Particle Acceleration in Weakly Magnetized Transrelativistic Shocks

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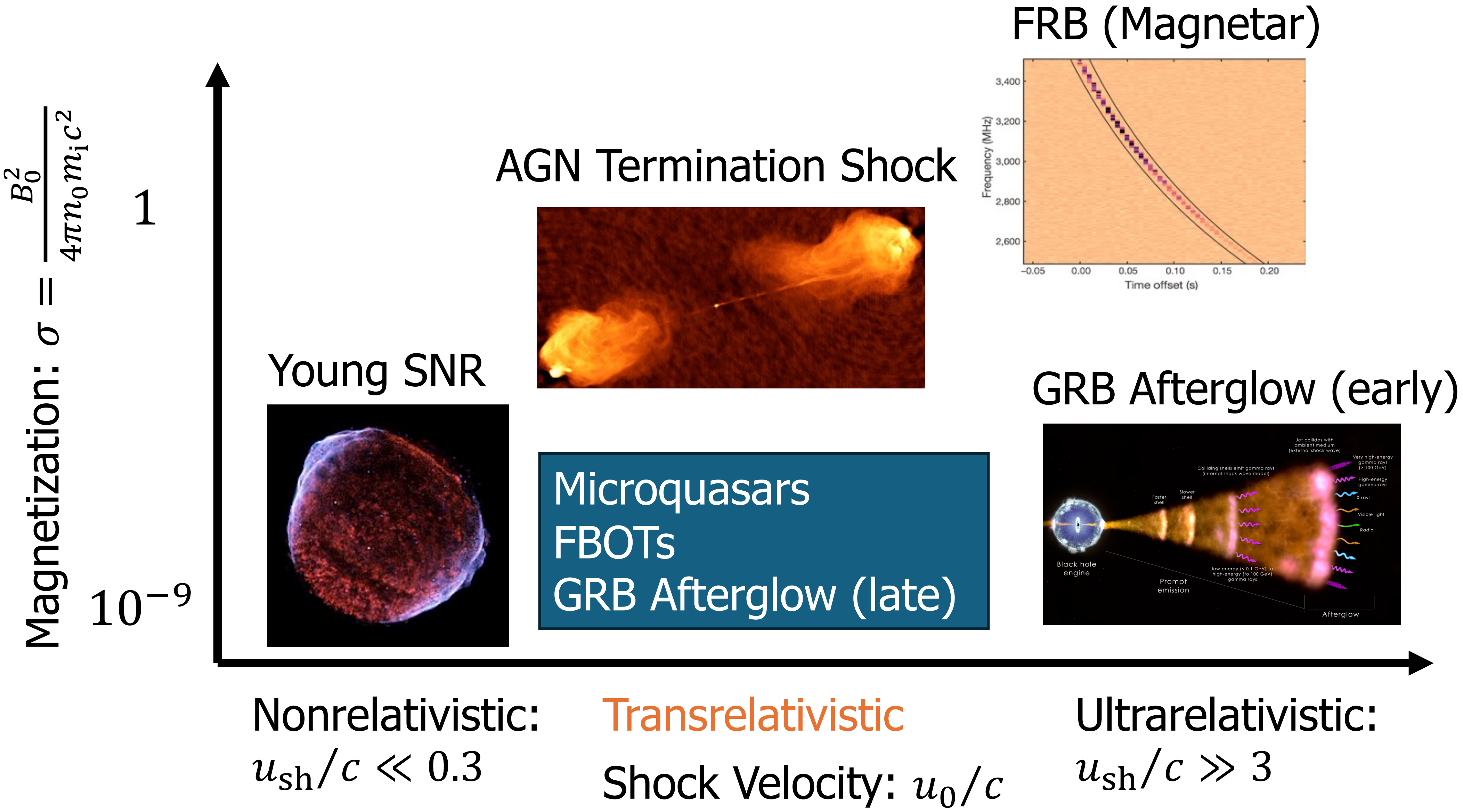
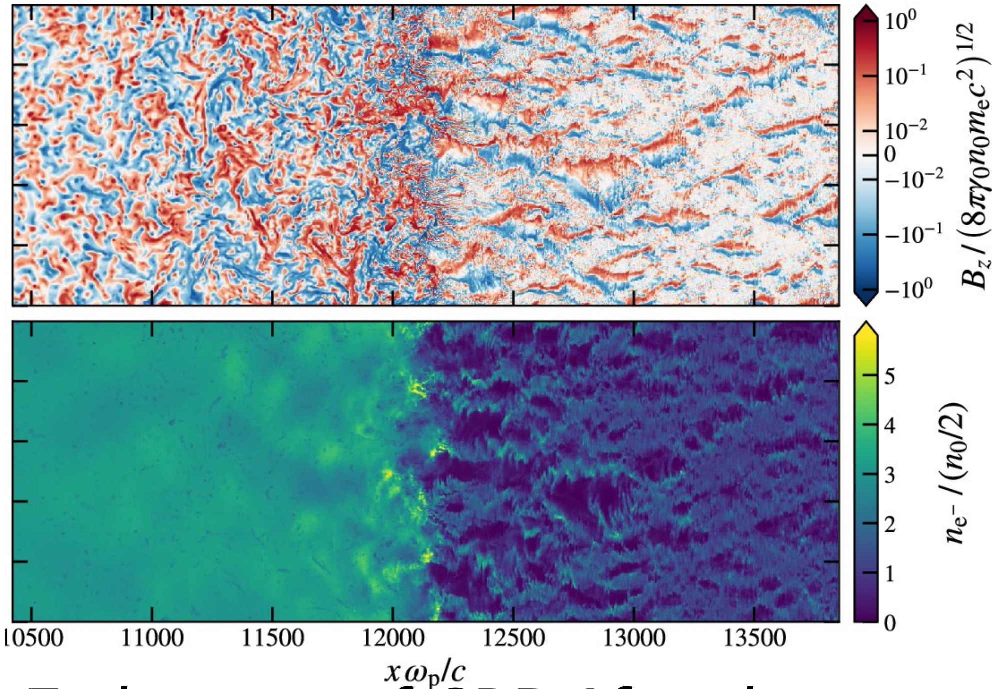
arXiv:2512.03169
arXiv:2607.05778

Astrophysical Shocks

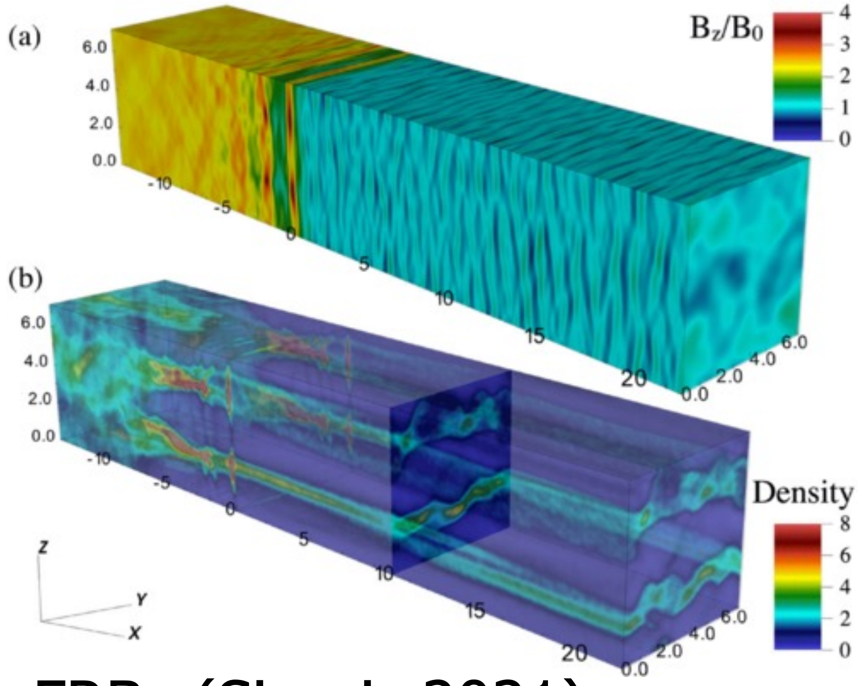


Why Shock Microphysics?

- Nonthermal emission: X-ray, gamma-ray, coherent radio
- Ultra-high-energy cosmic rays
- Ultrarelativistic shocks have been studied by PIC

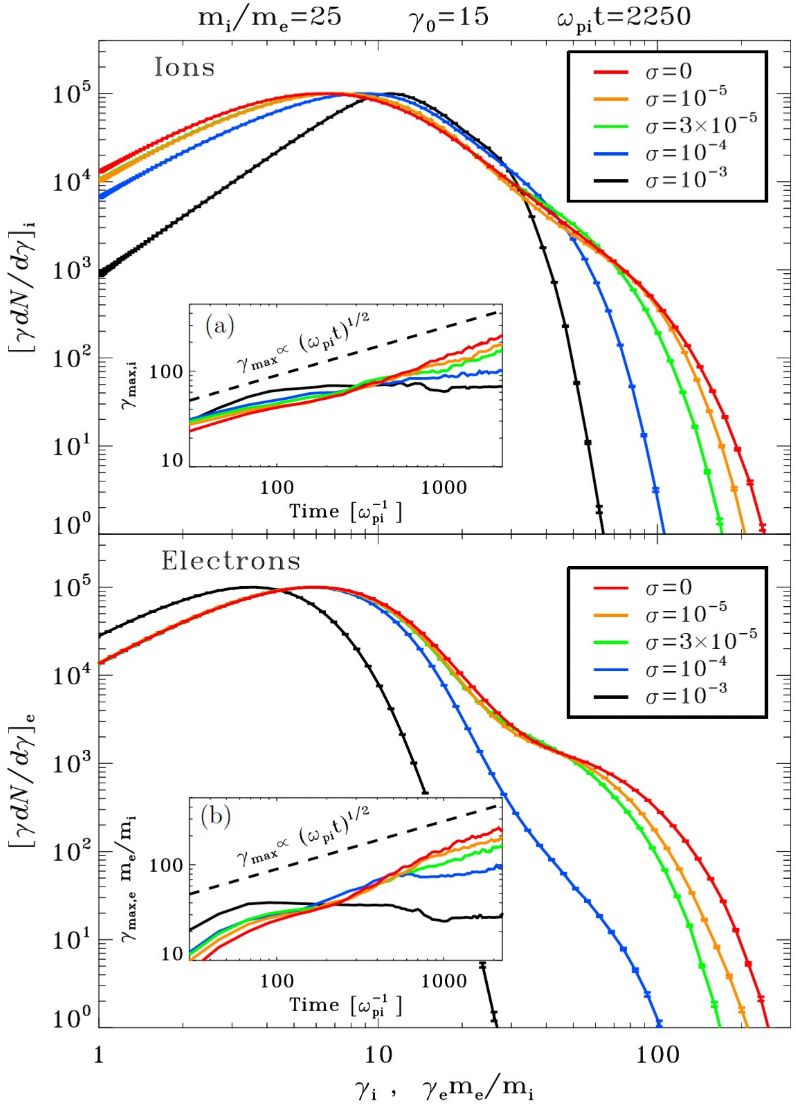


Early stage of GRB Afterglows (Grošelj +2024)



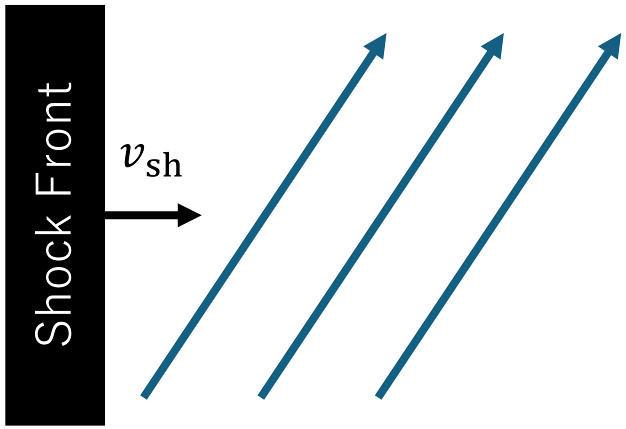
FRBs (Sironi+2021)

Acceleration in Ultrarelativistic Shocks

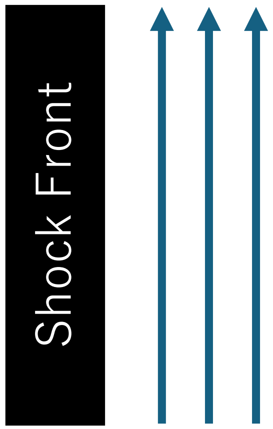


Sironi+2013

- Inevitably superluminal (magnetic field is perpendicular to shock normal)
- Maximum energy is limited by ambient magnetic field
- Ions and electrons share very similar spectra

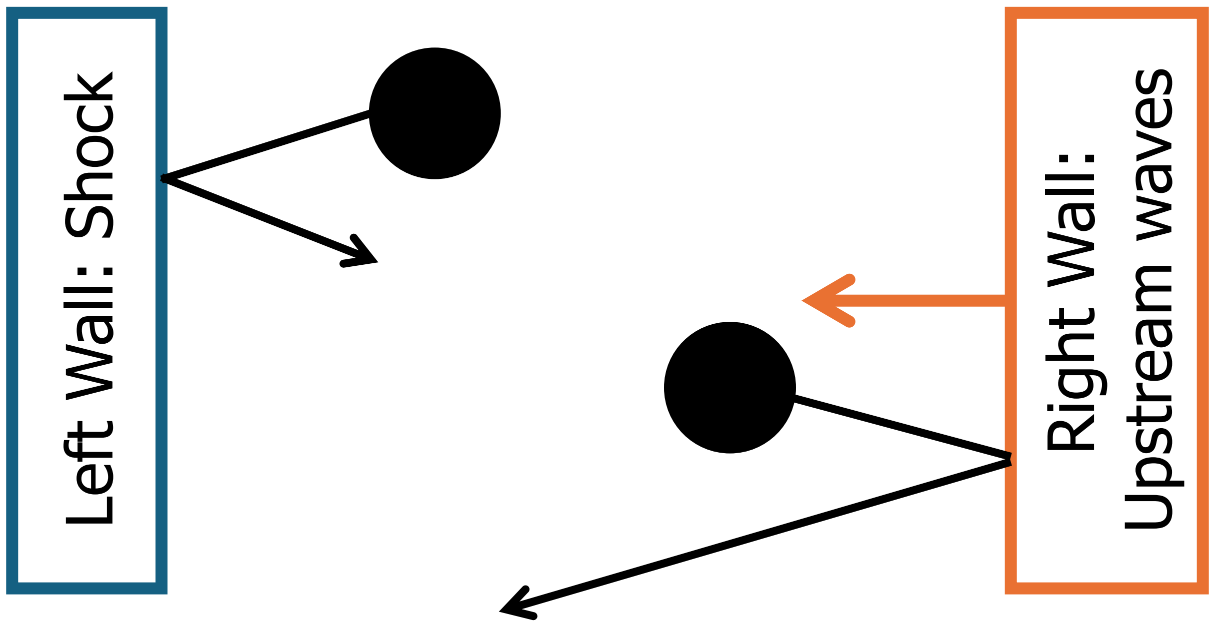


Upstream Frame



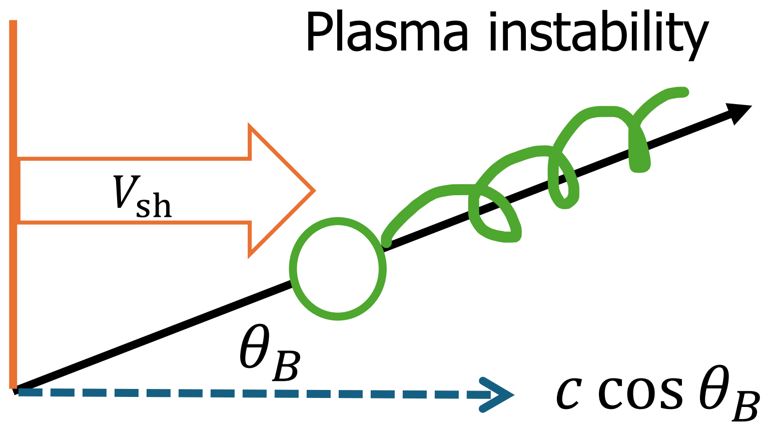
Shock Frame

Acceleration by Fermi Process



- Particle gain energy in between “contracting walls”
- In collisionless plasmas, magnetic fields act like the walls
- If subluminal, returning particles self-generate the right wall

Why Transrel? 1. UHECR



Subluminal: particles can outrun the shock
Generate plasma instabilities in upstream

Superluminal: shock always catch up
Advected downstream

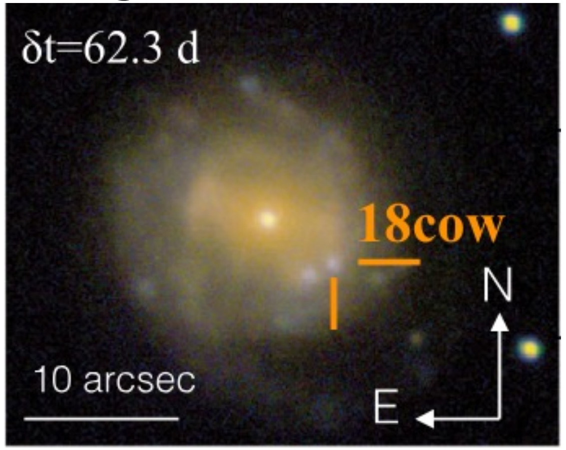
- Transrelativistic shocks can be subluminal
- Ambient magnetic field helps acceleration (opposite from ultrarel)

Why Transrel? 2. Variety in X-Ray

Late stage of GW170817 ~1200days
Shows clear signs of nonthermal electrons

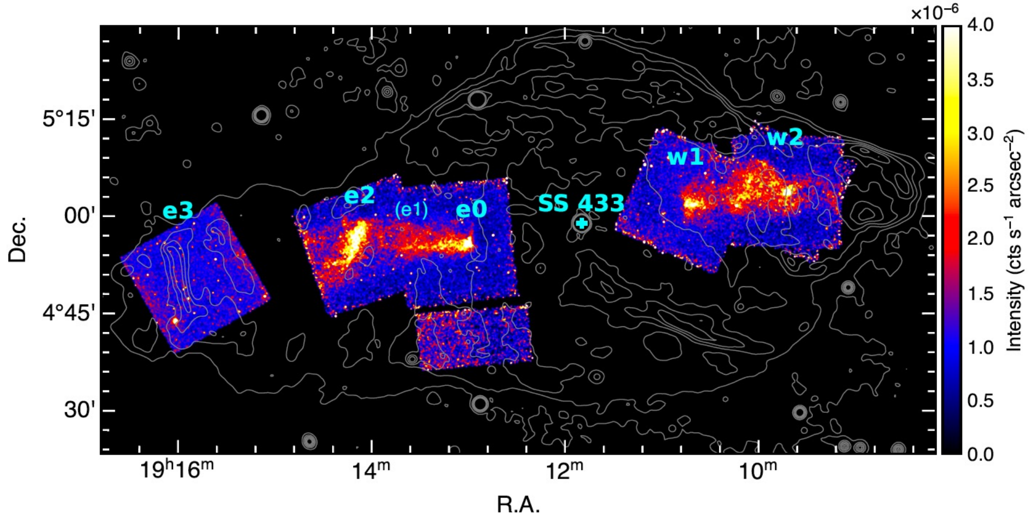
Haleja+2022

Margutti+2019



Radio emission from
FBOTs (AT 2018cow, AT 2020xnd, etc.)
suggest thermal electrons may be important

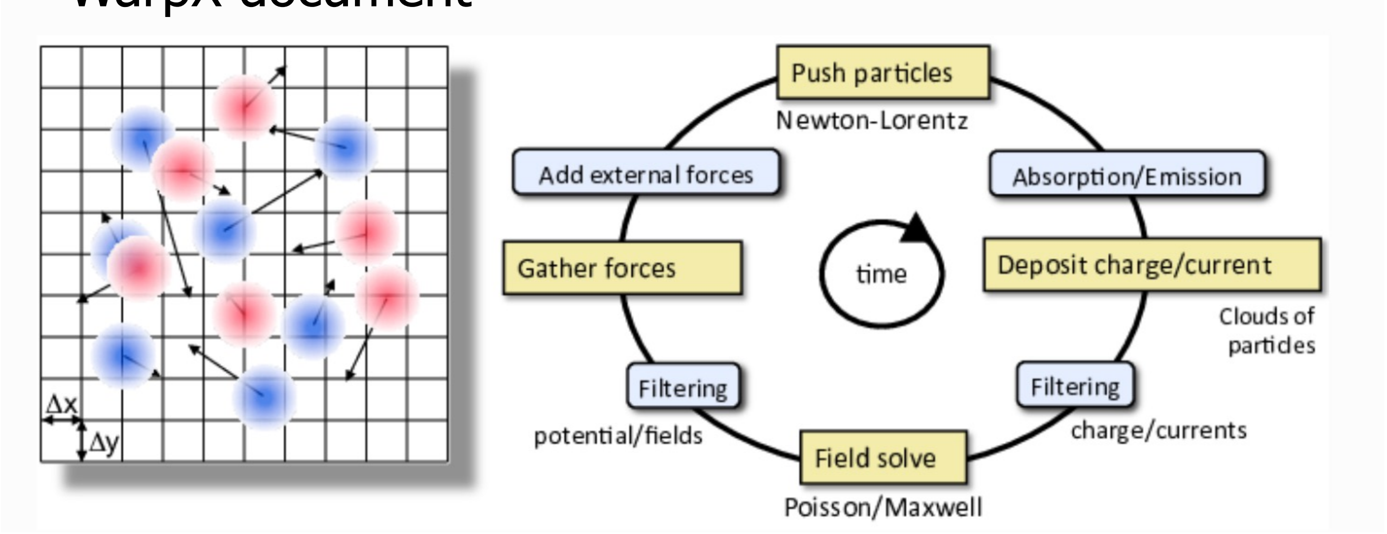
SS433: Always bright X-ray   Tsuji+2025



V4641 Sgr:
Only bright in X-ray during
outbursts every few years

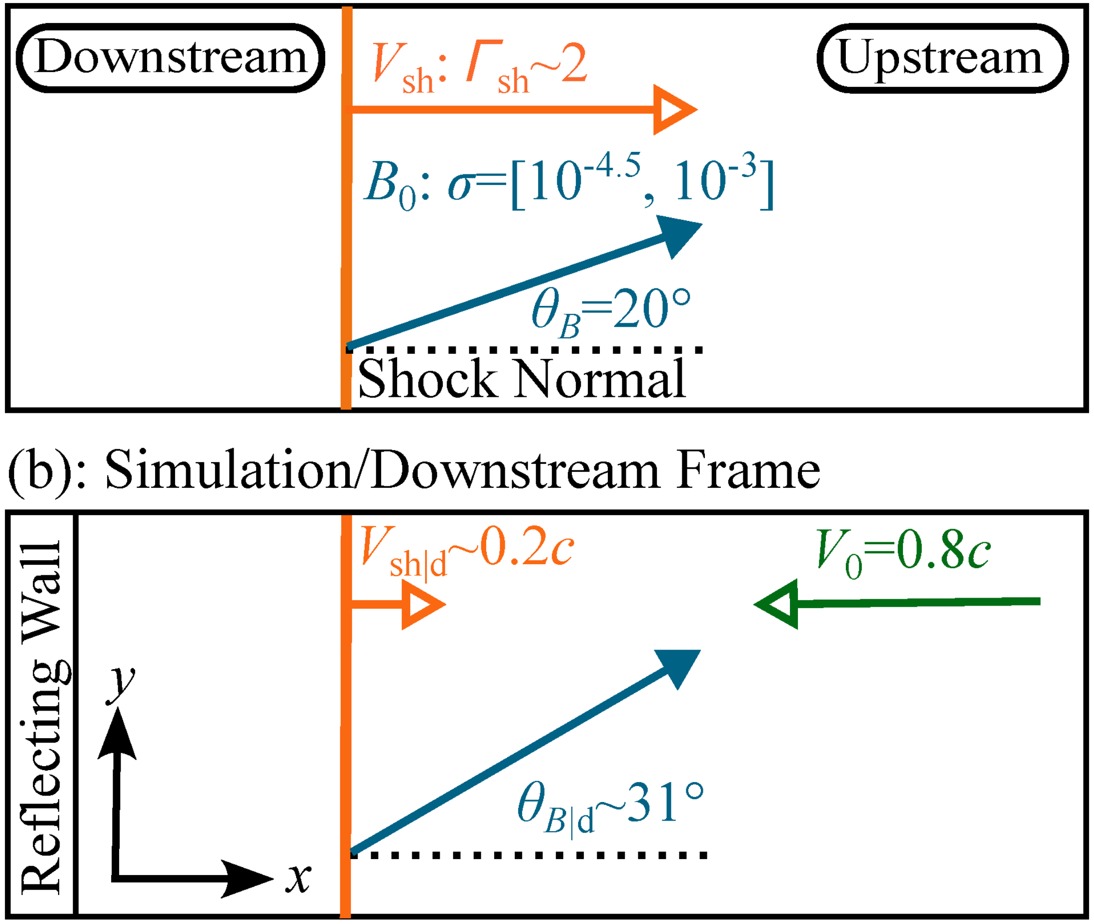
Particle-in-Cell (PIC) Simulations

WarpX document



(a): Upstream Frame

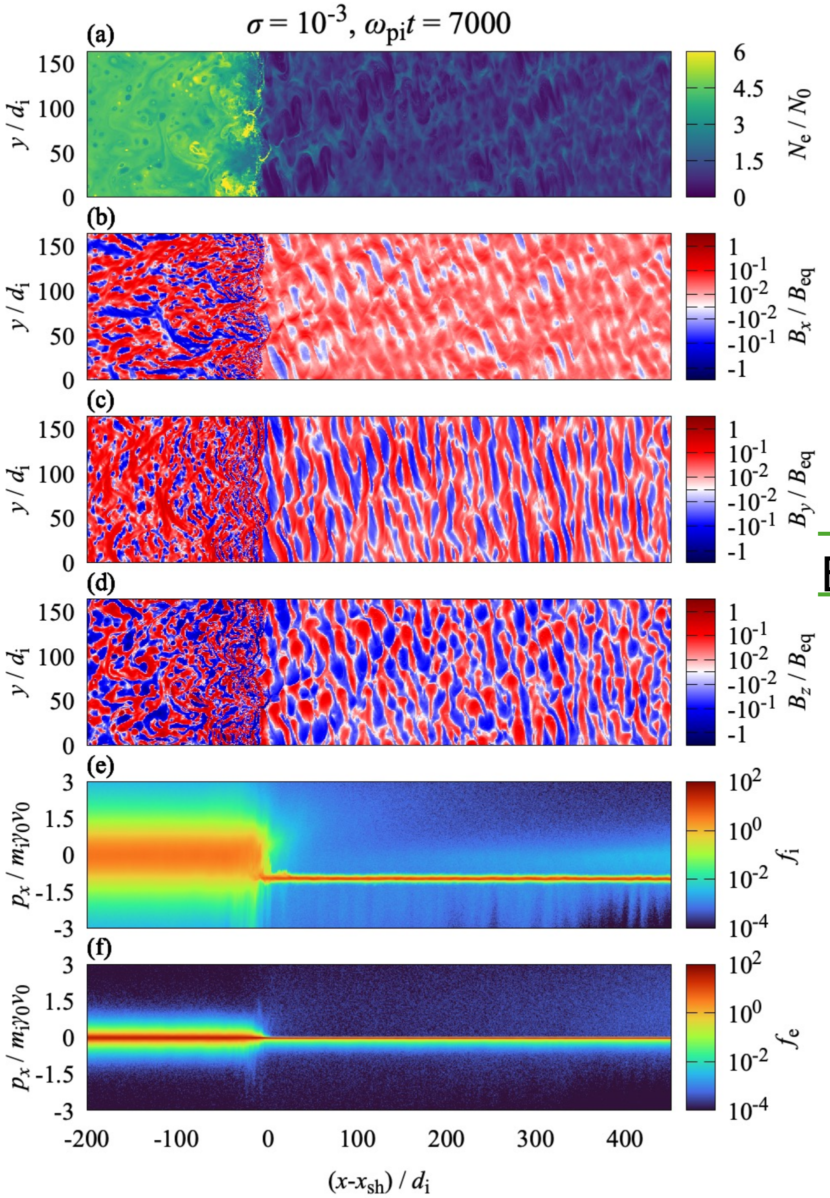
(b): Simulation/Downstream Frame



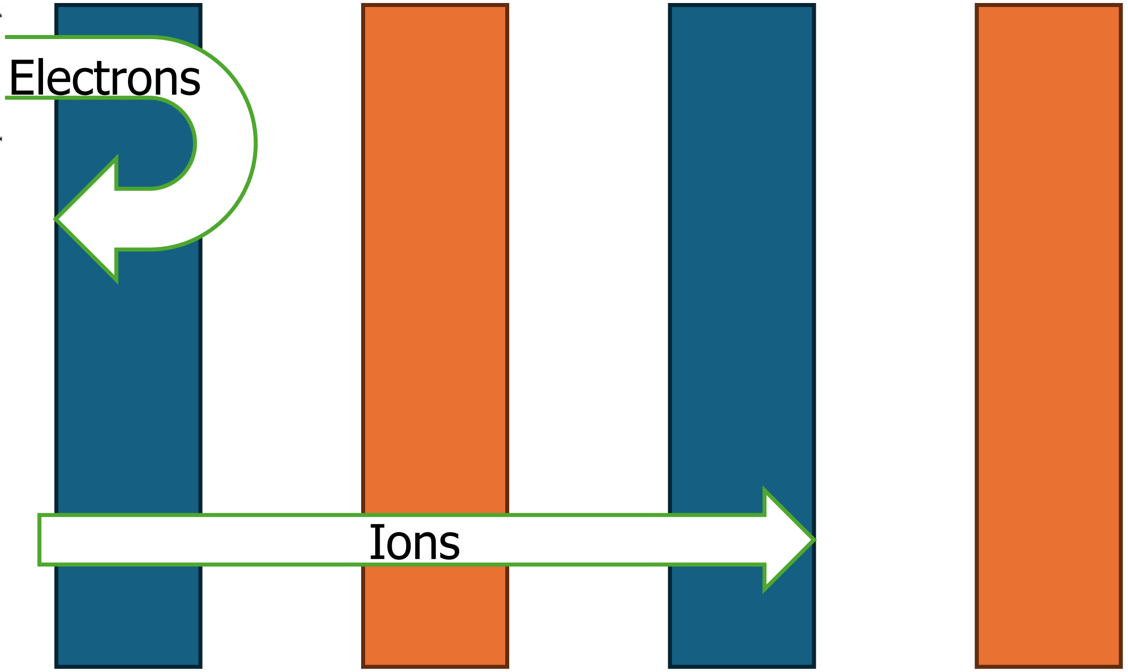
x_0: Shock Front

- Fully kinetic plasma simulation
- Self consistent magnetic field amplification and particle acceleration
- Solve both electrons and ions

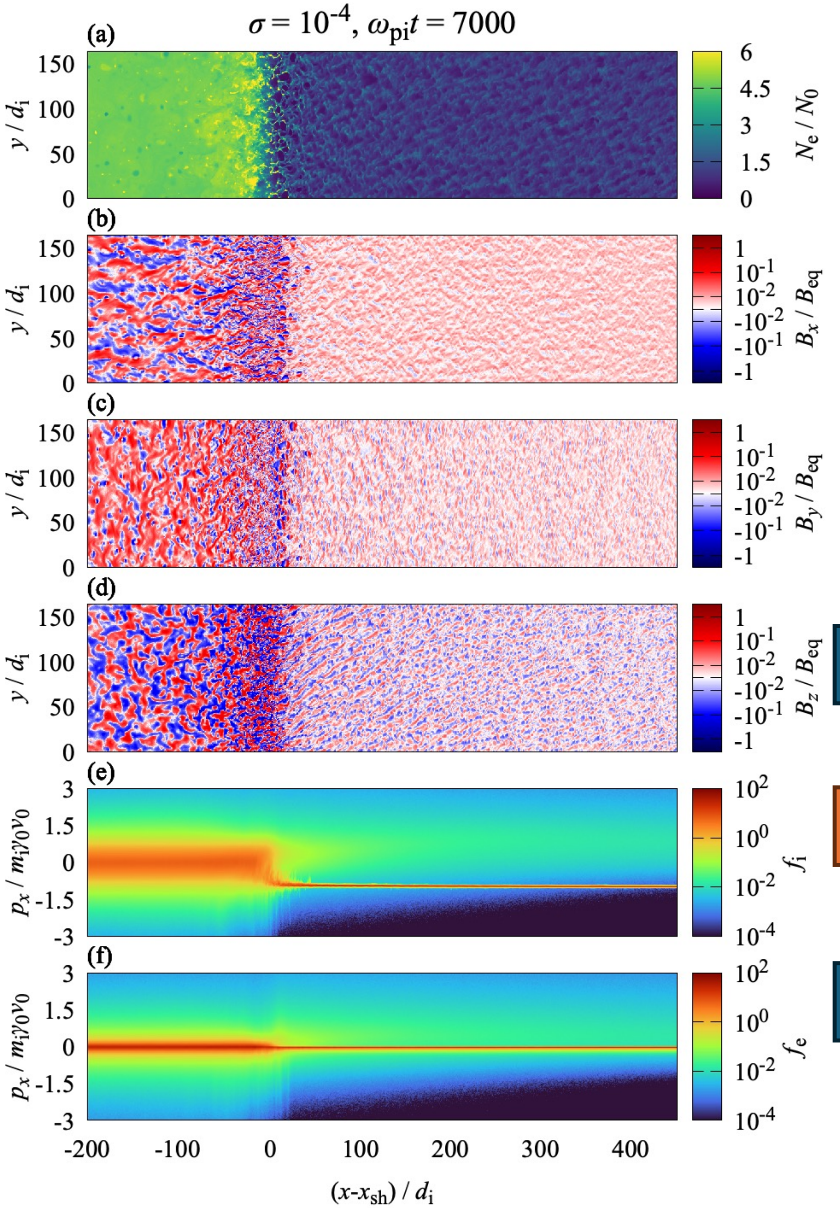
Bell-Dominated Regime: $\sigma = 10^{-3}$



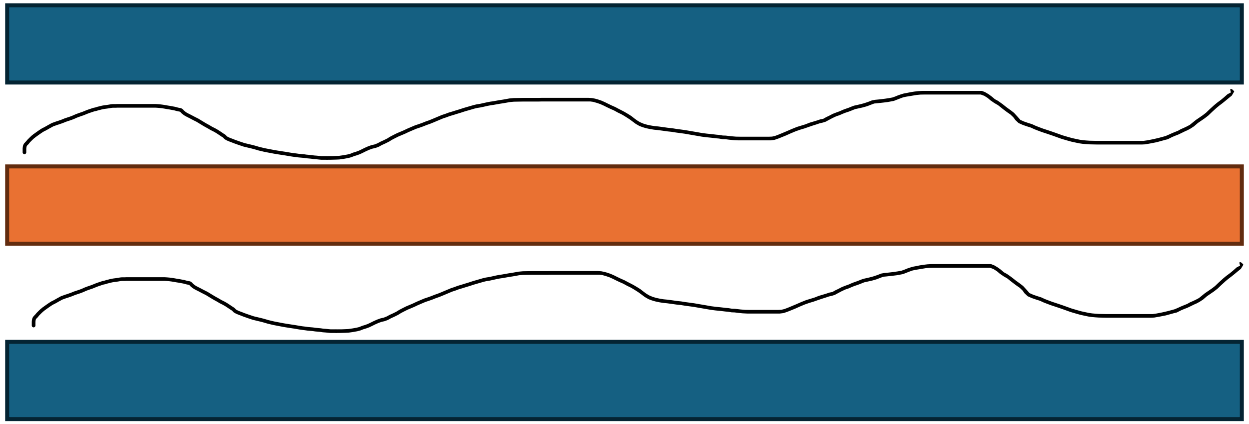
- Relatively large magnetization
- Bell instability: circular polarized, $\boldsymbol{k} \parallel \hat{\boldsymbol{B}}_0$
- Efficient ion acceleration
- Less non-thermal electrons in the downstream



Weibel-Dominated Regime: $\sigma = 10^{-4}$



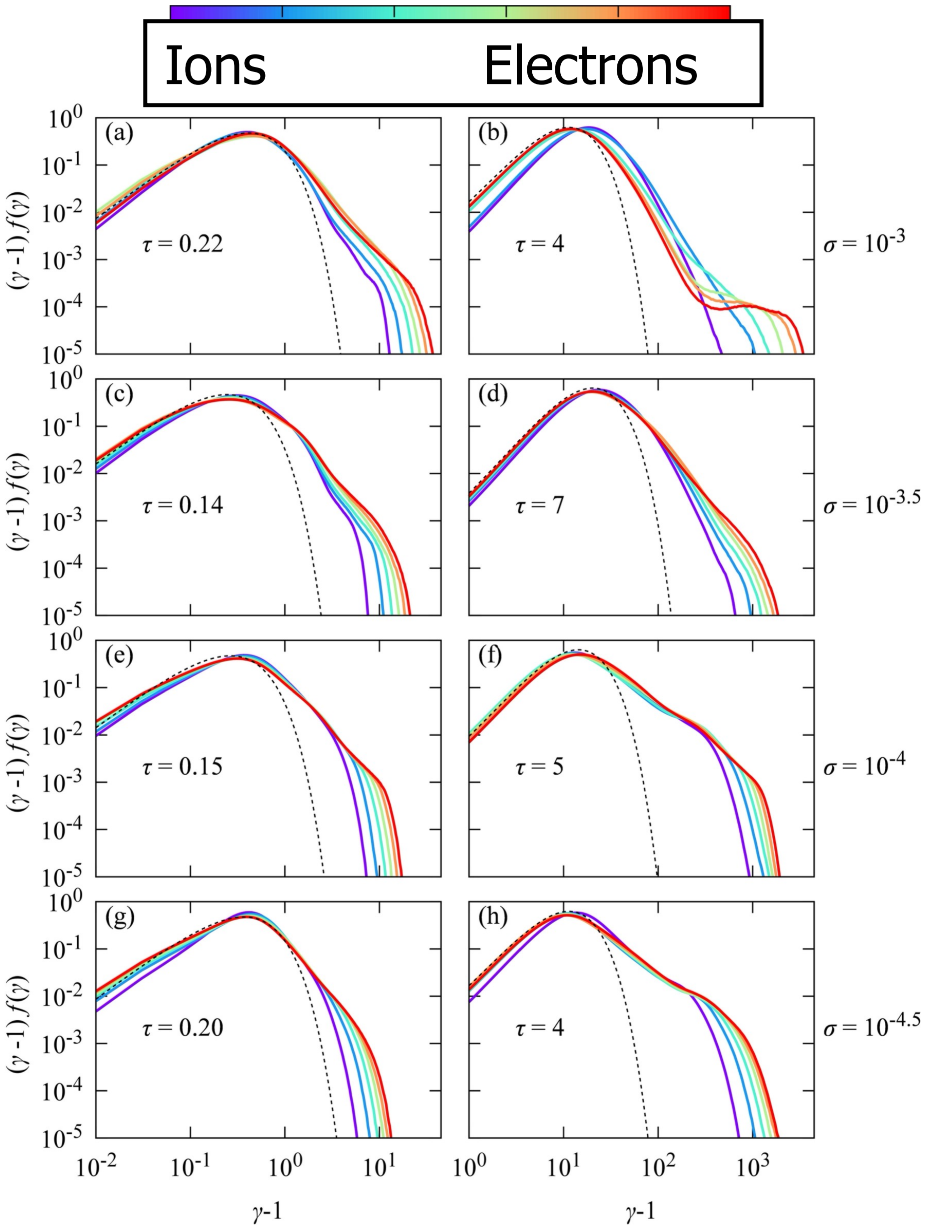
- Weibel-dominated at low magnetization
- Small scale magnetic field with $\boldsymbol{k} \perp \widehat{\boldsymbol{B}}_0$
- Accelerates both ions and electrons by small scale scattering
- Similar to ultrarelativistic unmagnetized shocks

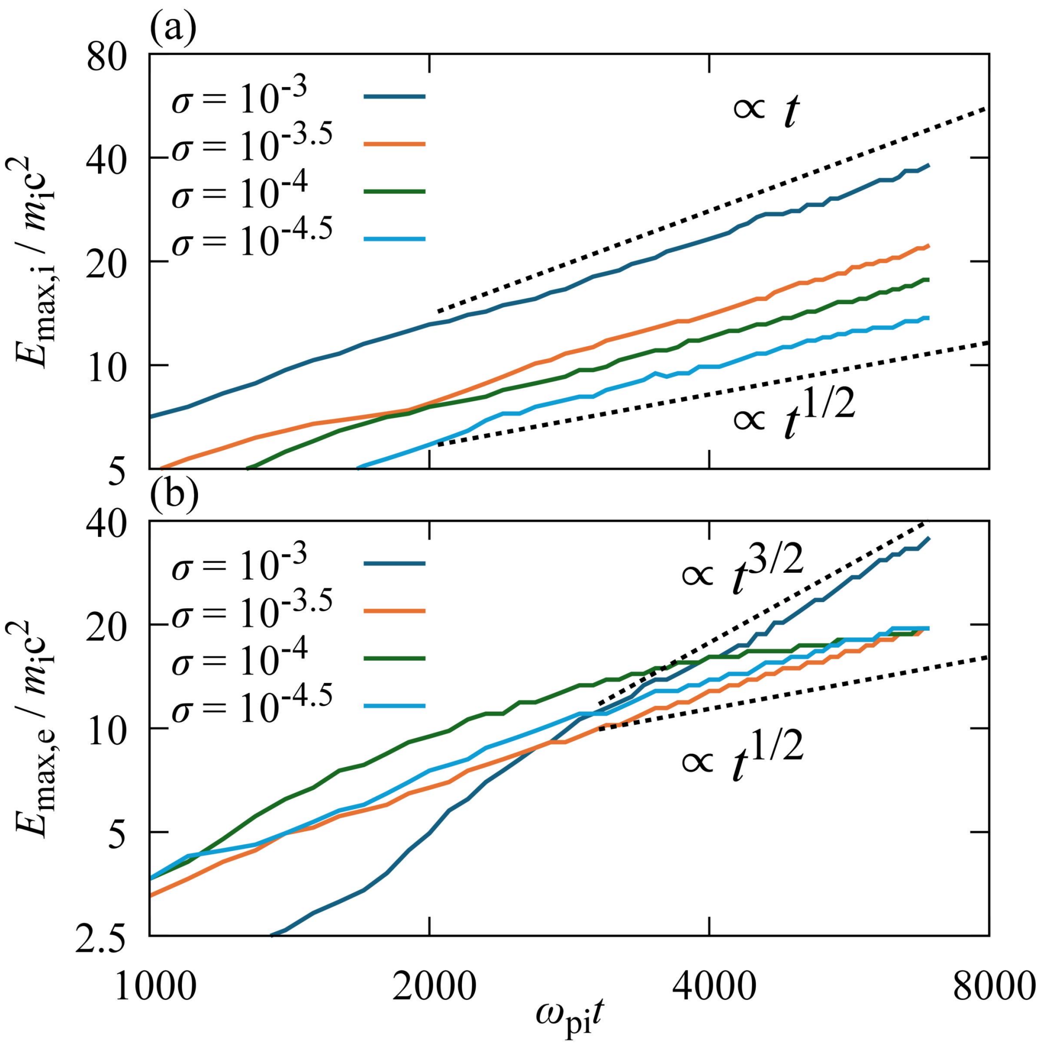


Particle Acceleration

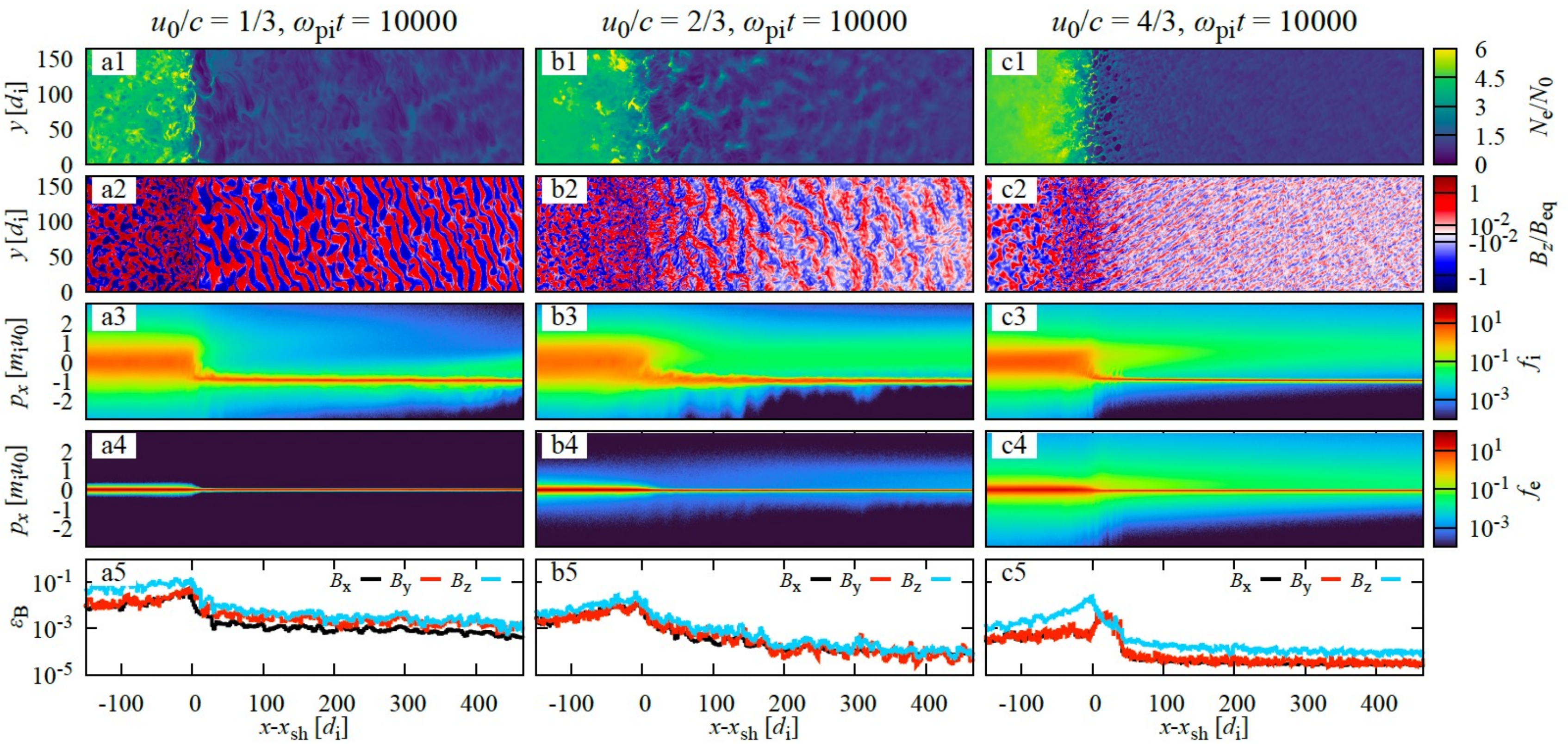
Bell:
Ions ◎
Electrons △

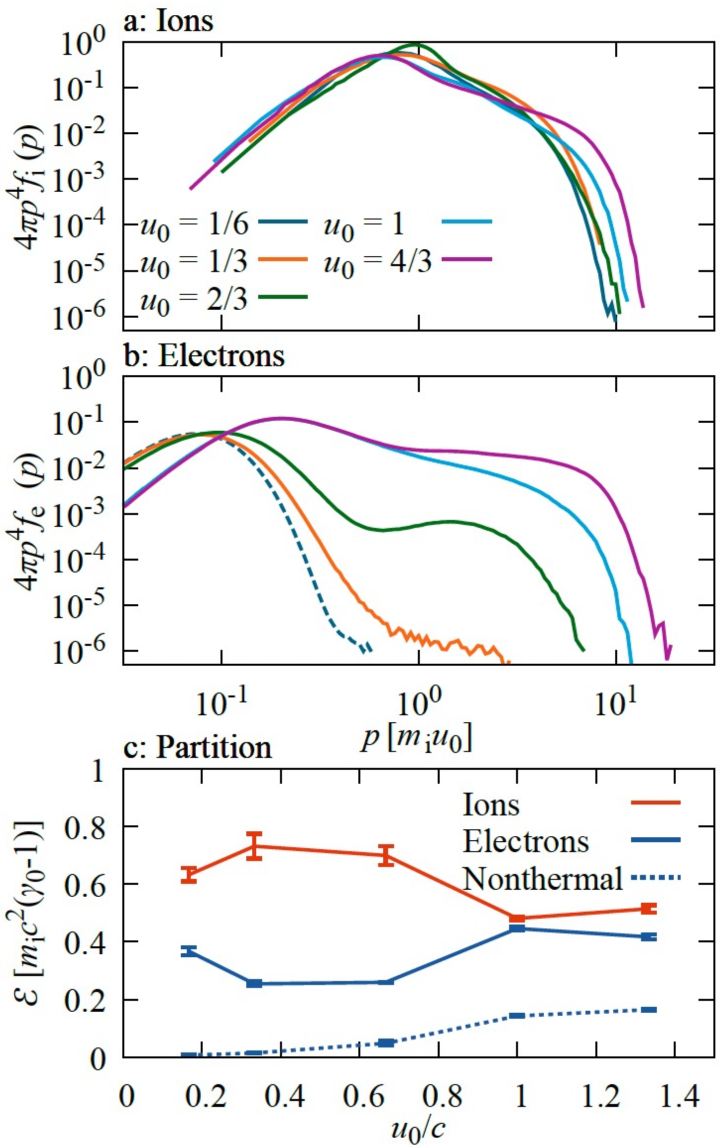
Weibel:
Ions ○
Electrons ○





Fixed Magnetization Variable Velocity





- Also shows transition from Bell to Weibel as shock velocity increases (in other words, Mach number increases)
- Qualitative difference in electron acceleration

Summary and Discussion

- Investigated magnetic field amplification and particle acceleration in transrelativistic shocks
- Low-Mach numbers (higher magnetization or lower velocities) prefer the Bell instability → Excellent ion accelerator
- Higher-Mach numbers (lower magnetization or faster velocities) are Weibel instability dominated → More electron acceleration

1. Strongly magnetized (still below unity) AGN jets are promising UHECR (protons) sources
2. Late-stages of short GRB afterglows should be Weibel-dominated, consistent with long-term observations of X-rays
3. Radio emission from some FBOTs can be thermal-electron dominated if they are Bell-dominated

Microquasars are Still Puzzling

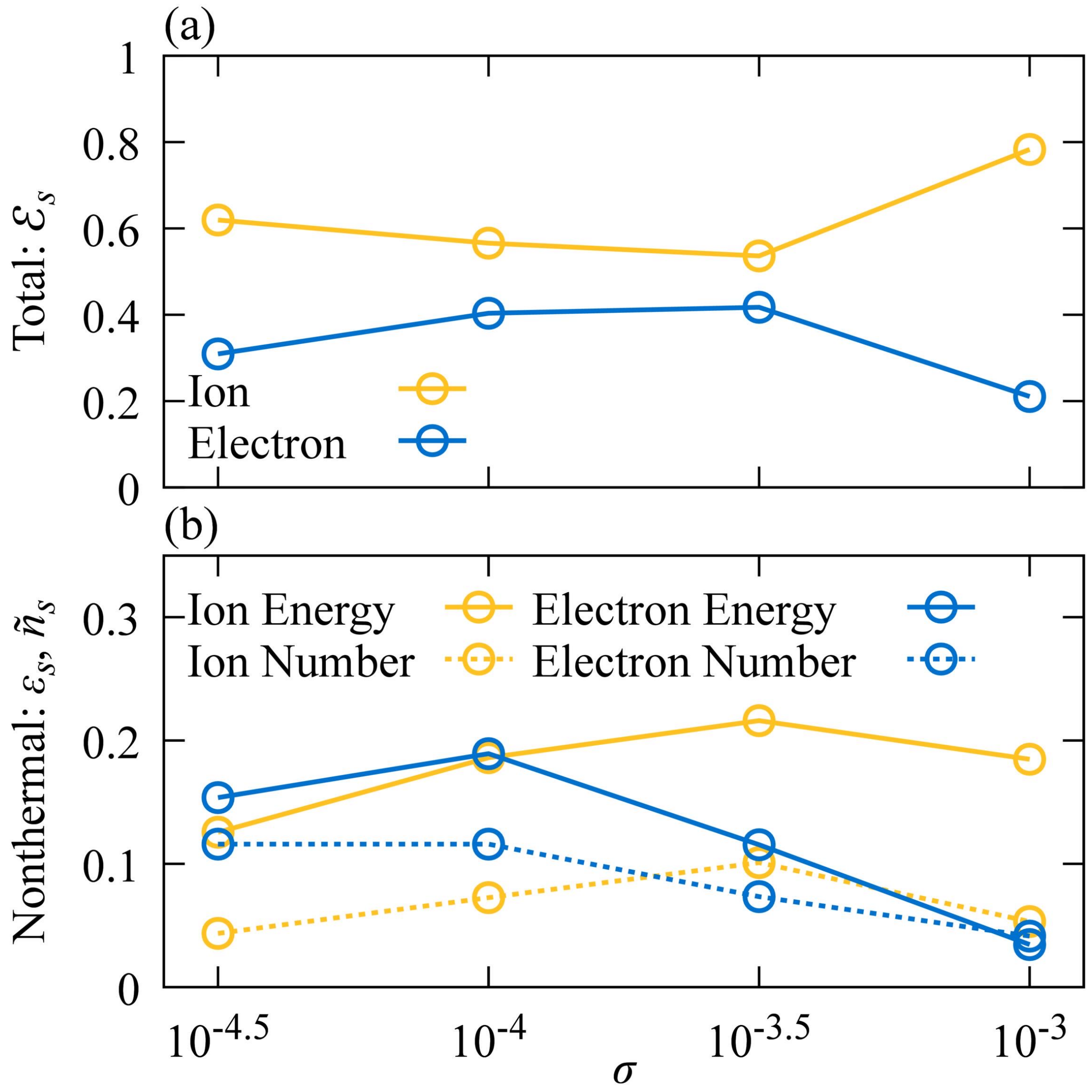
- Possible scenario

1. Gamma-rays have hadronic origin and $\sigma = [10^{-5}, 10^{-3}]$
2. V4641 have low Mach number in quiessent → Bell → Higher energy (800 TeV gamma-rays), only bright in X-rays when the shock velocity is faster (Weibel-dominated)
3. SS 433 are always Weibel dominated → Always bright in X-rays at the shock, slightly lower ion acceleration rate

- Recent observational and phenomenological works imply

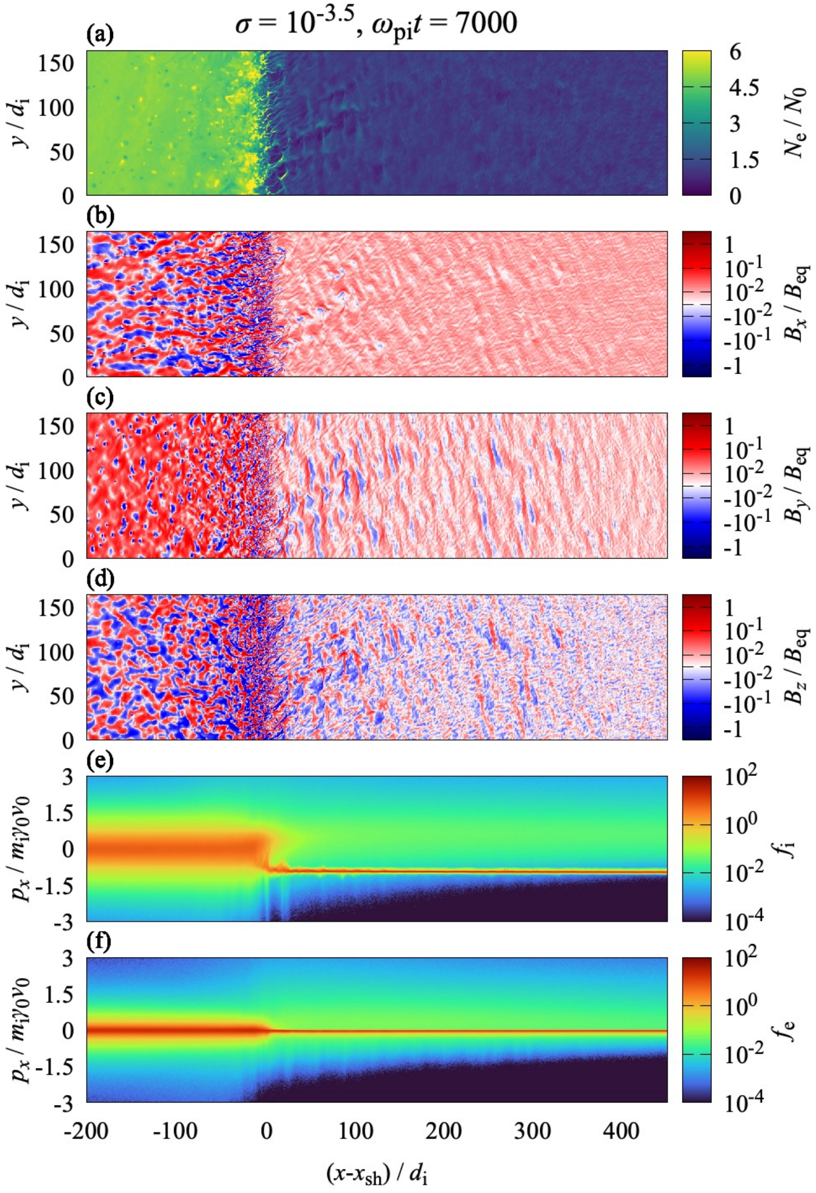
1. Gamma-ray emission may be leptonic
2. Acceleration is fast (may not be achieved by Weibel)
3. Magnetization may be much larger than 10^{-3}

Energy Partition in Fixed Velocity



- Total energy is near equipartition at $\sigma < 10^{-3.5}$, slightly less electron energy at $\sigma = 10^{-3}$
- Nonthermal ions always get ε_i~$0.1 - 0.2$ (different $E_{max}(t)$)
- Nonthermal electrons only dominate at low magnetizations

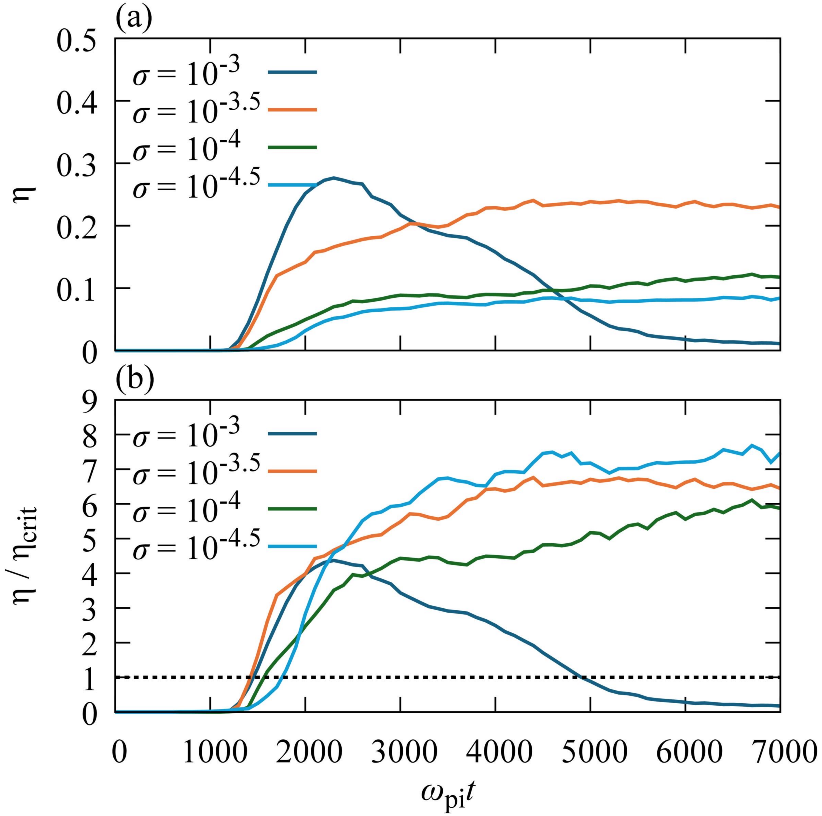
Intermediate Regime: $\sigma = 10^{-3.5}$

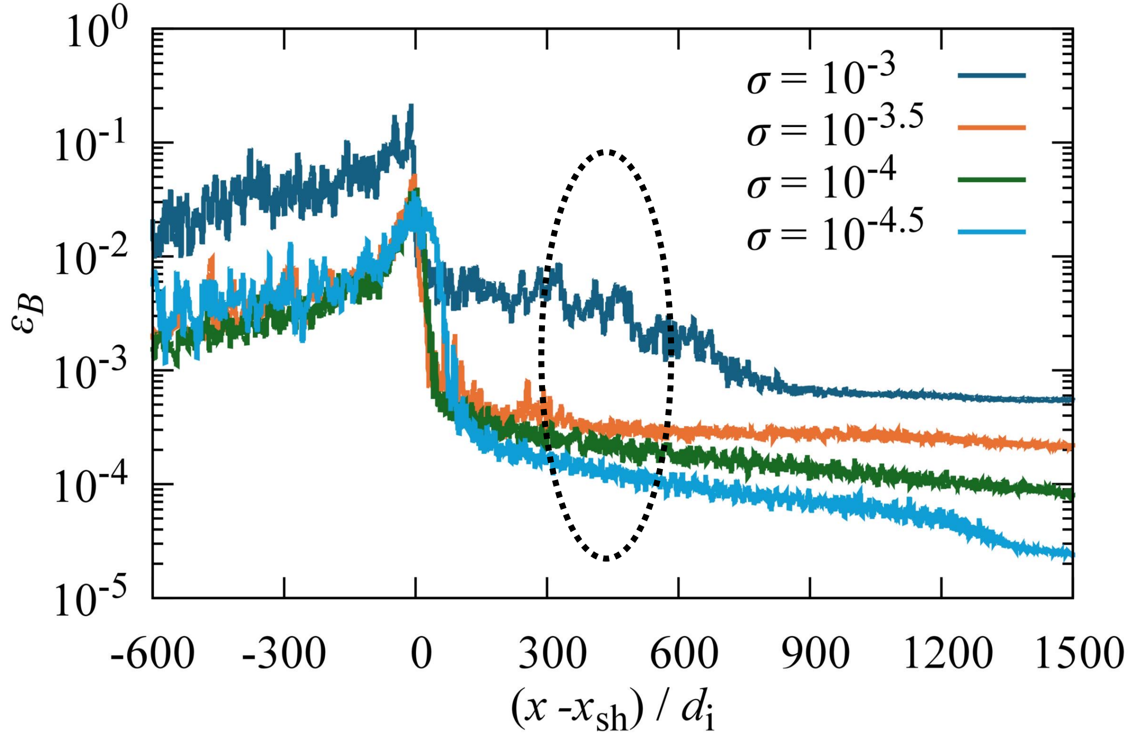


- Still looks like Bell in $B_y, \boldsymbol{k} \parallel \widehat{\boldsymbol{B}}_0$
- Amplitude is much smaller
- Bell's instability in the "high-current" regime (Weidl+2019, Lichko+2025)
- Bell becomes less efficient for smaller magnetizations
- Less ion vs. electron difference in downstream nonthermal particles

Upstream Condition

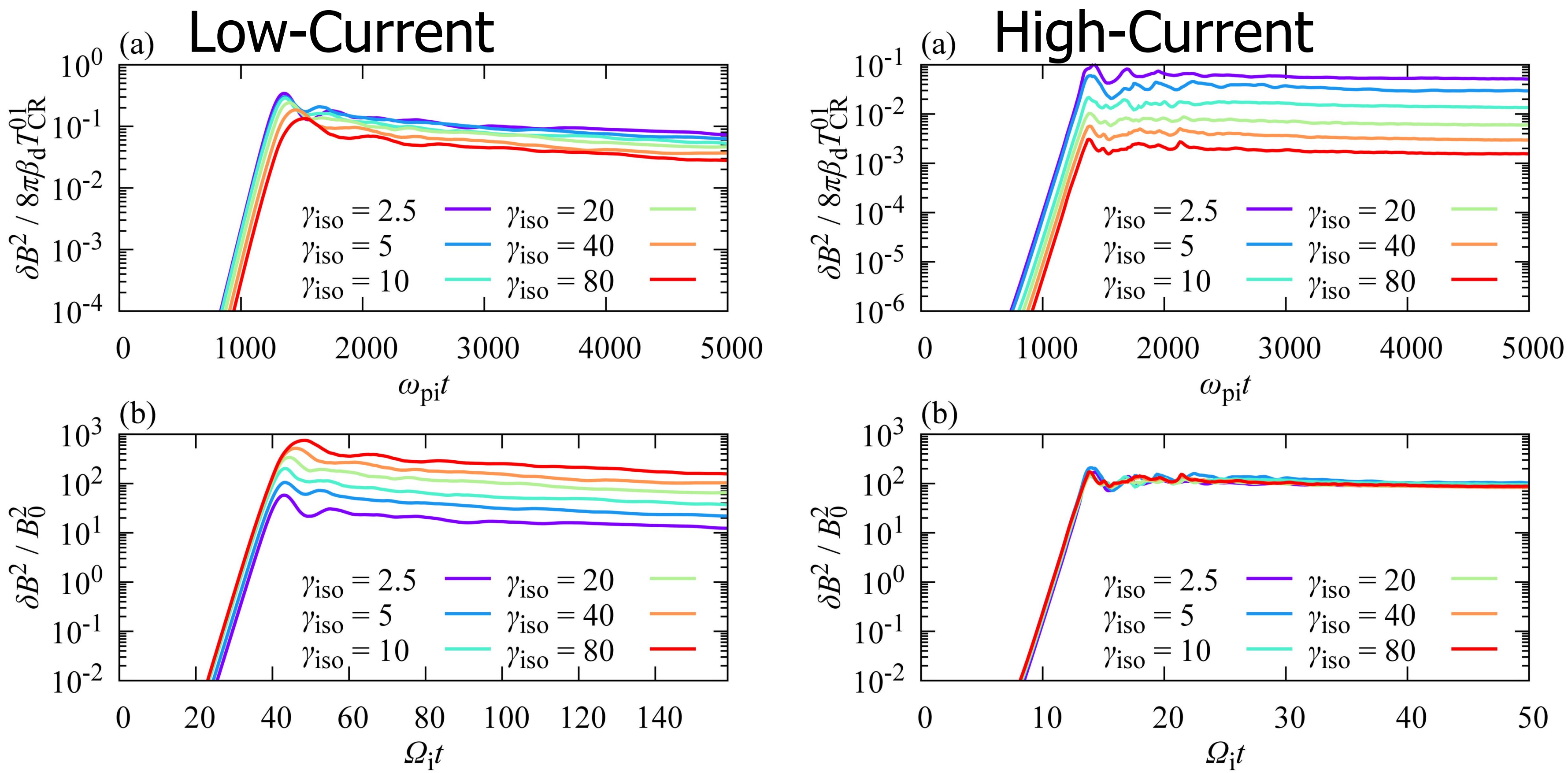
Low-current condition is essential for Bell





- Bell instability is efficient when driven slowly: $\Gamma_{\mathrm{Bell}} \ll \Omega_{\mathrm{i}}$
- Cosmic ray current condition: $\eta \ll \eta_{\mathrm{crit}} = 2\sigma^{1/2}$
- Only $\sigma = 10^{-3}$ case satisfies this condition
- Upstream magnetic field energy: $\varepsilon_B \gg \varepsilon_{B|\mathrm{Weibel}} \sim 10^{-4}$

Low-Current vs. High-Current Bell



- Bell instability is only efficient with low-current
- High-current Bell field is capped at fixed $\delta B / B_0$
- Weibel wins in low-magnetization environments