Observational Diagnostics of Magnetoconvection in a Sunspot Umbra

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in collaboration with Christoph U. Keller and Alexander Vögler

(Work done at Sterrekundig Instituut Utrecht and published as a part of NV's PhD thesis in 2011.)

SUNSPOT FORMATION: THEORY, SIMULATIONS AND OBSERVATIONS

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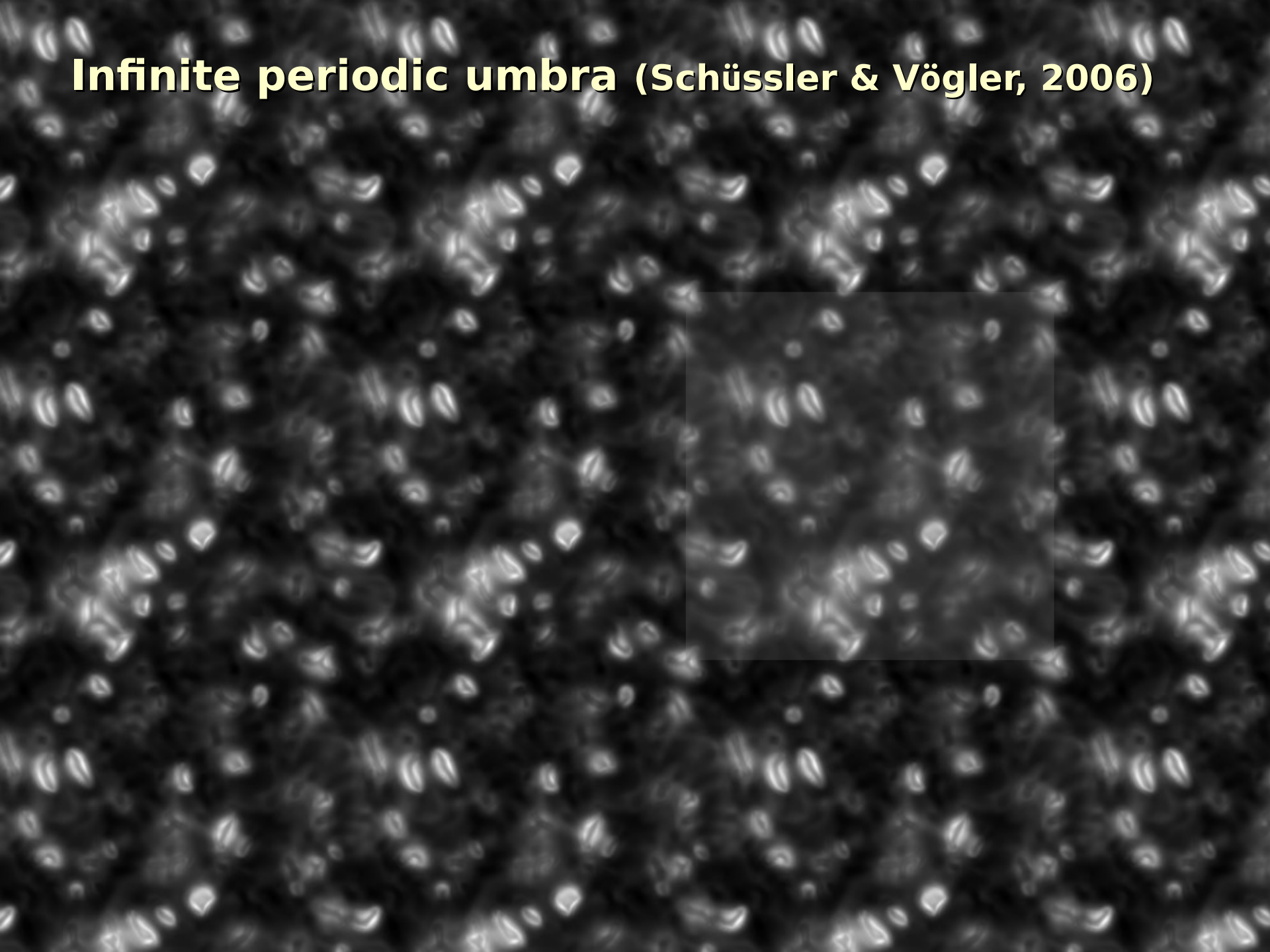
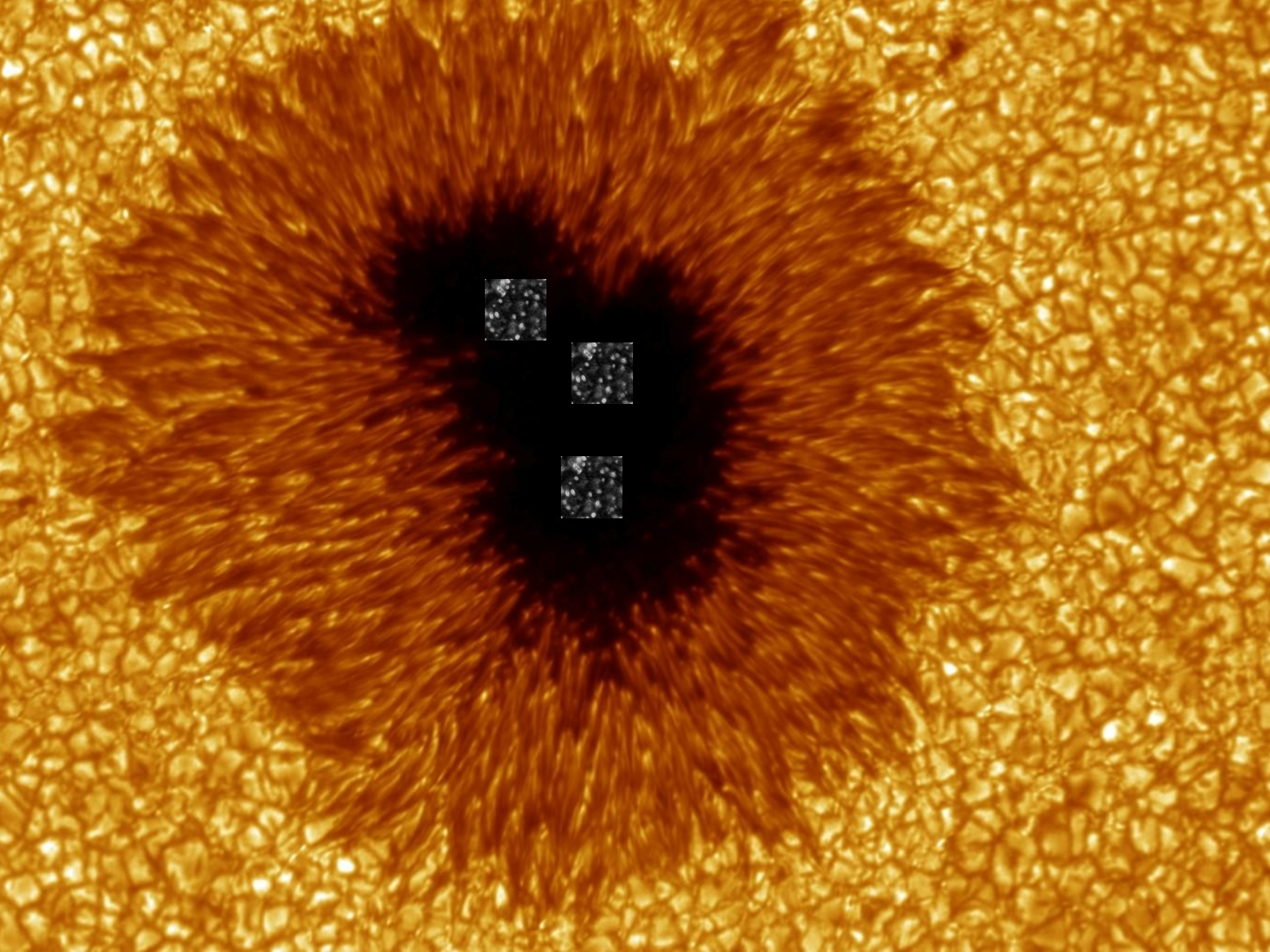
Instituto de Astrofisica de Canarias, Tenerife, Spain

Infinite periodic umbra (Schüssler & Vögler, 2006)





How *realistic* are the 3D simulations of magnetoconvection in a sunspot umbra?

Do the spectral diagnostics computed from the simulation match observations?

(1) Monochromatic continuum intensity, CLV.

(2) Spectral lines in polarization.

(observations and simulations: Socas-Navarro et al, 2004; Sobotka et al, 2005, 2007, 2009, Riethmuller et al, 2008, 2013, Ortiz et al, 2010, Watanabe et al, 2009, 2014, Bharti et al, 2010, 2013)

Do the measured physical parameters match the simulations?

Comparison has to take into account properties of

(1) the diagnostics,

(2) of the instrument (telescope, detector) and

(3) of the technique used in the measurement.

MURaM
(version by Vögler, 2003)

- fully compressible MHD;
- time-dependent, 3D Cartesian grid;
- non-local, non-gray radiative transfer;
- realistic equation of state including partial ionization;
- MPI parallelized.

The code has been used to simulate:

- **Quiet sun** (Voegler, 2005; Khomenko et al, 2005, Danilovic et al 2008, V. et al 2011)
- **Plage** (Keller et al 2004, Shelyag et al 2007++, V. et al 2009)
- **Pore** (Cameron et al, 2007)
- **Umbra** (Schuessler and Voegler, 2006; Bharti, 2010, 2013, V. (Thesis, 2011))
- **Active region & sunspot** (Rempel et al, 2009++; Cheung et al 2010++)
- **Flux emergence** (Cheung et al 2007++, Tortosa-Andreu & Moreno Insertis, 2010)
- **Local dynamo** (Voegler and Schuessler, 2007, Rempel 2014)

Magnetoconvection in sunspot umbra
(Schüssler & Vögler, 2006)

3D Cartesian grid: 288 x 180 x 288 grid points
(5.76 x 1.80 x 5.76 Mm)

Pixel size: 20 km = 0.027 arcsec

Optical surface: $\tau_{5000} = 1$ @ ~ 1.3 Mm (500 km photosphere)

Mean magnetic field: <B> = 2.5 kG

Top boundary closed

At **bottom** boundary (F_{RAD} = 20% of 6.34 x10^{10} erg s^{-1} cm^{-2})

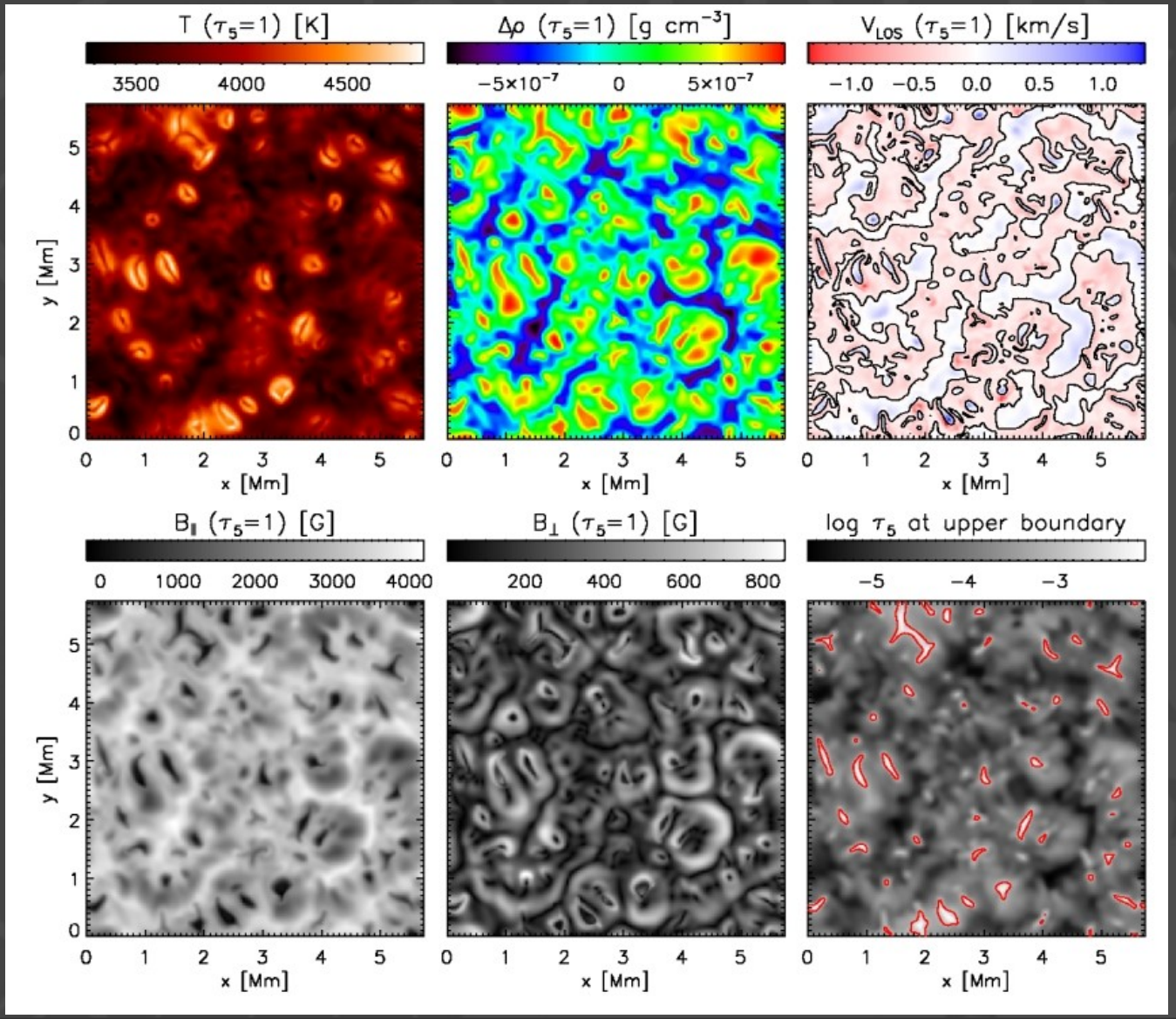
Diffusivity: Constant magnetic and hyperdiffusivity for other processes

Radiative transfer: LTE non-grey with 3 rays per octant

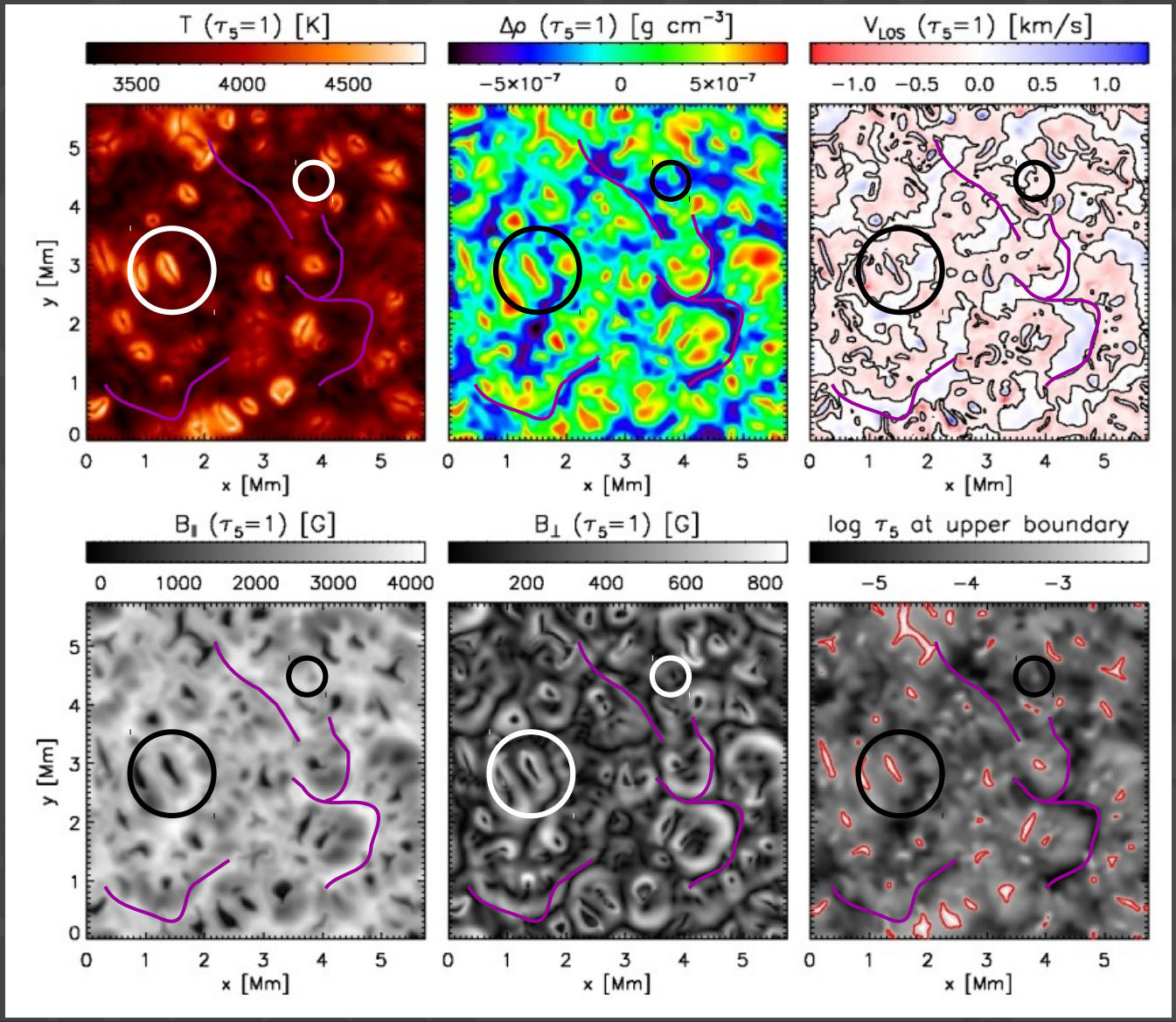
Opacities computed using ATLAS9 (Teff =3800K) and binned to 4 bins

Equation of state: ideal for realistic chem.composition and including partial ionization effects and formation of H2 molecules

Snapshot, section at τ(5000 A) = 1

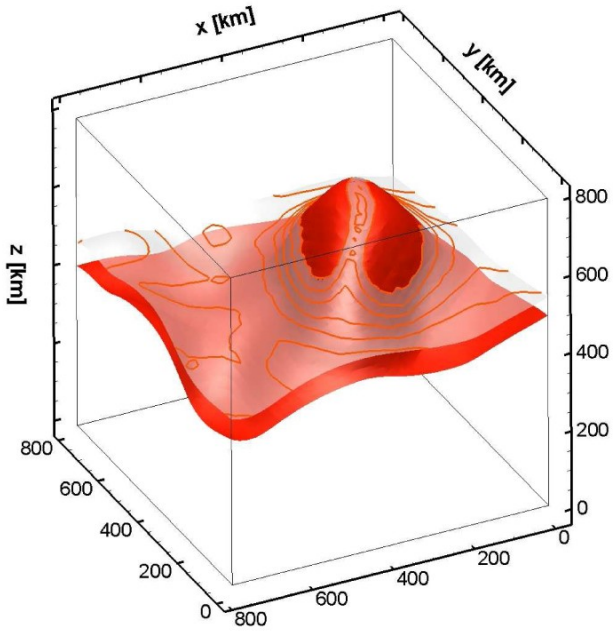


Snapshot, section at τ(5000 A) = 1

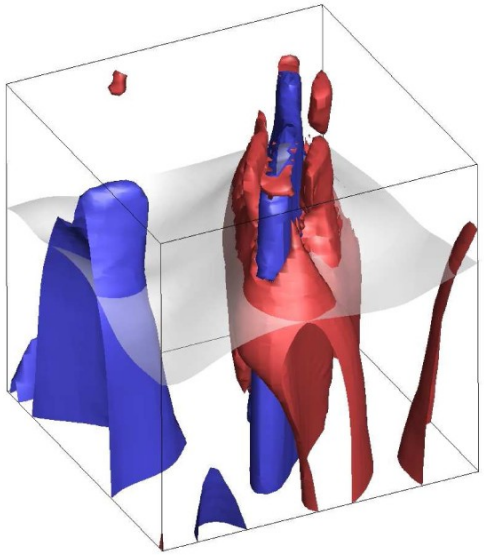


Umbral dot, 3D visualization

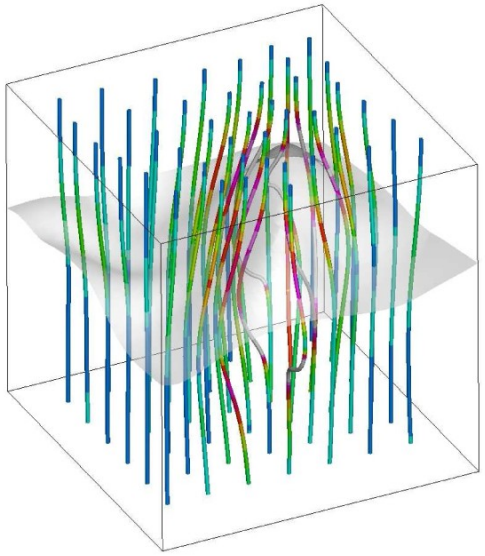
Temperature



Velocity

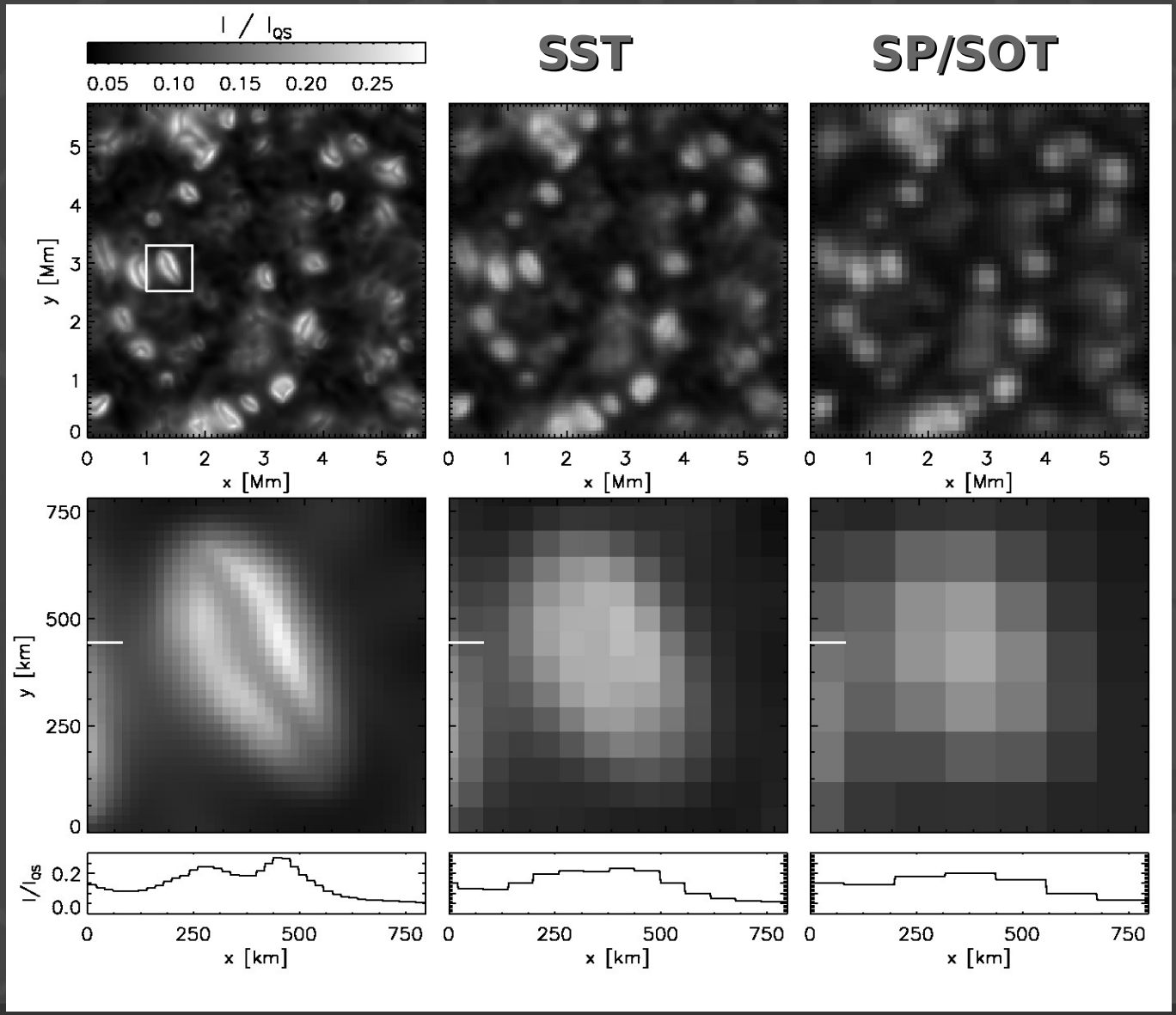


Magnetic field

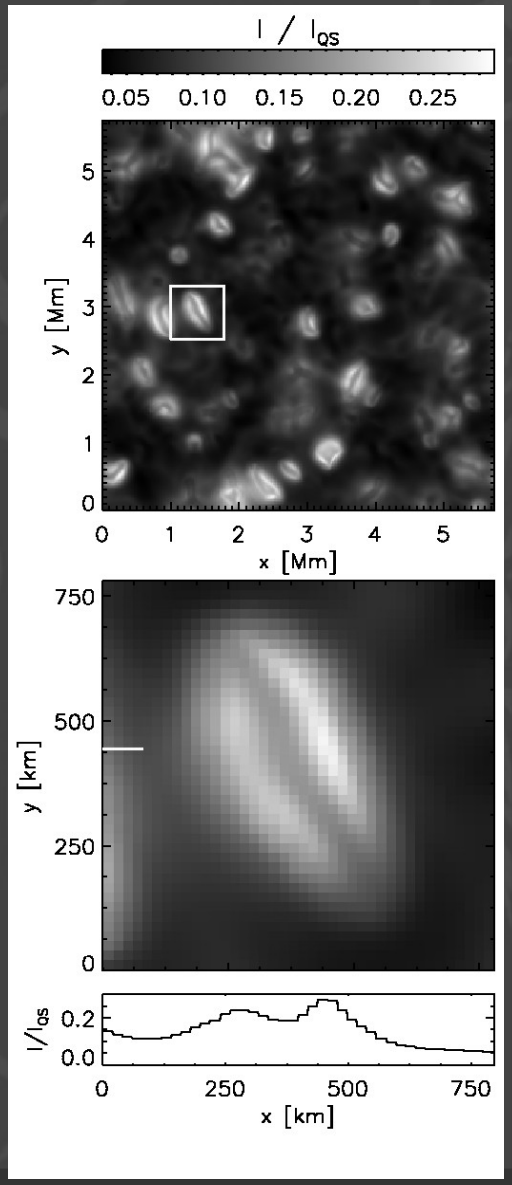


I. CONTINUUM INTENSITY AND ITS CENTER-TO-LIMB VARIATION

Continuum at 6300 A



Continuum at 6300 A



Efective radii and filling factors

I(UD)/I(DB) = 1.2 =>

D = 0.13 – 0.46 arcsec

ff = 18%

I(UD)/I(DB) = 1.6 =>

D = 0.08 – 0.36 arcsec

ff = 10%

Sobotka and Hanslmeier (2005):

D = 0.23”

ff = 9%

Riethmueller et al (2008):

D = 0.39”

ff = 11%

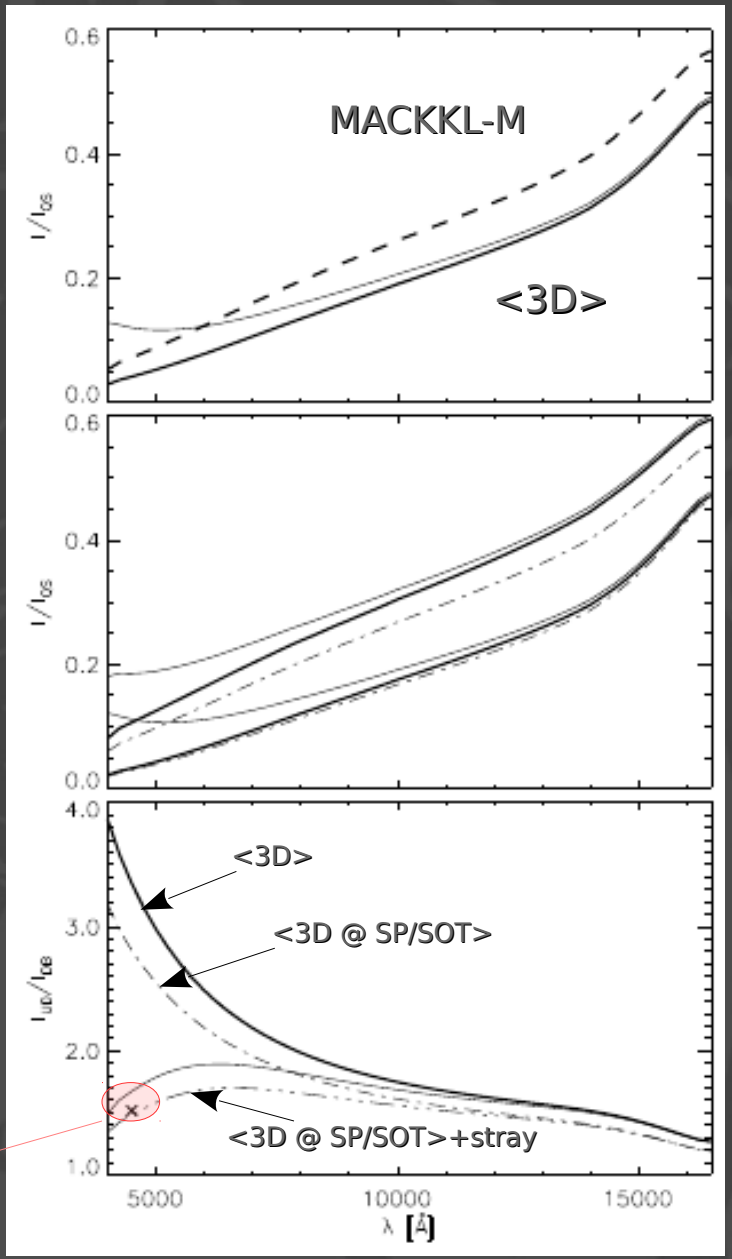
Continuum 4000 – 16000 A

<3D> vs. MACKKL-M

<3D>, <UD>, <background>

<UD>/<background>

Watanabe et al (2009)



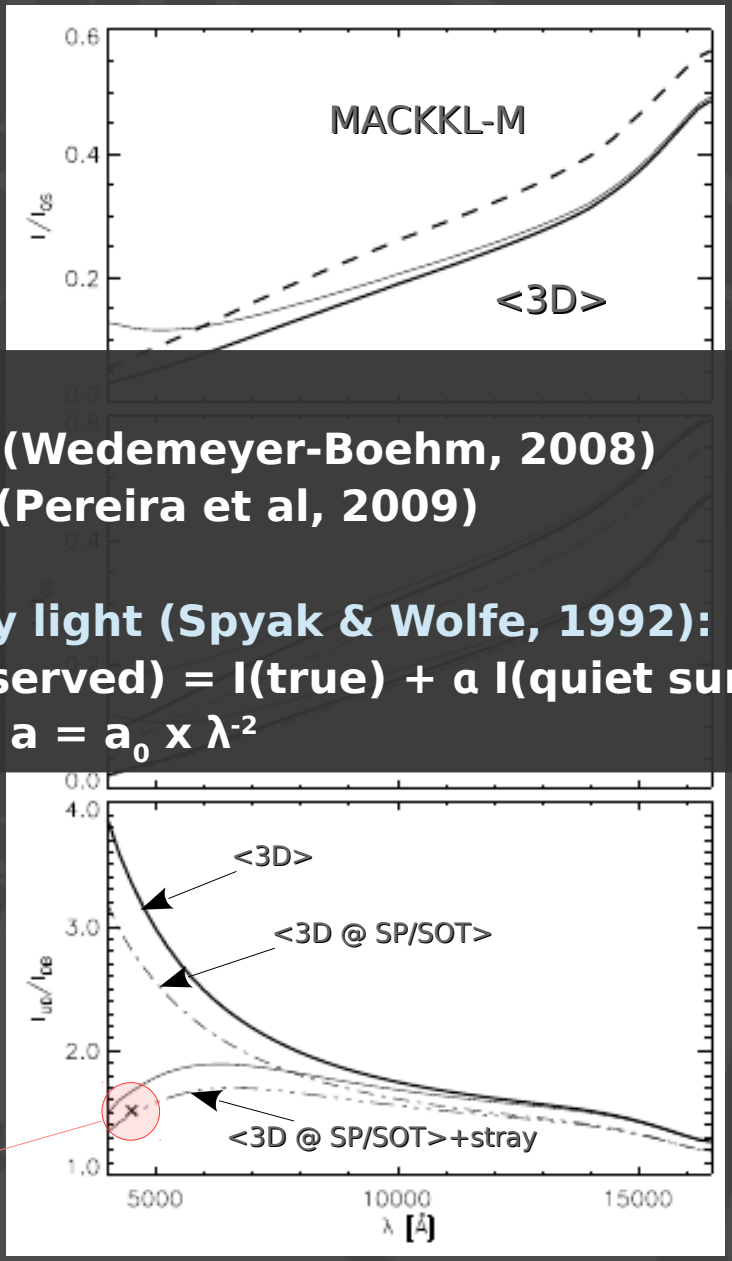
Continuum 4000 – 16000 A

<3DY> vs. MACKKL-M

<3D>, <UD>, <backgrou

<UD>/<background>

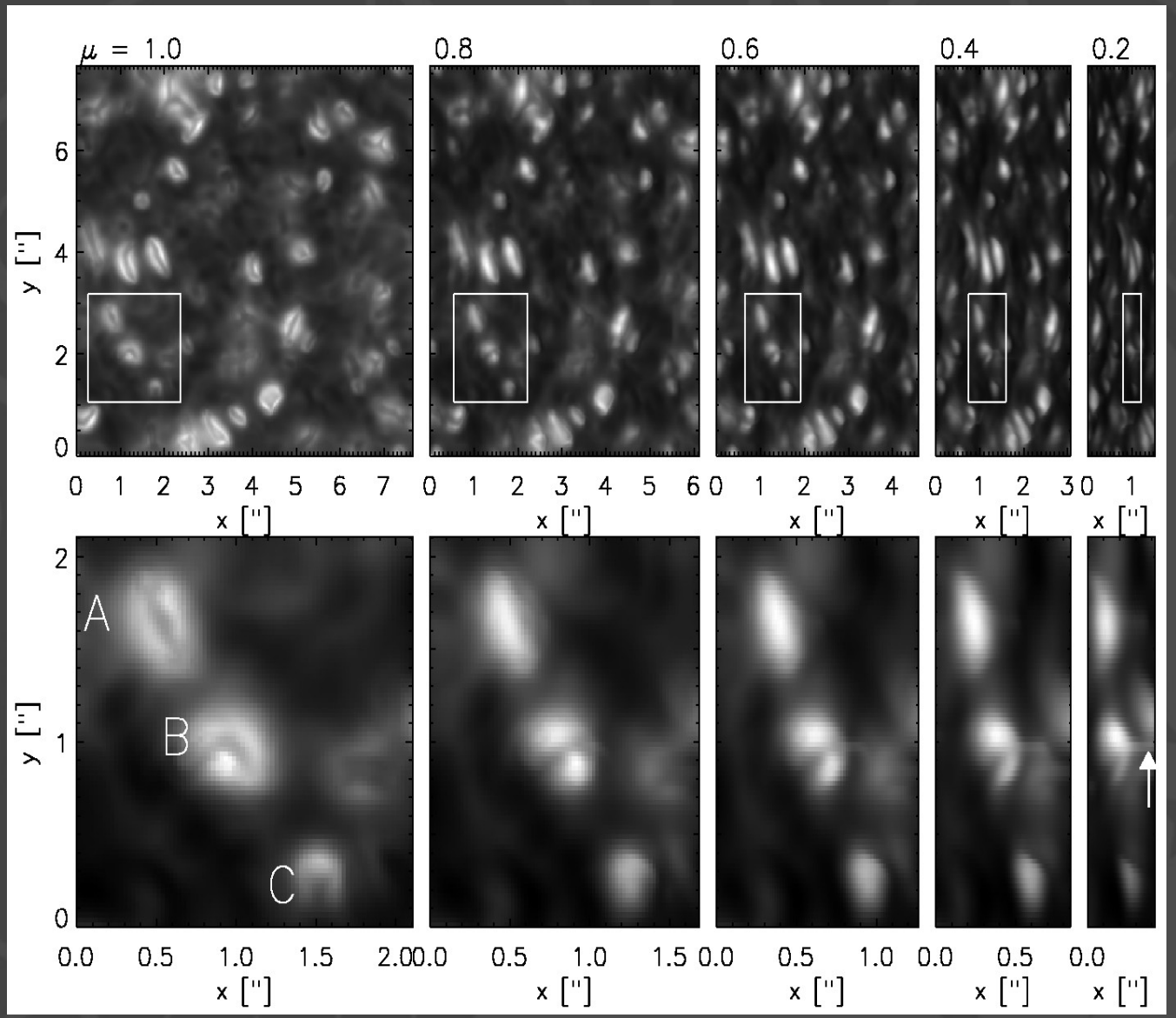
Watanabe et al (2009)



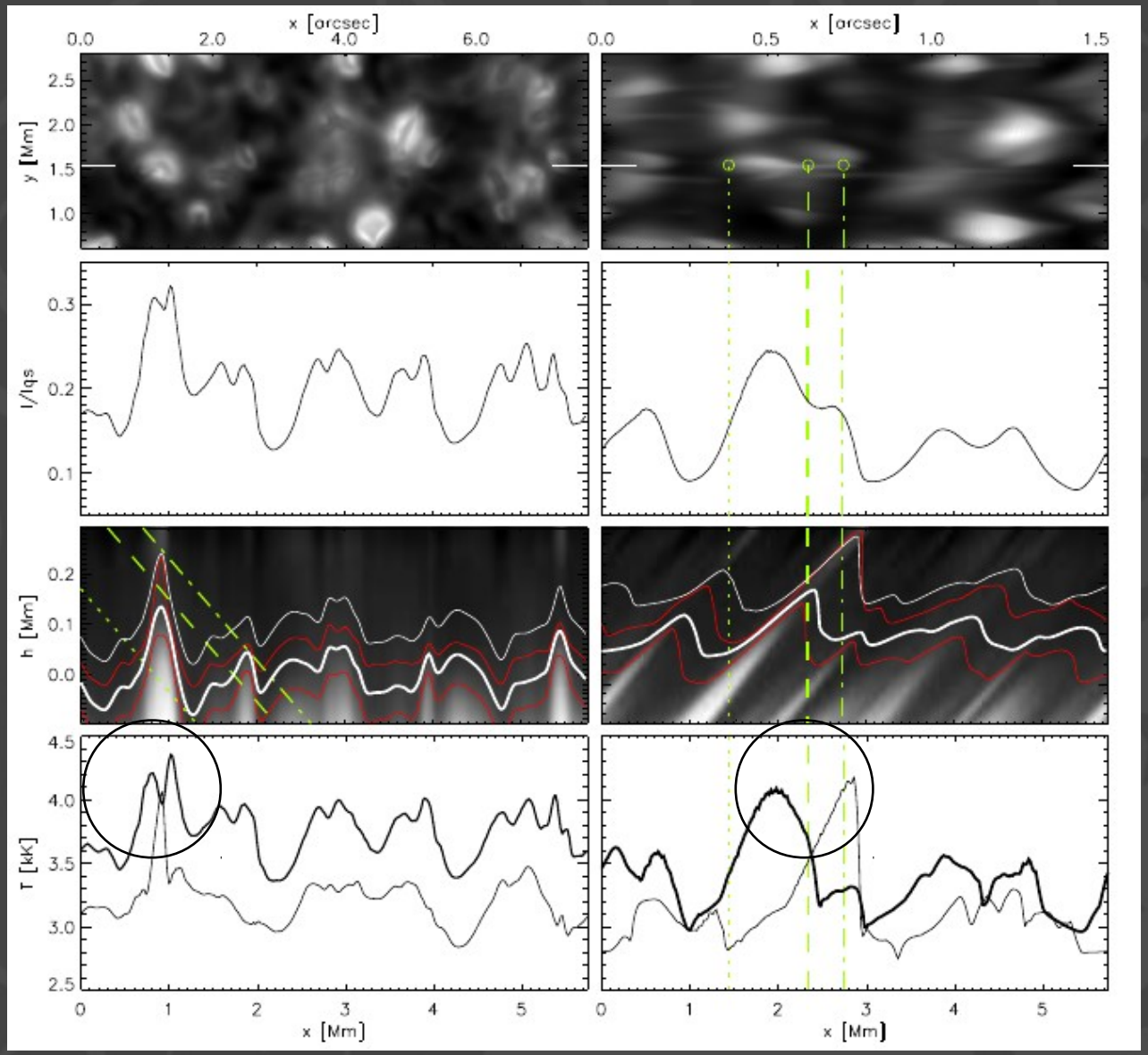
PSF:
SOT (Wedemeyer-Boehm, 2008)
SST (Pereira et al, 2009)

Stray light (Spyak & Wolfe, 1992):
I(observed) = I(true) + α I(quiet sun)
with $a = a_0 \times \lambda^{-2}$

Center-to-limb variation



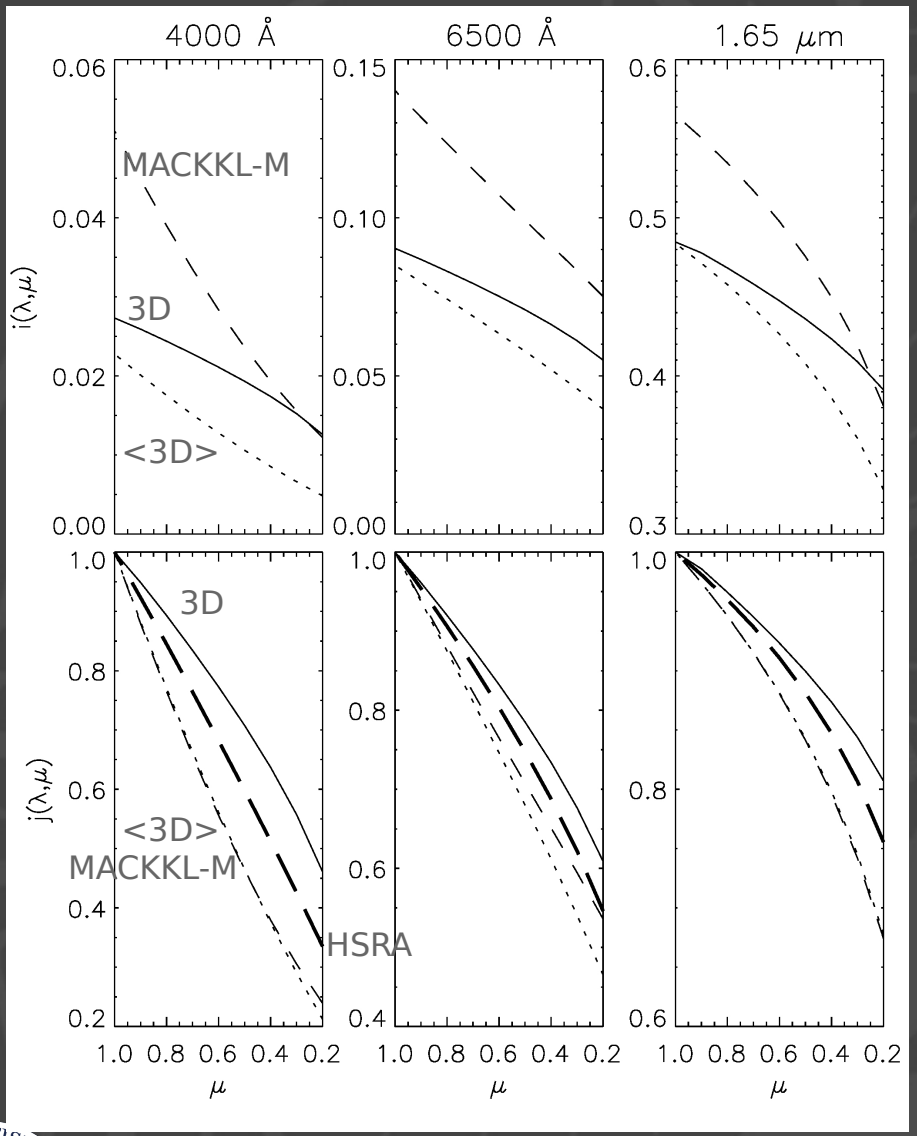
Center-to-limb variation



τ = 0.1

τ = 1

Center-to-limb variation



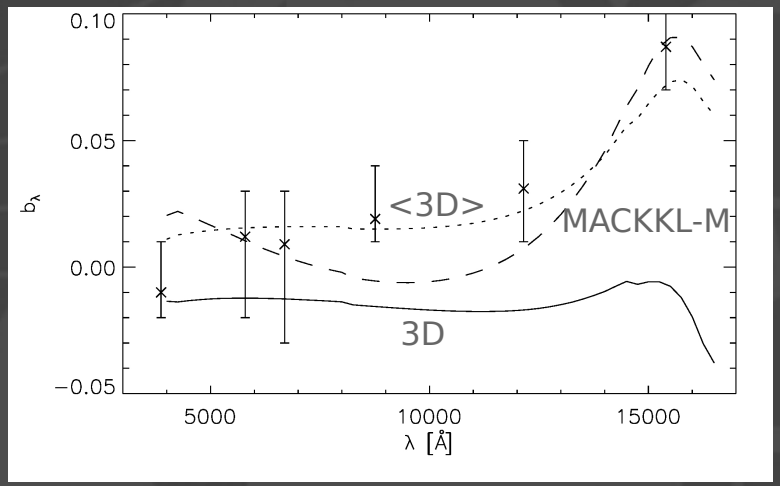
Observations:

Minnaert and Wanders (1932)

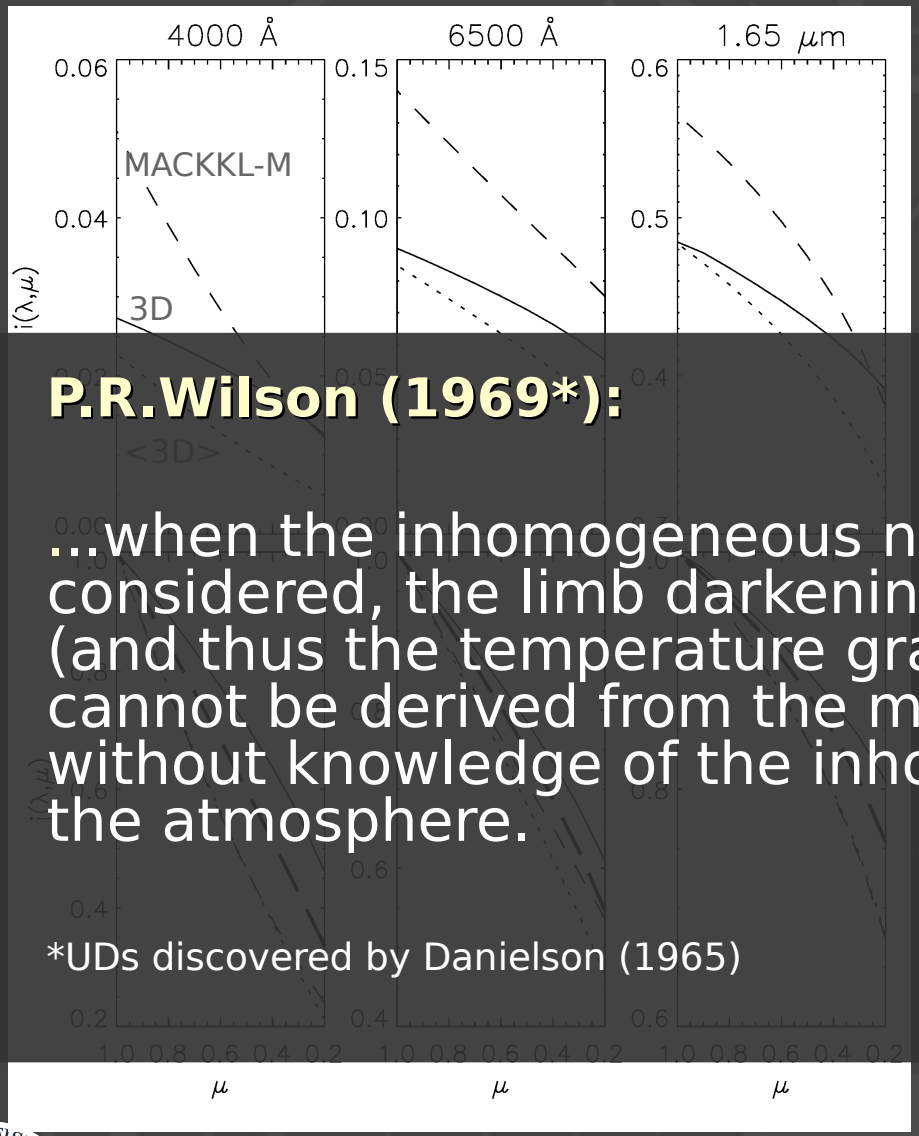
.....

Albregtsen et al (1984)

Norton & Gilman (2004, MDI)



Center-to-limb variation



Observations:

Minnaert and Wanders (1932)

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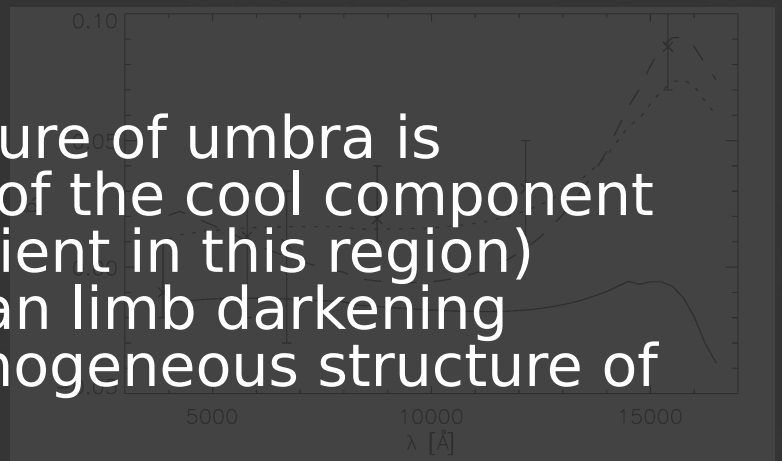
Albregtsen et al (1984)

Norton & Gilman (2004, MDI)

P.R.Wilson (1969*):

...when the inhomogeneous nature of umbra is considered, the limb darkening of the cool component (and thus the temperature gradient in this region) cannot be derived from the mean limb darkening without knowledge of the inhomogeneous structure of the atmosphere.

*UDs discovered by Danielson (1965)



II. Fe I 6302 Å spectral lines

Diagnostics:

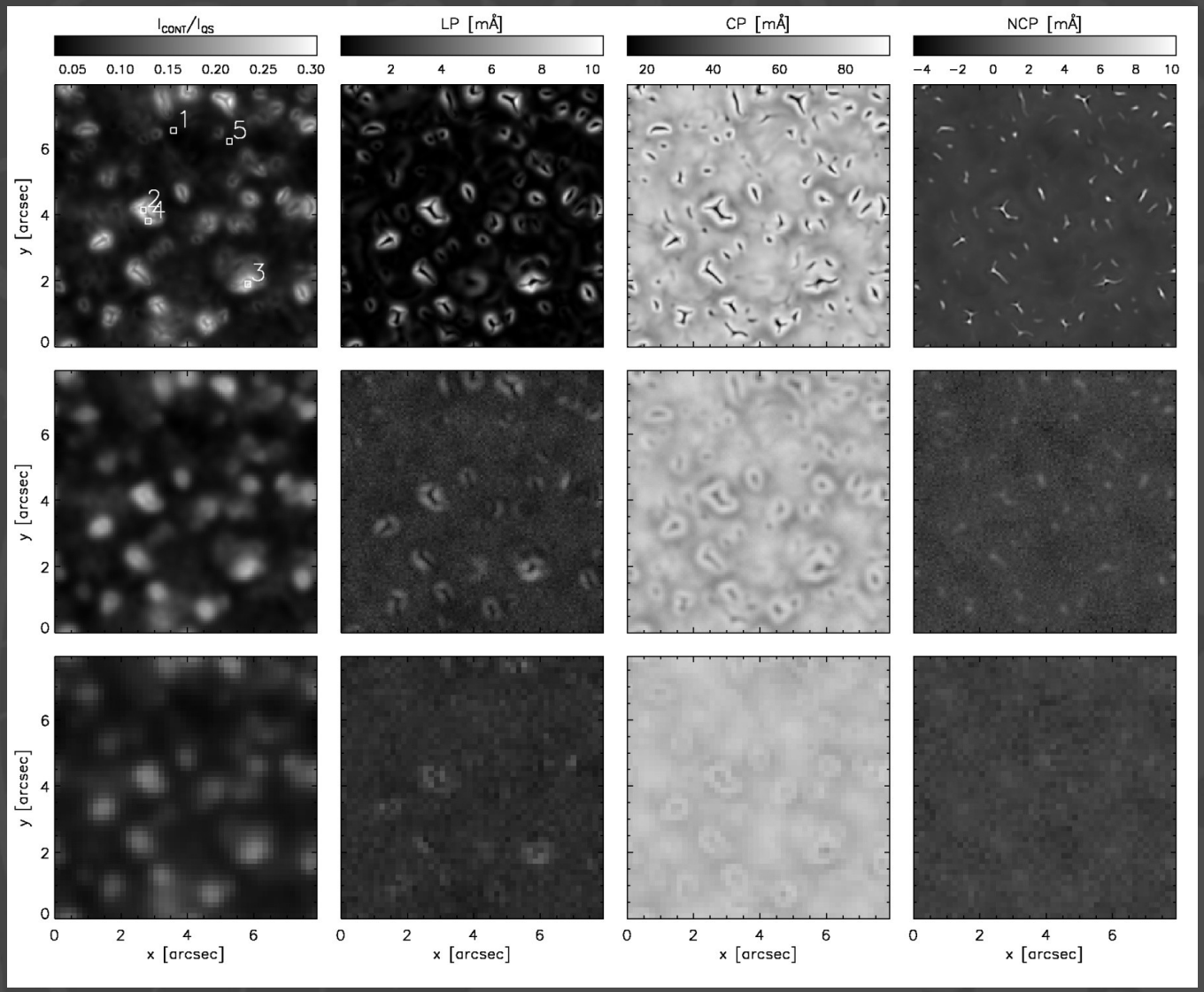
- **Profile shapes**
- **Profile-integrated parameters** (circular, linear, net polarization)
- **Center-of-gravity method**
- **Bisector method** applied to Stokes-I and –V
- **Milne-Eddington inversions** (MELANIE, Socas-Navarro)
- **LTE inversions** (LILIA, Socas-Navarro)

I_{cont}/I_{QS} Linear Circular Net circular

MURaM

SST

Hinode

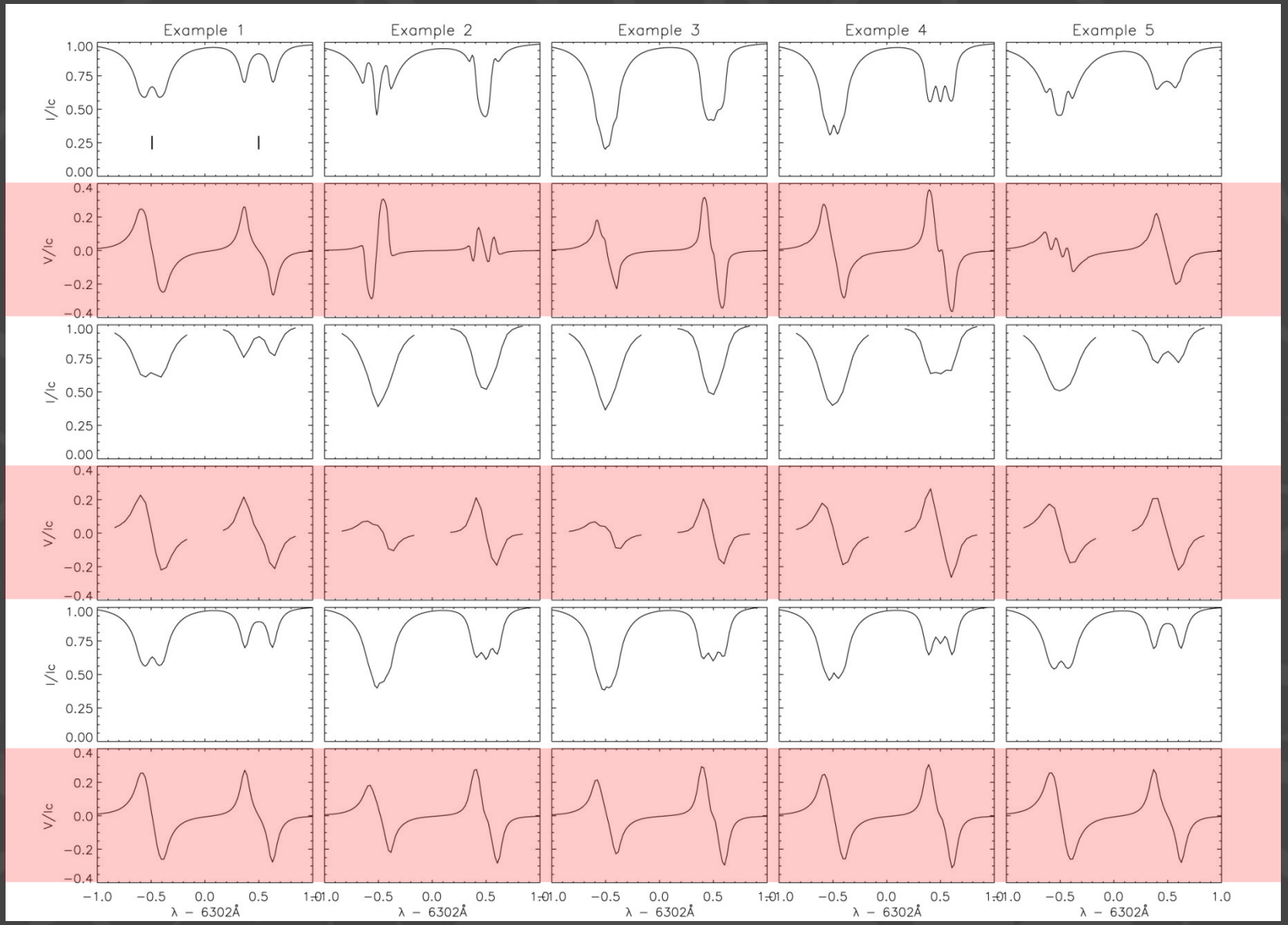


Background | UD lane | UD bright | UD bright | Subph. UD

MURaM

SST

Hinode



Center of gravity

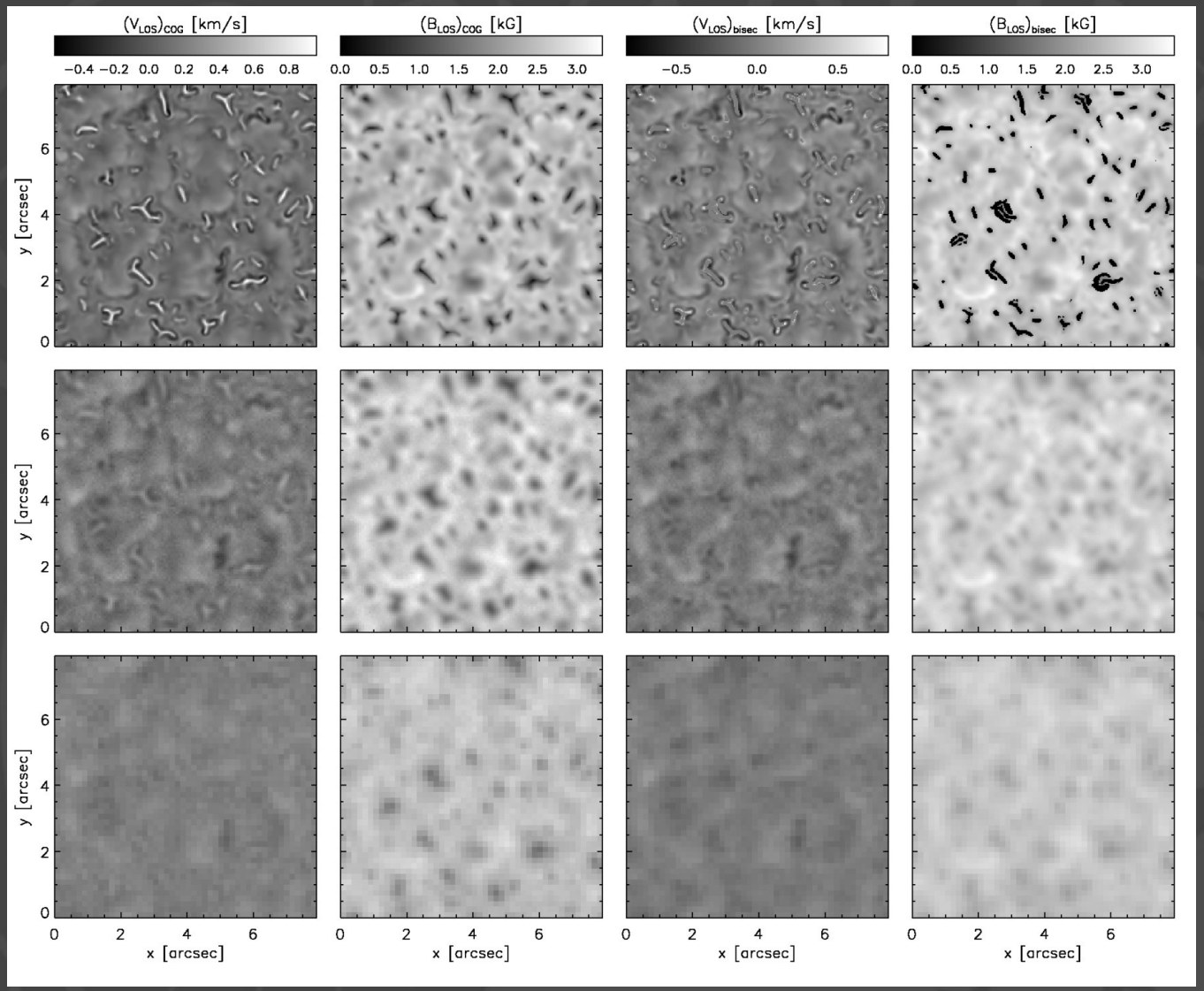
Bisectors

V_{LOS} B_{LOS} V_{LOS} B_{LOS}

MURaM

SST

Hinode



Milne-Eddington inversion

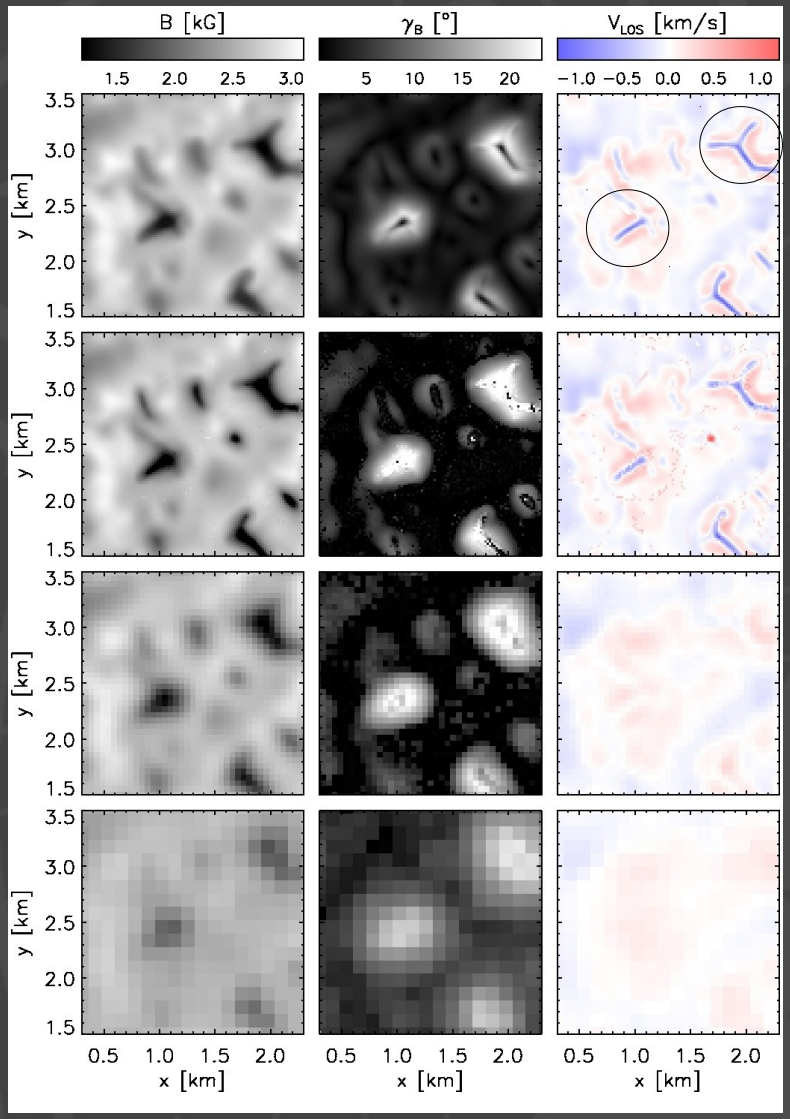
B **Inclin.** **V_{LOS}**

MURaM

DKIST?
MURaM-res
Instrument?

SST

Hinode



Milne-Eddington inversion

LTE SIR-like inversion

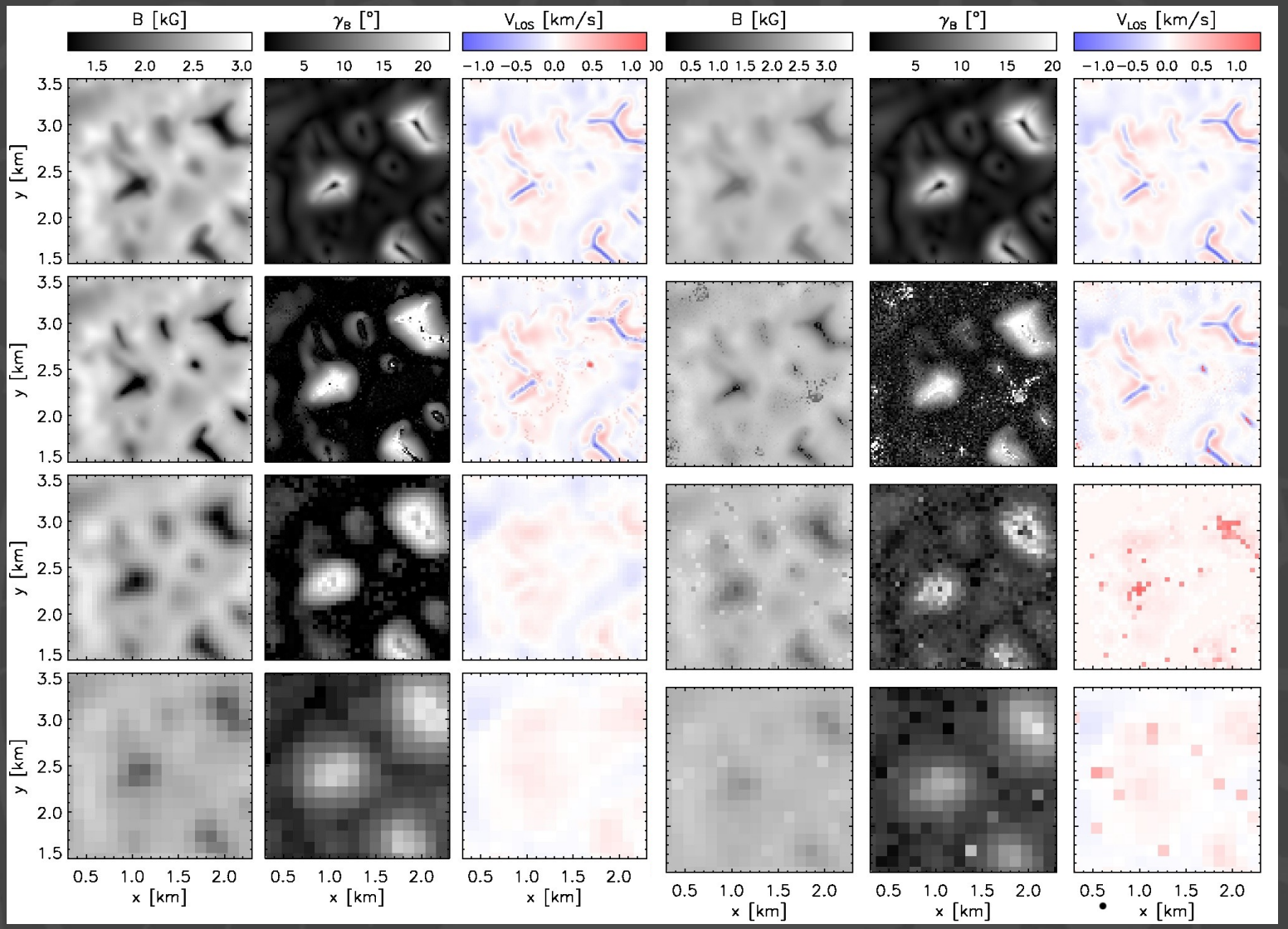
B Inclin. V_{LOS} B Inclin. V_{LOS}

MURaM

DKIST?
MURaM-res
Instrument?

SST

Hinode



LTE SIR-like inversion

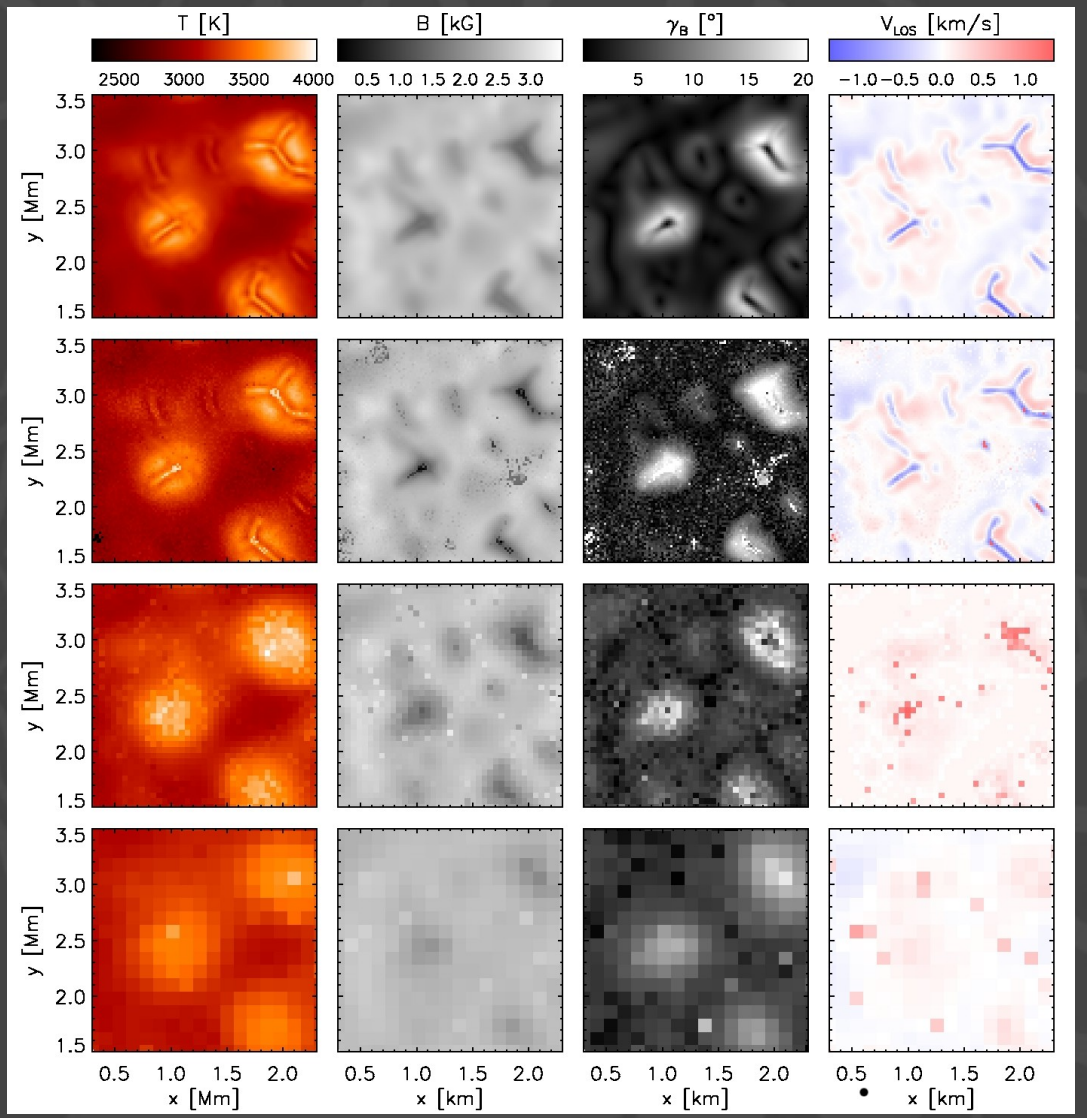
T B Inclin. V_{LOS}

MURaM

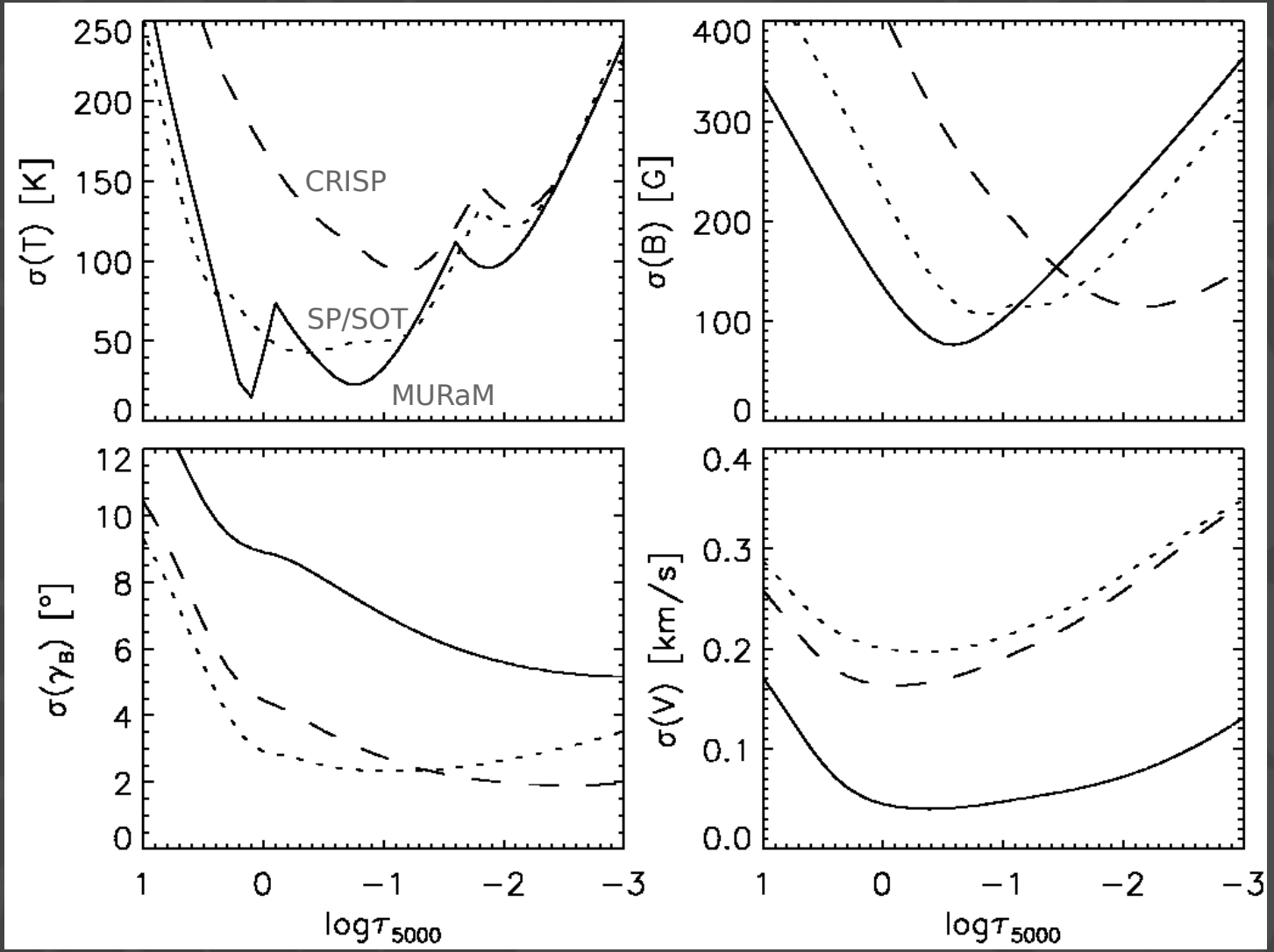
DKIST?
MURaM-res
Instrument?

SST

Hinode



Standard deviation of the simulation-observation difference as function of optical depth



CONCLUSIONS I

Umbral simulation is consistent with observations:

- **relative intensity, effective radius** and **filling factor** of UD's in agreement with observations ;
- snapshot **cooler** and **darker** than MACKKL-M model;
- **internal structure** of the simulated UD's is on the edge of visibility with available telescopes;
- appearance of dark lanes away from disk center depends on their orientation;
- **center-to-limb variation** in 3D dominated by UD's (consistent with some observations);
- **tiny tails** may be visible at limbward side of UD's at the resolution close to the resolution of the simulation (0.03arcsec);
- **stray-light modelling is critically important**.

CONCLUSIONS II

Umbral simulation is consistent with observations:

• Fe I 6302 A show **complex patterns** at the MURaM resolution, most of it **vanishes** at the SP/SOT or CRISP/SST spectral and spatial resolution;

• **COG, bisectors and ME** methods for B and V provide **reliable** estimate at their corresponding heights of formation of measurement (HOFM);

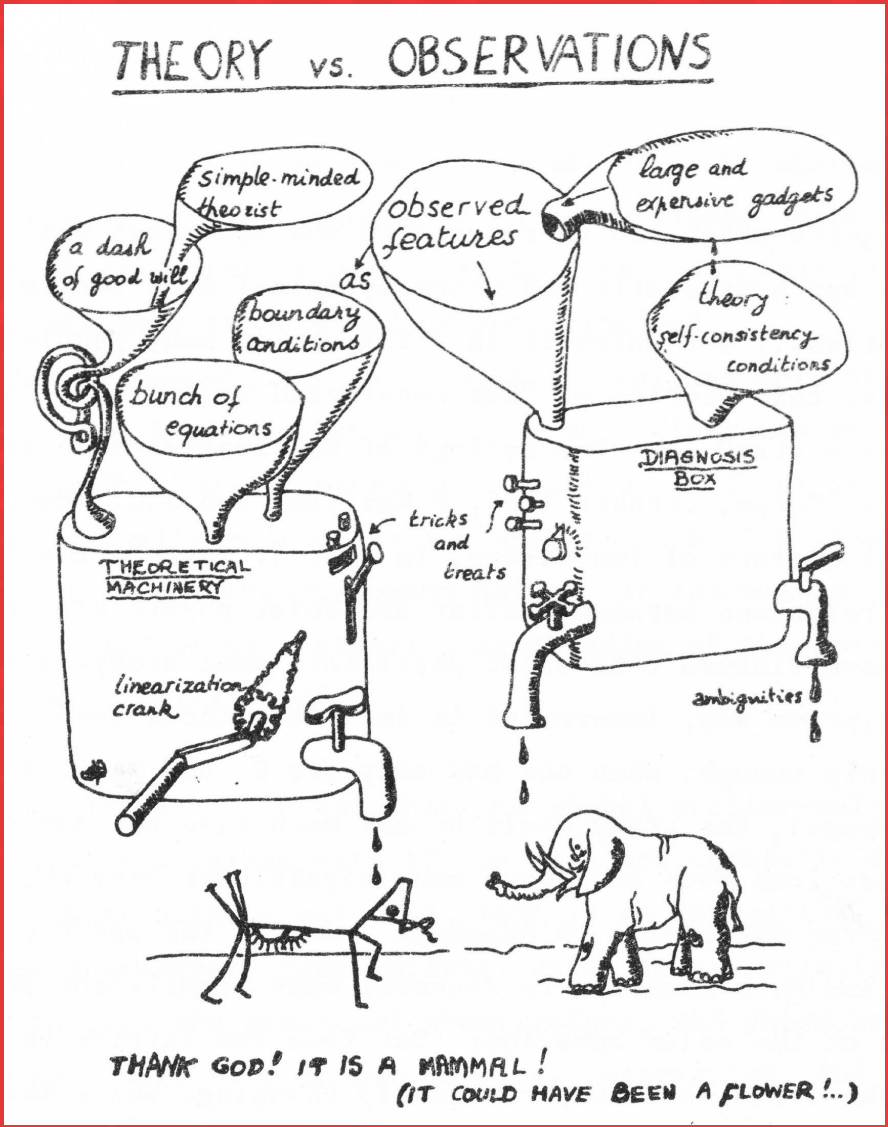
• **LTE inversions** provide reliable values within the formation range of Fe I 6302 A (std.dev. as reversed response function);

• **deviations** between the simulated values and the values retrieved from the synthetic profiles **depend on the spectral and spatial resolution** of the simulated observation;

• **Spatially-coupled inversions** (Van Noort, 2012; Ruiz Cobo & Asensio Ramos, 2013) are necessity, **other lines** (molecules, Ti I, C I 5380) welcome!

• **Riethmuller et al (2013)** in excellent agreement with the snapshot.

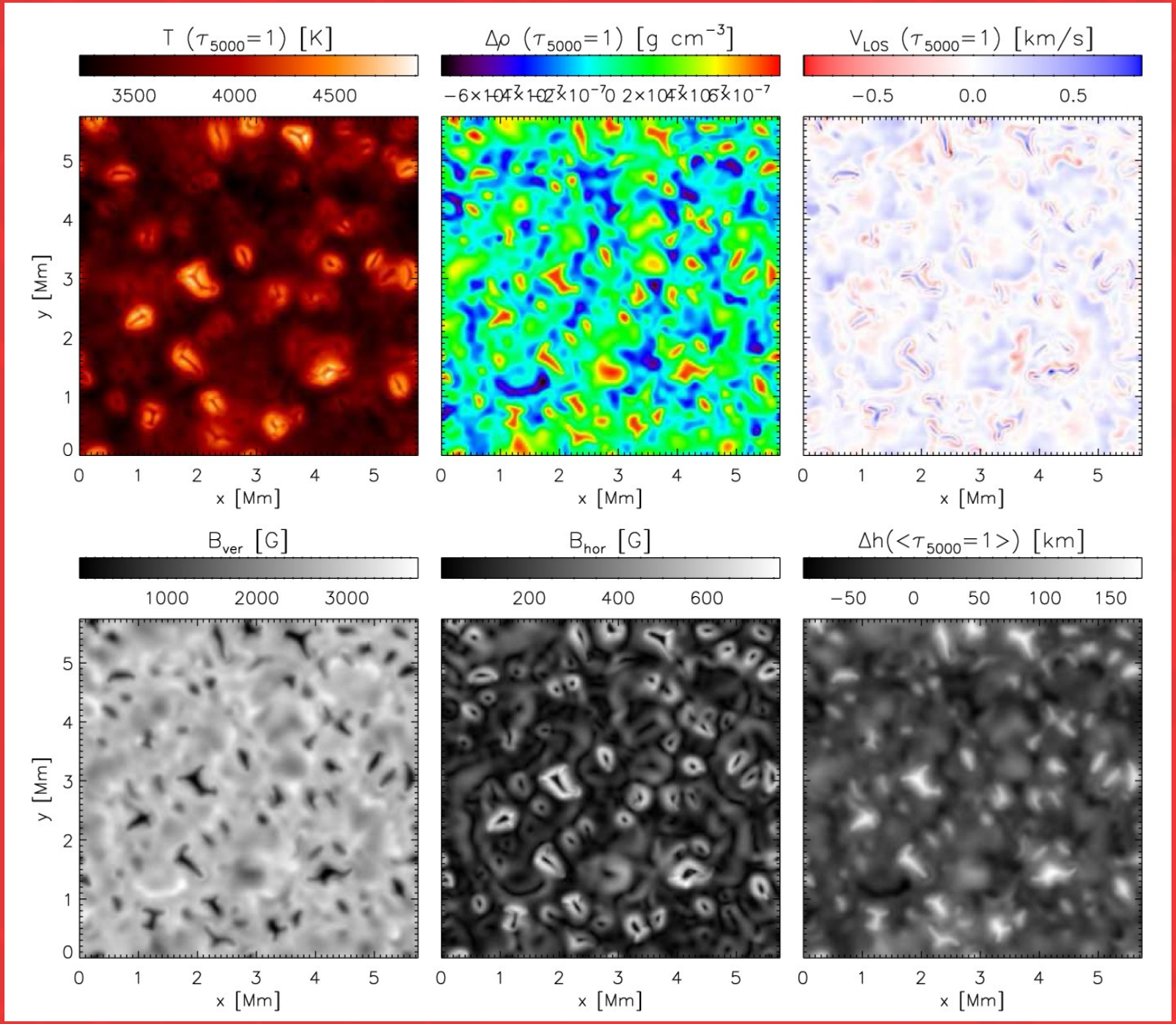
Theory vs. Observations (Pecker 1982)



It’s possible to make a fish soup of an aquarium...

...but not the other way around!

Simulation of magnetoconvection in sunspot umbra



Mean temperature