Nuclear Astrophysics:

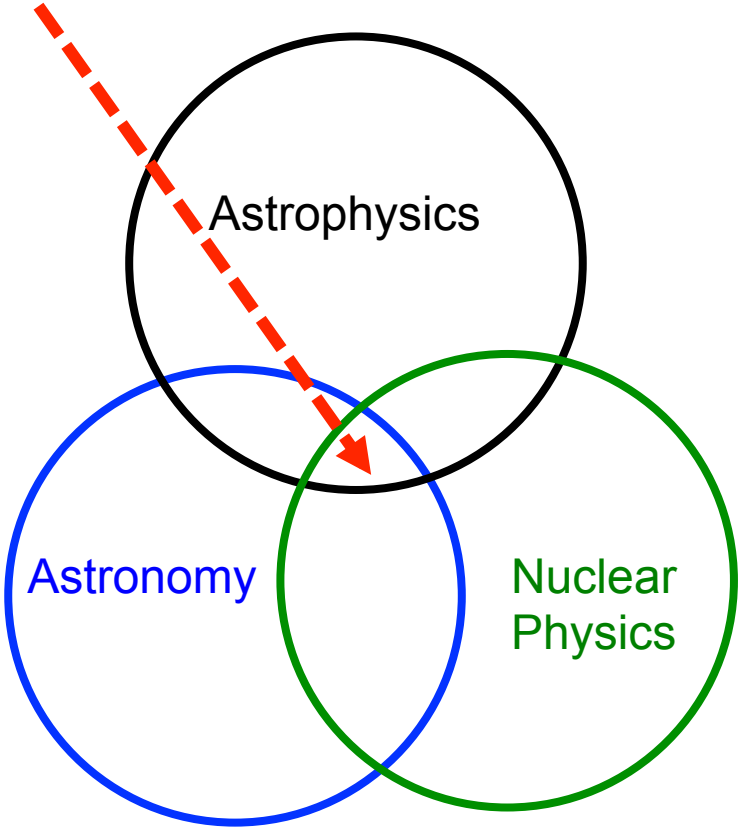
Nucleosynthesis and Chemical Evolution Studies

Astroparticle Physics in Germany: Status and Perspectives

Mainz, 19.09.2018

Daniel Bemmerer

Nuclear Astrophysics: The creation of the chemical elements



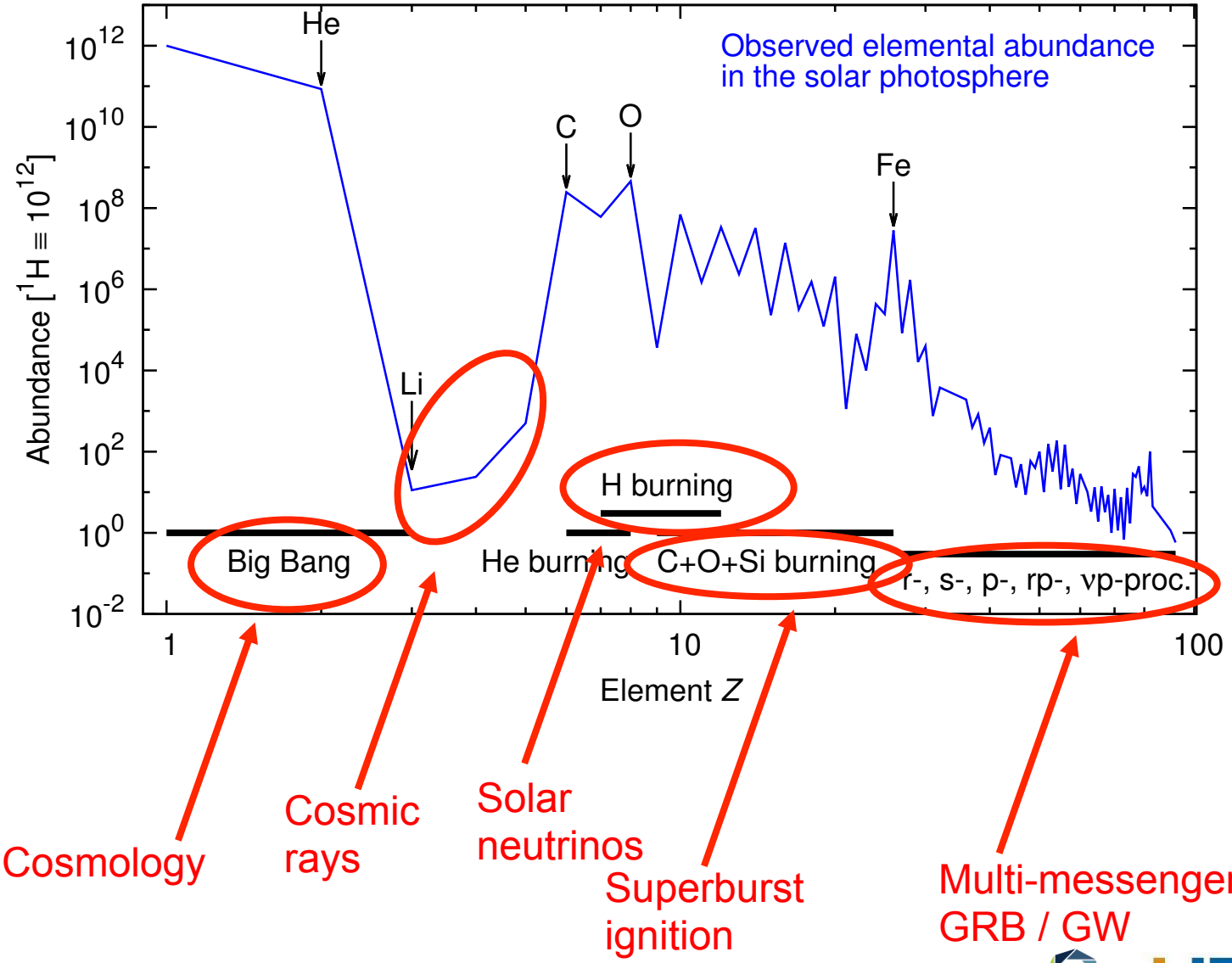
Connections to
astroparticle physics:

- Big Bang nucleosynthesis
- Solar neutrino fluxes
- Cosmic-ray cross sections
- r-process in explosive events

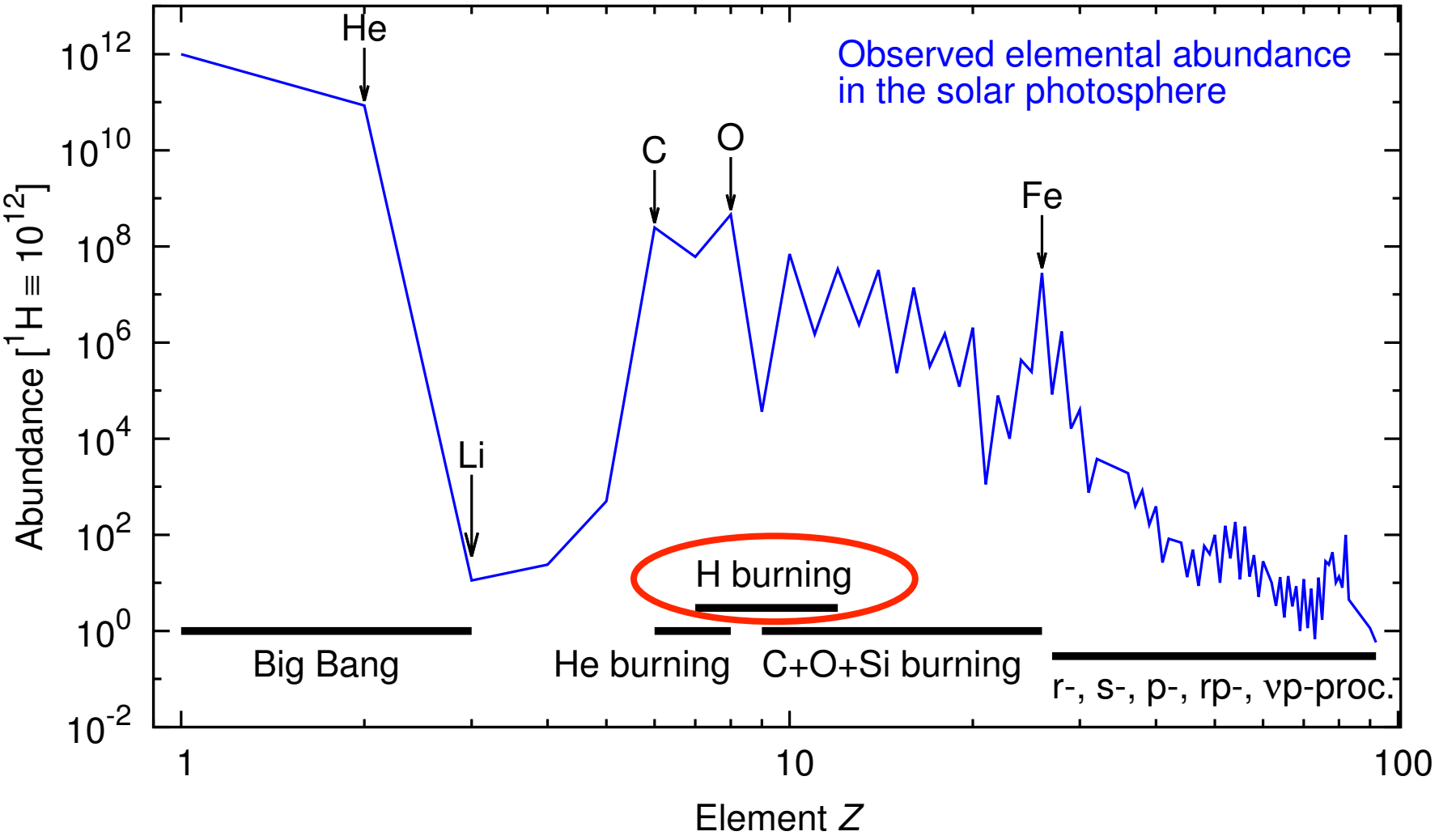
Experimental techniques

- Underground physics
- γ-ray satellites
- Radioactive (ion) beams

Nuclear Astrophysics: The production of the chemical elements



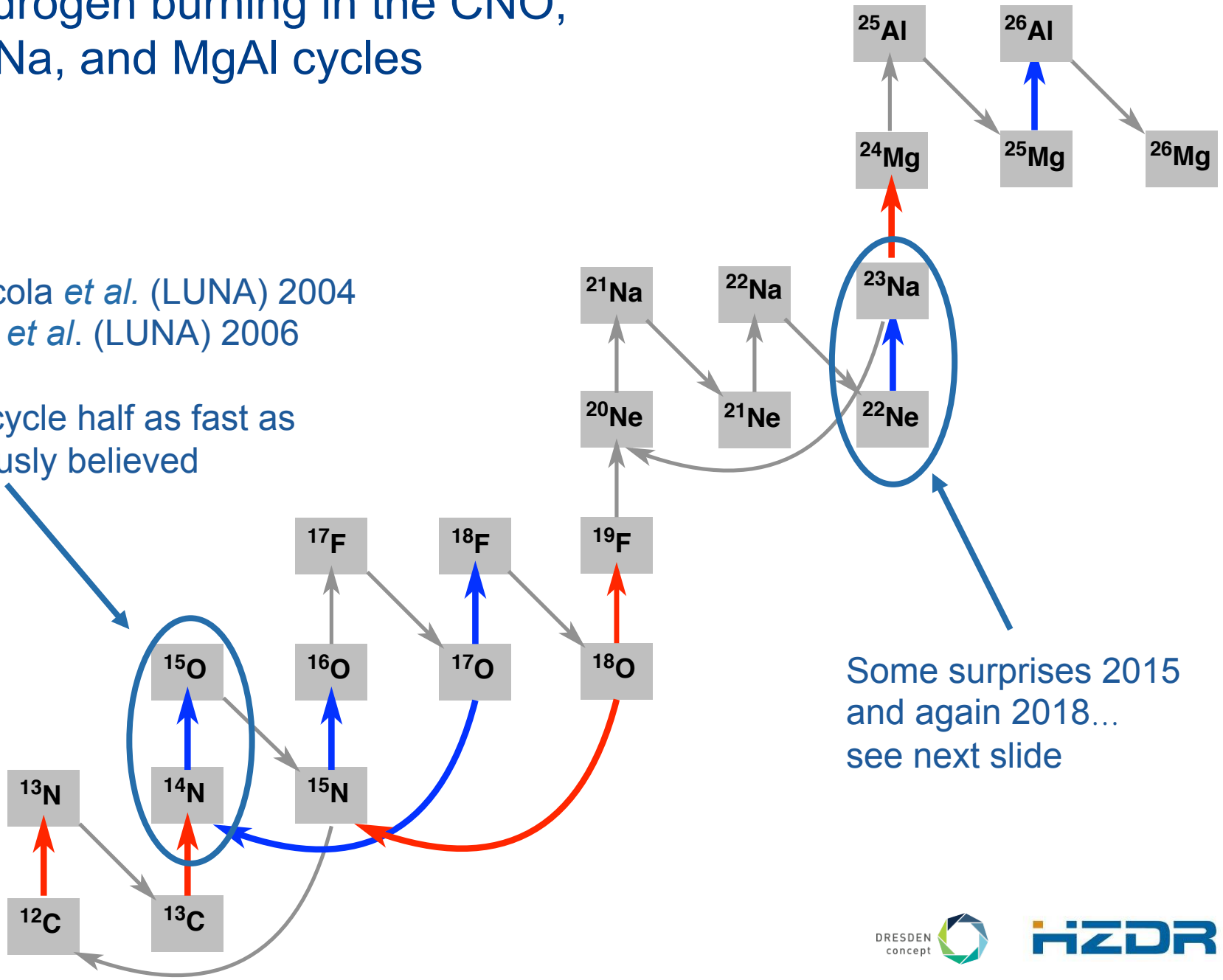
Hydrogen burning



Hydrogen burning in the CNO, NeNa, and MgAl cycles

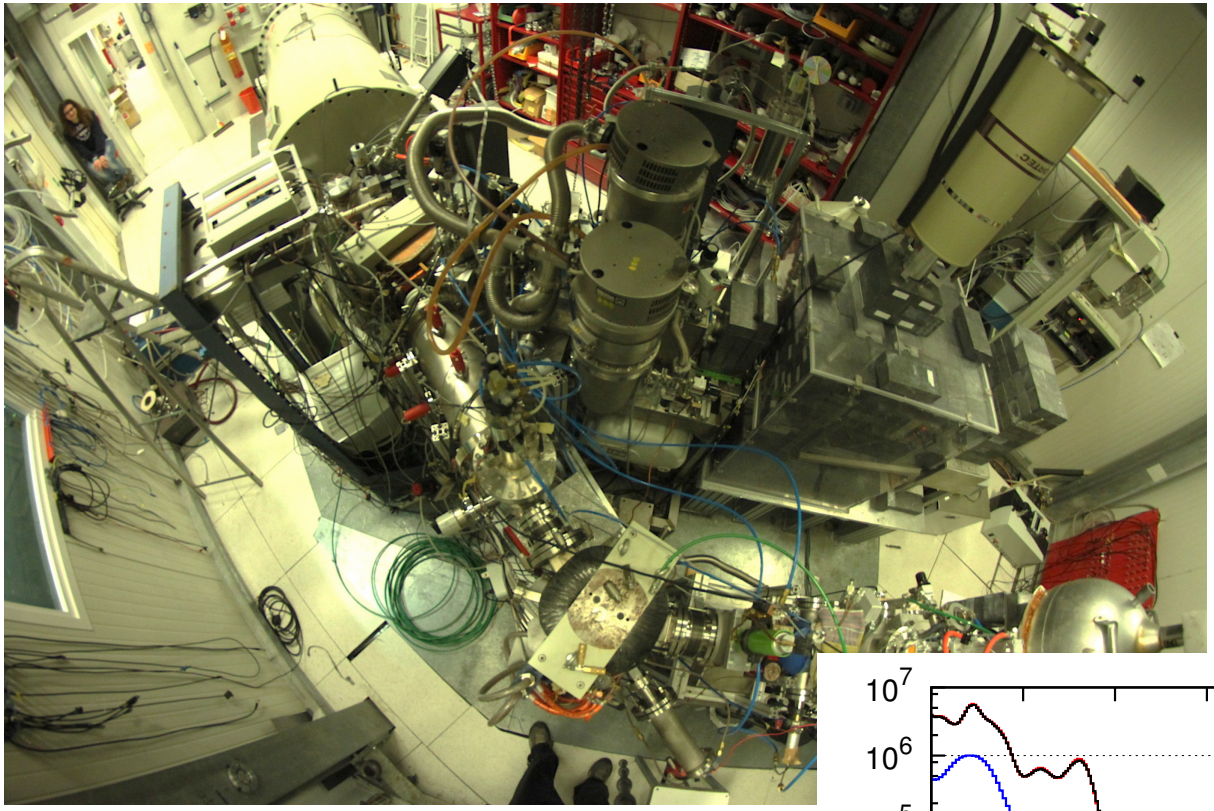
Formicola *et al.* (LUNA) 2004
Lemut *et al*. (LUNA) 2006

CNO cycle half as fast as previously believed



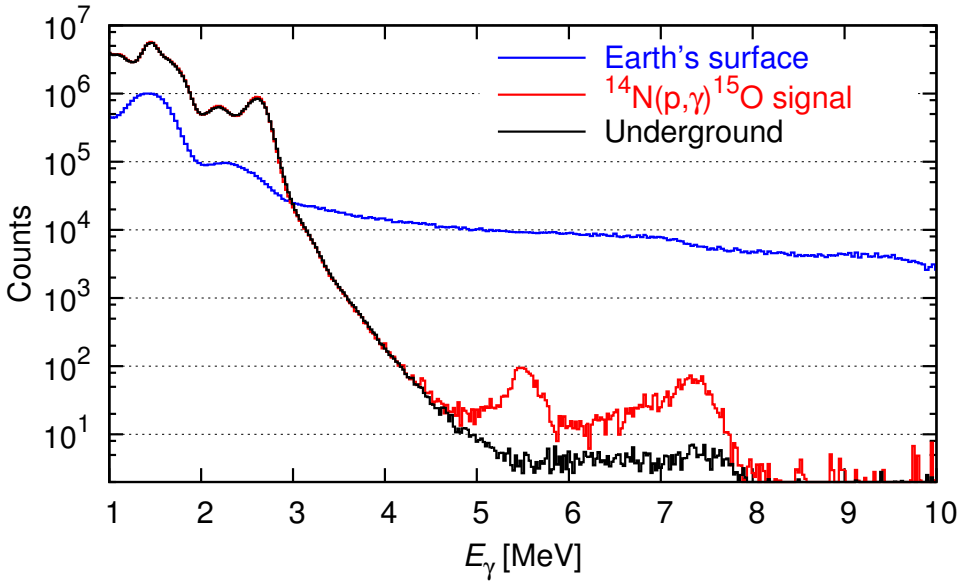
Some surprises 2015 and again 2018… see next slide

LUNA = Laboratory Underground for Nuclear Astrophysics

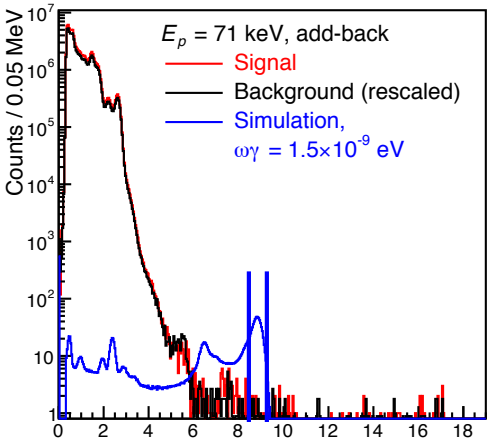


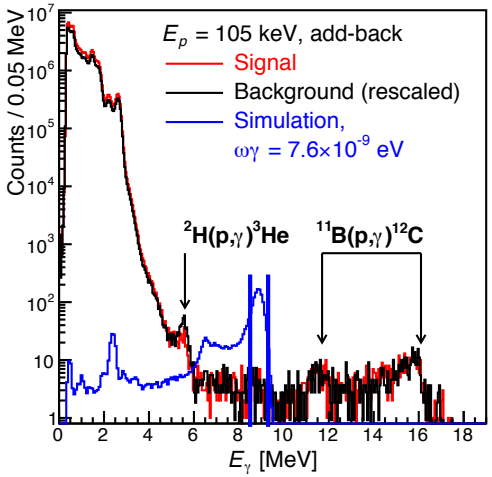
LUNA @ Gran Sasso
- Italy
- Germany (HZDR)
- UK
- Hungary

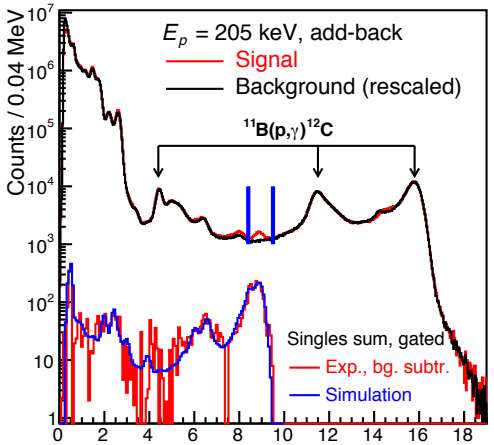
LUNA approach:
Measure nuclear reaction cross sections at or near the relevant energies (= Gamow peak), using
- high beam intensity
- low background
- great patience



$^{22}Ne(p,\gamma)^{23}Na$, part of the H-burning NeNa cycle







LUNA
Laboratory for Underground Nuclear Astrophysics

F. Cavanna *et al.* (LUNA)
Phys. Rev. Lett. 115, 252501 (2015)

D. Bemmerer *et al.* (LUNA)
Europhys. Lett. 122, 52001 (2018)

Three new resonances discovered!

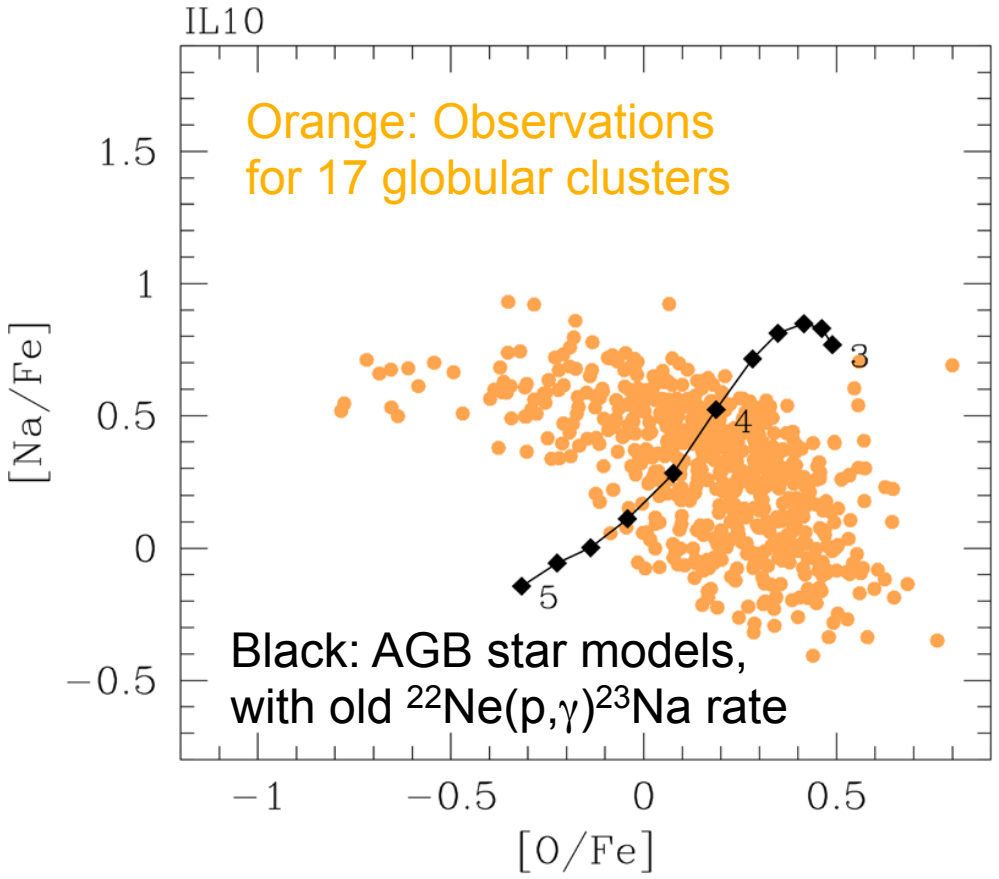
F. Ferraro *et al.* (LUNA)
Phys. Rev. Lett., submitted

Two old resonances ruled out!

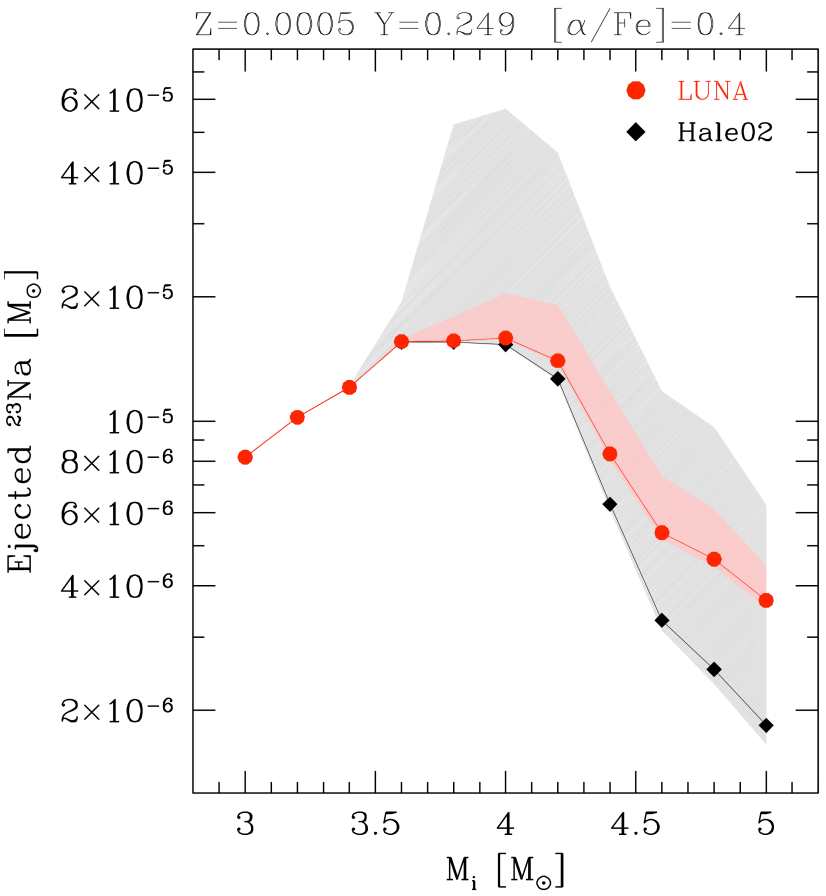
DRESDEN concept

HZDR

$^{22}Ne(p,\gamma)^{23}Na$ and the Na – O anticorrelation



A. Slemer *et al.*,
Mon. Not. Royal Astron. Soc.
465, 4817 (2017)



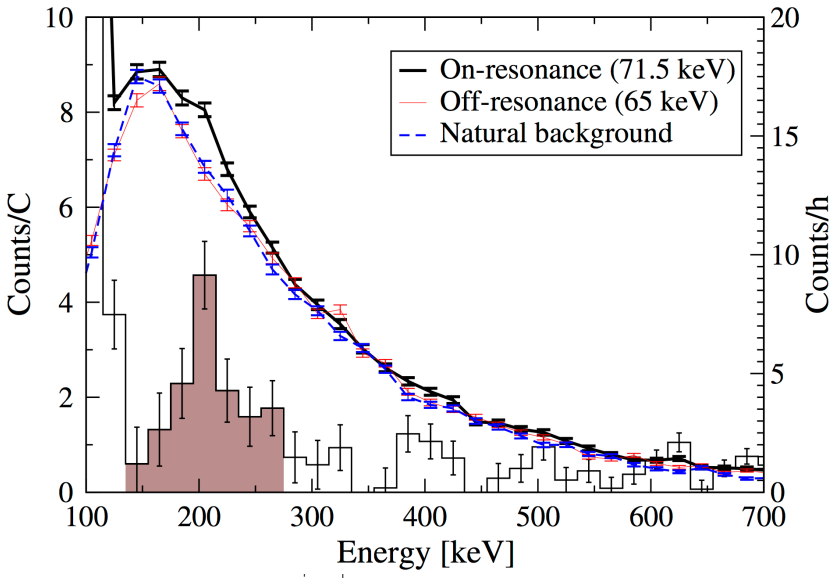
F. Ferraro *et al.* (LUNA),
preliminary

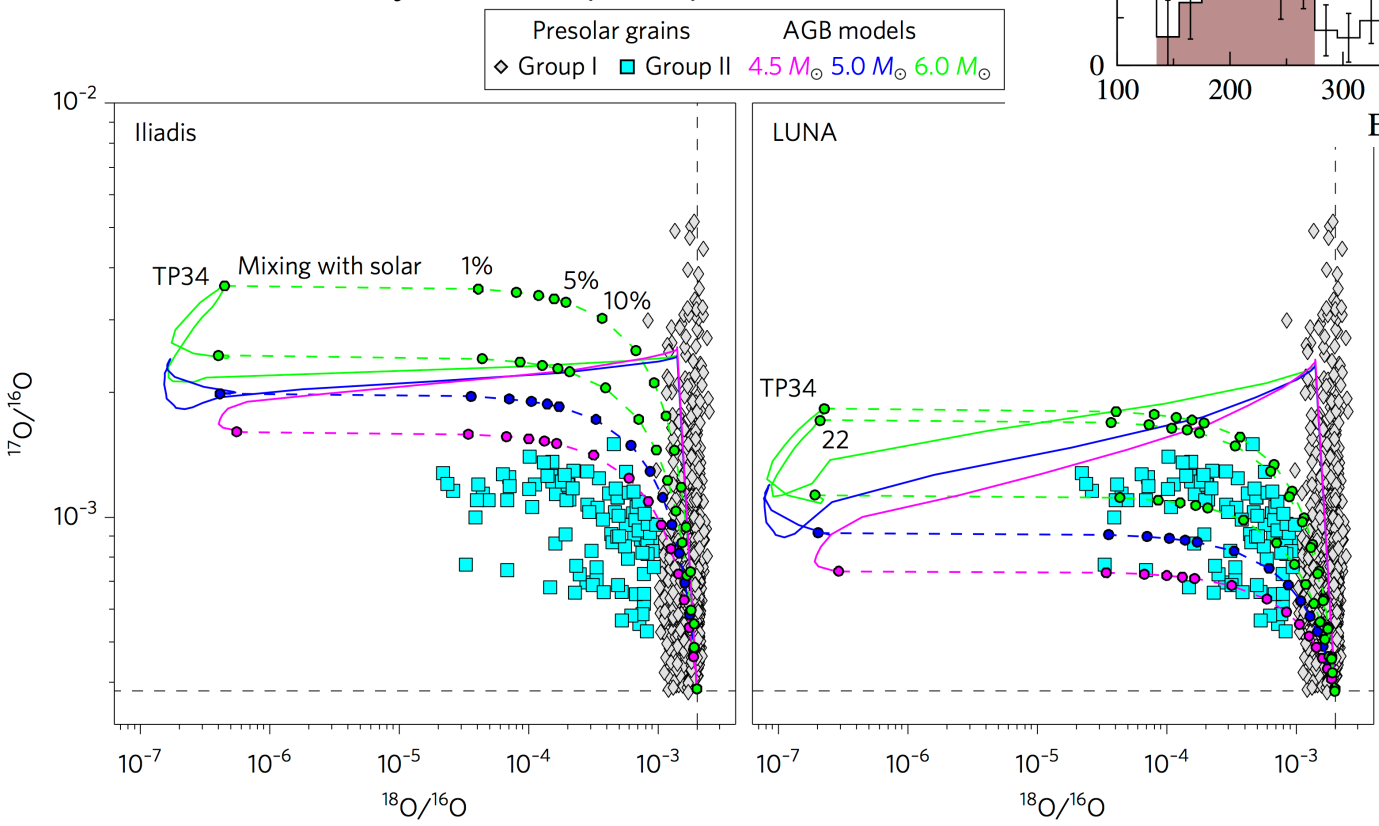
$^{17}O(p,\alpha)^{14}N$, low-energy resonance and its consequences

2× higher thermonuclear reaction rate leads to better explanation of oxygen abundance patterns in meteoritic grains.

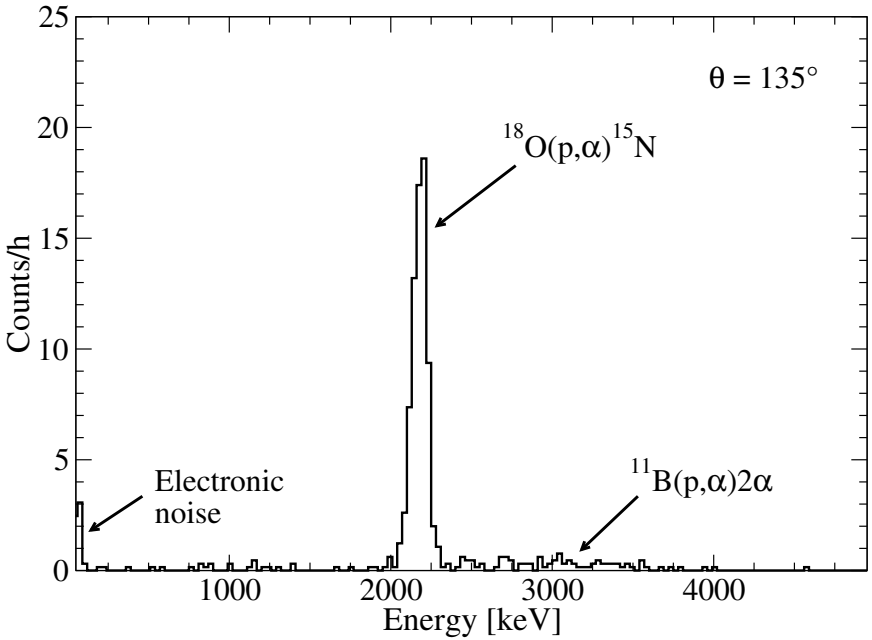
C. G. Bruno *et al.* (LUNA),
Phys. Rev. Lett. 117, 142502 (2016)

M. Lugaro *et al.* (LUNA),
Nature Astronomy 1, 0027 (2017)

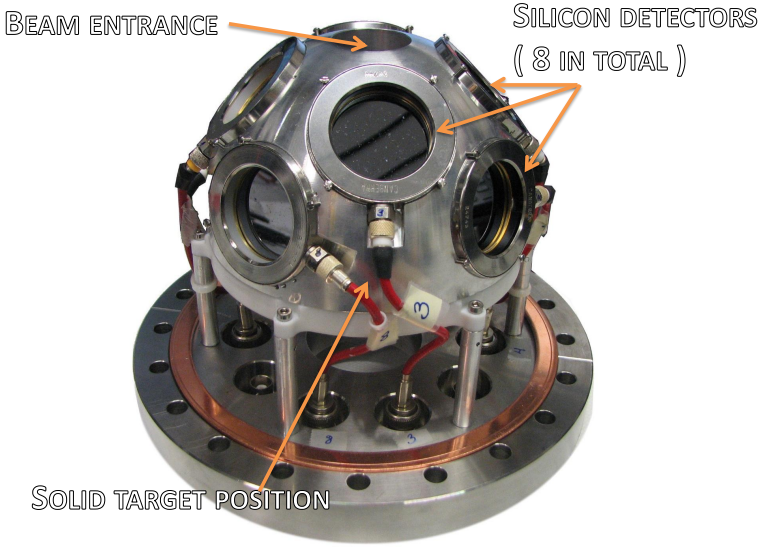




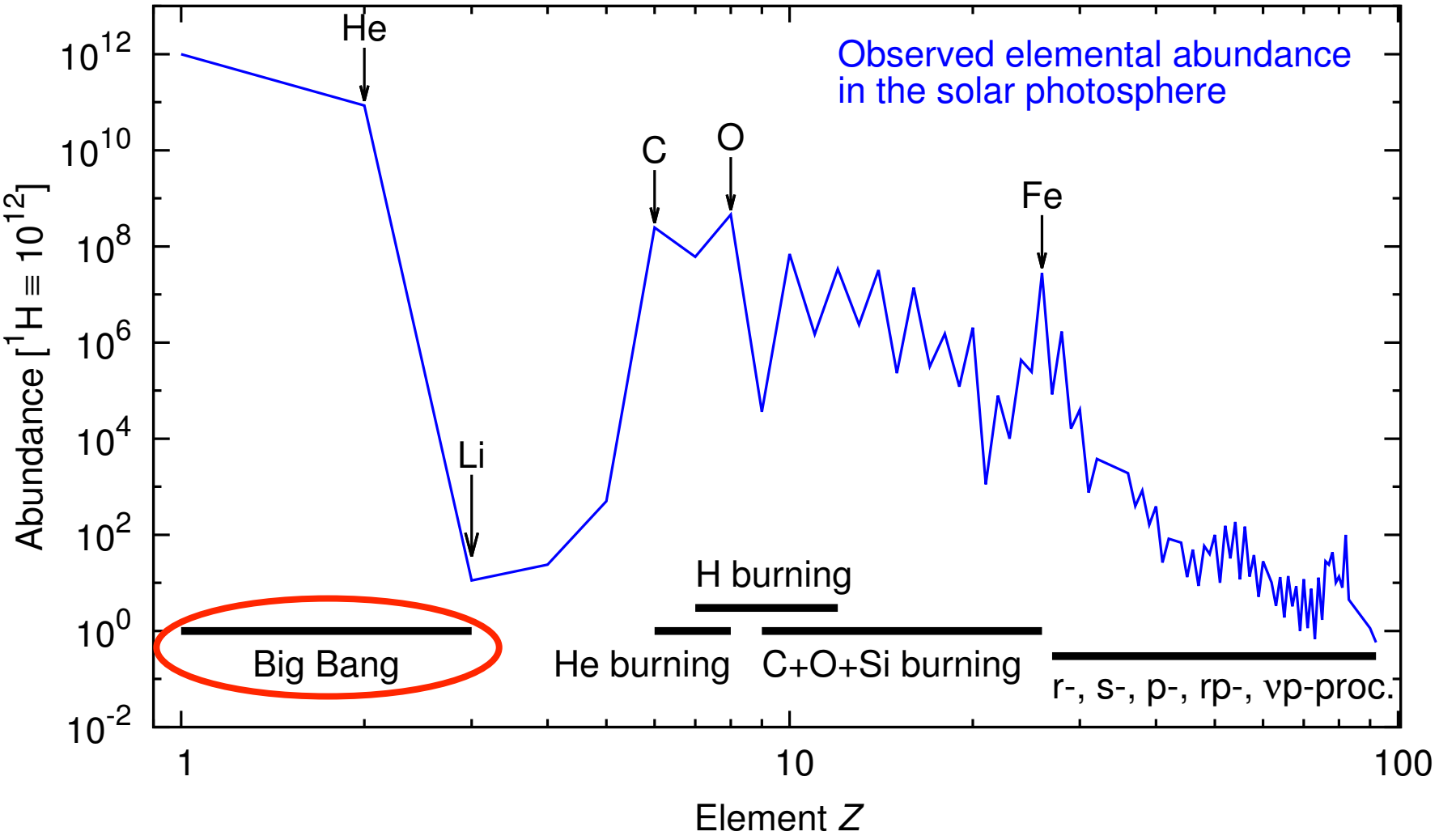
$^{18}O(p,\alpha)^{15}N$, yet another poorly known low-energy resonance



C. G. Bruno *et al.* (LUNA), preliminary

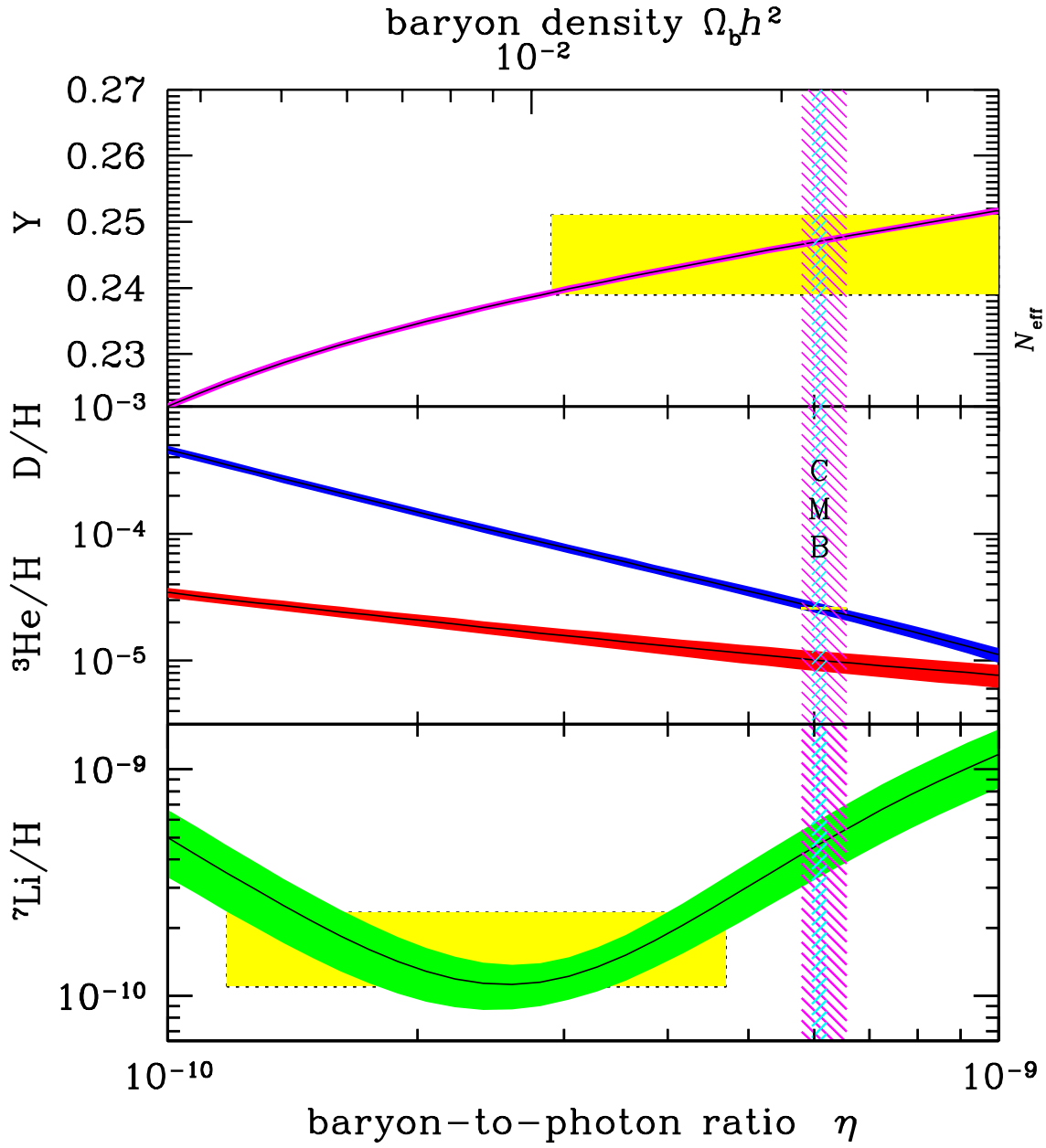


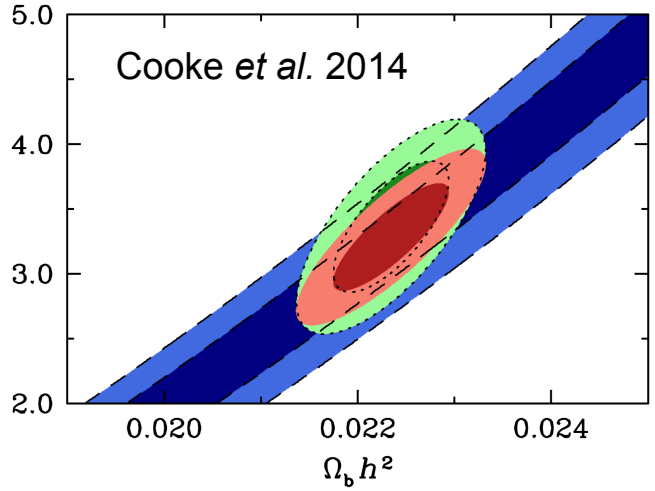
Big bang nucleosynthesis



Cosmology and ^{2}H

Blue band: ^{2}H
Green circle: CMB (Planck 2015)
Red circle: ^{2}H and CMB combined





1. Highly precise measurement of primordial ^{2}H abundance to ~1% (R. Cooke 2014 ff.)
2. Predicted ^{2}H abundance limited by nuclear physics of the ^{2}H(p,γ)^{3}He reaction.

LUNA
Laboratory for Underground Nuclear Astrophysics

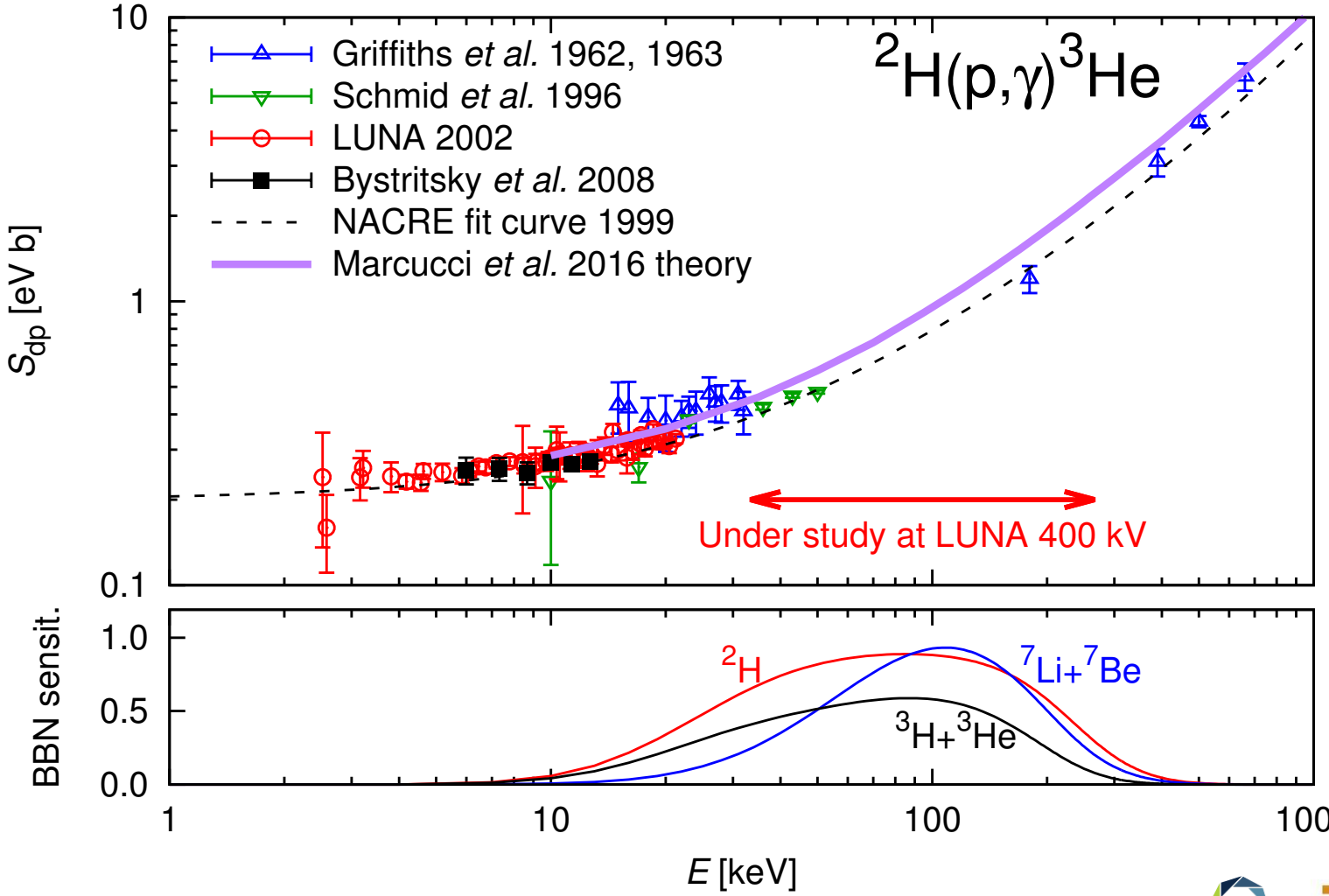
DRESDEN concept

HZDR

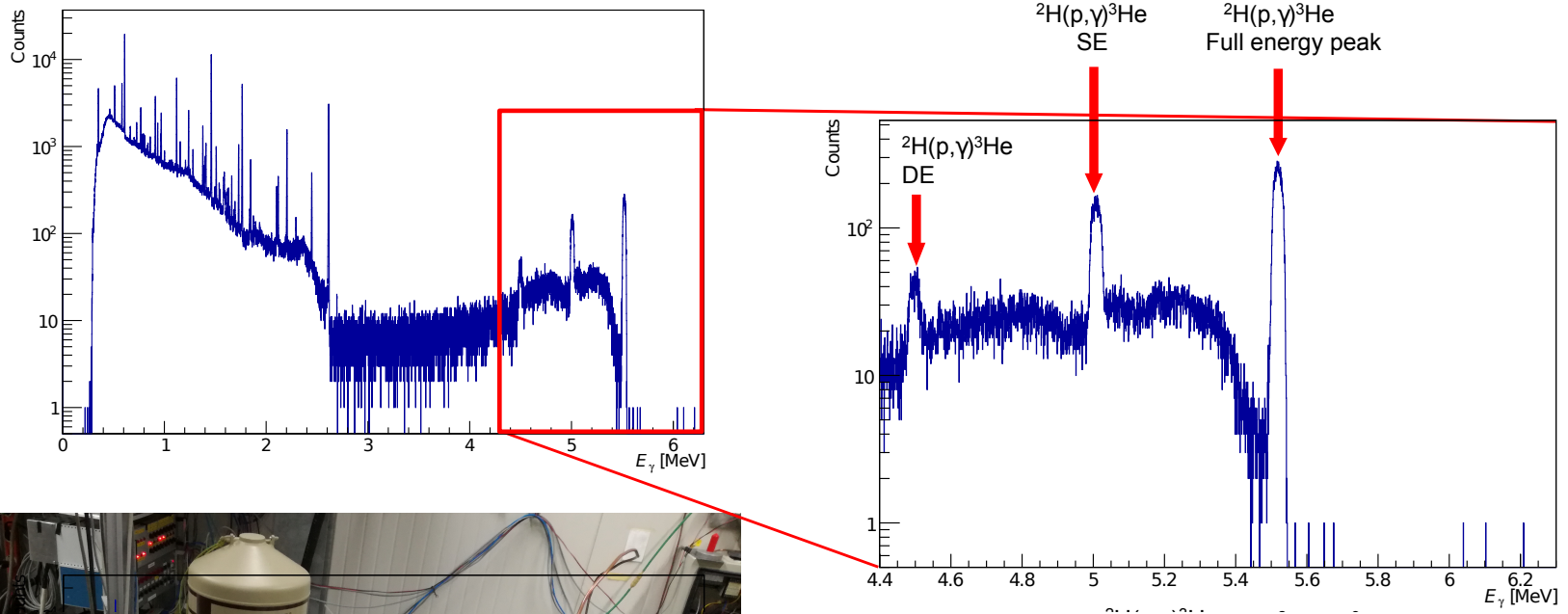
Cosmology and ^{2}H: The ^{2}H(p,γ)^{3}He cross section

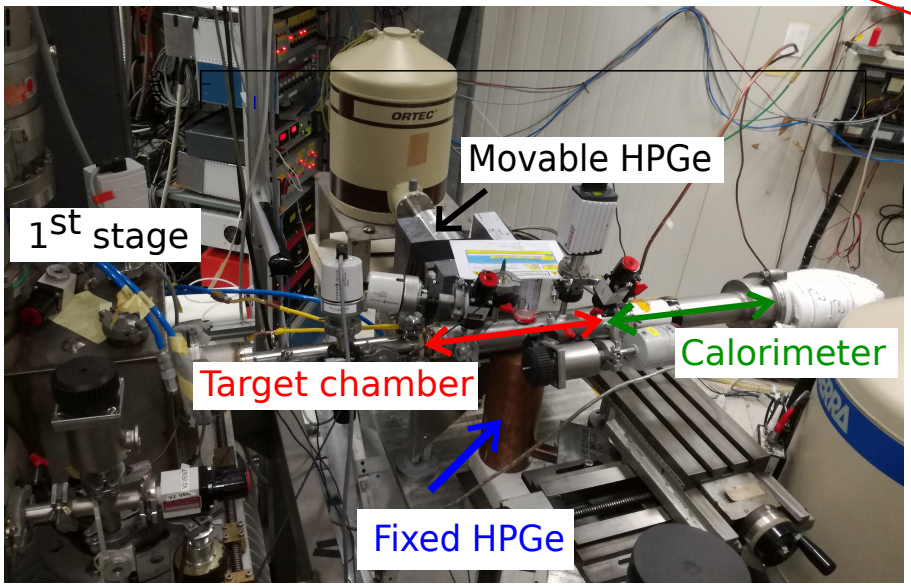
Status: 10% cross section discrepancy ~ 3% uncertainty on ^{2}H prediction

Aim: 3% cross section precision ~ 1% uncertainty on ^{2}H prediction



Cosmology and ^2H: The $^2H(p,\gamma)^3He$ cross section





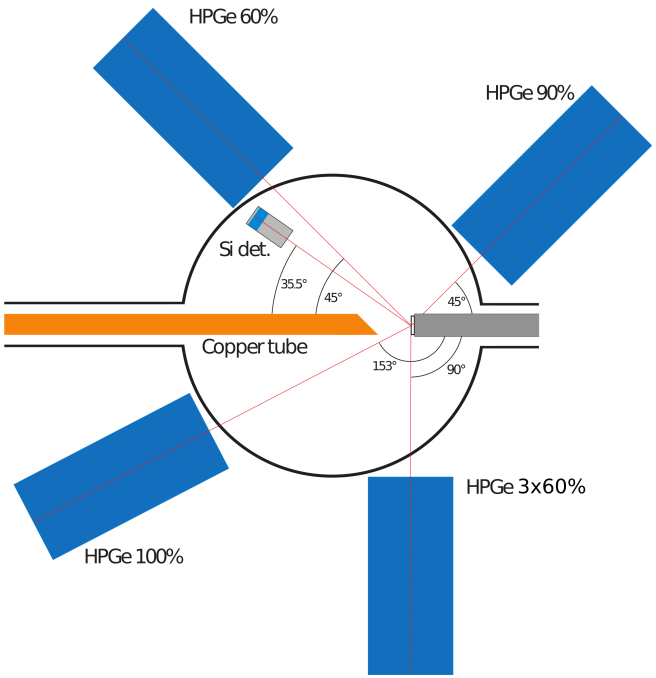
Klaus Stöckel's PhD project, HZDR & TU Dresden

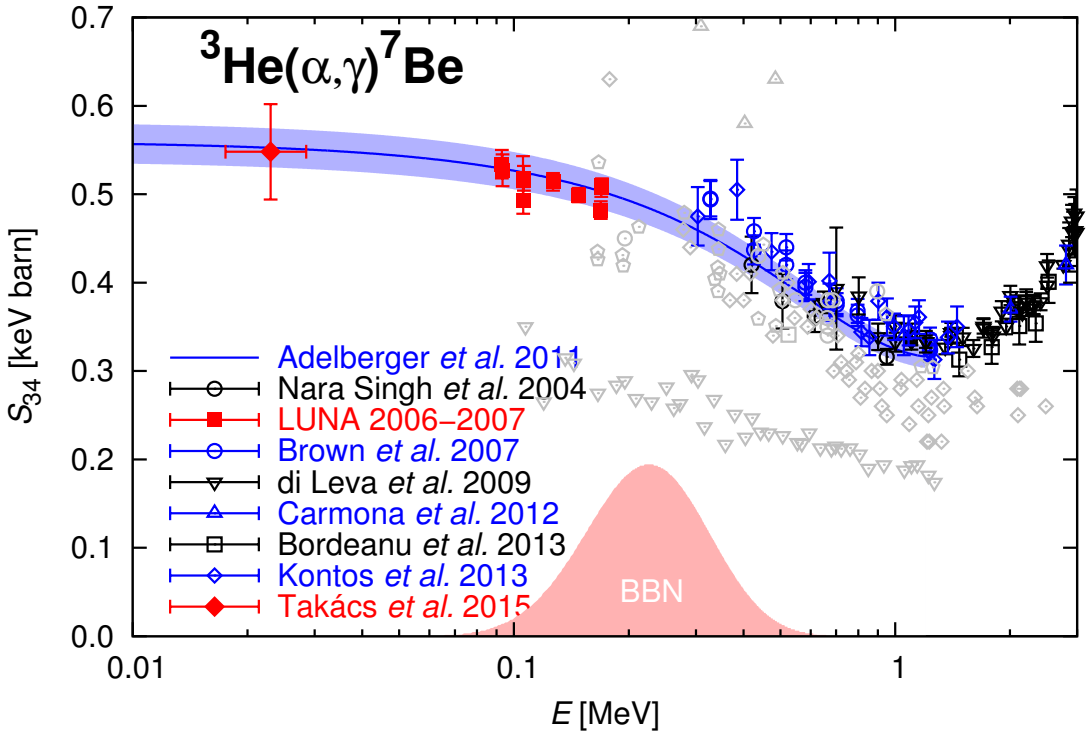
LUNA Laboratory for Underground Nuclear Astrophysics

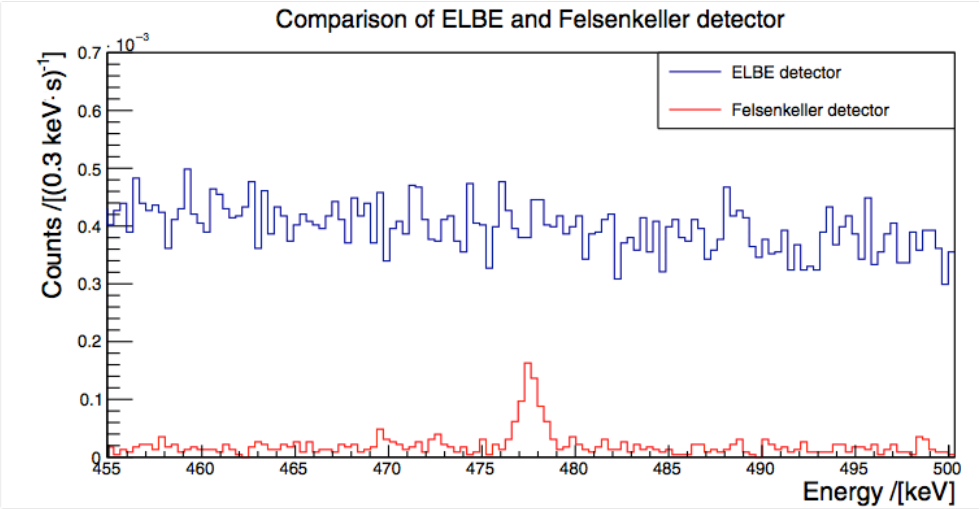
DRESDEN concept

HZDR

^{7}Li cosmology – and solar ^{7}Be neutrinos: ^{3}He(α,γ)^{7}Be

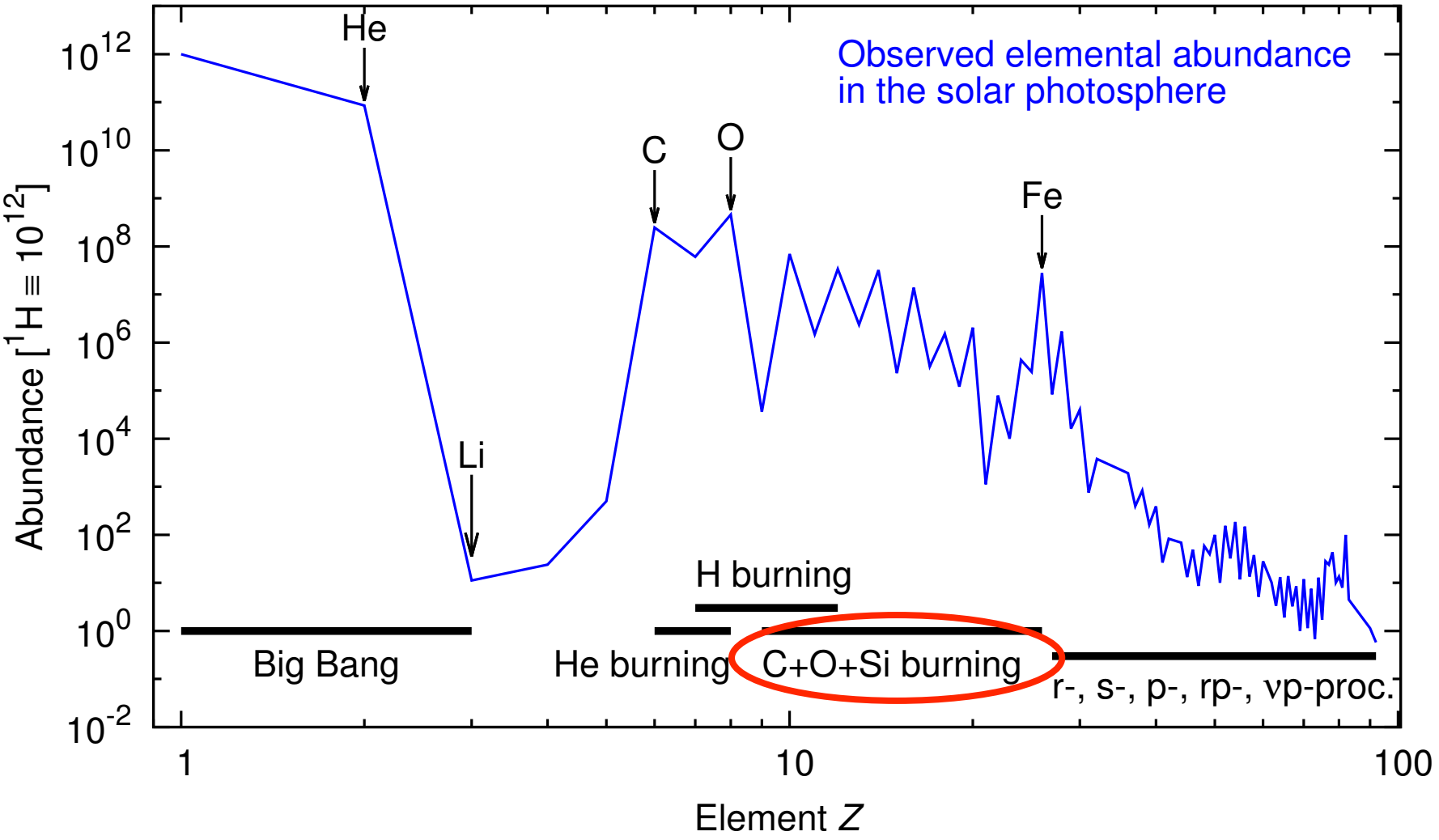




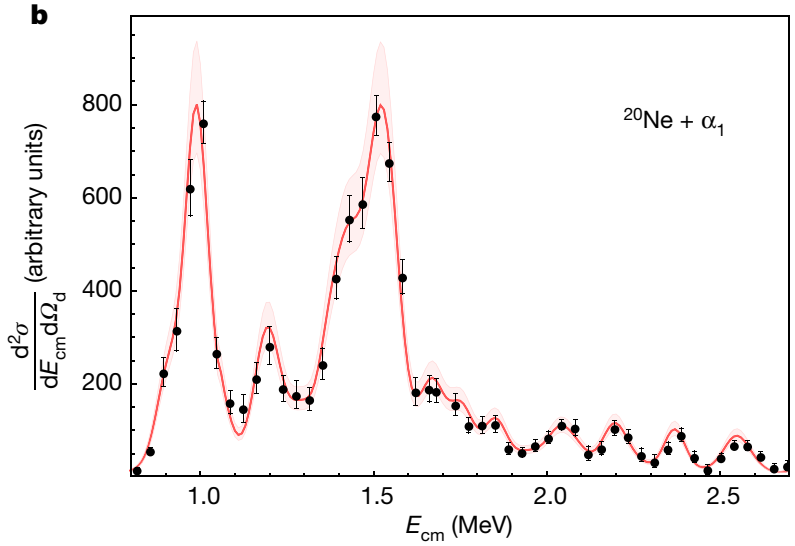


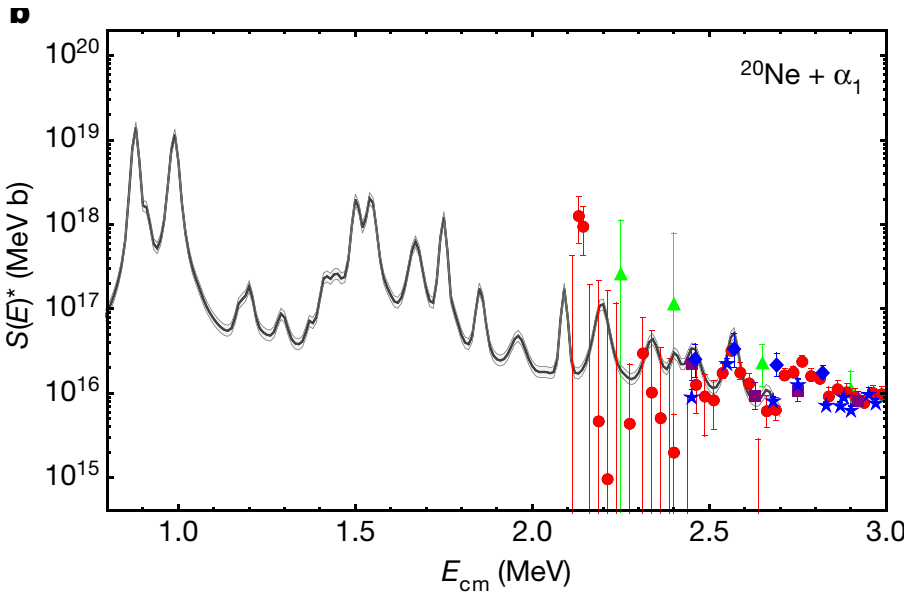
Steffen Turkat's PhD project, TU Dresden

Carbon burning



$^{12}C+^{12}C$ fusion studied by the Trojan Horse method, $^{12}C+^{14}N$

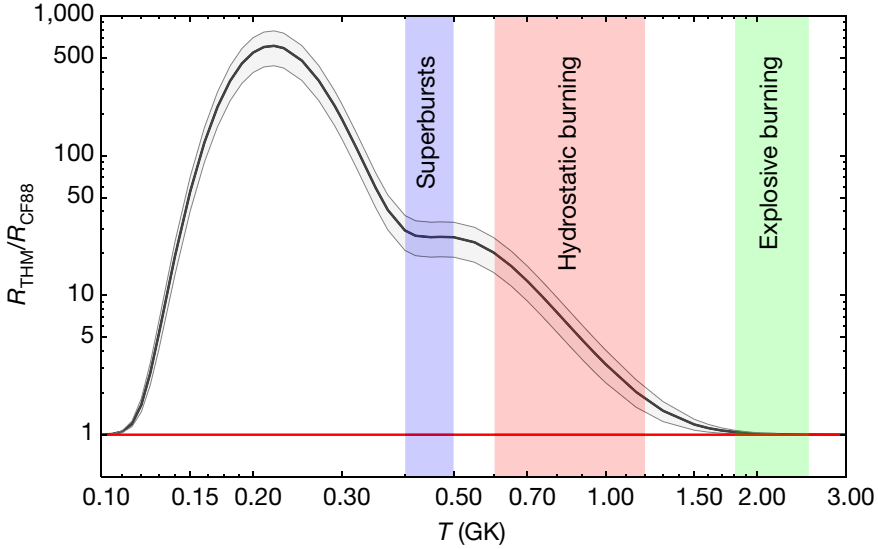




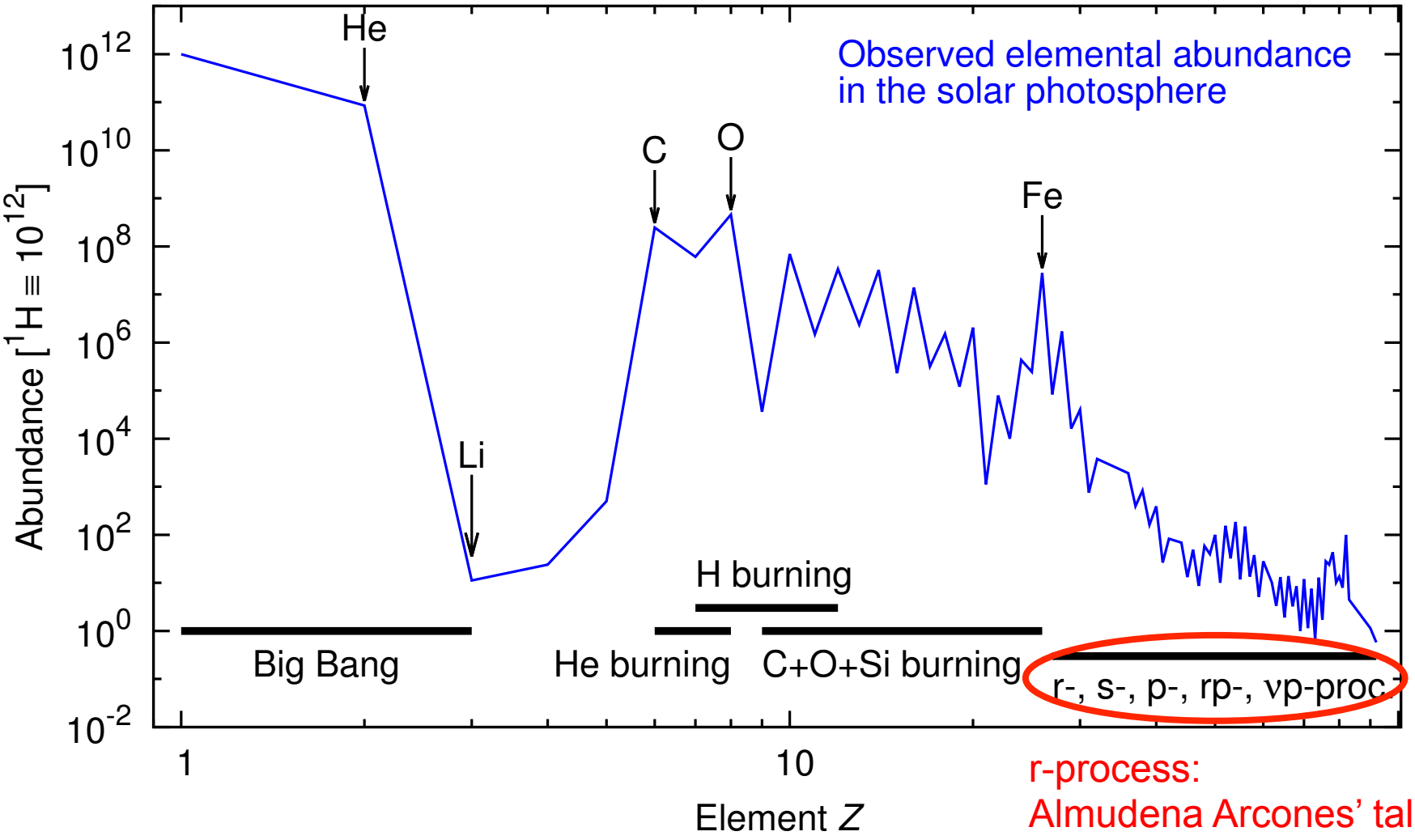
A. Tumino *et al.*,
Nature 557, 687 (2018)

INFN-LNS Catania

Earlier onset of C burning



The production of the chemical elements

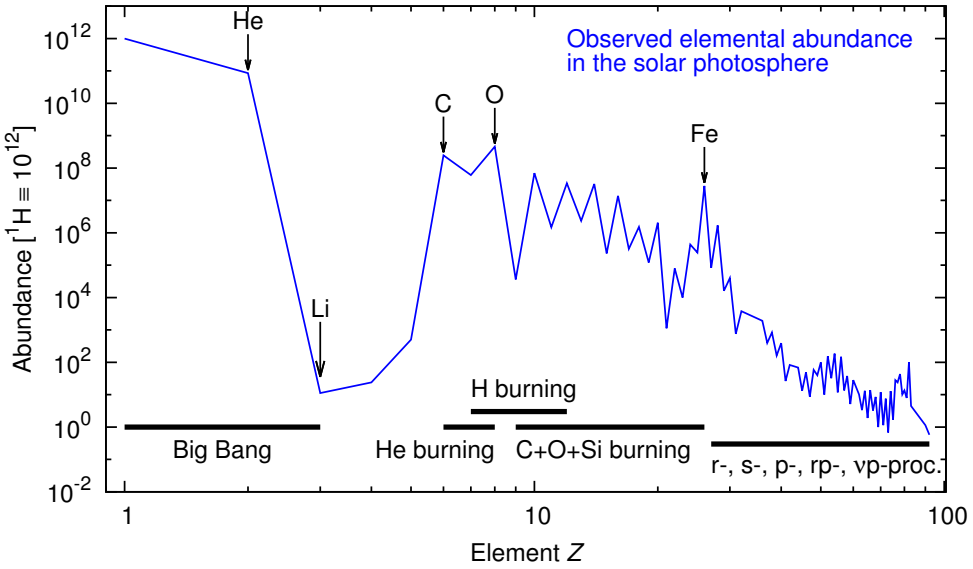


r-process:
Almudena Arcones' talk
Jochen Greiner's talk

New experimental facilities with strong impact on the field

LUNA-MV Italy
H, He, C burning
s-process neutron sources

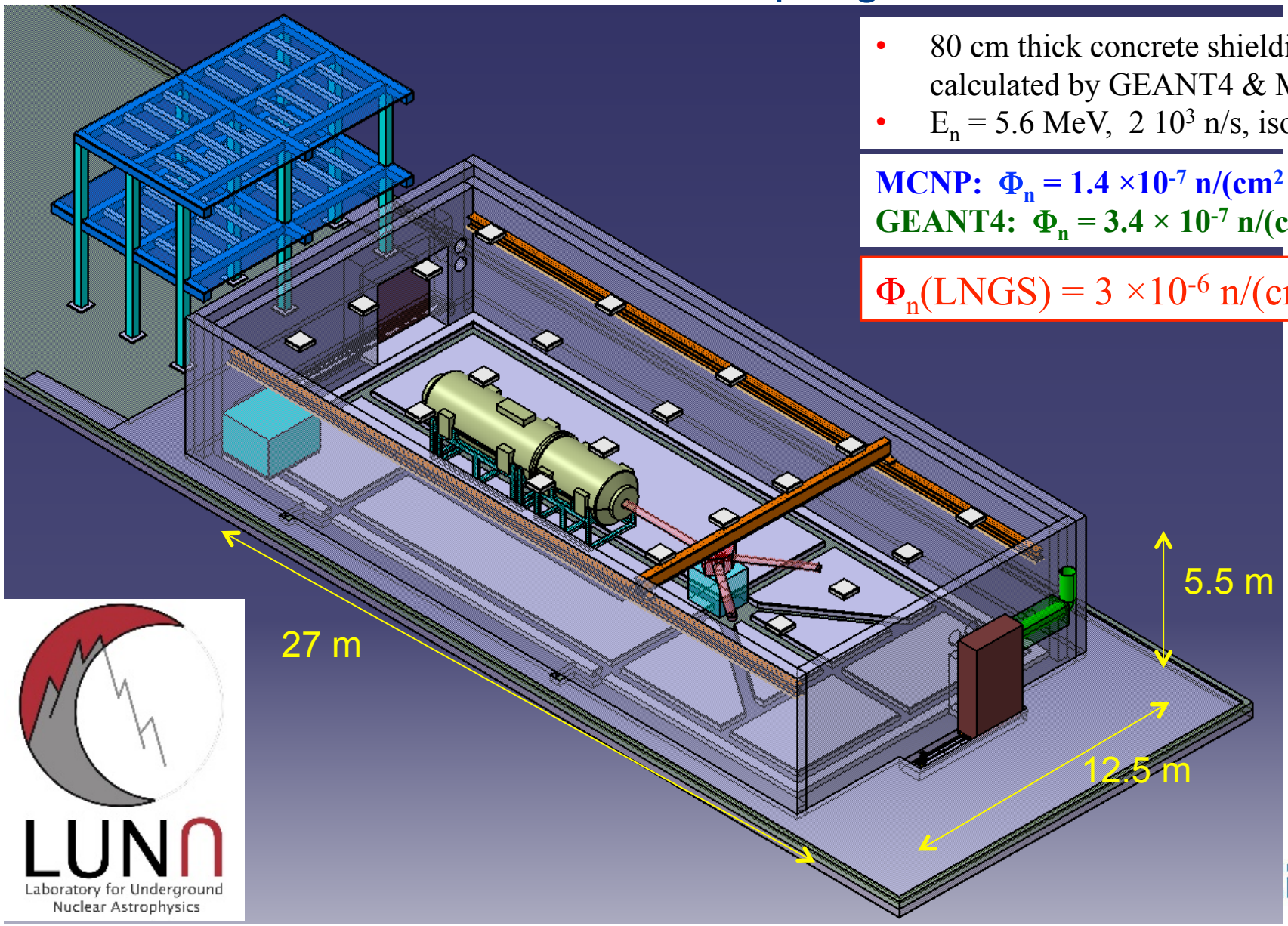
FAIR Darmstadt
r-process,
s-process



FRANZ Frankfurt
s-process

Felsenkeller Dresden
Solar fusion
He burning

New LUNA-MV 3.5 MV accelerator for ^{1}H, ^{4}He, ^{12}C beams: Installation in LNGS hall B from spring 2019



- 80 cm thick concrete shielding calculated by GEANT4 & MCNP
- E_n = 5.6 MeV, 2 10^3 n/s, isotropic

MCNP: $\Phi_n = 1.4 \times 10^{-7}$ n/(cm^2 s)

GEANT4: $\Phi_n = 3.4 \times 10^{-7}$ n/(cm^2 s)

Φ_n(LNGS) = 3×10^{-6} n/(cm^2 s)

LUNA
Laboratory for Underground Nuclear Astrophysics

LUNA MV- scientific program (2019 → 2024)

Commissioning measurement: $^{14}N(p,\gamma)^{15}O$. High scientific interest for revised data covering a wide energy range (400 keV- 3.5 MeV).

$^{12}C+^{12}C$: solid state target. Gamma and particle detection.

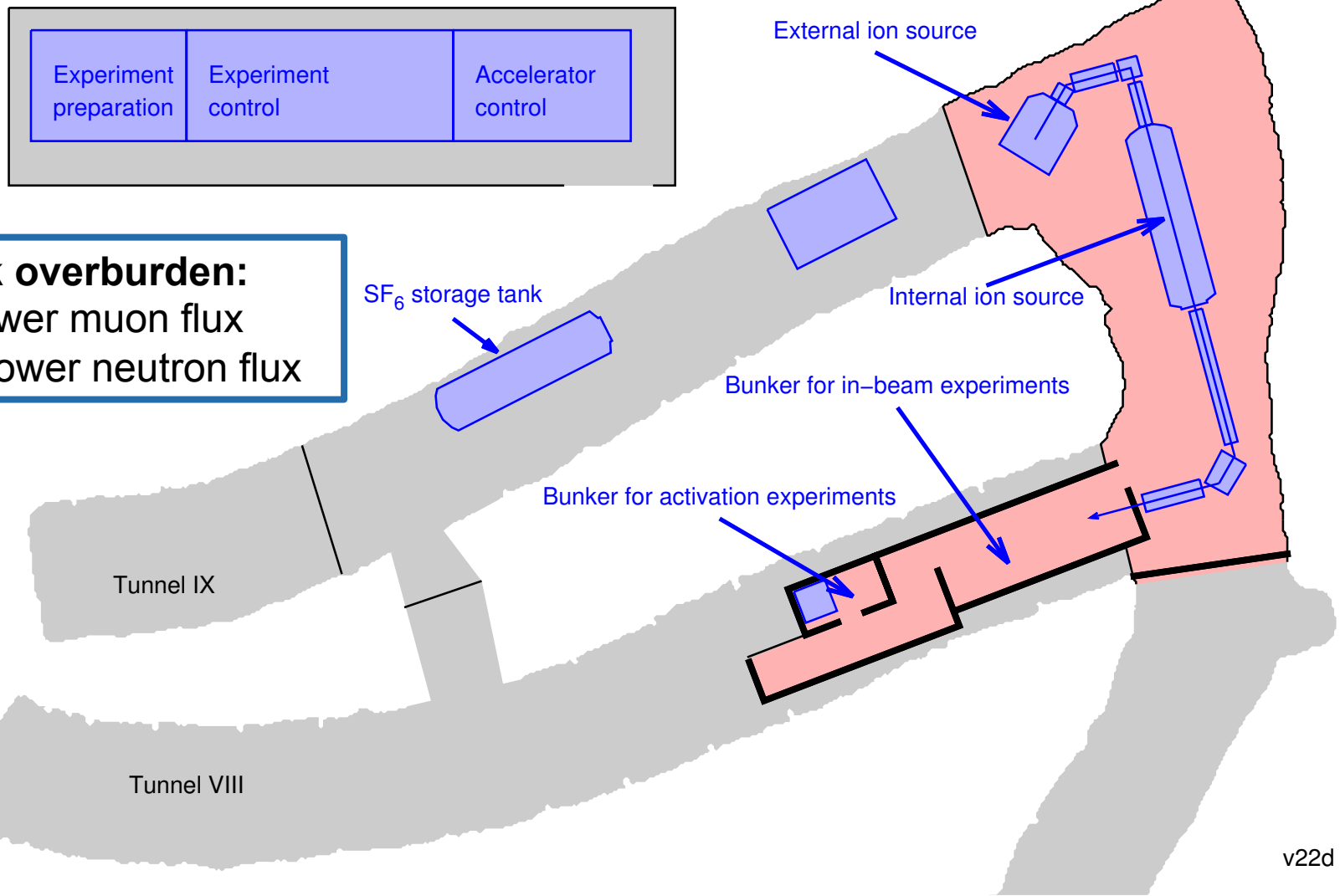
$^{13}C(\alpha,n)^{16}O$: enriched ^{13}C solid or gas target.
Data taking at LUNA 400 kV in 2017-2019.

$^{22}Ne(\alpha,n)^{25}Mg$: enriched ^{22}Ne gas target.

Next steps (not before 2024…):

$^{12}C(\alpha,\gamma)^{16}O$: ^{12}C solid target depleted in ^{13}C and alpha beam or α jet gas target and ^{12}C beam.

5 MV Pelletron in Felsenkeller Dresden, to start late 2018



45 m rock overburden:

- 40 × lower muon flux
- 180 × lower neutron flux

Installations under commissioning at Felsenkeller

Joint effort HZDR – TU Dresden

- **HZDR:** 5 MV Pelletron, 50 µA beams of $^{1}H^{+}$, $^{4}He^{+}$ (single-ended), $^{12}C^{+}$ (tandem)
- **TU Dresden:** 150% ultra-low-background HPGe detector for offline γ-counting

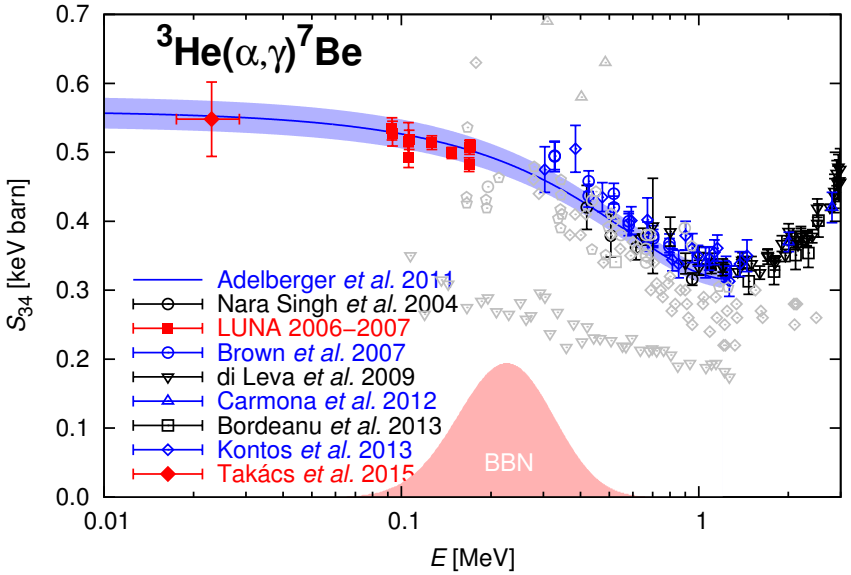
External sputter ion source: ^{12}C beam

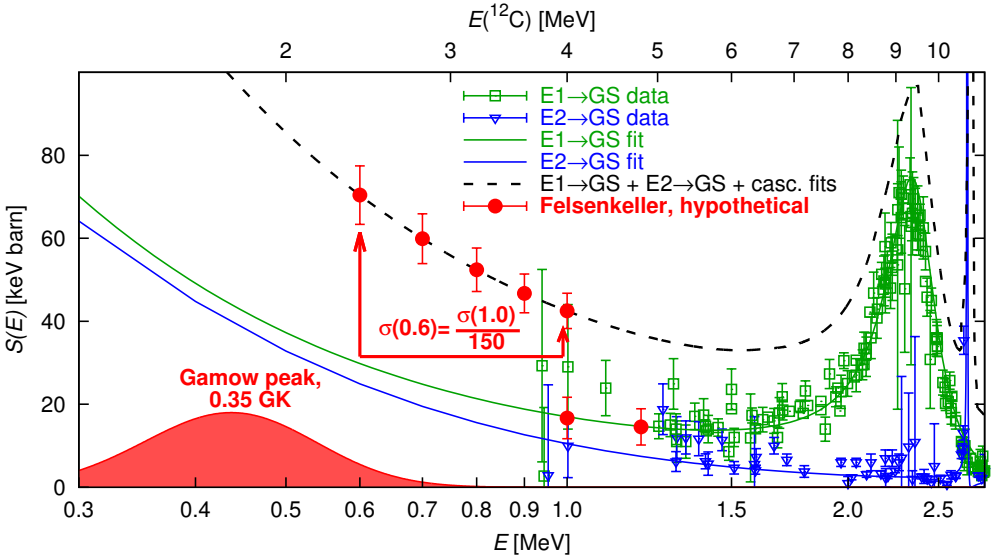
Internal radio-frequency ion source: ^{1}H, ^{4}He beams

Two measurement bunkers made of low-activity concrete

Counting room (at the Earth's surface, with daylight!)

Felsenkeller, scientific program and access





In-house research by HZDR and TU Dresden

- Complementary to LUNA-MV program for 2019-2023
- ^{3}He(α,γ)^{7}Be, ^{12}C(α,γ)^{16}O

Open as a facility to any scientific users worldwide, no cost for beam time.

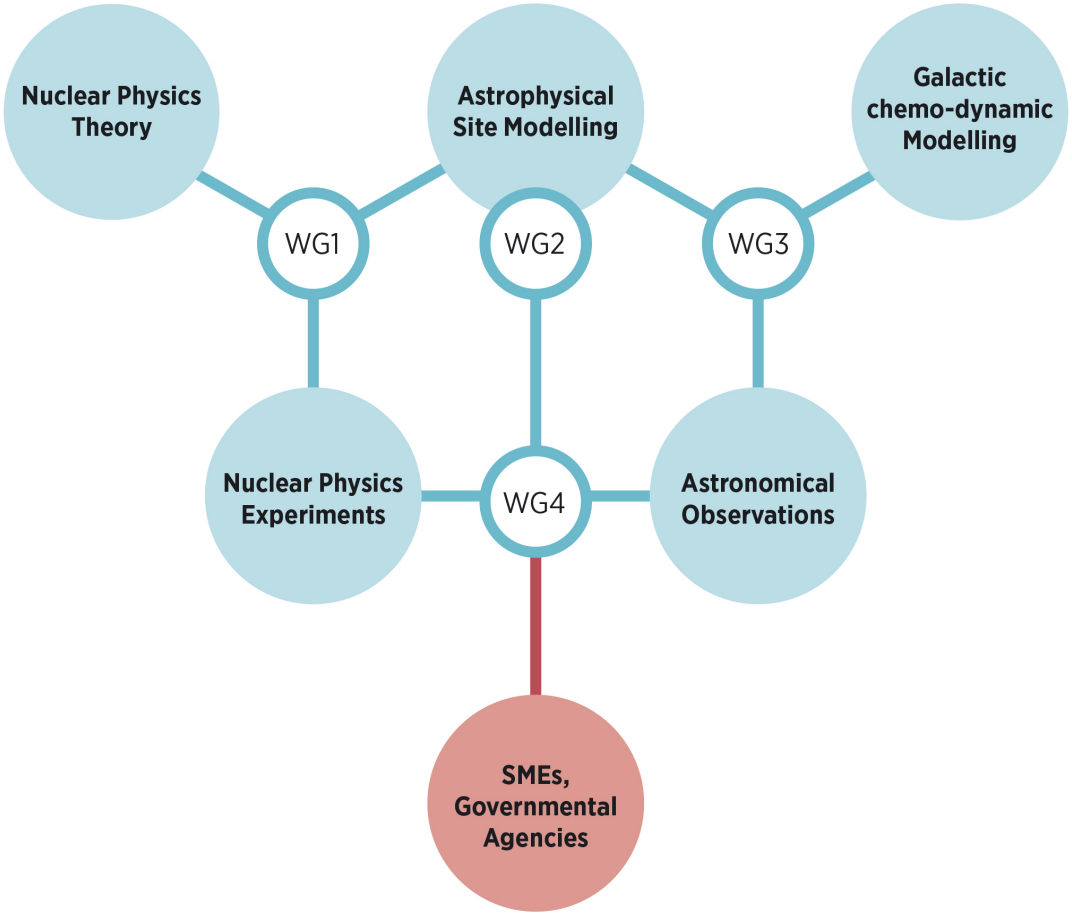
User selection based on the recommendations of an independent scientific advisory board

COST action ChETEK [ketek] on Nuclear Astrophysics

Chemical Elements as Tracers of the Evolution of the Cosmos

A network to bring European research, science and business together to further our understanding of the early universe

cost
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY



http://www.chetec.eu

- ~150 k€/year 2017-2021
- 30 European countries

Meetings:

- Conference on „Nuclear Physics of Stellar Explosions“, Debrecen/ HU 12-14 September
- School on Software Tools for Simulations in Nuclear Astrophysics, Hull/UK 17-19 September

Chair:

- Raphael Hirschi, Keele University/UK

ChETEC Action

55th Karpacz Winter School of Theoretical Physics
and
'ChETEC' COST Action Training School

Nuclear Astrophysics in the Multi-Messenger Era

EXPLOSIVE ASTROPHYSICAL PHENOMENA · ASTROPHYSICAL MESSENGERS · NUCLEAR ASTROPHYSICS EXPERIMENTS

Lecturers

A. Bauswein (GSI Darmstadt, Germany)
D. Bemmerer (HZDR, Germany)
R. Diehl (MPE Garching, Germany)
T. Foglizzo (CEA Orsay, France)
K. Kotake (Fukuoka Univ., Japan)
G. Martínez-Pinedo (GSI/TU Darmstadt, Germany)
A. Mirizzi (INFI Bari, Italy)
R. Reifarth/K. Göbel (Univ. Frankfurt, Germany)

Details

Feb. 24th – Mar. 2nd, 2019
Karpacz, Poland

Organizers

N.-U. Bastian, D. Bemmerer, D. Blaschke, M. Cierniak, T. Fischer (chair), M. Marczenko, E. Niemczura, K. Redlich, C. Sasaki, L. Turko

Sponsors

HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF
cost EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY
ChETEC Action
NAWA POLISH NATIONAL AGENCY FOR ACADEMIC EXCHANGE
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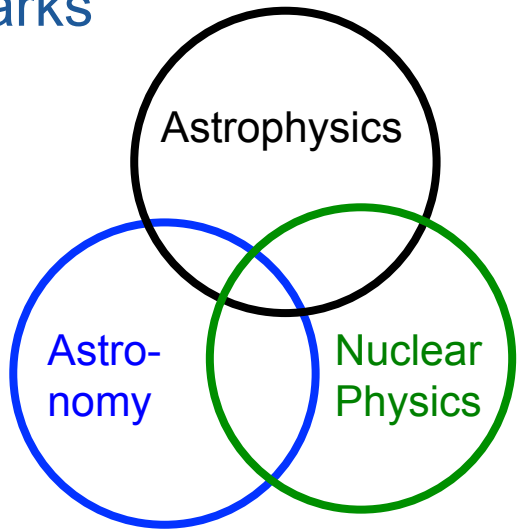
Wrocław miasto spotkań
Uniwersytet Wrocławski
Ministry of Science and Higher Education Republic of Poland

www.ift.uni.wroc.pl/~karp55

Nuclear Astrophysics: Some general remarks

Very active field at the intersection of

- Astrophysics
- Astronomy
- Nuclear physics



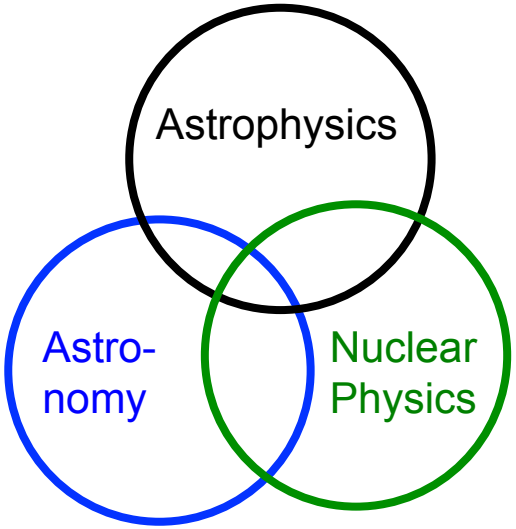
Europe plays a dominating role, and Germany plays a strong role

- Nuclei in the Cosmos conference (even years) every other time in Europe, 200-300 p.
- Nuclear Physics in Astrophysics conference (odd years) always in Europe, 200-300 p.
- 30 groups at German community meeting (November 2016)

Funding-wise in Germany at the intersection of

- BMBF KHuK, KAT, RDS
- DFG
- Helmholtz (Nuclear Astrophysics Virtual Institute, 2011-2016)

Nuclear Astrophysics: Summary

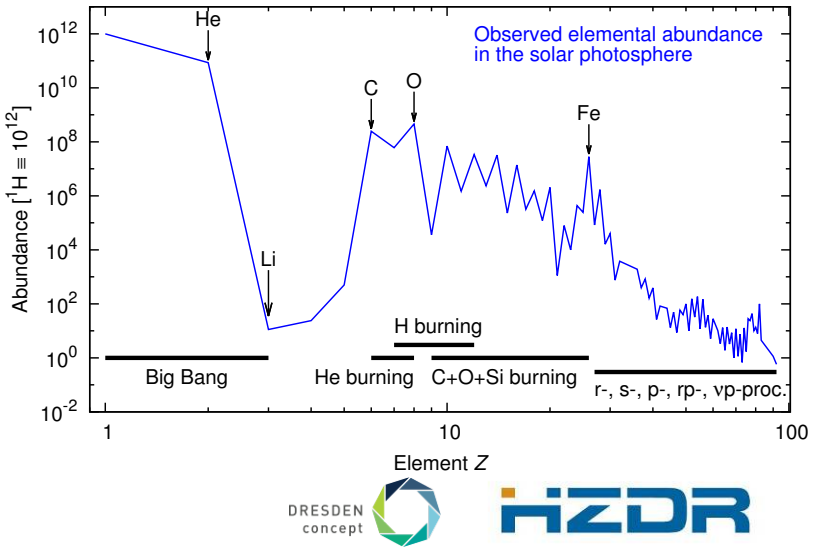


Strong links to astroparticle physics

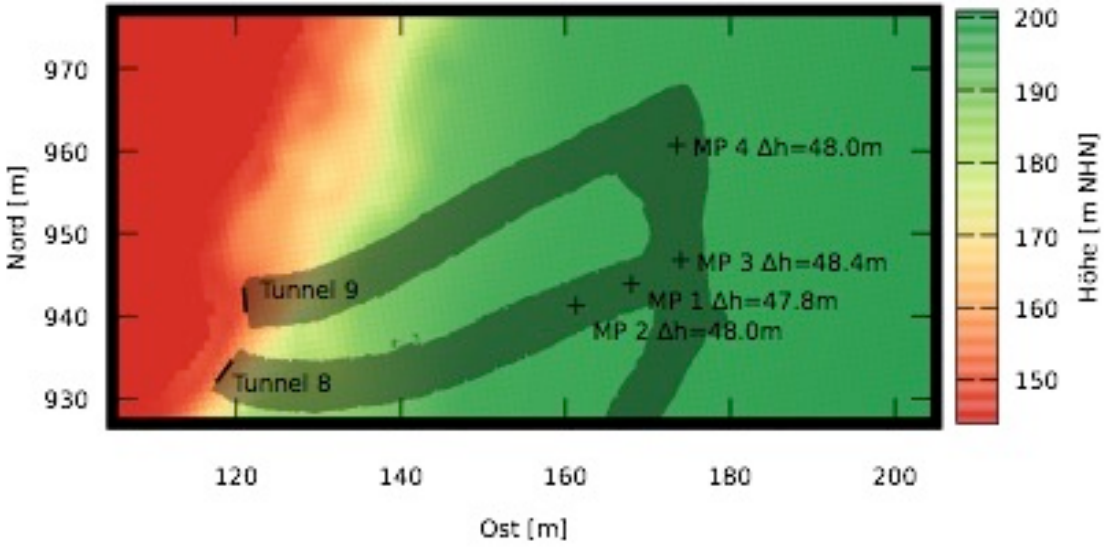
- Big Bang nucleosynthesis
- Solar neutrino fluxes
- Cosmic-ray cross sections
- r-process in explosive events

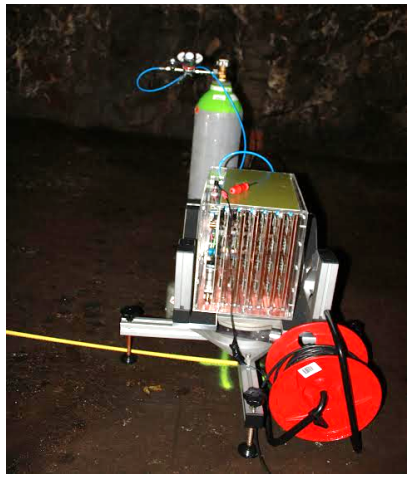
Experimental facilities with German involvement

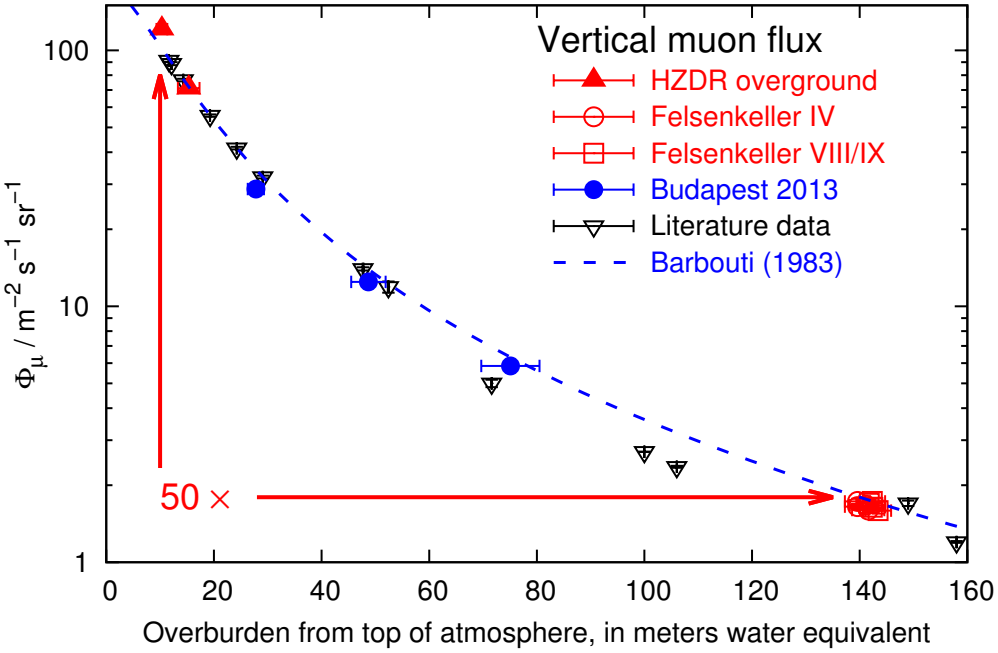
- LUNA 0.4 MV actively producing data
- LUNA-MV 3.5 MV at Gran Sasso,
  to be installed in 2019
- Felsenkeller 5 MV accelerator Dresden
  from late 2018
  Deepest underground lab in Germany.
- FRANZ Uni Frankfurt, to open soon
- FAIR Darmstadt

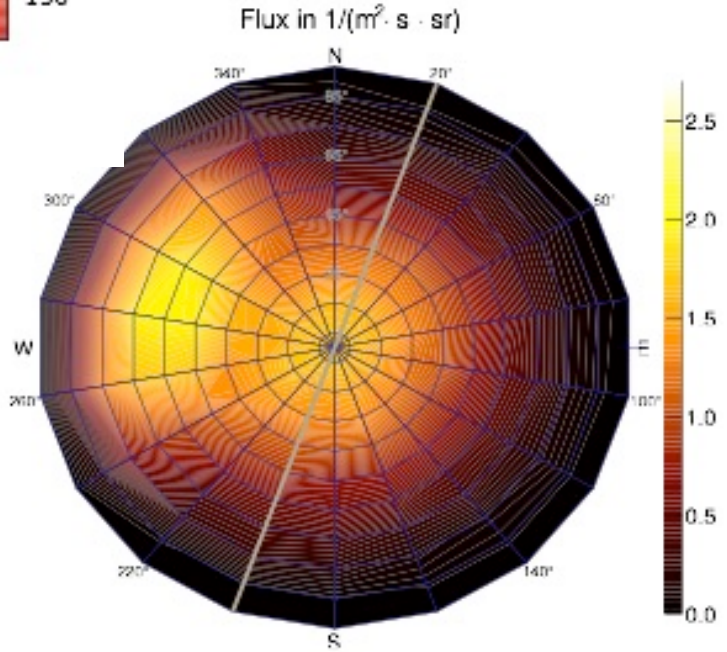


Felsenkeller, muon flux measurement









Felsenkeller, neutron flux measurement

- 25 × to 180 × lower neutron flux than at the Earth‘s surface
- Flux depends on local shielding
- Neutron data informed the construction project

	BELEN ^{3}He counters [10^{-4} cm^{-2} s^{-1}]
Tunnel	2.07 ± 0.07
Pb+Fe bunker	4.56 ± 0.16
Rock bunker	0.66 ± 0.04
Above ground	(121)