TURIN ASTRONOMICAL OBSERVATORY
KATHOLIEKE UNIVERSITEIT LEUVEN

Lagrangian MHD Particle-in-Cell simulations of coronal interplanetary shocks driven by observations

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Fabio BACCHINI[1]

prof. Giovanni LAPENTA[1]
dr. Alessandro BEMPORAD[2]
dr. Roberto SUSINO[2]

1. Katholieke Universiteit Leuven, Department of Mathematics, CmPA
2. Turin Astronomical Observatory

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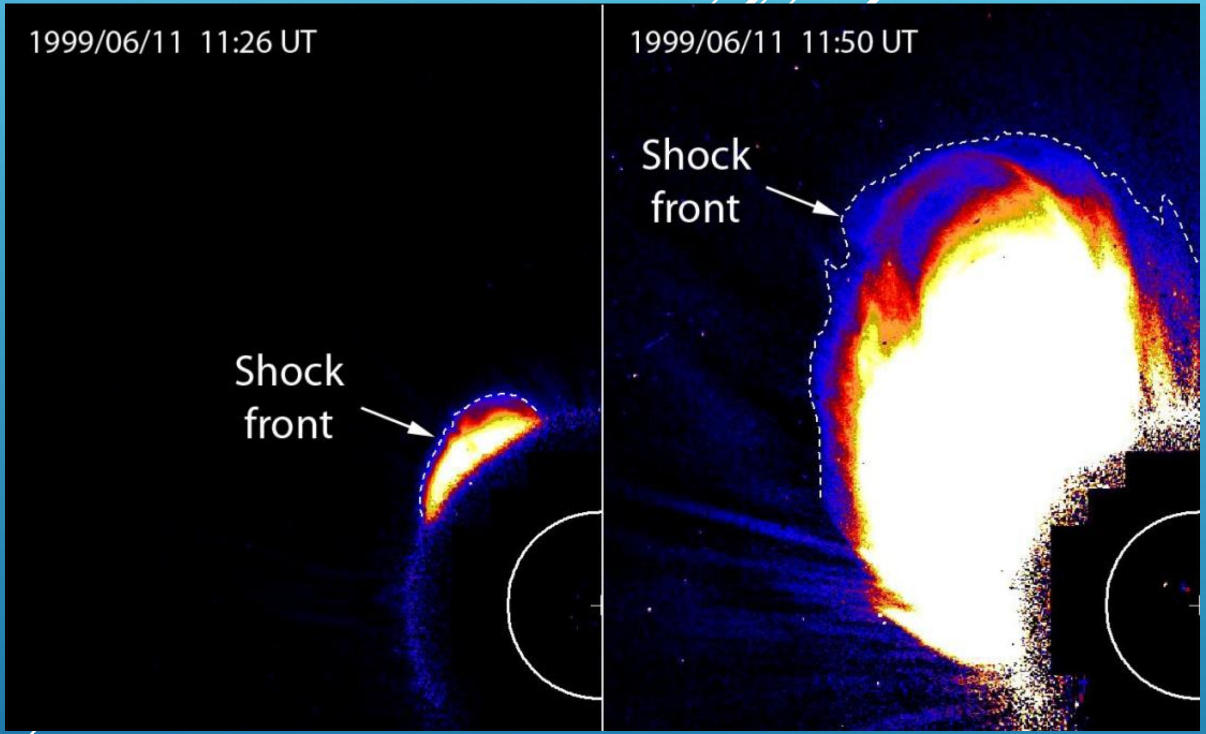
OUTLINE

- Comparison between the observed features of a CME-driven shock and the results of MHD simulations. The June 11, 1999 CME event is taken as a reference.
- 2D Particle-in-Cell, visco-resistive, Lagrangian MHD simulation of a CME-like wave propagating through a cylindrical domain with realistic initial conditions.
- 1D ideal Lagrangian MHD simulation of the proton-electron energy decoupling along the shock front.

STUDYING A CME-DRIVEN SHOCK

- Coronal Mass Ejections → massive, complex plasma structures often preceded by fast moving shocks
- Formation & propagation mechanism not completely understood
- Observations allow to retrieve upstream and downstream plasma parameters [Bemporad et al. (2014)]



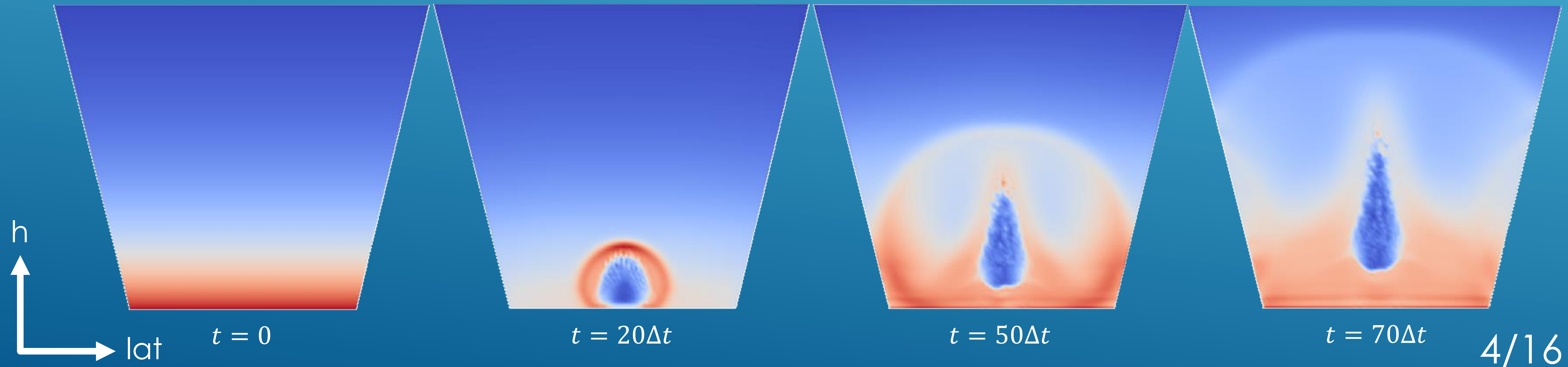
[Bemporad et al. (2011)]

SIMULATING A CME EVENT: FLIPMHD3D

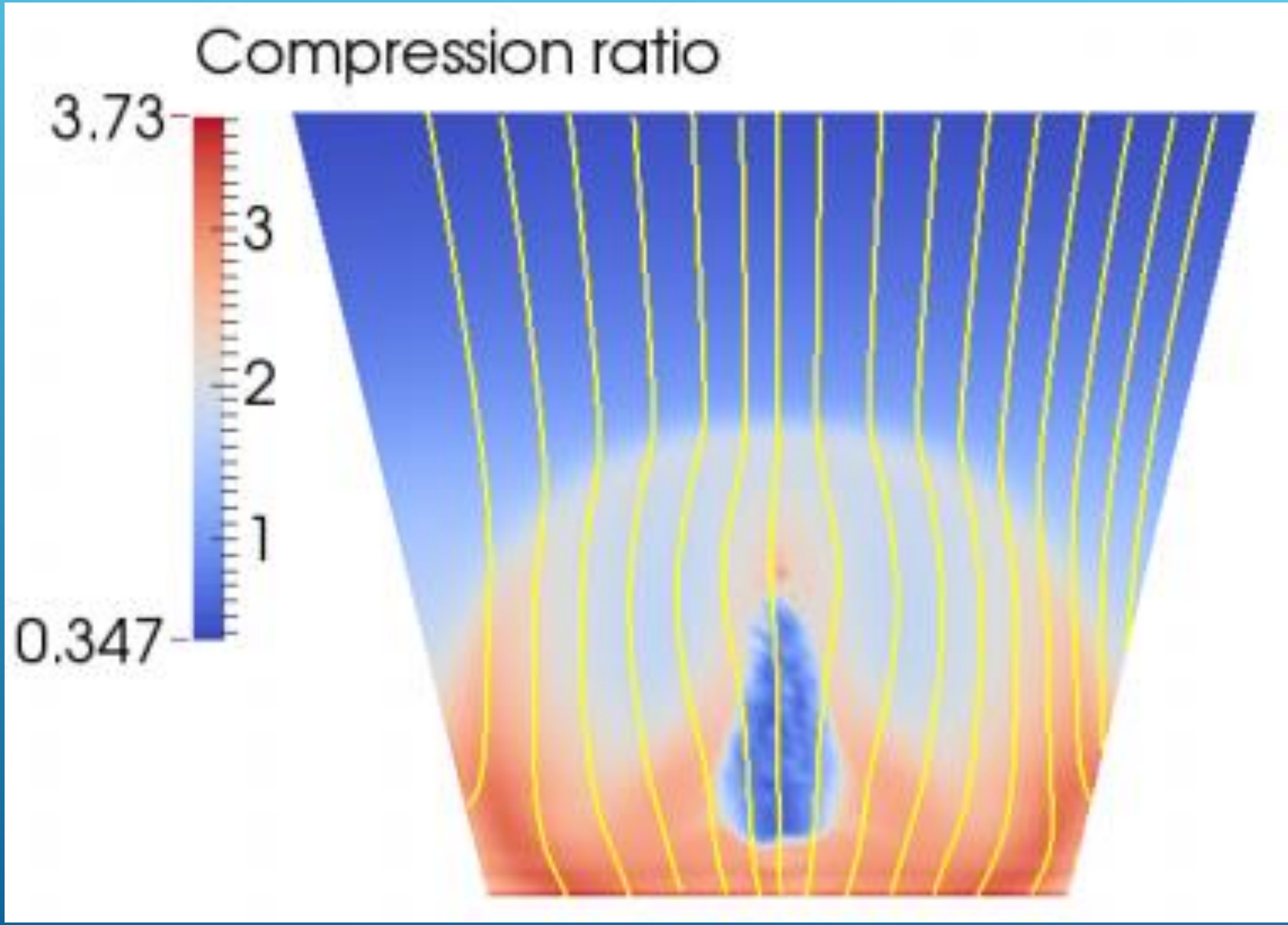
Initial profiles [Vasquéz et al. (2003)]:

$$n_e = 10^8 \left(\frac{77.1}{h^{31.4}} + \frac{0.954}{h^{8.3}} + \frac{0.55}{h^{4.63}} \right) \; [cm^{-3}] \qquad T_e = 8 \times \frac{10^5 (a_{eq} + 1.0)}{a_{eq} + b_{eq} h^{\alpha_{eq}} + \frac{1.0 - b_{eq}}{h^{\beta_{eq}}}} \; [K]$$

$$h\,[R_\odot] = heliocentric\ height,\ a_{eq} = 0.1,\ b_{eq} = 0.33,\ \alpha_{eq} = 0.55,\ \beta_{eq} = 6.6$$

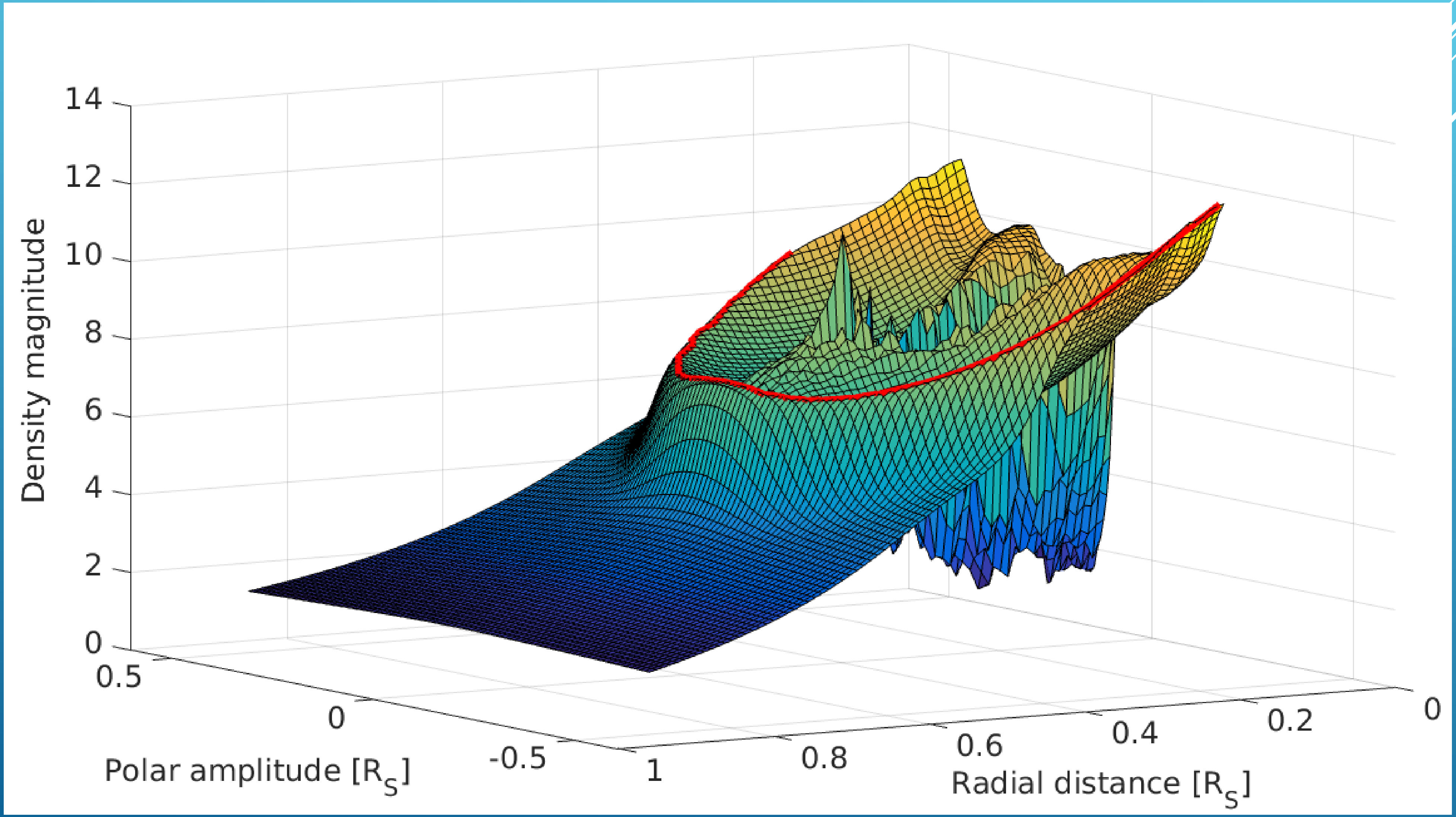


SIMULATING A CME EVENT: FLIPMHD3D



[Bacchini et al. (2015), submitted]

RETRIEVING THE PRE-SHOCK PARAMETERS



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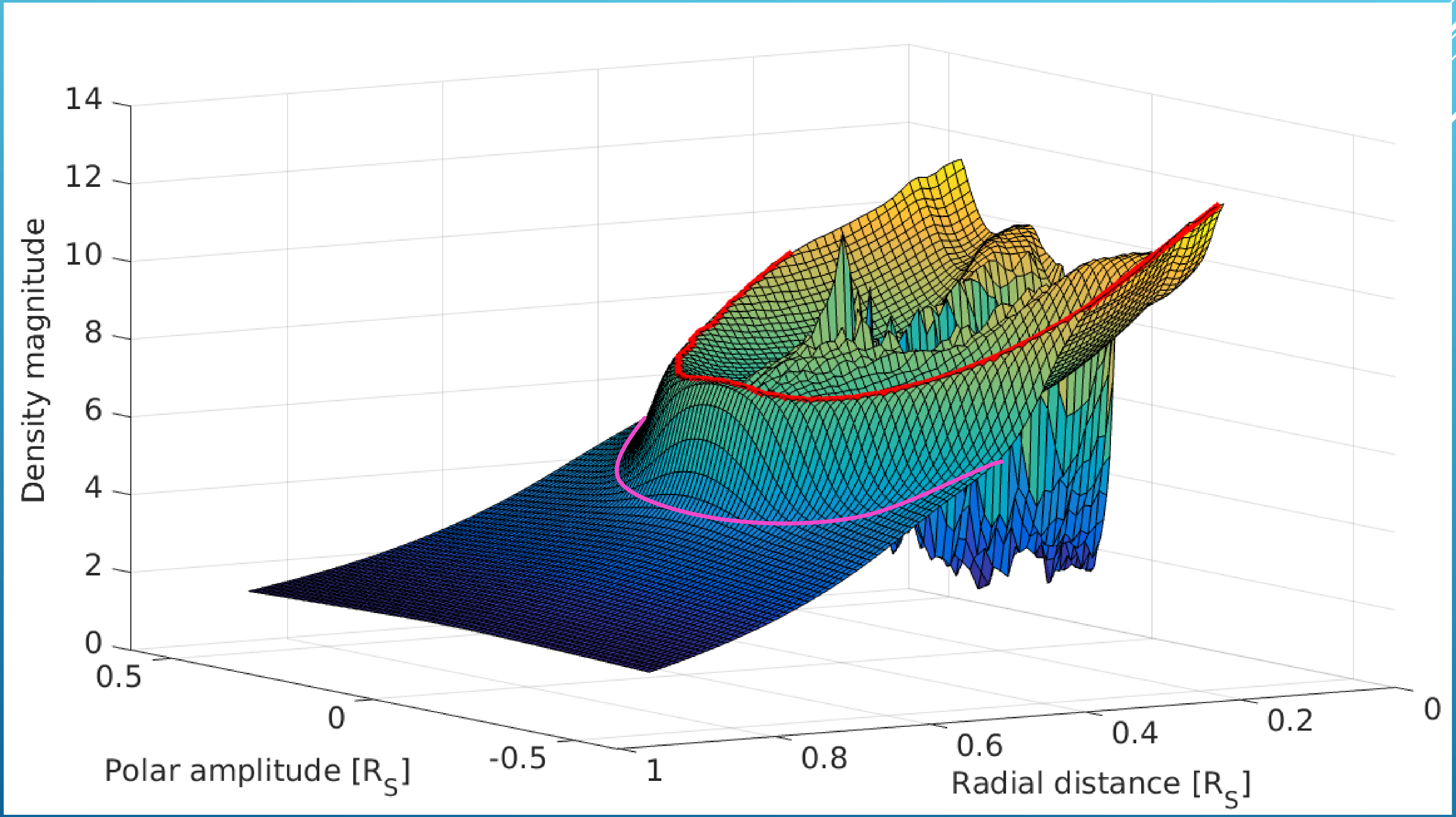

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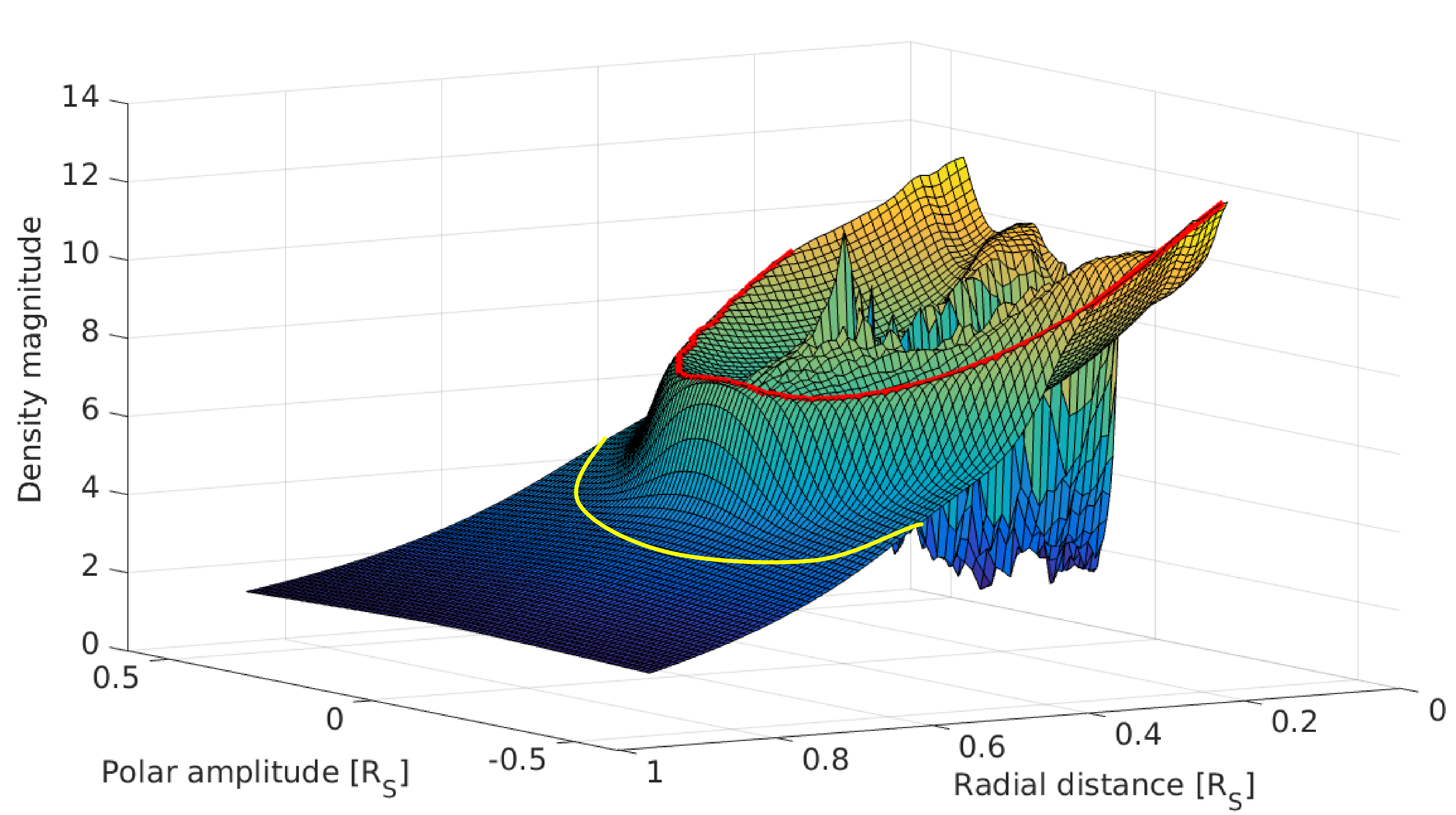

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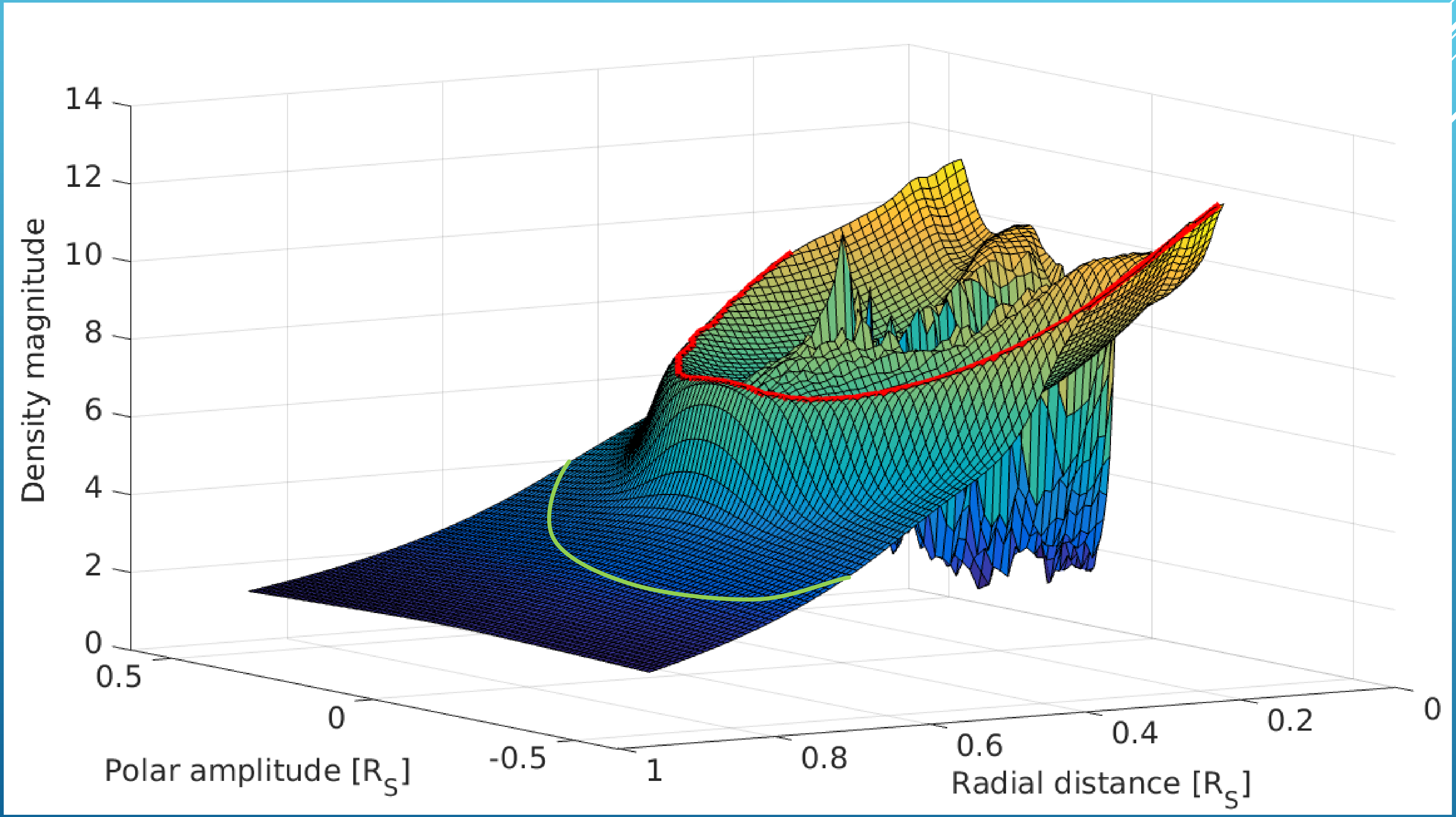

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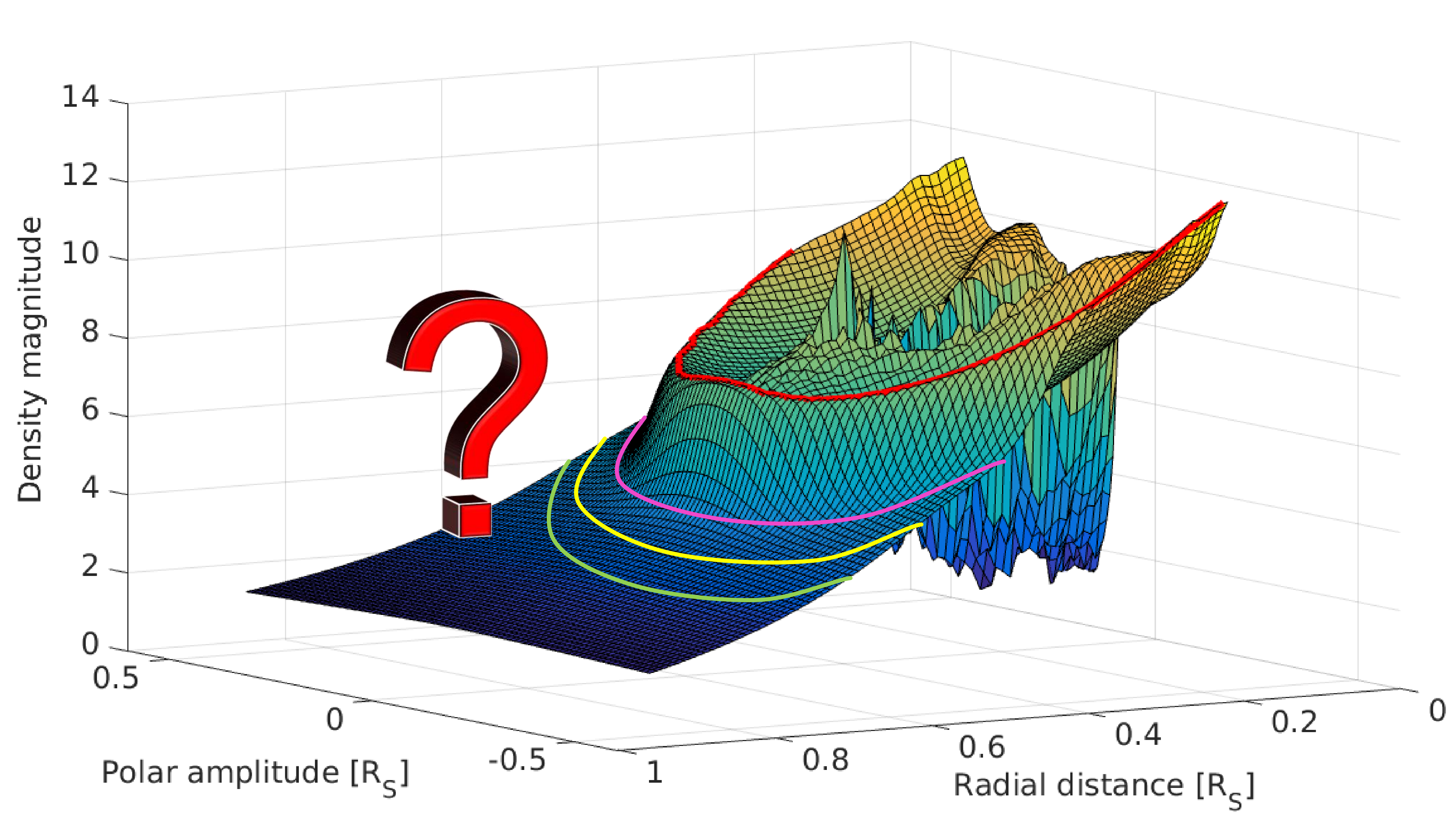


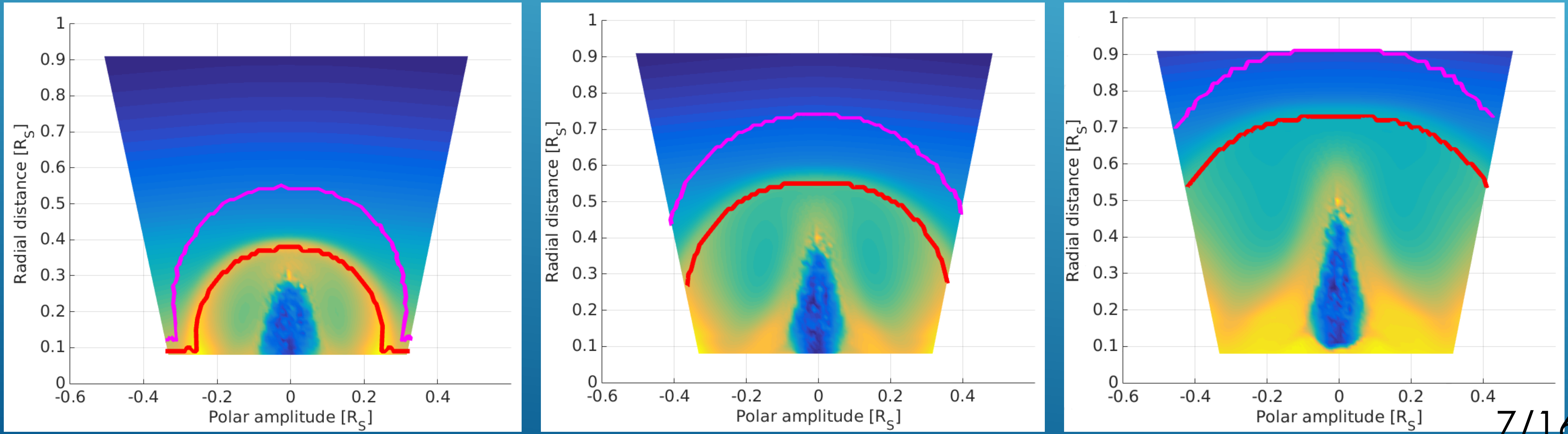
RETRIEVING THE PRE-SHOCK PARAMETERS

Proton-proton mean free path approximation:

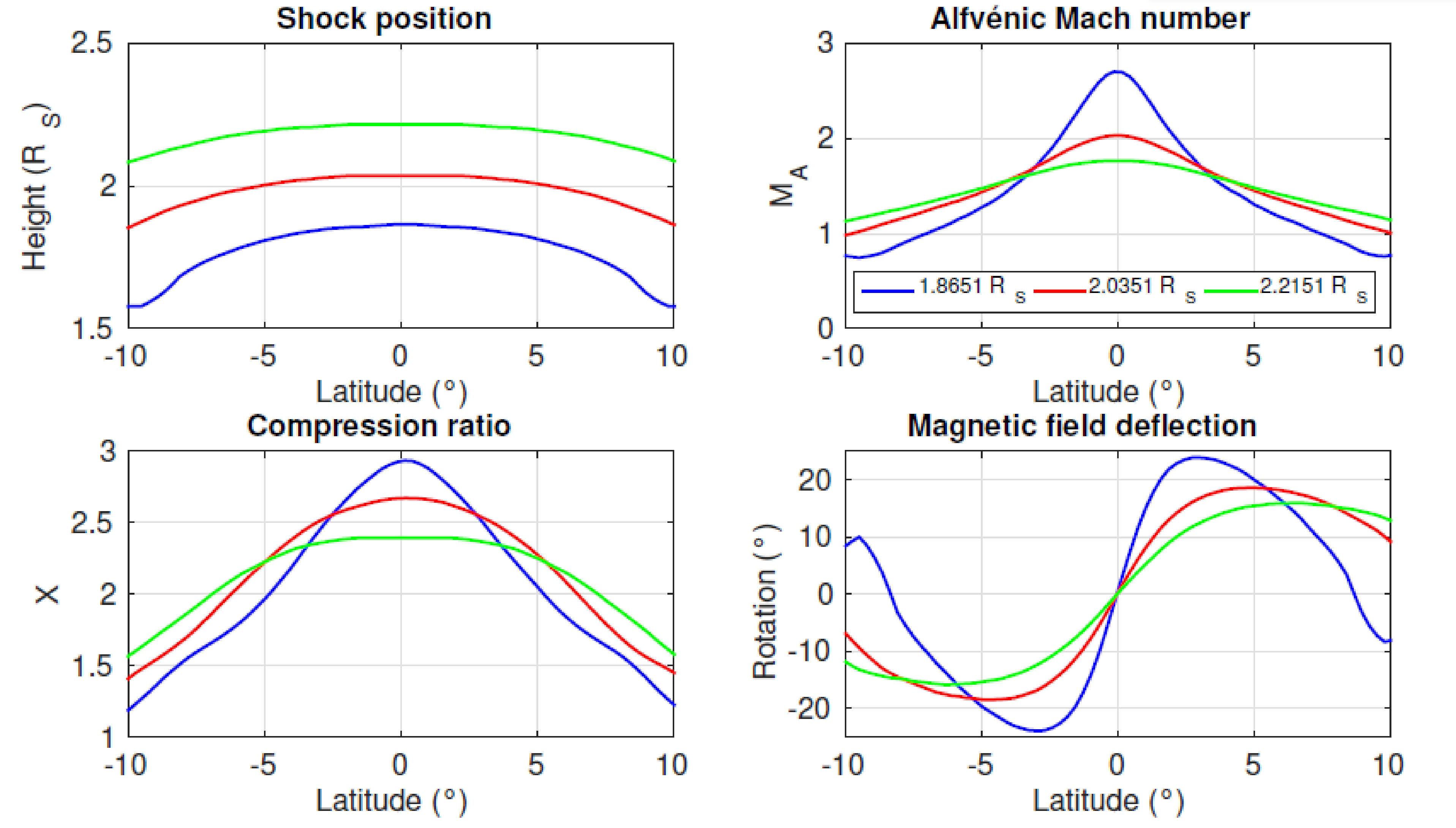
$$\delta_{sh} = k\lambda_p \; [R_\odot]$$ [Eselevich & Eselevich (2011, 2012)]

$$\lambda_p = 10^{-7}\frac{T^2}{n} \; [R_\odot]$$ [Zel'dovich & Raizer (1966)]

$$T\;[K] = plasma\ temperature,\ n\;[cm^{-3}] = particle\ density$$



SHOCK PARAMETER DISTRIBUTIONS ALONG THE FRONT



[Bacchini et al. (2015), submitted]

ALFVÉNIC MACH NUMBER RELATION VALIDATION

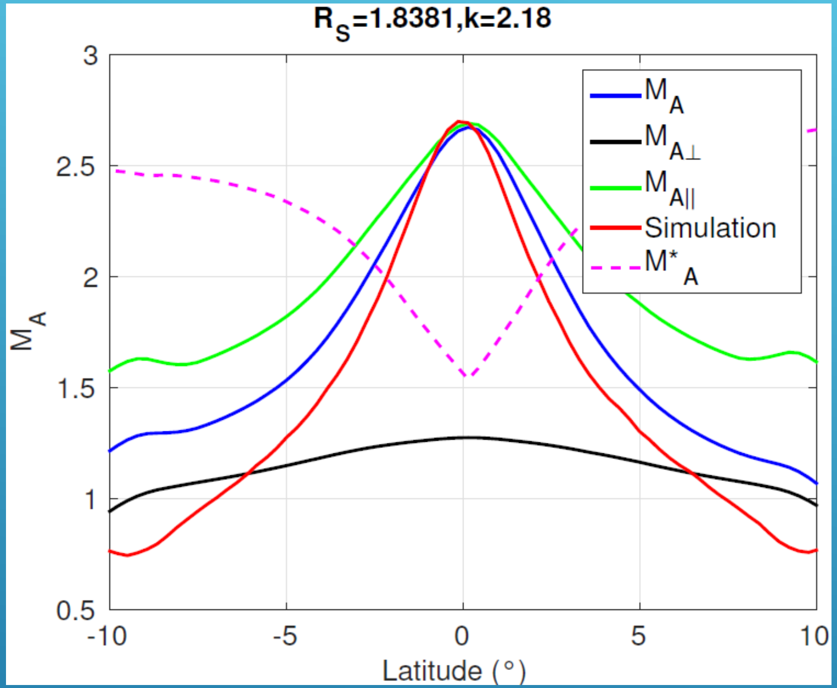
From the shock adiabatic equation [Mann et al. (1995)]:

For $\theta_{B_n} = 0, \quad M_{A\parallel} = \sqrt{\frac{5\beta_u X}{2(4-X)}}$

For $\theta_{B_n} = \pi/2, \quad M_{A\perp}^4 (X + \beta_u + 5) + M_{A,\perp}^2 2X(X - 5\beta_u - 4) + 5\beta_u X^2 = 0$

$M_{A\angle} = \sqrt{\left(M_{A\perp} \sin\theta_{B_n}\right)^2 + \left(M_{A\parallel} \cos\theta_{B_n}\right)^2}$ [Bemporad et al. (2014)]

ALFVÉNIC MACH NUMBER RELATION VALIDATION



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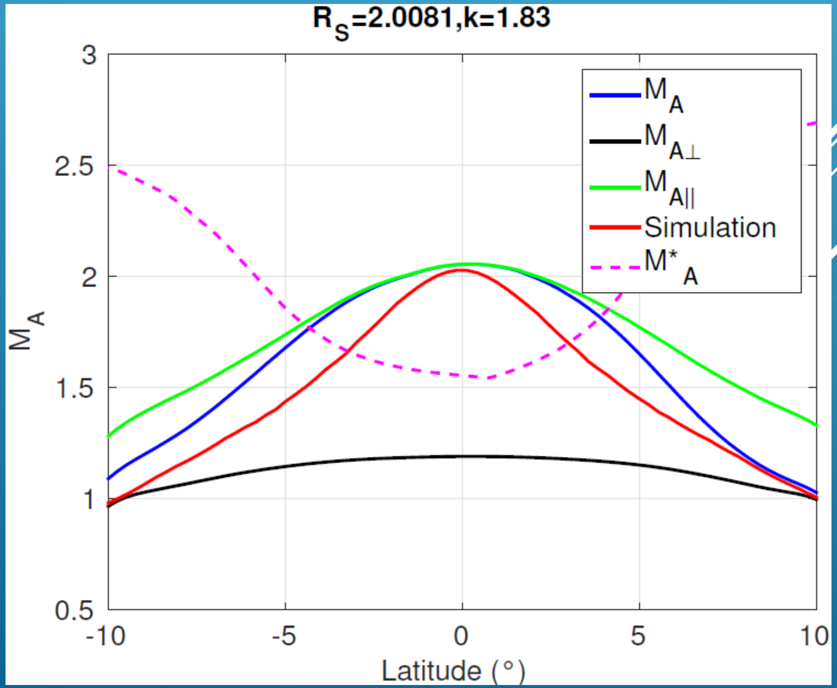
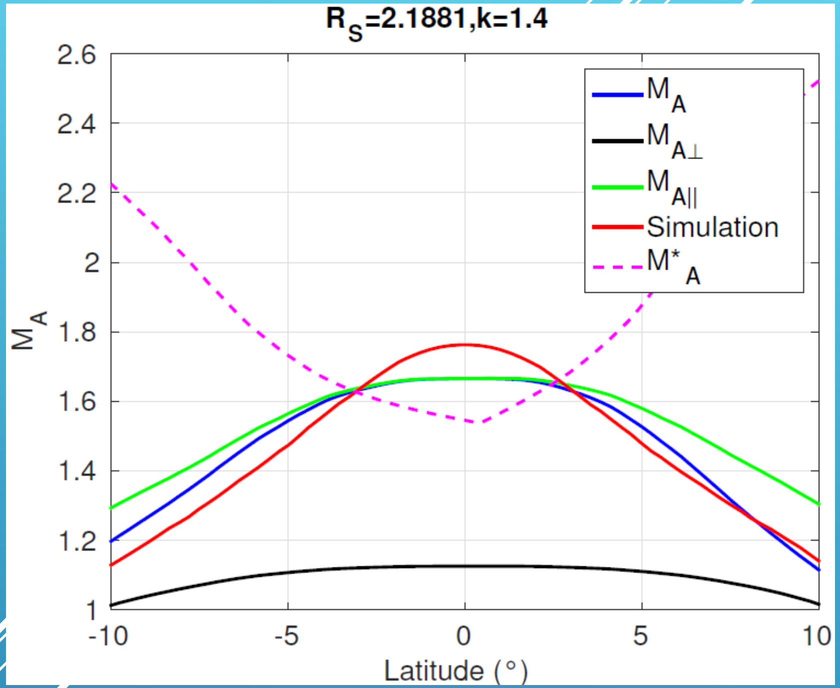


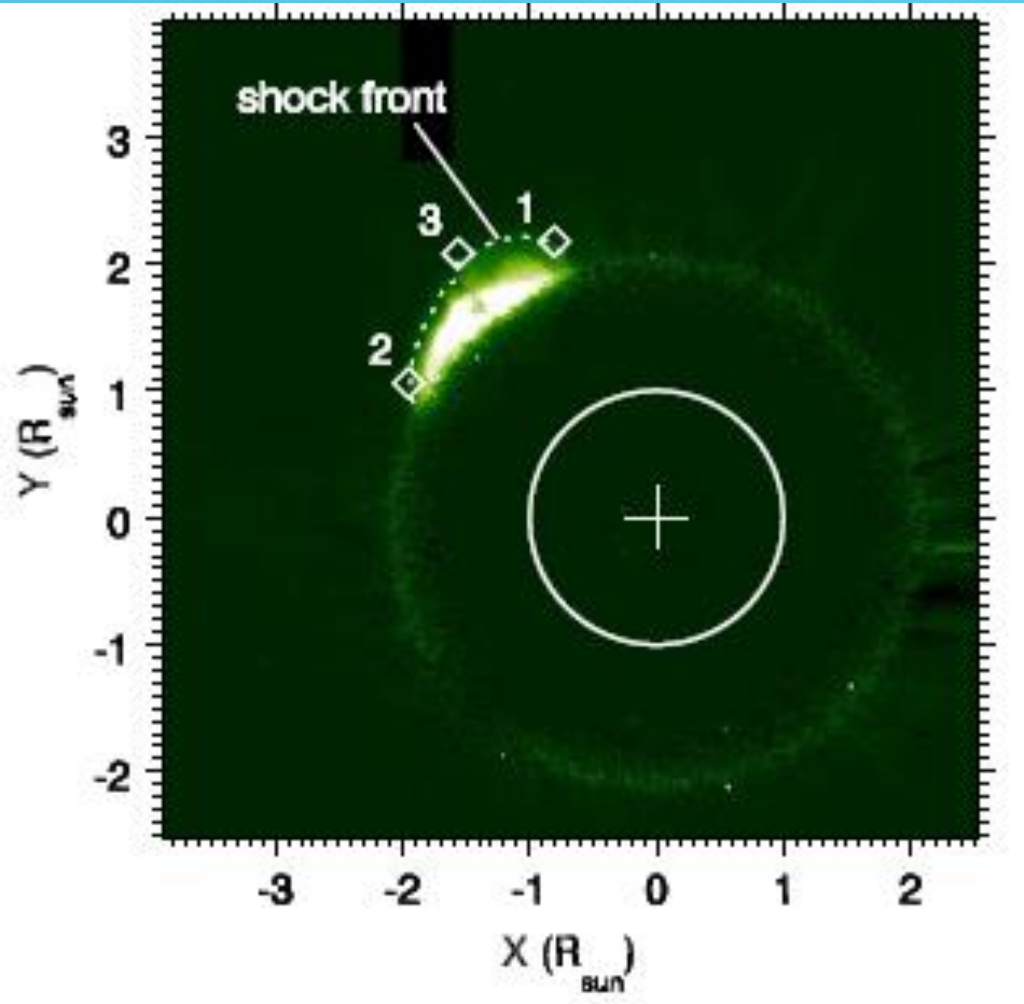


SIMULATING PROTON-ELECTRON DECOUPLING

- Electrons and protons are expected to behave differently when subjected to a shock transit [Manchester et al. (2012)]

- Electron temperature jump → adiabatic gas law;
  Protons temperature increase → shock compression + kinetic energy dissipation at the front;

- A 1D, two-temperature ideal MHD model is applied at three points along the shock



[Bemporad et al. (2014)]

TWO-TEMPERATURE MODEL

Artificial viscosity

Lagrangian 1D ideal MHD

Momentum: $\rho \frac{\mathrm{d}\mathbf{u}}{\mathrm{d}t} = -\nabla(p + q) + \frac{(\mathbf{B}\cdot\nabla)\mathbf{B}}{\mu_0} - \nabla\left(\frac{\mathbf{B}^2}{2\mu_0}\right)$

Induction: $\rho \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mathbf{B}}{\rho}\right) = (\mathbf{B}\cdot\nabla)\mathbf{u}$

Gauss's law: $\nabla \cdot \mathbf{B} = \mathbf{0}$

+ Energy equation & closure equation (for each species)

TWO-TEMPERATURE MODEL

Simple solar wind model
[van der Holst et al. (2014)]:

$$\frac{\mathrm{d}p_e}{\mathrm{d}t} = -\gamma p_e \nabla \cdot \mathbf{u}$$

$$\rho \frac{\mathrm{d}e_p}{\mathrm{d}t} = -(p_p + q)\nabla \cdot \mathbf{u}$$

$$p_p = (\gamma - 1)\rho e_p \,, \qquad \gamma = 5/3$$

NEW Variable-γ model:

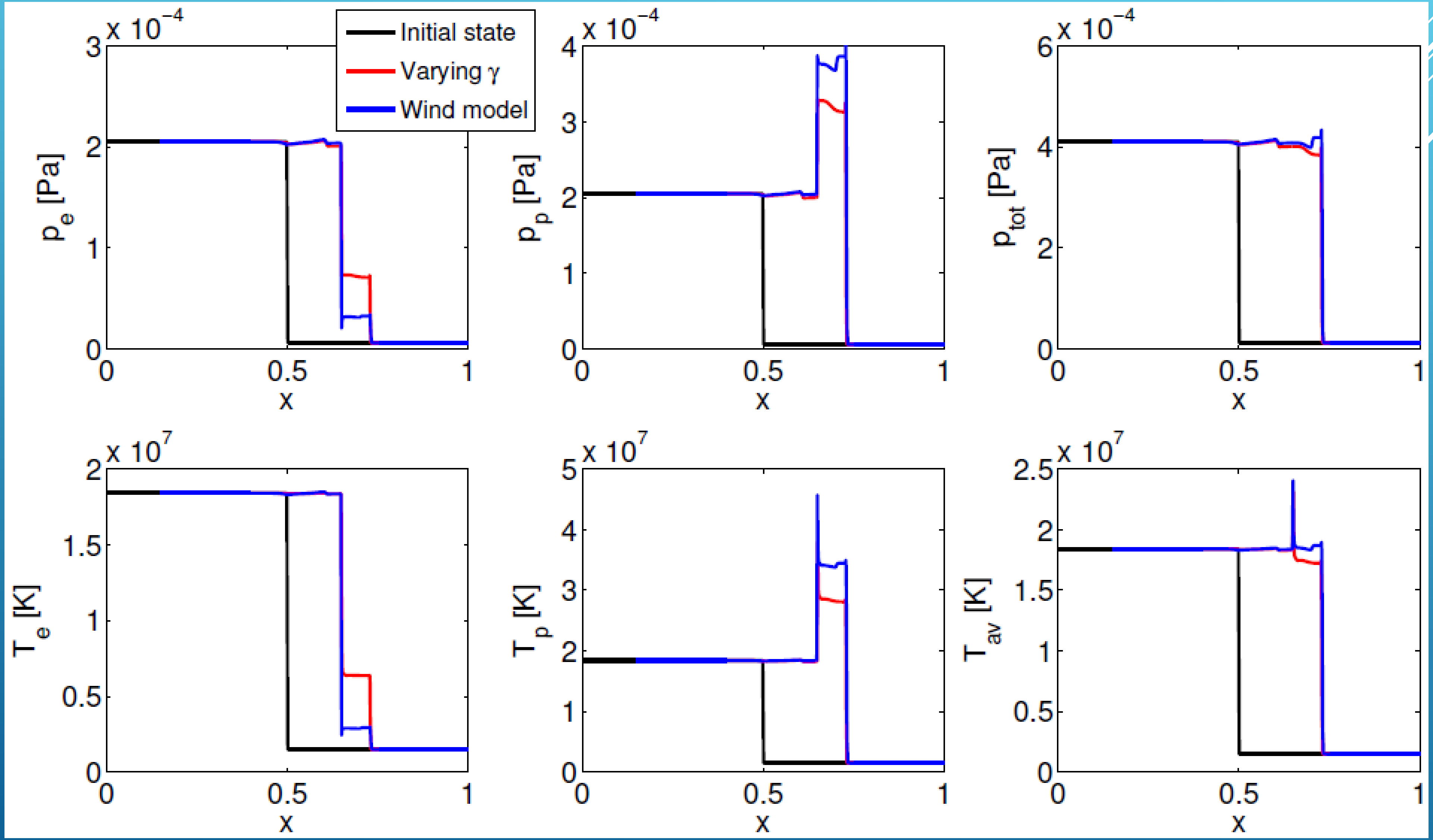
$$\rho \frac{\mathrm{d}e_e}{\mathrm{d}t} = -(p_e + q)\nabla \cdot \mathbf{u}$$

$$\rho \frac{\mathrm{d}e_p}{\mathrm{d}t} = -(p_p + q)\nabla \cdot \mathbf{u}$$

$$p_s = (\gamma_s - 1)\rho e_s$$

γ_s from [Gosling (1999)]

TWO-TEMPERATURE MODEL: RESULTS



[Bacchini et al. (2015), submitted]

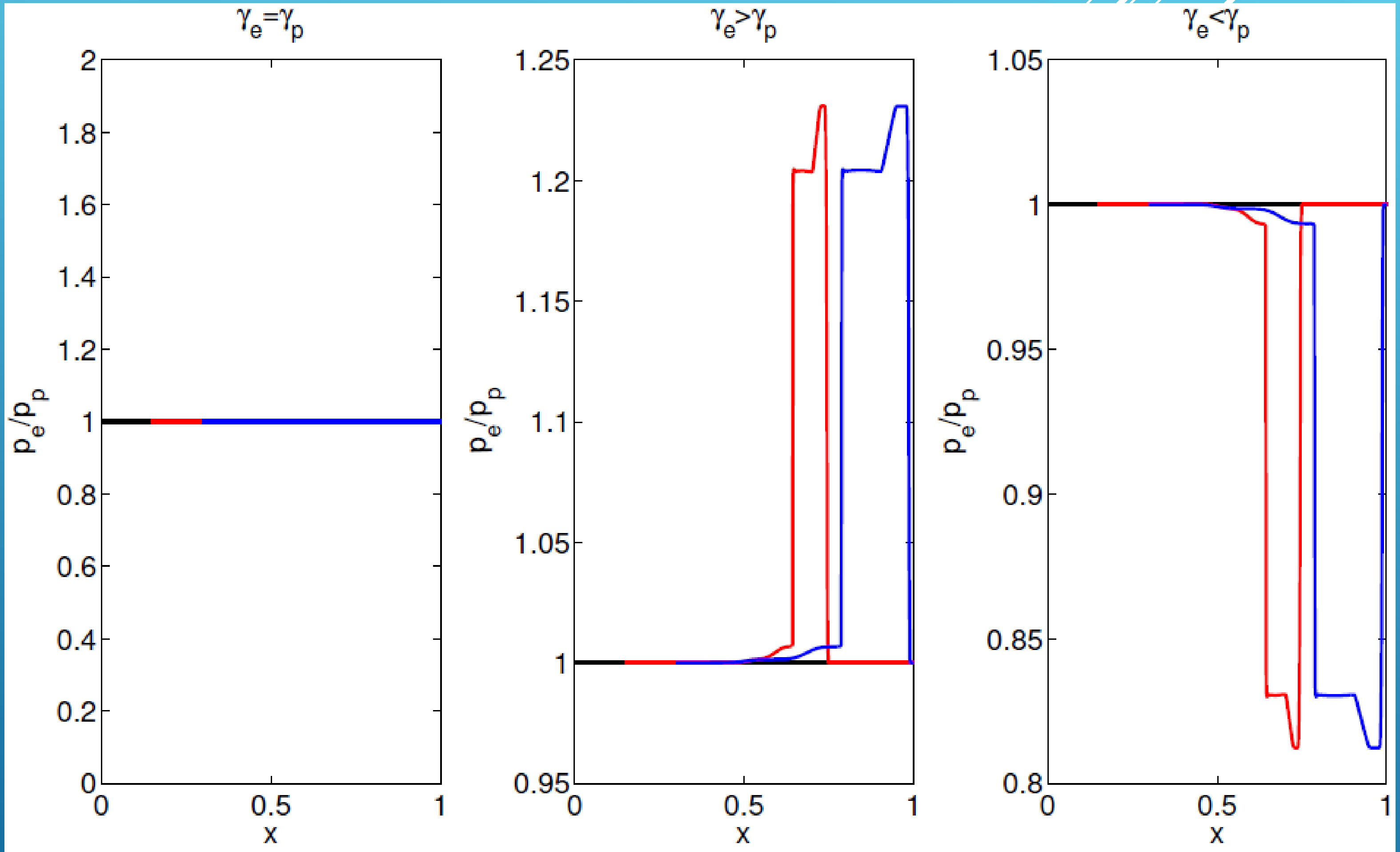
TWO-TEMPERATURE MODEL: RESULTS

$$\frac{d}{dt}\left(\ln\frac{p_e}{p_p}\right) = -(\gamma_e - \gamma_p)\nabla\cdot\mathbf{u}$$

At the shock front, $\nabla\cdot\mathbf{u} < 0$

$\Rightarrow \frac{p_e}{p_p}$ increases if $\gamma_e > \gamma_p$

$\Rightarrow \frac{p_e}{p_p}$ decreases if $\gamma_e < \gamma_p$



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CONCLUSIONS

- Comparisons between simulation results and observational data show good agreement on the spatial distribution of X, M_A and d along the shock front.
- As expected, the shock behaves as a parallel shock at the nose and as a perpendicular shock at the flanks. The semi-empirical expression for $M_{A,\angle}$ approximates the actual values of M_A very well. The shock is supercritical at the nose, over a zone less and less wide as it propagates.
- The simple solar wind model reproduces the expected proton-electron energy decoupling very well; the variable-γ model introduces some of the missing physics related to the additional electron heating due to secondary phenomena.