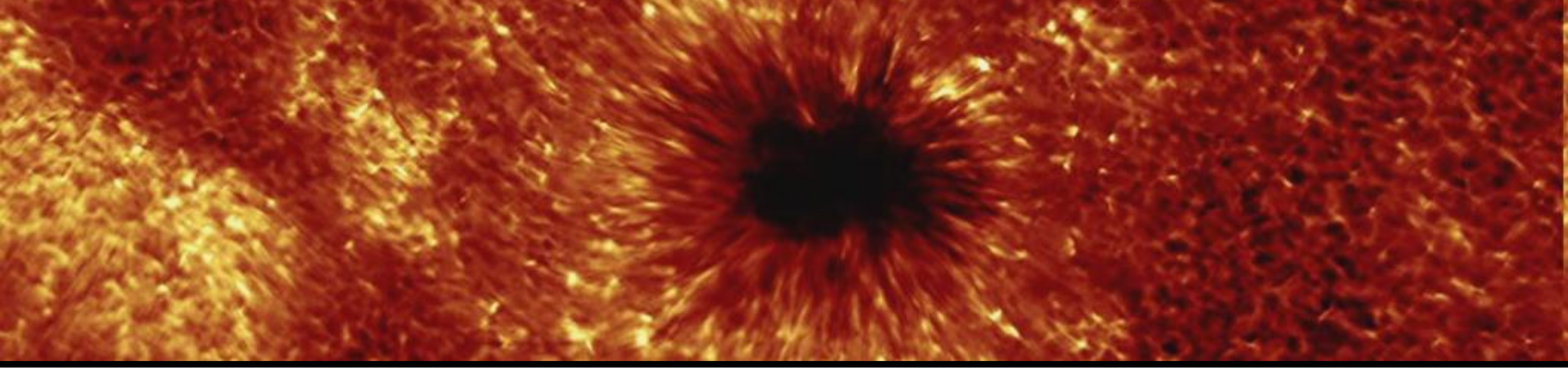

Magneto-convection and wave simulations of solar and stellar atmospheres

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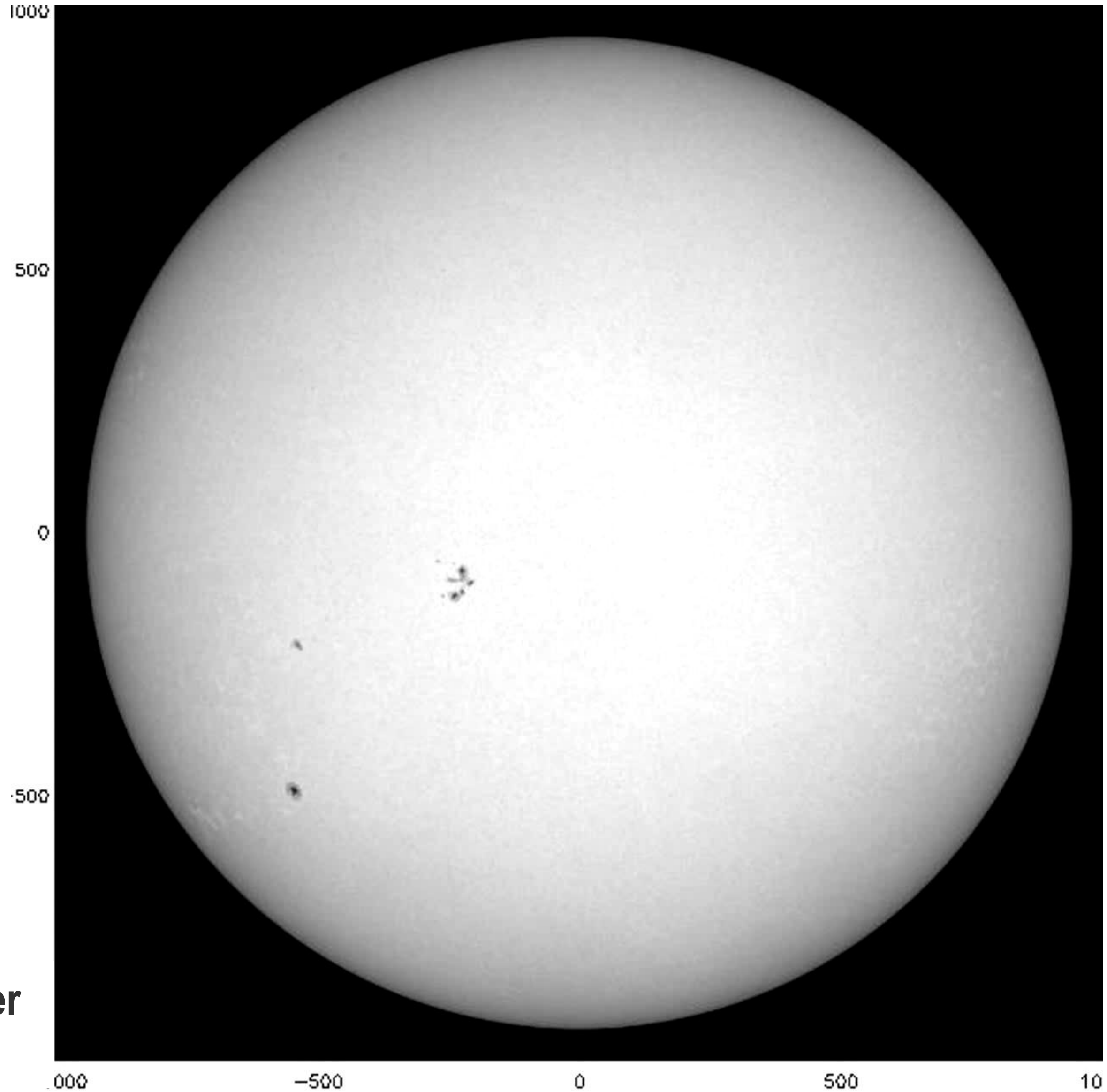
** In collaboration with: D. Fabbian, T. Felipe, F. Moreno-Insertis, A. Nordlund, V. Olshevsky, M. Stangalini*

RES Diffusion Sessions in the Canary Islands

Zoom-in into the Sun



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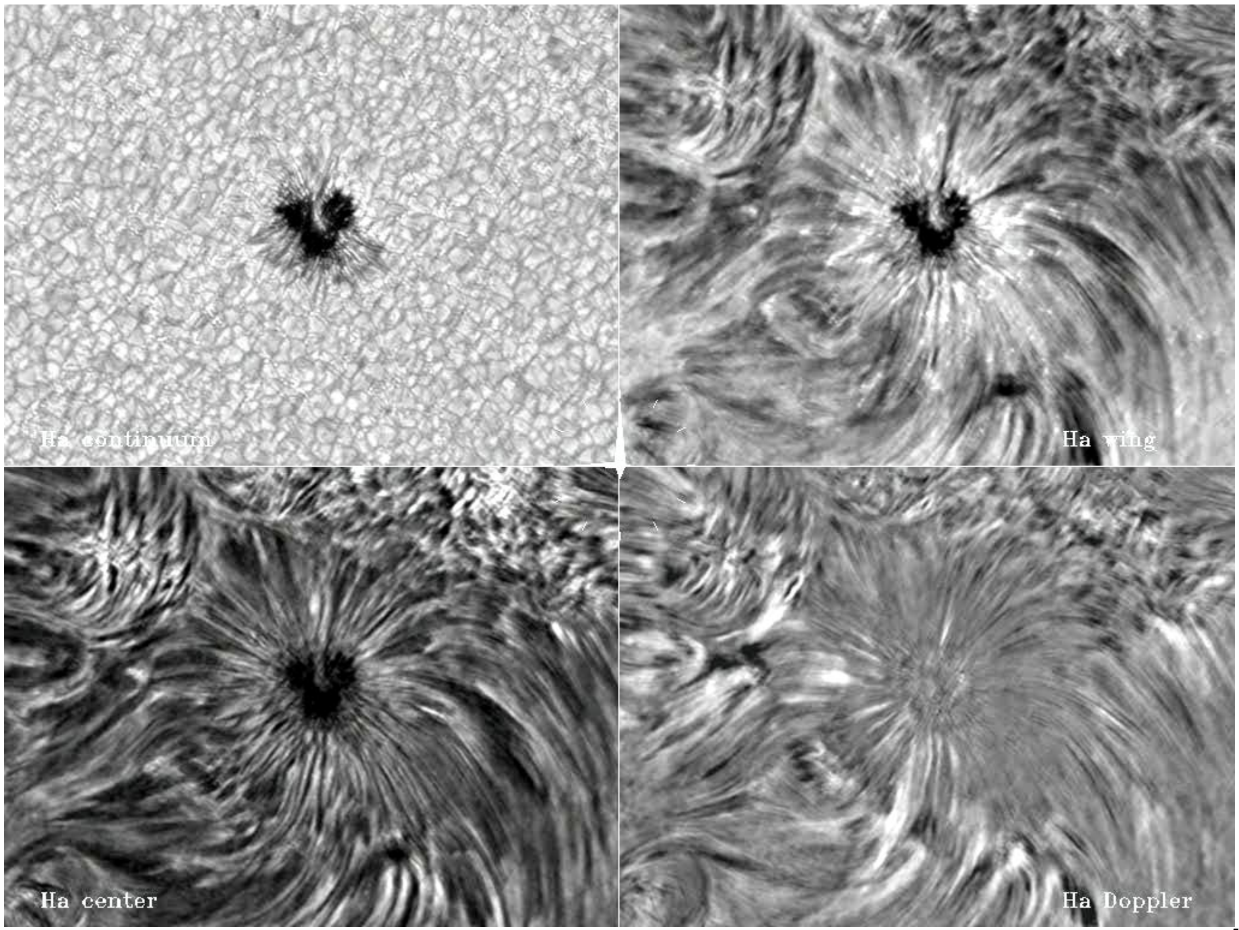
Sunspot dynamics from hi-res observations

Continuum,

deep photosphere

Hα wing,

middle photosphere



Hα core,

chromosphere

Hα Doppler,

chromosphere

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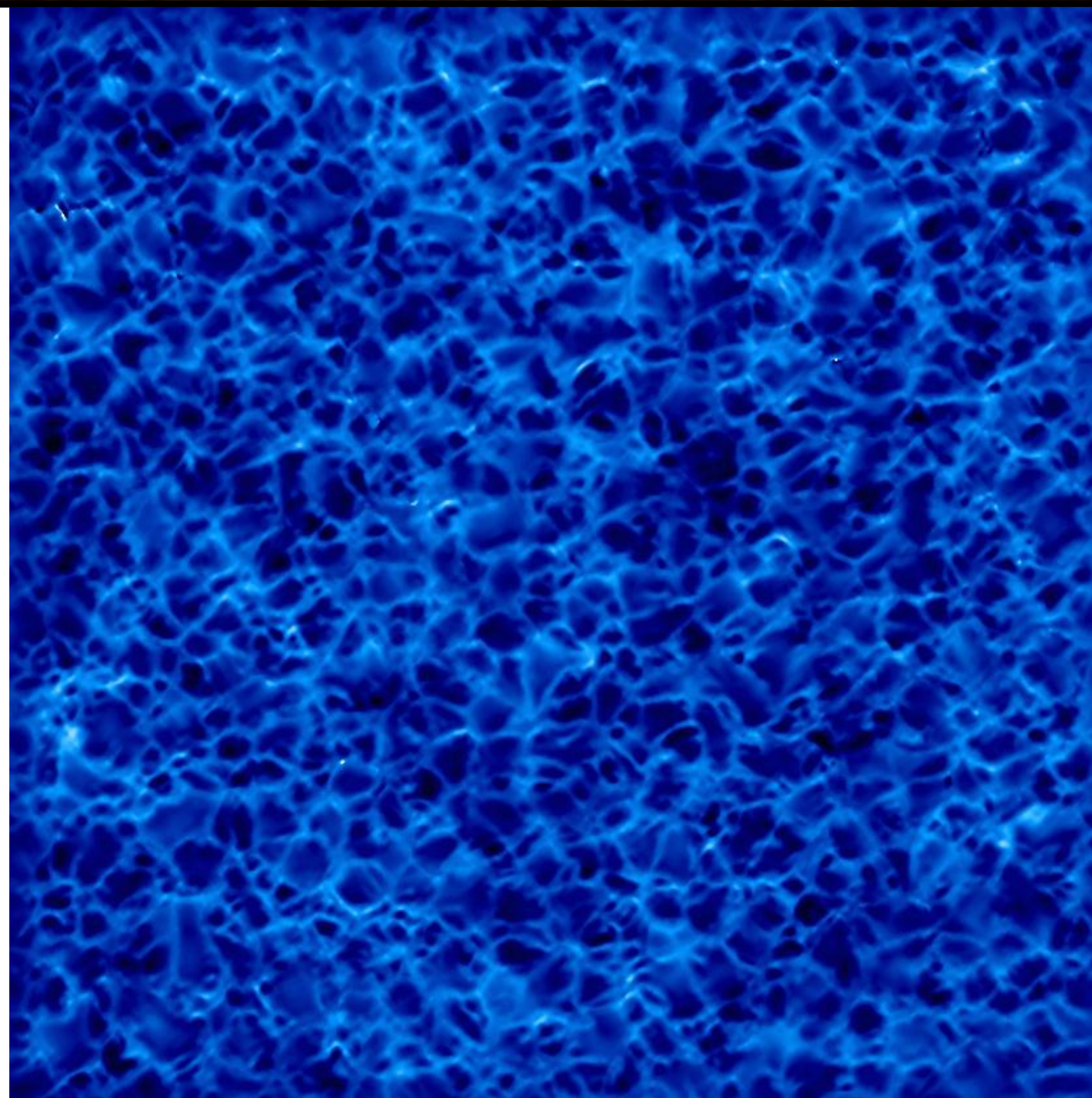
Quiet Sun velocity at 100 km resolution



Sunrise/ IMaX

Martínez Pillet et al (2010)

Objectives of our project

1. Abundance determination including 3D effects and magnetic fields
2. **Physics of waves** in solar magnetic structures
   - **Atmospheric** waves from the photosphere to the chromosphere
   - Energy propagation and wave modes
   - Simulations of the **observed magnetic structures**
   - **Helioseismology**
3. **Energetic phenomena**: reconnection and jets

Common factor: magnetic fields!

Equations solved

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{V}) = 0 \,,$$

$$\frac{\partial (\rho \vec{V})}{\partial t} + \vec{\nabla} \cdot [\rho \vec{V}\vec{V} + (P + \frac{\vec{B}^2}{8\pi})\mathbf{I} - \frac{\vec{B}\vec{B}}{4\pi}] = \rho \vec{g} \,,$$

$$\frac{\partial E}{\partial t} + \vec{\nabla} \cdot [(E + P + \frac{\vec{B}^2}{8\pi})\vec{V} - \vec{B}(\frac{\vec{B} \cdot \vec{V}}{4\pi})] = \rho \vec{V} \cdot \vec{g} + \rho Q \,,$$

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times (\vec{V} \times \vec{B}) \,,$$

3D MHD Mancha code

Reference: Felipe, Khomenko, Collados (2010)

*Solves **non-linear** equations for perturbations;*

Magneto-static equilibrium is explicitly removed from the equations;

4th order central difference in space and 4th order Runge-Kutta in time;

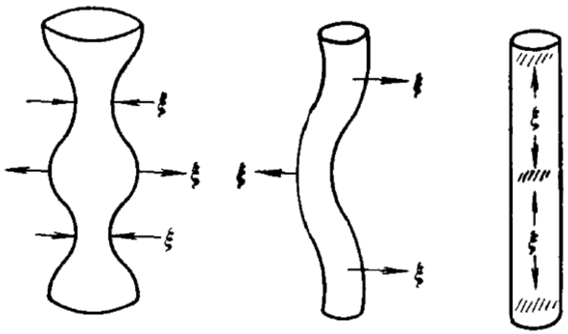
*Stabilized by **hyper-diffusive** terms;*

***PML** absorption layer boundary conditions;*

*Energy losses according to **Newton cooling** law;*

OPAL or ideal equation of state;

***MPI** parallelized using domain decomposition.*



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Copenhagen Stagger code

Reference: Nordlund, A., Galsgaard, K., 1997, Technical Report of the Copenhagen Observatory

*Solves full system of 3D **non-linear** MHD equations;*

6th order staggered in space and 4th order Runge-Kutta in time;

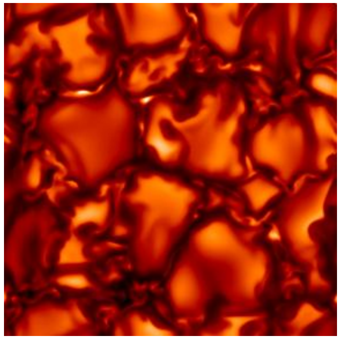
*Stabilized by **hyper-diffusive** terms;*

***Open**, closed or periodic boundary conditions;*

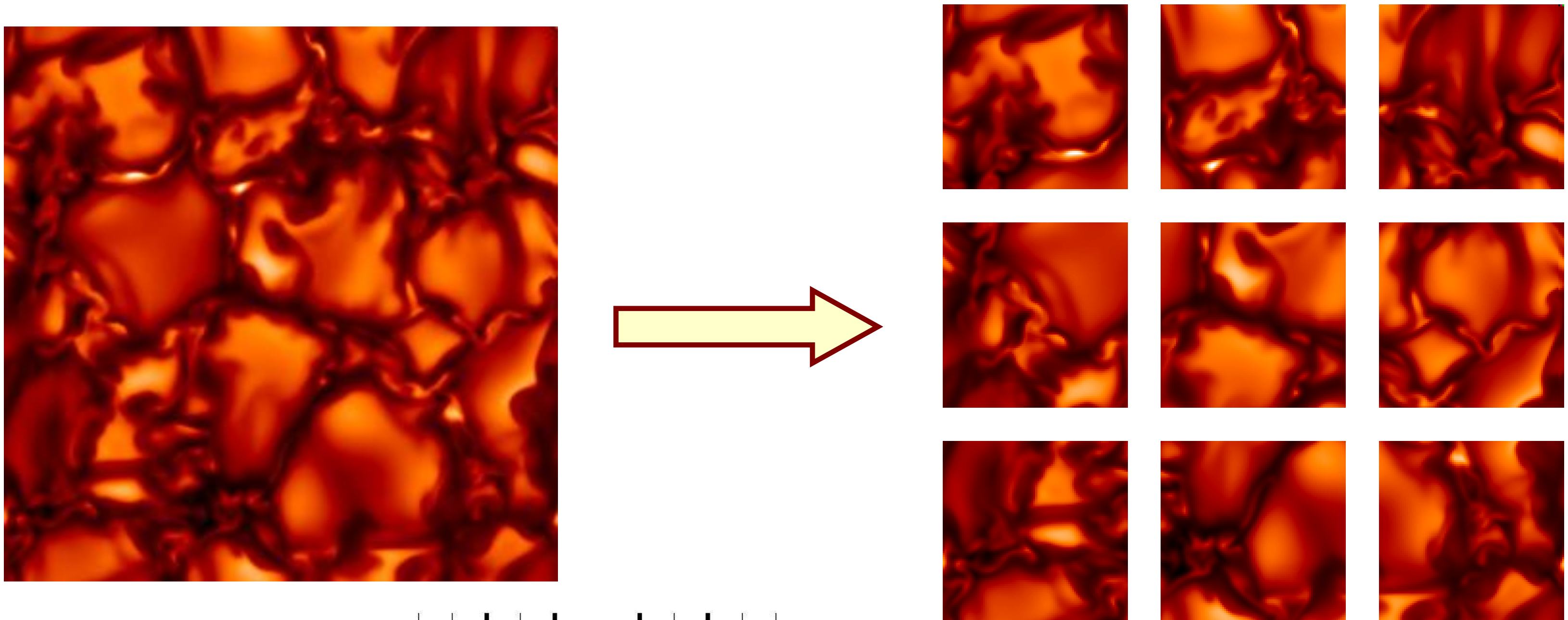
*LTE radiative transfer equation solution for **energy losses**;*

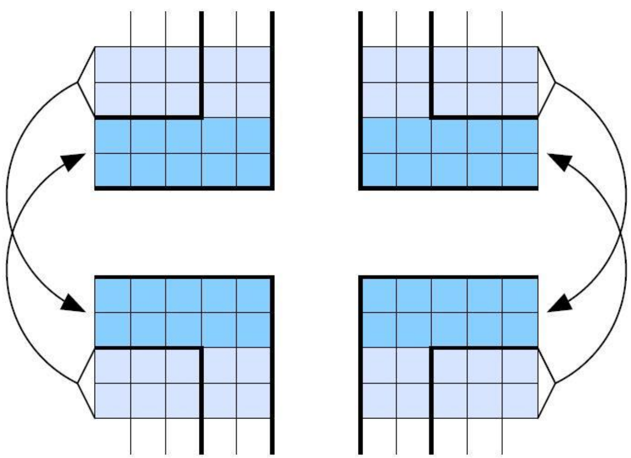
Realistic equation of state;

***MPI** parallelized using domain decomposition.*



Parallelization and execution





Typical run needs about 126 parallel processors

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Magnetoconvection & abundance determination

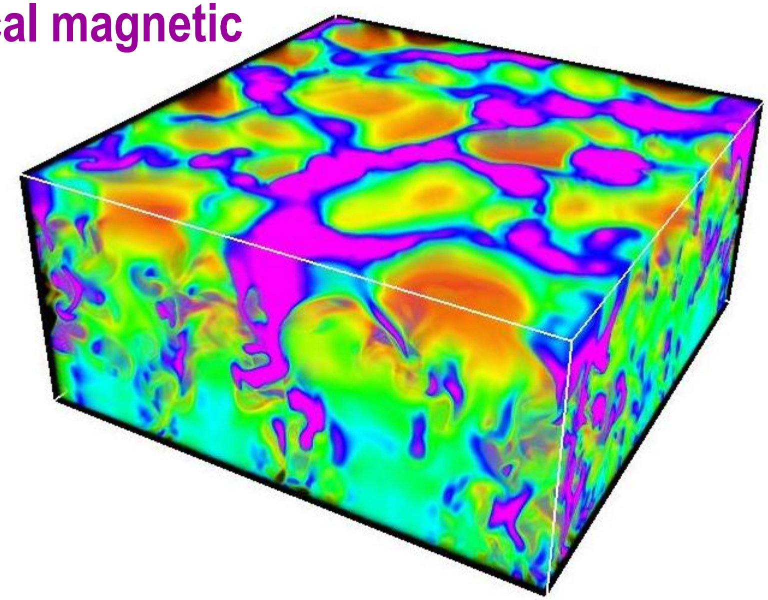
Objectives:

To produce 3D MHD time-dependent model atmospheres of the Sun and stars;

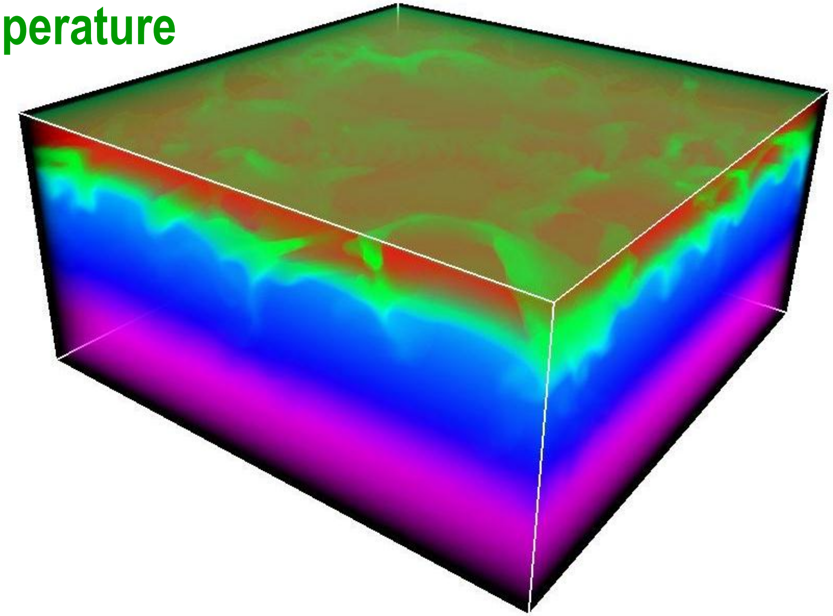
To derive synthetic spectra from them;

To perform abundance analysis, including 3D and magnetic field effects

Vertical magnetic field



Temperature



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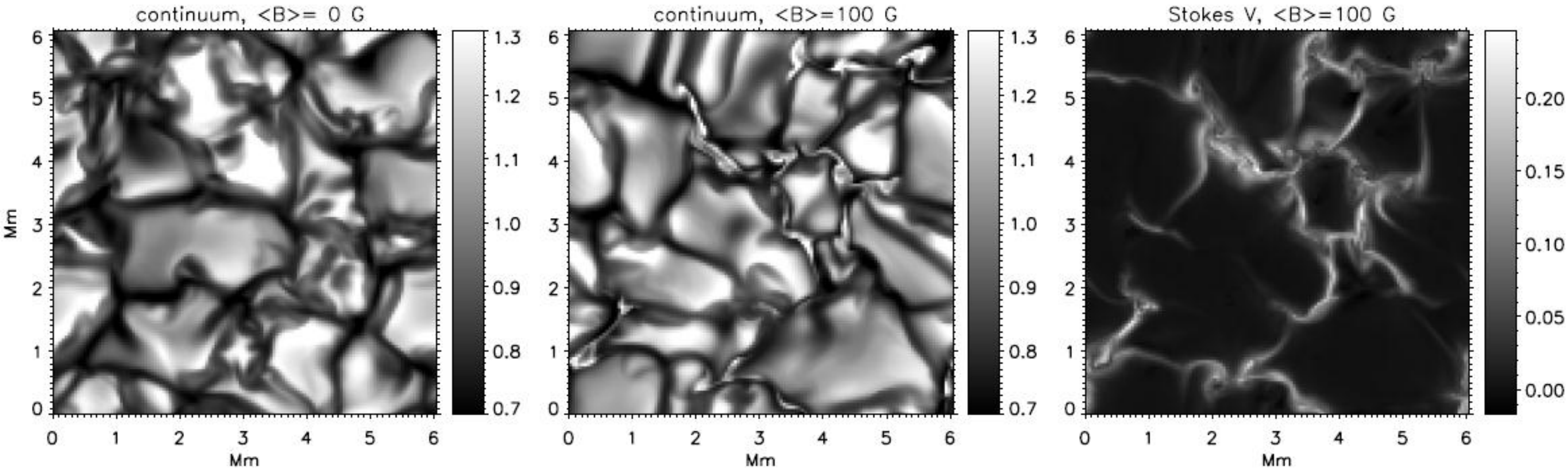
Magnetoconvection & abundance determination

LTE spectral synthesis of selected **Fe I lines** in time series of 3D MHD models

Average <B> from **50** to **200** G



Reference: Fabbian, Khomenko, Moreno-Insertis & Nordlund (2010)

Spectral code LILIA: Socas-Navarro 2001

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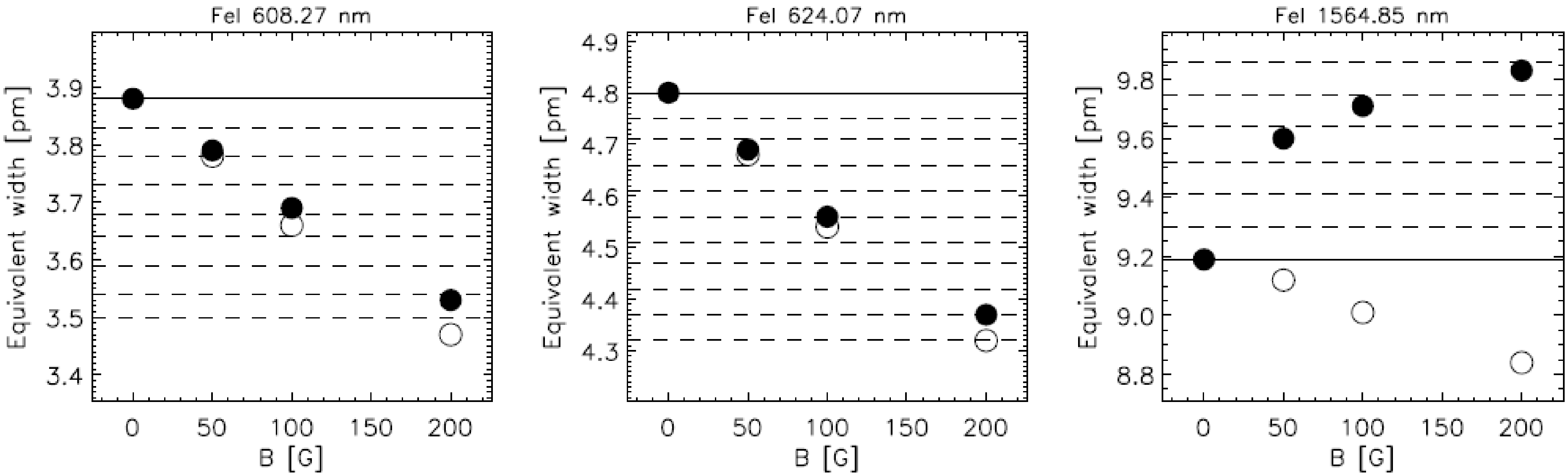
Magnetoconvection & abundance determination

Change of equivalent width of **FeI lines** in MHD models with **different <B>**



Fe abundance correction reaches 0.1 dex for <B>=200 G

Zeeman broadening and temperature effects act in different directions

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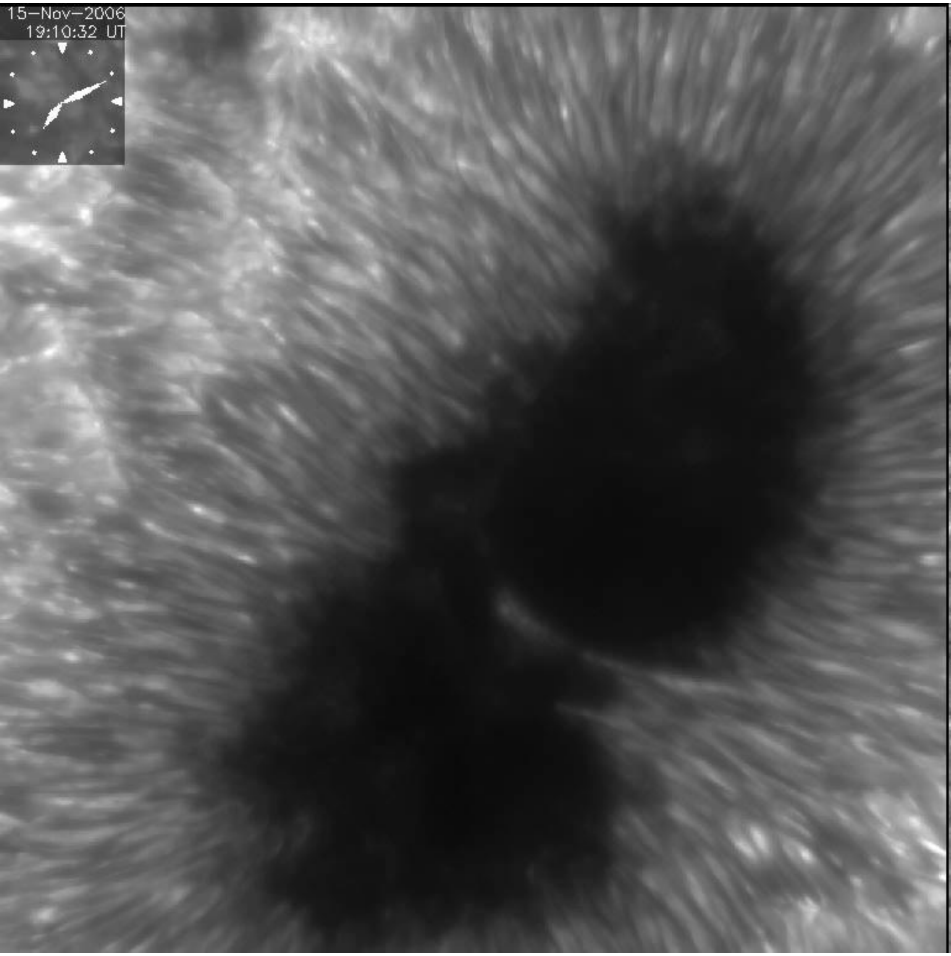
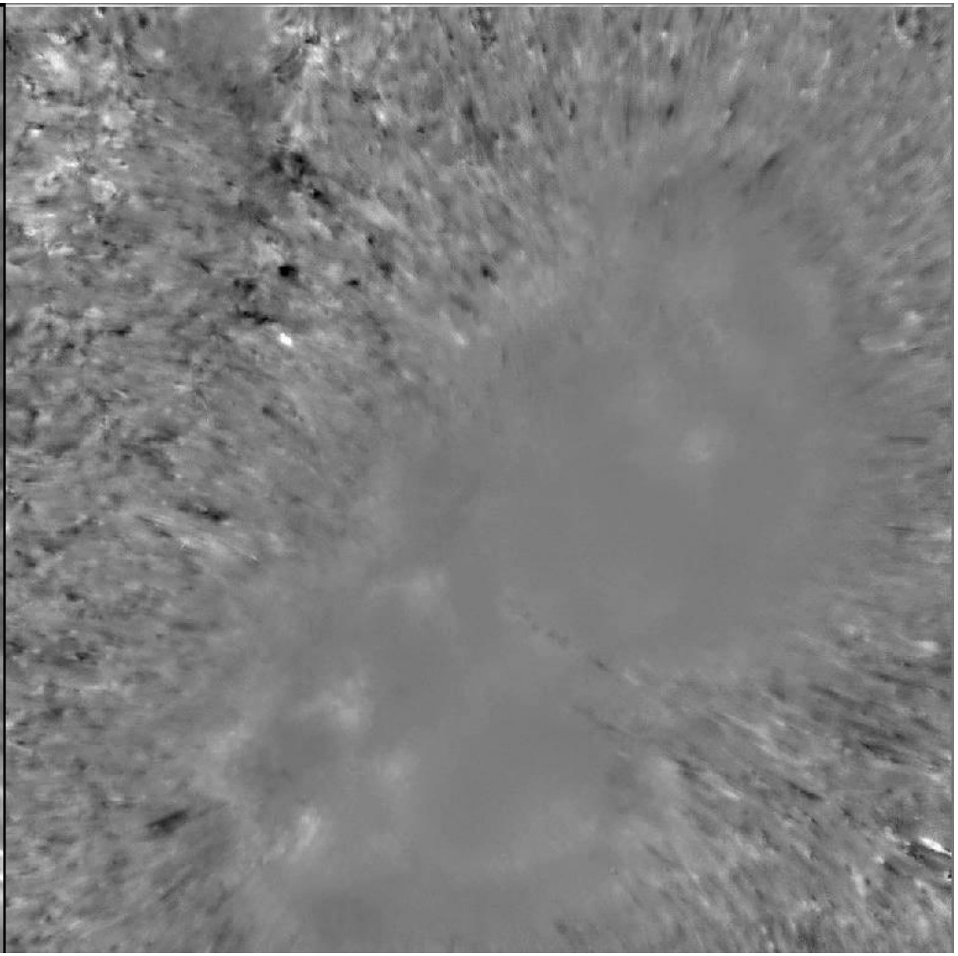
Physics of waves in solar magnetic structures



Ca II H intensity



Doppler velocity

HINODE

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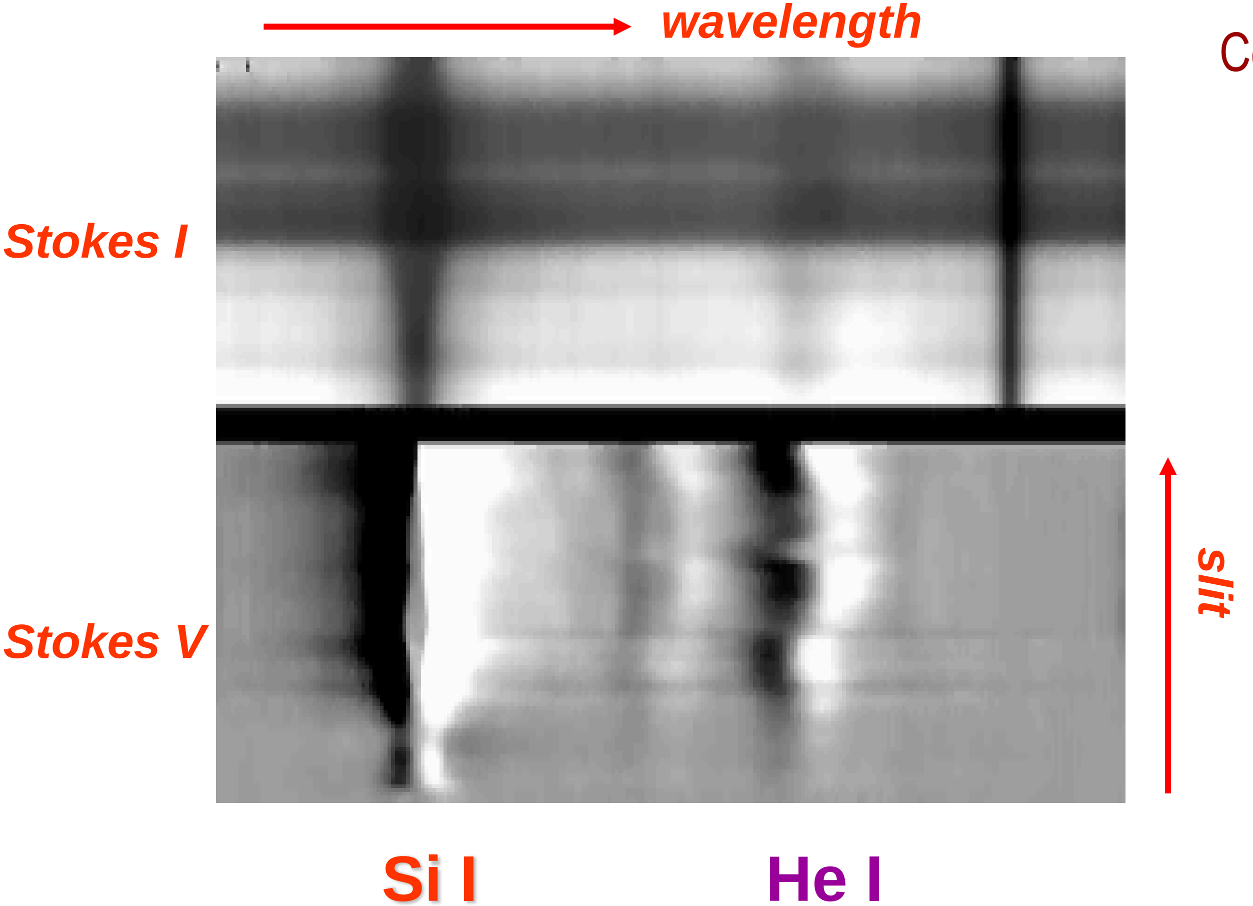
Physics of waves in **s**olar magnetic **s**tructures

TIP/VTT infrared observations at 10830 A



Centeno et al. (2005)

Collados et al. (2001)

Periods: 5 min (phot)

3 min (chrom)

Shock wave in the chromosphere

Propagation along the field lines

Delay of 6-7 min or

V_{phas} of 4-5 km/s

Photospheric pulse!

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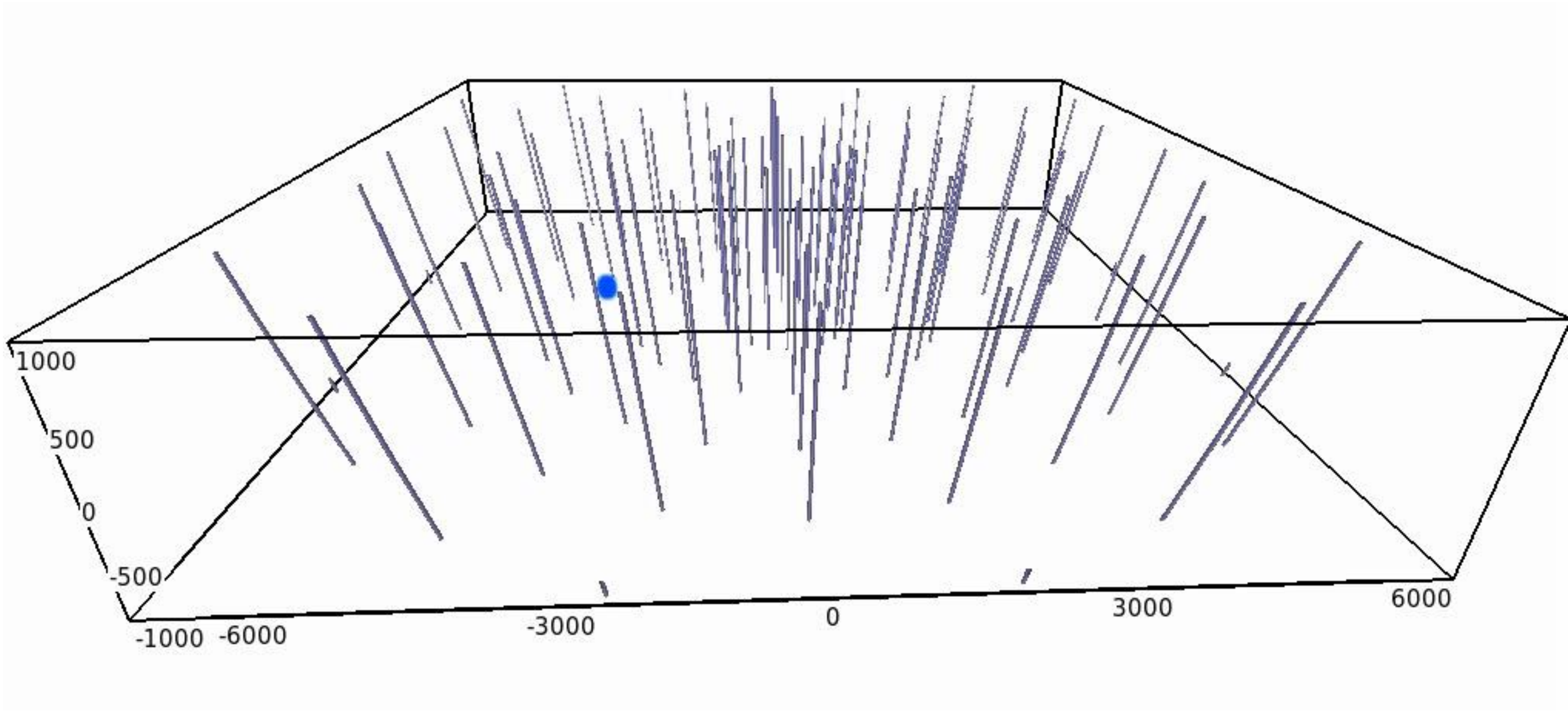
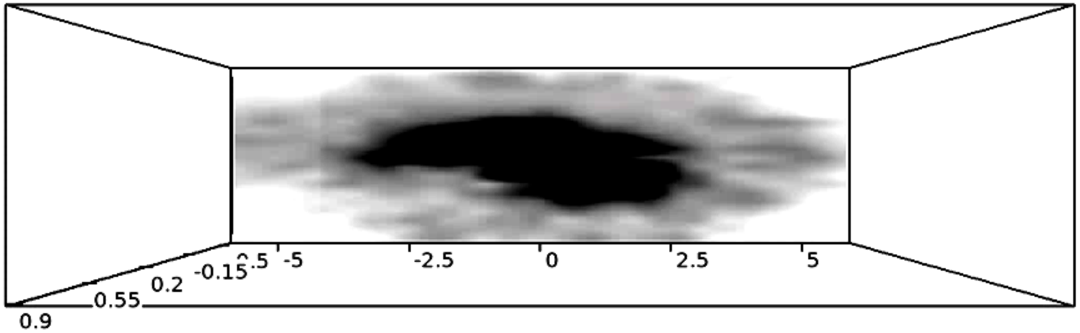
Simulations of 3D wave propagation in sunspots



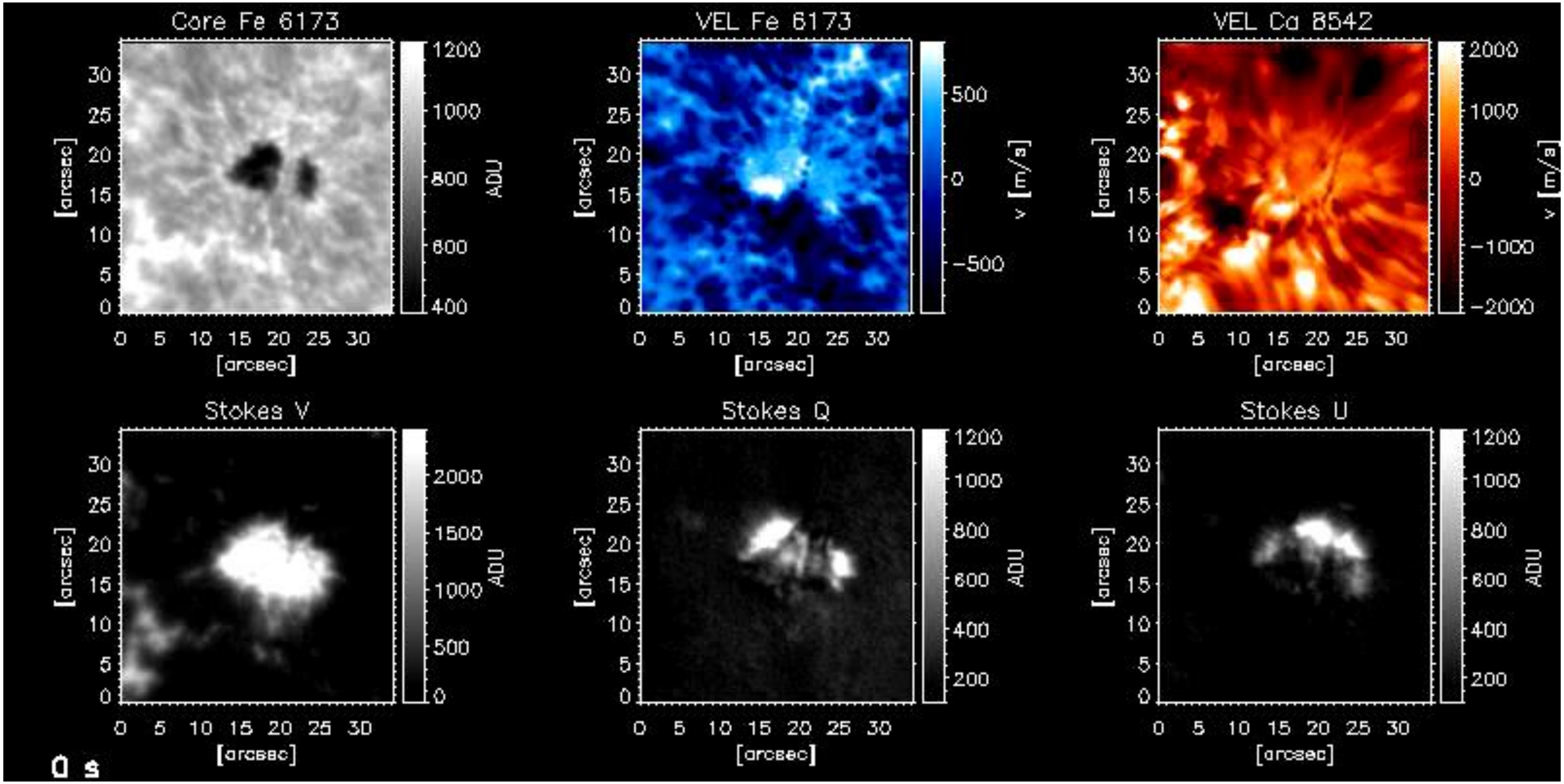
Reference: Felipe, Khomenko, Collados (2010)

Wave propagation in an observed sunspot



Reference: Felipe, Khomenko, Collados (2011)

Wave propagation in an observed pore



IBIS data

Reference: Stangalini, Del Moro, Berrilli & Jefferies (2011)

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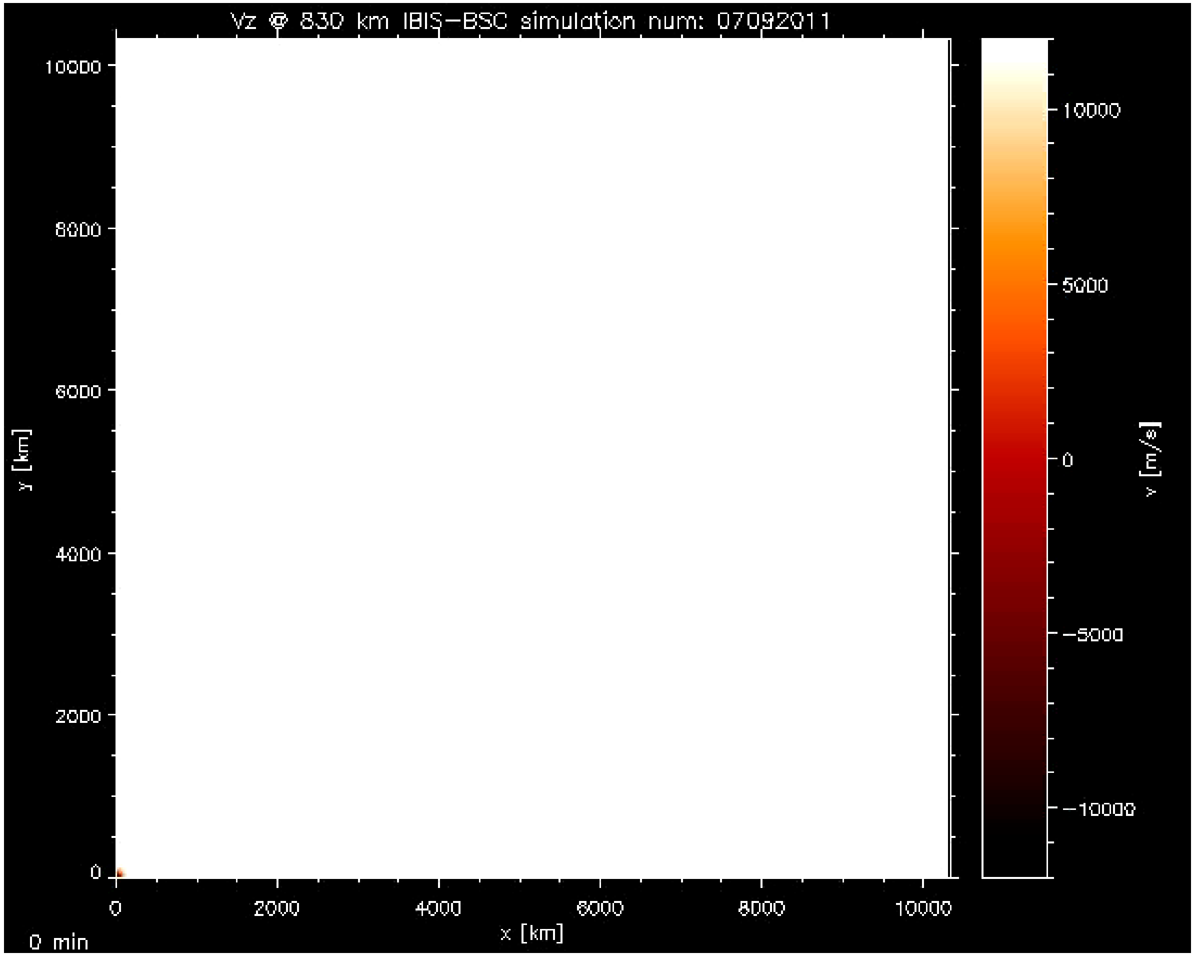
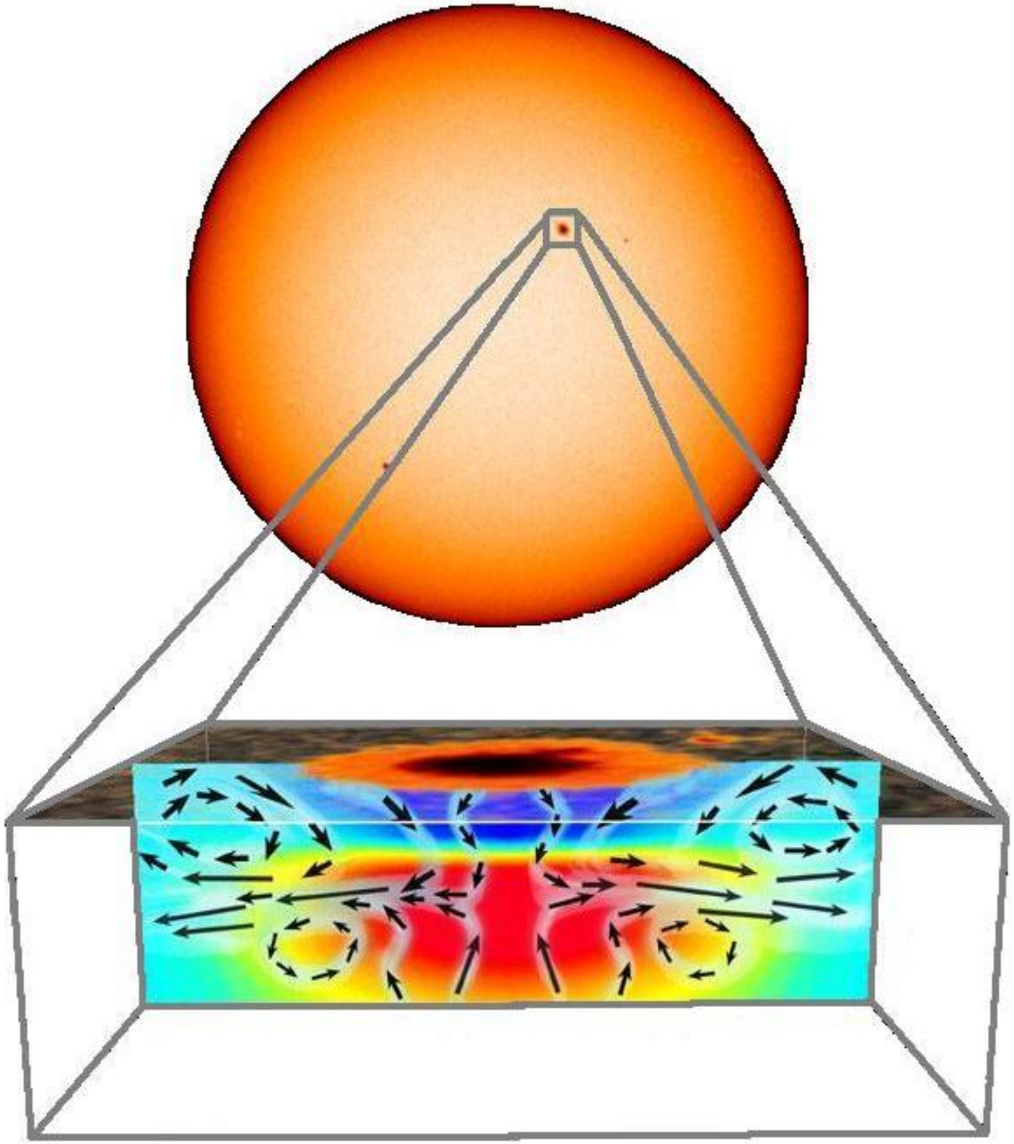
Wave propagation in an observed pore



Reference: Stangalini, et al. (2012, in preparation)

Helioseismology in active regions



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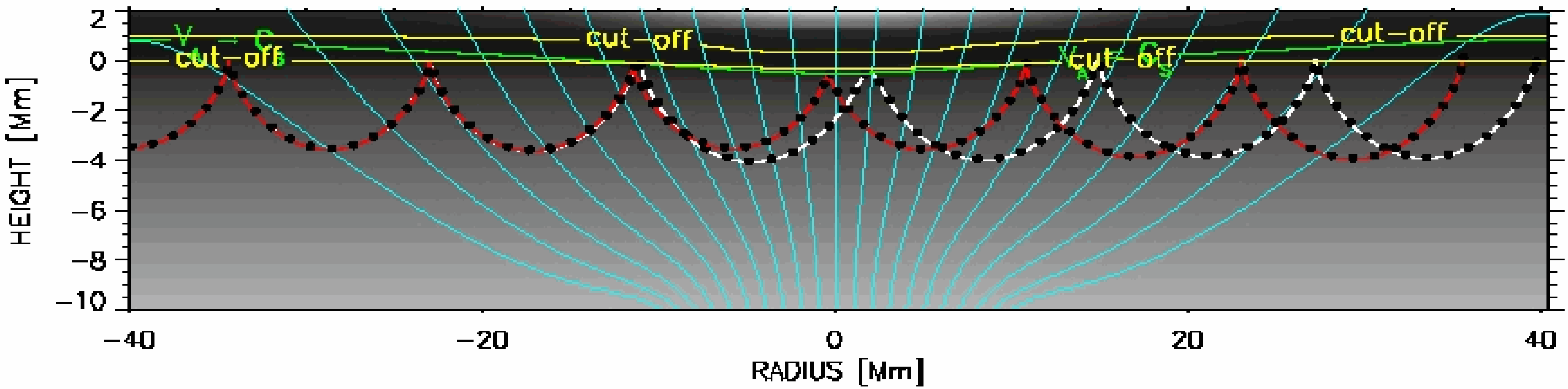
Helioseismology wave path below sunspot

Wave propagation below photosphere is affected by the magnetic field.
Magnetic field speeds up the waves.

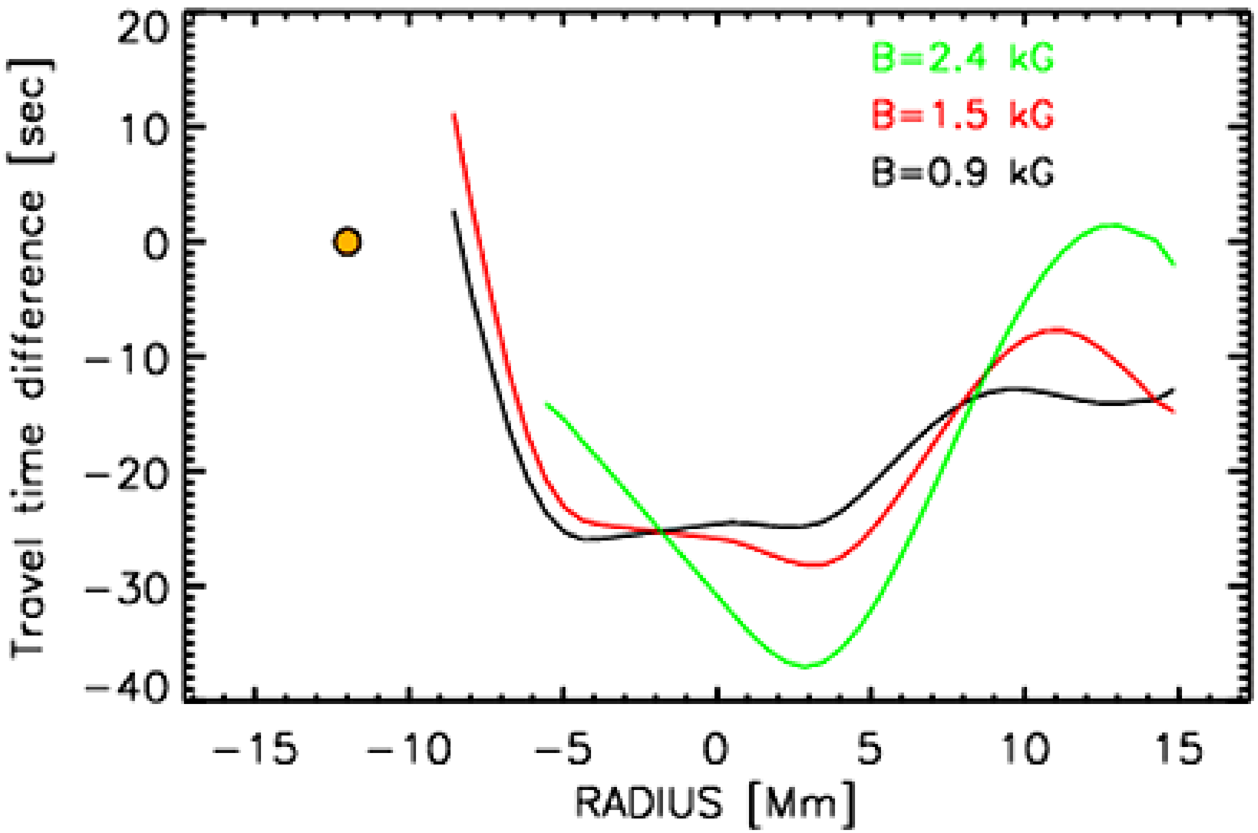


Magnetic field + sound speed perturbations

Only sound speed perturbations

Khomenko, Kosovichev, Collados, Parchevsky & Olshevsky (2009)

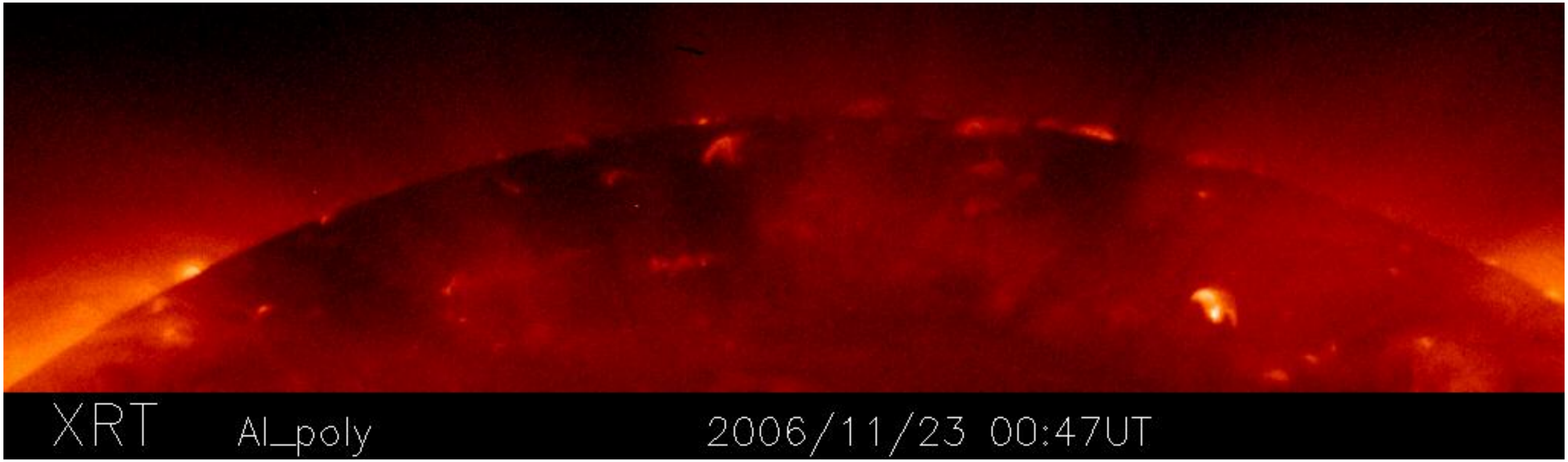
Travel time difference from simulations



Travel times *decrease* with *increasing* magnetic field.

Travel times from simulations are similar to observations.

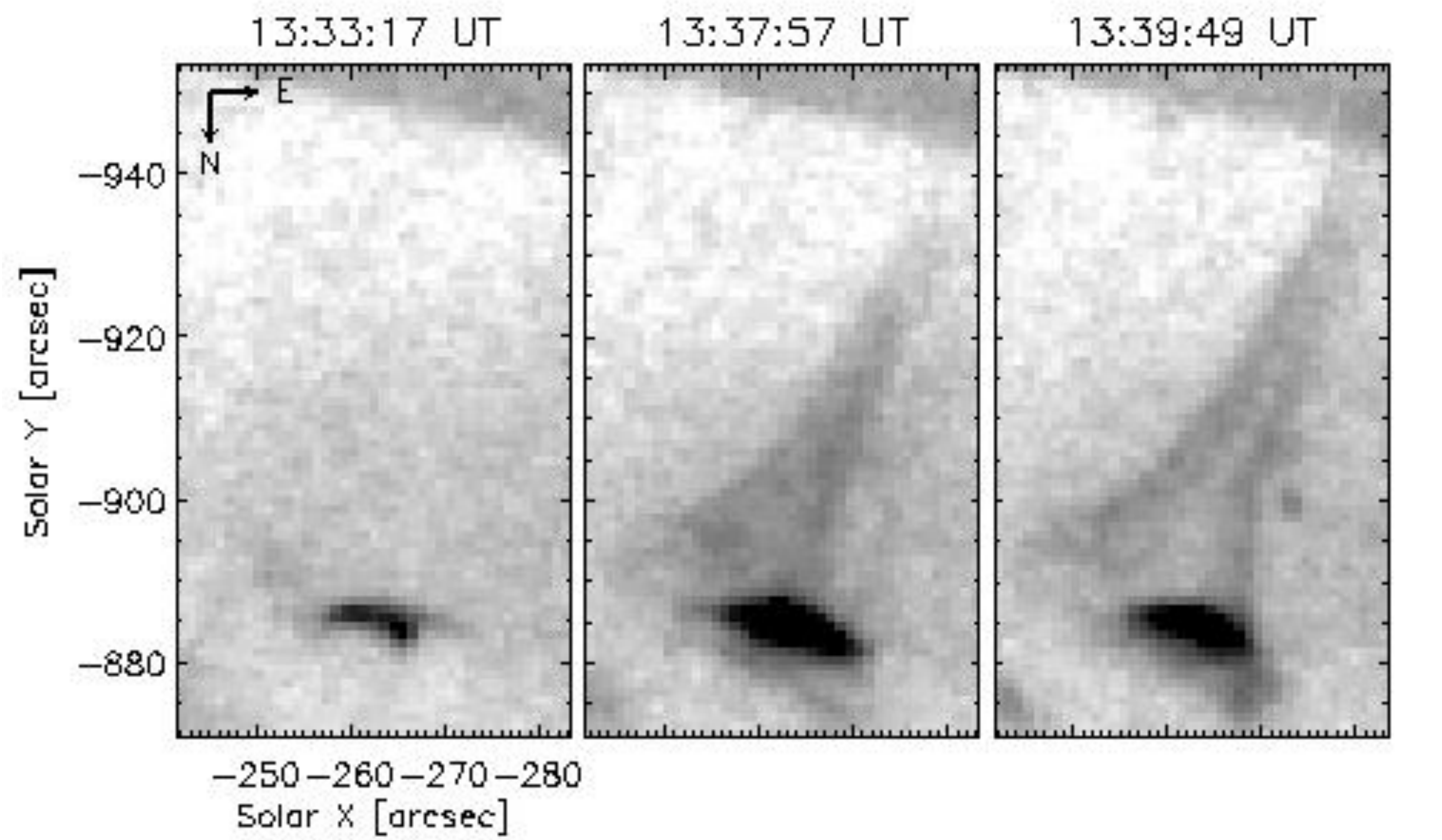
Energetic phenomena: reconnection and jets



- Hinode XRT: observation of X-Ray jets in coronal holes

Energetic phenomena: reconnection and jets

Inverted-Y jet shapes



- Hinode XRT: observation of X-Ray jets in coronal holes

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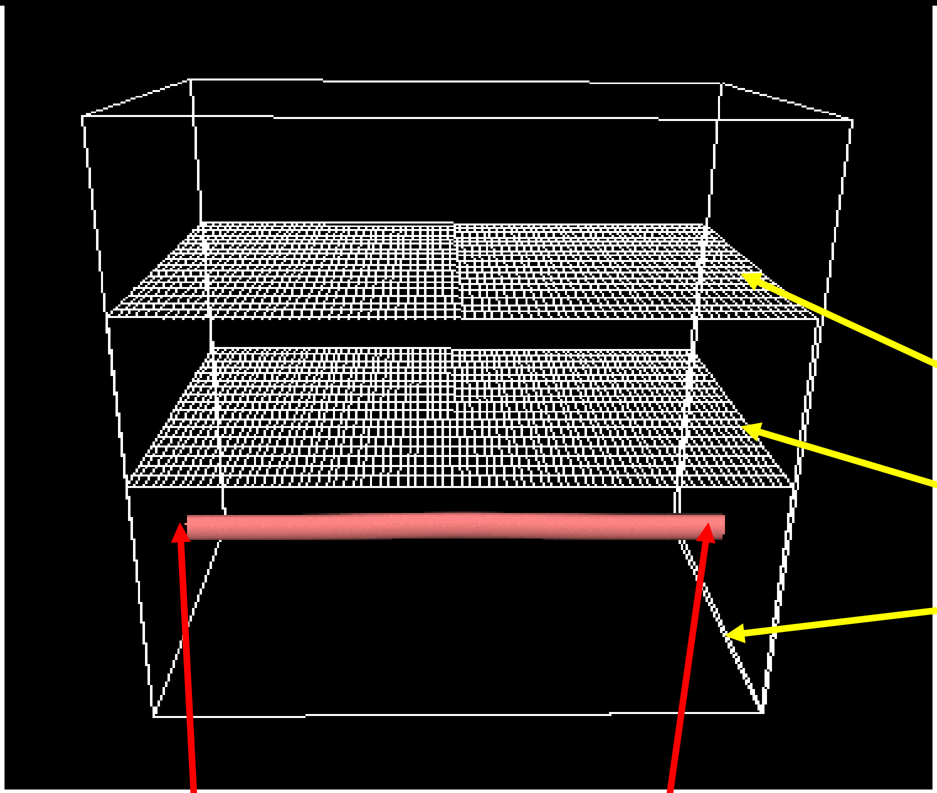
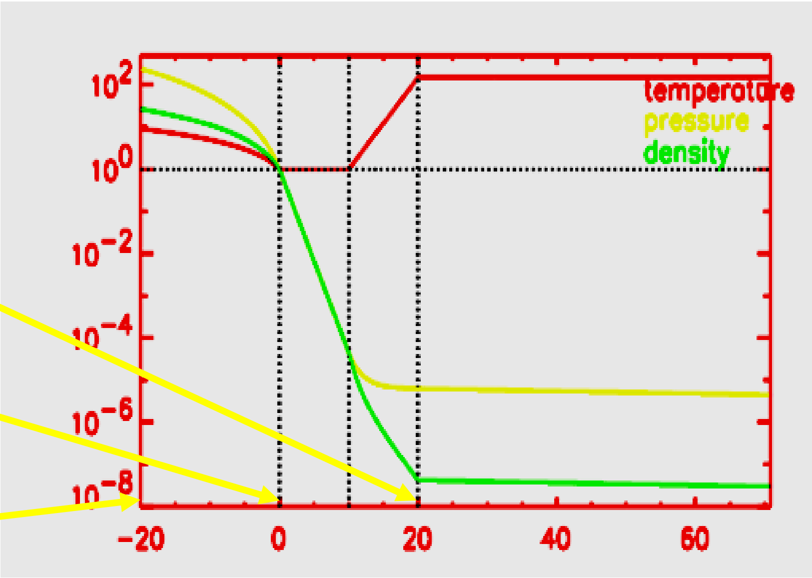
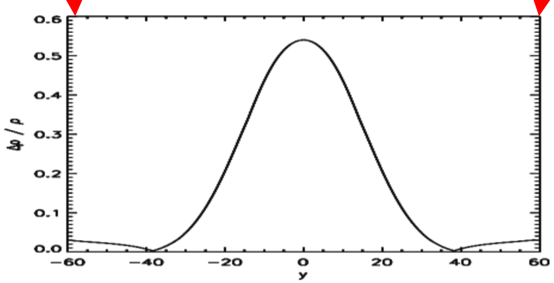
3D numerical experiment: the initial condition





The field lines are twisted around the tube axis



Reference: Moreno-Insertis, Galsgaard & Ugarte-Urra (2008)

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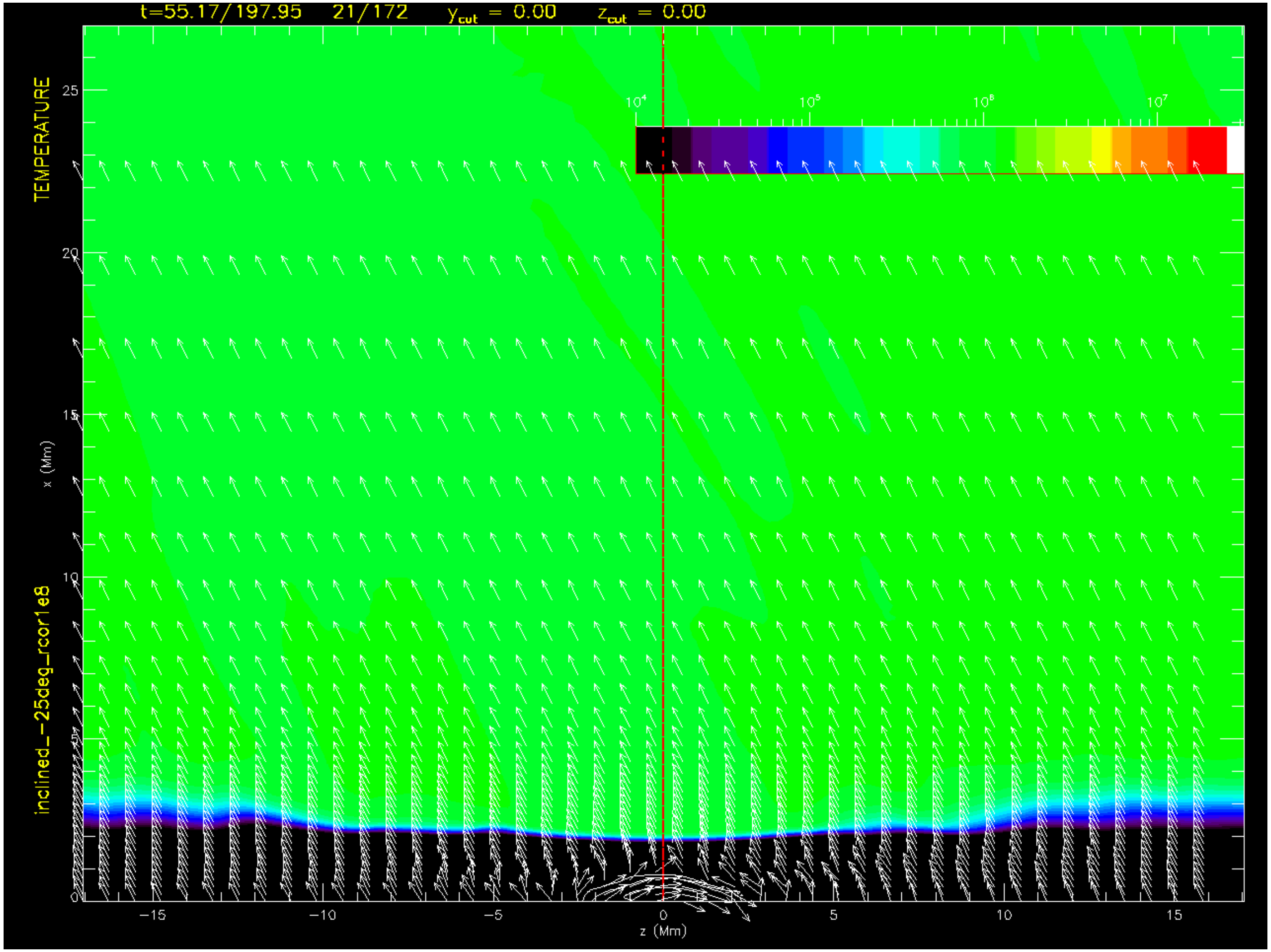
Energetic phenomena: reconnection and jets



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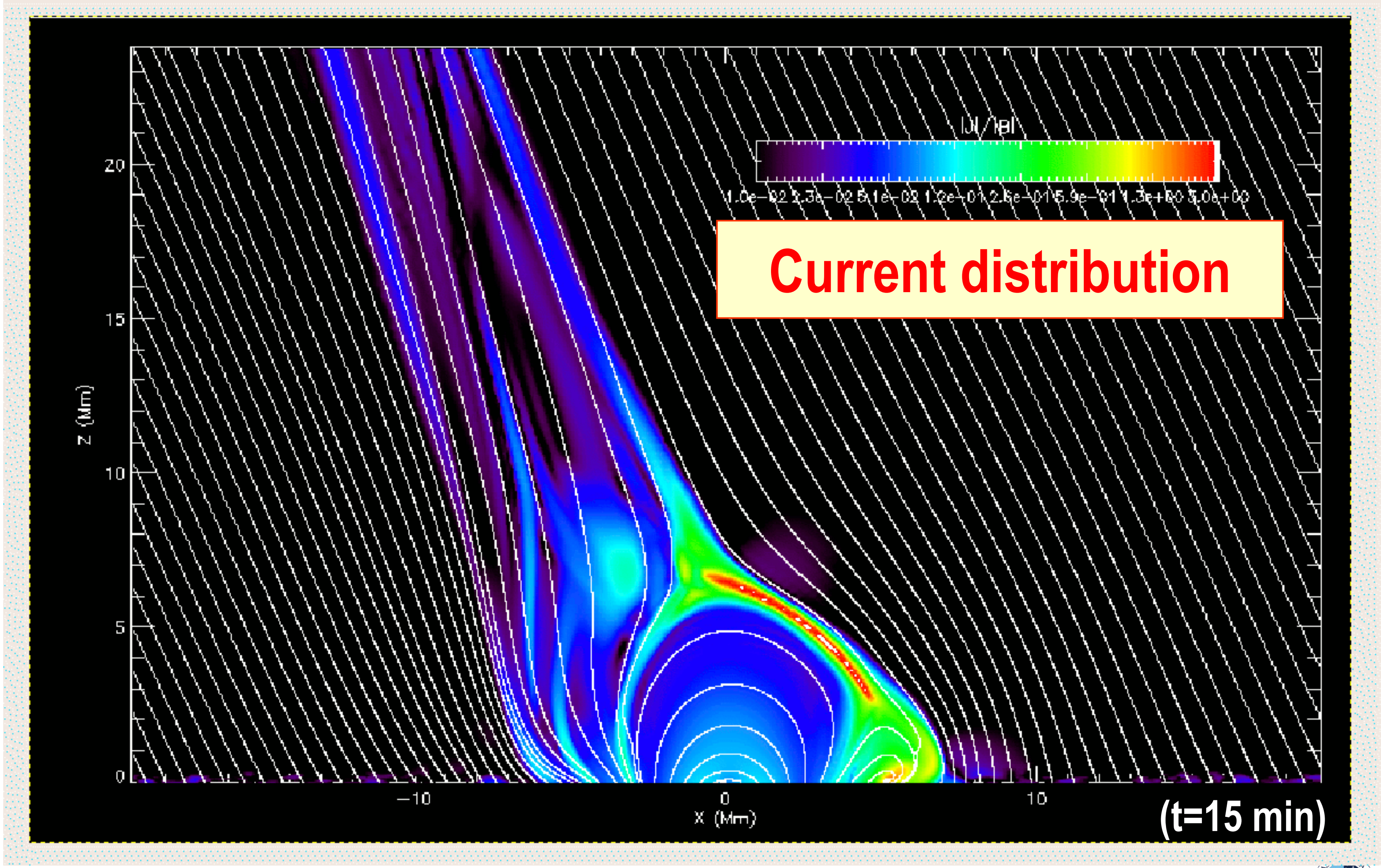
Energetic phenomena: reconnection and jets



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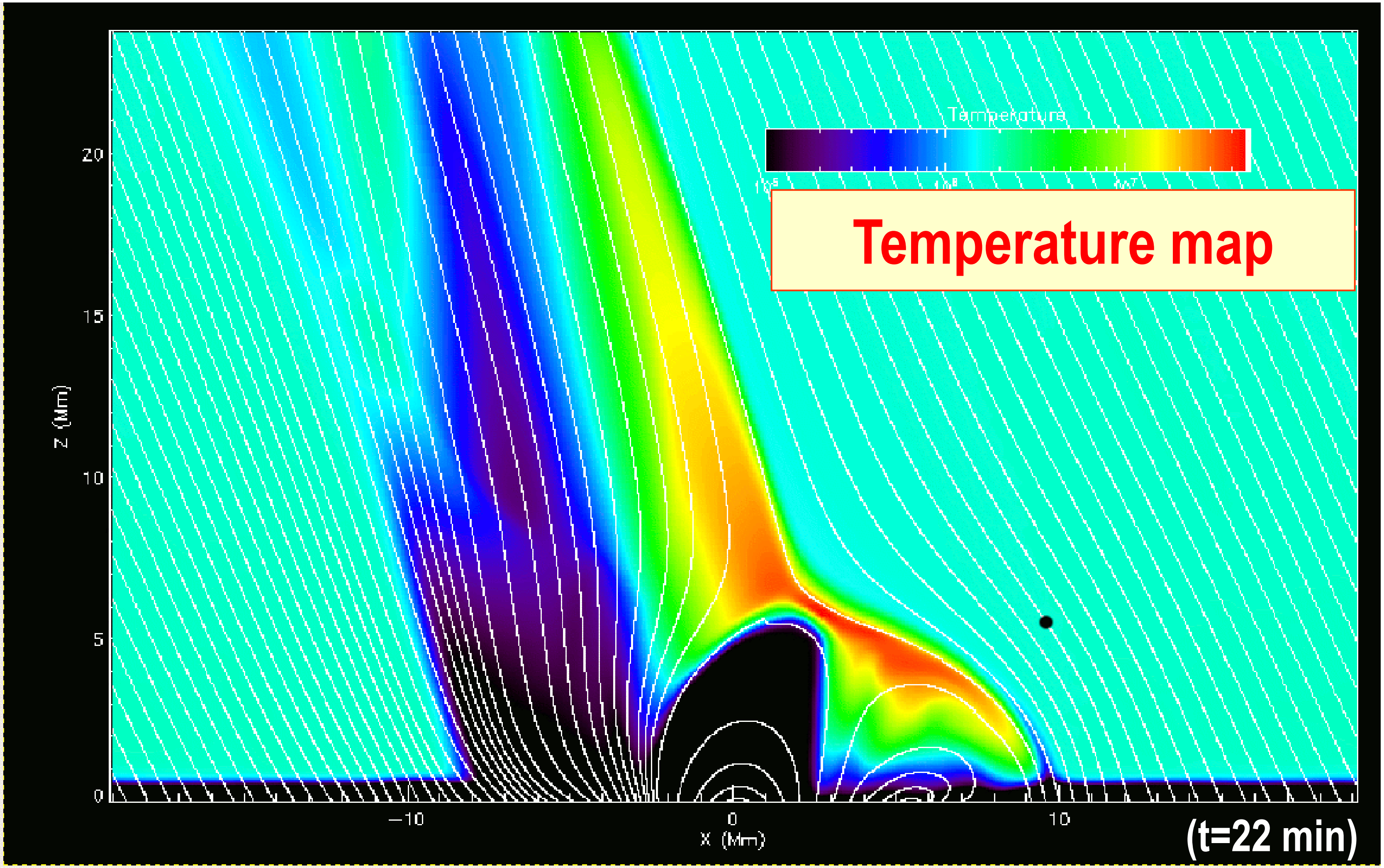
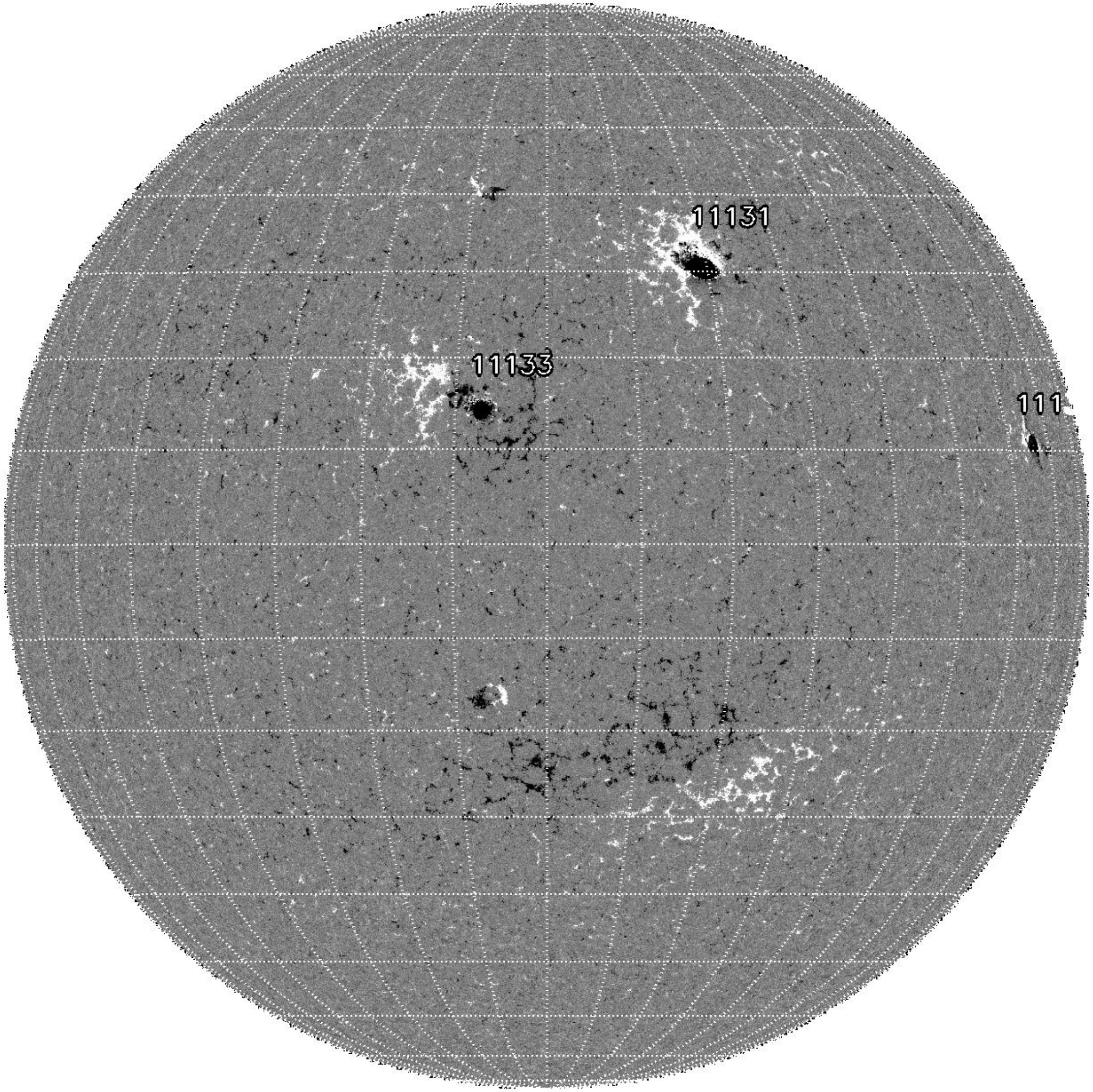
Energetic phenomena: reconnection and jets



Reference: Moreno-Insertis, Galsgaard & Ugarte-Urra (2008)

The Sun is smiling at us?



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