# Highlights of the solar research in the last decades: *Convergence* or *divergence?*

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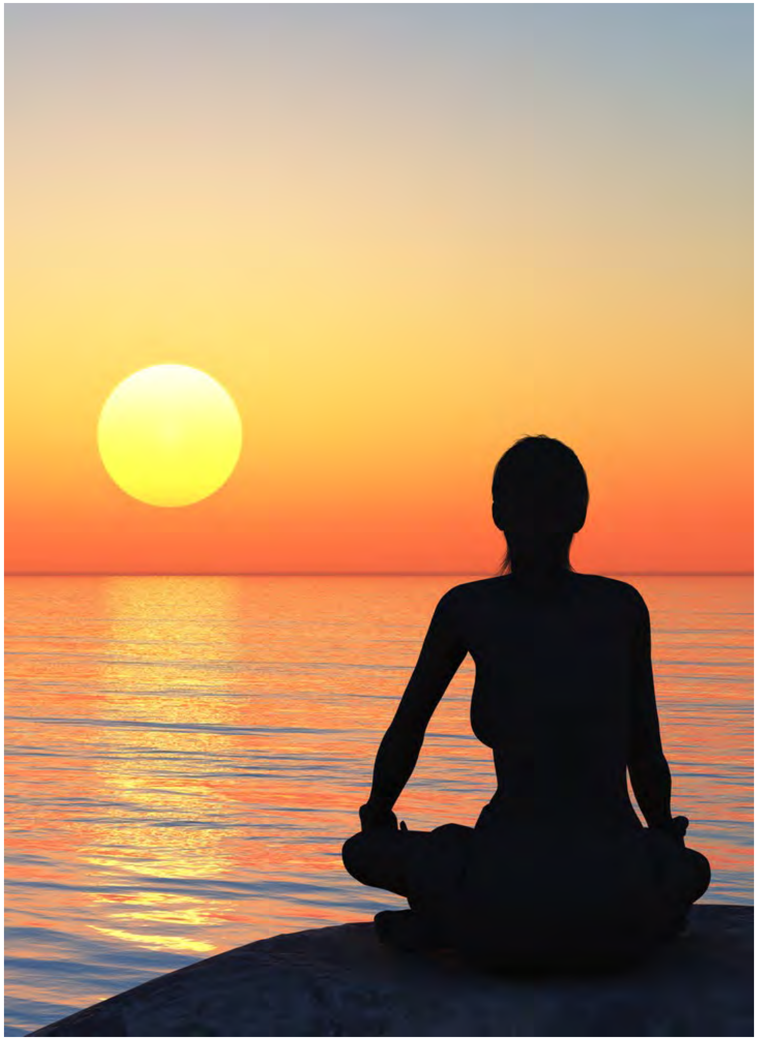
# Why do we study the Sun?

- It is a star
  - One of many
  - Very close = spatial resolution
- The distant laboratory of an extreme plasma physics
  - Interaction of plasma with magnetic field
- It is active
  - Solar activity may easily disturb our everyday's life

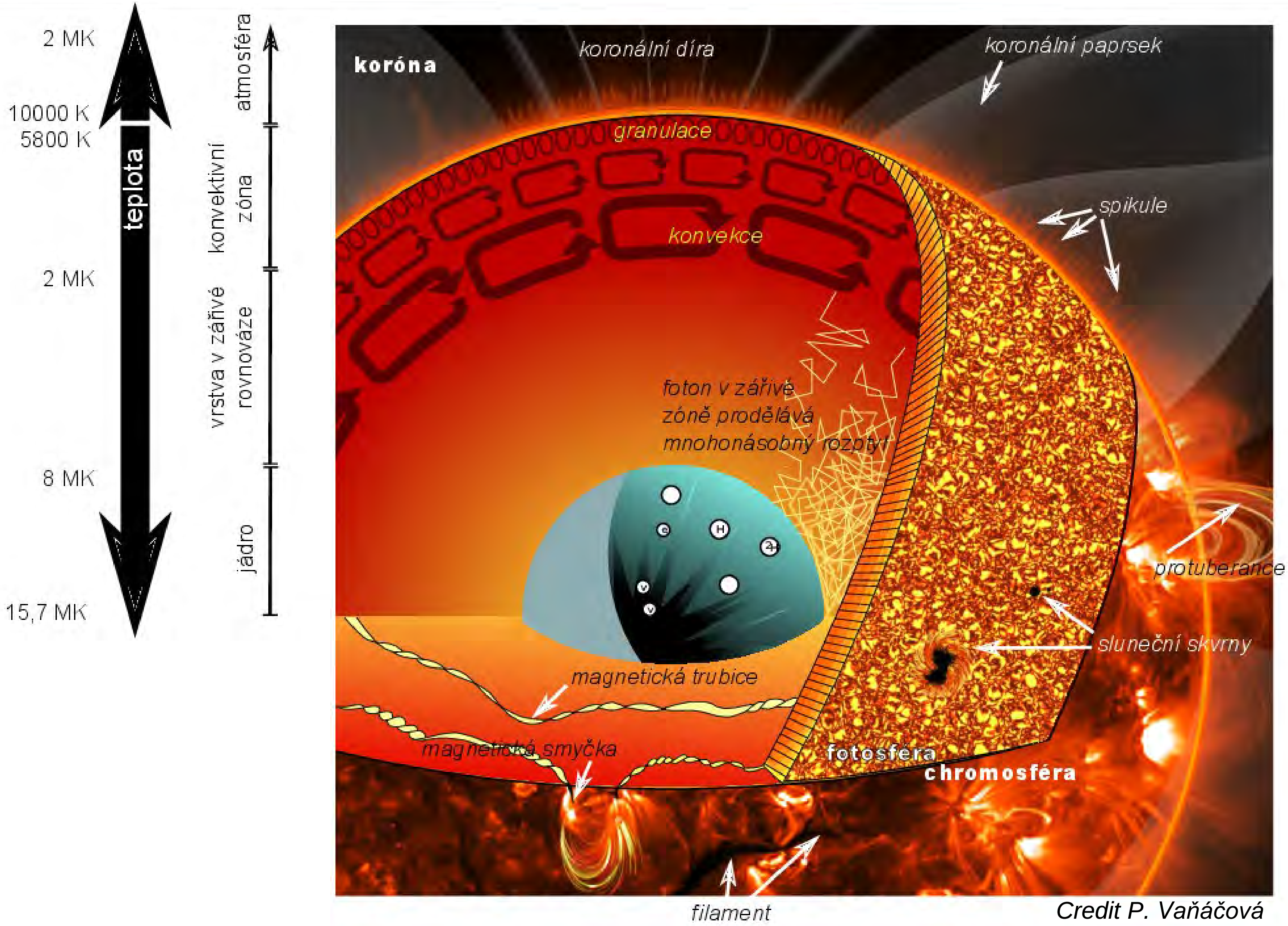


# Knowns and unknowns

- What do we know?
  - Internal stucture: pretty certain, subject to change of details
  - Atmospherics structure: to a very good detail
  - Evolution: both past and future
  - Empirical rules of the solar magnetism

- What don’t we know?
  - Chemical composition: some doubts
  - Convection and internal dynamics: a big puzzle!
  - Solar dynamo: how and why does it work?
  - Long-term solar activity: not fully understood
  - Heating of the solar atmosphere: which agent has a dominant role?

# The Sun: our closest star




Credit P. Vaňáčová

# How comes we know?

- Internal structure of stars described by equations (differential, partial)
  - Solutions possible
  - Various models agree quite well
- Solar analogues
  - Similar stars in a different evolutionary states or with (slightly) different fundamental parameters
    - Verify the models
- Helioseismology

$$\frac{\mathrm{d}m}{\mathrm{d}r} = 4\pi\rho$$

$$\frac{\mathrm{d}P}{\mathrm{d}r} = \frac{-Gm}{r^2}$$

$$\frac{\mathrm{d}L}{\mathrm{d}r} = 4\pi\rho r^2(\epsilon +$$

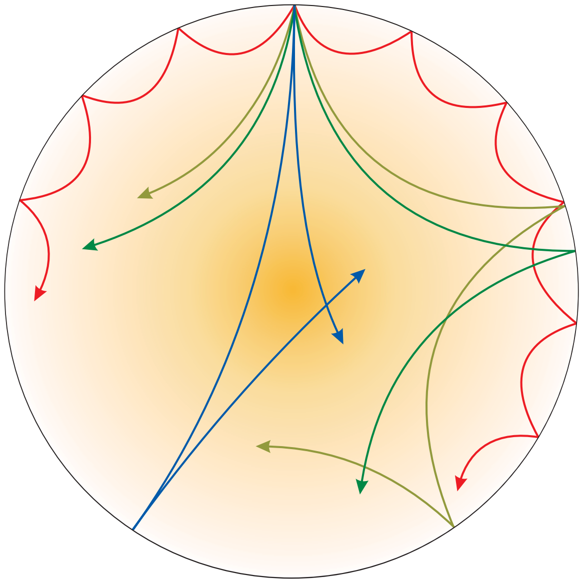
$$\frac{\mathrm{d}T}{\mathrm{d}r} = \frac{-GmT\rho}{r^2 P}\nabla \leftarrow \quad \nabla_{rad} = \quad \nabla_{ad} =$$

$$P = \frac{\Re\rho T}{\mu}, \quad \mu =$$

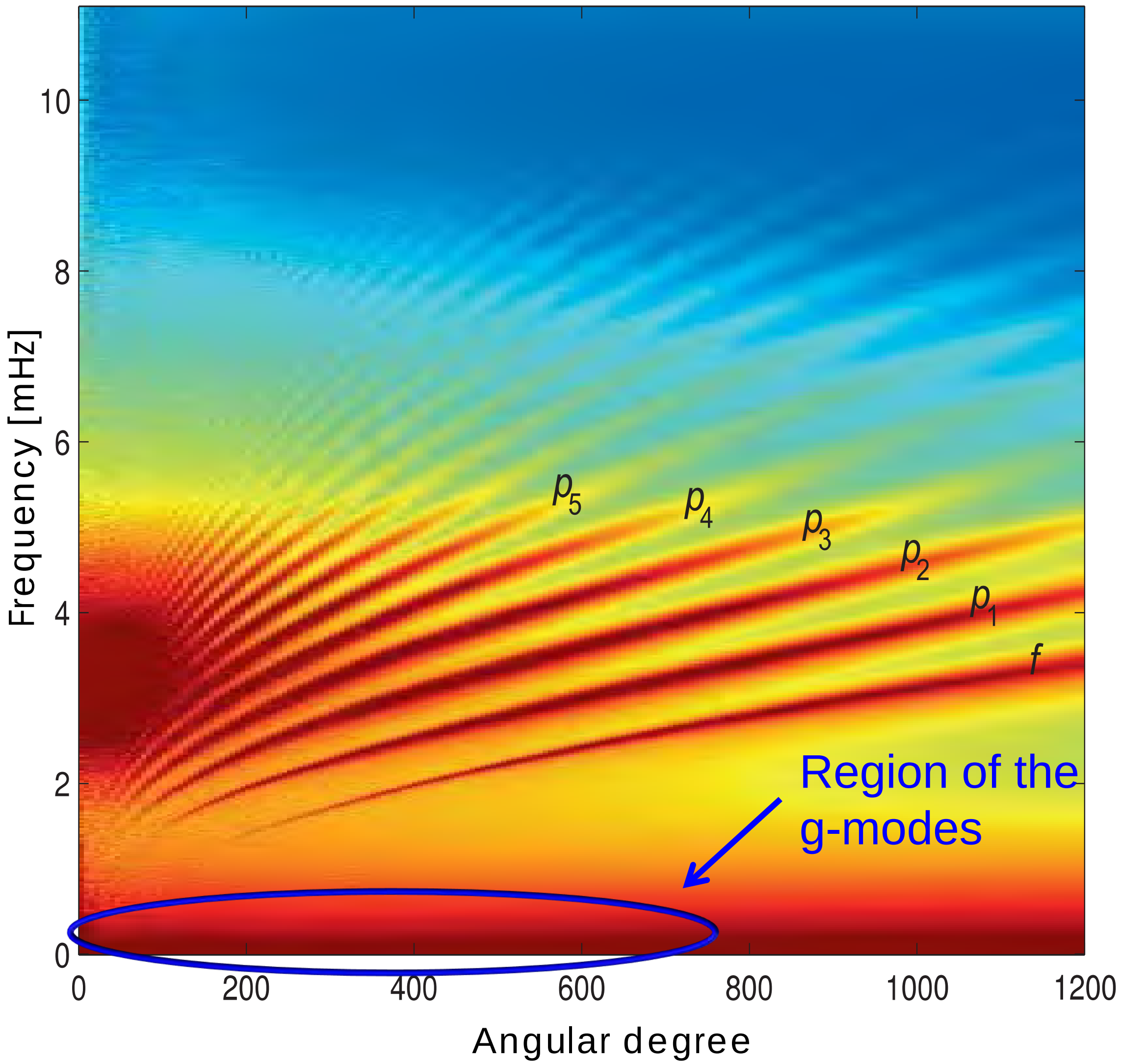
# The Sun oscillates

- Triggers: convective instability
  - The convection is vigorous, hence plenty of opportunities to excite waves
- Various types according to the restoring force
- Resonance
  - Depth localisation
  - Only certain modes prevail
  - *Trapped waves*

- *g*: internal gravity – in convectively stable
- *p*: pressure – in convectively instable environment
- *f*: surface gravity – similar to ocean waves

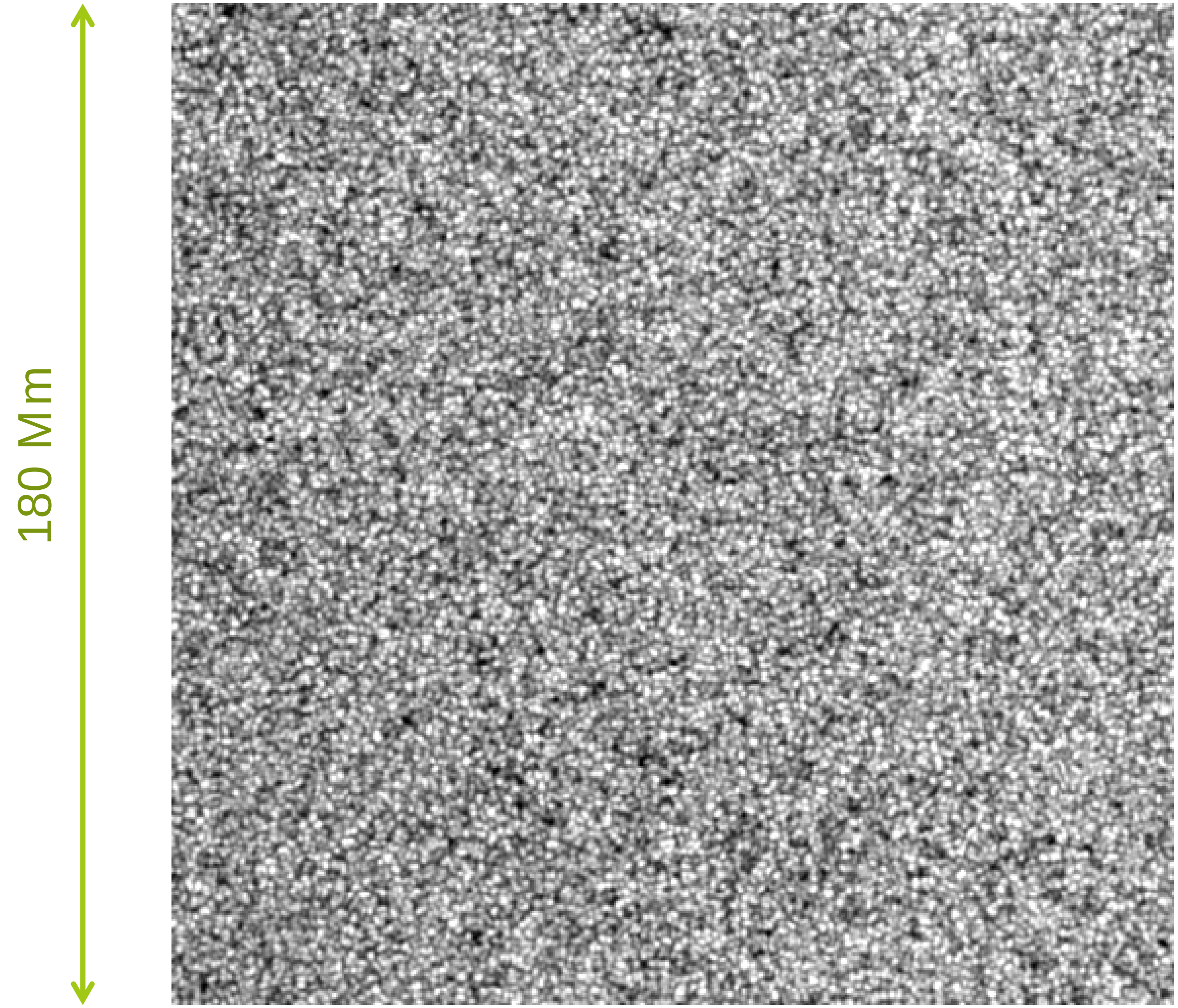


# k-ω (l-ν) diagram



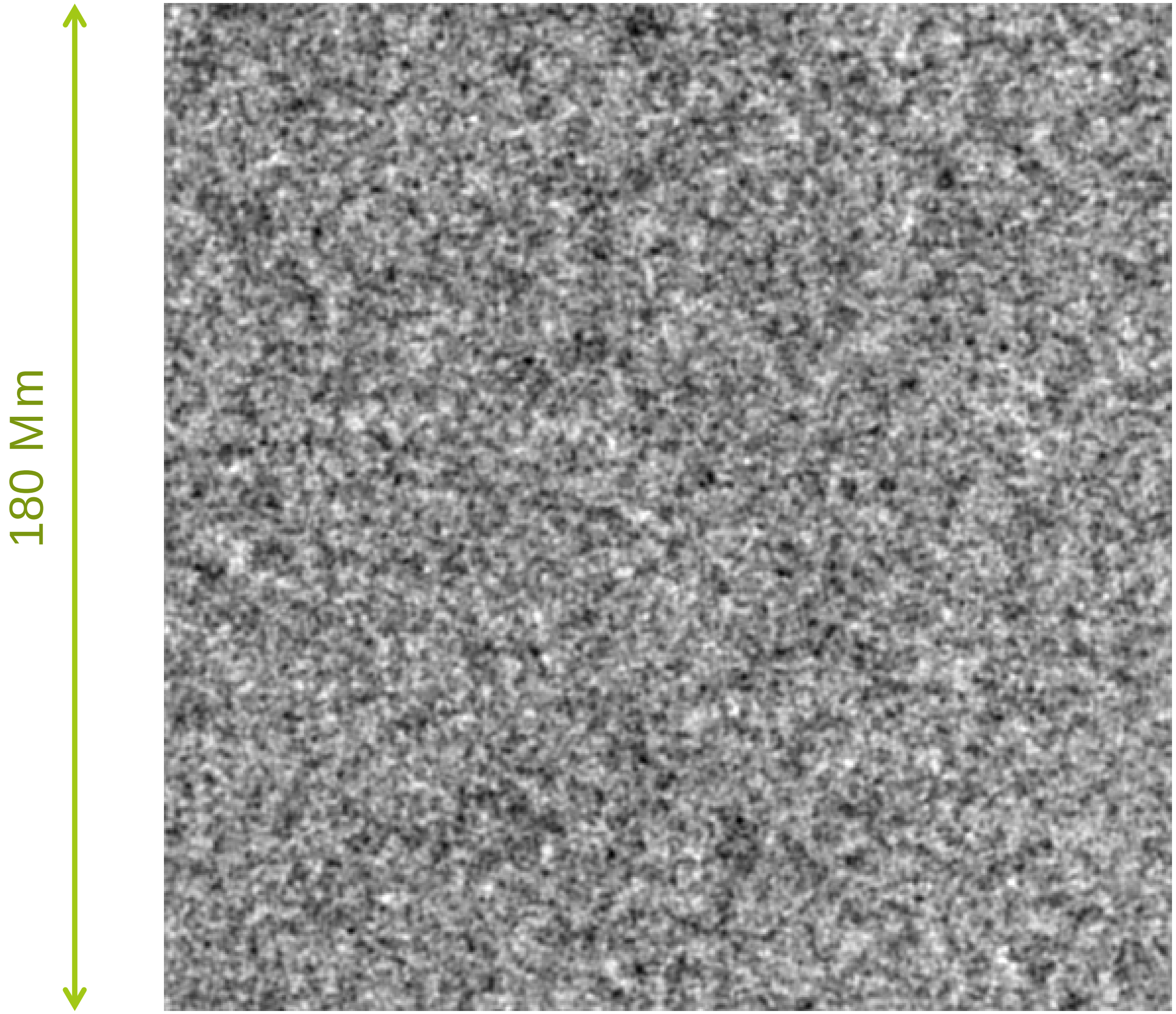

- Discovery 1960s
- Interpretation 1970s
- First inversions 1980s
- Golden era 1995-2010

# Solar oscillations seen in intensity



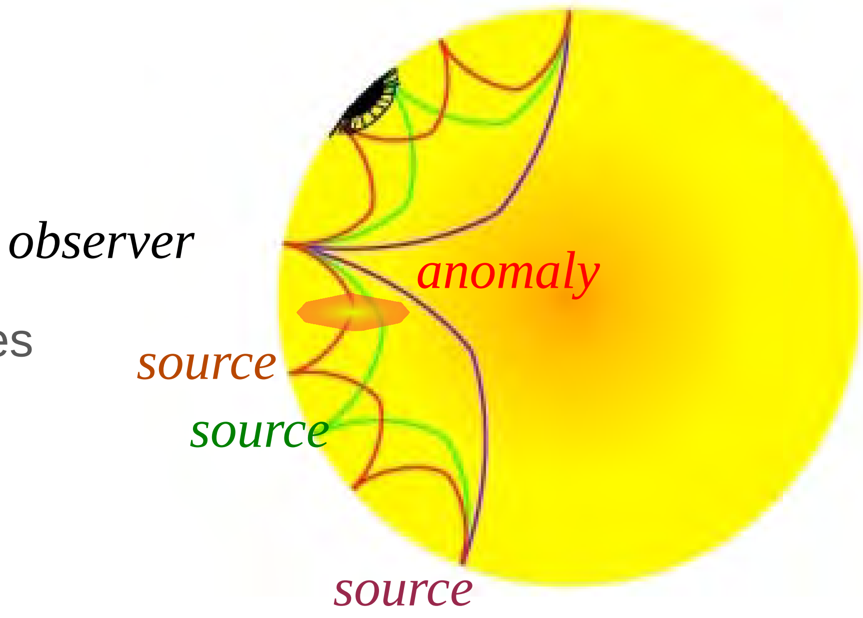

SDO/HMI, 12. May 2010, 00:00-06:00 UT, disc centre

# Waves only

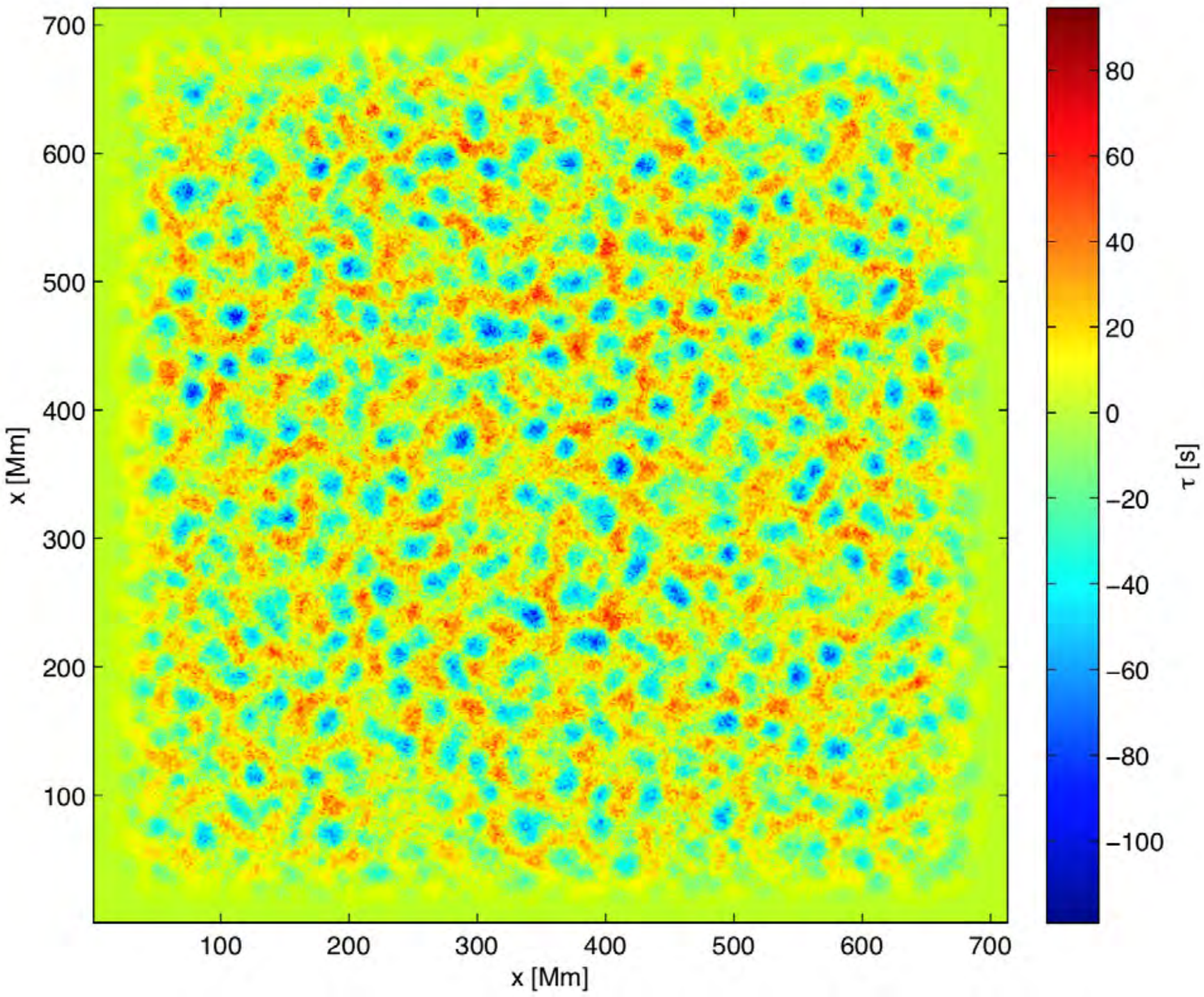


# Local helioseismology

- Local helioseismology: analysis of non-standing travelling waves
- They meet anomalies
  - Change of the wave properties
- Frequency shifts
- Travel-times (and their shifts)
- Sounding due to the artificial selection of the modes
- Inverse task possible (not simple though)

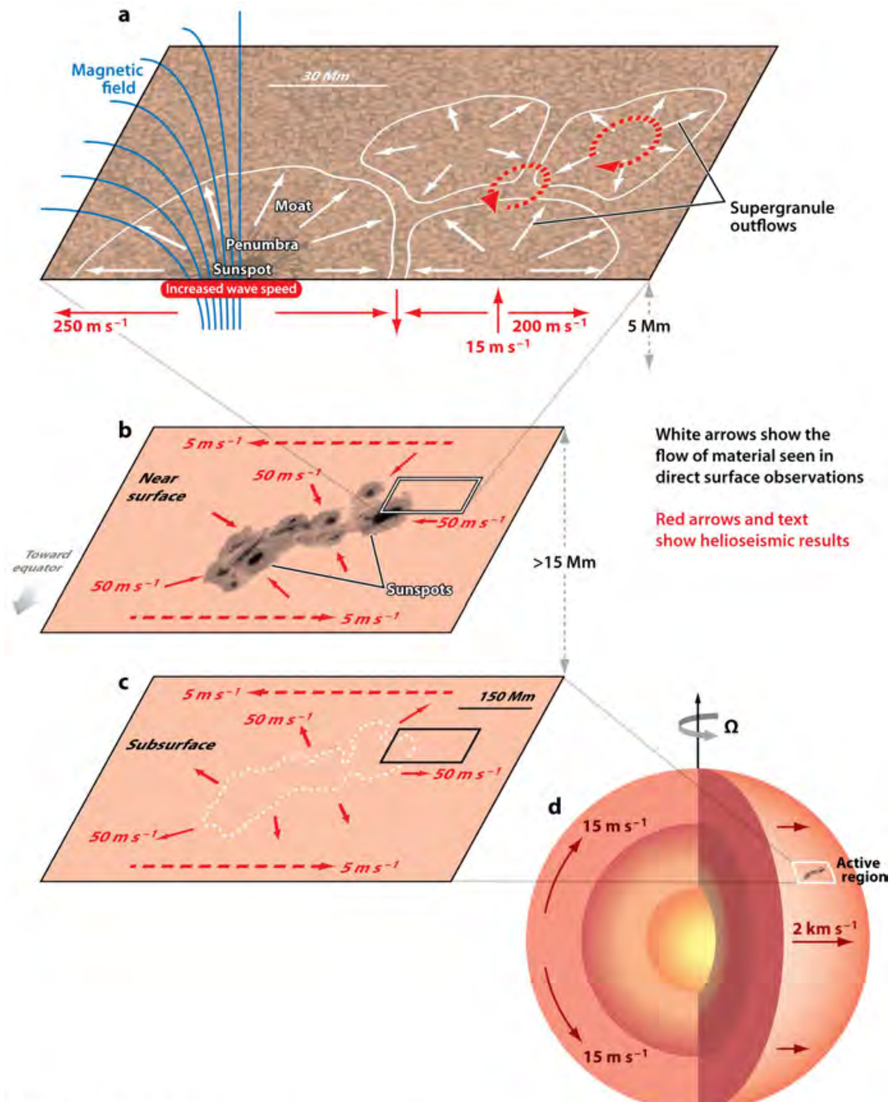


# Travel-time deviations map



# Principial results: Plasma dynamics

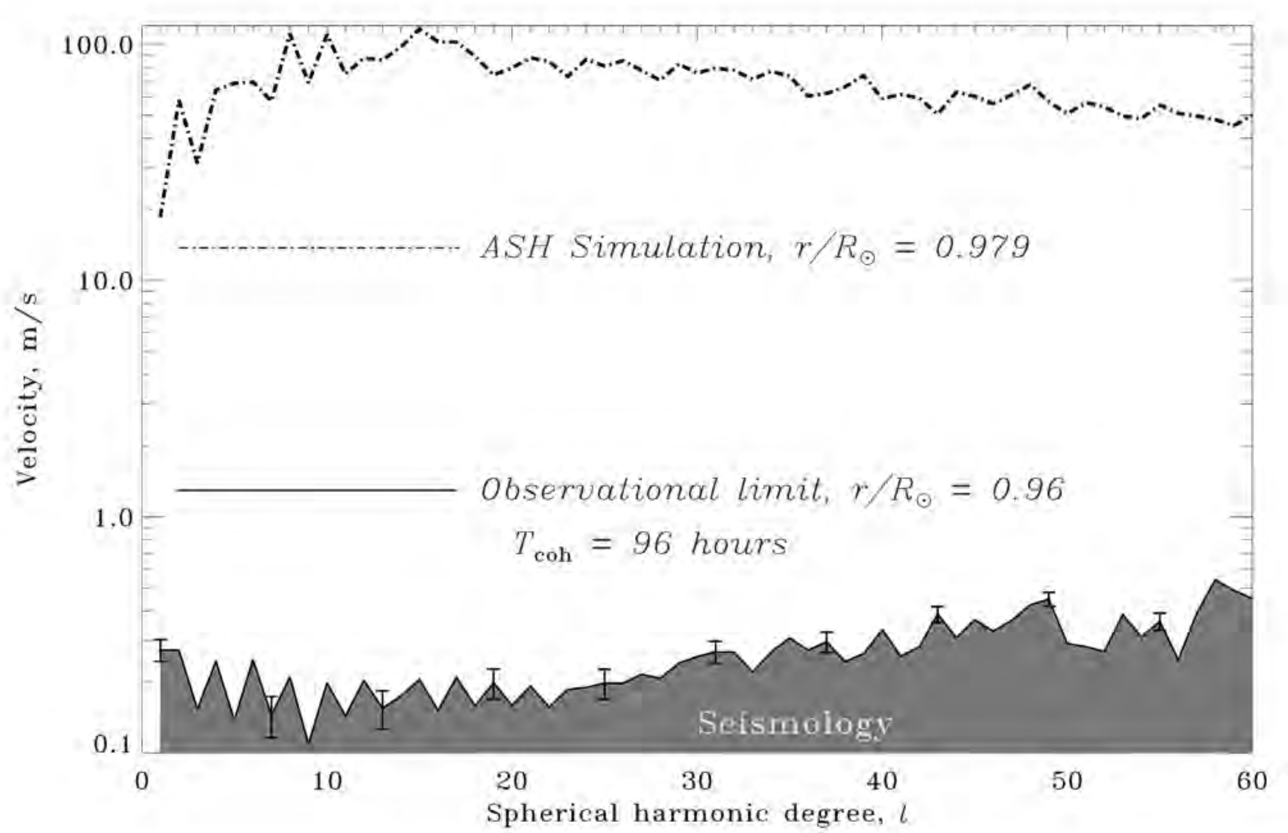
- Sub-surface plasma dynamics is multiscale
  - Convection
  - Large-scale motions
  - Rotation
  - Meridional flow
- Deeper than 30 Mm the findings are fuzzy
- Other findings also important




Gizon L, et al. 2010.
Annu. Rev. Astron. Astrophys. 48:289–338

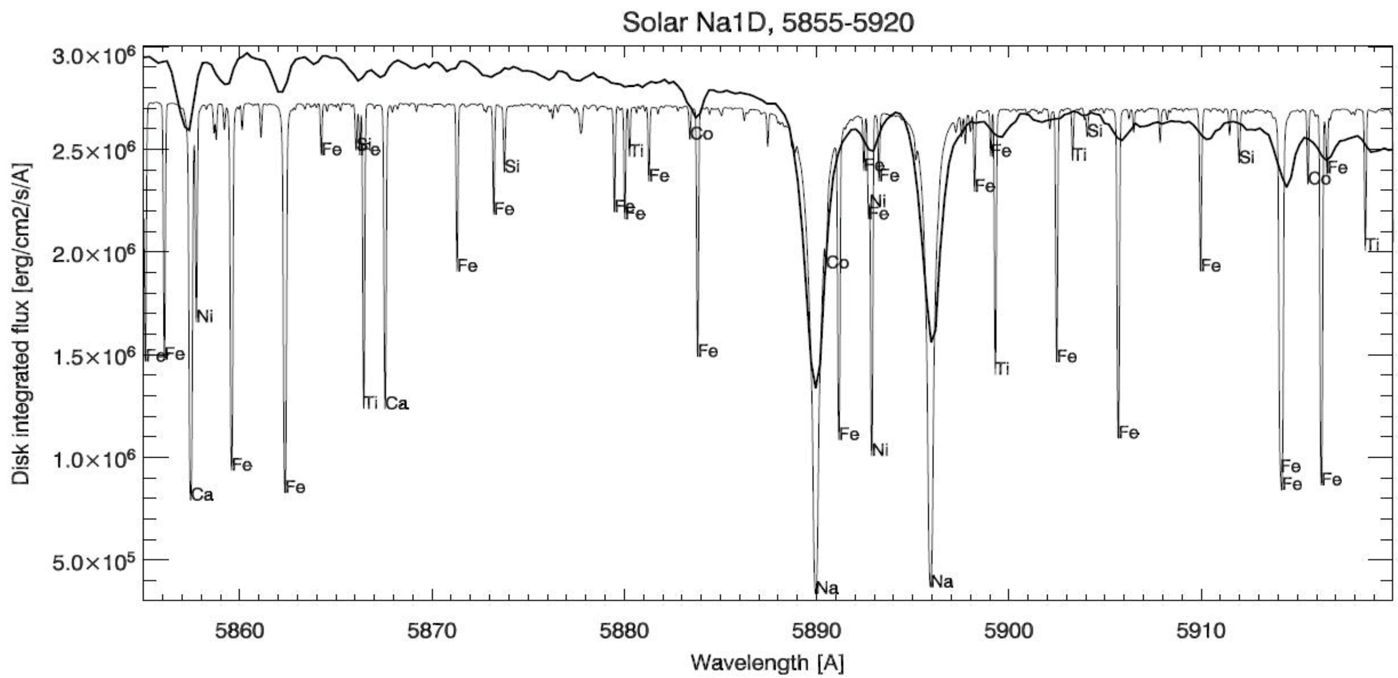
# But deeper down…

- Comparison of the simulations and observations does not work
- Issue with the description of the convection?



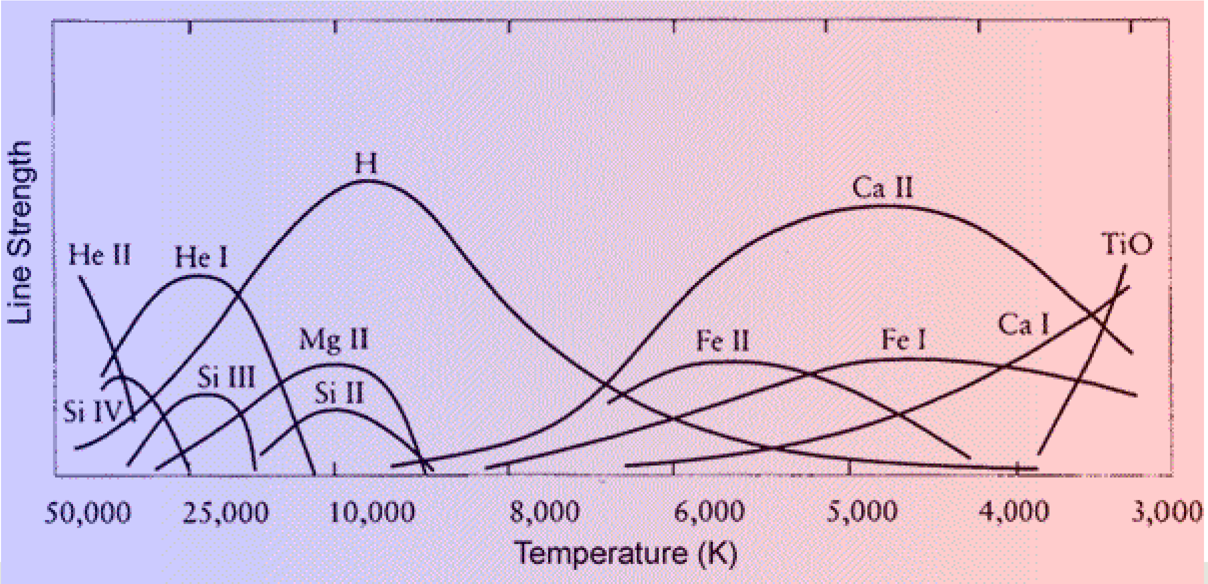
# Composition matters

- Helioseismology is based on models: the models depend (strongly) on chemical composition
- Chemical compositon is *not* measured, but *derived* (based on measurements)
  - Methodology matters



# Iron Sun?

- Simple approach: the Sun is made of metals, mostly iron
  - Many metal spectral lines in the photosphere
  - Iron-like elements have many electrons – opacity sources
- Ionisation and excitation equilibria matter!
  - Cecilia Payne (1925)
  - In the solar photosphere the temperature is “low” to excite hydrogen, hence limited hydrogen lines

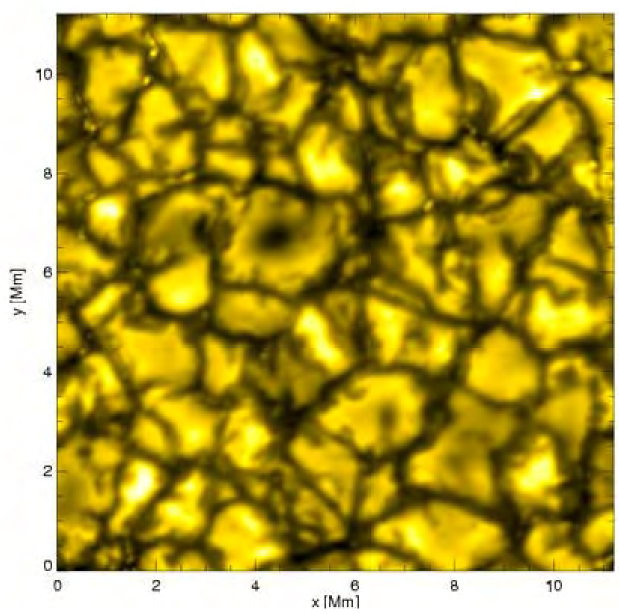


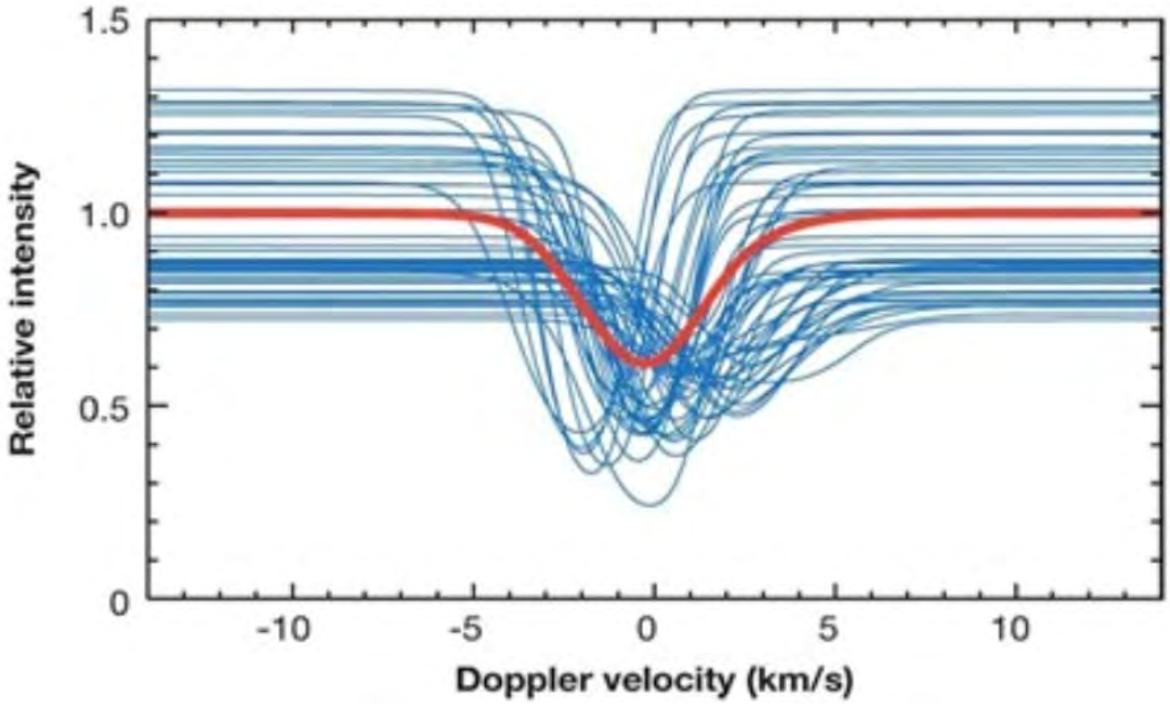
# Microphysics matters

- Opacity = ability to interact with the electromagnetic radiation
  - Wavelength dependent
  - Abundances dependent
  - Matter-light interaction dependent
    - Effective cross-sections, quantum physics
- Coupling of abundances and opacity non-trivial
  - Cross-sections measured or modelled
  - Reasonable knowledge for H, worse for He, good for H-like atoms, disaster for the heavy ions
  - Opacity inaccuracies in tens of per cents
  - Internal structure of the stars depend in details on the abundances
- Since about 2000 – big revisions
  - Disagreement with meteorites and surrounding stars (indicating lower Z)

# Departures from 1-D models

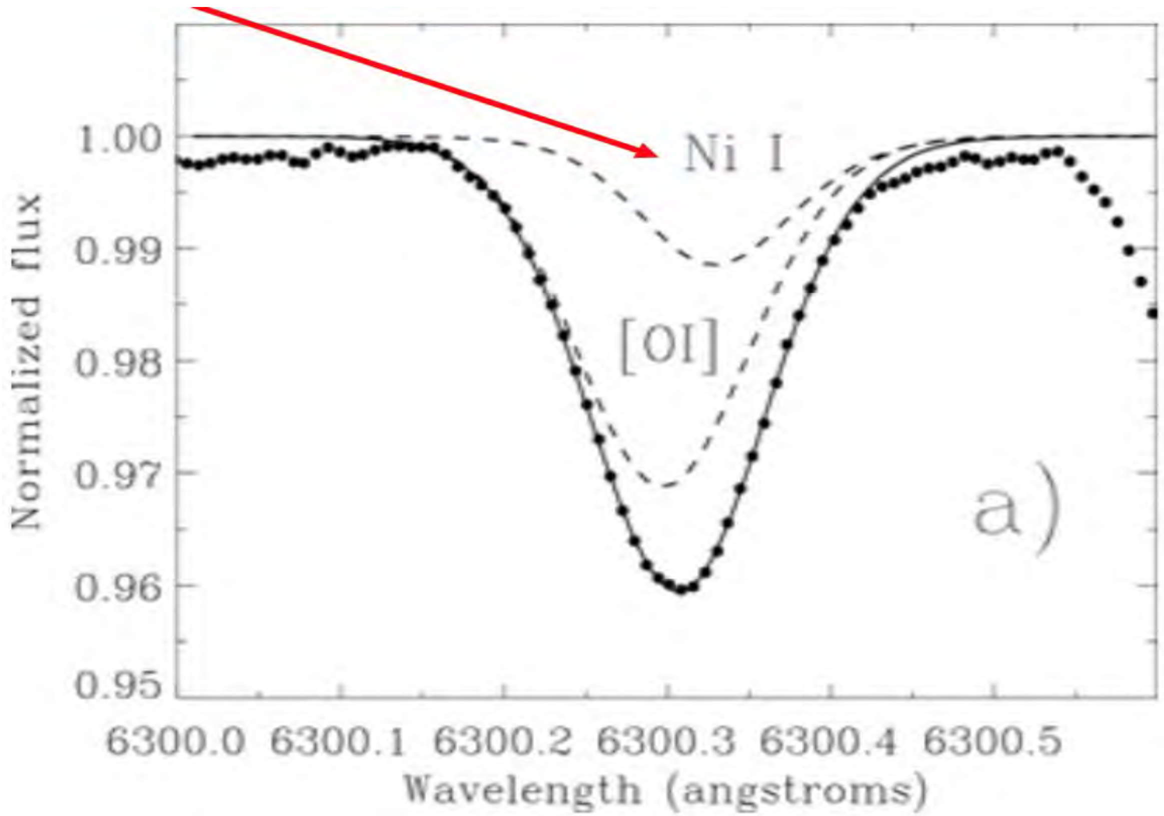
- The Sun – convective cells on the surface
  - Not flat (hence non-1D)
  - Spectral line influenced by the positions



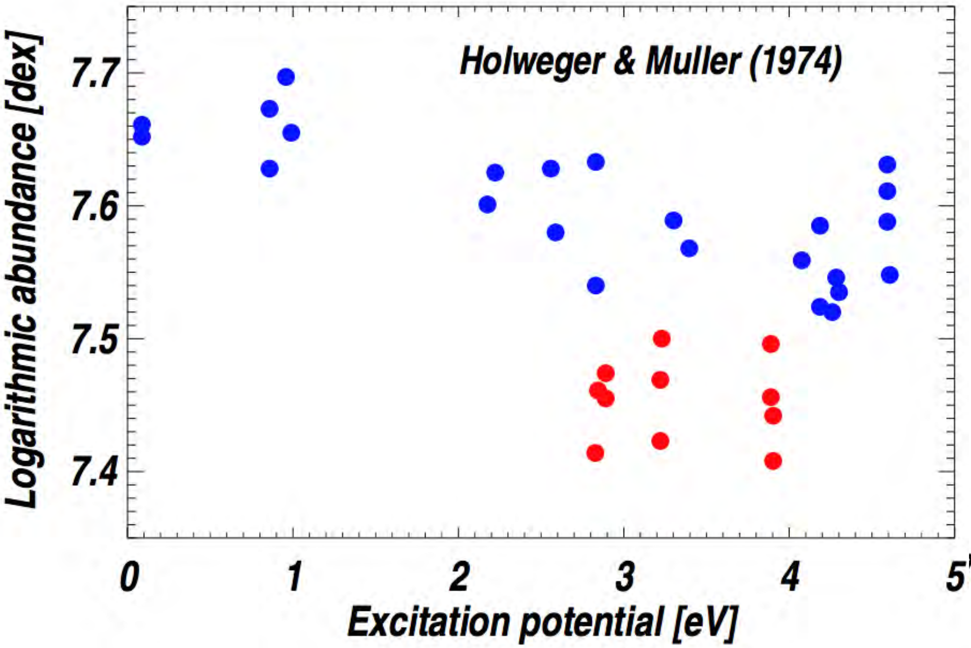



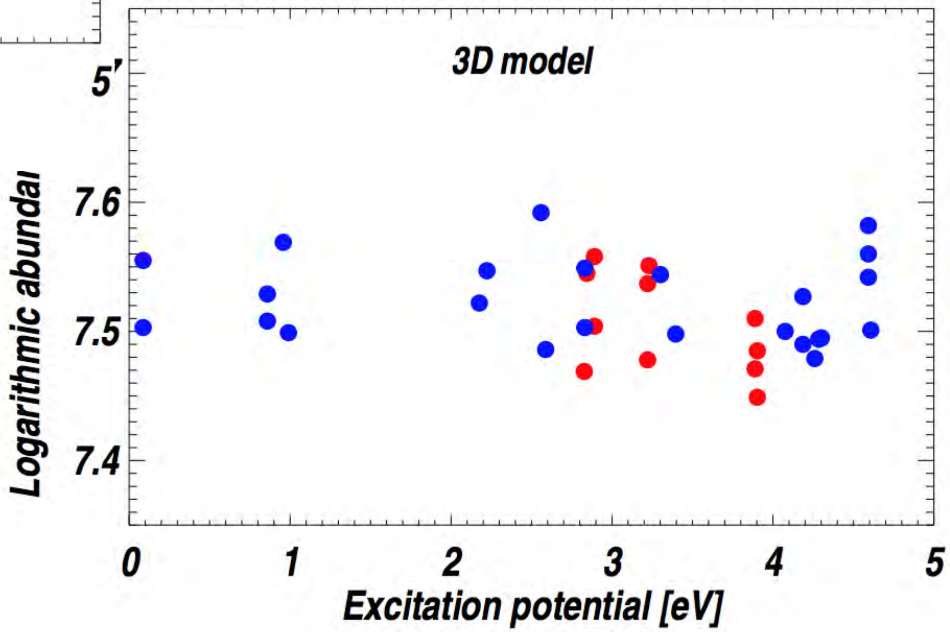
# Revisions of the spectral lines

- Hidden blends are the issue
- Non-equilibrium effects



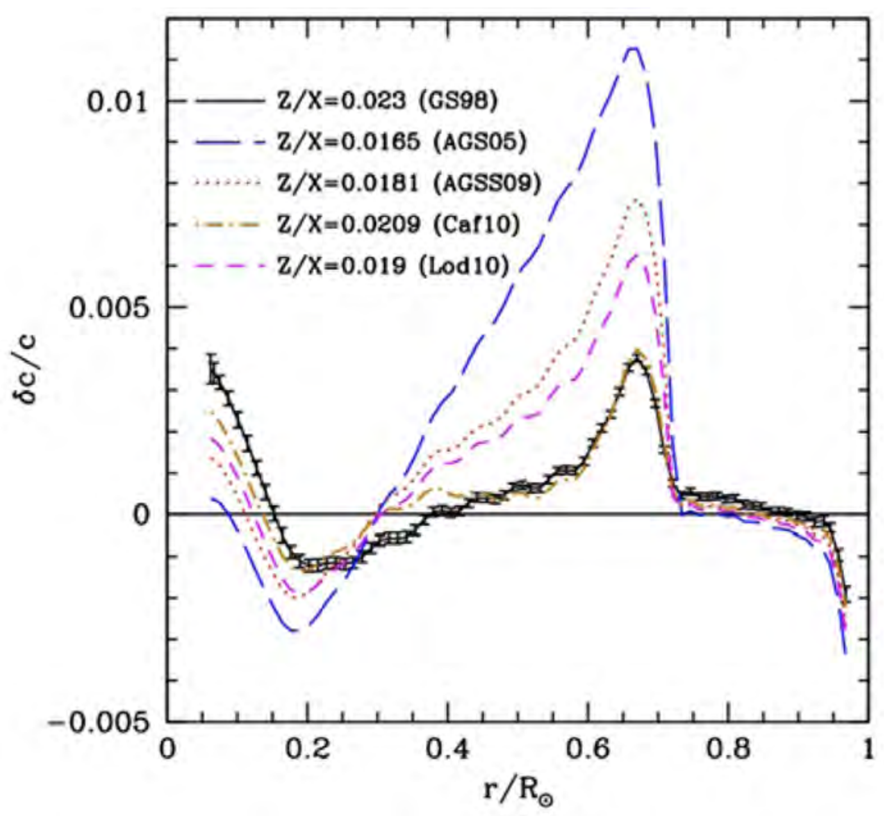
# Difference for the Fe I and Fe II



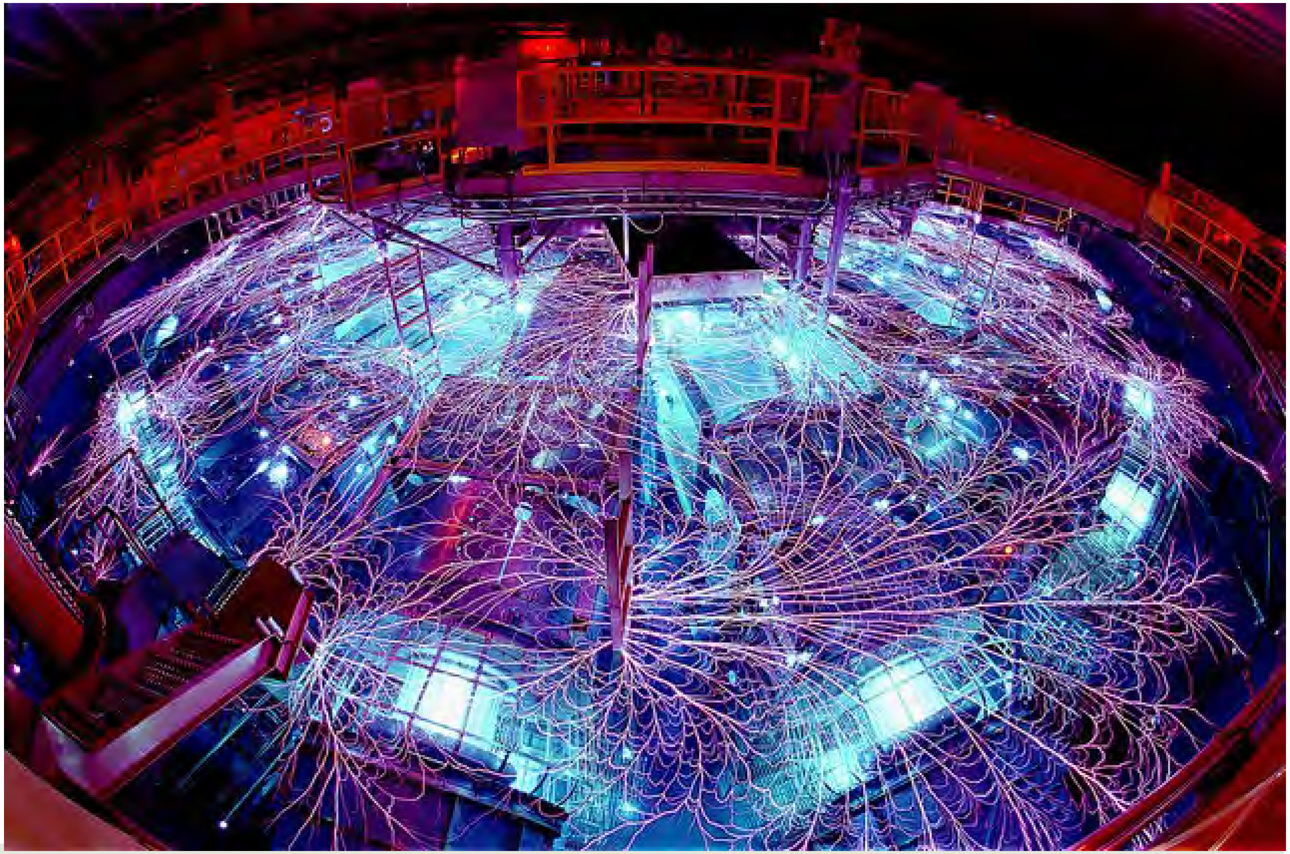
# “New” solar abundances

- ”Metal” abundances corrected, decrease of C, O, Ne
  - Z=0,0143
- Now agrees with meteorites
- Agreement with the stars in the neighborhood
- Agrees with high-resolution observations
- Issues for helioseismology
  - Disagreement huge
  - ? Convective overshoot ?
  - ? Additional mixing ?



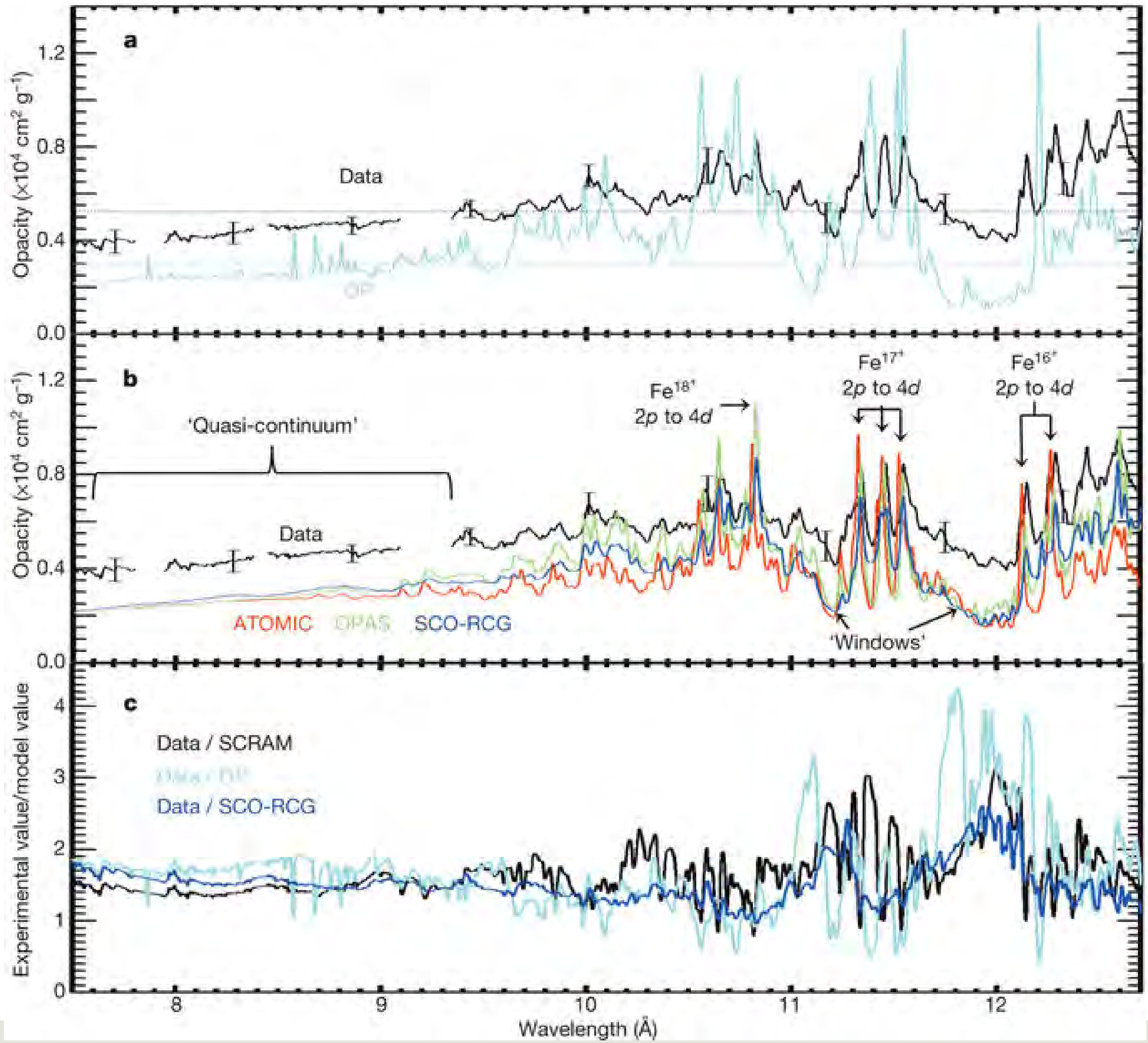
# Z-machine

- Governmental device to explore X-rays and their effects on matter (otherwise it is part of the research with a military value and pulse-driven hydrogen fusion)
- Opacities can be measured



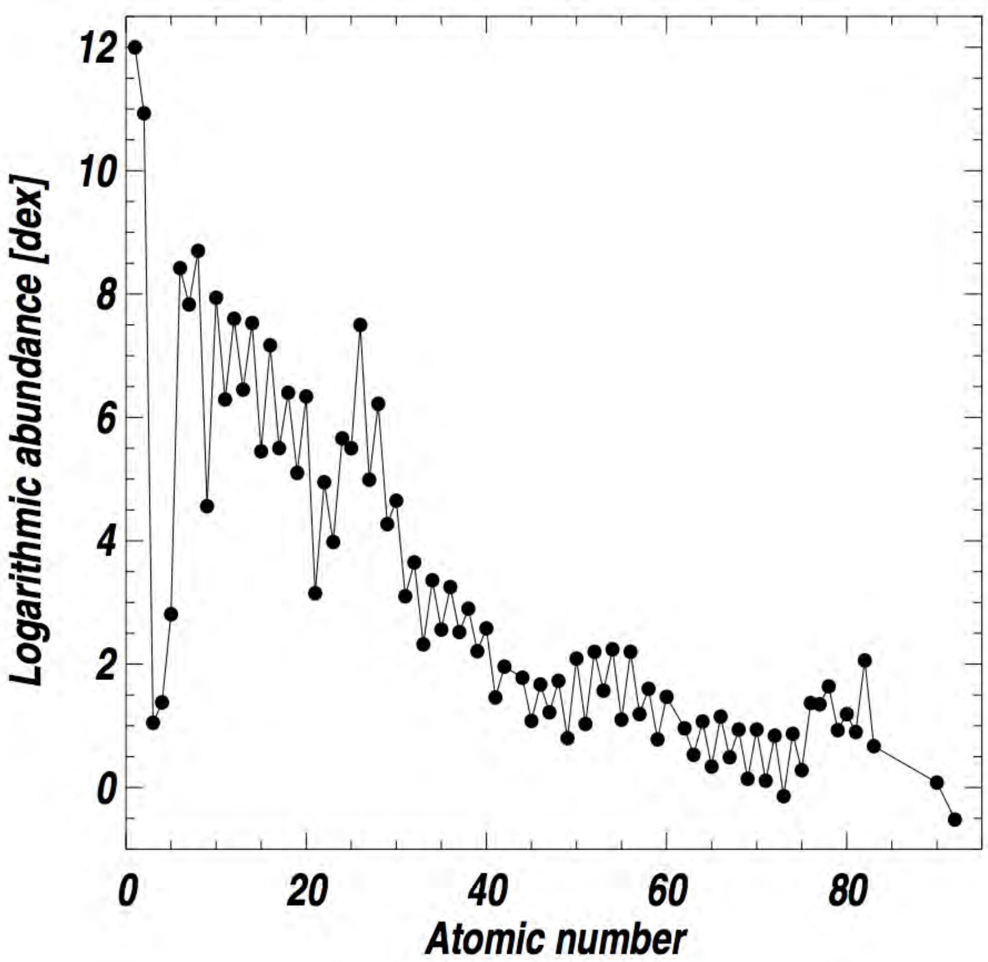
# Iron has a larger opacity…

… than expected



# Actual composition of the Sun

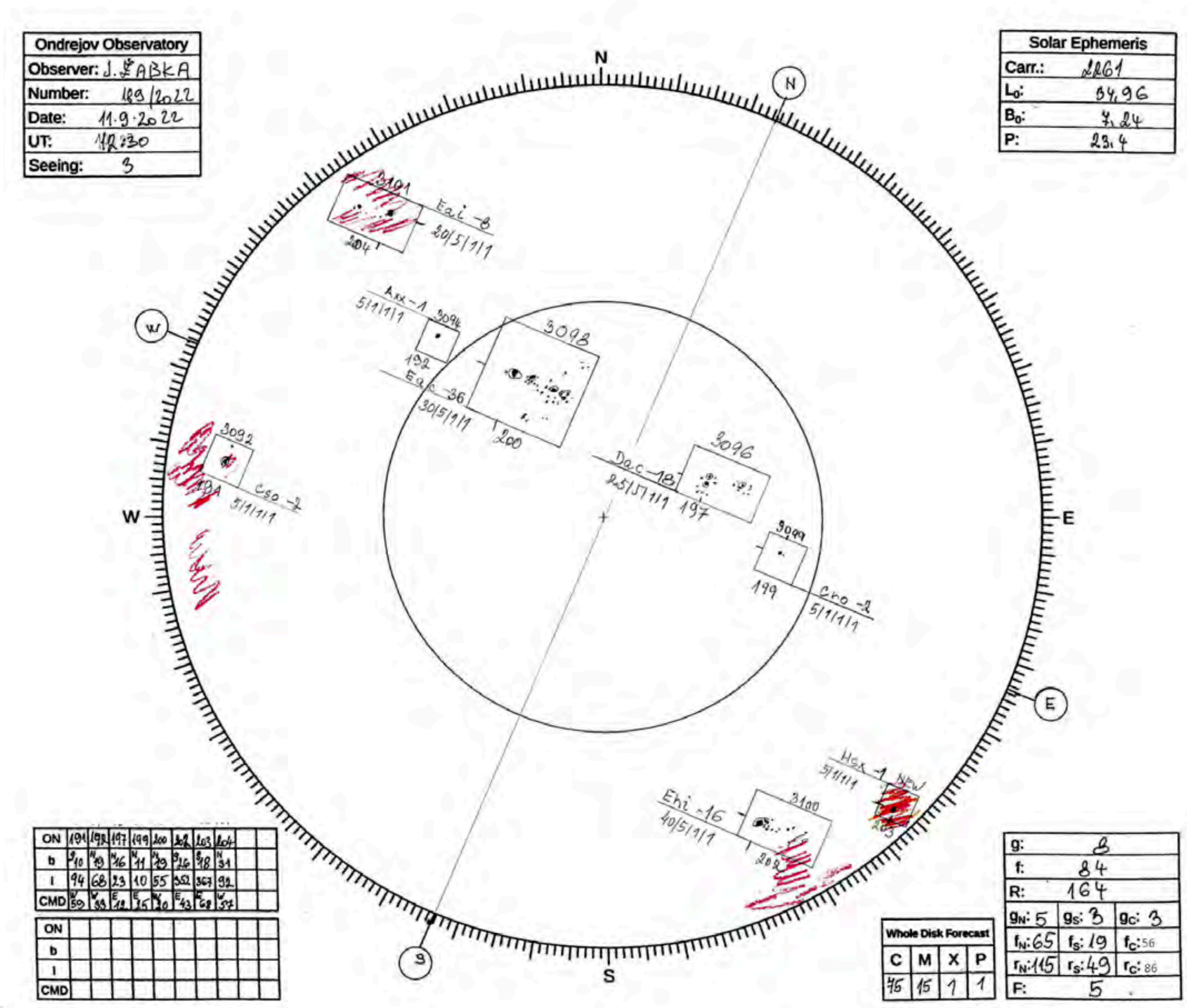
- H + He
- Z < 0.015
- Lithium  underabundant
  - Issues with models
  - Other stars richer in helium
  - Older stars seem to have lesser Li
  - ? Non-convective mixing that helps to destroy Li ?



# Back to the roots

- The Sun is too complicated to be properly described
- Indices of activity
  - A single number describing an overall level of activity at the given time
  - Good for describing the time evolution
  - Some physically motivated
  - Some “logical” (common sense)
  - Some arbitrary

# Drawing the Sun…



# Relative sunspot number

- R. Wolf (1851) combined number of sunspots and number of groups into one

  $R = 10g + f$

- Systematic observation, own network to fill in the gaps
- Explored historical records

**Sonnenfleckenbeobachtungen im Jahre 1849.**

| | I. | II. | III. | IV. | V. | VI. | VII. | VIII. | IX. | X. | XI. | XII. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 9.31 | 3. 6 | 4. – | 10.70 | 9.30 | 8.48 | 4.13 | 4 15 | 7.64 | 8.10 | 5.16 | — |
| 2 | 9.34 | 7.40 | 5. — | 7. — | 9.40 | 9.64 | 3. 3 | 6.18 | 5.35 | 7.10 | 7.41 | 8. 9 |
| 3 | 15. — | 2. — | 6.12 | 10.38 | 5.12 | 8 50 | 3. 6 | 6.15 | 4.27 | 3. 4 | 3.10 | 8.17 |
| 4 | 9.31 | 7.27 | 7.15 | 12.58 | 7.45 | 10.50 | 3 10 | 4.12 | 5.41 | 2. 3 | 4.31 | — |
| 5 | 9. – | 9.22 | 2. — | 8.20 | 8 50 | 8.45 | 7. — | 5.20 | 1. 1 | 1. 2 | — | 9.47 |
| 6 | 8. — | 10 34 | 7.24 | 10.60 | 7.38 | 7.45 | 4. 8 | 4.18 | 6.25 | 4. 6 | — | 2. 2 |
| 7 | — | 3. — | 3. — | 8.24 | 1. – | 5. — | 5.10 | 3.20 | 7.48 | — | 6.22 | — |
| 8 | 8.28 | 10.21 | 4. — | 6.20 | 6.20 | 5.12 | 6 15 | 3.15 | 5.38 | 5.16 | 7.35 | — |
| 9 | 8.30 | 10.35 | 3. — | 9.45 | 6.25 | 3. – | 7.20 | 4 14 | 7.50 | 5.26 | 6.20 | — |
| 10 | — | — | 2. – | 2. — | 2. — | 3. — | 3. 6 | 5.27 | 9.26 | — | — | — |
| 11 | — | 8.20 | 5.20 | 6.24 | 4.10 | 1. — | 2. 4 | 5.32 | 7.25 | 2. 5 | — | — |
| 12 | 7.28 | 9.56 | 7.30 | — | 1. 2 | 5.12 | 3. 8 | 7.25 | 6. — | — | — | — |
| 13 | — | 11.64 | — | 5.14 | 0. 0 | 5.14 | 4.10 | 7.24 | 4.40 | 4.26 | 5.11 | 3.22 |
| 14 | — | 7. — | 7.22 | 5 16 | 5.16 | 6.14 | 3.12 | 6.15 | 5.15 | — | 6.22 | 3.12 |
| 15 | 4. — | 2. 2 | 6.23 | 5.10 | 4. — | 4. 8 | 3.12 | 6 14 | 9.59 | — | 5.20 | 4.19 |
| 16 | 5. – | 6. — | — | 2. 2 | 4.25 | 3. 4 | 7.45 | 7.21 | 7.54 | 3. 5 | — | 3. 5 |
| 17 | 9.25 | 15.40 | 4.14 | 2. – | — | 4. 8 | 8.40 | 6. — | 6.32 | 4.21 | — | 5.22 |
| 18 | 11.60 | 8. — | 7.30 | 5. – | 4.30 | 5.35 | 9.30 | 6.30 | 5.19 | 4.25 | 2.22 | 7.37 |
| 19 | 10.25 | 11.36 | 4. — | 6.25 | 2. 2 | 5.35 | 7.22 | 5.26 | 3. 9 | 6.56 | 5.25 | 6.10 |
| 20 | 11.74 | 13.60 | 5.30 | 6.11 | 3.42 | 2. 5 | 7.22 | 3. 5 | 4.26 | 6.41 | 7.47 | 4. 5 |
| 21 | 12.75 | 12. — | 5 30 | — | 3.22 | 4.42 | 7.15 | 5.10 | 6.24 | 8.36 | 6.16 | 2. 2 |
| 22 | 9.46 | 10.21 | 6.35 | 6 36 | 3.28 | 6.56 | 6. 8 | 4. 4 | 7.28 | — | — | — |
| 23 | 10. — | 11.58 | — | 3.12 | 4.25 | 5.38 | 5.12 | 4. 7 | 7.34 | 7.49 | — | — |
| 24 | 10. — | 11.40 | — | 2.10 | 3. 8 | 2. — | 5. 9 | 3. 4 | 7.23 | 5. 8 | — | — |
| 25 | 10.65 | 10.68 | 3. — | 5.30 | 6.25 | 5.30 | 7.14 | 3.10 | 5.22 | 4. 4 | — | 11.43 |
| 26 | 10.76 | 10.35 | — | 4.10 | 5.12 | 4.25 | 4. 8 | 5.20 | 5.15 | — | — | 6.13 |
| 27 | 10.95 | 2. — | 4. — | 6.44 | 6.20 | 2.15 | 5. 7 | 5.21 | 8.15 | — | 9.68 | — |
| 28 | 9.63 | 7.36 | 12.50 | 3. – | 8.30 | 2.10 | 7.20 | 3.15 | 9.16 | 3. 4 | 11.72 | 5. 7 |
| 29 | 9.62 | | 2. — | 3.20 | 6.10 | 4. 6 | 7.24 | 4.24 | 8.17 | 5.11 | 13.74 | 8.52 |
| 30 | 9. — | | 9.31 | 3.20 | 7.40 | 1. 1 | 8.20 | 5.36 | 8.17 | 7.48 | 11.52 | 4.11 |
| 31 | — | | 11.58 | | 6.10 | | 6.16 | 6.45 | | 5.16 | | — |
| Mittel. | 144,0 | 128,1 | 100,7 | 87,9 | 83,3 | 88,1 | 80,4 | 67,5 | 92,6 | 82,0 | 96,4 | 92,1 |

# THE issue: one observer

- One observer = one place on Earth = data series *must* have gaps
- To complete – let's involve other observers
  - Different experience
  - Different condition
  - Different telescope
  - They observe the same Sun, but yet, their numbers are different
    - Conversion ("calibration") simplest possible
      $R_i = k\,(10g + f)$

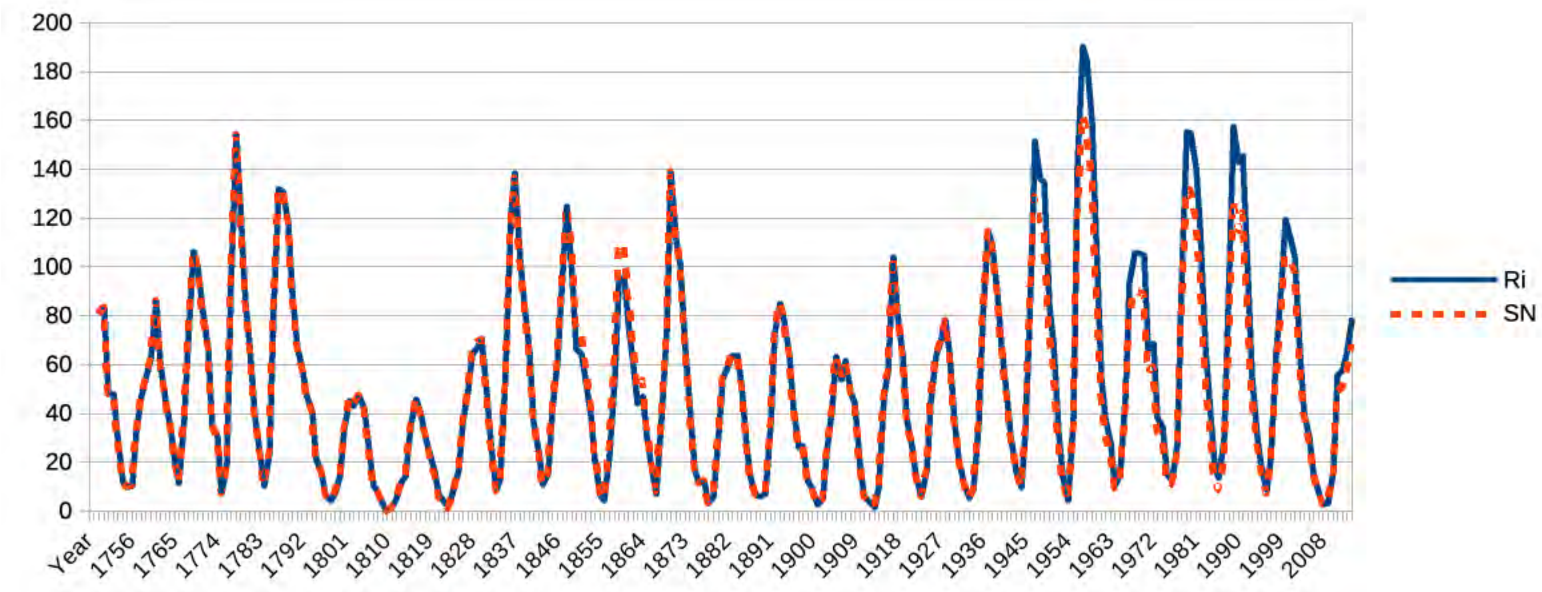
      $k$ is the personal coefficient
- Total series: the composite

# World-wide composited

- Reference station
  - SIDC
  - Historically – the “backbone” method
- Simple average
  - Sensitive to outliers
  - Local networks (ČAS)
- Weighted average
  - AAVSO (“american” relative number]
  - The weights indicate the ”quality” of the observers
- Iterative algorithm
  - *k* coefficients based: those are computed first
  - The the dayli average with new coefficients
  - WDC-SILSO

# 2015 and on

- Schizophrenia of the relative number
- Various disagreements between various “official” datasets
- Systematic errors and biases discovered
  - Working group to identify and correct those
  - New *sunspot number* $S_N$



# It's not the final answer!

- Versioning system
- The work goes on

- Paradox: The longest running solar observation (methodology from the medieval times) seem to have issues even in the modern (computerised) era!
- Is has effects (on dynamo investigation, climate forcing, …)
- How can we trust details if the overall picture is unsure?

# Open questions

- Solar physics has a future
- The devil is hidden in the details
- Many (re)open(ed) questions
  - Character of the convection (influences stellar physics)
  - Solar cycle, periodic and aperiodic components
  - Coronal heating
  - Acceleration of the solar wind
  - Details of solar flares and their effects
  - Sun-Earth relations
  - and others…