This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101008324 (ChETEC-INFRA).

Nuclear astrophysics in an underground lab

CELLAR Community Meeting

Dresden-Rossendorf, 28.-30.11.2022

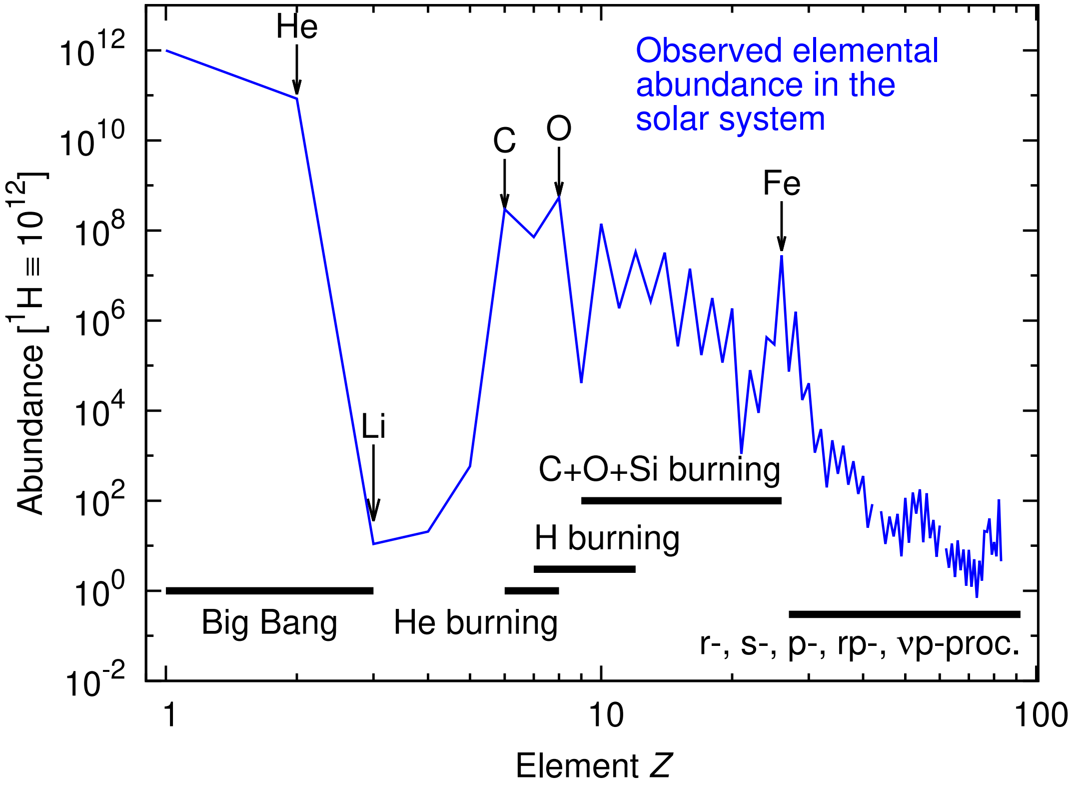
Daniel Bemmerer

Helmholtz-Zentrum Dresden-Rossendorf

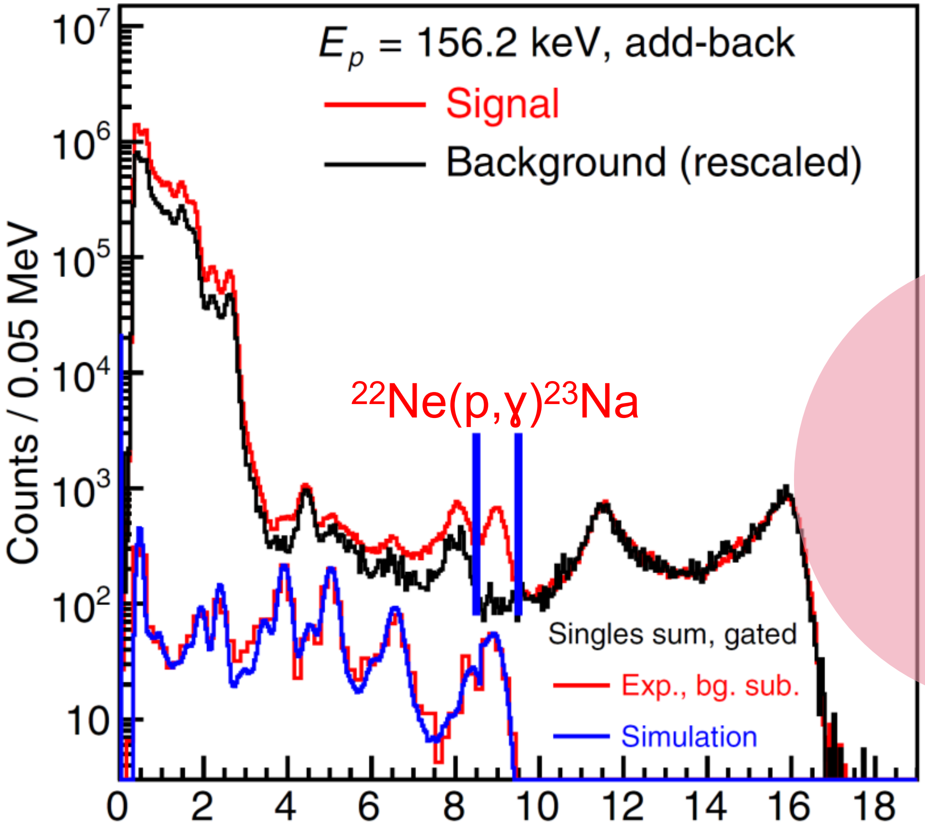
The periodic table of the elements… and their abundances

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															

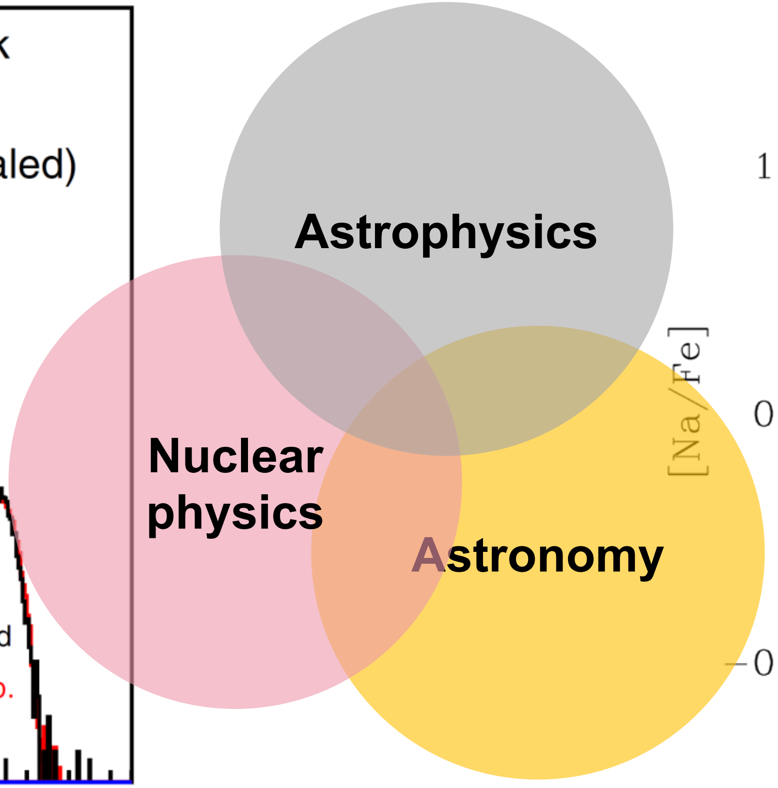
Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Th	Pa	U											

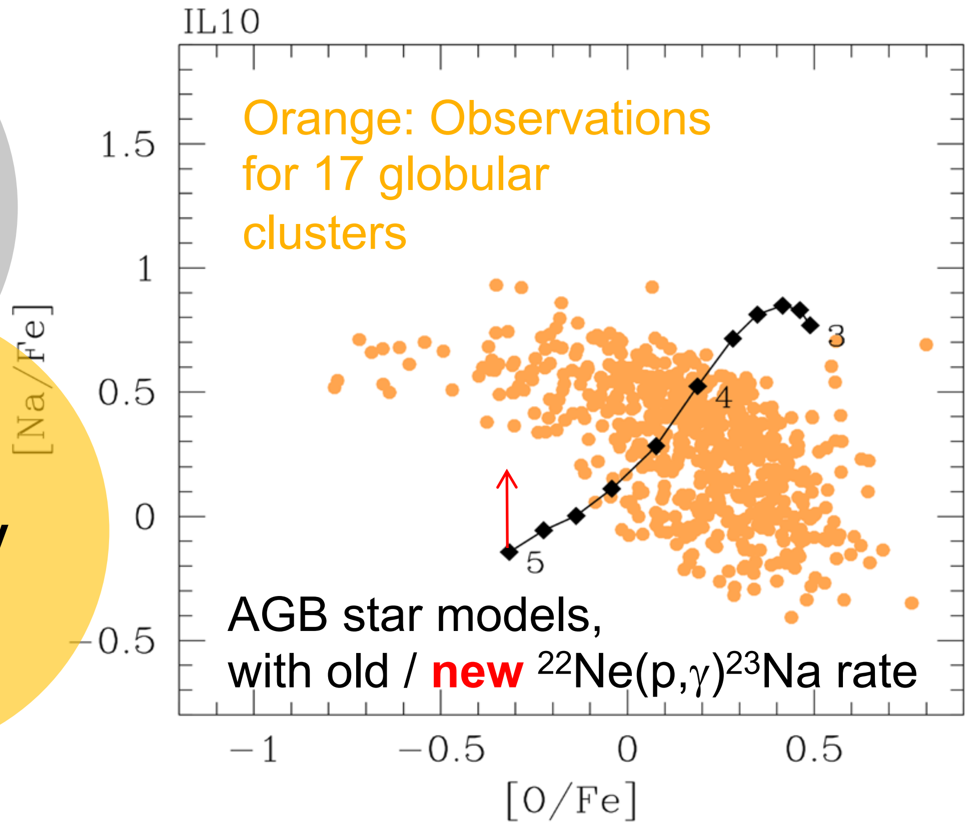


Nuclear astrophysics at the intersection of three disciplines



Ferraro, DB *et al.* PRL 121, 172701 (2018)





Slemer, DB *et al.* MNRAS 465, 4817 (2017)

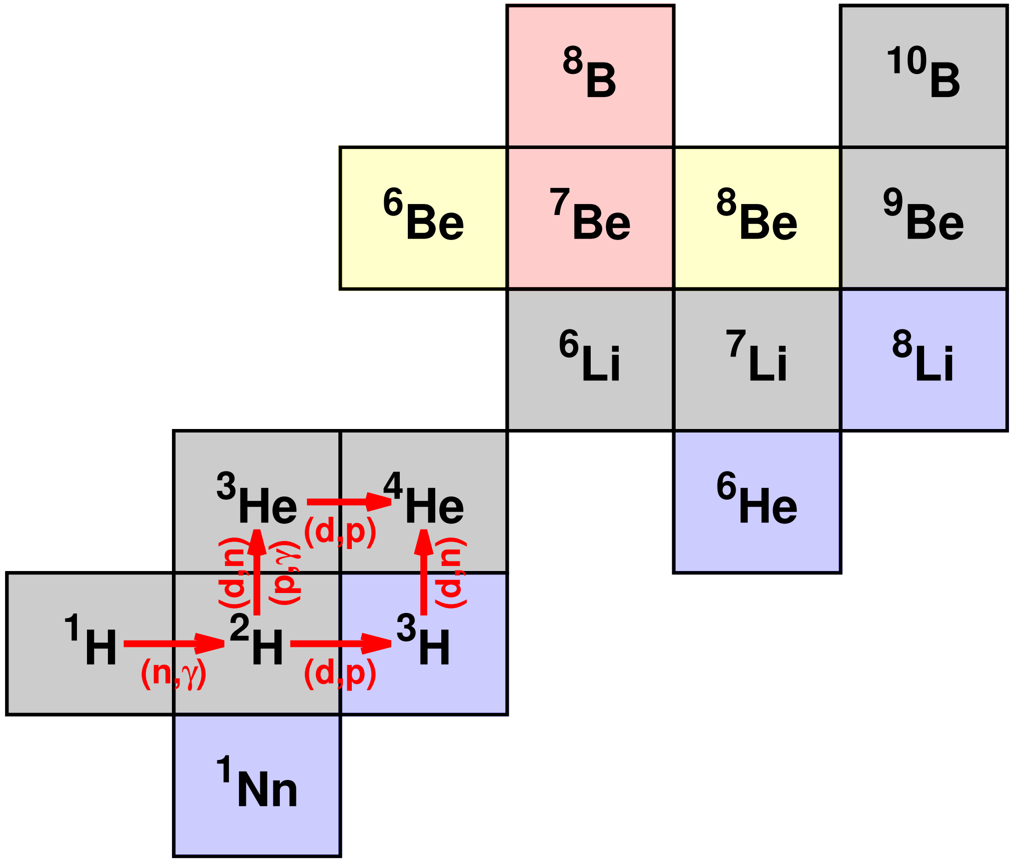
The periodic table: Big Bang Nucleosynthesis

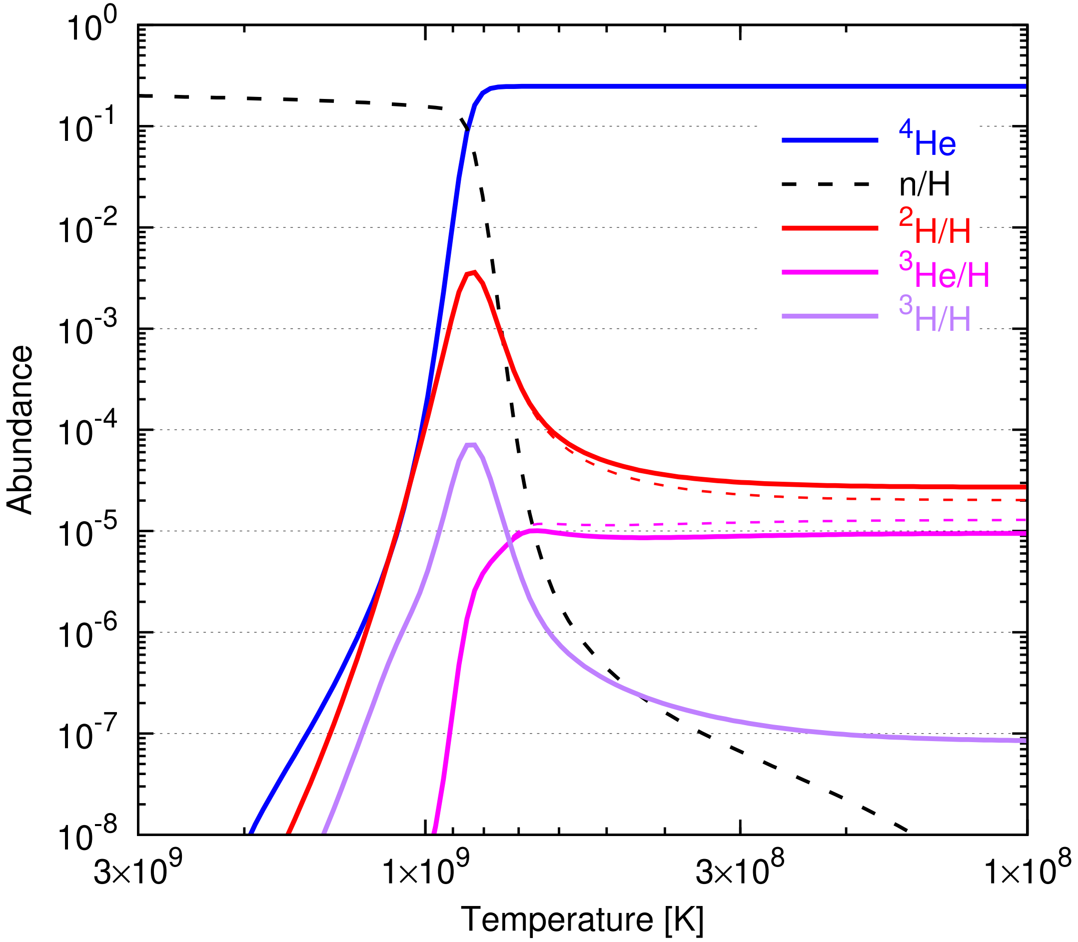
H																		He
Li	Be												B	C	N	O	F	Ne
Na	Mg												Al	Si	P	S	Cl	Ar
K	Ca	Sc		Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac																

Big Bang

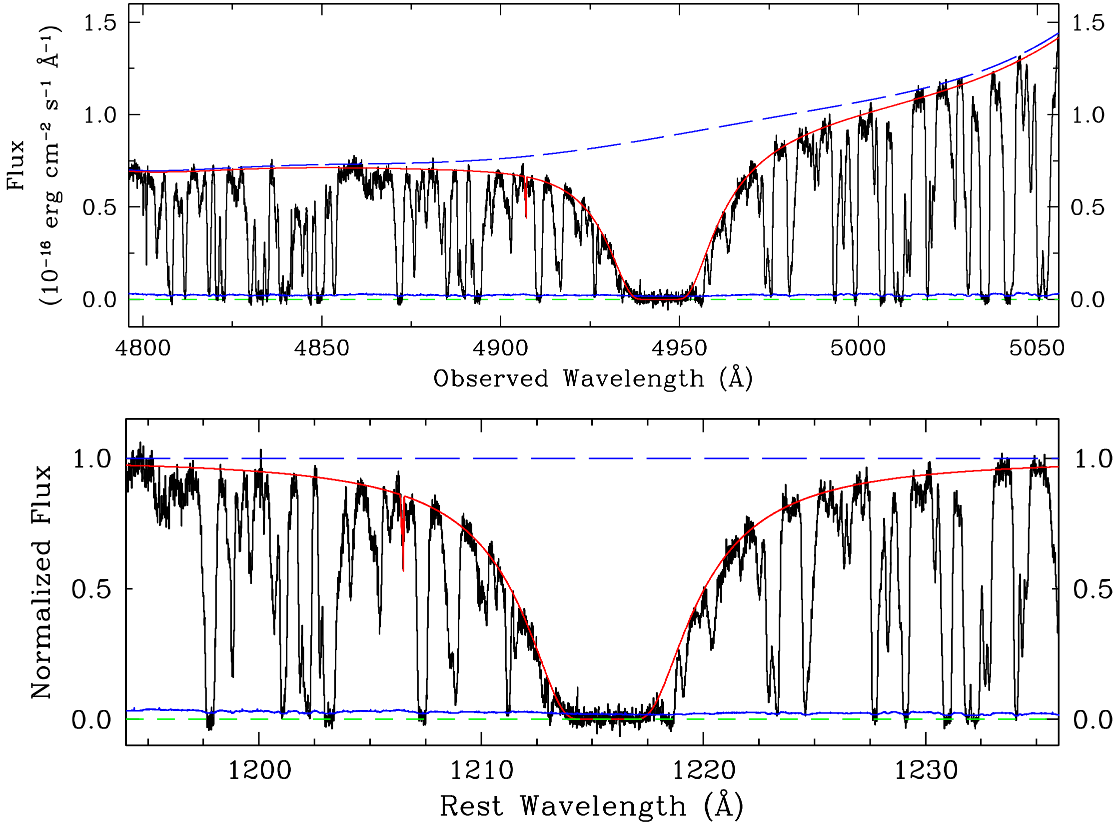
Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Th	Pa	U											

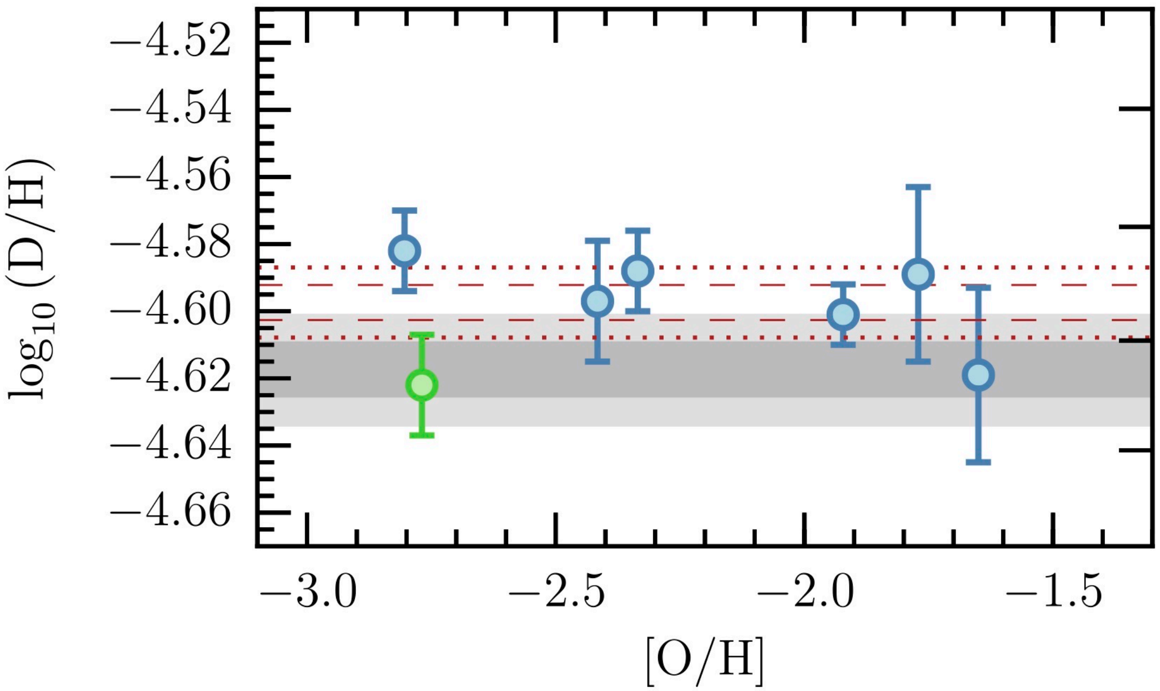
Big Bang Nucleosynthesis (BBN) and ^{2}H (D) as a cosmological probe





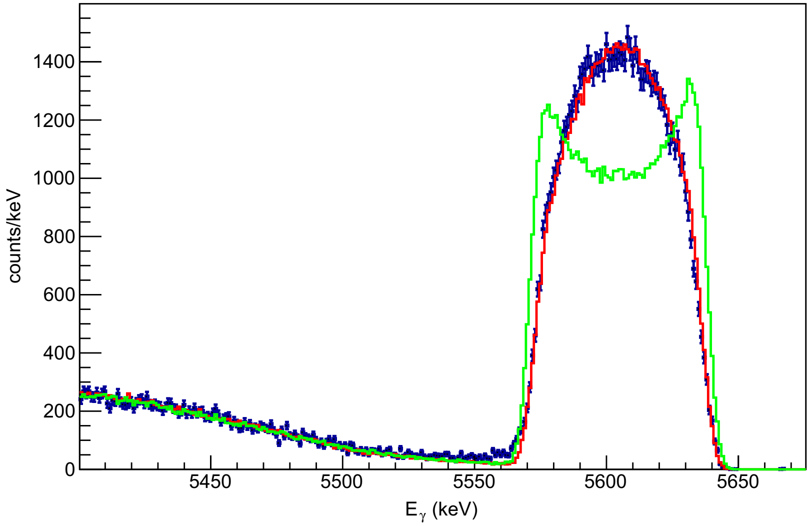
Big Bang Nucleosynthesis (BBN) and ^{2}H (D) as a cosmological probe

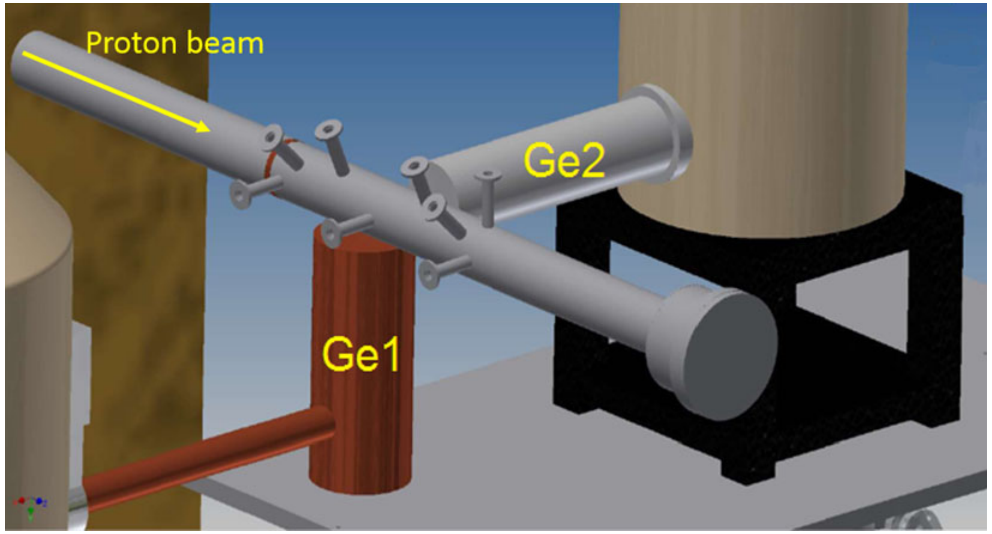




Astronomical ^{2}H observations:
Cooke *et al*. ApJ 855, 102 (2018)

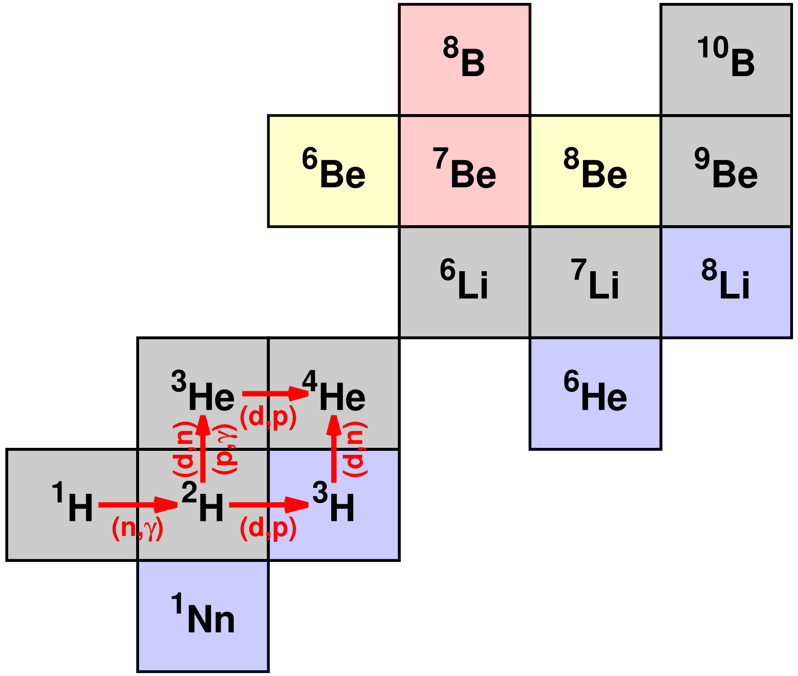
Big Bang Nucleosynthesis (BBN) and ^{2}H (D) as a cosmological probe

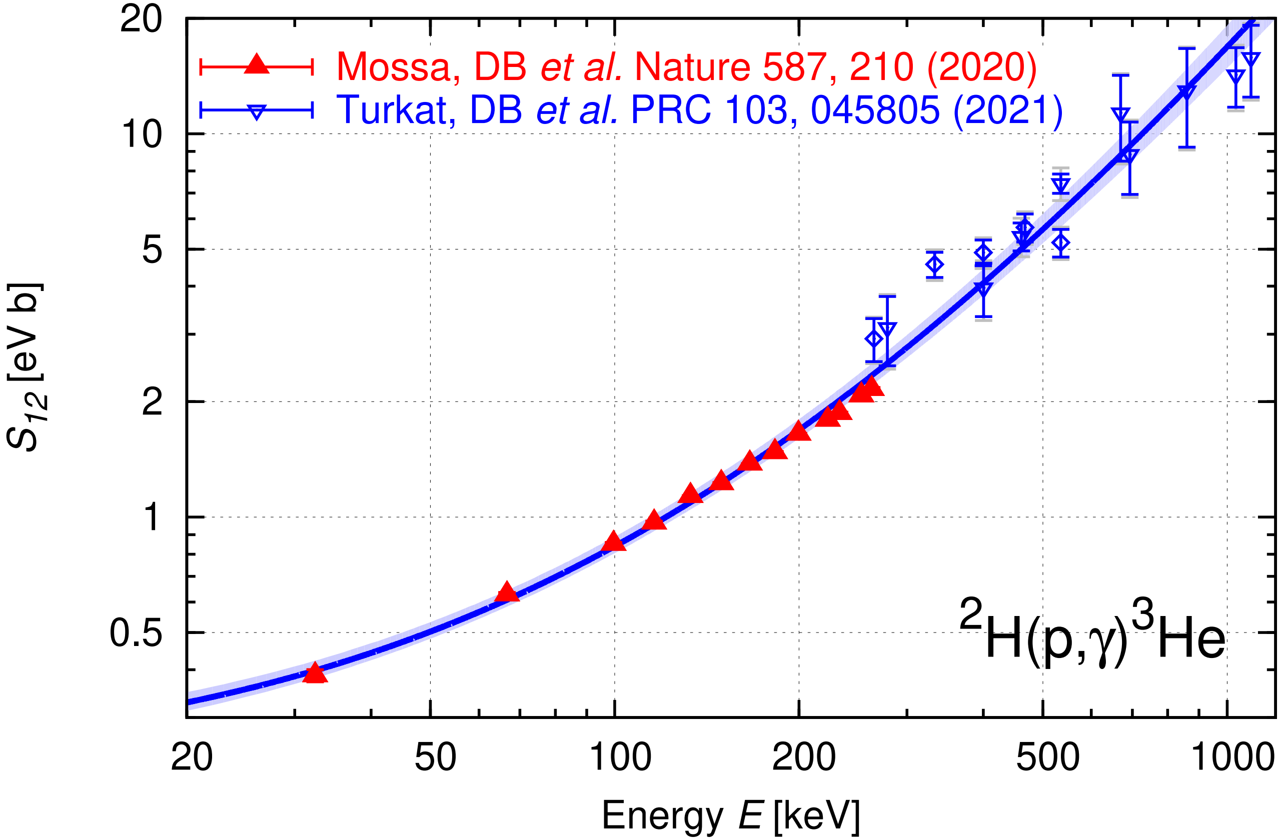




LUNA deep underground, Gran Sasso / Italy:
Mossa, DB *et al.* Nature 587, 210 (2020)

Big Bang Nucleosynthesis (BBN) and ^{2}H (D) as a cosmological probe





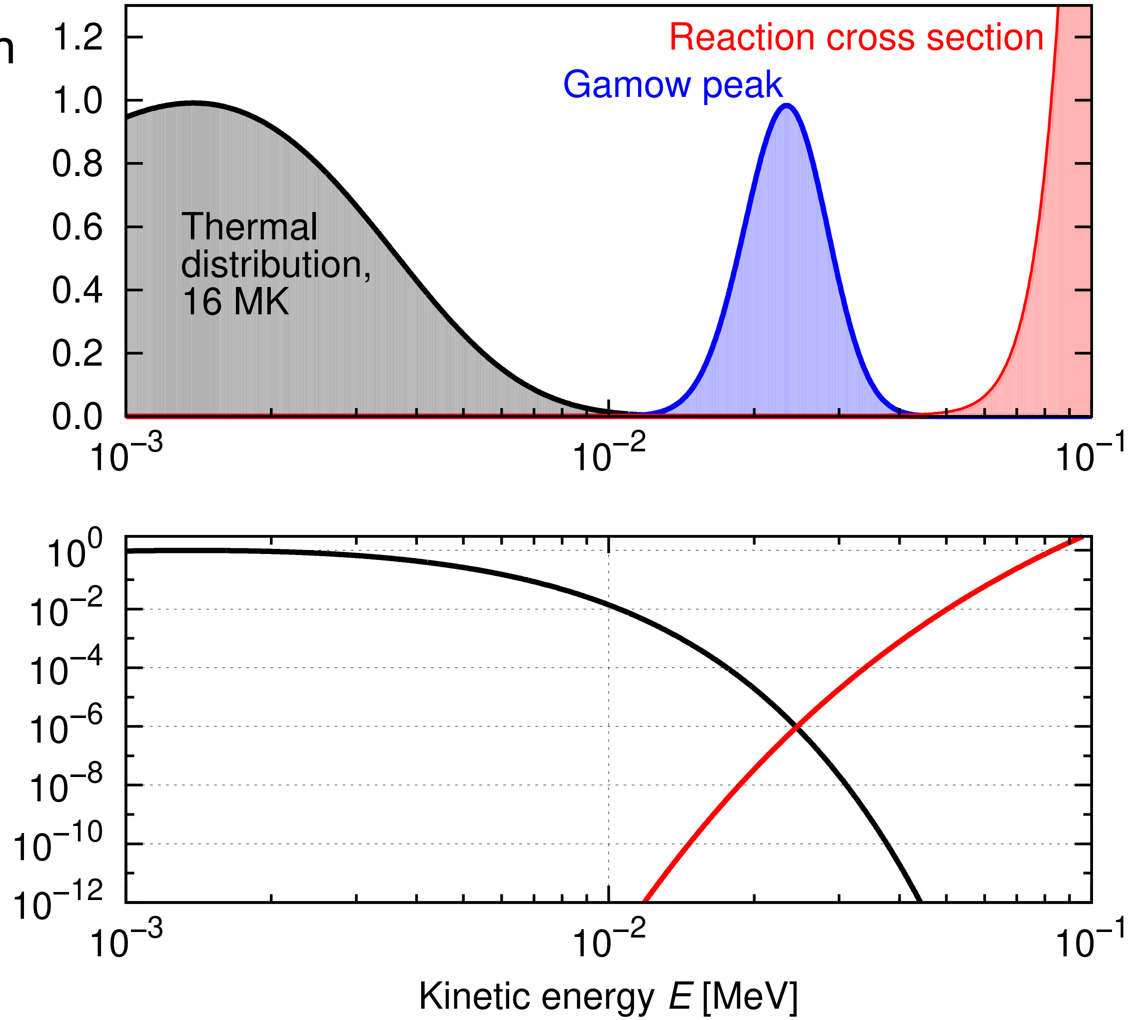
Using ^{2}H from BBN to determine the cosmic baryon density:

$$\Omega_b h^2 = 0.02271 \pm 0.00062 \quad \text{BBN, before new LUNA data}$$
$$\Omega_b h^2 = 0.02233 \pm 0.00036 \quad \text{BBN, including new LUNA data}$$
$$\Omega_b h^2 = 0.02236 \pm 0.00015 \quad \text{Cosmic Microwave Background}$$

Charged-particle induced nuclear reactions in a star

Thermal distribution of particles in a stellar plasma

$$P(E) = \frac{2\sqrt{E}}{\sqrt{\pi}(k_\mathrm{B}T)^{\frac{3}{2}}} \times \exp\left[-\frac{E}{k_\mathrm{B}T}\right]$$



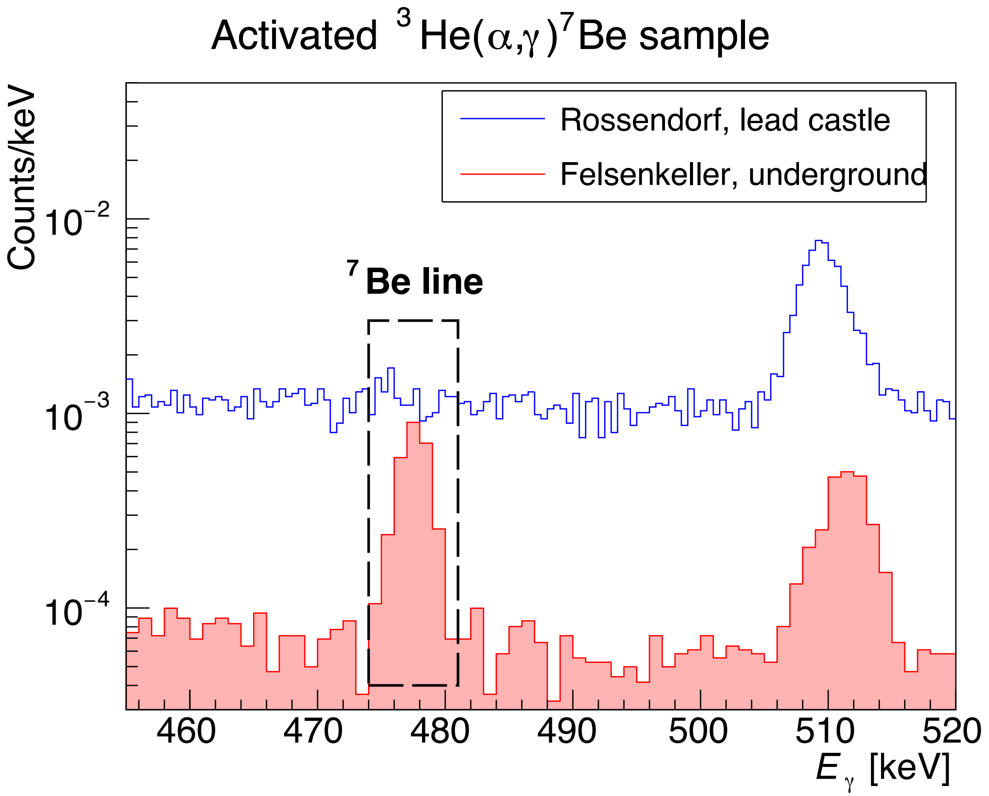
Nuclear reaction cross section far below the repulsive Coulomb barrier

picobarn – nanobarn

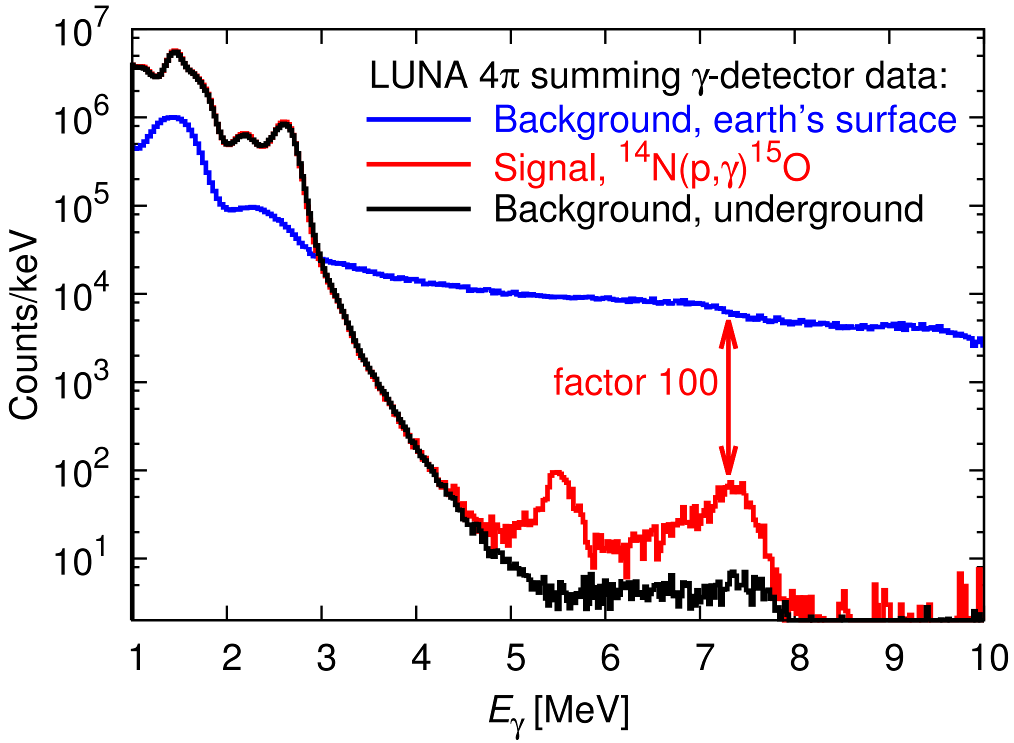
$$\sigma(E) = \frac{S(E)}{E} \exp\left[-\frac{b}{\sqrt{E}}\right]$$

S(E) = astrophysical S-factor

Measuring very small cross sections, two examples



Felsenkeller Dresden



LUNA, below the Gran Sasso mountain, Italy

The periodic table: Hydrostatic stellar burning

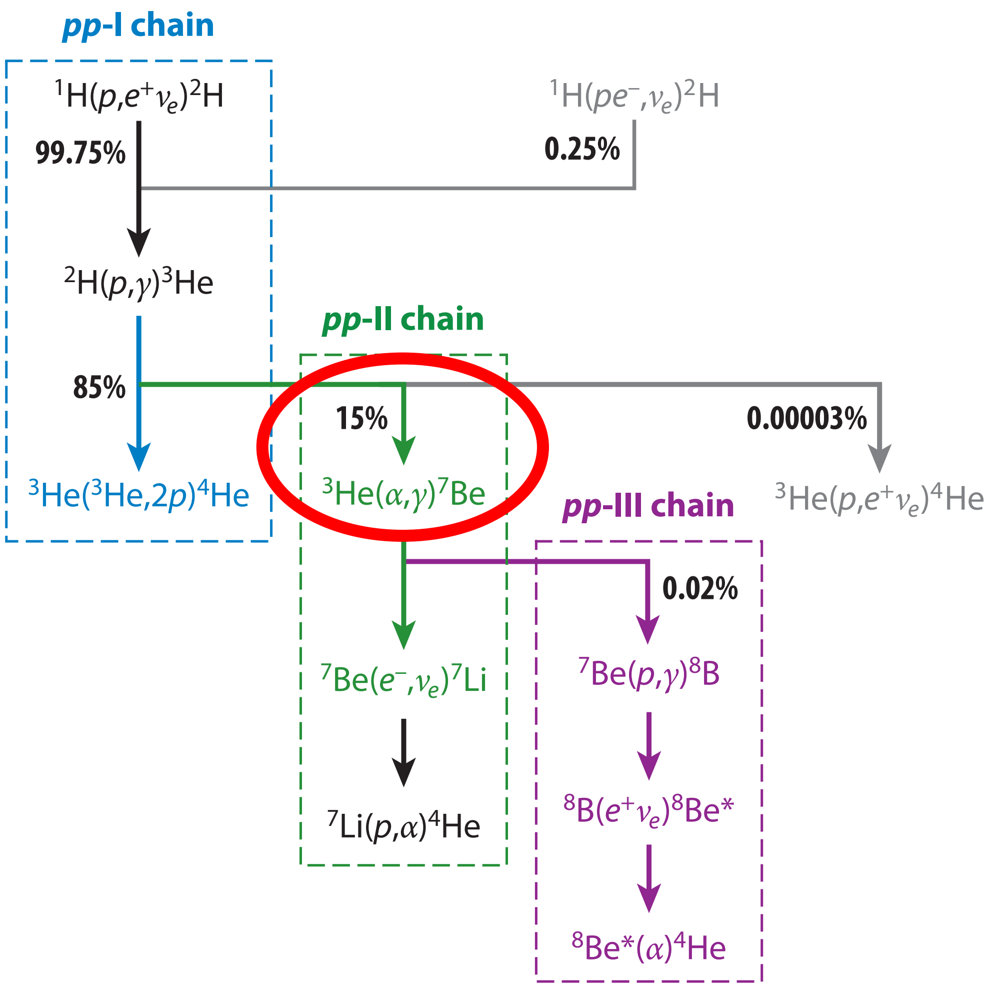
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															

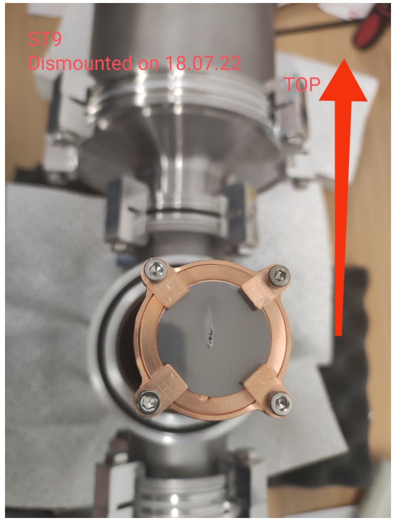
Big Bang

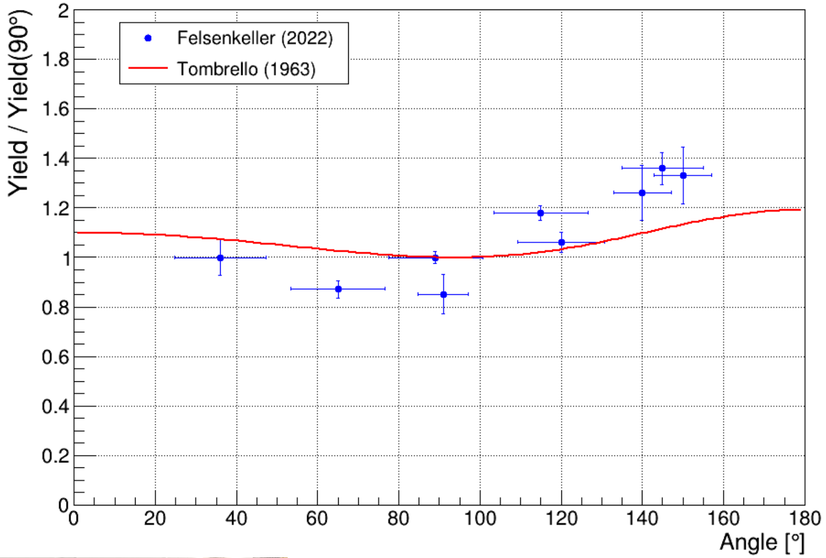
Stellar

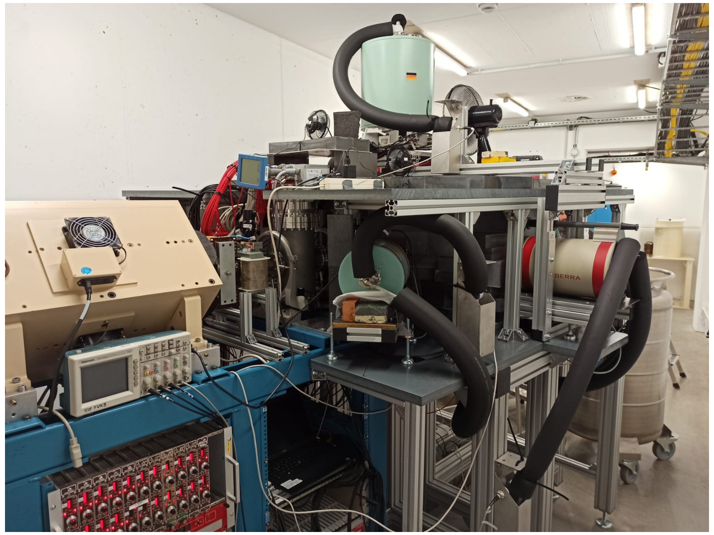
Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Th	Pa	U											

Study of the $^3He(\alpha,\gamma)^7Be$ γ-ray angular distribution at Felsenkeller

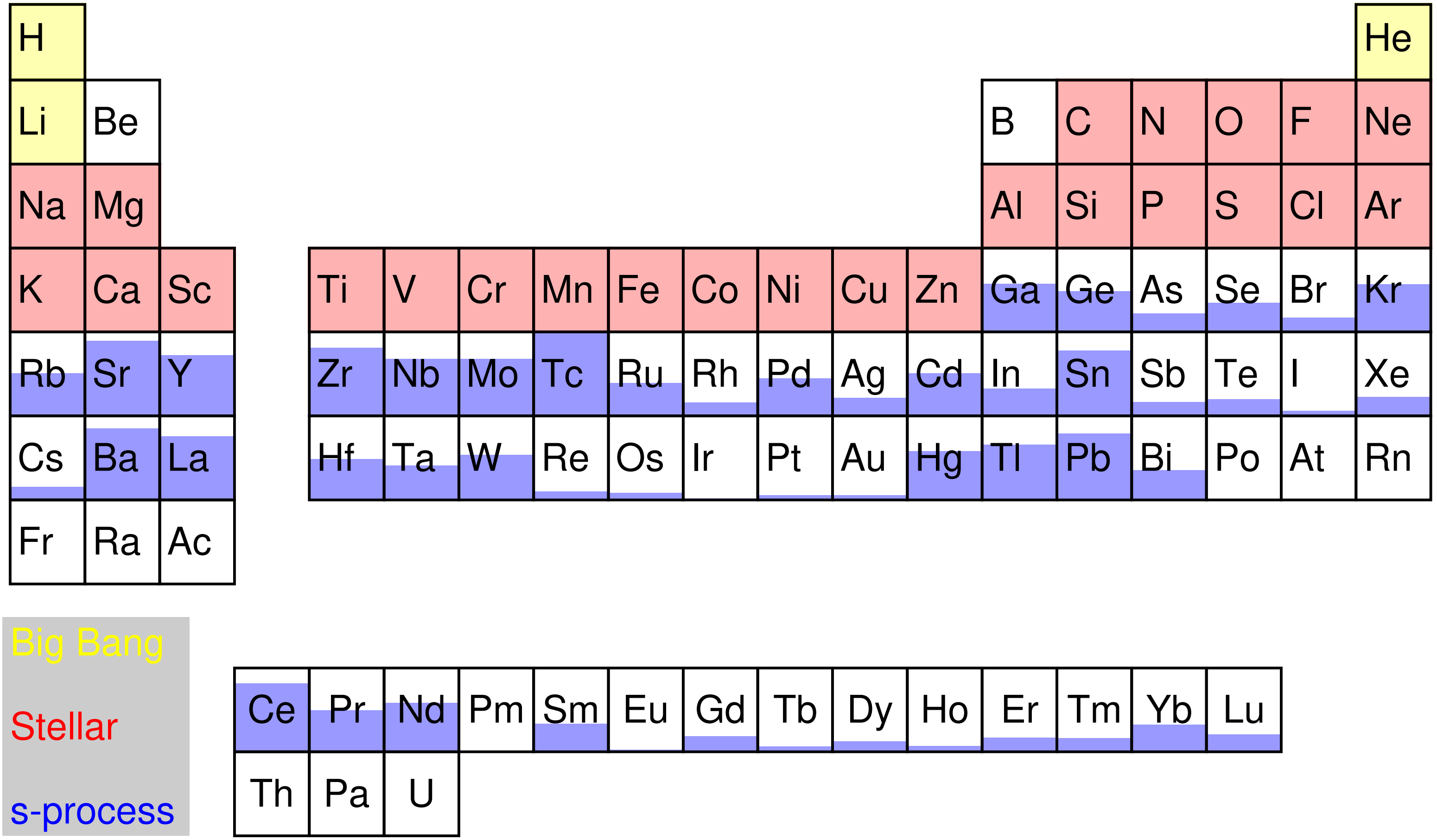




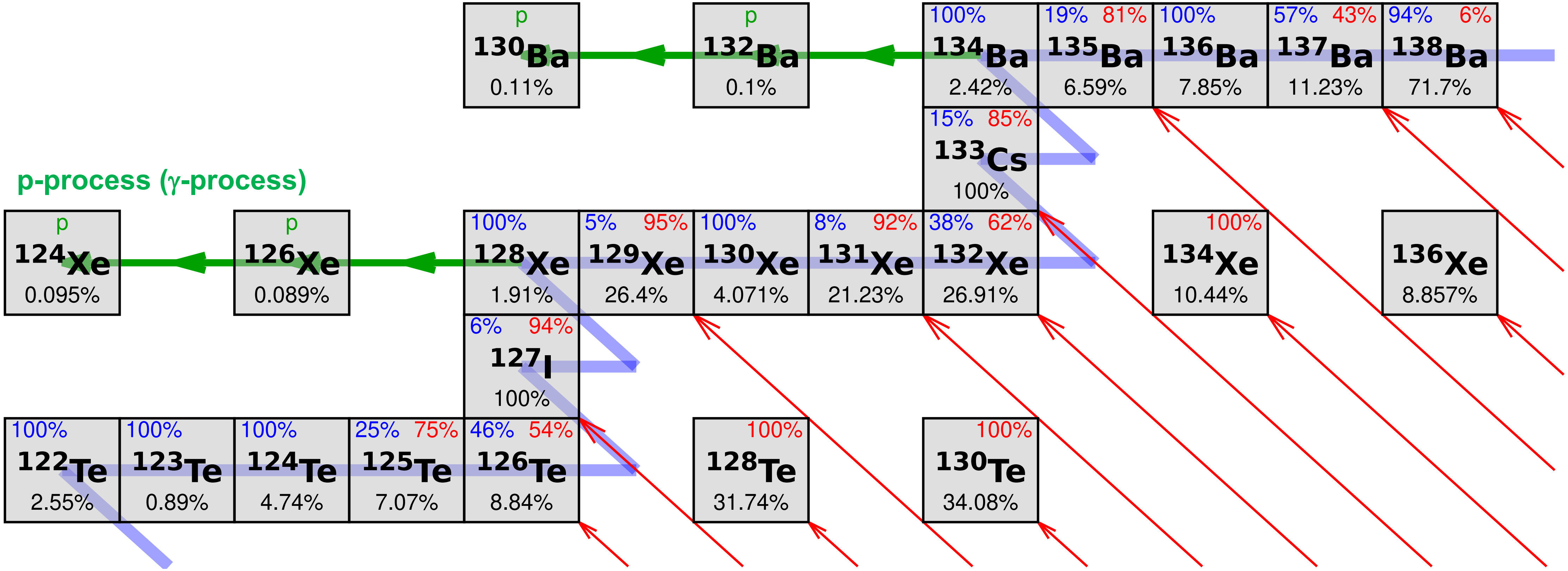




The periodic table: The slow neutron capture process (s-process)



The two astrophysical neutron capture processes, and the γ-process



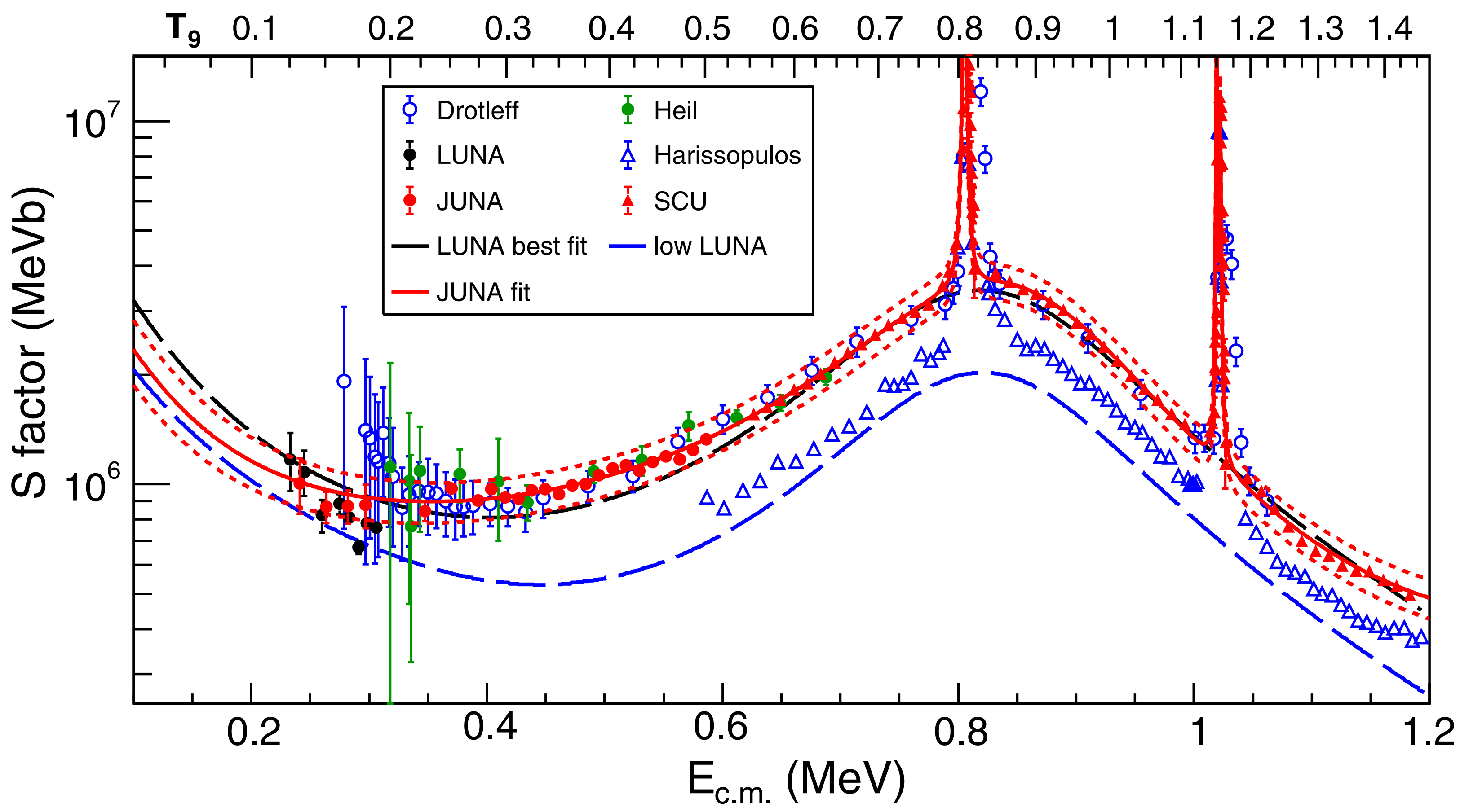
s-process

Neutron capture, immediately followed by β⁻ decay

r-process

Series of neutron captures, followed by a series of β⁻ decays

$^{13}C(\alpha,n)^{16}O$ neutron source for the astrophysical s-process

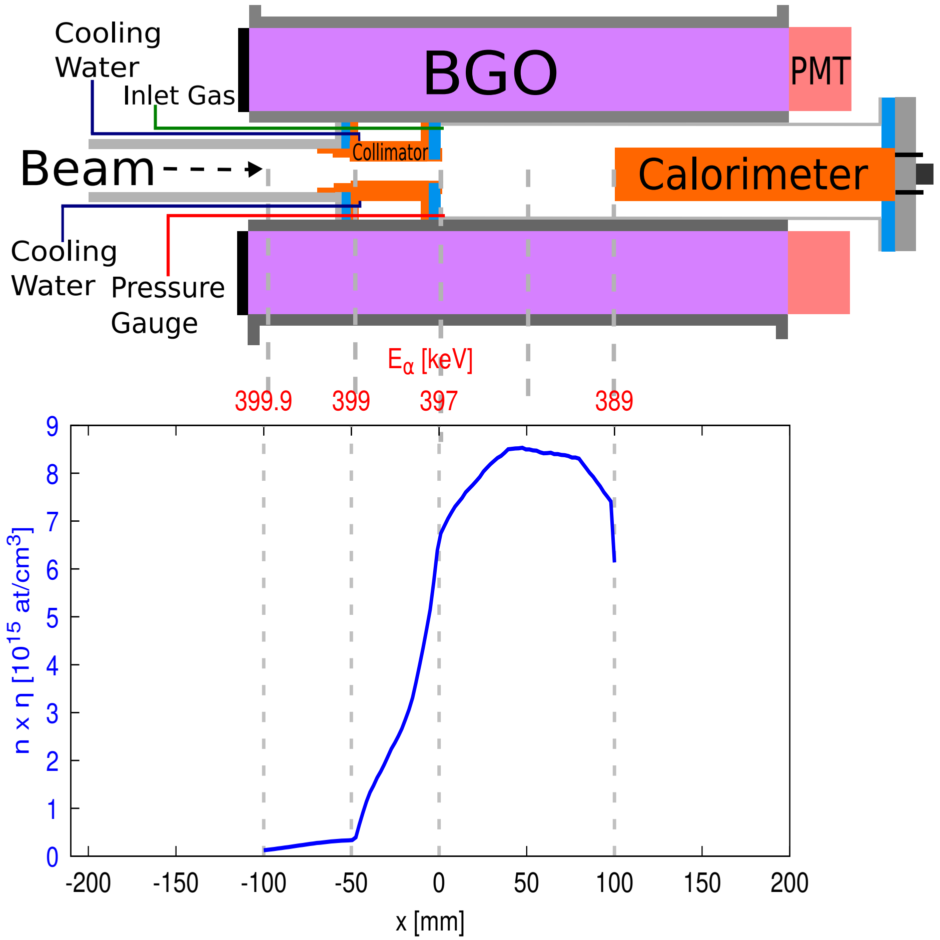


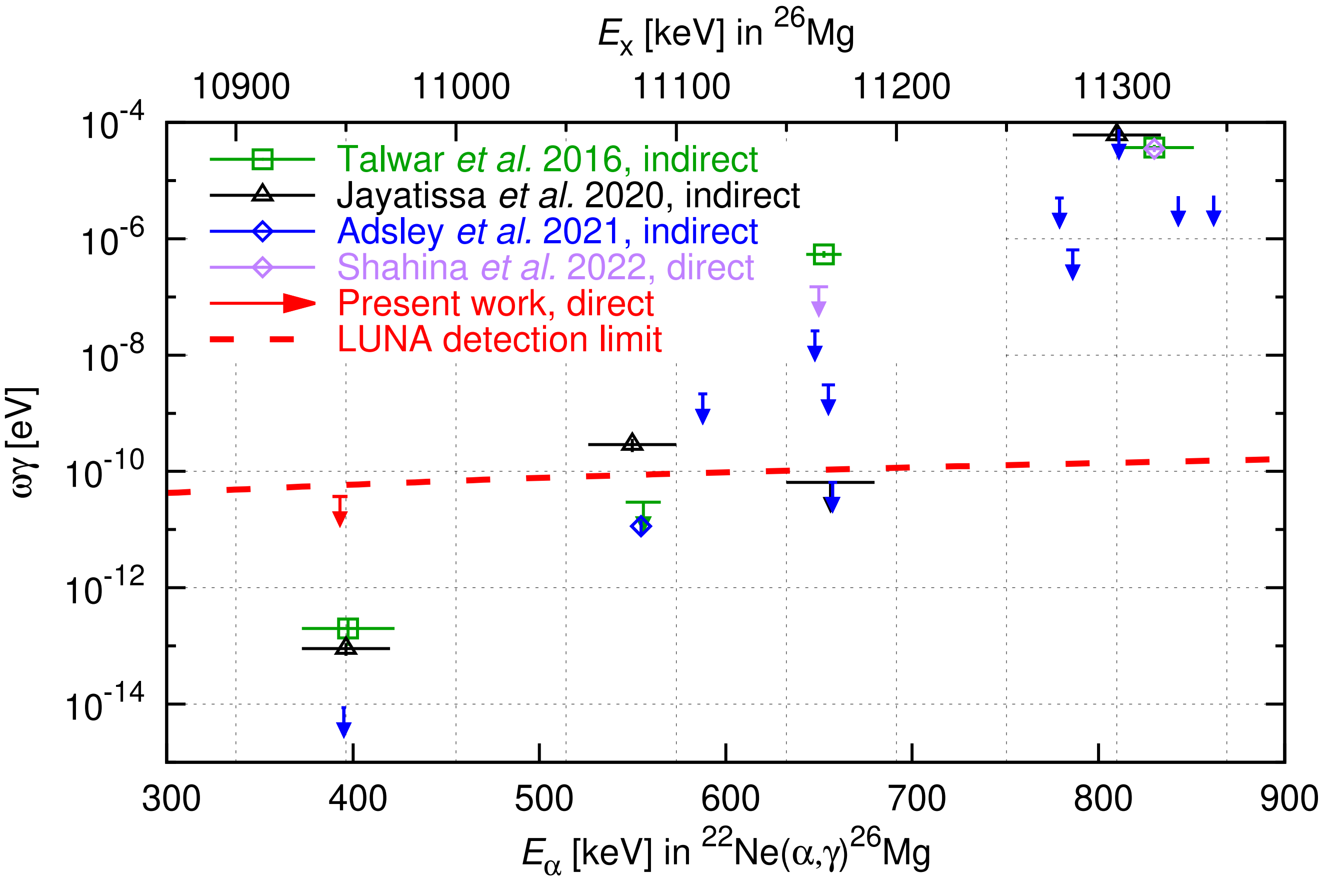
LUNA = deep underground Gran Sasso/Italy
Ciani, DB *et al.*
PRL 127, 152701 (2021)

JUNA = deep underground Jinping/China
Gao *et al.*
PRL 129, 132701 (2022)

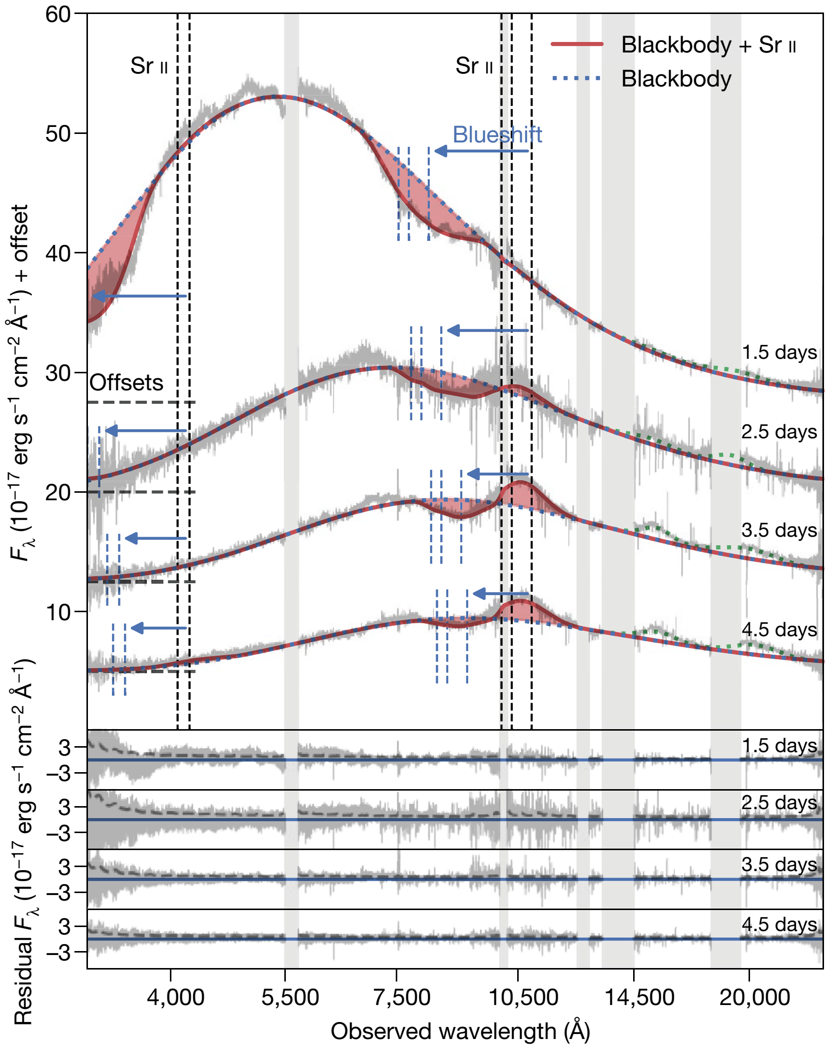
$^{22}Ne(\alpha,n)^{25}Mg$ neutron source for the astrophysical s- and r-processes

LUNA = deep underground Gran Sasso
Piatti, DB *et al.* EPJA 58, 194 (2022)





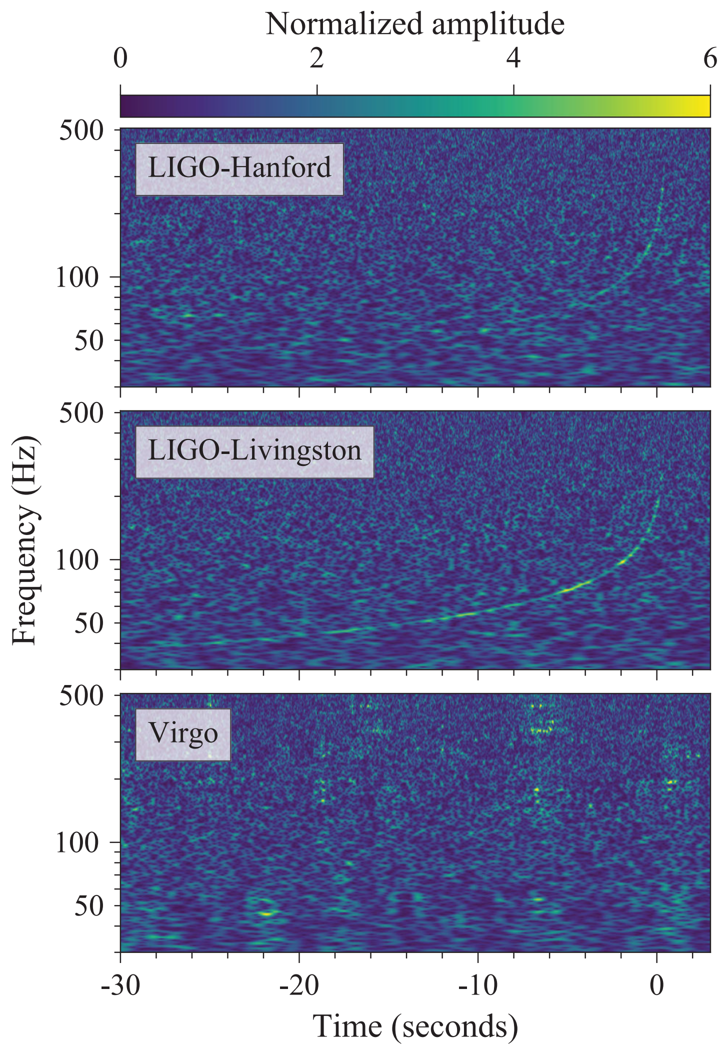
Rapid neutron capture in the r-process, strontium in kilonova AT2017gfo



Watson *et al.* Nature 574, 497 (2019)

GW170817
- Binary neutron star merger
- Total mass 2.7 $M_\odot$
- Distance 40 Mpc

AT2017gfo kilonova
- Spectra observed by X-shooter @ VLT, ESO
- Global analysis shows r-process pattern
- Spectral re-analysis reveals r-process strontium



Abbott *et al.* PRL 119, 161101 (2017)

Accelerator-based science underground, in Italy, USA, Germany, China

Laboratory for Underground Nuclear Astrophysics (LUNA) Italy

- LUNA 50 kV accelerator (1994-2001)
  Solar pp-chain, protostars
- LUNA 400 kV accelerator (2001-)
  Hydrogen burning in the sun and in asymptotic giant branch stars
- LUNA-MV 3.5 MV accelerator (2023-)
  Helium and carbon burning
- Gran Sasso Laboratory, Italy (1400 m rock, ~3400 m.w.e.)

The next generation

- CASPAR 1 MV accelerator (2017-)
  Hydrogen burning, astrophysical neutron sources
  Homestake underground lab, South Dakota, USA (~4000 m.w.e.)
- Felsenkeller 5 MV accelerator (2019-)
  Solar fusion, helium and carbon burning
- JUNO 400 kV accelerator (2020-)
  Hydrogen burning, astrophysical neutron sources
  Jinping underground lab, China (~6000 m.w.e.)

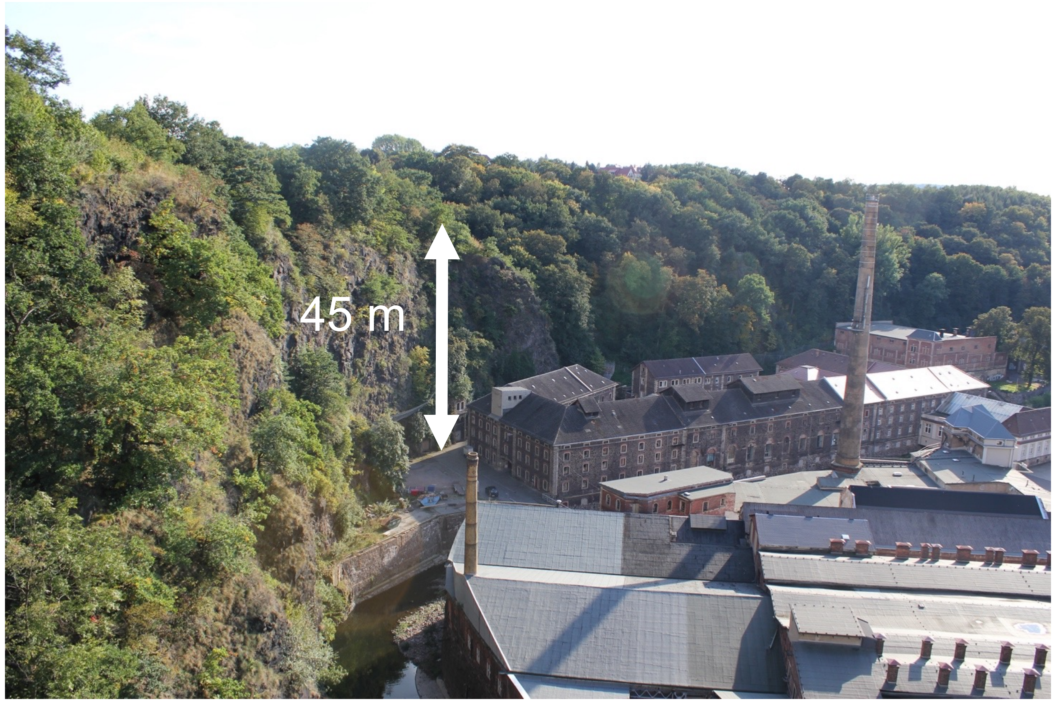
Dresden Felsenkeller underground lab, below 45 m rock (140 m.w.e.)

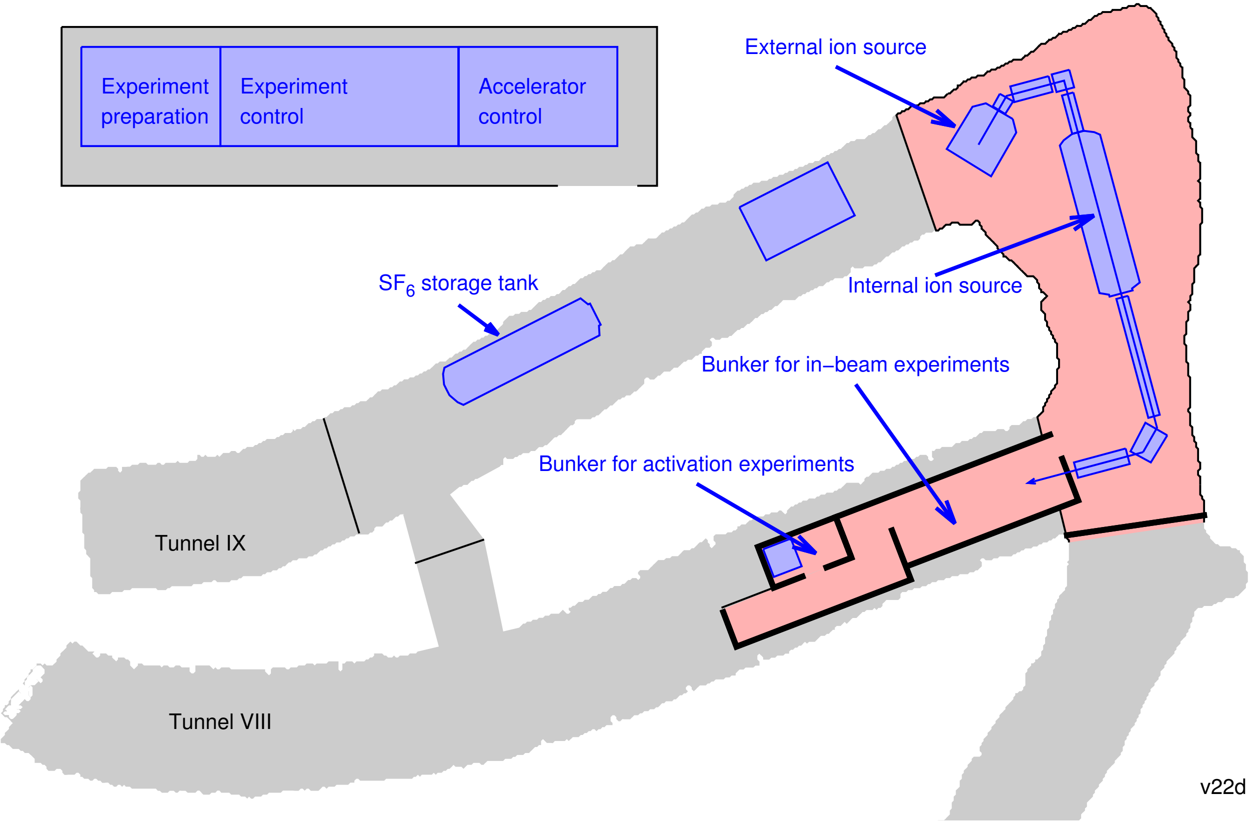
Joint effort HZDR – TU Dresden

- Investment by TU Dresden (Kai Zuber *et al.*) and HZDR (Daniel Bemmerer *et al.*)
- Day to day operations by HZDR

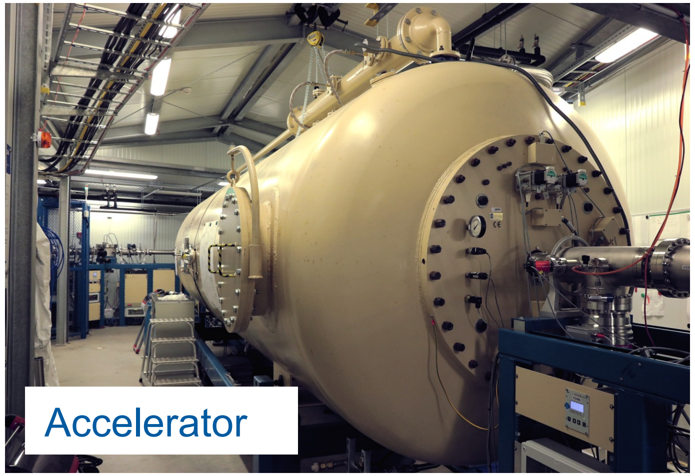
Two main instruments

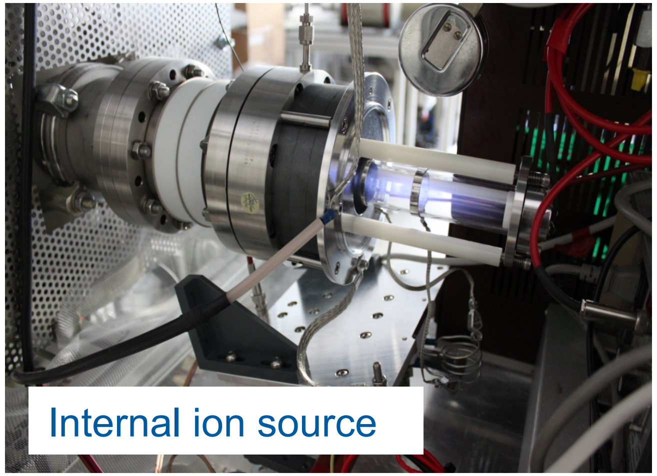
- **HZDR:** 5 MV Pelletron, 30 μA beams of $^{1}H^{+}$, $^{4}He^{+}$, $^{12}C^{+}$, ...
- **TU Dresden:** 163% ultra-low-background HPGe detector for offline radioactivity measurements



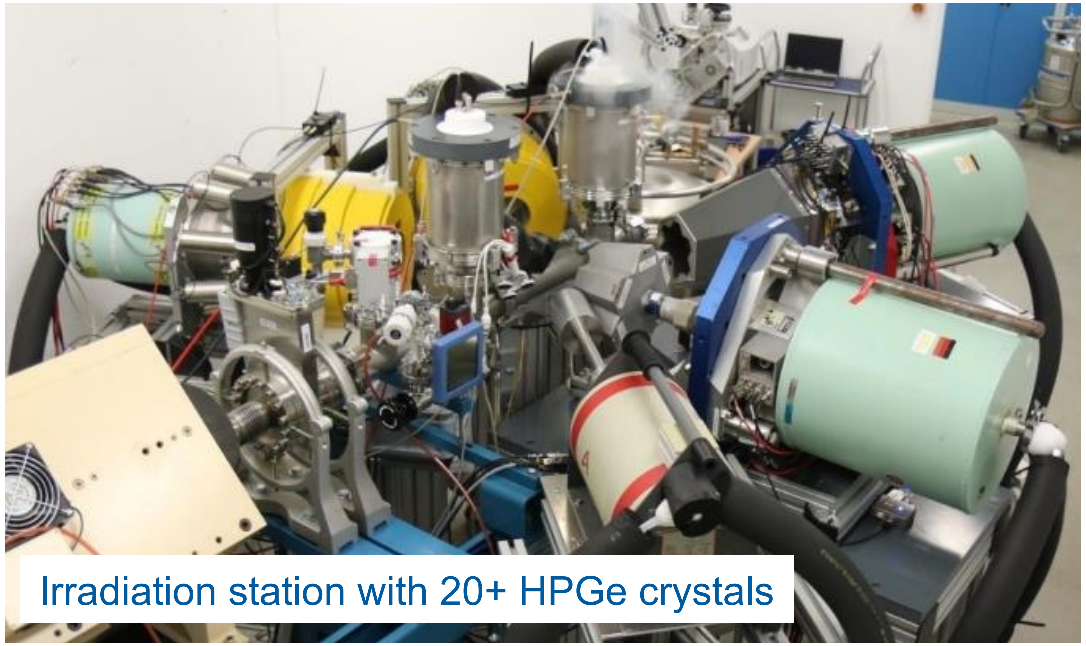


Felsenkeller 5 MV underground ion accelerator


Accelerator


Internal ion source


External ion source

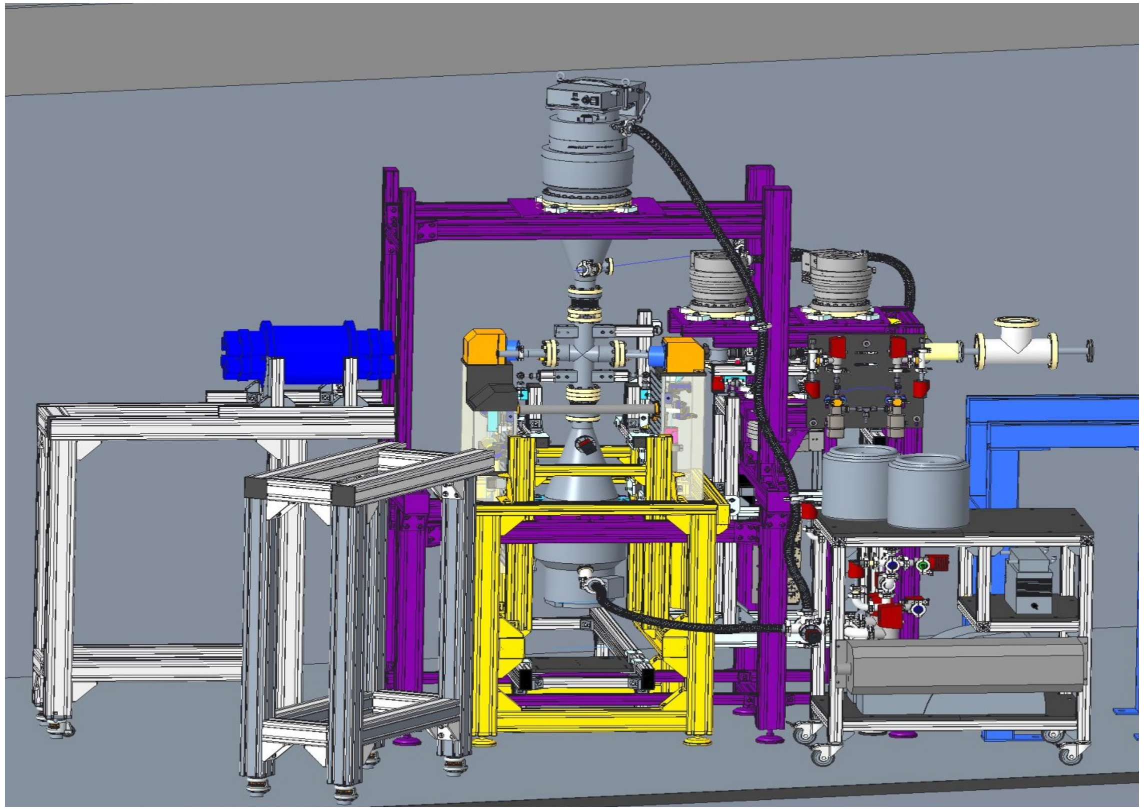

Irradiation station with 20+ HPGe crystals

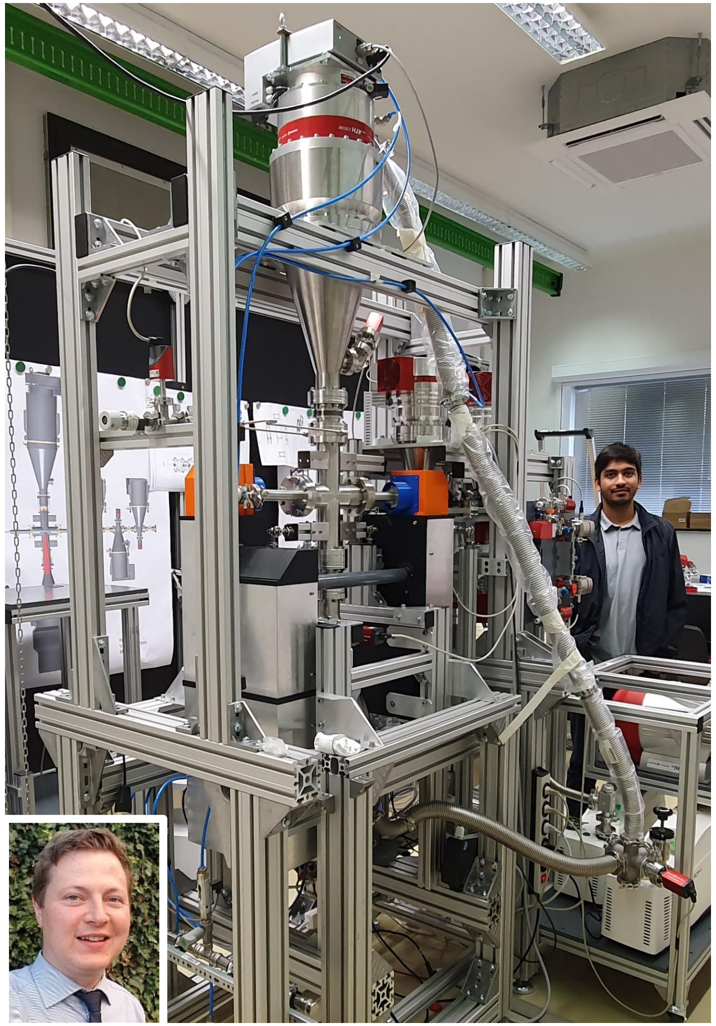
5 MV accelerator (0.4-3.8 MV), two alternative ion sources

- Internal RF ion source: 30 µA ^{1}H, ^{4}He
- SNICS sputter ion source: 30 µA ^{12}C

- 24 hour operation permitted even without operator
- Personnel is allowed at target while beam is on
- Control and counting rooms at surface
- EU-supported transnational access available

Work in progress: gas target (gas jet and static windowless)

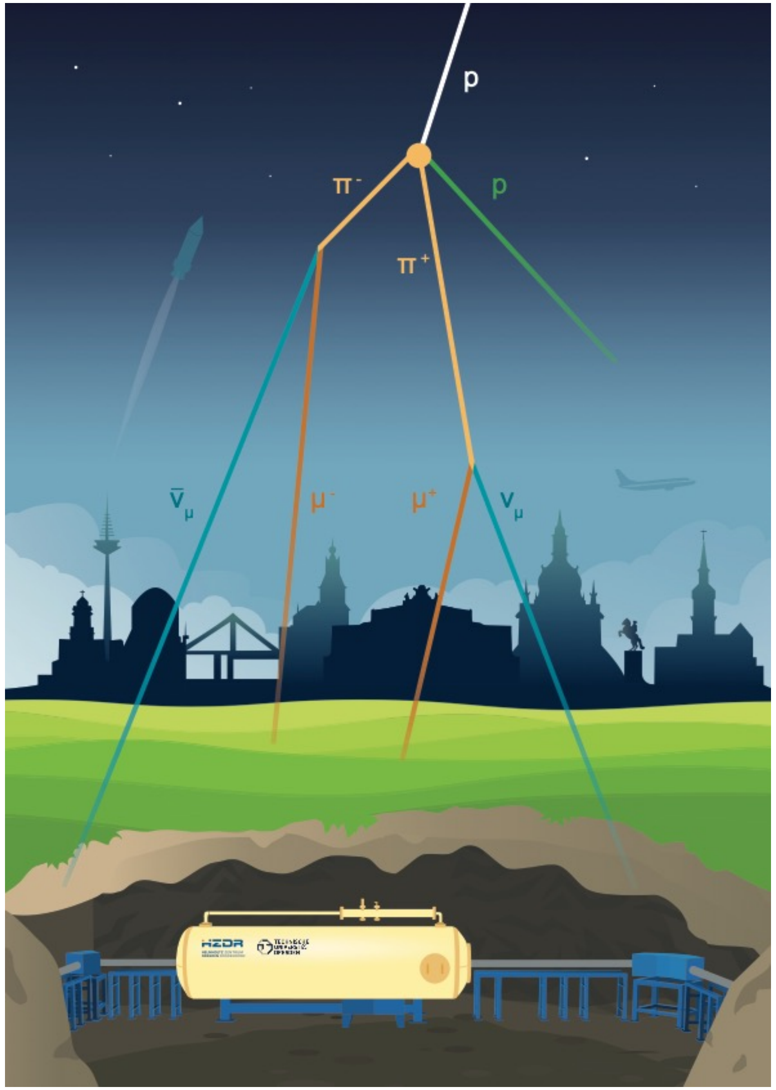


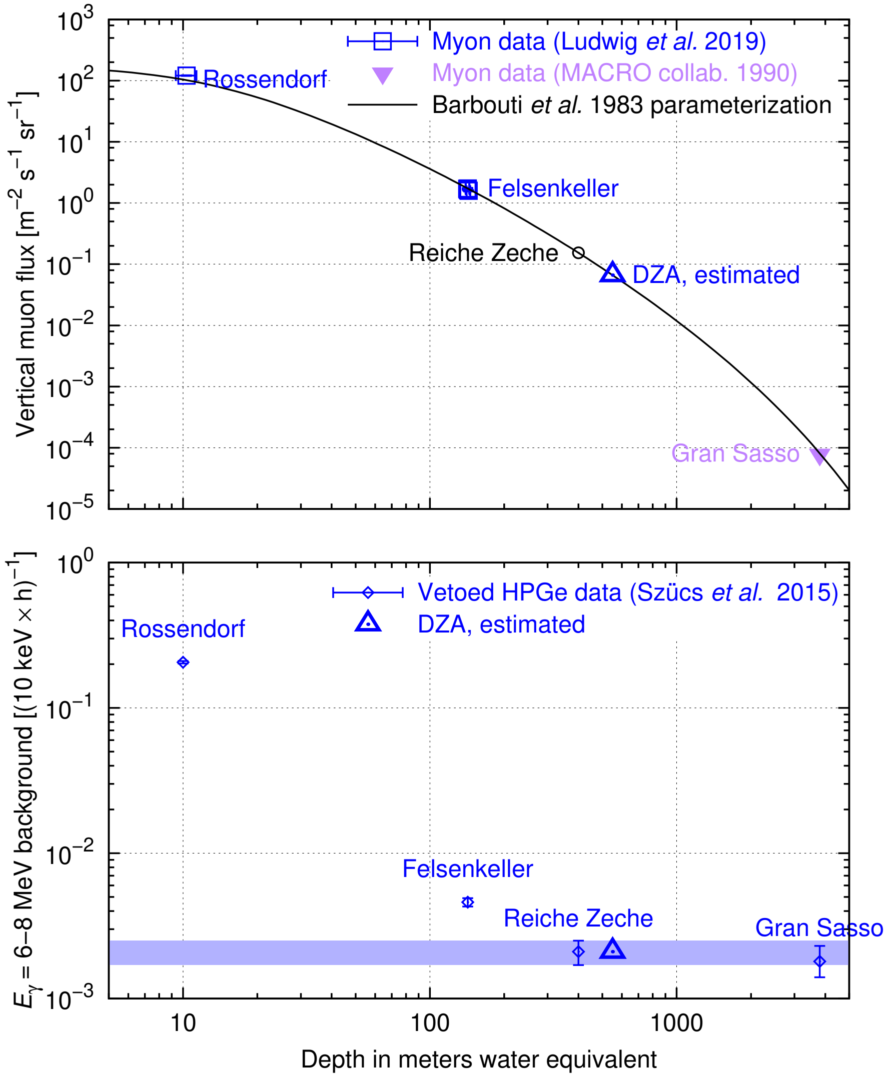


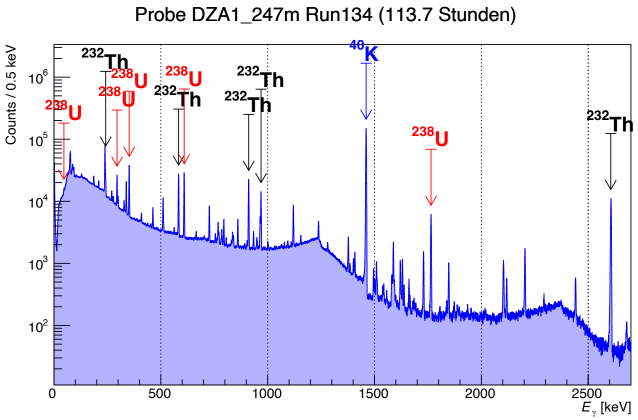
- 10^{18} cm^{-2} wall jet thickness, based on JENSA @ MSU
- 10x10 mm^2 wall, 0.1 mm thick
- Target thickness measured by laser interferometry
- Windowless static-type gas target attached, based on LUNA

ChETEC INFRA TECHNISCHE UNIVERSITÄT DRESDEN DRESDEN concept SCIENCE AND INNOVATION CAMPUS HZDR

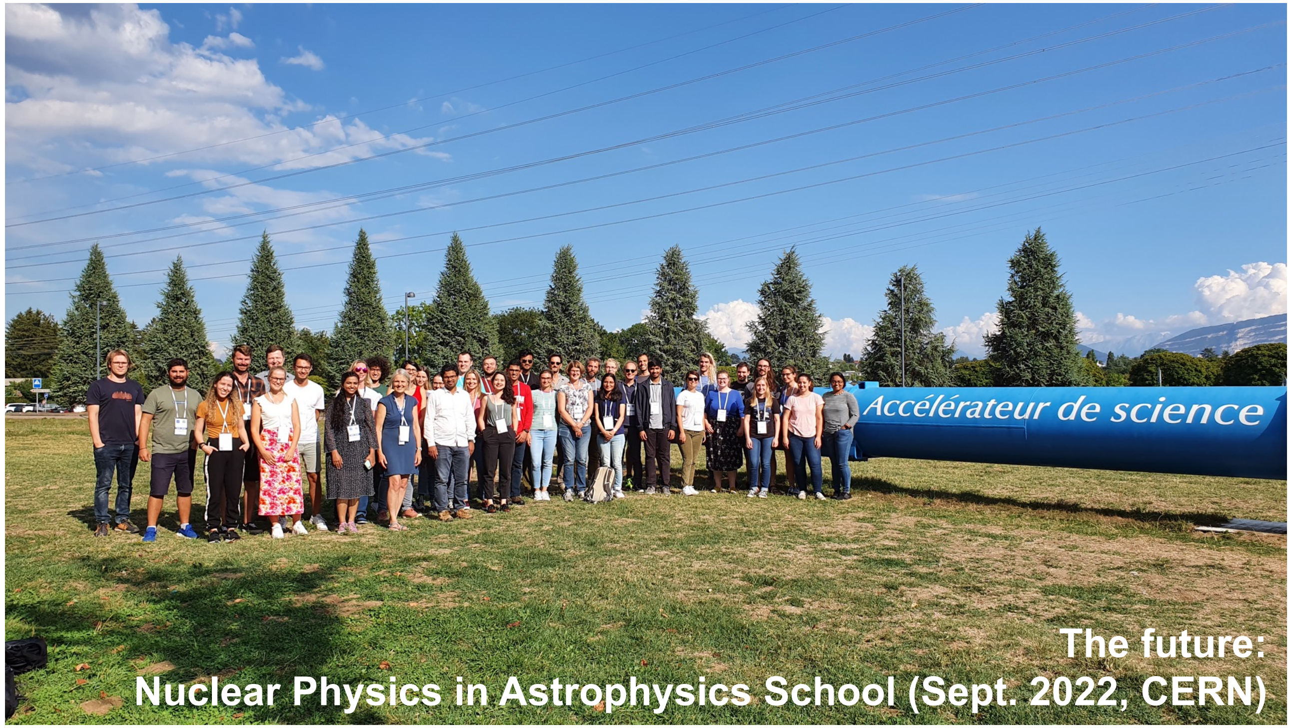
Felsenkeller, close to the „sweet spot“ for nuclear astrophysics







ChETEC-INFRA EU project for nuclear astrophysics [ketek-infra]



https://www.chetec-infra.eu

- **Starting Community** of research infrastructures
- **32 partners** in 17 EU+ countries
- May 2021 – April 2025
- 5 M€ support by EU

Acknowledgments

Topping out 28.06.2017,
A. McDonald

First beam 04.07.2019, T. Kajita

Funding
- Helmholtz NAVI, DTS, MML, ERC-RA
- DFG, DAAD
- TU Dresden Excellence Initiative funds (K. Zuber), DFG Großgerät (K. Zuber)
- European Union ChETEC-INFRA

Tom Cowan

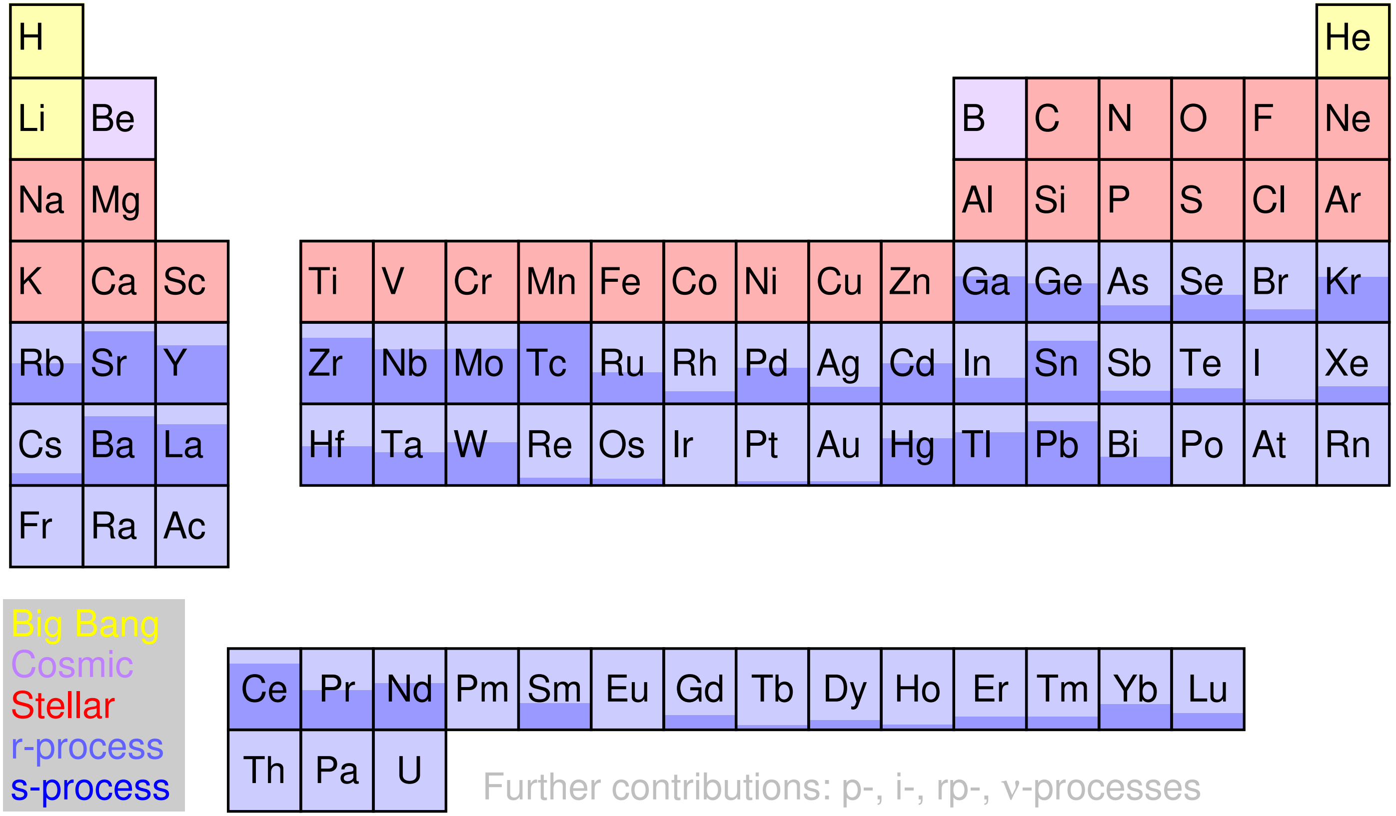
HZDR nuclear physics, HZDR ion beam ctr
LUNA & ChETEC-INFRA collaborations
...and many more!

Kai Zuber

The Felsenkeller team

ChETEC INFRA TECHNISCHE UNIVERSITÄT DRESDEN DRESDEN concept SCIENCE AND INNOVATION CAMPUS HZDR

Nuclear astrophysics in an underground lab



Further contributions: p-, i-, rp-, ν-processes

Nucleosynthesis processes,
and how to study them in the laboratory

- Big Bang Nucleosynthesis and ^{2}H
- Stellar burning of ^{12}C
- Neutron source reactions
- Link to multi-messenger observations

Felsenkeller underground laboratory

- Capabilities and work in progress

32 partners in ChETEC-INFRA

HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

universität wien

asu Astronomický ústav AV ČR

AARHUS UNIVERSITY

INSTITUT DE PHYSIQUE DU GLOBE DE PARIS
IPGP

AIP Leibniz-Institut für Astrophysik Potsdam

PTB
Physikalisch-Technische Bundesanstalt
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THE HEBREW UNIVERSITY OF JERUSALEM

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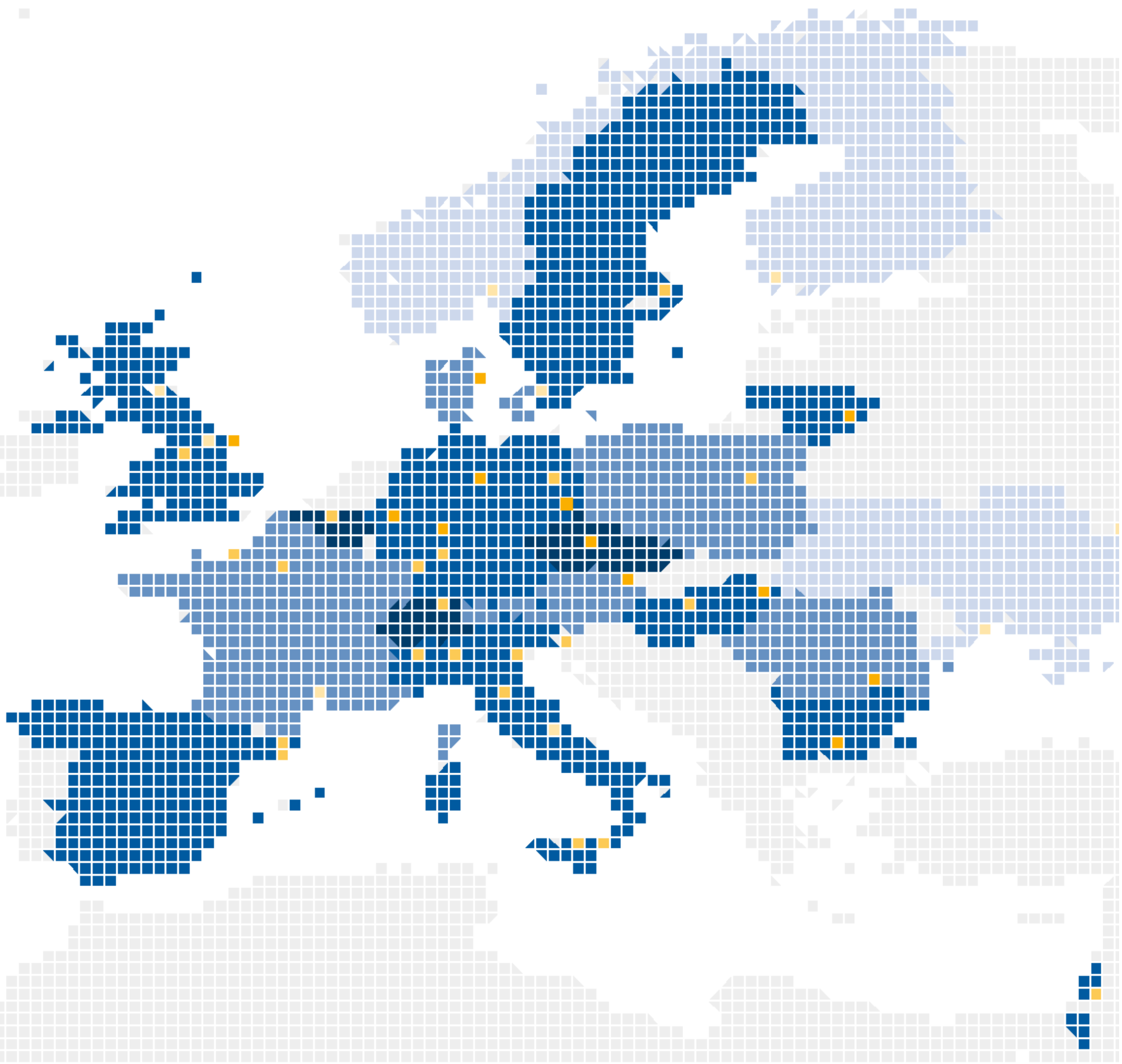
UNIVERSITÀ DEGLI STUDI DI MILANO

Narodowe Centrum Badań Jądrowych
National Centre for Nuclear Research
ŚWIERK

IFIN-HH
Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering

UPPSALA UNIVERSITET

ETH zürich



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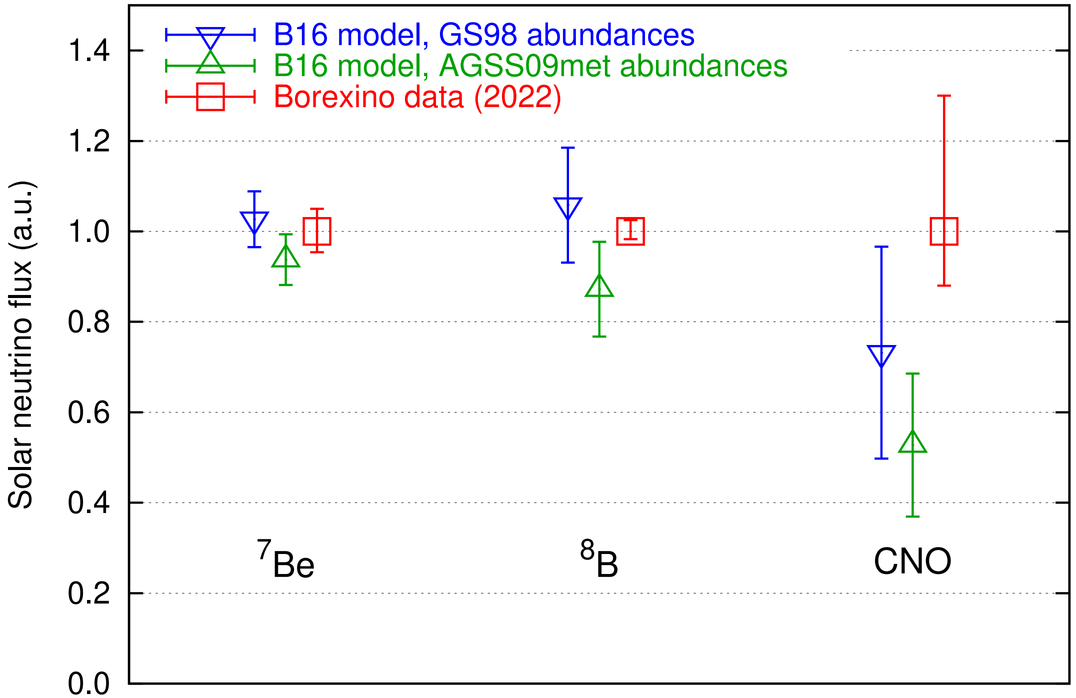
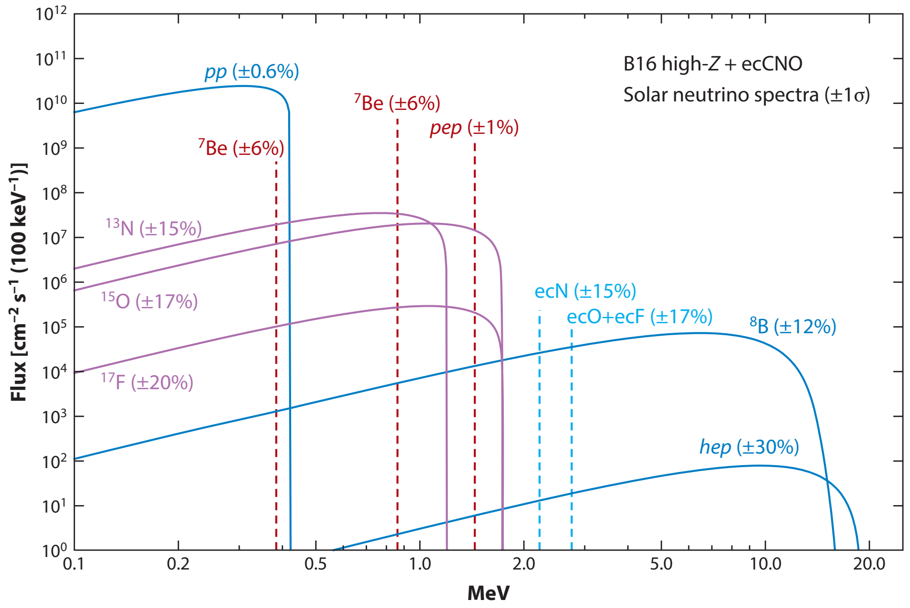
Solar neutrino fluxes and the solar abundance problem



Neutrino fluxes from B16 Standard Solar Model, Vinyoles *et al.* ApJ 2017

GS98 = Old, high CNO elemental abundances
also: Magg+ 2022

AGSS09 = New, low CNO elemental abundances
also: Asplund+ 2021



Neutrino flux data are more precise than the solar models!

Nuclear physics drives the uncertainties in the predicted solar neutrino fluxes

Dominant Theoretical Error Sources for Neutrino Fluxes and the Main Characteristics of the SSM

Quant.	Dominant Theoretical Error Sources in %							
$\Phi(pp)$	$L_\odot$:	0.3	S_{34}:	0.3	κ:	0.2	Diff:	0.2
$\Phi(pep)$	κ:	0.5	$L_\odot$:	0.4	S_{34}:	0.4	S_{11}:	0.2
$\Phi(hep)$	S_{hep}:	30.2	S_{33}:	2.4	κ:	1.1	Diff:	0.5
$\Phi(^7Be)$	S_{34}:	4.1	κ:	3.8	S_{33}:	2.3	Diff:	1.9
$\Phi(^8B)$	κ:	7.3	S_{17}:	4.8	Diff:	4.0	S_{34}:	3.9
$\Phi(^{13}N)$	C:	10.0	S_{114}:	5.4	Diff:	4.8	κ:	3.9
$\Phi(^{15}O)$	C:	9.4	S_{114}:	7.9	Diff:	5.6	κ:	5.5
$\Phi(^{17}F)$	O:	12.6	S_{116}:	8.8	κ:	6.0	Diff:	6.0

Vinyoles *et al.*, Astrophys. J. (2017)

S_{34}: $^3He(\alpha,\gamma)^7Be$

S_{114}: $^{14}N(p,\gamma)^{15}O$

S_{17}: $^7Be(p,\gamma)^8B$