# Exploring new frontiers in laser-driven ion acceleration with the aid of artificial intelligence

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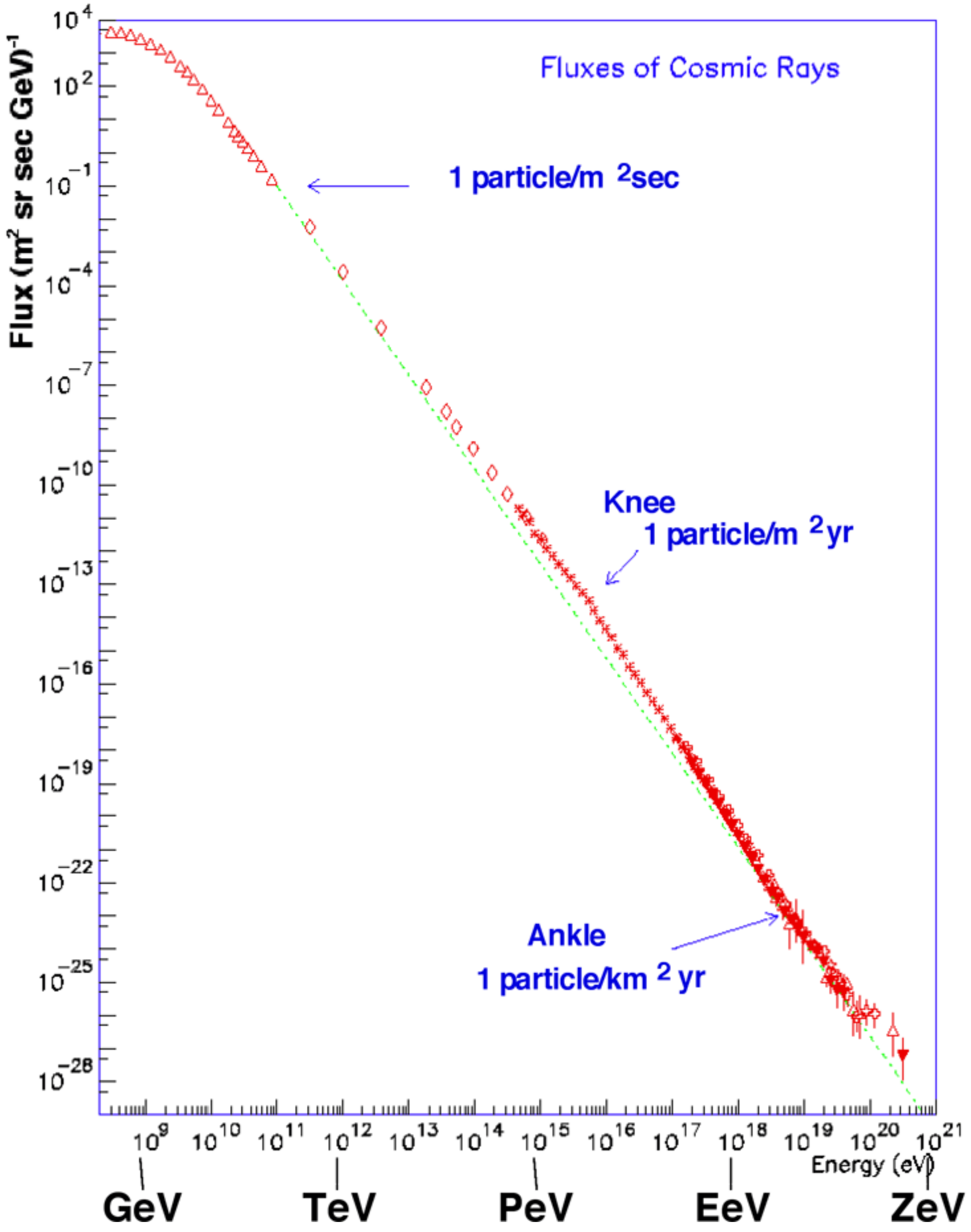
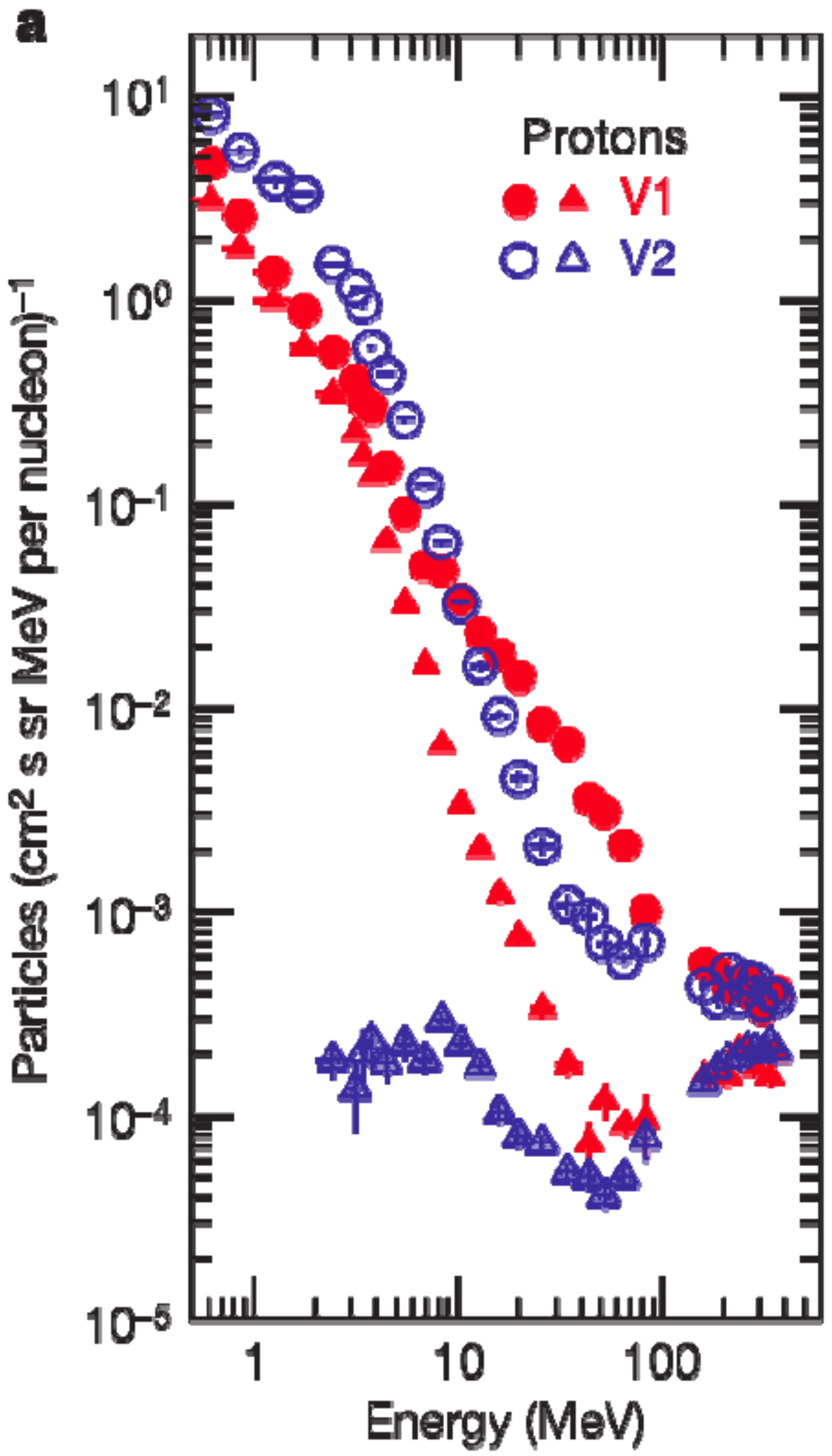
# Nonthermal Universe

## Cosmic Rays



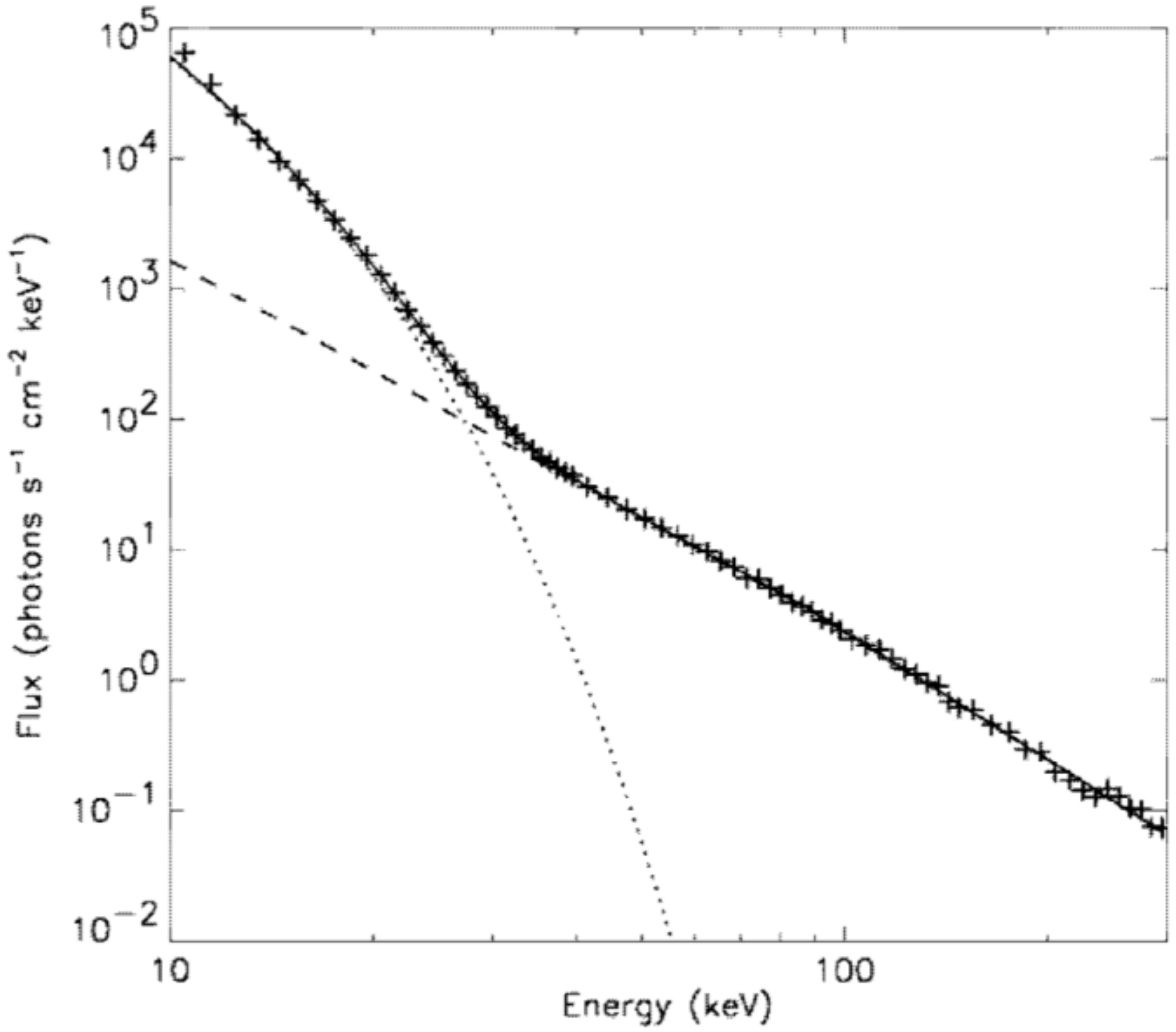

[Nagano & Watson, 2000]

## ACRs




[Stone et al., 2008]

## Solar Flares




[Lin et al., 2003]

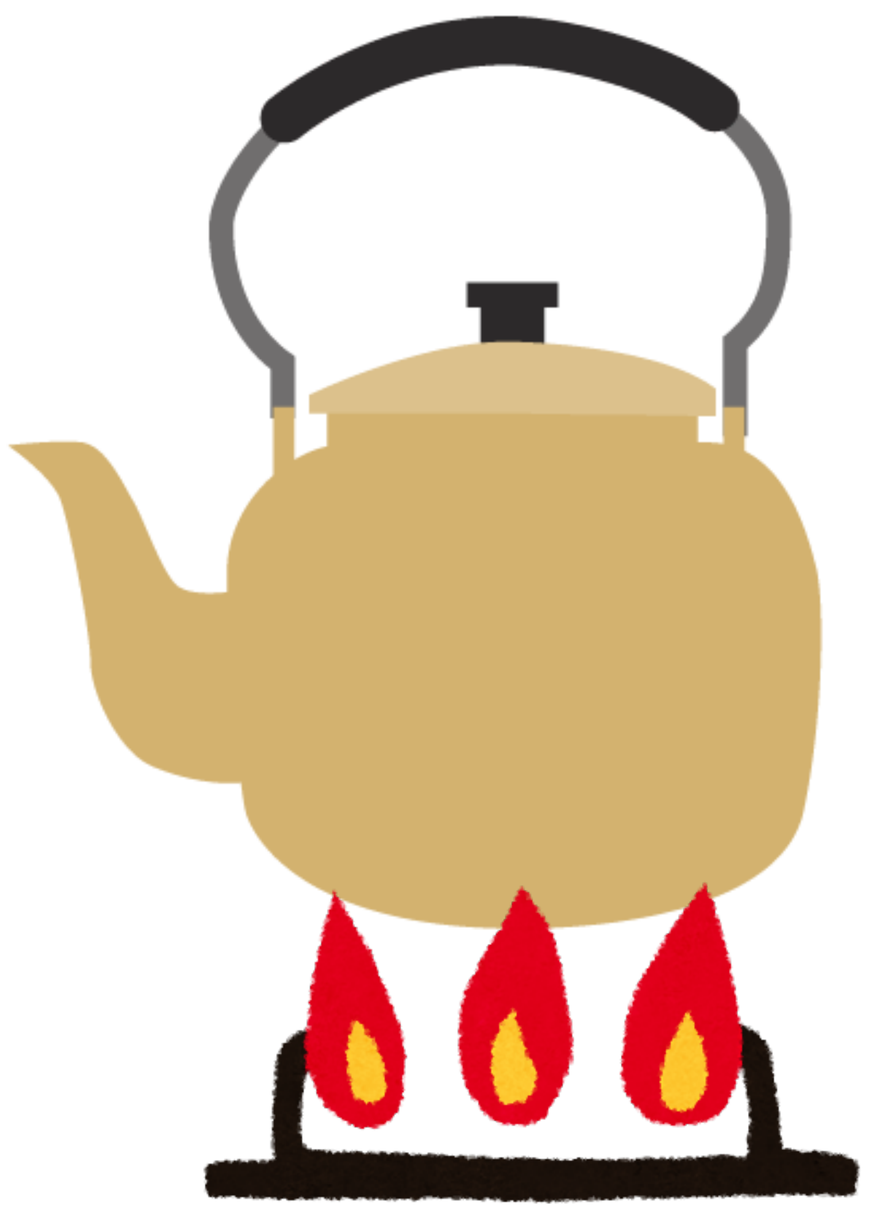
from Hoshino

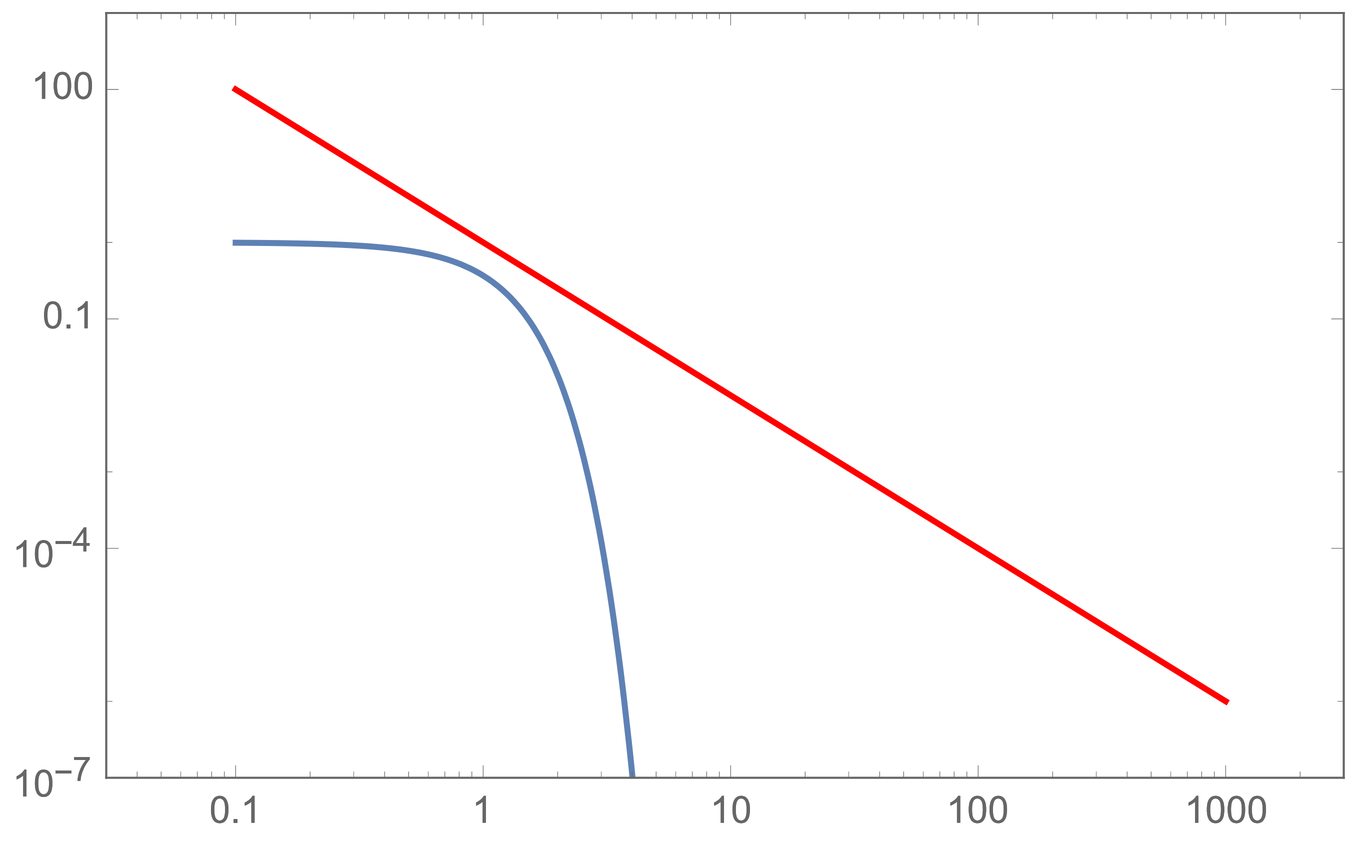
# Non-Thermal process

$T_{water}$

VΛ

$T_{fire}$





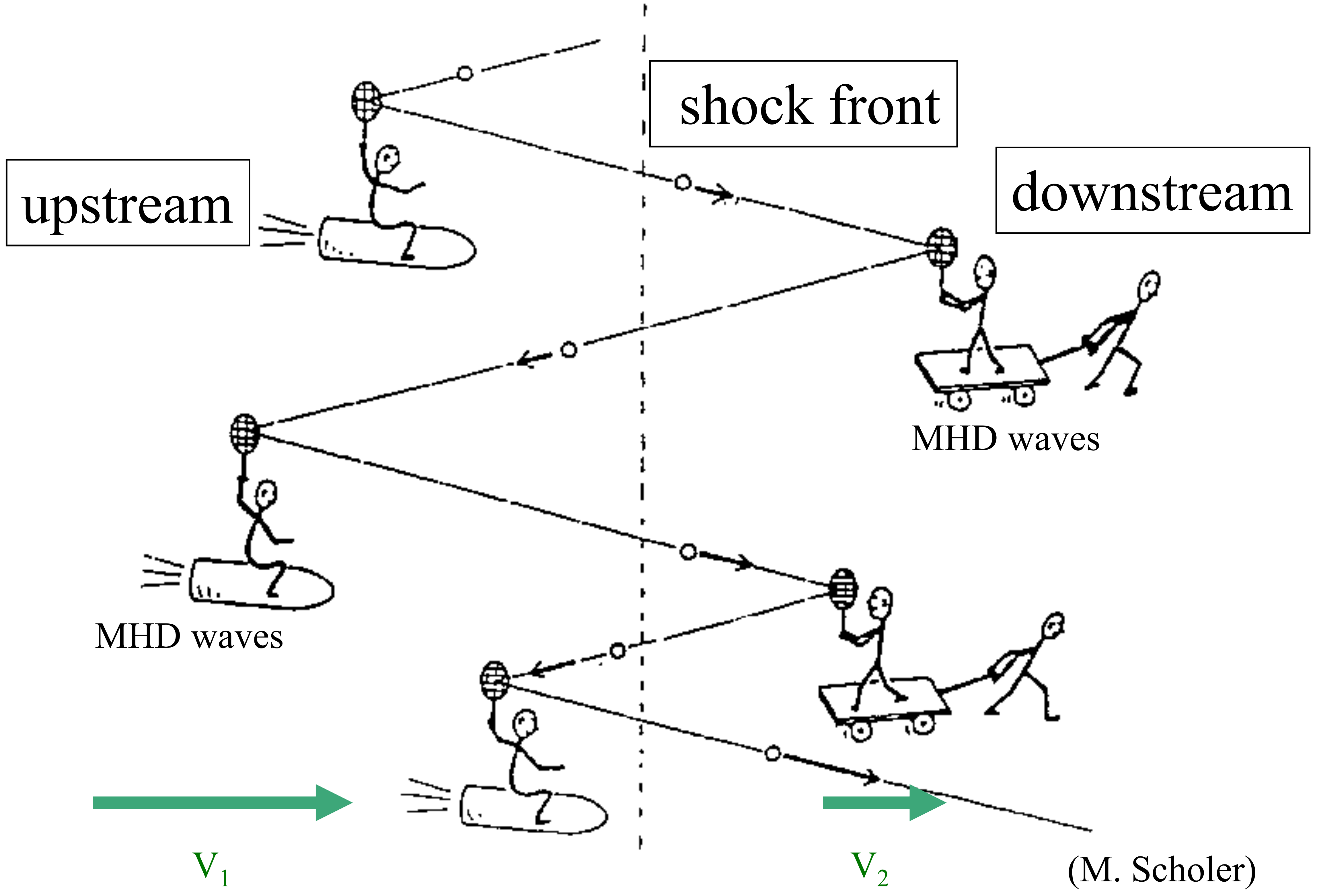

Thermal distribution

Nonthermal distribution

Water never be hotter than fire.

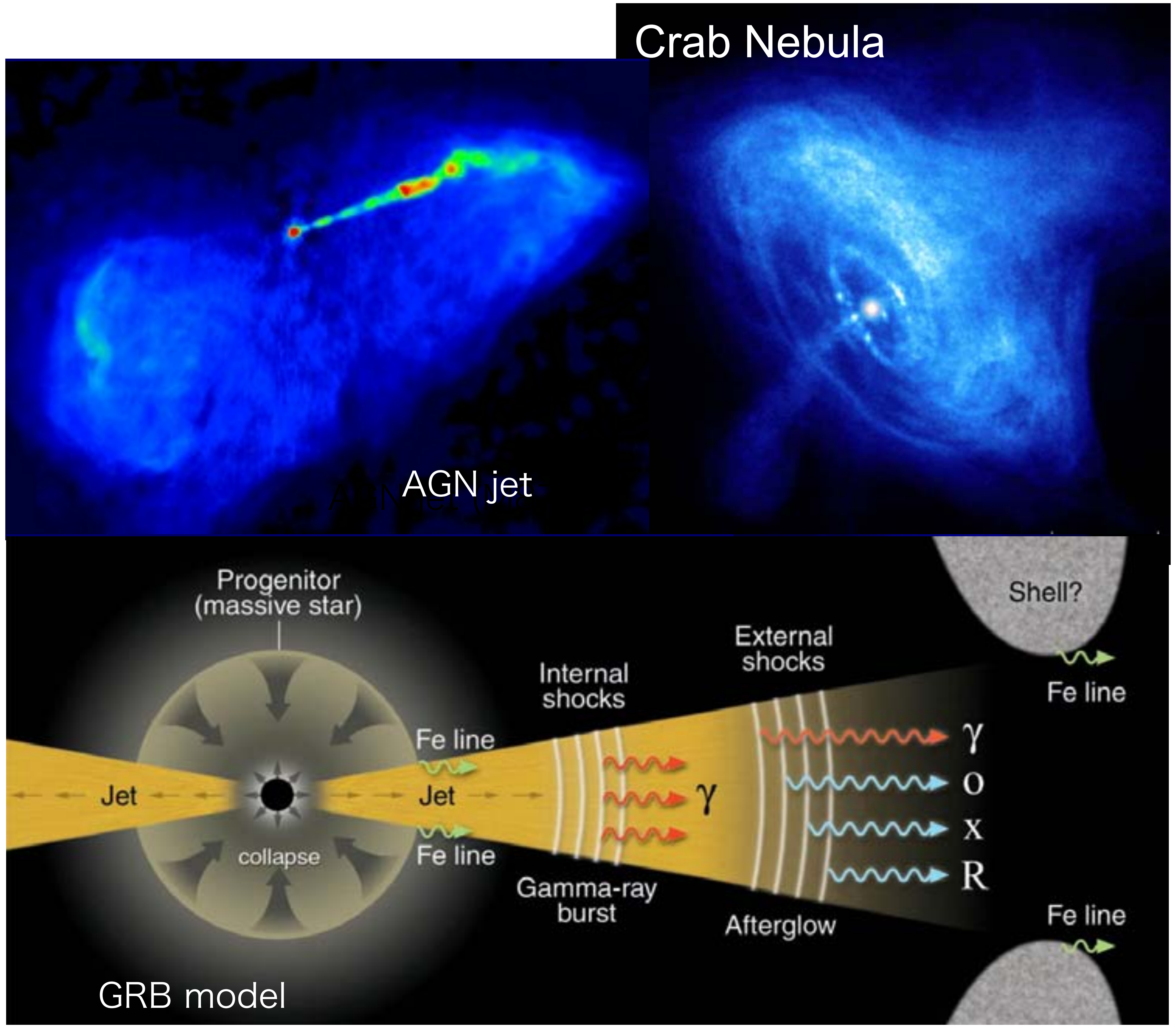
# Diffusive shock acceleration

- Fermi acceleration (1949)
  - cosmic ray acceleration by moving magnetic fields
- Diffusive shock acceleration (DSA), Axford et al. (1977), Bell (1978), Blandford & Ostriker (1978)
  - Fermi acceleration at collisionless shocks
  - Always acceleration due to U1>U2 for one cycle flight
  - High acceleration efficiency ~(U1-U2)/c
  - naturally and universally explains cosmic ray spectra,
    $f(\gamma) \propto \gamma^{-2}$



# 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+ …




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

$\omega_p/\omega_L$: frequency ratio between plasma and light

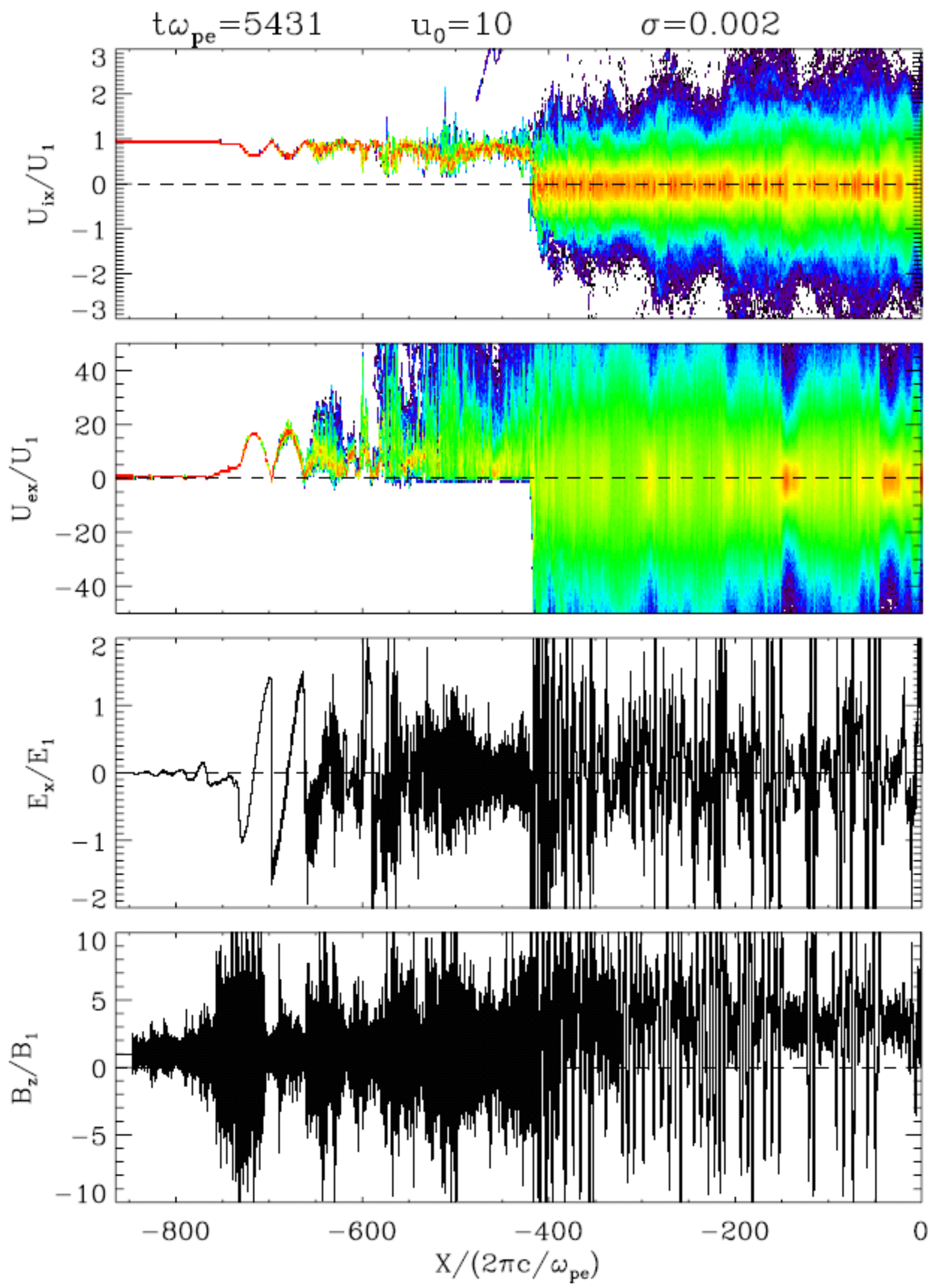
Upstream Downstream

ION

ELECTRON

Electrostatic Waves (Ex), (wakefield)

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

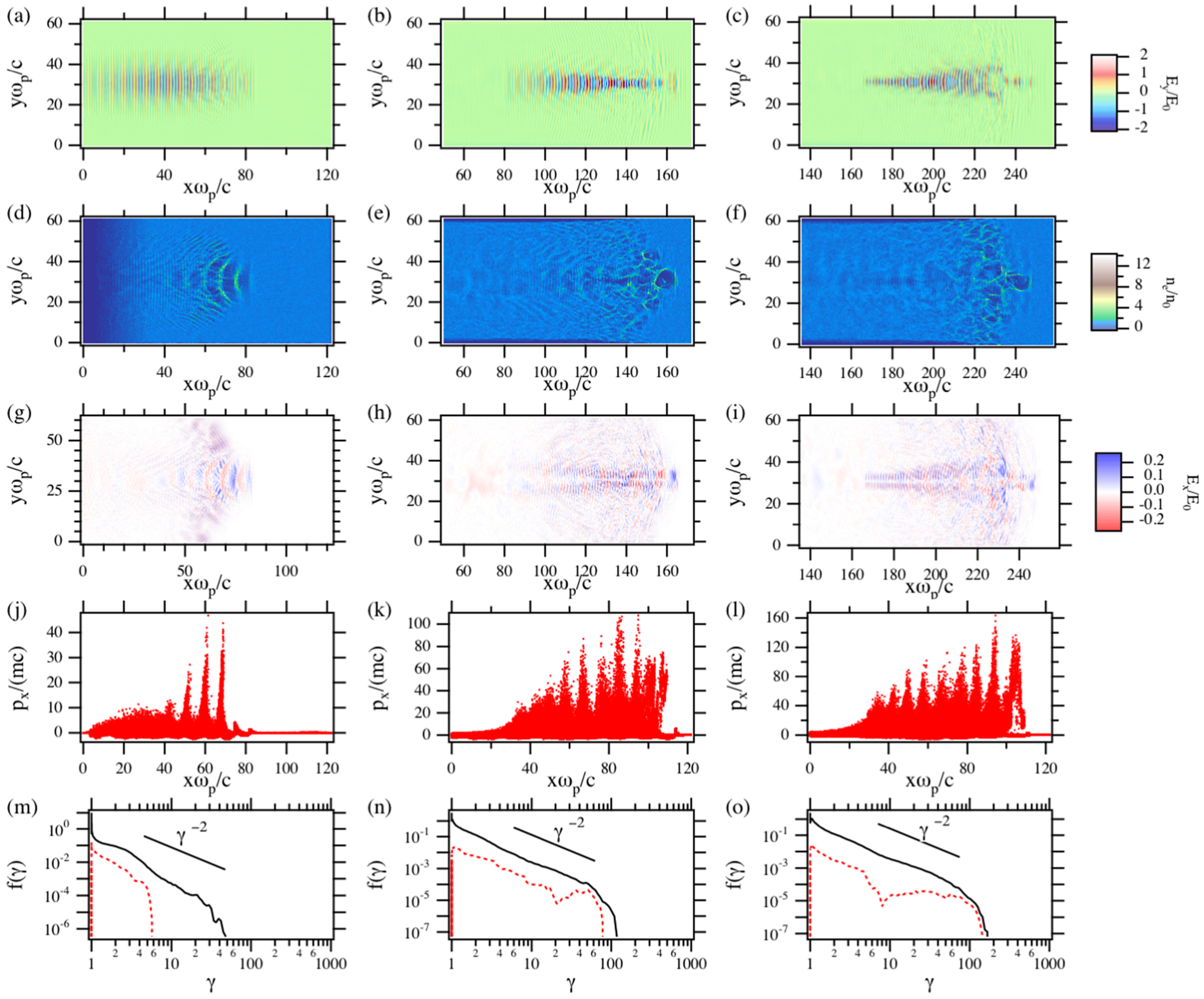



Pulse like structures

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 ~ $\omega_p/\omega_L$
- Independent of pulse shape
- Universal production of power law spectra with an index of ~ -2
- Cyclotron and synchrotron emission free.




Kuramitsu + 2008 ApJL, 2D PIC, shock upstream system

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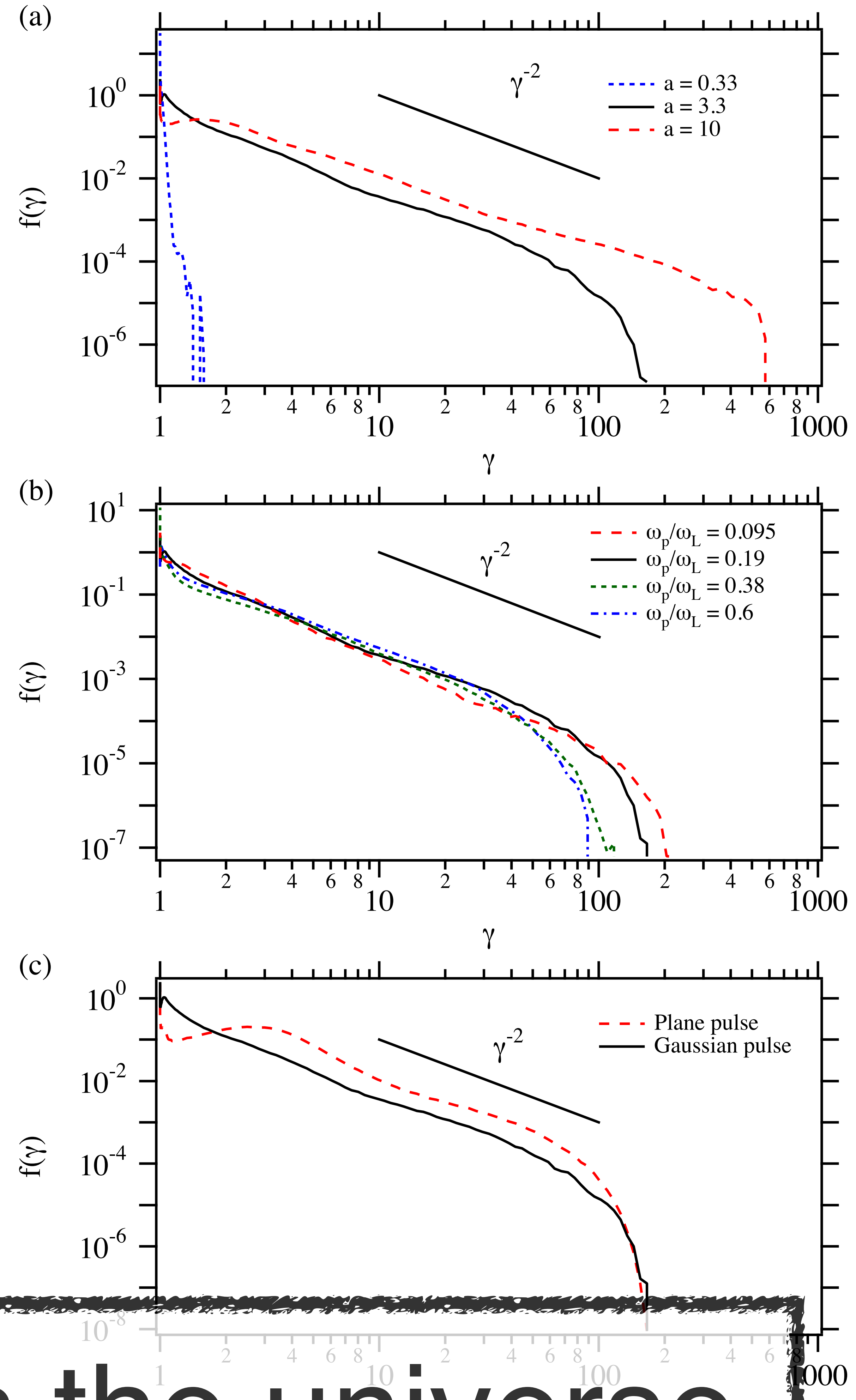



It is impossible to observe this in the universe.

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

# Model experiments of cosmic ray acceleration in laboratories (1)

- Astrophysical situation to be modeled is

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

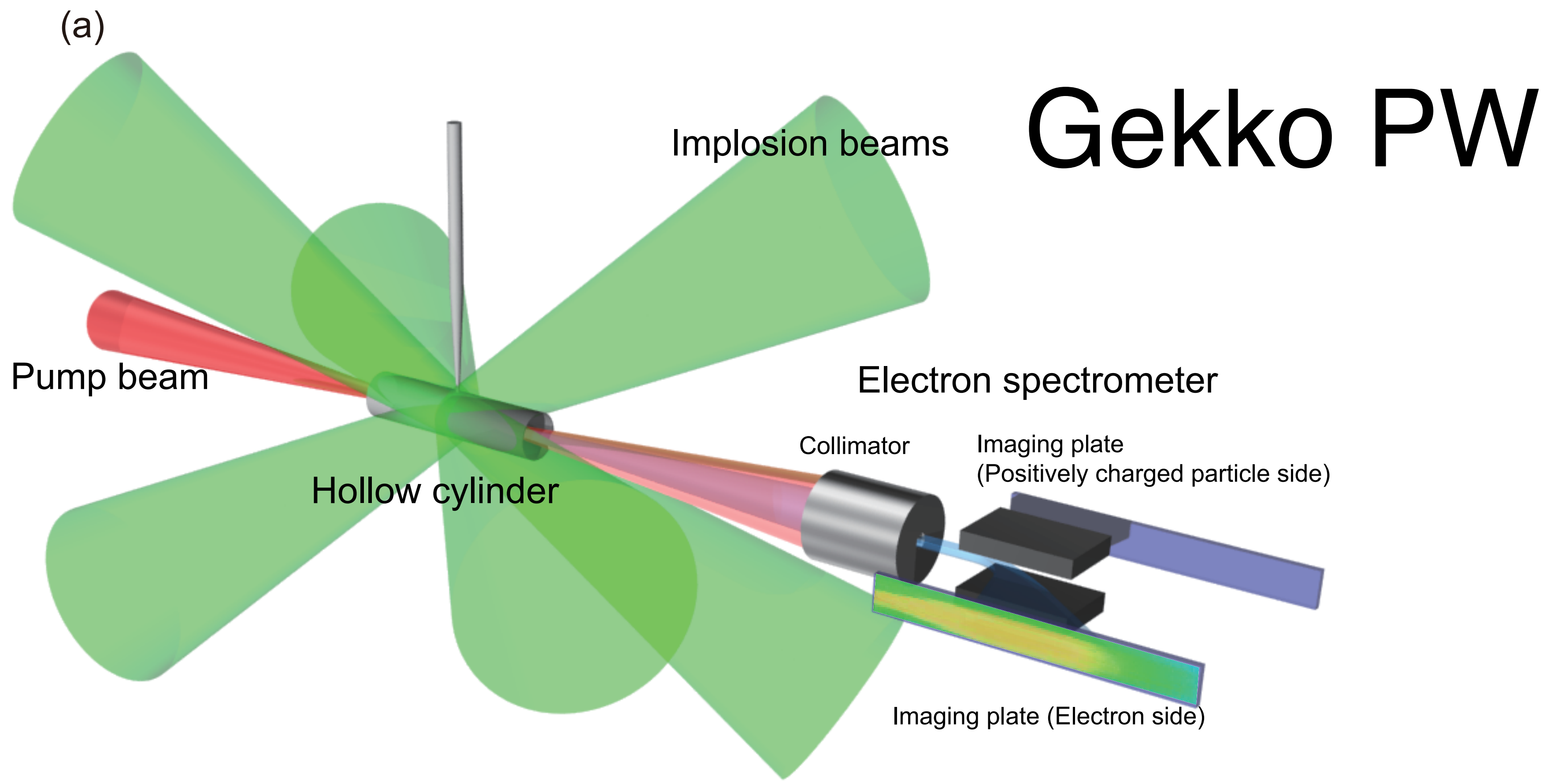
   ➡Gekko PW
   (100 J, 700 fs, $a_0 \sim 1.9$)

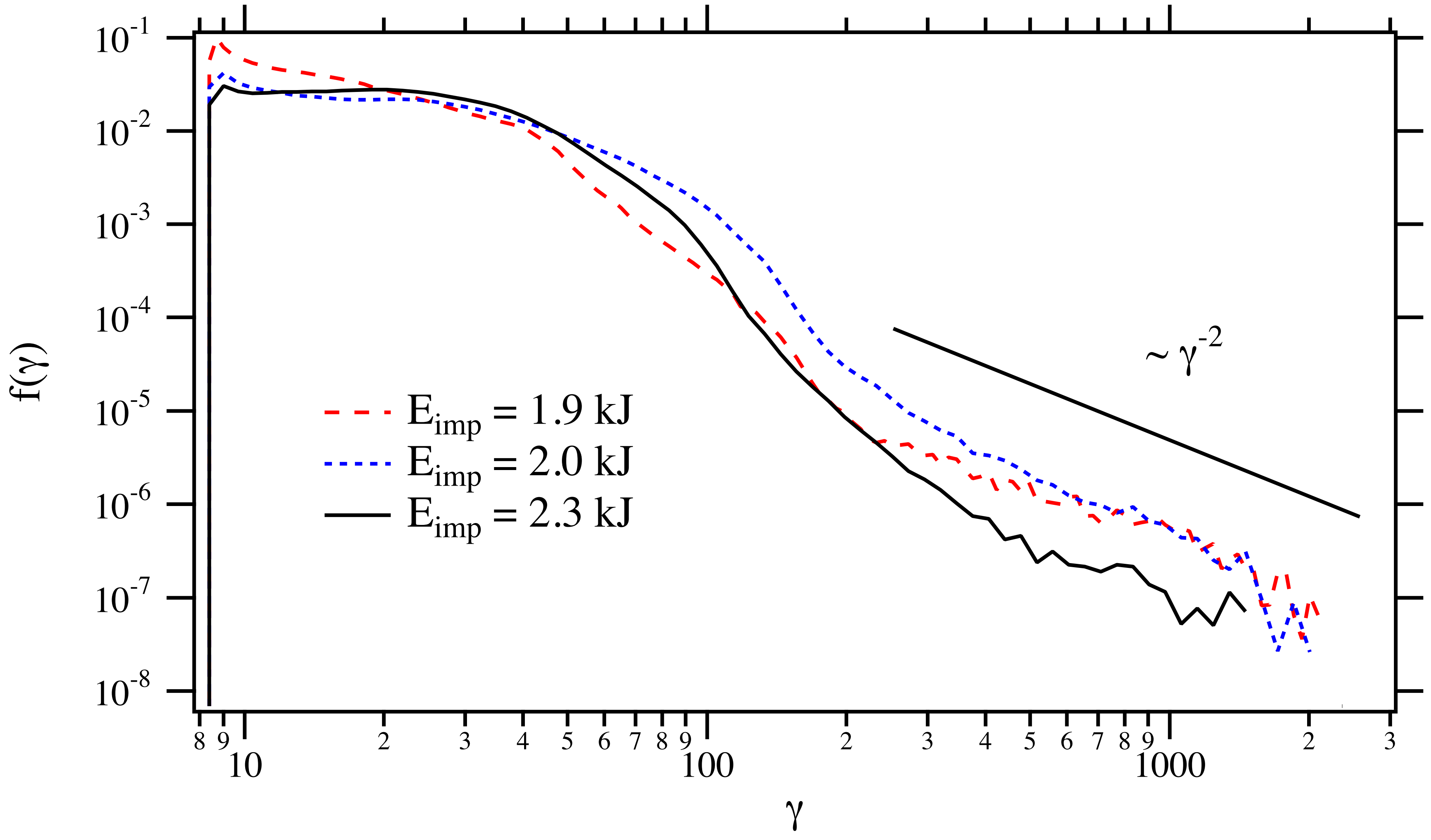
2. propagating in a plasma.

   ➡Hollow cylinder implosion with Gekko XII

- Distribution functions of accelerated electrons are measured with electron spectrometer (ESM).

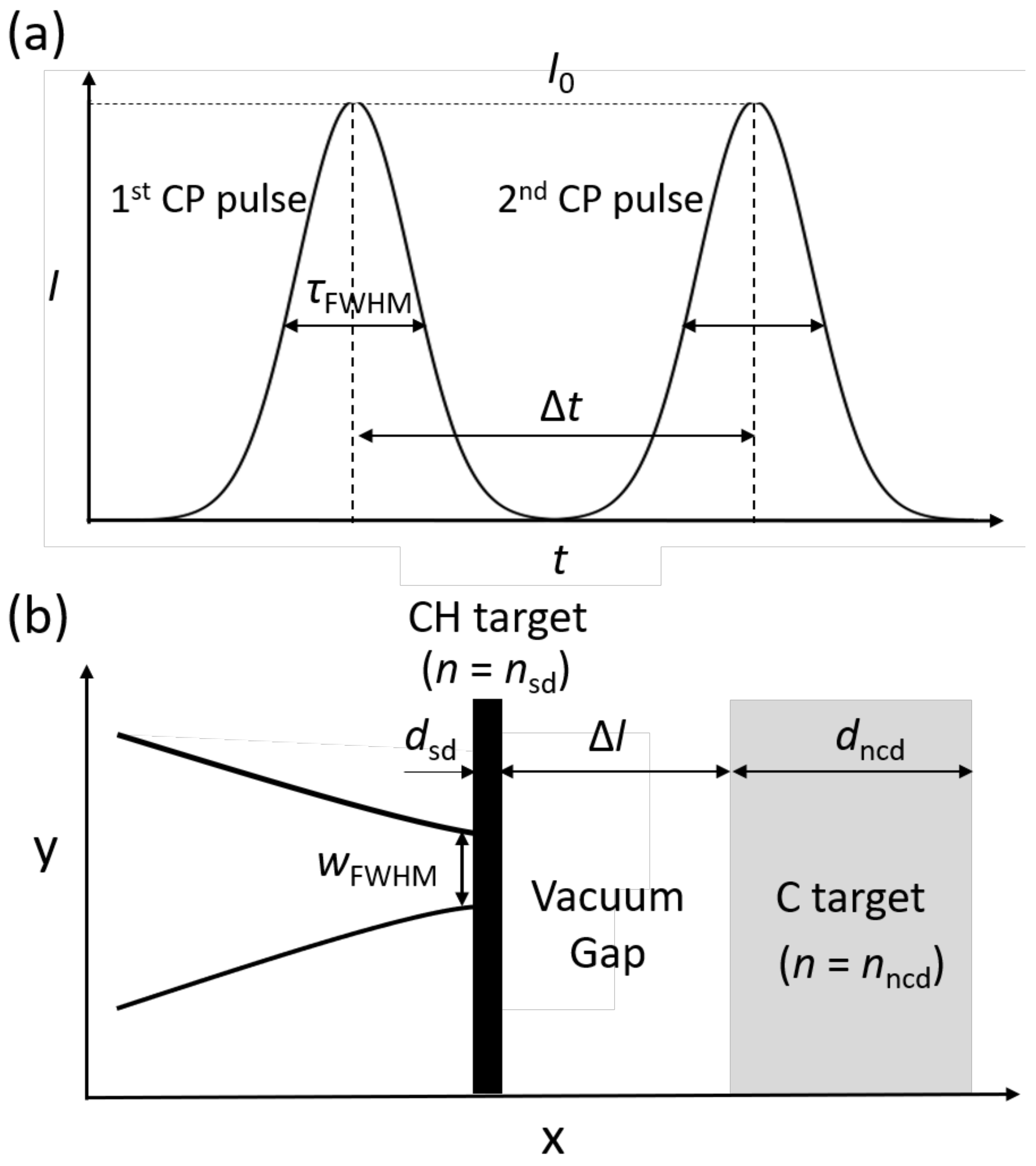
- Power law spectra independent of plasma density.



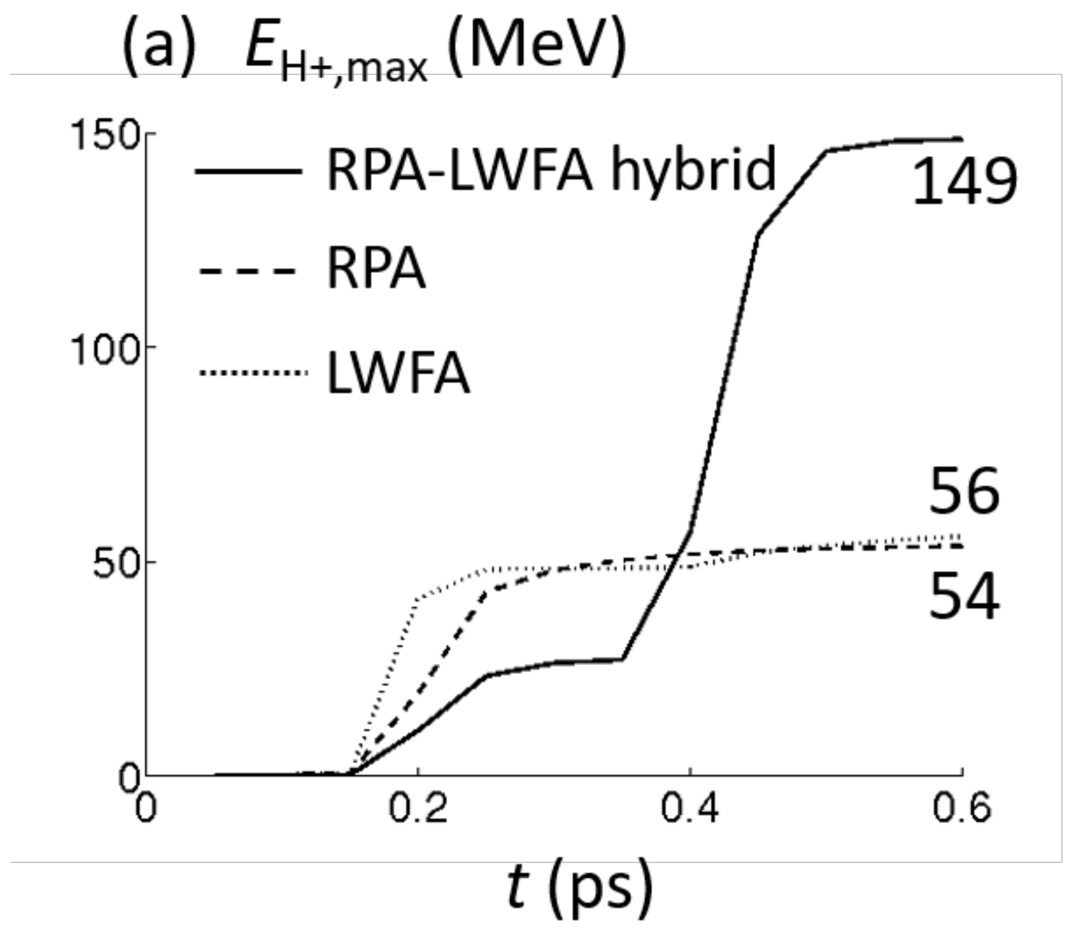




Kuramitsu + 2011 PoP, PRE

# Relativistic ion acceleration




100 TW laser




Controlled injection of energetic protons into the wakes

Isayama, Kuramitsu + 2021 PoP

- 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

# Frontiers

- Relativistic laboratory astrophysics
  - Energy Frontier
  - Relativistic ion acceleration
  - Relativistic ion detector
- Data science and Informatics
- Laser nuclear physics

- Extreme light field and plasmas
  - Induced Compton scattering from high brightness temperature radiation (13-5 Shuta Tanaka)
  - Tomson scattering of intense light from nonlinear plasmas (11-9 Kentaro Sakai)

# Energy frontier in laser-driven ion acceleration with large-area suspended graphene with the aid of machine learning

# Practical problems on ion acceleration experiment at relatively small laser facility

- radioactive contamination
- limited space and floor strength
- limited man power …

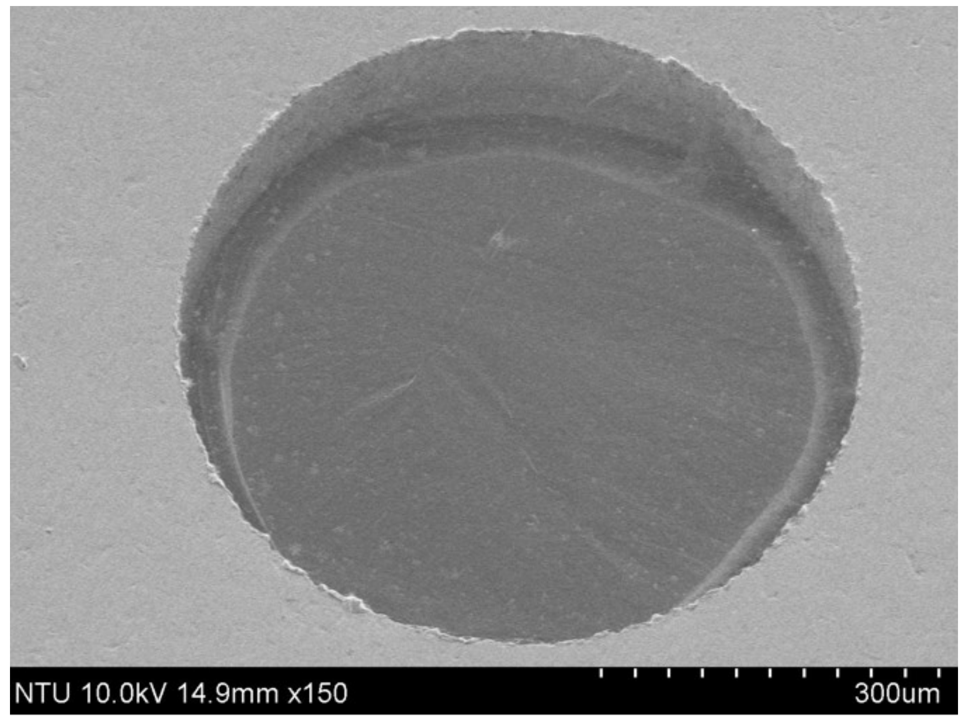
Need to suppress radiation from laser-matter interactions

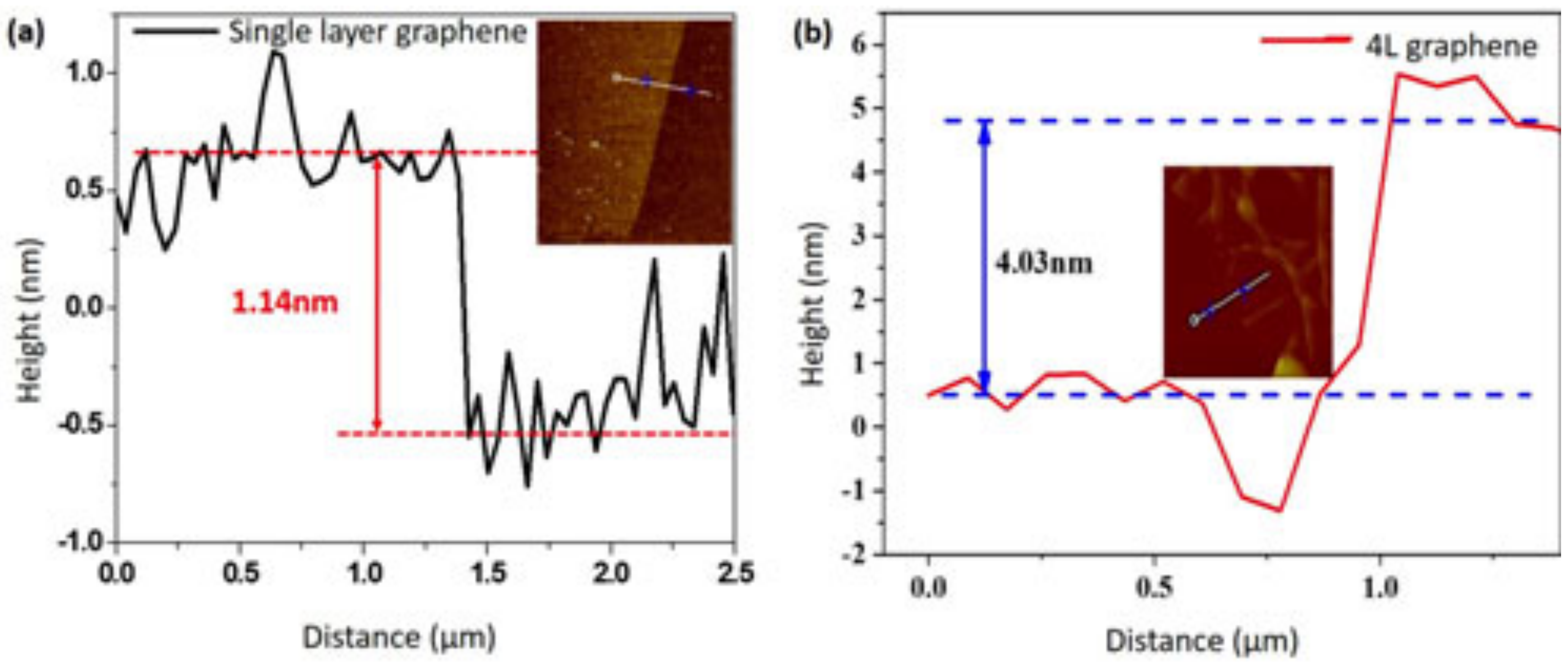
These are also the case for medical applications

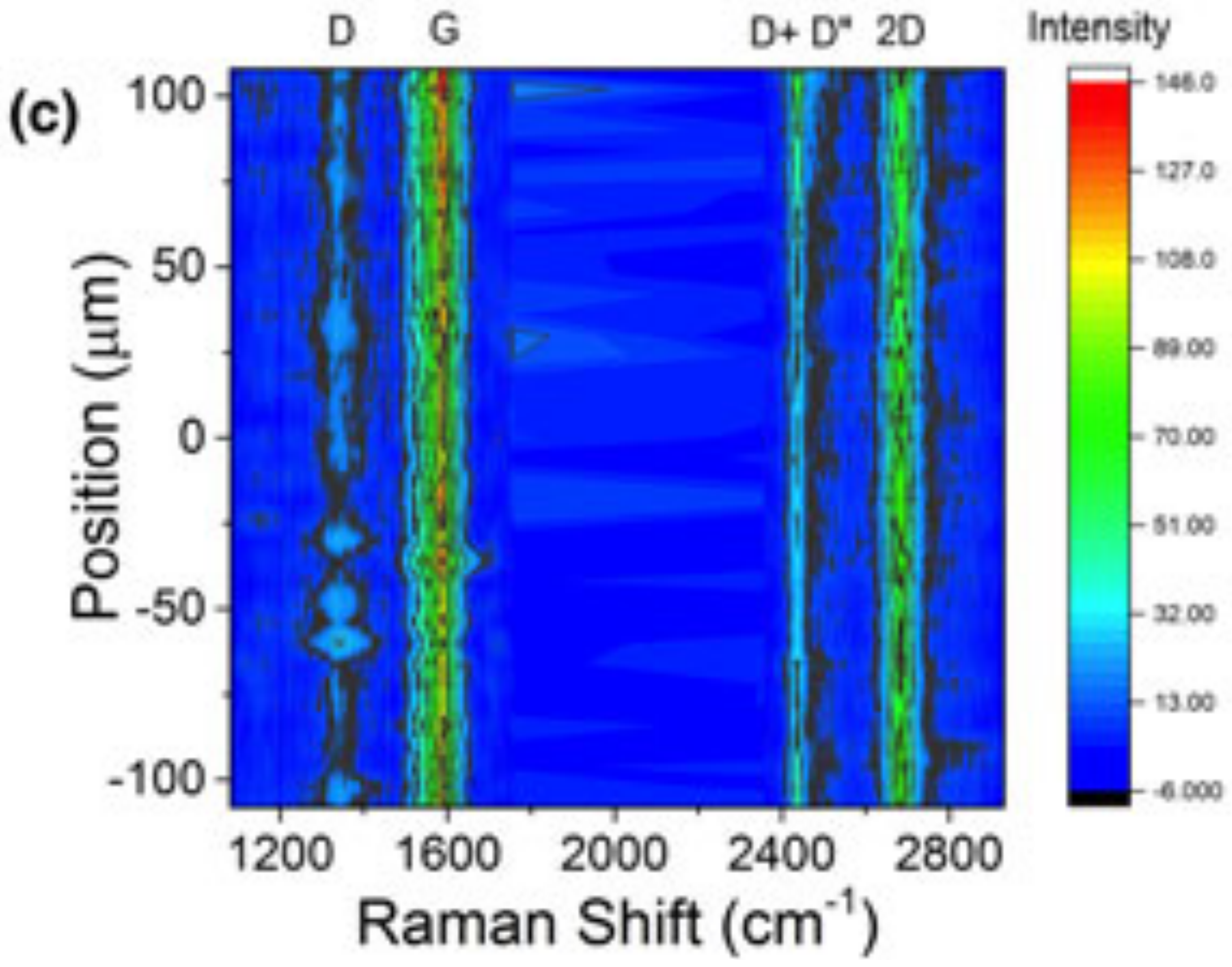
# Large-area suspended graphene (LSG)

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



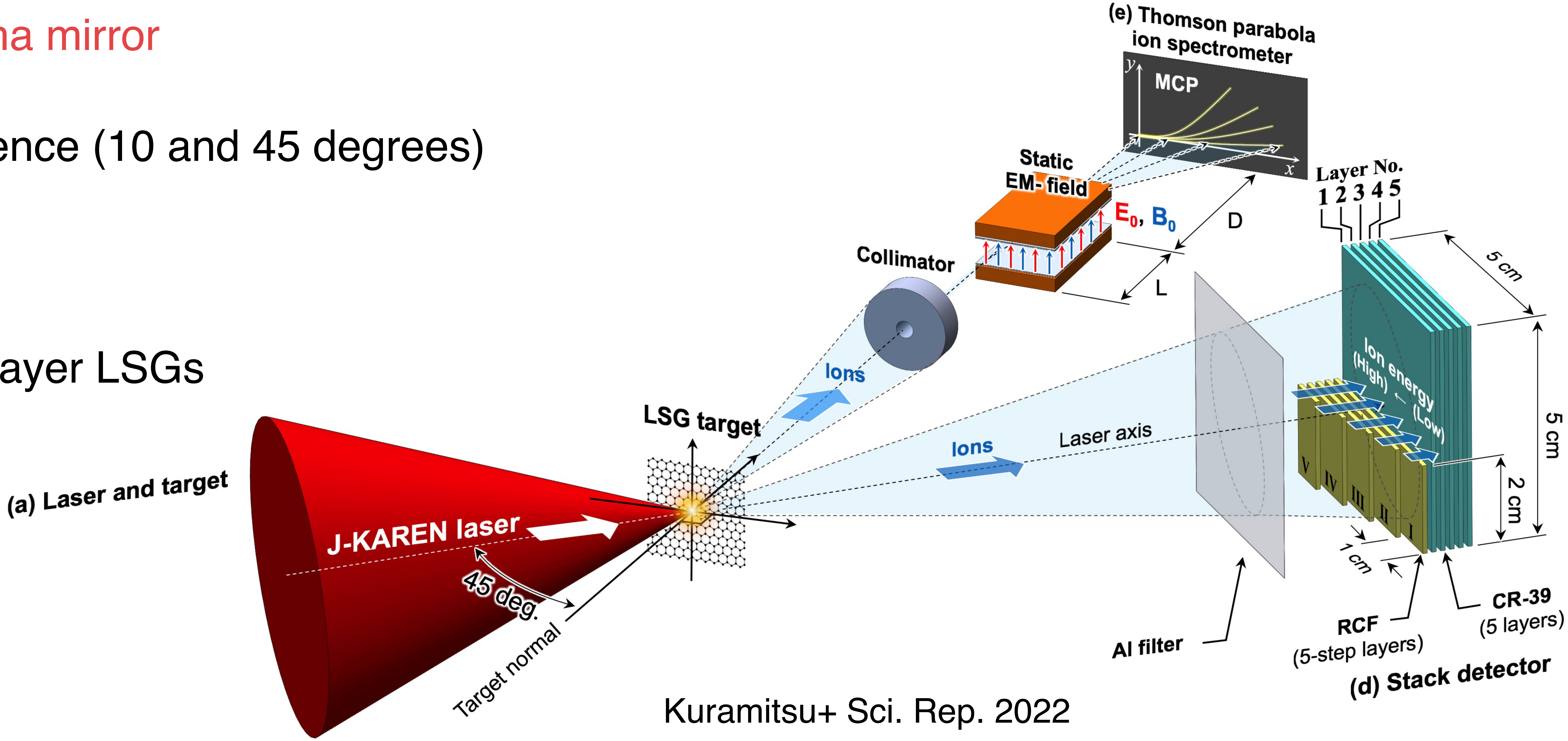




Khasanah +Kuramitsu HPL 2017

# 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

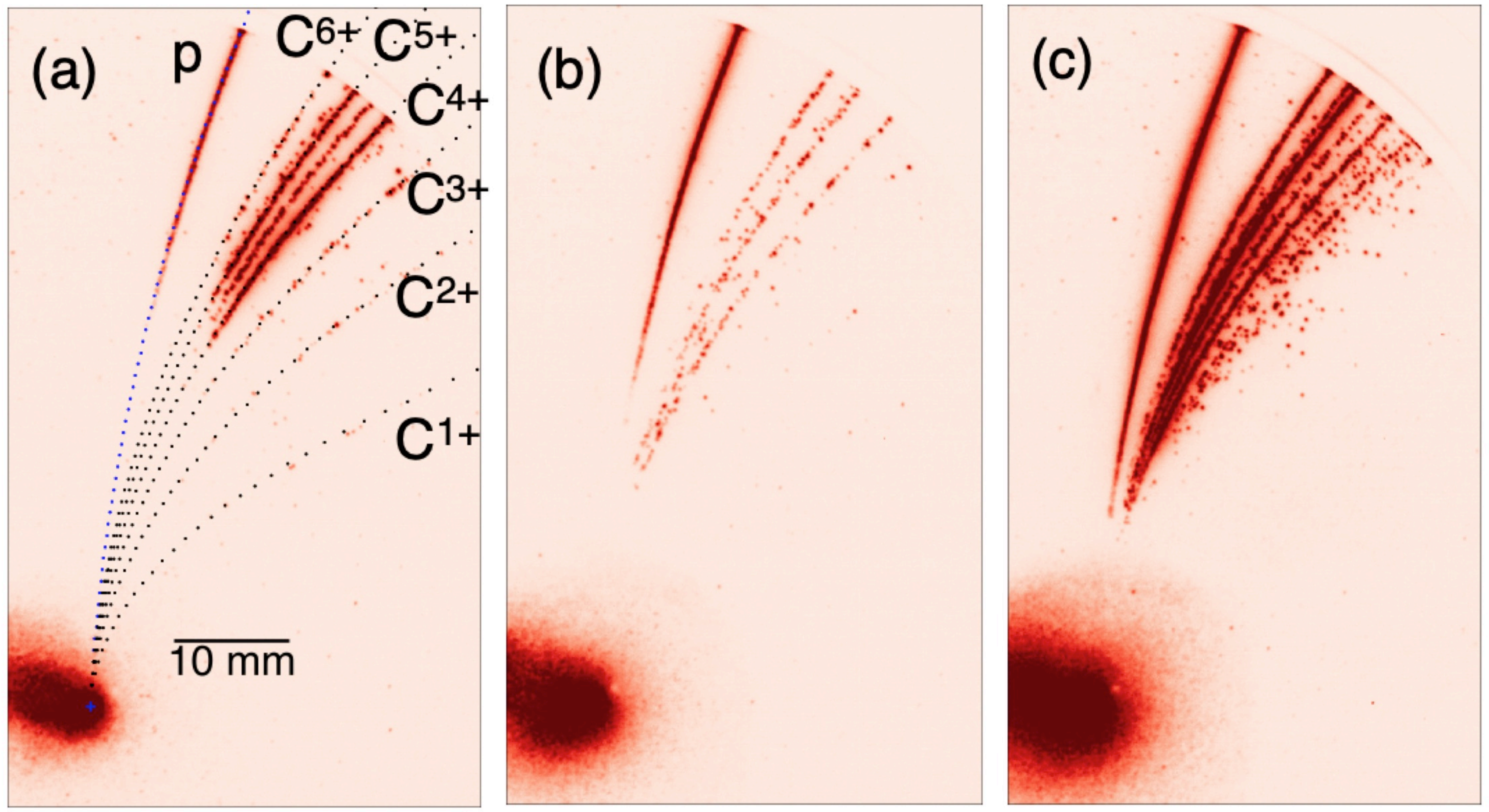
# Best focus relativistic laser intensities

- 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

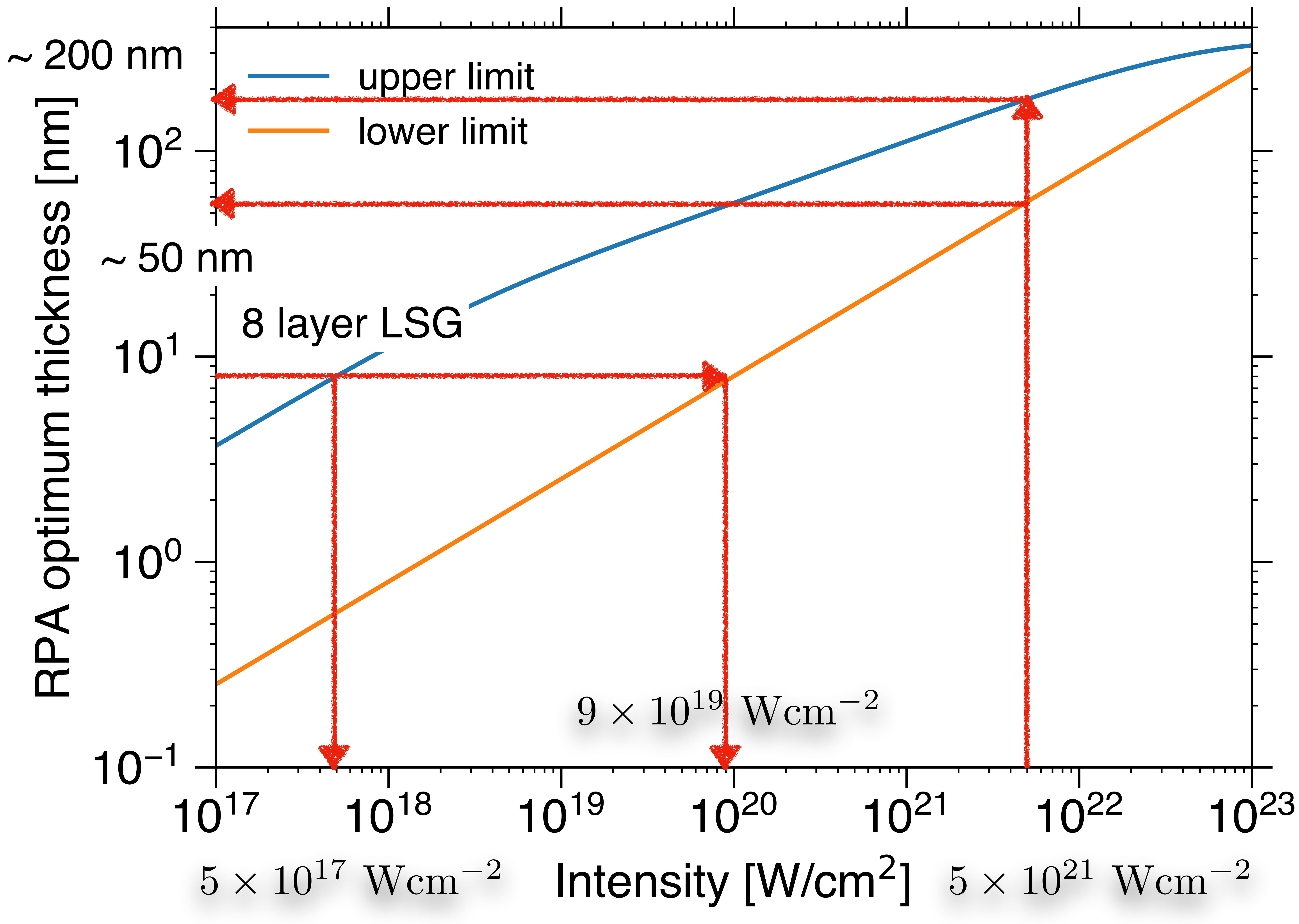
- Without plasma mirror




Kuramitsu+ Sci. Rep. 2022

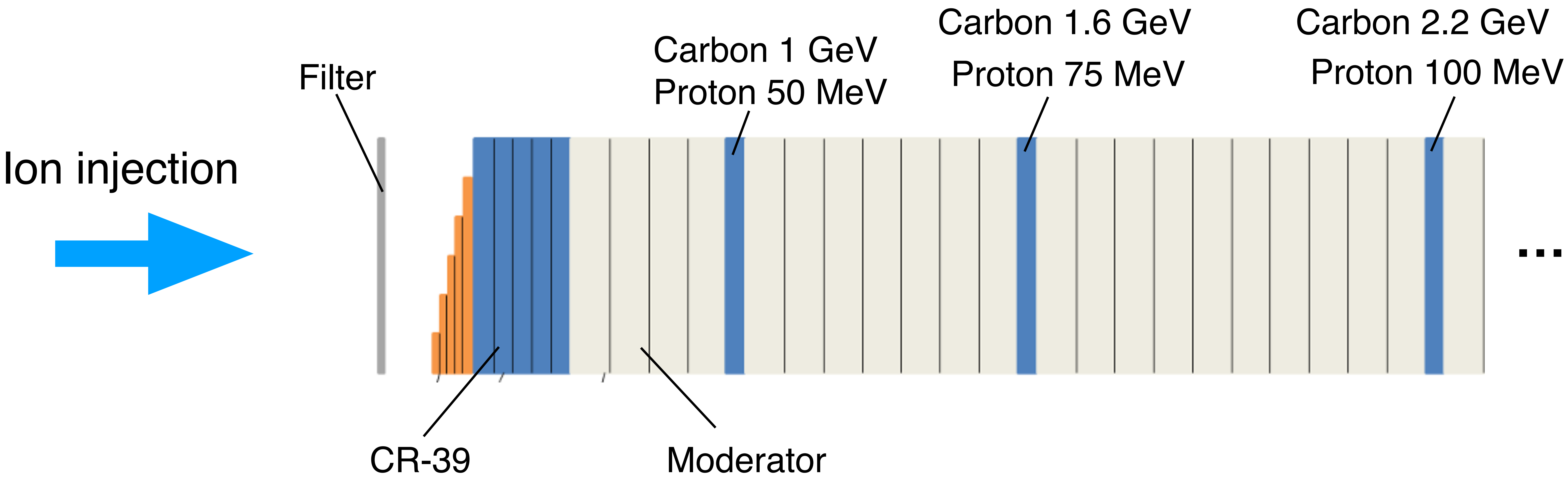
Irradiating the thinnest target by the highest intenstiy laser without plasma mirror to demonstrate robustness of LSG ➡ Not optimized yet!

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



# CR-39 stack

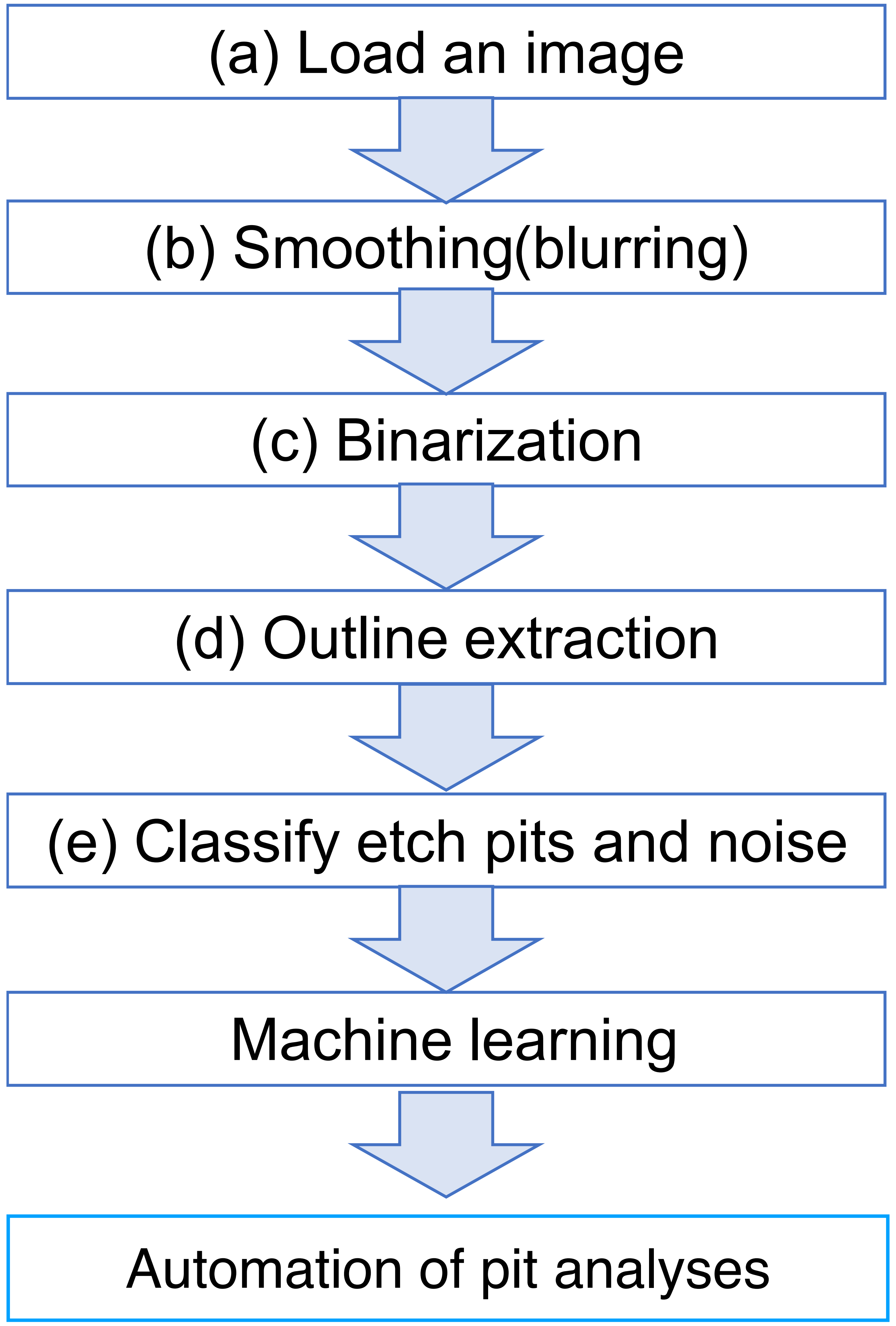
## To resolve ion energy using CR-39

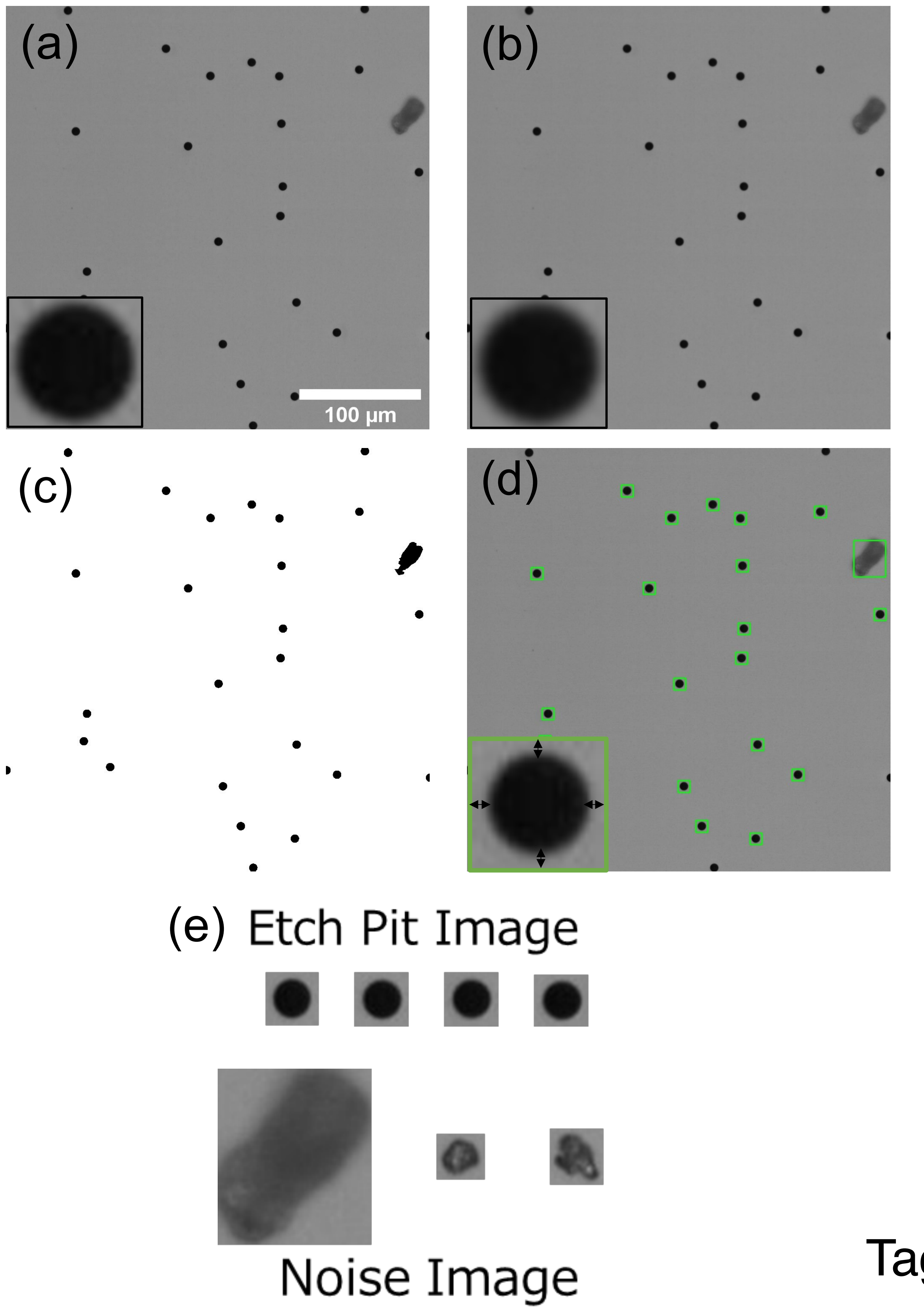



- To obtain ion spectra with CR-39 stack, it is required to find etch pits in large amounts of microscope images.
- ~10 CR-39 in 1 stack, ~10,000 microscope images in 1 CR-39 sheet
- **<u>Millions of images should be analyzed in 1 experiment series.</u>**

Minami + submitted

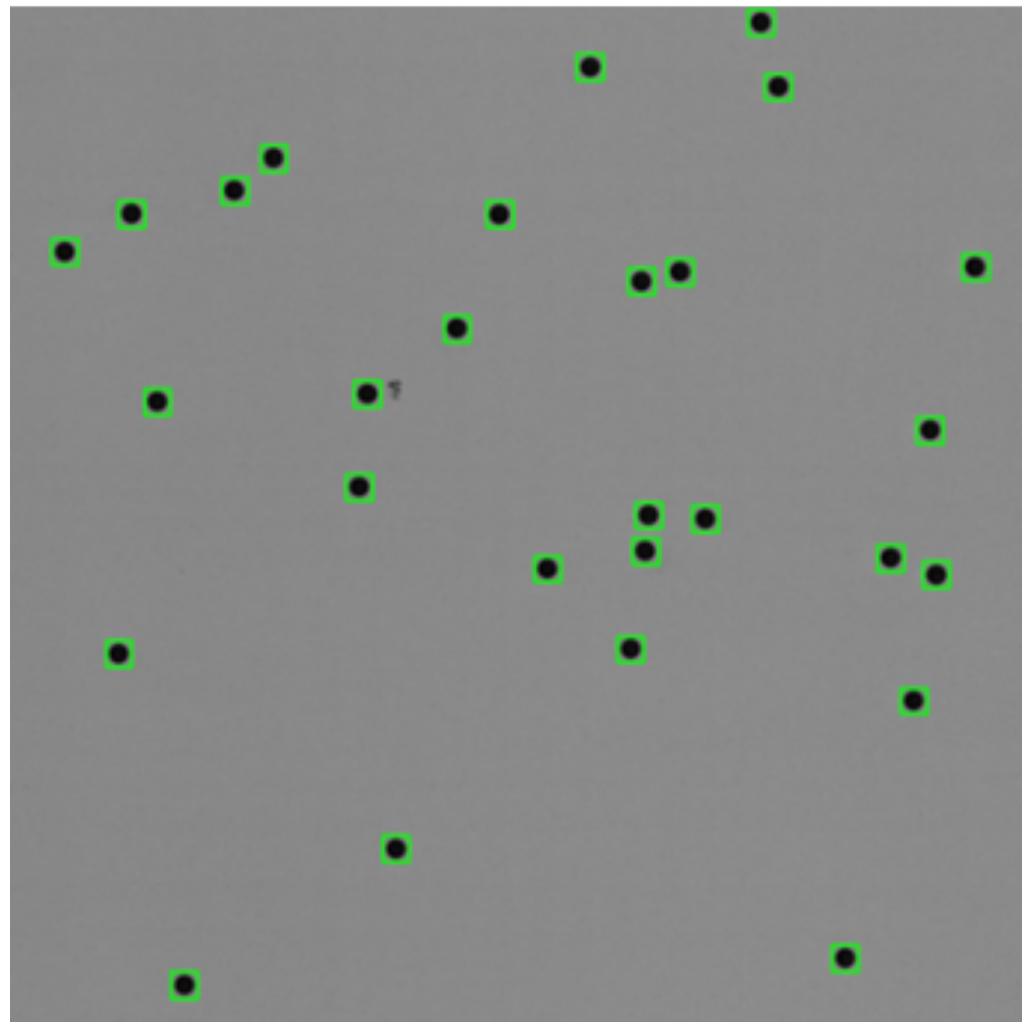
# Automation of ion pit analyses with machine learning (ML)



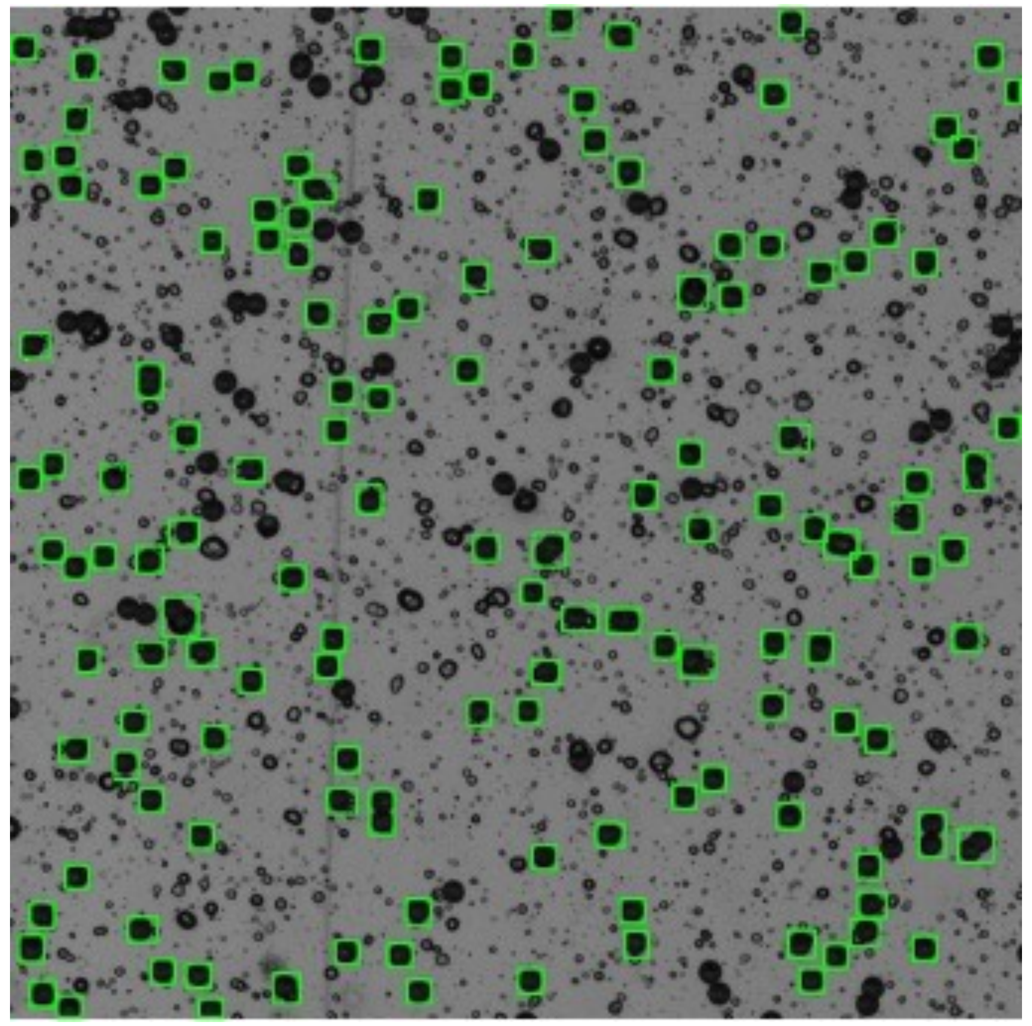




Taguchi + submitted

# ML (ExtraTreesClassifier)

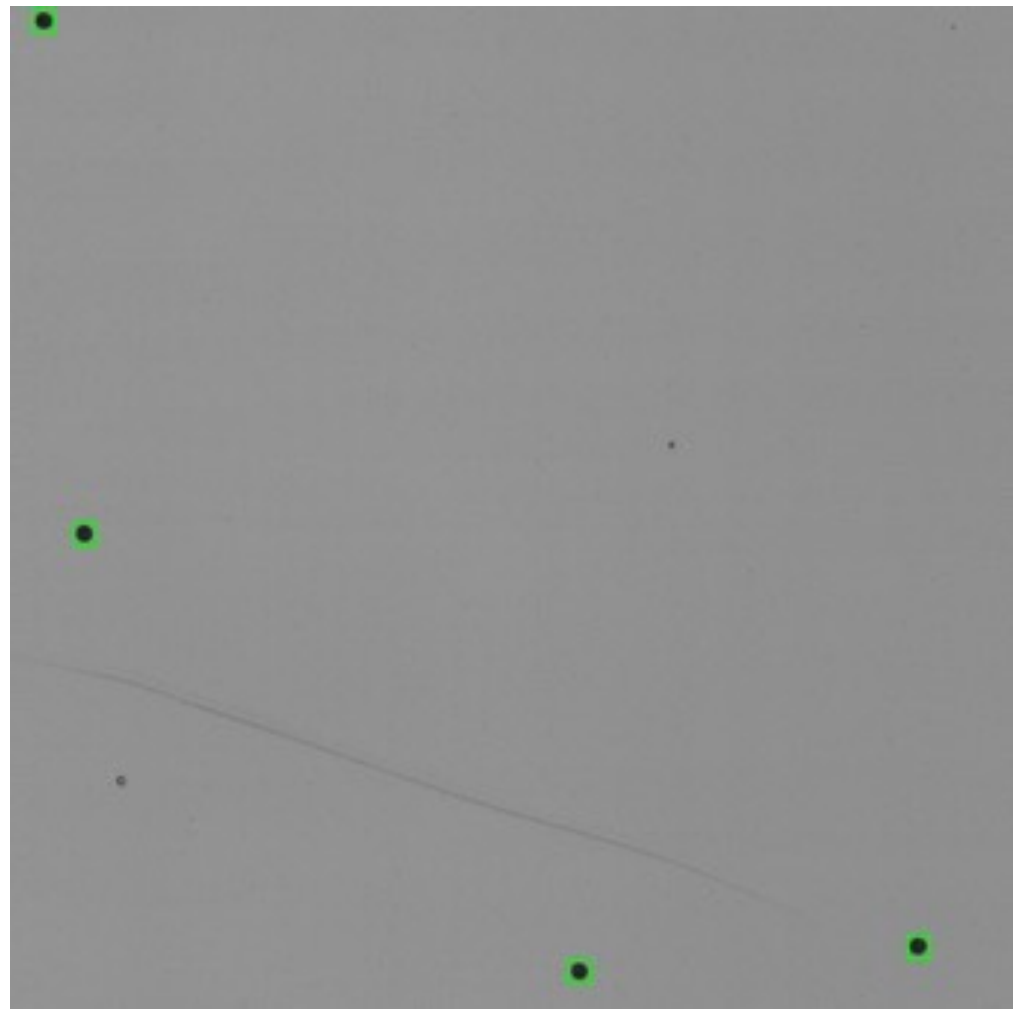


- HIMAC data
- Training data from HIMAC
- More than 5000 microscope images
- About $10^5$ pit detection
- Precision: 98%
- Recall: 98%

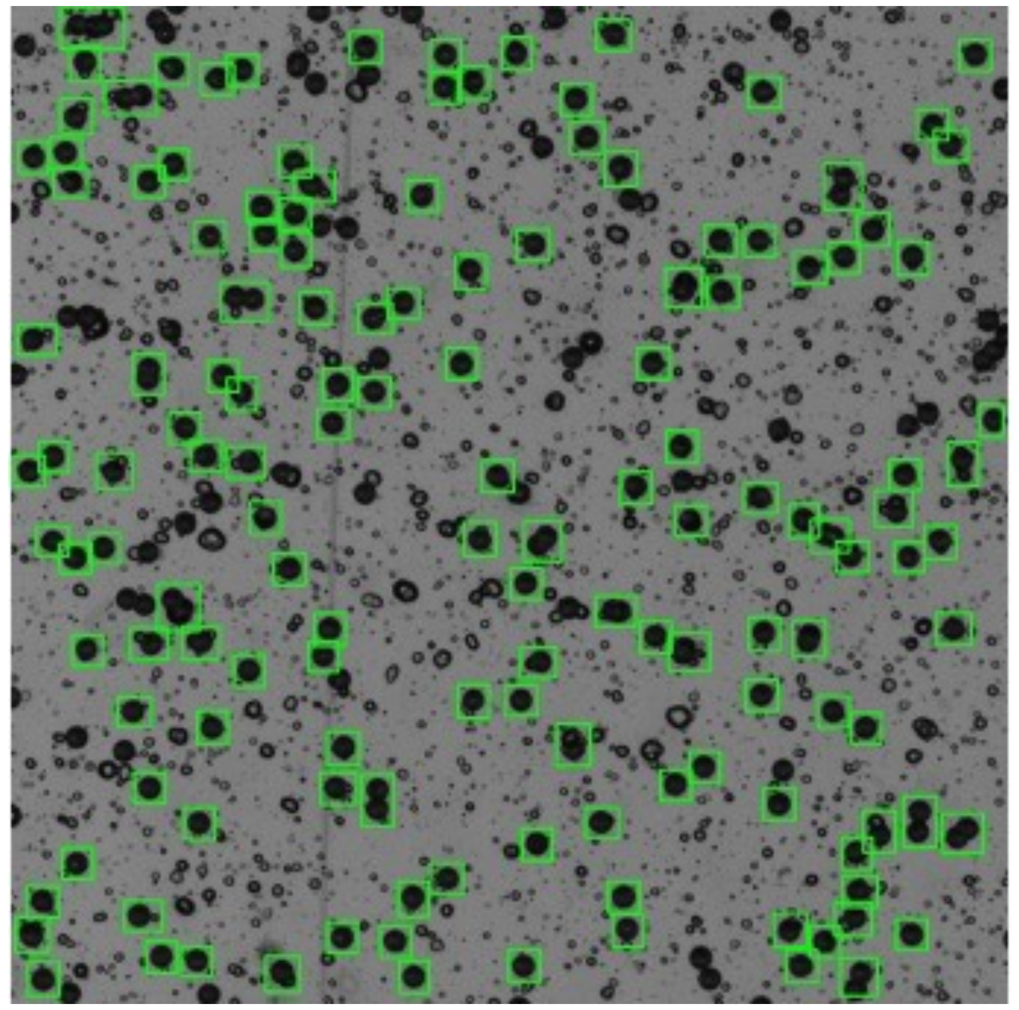


- LFEX data
- Training data from LFEX
- More than 17000 microscope images
- About $10^5$ pit detection
- Cropping margin: 3 pixels
- Precision: 95%
- Recall: 76%

# CNN (VGG16)



- LFEX data
- Training data from HIMAC
- All the ion pits are detected.



- LFEX data
- Training data from LFEX
- Cropping margin: 5 pixels
- Precision: 95%
- Recall: 83%

Kuramitsu + to be submitted

# Summary 1

- We are exploring relativistic laboratory astrophysics aiming at relativistic ion acceleration relevant to cosmic rays.
- We have developed large-area suspended graphene as targets for laser-driven ion acceleration.
- 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.

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