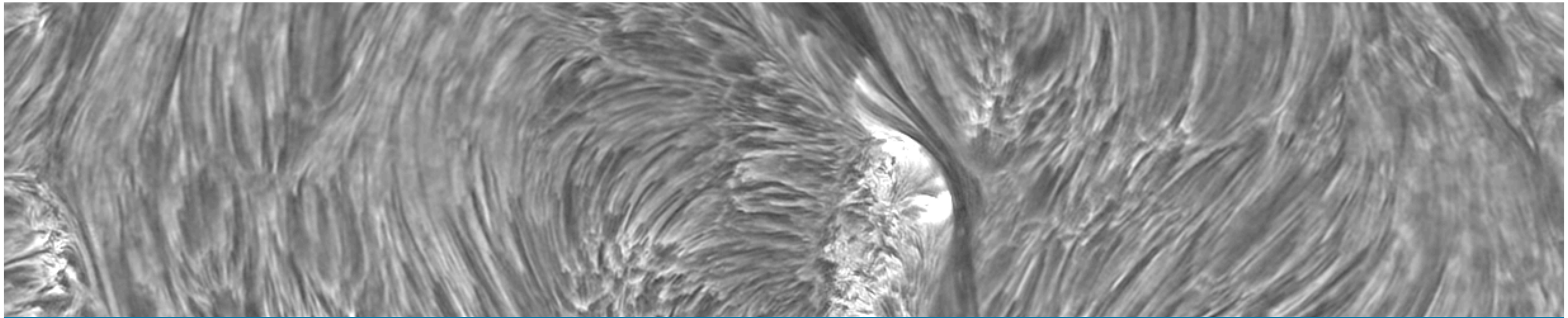

MODELING AND OBSERVATION OF PARTIALLY IONIZED PLASMA PROCESSES

Elena Khomenko

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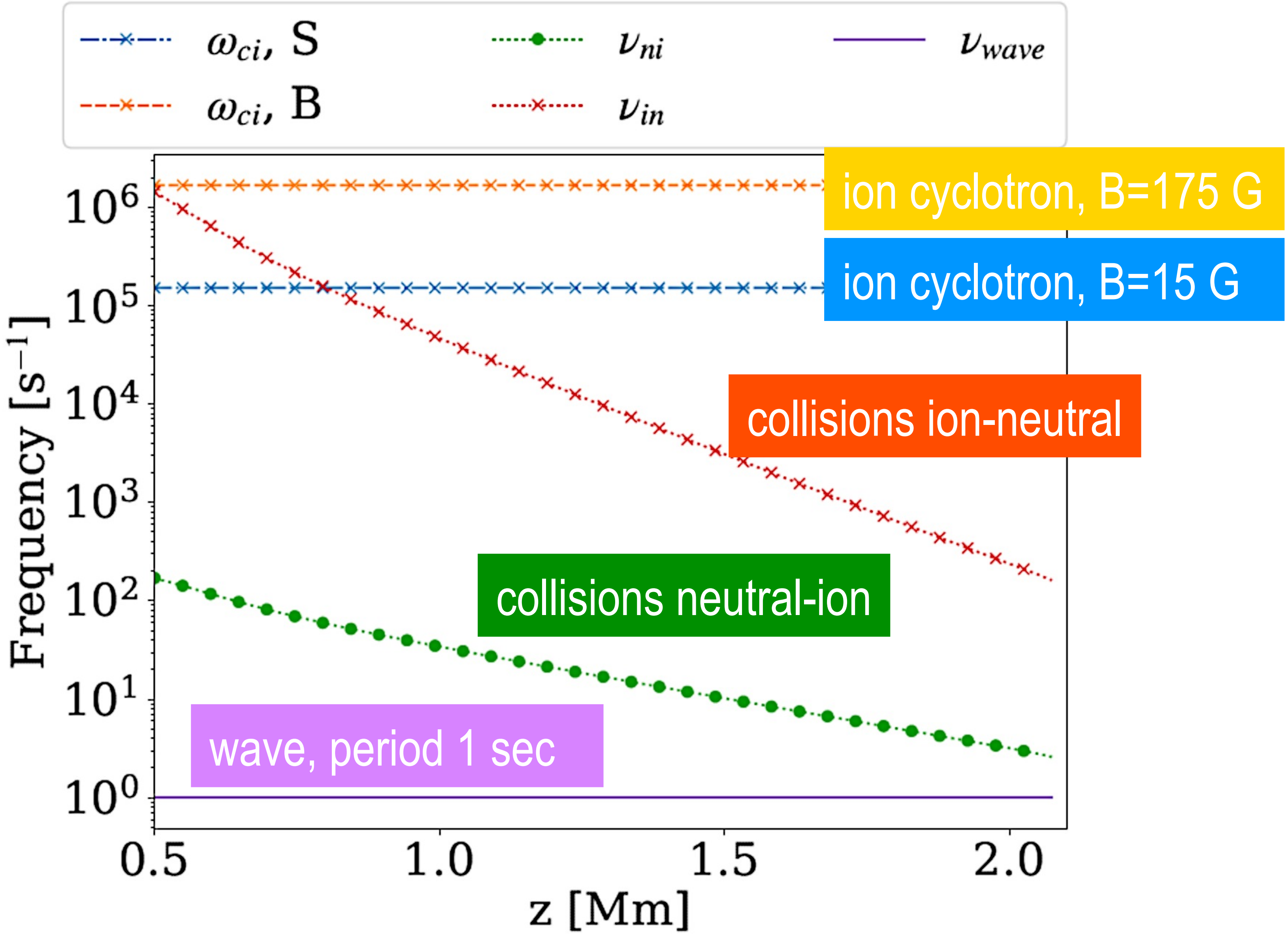
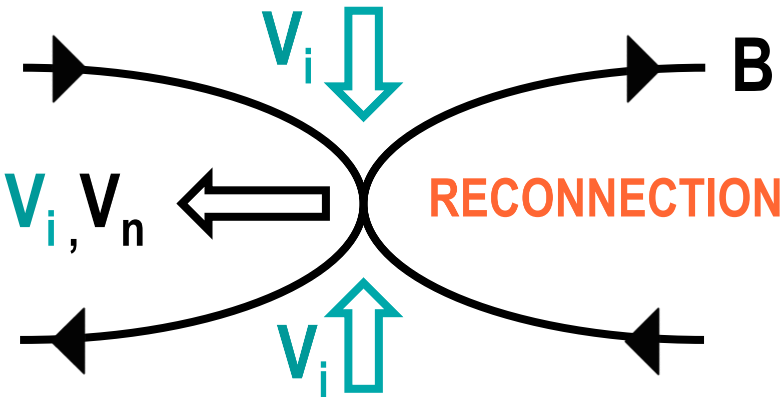
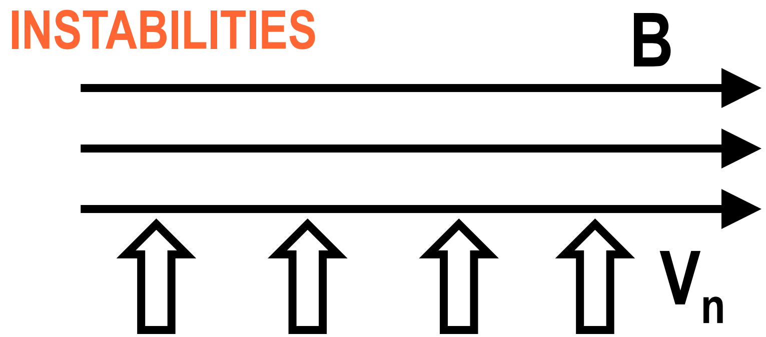
MULTI-FLUID CHROMOSPHERE

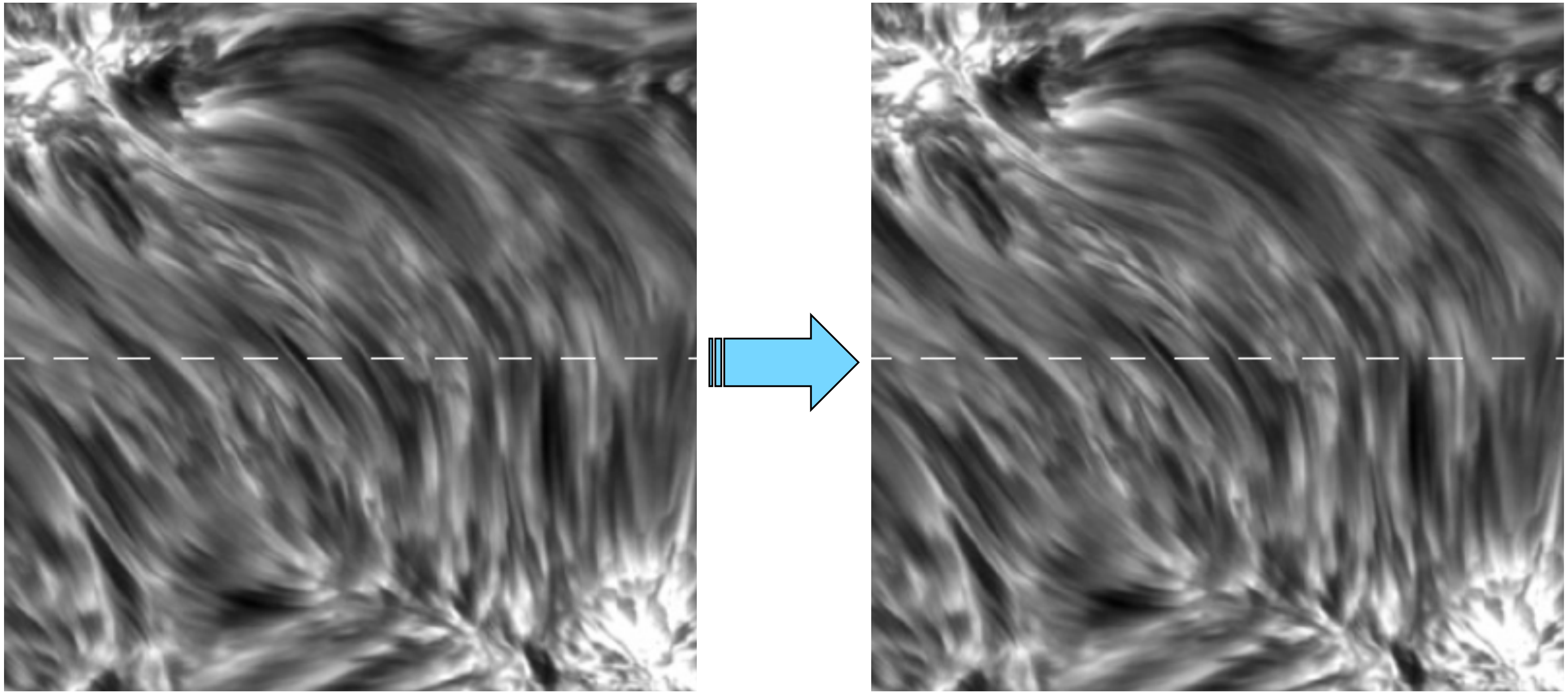


MULTI-FLUID IS CRUCIAL at SMALL SCALES





OBSERVATIONS vs MODELS



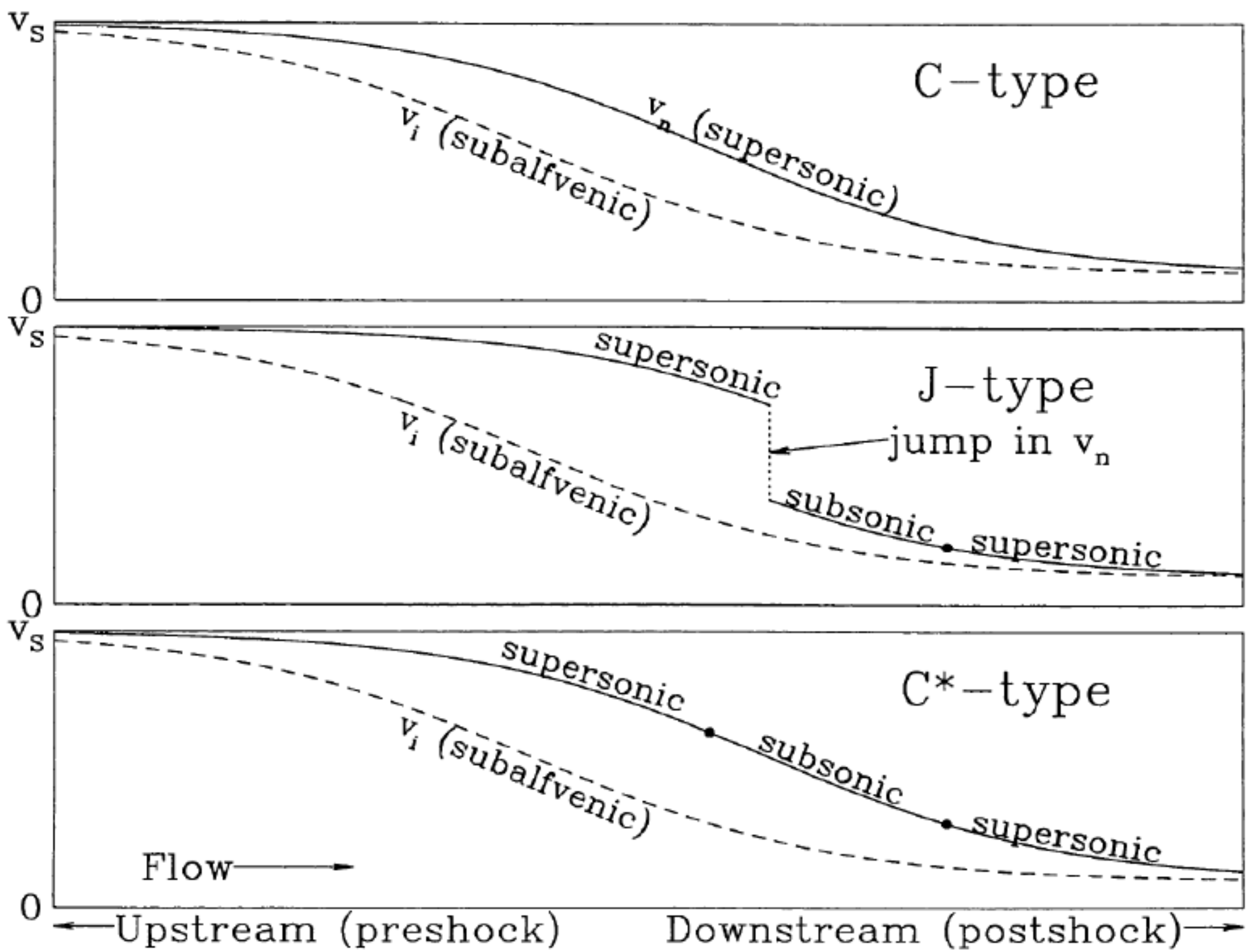
Leenaarts et al. 2015

MULI-FLUID EFFECTS

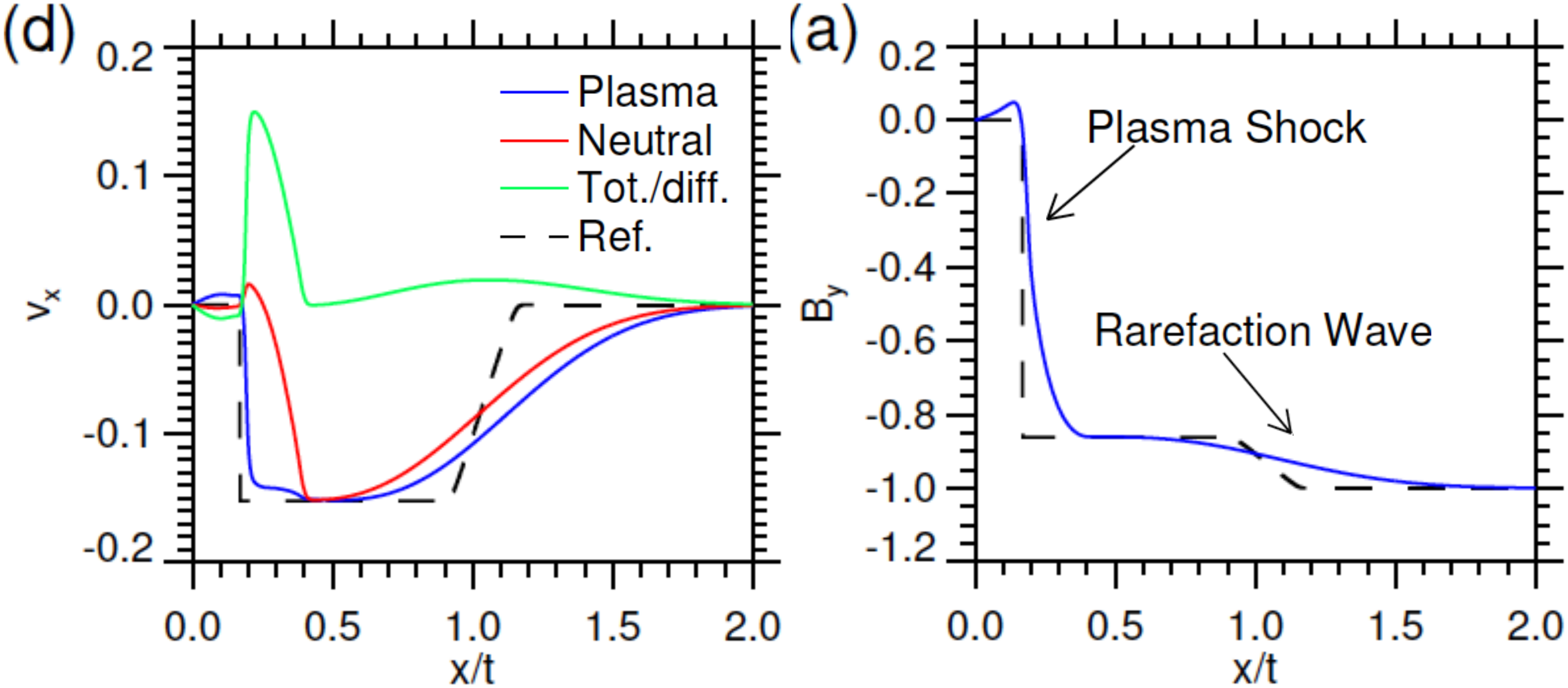
Where do we stand with multi-fluid simulations?

PI2FA
Partial Ionization Two Fluid Approach

FAST WAVE SHOCKS by Draine & McKee (1993)

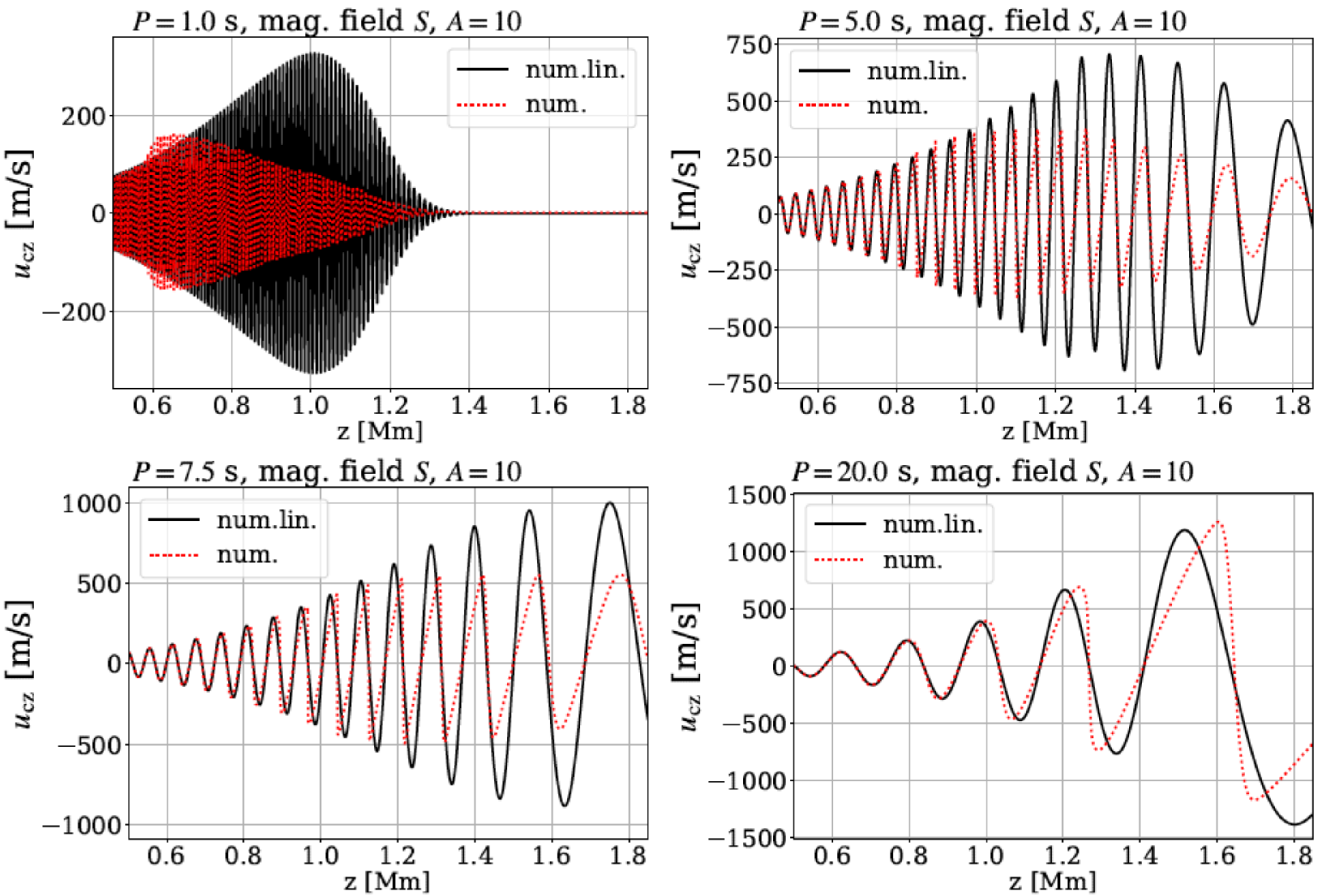


SLOW WAVE SHOCKS by Hillier et al (2016)



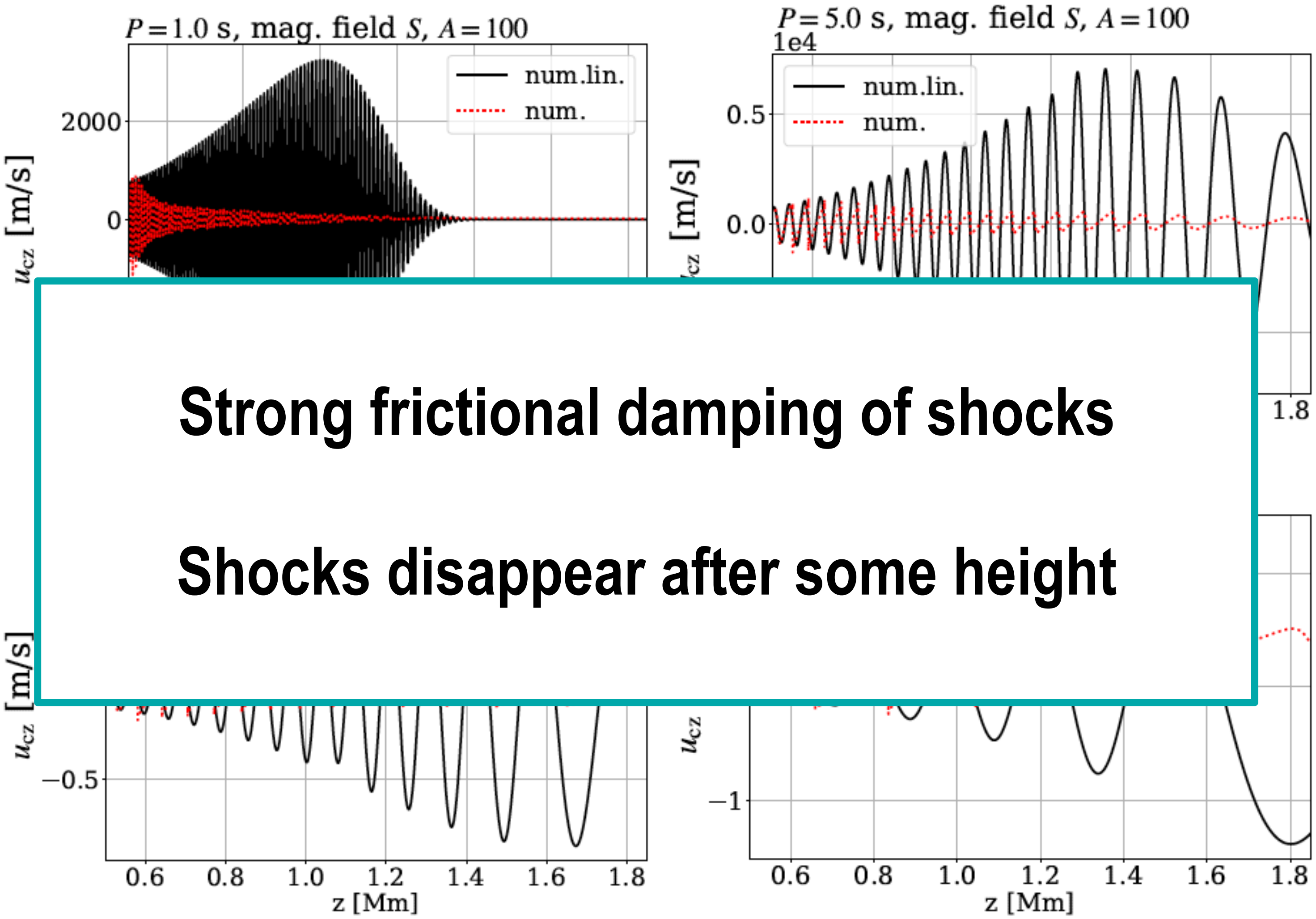
see also ***Snow and Hillier 2019*** *for polarity reversal at shock fronts*
Ballai et al. 2018 *for dispersive shocks including Hall currents*

FAST WAVE SHOCKS in the CHROMOSPHERE



Popescu Braileanu et al. 2019

FAST WAVE SHOCKS in the CHROMOSPHERE

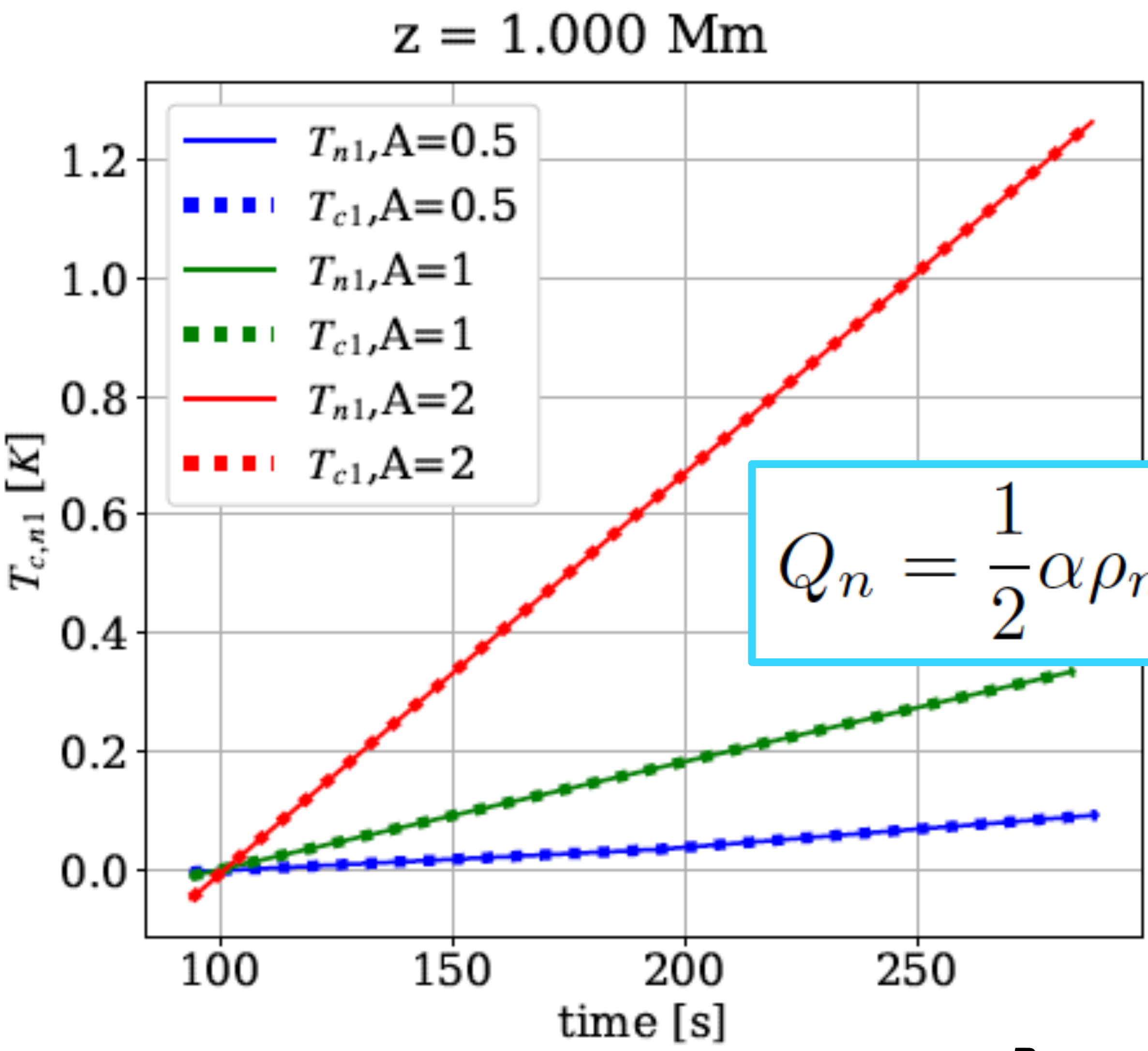


Strong frictional damping of shocks

Shocks disappear after some height

Popescu Braileanu et al. 2019

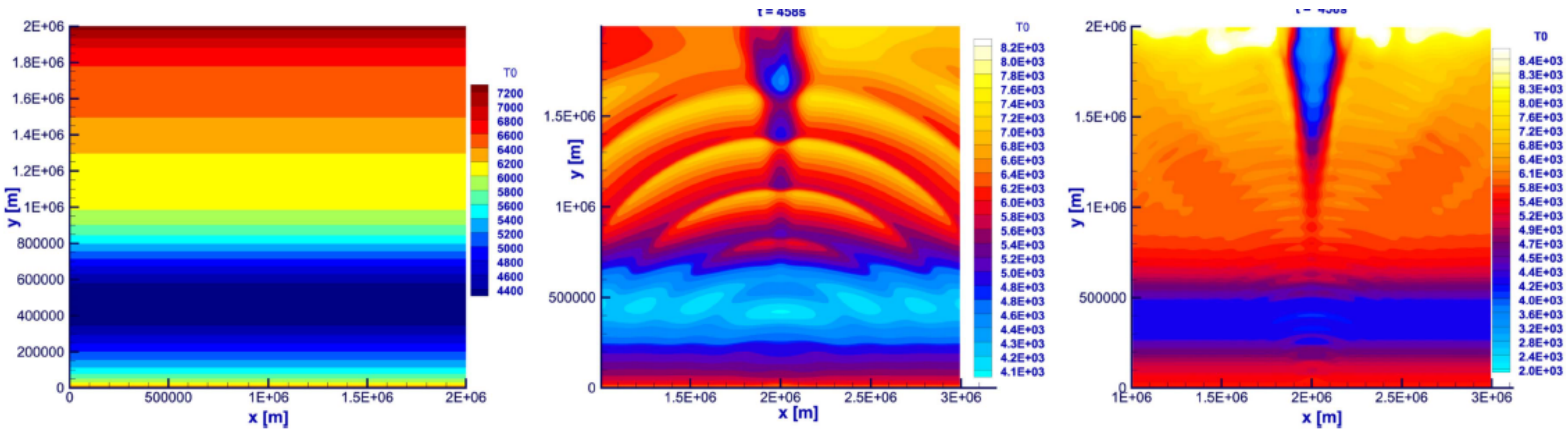
FRICTIONAL HEATING



$$Q_n = \frac{1}{2}\alpha\rho_n\rho_c(\mathbf{u}_c - \mathbf{u}_n)^2$$

Popescu Braileanu et al. 2019

FRICTIONAL HEATING: 2D SIMULATIONS



Interplay between frictional heating and ionization effects

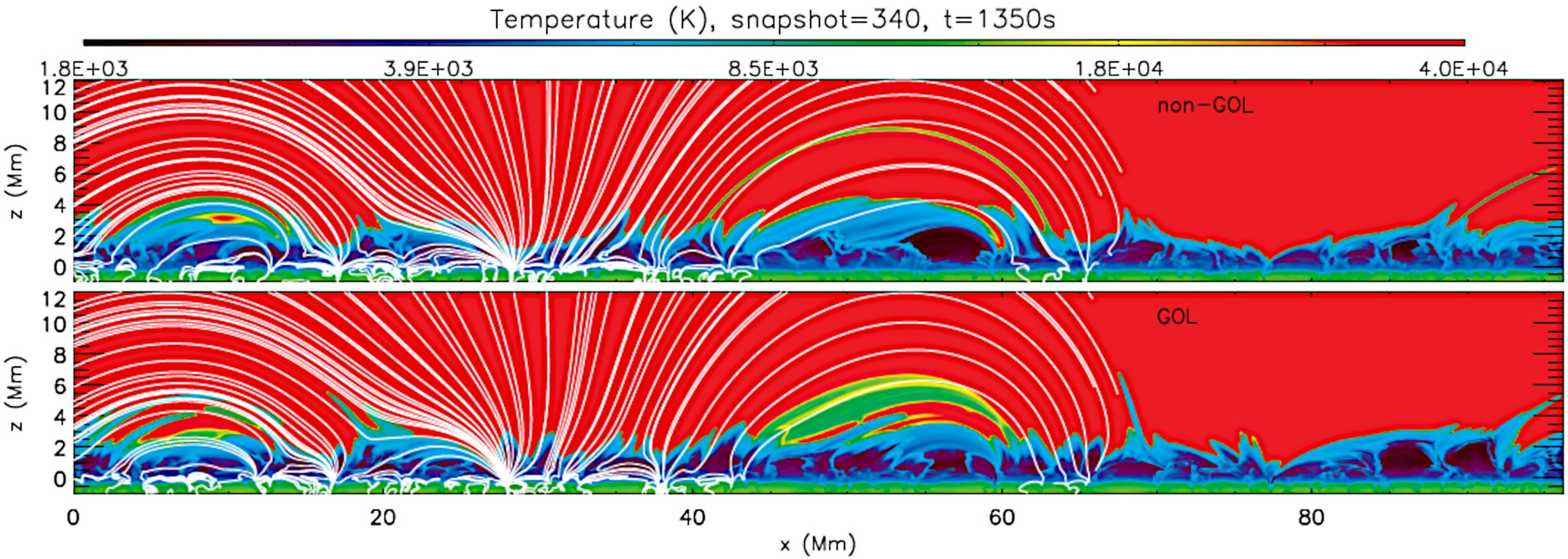
Multi-dimensional stratifications bring complexity

Maneva, Alvarez Laguna, Lani, Poeds (2017)

SINGLE-FLUID

Progress with realistic simulations including generalized Ohms law?

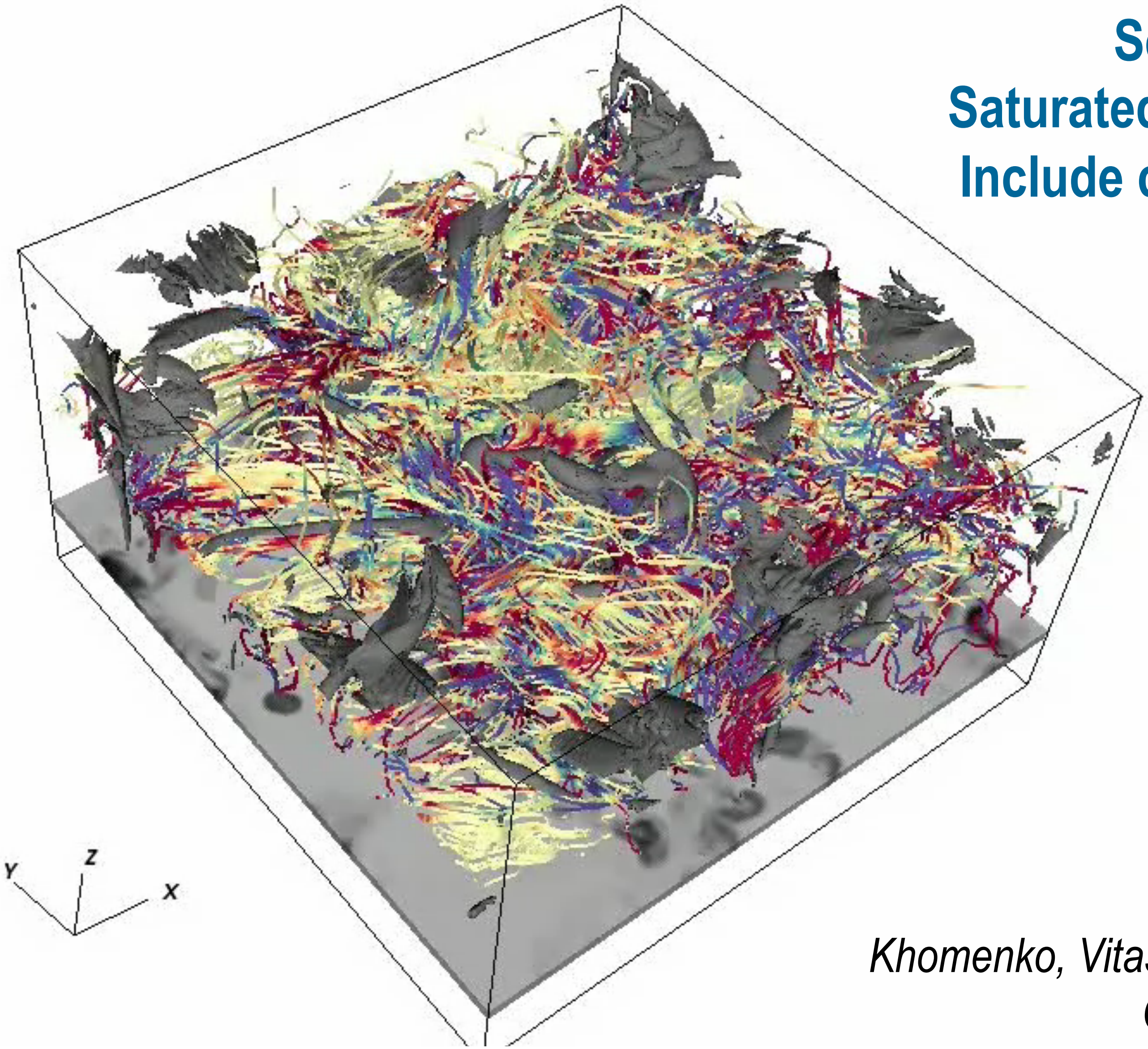
2D MAGNETO-CONVECTION & AMBIPOLAR DIFFUSION



(1) AD increases the temperature in the chromosphere;
(2) AD concentrates electrical currents, leading to more violent jets;
(3) Formation of longer and faster spicules;
(4) Decoupling of the plasma and magnetic field in spicules.

Martínez-Sykora et al. 2012, 2017

3D DYNAMO SIMULATIONS + AD + HALL EFFECT



Seeded by battery effect
Saturated field strength ~ 100 G
Include chromospheric heights

Ideal MHD (only battery effect)

↓

+ Ambipolar diffusion

↓

+ Ambipolar diffusion + Hall

Khomenko, Vitas, Collados, de Vicente 2018; Gonázlez-Morales et al. 2019

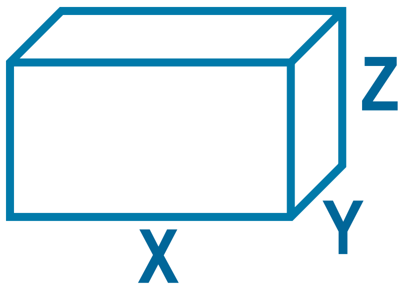
VERTICAL POYNTING FLUX: SPECTRA

V & B vectors

Calculate ideal PF

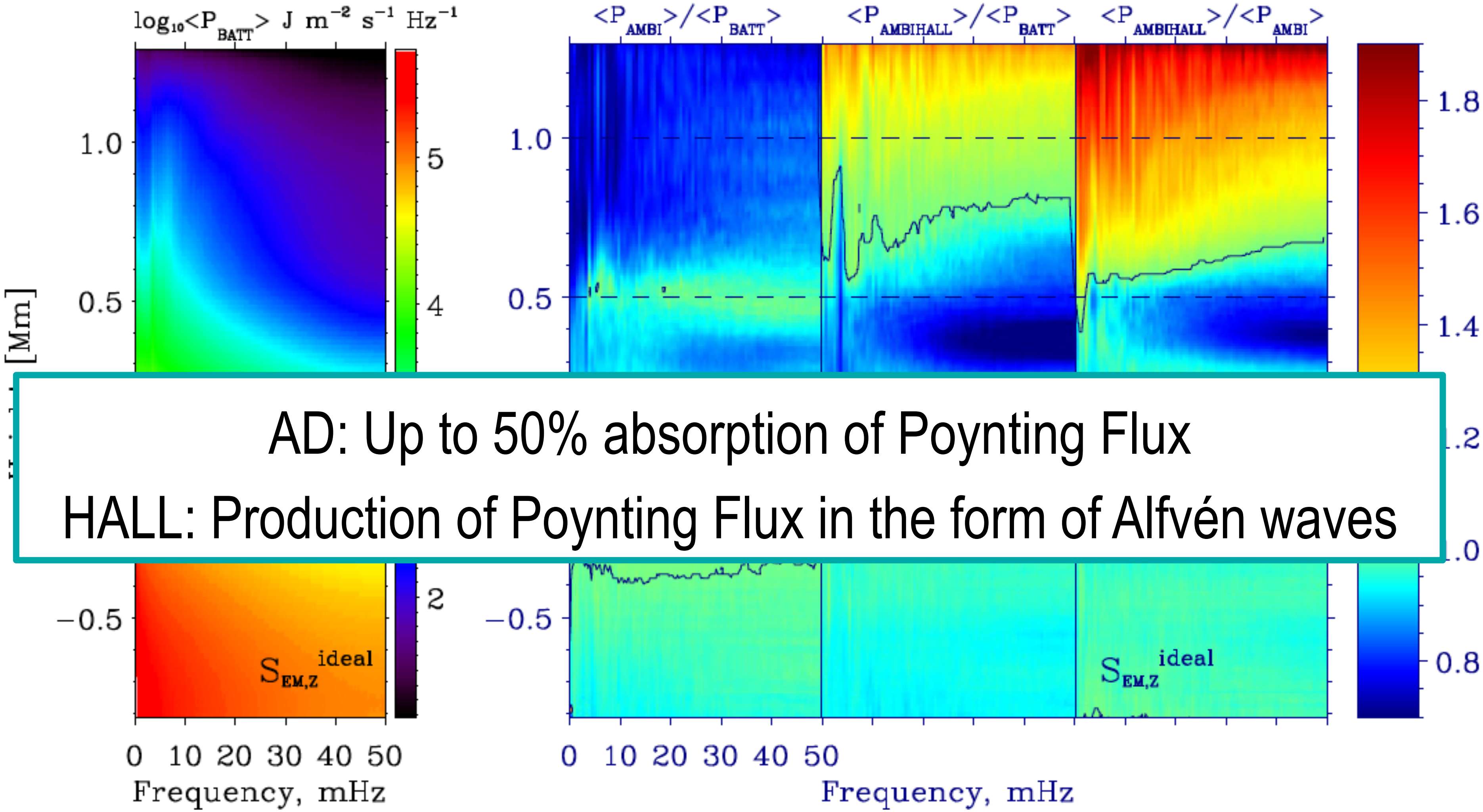
$$\frac{(\mathbf{v} \times \mathbf{B}) \times \mathbf{B}}{\mu_0}$$

Fourier-transform



Average power over horizontal directions, X-Y

POYNTING FLUX



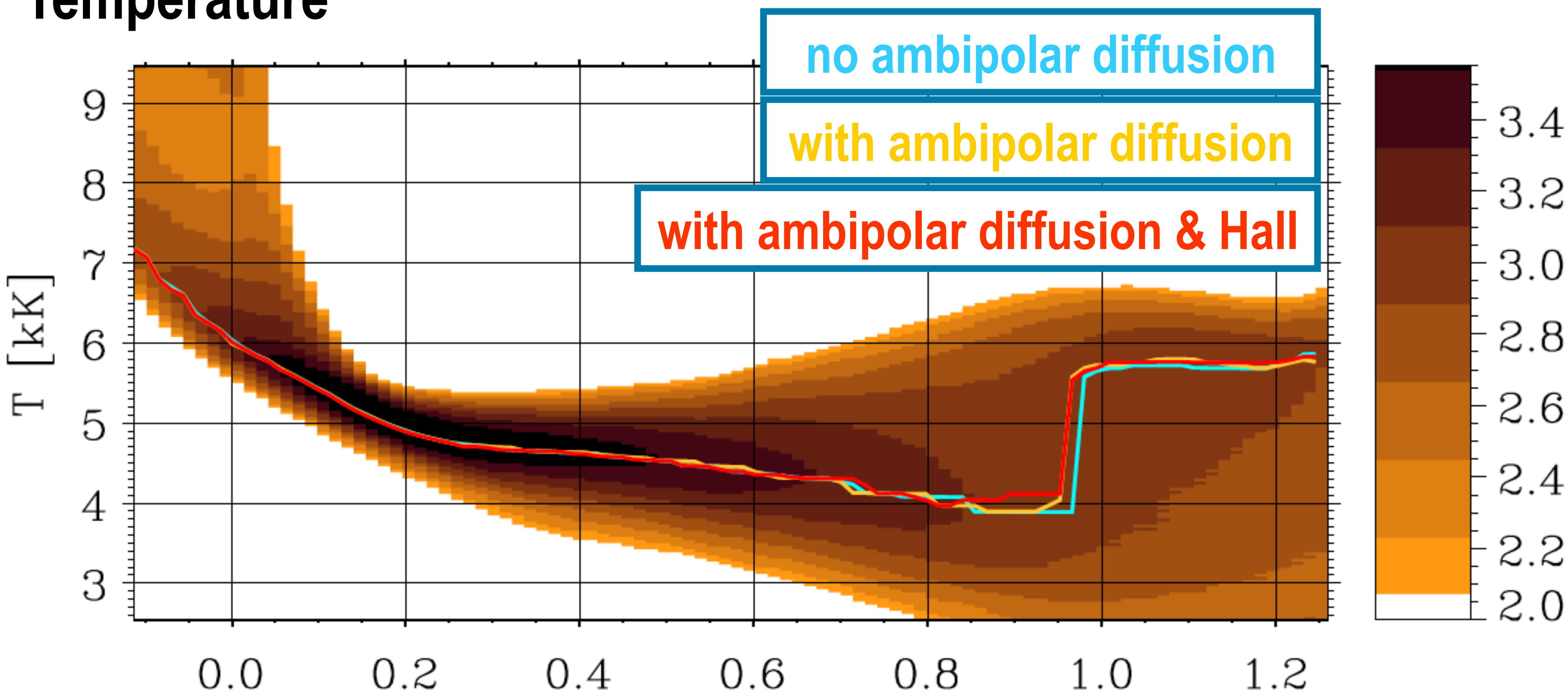
AD: Up to 50% absorption of Poynting Flux

HALL: Production of Poynting Flux in the form of Alfvén waves

Gonázlez-Morales et al. 2019

EFFECT FOR AVERAGE TEMPERATURE

Temperature



Low bond on the chromospheric temperature increase

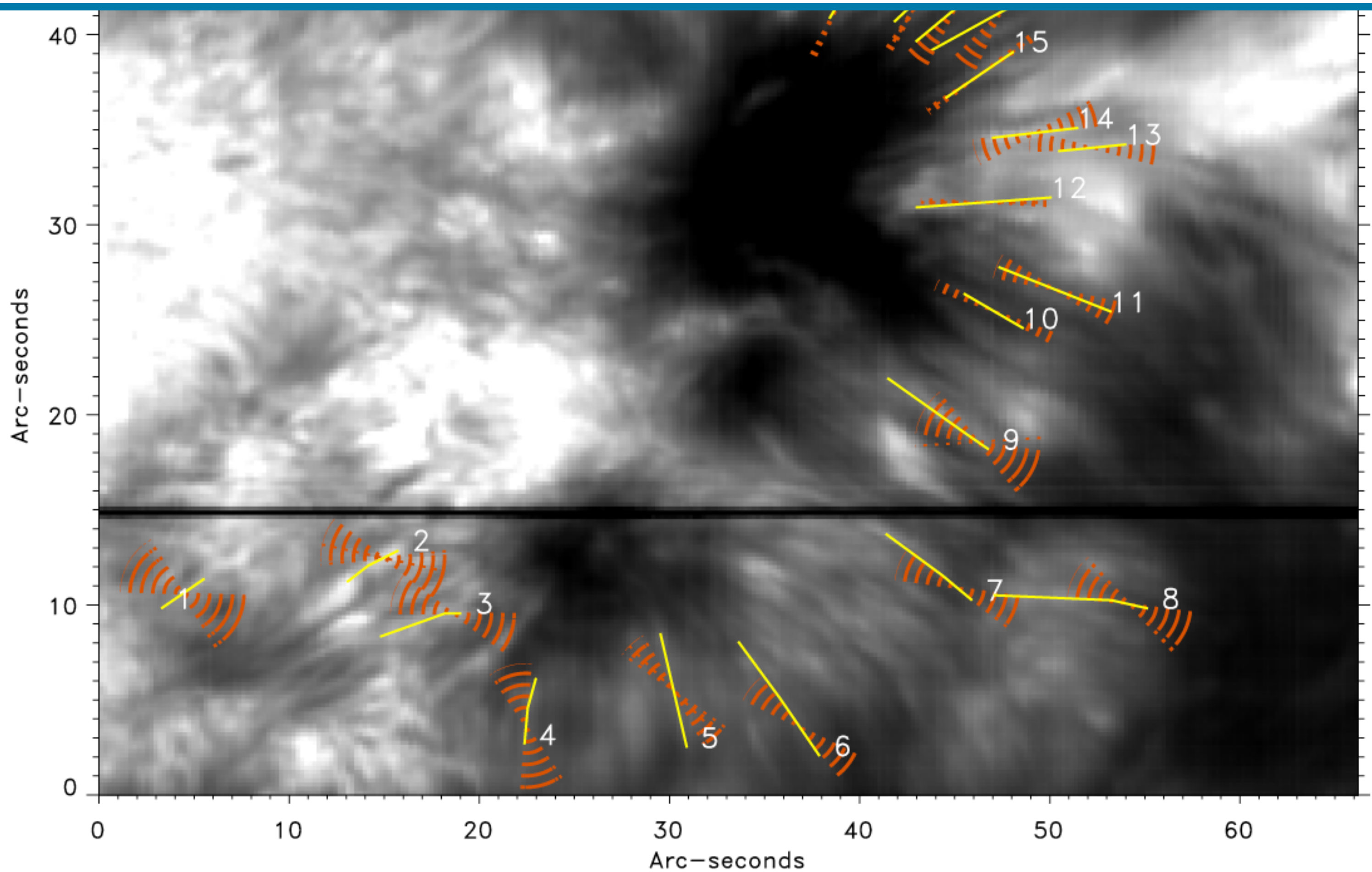
PI2FA Partial Ionization Two Fluid Approach

MULI-FLUID EFFECTS

Observational confirmation of multi-fluid effects ?

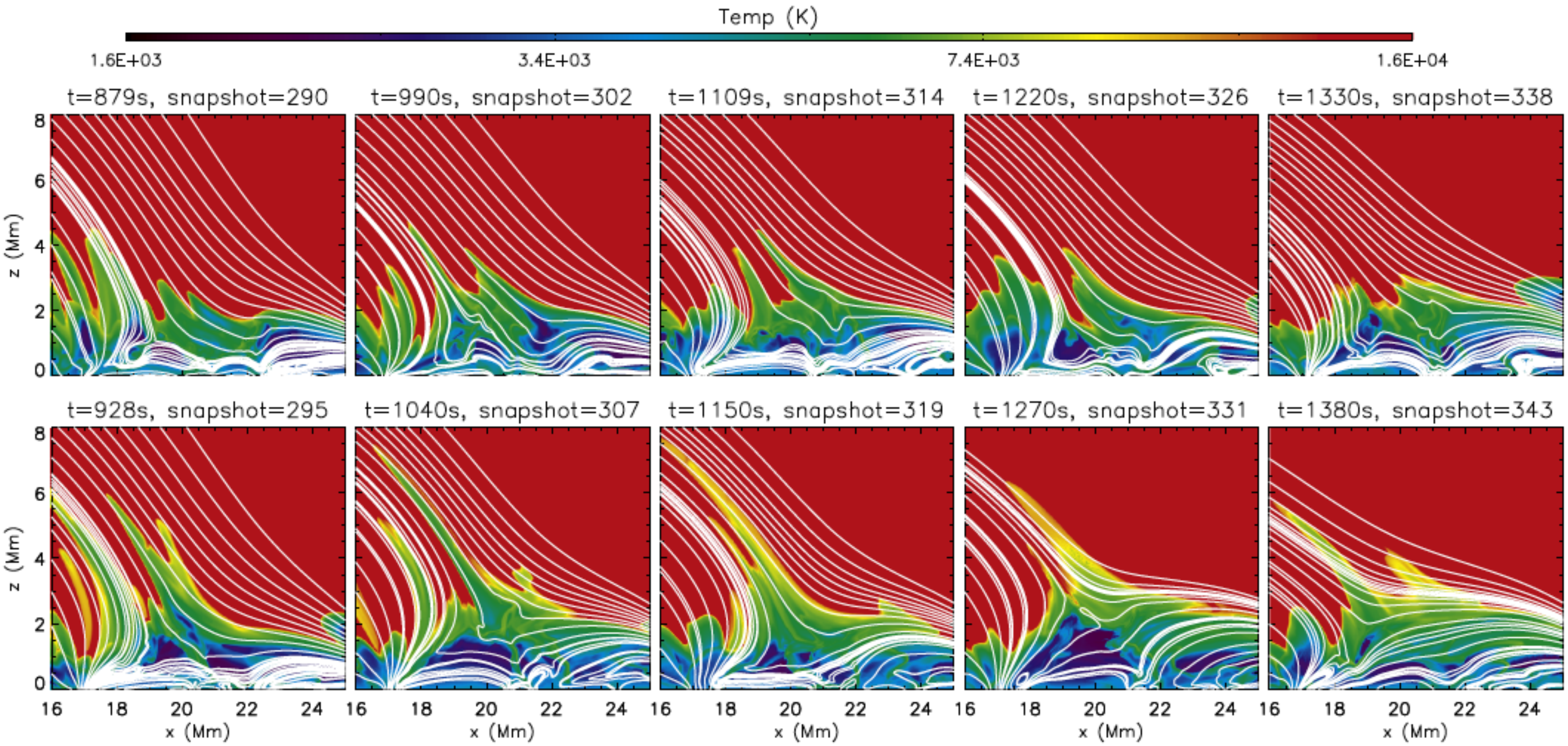
DIRECTION of CHROMOSPHERIC FILAMENTS

Misalignment between chromospheric fibrils and magnetic field



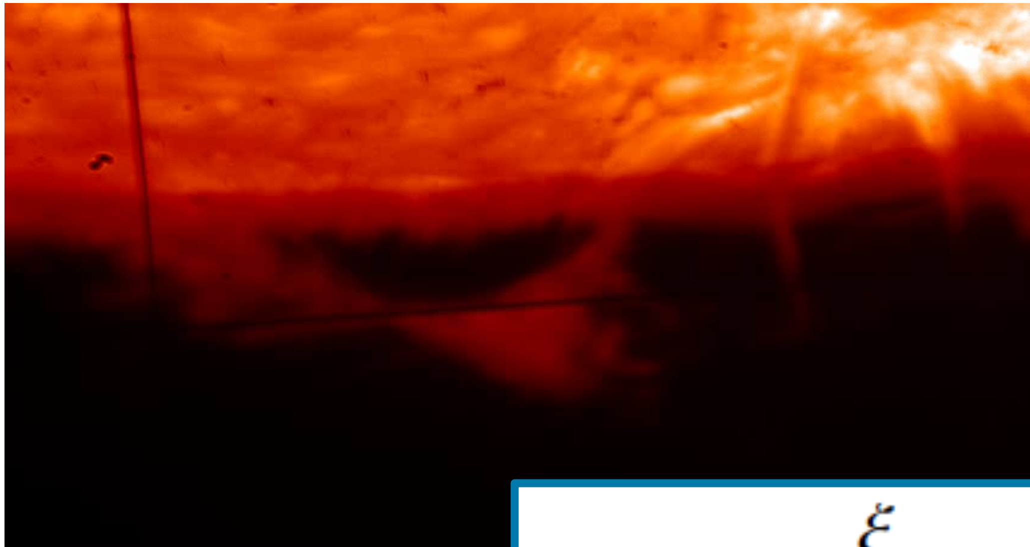
de la Cruz Rodríguez & Socas-Navarro 2011; Asensio Ramos, de la Cruz Rodrigues et al. 2017

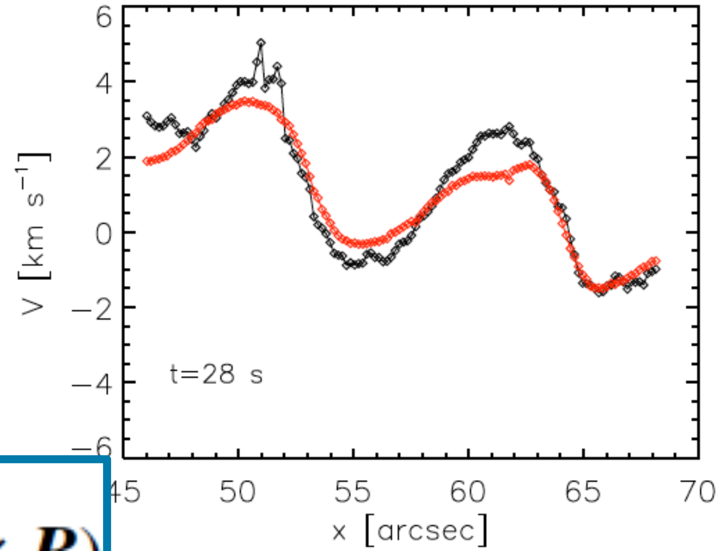
DIRECTION of CHROMOSPHERIC FILAMENTS



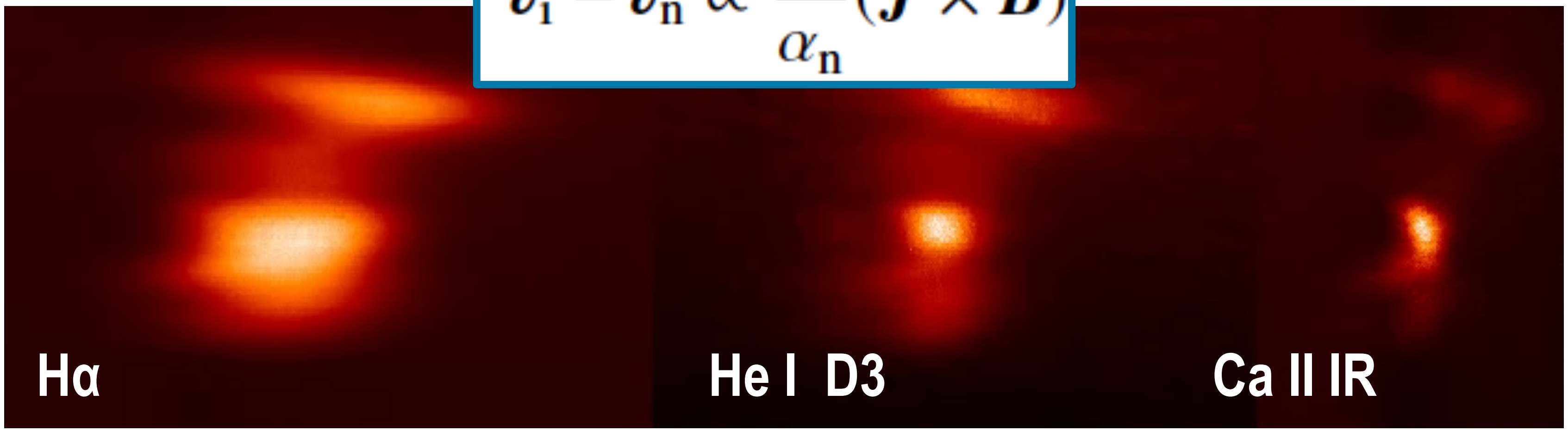
Martínez-Sykora, De Pontieu, Carlsson et al. 2017

DIRECT DETECTION of ION-NEUTRAL DRIFTS



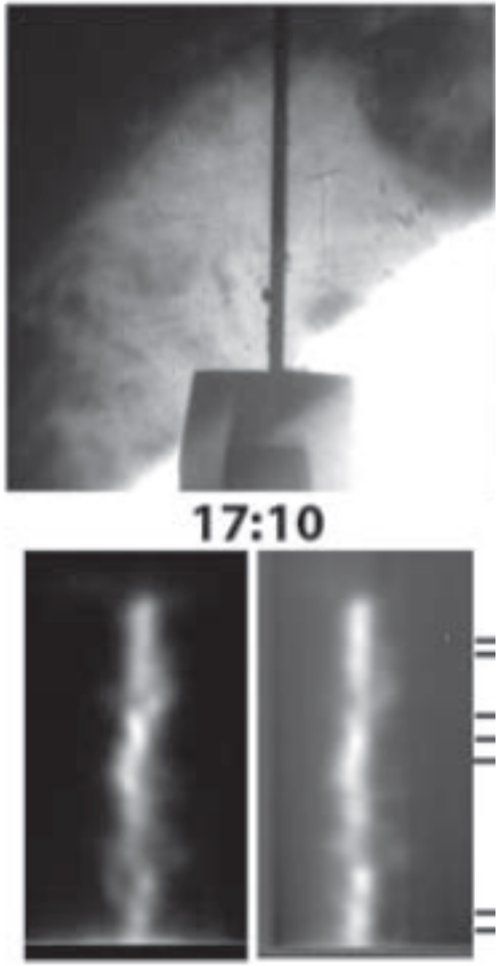


$$v_\mathrm{i} - v_\mathrm{n} \propto \frac{\xi}{\alpha_\mathrm{n}}(\boldsymbol{J} \times \boldsymbol{B})$$

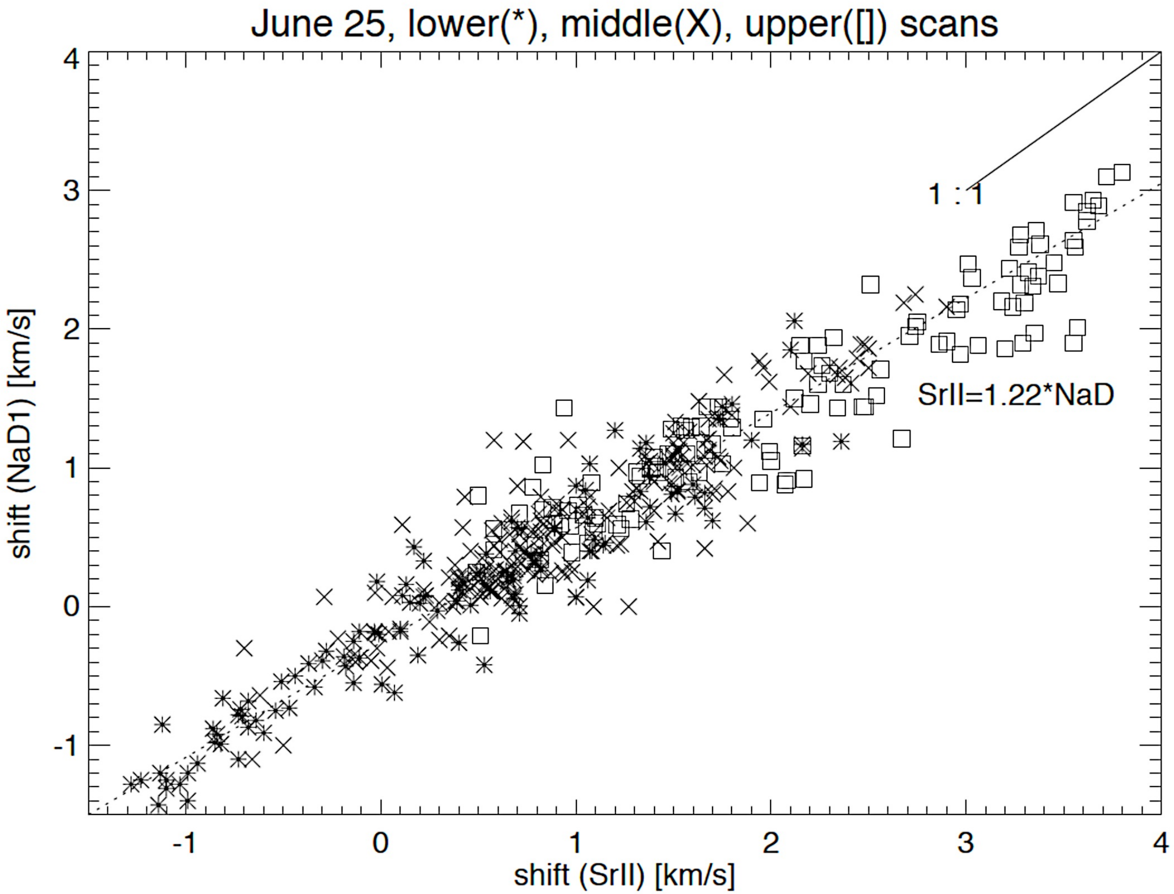


Khomenko, Díaz, Collados (2016)

DIRECT DETECTION of ION-NEUTRAL DRIFTS

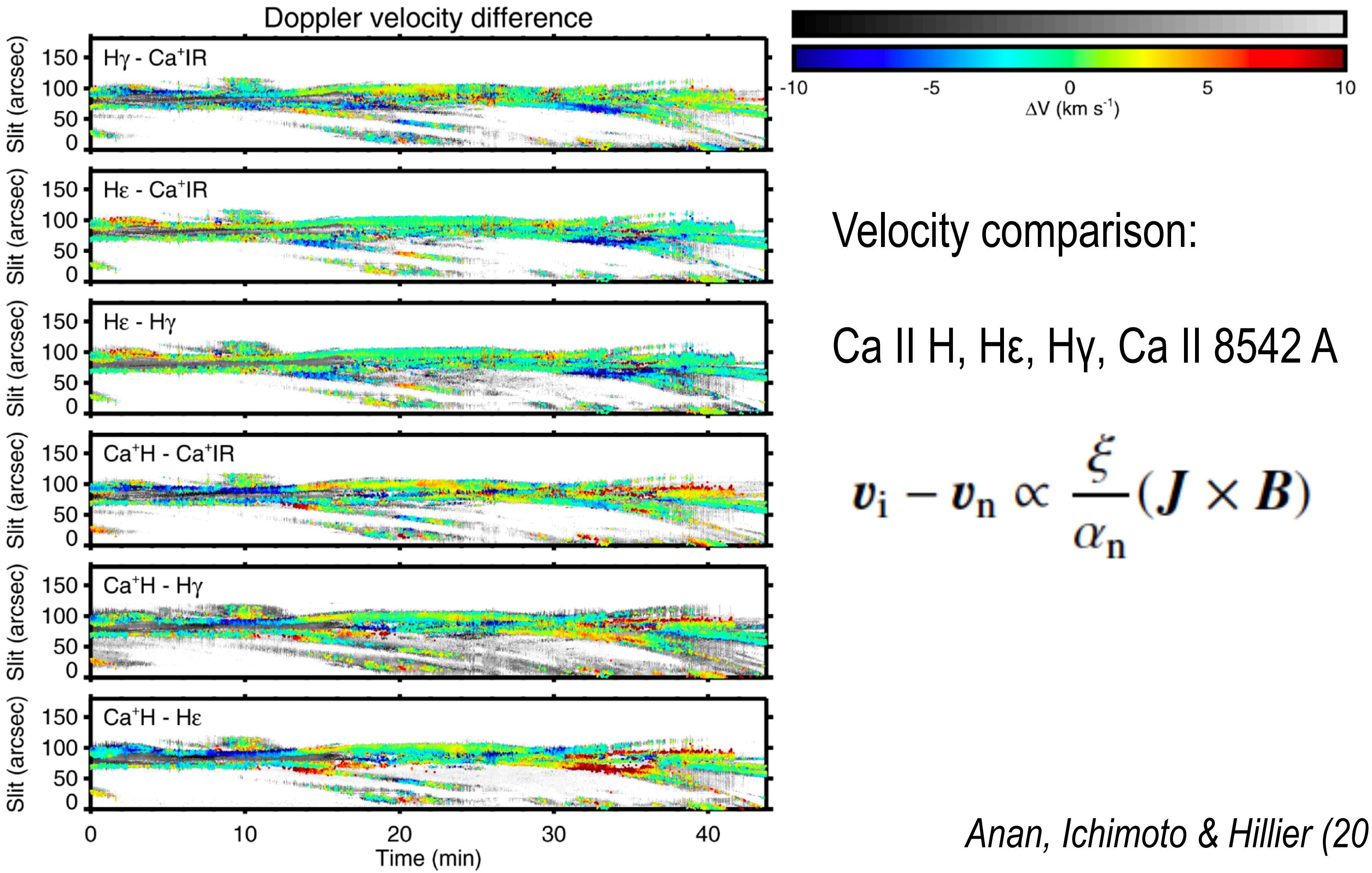


Velocity comparison: Sr II - Na I spectral lines



Wiehr, Stellmacher, Bianda (2019)

DIRECT DETECTION of ION-NEUTRAL DRIFTS



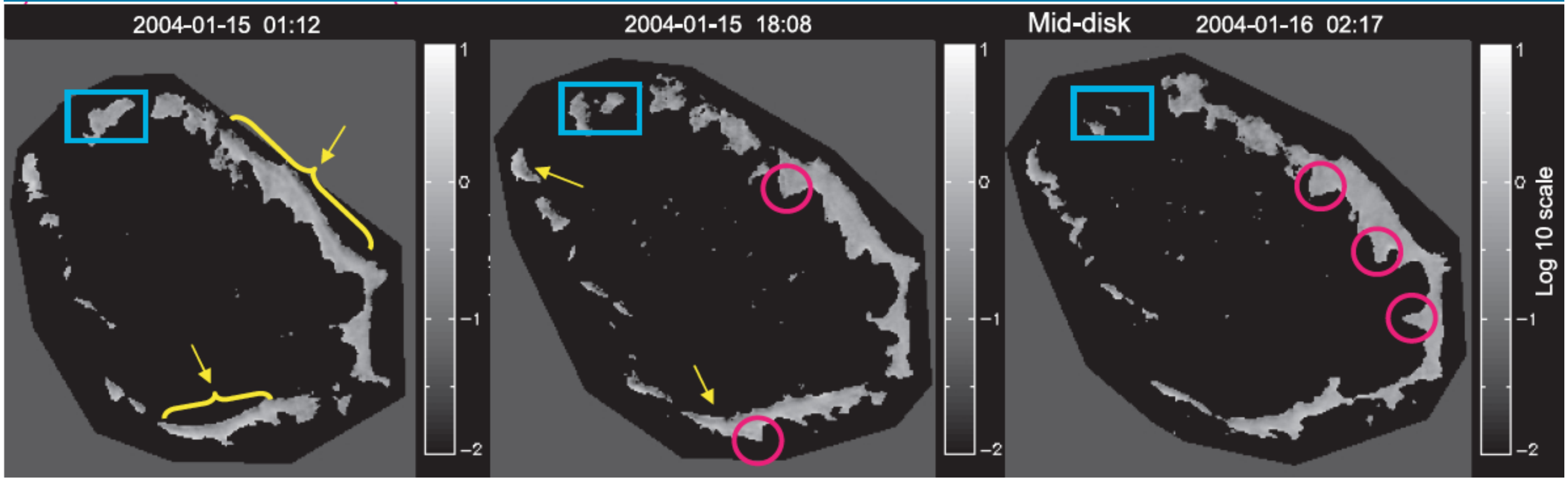
Velocity comparison:

Ca II H, Hε, Hγ, Ca II 8542 A

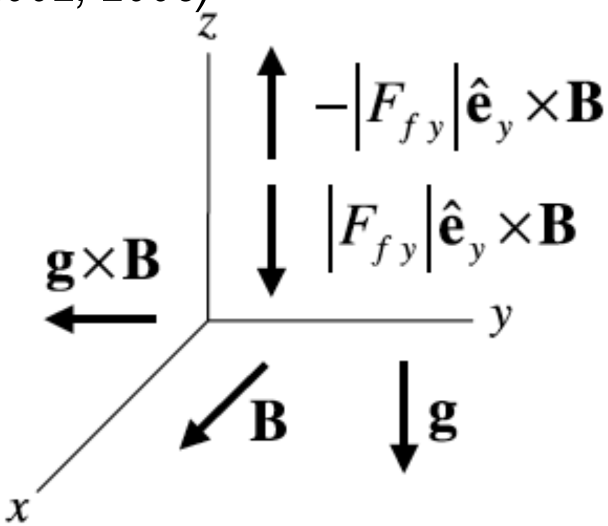
$$\boldsymbol{v}_{\rm i} - \boldsymbol{v}_{\rm n} \propto \frac{\xi}{\alpha_{\rm n}}(\boldsymbol{J} \times \boldsymbol{B})$$

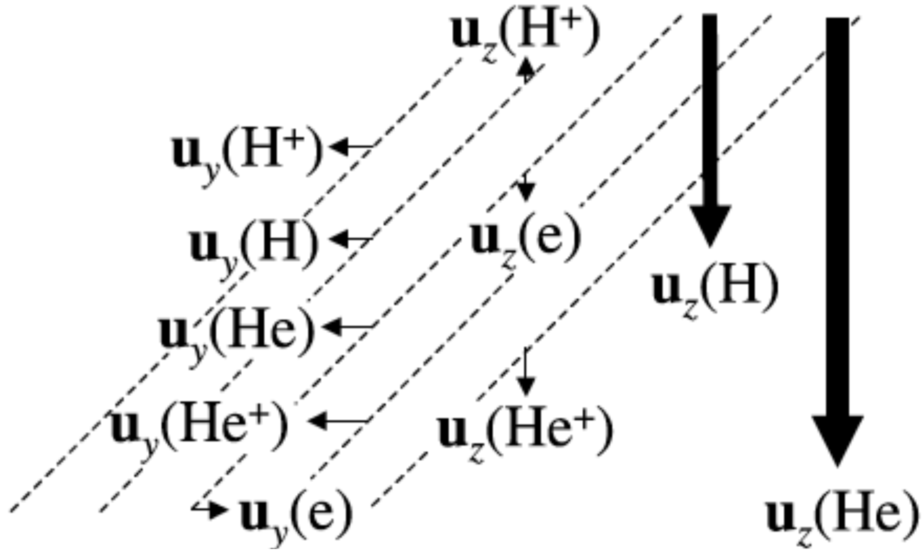
Anan, Ichimoto & Hillier (2017)

CROSS-FIELD DIFFUSION of NEUTRALS



Gilbert et al. (2002, 2008)





SUMMARY

Ion-neutral effects definitely play important role in the chromosphere

- ✓ At shocks, producing multi-fluid structure at shock fronts and frictional heating;
- ✓ At current layers, helping efficient dissipation of currents perpendicular to the magnetic field, contributing to the energy balance;
- ✓ By modifying the field structure and favoring production of Alfvén waves;
- ✓ In prominences, producing cross-field diffusion, and influencing stability;
- ✓ In filaments and spicules, by making the material moving not aligned with the field;
- ✓ For sure in reconnection & turbulence (could not cover the topic due to the lack of time)

PI2FA Partial Ionization Two Fluid Approach