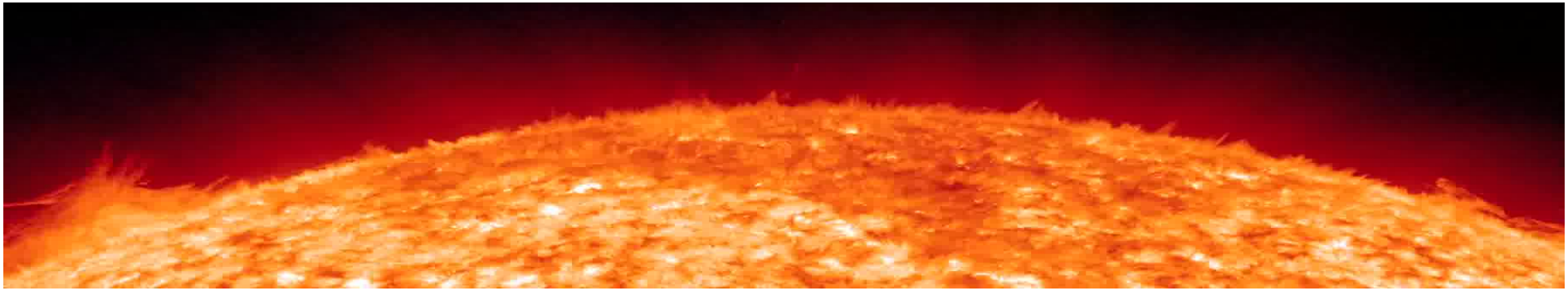
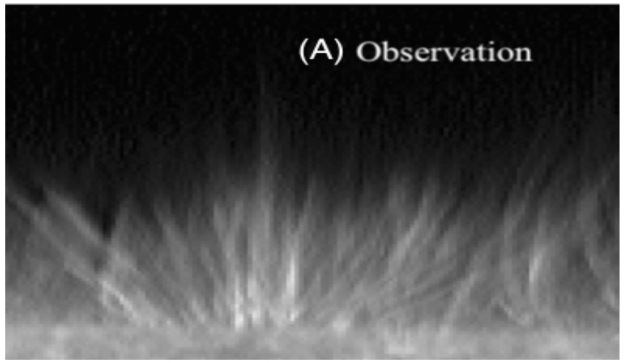
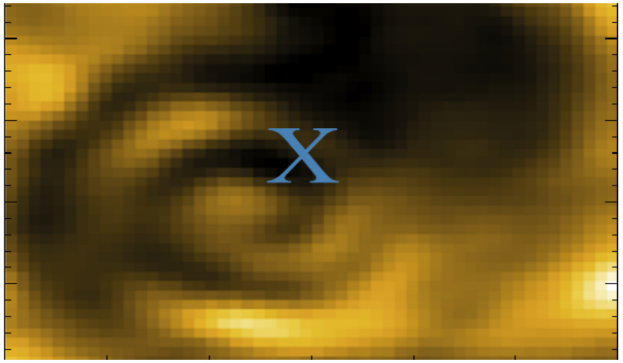


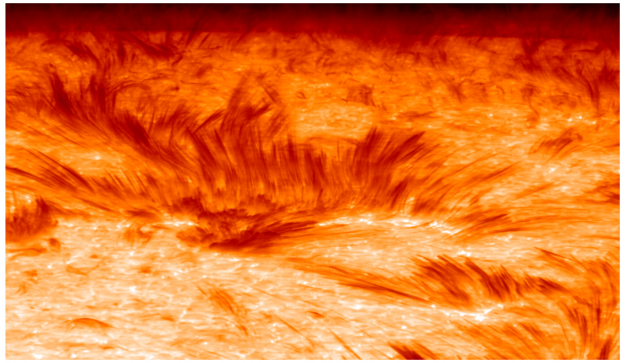
Solar spicules and swirls in MHD simulations

Sahel Dey[1,2], Piyali Chatterjee[1]

[1]Indian Institute of Astrophysics,[2]Joint Astronomy Programme, Indian Institute of Science







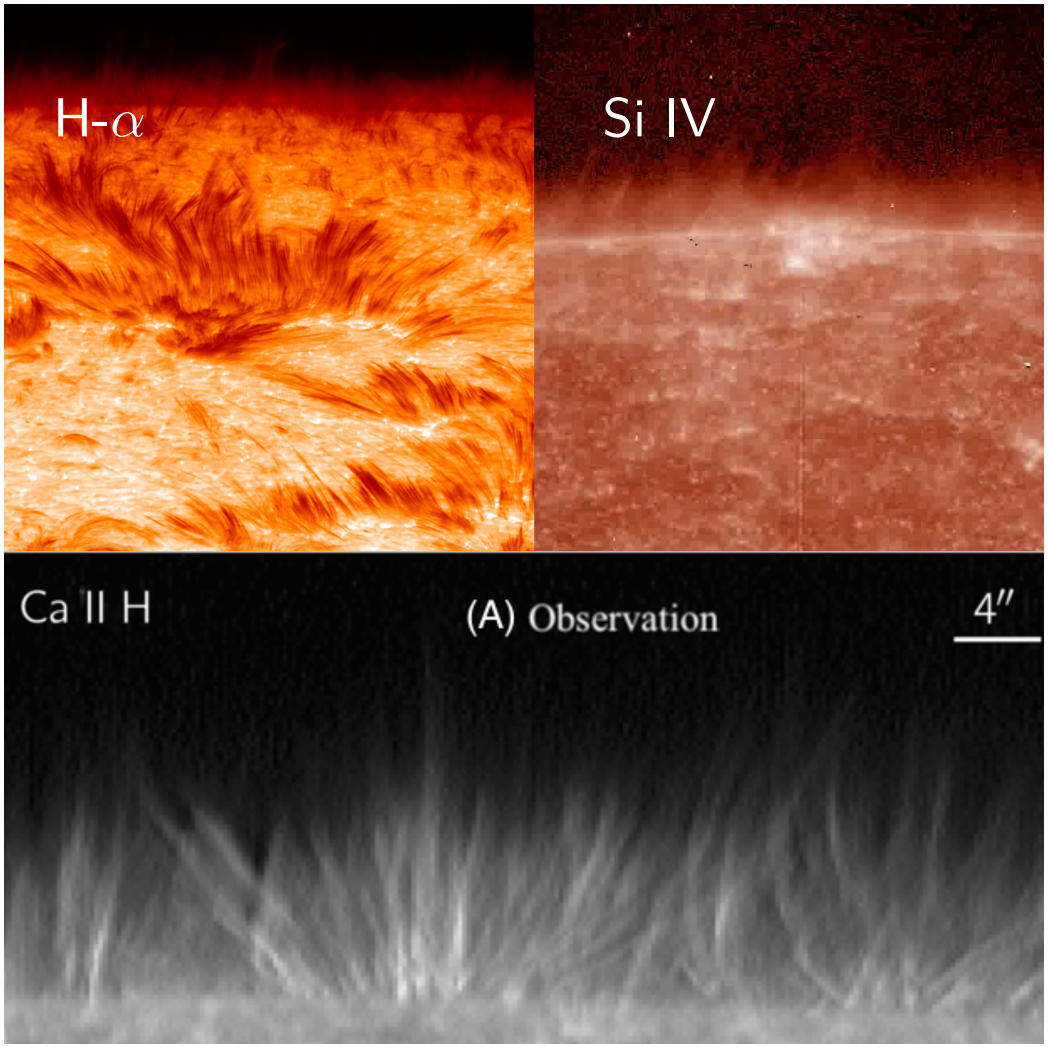
Motivation

What are Spicules ?

- Thin elongated spurting structures comprising of cold and dense chromospheric plasma

Why are they important ?

Positive feature !



Motivation

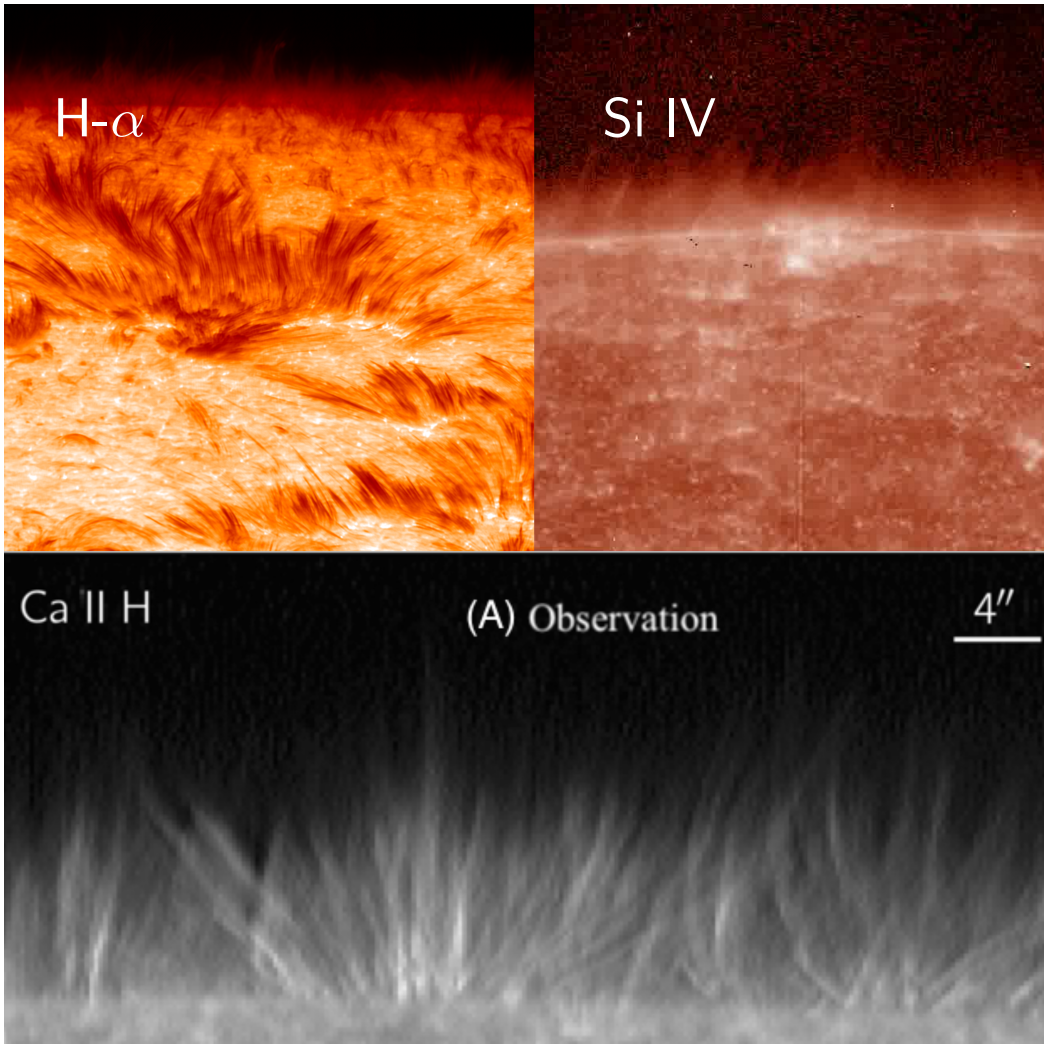
What are Spicules ?

- Thin elongated spurting structures comprising of cold and dense chromospheric plasma

Why are they important ?

- Potential candidate for channeling mass, momentum and energy flux to Solar corona.

Positive feature !



Motivation

What are Spicules ?

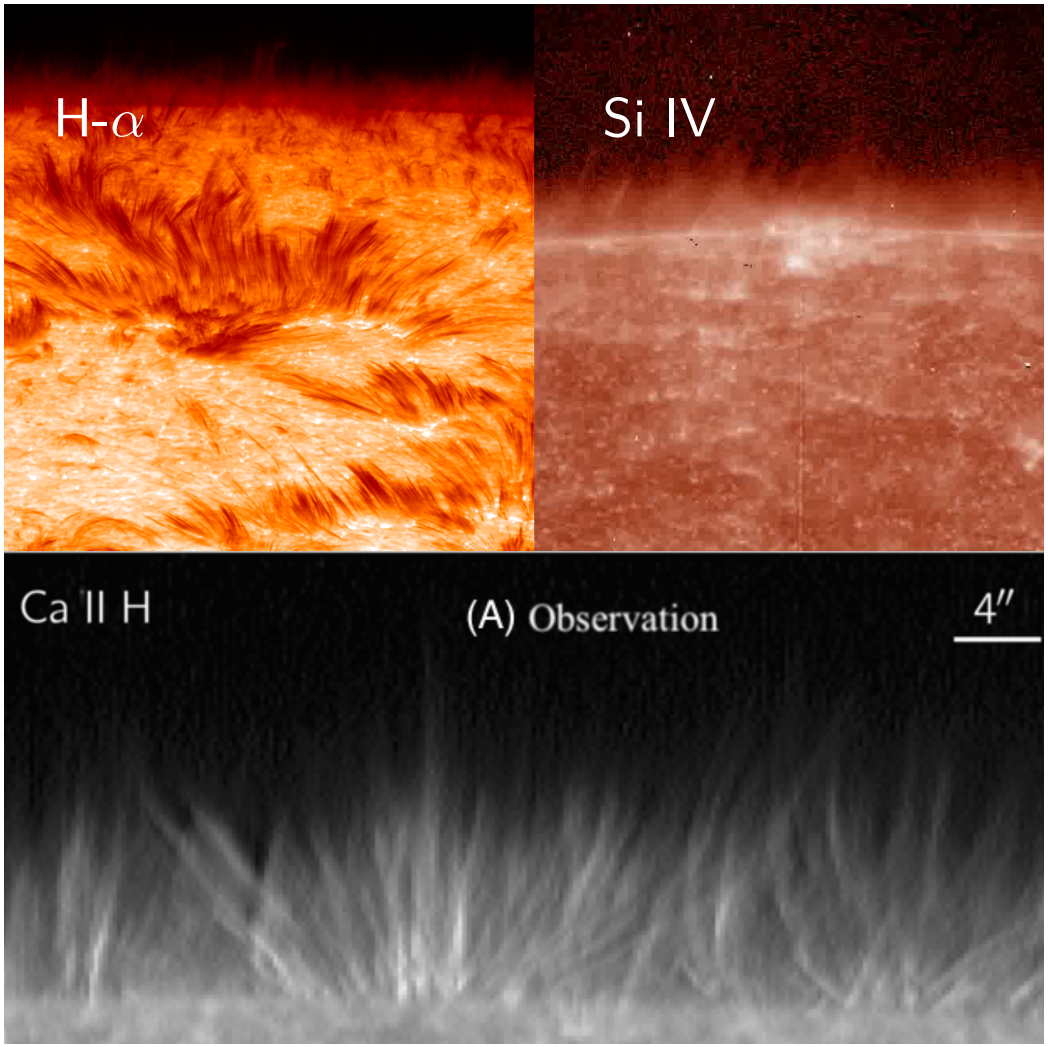
- Thin elongated spurting structures comprising of cold and dense chromospheric plasma

Why are they important ?

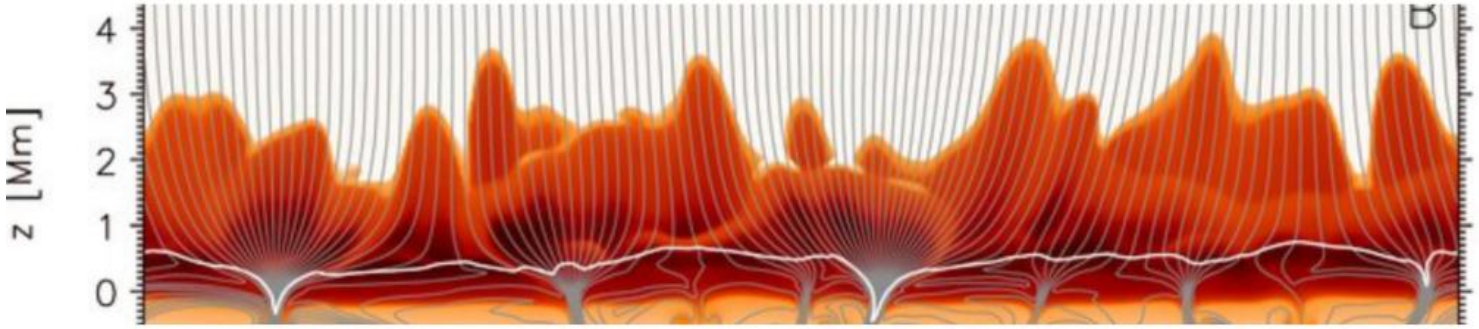
- Potential candidate for channeling mass, momentum and energy flux to Solar corona.

Positive feature !

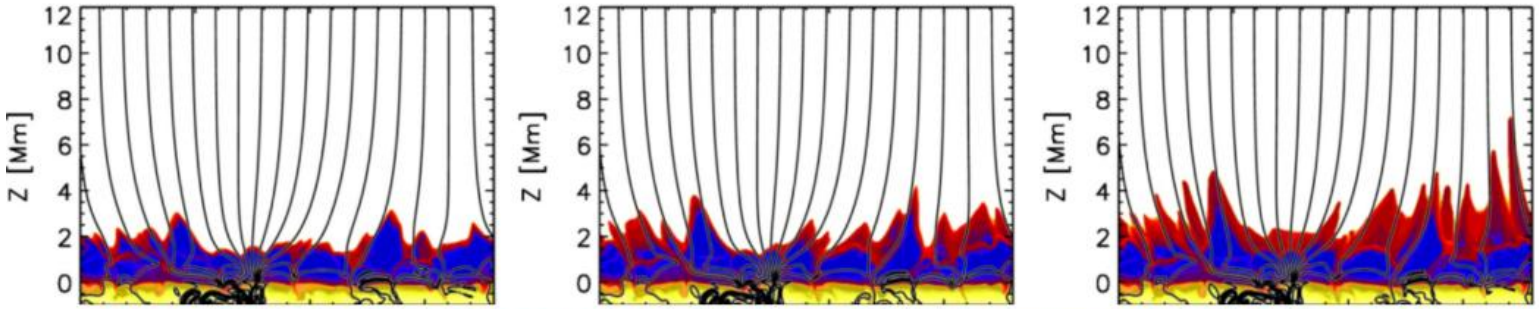
- Presence in a large no at any time over the entire Solar atmosphere like forest



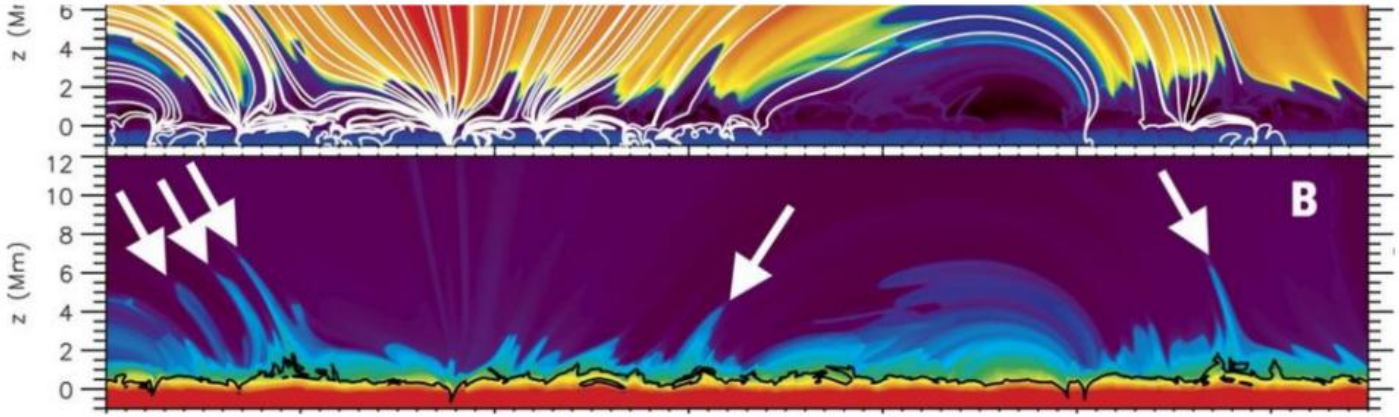
Previous significant numerical works on Spicules : including convection



Heggland et al., 2011



Iijima & Yokoyama 2015

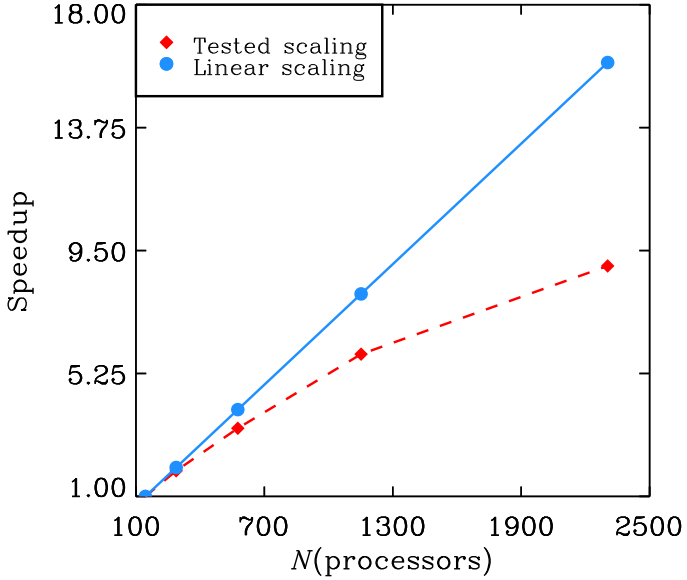


Martínez-Sykora et al., 2017

Most of the simulated spicules have height below 5 Mm, on contrary observed spicules can reach $\approx$ 10 Mm in atmosphere

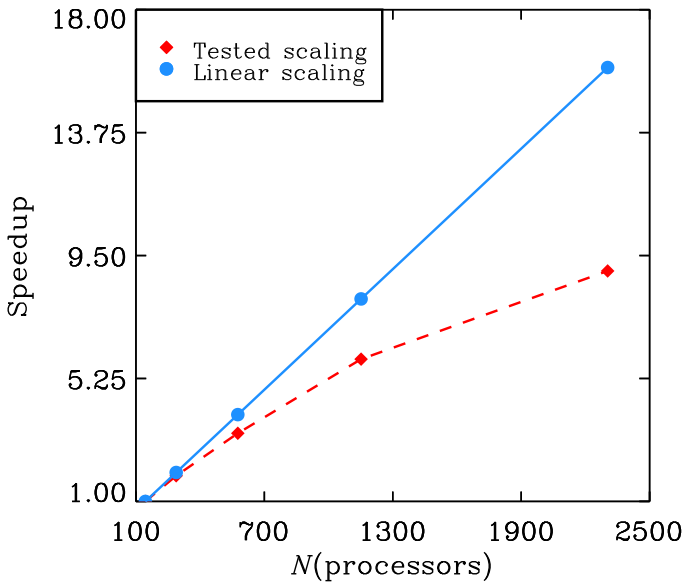
Simulation setup using Pencil Code

- Initial setup
  1. Domain size
     (I) 3d setup :
     horizontal direction :
     6 Mm $\times$ 18 Mm
     vertical direction:
     5 Mm of convection zone
     32 Mm of atmosphere



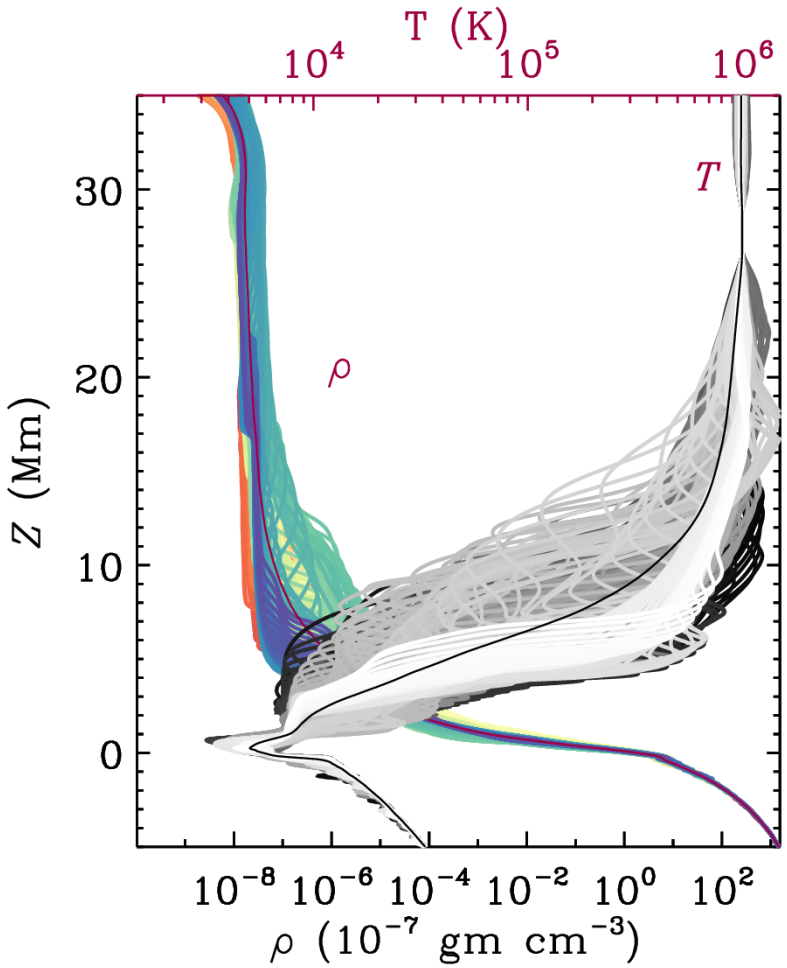
Simulation setup using Pencil Code

- Initial setup
  1. Domain size
     - (I) 3d setup :
       horizontal direction :
       6 Mm $\times$ 18 Mm
       vertical direction:
       5 Mm of convection zone
       32 Mm of atmosphere
  2. Spatial resolution
     - (I) 3d coarse grid : 48 km
     - (II) 3d fine grid : 24 km
- Scalibility test : Strong scaling approach Deviation from ideal linear scaling : inclusion of radiation module
- Proposal: Ignoring spatial points if the smallest time step constraint comes from very few points !



Simulation setup using Pencil Code

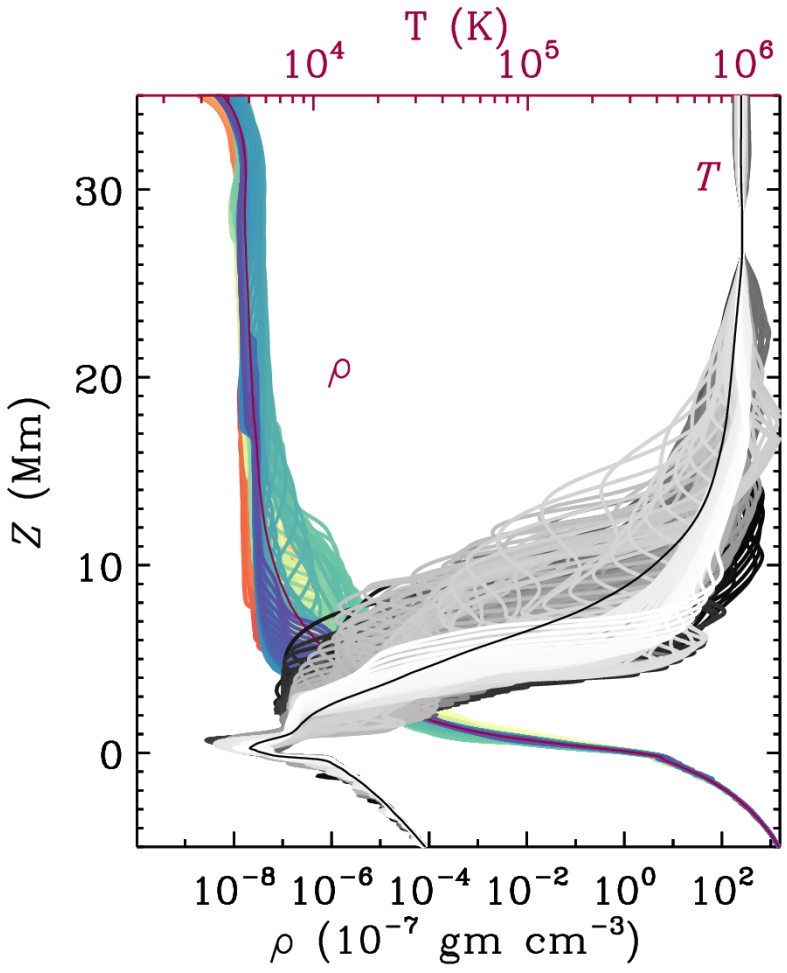
- Included approximations[a]
  1. Magnetohydrodynamics
  2. Local thermodynamic equilibrium
  3. Semi relativistic Boris Correction to Lorentz force
  4. Rosseland mean opacity for radiative transfer
  5. Anisotropic Spitzer's heat conductivity



[a] **Chatterjee 2019**.

Simulation setup using Pencil Code

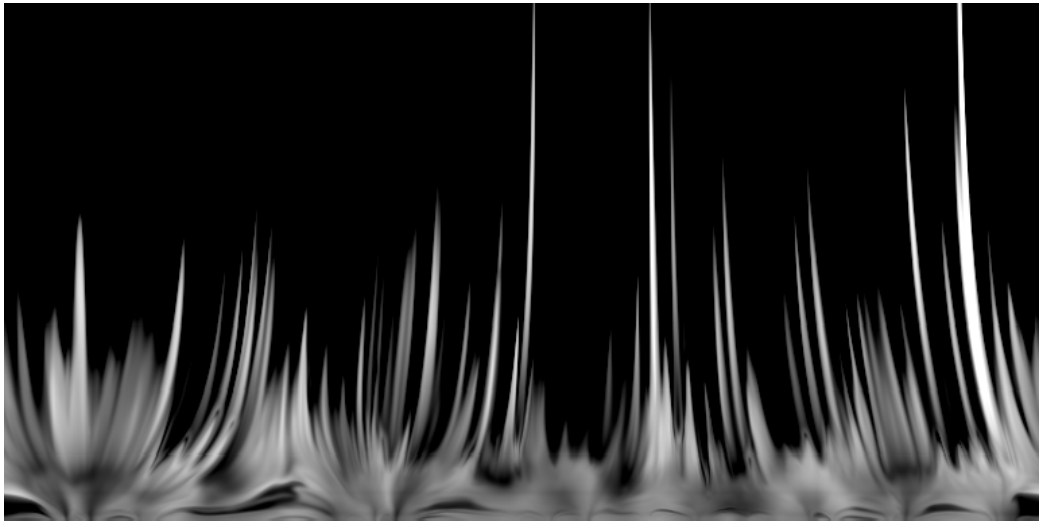
- Included approximations[a]
  1. Magnetohydrodynamics
  2. Local thermodynamic equilibrium
  3. Semi relativistic Boris Correction to Lorentz force
  4. Rosseland mean opacity for radiative transfer
  5. Anisotropic Spitzer's heat conductivity
- Background imposed $\vec{B}$ field
  1. 3D domain : Vertical and oblique field with strength of 5 & 25 G

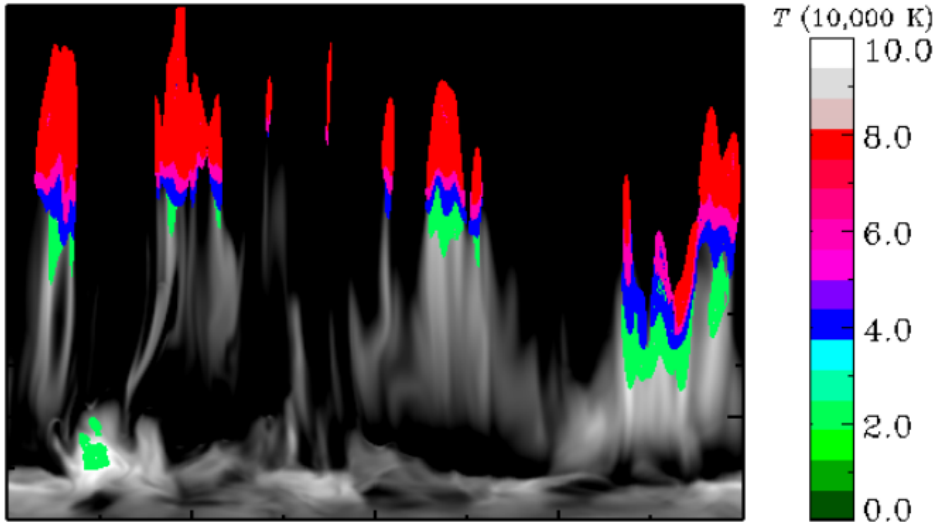


[a] **Chatterjee 2019**.

Synthetic intensity profile of spicule forest

- $\mathcal{S.I} : \int \left(\frac{\rho}{\overline{\rho}}\right)^2 \exp\left[-\left(\frac{\log(T/T_0)}{w}\right)^2\right] ds$ [a]
- $\overline{\rho}$: horizontal averaged plasma density, $T_0 = 10^4$k & w =0.78
- Top: include chrosmospheric plasma within temperature range of $6.4 \times 10^3 - 1.5 \times 10^4$ K : similar profile like Ca II filter
- s : line-of-sight distance (LOS)

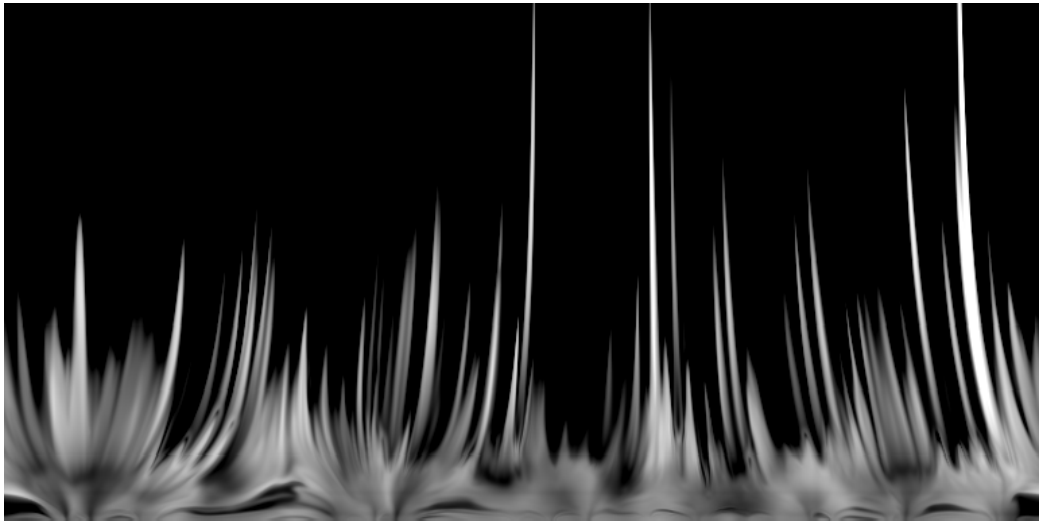


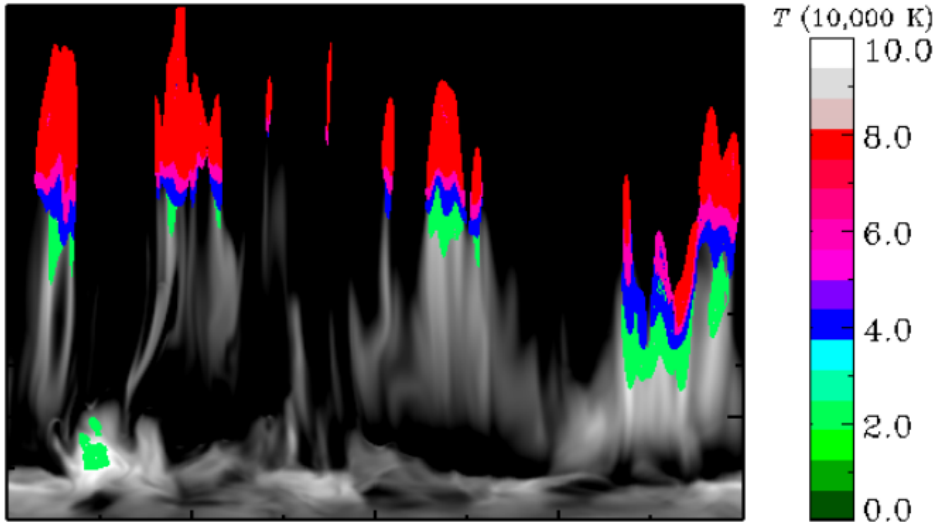


[a] **Iijima & Yokoyama, 2017.**

Synthetic intensity profile of spicule forest

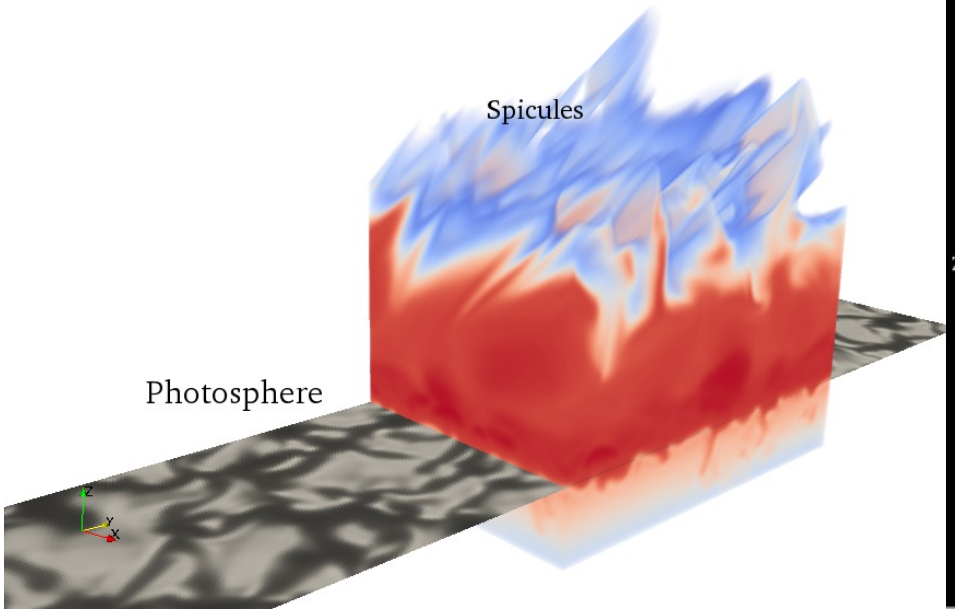
- $\mathcal{S.I} : \int \left(\frac{\rho}{\overline{\rho}}\right)^2 \exp\left[-\left(\frac{\log(T/T_0)}{w}\right)^2\right] ds$ [a]
- $\overline{\rho}$: horizontal averaged plasma density, $T_0 = 10^4$k & w =0.78
- Top: include chrosmospheric plasma within temperature range of $6.4 \times 10^3 - 1.5 \times 10^4$ K : similar profile like Ca II filter
- s : line-of-sight distance (LOS)
- Bottom: multi thermal structure of spicules
- Temperature ranges: 2 - 8 X10^4 K, similar to C II, Mg II k, Si IV filters
- It outlines spicules at different height of the atmosphere



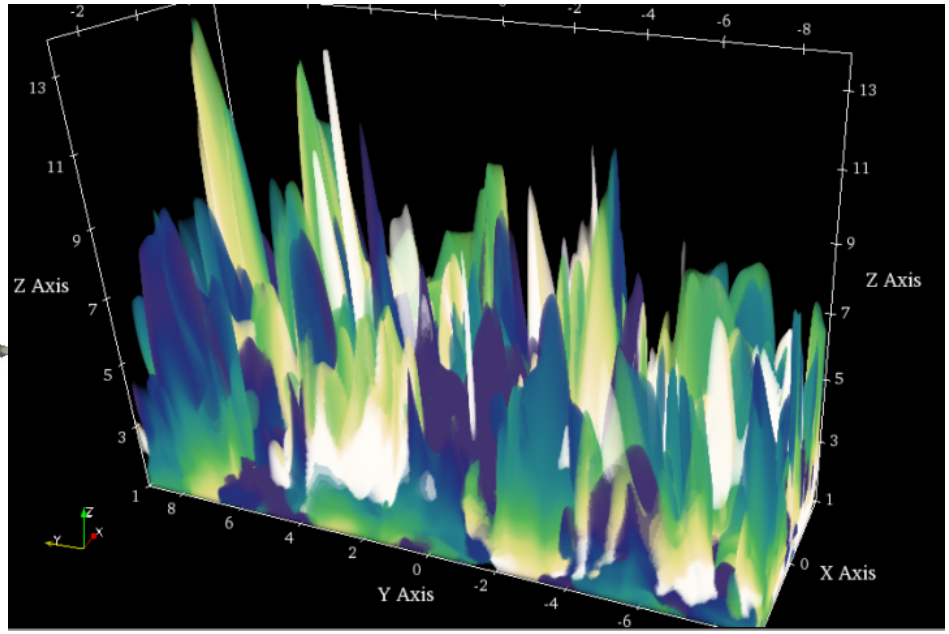


[a] **Iijima & Yokoyama, 2017.**

Spicules are indirect tracers of magnetic field!

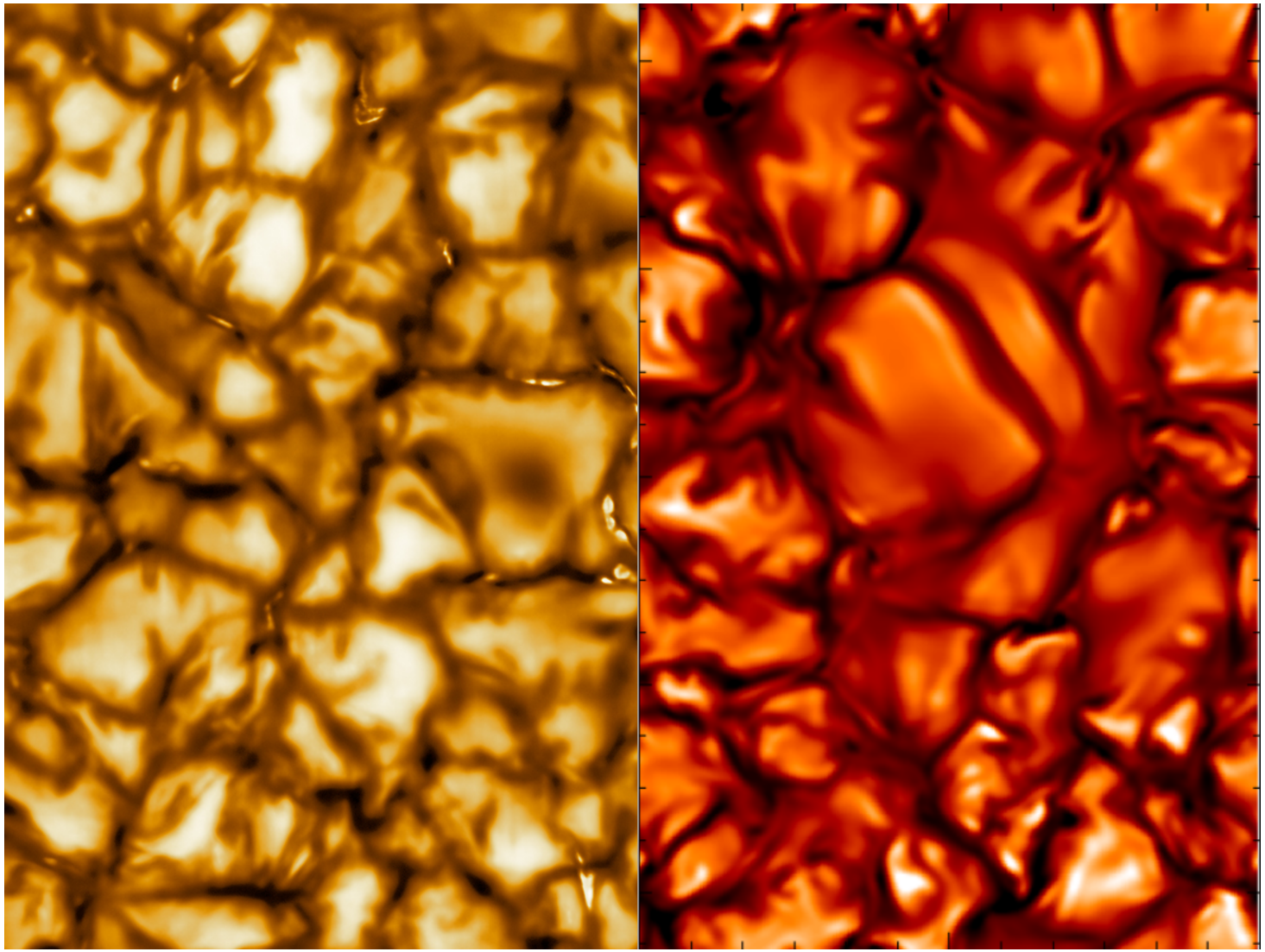


imposed field : oblique

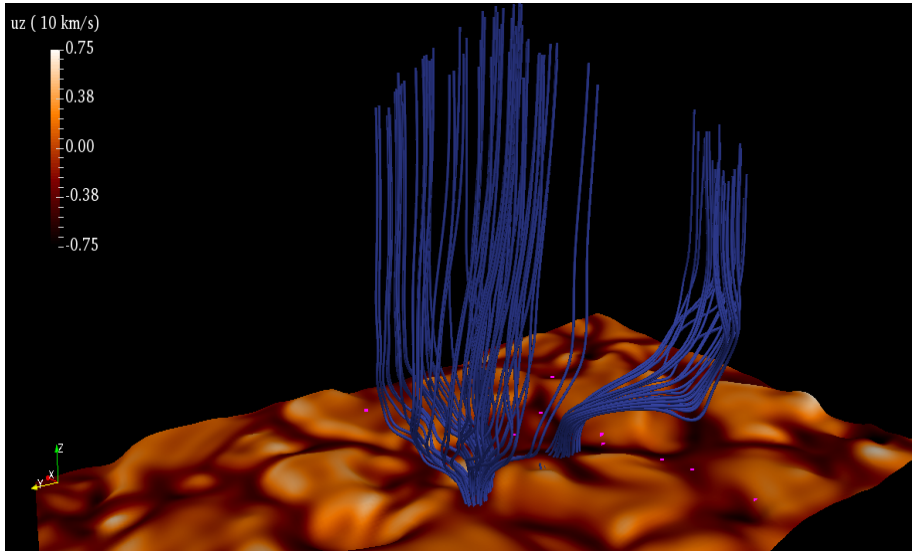


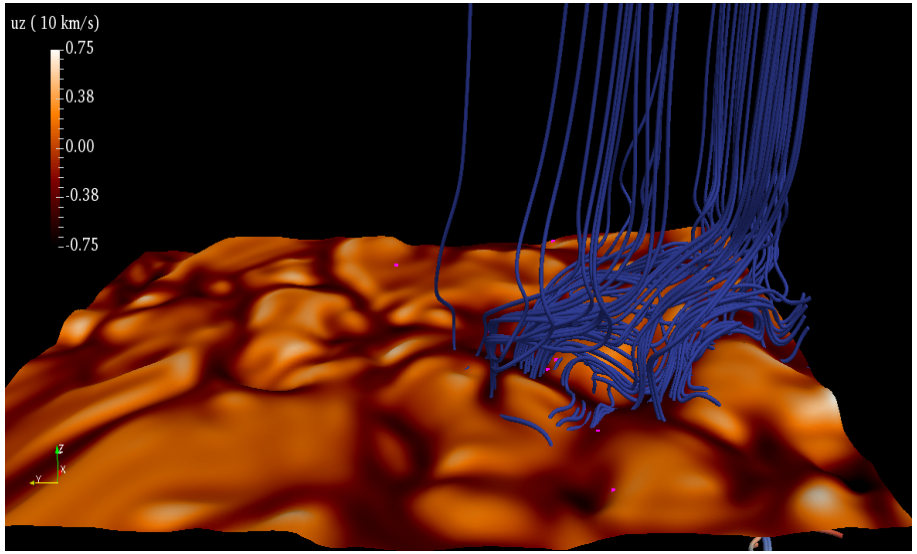
imposed field : vertical

Photospheric granulation in 3D setup: comparison with DKIST's 1st image



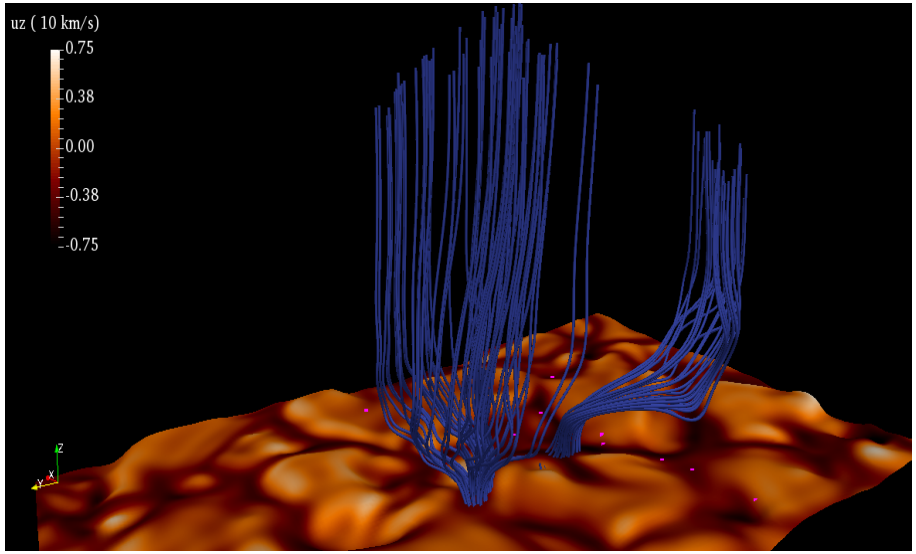
Different magnetic topologies at photosphere

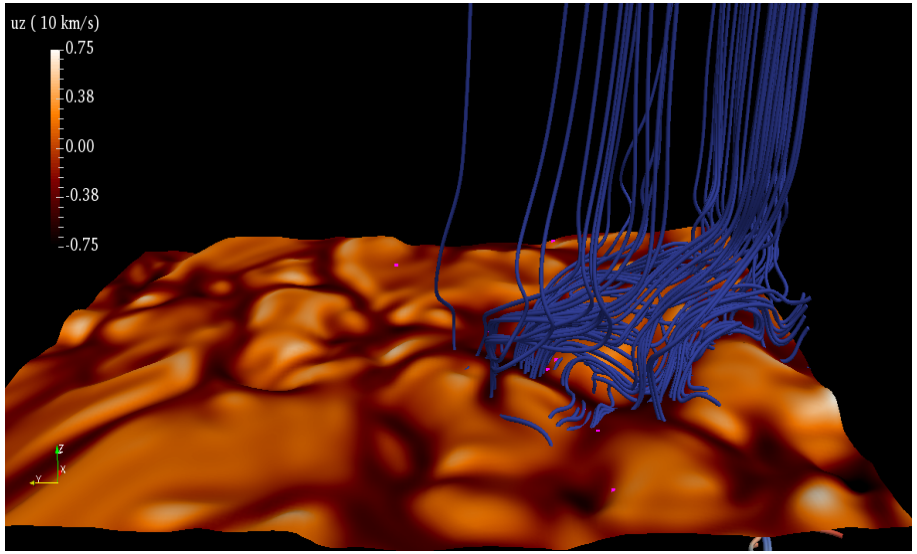




1. Magnetic flux-tube (left) : anchored in the inter granular lanes, fanned out below 1 Mm. In upper chromosphere and above, it becomes almost vertical

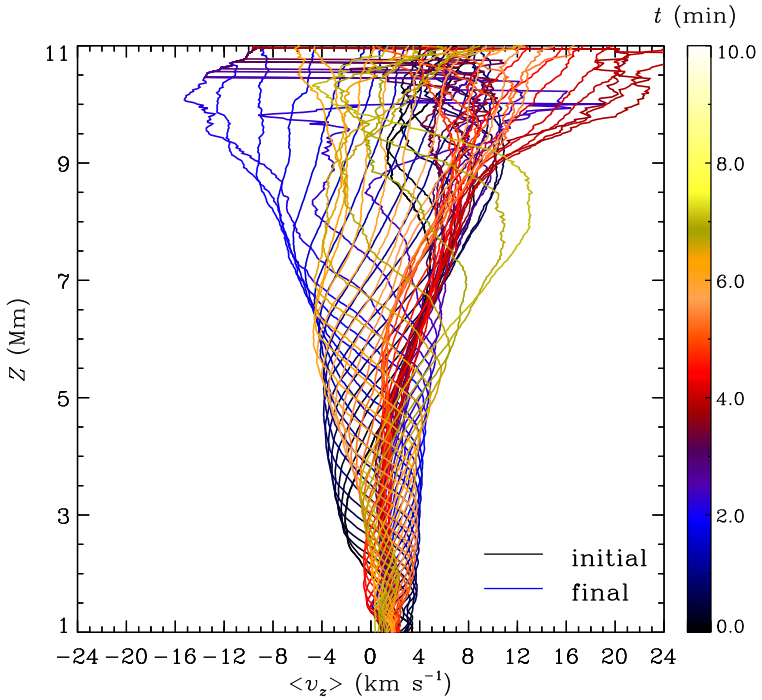
Different magnetic topologies at photosphere

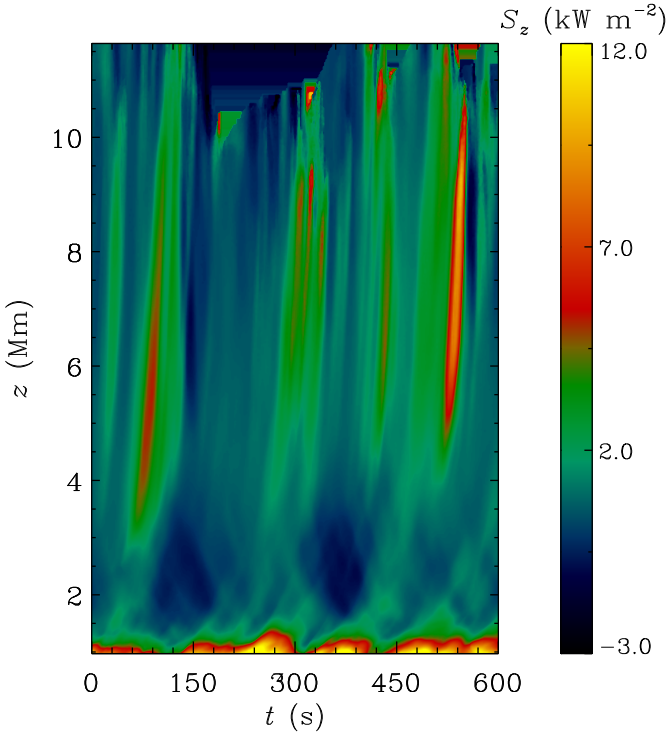




1. Magnetic flux-tube (left) : anchored in the inter granular lanes, fanned out below 1 Mm. In upper chromosphere and above, it becomes almost vertical
2. Horizontal magnetic field (right) : bended field lines over the granules, presence of strong current.

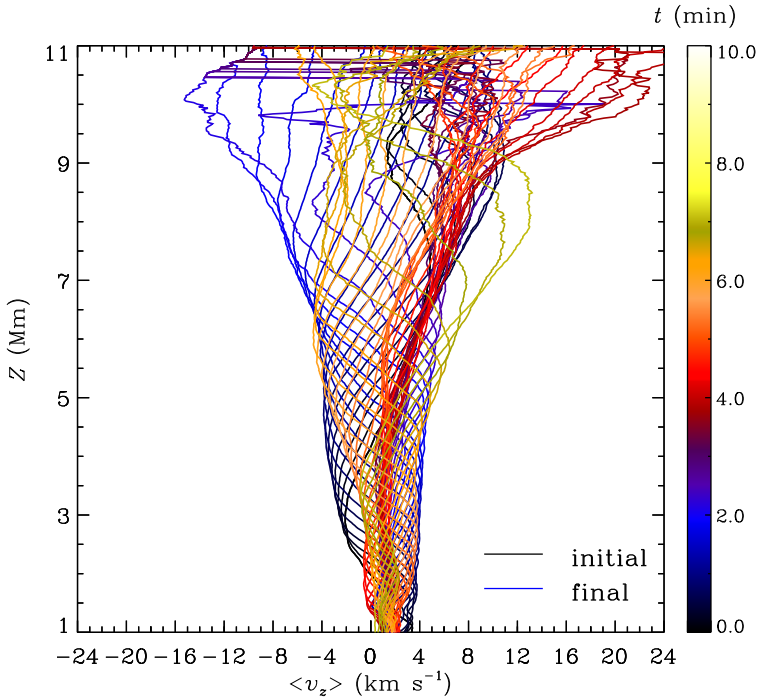
Mass-flow and Poynting flux through spicules: time domain analysis

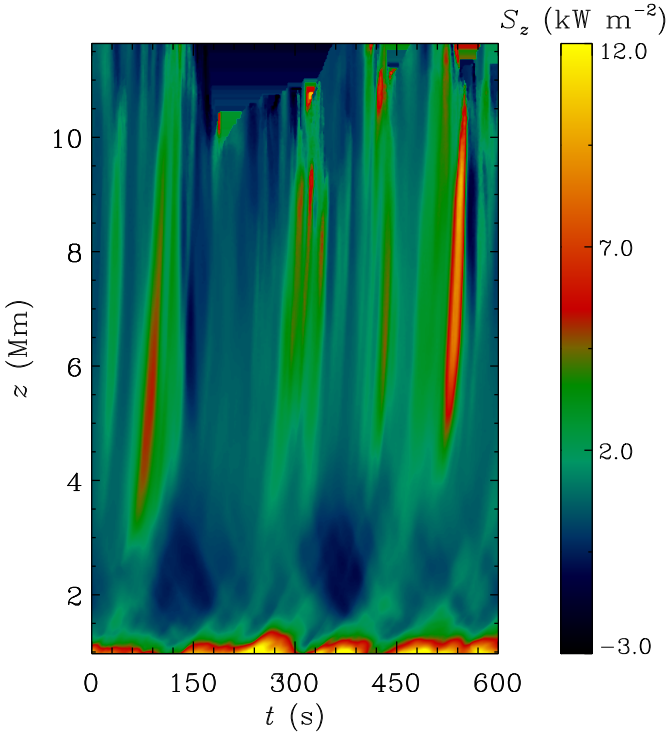




- Vertical plasma velocity of spicules increases with height
- For most of the time, vertical velocity is positive: a net positive mass flux

Mass-flow and Poynting flux through spicules: time domain analysis





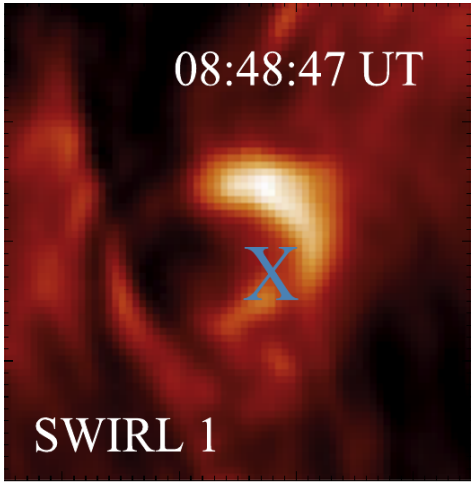
- Vertical plasma velocity of spicules increases with height
- For most of the time, vertical velocity is positive: a net positive mass flux
- Spicules can transport upto 12 kW m^{-2} of Poynting flux at lower coronal region
- A periodic nature in time-domain is prominent for the propagated flux

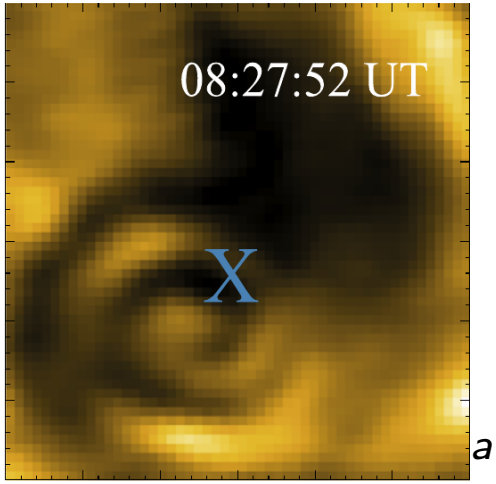
End of Part I

End Of Part I

Ubiquitous swirls of Solar atmosphere

- Solar swirls are hot spiraling plasma blobs observed at both photosphere and chromosphere region.





[a]

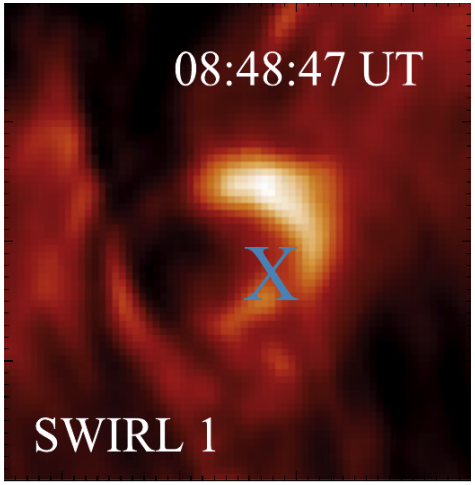
[a] **Wedemeyer-Bohm et al., 2012.**
[b] **Liu et al., 2019.**

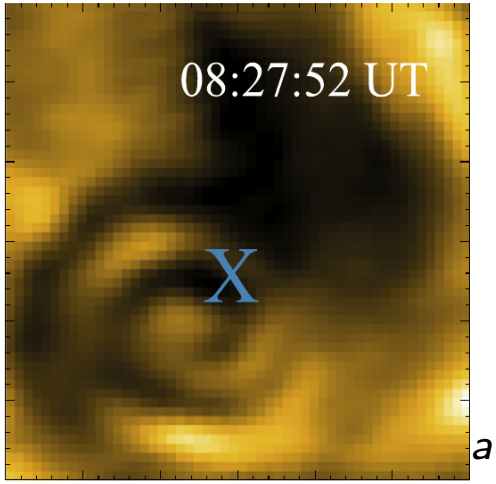
[a] **Shetye et al. 2019.**

Ubiquitous swirls of Solar atmosphere

- Solar swirls are hot spiraling plasma blobs observed at both photosphere and chromosphere region.
- Length scale: Tornado[a] like large (1500 km) scale structure to vortex pulse[b] like fine (300 km) structure
- Lifetime: decreases with spatial size, ranges between 10 min to 20 sec

[a] **Wedemeyer-Bohm et al., 2012.**
[b] **Liu et al., 2019.**





[a]

[a] **Shetye et al. 2019.**

Synthetic swirls near solar photosphere

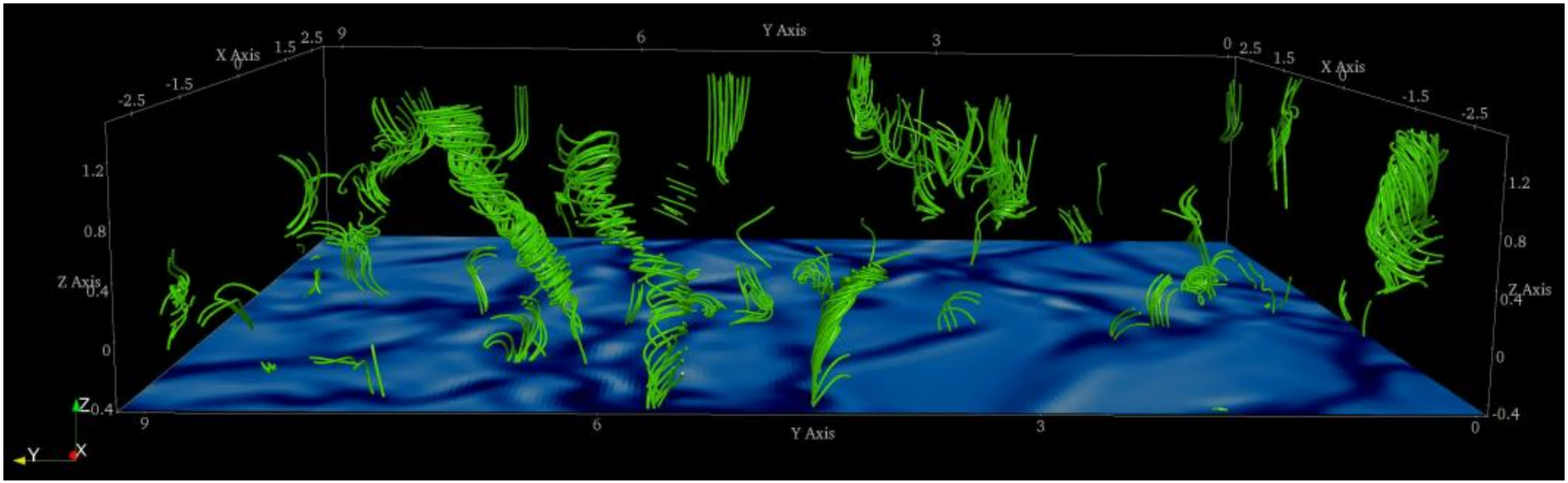
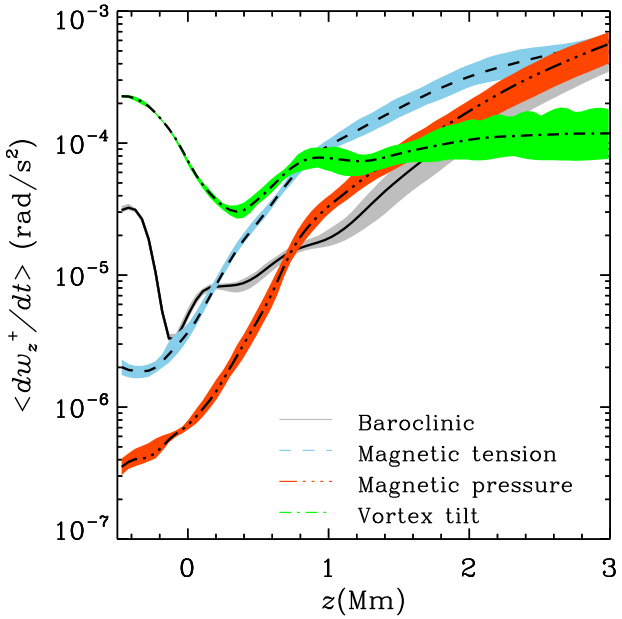


Figure: Low atmospheric swirls: green curves represent streamlines, blue surface corresponds to photosphere

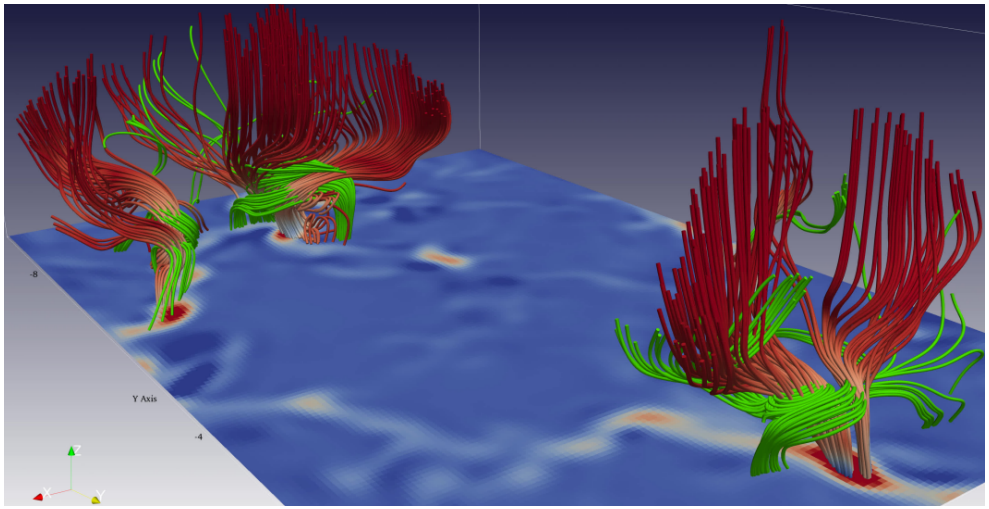
- Swirls are detected over the domain through Automatic Swirls Detection Algorithm(ASDA)[1]
- Most of the phtospheric swirls are rooted near Magnetic bright points (MBP)
- In general, streamlines and pathlines are not same : presence of unsteady flow

[1] **Liu et al., 2019**.

Sources of vorticity at solar atmosphere



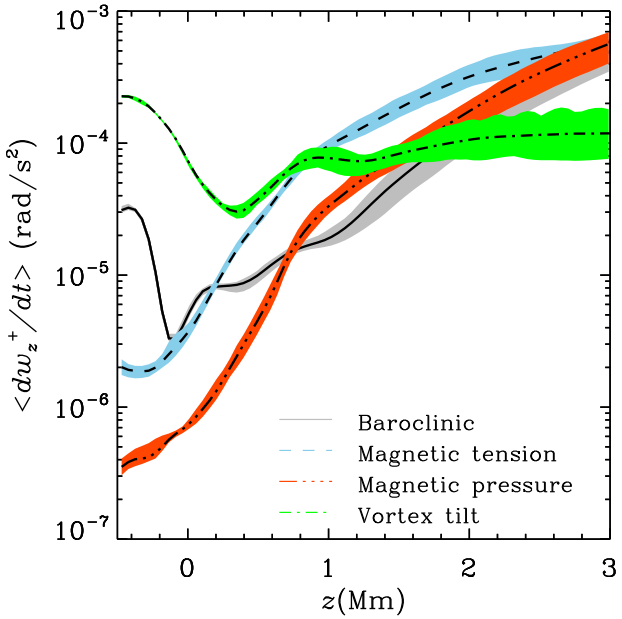
Magnetic flux-tubes(red) and streamlines(green)



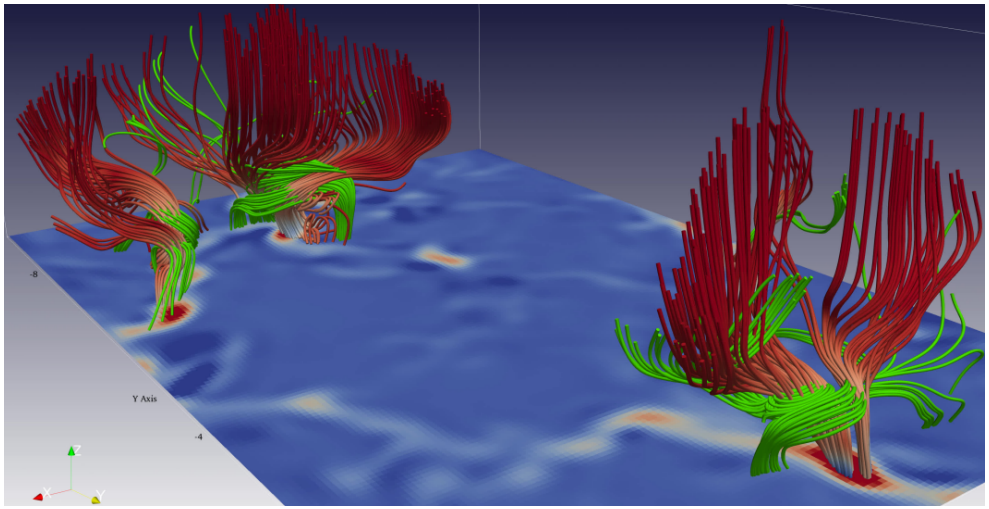
- Left: rate of increase of vertical vorticity is plotted for the lower atmosphere[2][3]
- Photospheric region: magnetic tension is the dominant source for most of swirls

[2] **Cuissa et al., 2020**.
[3] **Rajaguru et al., 2020 (in prep)**.

Sources of vorticity at solar atmosphere



Magnetic flux-tubes(red) and streamlines(green)

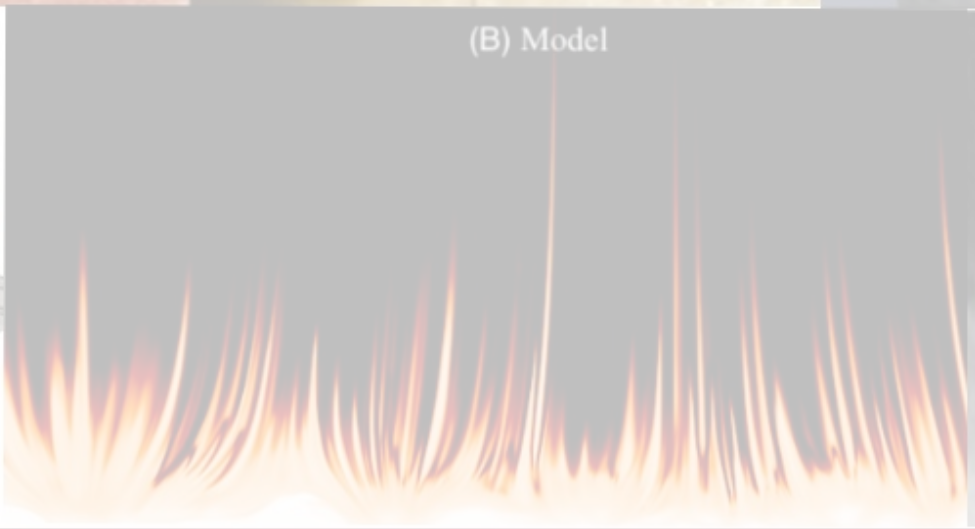


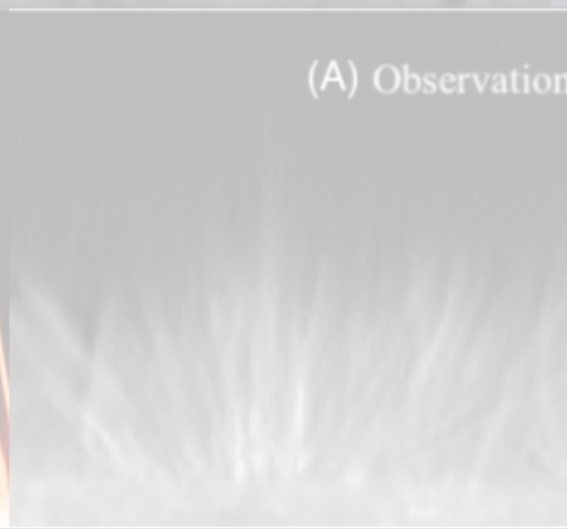
- Left: rate of increase of vertical vorticity is plotted for the lower atmosphere[2][3]
- Photospheric region: magnetic tension is the dominant source for most of swirls
- Right: instantaneous velocity fields are wrapped around flux-tubes : signature of swirls
- twisted field lines of flux-tube: signature of tension forces

[2] **Cuissa et al., 2020**.
[3] **Rajaguru et al., 2020 (in prep)**.

Conclusions

- No. density of spicules is quite large, which mimics Solar Spicule forest structure
- A large fraction($0.20 - 0.43$) of total spicules can reach more than 10 Mm height in upper atmosphere





[4] **Withbroe et al., 1977.**

Conclusions

- No. density of spicules is quite large, which mimics Solar Spicule forest structure
- A large fraction($0.20 - 0.43$) of total spicules can reach more than 10 Mm height in upper atmosphere
- Magnetic field determines overall motion of Spicules
- Apparent rotational motions are present in spicule's dynamics
- Spicule can transport a net positive vertical mass and poynting flux which is adequate to balance coronal losses[4]

[4] **Withbroe et al., 1977.**

Conclusions

- No. density of spicules is quite large, which mimics Solar Spicule forest structure
- A large fraction($0.20 - 0.43$) of total spicules can reach more than 10 Mm height in upper atmosphere
- Magnetic field determines overall motion of Spicules
- Apparent rotational motions are present in spicule's dynamics
- Spicule can transport a net positive vertical mass and poynting flux which is adequate to balance coronal losses[4]
- Ubiquitous swirls are excited, connecting the photospheric region to lower corona
- In general spicules and swirls are not co-spatial.
- Tension in local magnetic fields is the major source of photospheric swirls.

[4] **Withbroe et al., 1977**.