Origin of Cosmic Rays from the Pre-Structure Universe to Structure Formation Shocks

(1) Ha, Ryu and Kang 2023, The Astrophysical Journal, 943, 119

(2) Ha 2025, Universe, 11, 9

(3) Ha 2026, Astroparticle Physics, 181, 103264

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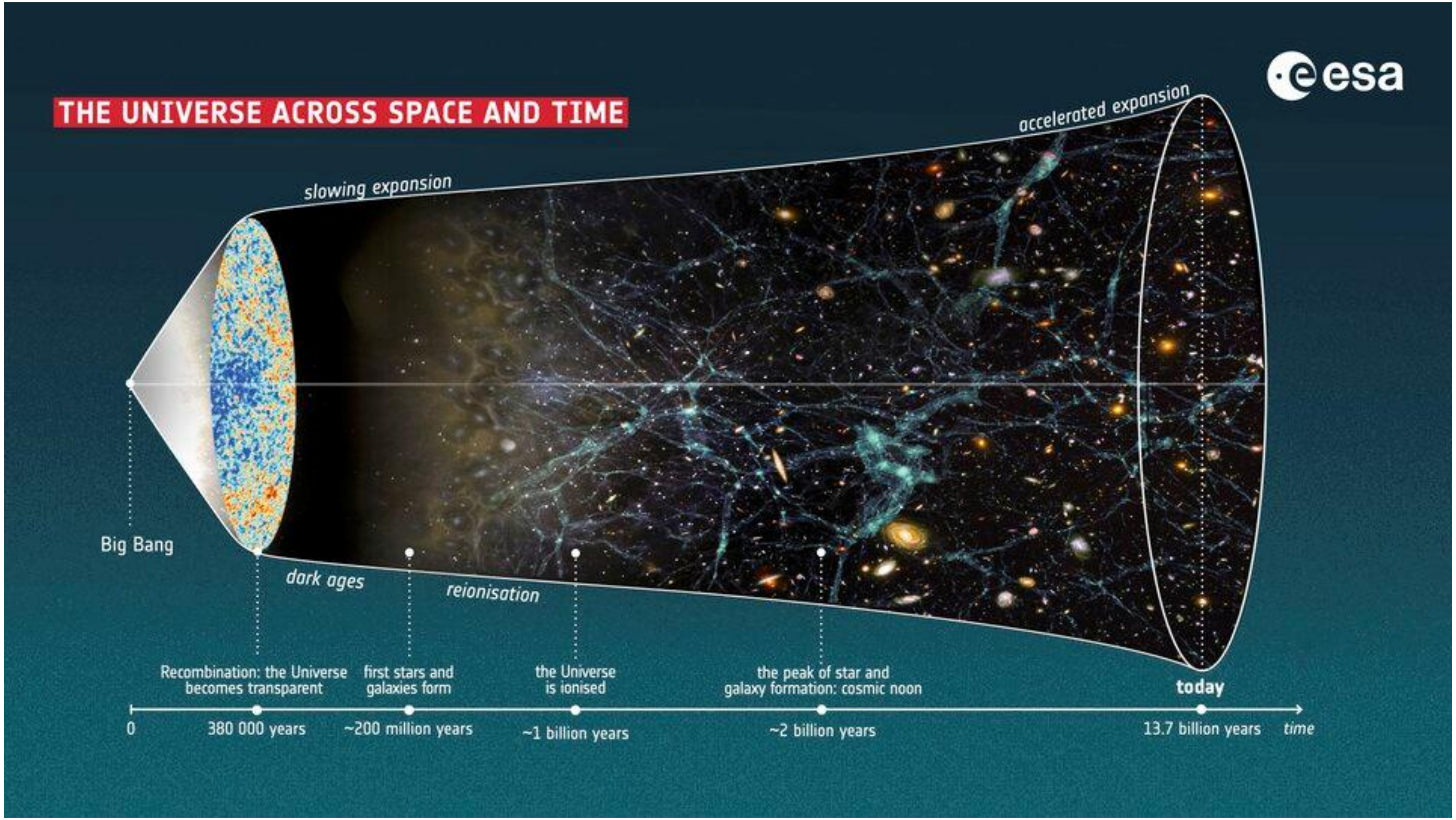
Overview



✓ **Magnetic field amplification in the pre-structure universe**

✓ **Structure formation shocks in and around galaxy clusters**

Plasma Instabilities

e.g., Schekochihin et al. 2005

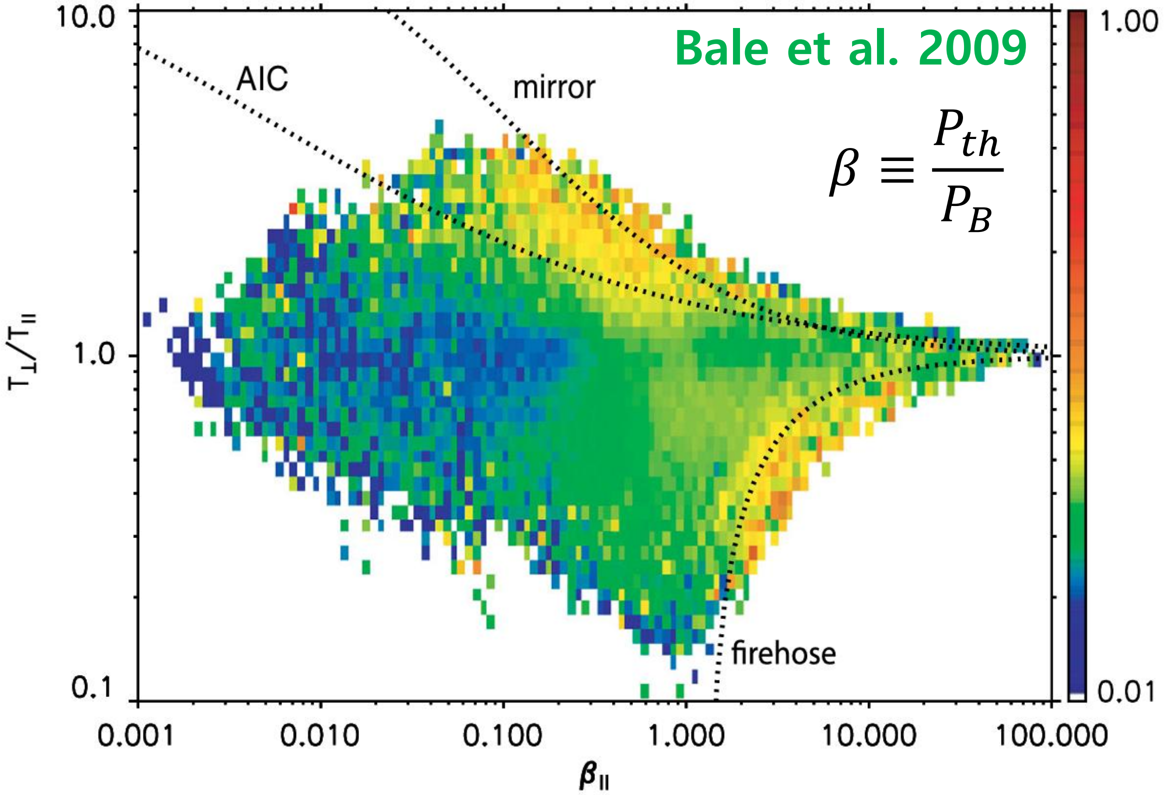
✓ Pressure Anisotropy

$$\Delta \equiv \frac{P_\perp - P_\parallel}{P_\perp}$$

$$\frac{d\Delta}{dt} \approx (1-\Delta)\frac{1}{B}\frac{dB}{dt} - \nu_{\rm scatt}|\Delta| - \nu_{ii}|\Delta|$$

Change in B drive anisotropy

Anisotropy modified by collisionless scattering and collisions



✓ **Magnetic field decreases:** $\Delta < 0$

Firehose: $\omega^2 = \frac{k_\parallel^2 v_{th,i}^2}{2}(\Delta + 2\beta^{-1})$

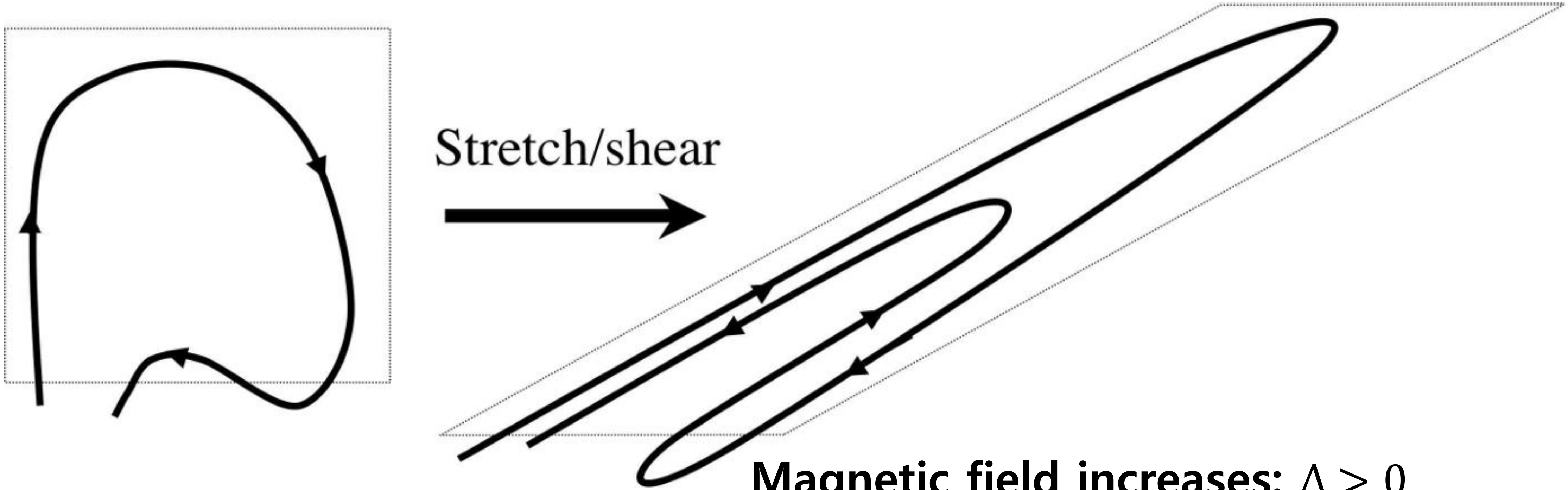
✓ **Magnetic field increases:** $\Delta > 0$

Mirror: $\Gamma = \frac{|k_\parallel| v_{th,i}}{\sqrt{\pi}}(\Delta - \beta^{-1})$

Plasma Instabilities and Turbulent Dynamo

e.g., Schekochihin & Cowley 2006

Magnetic field decreases: $\Delta < 0$
→ Firehose instability

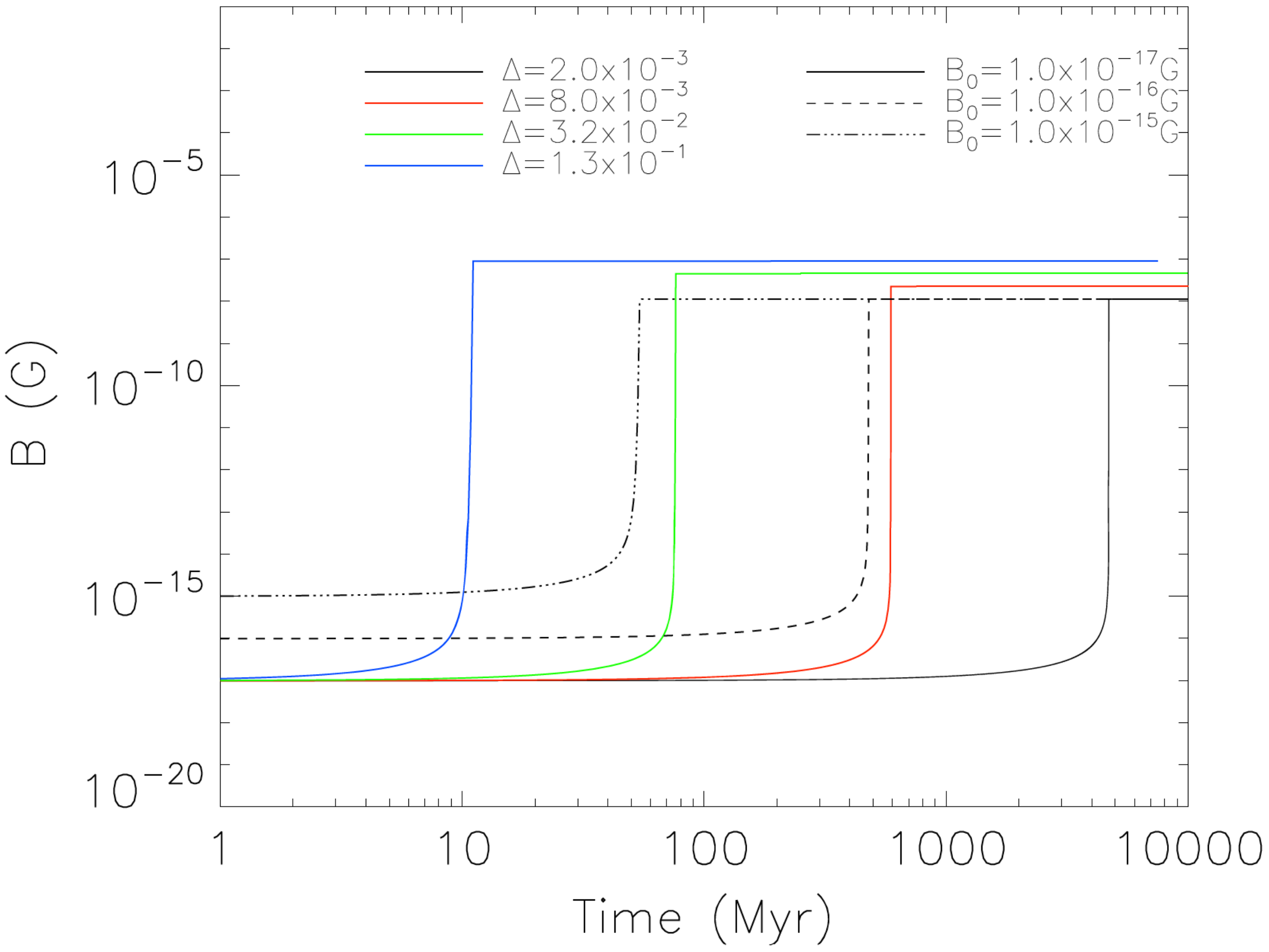


Magnetic field increases: $\Delta > 0$
→ Mirror instability

The feedback between magnetic-field evolution, pressure anisotropy, and plasma instabilities can significantly affect magnetic-field amplification by turbulence.

Plasma Instabilities and Magnetic Field Amplification

e.g., Falceta-Goncalves & Kowal 2015



(1) For $\nu_{\rm scatt} \gg \nu_{ii}$,

$$\frac{1}{B_0}\frac{dB}{dt} \approx \frac{(|\Delta| - 2\beta^{-1})^{3/2}}{1+|\Delta|}\left(\frac{B}{B_0}\right)^2$$

(2) The maximum value of B is determined by $|\Delta| \sim 2\beta^{-1}$

- stronger B requires larger |Δ| to sustain the instability
- Growth saturates when |Δ| can no longer be sustained.

$$\beta \equiv \frac{P_{th}}{P_B}$$

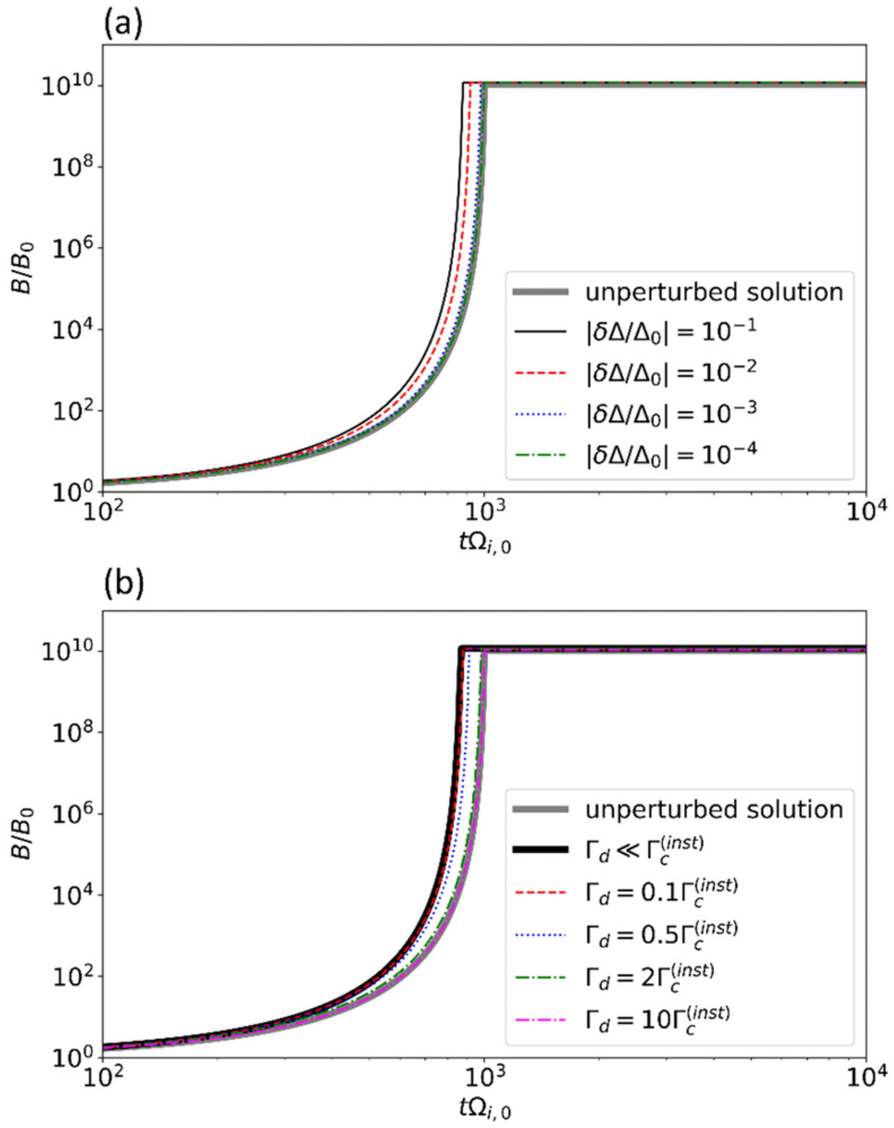
→ e.g., the initial seed field ($\beta \gg 100$)

→ e.g., Intracluster medium ($\beta \sim 100$)

Δ and B_0 determine the growth of cosmological magnetic fields.

Perturbations near the Marginally Stable State?

Ha 2025



Considering a pressure-anisotropy perturbation around the marginally stable state (i.e., $|\delta\Delta| \ll |\Delta| \sim 2\beta^{-1}$)

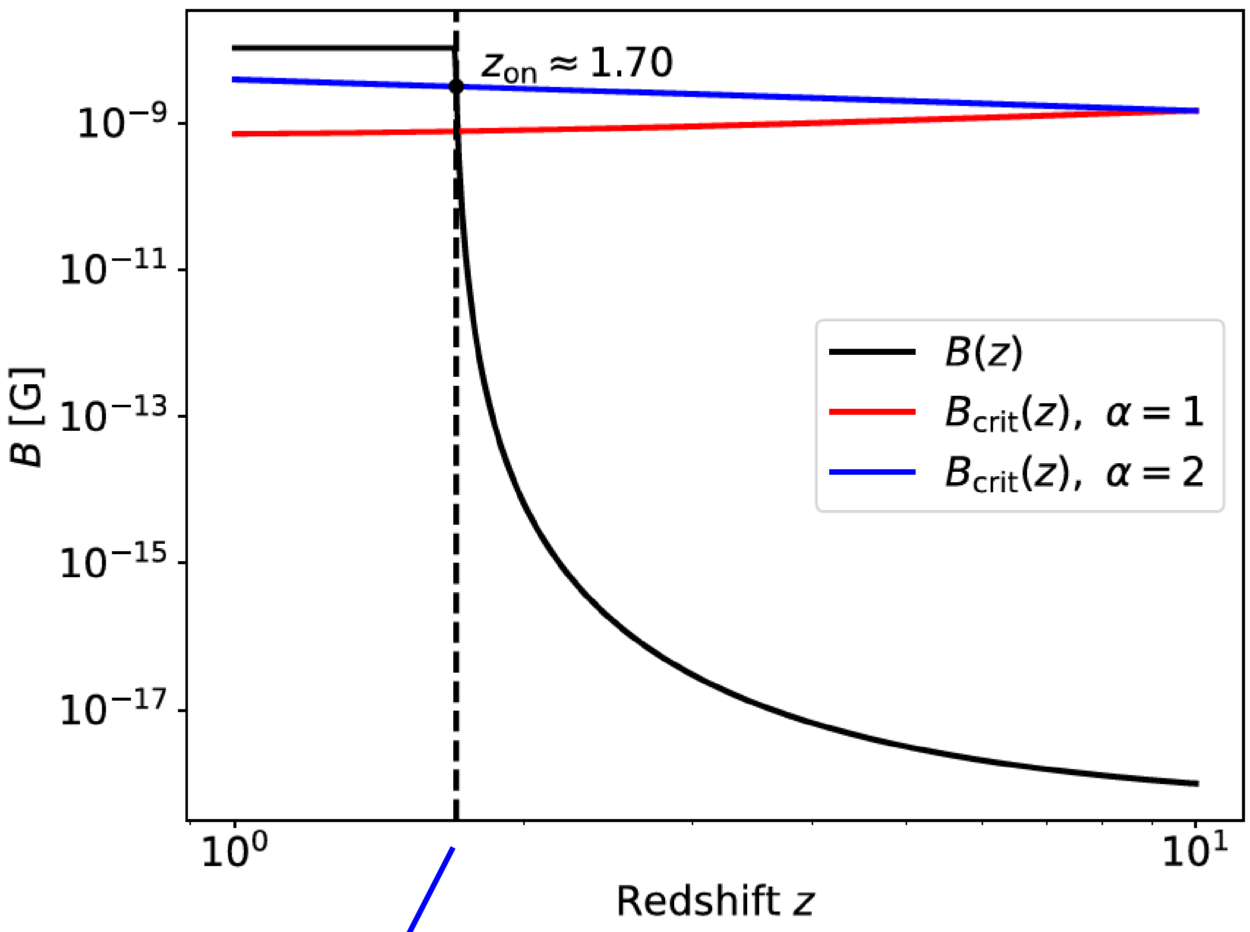
$$\frac{\Omega_{i,0}^{-1}}{B_0}\frac{dB}{dt} \approx \frac{(|\Delta| - 2\beta^{-1})^{\frac{3}{2}}}{1+|\Delta|}\left(\frac{B}{B_0}\right)^2 + \frac{2\exp\left(-\Gamma_d t - \frac{1}{2}\frac{\Gamma_d}{\Gamma_c^{(inst)}}\right)}{1+|\Delta|}\left(\frac{B}{B_0}\right)^2$$

- **Γ_d: damping rate of the pressure-anisotropy perturbation**
- **$\Gamma_c^{(inst)}$: characteristic growth rate of the plasma instability**

Slowly damped anisotropy perturbations can accelerate magnetic-field amplification without changing its final saturation level.

Condition for Acceleration in the Pre-Structure Universe?

Ha 2026



✓ Efficient particle acceleration is unlikely at z >~1.7

✓ Stochastic acceleration timescale:

$$\nu_{\mathrm{scatt}} \sim \Omega_i(|\Delta| - 2\beta^{-1})^{\frac{3}{2}}$$

$$t_{acc}(E,z) \sim \left(\frac{c}{v_{tur}(z)}\right)^2 \frac{v(E)}{c\nu_{\mathrm{scatt}}}$$

✓ Hubble timescale:

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$$

$$t_H(z) \sim H^{-1}(z)$$

✓ The minimum acceleration condition:

$$t_{acc}(E,z) < t_H(z)$$

Particle Acceleration in the Pre-Structure Universe?

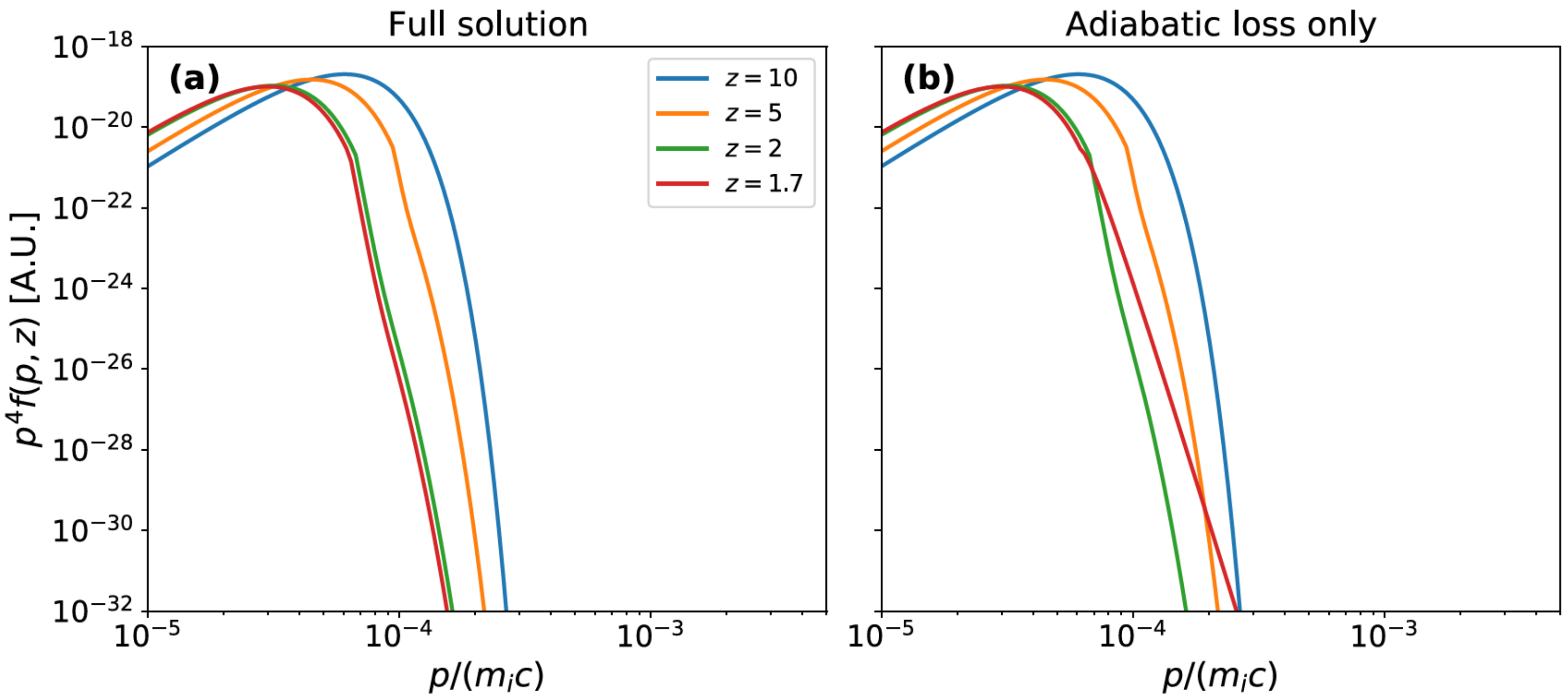
Ha 2026

✓ Fokker-Planck equation

$$-\frac{1+z}{t_H(z)}\frac{\partial f}{\partial z} \approx \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 \frac{p^2}{t_{acc}(z)}\frac{\partial f}{\partial p}\right] - \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 \dot{p}_{loss}(p,z) f\right],$$

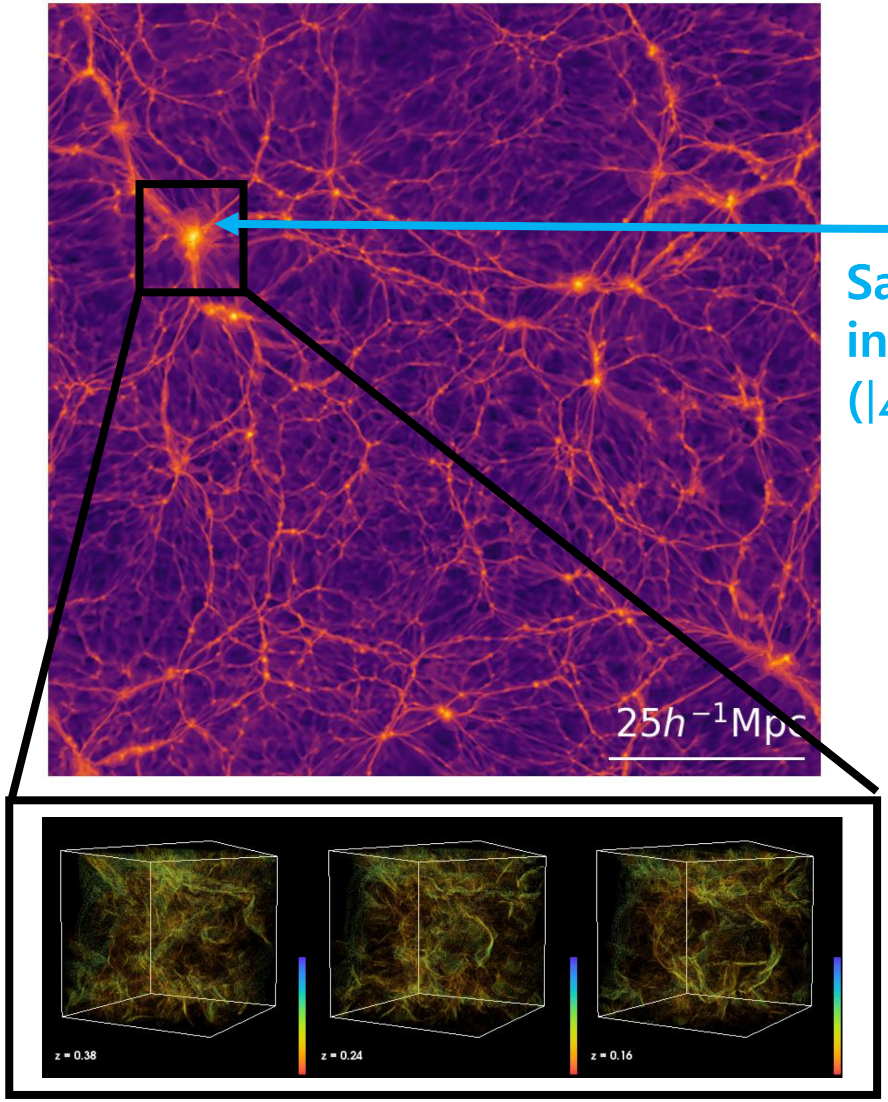
✓ Loss terms: adiabatic and Coulomb losses

$$\dot{p}_{loss}(p,z) = \dot{p}_{ad}(p,z) + \dot{p}_C(p,z)$$



Acceleration Scenario from the Pre-Structure Universe to Structure Formation Shocks

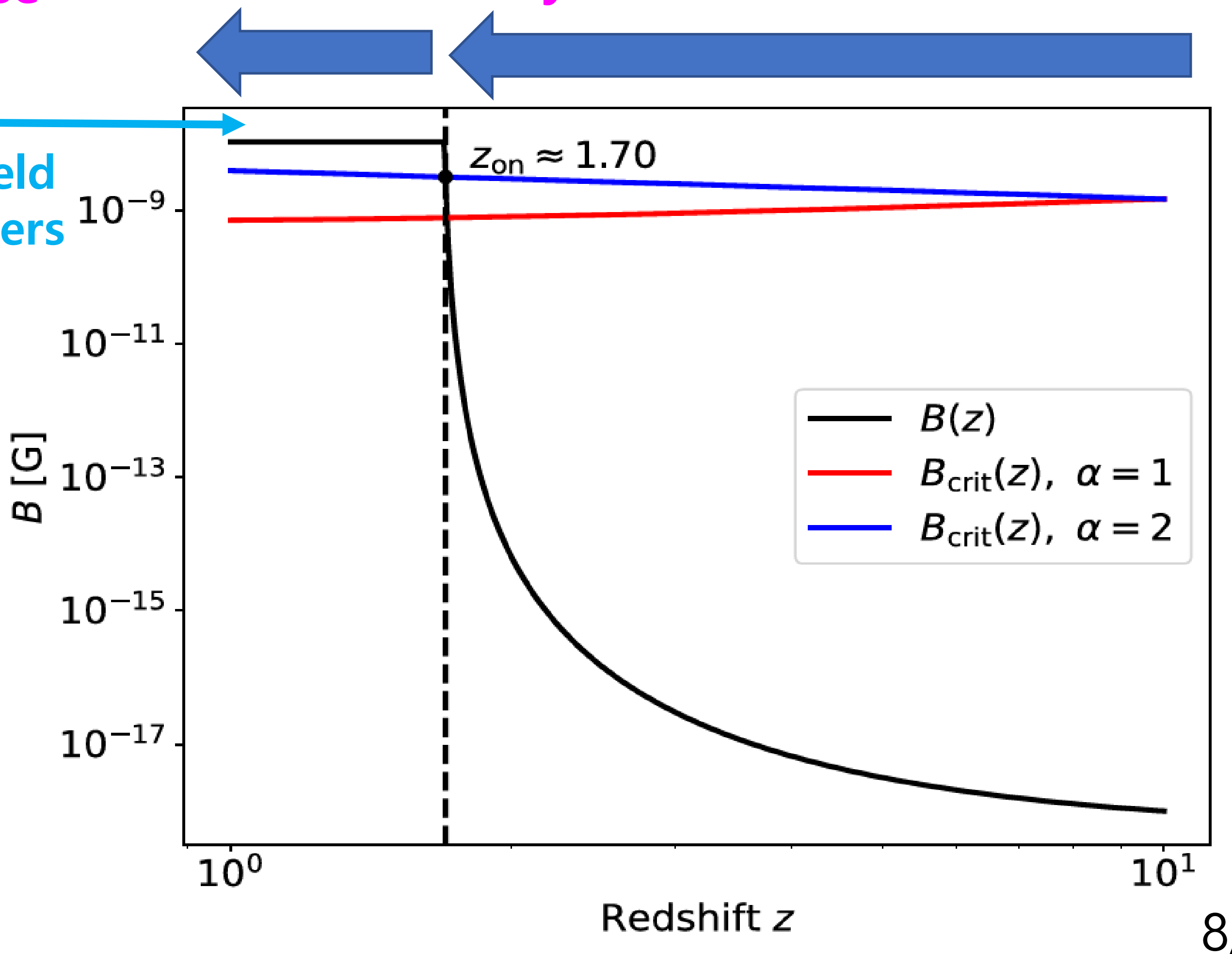
Cosmological Simulation
(e.g., Ha et al. 2018, 2020, 2023)



Shock acceleration in the large-scale structure of the universe

Stochastic acceleration in the pre-structure universe: very inefficient…

Saturated B-field in galaxy clusters ($|\Delta| \sim 2\beta^{-1}$)



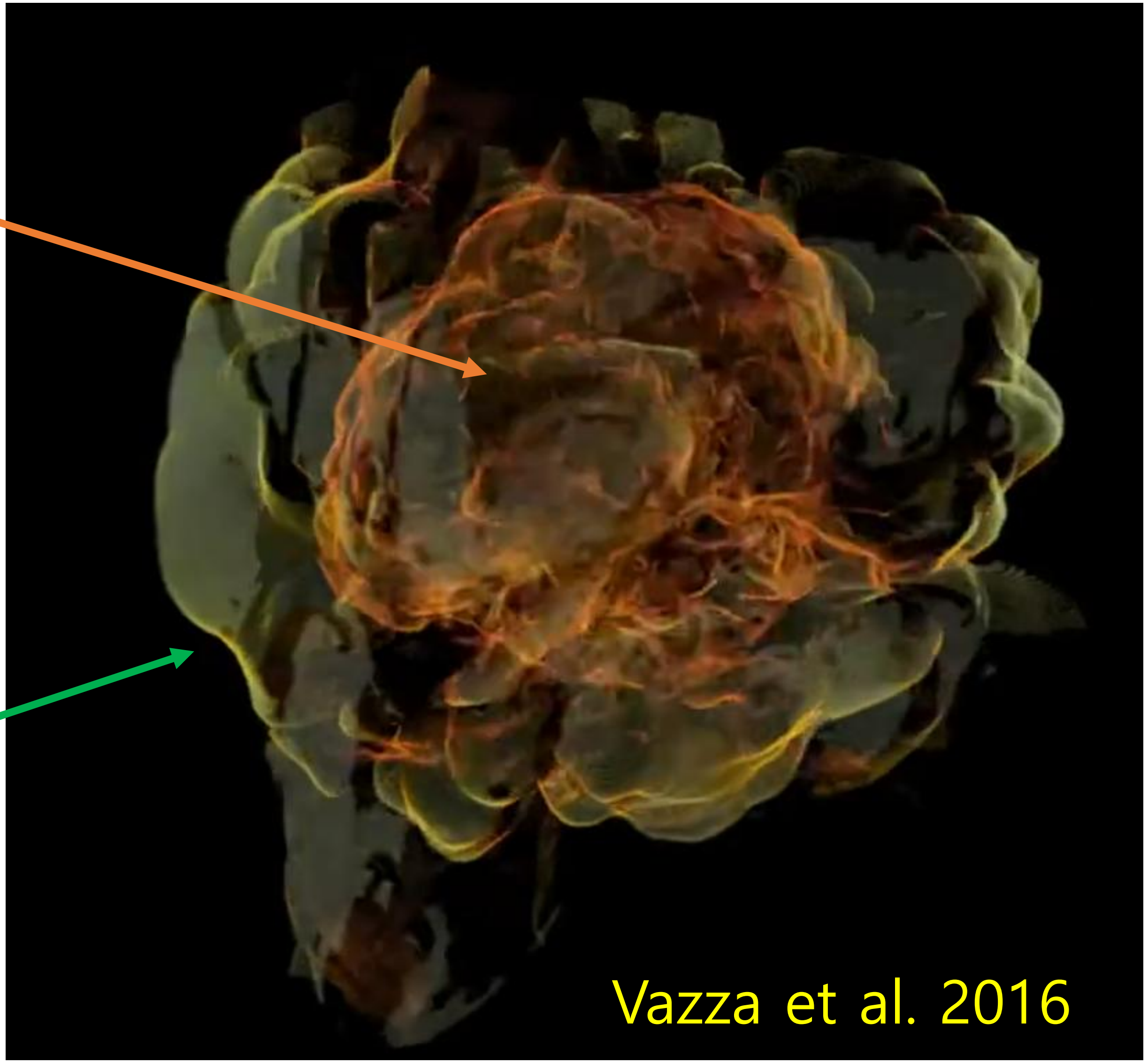
Structure Formation Shocks

weak intracluster shocks with M_s<~5 (orange)

- **mergers of clumps**
  (e.g., Ha et al. 2018; Lee et al. 2025)
- **gas infall along filaments**
  (e.g., Hong et al. 2014; Ha et al. 2023)
- **turbulent flows**
  (e.g., Porter et al. 2015)

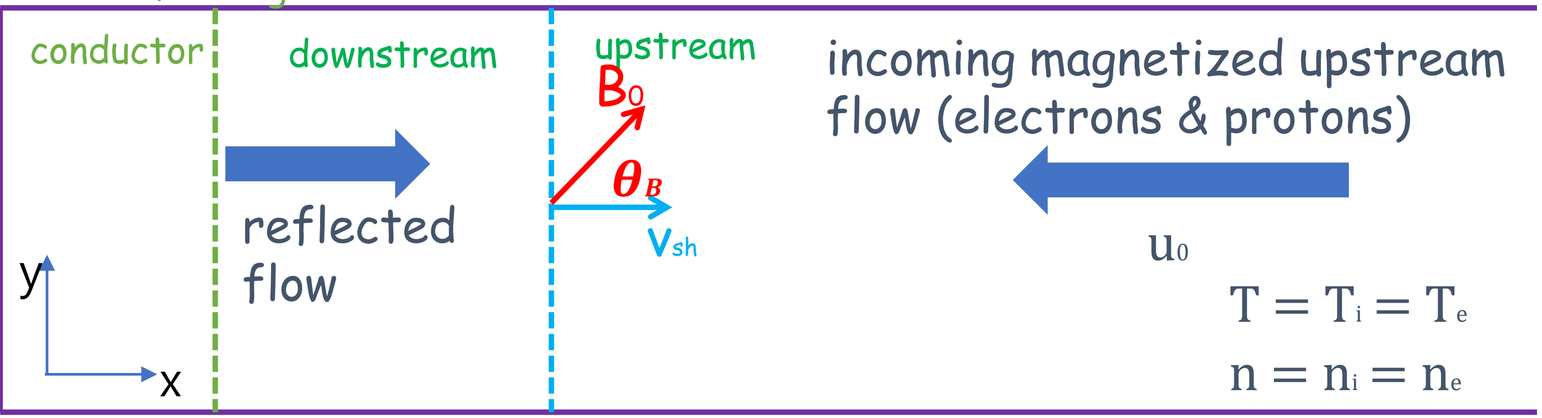
strong accretion shocks with M_s>~10 (green)

Shocks are ubiquitous in galaxy clusters!



Particle-in-Cell (PIC) Simulation

Simulation Setup (2D PIC simulation; TRISTAN-MP)



- **Two main mechanisms for creating collisionless shocks:**

1) For a sufficiently strong initial B-field, particles are deflected by compressed pre-existing fields

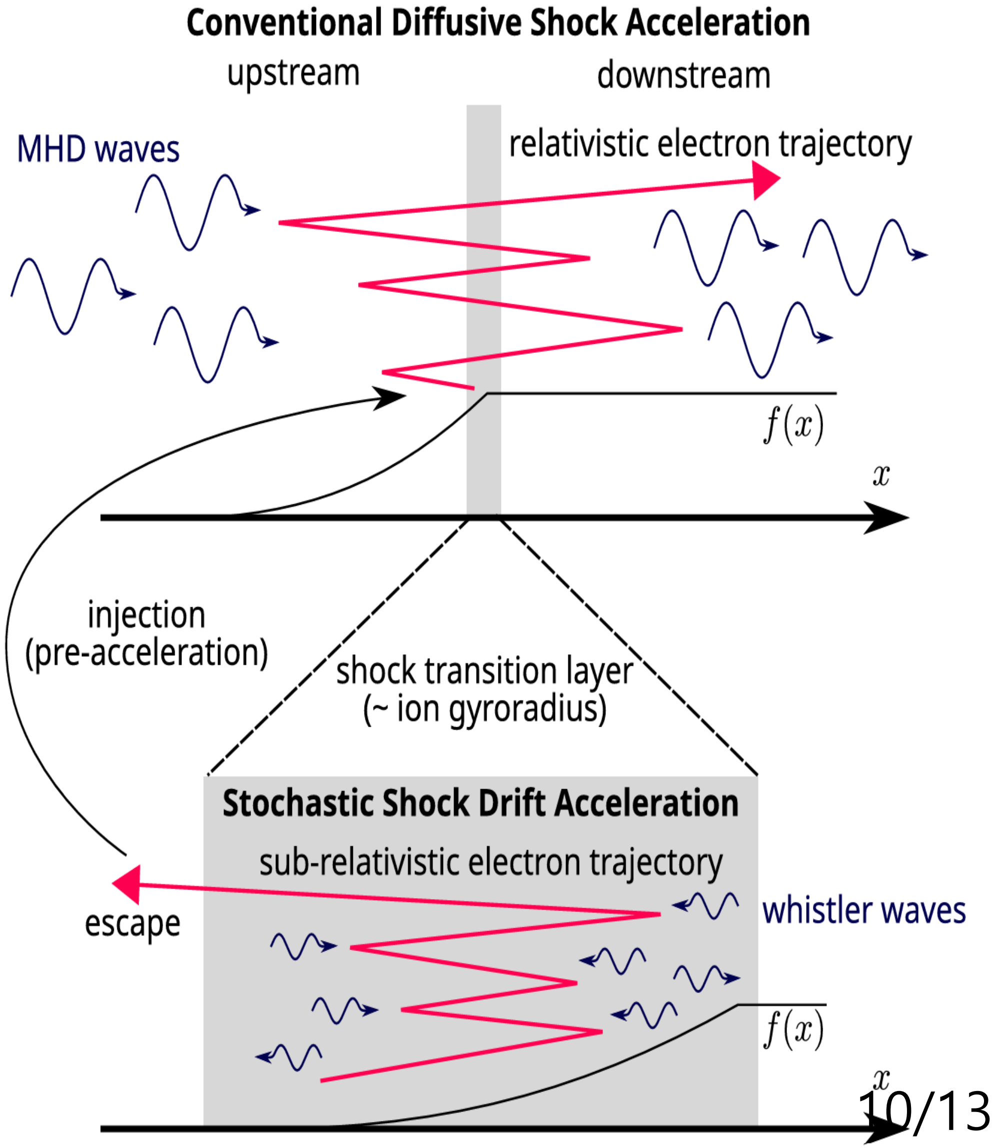
→ Intracluster shocks (Ms~3; beta~50)

2) For a weak initial initial B-field, particles are deflected by self-generated B-fields (e.g., Weibel instability)

→ accretion shocks (Ms~100; beta~1000)

Acceleration Mechanism

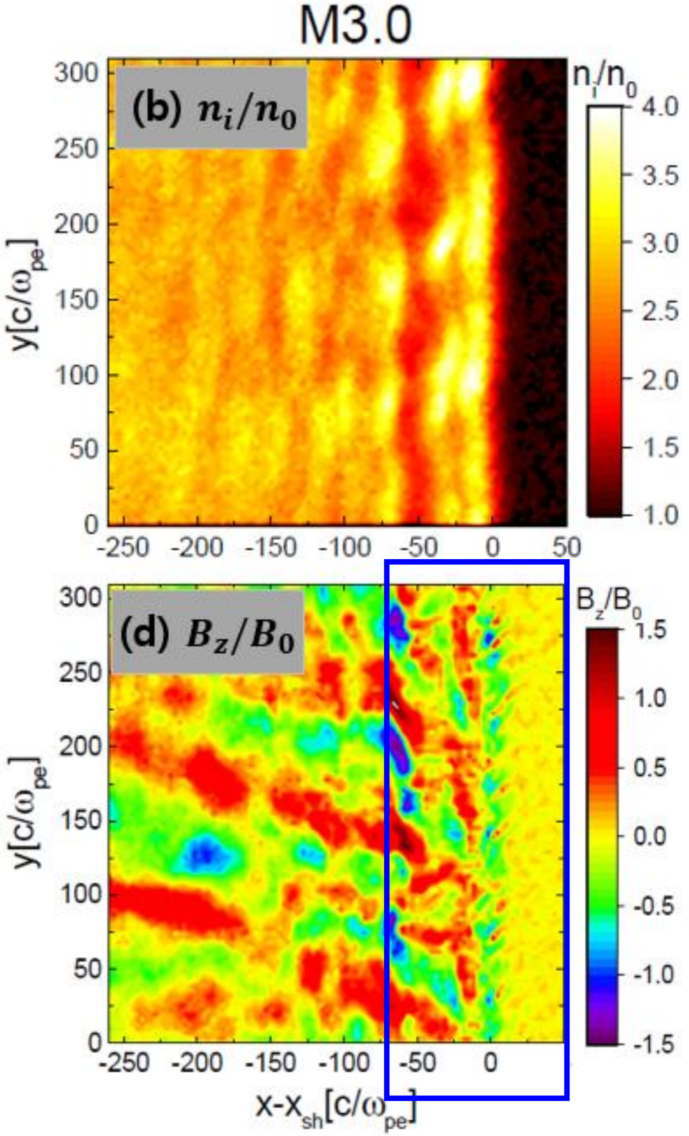
(Amano et al. 2020)

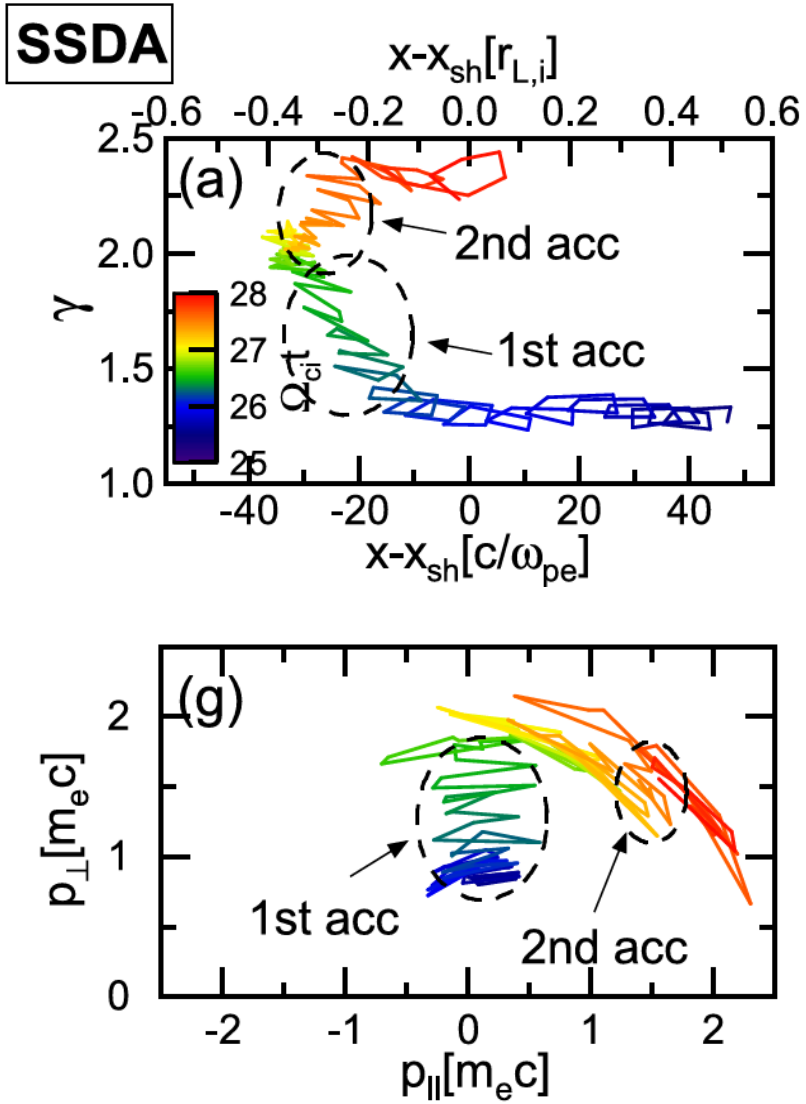


Particle Acceleration in Intracluster Shocks

e.g., Ha et al. 2021, 2022

2D PIC Simulation (Ms~3, beta~50)





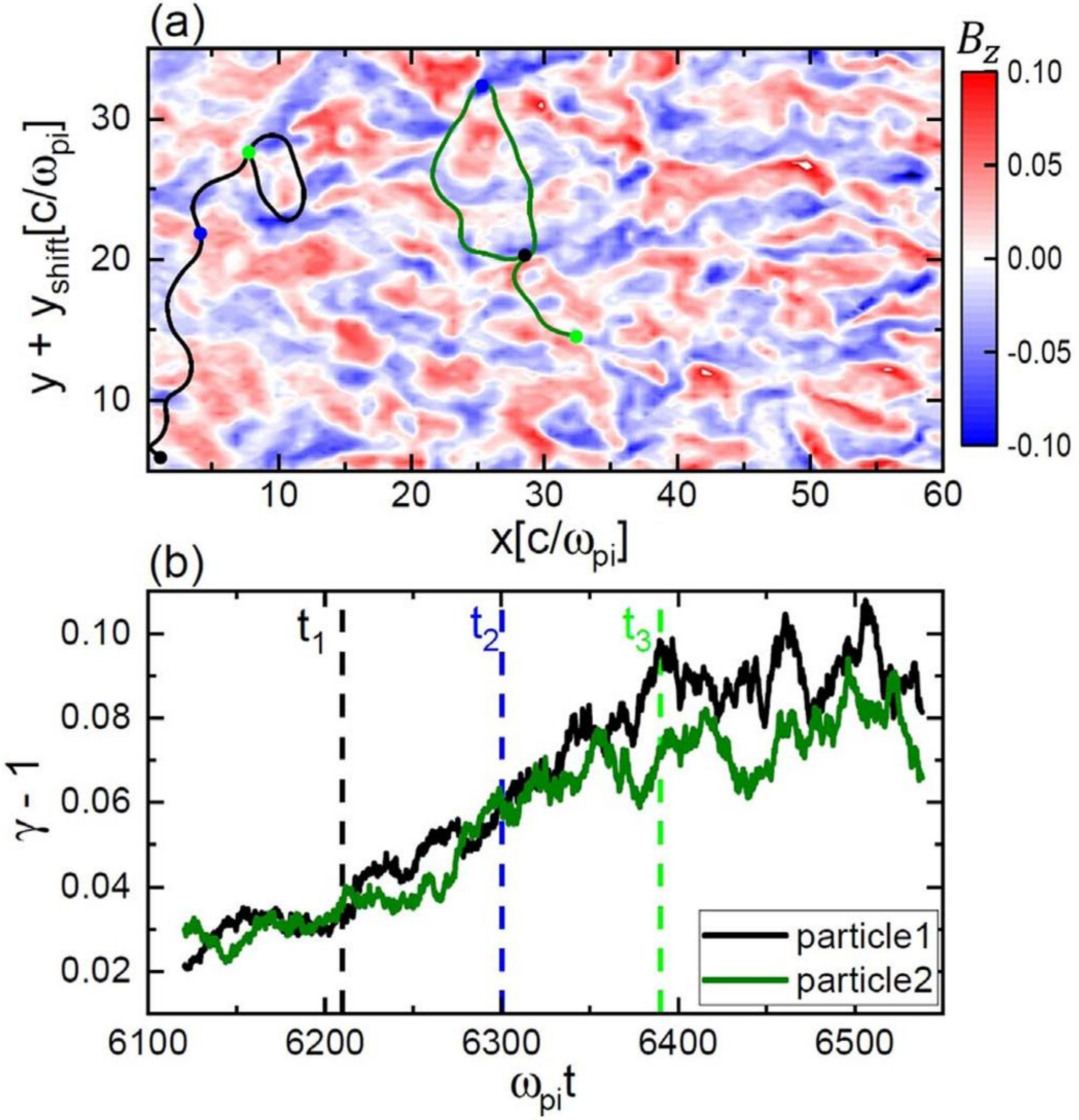
Intracluster shocks

Particle Acceleration in the Shock Transition Region

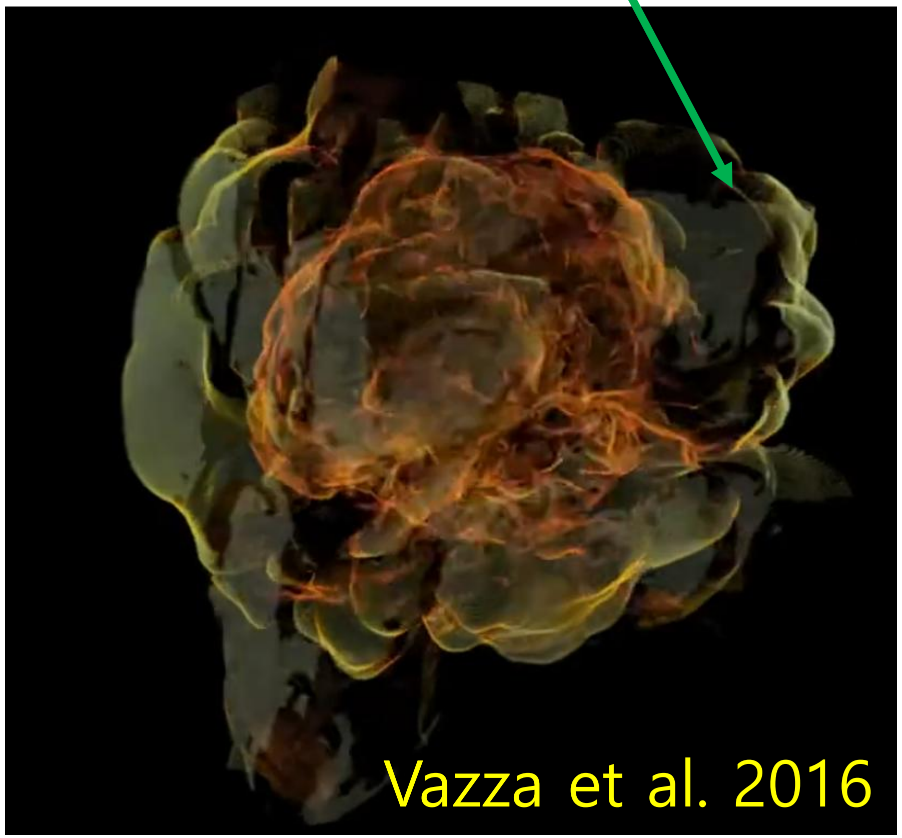
Particle Acceleration in Strong Accretion Shocks

e.g., Ha et al. 2023

2D PIC simulation (Ms~100, beta~1000)



Accretion shocks



Weibel-driven turbulence can contribute to stochastic particle acceleration

Summary

1. Plasma instabilities can amplify weak cosmological magnetic fields before nonlinear structure formation.

→ Pressure-anisotropy-driven instabilities regulate the magnetic-field evolution and provide the scattering environment required for particle energization.

2. Pre-structure stochastic acceleration is too inefficient to produce a significant cosmic-ray population.

→ Although stronger magnetization can shorten the acceleration time, efficient acceleration becomes possible only around $z \sim 1.7$, while cosmological expansion and collisional losses strongly suppress the nonthermal population.

3. Efficient cosmic-ray production emerges with structure-formation shocks.

→ Once nonlinear structures form, intracluster and accretion shocks provide much more favorable environments for particle acceleration, with different shock regimes governed by pre-existing and self-generated magnetic fields.

Thank you!

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