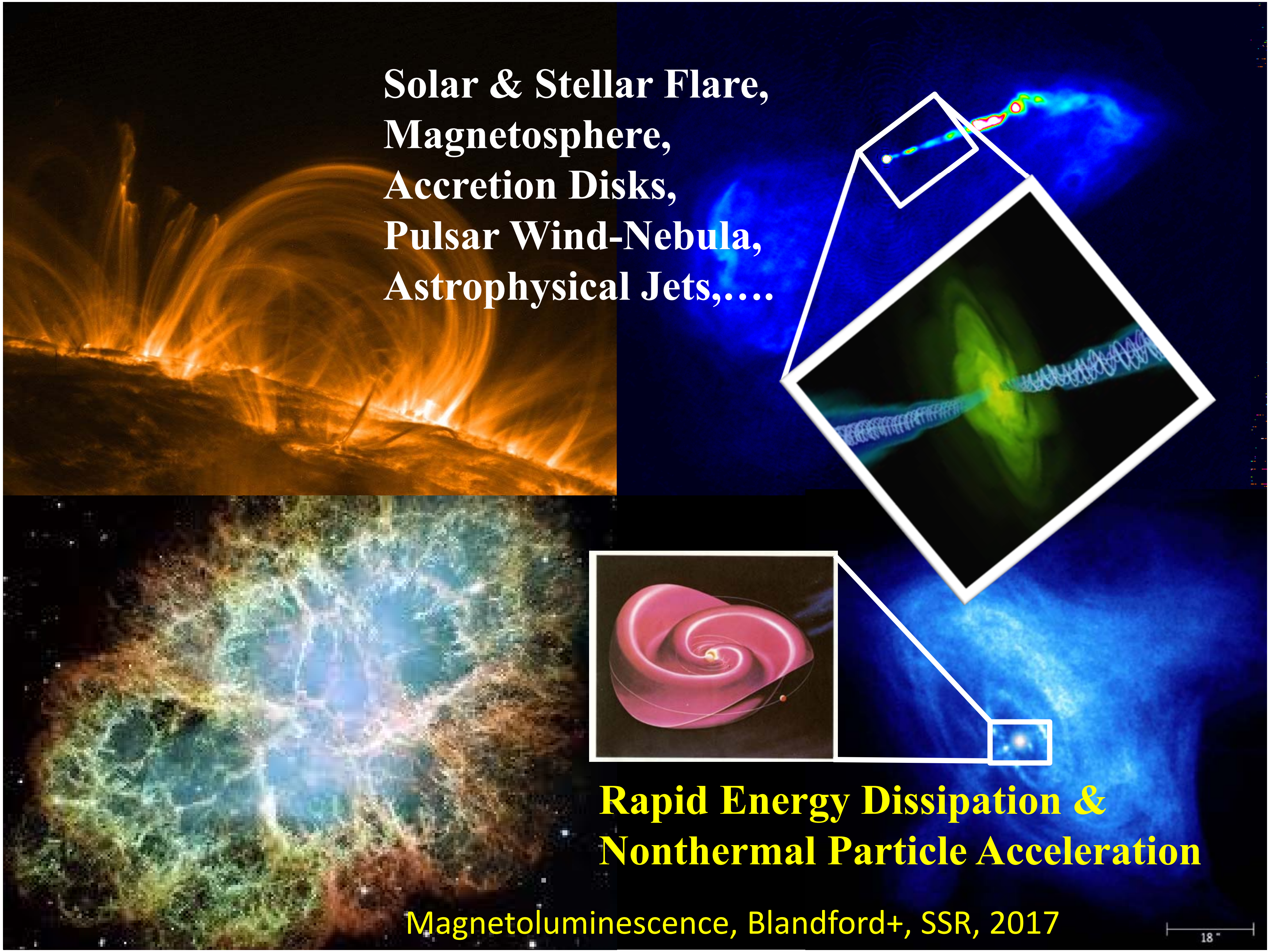
THE UNIVERSITY OF TOKYO

Particle Acceleration in Laboratory Plasma Astrophysics:

reconnection, shock wave & wakefield

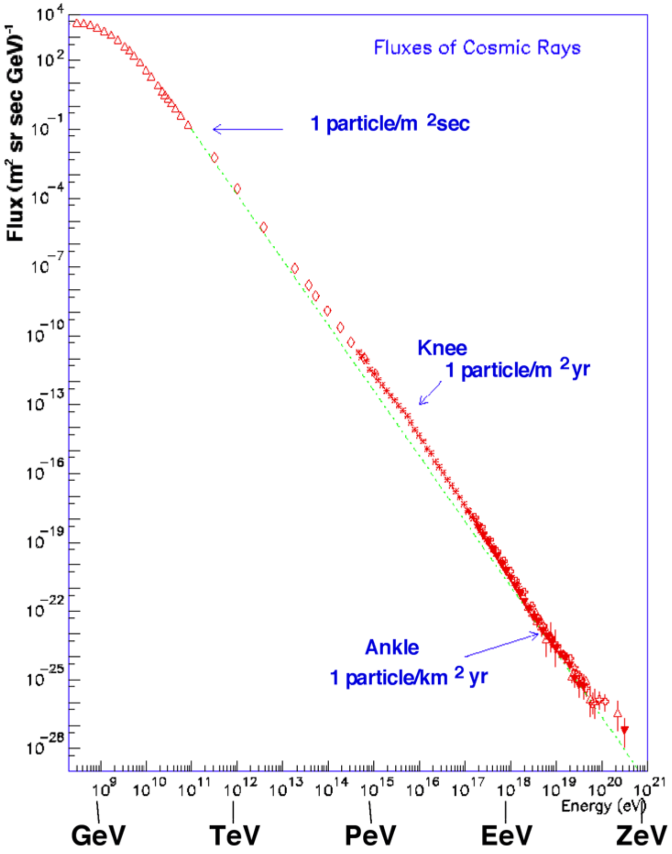
Masahiro Hoshino

University of Tokyo


Solar & Stellar Flare,
Magnetosphere,
Accretion Disks,
Pulsar Wind-Nebula,
Astrophysical Jets,….
Rapid Energy Dissipation &
Nonthermal Particle Acceleration
Magnetoluminescence, Blandford+, SSR, 2017

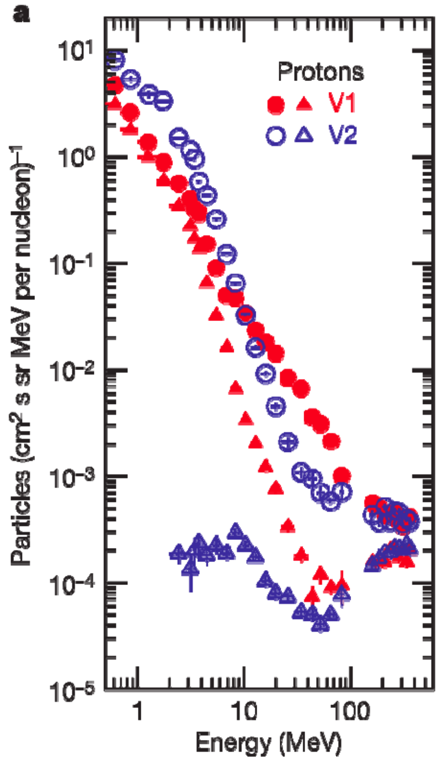
Nonthermal Universe

Cosmic Rays



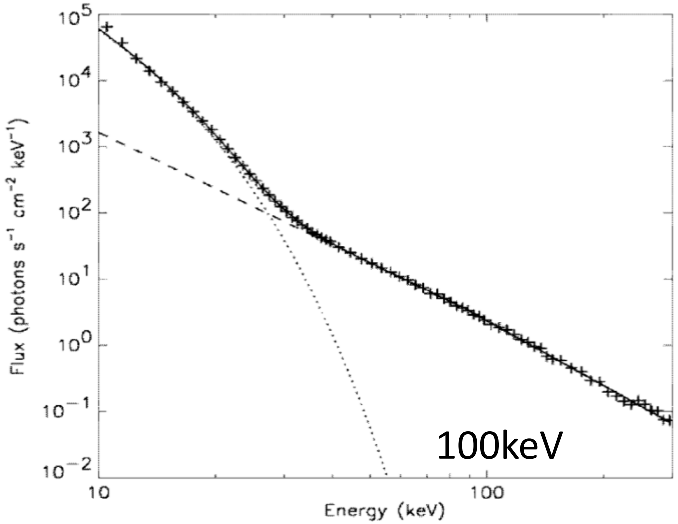
[Nagano & Watson, 2000]

Heliosphere Anomalous CRs



[Stone et al., 2008]

Solar Flares

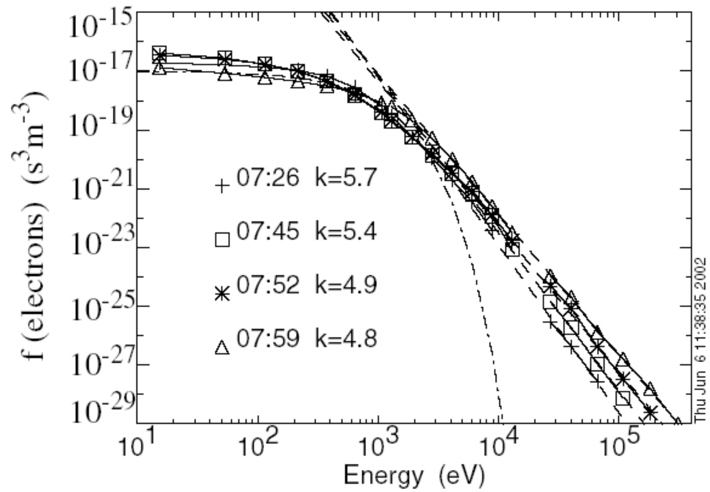


[Lin et al., 2003]

Earth's Magnetosphere

a)

electron distributions earthward of X-line



[Oieroset et al. 2002]

Nonthermal spectra are in common in our universe

Laser-Plasma Experiments

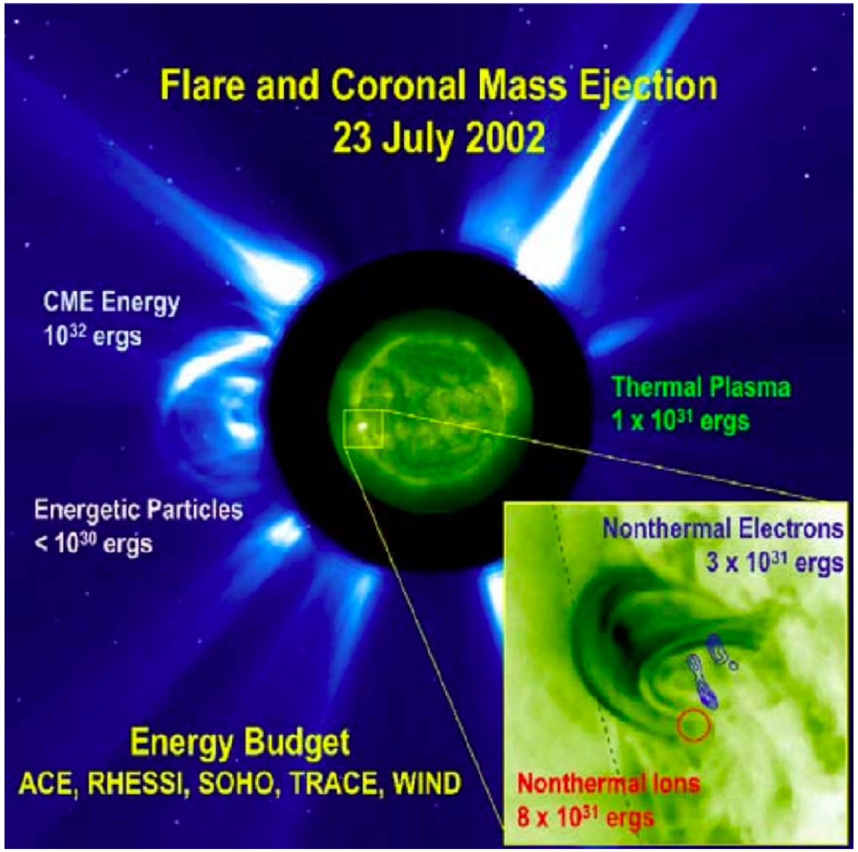
Laboratory experiments can achieve astrophysically relevant microscopic states:

Low collisions,
High speeds,
Large energy densities and fields.

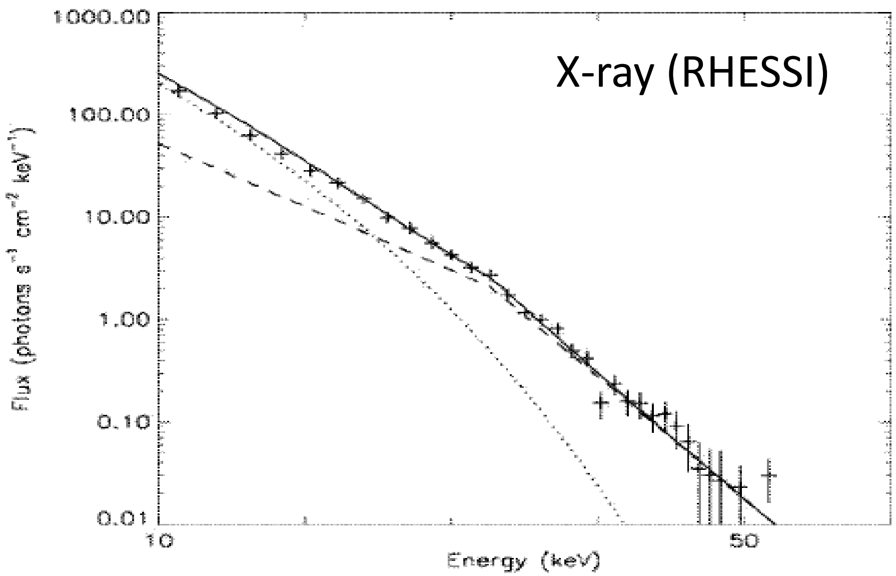
Laser–plasma experiments should be key to investigate plasma universe

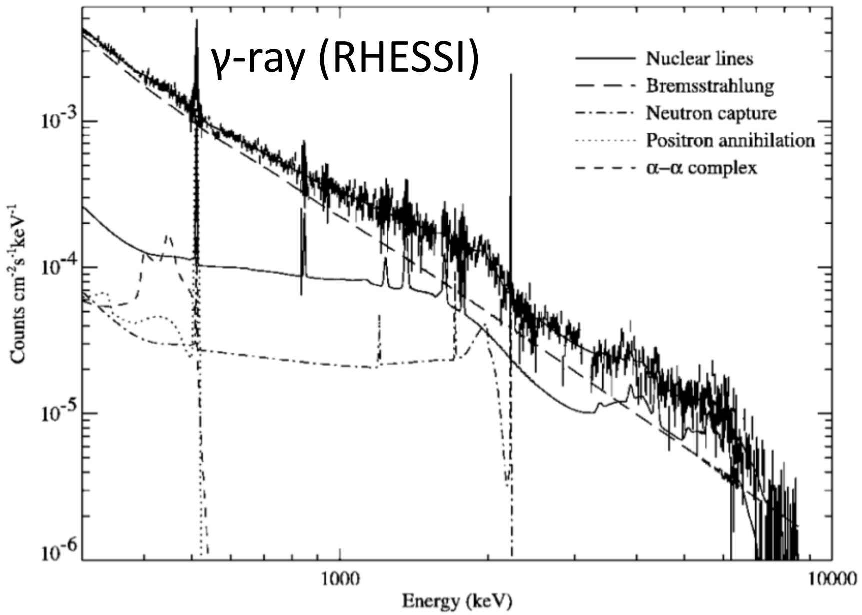
Energetic particles in Solar flares

(GOES class X4.8)



Emslie+ JGR 2004

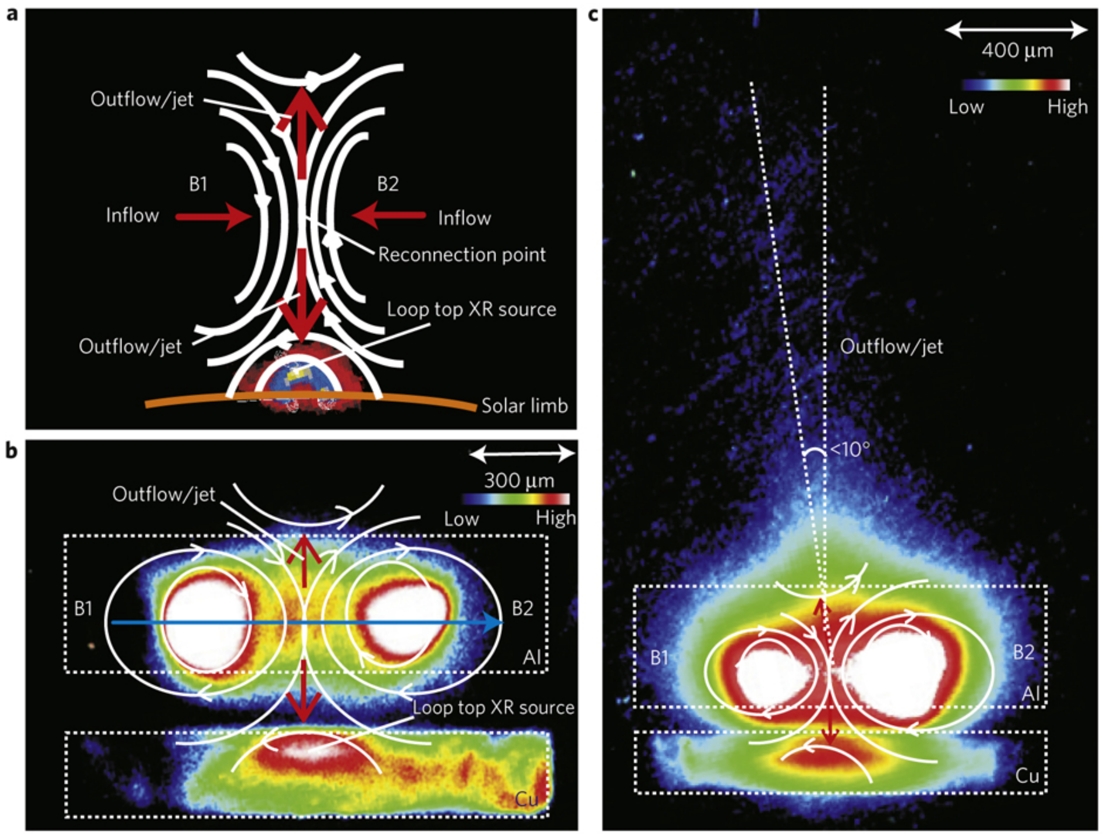




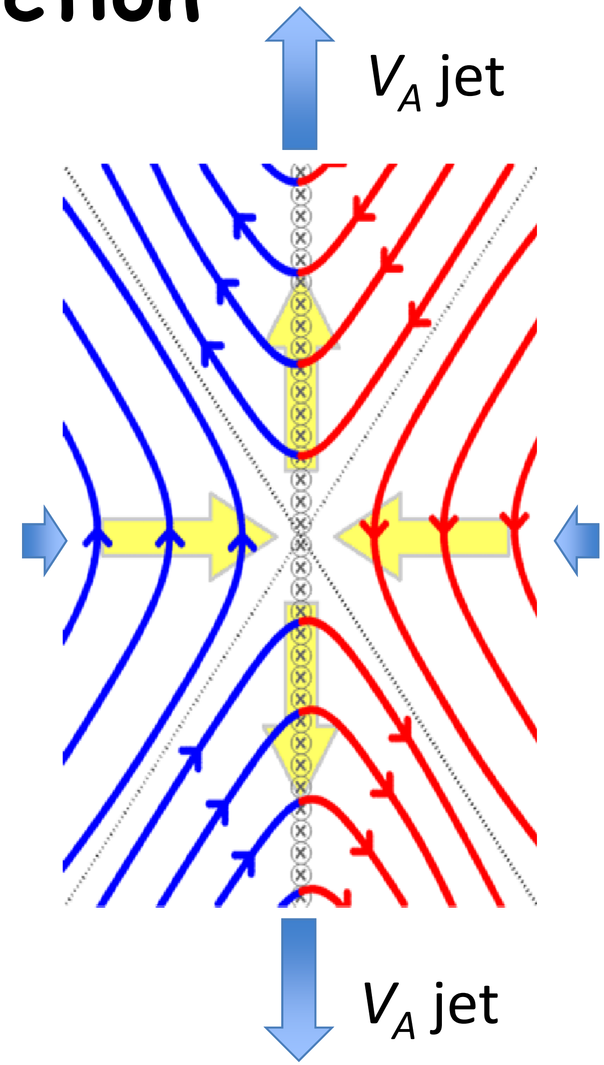
electrons up to tens of MeV,
ions up to tens of GeV
Lin+ ApJ 2003

On-Going Laboratory Challenge (1): Magnetic Reconnection

Laser experiment: Generation of Alfvénic jets and hot plasmas



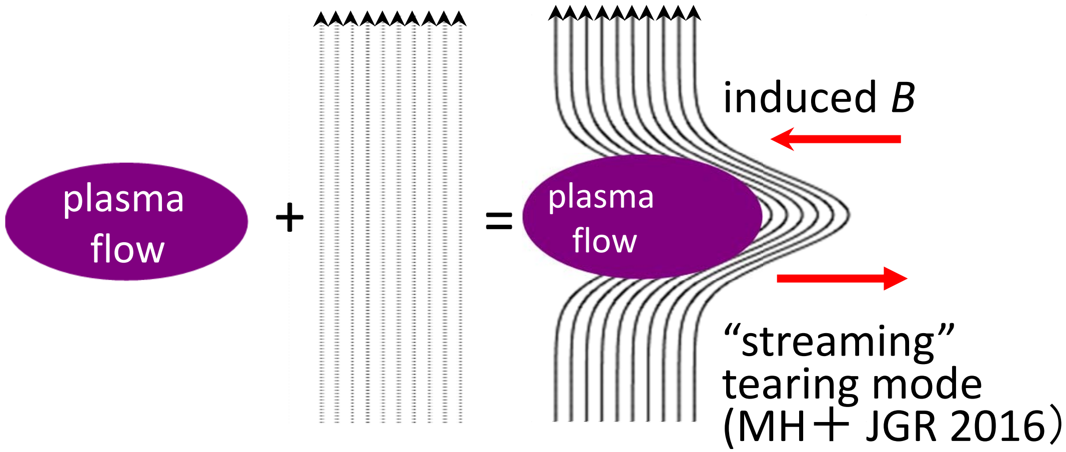
Zhong + Nature Physics 2010, Nilson+ PRL 2006; Li+ PRL 2007; Willingale+ PoP 2010; Dong+ PRL 2012

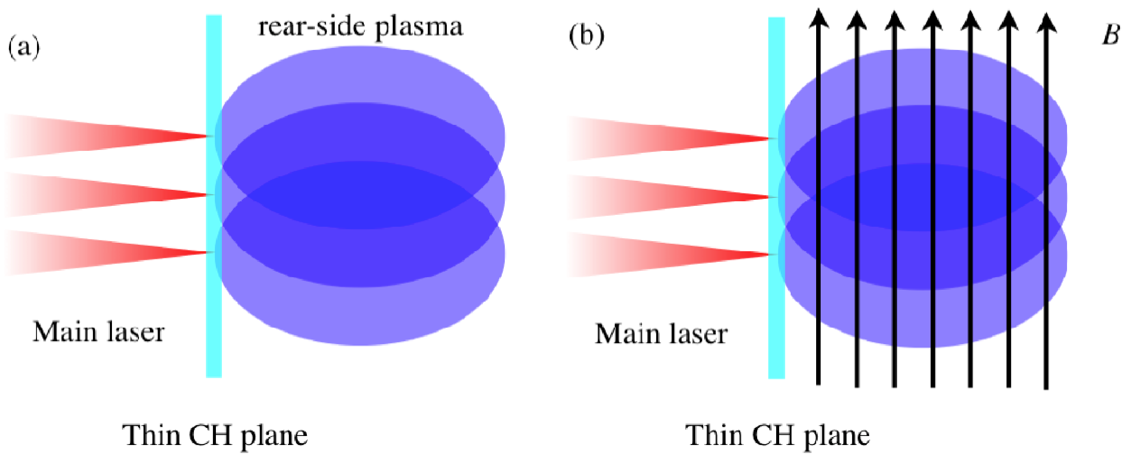


Giovaneli, Nature, 1949, Sweet 1958, Parker 1957, Petschek 1964, Furth, Killeen and Rosenbluth (FKR), 1964,…

Reconnection Jet under external B-field

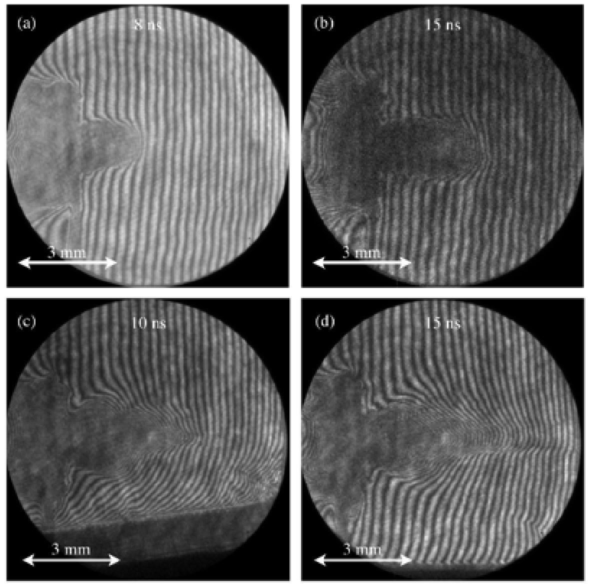
- GXII
  - 4 beams, 500 J, 500 ps
  - offsets 200 - 300 μm for directional expansion
- Single CH plane target 10 μm
- External magnetic field
  - a permanent magnet ~ 0.7 T at the surface
  - perpendicular to the plasma axis
- Target environment: vacuum





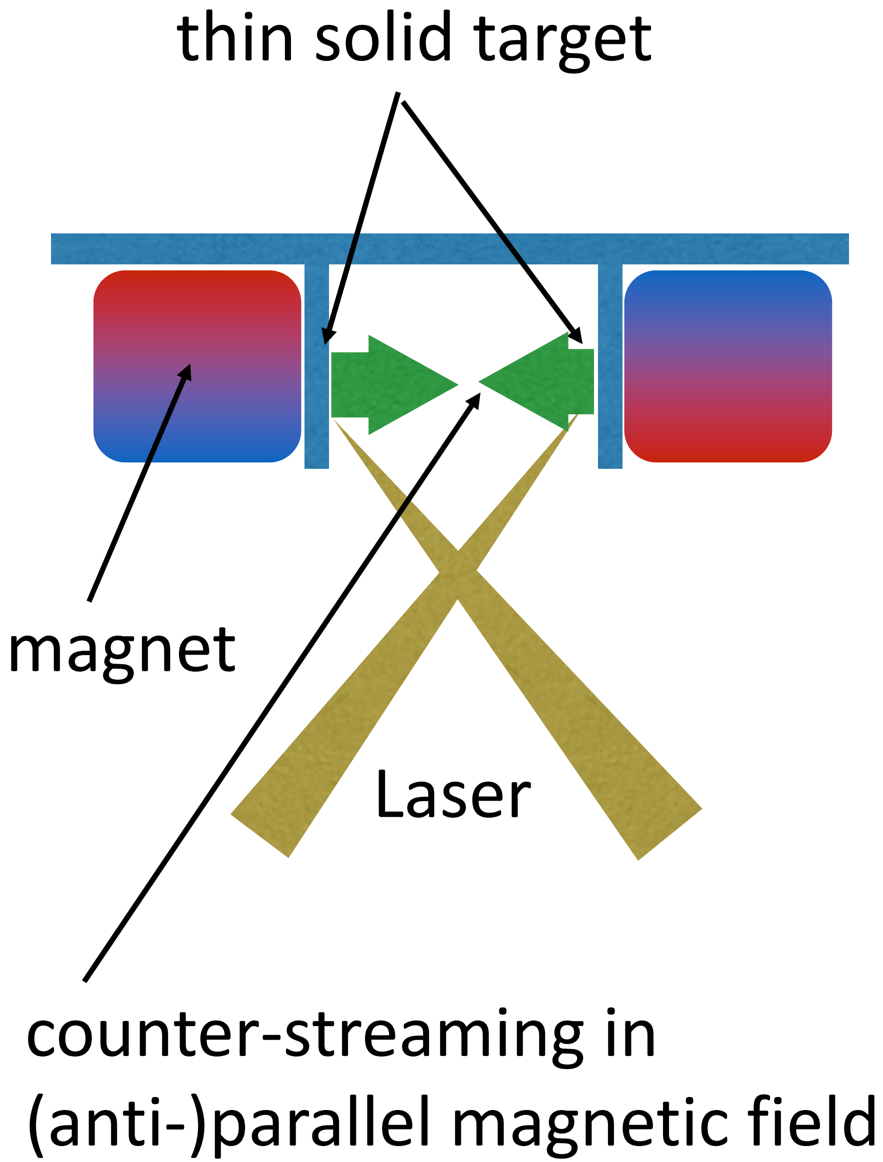
Kuramitsu, Sakawa, Moritaka et al. in prep.

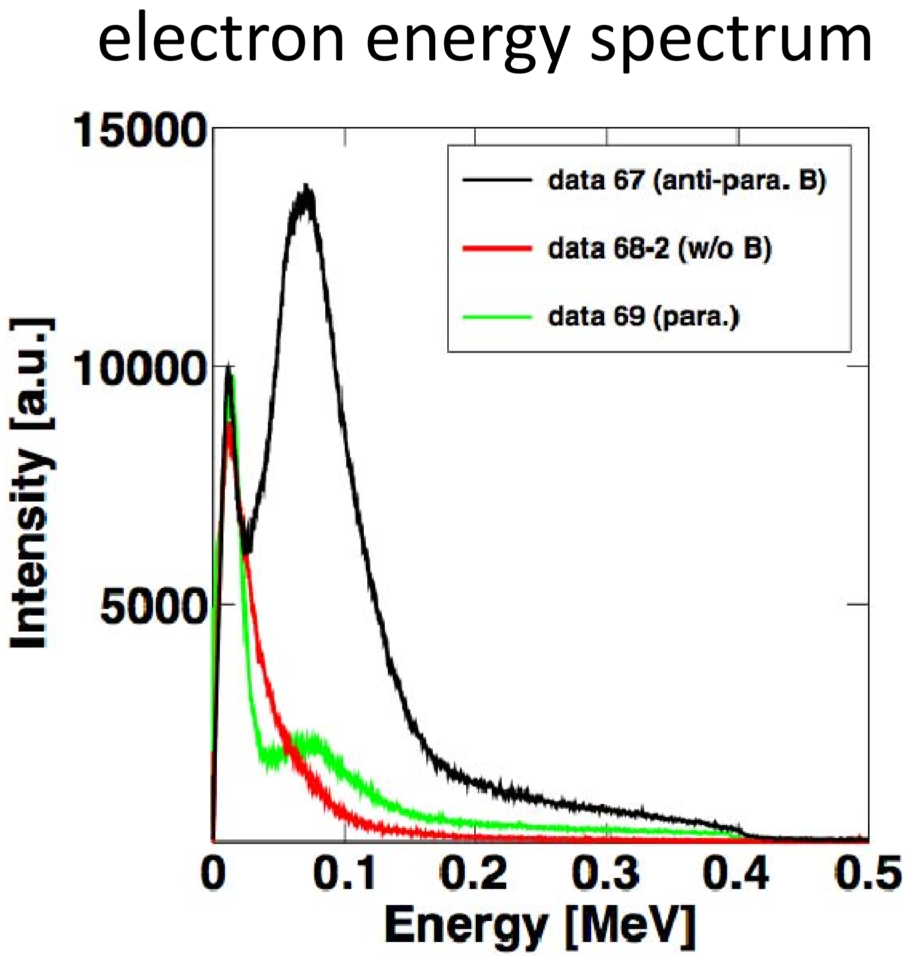
Interferograms



Collimation observed only when B exist

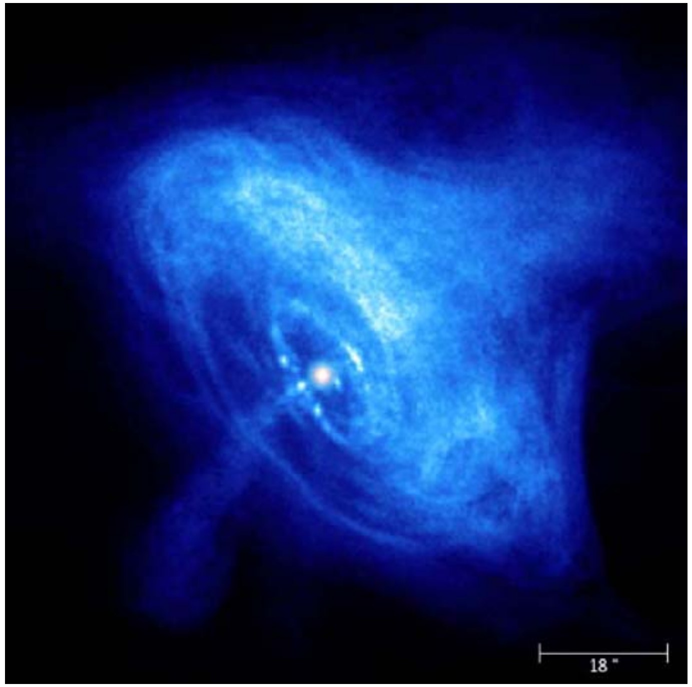
MeV electrons in SGII

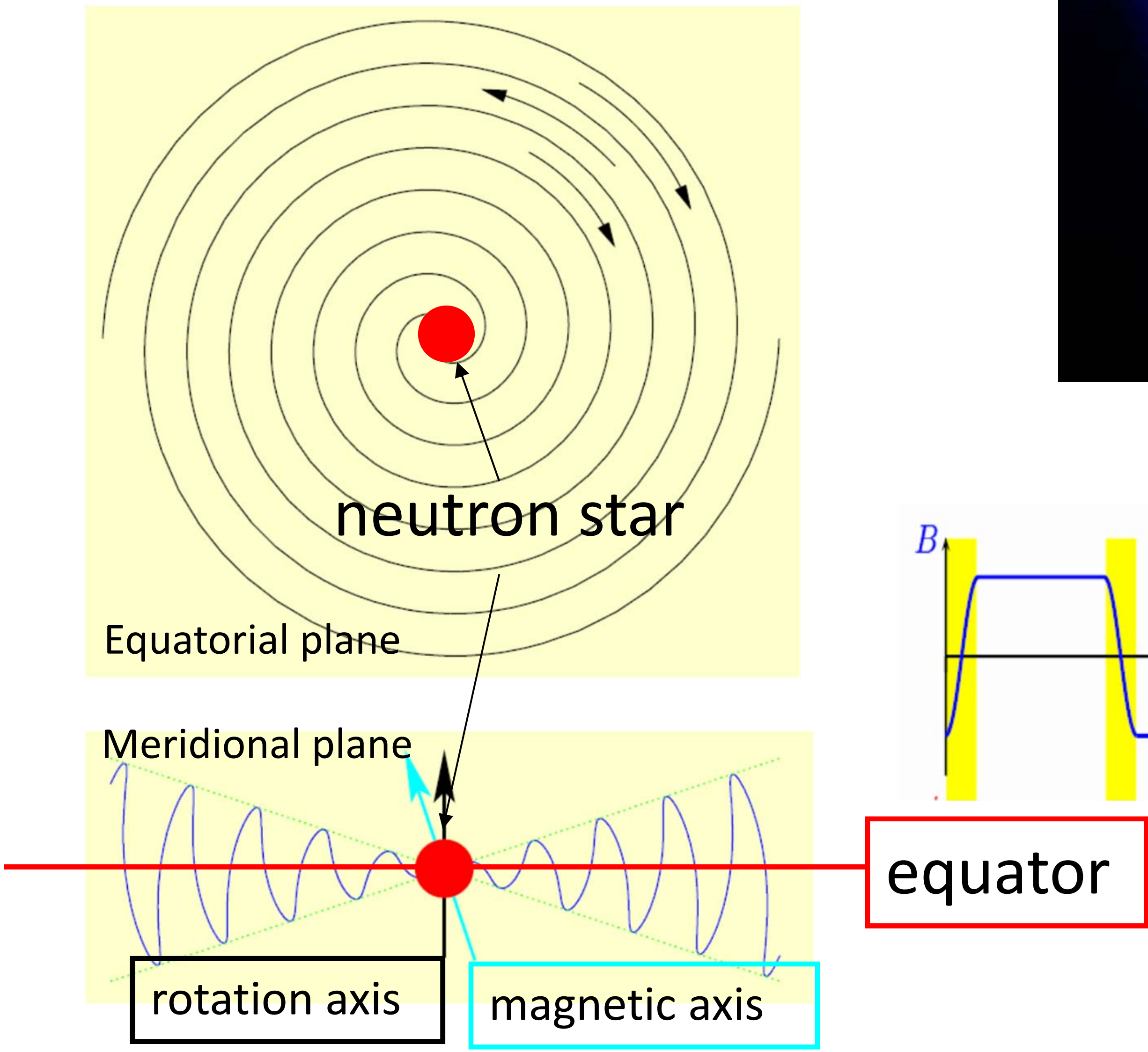


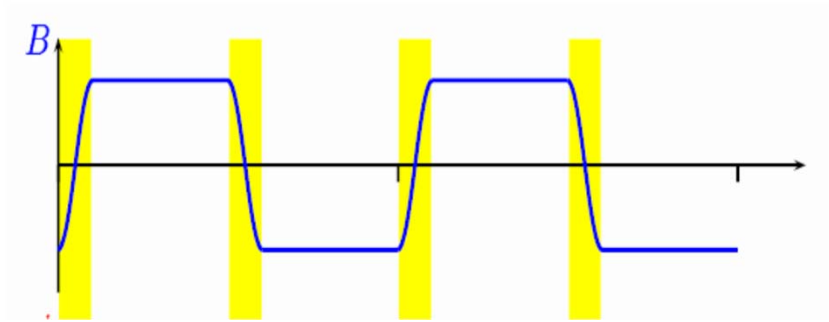


Morita + (in prep)

Relativistic Reconnection with Striped Wind in Crab Nebula

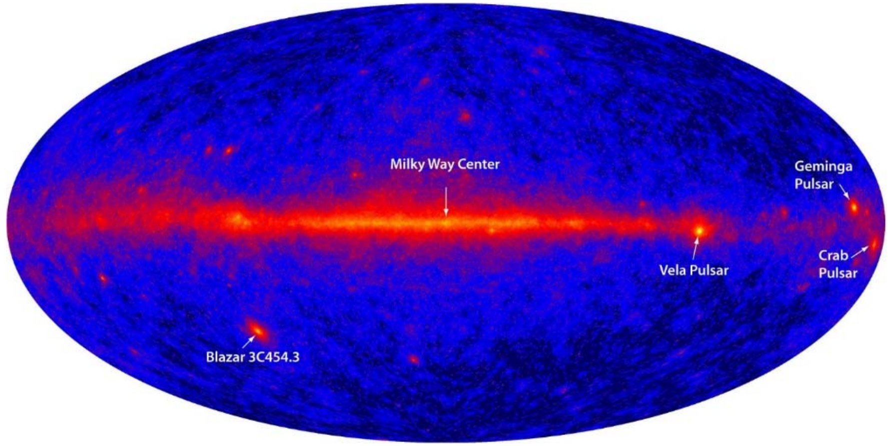




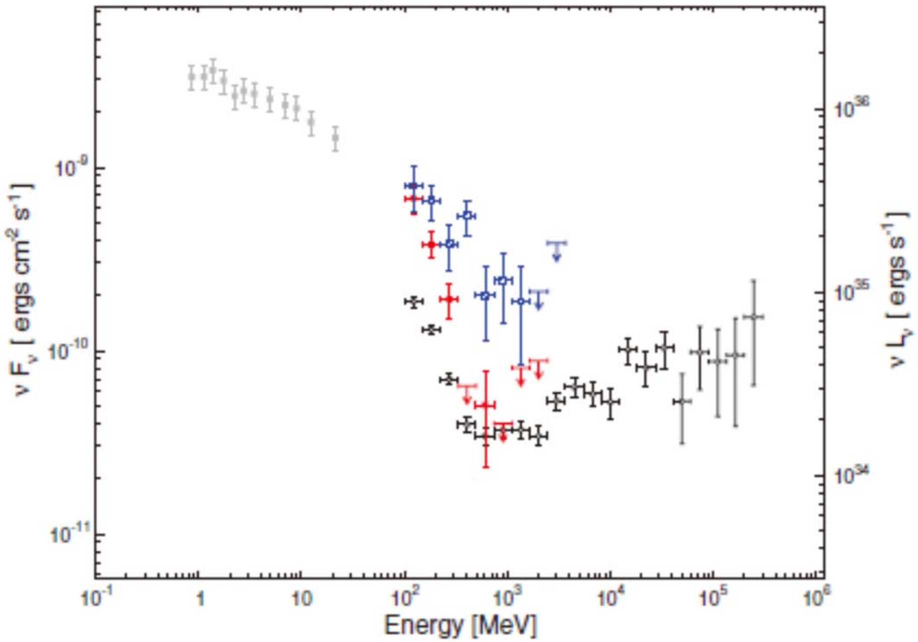


Coroniti, ApJ 1990,
Lyubarsky & Kirk ApJ 2001,
Kirk et al. PRL 2003

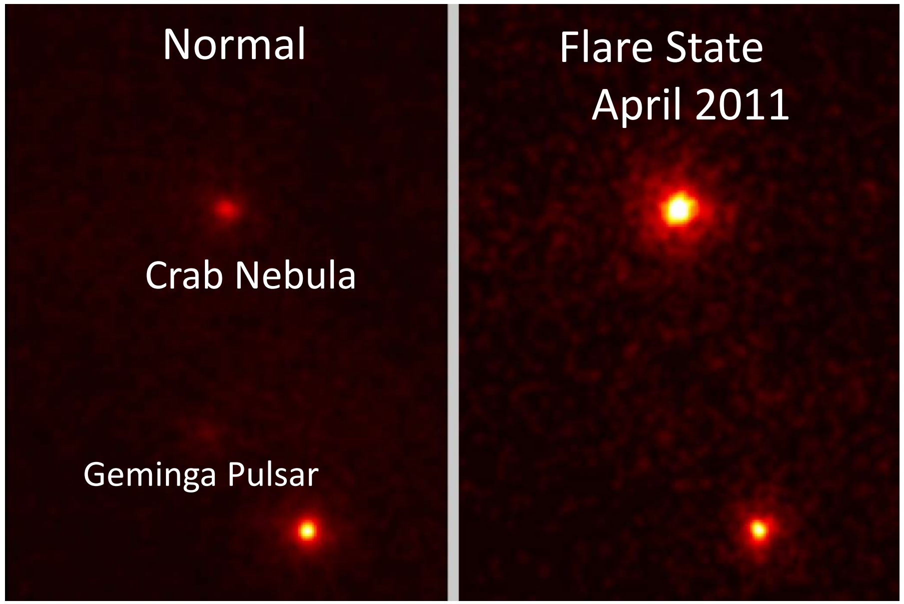
Gamma ray flares in Crab



Enhancement of gamma ray flux (E_γ > 100MeV) in a few days



(Tavani + Science 2011; Abdo + Science 2011)



Fermi LAT/R. Buehler

Radiation-reaction limit for synchrotron photon energy

Acceleration $F_e = eE$

Radiation loss $F_{rad} \approx \frac{2}{3} r_e^2 \gamma^2 B_\perp^2$

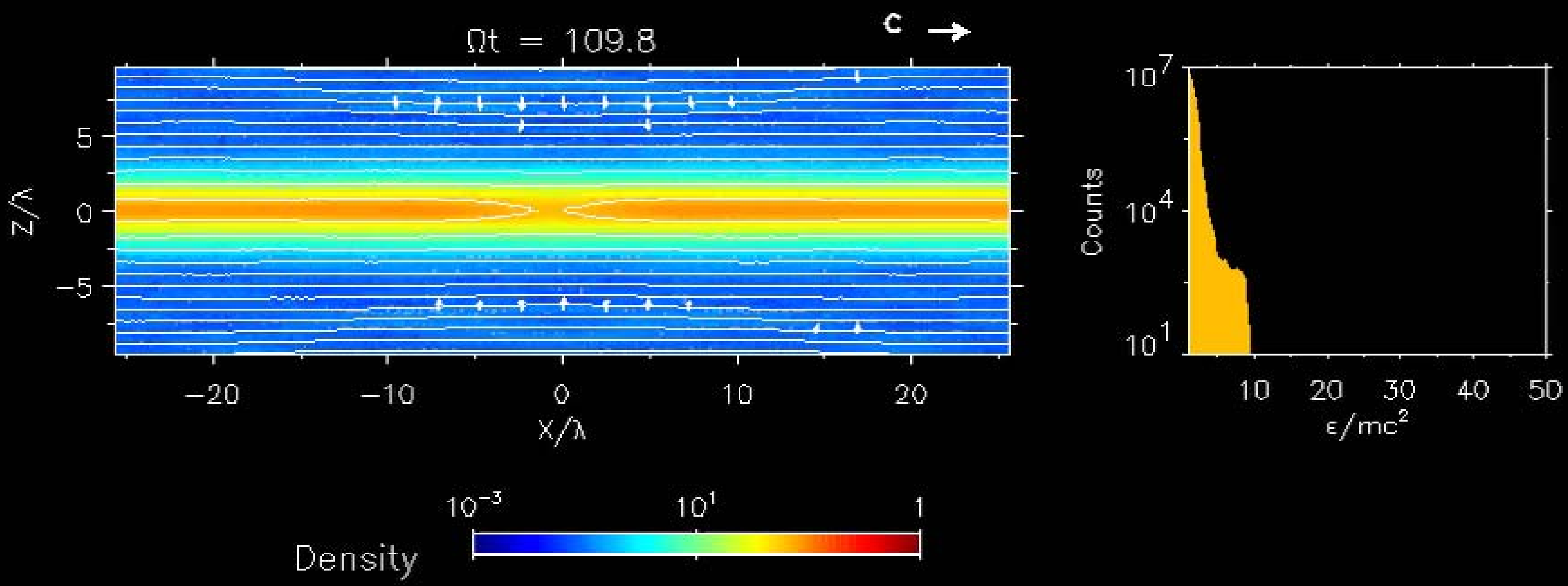
$F_e = F_{rad}$ $\gamma_{rad} = \left(\frac{3eE}{2 r_e^2 B_\perp^2} \right)^{1/2}$

Synchrotron photon energy

$$\varepsilon_{max} = \frac{3he}{4\pi mc} B_\perp \gamma_{rad}^2 = \frac{9}{4} \frac{mc^2}{\alpha_F} \frac{E}{B_\perp}$$

$$E = B_\perp \rightarrow \varepsilon_{max} = 160 \text{ MeV}$$

Relativistic Reconnection with PIC (electron & positron)



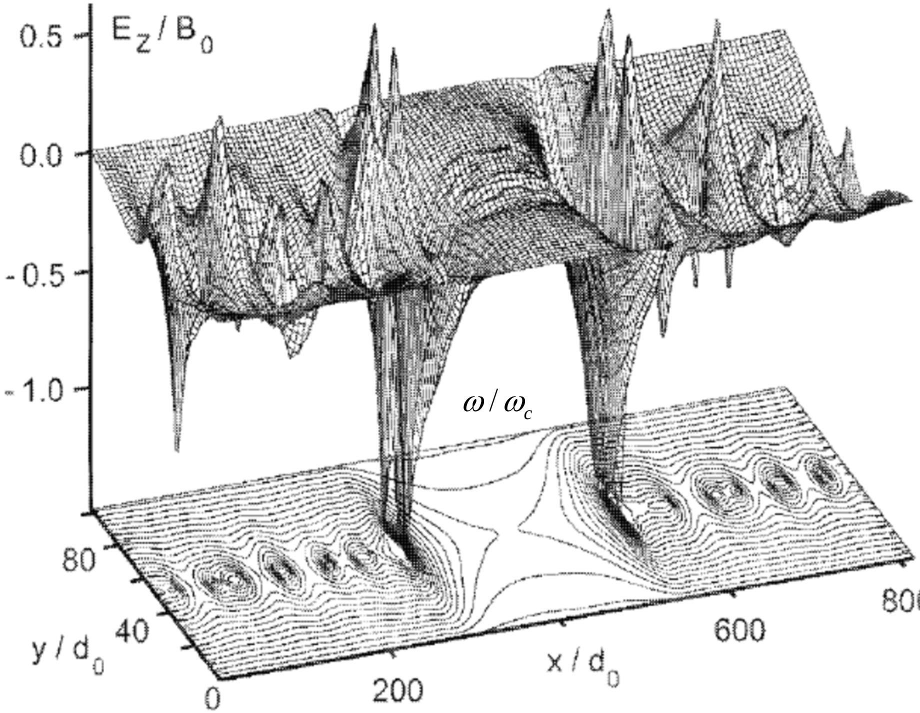
Non-thermal particle acceleration due to relativistic Speiser motion

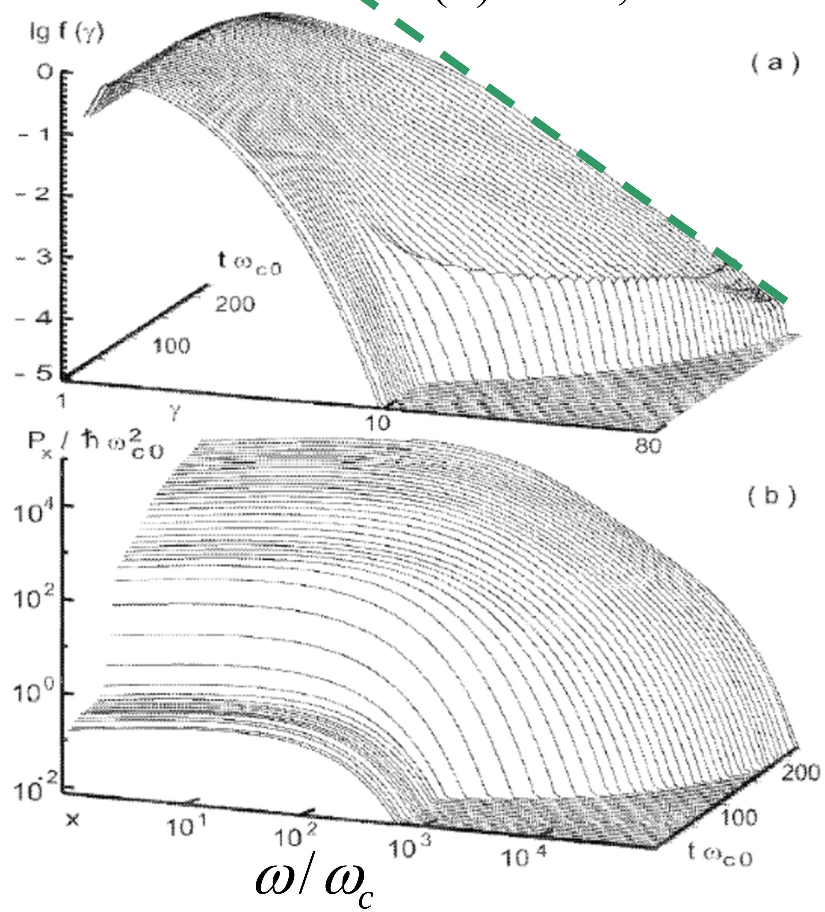
Zenitani & MH, ApJ 2001;
Jaroschek & MH PRL 2009

Large-Scale Evolution of MRX

Power-law Energy Spectrum

$$N(\varepsilon) \propto \varepsilon^{-s}, \quad s = 1 \sim 3$$

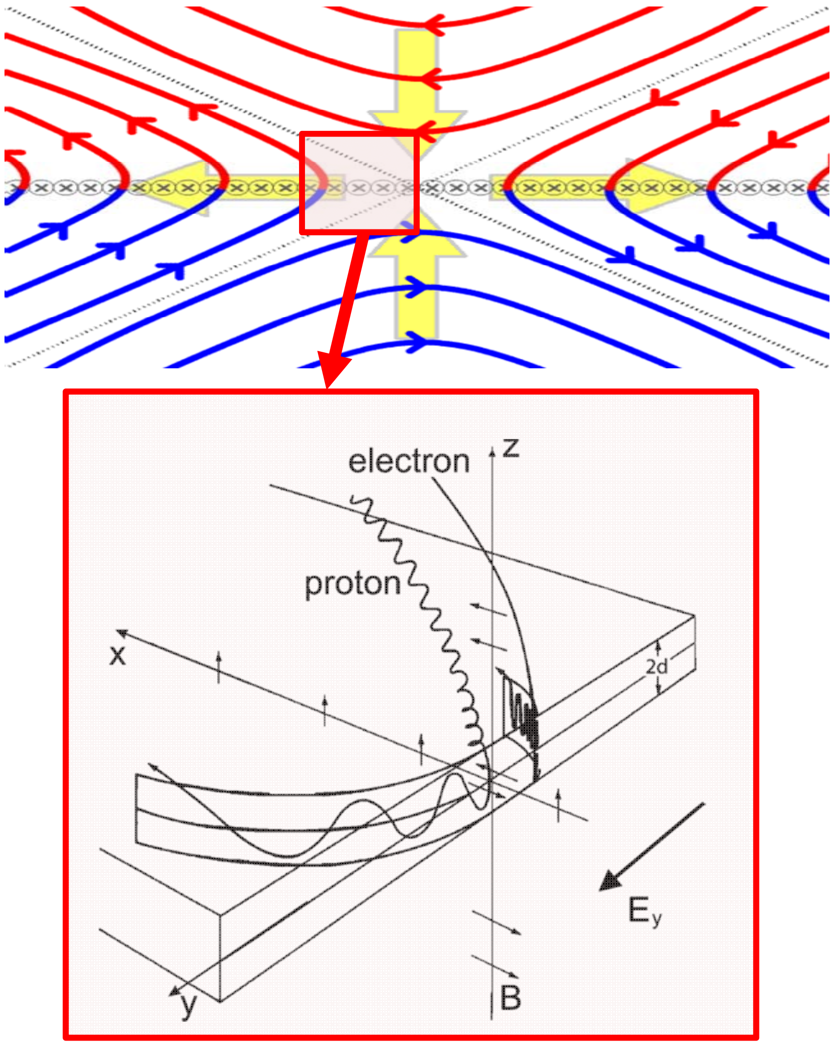




Synchrotron Spectrum

Jaroschek et al. ApJ 2004

Relativistic Magnetic Reconnection



Inflow and outflow around X-type region, associated with inductive electric field (E)

$$E = B \times \frac{V_A}{c}$$

Alfvénic outflow jet (V_A)

$$\frac{V_A}{c} = \sqrt{\frac{\sigma}{\sigma + 1}} \approx 1$$

magnetic energy dissipation at X-type region with $E \geq B$

Power-Law Spectrum in Reconnection

- Acceleration rate

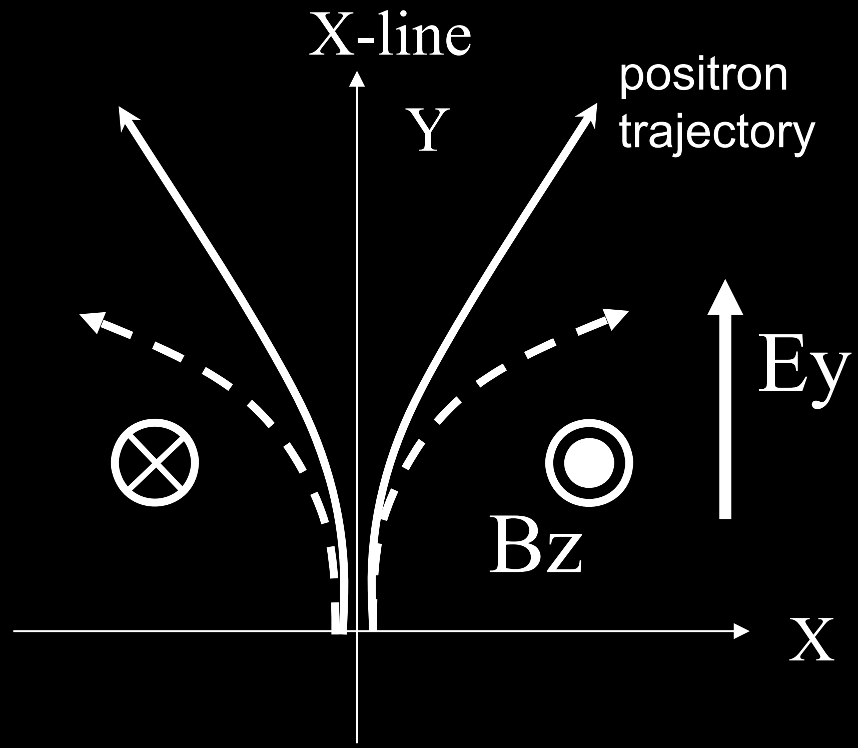
$$\frac{d\varepsilon}{dt} \approx eEc$$

- Loss rate

$$\frac{1}{N}\frac{dN}{dt} \approx -\frac{1}{\tau(\varepsilon)} \approx -\frac{m_0 c^2}{\varepsilon}\frac{eB}{m_0 c}$$

- Energy Spectrum

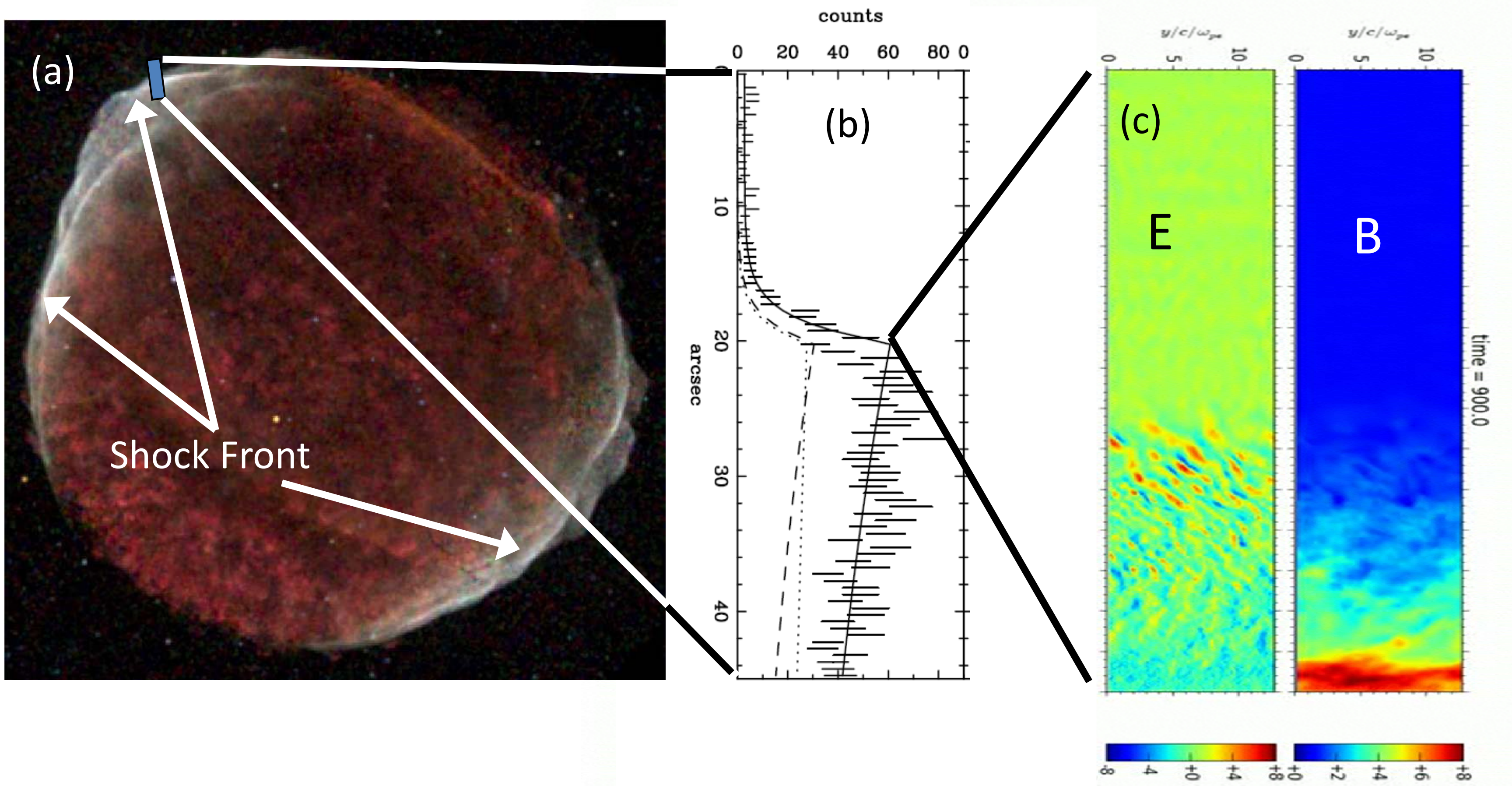
$$N \propto \varepsilon^{-s} \qquad s \approx E/B \approx 1$$



Collisionless Shocks & Particle Acceleration

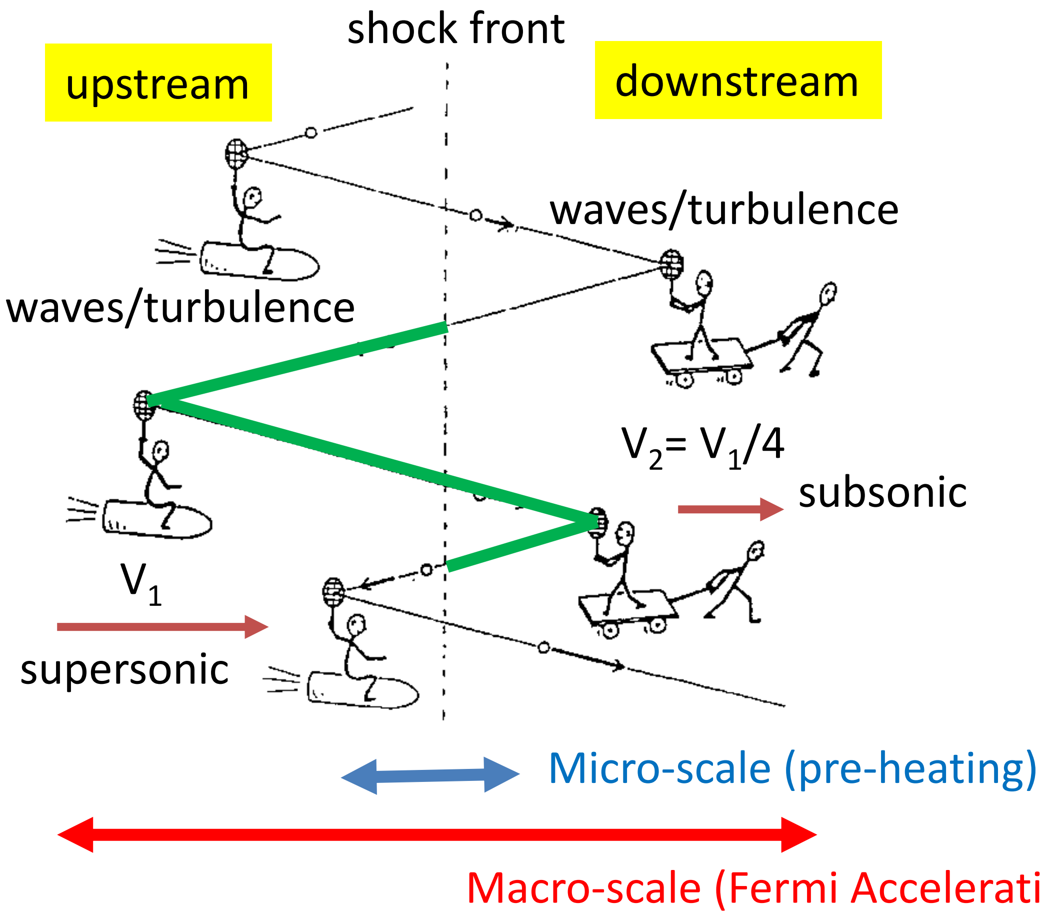
X-ray observations

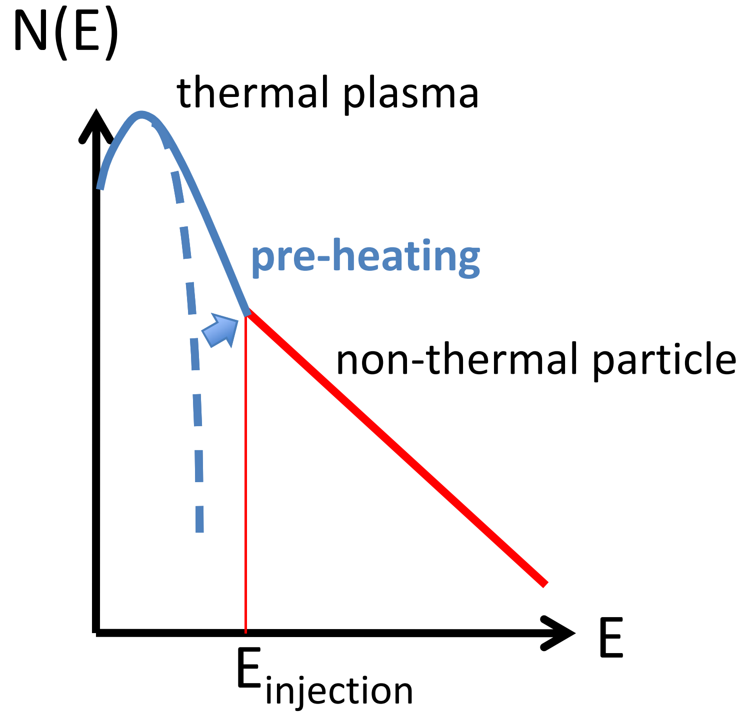
PIC simulation



(a) SN1006, Supernova remnant and shock front region observed by X-ray satellite "Chandra", (b) photon count of X-ray near shock front/filament, (c) Turbulent structure near high Mach number shock studied by Particle-in-Cell simulation

Shock Acceleration and Pre-heating



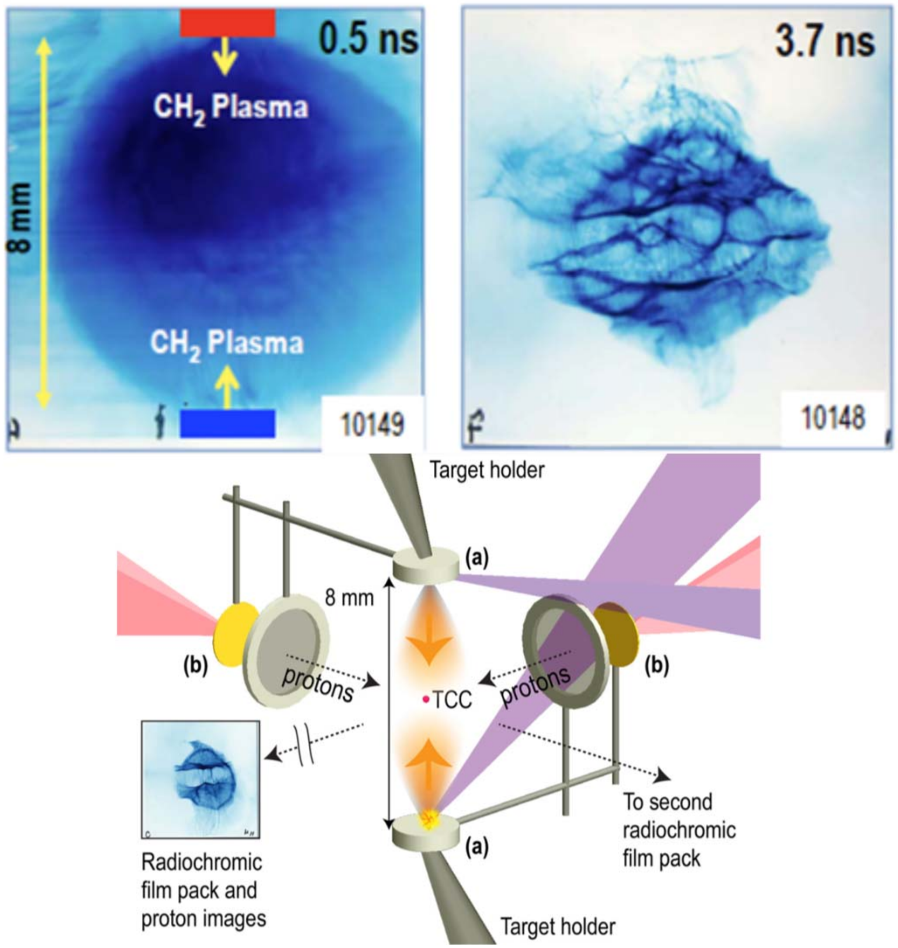


Initial pre-heating (shock injection problem) is not solved:

(gyro-radius for $E_{injection}$) > (shock thickness)

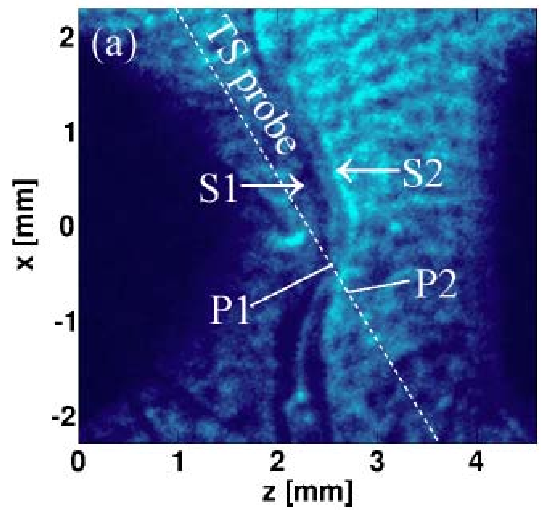
On-going Laboratory Challenge (2): Collisionless Shock Waves

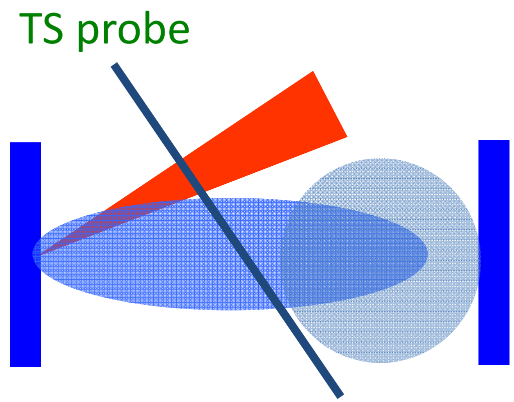
OMEGA



Huntington et al, Nature Phys (2015)
Kugland et al, Nature Physics (2012)
Ryutov et al, Phys. Plasmas (2013)

Gekko XII





Kuramitsu et al, Phys. Rev. Lett. (2011)
Morita et al, Phys. Plasmas (2013)

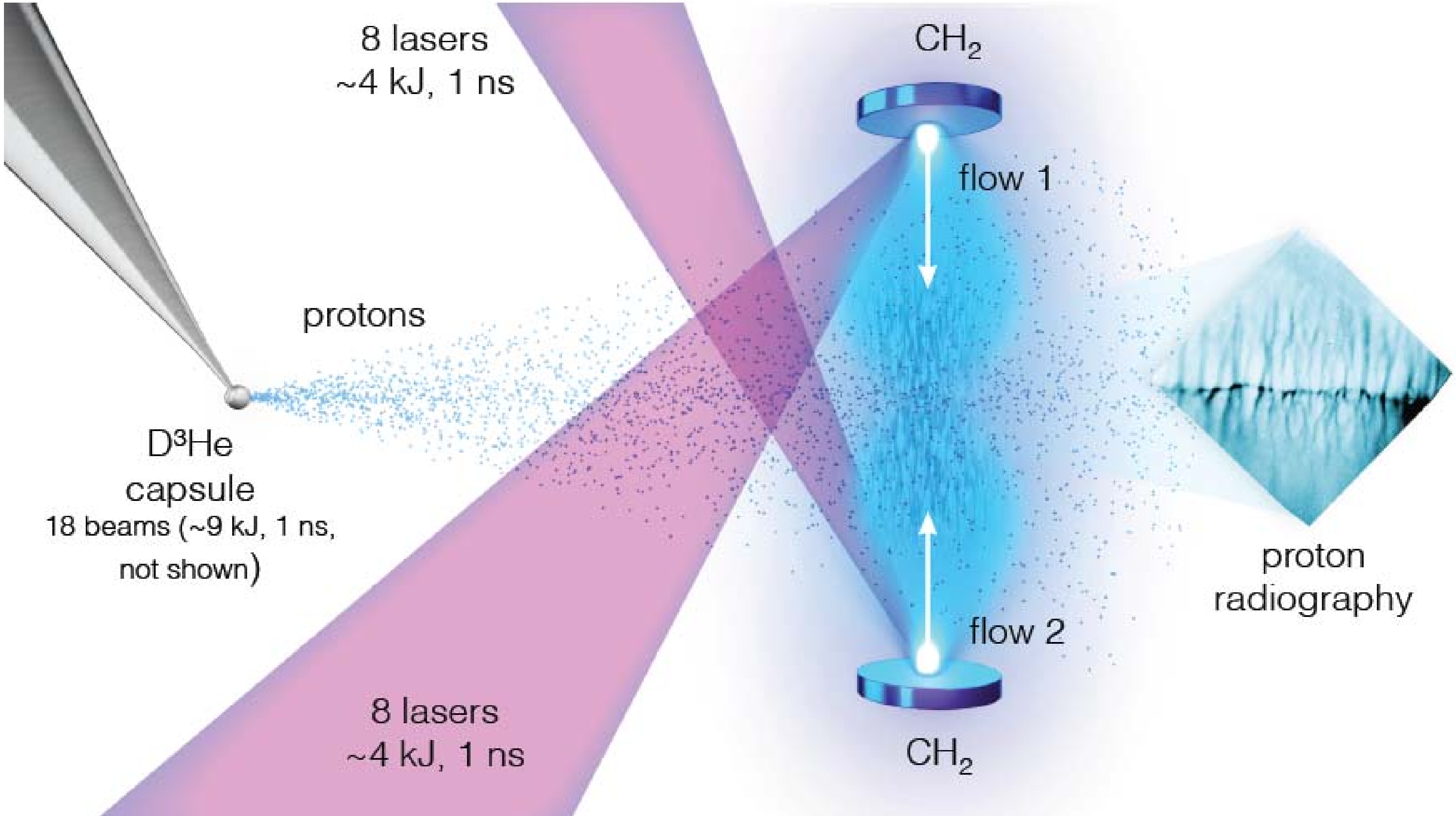
nature physics

LETTERS

PUBLISHED ONLINE: 19 JANUARY 2015 | DOI: 10.1038/NPHYS3178

Observation of magnetic field generation via the Weibel instability in interpenetrating plasma flows

D + ^3He → P (14.7 MeV) + He (3.6 MeV)



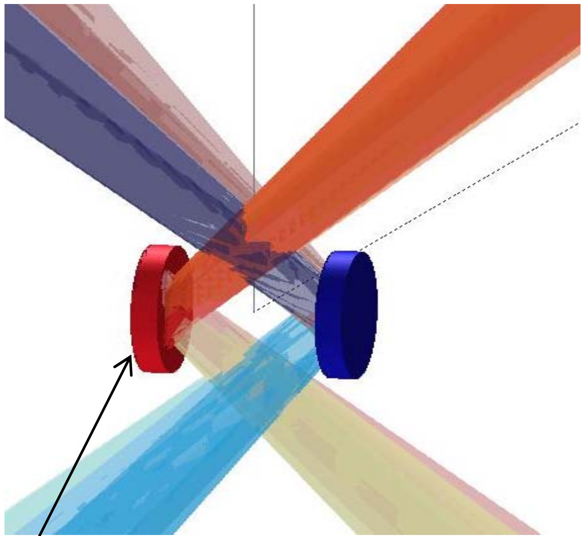
Huntington et al, Nature Physics (2015)

NIF shots were conducted in 2014 - 2017

July 2014 : 28 beams, 150 kJ per target

Oct. 2014: 48 beams, 250 kJ per target

June 2015: 48 beams, 250 kJ per target



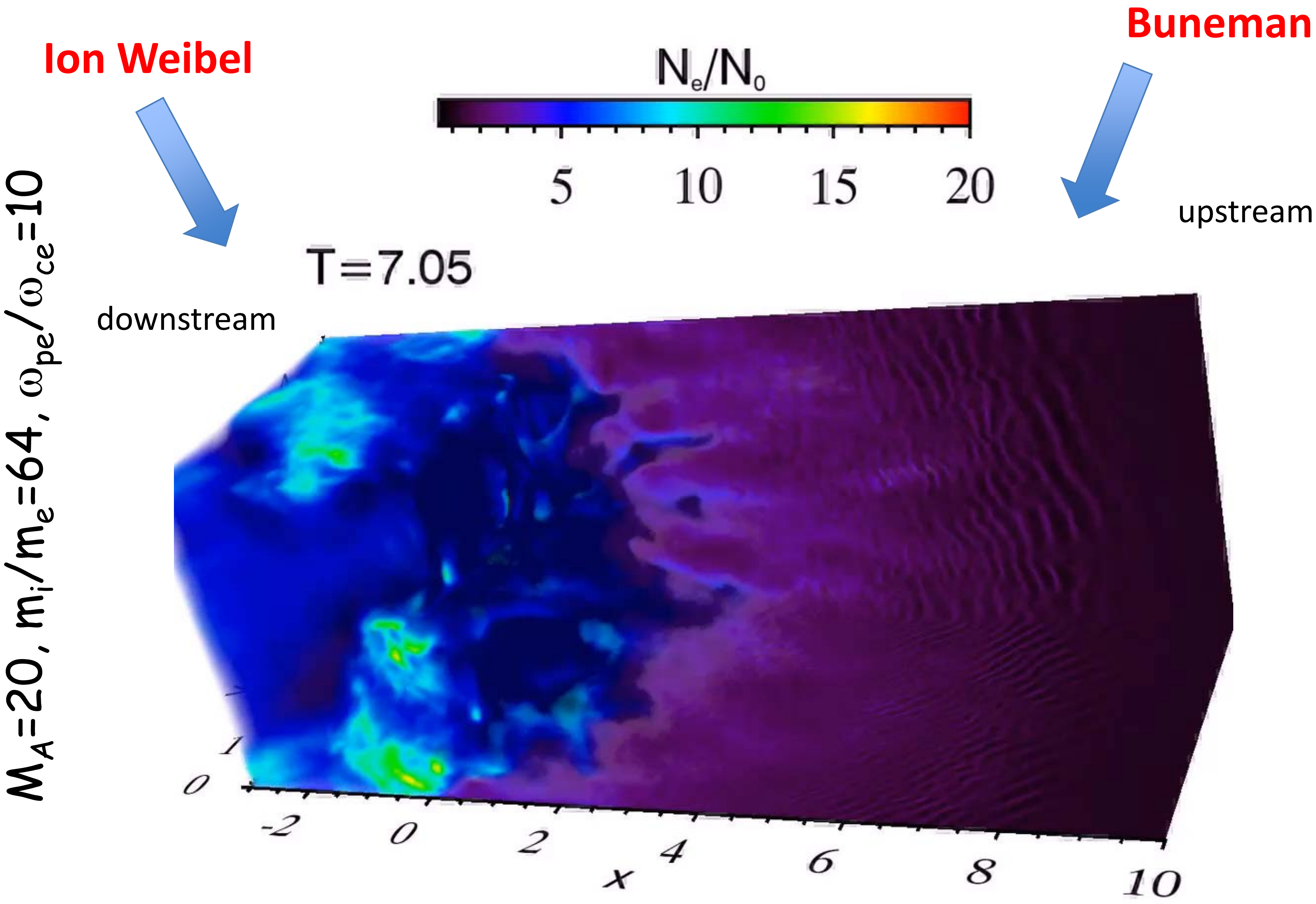
Target
CD/CD or CD/CH foils
6-10 mm separation

Collisionless Weibel Shock Generation in Counter-Streaming Plasmas
PI : Y. Sakawa (Osaka Univ., Japan)
Campaign RI : Hye-Sook Park (LLNL)

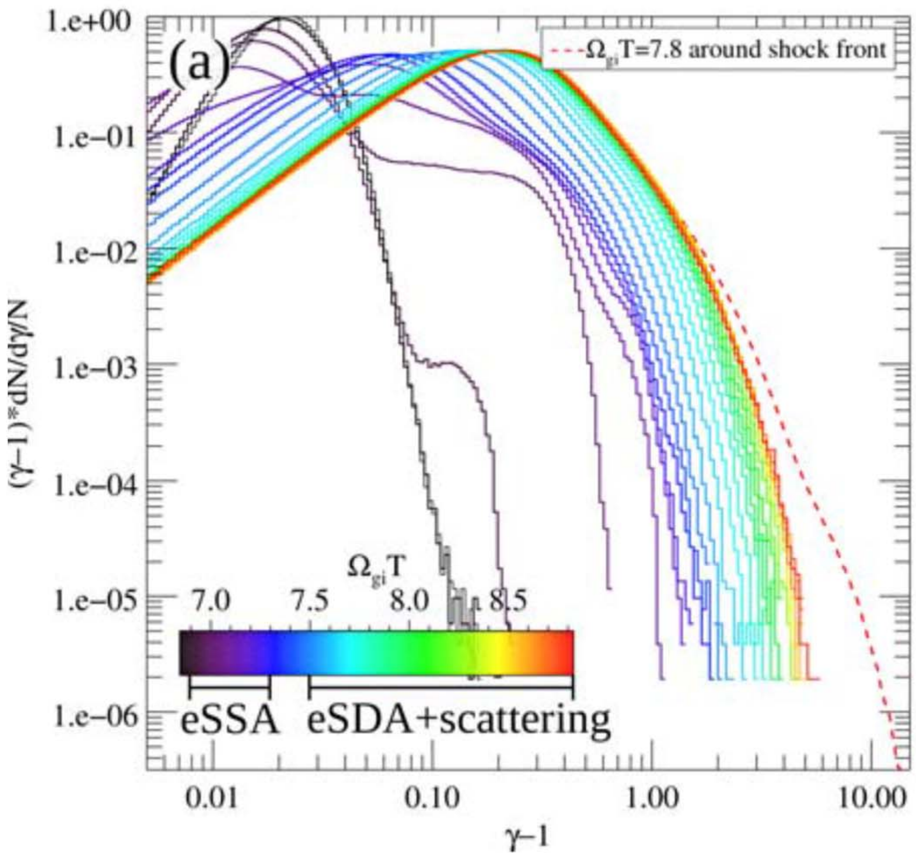
Proposed main diagnostics:
- Interferometry, Shadowgraphy
- Collective Thomson scattering
- Proton radiography
  - $D + {}^3He \rightarrow P$ (14.7 MeV) + He (3.6 MeV)

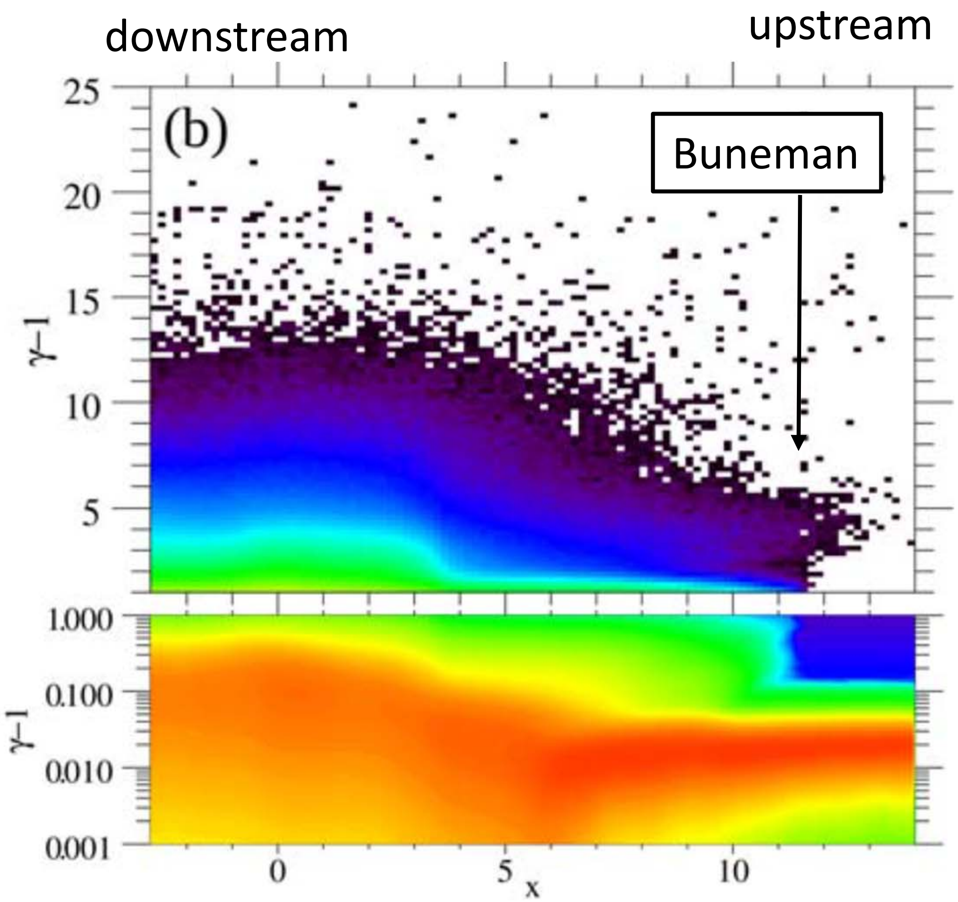
Main diagnostics:
- X-ray streak, imaging → shock formation
- Neutron diagnostics using CD target →Ti
- SRS Backscattered light spectroscopy → ne
- Proton imaging → shock structure
  - $D+D \rightarrow T + p$
  - $D+D \rightarrow {}^3He + n$

High Mach Number Magnetosonic Shock



Electron Energy Spectra & E-x diagram





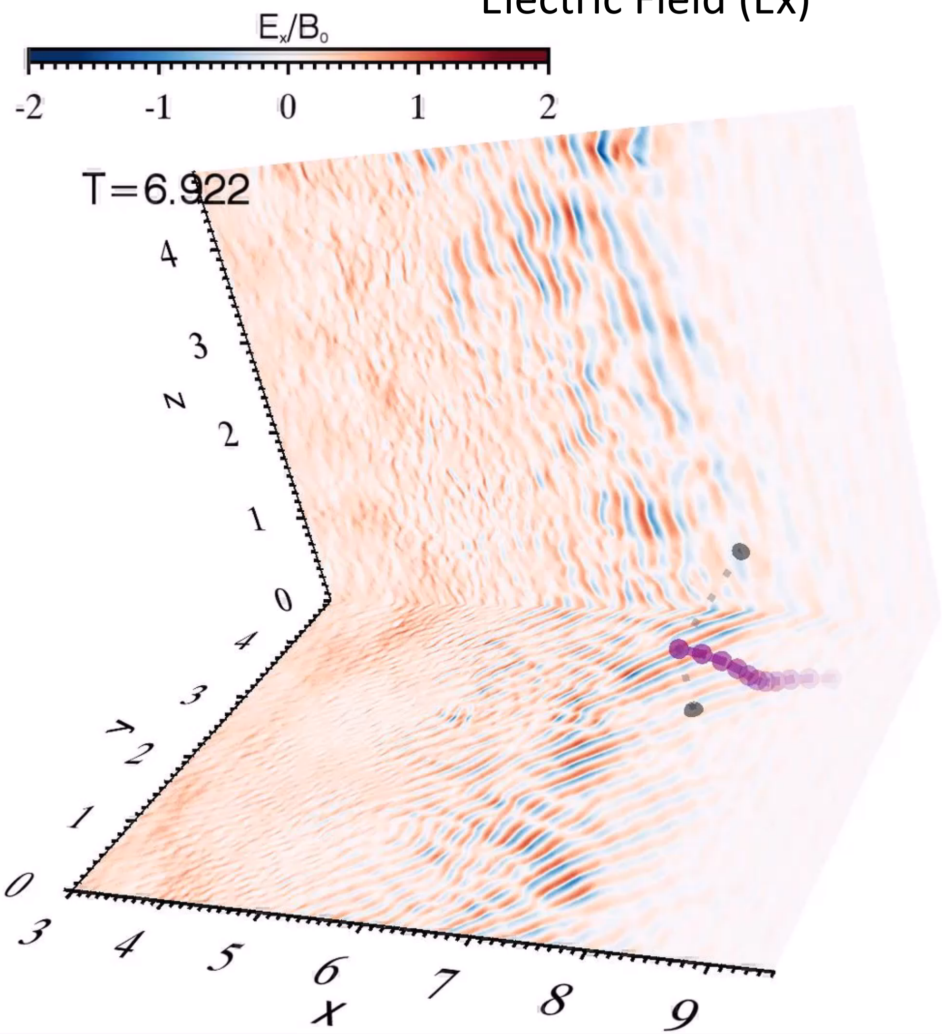
Pre-Acceleration:

electron surfing acceleration through Buneman instability

Buneman Inst & Shock Surfing

$M_A=20,\ m_i/m_e=64,\ \omega_{pe}/\omega_{ce}=10$

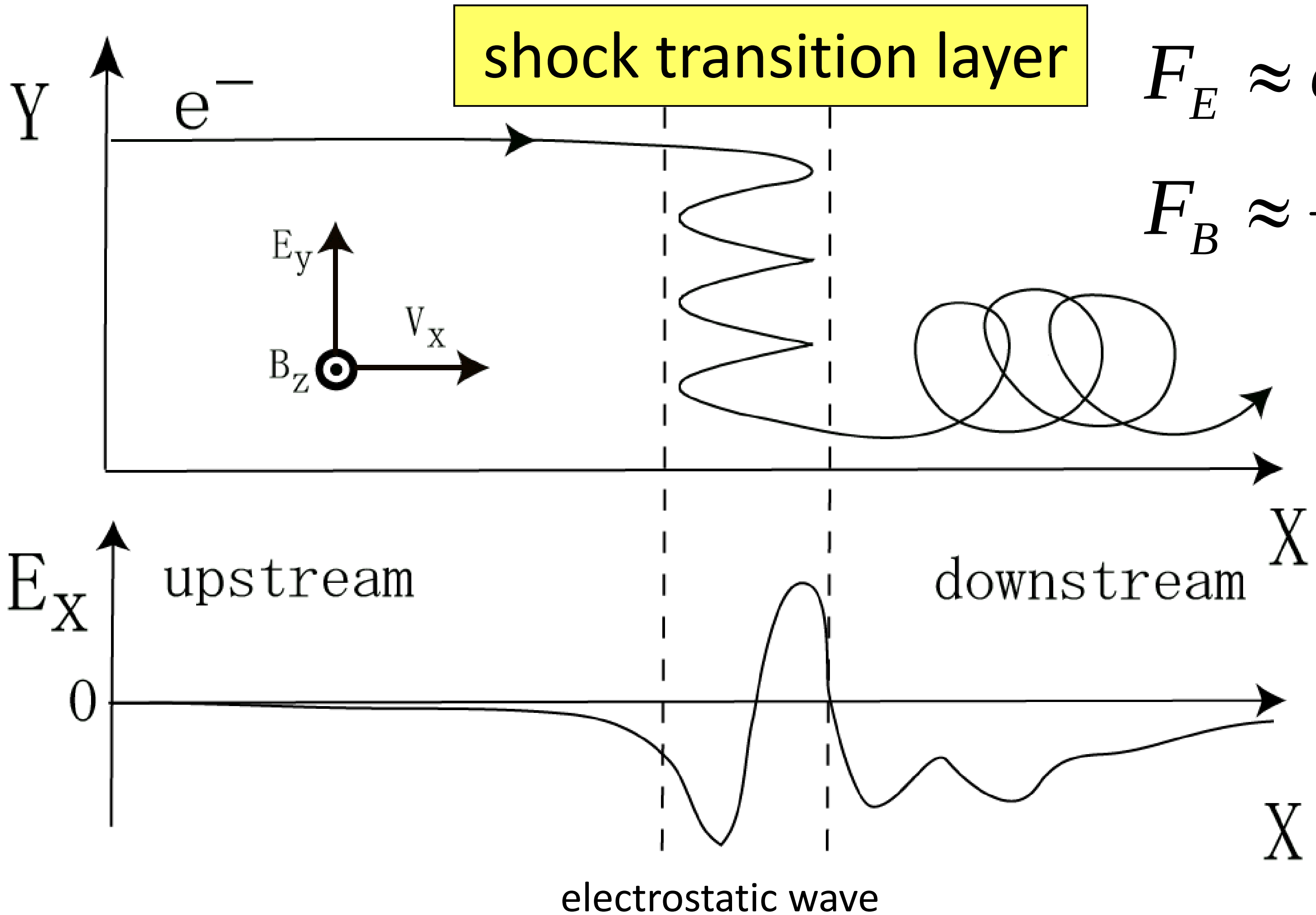
Electric Field (Ex)



Foreshock Region:

- ✓ "Coherent" Ex fields are maintained in the stage of nonlinear Buneman instability
- ✓ Ex > Et (shock motional electric field)

"Electron" Shock Surfing Mechanism



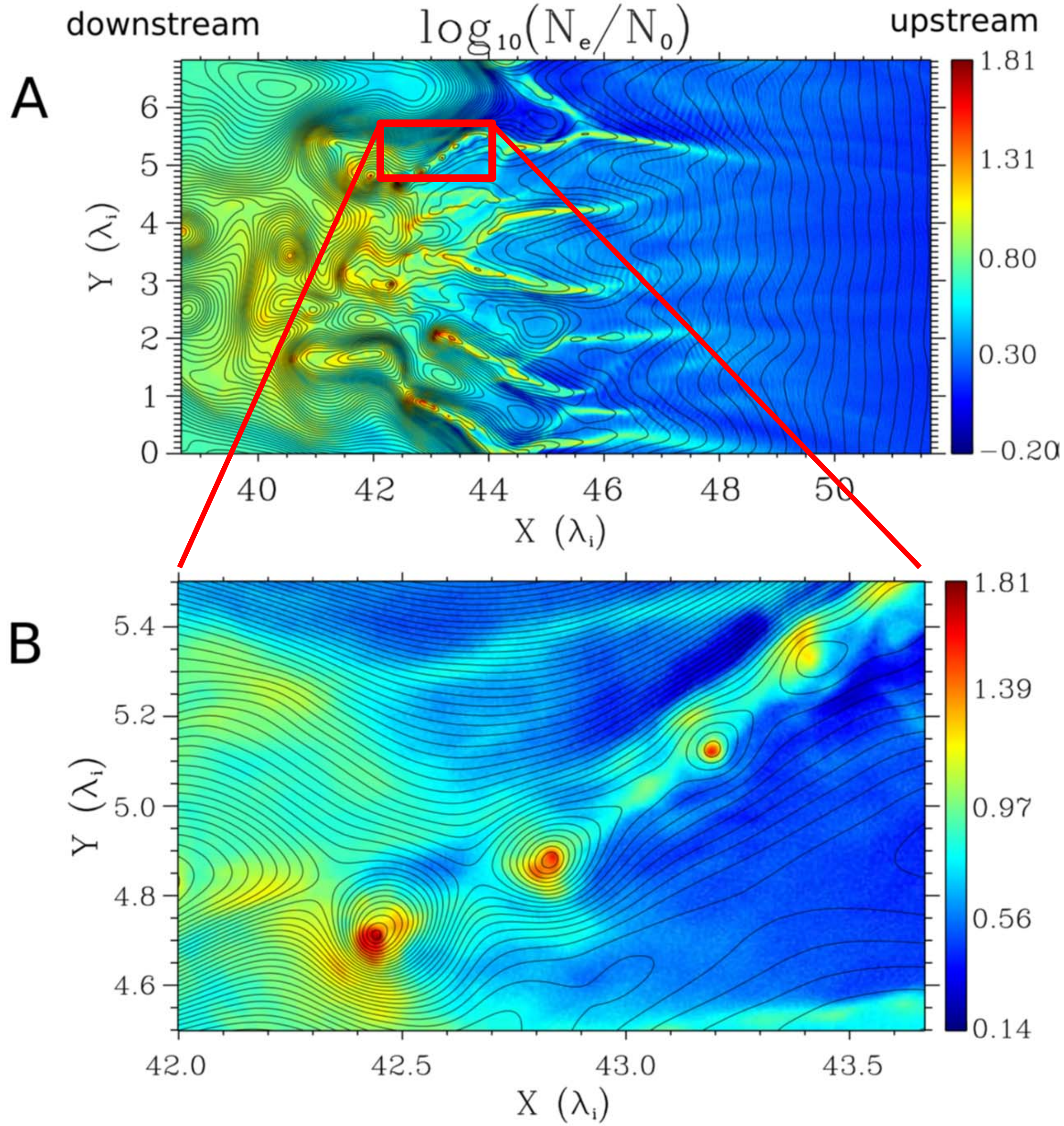
$$F_E \approx eE_x$$

$$F_B \approx \frac{e}{c} v_y B_z$$

e.g. Sagdeev (1966), Sagdeev and Shapiro (1973), Katsouleas and Dawson (1983), ..

Ion Weibel and Magnetic Reconnection

M_A=42, m_i/m_e=225, ω_{pe}/ω_{ce}=10



fast flow

Ion reflection from shock front

Temperature anisotropy

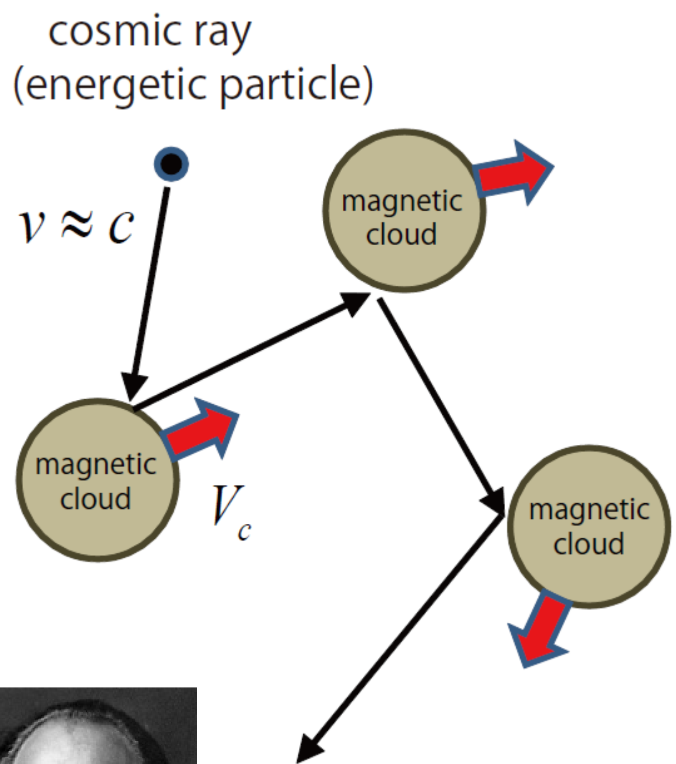
Weibel instability & B filed generation

Magnetic reconnection

Matsumoto, Amano, Kato & MH, Science 2015

Acceleration in many magnetic islands

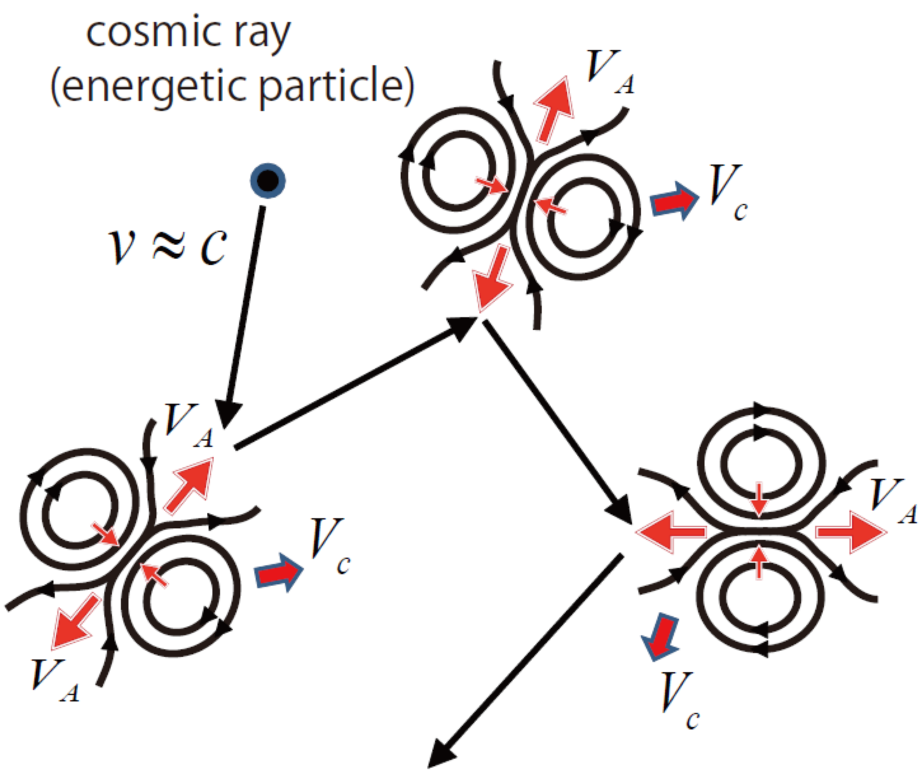
2^{nd} order Acceleration



$$\frac{\Delta\varepsilon}{\varepsilon} \approx \left(\frac{V_c}{c}\right)^2$$

Fermi, Phys. Rev. (1949)

1^{st} order Acceleration

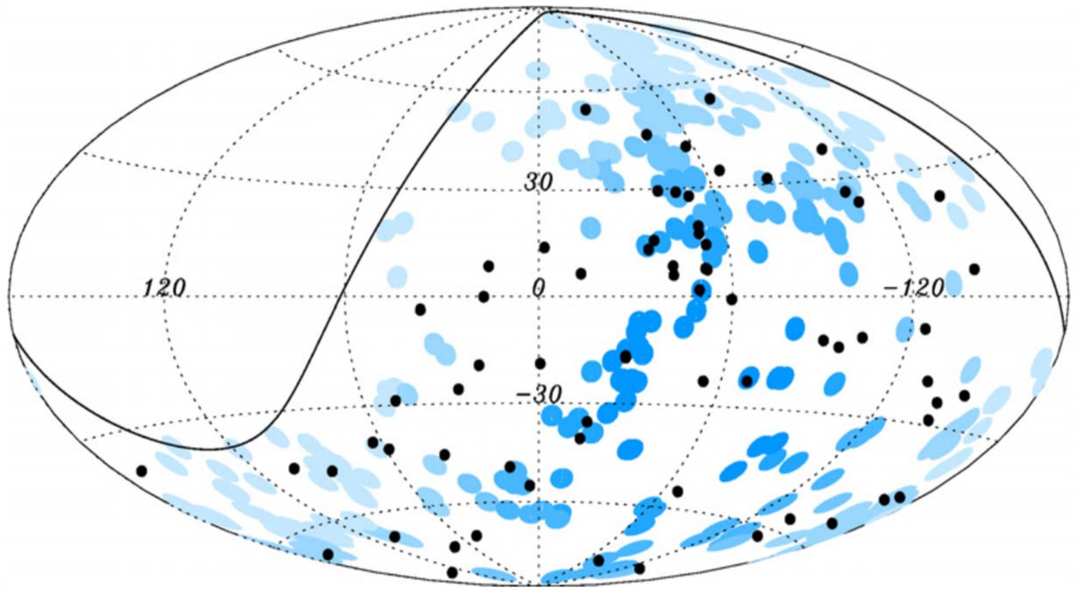


$$\frac{\Delta\varepsilon}{\varepsilon} \approx \left(\frac{V_A}{c}\right)$$

MH PRL (2012)

Ultra High Energy Cosmic Rays (~10^{20}eV)

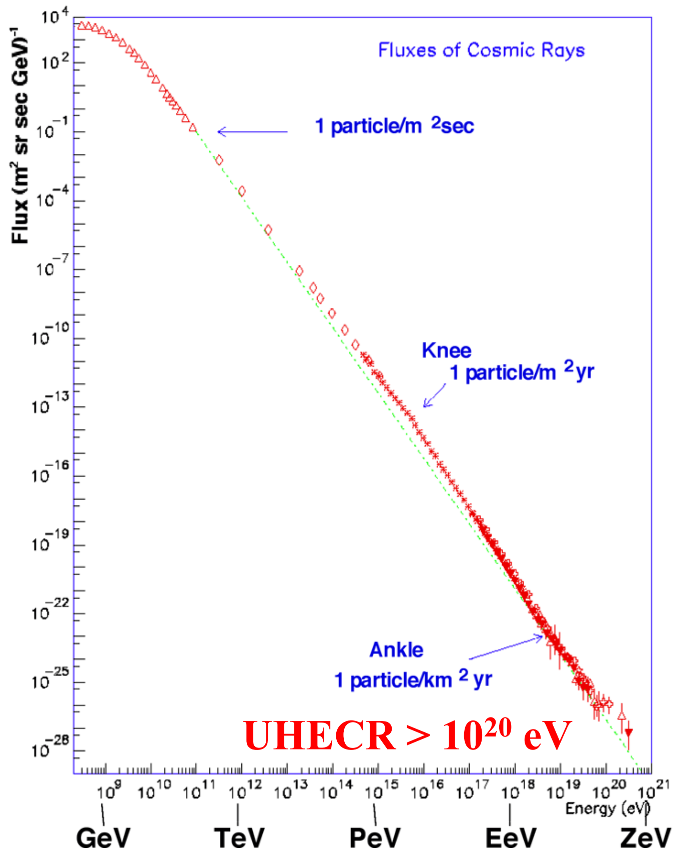
Auger Cosmic Ray Observation



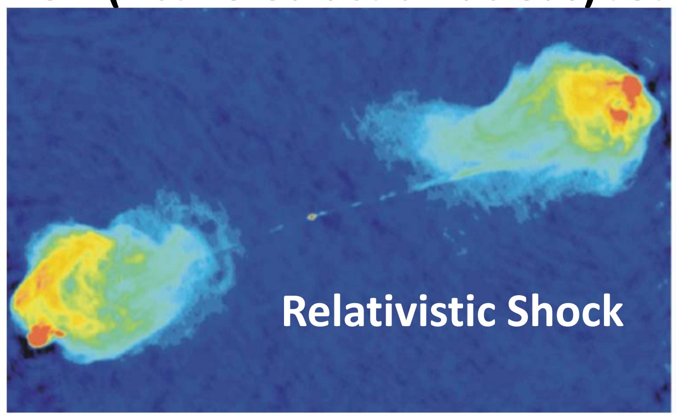
● Arrival Direction of 6×10^{19}eV

● Active Galactic Nuclei（AGN)

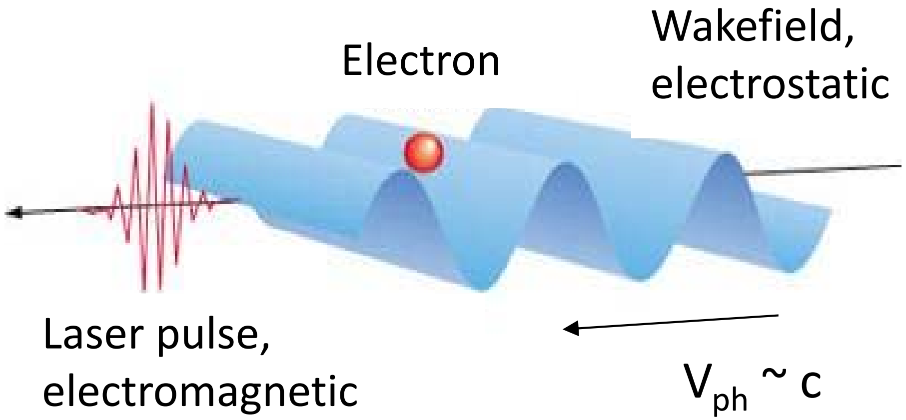
AstroParticle Phys 2010



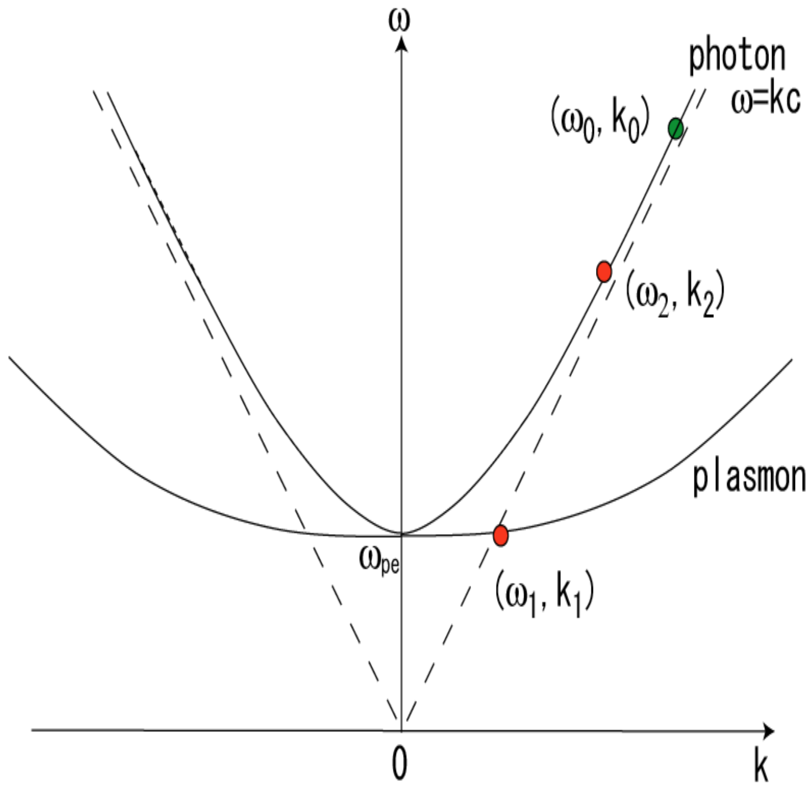
AGN (Active Galactic Nucleus) Jet



Laser Wakefield Acceleration & UHECRs



Tajima & Dawson, 1979

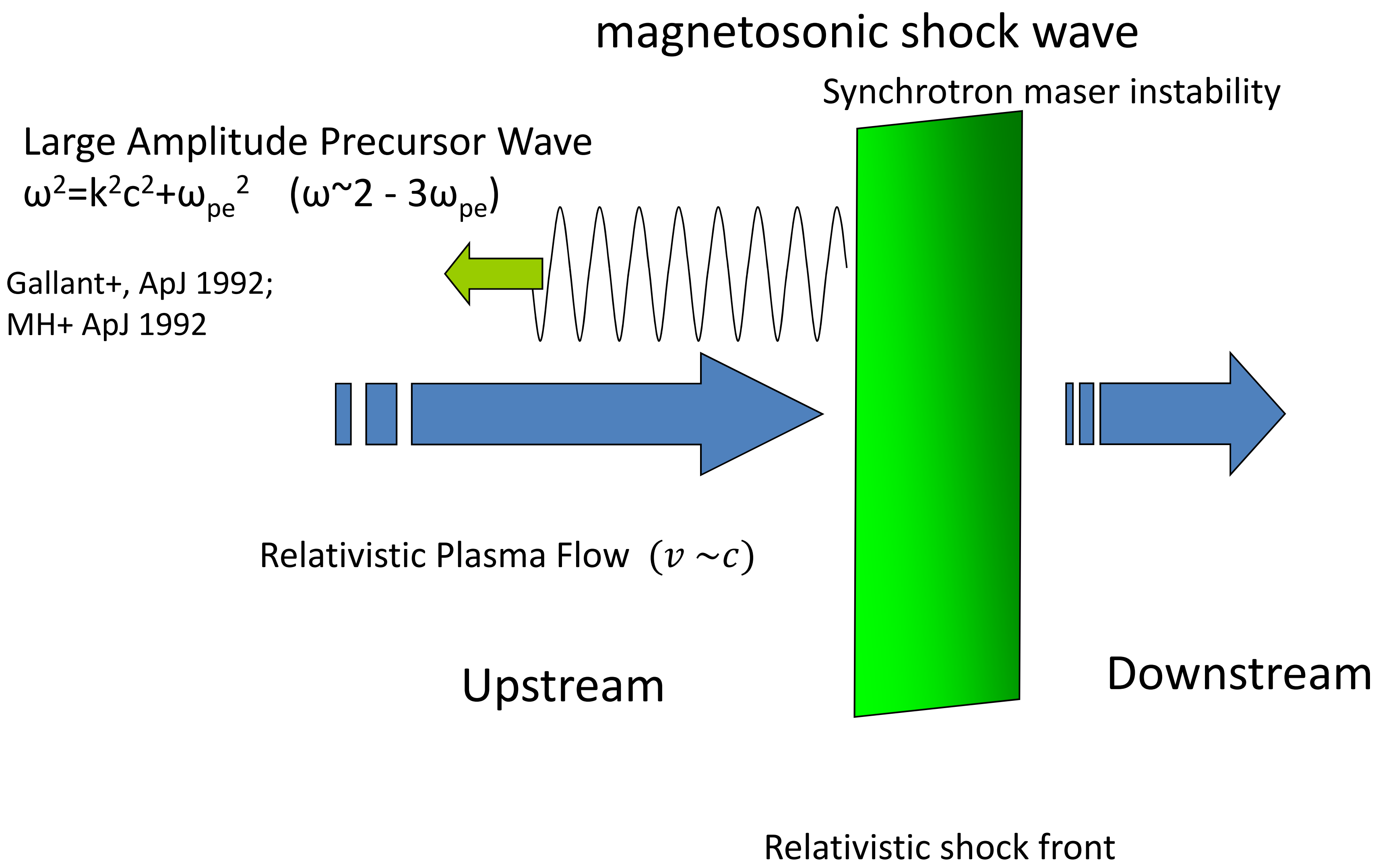


$$\omega_0 = \omega_1 + \omega_2 \qquad k_0 = k_1 + k_2$$

Chen+, PRL, 2002; Lyubarsky ApJ 2006; MH ApJ, 2008;….

- Wakefield by EM waves
- Possible acceleration for UHECR

Relativistic Shock & Precursor Waves



Relativistic Shock: Wakefield Acceleration

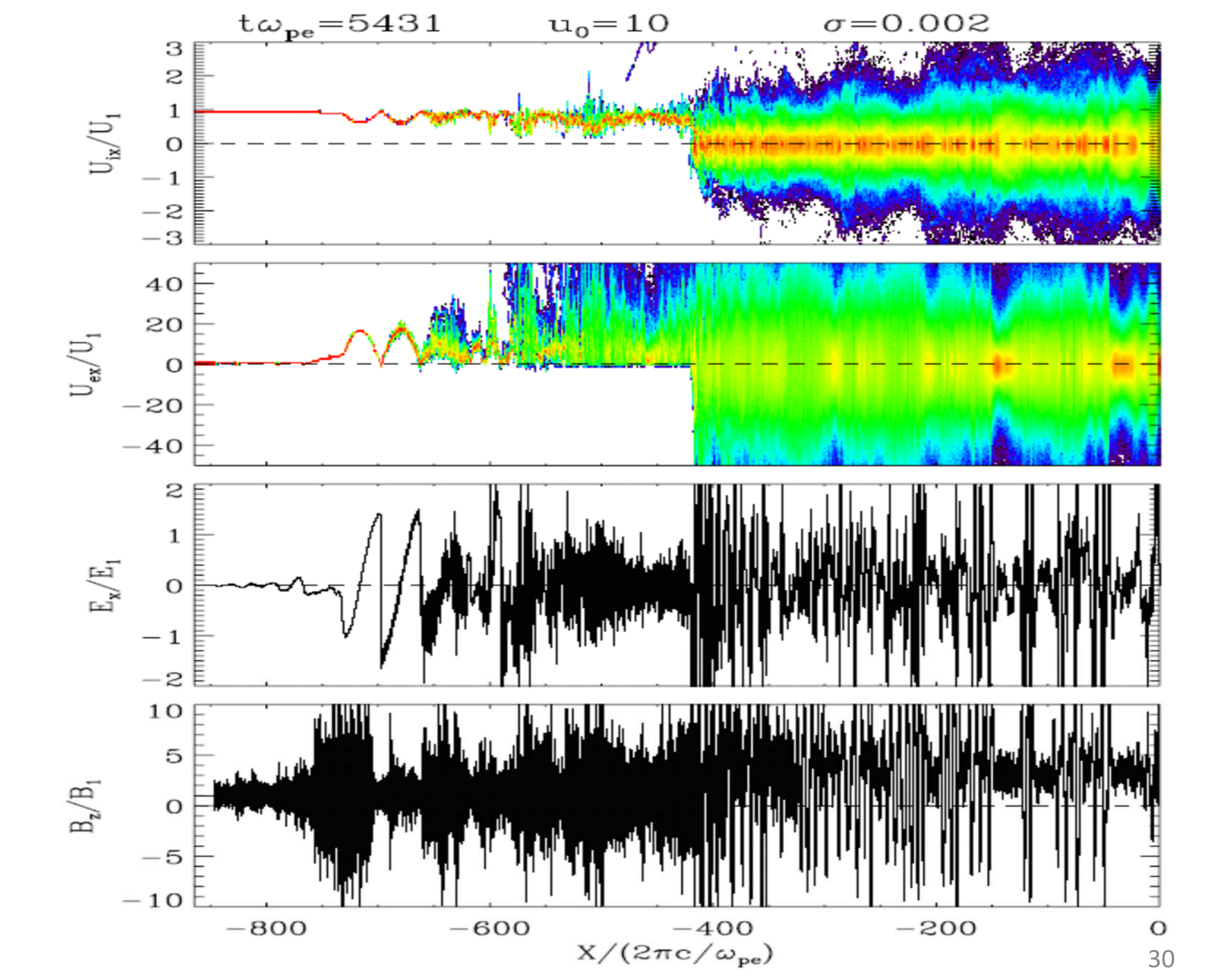
upstream (supersonic flow) downstream (sub-sonic)

$U_{x,ion}$

$U_{x,ele}$

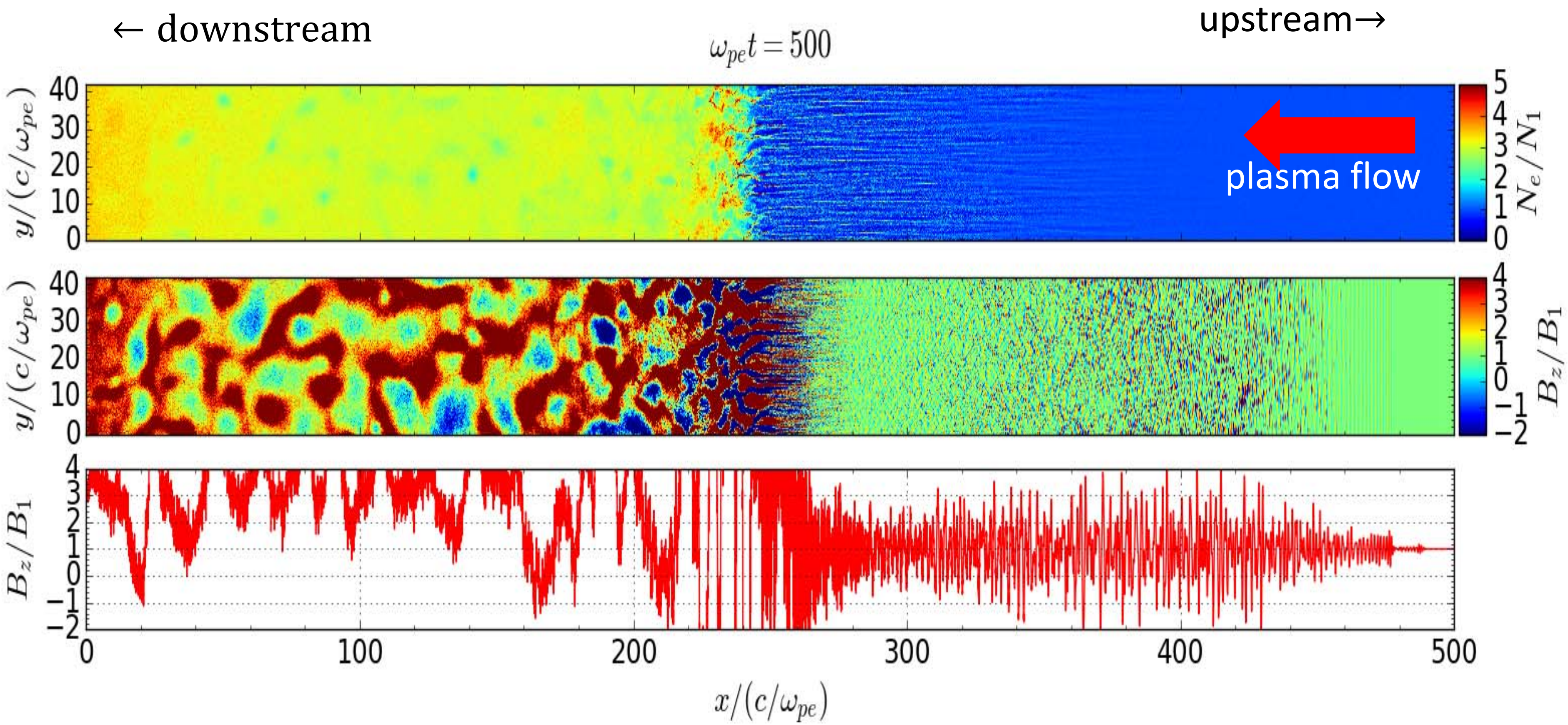
E_x
(ES,plasmon)

B_z
(EM,photon)



MH ApJ 2008

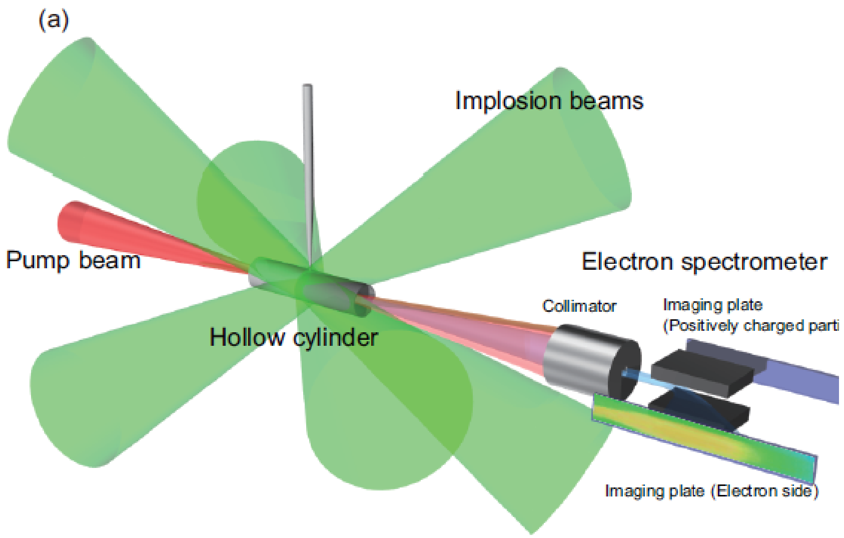
2d relativistic shock



Precursor waves are persistently generated under Weibel instability

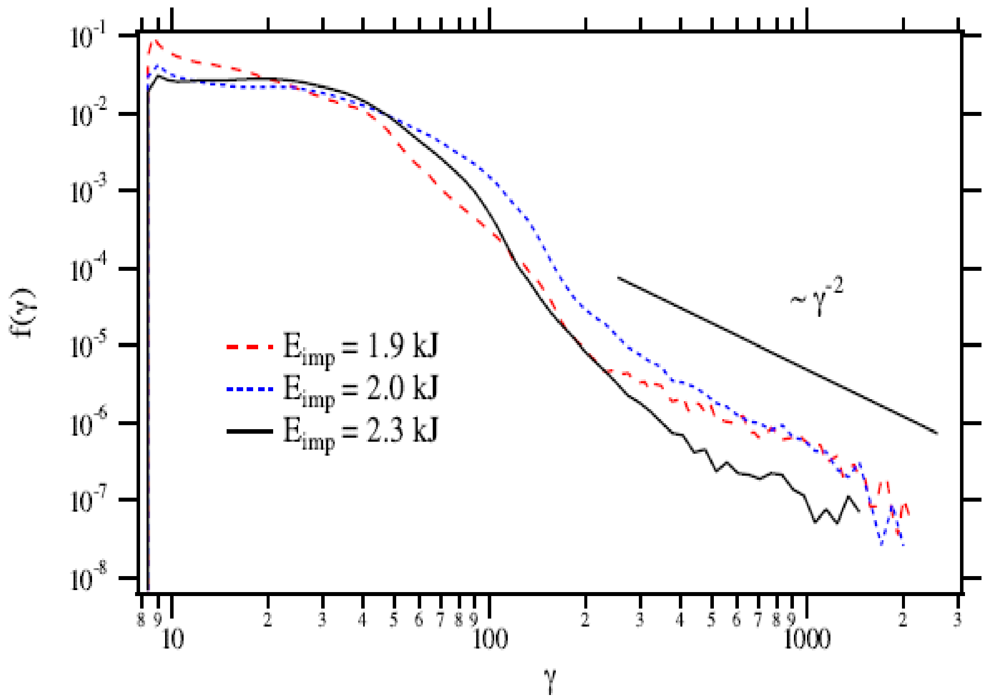
Iwamoto, Amano, Matsumoto & MH ApJ 2017

Laboratory Challenge (3) :
Incoherent Wakefield Acceleration



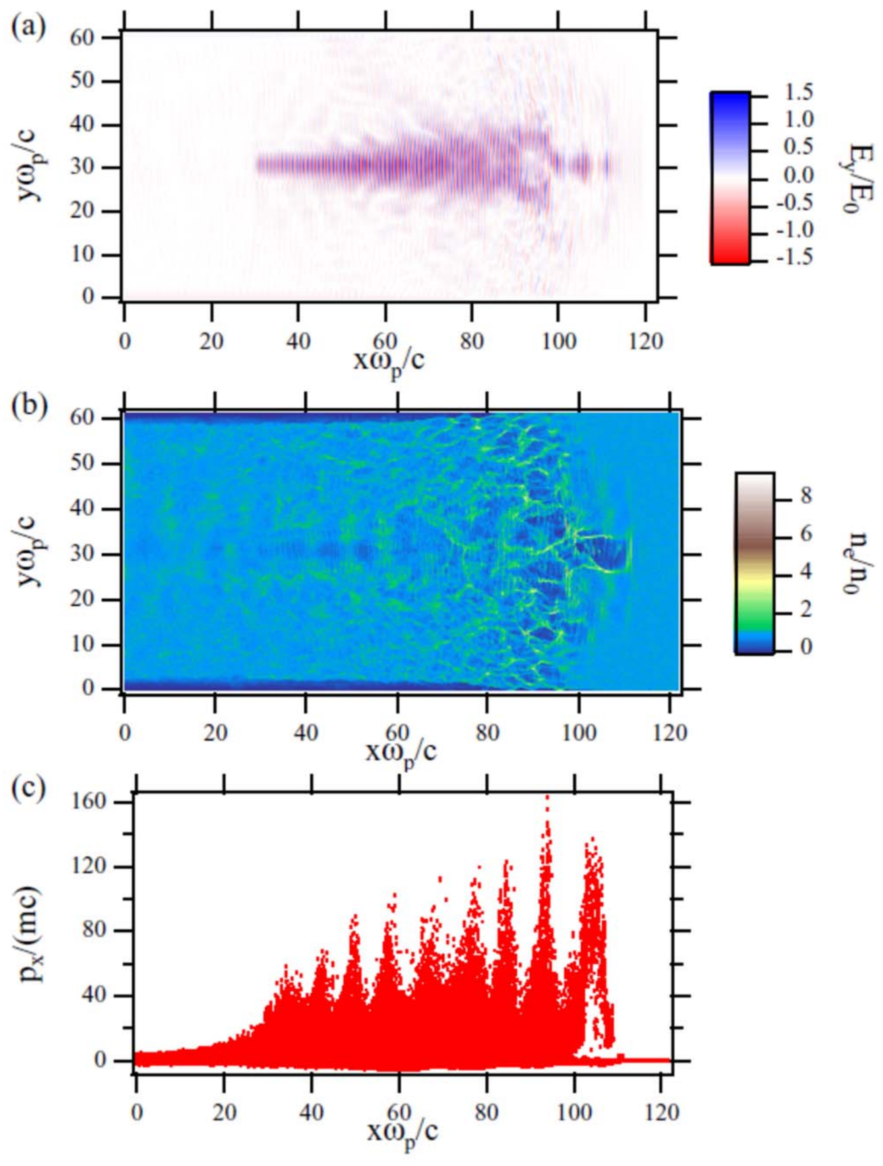
GEKKO XII Laser Plasma Experiment

Energy Spectra



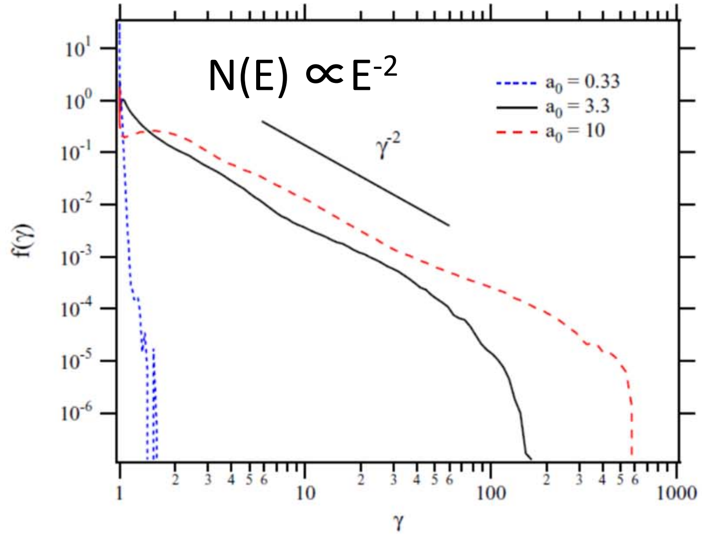
Kuramitsu et al. PoP (2011)

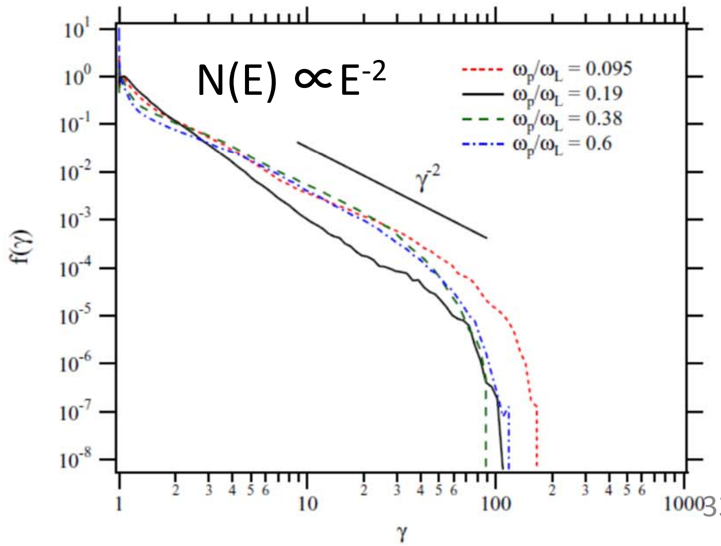
2D Simulation of Wakefield Acceleration



Kuramitsu et al, ApJ (2008)

Energy Spectra





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Summary

Most astrophysical phenomena involve plasmas such as shock waves, magnetic reconnection, wakefield, MRI instability, KH instability,…….

Laboratory Experiments have a potential to answer many long-standing questions in plasma astrophysics