Cosmic Ray acceleration in oblique astrophysical shocks using combined PIC and PIC-MHD simulations

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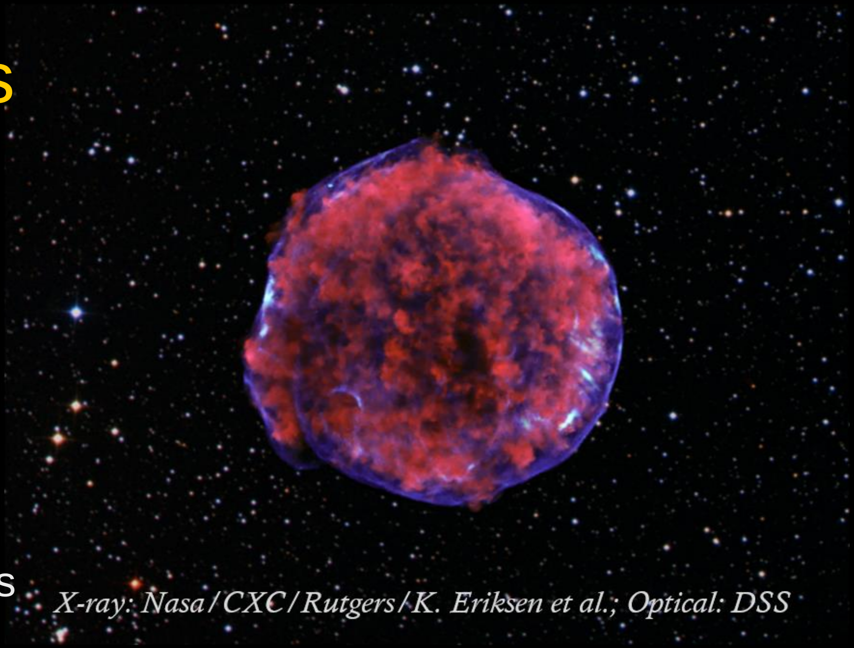
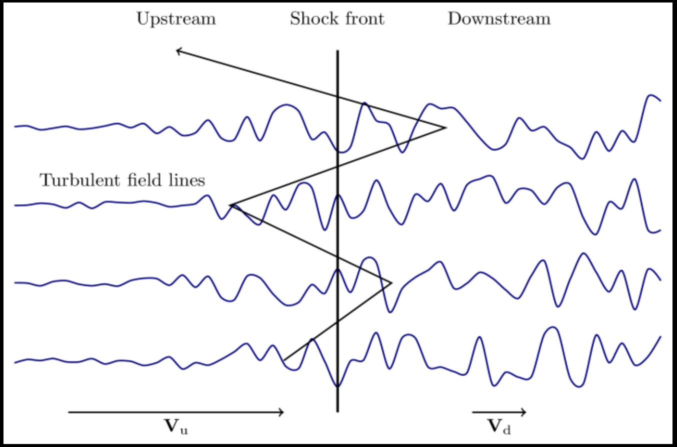
Acceleration of cosmic particles

- We know astrophysical shocks accelerate particles through Fermi 1 or diffusive shock acceleration (DSA). We observe them as cosmic rays.
- This process is self-induced and self-sustaining:
  - The presence of non-thermal particles triggers instabilities in the upstream magnetic field.
  - These instabilities then reflect particles across the shock, accelerating them further
  - The wavelength of the instabilities scales with the current, so the instabilities grow to match the energy of the particles
- What do we need to model this process computationally?
  - Astrophyiscal shocks are large-scale structures (AU-Mpc)
  - Particle acceleration involves micro-physics



X-ray: Nasa/CXC/Rutgers/K. Eriksen et al.; Optical: DSS



courtesy of Dr. Mark Pulupa's space physics illustration

Magnetohydrodynamics vs. Particle-in-cell

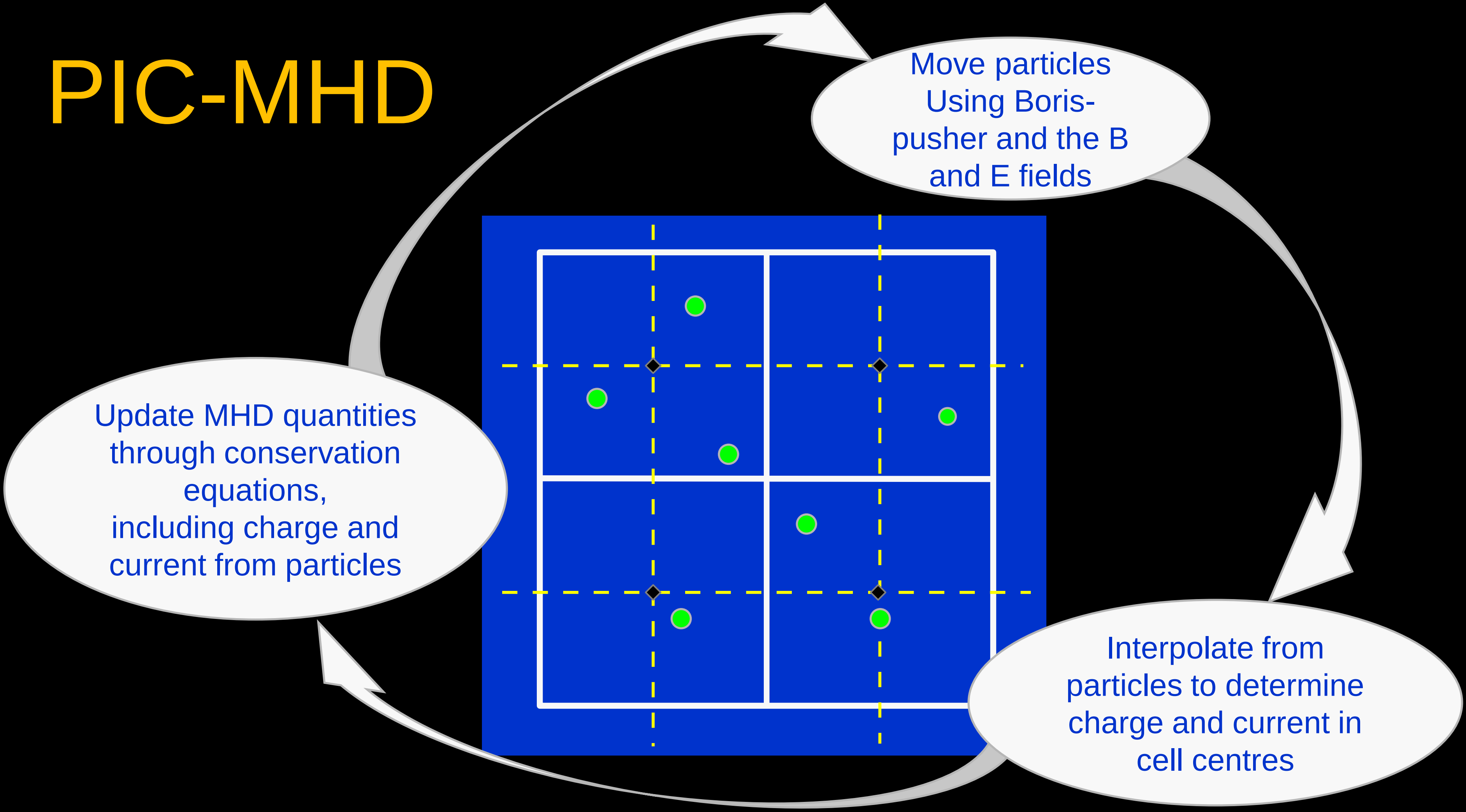
- Magnetohydrodynamics (mhd)
  - Based on statistical averages (mass-, momentum- & energy-density)
  - Good at large scale simulations
  - Computationally efficient
  - Cannot simulate micro-physics

- Particle-In-Cell (PIC)
  - Based on individual particles
  - Can simulate micro-physics
  - Can simulate non-thermal plasma
  - Computationally expensive on large scales
  - Numerical noise (Cherenkov waves)

We need aspects of both

PIC-MHD can accomplish this by treating the thermal plasma as a fluid and the non-thermal gas as particles

PIC-MHD



Move particles
Using Boris-pusher and the B and E fields

Interpolate from particles to determine charge and current in cell centres

Update MHD quantities through conservation equations,
including charge and current from particles

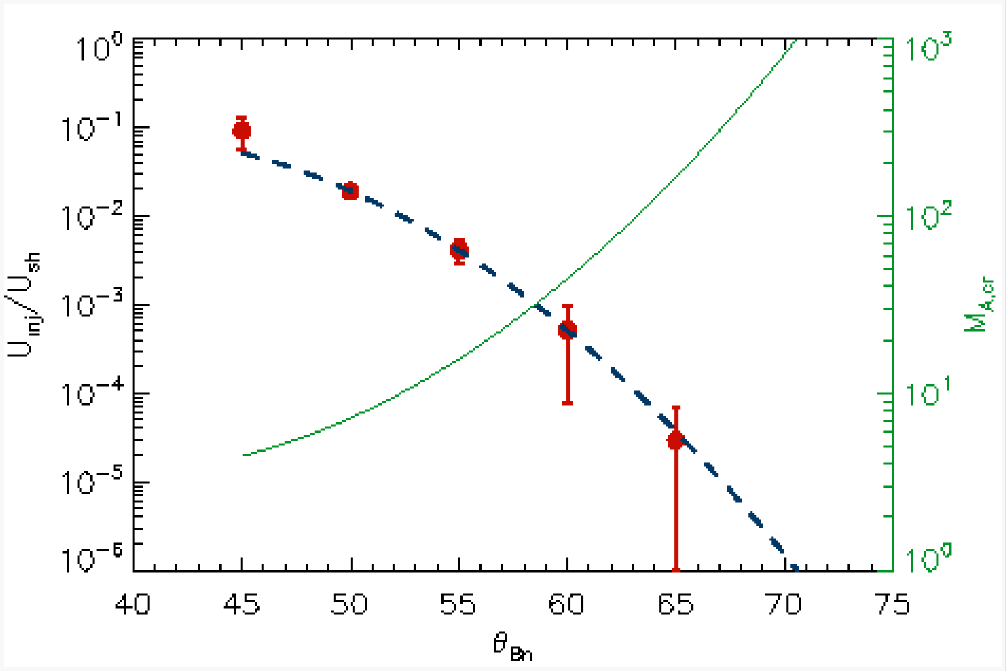
Constrained transport ensures div.B=0
MHD cell-centres function as PIC cell-corners

The influence of shock-obliquity

- Hybrid-PIC simulations (*Caprioli & Spitkovsky 2014, Haggerty & Caprioli 2019*) show NO B-field amplification or particle acceleration should occur at angles > ~60º.
- According to PIC-MHD simulations (van Marle et al. 2018) both happen, owing to long-wavelength instability that could not be captured by the hybrid-PIC simulations
- However,
  - the PIC-MHD simulation does not model internal structure of shocks
  - It relies on ad-hoc description of injection rate of non-thermal particles at shock front
  - van Marle et al. 2018 used injection fraction identical to that of parallel shock
- To improve the PIC-MHD results we need a 2-stage approach: use PIC to determine the injection fraction, then use PIC-MHD to follow the long-term evolution of the gas.

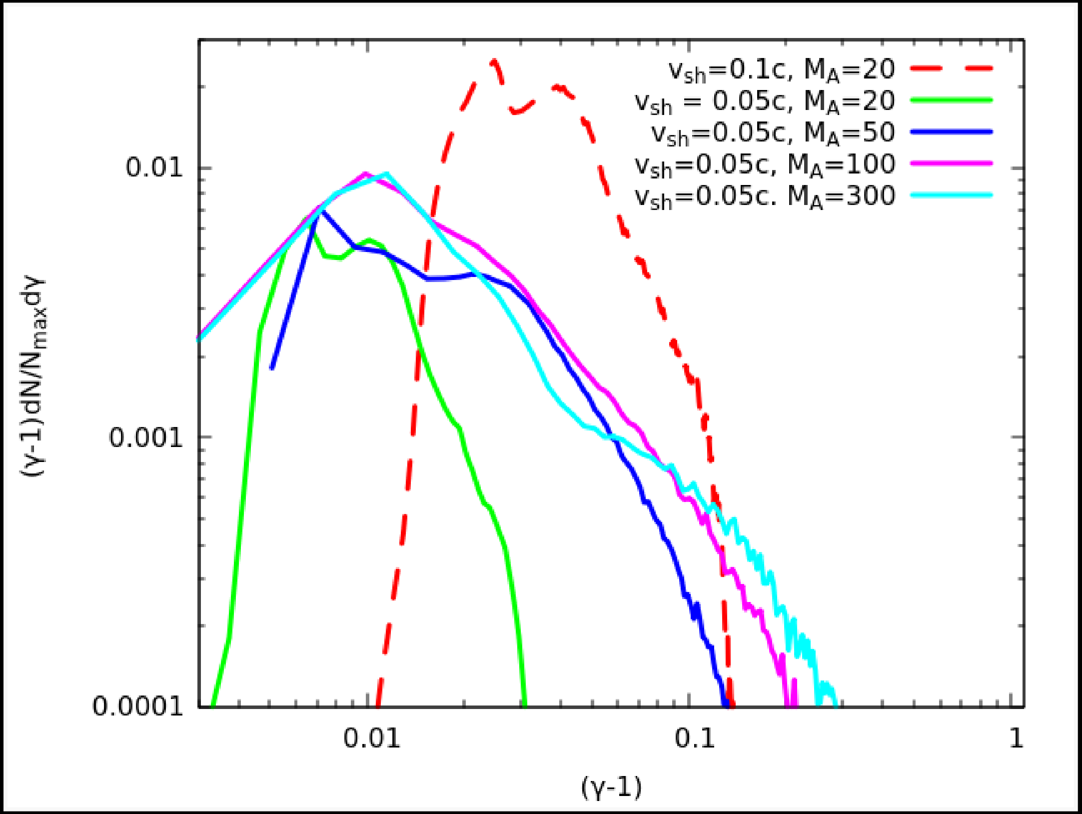
PIC results

- Assumption:
    - $U_{inj} > U_B$ to trigger instabilities
- 2-D simulations
- Θ_B =45-70
- Injection rate decrease rapidly
    - particles require higher velocity to move upstream
- At Θ_B =60, $n_{inj} \approx 5x10^{-5}$
    - (reflected into upstream medium)



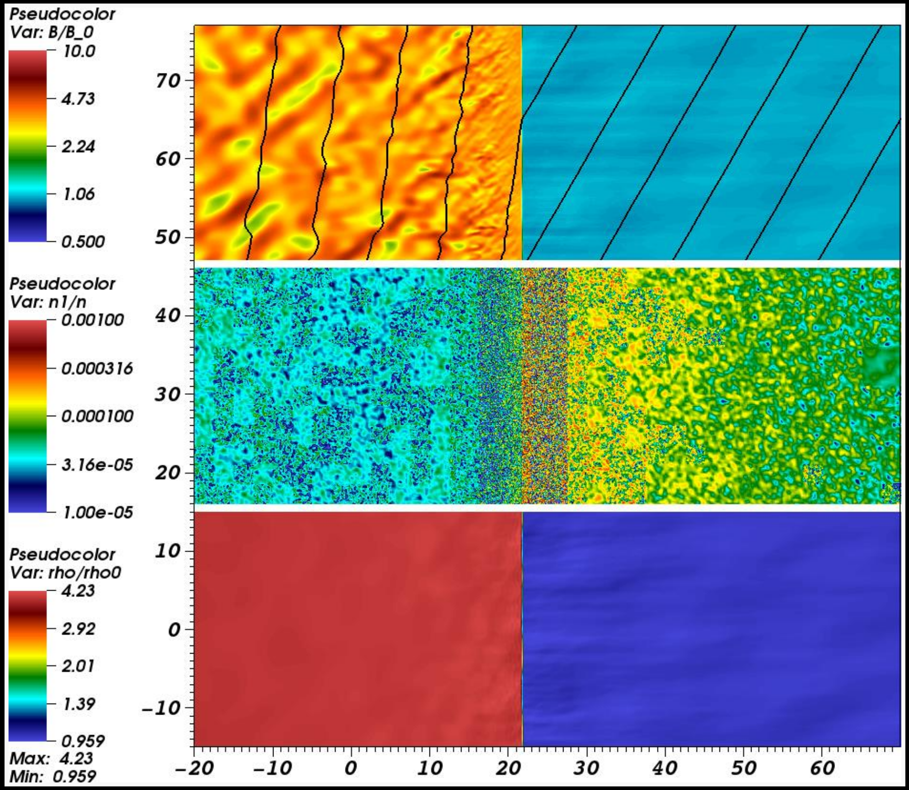
PIC-MHD results

- PIC-MHD simulations
  - Large-scale 2-D box
  - Inject at $n_{inj}=1\times10^{-4}$ (isotropically)
  - $\theta_B = 60^o$
- Constant gas parameters except for variation in M_A
- No significant DSA at $M_A=20$
- Start of DSA at $M_A=50$
- Efficiency increases with M_A



The characteristics of the plasma

- Plasma characteristics for the M_A=300 simulation:
  - Magnetic field amplification is low
  - Distortion of the upstream magnetic field is very small
- Therefore:
  - a large simulation box is required or particles will escape upstream before they can be reflected back toward the shock!



Conclusions

- The injection rate of non-thermal particles decreases rapidly for shocks with obliquity of 50+ degrees
- Particles can only trigger the streaming instability if the energy of the upstream particle flow exceeds the local magnetic field energy
- Therefore, only oblique shocks with a high Alfvénic Mach number are likely capable of triggering DSA .
- At 60 degrees, we need $M_A \geq 50$. At 70 degrees, we would need $M_A \approx 1000$