

The new Felsenkeller 5 MV underground accelerator: Status and Program



*Seminar, Institut für Kern- und Teilchenphysik
TU Dresden, 24.01.2019*

Daniel Bemmerer

<http://arxiv.org/abs/1810.08201>



Gefördert durch

DFG Deutsche
Forschungsgemeinschaft

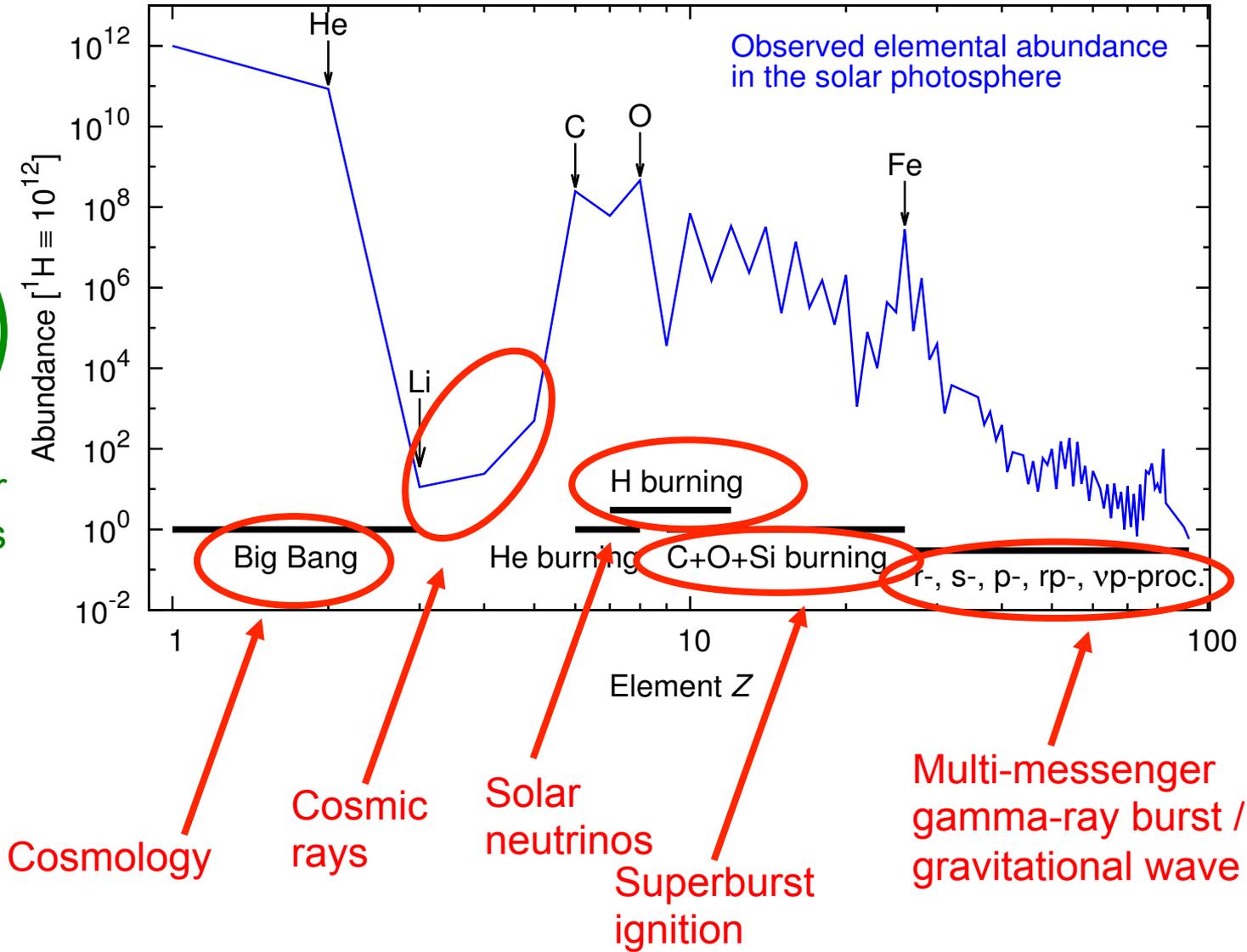
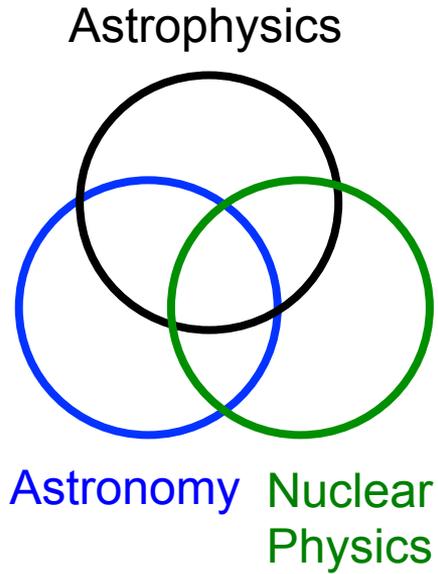
HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES



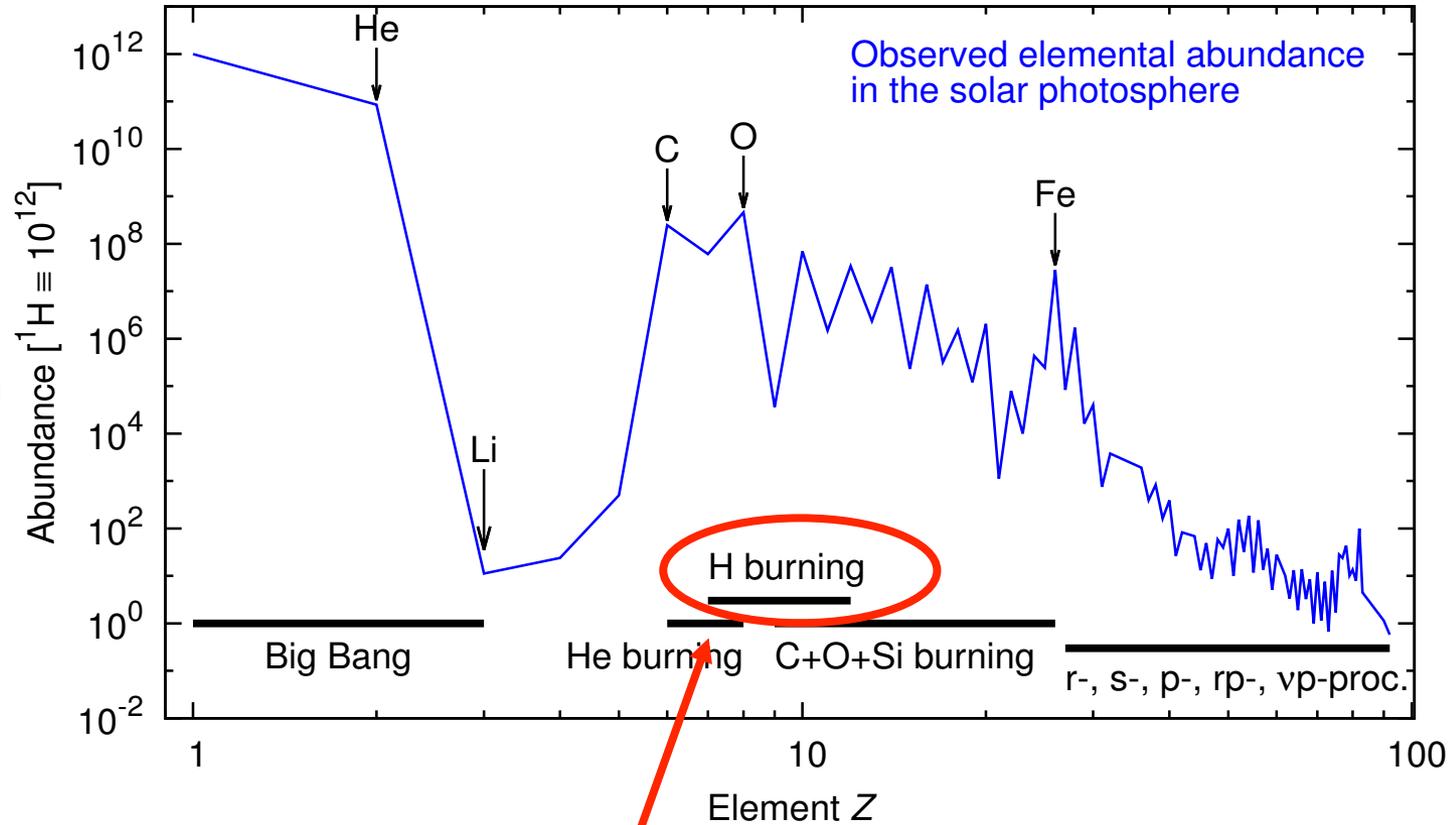
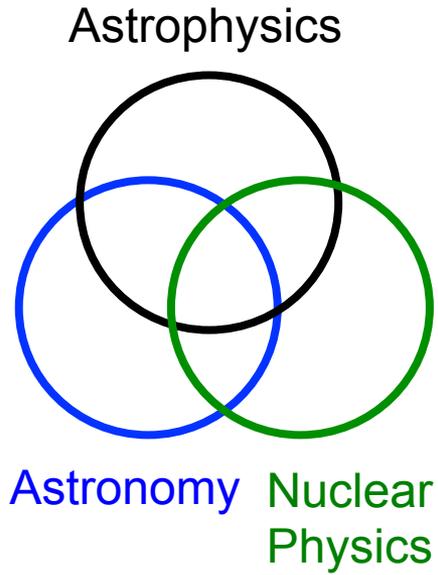
HZDR

HELMHOLTZ
ZENTRUM DRESDEN
ROSSENDORF

Nuclear Astrophysics: The production of the chemical elements



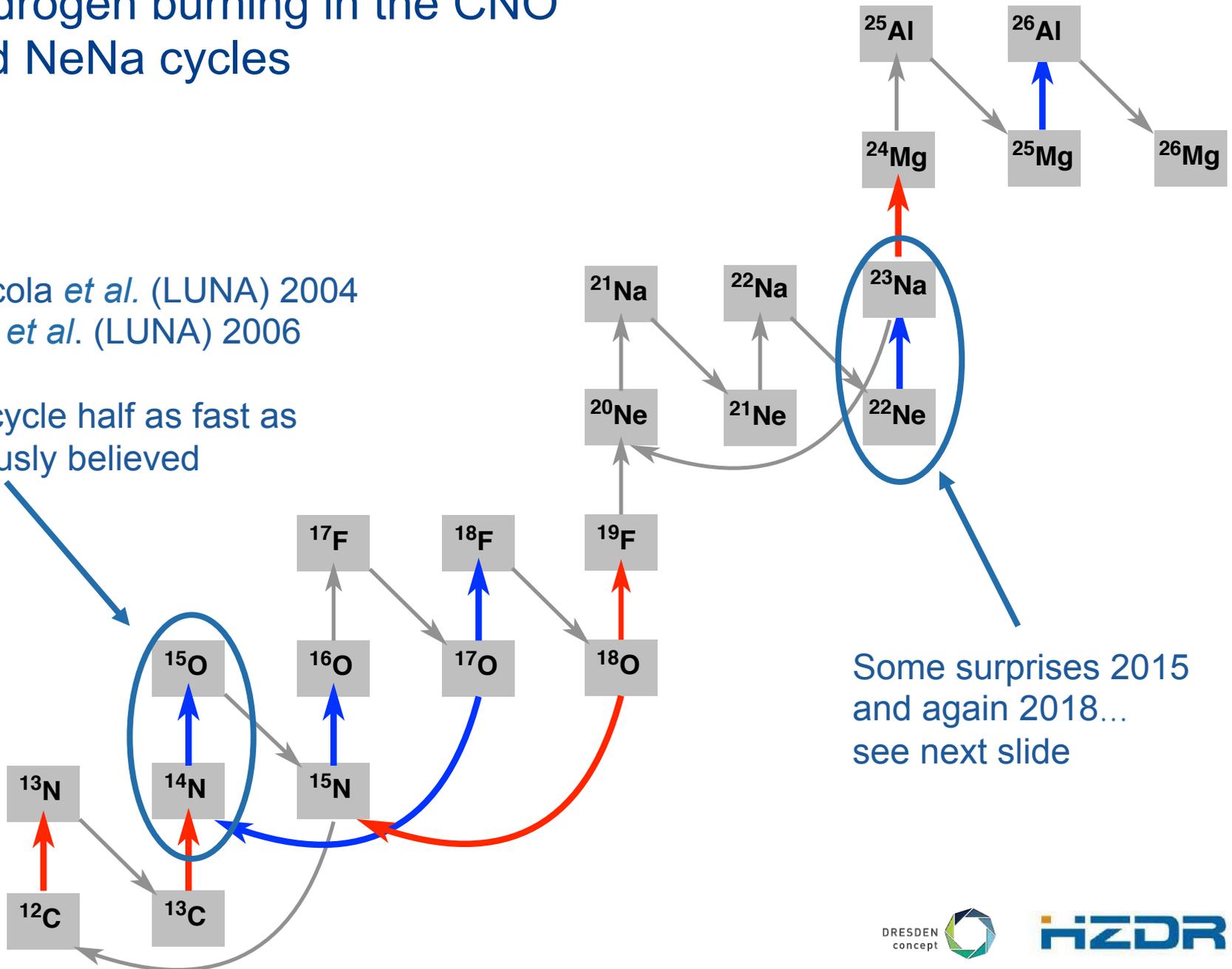
Nuclear Astrophysics: The production of the chemical elements



Hydrogen burning in the CNO and NeNa cycles

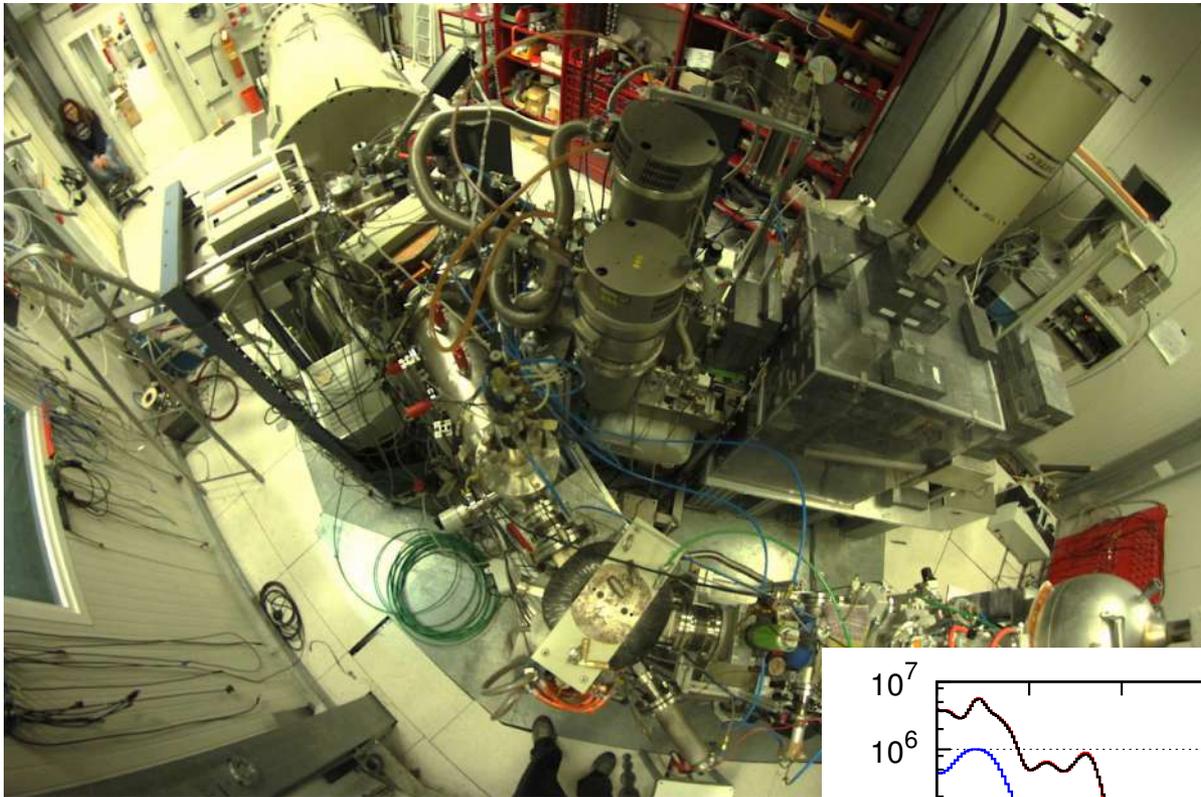
Formicola *et al.* (LUNA) 2004
Lemut *et al.* (LUNA) 2006

CNO cycle half as fast as
previously believed



Some surprises 2015
and again 2018...
see next slide

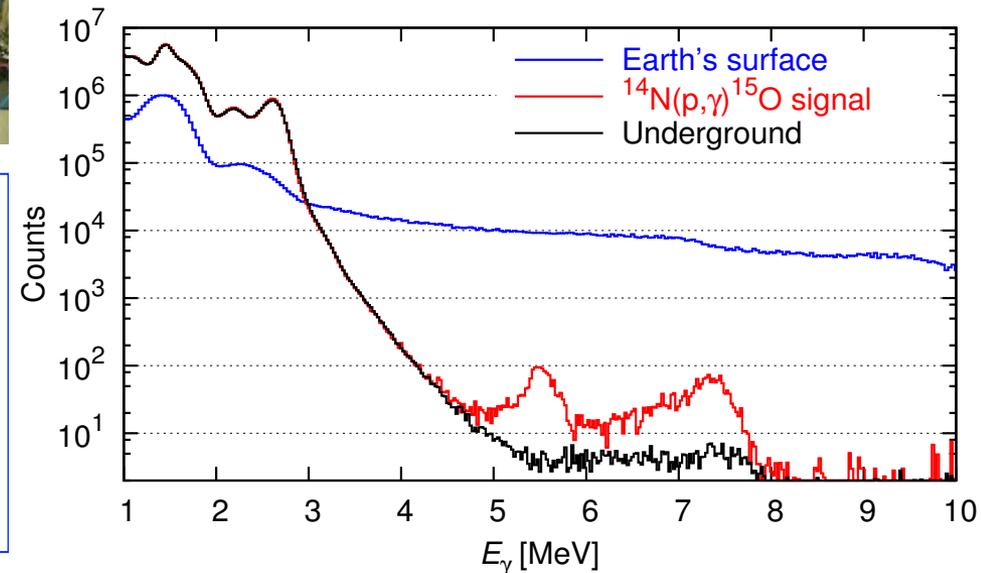
LUNA = Laboratory Underground for Nuclear Astrophysics



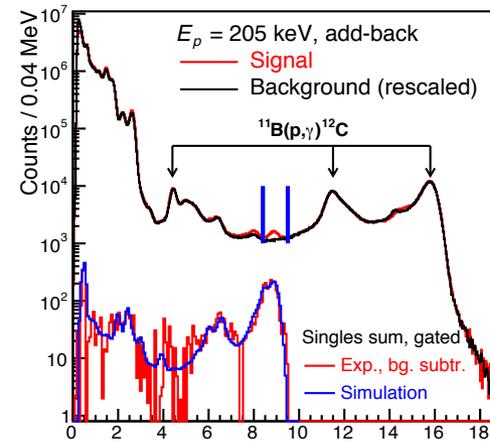
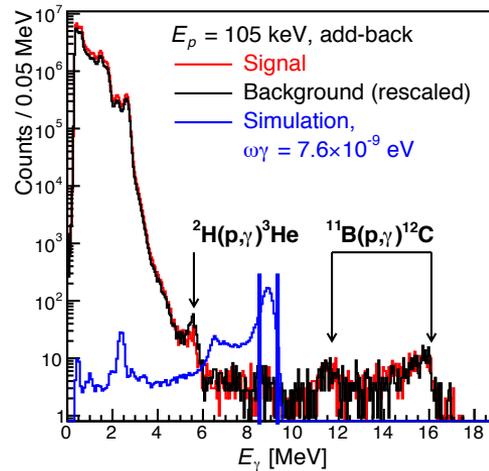
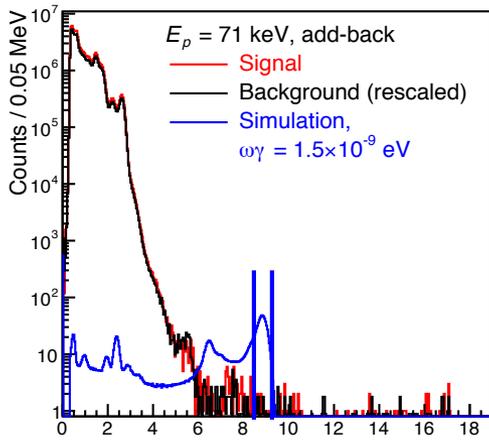
- LUNA @ Gran Sasso
- Italy
 - Germany (HZDR)
 - UK
 - Hungary

LUNA approach:
Measure nuclear reaction cross sections
at or near the relevant energies

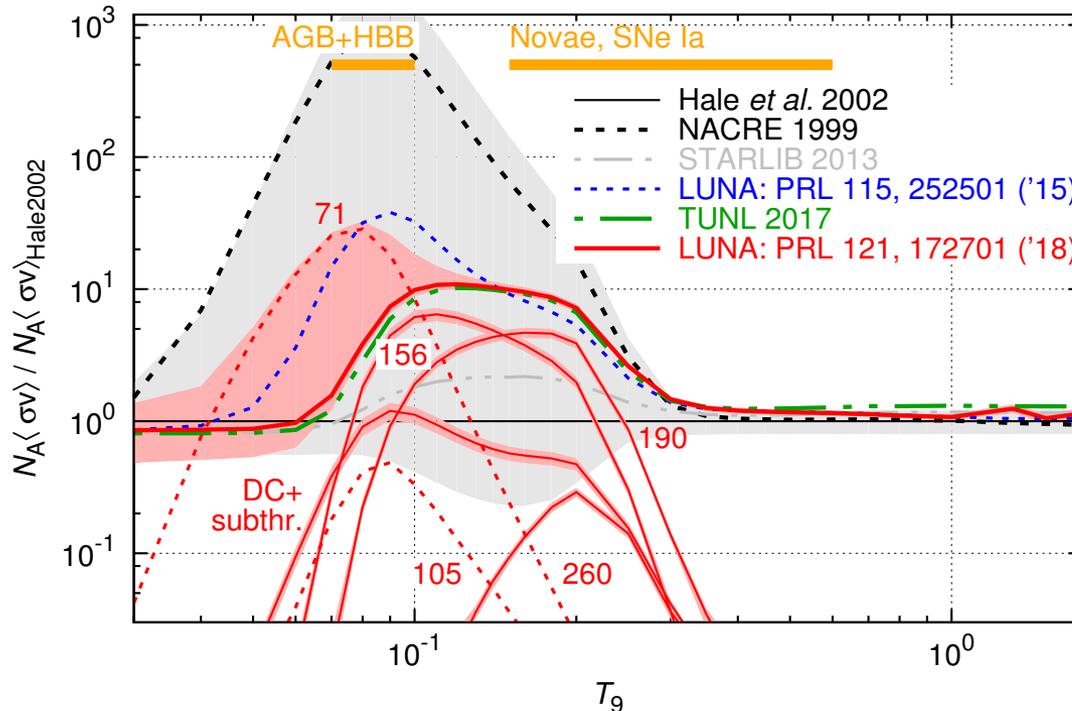
- (= Gamow peak), using
- high beam intensity
 - low background
 - great patience



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



$^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ thermonuclear reaction rate



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!

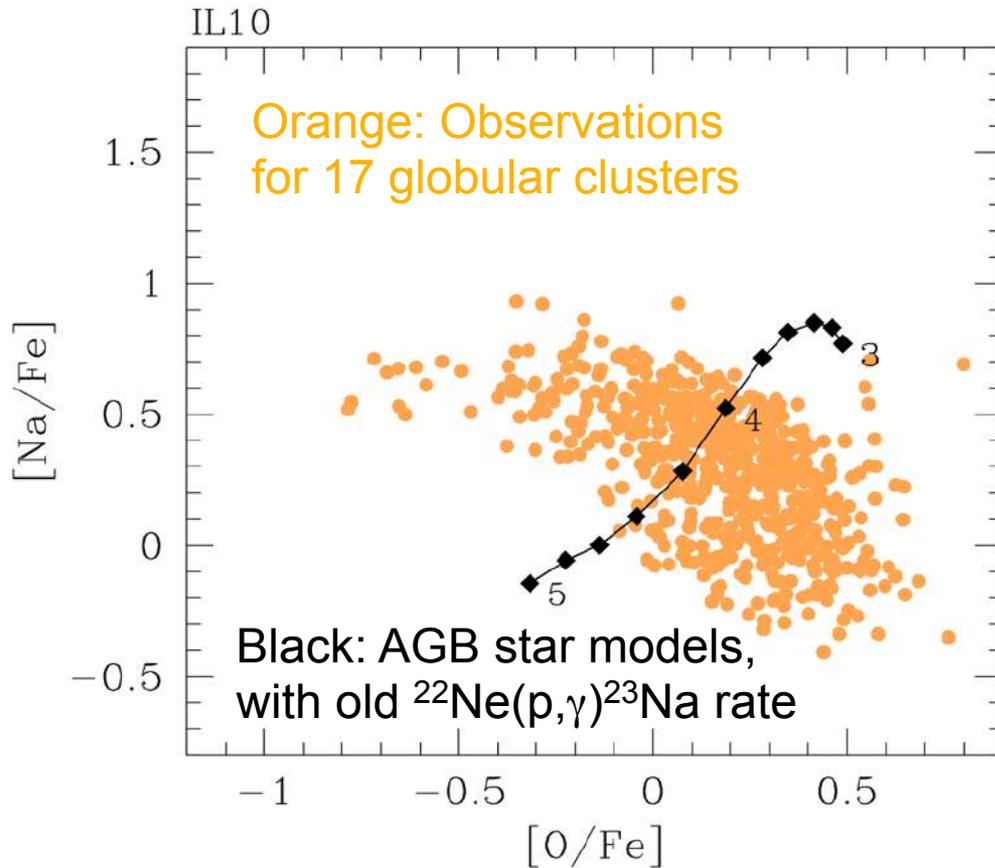
F. Ferraro *et al.* (LUNA)
Phys. Rev. Lett. 121, 172701 (2018)

Two old resonances ruled out!

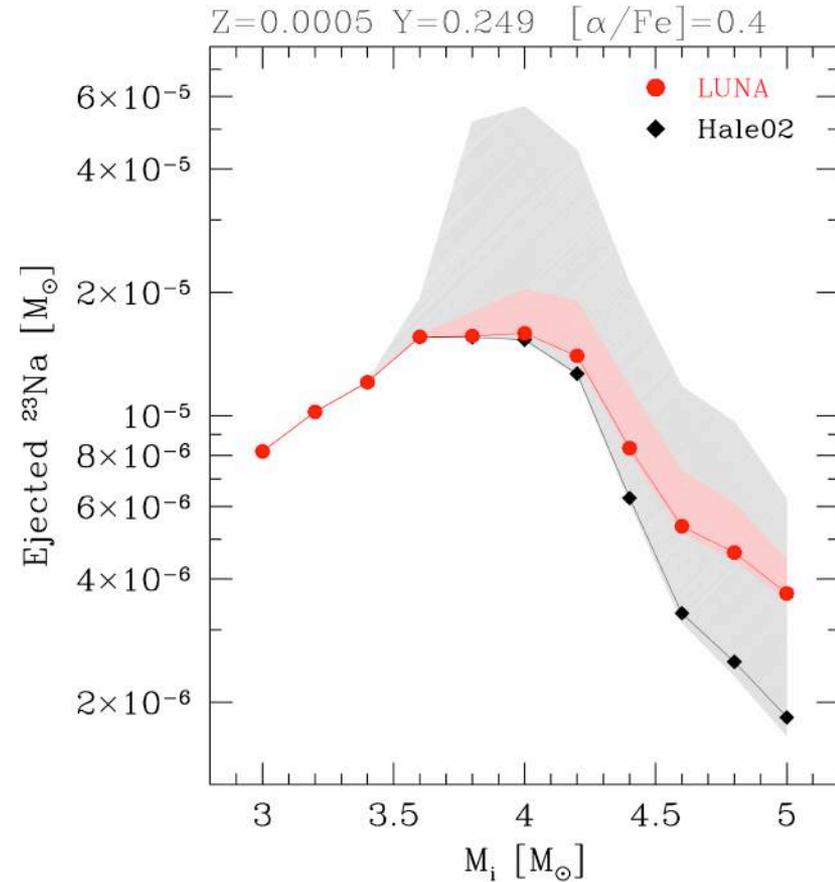
Master's project Franziska Schoger:
Higher-energy resonances



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



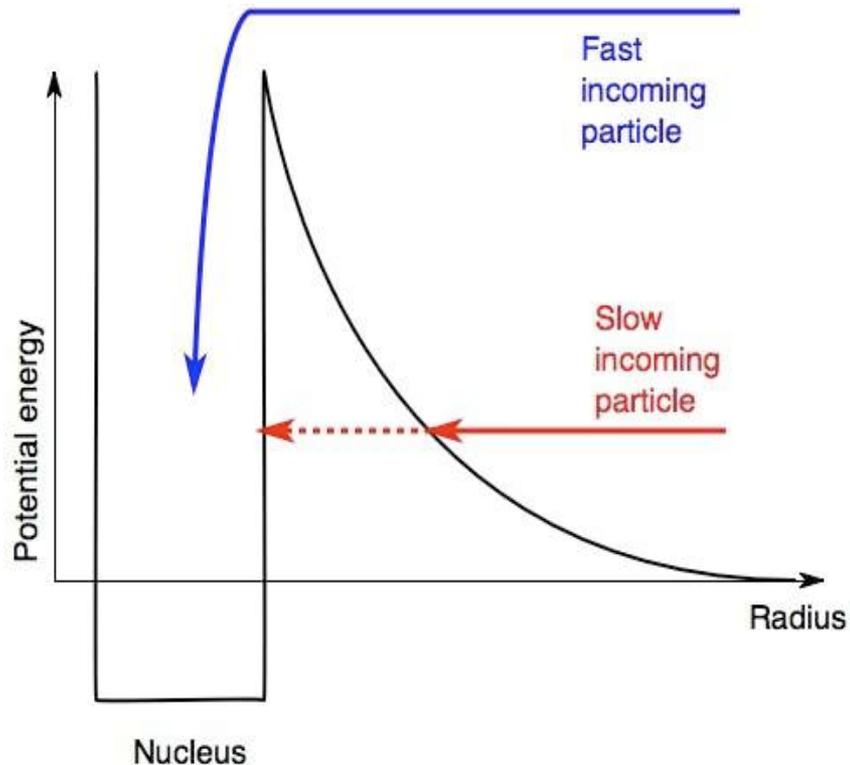
A. Slemer *et al.*,
 Mon. Not. Royal Astron. Soc.
 465, 4817 (2017)



F. Ferraro *et al.* (LUNA),
 Phys. Rev. Lett. 121, 172701
 (2018)



Nuclear reaction cross section σ for low-energy charged particles



- Typical Coulomb barrier height : \sim MeV
- Typical temperature $k_B * T \sim$ keV

→ Need quantum mechanical tunneling!



Definition of the astrophysical S-factor $S(E)$:

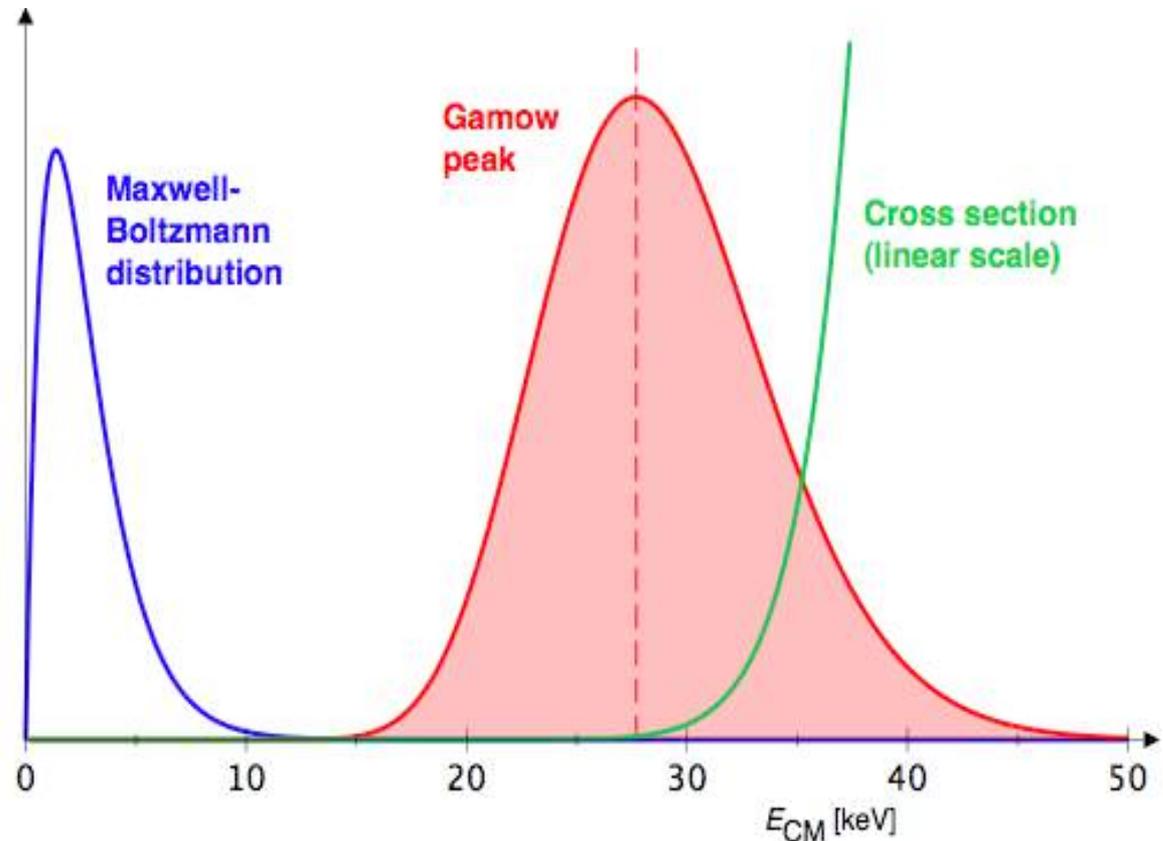
$$\sigma(E) = \frac{S(E)}{E} \exp\left(-2\pi Z_1 Z_2 \alpha \sqrt{\frac{\mu c^2}{2E}}\right)$$

At which energies do the reactions take place in a plasma?

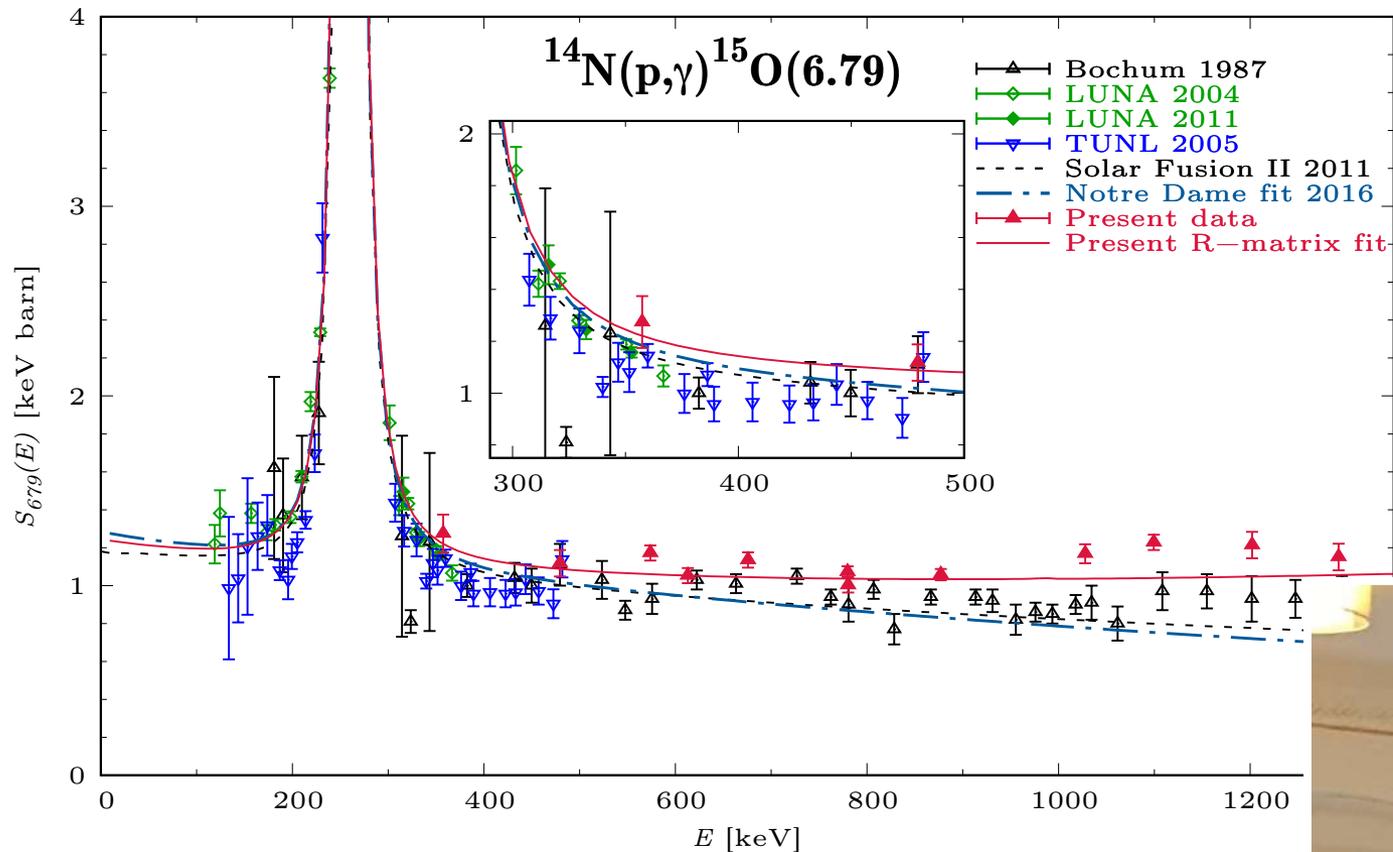
$$N_A \langle \sigma v \rangle = N_A \sqrt{\frac{8}{\mu\pi}} (k_B T)^{-\frac{3}{2}} \mathbf{S(E)} \int_0^\infty \exp \left[-\frac{b}{\sqrt{E}} - \frac{E}{k_B T} \right] dE$$

Thermonuclear
reaction rate

Aim for the
astrophysical
S-factor $S(E)$ at
Gamow peak
energies.



$^{14}\text{N}(p,\gamma)^{15}\text{O}$ for the CNO cycle re-studied in Dresden

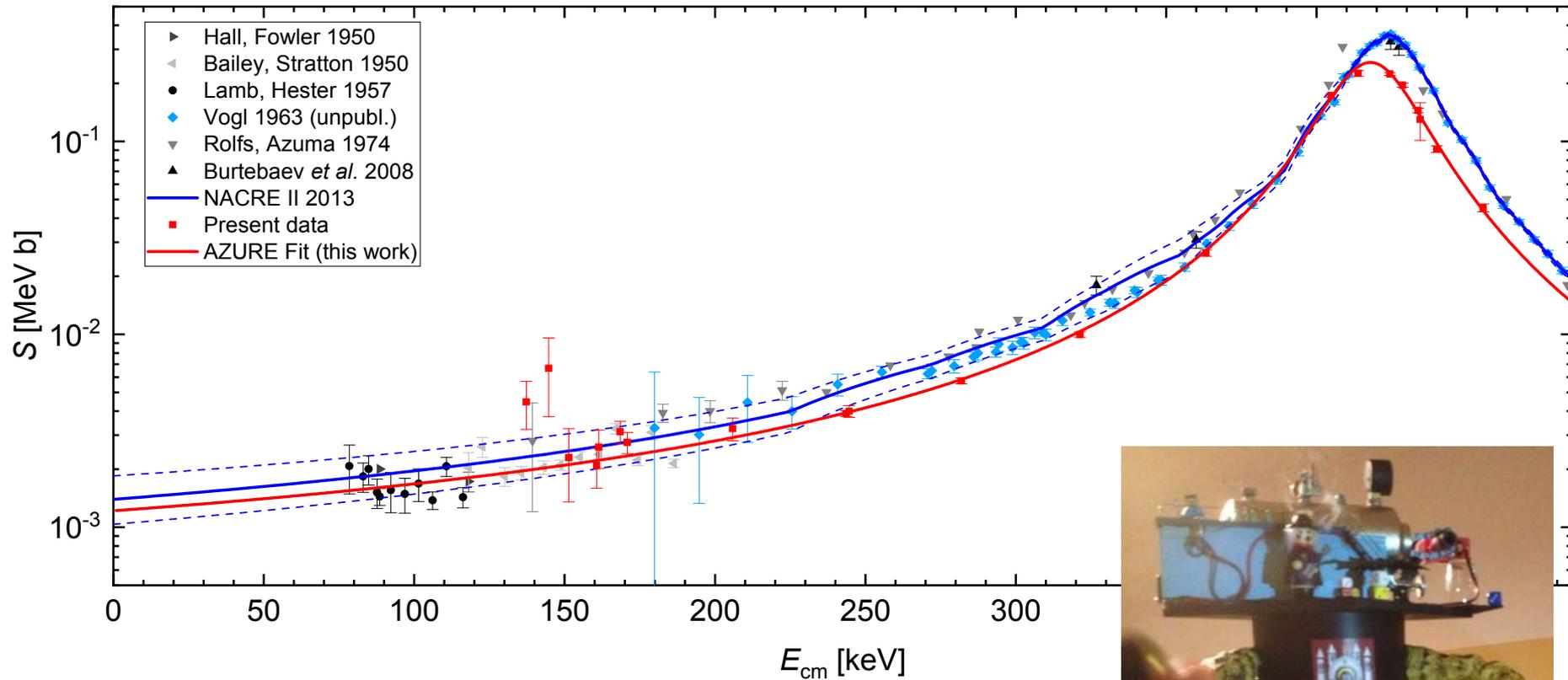


Louis Wagner *et al.*,
Phys. Rev. C 97, 015801 (2018)

Experiment at Rossendorf 3 MV Tandatron,
 $^1\text{H}^+$ beam



$^{12}\text{C}(p,\gamma)^{13}\text{N}$ for the CNO cycle re-studied in Dresden

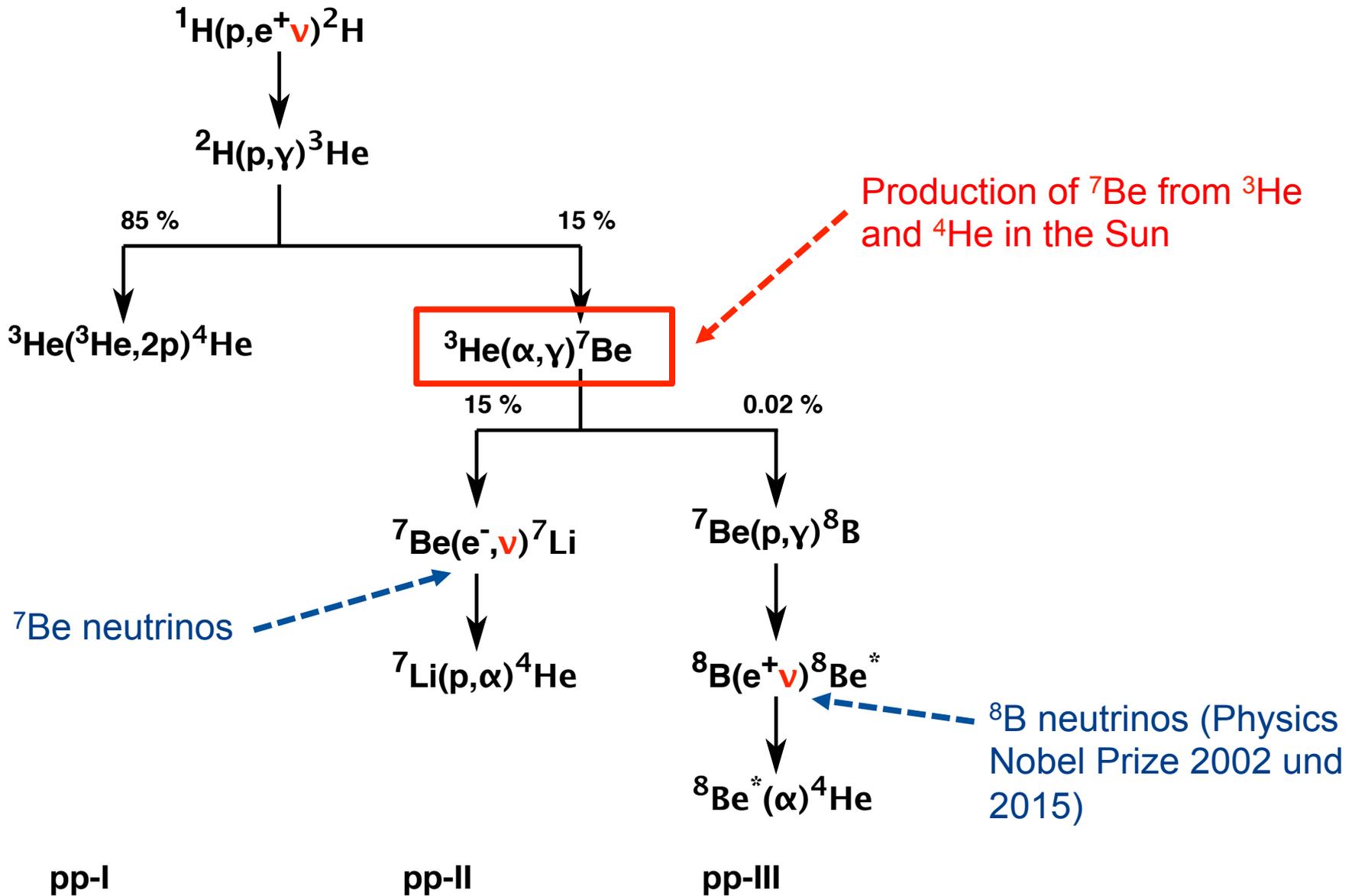


Stefan Reinicke *et al.*,
in prep.

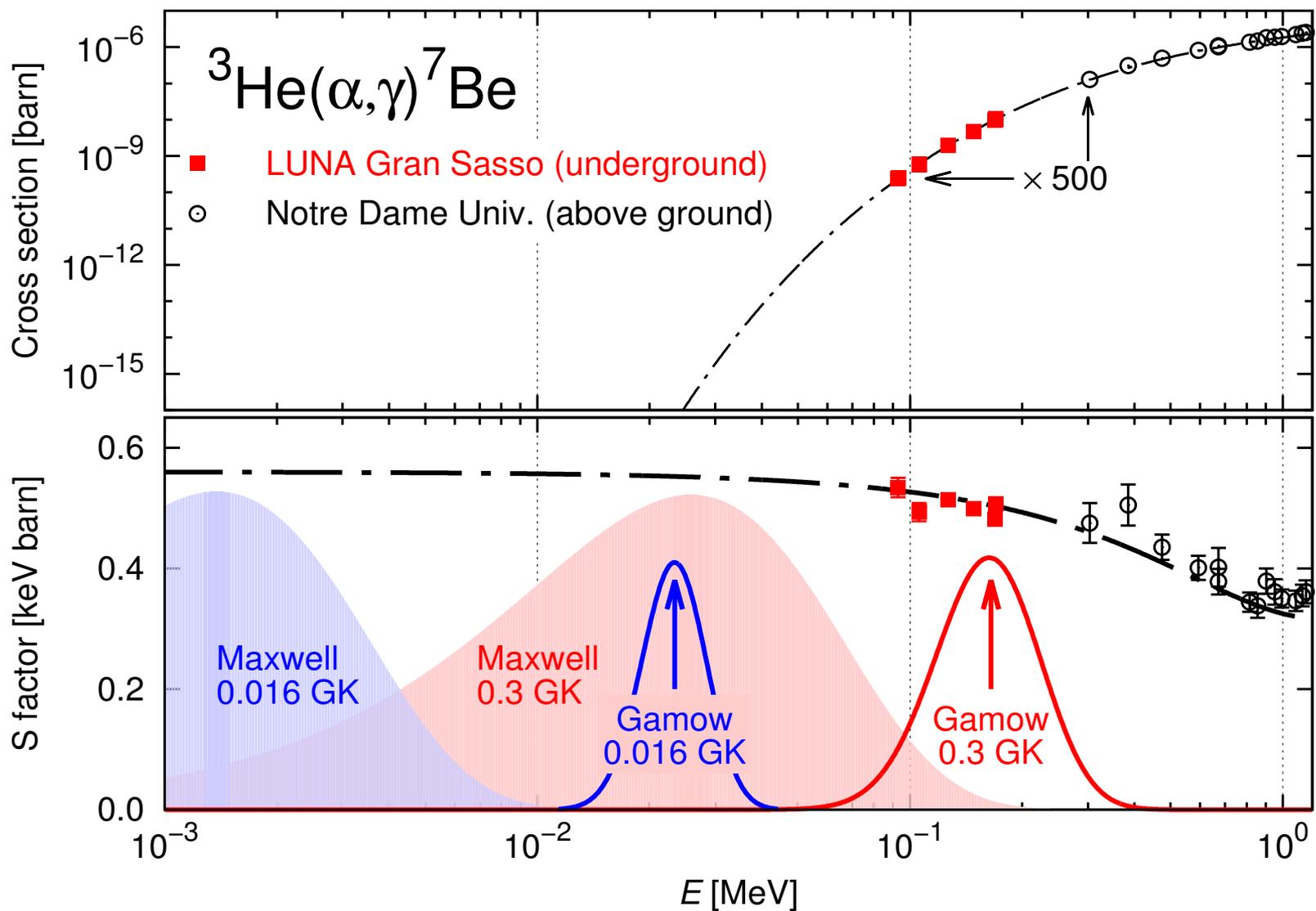
Experiment at Rossendorf 3 MV Tandetron,
 $^{12}\text{C}^{2+}$ beam



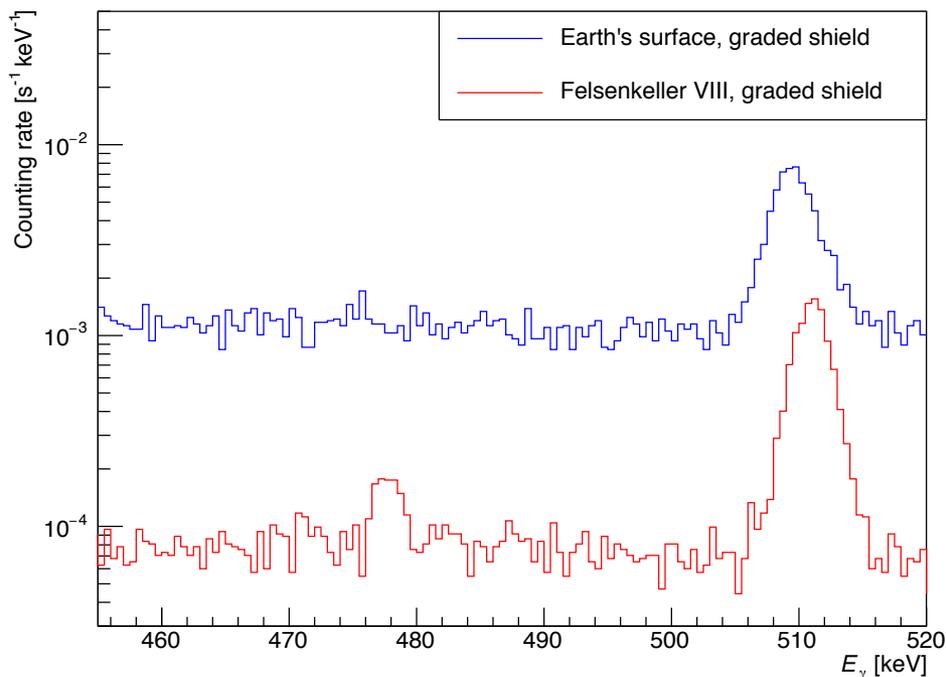
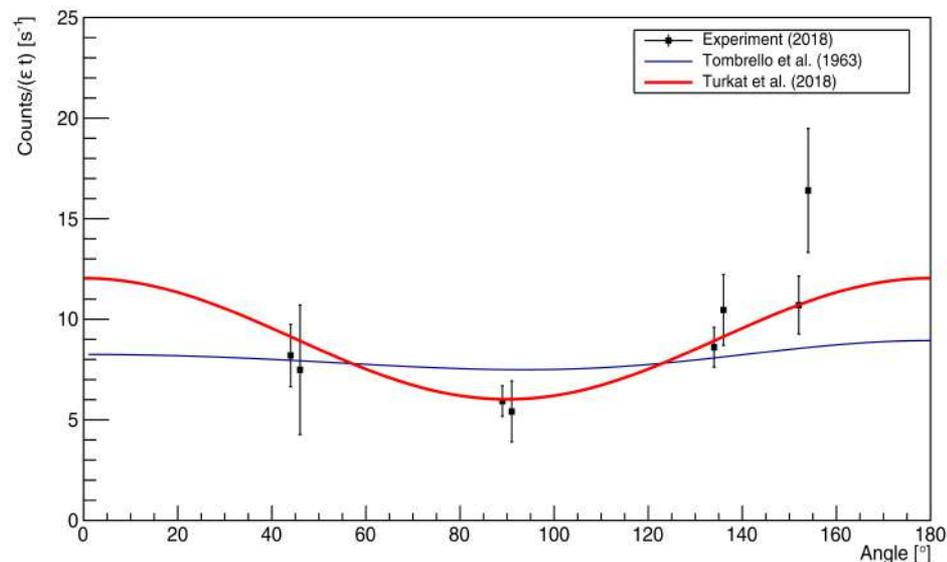
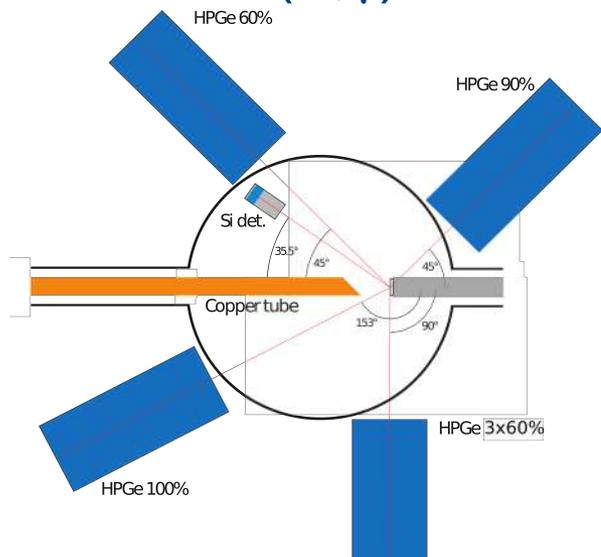
Solar fusion: Proton-proton chain



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



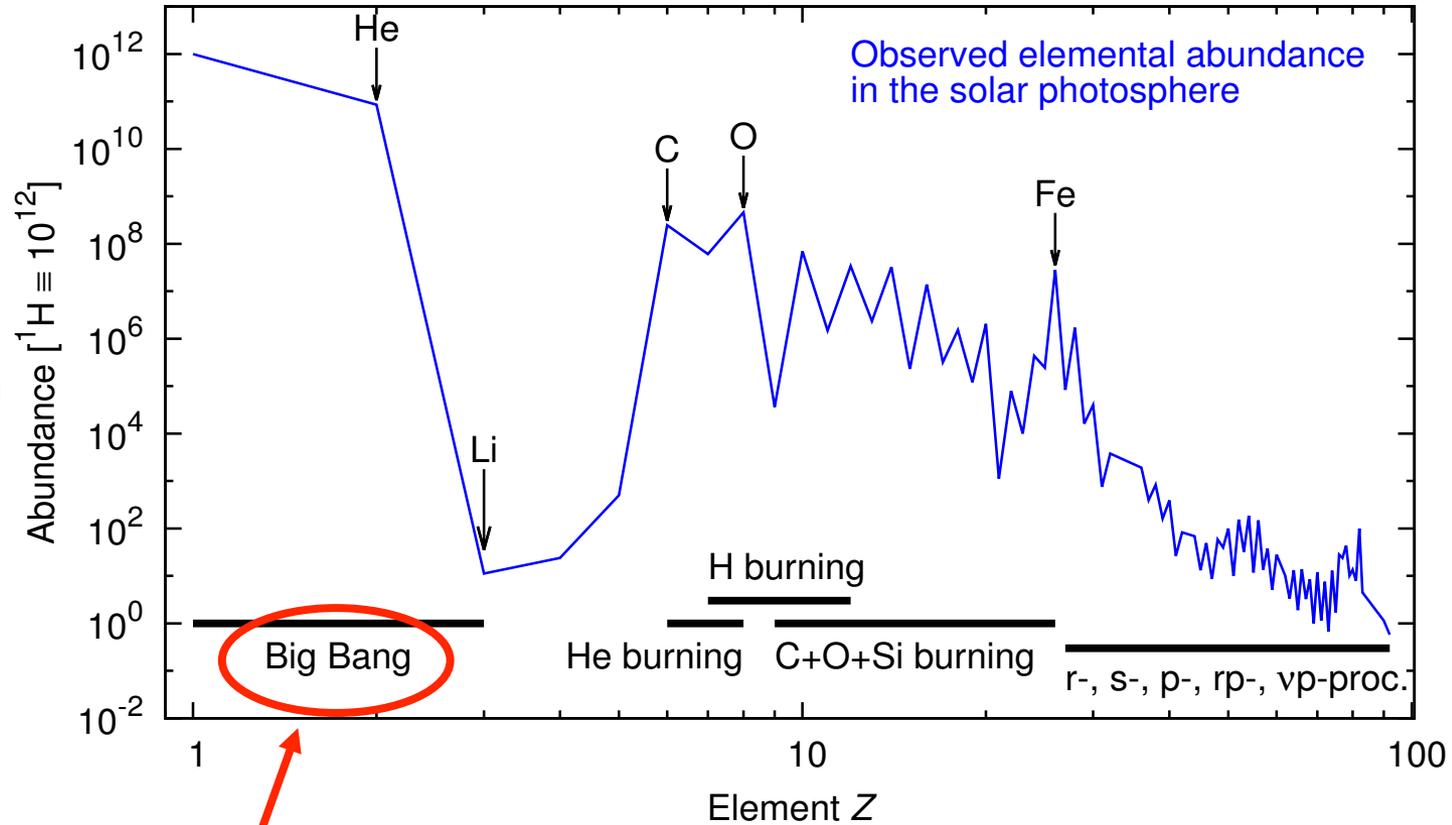
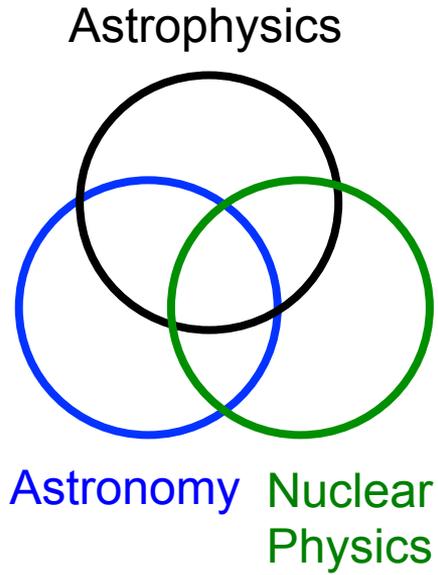
The ${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$ reaction re-studied in Dresden



PhD project Steffen Turkat
(TU Dresden)

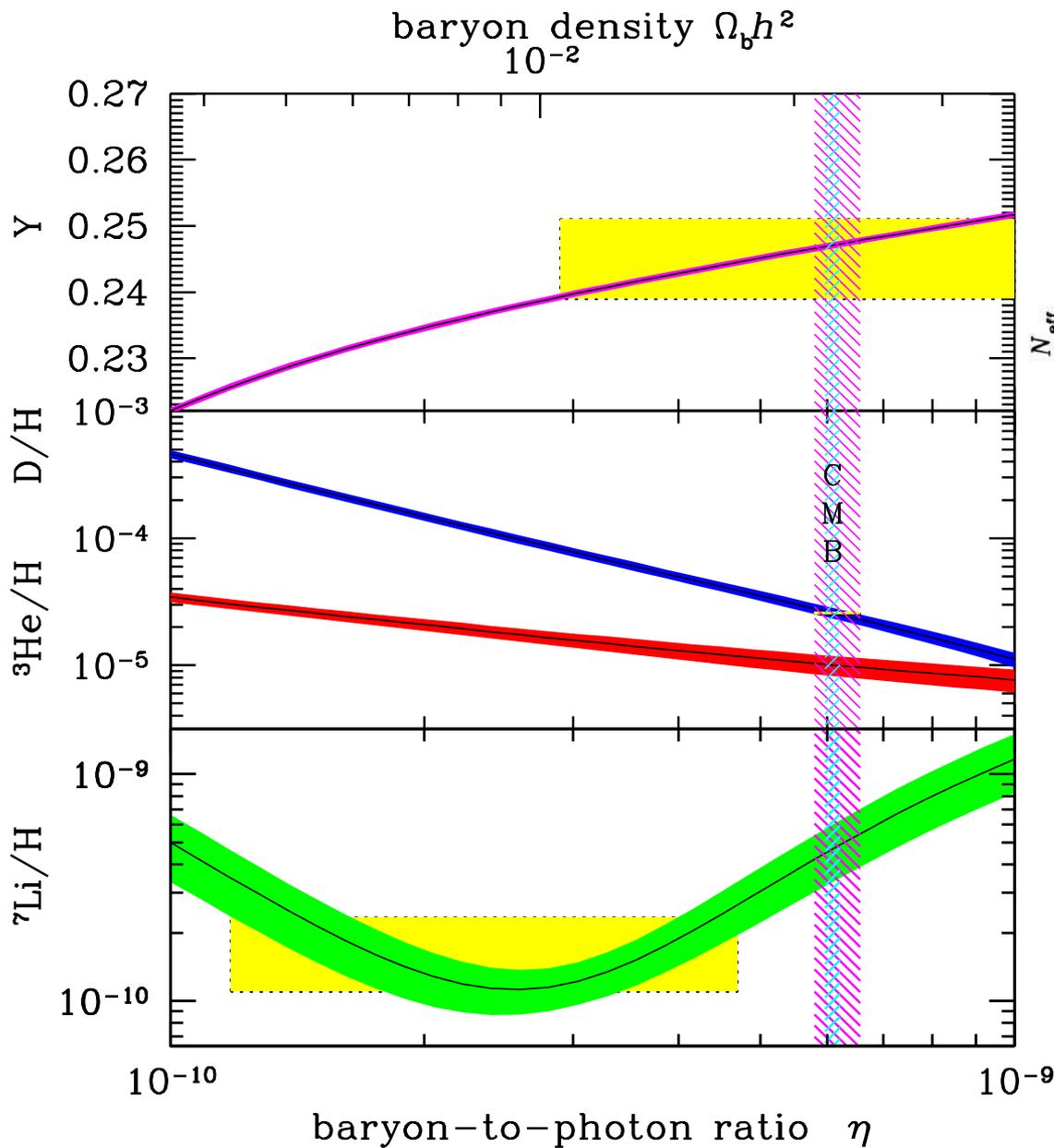
Experiment at Rossendorf 3 MV
Tandetron, ${}^4\text{He}^+$ beam,
and Felsenkeller HPGe detector

Nuclear Astrophysics: The production of the chemical elements



Cosmology

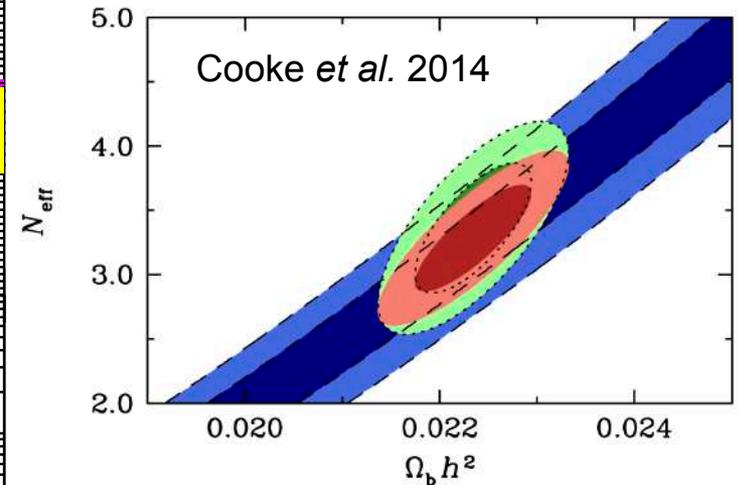
Cosmology and ^2H



Blue band: ^2H

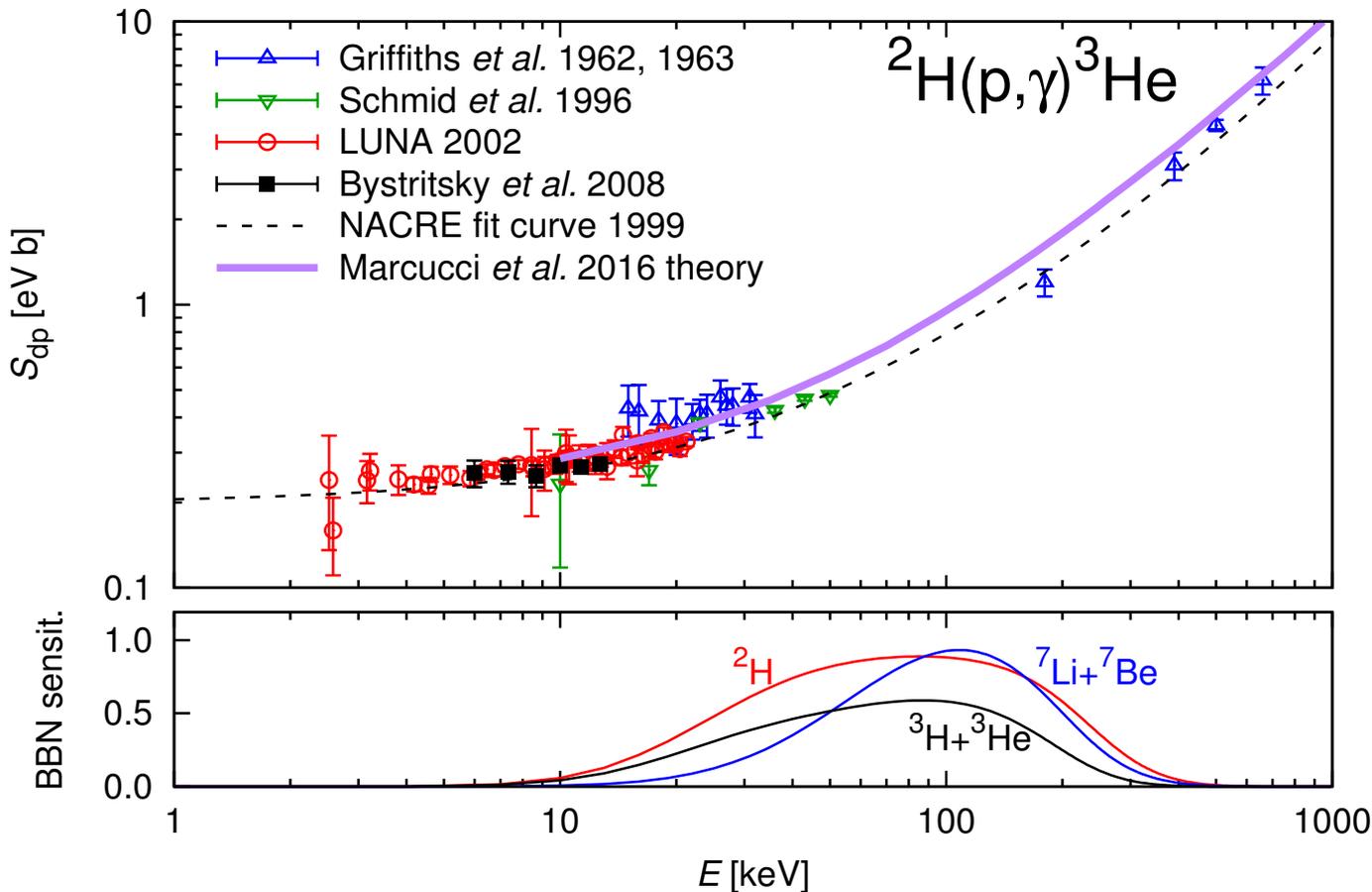
Green circle: CMB (Planck 2015)

Red circle: ^2H and CMB combined



1. Measurement of primordial ^2H abundance to $\sim 1\%$ (R. Cooke 2014 ff.)
2. Predicted ^2H abundance limited by nuclear physics of the $^2\text{H}(p,\gamma)^3\text{He}$ reaction.

Cosmology and ^2H



Master's project
Conrad Möckel
(BBN theory)

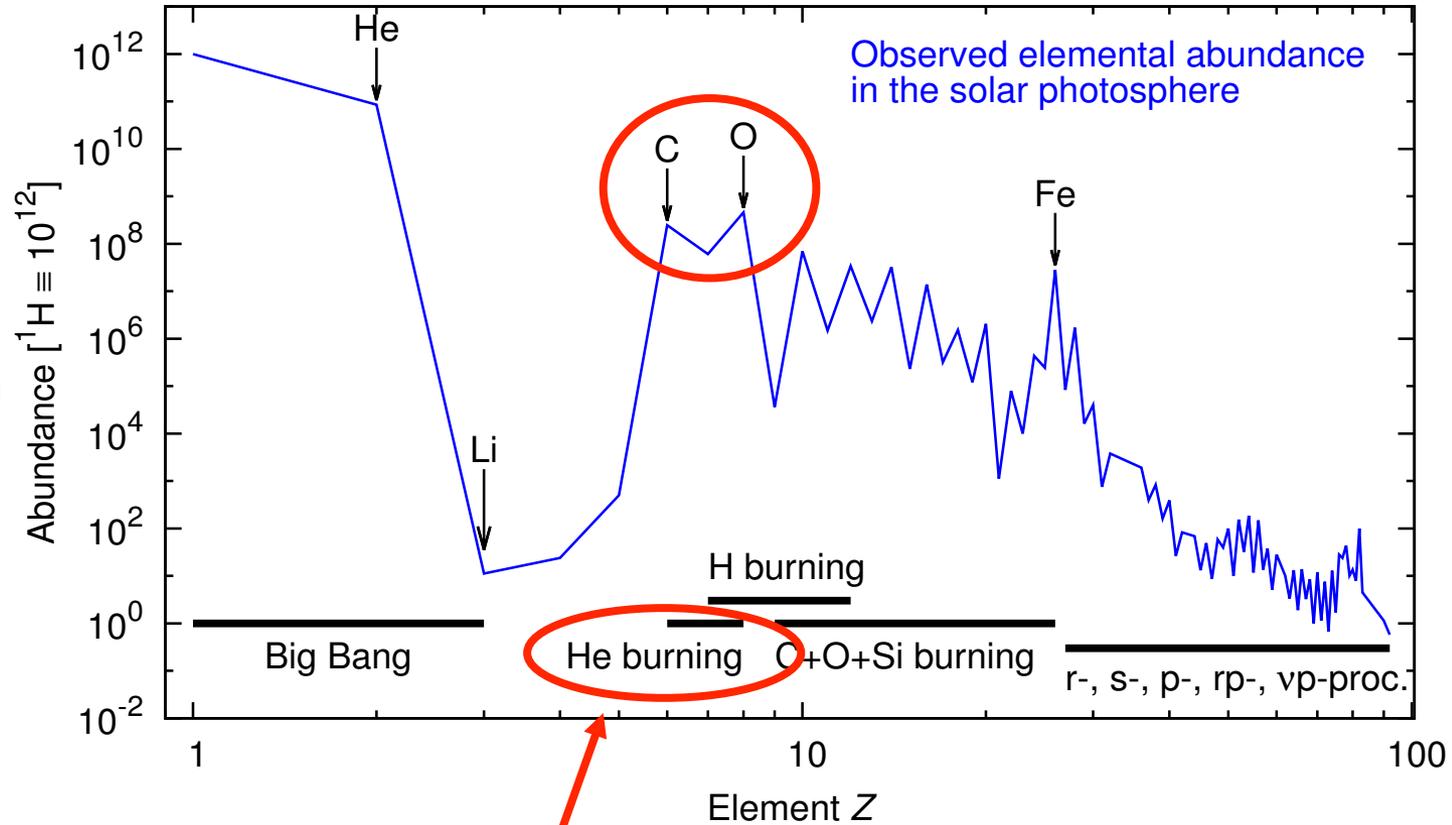
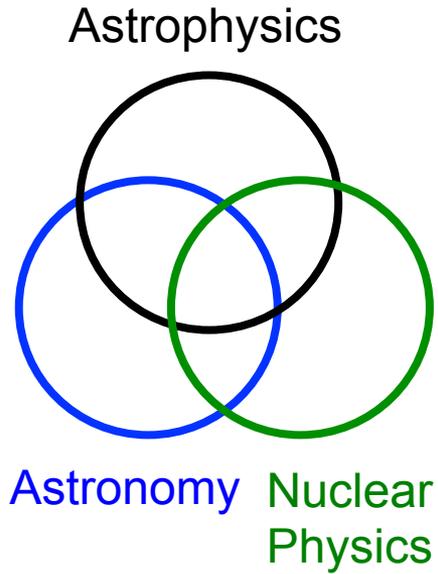


PhD project Klaus Stöckel
(HZDR & TU Dresden)
@ LUNA Italy

Master's project
Sebastian Hammer
@ Rossendorf 3 MV

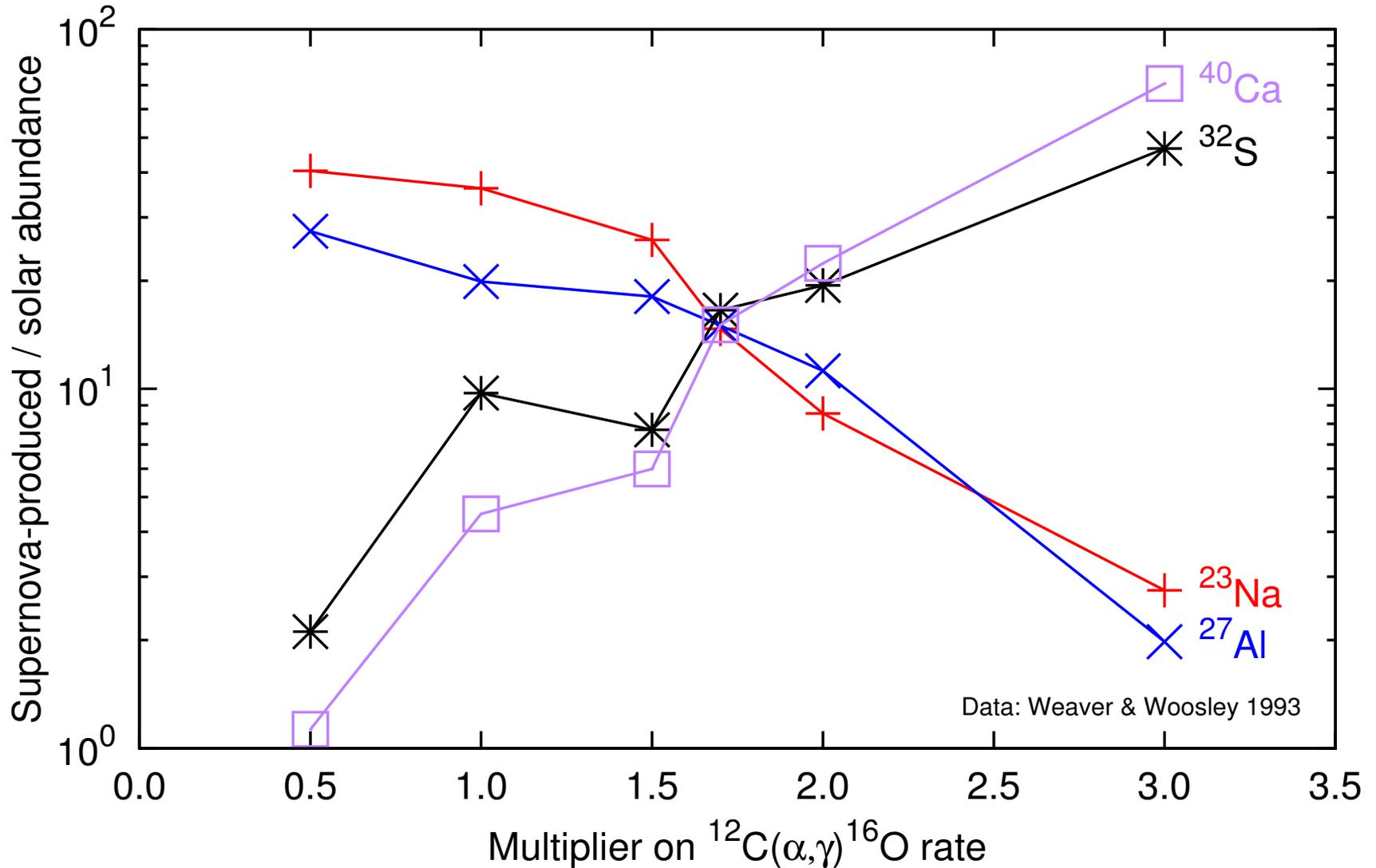


Nuclear Astrophysics: The production of the chemical elements

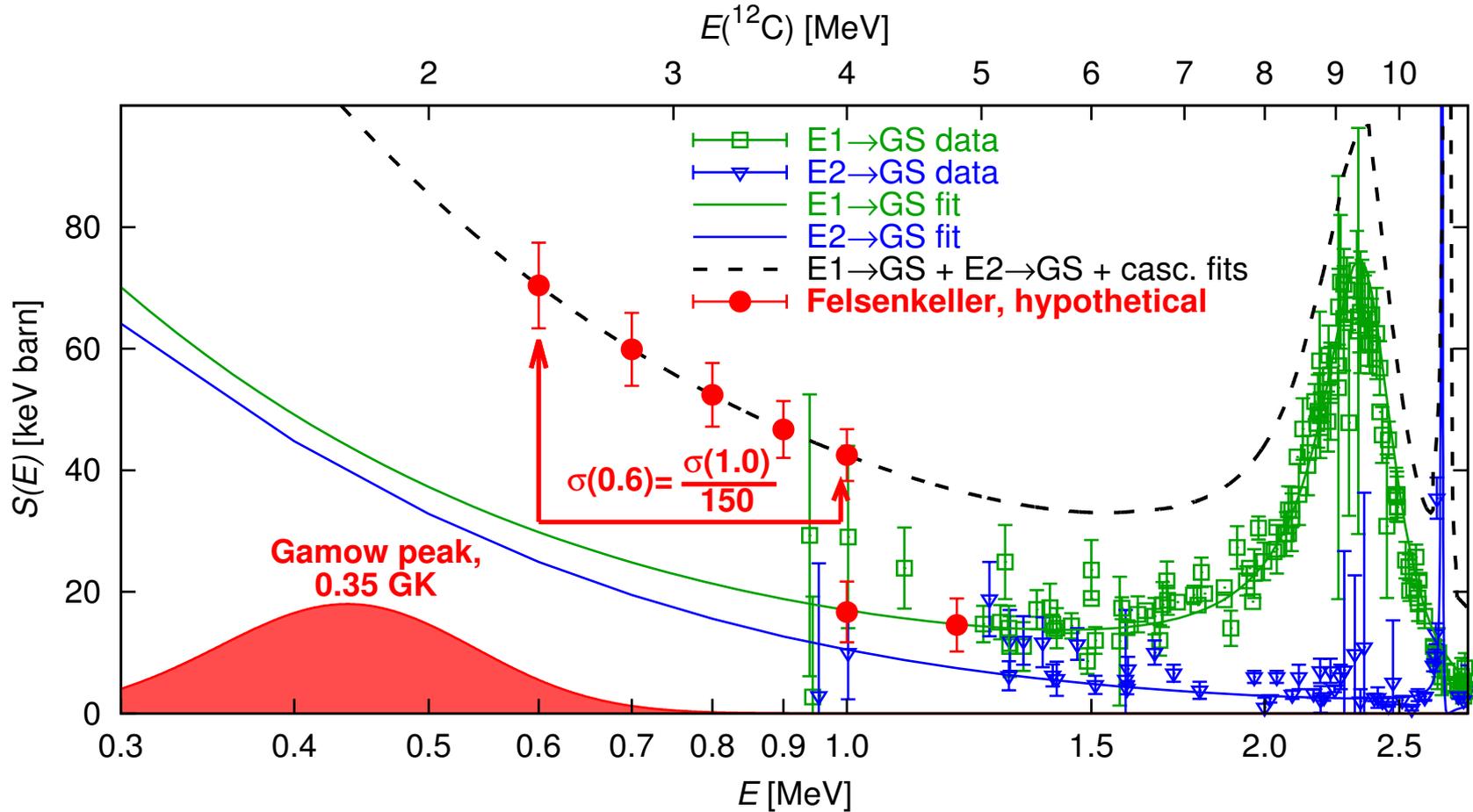


Building blocks for all elements beyond carbon

The $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ rate affects the production of many elements!

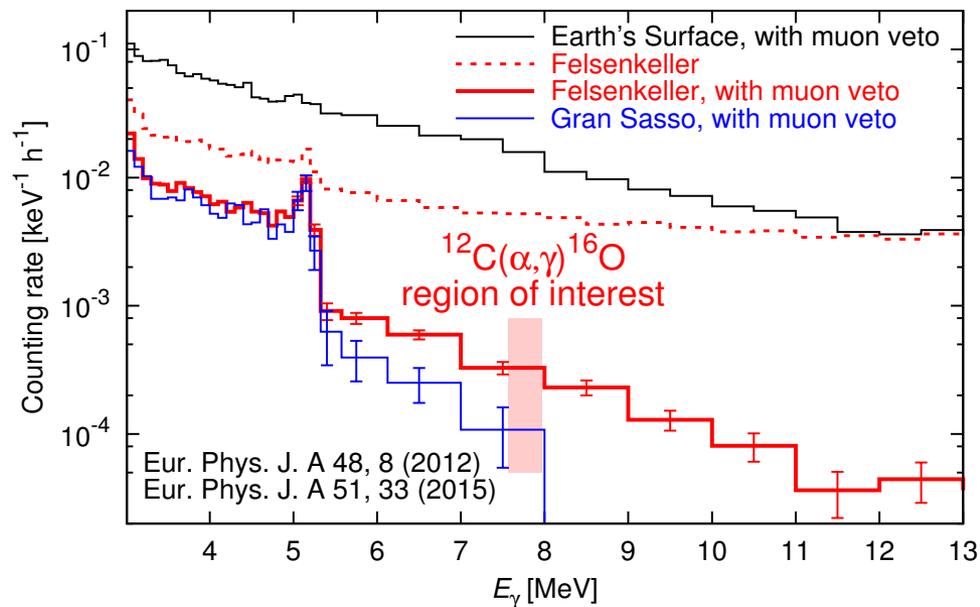
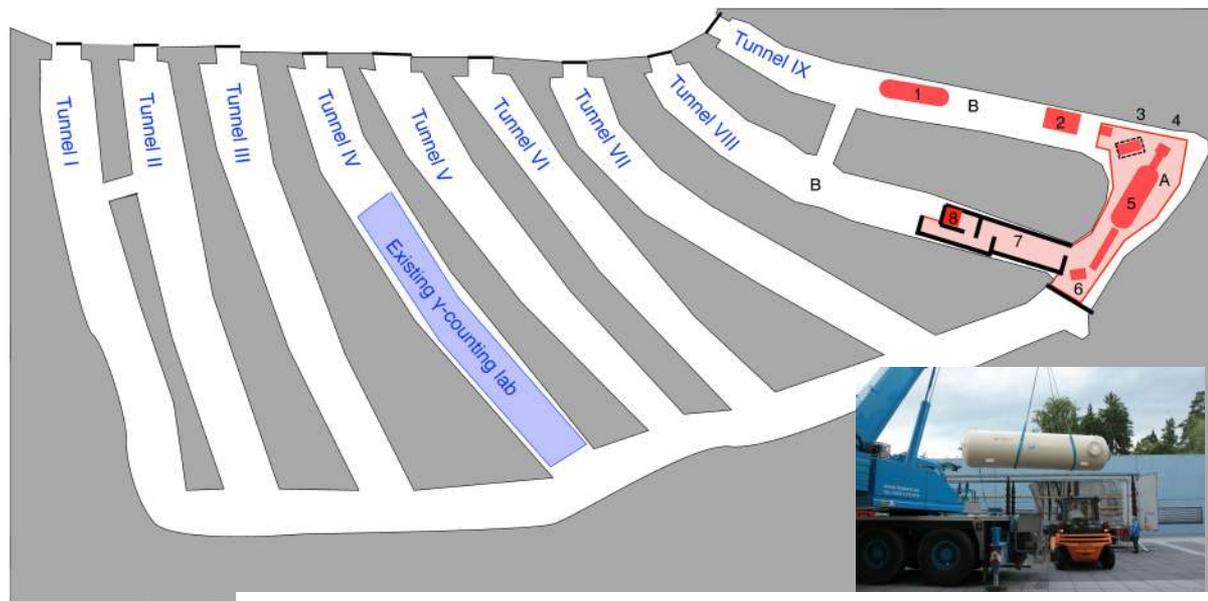


State of the art on $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ and potential for Felsenkeller... ...using 50 μA $^{12}\text{C}^+$ beam, windowless gas target, γ -calorimeter



New underground ion beam at Felsenkeller, Dresden

- ◆ System of nine tunnels built for Felsenkeller brewery in 1856-59
- ◆ 5 MV Pelletron ion accelerator for ^1H , ^4He , ^{12}C beams
- ◆ Combination of μ attenuation by 45 m rock and active μ veto



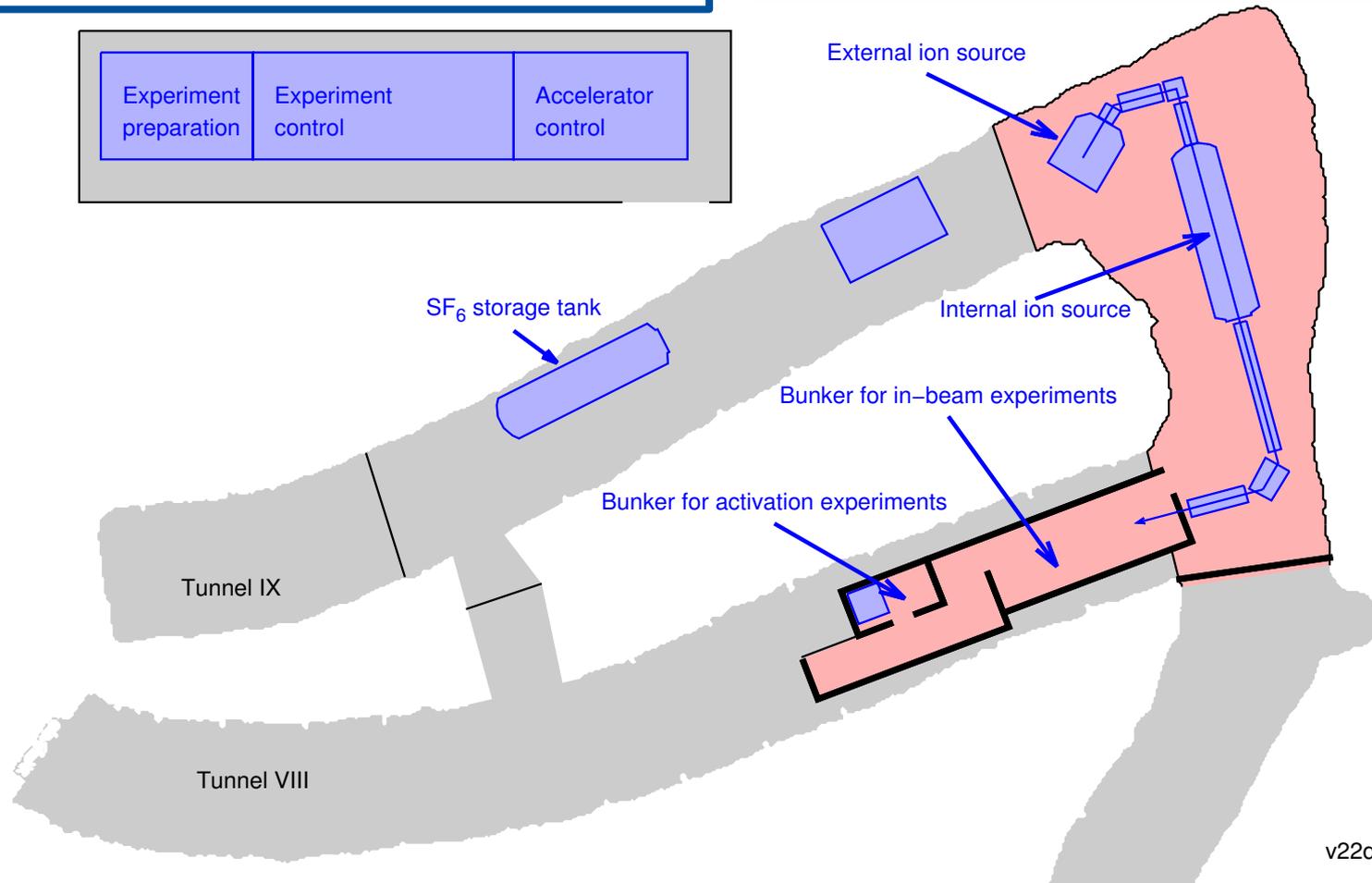
Installations in Felsenkeller, Dresden

Joint effort HZDR – TU Dresden

- ◆ Investment by TU Dresden (Kai Zuber *et al.*) and HZDR (Daniel Bemmerer *et al.*)
- ◆ Running cost covered by HZDR
- ◆ Engineering and technical staff by HZDR

Two main new instruments

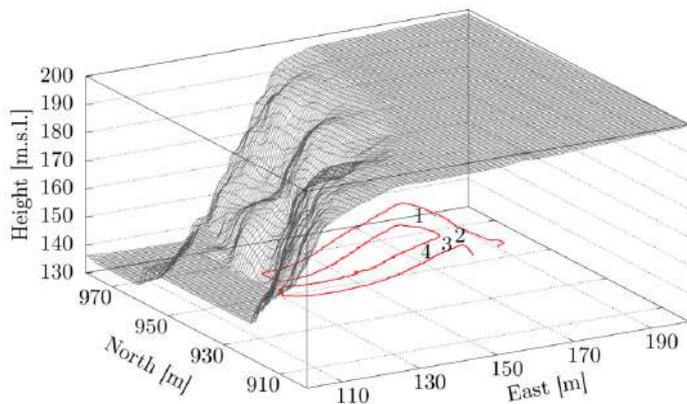
- ◆ **HZDR:** 5 MV Pelletron, 50 μA beams of $^1\text{H}^+$, $^4\text{He}^+$ (single-ended), $^{12}\text{C}^+$ (tandem)
- ◆ **TU Dresden:** 150% ultra-low-background HPGe detector for offline γ -counting



v22d

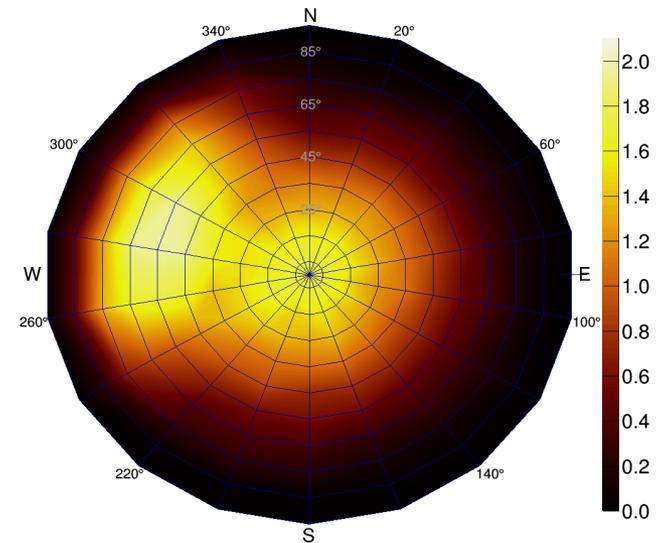
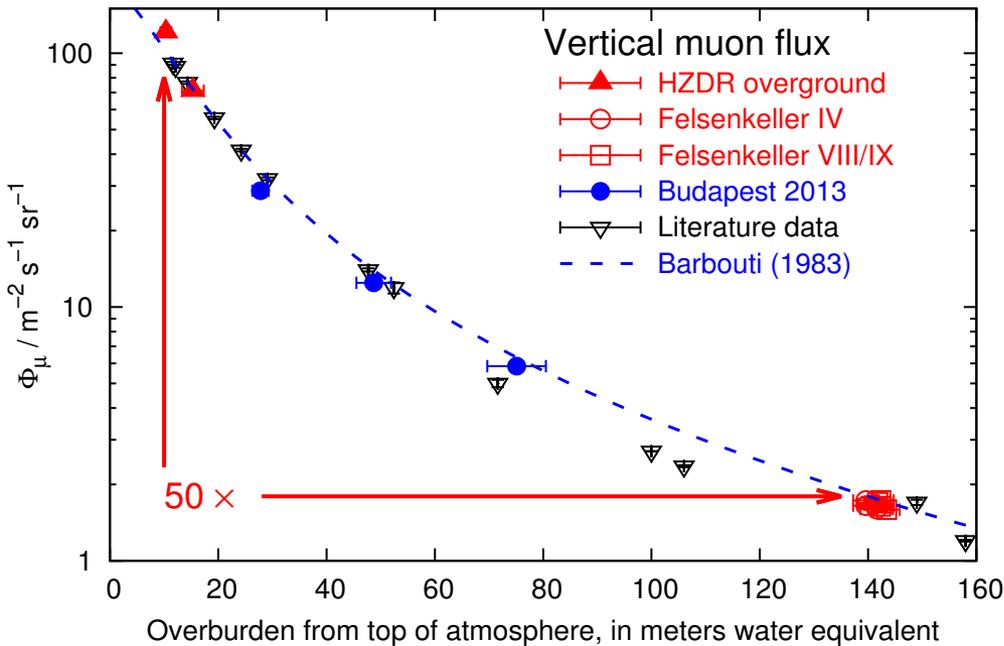


Felsenkeller, muon flux measurement



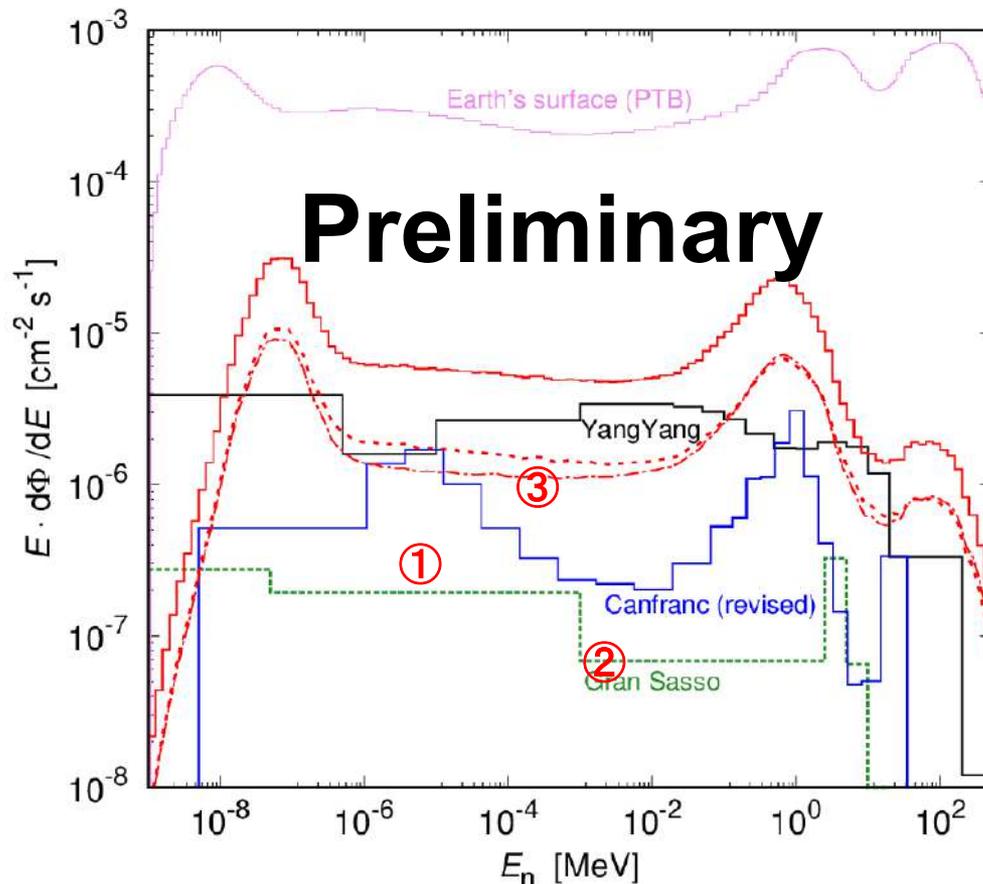
- ◆ Detailed map of μ flux shows strong attenuation
- ◆ Data matched by GEANT4 Monte Carlo simulation using the known terrain features

PhD project Felix Ludwig
(HZDR & TU Dresden)



Felsenkeller, neutron flux measurement

- ◆ 180 × lower neutron flux than at the Earth's surface
- ◆ Neutron data informed the construction project

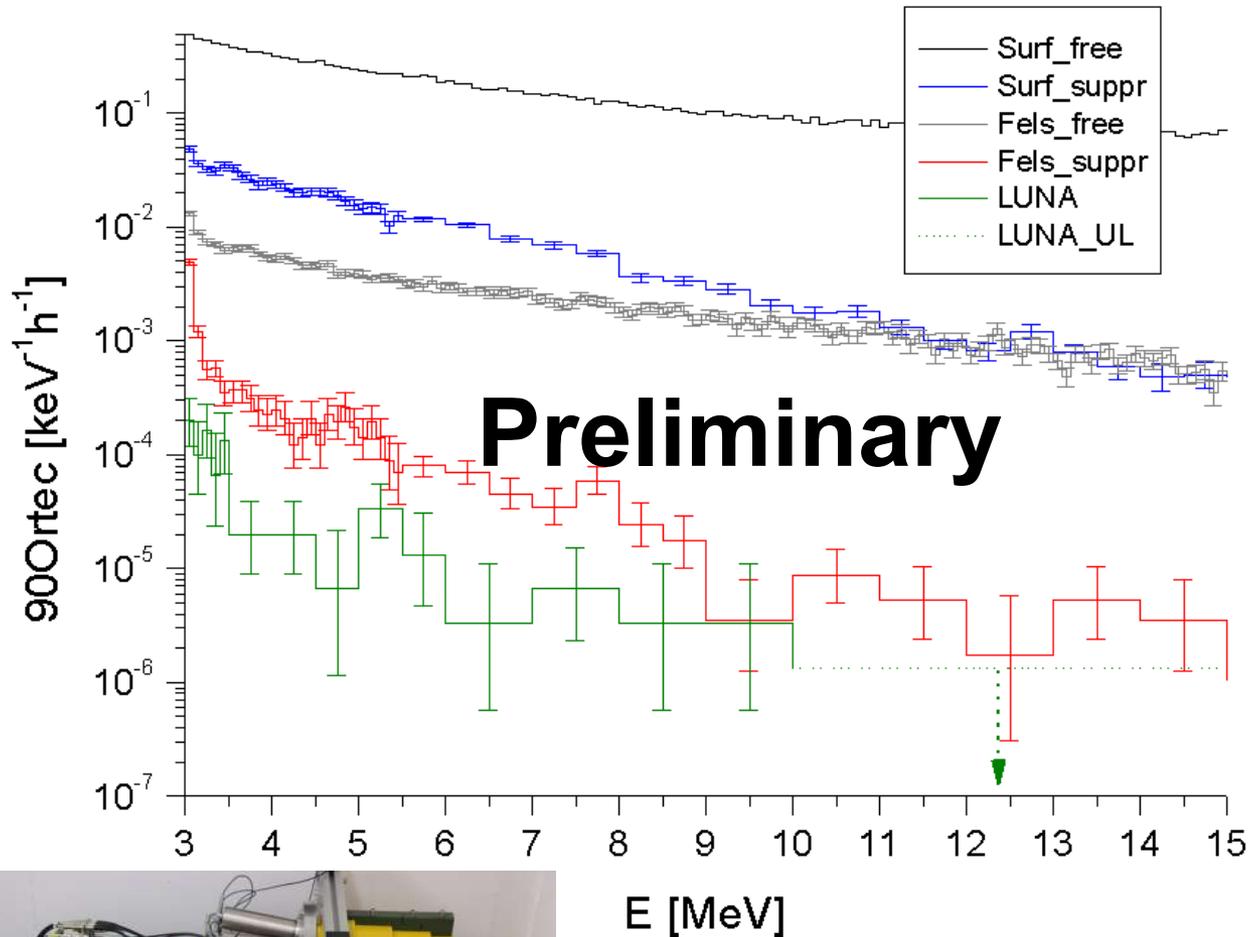


Location	Φ_n [$10^{-4} \text{cm}^{-2} \text{s}^{-1}$]
① Irradiation chamber	0.64 ± 0.06
② Activation bunker	0.72 ± 0.07
③ Technical room	2.3 ± 0.2
Overground	120

PhD project Marcel Grieger
(HZDR & TU Dresden)

Master's project Thomas Hensel

γ -background in Felsenkeller and deep underground



Postdoc project
Dr. Tamás Szücs
(HZDR)



5 MV Pelletron ion accelerator in York/UK, 1999-2012



National Electrostatics (NEC) tandem

- ◆ Second-hand machine from York/UK, was running there for ^{14}C analyses at 4.5 MV
- ◆ 5 MV acceleration potential
- ◆ Double pellet chains, 300 μA upcharge current
- ◆ Radio-frequency ion source added on the high voltage terminal



5 MV Pelletron tank inside Felsenkeller, 2017

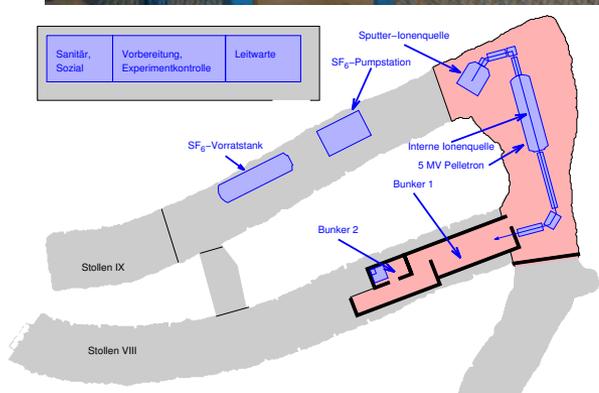
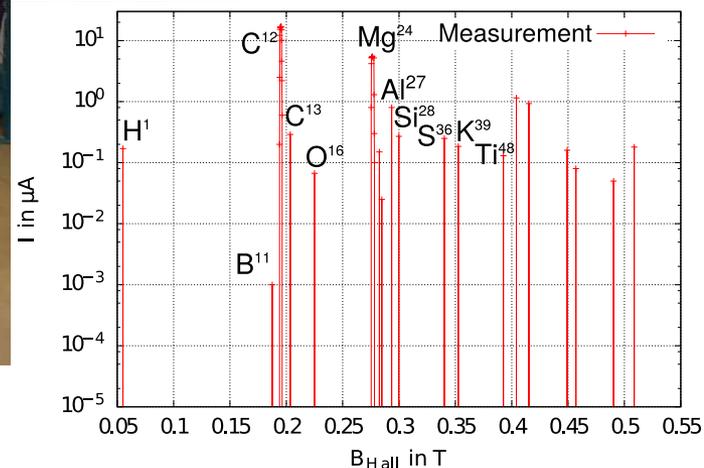


Photo: HZDR/O. Killig

External (=sputter) ion source for ^{12}C beam

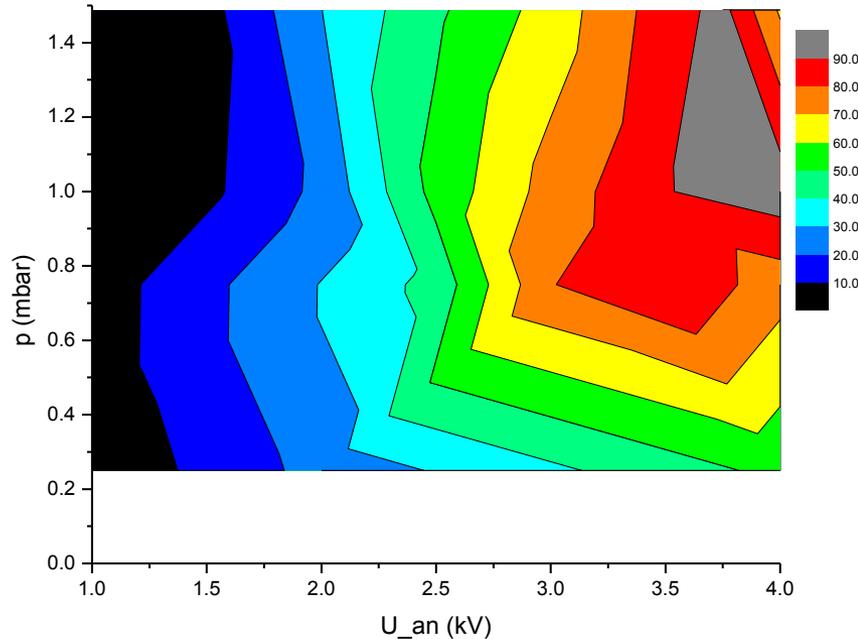
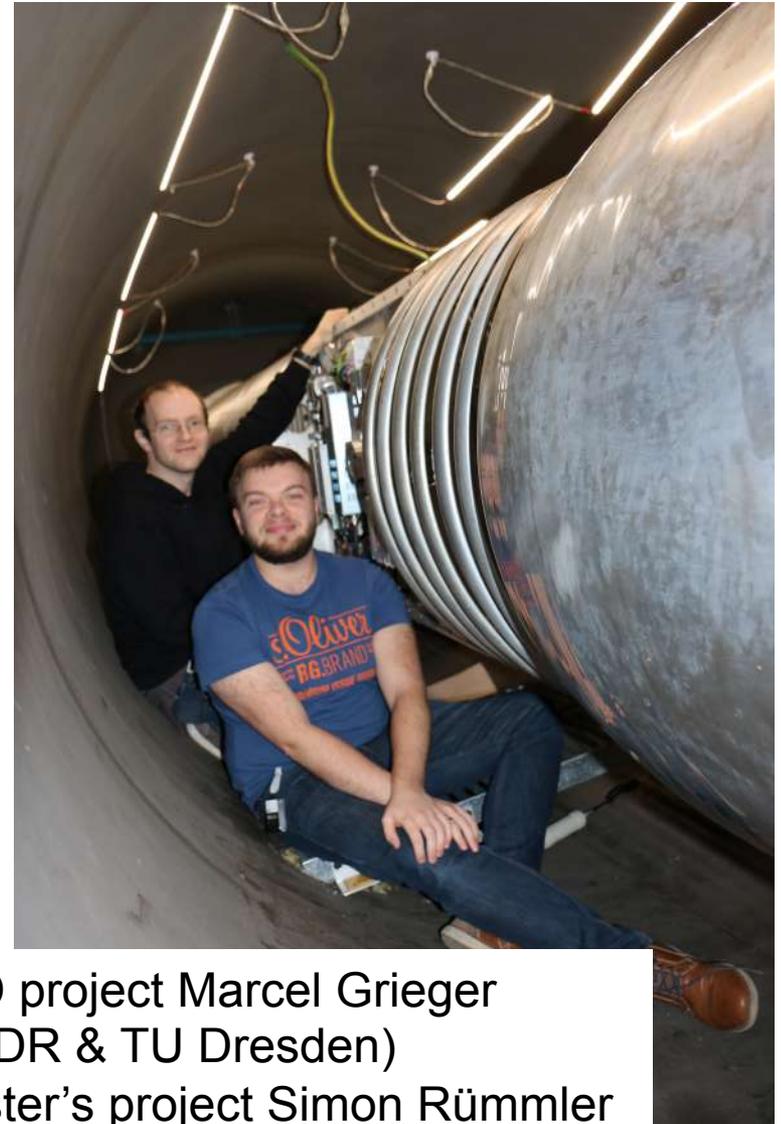
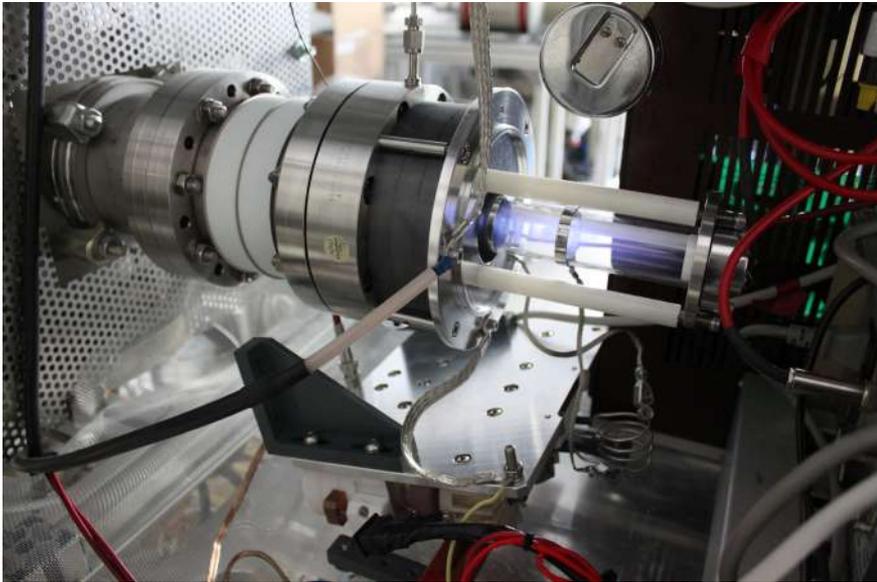


Cesium sputter ion source produces intensive ^{12}C - beam: 100 μA after the source



PhD project Felix Ludwig (HZDR & TU Dresden)
Bachelor's project Julia Steckling

Internal (=radio frequency) ion source for ^1H , ^4He beams



PhD project Marcel Grieger
(HZDR & TU Dresden)
Master's project Simon Rümmler

Felsenkeller, status of the accelerator beam lines

Low energy side

ion-source

deflector

L. E. magnet

accelerator



High energy side

accelerator

H. E. magnet

wall

target room



In-beam measurement bunker, made of low-activity concrete





- ◆ CANBERRA-Lingolsheim GX150-250R
 - ◆ Extended Range Crystal
 - ◆ Endcap: 1.6 mm ultrapure Al $\rightarrow E_{\gamma} > 15$ keV
 - ◆ Resolution $FWHM$ (1332 keV) = 1.98 keV
 $FWHM$ (121 keV) = 1.06 keV
- ◆ Passive shielding
 - ◆ 5 (+5) cm copper OFRP
 - ◆ 5 + 10 cm lead:
 - ◆ Inner layer: 5 cm (< 1.9 Bq/kg ^{210}Pb)
 - ◆ Outer layer: 10 cm (< 30 Bq/kg ^{210}Pb)
- ◆ Active shielding
 - ◆ Plastic muon veto detector
Four 100 x 100 x 6 cm³ panels

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



Work in progress

5 MV Pelletron ion accelerator

- ◆ Both ion sources work *in situ*!
- ◆ Re-commission SF₆ system
- ◆ Re-commission main accelerator
- ◆ Vacuum upgrade from cry to turbo
- ◆ Commission Labview control system

In-beam bunker and instrumentation

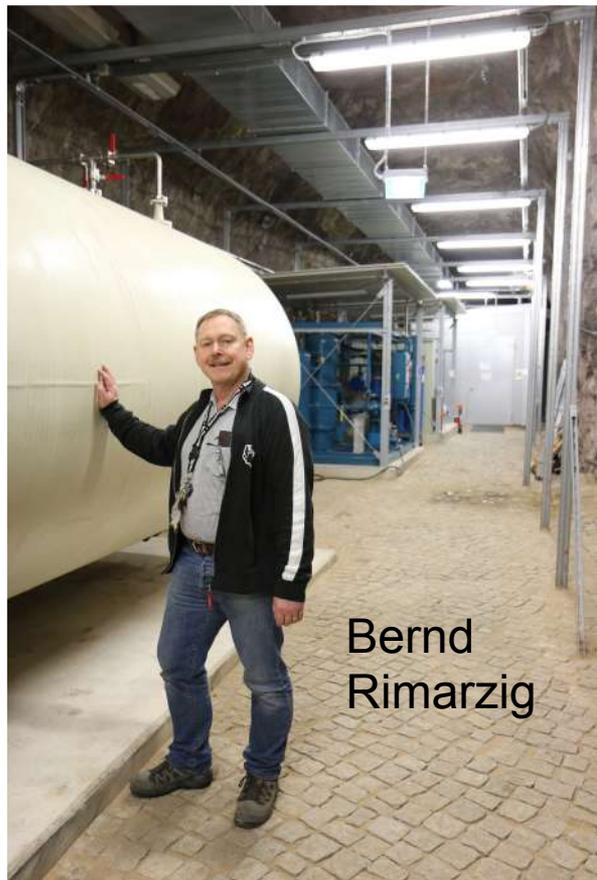
- ◆ 4 HPGe detectors available (HZDR), 10 - 30 years old
- ◆ Solid target assembly available (HZDR)
- ◆ Gas target still to be funded

Activation bunker (TU Dresden)

- ◆ Commission 150% HPGe detector
- ◆ Install 80% borehole HPGe detector



Engineering and technical staff, working on the machine



Bernd
Rimarzig



Toralf
Döring



Maik Görler

Felsenkeller, scientific user community

The accelerator will be open as a facility to any scientific users worldwide, at no cost .

User selection based on recommendations by an independent scientific advisory board

- ◆ Zsolt Fülöp (ATOMKI Debrecen / Hungary)
- ◆ Brian Fulton (University of York / UK)
- ◆ Alessandra Guglielmetti (Milano Uni and INFN / Italy)
- ◆ Jordi José (UPC Barcelona/Spain)

ENAUT collaboration (Experimentelle Nukleare Astrophysik unter Tage)

- ◆ Daniel Bemmerer (HZDR Dresden)
- ◆ Kai Zuber (TU Dresden)
- ◆ Shawn Bishop (TU München)
- ◆ René Reifarh (Uni Frankfurt)
- ◆ Andreas Zilges (Uni Köln)
- ◆ Failed BMBF-Verbundforschung project, 2017-2020 period... we will try again!

Scientific workshop and pre-opening, 26.-28.06.2017

3-day scientific workshop

- ◆ 22 talks
- ◆ 20 posters
- ◆ 58 scientific participants

Ceremonial pre-opening

- ◆ Minister of Science of Saxony State
- ◆ Physics Nobel Laureate Arthur McDonald
- ◆ 150 participants



HZDR

Acknowledgments

Postdocs

- ◆ Dr. Tamás Szücs (HZDR)
- ◆ Dr. Konrad Schmidt (TU Dresden)

PhD students

- ◆ Marcel Grieger (HZDR & TU Dresden)
- ◆ Felix Ludwig (HZDR & TU Dresden)
- ◆ Klaus Stöckel (HZDR & TU Dresden)
- ◆ Steffen Turkat (TU Dresden)

Master's students

- ◆ Sebastian Hammer
- ◆ Thomas Hensel
- ◆ Conrad Möckel
- ◆ Simon Rümmler
- ◆ Franziska Schoger

Bachelor's student

- ◆ Julia Steckling

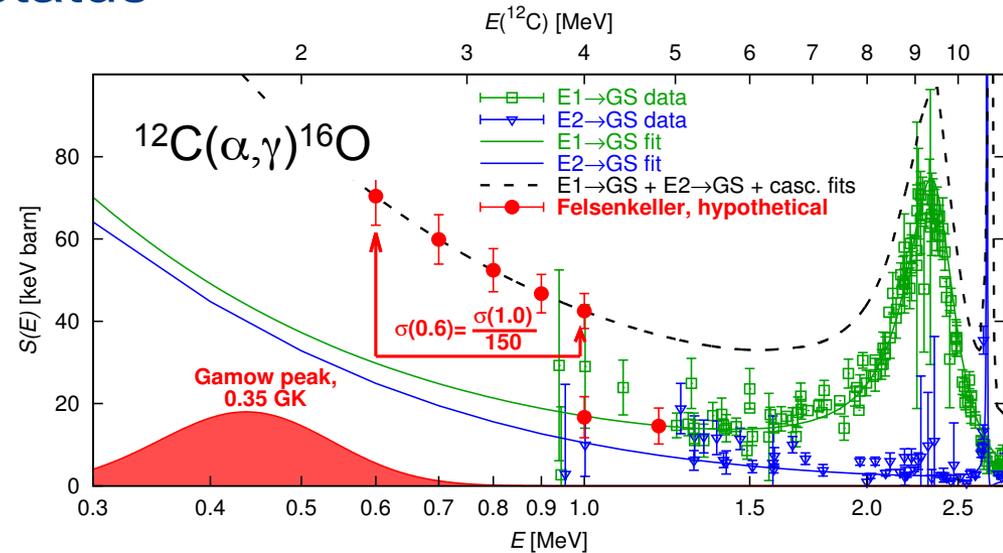
Engineering / technical support

- ◆ Dipl.-Ing. (FH) Bernd Rimarzig
- ◆ Toralf Döring
- ◆ Maik Görler



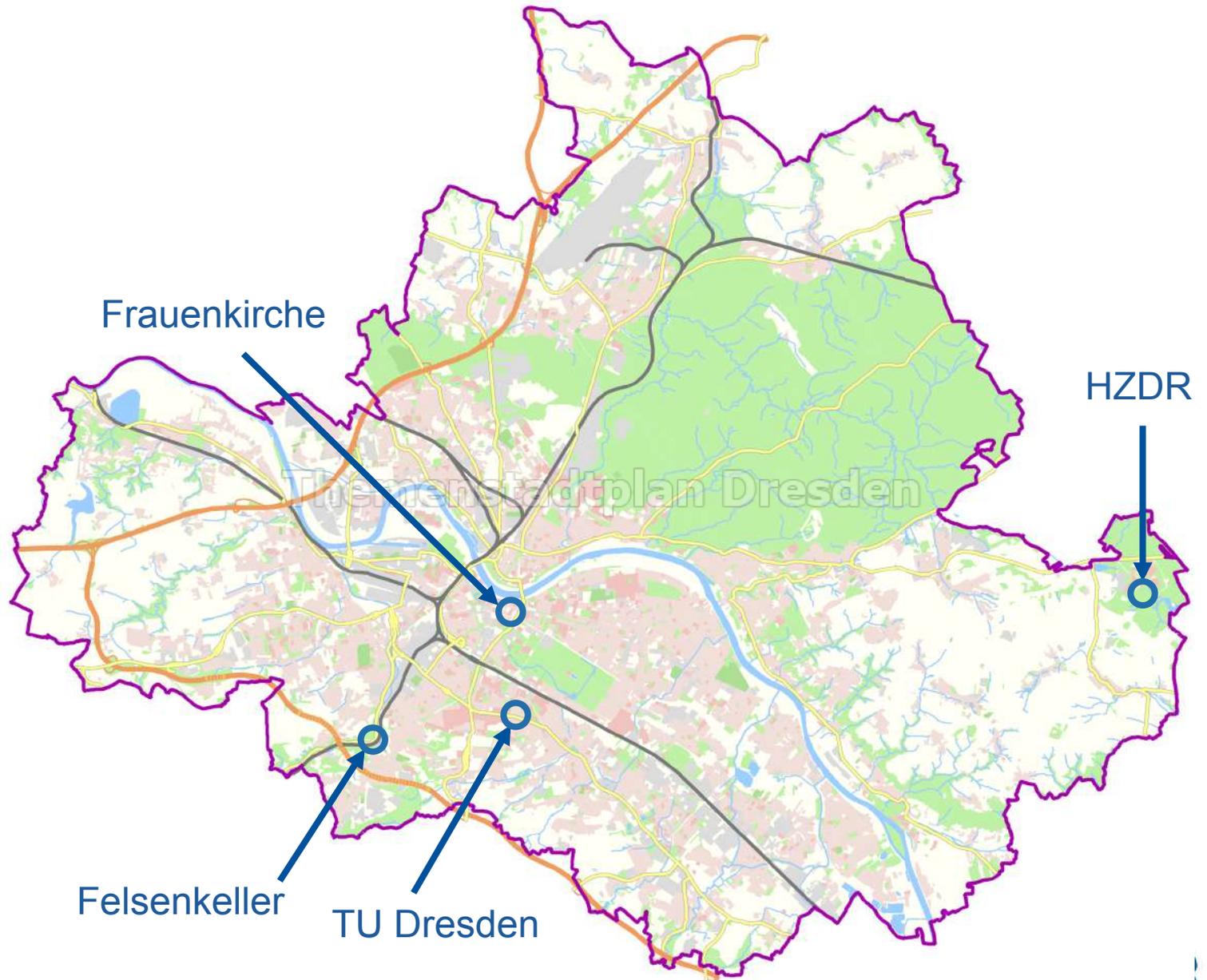
Felsenkeller, program and status

- ◆ Nuclear astrophysics is an emerging interdisciplinary field at the intersection of astronomy, astrophysics, and nuclear physics
- ◆ New nuclear data are needed for astrophysical scenarios including the Sun, the Big Bang, and hydrostatic helium burning
- ◆ The Felsenkeller 5 MV underground ion accelerator is ideally suited to address these challenges.
- ◆ The Felsenkeller laboratory is operational, 3 km from here
- ◆ Accelerator commissioning is underway
- ◆ Stay tuned!



55th Karpacz Winter school on Theoretical Physics, 24.02. – 02.03.2019:
“Nuclear astrophysics in the multi-messenger area”

Map of the city of Dresden



Background as a function of depth

