Neutron and ion sources with compact laser systems

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POLITECNICO
MILANO 1863

European Research Council
Established by the European Commission

ICUIL 2018, September 12th, Lindau, Germany

ERC projects @ Politecnico di Milano on laser-driven ion acceleration and its applications

Fundings from the European Research Council

Consolidator Grant

ENSURE

ERC-2014-CoG No. 647554

Proof of Concept

INTER

ERC-2016-PoC No. 754916

Hosting Institution

Politecnico di Milano, Department of Energy, NanoLab

Principal Investigator

Matteo Passoni

Team

PI
2 associate professors
1 assistant professor
3 post-docs
3 PhD students
MSc student: **F.M. Arioli**
support from NanoLab people

Goal: to study, with **theory** & experiments, enhanced laser-driven ion acceleration with advanced targets and some applications

This talk: focus on laser-driven neutron sources as an applications of laser-driven ion acceleration

Compact neutron and ion sources

Many different compact neutron and ion sources already exist:

- radioactive sources [n]
- Sealed Tube Neutron Generators [n]
- cyclotrons [i]

Commercial PET cyclotron
IBA RadioPharma Solutions

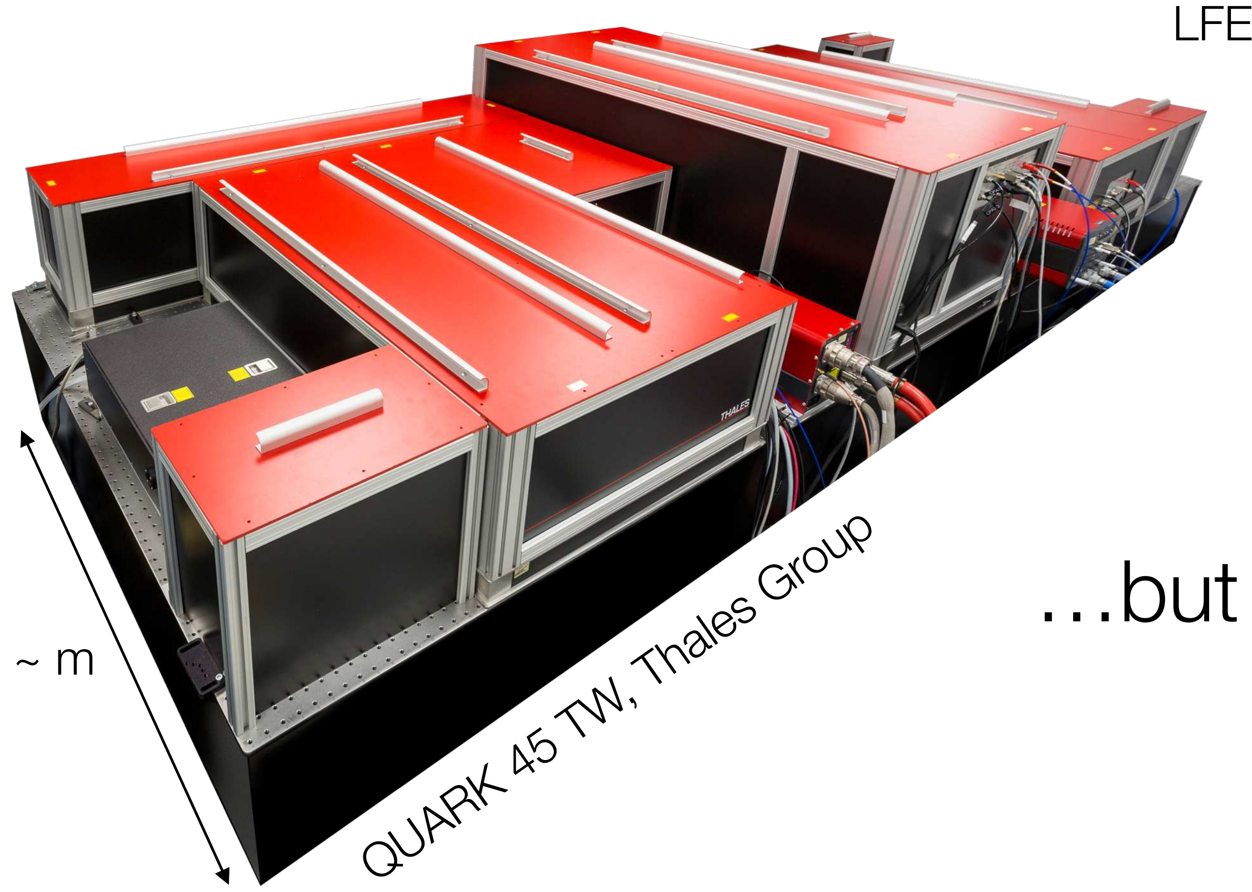
MP 320 Sealed Tube Neutron Generator
Thermo Fisher Scientific

Capsules of ^{252}Cf
Frontier Technology Corporation

With lasers, by "compact" we mean that we consider **~10 TW class systems, e.g. table-top Ti:Sapphire**, which usually are way smaller and cheaper than ~100TW - 1PW systems and have moderate pulse energy mJ - J and short duration ~10fs

Not quite like this…

LFEX and GEKKO lasers, Osaka, Japan



QUARK 45 TW, Thales Group

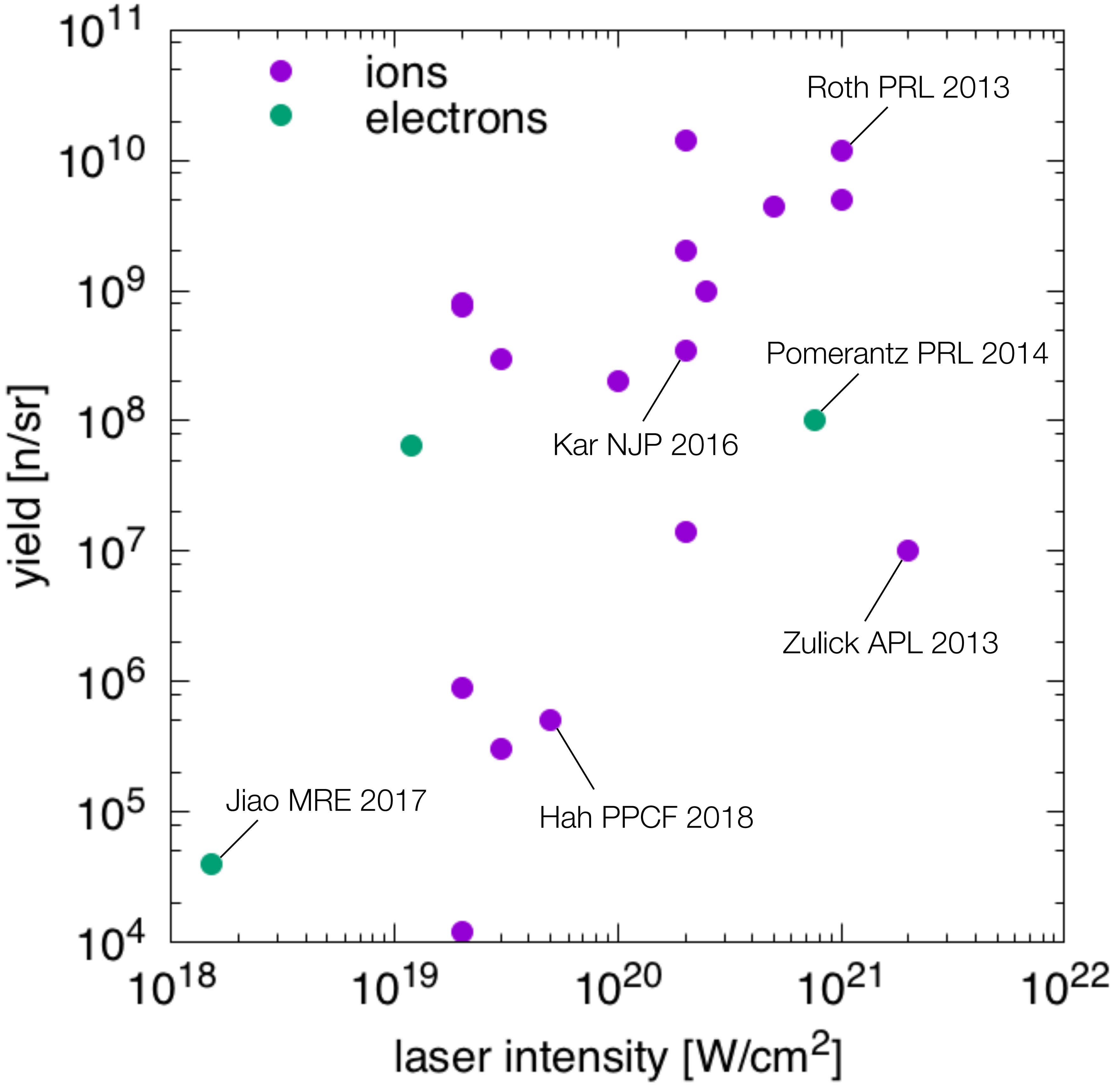
…but more like this

Why should we try with lasers?

Advantages

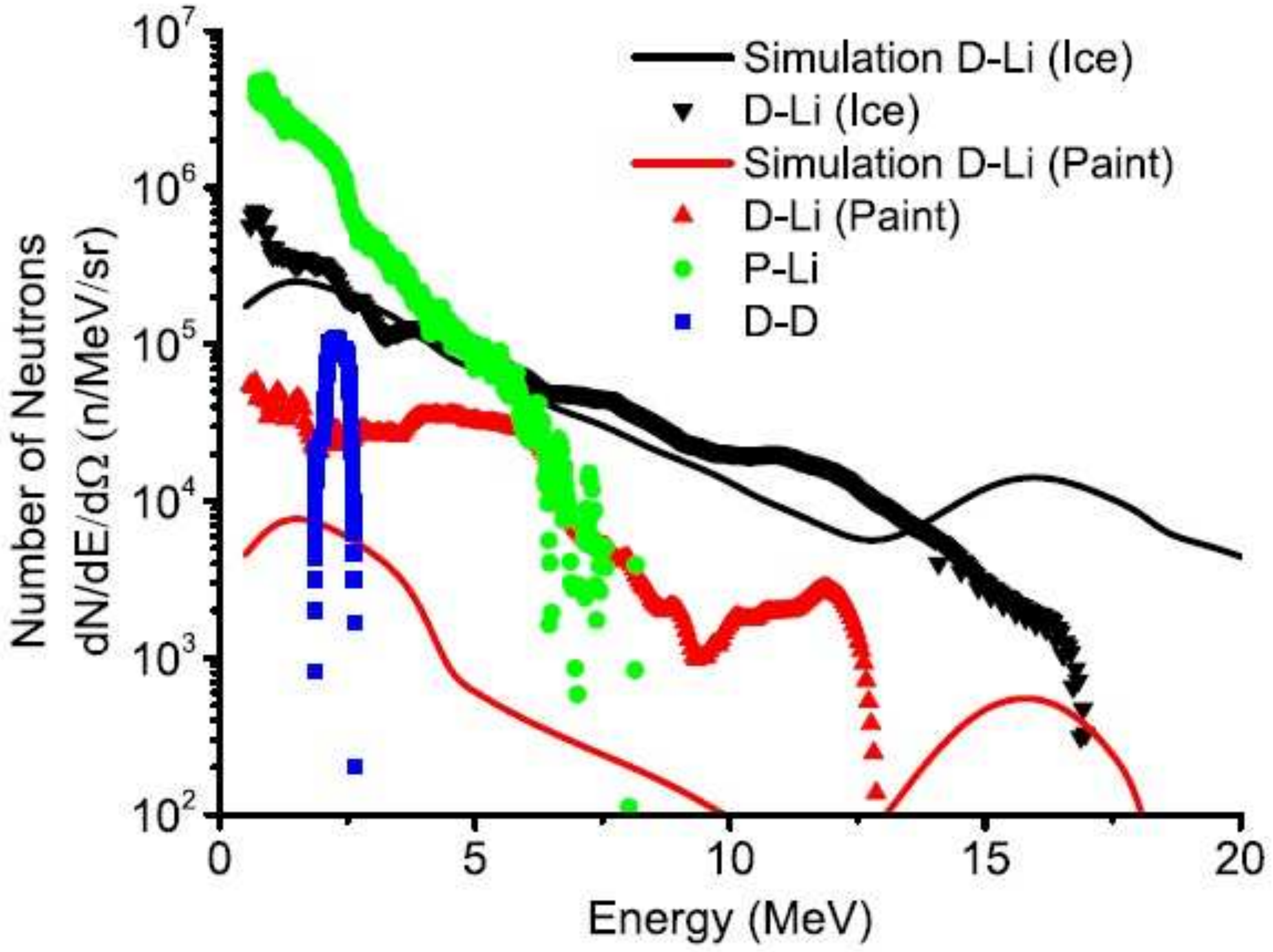
- **flexibility**: changing the laser/target parameters, you change the neutrons/ions properties
- **pulsed**: pump and probe experiments
- **ultra-short**: access to ultra-fast (~10 ps - ns) dynamics
- **point-like** source
- **multi-purpose**: with a single shot you can produce different types of radiation

Plus, significant neutron yields have already been observed with lasers



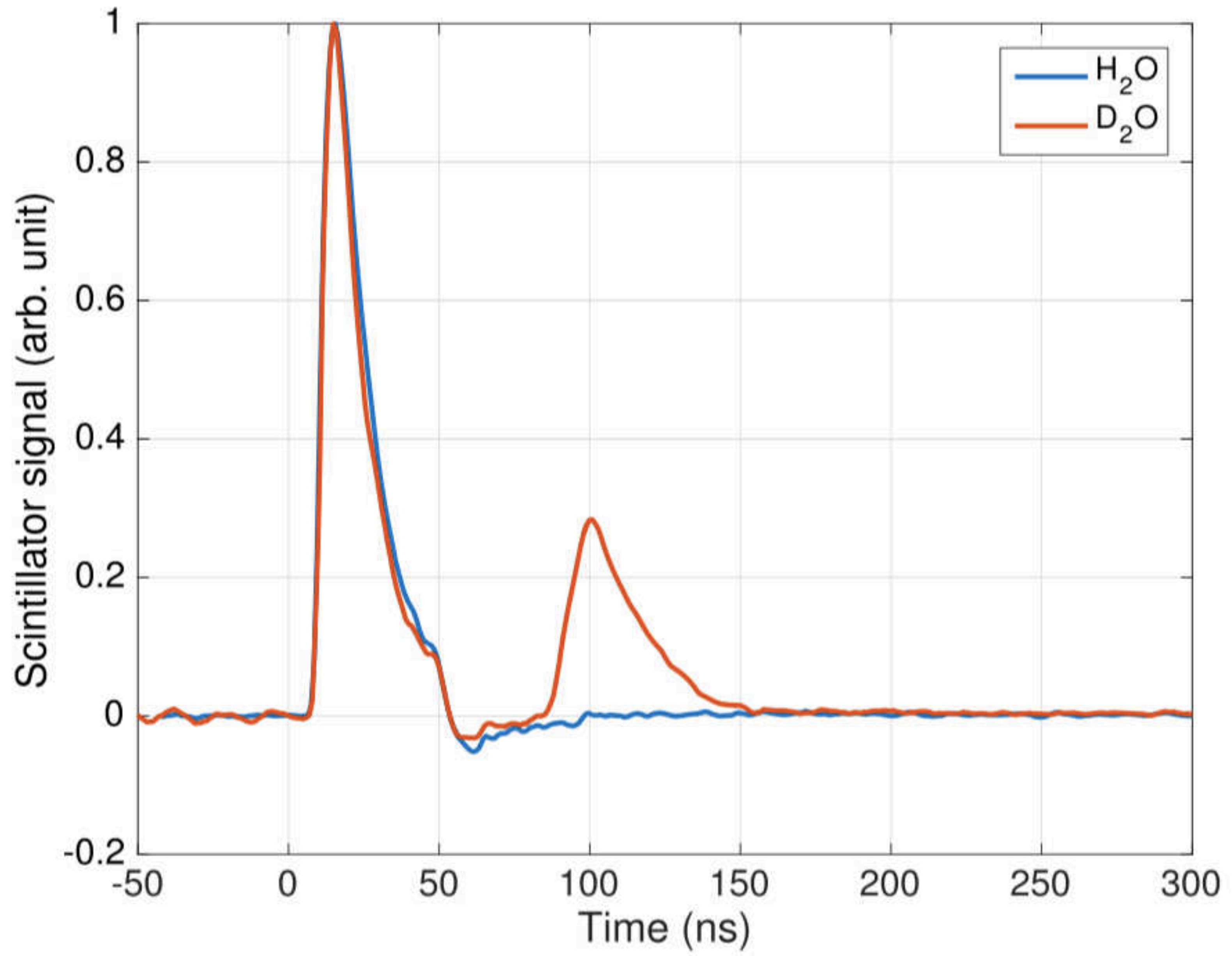
What has been done with compact systems?

Neutrons from TNSA protons and deuterons in a pitcher-catcher config with a LiF catcher
Zulick APL 2013



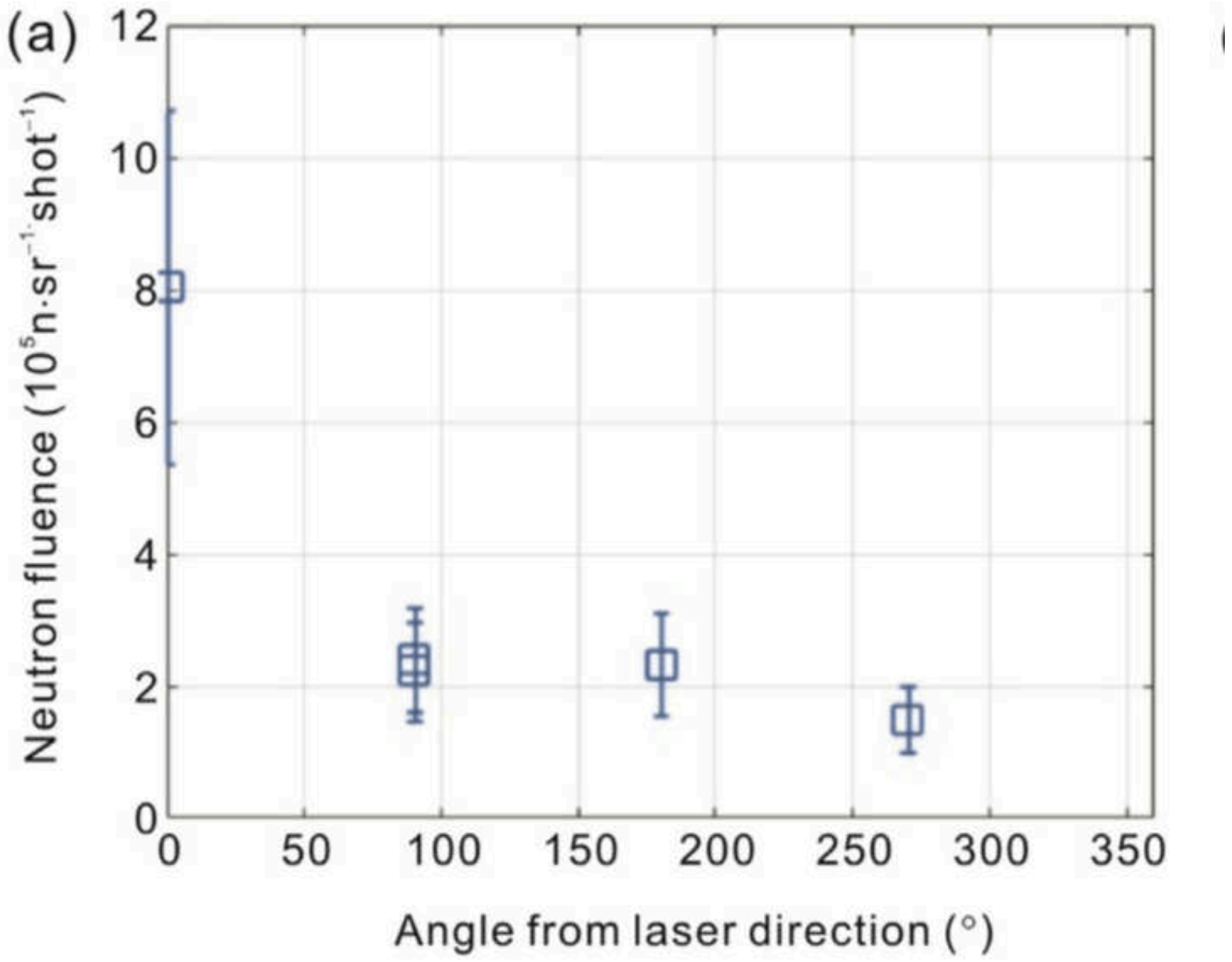
HERCULES, 1J, 10^{21}W/cm^2, 45fs
→ 10^7 n/sr forward

Neutrons from fusion reactions in a bulk config with flowing heavy-water jet target at high rep rate
Hah PPCF 2018



λ^3, 10 mJ, 10^{19} W/cm^2, 40 fs @ 0.5Hz
→ 2 x 10^5 n/s in 4π

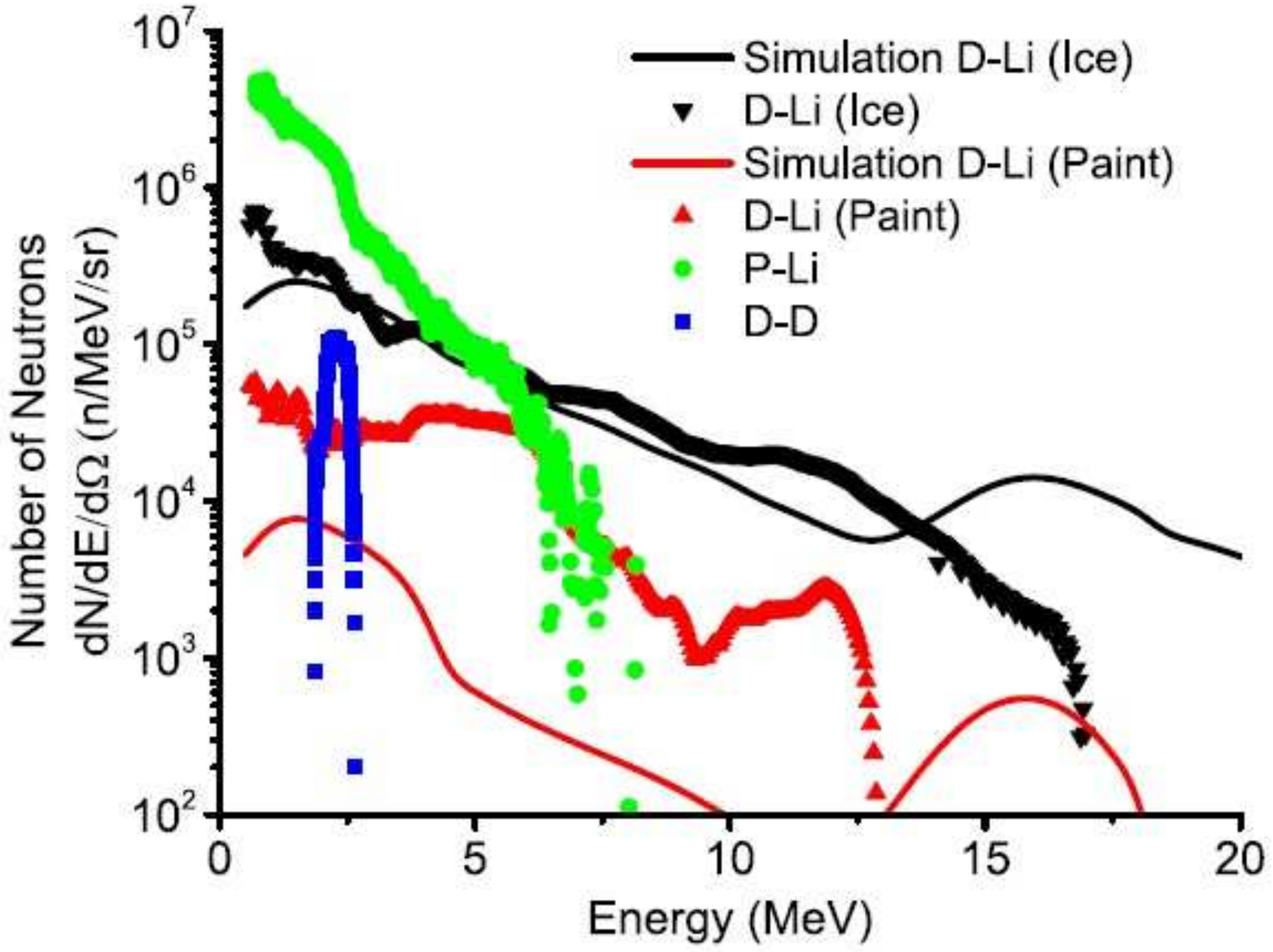
Photoneutrons from gammas from electrons accelerated via LWFA hitting a W converter
Jiao MRE 2017



UT^3, 0.5J,10^{18} W/cm^2, 40 fs
→ 10^4 n/sr

We want to further investigate this kind of approach

Neutrons from TNSA protons and deuterons in a pitcher-catcher config with a LiF catcher
Zulick APL 2013



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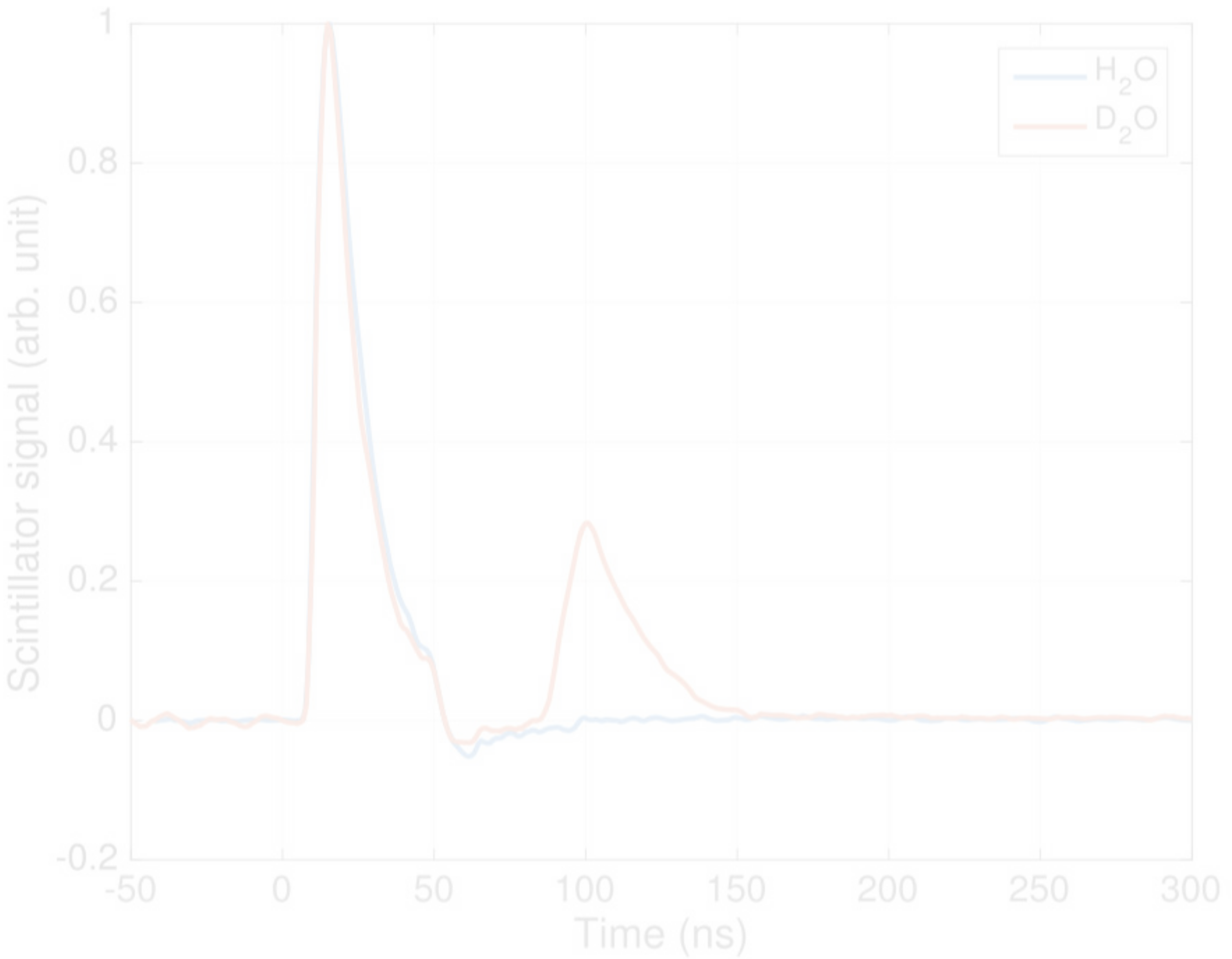

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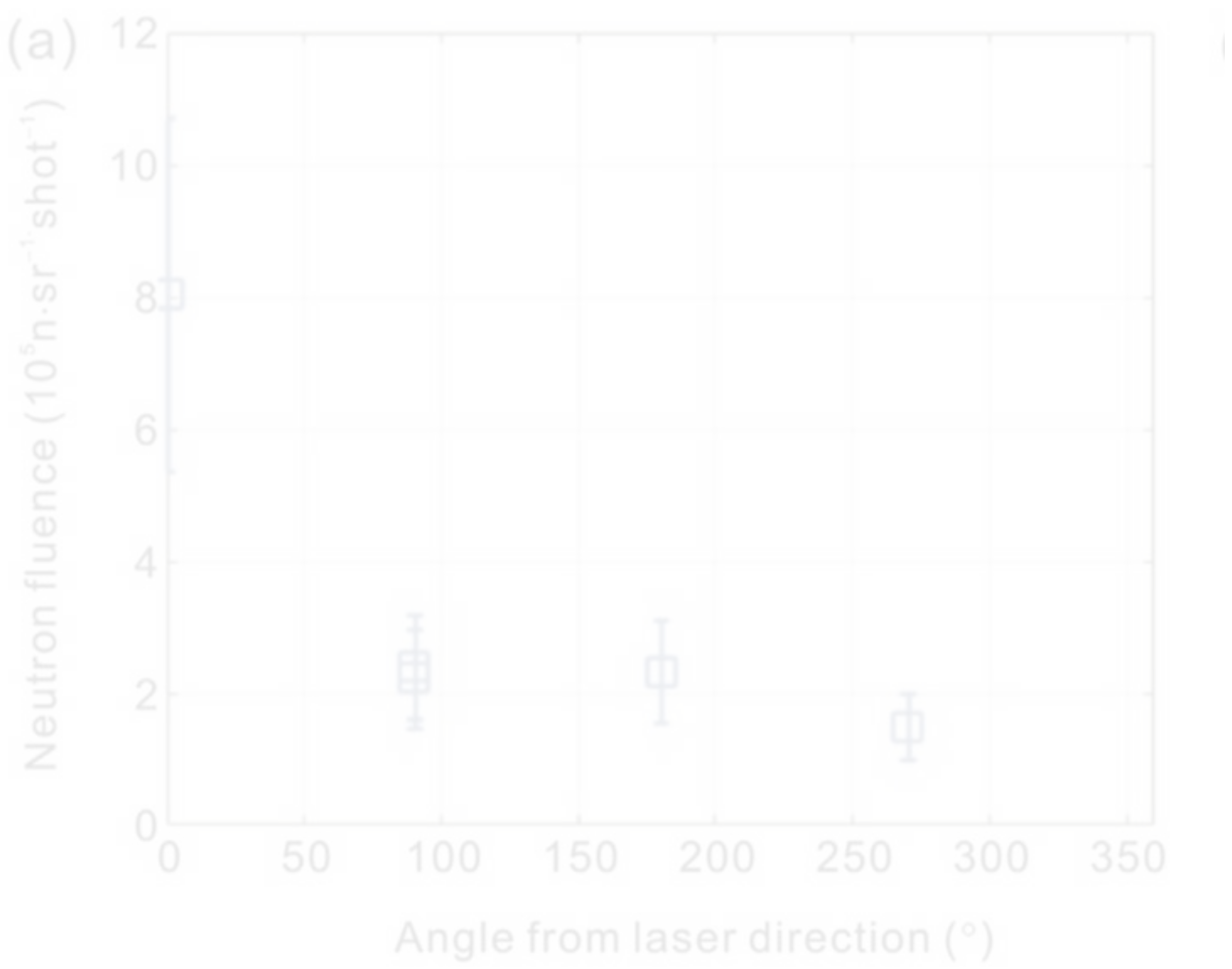

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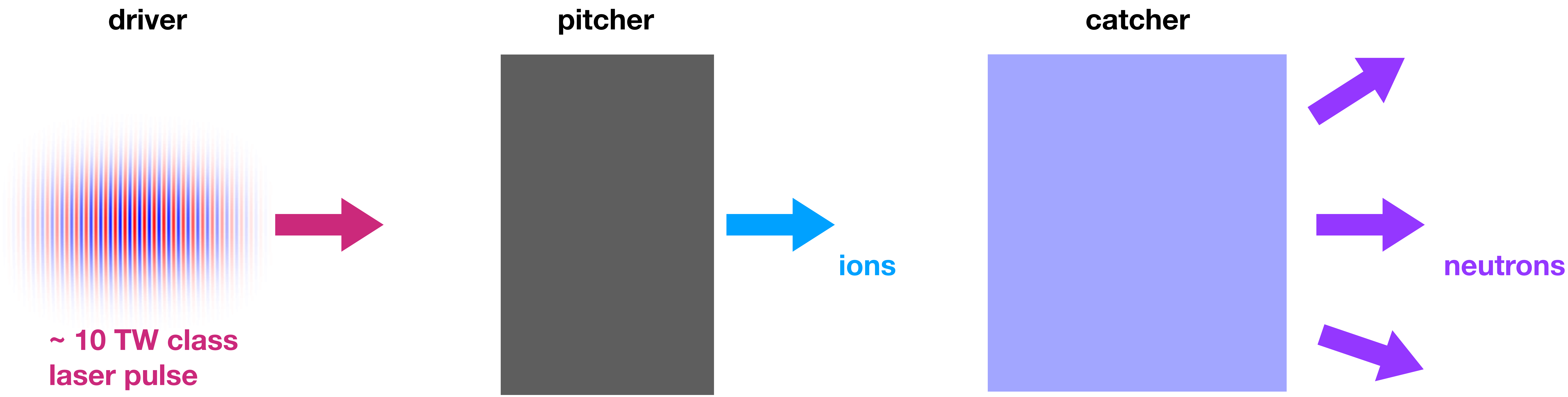
Compact neutron sources from TNSA-driven ions in a pitcher-catcher configuration

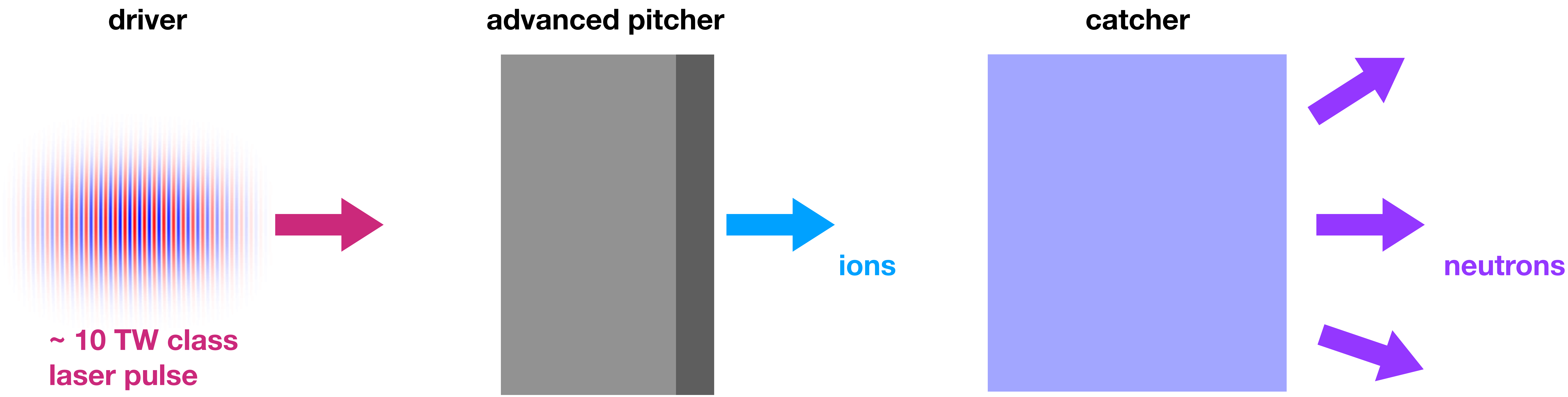


~ 10 TW class laser pulse

- ultra-intense
- ultra-short

Because we want to **lower as much as possibile the laser requirements**, we exploit an **advanced pitcher concept** to still have good performances in ion acceleration and, in turn, also in the neutron generation processes.

Compact neutron sources from TNSA-driven ions in a pitcher-catcher configuration



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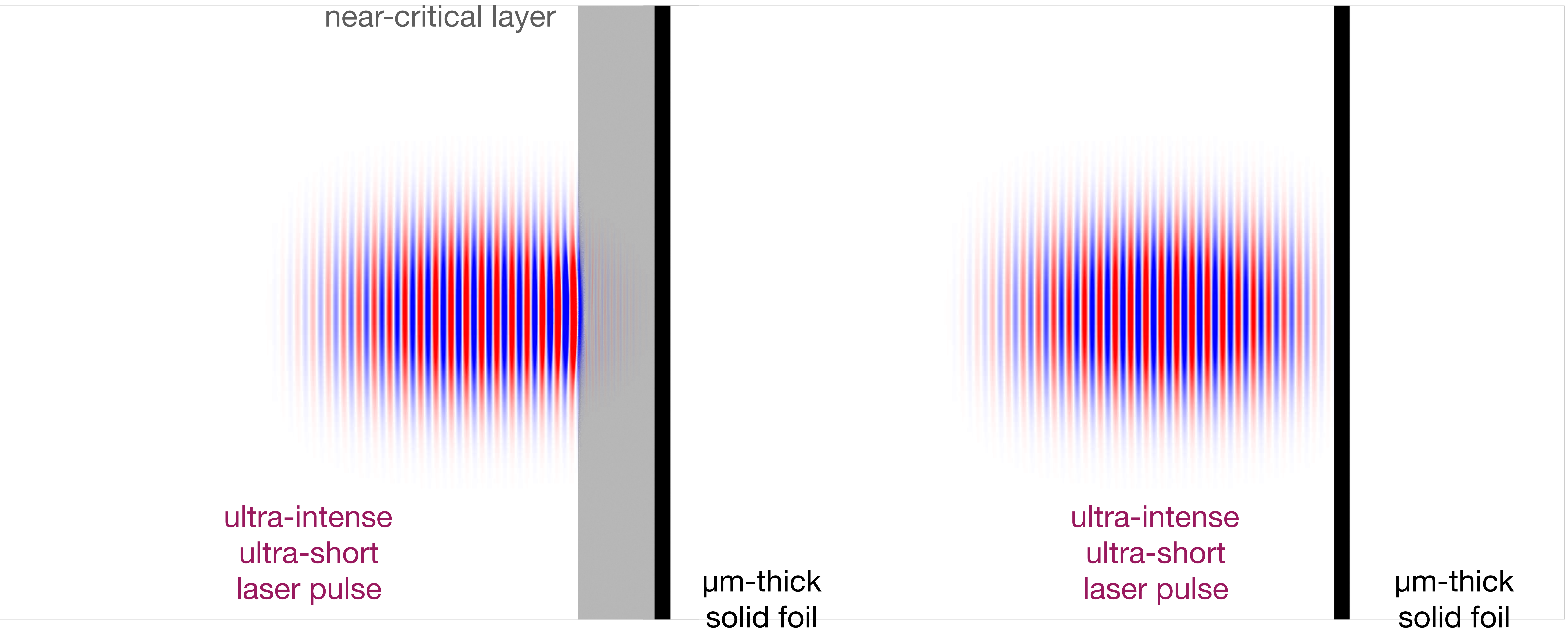
Enhanced TNSA via near-critical layer before the typical solid foil



Enhanced TNSA

Conventional TNSA

near-critical layer

ultra-intense
ultra-short
laser pulse

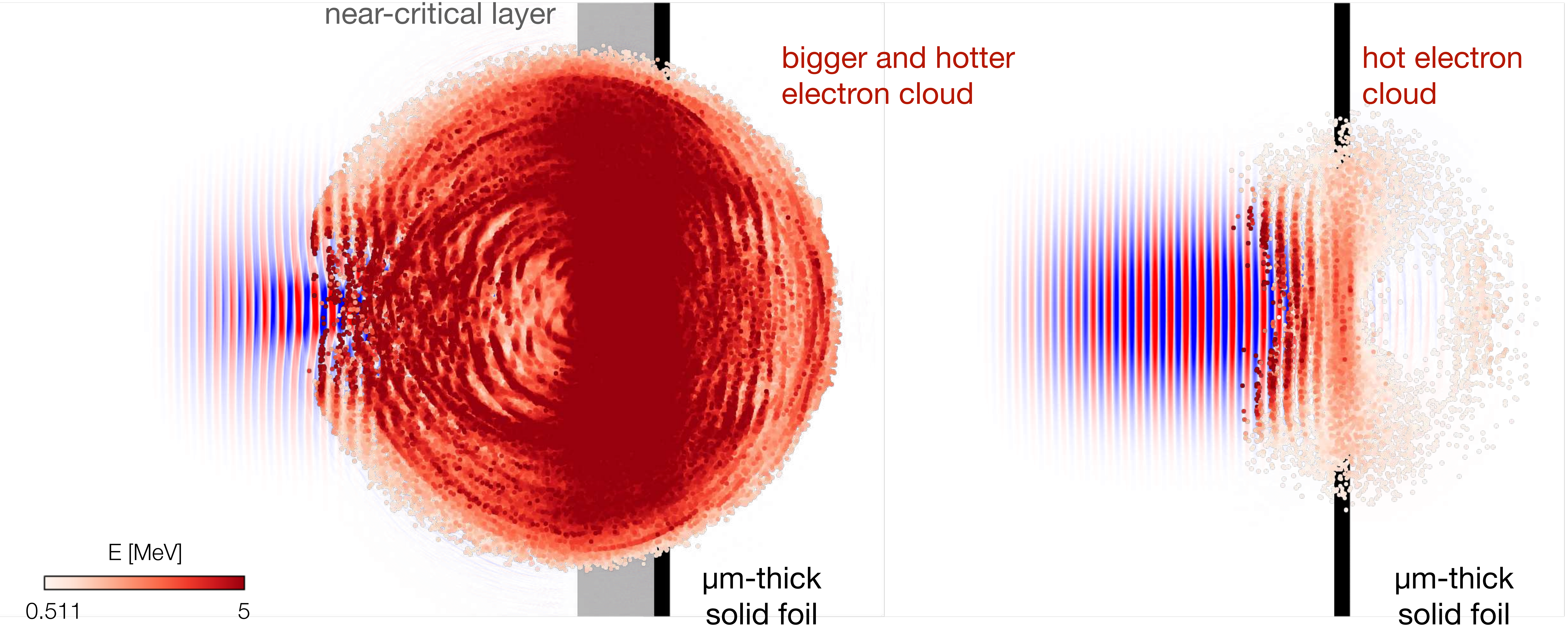
µm-thick
solid foil

ultra-intense
ultra-short
laser pulse

µm-thick
solid foil

t = 27 fs

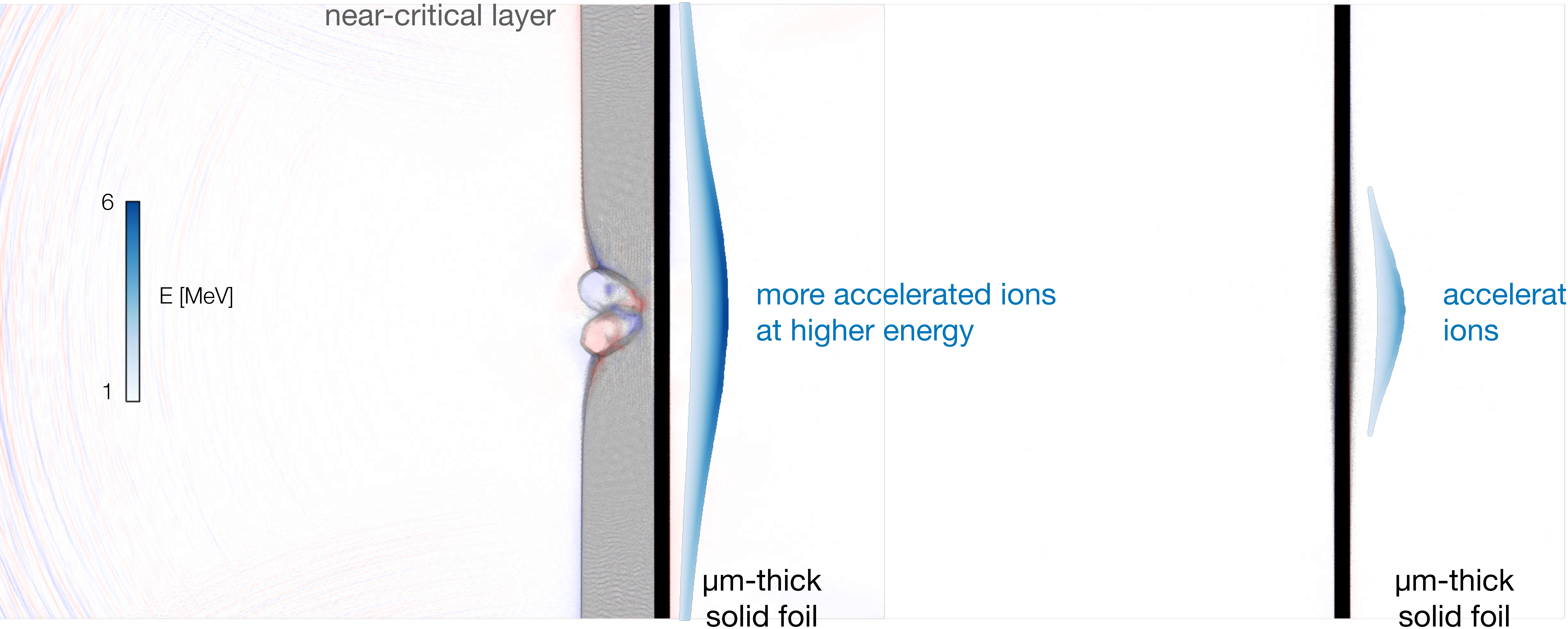
The near-critical layer leads to a better hot electron generation



t = 81 fs

Significant increase of ion total number and maximum energy

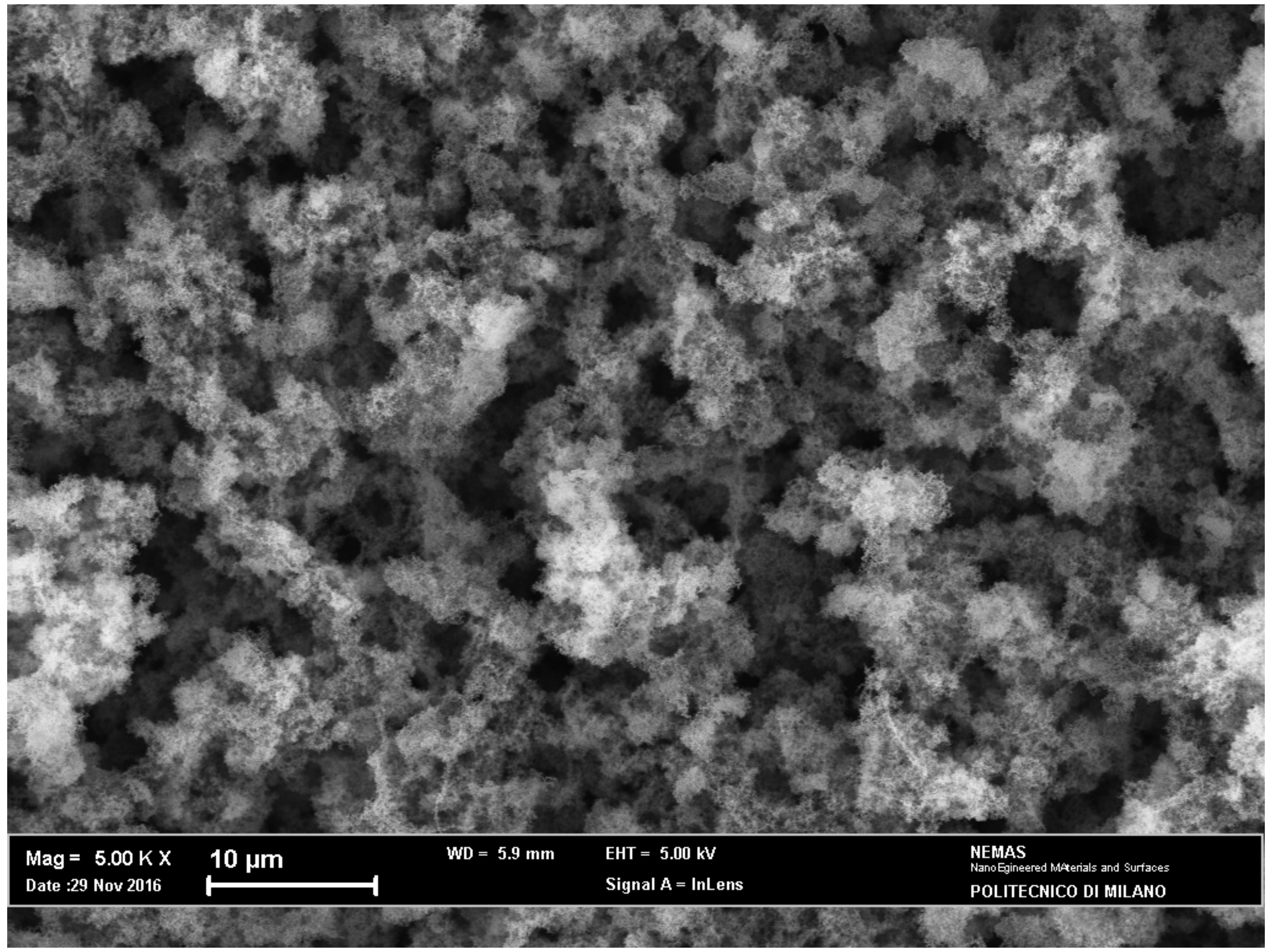
Enhanced TNSA **Conventional TNSA**



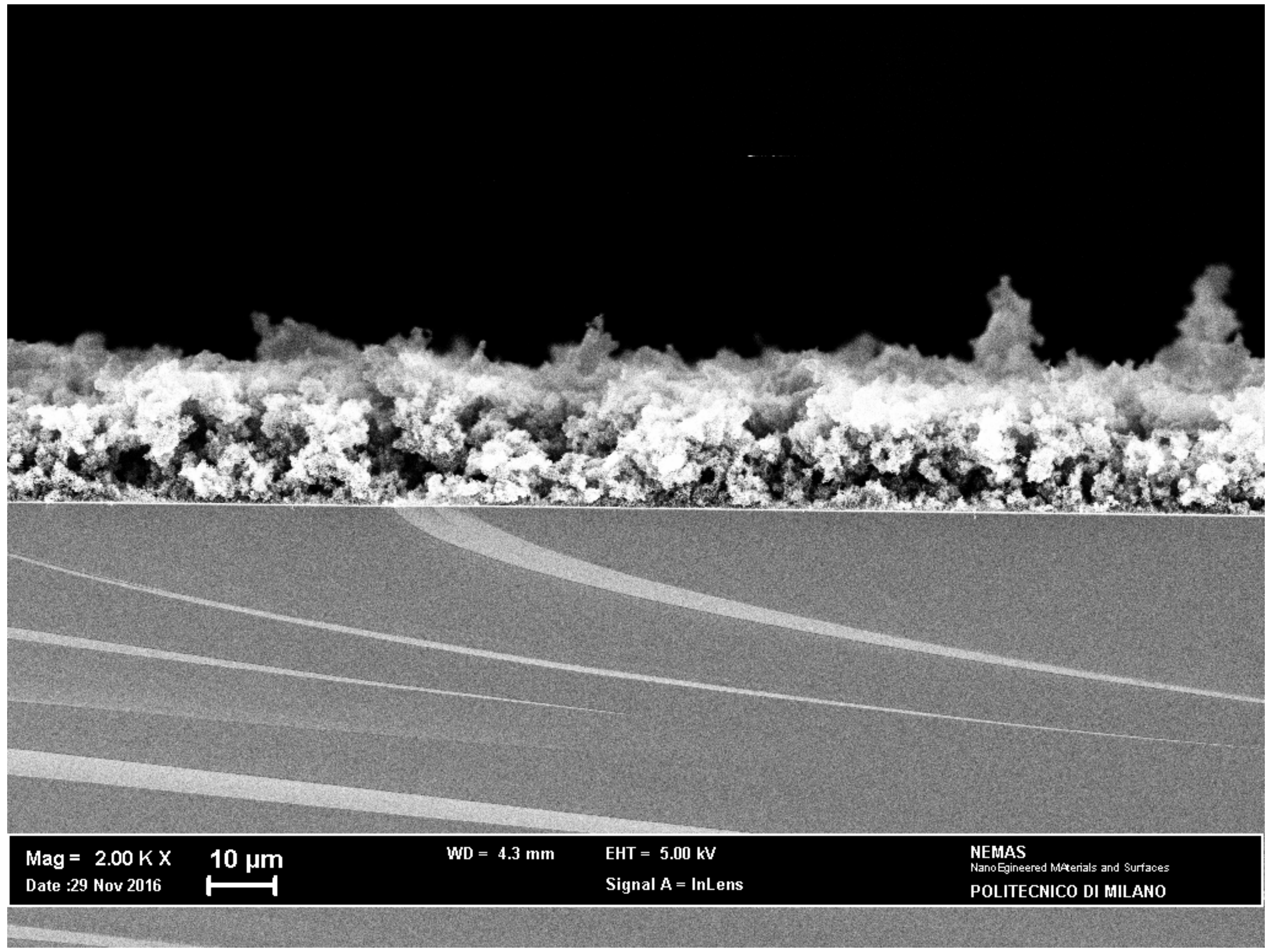
t = 189 fs

Carbon foams are one of the few solid near-critical materials for λ~1μm

top view SEM image

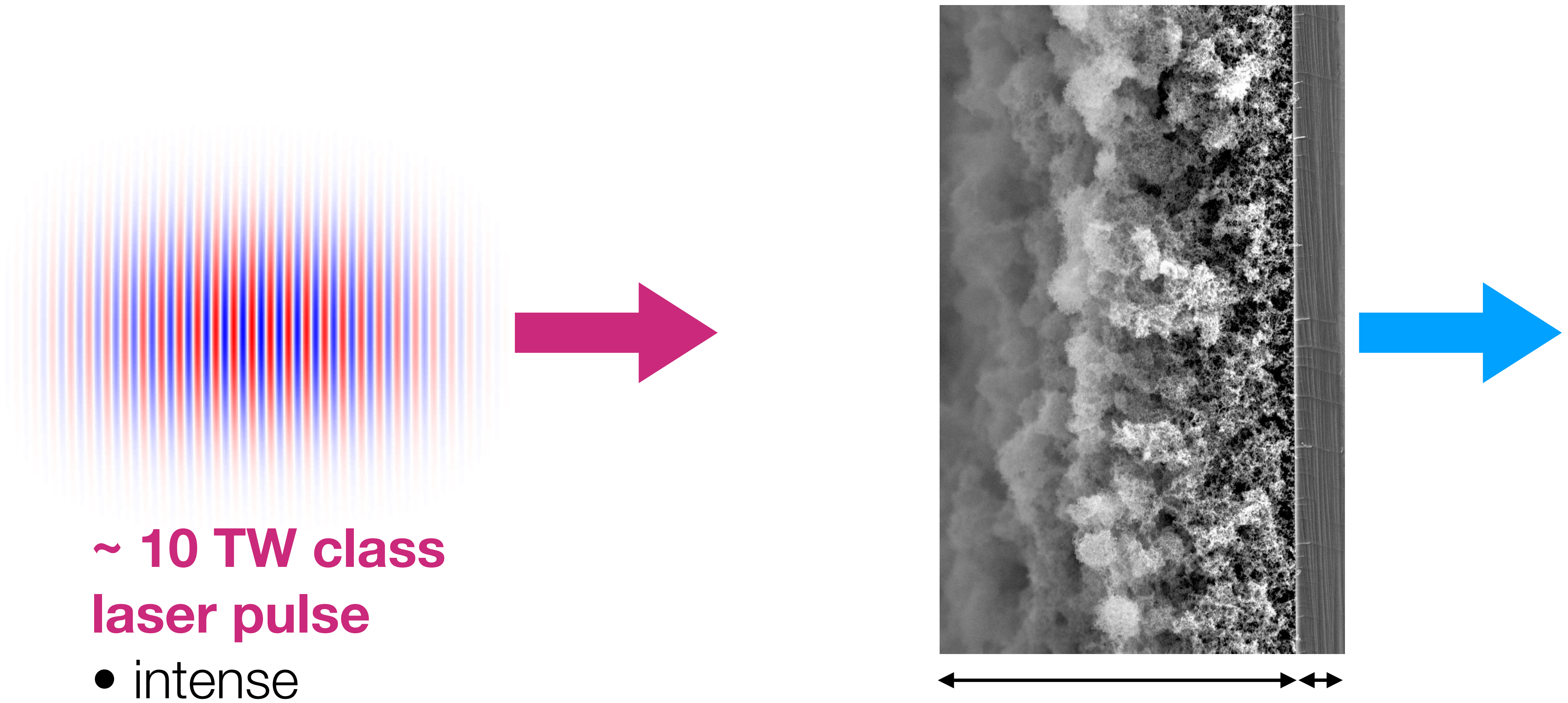


cross section SEM image



- high porosity → ultra-low average mass density (down to 10 mg/cm^3)
- aggregates of nanoparticles (radius ~ 10 - 20 nm)
- complex density profile coming from growth process (PLD, a PVD technique)

Compact neutron sources from enhanced TNSA with foam-attached targets



driver

~ 10 TW class laser pulse
- intense
- short

advanced pitcher

low density carbon foam

µm-thick solid foil

ions

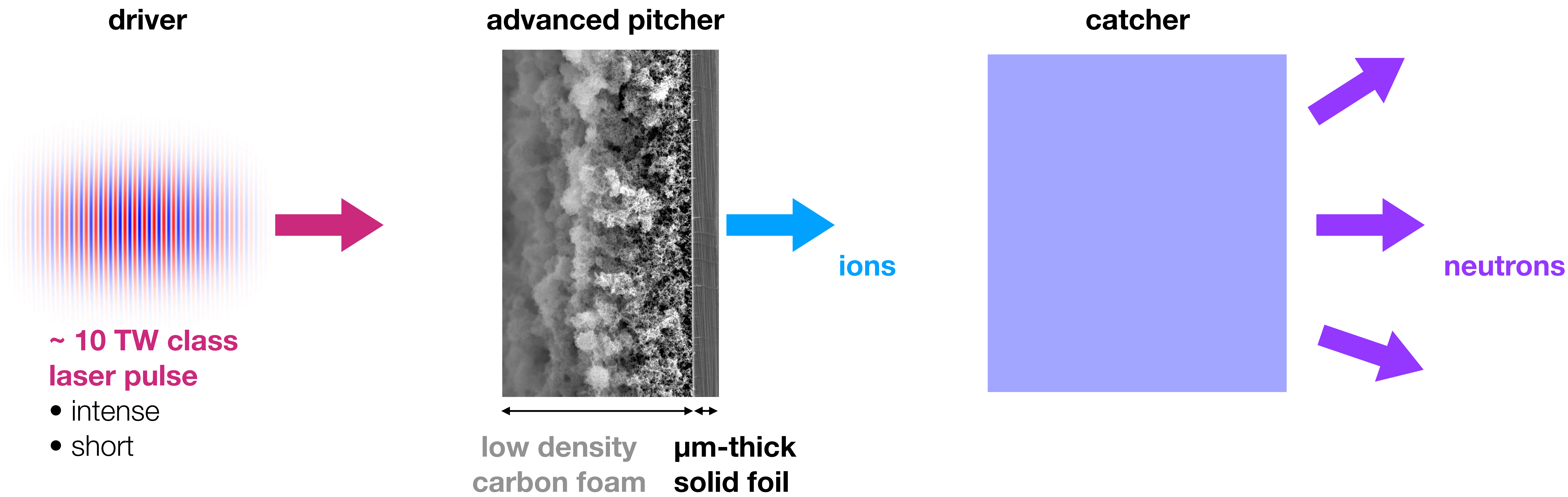
Benefits with foam targets

✓ **acceleration**
- more ions (~4 times)
- higher maximum energy (~2 times)

✓ **robustness**
- quite easy to handle
- suitable for high rep rate

✓ **flexibility**
- no polarization dependence

Compact neutron sources from enhanced TNSA with foam-attached targets



driver

~ 10 TW class laser pulse
- intense
- short

advanced pitcher

low density carbon foam

µm-thick solid foil

ions

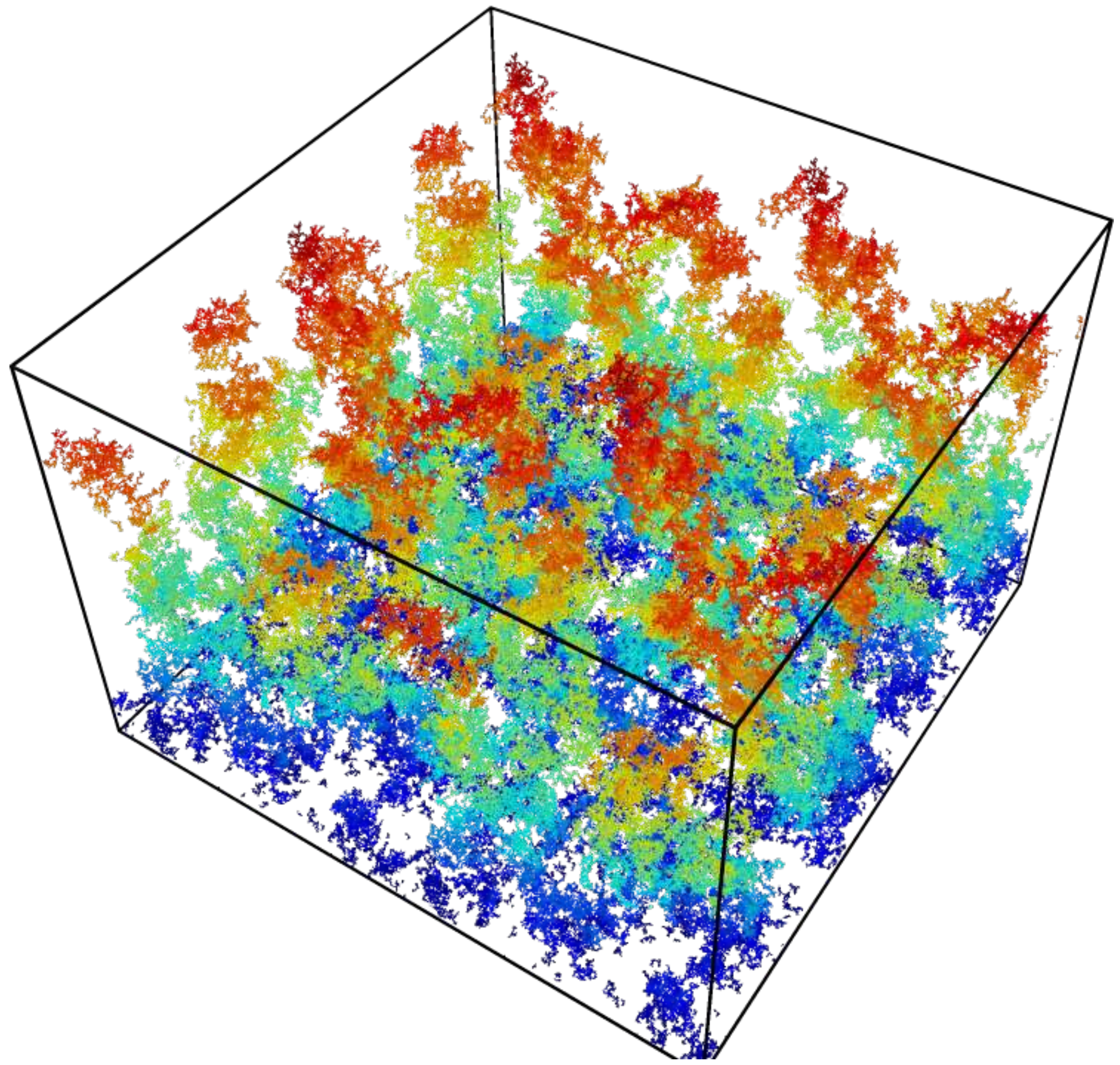
catcher

neutrons

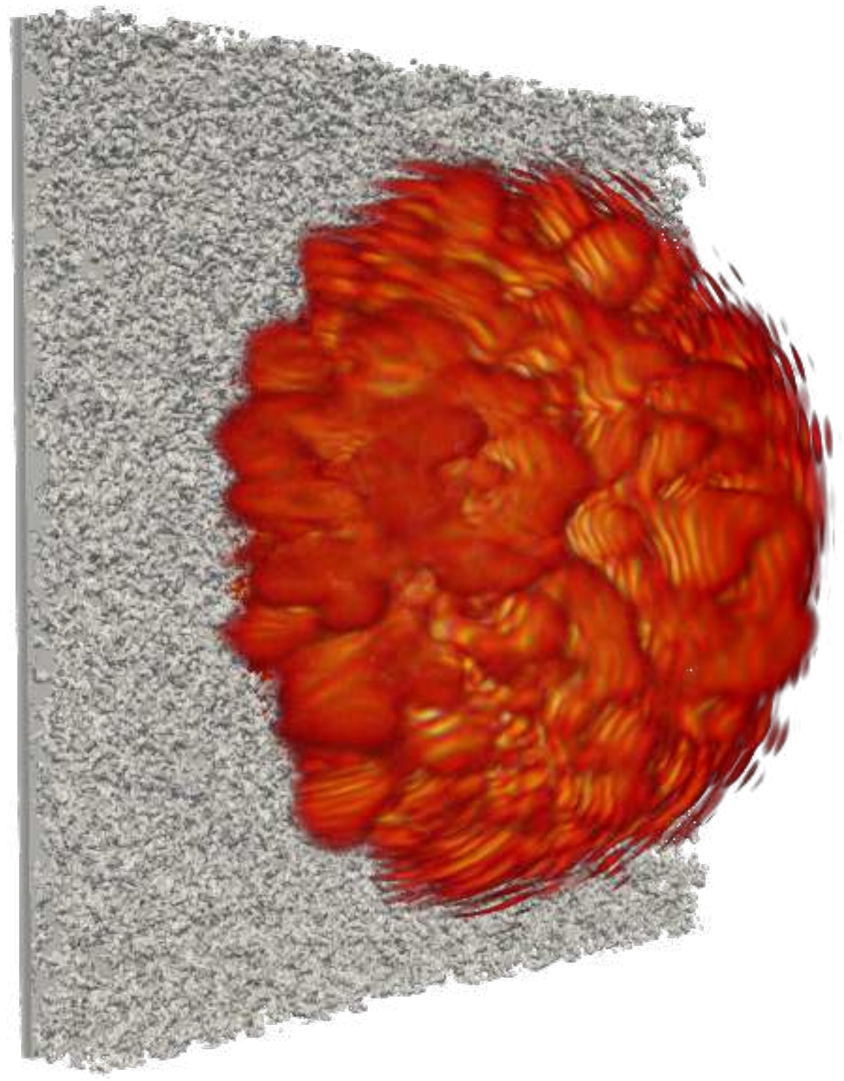
Goal: assess the feasibility of compact laser-driven neutron sources and design an optimized configuration to be tested experimentally. **How?**

We perform integrated, multi-physics, “realistic” simulations

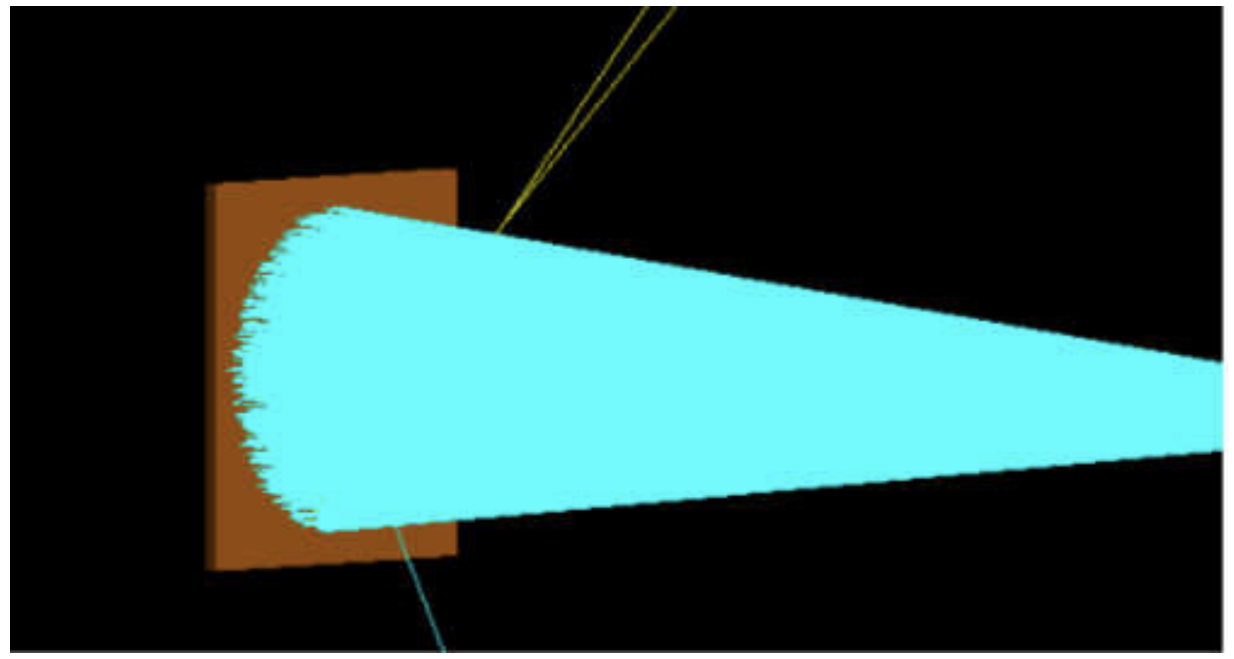
Realistic foam description



3D PIC simulations
of laser-driven ion acceleration

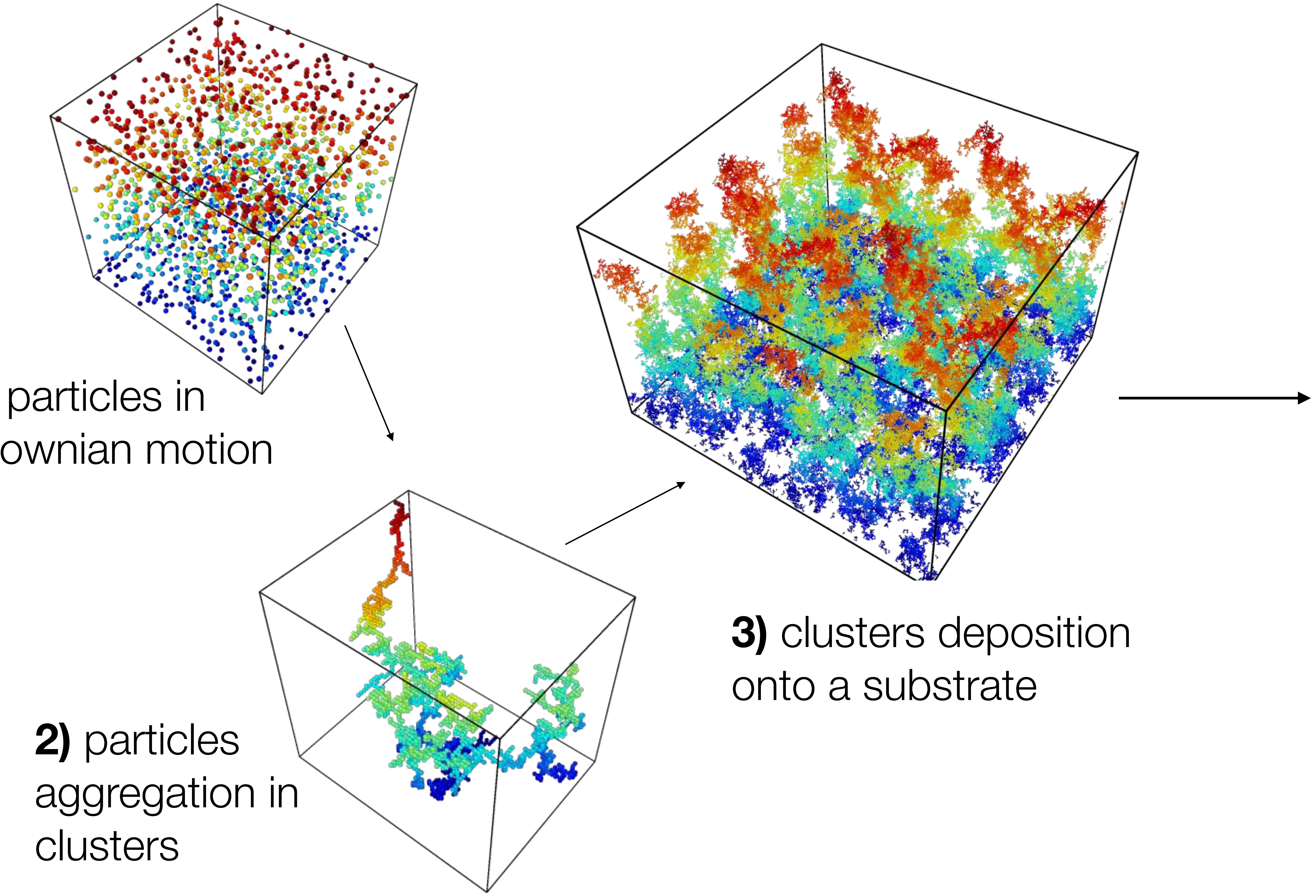


MC simulations
of neutron generation



Step 1 - Realistic description of the foam material

aggregation model that mimics the growth process

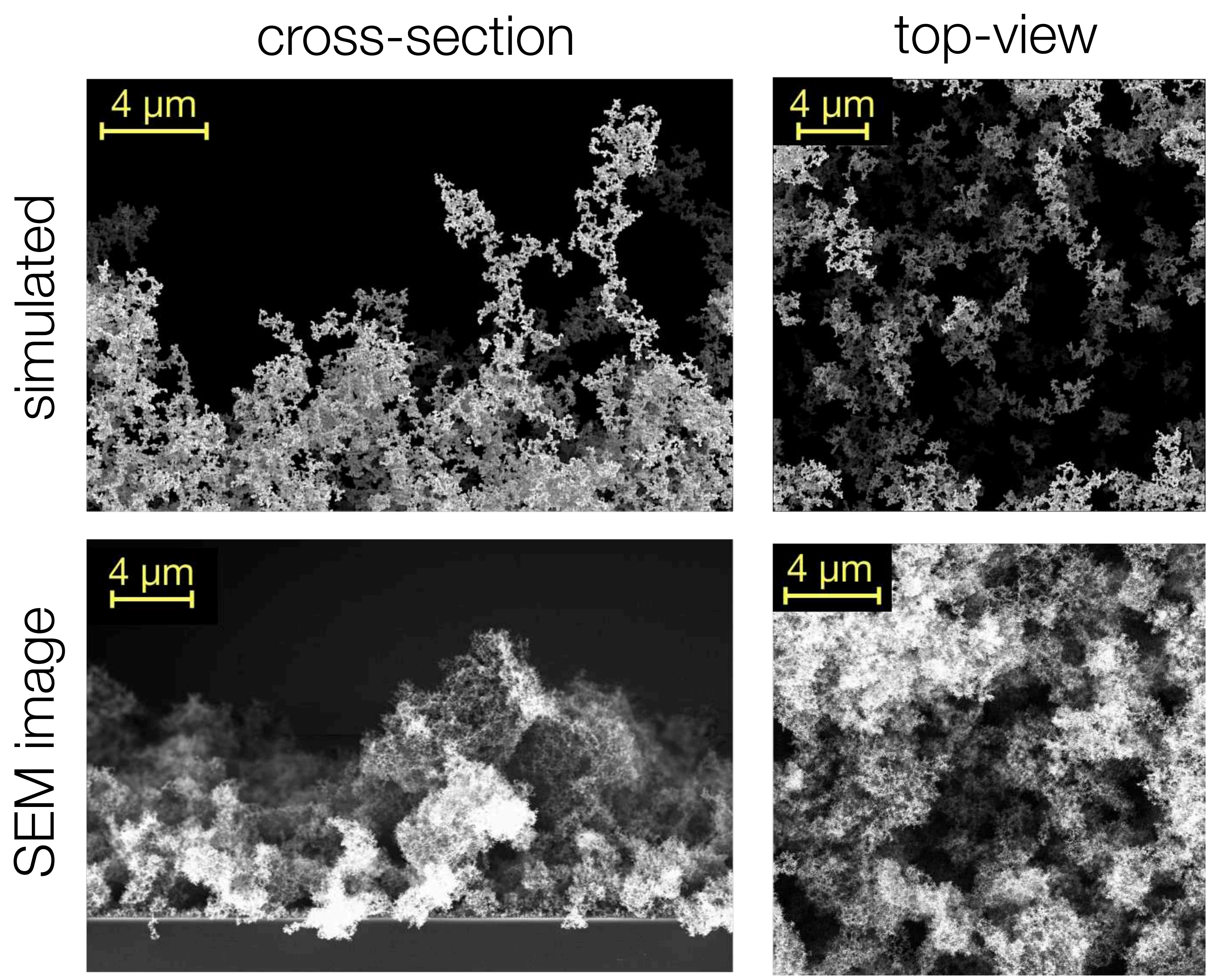


1) particles in Brownian motion

2) particles aggregation in clusters

3) clusters deposition onto a substrate

model vs. real



cross-section

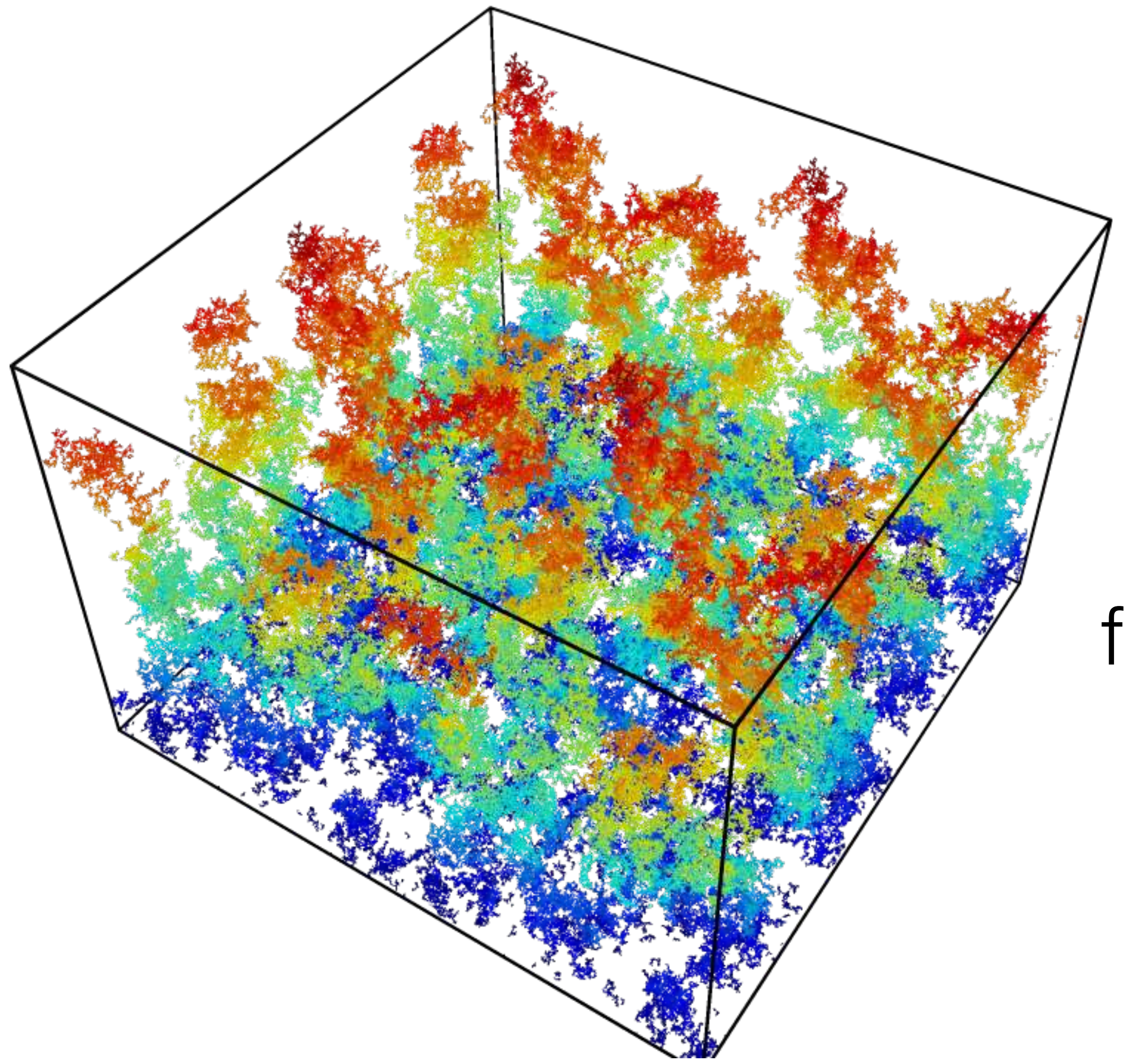
top-view

simulated

SEM image

nice agreement!

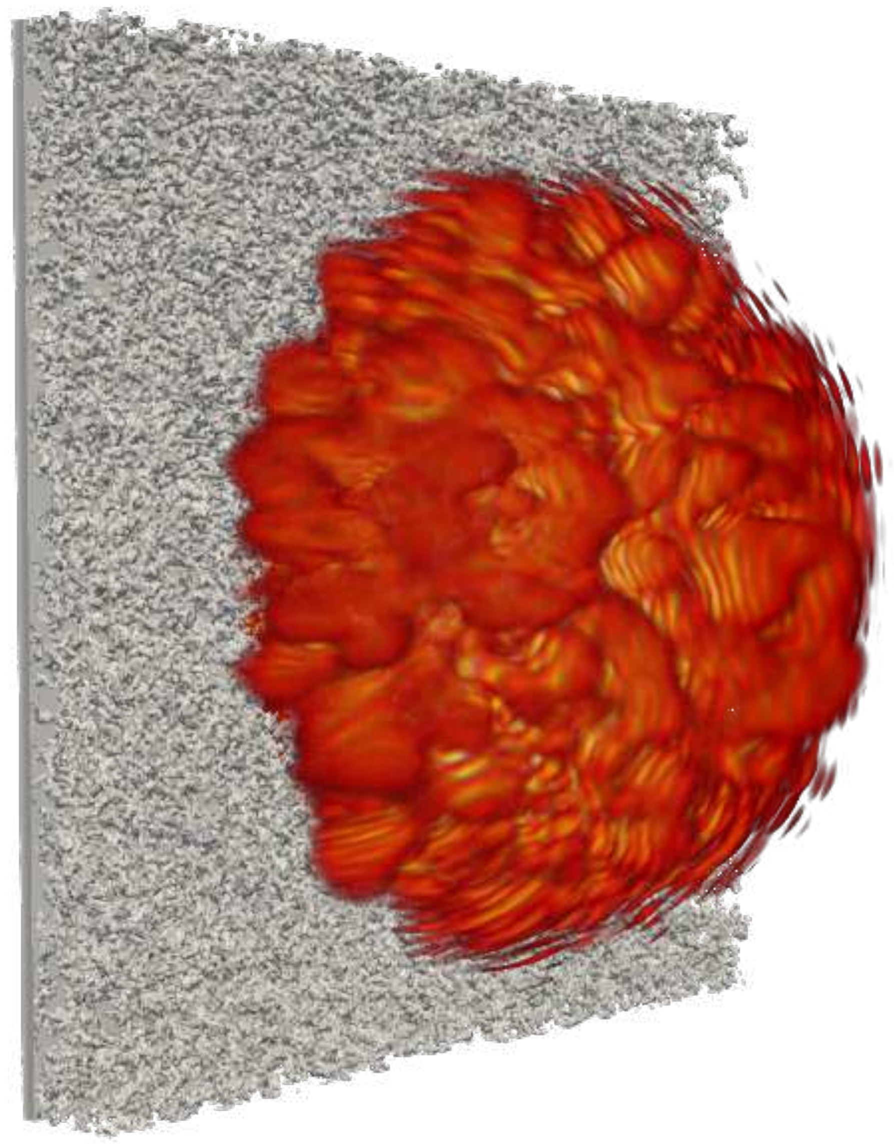
Step 2 - 3D PIC simulations of laser-driven ion acceleration



input

foam model

3D PIC simulation

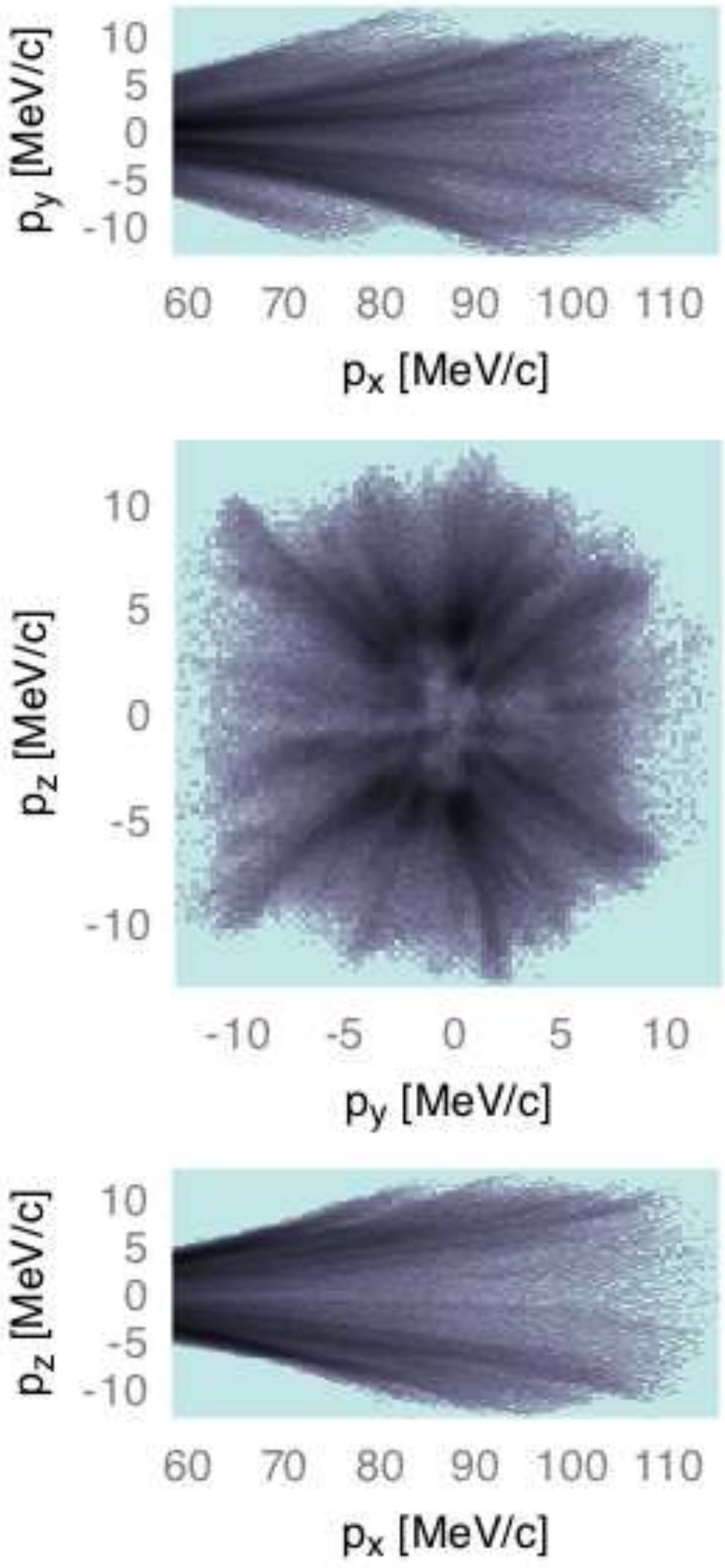


piccante

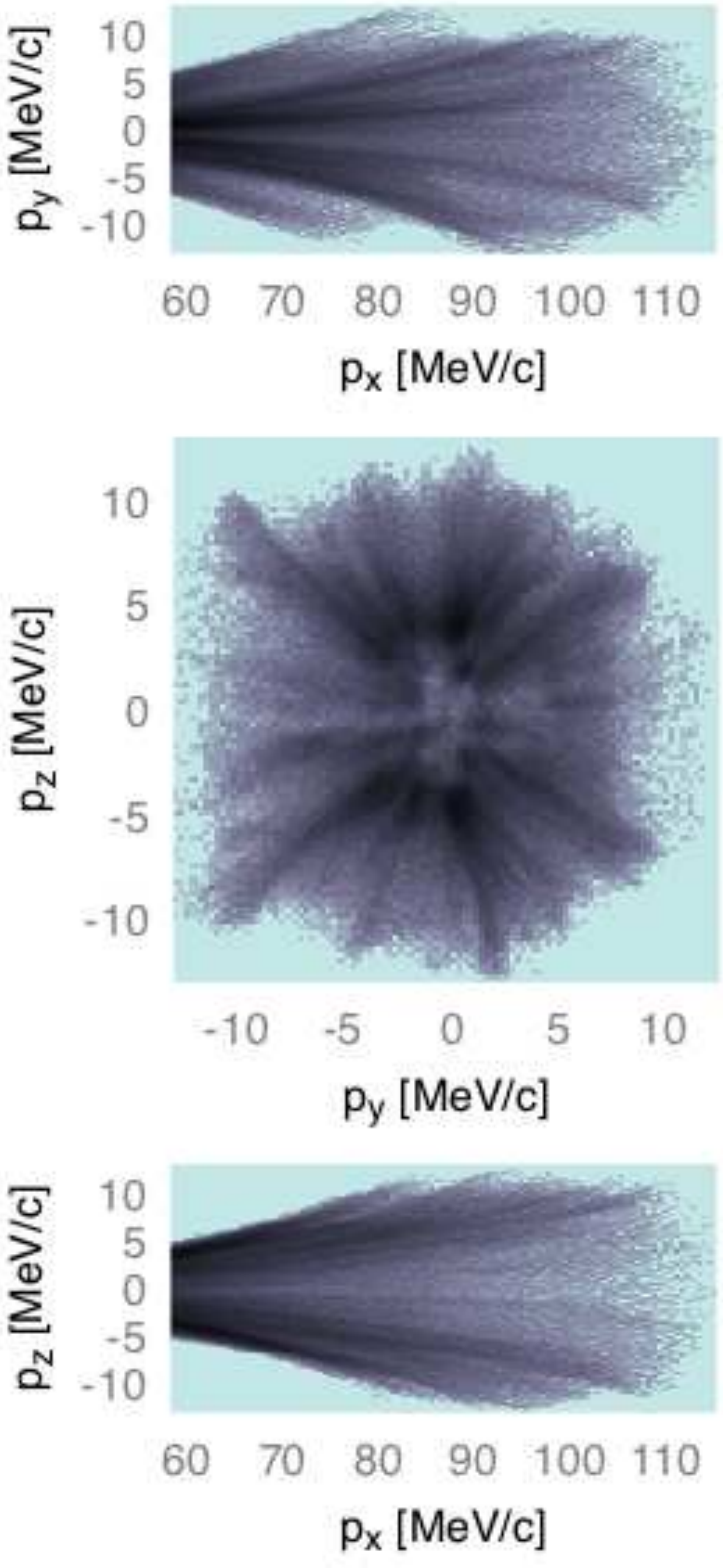
Open Source PIC Code

output

ion
momentum
distribution



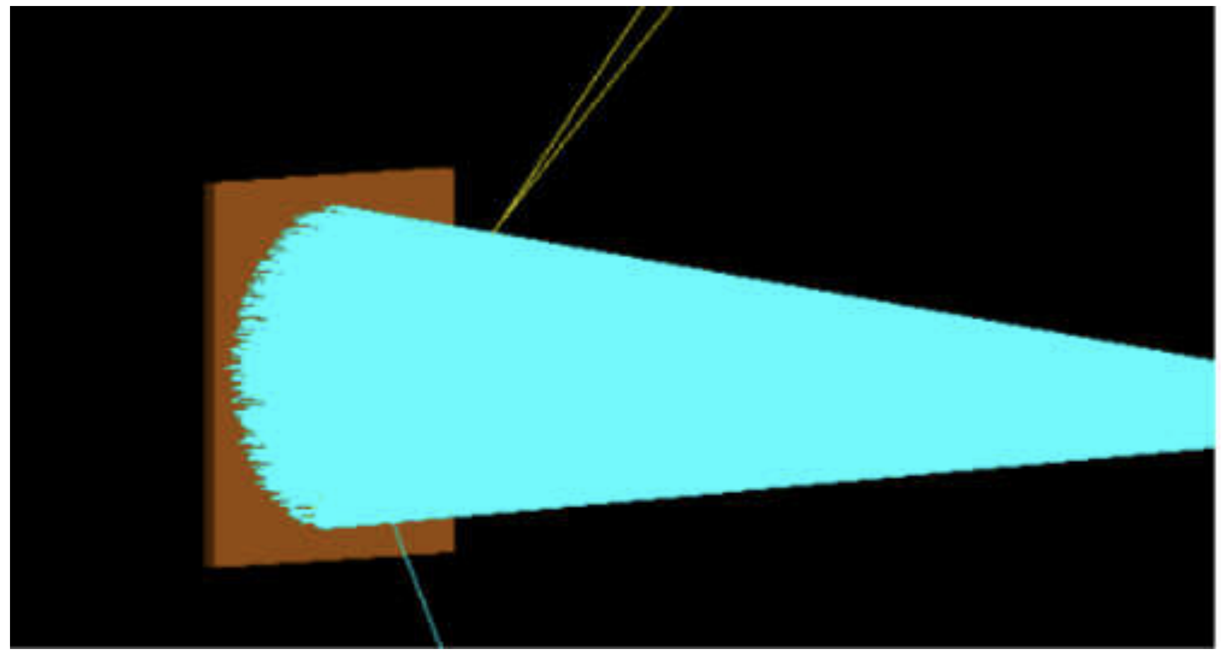
Step 3 - MC simulations of neutron generation



input →

ion
momentum
distribution

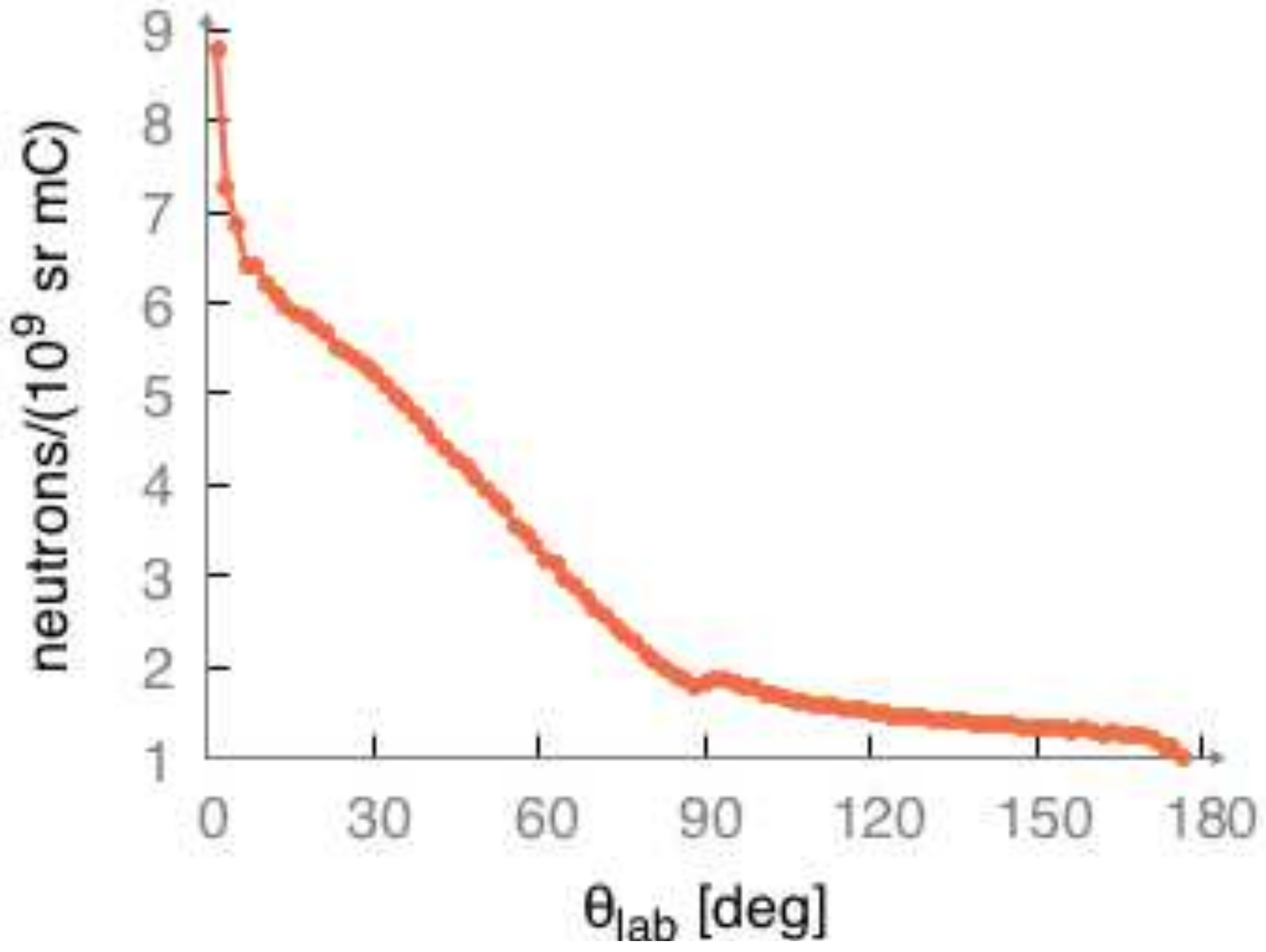
MC simulation

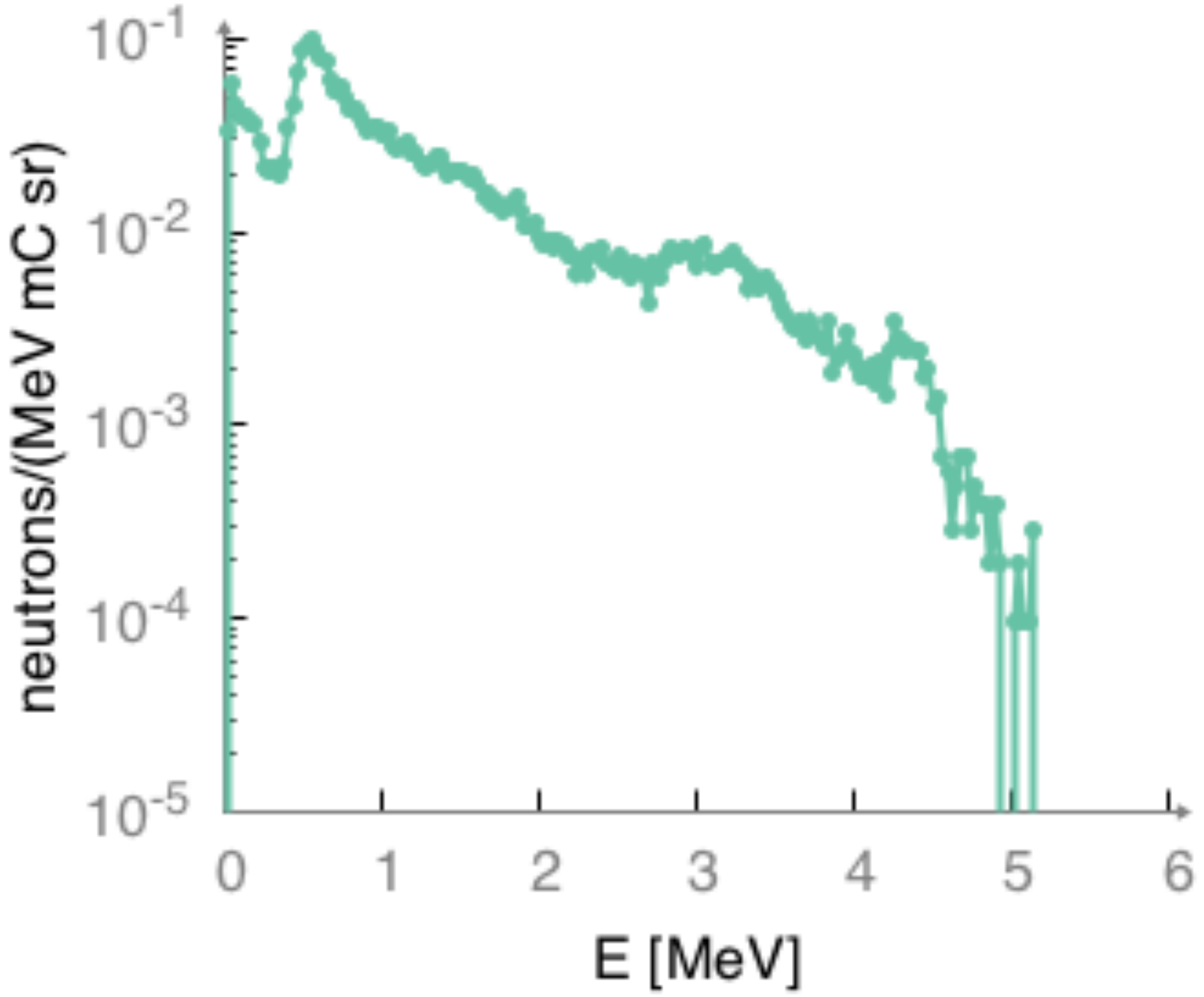


GEANT4
A SIMULATION TOOLKIT

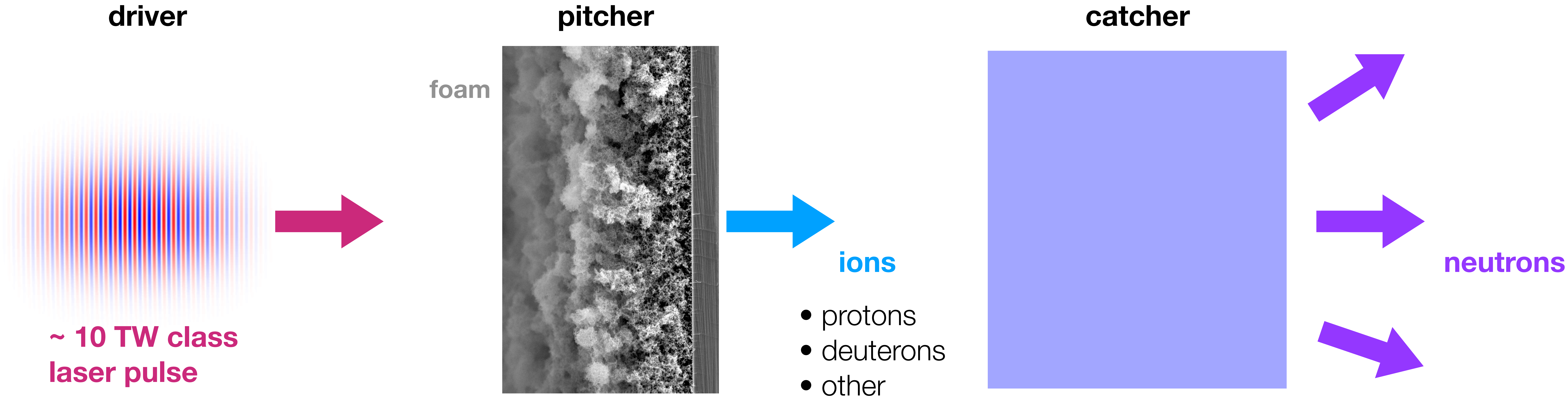
output →

neutron
angle and energy
distributions





We can tune several parameters to optimize the process



driver

pitcher

catcher

foam

~ 10 TW class laser pulse

ions

- protons
- deuterons
- other

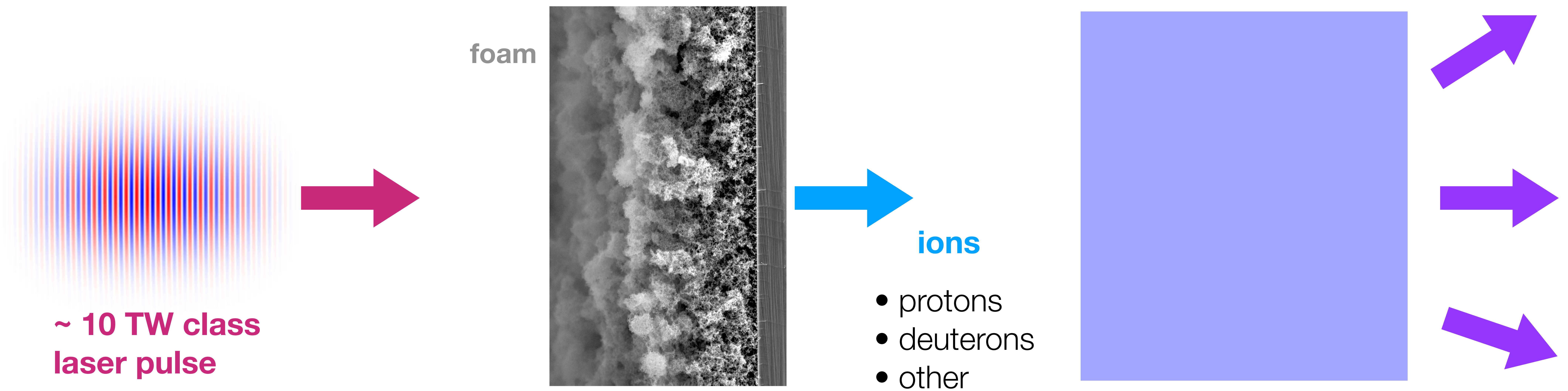
neutrons

fixed, let's say:
$\lambda = 0.8\ \mu m$, $\tau = 30$ fs,
w = 5 μm, $a_0 = 3.5$,
$\varepsilon \sim 600$ mJ, P ~ 20 TW

- foam density
- foam thickness
- foam morphology
- target composition

- composition
- reactions
- thickness

We can tune several parameters to optimize the process



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laser pulse

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pitcher

foam

- foam density
- foam thickness
- foam morphology
- target composition

ions

- protons
- deuterons
- other

catcher

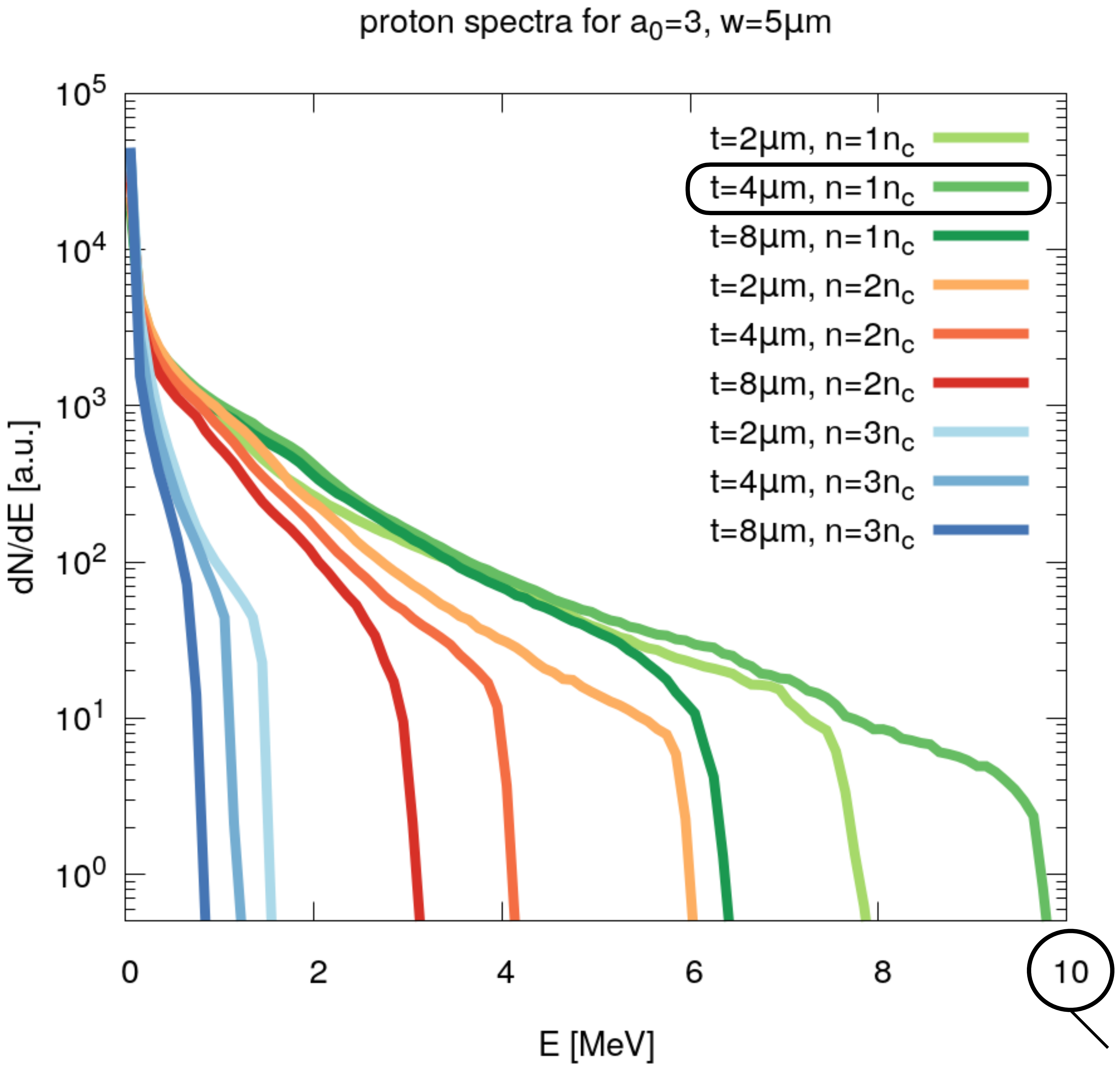
neutrons

- composition
- reactions
- thickness

There's a complex interplay between all the degrees of freedom we can play with, so that there's no universal recipe for optimization.
In the following: one possible strategy.

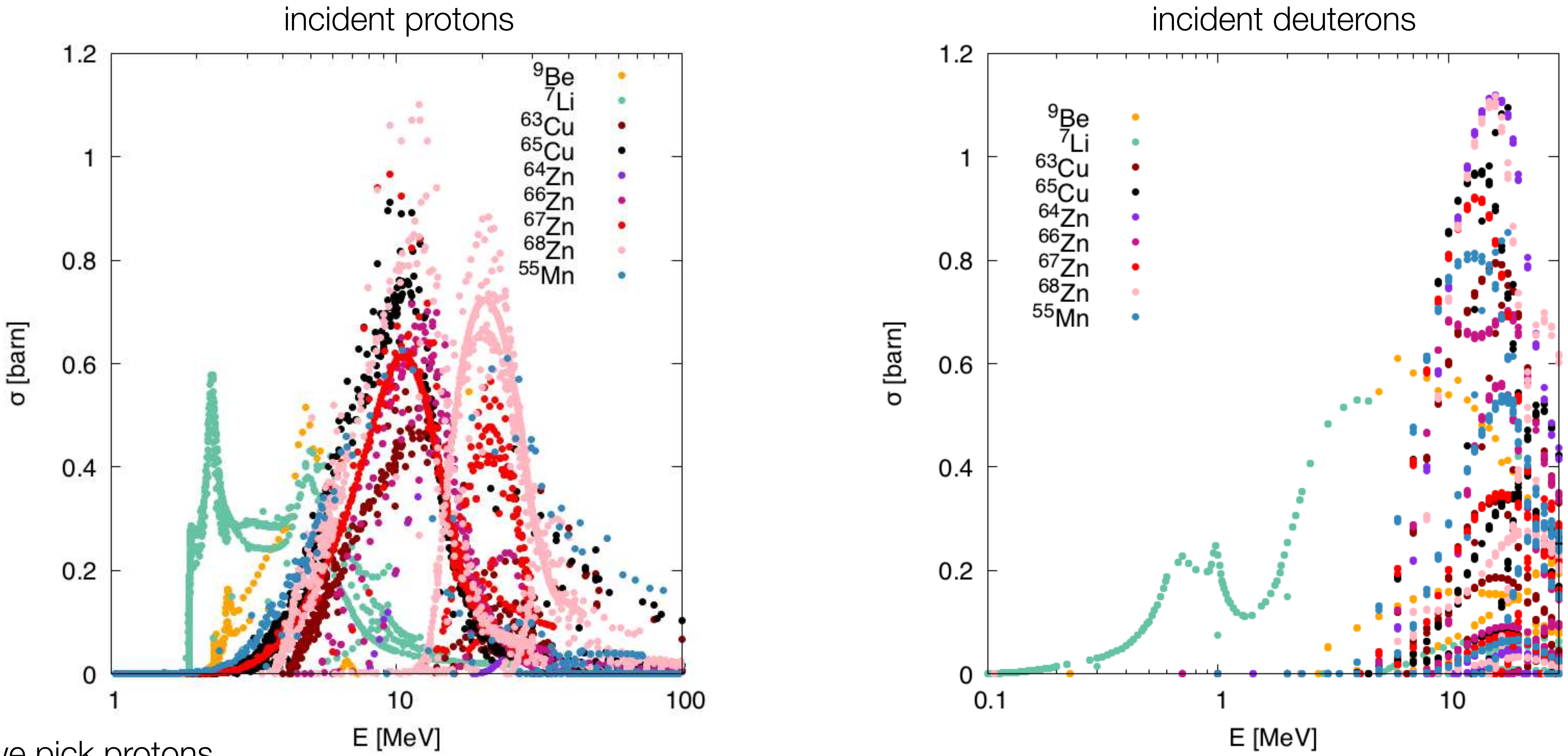
Step 1: design the foam-attached target via 2D PIC simulations

Use different foams targets and **pick the one that leads to higher ion energy and number**: here would be the foam with 4μm thickness and1n$_c$ density



in 3D would be something like 5 MeV

Step 2: pick what species to accelerate



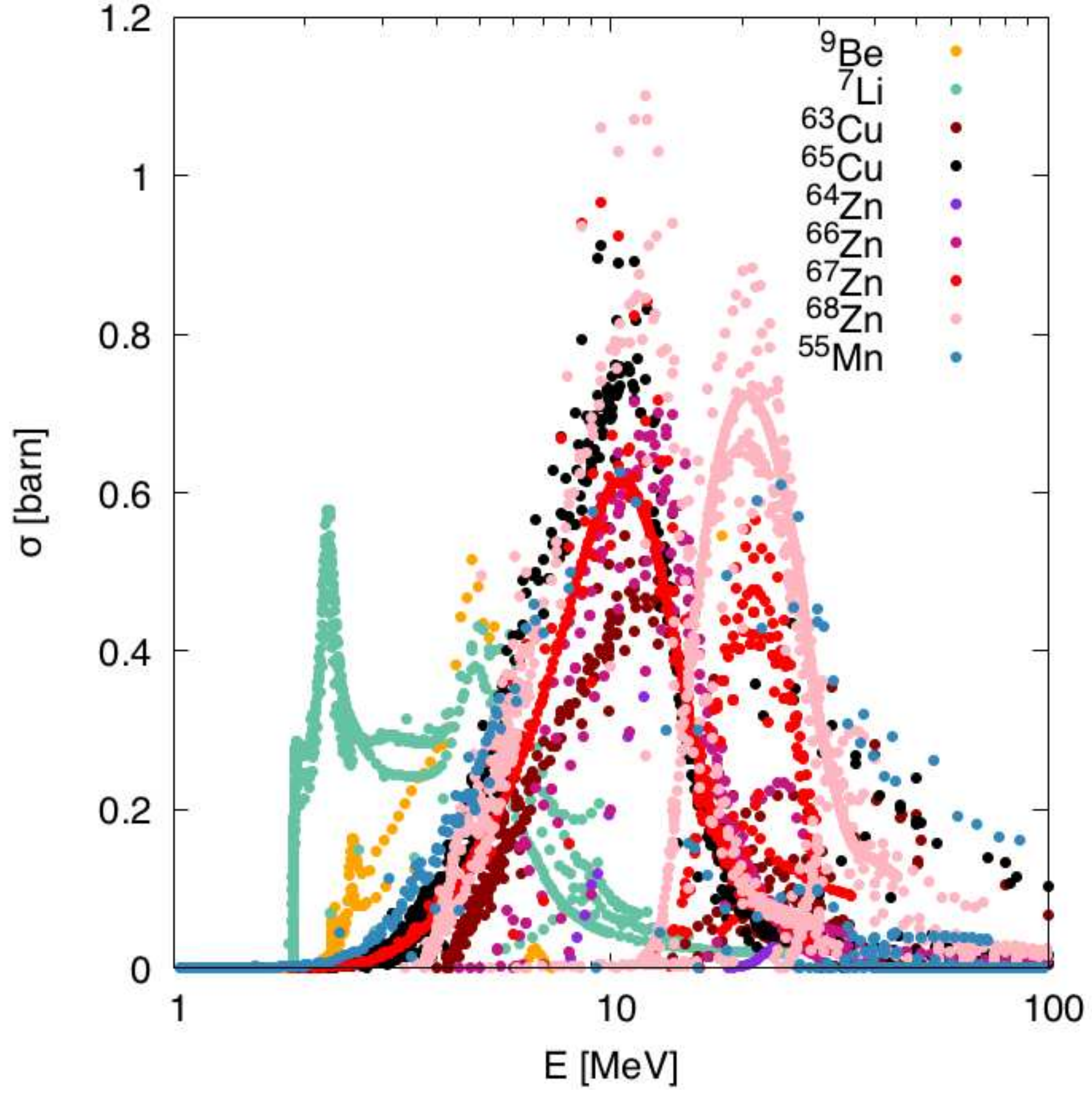
Let's say we pick protons
because it's easier to make the target

Plus, consider the reactions **Q-value**

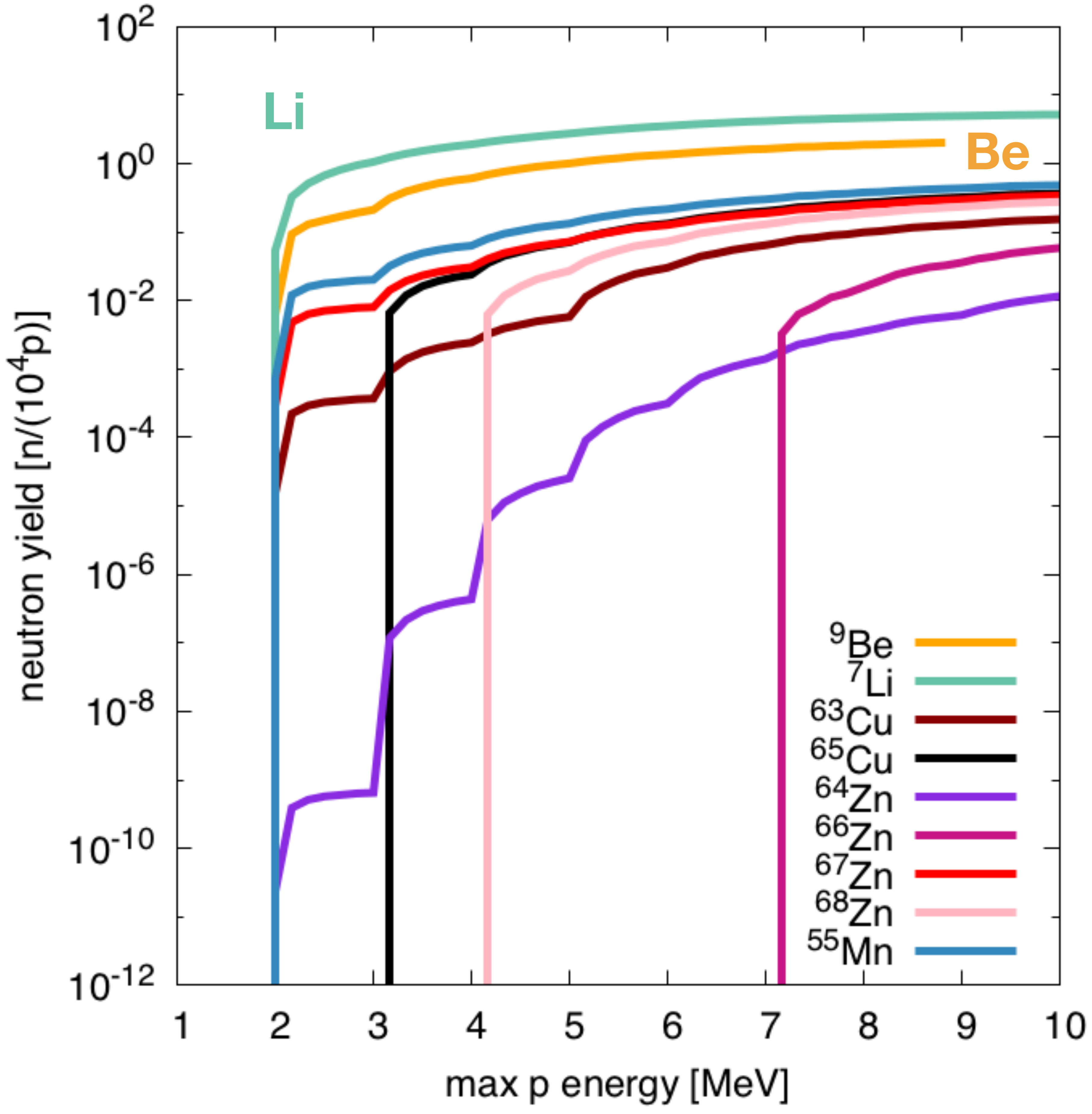
Step 3: design the converter: composition

$$Y(E_{max}) = \int_0^{E_{max}} \frac{dN_p}{dE_p}(E_p)\left(\int_{E_p}^{0} \sigma(\tilde{E}_p)\frac{d\tilde{E}_p}{SP(\tilde{E}_p)}\right) dE_p$$

EXFOR cross-section data for (p,xn) reactions

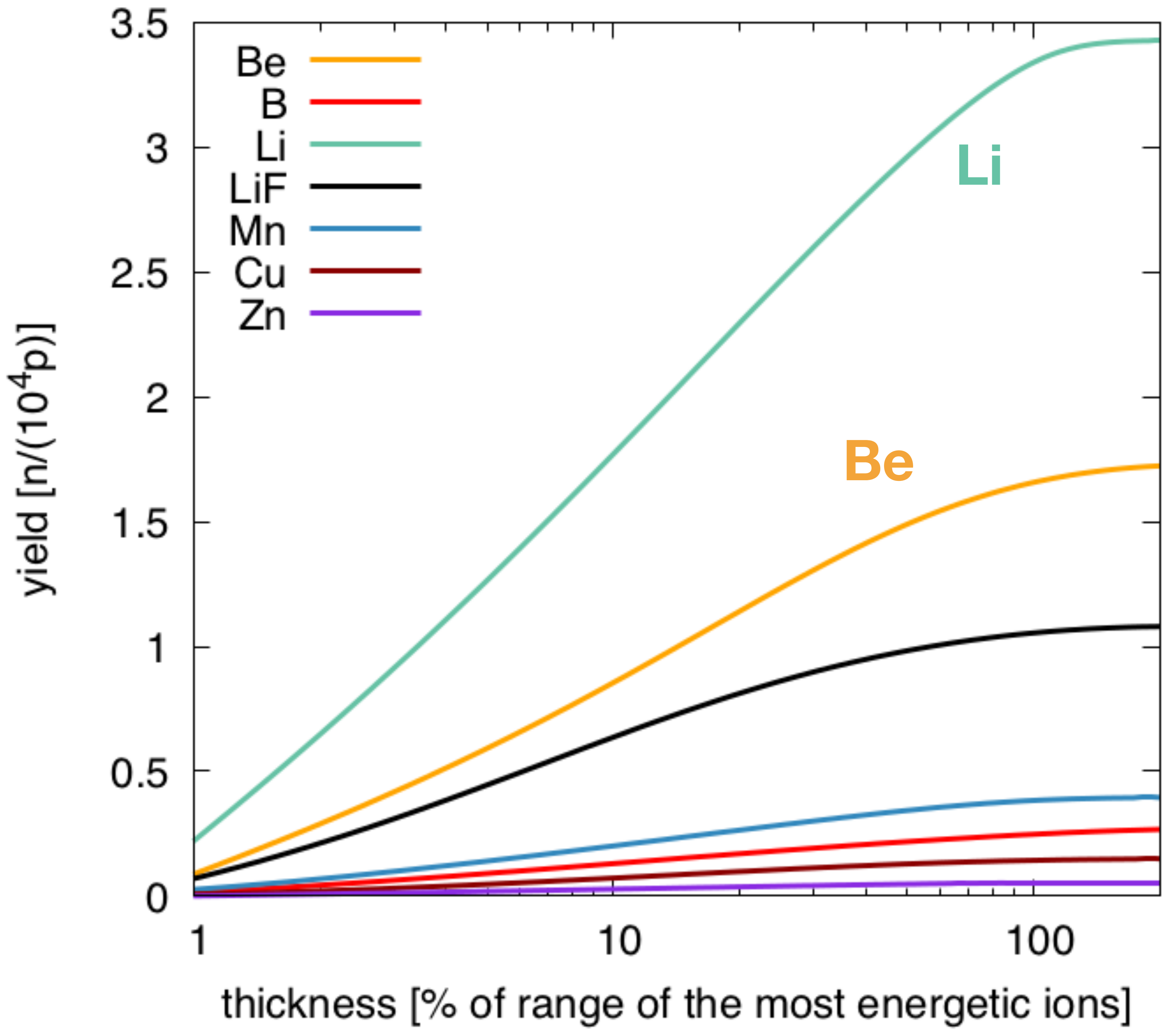


plus other n-generating reactions



Step 4: design the converter: thickness and others

thickness



- too thin: not all ions converted, easier to melt
- too thick: less energy and collimation of neutrons

other issues

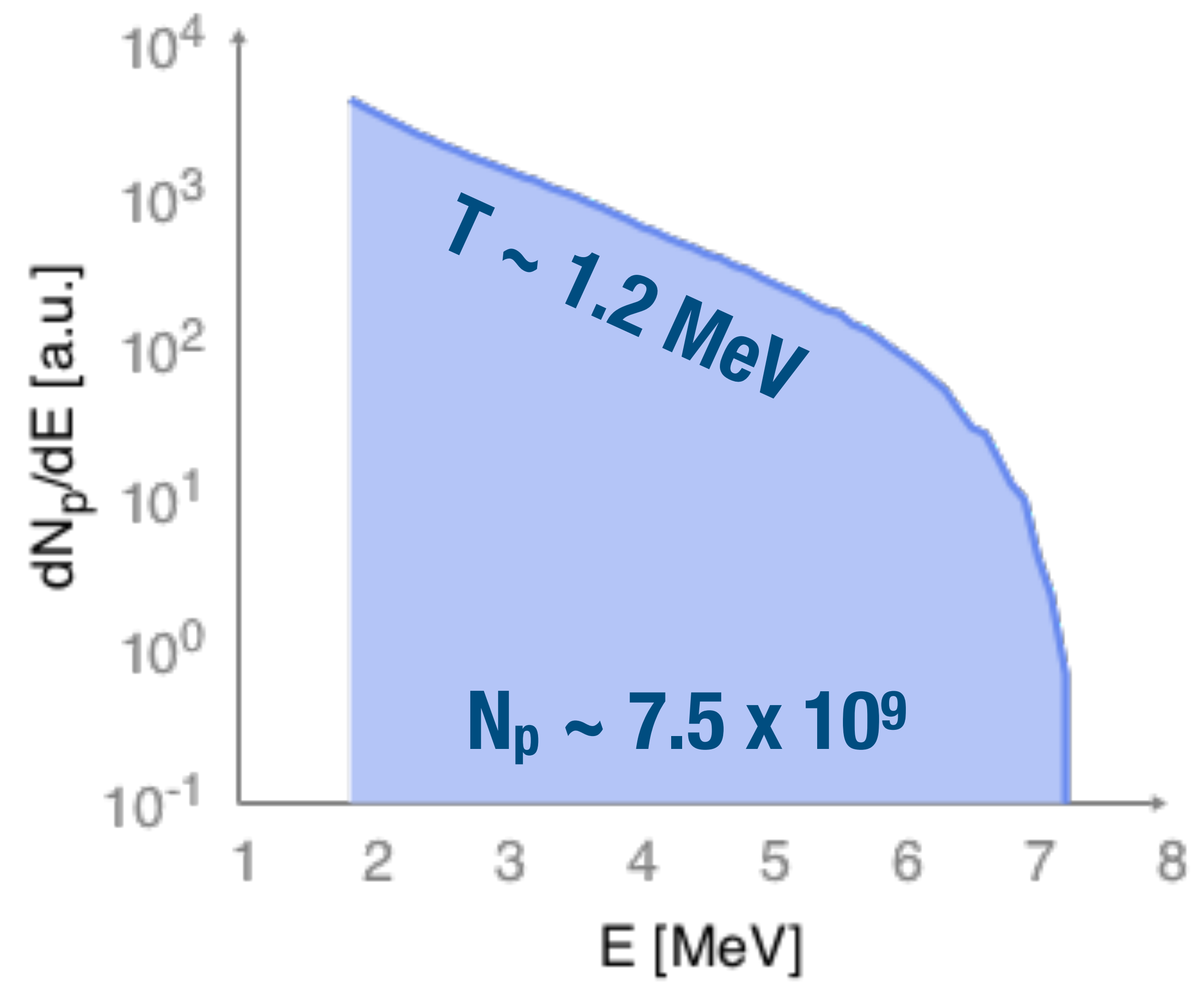
- Li is explosive
- Be is toxic
- medium-Z materials lead to long-lived radioactive isotopes
- radioprotection
- need for cooling
- hydrogen embrittlement
- melting

→ In the end, we picked **lithium with thickness equal to range of most energetic particles**, even tough it comes with several issues

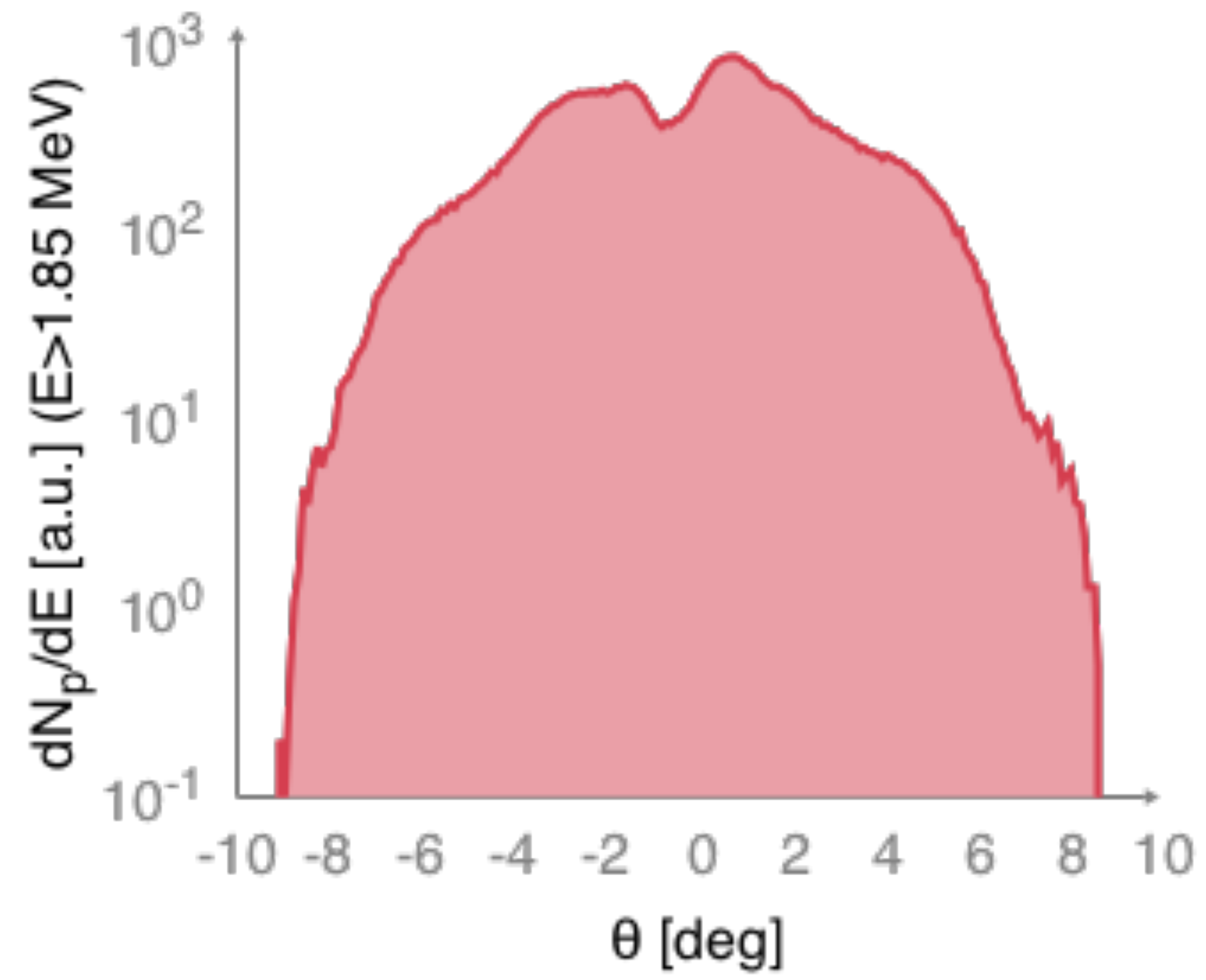
Some results with a 20 TW, 0.6 J, 30 fs laser

protons

energy distribution

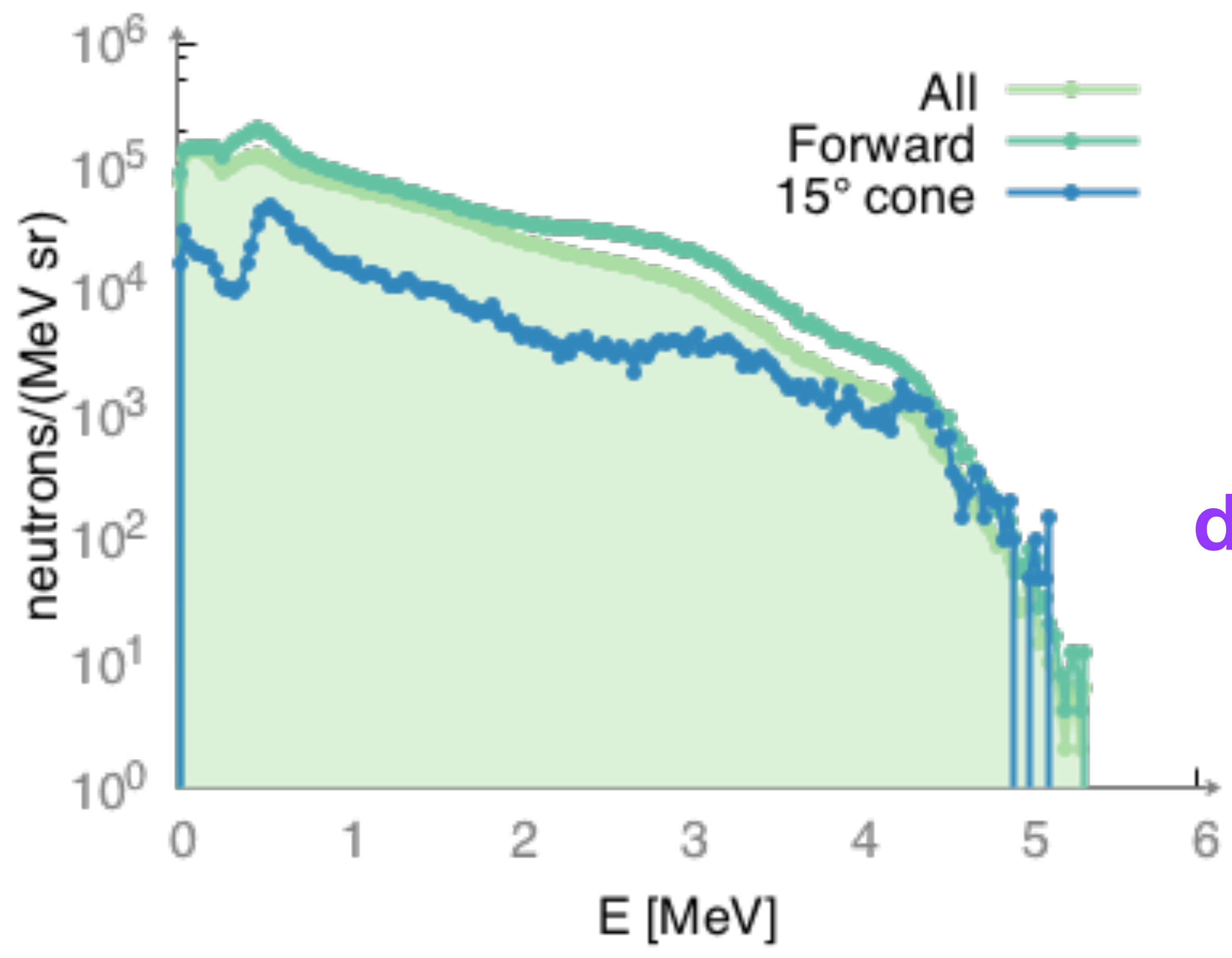


angular distribution



neutrons

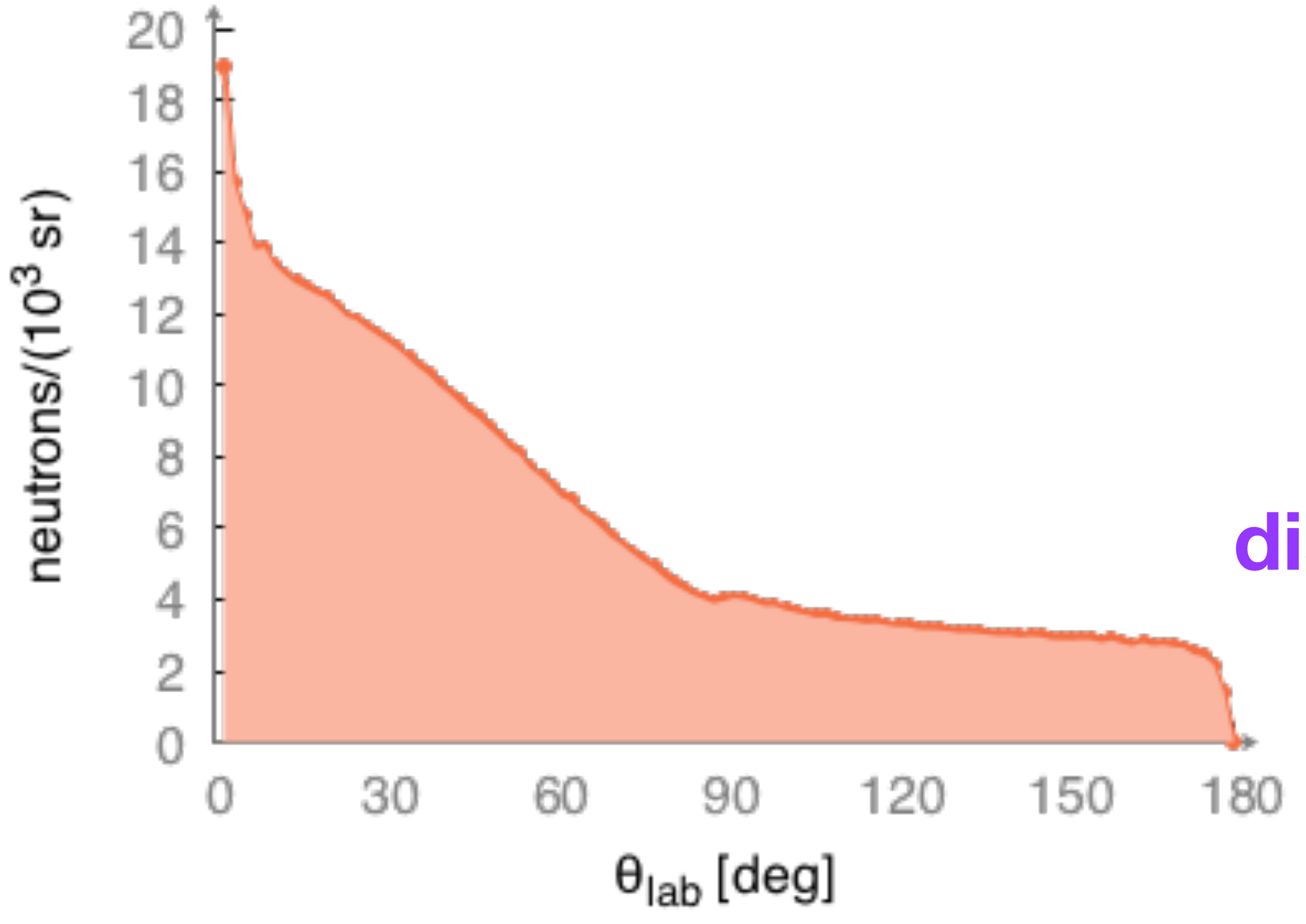
energy distribution



$Y_{4\pi}$~ 1.7 x 10^5 n/sr

$Y_{15°cone}$~4.2 x 10^4 n/sr

angular distribution

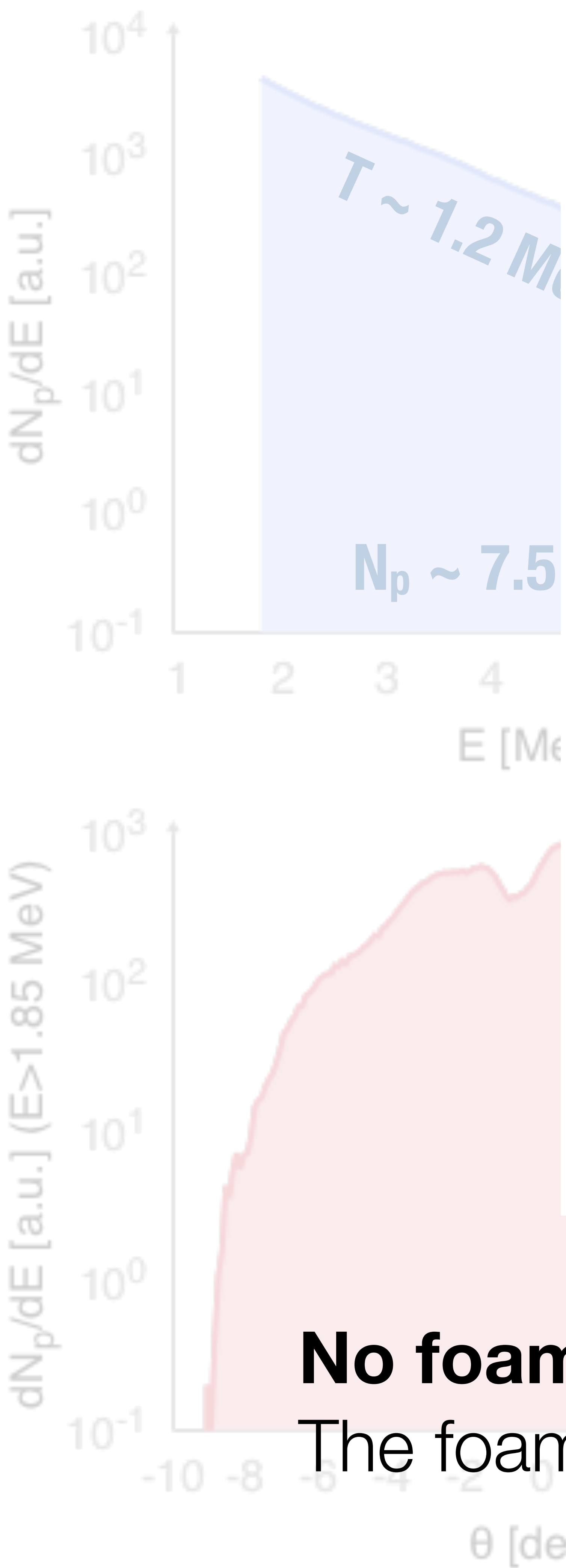


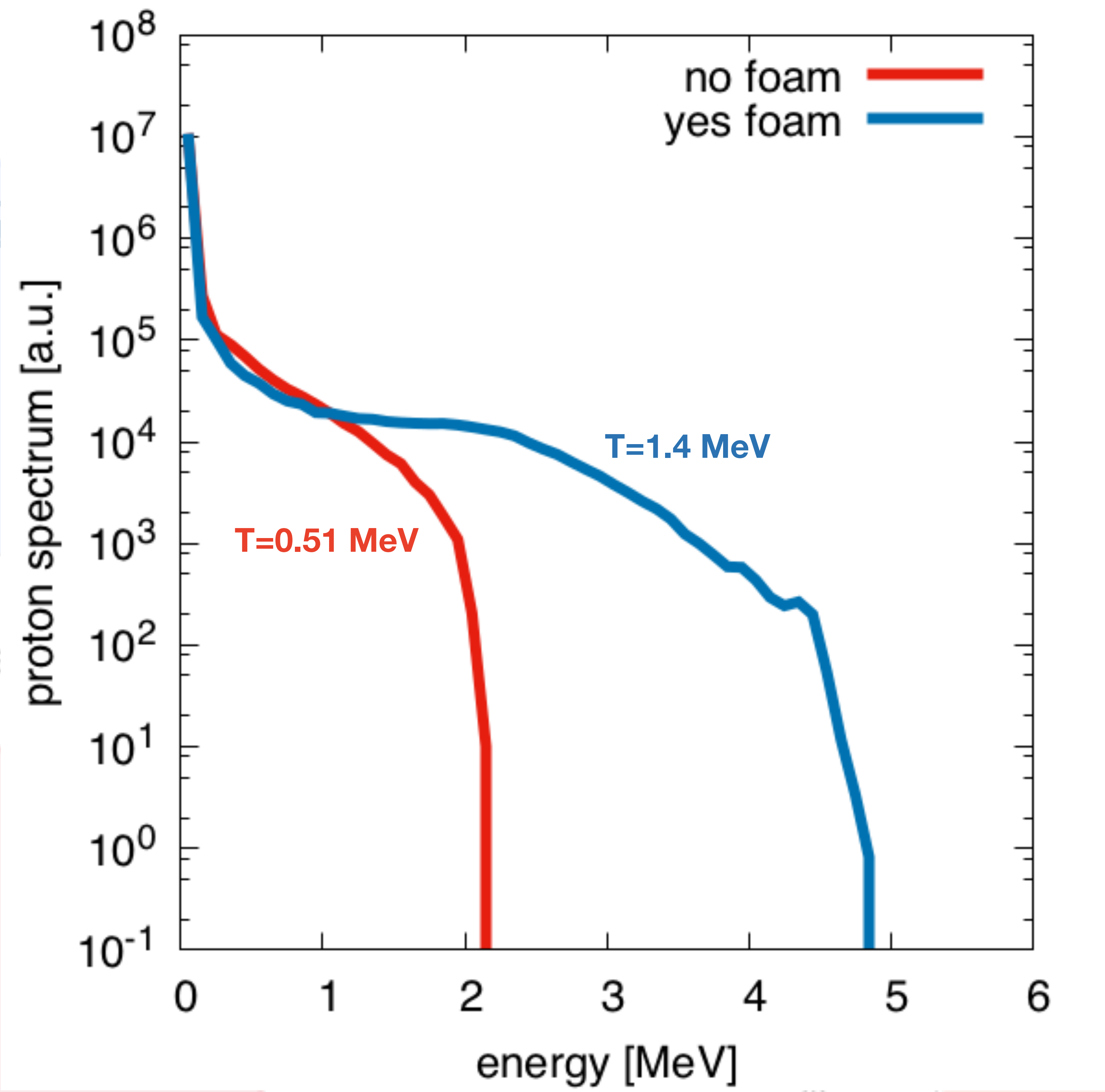
Some results with a 20 TW, 600 mJ, 30 fs laser

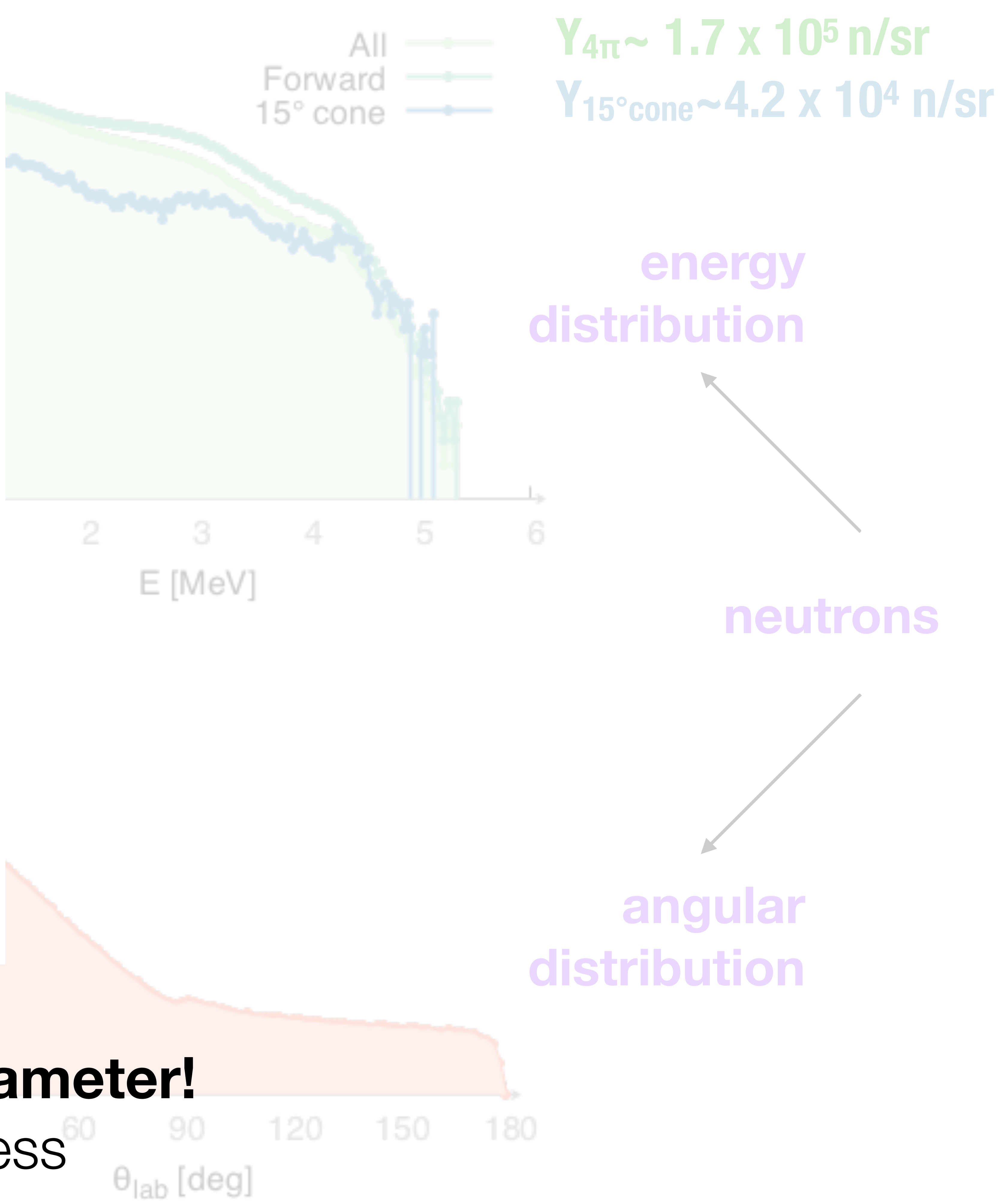
energy distribution

protons

angular distribution







energy distribution

neutrons

angular distribution

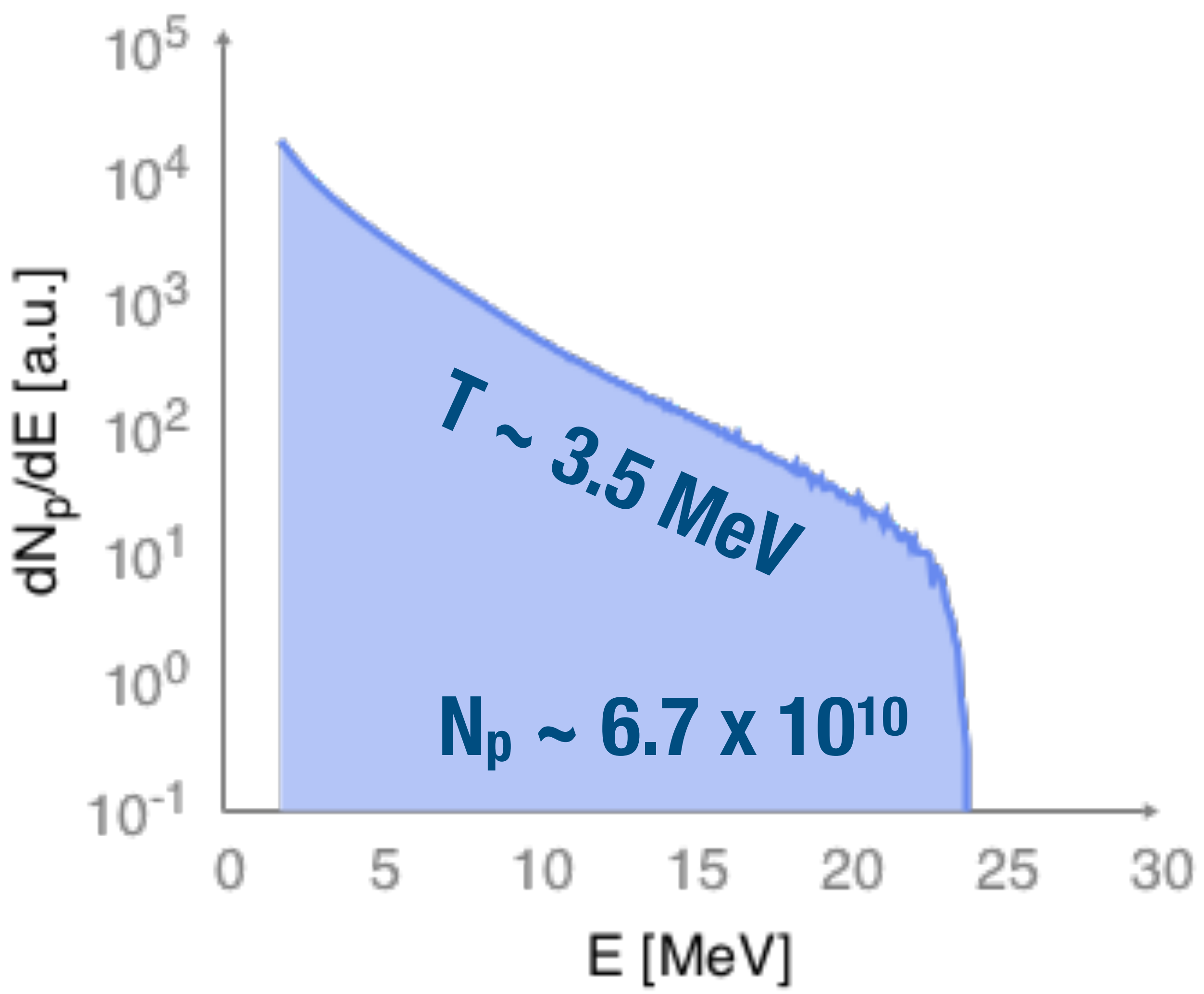
No foam, no neutrons with these laser parameter!

The foam enables the neutron generation process

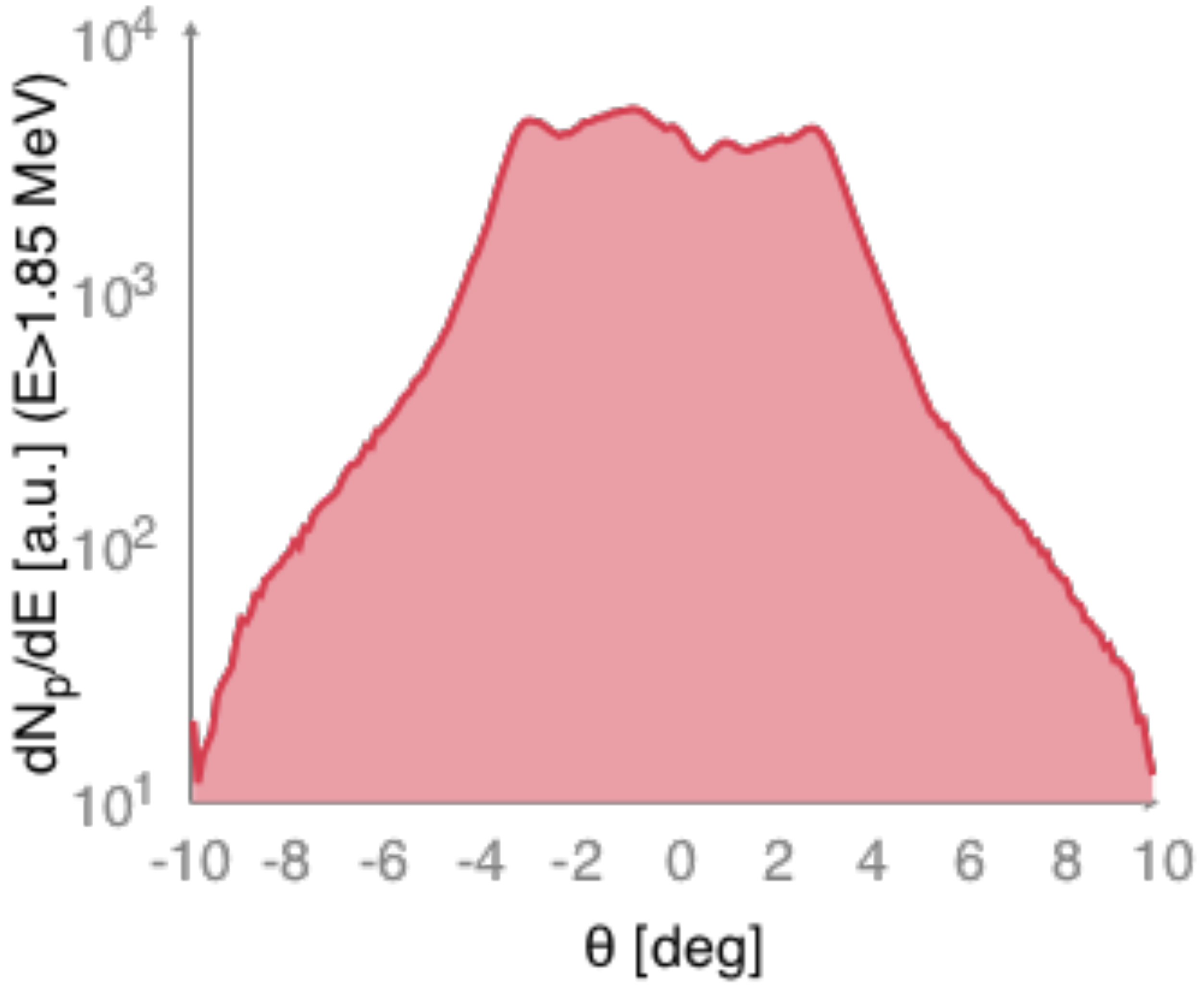
Some results with a 75 TW, 2.2 J, 30 fs laser

protons

energy distribution

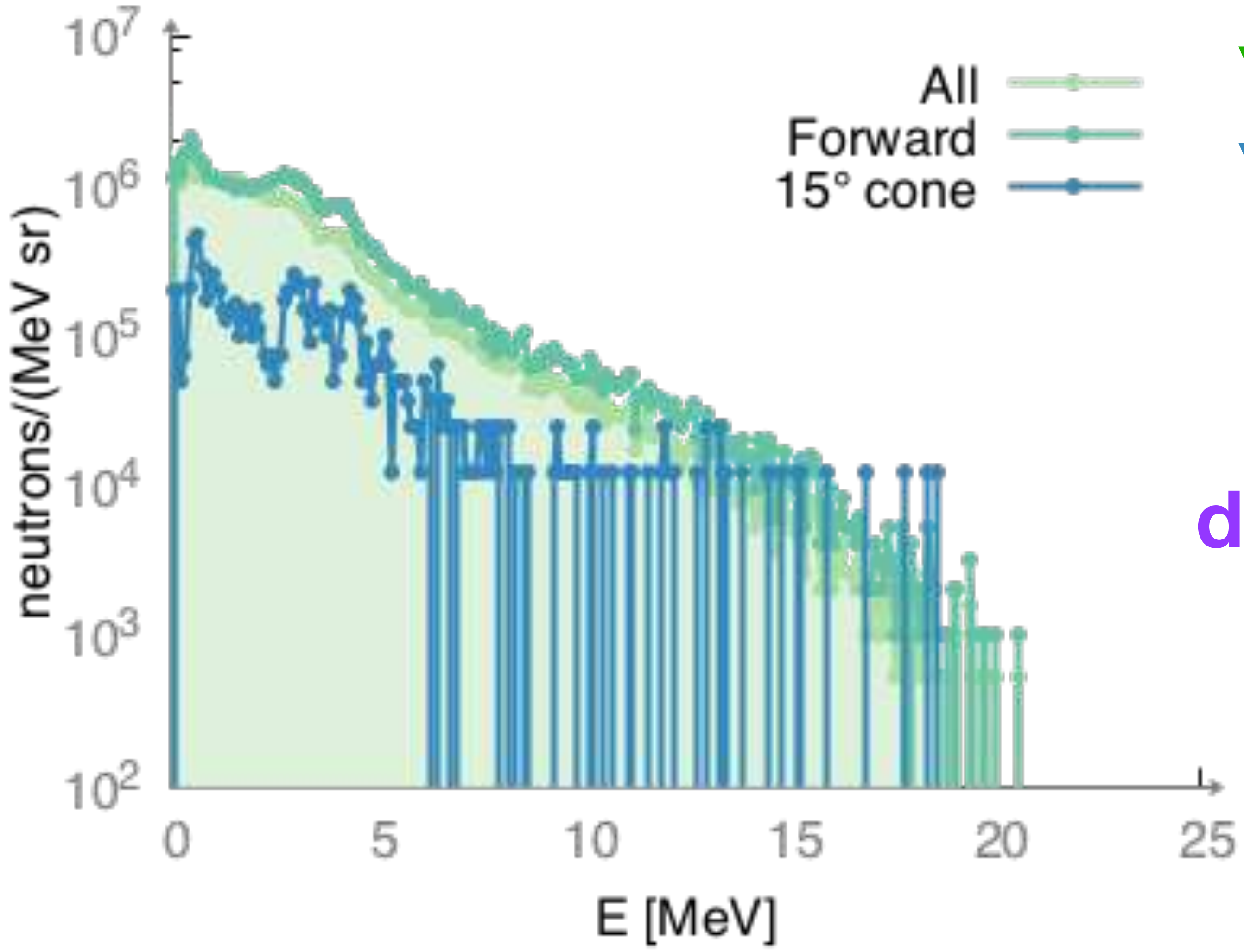


angular distribution



neutrons

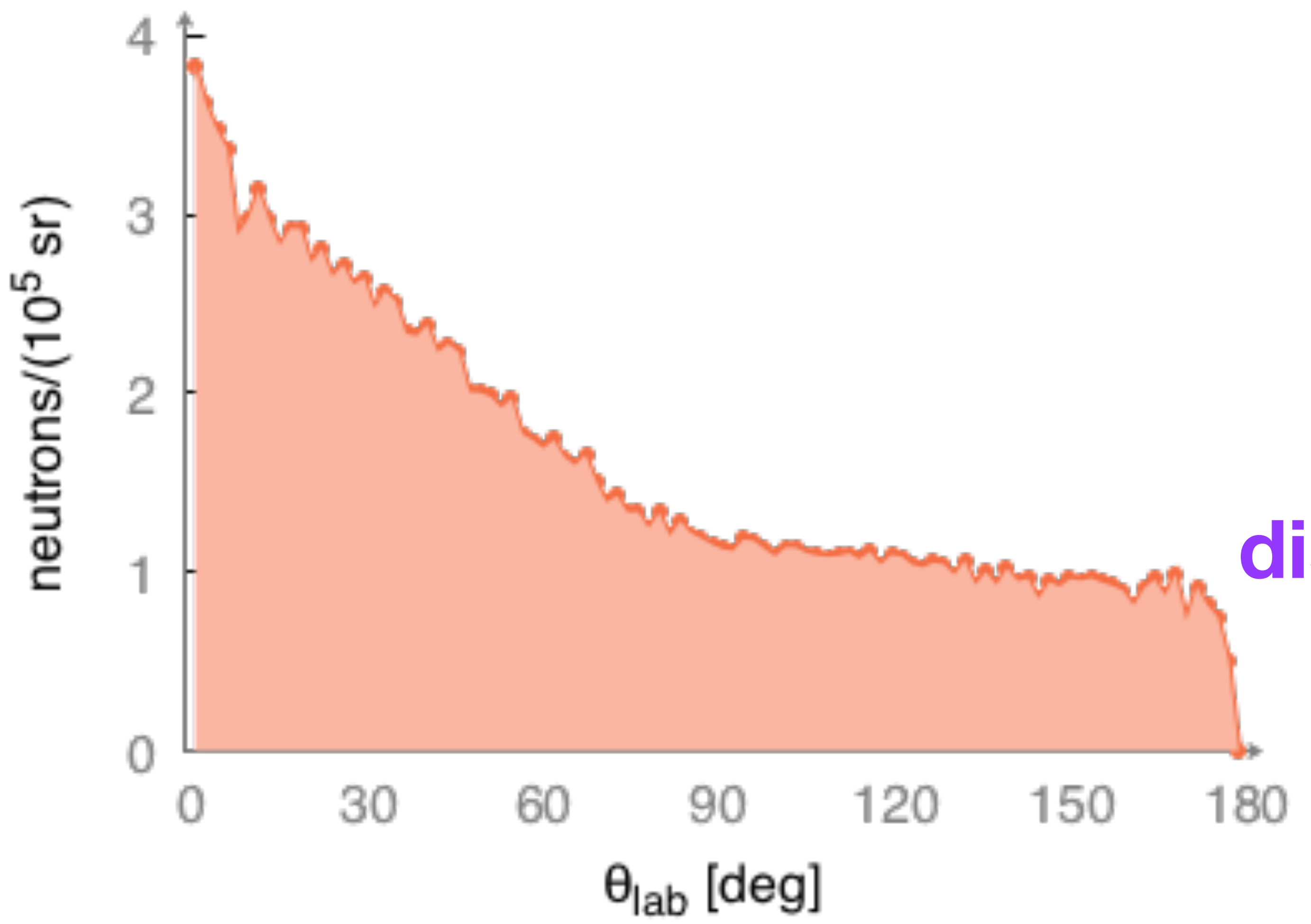
energy distribution



$Y_{4\pi}$~ 4.6 x 10^6 n/sr

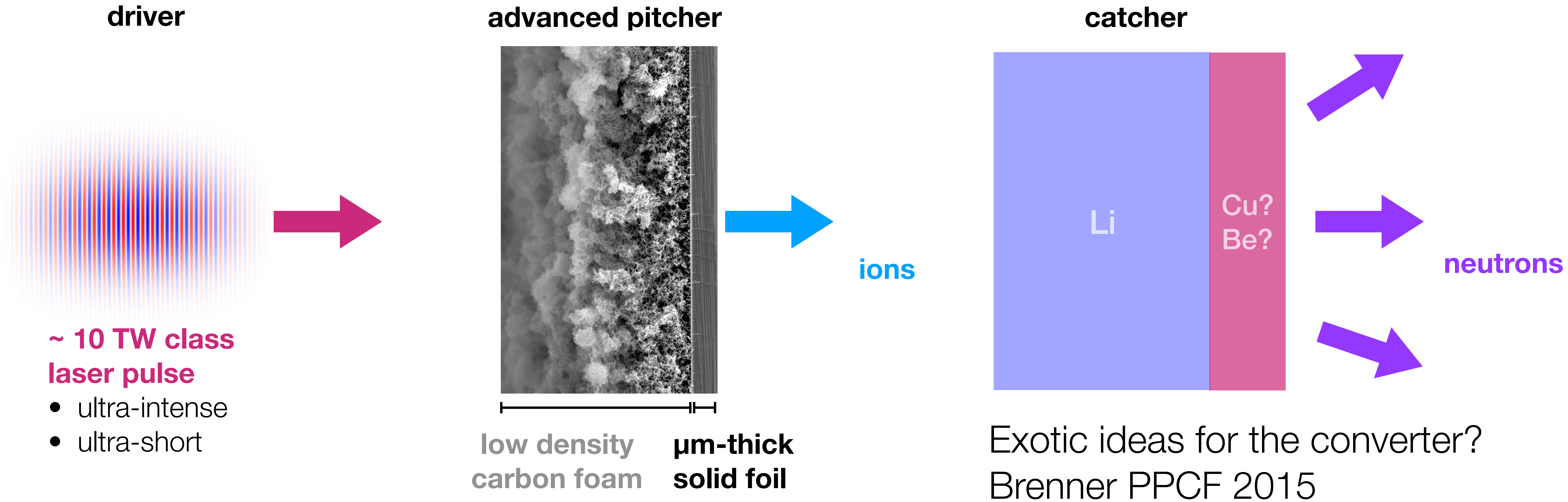
$Y_{15°cone}$~9.3 x 10^5 n/sr

angular distribution



Conclusions and perspectives

- We developed an integrated, multi-physics, “realistic” simulation approach to study laser-driven neutron sources from enhanced TNSA ions with foam-attached targets in a pitcher-catcher configuration
- Our results show that with ~ 10 TW class lasers you can obtain nice yields ~ 10^5-10^6 n/sr in 4π



driver

~ 10 TW class laser pulse

- ultra-intense
- ultra-short

advanced pitcher

low density carbon foam

µm-thick solid foil

ions

catcher

Li

Cu?
Be?

neutrons

Exotic ideas for the converter?
Brenner PPCF 2015

NEXT - FURTHER OPTIMIZATIONS & EXPERIMENTS

Thank you!

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