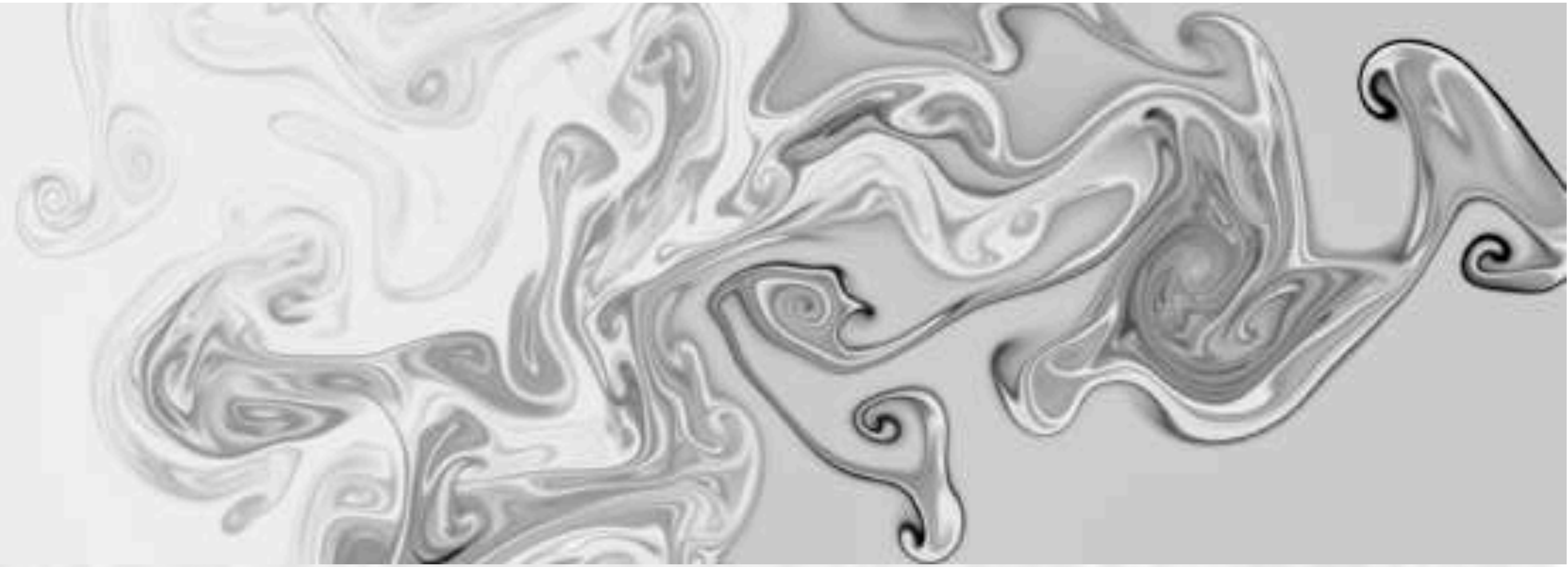
Realistic simulations of the solar magneto-convection including effects of partial ionization



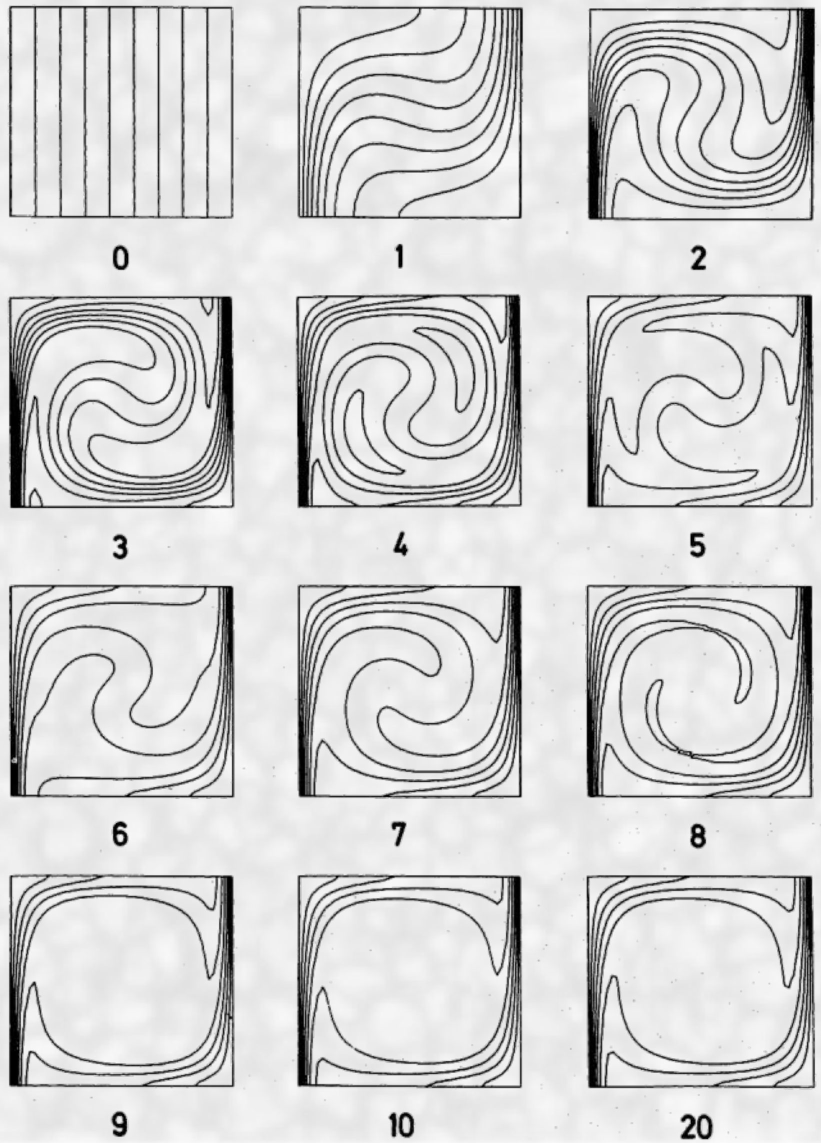
E. Khomenko[1,2] & PI2FA team

[1]Instituto de Astrofísica de Canarias, Spain

[2]Departamento de Astrofísica, Universidad de La Laguna, Spain

Realistic simulations of (solar) magneto-convection

Starting from first experiments by Galloway & Weiss 1981



Simple & idealized, but

- Reproduce basic processes of the magnetic **flux expulsion** to the border of convection cells
- Resistivity causing **cancellation of opposite polarity** magnetic fields inside convection cells

“Realistic” simulations require several ingredients:

- Model for interaction of plasma & radiation
- Realistic equation of state, instantaneous or time-dependent
- Model for heat conduction
- Specific boundary conditions

Realistic simulations of (solar) magneto-convection

Nowadays it is an extremely vast subject

Realistic simulations are used alongside with observations for:

- Getting insights into the physics of the solar atmosphere
- Predicting observables
- Developing new instrumentation
- Training and testing inversion methods
- Etc…

Several major codes, used with different purposes:

- MURaM (Vogler et al. 2007, Rempel 2017, Przybylski et al. 2022)
- Stagger (Stein et al. 2024)
- Co5BOLD (Freytag et al. 2011)
- Bifrost (Gudiksen et al. 2011)
- MANCHA3D (Khomenko & Collados 2006, Felipe et al 2010, Modestov et al. 2024)
- Antares (Muthsam et al. 2010); RAMSES (Iijima & Yokoyama 2015); R2D2 (Hotta et al. 2019)

Realistic simulations of (solar) magneto-convection

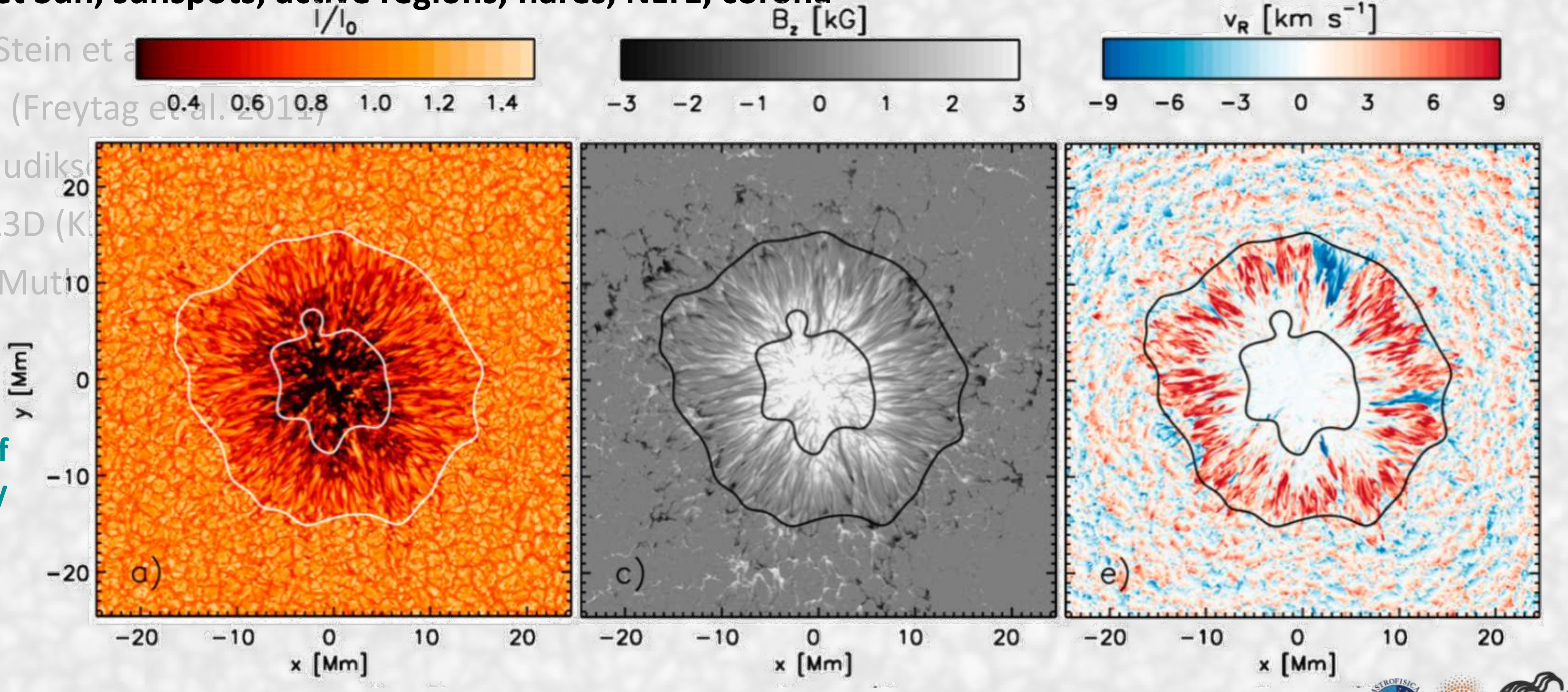
Several major codes, used with different purposes:

- MURaM (Vogler et al. 2007, Rempel 2017, Przybylski et al. 2022)

  quiet Sun, sunspots, active regions, flares, NLTE, corona

- Stagger (Stein et a
- Co5BOLD (Freytag et al. 2011)
- Bifrost (Gudiks
- MANCHA3D (K
- Antares (Mut

Simulations of sunspot decay



Rempel 2015

Realistic simulations of (solar) magneto-convection

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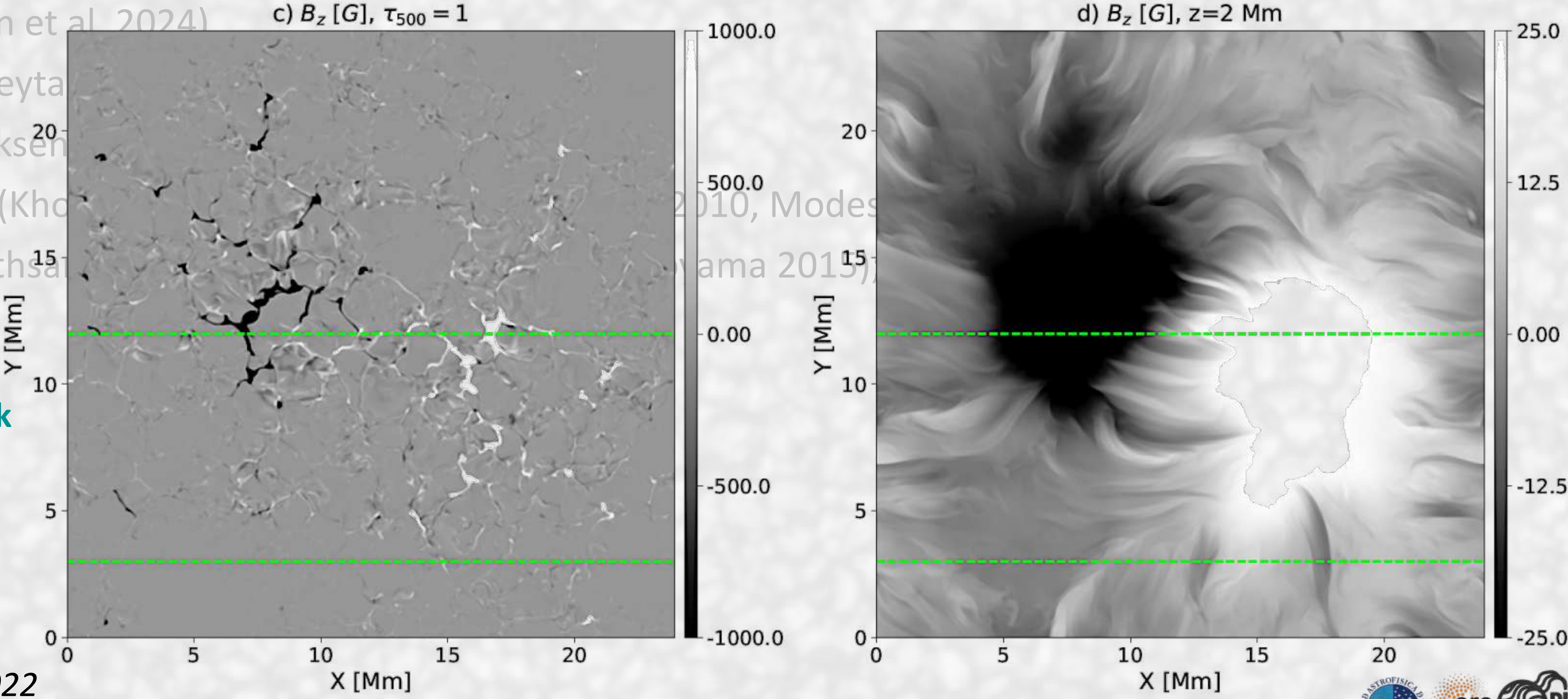
- Bifrost (Gudiksen
- MANCHA3D (Kho … 2010, Modes
- Antares (Muthsa … yama 2015)



Enhanced network chromosphere

Przybylski et al. 2022

Realistic simulations of (solar) magneto-convection

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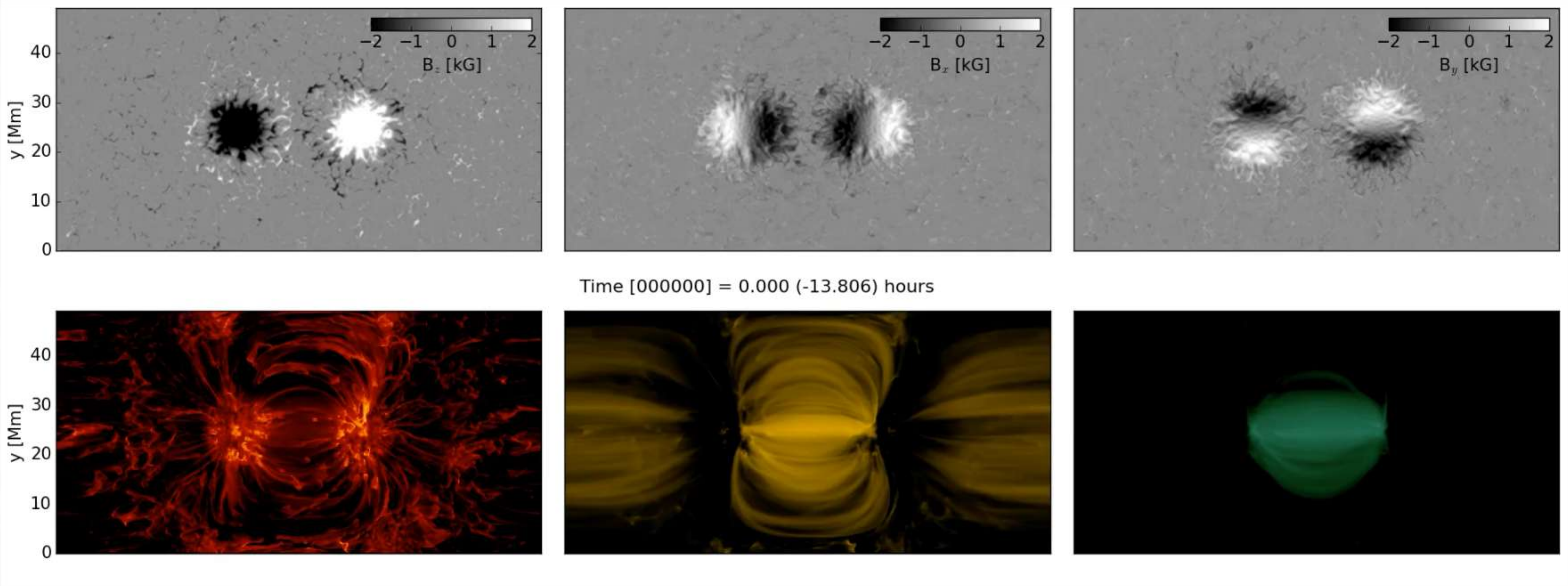
  quiet Sun, sunspots, active regions, flares, NLTE, corona



Rempel et al. 2023

simulation of a C class flare

Realistic simulations of (solar) magneto-convection

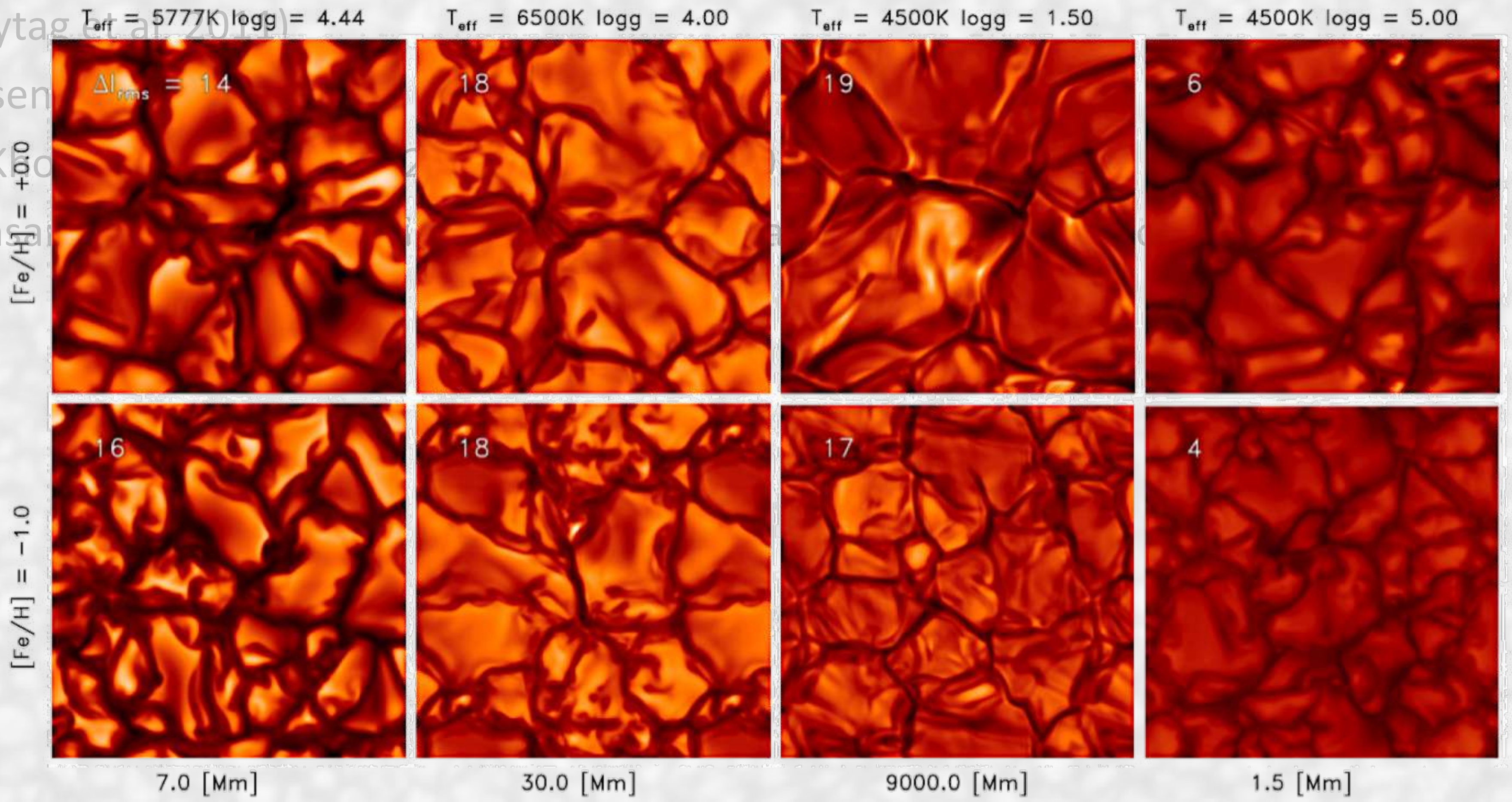
Several major codes, used with different purposes:

- Stagger (Stein et al. 2024)

  quiet Sun, solar abundances; stellar applications

- Co5BOLD (Freytag et al. 201
- Bifrost (Gudiksen
- MANCHA3D (K
- Antares (Muthsa

Grid of cool stellar convection models



Magic et al. 2013

Realistic simulations of (solar) magneto-convection

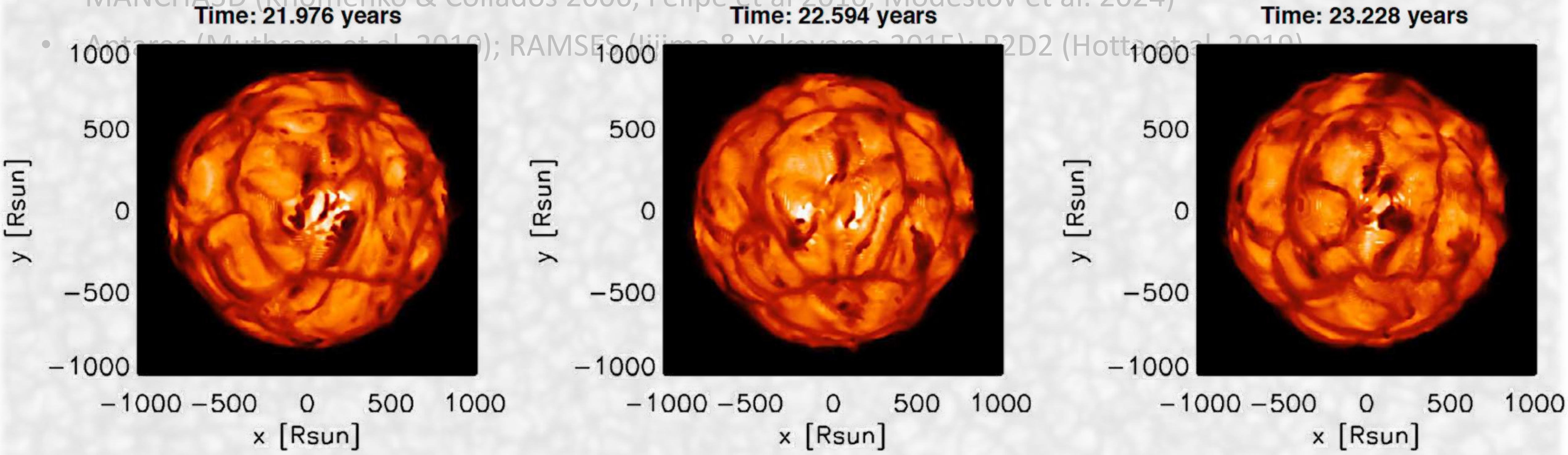
Several major codes, used with different purposes:

- Co5BOLD (Freytag et al. 2011)

  local & global solar and stellar models

- Bifrost (Gudiksen et al. 2011)
- MANCHA3D (Khomenko & Collados 2006, Felipe et al 2010, Modestov et al. 2024)
- Antares (Muthsam et al. 2010); RAMSES (Iijima & Yokoyama 2015); R2D2 (Hotta et al. 2019)

convection on red supergiant star



Chiavassa et al. 2009

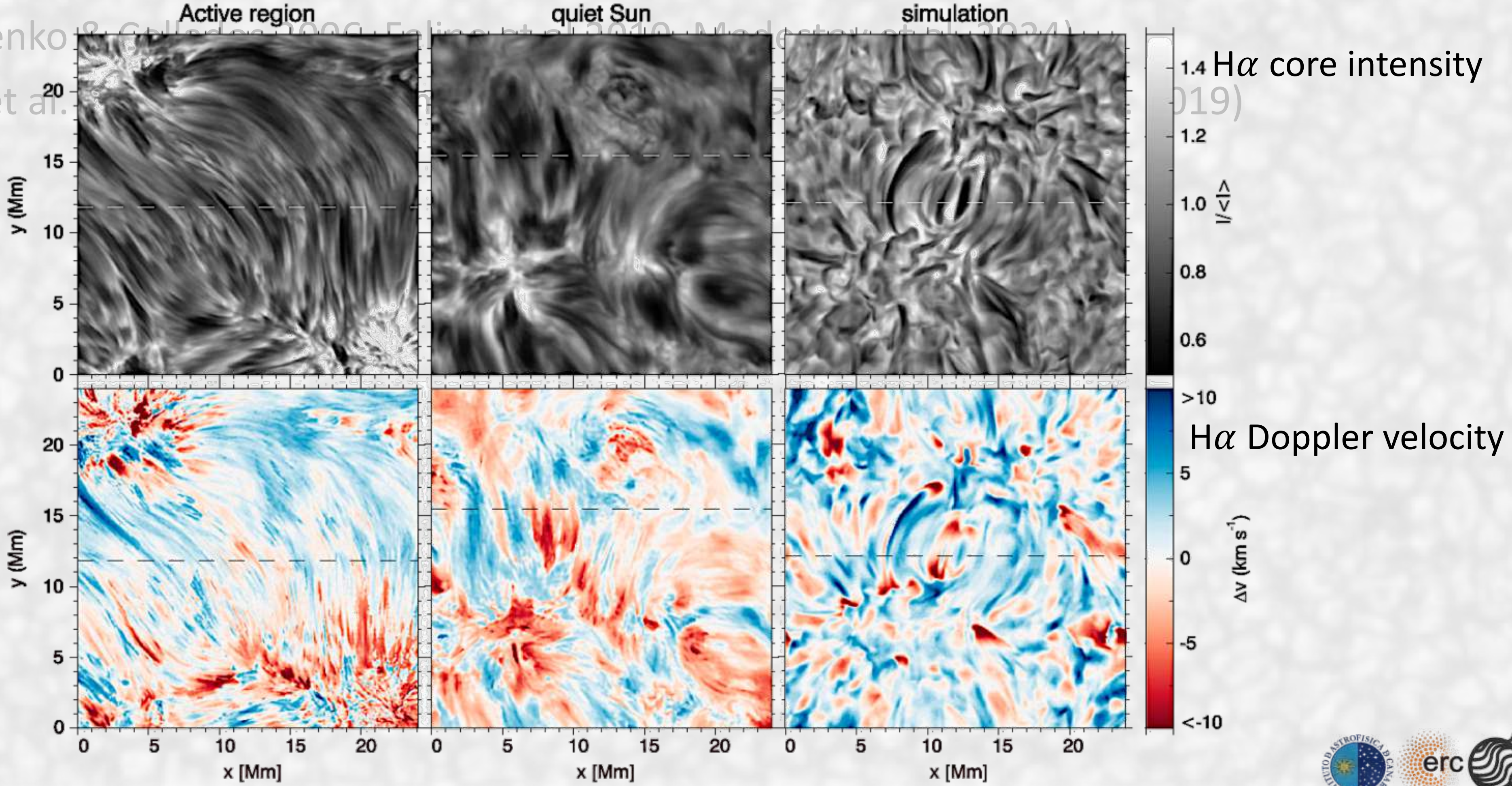
Realistic simulations of (solar) magneto-convection

Several major codes, used with different purposes:

- Bifrost (Gudiksen et al. 2011)

  quiet and active regions, magnetic flux emergence, eruptive events, corona, NLTE & partial ionization

- MANCHA3D (Khomenko & Collados 2006, Felipe et al. 2010, Modestov et al. 2024)
- Antares (Muthsam et al. … 2019)



Carlsson 2016,
Leenaarts et al. 2015

Realistic simulations of (solar) magneto-convection

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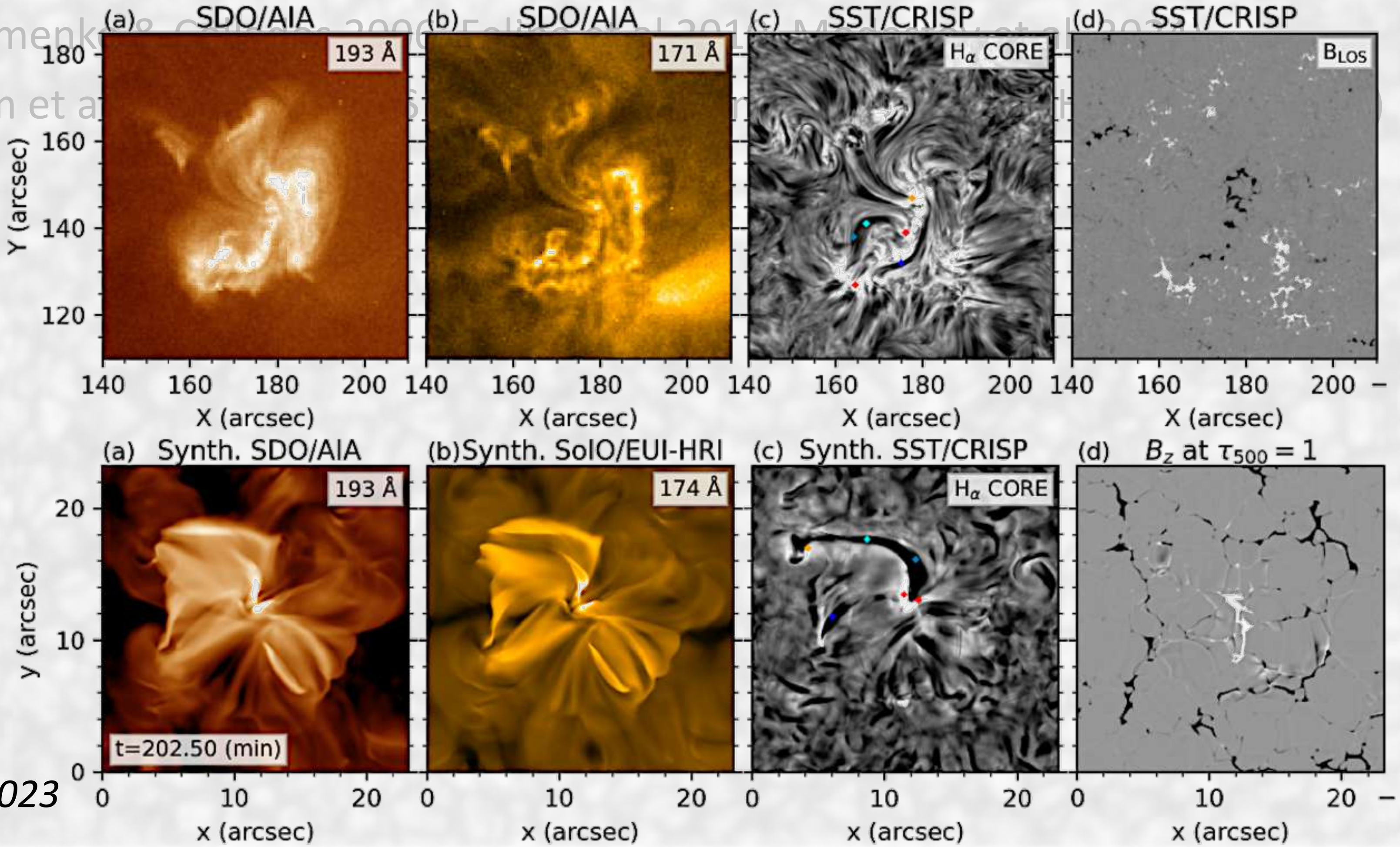


simulations of coronal bright points

Nobrega-Siverio et al. 2023

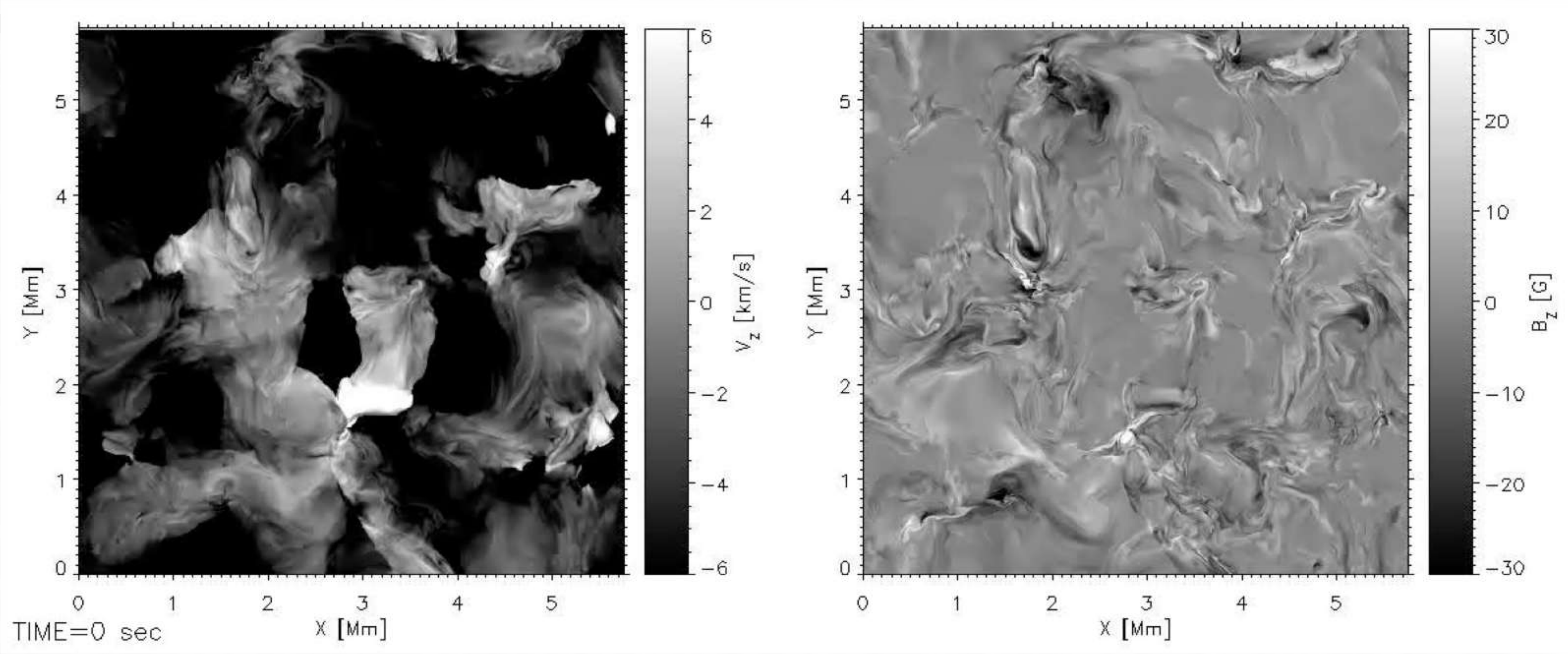
Realistic simulations of (solar) magneto-convection

Several major codes, used with different purposes:

- MANCHA3D (Khomenko & Collados 2006, Felipe et al 2010, Modestov et al. 2024)

  quiet Sun, partial ionization effects

- Antares (Muthsa



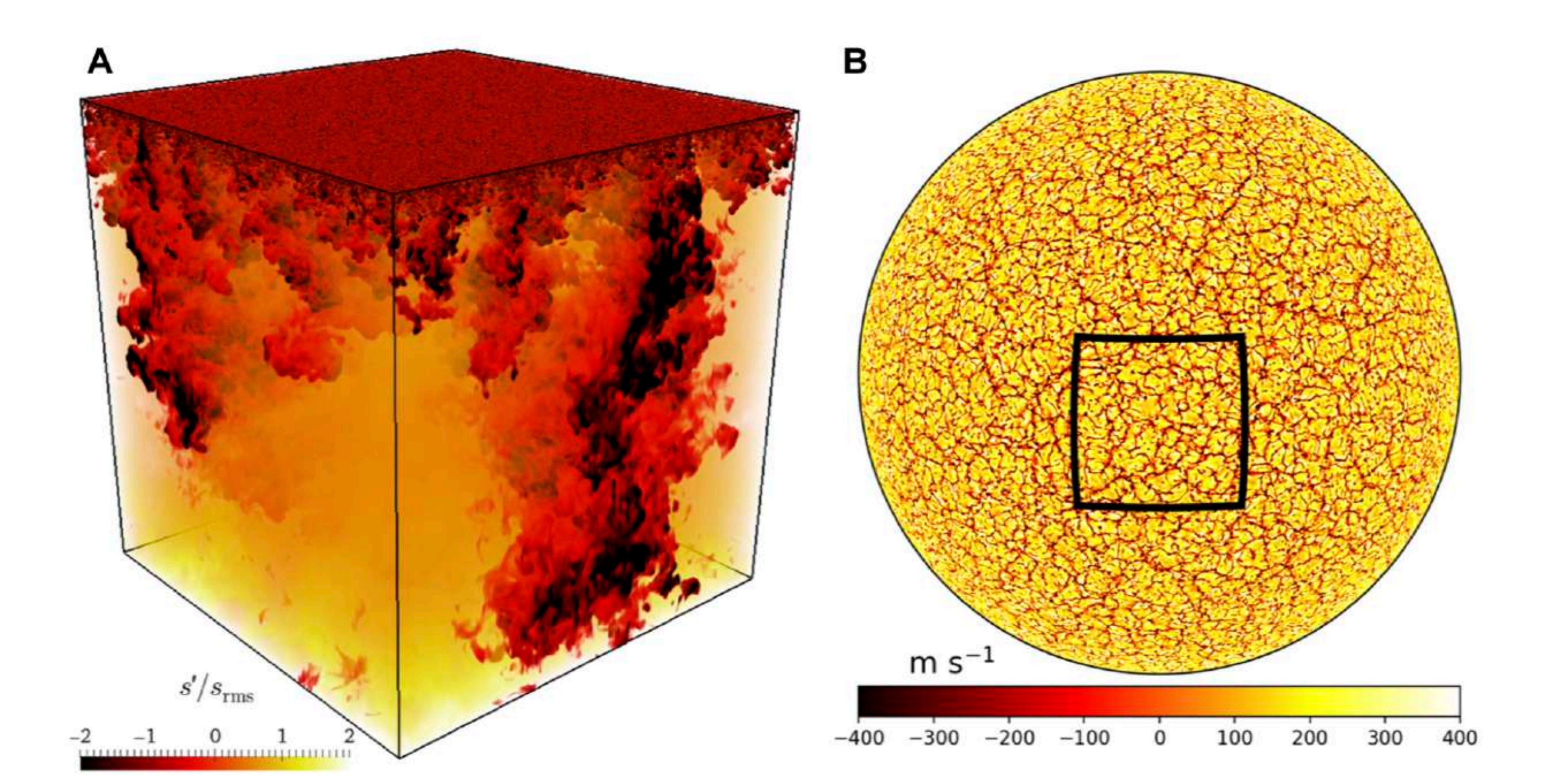
Khomenko et al. 2025

Realistic simulations of (solar) magneto-convection

Several major codes, used with different purposes:

- Antares (Muthsam et al. 2010); RAMSES (Iijima & Yokoyama 2015); R2D2 (Hotta et al. 2019)

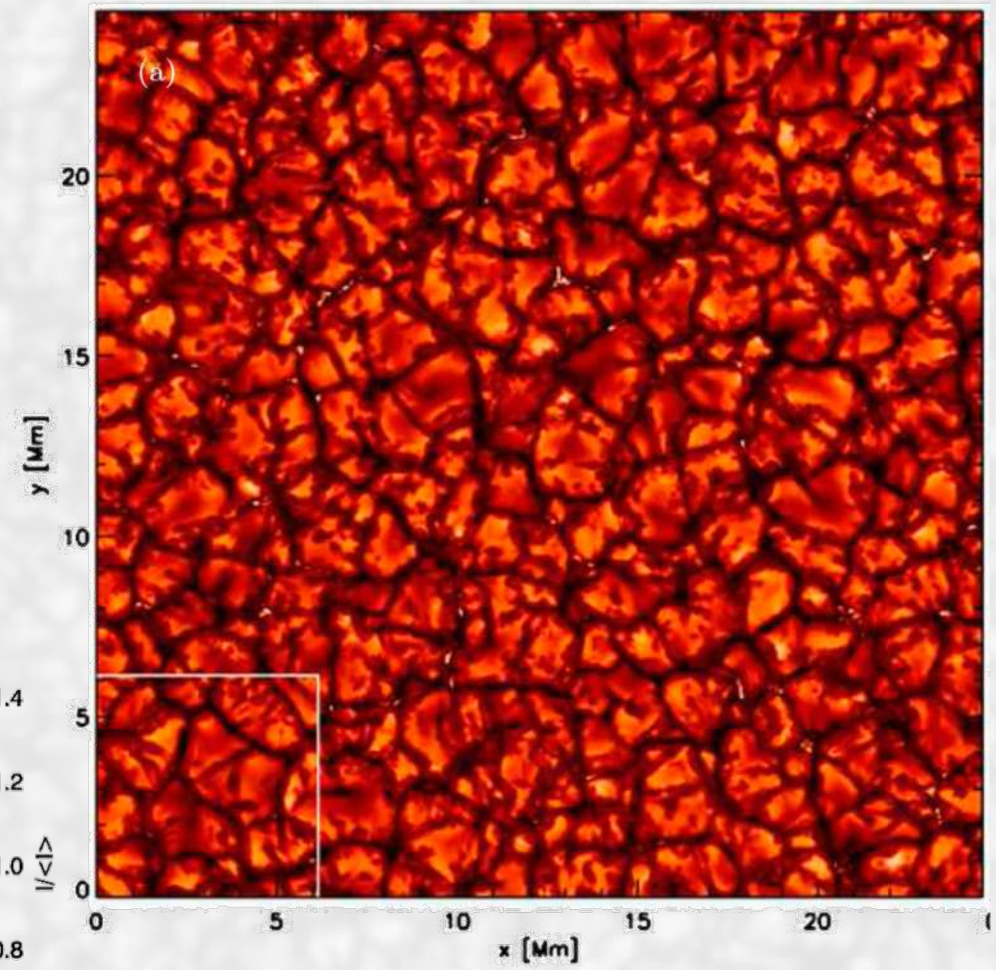
  solar granulation; spicules, flux emergence in star in a box



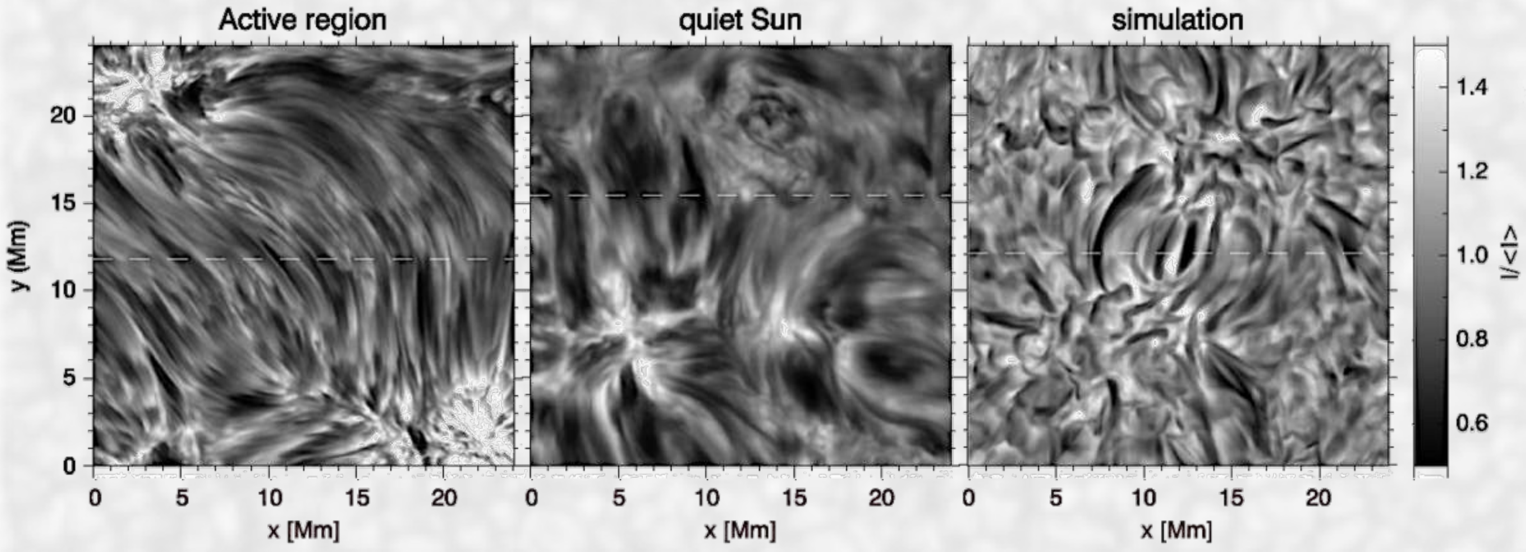
Hotta et al. 2019

So how realistic are realistic simulations?

Simulations in general reproduce photosphere rather well
(*e.g., Rempel et al. 2014 and many other*)



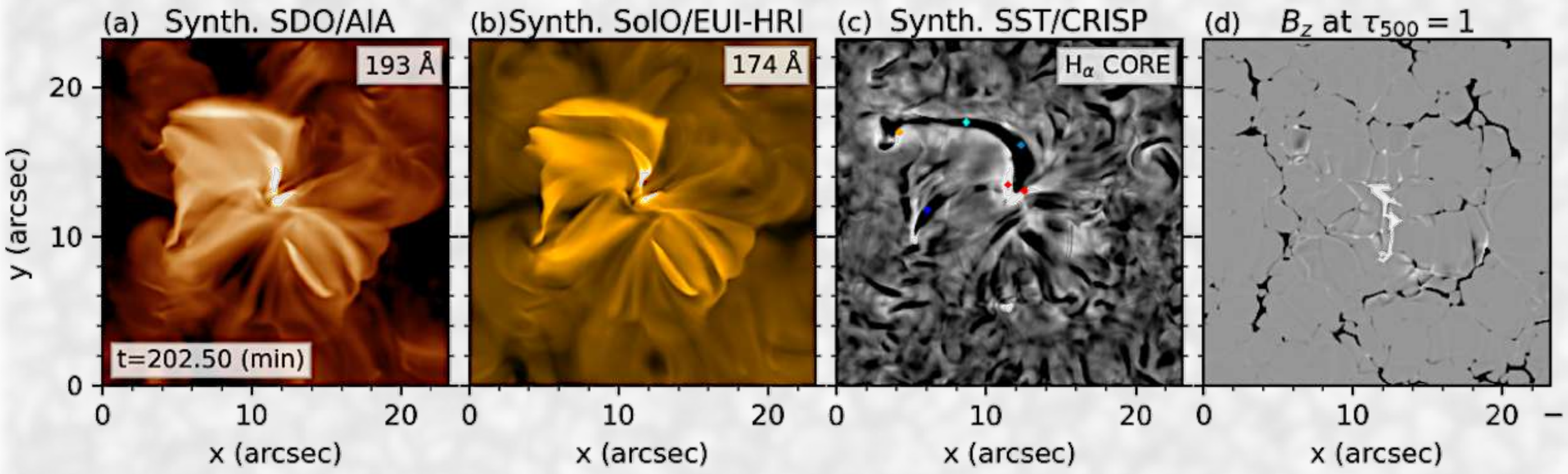
Not so good so far for the chromosphere
(see the comparison in e.g., Leenaarts et al. 2015



So how realistic are realistic simulations?

Heating of chromosphere and corona is maintained through the "physical-like" mechanisms of numerical viscosity and diffusivity

(see e.g., Gudiksen & Norlund 2005, Nobrega-Siverio et al. 2023 and many others)



Physical dissipation/heating mechanisms are typically not resolved in the realistic models

Chromospheric physics is challenging because of non-locality of radiation field and time-dependent ionization, and **weak plasma ionization**

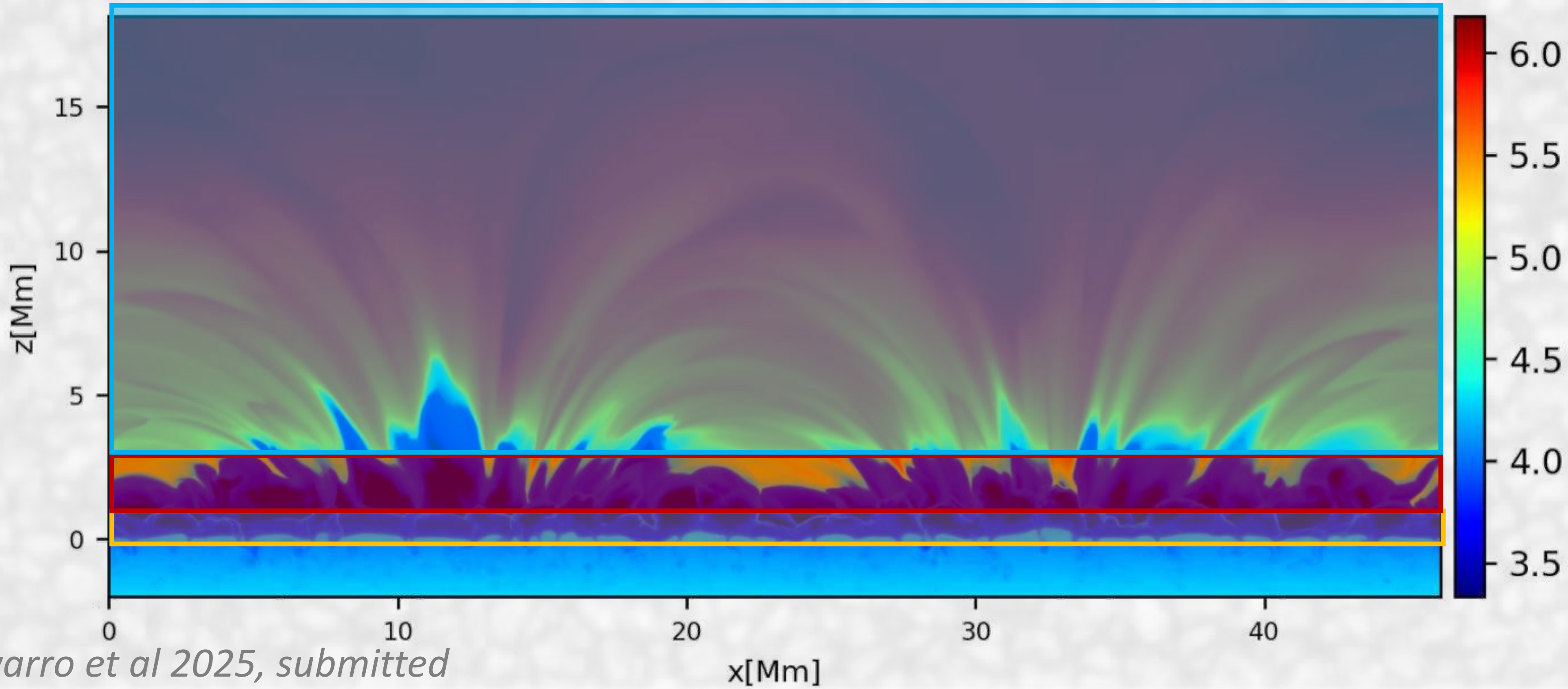
Conditions in the solar atmosphere

Solar atmosphere is a strongly stratified medium

Photosphere is strongly collision-coupled very weakly ionized gas, dominated by gas pressure forces

Chromosphere is much less collision-coupled half-neutral plasma, dominated by magnetic forces

Corona is almost collisionless fully ionized plasma dominated by magnetic forces



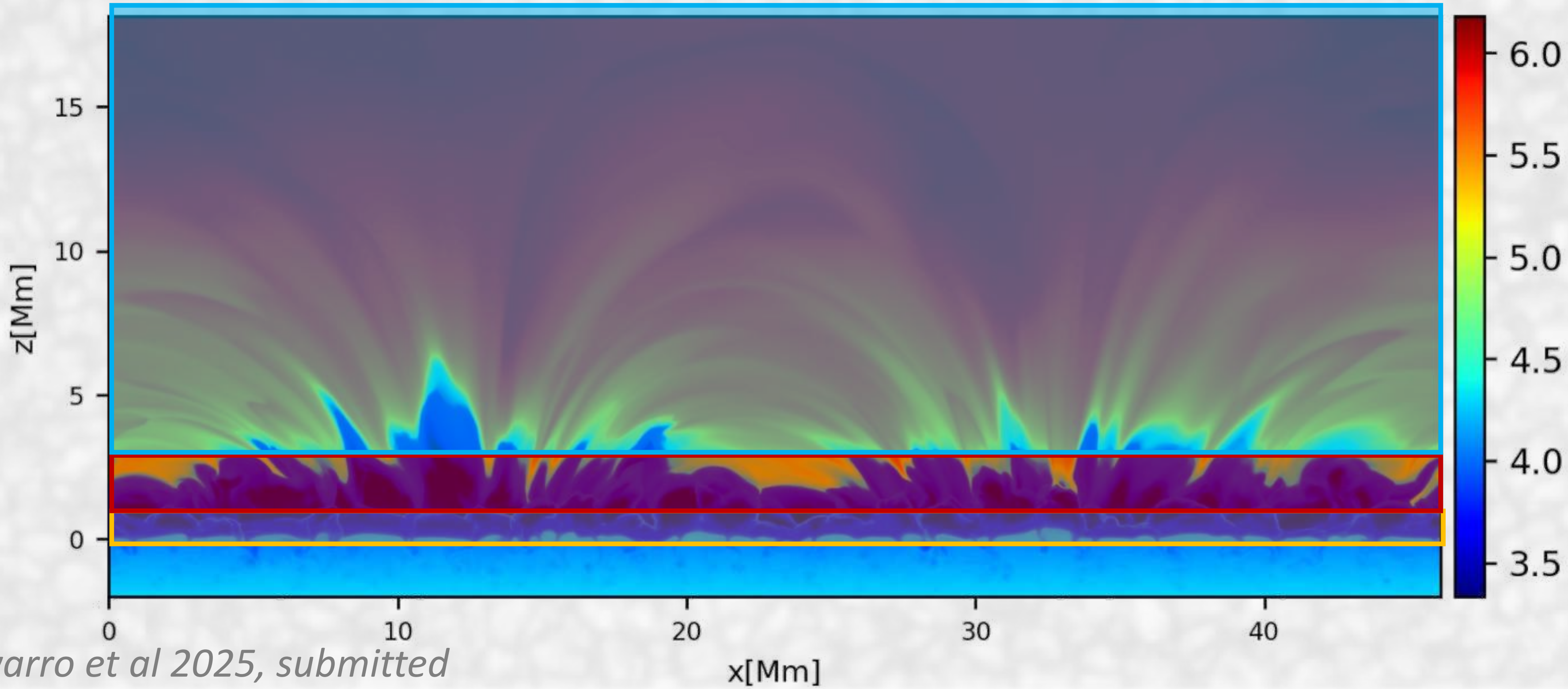
MAGEC code: Navarro et al 2025, submitted

Do we need to care about neutrals?

Q1: What effects are caused by the neutrals on the magnetic connectivity from the interior to the corona ?

Q2: Can we resolve dissipation/heating scales due to neutrals in realistic models?

Q3: Does it help making chromospheric models more realistic?



MAGEC code: Navarro et al 2025, submitted

Main effects caused by neutrals

Assuming plasma is strongly collisional : treat everything as a single fluid

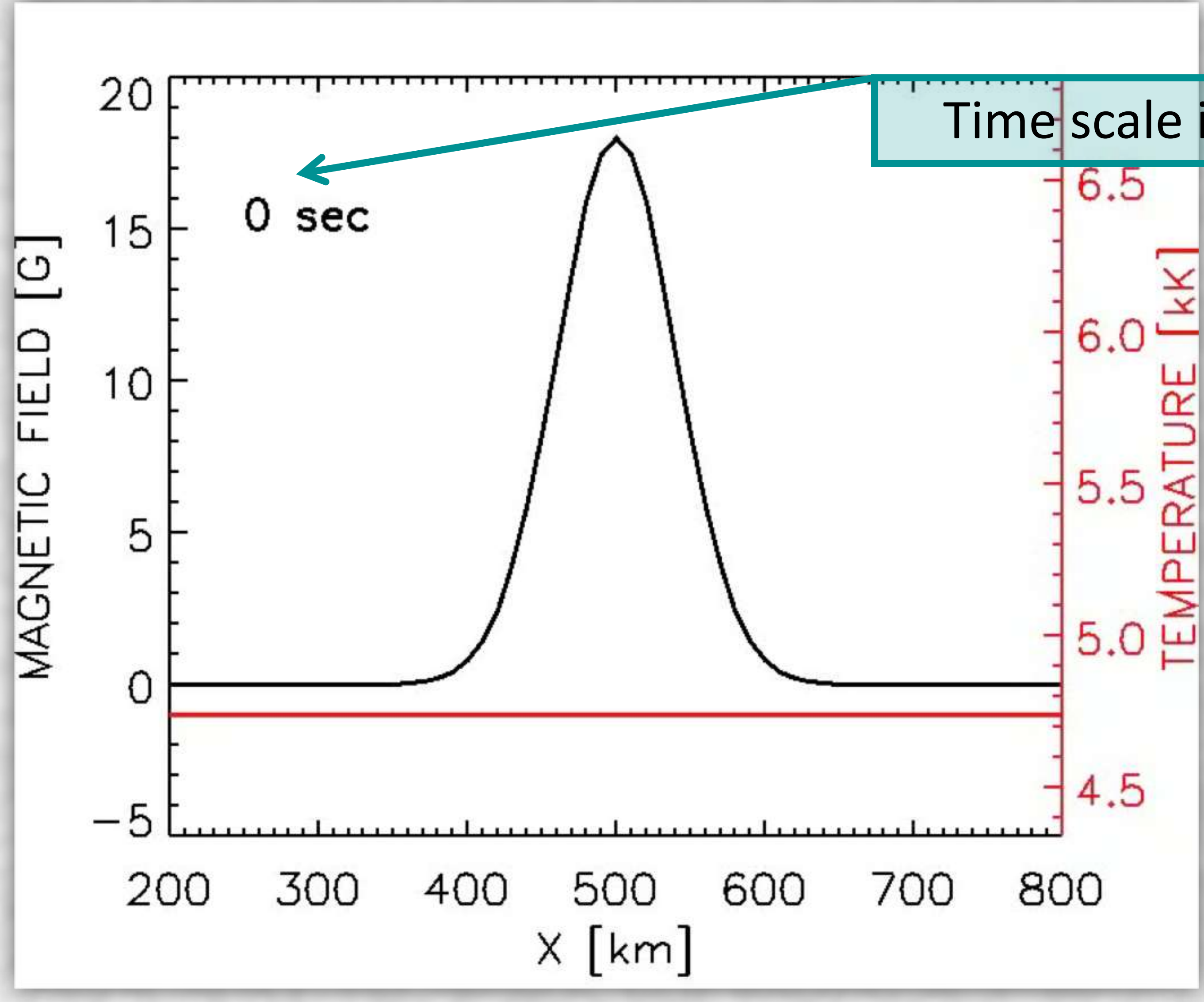
Magnetic field evolution =
- Advection
- Ohmic diffusion
- Hall effect
- Bierman battery effect
- Ambipolar diffusion

Energy evolution =
- Advection
- Radiation
- Ohmic heating
- Ambipolar heating
- …

Ambipolar diffusion

Heating by dissipation of currents perpendicular to the magnetic field

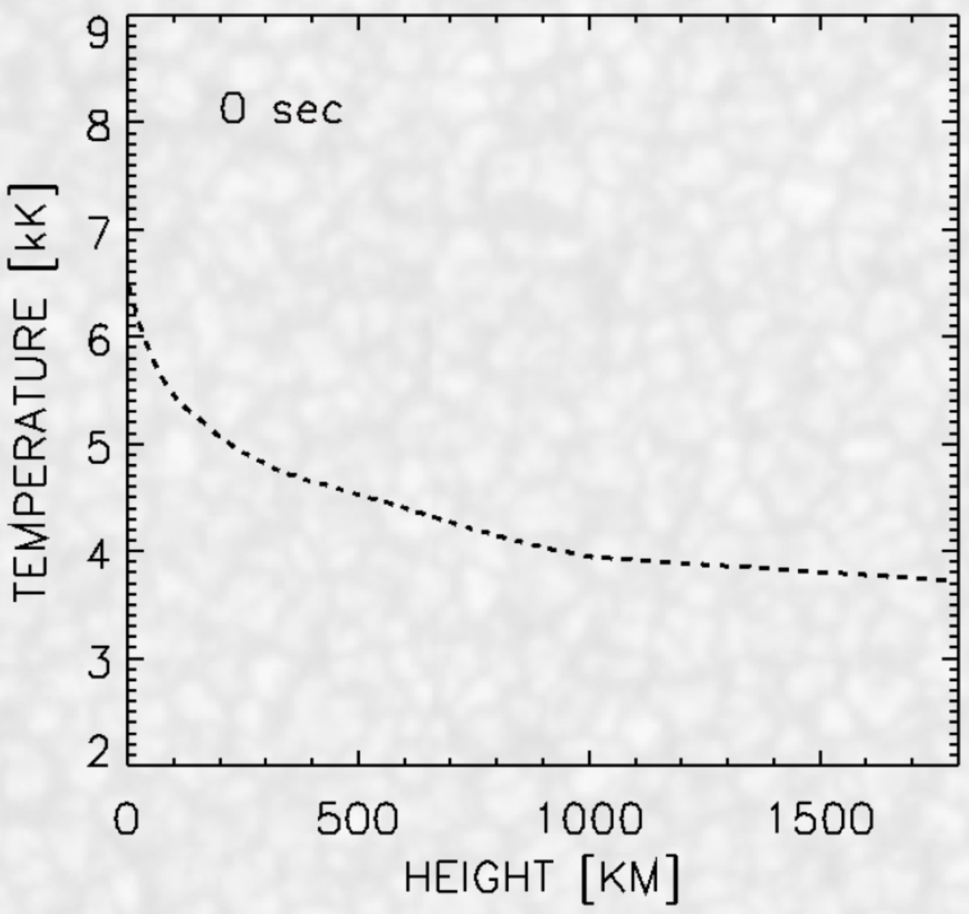
Osterbrock 1961
De Pontieu 1998
Soler et al. 2009, 2015, 2018
Song & Vasyliunas 2011
Khomenko & Collados 2012
Leake & Arber 2006
Martinez Sykora et al. 2012, 2016, 2017, 2023
Khomenko et al. 2018, 2020, 2025

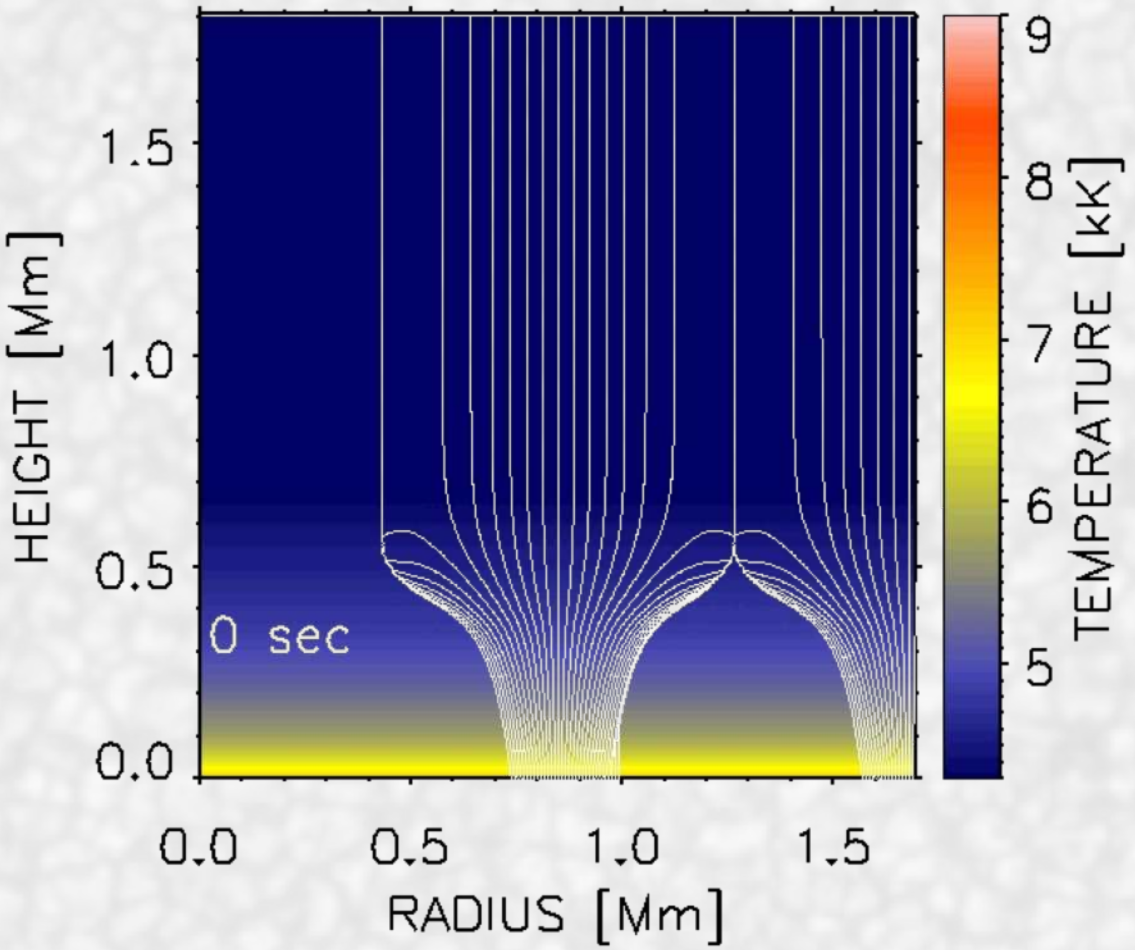


Time scale is important

Ambipolar diffusion

Ambipolar heating could potentially balance radiative losses





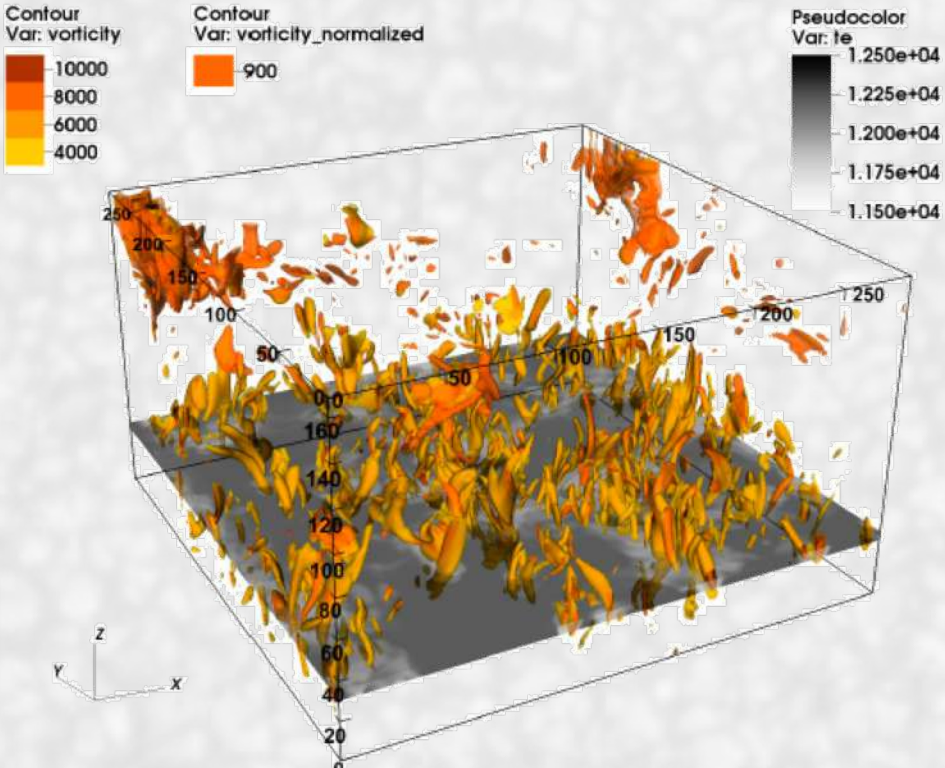
Khomenko & Collados 2012

Hall effect

Partially ionized Hall effect: affects vorticity, generates Alfvén waves; inversely proportional to (very low) ion fraction

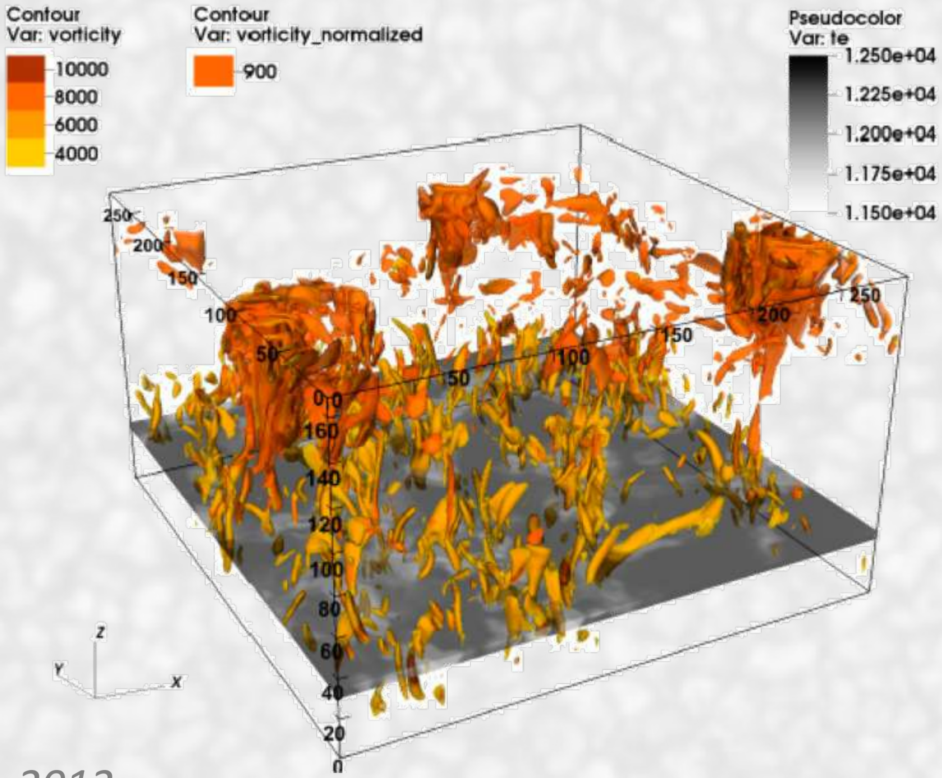
$$|B|_{\text{Hall}} \sim |\vec{\nabla} \times \vec{v}| \frac{\mu_i m_p}{e\xi_i}$$

Hall effect "off"



Hall effect "on"

Stronger vorticity in the chromosphere



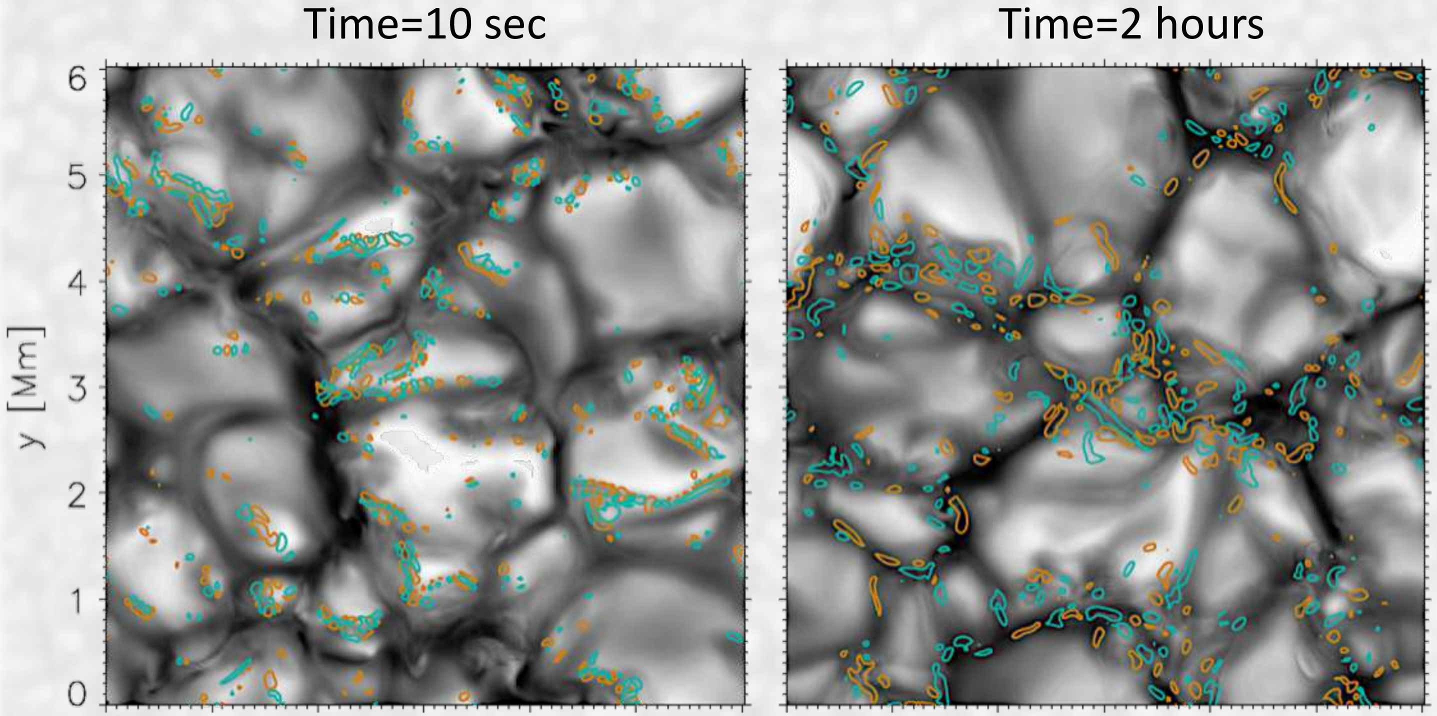
Pandey & Wardle 2008 Pandey 2008, Cheung & Cameron 2012,
Cally & Khomenko 2015, González-Morales et al. 2019, Khomenko et al.2020

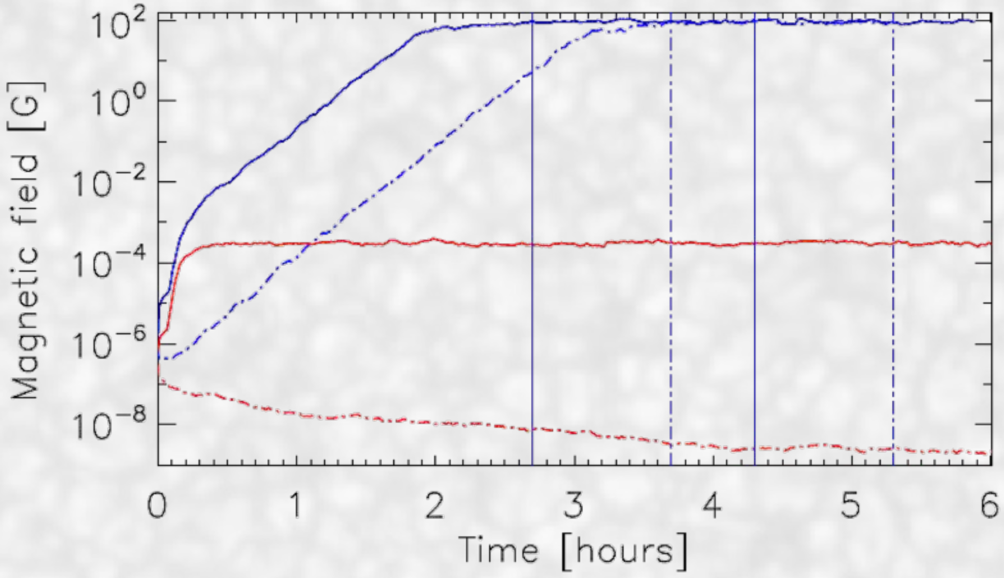
Biermann battery

Seeds magnetic field for local dynamo

$$|B|_{\mathrm{batt}} \sim |\vec{\nabla} \times \vec{v}| \frac{\mu m_p}{e}$$

Cattaneo 1999, Vögler & Schüssler 2007, Rempel 2014, Danilovic 2016, Khomenko & et al. 2018





Codes which incorporate partial ionization effects in solar physics

Bifrost (Nobrega-Siverio et al. 2020)
MURaM (*Rempel & Przybylski 2021*)
Mancha3D (*Khomenko & Collados 2012, González-Morales et al. 2019*)
Lare3D (*Arber et al. 2001*)
AMRVAC (*Keppens et al. 2023*)

} "realistic" simulations

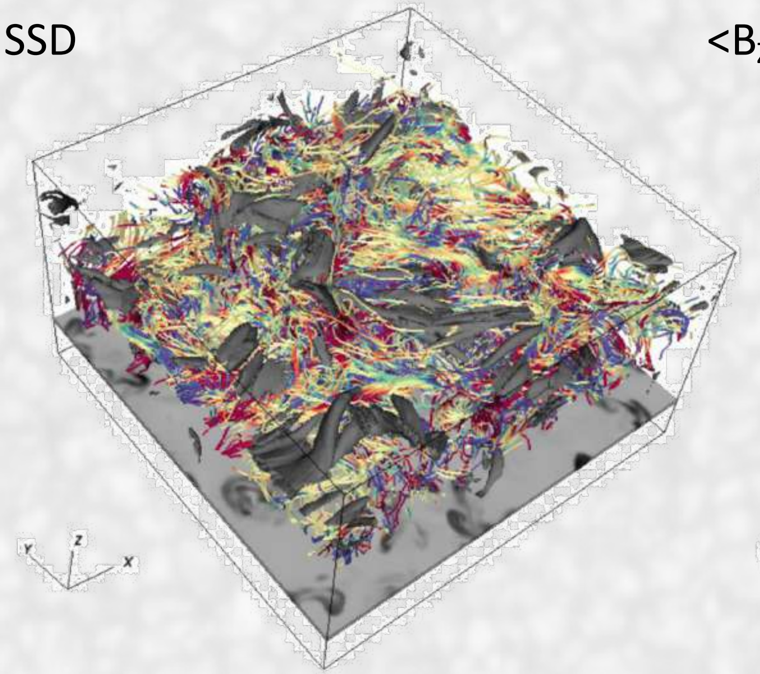
Partial ionization effects are commonly used in general astrophysical codes

PENCIL:: https://pencil-code.nordita.org
ATHENA++:: https://www.athena-astro.app
PLUTO :: https://plutocode.ph.unito.it
RAMSES:: https://ramses.cnrs.fr
ENZO:: https://enzo-project.org

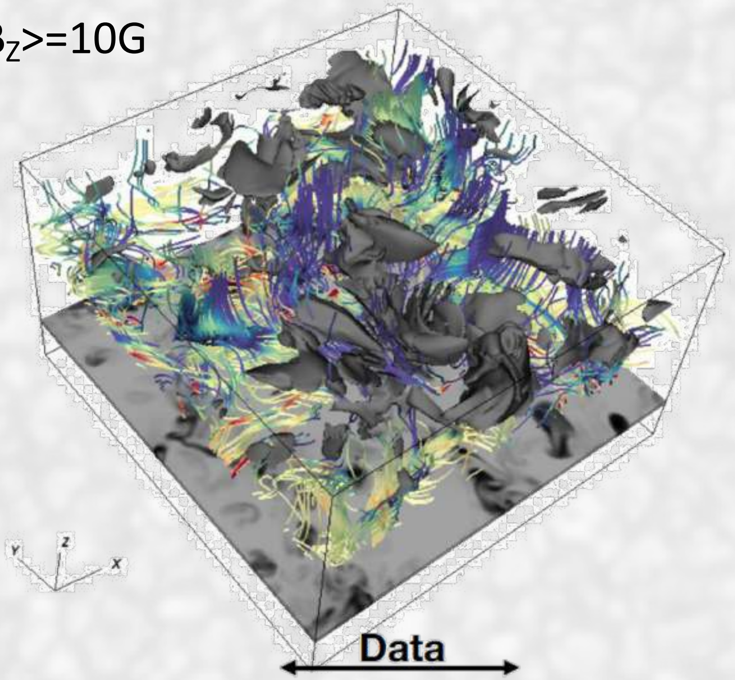
etc..

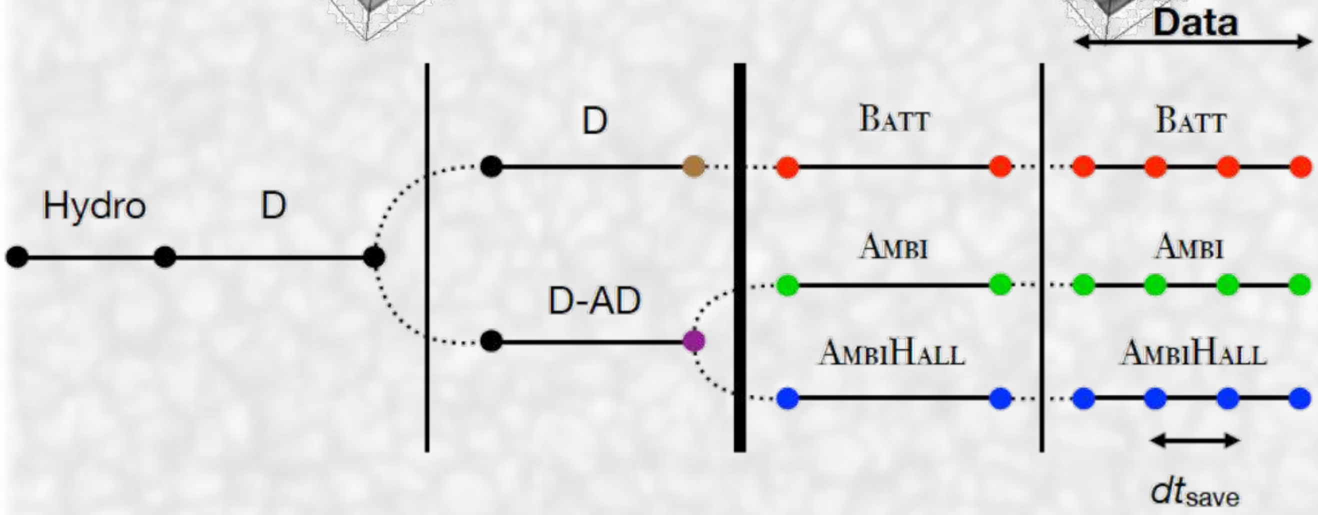
Chromospheric heating by ambipolar diffusion in realistic 3D experiments

SSD

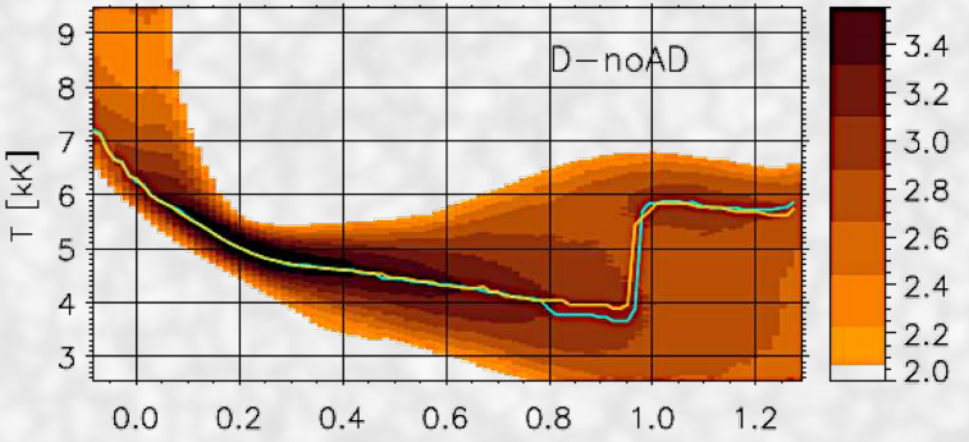


$\langle B_Z \rangle$=10G





SSD



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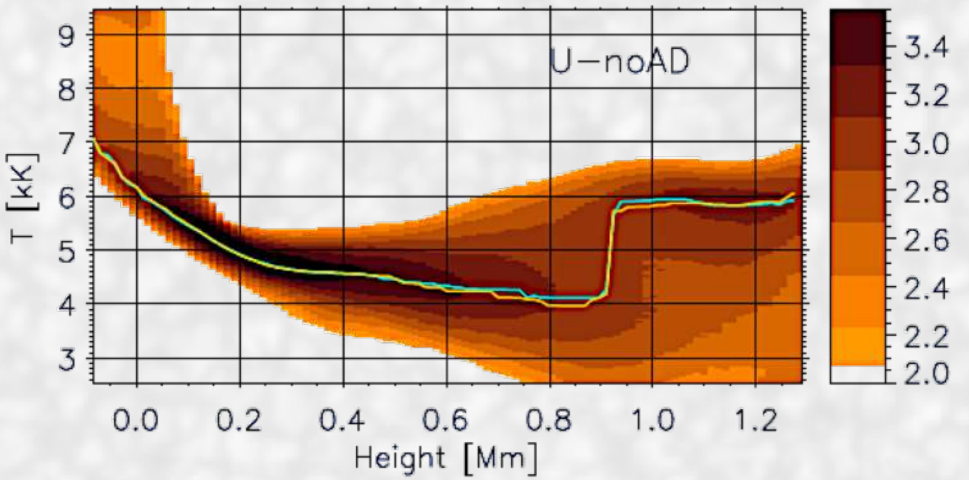
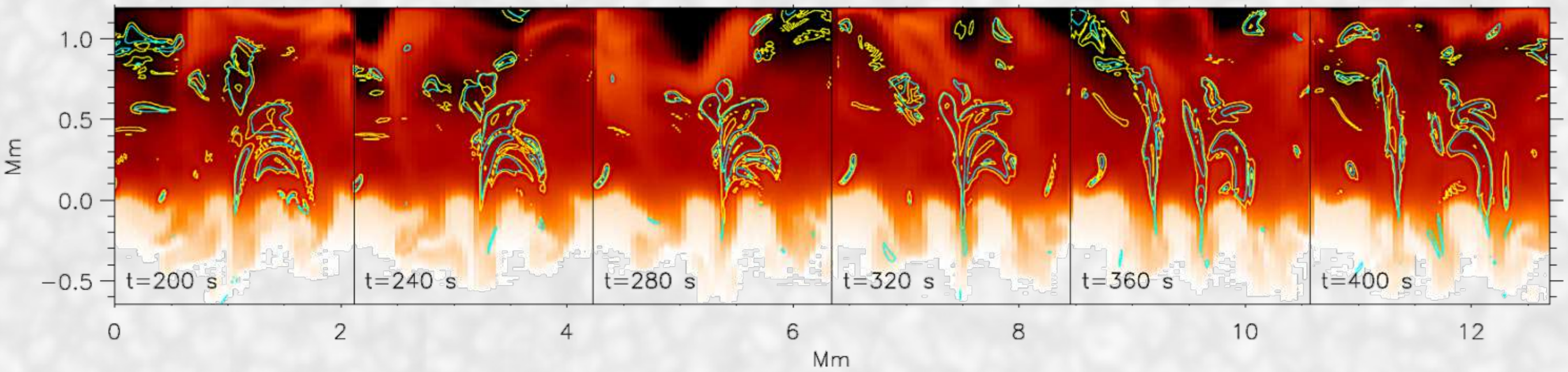


Khomenko, Vitas, Collados, de Vicente 2018; Gonázlez-Morales et al. 2019; Khomenko et al. 2020

Chromospheric heating by ambipolar diffusion in realistic 3D experiments

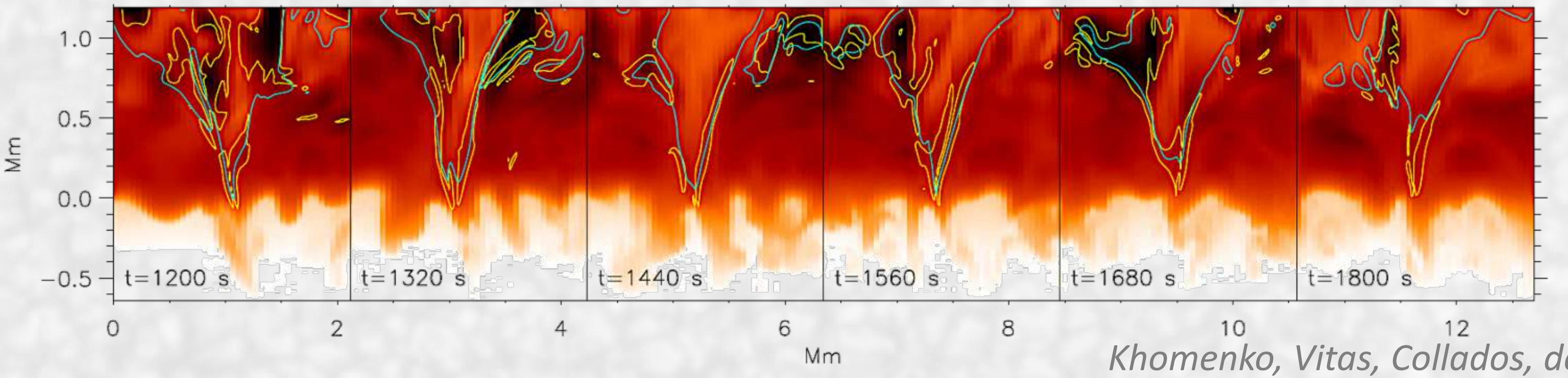
SSD model :: heating along magnetic loops, no relation to shocks



$$\eta_A J_\perp^2$$

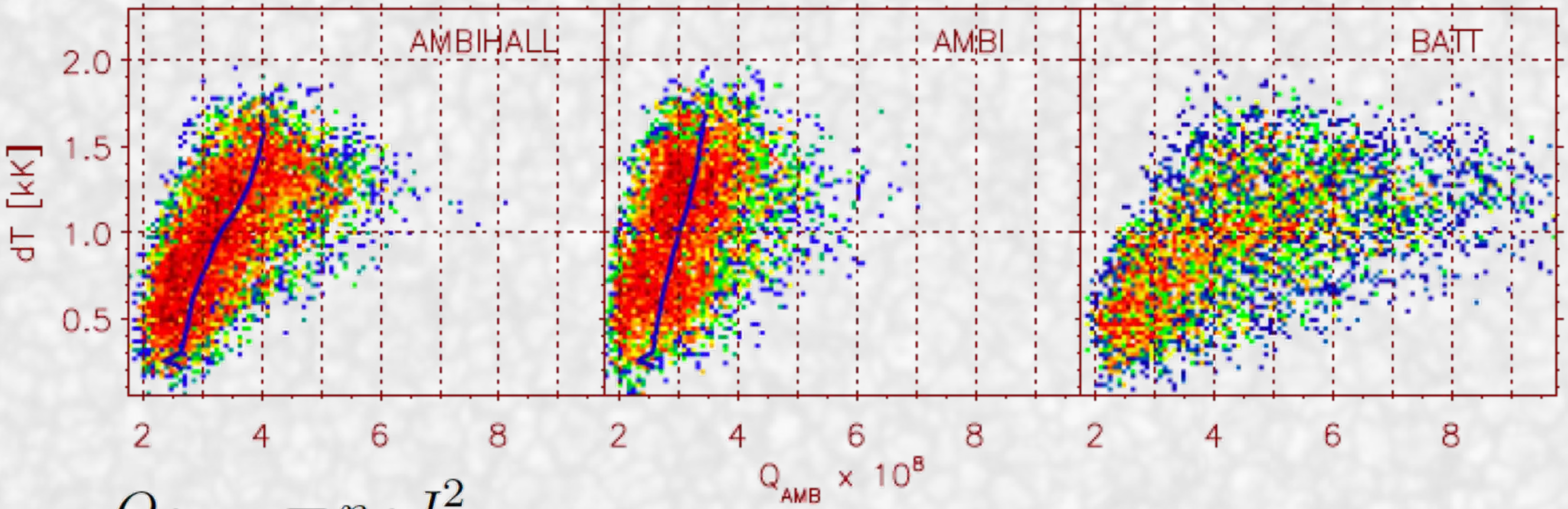
$$\eta_A = \frac{\xi_n^2 |B|^2}{\alpha_n}$$

Unipolar B model :: heating in rarefactions associated to shocks



Khomenko, Vitas, Collados, de Vicente 2018; Gonázlez-Morales et al. 2019; Khomenko et al. 2020

Chromospheric heating by ambipolar diffusion in realistic 3D experiments

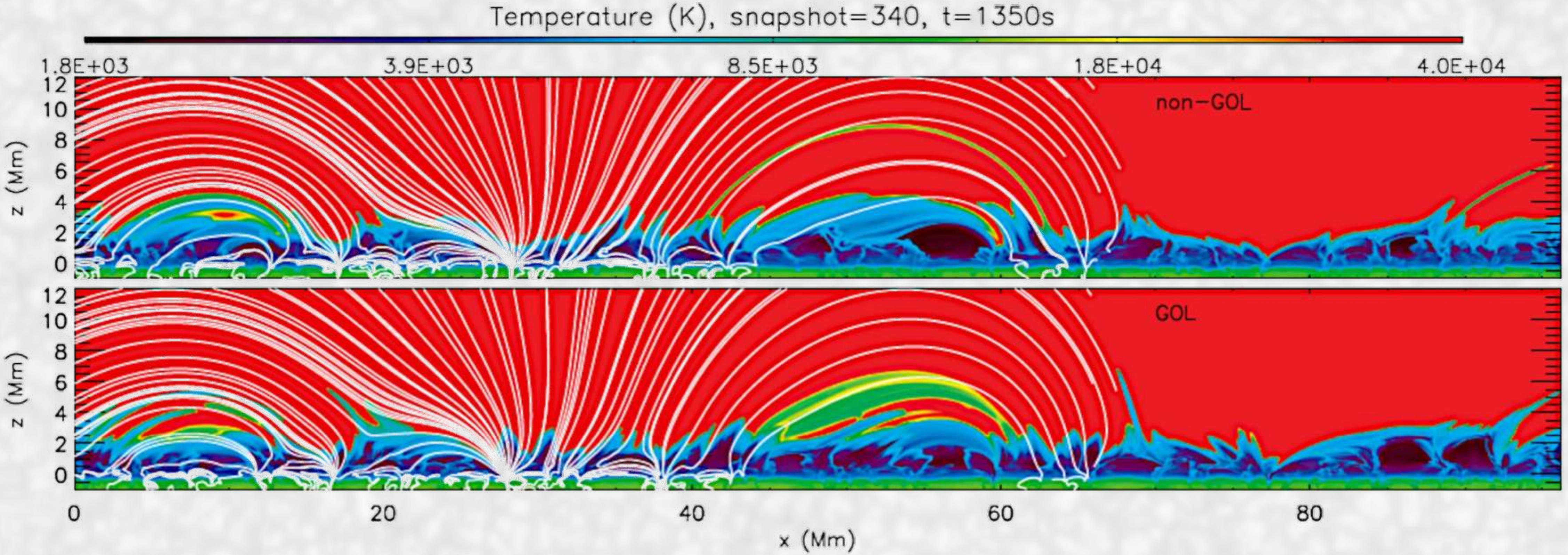


$$Q_{\rm AMB} = \eta_A J_\perp^2$$

- ✓ Temperature difference between snapshots separated 100 s in time vs Q_{AMB}
- ✓ Strong correlation only in models with ambipolar diffusion
- ✓ Evidence of efficient heating due to partial ionization effects

Gonzalez-Morales & et al. 2020; Khomenko & et al. 2020

Chromospheric heating by ambipolar diffusion in realistic experiments

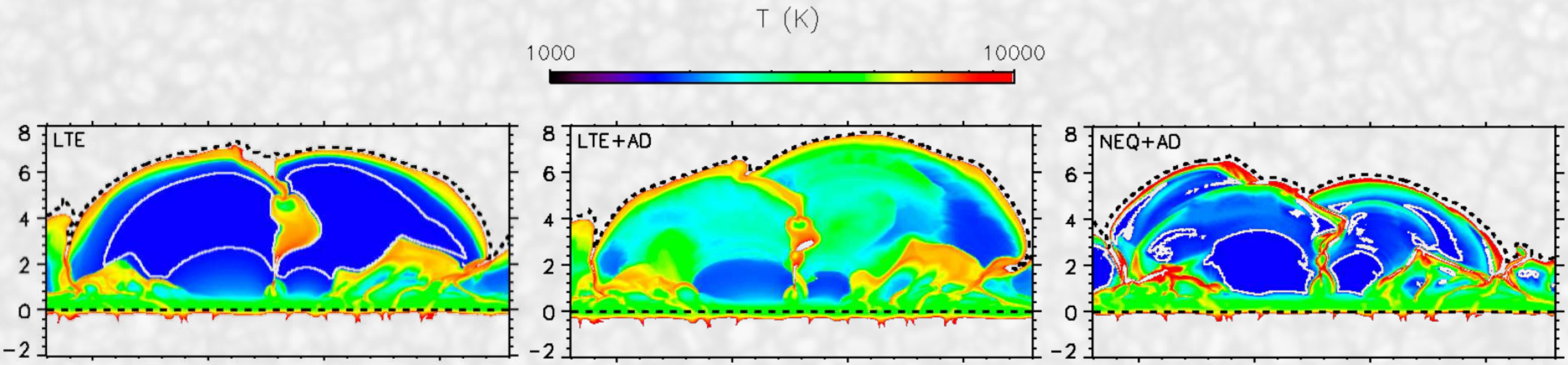


- AD increases the temperature in the chromosphere
- AD concentrates electrical currents, leading to more violent jets
- **Formation of longer and faster spicules**
- Decoupling of the plasma and magnetic field in spicules

Martínez-Sykora et al. 2012, 2017

There is more to the story: non-equilibrium ionization of Hydrogen, etc

2.5D flux emergence experiments



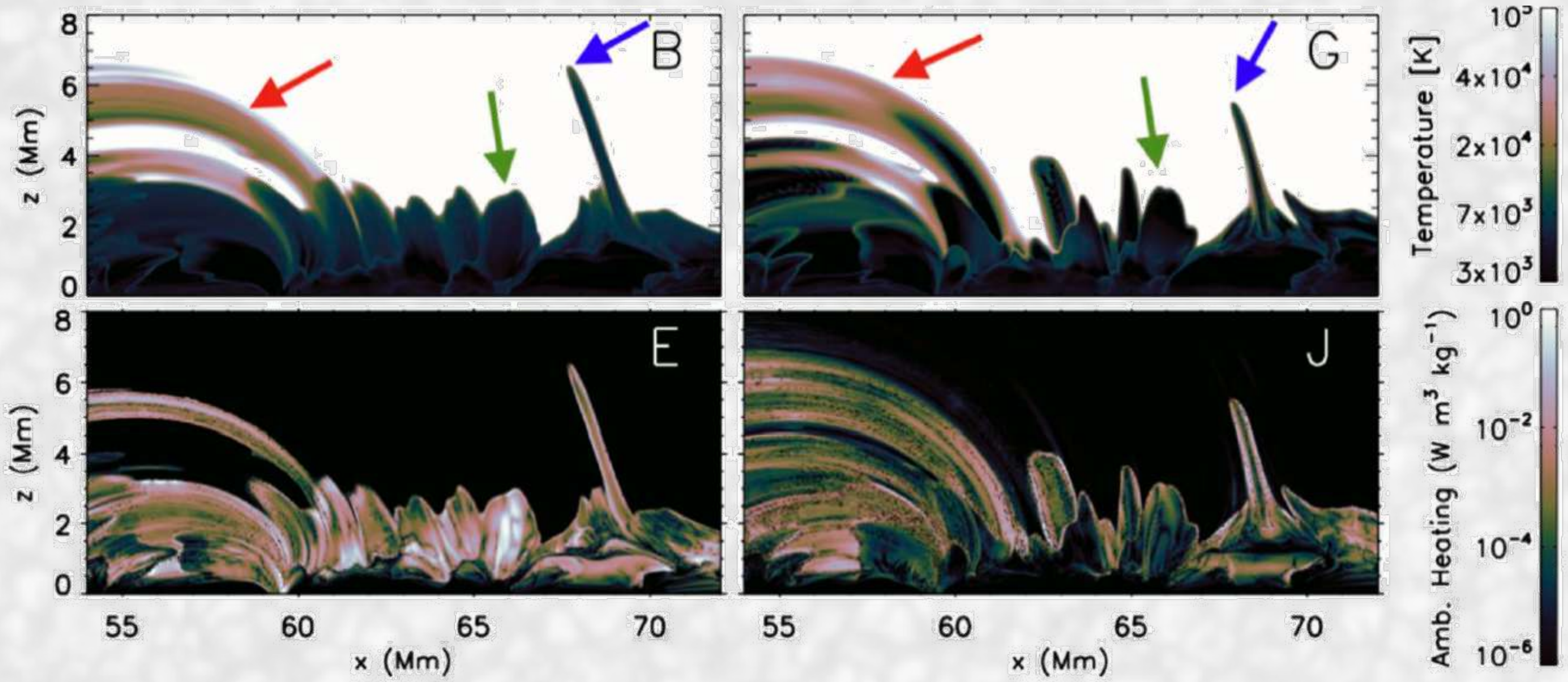
- Non-equilibrium ionization (NEI) + AD are crucial for the resulting temperature structure
- AD removes cool temperatures associated with flux emergence
- NEI results in higher ionization fraction and makes AD less effective

Nobrega-Siverio et al 2020

There is more to the story: non-equilibrium ionization of Hydrogen & Helium

Thermal structure of shocks, spicules, low-lying loops, and the transition region is affected by both:
AD and non-equilibrium ionization

Instantaneous ionization (LTE) Time-dependent ionization (NEI)



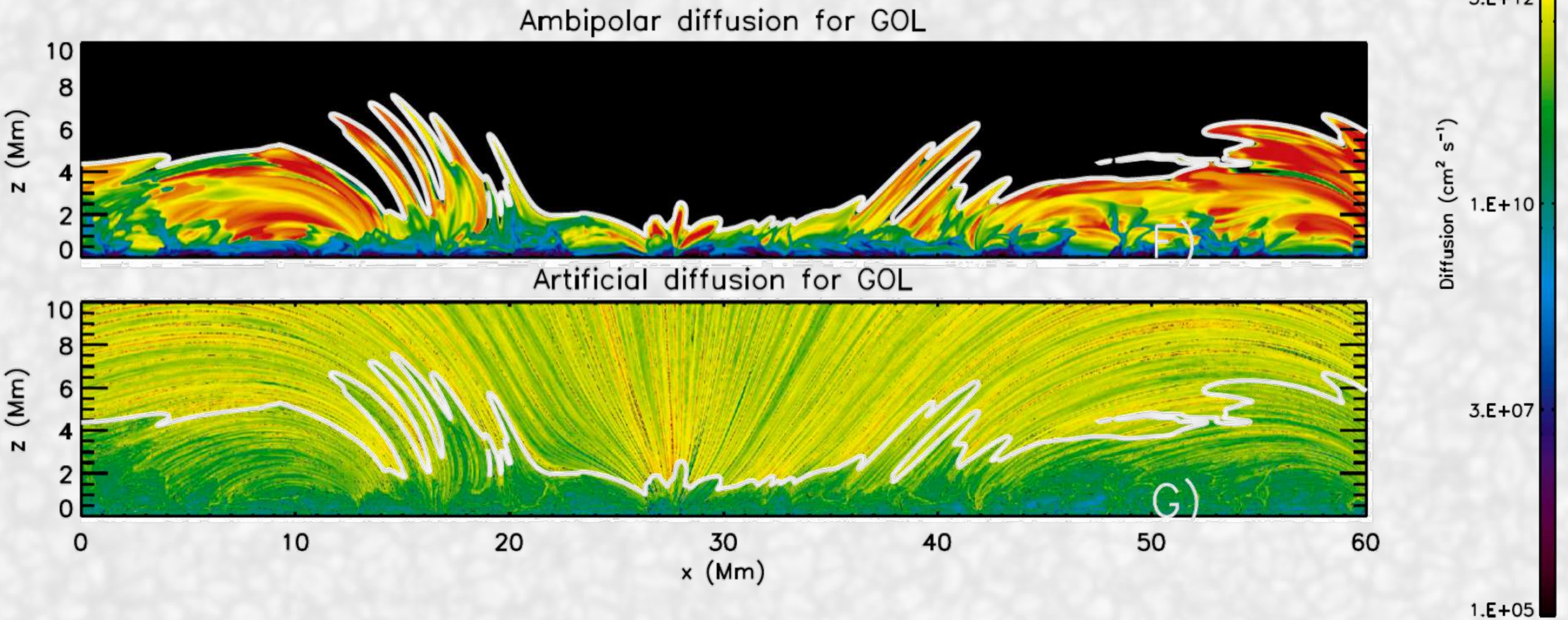
- Ionization fraction in NEI vs LTE is high in the cool rarefied regions => AD action decreases by orders of magnitude
- Ionization fraction in NEI vs LTE decreases for T> 10^4 compared to => AD becomes much larger in high chromosphere

Martínez-Sykora et al. 2017, 2020

How large is ambipolar heating compared to numerical heating?

AD diffusion is firmly above the numerical one in the upper chromosphere and spicule material

AD typical scales reach p to 10-100 km, compared to grid size of 16 km in *Martinez-Sykora et al. 2020*

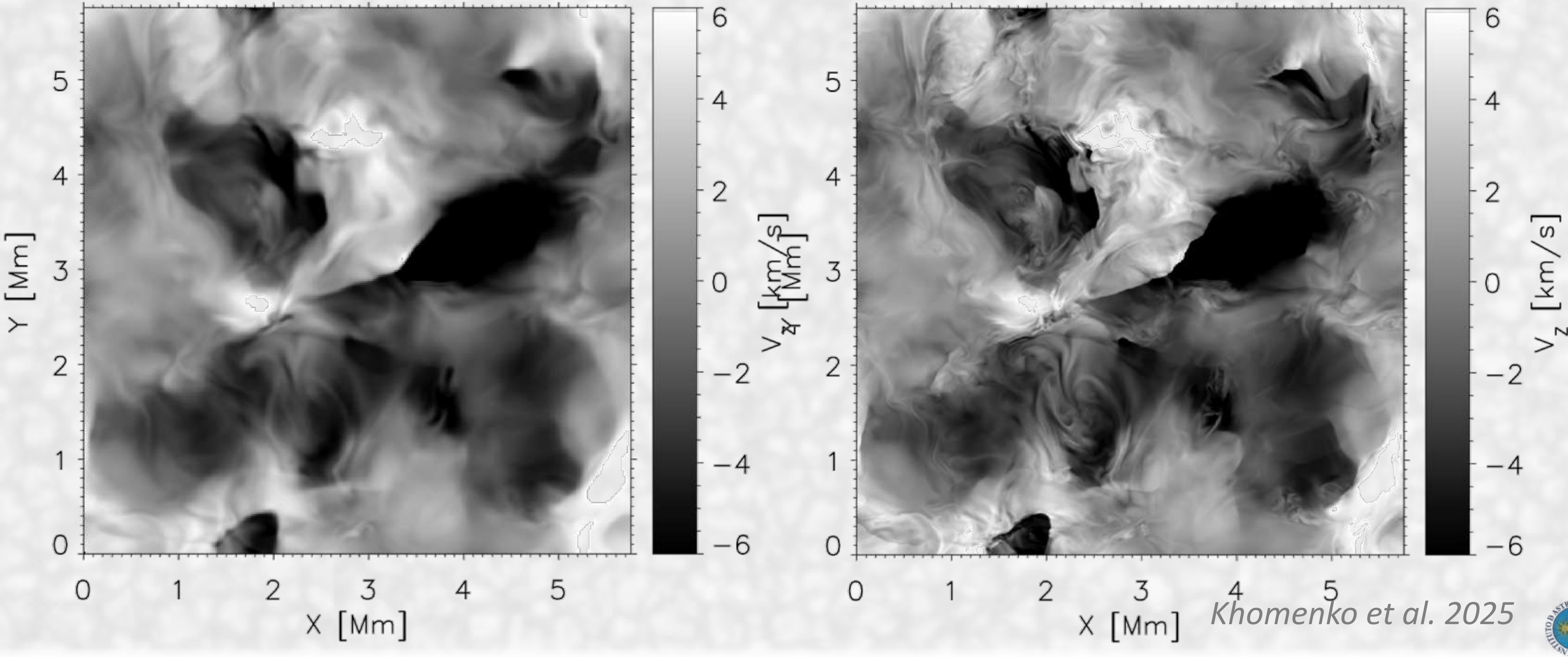


Rempel & Przybylski 2021; Martínez-Sykora et al. 2017, 2023

AD effect scaling with numerical resolution in realistic experiments

- Series of numerical experiments at **20, 10 & 5 km** horizontal resolution
- SSD and vertical implanted field models
- Compare **simulations with/without ambipolar diffusion "one-to-one"** (AD, main PI effect)

SSD **20 km** Velocity at 840 km above the photosphere SSD **5 km**



Khomenko et al. 2025

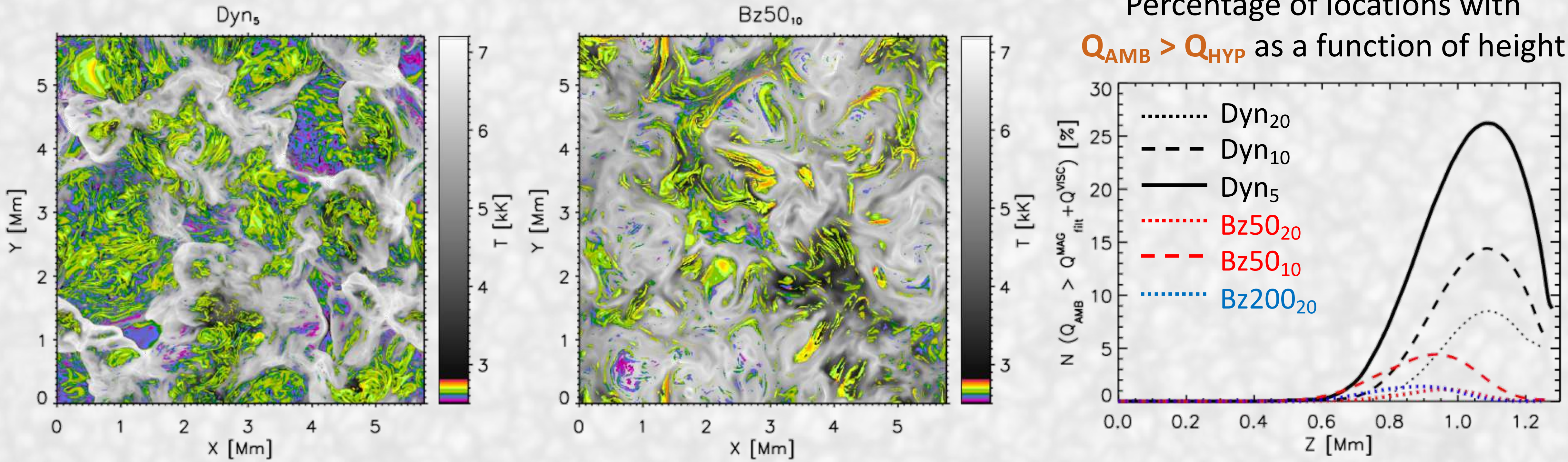
How well do we resolve the scales?

Compare Q_{HYP} with ambipolar heating Q_{AMB}

Color marks locations with $Q_{AMB} > Q_{HYP}$ **at ~1 Mm** above the photosphere

Percentage of locations with

$Q_{AMB} > Q_{HYP}$ as a function of height

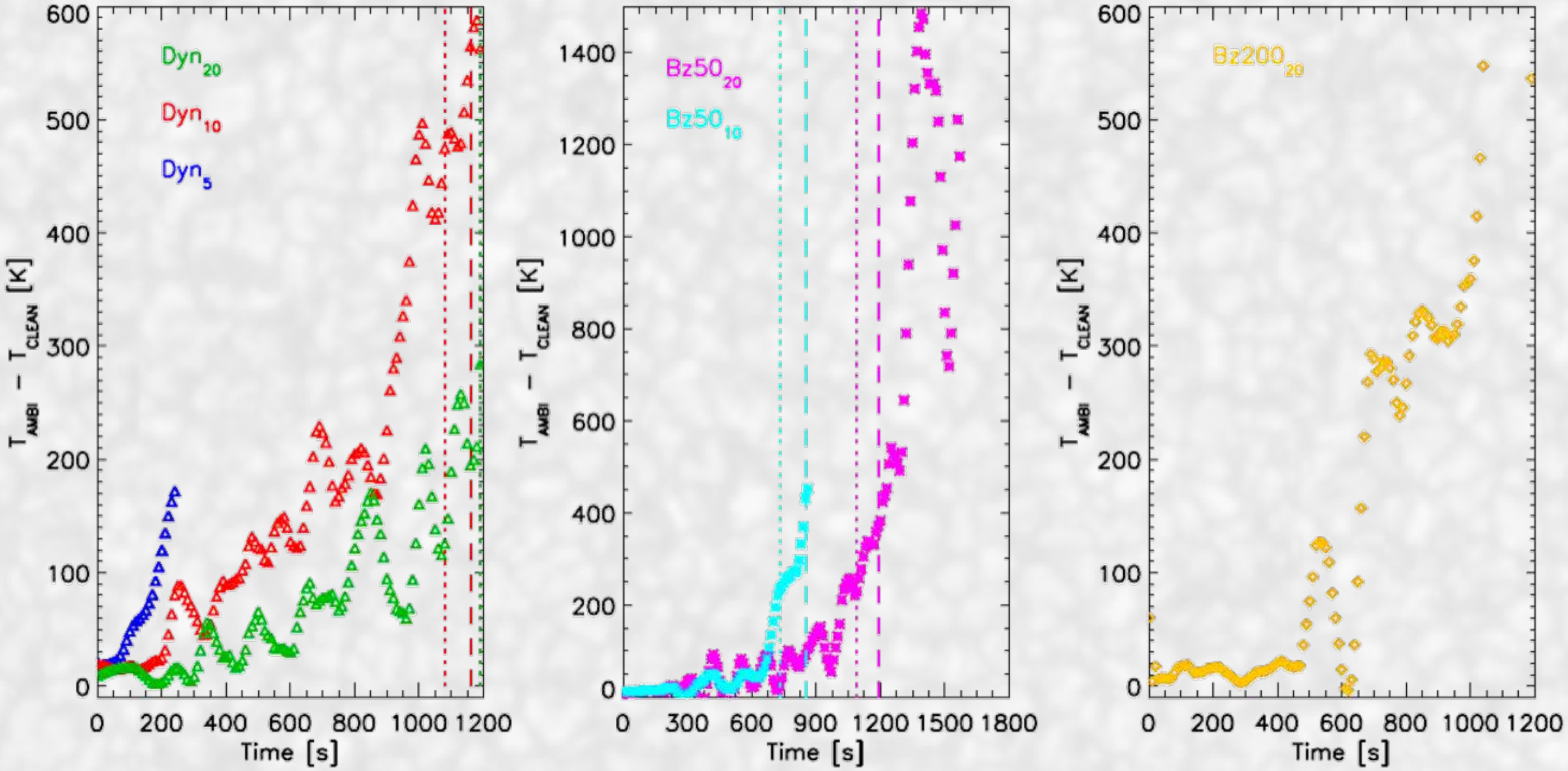


- Percentage of the "resolved" points increases with resolution
- We resolve ambipolar heating in 25% of points in the best case of Dyn_5
- "Resolved" point mostly belong to cool rarefied areas

Khomenko et al. 2025

Effects for temperature: time evolution

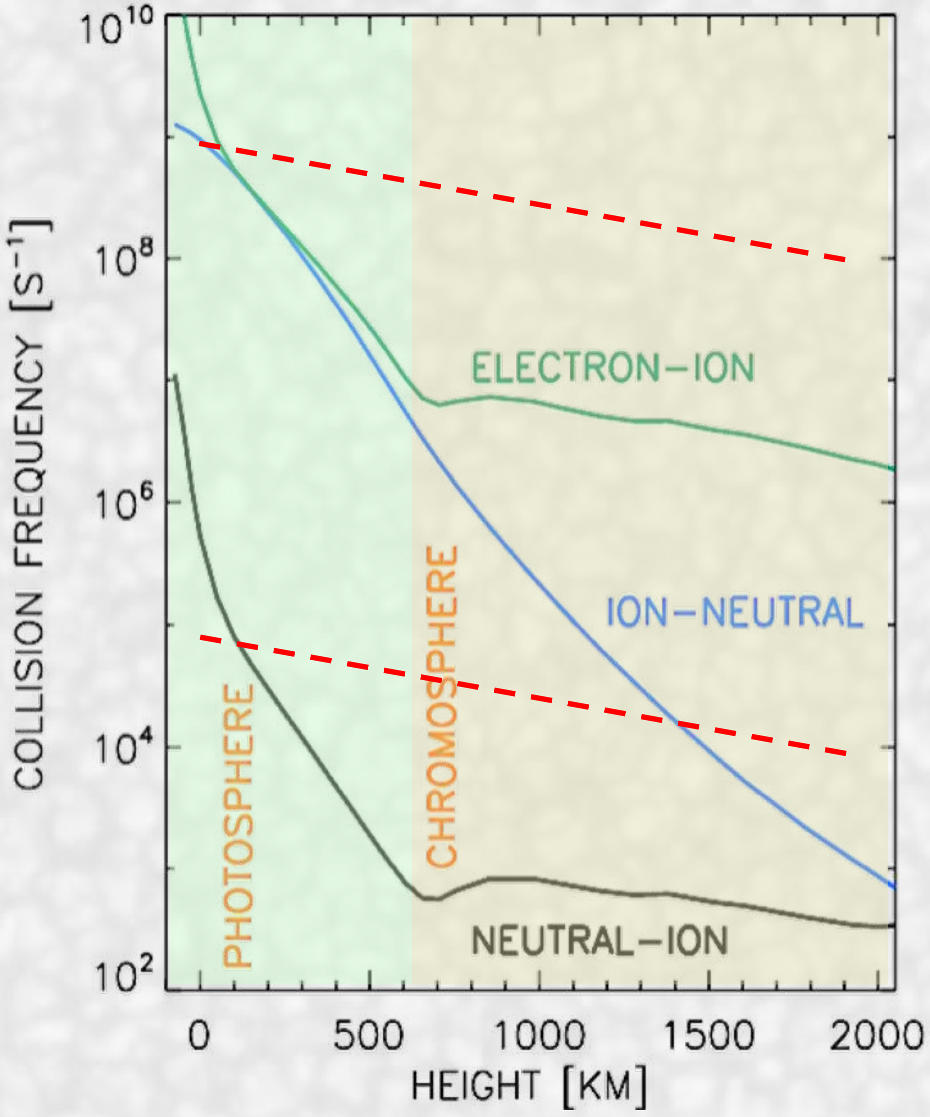
T_{AMBI} - T_{CLEAN} at the locations locations with **$Q_{AMB} > Q_{HYP}$ & heights between 1.0-1.3 Mm** as a function of time



- "Ambipolar" runs are hotter, temperature difference increases with time
- The magnitude of the temperature increase scales with the resolution
- No signs of saturation at our best 5 km resolution

Is ambipolar diffusion all we need?

Upper chromosphere can be intrinsically multi-fluid: ionized and neutral species are not collisionally-coupled



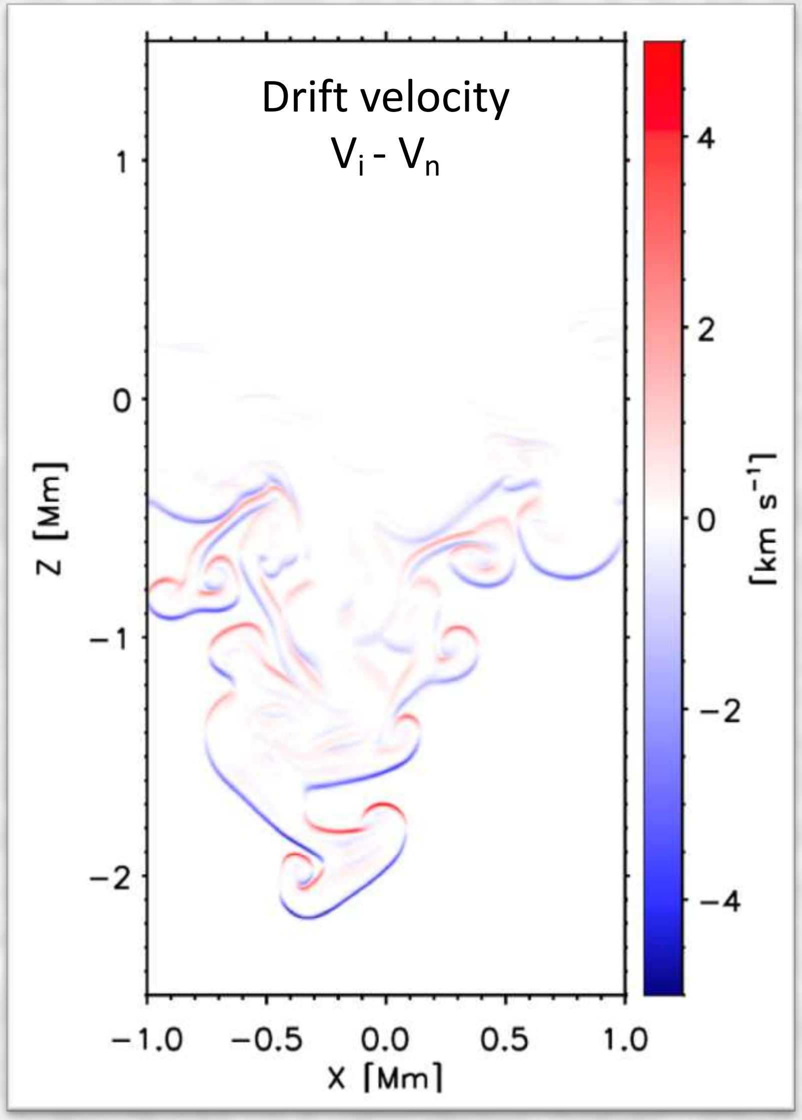
Multi-fluid simulations is a new exciting area

Growing evidence of uncoupled behavior of neutrals & charges at the transition layers: **simulations and observations**

(*Popescu Braileanu et al. 2021ab, 2023, Popescu Braileanu & Keppens 2025, Martinez Gomez et al. 2022, Khomenko et al. 2015, 2016, Wiehr et al. 2019, 2021, 2025; Gomzalez Manrique et al. 2024*)

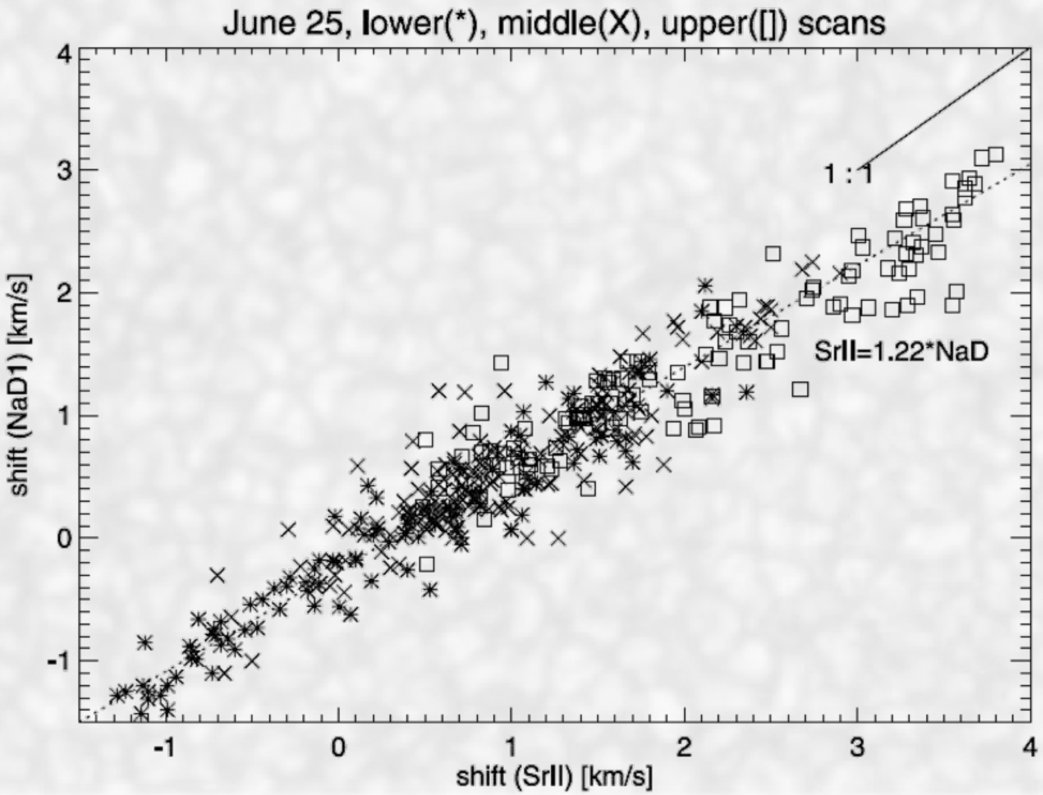
Is ambipolar diffusion all we need?

Upper chromosphere can be intrinsically multi-fluid: ionized and neutral species are not collisionally-coupled



Growing evidence of uncoupled behavior of neutrals & charges at the transition layers: **simulations and observations**

Wiehr et al. 2019



Multi-fluid physics: multiple ionized & neutral species evolving separately

Codes that can do multi-fluid

PIP (Hillier et al. 2016)

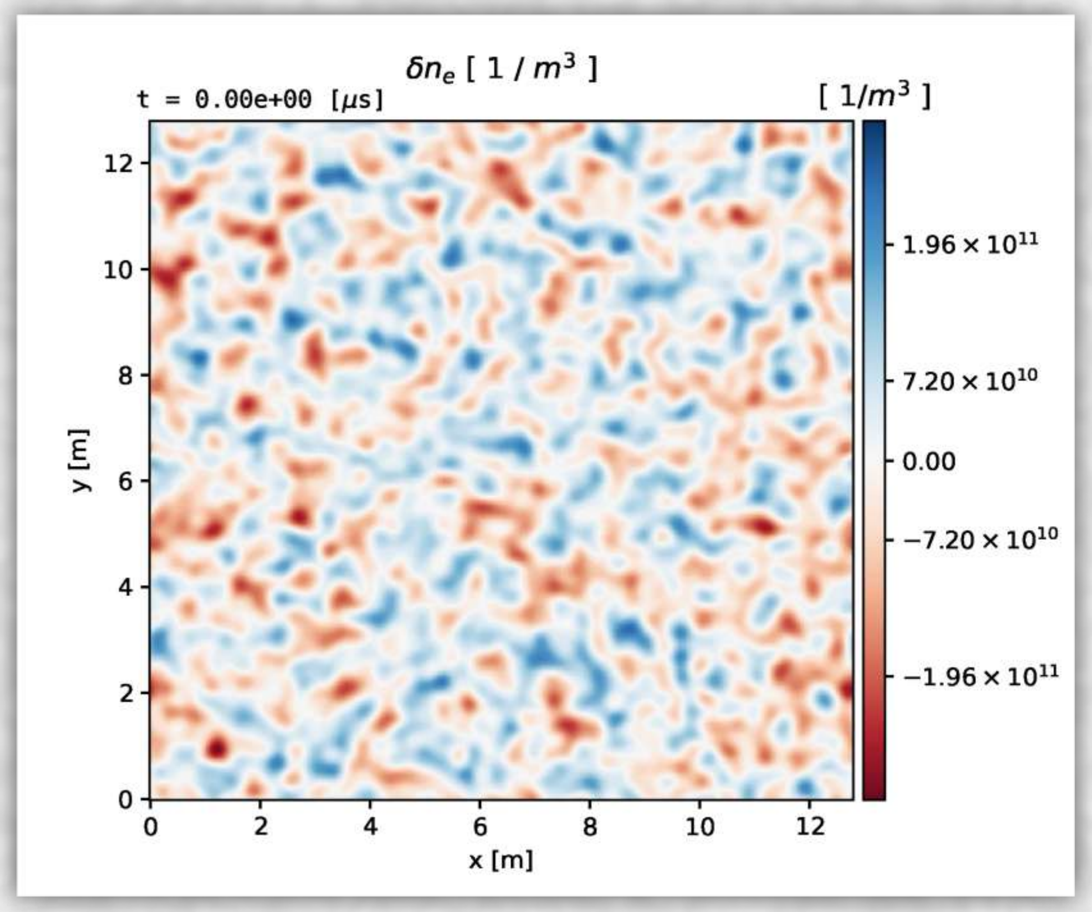
Mancha-2f (Popescu Braileanu et al. 2019a)

AMRVAC (Keppens et al. 2023)

Ebysus (Martinez-Sykora et al. 2020, 2023)

Joanna (Wójcik et al. 2020)

None of them is capable yet of fully realistic simulations



New effects

Farley-Buneman instability :: neutral drag on ions across magnetic field while electrons stay magnetized

(Fontenla et al 2005, 2008, Madsen et al 2014, Fletcher et al 2018, Evans et al. 2023)

Multi-fluid physics: multiple ionized & neutral species evolving separately

Codes that can do multi-fluid

PIP (Hillier et al. 2016)

Mancha-2f (Popescu Braileanu et al. 2019a)

AMRVAC (Keppens et al. 2023)

Ebysus (Martinez-Sykora et al. 2020, 2023)

Joanna (Wójcik et al. 2020)

None of them is capable yet of fully realistic simulations

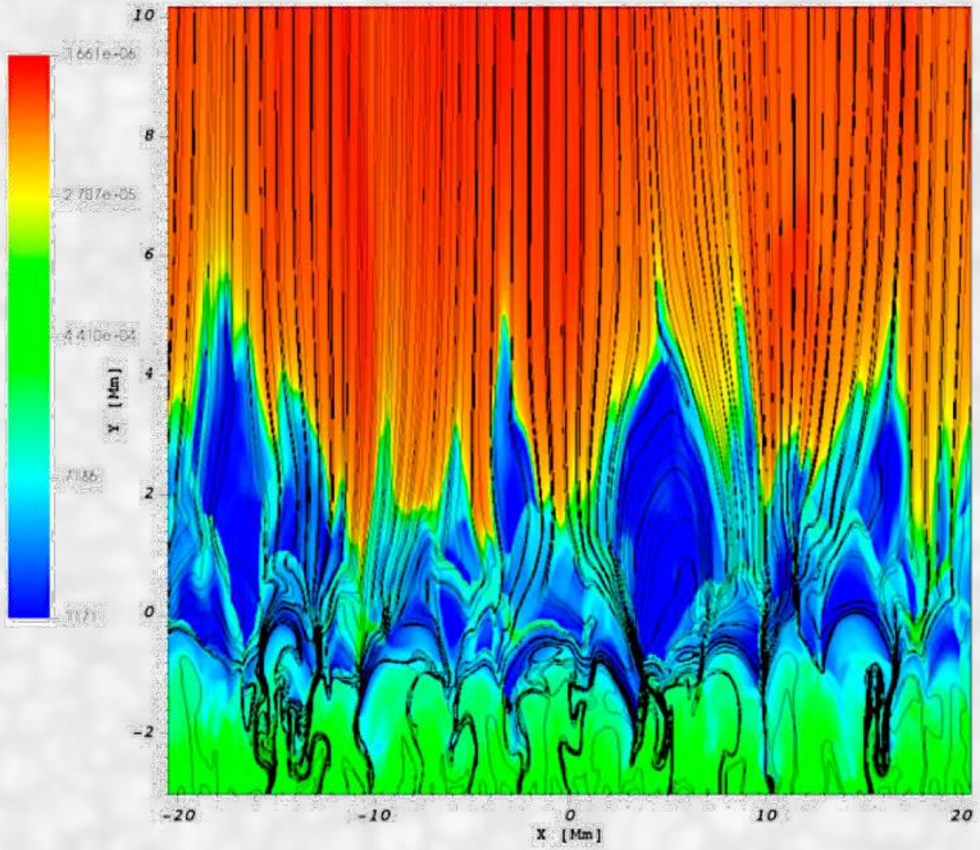
New effects

Ponderomotive force & FIP effect :: Low-FIP elements, which are mostly ionized in the chromosphere, feel the force and are accelerated upward toward the corona

(Laming 2004, 2015, Martinez-Sykora et al. 2023)

Multi-fluid physics: multiple ionized & neutral species evolving separately

Codes that can do multi-fluid



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Joanna (Wójcik et al. 2020)

None of them is capable yet of fully realistic simulations

New effects

Frictional heating by dissipation of chromospheric waves generated by magneto-convection flows

(Niedziela et al. 2024ab, Kuzma et al. 2024, Pelekhata et al 2023)

Conclusions

- ✓ Realistic simulations of magneto-convection is as an ever growing field
- ✓ Simulations successfully reproduce large-scale plasma behavior, for the quiet Sun, magnetic flux emergence, sunspot formation, flares, etc
- ✓ Photospheric simulations are most realistic
- ✓ Chromospheric simulations is a developing field
- ✓ New physical effects from the presence of neutrals are being evaluated for their role for chromospheric heating
- ✓ Ambipolar diffusion is about to be resolved in realistic models and provides a real physical heating mechanism
- ✓ Hall effect in realistic models is scarcely investigated

Future prospects

- ✓ Till mid-chromosphere one can use a much simpler single fluid approximation
- ✓ Upper chromosphere and transition region might need multi-fluid treatment
- ✓ Multi-fluid models provide new physical effects and are worth exploring in realistic models
- ✓ Coupling of plasma and radiation in the chromosphere required non-local treatment and is only implemented in a few codes. Need new efficient numerical methods (e.g. machine learning)
- ✓ Exploration of non-ideal effects in realistic simulations of chromospheres of cool stars is definitely interesting