MPI-AMRVAC and application to prominences

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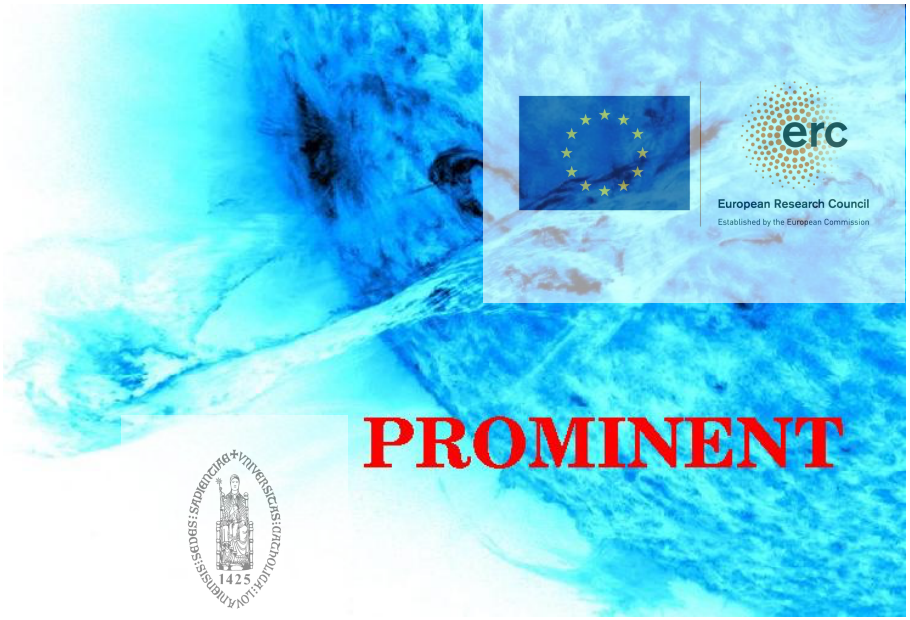

MPI-AMRVAC 3.0

The MPI - Adaptive Mesh Refinement - Versatile Advection Code

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Welcome page

Introduction

This is the documentation for the development version of MPI-AMRVAC. The code is available on Github, and the documentation on amrvac.org. If you have questions about MPI-AMRVAC, please send them to the mailing list: amrvacusers@ls.kuleuven.be, which you can also subscribe to and search.

Quick links

- Installation
- Getting started
- Setting parameters
- Frequently Asked Questions
- Contributing to MPI-AMRVAC and its documentation
- Publications related to MPI-AMRVAC
- Acknowledgments
- Recent changes

Recent code overview paper

Keppens et al. 2021, Computers & Mathematics with Applications 81,316

MPI-AMRVAC3.0: updates to an open-source simulation framework

http://amrvac.org

A&A publication, under review

- On dynamic, block-adaptive grid, `MPI-AMRVAC` solves PDE set

$$\partial_t \mathbf{u} + \nabla \cdot (\underbrace{\mathbf{F}(\mathbf{u})}_{\text{fluxes}}) = \underbrace{\mathbf{S}_\mathbf{u}}_{\text{sources}}$$

$\Rightarrow$ e.g. gas dynamics (HD), magnetohydrodynamics (MHD), reaction-diffusion systems, . . . in any dimensionality (1D, 2D, 3D)

$\Rightarrow$ support for elliptic solver: 'A geometric multigrid library for quadtree/octree AMR grids coupled to MPI-AMRVAC', Teunissen & Keppens, 2019, CPC 245, 106866

- **released** `MPI-AMRVAC 3.0` **Nov. 2022**

$\Rightarrow$ Radiative Hydro using Flux Limited Diffusion (Moens et al. A&A 657, A81, 2022);

$\Rightarrow$ ambipolar diffusion and full 2-fluid plasma-neutral model (Popescu & Keppens, A&A 653, A131, 2021; A&A 664, A28, 2022)

- current physics modules are
  - ⇒ `src/rho`: linear advection (for testing)
  - ⇒ `src/nonlinear`: Burgers and KdV equations
  - ⇒ `src/rd`: reaction-diffusion systems
  - ⇒ `src/ard`: advection-reaction-diffusion systems
  - ⇒ `src/hd`: Euler gas dynamics (+ dust)
  - ⇒ `src/rhd`: radiative HD with flux limited diffusion
  - ⇒ `src/mf`: **Magnetofrictional module**
  - ⇒ `src/mhd`: **MHD (+Hall/Ambipolar)**
  - ⇒ `src/twofl`: **plasma-neutral 2-fluid** (Popescu)
  - ⇒ `src/particle`: **particles** (sample/advect/Lorentz)
- note: all **any-D, geometry, compatible with AMR and solvers**

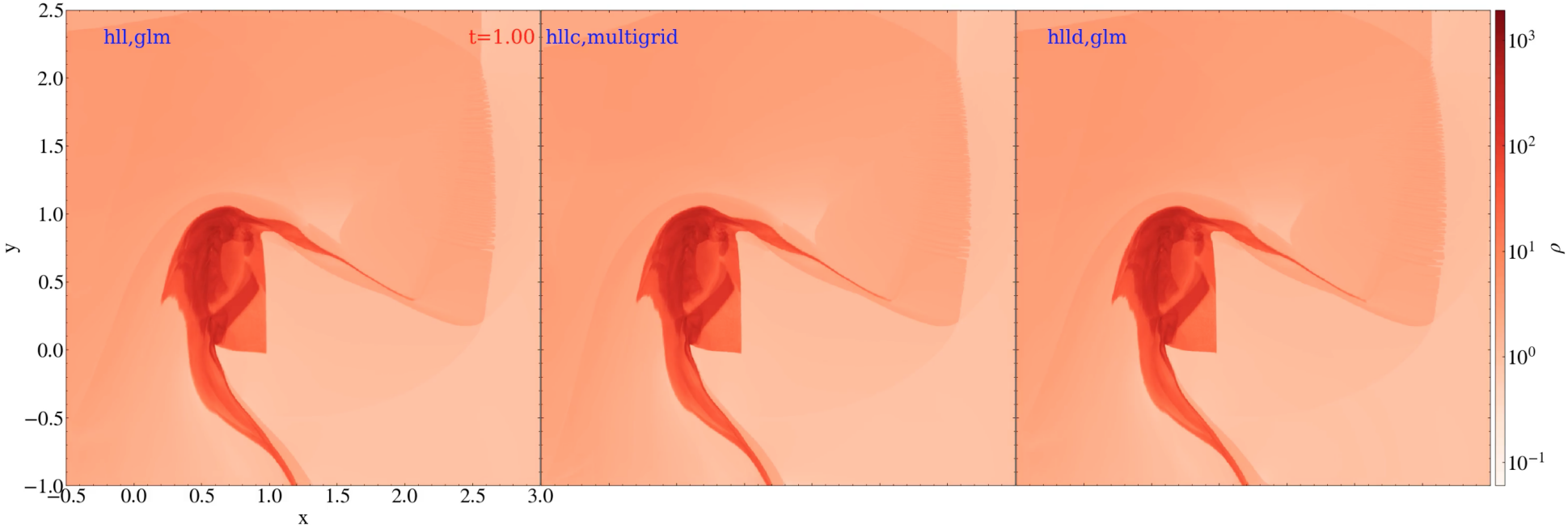
- other modules for certain sources: in `src/physics`, e.g.
  - ⇒ `mod_viscosity.t` for viscous sources
  - ⇒ `mod_gravity.t` for (external) user-coded gravity field
  - ⇒ `mod_thermal_conduction.t` conduction
  - ⇒ `mod_lfff.t` LFFF extrapolation from LOS magnetogram (3D MHD only)
  - ⇒ `mod_thermal_emission.t` on-the-fly EUV/SXR
  - ⇒ `mod_radiative_cooling.t` for opt. thin rad. loss (any-D HD-MHD, 20 tables available)
  - ⇒ `mod_rbsl.t` Regularized Biot-Savart-Law flux rope insertion (Titov 2018)

Curious? See: `http://dev.amrvac.org`

Scheme & $\nabla \cdot \mathbf{B}$ strategy

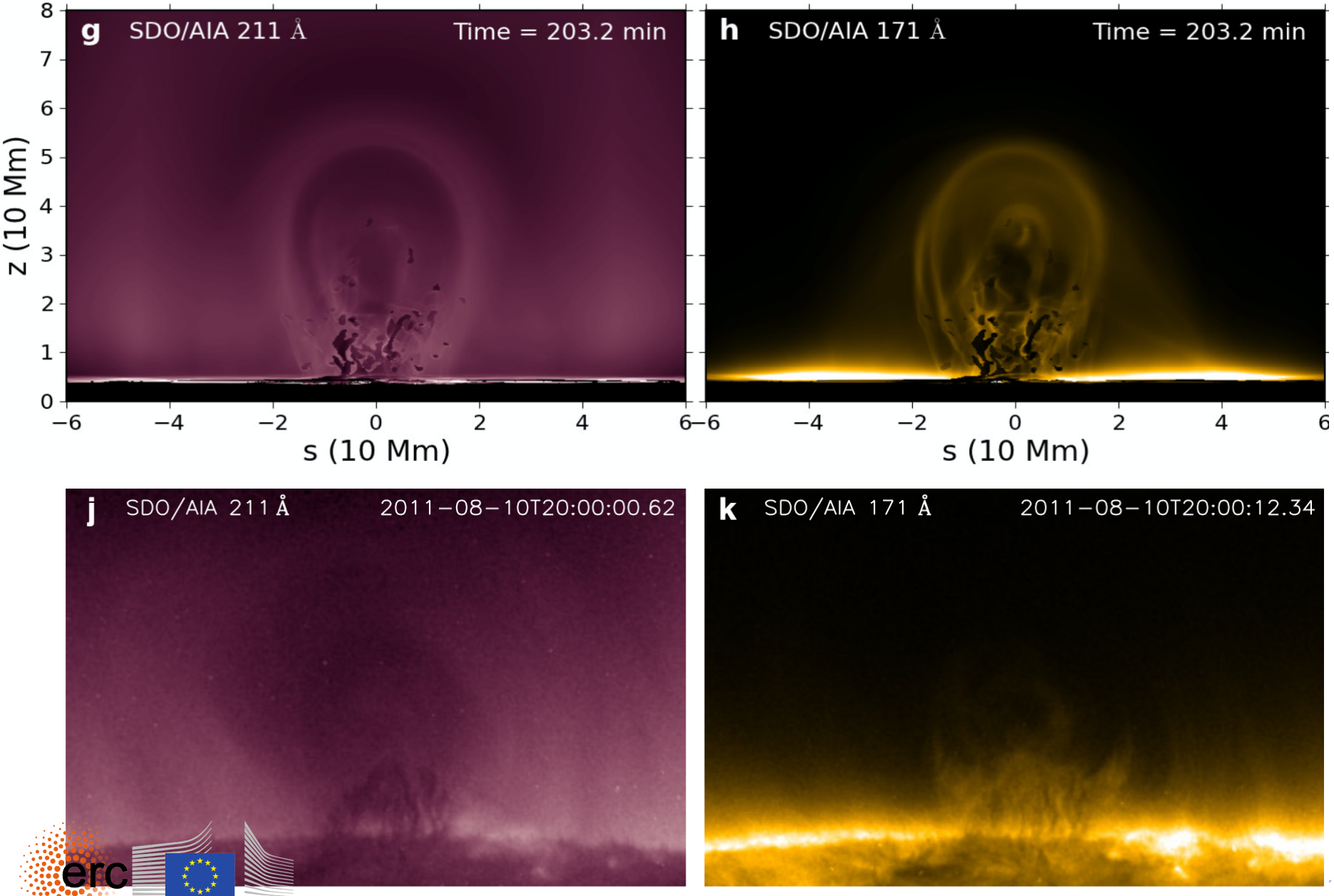
Alfven test

HLL-HLLC-HLLD schemes with elliptic/hyperbolic cleaning strategy



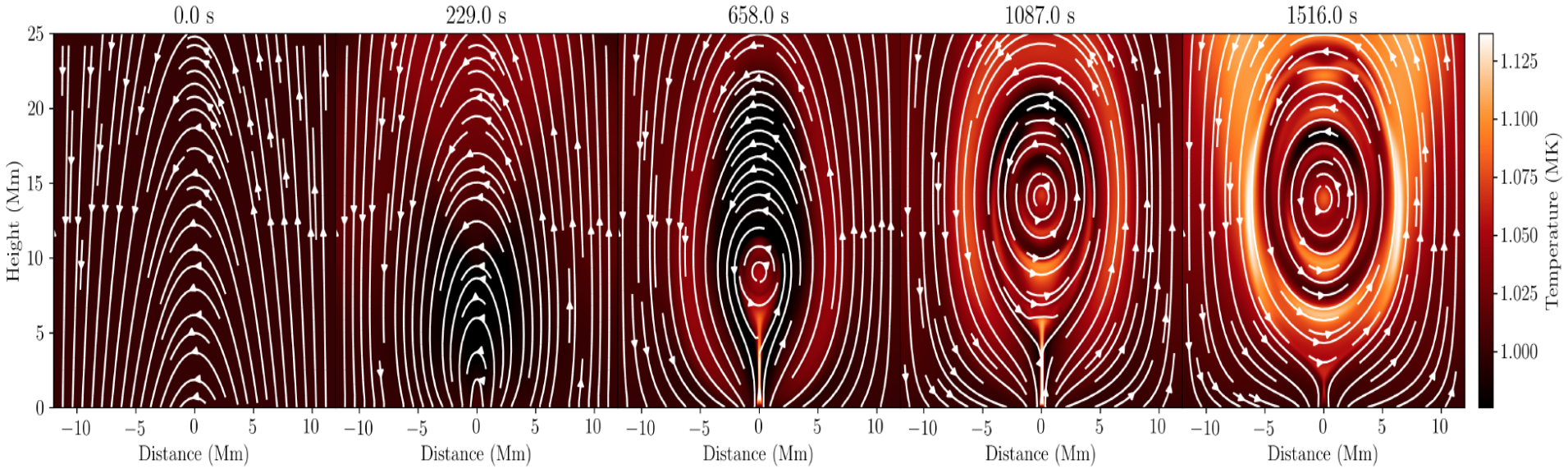
demonstrates input from external file, shock-cloud scenario (Corrugation!)

- Xia & RK 2016: prominence mass circulation in FR **SDO/AIA**



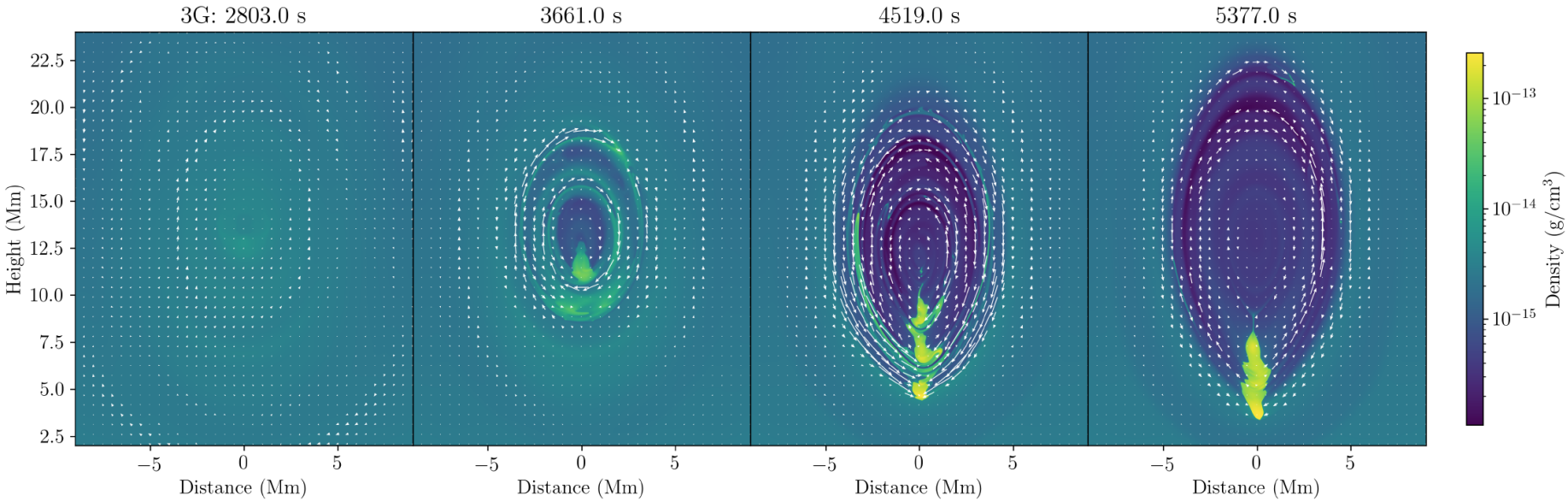
Forming prominences in flux ropes

- Jenkins & RK, A&A 646, A134 (2021)



$\Rightarrow$ deform arcade into fluxrope by footpoint motions

- thermal instability (optically thin radiation) triggers condensation
  - $\Rightarrow$ levitation-condensation (Kaneko & Yokoyama, 2015)
- High (5.6km) resolution: **initial fine-structure**
  - $\Rightarrow$ density $\rho(x, y)$ views



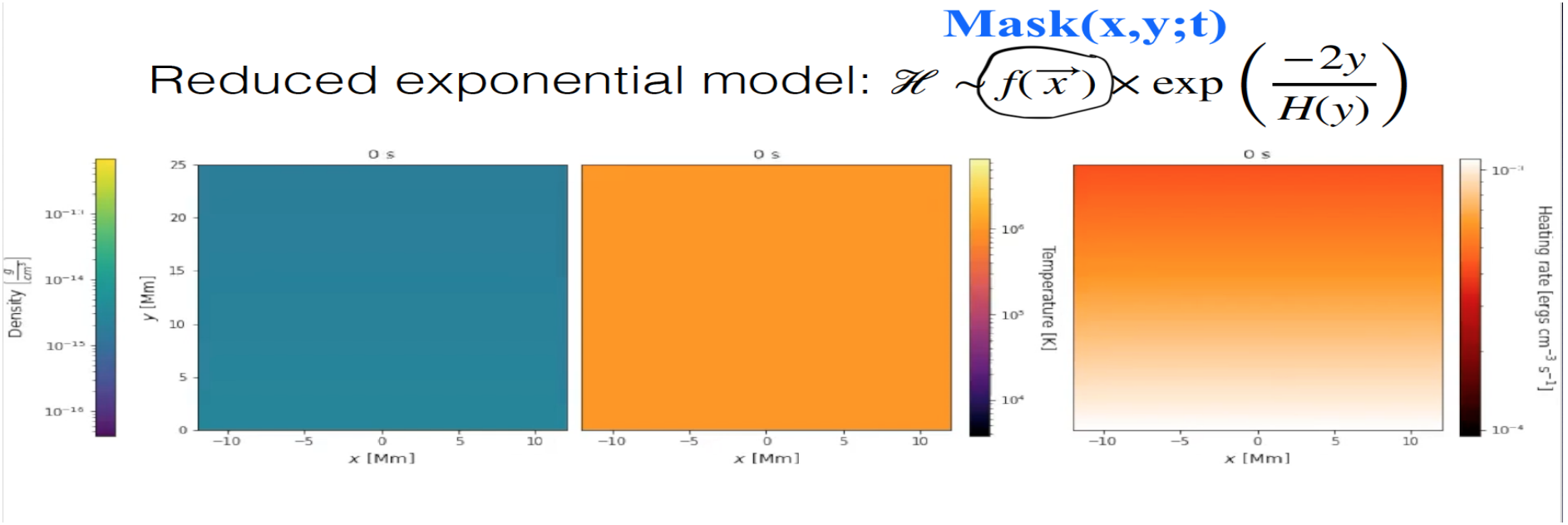
  - $\Rightarrow$ can identify various (linear MHD) instability roles!

Explore background heating

- Nicolas Brughmans et al (2022, A&A 668, A47)

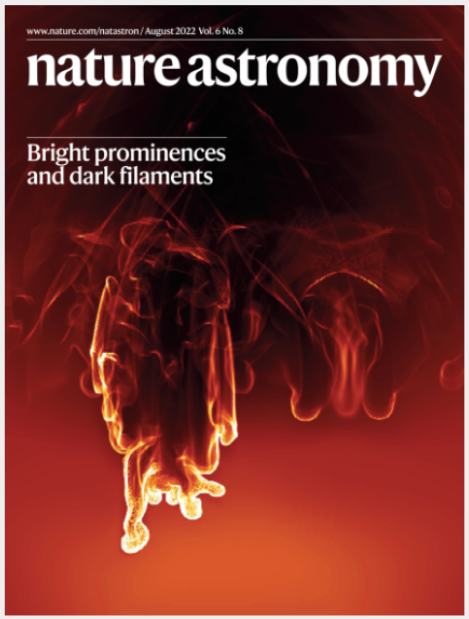
  $\Rightarrow$ exploring the assumed background heating

Reduced exponential model: $\mathscr{H} \sim f(\vec{x}) \times \exp\left(\frac{-2y}{H(y)}\right)$ **Mask(x,y;t)**



with dynamically reduced heating: form more massive prominences

Volume 6 Issue 8, August 2022



Bright prominences and dark filaments

Solar prominences appear as bright loops at the Sun's limb and as dark filaments if they are observed against the solar disk. A MHD simulation shows that the development of the magnetic Rayleigh–Taylor instability is essential for the formation of these features and can explain their difference in appearance.

See Jenkins et al.

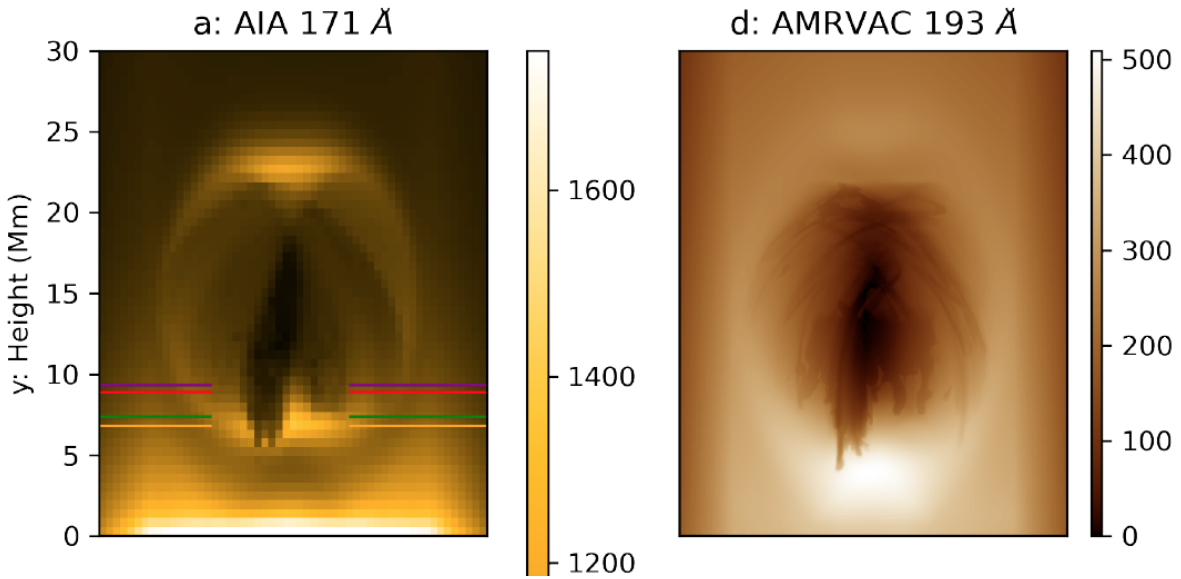
Image: Jack M. Jenkins, Centre for mathematical Plasma Astrophysics, KU Leuven. Cover Design: Bethany Vukomanovic

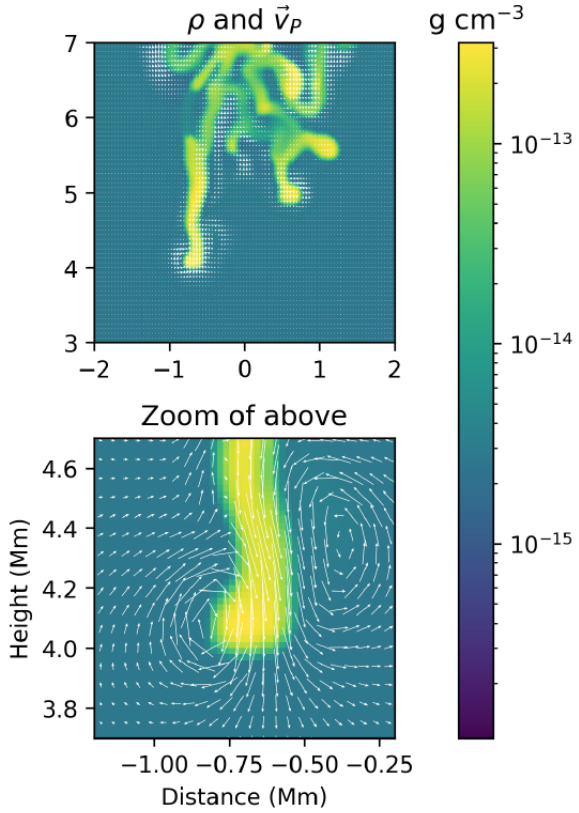
Jenkins & RK, Nat. Astronomy, August 2022

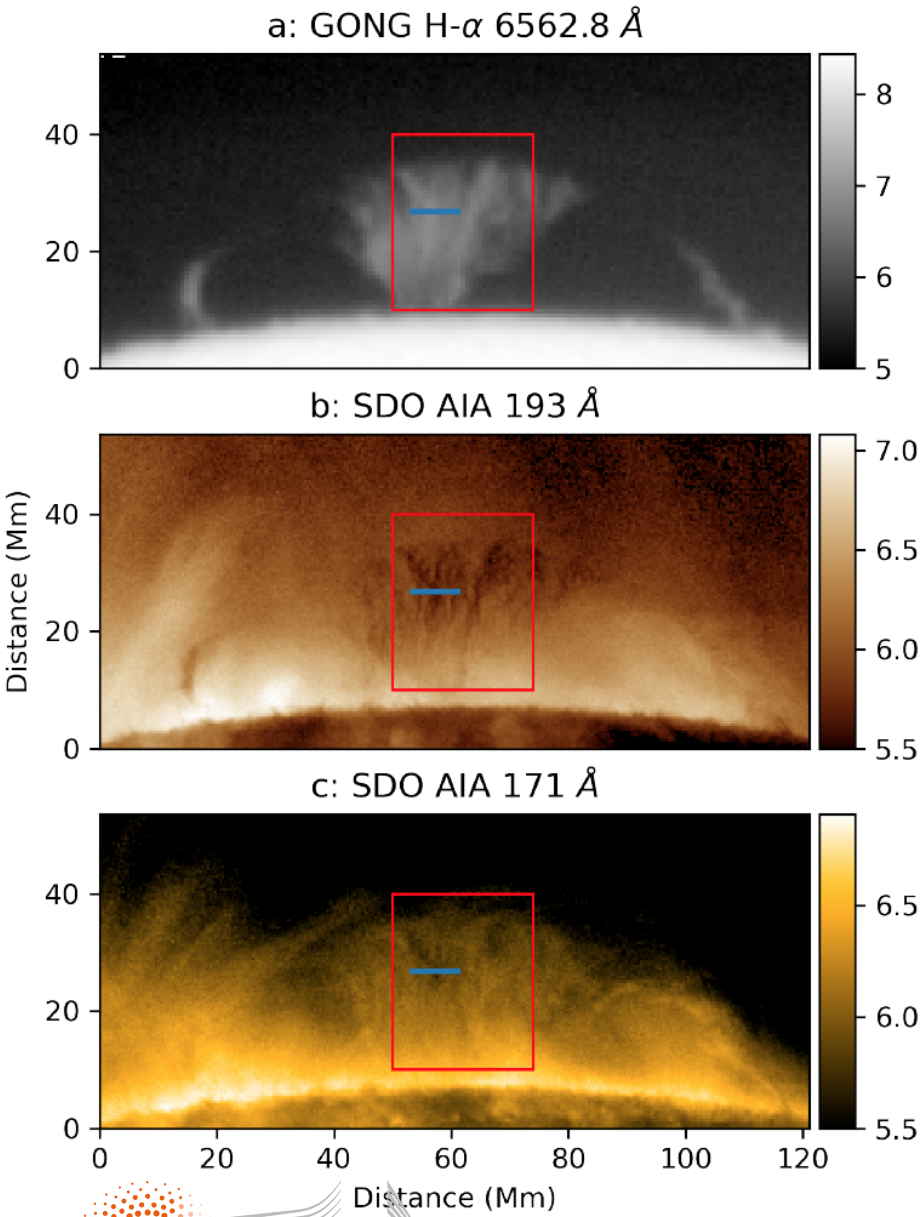
need 3D to allow $\mathbf{k} \cdot \mathbf{B} = 0$ (minimal fieldline bending)

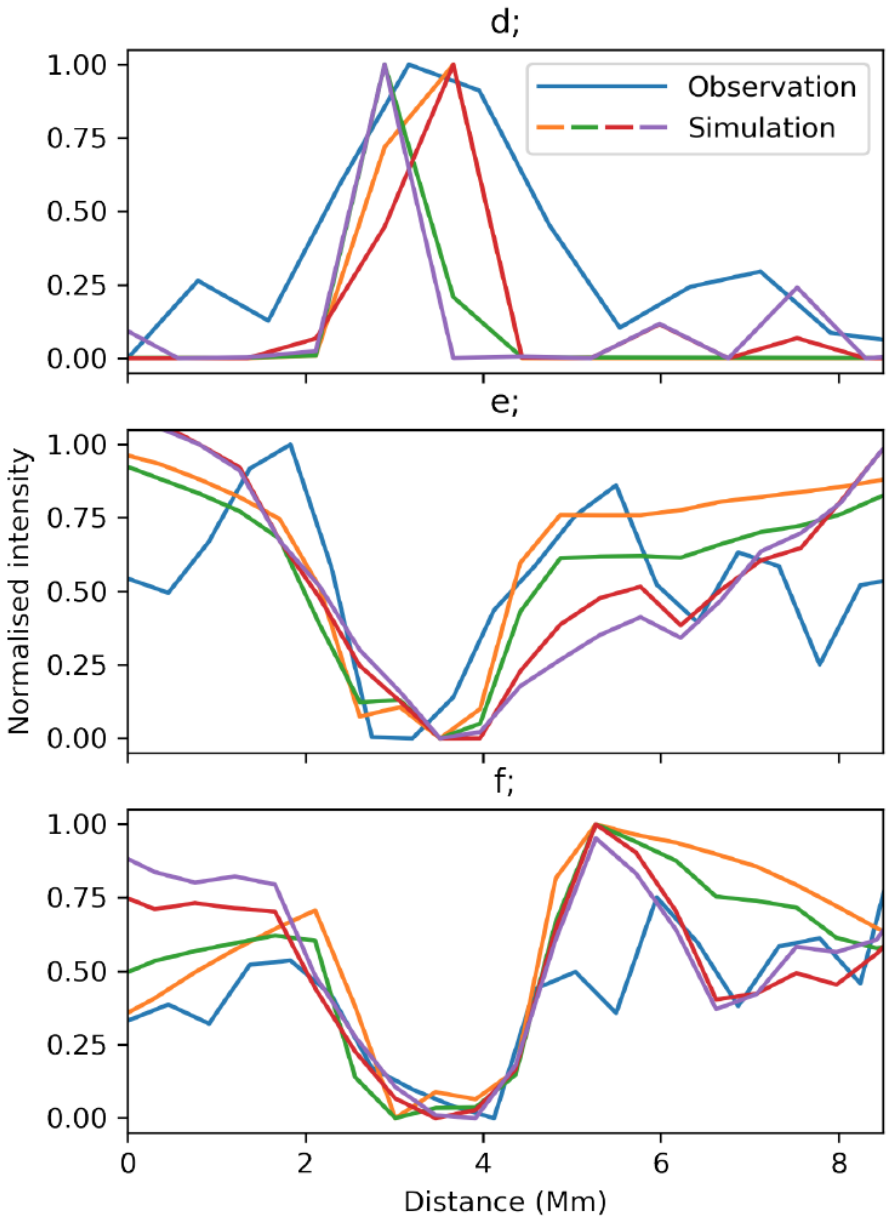
3D prominence/filament formation: mRTI

3D prominence rendering

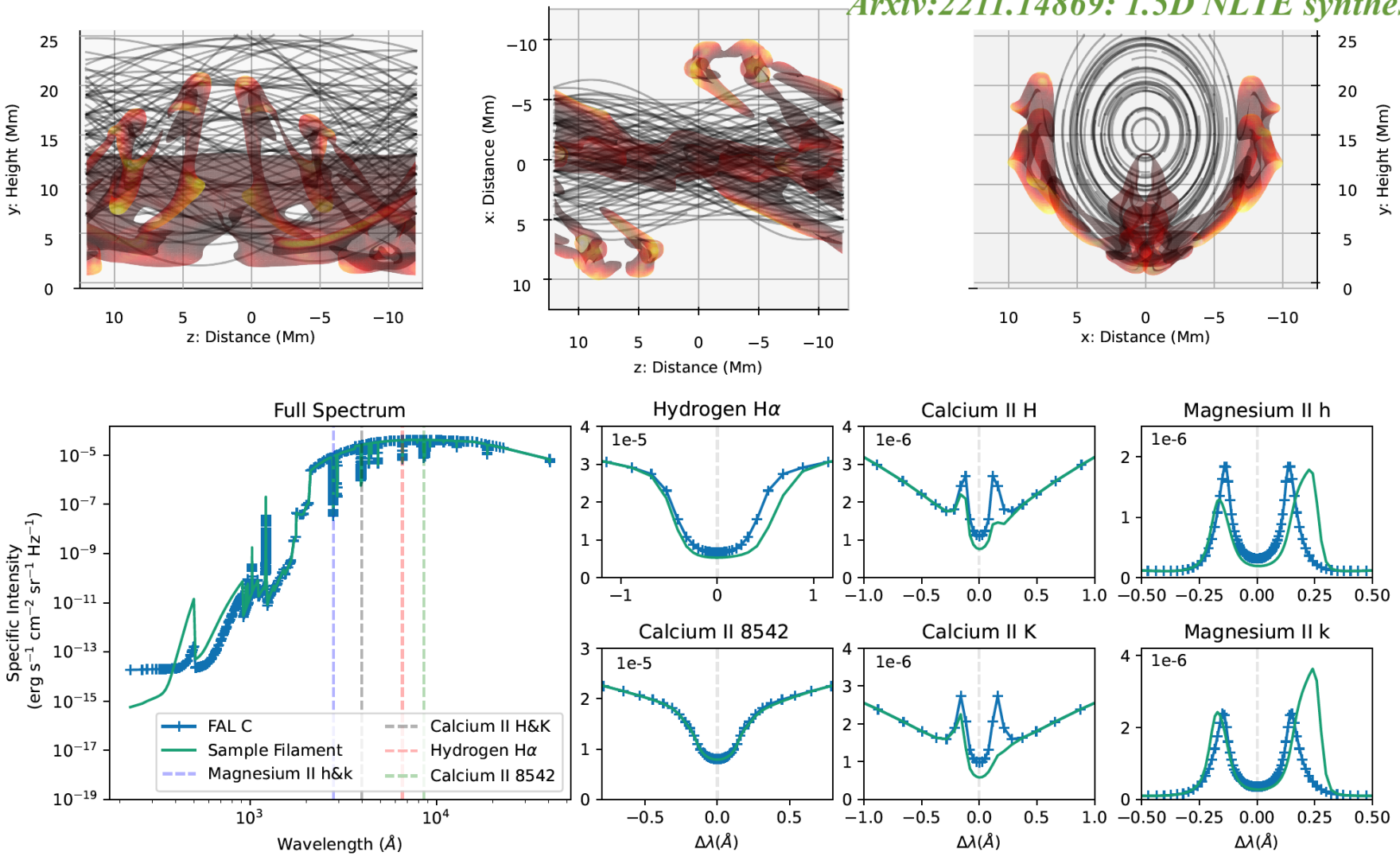




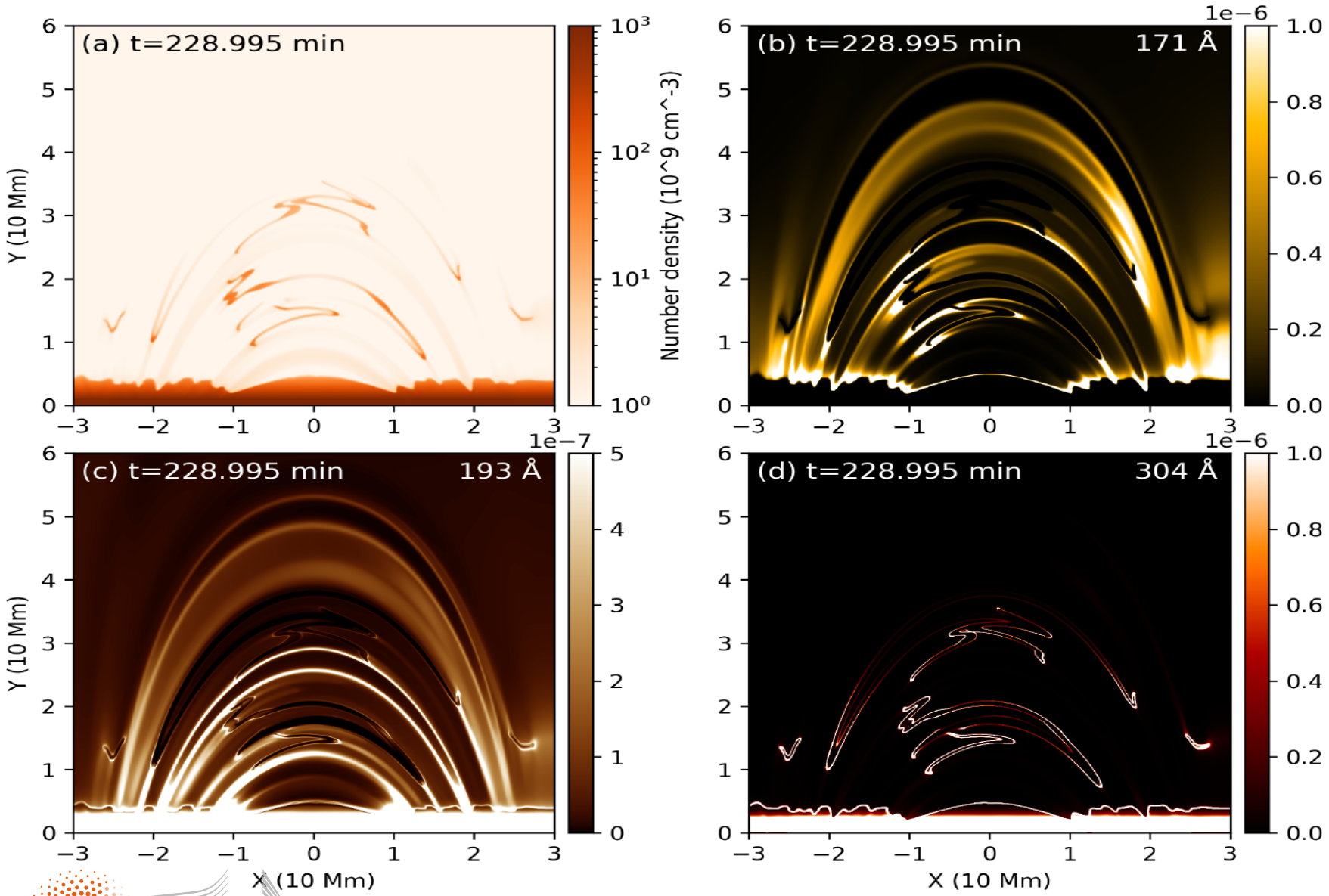

a: GONG H-α 6562.8 Å
b: SDO AIA 193 Å
c: SDO AIA 171 Å
Distance (Mm)
Distance (Mm)


d;
e;
f;
Observation
Simulation
Normalised intensity
Distance (Mm)

Arxiv:2211.14869: 1.5D NLTE synthesis



Li et al., Coronal rain in randomly heated arcades [ApJ 926, 216 (2022)]



Outlook for http://(dev.)amrvac.org

- **MPI-AMRVAC 3.0**: **feel free to use/contribute/develop!**
- solar applications: **Veronika, Samrat, Madhurjya, Valeriia**

- talk on 3D solar flare turbulence **Wenzhi Ruan**
  - ⇒ **First self-consistent flare model**: ApJ 896, 97 (2020)
- spin-off codes:
  - ⇒ **BHAC** used in EHT: GRMHD on block-adaptive grids: See: http://bhac.science
  - ⇒ **GR-AMRVAC** DOI 10.1088/0264-9381/33/15/155010
  - ⇒ **Gmunu**: GRMHD + metric 10.1093/mnras/stab2606
  - ⇒ **ICARUS**: grid-adaptive space-weather MHD
  - ⇒ EUHFORIA upgraded! A&A 662, A50 http://euhforia.com