Detecting shock waves in SPH simulations

“Simulations with Gadget”

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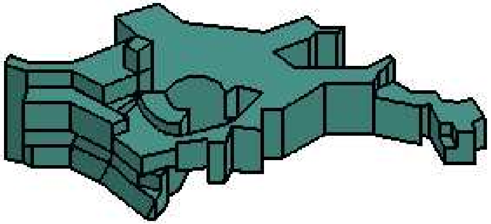
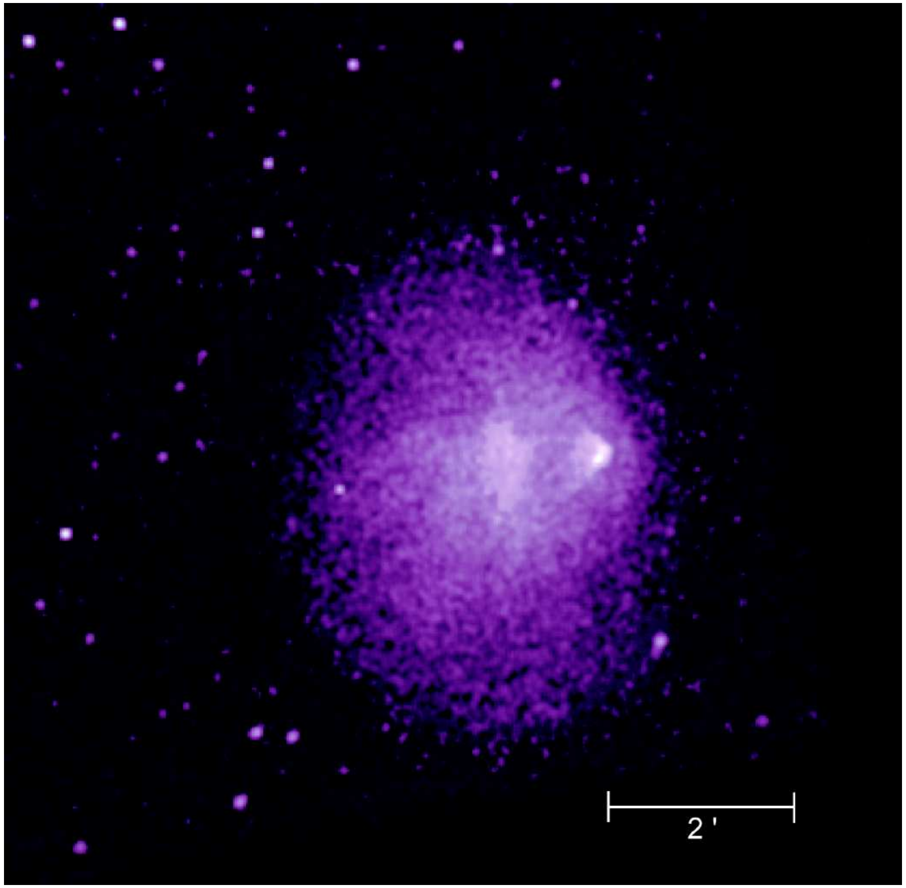
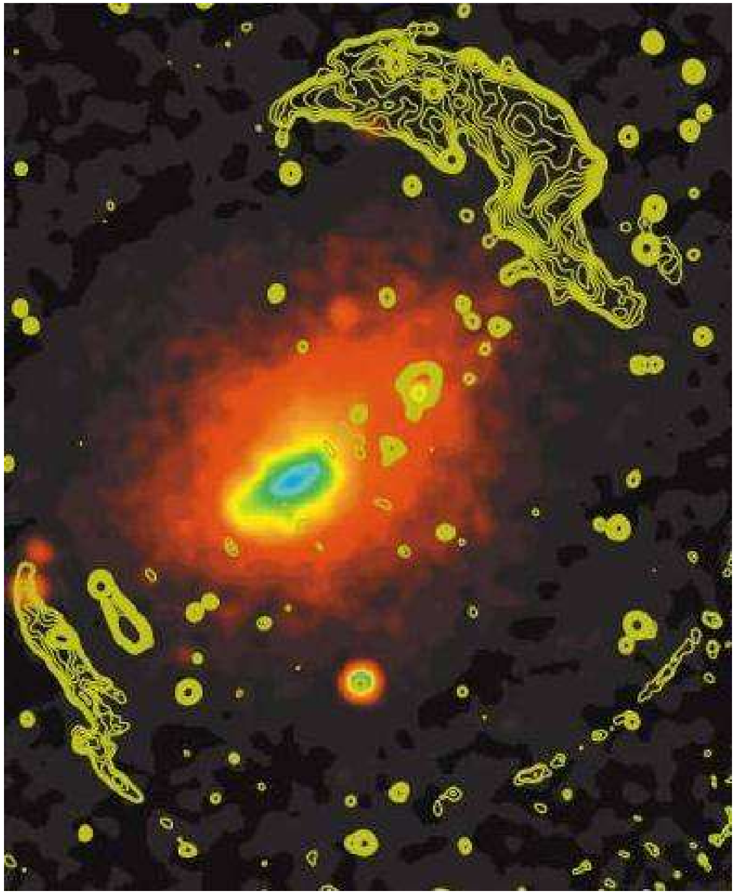


Shock waves in galaxy clusters



1E 0657-56 ("Bullet cluster")

(NASA/SAO/CXC/M.Markevitch et al.)



Abell 3667

(Radio: Australia Telescope Comp. Array. X-ray: ROSAT/PSPC.)

Motivation

- cosmological shocks dissipate gravitational energy into thermal gas energy
- shock waves are tracers of the large scale structure and contain information about its dynamical history (warm-hot intergalactic medium)
- shocks accelerate energetic particles (cosmic rays) through diffusive shock acceleration at structure formation shocks
- cosmic ray injection by supernova remnants (when combined with radiative dissipation and star formation)
- shock-induced star formation in the interstellar medium

This work: Christoph Pfrommer, Volker Springel, Torsten Enßlin, & Martin Jubelgas, MNRAS submitted

Idea

- SPH shock is broadened to a scale of the order of the smoothing length h, i.e. $f_h h$, and $f_h \sim 2$
- approximate instantaneous particle velocity by pre-shock velocity (denoted by $v_1 = \mathcal{M}_1 c_1$)

Using the entropy conserving formalism of Springel & Hernquist 2002 ($A(s) = P\rho^{-\gamma}$ is the entropic function):

$$\frac{A_2}{A_1} = \frac{A_1 + \mathrm{d}A_1}{A_1} = 1 + \frac{f_h h}{\mathcal{M}_1 c_1 A_1} \frac{\mathrm{d}A_1}{\mathrm{d}t} = \frac{P_2}{P_1} \left(\frac{\rho_1}{\rho_2} \right)^{\gamma}$$

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma + 1)\mathcal{M}_1^2}{(\gamma - 1)\mathcal{M}_1^2 + 2}$$

$$\frac{P_2}{P_1} = \frac{2\gamma\mathcal{M}_1^2 - (\gamma - 1)}{\gamma + 1}$$

Complications

1. Broad Mach number distributions $f(\mathcal{M}) = \frac{\mathrm{d}u}{\mathrm{d}t\,\mathrm{d}\log\mathcal{M}}$ because particle quantities within the (broadened) shock front do not correspond to those of the pre-shock regime.
   Solution: introduce decay time $\Delta t_{\mathrm{dec}} = f_h h/(\mathcal{M}_1 c)$, meanwhile the Mach number is set to the maximum (only allowing for its rise in the presence of multiple shocks).
2. Weak shocks imply large values of Δt_{dec}:
   Solution: $\Delta t_{\mathrm{dec}} = \mathrm{min}[f_h h/(\mathcal{M}_1 c), \Delta t_{\mathrm{max}}]$
3. Strong shocks with $\mathcal{M} > 5$ are slightly underestimated because there is no universal shock length.
   Solution: recalibrate strong shocks!

How to use the shock finder:

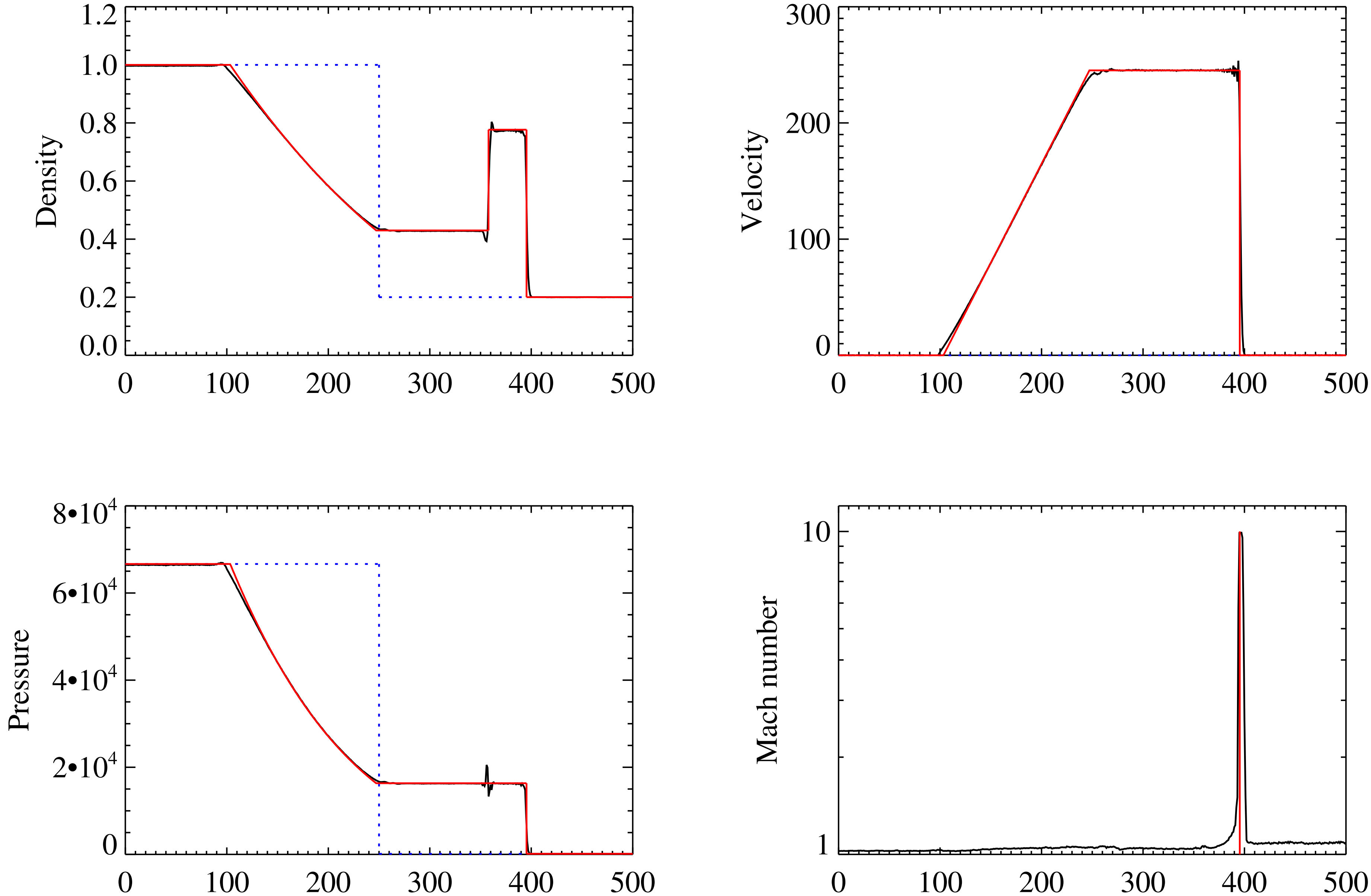
Switches:

- -DMACHNUM: Mach number master switch
- -DMACHSTATISTIC: output of $\frac{\mathrm{d}\varepsilon_{\mathrm{diss}}(a)}{\mathrm{d}\log a}$
- -DCR_OUTPUT_JUMP_CONDITIONS: output of density and thermal energy jump at shocks in the case of cosmic rays

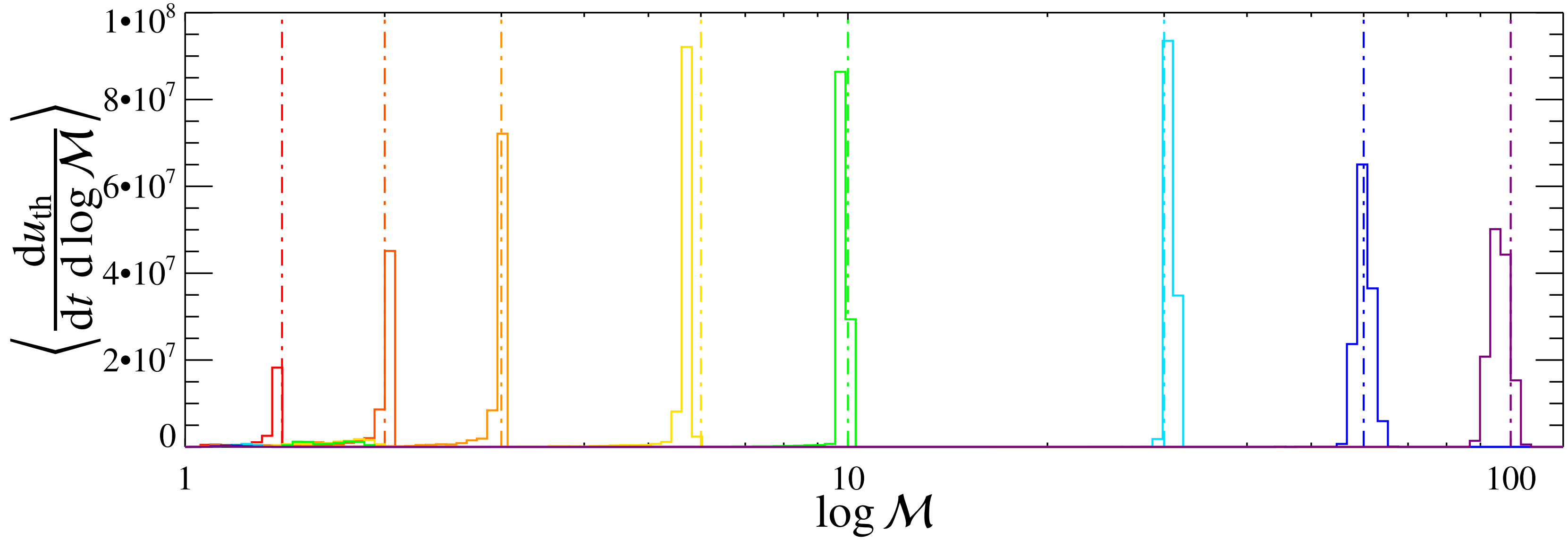
Parameters:

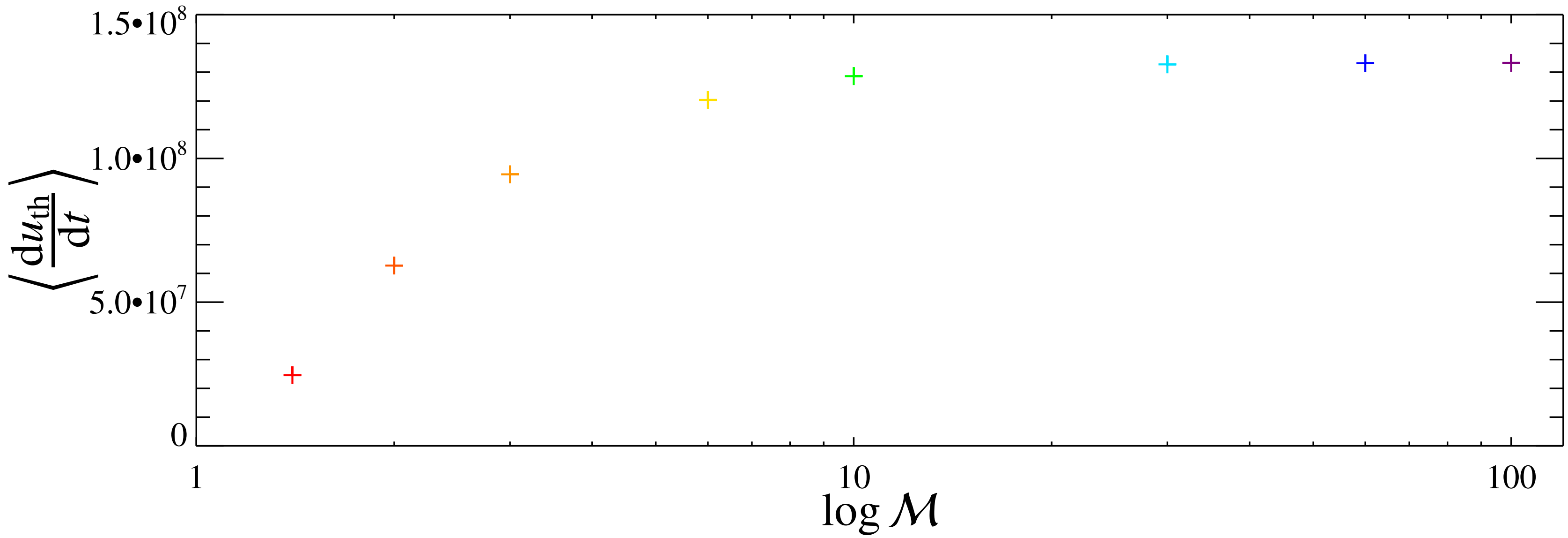
- Shock_LengthScale $= f_h \simeq 2.0$
- Shock_DeltaDecayTimeMax $= \Delta t_{\mathrm{max}} \simeq 0.0025$

Shock tube: thermodynamics

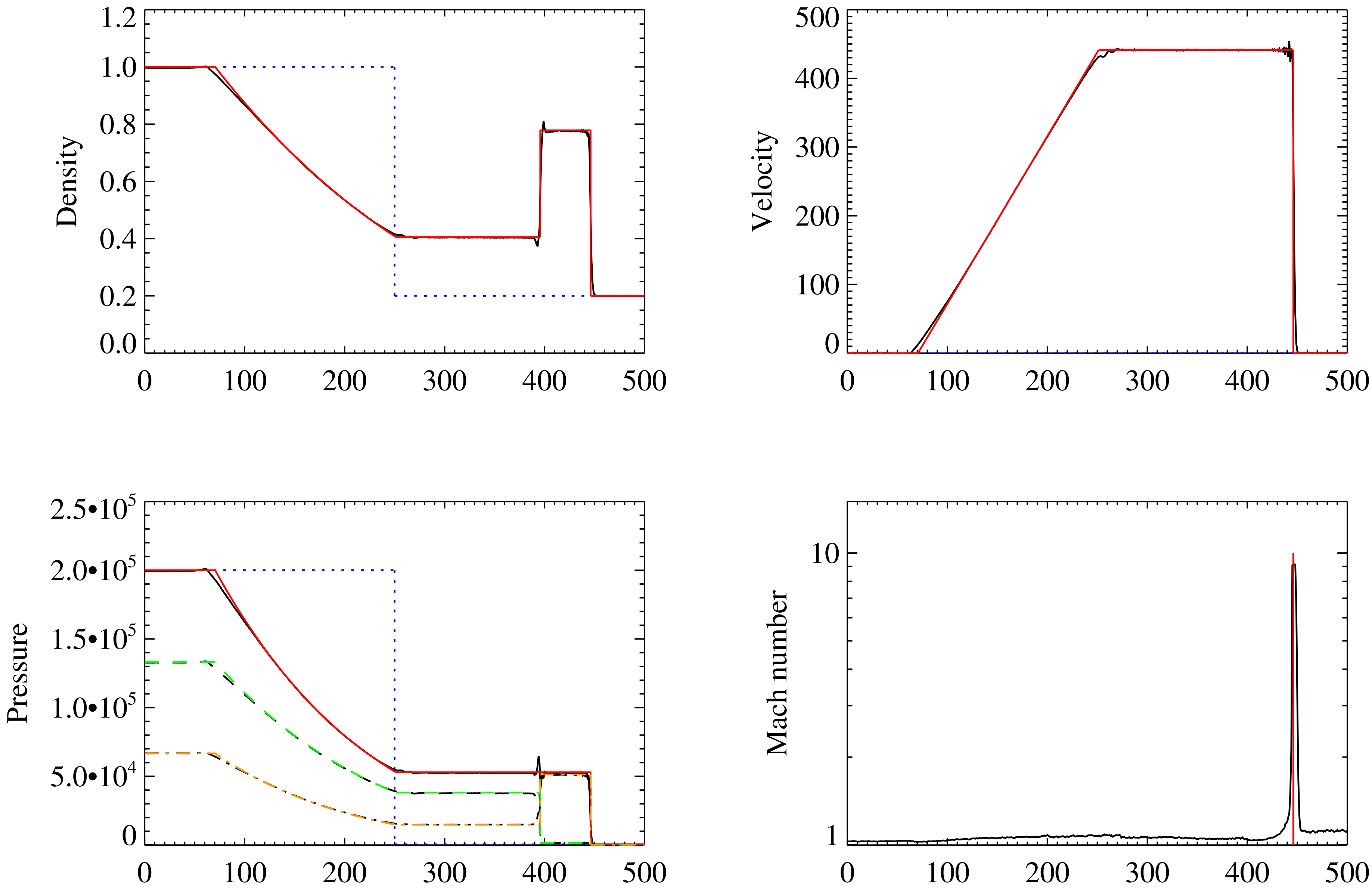


Shock tube: Mach number statistics

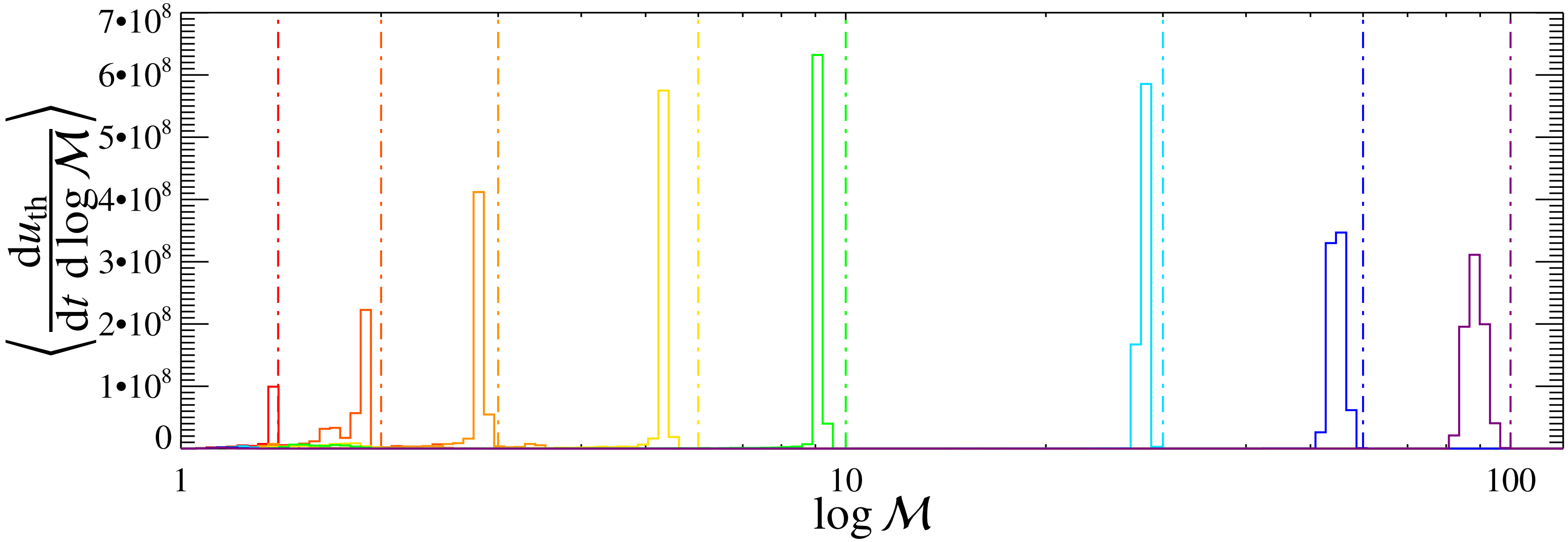


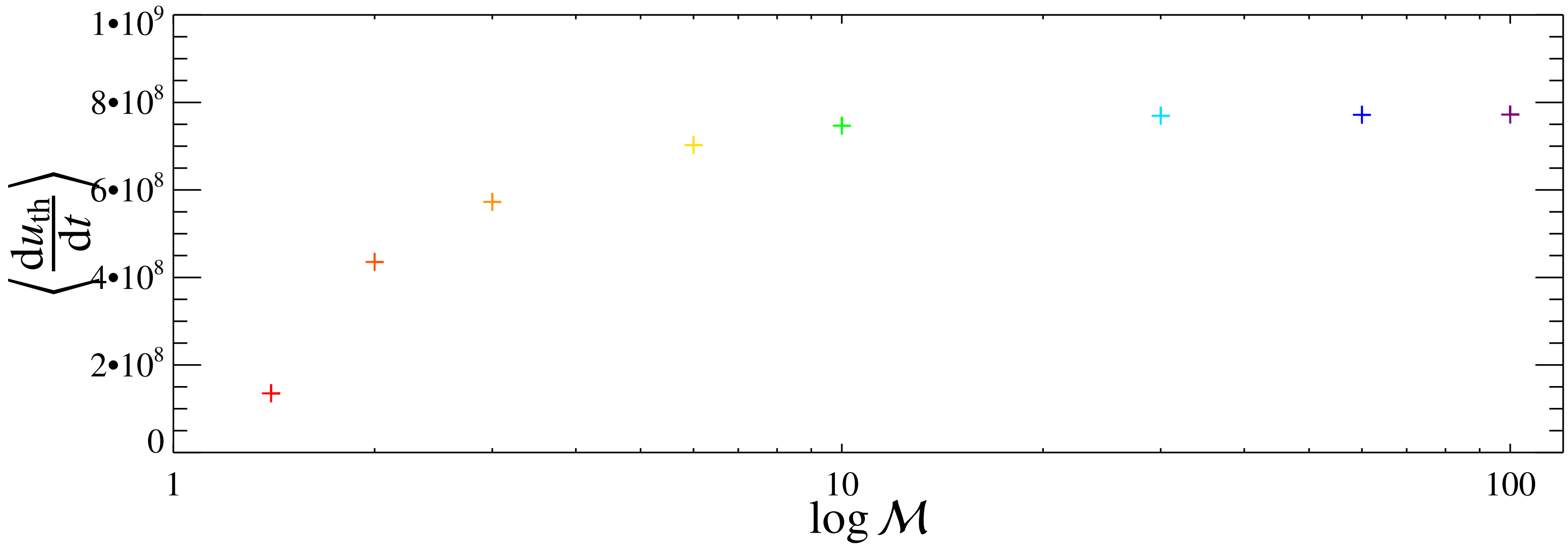


Shock tube (CRs & gas)

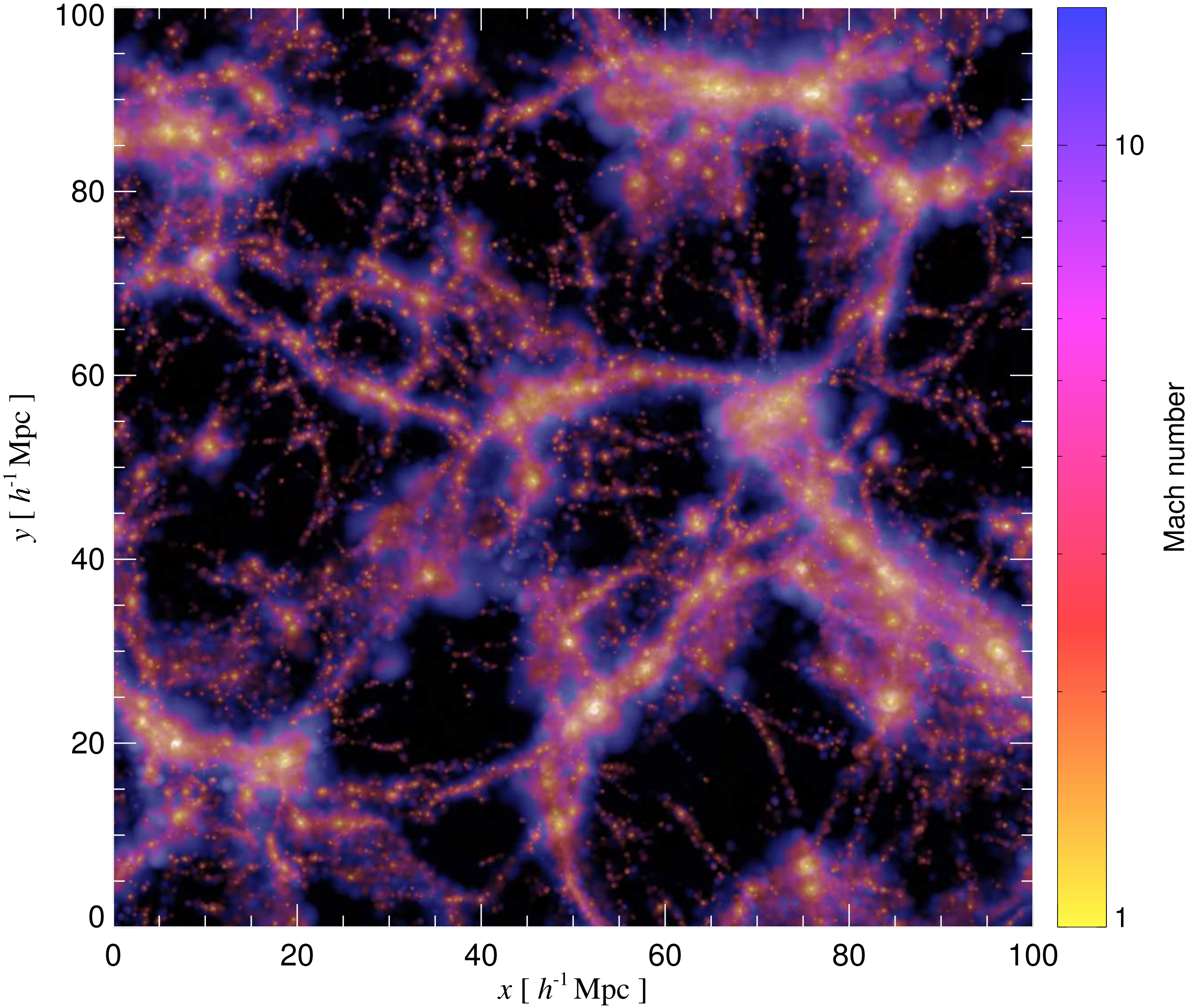


Shock tube (CRs & gas)





Cosmological simulation



Cosmological statistics