Rayleigh-Taylor instability in partially ionized prominences

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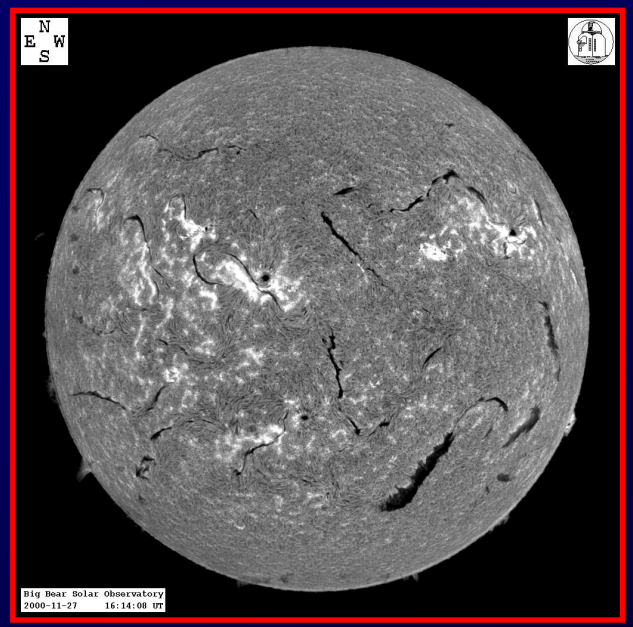
Outline of the talk

- Introduction
- Observational evidence of RTI in prominences.
- Theoretical models and simulations (fully ionized plasmas).
- One fluid and two fluid approaches for partially ionized plasmas. Linear theory & boundary conditions.
- Results: two-fluid approach
- Results: one-fluid approach
- Numerical simulations.
- Conclusions and future work.

Prominences

- Cool and dense clouds supported against gravity and insulated from the corona by the magnetic field.
- Lifetimes and properties (quiescent).

Lifetime	up to 5 months
Particle density	10^{17} m^{-3}
Temperature	7000 K
Magnetic field strength	5-20 G
Ionization degree	~50%
Length	60-600 Mm
Heigh	10-100 Mm
Width (Hα)	4-15 Mm



Hα images (Big Bear Observatory)

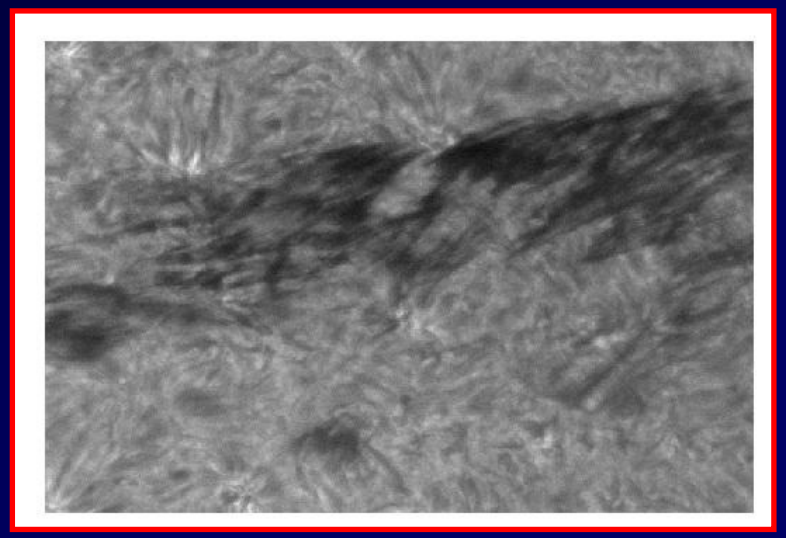
Prominence observational features

- Form between regions of photospheric opposite polarity magnetic fields where $B_z = 0$ (Polarity Inversion Line): filament channel.
- Magnetic field inside the filament forms an angle of 10-20º with the axis. Direct polarity (30%) and inverse polarity (70%) with respect to the photospheric field near the PIL.
- EUV extensions: prominences are wider in EUV than in Hα. Evidence of overlying stabilizing arcade.
- Recent efforts for measuring directly the magnetic field (Lopez-Ariste et al. 06, Paletou 08, Xu et al. 12): horizontal diped fields.

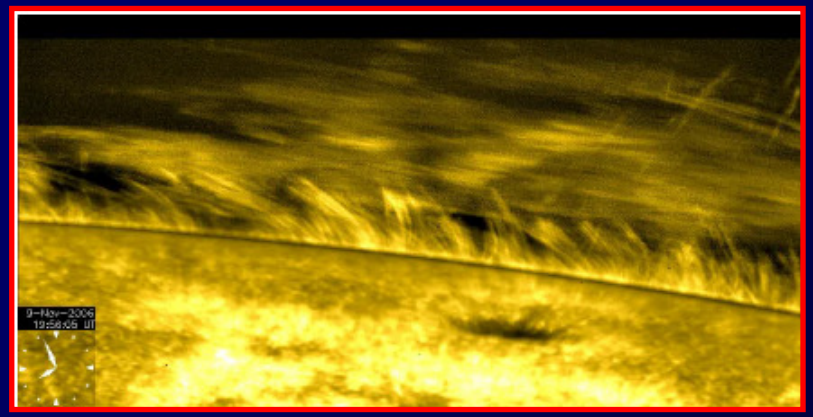
Reviews: Tandberg-Hanssen 95; Labrosse et al. 10; Mackay et al 10.

Prominence threads

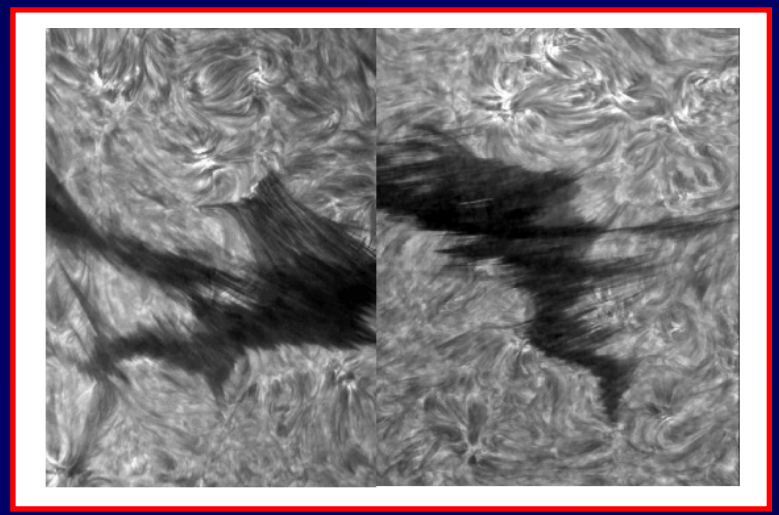
- Observations suggest that filaments have a fine structure (threads).



- Very thin: ~0,3” (of the order of the instrument resolution).



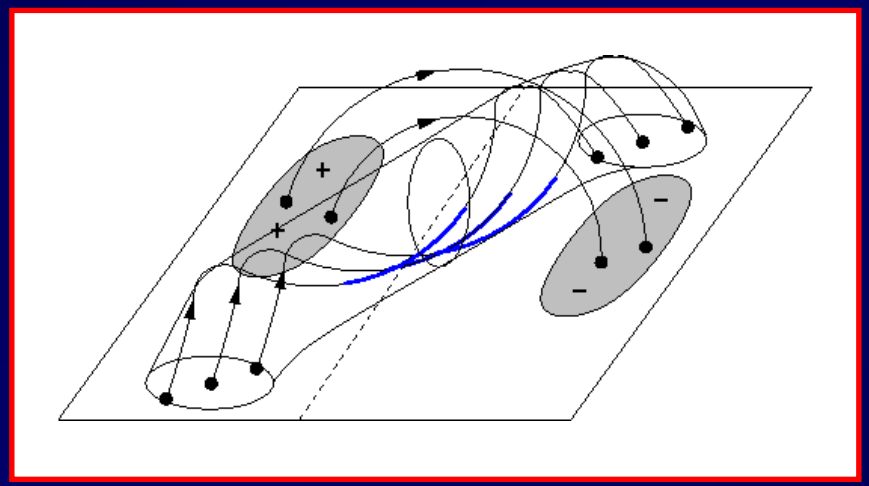
Okamoto et al. 07 (Hinode)

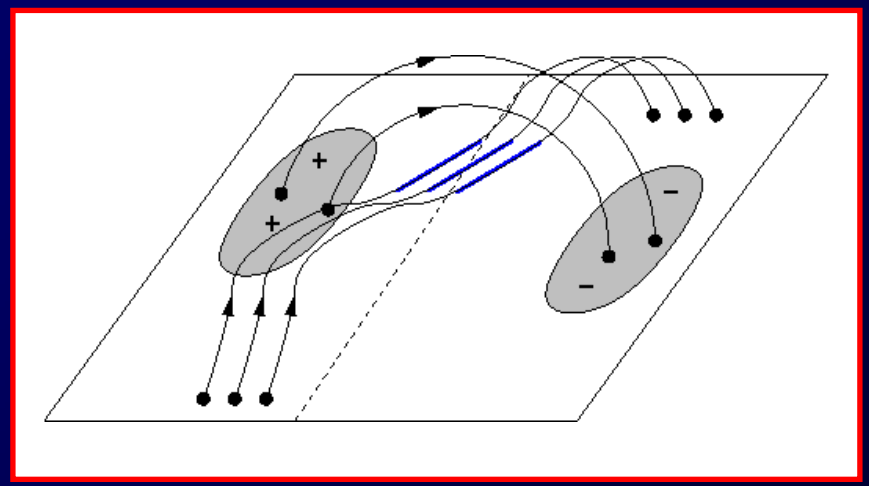


Lin et al. 04, 07, 09 (SST)

Prominence equilibrium models

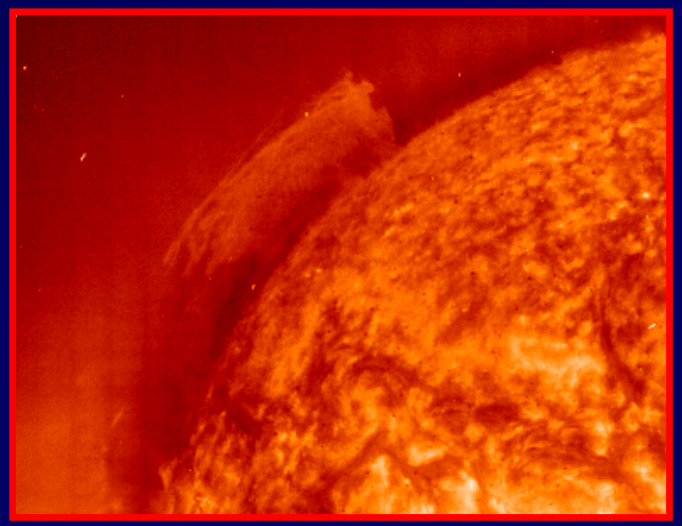
- Dense plasma assumed to lay in magnetic dips (near the PIL).
- Two types of "static" models:
  - Weight affects the formation of the dip: sheared arcades.
  - Dips inherent to the magnetic structure and topology: flux ropes.
- Overlying arcade helps to stabilize the prominence.



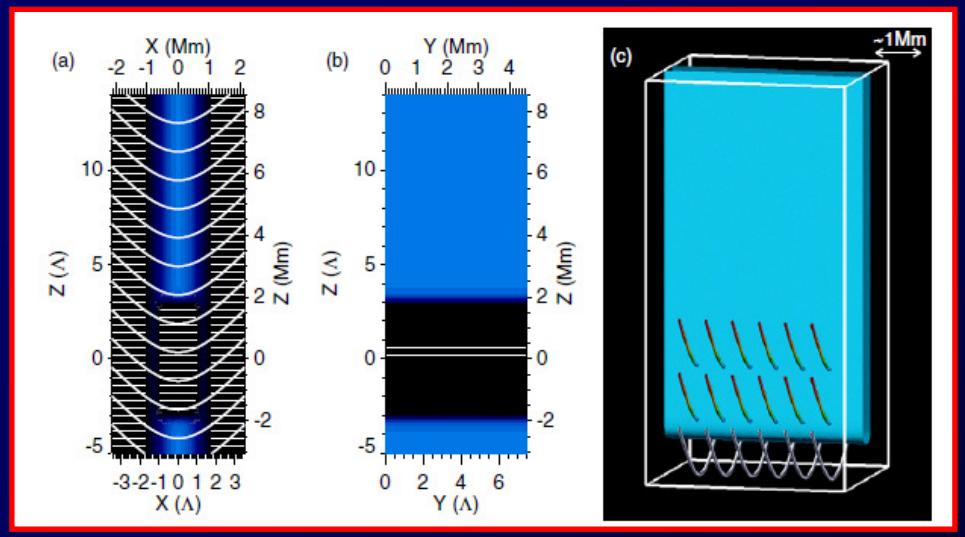


Prominence equilibrium models

- Non-potential supporting fields (shear) and quite dynamical on short scales (minutes). Formation and dynamics still not well understood (injection vs. levitation models).
- Problem of neutrals: Lorentz force can't support them (Gilbert et al. 02) or stabilize them against RTI.



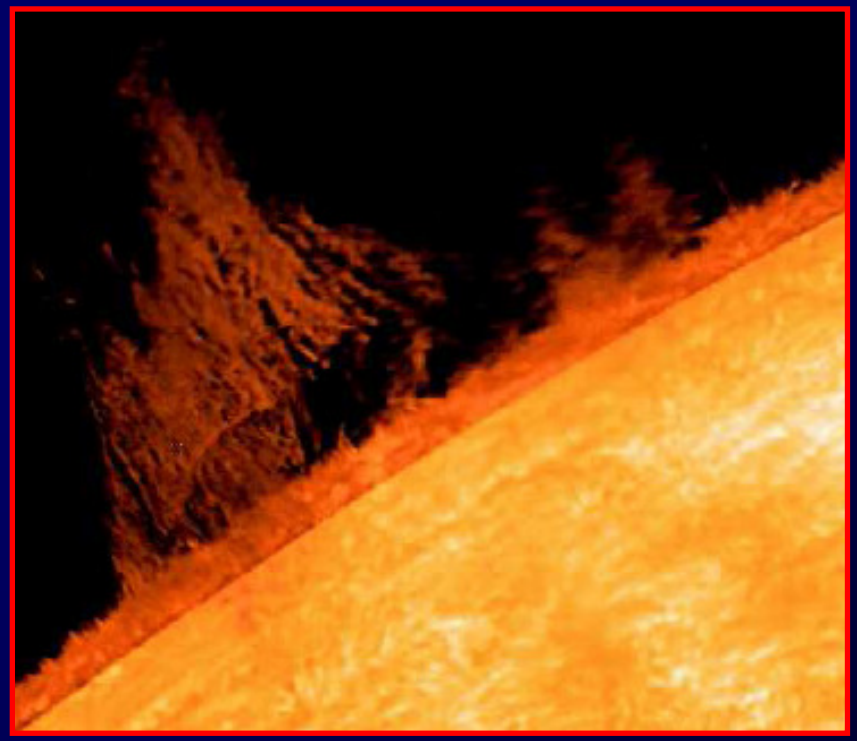
TRACE image



Hillier et al. 11

Challenge of "hedgerow" prominences

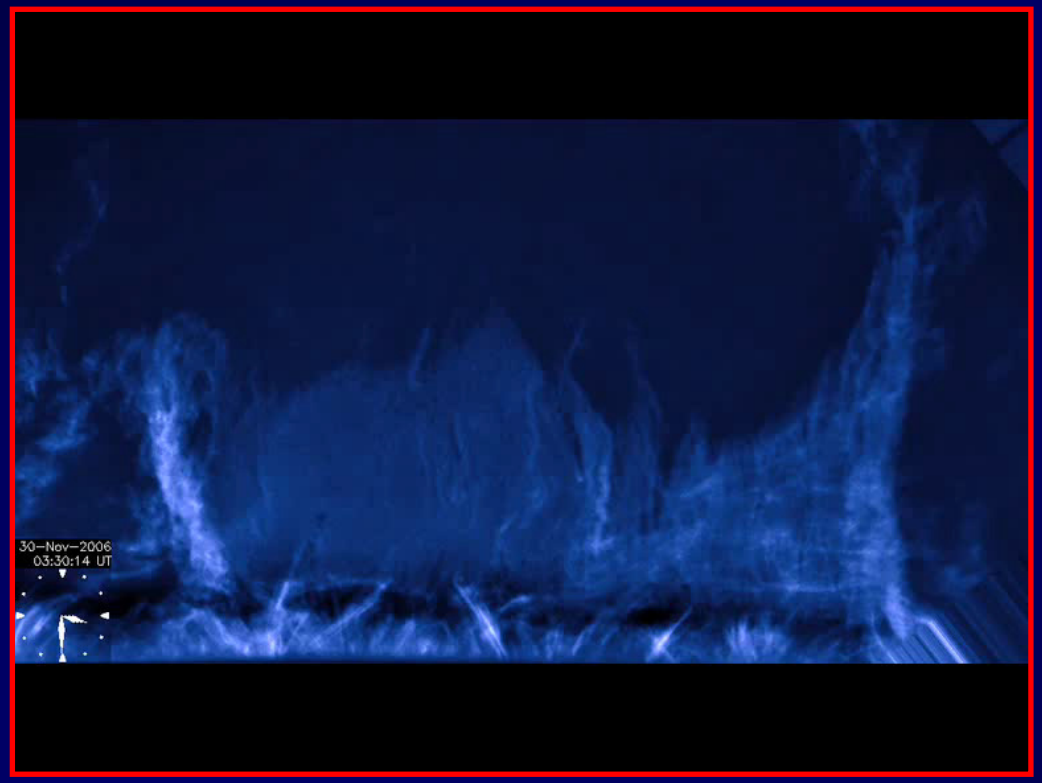
- Hedgerow prominences: the fine threads are vertical!
- Two possible explanations:
  - Magnetic field vertical (not measured, no plasma support),
  - Flow across the field line (violation of frozen-flux theorem).
- Signature of RTI?
- Responsible of vertical flows seen in Dopplergrams?



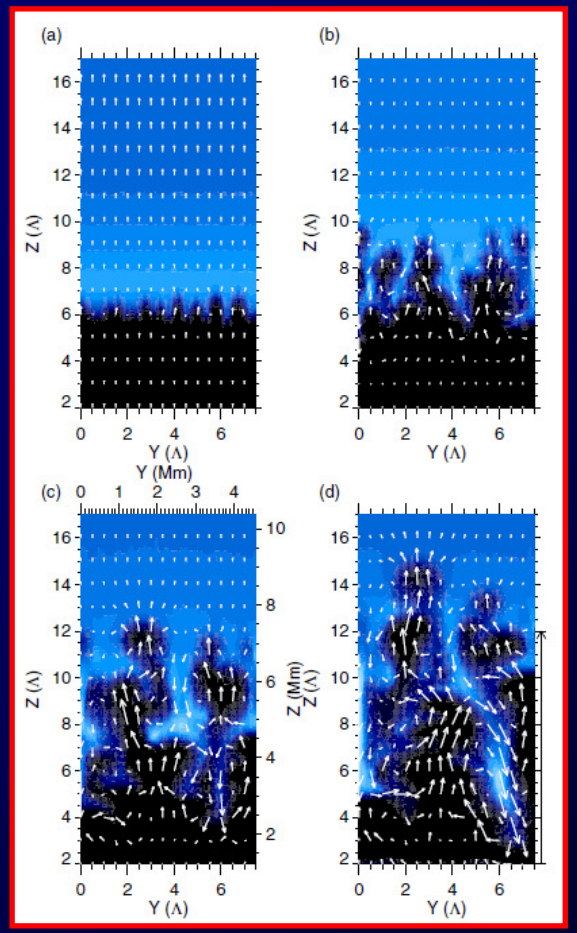
Heinzer et al. 08

Bubles and cavities

- Observational evidence of bubbles and cavities (Berger et al. 08).
- Identified as the signatures of RTI (Hillier et al. 11, 12)



Berger et al. 08



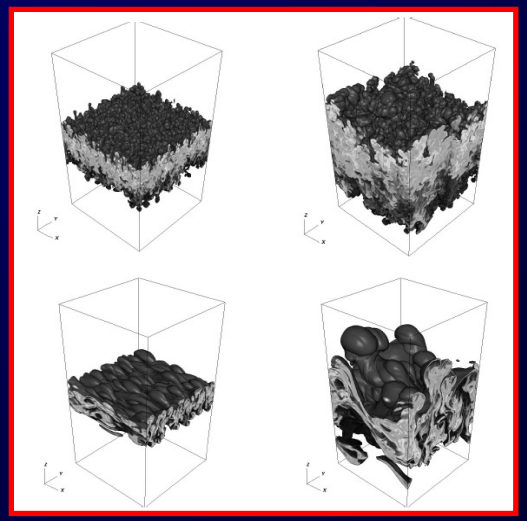
Hillier et al. 11

Classical RTI

- Rayleigh-Taylor instability in hidrodynamics: a heavier fluid on the top of a higher one is always unstable.
- Incompressible fluids with contact interface and horizontal magnetic field; linear theory (Chandrasekhar 61, Priest 82).

$$\omega^2 = -gk\frac{\rho_2 - \rho_1}{\rho_1 + \rho_2} + \frac{2B_0^2 k_x^2}{\mu(\rho_1 + \rho_2)},$$

- Magnetic field stabilizes parallel perturbations for wavenumbers big enough, but does not affect perpendicular propagation.
- Compressibility lowers the growing rate, but does not affect the instability threshold.
- Non-linear simulations: secondary instabilities inhibited (faster growing rate).



Stone & Gardner 07

MRTI in partially ionized plasmas

- Rayleigh-Taylor instability present in astrophysical plasmas (prominences, supernova remanants, radio jets in galaxy clusters…)
- How is it affected by partial ionization?
  - Neutrals do not feel the stabilizing effect of the field,
  - Neutrals also affect the ions and electrons due to collisions.
- Two different approaches considered so far (linear theory):
  - Two fluids, only ion-neutral collisions
  - One fluid, generalized induction equation.
- Non linear simulations in process.

RTI in partially ionized two-fluid

- Motion equation for neutrals and ion-electron fluid: (electron collisions neglected).

$$\rho_i \left(\frac{\partial \mathbf{v}_i}{\partial t} + \mathbf{v}_i \cdot \nabla \mathbf{v}_i \right) = -\nabla p_{ie} + \mathbf{J} \times \mathbf{B} + \rho_i \mathbf{g} - \alpha_{in} \left(\mathbf{v}_i - \mathbf{v}_n \right),$$

$$\rho_n \left(\frac{\partial \mathbf{v}_n}{\partial t} + \mathbf{v}_n \cdot \nabla \mathbf{v}_n \right) = -\nabla p_n + \rho_n \mathbf{g} - \alpha_{in} \left(\mathbf{v}_n - \mathbf{v}_i \right)$$

- From electron's equation of motion: generalized Ohm's law and induction equation (no inertial terms).

$$\mathbf{E} + \mathbf{v}_e \times \mathbf{B} = \frac{1}{e n_e} \left(-\rho_e \mathbf{g} - \nabla p_e \right),$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left(\mathbf{v}_i \times \mathbf{B} \right) + \nabla \times \left[\frac{1}{e n_e} \left(\mathbf{J} \times \mathbf{B} - \nabla p_e - \rho_e \mathbf{g} \right) \right].$$

- No magnetic diffusion terms, so a very simple induction equation is obtained.

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left(\mathbf{v}_i \times \mathbf{B} \right).$$

- New terms also in the energy equation!

RTI in patially ionized two-fluid

- Linealized equations

  $\boldsymbol{B}_0 = B_0\, \boldsymbol{e}_x \qquad \boldsymbol{g} = -g_0\, \boldsymbol{e}_z$

$$\rho_{0i}\frac{\partial \mathbf{v}_i}{\partial t} = -\nabla p_{ie} + \frac{1}{\mu}(\nabla \times \mathbf{b}) \times \mathbf{B}_0 - \rho_i \mathbf{g} - \alpha_{in}(\mathbf{v}_i - \mathbf{v}_n),$$

$$\rho_{0n}\frac{\partial \mathbf{v}_n}{\partial t} = -\nabla p_n - \rho_n \mathbf{g} - \alpha_{in}(\mathbf{v}_n - \mathbf{v}_i)$$

$$\frac{\partial \mathbf{b}}{\partial t} = \nabla \times (\mathbf{v}_i \times \mathbf{B}_0),$$

$$\frac{\partial p_{ie}}{\partial t} = -\gamma p_{0ie} \nabla \cdot \mathbf{v}_i,$$

$$\frac{\partial p_n}{\partial t} = -\gamma p_{0n} \nabla \cdot \mathbf{v}_n,$$

$$\frac{\partial \rho_i}{\partial t} = -\rho_{0i} \nabla \cdot \mathbf{v}_i,$$

$$\frac{\partial \rho_n}{\partial t} = -\rho_{0n} \nabla \cdot \mathbf{v}_n.$$

- The new terms in the energy equation are negligible (adiabatic only relevant).

- Boundary conditions

  $[v_n]=0,\ [p_T]=0$ (each species)

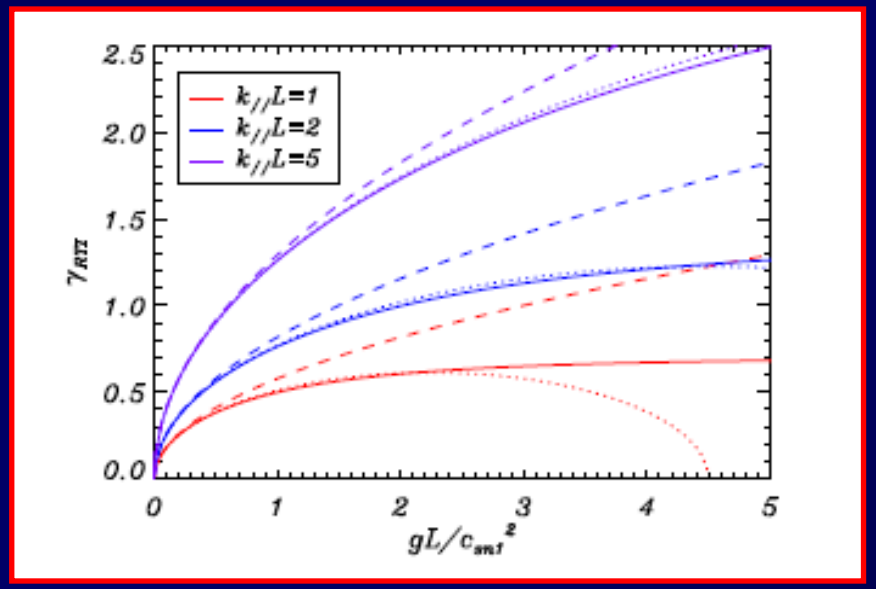
  Matches the bc obtained directly from the linearized equations.

- Linear growth rate $\boldsymbol{v} \sim e^{+\gamma t}$

$$\gamma = \frac{\mathrm{Im}[\omega]\, L}{c_{\mathrm{sn1}}},$$

Collisionless neutral fluid

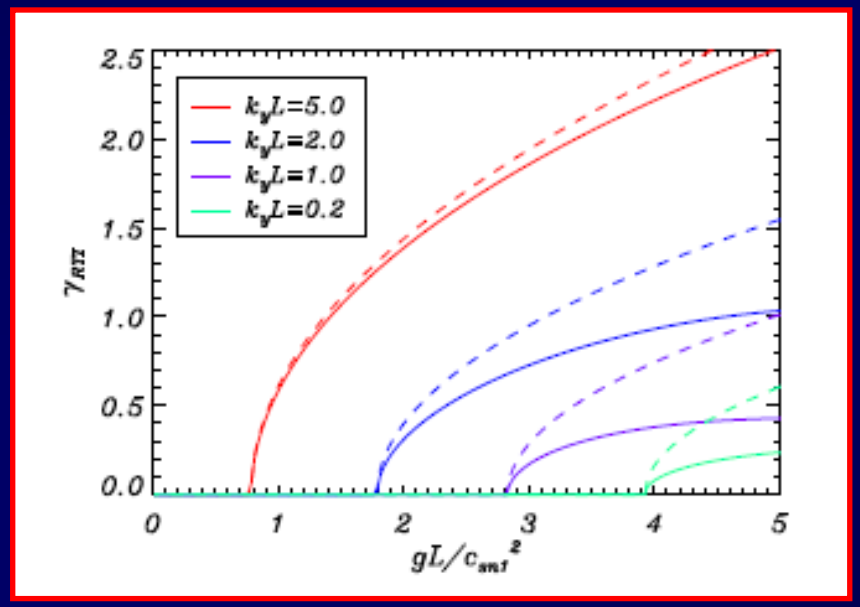
- HD case



- Relevant features:
  - Threshold not modified (always unstable),
  - Linear growth rate decreased from the classical formula (compressibility).

Collisionless ion-electron fluid

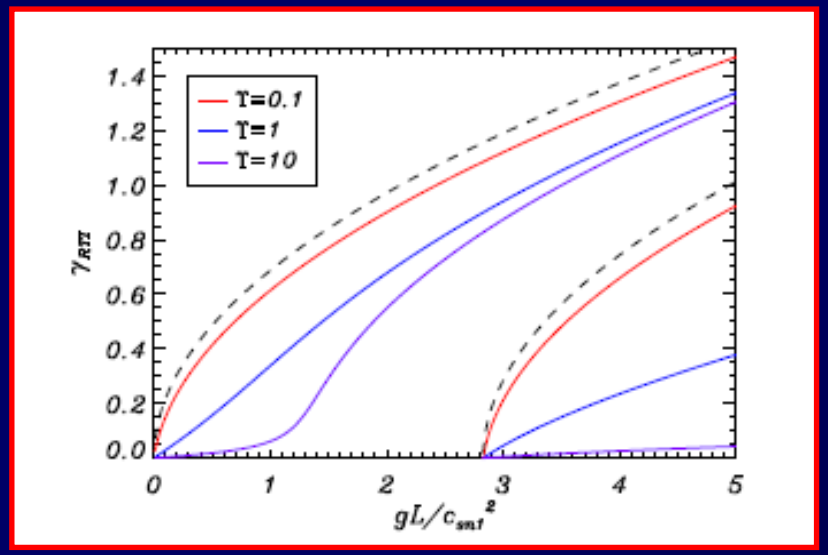
- MHD case

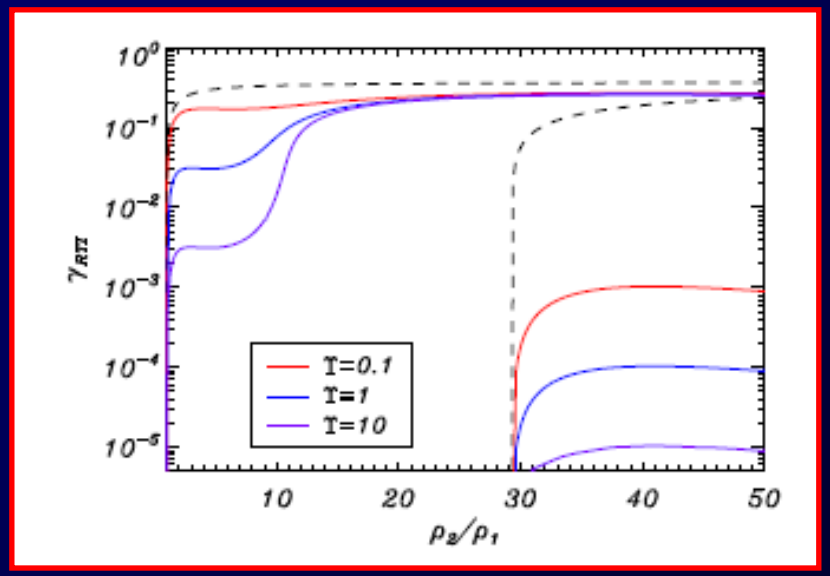


- Relevant features:
  - Threshold not modified (described by classical formula), magnetic field can stabilize longitudinal perturbations.
  - Linear growth rate decreased from the classical formula (compressibility).

RTI in partially ionized two-fluid

- Linear growth rate (γ_{RTI}) for different values of the ion-neutral collisions ($Y \sim \nu_{in}$).
- Main effects:
  - Threshold not modified (always unstable because of neutrals),
  - Linear growth rate decreased (orders of magnitude depending on the parameters).





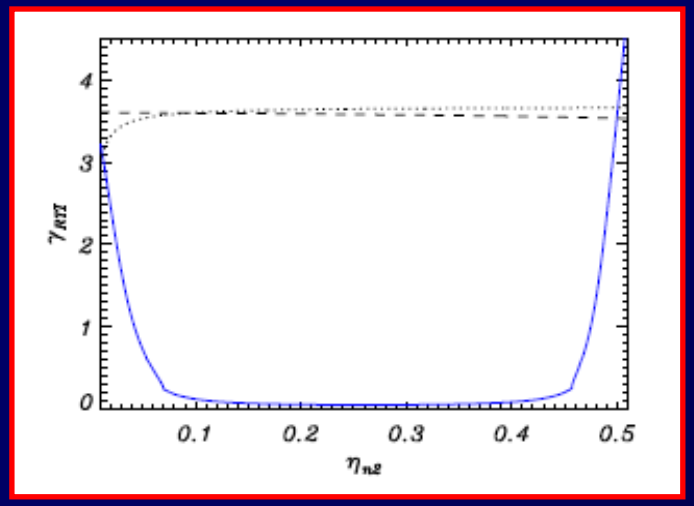
Application to prominences

- Ion-neutral collisions (hydrogen plasma).
  High collisions regime.

$$\nu_{\rm in} = \frac{\rho_i}{2m_{\rm p}}\sqrt{\frac{16k_{\rm B}T}{\pi m_{\rm p}}}\,\sigma_{\rm in},$$

- Dependence on neutral fraction,

$$\eta_n = \rho_n/\rho$$



- Growth rate lowered an order of magnitude (classical formula gives around 1 min for time scale).

$$\tau_{\rm RTI} = \frac{L}{c_{\rm sn1}}\frac{1}{\gamma_{\rm RTI}} \approx 30\,min.$$

- Of the order of magnitude of the lifetime of the threads.

RTI in partially ionized single fluid

- Induction equation is modified (Ohm's law). Gravity terms are new, but an order of magnitude small in general.

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times \left[(\vec{u} \times \vec{B}) - \frac{\vec{J}}{\sigma} - \left(\frac{1 - 2\varepsilon\xi_n}{en_e} \vec{J} \times \vec{B} \right) + \left(\frac{\xi_n^2}{\alpha_n} (\vec{J} \times \vec{B}) \times \vec{B} \right) - \left(\frac{\varepsilon \vec{G} - \vec{\nabla} \overleftrightarrow{P}_e}{en_e} \right) - \left(\frac{\xi_n}{\alpha_n} \vec{G} \times \vec{B} \right) - \left(\frac{\xi_n^2 \rho_e}{\alpha_n} \vec{g} \times \vec{B} + \frac{\rho_e}{en_e} (1 + \xi_n \epsilon) \vec{g} \right) \right]$$

- Start with the ambipolar term only (most relevant term).

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left(\mathbf{u} \times \mathbf{B} + \eta_A \left\{ (\nabla \times \mathbf{B}) \times \mathbf{B} \right\} \times \mathbf{B} \right).$$

$$\eta_A = \frac{\xi_n^2}{\alpha_n \mu},$$

- Using the ion-neutral collision rates,

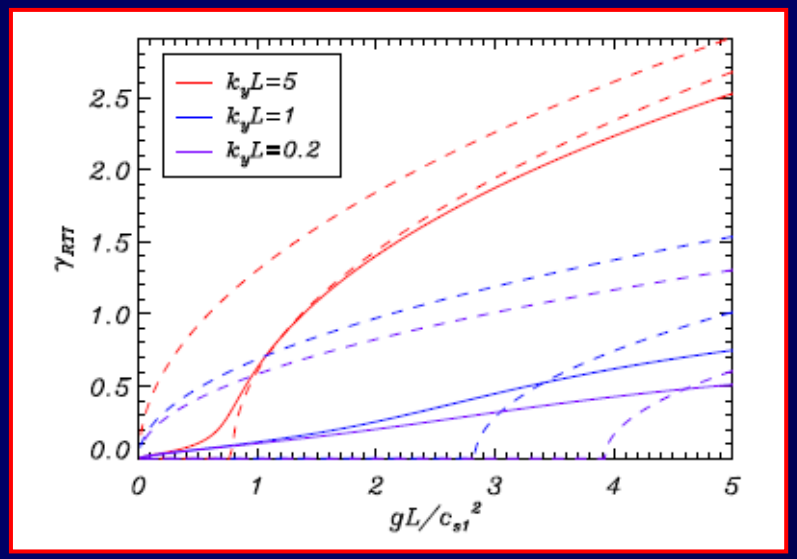
$$\eta_A = \frac{1}{H} \frac{\xi_n^{3/2} c_A^2}{\rho_0 c_s (1 - \xi_n)}.$$

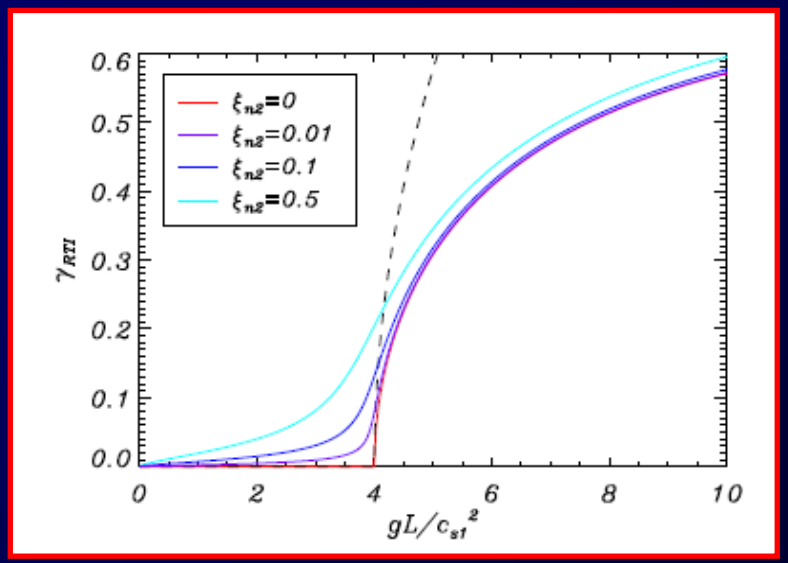
$$H = \frac{\sigma_{in}}{m_p} \left[\frac{2}{\pi\gamma} \right]^{1/2} = 1.86 \cdot 10^9 \, \mathrm{m^2 kg^{-1}},$$

- Linealized equations (and bc deduced from them again).

RTI in partially ionized single fluid

- Main features
  - Threshold modified (always unstable),
  - In the classical unstable regime: growth rate decreased,
  - In the classical stable regime: small growth rate.
- As plasma becomes fully ionized the MHD limit is approached (threshold frequency and stable regime).





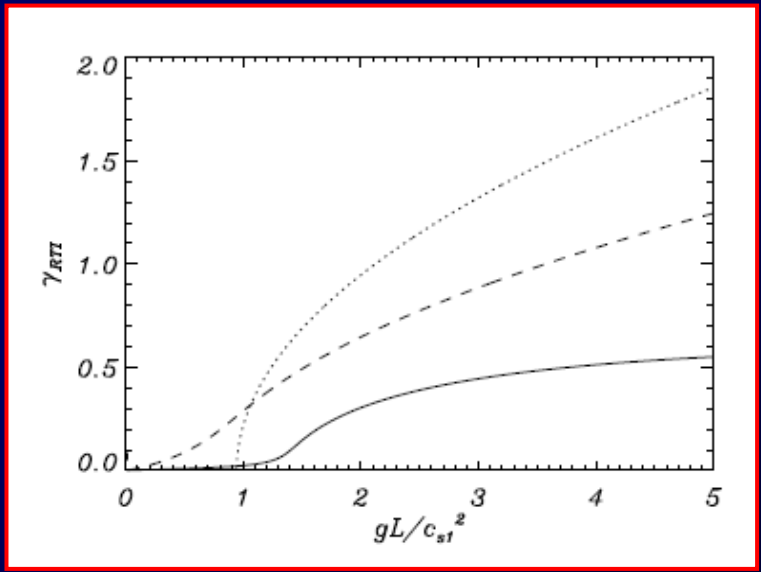
RTI in partially ionized fluids

- The two descriptions take into account different effects.

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v}_i \times \mathbf{B}) = \nabla \times (\mathbf{v} \times \mathbf{B}) + \nabla \times (\xi_n \mathbf{w} \times \mathbf{B})$$

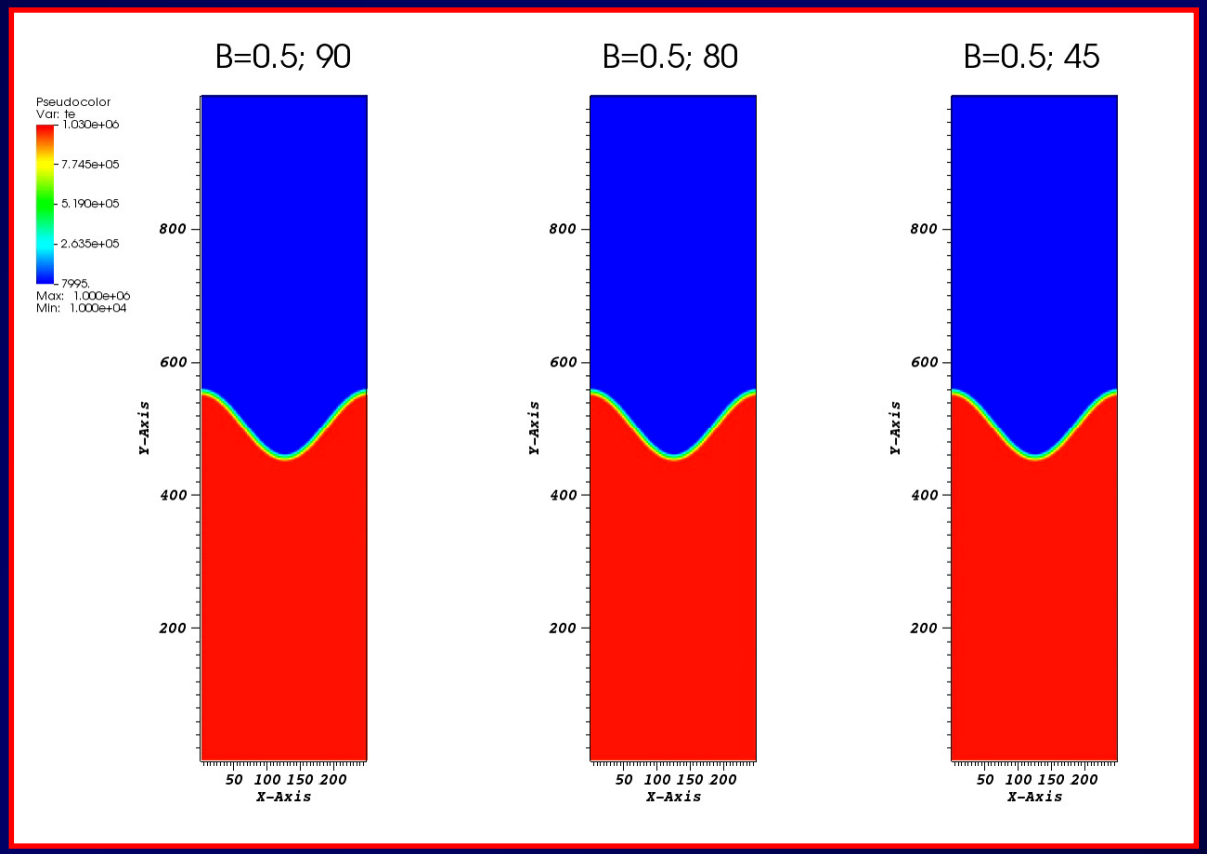
Diffusion velocity

- Main results are still valid:
  - The configuration is always unstable because the presence of neutrals.
  - Linear growth rate is lowered.



Numerical simulations

- Linear analysis only gives the stability threshold and the growth rate in the initial stages. To compare with observations numerical simulations are required.



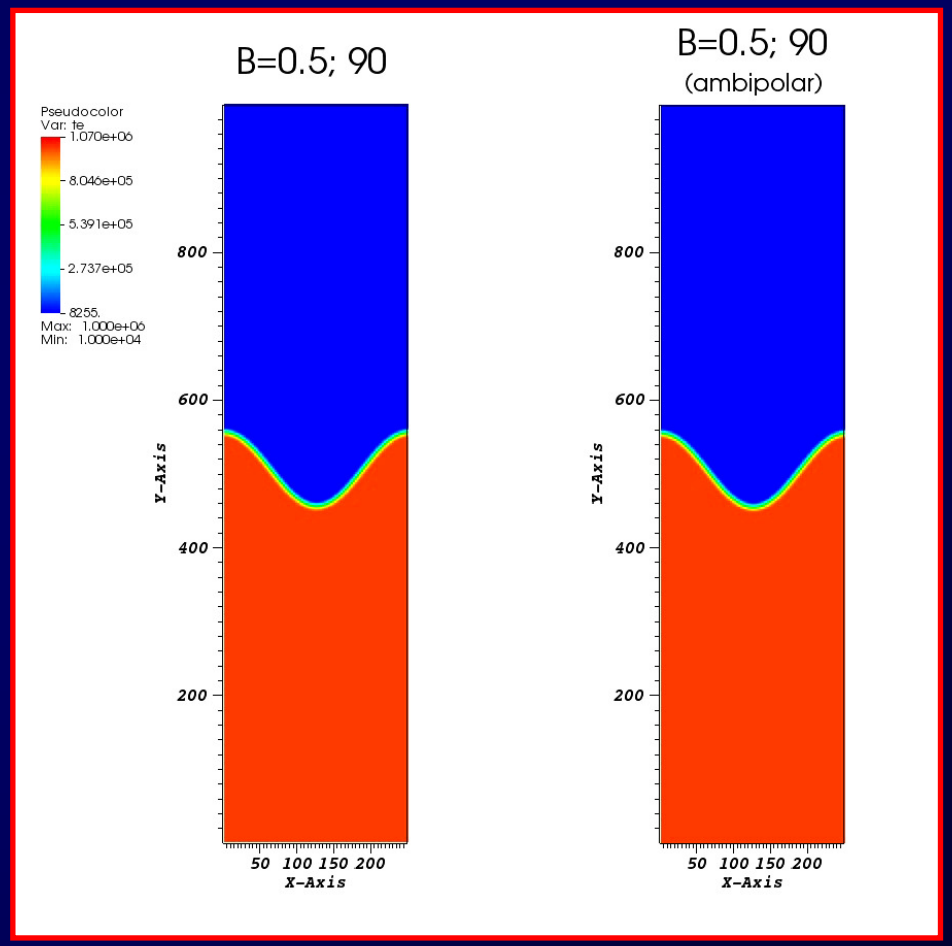
MHD theory
(fully ionized)

Numerical simulations

- Work in progress! Results from linear analysis (ambipolar term) still to be checked.

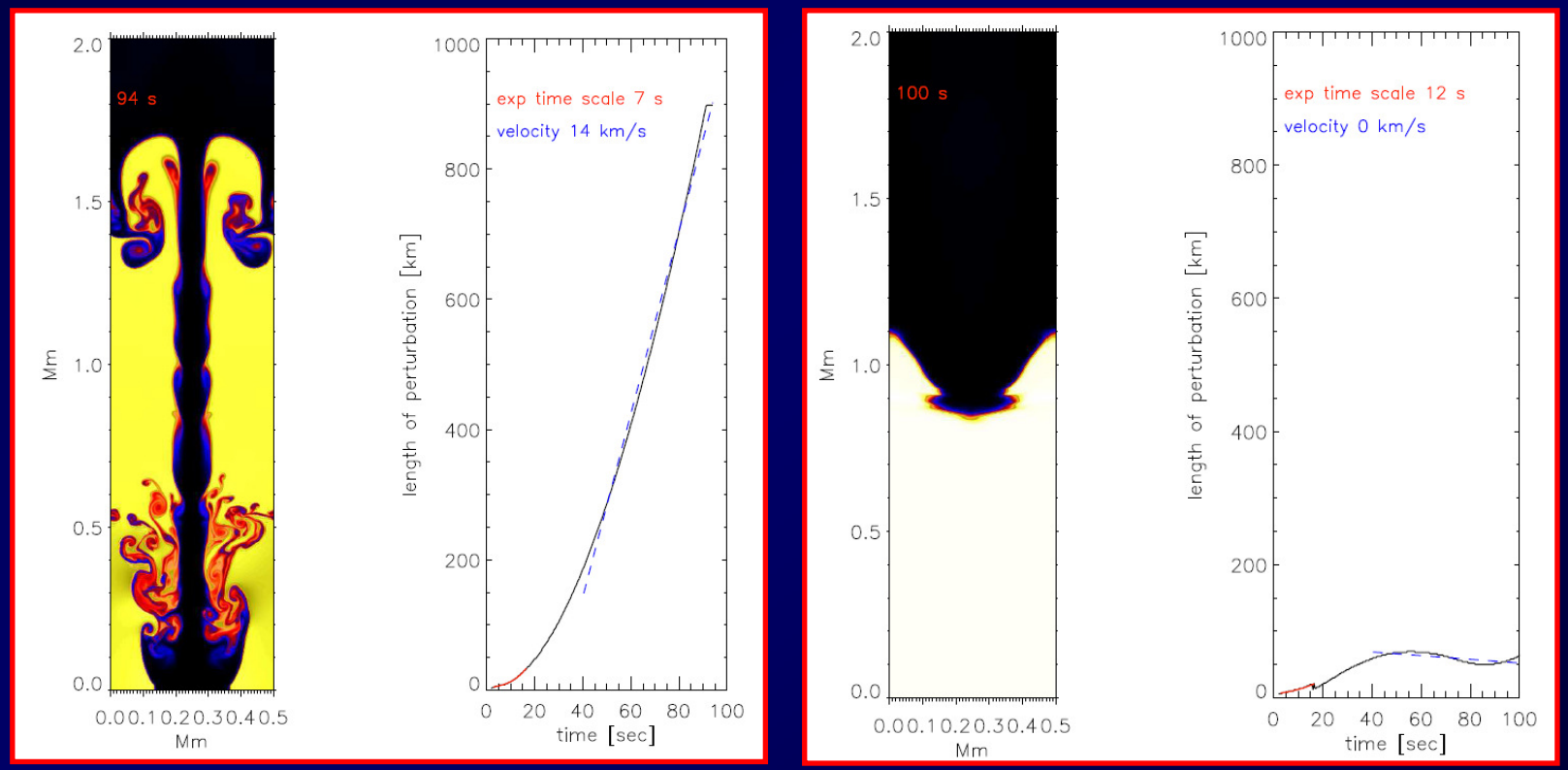
- Differences in the small scale vortexes (secondary KHI).

- Magnetic field still very low!



Numerical simulations

- Raising bubles and secondary instabilities appear, but after the exponential phase a constant speed is achieved.



- Related with the downflows in prominences?

Conclusions and further work

- The effects of partial ionization can modify substantially the Rayleigh-Taylor instability (no stability region, but lower growth rate).
- Depending on the physical situation, different approaches might be useful. Other terms need to be tested.
- Numerical simulations are required to detailed comparisons with the observations and to test whether the simplified models capture the basic features.
- RTI present in prominences, coherent with lifetimes if PI are considered.

Thank you for your attention.