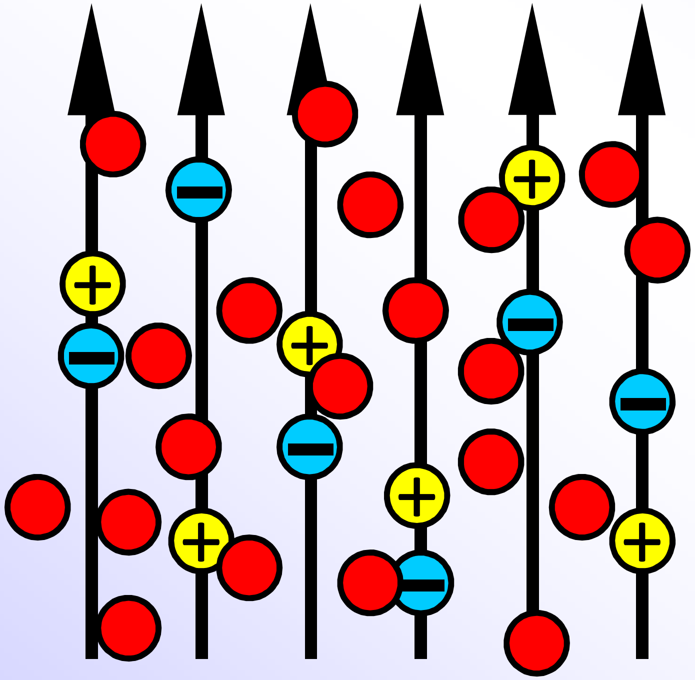

Multi-fluid effects in the solar atmosphere

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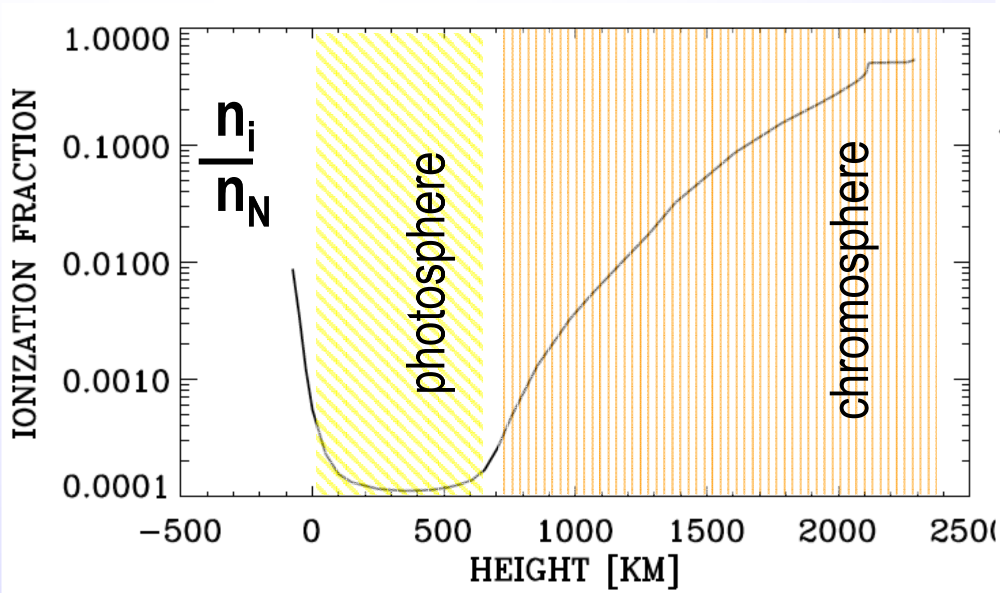
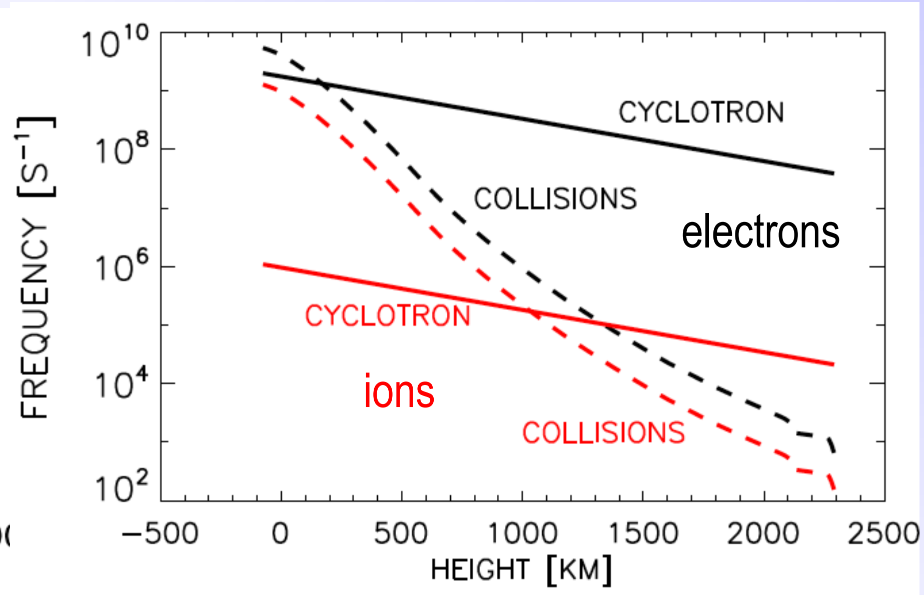
Instituto de Astrofísica de Canarias

Partial ionization





Two factors:

- ✓ Low ionization
- ✓ Low collisional coupling

Non-ideal plasma:

Hall effect and Ambipolar diffusion

Low Reynolds numbers

Important at scales around 10 km & 1 s

Partial ionization

(Potential) Consequences

- Flux emergence
- Equilibrium of magnetic structures
- Instabilities
- Energy dissipation and heating
- Wave propagation
- …

Multi-component single-fluid equations

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}\left(\rho \vec{u}\right) = \sum_{\alpha=1}^{2N+1} S_\alpha = 0$$

$$\rho \frac{D\vec{u}}{Dt} = \vec{J} \times \vec{B} + \rho \vec{g} - \vec{\nabla}\hat{\mathbf{p}} - \vec{\nabla}\hat{\mathbf{P}}_R$$

$$\frac{\partial}{\partial t}\left(e + \frac{1}{2}\rho u^2\right) + \vec{\nabla}\left(\vec{u}\,(e + \frac{1}{2}\rho u^2) + \hat{\mathbf{p}}\vec{u}\right) + \\ + \vec{\nabla}\vec{q}' + \vec{\nabla}\vec{F}_R = \boxed{\vec{J}\vec{E}} + \rho\vec{u}\vec{g}$$

Energy dissipation due to collisions

$$e = \frac{3}{2}p + \sum_{\alpha=1}^{2N} \chi_\alpha$$

Multi-component single-fluid equations

Generalized induction equation

Ohmic term

Hall term

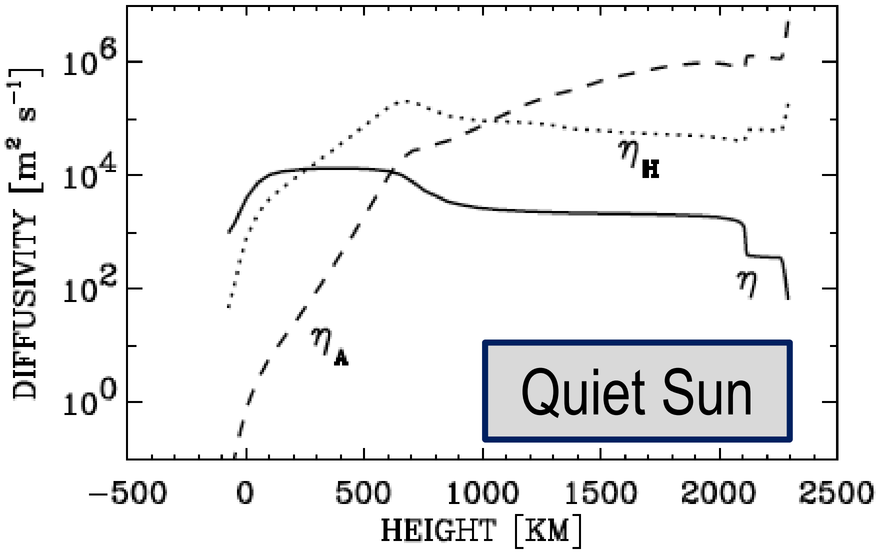
Ambipolar term

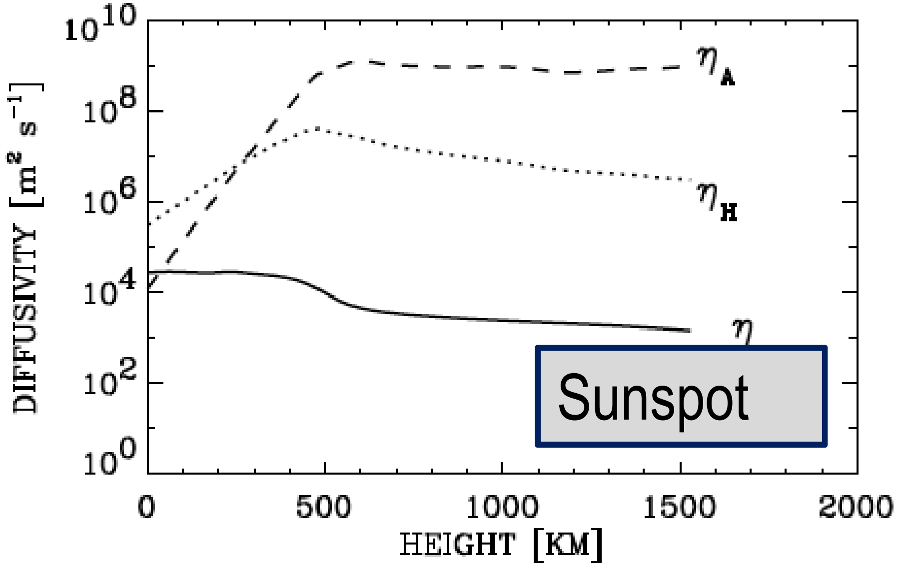
Biermann battery term

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times \left[(\vec{u} \times \vec{B}) - \eta \mu \vec{J} - \frac{\eta_H \mu}{|B|} [\vec{J} \times \vec{B}] + \frac{\eta_A \mu}{|B|^2} [[\vec{J} \times \vec{B}] \times \vec{B}] + \frac{\eta_p \mu}{|B|} \vec{\nabla} \hat{\mathbf{p}}_e - c_{pt} \vec{G} - c_{ptb} [\vec{G} \times \vec{B}] \right]$$

Multi-component single-fluid equations

Generalized induction equation



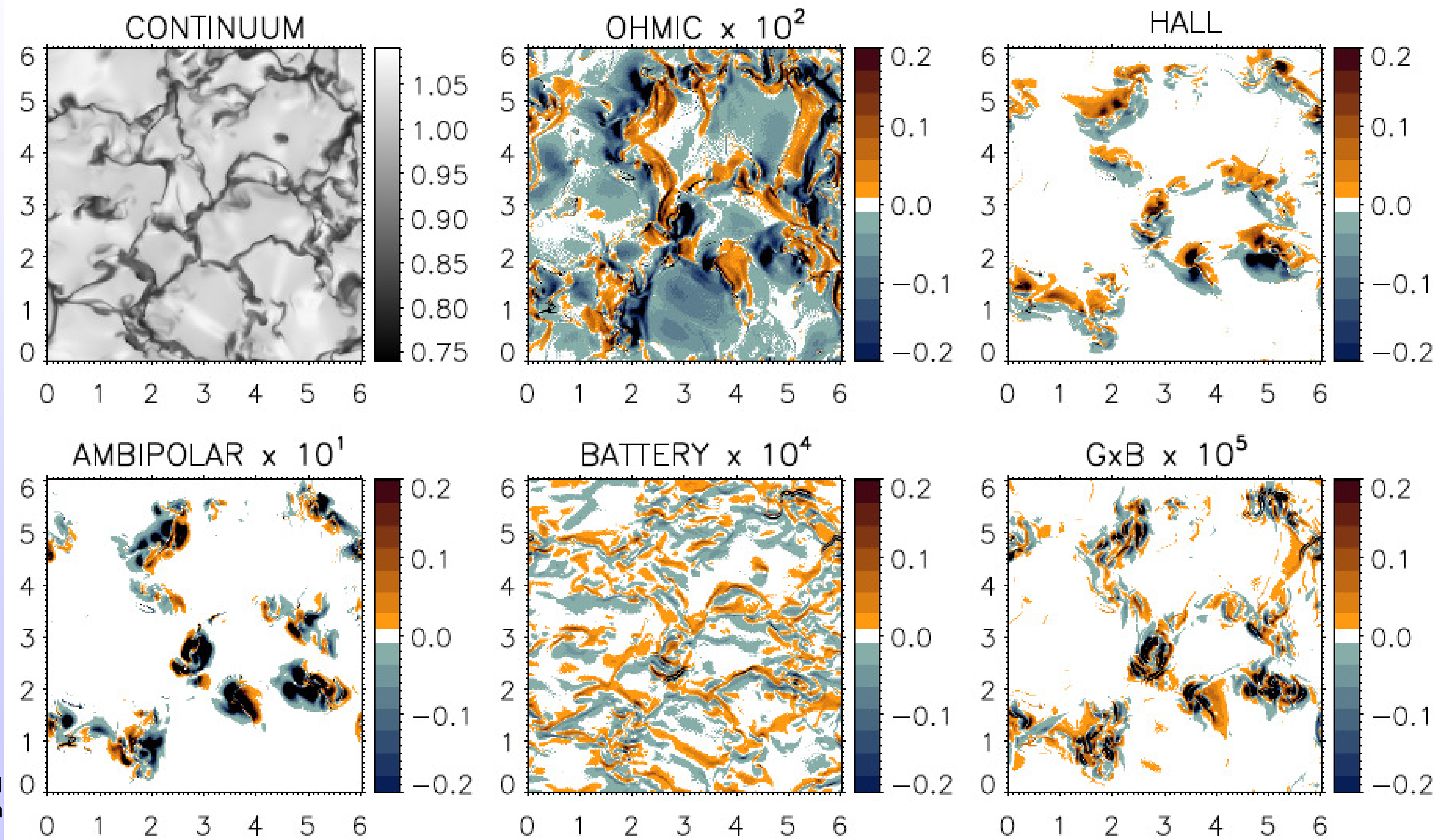


$$\eta = \frac{\alpha_e}{(e n_e)^2 \mu} \qquad \eta_H = \frac{|B|}{e n_e \mu} \qquad \eta_A = \frac{\xi_n^2}{\alpha_n \mu} |B|^2$$

Depends on neutron fraction, collision frequency and B.

Generalized induction equation

Photospheric magneto-convection snapshot from Vögler et al (2005);
z=600 km, B=180 G



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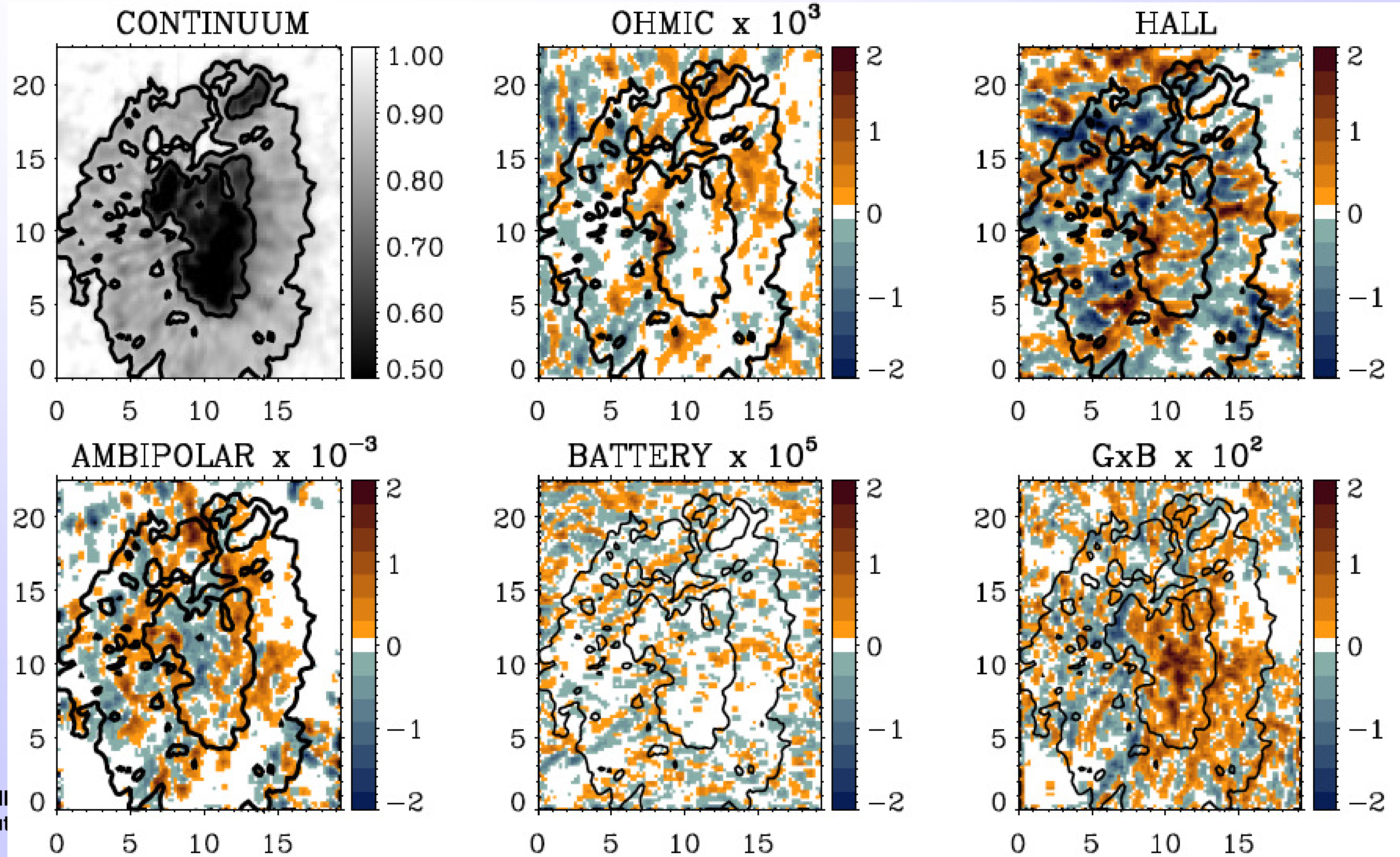
Generalized induction equation

Inversion of chromospheric sunspot observations by Socas-Navarro (2005);
z=1400 km; B =2500 G



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Institut

Multi-component single-fluid equations

Internal energy conservation equation

$$\frac{De_{\text{int}}}{Dt} + \gamma e_{\text{int}} \vec{\nabla} \vec{u} = \eta \vec{J}^2 + \eta_A \vec{J}_{\perp}^2$$

Ohmic term Ambipolar term

Since Ambipolar diffusivity is **several orders of magnitude** larger than the Ohmic diffusivity, **important heating** is expected due to current dissipation.

Partial ionization

(Potential) Consequences

- Flux emergence
- Equilibrium of magnetic structures
- Instabilities
- Energy dissipation and heating
- Wave propagation
- …

Partial ionization

(Potential) Consequences

- Flux emergence
- Equilibrium of magnetic structures
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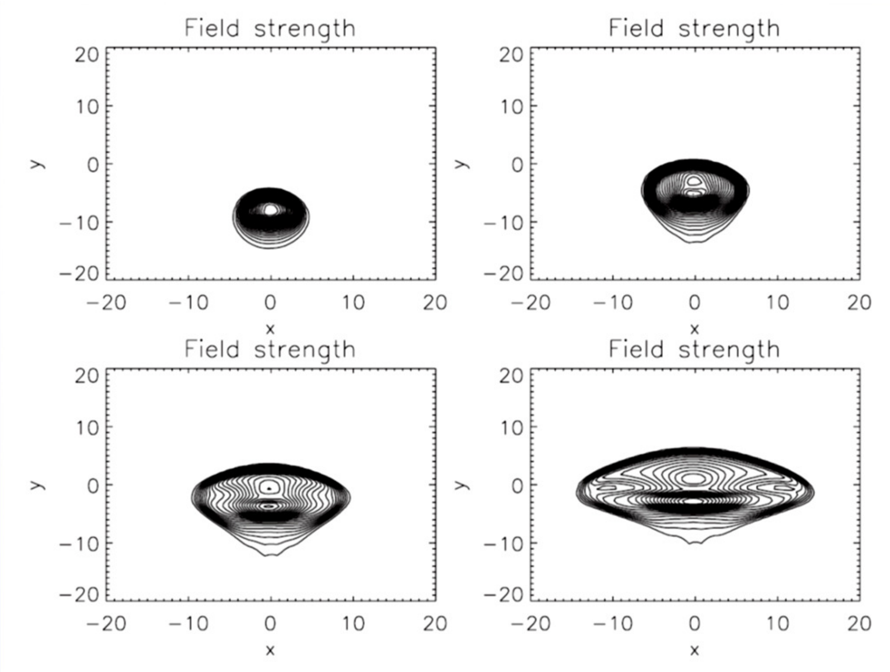
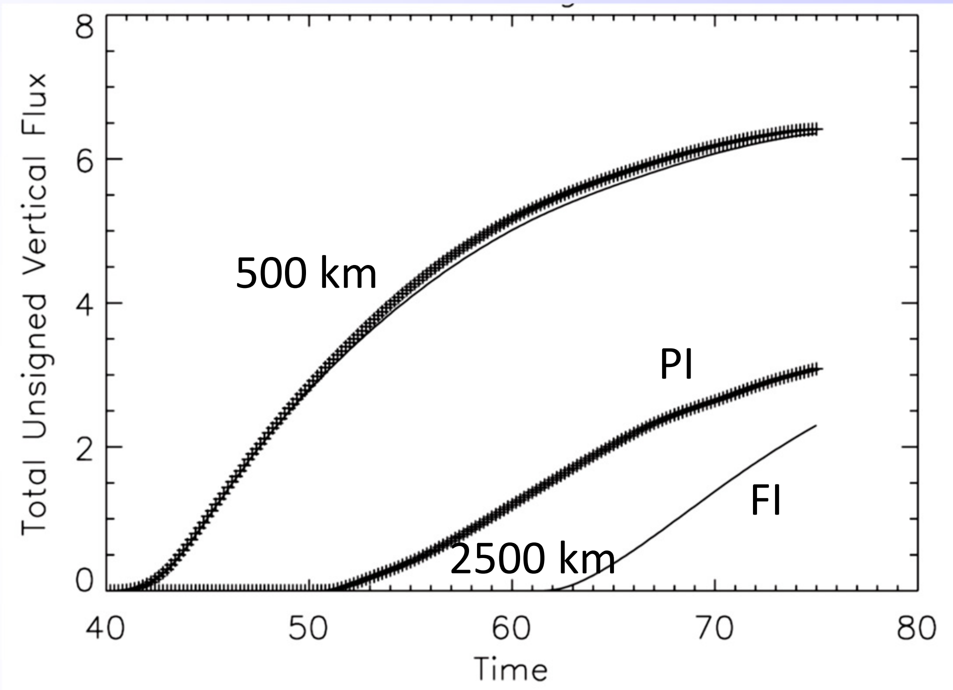
Equilibrium

Flux emergence



Buoyant twisted flux tube



Leake & Arber 2006

The rates of emergence of magnetic field is greatly enhanced by the partially ionized atmosphere

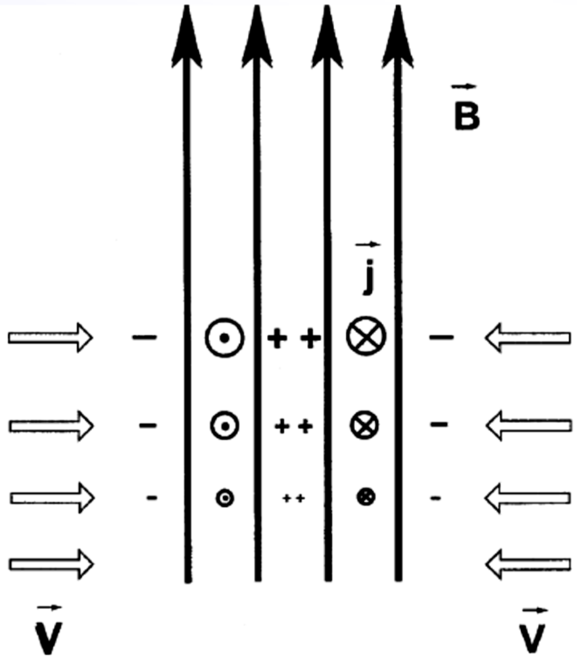
Partial ionization

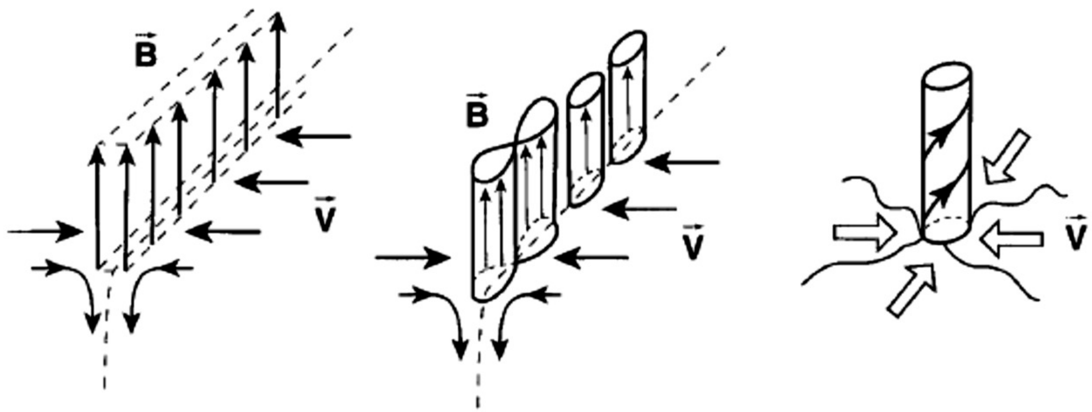
(Potential) Consequences

- Flux emergence
- Equilibrium of magnetic structures
- Instabilities
- Energy dissipation and heating
- Wave propagation
- ...

Equilibrium

Intense magnetic flux tube formation





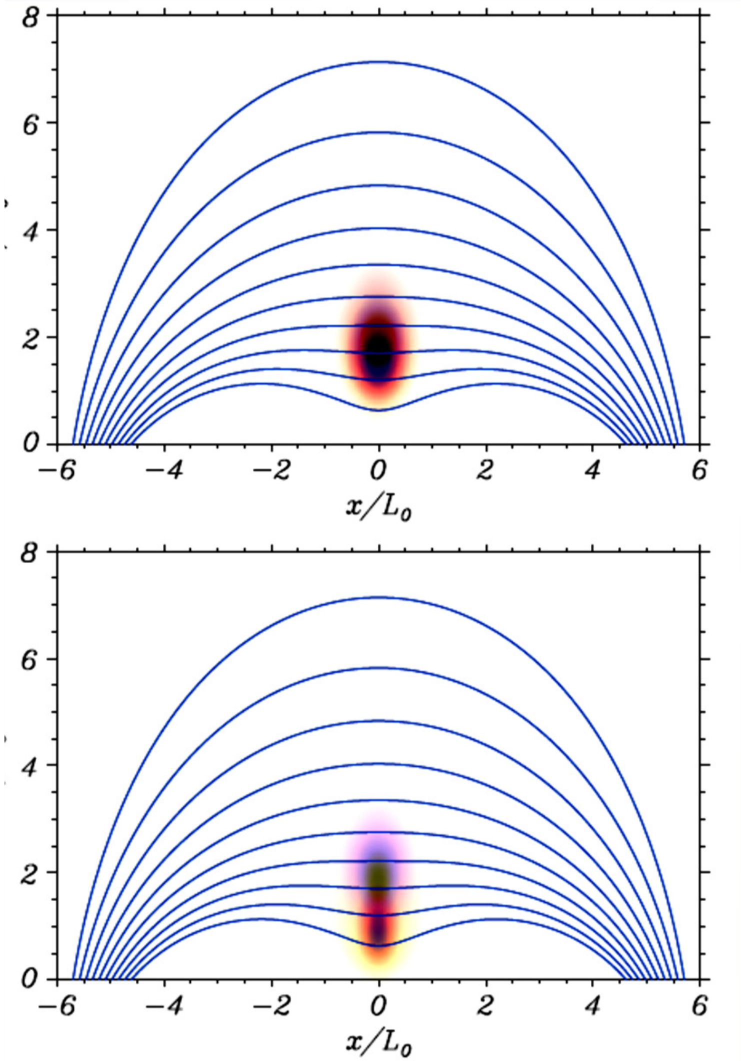
Khodachenko & Zaitsev 2002

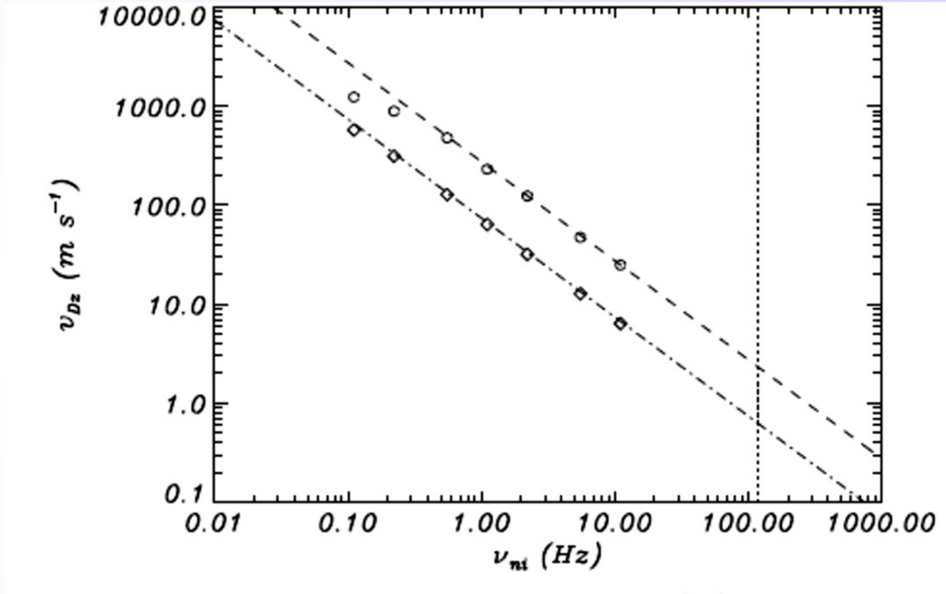
Different e-i magnetization leads to charge separation

Hall current can amplify the field to 1-2 kG

Equilibrium

Prominences



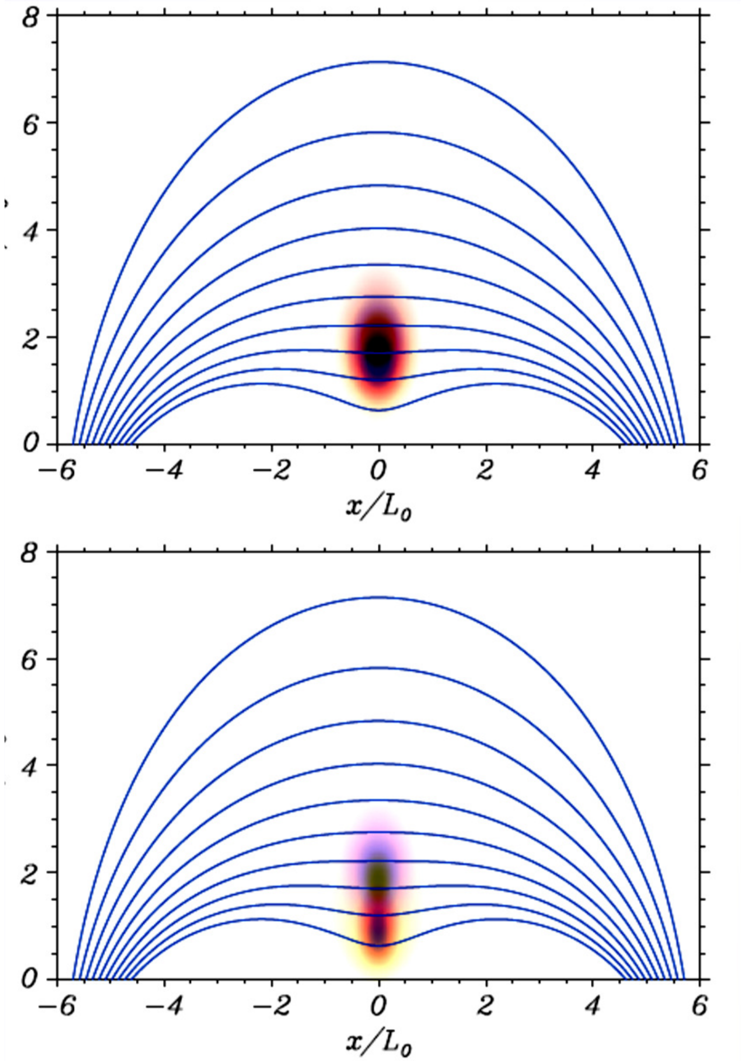


Terradas et al 2015

Velocity of neutrals too small

Equilibrium

Prominences



$$\tau_{\rm H} \approx \frac{h_{\rm prom}}{|u_{{\rm H}\,z}|} \qquad u_{{\rm H}\,z} \approx \frac{-g + \nu_{\rm H\,He} u_{{\rm He}\,z}}{\nu_{\rm H\,H^+}}$$

$$\tau_{\rm He} \approx \frac{h_{\rm prom}}{|u_{{\rm He}\,z}|} \qquad u_{{\rm He}\,z} \approx \frac{-g}{\nu_{\rm He\,H^+} + \nu_{\rm He\,H} + \nu_{\rm He\,He^+}}$$

$$\tau_{\rm H} \approx 520 \left[\frac{h_{\rm prom}(R_\odot)}{0.01\ R_\odot}\right] \left[\frac{n({\rm cm}^{-3})}{10^{10}\ {\rm cm}^{-3}}\right] {\rm hr} \approx 22\ {\rm days}$$

$$\tau_{\rm He} \approx 24 \left[\frac{h_{\rm prom}(R_\odot)}{0.01\ R_\odot}\right] \left[\frac{n({\rm cm}^{-3})}{10^{10}\ {\rm cm}^{-3}}\right] {\rm hr} \approx 24\ {\rm hr}$$

Gilbert et al 2002

Partial ionization

(Potential) Consequences

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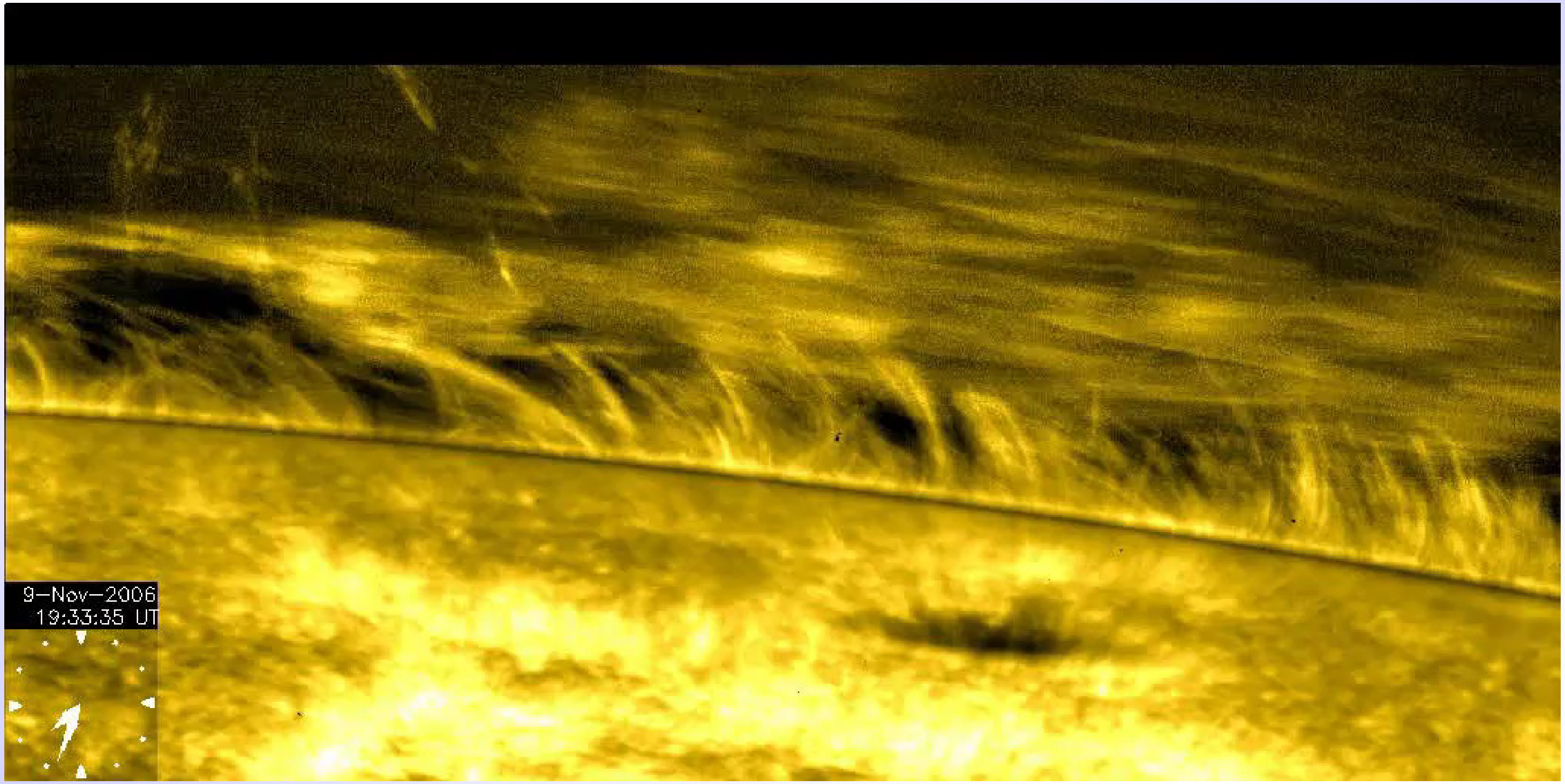
- ...

Solar prominence dynamics

HINODE observations of solar prominences



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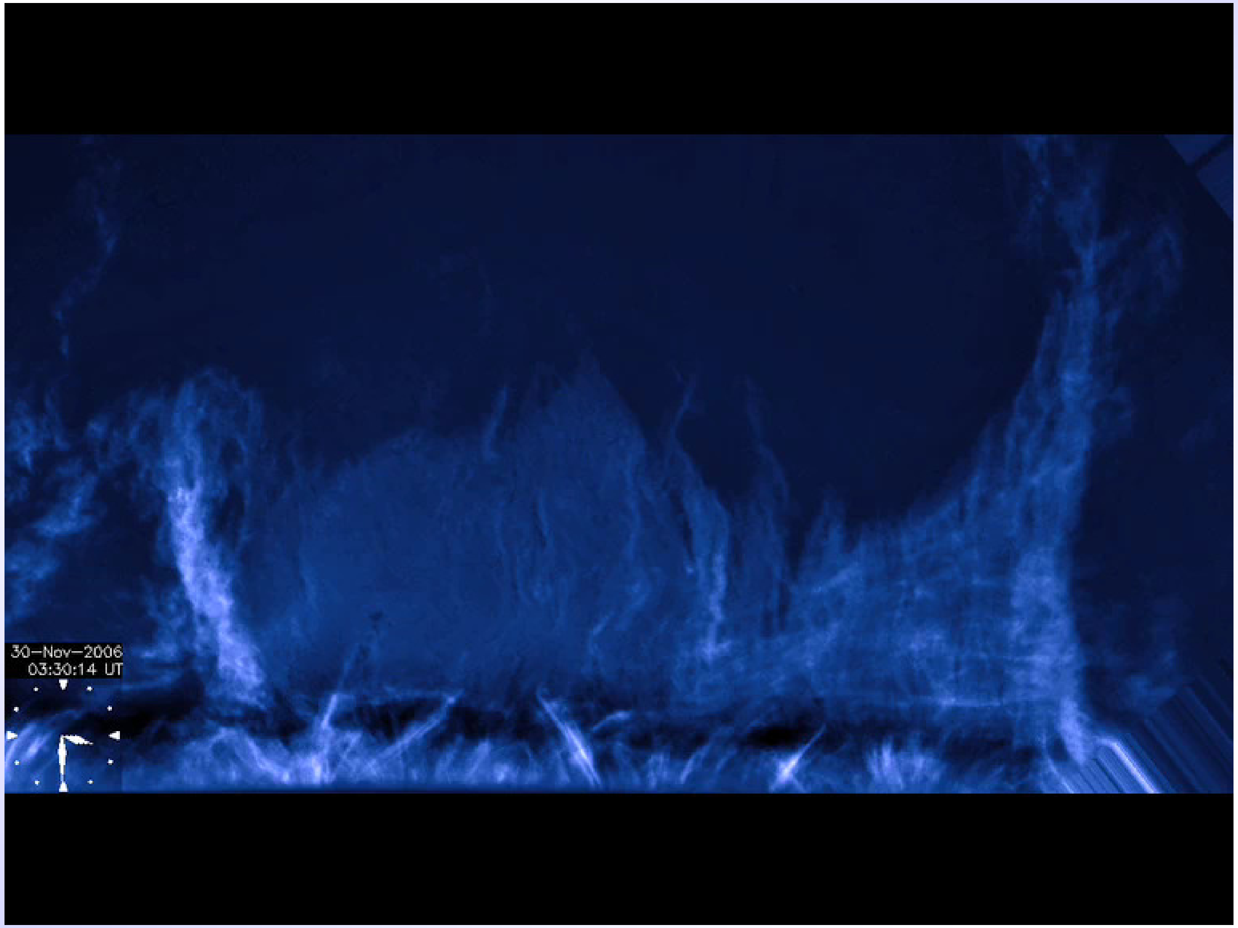
Solar prominence dynamics

HINODE observations of solar prominences



Berger et al. 2008

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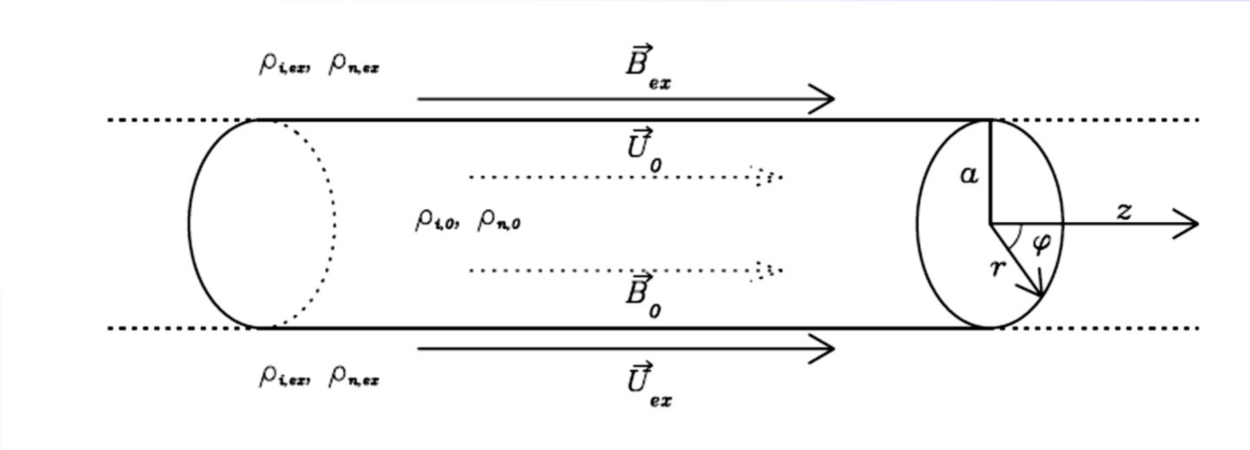
Magnetic KHI in prominences



The presence of neutrals contribute to the onset of the KHI. Collisions between ions and neutrals reduce the growth of unstable modes but cannot completely suppress the instability

Ballai et al (2015)
Martínez-Gómez et al (2015)

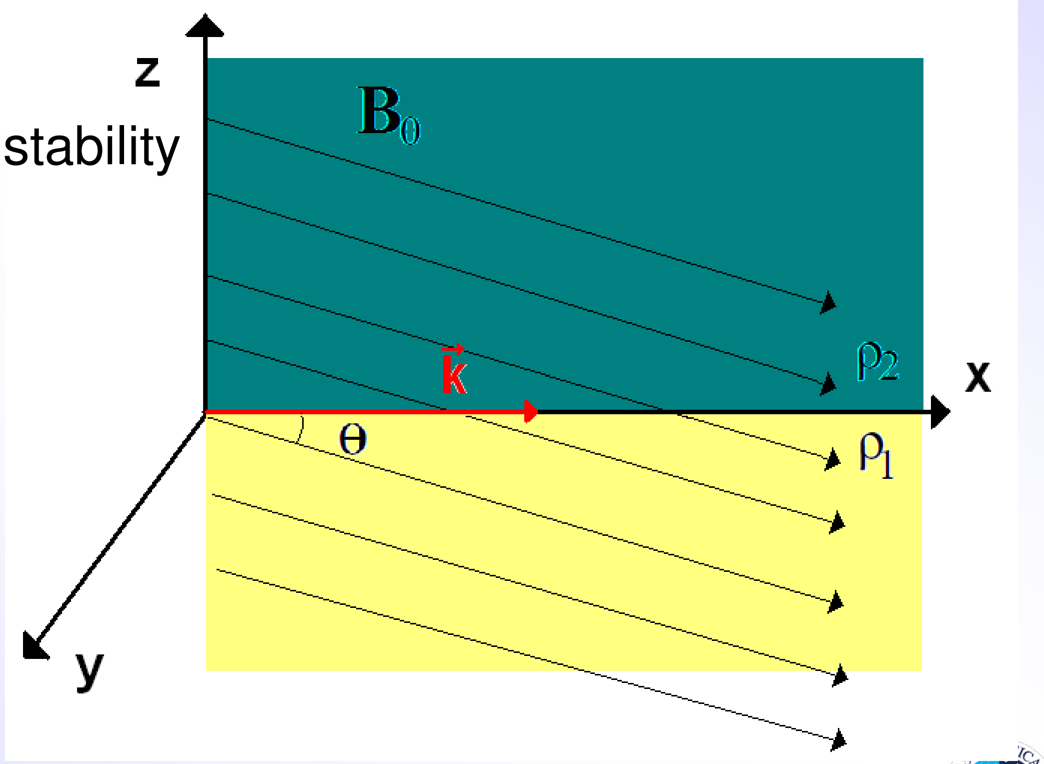
Magnetic RTI in prominences

Linear growth rate (Chandrasekhar 1961)

$$\omega^2 = -gk\frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} + \frac{2(\boldsymbol{B}_0\boldsymbol{k})^2}{\mu(\rho_2 + \rho_1)}$$

Critical wavelength below which instability is completely suppressed

$$\lambda_c = \frac{B_0^2 \cos^2\theta}{(\rho_2 - \rho_1)g}$$



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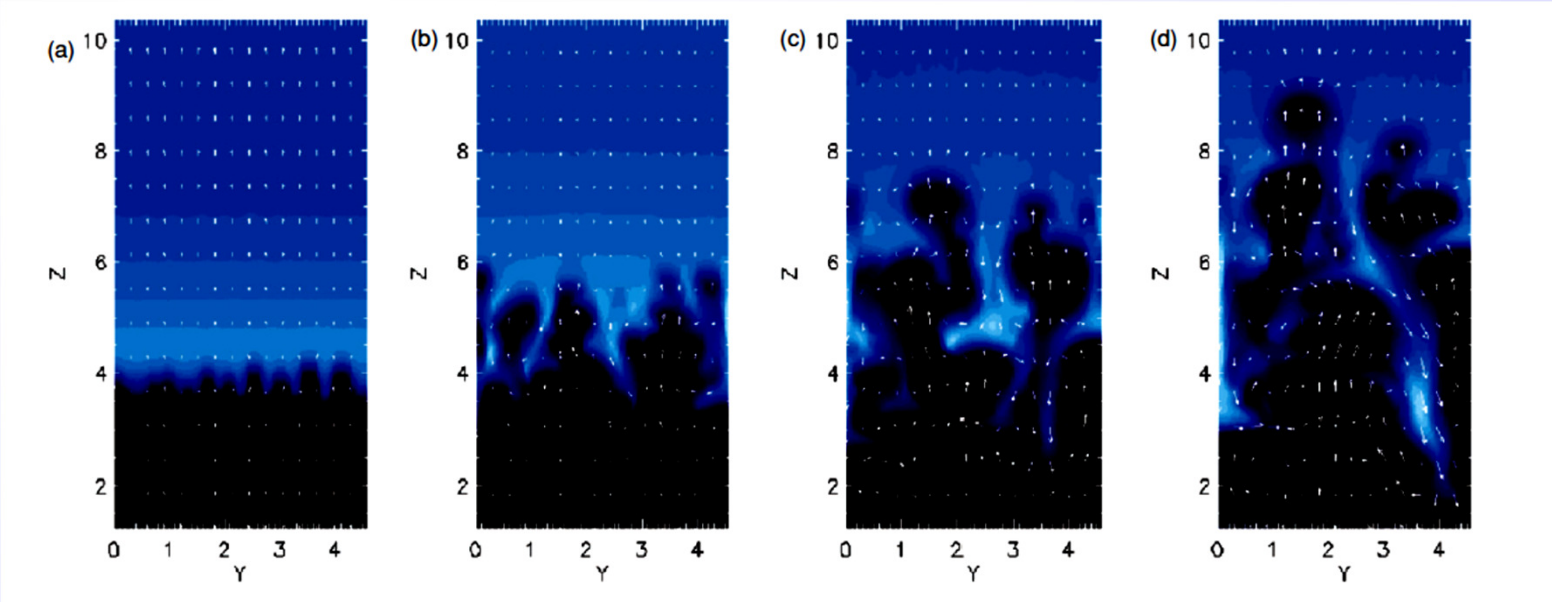
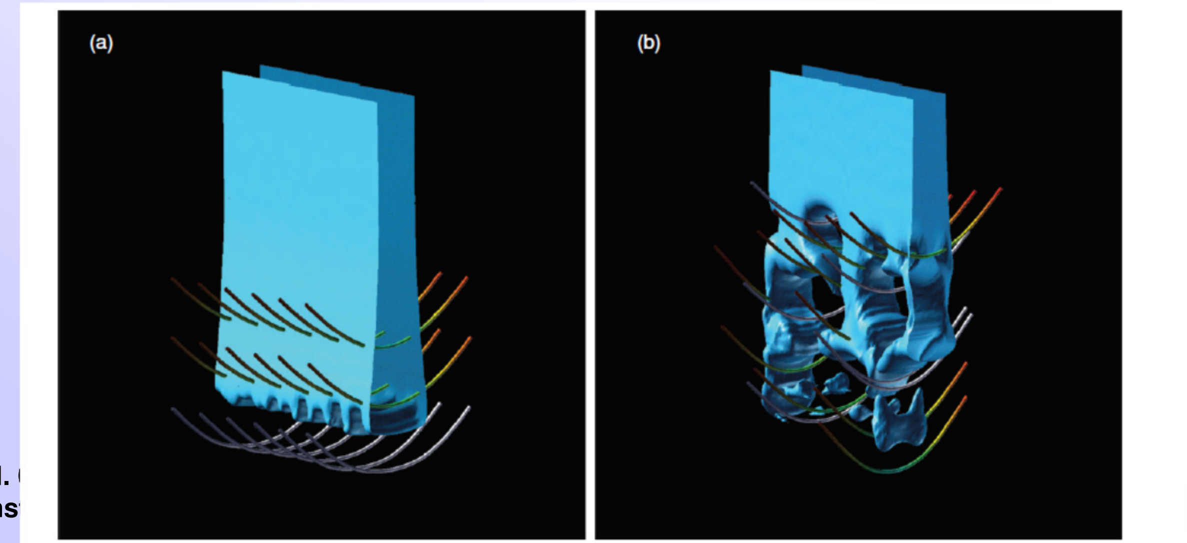
Magnetic RTI in prominences



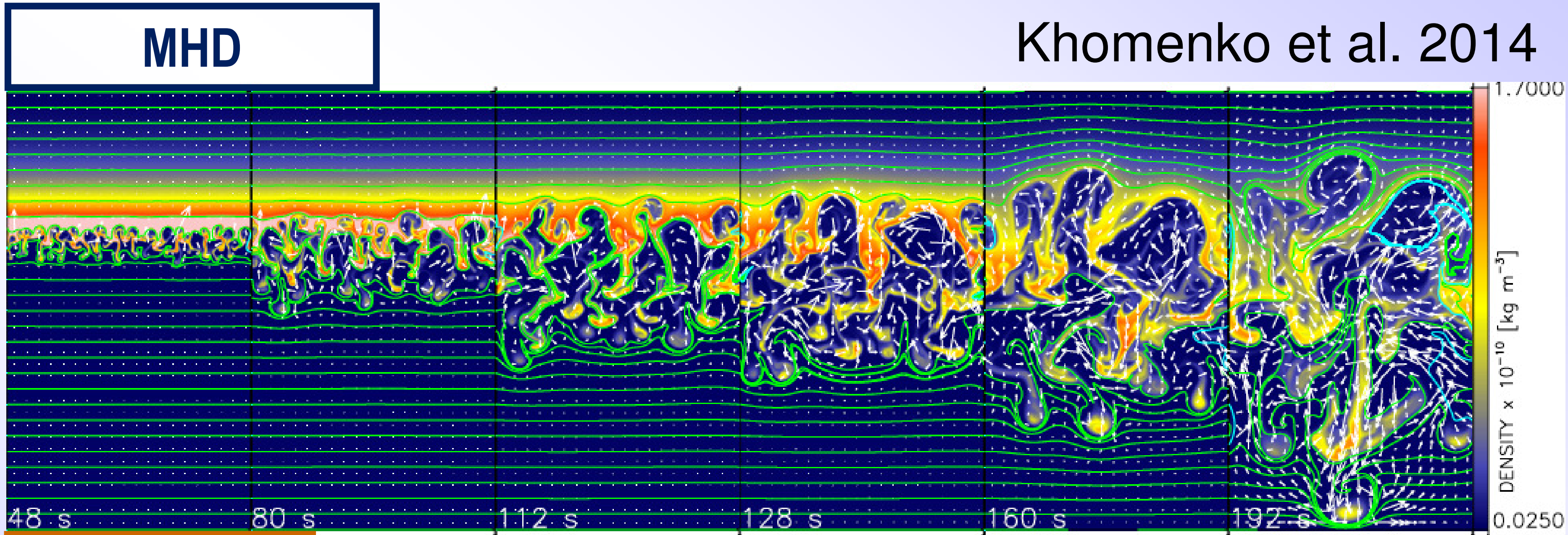


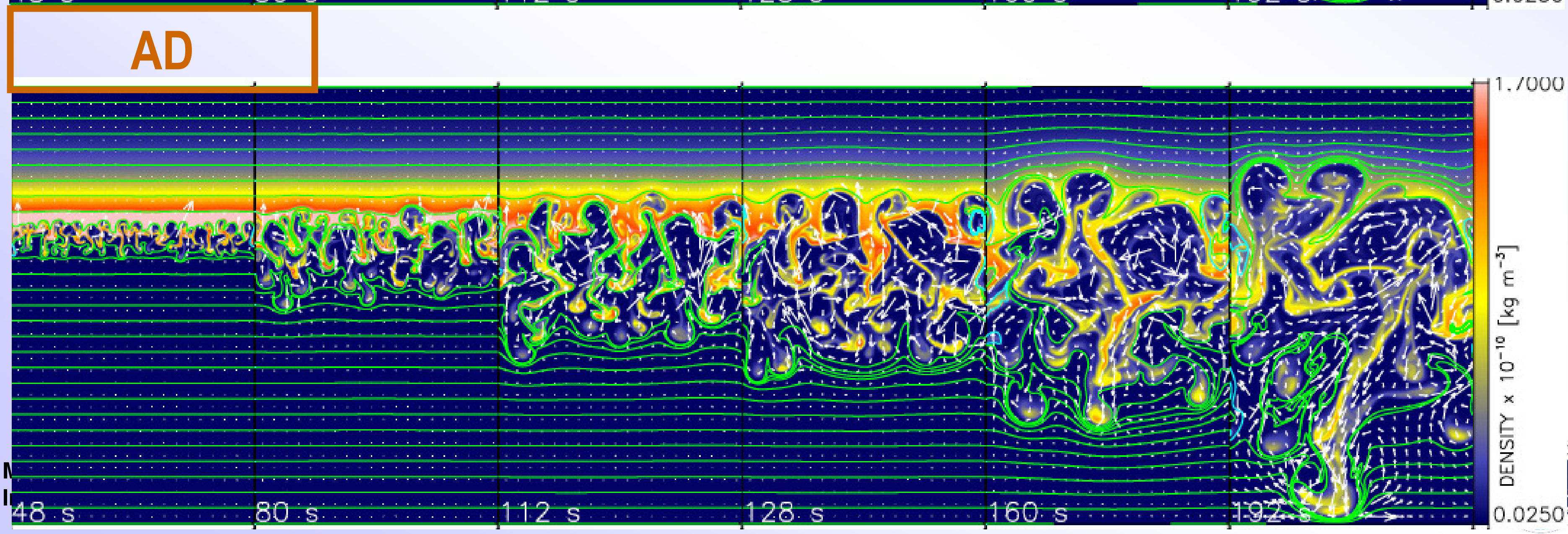
Hillier et al. 2011, 2012

Terradas et al 2015

Magnetic RTI in prominences

Khomenko et al. 2014





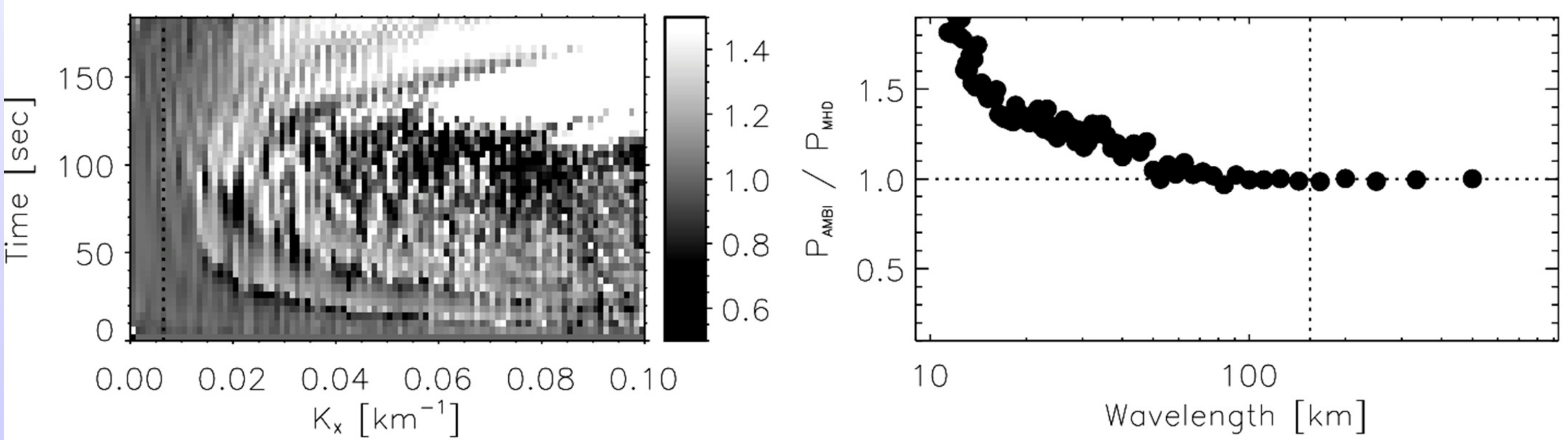
Magnetic RTI in prominences

"ambipolar" model shows larger growth rate at small scales, compared to "mhd" model

Change of behavior at λ~λc

$$\lambda_c = \frac{B_0^2 \cos^2 \theta}{(\rho_2 - \rho_1) g}$$

Power (ambipolar) / Power (mhd)



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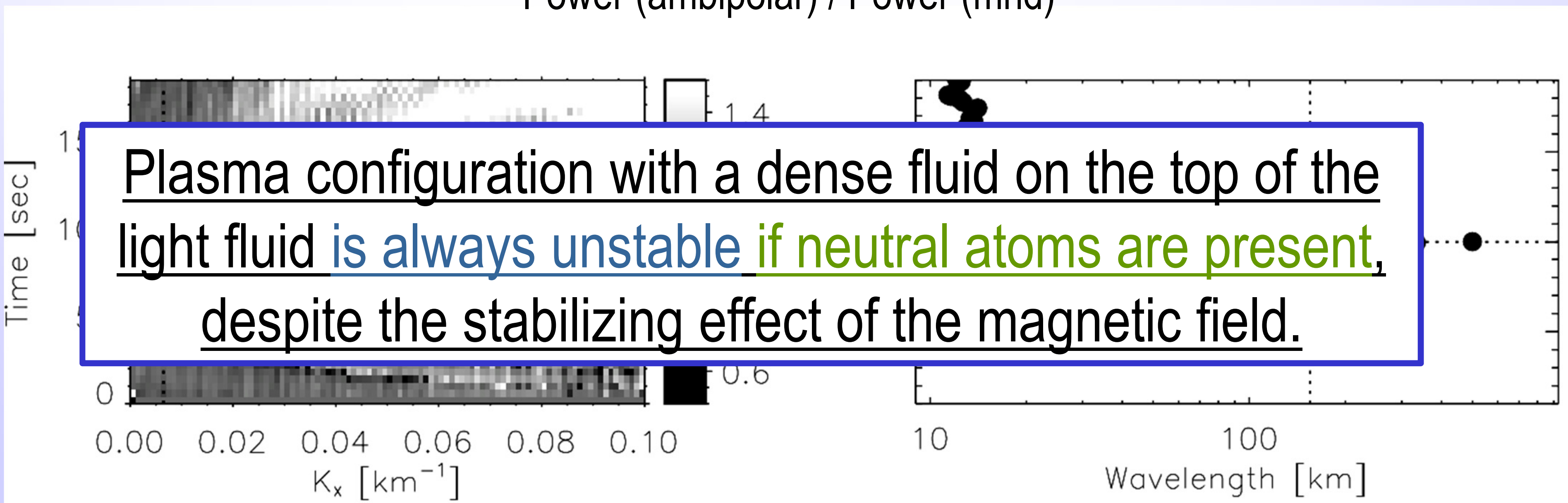
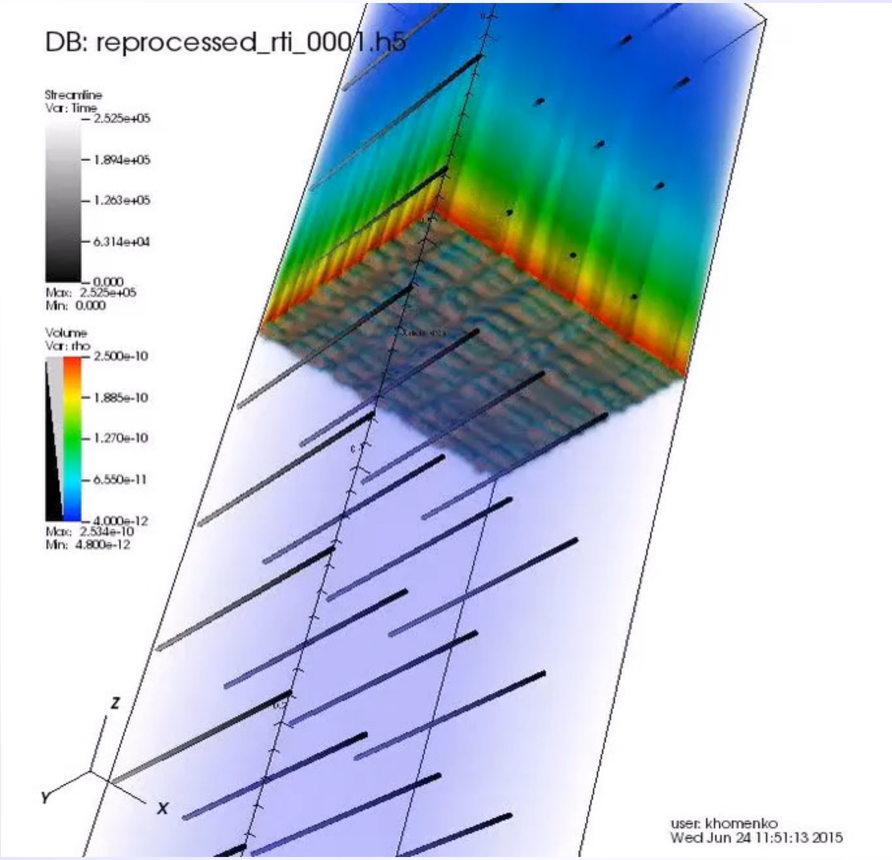


Plasma configuration with a dense fluid on the top of the light fluid is always unstable if neutral atoms are present, despite the stabilizing effect of the magnetic field.

Magnetic RTI in prominences



Observations of PI effects in prominences

Ion-neutral drift velocity

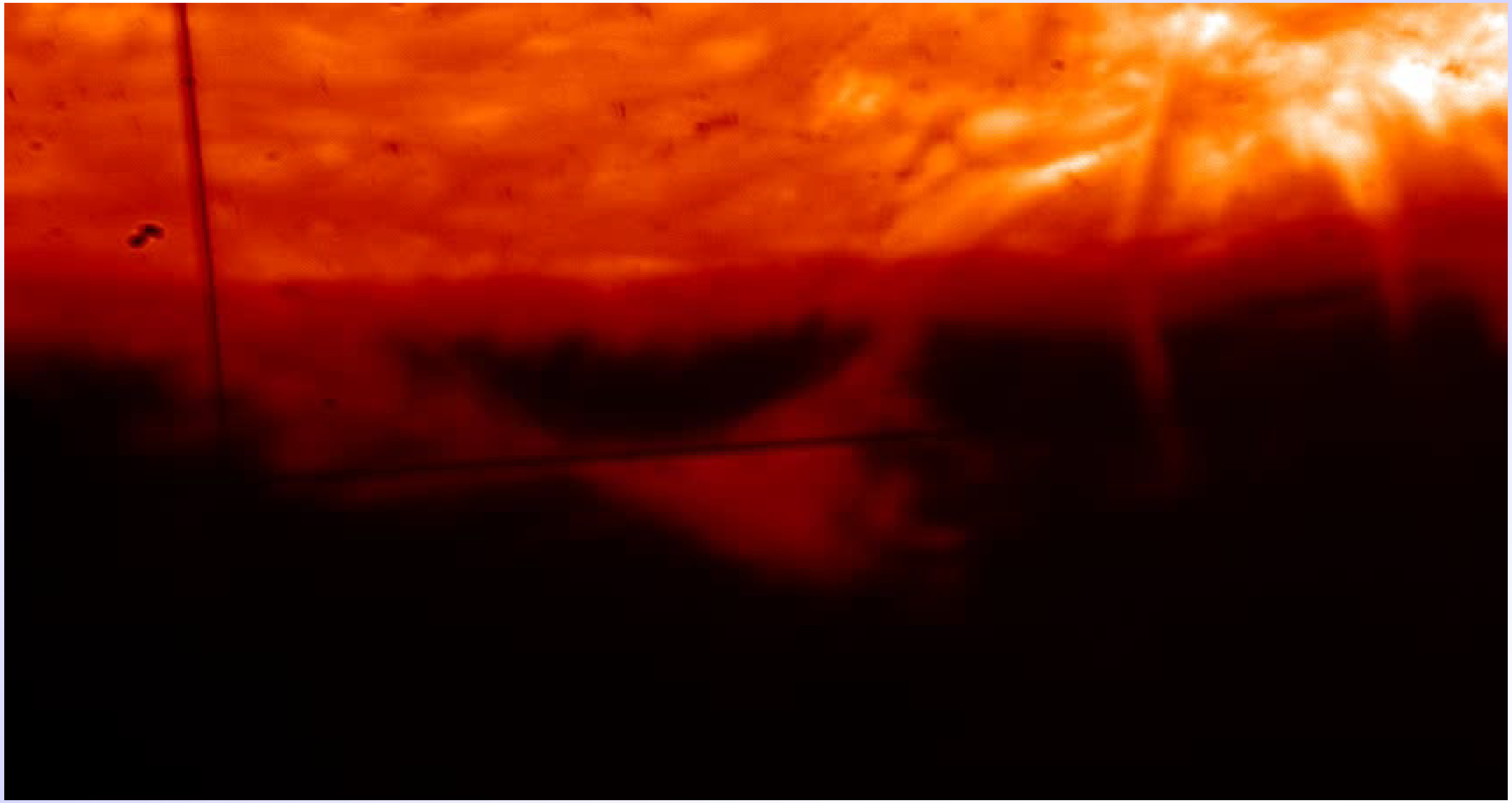
$$\boldsymbol{w} = \boldsymbol{u}_i - \boldsymbol{u}_n = \frac{\xi_n}{\alpha_n}[\boldsymbol{J} \times \boldsymbol{B}] - \frac{(2\xi_n \boldsymbol{\nabla} p_e - \xi_i \boldsymbol{\nabla} p_n)}{\alpha_n}$$

Currents

Gradients of partial pressures

Simultaneous observations of ionized and neutral species in prominences

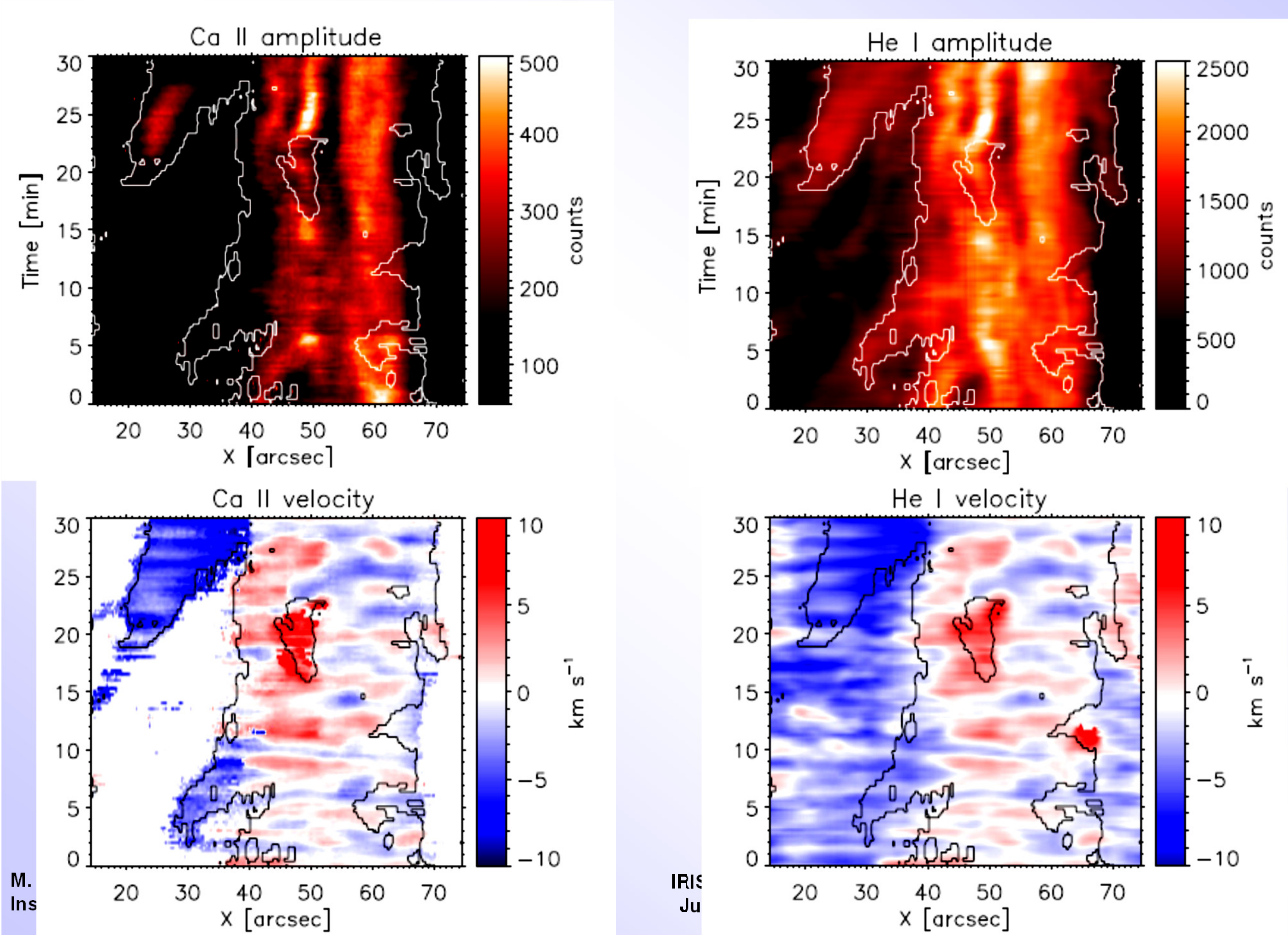
Observations of PI effects in prominences



Khomenko et al. 2016

See poster by Khomenko et al.

Observations of PI effects in prominences



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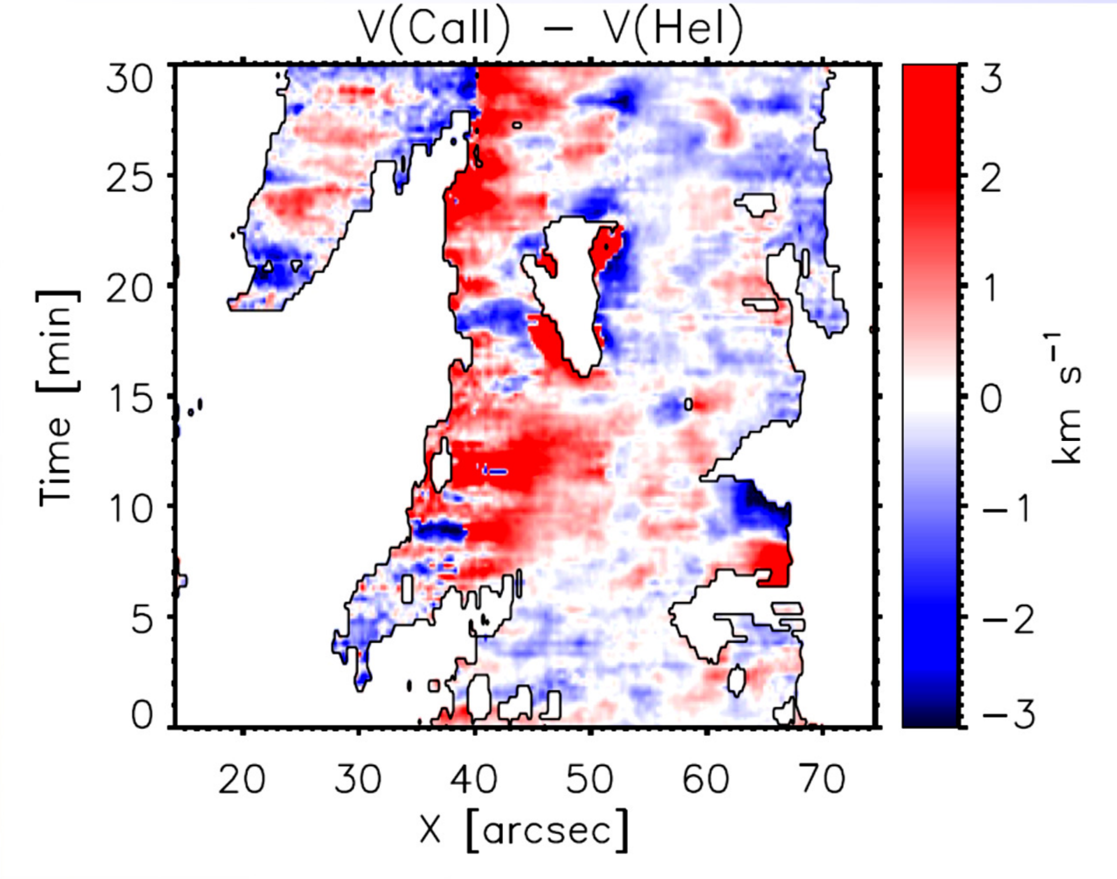
Observations of PI effects in prominences



Khomenko et al. 2016

Partial ionization

(Potential) Consequences

- Flux emergence
- Equilibrium of magnetic structures
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- Energy dissipation and heating
- Wave propagation
- …

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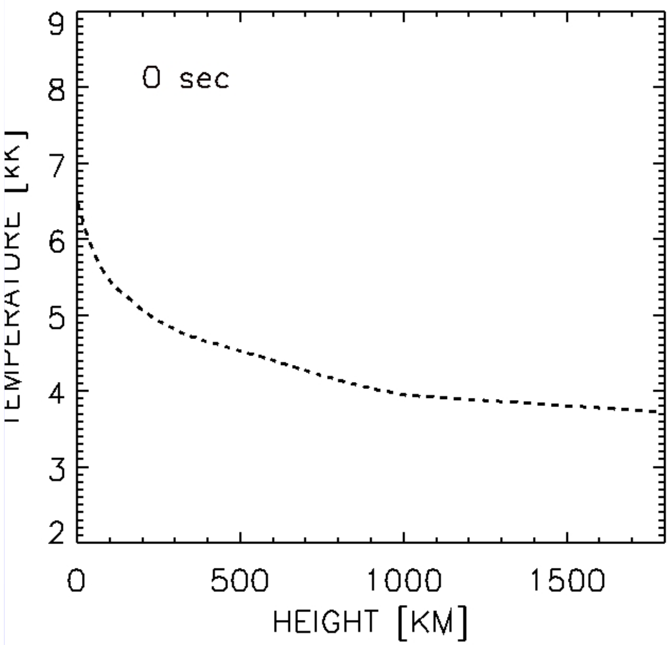
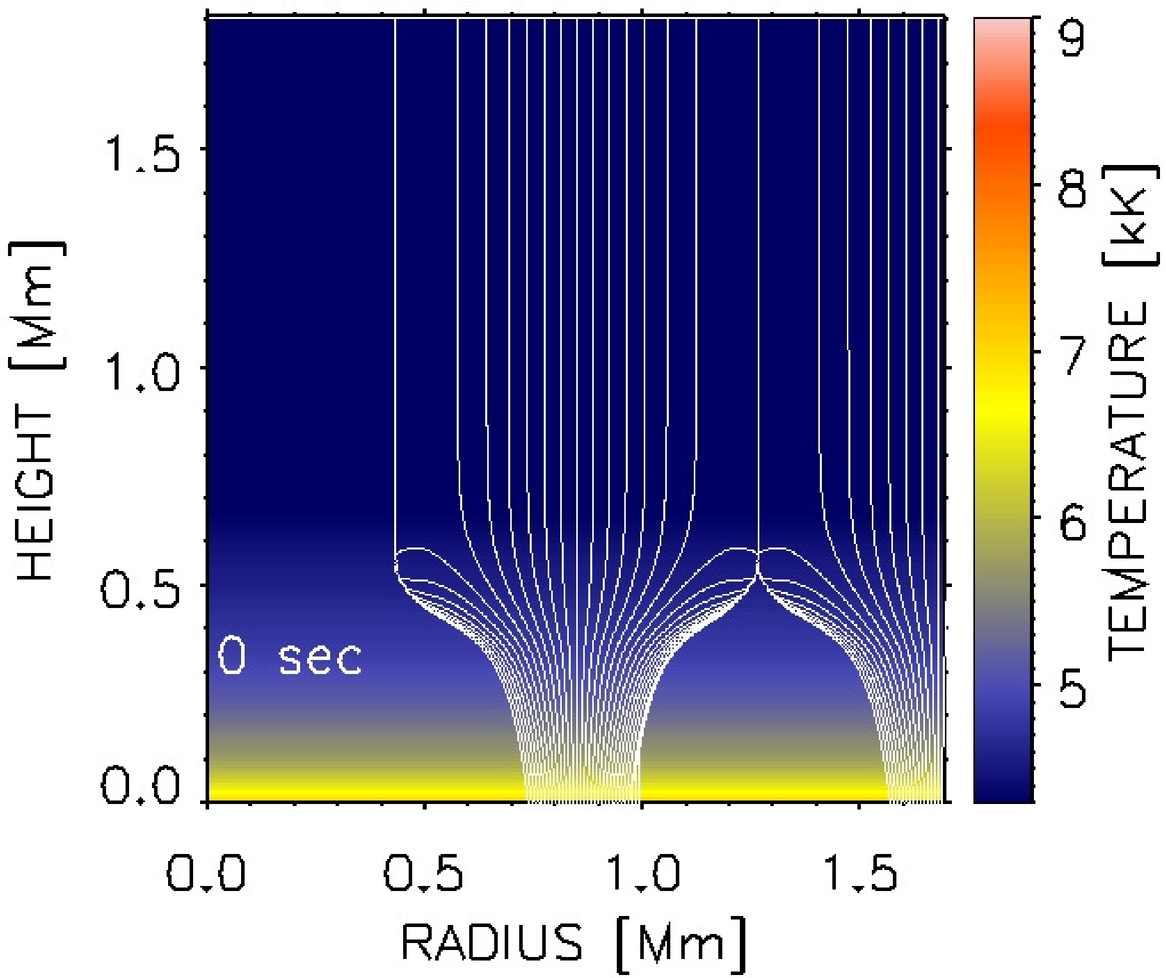
Fluxtube heating





Khomenko & Collados 2012

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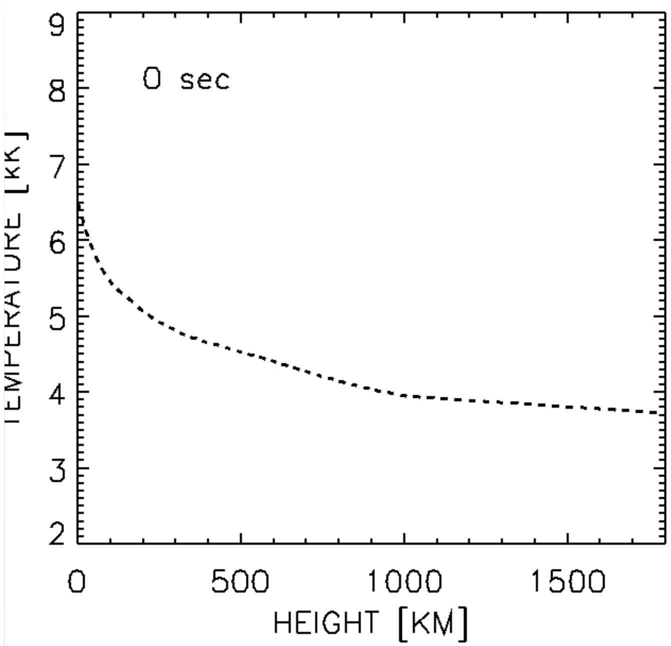
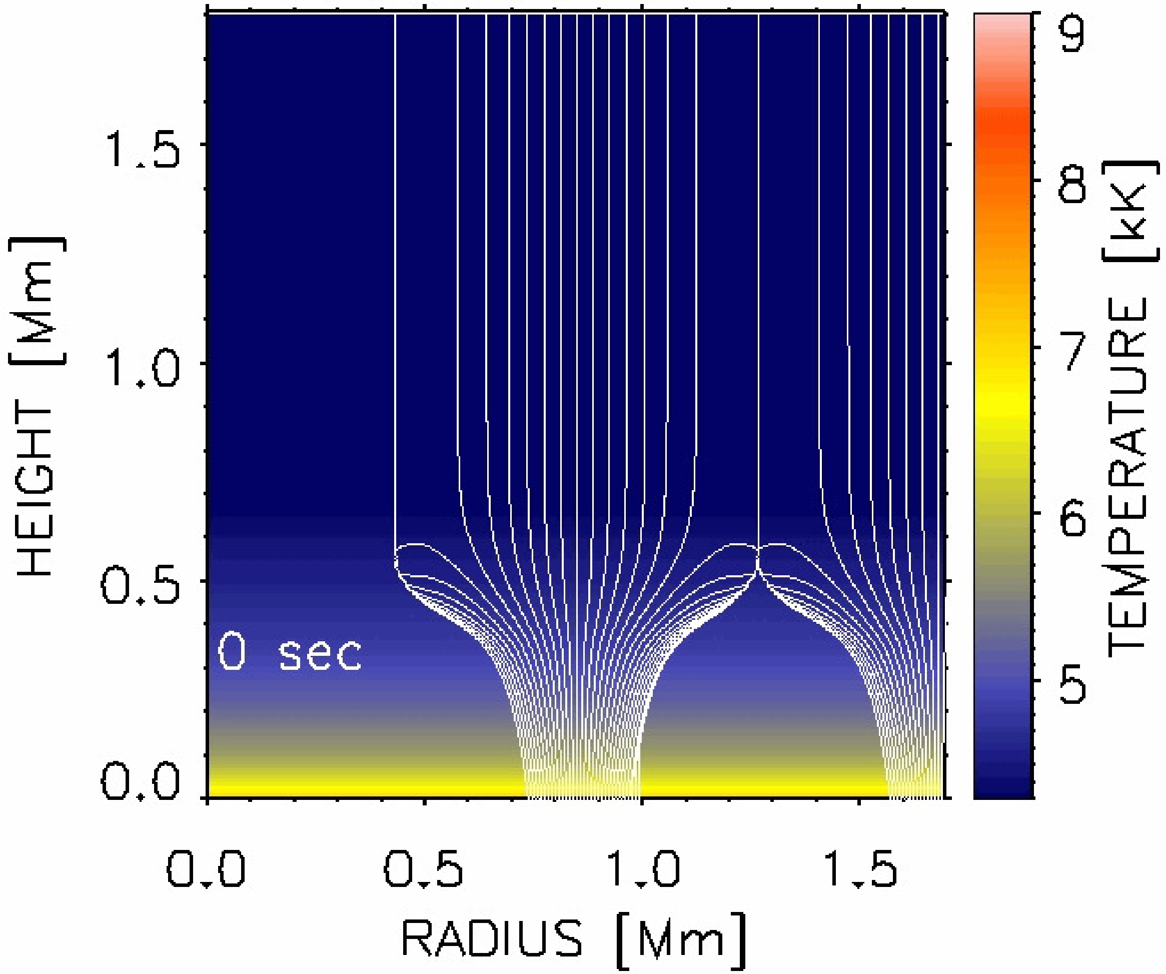
Fluxtube heating

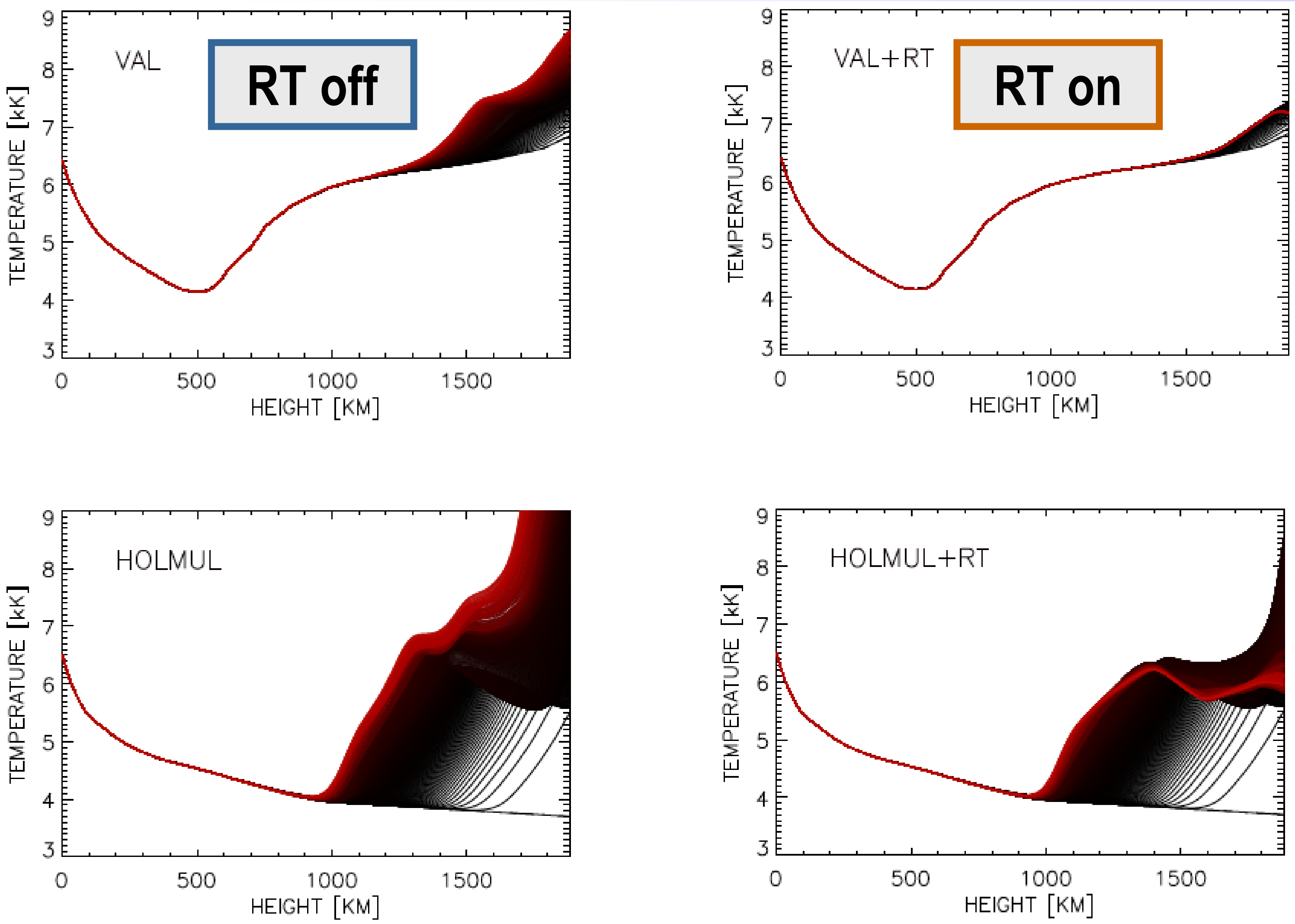




No radiative losses

Khomenko & Collados 2012

Fluxtube heating



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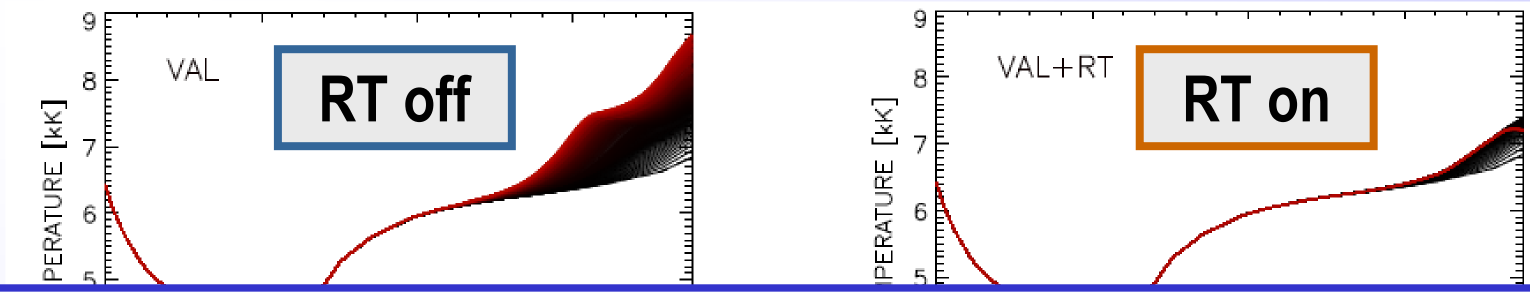
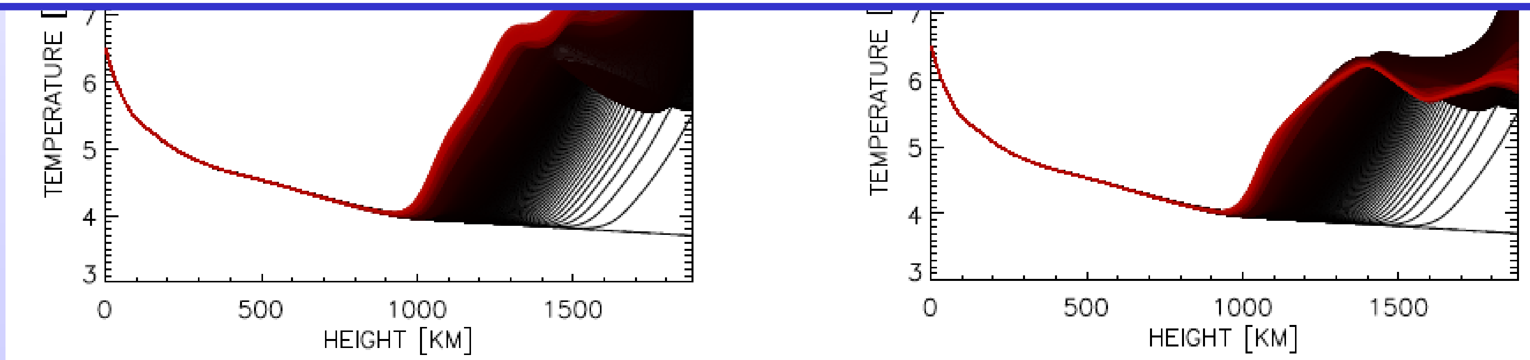
Fluxtube heating



The magnetized **chromosphere**
can be significantly heated within minutes
(~2000 K above initial temperature).

A weak (10-40 G) non-potential magnetic field is enough.



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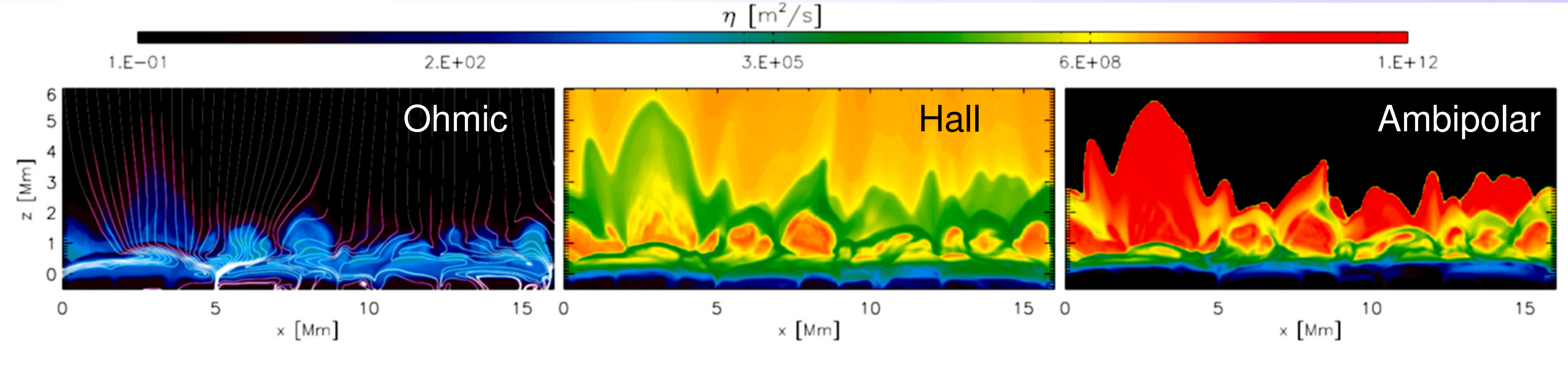
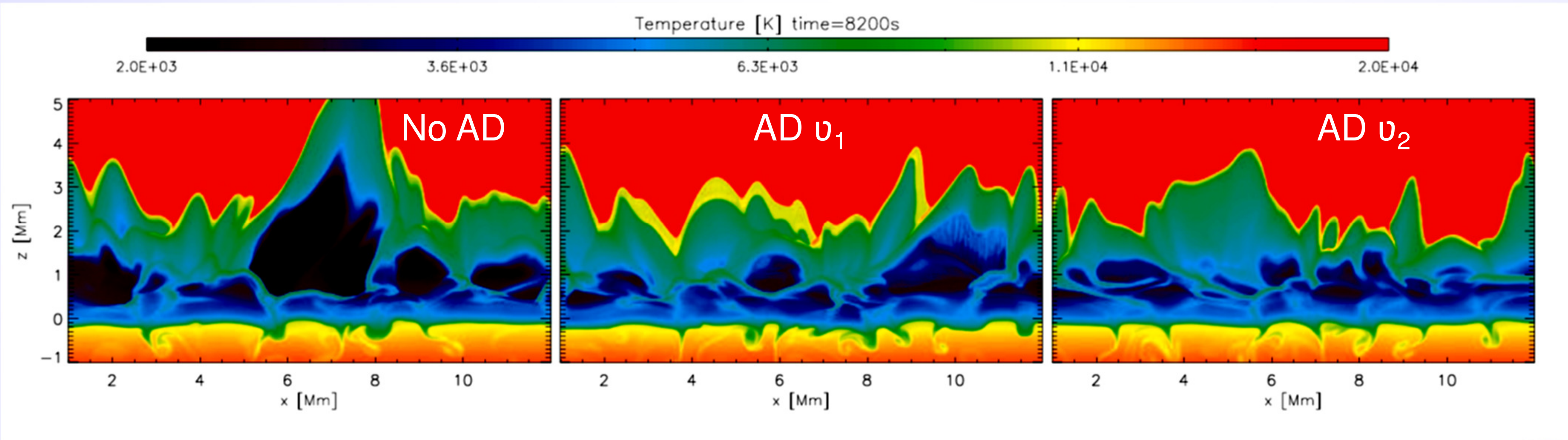
Heating



Juan's talk after this one!

Martínez-Sykora et al 2012



Partial ionization

(Potential) Consequences

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- Wave propagation
- …

MHD Wave propagation

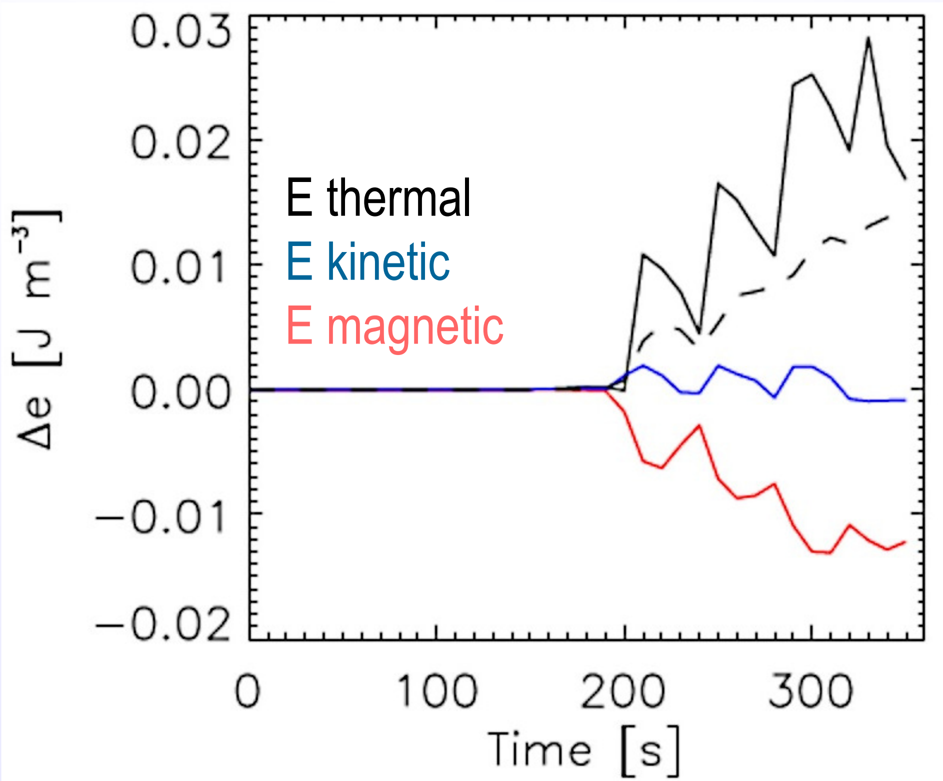
Parameters influenced by PI:

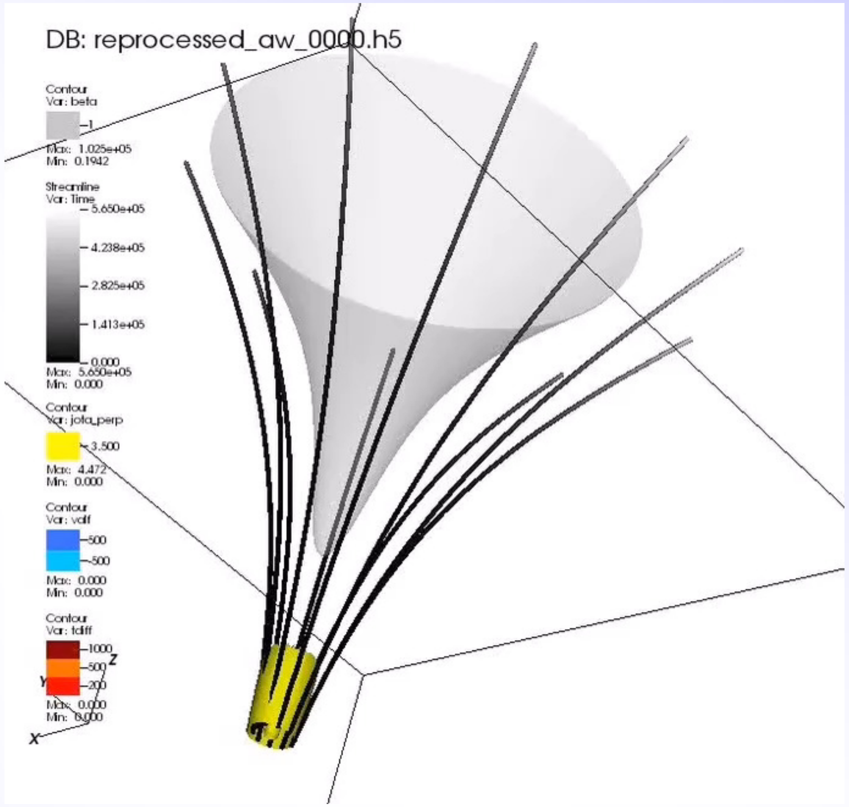
- Wave Generation
- Cut-off frequency/wavelength (propagation/evanescence)
- Wave energy dissipation and heating

And all this depending on the wave type

MHD Wave propagation

Wave energy dissipation and heating



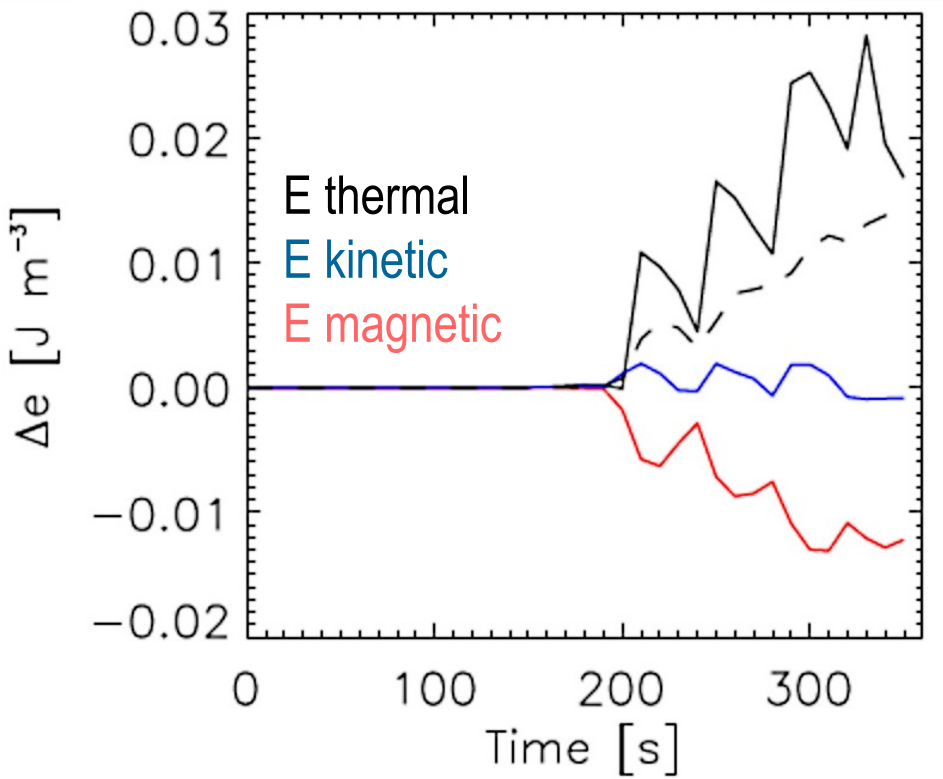


Alfvén wave – T = 40 s

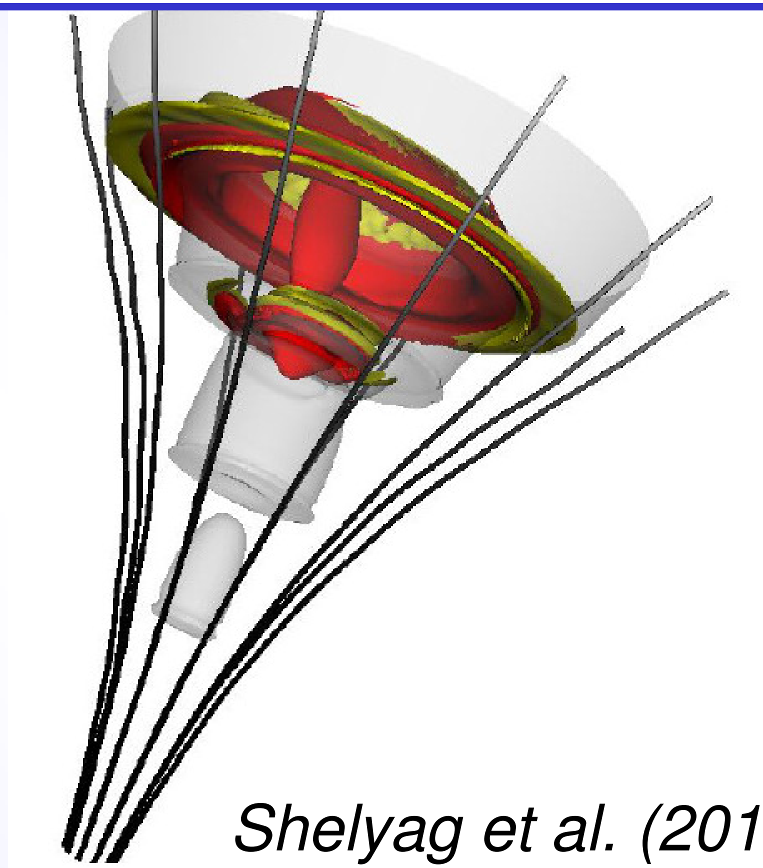
Shelyag et al. (2016)
de Pontieu & Harendel (1998)

MHD Wave propagation

Wave energy dissipation and heating



Currents and temperature increase



Alfvén wave – T = 40 s

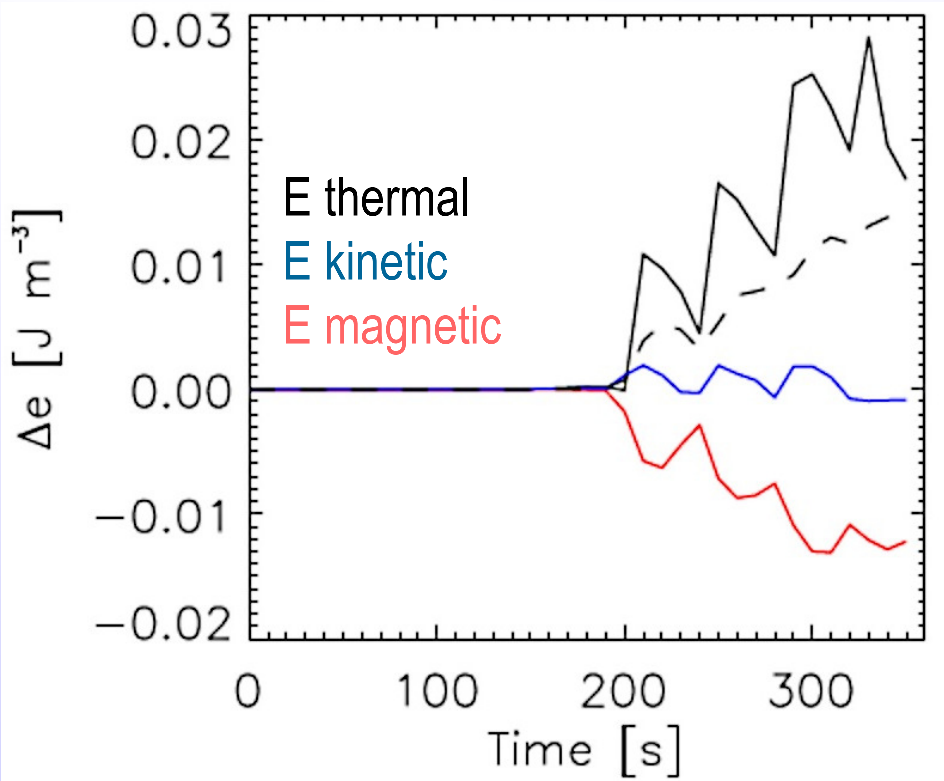
Shelyag's talk tomorrow!

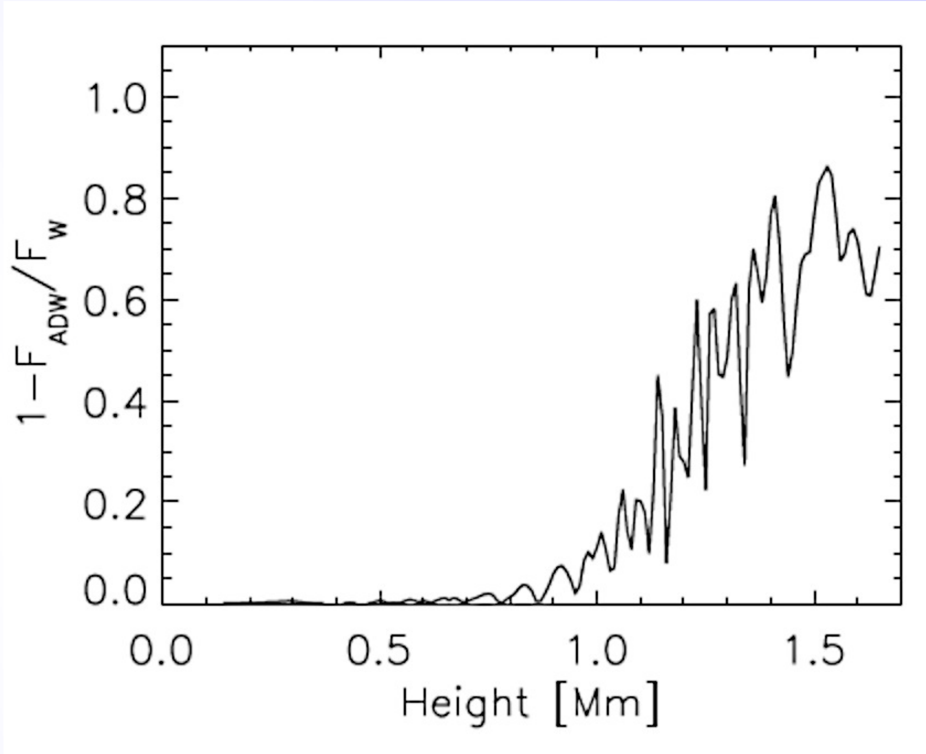
Shelyag et al. (2016)

de Pontieu & Harendel (1998)

MHD Wave propagation

Wave energy dissipation and heating





Up to 80% of the wave Poynting flux is dissipated into heat!

Shelyag et al. (2016)
de Pontieu & Harendel (1998)

CONCLUSIONS

Partial ionization

(Potential) Consequences

- Flux emergence
- Equilibrium of magnetic structures
- Instabilities
- Energy dissipation and heating
- Wave propagation
- …

PIPA2

Partially Ionised Plasmas in Astrophysics (PIPA)

La Laguna, 29th August - 2nd September 2016

http://www.iac.es/congreso/PIPA2016/

SOC

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