The solar oxygen abundance as derived using MHD simulations

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Outline

- Introduction
- MHD simulations, LTE and NLTE spectral synthesis from output snapshots
- Is the solar O abundance affected?
- Conclusions / to do / outlook

Intro

Importance of solar abundances

- Affect all fields from solar system to planetary science to abundance ratios for GCE to the high-z Universe

- Drastic downward revision in the past decade of earlier estimates: log ε_O=8.93 **(Anders and Grevesse 1989)** to 8.66 **(Asplund et al. 2004).** Caused intense debate **(e.g., Asplund 2005 & 2009; Ayres 2008; Caffau et al. 2010)** and disagreement with helioseismic predictions **(e.g., Bahcall et al. 2005; Antia & Basu 2006).**

- Need to find good agreement (or understand reason for mismatch) with all of meteoritic, solar neighbourhood and helioseismology constraints

A bit of wizardry

Abundance determination from comparison of observed spectra against theoretical ones

Uncertainties in …

- comparison with observations → error prone (adopted log gf, collisions, continuum placement, EW measurements)
- input atomic data
- atmospheric models → great advancement from static plane-parallel 1D models to HD 3D models of Asplund & co. and those of Ludwig & co. Improved agreement between atomic and molecular lines. But: what about magnetic fields?

Tools, methods & techniques

Aim: explore abundance effects in 3D MHD models

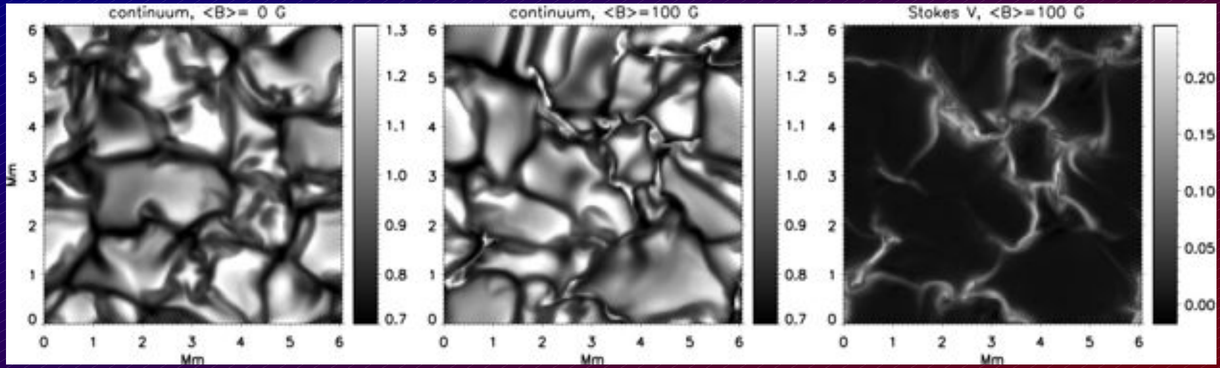
→ **collaborators: Moreno-Insertis, Khomenko, Nordlund, Beck**

- Nordlund's CPH radiation-hydro Stagger code
- LILIA **(Socas-Navarro 2001)** → I, Q, U, V in LTE
- MULTI **(Carlsson 1986)** → multi-level non-LTE R.T.
- Latest atomic data: NIST & VALD databases

(Magneto)-convection simulations

Fabbian et al. 2010 (ApJ 724, 1536)

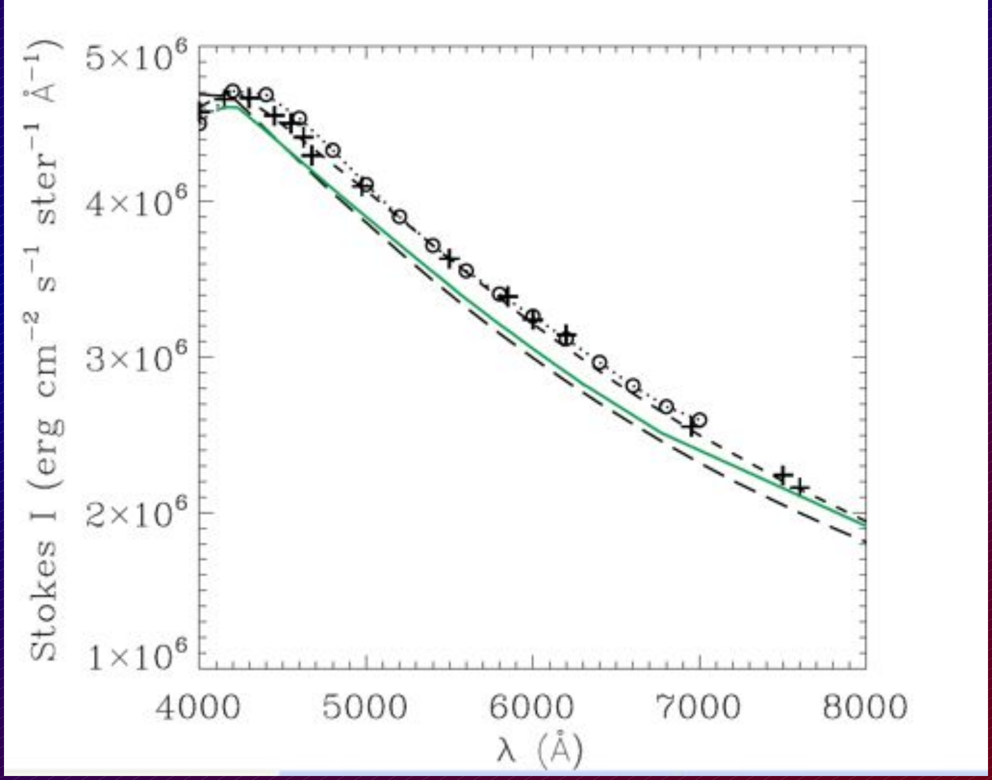
- 252 uniformly-spaced grid points over 6 Mm in each horizontal direction, 126 points vertically over 3 Mm (sampling of ~ 23.8 km horizontally and at best ~ 15 km vertically)
- 4 series: <B>=0, 50, 100 and 200 G (weak magnetic fields cover most of the Sun's surface, flux density of ~10^2 G nowadays considered good reference value, e.g. Trujillo Bueno et al. 2004; Nordlund et al. 2009). Bright points appear as per observations



Solar disk center continuum intensity

Good fit to observational data **(Neckel & Labs 1984)**

Other data: semi-empirical MACKKL by **Maltby et al. 1986** (short-dashed line); photospheric ``thermal profiling'' analysis by **Ayres et al. 2006** (dotted line with open circles) and single 3D HD snapshot by **Asplund et al. 2000** (long-dashed line)

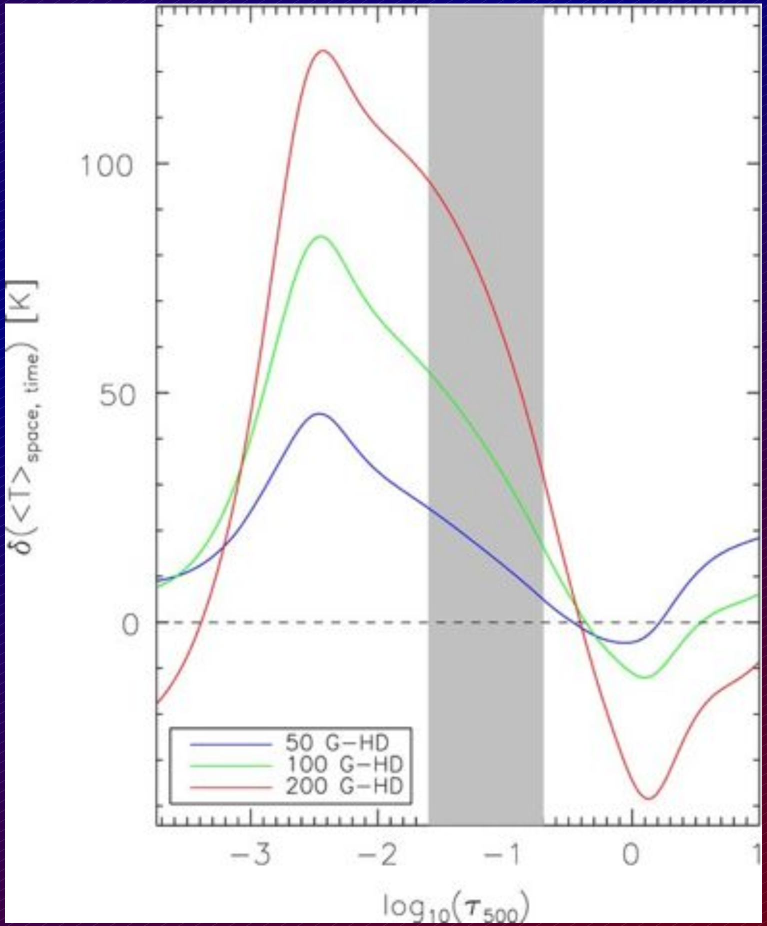


T-tau stratification changes

Warmer in MHD

→ B makes granules smaller,
even stronger fields tend to
suppress granulation

→ lower density in
magnetic concentrations
makes photospheric
material more transparent,
radiation comes from hotter layers

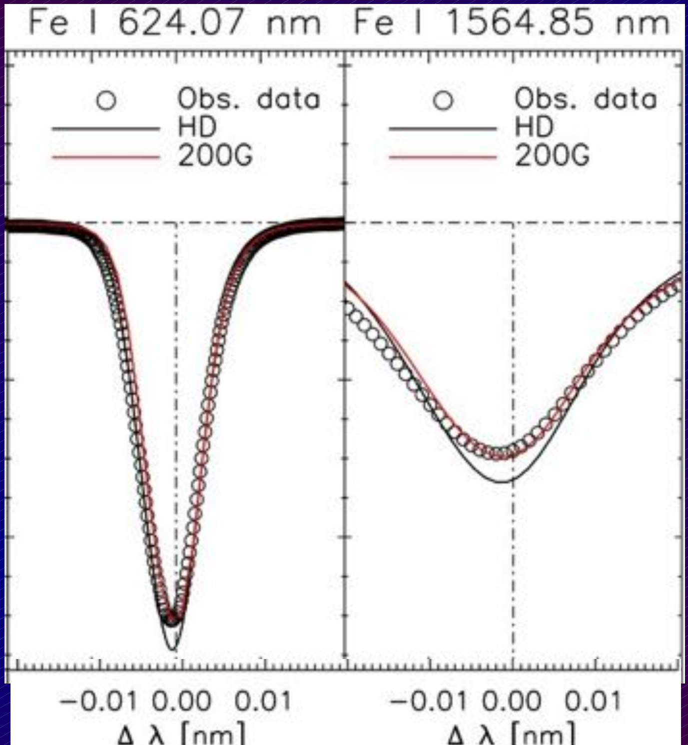


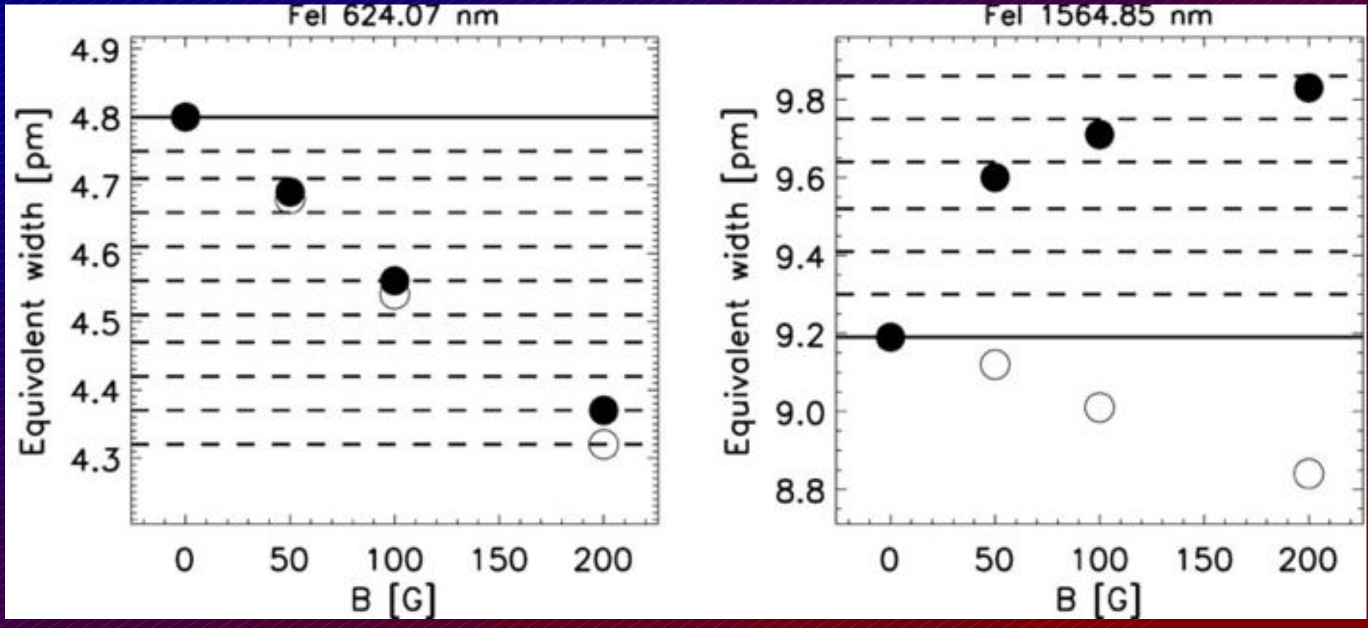
of the atmosphere **(Stein & Nordlund 2000)** where flux tubes are also heated through influx from surrounding material **(Spruit 1976)**.

Direct vs. indirect effect of B

- Indirect effect weakens Fe lines in the visible

- Direct (Zeeman broadening) effect of B on magnetically-sensitive lines prevails only in IR





Extension to 28 Fe lines

Fabbian et al. 2012 (A&A submitted)

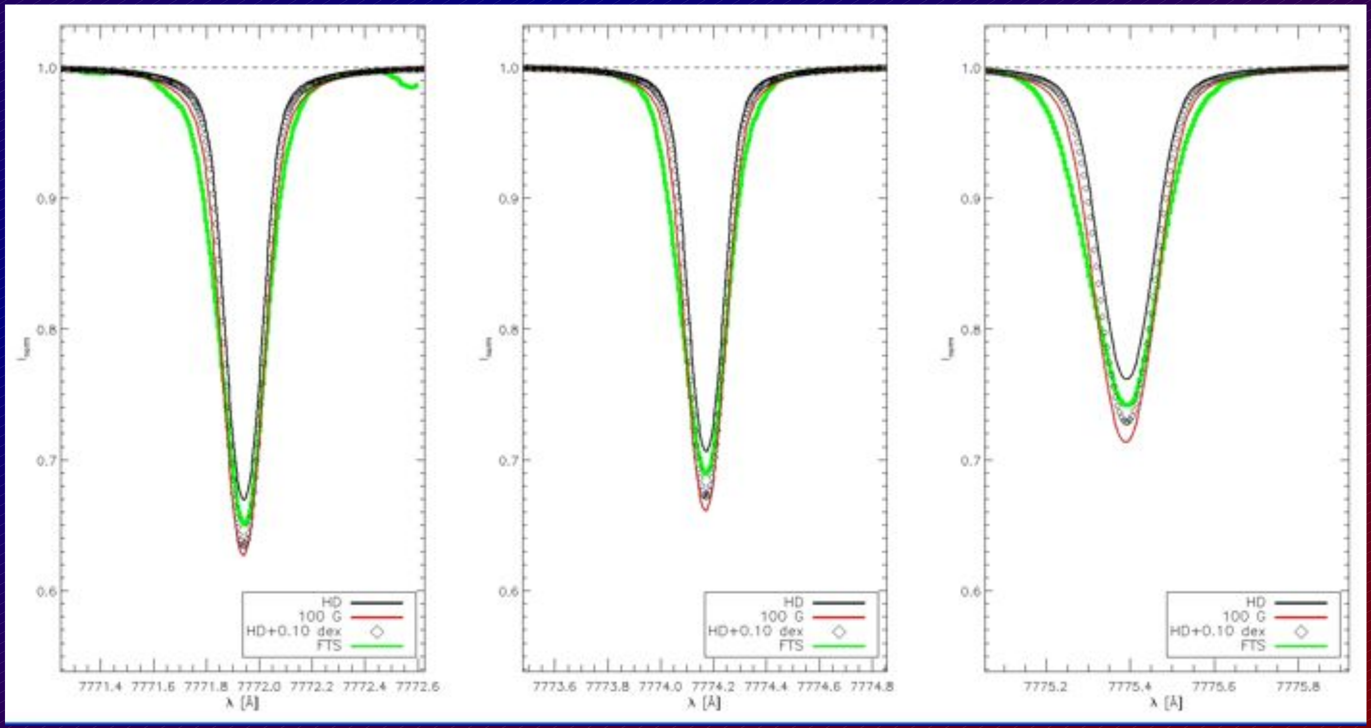
Solar Fe abundance affected ! Is it > 7.50 ?

→ average value derived from 5 lines in the visible in common with **Asplund et al. 2000** increases by up to ~ 0.1 dex for <B> = 200 G

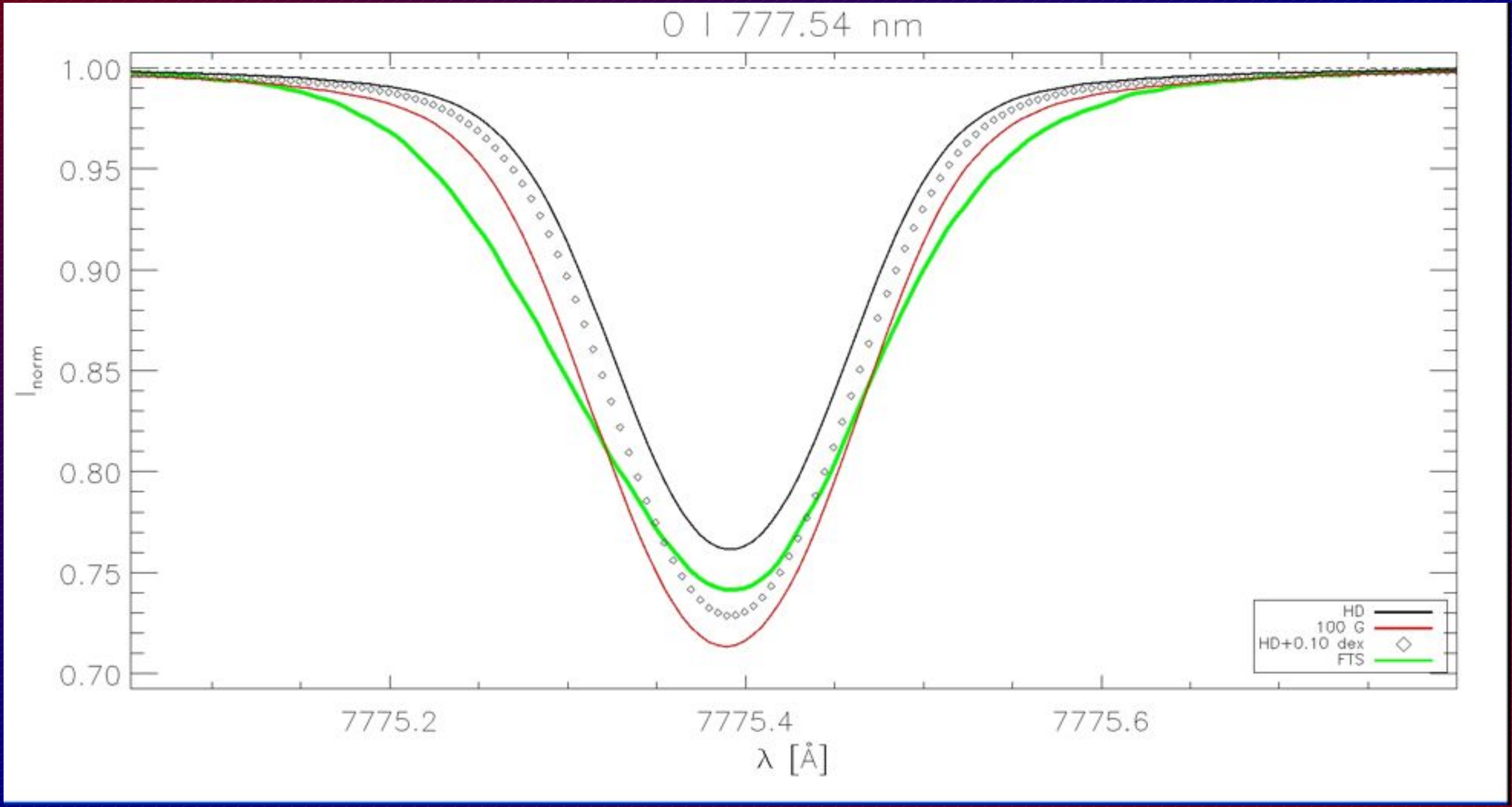
	$\Delta\log\epsilon(\mathrm{Fe})_\odot$ [dex] (50 G - HD)	$\Delta\log\epsilon(\mathrm{Fe})_\odot$ [dex] (100 G - HD)	$\Delta\log\epsilon(\mathrm{Fe})_\odot$ [dex] (200 G - HD)
⟨⟩	0.019 ±0.011	0.040 ±0.023	0.061 ±0.035
⟨⟩*	0.032 ±0.008	0.070 ±0.014	0.110 ±0.020

NLTE synthesis of oxygen lines

- 54-level model atom **(Fabbian et al. 2009)**
- Adopted O abundance = 8.69 **(Asplund et al. 2009)**
- H collision: **Drawin (1968, 1969)**; e coll.: **Barklem (2007)**
- Example: (B + T sensitive) O I 777 nm triplet



NLTE synthesis of oxygen lines



Van der Waals broadening:
Ünsold (1955) with x3 enhancement

NLTE synthesis of oxygen lines

- Preliminary EW results [in mÅ] (no blends considered):

	HD	"100 G"	HD (O+0.10dex)	FTS / Kiselman93
λ777.19 nm	64.0	83.0	73.7	87.0 / 81.8
λ777.42 nm	54.1	71.4	62.8	73.3 / 70.5
λ777.54 nm	40.7	55.3	47.9	57.2 / 56.8

Main message:

B introduces important <u>relative</u> abundance corrections

Oxygen abundance

- O I 777 nm triplet affected: relative MHD-HD abundance correction due to temperature change is negative (opposite behaviour to Fe: expected, on the basis of ionization fraction)

- Degeneracy between non-LTE and B effects: if S_H~0, best match when including B may be achieved with solar O abundance < 8.70 (i.e., even lower than **Asplund 2009**) → more friction with helioseismology ahead ? More likely, S_H~1 and $\langle B \rangle < 100$ G → O abundance > 8.70

- Absolute match of profiles to be improved with ABO collisions → plan to test using NICOLE code **(Socas-Navarro, de la Cruz & Asensio Ramos)**

Conclusions

- The inclusion of magnetic fields in 3D photospheric simulations is an important new step:
  - **changes thermodynamic structure**
  - **introduces line broadening via the Zeeman effect**
- Impact on solar abundances indirectly spreads to other fields of astrophysics
- Definite conclusions for O to be gained through an encompassing study using many lines
- To do: absolute abundance from fitting of intensity profiles (VTT observations for various atomic lines in hand and reduced), Stokes parameters, CLV, more chemical elements, other stars …

The eternal question … :)

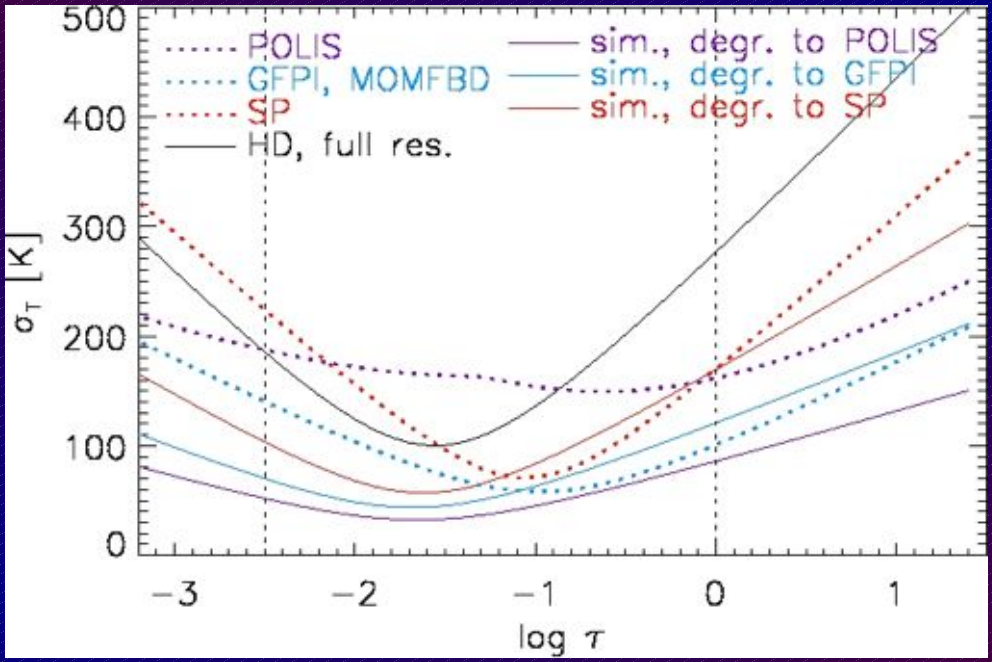
What will solar abundances be (in particular, for C, N, O, Si and Fe) once spatial variations in temperature, density, velocity field, magnetic field intensity, and NLTE effects are fully taken into account ?
(Sukhorukov & Shchukina 2012)

i.e.: are we finally converging on solar abundances?

THANKS … & QUESTIONS ?

Thermodynamics

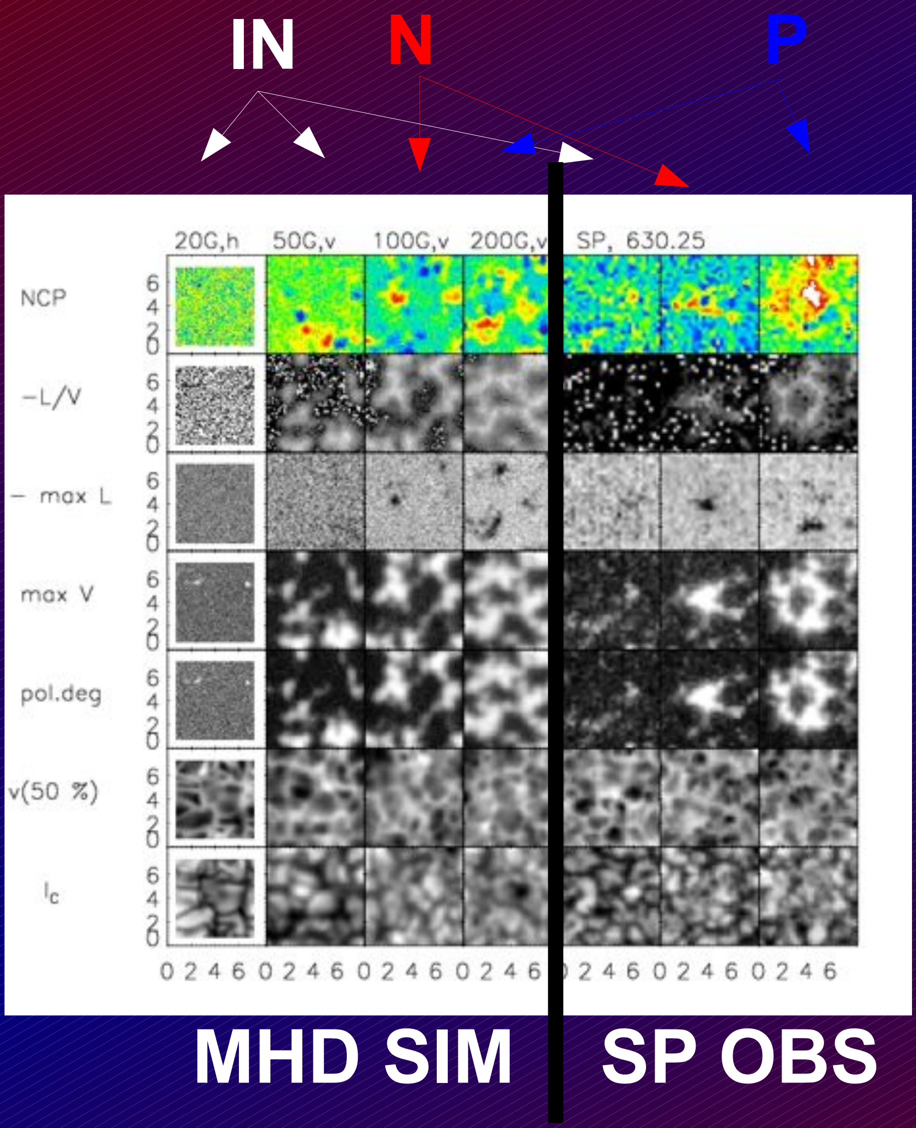
- Radiative transfer in simulations is partially limited by approximations used
- Does this yield excessive thermodynamic fluctuations in the simulations ? No:



- Inversion of observations and degraded simulations
- rms fluctuations of T in degraded simulations are lower than in observations

Beck et al. 2012, in prep.

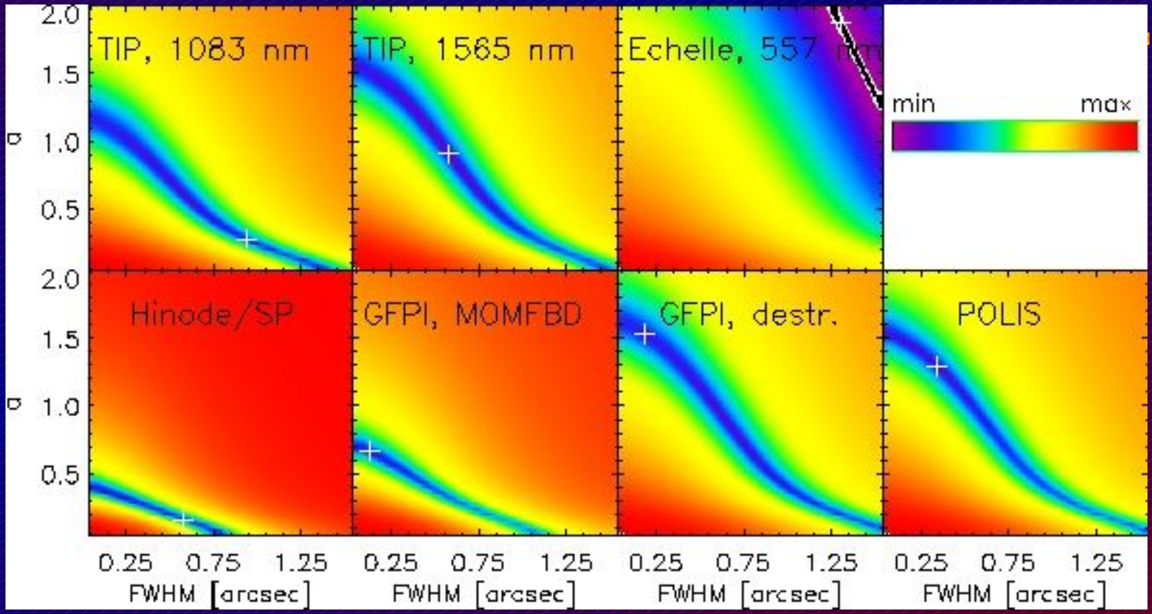
Magnetic parameters in degraded simulation vs. Hinode/SP observations



- observed polarization signals in internetwork (IN) between 20 and 50 G MHD runs
- 100 and 200 G MHD runs correspond to network (N) and strong network/ plage
- abnormal granulation results from BPs+ granulation

Spatial degradation

- Combination of Gaussian (FWHM) and Lorentzian (a) as spatial 2D convolution kernel
- Variation of kernel, fit of Gaussian to histogram of I_c, subtraction from observed histogram
  → χ^2-surface, highest spatial resolution == minimal χ^2 in lower left corner



degenerate χ^2-surface, manual selection of best match by visual impression of I_c maps

Stray light estimates

- Creation of 2D spatial kernel K(x,y) from 1D kernel assuming axisymmetry
- stray light: $I_{stray}(x_0,y_0) = \sum_{i,j\neq 0} K(x_i,y_j) * I(x_i,y_j)$
- continuum wavelength in $I_{stray}(x_0,y_0)$ == stray light coefficient α
- width of kernel K(x,y) == spatial resolution

data	SP	GFPI, MOMFBD	GFPI, destr.	POLIS	TIP, 1083	TIP, 1565	Echelle 557
α [%]	28	19	30	31	34	33	40
width at 25 % [“]	0.58 (0.6)	0.47 (0.3-0.4)	0.55 (0.6)	0.58	0.74	0.66	0.87