2nd Symposium on new trends in Nuclear and Medical Physics

hosted by JAGIELLONIAN UNIVERSITY IN KRAKÓW

AGH

RESEARCH UNIVERSITY

24-26 September 2025

Faculty of Physics, Astronomy and Applied Computer Science,
Jagiellonian Universityin Krakow, Poland

Proton-induced nuclear reactions in the hadrontherapy energy range

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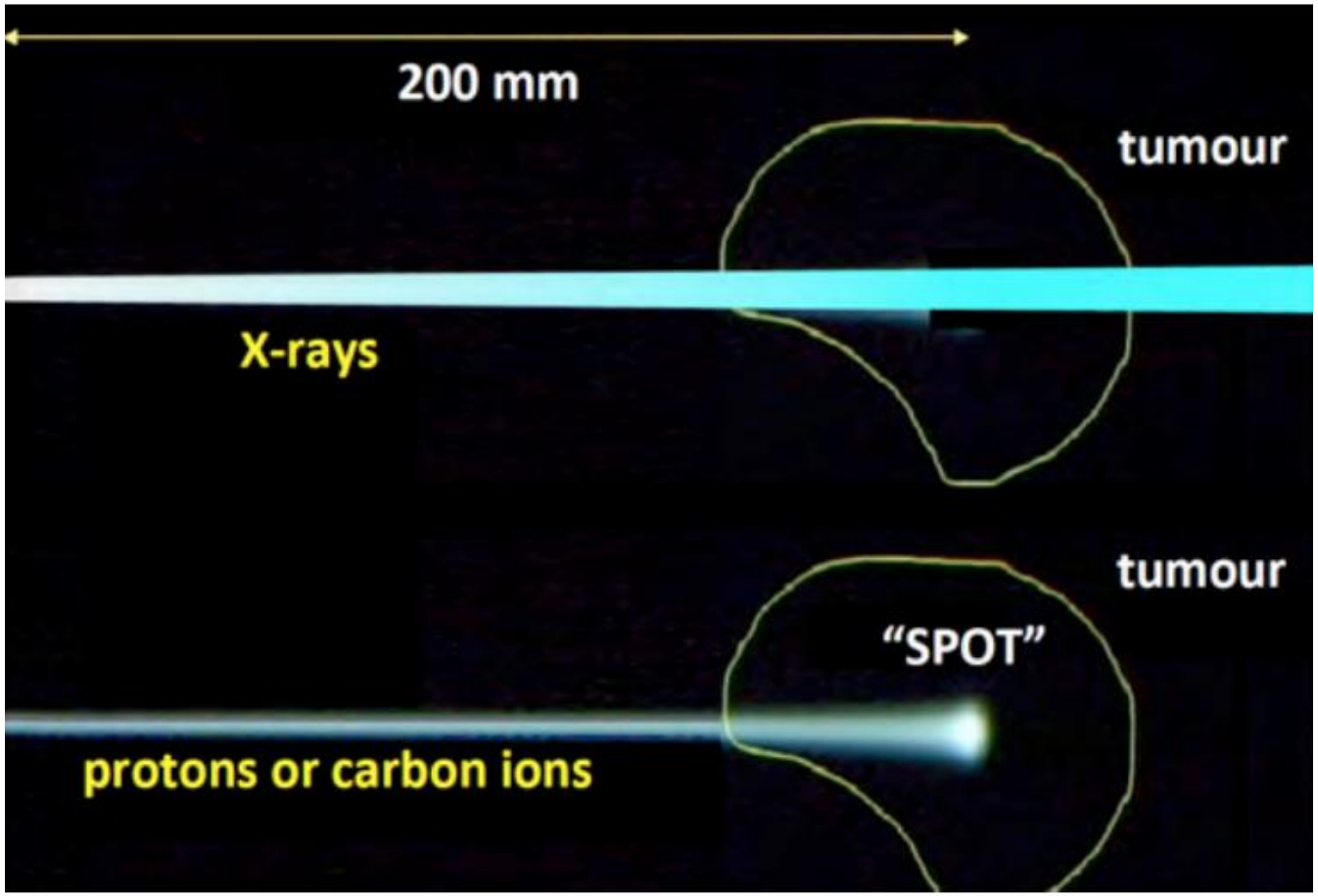
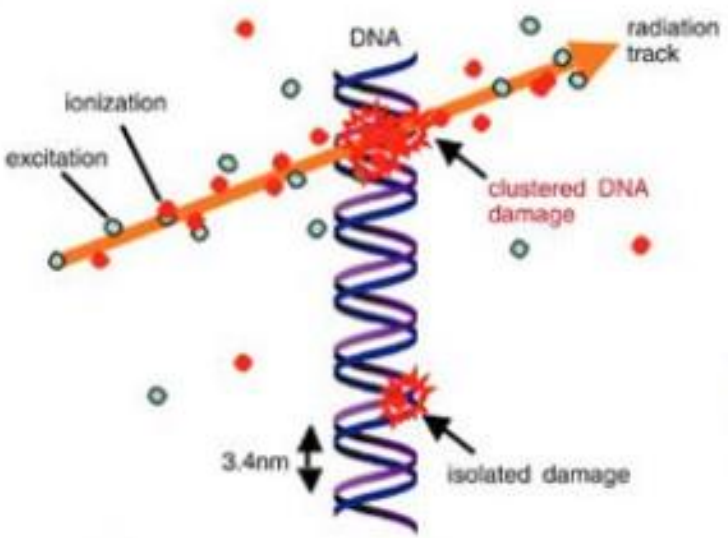
Agenda

- Proton-induced nuclear reactions during protontherapy: limited knowledge
- Experimental procedure
- Results on β^+ isotopes
  - $p+^{12}C \rightarrow {}^{11}C$ NIM A1040 (2022)
  - $p+^{14}N \rightarrow {}^{11}C, {}^{13}N$ APPB 17, 3-A37 (2024)
  - $p+^{16}O \rightarrow {}^{11}C, {}^{13}N, {}^{15}O$ EPJA 60:203 (2024)
  - p+tissue $\rightarrow {}^{11}C, {}^{13}N, {}^{15}O, {}^{18}F$
- Conclusions

Principle of ion-beam therapy

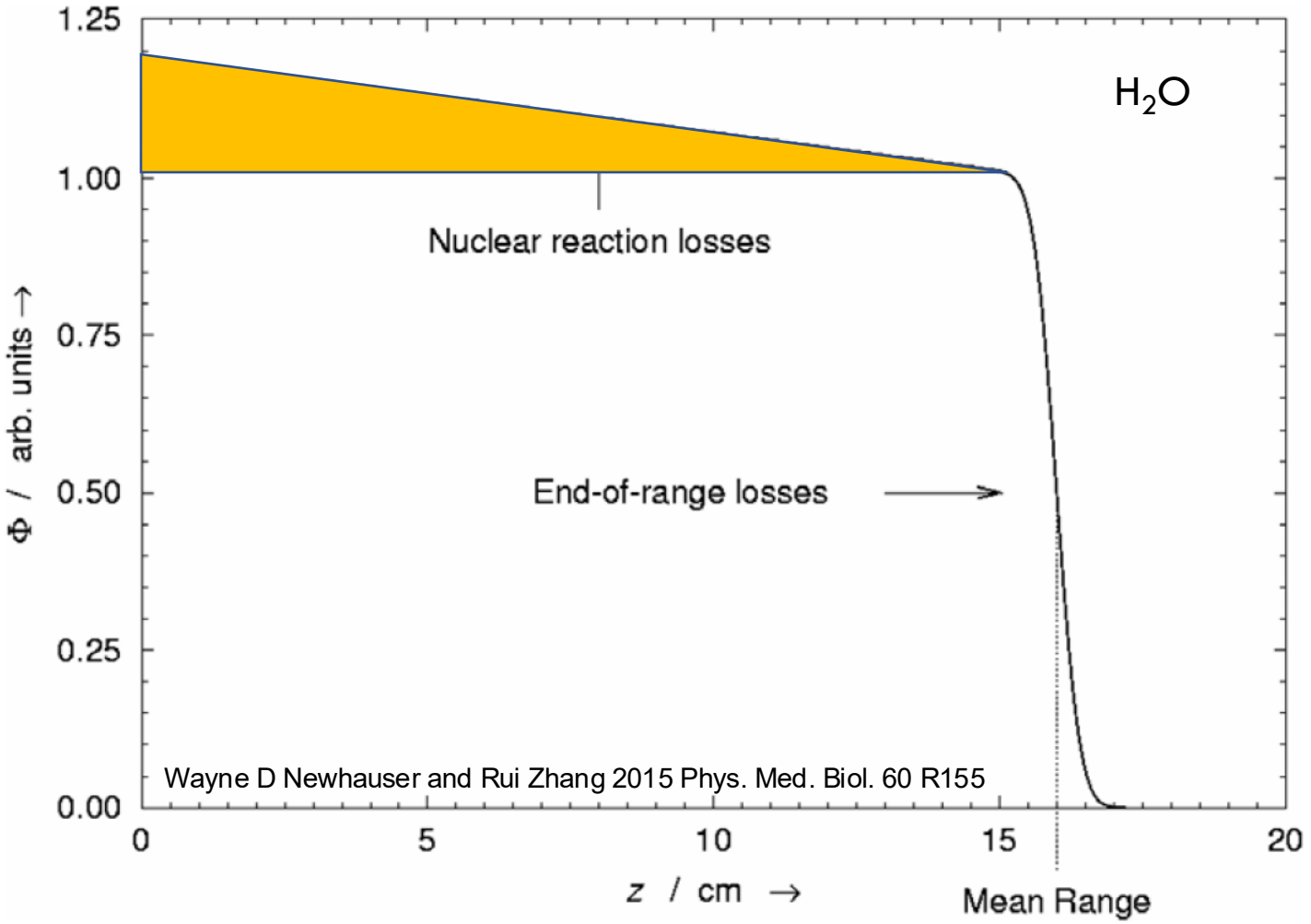




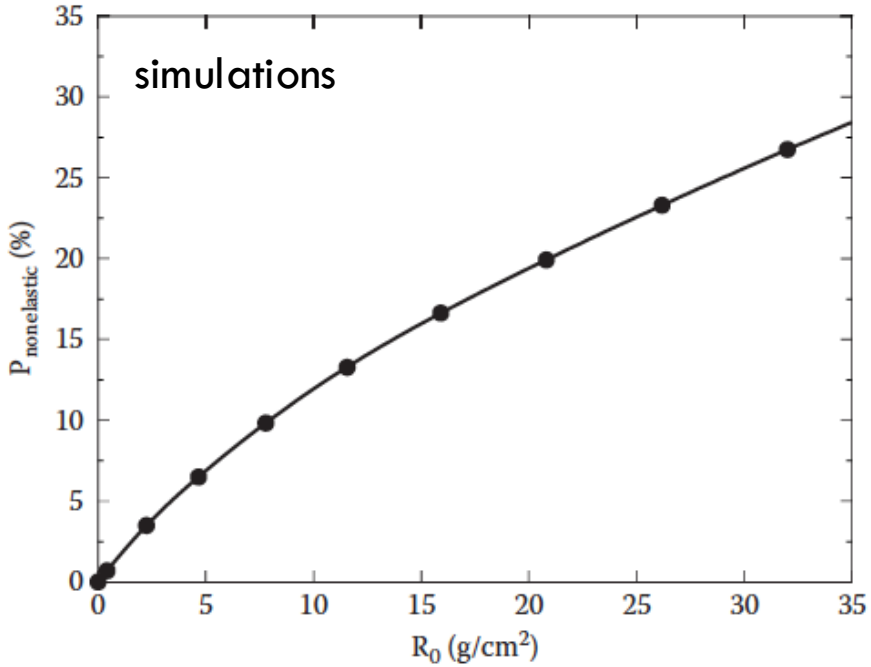
Effect on cellular DNA

Idea:
Robert Wilson (1946)
„Radiological use of fast protons"

Nuclear interactions during proton therapy



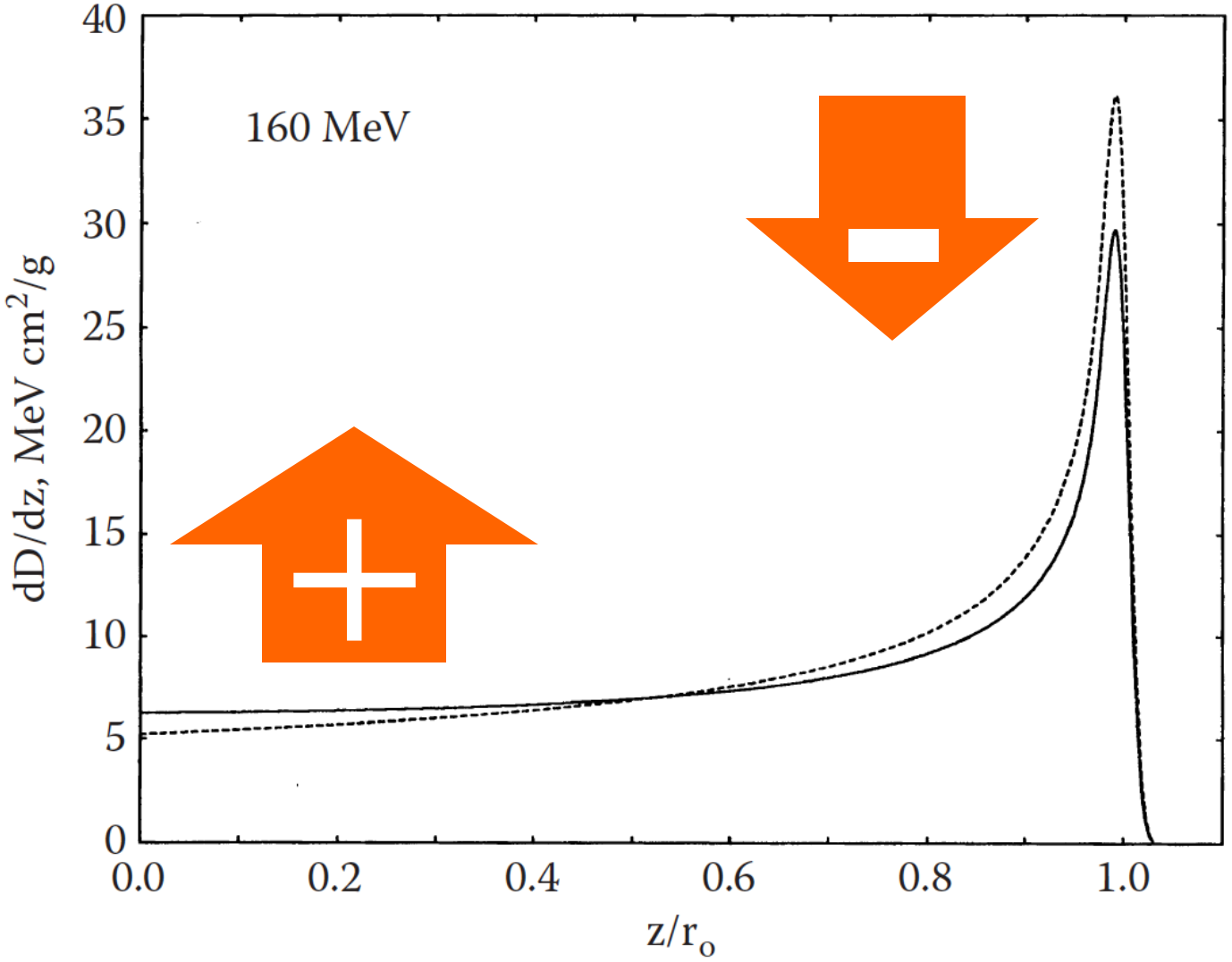
Probability of inelastic nuclear reactions



The influence of nuclear reactions is non-negligible

Nuclear interactions during proton therapy

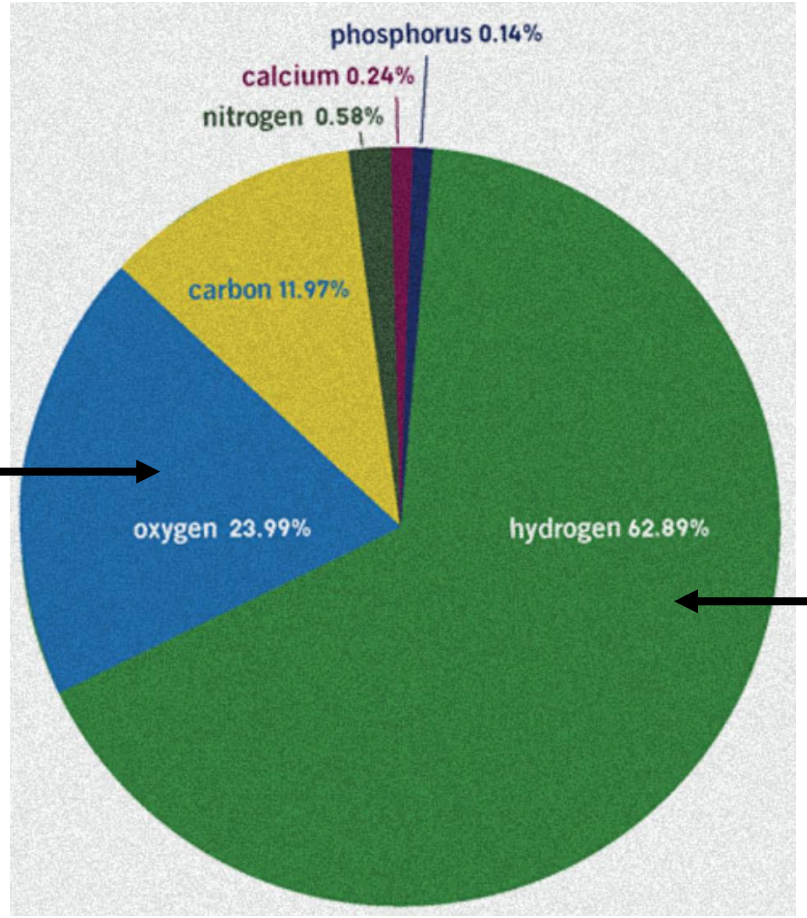
- Increase the dose at entrance
- Reduce the dose around the Bragg peak



Martin J. Berger, NIST technical note NISTIR 5226 (1993)

Composition of human tissue

inelastic reactions on those nuclei possible for therapeutic proton beam



% of atoms

inelastic reaction on hydrogen only above pion production threshold ~300 MeV

Production of $\beta+$ emitters:

1. ^{11}C ($T_{1/2}$ ~ 20 min)
2. ^{13}N ($T_{1/2}$ ~ 10 min)
3. ^{15}O ($T_{1/2}$ ~ 2 min)

→online PET?

Produced nuclei are often β^+ radioactive

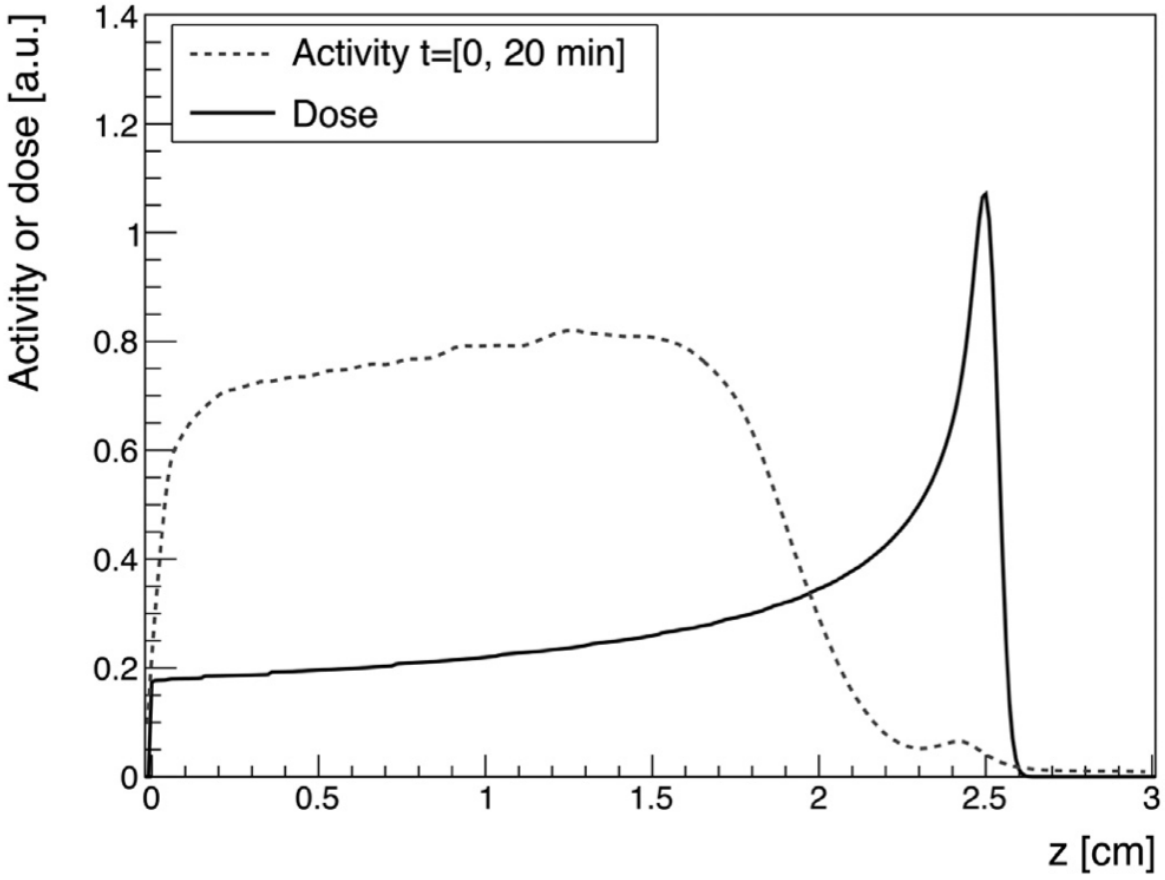
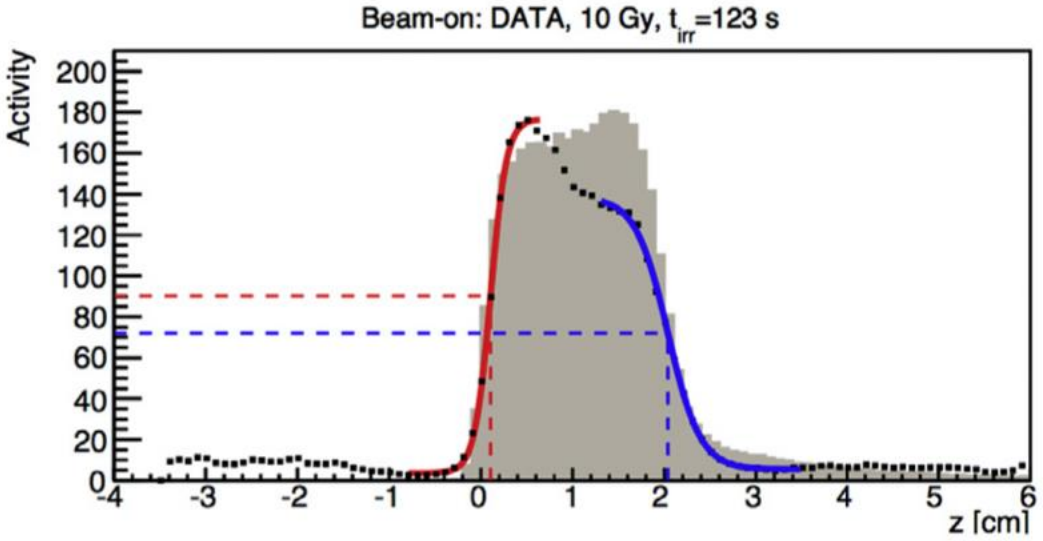


Figure 1. Simulated Bragg peak and activity 1-D profile along the *z*-direction (beam direction) of 58 MeV protons on a PMMA target, obtained with a FLUKA Monte Carlo simulation of 800 M protons.

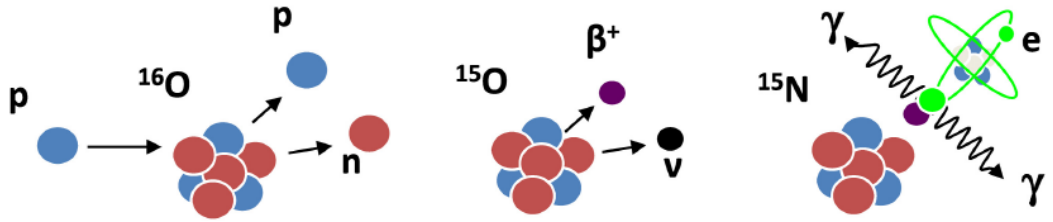


Experimental β^+ activity of PMMA compared to FLUKA simulations (shaded area)

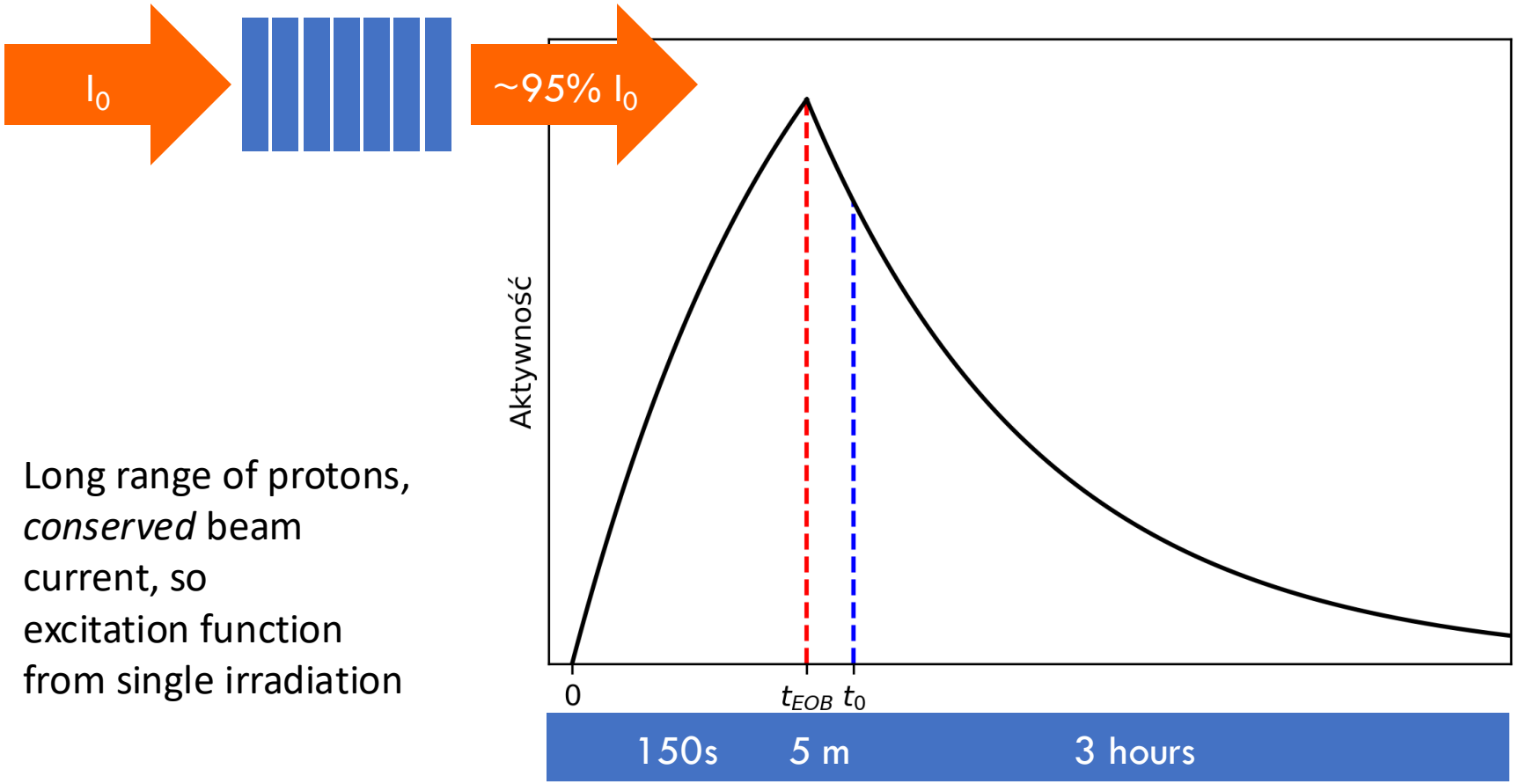
A.C.Kraan et al., Physica Medica 30 (2014) 559

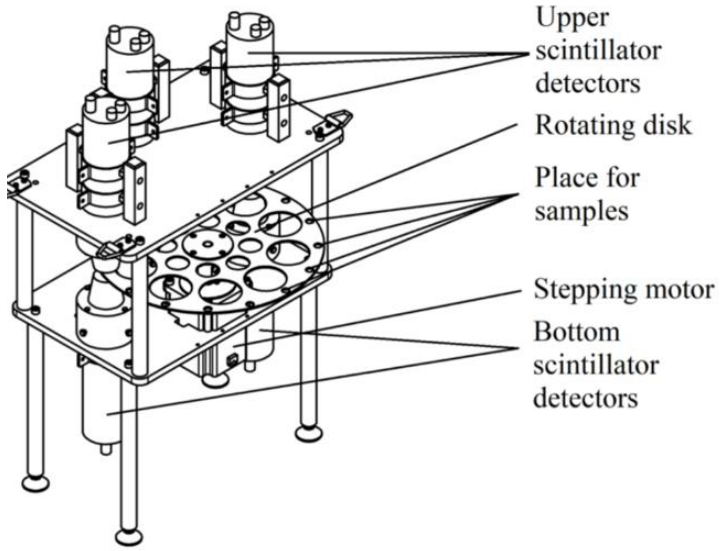
Simultaneous irradiation of several targets

activation



β+ decay

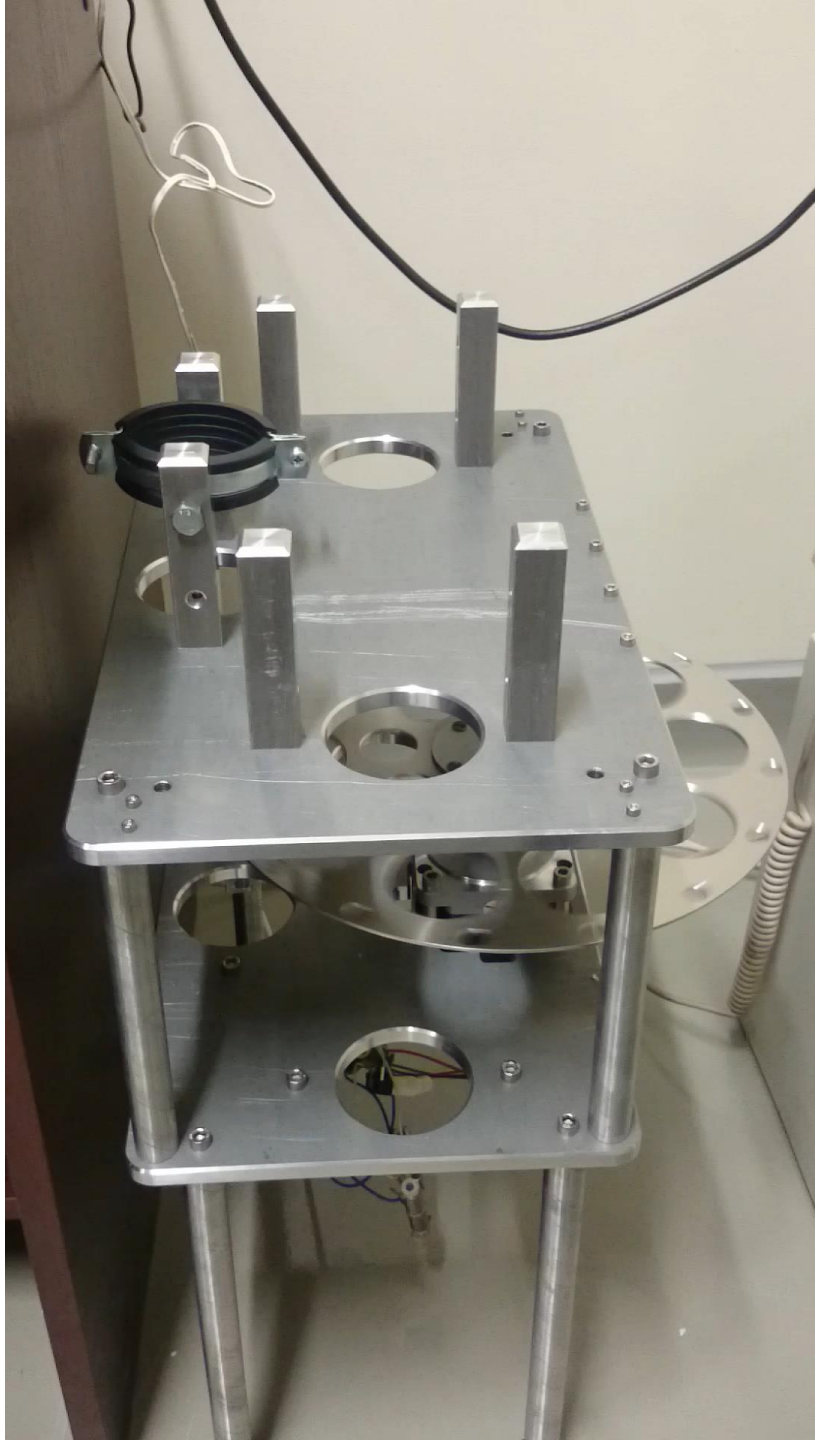




Long range of protons, *conserved* beam current, so excitation function from single irradiation

Irradiation and detection

eye therapy unit, beam from AIC-144 IFJ PAN
(very precise dose delivered)
Leader: prof. J. Swakoń



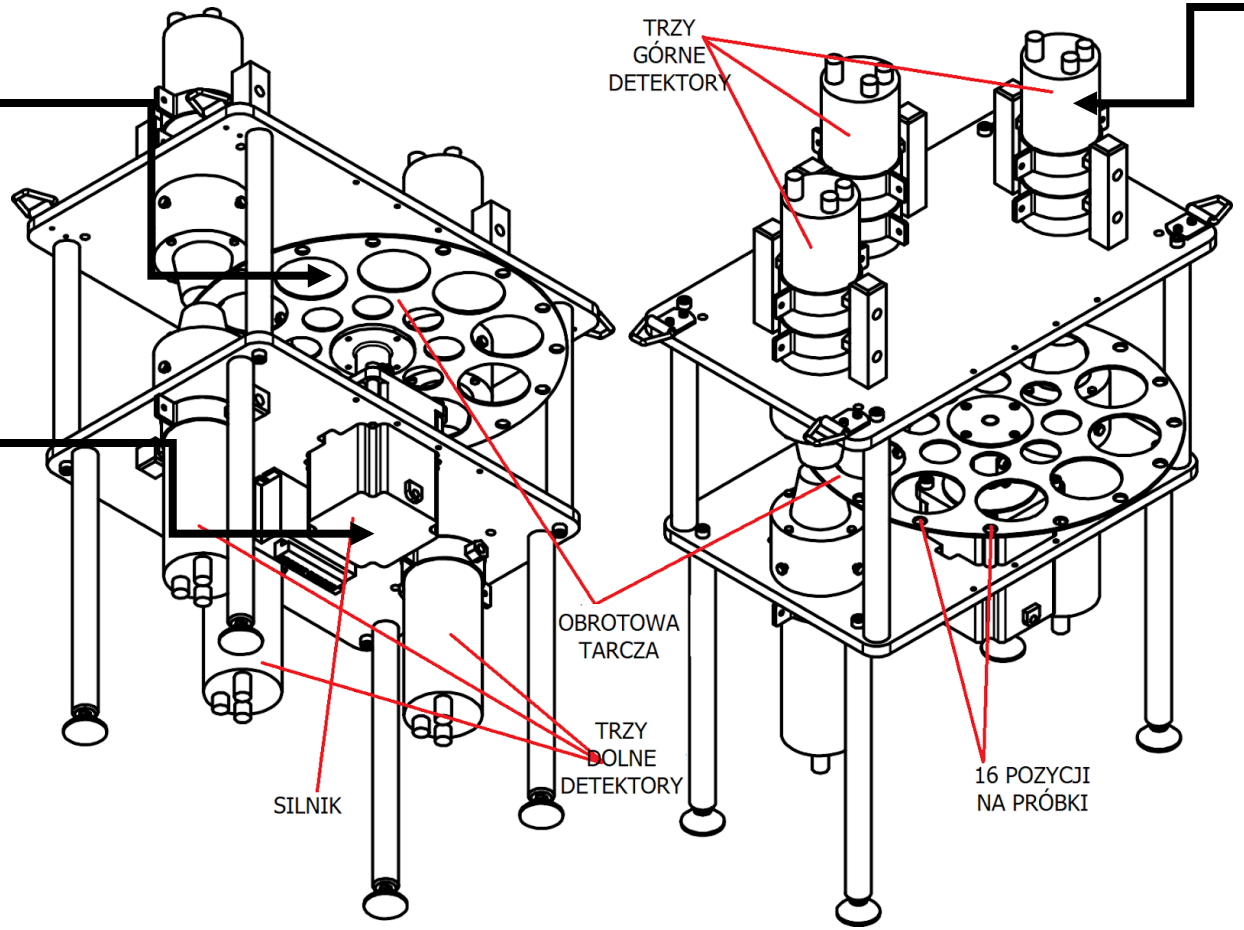
Spectroscopy setup

rotating plate

for up to 16 irradiated targets

stepping motor

with **programmable rotation sequence**: short time between rotations to capture initial activity of all targets, later increased for adequate statistical accuracy



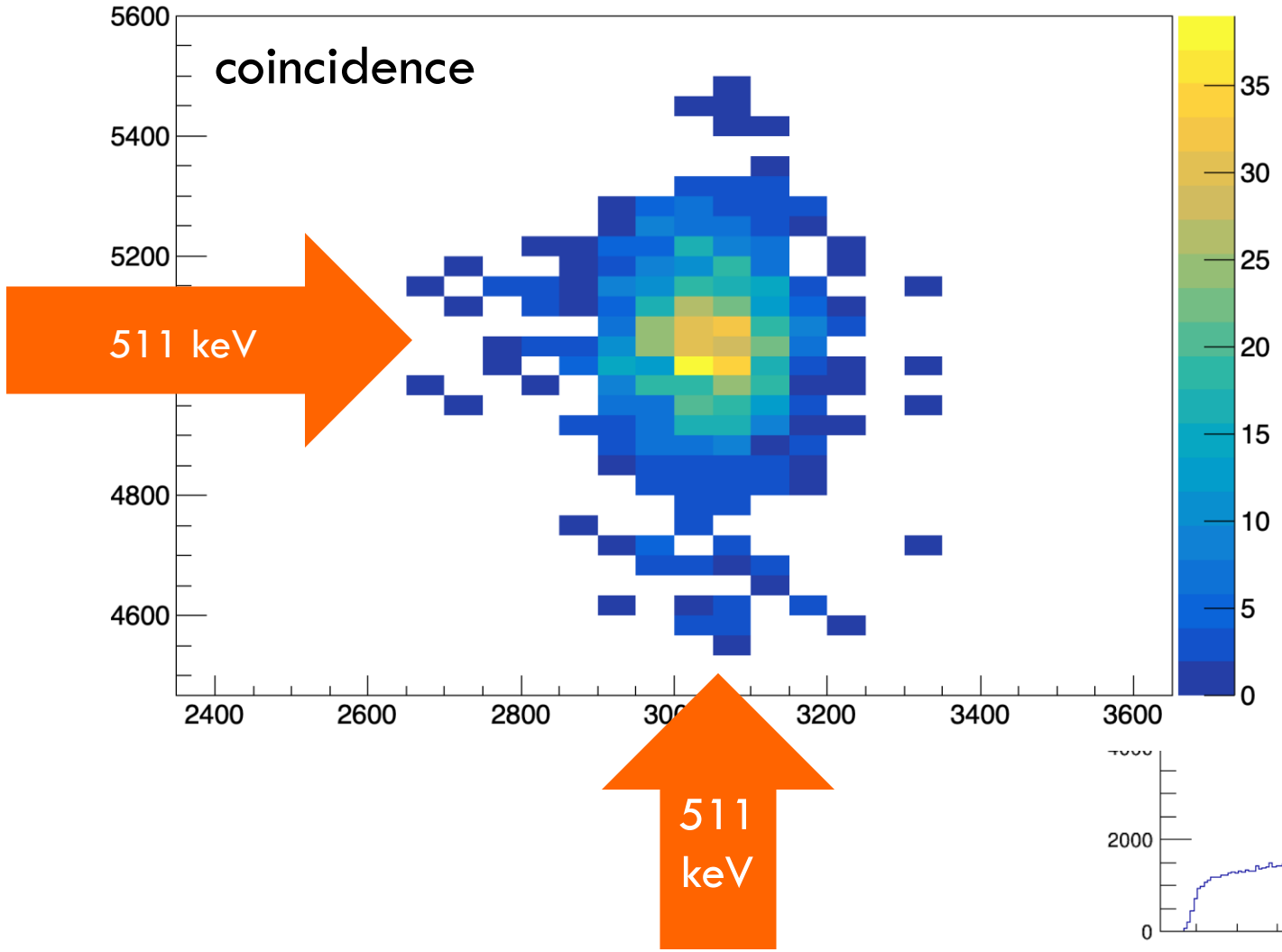
$LaBr_3$ detectors

1 inch on top
1.5 inch on bottom
~1,8% efficiency for one pair to detect both 511 keV photons

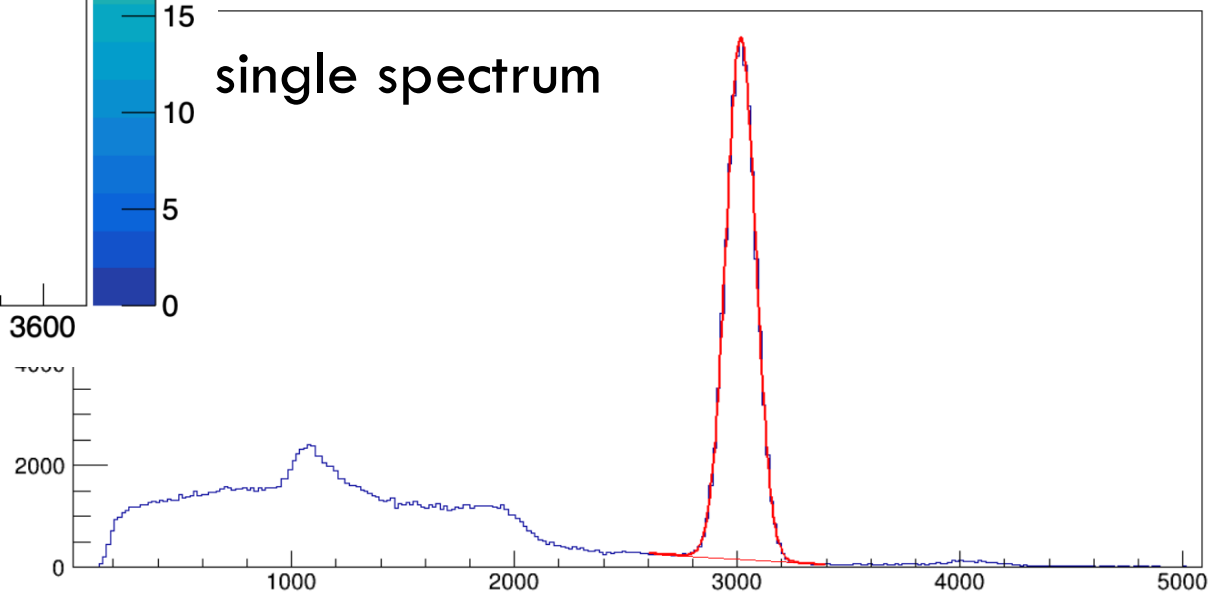
+ CAEN digitizer

500 MHz CAEN digitizer DT5730SB (triggerless)

Measurement



511 keV photons from e^+e^- annihilation



Targets

elementary

- Carbon
- Boron nitride (BN)
- Silicon dioxide (SiO_2)

animal tissue

- Pork liver, kidney, heart
- Beef bone

$^{16}O(p,d)^{15}O$ & $^{16}O(p,\alpha)^{13}N$ & $^{16}O(p,\alpha d)^{11}C$

Selection – SiO_2

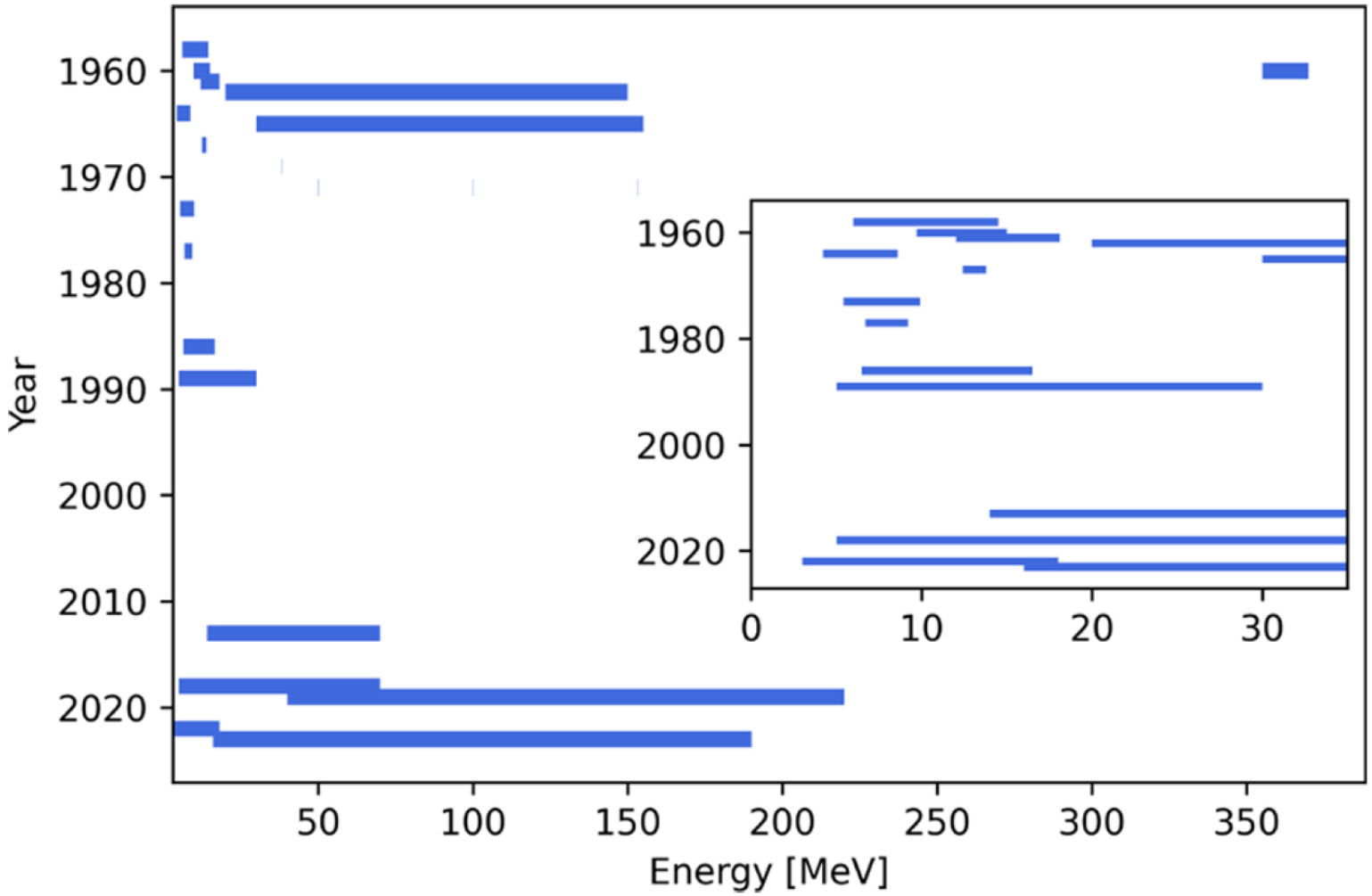
- proton-induced reactions on ^{28}Si produce:
  - short-lived β^+ nuclei
    ^{27}Si $T_{1/2}$=4s,
    ^{25}Al $T_{1/2}$=7s,
    ^{23}Mg $T_{1/2}$=11s
  - long-lived ^{18}F $T_{1/2}$=110 m
- availability of optical quality wafers of requested thickness

$^{16}O(p,d)^{15}O$ & $^{16}O(p,\alpha)^{13}N$ & $^{16}O(p,\alpha d)^{11}C$

- First measurements around 1960
- 511 keV activity from e^+e^- observed mainly with NaI(Tl) detector(s)

- Refreshed interest due to importance for therapy with proton beam
- Mesurements with PET scanners in medical centers after 2010

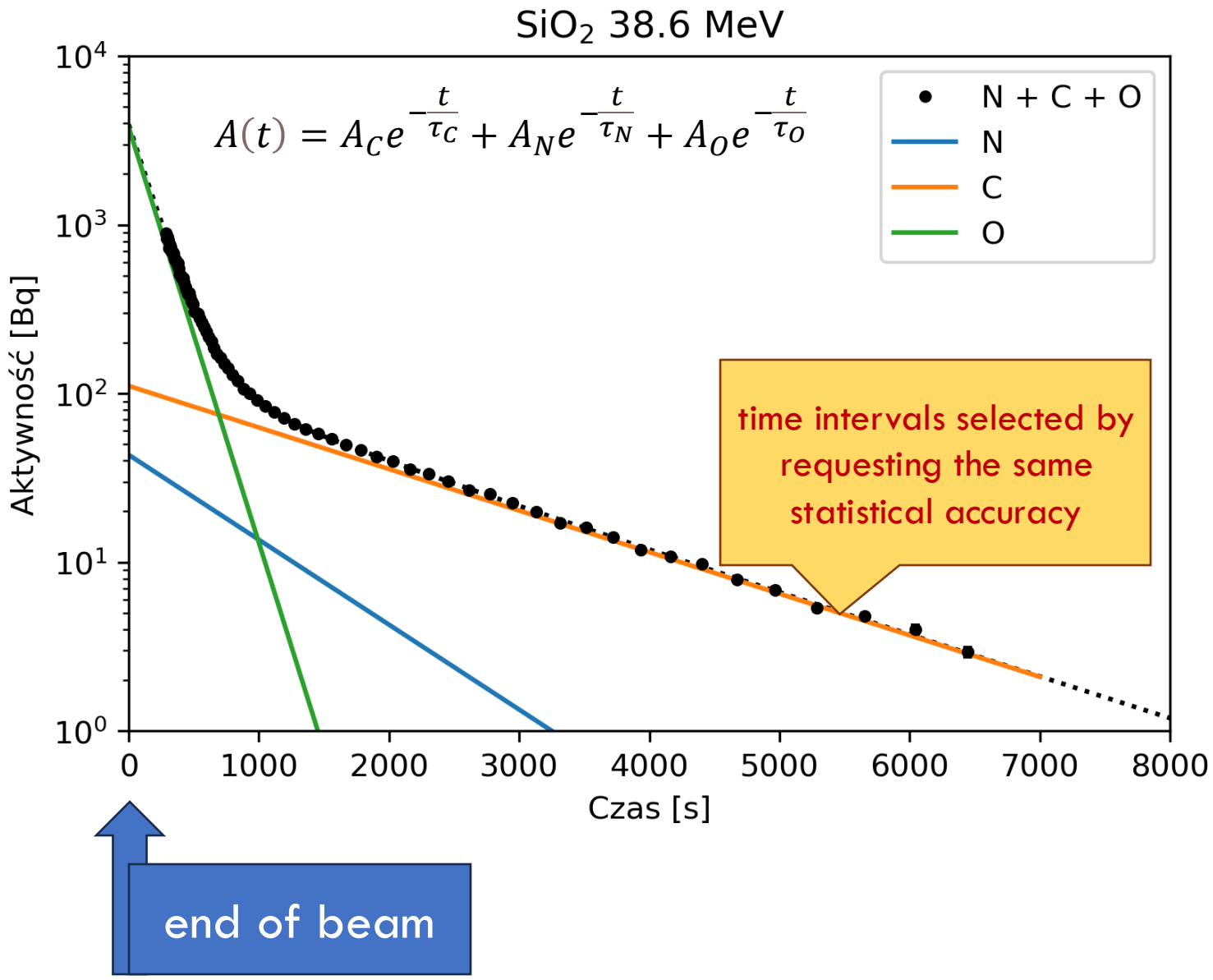
- The results are not fully consistent



$^{16}O(p,d)^{15}O$ & $^{16}O(p,\alpha)^{13}N$ & $^{16}O(p,\alpha d)^{11}C$

Two types of measurements:

1. Continous (3 irradiated targets placed between 3 pairs of detectors)
2. Sampled (15 irradiated targets rotated between 3 pairs of detectors)

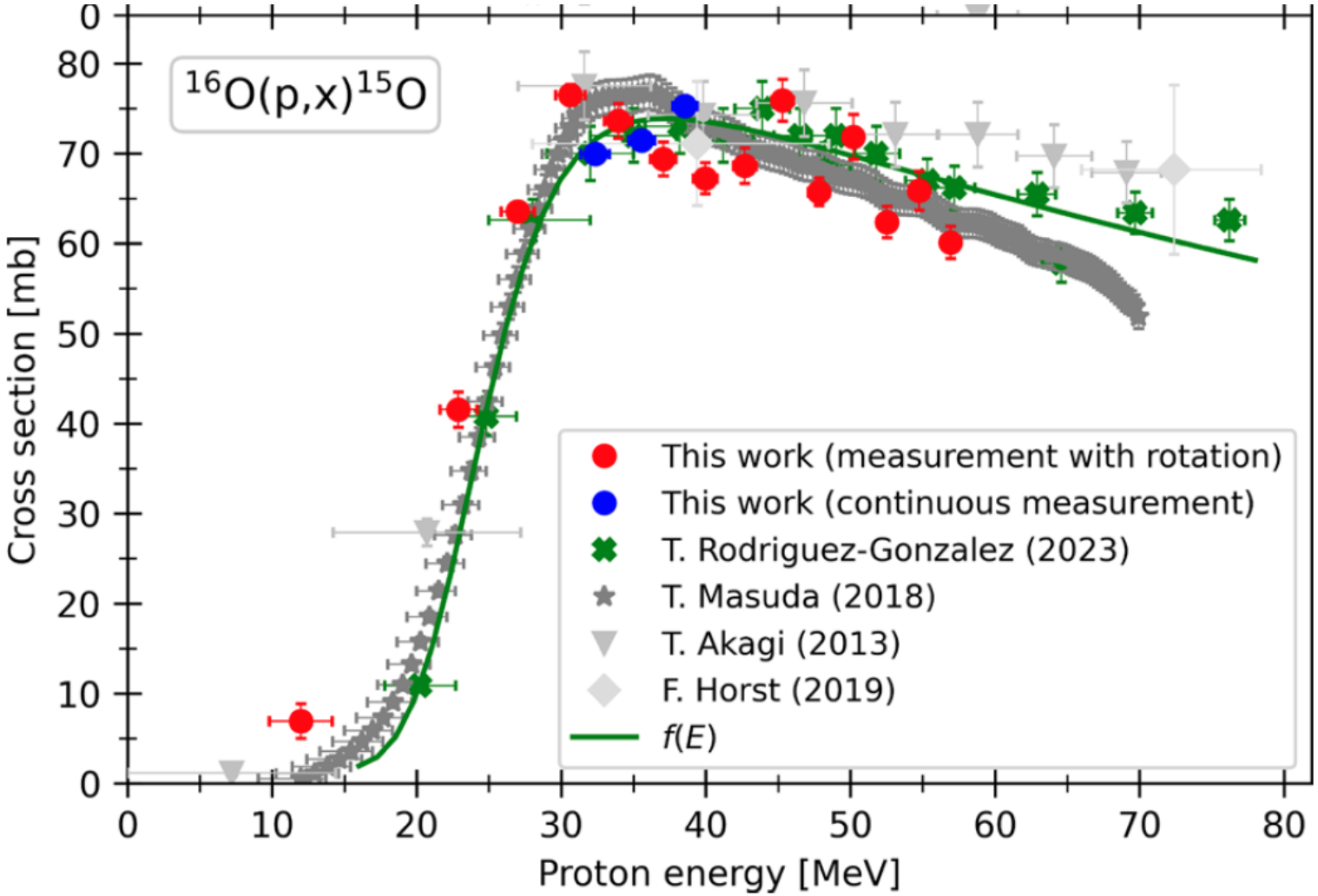


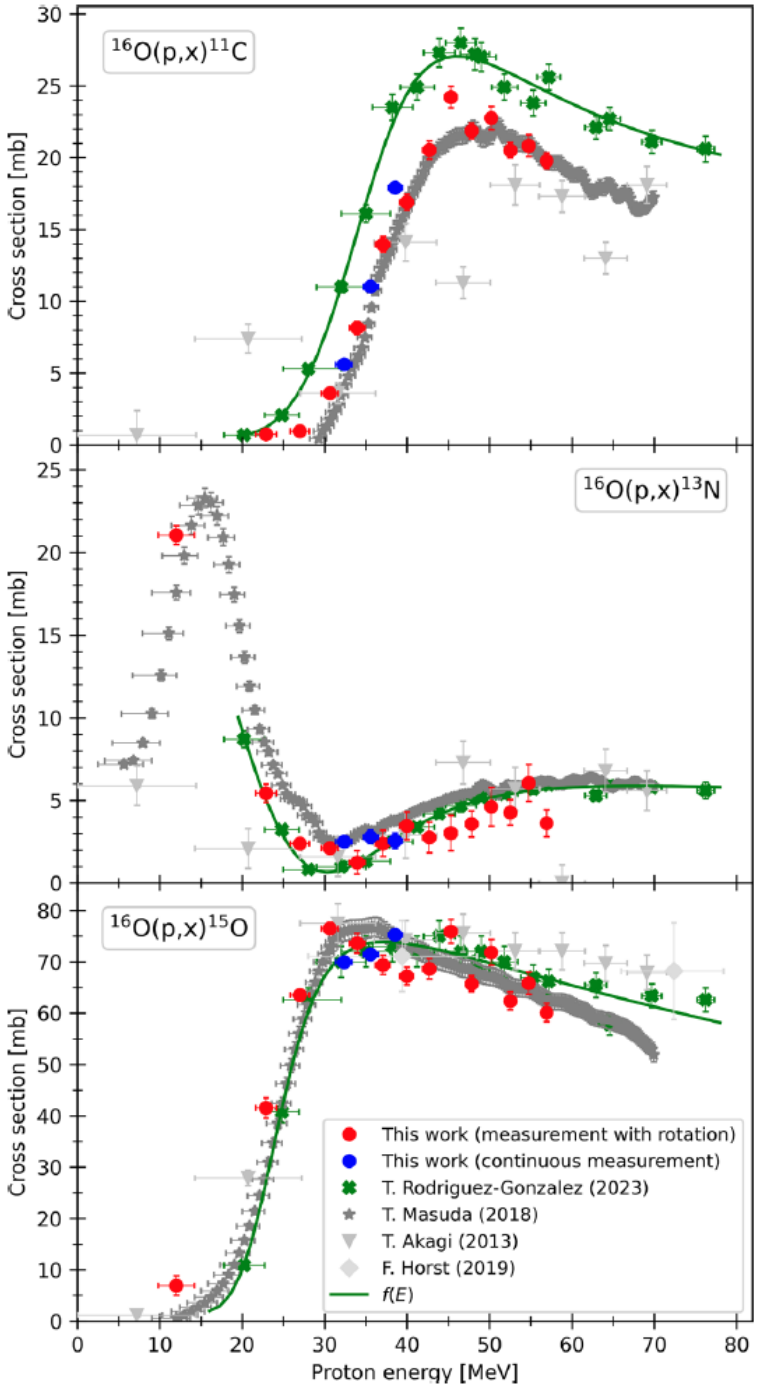
$^{16}O(p,d)^{15}O$

- General agreement with recent measurements (mainly PET)
- The results from novel technique of Cherenkov radiation are confirmed
- Sampled and continuous measurement of activity provides consistent results

Eur. Phys. J. A (2024) 60:203
https://doi.org/10.1140/epja/s10050-024-01420-5
THE EUROPEAN PHYSICAL JOURNAL A
Regular Article - Experimental Physics

Measurement of cross section of proton-induced reactions on oxygen with silicon dioxide target





p+^{16}O → ^{11}C, ^{13}N, ^{15}O

- The cross section for ^{13}N production agrees with previous measurements, but the recent measurements of Rodriguez-Gonzalez et al. (2023) are well above all others in the ^{11}C production (seems to be an easy detection of long-lived nuclei)
- Again, Cherenkov method (Masuda et al. 2018) applied to bulk SiO_2 provides consistent results

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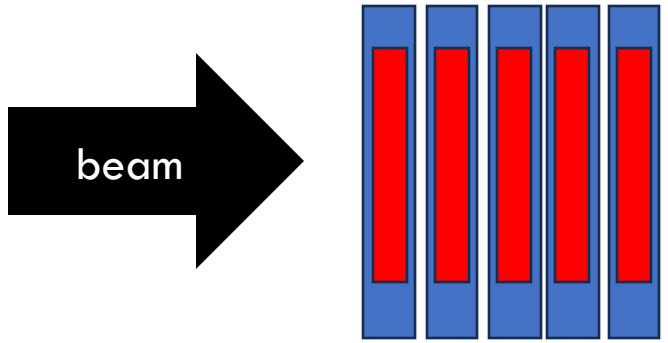
Animal tissue target



- Pork liver, heart, kidney and beef bone
- Mylar foil as windows glued to 12 mm diameter 3D printed cylinders
- Targets frozen after preparation
- High initial activity of short-lived ^{15}O in all samples
- Observation of ^{18}F ($T_{1/2}$~2h) activity in irradiated bones

Conclusions

- New precise results on proton-induced reactions on elementary targets present in tissue: C, N, O
- Initial results of activity of irradiated tissues under analysis (comparison with model calculations)

- Next: higher-energy (70 MeV-230 MeV) measurements at Proteus CCB and low energy scan of BN target below 30 MeV at AIC-144 cyclotron (both IFJ PAN, Kraków)

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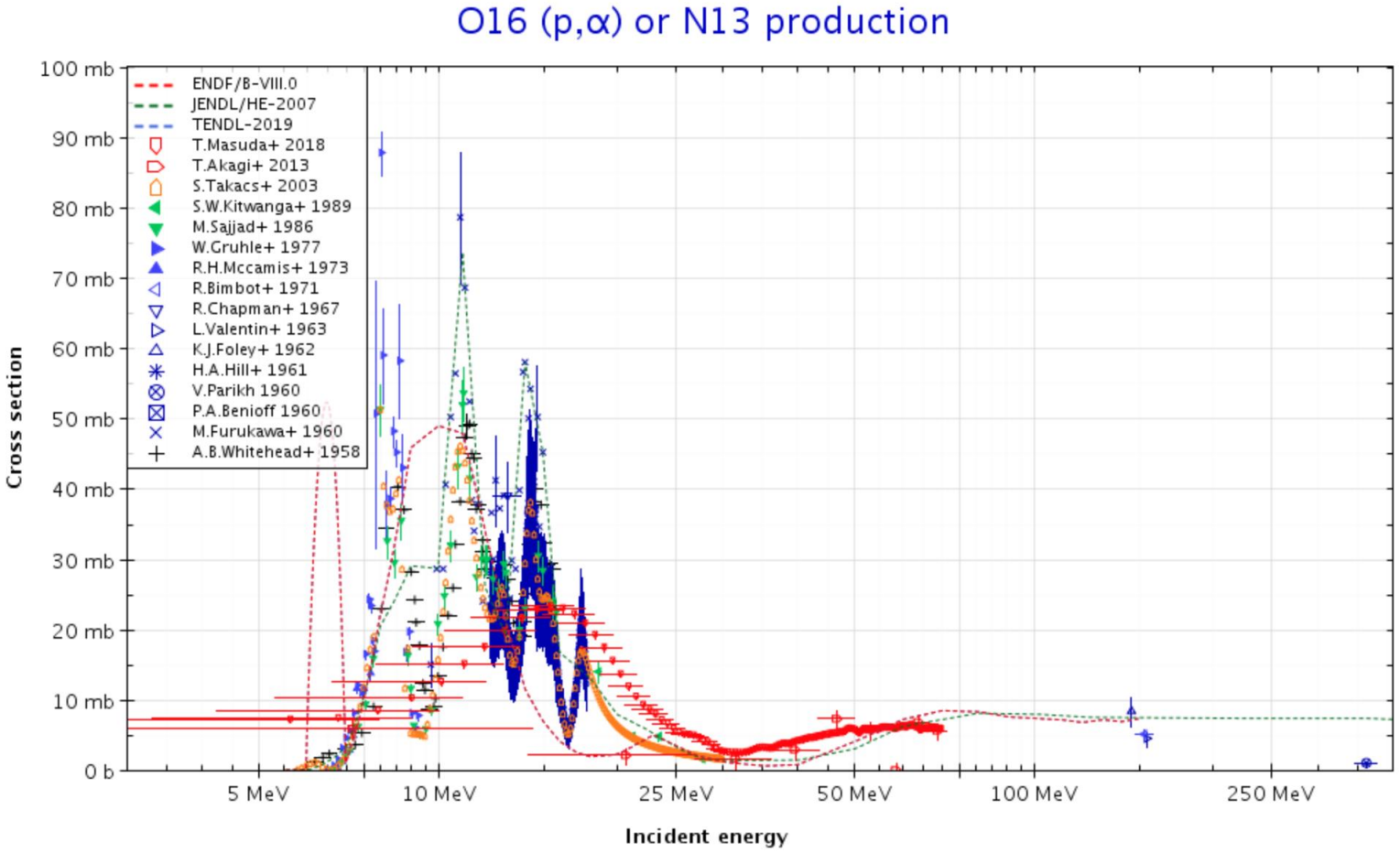
Evaluation of results?



- PDG 😀
- CNO Reactions Group?

Nuclear Energy Agency *JANIS Book*
www.oecd-nea.org/janis