Nuclear spallation by irradiating an atomic thin graphene target with an intense laser

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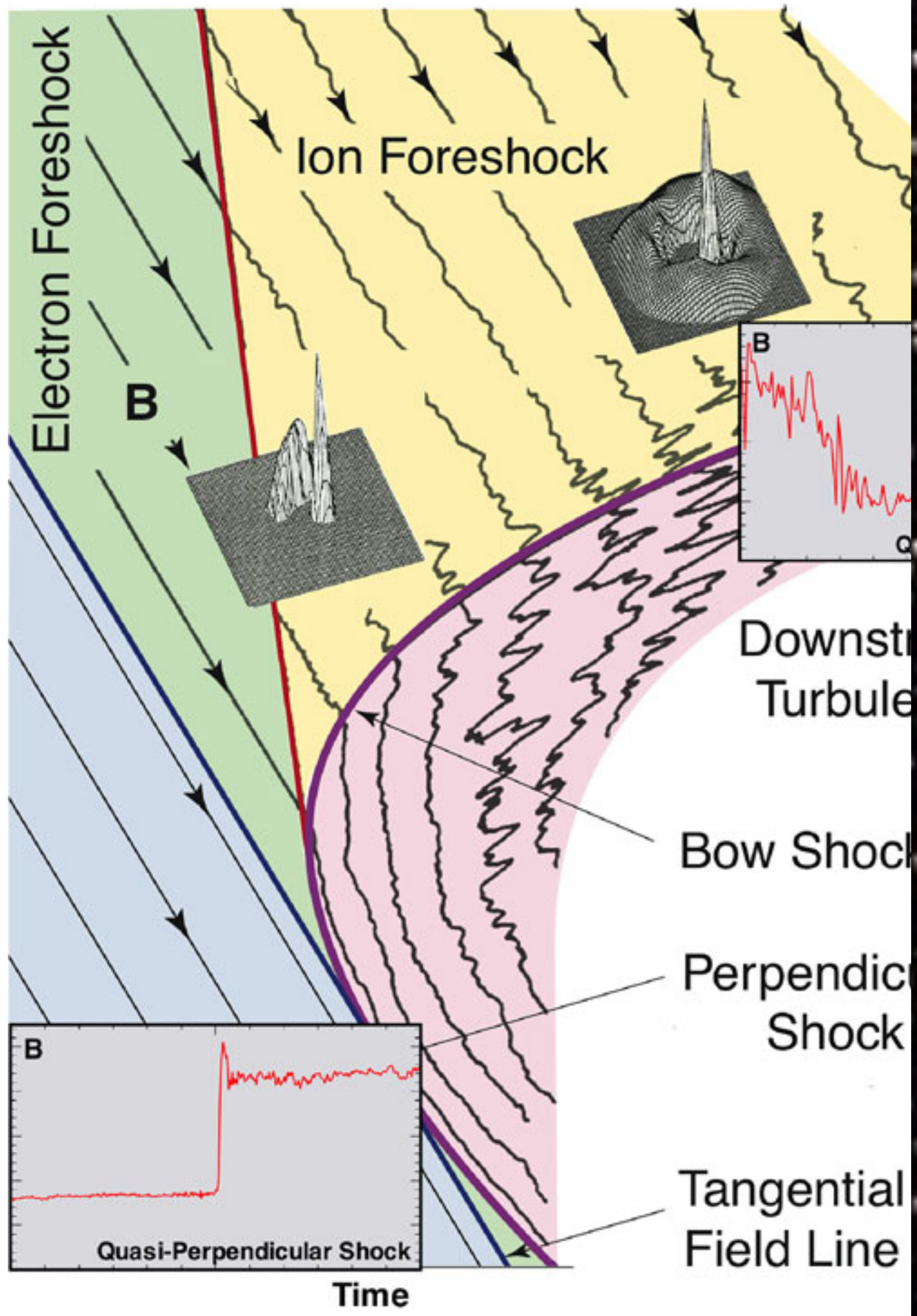
New opportunities and challenges in nuclear physics with high power lasers
Monday, 1 July 2024 - Friday, 5 July 2024
ECT*

Outline

- Background
- Laser-driven ion acceleration with large-area suspended graphene (LSG)
- Energy Frontier and Monoenergeticity
- Nuclear spallation

Laboratory astrophysics

Space

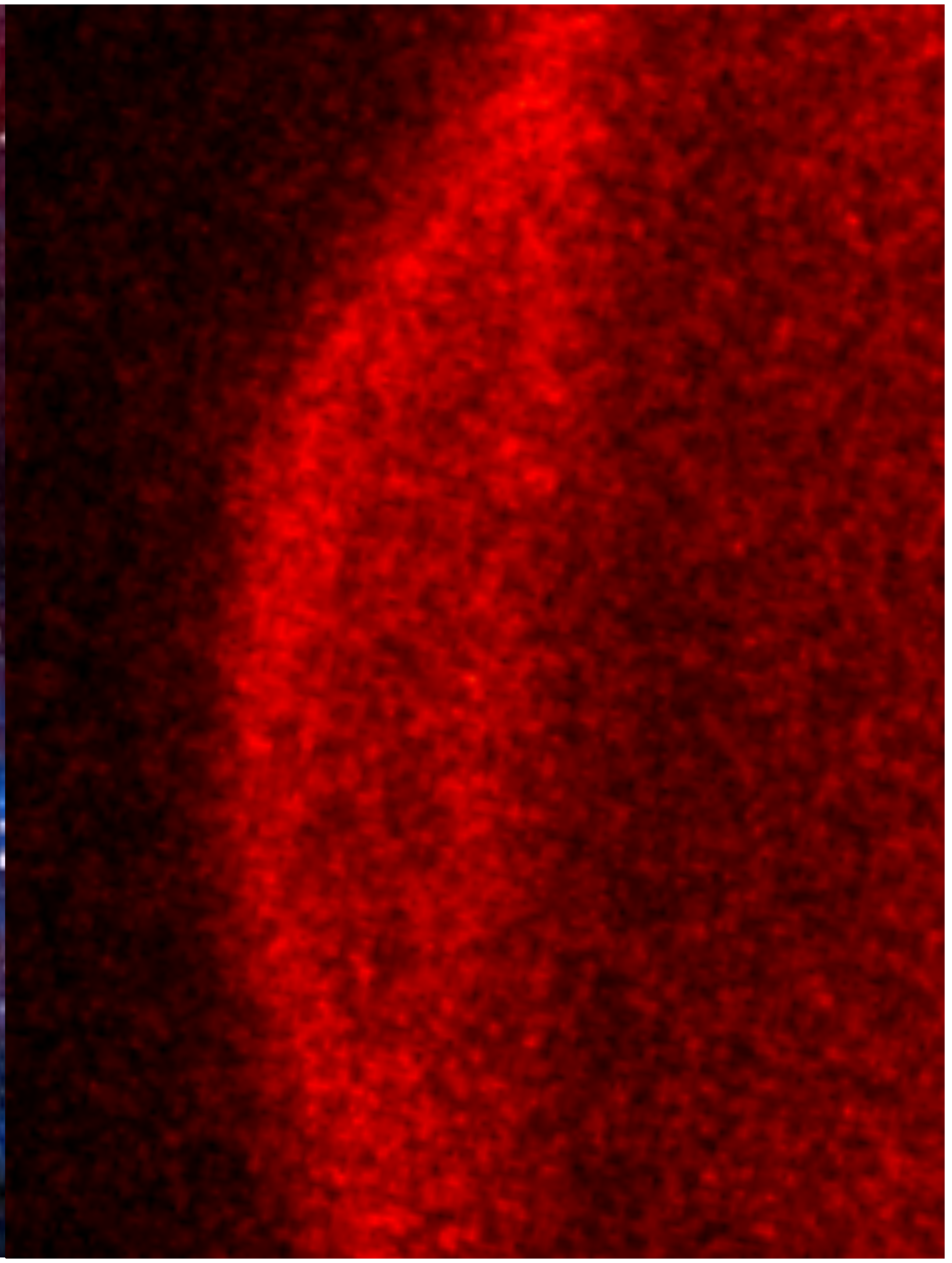


Burgess+ 2012 SSR

Astro.

NASA/NRAO/NOAO

Lab.

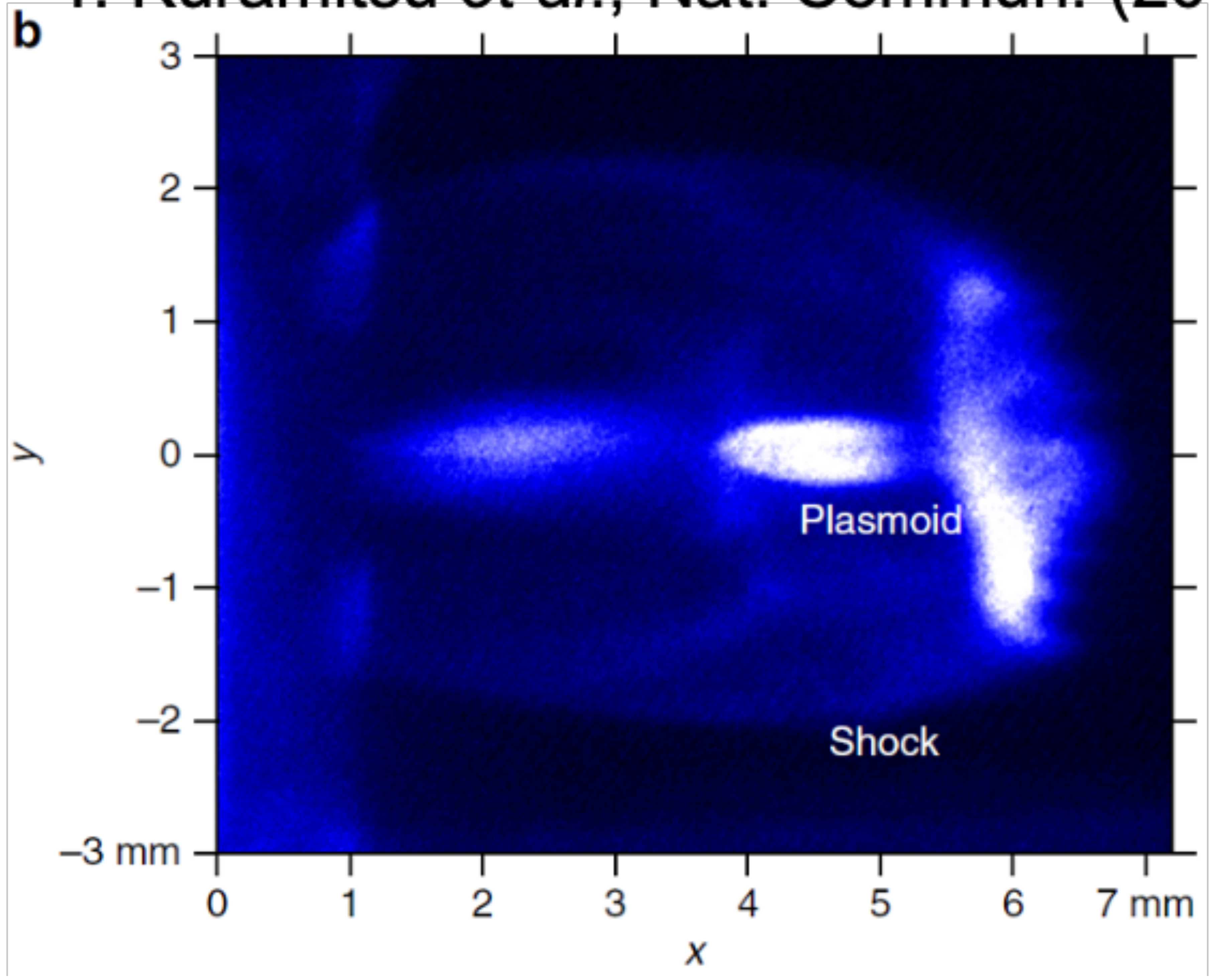


Kuramitsu+ 2011 PRL

Electron scale magnetic reconnections with Gekko XII laser

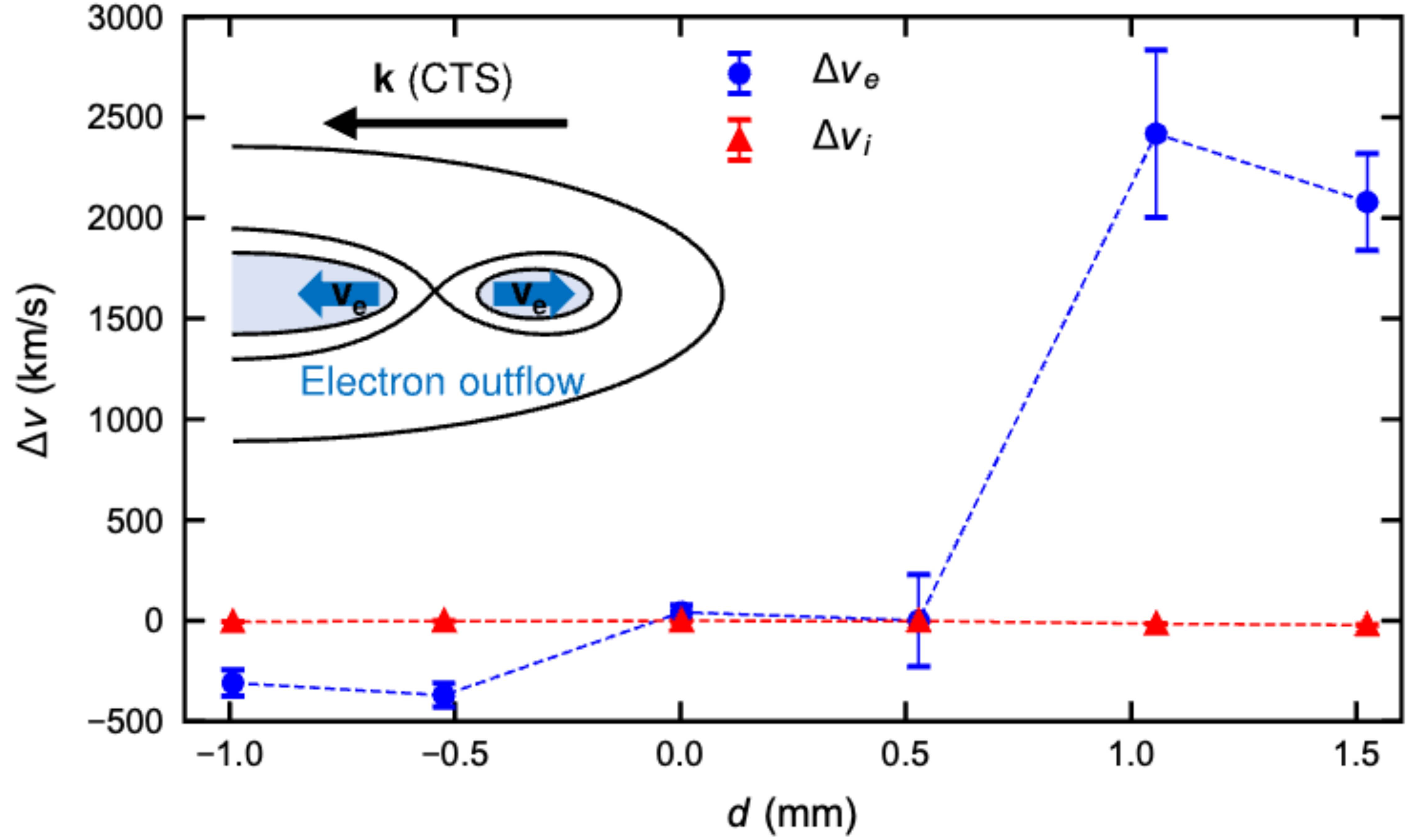
Global observation

Y. Kuramitsu *et al.*, Nat. Commun. (2018)



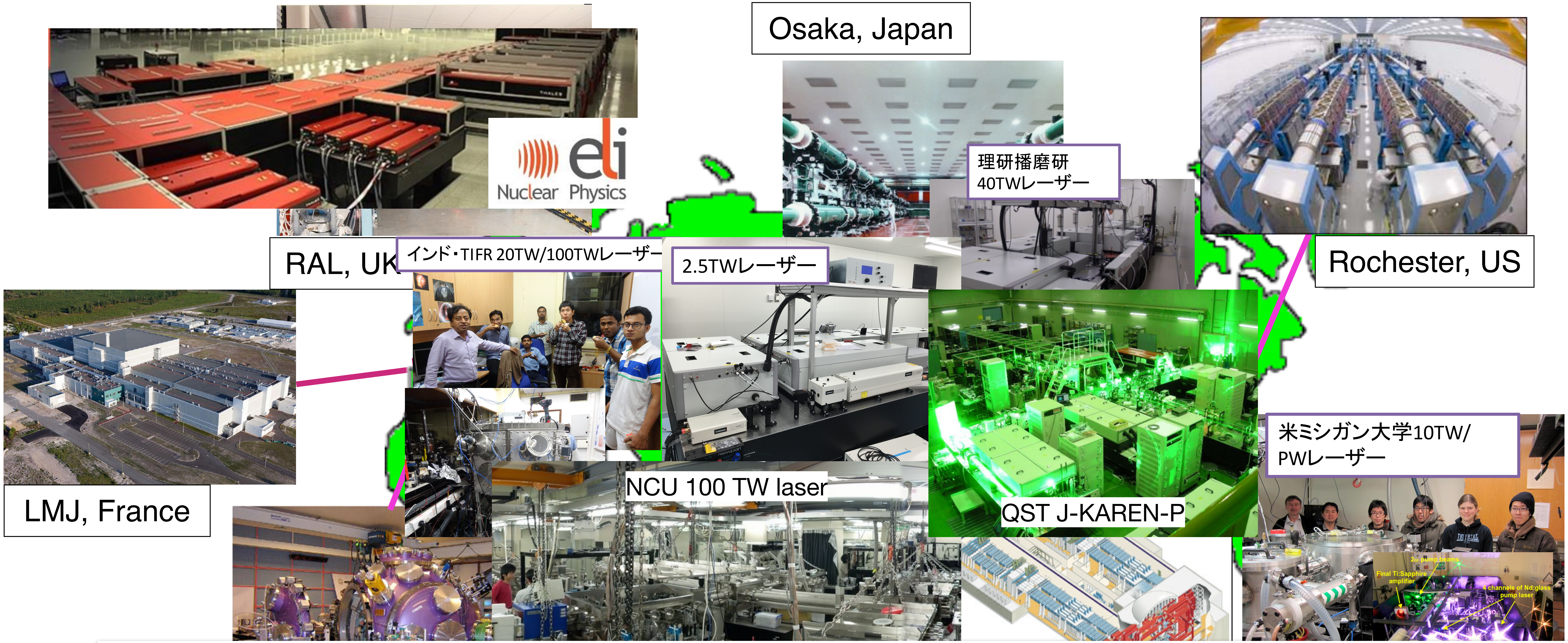
Local observation

K. Sakai *et al.*, Sci. Rep. (2022)



Global imaging of cusp and plasmoid and local measurements of pure electron outflows.

Large laser facilities in the world



Osaka, Japan

理研播磨研
40TWレーザー

Rochester, US

RAL, UK

インド・TIFR 20TW/100TWレーザー

2.5TWレーザー

LMJ, France

NCU 100 TW laser

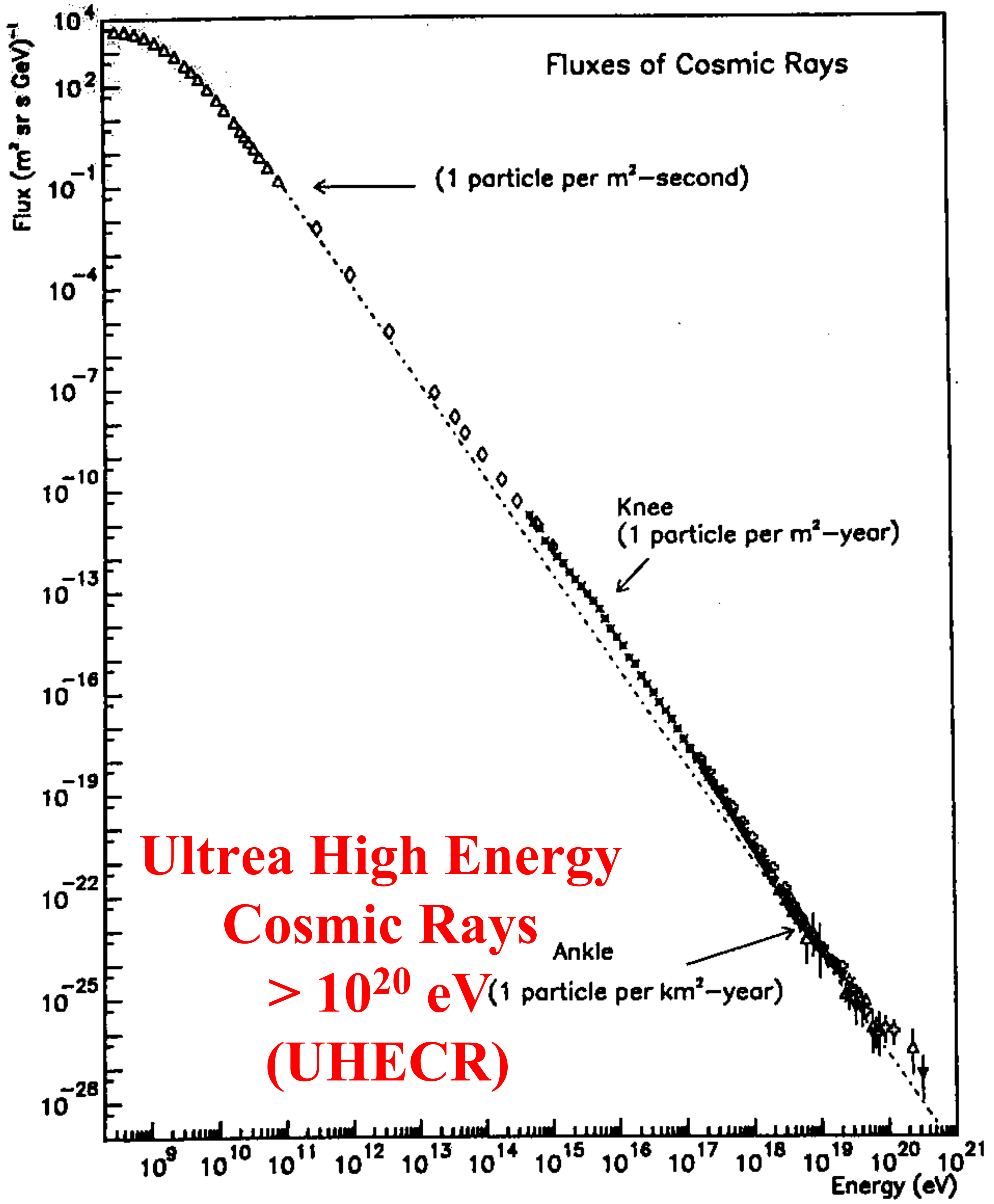
QST J-KAREN-P

米ミシガン大学10TW/
PWレーザー

From non-relativistic to relativistic phenomena
using intense short-pulse lasers

Origins of cosmic rays

- $<10^{15.5}$ eV
  - Galactic source
  - Supernova remnants (SNRs)
  - First order Fermi acceleration or diffusive shock acceleration (DSA)
  - naturally and universally explains cosmic ray spectra,
    $f(\gamma) \propto \gamma^{-2}$
- $>10^{15.5}$ eV
  - Extra galactic source
  - not well understood

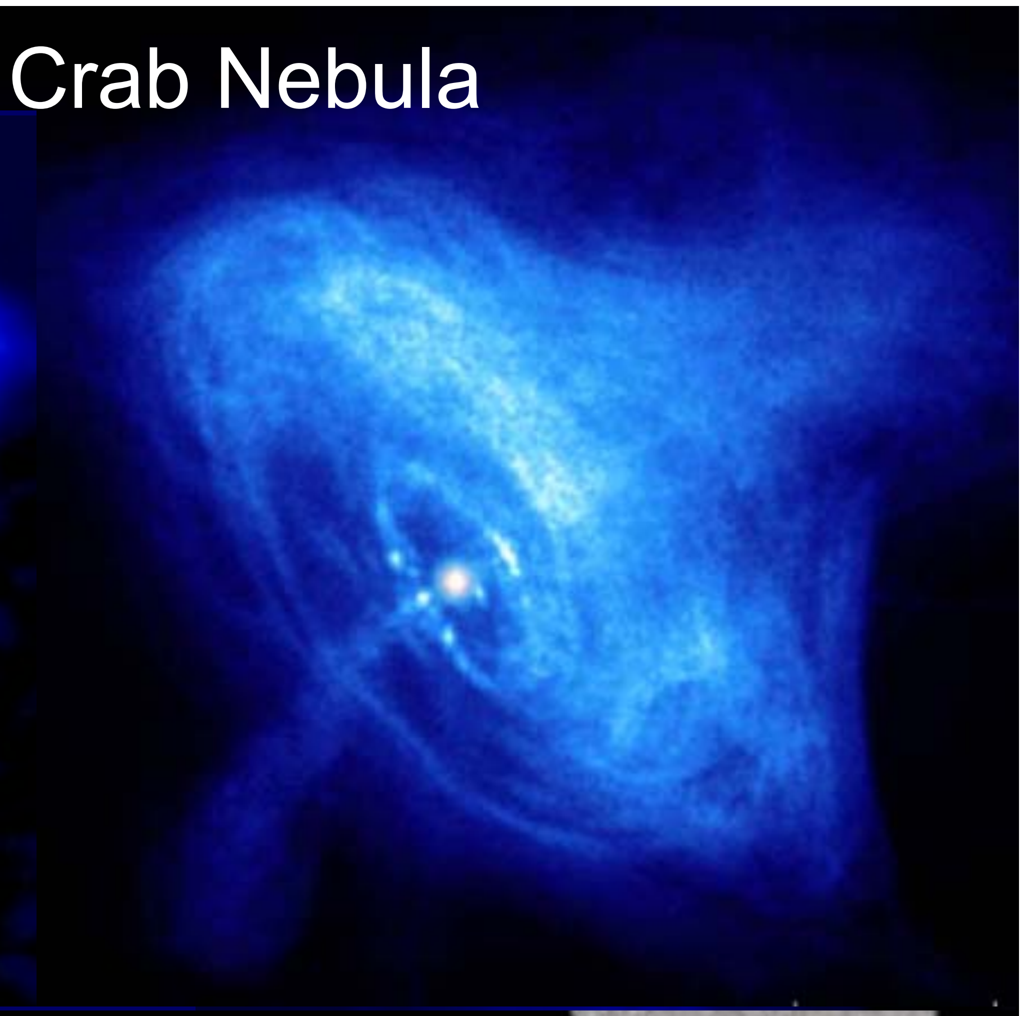


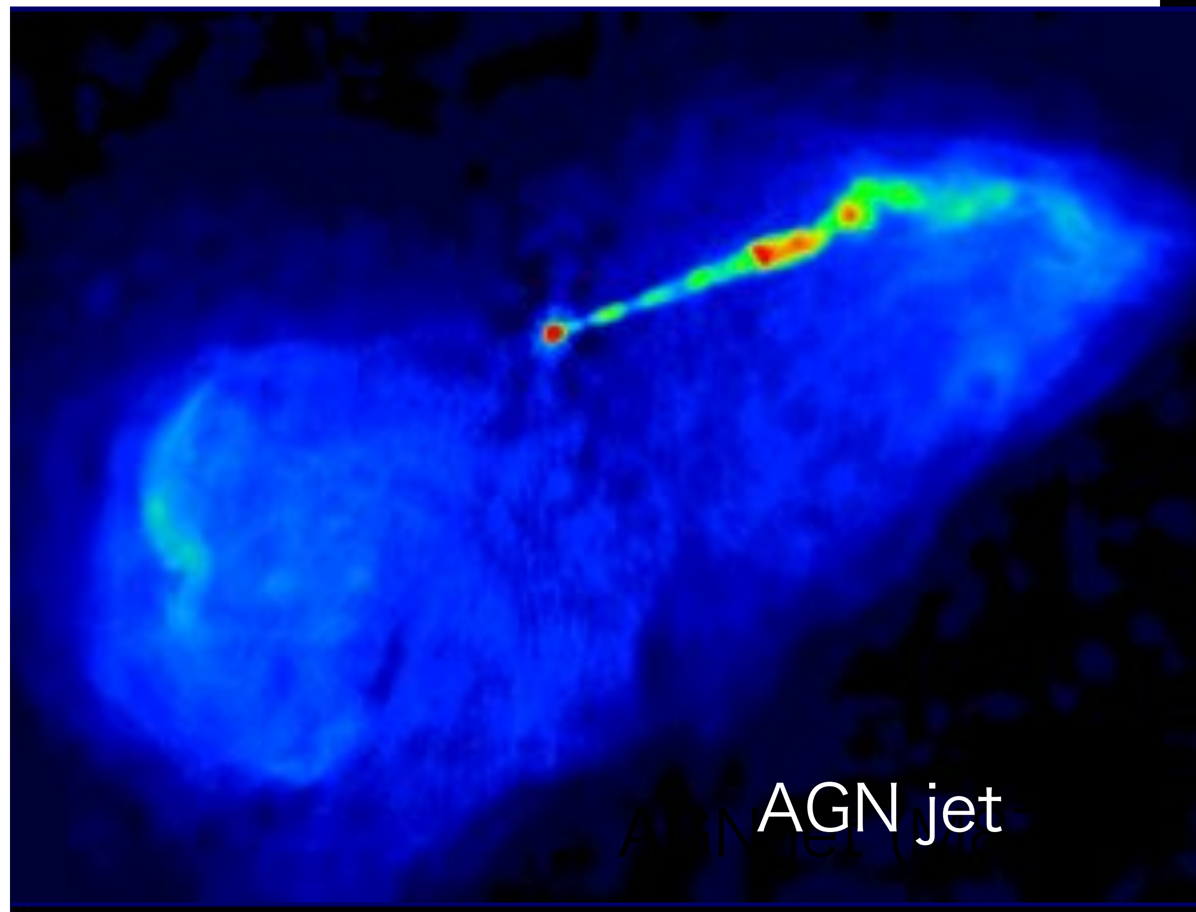
Ultrea High Energy Cosmic Rays $> 10^{20}$ eV (UHECR)

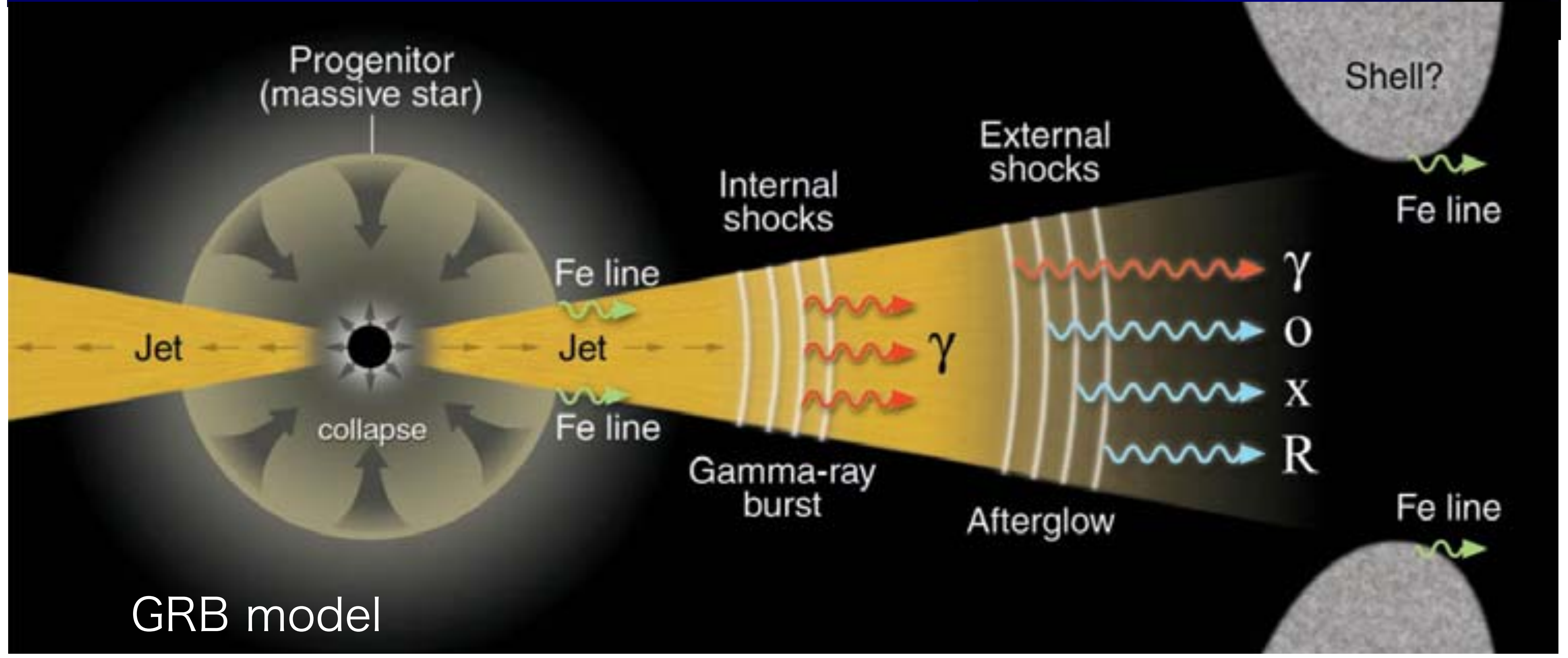
S. Swordy

Extragalactic cosmic rays

- Possible sources: Relativistic collisionless shocks
  - Active galactic nucleus (AGN) jets ($\gamma \sim 10$)
  - Gamma-ray bursts ($\gamma > 100\text{-}1000$)
  - Pulser wind ($\gamma \sim 10^{6\text{-}7}$)
- A possible mechanism
  - wakefield acceleration
    Chen+ 2002 PRL
    Lyubarsky 2006 ApJ
    Hoshino 2008 ApJ
    Kuramitsu+ 2008 ApJL
    …
    Iwamoto+ …


Crab Nebula


AGN jet



GRB model

from Hoshino

Wakefield Acceleration By Radiation Pressure In Relativistic Shock Waves

1. Shock formation
2. Excitation of electromagnetic (light) waves
3. Electrostatic field (wakefield) excitation by the light
4. Acceleration of particles by the wakefield

Two governing parameters

a_0: normalized wave amplitud

ω_p/ω_L: frequency ratio between plasma and light

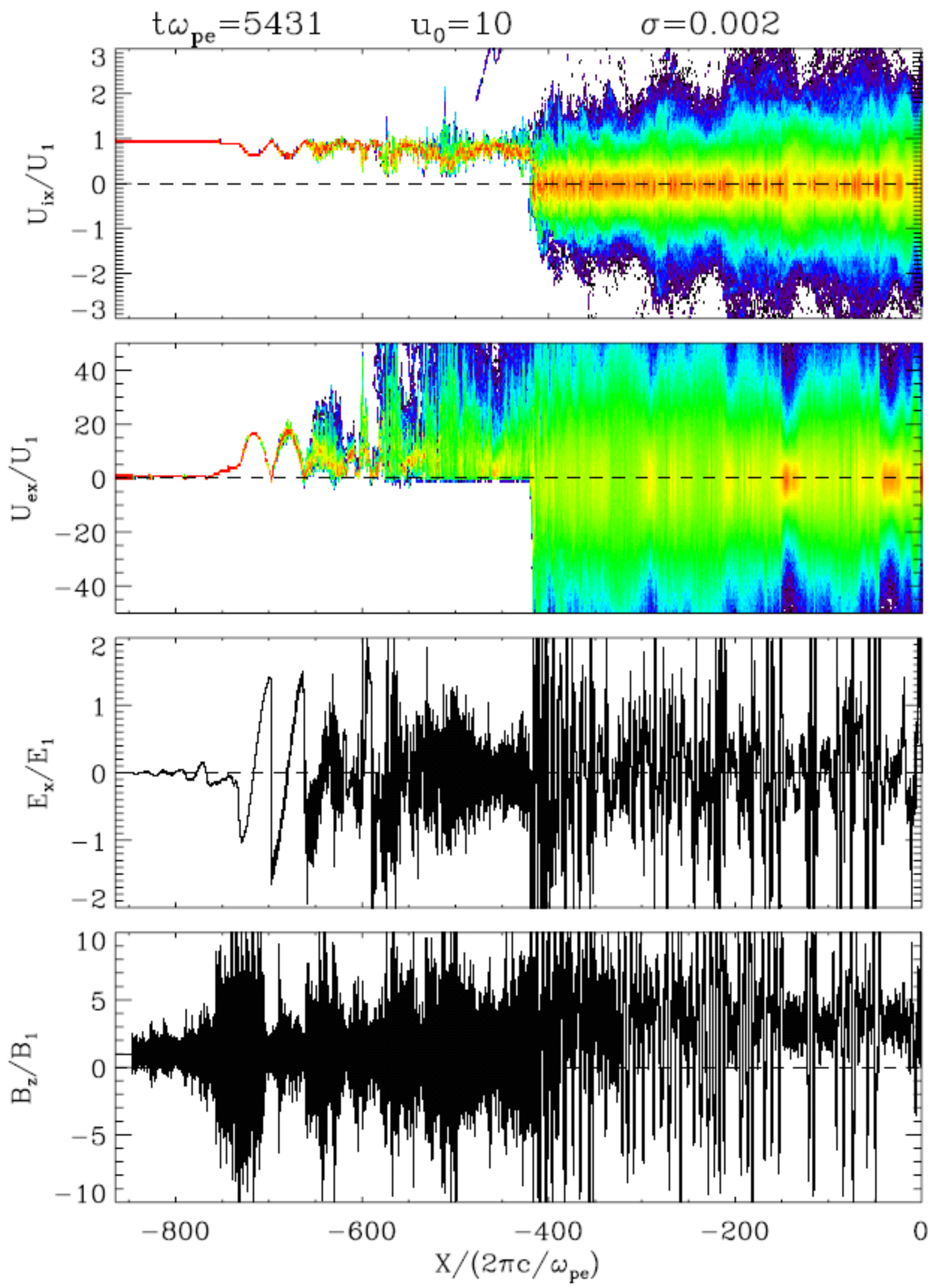
Upstream Downstream

ION

ELECTRON

Electrostatic Waves (Ex), (wakefield)

Electromagnetic Waves (Bz), (precursor wave → laser beam)



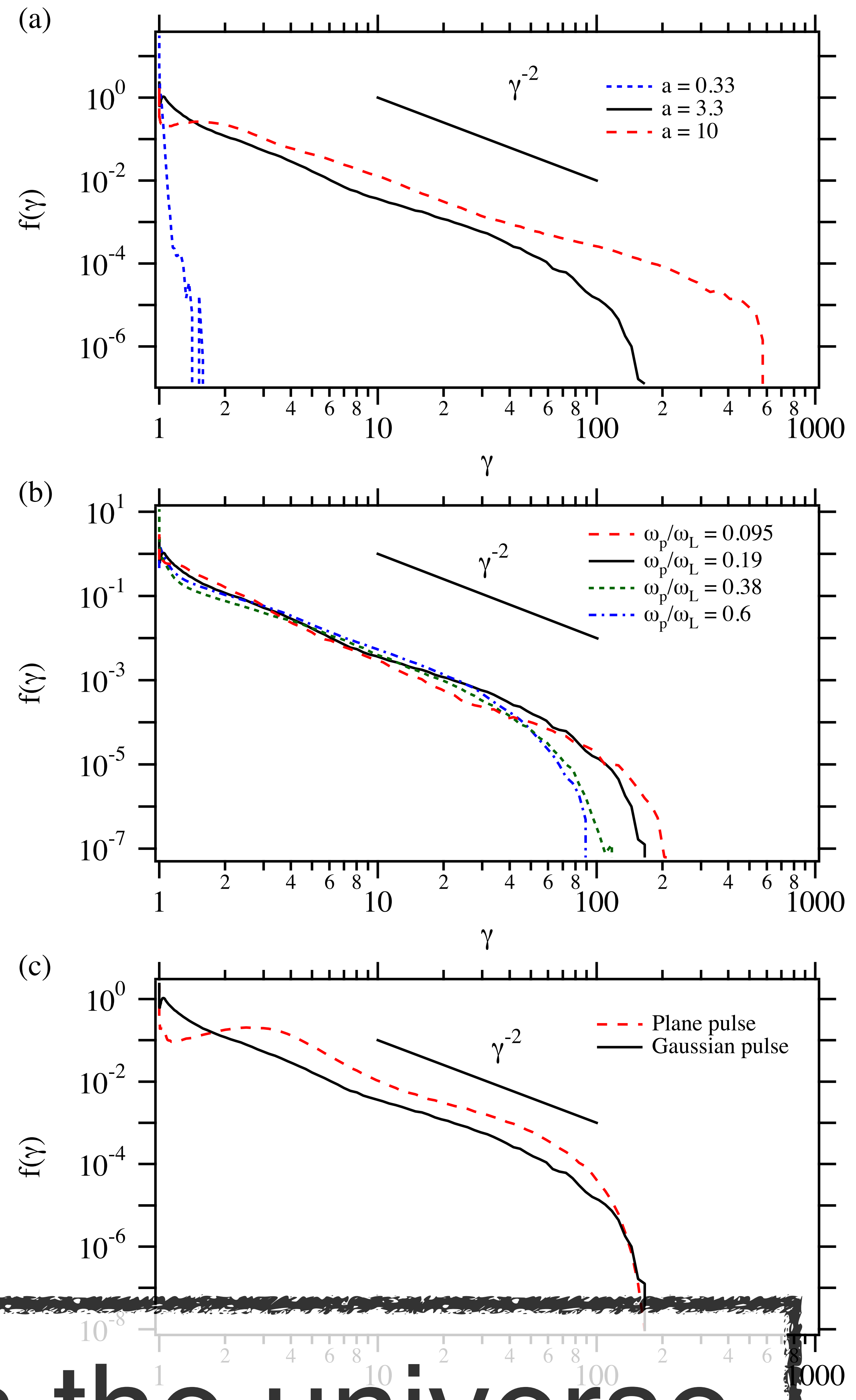
$$a_0 \sim \gamma_1$$

Pulse like structures

Hoshino 2008 ApJ, 1D PIC, shock downstream system

Nonthermal electron acceleration by turbulent wakefield

- Assuming large amplitude light waves propagating in a plasma,
- Independent of light amplitude ~ *a*
- Independent of plasma density ~ ω_p/ω_L
- Independent of pulse shape
- Universal production of power law spectra with an index of ~ -2
- Cyclotron and synchrotron emission free.



It is impossible to observe this in the universe.

Kuramitsu + 2012 HEDP, 2D PIC, shock upstream system

Model experiments of cosmic ray acceleration in laboratories

- Astrophysical situation to be modeled is

1. a large amplitude light pulse ($a > 1$)

   ➡Gekko PW
   (100 J, 700 fs, $a_0 \sim 1.9$)

   ➡NCU 100 TW
   (3 J, 30 fs, $a_0 \sim 5.2$)

2. propagating in a plasma.

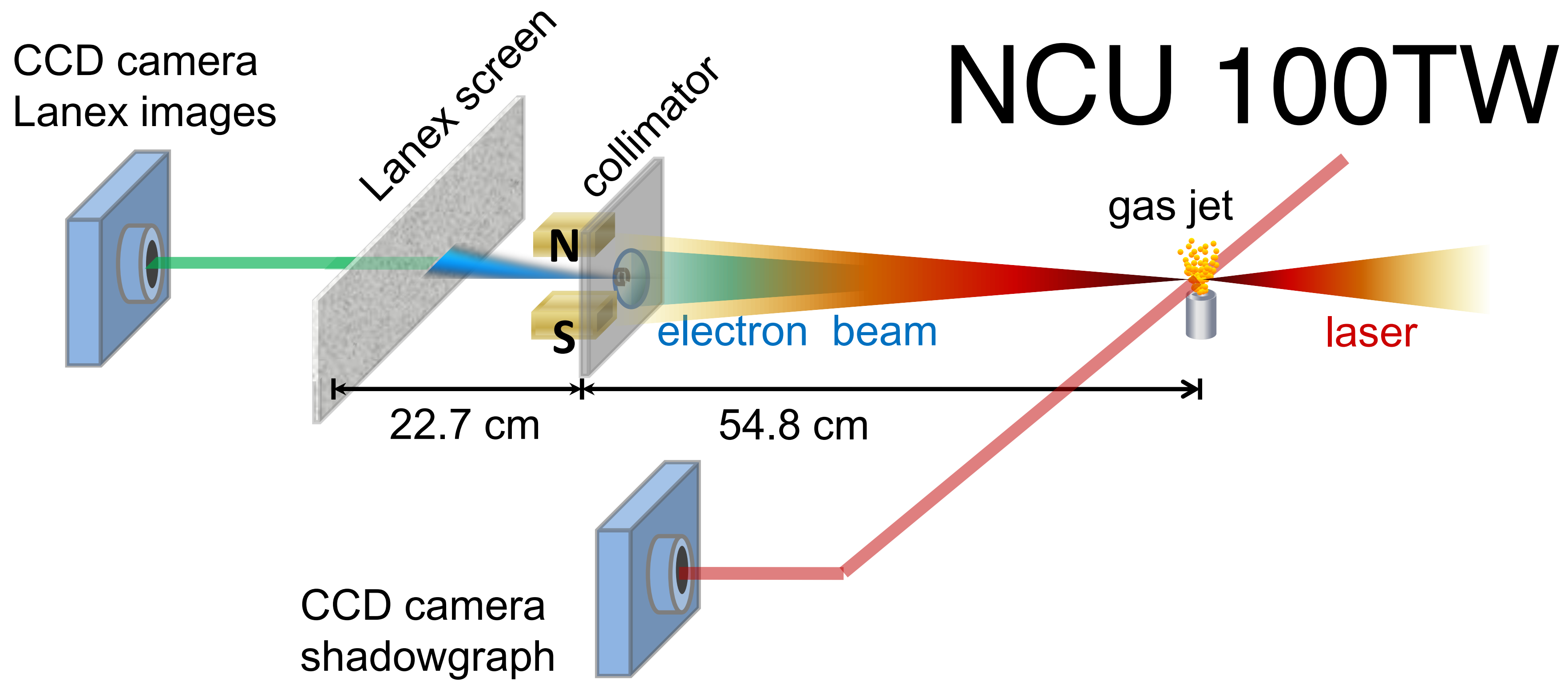
   ➡Hollow cylinder implosion with Gekko XII

   ➡Gas jet

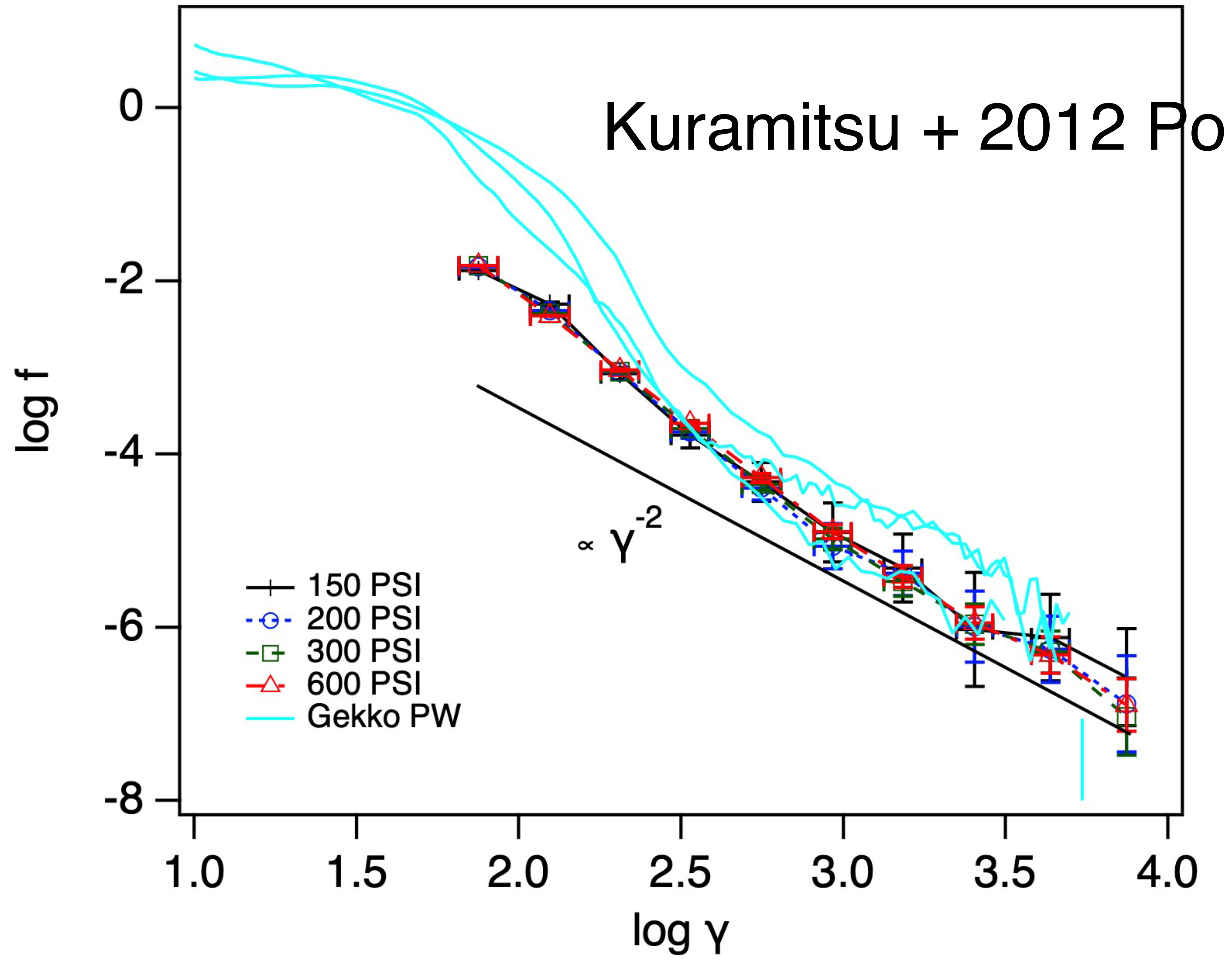
- Distribution functions + spatial distribution of plasmas are measured with ESM and shadowgraphy, respectively.

- Power law spectra independent of plasma density and intensity.

NCU 100TW



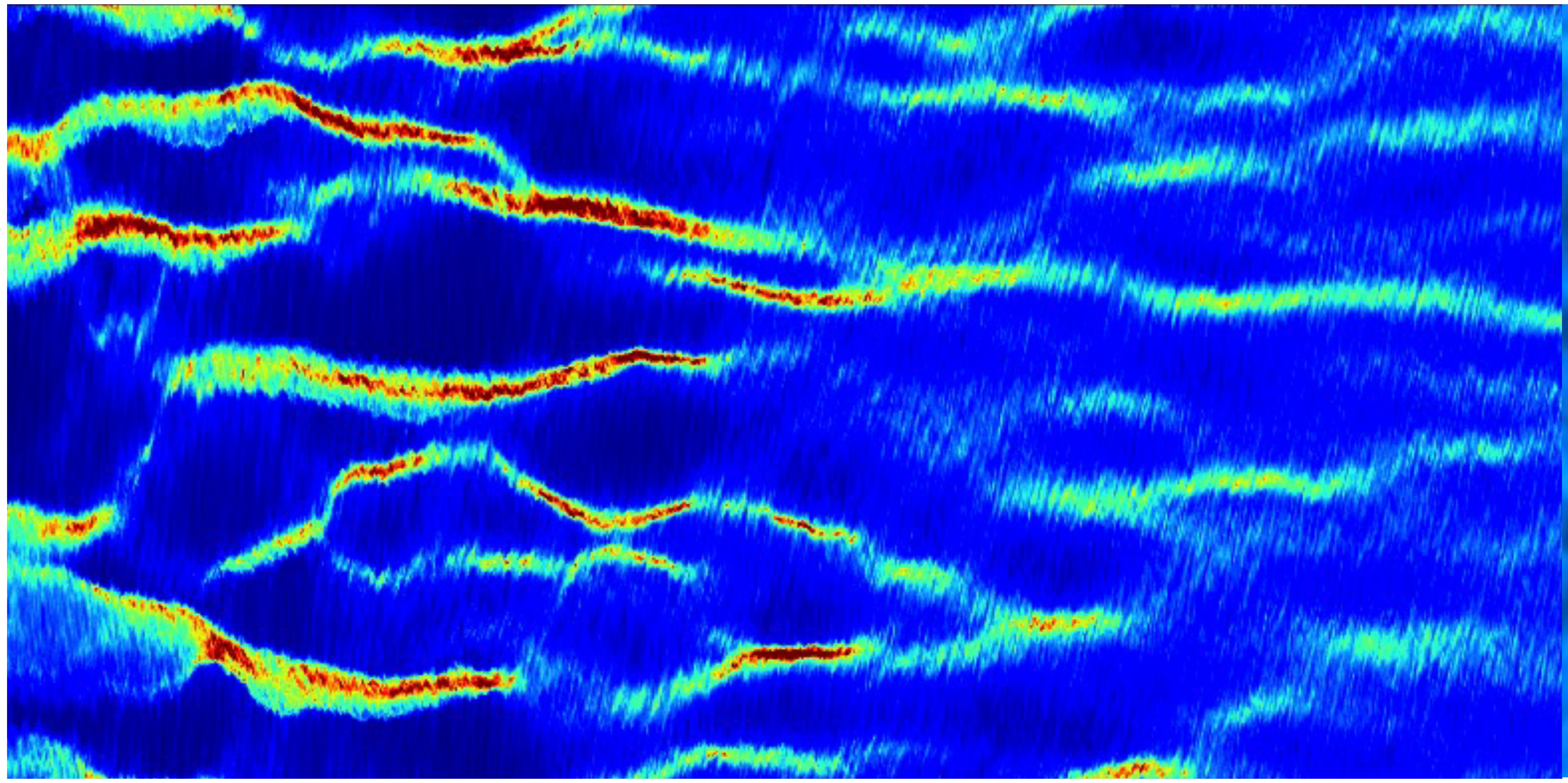
Kuramitsu + 2012 PoP, PRE



Kuramitsu + in prep.

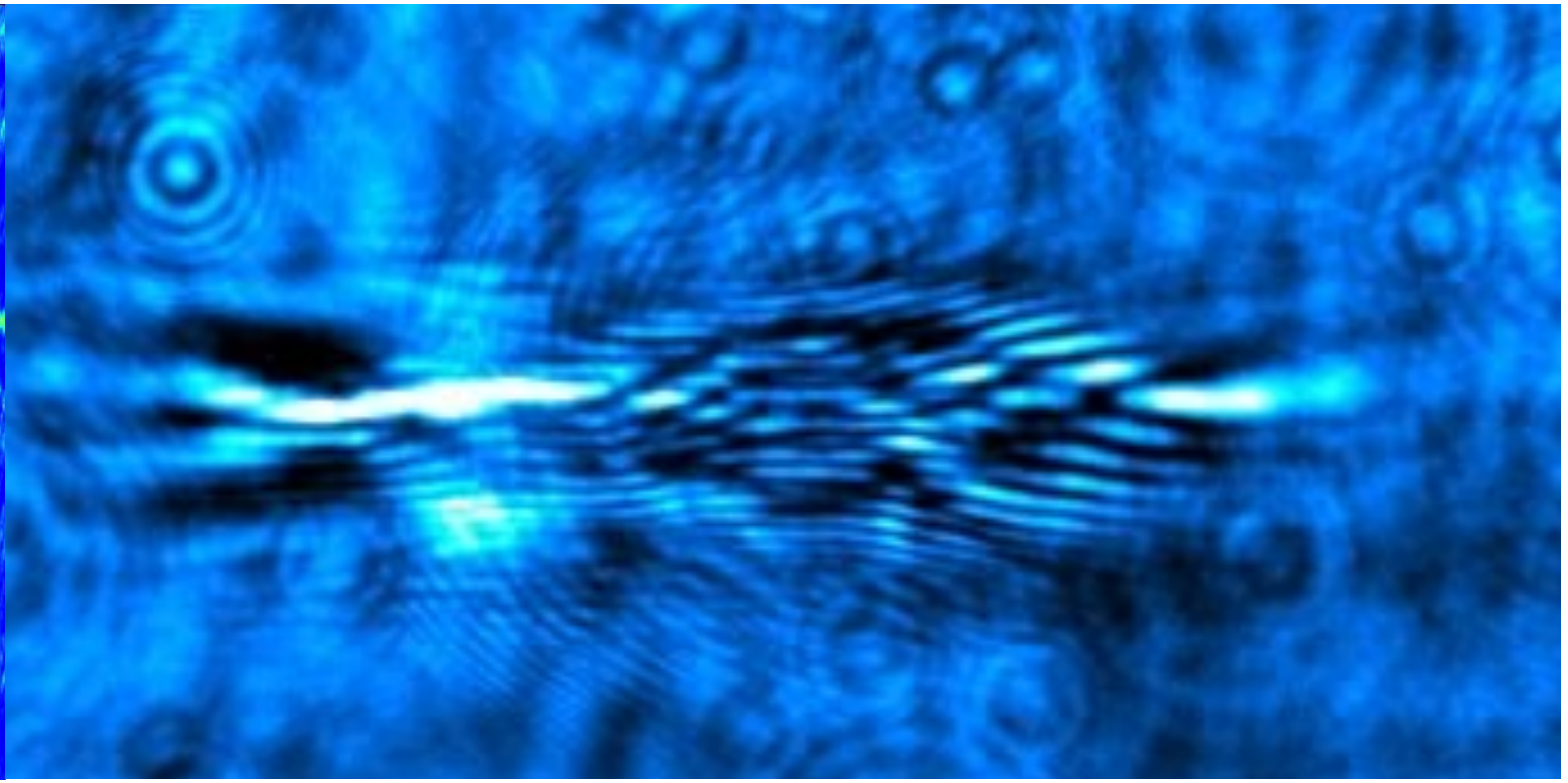
Turbulent filaments

Relativistic shock



Relativistic
background ions

Laser wakefield

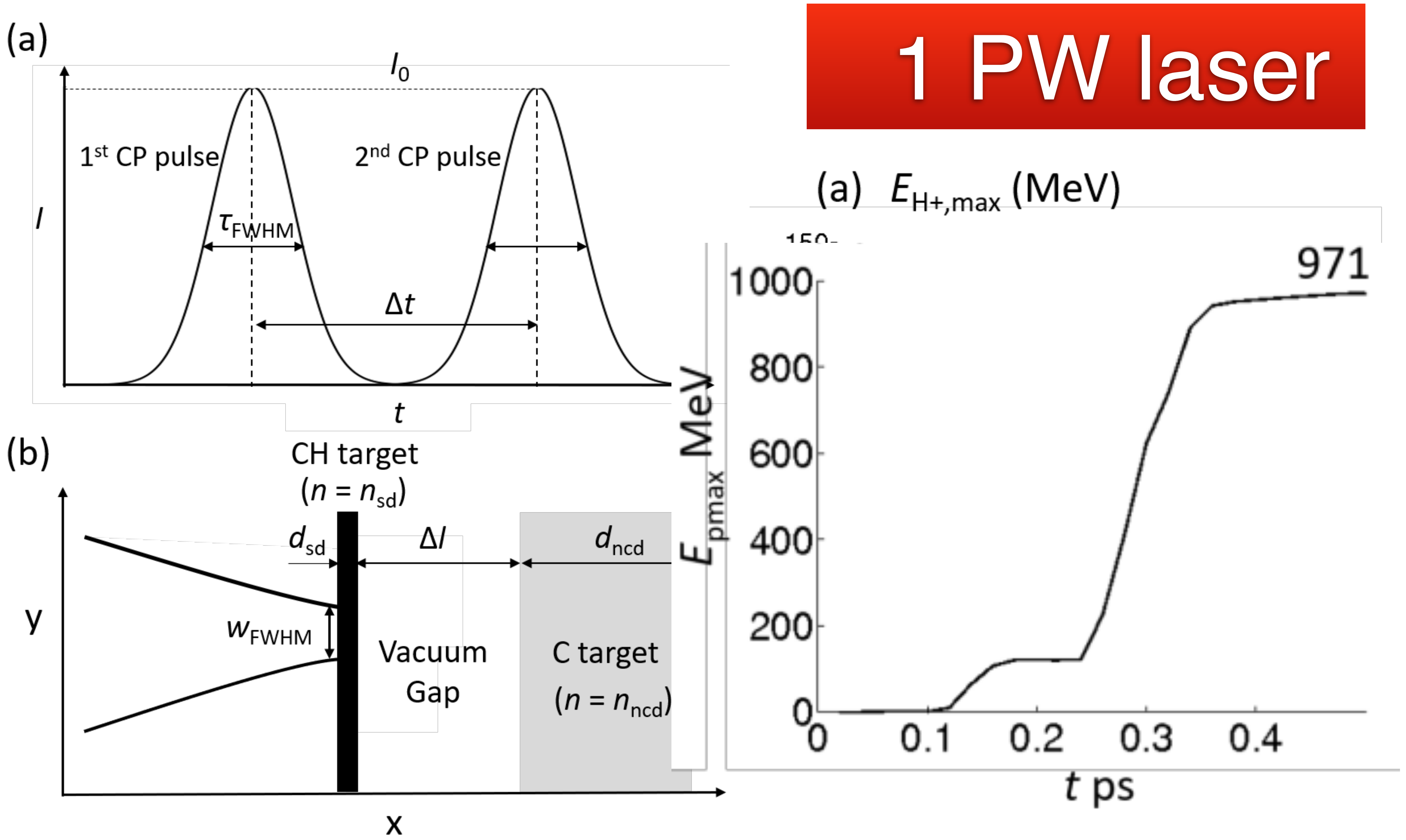


Non-relativistic
background ions

Hard to inject non-relativistic ions
into relativistic wake.

Relativistic ion acceleration

1 PW laser



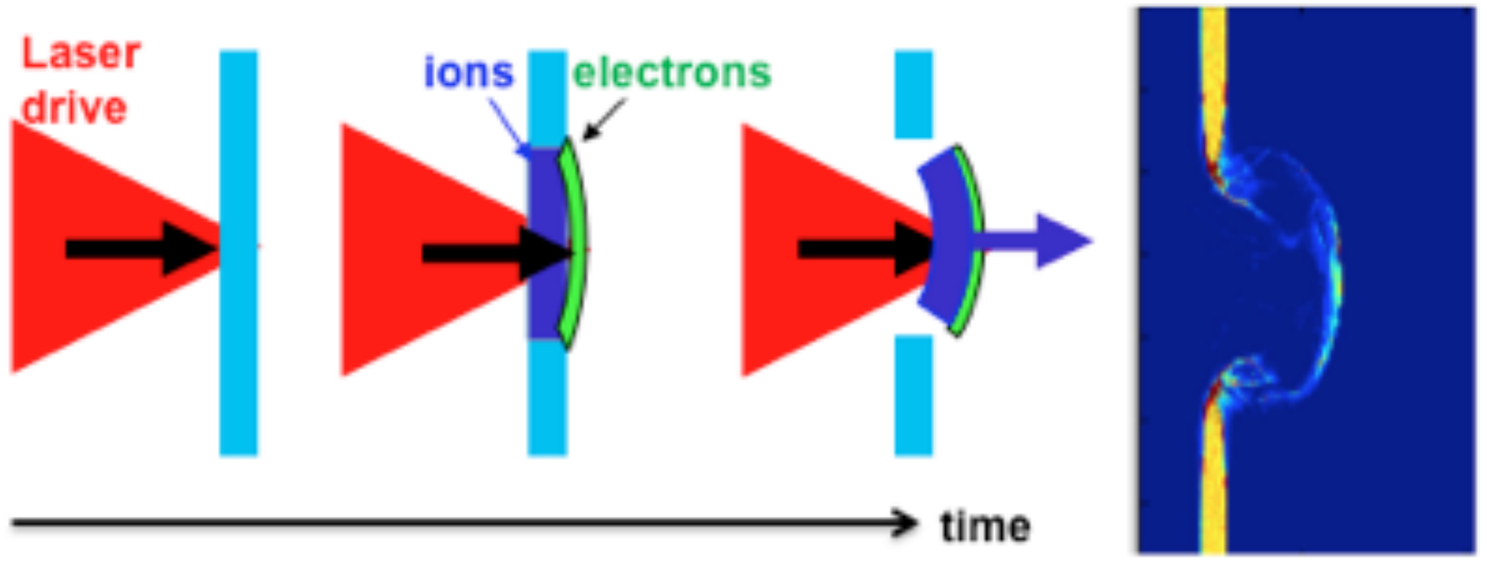
Controlled injection of energetic protons into the wakes

- Graphene ion acceleration as the first stage
- Wakefield acceleration in the form target as the second stage
- Relativistic ion detectors
- Wakefield imaging with nonlinear Thomson scattering
- Machine learning on the detector

Isayama, Kuramitsu + 2021 PoP

Laser-driven ion acceleration with large-area suspended graphene

Radiation pressure acceleration for the pre-acceleration



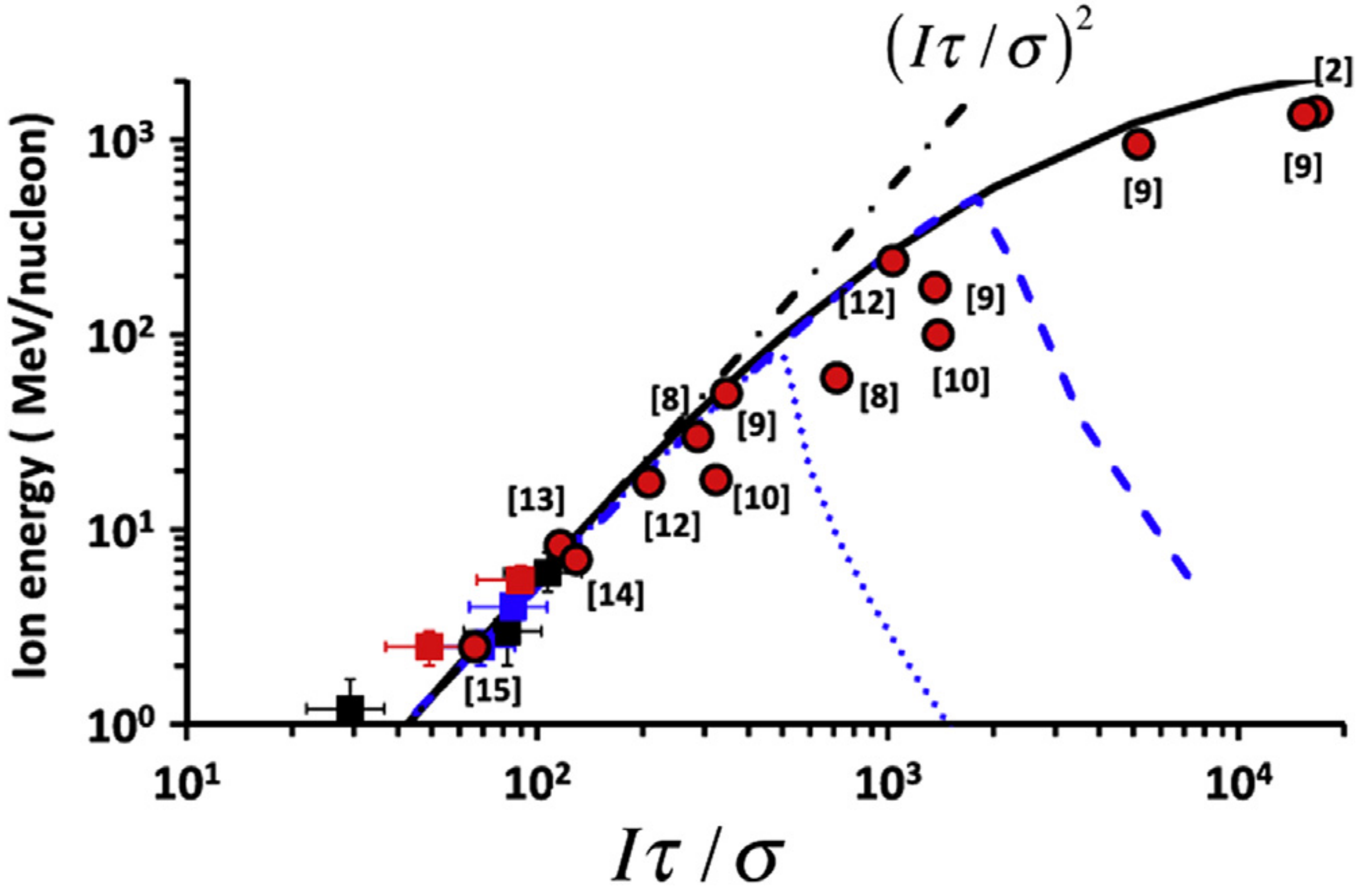


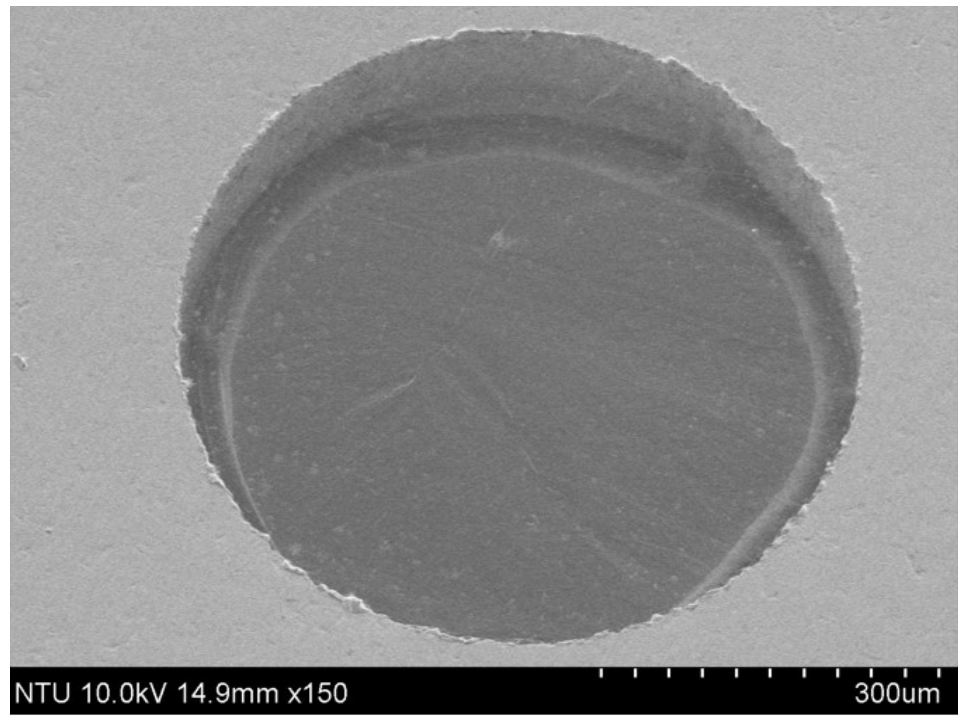
Fig. 3. LS energy scaling: experimental points (squares) and PIC predictions from literature (circles) are plotted against the simple ($(I\tau\sigma^{-1})^2$) scaling (dashed line) and a more extensive model including relativistic effects (solid line) (from [44], where references are provided for the simulations data shown).

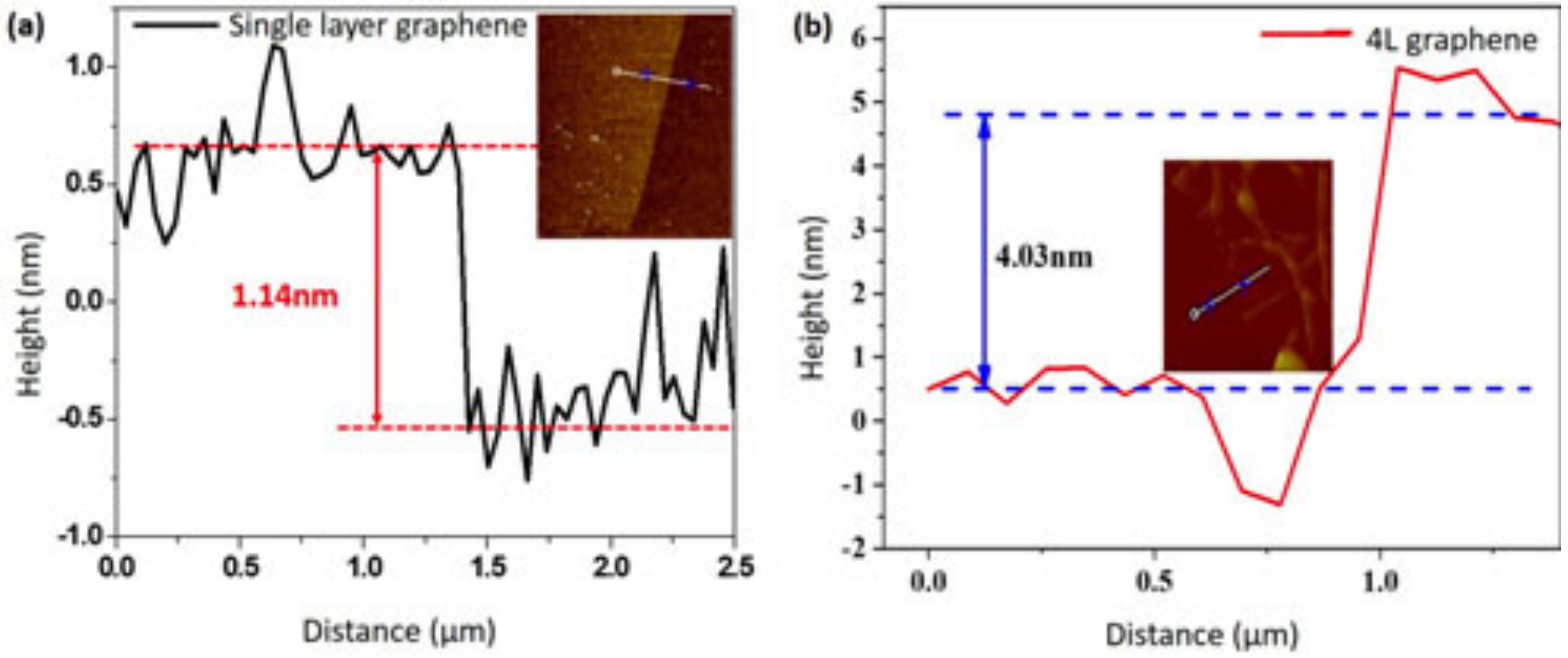
Laser-driven ion acceleration: State of the art and emerging mechanisms, M. Borghese, Nuclear Instruments and Methods in Physics Research A 740 (2014) 6–9

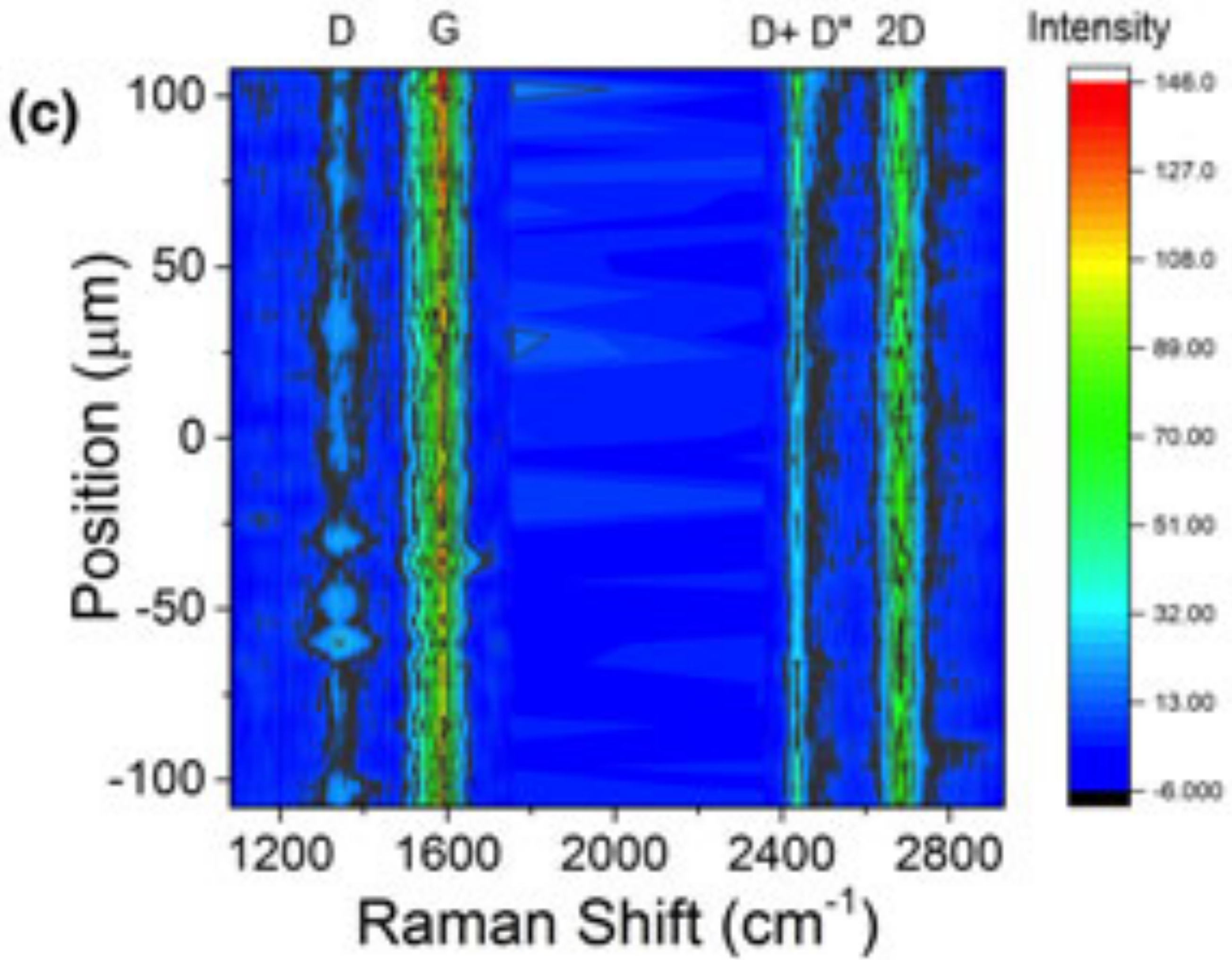
Large-area suspended graphene (LSG)

We have developed a large-area suspended graphene (LSG),

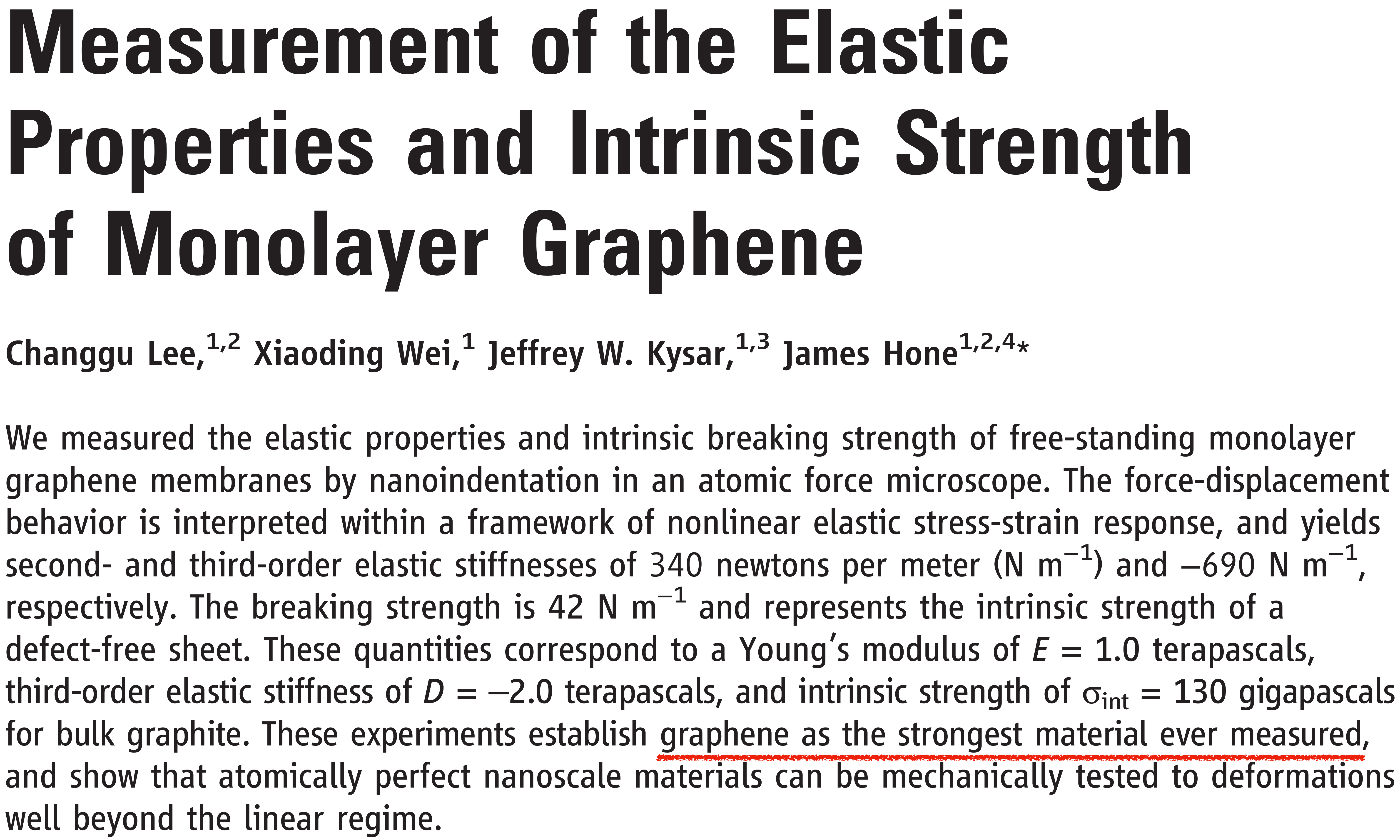
- Thinnest
- Lightest
- Strongest
- Transparent
- Thickness control at 1 nm by transferring layer by layer
- Extremely high thermal and electrical conductivity within the layer
- Reasonable







Khasanah +Kuramitsu HPL 2017



Measurement of the Elastic Properties and Intrinsic Strength of Monolayer Graphene

Changgu Lee,[1,2] Xiaoding Wei,[1] Jeffrey W. Kysar,[1,3] James Hone[1,2,4]*

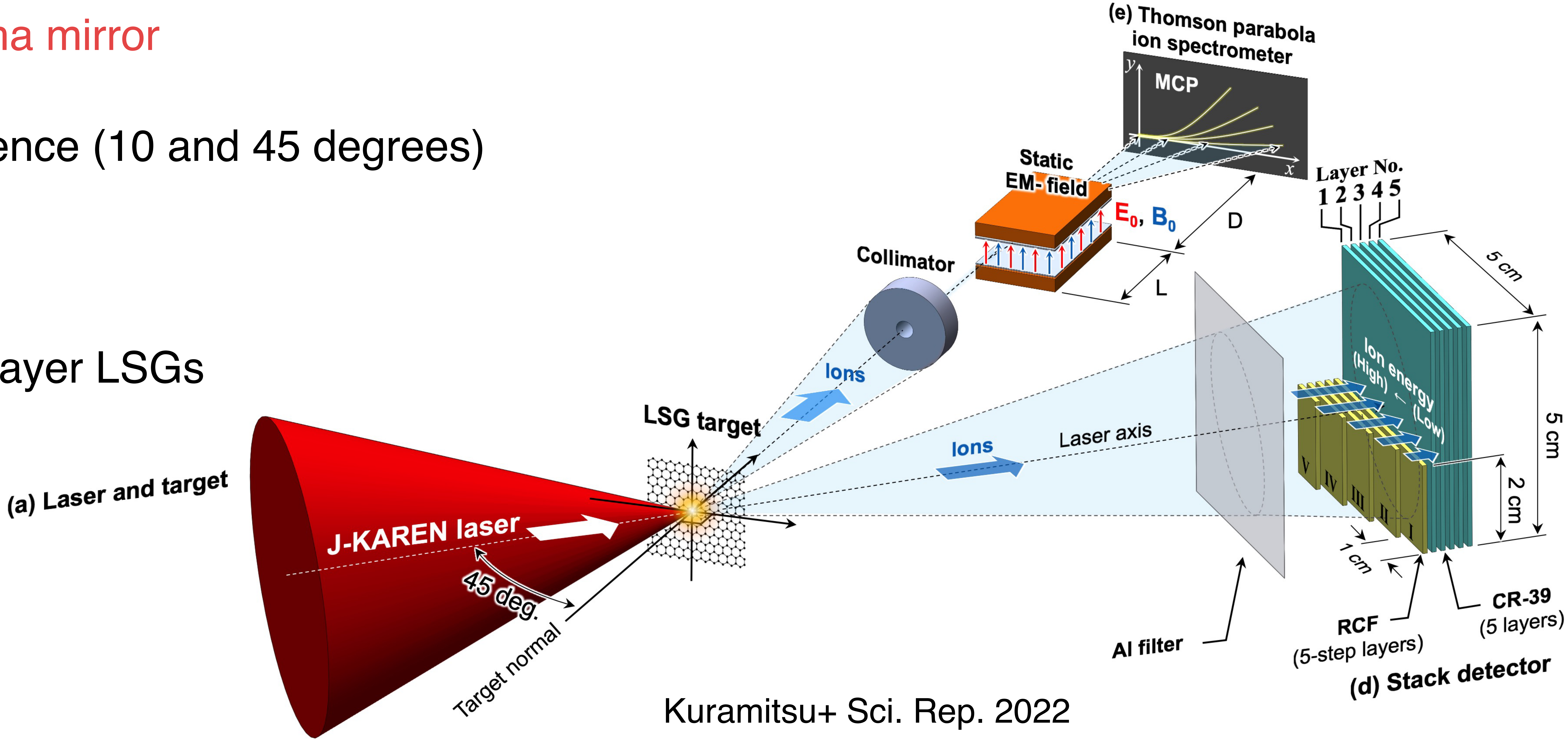
We measured the elastic properties and intrinsic breaking strength of free-standing monolayer graphene membranes by nanoindentation in an atomic force microscope. The force-displacement behavior is interpreted within a framework of nonlinear elastic stress-strain response, and yields second- and third-order elastic stiffnesses of 340 newtons per meter (N m^{-1}) and –690 N m^{-1}, respectively. The breaking strength is 42 N m^{-1} and represents the intrinsic strength of a defect-free sheet. These quantities correspond to a Young's modulus of $E = 1.0$ terapascals, third-order elastic stiffness of $D = -2.0$ terapascals, and intrinsic strength of $\sigma_{int} = 130$ gigapascals for bulk graphite. These experiments establish graphene as the strongest material ever measured, and show that atomically perfect nanoscale materials can be mechanically tested to deformations well beyond the linear regime.

Changgu Lee, *et al.*
Science **321**, 385 (2008);
DOI: 10.1126/science.1157996

cited 13777

J-KAREN experiments

- 800 nm, 30 fs, 10J, 0.1 Hz, F/1.35, 5e21 W/cm²
- Without plasma mirror
- Oblique incidence (10 and 45 degrees)
- Targets
    - 2, 4, and 8 layer LSGs



Kuramitsu+ Sci. Rep. 2022

Defocused sub-relativistic laser intensities

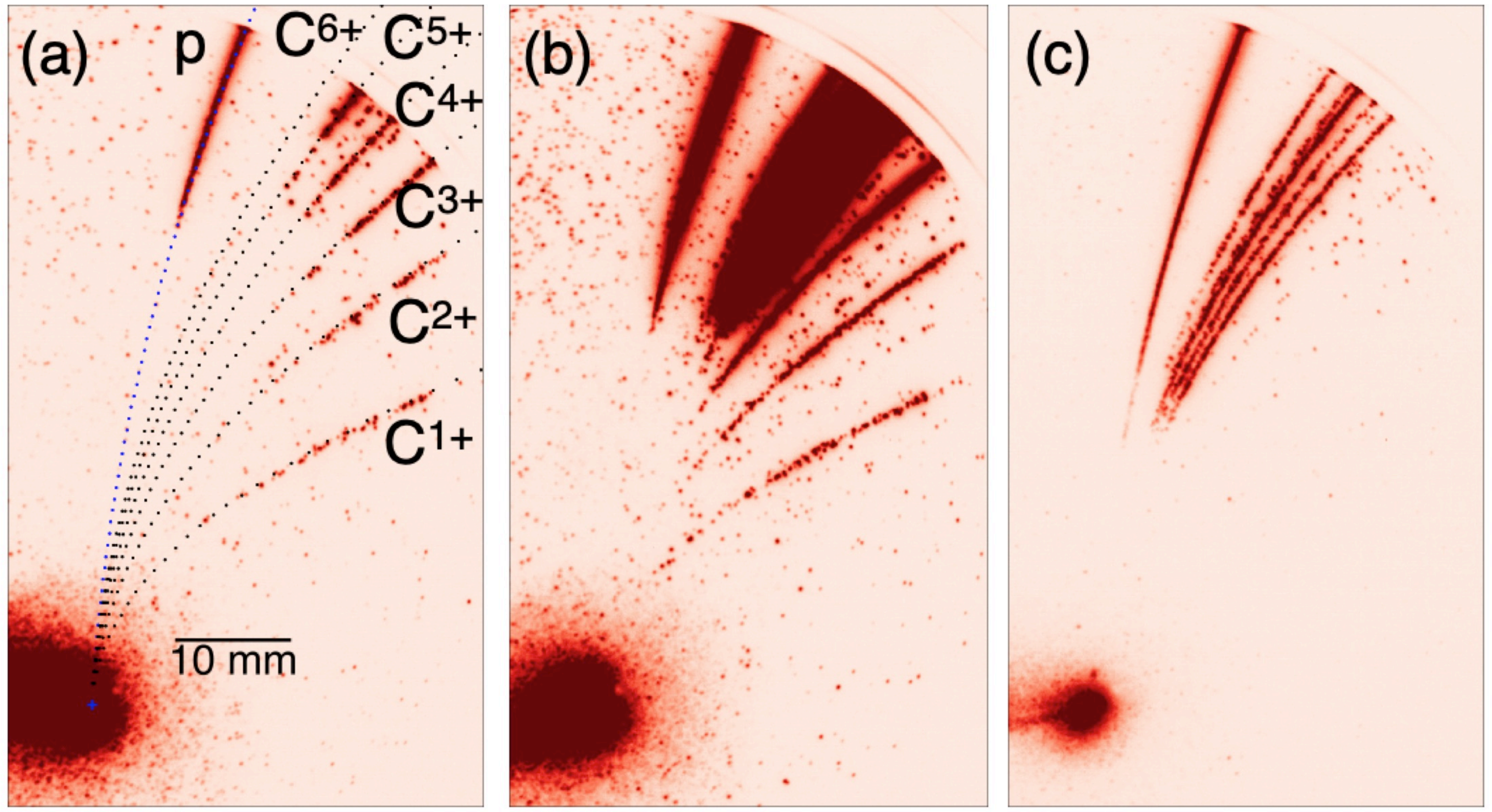
- Thomson parabola spectrometer with 4 layer LSGs

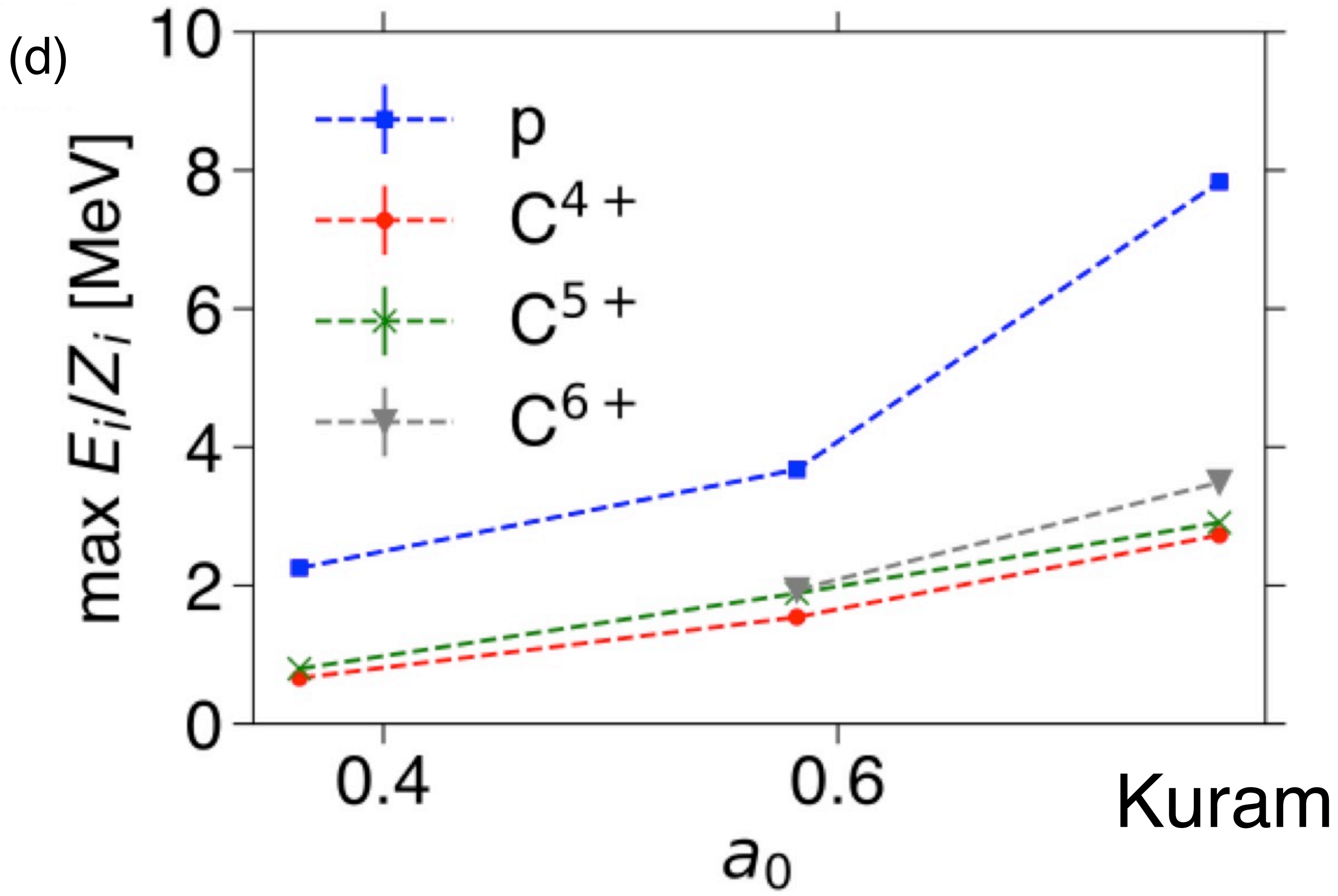
  (a) 2.78 e17 $\mathrm{Wcm^{-2}}$
  (b) 7.15 e17 $\mathrm{Wcm^{-2}}$
  (c) 1.25 e18 $\mathrm{Wcm^{-2}}$

- MeV protons and carbons at sub-relativistic intensities

- Twice proton energy than carbon per Z

➡ Acceleration by the same potential field





Kuramitsu+ Sci. Rep. 2022

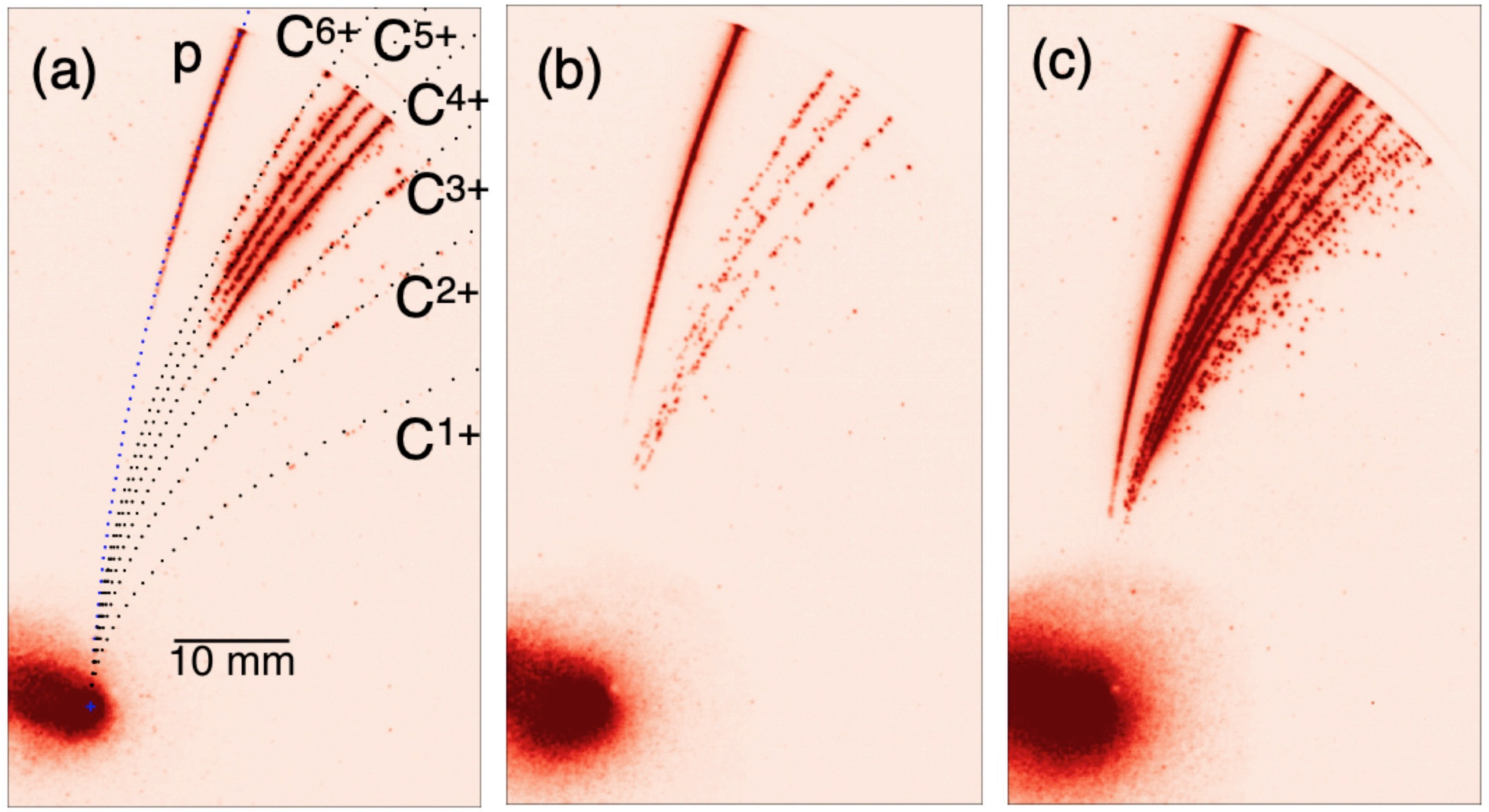
Best focus relativistic laser intensities

- Thomson parabola spectrometer with 8-layer LSGs

  (a) 1.06 e21 Wcm^{-2}
  (b) 2.86 e21 Wcm^{-2}
  (c) 4.83 e21 Wcm^{-2}

- ~15 MeV protons and ~ 60 MeV carbons

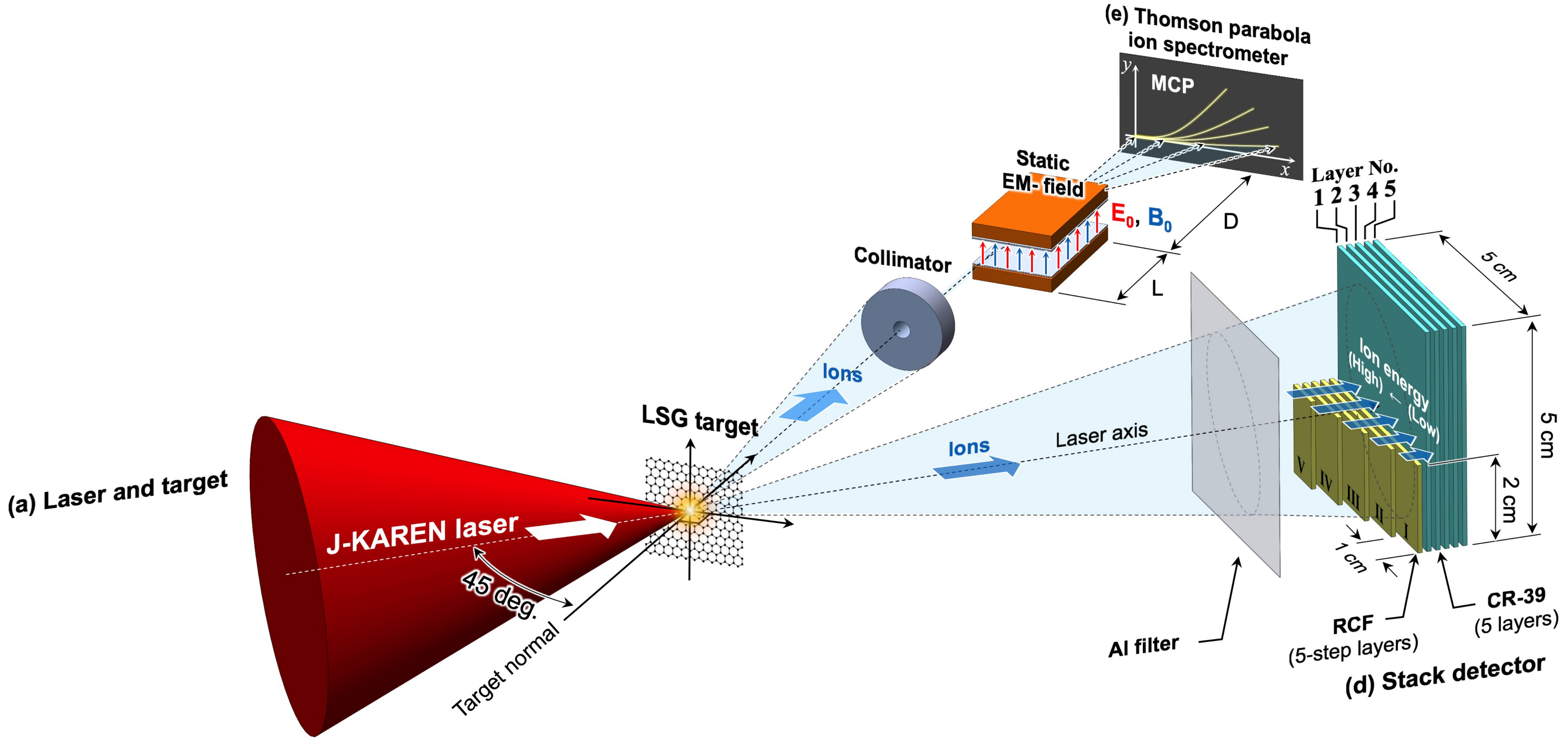
- Without plasma mirror



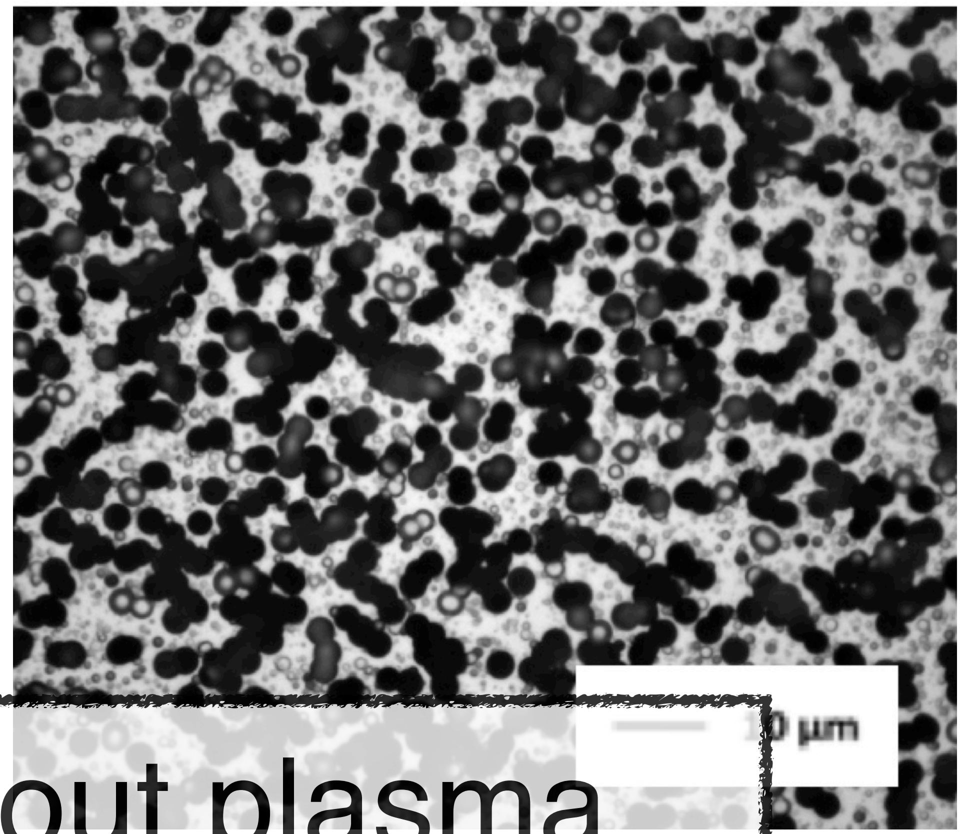
Kuramitsu+ Sci. Rep. 2022

Laser-driven ion acceleration with large-area suspended graphene

- Direct irradiations of the LSG targets generate MeV protons and carbons
- From sub-relativistic to relativistic laser intensities
- From low contrast to high contrast conditions
- All the graphene carbons are accelerated.
  ➡ Extremely high acceleration efficiency



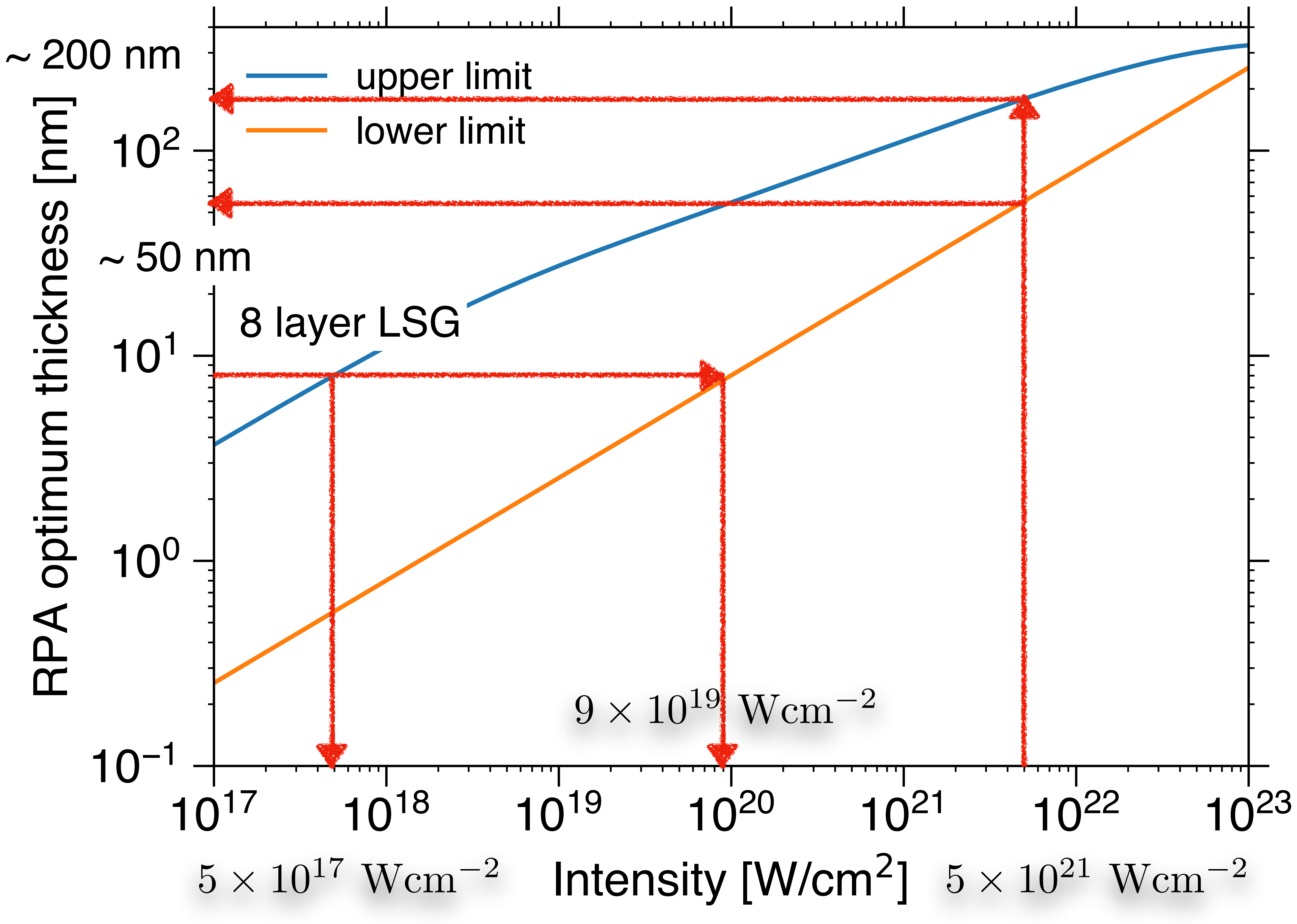
Kuramitsu+ Sci. Rep. 2022



Irradiating the thinnest target by the highest intenstiy laser without plasma mirror to demonstrate robustness of LSG ➡ Not optimized yet!

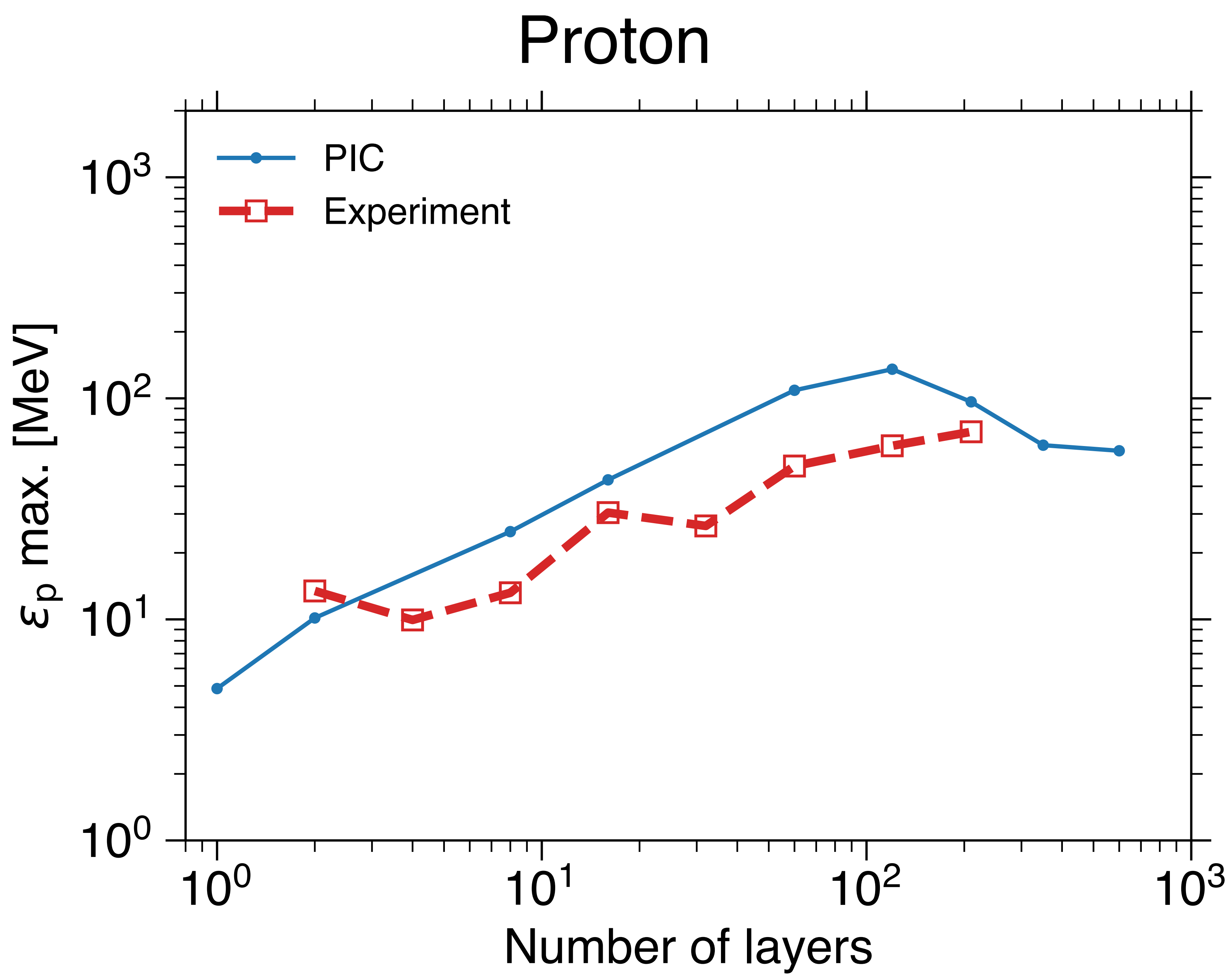
Energy frontier

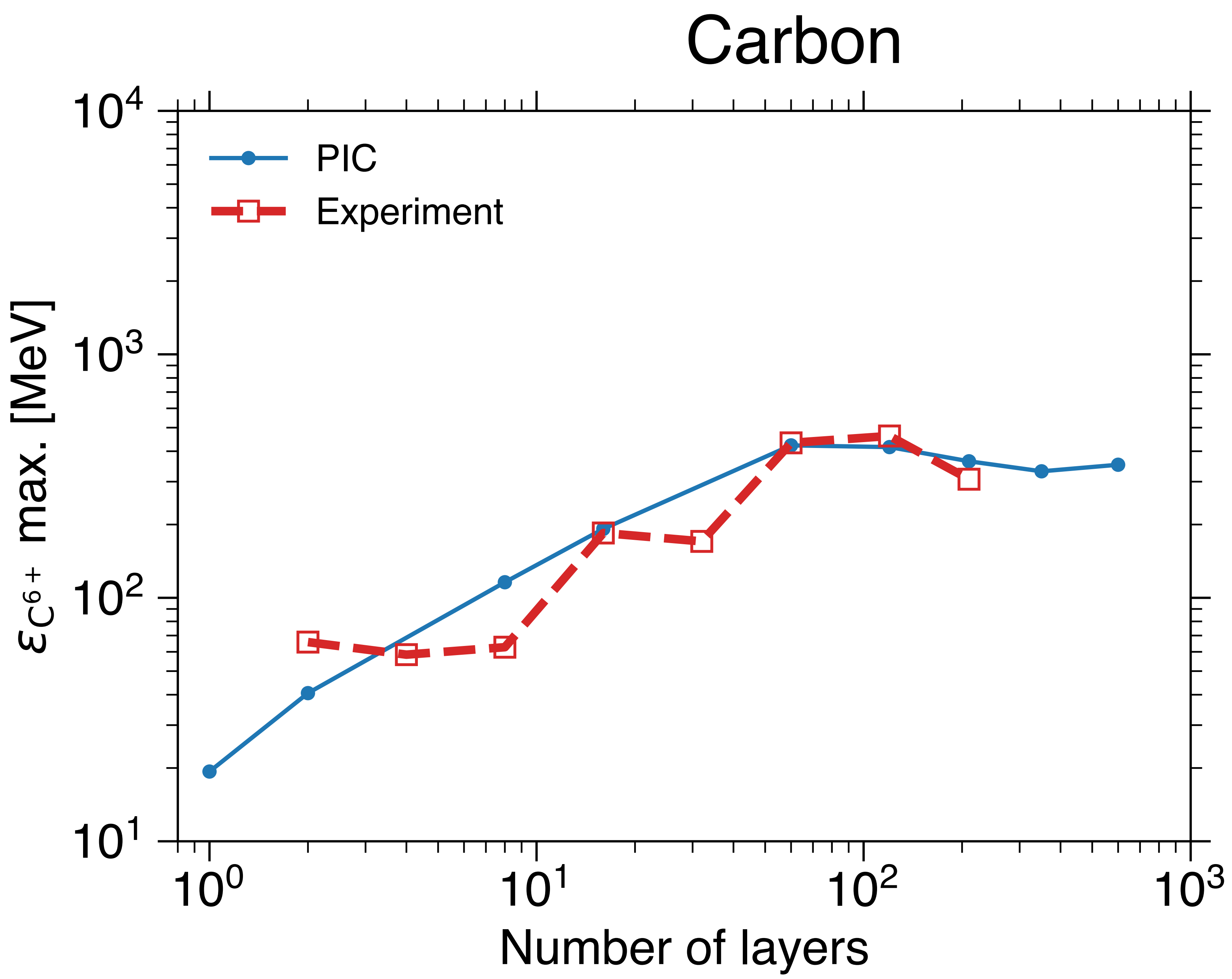
1. LSG optimization to J-KAREN laser
2. J-KAREN optimization to LSG



1. LSG optimization to J-KAREN laser

Energy scaling against LSG thickness


Proton

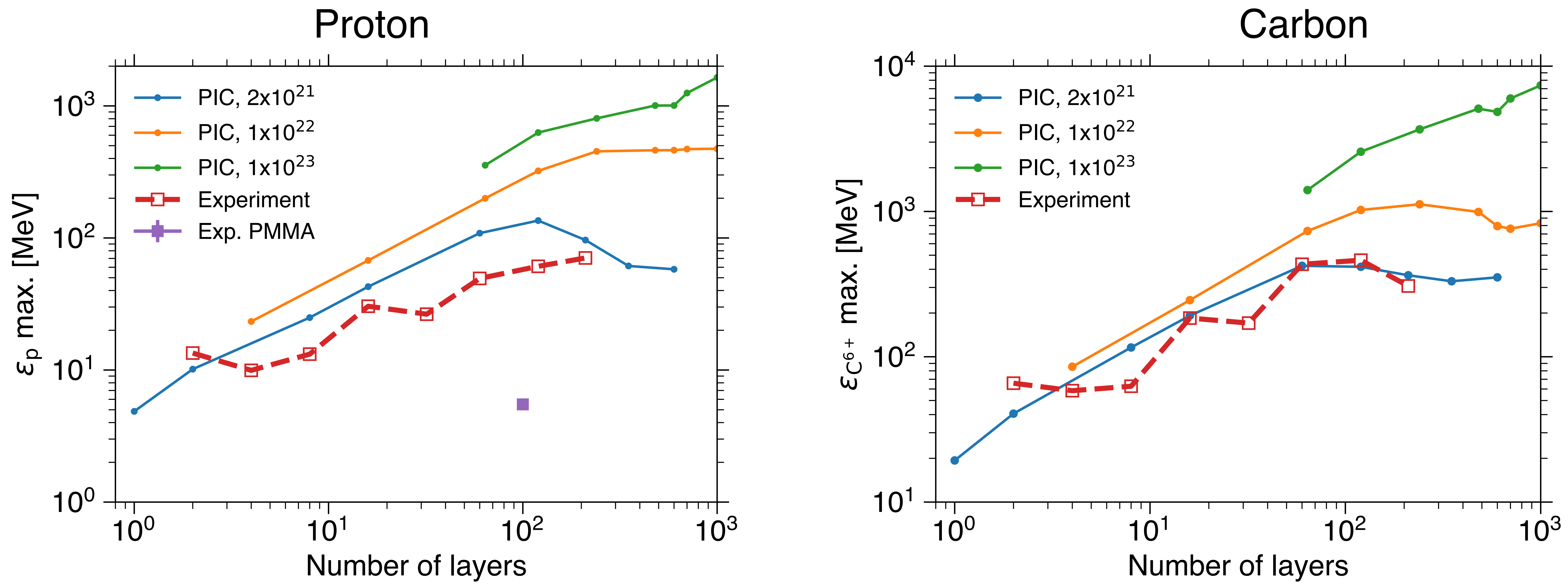

Carbon

T. Minami et al, in preparation.

- Proton energies are slightly lower than the PIC expectations.
- Carbon energies agree very well with the PIC simulations.
- Note that no prepulse is considered.

1. LSG optimization to J-KAREN laser

Energy scaling against LSG thickness

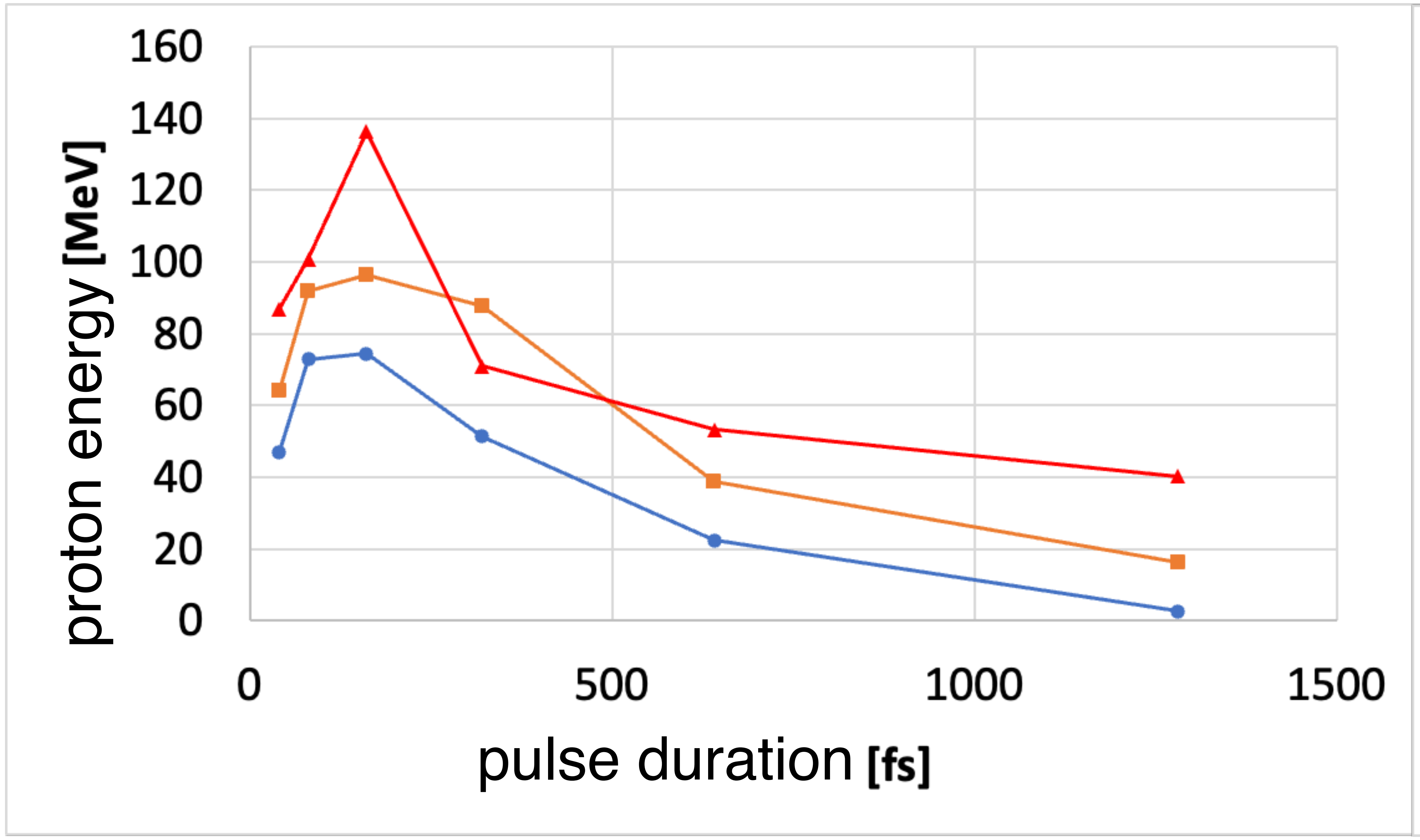


T. Minami et al, in preparation.

- PIC results with higher intensity 10^{22} or 10^{23} W/cm^2 predict higher ion energies.
- Over GeV proton with 10^{23} W/cm^2, and carbons with 10^{22} W/cm^2.

2. J-KAREN optimization to LSG
Top 1% proton energy vs laser pulse duration from 2D PIC

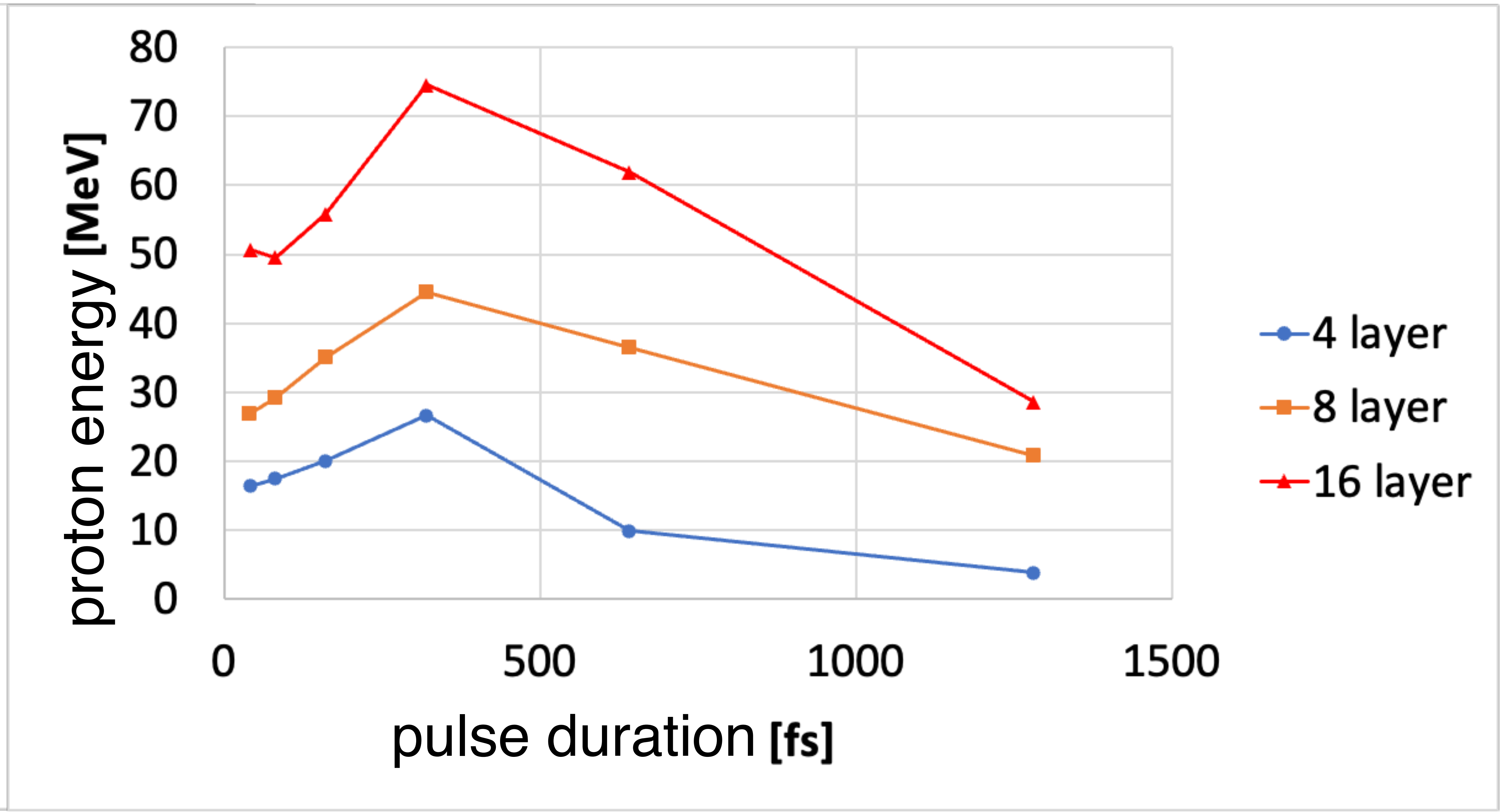
F/1.3



Peak at τ = 160 fs

independent of target thickness

F/3



Peak at τ = 320 fs

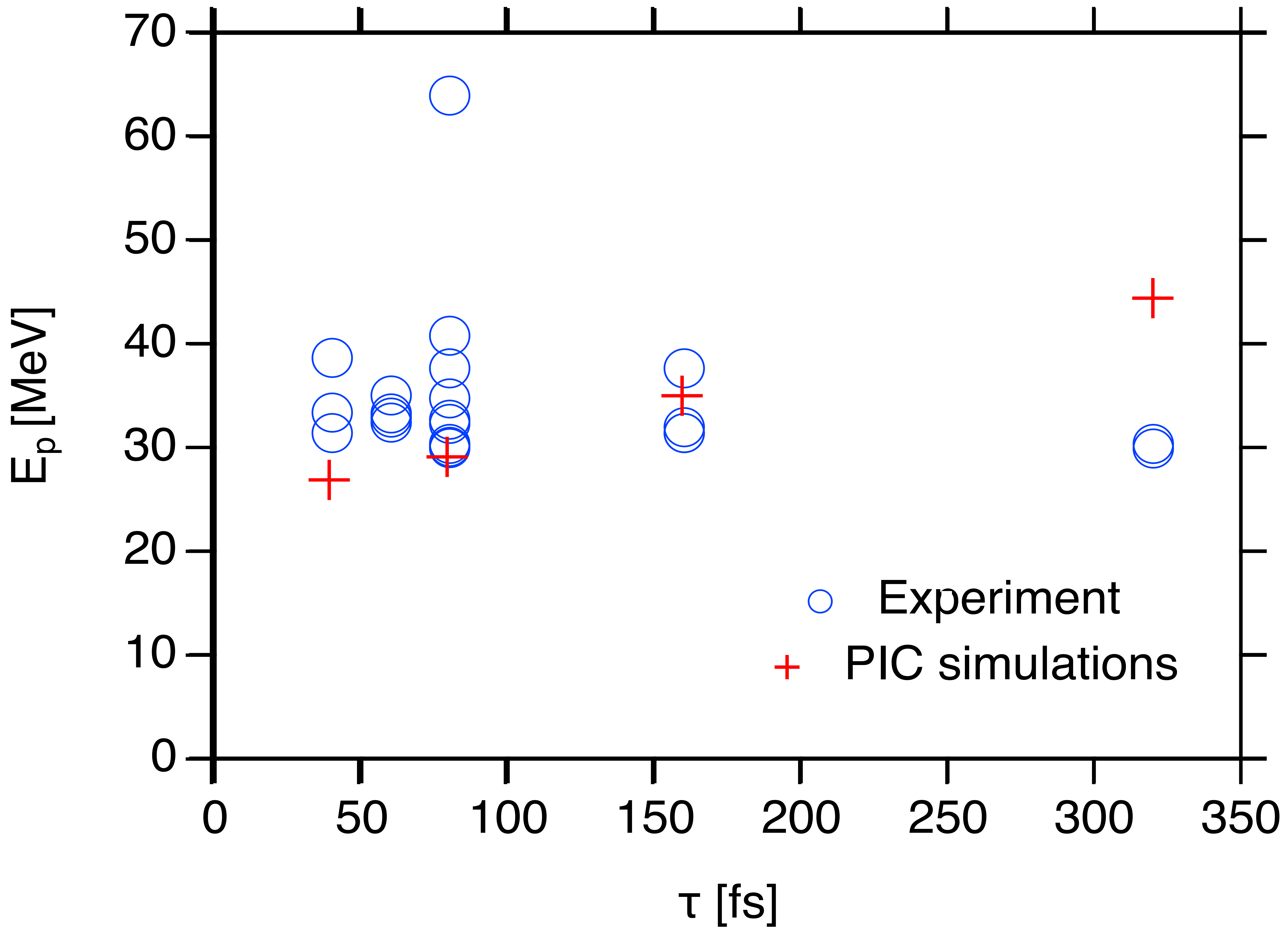
independent of target thickness

Suzuki+ JPS 2022 fall

2. J-KAREN optimization to LSG
Multi-stage scintillation counter

- First demonstration of multi-stage scintillation counter in laser ion acceleration.
- Yet the time of flight measurement only.
- Experimental proton energies decrease for longer pulse duration > 160 fs.
- Higher proton energies than PIC ~ 160 fs.
- Indicating the laser intensity is not essential in the extremely thin target regime.

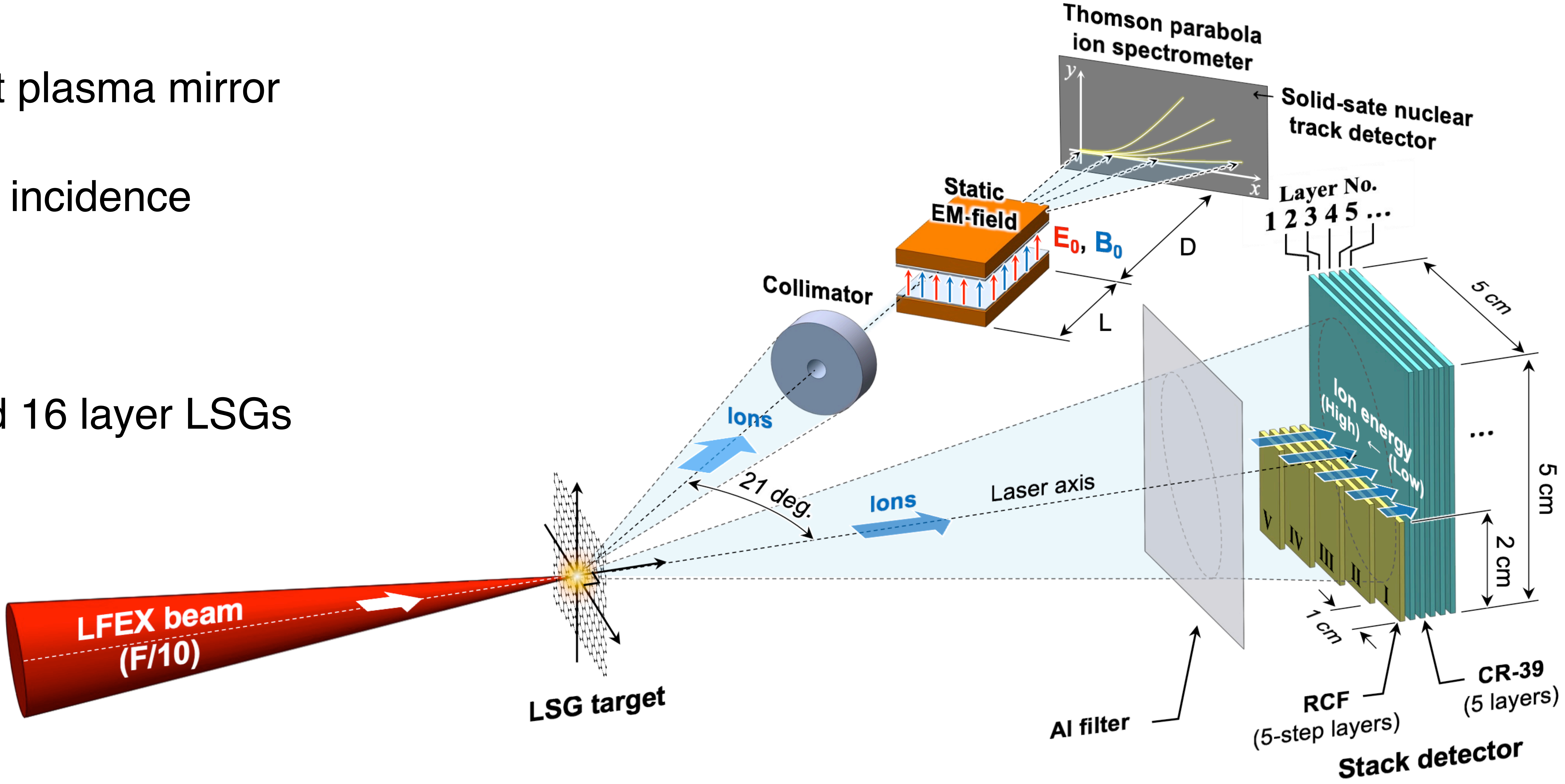
8 layer LSG with F/3



Abe + in preparation

Energy frontier with LFEX laser and machine learning

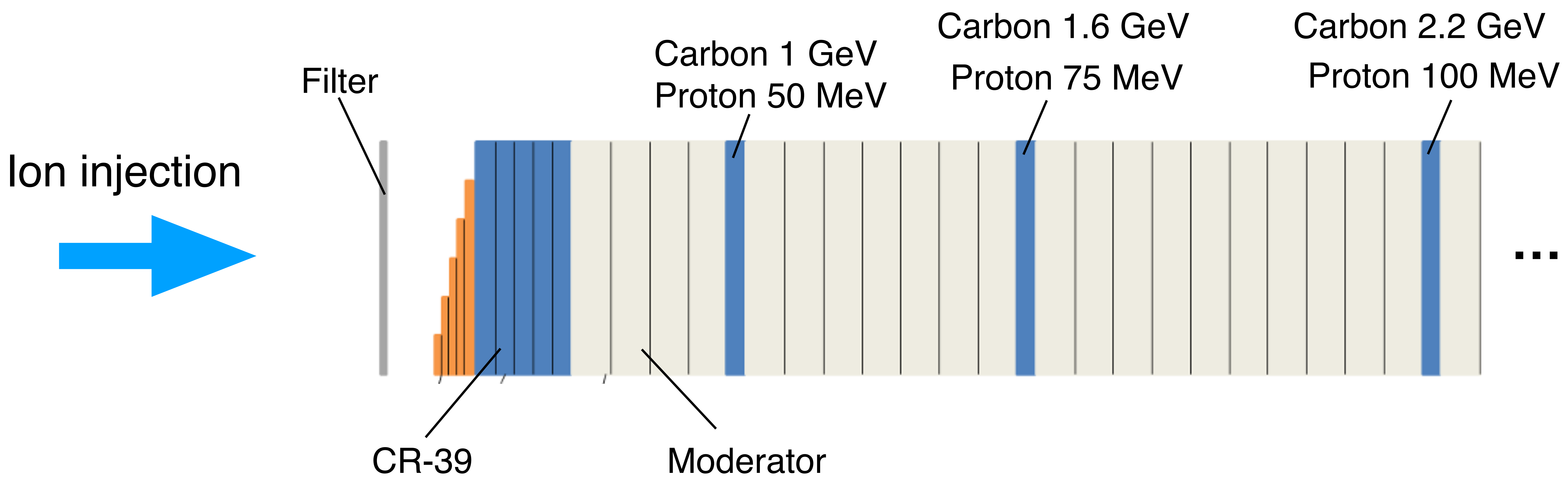
- 1053 nm, 1.5 ps, F/10, 700 J per beam, 1e19 W/cm²
- Without plasma mirror
- Normal incidence
- Targets
  - 8 and 16 layer LSGs



Minami + submitted

CR-39 stack

To resolve ion energy using CR-39

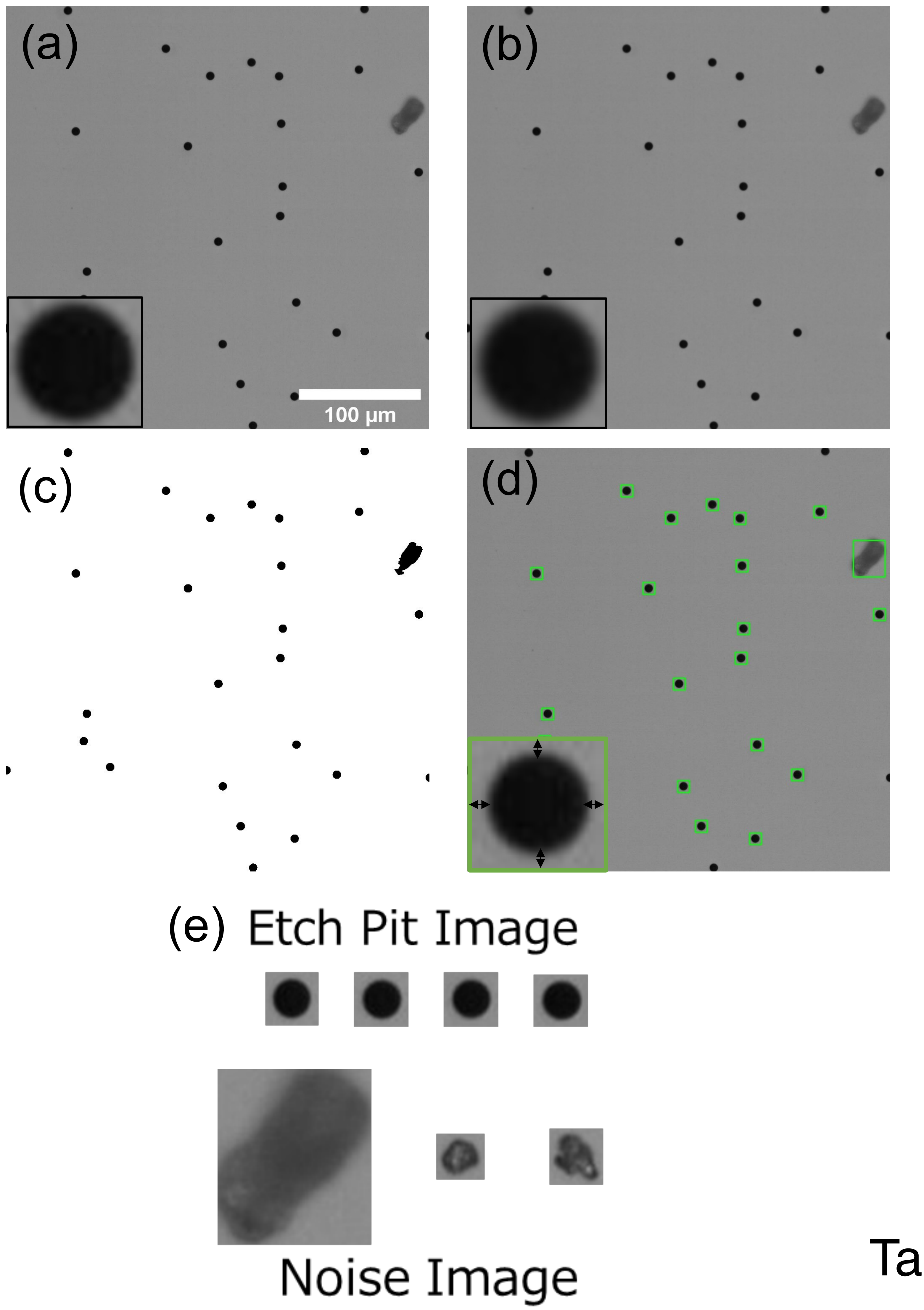


- To obtain ion spectra with CR-39 stack, it is required to find etch pits in large amounts of microscope images.
- ~10 CR-39 in 1 stack, ~10,000 microscope images in 1 CR-39 sheet
- **Millions of images should be analyzed in 1 experiment series.**

Minami + submitted

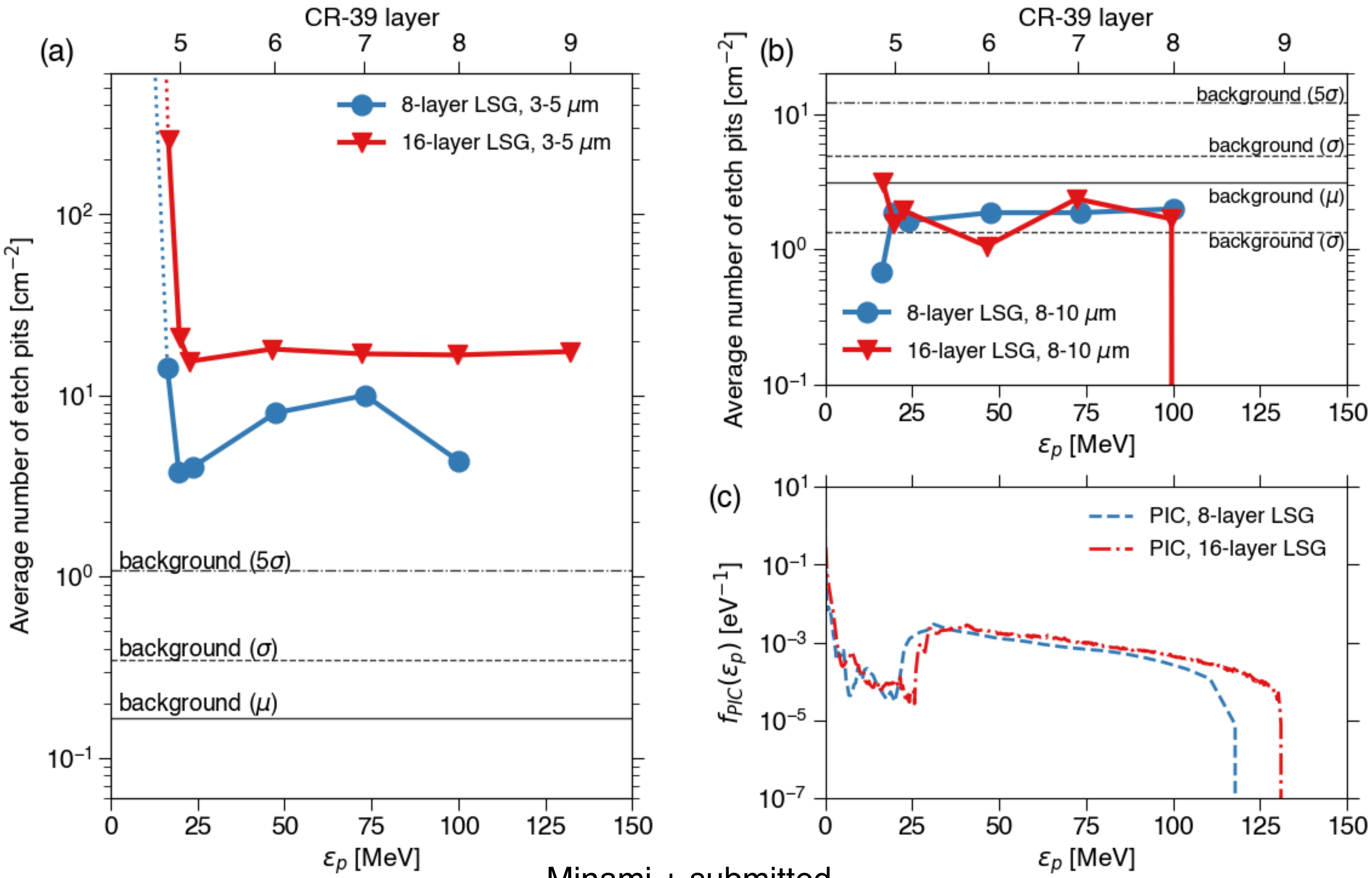
Automation of ion pit analyses with machine learning (ML)

(a) Load an image
(b) Smoothing(blurring)
(c) Binarization
(d) Outline extraction
(e) Classify etch pits and noise
Machine learning
Automation of pit analyses



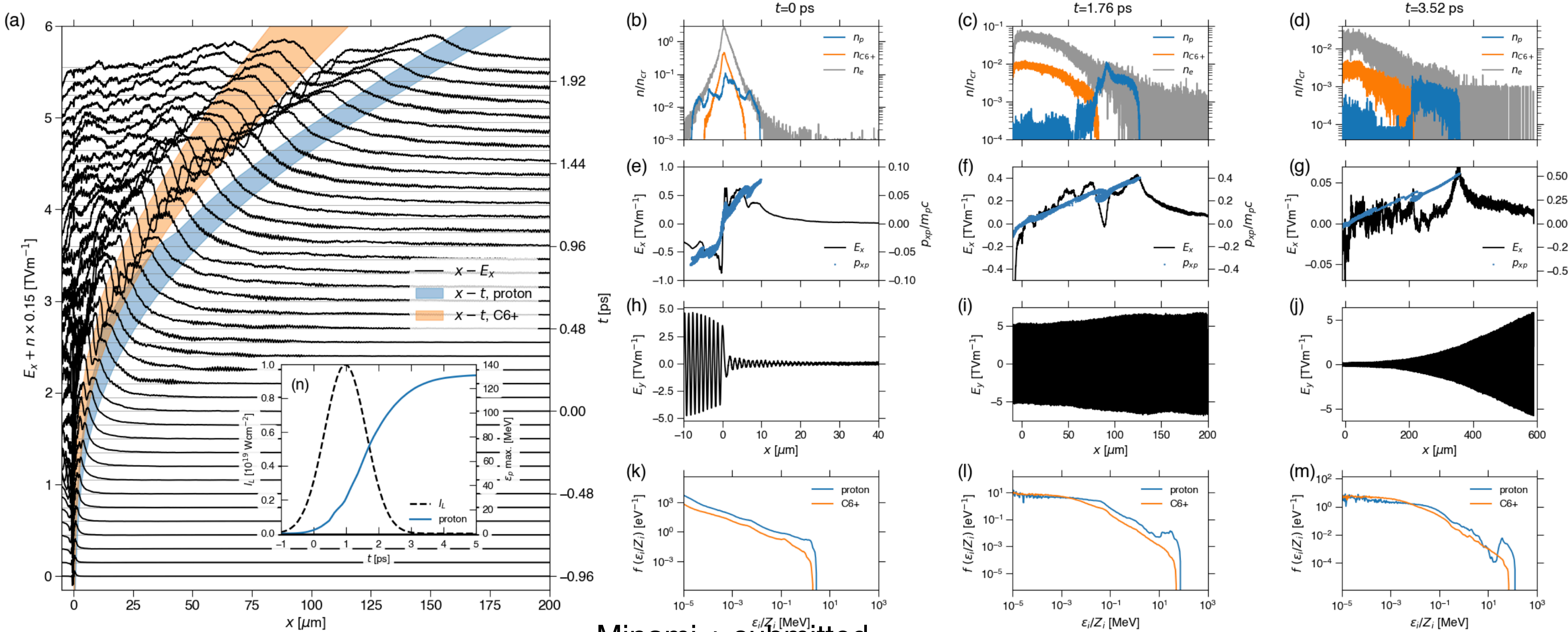
Taguchi + RSI 2024

Proton energy > 100 MeV



Minami + submitted

Proton surfing acceleration

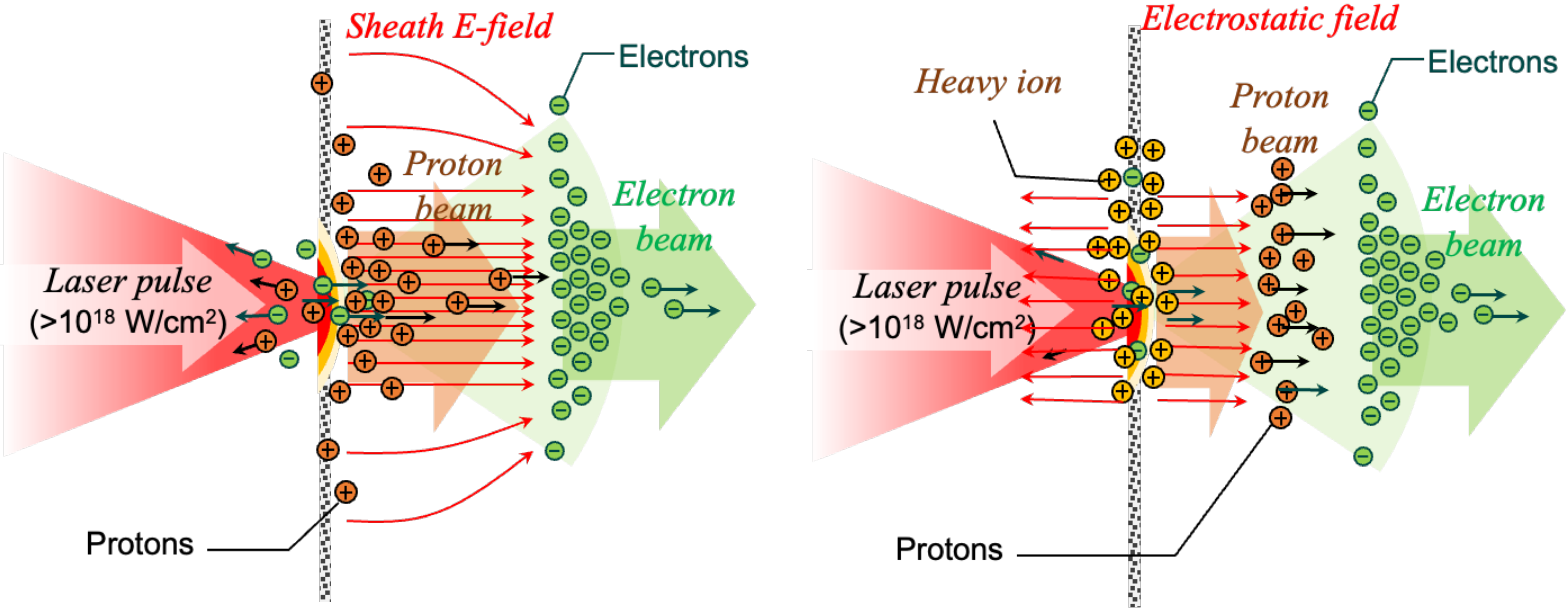


Minami + submitted

- We optimize the ion acceleration in two ways, LSG to laser and laser to LSG, and both successfully produce energetic protons and carbons.
- 132 MeV protons are accelerated with long (1.5 ps) and lower intensity laser (~10^{19} Wcm^{-2}) and identified with machine-aided ion pit analyses.

Monoenergetic ion acceleration with nanolayer targets

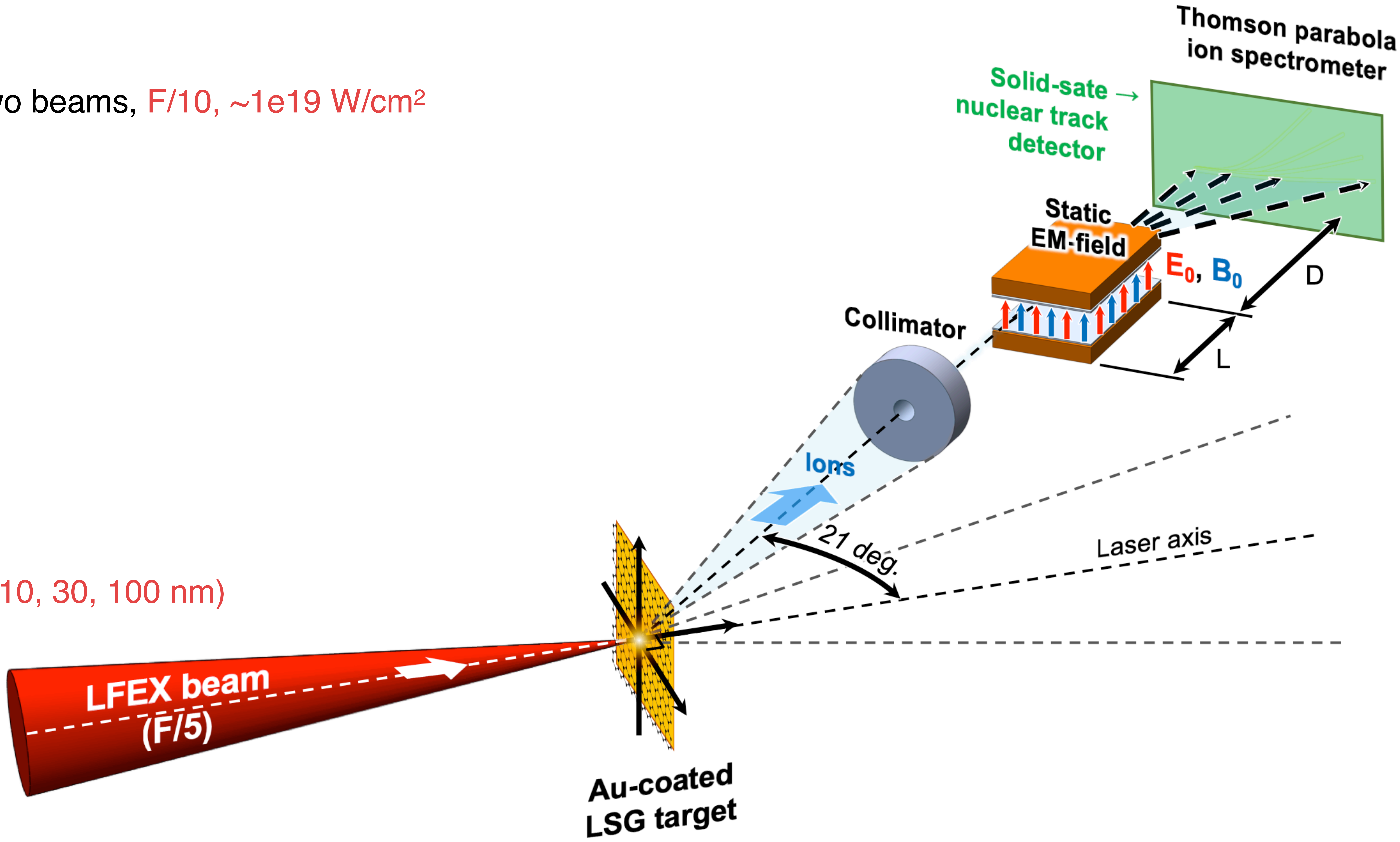
Nanolayer target with heady ions



R. Kitamura Undergraduate thesis 2024

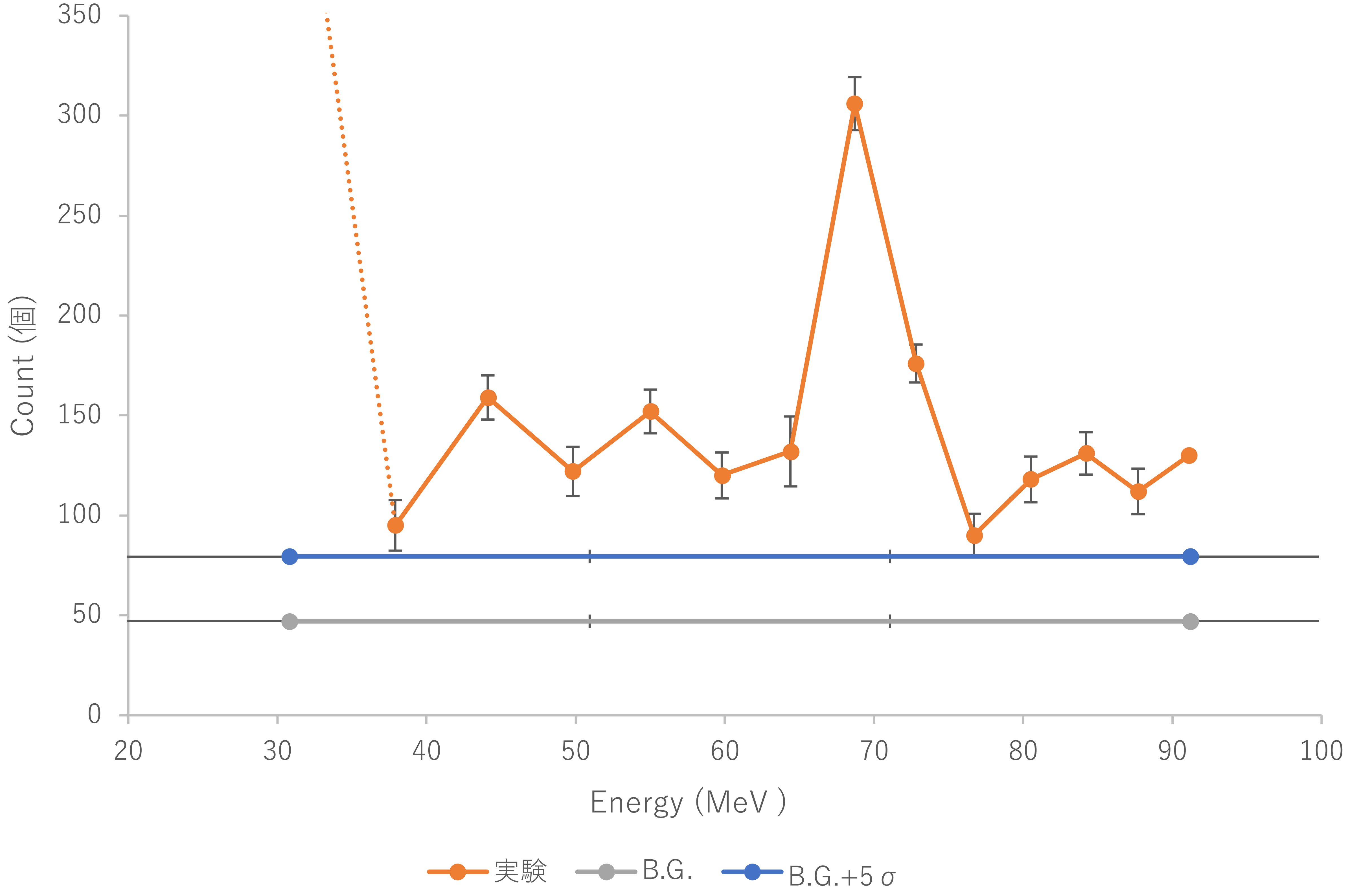
LFEX Laser

- ω, 1.5 ps, 350 J / beam, two beams, F/10, ~1e19 W/cm^2
- without plasma mirror
- Target normal incidence
- Targets
  - 4, 8, 12, 16-layer LSG
  - LSG suspended PMMA
  - 4L-LSG suspended Au (10, 30, 100 nm)

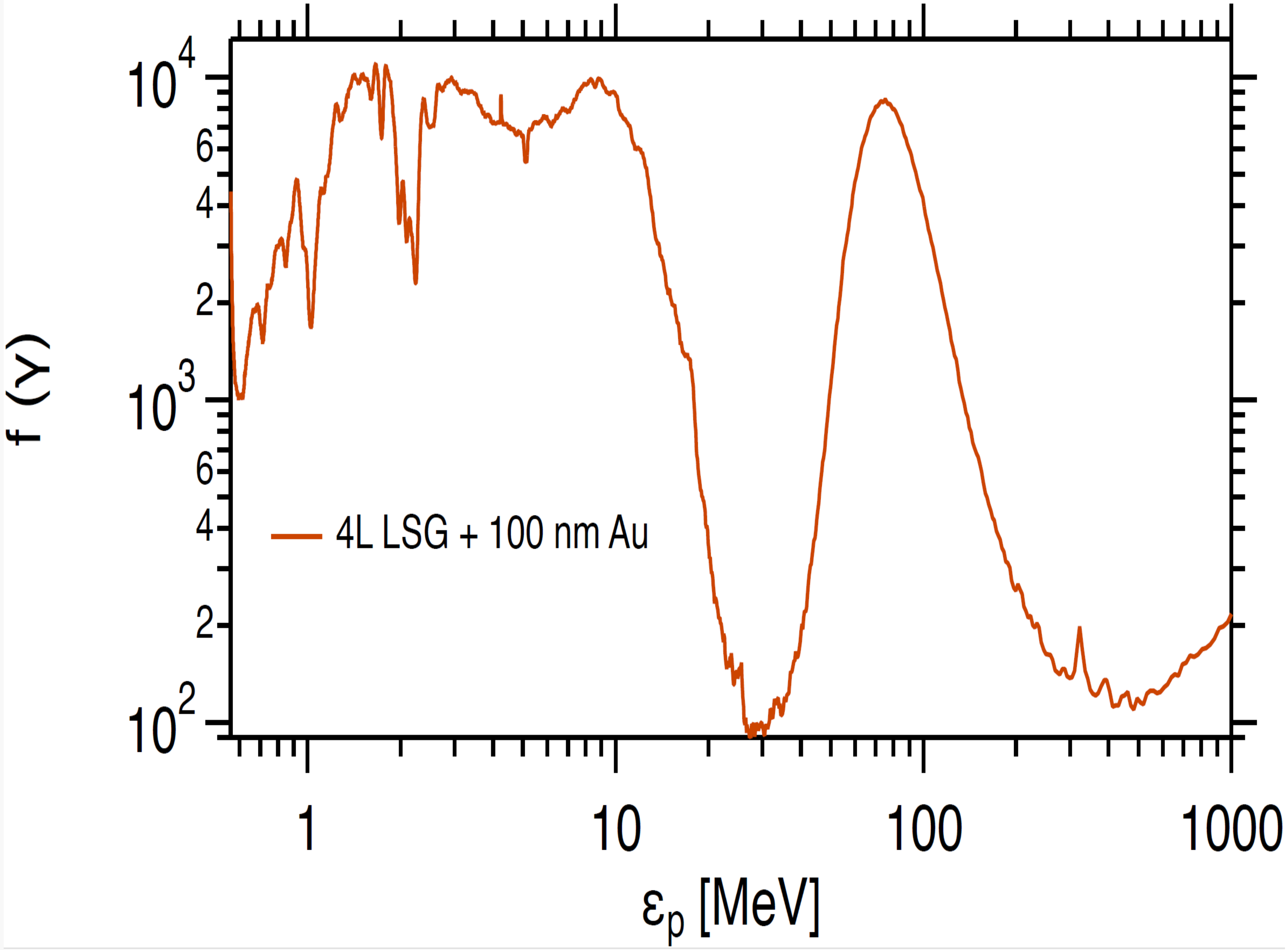


Results
4L LSG + 100 nm Au

Stack detector



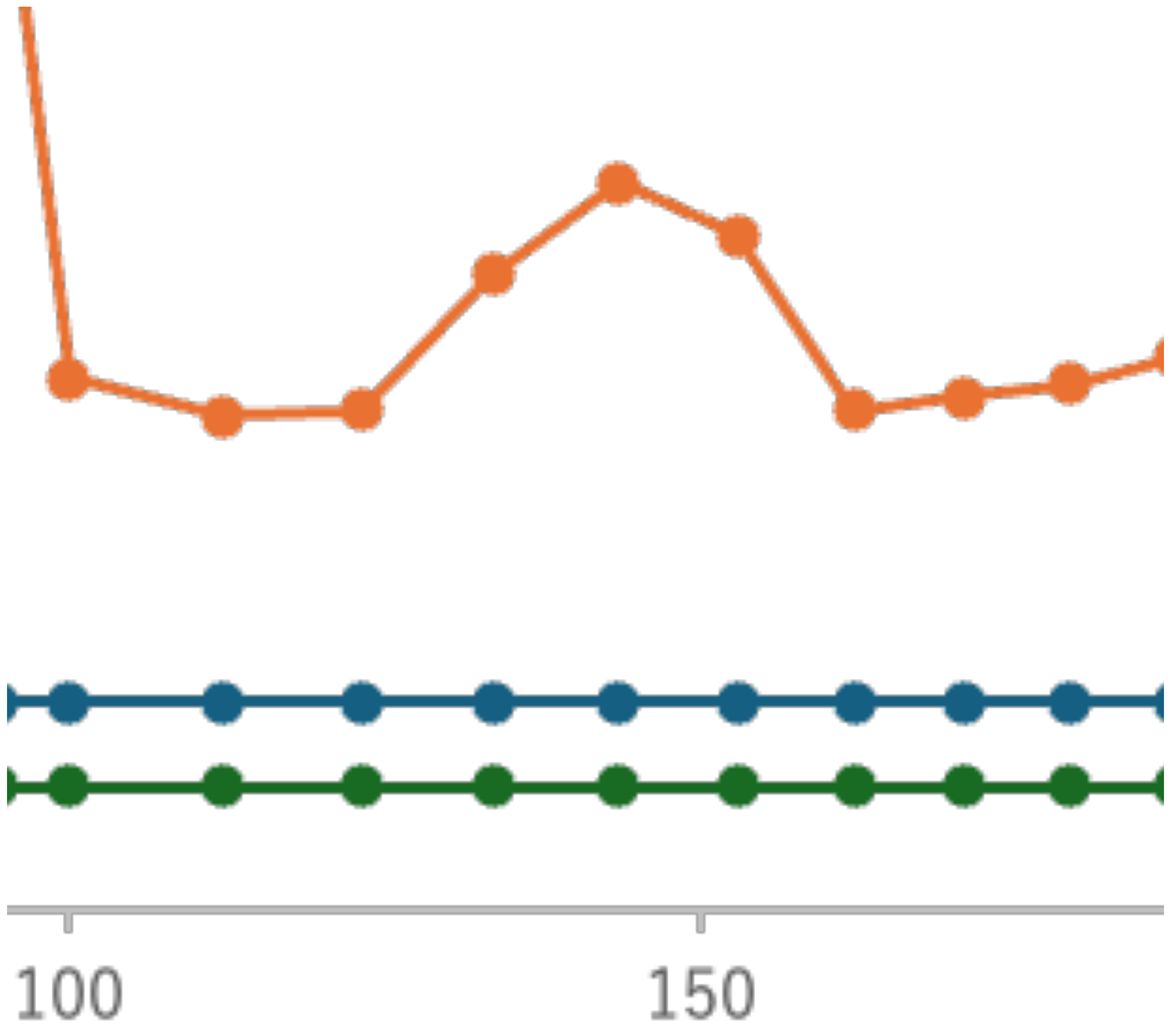
Ion spectrometer



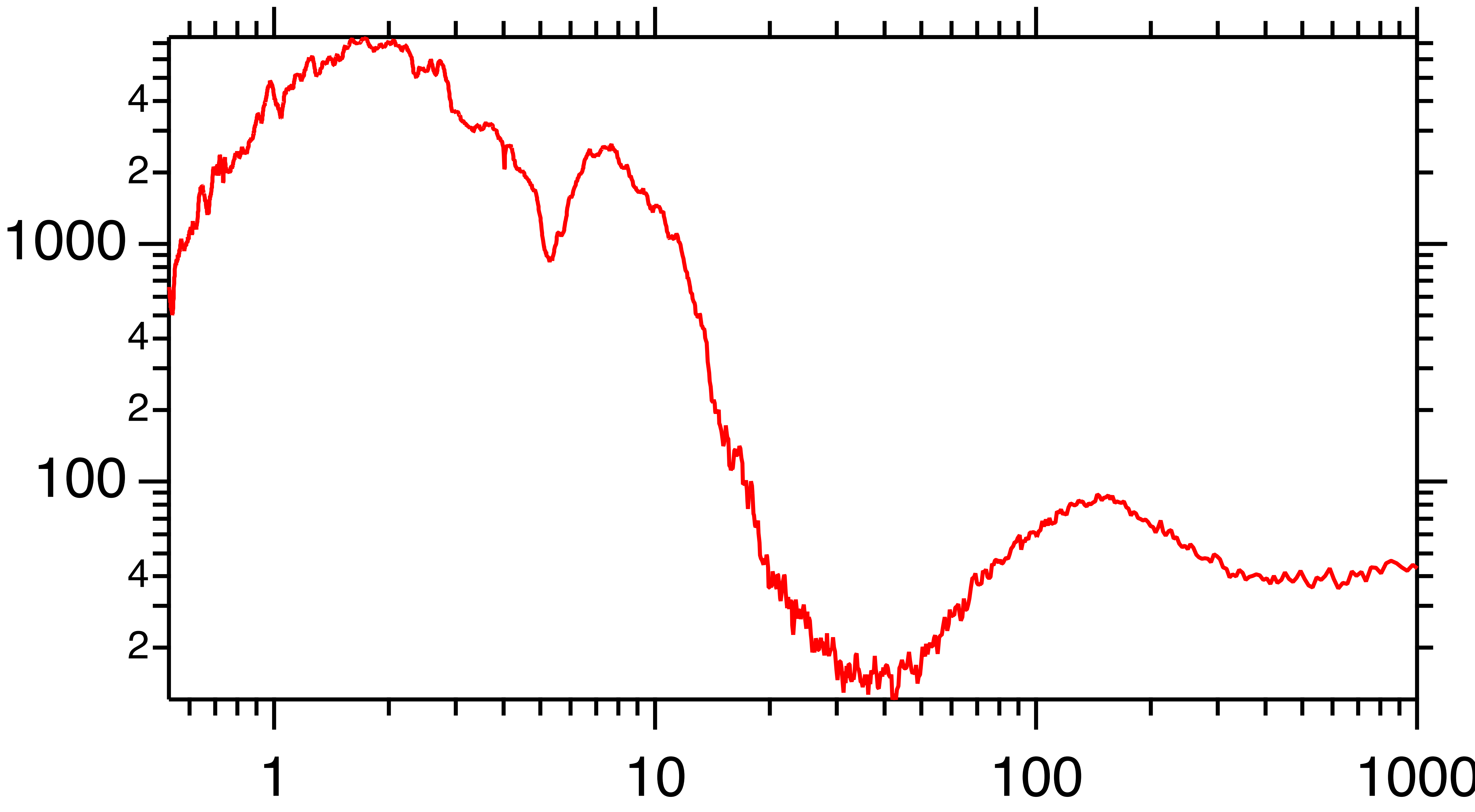
R. Kitamura Undergraduate thesis 2024

Results
10 nm Au + 4L LSG

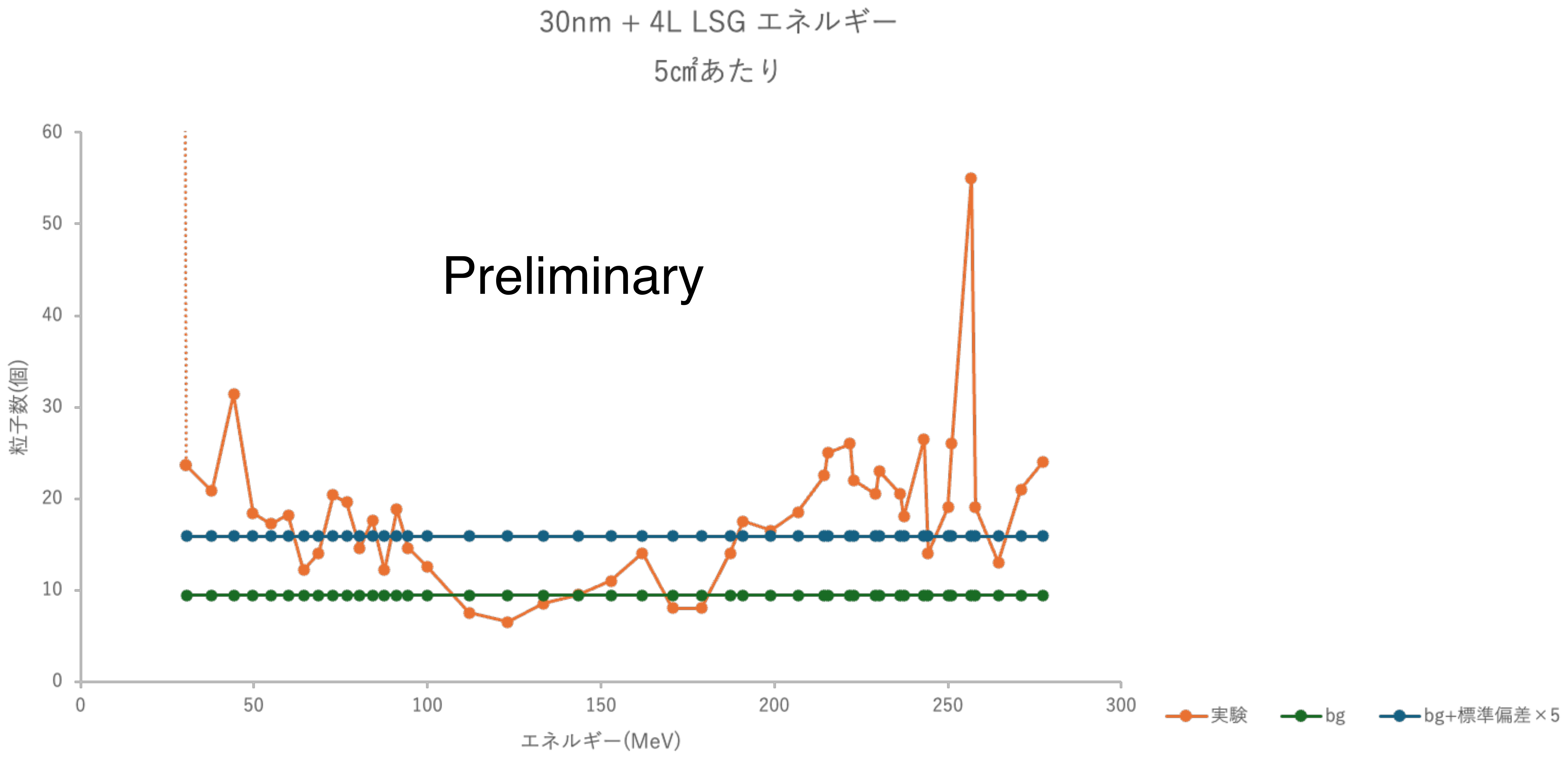
Stack detector



Ion spectrometer



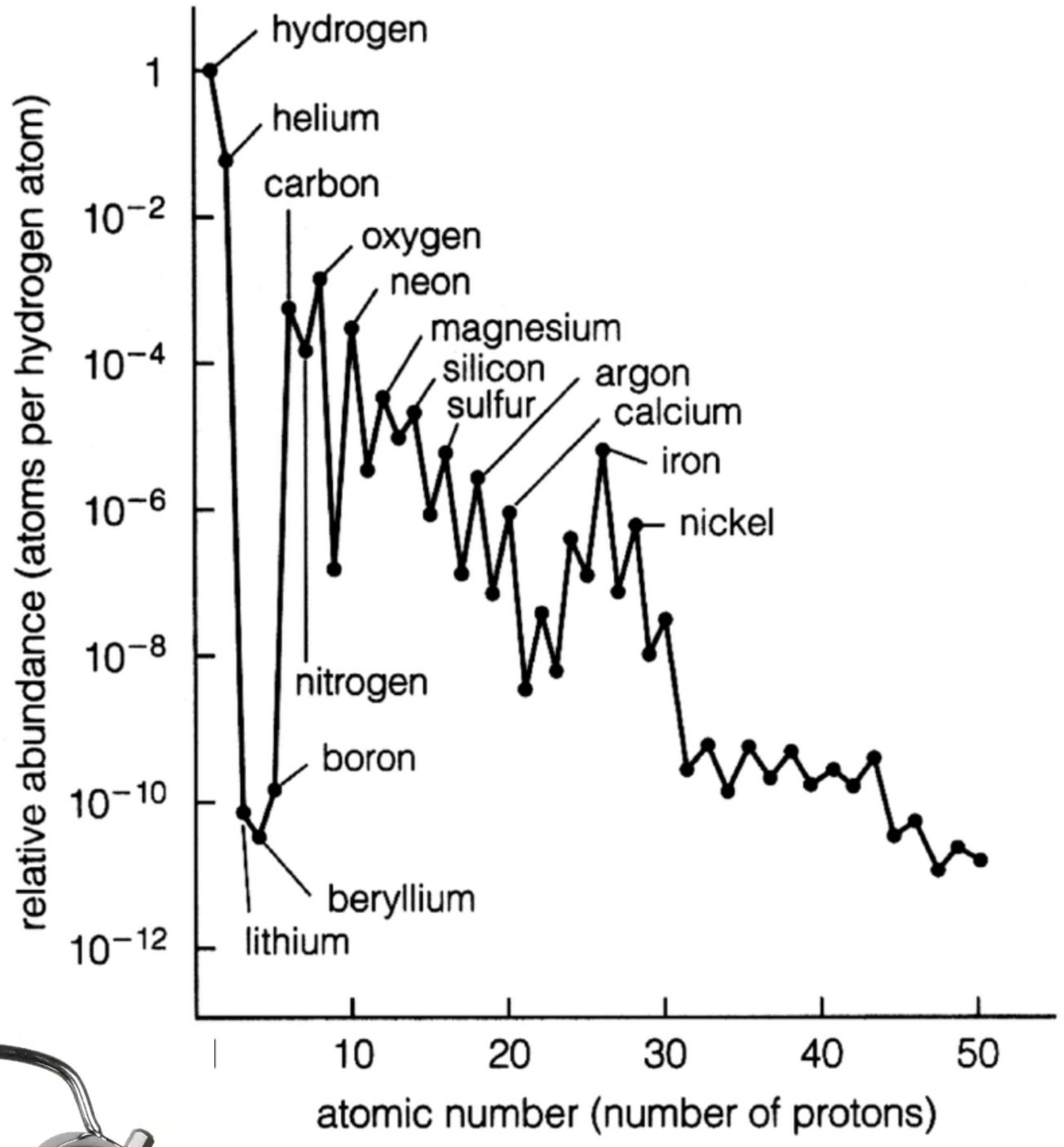
Monoenergetic protons ~ 150 MeV with the Au mounted on LSG

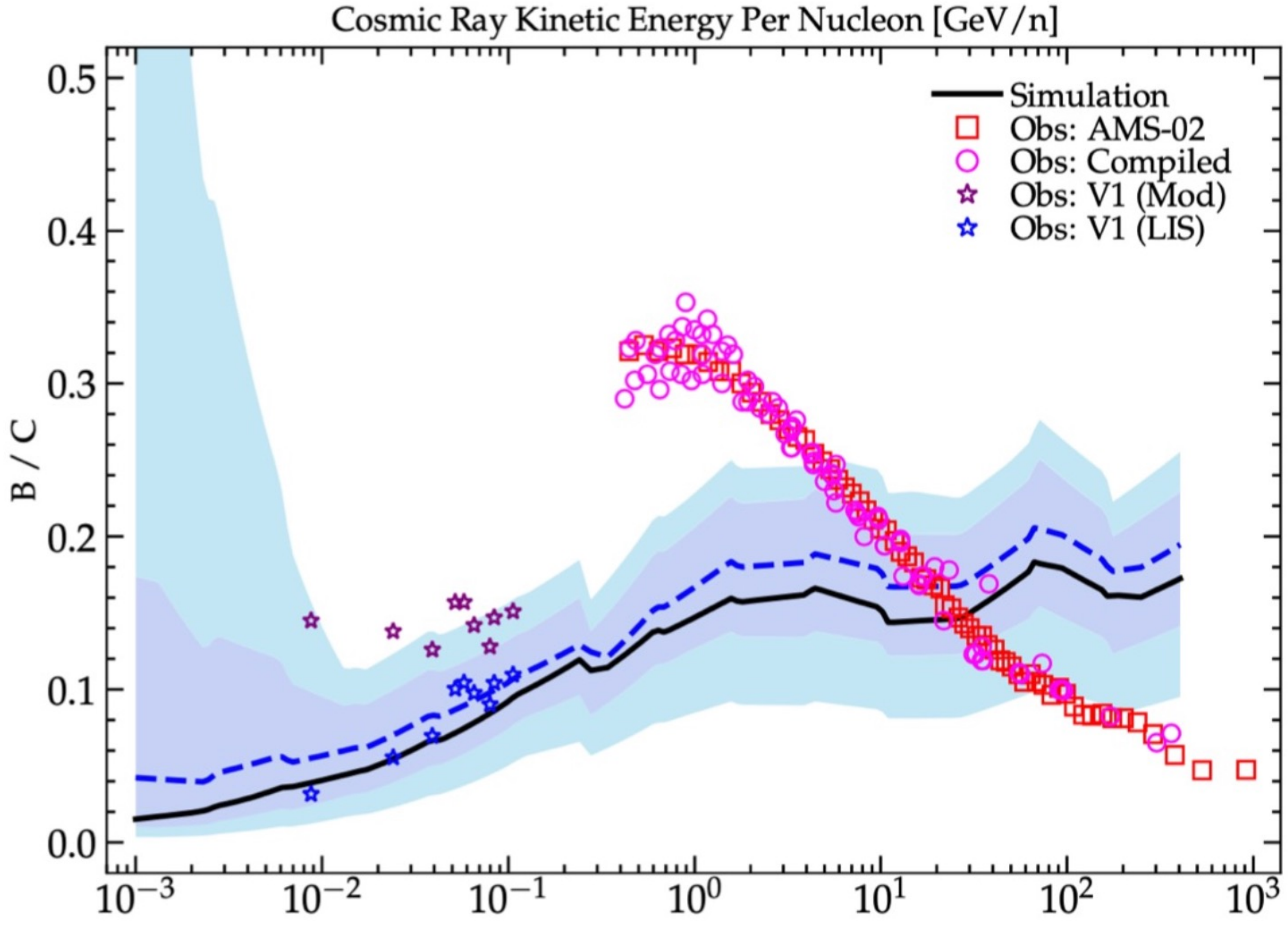


Preliminary

Model experiment of cosmic ray spallation with an intense laser

Spallation reactions & energy dependence of CR transport





$$\frac{n_{\mathrm{B}}}{n_{\mathrm{C}}} \approx \bar{n}_{\mathrm{H}} \beta c \sigma_{\mathrm{C}\to\mathrm{B}}\, \tau$$

$$\boxed{\kappa \propto \tau^{-1} \propto E^{0.33}}$$

$$\frac{n_{\mathrm{B}}}{n_{\mathrm{C}}} = 0.65\beta \left(\frac{R}{\mathrm{GV}}\right)^{-0.33}$$

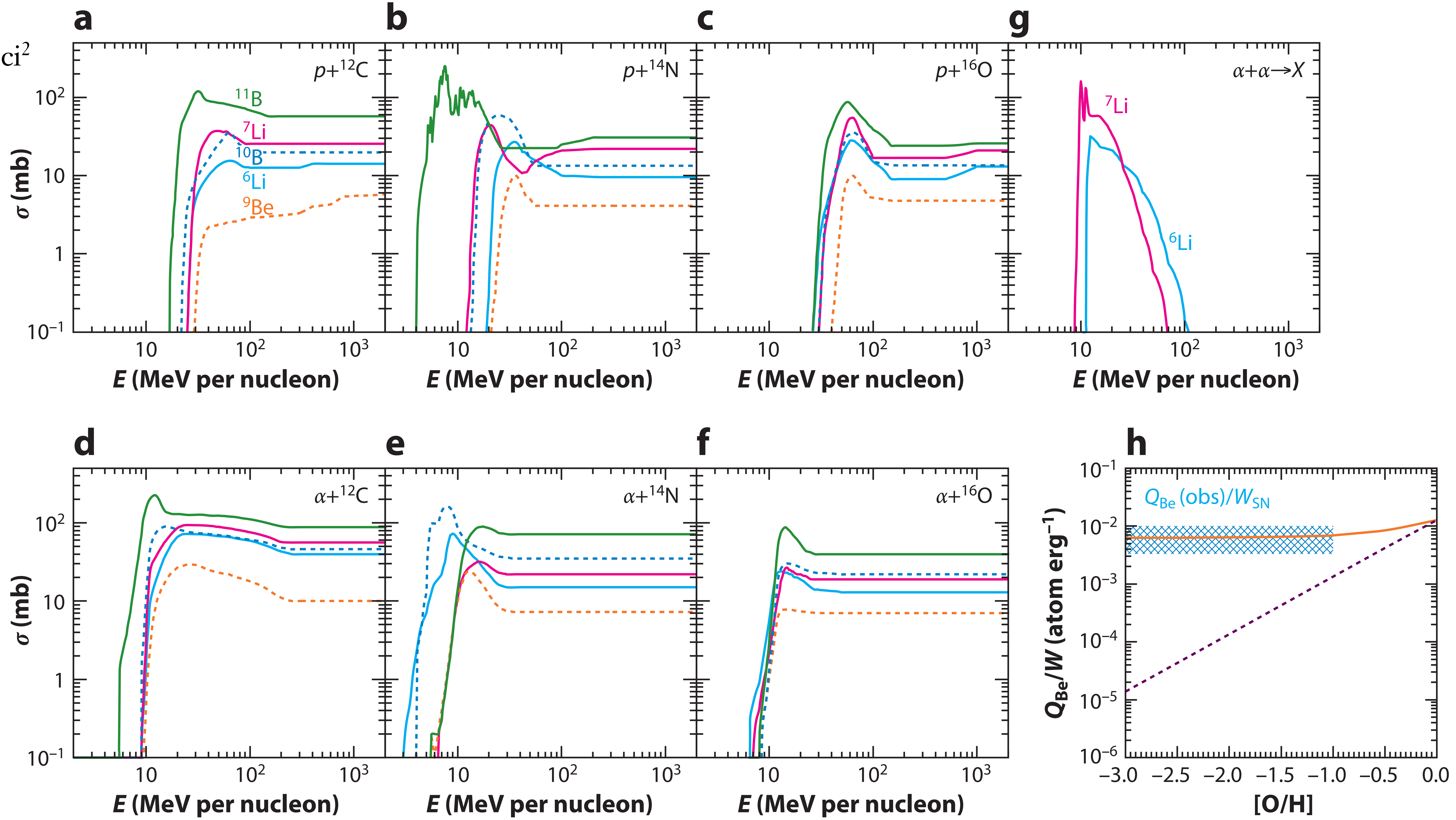
$$R \equiv r_{\mathrm{g}} B = \frac{p_{\perp} c}{Ze}$$

from Mateusz Ruszkowski

Particle Acceleration by Supernova Shocks and Spallogenic Nucleosynthesis of Light Elements

Annu. Rev. Nucl. Part. Sci. 2018. 68:377–404

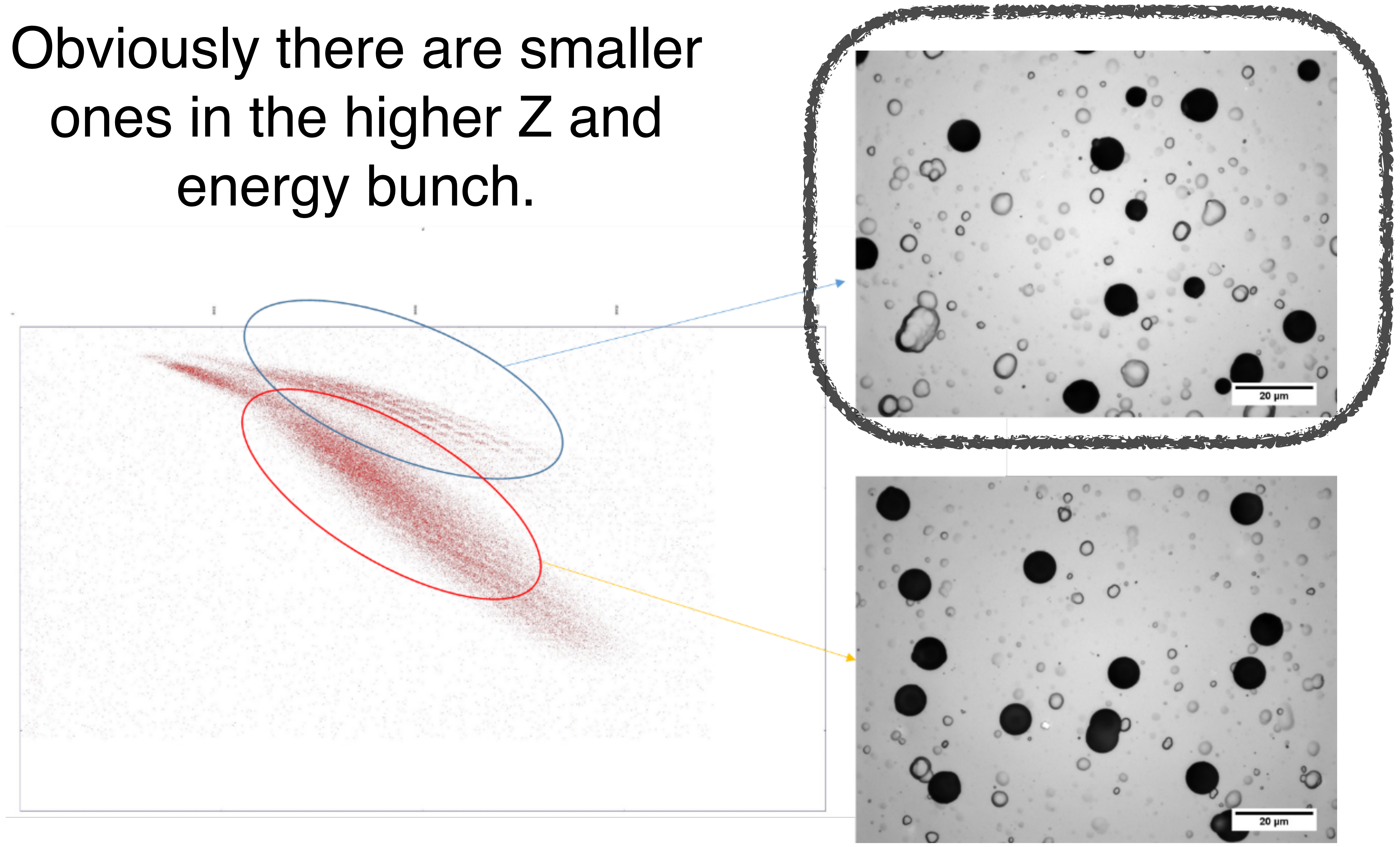
Vincent Tatischeff[1] and Stefano Gabici[2]



Kapton in TPS

- Now we can distinguish ion species from the pit size and the growth curves.
- Since the Kapton is in TPS, the ion pits in a microscope image should be the same size if they are the same ion species.

Obviously there are smaller ones in the higher Z and energy bunch.

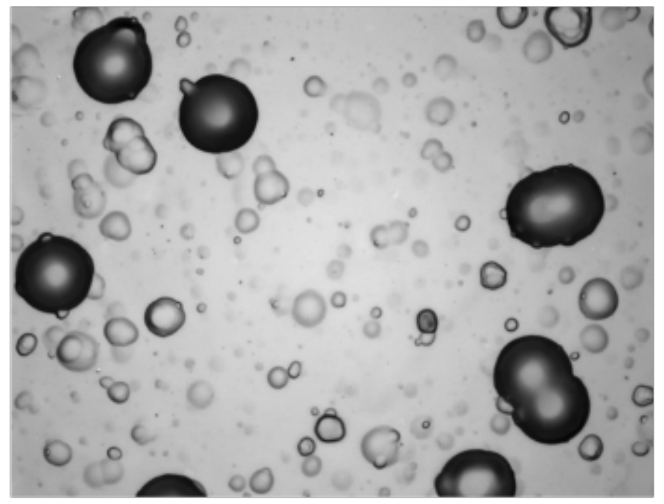


LFEX
4L-LSG suspended Au (10, 30, 100 nm)

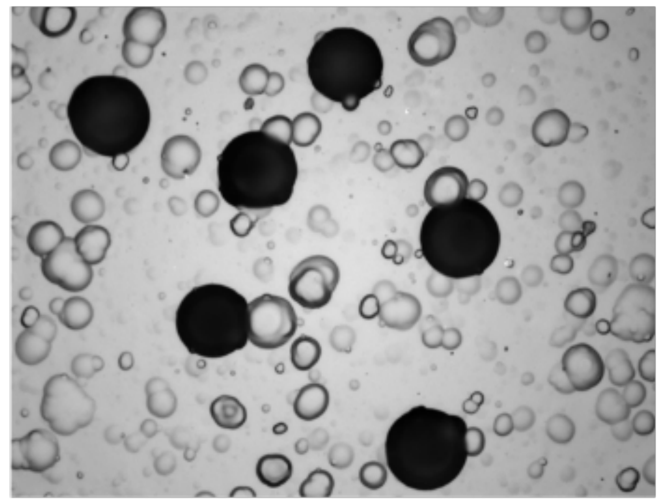
Kapton in TPS

青の領域

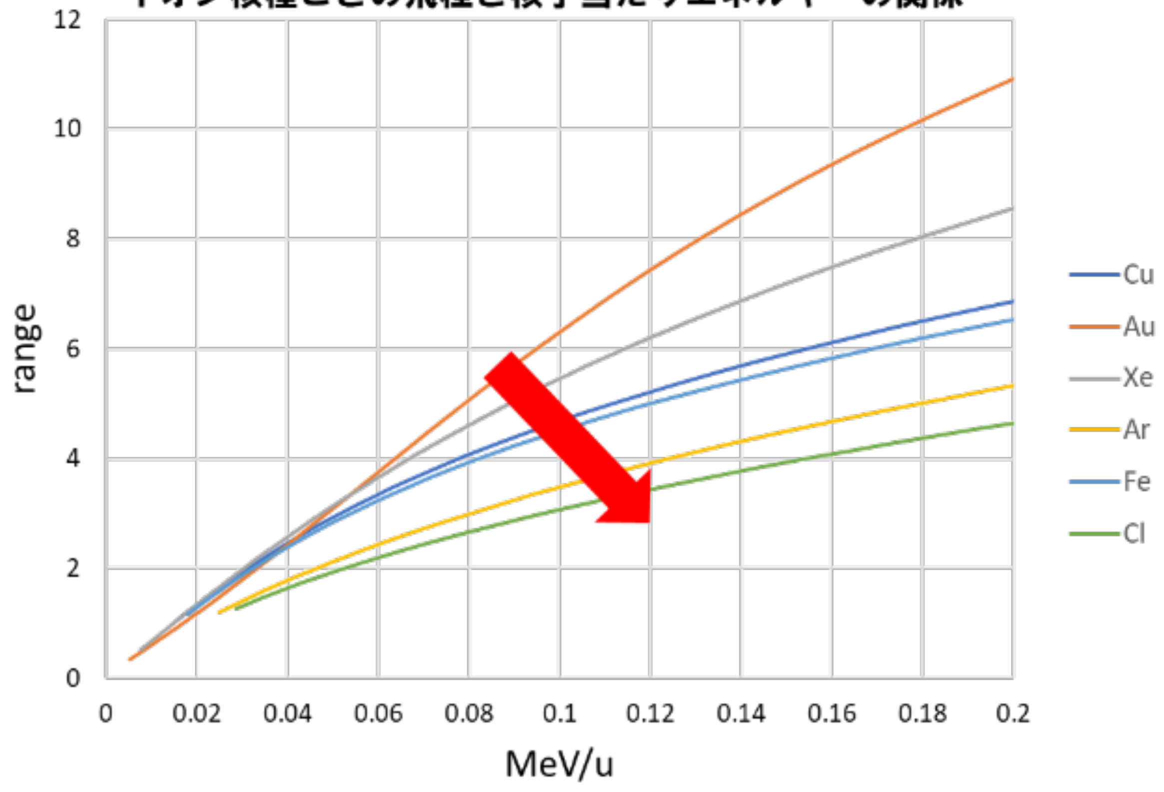
20h etching



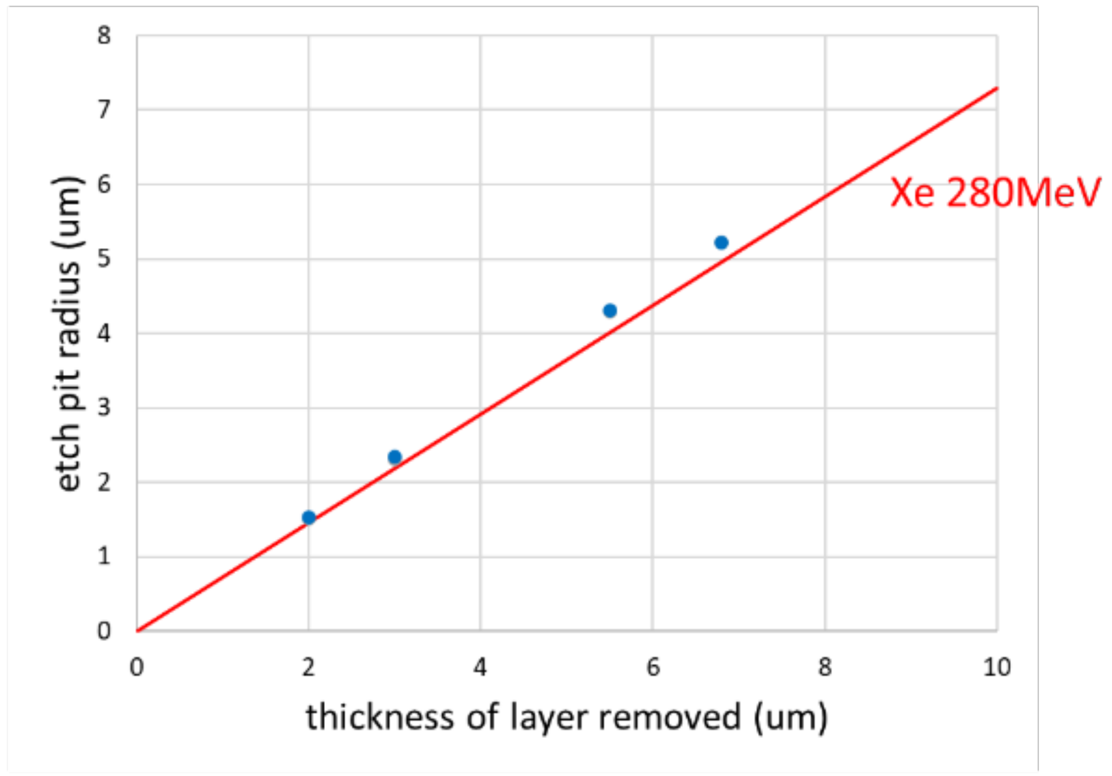
赤の領域



イオン核種ごとの飛程と核子当たりエネルギーの関係



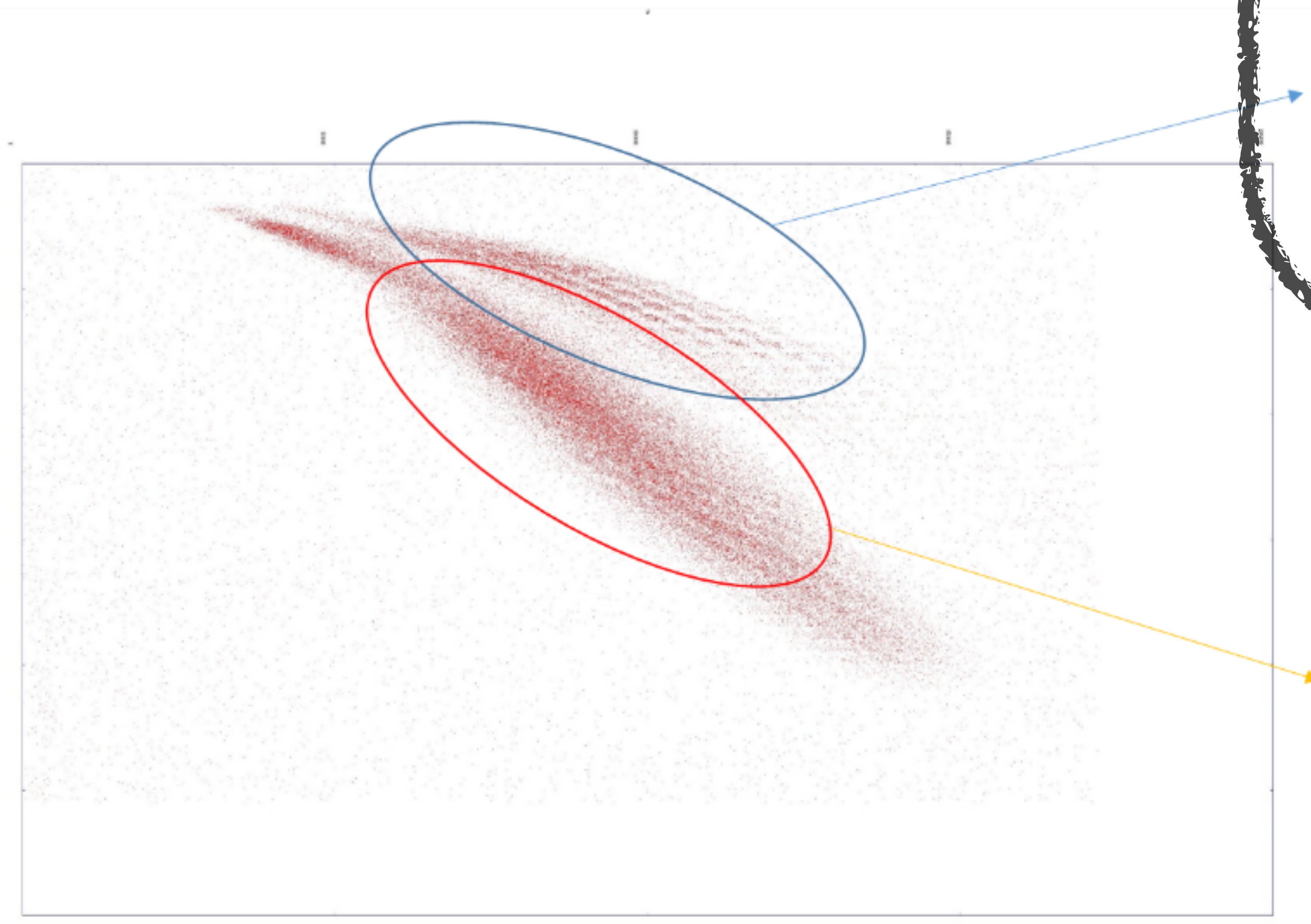
赤の領域のエッチピットとXeイオンの成長曲線

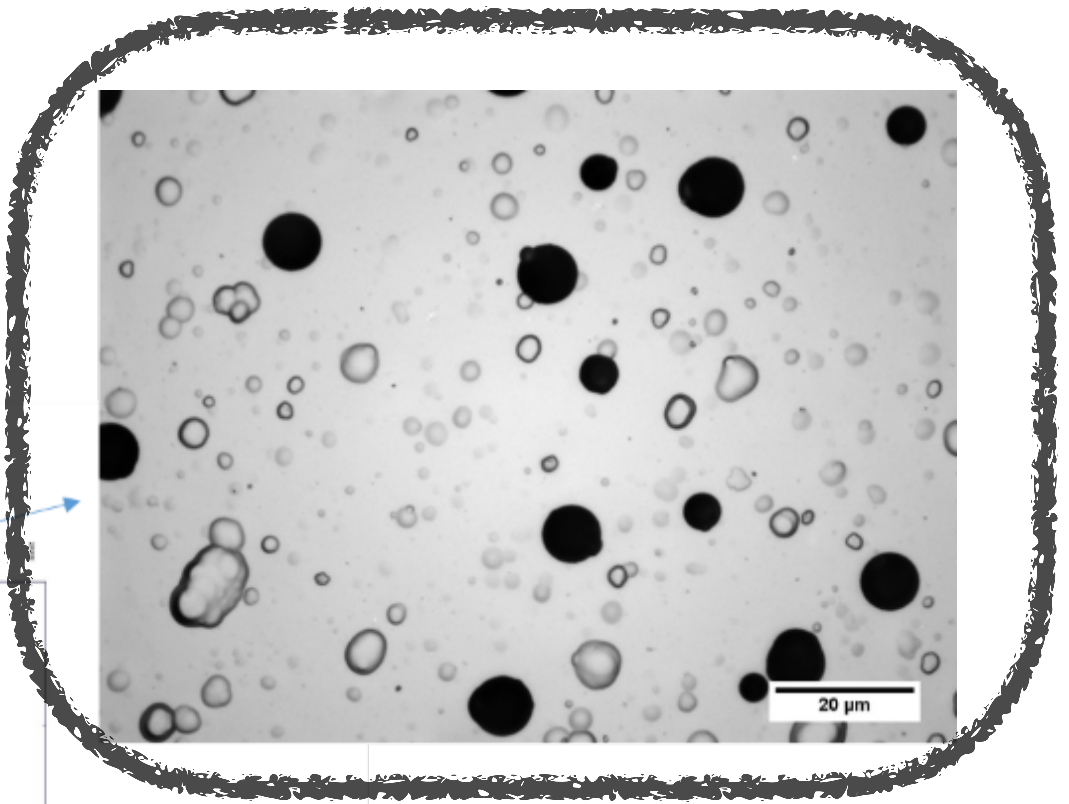


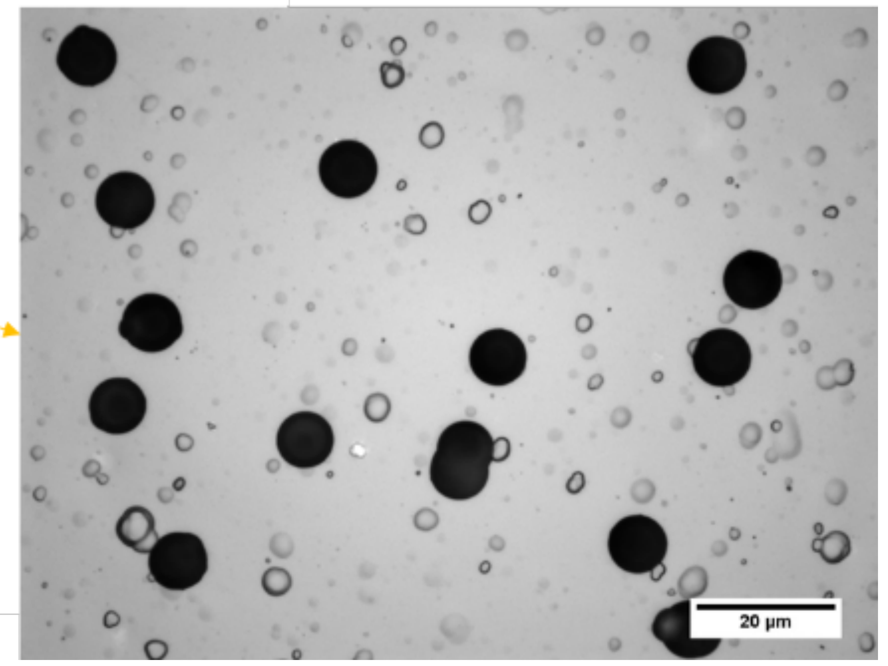
The larger pits in the blue region show round-out, i.e., lower energy than the pits in red regions.

Obviously there are smaller ones in the higher Z and energy bunch.

Two unknown species



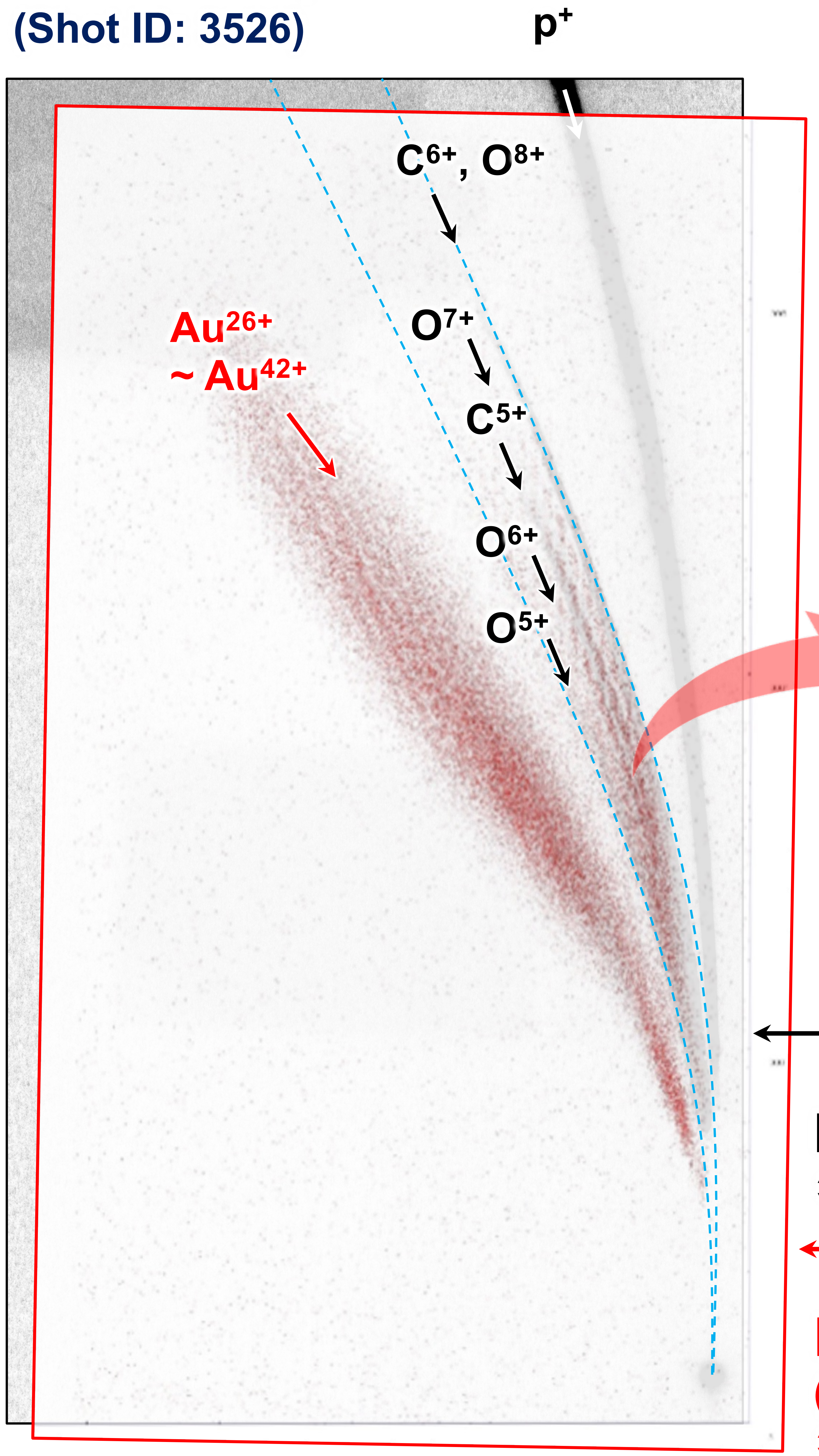




In TPS the same displacement is the same energy if the same ion species.

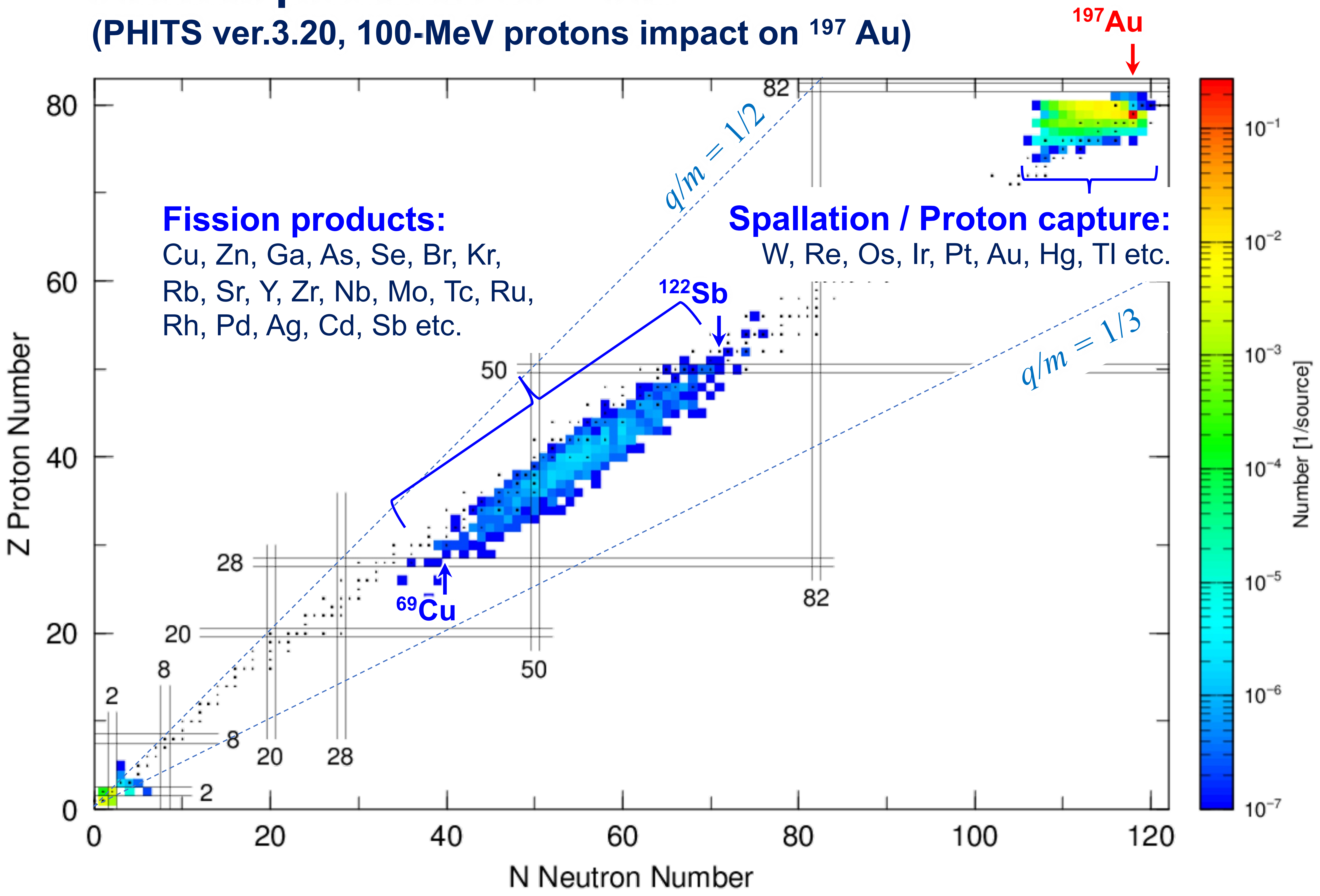
Thomson parabola result

(Shot ID: 3526)



Fission products of ^{197}Au

(PHITS ver.3.20, 100-MeV protons impact on ^{197} Au)



IP image

➲ Signal for all charged particles

Nuclear track detector

(Kapton film)

➲ Etch pit for Z > 13 (Al)

From Y. Abe

Pure graphene shot

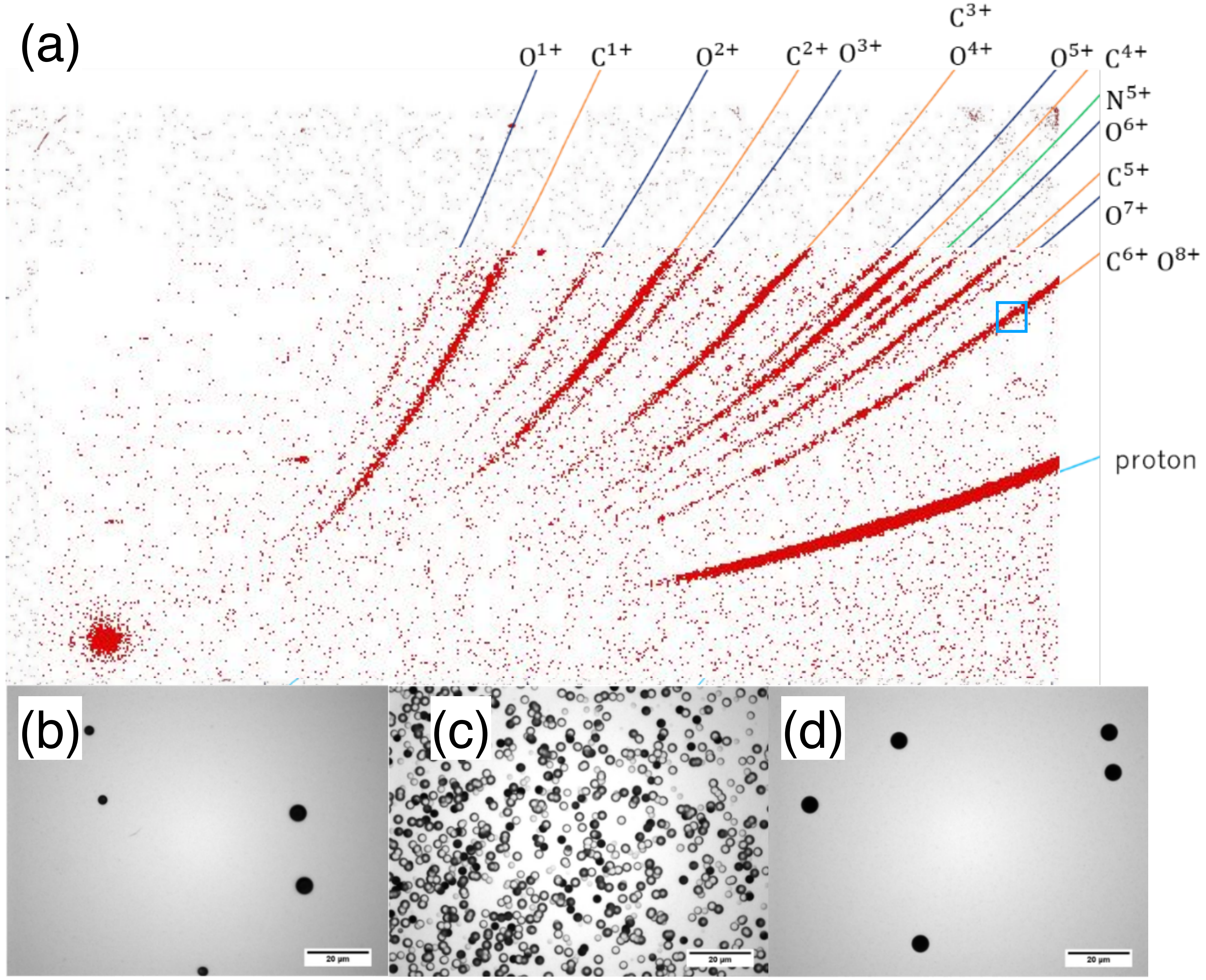
(a) Revisited CR-39 in TPS

(b) On *q*/*m* = 1/2, there are smaller pits.

(c) The lowest energy protons with this TPS, i.e., the largest pit size.

(d) Carbon pit from calibration experiment.

- Larger than proton and smaller than carbon with *q*/*m* = 1/2
- D or He?
- Carbon spallation



Particle Acceleration by Supernova Shocks and Spallogenic Nucleosynthesis of Light Elements

Vincent Tatischeff[1] and Stefano Gabici[2]

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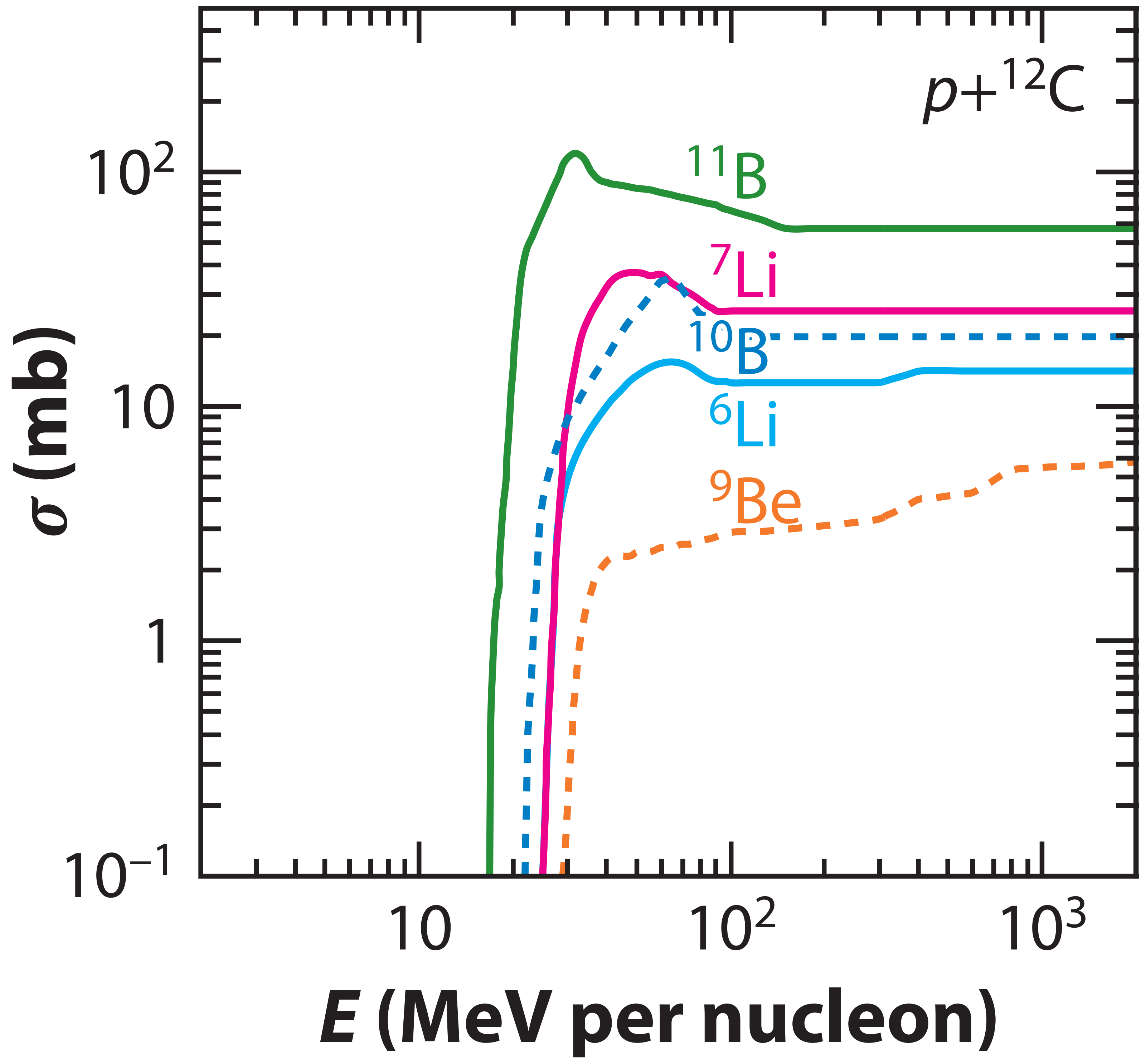


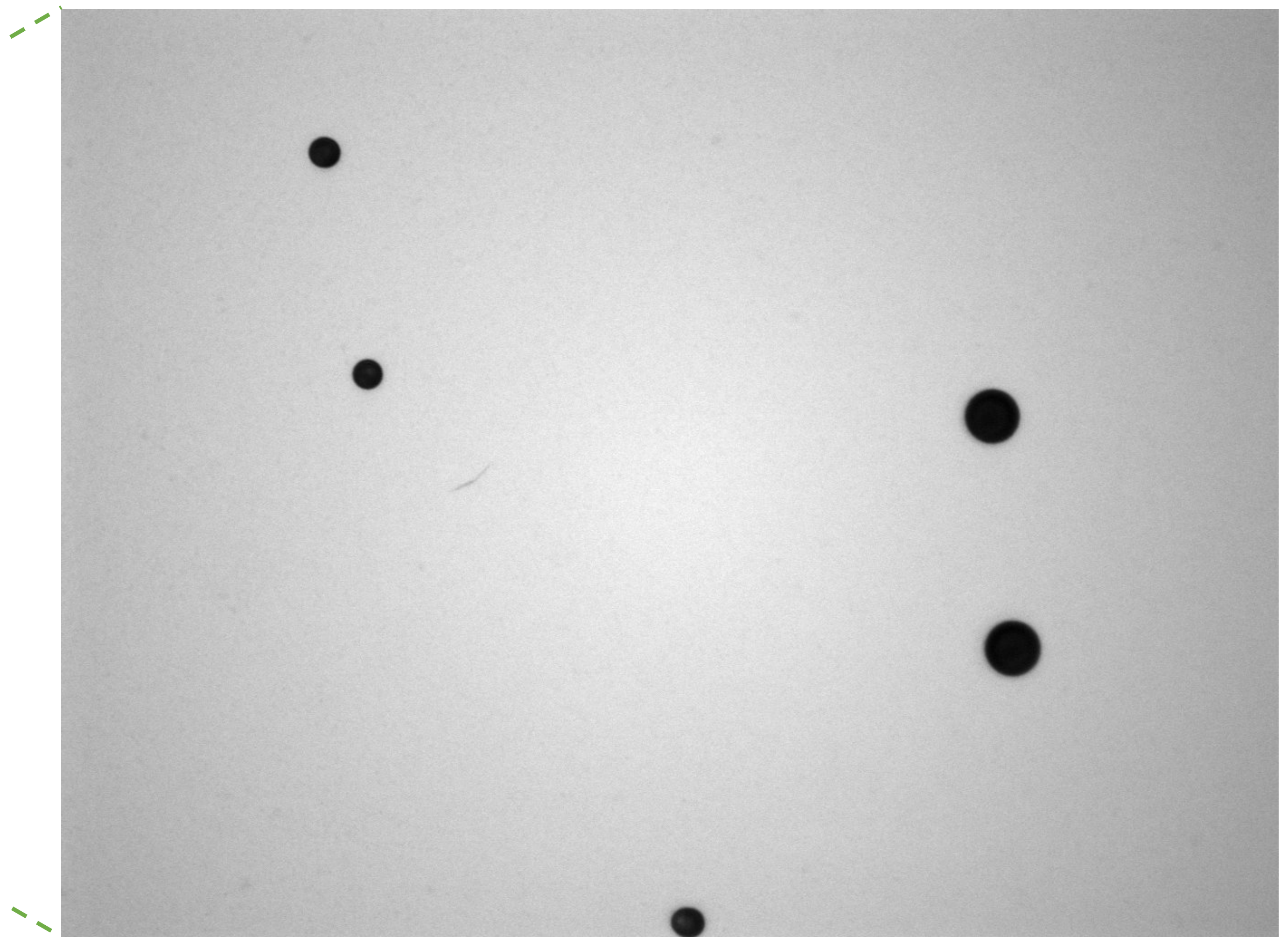
# of spallations

$$RDS\Delta t = \sigma n_C n_p v_p D S \Delta t \sim 6\times 10^4$$
$$\sigma = 100\mathrm{mb} = 10^{-25}\mathrm{cm}^{-2}$$
$$n_C \sim n_p = 10^{23}\mathrm{cm}^{-3}$$
$$v_p = 0.1c = 3\times 10^9\mathrm{cm/s}$$
$$D = 8/3\ \mathrm{nm}$$
$$S = \pi(50\mu\mathrm{m})^2$$
$$\Delta t = 1.5\mathrm{ps}$$

# of accelerated carbons

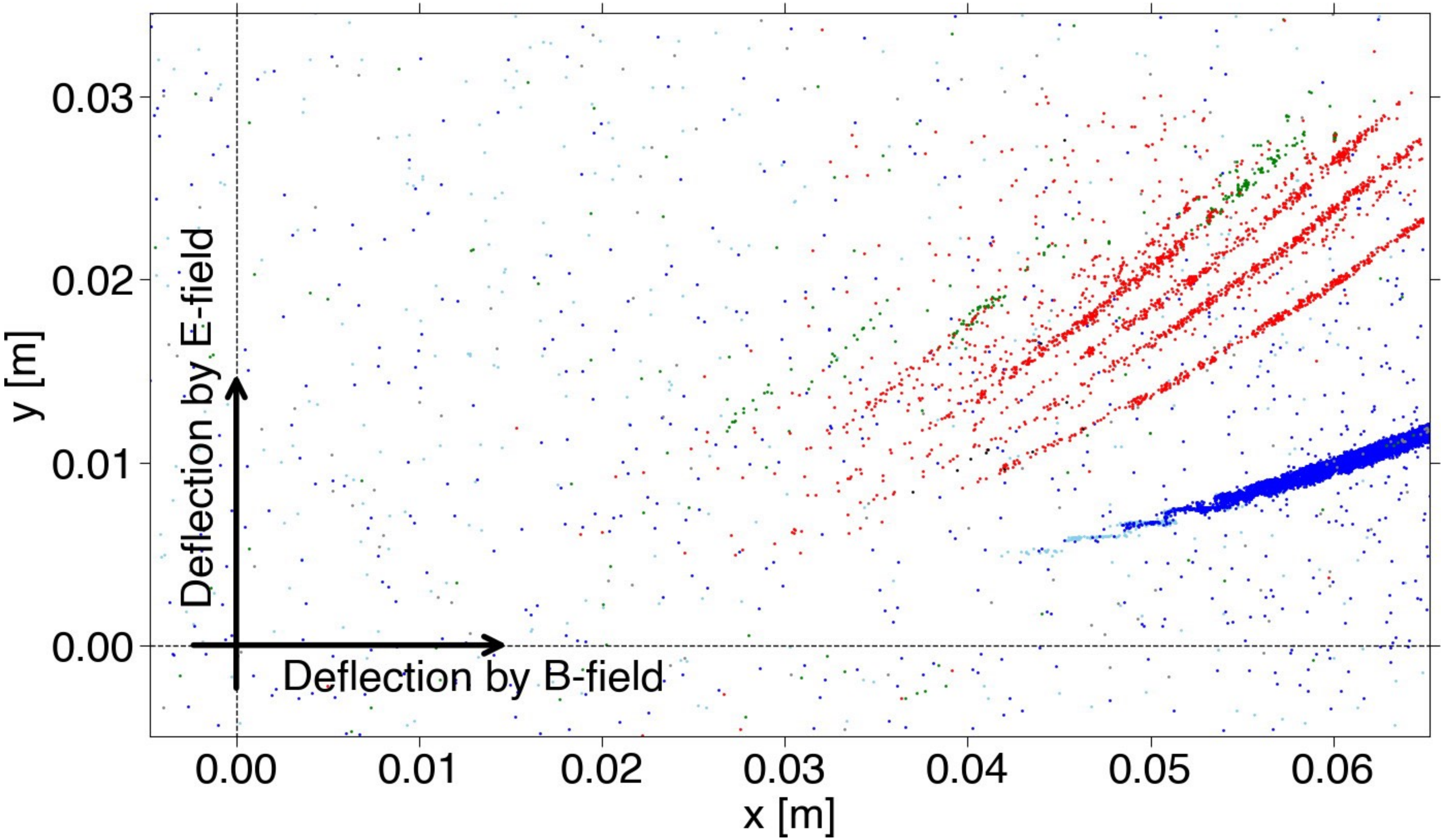
$$n_C D S \sim 3\times 10^{11}$$

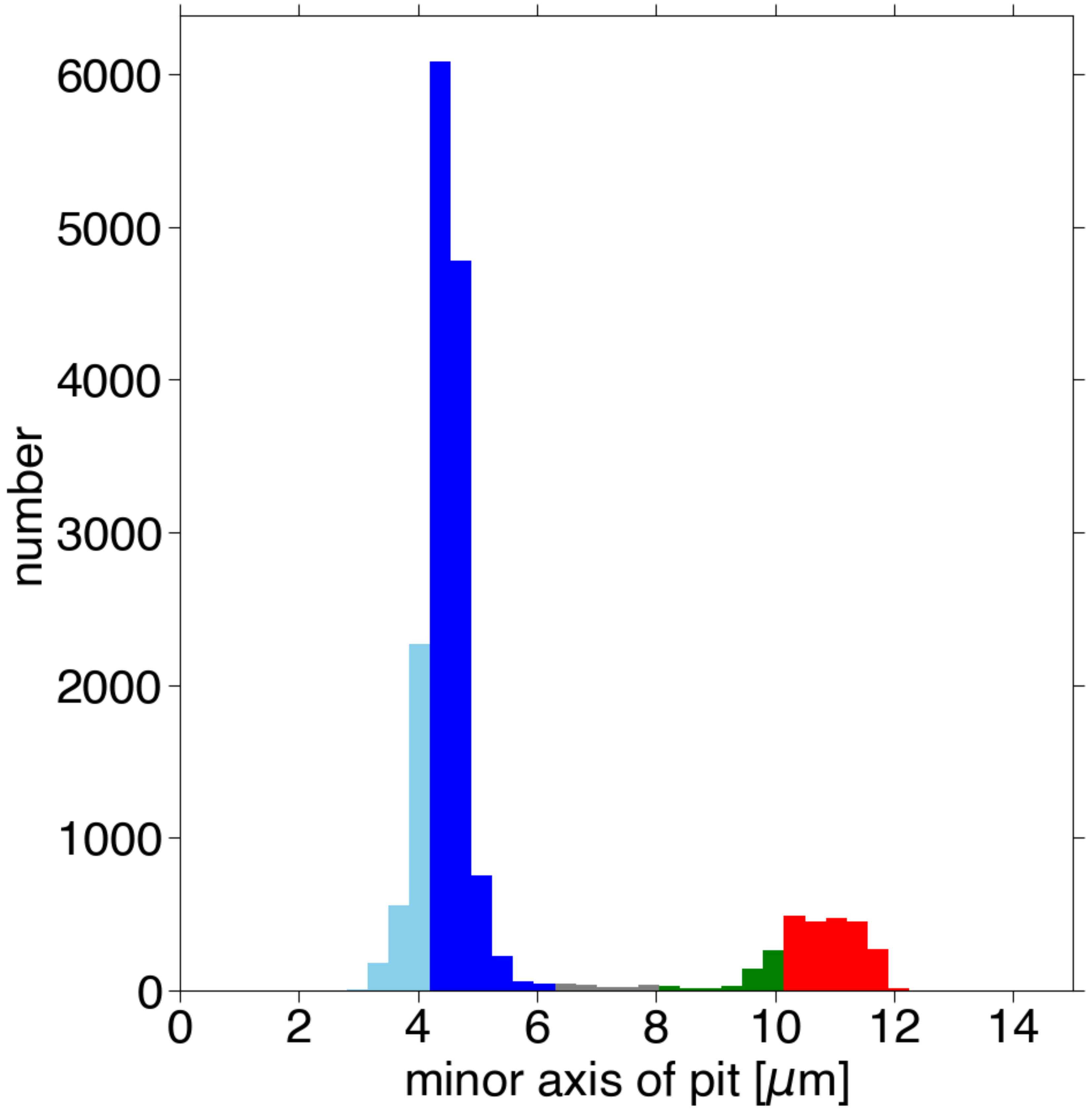
Our data show
# of D or alpha ~ # of carbons



Assuming a most optimistic condition, there will be one reaction out of all the carbons we measured.

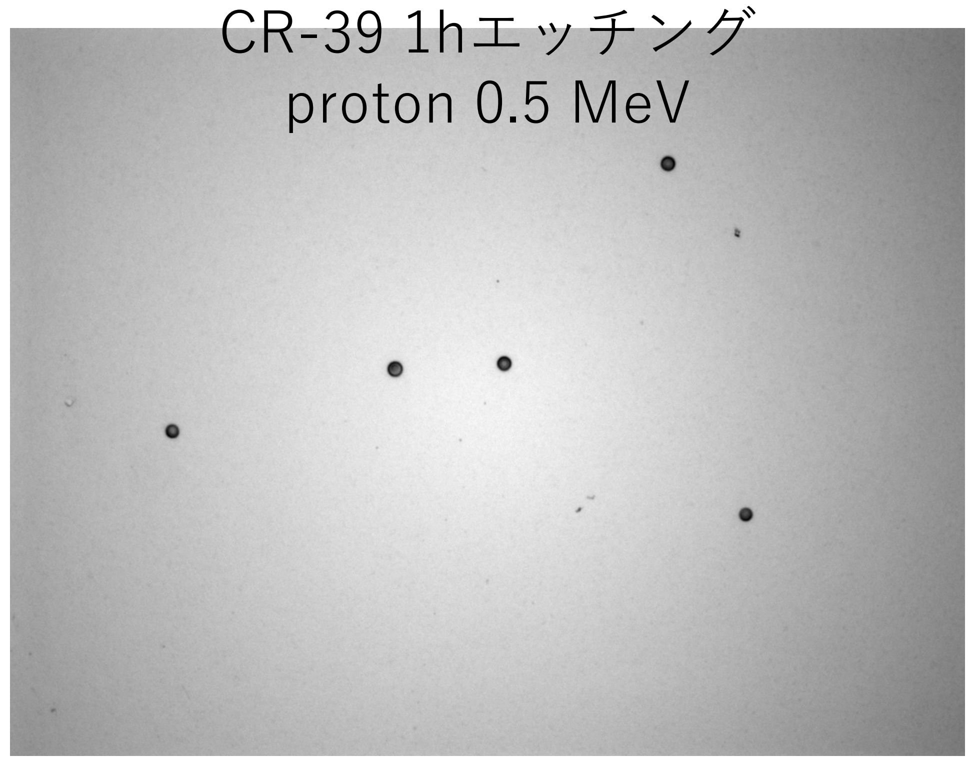
Model experiment of cosmic ray spallation



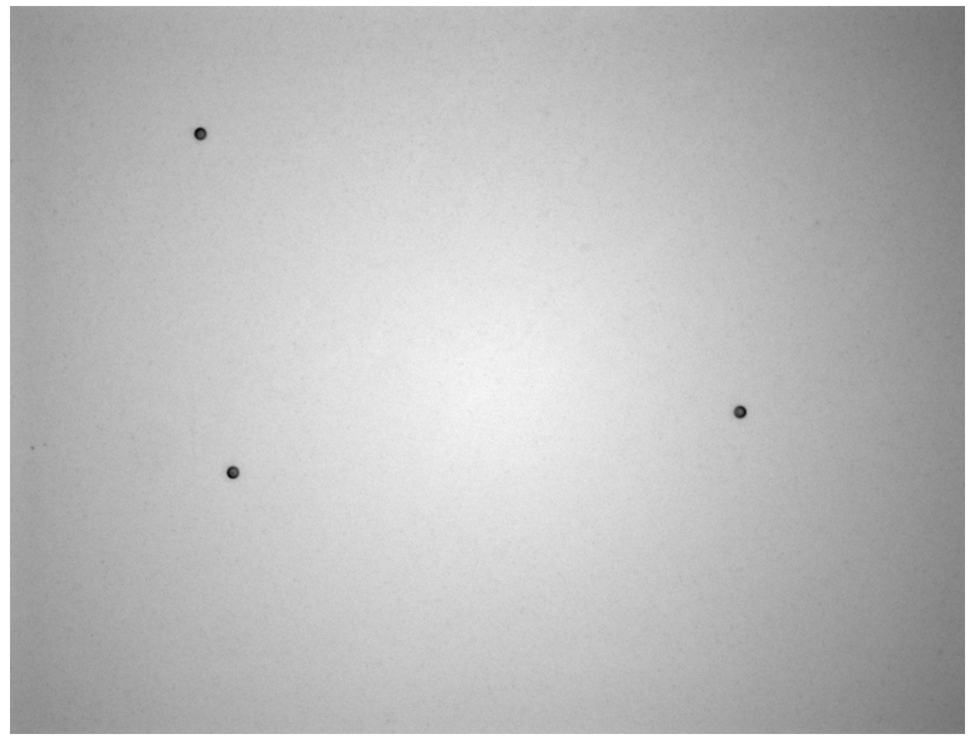


H calibration with known energies from conventional accelerator

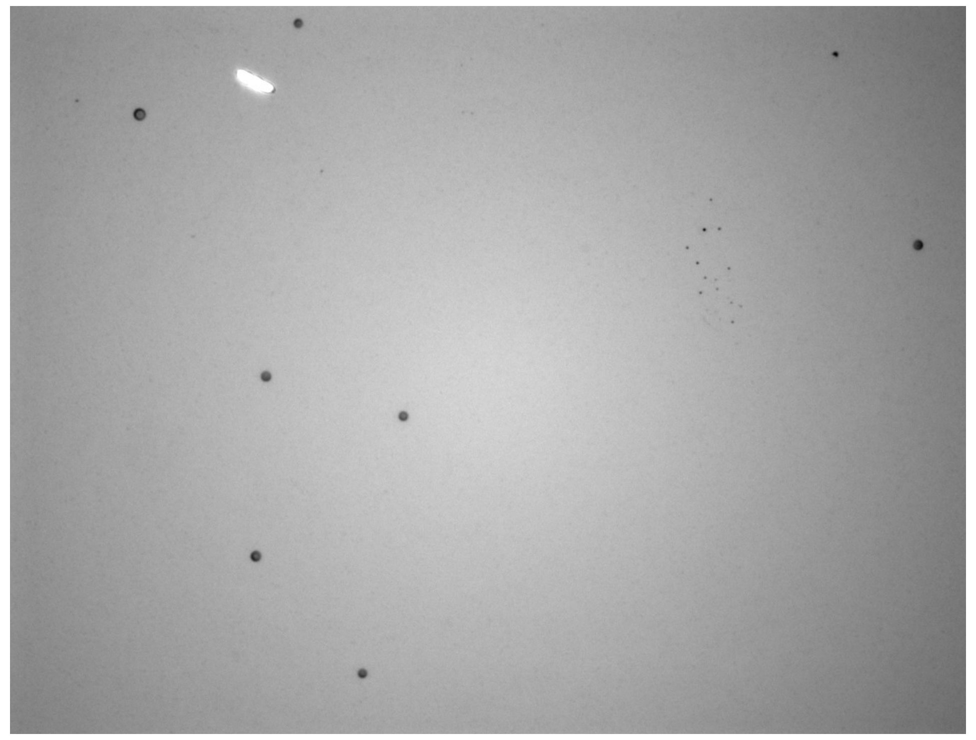
HIMAC 2018
CR-39 1hエッチング
proton 0.5 MeV

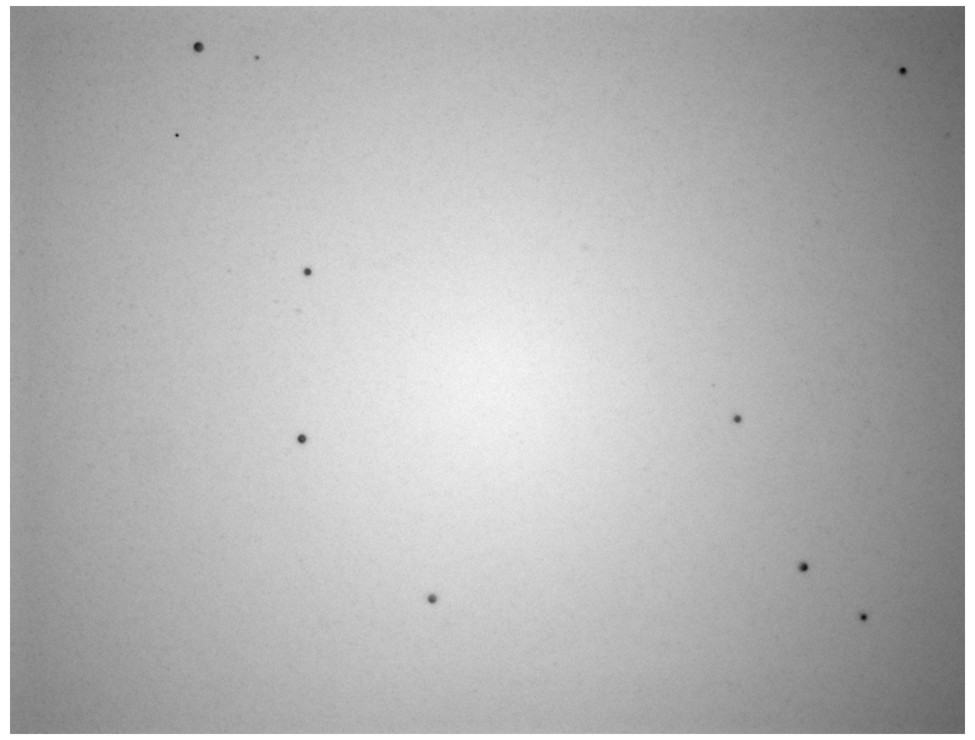


1 MeV

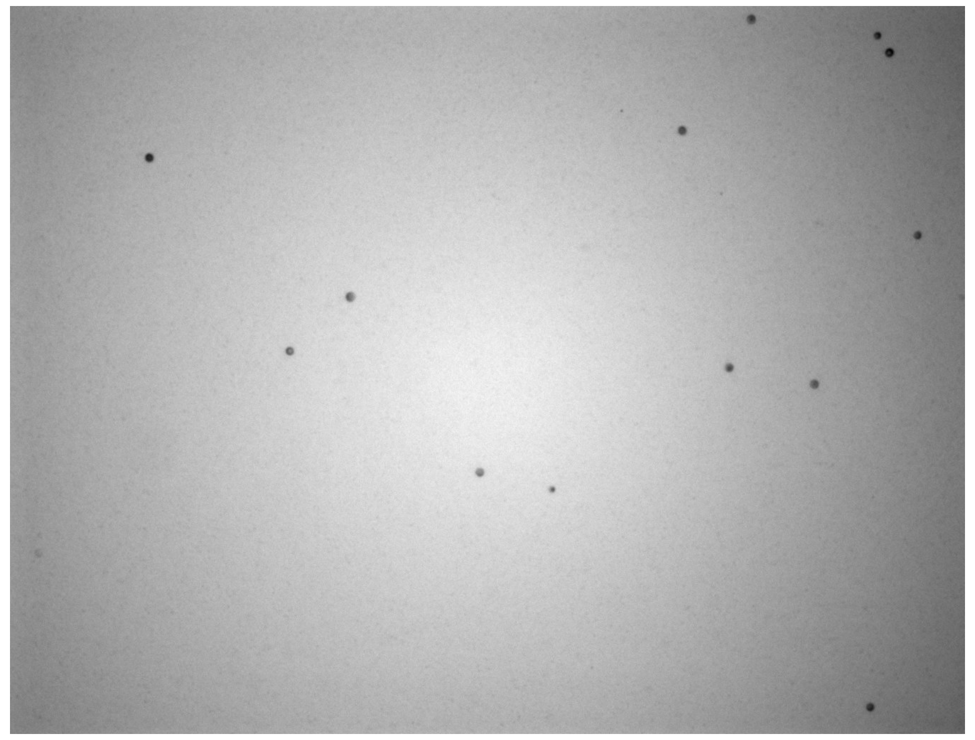


2 MeV

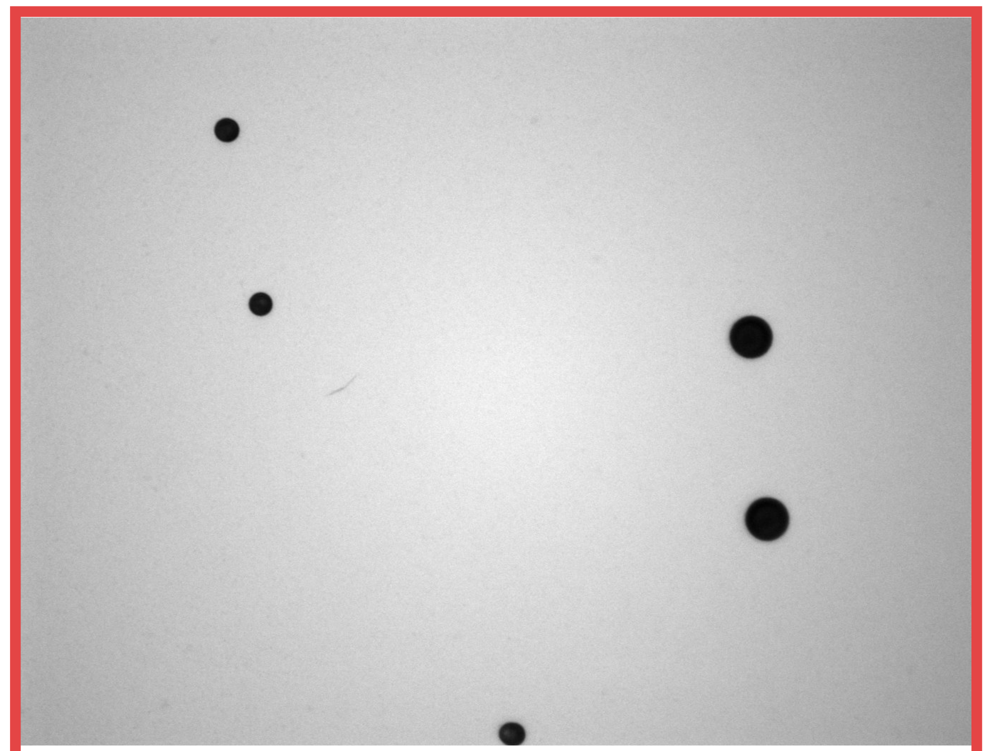




3 MeV



4 MeV

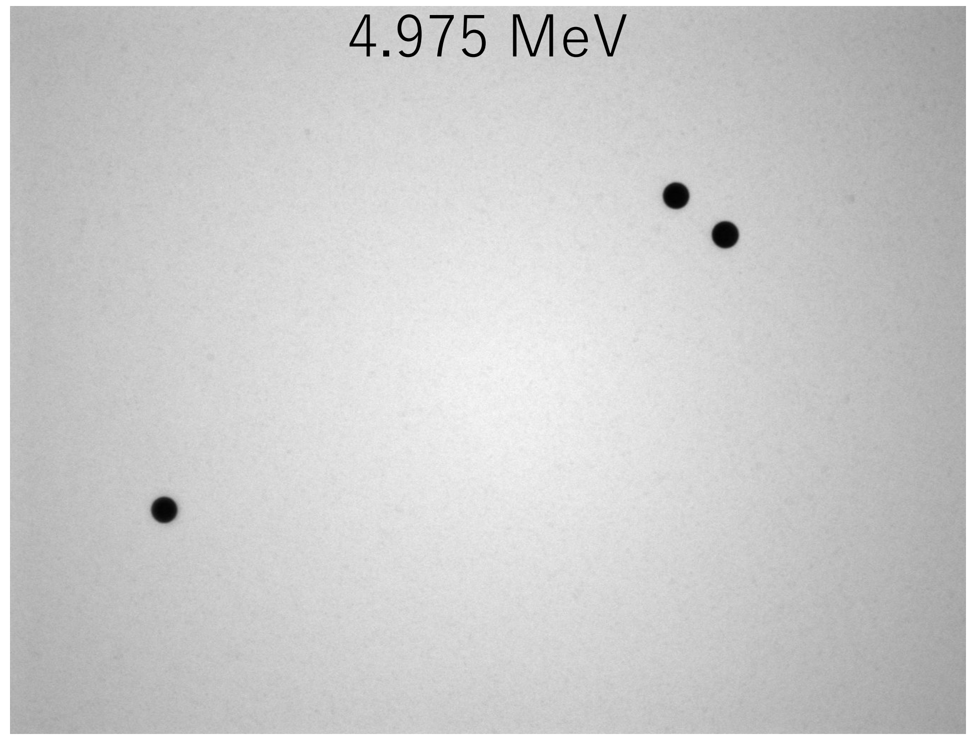


CR-39 LFEX 4LLSG TP½ライン

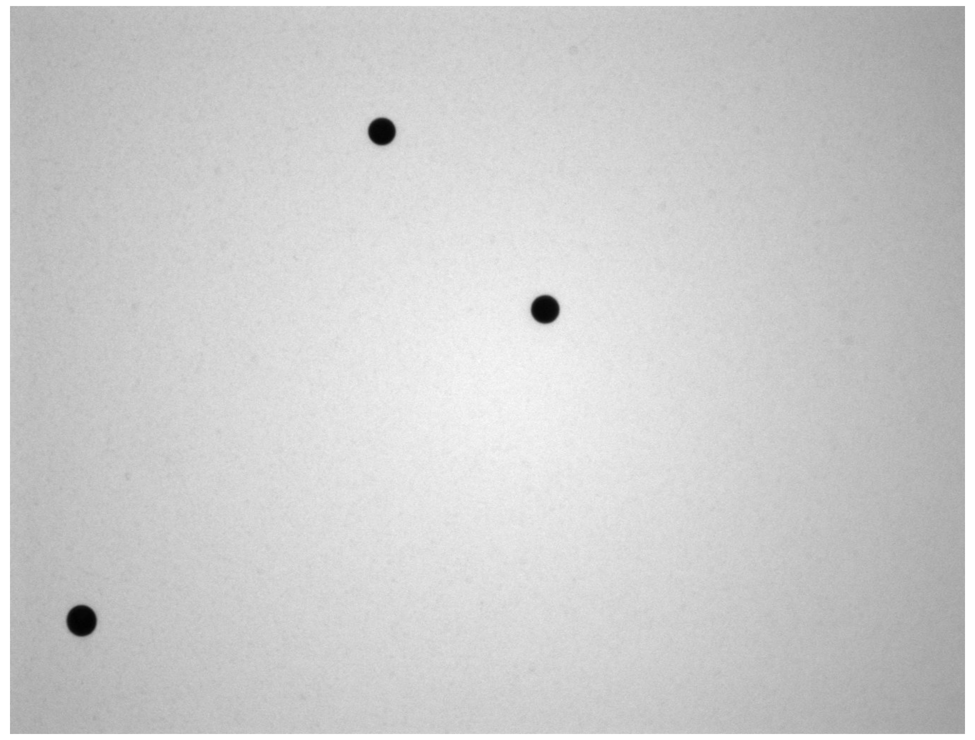
The smaller pits are obviously larger than H.

He calibration with known energies from conventional accelerator

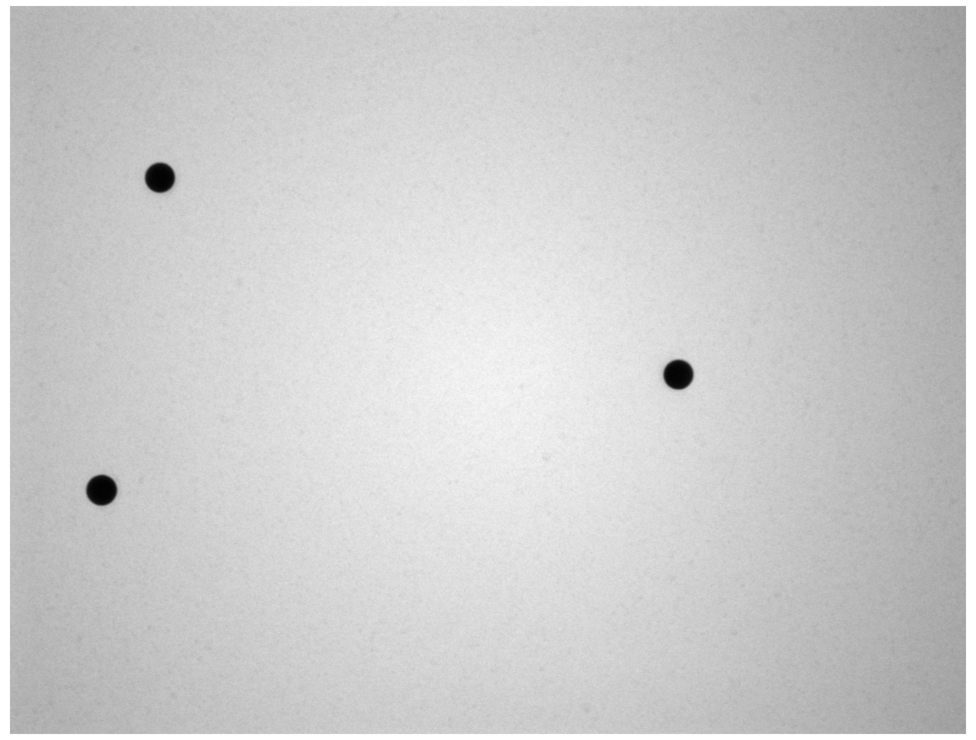
CR-39 He 1hエッチング
4.975 MeV

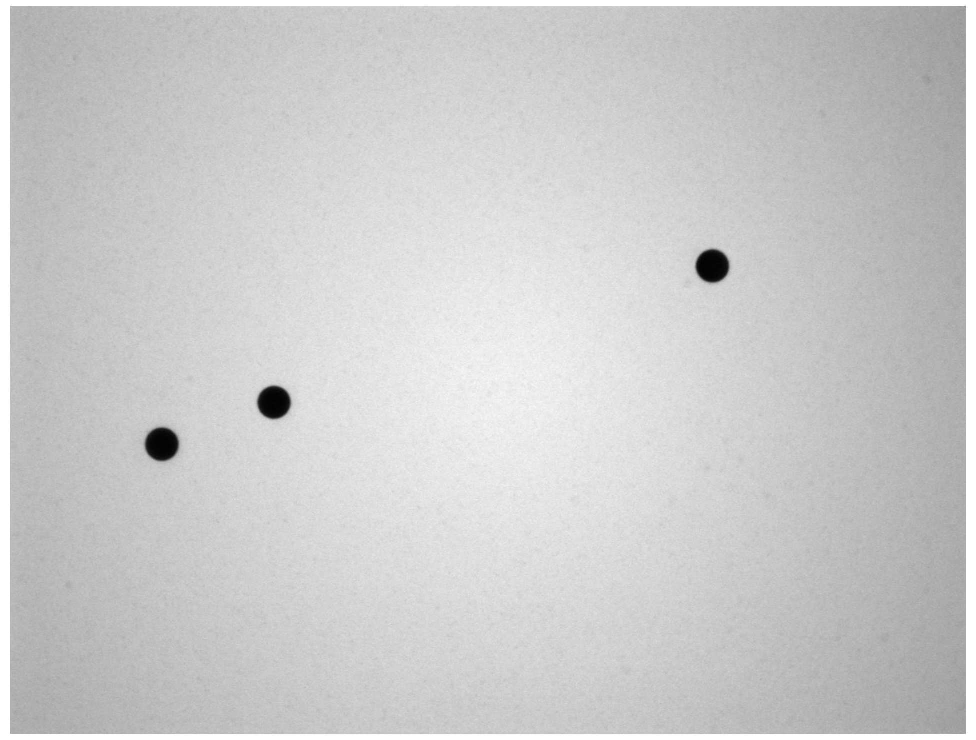


3.957 MeV

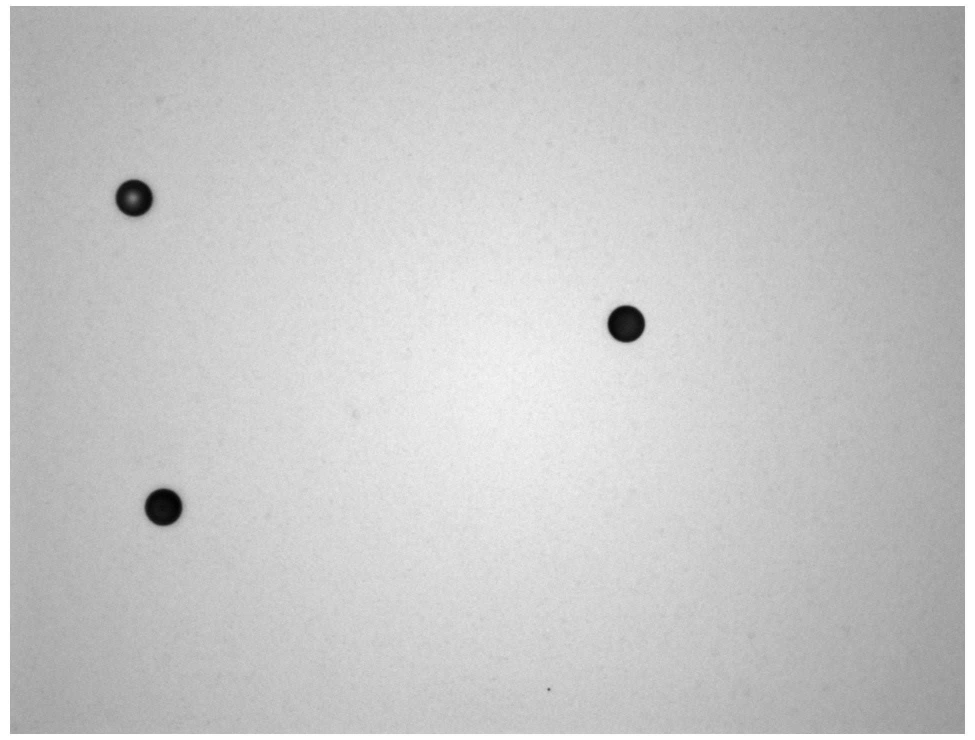


3.002 MeV

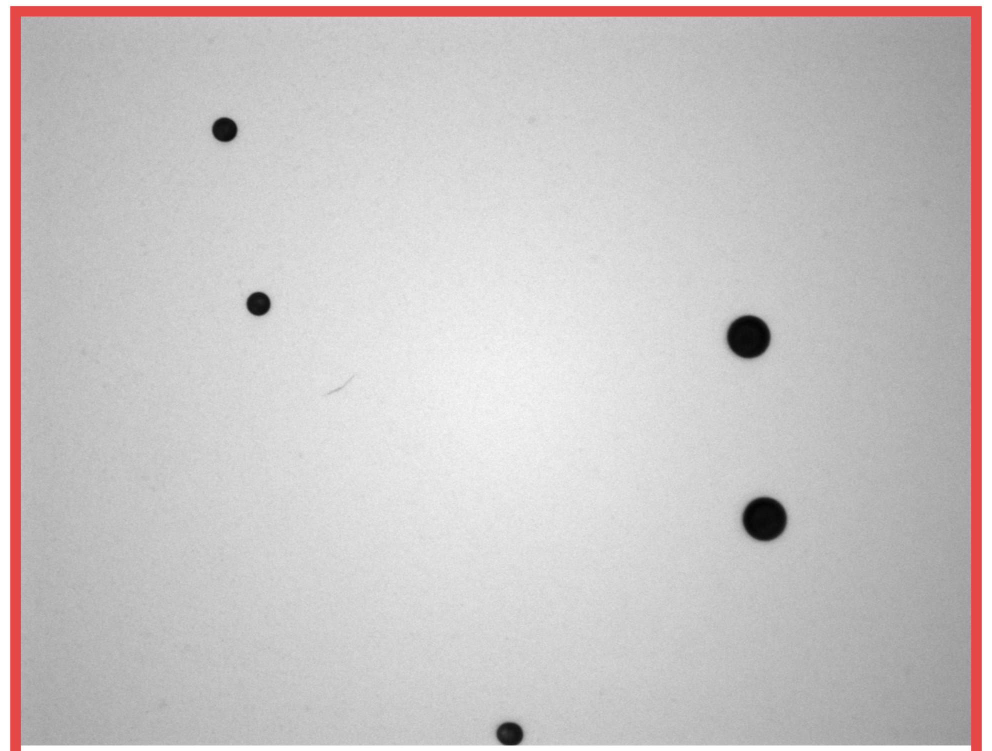




2.065 MeV



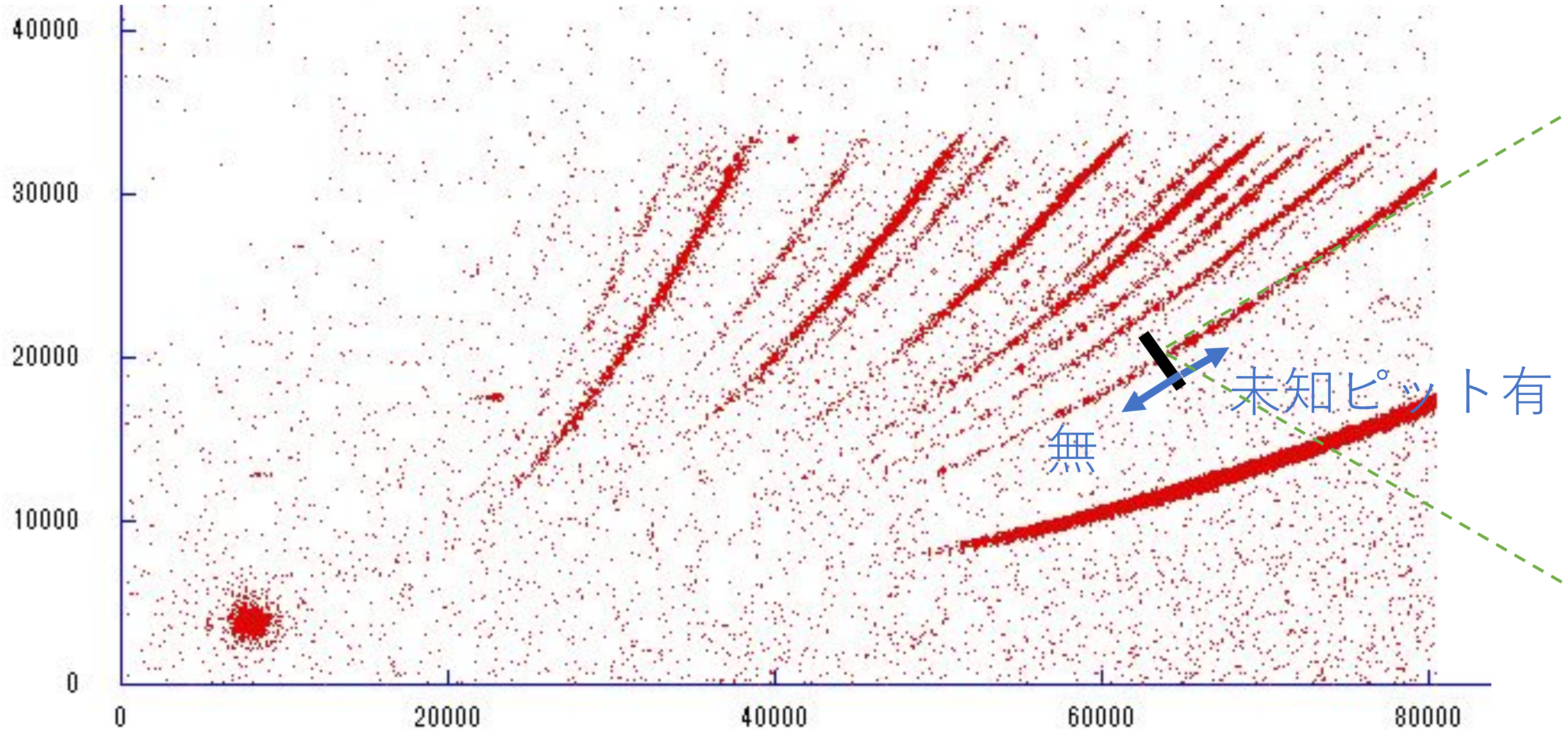
1.125 MeV

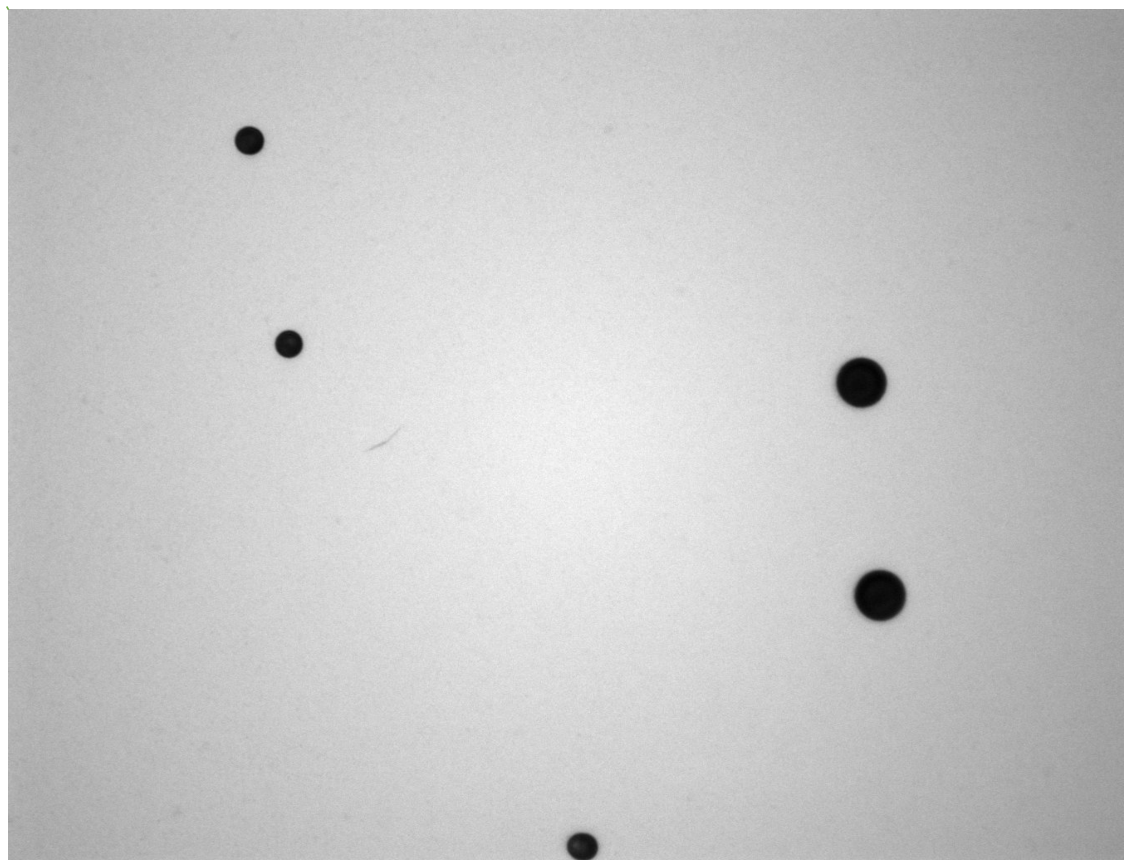


CR-39 LFEX 4LLSG TP½ライン

If the smaller pits are He, it should be higher than 5 MeV.

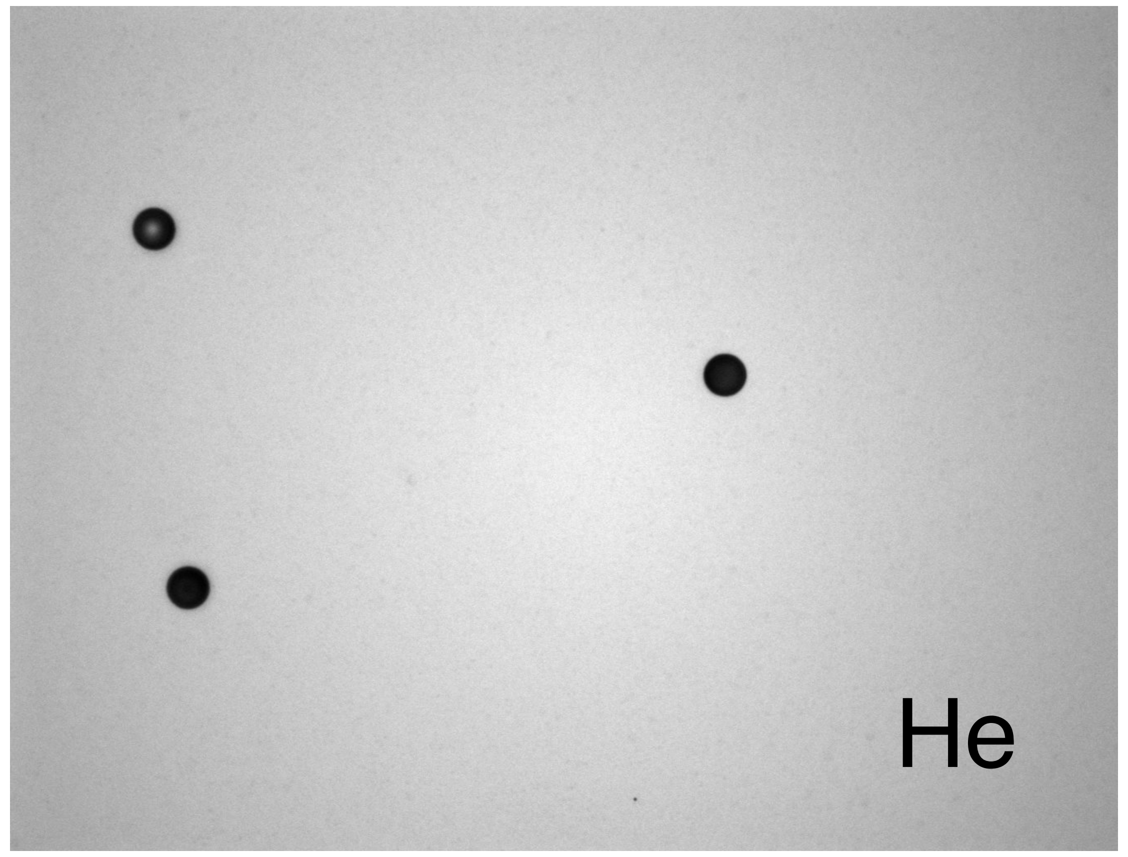
He calibration with known energies from conventional accelerator





If the smaller pits are He, the energy is ~ 1.2 MeV from TPS analysis, which has to be much larger pit size from the calibration.

Remaining possibility is D?



1.125 MeV

Summary

- We have been exploring relativistic laboratory astrophysics relevant to the origins of cosmic rays.

- As the first step, we have been investigating laser-driven ion acceleration using atomic thin large-area suspended graphene.

- We have realized energetic protons > 100 MeV by optimizing the acceleration conditions.

- We have observed evidence of extremely efficient nuclear spallations by irradiating ultra-thin targets with intense lasers.

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Y.C. Chen[4], Y.L. Liu[5], S. Isayama[6], N. Saura[7], S. Benkadda[7], **M. Kanasaki**[8], **Y. Fukuda**[9], T. Hayakawa[9], C.M. Chu[10], K.T. Wu[10], S.H. Chen[10], **A. Tokiyasu**[11], **H. Kohri**[12], K. H. Sudhan[13], N. Ohnishi[13],
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Core-to-Core Program

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