The Solar Chemical Composition: Past and Present

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Université de Liège, Belgium

Solar abundances...PAST...in short...

- RUSSELL (1929) – 56 elements – H most abundant element!

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Progress : - curve of growth (Minnaert, 1931)
- continuous opacity H^- (Wildt, 1939)
- photospheric models (Strömgren, 1940)

- Unsöld (1948) - ~ Russell
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Progress : - better quality photospheric spectra
- synthetic spectra
- **better atomic data** (transition probabilities)

- L.H. Aller, D.L. Lambert, H. Holweger, E. Biémont, N. Grevesse, A. Noels, A.J. Sauval, …

Reviews: - Anders, Grevesse 1989
- Grevesse, Noels 1993
- Grevesse, Sauval 1998

Progress: more accurate atomic data

SOURCES of solar abundances ?
(see also next slide)

- Photosphere
- (Sunspots)
- Chromosphere SPECTROSCOPY
- Corona

- Solar Wind (SW)
- Solar Energetic Particles (SEP)

- Helioseismology (He)

- (Flares : spectra →)
- (Moon! From past solar wind)

SOURCES of solar abundances

- PHOTOSPHERE : SPECTROSCOPY-**MAIN SOURCE**

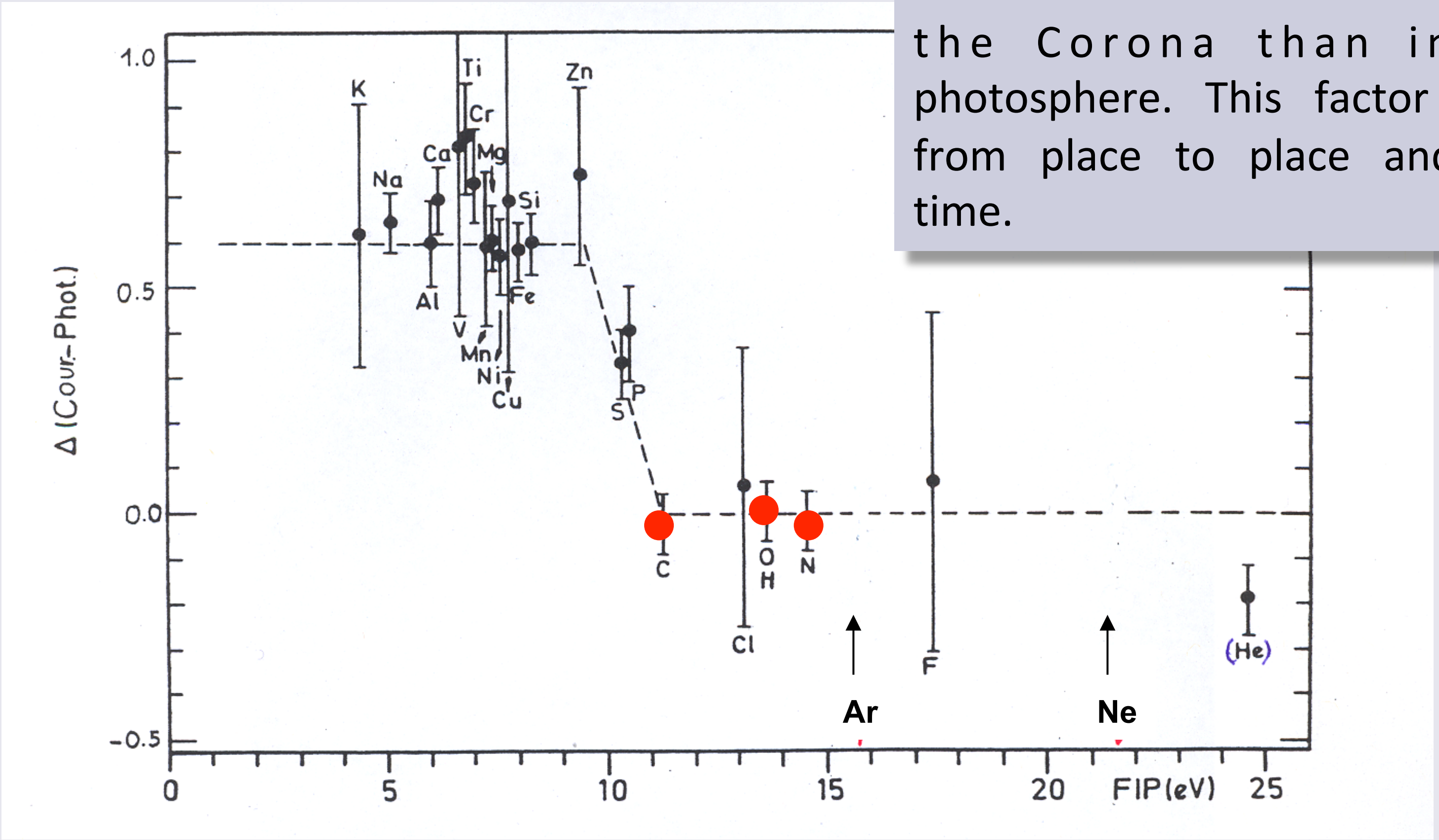
BECAUSE…

- Chromosphere, Corona, Solar Wind (SW), Solar Energetic Particles (SEP)

show **FRACTIONATION, the FIP Effect**!!!

Elements with FIP lower than about 10 eV i.e. easily ionized, show very large variations of their abundances, whereas elements with higher FIP, for example O, Ne, … do not show any variation. An exception however: HELIUM, which varies tremendously!!!

The FIP effect



Low FIP elements are about a factor 3 to 4 more abundant in the Corona than in the photosphere. This factor varies from place to place and with time.

Solar Photospheric Spectra

- Wollaston (1802) – Dark lines
- Fraunhofer (1814) – *A,B,C,D,….,H,K,….* Fraunhofer lines
- Kirchhoff & Bunsen (1850) Absorption lines

  ……….. Identifications (ex: 1896 : 36 elements)
- Rowland (1895-1897)

  ……….. Identifications (ex: 1928 : 57 elements)
- Minnaert, Mulders, Houtgast (1940) - *Atlas 3612-8771Å*
- Moore, Minnaert, Houtgast (1966) – Identifications

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- **Kitt Peak**
- **ATMOS – IR : First solar spectra from space in the IR**
- **Also ACE IR from space**

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- Lines of neutral and once ionized species
- Lines of diatomic molecules [H,C,N,O,(Si,Mg)]

Atlas of the Solar Spectrum (L. Delbouille, G. Roland, L. Neven)

Jungfraujoch

3580 m

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New Solar Chemical Composition

M. Asplund, N. Grevesse, A.J. Sauval, P. Scott,
Annual Rev. Astron. Astrophys. 47, 481, 2009

Also E. Caffau, H. G. Ludwig, M. Steffen et al.


P. Scott
M. Asplund
N. Grevesse
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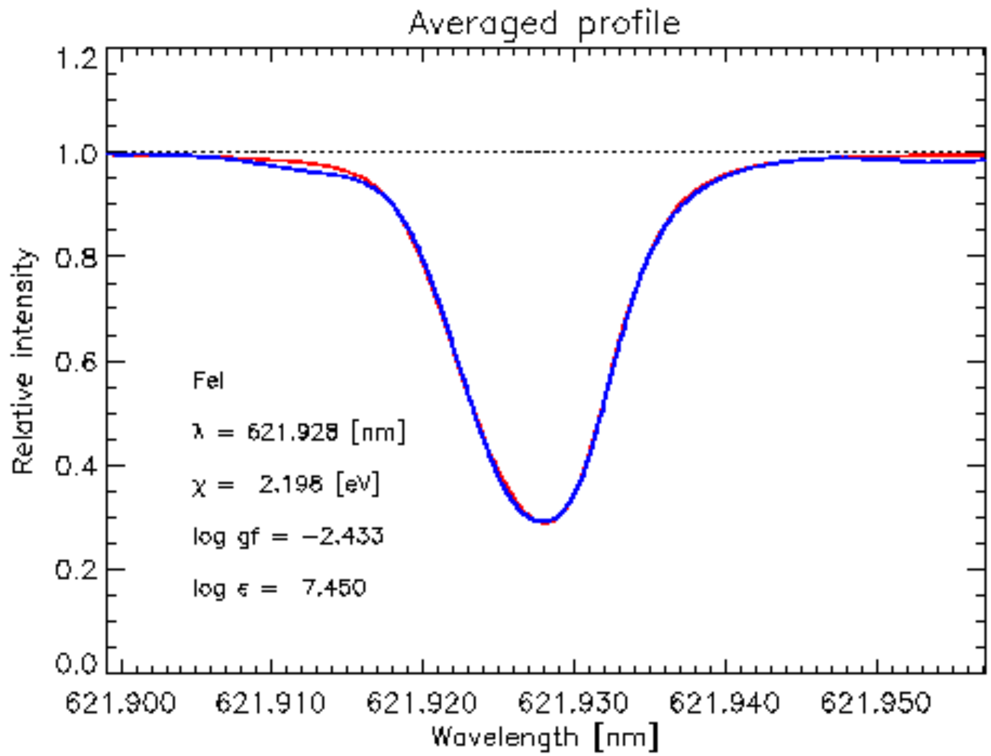
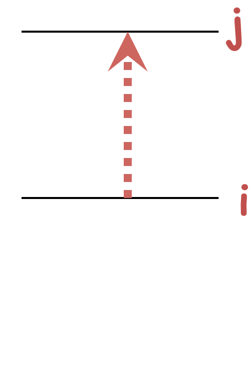
The END RESULT: a COMPREHENSIVE and HOMOGENEOUS redetermination of the abundances of all the elements in the sun.

HOW ? From the absorption lines...





Absorption depends on ratio $\kappa_{line}/\kappa_{cont}$ i.e. $\div(N_{el}/N_H)$

I_{line} (W_λ) depends

- Ni* x A^+_{ij} (or gf_{ij}-values)
- Physical processes (LTE-NLTE)
- Physical conditions :T,P=f(z;Model)

*Number of atoms or ions that are in the level i

+Transition probability

Redetermination of the abundances of nearly all available elements

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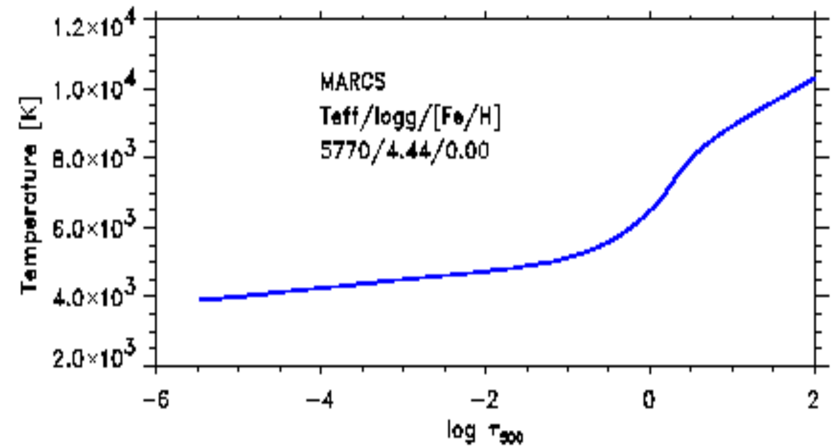
1D solar atmosphere models

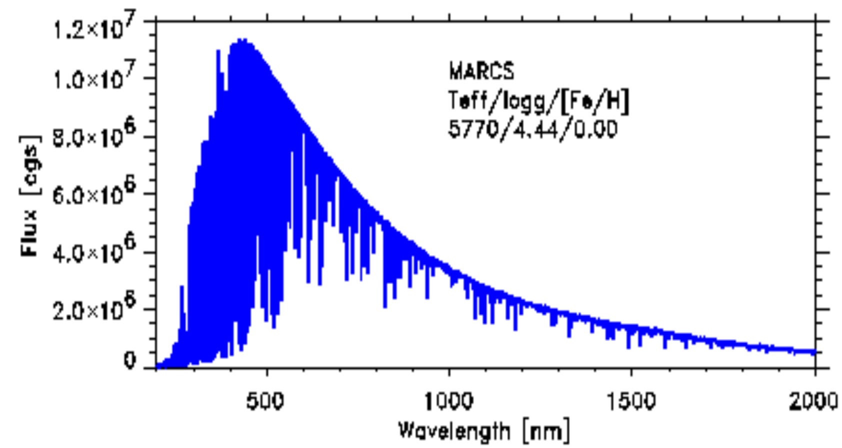
Theoretical models:

- Hydrostatic
- Time-independent
- 1-dimensional
- Convection a la mixing length theory
- LTE
- Detailed radiative transfer
- MARCS, Kurucz etc

Semi-empirical models:

- Temperature structure from observations
- Holweger-Müller (1974)





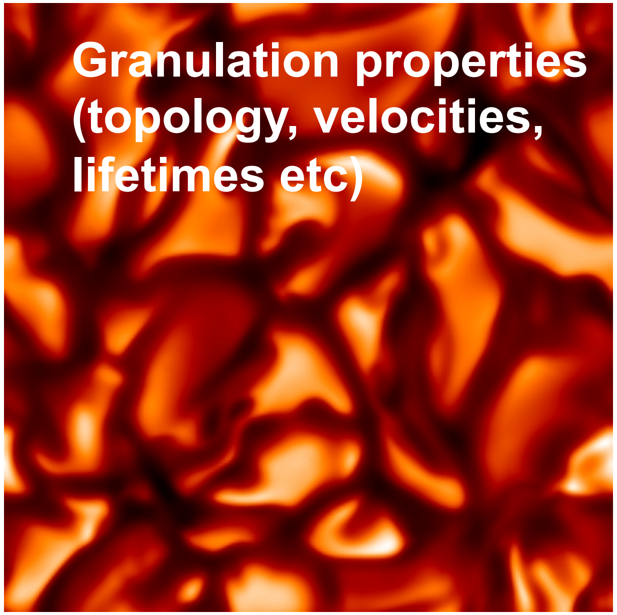
3D models

From Hydrodynamics (conservation of mass, momentum, energy) … … coupled with tranfer of radiation along various directions

(6000*6000*3600km; ~10 granules; Stein & Nordlund 1998)

Mats Carlsson (Oslo)
Remo Collet (Aarhus)
Åke Nordlund (Copenhagen)
Bob Stein (Michigan State)
Regner Trampedach (Colorado)

Observational tests



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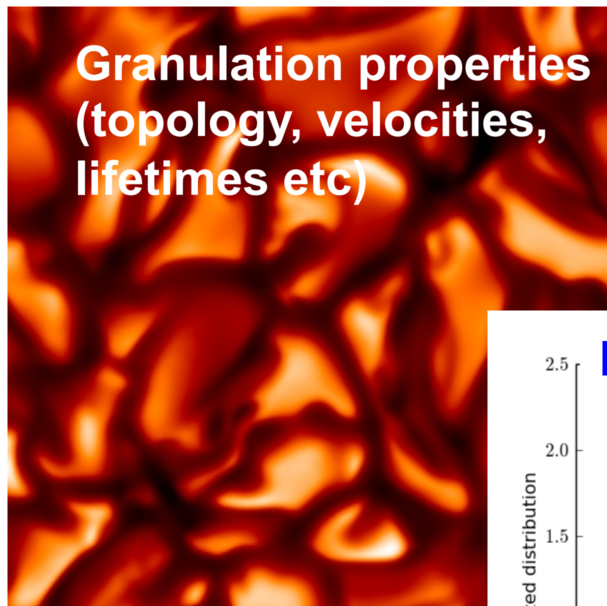
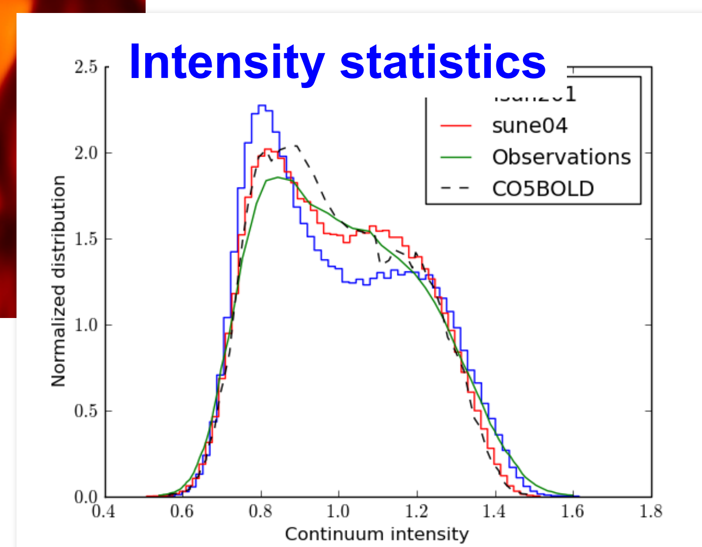
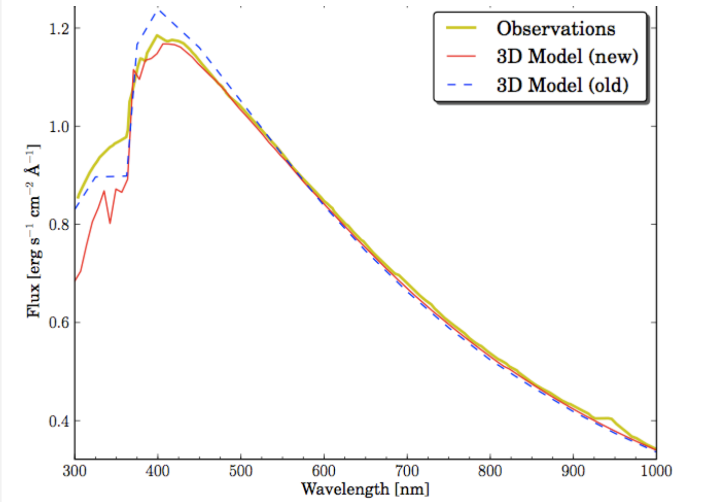
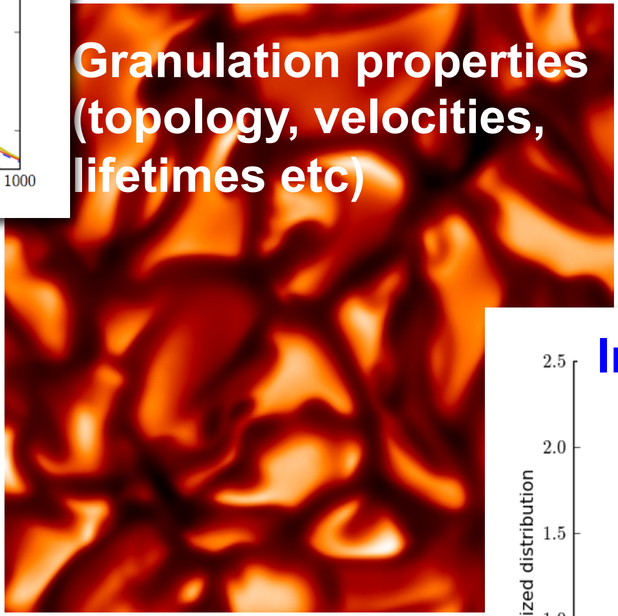


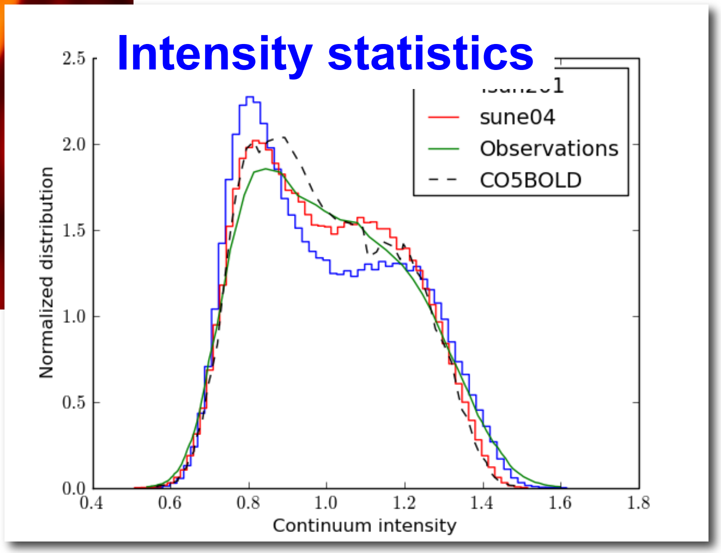


Observational tests

Spectral energy distribution







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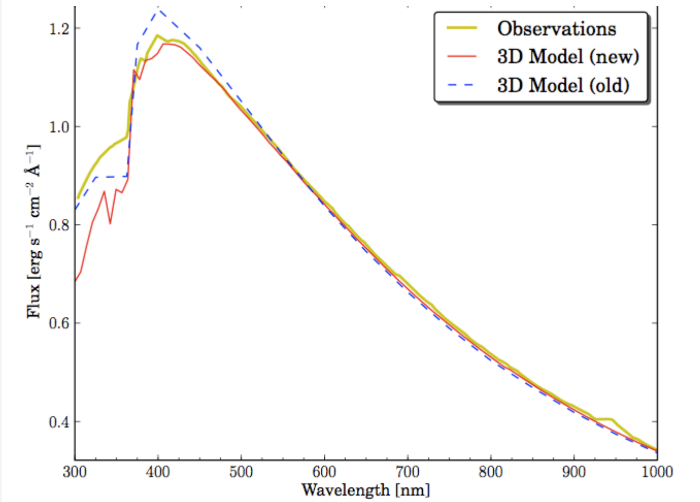
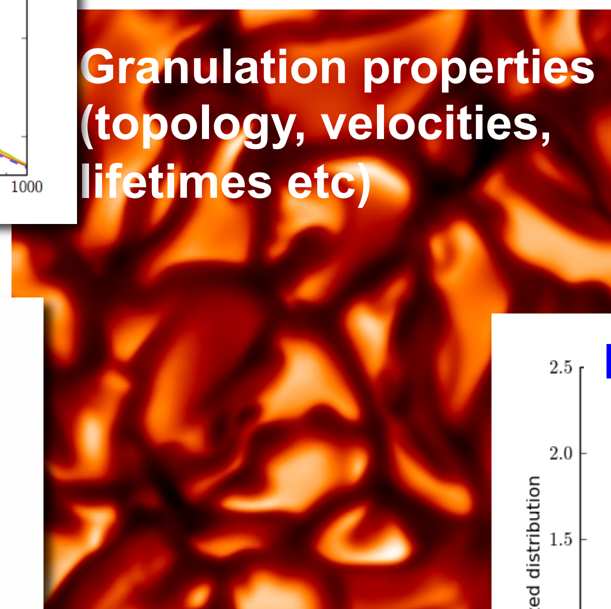
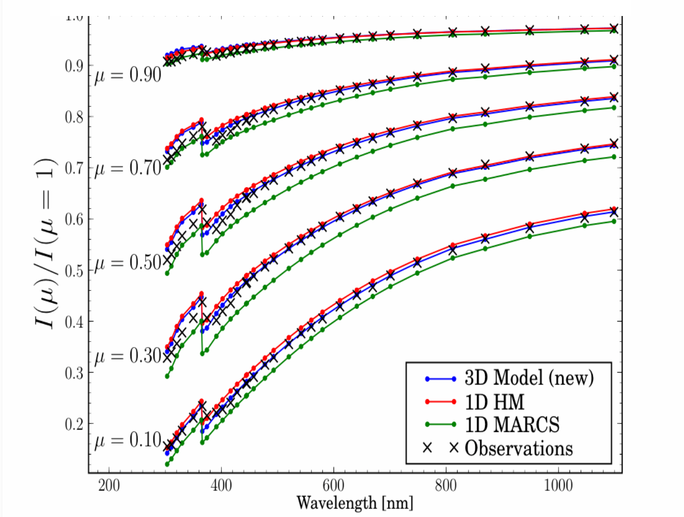
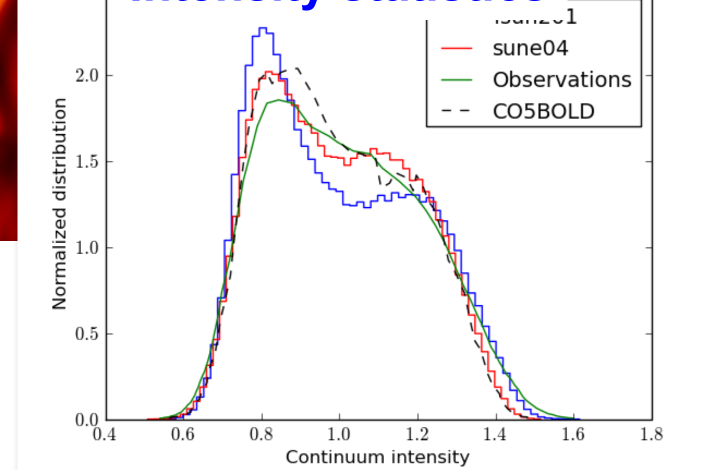




Center-to-limb variation



Intensity statistics



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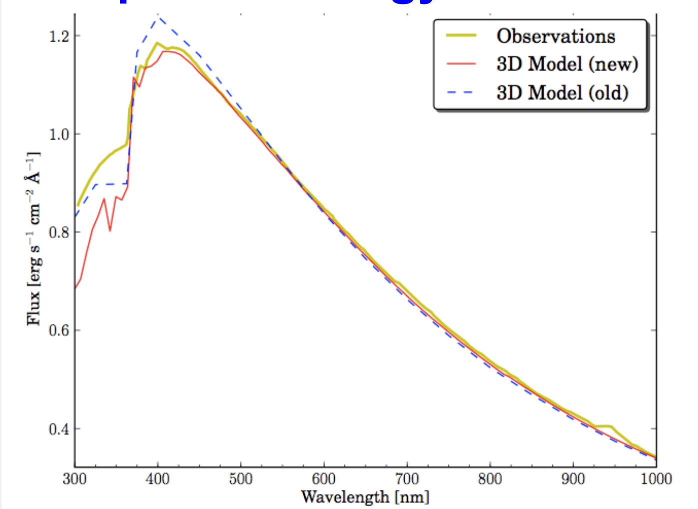
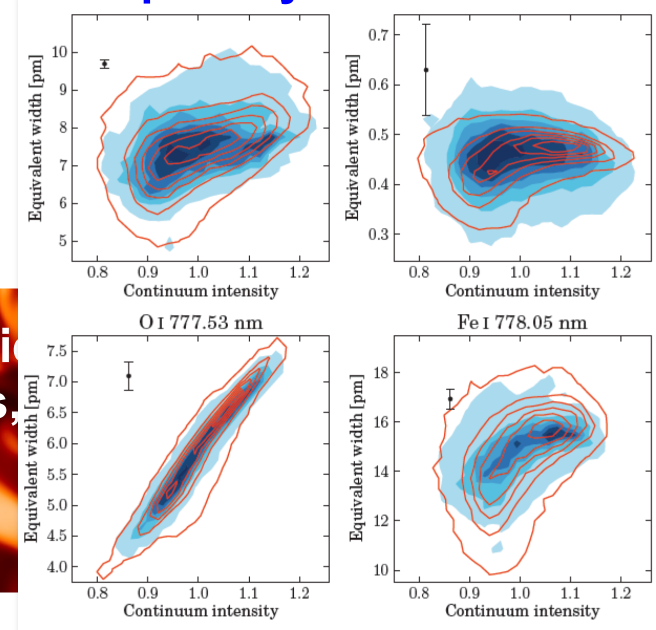
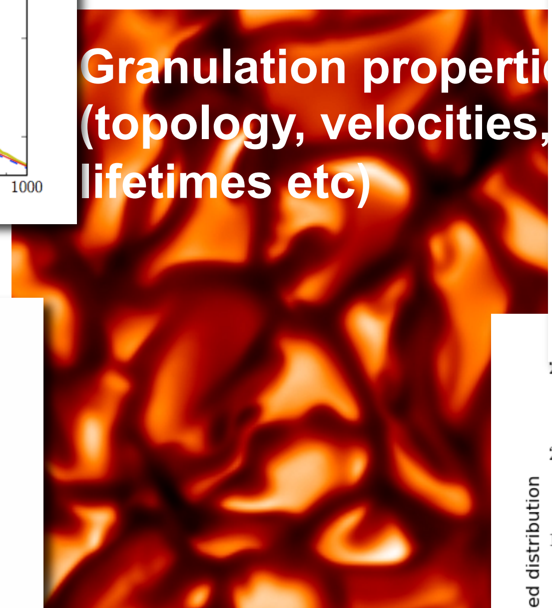


Spatially resolved lines





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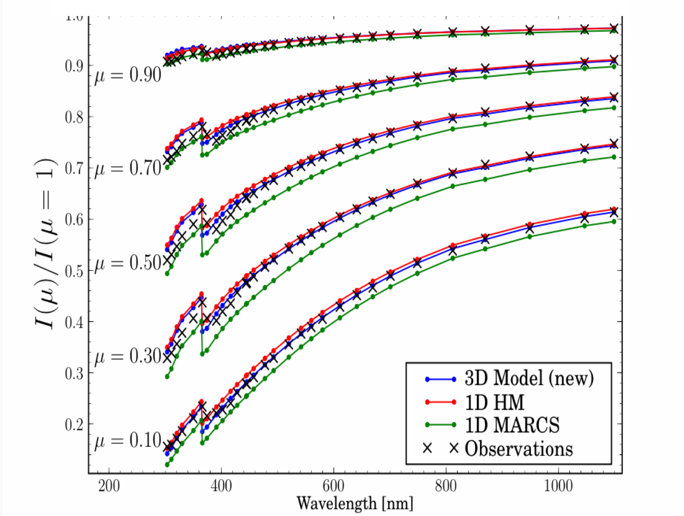

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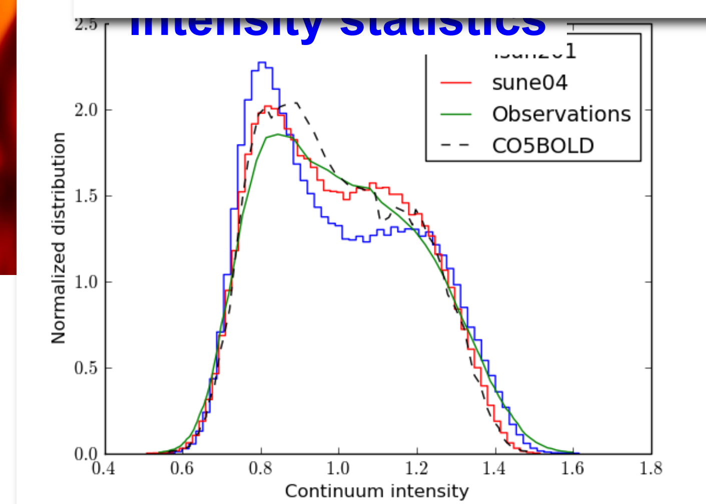

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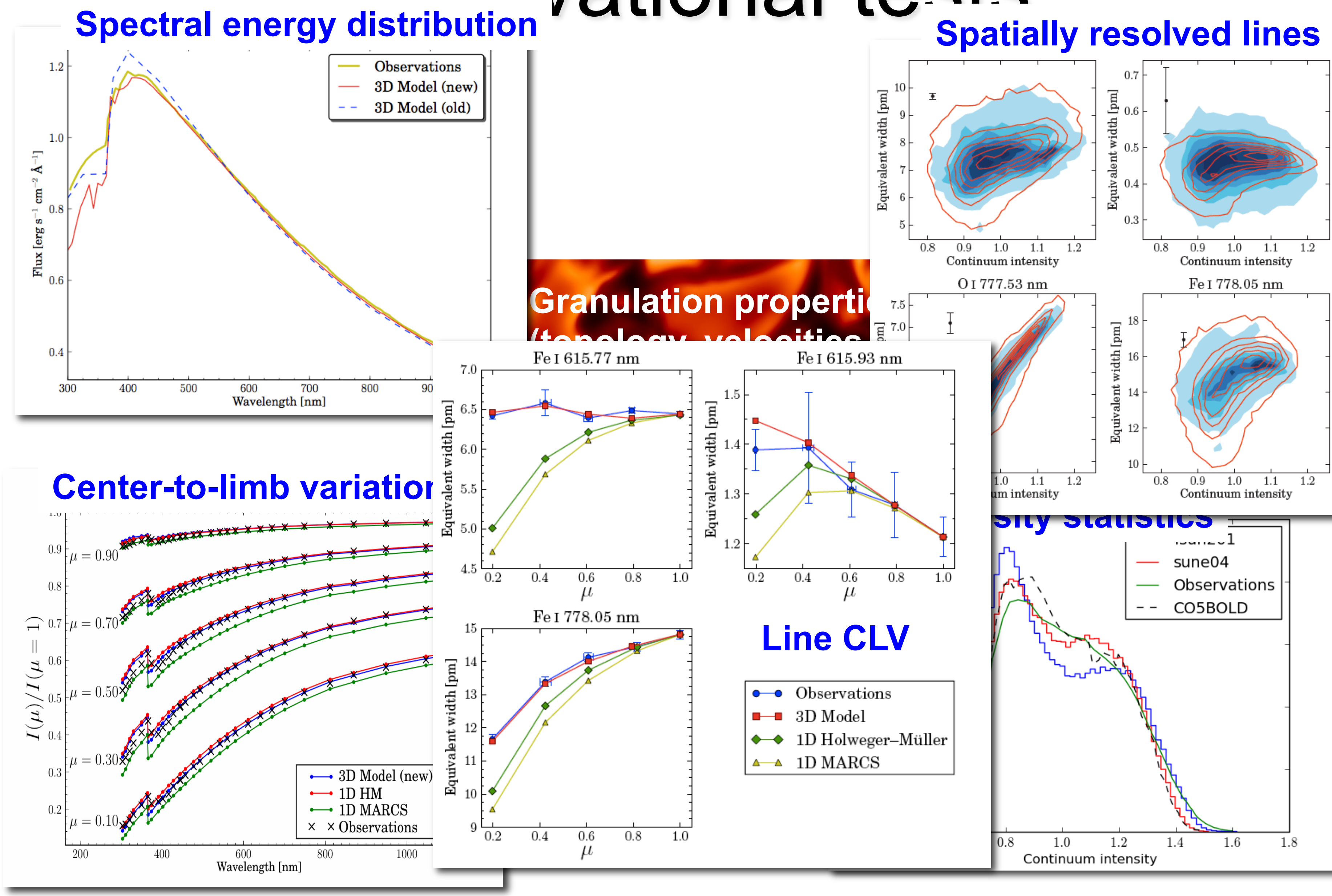

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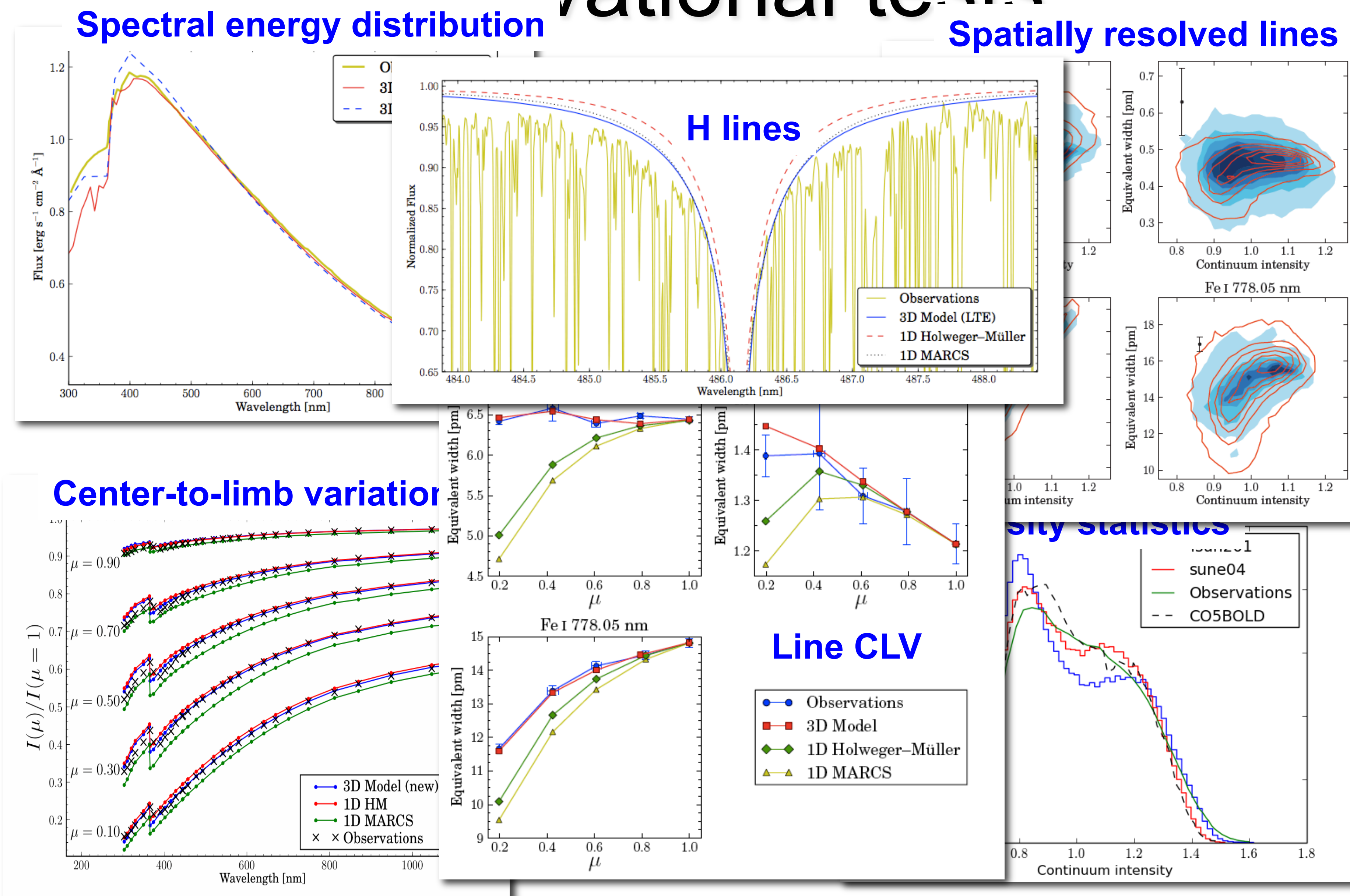

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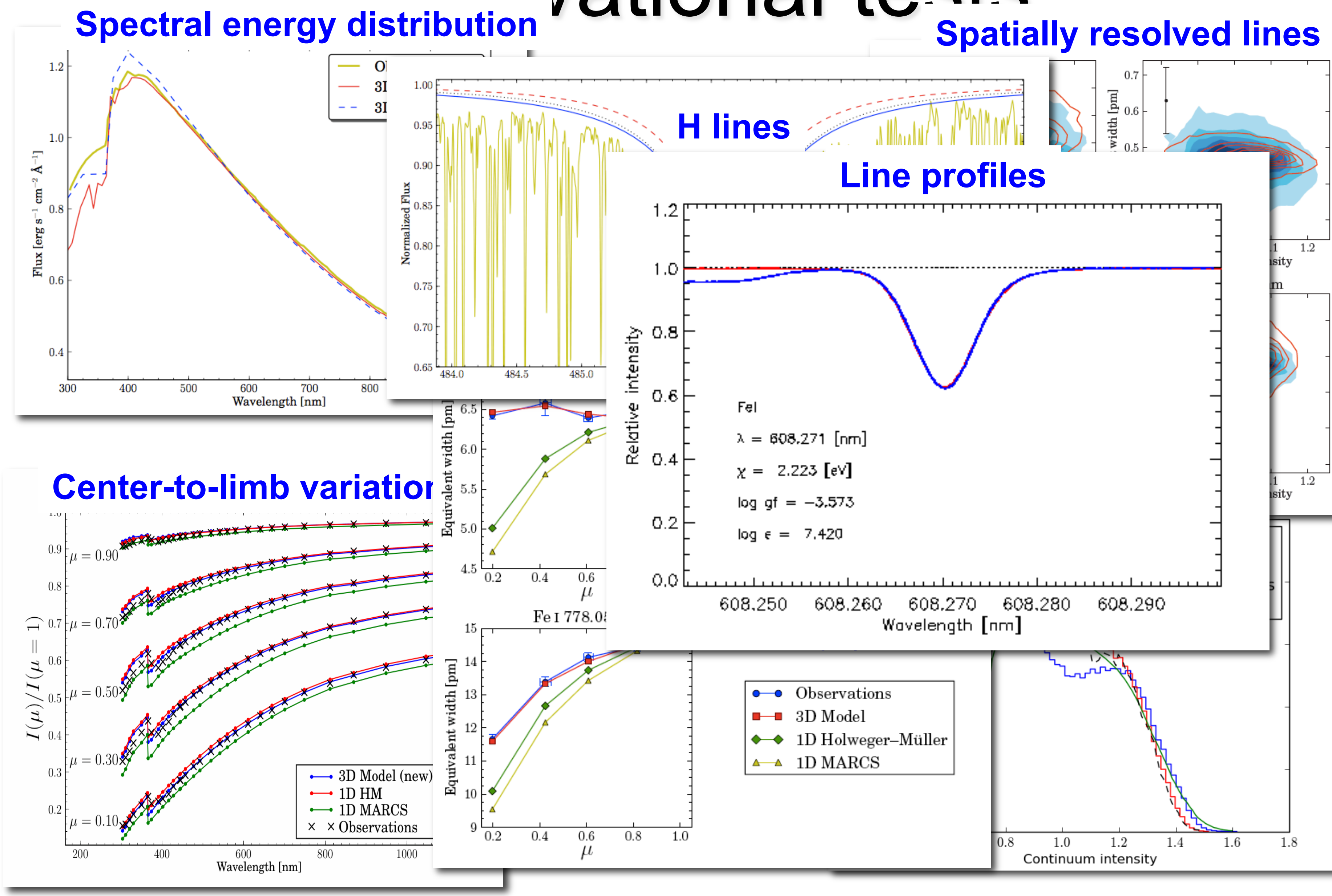

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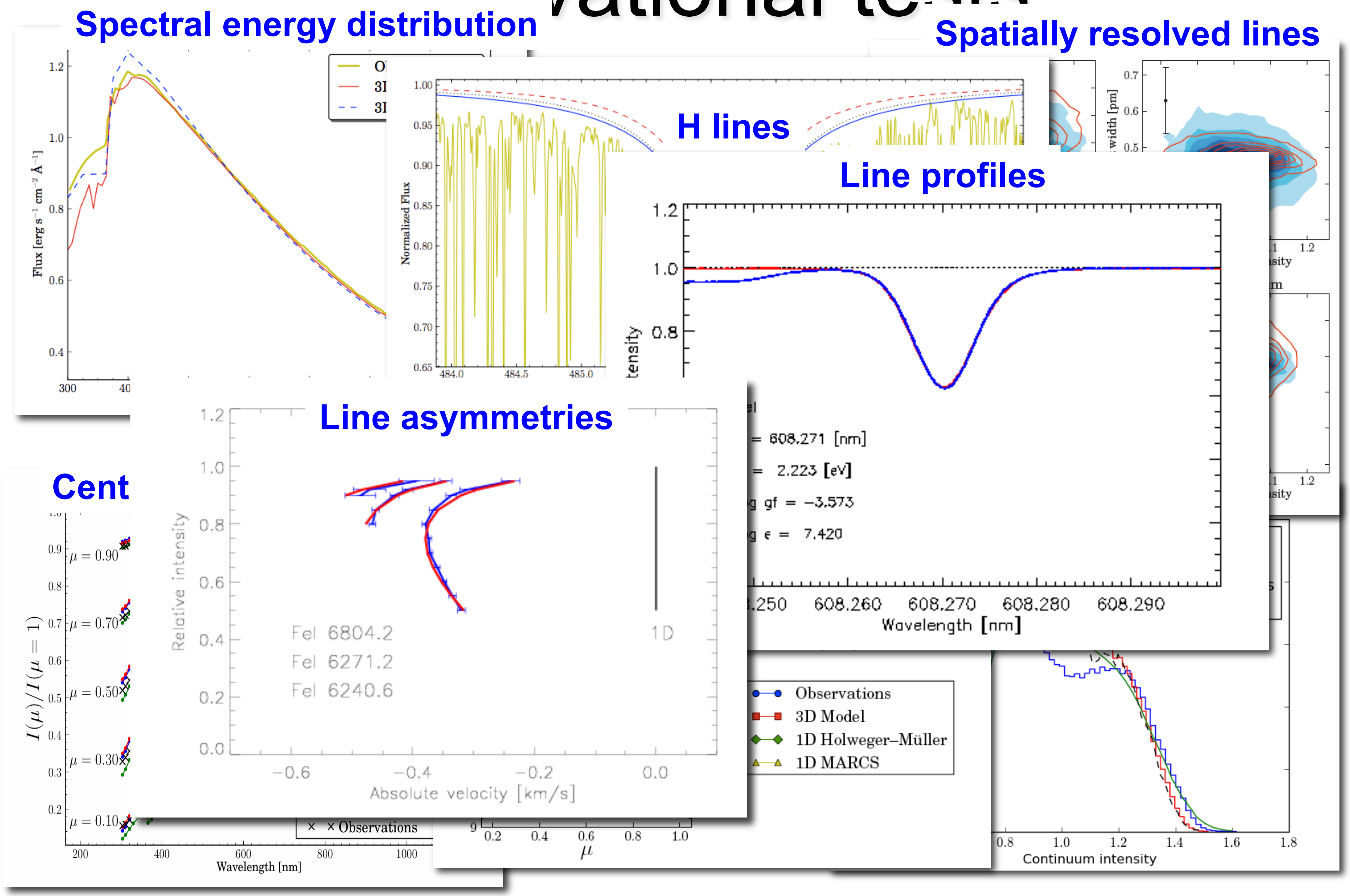

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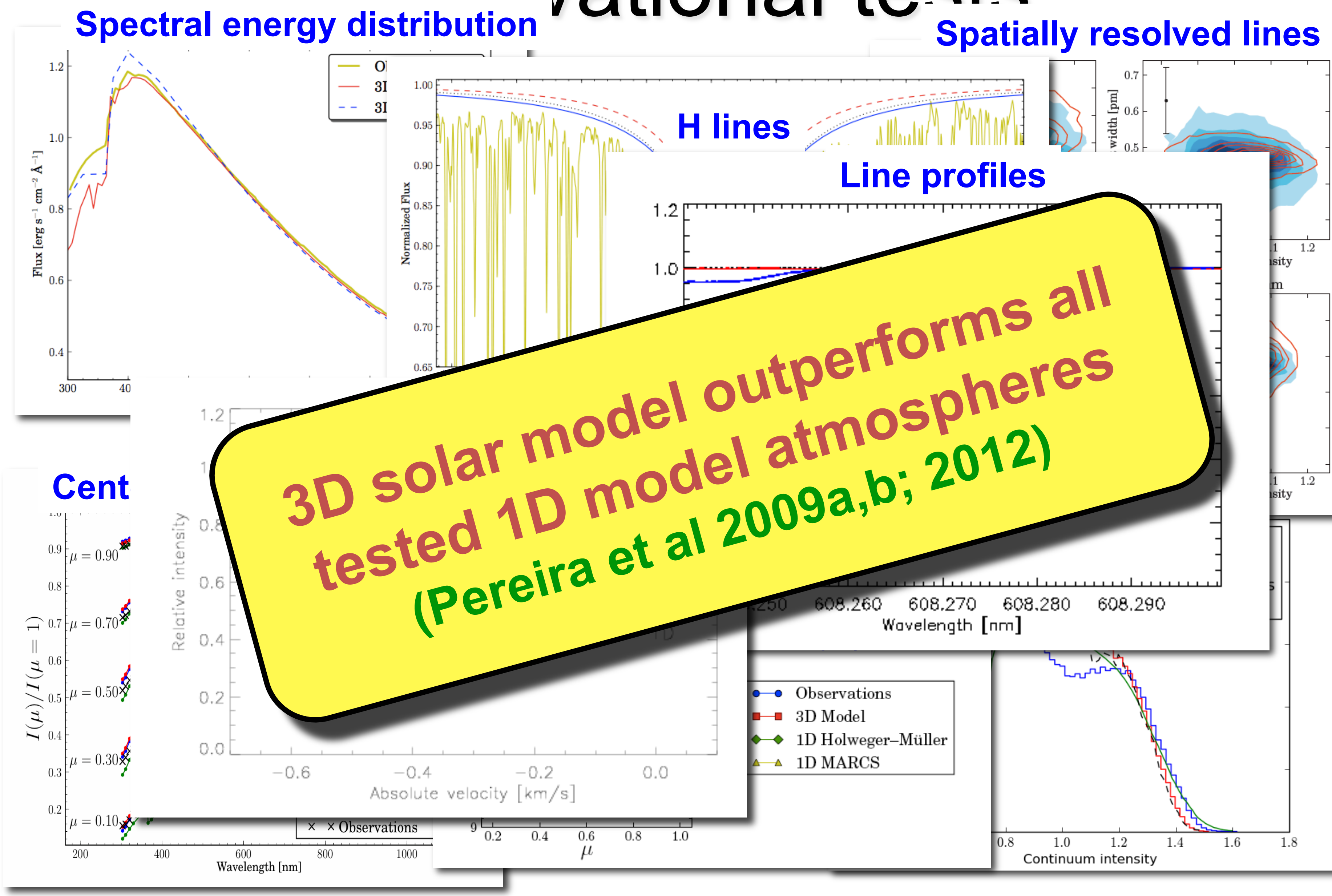

Redetermination of the abundances of nearly all available elements

Basic ingredients:

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Observations
All non-blended line profiles show …

- Widths much larger than thermal widths
  (with 1D models…microturbulence!!!)

- λ_{center} blueshifted (2 mA ~ 100 m/s at 600 nm)

- Asymmetries (C shapes : ~ 300 m/s i.e. 6 mA)

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Most important elements (after H and He)

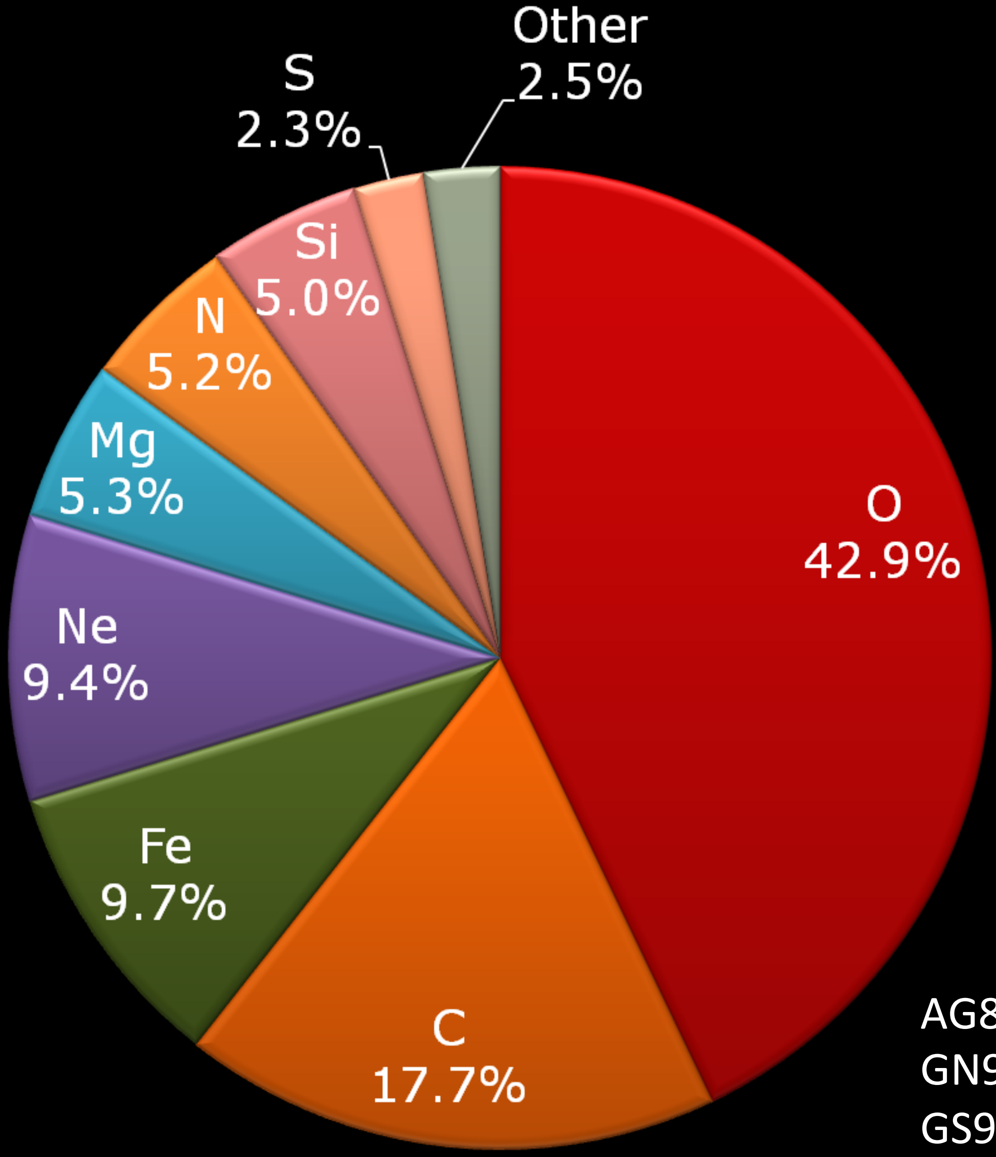
---

* Largest contributors to Z (next slide)

* Largest contributors to the opacity (next slide)

NEW SOLAR METALLICITY: X=0.7381, Y= 0.2485, Z=0.0134

Z/X=0.0181



O+C+N=2/3Z

O+C+Fe+Ne=0.8Z

AG89 Z=0.020 Z/X=0.027

GN93 Z=0.018 Z/X=0.024

GS98 Z=0.017 Z/X=0.023

Contibutors to Z

O ↘30% with AGSS09
Ne OK

C Blancard, P. Cossé et G. Faussurier, ApJ 745, 10, 2012
Composition Grevesse-Sauval 98

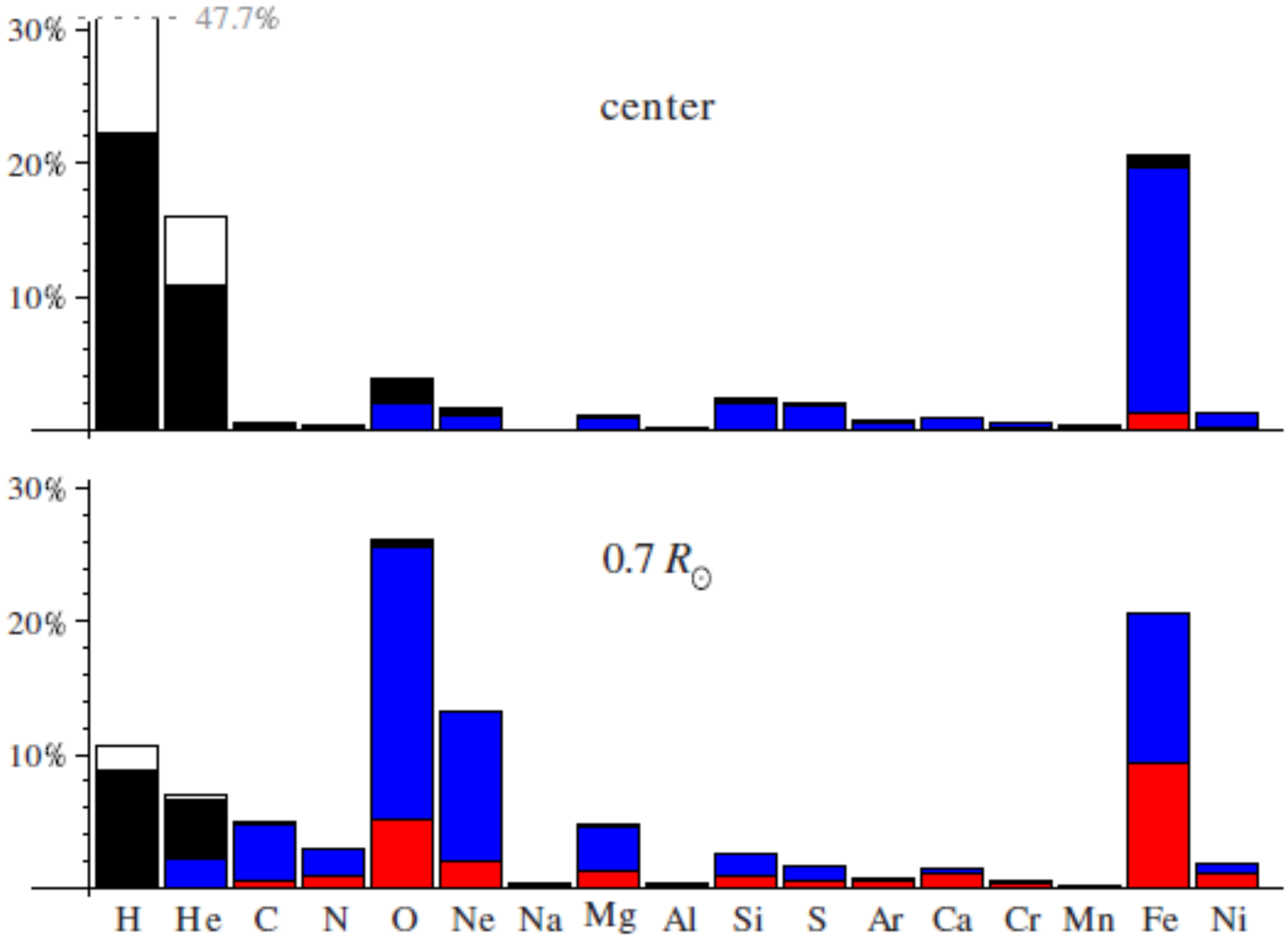


Figure 2. Relative contributions of each element to the OPAS Rosseland mean opacity of the mixture. Scattering (white), free–free (black), bound–free (blue), and bound–bound (red) contributions are indicated.

Here I shall essentially discuss and comment on O (C and N similar to O) and Ne

The other elements have hardly changed

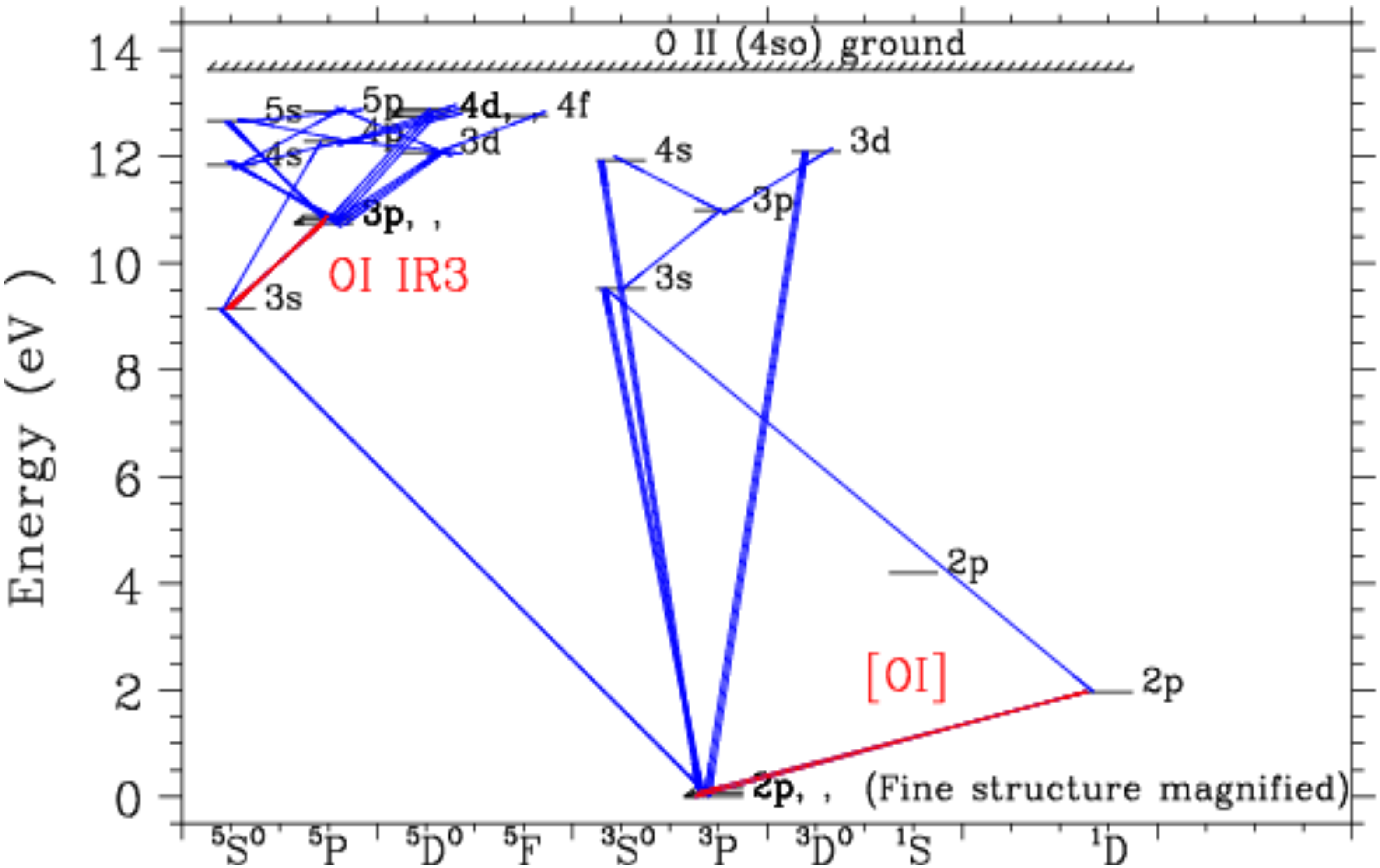
Oxygen diagnostics

*3 forbidden lines of very low excitation

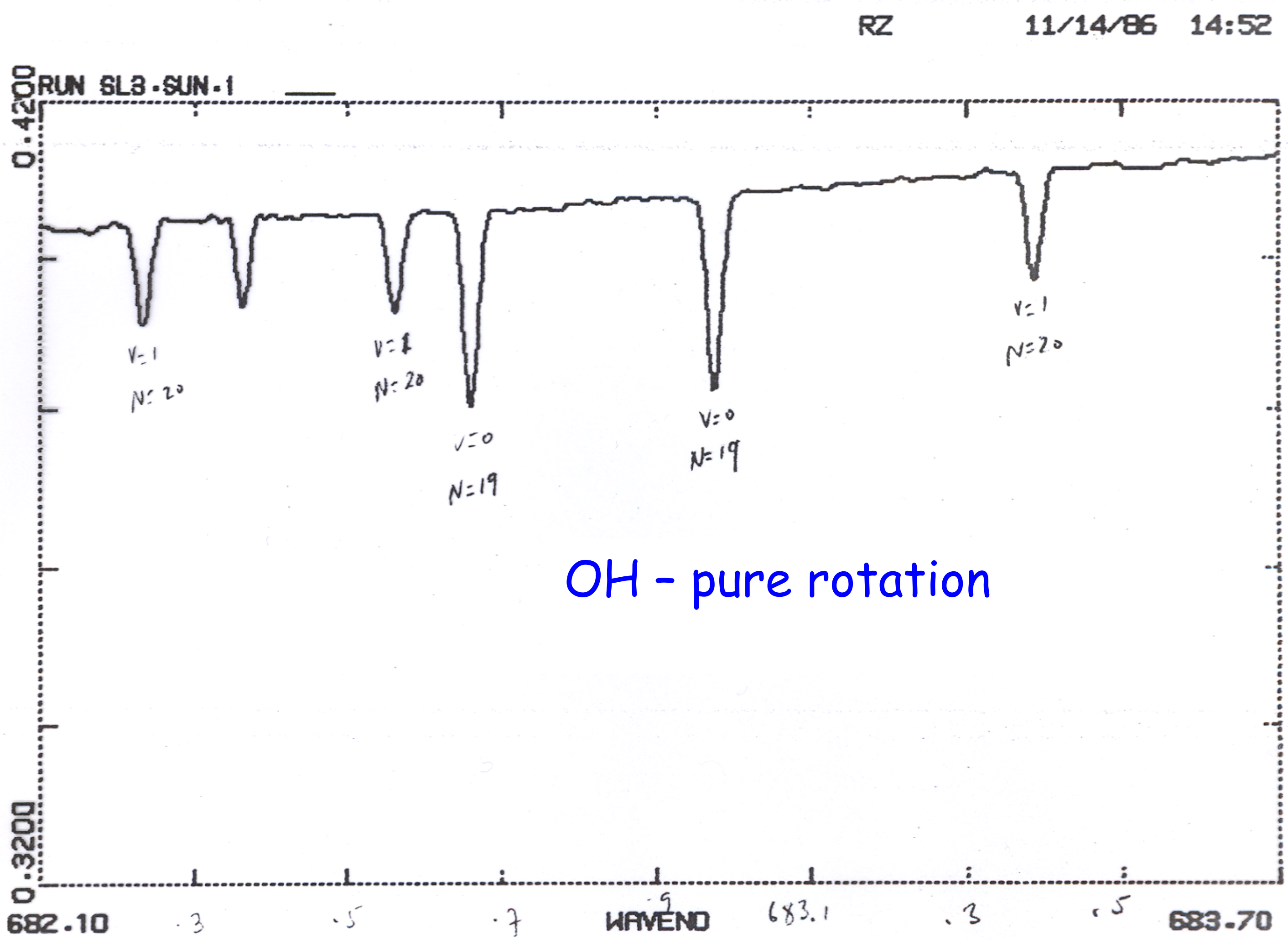
*8 permitted lines of very high excitation

*A very large number of lines of OH in the IR
(pure rotation at large lambda 9-15 microns)
(vibration rotation around 3 microns)

O I lines



O II (4so) ground
5s
5p
4d,
4f
4p
3d
4s
3p,
OI IR3
3s
4s
3d
3p
3s
2p
[OI]
2p
2p,
(Fine structure magnified)
Energy (eV)
14
12
10
8
6
4
2
0
⁵S⁰ ⁵P ⁵D⁰ ⁵F ³S⁰ ³P ³D⁰ ¹S ¹D



RZ
11/14/86 14:52
RUN SL3-SUN-1
0.4200
0.3200
682.10
683.70
WAVENO
V=1
N=20
V=0
N=19
OH – pure rotation

14.6 microns

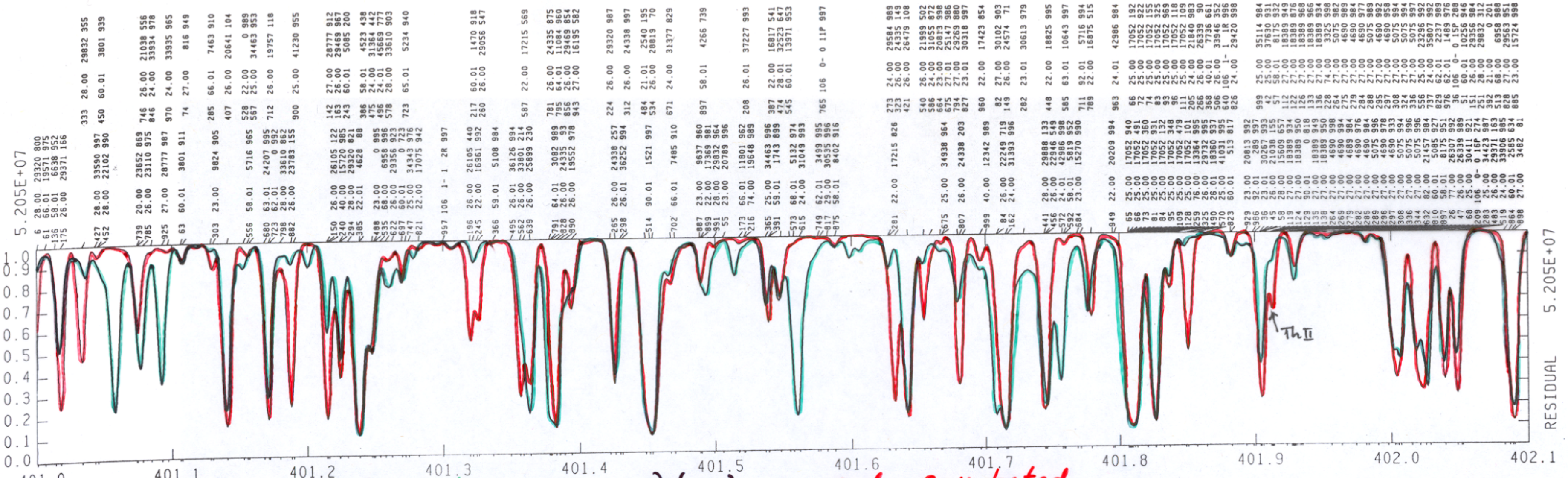
401.0 nm

KURUCZ
17:20:51
6-FEB-91
7VZ9LJOQA

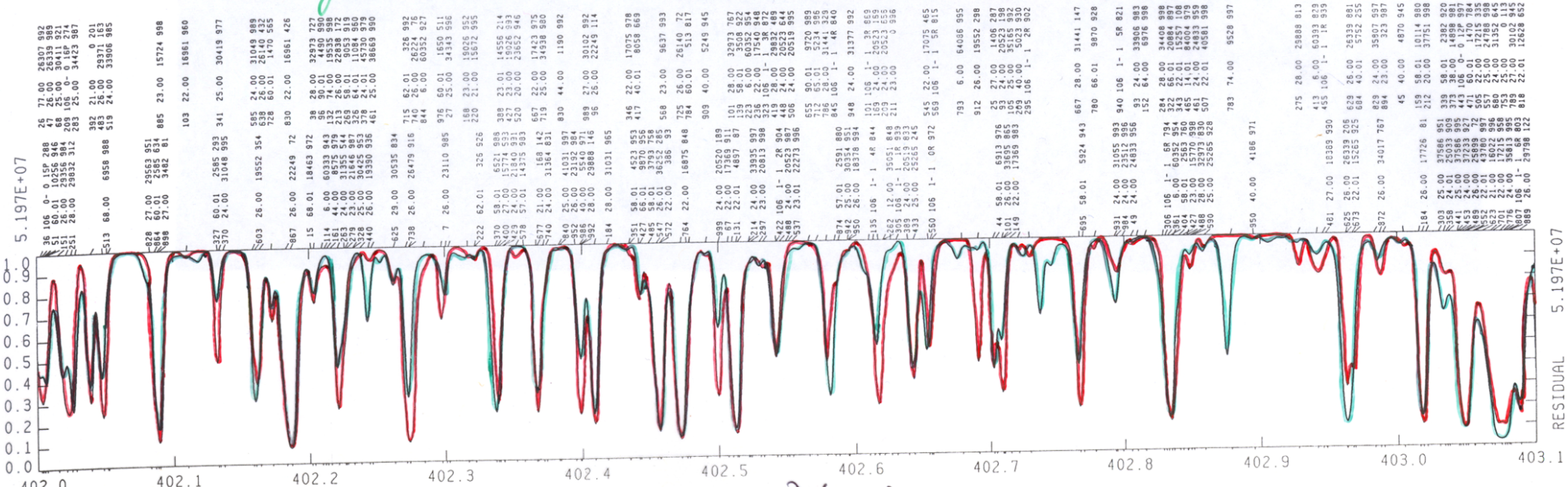
S401
CENTRAL INTENSITY
AVRETT MODC (OSLO) SOLAR MODEL WITH DEPTH DEPENDENT MICROTURBULENCE
1.5 KM/S MACROTURBULENCE

FTS SCAN 36 (-.673 KM/S) -.636 KM/S GRAVITATIONAL RED SHIFT
419000 INTRUMENTAL RESOLUTION
THE CONTINUUM LEVEL HAS NOT BEEN DETERMINED

401.0



green: observed λ(nm) red: computed



λ(nm)

R.L. KURUCZ

Suppose you have 10^9 atoms of O, how many are distributed in the lower levels to produce the very low excitation forbidden O I lines, the very high Exc (> 9 eV) permitted O I lines and the low Exc vr and pr lines of OH?

Answer: [O I] ~ 10^9

O I ~ ONE!!!

OH ~ 10^3 to 10^4

(CO ~ 10^8)

Conclusions: **Forbidden lines better than OH lines themselves much better than permitted lines**

Important remark: **MOLECULAR lines are NOT more sensitive than the high Exc ATOMIC lines to TEMPERATURE**

Forbidden [O I] lines

- LTE… BUT…STRONG BLENDS !!!!

- 6300 blend with Ni I line (O: 63% of observed EW)
- 6363 blend with two CN lines (O: 69% of observed EW)
- 5577 blend with two C_2 lines (O: 37% of observed EW)

- We estimated the contributions of the blends independently of any model, in a purely empirical way, from observations of other lines of Ni I, C_2 and CN

Permitted O I lines

- High Exc lines
- LARGE NLTE effects[Δ~-0.25(F) to -0.15(I) dex]
- Strongly dependent on collisions with H atoms
- Cross sections were not well known until very recently (Amarsi, Barklem et al.A&A,March2018)

Solar CNO abundances

- 3D solar model atmosphere
- Non-LTE line formation when possible
- Atomic and molecular lines with improved data
- Asplund et al. (2005a,b, 2009)

Element	Anders & Grevesse (1989)	3D	Difference
Carbon	8.56+/-0.06	8.43+/-0.05	-0.13 dex
Nitrogen	8.05+/-0.04	7.83+/-0.05	-0.22 dex
Oxygen	8.93+/-0.03	8.69+/-0.05	-0.24 dex

Note: logarithmic scale with H defined to have 12.00

Three Questions

1- Why have the abundances of CNO decreased during the last 10 to 20 years?

2- Why are the results of Caffau et al. larger than ours?

3- What are the impacts of our photosheric results…?

1- Why has the abundance of O decreased during the last 10 to 20 years?

In the nineties, with 1D HM Model…(EA,AN,JS,NG)

- Forbidden lines - ~8.95
- Permitted lines - ~ 8.87
- Molecular lines - ~ 8.87

Good agreement: HIGH O

Today…(AGSS09)

- Forbidden lines – Blends ! O down to 8.70 (+ influence of model)
- Permitted lines – NLTE ! O down to 8.69 (+ influence of model)
- Molecular lines – Model ! O down to 8.69 (model !!!)
- **Good agreement : LOW O**

Summary (all elements)

- 3D : Granulation and line profiles
- NLTE when possible
- All indicators agree
- No dependence on I or E_{exc}

C,N,O ↘

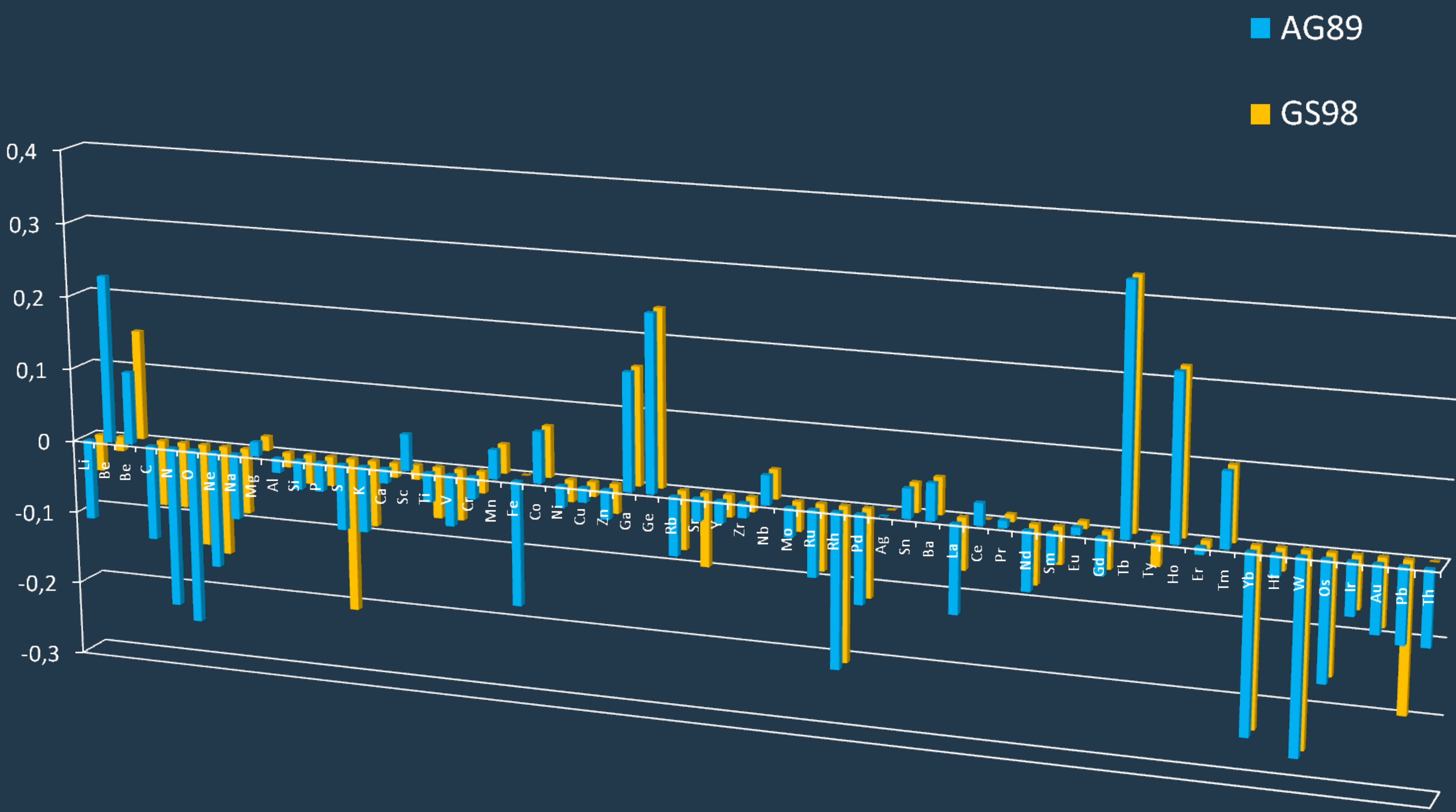
Z

2% ↘ 1.3%

Other elements ↘

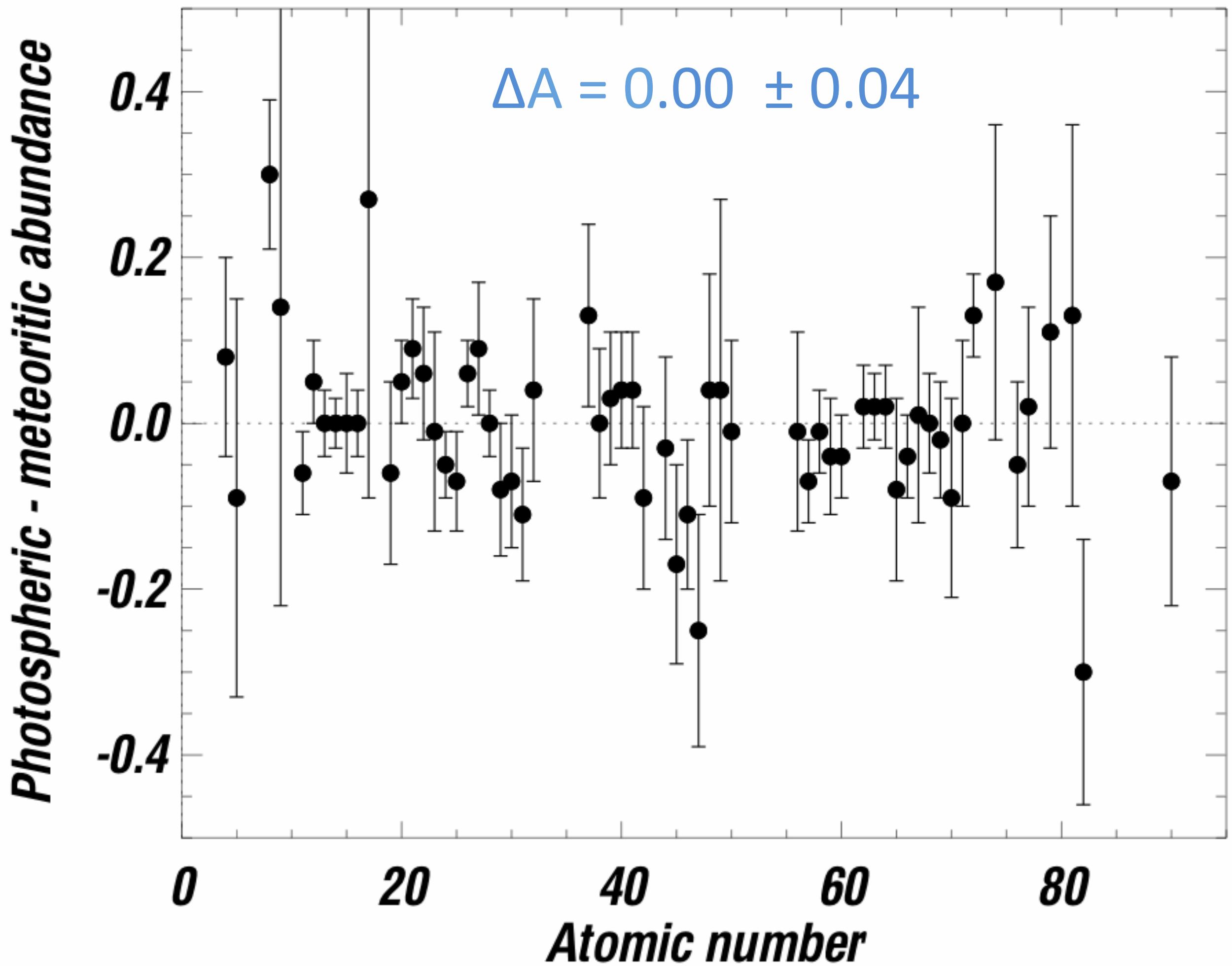
…but some increase!

(see next slide a comparison New-Old with AG(Anders and Grevesse,1989) and GS(Grevesse and Sauval,1998)


AG89
GS98
0,4
0,3
0,2
0,1
0
-0,1
-0,2
-0,3
Li
Be
Be
C
N
O
Ne
Na
Mg
Al
Si
P
S
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
Rb
Sr
Y
Zr
Nb
Mo
Ru
Rh
Pd
Ag
Sn
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Ho
Er
Tm
Yb
Hf
W
Os
Ir
Au
Pb
Th

Meteorites…

Excellent agreement with the CI chondrites



...Meteorites !

CI meteorites were believed to be the least fractionated meteorites, and represent the original solar system material.

There are now good reasons to doubt that they are samples of that original matter !!! (John Wasson)

Meteoritic abundances cannot be used as substitutes of higher precision to the photospheric abundances !!!

Independent analysis

3D-based solar analysis by CO5BOLD collaboration

Caffau, Ludwig, Steffen, Freytag et al.

Element	Caffau et al. (2008, 2009a,b)	Asplund et al. (2012)
Carbon	8.54+/-0.13	8.43+/-0.05
Nitrogen	7.86+/-0.12	7.83+/-0.05
Oxygen	8.76+/-0.07	8.69+/-0.05

Very good agreement when same input data are used

- **Selection of lines**
- **Equivalent widths**
- **Non-LTE corrections**

(Caffau et al. do not consider molecular lines)

2-WHY difference Caffau et al. vs Us? O: 8.76(Caffau,Ludwig,Steffen,Bonifacio,Freytag,Ayres, Cayrel,Plez, 2008) - 8.69(AGSS)?

- Caffau et al. -0.02 dex for weighting
- Caffau et al. -0.03 dex for NLTE
- Caffau et al. -0.02 dex for equivalent widths and blends for forbidden lines
- Caffau et al. Atomic lines only

- Total Caffau et al. -0.07 dex. And 8.76-0.07= 8.69 in perfect agreement with us and the low O abundance!

Solar Ne ? ...

- No Neon I line in photospheric spectrum

HOW ?

Ne lines in corona, flares,...
Ne in SW and SEP
Very difficult to measure Ne/H
So relative Ne...Ne/O !

Ne/O in CORONA, SW,SEP ?

Large FIP effects, even among high FIP
Ne/O (two high FIP) also VARIES
(different types of solar matter, wind speed, solar cycle; the smallest values, 0.08, at solar MAX and the largest, 0.25, at solar MIN)

...Solar Ne

SOLUTION: QUIET SUN

where FIP is the smallest
where the absence or very low activity has probably depressed the mechanisms (Alfvén waves and ponderomotive force) responsible for the observed FIP effects

Young (2005) Ne/O=0.175 (from XUV spectra)
Value adopted in our tables...A(Ne)=7.93

REVISION Young (2018) Ne/O=0.244+/-0.050
(due to new atomic data, ionization and recombination rates)

A(Ne)=8.08+/-0.09

3-(Some) Implications

The SOLAR ABUNDANCE PROBLEM !!!

Standard Solar Models (SSM) computed with the new abundances are in conflict with the observations of helioseismology !

- The terrible tragedy of Science is the murder of beautiful theories by ugly facts. (W. Fowler)

***The most interesting topics are the ones where Theory and Observations disagree.**

Thanks to these challenges Progress is made in both fields

Solar ABUNDANCE Problem ? NO

Solar Modelling Problem... ???

Solar OPACITY Problem? YES

O P A C I T I E S !!!

Increases needed to reconcile SSM (with the new solar composition) and Helioseismology

15 to 20% base CZ (O, Ne,Fe)

Smoothly decreasing to 3 to 5% Center

(Joergen Christensen-Dalsgaard, Aldo Serenelli, Francesco Villante, ….)

WHY opacities uncertain ?

Radiative opacities result from sophisticated and still incomplete theoretical calculations of interactions of rather highly ionized atoms with radiation in extremely dense plasma.
(Bergemann and Serenelli, 2014)

WHY Opacities underestimated?

COLUMBUS-OHIO- Anil PRADHAN-Sultana NAHAR and ……

Fe XVII i.e. just below CZ

- Fe opacity ≈ 50% larger than OP and other tables ….
- Opacity is underestimated …

Q U E S T I O N S

-1- What about the other main contributors O, Ne,…?

Underestimated but less than Fe

-2- What about when going to the center?

Underestimation decreases …

-WHY 1 and 2 ? Problem of electronic structure

less complex from Fe to O at CZ and from CZ to center

OUR ADVICE…

If you need to refer to solar photospheric abundances

Don’t use anymore the older solar abundance tables: Anders and Grevesse(1989), Grevesse and Noels(1993), Grevesse and Sauval(1998)

Use Asplund, Grevesse, Sauval and Scott, ARAA 47, 481, 2009 (AGSS09)

(possibly **updated for VERY MINOR REVISIONS** by Scott et al. 2015a, Scott et al. 2015b, Grevesse et al. 2015, Lind et al. 2017, Bergemann et al. 2017, Amarsi and Asplund 2017 and for the **Ne value discussed here**)

SOLAR ABUNDANCES - June 2018

	AGSS09	2018	2018/2009
O	8.69	8.69	unchanged
C	8.43	8.43	unchanged
N	7.83	7.83	unchanged
Ne	7.93	8.08	+ 41%
Mg	7.60	7.56	- 10%
Al	6.45	6.43	- 5%
Si	7.51	7.51	unchanged
S	7.12	7.13	+ 2%
Ca	6.34	6.32	- 5%
Fe	7.50	7.48	- 5%
Ni	6.22	6.20	- 5%

Thank you