Emulation of cosmic ray generation in random plasma wakes

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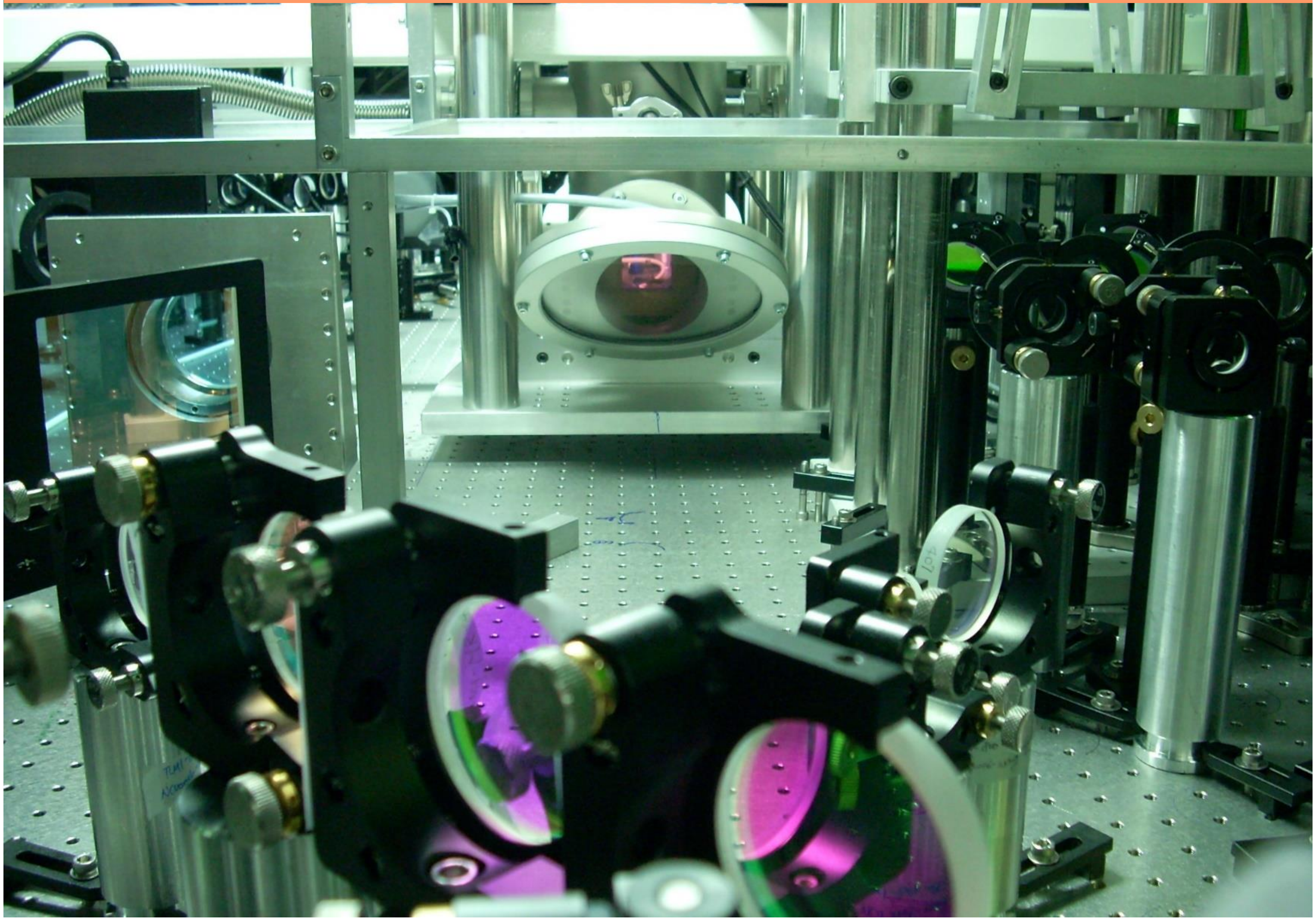
The NCU 100-TW laser

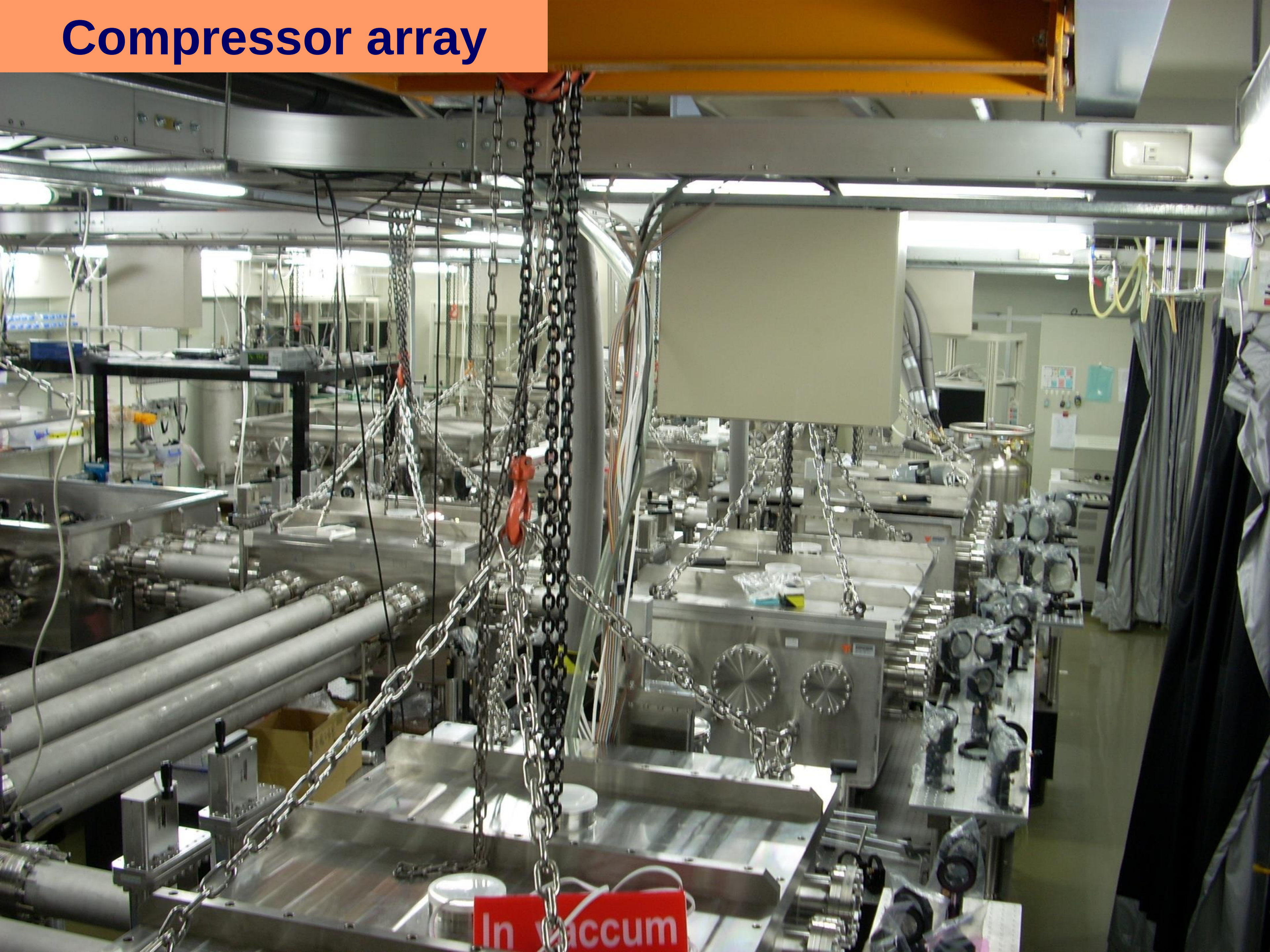
50-km south of Taipei

100-TW laser at Nat'l Central Univ

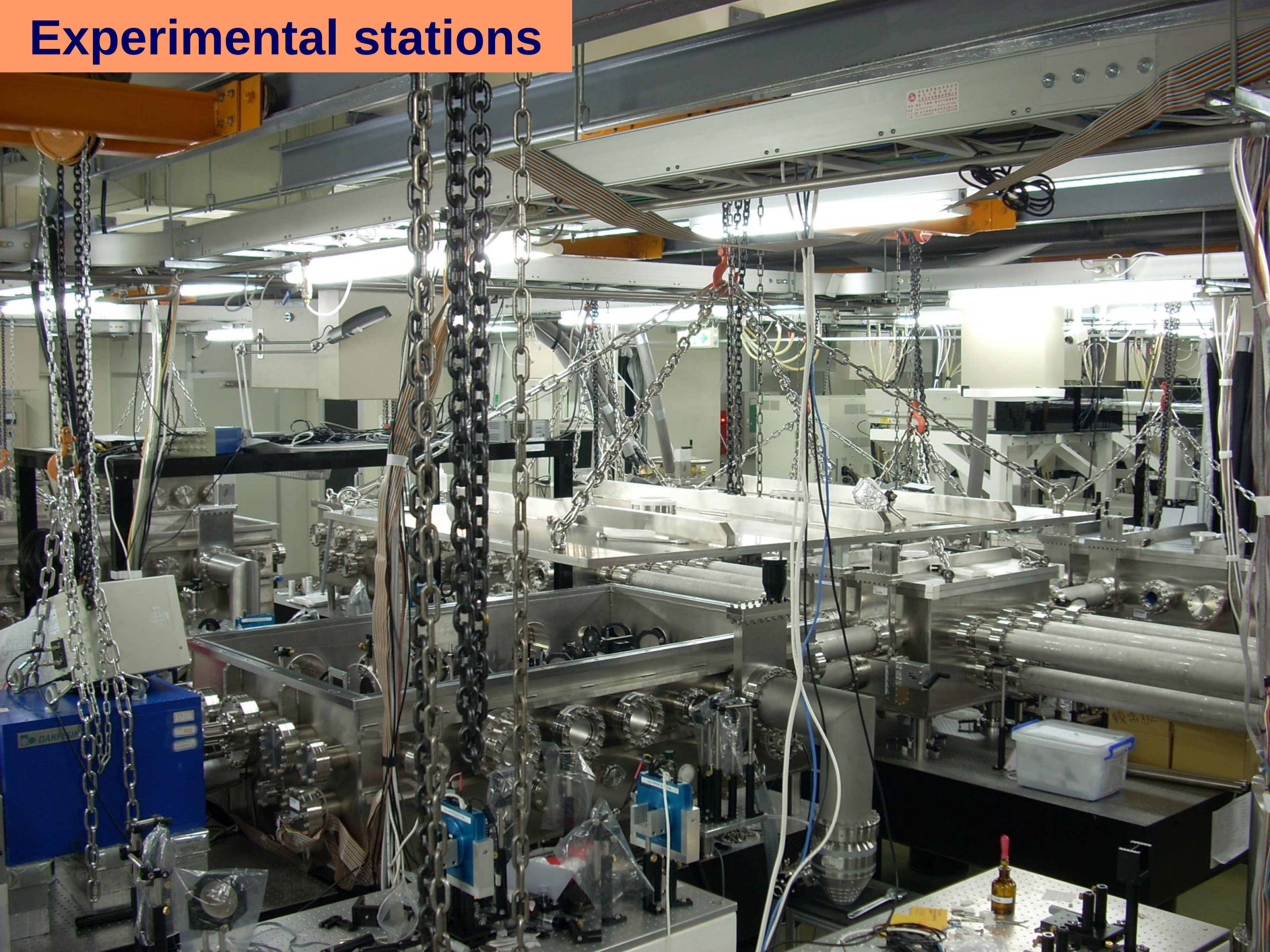
Constructed with the technique of chirped-pulse amplification



Compressor array

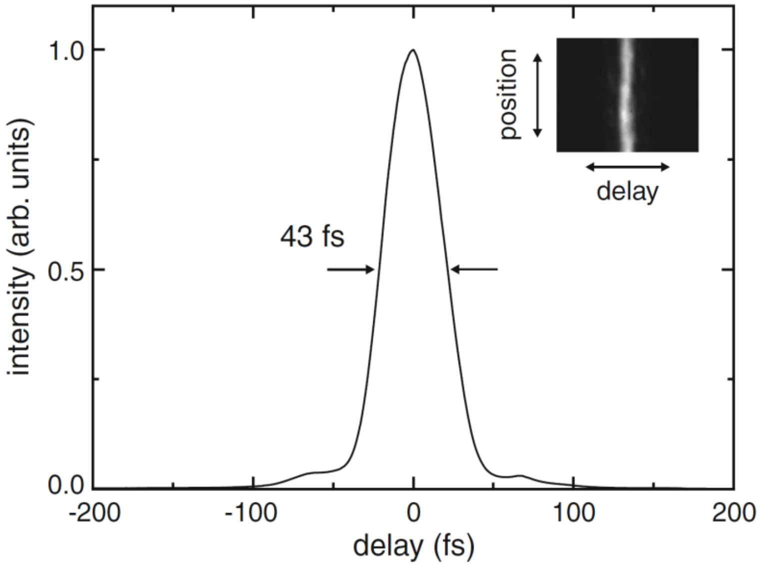


Experimental stations



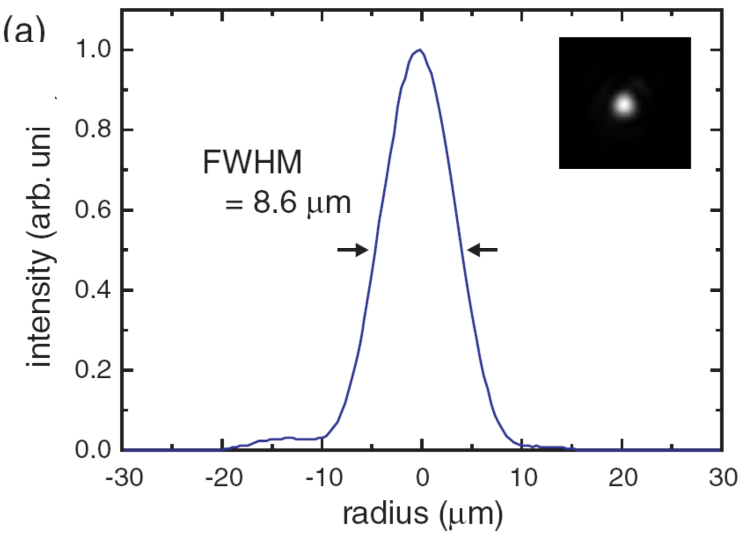
Compressed and focused pulse

autocorrelation trace



corresponding to a pulse duration of 30 fs

camera lineout



NA=1/8. If adaptive mirrors are used, it is possible to focus down to 1-μm diameter.

Appl. Phys. B **117**, 1189 (2014)

100-TW laser focused to 10-μm diameter

- peak intensity: 10^{20} W/cm^2 (sunshine at noon = 0.1 W/cm^2)
- electric field: 3.2×10^{13} V/m (50× Coulomb field in hydrogen)
- magnetic field: 1.1×10^{5} T (10^9 × earth surface magnetic field)
- optical pressure: 6.7×10^{10} bar (1/4× center of the Sun)
- plasma temperature: 10^7 K (center of the Sun)
- energy density: 10^9 J/cm^3 (B83 H-bomb, 1.2 MT of TNT)

Laser wakefield accelerator

Ponderomotive force on free electrons

$$\mathbf{a} = -\frac{e\mathbf{E}}{m}$$ nonrelativistic, ignoring $\frac{\mathbf{v}}{c} \times \mathbf{B}$

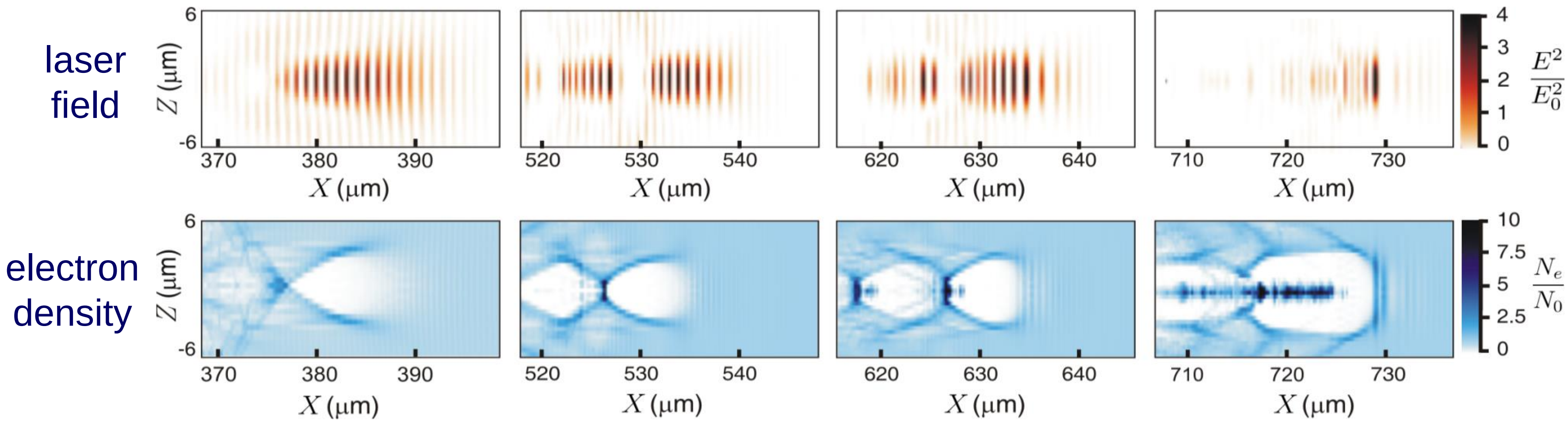
electron displacement $\mathbf{x} = \frac{e\mathbf{E}}{m\omega^2}$ opposite to the electric force

dipole moment $\mathbf{p} = -\frac{e^2\mathbf{E}}{m\omega^2}$ $\omega_0 \ll \omega$

force on dipole $\mathbf{F} = (\mathbf{p} \cdot \nabla)\mathbf{E} = -\frac{e^2}{2m\omega^2}\nabla(\mathbf{E} \cdot \mathbf{E})$

An intense laser pulse expels electrons with a ponderomotive force of ~GeV/cm.

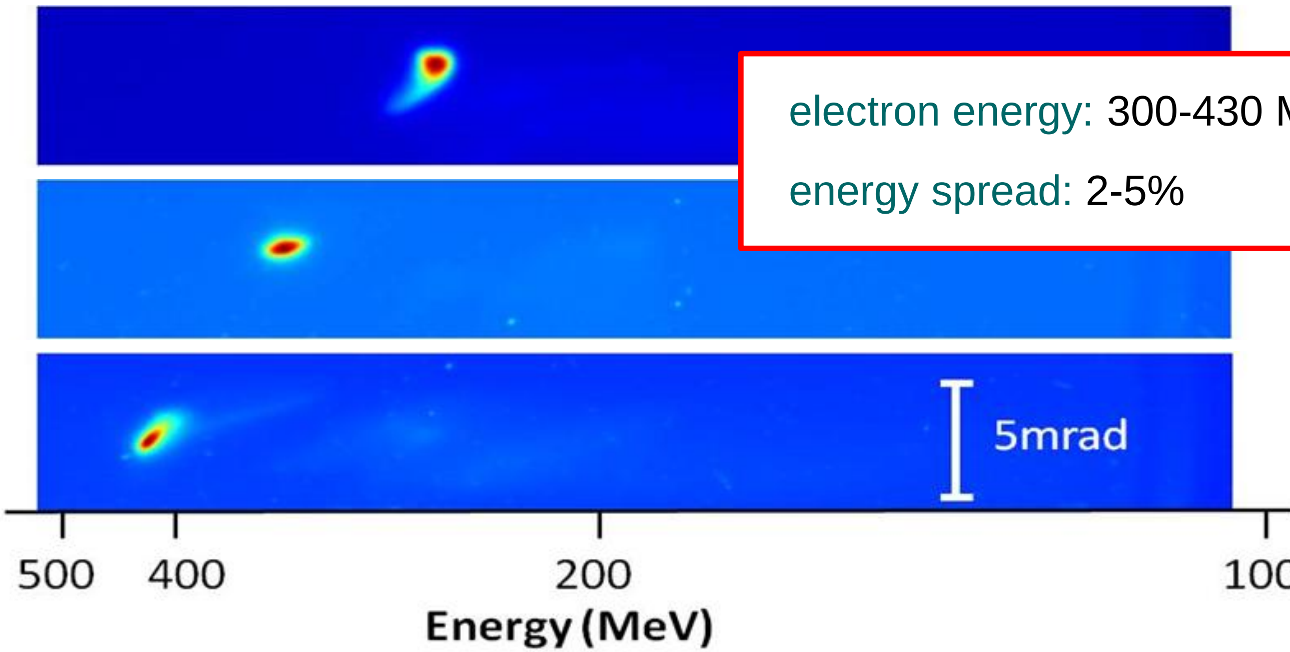
Laser wakefield electron accelerator



- After nonlinear propagation, the laser pulse becomes spatially self-focused and temporally compressed.
- The ponderomotive force expels electrons, resulting in an ion cavity following laser pulse. The electric field at the rear edge of the cavity is ~3×10^{11} V/m.
- Electrons turn back to collide at the tail of the cavity. Some are injected into the cavity, trapped and accelerated.

Electron acceleration with low energy spread

laser beam guided by self-focusing in a 4-mm helium jet



electron energy: 300-430 MeV

energy spread: 2-5%

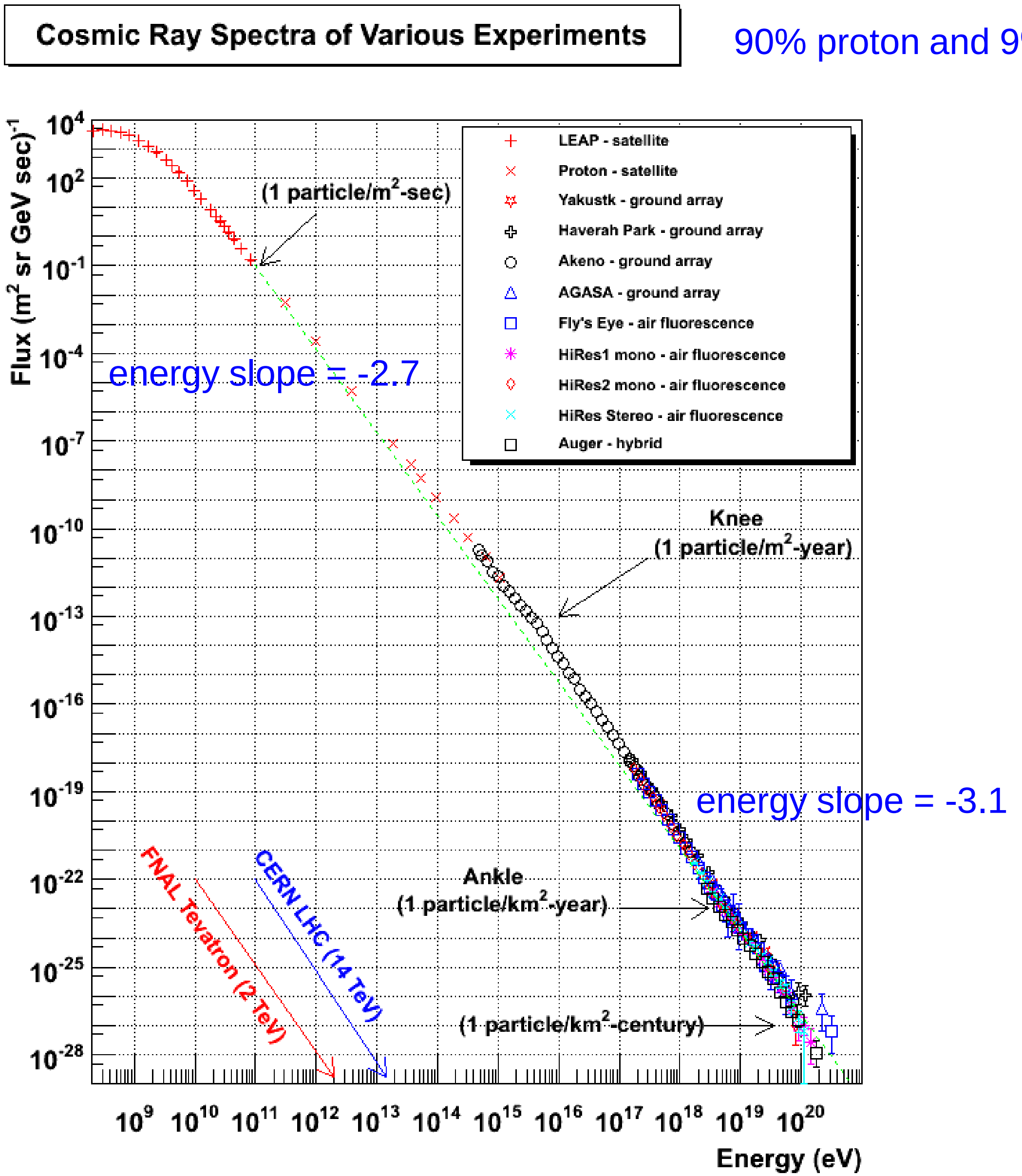
laser wakefield accelerator:
1 GeV/cm

conventional accelerator:
200 keV/cm

Random-wave acceleration model of cosmic ray

Observed energy spectrum of cosmic ray

90% proton and 9% alpha particle



http://www.physics.utah.edu/~whanlon/spectrum.html

Particle acceleration by random collision with magnetic field

PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

On the Origin of the Cosmic Radiation

ENRICO FERMI
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(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magmetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

the energy. An elementary calculation shows that the probability for a particle to have energy between w and $w+dw$ is given by

$$\pi(w)dw=(\tau/B^2T)(Mc^2)^{\tau/B^2T}dw/w^{1+\tau/B^2T}. \quad (10)$$

It is gratifying to find that the theory leads naturally to the conclusion that the spectrum of the cosmic radiation obeys an inverse power law. By

τ = mean free time

$B = v/c$

cT = mean free path

Particle acceleration by random plasma wakefield

VOLUME 89, NUMBER 16 PHYSICAL REVIEW LETTERS 14 OCTOBER 2002

Plasma Wakefield Acceleration for Ultrahigh-Energy Cosmic Rays

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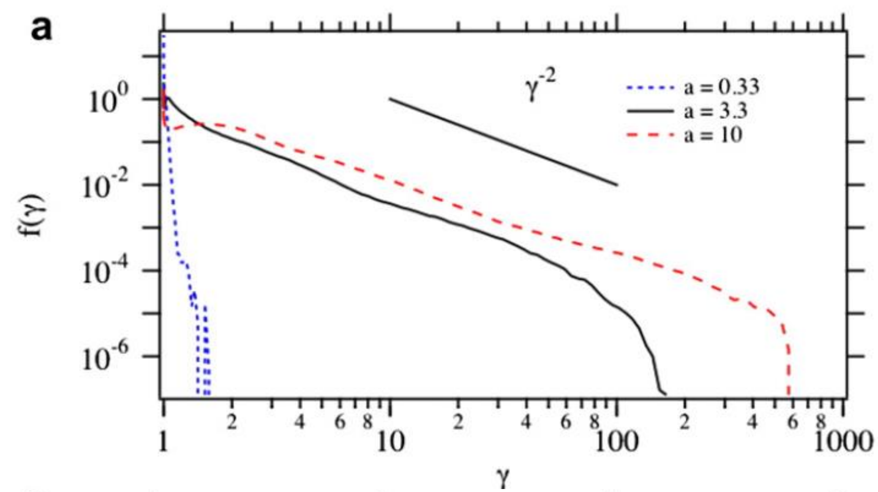
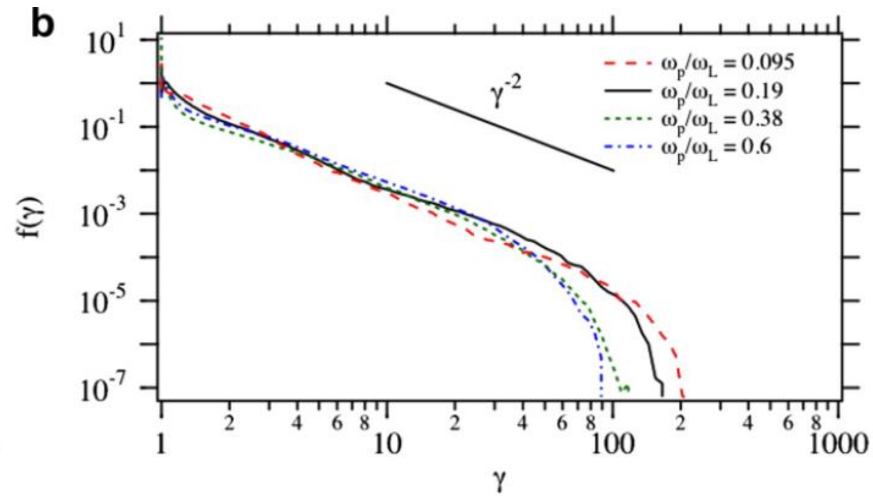
(Received 14 June 2002; published 27 September 2002)

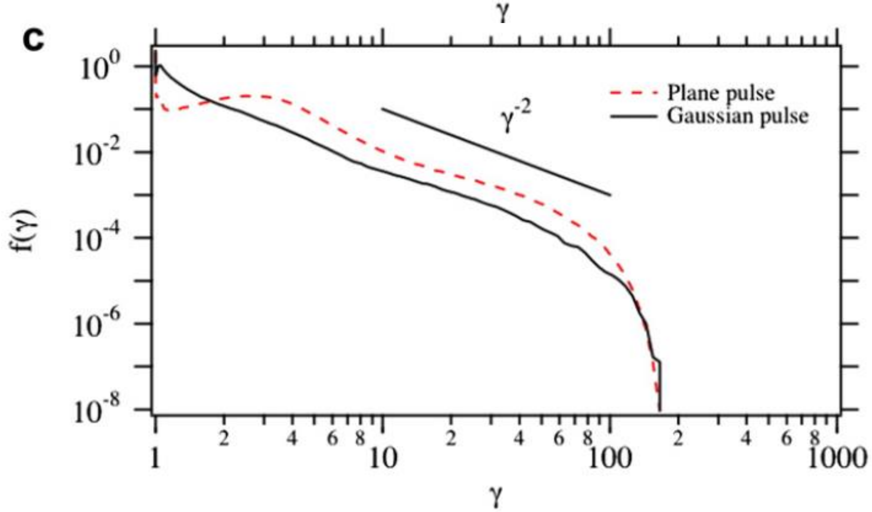
A cosmic acceleration mechanism is introduced which is based on the wakefields excited by the Alfvén shocks in a relativistically flowing plasma. We show that there exists a threshold condition for transparency below which the accelerating particle is collision-free and suffers little energy loss in the plasma medium. The stochastic encounters of the random accelerating-decelerating phases results in a power-law energy spectrum: $f(\epsilon) \propto 1/\epsilon^2$. As an example, we discuss the possible production in the atmosphere of gamma ray bursts of ultrahigh-energy cosmic rays (UHECR) exceeding the Greisen-Zatsepin-Kuzmin cutoff. The estimated event rate in our model agrees with that from UHECR observations.

DOI: 10.1103/PhysRevLett.89.161101 PACS numbers: 96.40.–z, 52.27.Ny, 98.70.Sa

2D particle-in-cell simulation



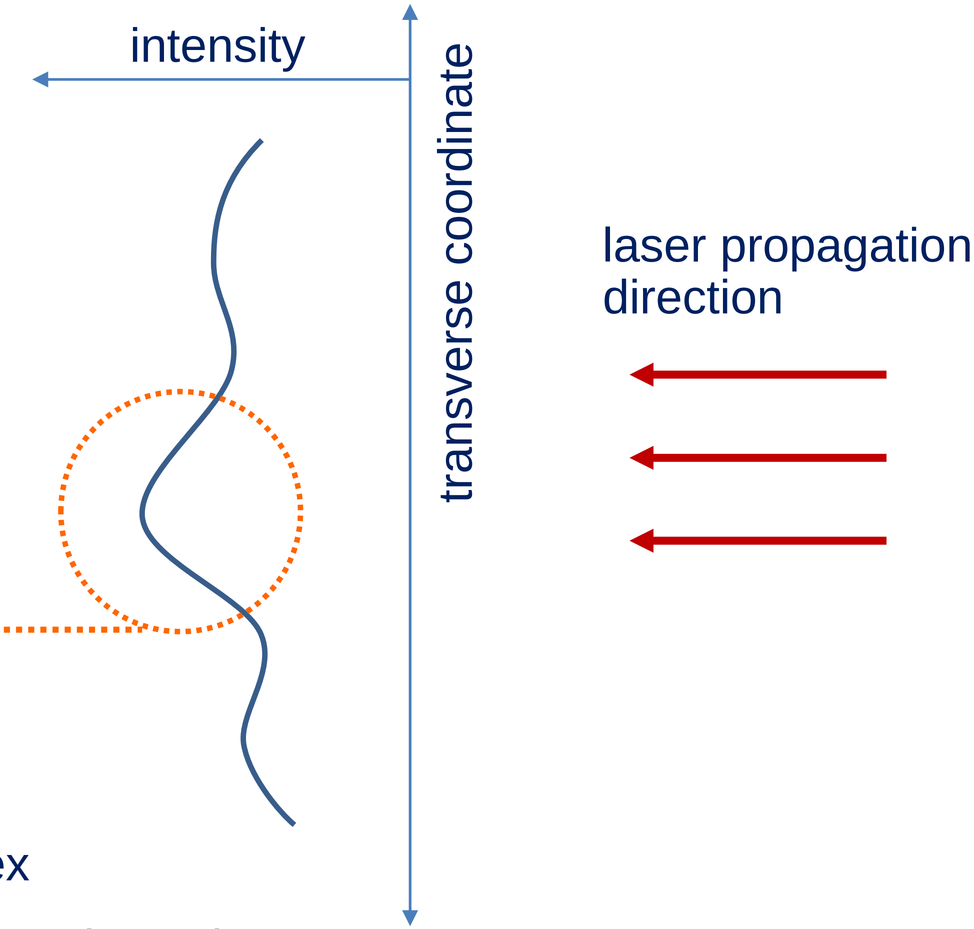




Similar results are obtained for different laser power, focal spot size, and plasma density.

Y. Kuramitsu *et al,* High Energy Density Physics **8,** 266 (2012)

Filamentation instability



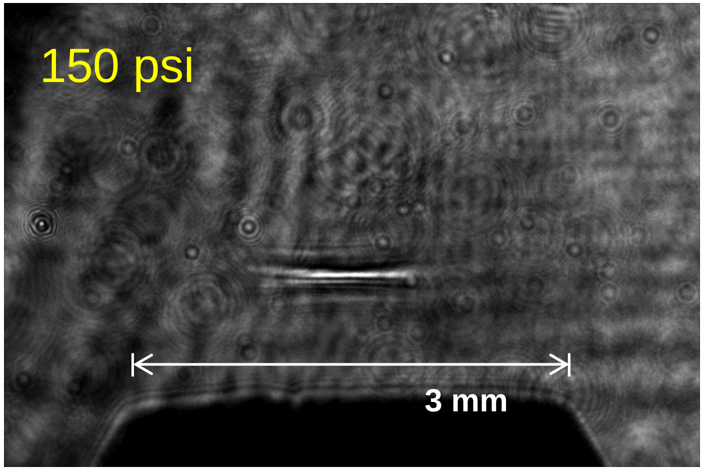
local high intensity

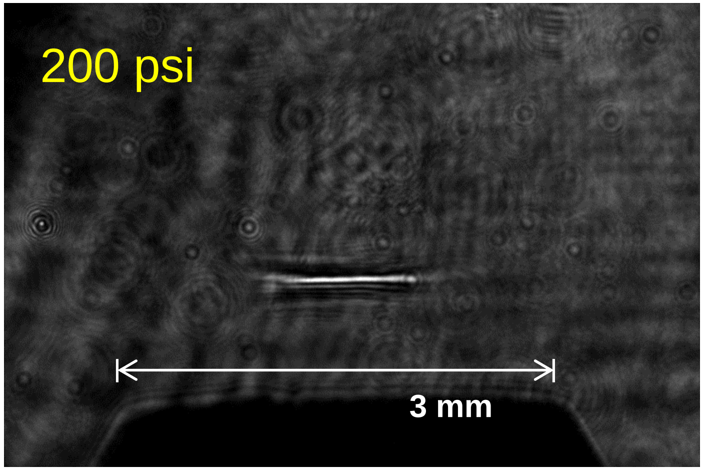
→ local low density

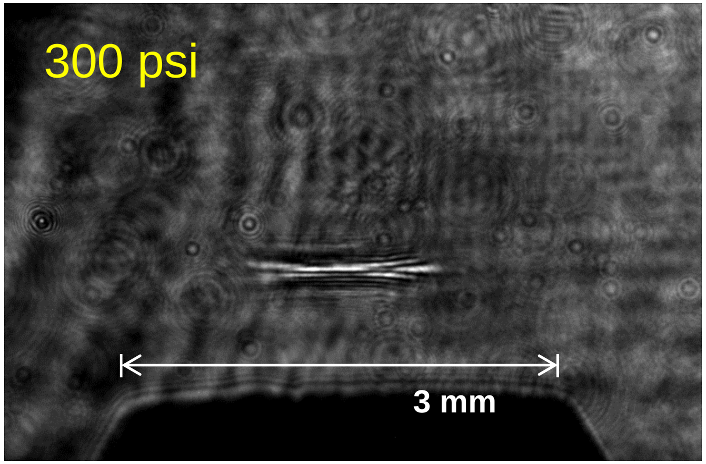
→ local high refractive index

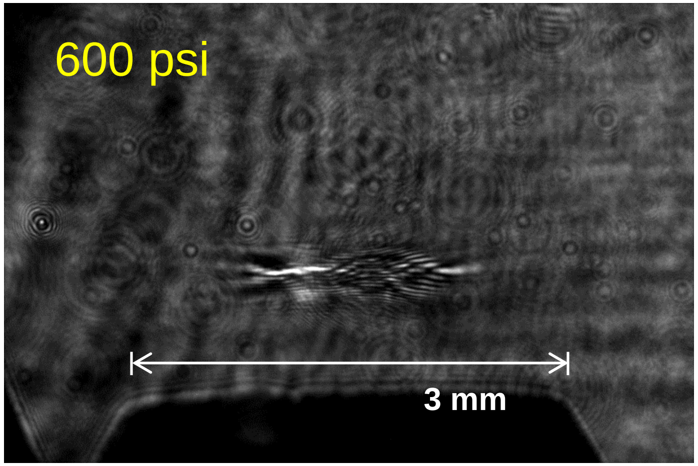
→ self-focusing that increases intensity

NCU experimental data: Shadowgrams of random wakes

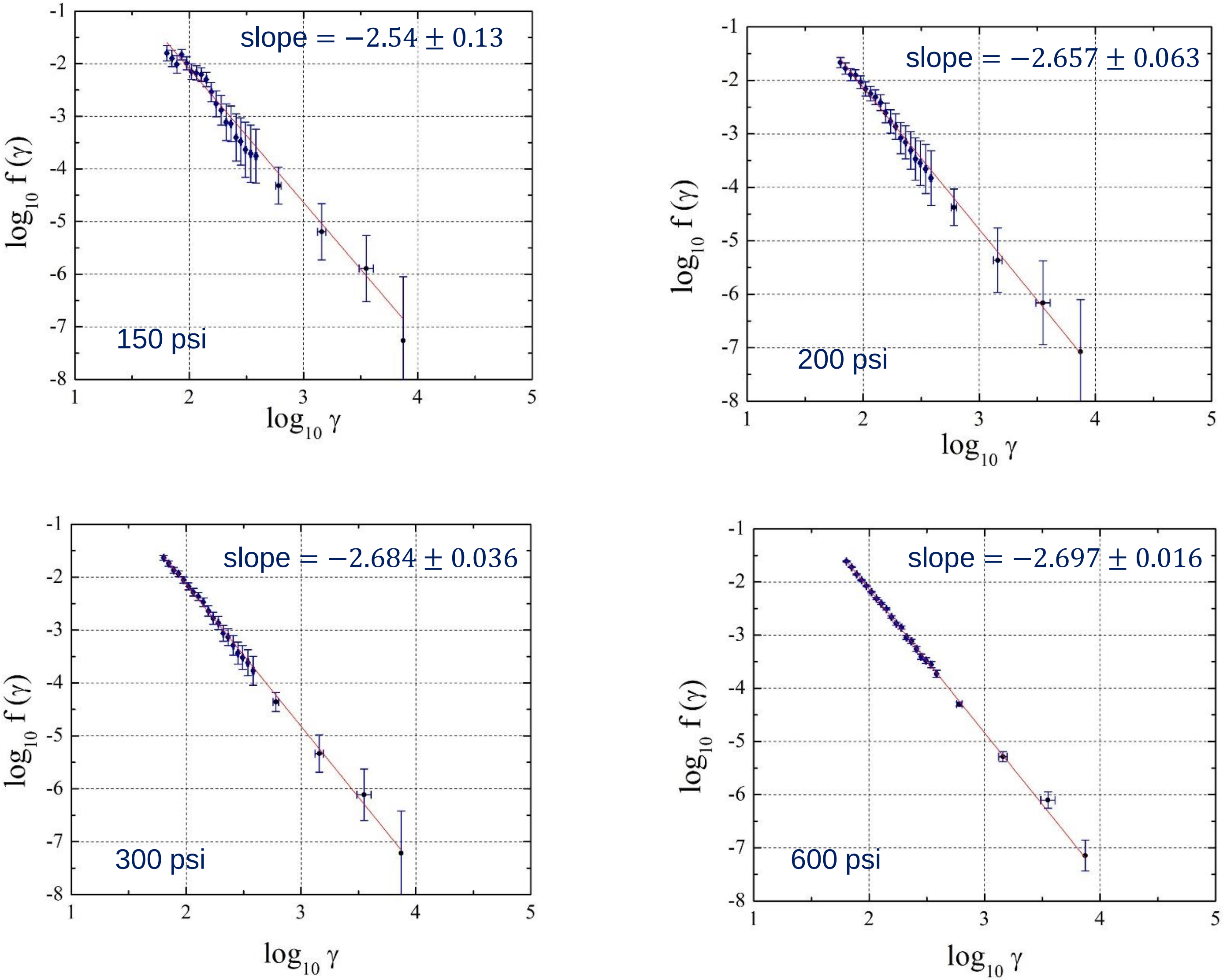








NCU experimental data: Electron energy spectrum



High-field laser is leading us to new realms of physics!

Thank you for your attention