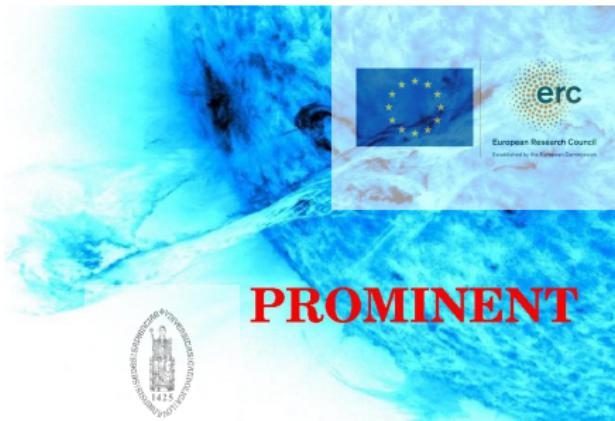


Insights on coronal rain dynamics from multidimensional simulations

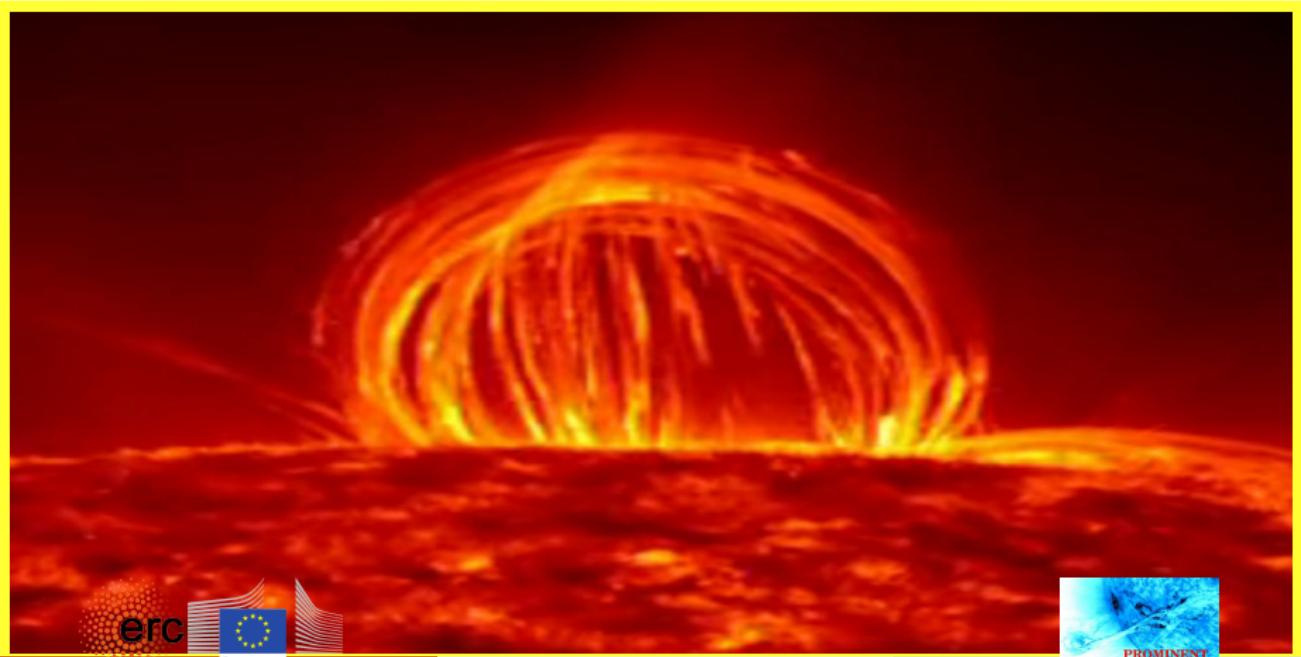
Rony Keppens [& Chun Xia, Niels Claes, ...]



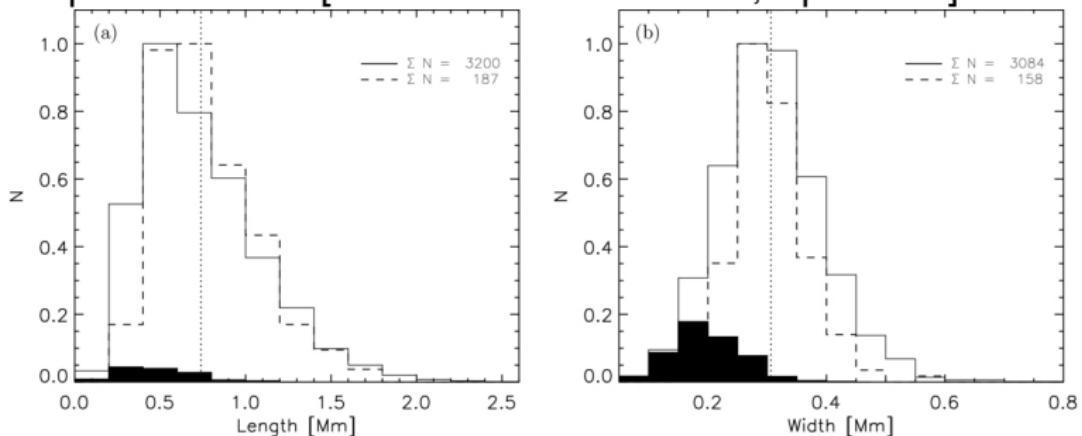
Centre for mathematical Plasma-Astrophysics
Department of Mathematics, KU Leuven

Coronal Rain

- fragmented material, condensing & ‘falling’ to solar surface
 - ⇒ key role in mass cycle between chromosphere-corona
 - ⇒ quiescent coronal rain (non-flaring ARs) or **flare-driven**



- flare-driven [Scullion et al, ApJ 2016]:
 - ⇒ post-flare decay phases end in catastrophic cooling
 - ⇒ number densities $\mathcal{O}(10^{12})\text{cm}^{-3}$ cools at up to 22,700 K/s
 - quiescent rain [Antolin & van der Voort, ApJ 2012]: statistics

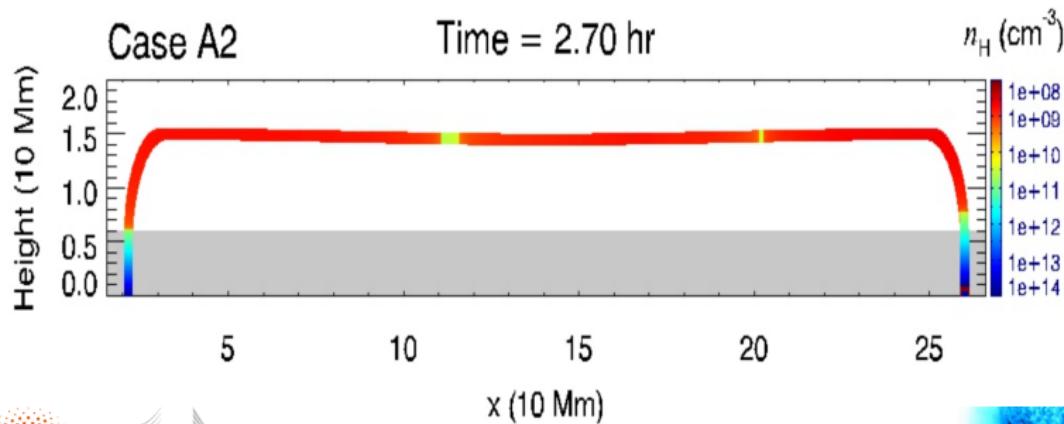


⇒ H α condensations with 500 km length, 310 km width

- 1 Coronal rain: 1D prelude
- 2 Coronal rain: multi-D effects
- 3 Back to basics

Coronal rain in a 1D world

- study of coronal rain
 - ⇒ form along **B** lines, consistent with observations
 - ⇒ model ingredients: ∇p , **g**, thermal conduction, optically thin radiative losses, coronal heating
- thermal instability



- reduced to 1D radiative hydro in form

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial s}(\rho v) = 0,$$

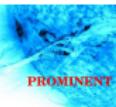
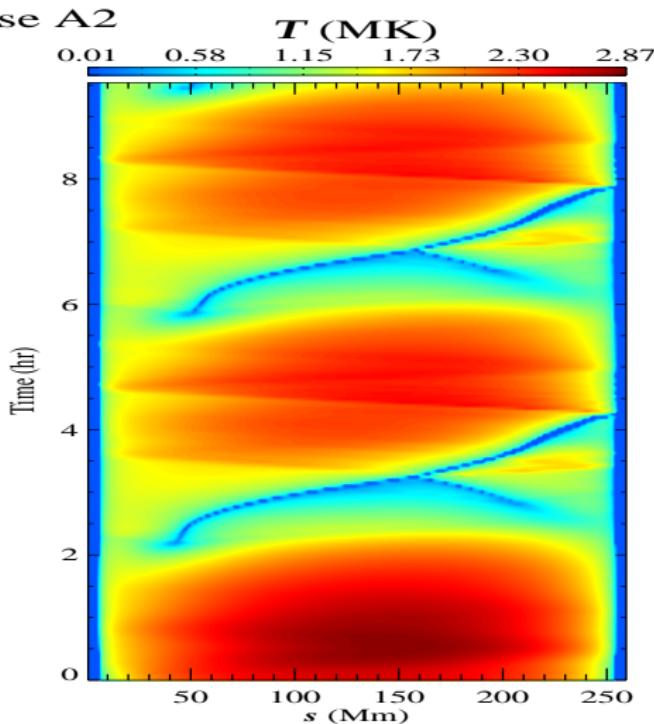
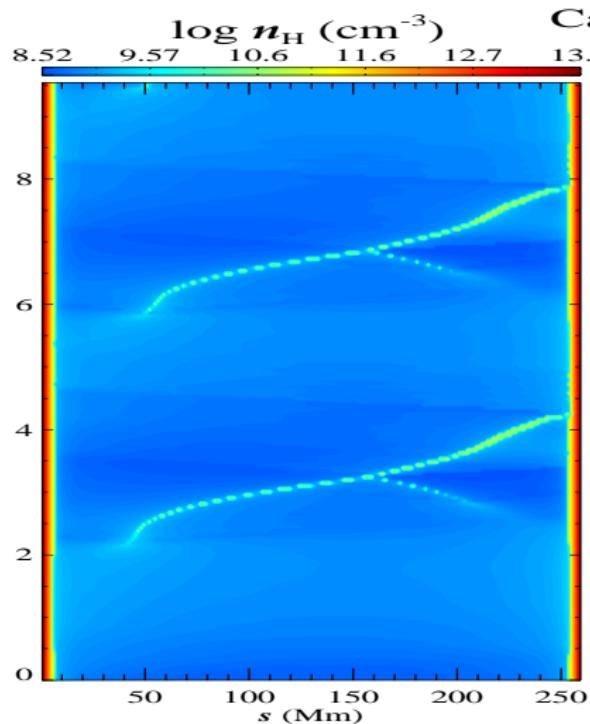
$$\frac{\partial}{\partial t}(\rho v) + \frac{\partial}{\partial s}(\rho v^2 + p) = \rho g_{||}(s),$$

$$\frac{\partial e}{\partial t} + \frac{\partial}{\partial s}(ev + pv) = \rho g_{||}v + H(s) - n_{\text{H}}n_{\text{e}}\Lambda(T) + \frac{\partial}{\partial s}\left(\kappa_{TC}\frac{\partial T}{\partial s}\right),$$

⇒ only physics: **pressure differences, gravity, siphon flows, conductive/radiative timescales**

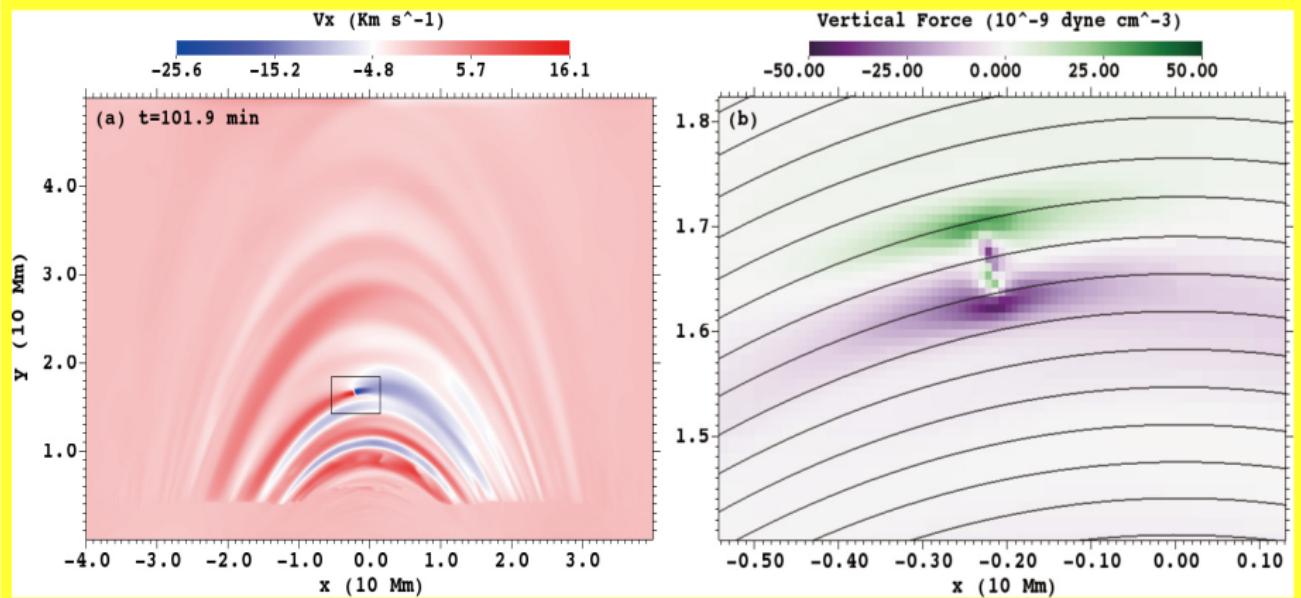
- see e.g. Antiochos et al., 1999; Karpen et al., 2001; Muller et al, 2005; Xia et al., 2011 and many others ...

- Asymmetric heating: limit cycles



- 1 Coronal rain: 1D prelude
- 2 Coronal rain: multi-D effects
- 3 Back to basics

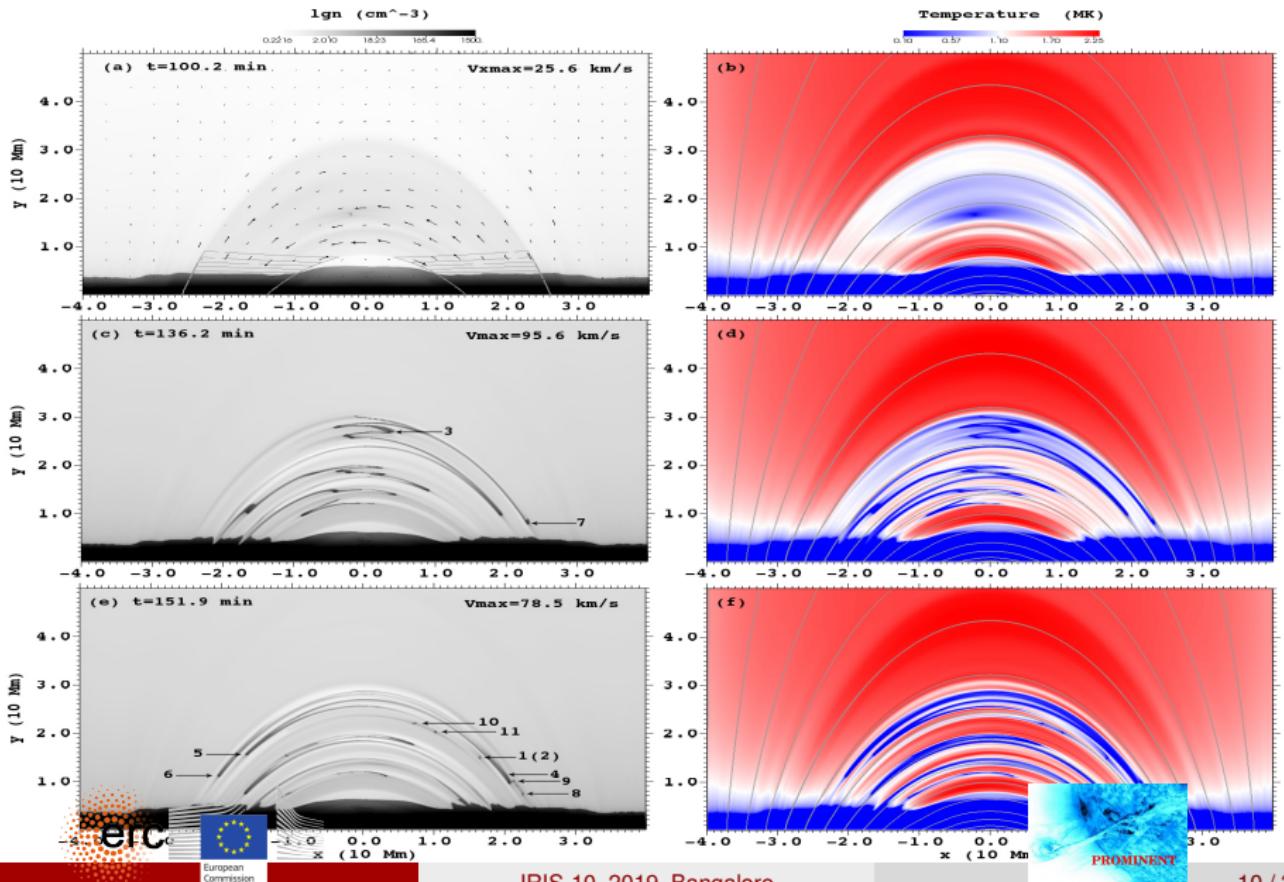
- 2.5D setups: arcade configuration
⇒ [Fang et al, 2013 ApJ Letter] first condensation:



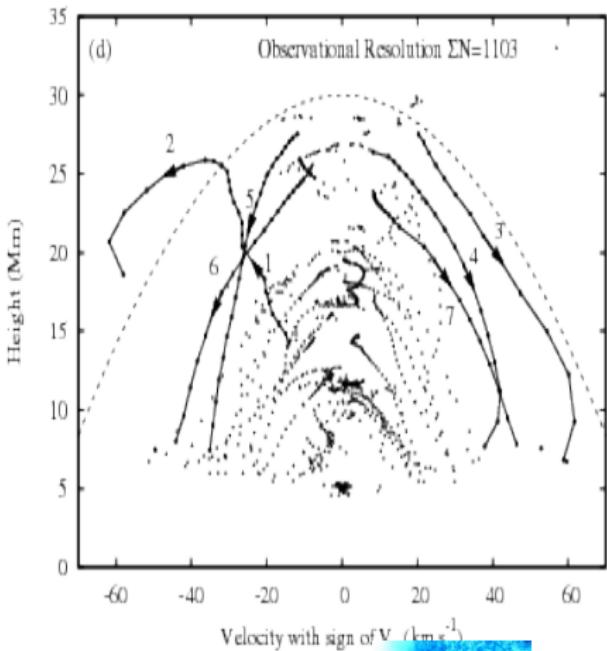
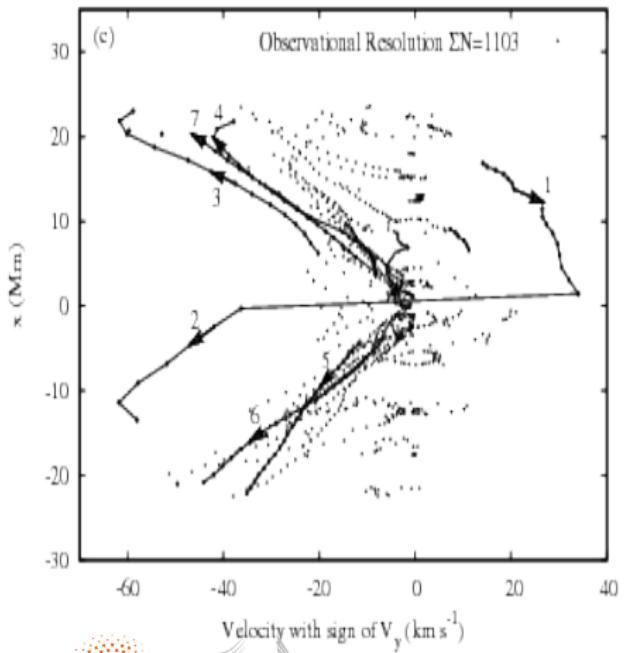
⇒ perturbed vertical force: typical loop strand width



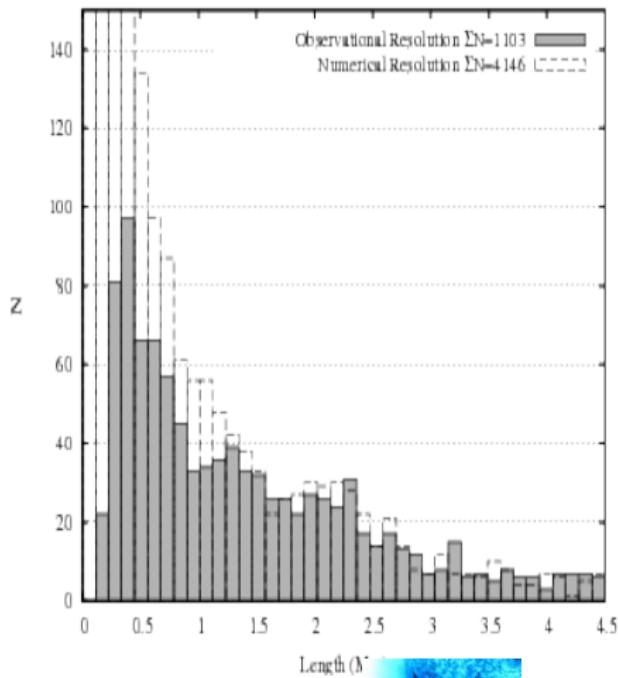
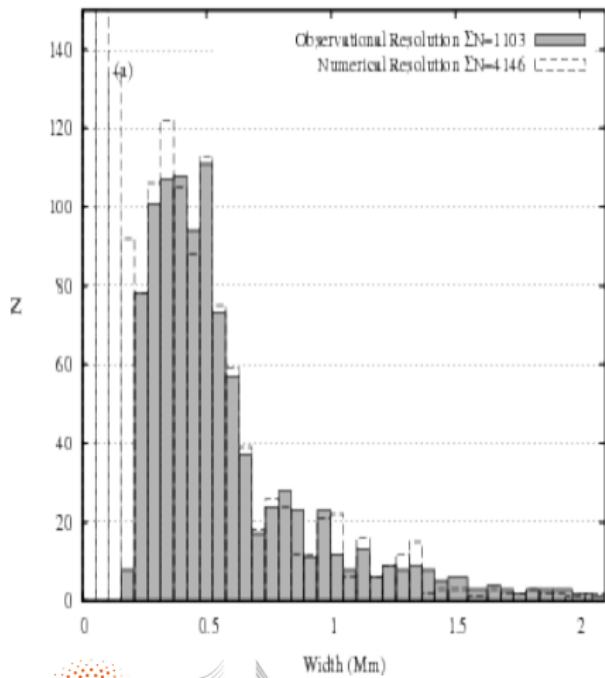
- simulated over 80 minutes **coronal rain ballet**

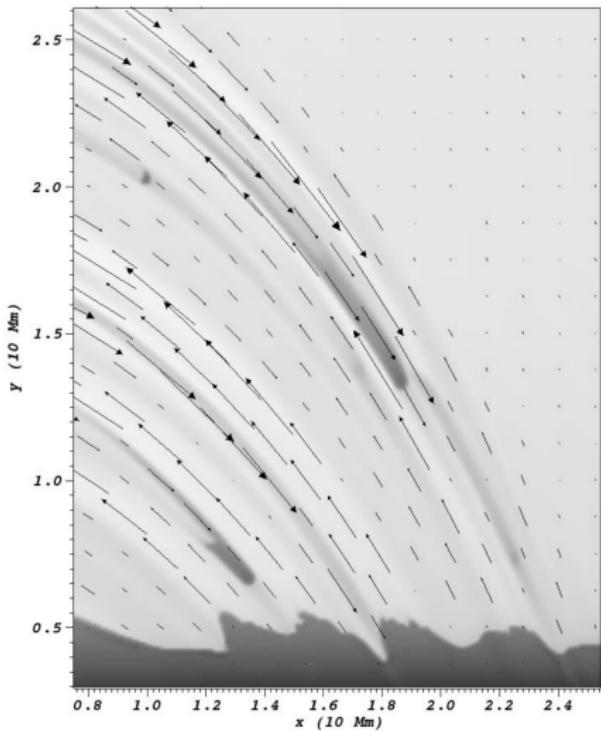


- rich dynamics: **evaporation in situ, merging and levitation**
 ⇒ phase-space trajectories: siphoning over loop tops

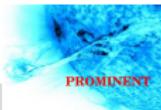


- blob size statistics, match observational knowledge

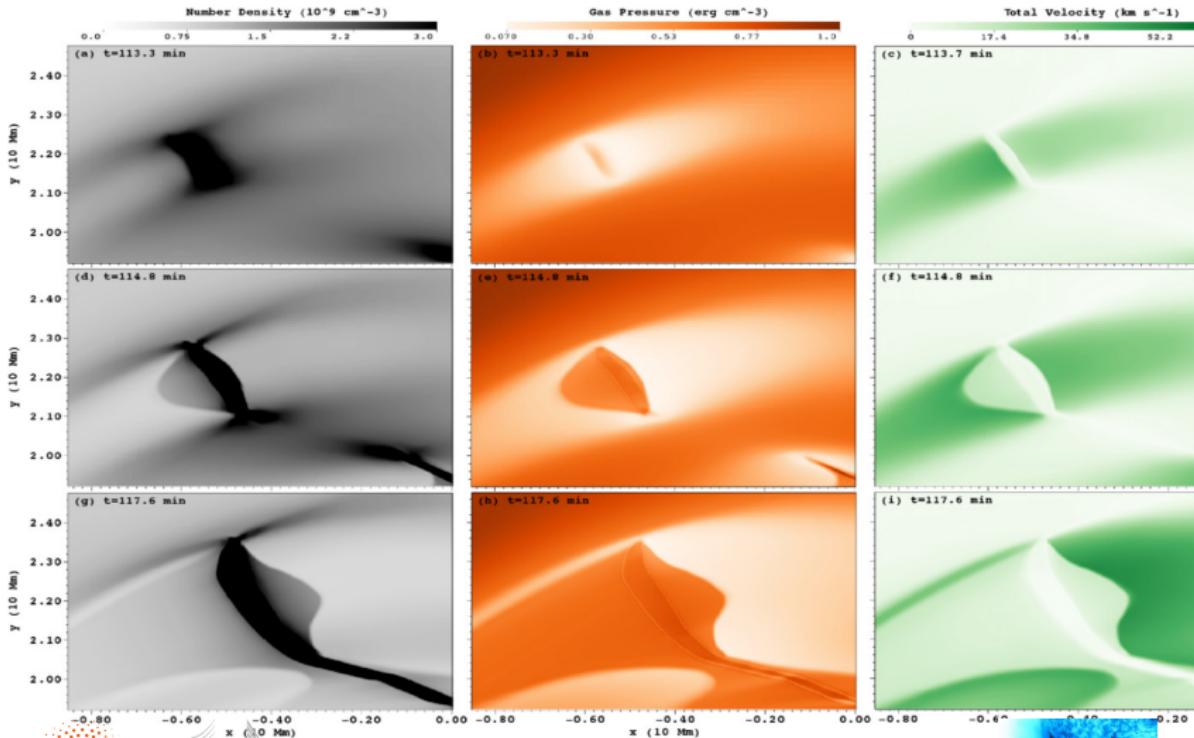




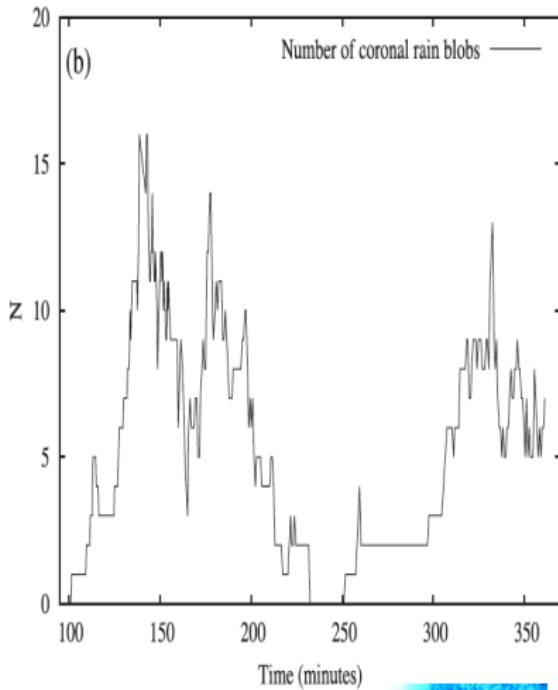
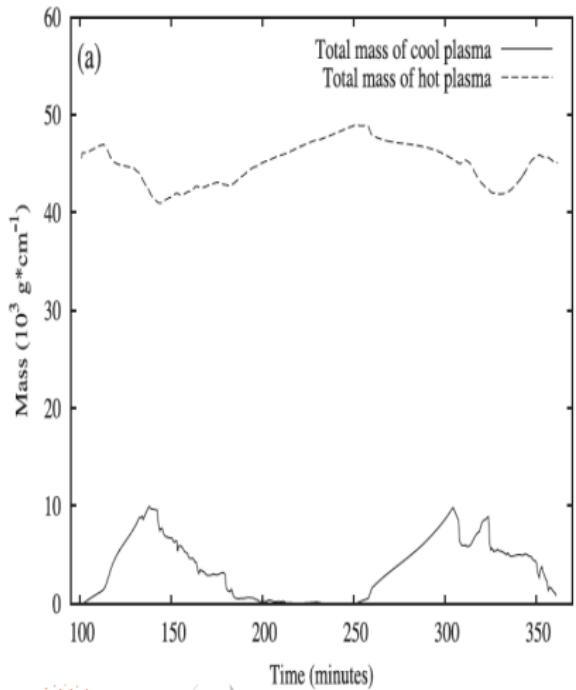
shear flow effects



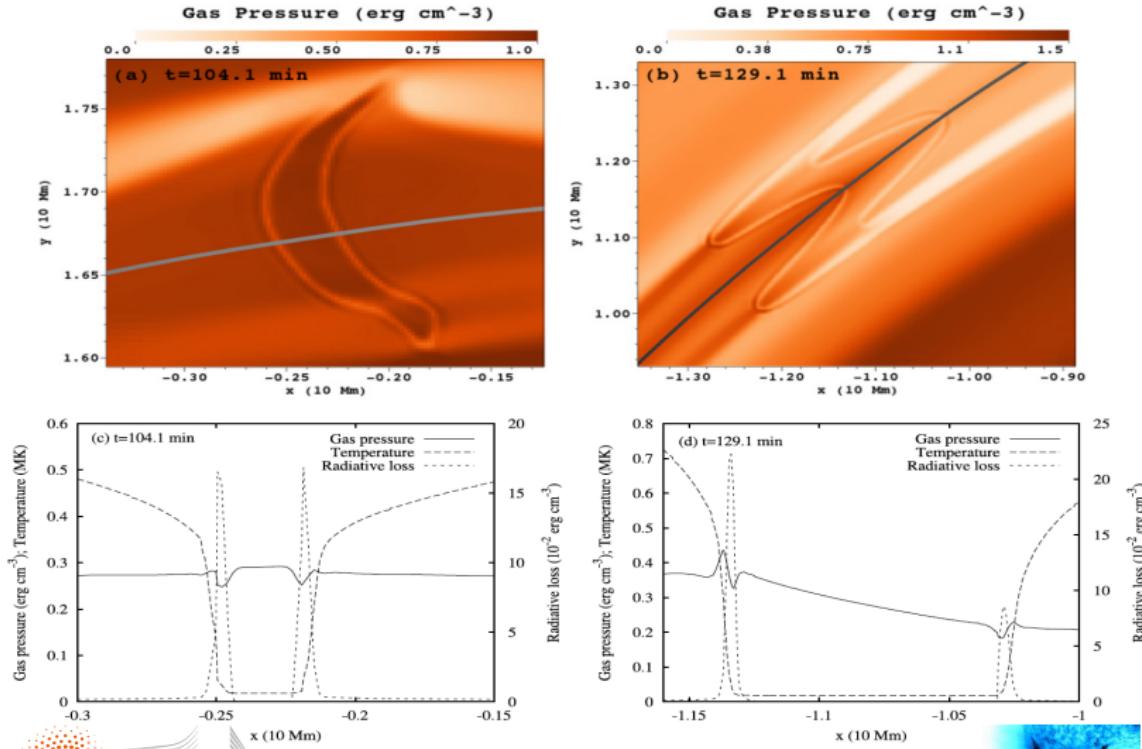
- [Fang et al, 2015, ApJ] rebound shocks: asymmetric aspects



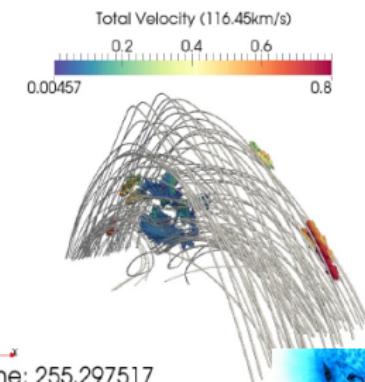
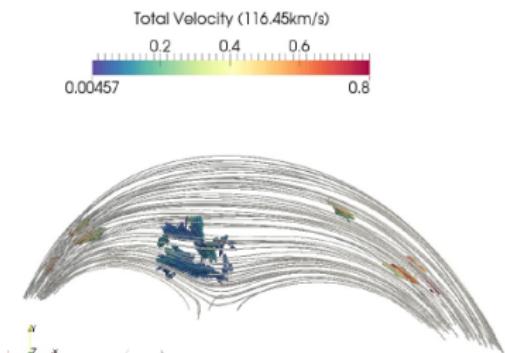
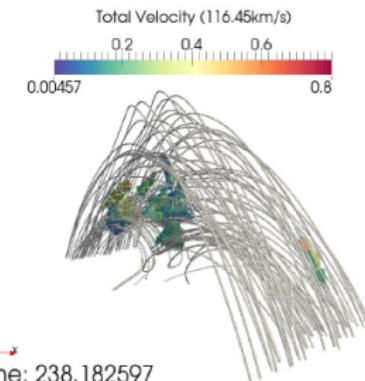
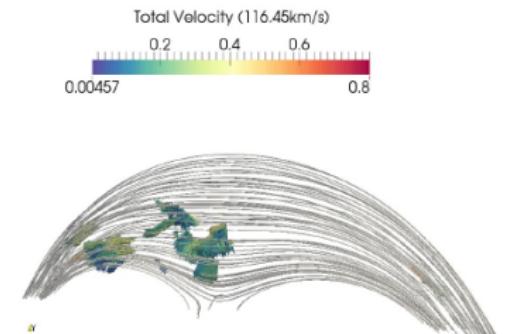
- [Fang et al, 2015, ApJ] limit cycles: mass recirculation



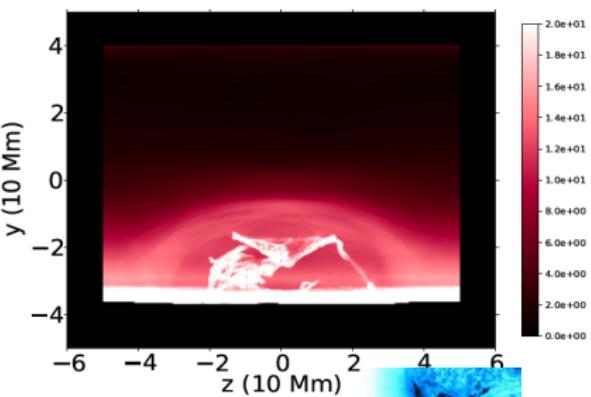
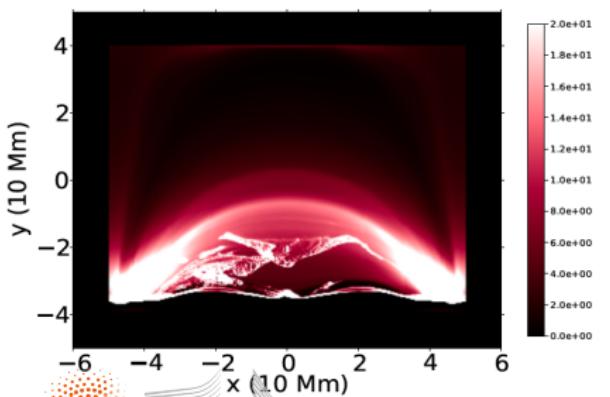
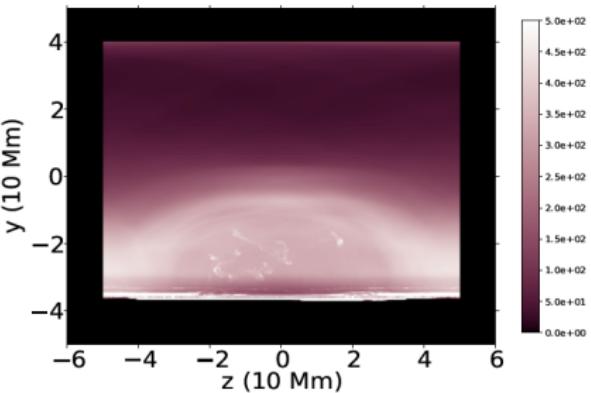
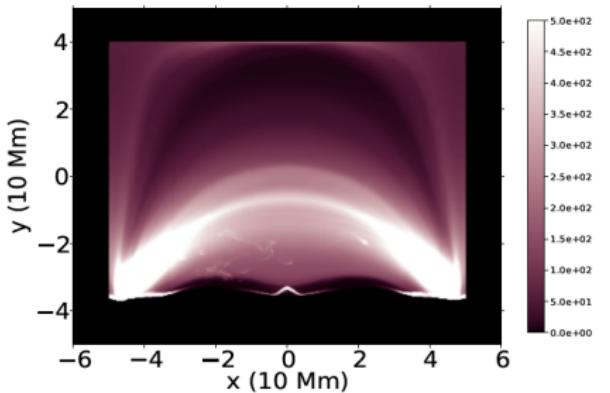
- [Fang et al, 2015, ApJ] detailed rain-TR-corona interface



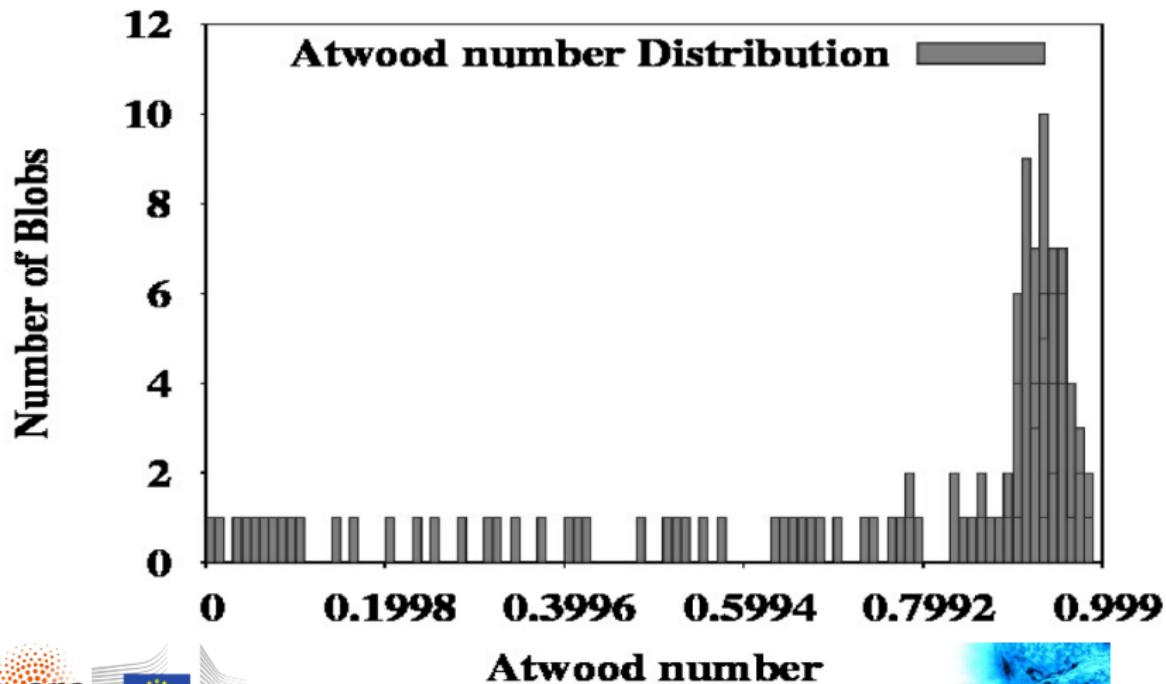
- 3D rain [Moschou et al, 2015, Advances in Space Research, 56]



AIA 211 and 304 Å



- Atwood number: $\frac{\rho_h - \rho_l}{\rho_h + \rho_l}$
⇒ typical density contrast of 20

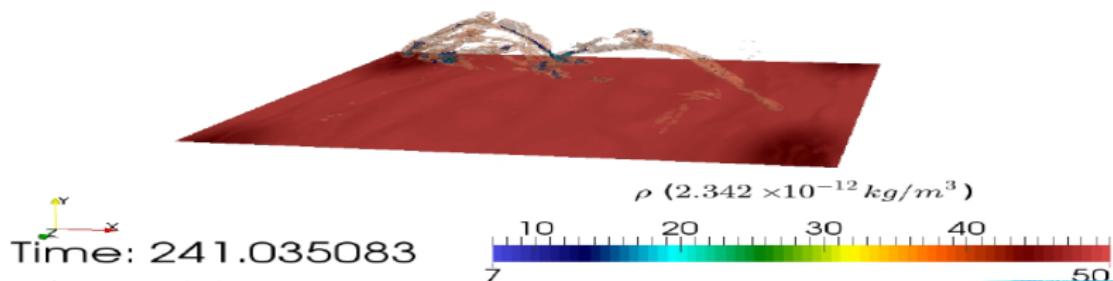
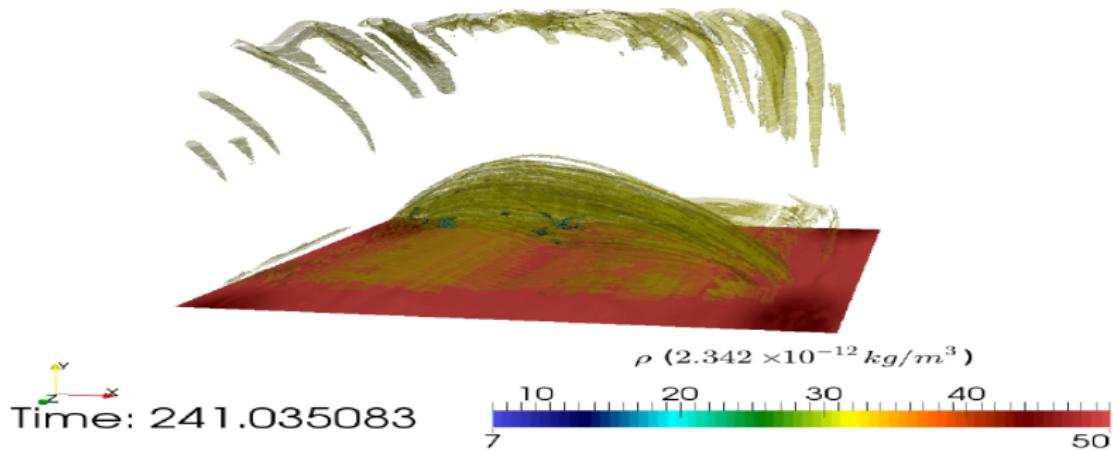


$$N_B^2 = \frac{1}{\rho^2} \frac{dp}{dy} \left(\frac{d\rho}{dy} - \frac{\rho}{\gamma p} \frac{dp}{dy} \right),$$

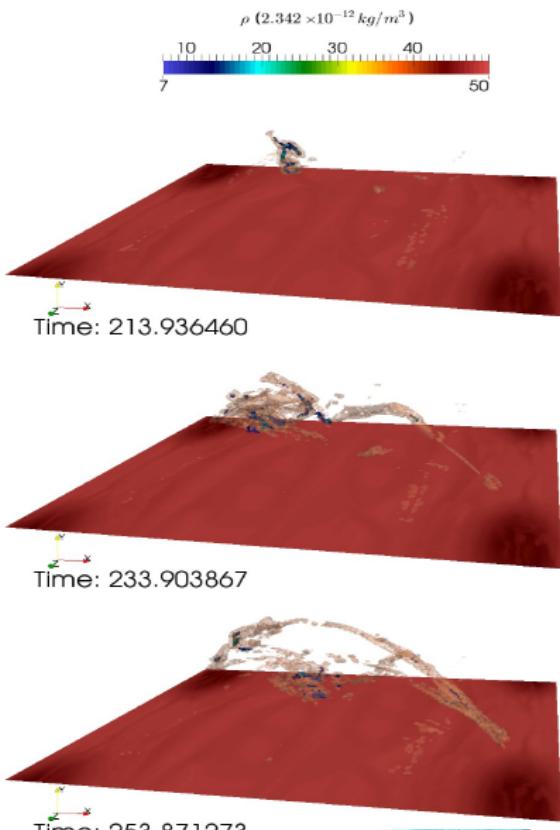
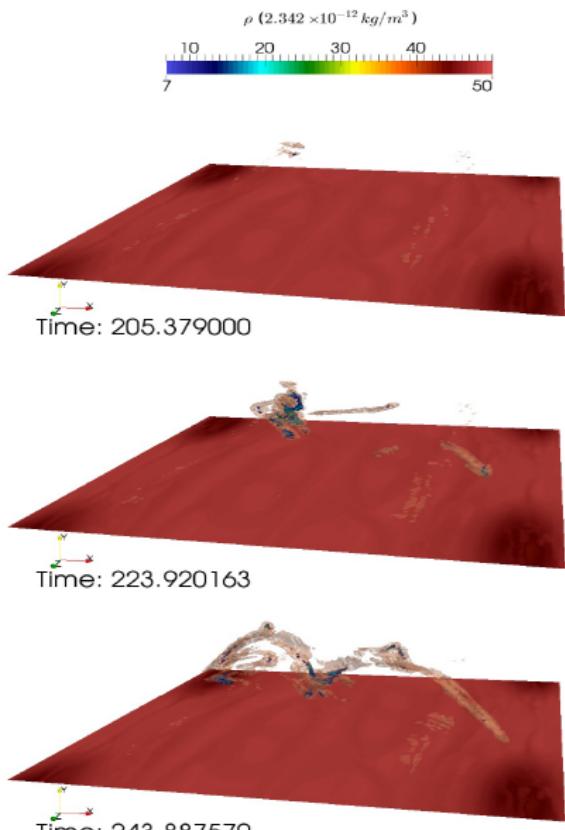
$$N_m^2 = \frac{1}{\rho^2} \frac{dp}{dy} \left(\frac{d\rho}{dy} - \frac{\rho}{\gamma p + B^2} \frac{dp}{dy} \right),$$

$$N_{B,p}^2 = \left[\frac{\vec{B}_p \cdot \nabla p}{\rho B} \right] \left[\frac{\vec{B}_p}{\rho B} \cdot \left(\nabla \rho - \frac{\rho}{\gamma p} \nabla p \right) \right],$$

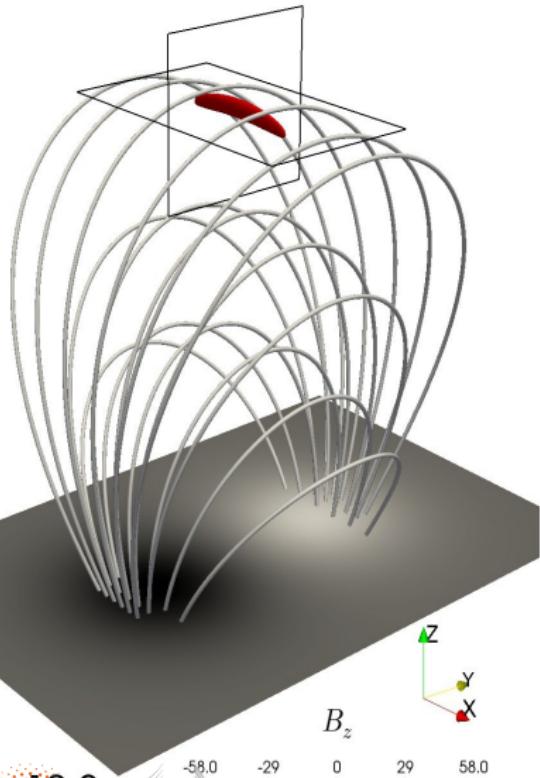
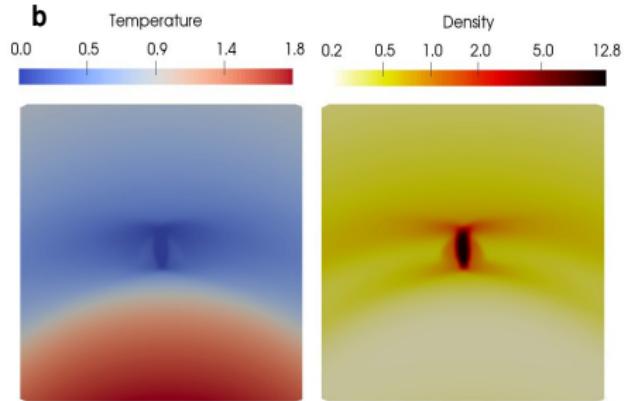
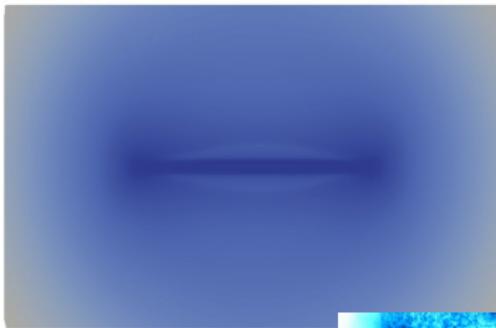
$$N_{m,p}^2 = \left[\frac{\vec{B}_p \cdot \nabla p}{\rho B} \right] \left[\frac{\vec{B}_p}{\rho B} \cdot \left(\nabla \rho - \frac{\rho}{\gamma p + B^2} \nabla p \right) \right],$$



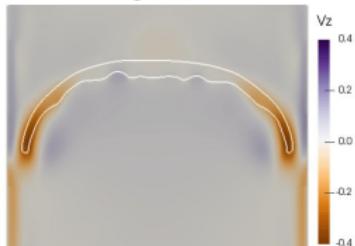
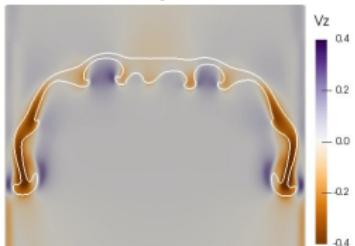
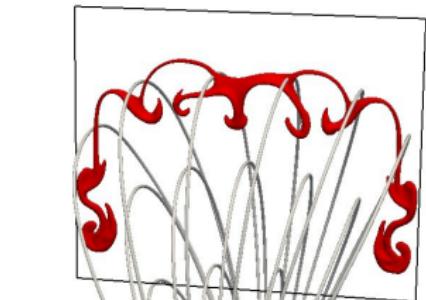
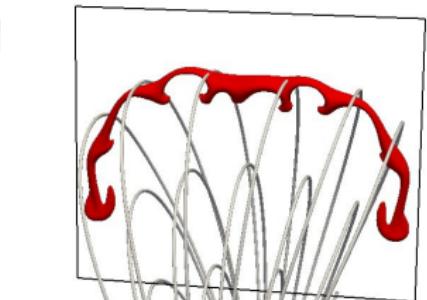
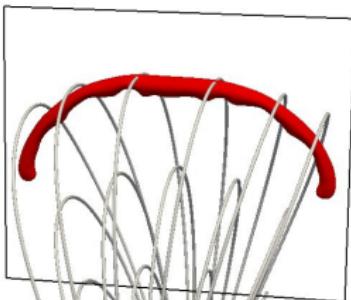
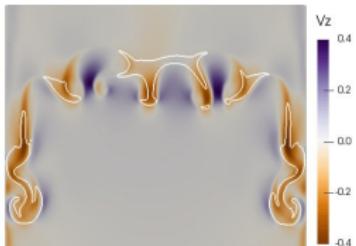
Coronal rain: multi-D effects



- [Xia et al, 2017 A&A 603]: rain in weak bipole

a**b****c**

- higher beta conditions at top: **RT deformations**

a**b****c**

Time

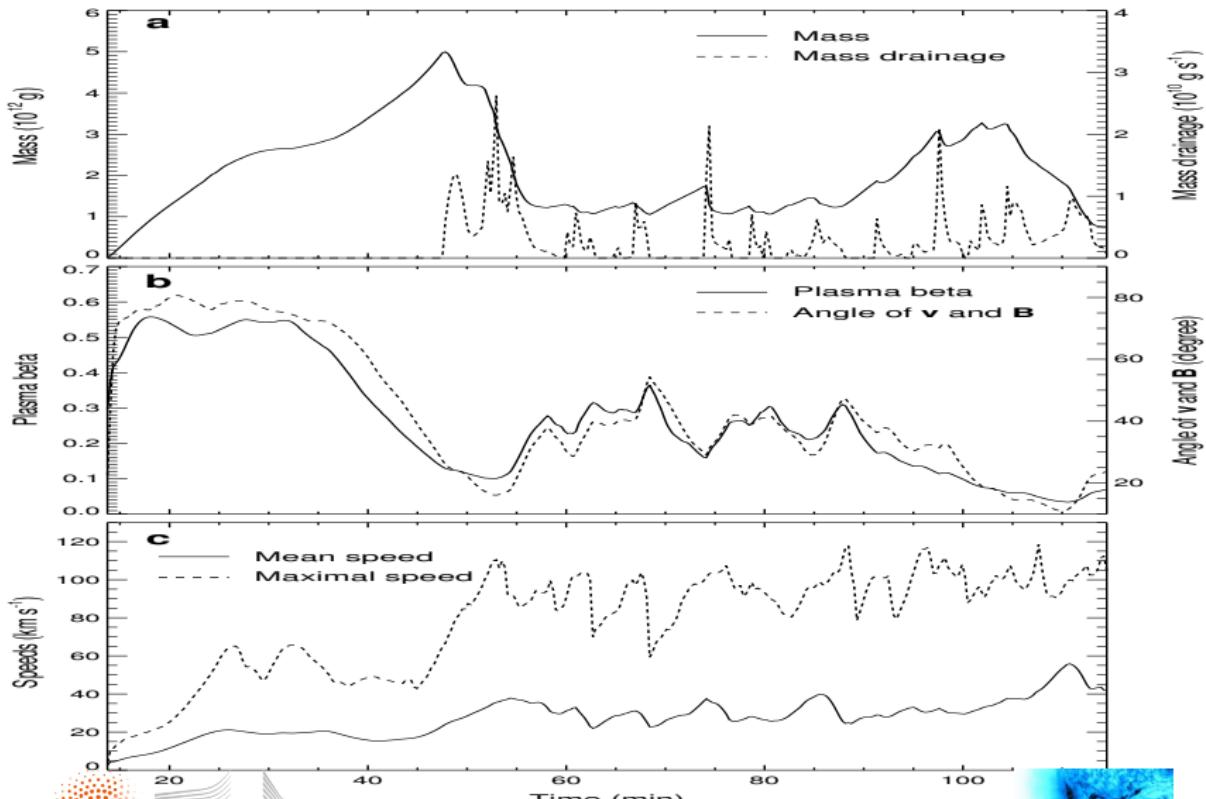
16.2

Time : 18.2

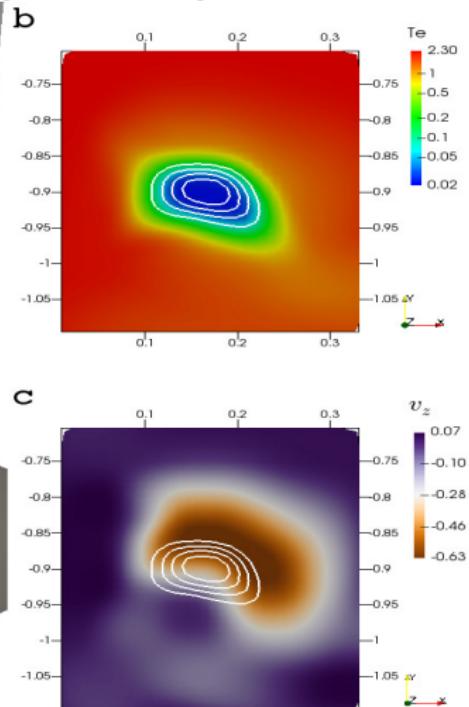
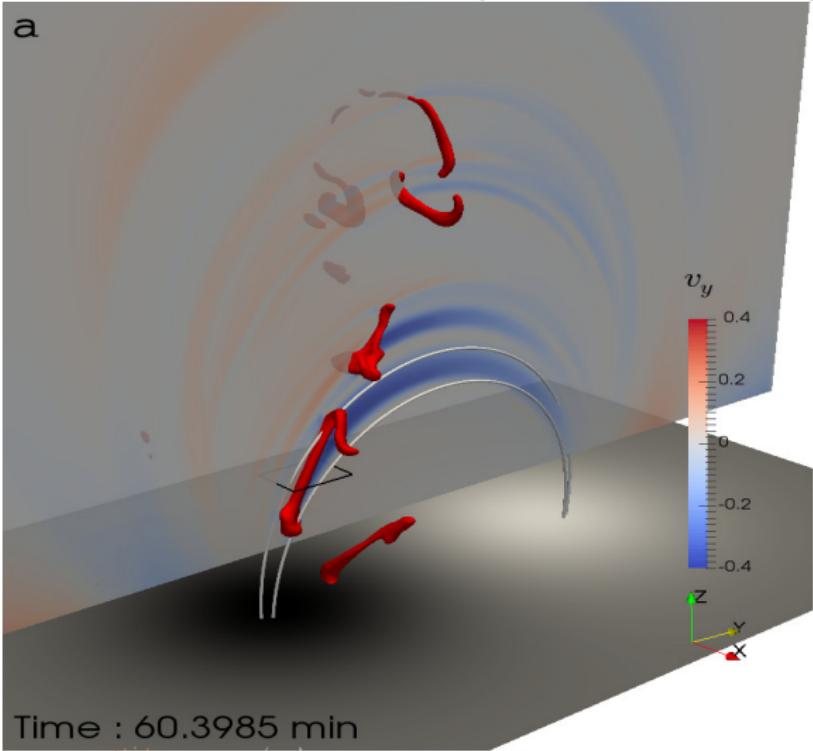
Time : 20.2



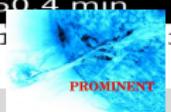
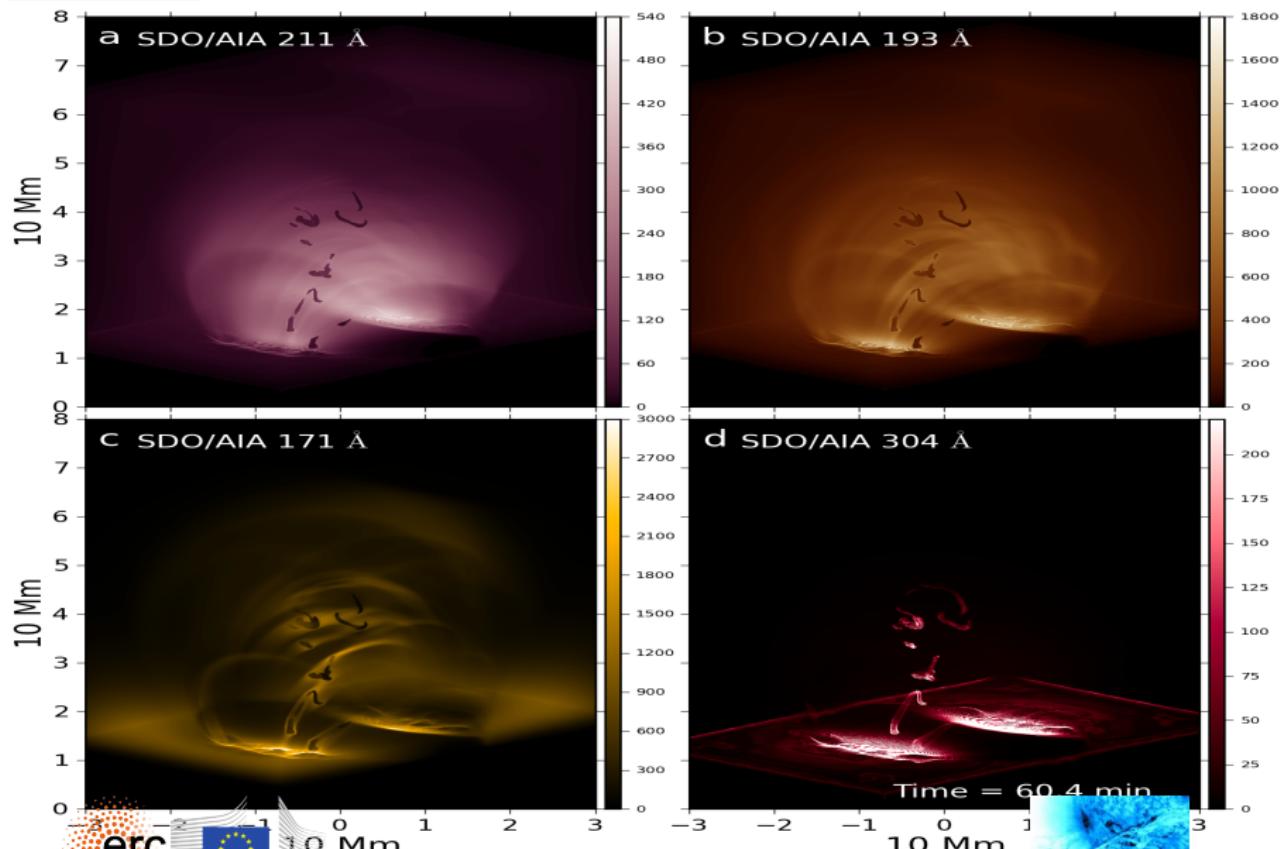
- flow and field alignment follows local β trend



- shear flows in conjunction with falling/deforming blobs

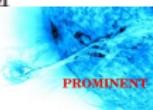
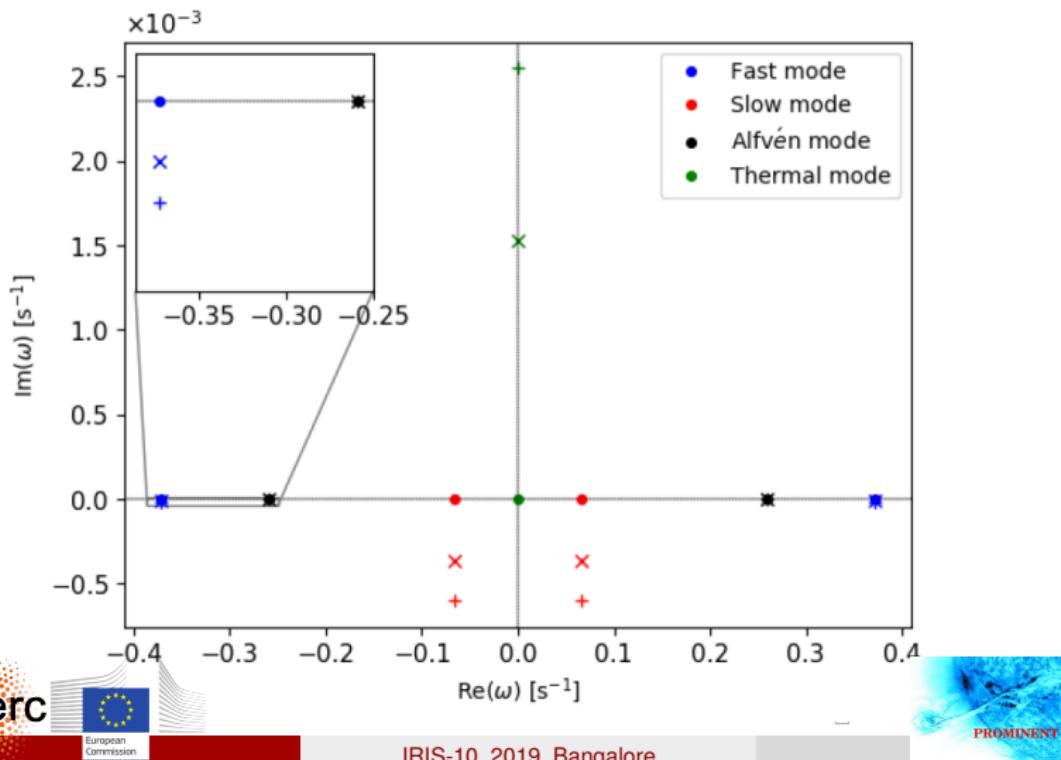


AIA views

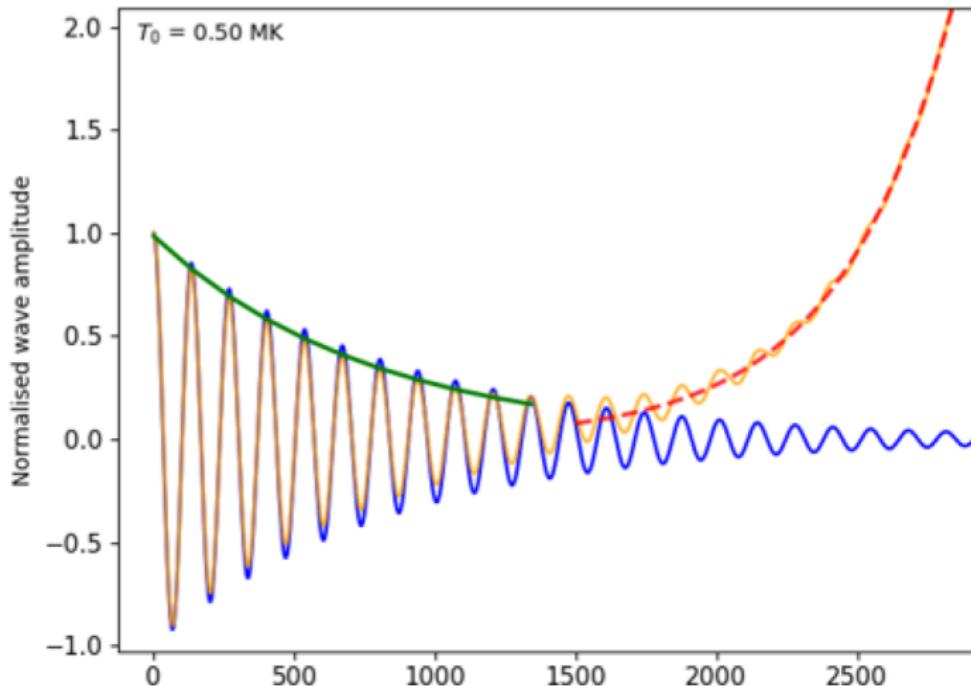


- 1 Coronal rain: 1D prelude
- 2 Coronal rain: multi-D effects
- 3 Back to basics

- condensation trigger: **thermal instability**
⇒ orientation of blobs with respect to magnetic field?
- revisit wave/instability in uniform media [Claes & RK, A&A 624, 2019]

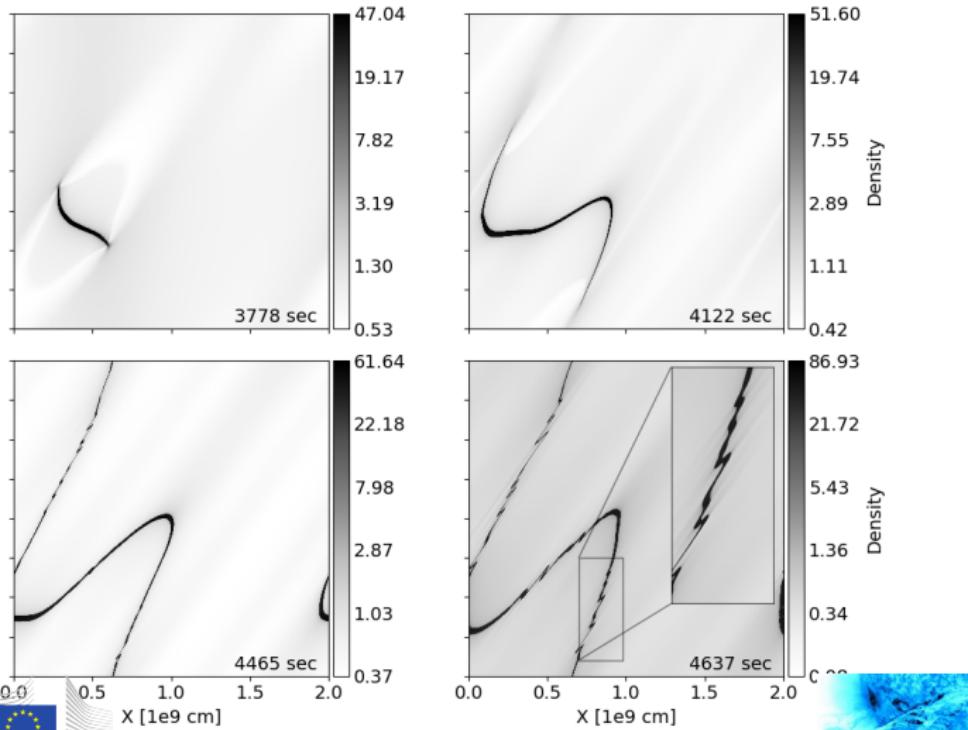


Propagating (damped) slow waves ultimately trigger thermal mode!

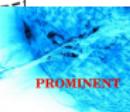
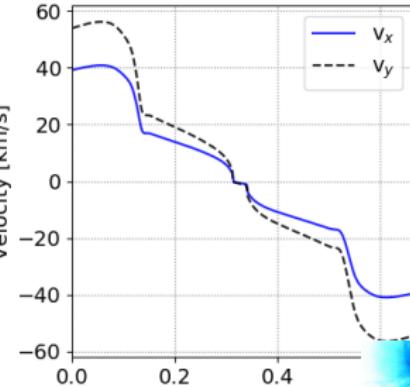
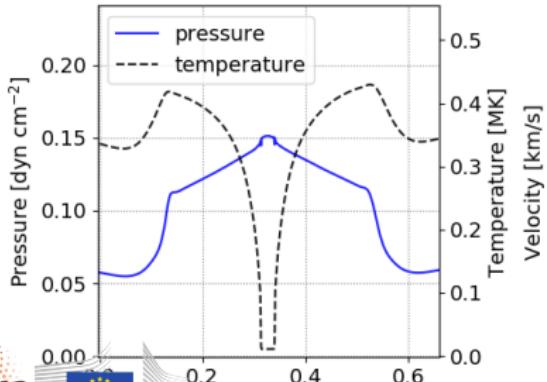
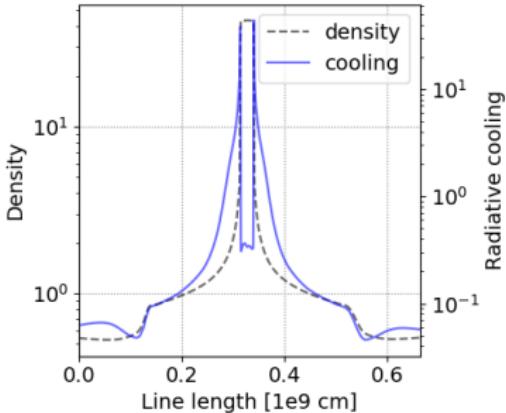
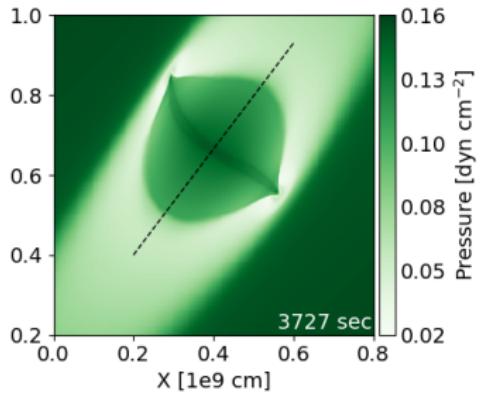


Slow waves interactions and fine structure evolution

- $T = 0.5\text{MK}$, $B = 10\text{G}$ at angle 0.3π , $\rho = 2.34 \times 10^{-15}\text{g/cm}^3$
 \Rightarrow down to 3 km resolution, 7 AMR levels



role of ram pressure and rebound shock physics



Outlook

- in-situ formation versus thermal non-equilibrium
- bridge gap linear theory & nonlinear MHD
 - ⇒ role of heating prescription?
 - ⇒ role of wave propagation?
- cause of fine structure? orientation with respect to **B**?
- onwards to realistic coronal rain simulations
 - ⇒ open-source software MPI-AMRVAC: amrvac.org
 - ⇒ RK, JCP 2012; Porth, ApJS 2014; Xia, ApJS 2018