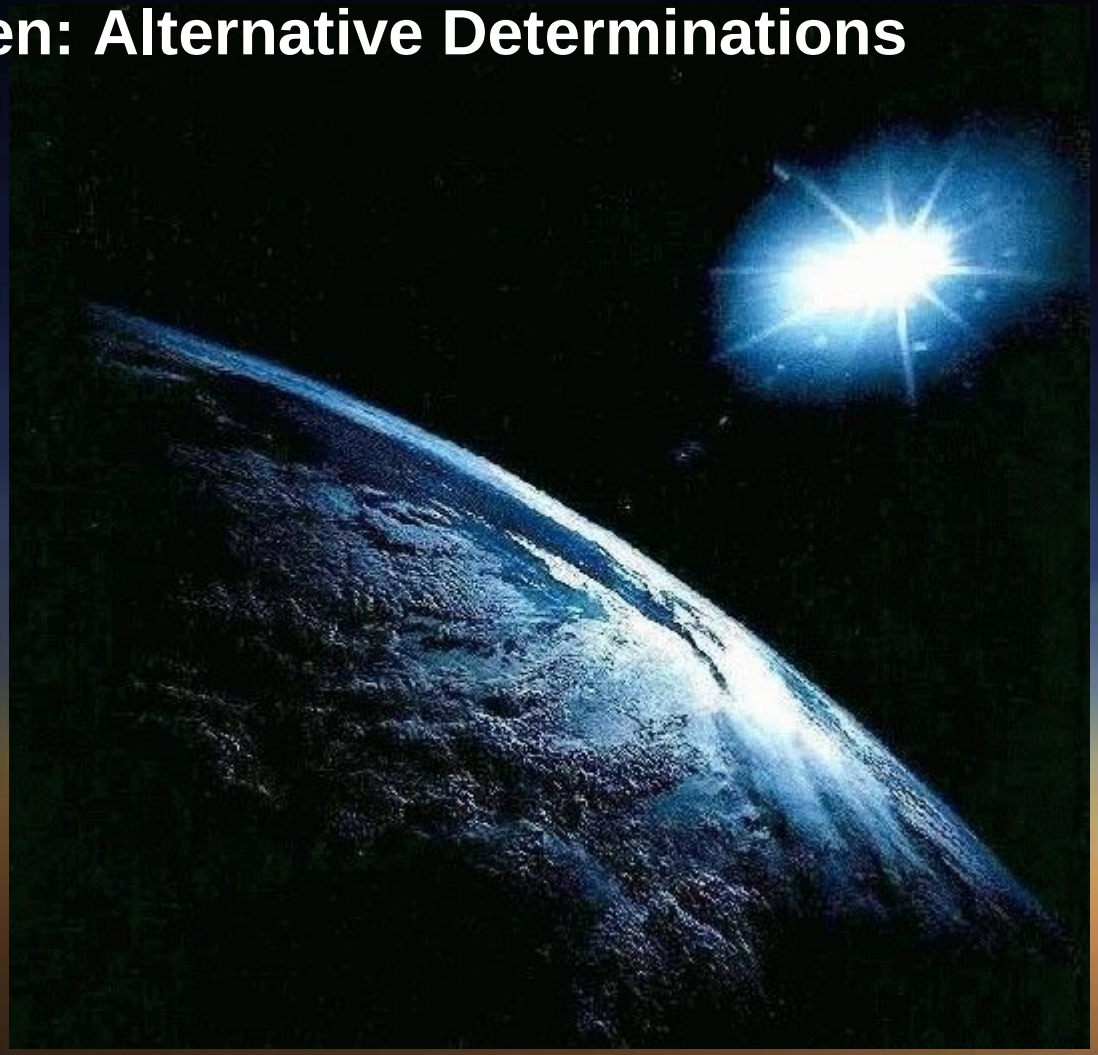
Solar Oxygen: Alternative Determinations



May-2012

Héctor Socas Navarro
Instituto de Astrofísica de Canarias

Introduction: Oxygen is pivotal

- Accounts for most of the heavy-element mass fraction
- Difficult to measure:
  - Very few lines (most forbidden, others NLTE)
  - Volatile (can't use meteorites)
- Some other important elements can only be measured relative to O (e.g., N, C, Ne)
  - Changes in electron density and opacities
- The low abundance (8.6) fits better with the solar environment but ruins the agreement with helioseismology (8.8)
- Converging to 8.7?

Deriving abundances

- Take a model atmosphere:
  - 1D (from observations)
  - 3D (from simulations)
- Assume abundances
- Compute spectral lines
- Compare synthetic lines to observations:
  - Spatially unresolved observations
  - When using 3D models, average before comparing
- Iterate

Deriving abundances

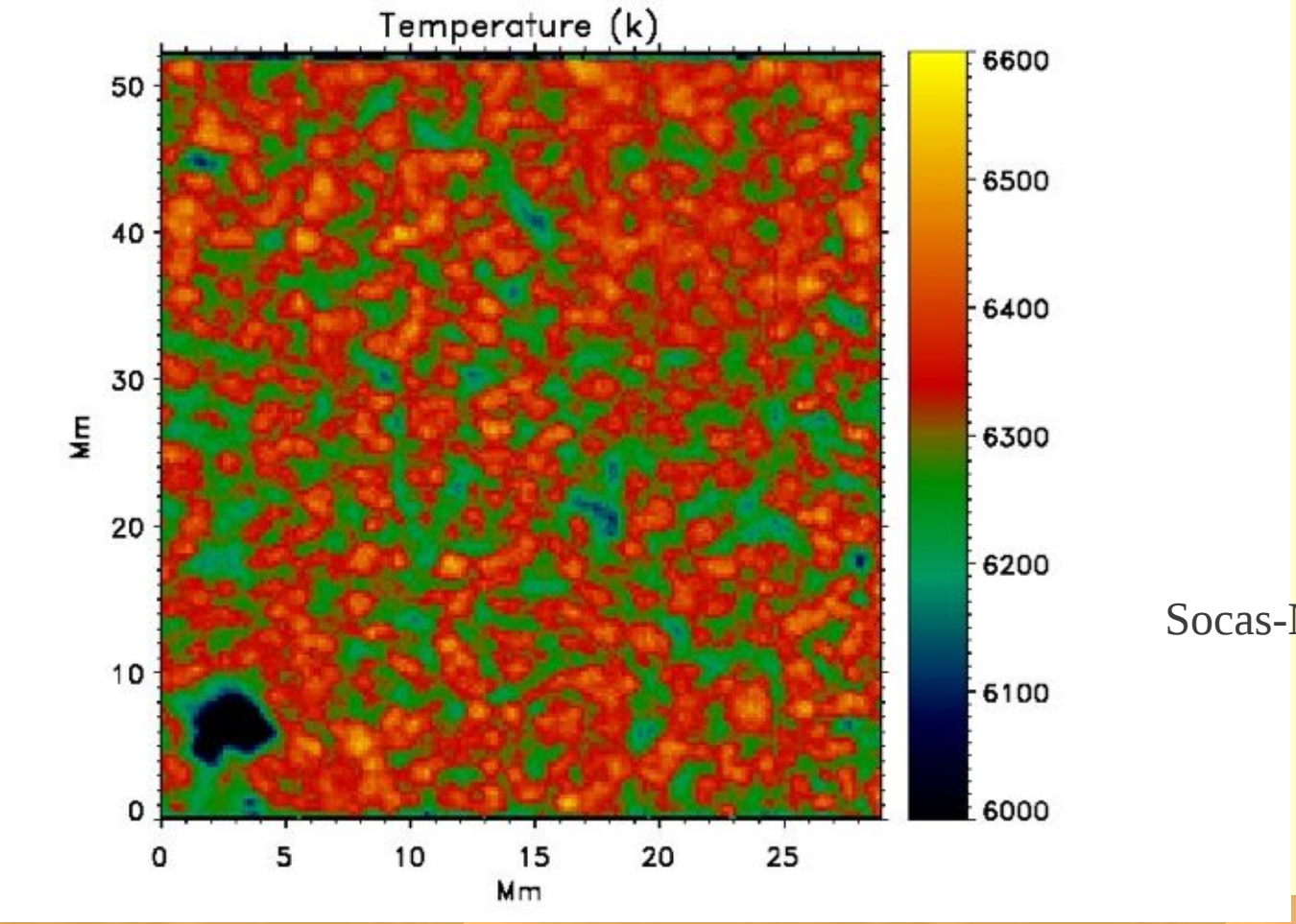
- Take a model atmosphere:
  - 1D (from observations)
  - 3D (from simulations)
- Assume abundances
- Compute spectral lines
- Compare synthetic lines to observations:
  - Spatially unresolved observations
  - When using 3D models, average before comparing
- Iterate

Alternate derivations

- Invert for abundances
  - Seek model and abundances simultaneously (many lines/elements)
  - MISS code (Allende Prieto et al 1998)
- Invert and fit abundance pixel by pixel (Socas-Navarro & Norton 2007)
  - Use a 3D model obtained from observations
- Use polarimetry to determine O/Ni in a sunspot (Centeno & Socas-Navarro 2008)
  - Blends look very different in Stokes V!
- Pixel-by-pixel approach again, with a better model (Socas-Navarro 2012)
  - Observations from the Hinode satellite

Empirical 3D model: 1st attempt

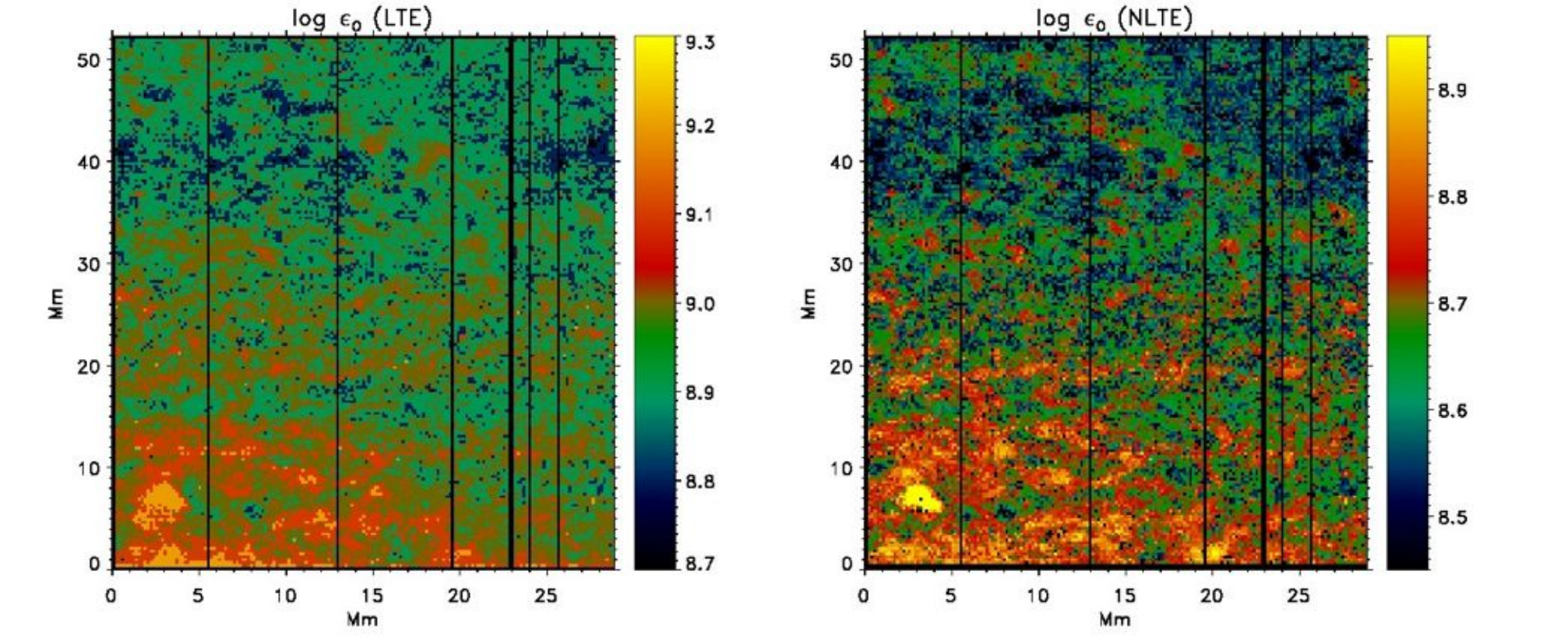
- Observations from the (back then) new SPINOR
  - 2D spectro-polarimetric scan of a quiet region
  - FeI 6301.5 and 6302.5 + OI IR triplet



Socas-Navarro & Norton (2007)

Empirical 3D model: 1st attempt

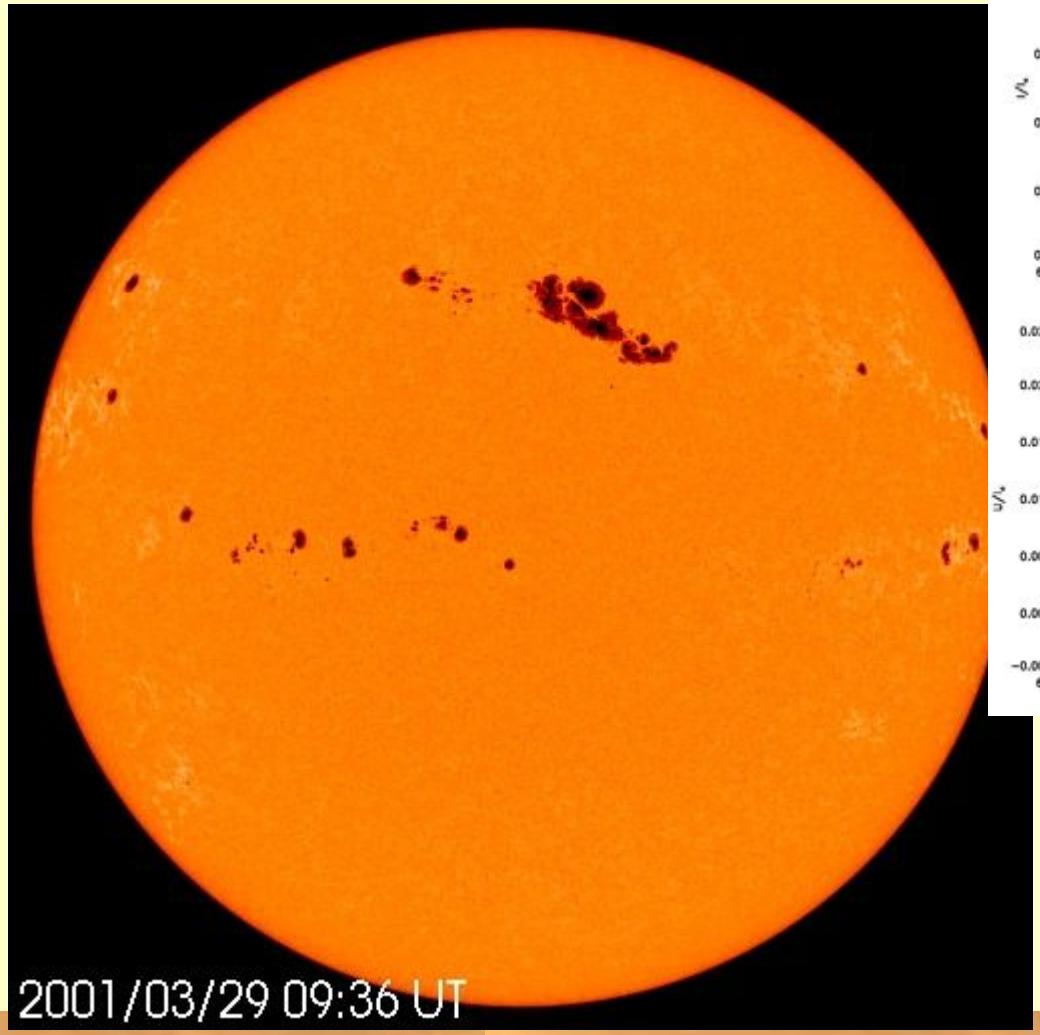
- Pixel-to-pixel abundance fluctuation
  - Bad data? (stray light, etc)
  - Uncertain NLTE physics?

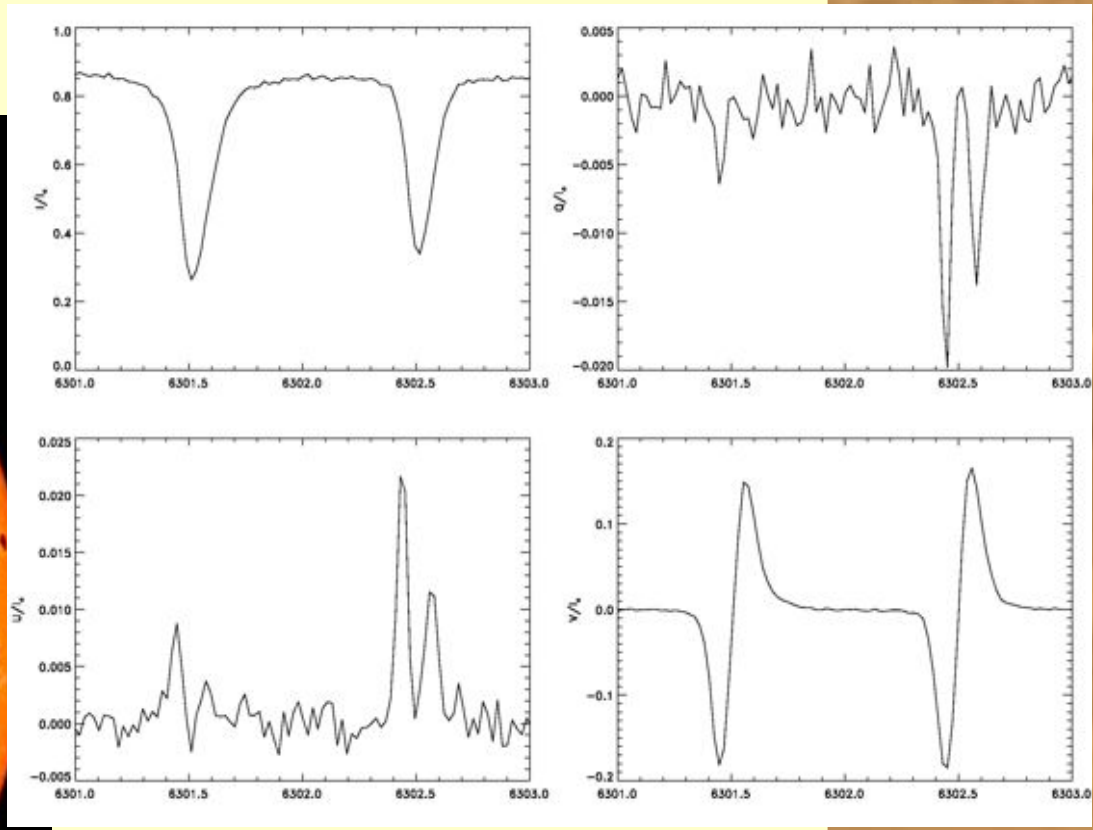


Another try: Polarization

- Magnetic fields → Stokes I, Q, U, V
- Study asymmetry in [OI] 6300

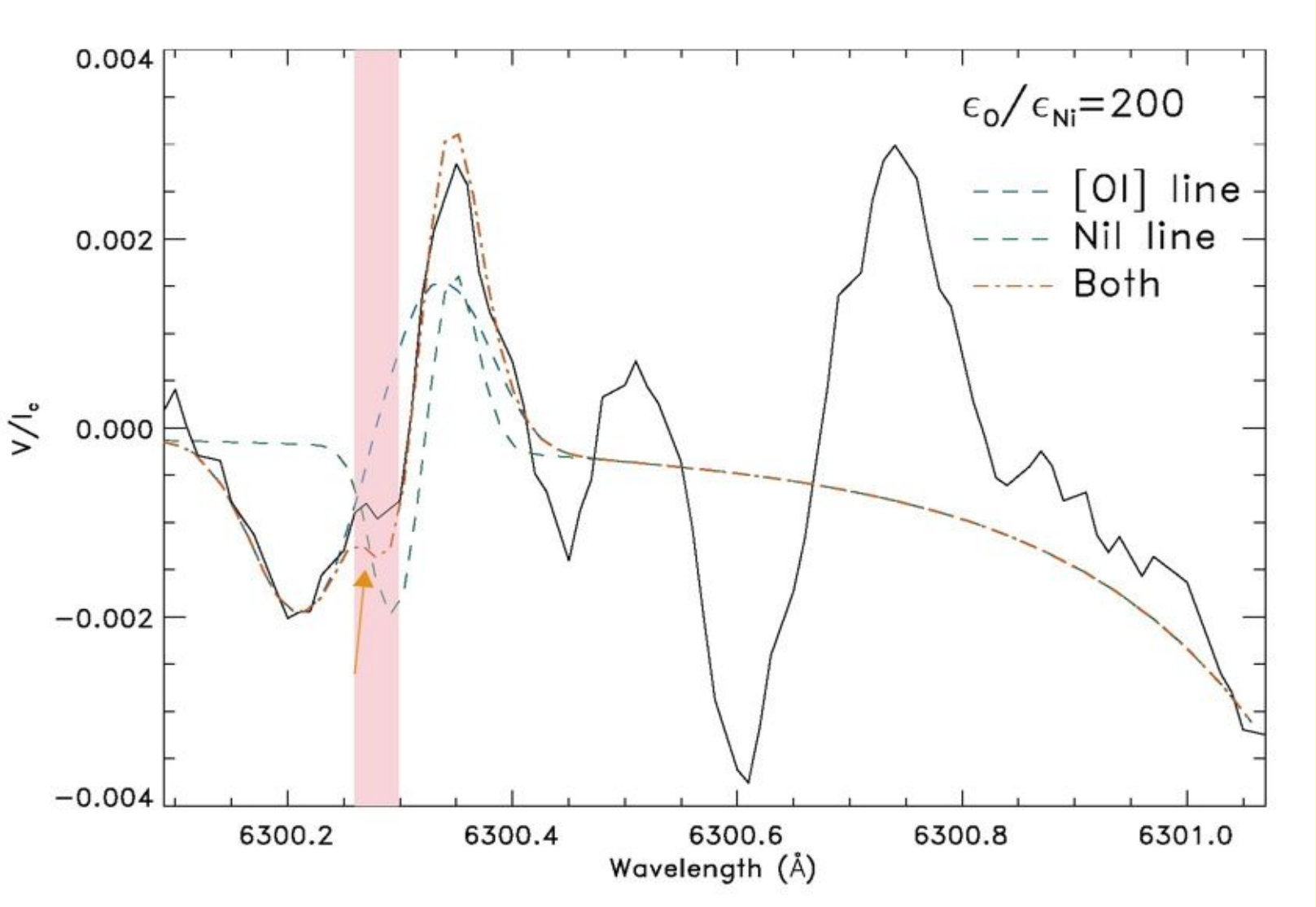
Centeno & Socas-Navarro (2008)





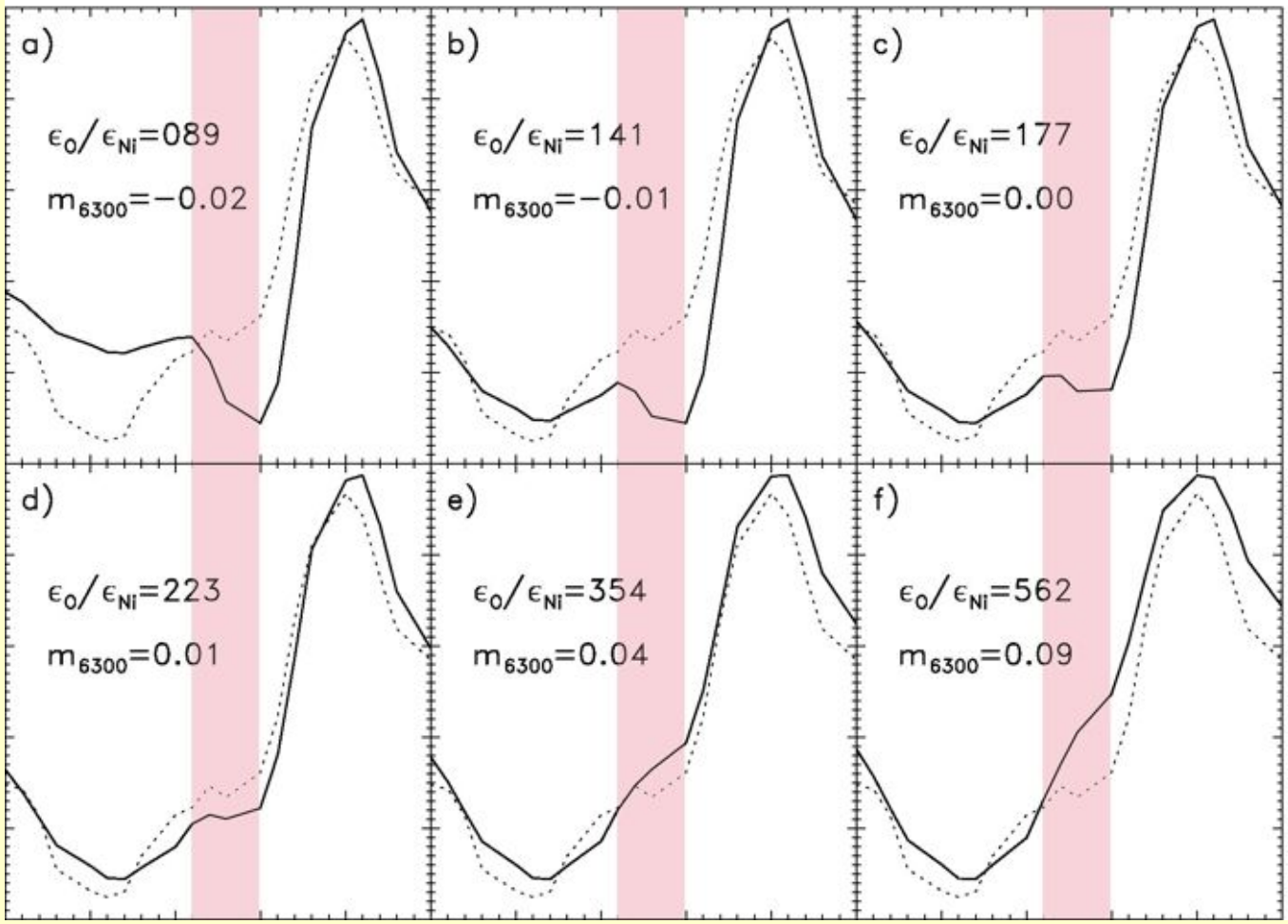
Another try: Polarization

- The blend: [OI]/Ni



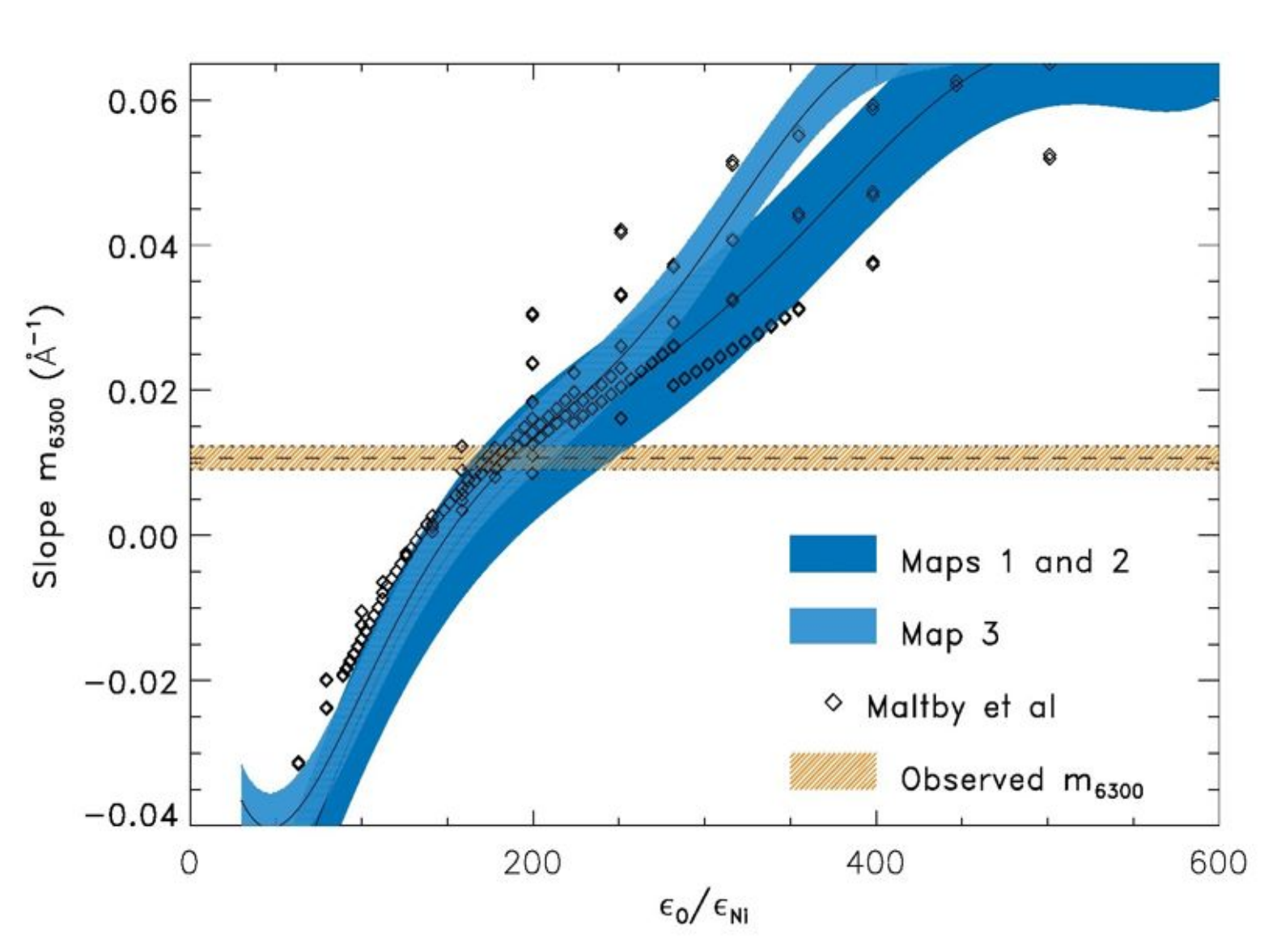
Another try: Polarization

- The blend: [OI]/Ni



Another try: Polarization

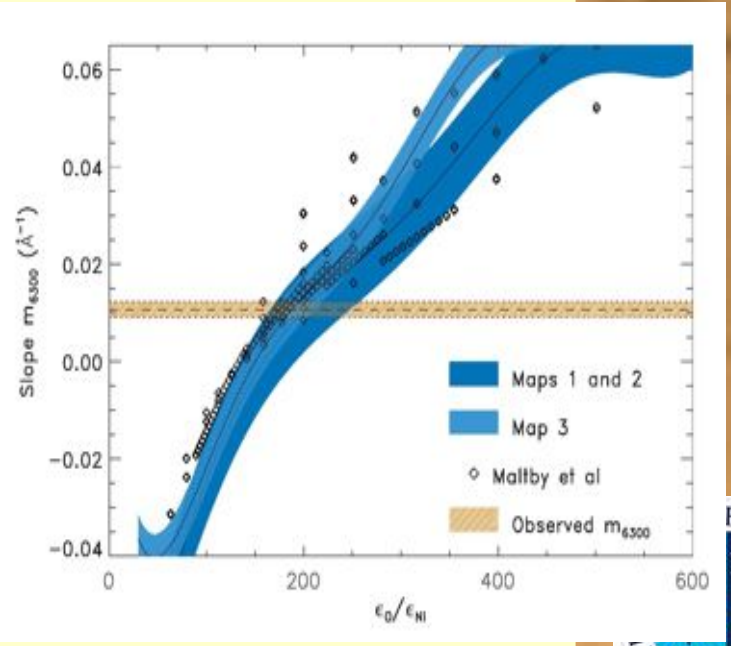
- A **nearly** model-independent determination



Another try: Polarization

- A **nearly** model-independent determination
  - Polarimetry gives new insights (limited to sunspots in this case)
  - Use the shape, not the “size” of the feature: It's less model-dependent
  - Result: $\varepsilon_O/\varepsilon_{Ni} = 210 \pm 24$
  - Our result: 8.86 ± 0.07 (correcting for CO)

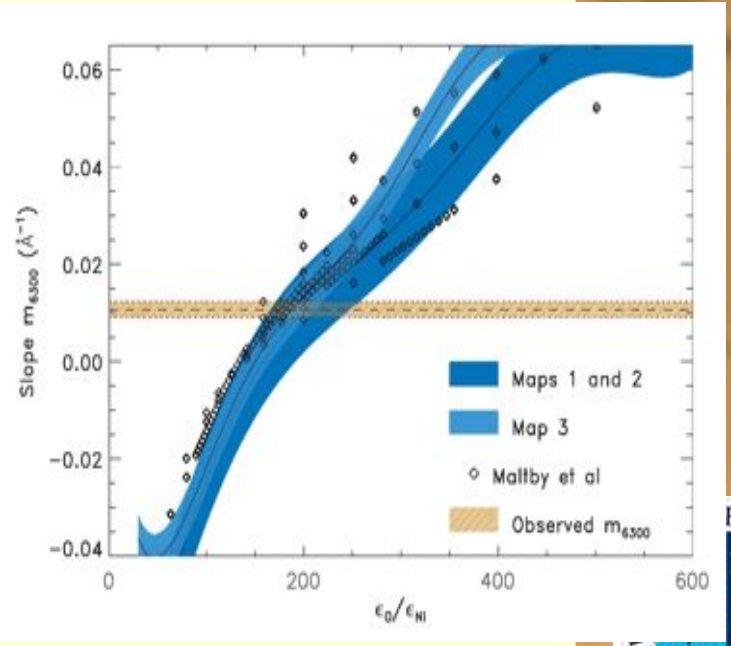
Centeno & Socas-Navarro (2008)



Another try: Polarization

- A **nearly** model-independent determination
  - Polarimetry gives new insights (limited to sunspots in this case)
  - Use the shape, not the “size” of the feature: It's less model-dependent
  - Result: $\varepsilon_O/\varepsilon_{Ni} = 210 \pm 24$
  - Our result: 8.86 ± 0.07 (correcting for CO)

Centeno & Socas-Navarro (2008)

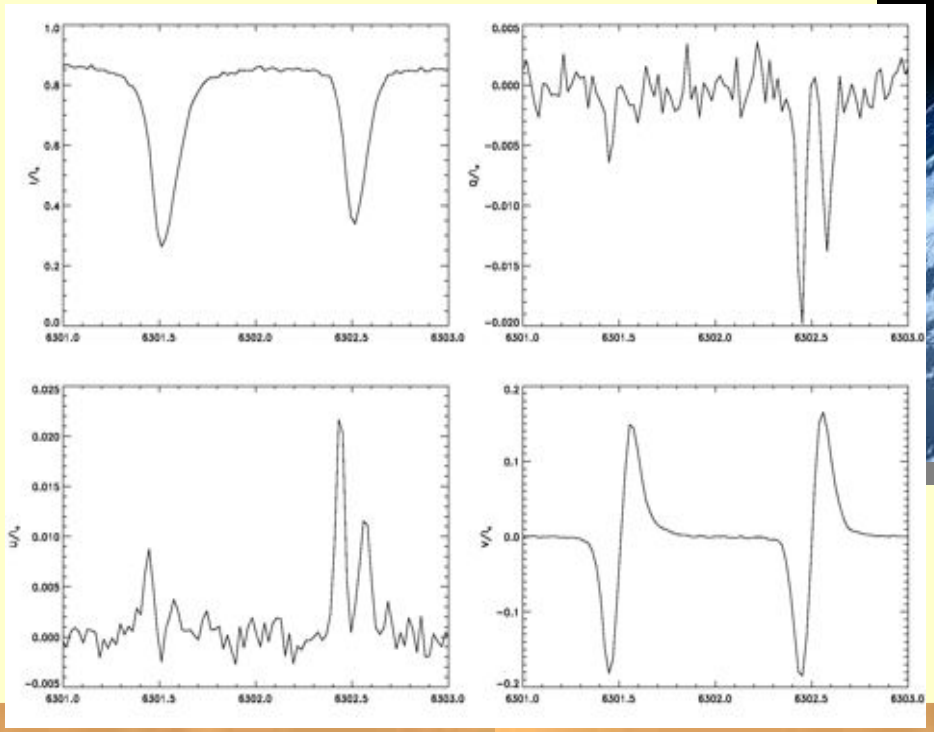


- Later revised by Scott et al (2009):
  - Updated log(gf)
  - Updated Ni abundance
  - Their result: 8.71

An improved 3D model from observations

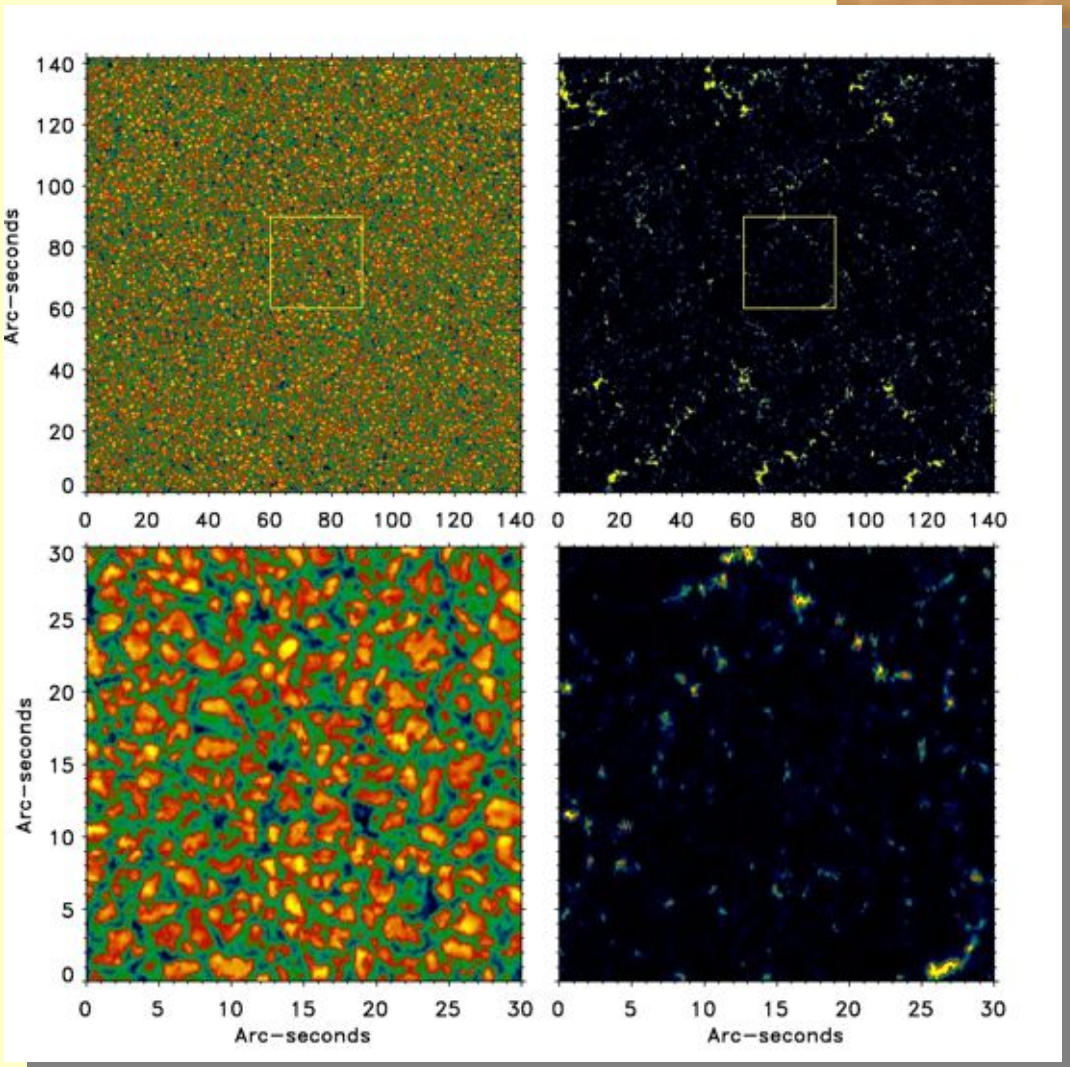
Socas-Navarro (2012)

- Data from the Hinode SP (public)
  - Spectral region: 6300 Å (2 FeI lines)
  - Sampling: 21.4 mÅ
  - Spatial resolution 0.3”
  - Slit scanning in *x*
  - Simultaneous I,Q,U,V



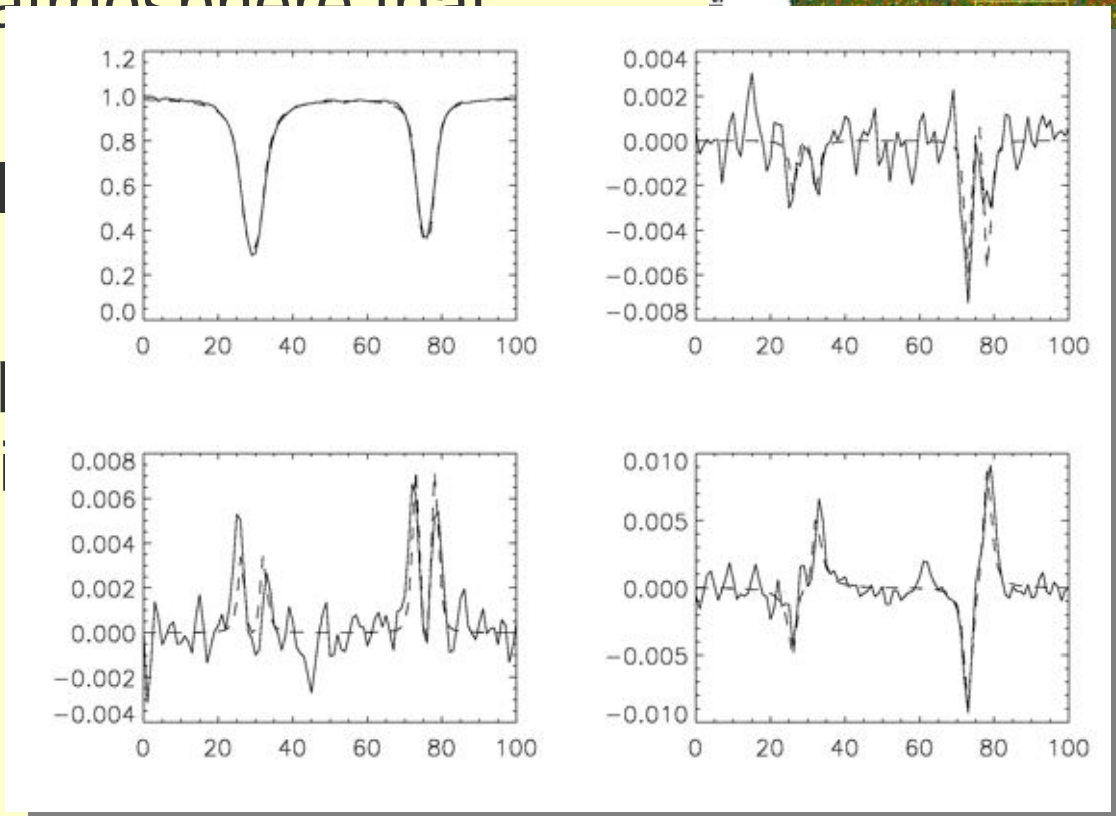
An improved 3D model from observations

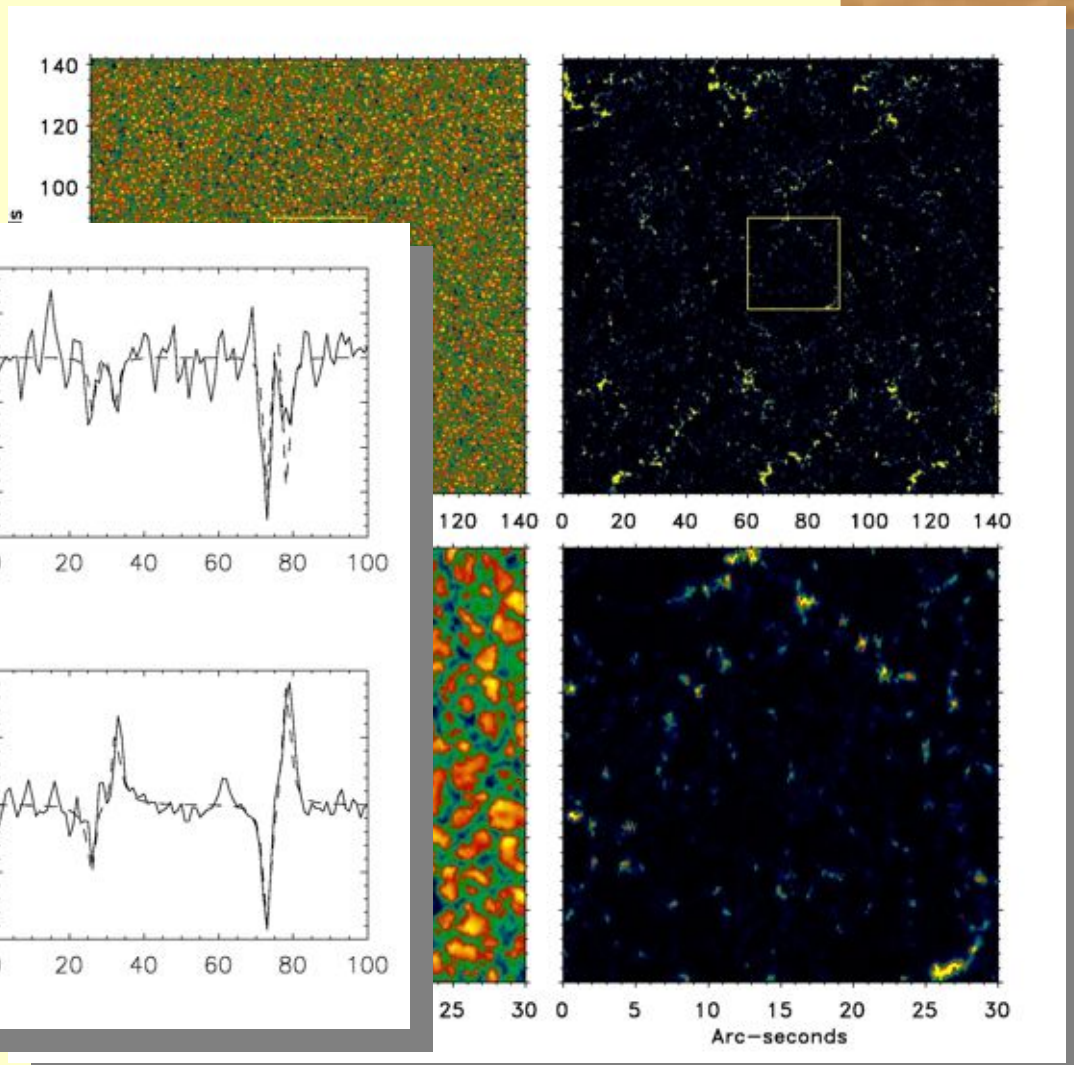
- Hinode's SP delivers a 2'x2' field of view: Smaller subfield selected for analysis
- Inversions with NICOLE
- Find atmosphere that yields best fit to observed profiles (T, *B*, v)
- Each pixel fitted Independently
- No microturbulence!!

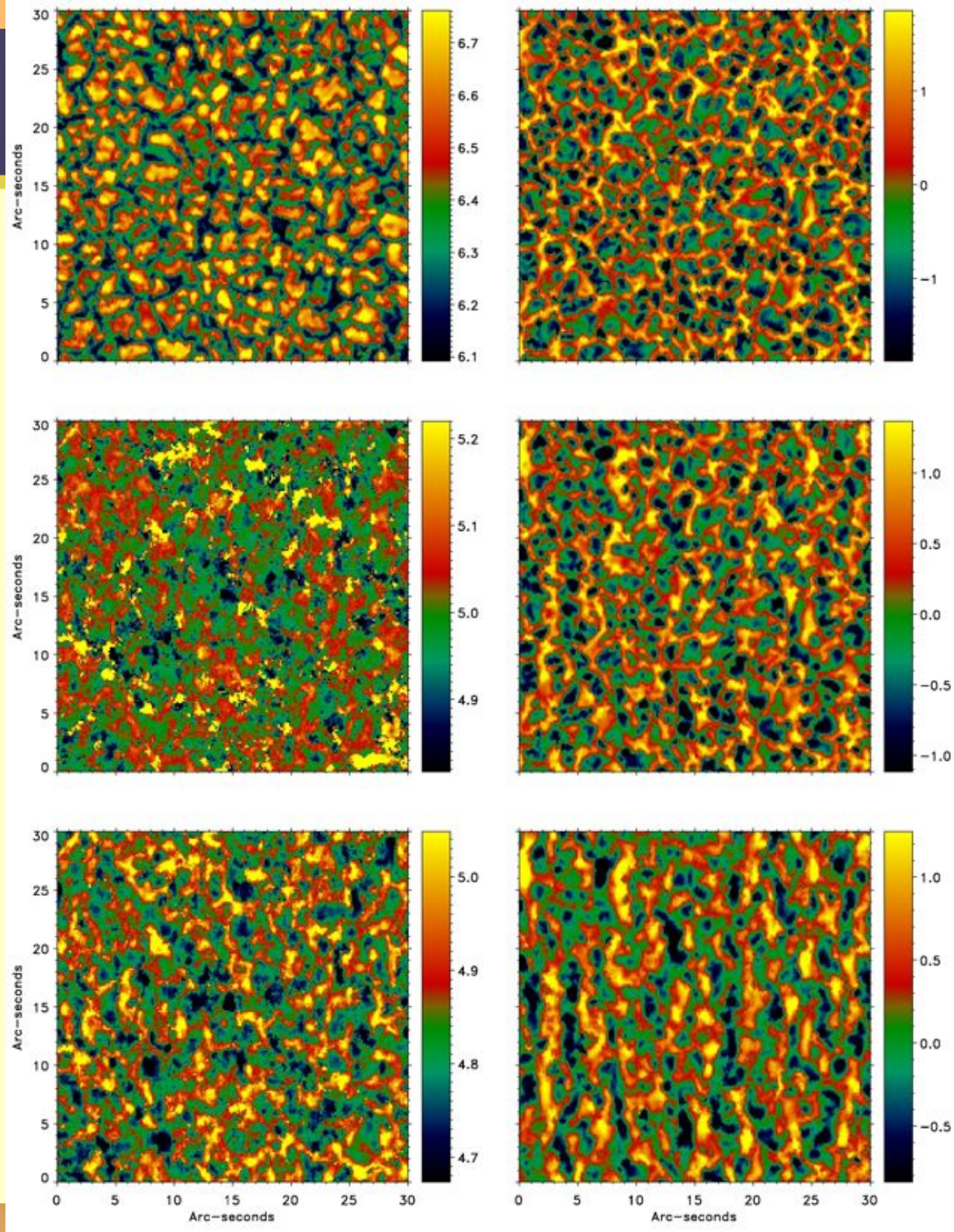


An improved 3D model from observations

- Hinode's SP delivers a 2'x2' field of view: Smaller subfield selected
  for analysis
- Inversions with NICOLE
- Find atmosphere that
  yield
  profil
- Each
  Indep
- No mi



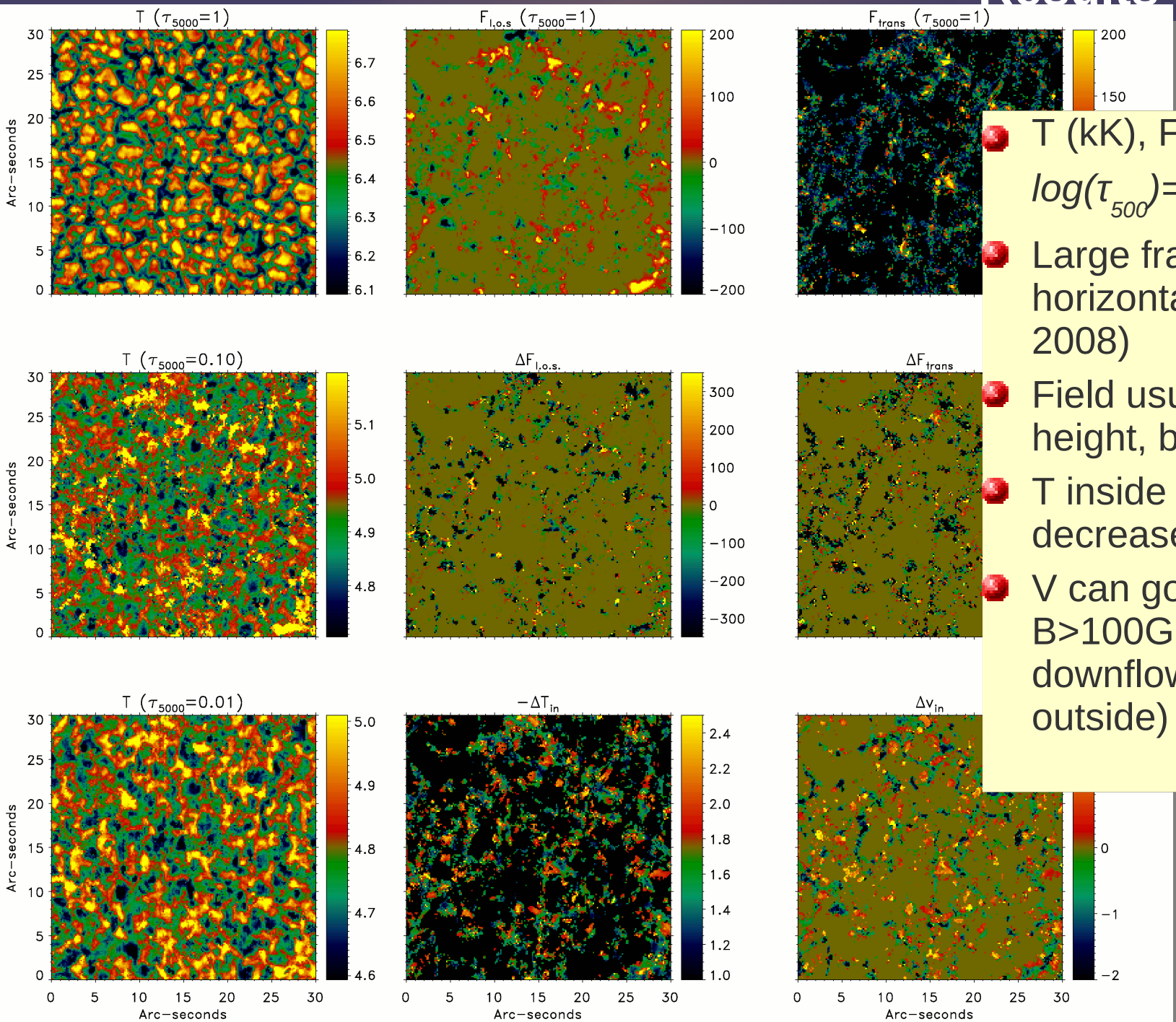




Results (T & v)

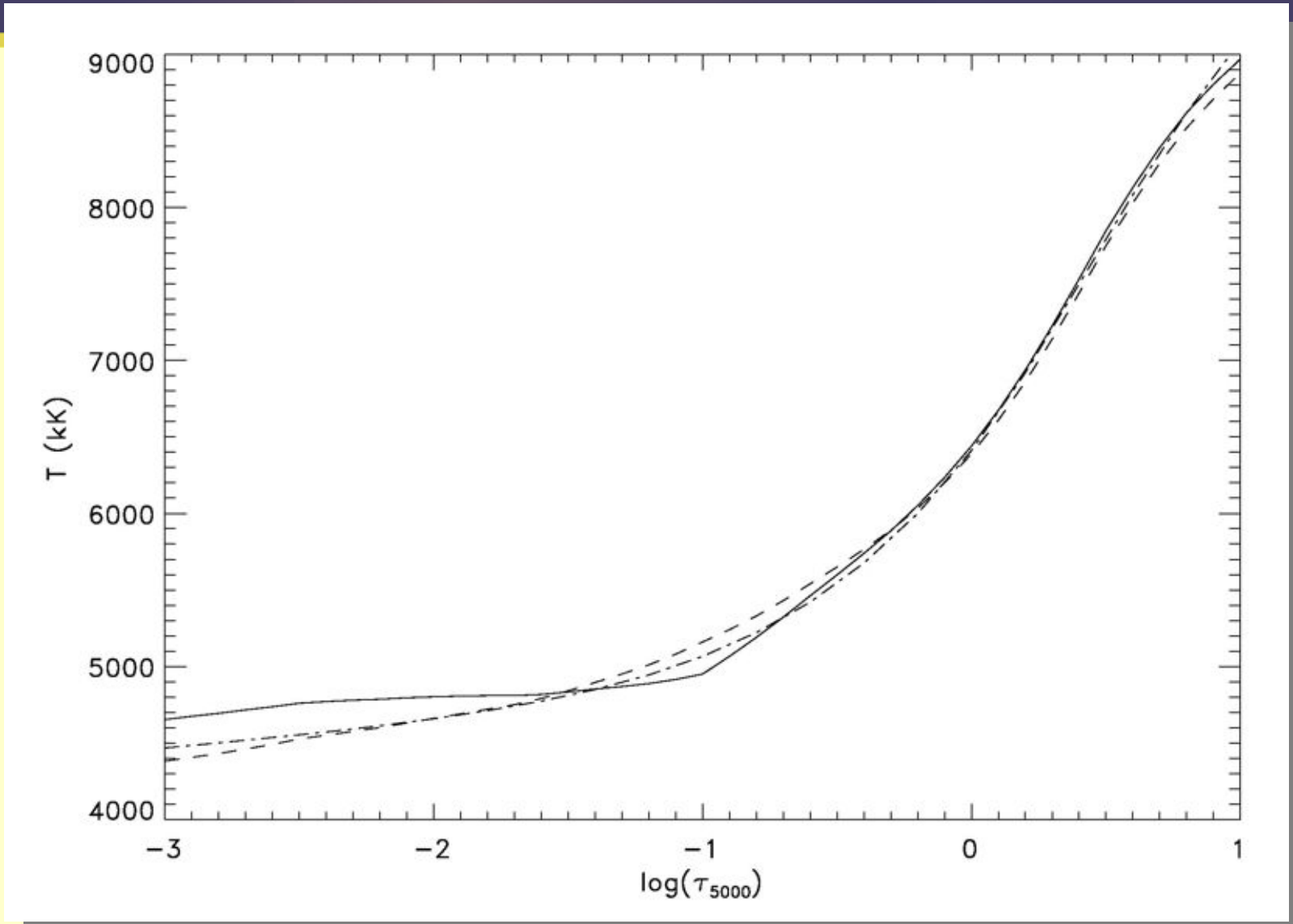
- T (kK) and v (km/s) at $log(\tau_{500})$=0,-1 & -2
- Averaged for 2-comp case
- Reversed granulation in T at the top
- Vertical structures at the top, probably artifact from slit

Results (T & B)



- T (kK), F_{ver} and F_{hor} (km/s) at $log(\tau_{500})$=0,-1 & -2
- Large fraction of area with horizontal fields (Lites et al 2008)
- Field usually decreases with height, but not always
- T inside magnetic elements decreases with height
- V can go up or down, but if B>100G, 84% of pixels have downflows (both inside and outside)

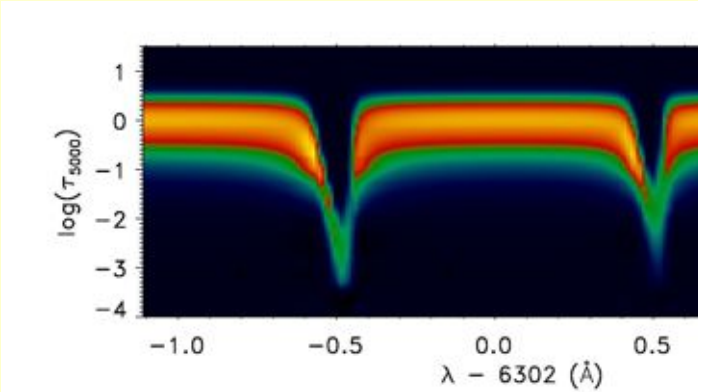
Average model (comparison)

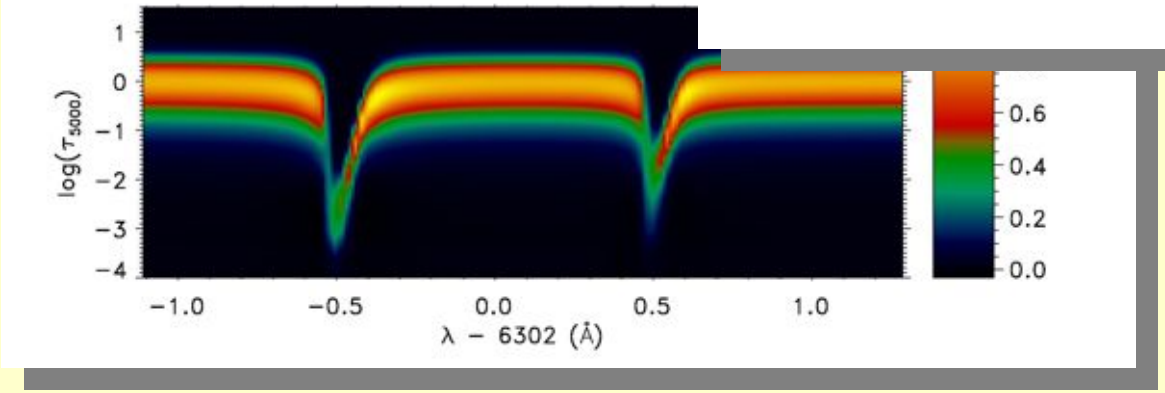


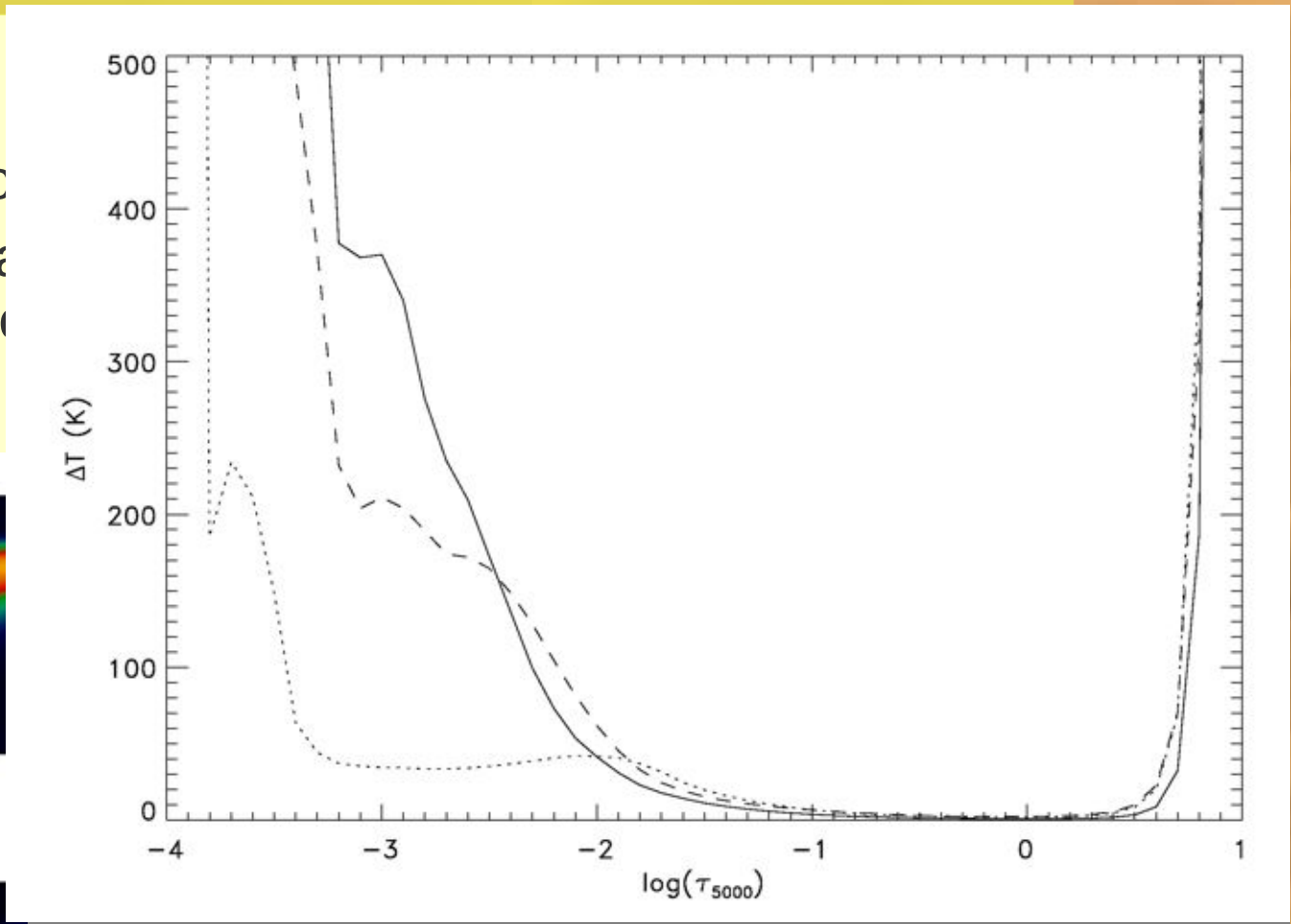
Solid: Socas-Navarro (2011). Dashed: Harvard-Smithsonian Reference Atmosphere (1D). Dash-dotted: Average of Asplund et al (3D)

Uncertainties

- Absolute photometry
  - Intensity is relative to
  - Small errors in norma
    photospheric averag
- Sensitivity range

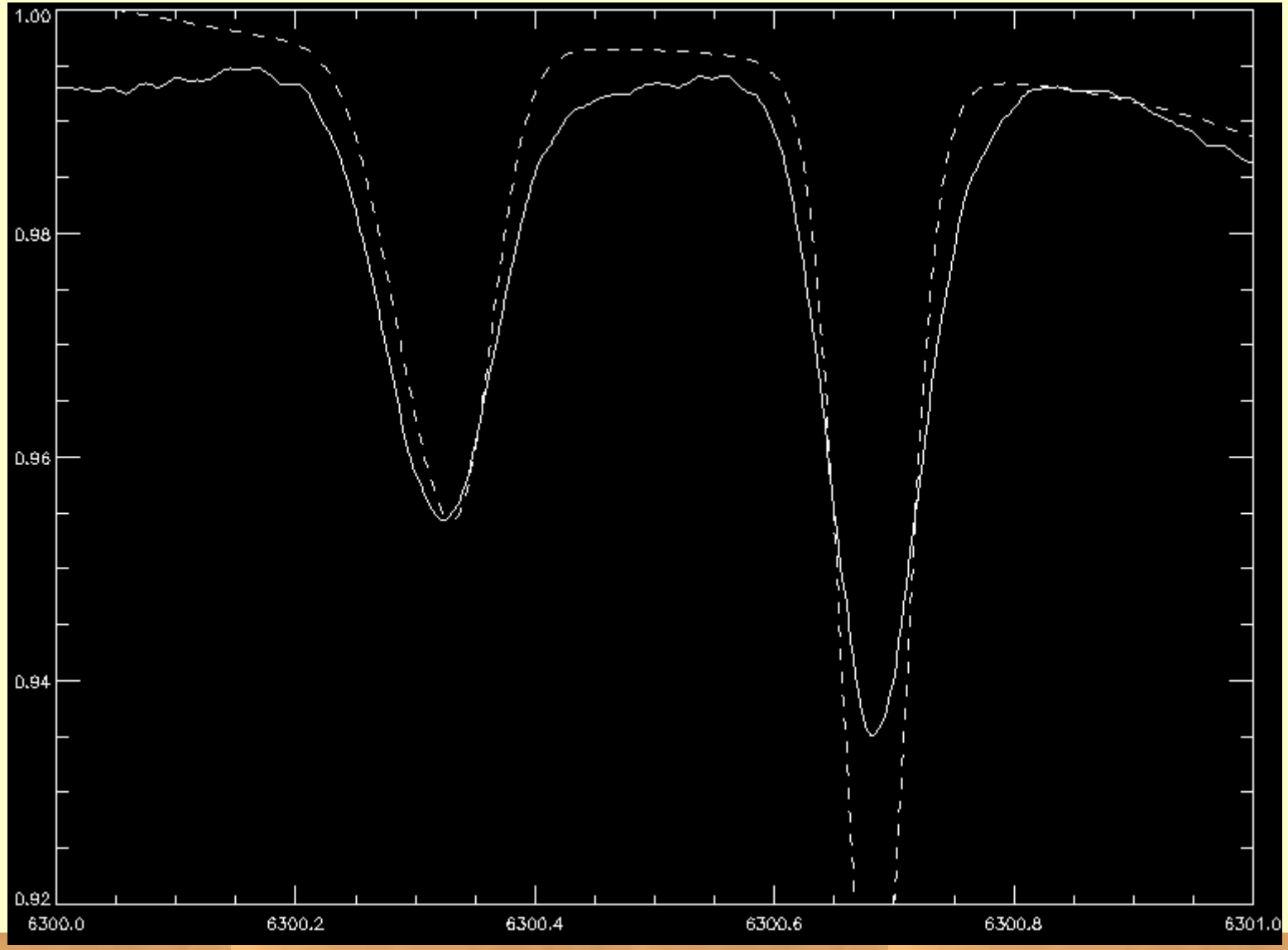






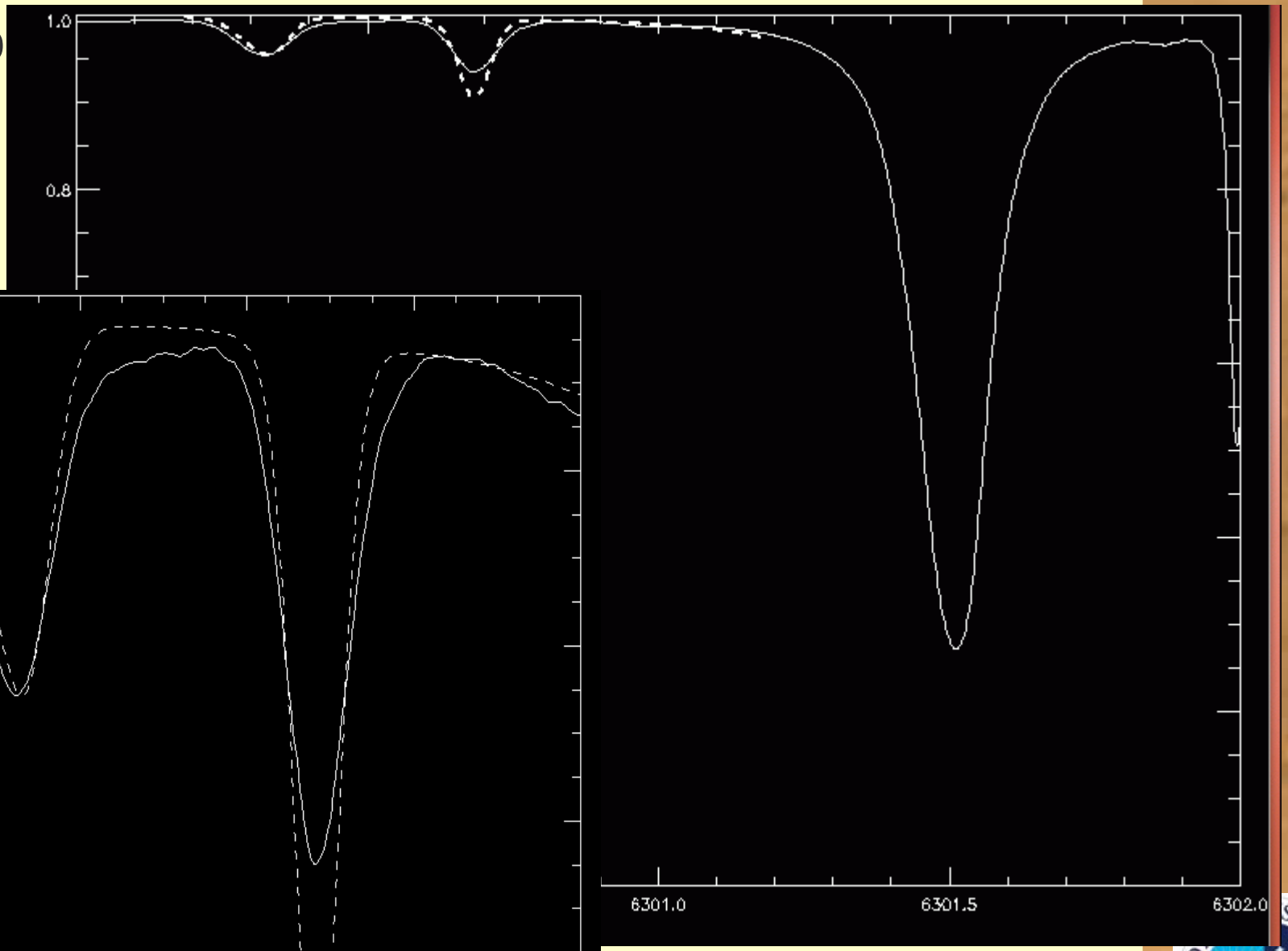
Deriving abundances

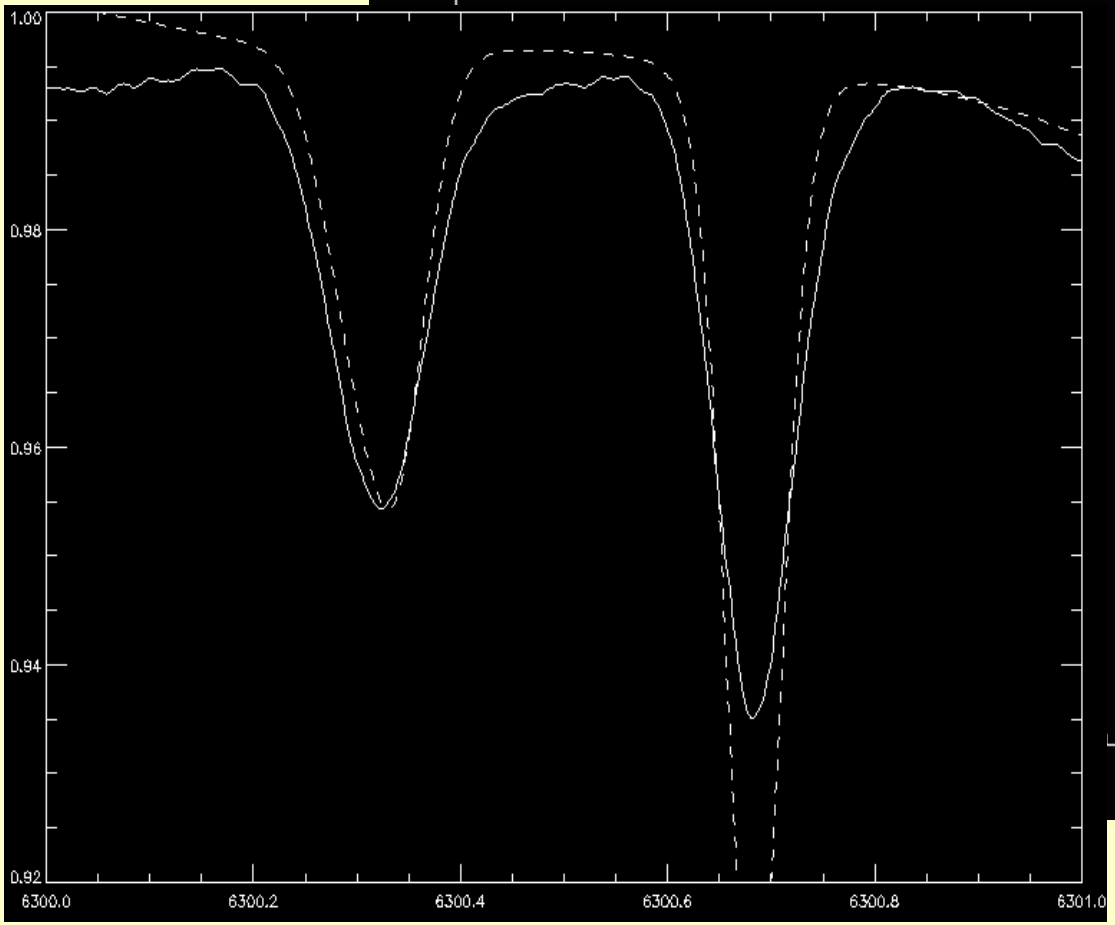
- A first problem: The ScII line is too narrow



Deriving abundances

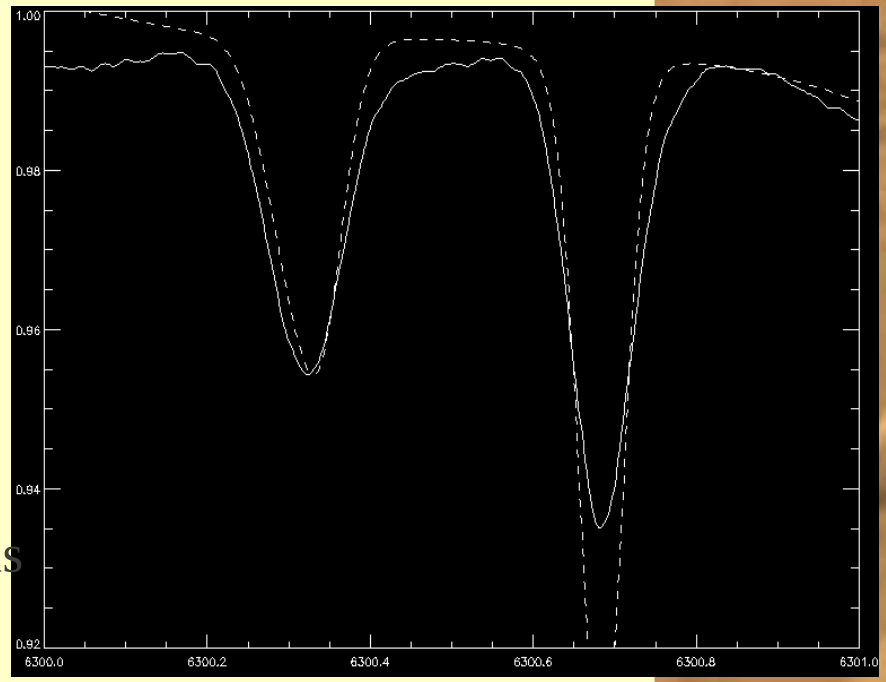
- A first pro





Deriving abundances

- A first problem: The ScII line is too narrow
  - Insufficient dynamics (resolution)
  - Photospheric rms velocity:
    - My model: 0.83 km/s
    - Asplund et al: 2.47 km/s

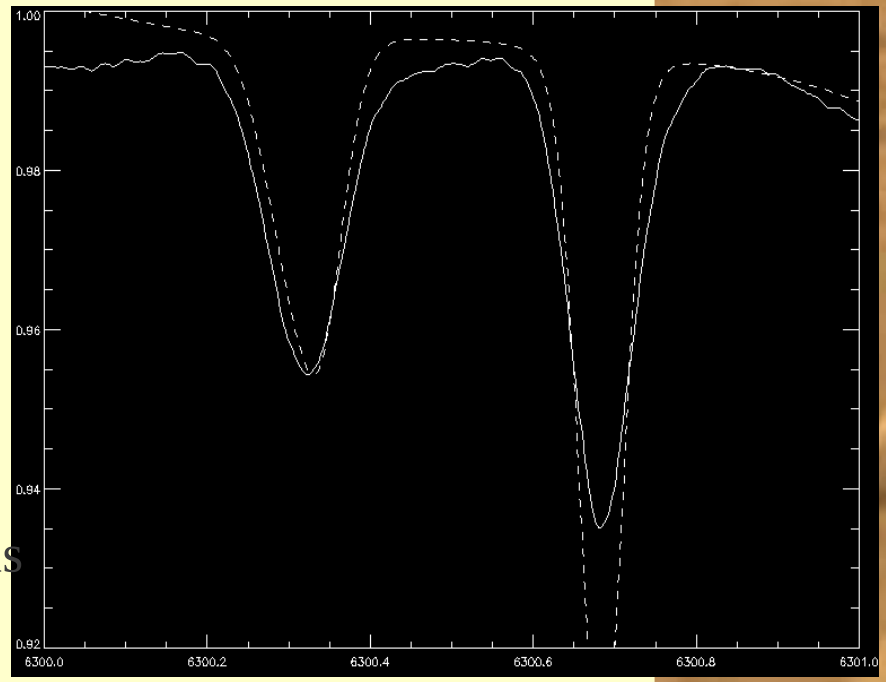


Already predicted by Ayres 2008(!)

"A possible disadvantage is that the derived motions will depend on resolution and might not be as vigorous as in fully resolved 3D theoretical model"

Deriving abundances

- A first problem: The ScII line is too narrow
  - Insufficient dynamics (resolution)
  - Photospheric rms velocity:
    - My model: 0.83 km/s
    - Asplund et al: 2.47 km/s



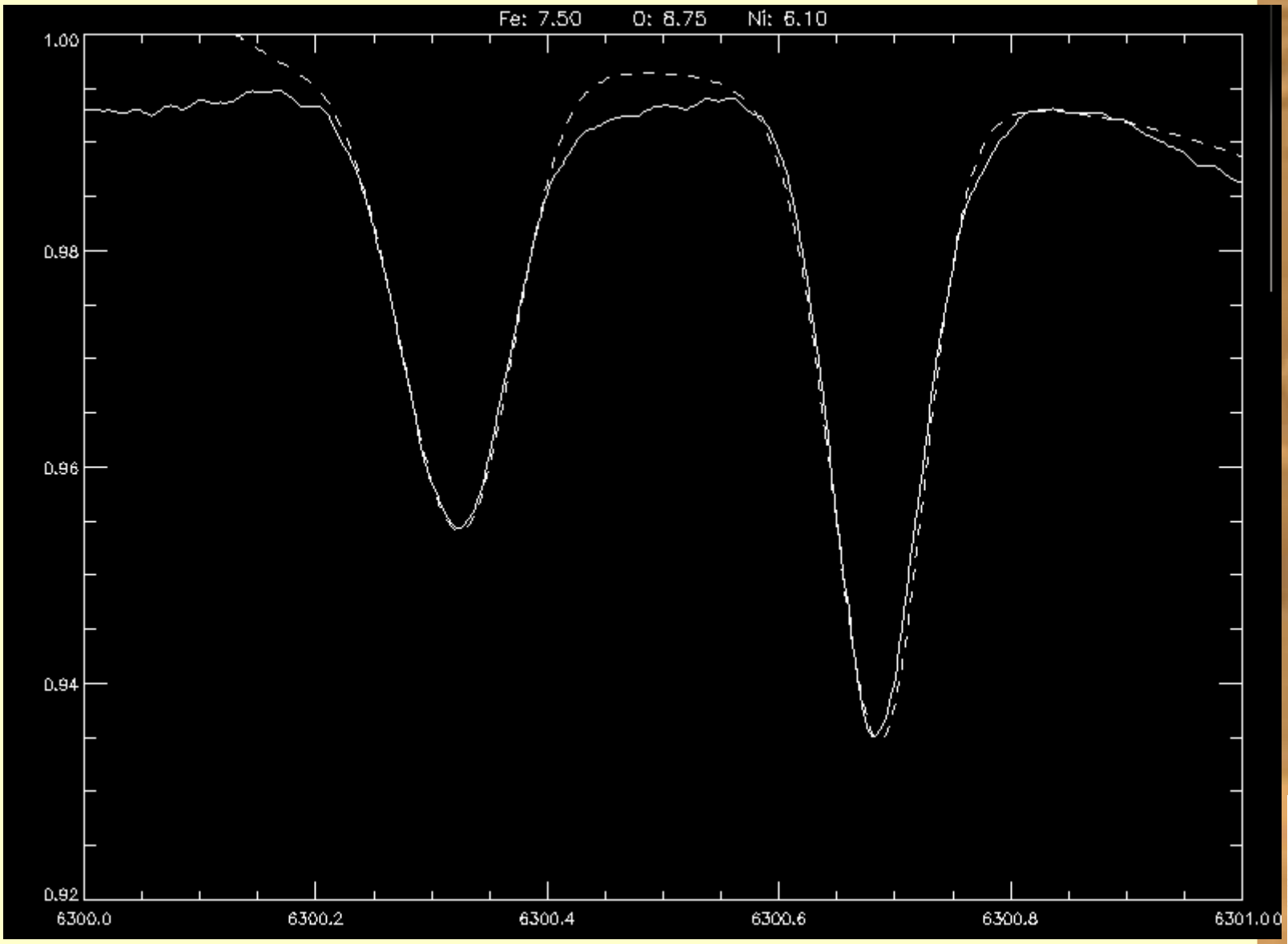
Already predicted by Ayres 2008(!)

"A possible disadvantage is that the derived motions will depend on resolution and might not be as vigorous as in fully resolved 3D theoretical model"

- Solution: Use the ScII line to calibrate velocity rms!
  - Need rms velocity of 2 km/s

Deriving abundances

- Results (Work in progress!!!)



Deriving abundances

- What I've learned:
  - 3D model based on Hinode observations works but needs a x2 velocity enhancement
    - Would be interesting to try with even higher resolution observations (SST, Sunrise???)
  - The ScII line is a good calibration tool
  - Tentative results: ε_O=8.75, ε_{Ni}=6.10 (need to formalize error bars but probably ~0.03)
- Better data than in Socas-Navarro & Norton (2007) BUT:
  - No simultaneous [OI] data so need to fit atlas observations → Don't have pixel-to-pixel results :(

Conclusions

- The solar case allows for “alternative” methods of abundance derivation (spatially resolved observations, polarimetry, etc)
- Choosing between 1D empirical vs 3D theoretical no longer necessary (can do 3D empirical)
- Three examples:
  - SN & Norton 07: Spatially resolved observations of FeI (to derive 3D model) and OI (for abundance): Results in abundance maps. Results not reliable :(
  - Centeno & SN 08: Polarimetry in a sunspot. Use *shape* instead of *strength* to determine $\varepsilon_O/\varepsilon_{Ni}$
  - SN 12: Use Hinode data to derive 3D model, use ScII line to calibrate dynamics. Downside: No spatially resolved [OI] data