Solar simulation research focused on space weather

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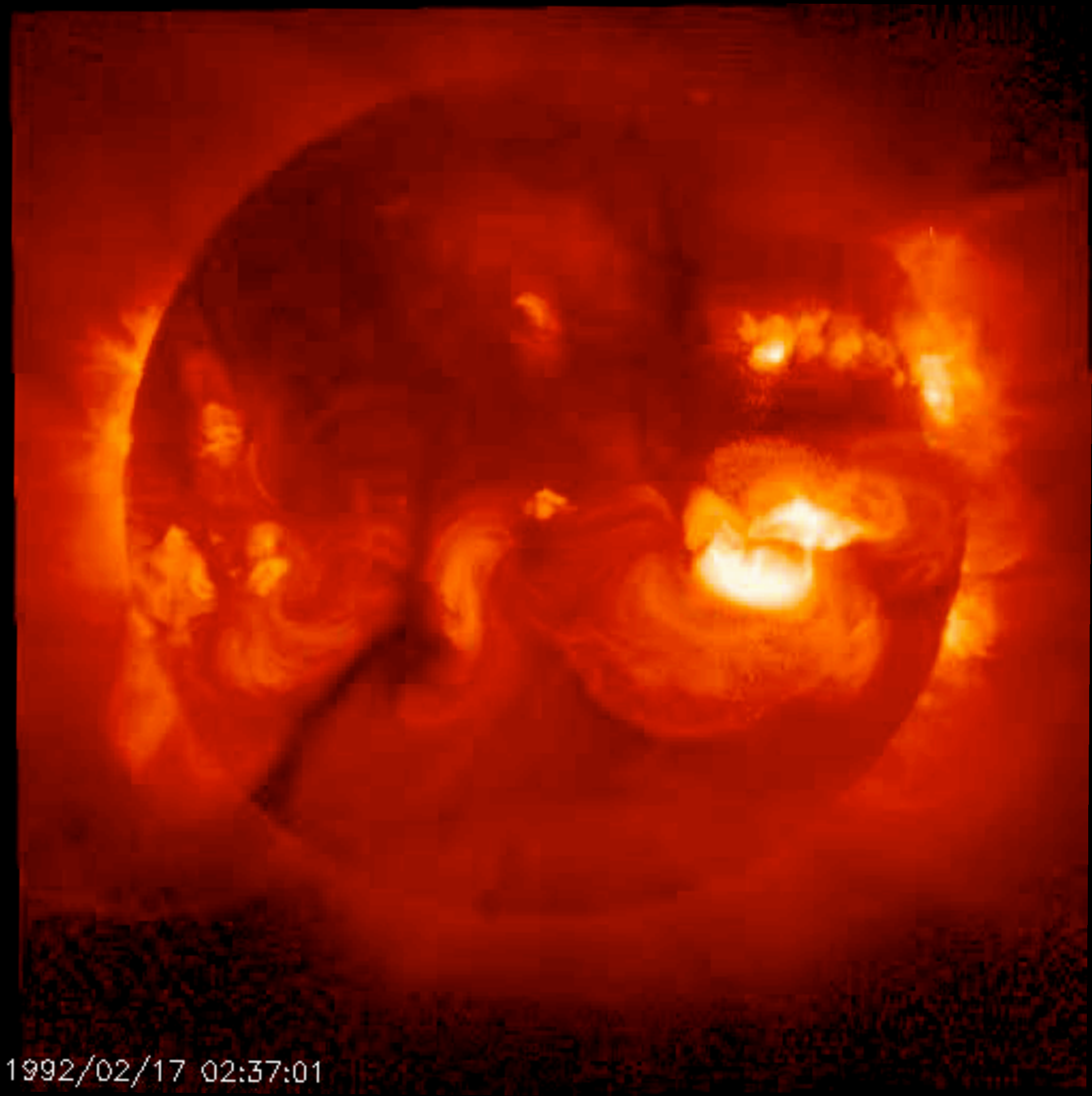
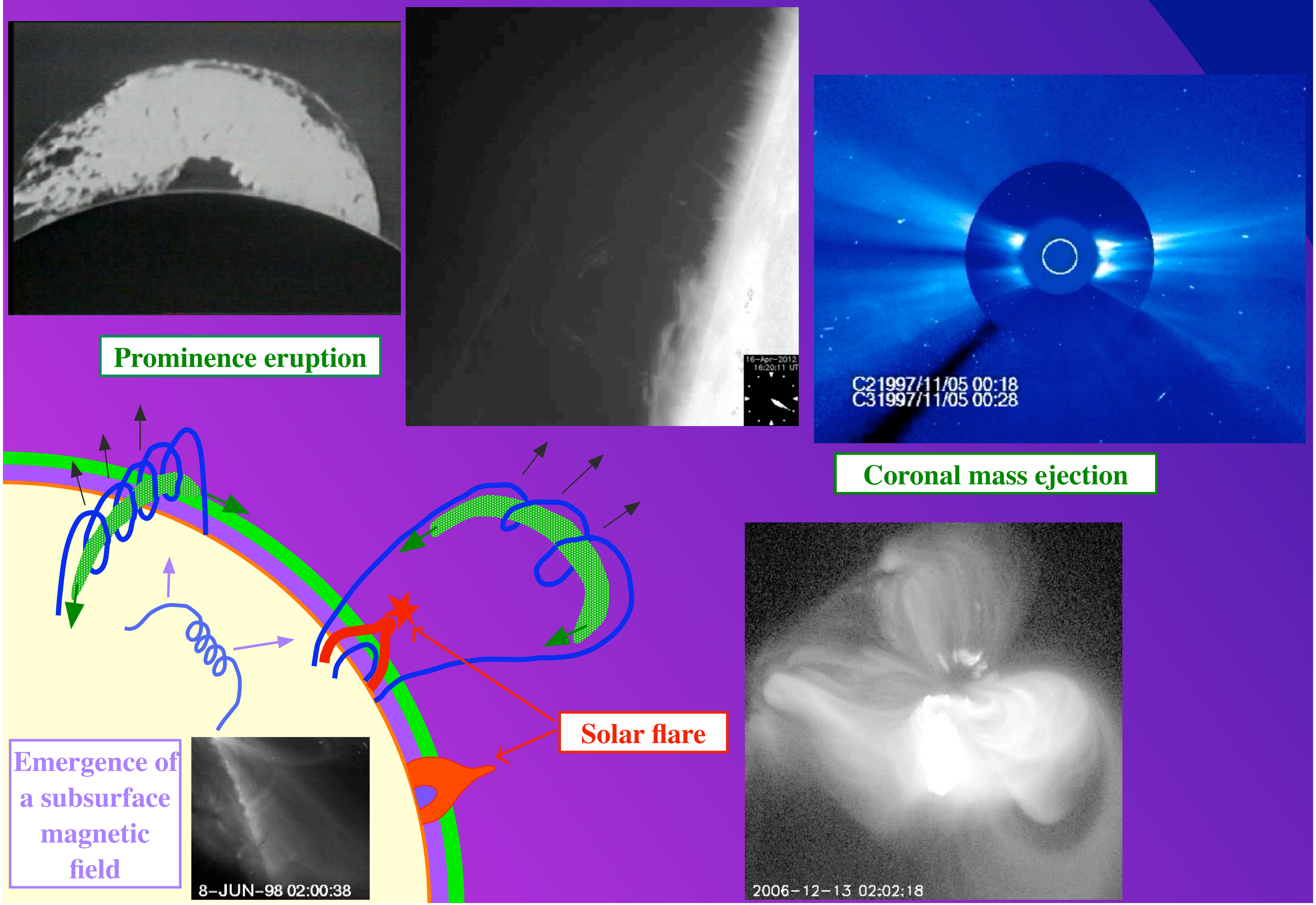
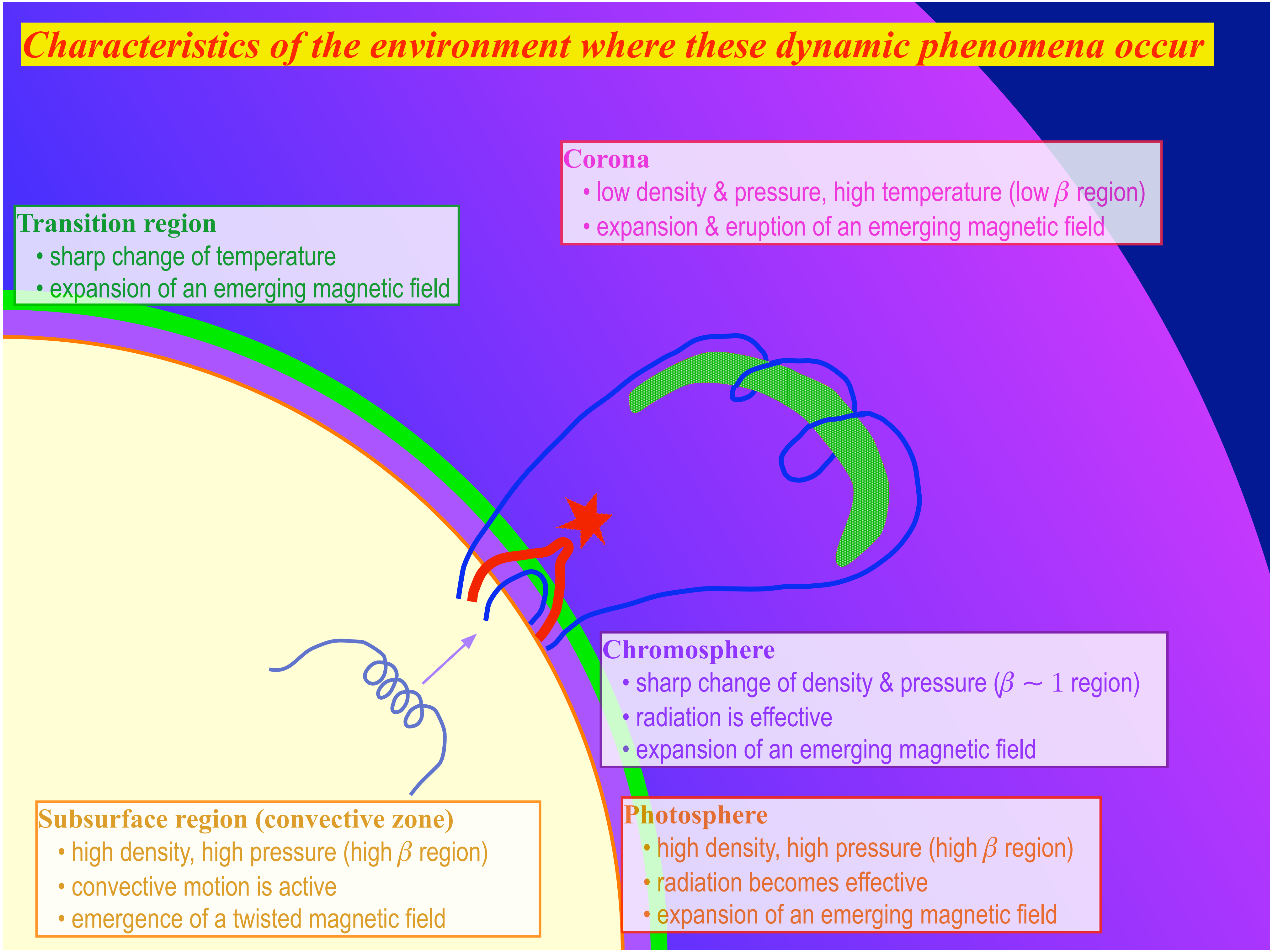
The Sun is full of dynamic phenomena



Observed by *Yohkoh*

Various solar dynamic phenomena




Characteristics of the environment where these dynamic phenomena occur
Corona
• low density & pressure, high temperature (low β region)
• expansion & eruption of an emerging magnetic field
Transition region
• sharp change of temperature
• expansion of an emerging magnetic field
Chromosphere
• sharp change of density & pressure ($\beta \sim 1$ region)
• radiation is effective
• expansion of an emerging magnetic field
Photosphere
• high density, high pressure (high β region)
• radiation becomes effective
• expansion of an emerging magnetic field
Subsurface region (convective zone)
• high density, high pressure (high β region)
• convective motion is active
• emergence of a twisted magnetic field

Targets of solar simulation research

Target IV: Observational data assimilation

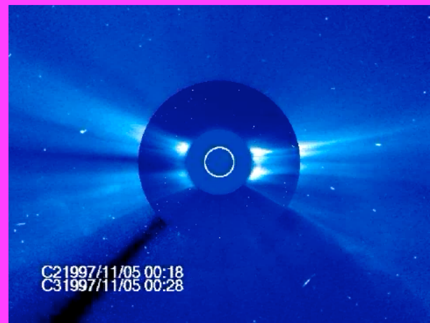
Corona

Transition region

Chromosphere

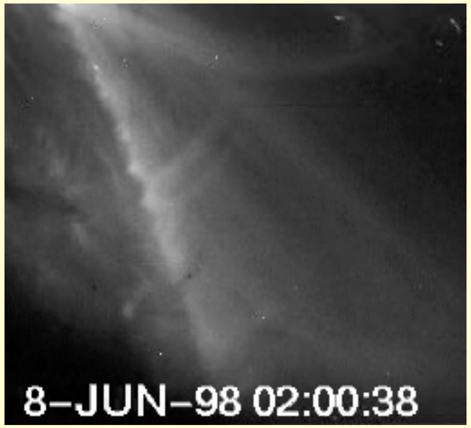
Photosphere

Target III: Global phenomena



Subsurface region (convective zone)

Target I: Flux emergence



Target II: Coronal loops

Flux emergence

To reproduce the emergence of a subsurface magnetic field into the corona

Domain: convective zone ~ corona (highly stratified), local Cartesian

Essential ingredients: gas pressure, magnetic field, gravitational field, compressible, viscosity, thermal conduction, radiative cooling

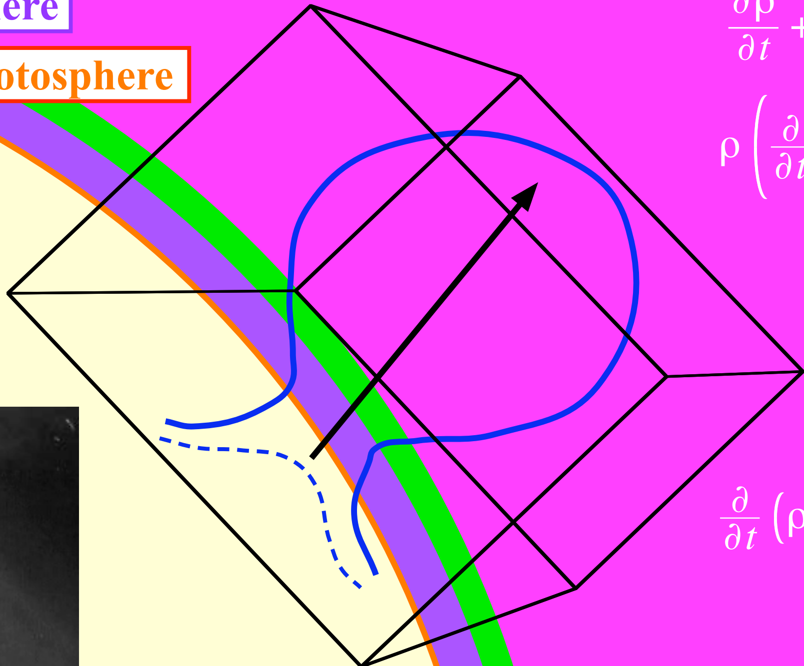
Simulation features: fully compressive, ideal or diffusive MHD

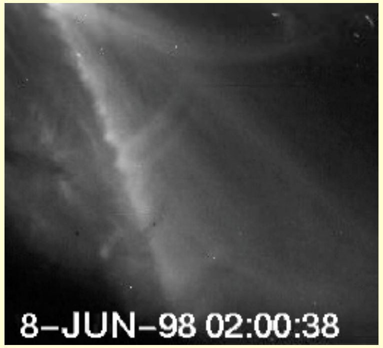
Transition region

Chromosphere

Photosphere

Corona





$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_k}\left(\rho\, u_k\right) = 0$$

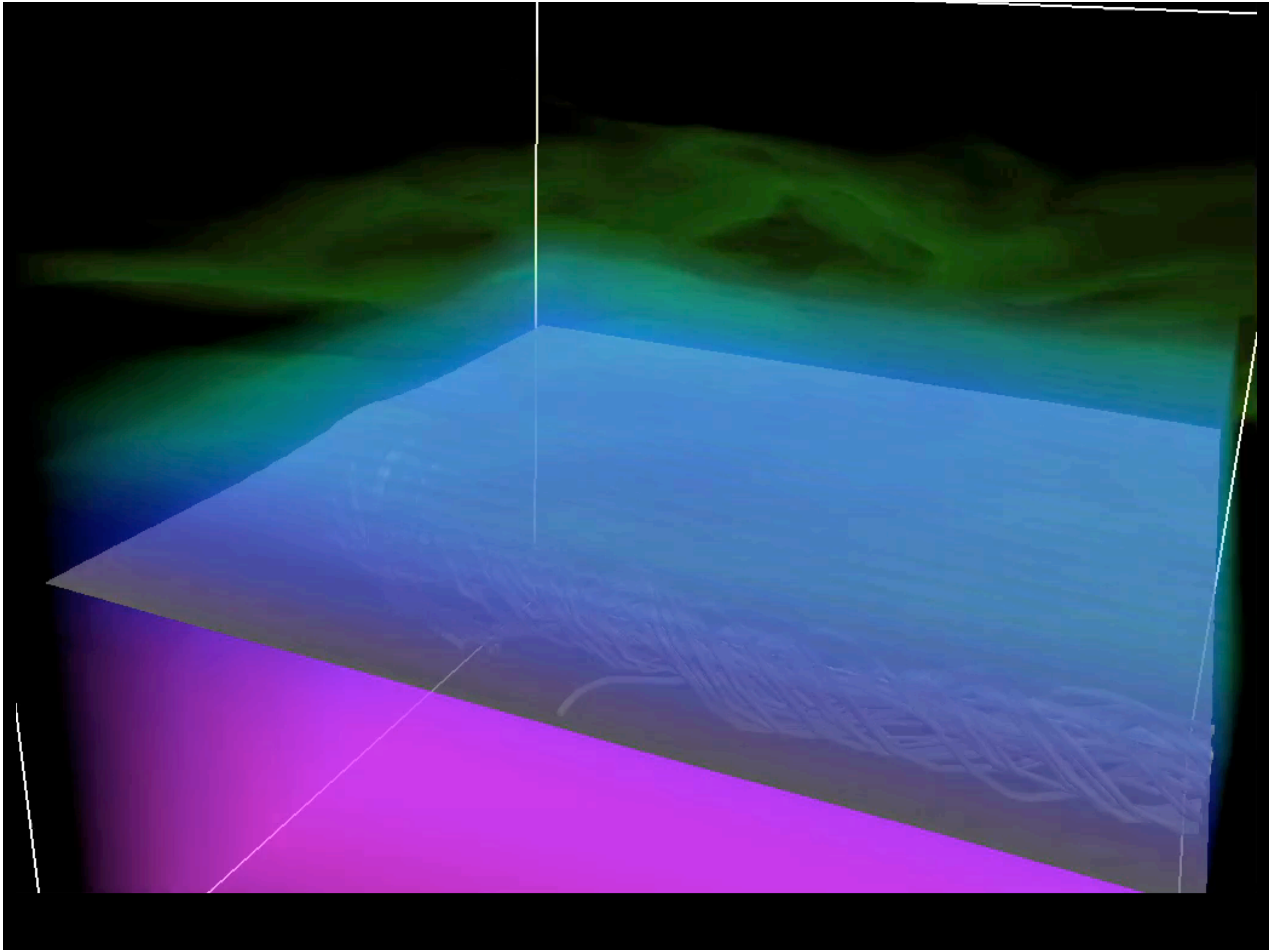
$$\rho\left(\frac{\partial}{\partial t}\boldsymbol{u} + \boldsymbol{u}\bullet\nabla\,\boldsymbol{u}\right) = \boldsymbol{j}\times\boldsymbol{B} - \frac{\partial}{\partial x_k}\left(P\,\delta_{ik} - \pi_{ik}\right) + \rho\,\boldsymbol{g}_0$$

$$\boldsymbol{g}_0 \equiv -G\,\frac{M_\odot}{R_\odot}$$

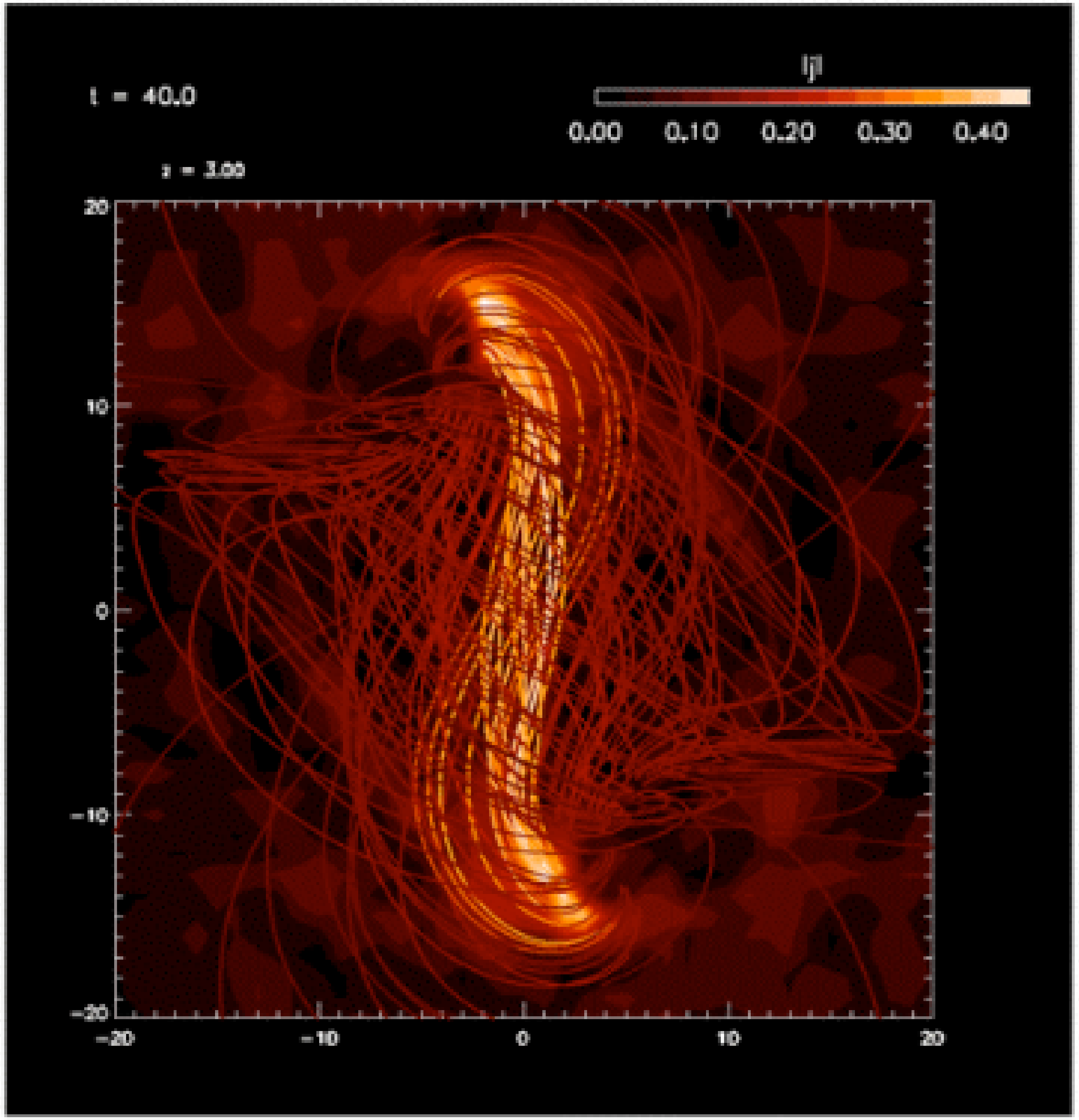
$$\frac{\partial}{\partial t}\left(\rho\,\varepsilon\right) + \frac{\partial}{\partial x_k}\left(\rho\,\varepsilon\,u_k\right) = -P\,\frac{\partial u_k}{\partial x_k} - \frac{\partial \mathscr{T}_k}{\partial x_k} + \Psi + \frac{j^2}{\sigma} - L_r$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla\times\left(\boldsymbol{v}\times\boldsymbol{B} - \eta_{diff}\,\nabla\times\boldsymbol{B}\right)$$

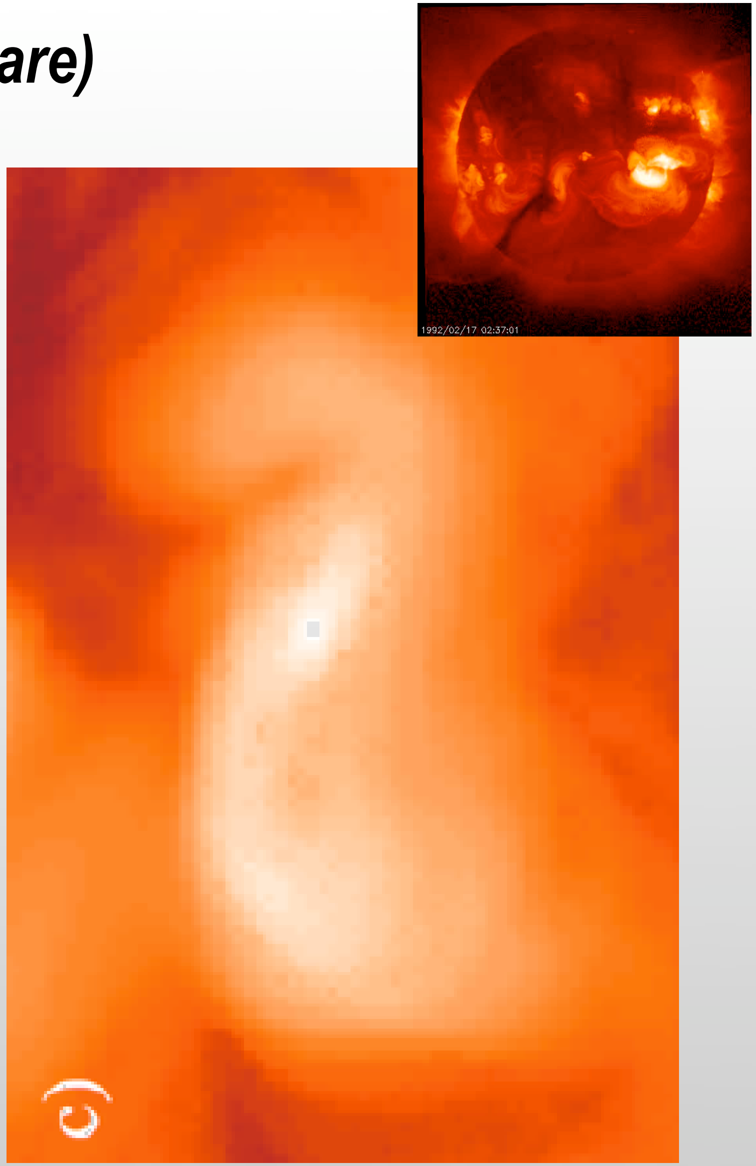
Subsurface region (convective zone)



Formation of a sigmoid (precursor of a solar flare)

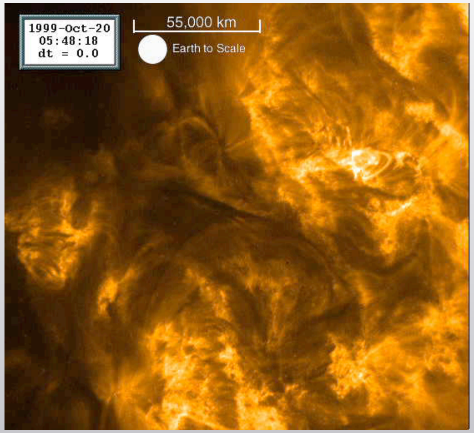


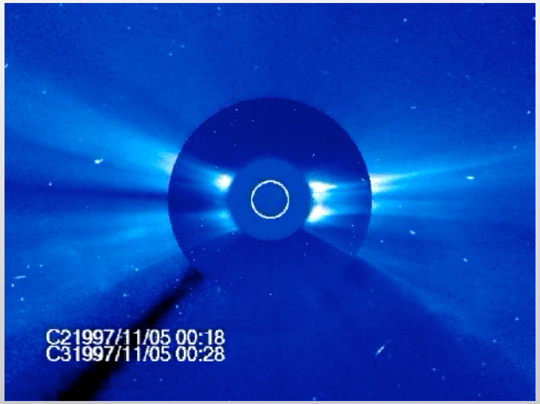
Inverse-S sigmoidal structure obtained from a simulation (emerging flux tube of left-handed twist)



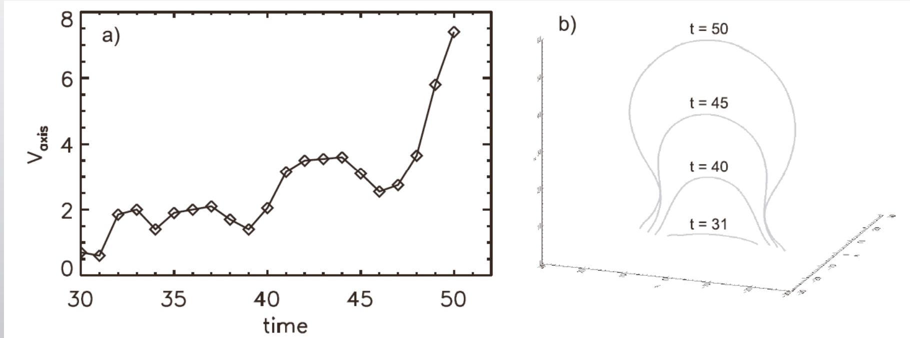
Inverse-S sigmoidal structure obtained from an observation (Yohkoh)

Coronal mass ejection (filament eruption)





Magara (2013)

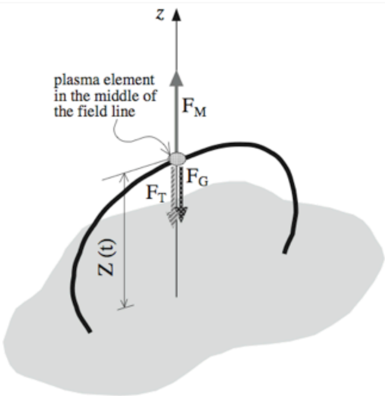


$$\rho \frac{d^2 Z}{dt^2} = F_M - F_T - F_G$$

$$= \frac{B^2}{4\pi}\left(\frac{1}{H} - \kappa\right) - \rho\, g$$

$F_M = \frac{B^2}{4\pi}\frac{1}{H}$ ... *magnetic pressure force*

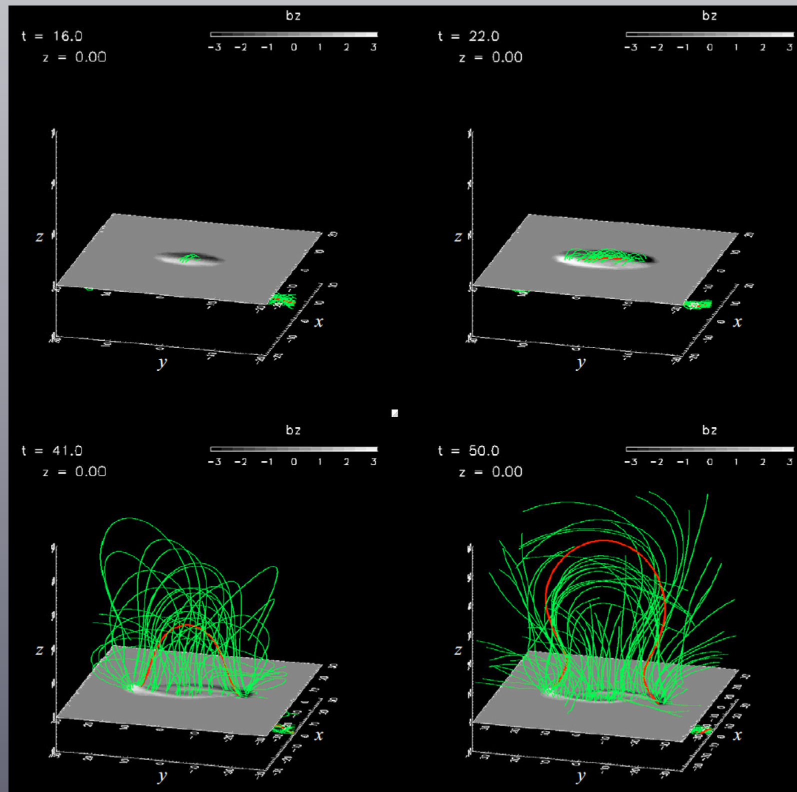
$F_T = \frac{B^2}{4\pi}\kappa$ ... *magnetic tension force*



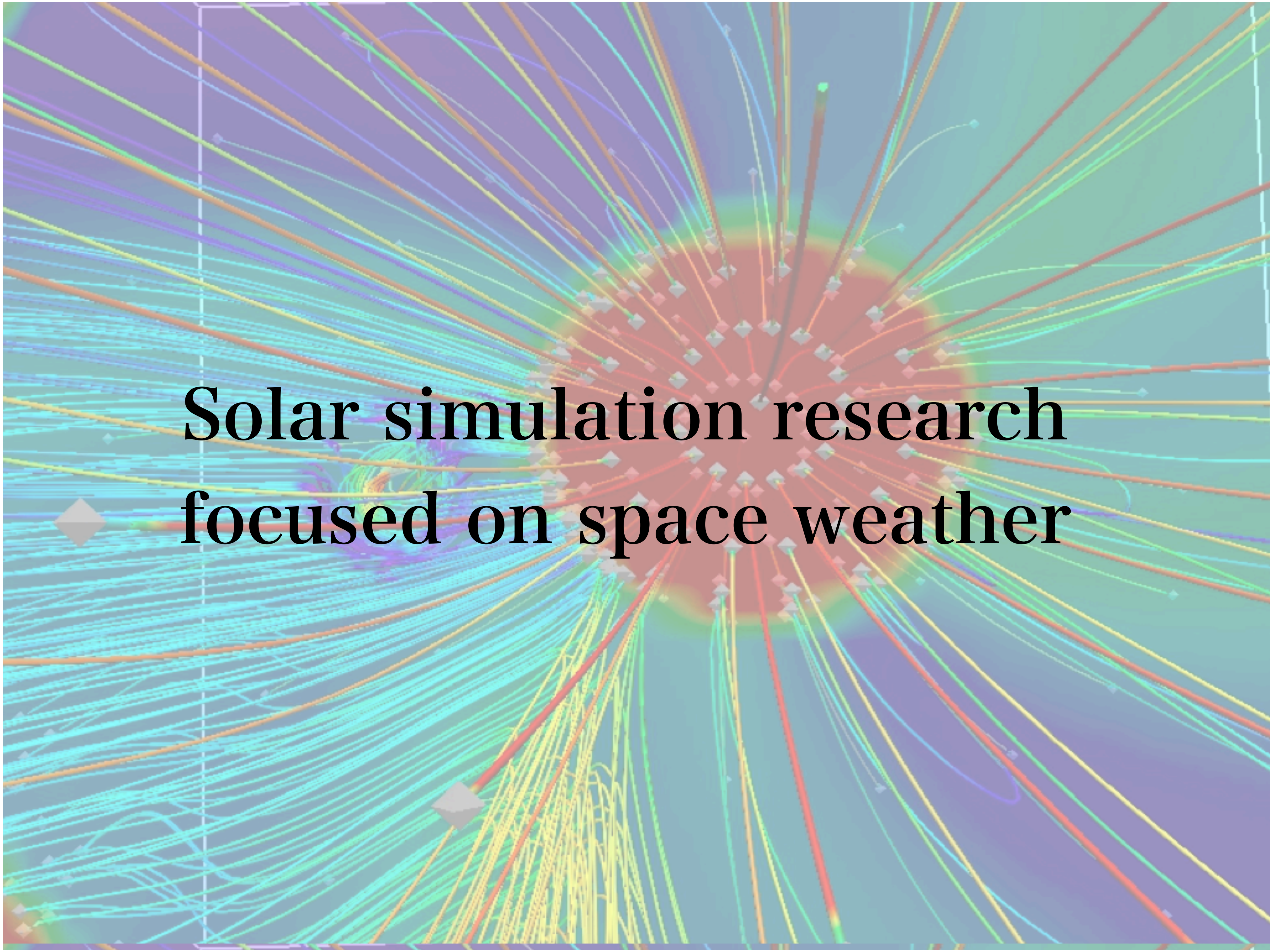
κ... curvature of an emerging loop **(represents magnetic tension force)**

H... field-strength scale height of emerging field **(represents magnetic pressure force)**

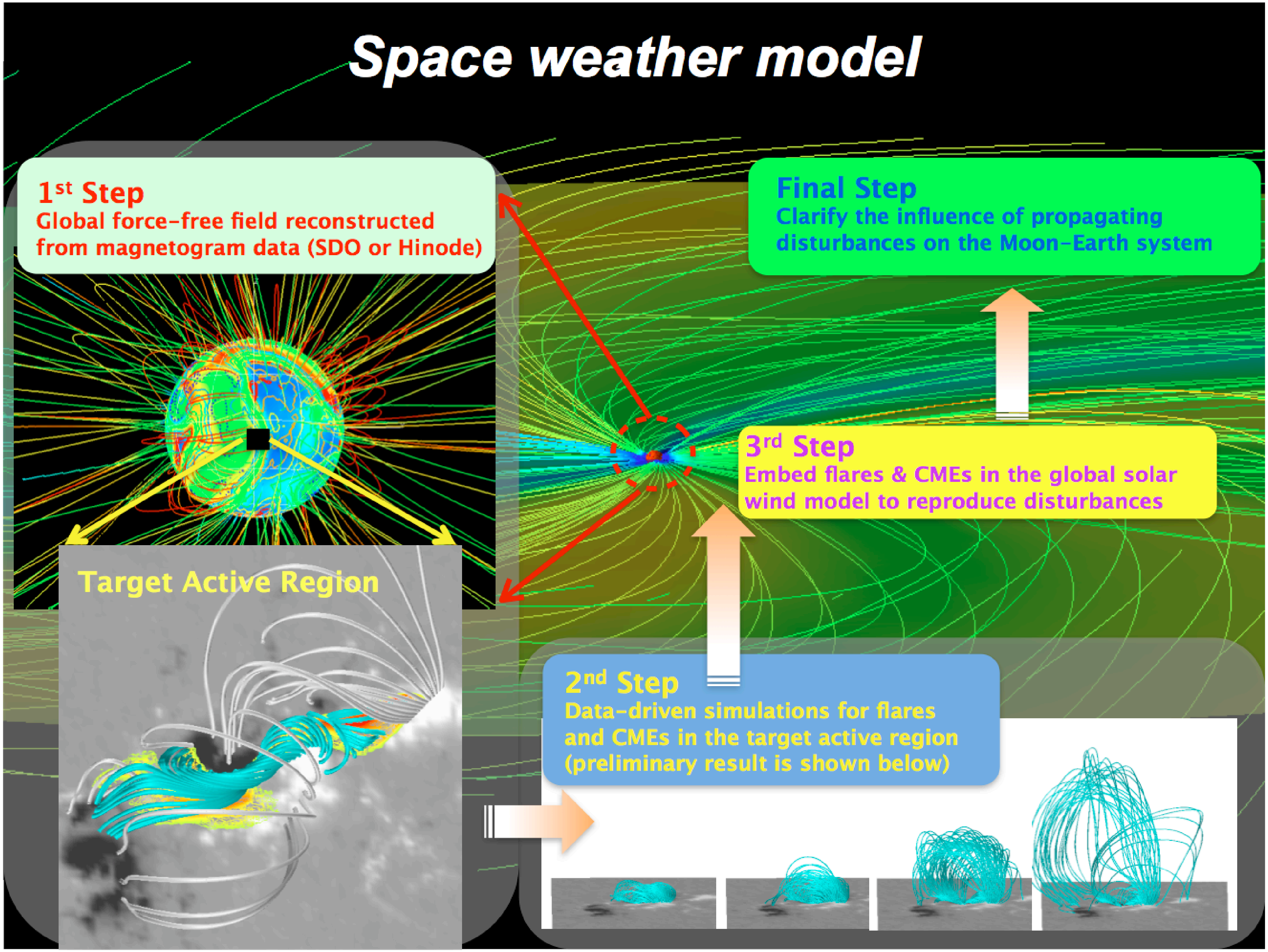
Magara (2004)



An & Magara (2013)



Solar simulation research focused on space weather


Space weather model
1st Step
Global force-free field reconstructed from magnetogram data (SDO or Hinode)
Target Active Region
2nd Step
Data-driven simulations for flares and CMEs in the target active region (preliminary result is shown below)
3rd Step
Embed flares & CMEs in the global solar wind model to reproduce disturbances
Final Step
Clarify the influence of propagating disturbances on the Moon-Earth system

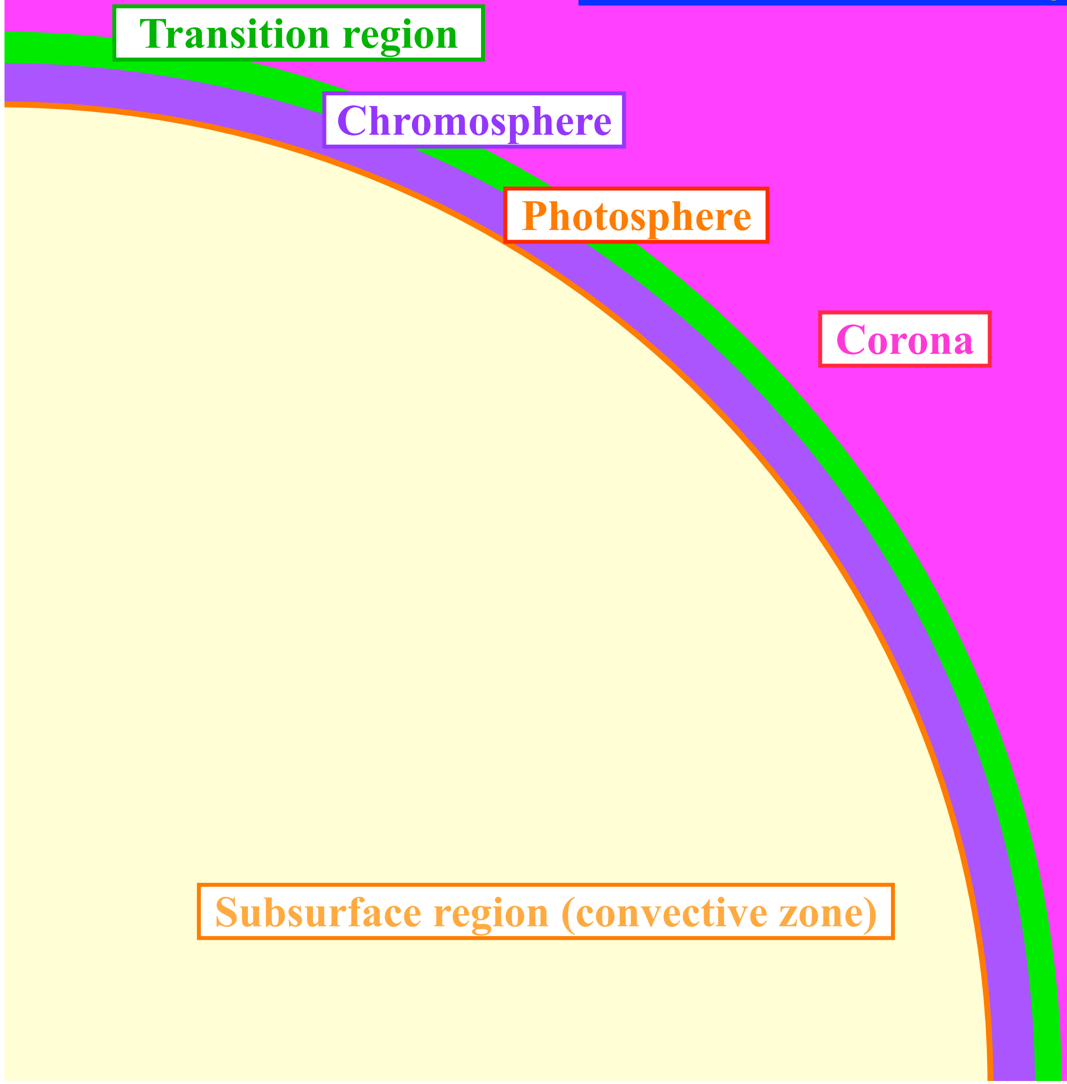
Observational data assimilation

To reproduce the evolution of a real active region using observational data

Domain: corona (high temperature, weakly stratified), zero-β MHD

Essential ingredients: magnetic field, resistivity, (artificial) viscosity

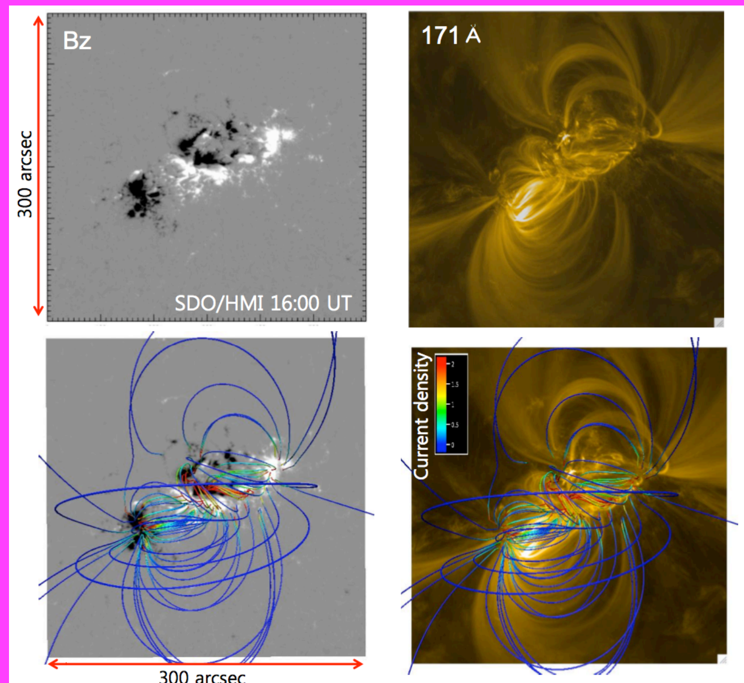
Simulation features: zero-β, no stratification, diffusive MHD



$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_k}\left(\rho u_k\right) = 0$$

$$\rho\left(\frac{\partial}{\partial t}\boldsymbol{u} + \boldsymbol{u}\bullet\nabla\boldsymbol{u}\right) = \boldsymbol{j}\times\boldsymbol{B} + \mu\nabla^2\boldsymbol{u}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla\times\left(\boldsymbol{v}\times\boldsymbol{B} - \eta_{diff}\nabla\times\boldsymbol{B}\right)$$



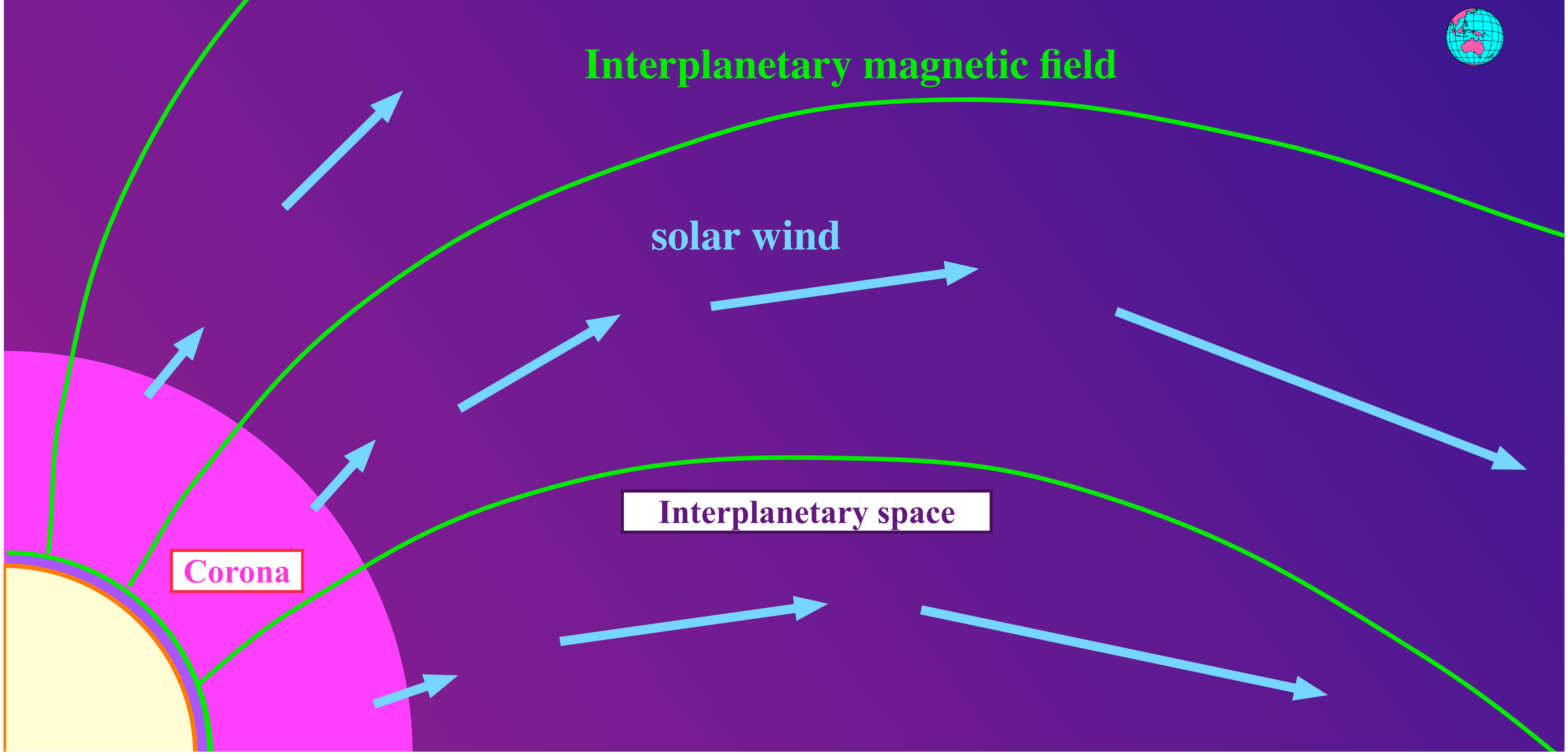
Global phenomena

To reproduce the global structure of a solar wind and interplanetary magnetic field

Domain: corona ~ interplanetary space (including terrestrial space), 3D global region

Essential ingredients: gas pressure, magnetic field, gravitational field, compressible

Simulation features: fully compressive, ideal or diffusive MHD



SOLAR WIND MODEL (MODIFIED FROM NAKAMIZO ET AL., 2009) : BASIC EQUATIONS

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{V}) = 0, \tag{1}$$

$$\frac{\partial (\rho \boldsymbol{V})}{\partial t} + \nabla \cdot \left(\rho \boldsymbol{V}\boldsymbol{V} + p\boldsymbol{I} + \frac{B^2 - B_0^2}{2\mu_0}\boldsymbol{I} - \frac{\boldsymbol{B}\boldsymbol{B} - \boldsymbol{B}_0\boldsymbol{B}_0}{\mu_0} \right)$$
$$= -\rho \frac{GM_s}{r^2}\hat{\boldsymbol{r}} - 2\rho\boldsymbol{\Omega} \times \boldsymbol{r} - \rho\boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \boldsymbol{r}), \tag{2}$$

$$\frac{\partial \boldsymbol{B}_1}{\partial t} + \nabla \times (\boldsymbol{V} \times \boldsymbol{B}) = 0, \tag{3}$$

$$\frac{\partial U_1}{\partial t} + \nabla \cdot \left[\boldsymbol{V} \cdot \left(U_1 + p + \frac{B_1^2}{2\mu_0} \right) - \frac{\boldsymbol{B}_1(\boldsymbol{V} \cdot \boldsymbol{B}_1)}{\mu_0} - \frac{\boldsymbol{B}_0(\boldsymbol{V} \cdot \boldsymbol{B}_1)}{\mu_0} + \frac{\boldsymbol{V}(\boldsymbol{B}_1 \cdot \boldsymbol{B}_0)}{\mu_0} \right]$$
$$= \rho\boldsymbol{V} \cdot \left(-\frac{GM_s}{r^2}\hat{\boldsymbol{r}} \right) - \rho\boldsymbol{V} \cdot [\boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \boldsymbol{r})], \tag{4}$$

$$U_1 = \frac{\rho v^2}{2} + \frac{p}{\gamma - 1} + \frac{B_1^2}{2\mu_0}, \tag{5}$$

$$\boldsymbol{B}_1(\boldsymbol{r}, t) \equiv \boldsymbol{B}(\boldsymbol{r}, t) - \boldsymbol{B}_0(\boldsymbol{r}) \qquad \gamma = \frac{5}{3}$$

Key factor in a modeling of global phenomena => grid system

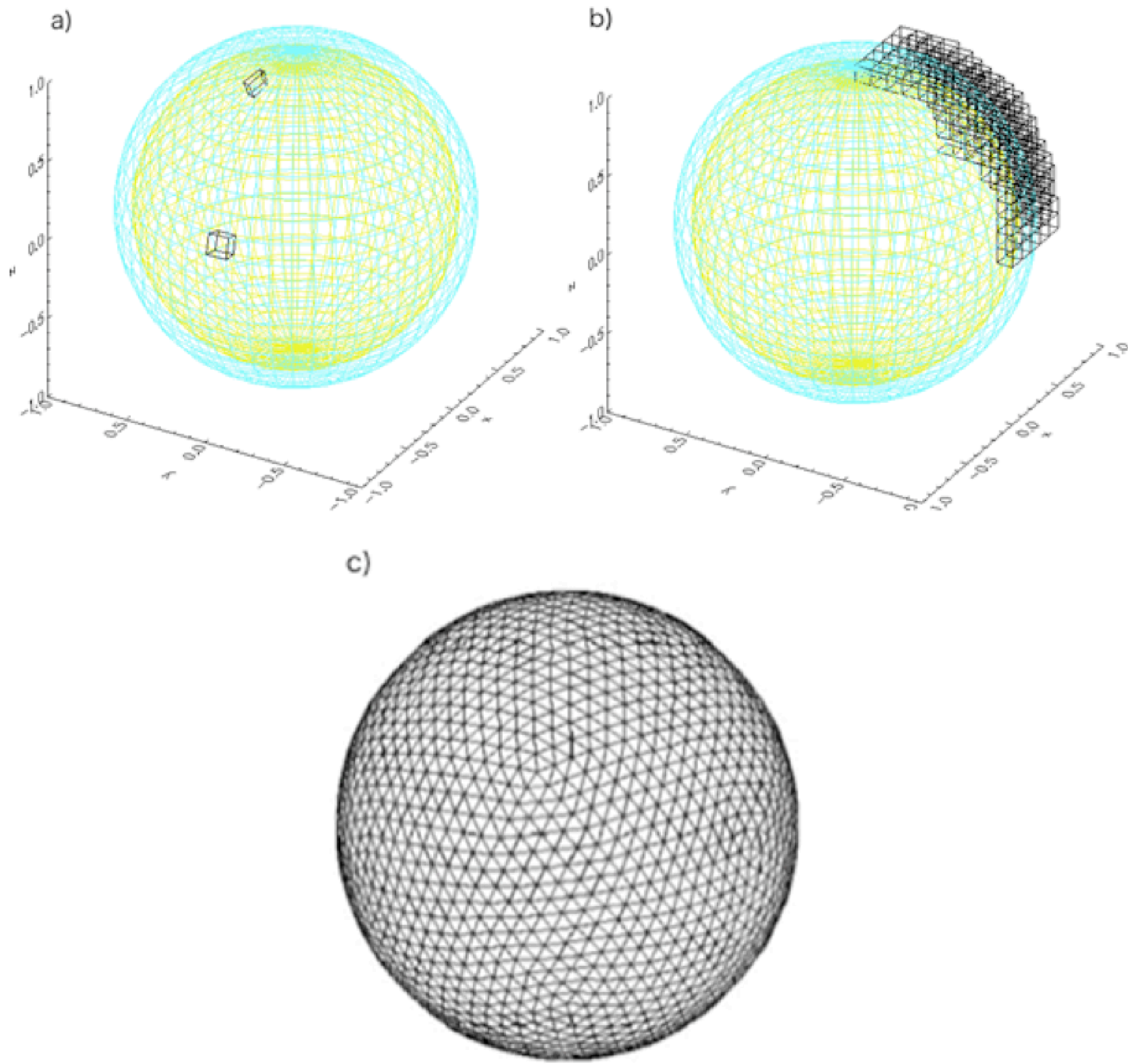
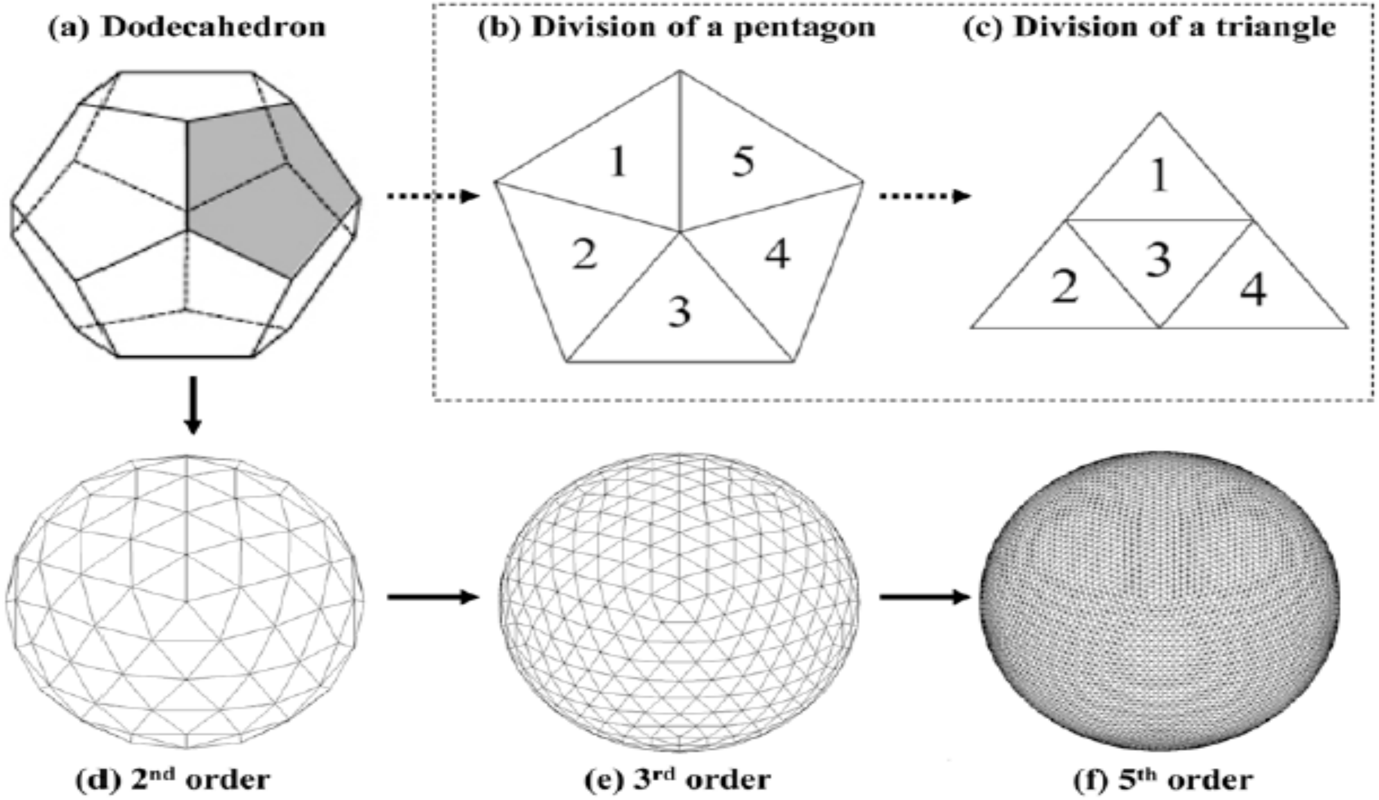


Figure 14. Spherical coordinate (a) Cartesian (b) and triangular (c) grid systems

SOLAR WIND MODEL : GRID SYSTEM

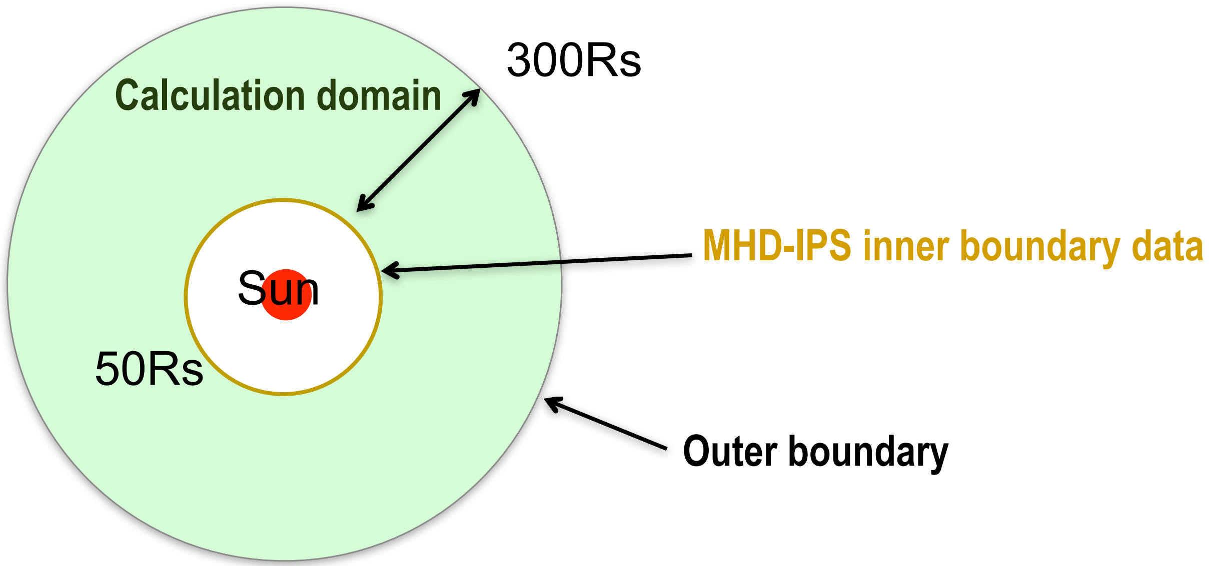


Unstructured grid system (triangle grid)

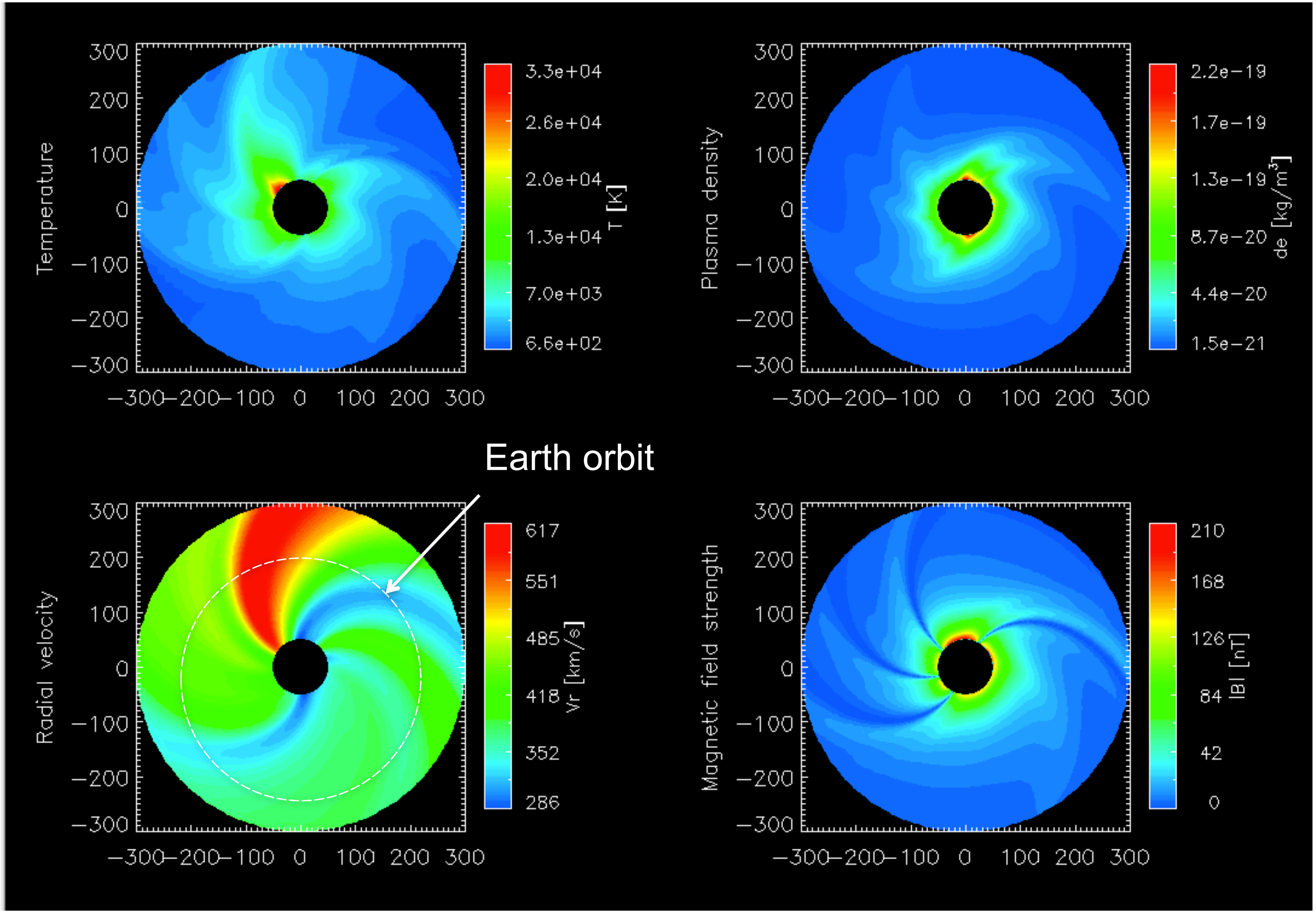
➔ Avoid the singularity at the north and south poles and therefore relax tight Courant –Friedrichs-Lewy (CFL) conditions around the poles, both of which would arise in the spherical coordinate system (Tanaka, 1994)

BOUNDARY & INITIAL CONDITIONS

Calculation domain	**50Rs ~ 300Rs**
Inner boundary condition (50Rs)	MHD-IPS tomography data during 1 Solar rotation (Hayashi et al., 2003) : velocity (v), density (n(v)), pressure (p(v)), magnetic field (based on PFSS)
Outer boundary condition (300Rs)	Same as Nakamizo et al., 2009
Initial condition	Density, pressure : decreases with 1/r^2 Vr : 400 km/s (other components are 0) Magnetic field : Extrapolated from PFSS

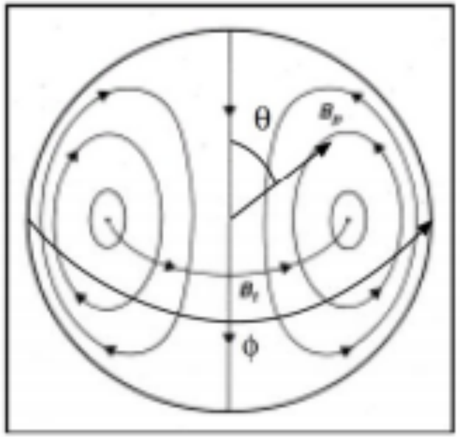


RESULT : Background solar wind (CR2142, solar maximum)



CME MODEL

- Simple spheromak type CME model
- Gibson and Fan (2008) discuss that this type of CME may be produced by magnetic reconnection



- Basic equation

$$B_r = 2B_0 \frac{j_1(\alpha r)}{\alpha r} \cos(\theta) \qquad (1)$$

$$B_\theta = -\frac{B_0}{\alpha r}\left(j_1(\alpha r) + \alpha r j_1'(\alpha r)\right) \sin(\theta) \qquad (2)$$

$$B_\phi = B_0 j_1(\alpha r) \sin(\theta) \qquad (3)$$

where, $j_1(x) = \frac{\sin(x) - x\cos(x)}{x^2}$, $j_1' = \frac{2x\cos(x) + (x^2 - 2)\sin(x)}{x^3}$
and $\alpha = 4.493409458a^{-1}$ to have a value $B_r = 0$ at r=a.

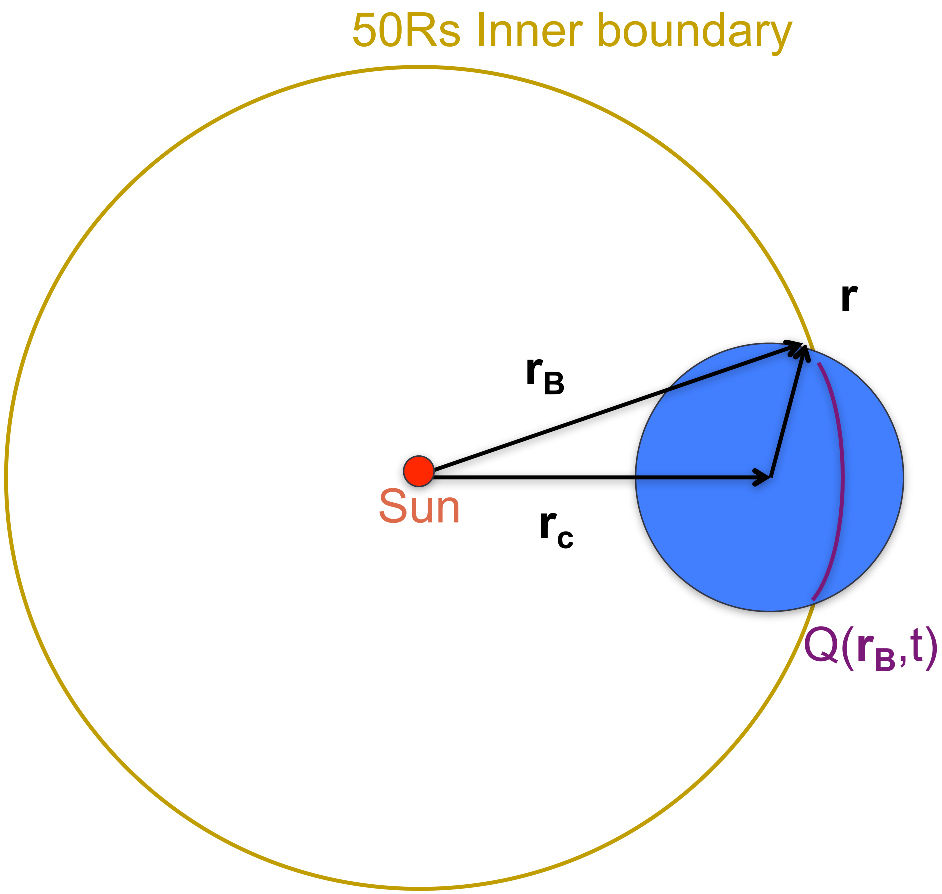
(Kataoka et al., 2009)

Injection of an ICME

an ICME is injected gradually through the inner boundary

→ **This is done by introducing a time-dependent inner boundary condition**

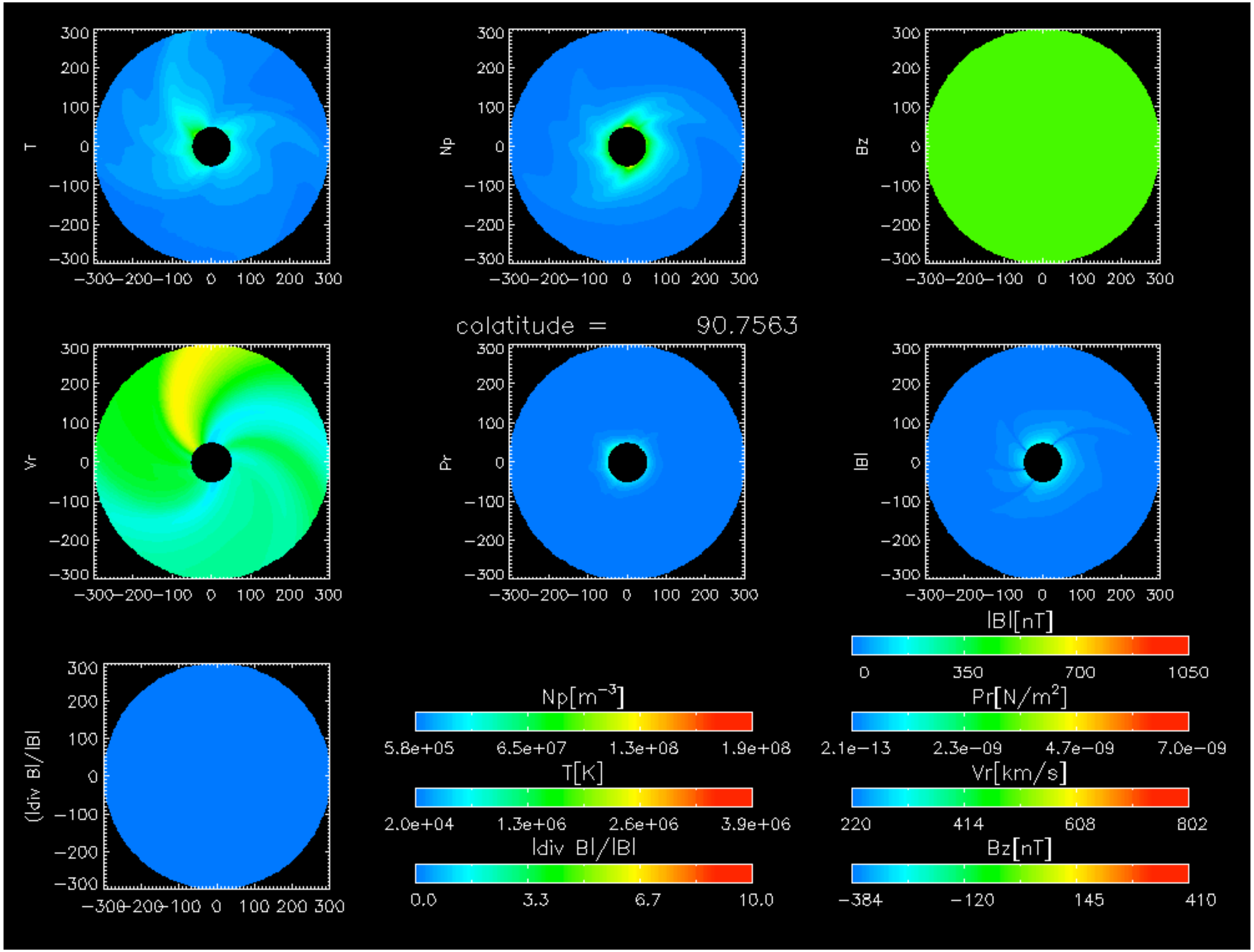
How to inject a spheromak through I.B.



- $\mathbf{r_c} = \mathbf{r_0} + \mathbf{v}*t$ → known (if **v** is assumed)
- Q(**r**) : A certain physical variable as a function **r** → Known (predetermined by some assumptions)
- From the condition $|\mathbf{r_B}|$ = 50Rs and $|\mathbf{r}|$ = CME radius, we can obtain $\mathbf{r}(\mathbf{r}_B)$ at each time step
- At each time step, Q($\mathbf{r}_B$(t)) is determined

$\mathbf{r_B}$: Vector from the Sun to the crossing boundary (purple colored) $\mathbf{r_c}$: Vector from the Sun to the CME center **r** : Vector from the CME center to the end point of $\mathbf{r_B}$ vector ($\mathbf{r} = \mathbf{r_B} - \mathbf{r_c}$)

RESULT



T
Np
Bz
colatitude = 90.7563
Vr
Pr
|B|
(|div B|/|B|
|B|[nT]
0
350
700
1050
Np[m^{-3}]
5.8e+05
6.5e+07
1.3e+08
1.9e+08
Pr[N/m^2]
2.1e−13
2.3e−09
4.7e−09
7.0e−09
T[K]
2.0e+04
1.3e+06
2.6e+06
3.9e+06
Vr[km/s]
220
414
608
802
|div B|/|B|
0.0
3.3
6.7
10.0
Bz[nT]
−384
−120
145
410

KEY PARAMETERS

Parameters for a spheromak type ICME model

- Magnetic field strength :
- Orientation of a spheromak :
- Twistness :
- Density :
- Pressure :
- (radial) Velocity :
- Propagation direction :
- Initial position :
- CME radius :
- Injection speed (function of v(t)) :

- Magnetic field strength : **Typical amount of magnetic flux 2.55 x 10^21 Mx (Kataoka et al. 2009, Shiota et al. 2010), magnetic field observation at a photospheric footpoint of an ICME etc.**
- Orientation of a spheromak : **Magnetic Field observation**
- Twistness : **Vector magnetogram + NLFF modeling, etc.**
- Density : **2 x background solar wind density, etc.**
- Pressure : **4 x background solar wind pressure, etc.**
- (radial) Velocity : **From average transit time from the Sun to the Earth, etc.**
- Propagation direction : **CME cone model (LASCO C3), etc.**
- Initial position : **By assuming radial propagation direction, etc.**
- CME radius : **CME cone model, free parameter, etc.**
- Injection speed (function of v(t)) : **By assuming from averaged transit time from the Sun to the Earth, etc.**

SUMMARY & DISCUSSION

- We developed 3-D MHD code to reproduce the structure of a solar wind, the propagation of an ICME.
- By using IPS data to derive the background steady solar wind, we can perform a more realistic data-driven simulation.
- We can investigate an ICME event by introducing a time-dependent boundary condition into a TVD scheme with an unstructured grid system.
- However, since there are many ambiguities and uncertainties in determining initial parameters of an ICME model, much more efforts are needed to derive realistic ICME properties.