Modelling the interaction between an $e^- - e^+$ beam and a thermal plasma

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Origin of gamma-ray halos

- Observations by HESS (*Abdalla et al. 2013*) and HAWC (e.g. *Abeysekara et al. 2017*) show TeV halos around young & middle-aged pulsars
- This indicates local diffusivity for high energetic particles is low compared to the ISM
- Likely explanation: high turbulence. But why?
- One explanation: Turbulence is self-induced by the high-energy particles (Evoli et al. 2018)
- We intend to test this theory numerically.

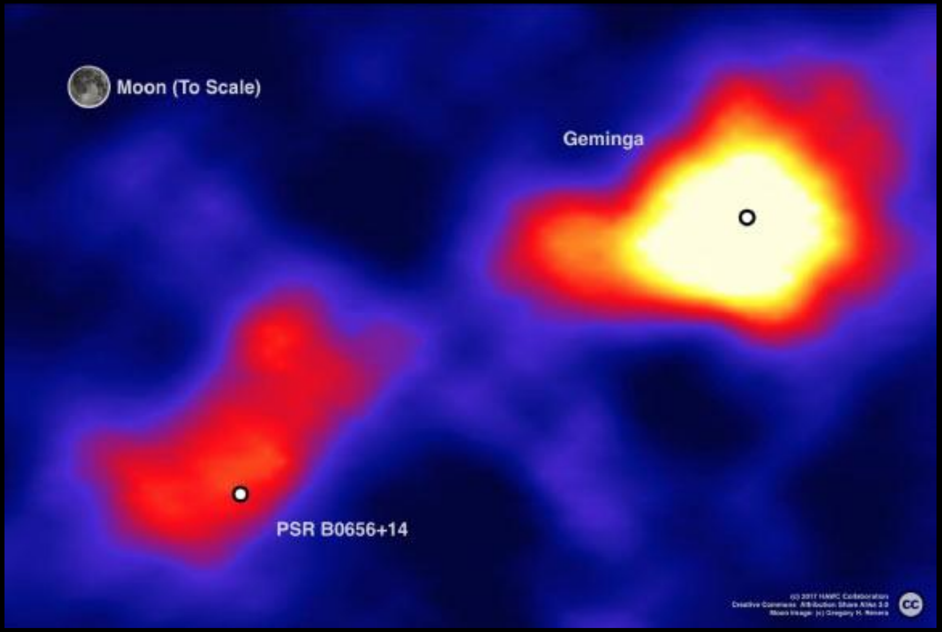


Image credit J. Pretz

Modelling interaction between non-thermal particles and the thermal gas

- We know non-thermal particles can trigger instabilities and turbulence in a local magnetic field (E.g. Bell 2004)
  - (This is the same process that induces Fermi 1 particle acceleration in shocks)
- Whether this occurs would depend on the energy density of the non-thermal particles
- We need numerical models of this process to determine whether it is a viable solution.
- The problem: While astrophysical structures tend to be large, the interaction between particles and a local magnetic field involved physics on a micro scale. This creates a numerical problem.

Magnetohydrodynamics
vs.
Particle-in-cell

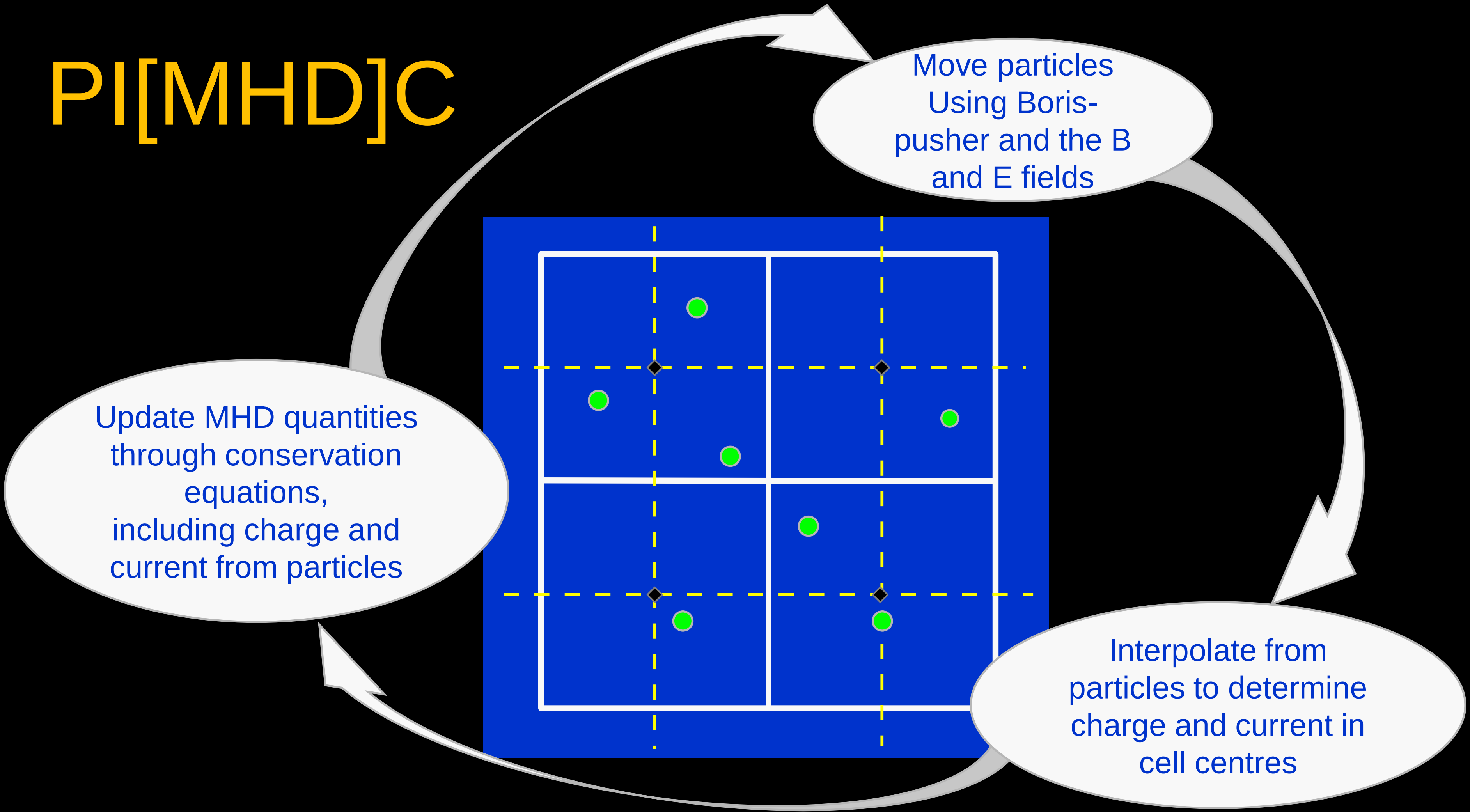
- Magnetohydrodynamics (mhd)
  - Based on statistical averages (mass-, momentum- & energy-density)
  - Good at large scale simulations
  - Computationally efficient
  - Cannot simulate micro-physics
- Particle-In-Cell (PIC)
  - Based on individual particles
  - Can simulate micro-physics
  - Can simulate non-thermal plasma
  - Computationally expensive on large scales
  - Numerical noise (Cherenkov waves)

We need aspects of both

Introducing Particles in MHD Cells (PI[MHD]C)

- Basic assumption: The gas can be described as a thermal plasma with a small, non-thermal component
- We split the work:
  - MHD code (MPI-AMRVAC, *Keppens et al. 2012*, https://homes.esat.kuleuven.be/~keppens/) describes the thermal plasma, particles represent the supra-thermal component
    - The MHD grid serves as cells for the PIC
    - Lorentz force gives us the effect of electromagnetic field on particles
    - Effect of supra-thermal particles on thermal plasma can be treated through Ohm's law (*Bai et al. 2015*)
- Advantages
  - ✓ Can simulate particle acceleration and feedback (unlike MHD)
  - ✓ No need for a huge particle population that represents the thermal gas (unlike PIC)
- Disadvantages
  - Limited regime: $n_{thermal} >> n_{non\text{-}thermal}$
  - Some restrictions owing to use of grid-MHD
    - In particular:it cannot model the transition from non-thermal to thermal so, the injection rate has to be parametrized.

PI[MHD]C



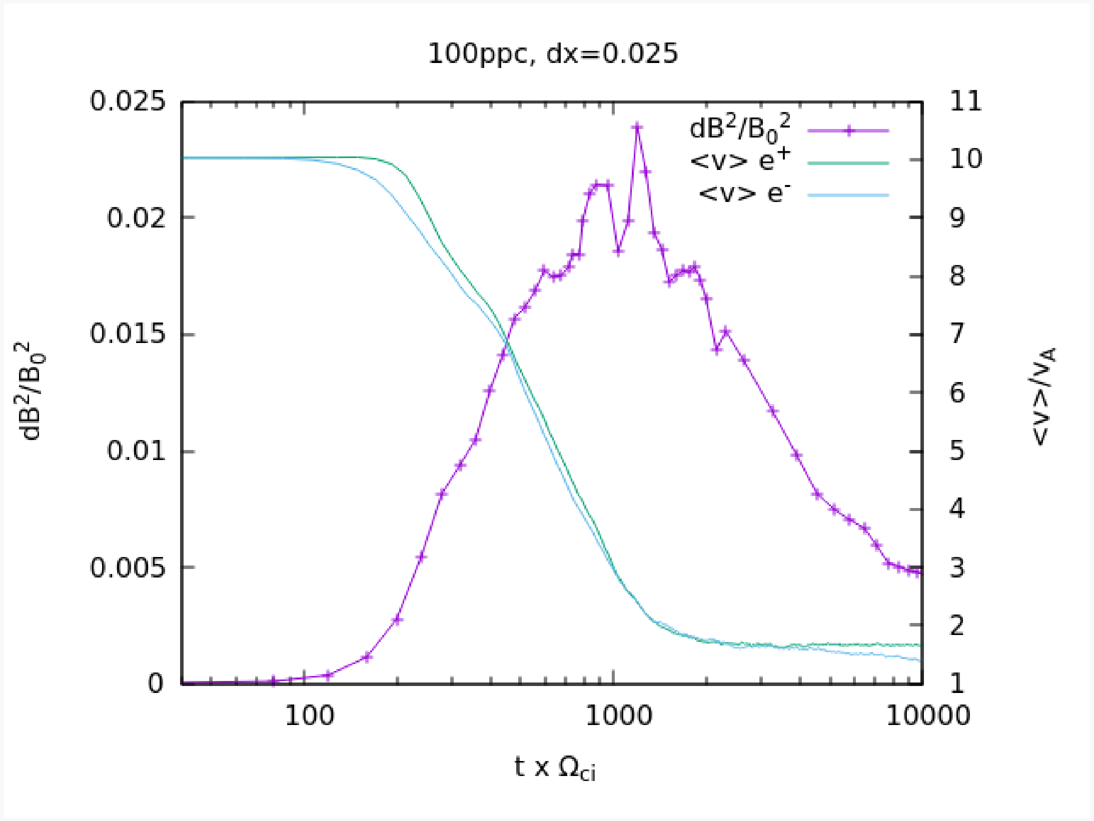
Applications of the code shown in:
van *Marle Casse & Marcowith 2018 ‘19*, &
van Marle 2020)

Testing the concept

- Setup, based on initial PIC runs using the SMILEI (Derouillat et al. 2018) code :
  - Homogeneous thermal background
  - Alfvén speed: 0.01c
  - Injection of e^+ -e^- beam
  - Particle density ratio beam/background gas = 10^{-2}
  - Drift speed: 0.1c
  - Beam temperature T=10 $m_e c^2$ (Maxwell-Juttner distribution)
  - $m_p/m_e = 100$
  - dx = 0.025 R_l, 100 particles per cell
- Expected saturation (Bai et al. 2019)
  - $\left(\frac{\delta B^2}{B^2}\right) \sim \left(\frac{8}{3}\right)\left(\frac{<p>}{m_e c}\right)\frac{n_e}{n_B}\left(\frac{V_D}{V_a} - 1\right)\frac{m_e}{m_i}$
  - For our input, we expect saturation at: $\left(\frac{\delta B^2}{B^2}\right) \approx 0.024$

PI[MHD]C: B-field amplification and beam deceleration

- The e^+-e^- beam loses kinetic energy
- Magnetic energy increases to expected saturation levels
- Difference between e^+ and e^- velocity (Matches results obtained with SMILEI PIC code)



PI[MHD]C: B-field amplification and beam deceleration

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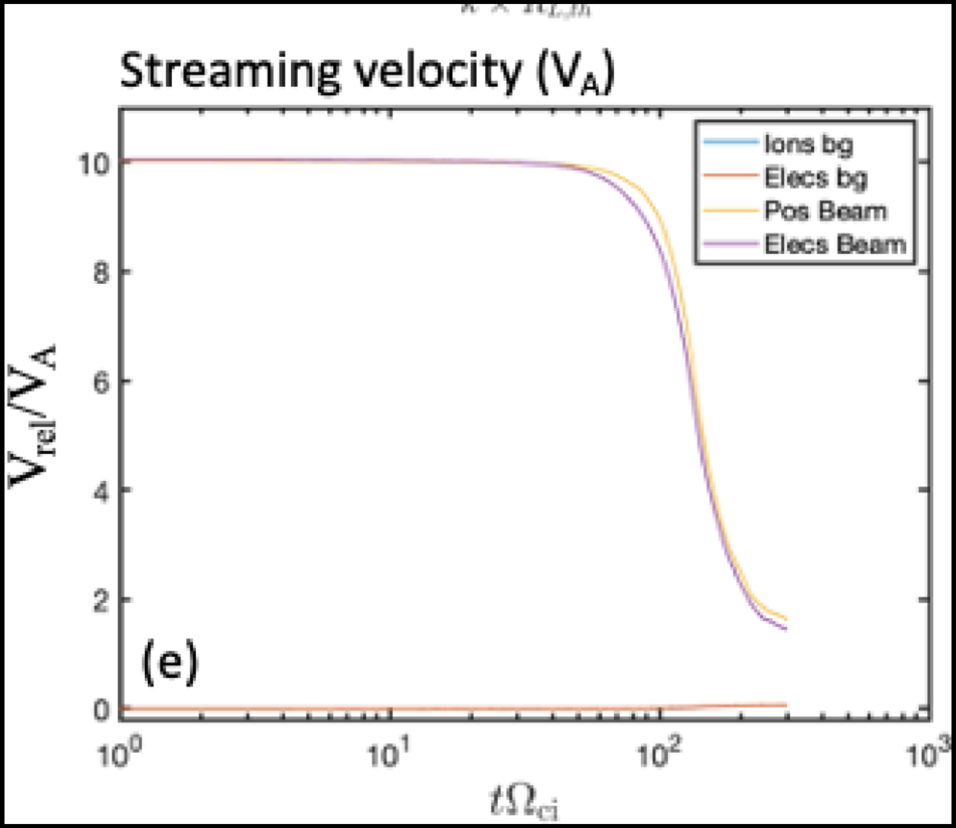

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Conclusions and Perspective

- Conclusions:
  - Results agree with analytical prediction
  - High resolution (Both spatially and in # particles are required)
  - The presence of an e+ e- beam can trigger instabilities (and therefore turbulence) in the local magnetic field
  - What causes the difference between electron and positron velocity?
- For the future
  - Increase scale and resolution of PIC-MHD simulations
  - Add non-thermal proton component.