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Hybrid-Kinetic Simulations of Quasi-perpendicular Shocks in High Beta Cosmic Plasmas

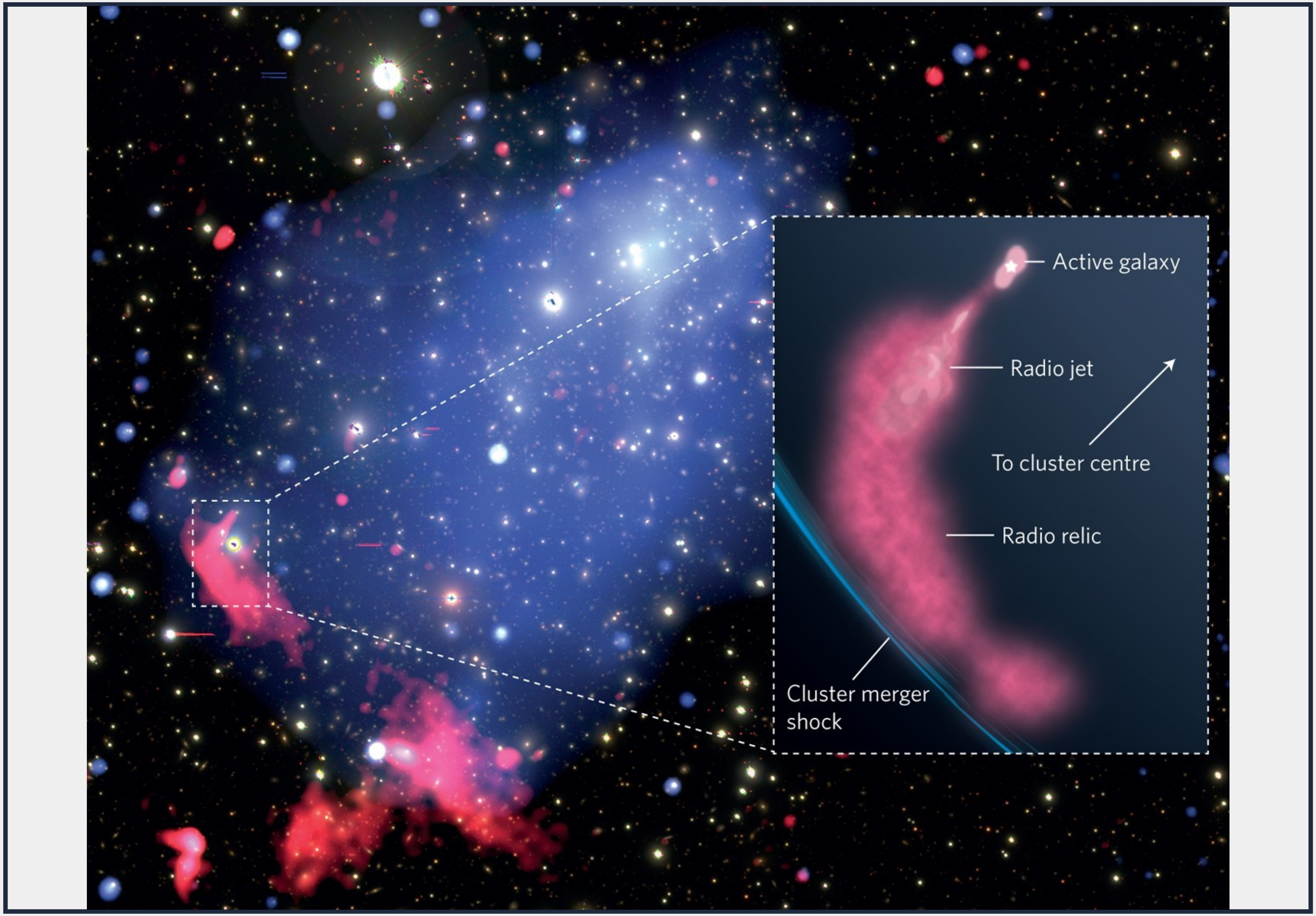
Stella S. Boula

Collaborators:
Jacek Niemiec (IFJ PAN), **Takanobu Amano** (University of Tokyo),
Oleh Kobzar (Cracow University of Technology), **Martin Pohl** (DESY/University of Potsdam

This research was supported by PLGrid Infrastructure through grants “astropic22” and “ast

Outline

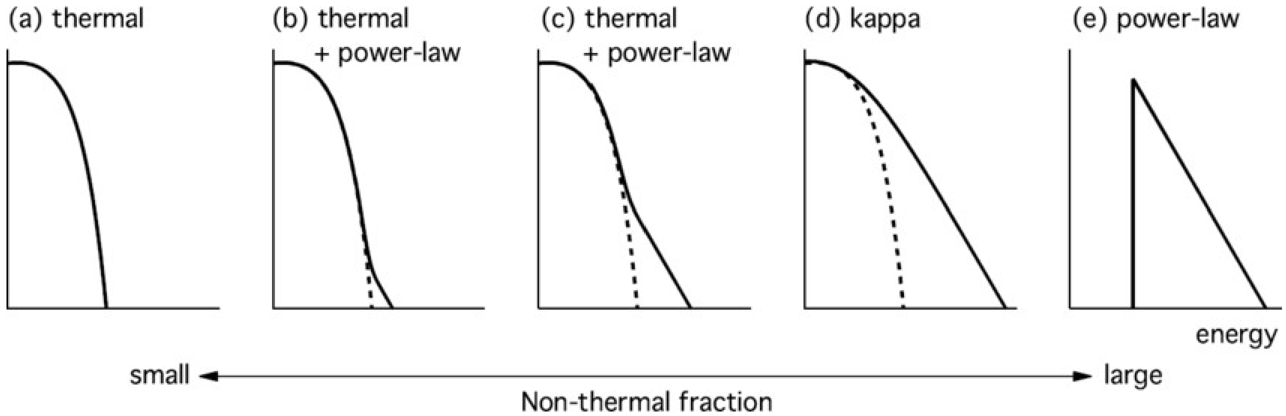
1. Cosmic Accelerators
2. Numerical Methods
3. Hybrid Code
4. Particle Acceleration
5. Results
6. Summary

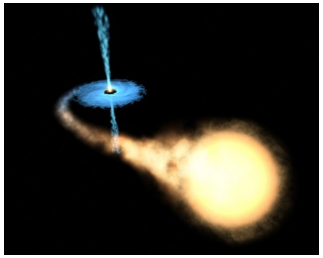


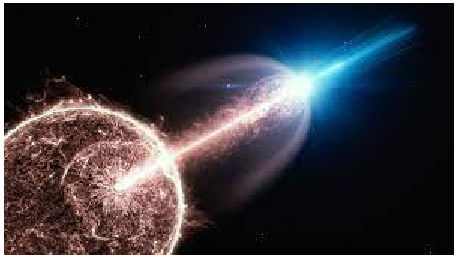
Credit: Nature Astronomy

Who is responsible for the non-thermal emission???

Credit: C. C. Chaston

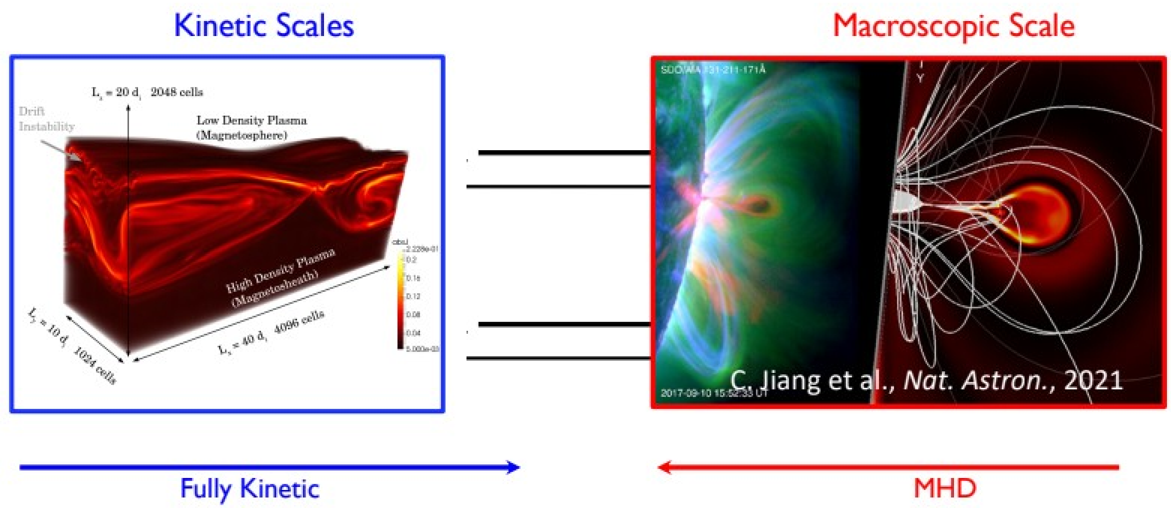





Images credits: NASA, ESA/Hubble, NASA, JPL, DESY, Science Communication Lab, Francesco de Gasperin

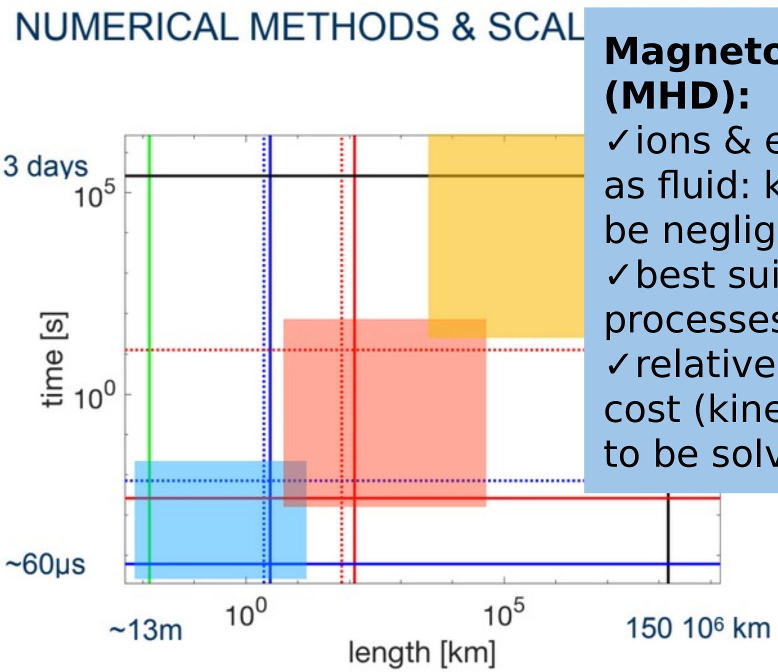
Numerical Methods



Credit: Adam Stanier

Particle acceleration processes:

- Magnetic reconnection
- Stochastic acceleration
- Diffusive stochastic acceleration
- Shock drift acceleration



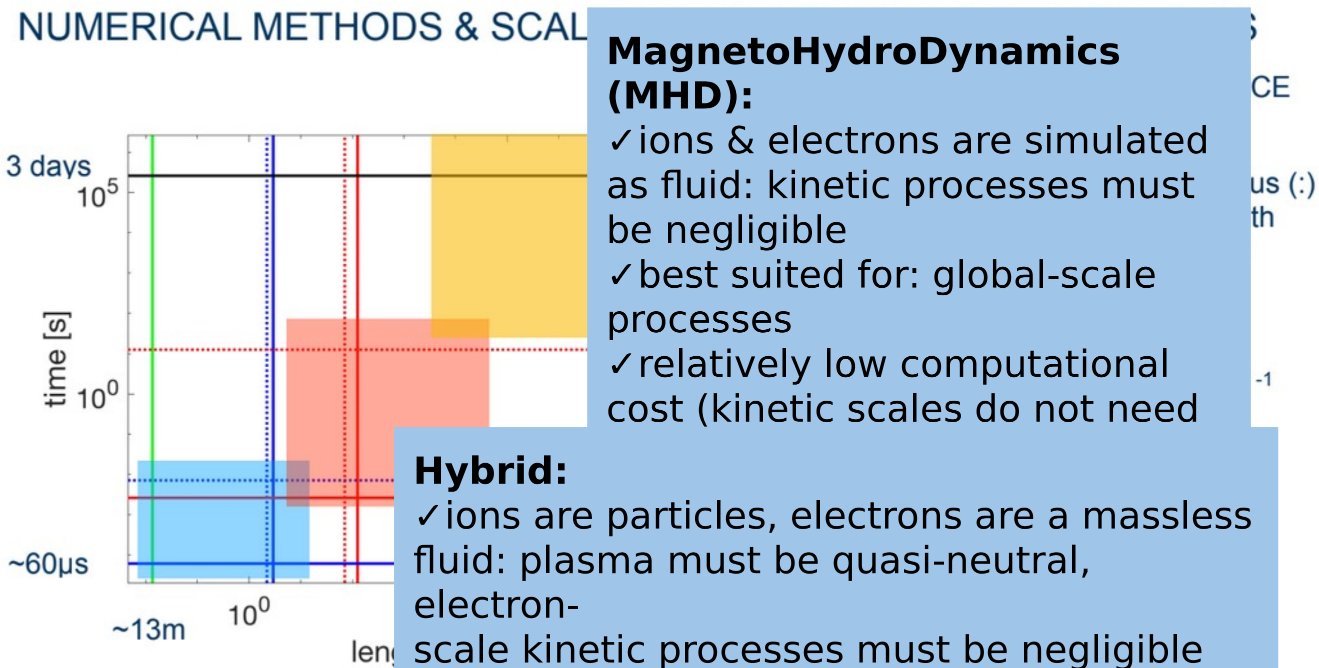
MagnetoHydroDynamics (MHD):

✓ions & electrons are simulated as fluid: kinetic processes must be negligible

✓best suited for: global-scale processes

✓relatively low computational cost (kinetic scales do not need to be solved)

Credit: Maria Elena Innocenti



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Hybrid:
✓ions are particles, electrons are a massless fluid: plasma must be quasi-neutral, electron-
scale kinetic processes must be negligible

✓best suited for: ion scale processes
✓moderate computational cost (need to resolve
smallest, fastest ion scales)

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NUMERICAL METHODS & SCAL

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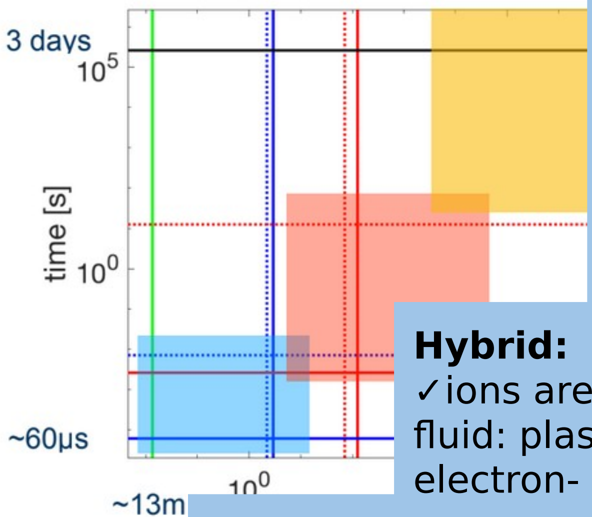

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Explicit Particle in Cell, PIC:
✓electrons and ions are particles: no assumptions on the state of the plasma
✓best suited for: electron scale processes
✓high computational cost (need to resolve smallest, fastest electron scales)

Credit: Maria Elena Innocenti

Generalized Hybrid Code
by Takanobu Amano (University of Tokyo)

3D Numerical code, basic assumptions:

• collisionless quasi-neutral plasmas

• Kinetic ions and fluid electrons

• Kinetic species dynamics is governed by theVlasov equation

Energetic Particle population interacting self-consistently with the MHD fluid.

Numerical schemes are

(a) the PIC solver for kinetic species and

(b) the Riemann solver for the fluid equations.

The code employs the exact form of the generalized Ohm’s law.

Code details

- C++ compiler
- MPI library
- HDF5 library
  - requires parallel extention (--enable-parallel)
  - C++ extension is not necessary
- blitz
  - https://github.com/blitzpp/blitz/releases

Run the code via

$ mpiexec ./shock -c shock.cfg -x 16 -y 1 -z 1

where shock.cfg is the configuration file.
The options -x -y -z are used to specify the domain decomposition in each direction.

Simulation results will be saved to

field.h5: electromagnetic fields and fluid quantities

moment.h5: moment quantities of kinetic components

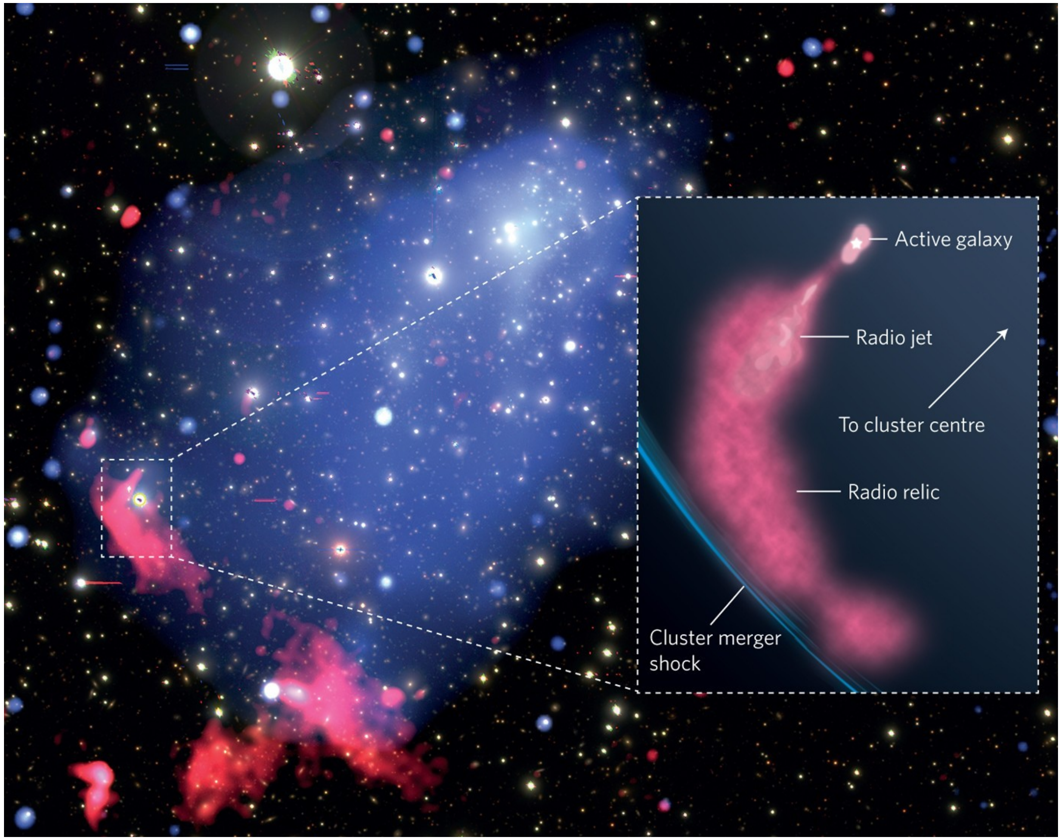
particle.h5: entire particle data

“

Particle acceleration and galaxy clusters

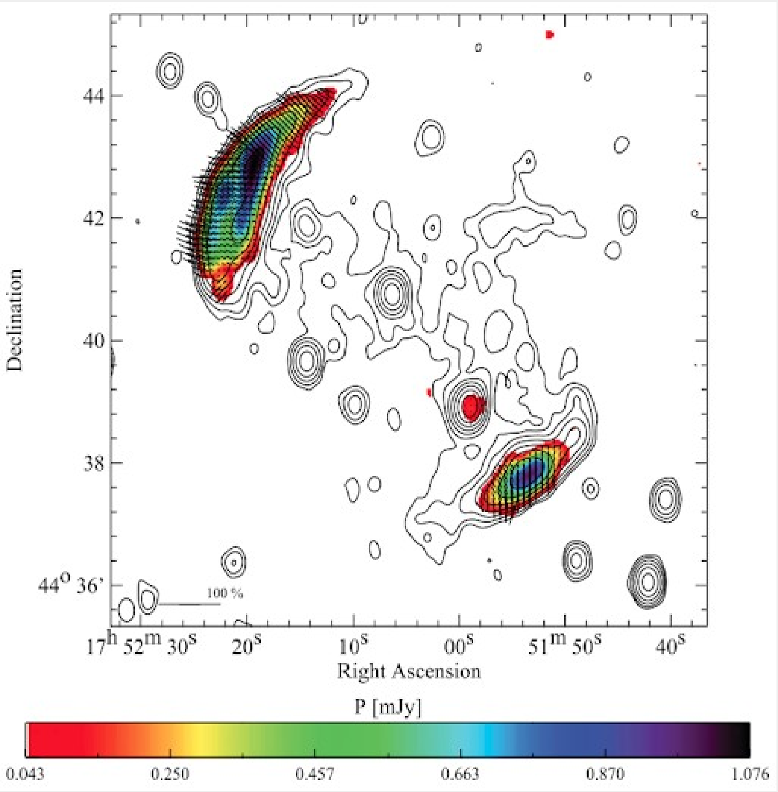
This work has been supported by Narodowe Centrum Nauki through research project 2019/33/B/ST9/02569.
This research was supported in part by PLGrid Infrastructure

Electron injection at shocks in merging galaxy clusters



Credit:
M. Johnston - Hollitt
nature astronomy

- Supersonic flows of baryonic matter induced during large-scale structure formation of the Universe produce shocks in hot intracluster medium (ICM) with high beta ($\beta >> 1$)
- Merger shocks are observed in radio and X-rays as so-called radio-relics
- Most energetic merger shocks have low Mach numbers ($M_s < 5$, $M_A < 10$)
- Diffusive Shock Acceleration (DSA) assumed to operate these shocks



$$M_A = \frac{u_{sh}}{u_A} \quad M_s = \frac{u_{sh}}{c_s} \quad \beta = \frac{p_{th}}{p_{mag}}$$

$$u_A = \frac{B_0}{\sqrt{\mu_0 (N_e m_e + N_i m_i)}} \quad c_s = \sqrt{2\Gamma k_B T_i / m_i}$$

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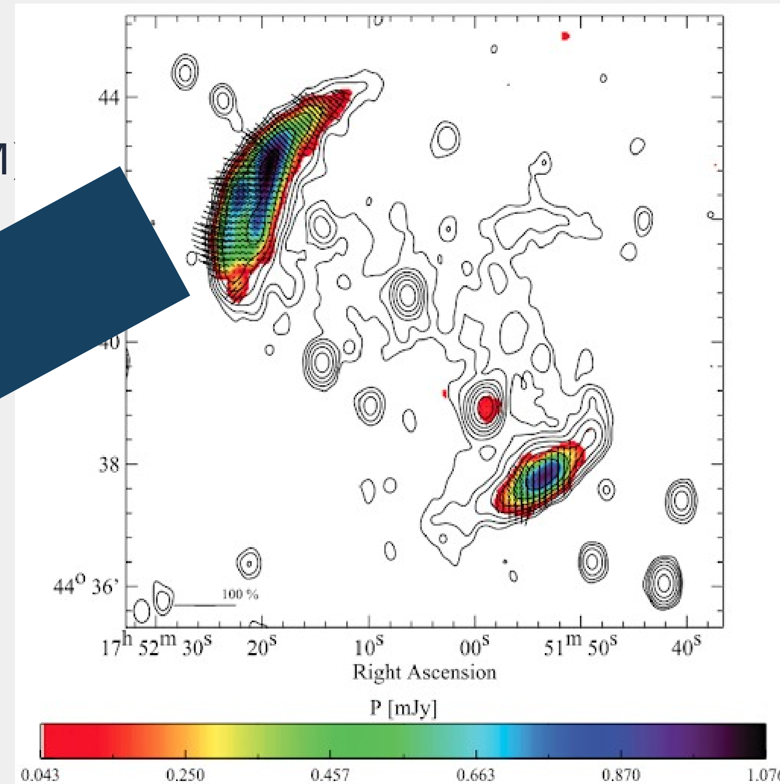
But what about electron injection???



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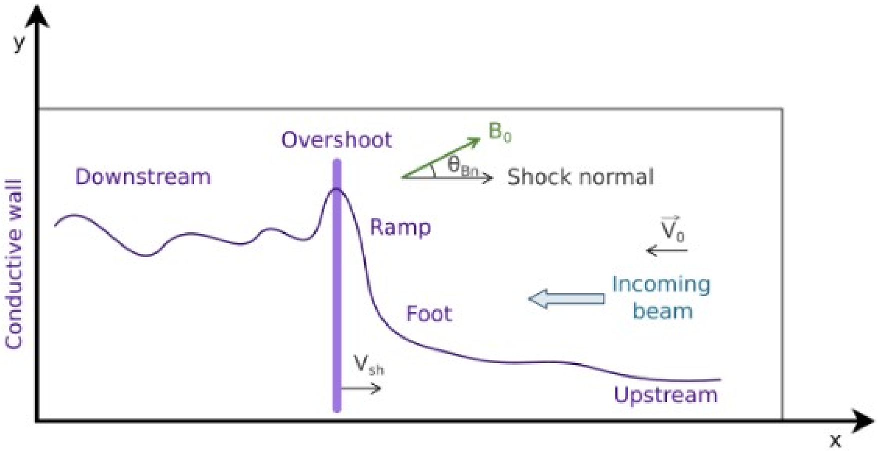
Quasi-perpendicular shocks



Electron injection effective mainly in Q⊥-shocks

Key elements:

(i) particle reflection at the shock ramp due to magnetic mirror forces.

(ii) energy gain from the motional electric field in the upstream region (SDA/SSA/particle-wave interactions)

(iii) trapping of electrons near the shock due to the scattering by upstream waves → multiple cycles of SDA or SSA

Shock acceleration

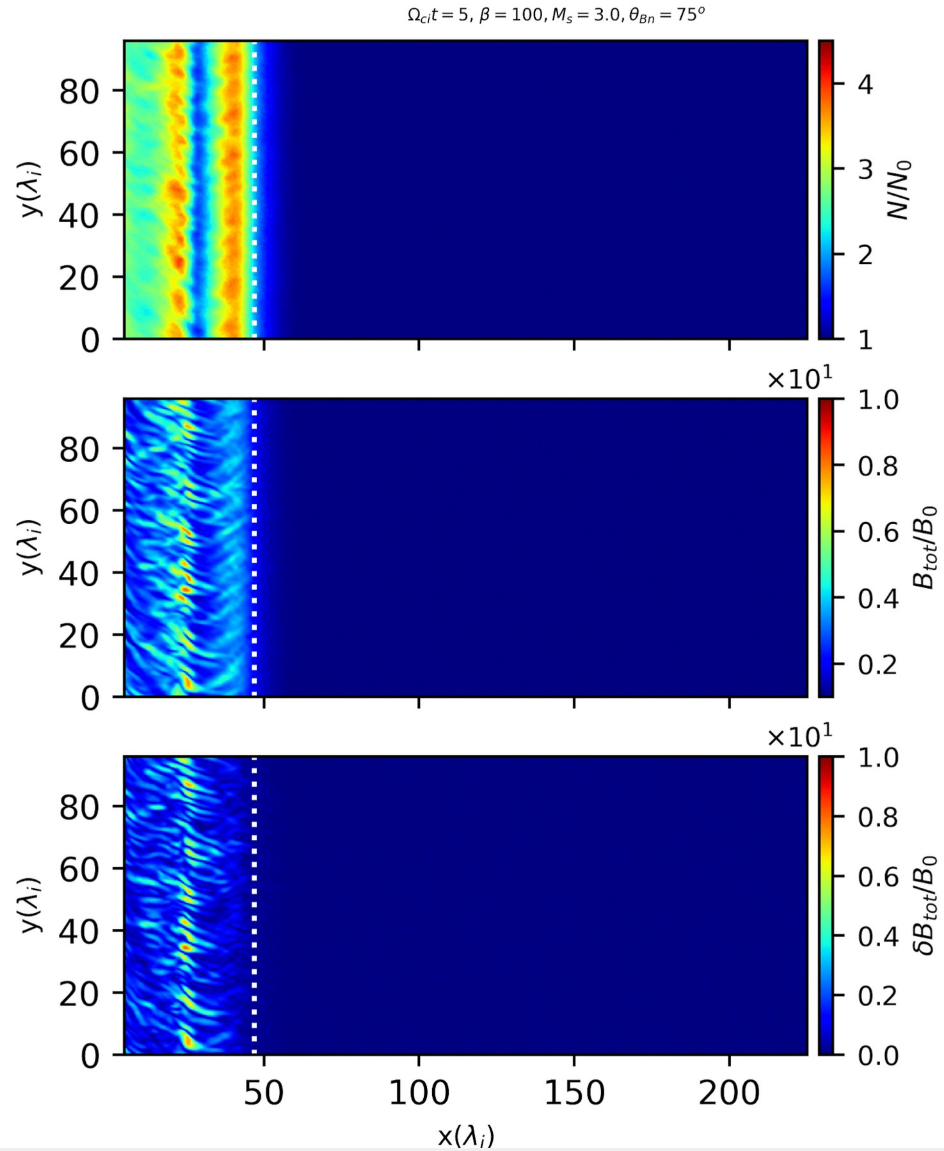
Microinstabilities

Wave-particle interactions

self-generated upstream waves

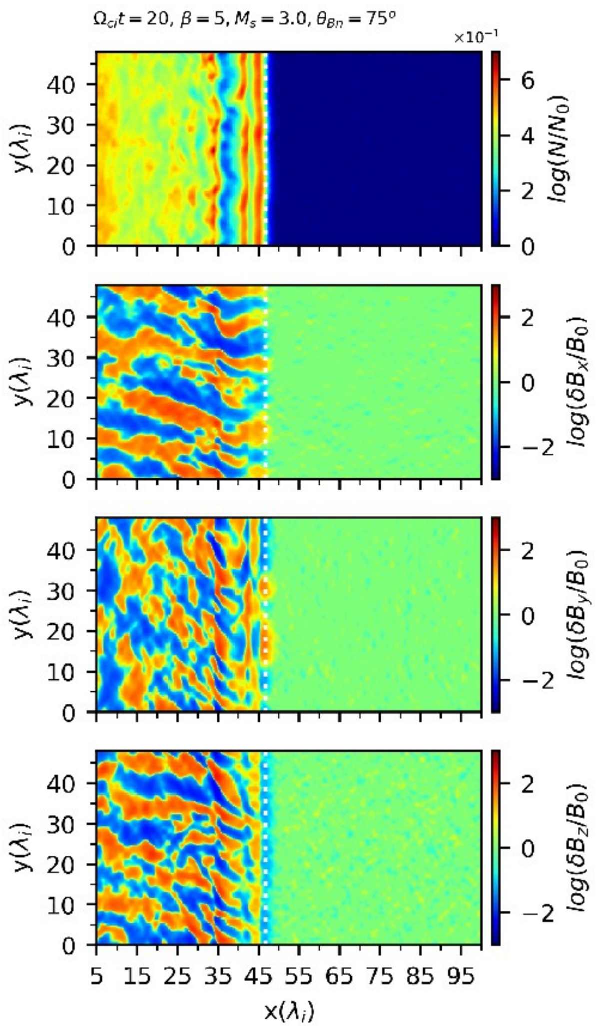
Basic shock parameters:

- ★ plasma β
- ★ sonic Mach Number
- ★ Alfvén Mach Number
- ★ obliquity angle
- ★ adopted ion-to-electron mass ratio



$\Omega_{ci}t = 5$, $\beta = 100$, $M_s = 3.0$, $\theta_{Bn} = 75^o$
$y(\lambda_i)$
N/N_0
$\times 10^1$
B_{tot}/B_0
$\delta B_{tot}/B_0$
$x(\lambda_i)$

Dependence on plasma β



Features of multi-scale turbulence similar in all cases

- longer-wavelength ripples with growing β

modes with increasing β (after amplification in rippled shocks)

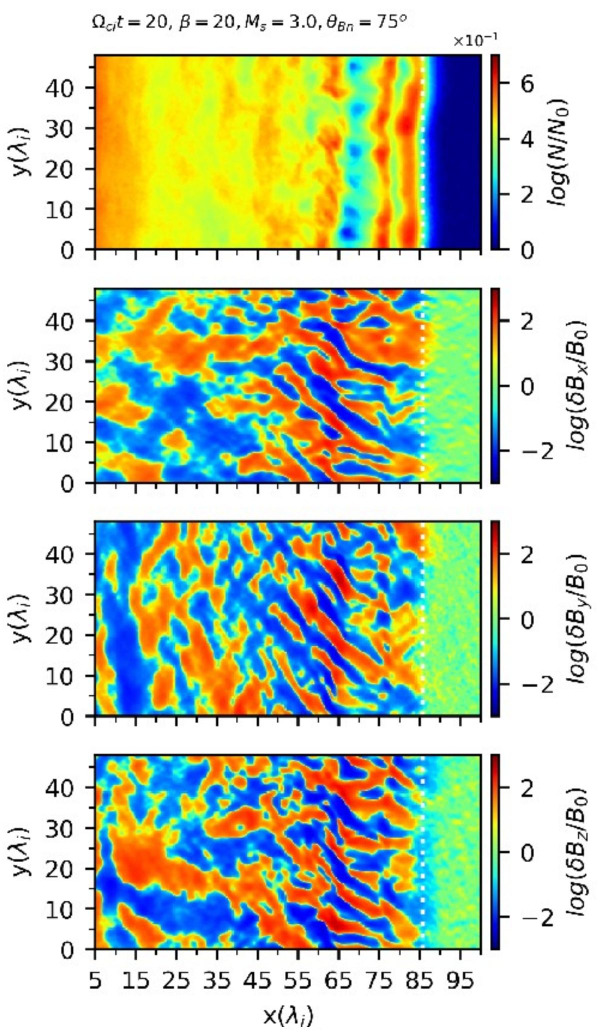
AIC important to rippling / the role of reflected ions to critical Mach numbers

Exploration of plasma β impact

A lot of computational power

Hybrid Simulations

Dependence on plasma β



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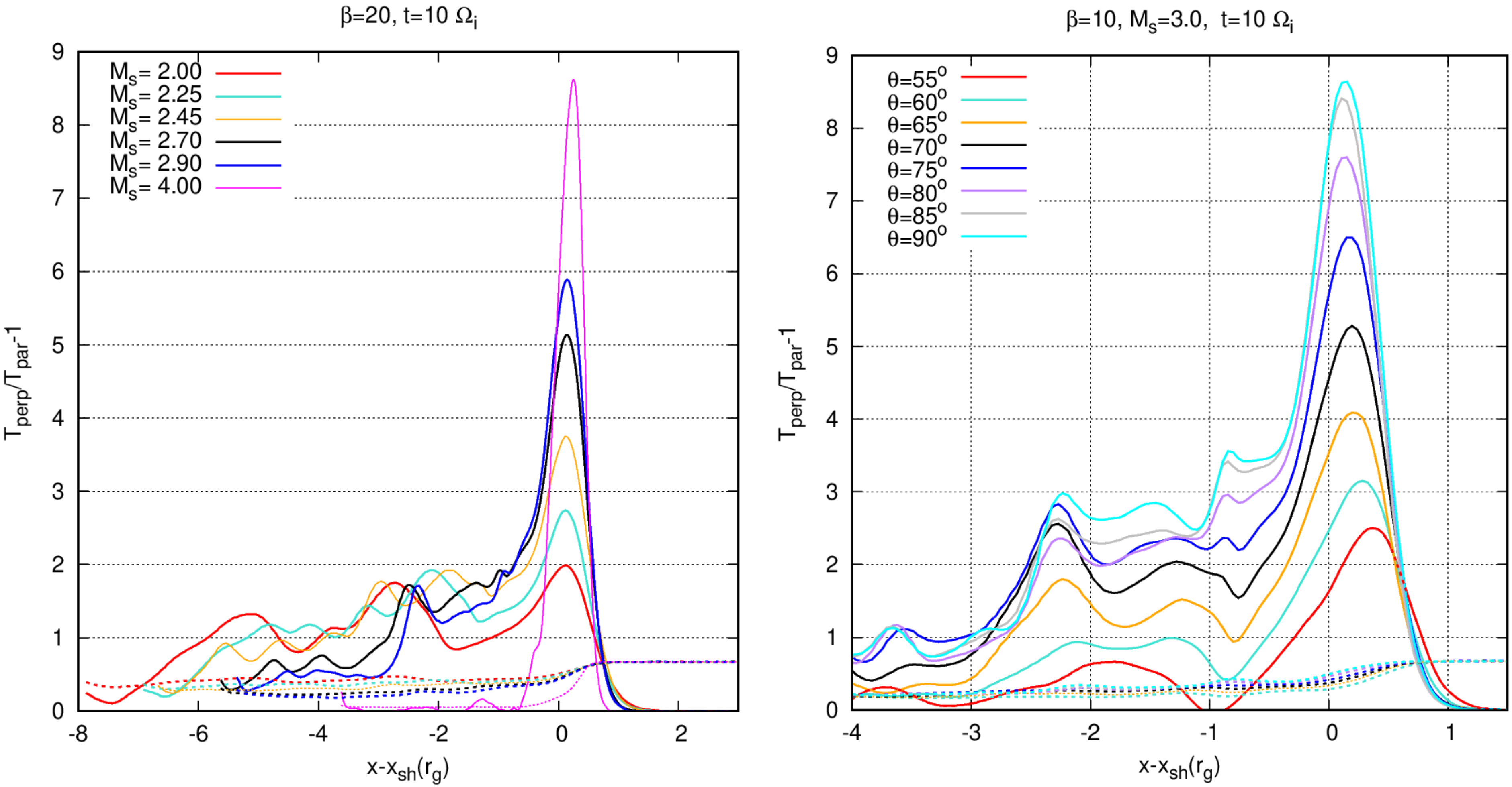
Hybrid Simulations 😀



β=20, t=10 Ωi
Ms= 2.00
Ms= 2.25
Ms= 2.45
Ms= 2.70
Ms= 2.90
Ms= 4.00
Tperp/Tpar-1
x-xsh(rg)
β=10, Ms=3.0, t=10 Ωi
θ=55°
θ=60°
θ=65°
θ=70°
θ=75°
θ=80°
θ=85°
θ=90°
Tperp/Tpar-1
x-xsh(rg)

Main goals:

Boula et. al, In prep

- To find the critical Mach number to trigger Alfvén Ion Cyclotron (AIC) Instability and the shock surface rippling in high plasma β.

  - ★ critical shock Mach numbers: ion reflection & upstream wave generation
  - ★ AIC: ion cyclotron freq. ~ Alfvén freq. → unstable plasma → EM waves generation.

- To explore how the ion kinetic instabilities are related to the electron preacceleration

About 150 simulations have been performed to scan the shock parameter space, such as the plasma β, the Mach numbers, and the angle θ_{Bn}. The simulations produced ~500 TB of data and used ~ million CPU hours.

Dziękuje!