

Nonlinear Physics of Magnetic Turbulence, Shock Formation, and Particle Acceleration via Weibel Instability in Laser Astrophysics

= Theory, PIC Simulation and Laser Experiment =

Hideaki Takabe^{1,2}

¹ Leung Center for Cosmology and Particle Astrophysics (LeCosPA),
National Taiwan University

No.1, Sec.4, Roosevelt Road, Taipei 10617, Taiwan

²Institute of Laser Engineering (ILE) and Faculty of Engineering, Osaka
University

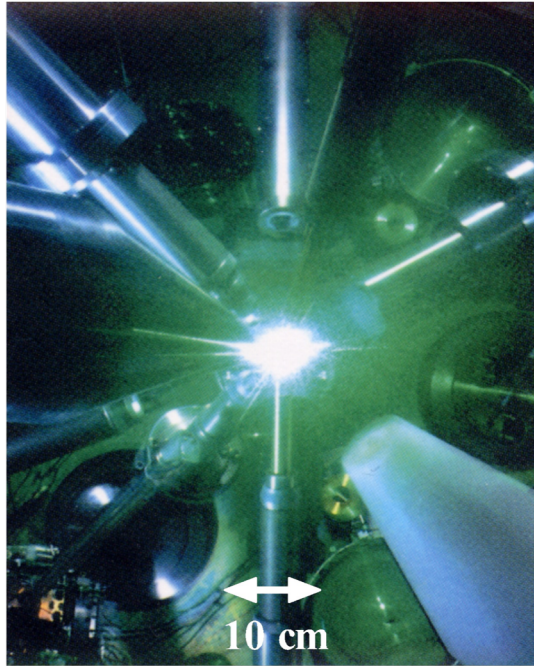
Suita Osaka 565-0871, Japan

(Colloquium, Academia Sinica, June 14, 2022)

Outline of my talk

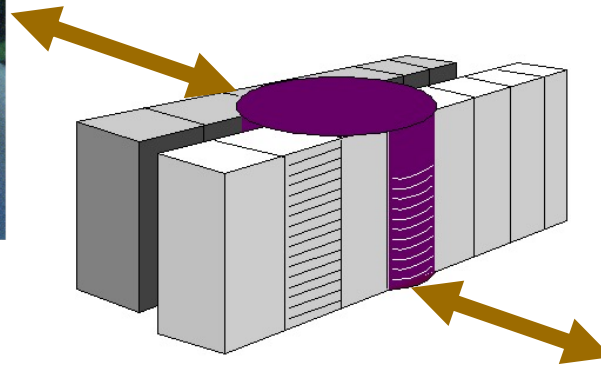
- Motivation
- Collisionless shock formation by 2-D PIC simulation 1. 2D PIC simulation
- Experimental demonstration: We need the biggest laser NIF in LLNL
- International team (ACSEL) lead by Hye Sook Park, LLNL.
- Nonlinear Weibel and shock formation are observed. 2. NIF experiment
- Theory of inverse-cascade magnetic turbulence is proposed to explain PIC and experimental results. 3. Theory development
- It gives k^{-2} power law spectrum of B-energy. It looks universal in many cases.
- Particle acceleration is also observed.
- Conclusion

What is Laboratory (Laser) Astrophysics ?

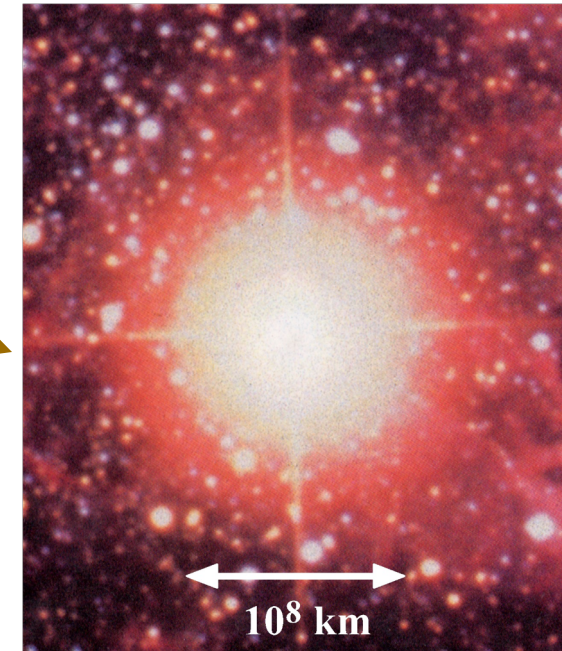


Model Experiment

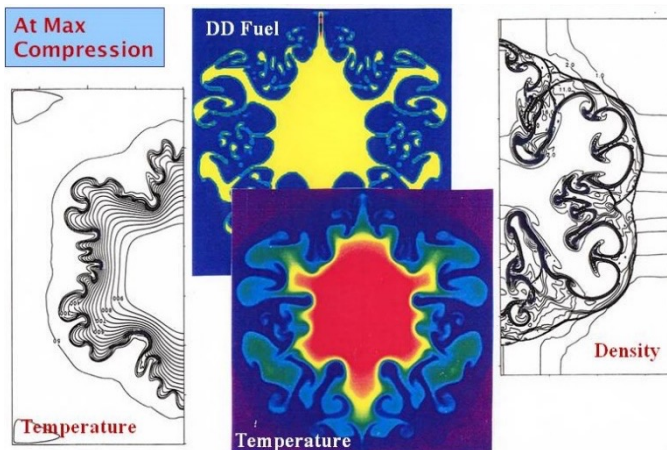
1. Test bed for Numerical Astrophysics
2. New Finding of Physics not Expected
3. Prediction of Astrophysical Phenomena
4. Providing Challenging Plasma Physics



Supercomputer

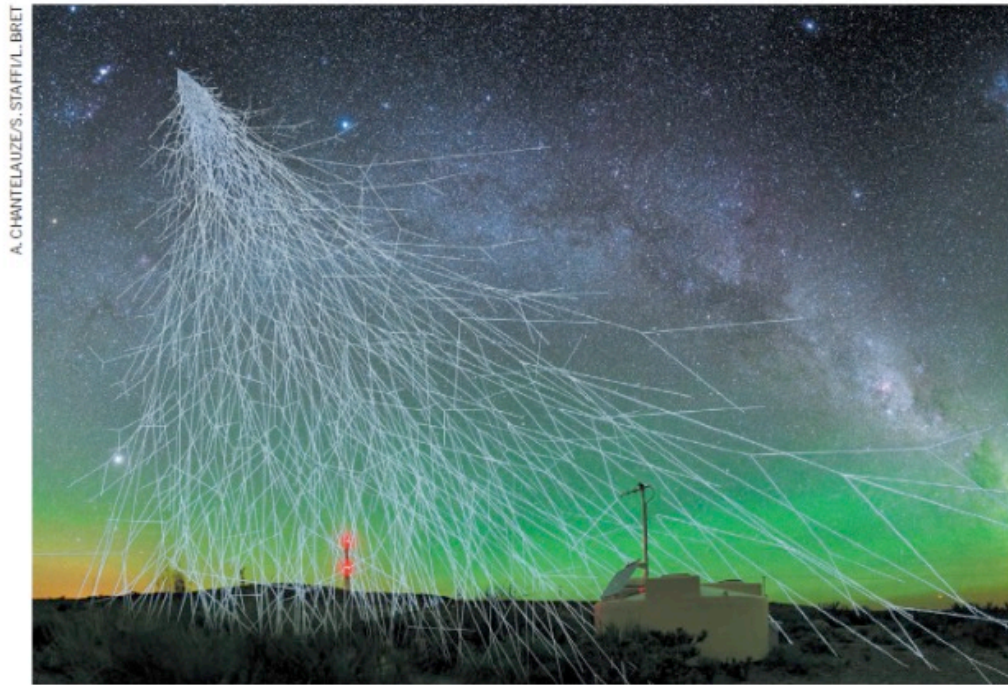


Supernova 1987A



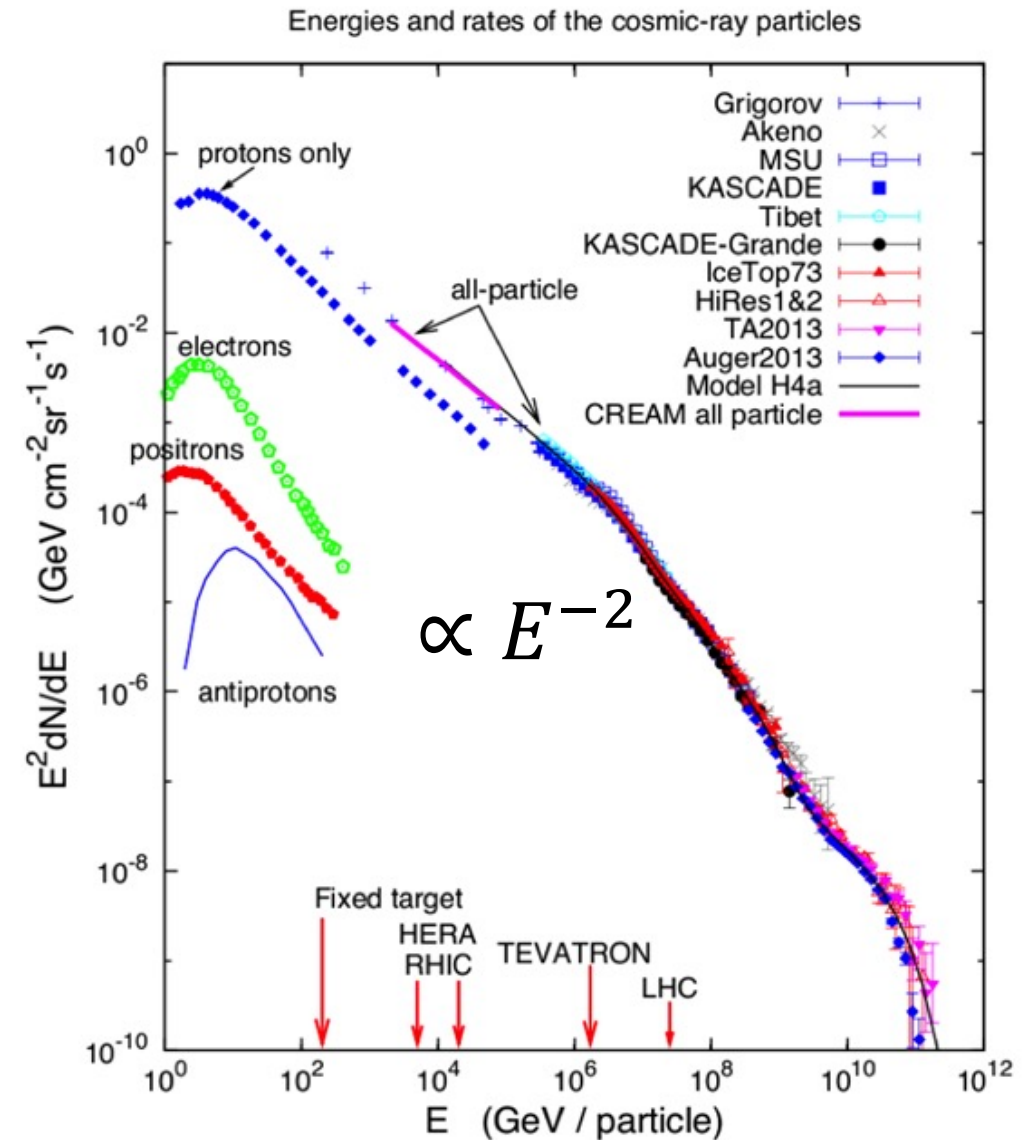
Space & Time ($\times 10^{14}$)

Physics of Cosmic-rays is a key issue in Universe, Space, and Laboratory



An artist's impression shows how a high-energy cosmic ray creates a broad spray of particles.

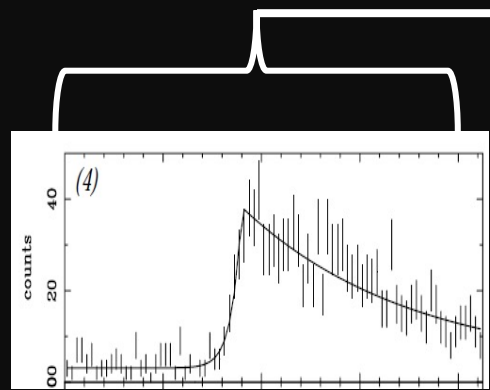
D. Castelvechi, Nature **549**, 440 (2017).



T. Gaisser, arXiv:1704.00788v1, astro-ph.HE (2017)

Supernova Remnant
SN1006 (Newton X-ray S)

$$E=10^{44}\text{J}$$

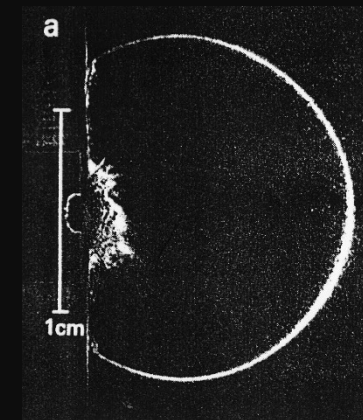


Synch. X-rays
(blue: tracing $\sim 10\text{TeV } e^-$)

Cassam et al. ApJ **680**, 1180 (2008)

Big difference is
not the energy
But the physics

$$E=100\text{ J}$$



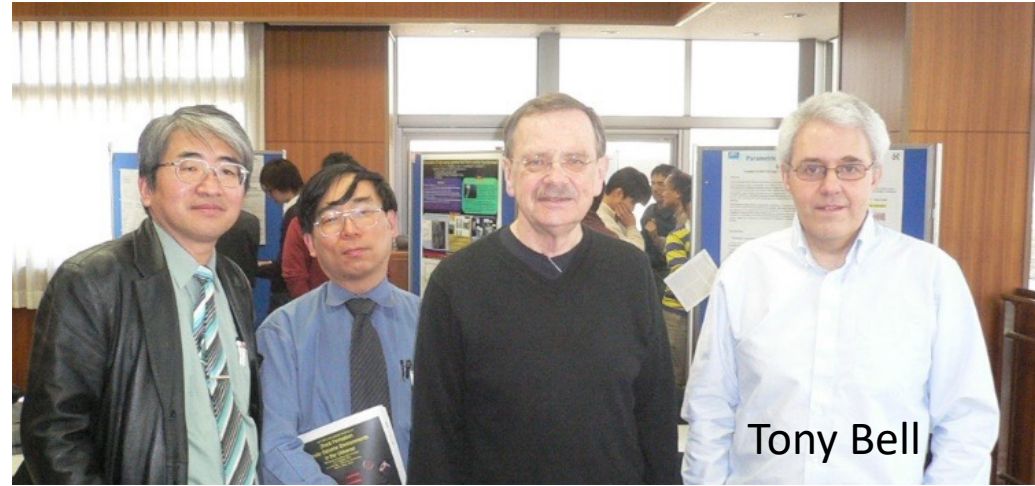
B. Ripin et al.

Theory of 40 years old

Diffusive Shock Acceleration (DSA) Model (1978)

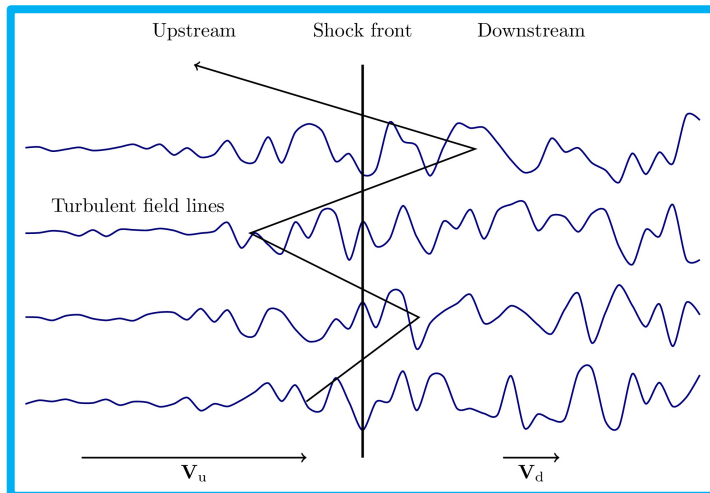
*A. Bell

*Blandford & Ostriker



Tokyo I T, Feb. 22, 2007

$$\frac{\partial f}{\partial t} + (u + v) \frac{\partial f}{\partial z} - \frac{1}{3} \frac{\partial u}{\partial z} p \frac{\partial f}{\partial p} - \frac{\partial}{\partial z} \left(\kappa(z, p) \frac{\partial f}{\partial z} \right) = 0.$$



$$n dp \propto p^{-(r+2)/(r-1)} dp.$$

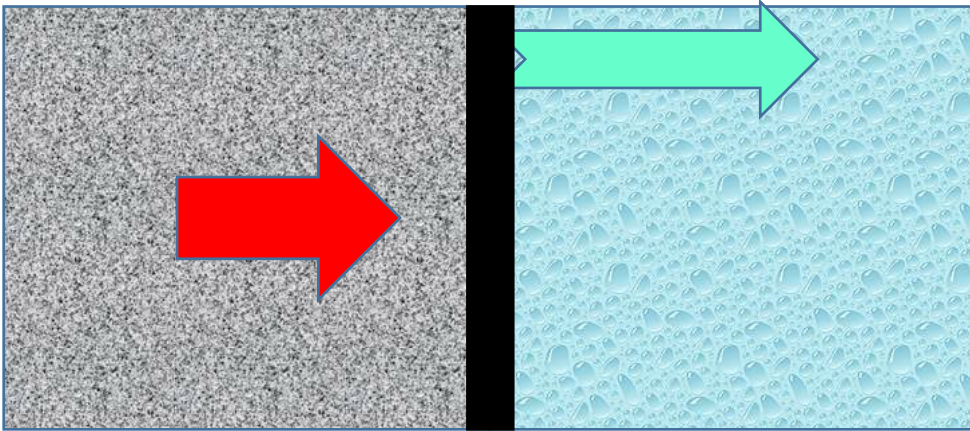
$$[N(E) \sim E^{-2} \text{ for } r=4]$$

E. Fermi, *Astrophys. J.* **119**, 1 (1954).

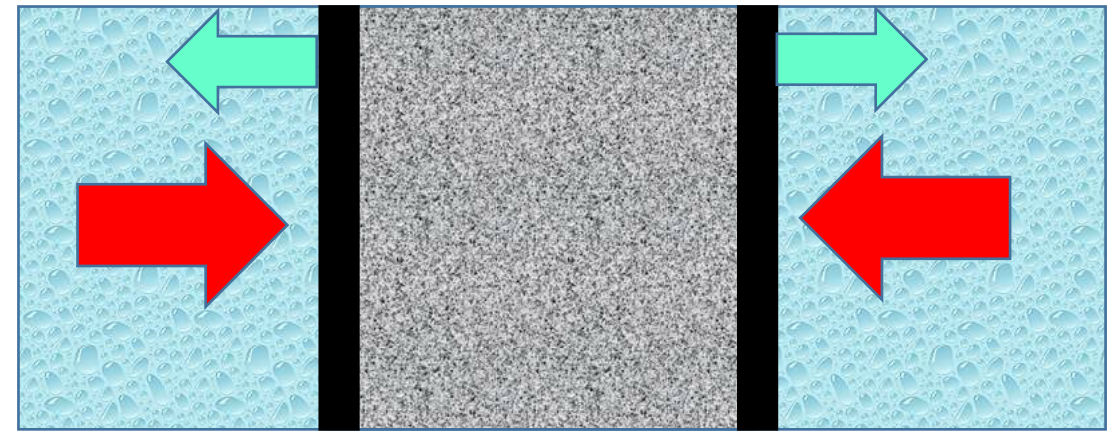
A. R. Bell, *Mon. Not. R. Astro. Soc.* **182**, 147 (1978).

K. M. Shure et al., *Space Science Review* **173**, 491 (2012)

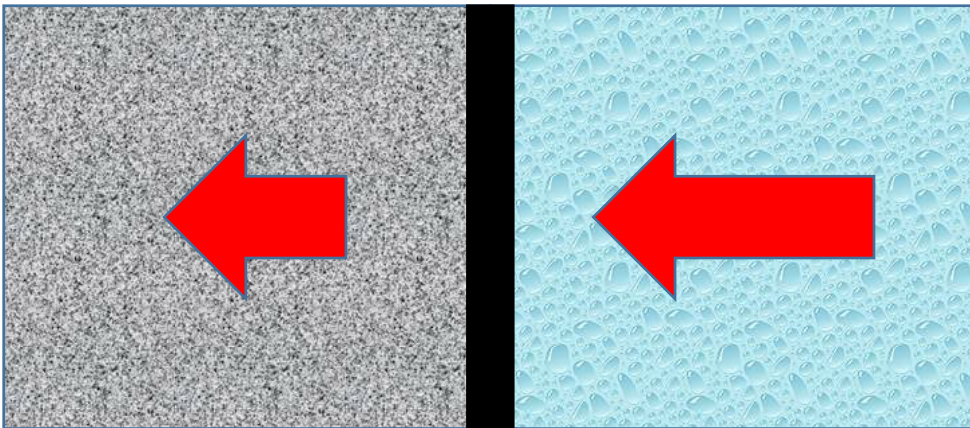
SNR shock



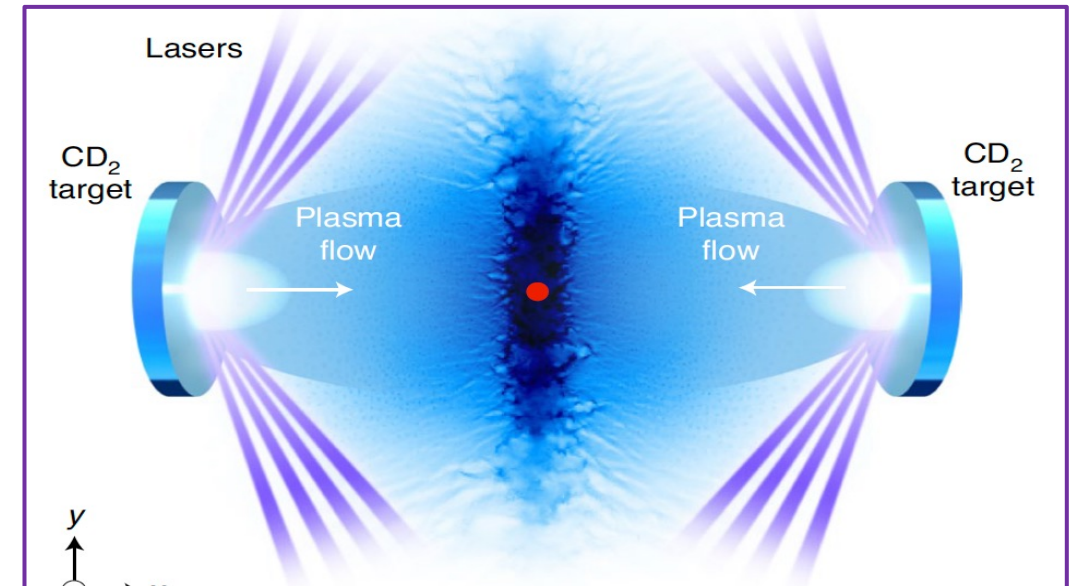
Counter streaming plasmas

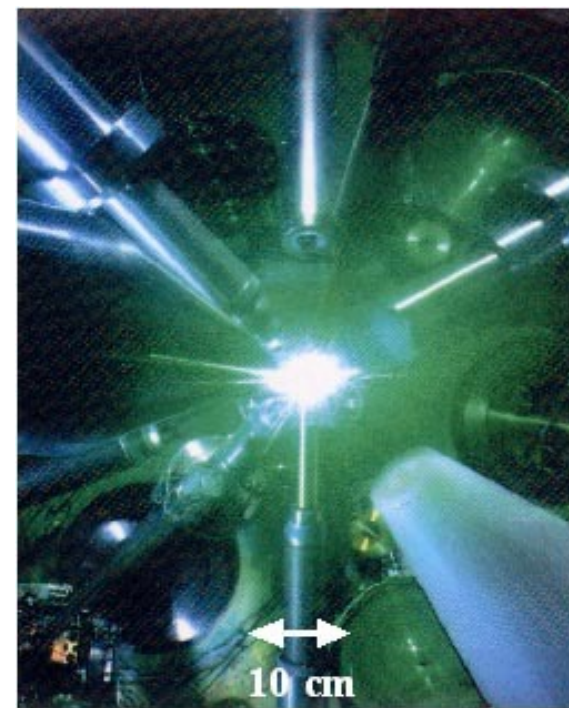
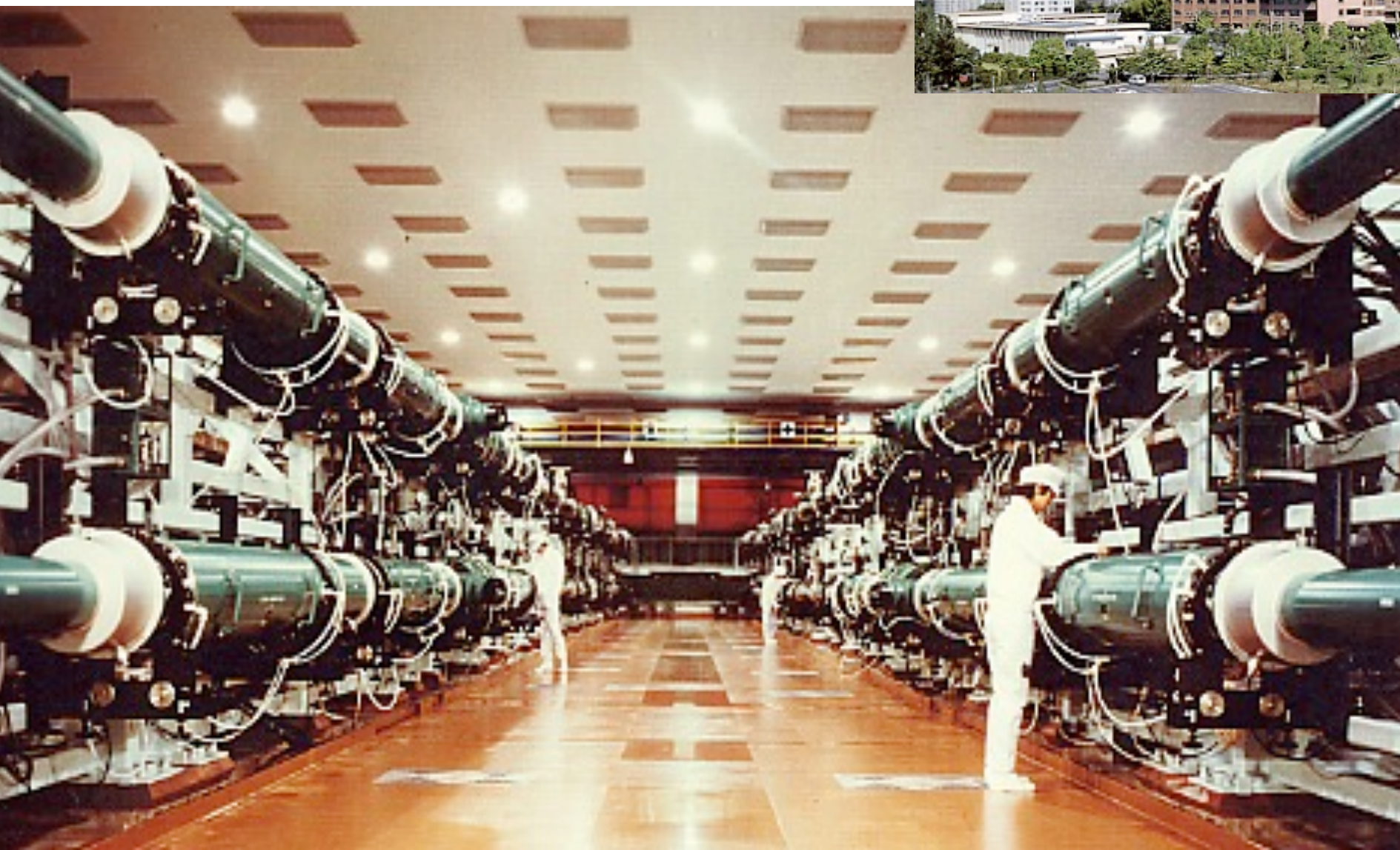


Shock frame



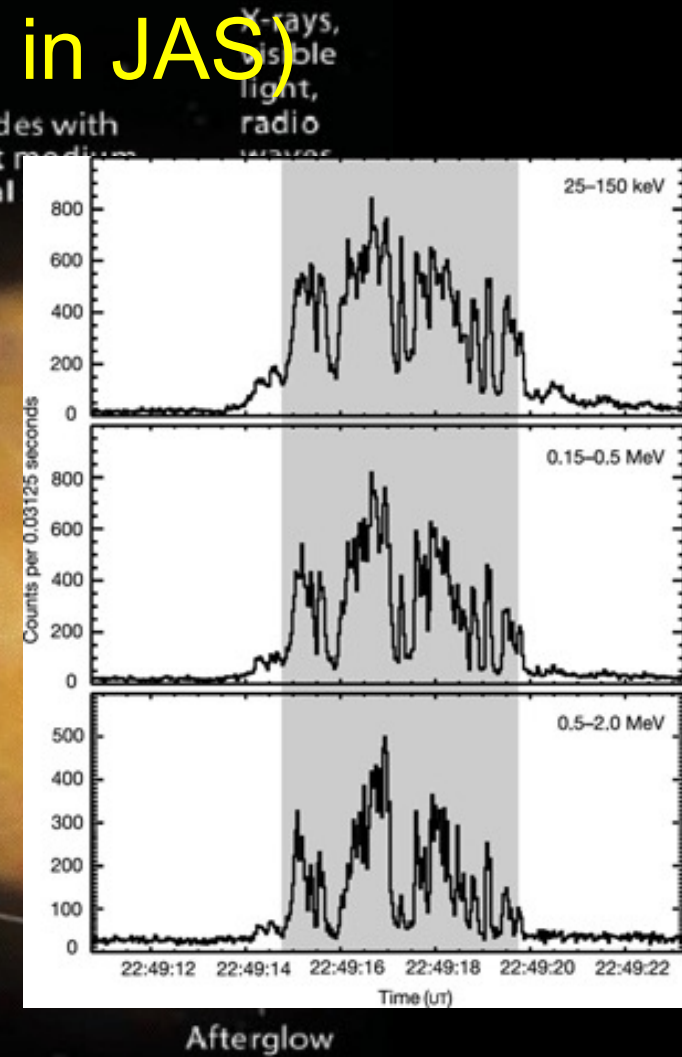
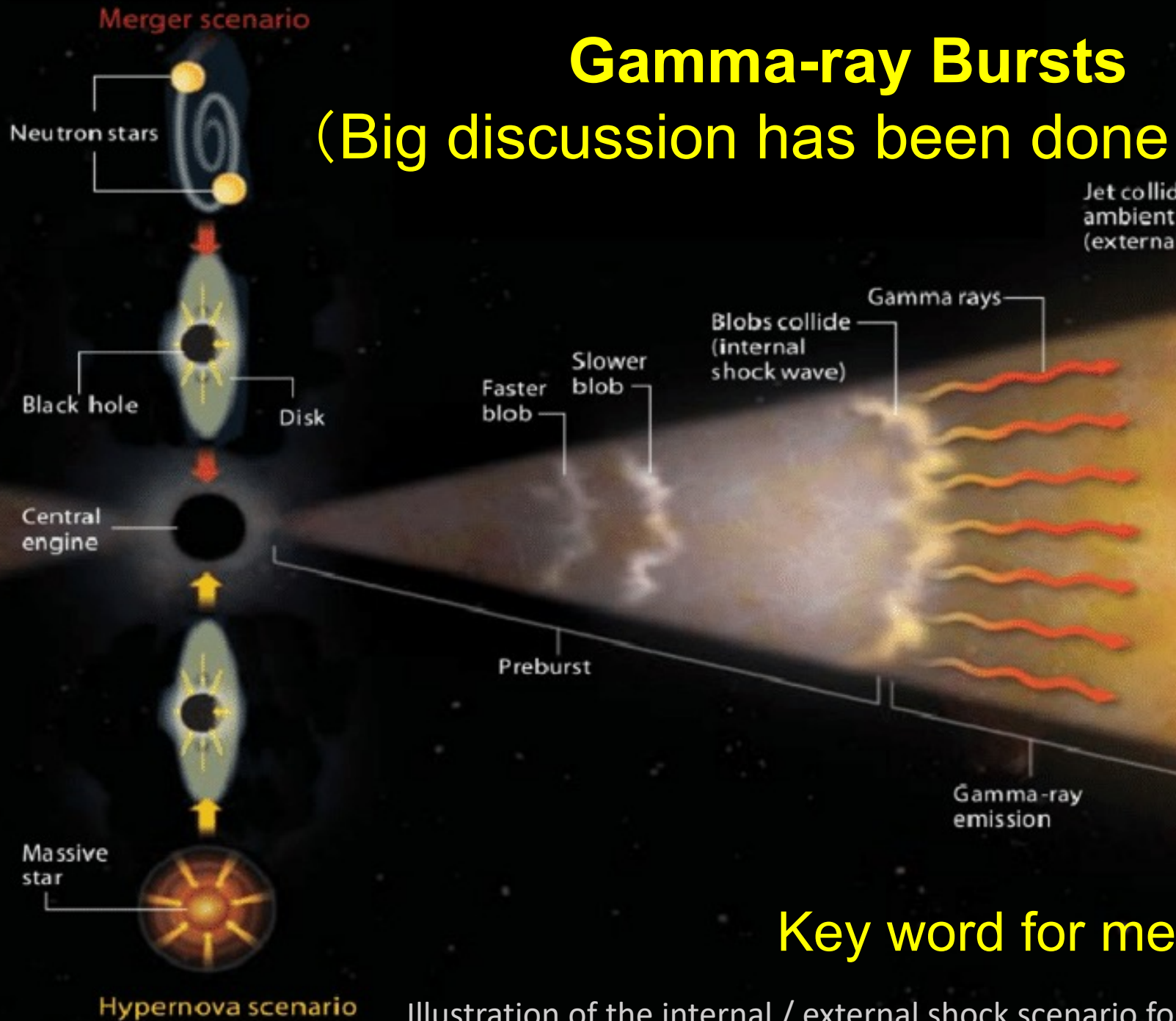
Laser ablation experiments





Gamma-ray Bursts

(Big discussion has been done in JAS)



Key word for me; Weibel instability

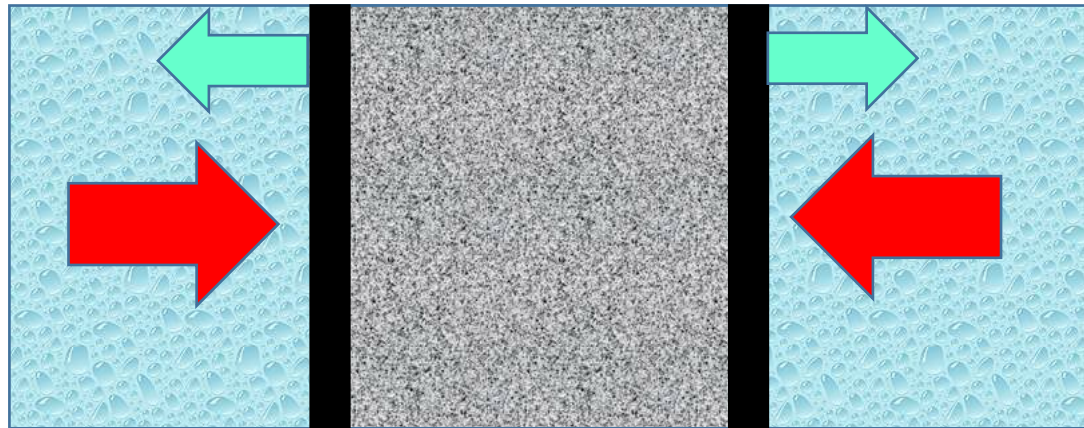
Illustration of the internal / external shock scenario for gamma-ray bursts (credit NASA).

2-D PIC simulation

This is a gamble

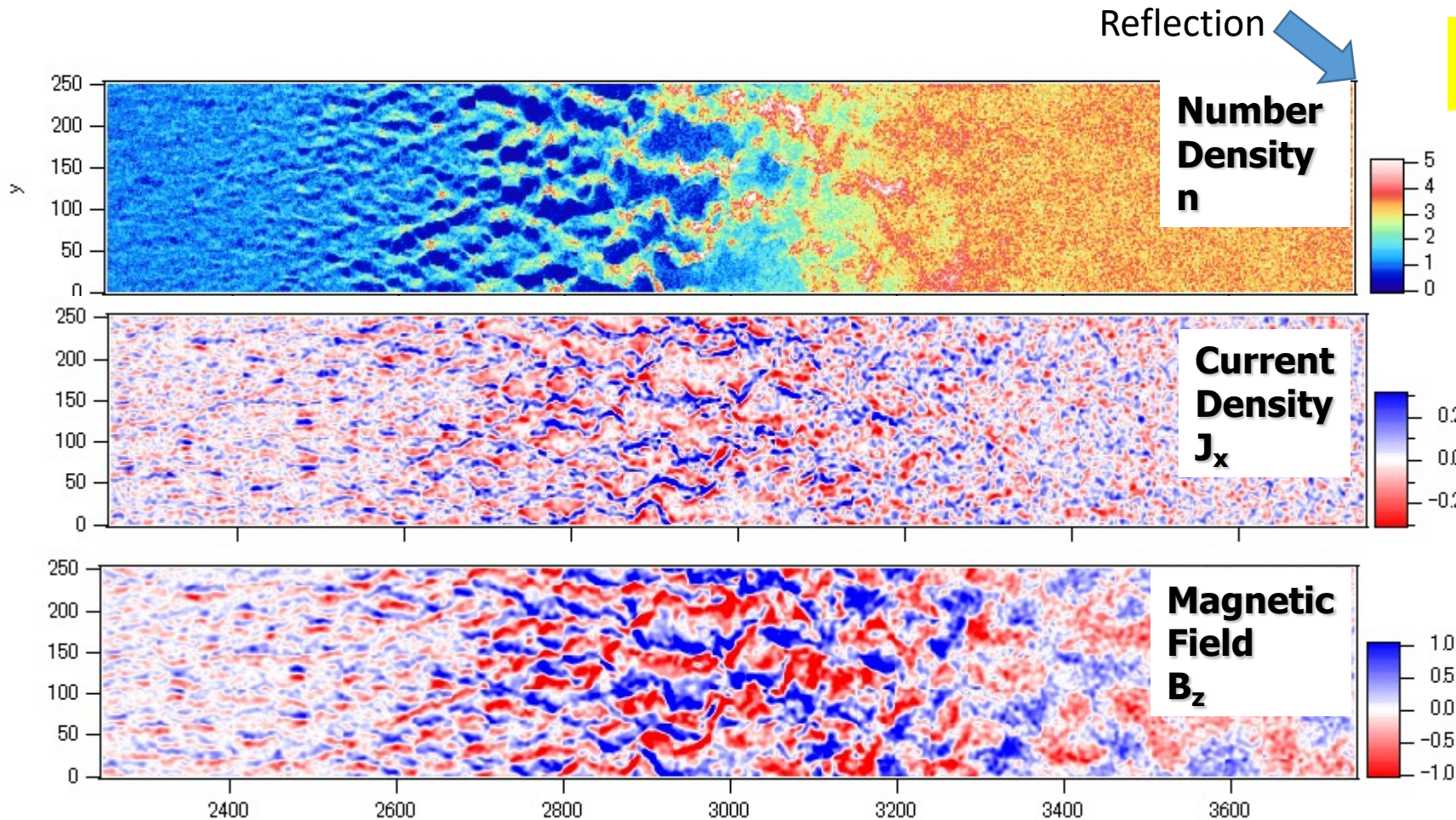
1. Two-stream electro-static instability is dominant than Weibel magnetic instability in non-relativistic regime?
2. How long we have to wait for ion Weibel instability to grow turbulent then to form shock waves?
3. Can we make collisionless counter streaming plasmas?
4. How much laser energy is necessary to see the shock formation?

Counter streaming plasmas



$V=1000 \text{ km/s}$
Ion-electron flow
Ion Weibel instability

NON-RELATIVISTIC COLLISIONLESS SHOCKS IN UNMAGNETIZED ELECTRON-ION PLASMAS



Electron Weibel (linear)

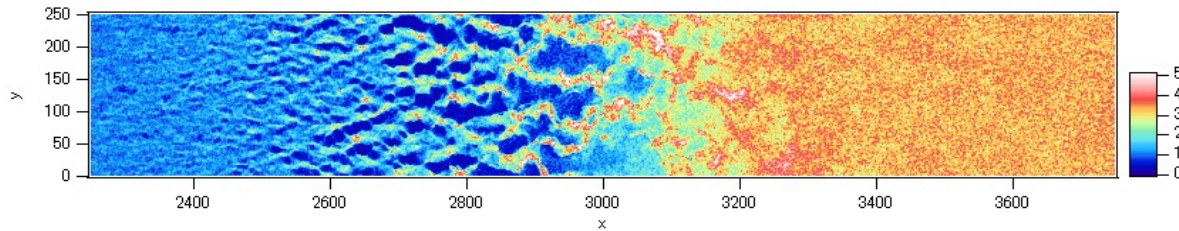
E. S. Weibel PRL 2, 83 (1959)

Ion Weibel (2D PIC)

- T. N. Kato and H. Takabe, Astrophysical J 681, L93-L96, (2008).
- H. Takabe et al., Plasma Phys. Control Fusion 50, 124057 (2008).

Magnetic turbulence sustains shock structure (Chao and Order)

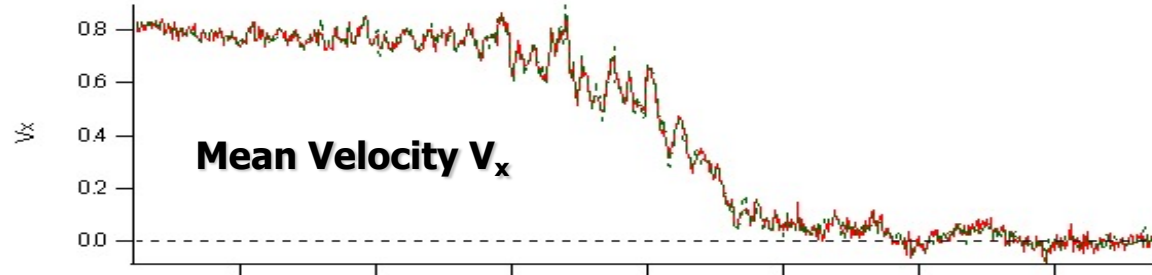
Transition Region



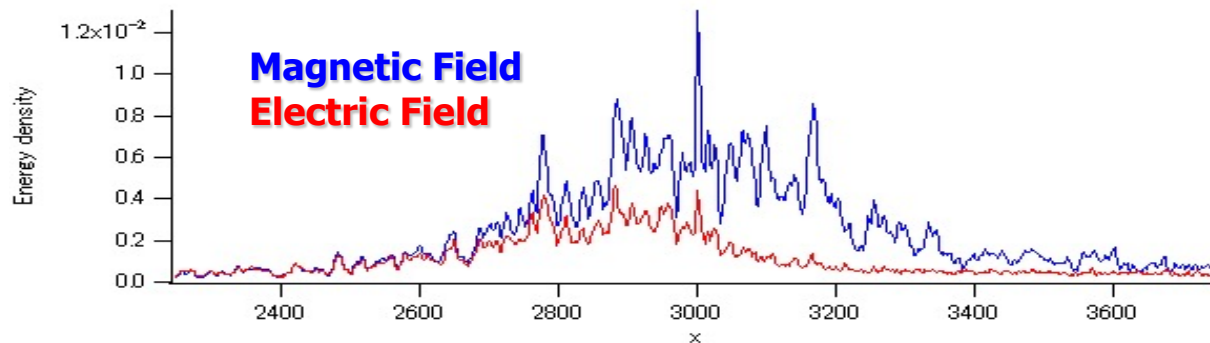
Number Density



Mean Velocity V_x



Magnetic Field Electric Field

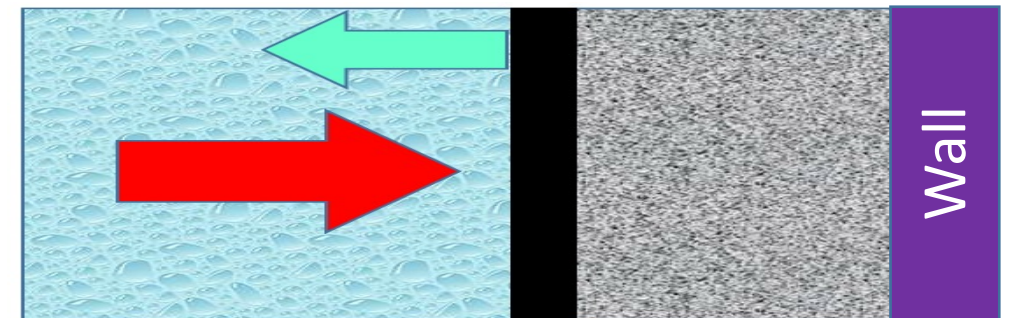


x

Only 1% of flow energy

Shock Wave Formation and Profiles

Strong magnetic field provides an **effective dissipation mechanism** for the upstream plasma



Phase space V_x and X

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$\omega_{pe}t=2100$

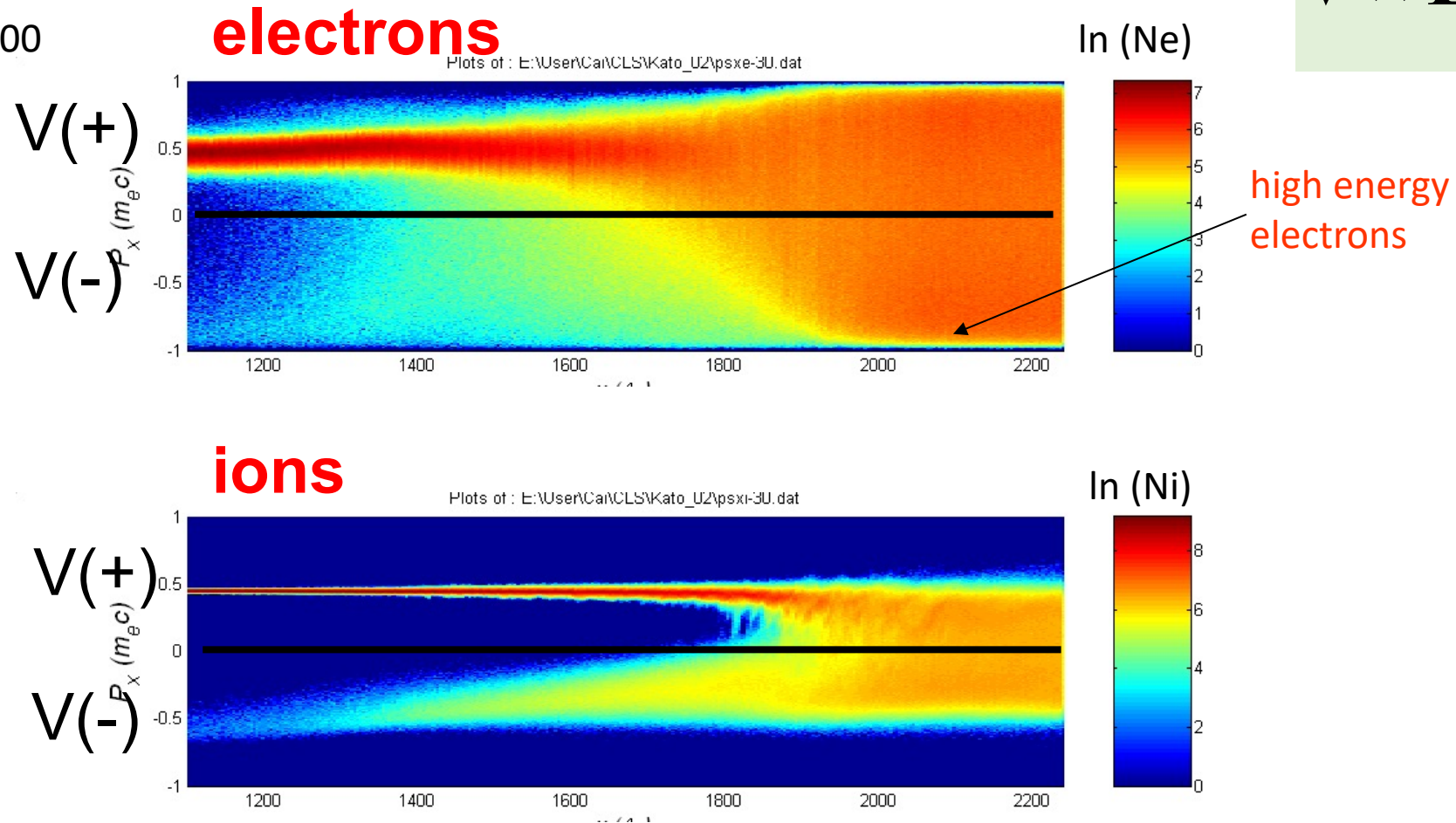


Fig. (A) shows that a large fraction of electrons have been accelerated to light velocity in the shock transition region. However, the acceleration mechanism is not very clear. It may due to the shock acceleration!

Gekko-XII is too small

We Need NIF to Demonstrate Universality (2008)

1. Shock width

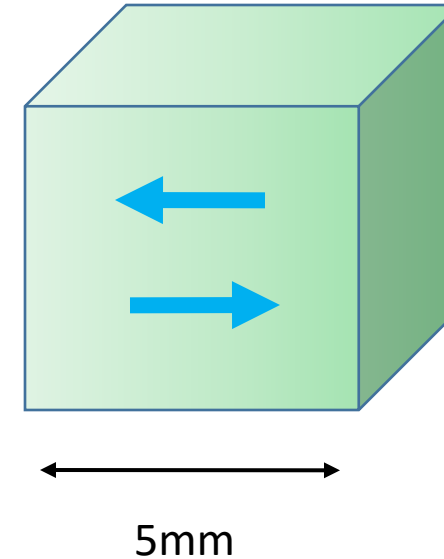
$$\Delta X = 0.2 \text{ cm} \times \frac{1}{Z} \sqrt{\frac{A}{n_{20}}}$$

2. Coulomb mean-free-path

$$l = \frac{1}{n\sigma_0 \ln\Lambda} = 20 \text{ cm} \times \frac{A^2 V_8^4}{Z^4 n_{20}}$$

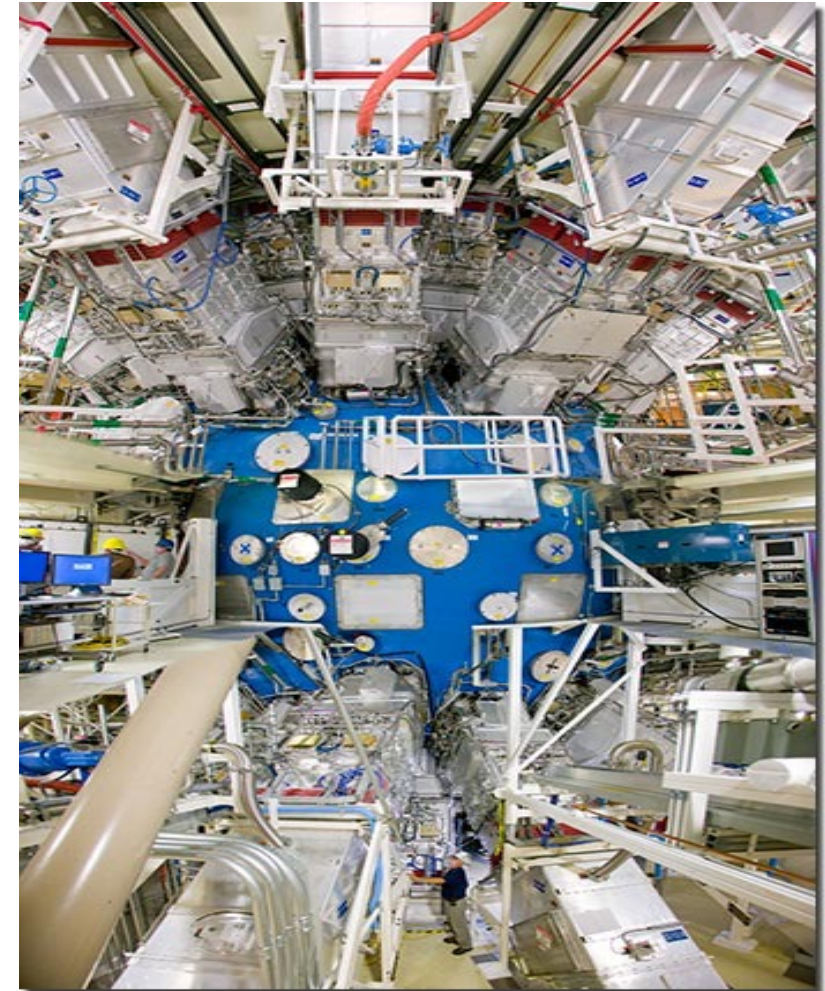
3. Energy of counter-streaming plasma

$$\begin{aligned} E &= Z m_p n_i V^2 L^3 \\ &= 70 \text{ kJ} \end{aligned}$$



$$\begin{aligned} n_{20} &= n / 10^{20} \text{ cm}^{-3} \\ V_8 &= V / 10^8 \text{ cm/s} \end{aligned}$$

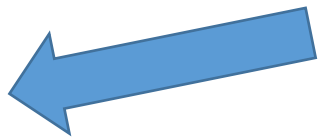
National Ignition Facility at Lawrence Livermore National Laboratory, CA, USA



Cost: USD 4 Bill.
3 shots/day, USD 0.5 Mill./shot

$$\frac{1}{2}MV^2 = E_L = 1.8 \text{ [MJ]}$$

$M=1000\text{kg}$
 $V=200\text{km/h}$



NIF Experiment

Science on NIF Committee just after the Evaluation

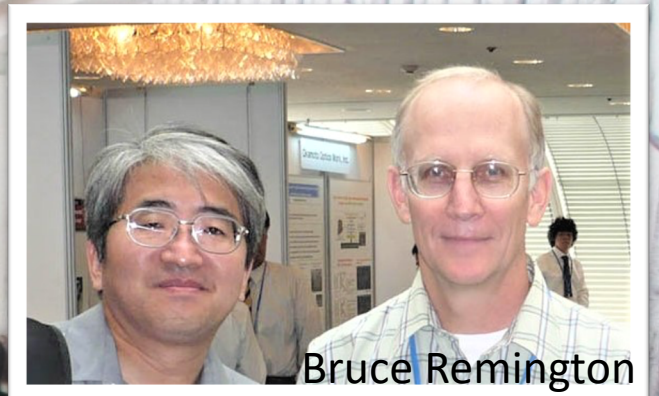
July 15, 2010 at LLNL

David Arnett*, University of Arizona
Riccardo Betti, University of Rochester
Roger Blandford, Stanford University
Nathanial Fisch, Princeton University
Ramon Leeper, Sandia National Lab.
Christopher McKee, UC Berkeley

Mordecai Rosen, LLNL
Robert Rosner, The Univ. of Chicago (Chair)
John Sarrao, Los Alamos National Laboratory
Hideaki Takabe, ILE, Osaka University
Justin Wark, University of Oxford
Choong-Shik Yoo, Washington State University



ACSEL Lunch Meeting at the 10th HEDLA,
Bordeaux, France , May 14, 2014



Bruce Remington



Y Sakawa

Hye-Sook
Park



ACSEL Project Team List

Japan

Osaka University (Japan):

Y. Sakawa, Y. Kuramitsu, T. Morita, H. Ide, K. Tsubouchi,
Y. Yamaura, T. Ishikawa, T. Norimatsu, N. Ozaki, R. Kodama,
A. Nishida, K. A. Tanaka, T. Sano, T. Moritaka, H. Takabe
T. N. Kato; Y. Matsumoto

Hiroshima U; Chiba U (Japan) :

M. Hoshino, Y. Ono; T. Sugiyama

U. Tokyo (Japan); JAMSTEC (Japan) :

N. Ohnishi ; A. Mizuta; H. Yoneda, K. Nagamine

Tohoku U; KEK; U Elect. Comn (Japan) :

Kyusyu University (Japan):

K. Tomita, K. Inoue, R. Shimoda, K. Uchino, S. Matsukiyo

York University (UK):

N. Woolsey, C. Gregory, J. Waug, R. Crowston

Oxford University(UK):

G. Gregori, C. Murphy, A. Bell, H. Doyle, J. Meinecke

LULI (France); CEA (France) :

M. Koenig, A. Ravasio, A. Pelka, A. Diziere; B. Loupias

LUTH (France):

C. Michaut, P. Barroso

ETH Zurich (Switzerland):

F. Miniati

IOP (China) ; NAO (China) :

D. Yuan, Q. Dong, Y. Li; J. Zhong, K. Zhang, F. Wang

Shanghai Jiao Tong University (China) :

J. Zhang

LLNL (USA):

H-S. Park, D. Ryutov, B. Remington, S. Pollaine,

S. Ross, N. Kugland, C. Plechaty

Princeton University (USA):

A. Spitkovsky, L. Gargate, L. Sironi, H. Ji

LLE, Univ. of Rochester (USA):

D. Froula, J. Knauer, G. Fiskel

Rice University (USA):

E. Liang

University of Michigan (USA):

E. Rutter, M. Grosskopf, C. Kuranz, P. Drake

University of Nevada, Reno (USA):

R. Presura

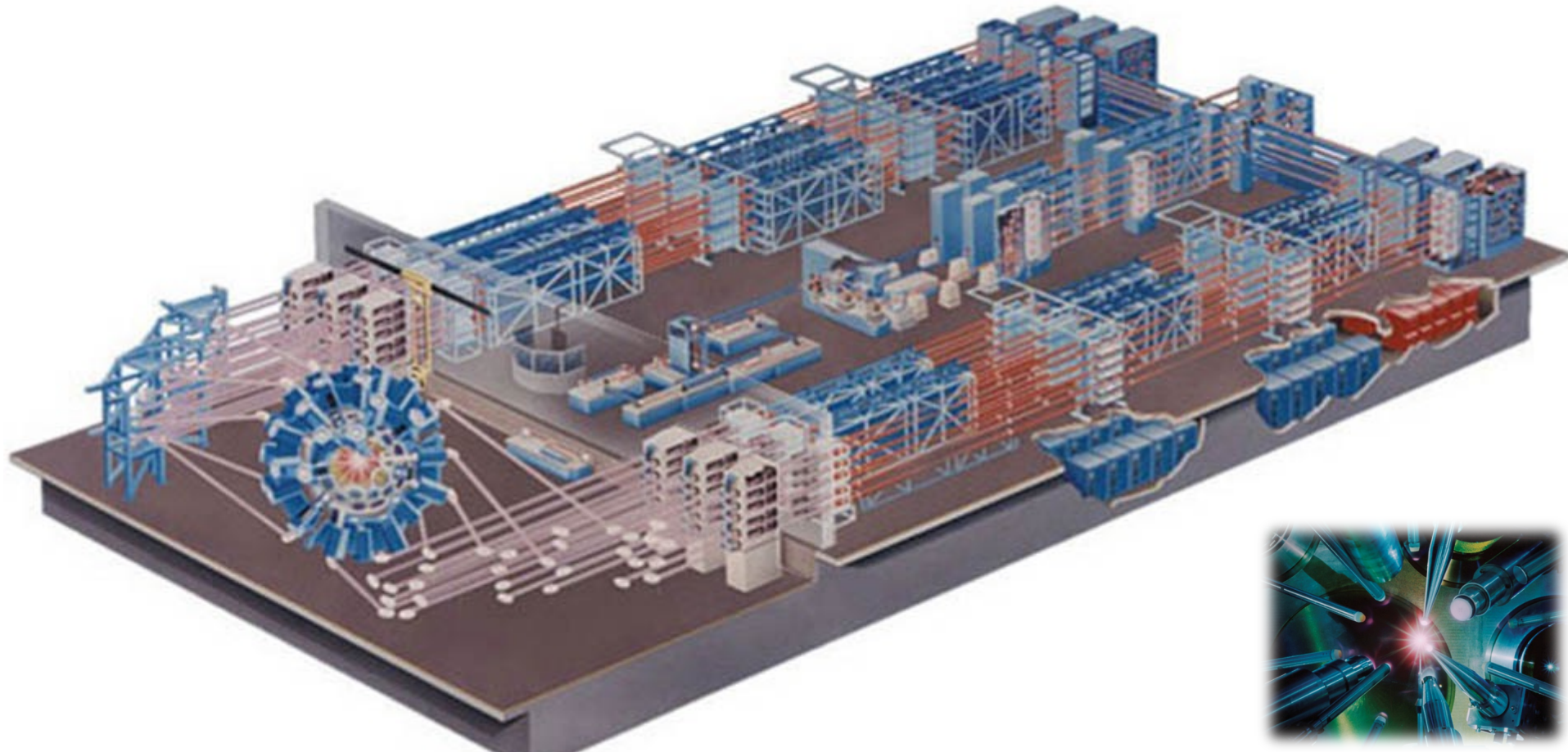
EU

China

USA

8. 8 Omega Experiments

OMEGA Laser at U of Rochester, NY, USA



NL Kugland,H Takabe, HS Park “Self-organized electromagnetic field structures in laser–produced counter– streaming plasmas”, **Nature Physics** 8, 809–812 (2012)

Y. Sakawa



Y Kuramitsu

by eugene kowalik outside the OMEGA Control Room

OMEGA experiment (2011)



2014



NIF experiment (2014)



OSAKA UNIVERSITY



UNIVERSITY OF OXFORD



THE UNIVERSITY OF CHICAGO

Lawrence Livermore National Laboratory

THE UNIVERSITY of York

PRINCETON UNIVERSITY



RICE

MIT PSTC



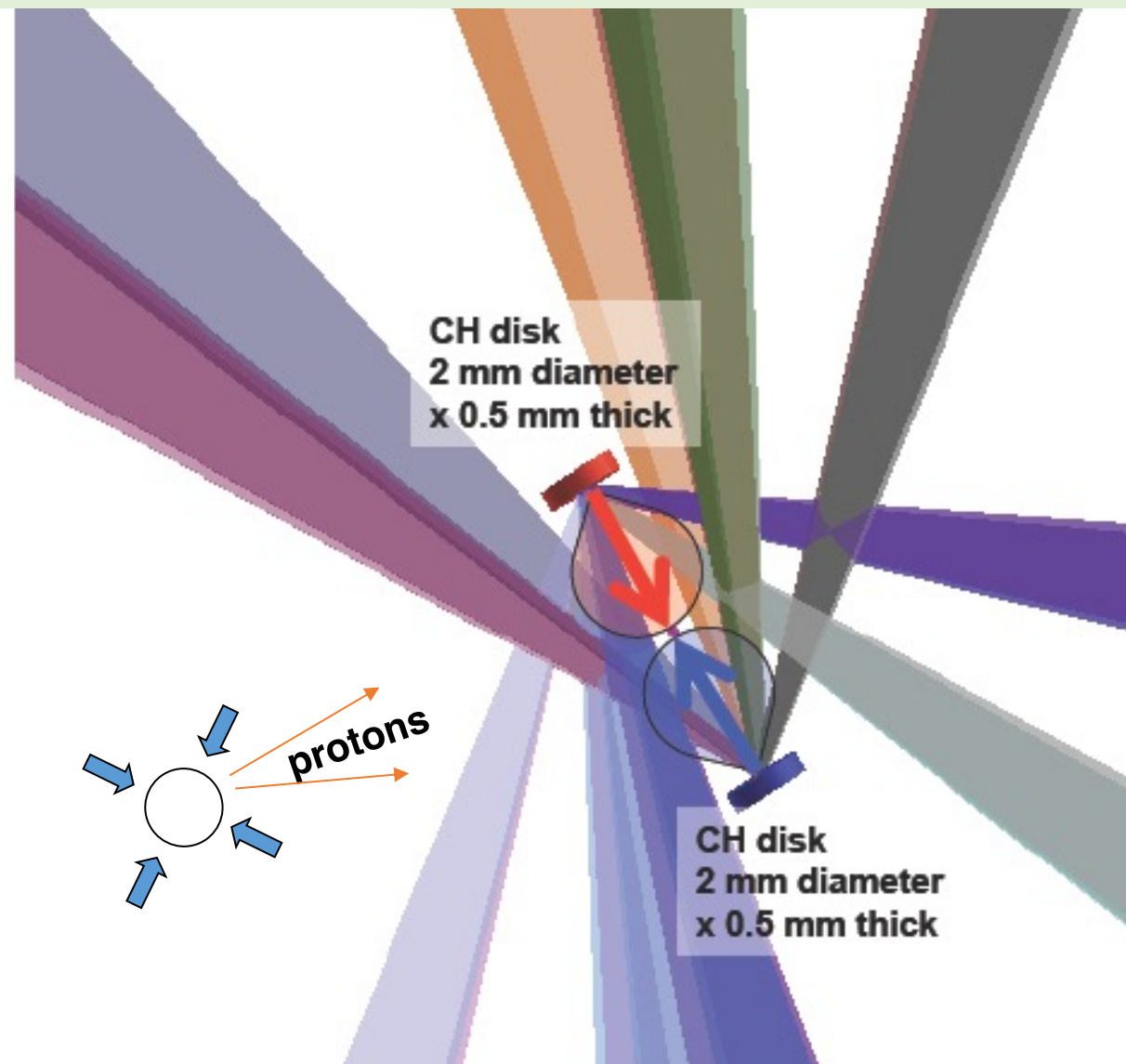
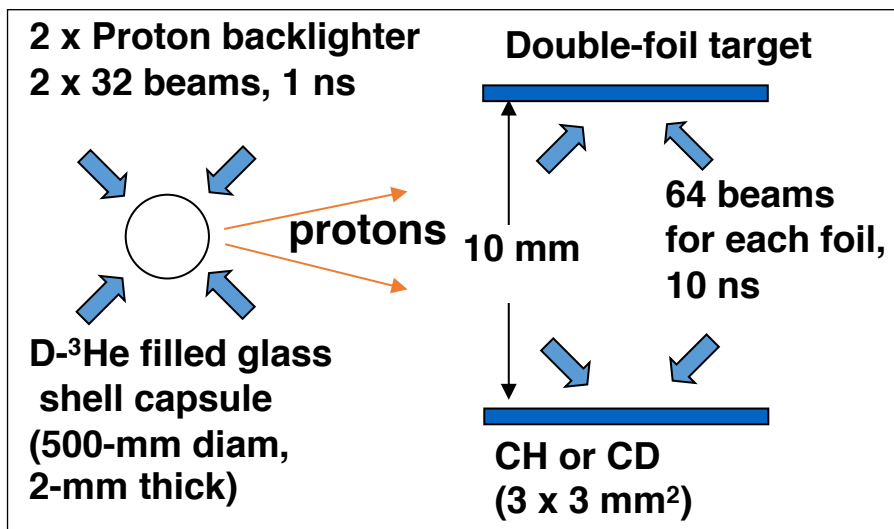
Collisionless shock experiments with OMEGA and NIF

Drive beam

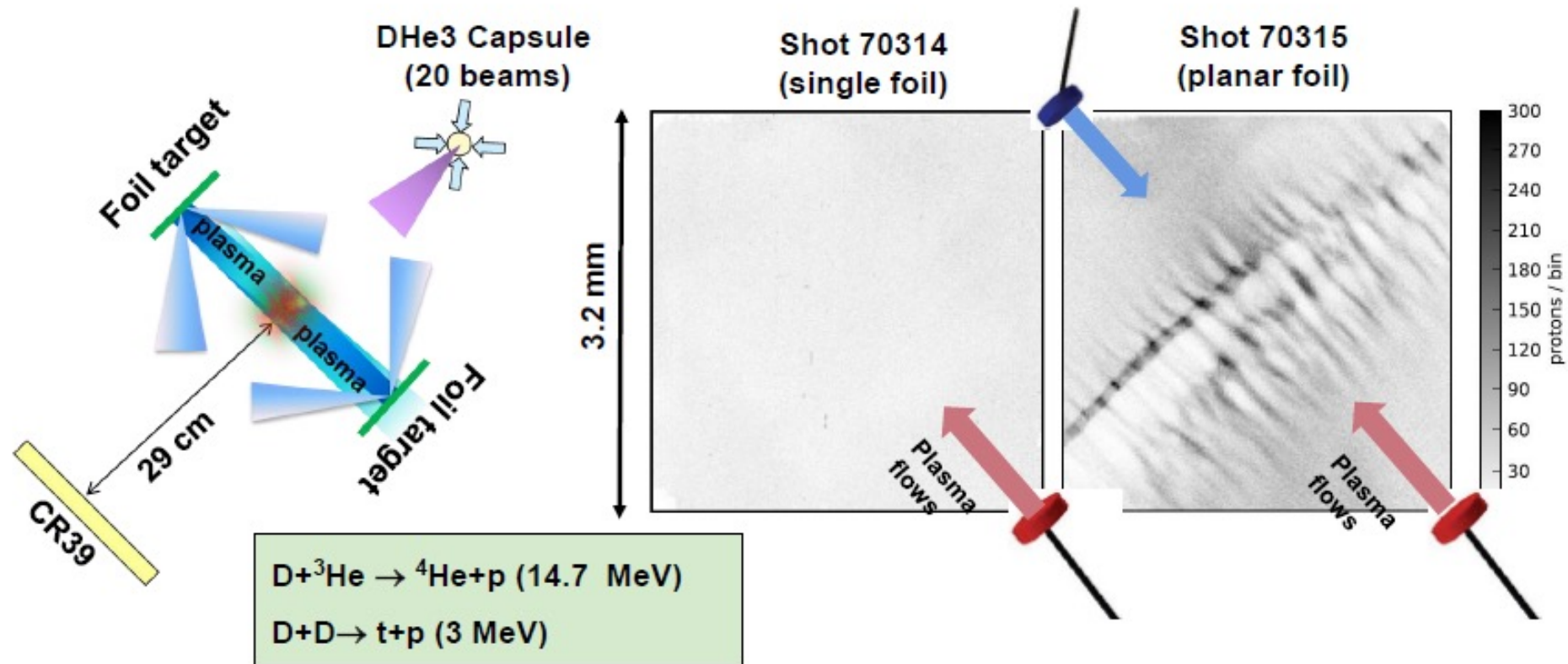
10 kJ/ beam x 64 beams
for each foil, 10 ns

D-He³ implosion beam

1.5 kJ / beam x 64 beams, 1 ns



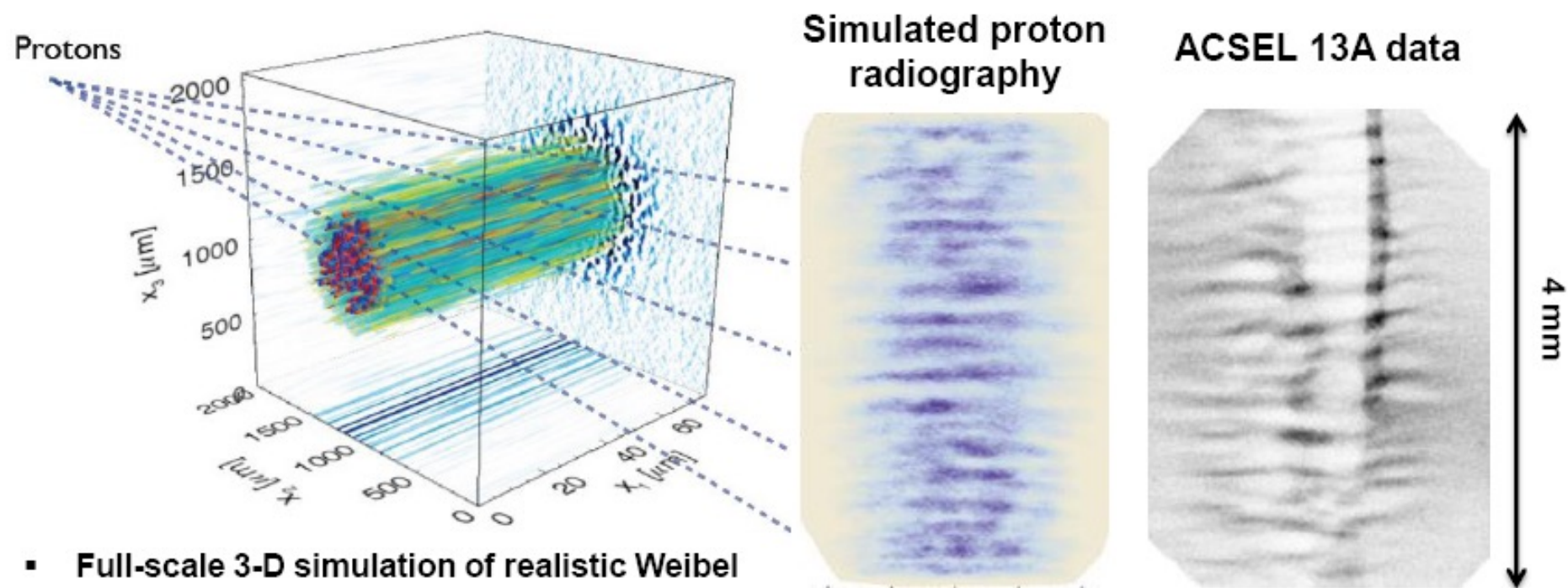
We observe filamentary striations using a mono-energetic proton probe created by a D³He imploding capsule



- DHe3 proton backlighter (14.7 MeV) radiographed the electromagnetic field structures in the middle of the counter streaming plasma flows
- Strong striation features are observed

C. M. Huntington et al, Nature Physics **11**, 173 (2015)

Post-processed full-scale 3D PIC simulations qualitatively reproduce the observed filamentary structures



- Full-scale 3-D simulation of realistic Weibel fields
- 2mm x 2mm extent (from PIC simulation)
- Weibel filamentation size ~200 μm
- $B \sim 0(1)$ MG
- $v/c \sim 3 \cdot 10^{-3}$
- $\text{Ne} \sim 10^{19}/\text{cc}$

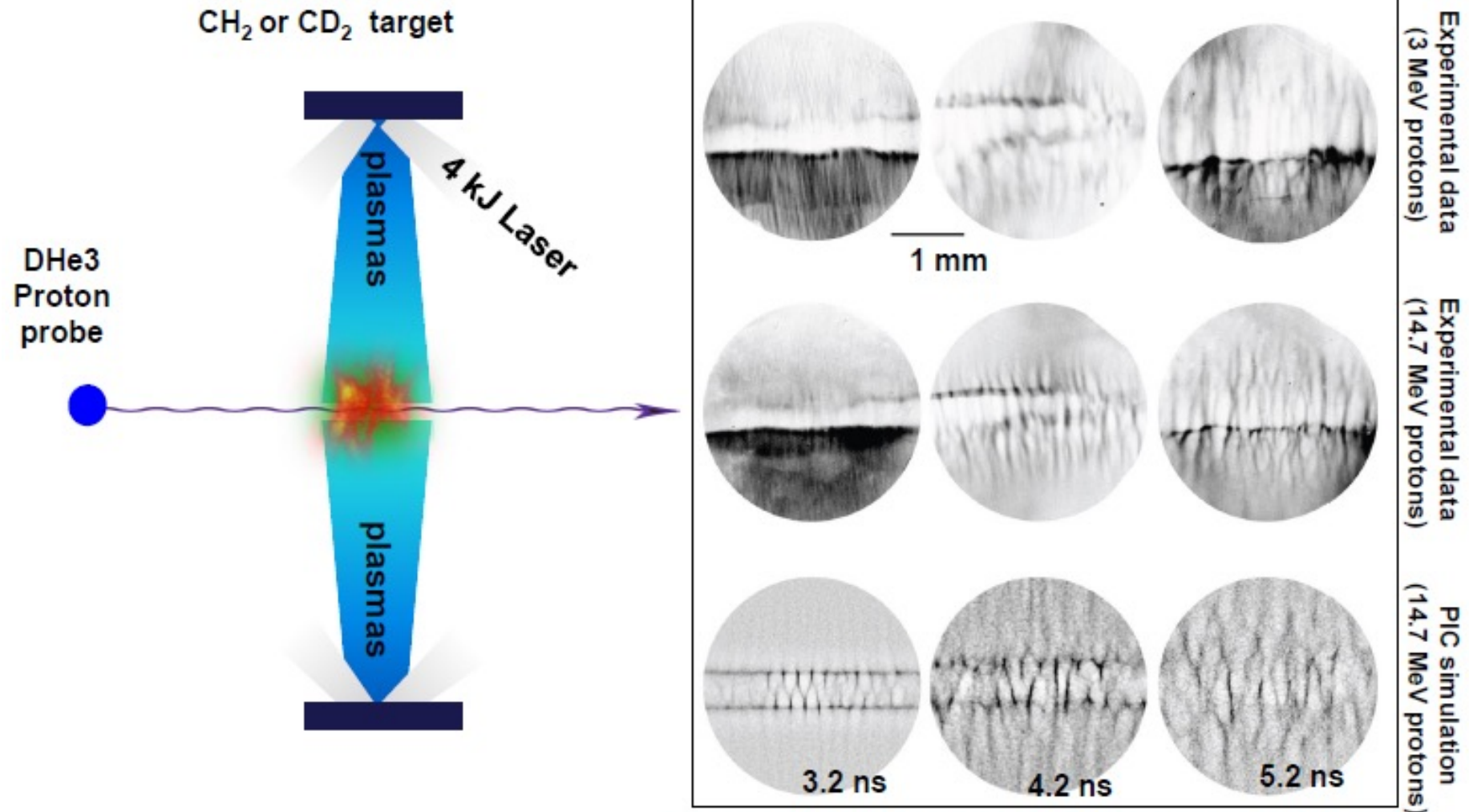
[Levy]

Characteristic wavelength
is ~200 μm

Our data is not inconsistent with Weibel; further investigation is in progress

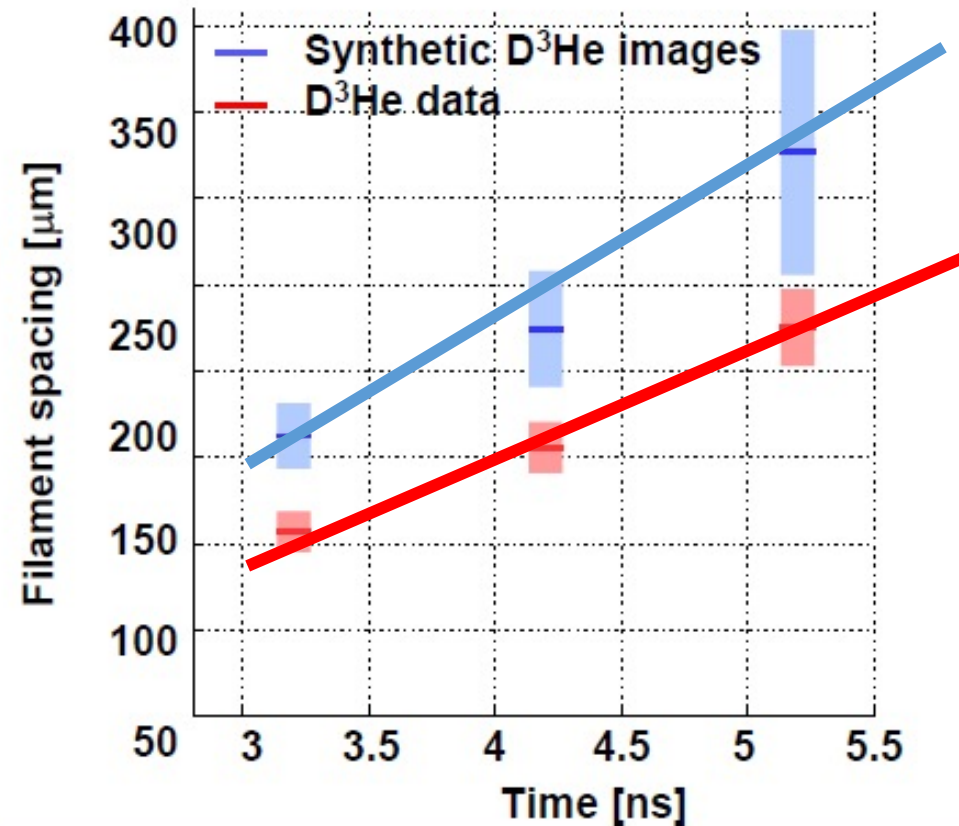
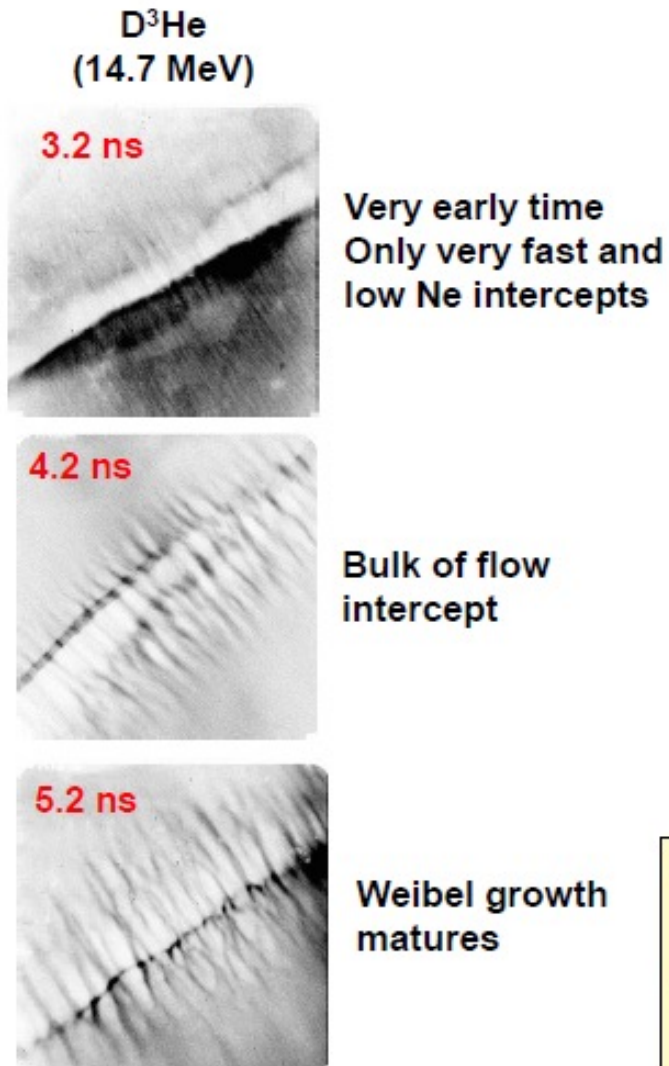
Omega experiments observed clear Weibel filaments from high velocity counter-streaming plasmas using proton probes

C. M. Huntington et al, Nature Physics **11**, 173 (2015)



Proton deflection difference at 3 MeV vs. 14.7 MeV indicate the structures are magnetic fields

OMEGA Experiment



Filament size

$$\langle \lambda(t) \rangle \propto \frac{1}{\langle k(t) \rangle} \propto t$$

$$\left\langle \frac{d\lambda}{dt} \right\rangle = 5.4 \sim 6.0 \times 10^6 \text{ cm/s}$$

- The magnetization level evaluated from the experimental measurement is ~1%
- This indicates that the magnetization observed in GRBs behind the shock is possible

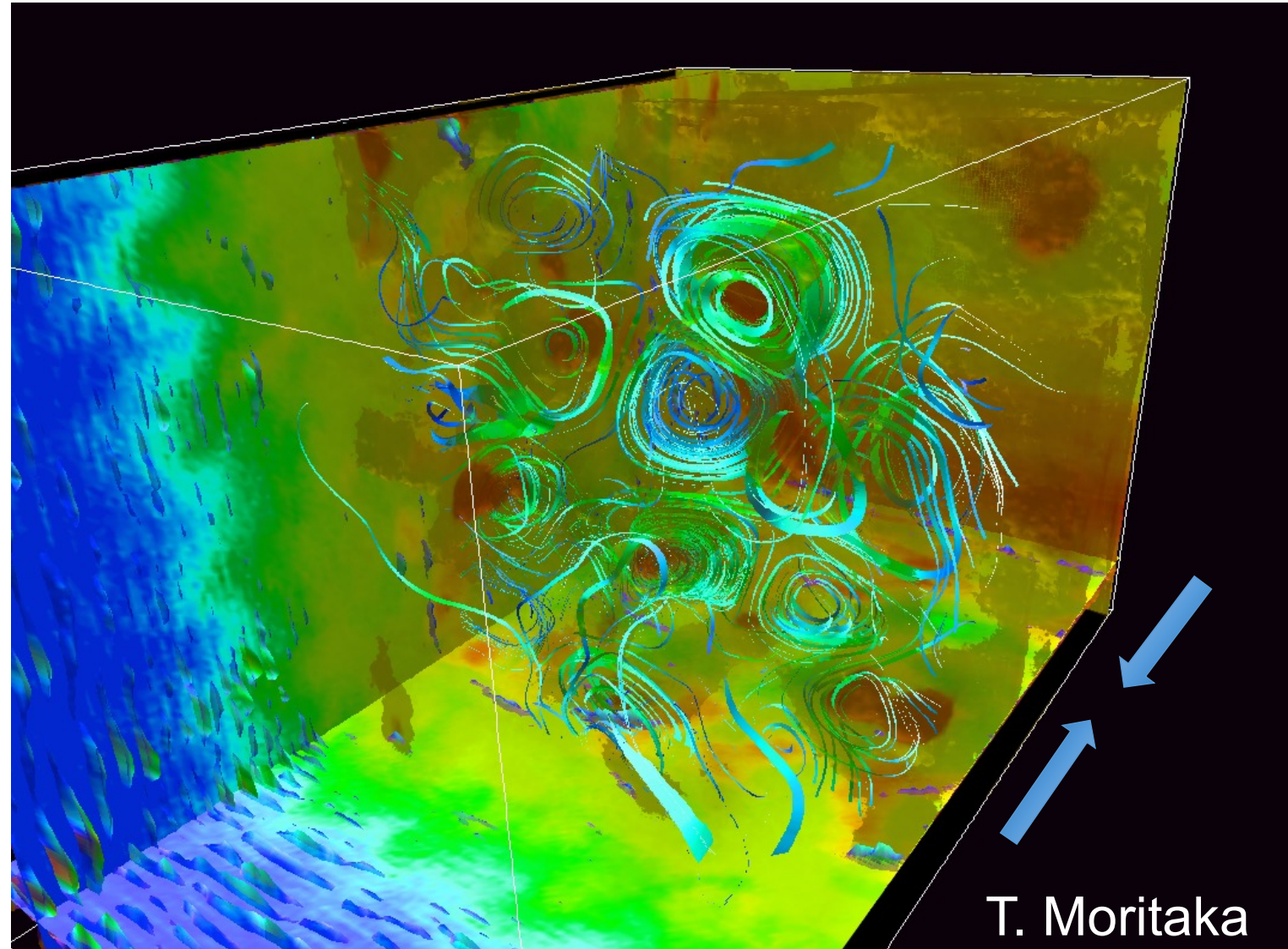
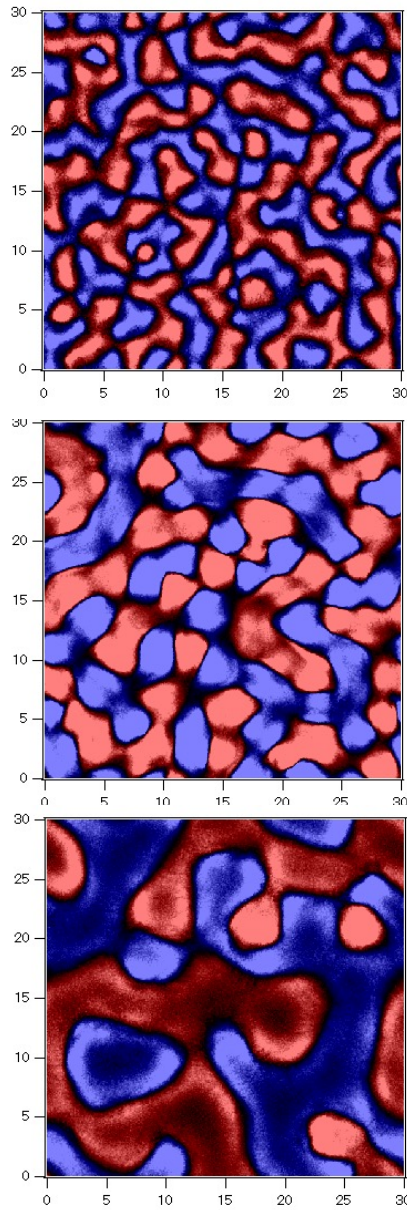
C. M. Huntington et al, Nature Physics, Accepted, Oct 2014

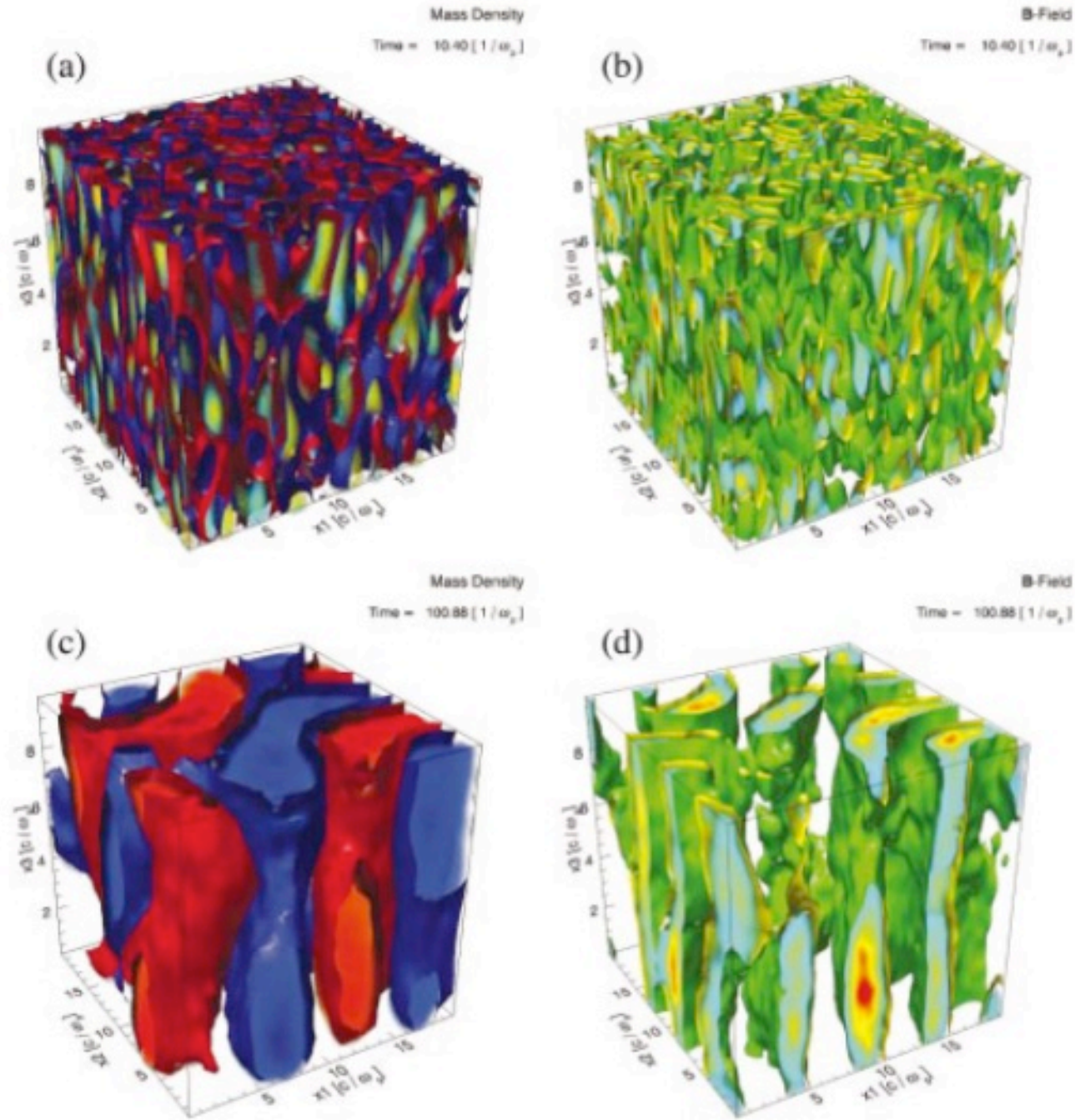
Theoretical model

Bird's eye view of density and magnetic field at shock surface

Current density

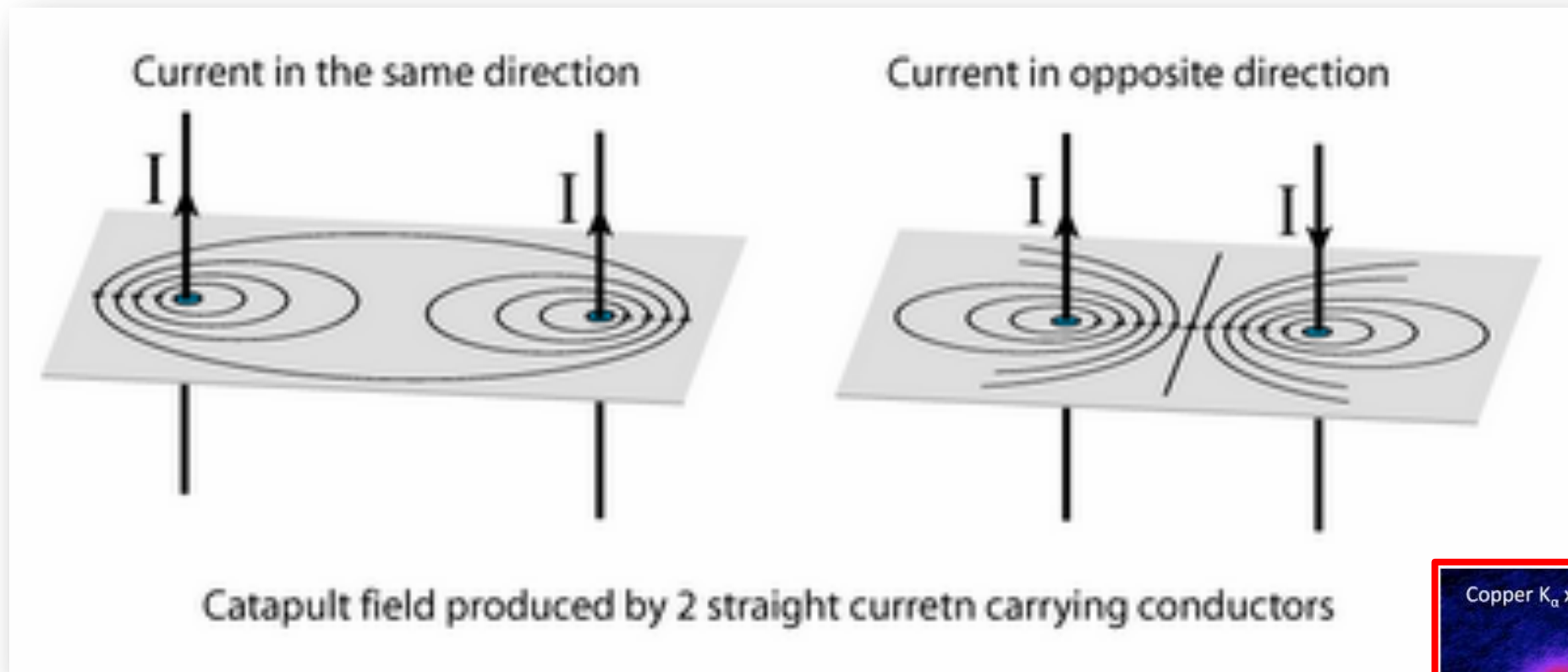
Time





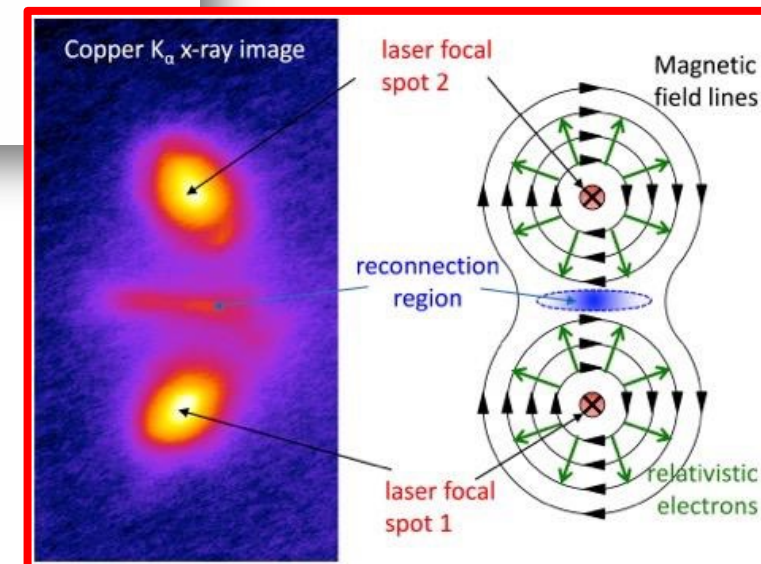
3D-PIC OSIRIS code was used to study 3D evolution of Weibel instability in the counter streaming electron-positron plasma modeling the inside of fireball of Gamma-Ray Bursts in the universe. Current filaments and magnetic field structure is plotted at time $t_1 = 10.4 \, w_{pe}^{-1}$ and $t_2 = 100 \, w_{pe}^{-1}$. (a) and (c) are iso-surface of mass density above 10% of the initial density at t_1 and t_2 , respectively. The difference of color is the flow up or down. (b) and (d) are iso-surface of the magnetic field energy above 15% of the maximum energy density

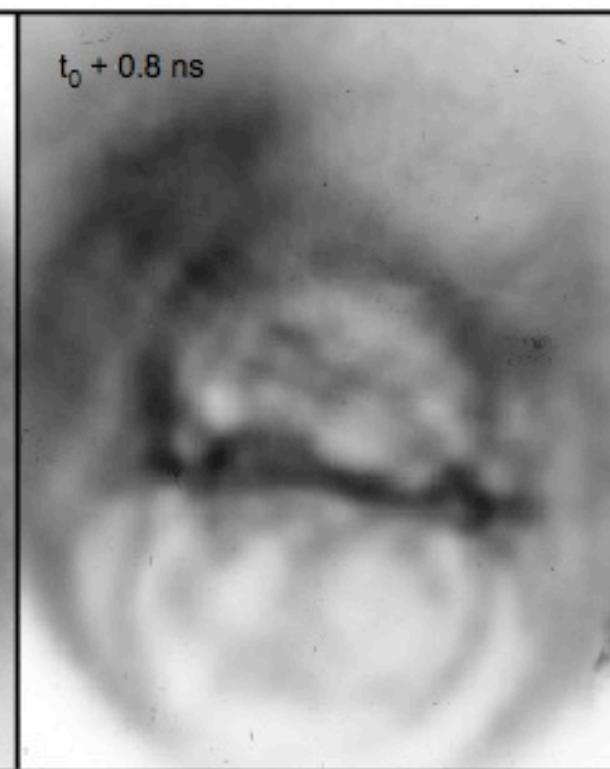
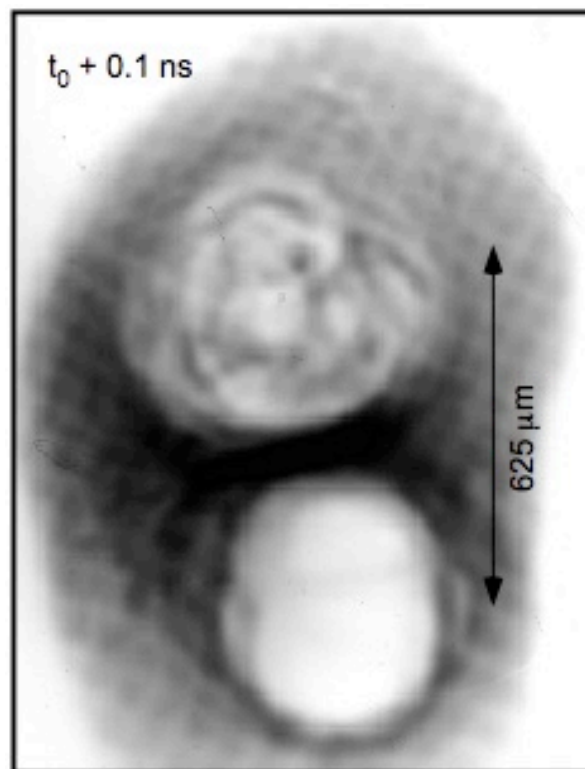
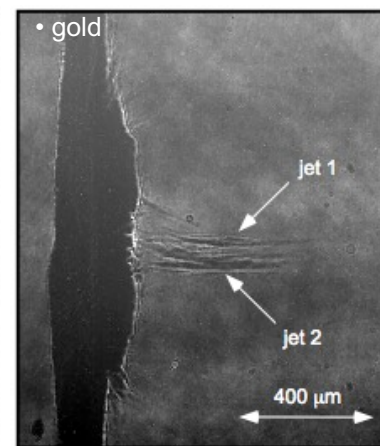
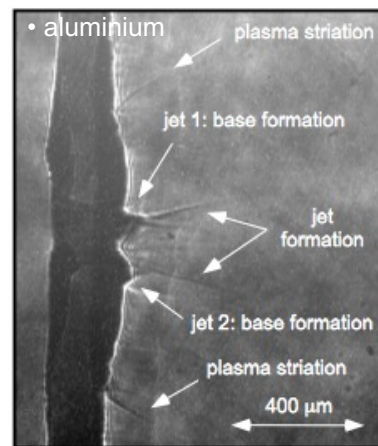
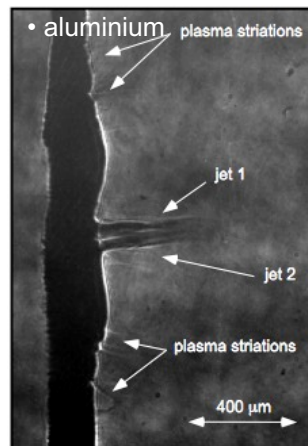
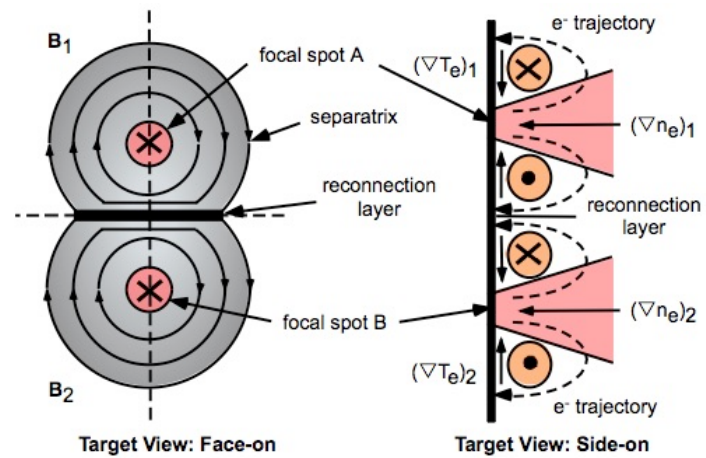
R. A. Fonseca et al., Physics Plasmas, 10, 1979 (2003)



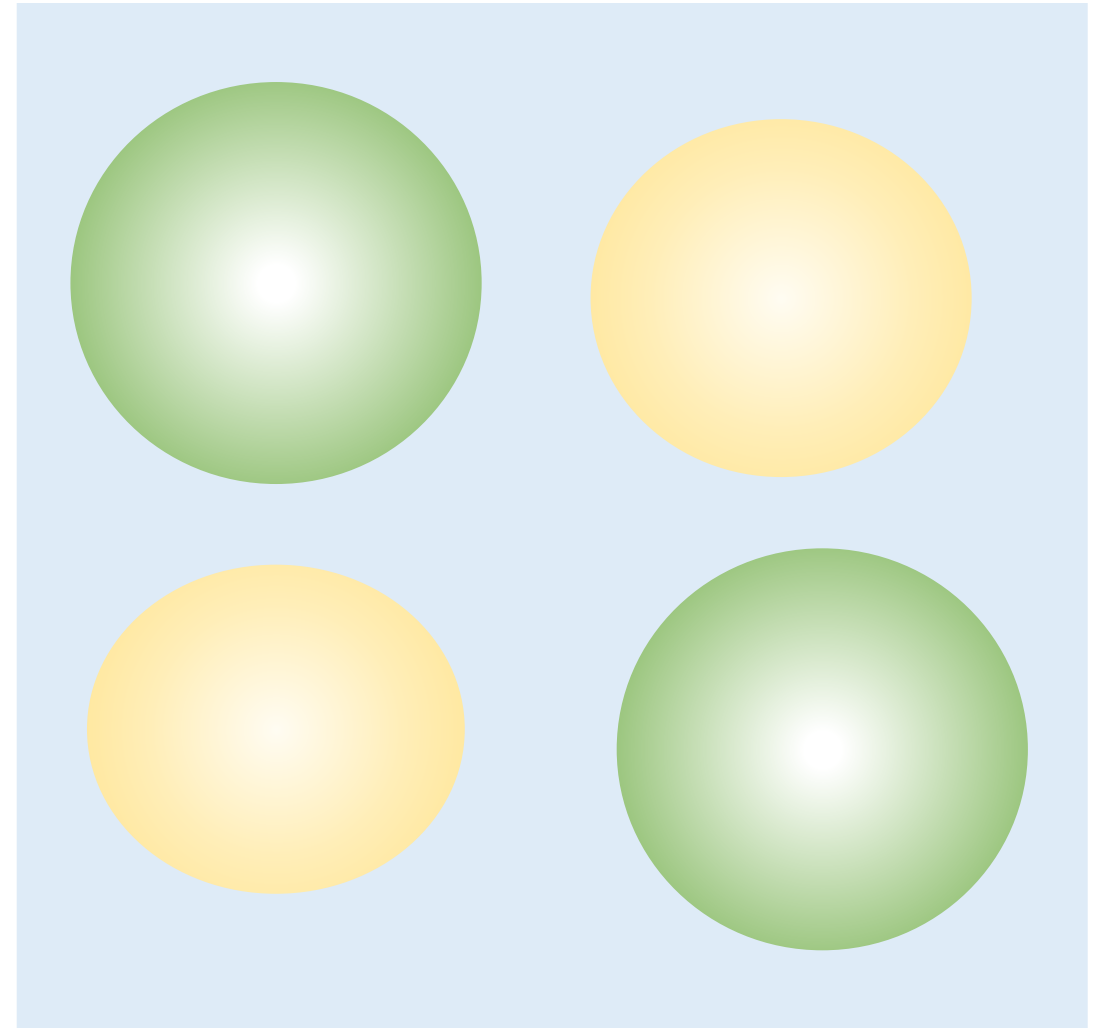
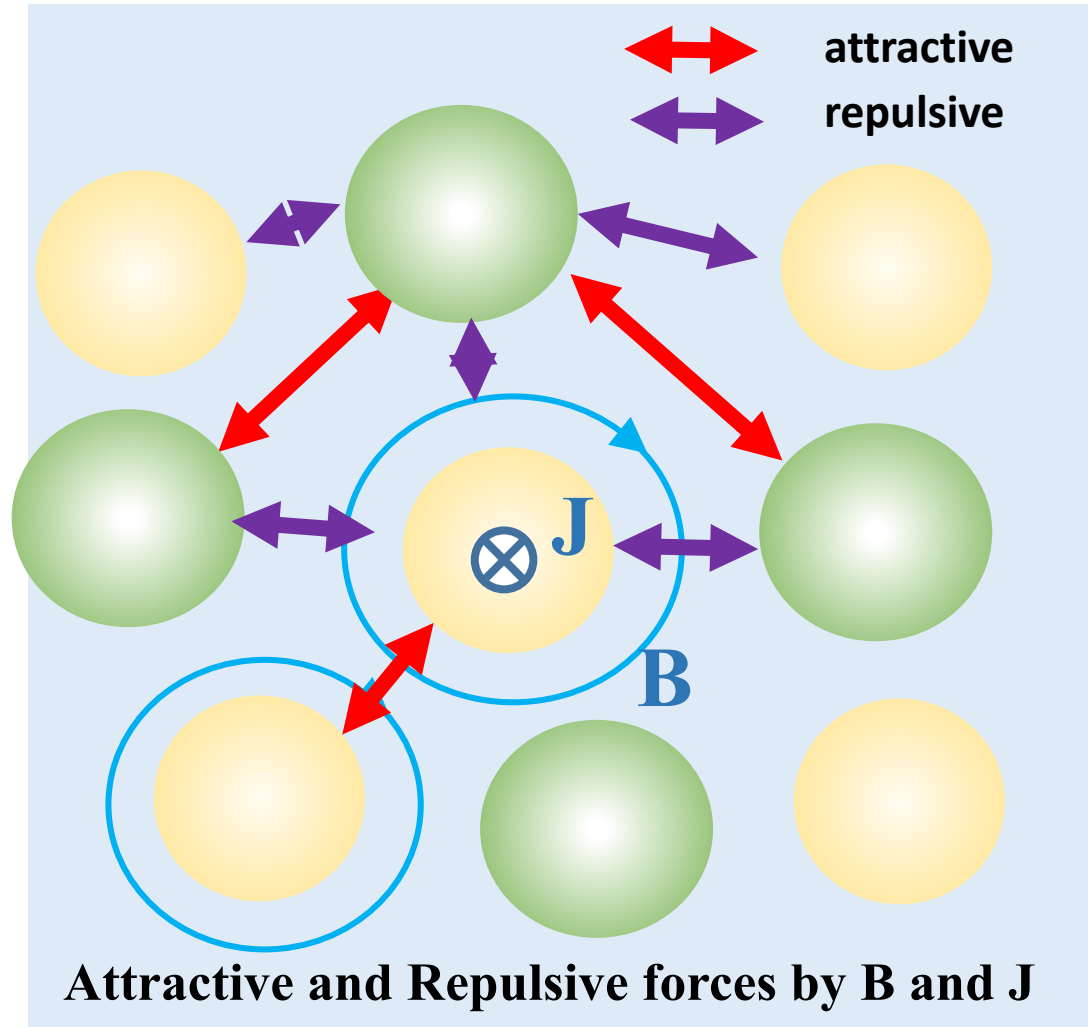
Lorentz force

1. Attractive force (parallel currents)
2. Repulsive force (anti-dir. currents)



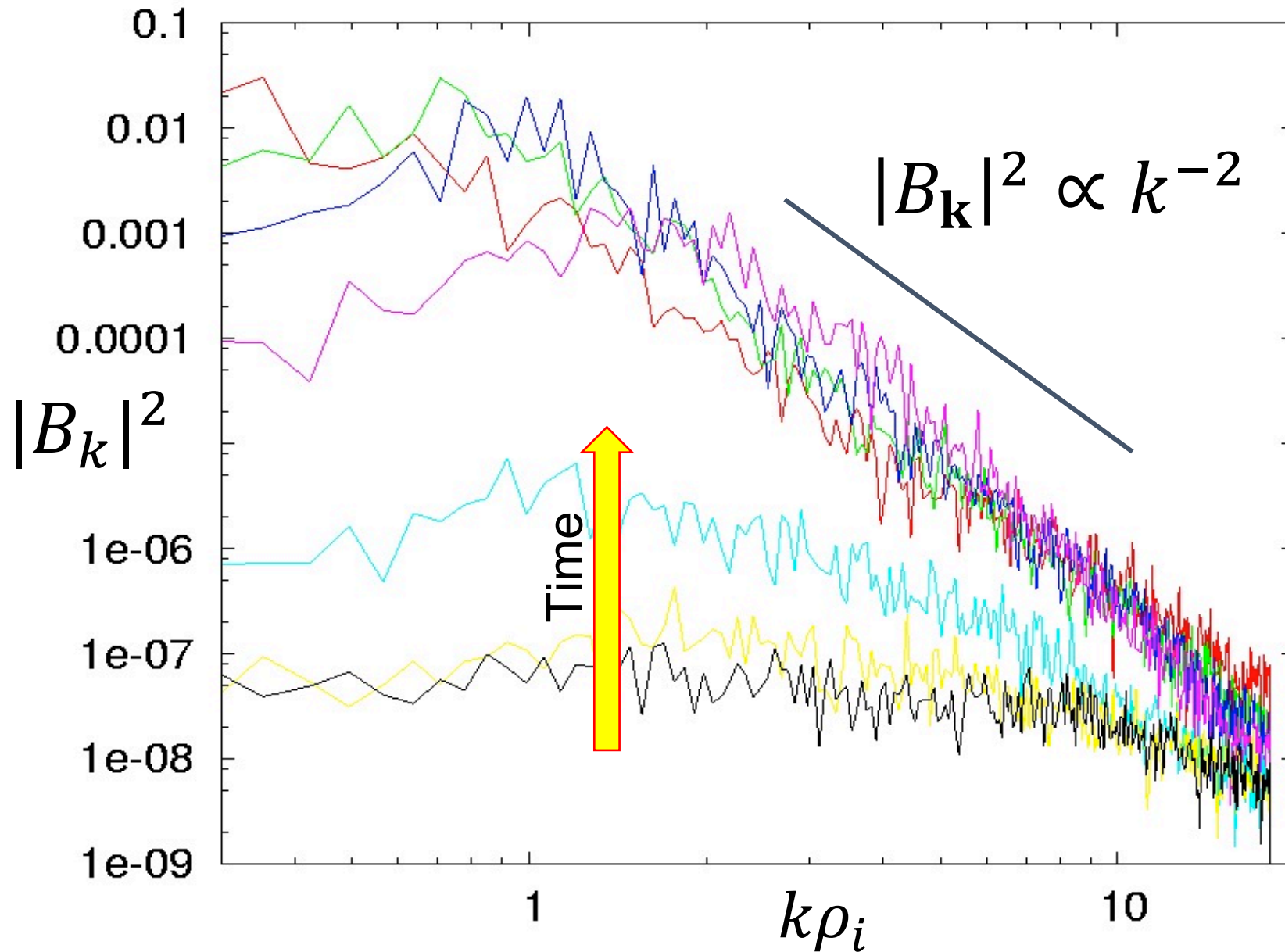


Filament coalescence

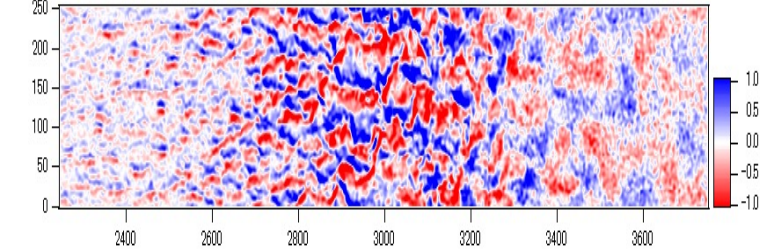


time

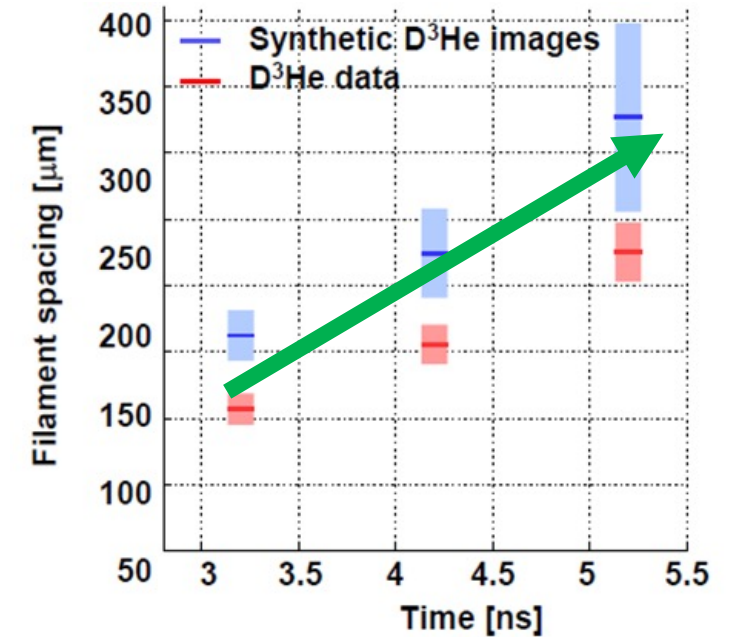
B Power Spectrum (2D PIC)

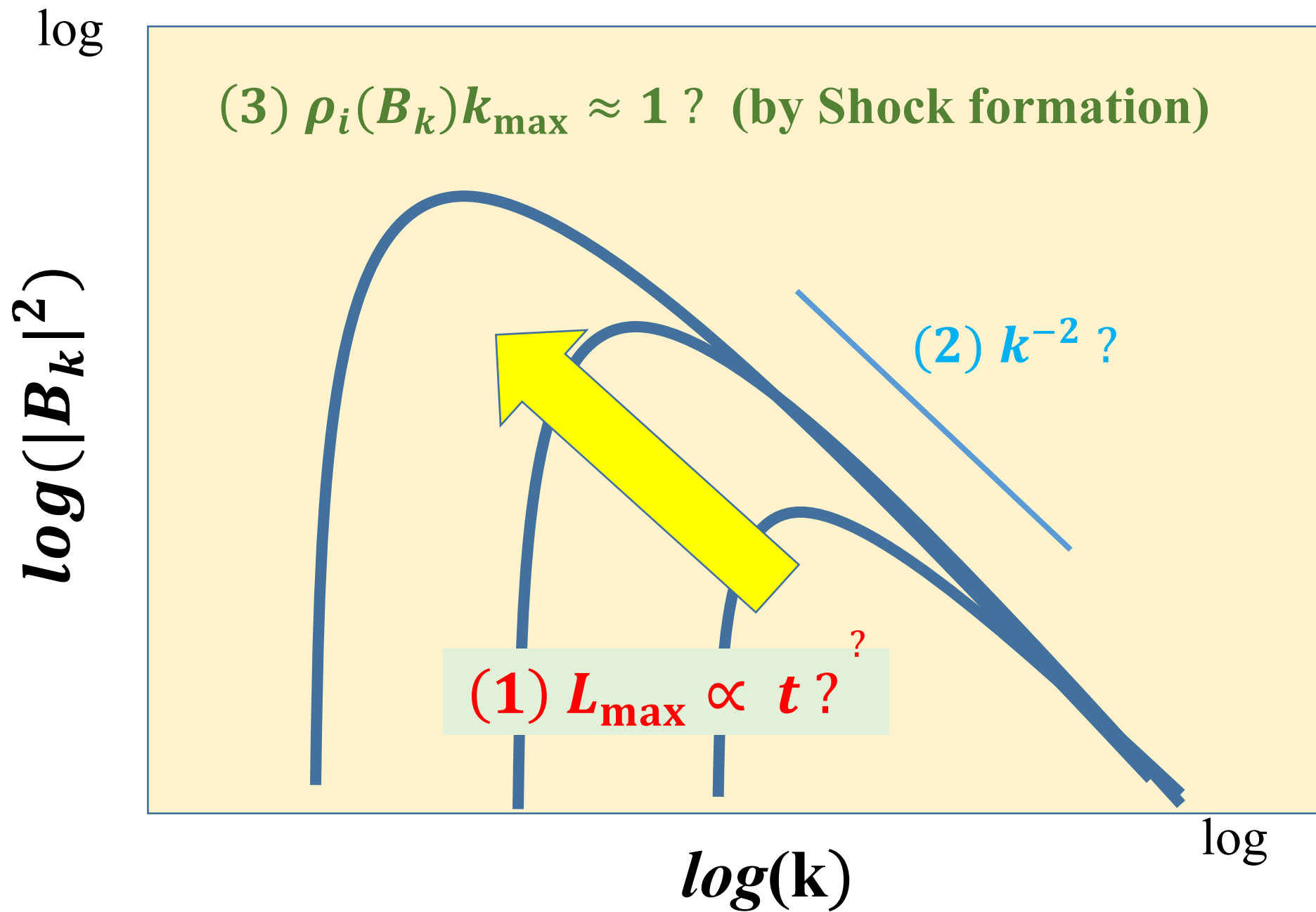


2D PIC Simulation

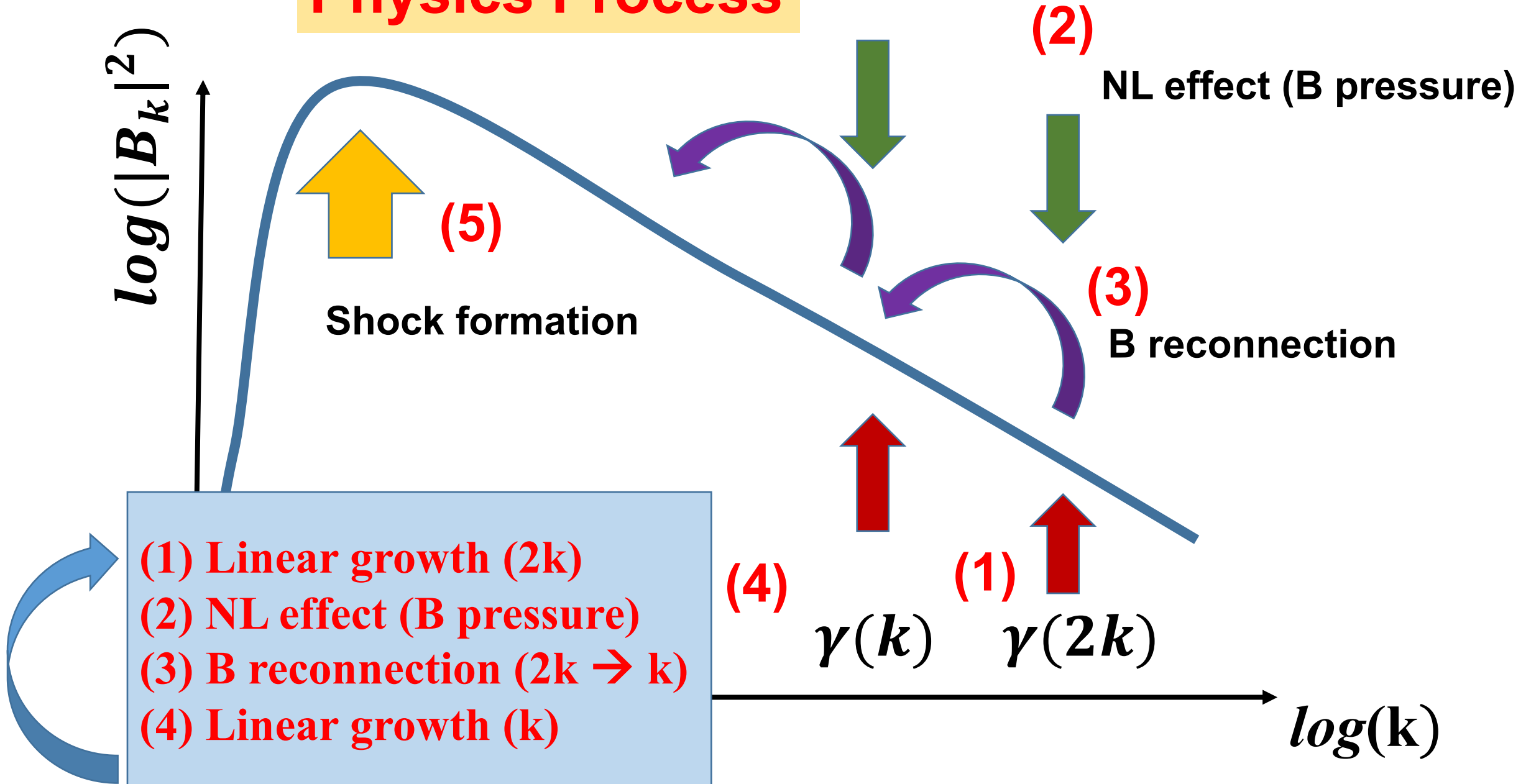


NIF Experiment





Physics Process



Electron Weibel

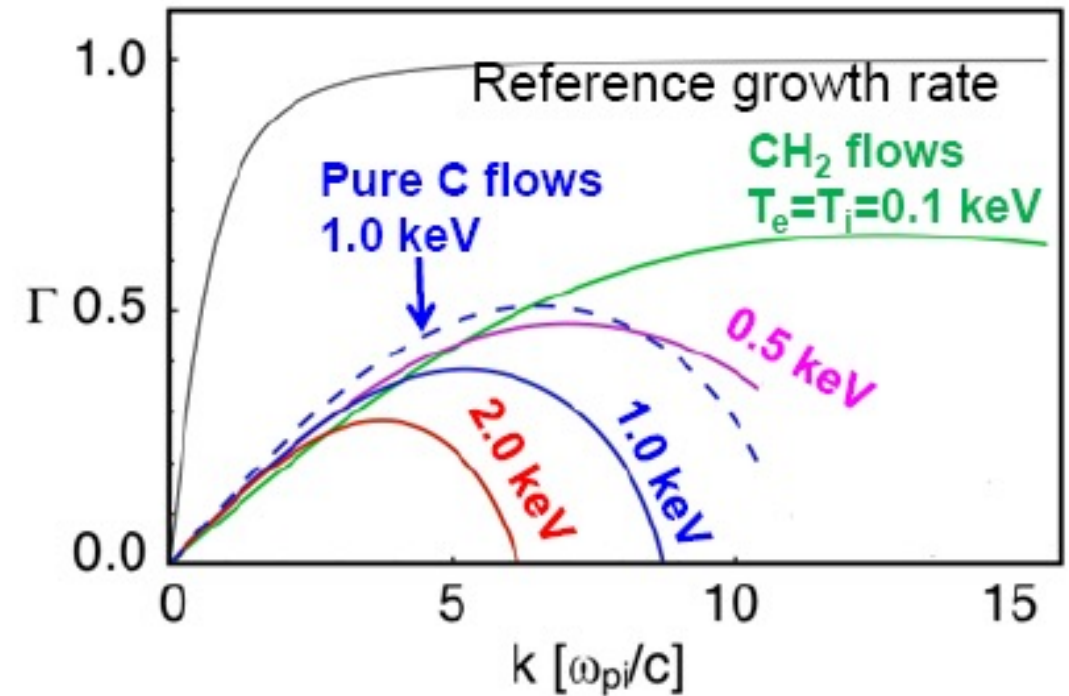
$$\omega^2 - c^2 k^2 = \omega_{pe}^2 \left(1 + \frac{u_0^2}{(\omega/k)^2 - v_e^2} \right)$$

$$\gamma = |\omega| = \frac{k u_0 \omega_{pe}}{\sqrt{k^2 c^2 + \omega_{pe}^2}}$$

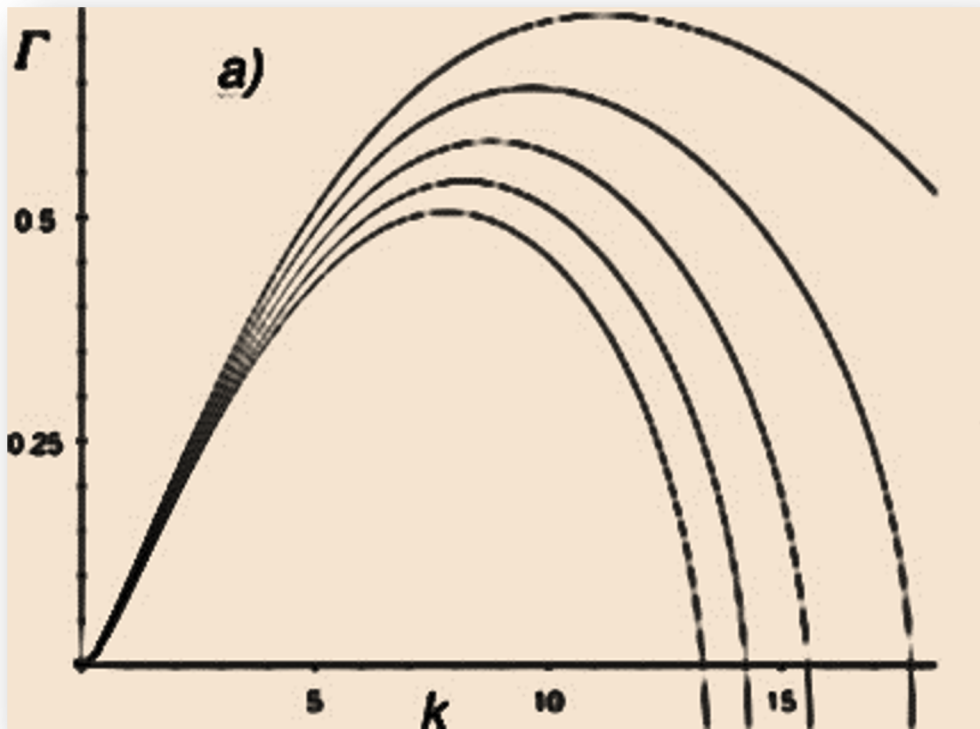
Ion Weibel

$$\omega^2 = c^2 k^2 + \omega_{pe}^2 + \omega_{pi}^2 + \frac{k^2 u_0^2}{\omega^2} \omega_{pi}^2$$

$$\Gamma = -\frac{\omega}{\omega_{pi}} \frac{c}{u_0}, \quad k = \frac{\omega c}{\omega_{pi}}$$



(1) Modeling the linear growth rate



$$\Gamma = \omega_{pi} \frac{u_0}{c}$$
$$k = \frac{\omega_{pi}}{c}$$

$$\gamma = 0.1 u_0 k$$

(2) NL Saturation of Weibel Instability

$$m_e \frac{d\mathbf{u}_e}{dt} = -e(\mathbf{E} + \mathbf{u}_e \times \mathbf{B})$$

$$\mathbf{u}_e = \mathbf{u}_0 + \delta\mathbf{u}_e \quad \mathbf{j}_e = -en_e\delta\mathbf{u}_e$$

$$\mathbf{u}_e \times \mathbf{B} = \mathbf{u}_0 \times \mathbf{B} - \frac{1}{en_e} \mathbf{j}_e \times \mathbf{B}$$

$$\mathbf{j}_e \times \mathbf{B} = -\nabla \left(\frac{B^2}{2\mu_0} \right)$$

$$u_0 B \sim \frac{2\pi}{en_e L_e} \frac{B^2}{2\mu_0}$$

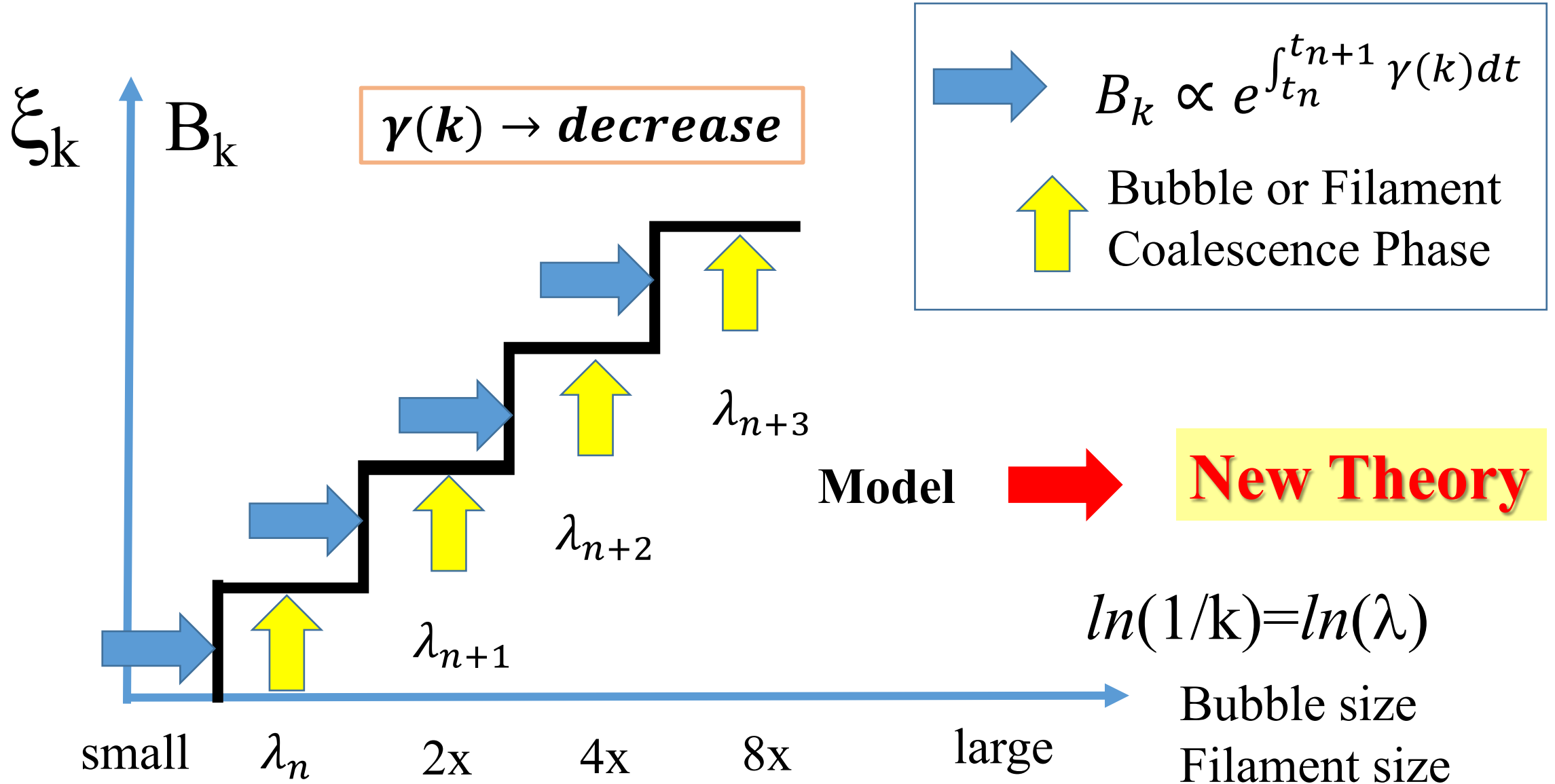
$$\frac{B_k^2}{2\mu_0} = Ck^{-2}$$

$$k = \frac{2\pi}{2L_e}$$



$$B_k \propto 1/k$$

(3) Modeling B reconnection



(4) Inverse Cascade Equation

$$B_k(t) = B_{k,0} \exp \left[\int \gamma(k) dt \right]$$

$$\frac{1}{B_k} \frac{d}{dt} B_k = \gamma(k) \propto k$$

Size of filaments

$$L_i(t) = \frac{\pi}{k(t)} = At$$

$$B_k(t) \propto 1/k(t)$$

← (2) B Saturation

(1)-(4) Compared with NIF Experiment

Filament size

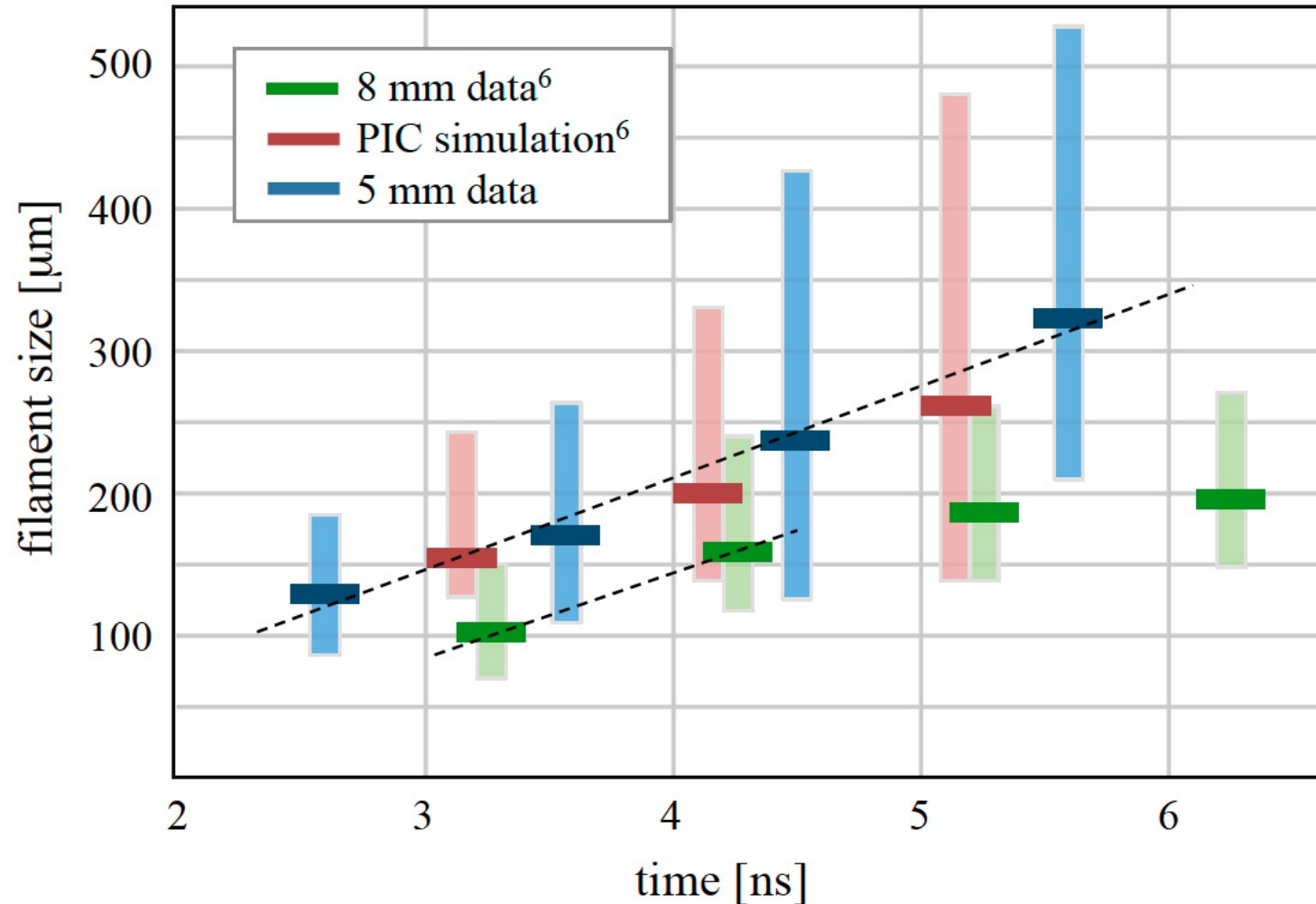
$$\langle \lambda(t) \rangle \propto \frac{1}{\langle k(t) \rangle} \propto t$$

$$\left\langle \frac{d\lambda}{dt} \right\rangle = 6.8 \times 10^6 \text{ cm / s}$$

Assume a time lag fraction α

$$\gamma = \alpha \times 0.1 u_0 k$$

$$\alpha = 0.3$$

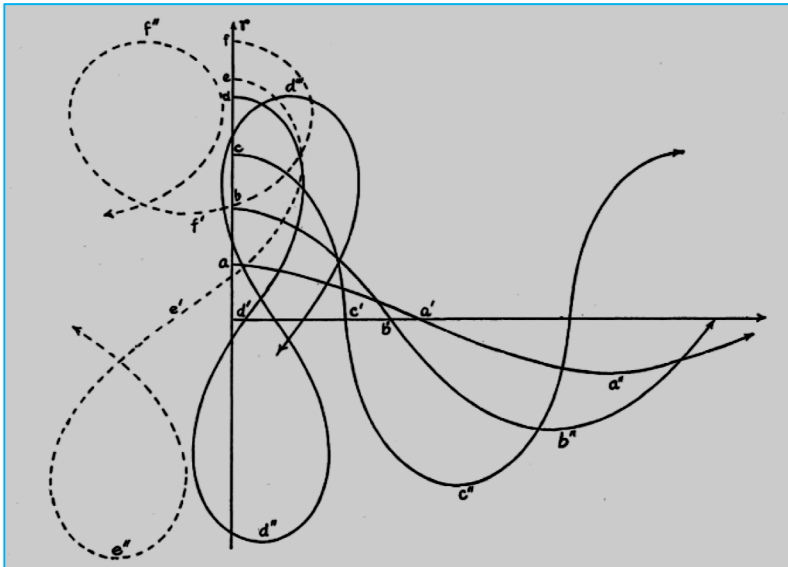


H.-S. Park et al., Physics of Plasmas 22, 056311 (2015).

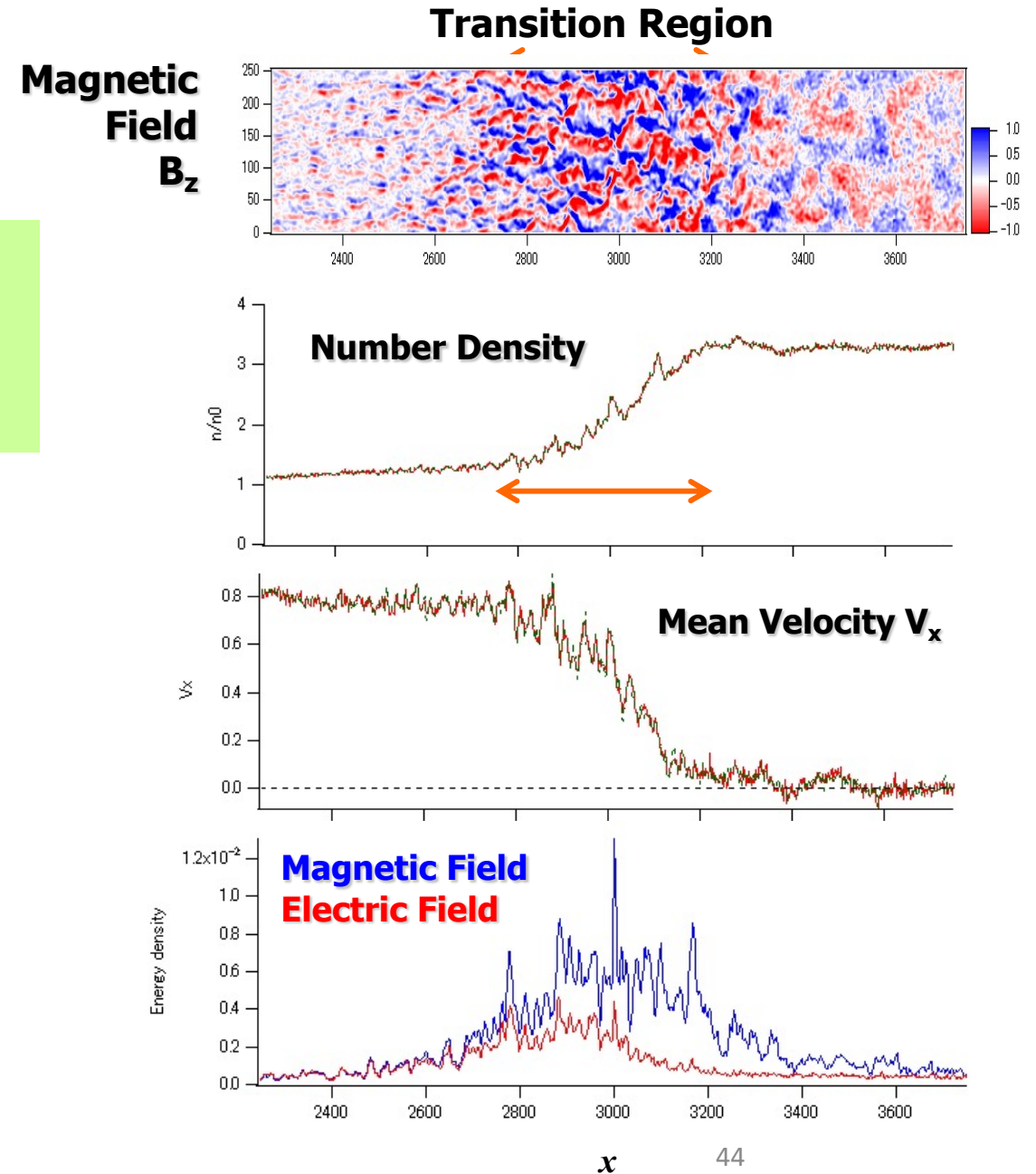
(5) Shock formation

$$\frac{\lambda}{2} \approx \frac{\pi}{\langle k(t) \rangle} \approx 2r_L \Rightarrow B_k^2 = C$$

Alfven current limit



H. Alfven, Phys. Rev. 55, 425, (1939)



Weibel shock can explain observation Data of SN1006

$$V = 3000 \text{ km / s } (= 0.01c)$$

$$T_i = 15 \text{ keV}$$

$$T_e = 0.1 - 1 \text{ keV}$$

$$n_i = 1 \text{ cm}^{-3}$$

$$B_{\text{max}} = 300 \mu\text{G} (>> B_U \approx 1 \mu\text{G})$$

$$\Delta x = 100 \frac{c}{\omega_{pi}}$$



Magnetic field generation and amplification are demonstrated

Theoretical model, universal ?

Outlook

$$|B_k|^2 \propto k^{-2}$$

Astrophysics

Hydrodynamics

**Turbulent
mixing by RT
(2D,3D fluids)**

Magnetic fusion

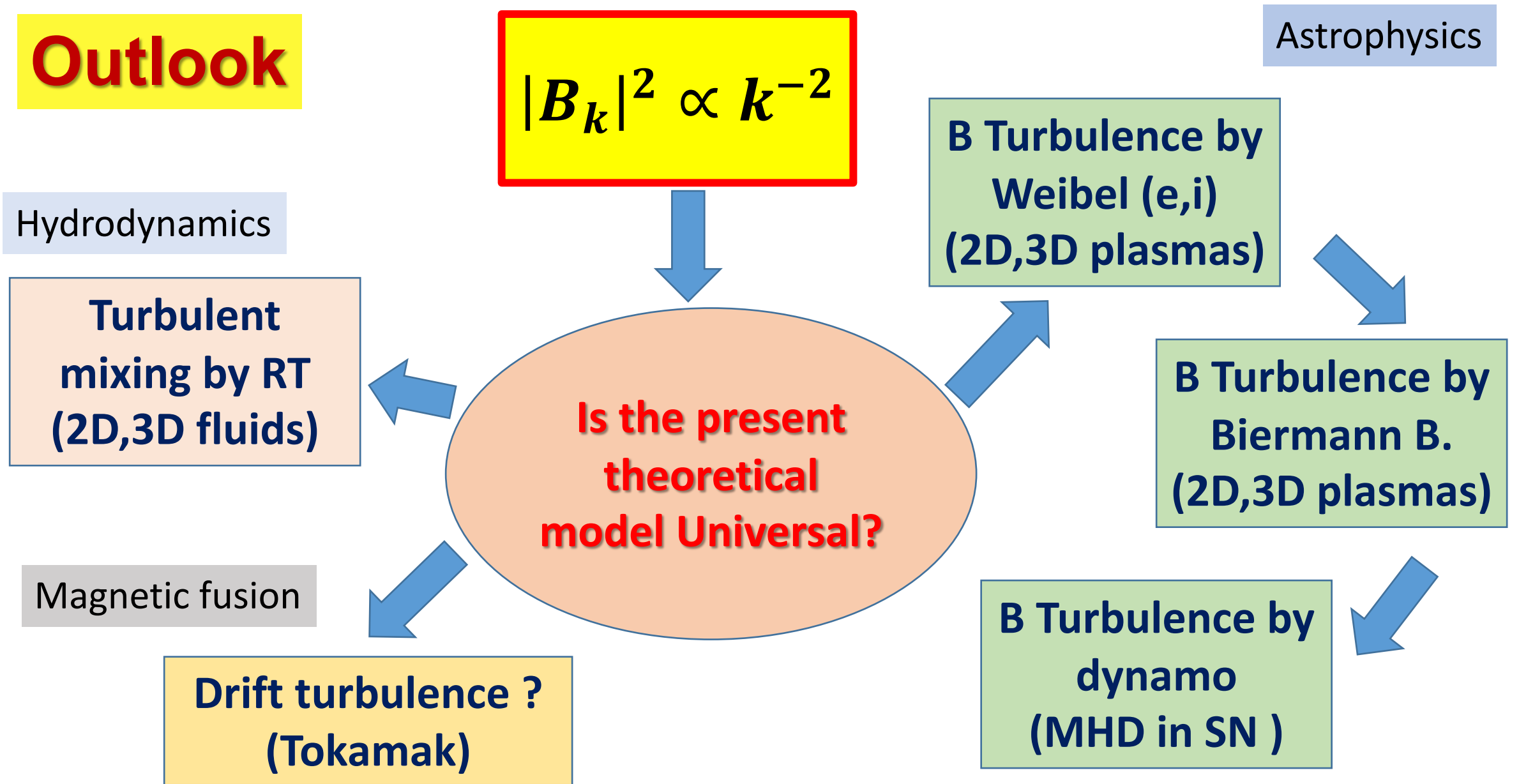
**Drift turbulence ?
(Tokamak)**

**Is the present
theoretical
model Universal?**

**B Turbulence by
Weibel (e,i)
(2D,3D plasmas)**

**B Turbulence by
Biermann B.
(2D,3D plasmas)**

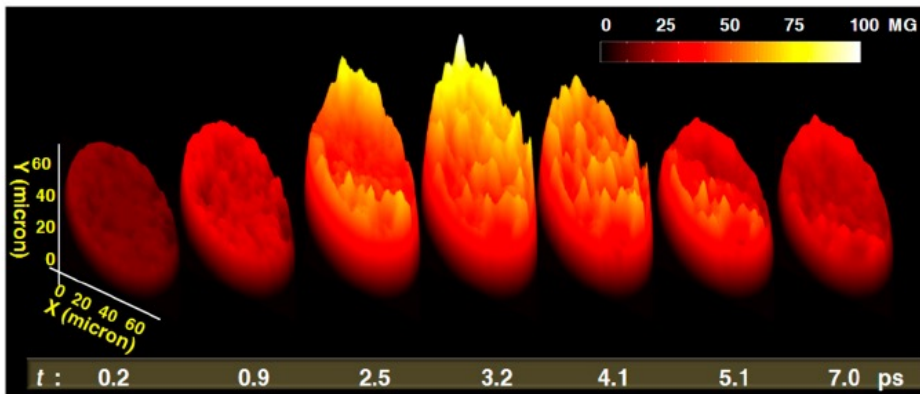
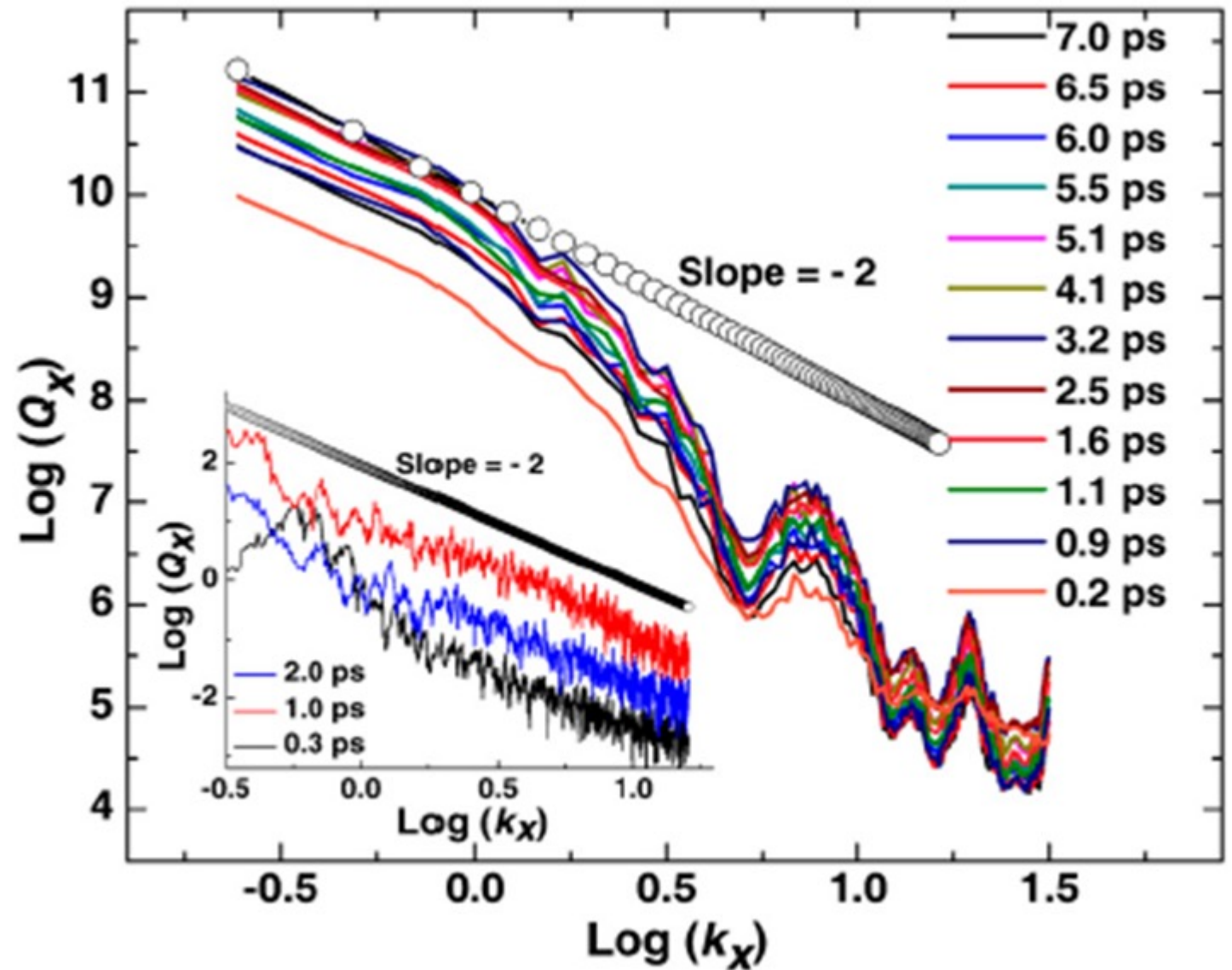
**B Turbulence by
dynamo
(MHD in SN)**



Electron Weibel

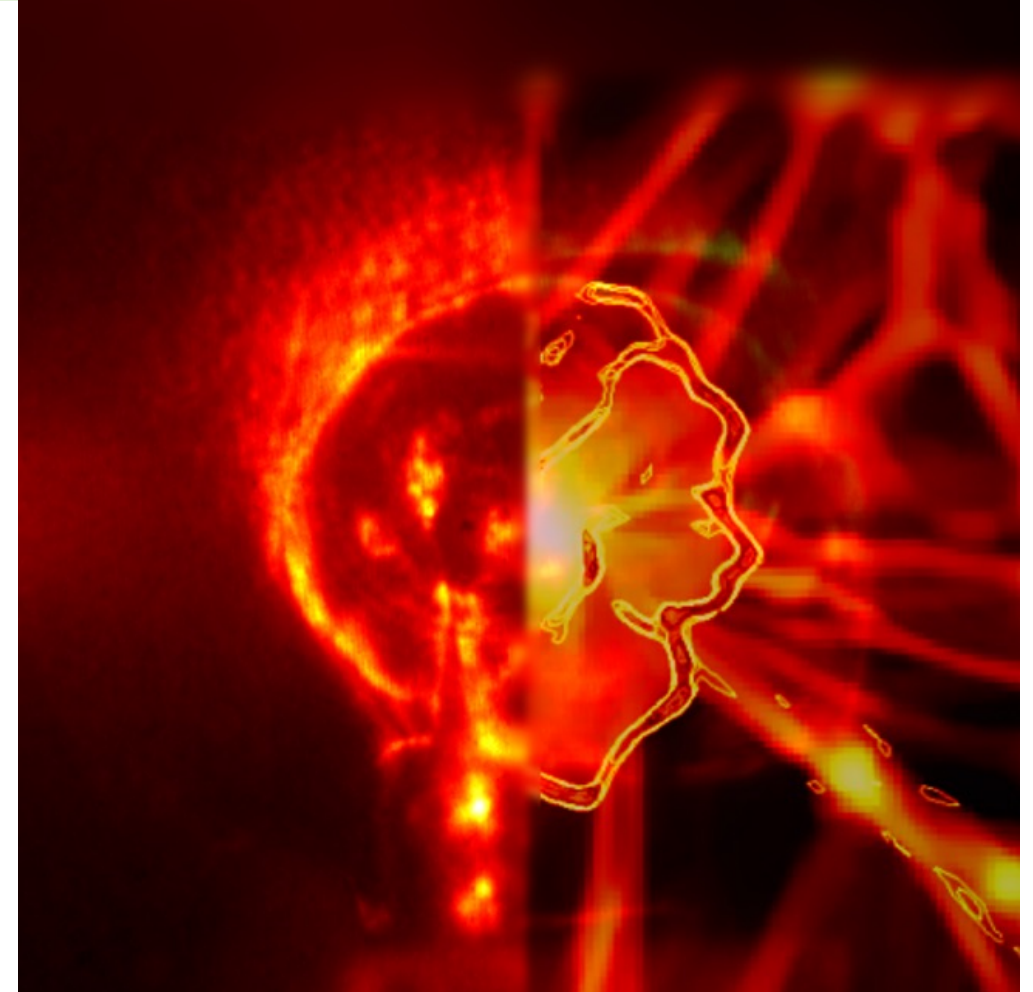
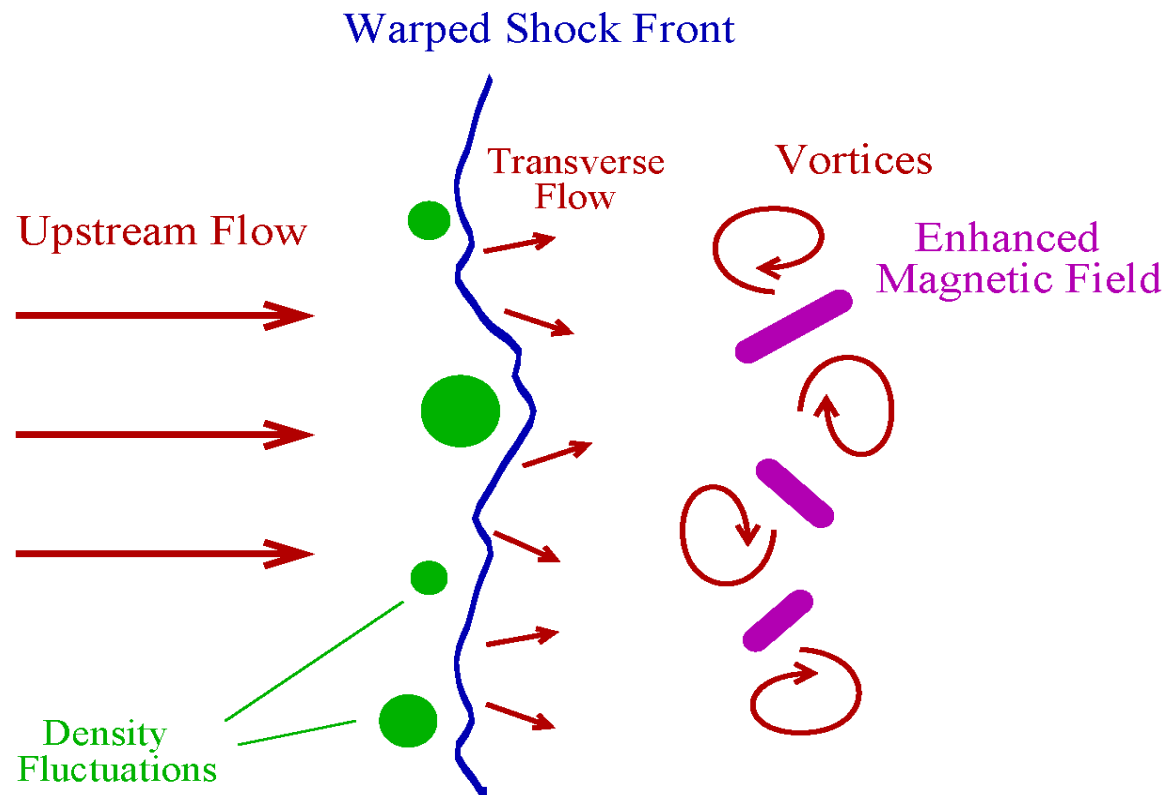
$$|B_{\mathbf{k}}(t)|^2 \propto t^2 \propto k^{-2}$$

- S. Modal et al.,
PNAS, 109, 8011
(2012)
- G. Chatterjee et al.,
Nature Comm., 8,
15870, (2017)



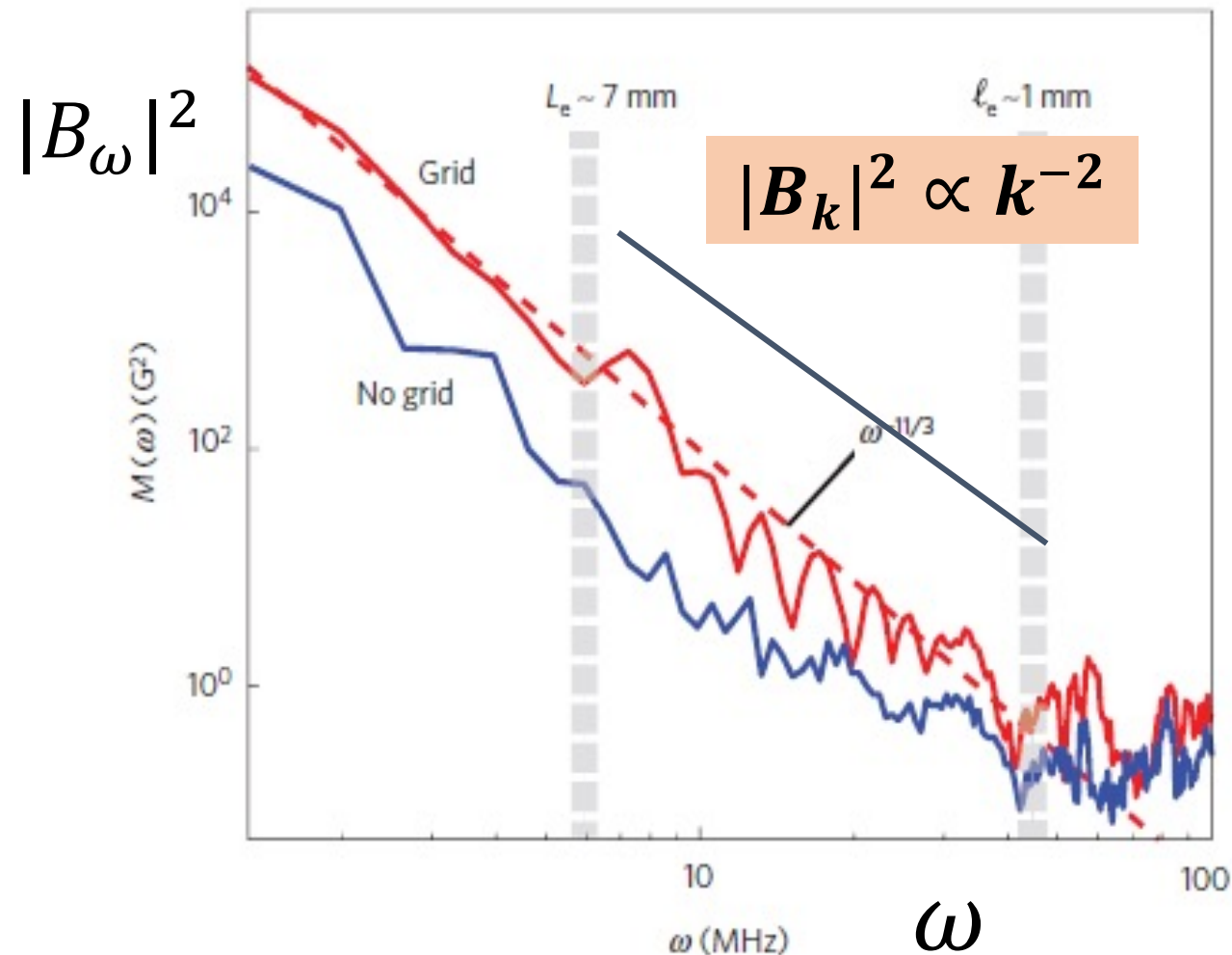
LA experiment of cosmic background B

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left(\frac{1}{en_e} \nabla P_e \right) = - \frac{1}{en_e^2} \nabla n_e \times \nabla P_e$$



(by Gianluca Gregory, Oxford, 2018)

B spectrum (Biermann B. Exp. by Oxford)



$$\omega \approx k$$

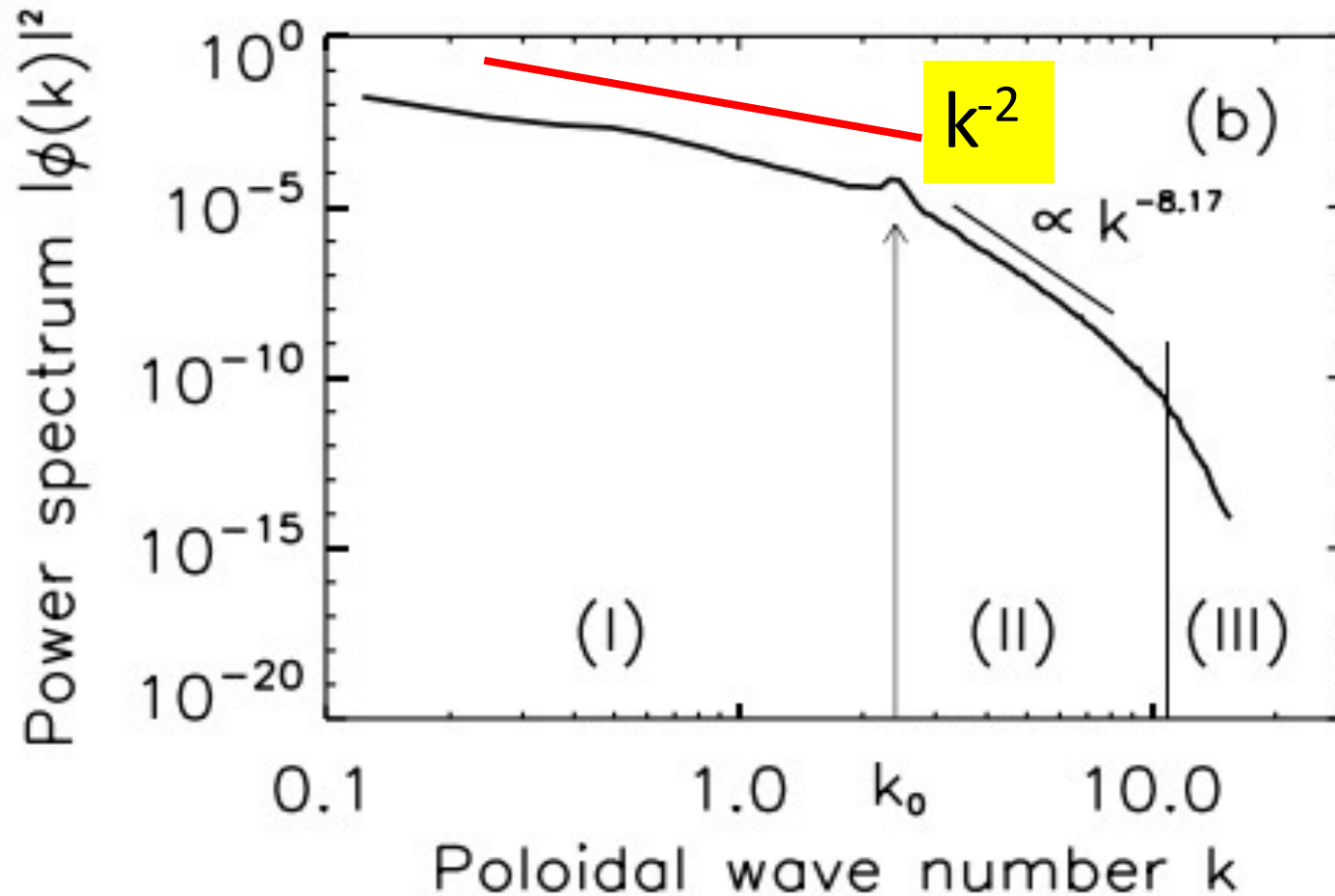
$$M(k) = |B_k|^2 \propto k^{-2}$$

(by G. Gregori)

- J. Meinecke et al, Nature Physics 10, 520 (2014)
- J. Meinecke et al., PNAS, 112, 8211 (2015)

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left(\frac{1}{en_e} \nabla P_e \right) = -\frac{1}{en_e^2} \nabla n_e \times \nabla P_e$$

Drift wave turbulence in Tokamak



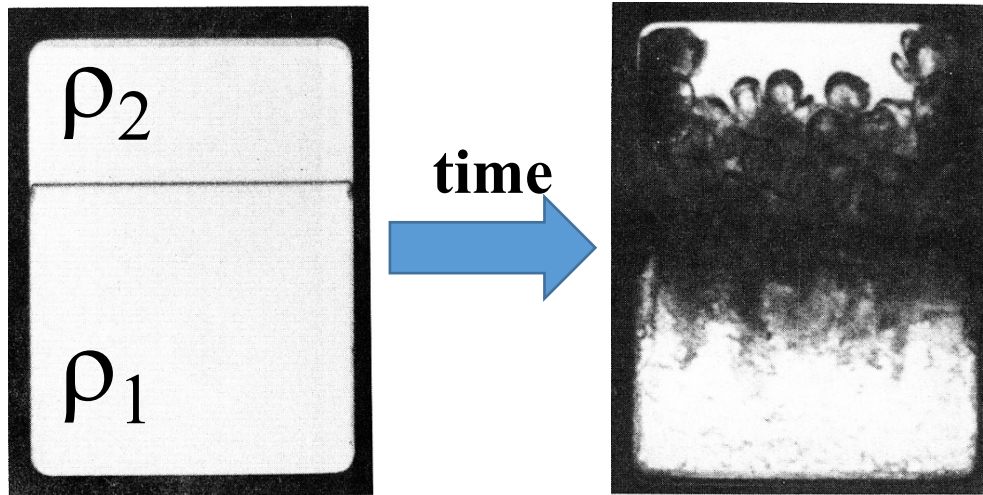
T. T. Tran,^a et al., PoP, 24, 102318 (2017)

Turbulent Mixing (fluid turbulence)

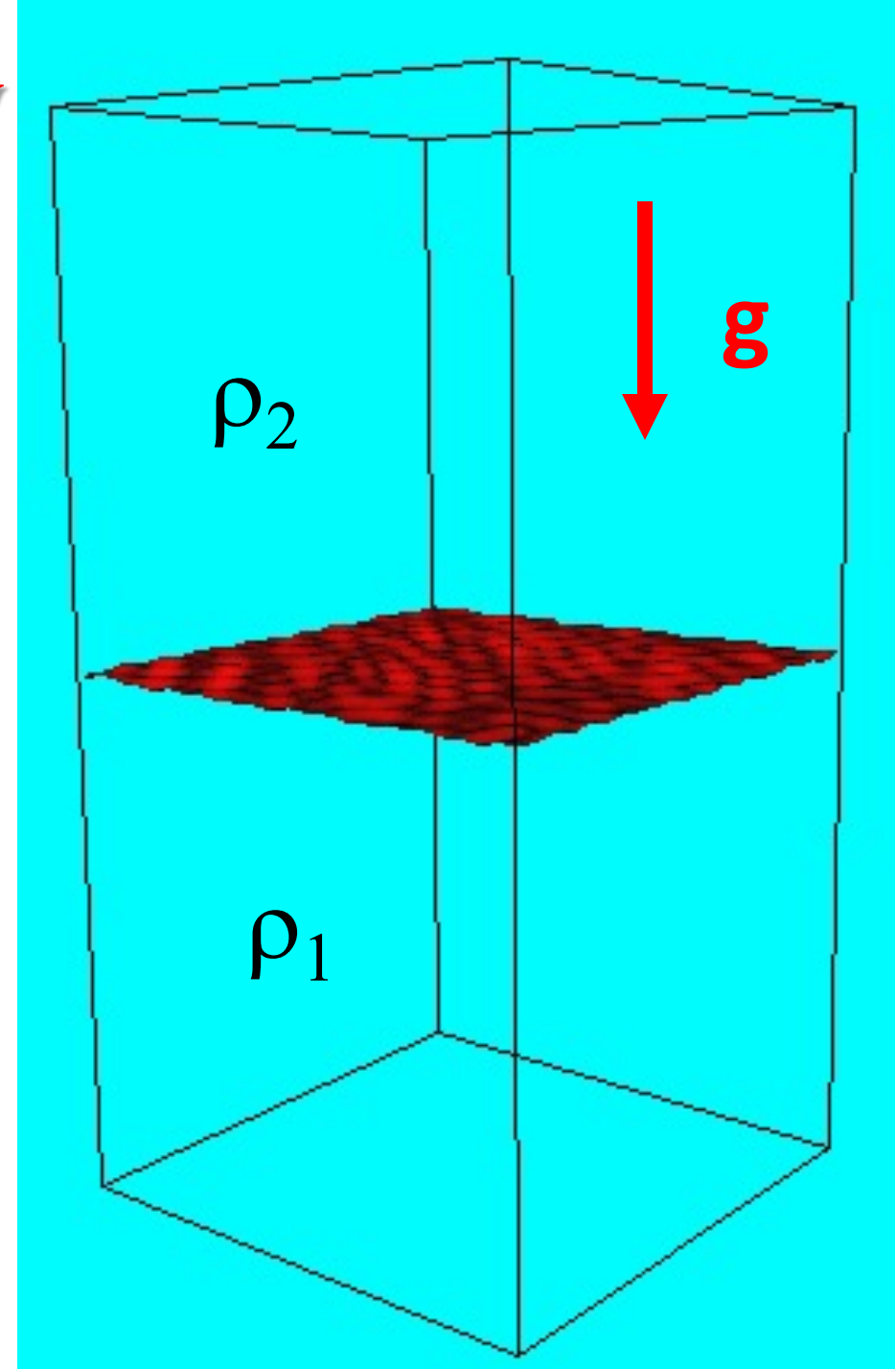
RT Rayleigh-Taylor Instability and Turbulent Mixing

$$\gamma = \sqrt{\alpha_A k g} \quad \rho_2 > \rho_1$$

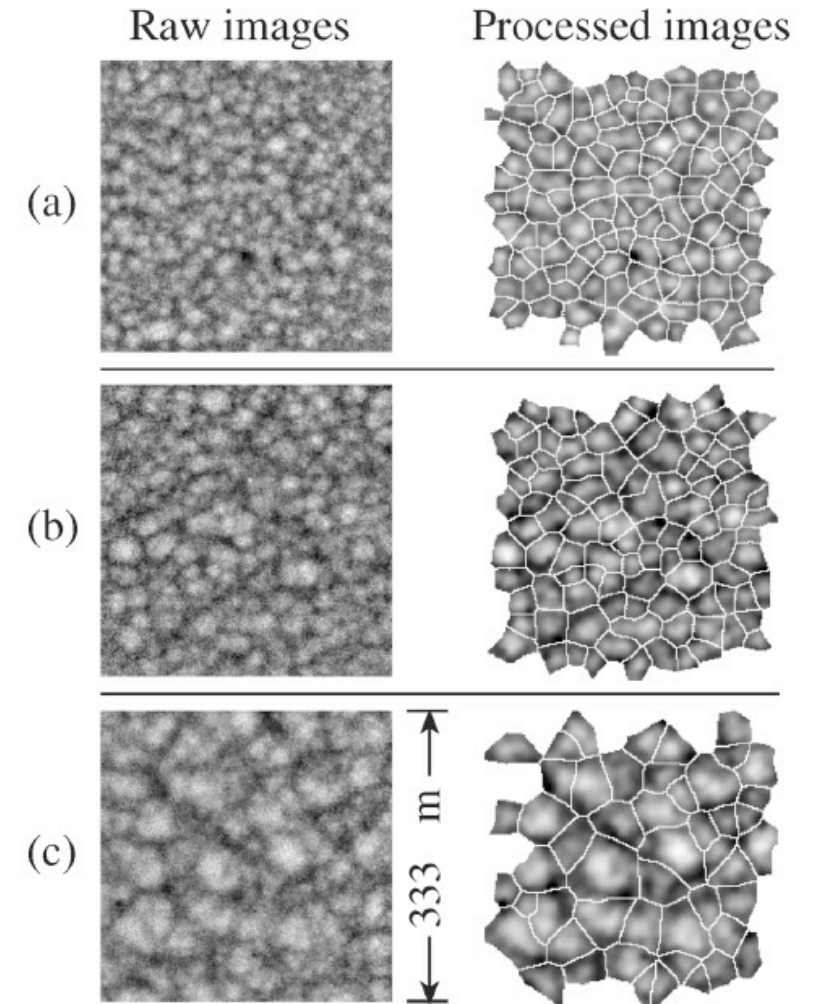
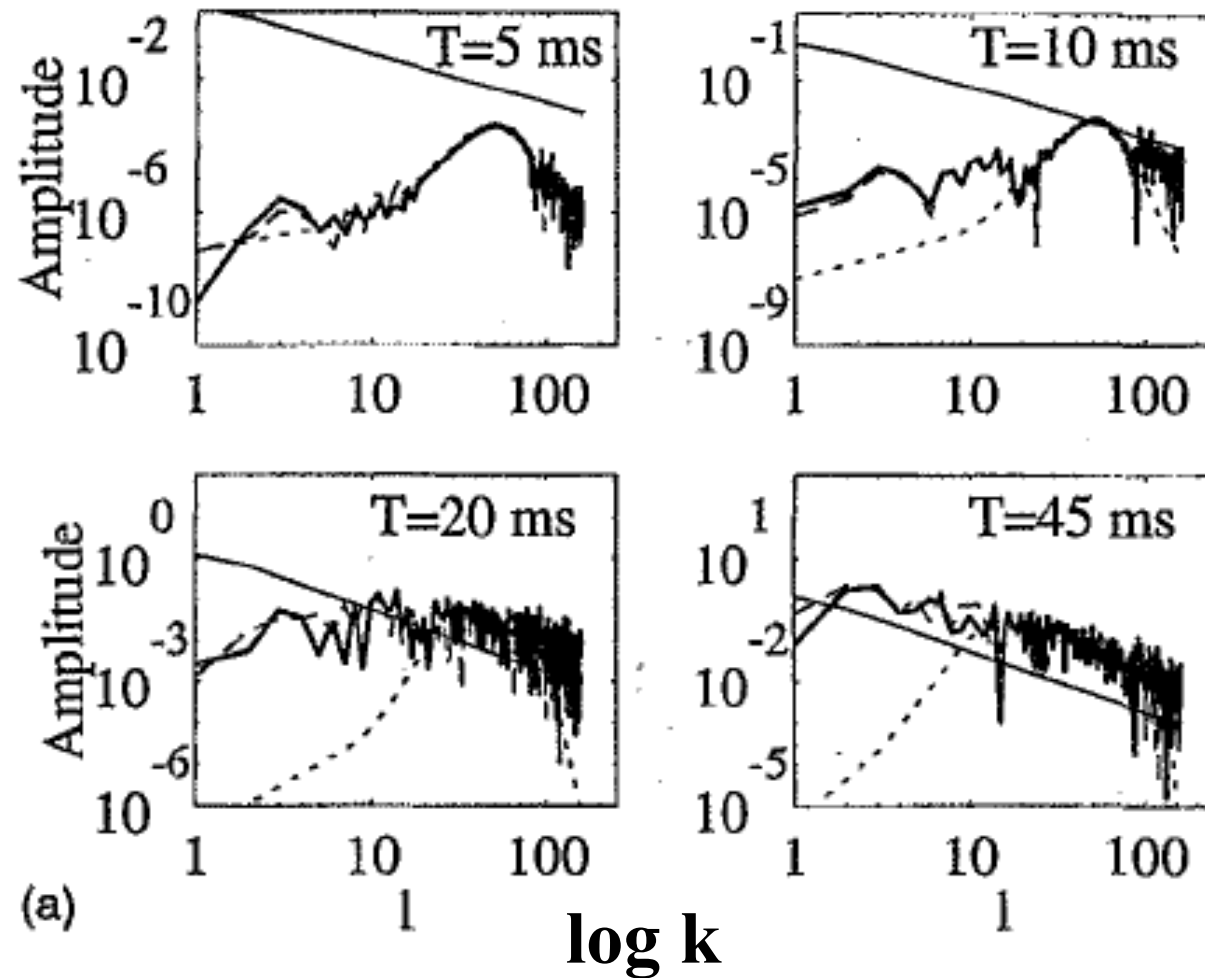
$$h(t) = 0.07 g t^2$$



K. L. Read and D. L. Youngs
Physica 12D, 45, 1984

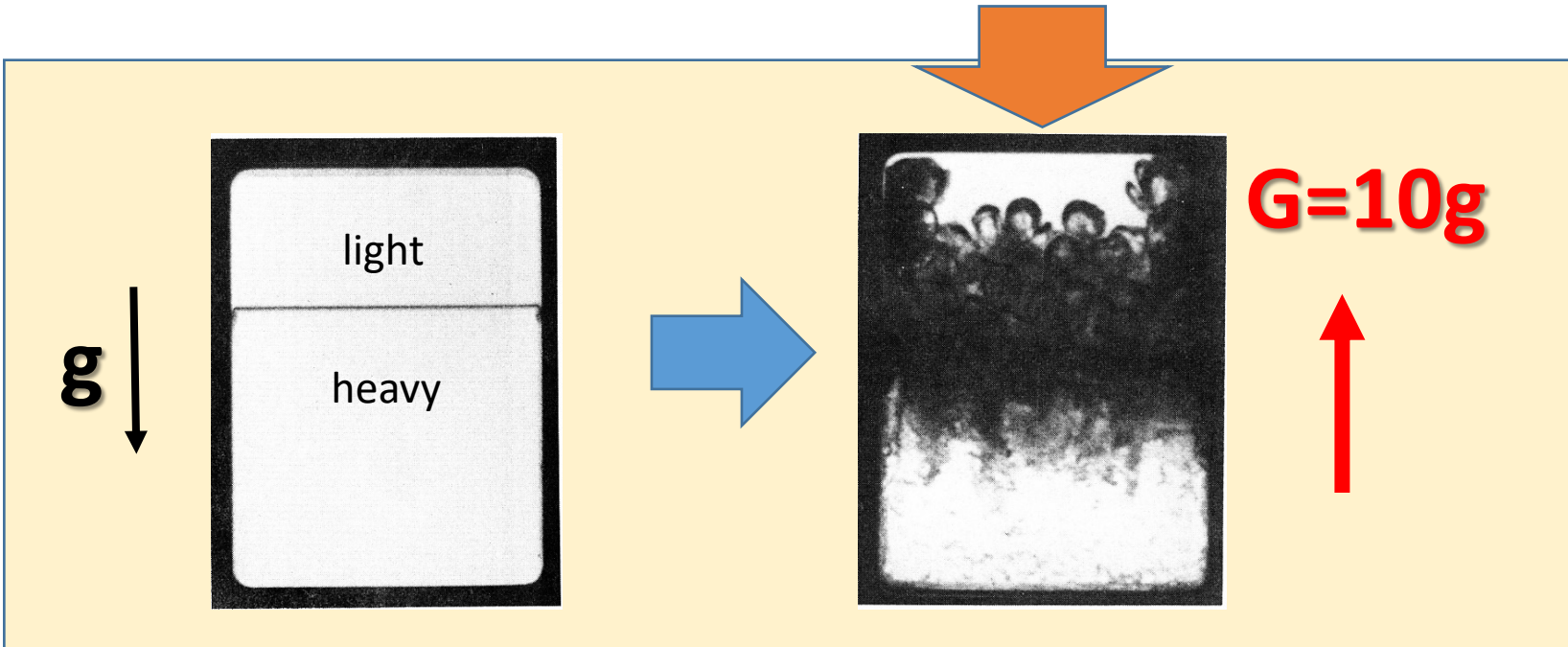


The nonlinear evolution of hydrodynamic structure involves bubble merger



1. D. Oron et al., Physics of Plasmas **8**, 2883 (2001)

1. L. Gao et al., Phys. Rev. Lett. **110**, 185003 (2013)



K. L. Read, Physica 12D, 45 (1984)

Fluid mixing induced by Rayleigh-Taylor Instability

G. Dimonte et al., Phys. Fluids, 16, 1668 (2004)

**Hydrodynamic
Instability and
Turbulent Mixing**

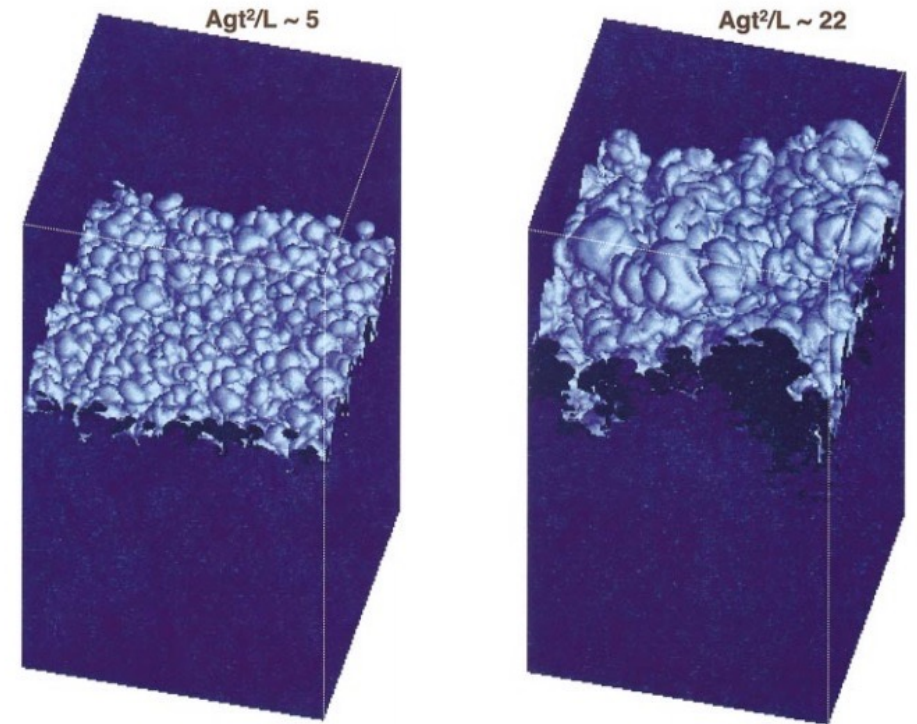


FIG. 6. (Color) Isosurfaces from TURMOIL 3D where "heavy" fluid concentration=0.99.

Power spectra of RT turbulence

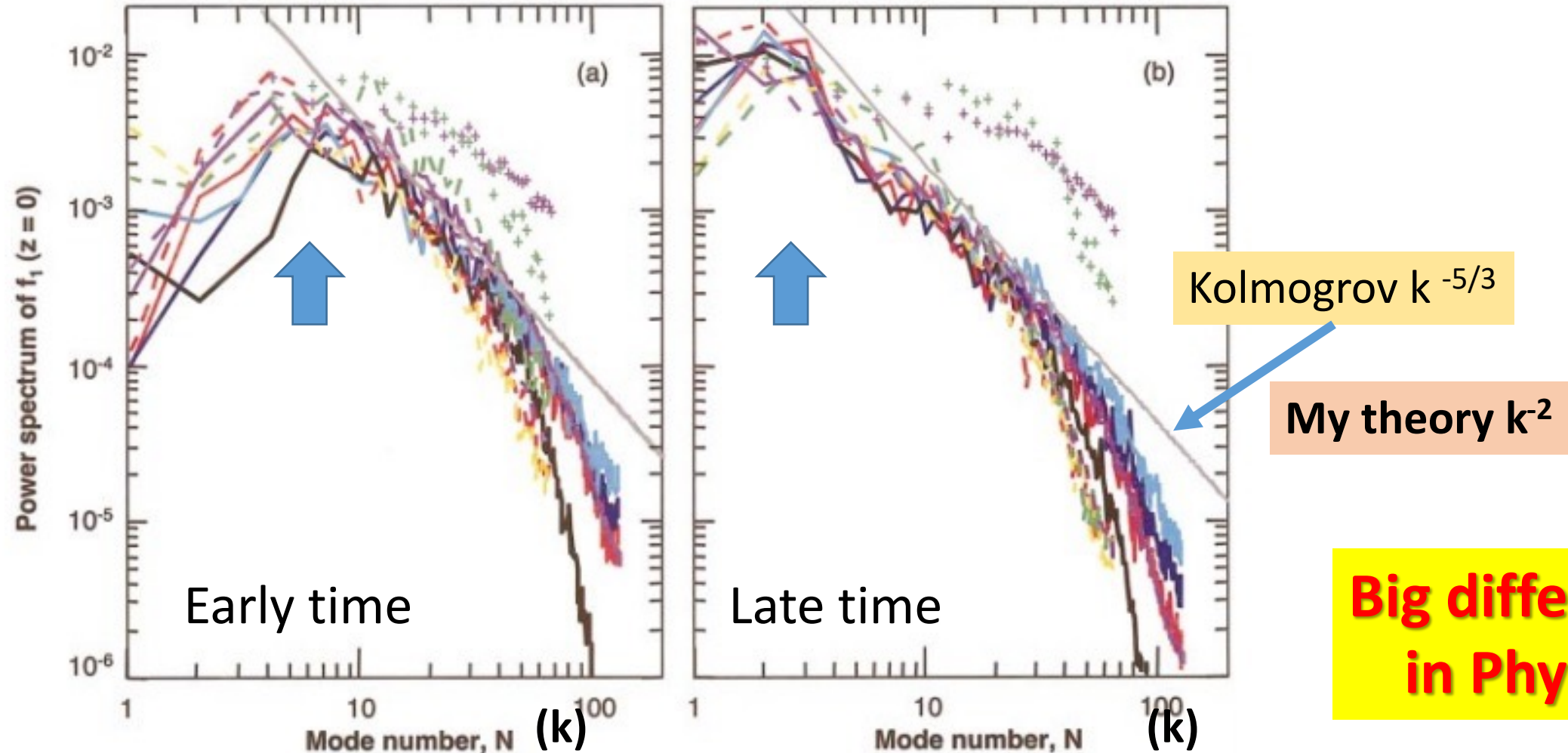


FIG. 33. (Color) Power spectrum of volume fraction at original interface $Z=0$ for (a) early and (b) late times: Kolmogorov-type spectrum $\propto N^{-5/3}$.

G. Dimonte et al., Phys. Fluids, 16, 1668 (2004)

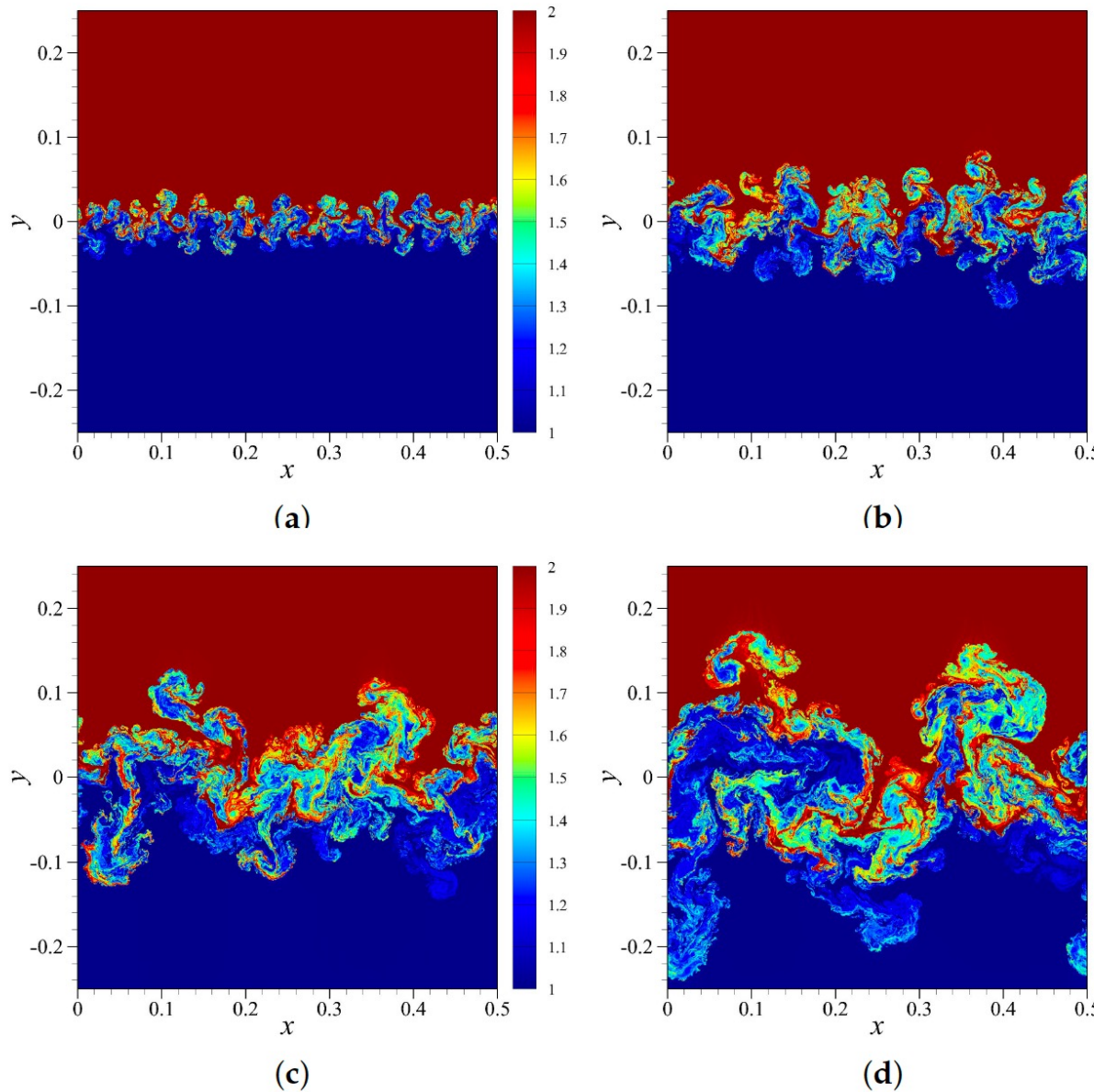
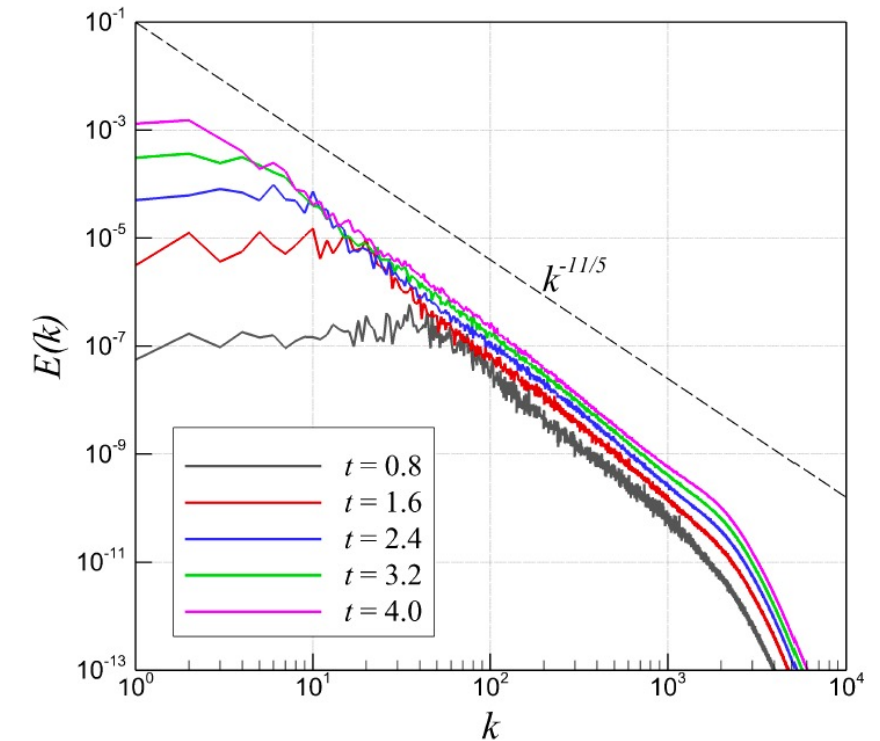
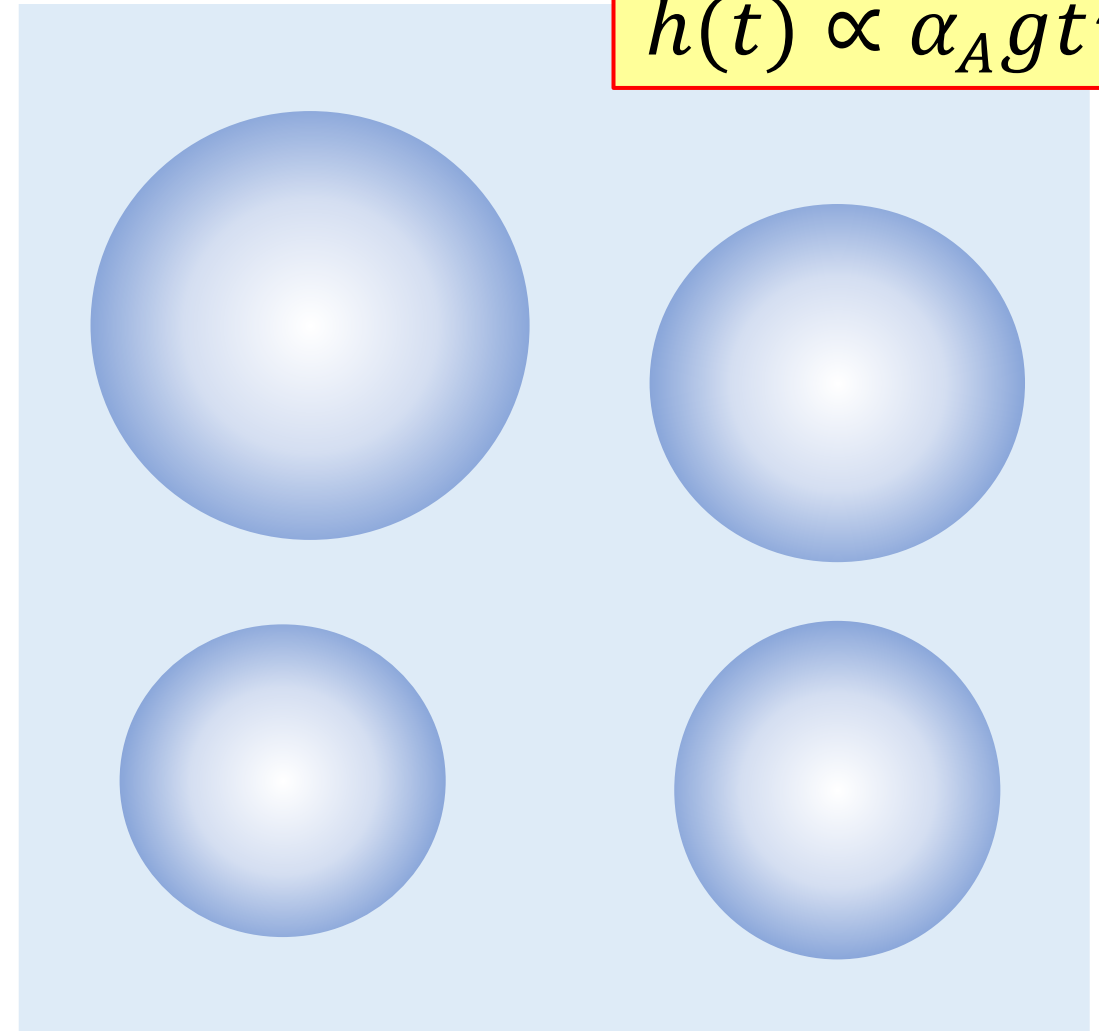
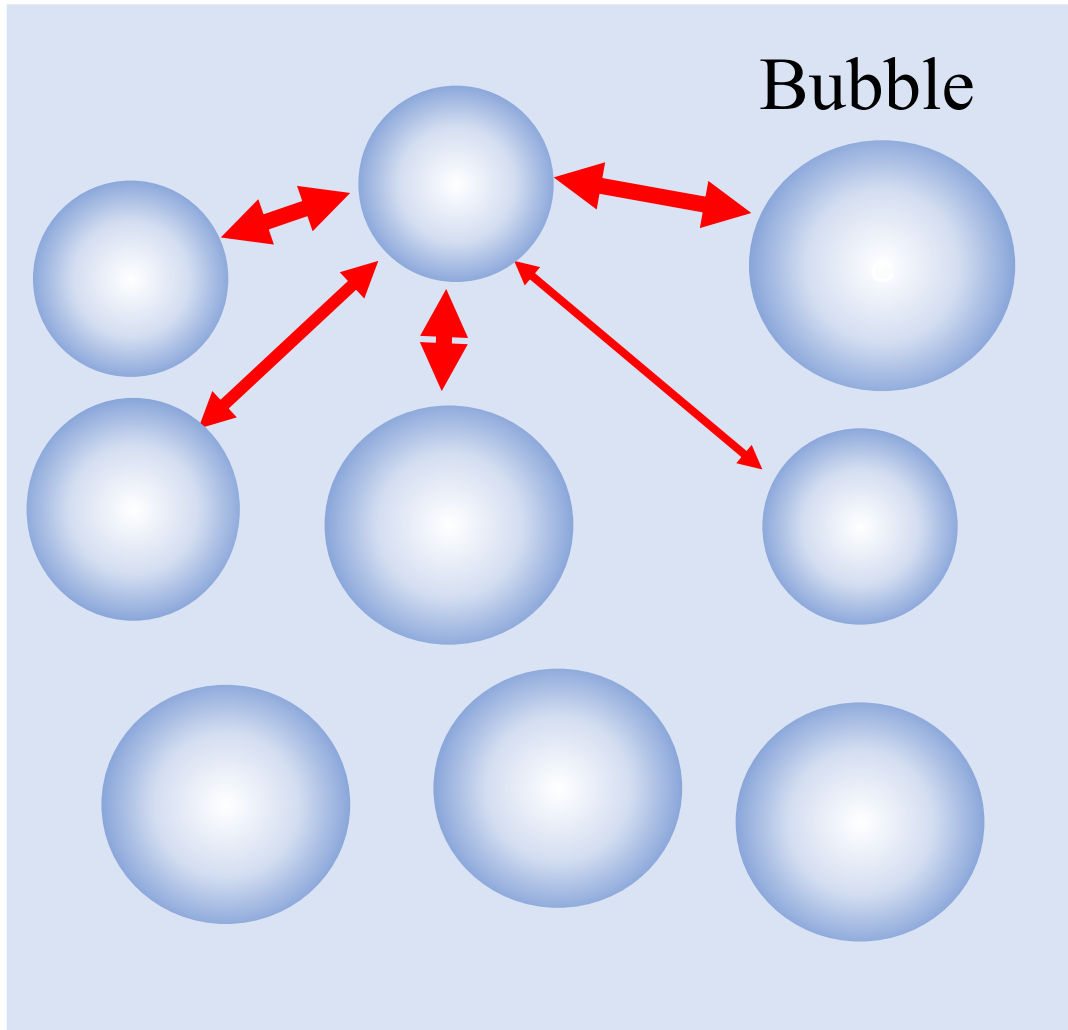


Figure 3. Time evolution of density field for the RTI problem with multi-mode perturbation: (a) $t = 1.6$; (b) $t = 2.4$; (c) $t = 3.2$; (d) $t = 4.0$. Results are obtained by the ILES-Roe scheme at a resolution of 16384×24576 .



RT

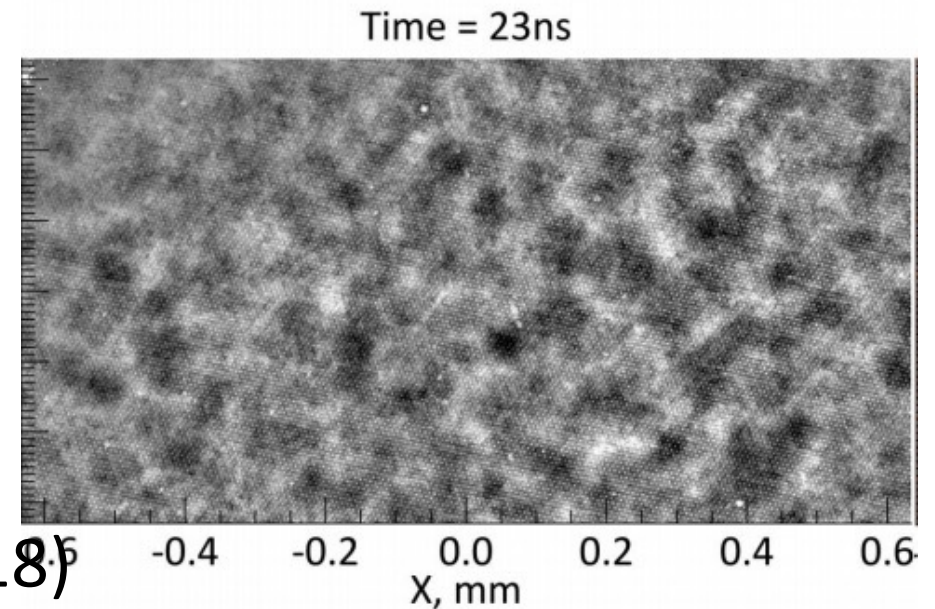
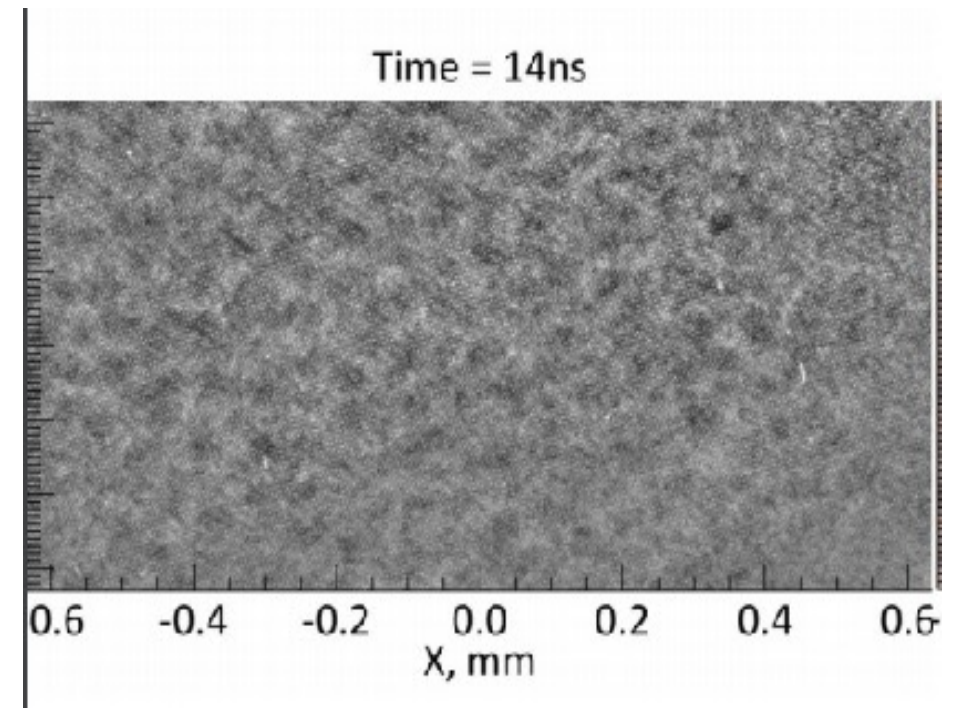
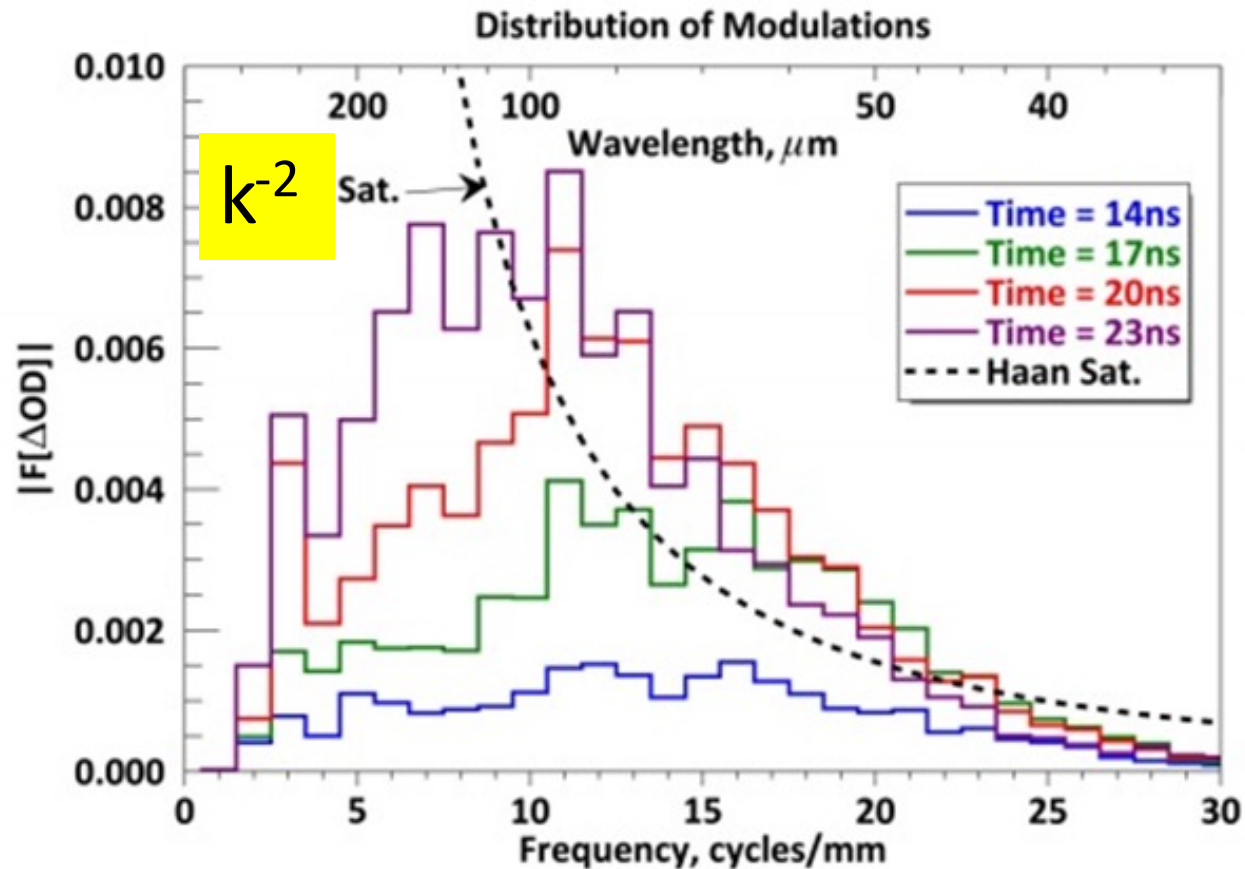
Bubble Coalescence in RT and Mixing (Top view)



$$h(t) \propto \alpha_A g t^2$$

time

K^{-2} is also observed in NIF R-T experiment



(by S. Khan, LLNL, 2018)

5. Conclusion

- Motivation (2007)
- 2D PIC simulation (2008)
- Proposal to NIF (2010)
- ACSEL team (2010)
- Verification with NIF (2014)
- Theoretical model (2018)
- Dawson award (APS) (2020)

Shock formation has been demonstrated at NIF

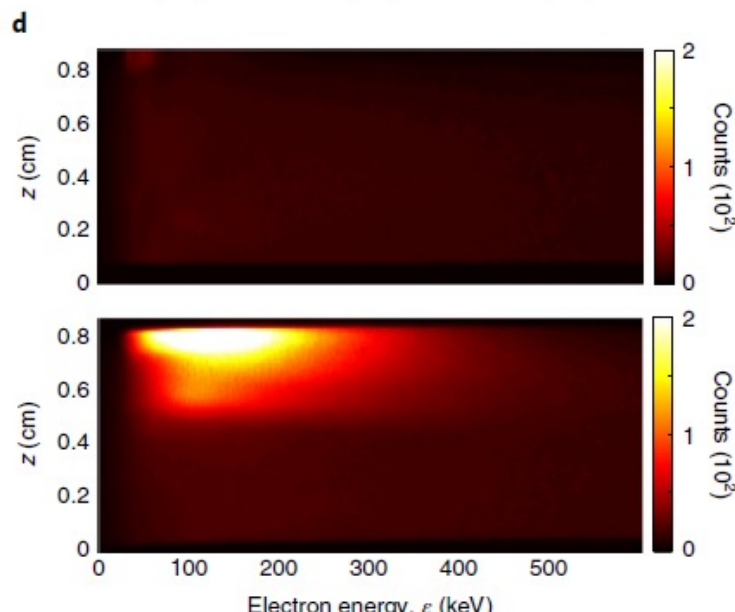
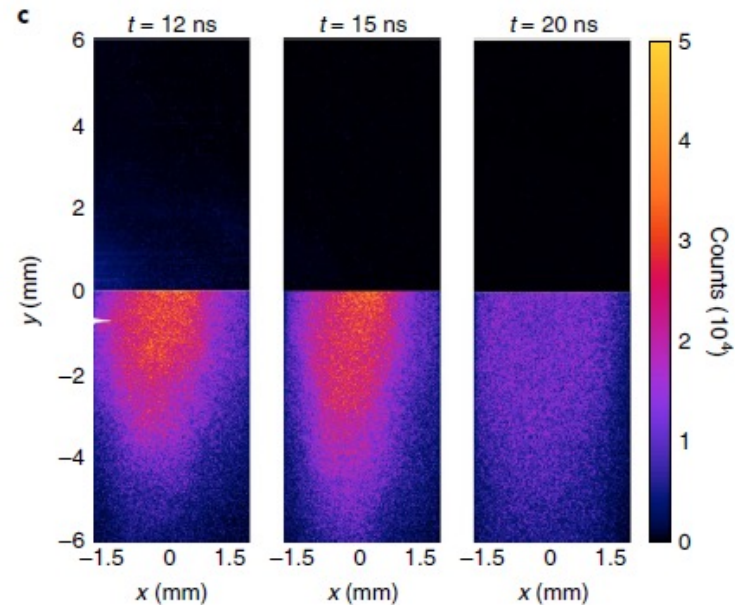
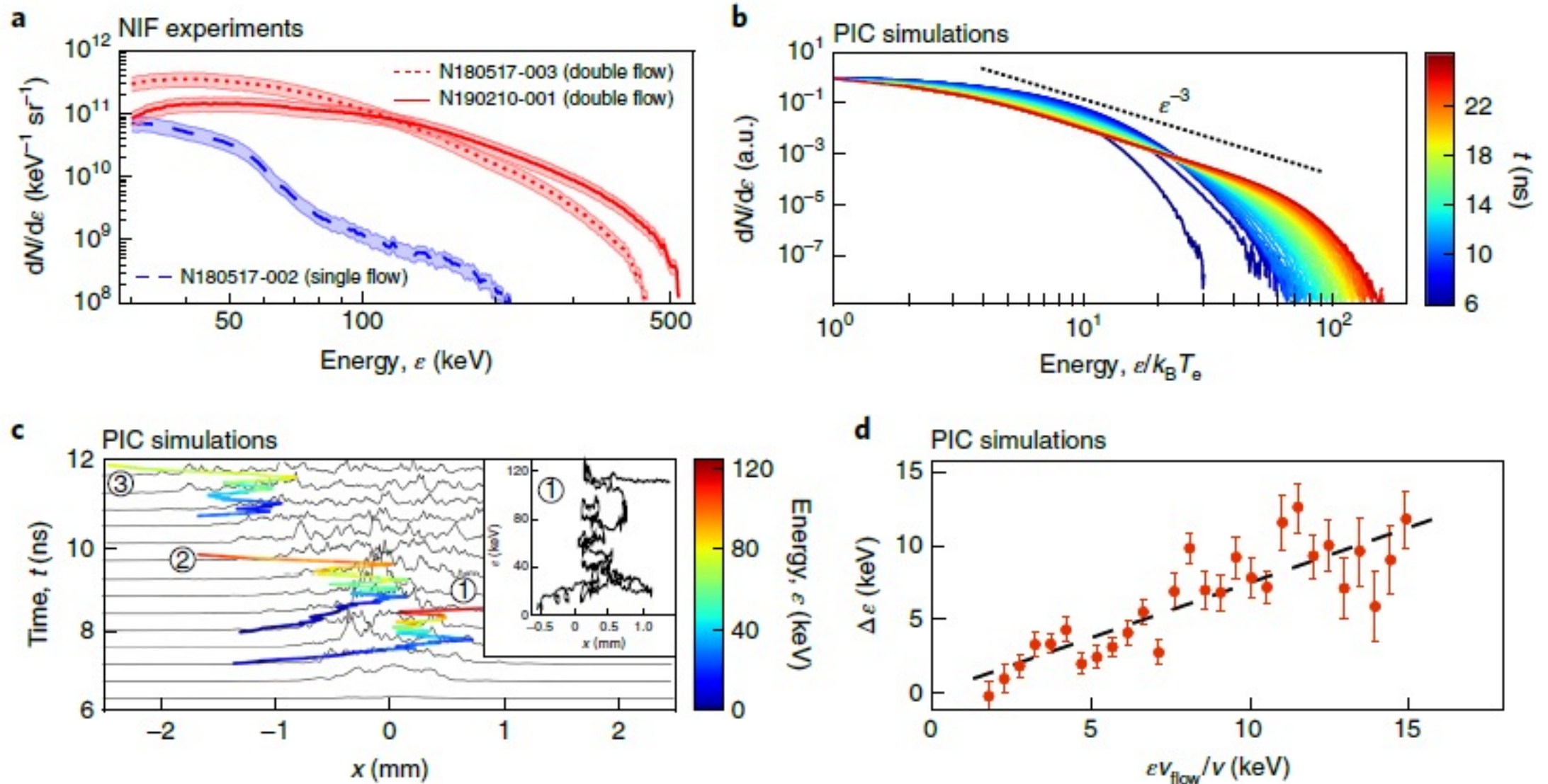


Table 1 | Comparison between plasma parameters in NIF experiments and young SNR shocks

Parameter	NIF experiments	Typical young SNR (for example, SN 1006)
Shock velocity (km s^{-1})	1,000–2,000	3,000–5,000
Ambient magnetic field (G)	2×10^4	3×10^{-6}
Ambient plasma density (cm^{-3})	5×10^{19}	0.2
Ambient plasma temperature (eV)	500	1
System size (cm)	2.5	3×10^{19}
Collisionality ($L_{\text{system}}/L_{\text{m.f.p.}}$)	0.03	0.01
Sonic Mach number (v_{sh}/c_s)	12	400
Alfvén Mach number (v_{sh}/v_A)	400	400

F. Fiuza et al., Electron acceleration in laboratory-produced turbulent collisionless shocks, *Nature Physics* **16**, 916–920(2020)

Electron acceleration has been demonstrated



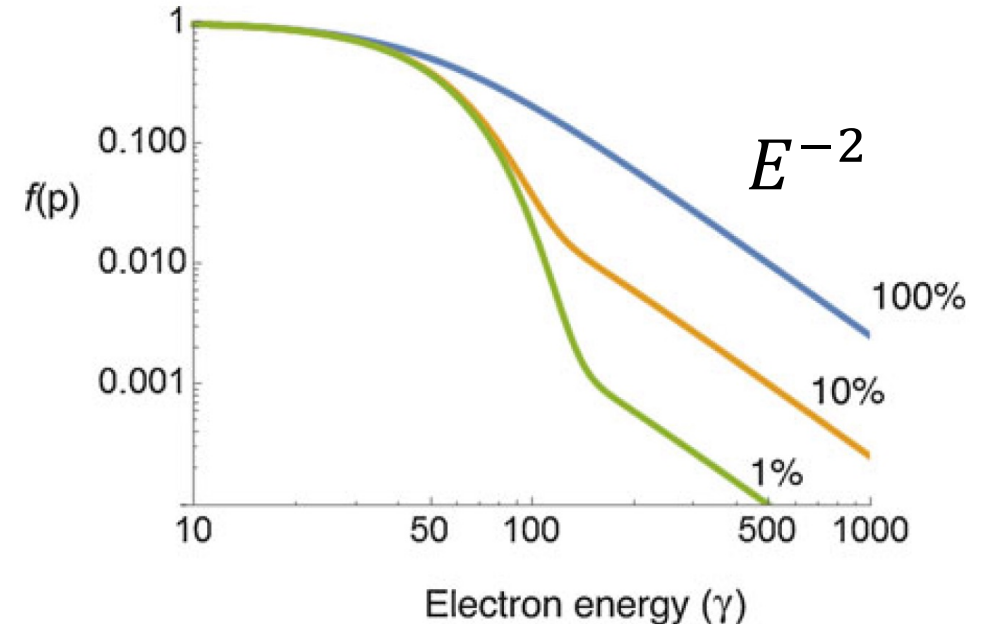
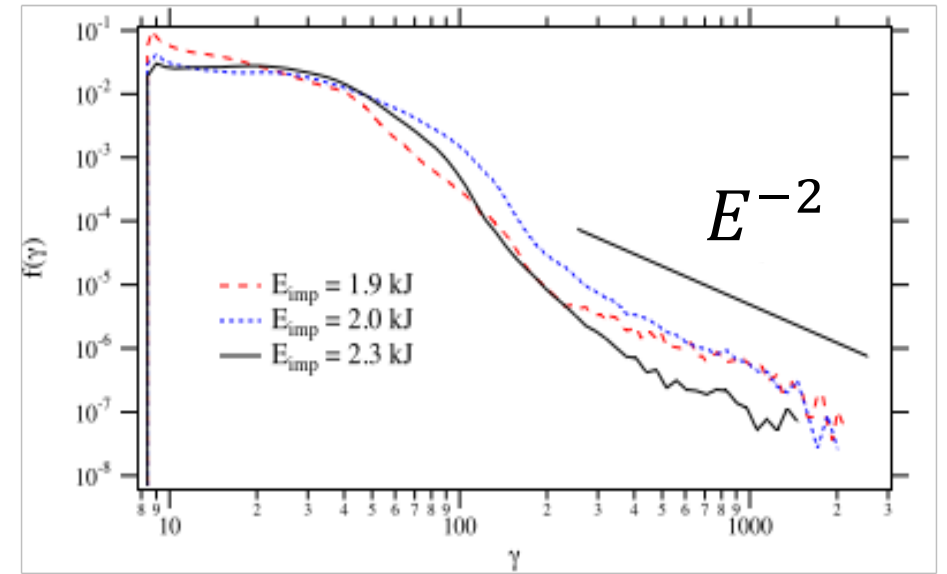
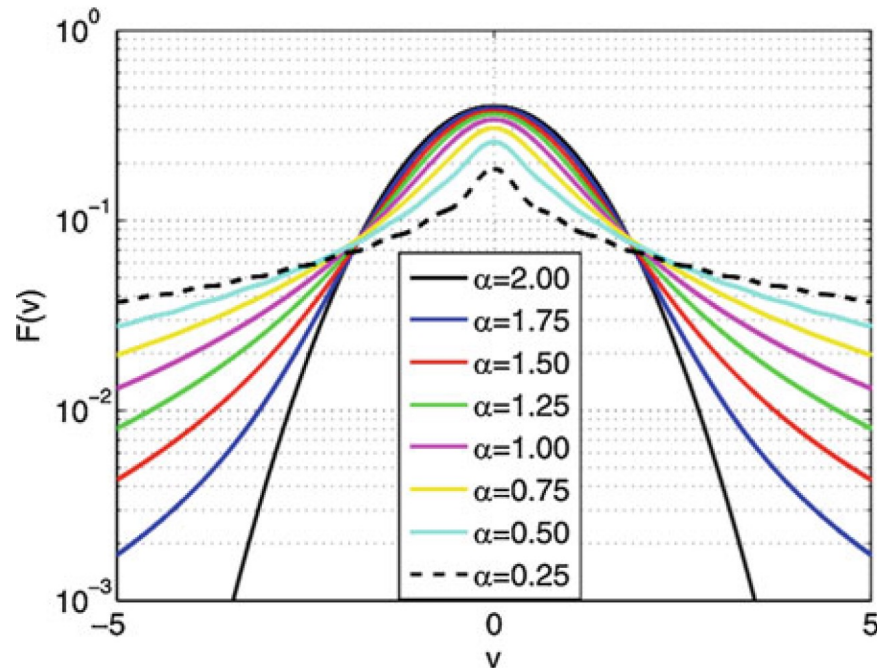
F. Fiuza et al., Electron acceleration in laboratory-produced turbulent collisionless shocks, *Nature Physics* **16**, 916–920(2020)

Levy's nonlocal transport (FFPE) can explain the non-thermal components

$$\frac{\partial}{\partial t} f(p, t) = D \frac{\partial^2}{\partial p^2} f(p, t), \quad D = \left\langle \frac{(\Delta p)^2}{2\Delta t} \right\rangle$$

$$\frac{\partial^\alpha}{\partial |p|^\alpha} \equiv \frac{1}{2\pi} \int_{-\infty}^{\infty} |k|^\alpha e^{-ikp} dk \quad -k^2 \Rightarrow -|k|^\alpha$$

$$\frac{\partial}{\partial t} f = D \frac{\partial^\alpha}{\partial |p|^\alpha} f \quad f^\alpha(p, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \exp(-Dt|k|^\alpha + ikp) dk$$



LFEX experiment at ILE, Osaka U.



蔵満 (阪大)

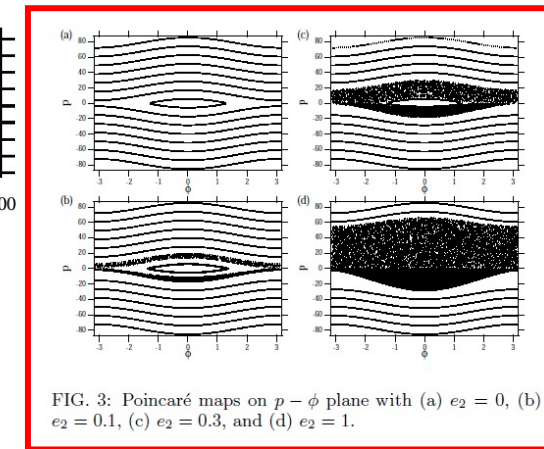
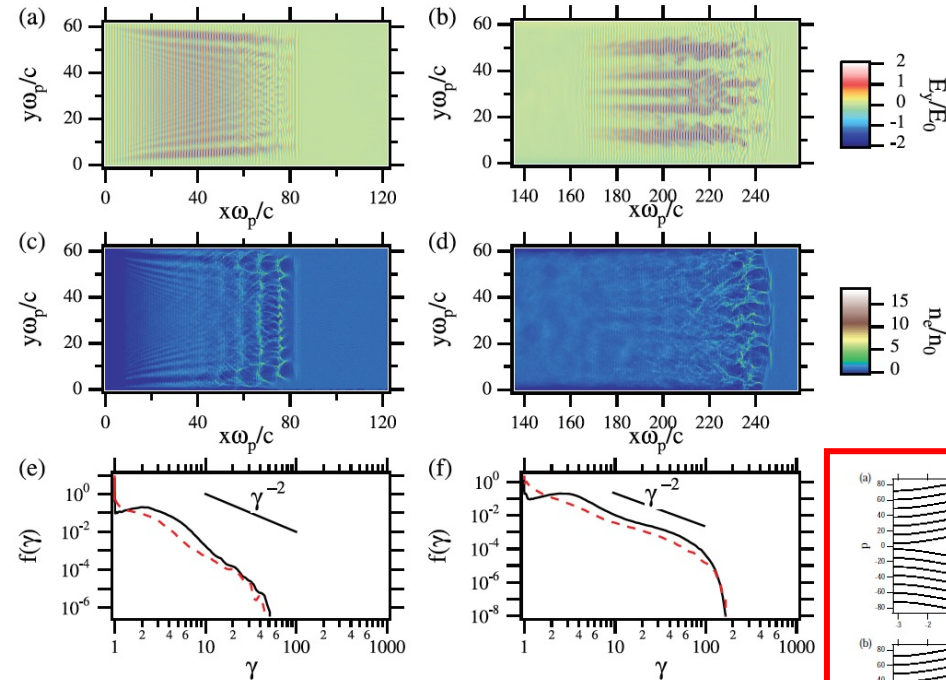
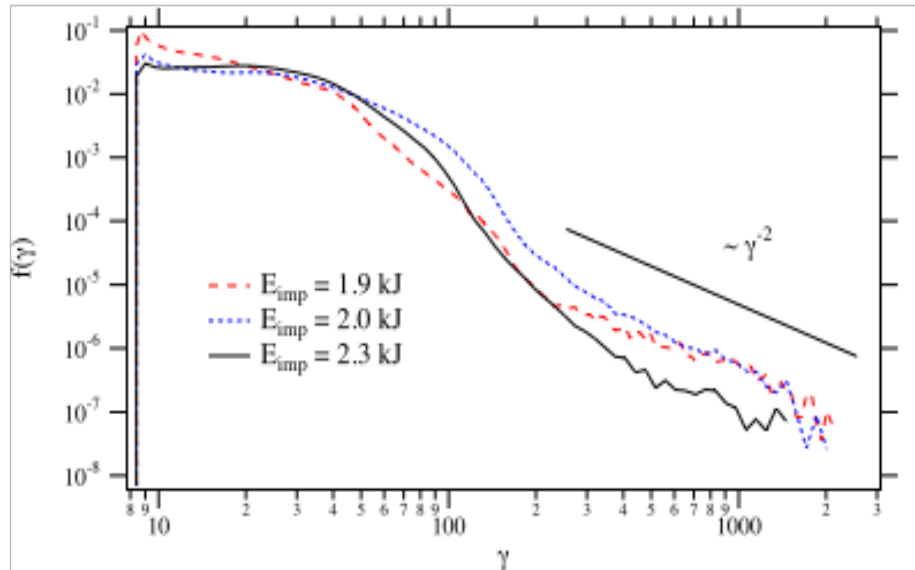
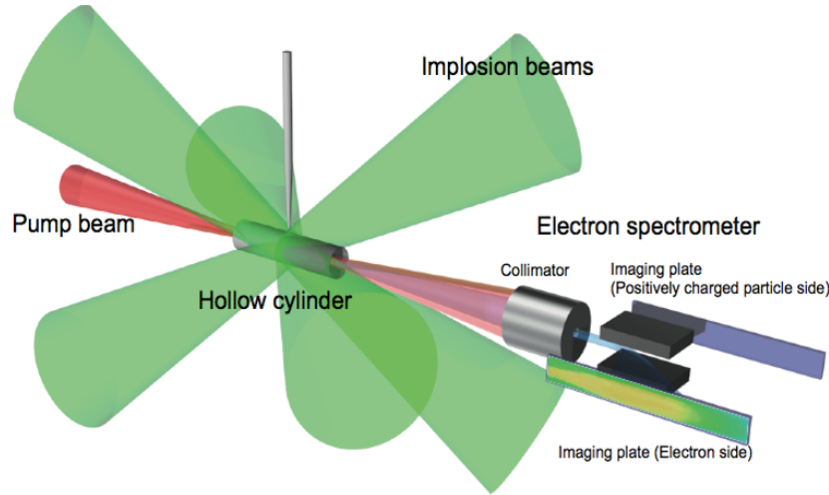


FIG. 3: Poincaré maps on $p - \phi$ plane with (a) $e_2 = 0$, (b) $e_2 = 0.1$, (c) $e_2 = 0.3$, and (d) $e_2 = 1$.

Y. Kuramitsu, *Model Experiment of Cosmic Ray Acceleration due to an Incoherent Wakefield Induced by an Intensive Laser Pulse*, Physics of Plasmas (Letter), **18**, 010201 (4 pages), (2011),

Y. Kuramitsu et al, *NONTHERMAL ACCELERATION OF CHARGED PARTICLES DUE TO AN INCOHERENT WAKEFIELD INDUCED BY A LARGE-AMPLITUDE LIGHT PULSE*, The Astrophysical Journal, 682: L113 (2008)

Leung Center for Cosmology and
Particle Astrophysics (**LeCosPA**),
National Taiwan University (NTU)
<https://lecospa.ntu.edu.tw/>

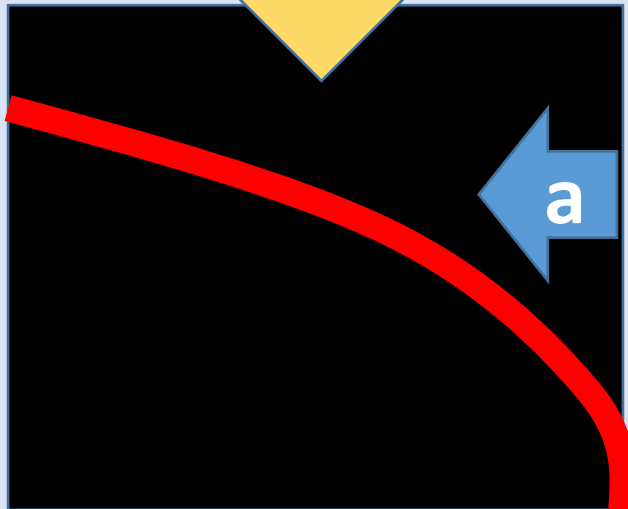


Analog Black Hole Experiment (AnaBHEL)

1. General relativity (Einstein)
2. Quantum Field Theory in Curved Spacetime (Hawking et al)



Equivalence principle



Hawking radiation from Black Hole

$$T_{BH} = 6 \times 10^{-8} \left(\frac{M_{sun}}{M} \right) [K]$$

Unruh radiation from accelerating system

$$T_U = 4 \times 10^{-21} \left(\frac{a}{1m/s^2} \right) [K]$$

$$a \approx \frac{V}{\Delta t} \sim \frac{c}{fs}$$