Recent Results on Particle Acceleration at Non-relativistic Shocks

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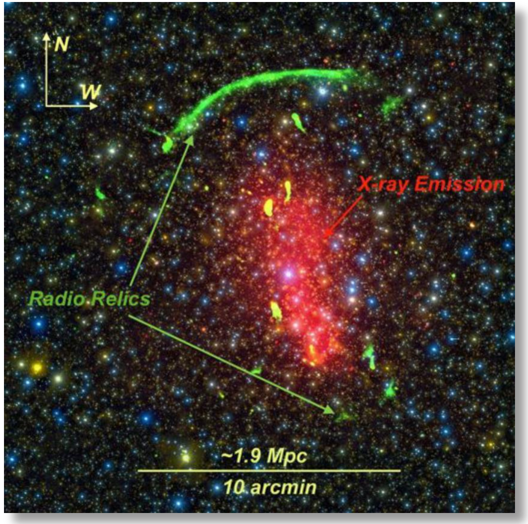
Astrophysical aspects related with particle acceleration

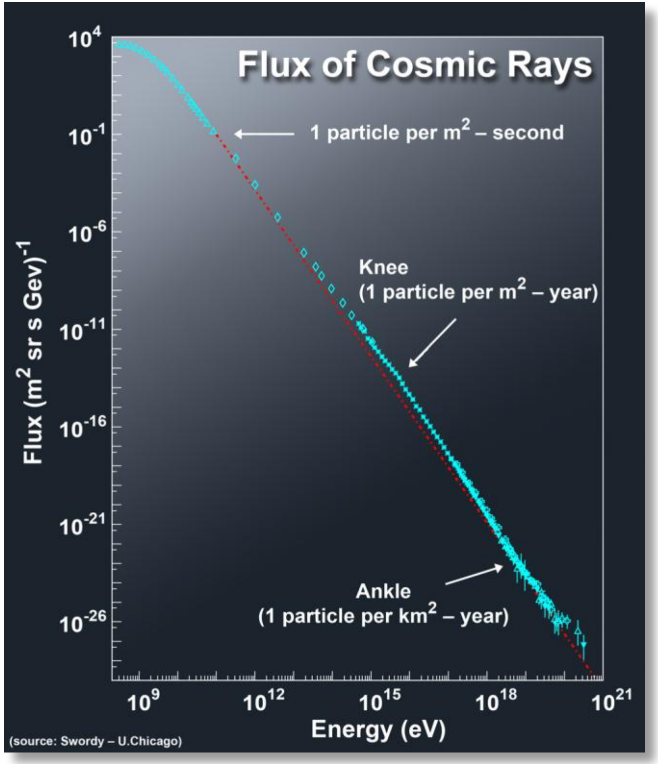
➢ **Acceleration is a cornerstone problem in astrophysics**

- High-energy emission (X-ray, γ)
- Radio synchrotron emission

Generated by relativistic particles

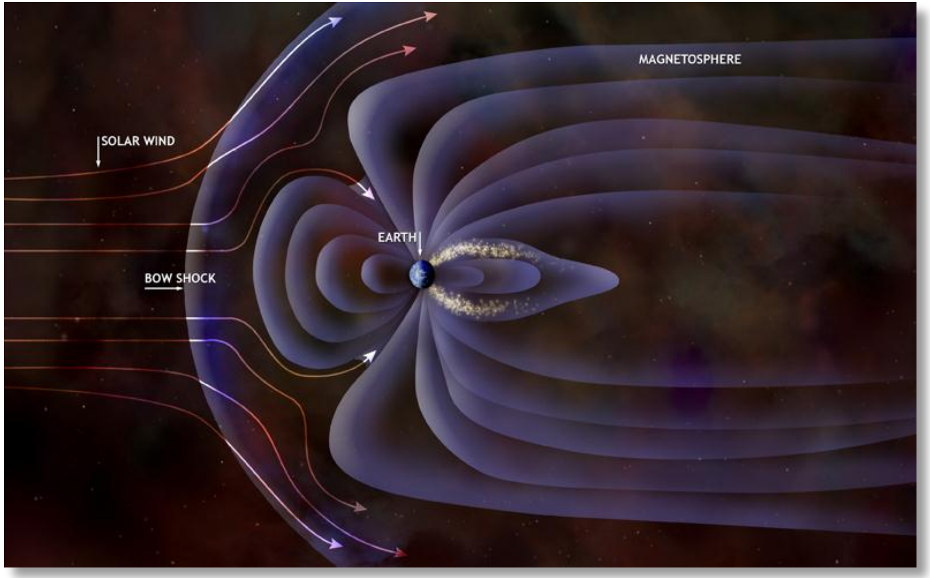


- Cosmic Rays
- including **UHECR** with energies up to $E \sim 10^{20}$ eV



Shock waves on various scales

- **Earth's bow shock**
- Solar flare shocks
- Solar wind termination shock
- Supernova remnant (SNR) shocks
- Active galactic nuclei (AGN) shocks
- Large-scale shocks in the galaxy clusters:
  - turbulence shocks
  - infall shocks
  - merger shocks



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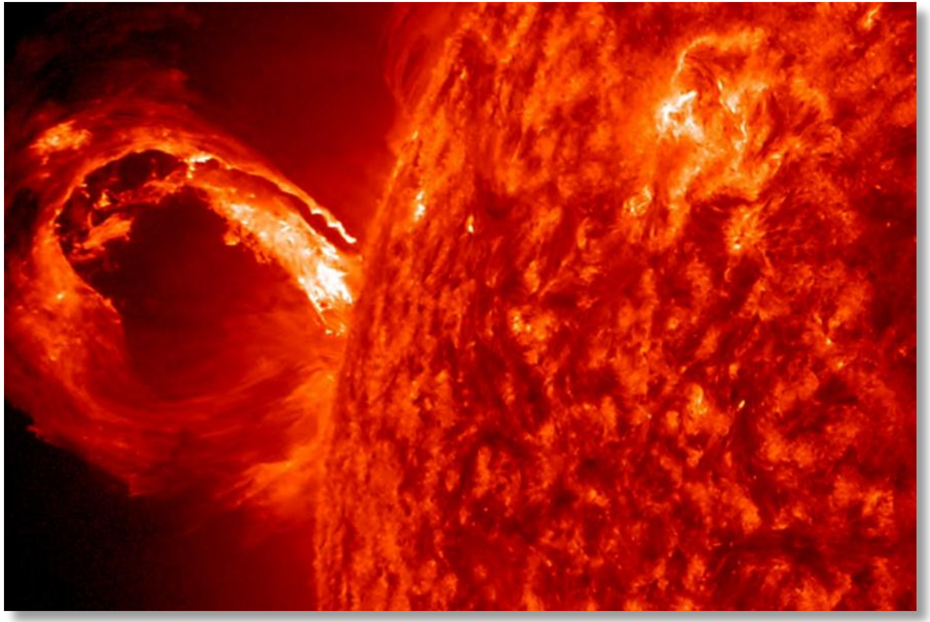

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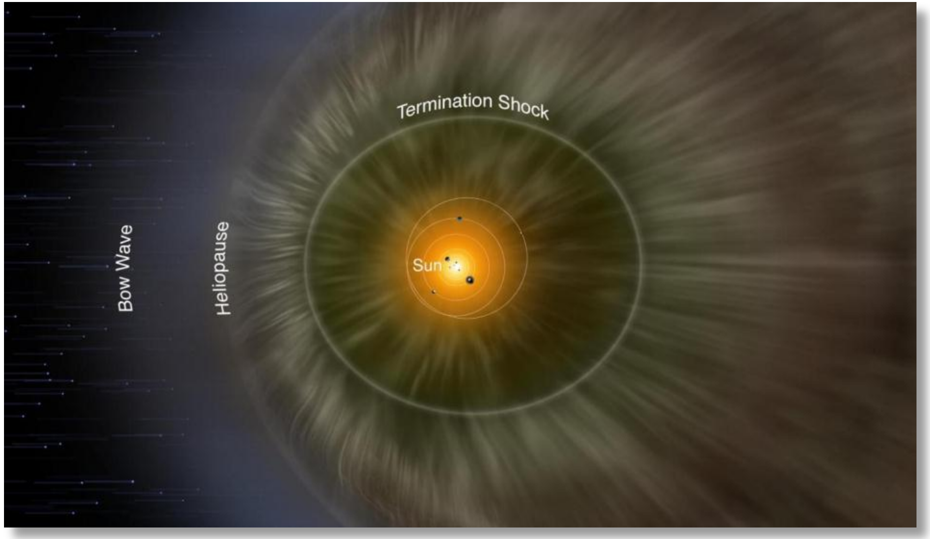

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White – optical
Blue – X-ray
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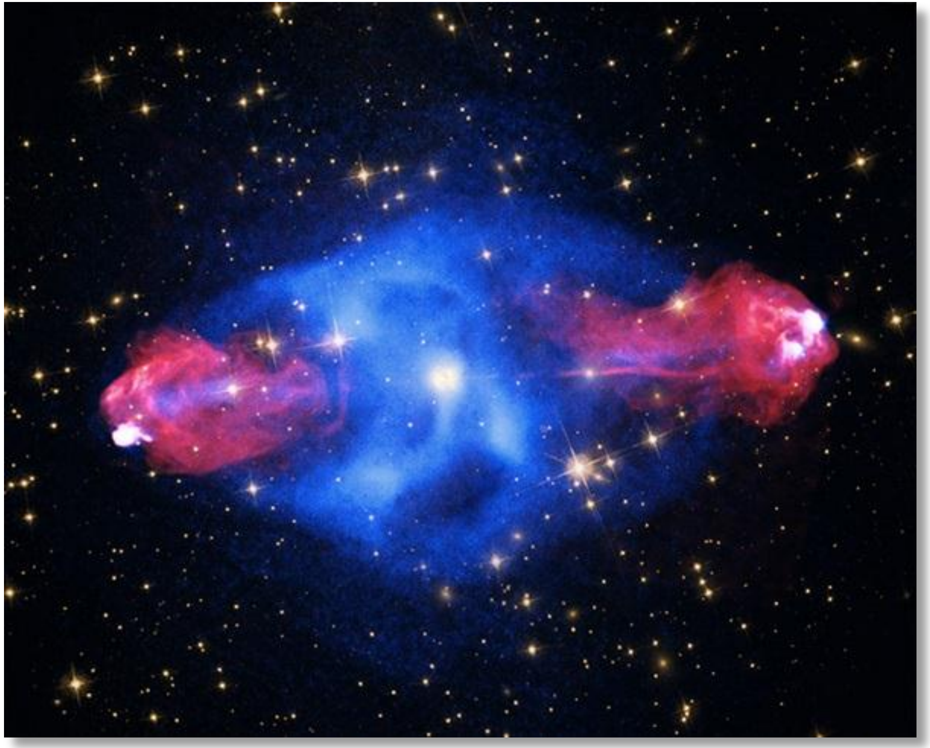

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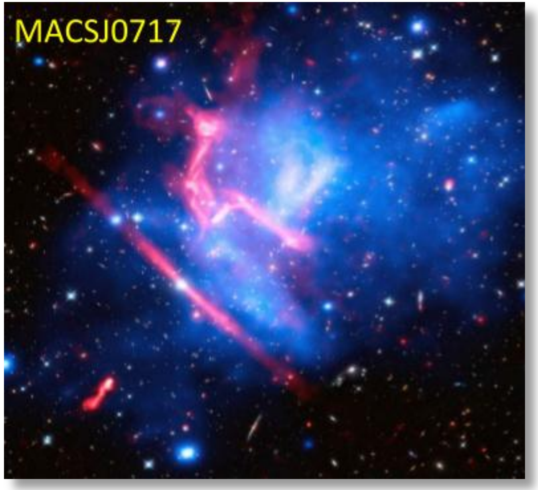

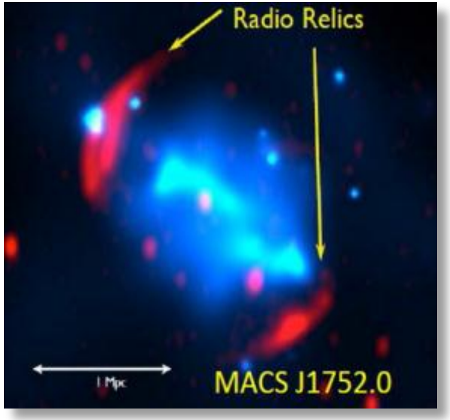

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Signatures of the astrophysical shocks:
X-ray and **radio** synchrotron emission.

Indication of the **electron acceleration**.

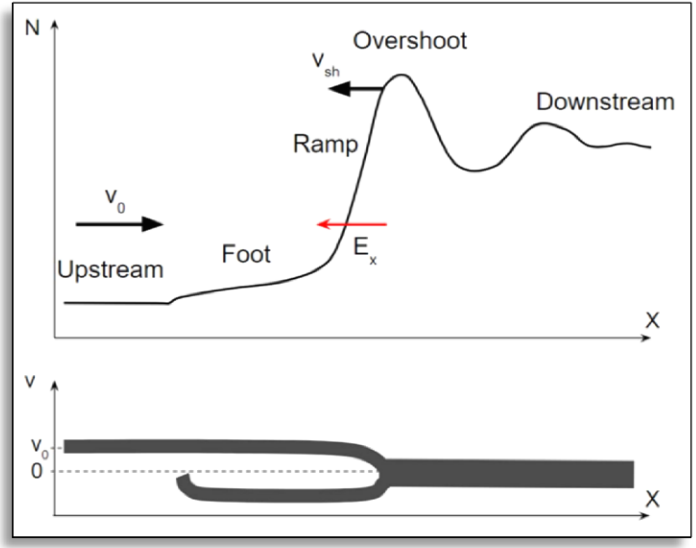
UHECR sources – ???

Astrophysical shock structure and particle acceleration

Perpendicular shock structure

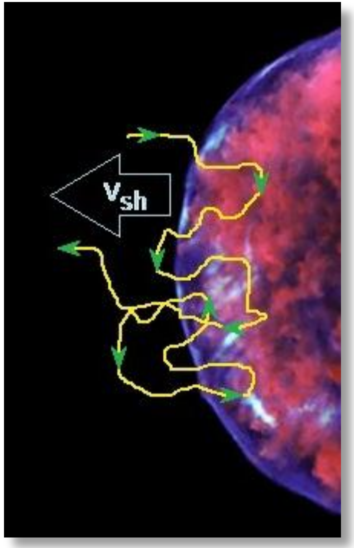
Top: The particle number density profile. The shock transition consists of a **foot**, a **ramp**, and an **overshoot**. E_x is the shock potential.

Bottom: The x-component of the ion velocity.



Diffusive Shock Acceleration (DSA)

can produce most energetic particles, eg. Galactic CRs with energies up to $E \sim 10^{15}$ eV accelerated at SNR shocks.



Necessary conditions:

- **EM turbulence** both downstream and upstream of the shock
- Particle **gyro-radius > thickness** of the shock transition.
- **The injection is required:** to be involved in DSA particle should have momentum $p \gtrsim (3-5)p_{\mathrm{i,th}}$

$$\frac{dN(E)}{dE} \sim E^{-\alpha}$$

$$\alpha \gtrsim 2$$

The injection problem:

Pre-acceleration is required for particles to be involved in DSA. This is especially critical for electrons.

Numerical methods applied in shock physics

- Application of analytic methods is limited because of strong nonlinearity of a system.

Magneto-Hydro-Dynamic (MHD simulations)

Plasma is treated as continuum

Individual particles are not resolved

Appropriate for:

Study of global system dynamics and large-scale structures (shock waves, magnetic turbulence etc.)

Kinetic simulations (Particle-In-Cell)

Individual particles are followed (electrons and ions)

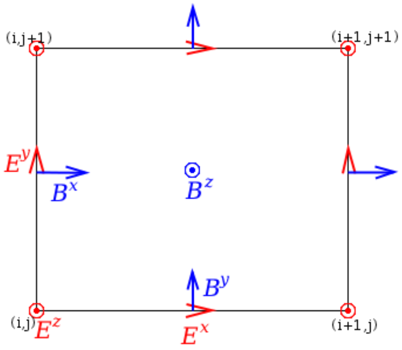
Macroscopic parameters are derived from distributions of microscopic ones

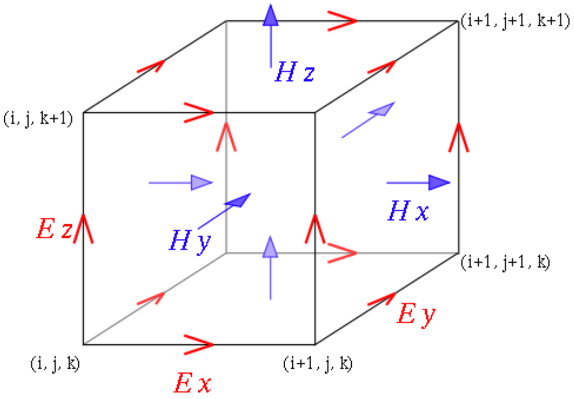
Appropriate for:

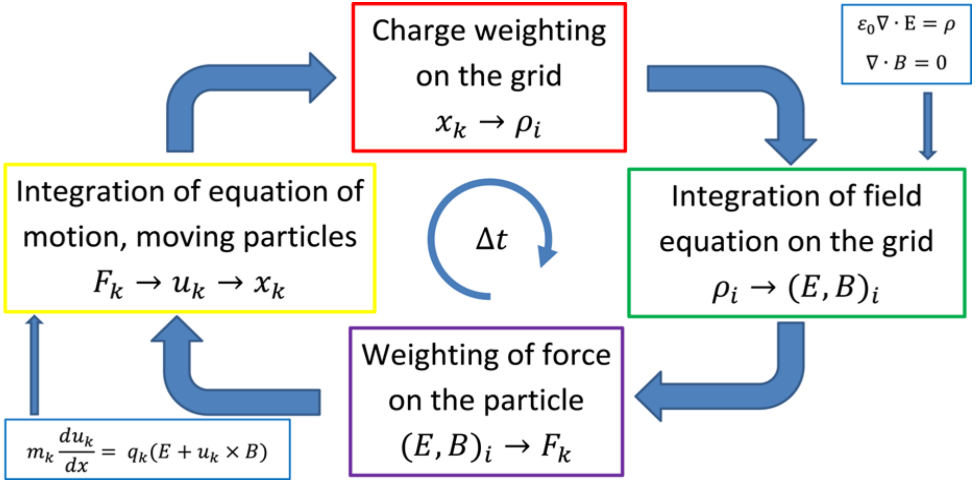
Study of plasma microphysics, including the processes of **particle acceleration**

PIC-simulation method

- EM fields are defined for grid elements.
- Particles motion is continuous in space with finite time steps.







Super-computer clusters are used for PIC-simulations.

Electron acceleration at (quasi-)perpendicular SNR shocks

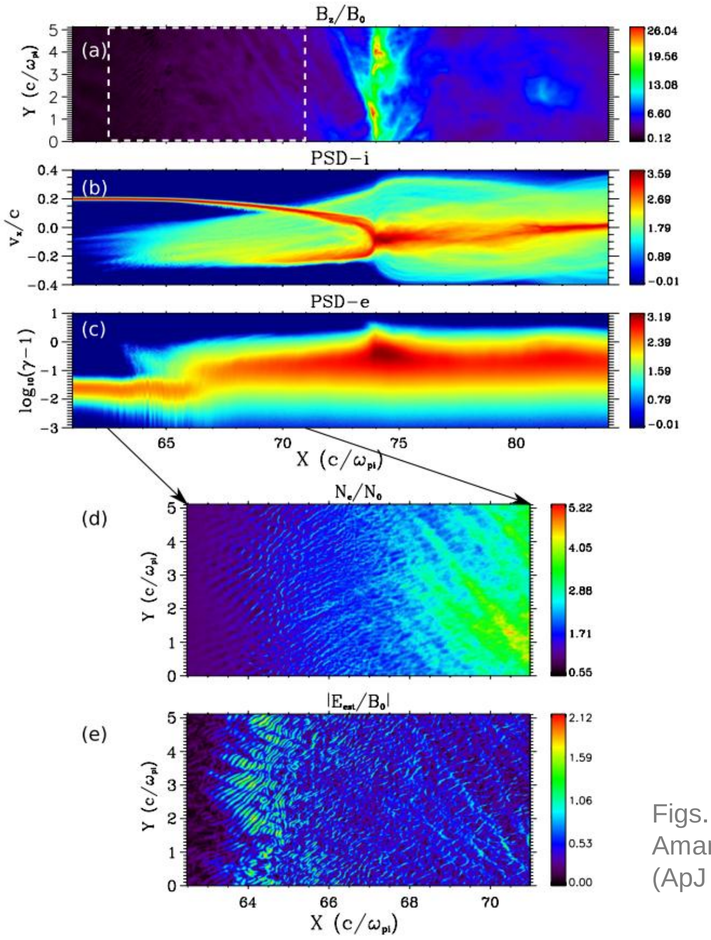
- **Shock Drift Acceleration (SDA)**
  - Electrons undergo the $|\boldsymbol{B}|$-gradient drift in the shock transition region.
  - Acceleration is due to motional $\boldsymbol{E}$ field:

$$\Delta\gamma = \frac{-e}{mc^2}\int E_z dz \approx \frac{-e}{mc^2}E_z^{\mathrm{up}}\Delta z$$

- **Shock Surfing Acceleration (SSA)**
  - If shock Mach number is high enough

$$M_{\mathrm{A}} \geq (1+\alpha)\left(\frac{m_{\mathrm{i}}}{m_{\mathrm{e}}}\right)^{\frac{2}{3}}$$

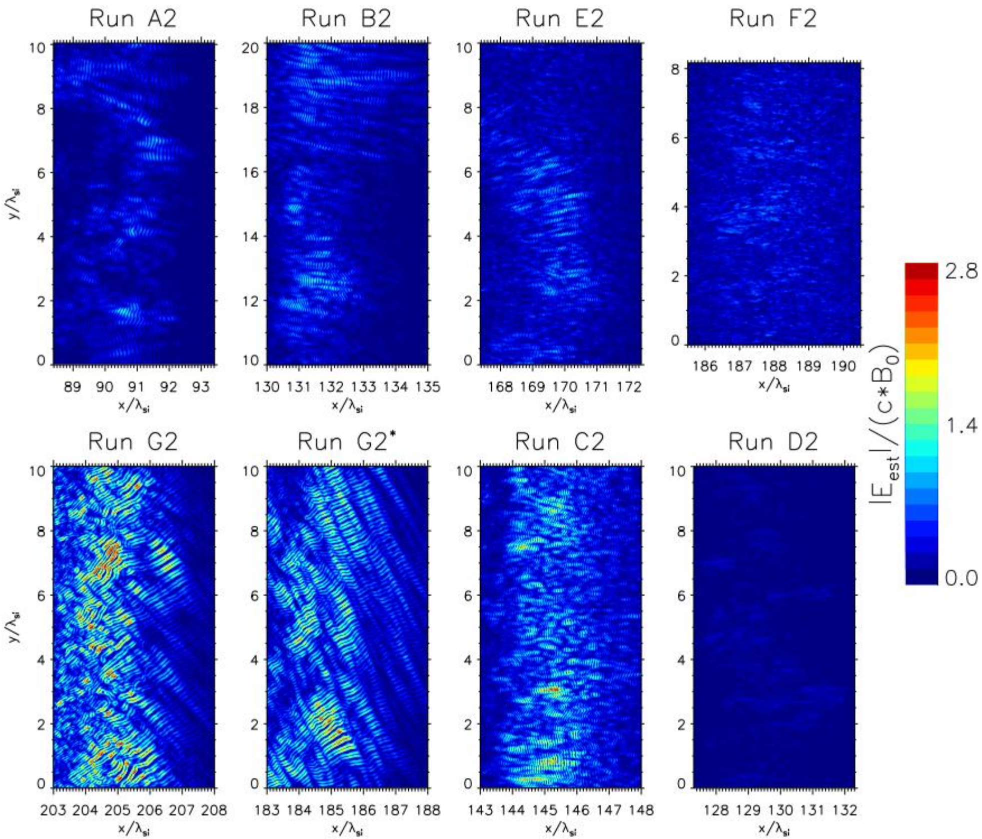
  - Electrostatic waves are generated ahead of shock due to the Buneman instability.
  - Electrons are trapped by the electrostatic potential and accelerated in the same way.

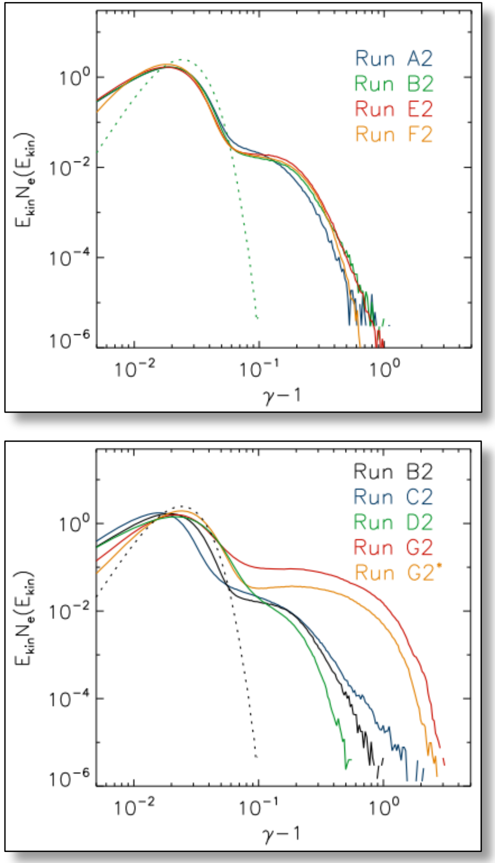


Figs. by Matsumoto, Amano & Hoshino (ApJ 2012)

Electron acceleration at (quasi-)perpendicular SNR shocks

➢ **Role of the Buneman instability for SSA**

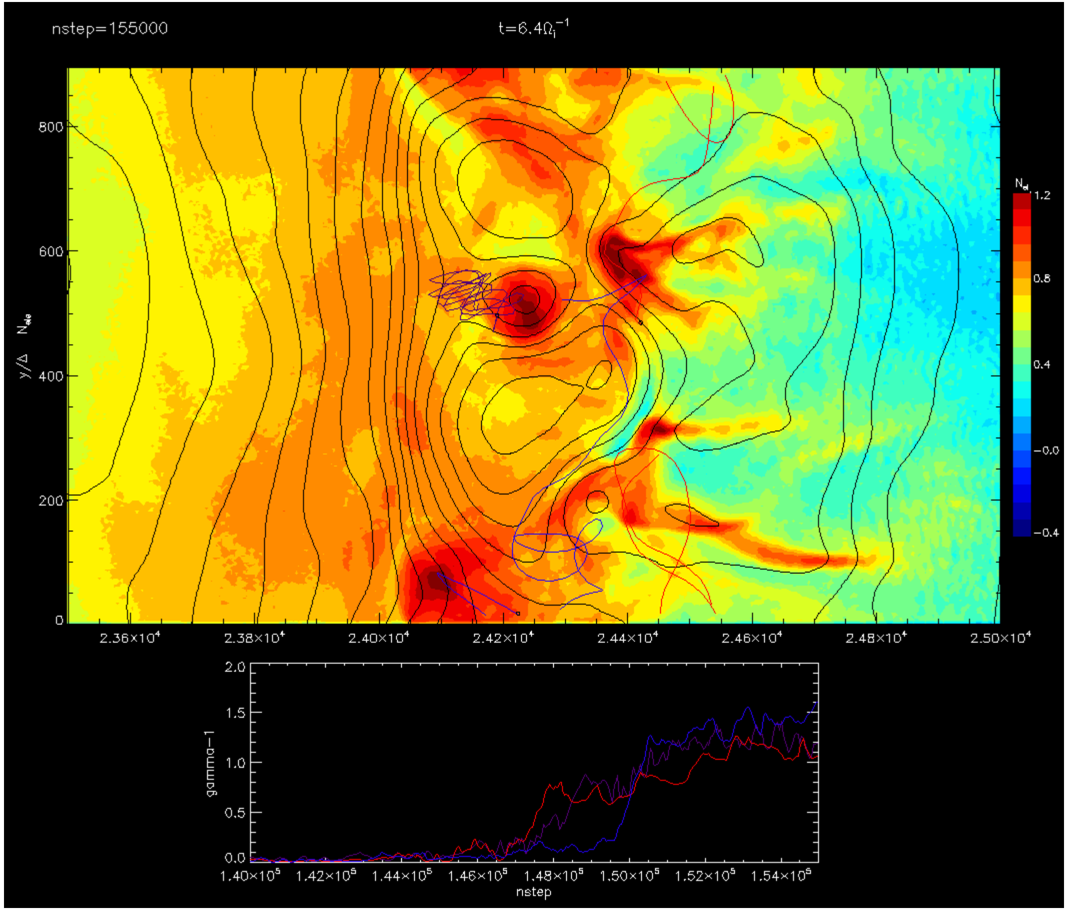




Figs. by Bohdan et al. (ApJ 2019)

Electron acceleration at (quasi-)perpendicular SNR shocks

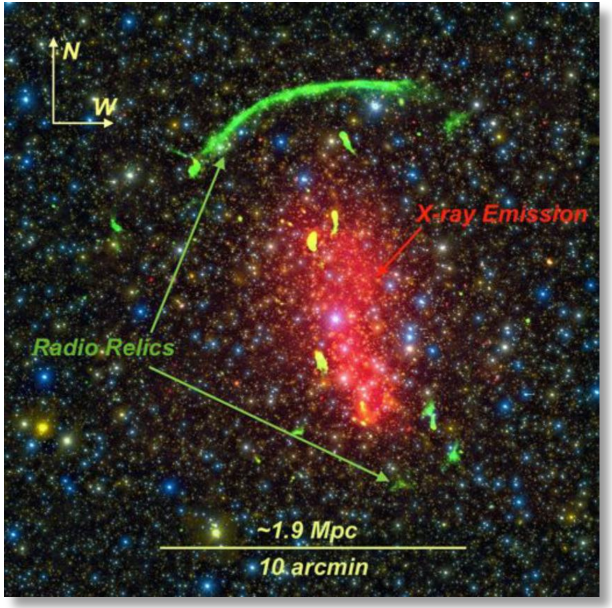
- **SSA accompanied by acceleration at the magnetic reconnection regions**
  - Ion Weibel instability results in the strong magnetic turbulence in the transition region.
  - Filaments with magnetic islands arise.
  - Electrons are accelerated at the reconnection X-points.



Electron acceleration at shocks in galaxy clusters

Mpc-scale merger shocks in galaxy clusters:

- Propagate in hot weakly magnetized plasma with high plasma beta $\beta \gg 1$.
- Have low Mach numbers $M \lesssim 4$.
- Physical conditions are not appropriate for SSA or Buneman instability.
- **X-ray** and synchrotron **radio emission** indicate the electron acceleration to non-thermal energies.



Series of recent studies showed the important role of **SDA** or stochastic SDA (**SSDA**) processes for electron acceleration at such physical conditions.

SSDA is a kind of SDA process accompanied by the elastic pitch-angle scattering of electrons by the magnetic turbulence.

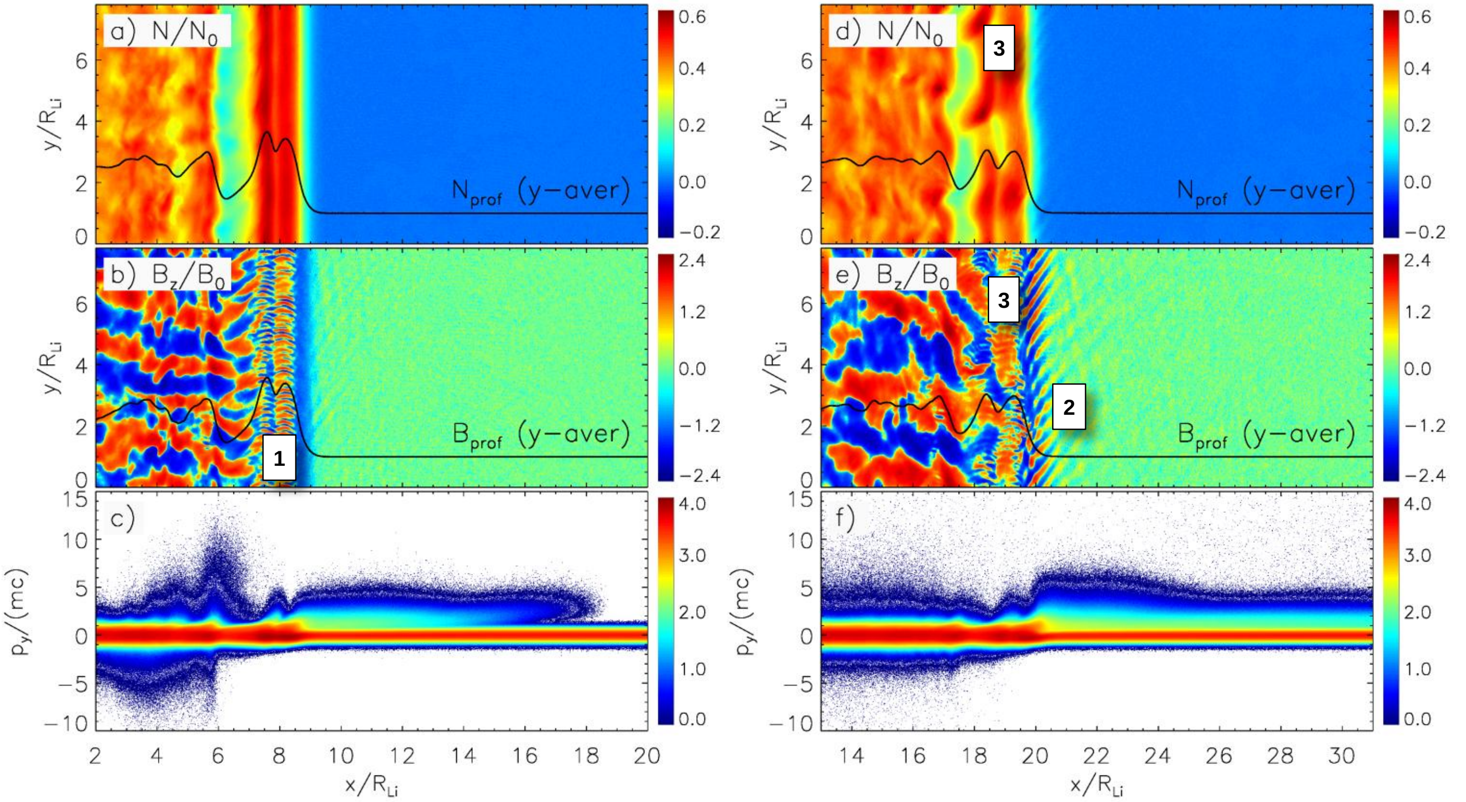
Electron acceleration at shocks in galaxy clusters

➢ Shock parameters

- Quasi-perpendicular.
- Sonic Mach number $M = 3$.
- Plasma temperature $T = 5 \cdot 10^8$ K (43 keV).
- Plasma beta $\beta = 5$.

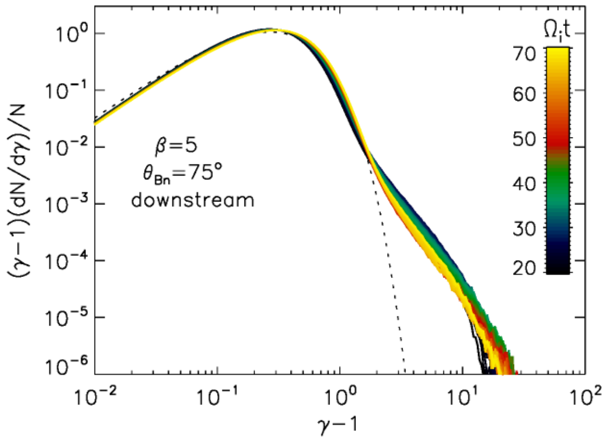
➢ Wave modes

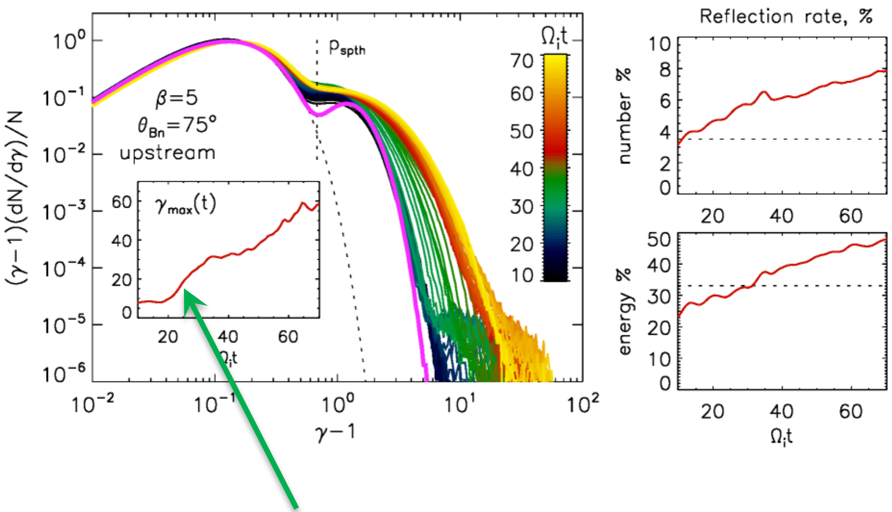
1. Electron **whistlers**.
2. Magnetic waves due to oblique mode of electron firehose instability (EFI), or **EFI-waves**.
3. Shock **rippling modes** due to Alfven ion cyclotron (AIC) instability.



Electron acceleration at shocks in galaxy clusters

➢ **Evolution of the electron energy distributions**





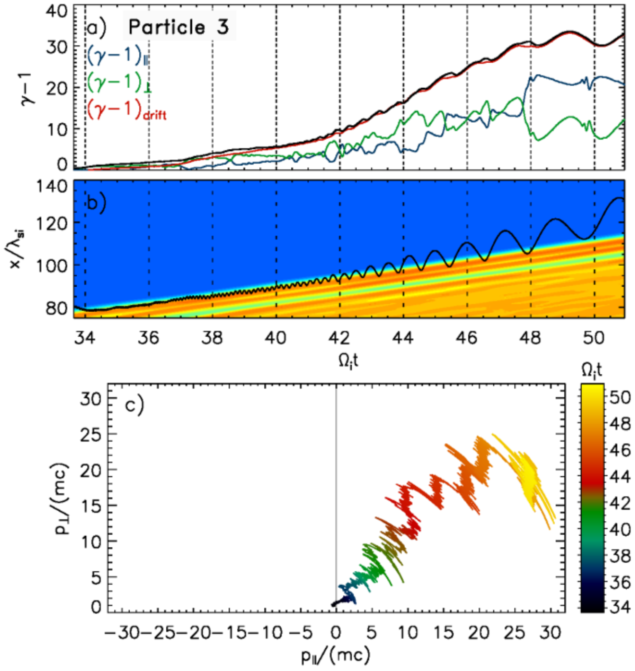
Electron kinetic energies reach the values much higher than SDA theory prediction.

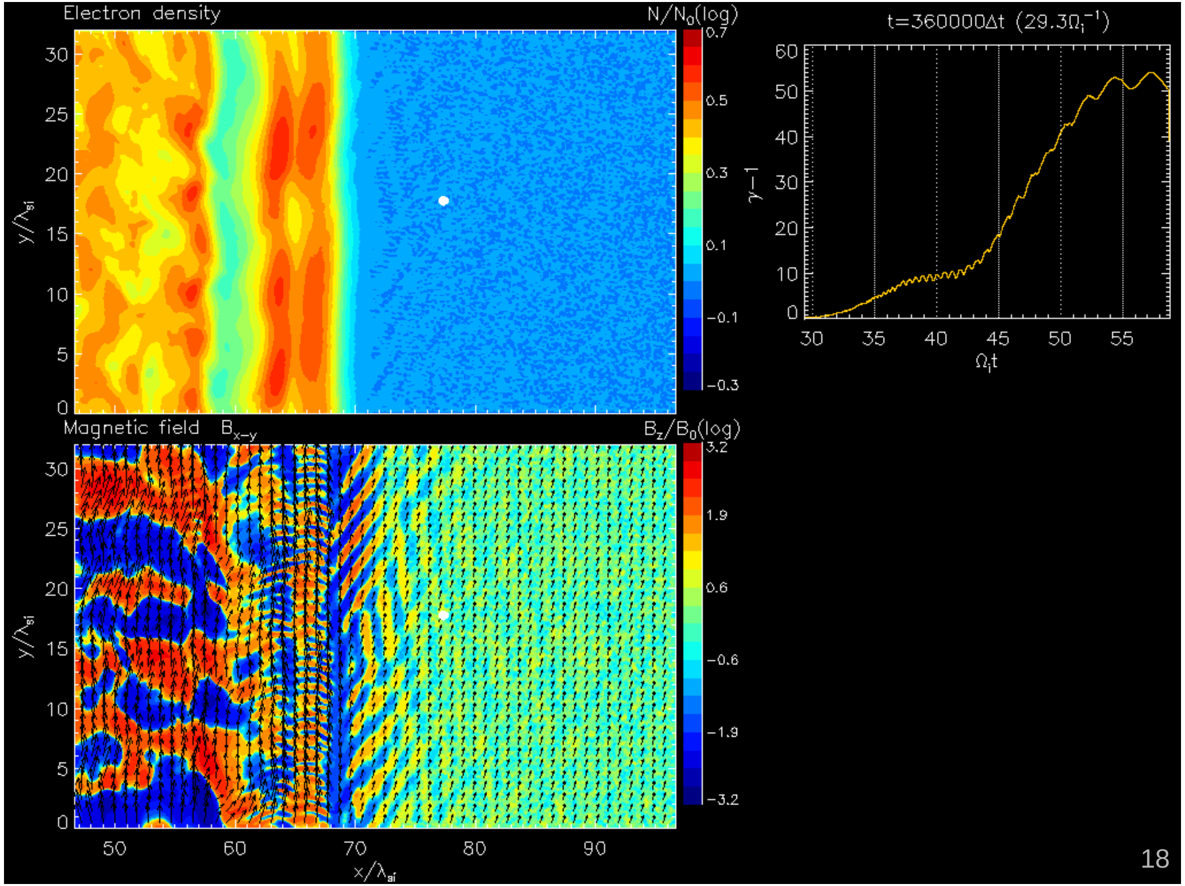
The dominating process is SSDA.

This correlates with appearance of the shock rippling.

Electron acceleration at shocks in galaxy clusters

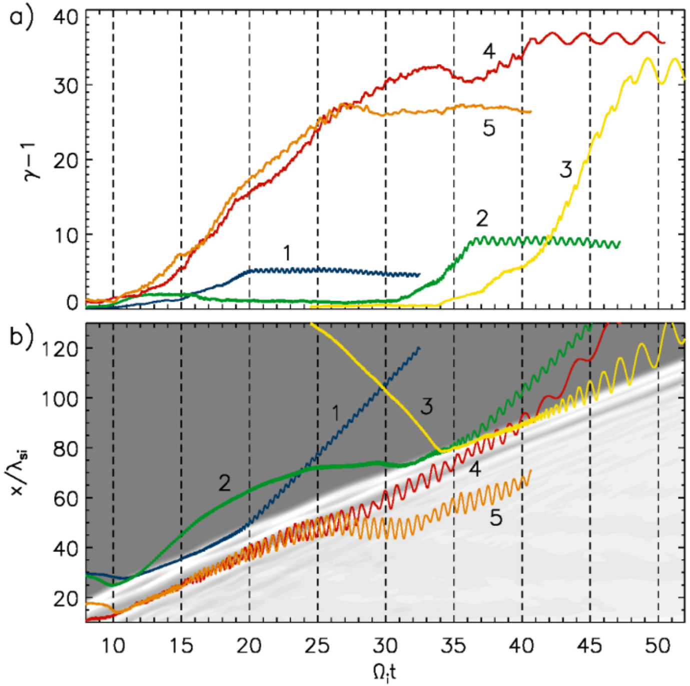
- **SSDA process**





Electron acceleration at shocks in galaxy clusters

➢ **Possible types of the electron acceleration at the rippled shock**



1. Single-cycle SDA process − regular.
2. Double-cycle SDA process − rare, second cycle occurs at rippled shock.
3. The **SSDA** process − typical for rippled shock.
4. Accelerated via **SSDA** in the undershoot and **scattered to the upstream**.
5. Accelerated via **SSDA** in the undershoot and **scattered to the downstream**.

Conclusion:

The dominant acceleration mechanism is SSDA.

Circumstance:

Gradual increase of the turbulence scale:
whistlers → EFI-waves → rippling modes.

Summary

- Shock waves in cosmic plasma can accelerate particles to high energies through 1-st order Fermi mechanism – Diffusive Shock Acceleration (DSA).
- (Quasi-)parallel shocks are more efficient for ion acceleration, while
- (quasi-)perpendicular shocks are more efficient for electron acceleration.
- Pre-acceleration (injection) is necessary for particles to be involved in DSA.
- Shock Surfing Acceleration (SSA) and Shock Drift Acceleration (SDA) can be the plausible pre-acceleration mechanisms for the following injection to DSA.
- Plasma instabilities are crucially important for the efficiency of pre-acceleration.
- Particle-wave interaction with magnetic turbulence through pitch-angle scattering results in stochastic SDA (SSDA).
- The SSDA process is found to be much more efficient than regular SDA, and it is potentially able to give the particle energy enough for injection to DSA.

Thank You!