Stratification of canopy magnetic fields in a plage region:

Constraints from a spatially-regularized weak-field approximation method

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CHROMOSPERIC HEATING PROBLEM:

→ The chromosphere is <u>not in radiative equilibrium.</u>

What kind of physical processes can provide the energy necessary to sustain the radiative losses that are observed?

Key ingredient:

Magnetic Fields

Dynamics

Energy balance

Atmospheric structure

Cannot be directly observed
→ Imprint in the <u>polarization</u> properties of spectral lines
→ Stokes parameters

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Spatially-regularized WFA

WFA (for $B_{||}$): $V(\lambda) = -C_1 B_{\parallel} \frac{dI}{d\lambda} \rightarrow \chi^2 = \frac{1}{N} \sum_{i=\lambda_0}^{\lambda_n} \left(\frac{V_{obs}^i - V_{synt}^i}{\sigma_i} \right)^2 = \frac{1}{N} \sum_{i=\lambda_0}^{\lambda_n} \frac{1}{\sigma_i^2} \left(V_{obs}^i - \left(-C_1 \frac{dI_i}{d\lambda} B_{\parallel} \right) \right)^2$

Added Tikhonov regularization to the WFA:

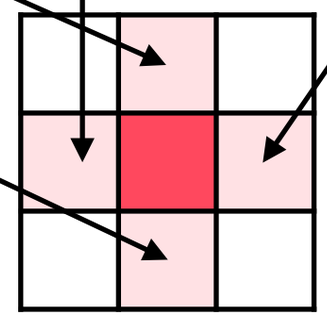
For a given linear problem $\boldsymbol{Ax} = \boldsymbol{b}$

USUAL APPROACH: $||\boldsymbol{Ax} - \boldsymbol{b}||^2 = 0$

WITH TIKHONOV REG.: $||\boldsymbol{Ax} - \boldsymbol{b}||^2 + ||\boldsymbol{\Gamma x}||^2 = 0$

Spatially-regularized WFA (for $B_{||}$):

$$\chi^2 = \sum_{i=\lambda_0}^{\lambda_n} \left(V_i - C_1 \frac{dI_i}{d\lambda} B_{\parallel}^{(x,y)} \right)^2 + \alpha \left[\left(B_{\parallel}^{(x,y)} - B_{\parallel}^{(x,y-1)} \right)^2 + \left(B_{\parallel}^{(x,y)} - B_{\parallel}^{(x,y+1)} \right)^2 + \left(B_{\parallel}^{(x,y)} - B_{\parallel}^{(x-1,y)} \right)^2 + \left(B_{\parallel}^{(x,y)} - B_{\parallel}^{(x+1,y)} \right)^2 \right]$$



Now the problem becomes **global** and the solution for the entire FOV needs to be computed.

Similar procedure for $B_{\perp}$ and ϕ.

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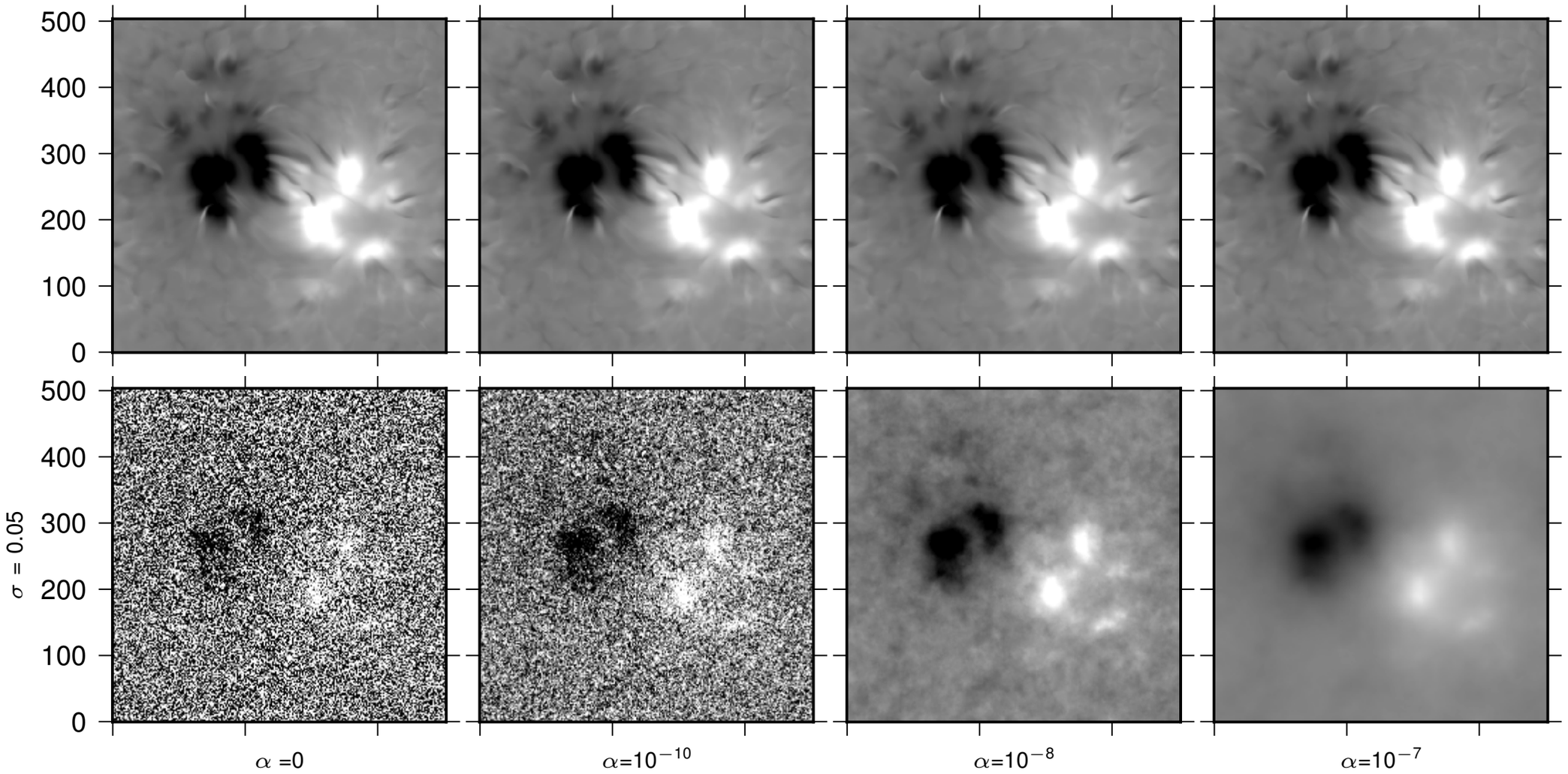
Test on synthetic data



Top row: $B_{||}$obtained from MHD model

Bottom row: $B_{||}$ obtained when a noise value σ is applied to the data for three different value of the regularization parameter α

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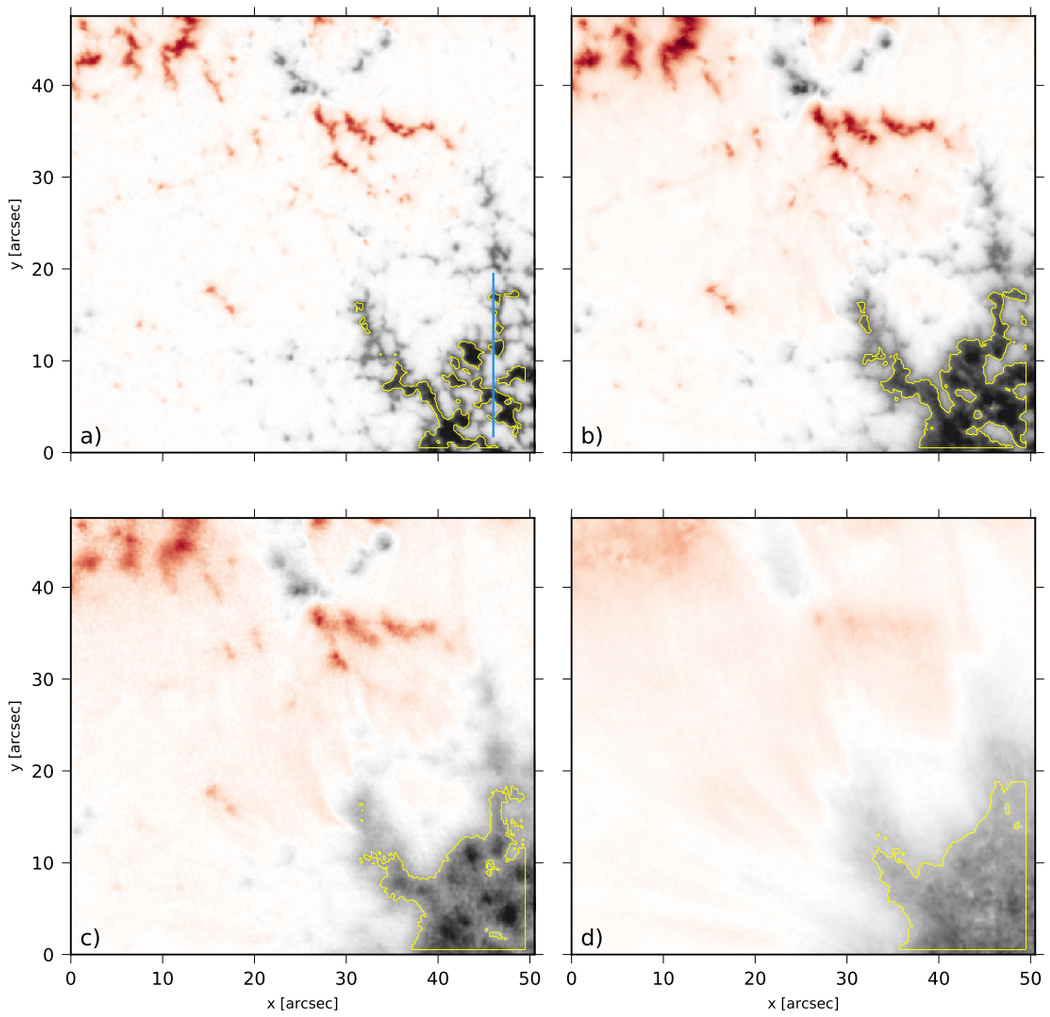
Application to real data

> Swedish 1-m Solar Telescope (SST) with CRisp Imaging Spectro-Polarimeter (CRISP)
> 2018-06-19 at 07:33:14 UT
> Plage region at (X,Y)=(229",61"), μ=0.97

Label	Atom	Line [Å]	$\bar{g}_{\rm eff}$	G	λ_i [mÅ]	$\langle z \rangle$ [km]	$\langle B_{\parallel} \rangle$ [G]	$\langle B_{\parallel} \rangle$ [G] (2D)
a)	Na I	5895.824	1.33	1.33	[−360, −300, −240, 240, 300, 360]	157 ± 18	398 ± 206	719 ± 88
b)	Na I	5895.824	1.33	1.33	[−120, 60, 60, 120]	474 ± 40	546 ± 161	692 ± 94
c)	Mg I	5172.684	1.75	2.87	[−40, 0, 40]	760 ± 45	502 ± 118	558 ± 103
d)	Ca II	8542.091	1.10	1.21	[−110, −55, 0, 55, 110]	1168 ± 122	417 ± 69	444 ± 83



<u>Panel (a)</u>: Photosphere, far wings of the Na I 5896 Å line.
<u>Panel (b)</u>: Upper photosphere, inner wings of the Na I 5896 Å line.
<u>Panel (c)</u>: Lower chromosphere, core of the Mg I 5173 Å line.
<u>Panel (d)</u>: Chromosphere, core of the Ca II 8542 Å line.

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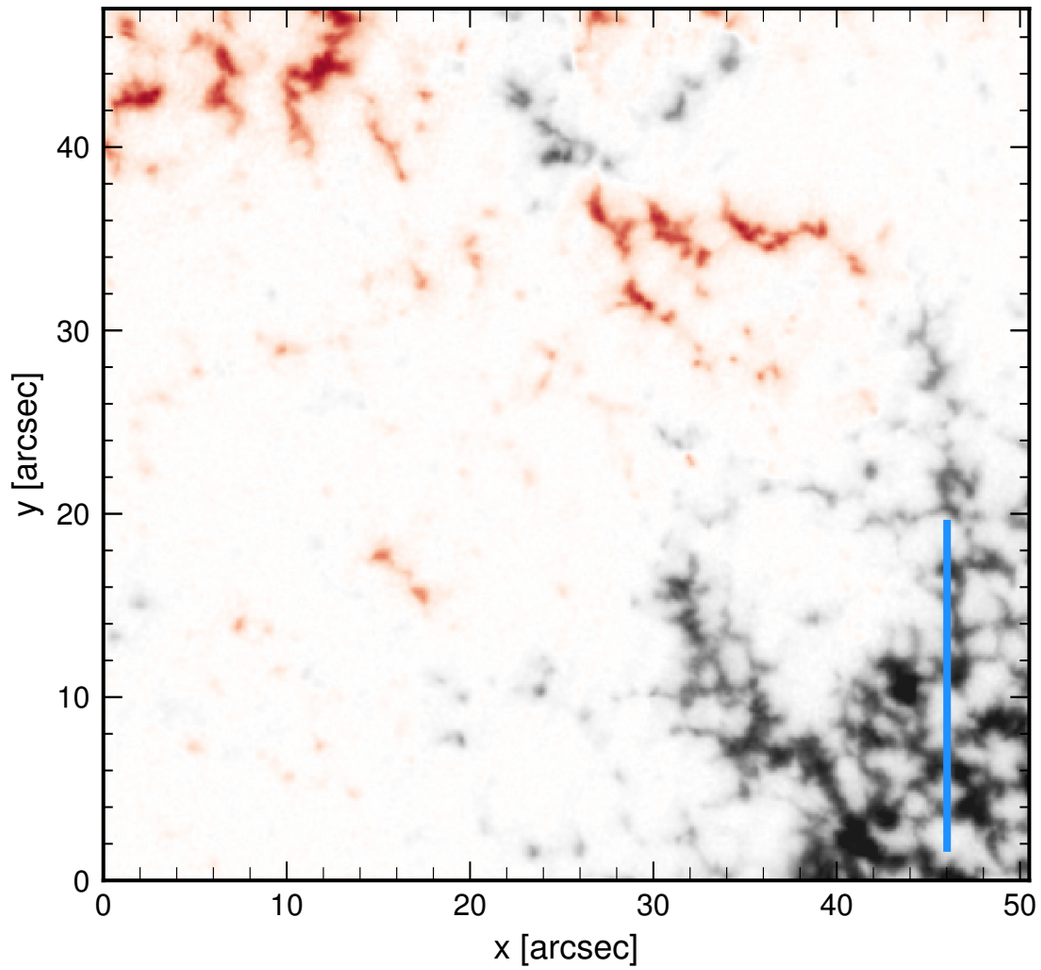
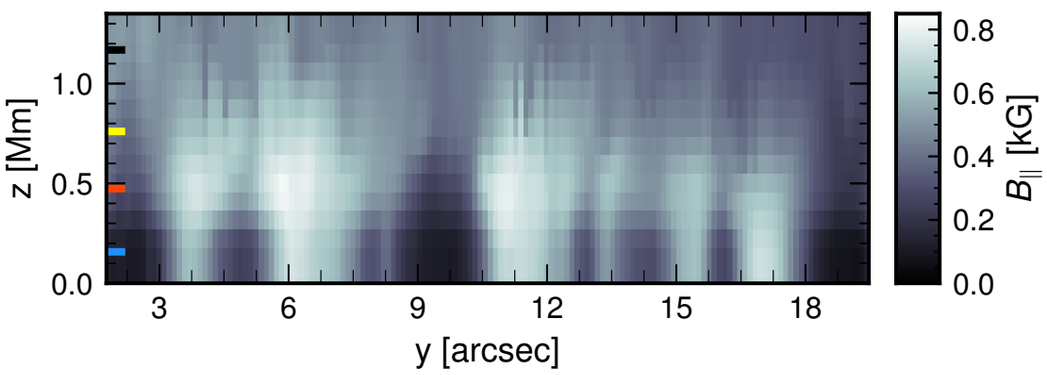
Stratification of **B**





> Edge of the magnetic canopy: between 300km and 600km

> $< B_{||} >$ = 449 G at z =1000km

> Pietrow et al. (2020) in a parallel study (using a different technique) recovered very similar values.

Colored ticks = mean formation region:
blue : panel (a)
red : panel (b)
yellow : panel (c)
black : panel (d)

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~Summary~

- Adding spatial constraints to WFA allows improving the fidelity of the reconstruction of **B**;
- The reconstructed stratification is consistent with a topology in which P_{gas} dominates in the photosphere and P_B in the chromosphere: **B** can expand forming a hot magnetic canopy in the chromosphere;
- *Chromospheric heating* in plage is expected to be dominated by processes associated with the presence of **B:** by setting constraints on topology and strength we can help to discern which mechanisms are more likely to happen over plage.

On GitHub:

https://github.com/morosinroberta/spatial_WFA

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