A 3D MHD Model for Metis CMEs (a work very much in progress)

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9th Metis Workshop

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What is a 3D MHD model here?

Time dependent

$$\frac{\partial}{\partial t}$$

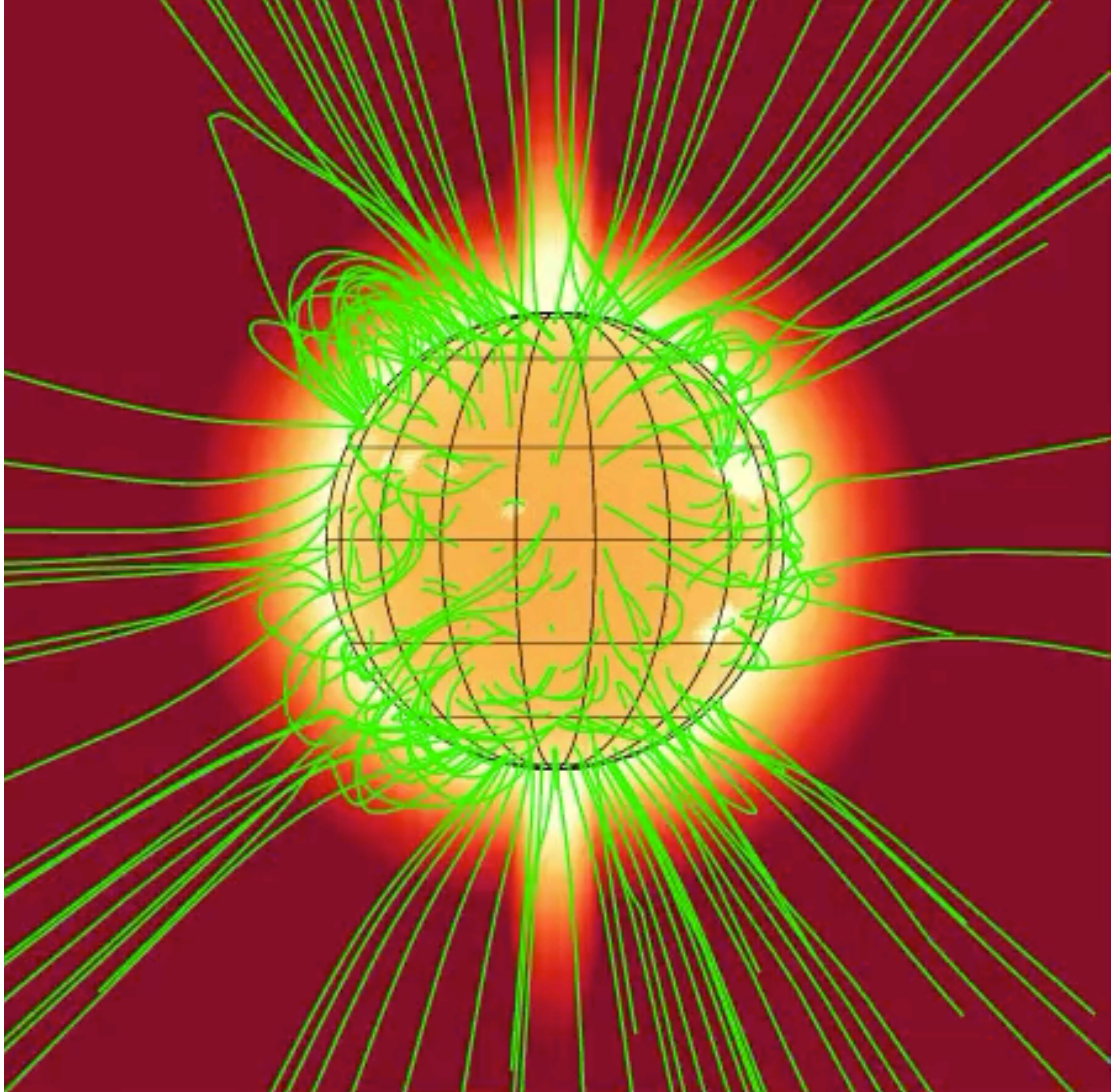
$$1R_{\odot} < r < \sim 100R_{\odot}$$
$$0 < \theta < \pi$$
$$0 < \phi < 2\pi$$

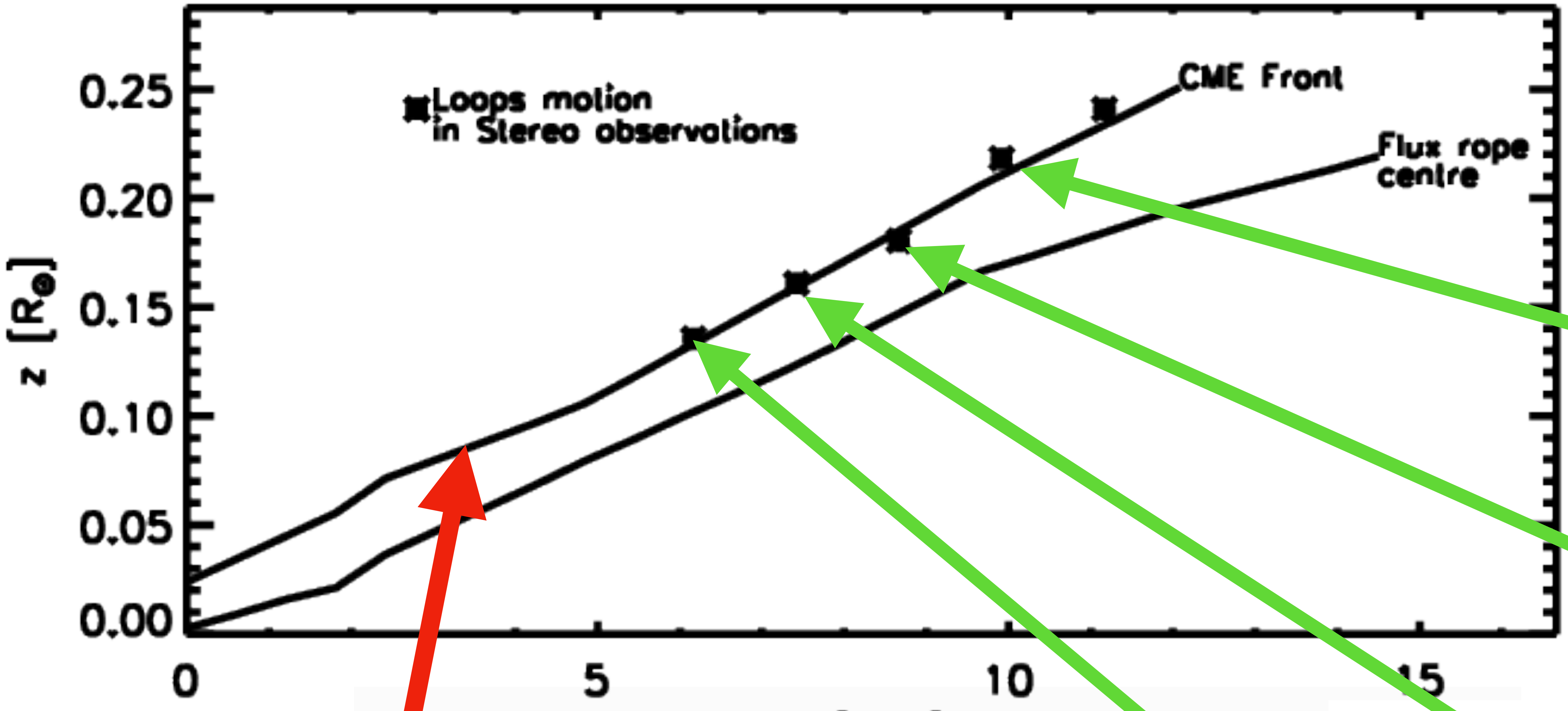
Magnetic field+Plasma

$$10^{-3} < \beta < 10^{2}$$

Background corona
$\tau \sim$ weeks

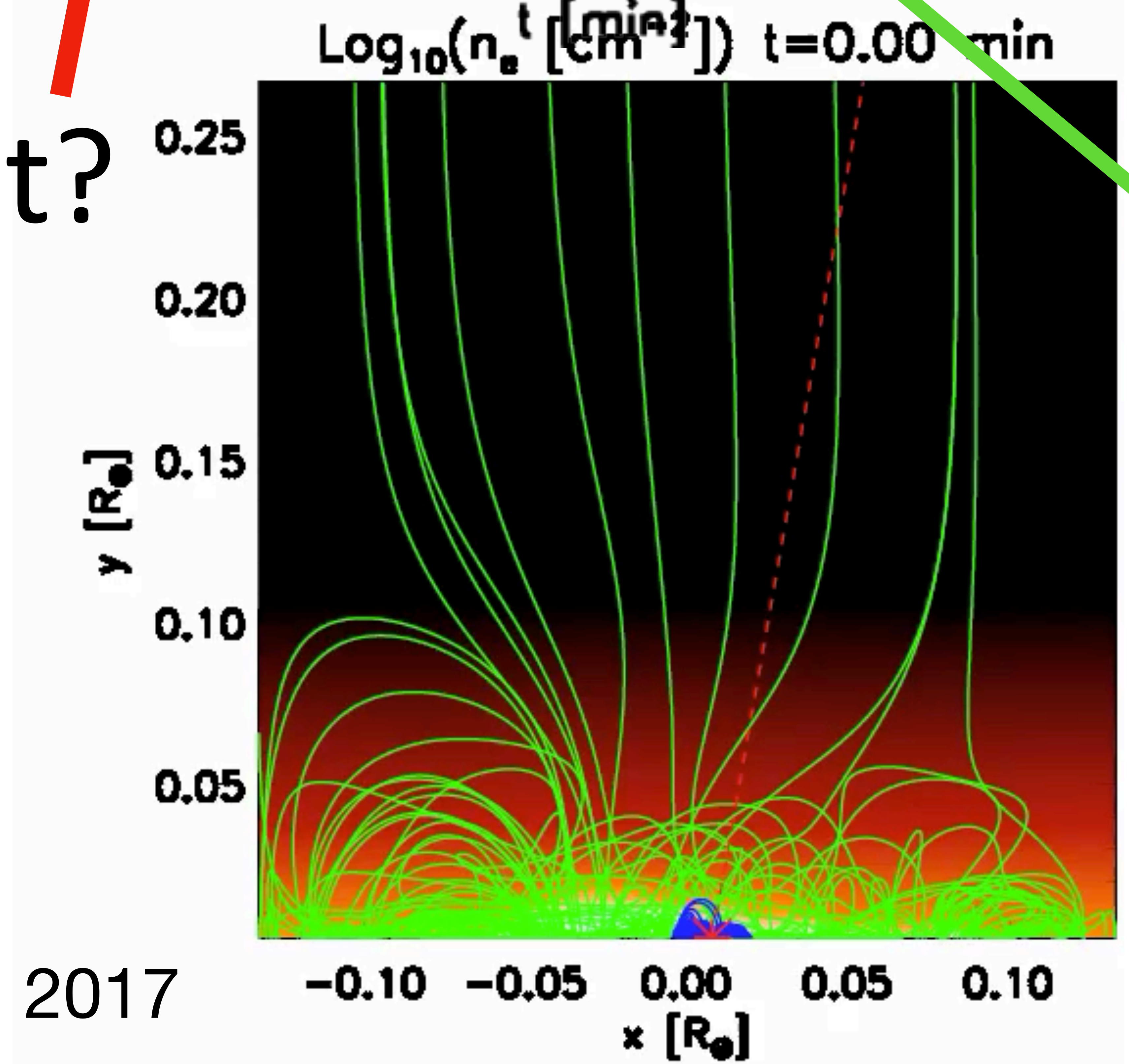
CME evolution
$\tau \sim$ hours





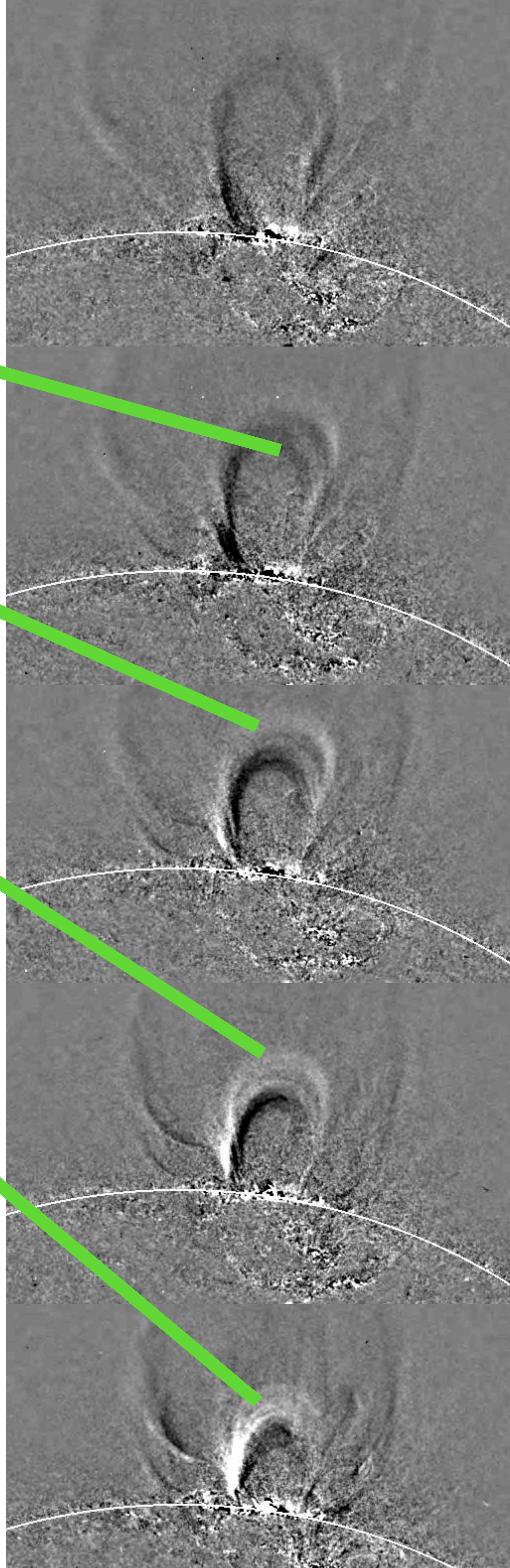
Why do we need it?

CME physics



Rodkin et al., 2017

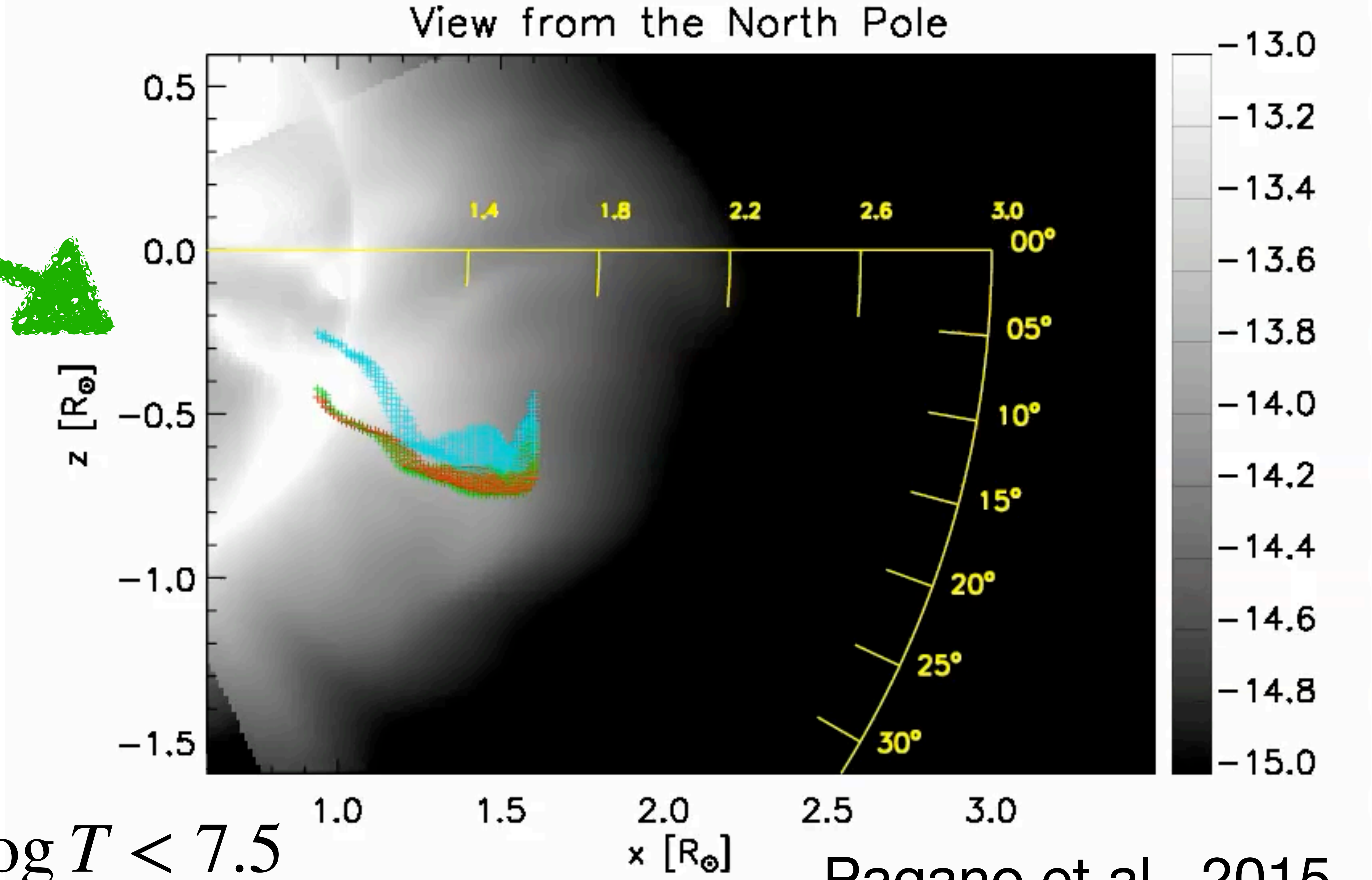
t



Why do we need it?

CME background

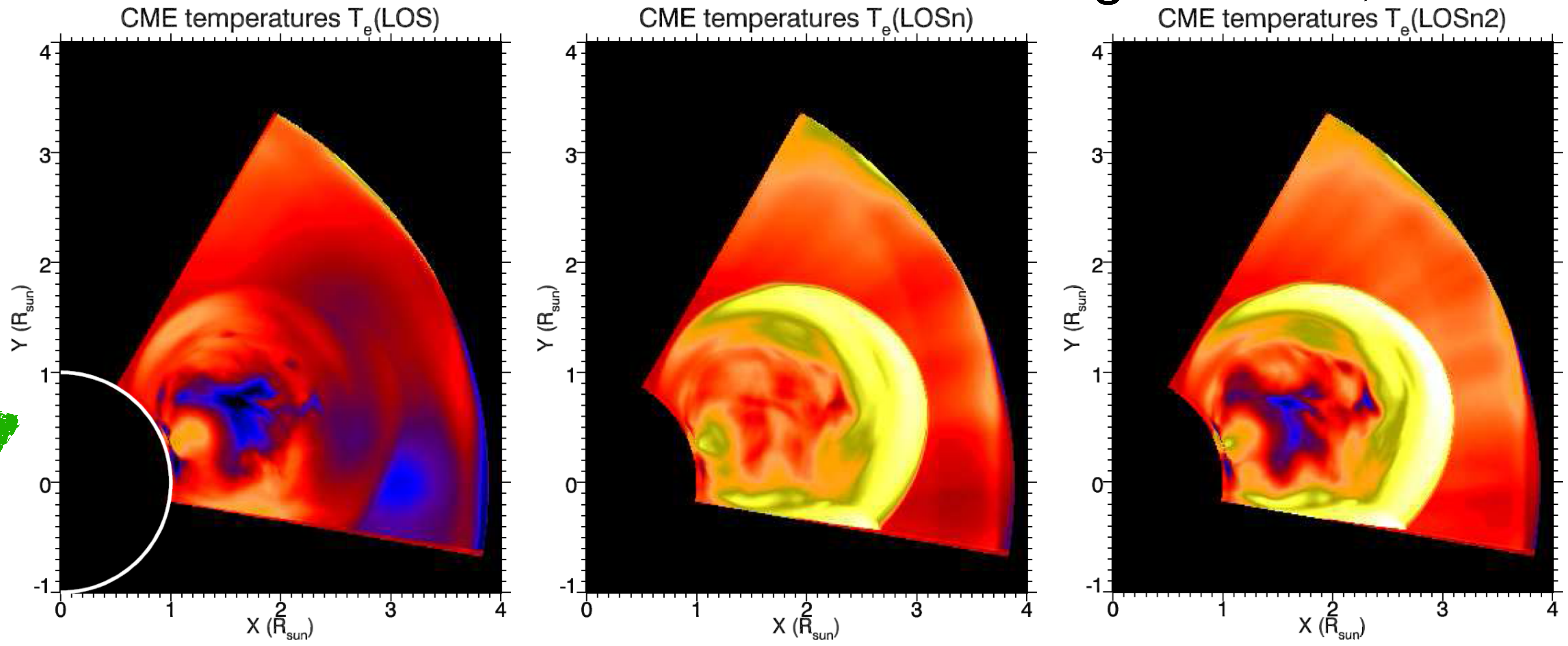
CME trajectory reconstruction



Pagano et al., 2015

CME temperature

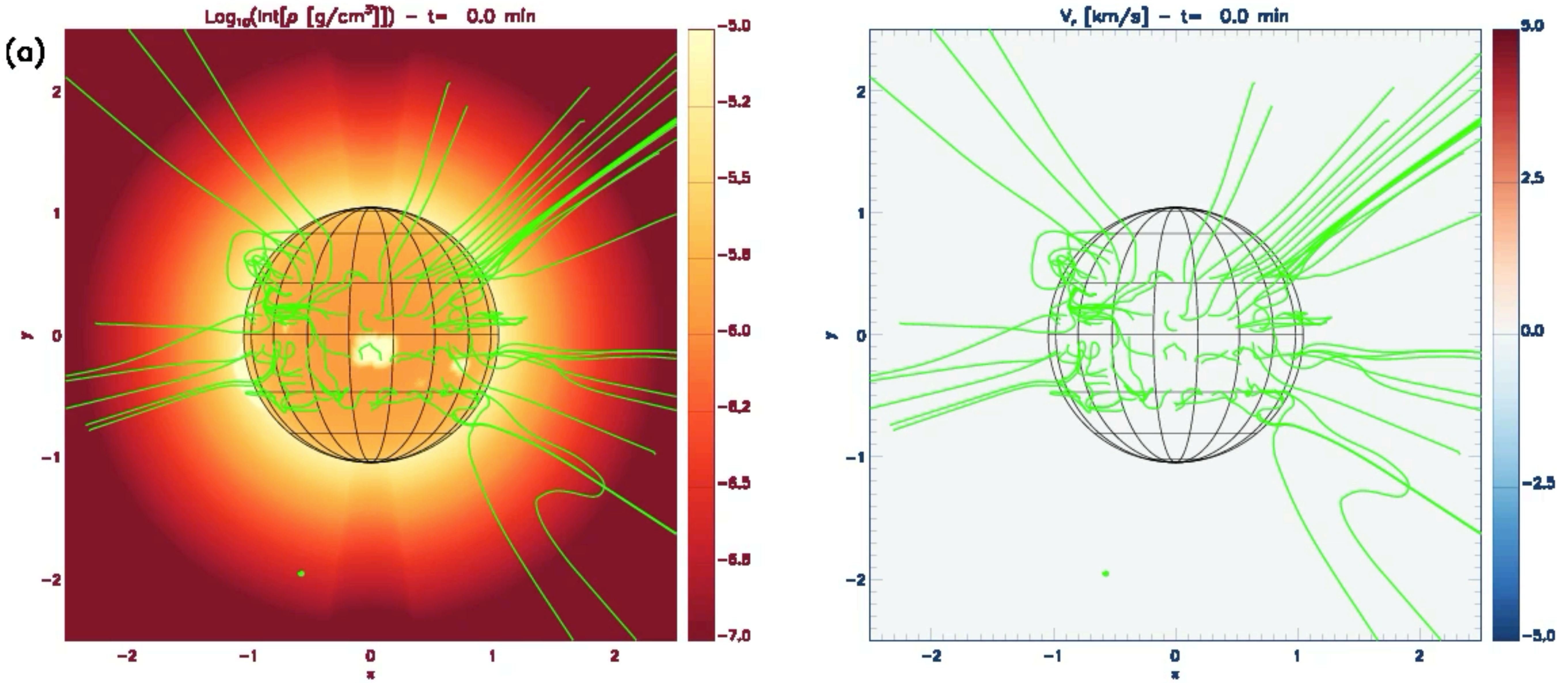
$5.5 < \log T < 7.5$



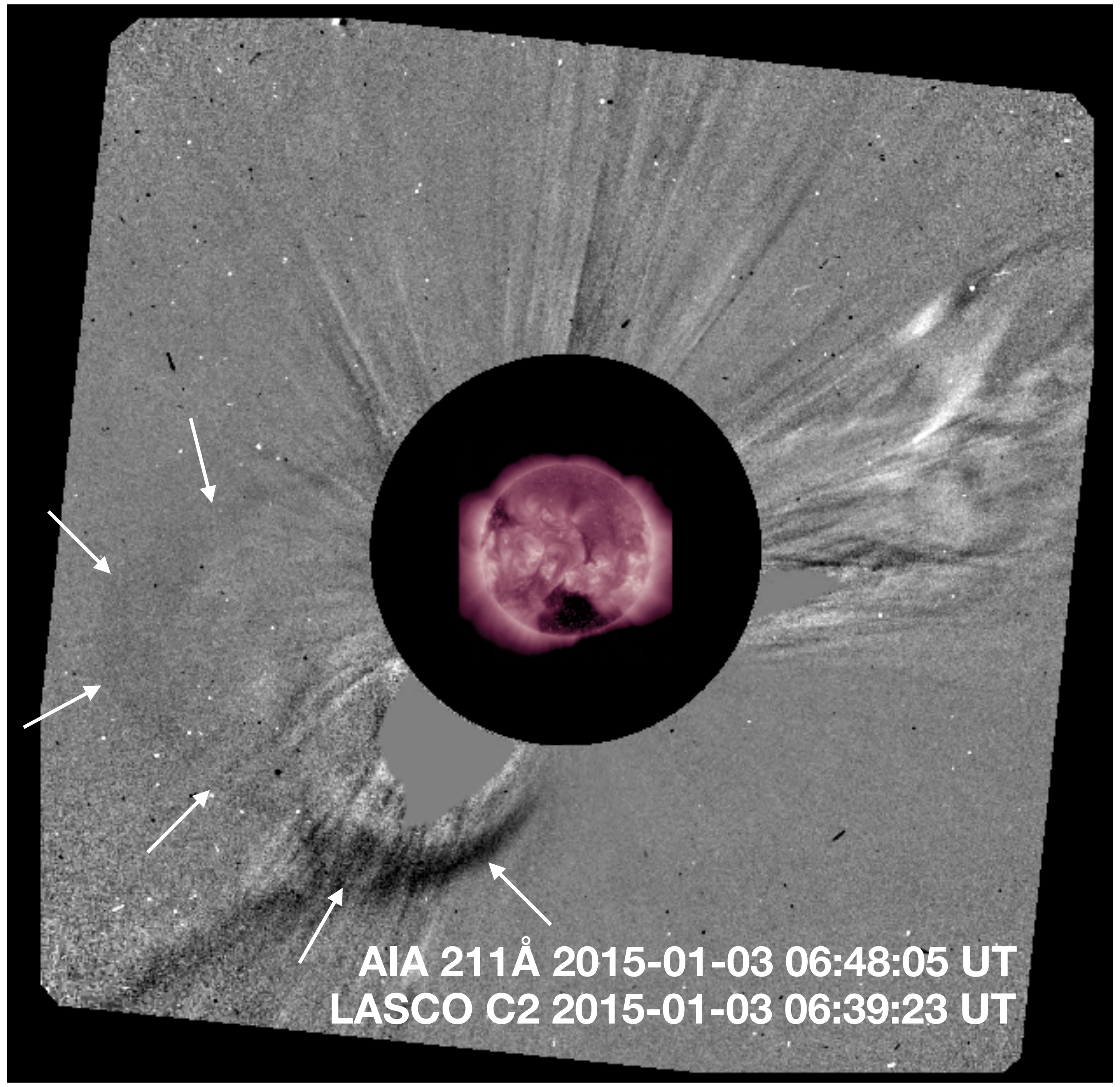
Bemporad et al., 2018

Why do we need?

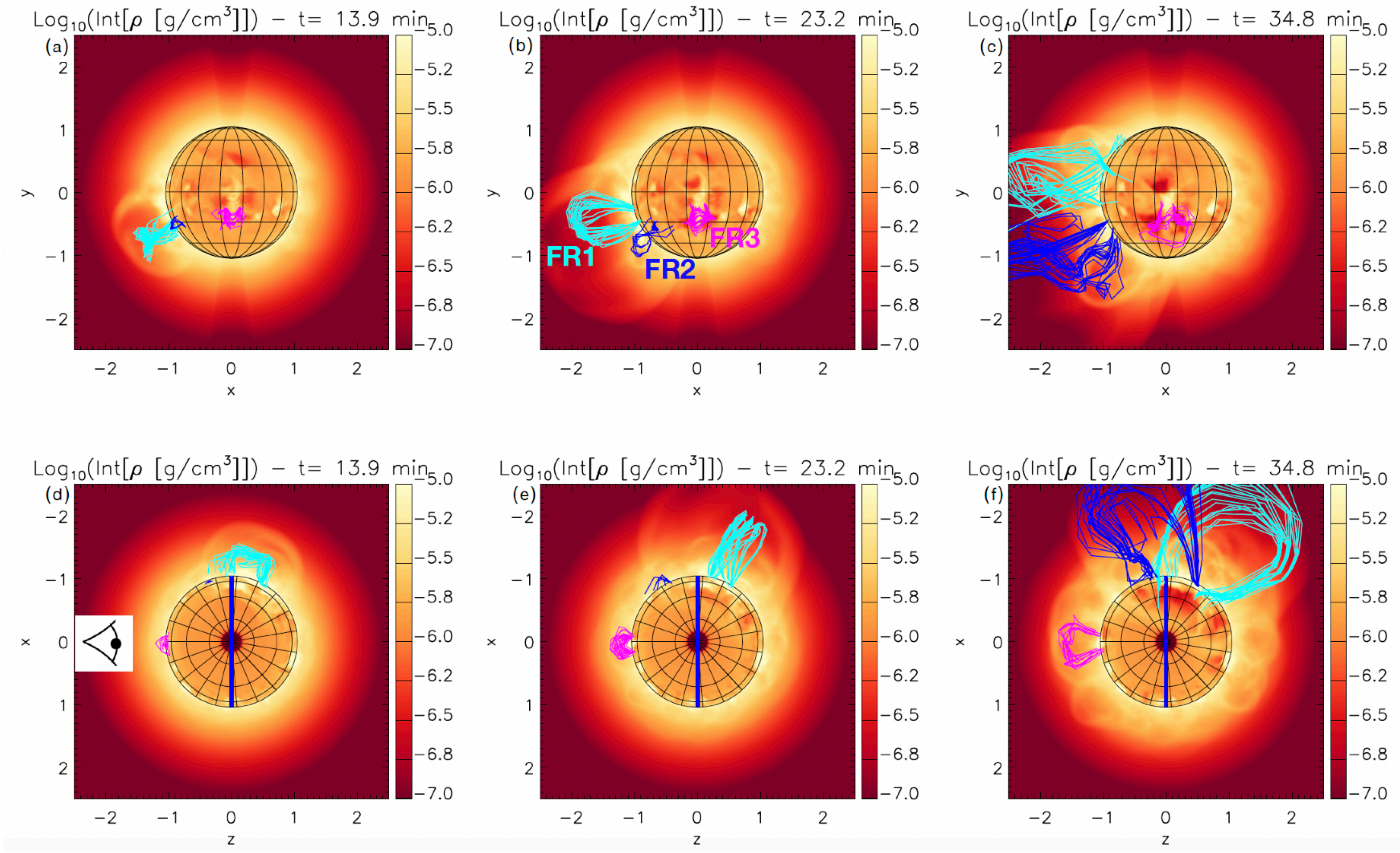
Magnetic connectivity during CMEs



Non ideal, transient effects on magnetic topology



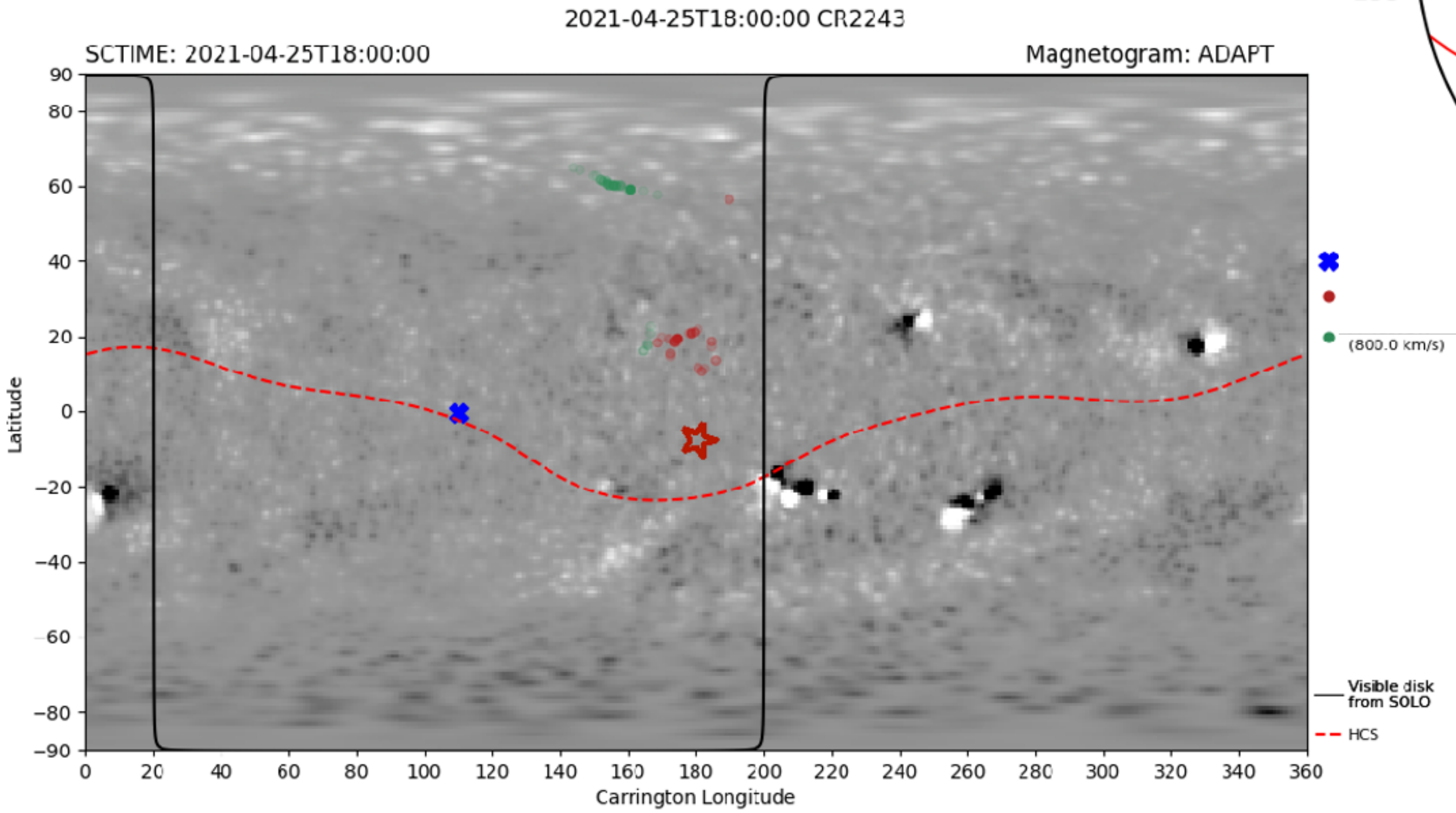
Yardley et al., 2021

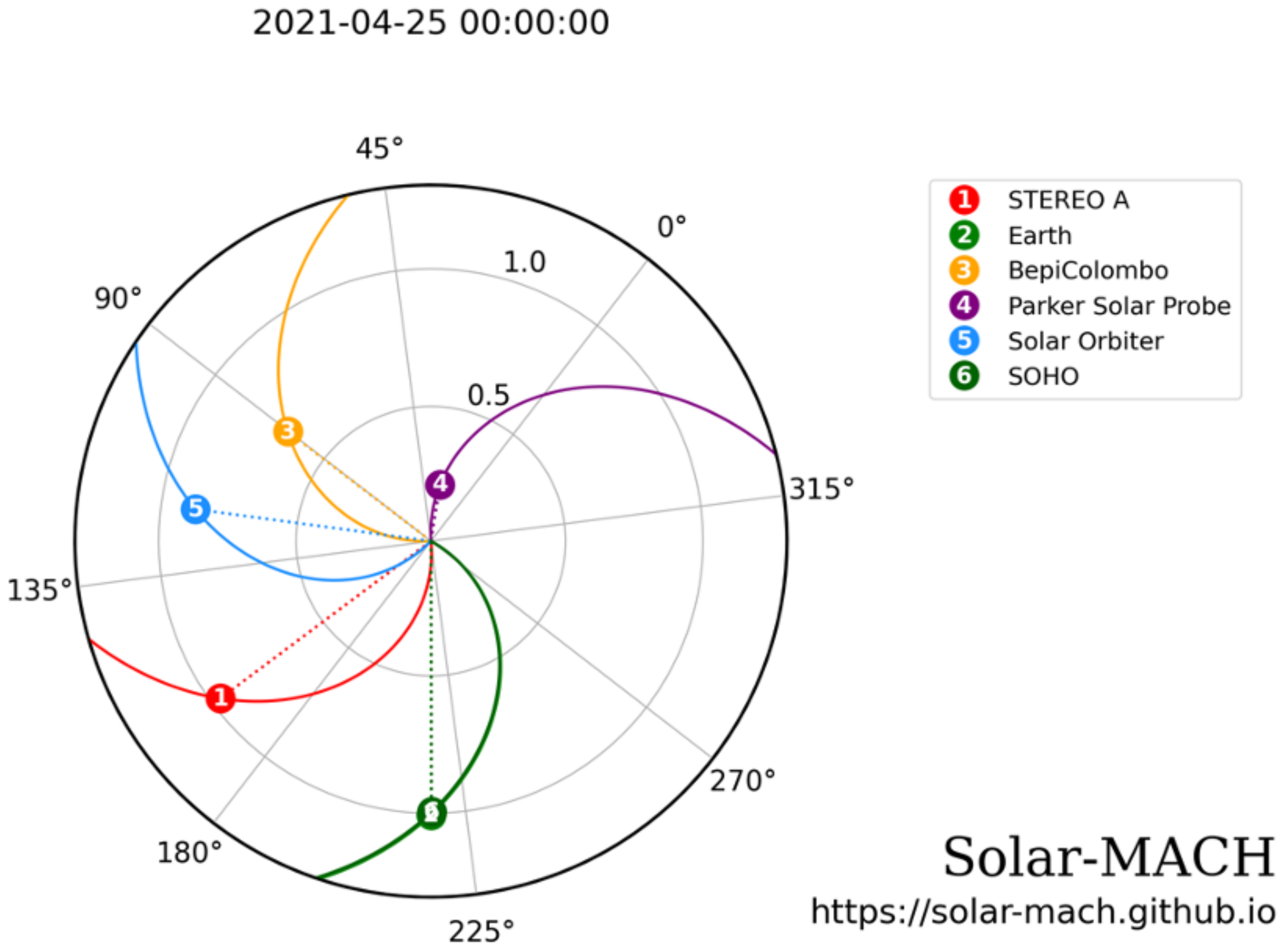


Event 25/04/2021

Event lifting off on April, 25th around 17:00 and enters the Metis FOV at 18:20 in quadrature with Lasco

Source region is AR12820





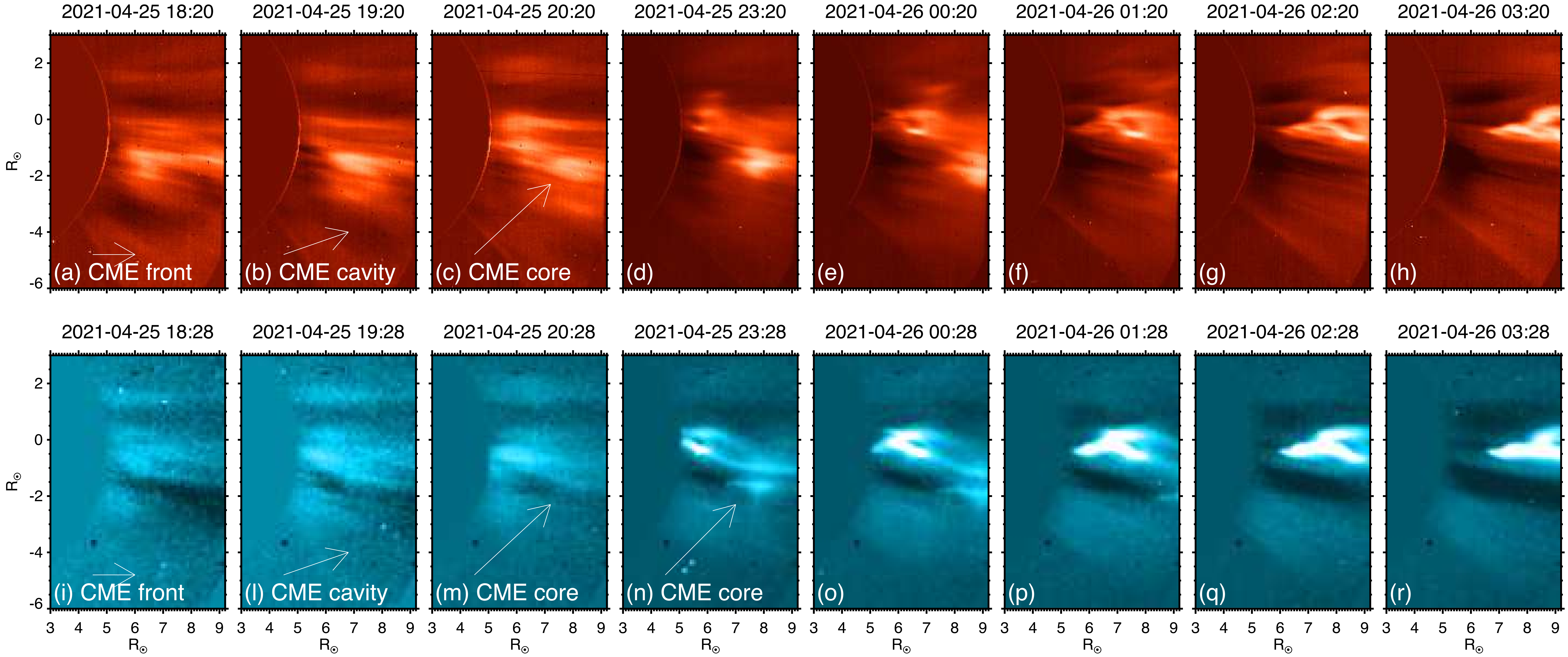
Event 25/04/2021

Pre-existing streamer with density contrast ~7

Isolated event, near the solar minimum.

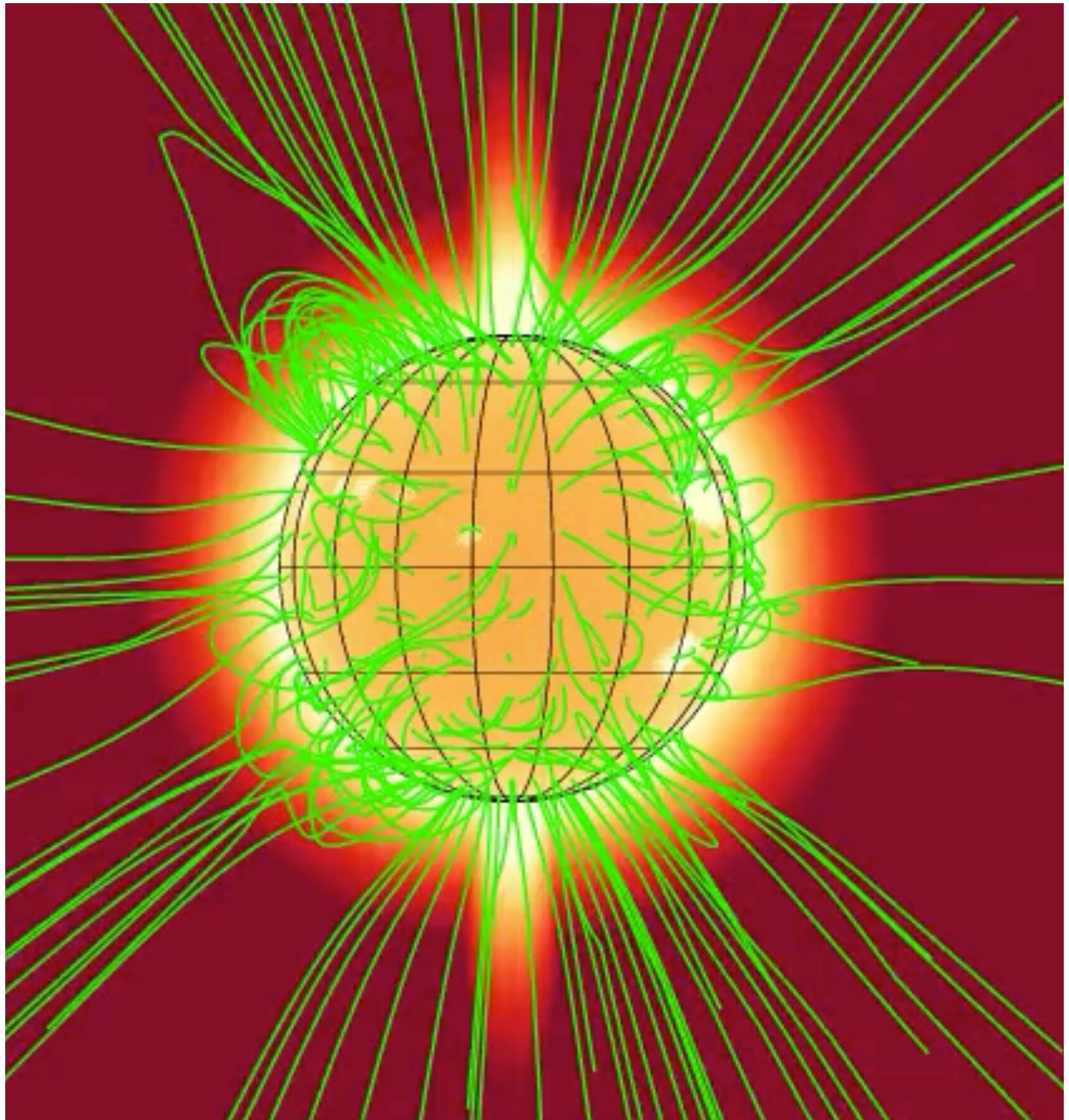
Isolated active region.

Active region on the Earth-side of the Sun with updated magnetograms



How do we do?

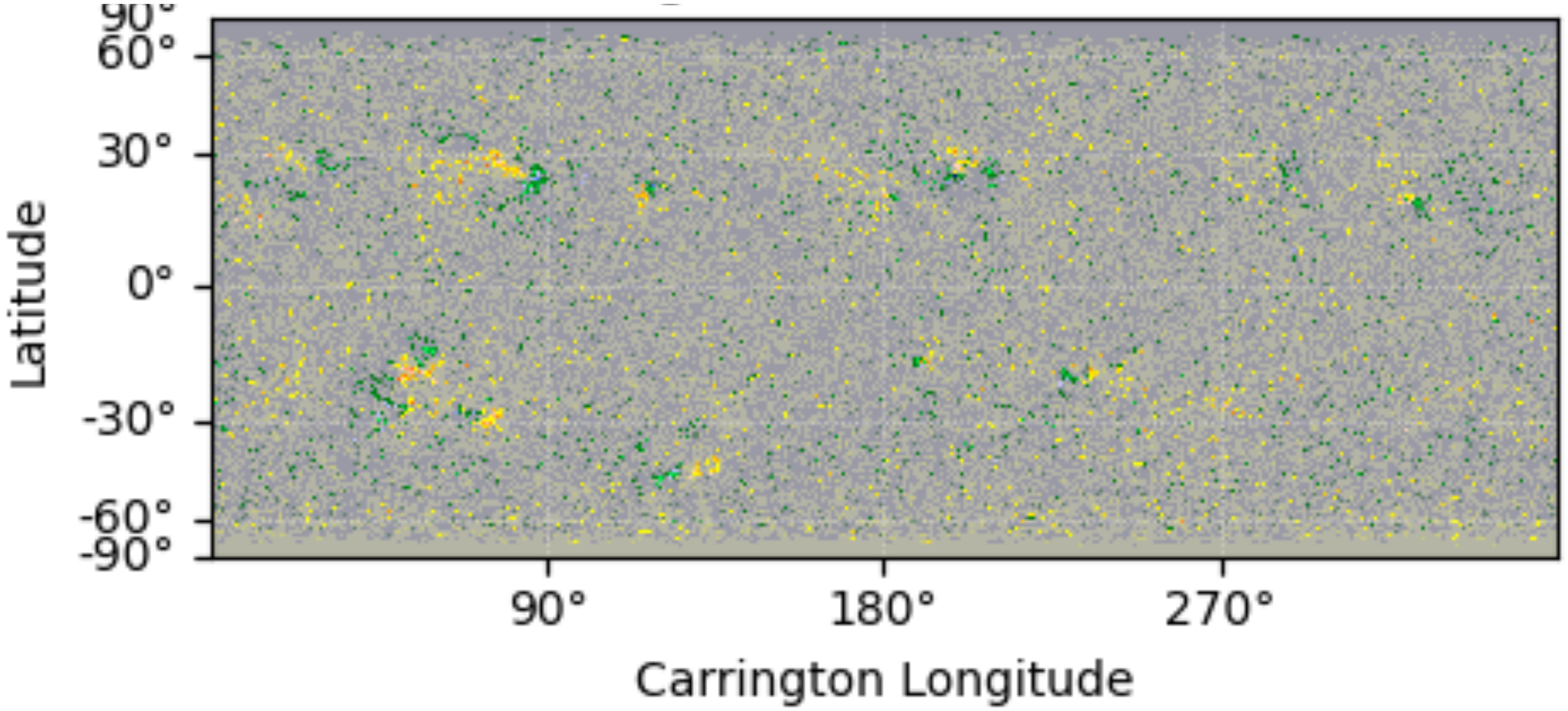
Magnetohydrodynamics



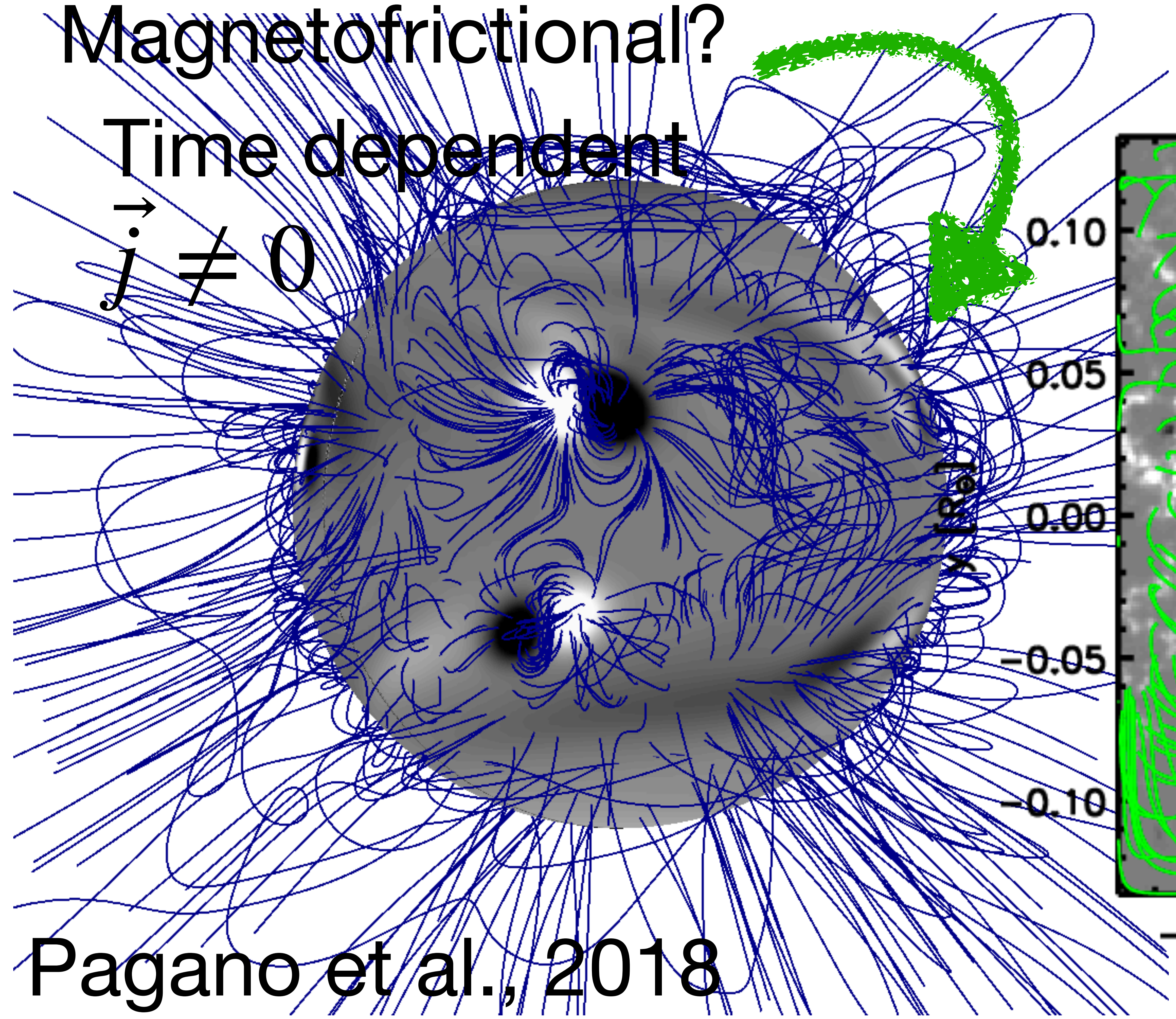
How do we do?

Magnetic field

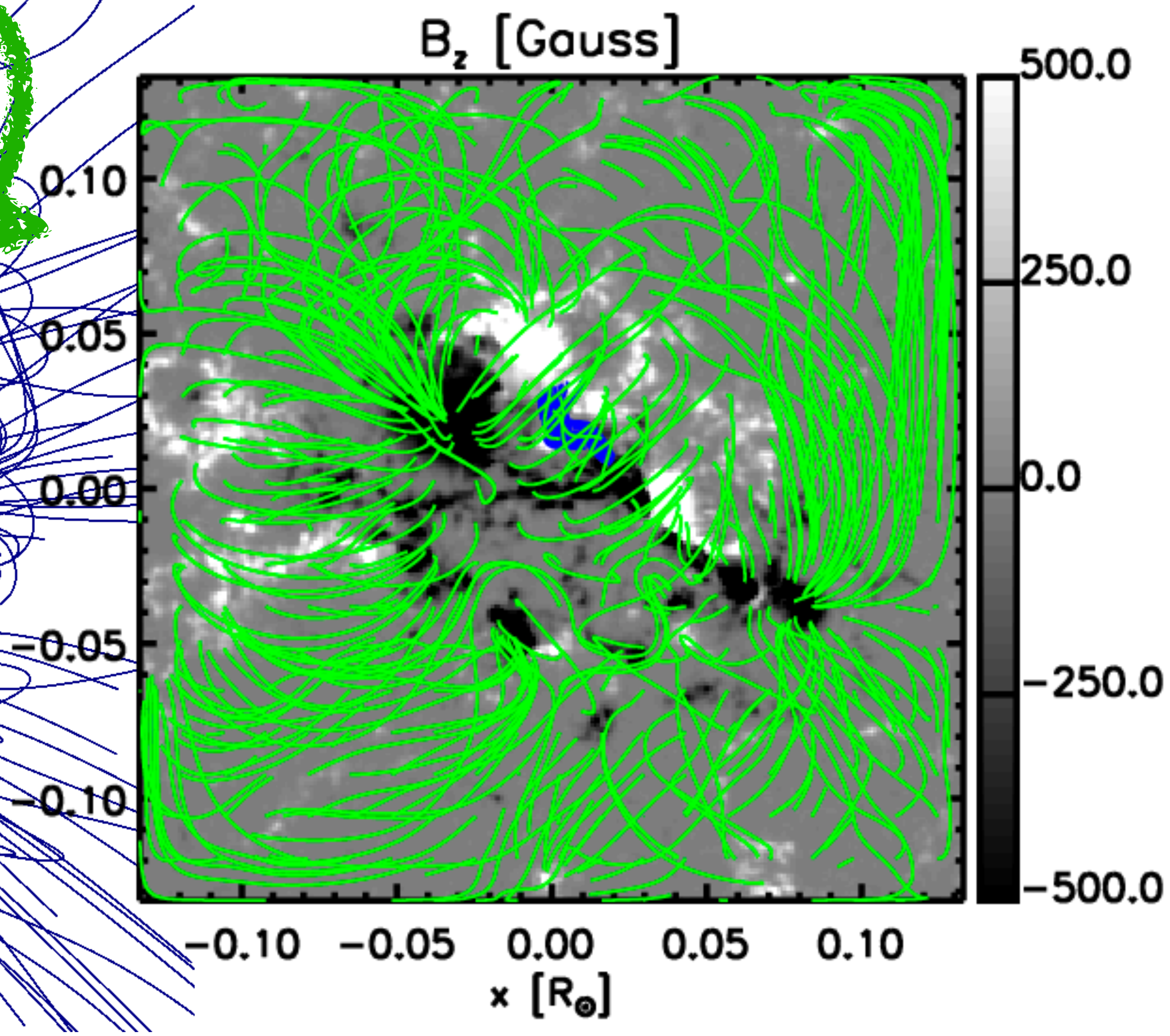
PFSS
from pfsspy
$\vec{j} = 0$

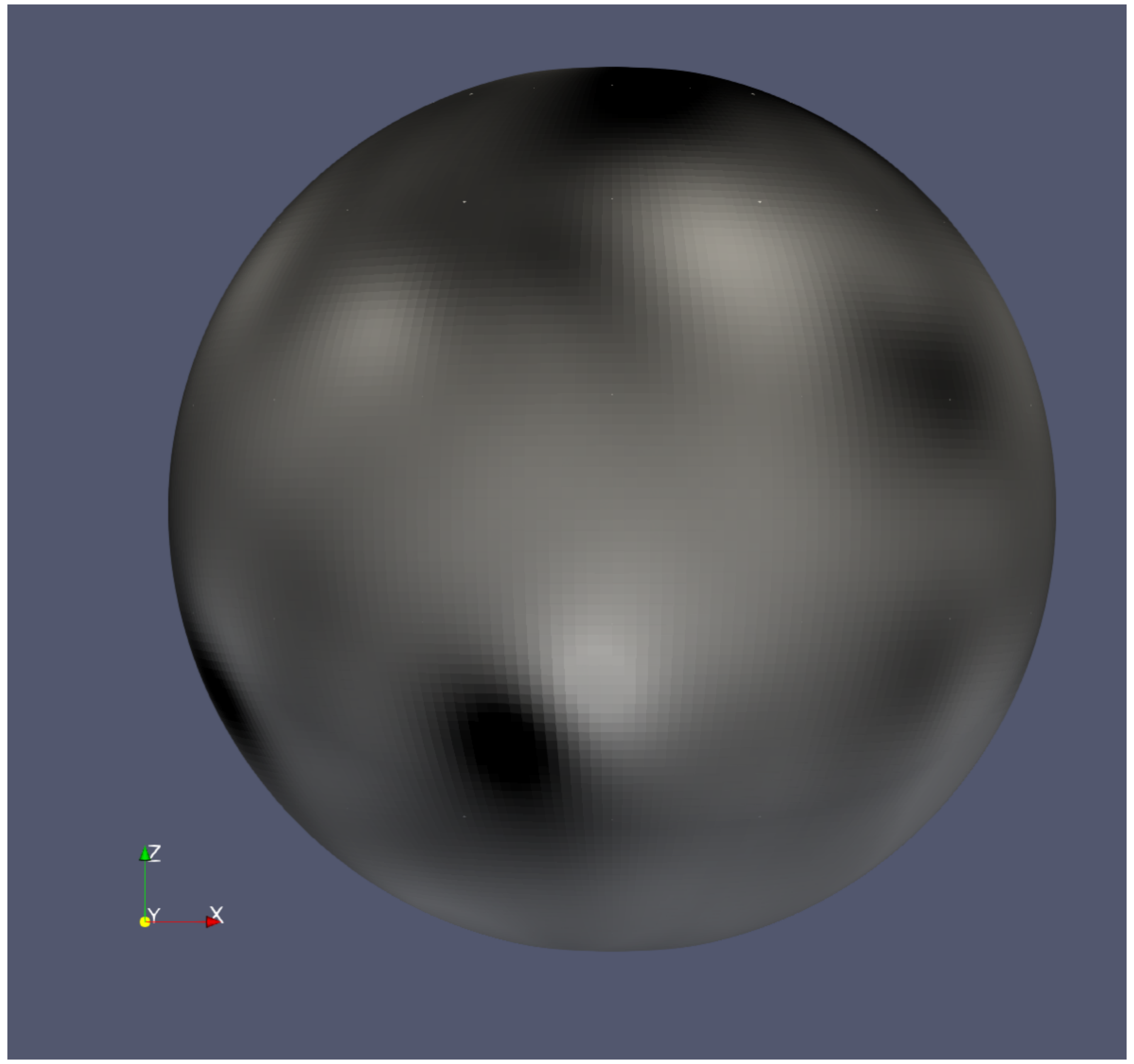


Magnetofrictional?
Time dependent
$\vec{j} \neq 0$



Pagano et al., 2018





Plasma

$$0.99R_\odot < r < r_{max} = 201R_\odot$$

$$r_\star = 0.163R_\odot$$

(arbitrarily chosen)

Low corona

(loop-like physics)

$$r < r_\star$$

Radiative losses
thermal conduction
Background heating

Inputs

T_M Mikić Temperature

$T < T_{min}$ floor temperature

Outer corona

(solar wind physics)

$$r > r_\star$$

Inputs

T_0 isothermal solar wind T

$\rho_0 = \rho(r_\star)$

Outer corona

(solar wind physics)

Runge-Kutta solver

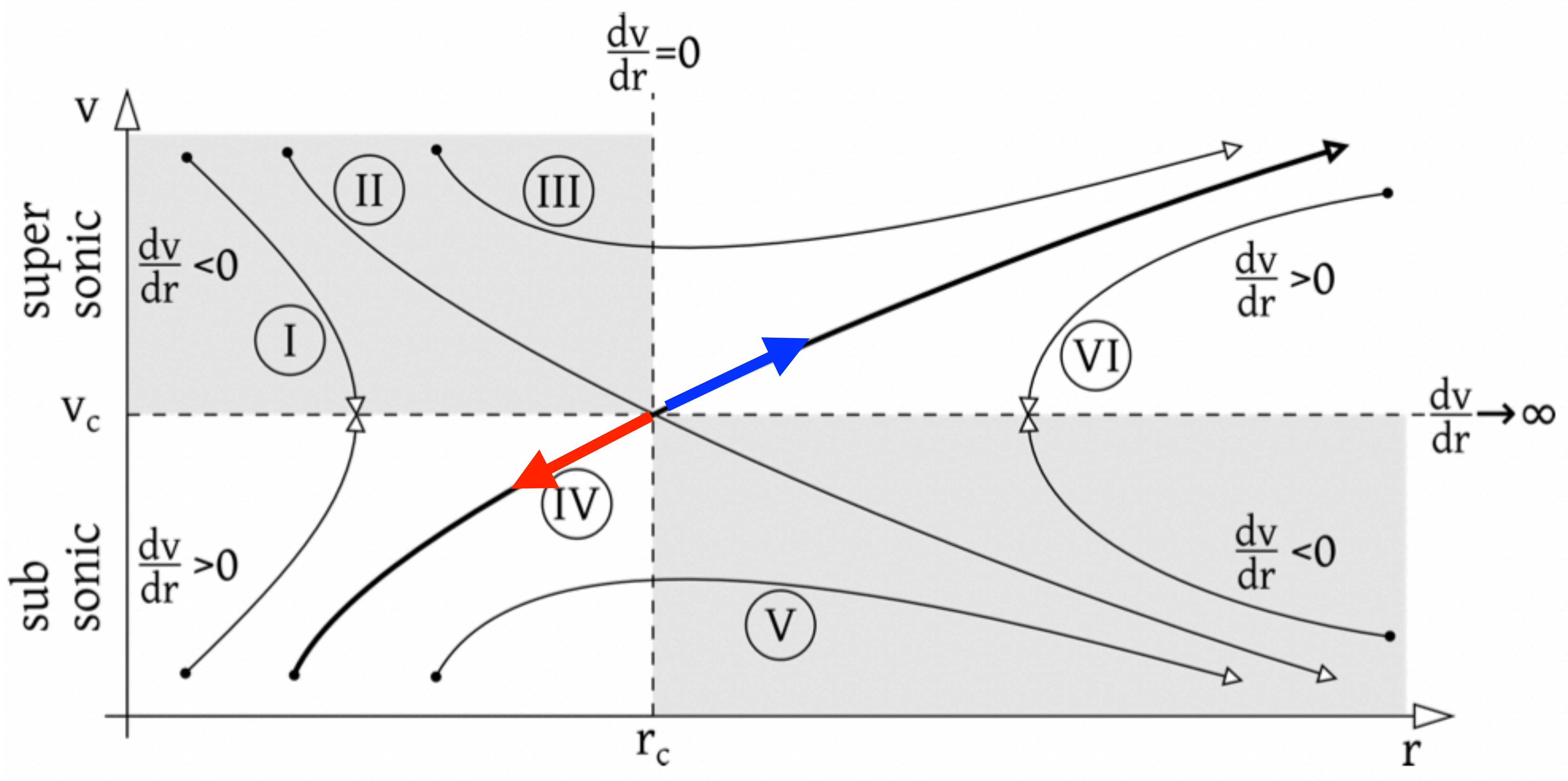
1

$$\frac{dv_r}{dr} = \frac{2\frac{c_s^2}{r} - \frac{GM_\odot}{r^2}}{v_r - \frac{c_s^2}{v}}$$

$$c_s = \sqrt{\frac{k_b T}{m_p \mu}} \qquad r_c = \frac{GM_\odot}{2c_s^2}$$

b.c. $v(r_c) = c_s$

We start from the sonic points and we integrate the equation up to r_{max} and down to $r_\star$



Plasma

Low corona

(loop-like physics)

we solve from $r_\star$ downwards from the solution found with the solar wind equations

Runge-Kutta solver

1

$$\frac{dP}{dr} = g(r)\rho = g(r)\frac{m_p \mu P}{2k_b T} \qquad g(r) = G\frac{M_\odot}{r^2}$$

b.c. $P(r_\star) = \frac{2\rho(r_\star)}{\mu m_p} k_b T$

2

$$\frac{dT}{dr} = \frac{Fc_r}{\kappa r^2}$$

- if $T < T_{min}$ then $\frac{dT}{dr} = 0$ (to make a chromosphere)
- $\kappa = \kappa_0 T^{\frac{5}{2}}$ if $T < T_M$ then $\kappa = \kappa_0 T_M^{\frac{5}{2}}$

b.c. $T(r_\star) = T_0$

3

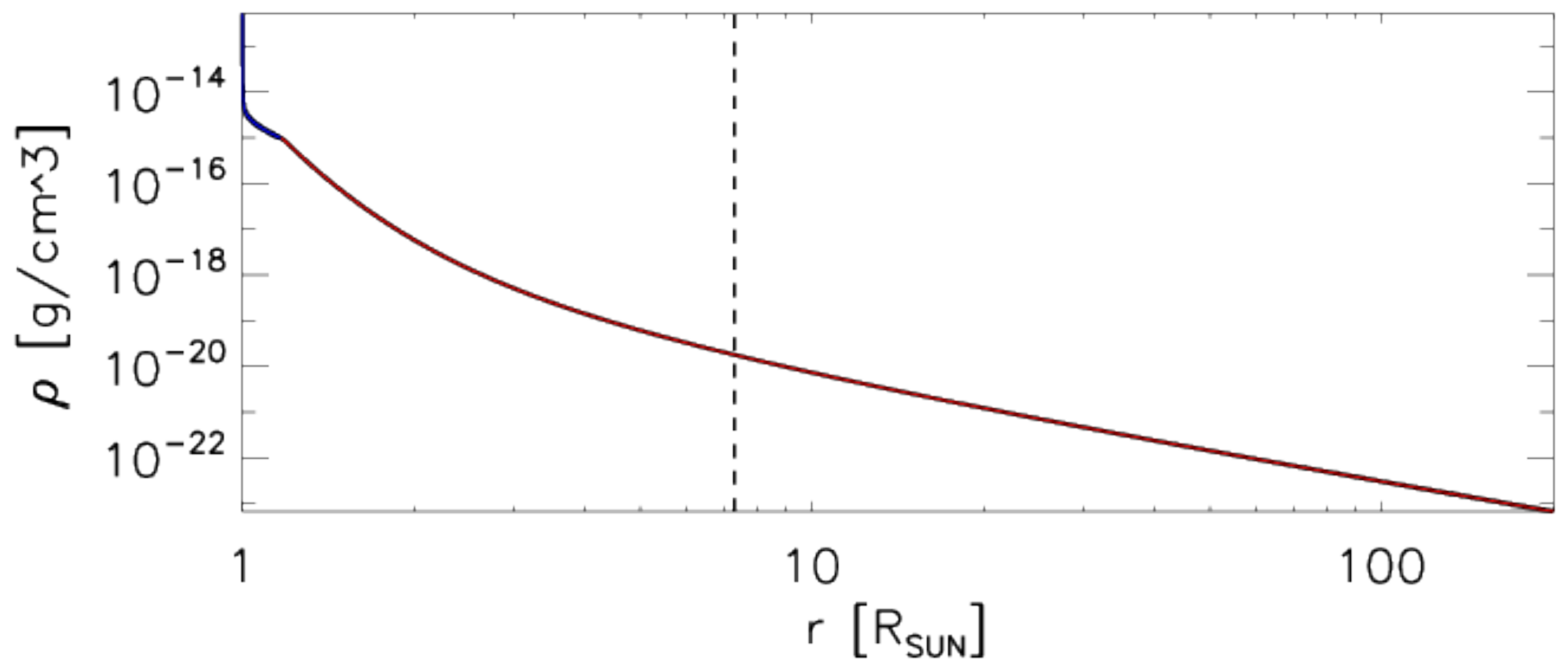
$$\frac{dFc_r}{dr} = \left(n^2\Lambda(T) - H\right) r^2 = \left[\left(\frac{P}{2k_b T}\right)^2 \Lambda(T) - H_0\right] r^2$$

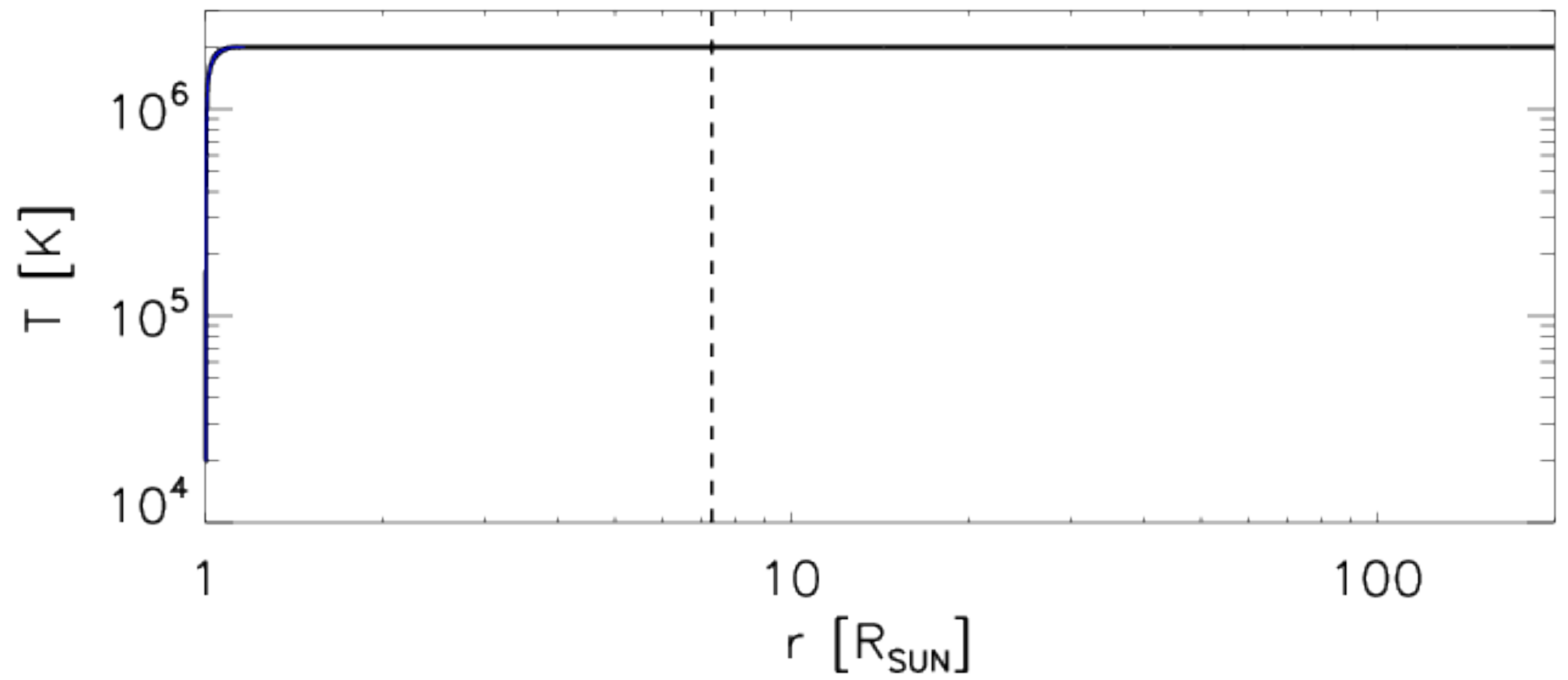
- if $T < T_{min}$ then $\frac{dFc_r}{dr} = 0$
- piece-wise power law $\Lambda(T)$

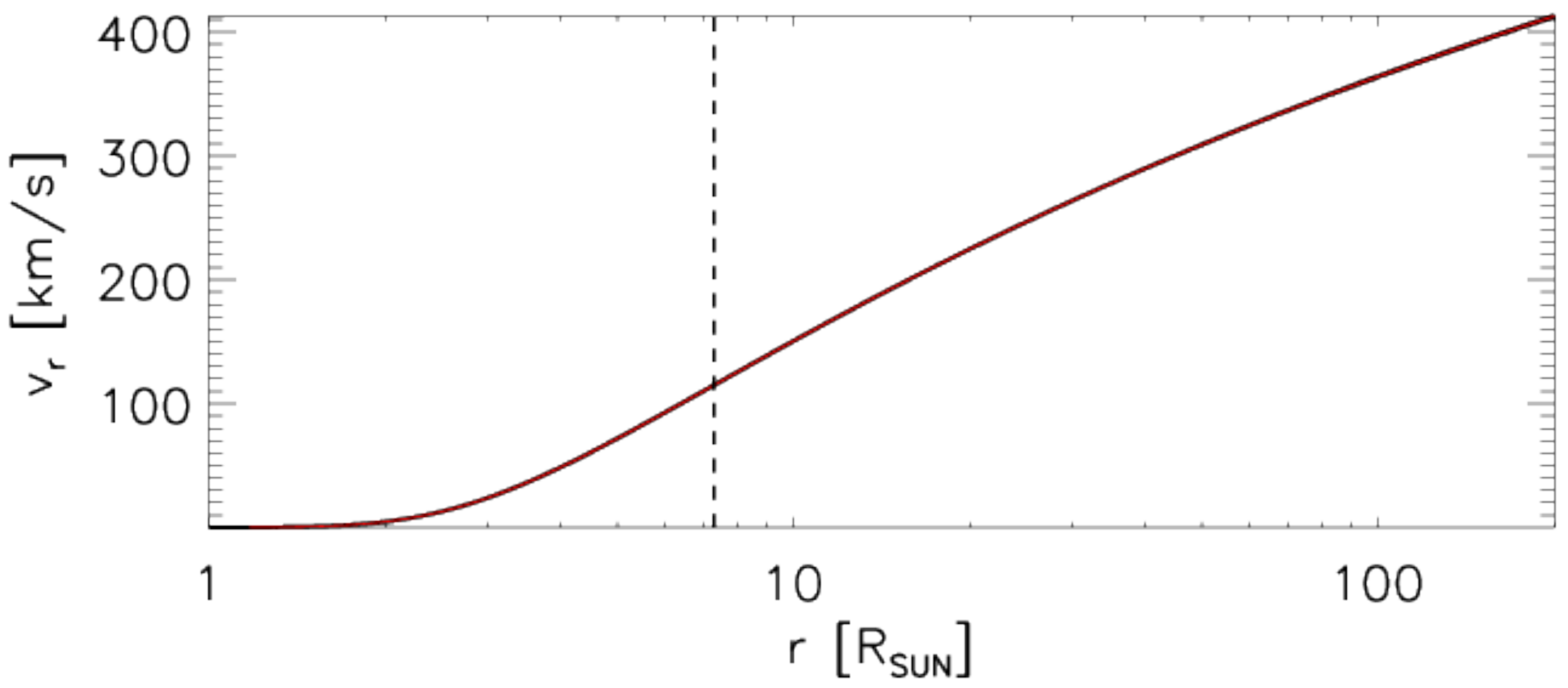
  if $T < T_M$ then $\Lambda = \Lambda\left(\frac{T}{T_M}\right)^{\frac{5}{2}}$

b.c. $Fc_r(r_\star) = 0$

Plasma



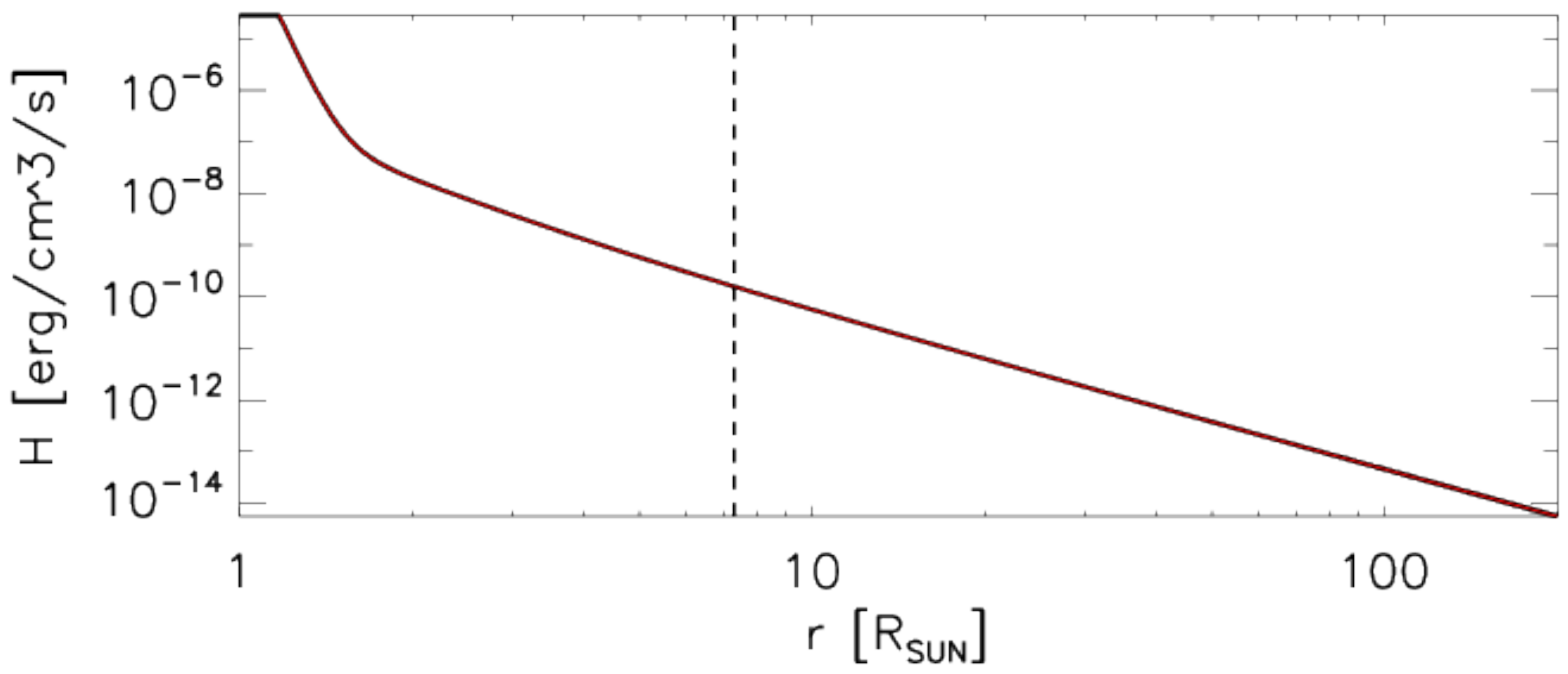




in solar wind part we estimate how much heating is needed to support the wind

$$H = \frac{d}{dr}(K+U)\frac{1}{r^2} + \left(\frac{P}{2k_bT}\right)^2 \Lambda(T_0)$$

$$H_0 = H(r_\star)$$



3D MHD Model

PLUTO

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v}) = 0$$

$$\frac{\partial \rho \vec{v}}{\partial t} + \nabla \cdot (\rho \vec{v}\vec{v} - \vec{B}\vec{B} + p_t I) = \rho \vec{g}$$

$$\frac{\partial \vec{B}}{\partial t} - \vec{\nabla} \times (\vec{v} \times \vec{B}) = 0$$

$$\frac{\partial E}{\partial t} + \nabla \cdot ((E + p_t)\vec{v} - \vec{B}(\vec{v} \cdot \vec{B})) = \rho \vec{v} \cdot \vec{g} - n_e n_H \Lambda(T) + H - \nabla \cdot \vec{F_c}$$

$$E = \frac{p}{\rho(\gamma - 1)} + \frac{1}{2}\vec{v}^2 + \frac{\overrightarrow{B^2}}{8\pi\rho}$$

110K CPU hours
@CINECA
Leonardo

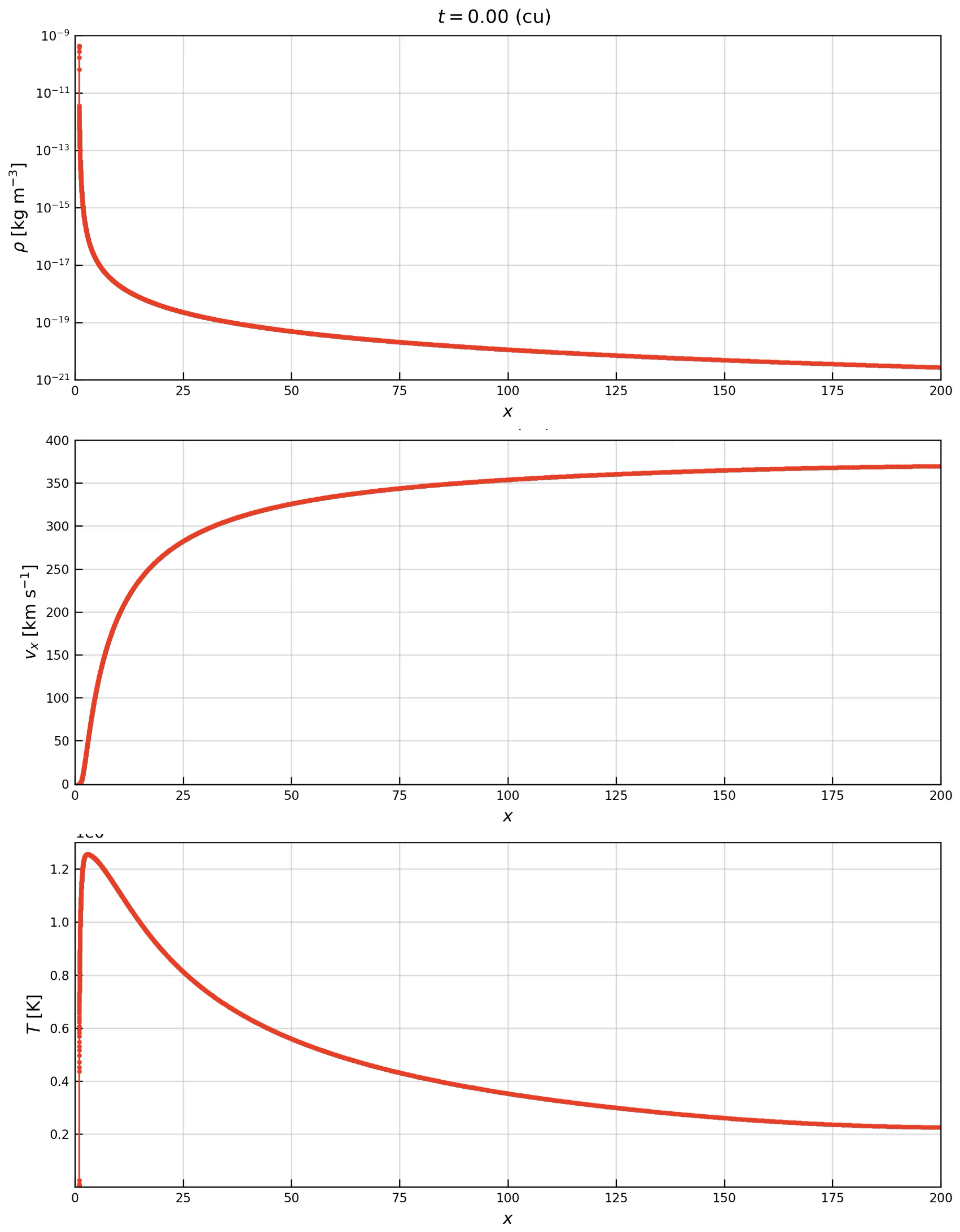
TOP 500 The List.

6 **Leonardo** - BullSequana XH2000, Xeon Platinum 8358 32C 2.6GHz, NVIDIA A100 SXM4 64 GB, Quad-rail NVIDIA HDR100 Infiniband, EVIDEN
EuroHPC/CINECA

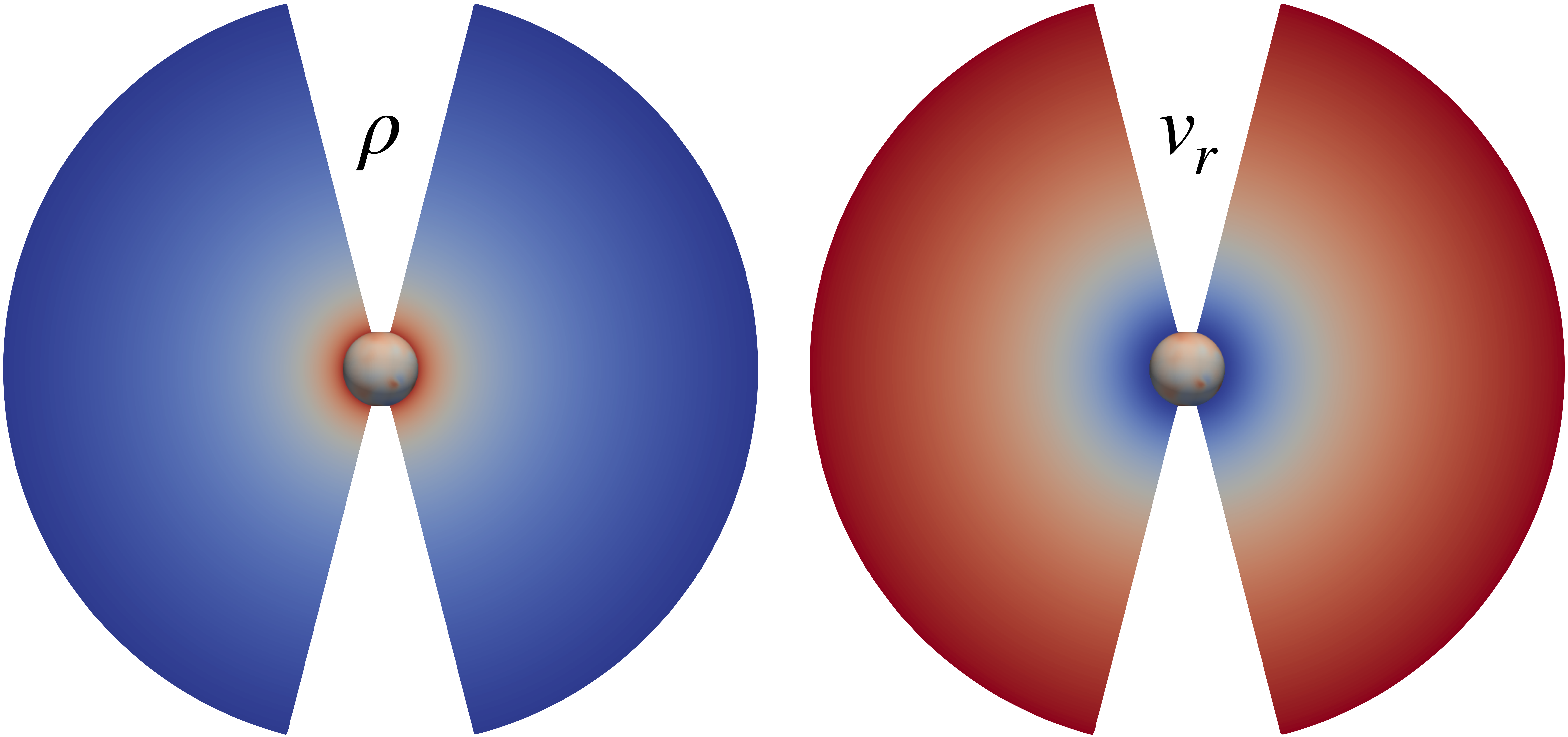
Mikić transition region
$\kappa(T)\Lambda(T)$ constant

towards the 3D MHD Model

1D relaxation

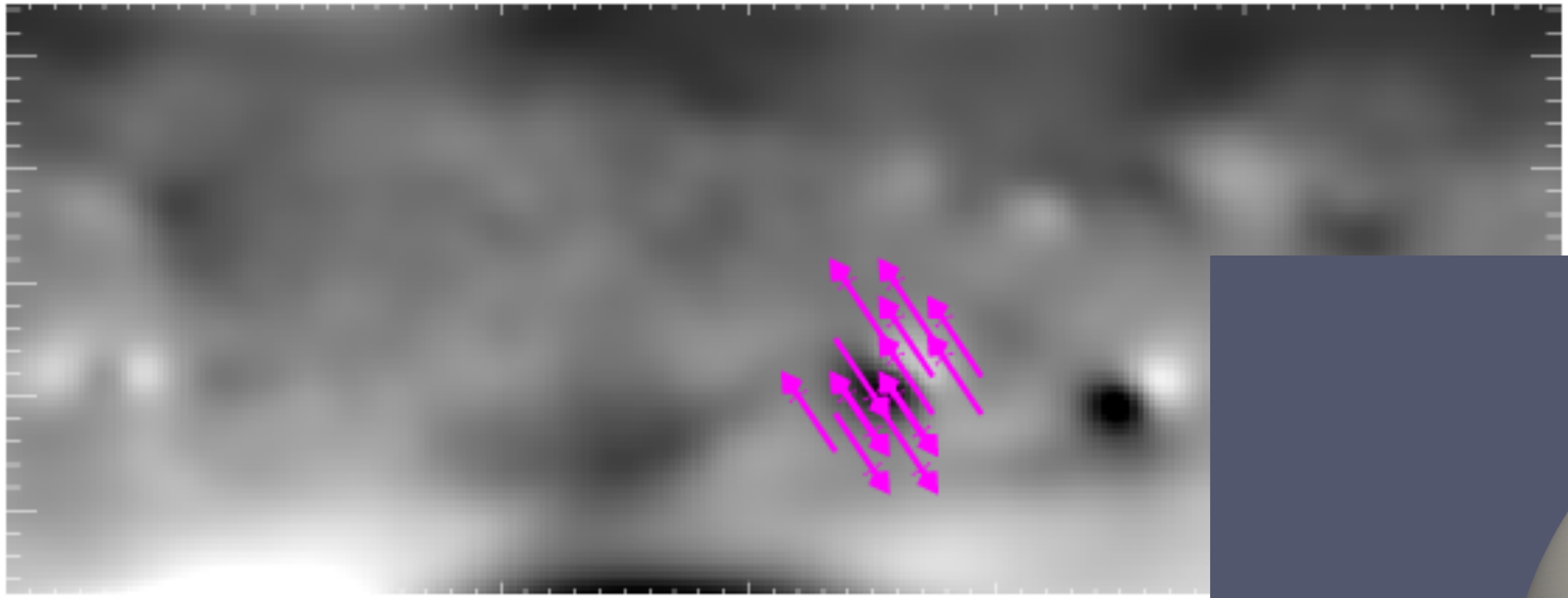


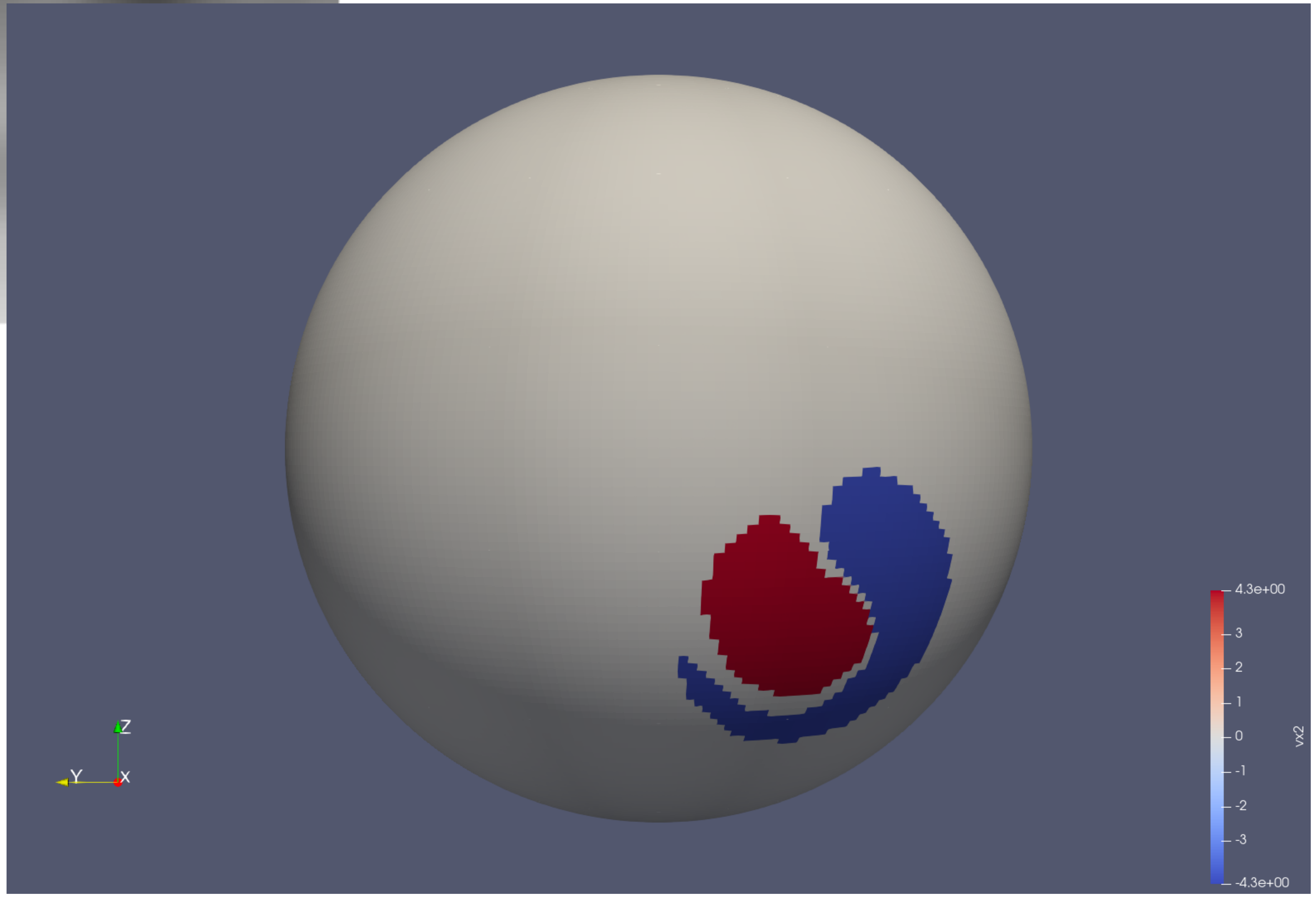
3D MHD Model

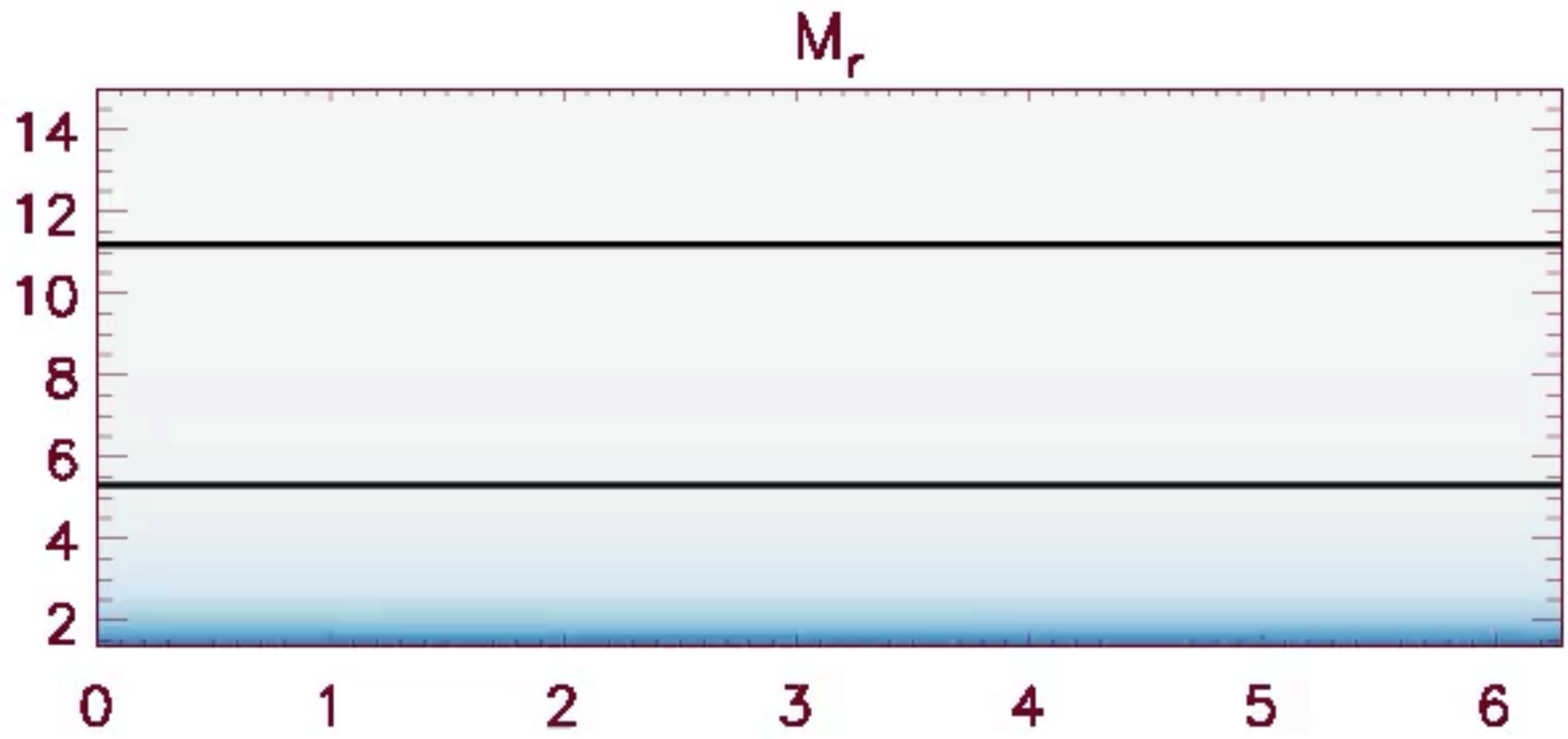


CME Triggering Mechanism

Active region shearing







M_r
14
12
10
8
6
4
2
0
1
2
3
4
5
6

or… integration with S^2WARM

Pagano et al., 2019a

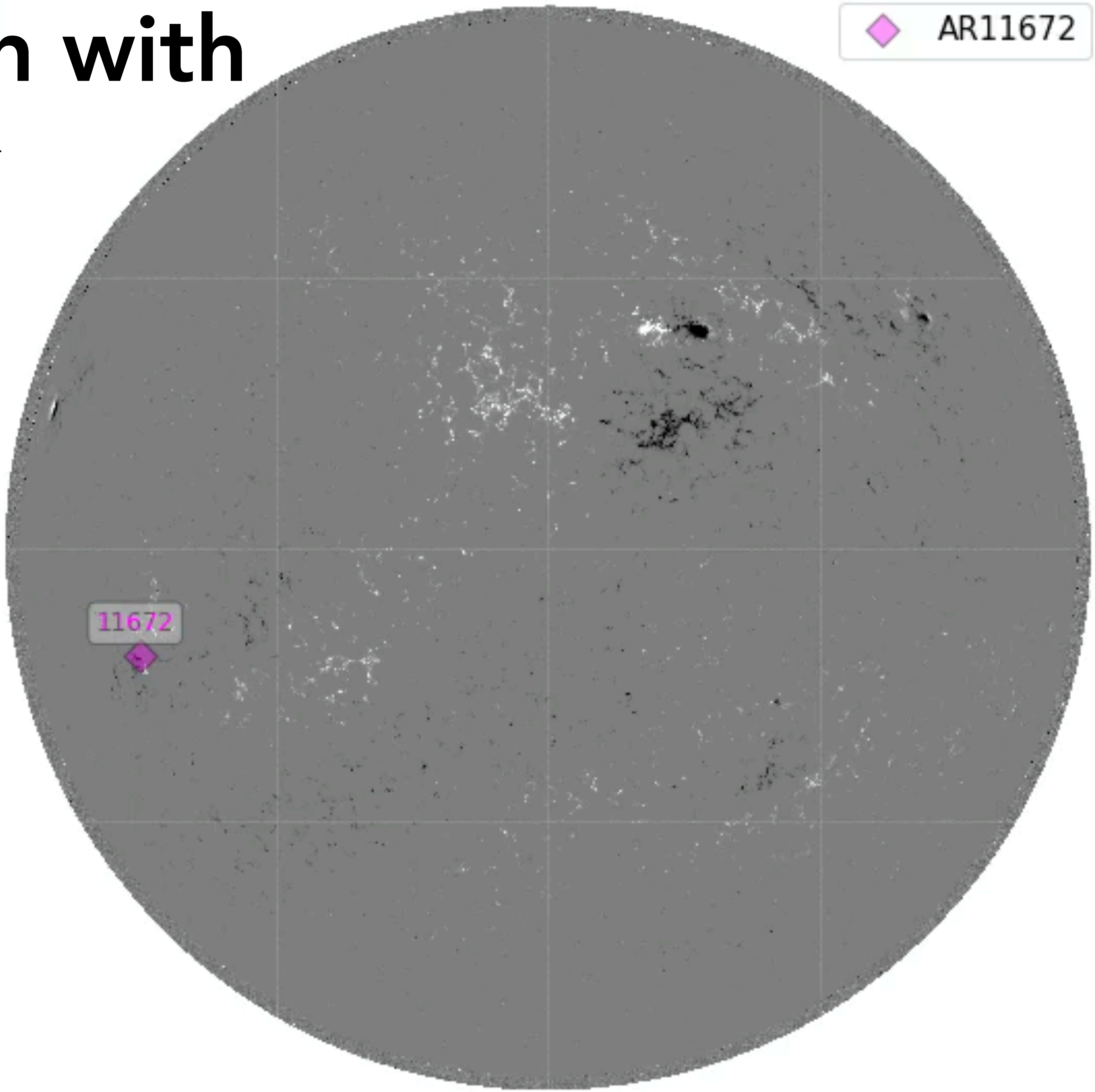
Pagano et al., 2019b

Ramp-up phase

Non-eruptive

Amber risk

Eruptive



Conclusions

When working, we will have a new tool to study any Metis CME

will open the way to:

1. new testing framework for diagnostics
2. study of the initiation mechanisms
3. study of the propagation physics
4. magnetic topology evolution during eruptions

Model to compute an initial guess for a numerical simulation of the solar wind

It is not a solar wind solution, because the physics equations are not even consistent throughout the domain

We aim at profiles of

$$\rho$$
$$P$$
$$T$$
$$v_r$$

from the chromosphere to the outer corona

Solar wind

From the Runga Kutta solver we have

v_r

T

We need to find

ρ

P

Conservation of mass $$\rho = \rho_0 \frac{r_\star^2 v_r(r_\star)}{r^2 v_r}$$

Equation of state $$P = \frac{2\rho}{\mu m_p} k_b T$$

Low corona

From the Runga Kutta solver we have

$$P$$

$$T$$

We need to find

$$\rho$$

$$v_r$$

Equation of state

$$\rho = \frac{\mu m_p P}{2 k_b T}$$

Conservation of mass

$$v_r(r) = v(r_\star)\left(\frac{r_\star}{r}\right)^2 \frac{\rho(r_\star)}{\rho}$$