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Laser-driven ion sources for medical radioisotope generation

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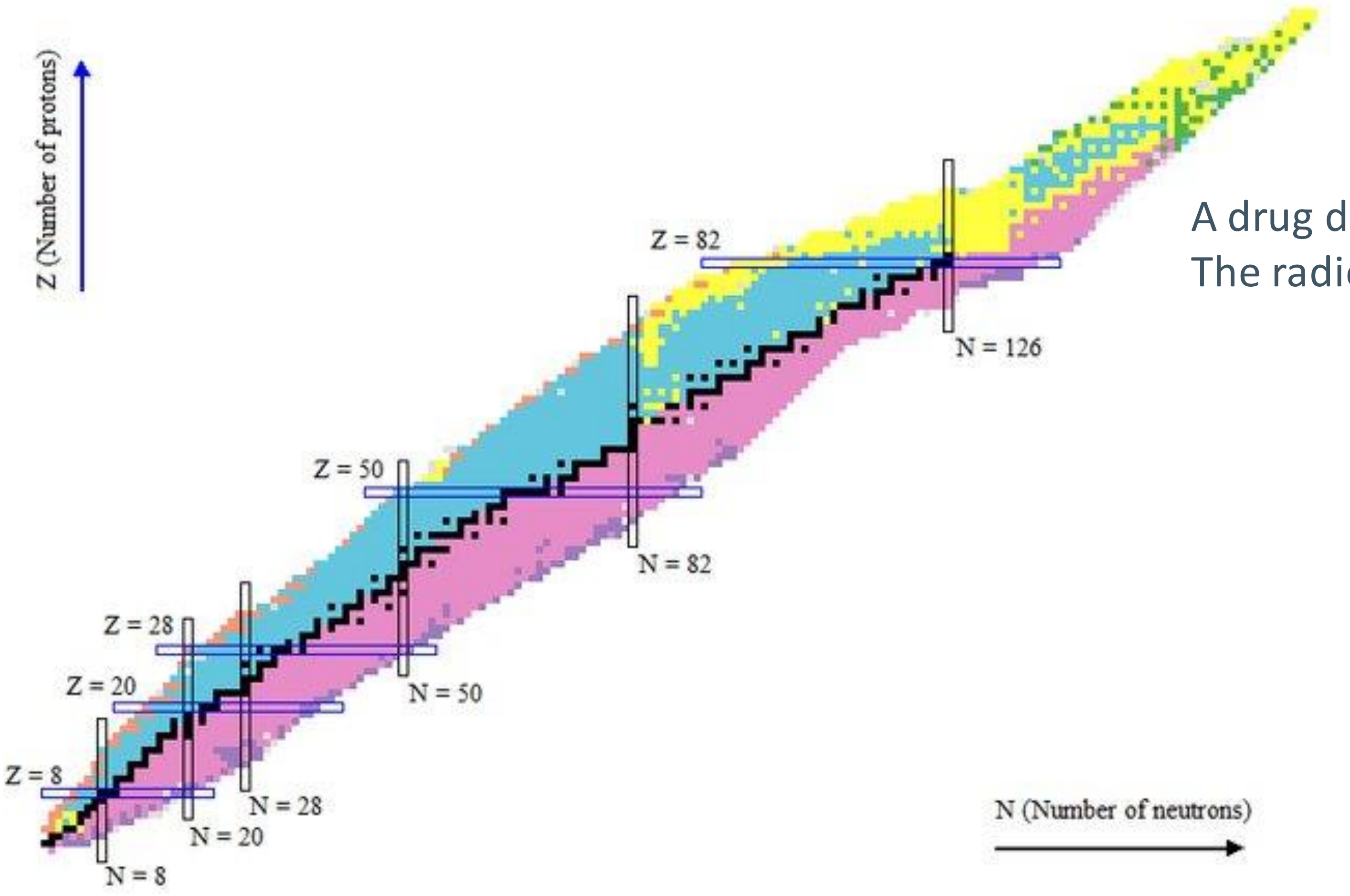
Laser-driven ion sources for **medical radioisotope** generation

Radioisotopes in Nuclear Medicine

Application of radioisotopes for the diagnosis and treatment of deseases.



A drug delivers radionuclides to biological target sites

The radioactive decay is exploited to:

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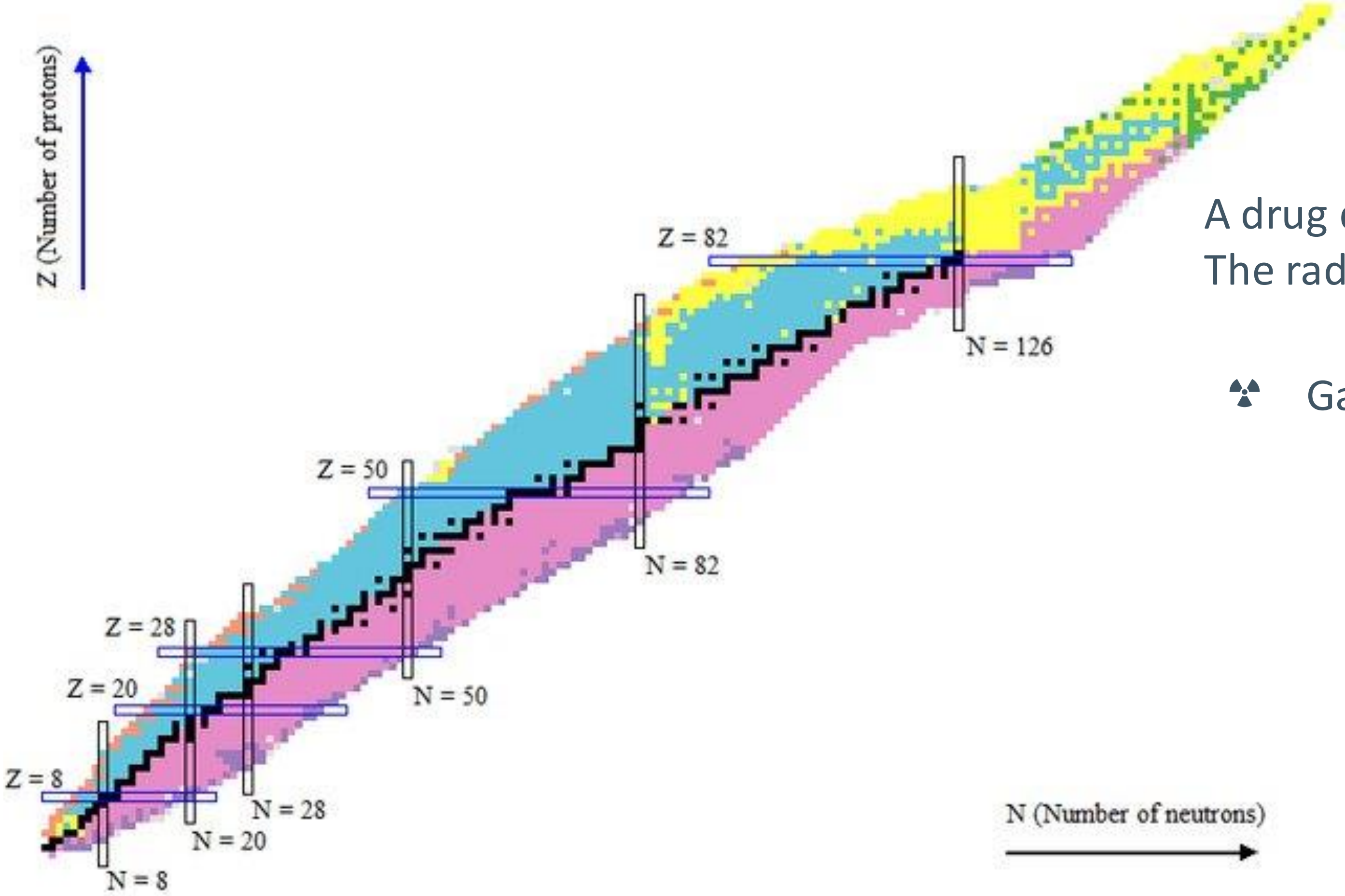

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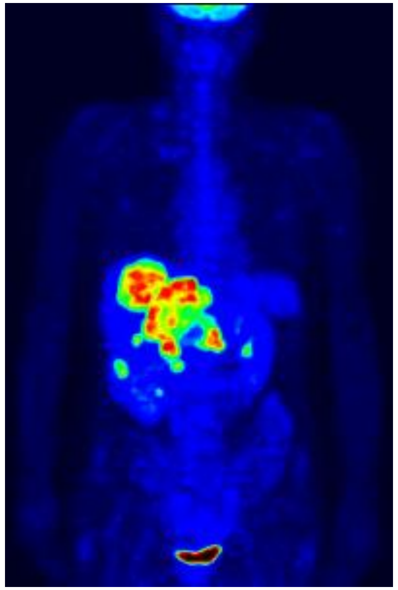
The radioactive decay is exploited to:

- Gather **anatomical** and **functional** information



Radioisotopes in Nuclear Medicine

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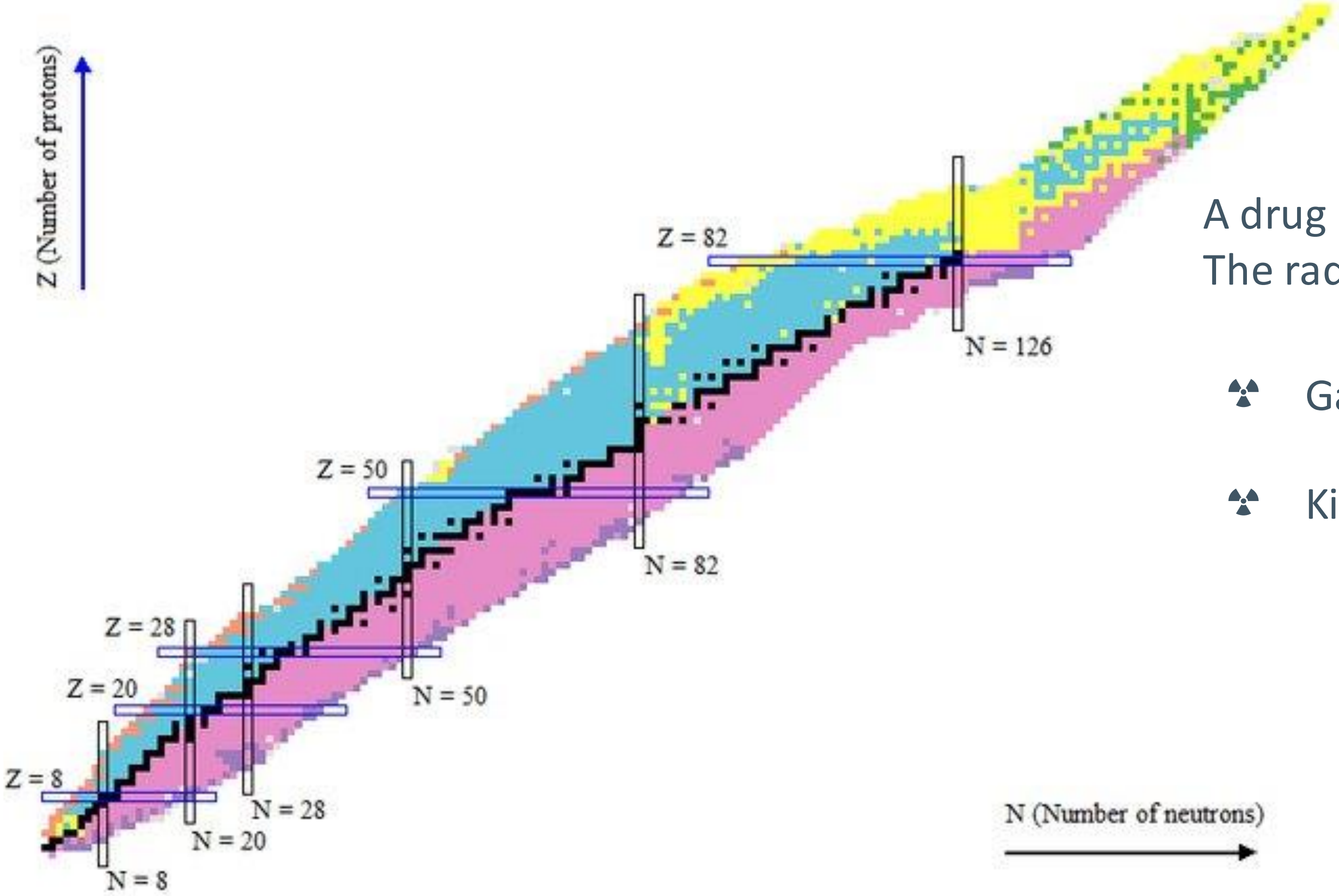
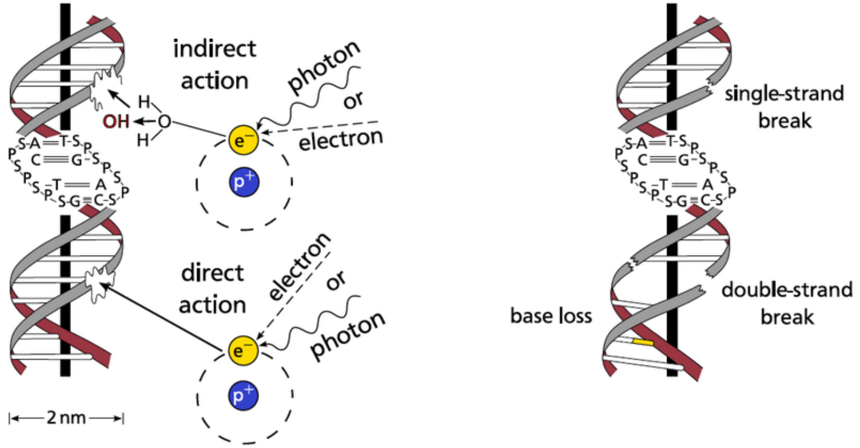


A drug delivers radionuclides to biological target sites
The radioactive decay is exploited to:

- Gather **anatomical** and **functional** information
- Kill malignant cells breaking their **DNA**

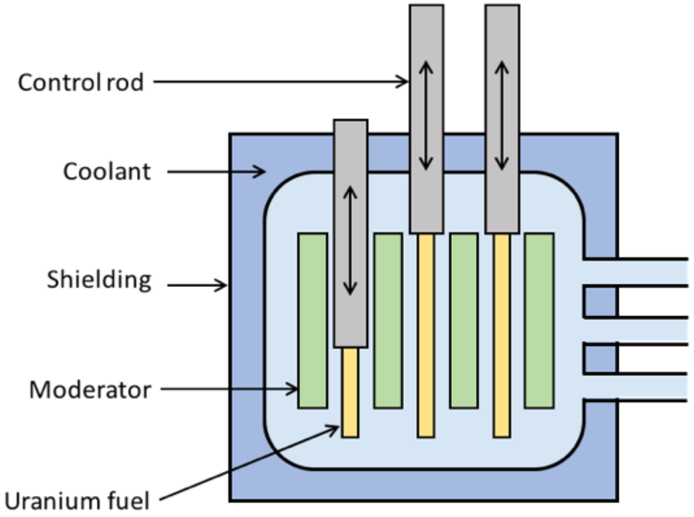


Production of medical radionuclides

Radionuclides decay: cannot be stored indefinitely. Constant production is required, even *in situ*

Nuclear fission reactors

$$\Phi = 10^{10} \div 10^{16}\, neutrons/_{cm^2 \cdot s}$$



^{99m}Tc used in 80% of nuclear diagnostics exams
^{133}I treating and imaging of thyroid
^{133}Xe - lung studies, half-life 5 days

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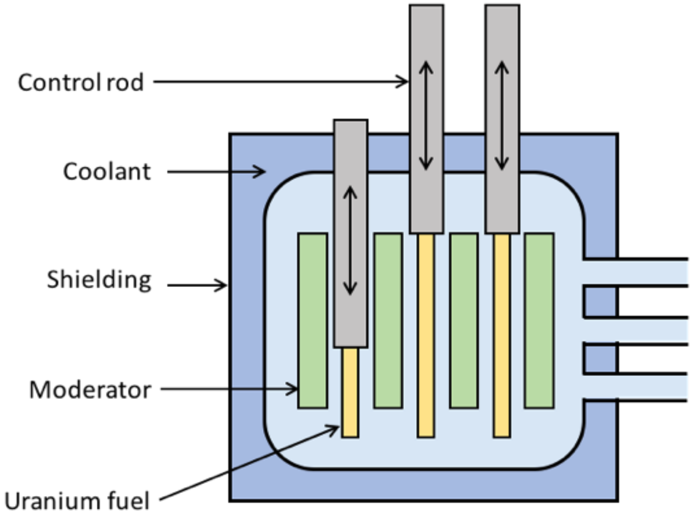

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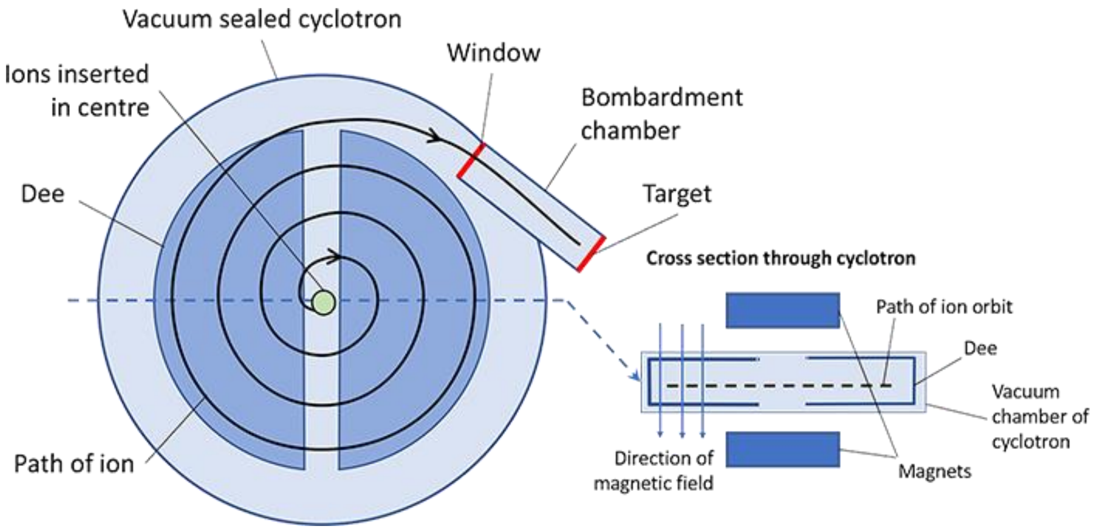
Conventional accelerators (mainly cyclotrons)



^{18}F for PET scanning (half-life 1.87 hours)
^{67}Ga for imaging of inflammation / tumors
^{81m}Kr for lung studies (half-life 13 s!)

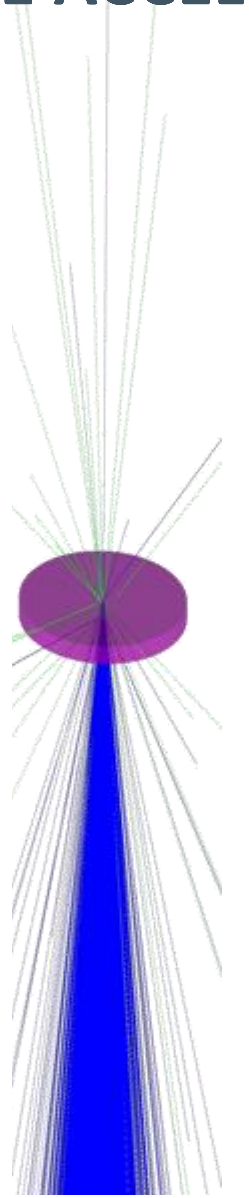
PARTICLE ACCELERATORS

CONVENTIONAL

The current state of the art is the **CYCLOTRON**

PROS

- High current: 10 – 100 μA
- High energy: 10 - 30 MeV
- High activity produced



CONS

- Neutron – gamma flux: Activation of the component, Shielding, Waste
- Dimension and costs
- Limited versatility: particles and energy are difficult to change

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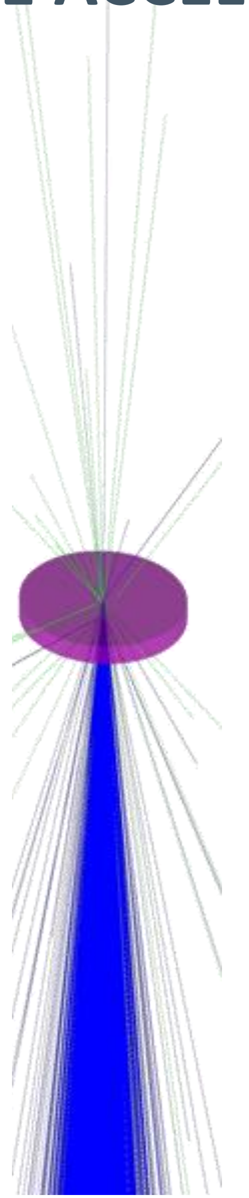
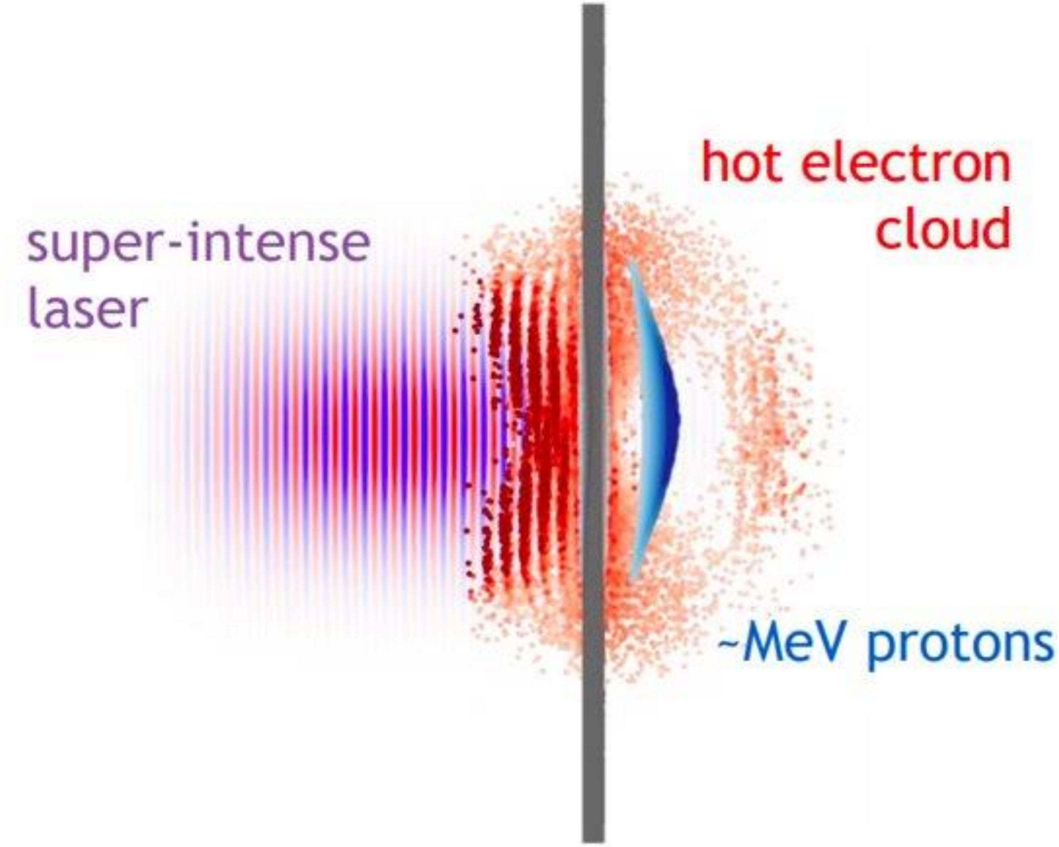


LASER-DRIVEN

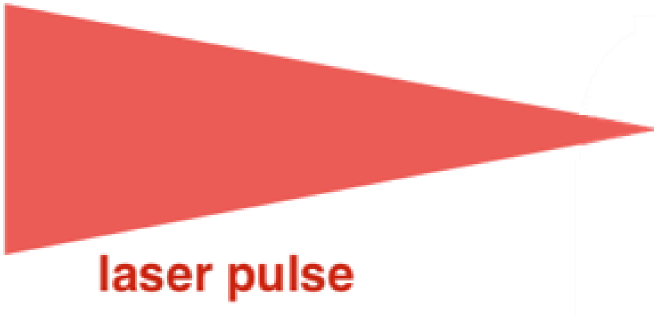


Potential for **flexibility** and cost **reduction**!

A. Macchi at al., Rev. Mod. Phys. 85, 751 (2013)

Laser-driven ion sources for medical radioisotope generation

Laser-Driven Particle Acceleration



I > 10^{18} W/cm^2

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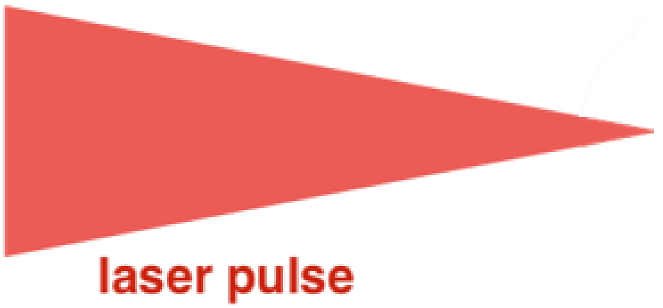

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Different laser systems:

- 0.1-10 J, 30 fs, high rep rate(compact)
- 10 J-1 kJ, ps, low rep rate (large)

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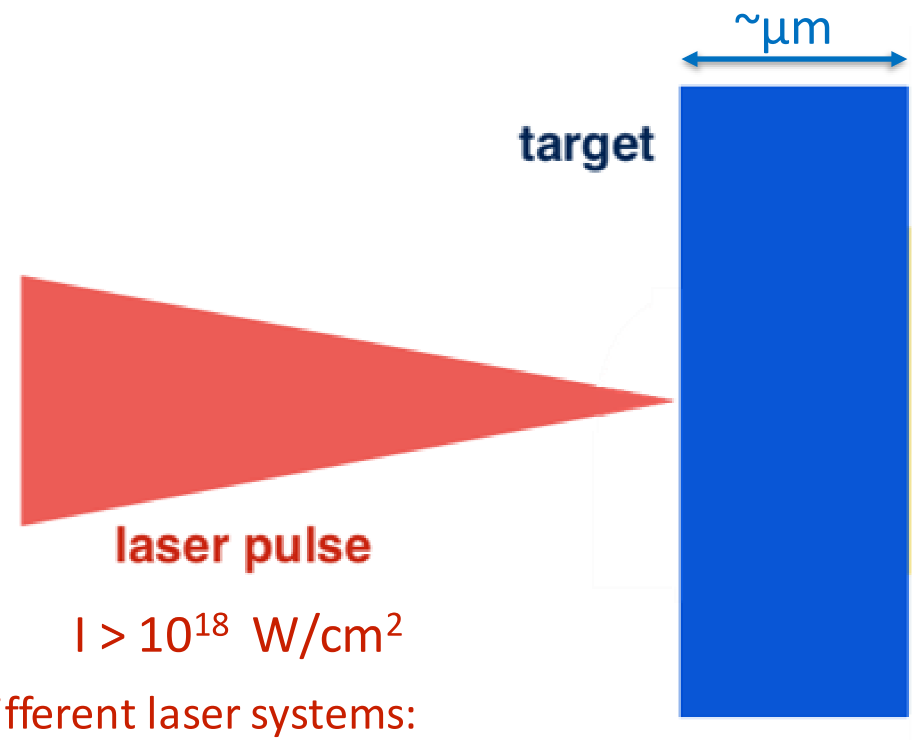

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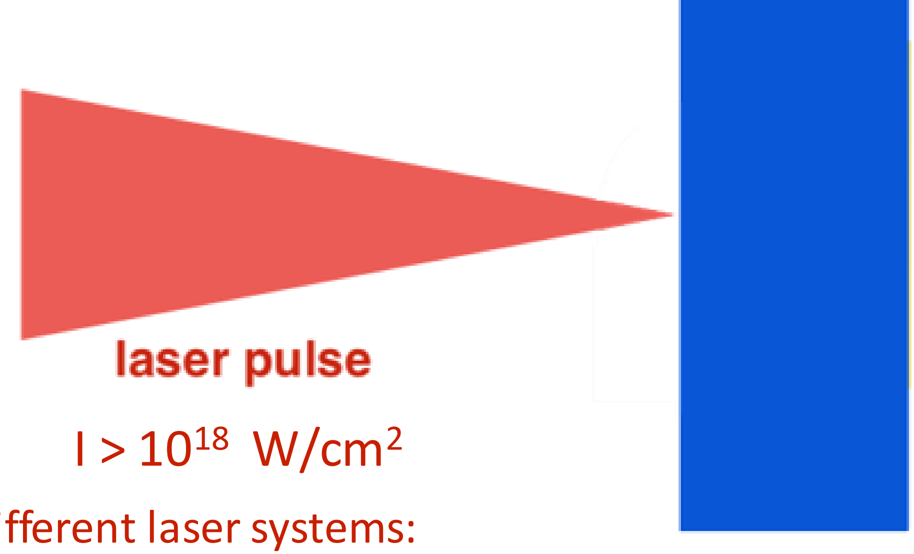
Different target concepts:

- Simple micrometric foil
- Advanced target schemes (e.g. **double layer targets**)

M. Passoni et al., PPCF 61, 014022 (2020)



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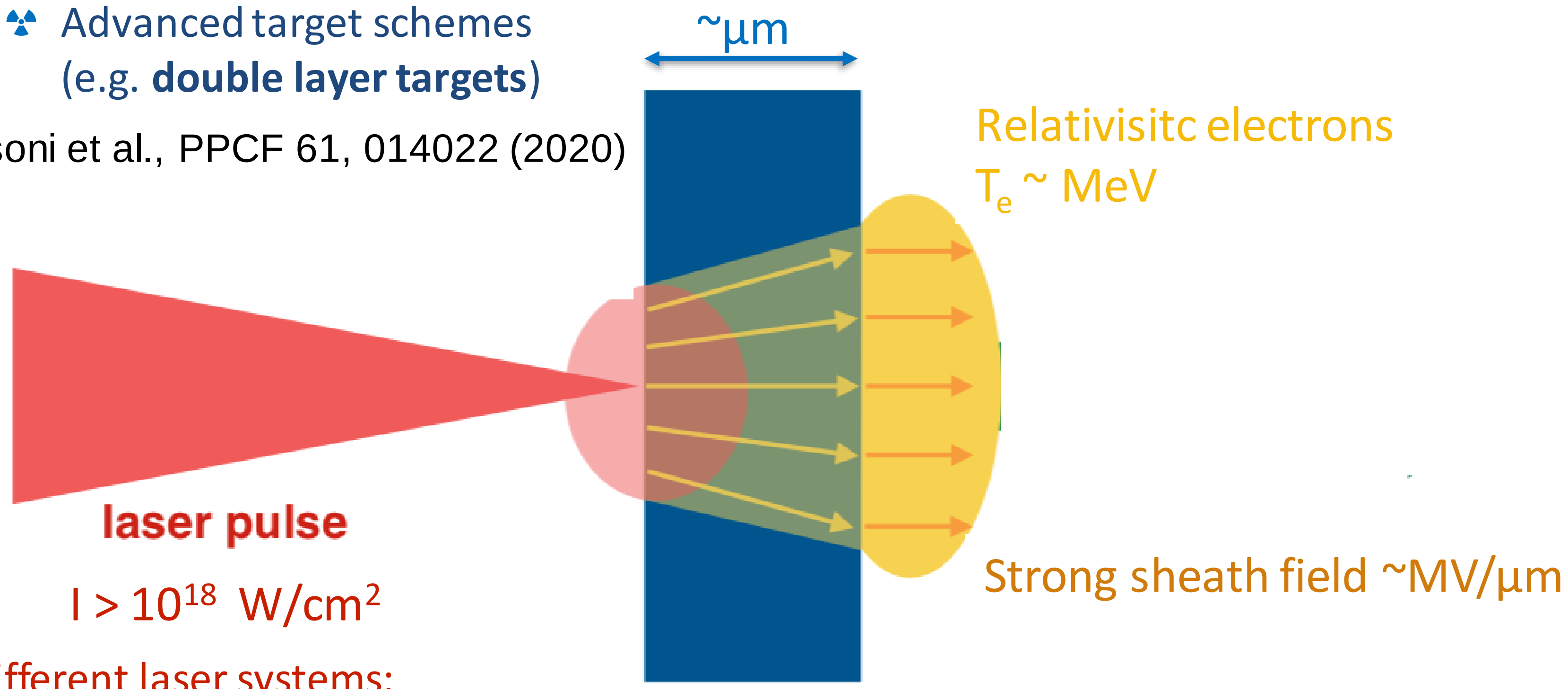

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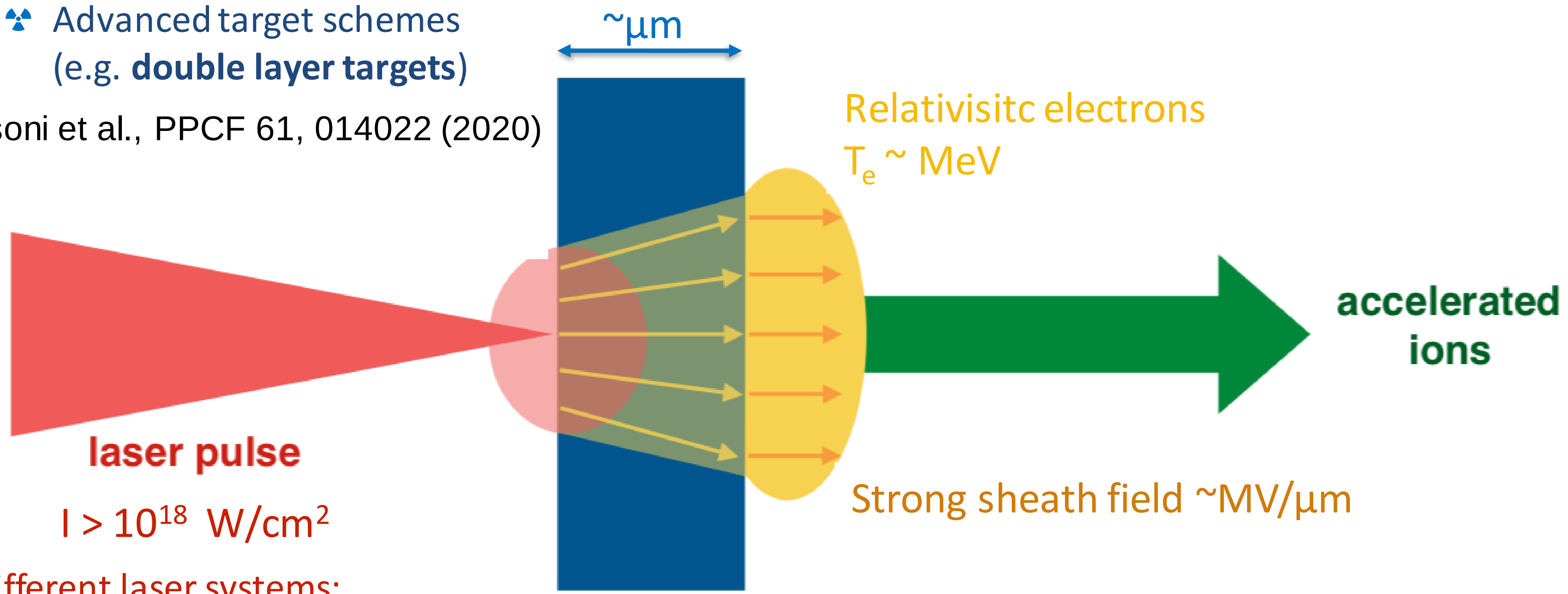

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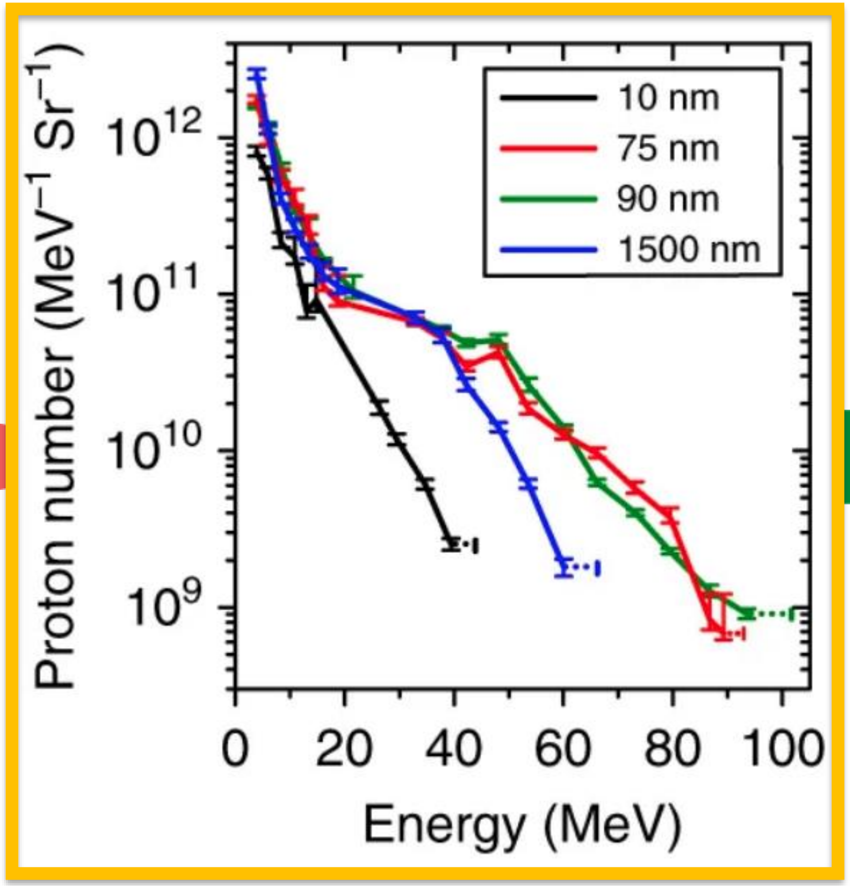
Target Normal Sheath Acceleration



Exponential
Proton Spectrum

laser pulse

$I > 10^{18}$ W/cm^2

accelerated ions

T_p ~ a few MeV
E_{max} ~ 10s of MeV

A. Higginson et al., Nature Comm. 9, 724 (2018)

Laser-driven ion sources for medical **radioisotope generation**

A few works in literature which use laser-driven accelerators to produce radioisotopes....

Experimental

- S. Fritzler, V. Malka, G. Grillon, J. P. Rousseau et al.
  Proton beams generated with high-intensity lasers: Applications to medical isotope production.
  Applied Physics Letters, 2003.

TW - laser
E_{max} 10 MeV
^{11}B (p,n) ^{11}C

- K.W.D. Ledingham, P. McKenna, T. McCanny, S. Shimizu et al.
  High power laser production of short-lived isotopes for positron emission tomography.
  Journal of Physics D: Applied Physics, 2004.

PW - laser
E_{max} 30 MeV
^{18}O (p,n) ^{18}F

- I. Spencer, K.W.D. Ledingham, R. P. Singhal, T. McCanny et al.
  Laser generation of pro- ton beams for the production of short-lived positron emitting radioisotopes.
  Nuclear Instruments and Methods in Physics Research, 2001.

PW - laser
E_{max} 37 MeV
^{18}O (p,n) ^{18}F

Theoretical

- A. Italiano, E. Amato, F. Minutoli, D. Margarone et al.
  Production of 68Ge, 64Cu, 86Y, 89Zr, 73Se, 77Br and 124I
  positron emitting radionuclides through future laser-accelerated proton beams
  at Eli-Beamlines for innovative PET diagnostics, 2016

PW - laser
TALYS code

A.J. Koning et al., AIP Conference Proceedings 769, 1154 (2005)

Laser-Driven radioisotope generation: what is missing?

- Selection of medical **radioisotopes that could benefit more** from the laser-driven technology

- A **complete numerical simulation** of the process, from laser-driven ion acceleration to ion transport and radionuclide generation

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Best suited radionuclides for a feasibility study

^{18}F one of the most used (PET), produced via (p,n)...

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FOCUS ON THE STRENGHTS OF THE LASER-DRIVEN TECHNOLOGY

Cost reduction, portability

Versatility

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Cost reduction, portability

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ULTRASHORT-LIVED ISOTOPES

^{11}C

β⁺ PET

Very short $T_{1/2}$ ~ 20 min

^{11}B (p,n) ^{11}C

Target: $^{11}B_2O_3$

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Very short $T_{1/2} \sim 20$ min

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Target: $^{11}B_2O_3$

Versatility

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EMERGING ISOTOPES

^{64}Cu

Odd-odd nuclei:

β^- TRT

β^+ PET → THERAGNOSTIC

^{64}Ni (p,n) ^{64}Cu

Target: 100% ^{64}Ni

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→ THERAGNOSTIC

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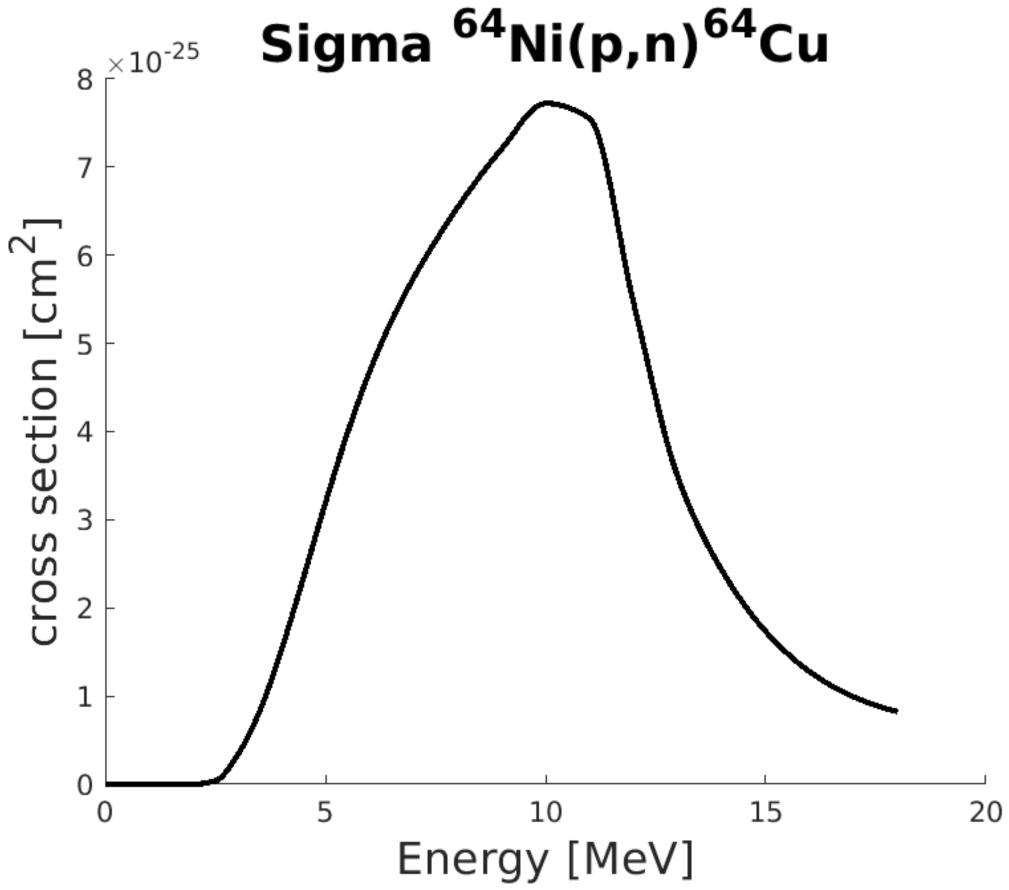
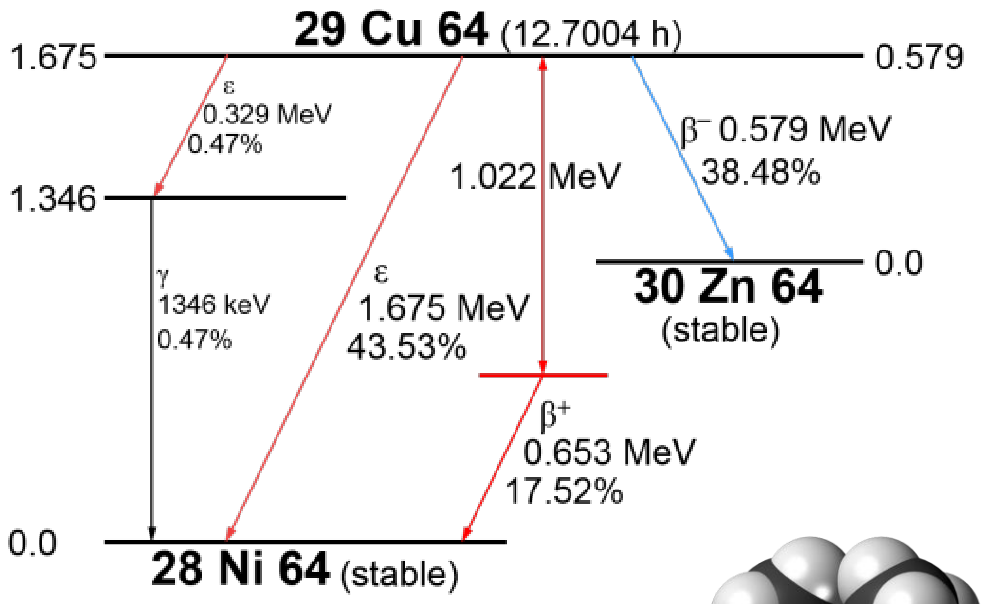
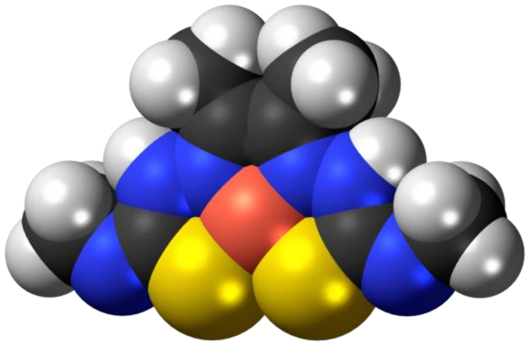
Target: 100% ^{64}Ni

^{64}Cu for theragnostics



Reasoably high cross section for proton energy easily **achievable with today's laser** technology





^{64}Cu-ATSM – copper(II) (diacetyl-bis (N4-methylthiosemicarbazone))

Cyclotron Produced Radionuclides: Emerging Positron Emitters for Medical Applications: 64Cu, IAEA Technical reports 2016

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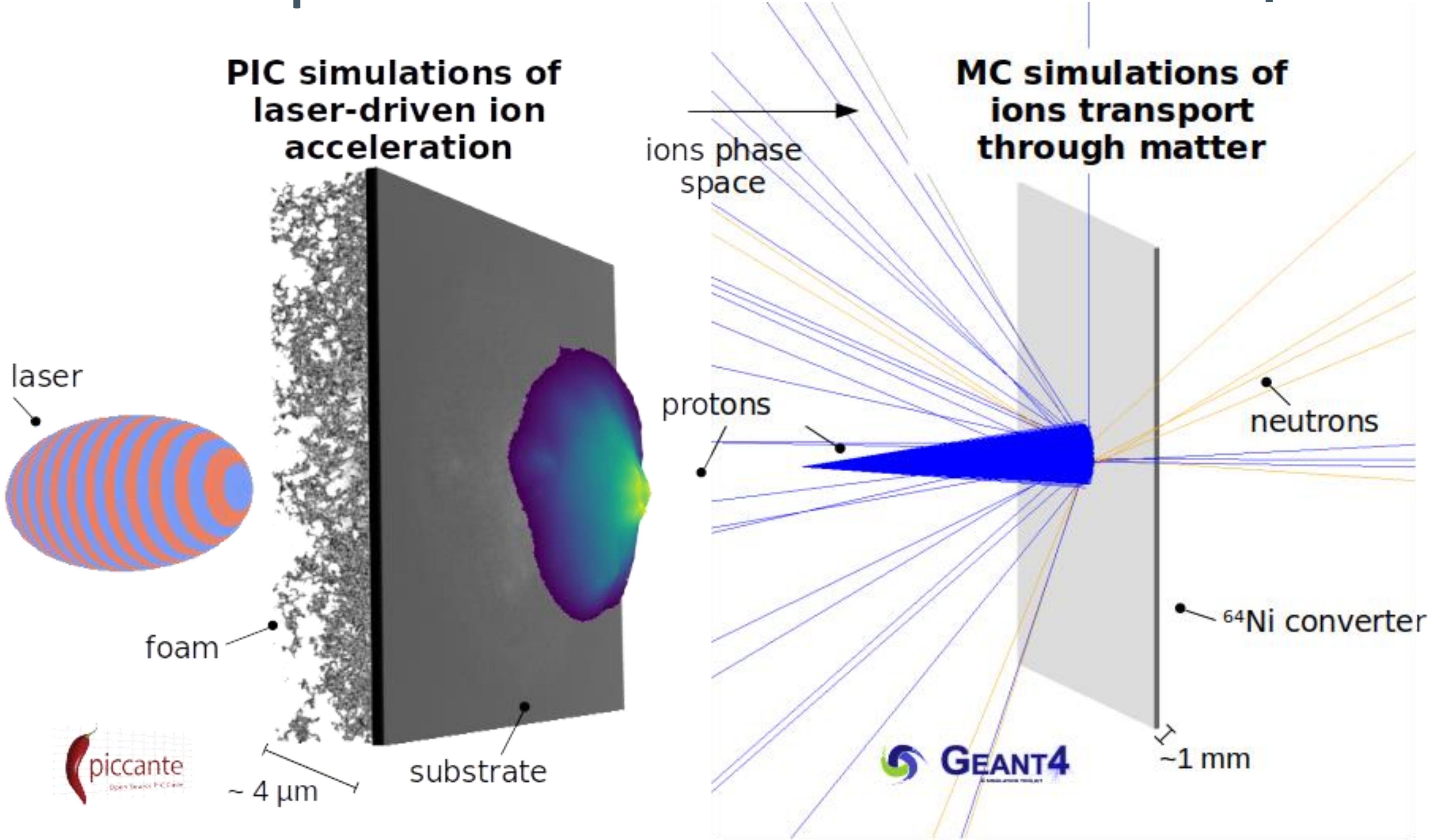
A complete numerical simulation of the whole process



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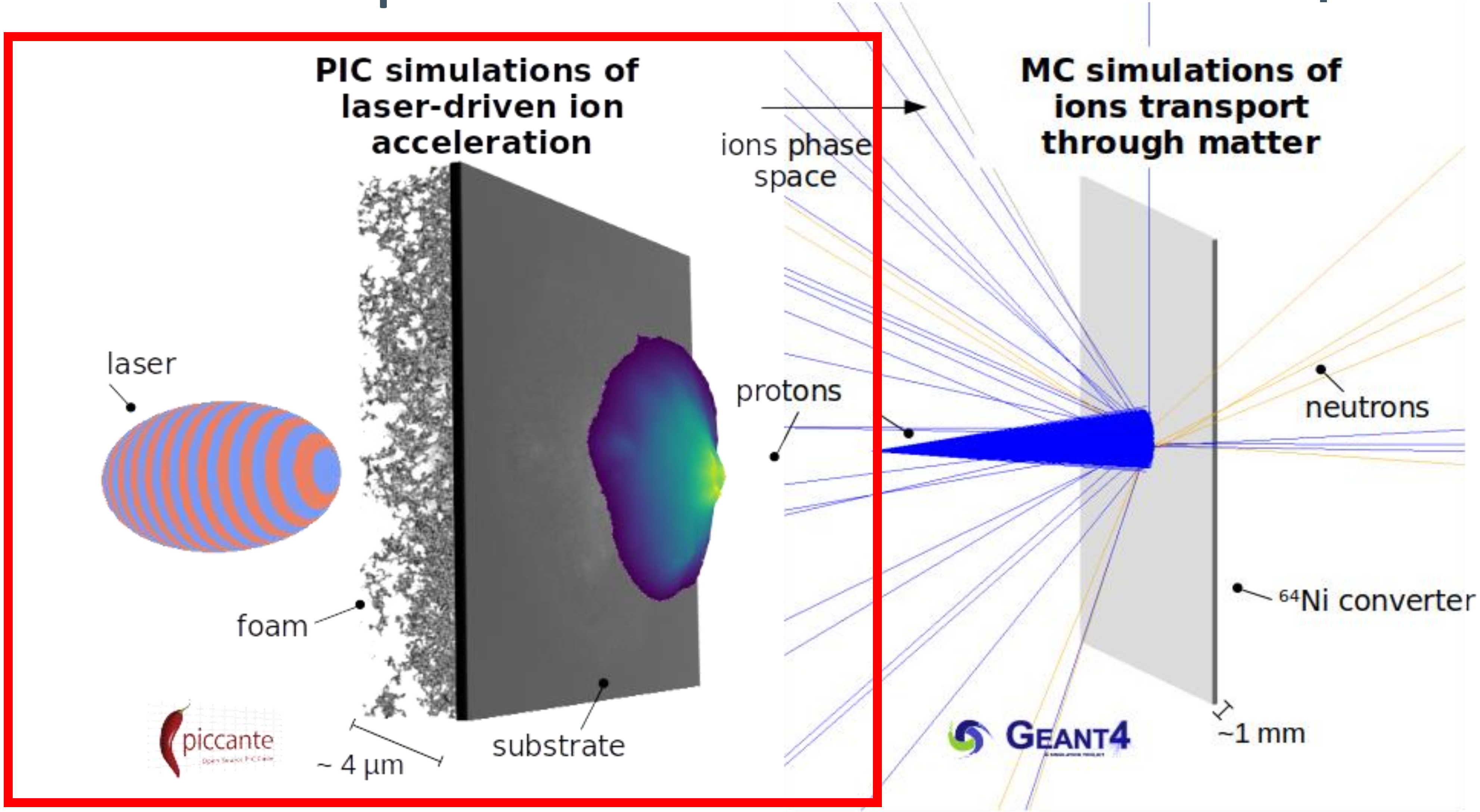

Particle-In-Cell simulations

Particle-in-Cell simulations

Simulation setup:

Full 3D PICs
a0=16
Spot size = 5λ
Pulse duration =15 λ/c
Four target configurations:

- **Simple foil, 0° incidence**
- **Simple foil, 45° incidence**
- **DLT, 0° incidence**
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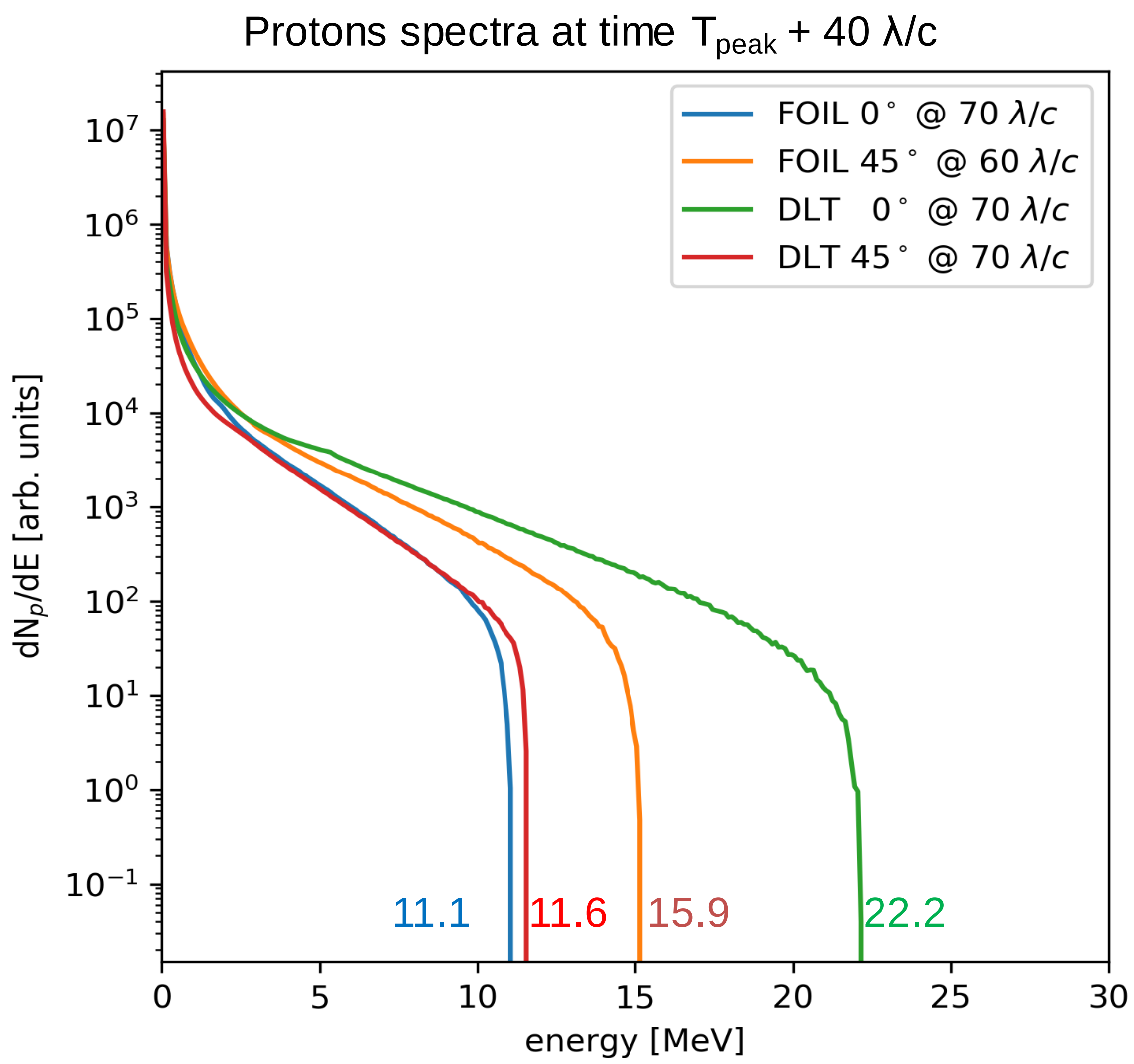

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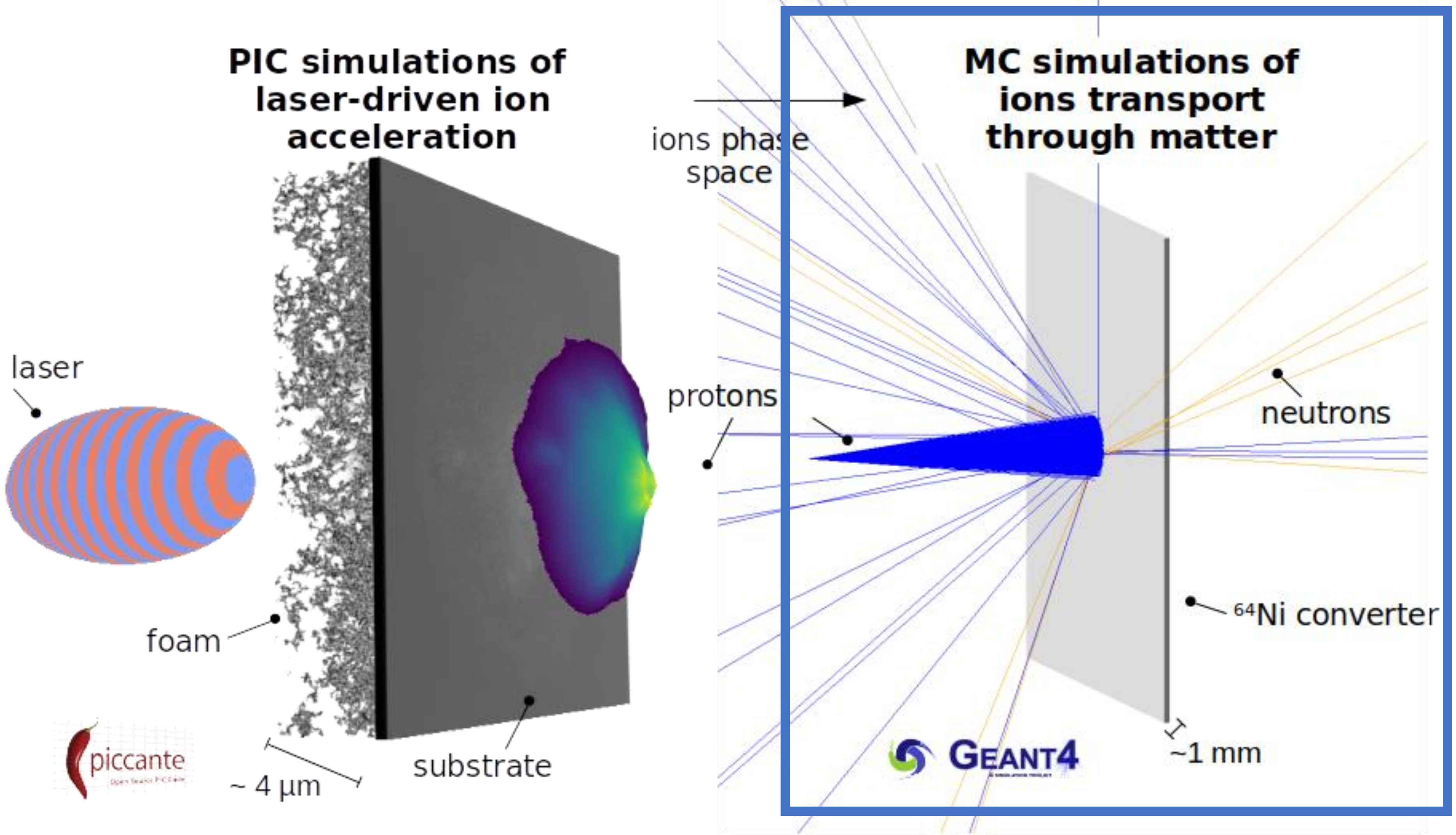


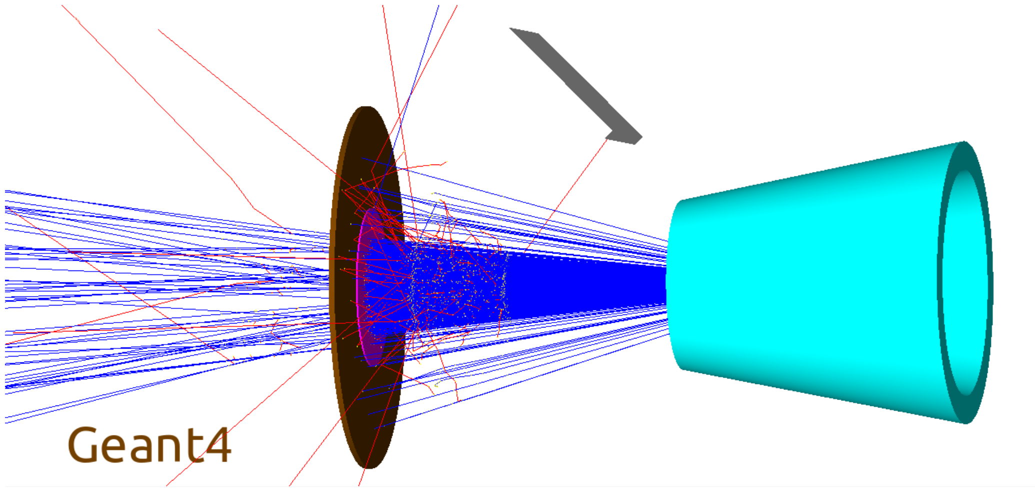
Monte Carlo simulations

Monte Carlo simulation of proton transport and reaction

(GEometry ANd Tracking)

The toolkit allows to:

- Create a geometrical model → Different shapes; Different materials
- Select a set of particles
- Physics processes → Physics Lists



Monte Carlo simulation of proton transport and reaction

GEANT4 — A SIMULATION TOOLKIT (GEometry ANd Tracking)

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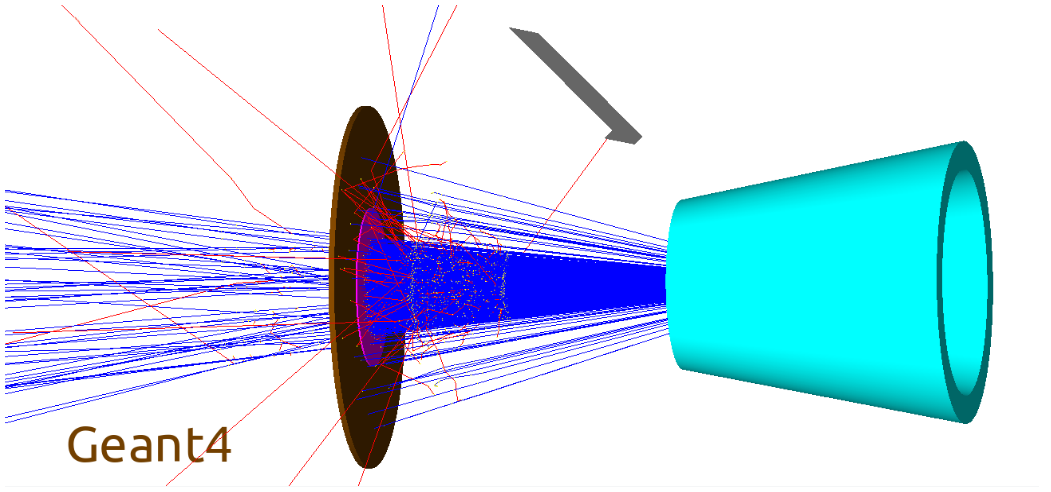
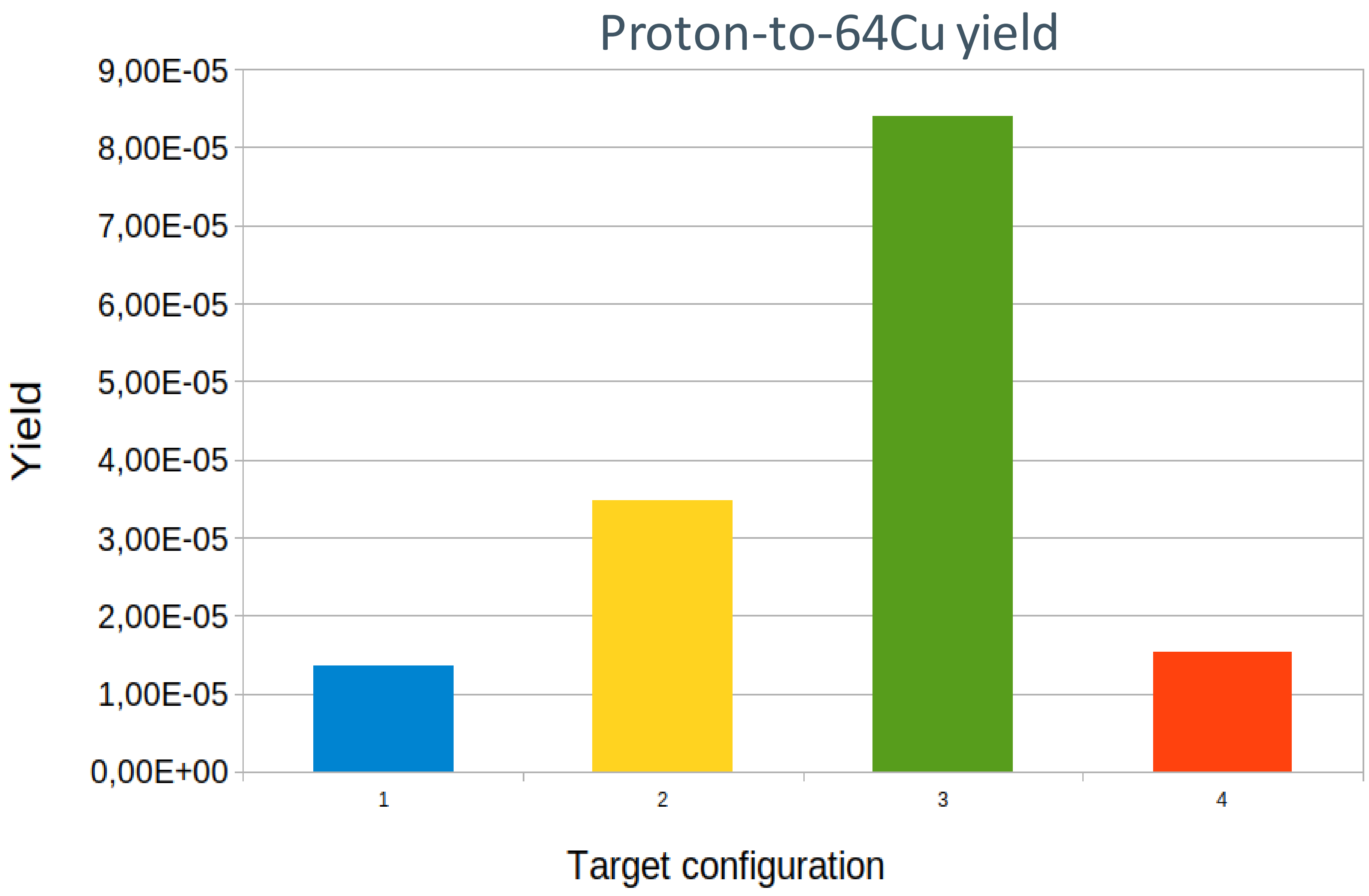


Setup:
1 mm thick, pure ^{64}Ni target
$4*10^6$ proton per run
Proton sampled from PIC output spectra

Goal: to determine the proton-to-^{64}Cu **Yield** (i.e. number of ^{64}Cu per incident proton)

Coupling PIC and Monte Carlo

- Simple foil, 0° incidence
- Simple foil, 45° incidence
- DLT, 0° incidence
- DLT, 45° incidence



Coupling PIC and Monte Carlo

- Simple foil, 0° incidence
- Simple foil, 45° incidence
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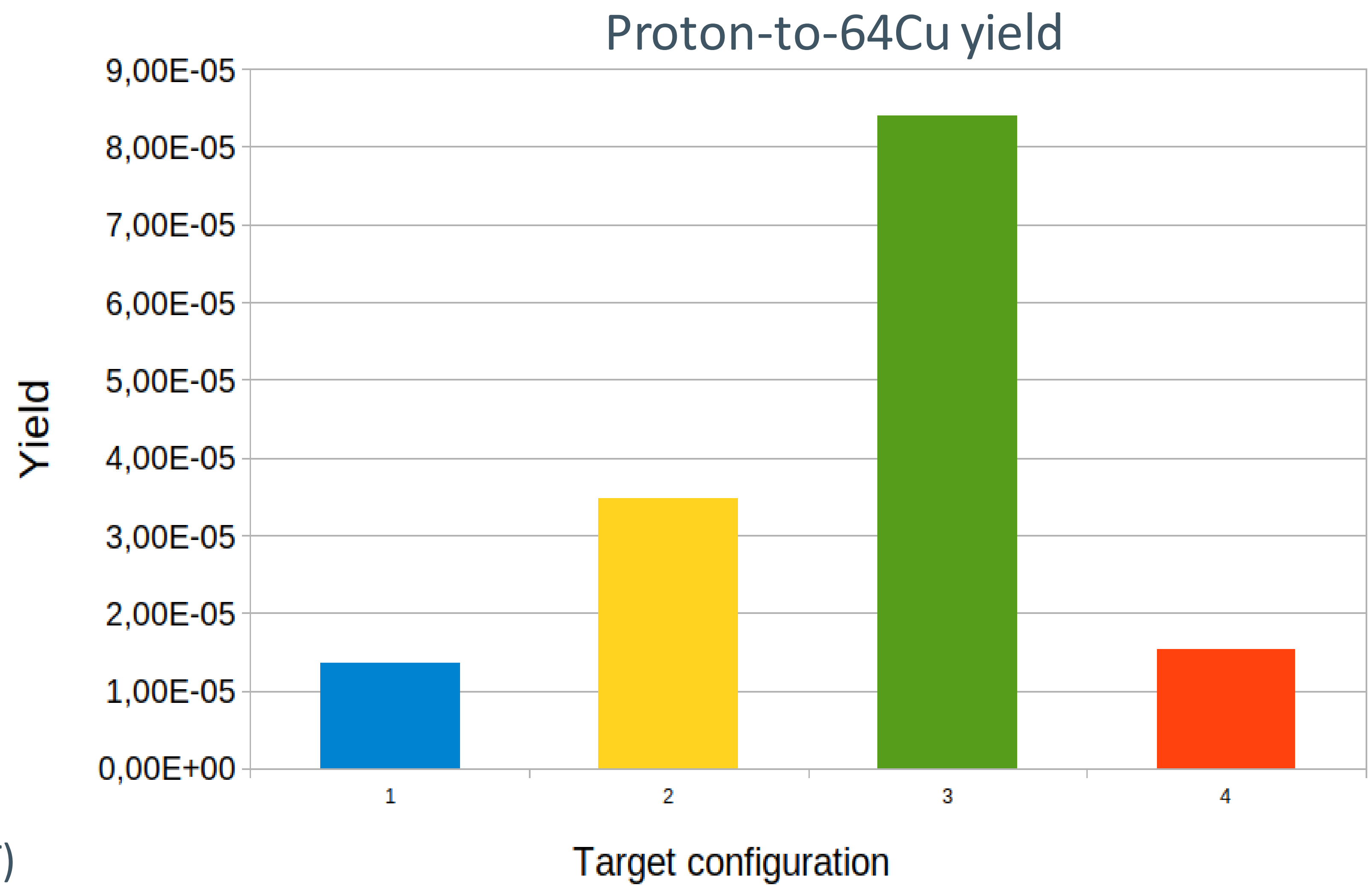
Considering
- 10 Hz rep. Rate,
- 10^{10} proton >1 MeV:

~ 80 MBq activity (40% of a standar PET)



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Analytical modeling to obtain predictive scaling laws

$$\frac{dN_{iso}}{dt} \propto \int_0^{Eco} f_p(E_i)\, n_{p,tot} \left(\int_0^{E_i} \frac{\sigma(E_s)}{S(E_s)}\, dE_s \right) dE_i$$

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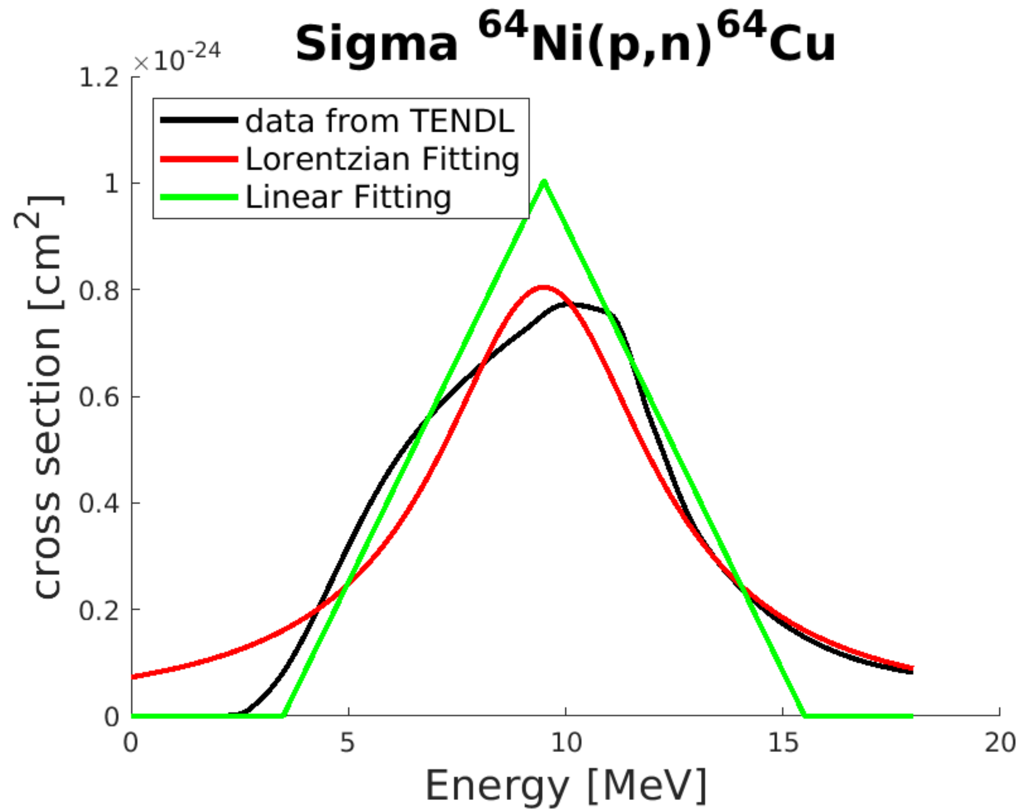

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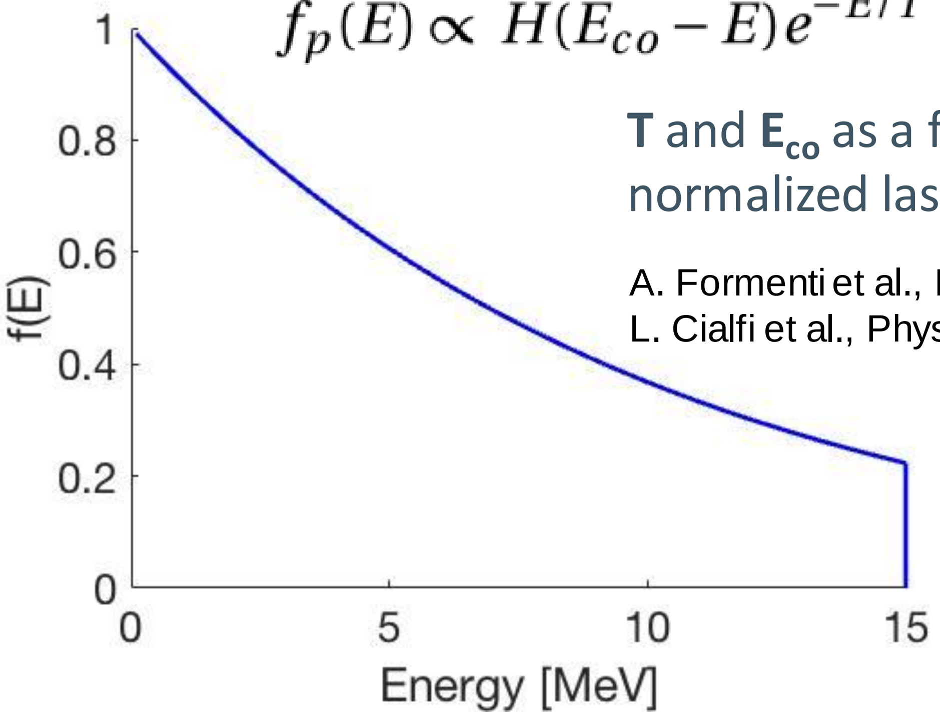
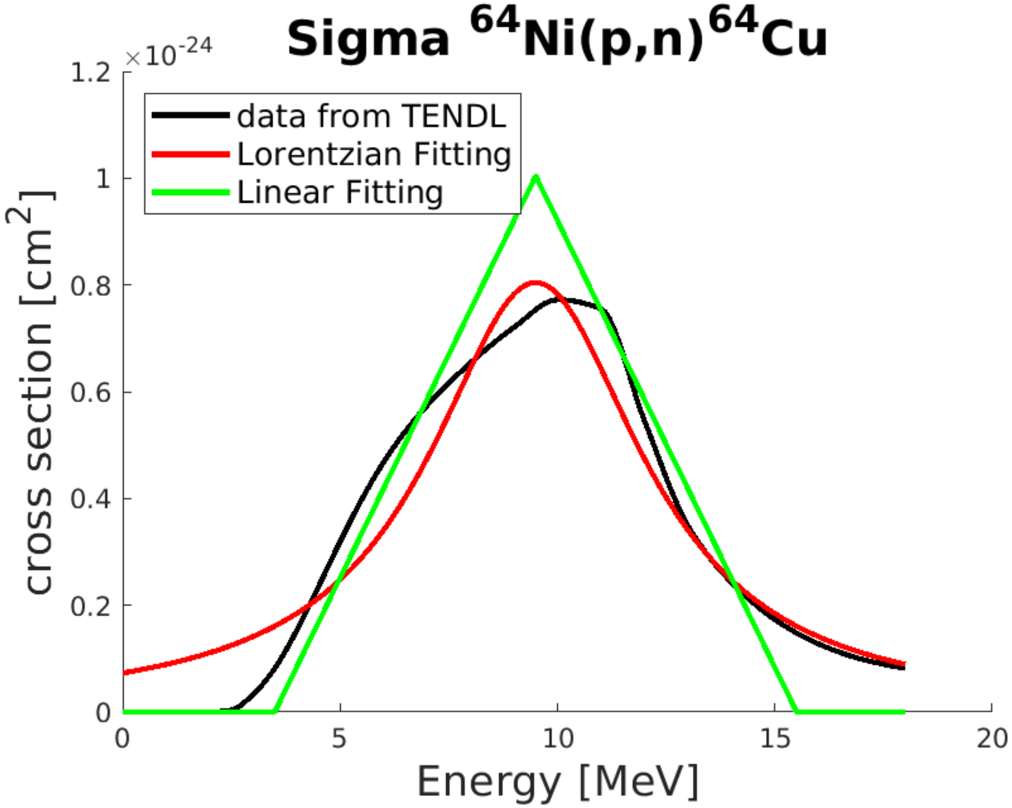
$$f_p(E) \propto H(E_{co} - E)\, e^{-E/T}$$



T and **E$_{co}$** as a function of normalized laser intensity **a$_0$**

A. Formenti et al., N. Jour. Physics 22, 053020 (2020)
L. Cialfi et al., Phys. Rev. E 94, 053201 (2016)



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