TECHNISCHE UNIVERSITÄT DARMSTADT

FONDAZIONE BRUNO KESSLER

ECT*
EUROPEAN CENTRE
FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

Nuclear Physics under the low-energy, high intensity frontier

Ideas for delayed and prompt nuclear spectroscopy at HPLS

Menu ...

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"What an HPLS can do differently to forward the field of nuclear/particle physics in a way, that an existing accelerator can not provide?" **... from the indico of this workshop!**

Nuclear spectroscopy at HPLS of ELI-NP

Physics case motivated by γ-astronomy: ^{26}Al
- depletion of ground state under stellar conditions by electromagnetic excitations

Experiments in the laboratory
- production and „destruction“ of ^{26}Al

Nuclear spectroscopy experiments at HPLS ...
- prompt spectroscopy
- delayed spectroscopy
- AMS

ELI-NP … what is it for?

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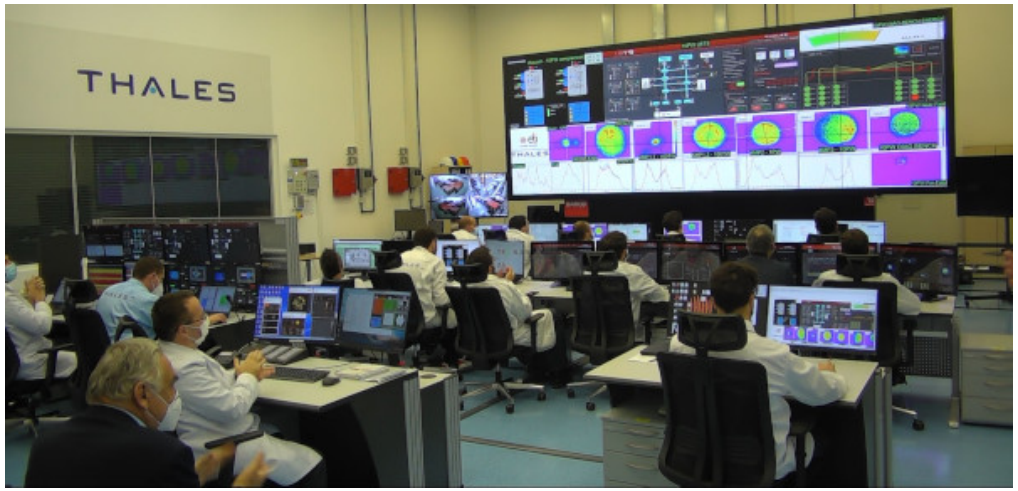
„… it will also open up entirely new research programmes in areas as diverse as laboratory astrophysics, extreme material science, turbulence and fundamental atomic, nuclear and plasma physics“

G. Mourou (Nobel prize awardee and one of the founders of ELI)
Plasma Phys. Control. Fusion 49 (2007) B667



2 x 10 PW (1 PW = 10^{15} Watt)
@ 1 shot per minute



World Record, ELI-NP delivers 274 shots in one day at 10 PW output of its High Power Laser System

„This unparalleled operational record underscores ELI-NP's capacity to enable groundbreaking research in high-power laser physics and beyond.“

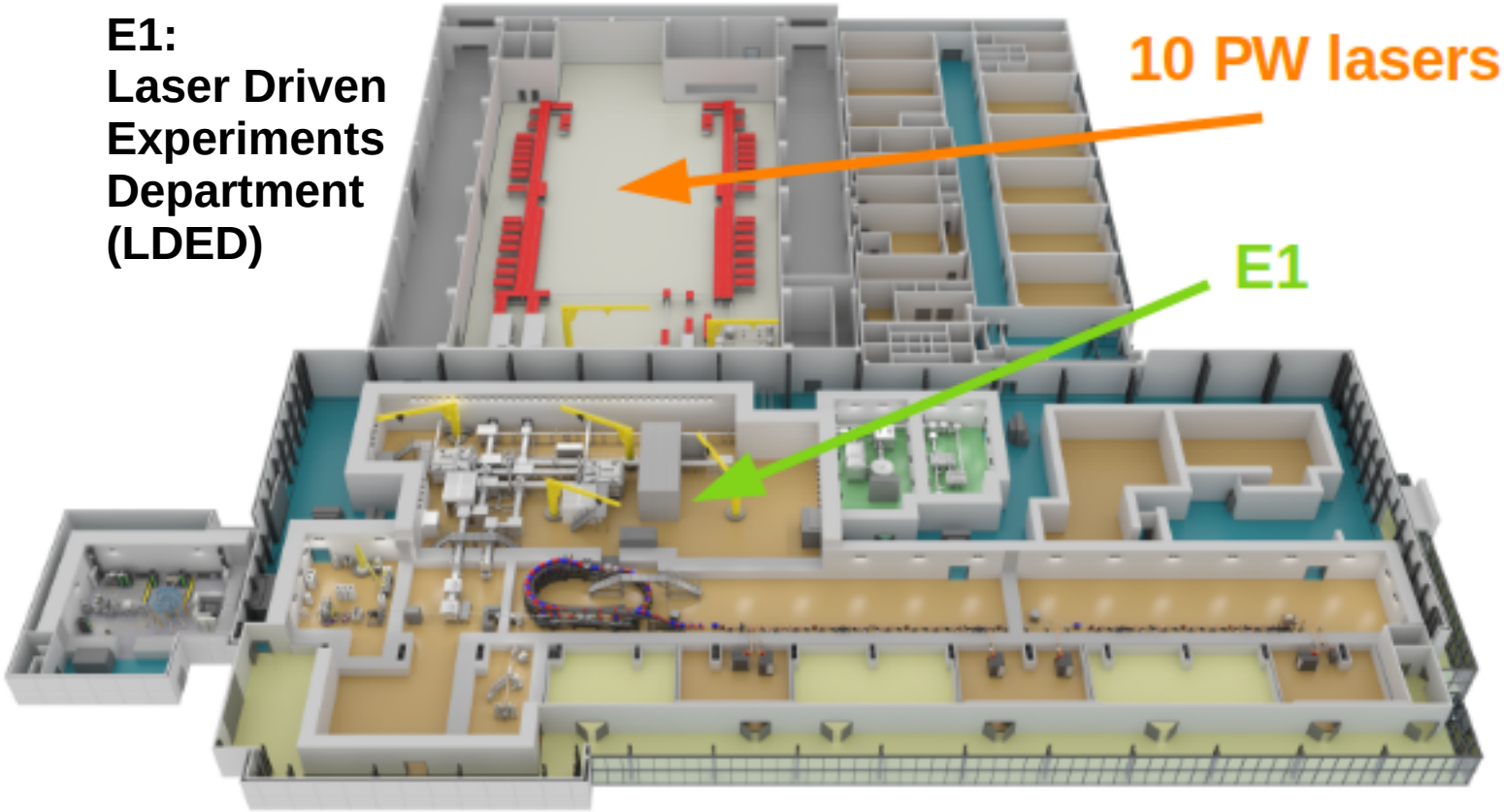
https://www.eli-np.ro/78-article.html (08.01.2025)

It‘s NOW time for the experimental programme to exploit these fantastic science opportunities!!!!

Layout of facility



E1:
Laser Driven Experiments Department (LDED)



Operated by IFIN-HH
… strong expertise in experimental nuclear physics next door!!

adapted from https://www.eli-np.ro/labs.php

^{26}Al - γ-astronomical observations

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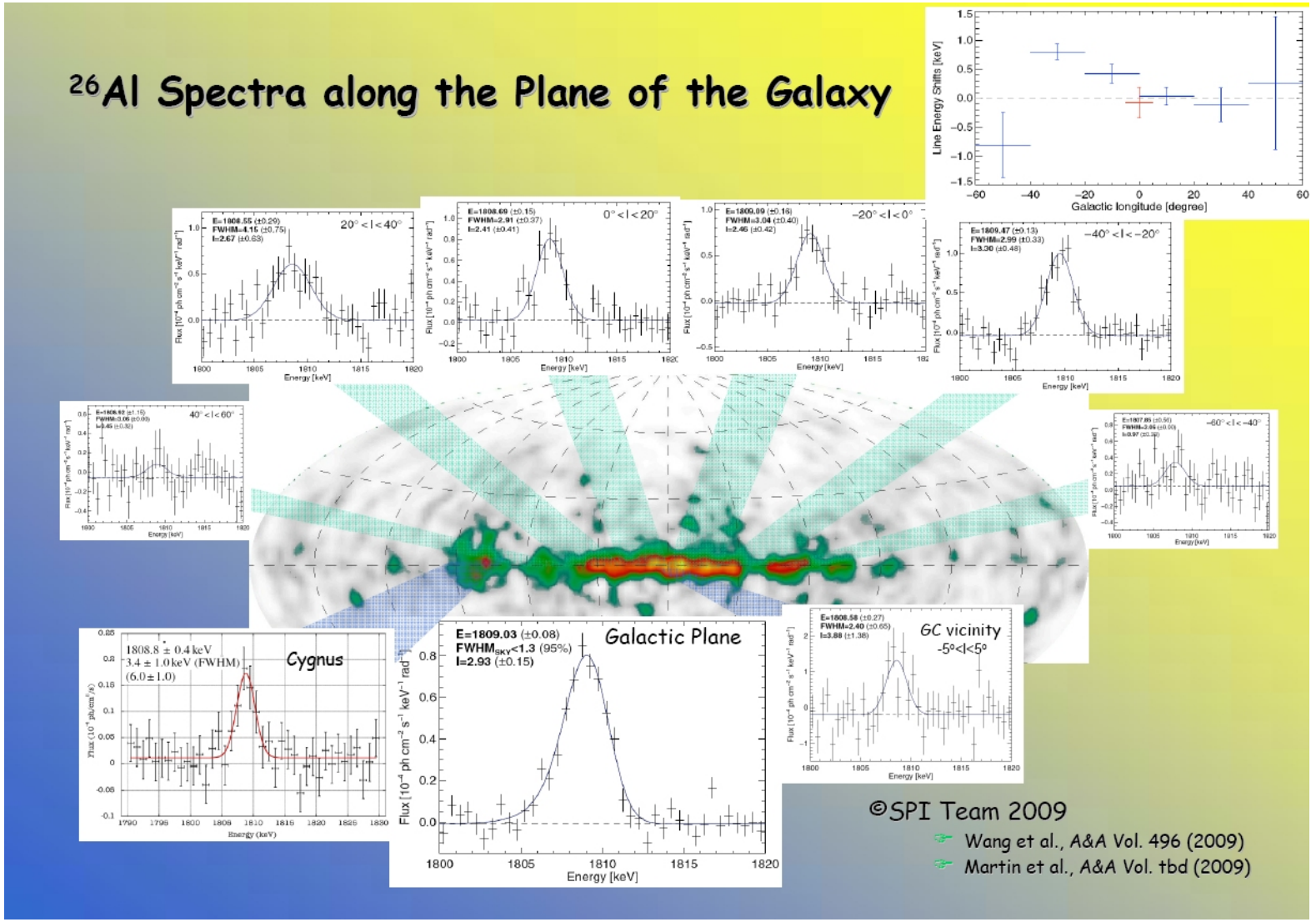
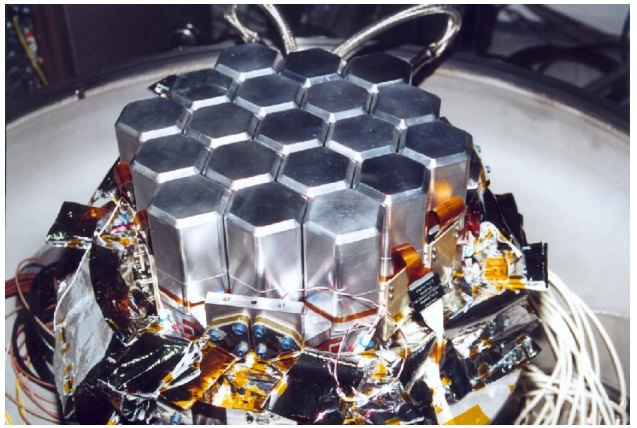






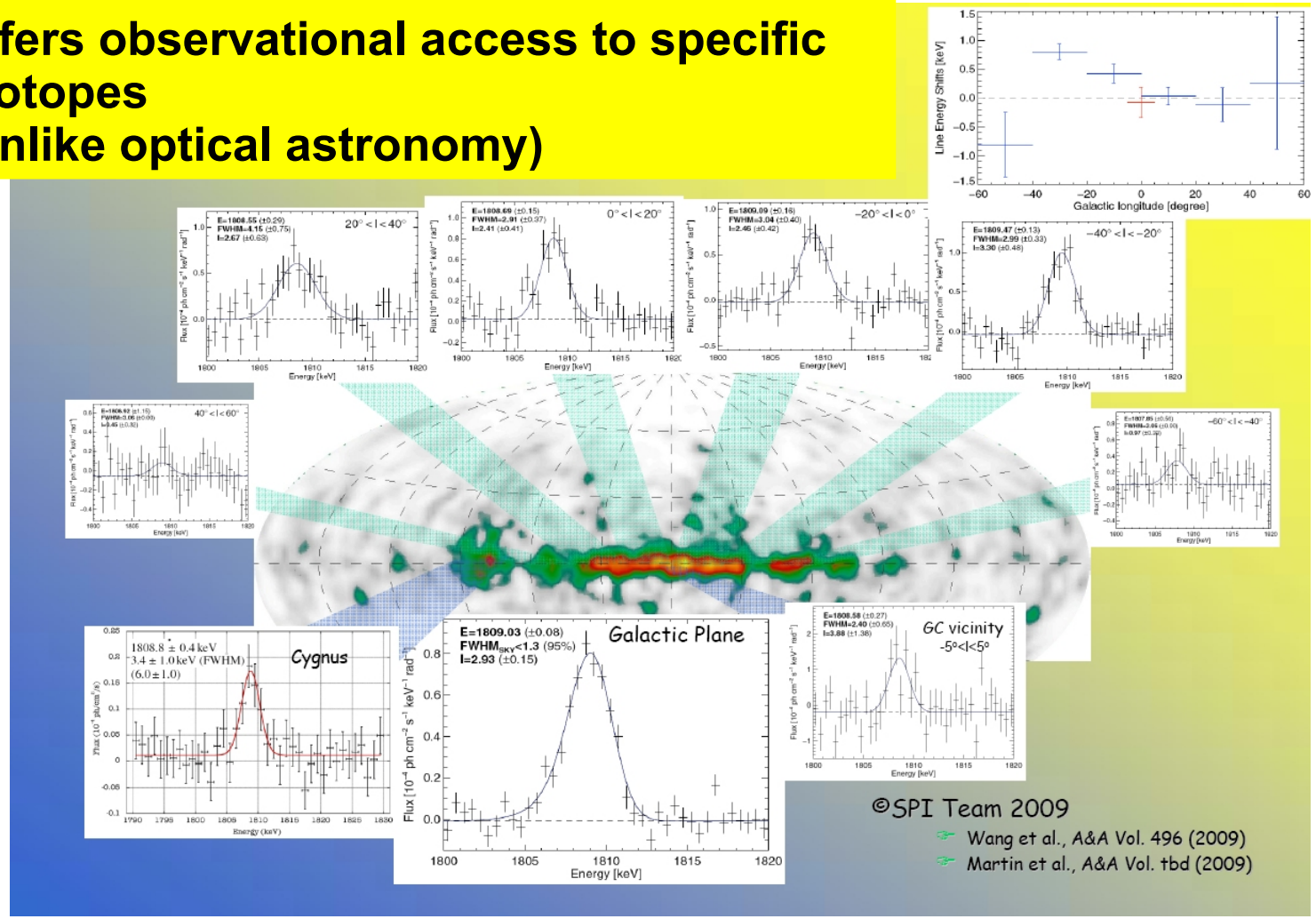
SPI on INTEGRAL:
HPGe detector technology from EUROBALL!!!

https://sci.esa.int/s/8DqDj6A

^{26}Al - γ-astronomical observations

nuclear spectroscopy ⇔ γ-ray astronomy

offers observational access to specific isotopes
(unlike optical astronomy)





INTEGRAL was operated for 22 years until 2025
(more data from previous missions)

^{26}Al: Best γ-astronomical data set from observations covering different sites in our galaxy

^{26}Al production yields deduced from γ-ray intensity are affected by existence of isomeric state („astromer“) in ^{26}Al

https://sci.esa.int/s/8DqDj6A

… connection to HPLS

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Theoretical study for ELI-NP on the feasibility to study the impact of the stellar environment on the abundance of isotopes … with ^{26}Al as benchmark:

galaxies

MDPI

Article

Theoretical Discourse on Producing High Temporal Yields of Nuclear Excitations in Cosmogenic ^{26}Al with a PW Laser System: The Pathway to an Astrophysical Earthbound Laboratory

Klaus Michael Spohr [1,*], Domenico Doria [1] and Bradley Stewart Meyer [2]

Galaxies **2018**, *7*, 4; doi:10.3390/galaxies7010004

… and how to do this in practice!?!

Impact of high-power laser pulse on target

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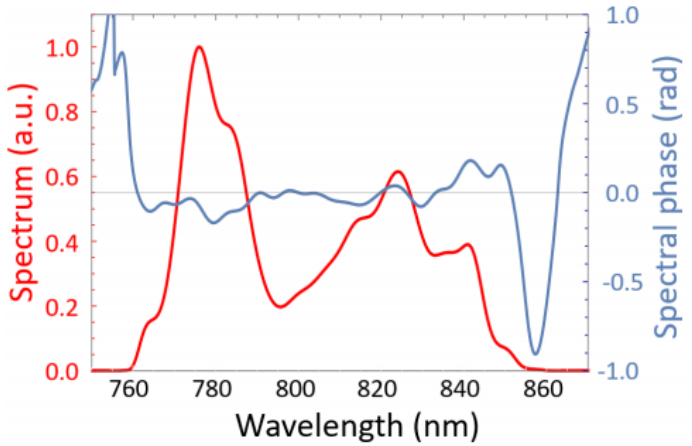
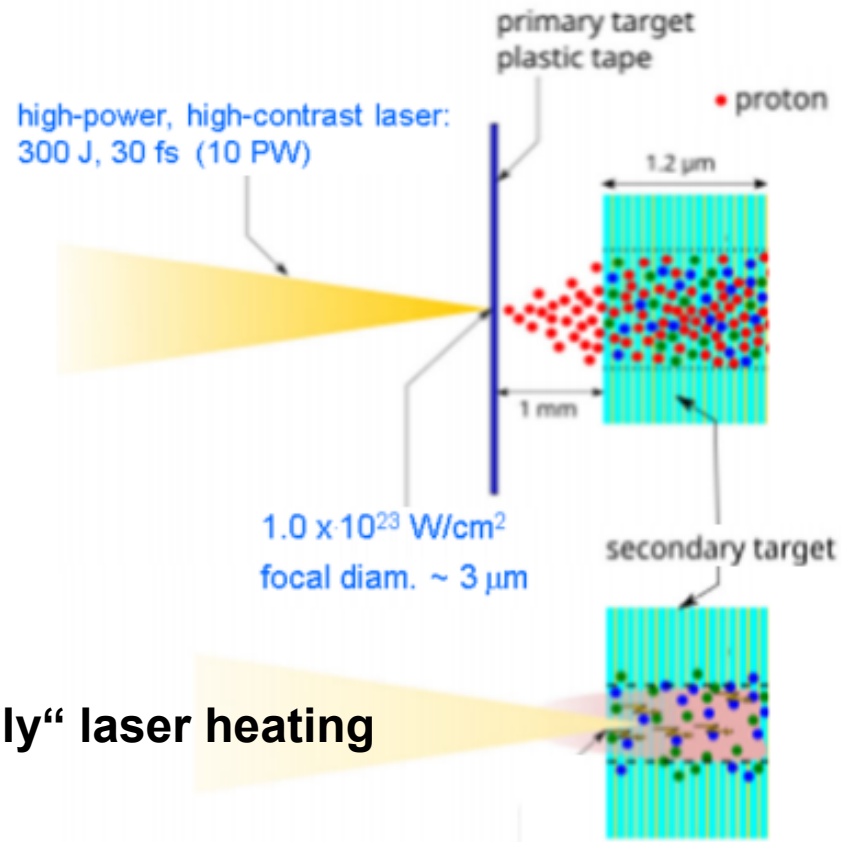
2 x 10 PW (1 PW = 10^{15} Watt) @ 1 shot per minute



C. Radier et al., High Power Laser Science and Engineering, Vol. 10, e21 (2022)

proton acceleration



„only“ laser heating

adapted from
F. Negoita et al., AIP Conf. Proc. 1645, 228 (2015)
K. M. Spohr et al., Eur. Phys. J. A 59, 281 (2023)

- **Φ_p is during pulse $10^{8\text{-}9}$ times higher than at RF accelerator → instantaneous yield**
- **estimated production of ^{26}Al > $5 \cdot 10^5$/shot**

^{25}Mg(p,γ)^{26gs,m}Al or ^{26}Mg(p,n)^{26gs,m}Al

HOT photon bath
… from Bremsstrahlung of accelerated electrons
… environment available only in stars and at ELI-NP

Characterisation of impact

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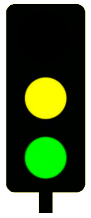
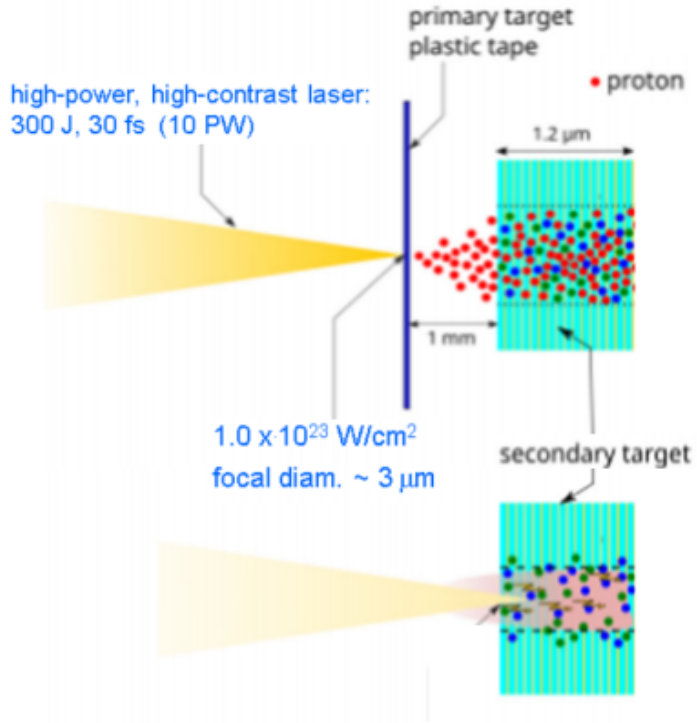
Characterisation of targets after impact of laser pulse
- measurement of x-rays, γ-rays, protons, neutrons
  → "temperature"
- reproducibility of pulses / monitoring of each pulse

Methodological approach 🛠
- fast detectors
- new neutron detectors employing ToF
- high-energy γ-rays by pair spectrometer
- full digital pulse processing
  → readout of entire traces, digital filters applied offline
- AI methods for signal extraction
- benchmark for PHITS simulations



Risks
electromagnetic pulse (EMP)



adapted from
F. Negoita et al., AIP Conf. Proc. 1645, 228 (2015)
K. M. Spohr et al., Eur. Phys. J. A 59, 281 (2023)

^{26}Al – production in stars

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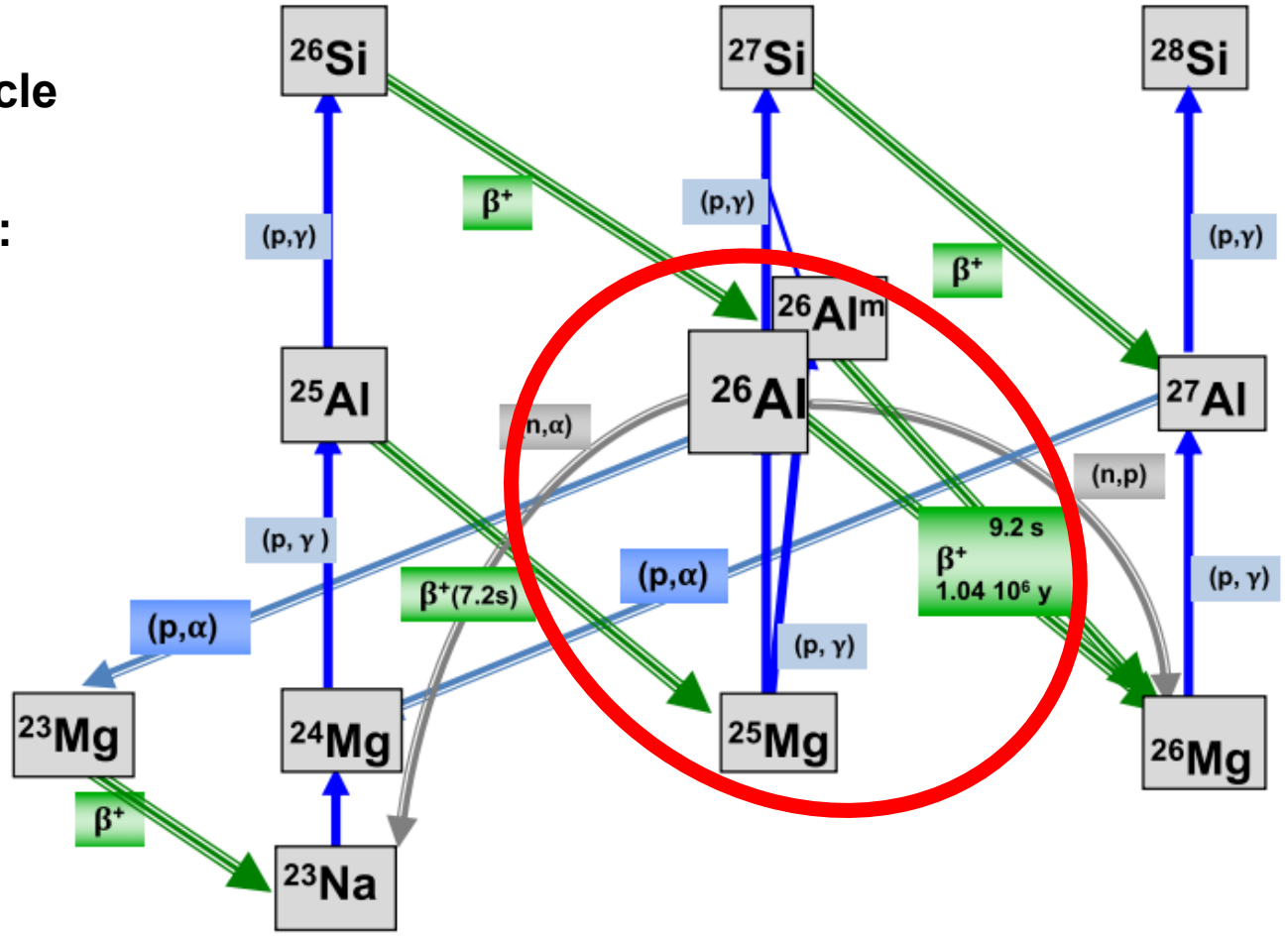
Slowest reaction within the Mg-Al cycle

- main production via proton capture:

$$^{25}Mg(p,\gamma)^{26gs,m}Al$$

- decay to ^{26}Mg



R. Diehl et al., Publications of the Astronomical Society of Australia 38, e062 (2021)

$^{25}Mg(p,\gamma)^{26}Al$ – reaction

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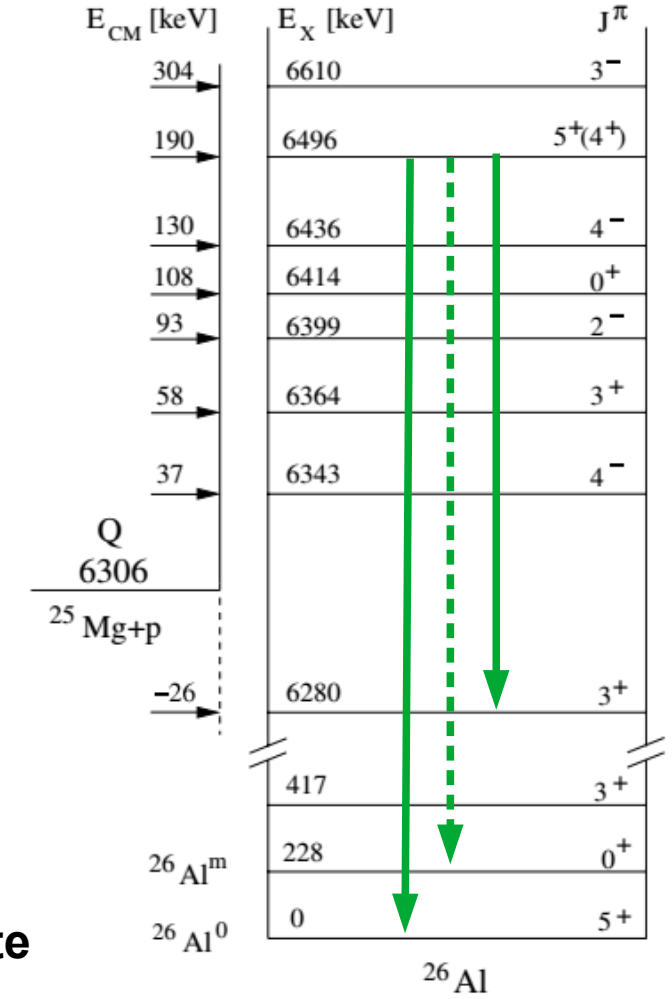
resonances

Q value > 0
exothermic

astromer

ground state



F. Strieder et al., Physics Letters B 707, 60 (2012)

- population of high-lying resonances in ^{26}Al

- Coulomb barrier around 300 keV (CMS)
  … quantum-mechanical tunneling
  … low rate (limitation in lab experiments)

- low-lying states, e.g. ground state and isomer (astromer), are populated by γ-rays feeding from above (shown schematically)

- $^{26}Mg(p,n)^{26}Al$ … in the lab
  R. T. Skelton et al., Phys. Rev. C 35, 45 (1987)

  - Q value = - 5.07 MeV
  - protons with energies > 5 MeV populate low-lying resonances
  - above Coulomb barrier … higher rates
  - monitoring by neutron detection

^{26}Al ↔ astrophysical scenarios

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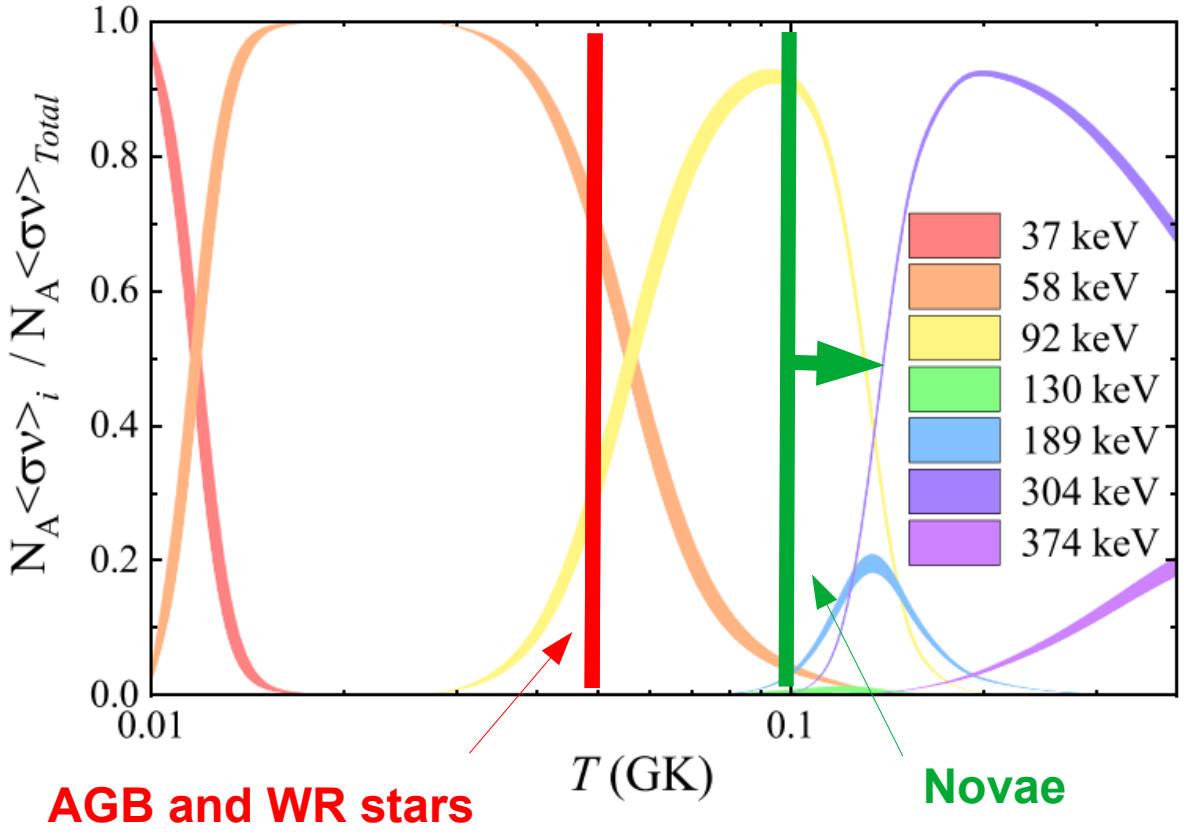
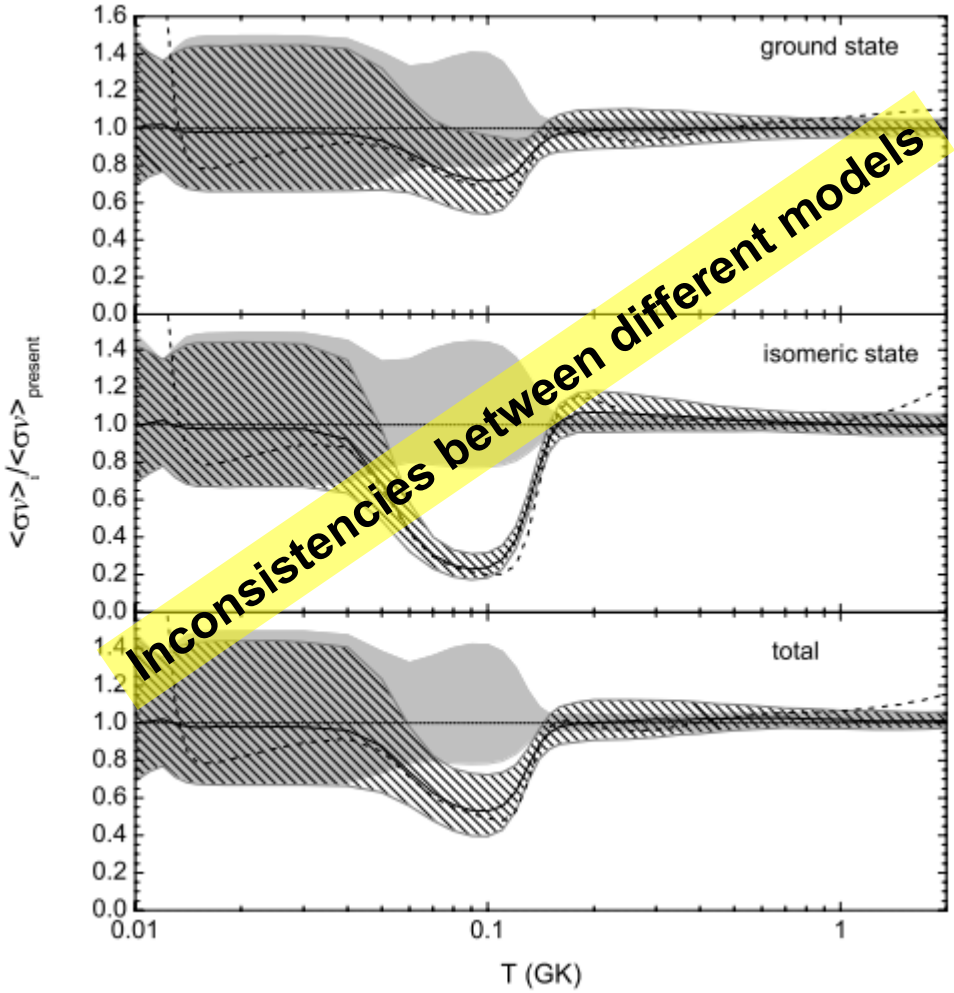
Contributions of resonances to total reaction rate



H. Zhang et al., Phys. Rev. C 107, 065801 (2023)



O. Straniero et al., ApJ 763, 100 (2013)

^{26}Al - decay

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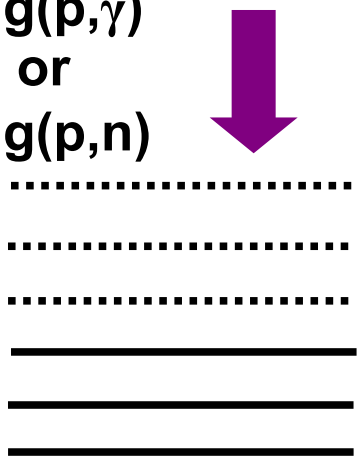
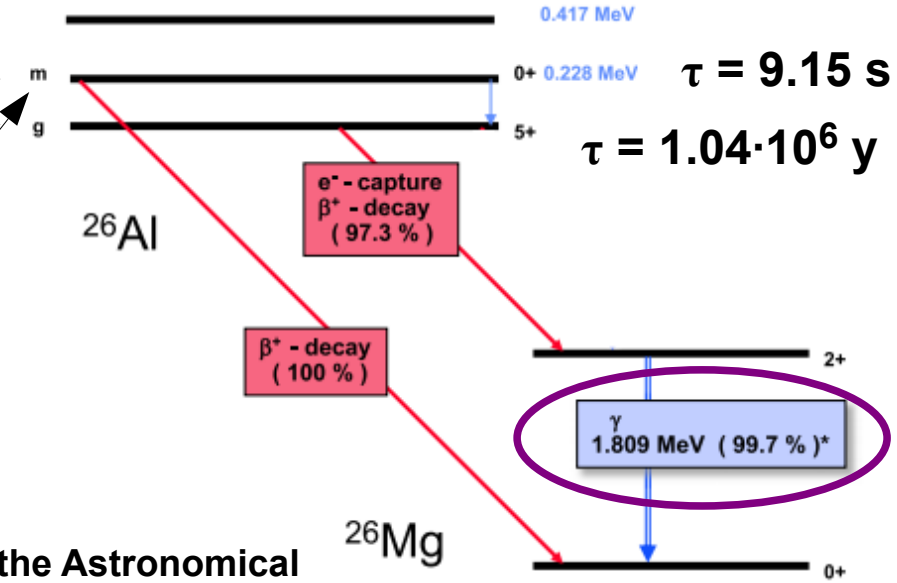
^{25}Mg(p,γ)
or
^{26}Mg(p,n)



Only the decay of the ground state is observed by γ-astronomy!!!

Deduction of ^{26}Al production in stellar environments from observed γ-ray intensity and assumed ^{26m}Al/^{26gs}Al ratio ↔ comparison with astrophysical models for ^{26}Al production



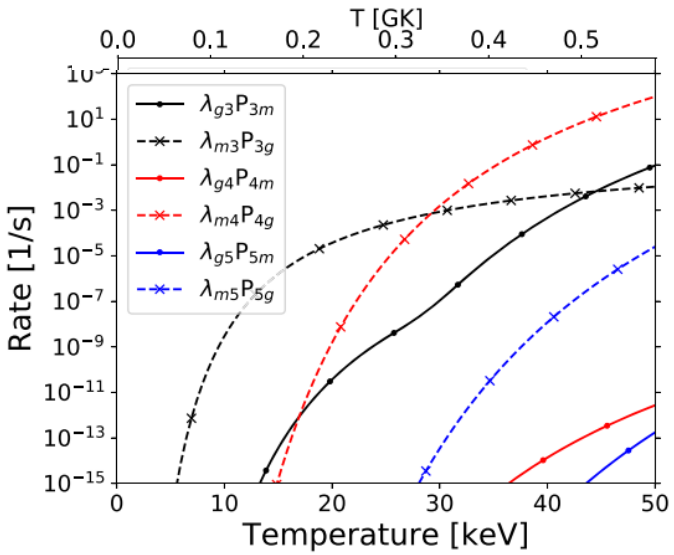
astromer
isomeric state with astrophysical importance

adapted from
R. Diehl et al., Publications of the Astronomical Society of Australia 38, e062 (2021)



Observed from satellites

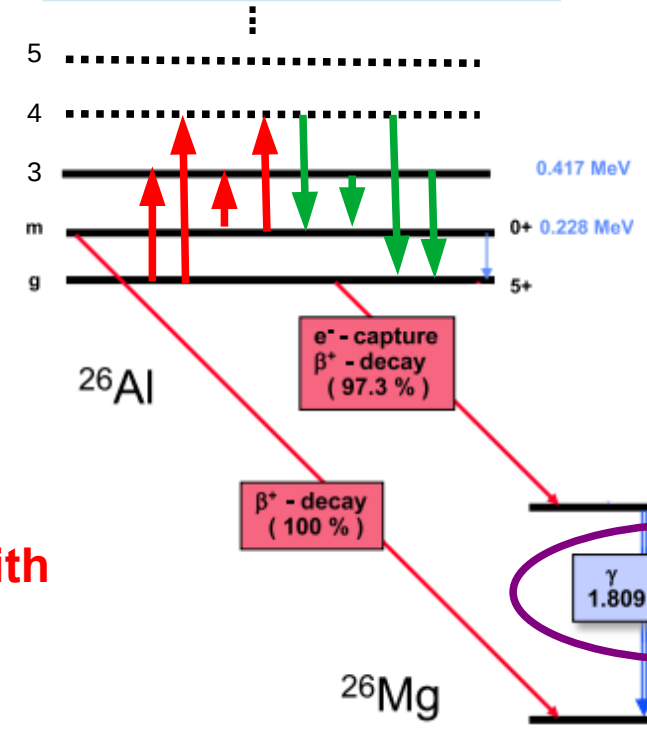
^{26}Al – depletion of ground state

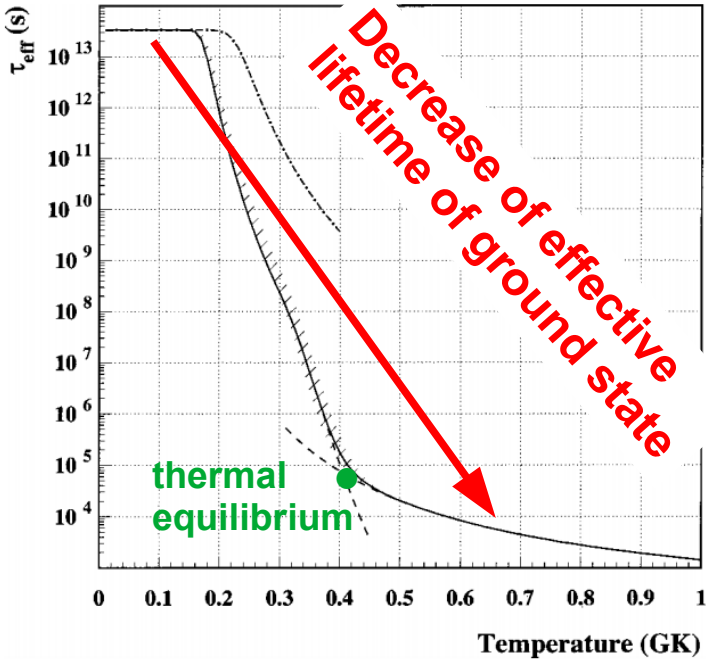


G. W. Misch et al., ApJS 252 2 (2021)

m: astromer
τ = 9.15 s $\ll$ T_{Laser}
g: ground state
τ = 1.04·10^6 y $\gg$ T_{Laser}

photon absorption





A. Coc et al.,
Phys. Rev. C 61, 015801 (1999)

„thermal“ or electromagnetic excitation with real photons in hot stellar environment
↔ multiple Coulomb excitation
multiple absorption of virtual photons
electromagnetic matrix elements are not known

Observed from satellites



adapted from
R. Diehl et al., Publications of the Astronomical Society of Australia 38, e062 (2021)

$^{25}Mg(p,\gamma)^{26}Al$ – prompt spectroscopy

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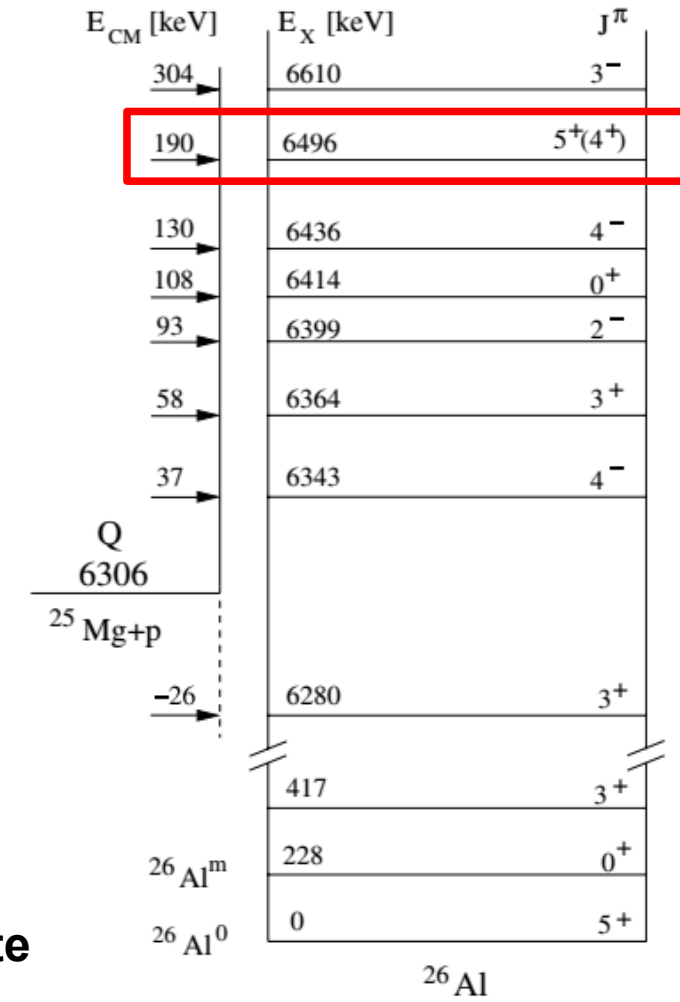
resonances

Q value > 0
exothermic

astromer

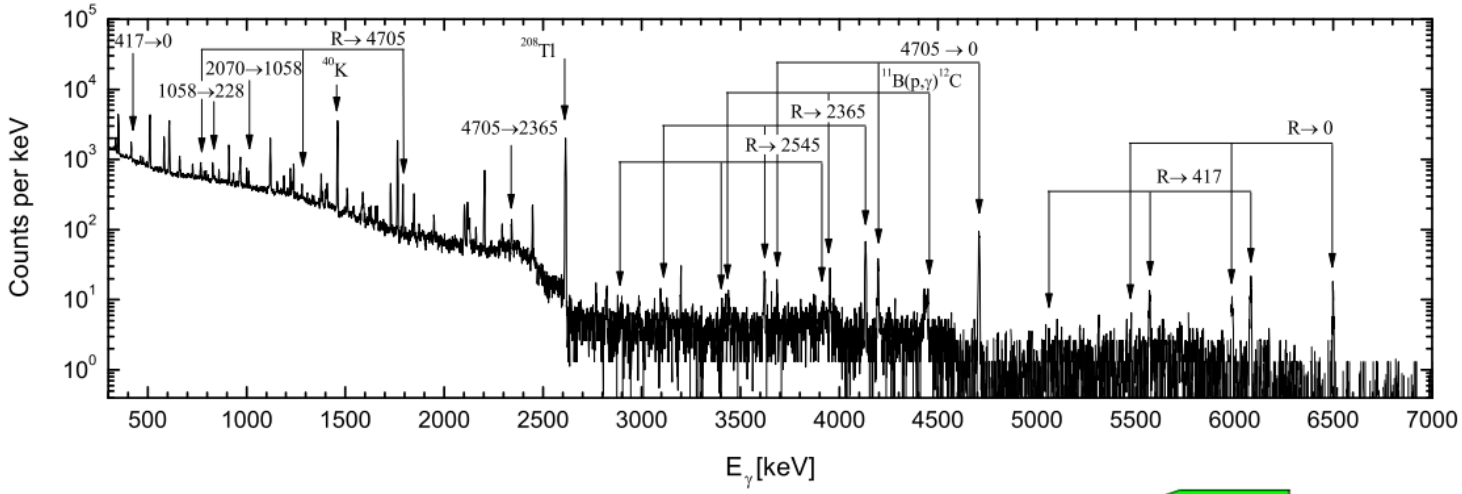
ground state



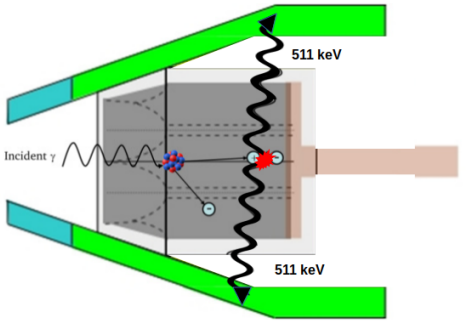
F. Strieder et al., Physics Letters B 707, 60 (2012)

high-resolution γ-ray energy spectrum
following reaction with monoenergetic(!) protons

O. Straniero et al., ApJ 763, 100 (2013)



HPGe-BGO pair spectrometer … offers unprecedented selectivity at high γ-ray energies



I. Homm, Th. Kröll et al., EPJ Techniques and Instrumentation 12, 5 (2025)

Prompt spectroscopy at E1

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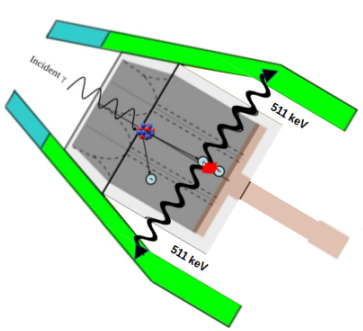
- photons, protons, neutrons
- PHITS simulations

→ characterisation of “photon bath“ available in target

Laser from back



Reaction chamber of area E1



neutron detectors
- plastic scintillators
- ToF method (start from laser pulse)
- γ/n discrimination by pulse shape analysis

HPGe-BGO pair spectrometer

adapted from
I. Homm, Th. Kröll et al.,
EPJ Techniques
and Instrumentation 12, 5 (2025)

Not to be placed at 0º to reduce photons from γ-flash!!!

New instrumentation ...

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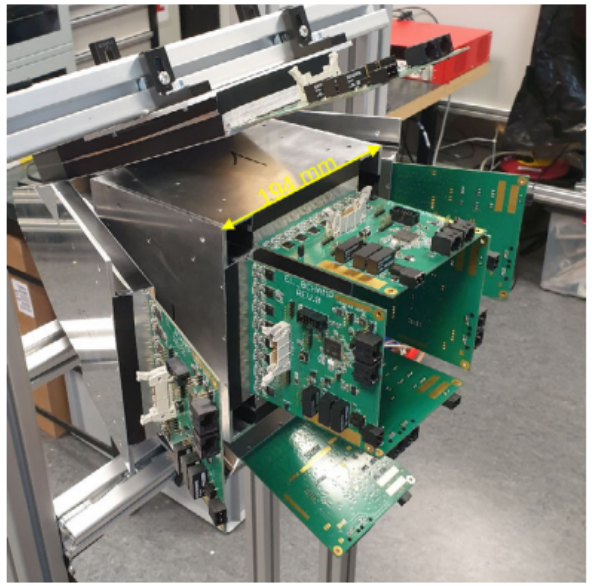
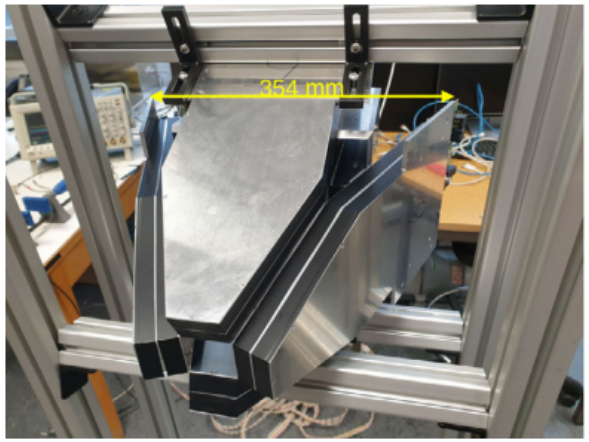
HPGe detector
e.g. from ELI-NP's ELIADE array

Active high-granularity AC shield with 64 BGOs





Homm et al. *EPJ Techniques and Instrumentation* (2025) 12:5
https://doi.org/10.1140/epjti/s40485-025-00118-2
EPJ.org
EPJ Techniques and Instrumentation
RESEARCH ARTICLE Open Access

A novel HPGe-BGO pair spectrometer

Ilja Homm[1*], Thorsten Kröll[1*], Corinna Henrich[1], Han-Bum Rhee[1], Diandra Richter[1], Matthias Rudigier[1], Martin von Tresckow[1], Felix Dunkel[2], Christoph Fransen[2], Vasil Karayonchev[2,5], Franziskus von Spee[2,6], Giacomo Colombi[3,7], Caterina Michelagnoli[3], Richard Pommier[3], Dimiter L. Balabanski[4], Gabriel Suliman[4] and Calin A. Ur[4]

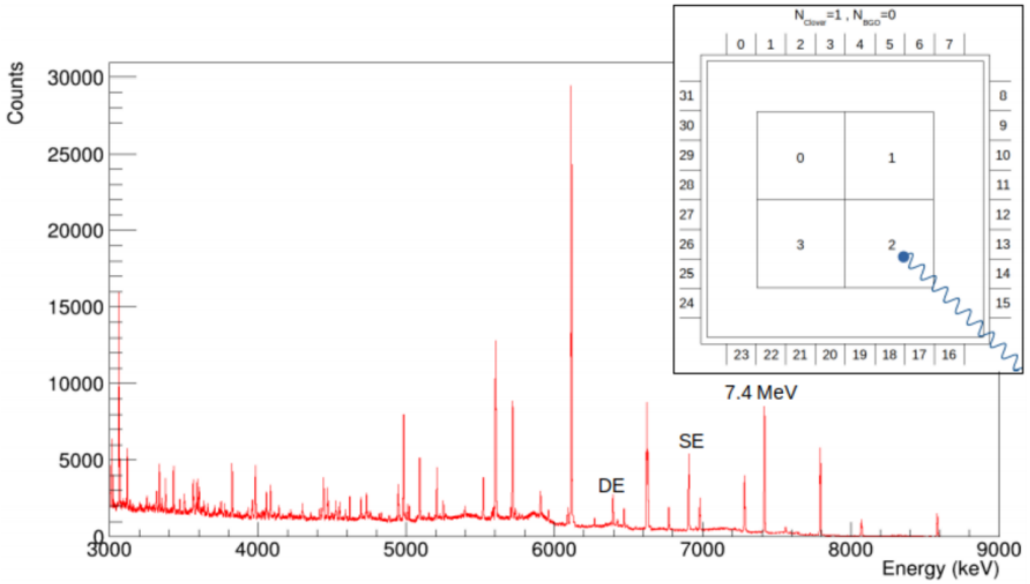
Supported by

SPONSORED BY THE
Federal Ministry of Education and Research

Nuclear Photonics

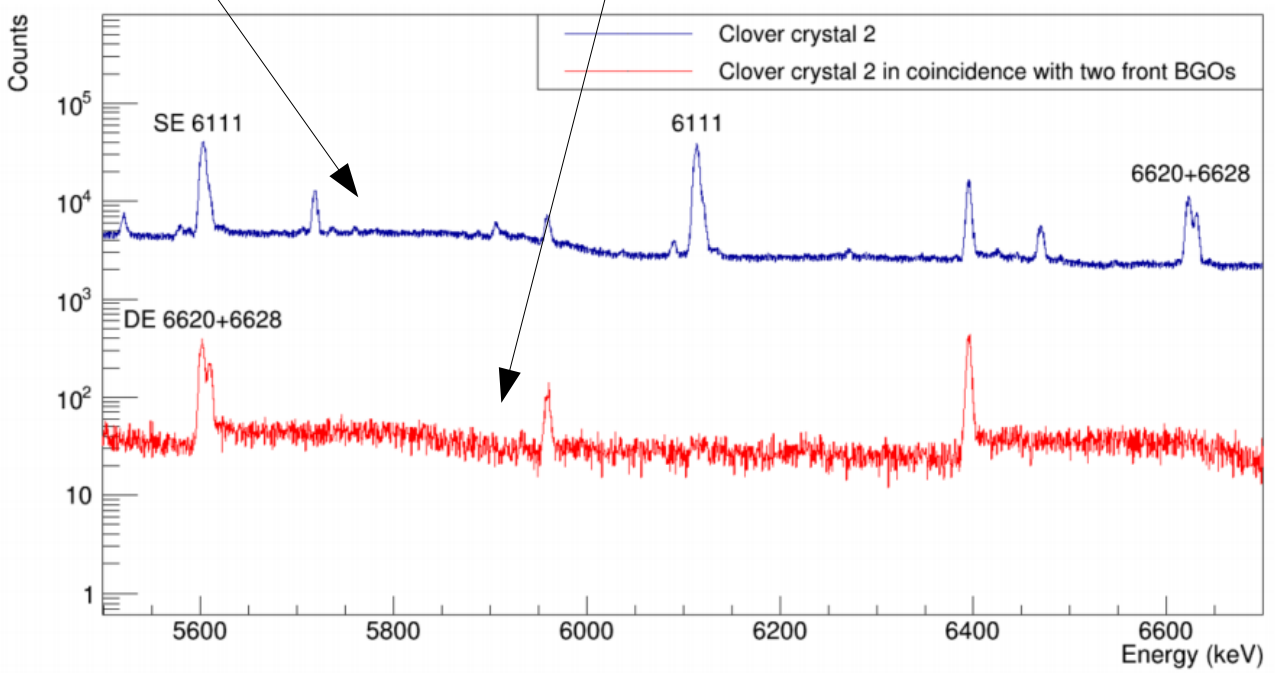
now BMFTR

Selectivity to high-energy γ-rays



Singles spectrum of one HPGe detector

… and requesting two 511 keV back-to-back in coincidence



- $^{35}Cl(n,\gamma)^{36}Cl$ reaction at ILL to produce high-energy γ-rays

- also tested with γ-rays up to 17.6 MeV with $^{7}Li(p,\gamma)^{8}Be$ at the tandem in Cologne

I. Homm, Th. Kröll et al., EPJ Techniques and Instrumentation 12, 5 (2025)

Does the EMP make prompt spectroscopy impossible? NO!!!

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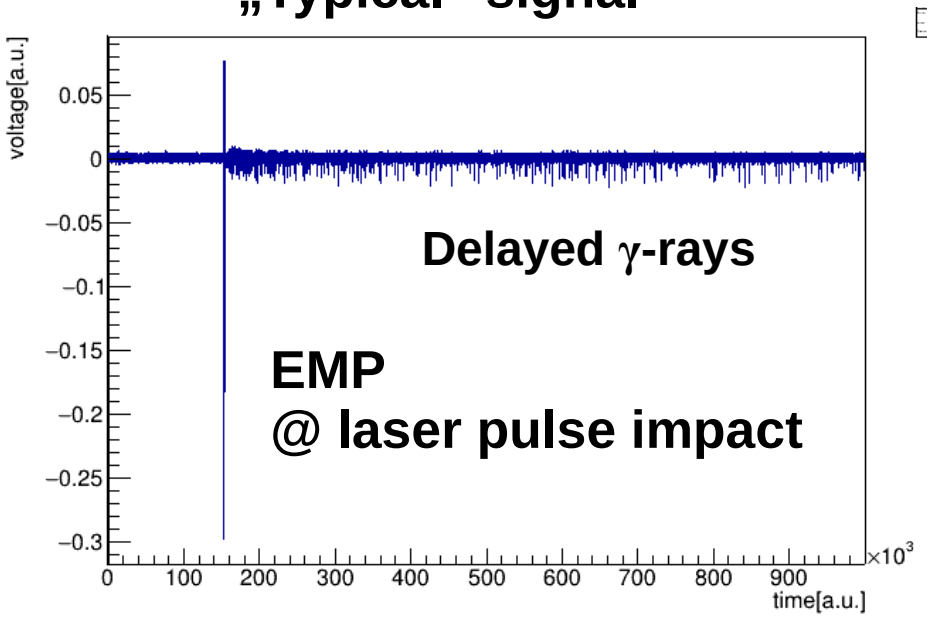
Triggering on „real“ signals is NOT possible!!!

Classical solutions for EMP resilience:
- **shielding … yes, but not useful for radiation detectors which have to see radiation!!!**
- **active reset of pre-amp / switchable HV at PMT …**
  .. .not applicable for „real“ prompt spectroscopy

Innovative solution:
- **digital sampling of entire pulse**
- **offline processing by applying AI techniques**

Prerequisits:
- **detailed understanding of signal shape**
- **digital filters to be run on sampled signals**
- **pattern recognition / signal decomposition by AI**

„Typical“ signal



From HPLS to neutrons ….

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ARTICLE

https://doi.org/10.1038/s41467-022-28756-0 OPEN

Check for updates

Demonstration of non-destructive and isotope-sensitive material analysis using a short-pulsed laser-driven epi-thermal neutron source

Marc Zimmer[1✉], Stefan Scheuren[1], Annika Kleinschmidt[2,3], Nikodem Mitura[1], Alexandra Tebartz[1], Gabriel Schaumann[1], Torsten Abel[1], Tina Ebert[1], Markus Hesse[1], Şêro Zähter[2], Sven C. Vogel[4], Oliver Merle[5], Rolf-Jürgen Ahlers[5], Serge Duarte Pinto[6], Maximilian Peschke[7], Thorsten Kröll[1], Vincent Bagnoud[2], Christian Rödel[1] & Markus Roth[1]

Nuclear Photonics

… performed within the LOEWE Research Cluster „Nuclear Photonics“ at TU Darmstadt

Shot @ PHELIX (GSI)

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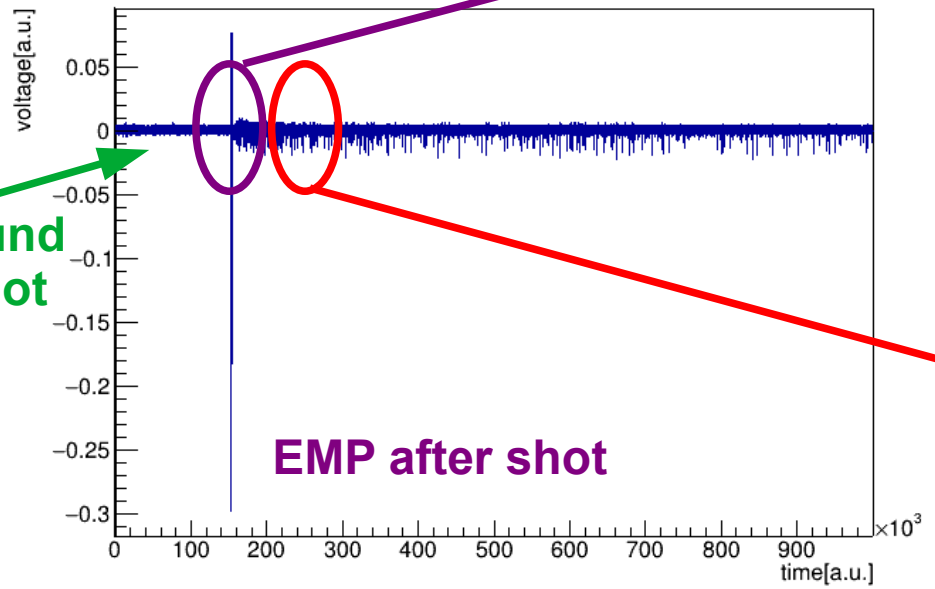
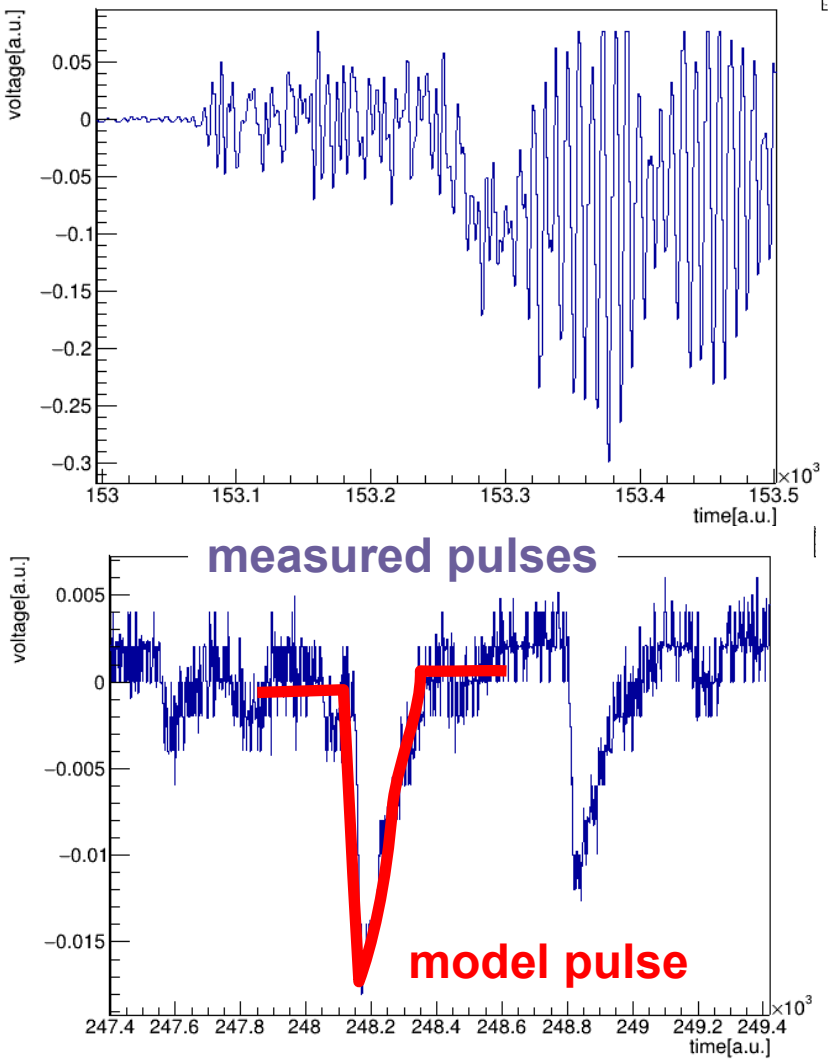
- $LaBr_3(Ce)$ with PMT
- 13 bit @ 5 GSamp/s





Separation of γ-ray signals from EMP
- impossible with analogue electronics, e.g. triggering
→ offline processing of sampled pulse
→ signal decomposition by AI methods

Knowledge already existing ...

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… on digital signal processing and application of AI techniques

Nuclear Instruments and Methods in Physics Research A 344 (1994) 607–610

A position sensitive gas counter with resistive layer cathode decoded by a neural network algorithm

K. Vetter [a], Th.W. Elze [a], M. Kaspar [a], T. Kröll [a], J. Gerl [b,*]

[a] *Institut fur Kernphysik, Universität Frankfurt, Frankfurt, Germany*
[b] *GSI, Darmstadt, Germany*

Digital Signal Processing and Algorithms for γ-Ray Tracking

W. Gast, R. M. Lieder, L. Mihailescu, M. J. Rossewij, H. Brands, A. Georgiev, J. Stein, and Th. Kröll

Nuclear Instruments and Methods in Physics Research A 565 (2006) 691–703

A genetic algorithm for the decomposition of multiple hit events in the γ-ray tracking detector MARS

Th. Kröll[a,*], D. Bazzacco[b]

[a] *INFN - Laboratori Nazionali di Legnaro, Viale dell' Università 2, 35020 Legnaro (PD), Italy*
[b] *Dipartimento di Fisica and INFN, Sezione di Padova, Via Marzolo 8, 35131 Padova, Italy*

Examples for PSA

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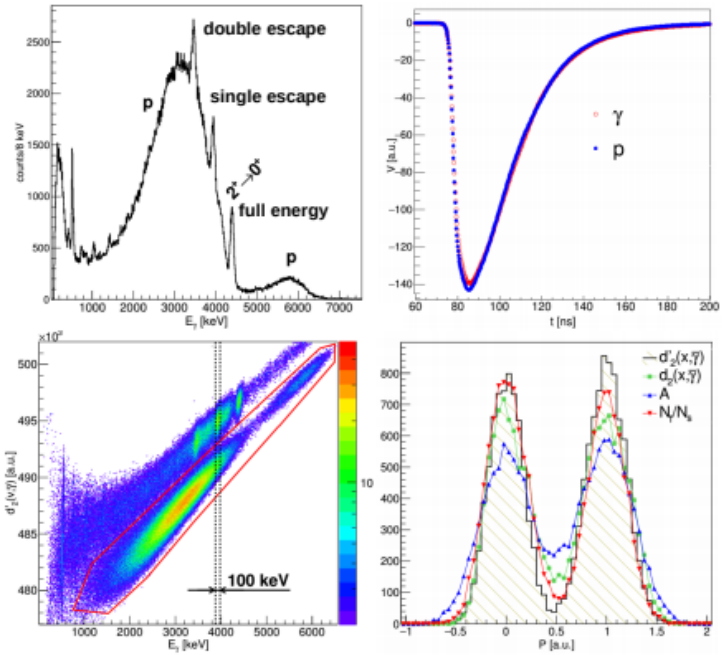
Proton/γ discrimination in $LaBr_3(Ce)$

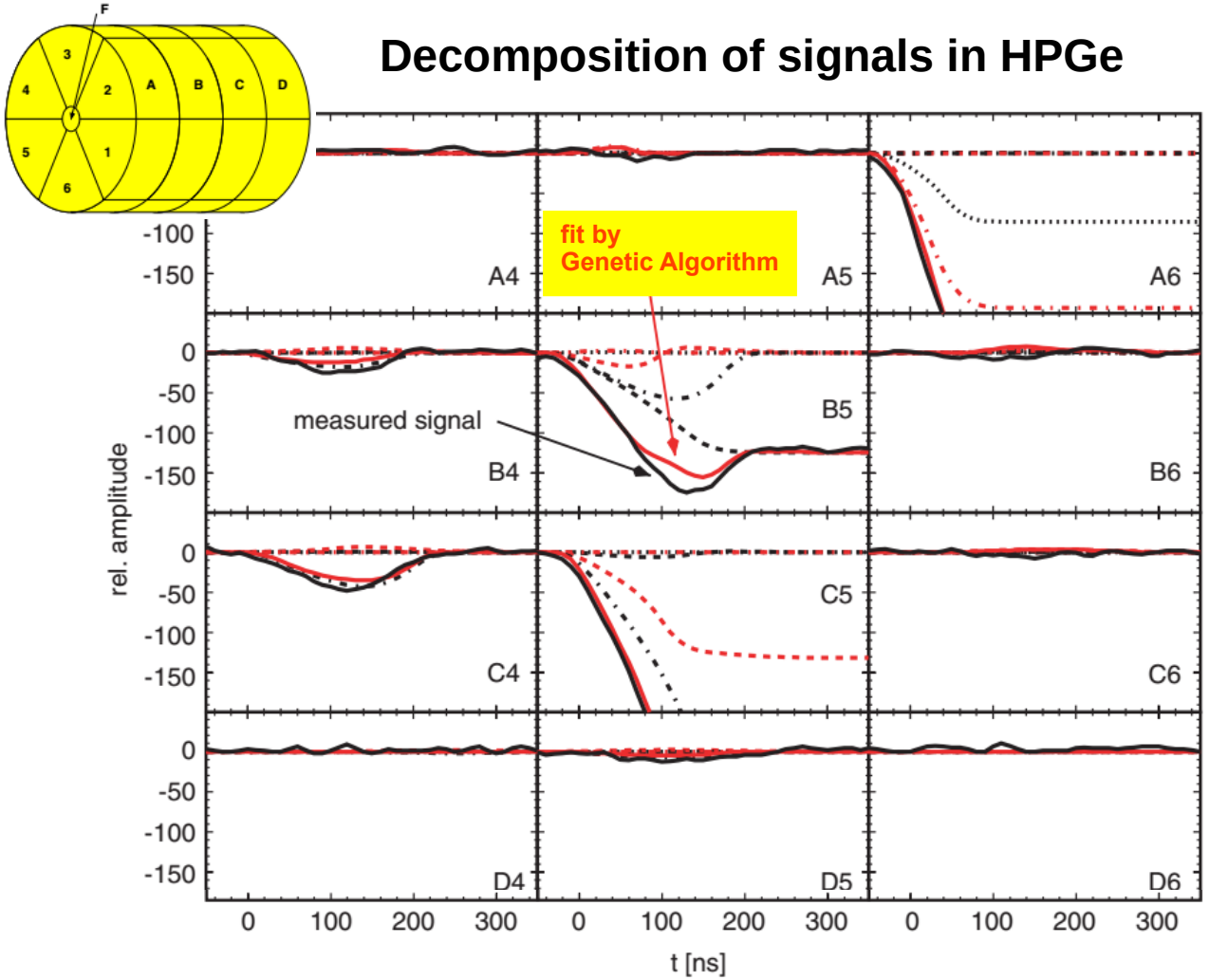


G. Fernández Martínez, Doctoral Thesis, TU Darmstadt (2018)

PSA for n/γ discrimination in plastic detectors
Is an established technique … has to digital too

8 bit @100 Msamp/s … :-/

Decomposition of signals in HPGe



Th. Kröll, D. Bazzacco, NIM A565, 691 (2006)

Prompt spectroscopy

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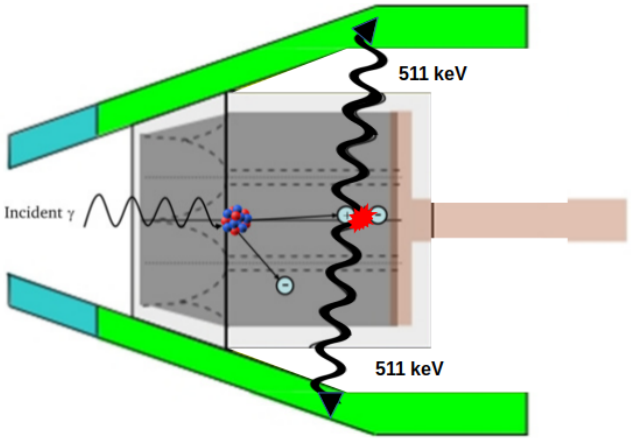
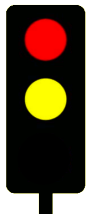
Prompt spectroscopy of reaction products
- reaction rate from high-resolution prompt γ-ray spectroscopy

Methodological approach 🛠
- fast detectors
- EMP-hard electronics for HPGe detectors
- high-energy γ-rays by pair spectrometer
  unique pattern of matter-antimatter annihilation
  unprecedented selectivity to pair production
- full digital pulse processing
  → readout of traces, digital filters applied offline
- AI methods for pattern recognition



adapted from
I. Homm, Doctoral Thesis, TU Darmstadt (2023)



Risks
electromagnetic pulse (EMP)
peak-to-EMP ratio low

Delayed spectroscopy

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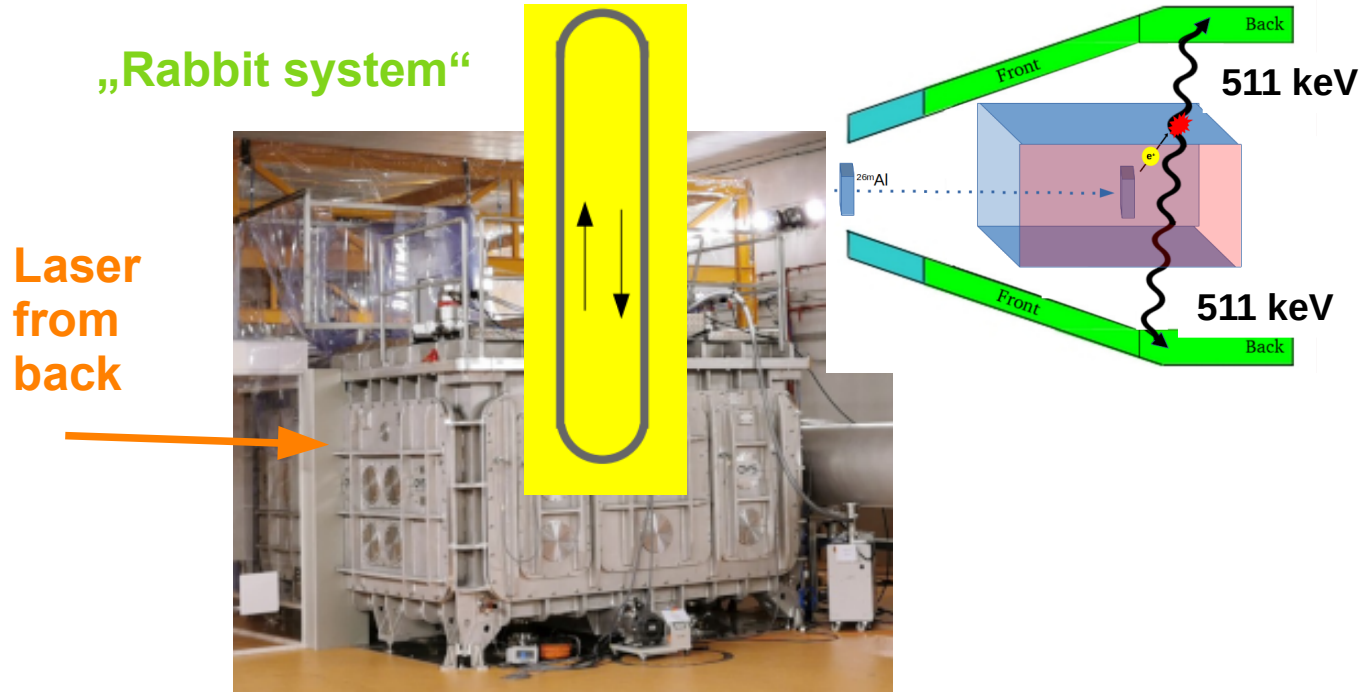
Activation with multiple laser shots

„Rabbit system“

Laser from back



Reaction chamber of area E1

Delayed spectroscopy

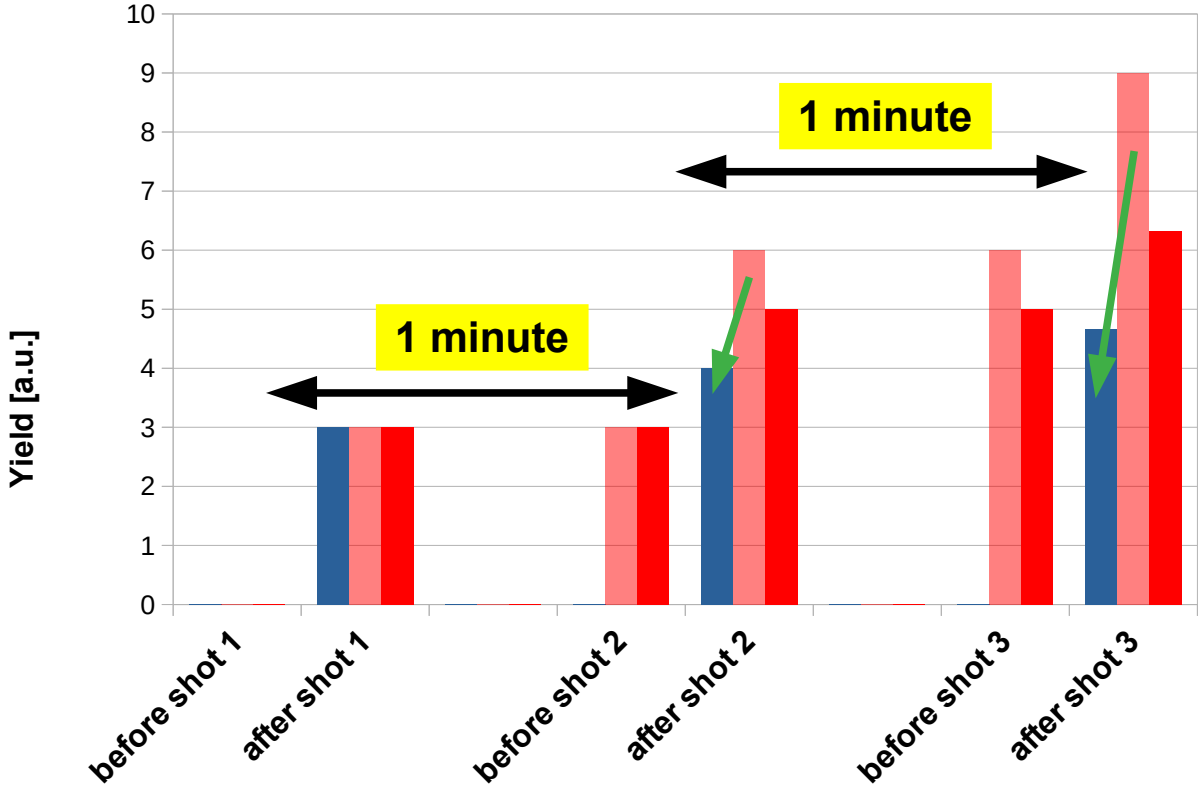
- transport of activated samples out of the chamber *after each shot*
- measure positrons from β^+ decays
  → yield for the astromer

Activation analysis

- measure positrons and γ-ray from its decay *after multiple shots*
  → yield for the ground state

Multiple-shot activation

- Prompt spectroscopy … measure ^{26}Al nuclei at their creation
- Delayed spectroscopy … measure ^{26}Al nuclei at their decay





$\tau = 9.15\ s \ll T_{Laser}$

$\tau = 1.04 \cdot 10^6\ y \gg T_{Laser}$

… multiple shots

… reproducibility of properties
… monitoring of each shot

Delayed spectroscopy of ^{26gs}Al decay

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What rate to expect?

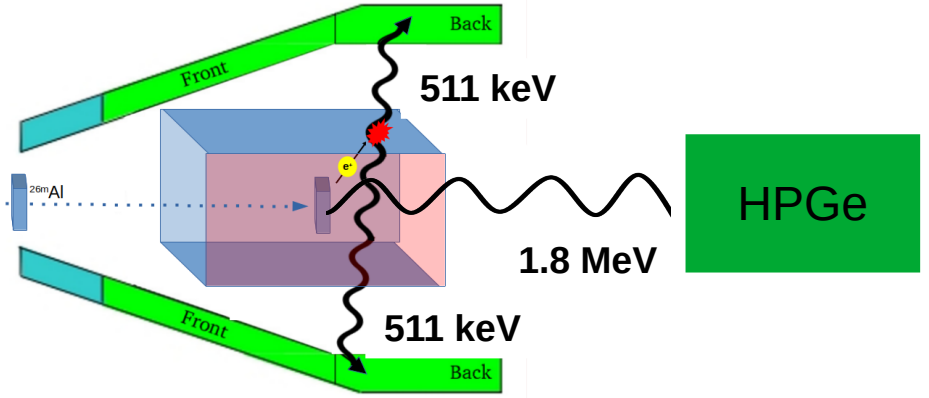
- **estimated production of ^{26}Al 10^{5-7}/shot**
  K.M. Spohr et al., Galaxies 7, 4 (2028)
- **about 2 weeks of activation (target ???)**

→ 10^{10} ^{26gs}Al produced

→ 1/h decay activity

Doable: e.g. ^{100}Sn decay at GSI (@ focal point of fragment separator … not the most „quiet“ location… but selectivity helps!!!)
C. B. Hinke et al., Nature 486, 341 (2012)

IFIN-HH operates also a deep-underground lab … as alternative



adapted from
I. Homm, Doctoral Thesis, TU Darmstadt (2023)

Positron „tag“
- hit in plastic detector (as used in βγ fast timing)
- metal plate behind to stop e^+
- 2 back-to-back 511 keV in coincidence

Delayed spectroscopy

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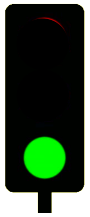
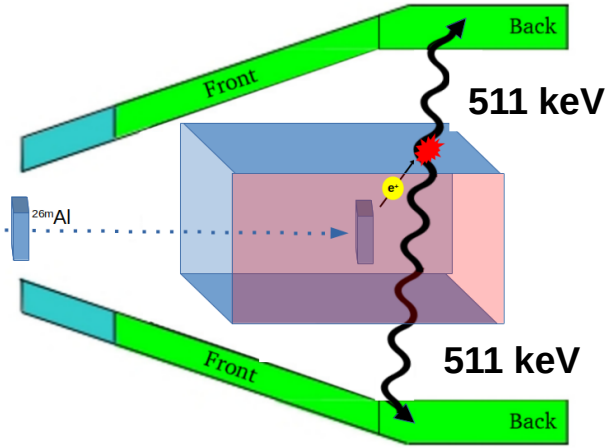
Detection of decays of the astromer

Methodological approach 🛠
- activation of sample by multiple shots
- fast transport to detection area
- detection of decay (positrons from β^+)
  unique pattern of e^+e^- annihilation
- AI methods for pattern recognition



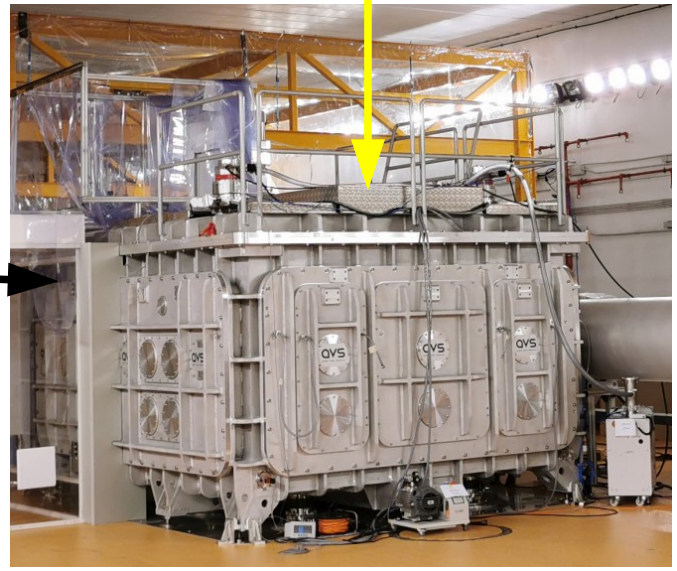
Risks
low activity
background from activation



adapted from
I. Homm, Doctoral Thesis, TU Darmstadt (2023)

„Rabbit system“ to transport samples

Laser from back



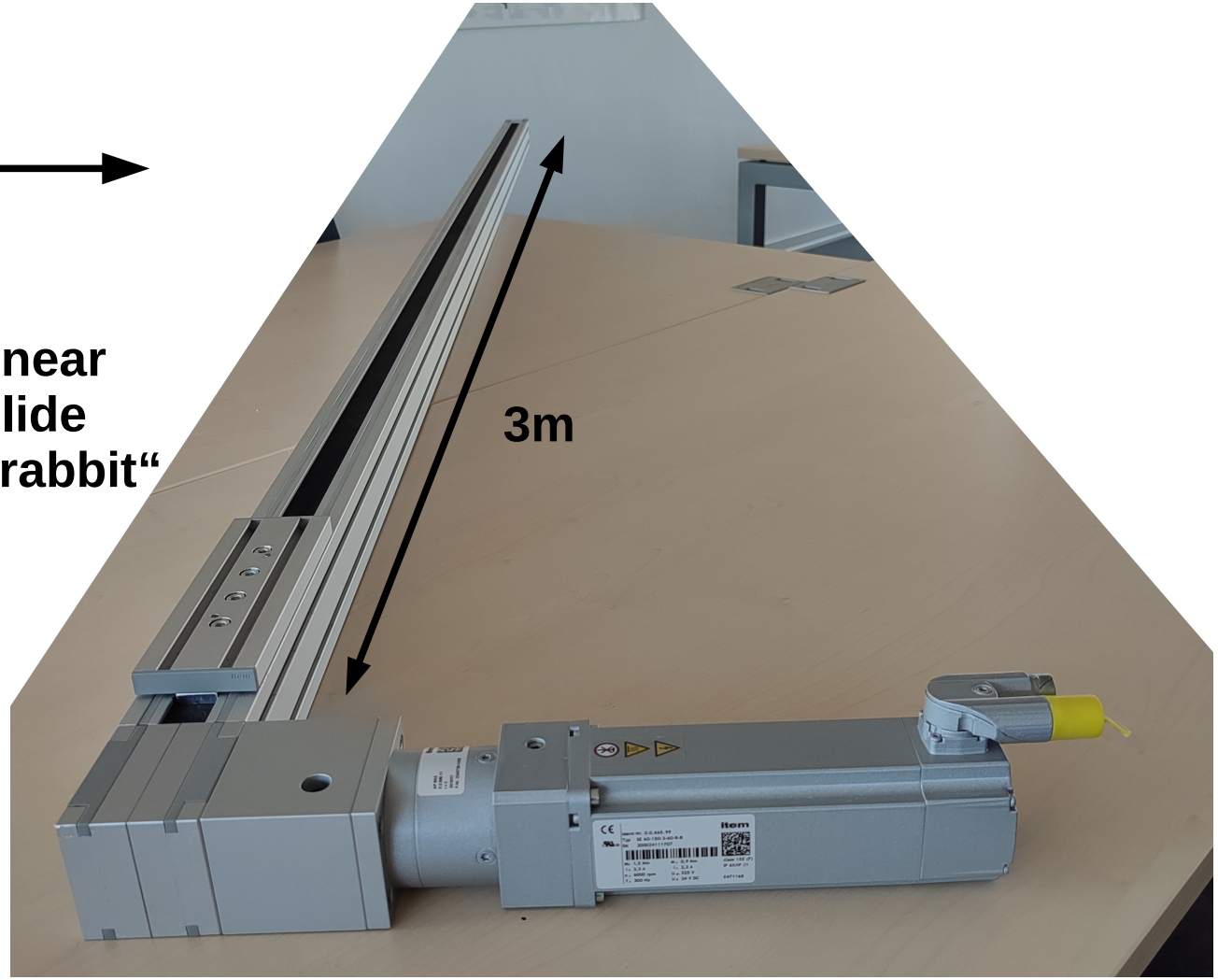
Reaction chamber of E1

„rabbit system“

… advanced target design ☺



linear slide „rabbit“



Stepping motor

Activated sample is moved outside of the E1 chamber (inside of a vacuum tube)

Decays measured between the laser shots

Supported by Nuclear Photonics

Activation analysis

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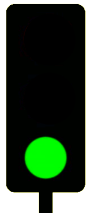
Detection of decay of the ground state

Methodology 🛠
- decay spectroscopy (x-rays, γ-rays, positrons)
… established techniques



Risk
low activity
background from activation

AMS

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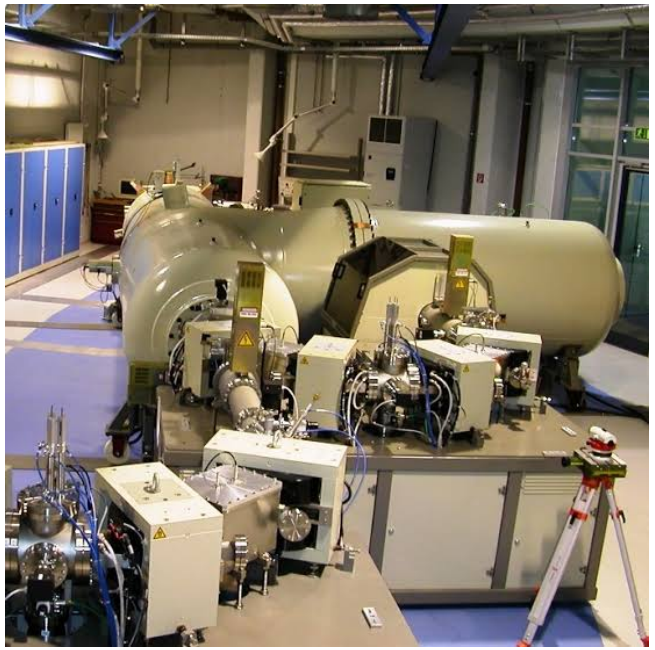
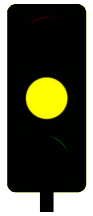
Cross-check yield for the ground state population determined by prompt/delayed spectroscopy

Methodology 🛠

- **Accelerator Mass Spectrometry (AMS)**
- **established method for cosmogenic ^{26}Al in grains on earth and from meteorites**
- **^{25}Mg/^{26}Al and ^{26}Mg/^{26}Al standards to be developed**



CologneAMS University of Cologne - Centre for Accelerator Mass Spectrometry



Risk

activated region is small

… preparation for AMS

Conclusion ...

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Nuclear spectroscopy at HPLS looks feasible

EMP resilience of hardware

Activation experiments
- delayed or decay spectroscopy
- AMS as cross-check

Prompt spectroscopy
- approach beyond traditional methods required
- sampling of whole signal for longer period
- off-line decomposition by AI techniques

Physics outcome with immediate impact on nuclear astrophysics: depletion of ground state
By ectromagnetic excitation to the astromer in ^{26}Al … can be measured only at HPLS facilities

Still „some“ work to do to be ready for real experiments!!!

… and start of discussion!!!

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Thanks ...