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Chromospheric heating and flux emergence in coronal hole simulations

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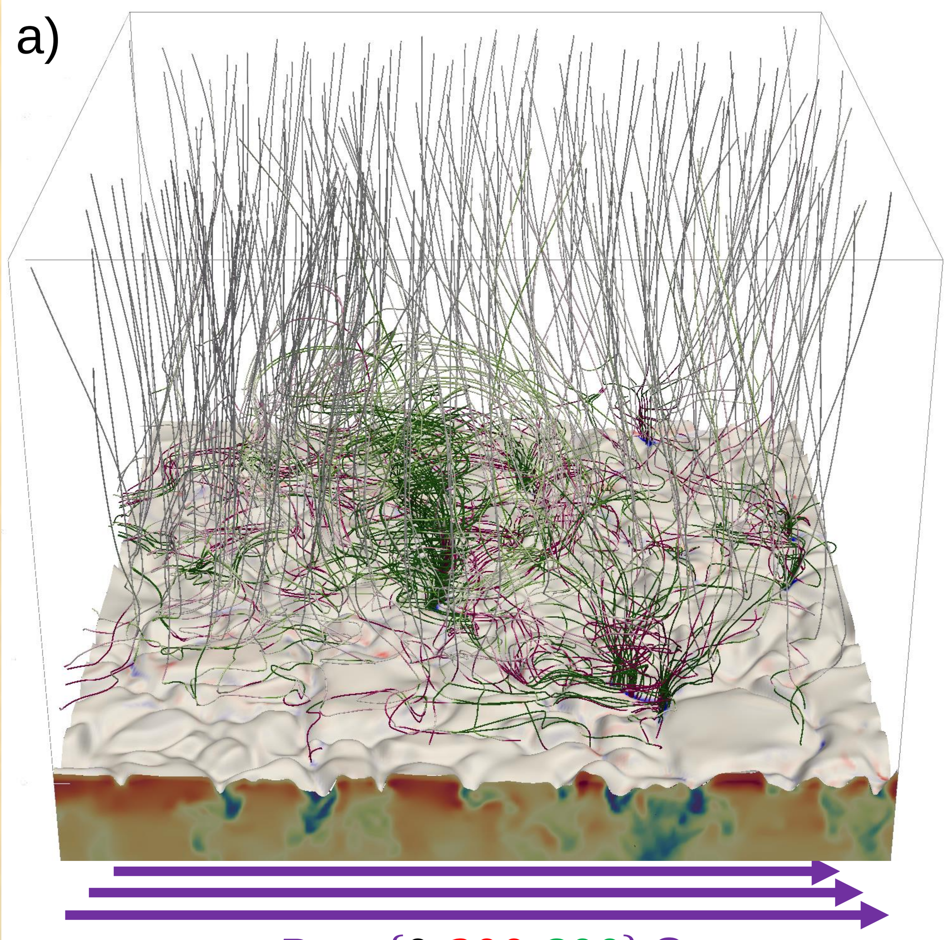
Context

A large variety of dynamical processes contribute to the **heating of the solar atmosphere**. Recent observations and simulations have highlighted the importance of **waves and magnetic reconnection** in the chromosphere, providing energy to balance the radiative cooling. However, the **relative contributions** of different processes in various solar regions (e.g., coronal holes, quiet sun) remains questioned (Carlsson et al. 2019).
Numerical simulations have especially demonstrated that the **braiding of magnetic field** lines by photospheric convection can sustain a million-degree corona by **injecting energy through Poynting flux** (Gudiksen & Nordlund 05, Finley+22). Nevertheless, **initial magnetic field configurations** in these models are not constrained yet. In this context, the exact impact of flux emergence configuration and the subsequent energy injected by magneto-convection into the chromosphere is still open for investigation.

In this context, we perform a **numerical parametric study**, where we investigate the **chromosphere heating** and dynamics under **different flux emergence configurations**, using high-resolution *Bifrost* simulations of coronal holes magnetic configurations.

Numerical parametric study

a)

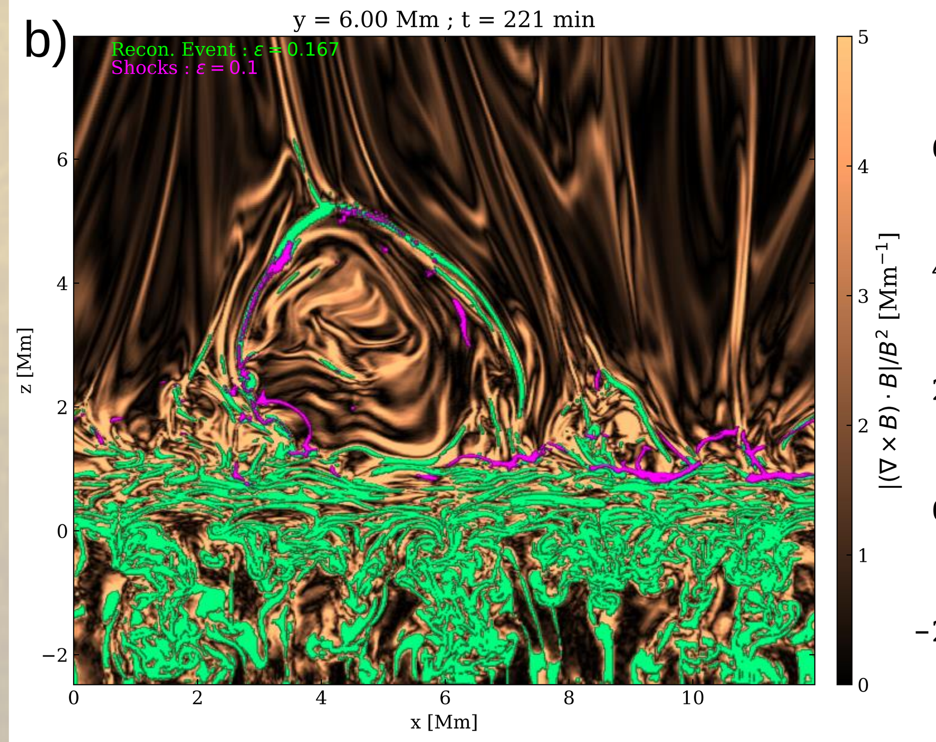


Code: ***Bifrost*** (Gudiksen+11)
Size: 12 x 12 x 10.5 Mm
Resolution:
- Horizontal 23 km
- Vertical from 70 to 12 km

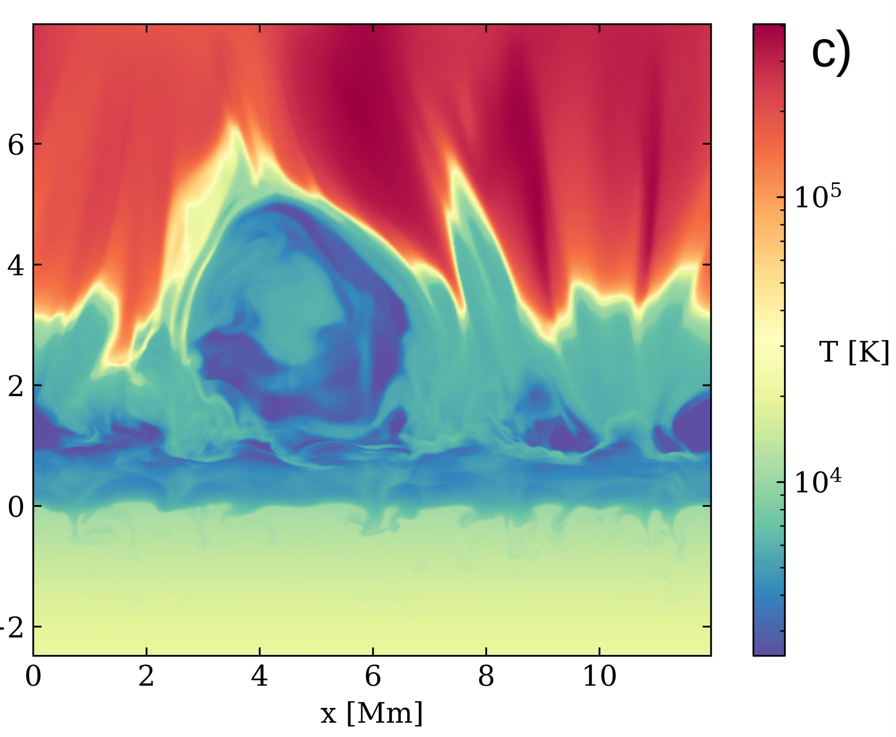
Coronal hole configuration
$\langle B_z \rangle = 2.5\ G$

Using this reference setup, we vary the amount of **upwardly advected magnetic field** at the bottom boundary ($z = 2.5$ Mm), in 3 models with
B_y **= 0, 200 and 800 G**.

b)



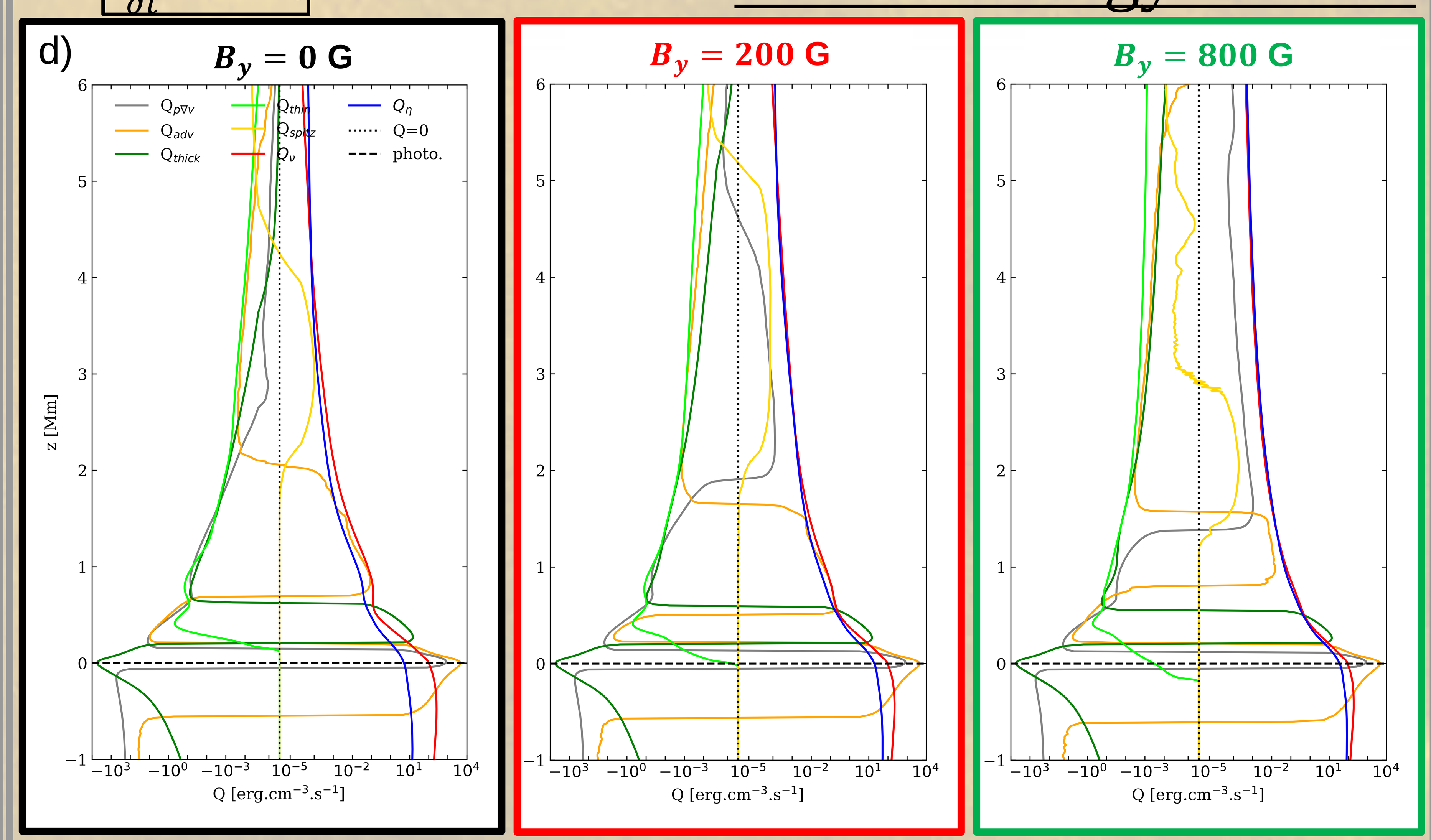
c)



Internal energy balance

1) $\frac{\partial e_{int}}{\partial t} = \Sigma Q$

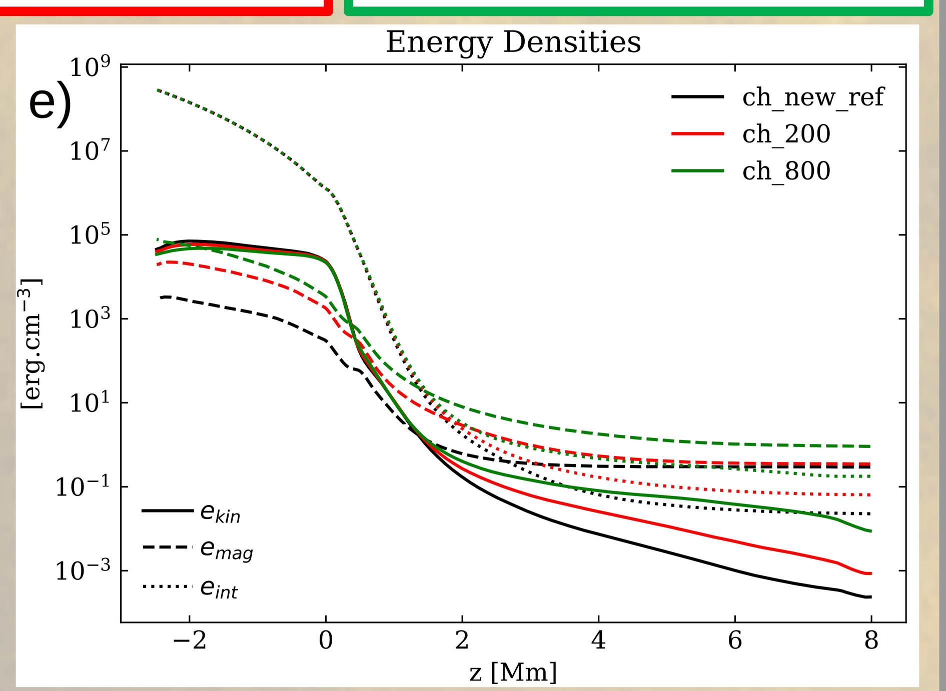
d)



The atmospheric temperature profile (c) is sustained by the equilibrium of several **heating/cooling processes**. We show in Figures d) their contribution profiles to this balance (1). **Ohmic heating and radiative cooling increases** when we increase the emerging-flux amplitude we impose.

Looking at energy profiles (e), we see that **magnetic energy dominates** the kinetic one **from mid-chromosphere**, and even from **its bottom** in the B_y = **800 G** case.

e)

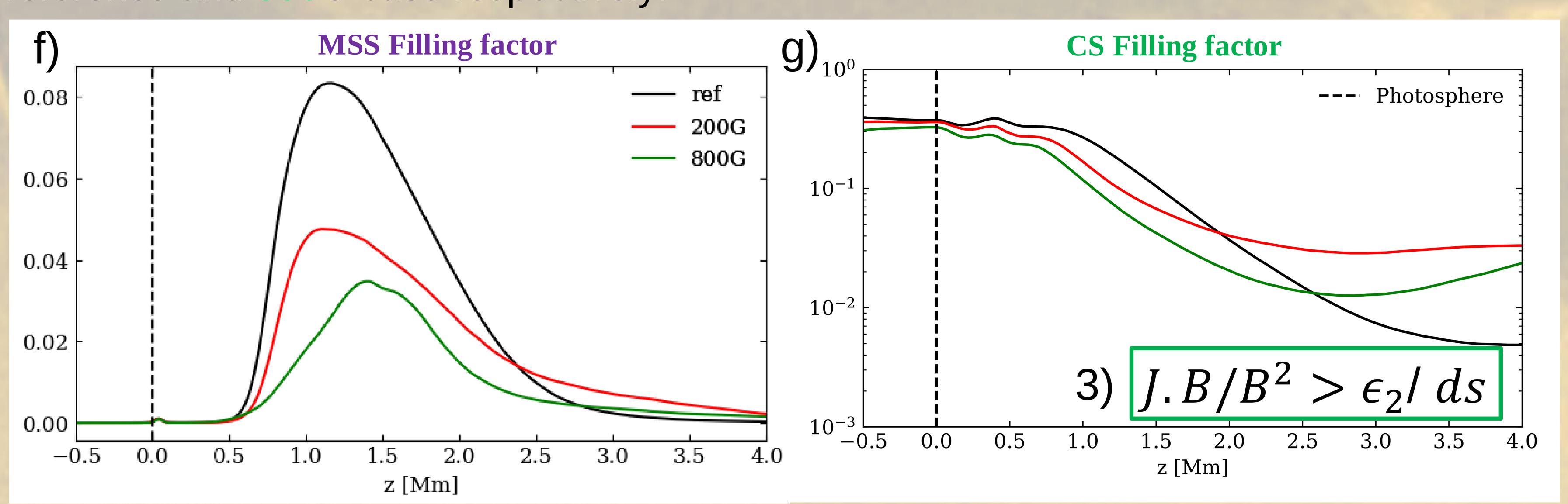


Shocks and Reconnection

2) $-\nabla \cdot v > \epsilon_1 \cdot c_S \,/\, ds$

Magneto-sonic waves rising through the **chromosphere** can produce **shocks** (colored in magenta in Figure b). We **locate** these shocks following the sound-speed c_S criteria 2), where ds is the local-maximum size of the grid and ϵ_1 a parameter we calibrate to **distinguish shocks from** compression by **linear-wave** propagation (see Wang & Yokoyama 20, Finley+22).
The volume filled by magneto-sonic shocks **(MSS)** is globally **small and decreasing** as a function of the imposed B_y (f), especially **in the chromosphere. However,** they nonetheless contribute **from 27 to 10% of the total viscous & ohmic heating** (h), in the reference and **800**G case respectively.

f) g)

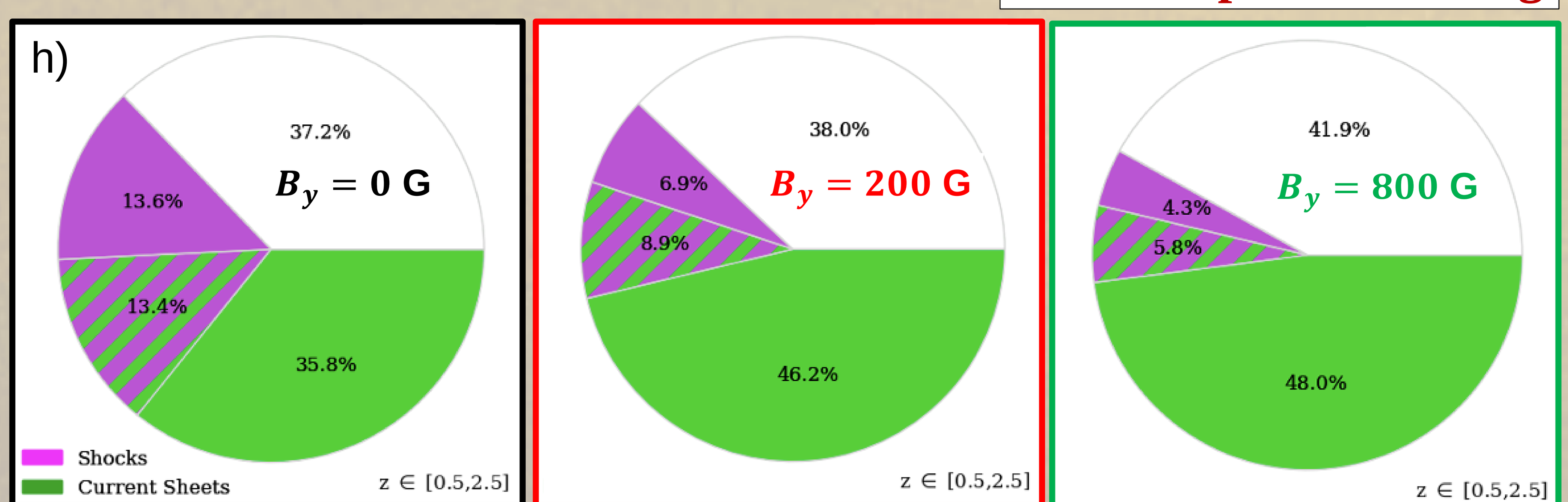


3) $J.B/B^2 > \epsilon_2 / ds$

Magnetic reconnection events are located using the criterion (3), where ϵ_2 is calibrated to locare **Current Sheets (CS)** (Hesse & Schindler 88, Aulanier+05). **As horizontal field is fed** (in **200**G & **800**G cases), low-chromosphere magnetic field is stronger, which **decreases the CS occurrence** (g). Mass-loading dynamics is also changed, bringing more magnetized material above the chromosphere, where this occurrence now increases. However, **ohmic dissipation in CS becomes locally stronger**, keeping then their overall contribution to chromospheric heating significant (≥50%).

Chromospheric Heating

h)



Contribution of **shocks** and **current sheets** to the total **chromospheric heating** (joule and viscous dissipation between 0.5 and 2.5 Mm above the photosphere)

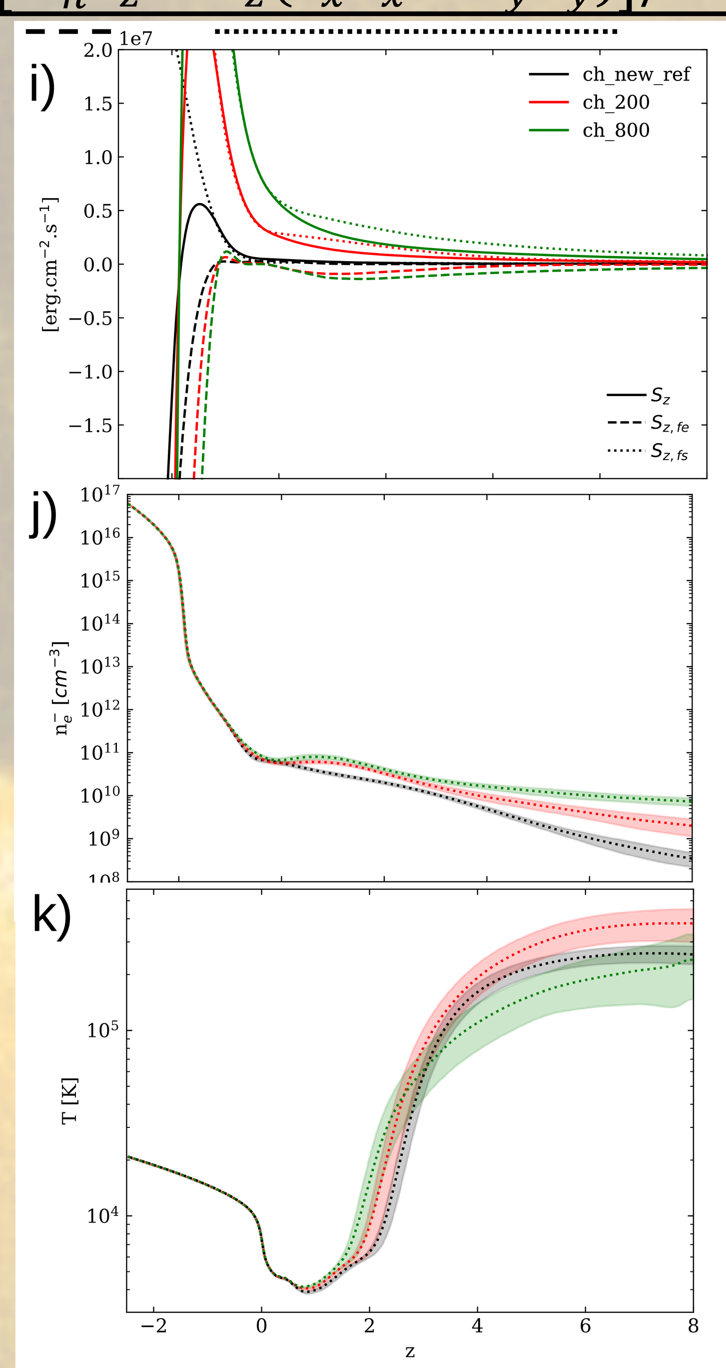
Atmospheric response

$S_z = \left[B_h^2 v_z - B_z(v_x B_x + v_y B_y) \right] / 4\pi$

Part of the atmospheric heating balance is sustained by the transport of hot/cold material (Q_{adv} in eq. 1). The upward transport is enhanced **as we increase** the imposed $\boldsymbol{B_y}$ (Figs. i,j) changing then:
the **chromosphere**, partially ionized, where the temperature and thus electron density n_{e^-} are higher (j), likely due to the significant increase in Ohmic heating (d) ;
the **transition region**, which is formed at a higher column mass ;
the **low-corona**, fully ionized, where density, thus n_{e^-}, have been increased, triggering radiative cooling (d). This latter is moderate in the **200**G case, where **coronal temperature** $\boldsymbol{T_c}$ is increased, but stronger in the **800**G case and **decreases** $\boldsymbol{T_c}$ (k).

This dynamics also quickly become magnetically dominated when going through the chromosphere (e), and the Poynting flux $\vec{S}$, quantifying the **transport of magnetic energy**, increases with the imposed $\boldsymbol{B_y}$ .Looking at its vertical-component S_z profile (i), it is then oriented upward and dominated by magnetic **field shaking** (“fs”) **above the photosphere**, arising from the shear/twist of vertical field lines by horizontal flows (a).

i) j) k)



Summary & Perspectives

We present a parametric study with a specific focus on coronal holes, where we increase the upwardly advected magnetic field $\boldsymbol{B_y}$ at the bottom boundary. We report a notable **enhancement** in both atmospheric Ohmic **heating** and radiative **cooling** (d), especially focused on the **chromosphere** for the former case, and the **low corona** for the latter. The augmented Ohmic heating is related to the increased amplitude of **upward Poynting flux**, whereas the radiative cooling is likely to be triggered by **mass loading** (i,j).
We currently investigate the specific magnetically-driven processes at play, with **MSS and CS** contributing significantly to the chromospheric heating (h) and their occurrence diminishing in the chromosphere as the imposed ***B_y*** increases (f,g). Future comparisons of these models with **forthcoming observations**, from the IRIS mission and the exploration of polar caps by Solar Orbiter, hold the promise of providing more precise insights into the dynamics of coronal holes and the energy injection into the solar wind.