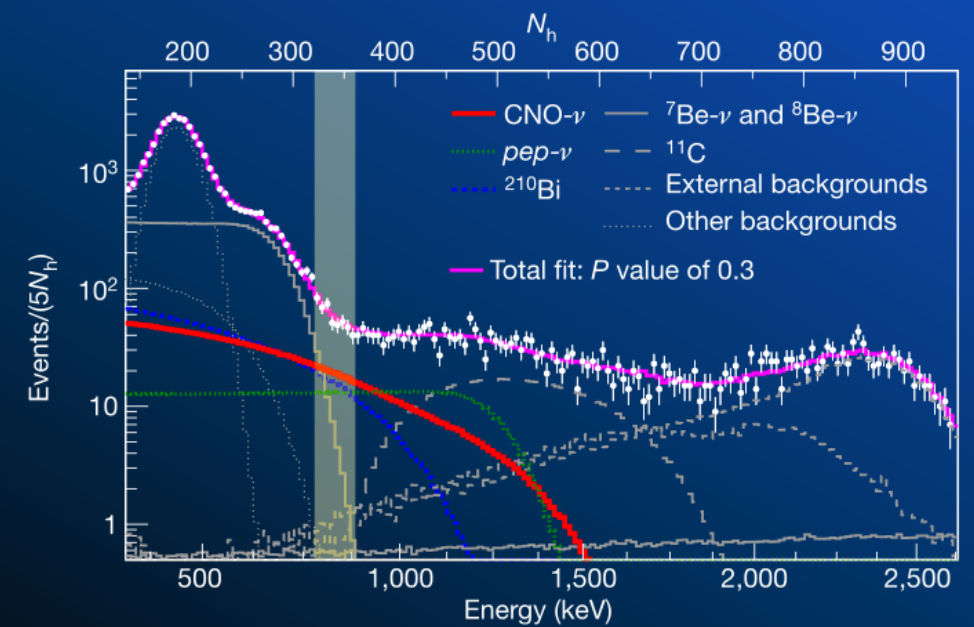
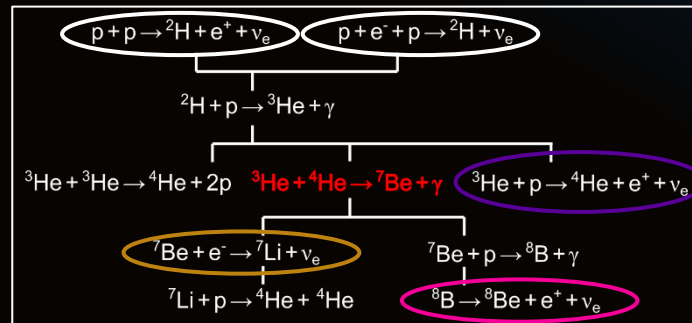
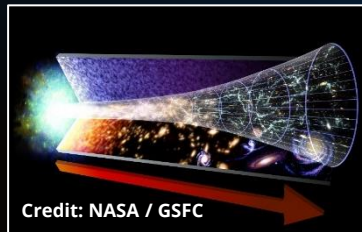
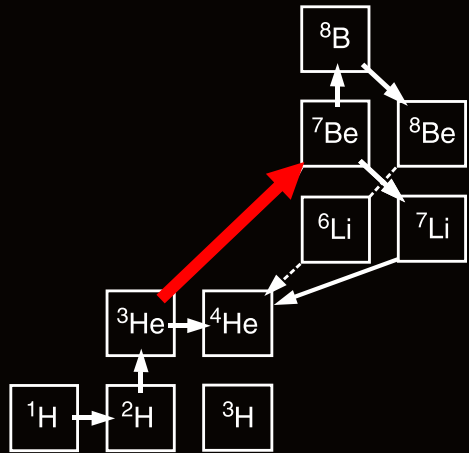
The new Felsenkeller underground laboratory



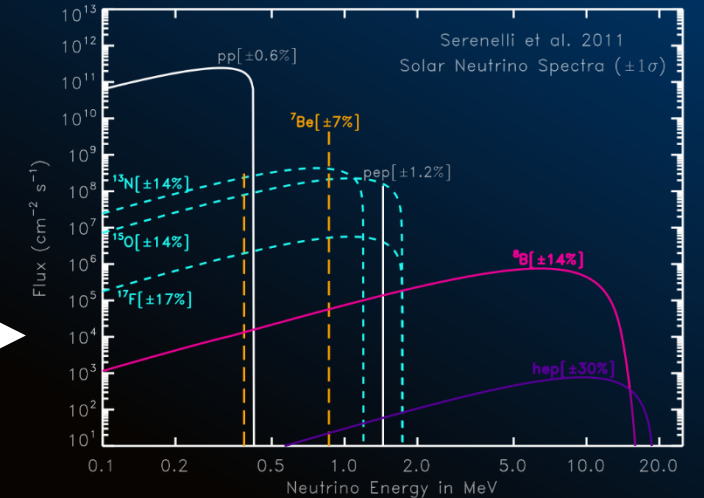
- External ion source
 - Carbon beam ($^{12}\text{C}^-$) in tandem mode
- 5MV Pelletron accelerator
 - Carbon beam in tandem mode
- Internal ion source
 - H & He beam in single end mode
- Current experimental setup
 - $^3\text{He}(\alpha, \gamma)^7\text{Be}$ campaign



The ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$ reaction



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



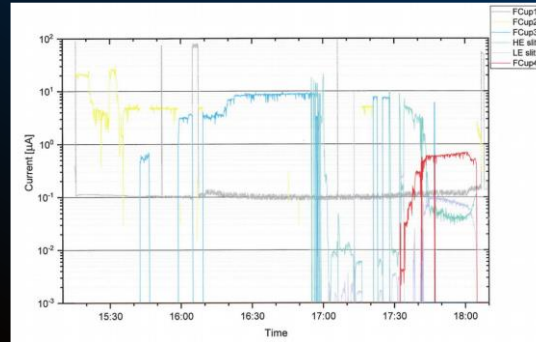
Haxton et al. Annu. Rev. Astron. Astrophys. 51 1 (2013)

Timeline of the last three years



Credit: Philipp Lindenau (TU Dresden)

28.06.2017: Topping out ceremony



03.07.2019: First light at FK (external ion source)



09.11.2020: Stable beam (internal ion source)



26.11.2020: Beam quality improvements

13.08.2018: Last beam line component underground



04.07.2019: Inauguration



Credit: Andre Wirsig (HZDR)

16.11.2020: First ${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$ reaction

