Phenomenology and physics of late-type (cool) stars

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Cool stars

* Phenomenology
* Physical properties: the Sun
* Observations

} Lecture 1

* Models and synthetic spectra

} Lecture 2

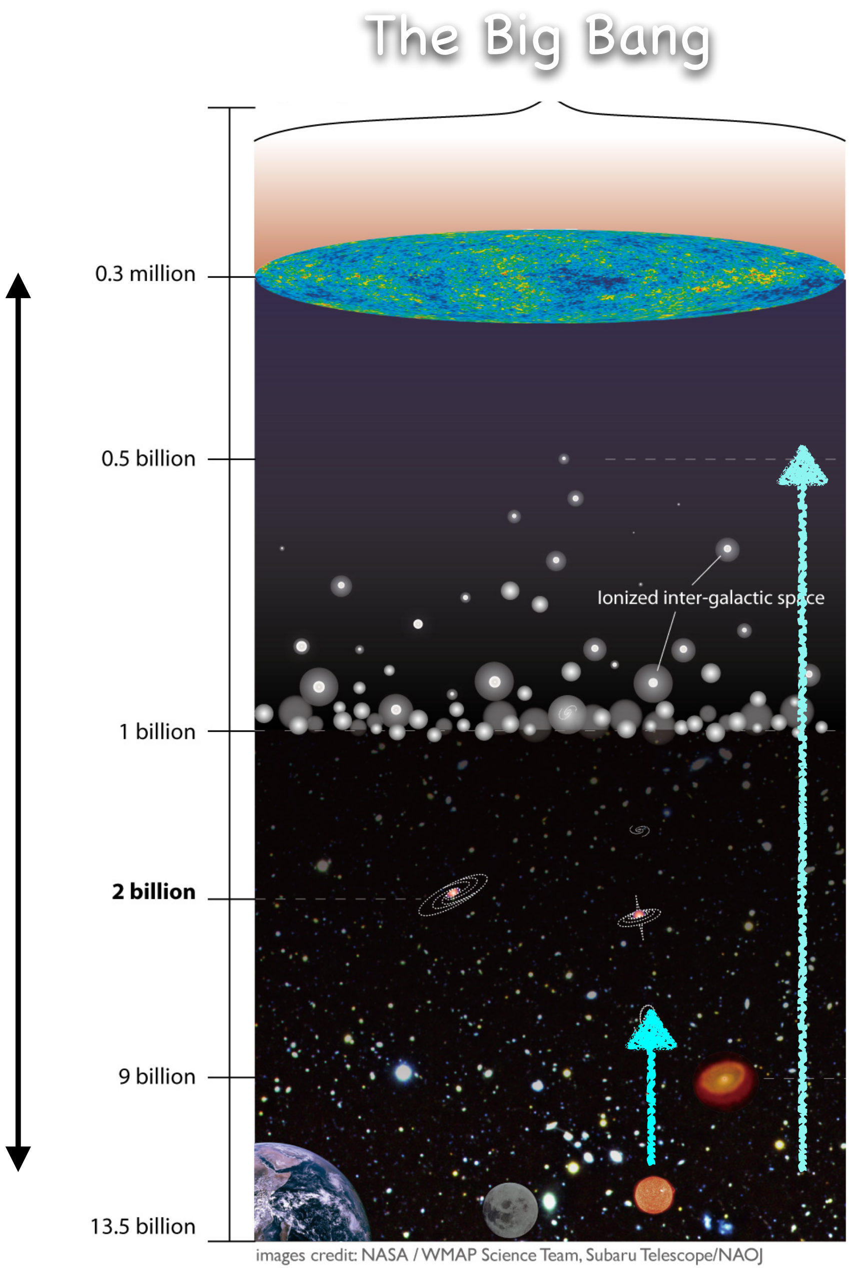
* Applications: stellar abundances and fundamental parameters
* Exotic stars and the early Galaxy

} Lecture 3

Lecture 1

Stars

- young and old
- occur in all stellar populations
- participate in **chemical enrichment**



H, He, Li

ISM: Be, B

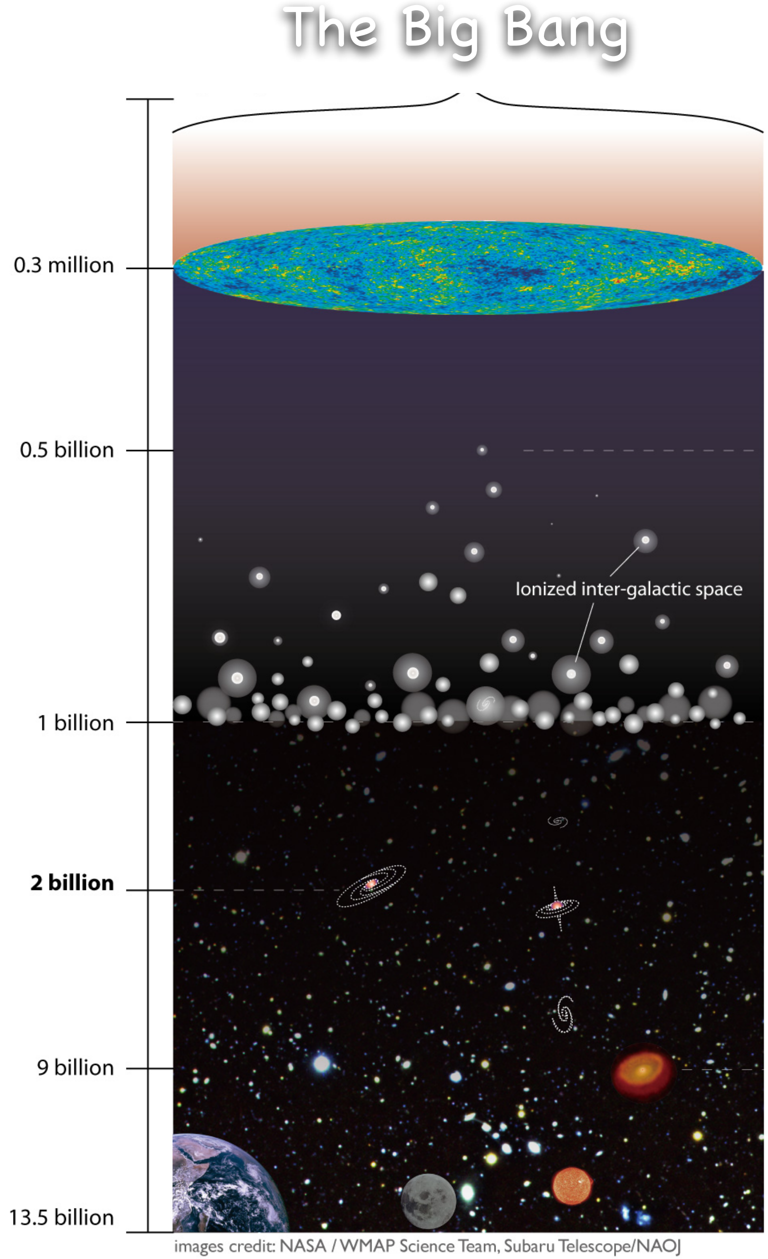
chemical enrichment

production of heavy elements –

metals –

in stars

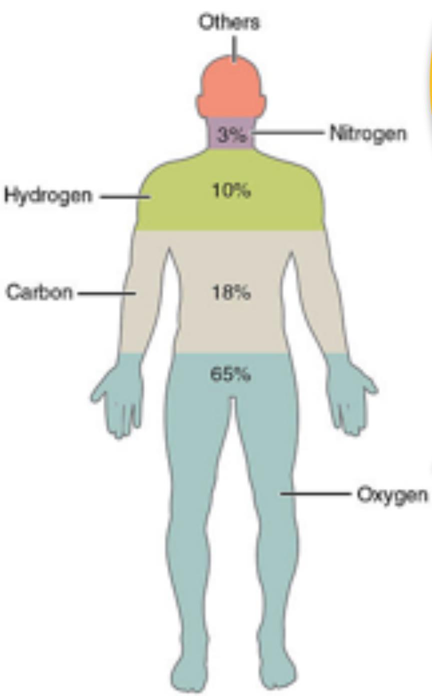
Time



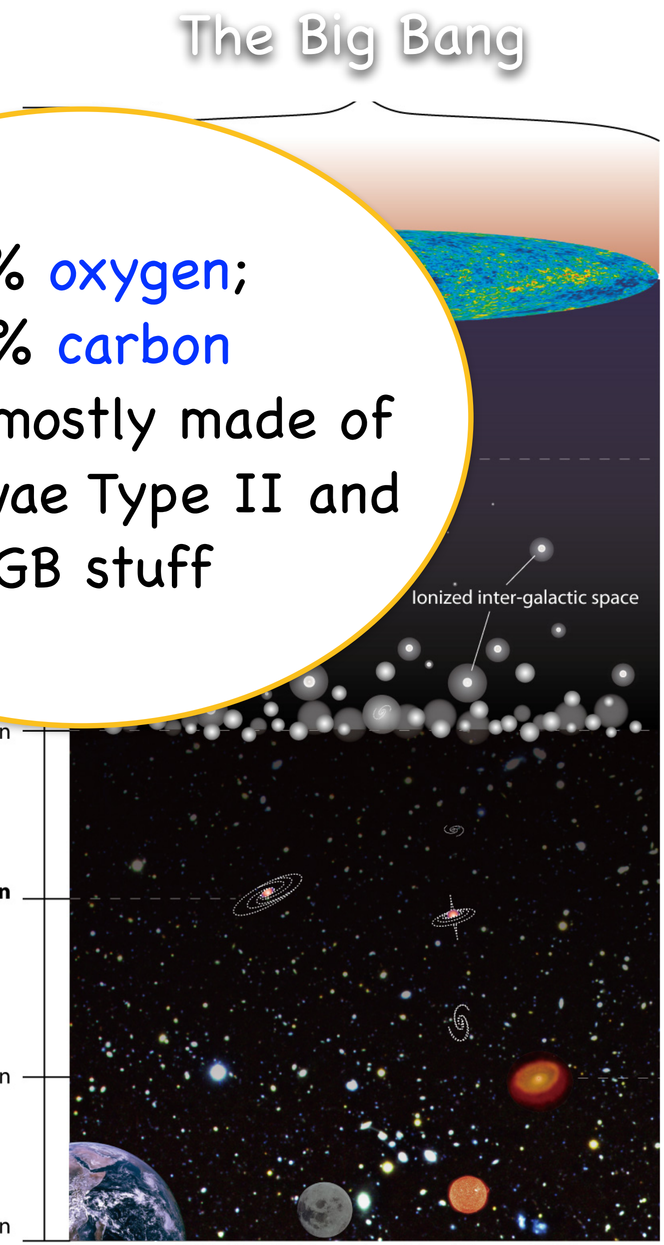
H, He, Li, Mg, Fe, C, N, O, Au, U, Pt, ...

Stars as **tracers** and **drivers** of chemical enrichment in the Universe

H, He, Li



65% **oxygen**;
18% **carbon**
We are mostly made of Supernovae Type II and AGB stuff

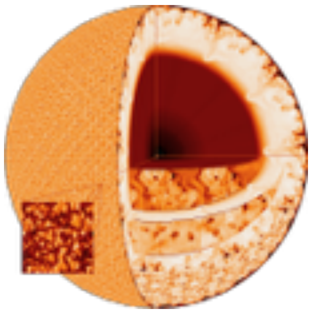


images credit: NASA / WMAP Science Team, Subaru Telescope/NAOJ

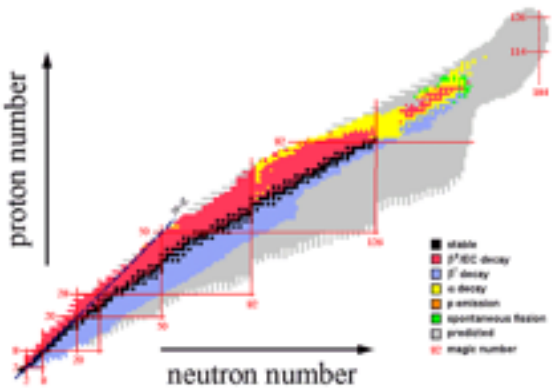
Stars as **tracers** and **drivers** of chemical enrichment in the Universe

H, He, Li, Mg, Fe, C, N, O, Au, U, Pt, ...

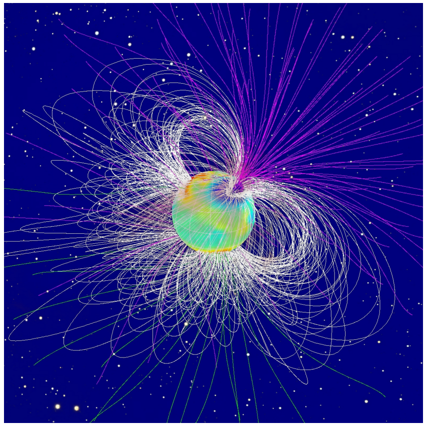
Physics of stars



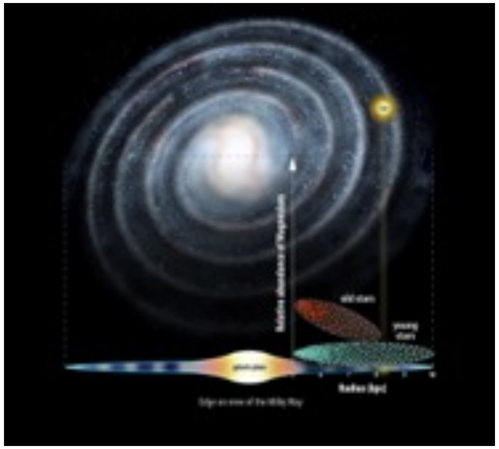
Nucleosynthesis and the origin of chemical elements



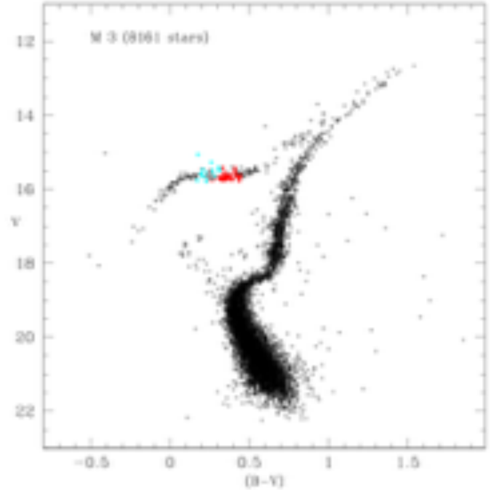
Rotation, Activity, Magnetism



Galactic archeology and the first stars



Star clusters: formation and dissolution



Stars in galaxies, chemical evolution and near-field cosmology

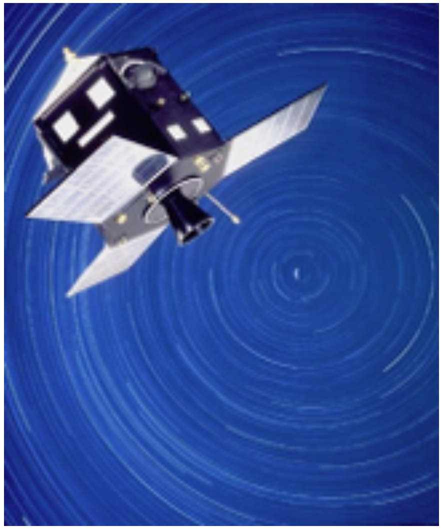
What is a late-type star?

Wikipedia

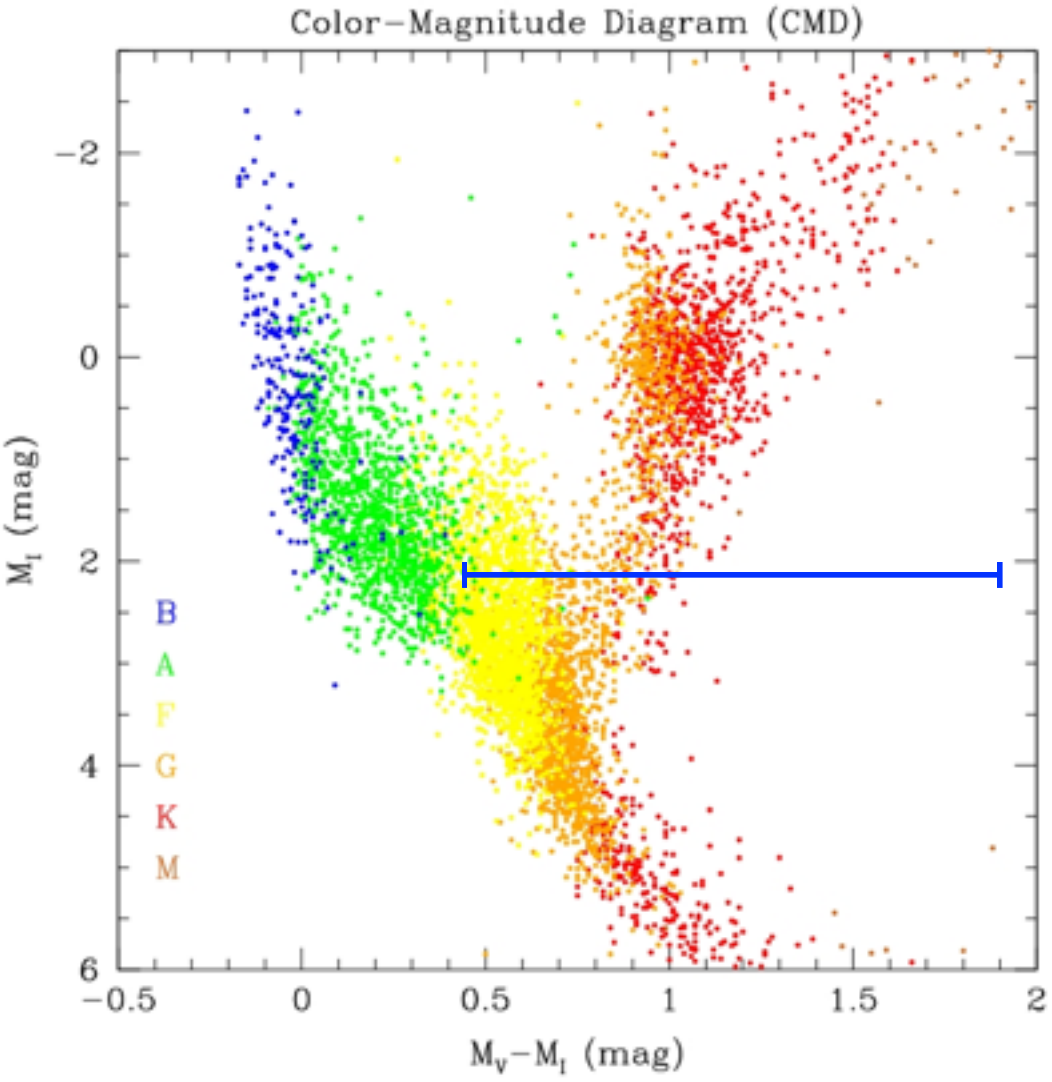
late-type star

A late-type star is a star of spectral type K, M, S, or C, with with a surface temperature lower than that of the Sun. The term dates from when astronomers thought that all cooler, redder stars like these were at a later stage of evolution than the hot blue, white, and yellow-white stars of spectral types O, B, A, and F which were said to be called early type.

Hipparcos astrometry mission



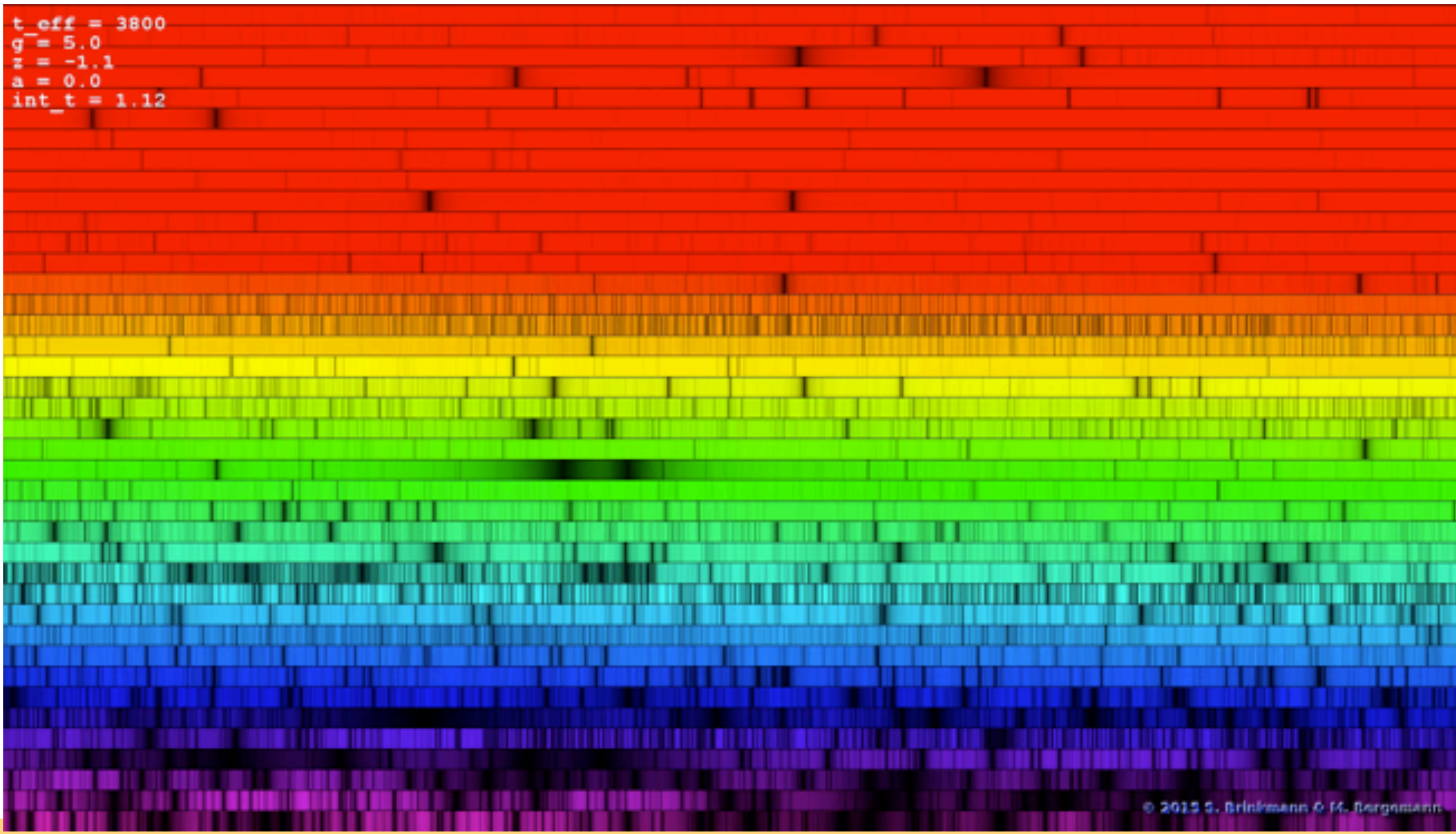
late-type



Late-type (FGKM) stars

the defining astrophysical parameter is T_{eff} ($F_{bol} = \sigma_{SB} T_{eff}$)

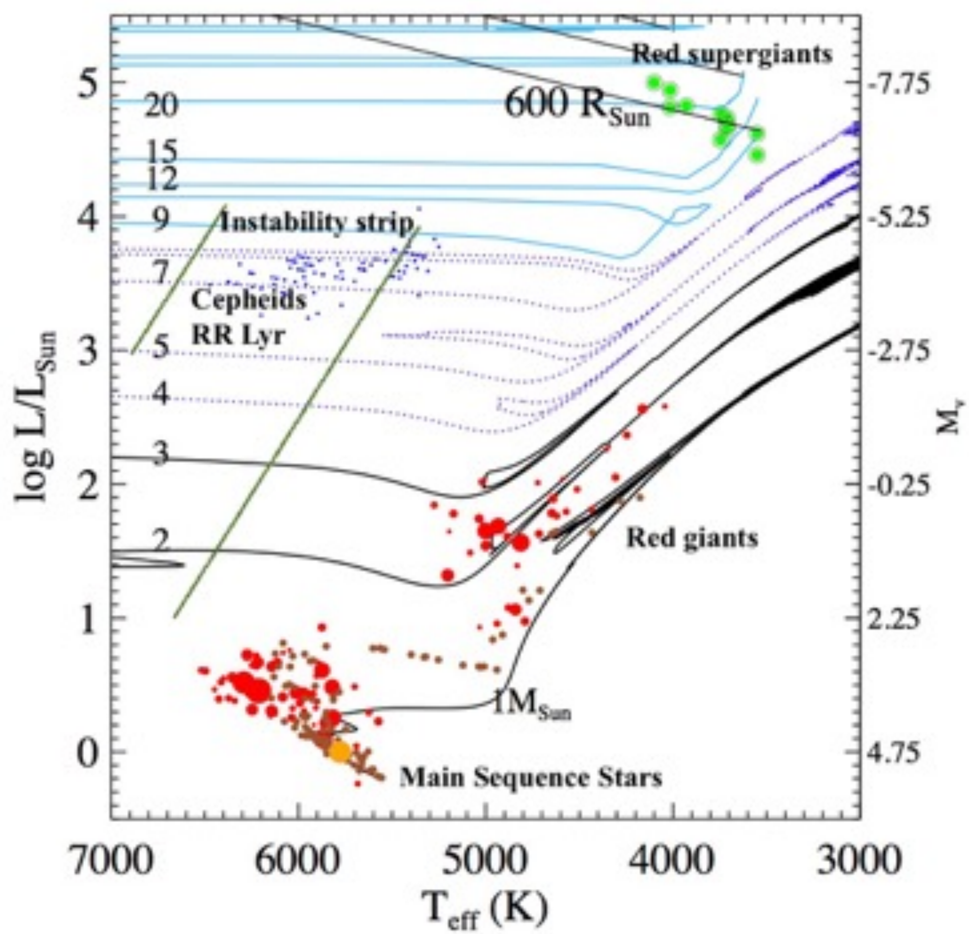
➡ $T_{eff} < 8000$ K



Late-type (FGKM) stars

the defining astrophysical parameter is T_{eff} ($F_{bol} = \sigma_{SB} T_{eff}$)

- $T_{eff} < 8000$ K
- different evolutionary stages
  pre-MS to AGB
- different masses
  0.5 to 40 M_{Sun}
- different sizes
  0.01 to 1500 R_{Sun}
- different physics:
  pulsations, convection
  dust shells, winds,
  mass loss...



Main-sequence stars

low-mass, M < 2 M_{Sun}

all ages → trace composition of the ISM

now and in the past

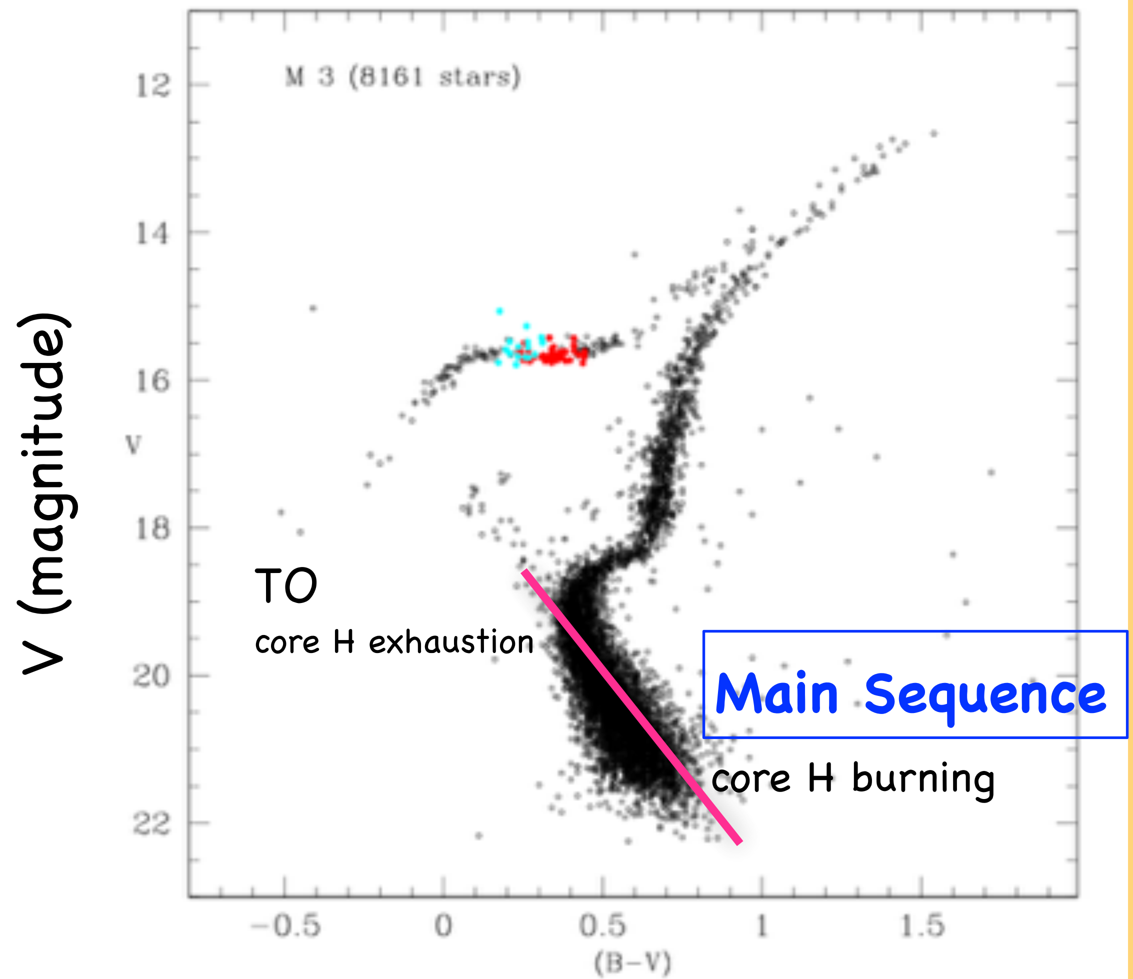
T_{eff} : 4500 … 8000

log(g): 4 - 5

L ~ 1 - 10 L_{Sun}

→ can be observed across **the Milky Way**

→ principle diagnostic of **ages of stellar populations**



Red giants

low-mass, M < 2 M_{Sun}

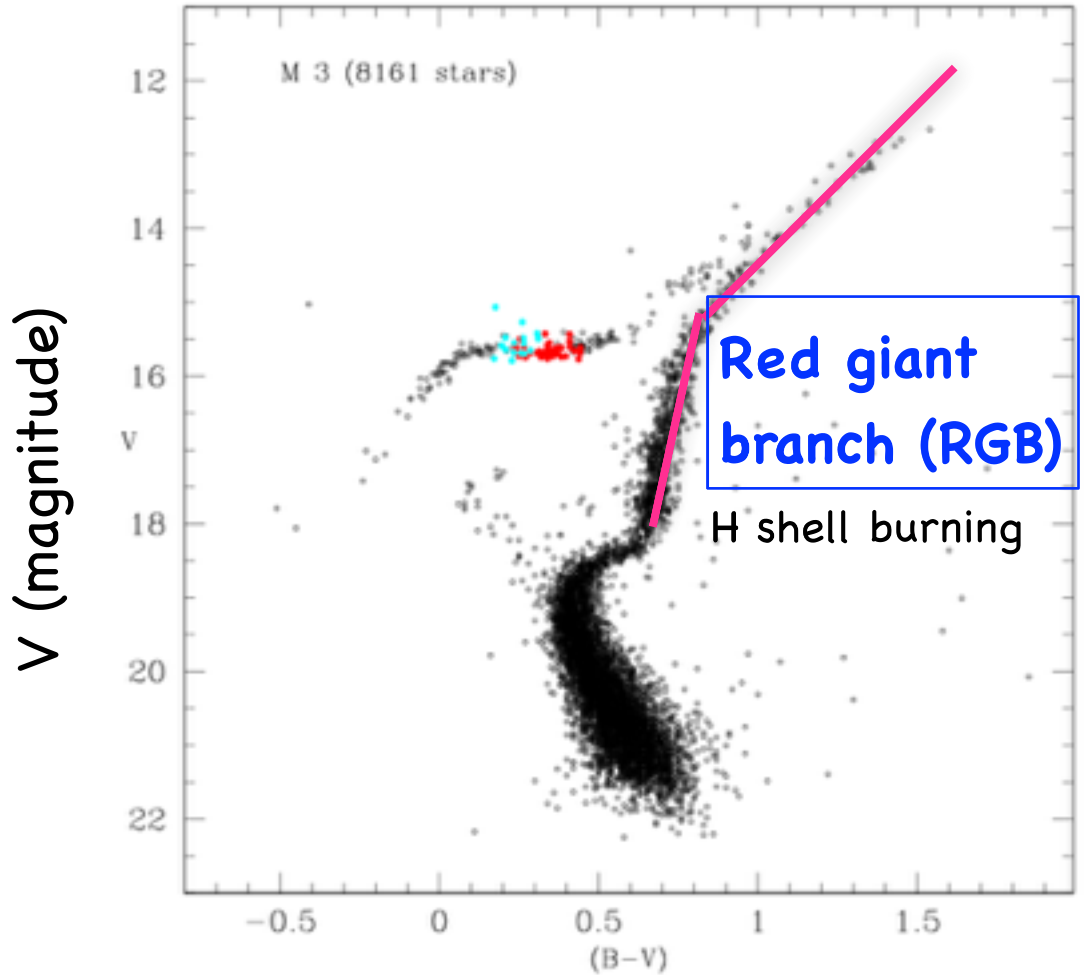
all ages → trace composition of the ISM **now and in the past**

T_{eff} : 4500 … 5500

log(g): 1 – 3

L ~ 10 – 10^3 L_{Sun}

very luminous → can be observed across the Milky Way and its satellites, also in other Local Group galaxies (M31, M33…)



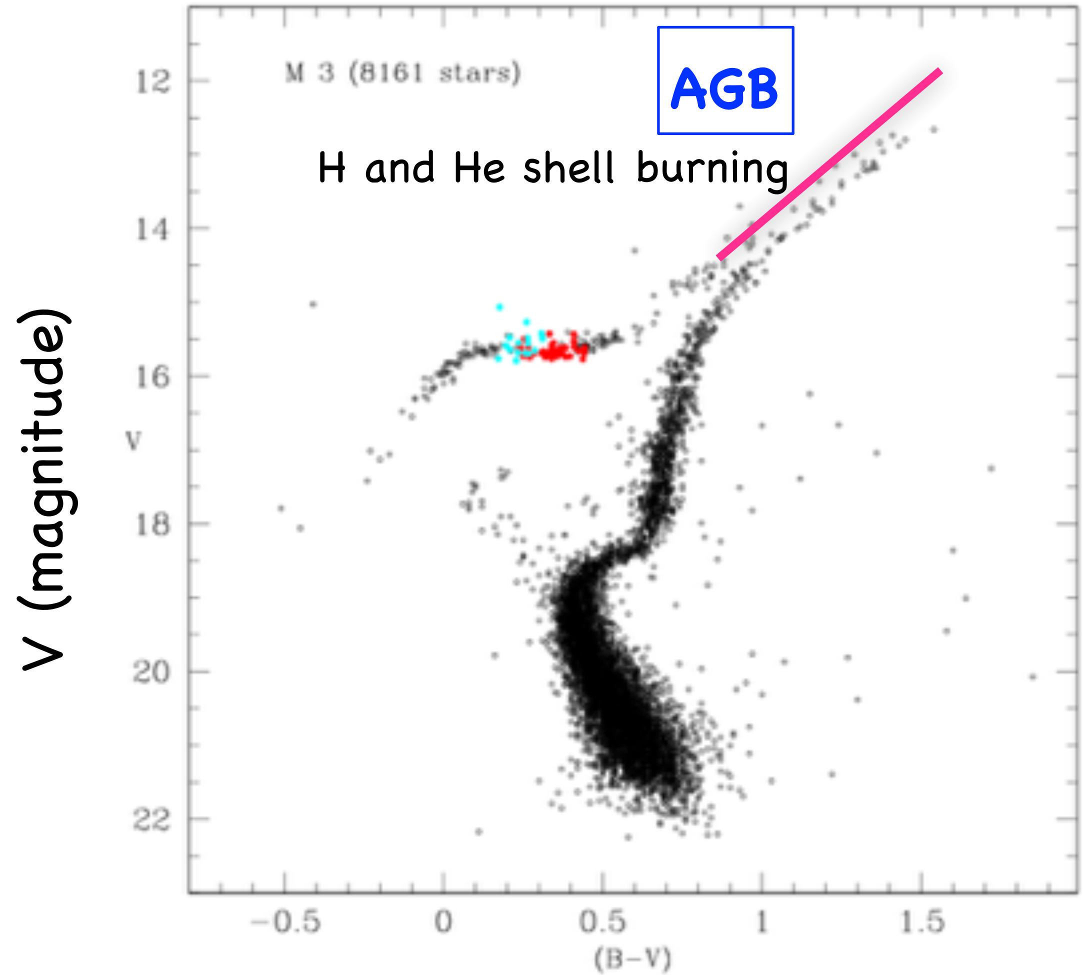
Asymptotic Giant Branch stars

low and intermediate-mass,
 $M < 8\ M_{Sun}$
dominate light of stellar
 populations after
 $10^8 - 10^9$ years

pulsators, $P \sim 10^2 - 10^3$ d
T_{eff}: 2600 - 3500 K
log(g): -1 to 1.5
$L \sim 10^2 - 10^4$ L

luminous

participate in the **chemical**
 evolution of the ISM
 He, ^{13}C, N, s-process

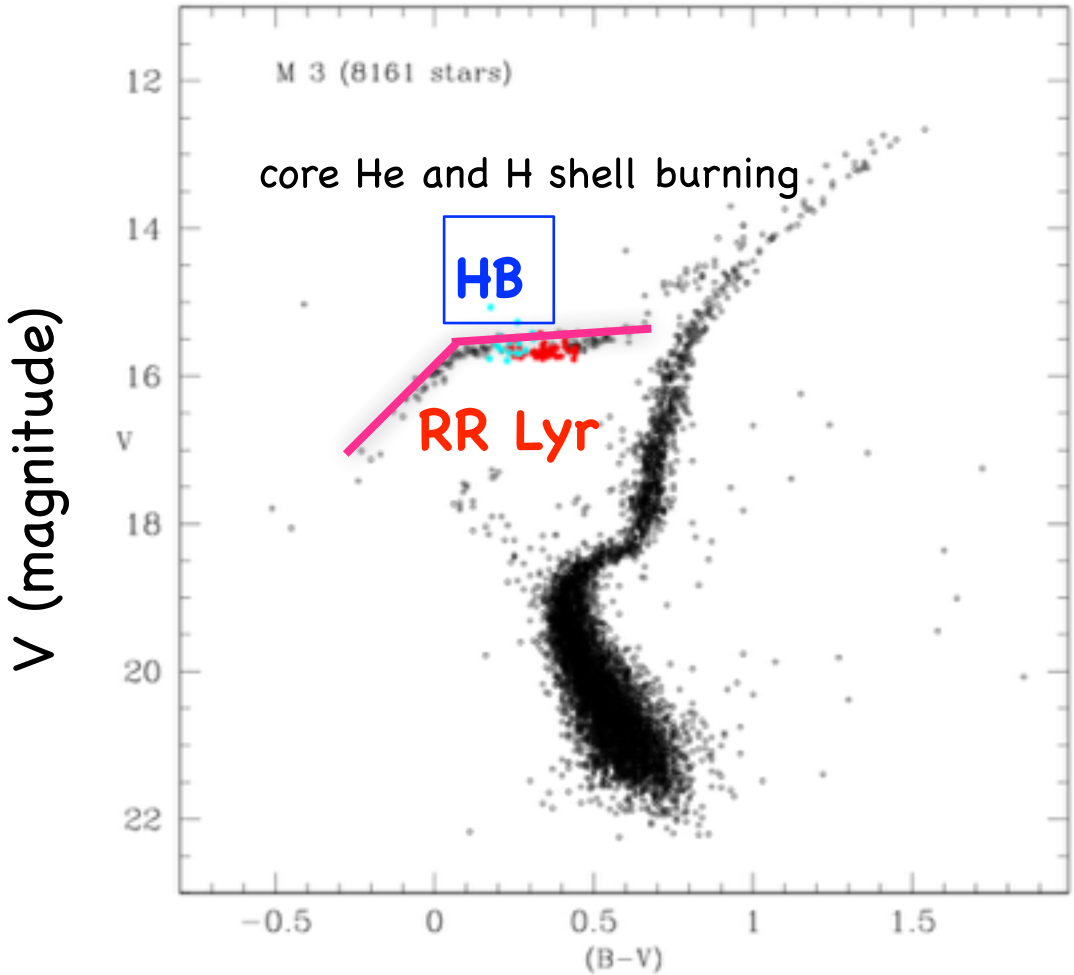


Horizontal Branch stars

low-mass, M < 2 M_{Sun}
similar core masses, similar luminosities

some pulsate, P ~ 1 d
Teff: 4000 - 10000… K
log(g): 1.5 to 3
L ~ 10^2 - 10^3 L

luminous
~ constant luminosity - especially valuable as distance indicators

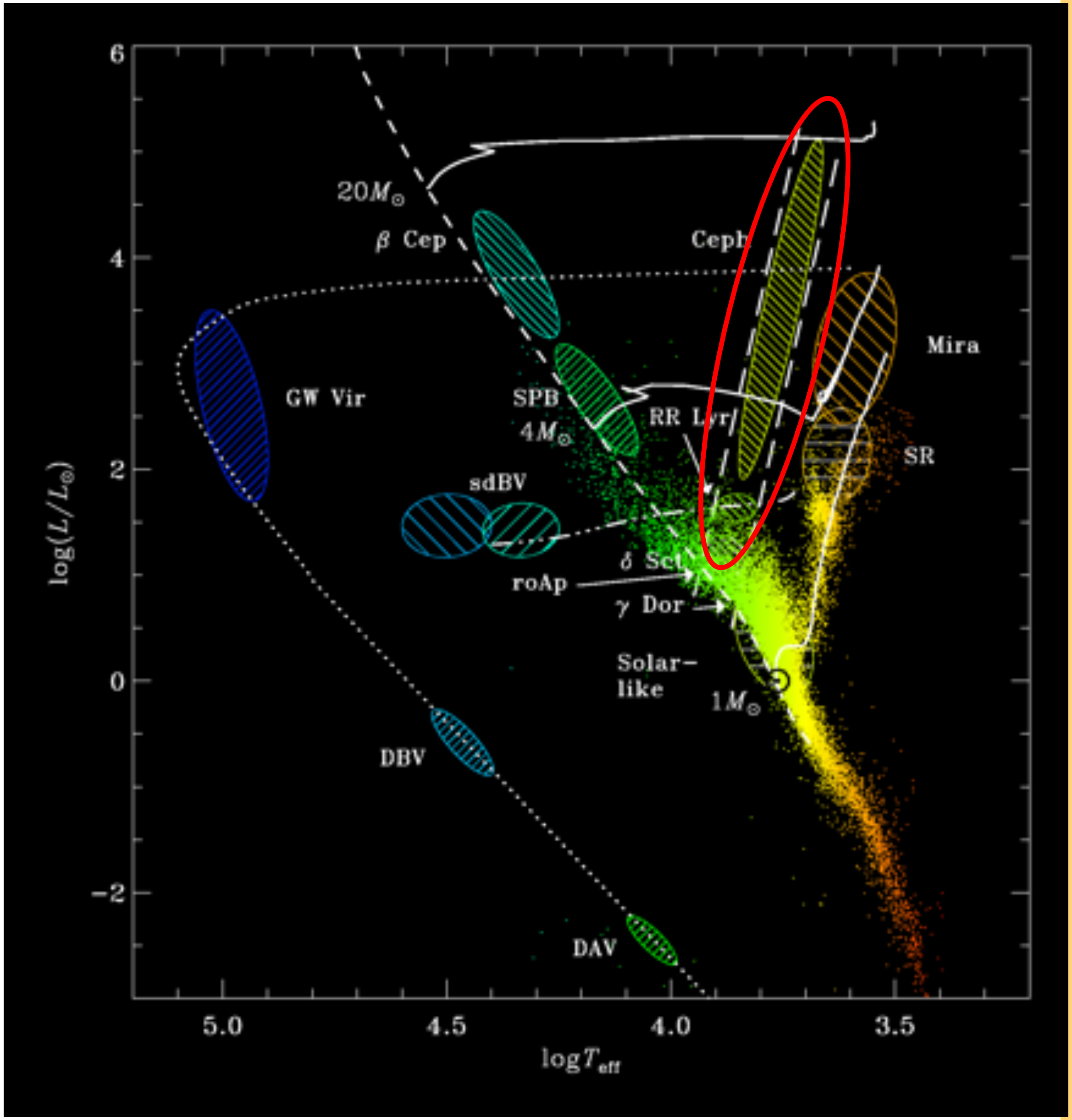


Cepheids

Cepheid Type I
high-mass, 3 < M < 10 M_{Sun}

radial pulsators, P ~ 2d - 50 d
Teff: 4000 - 7000... K
log(g): 1.5 to 3
L ~ 10^2 - 10^5 L

Period - Luminosity relationship - especially valuable as extragalactic distance indicators



Red supergiants (RSG)

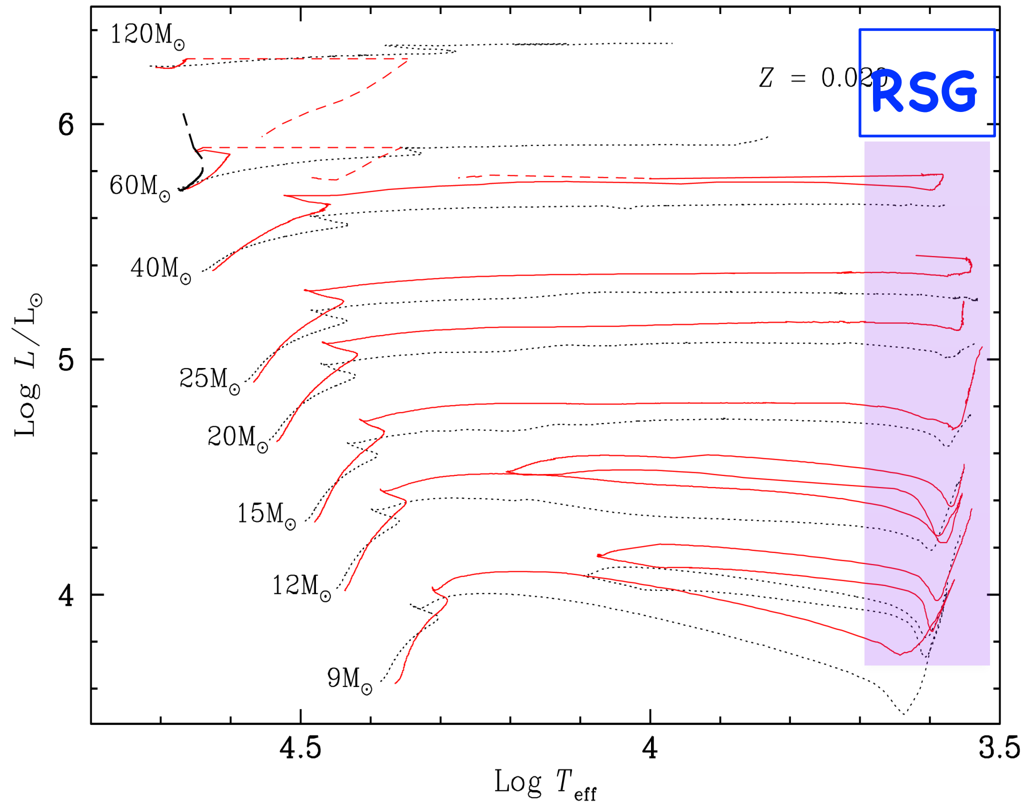
massive stars ($10 < M_{Sun} < 30$)
→ evolve and explode quickly

young (< 50 Myr) → trace composition of the present-day ISM

$L \sim 10^4 - 10^6$ L

T_{eff}: 3500 – 4500 K

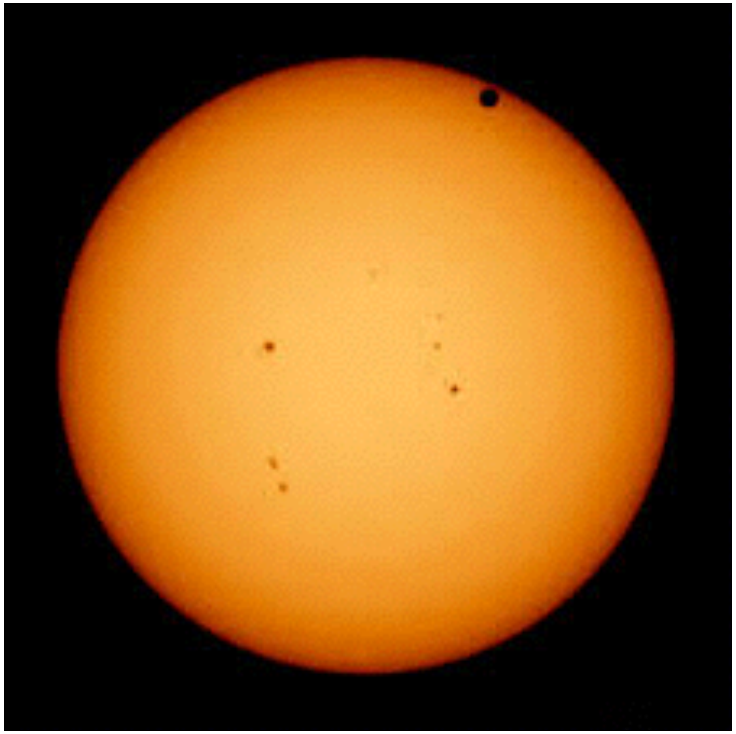
RSG's observable with modern instruments to distances of several Mpc (outside the Local Group)

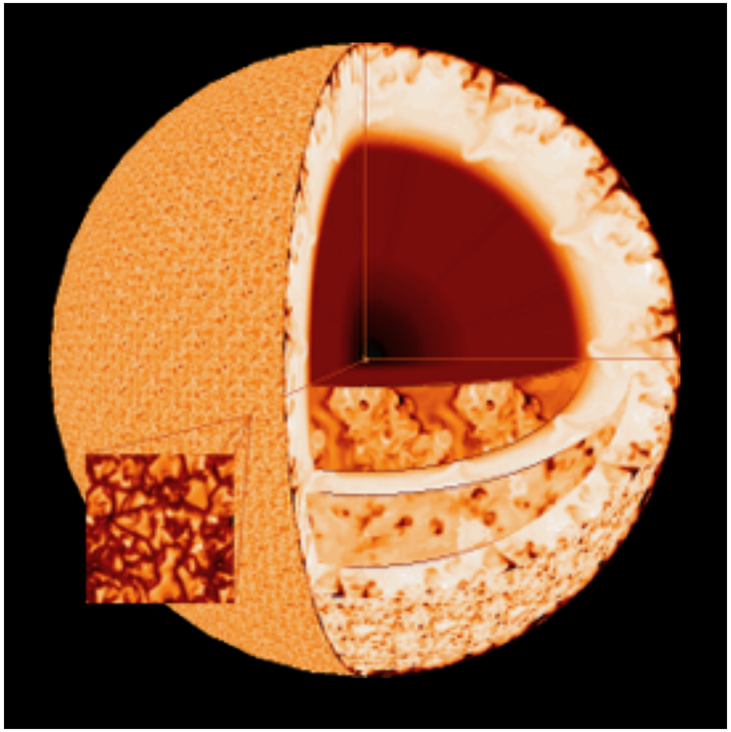


Maeder (2009)

integrated light of young stellar populations in star forming galaxies → out to few 10's Mpc

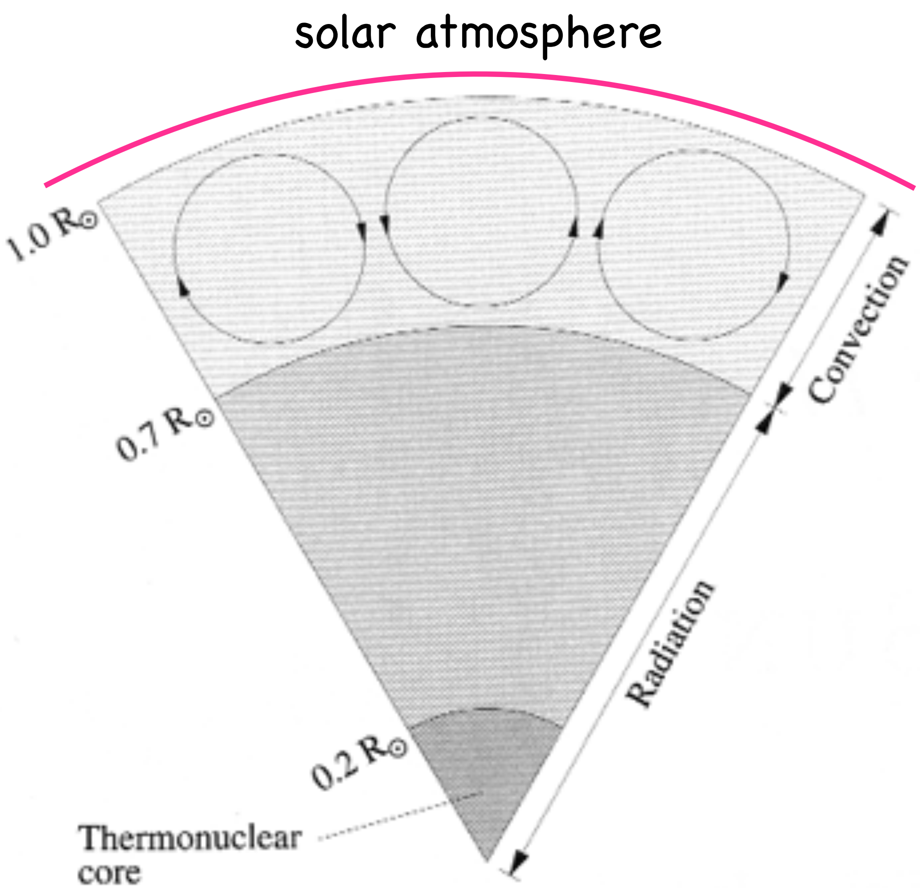
Surface and interior structure of cool stars





(c) A. Nordlund

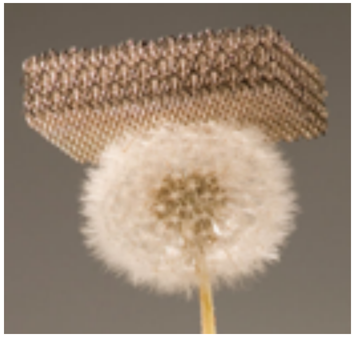
The Sun



- surface temperature allows formation of H^-
  strong opacity source

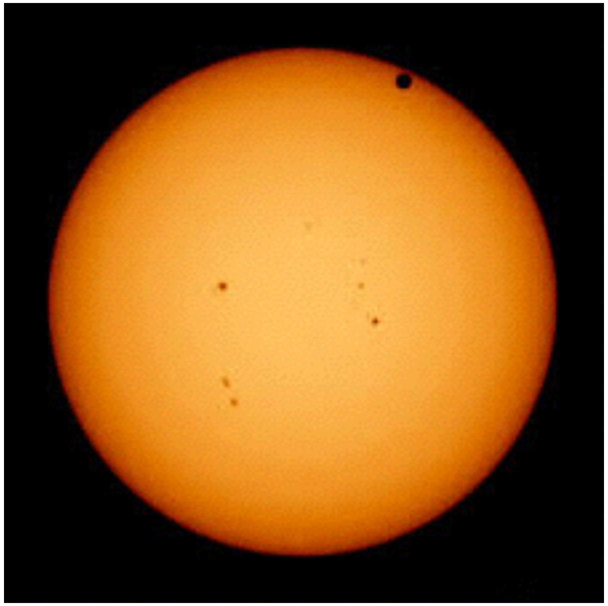
  - **convective envelope**

- H-burning dominated by pp-chain burning
  - **radiative core**

		T(K)	ρ(g cm^{-3})	λ (cm)
core		15×10^7	160	0,003
envelope		7×10^5	1.8×10^{-2}	0,770
photosphere		6000	3.5×10^{-7}	4×10^6
chromosphere		9000	3×10^{-13}	1.7×10^{13}
corona		2×10^6	2×10^{-18}	infinite
ISM		$10 - 10^4$	$10^{-24} - 10^{-23}$	infinite

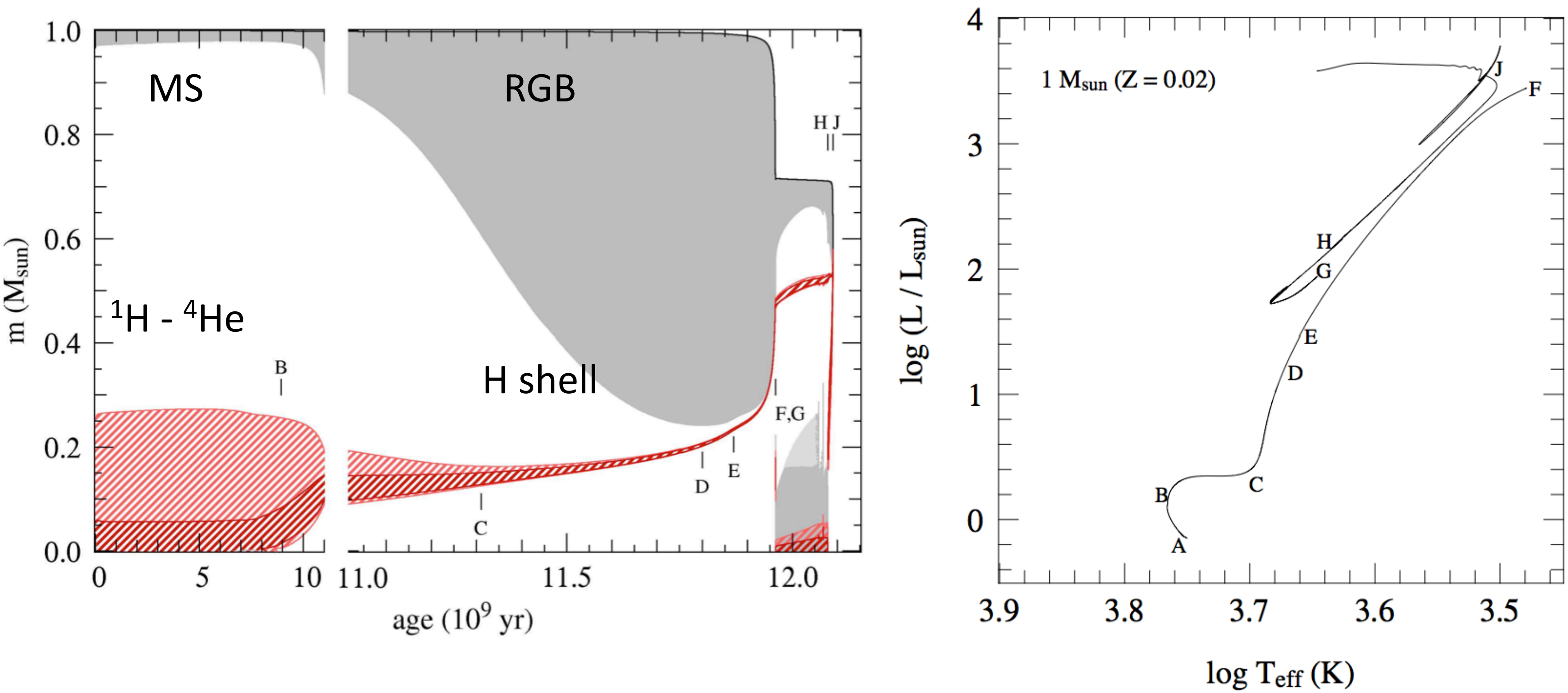
How do we know about the structure of stars?

the Sun as the testbed of all theories



- Stellar evolution models (The Standard Solar Model) and helioseismology
- Multi-messenger diagnostic
  - neutrinos
  - solar wind
  - EM radiation: spectra, imaging

The standard solar model



1D stellar evolution model of an 1 M_{sun} star
from a homogeneous pre-MS model to the present-day age of the Sun
t = 4.57 Gyr (from meteorites)

The standard solar model

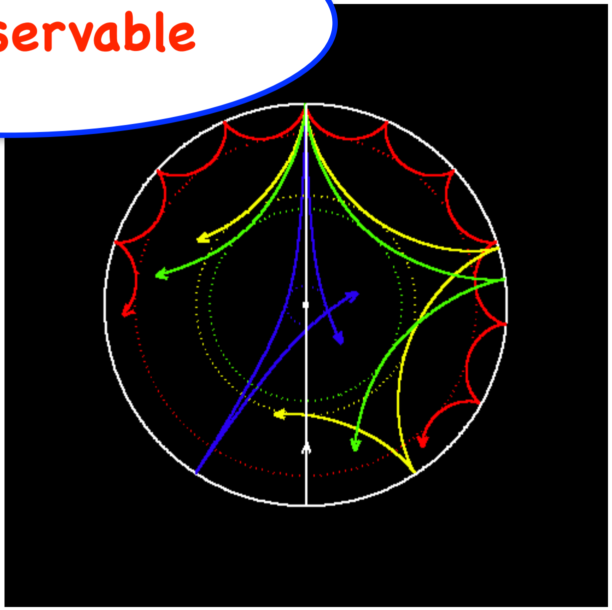
The SSM must satisfy 3 observational constraints:

L_{Sun} = 3.8418 x 10^{33} erg/s

R_{Sun} = 6.9598 x 10^{10} cm

and surface metal abundances

key observable



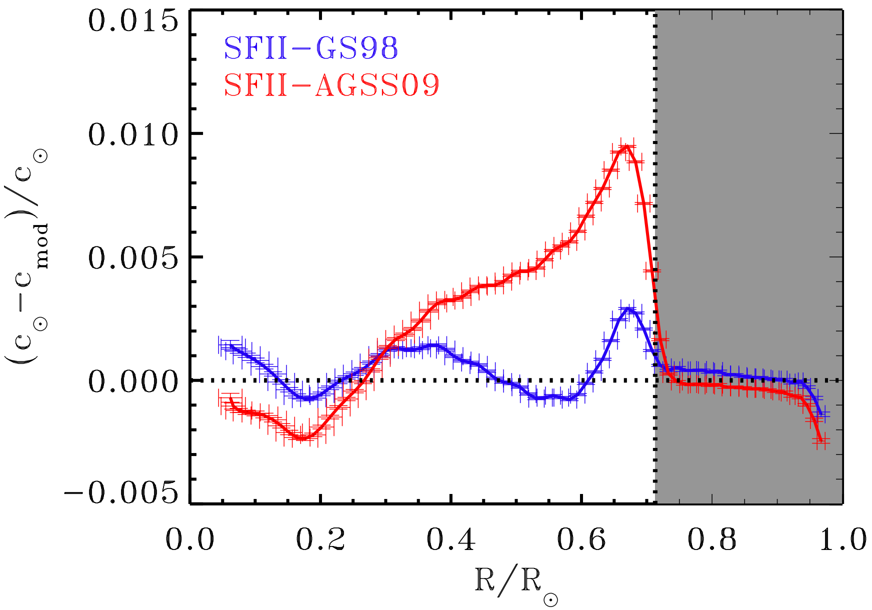
$\ell = 2$ $\ell = 20$ $\ell = 25$

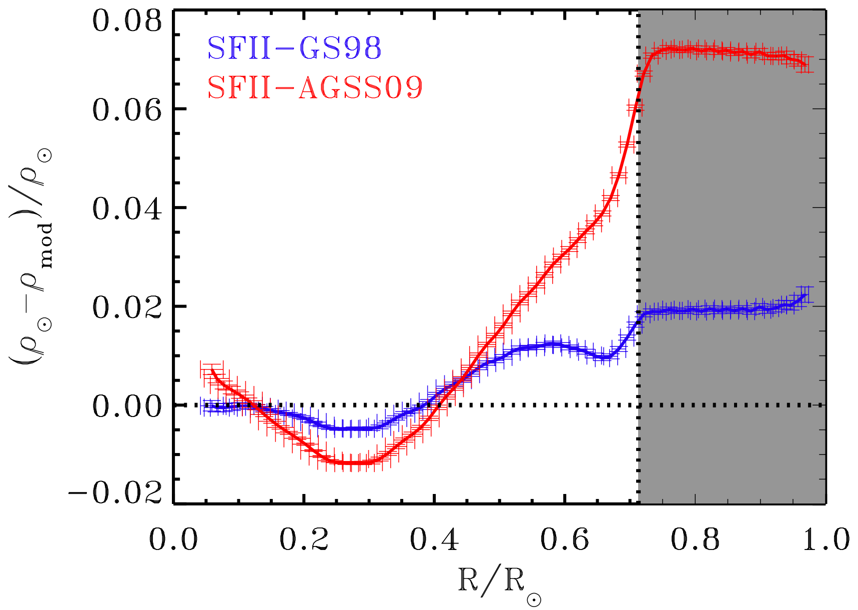
Predictions

internal density profile, sound speed profile, surface abundance of He

can be tested using helioseismology
the most stringent constraints on the interior structure of the Sun

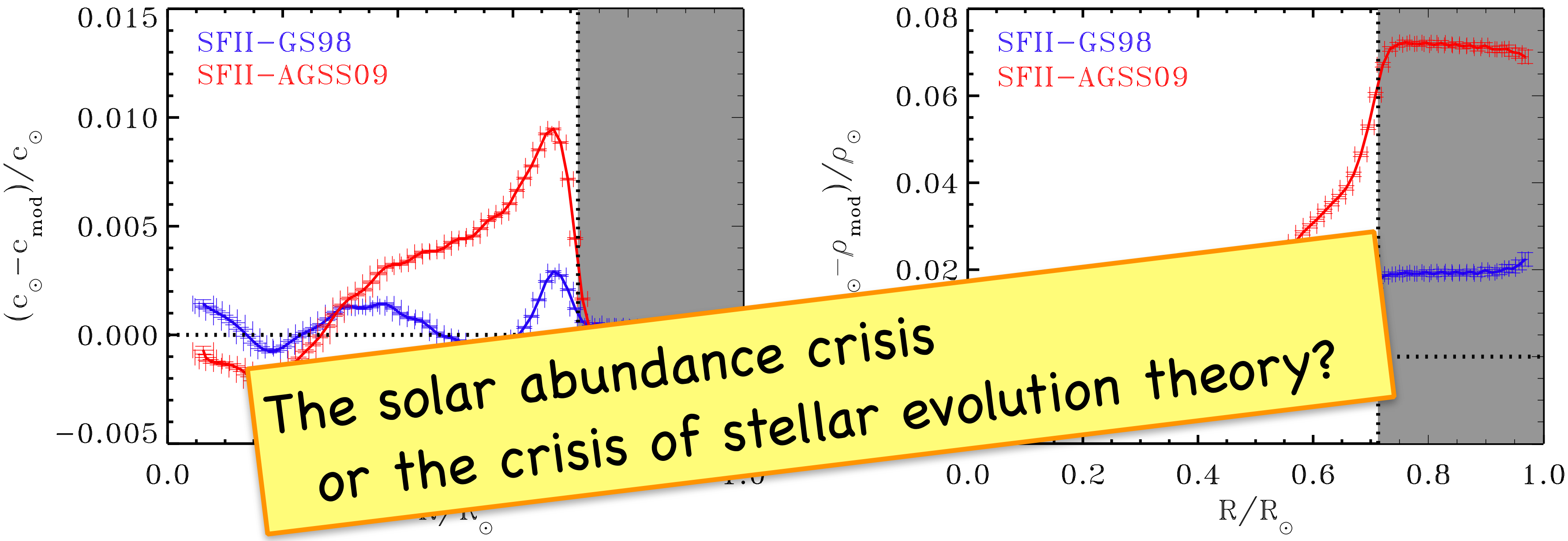
The standard solar model





Serenelli et al. (2011)
Villante et al. (2014)

The standard solar model

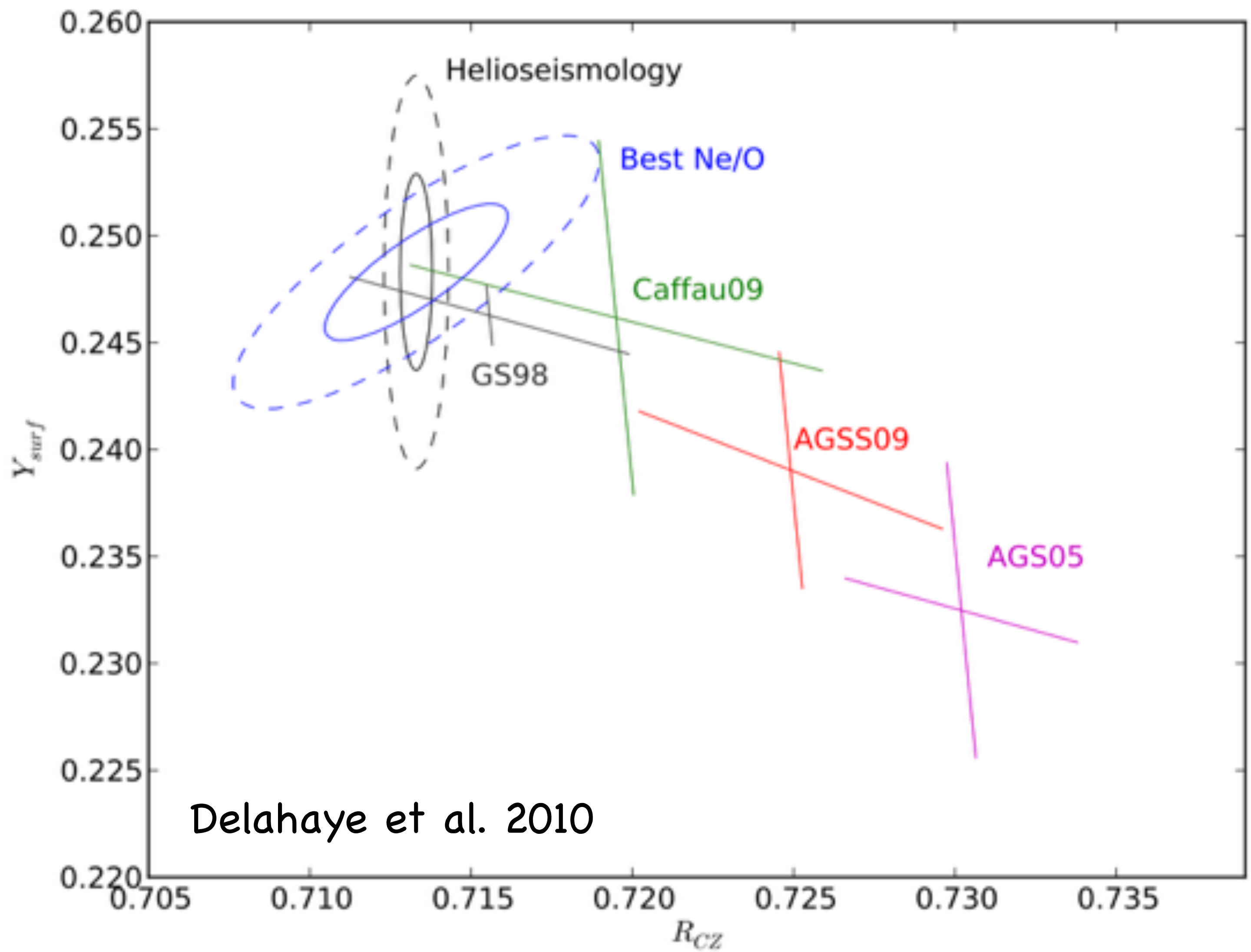


Serenelli et al. (2011)

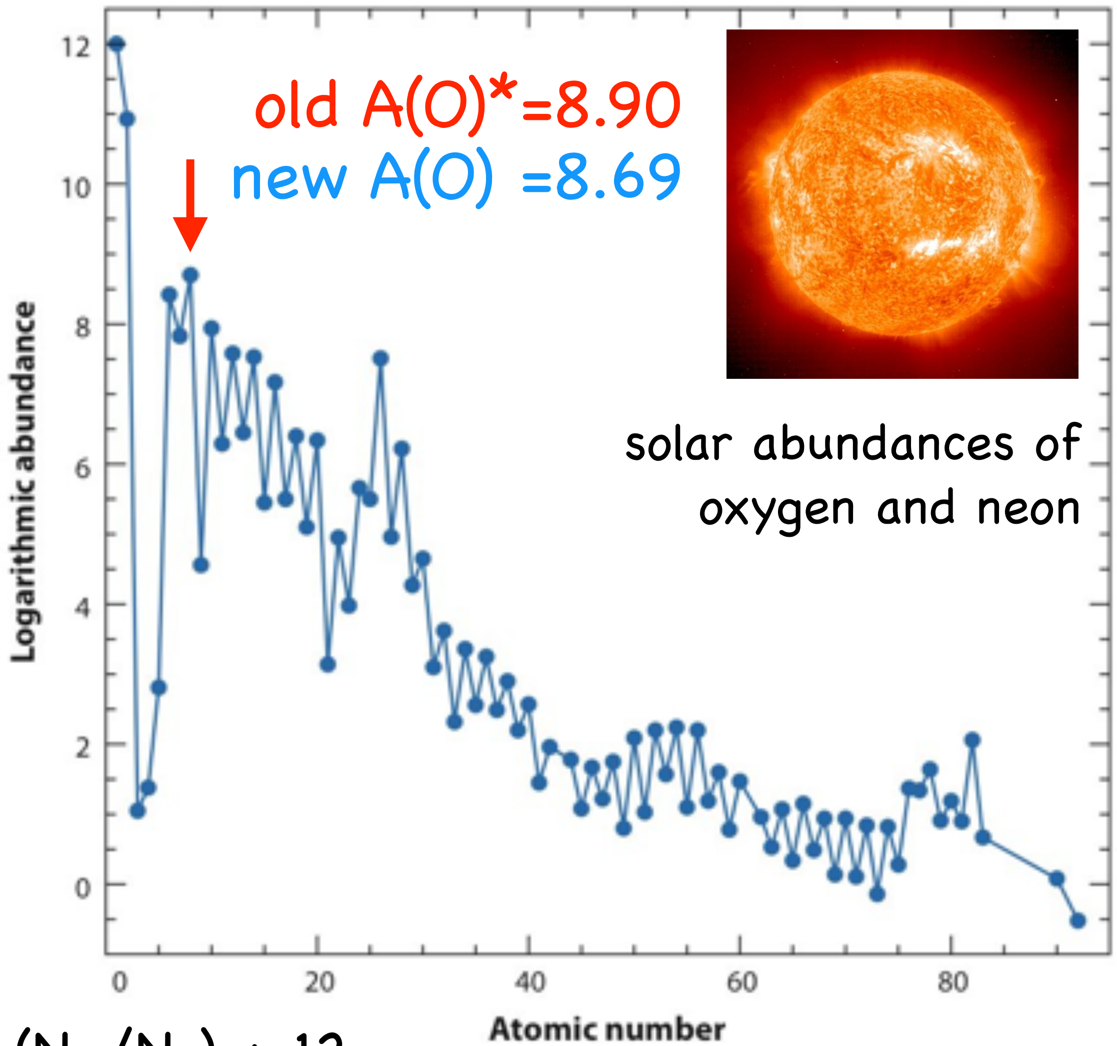
- wrong depth of the solar convective envelope
- wrong surface He abundance
- wrong sound speed profile

	GS98	AGSS09	Helios.
$(Z/X_\odot)$	0.0229	0.0178	—
$R_{CZ}/R_\odot$	0.712	0.723	0.713 ± 0.001
Y_S	0.2429	0.2319	0.2485 ± 0.0034
$\langle \delta c/c \rangle$	0.0009	0.0037	—
$\langle \delta \rho/\rho \rangle$	0.011	0.040	—

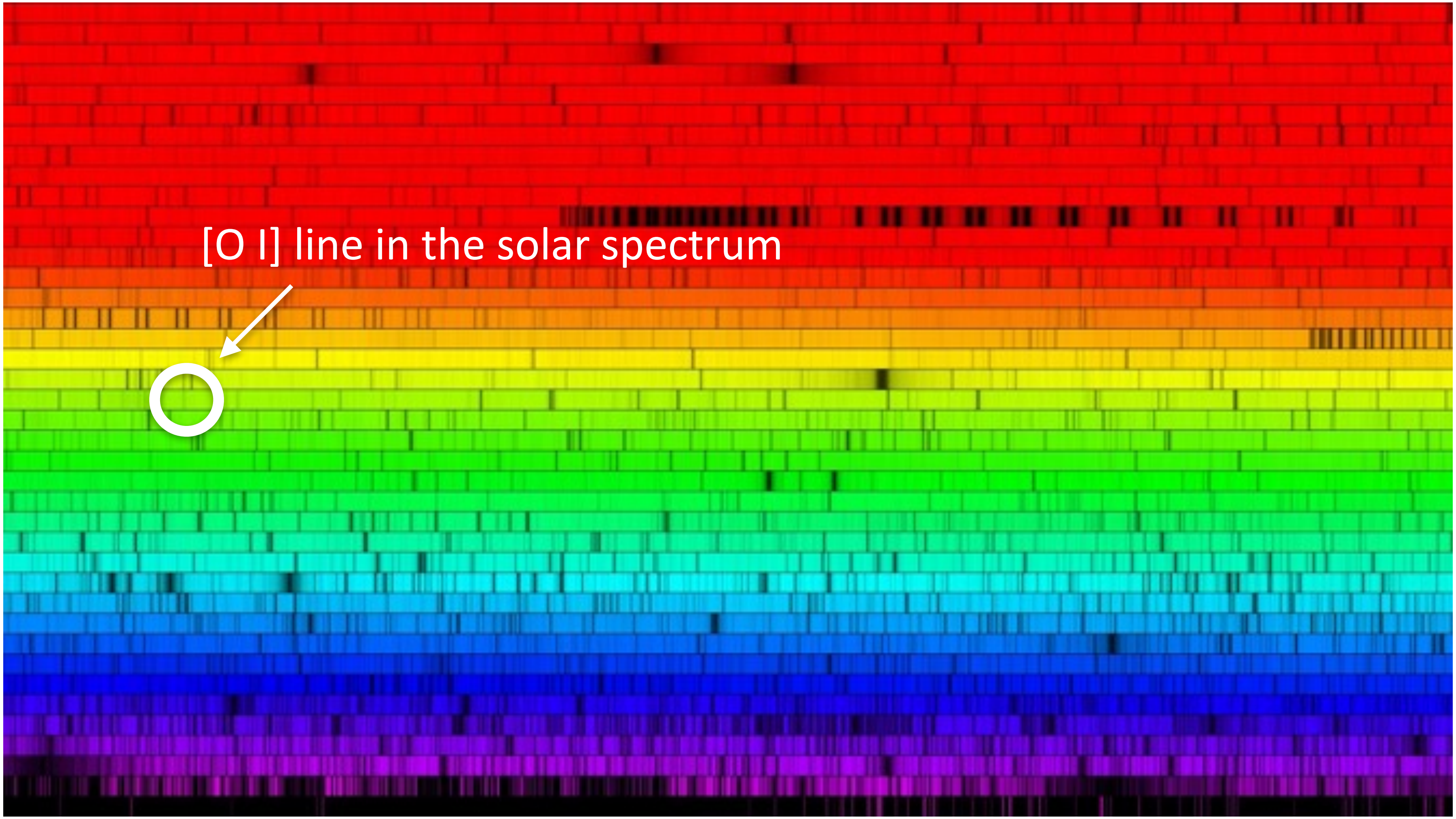
The standard solar model

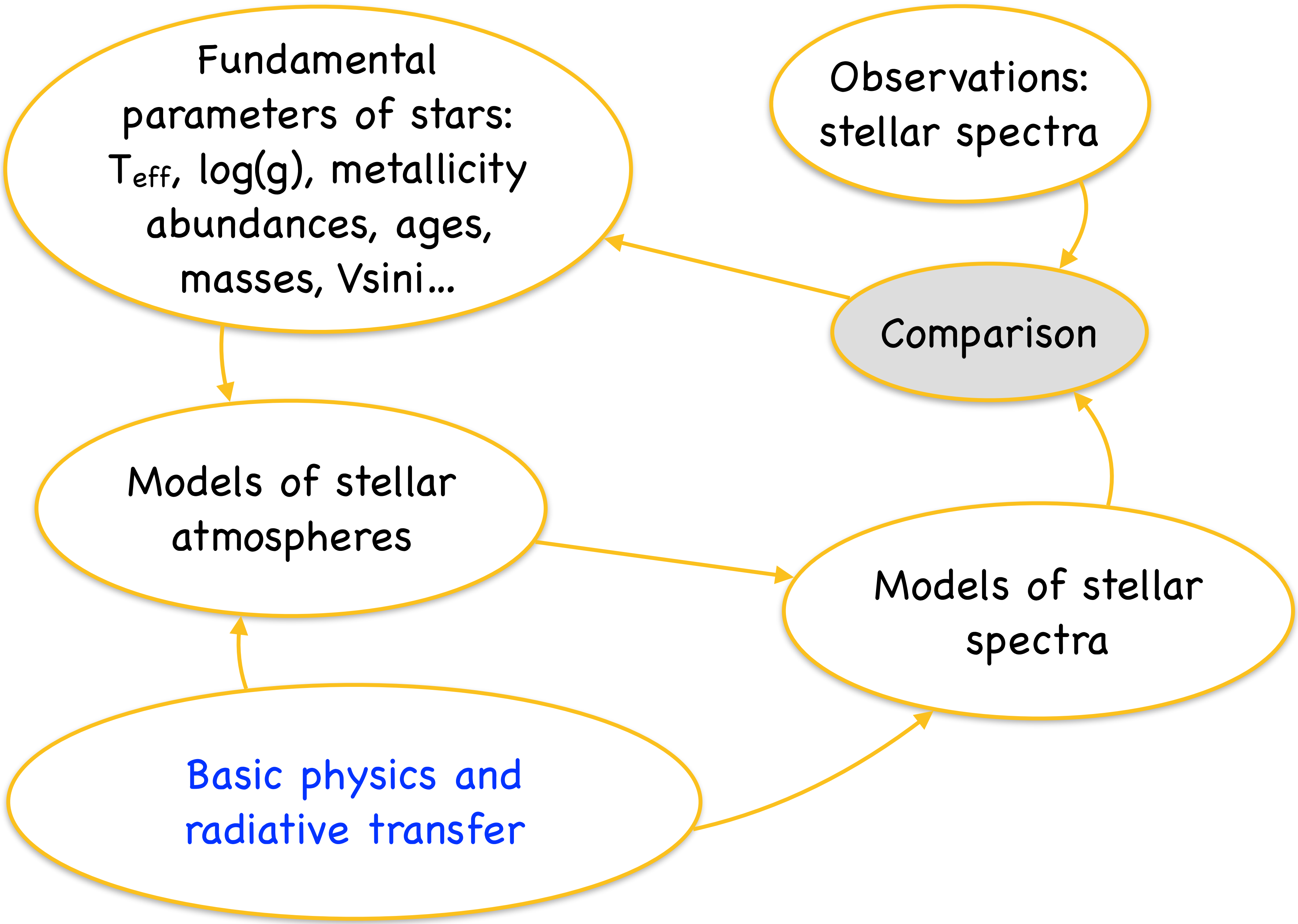


The roots of the Solar crisis - radiative transfer in OI lines



*$A(el) = \log (N_{el}/N_H) + 12$


[O I] line in the solar spectrum


Fundamental parameters of stars: T_{eff}, log(g), metallicity abundances, ages, masses, Vsini...
Observations: stellar spectra
Comparison
Models of stellar atmospheres
Models of stellar spectra
Basic physics and radiative transfer

Atmospheres of cool stars

- Hydrodynamics and convection
- Non-local thermodynamic equilibrium
- Chromospheres
- Coronae
- Pulsations
- Winds and mass loss
- Asymmetric shapes with 'hot spots'
- MOLsphere (H_2O, SiO)
- Non-equilibrium chemistry

Atmospheres of cool stars

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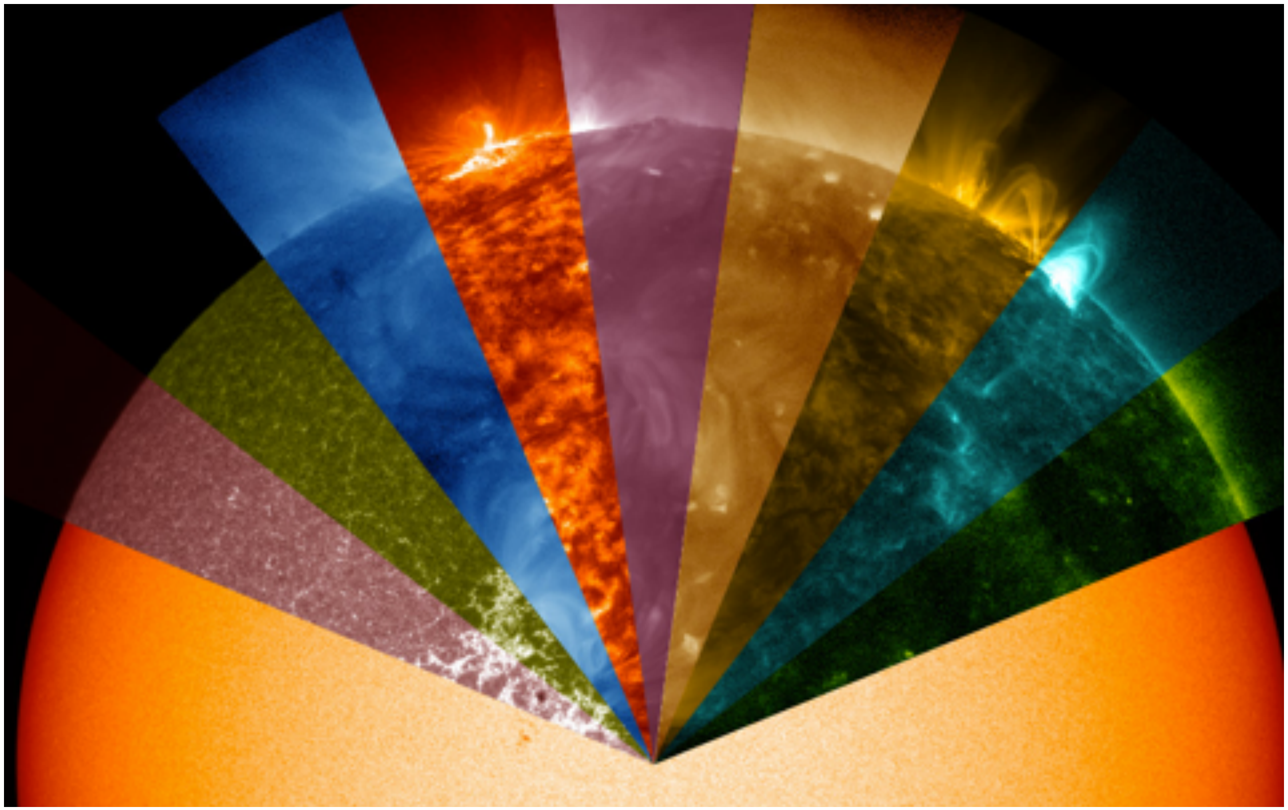
do we really need all that stuff?

The solar surface

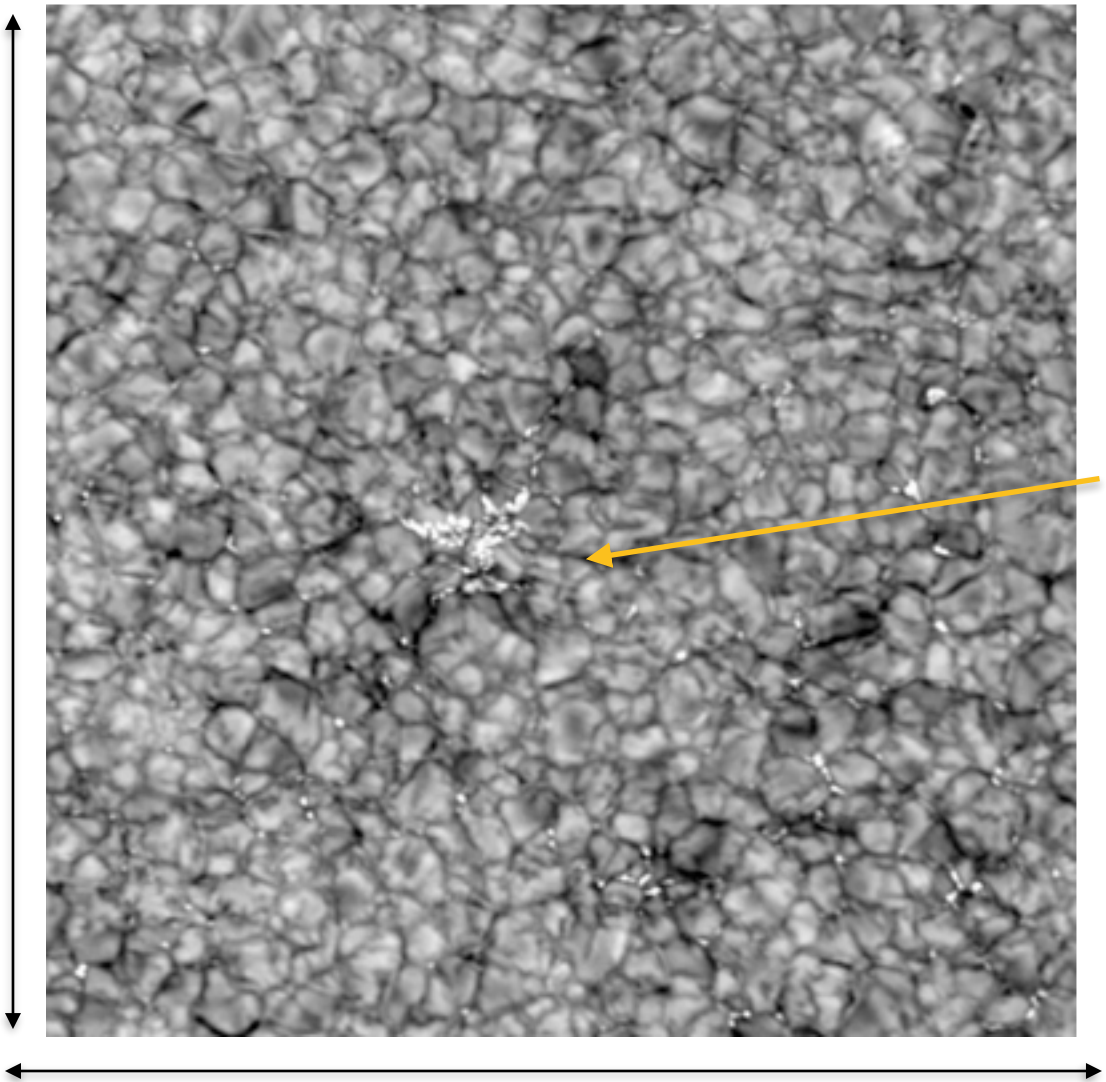


multi-wavelength observations of the **Sun** (SDO)

(C) GSFC Scientific Vizualisation Studio, NASA

The Sun: observed granulation (Swedisch Solar Telescope, La Palma, 6563 A)

25000 km



bright granules

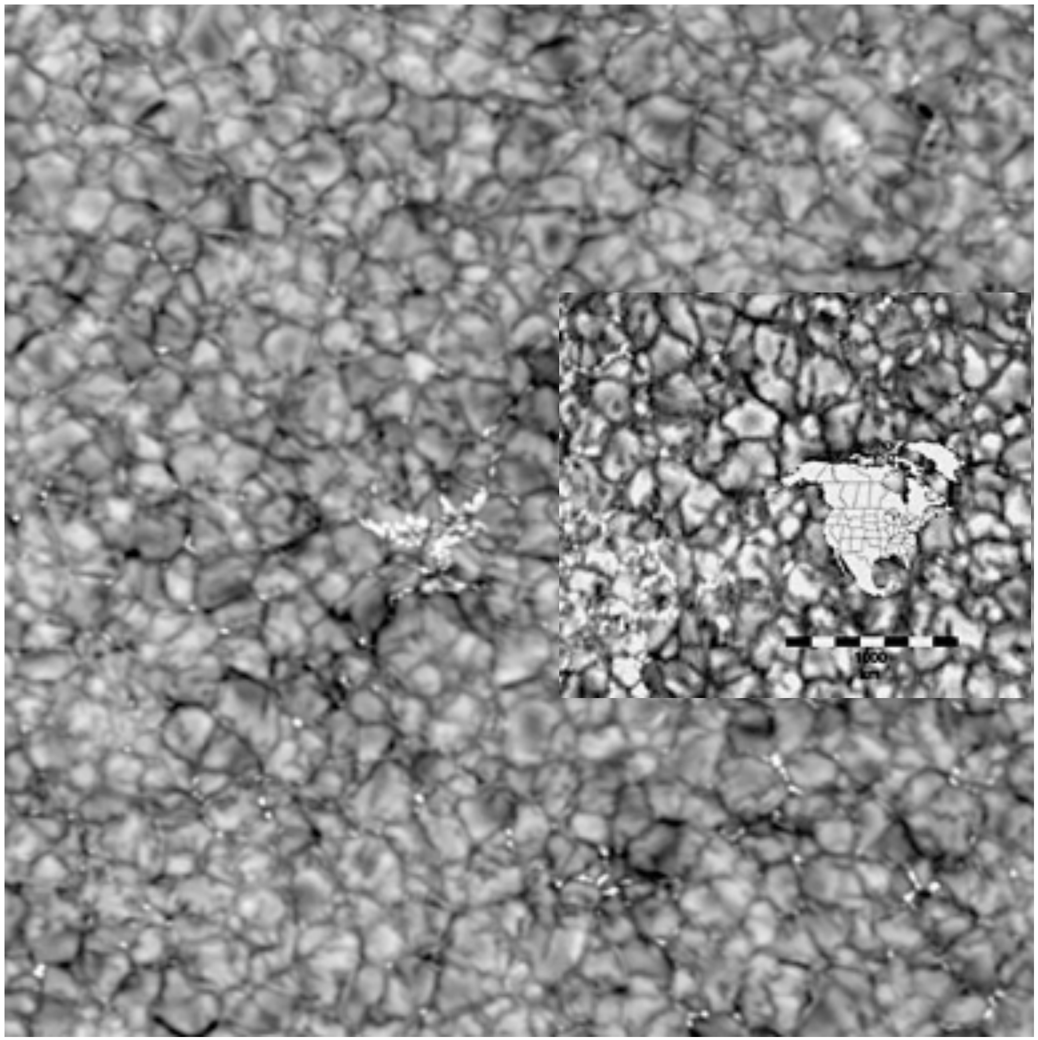
dark inter-granular lanes

variability ~ minutes
size ~ 1000 km

(c) Van der Voort Oslo

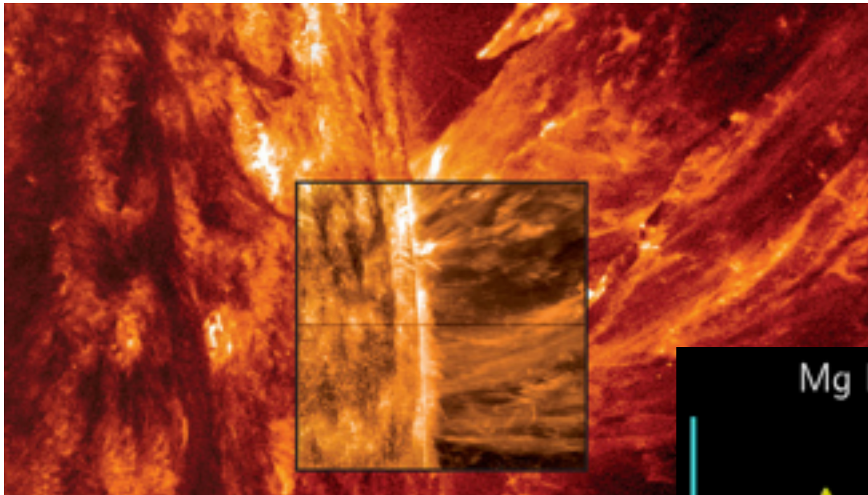
The Sun: observed granulation (Swedisch Solar Telescope, La Palma, 6563 A)

25000 km

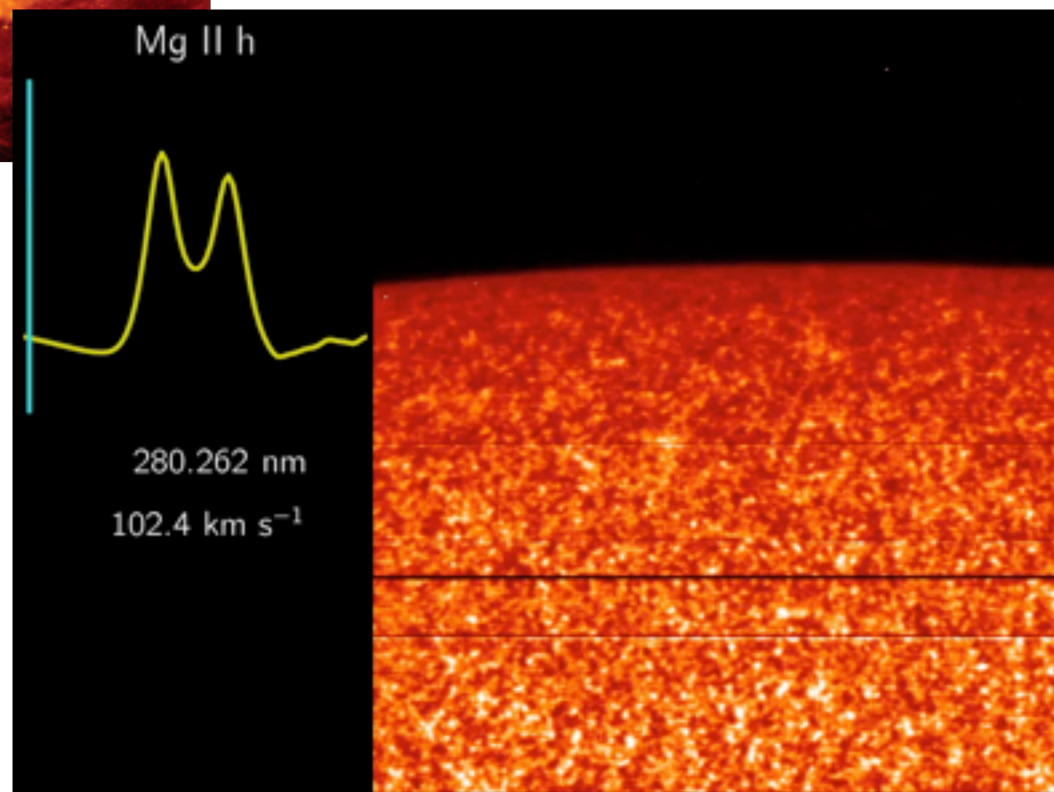


(c) Van der Voort
Oslo

Solar surface dynamics



Credit: NASA / Pereira

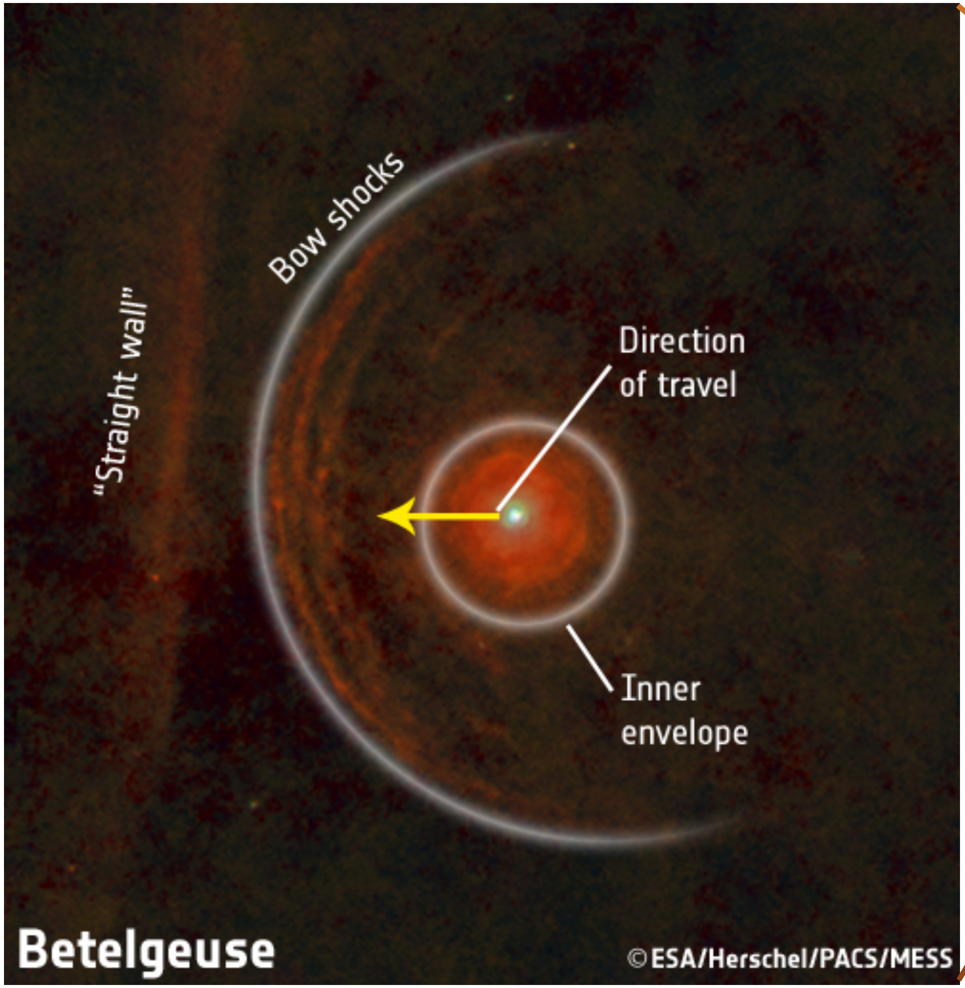


NASA / IRIS

Mini-tornadoes
plasma racing around
loops of twisted
magnetic field lines

Observations: imaging

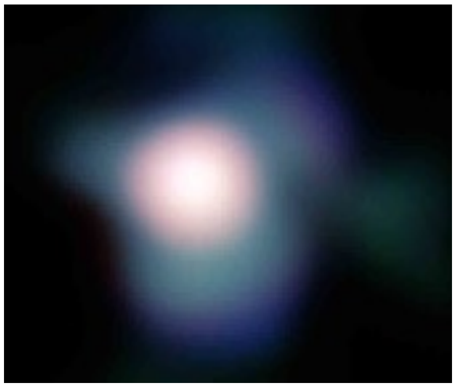
Herschel Space Observatory
(observations at 60 – 600 mikron)



Decin et al. (2012)

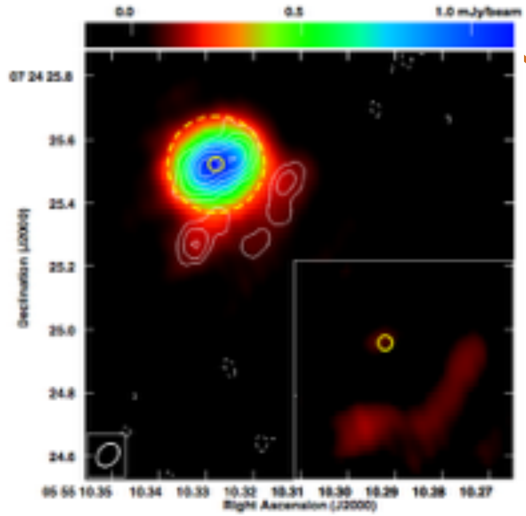
Observations: interferometry

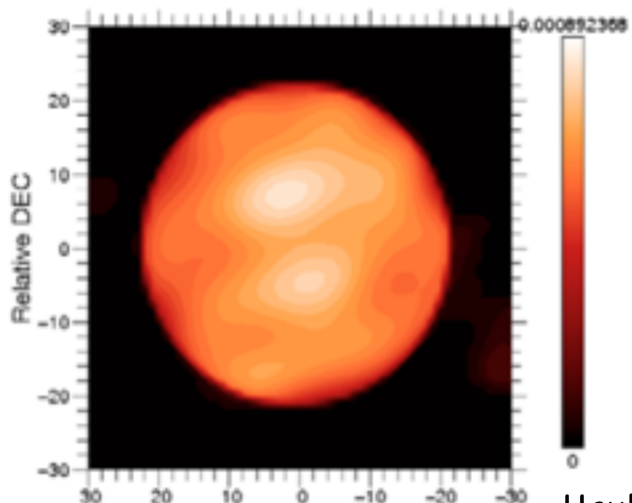
optical interferometry (VLT)



ESO VLT
Kervella et al. (2009)

radio interferometry (5 cm)



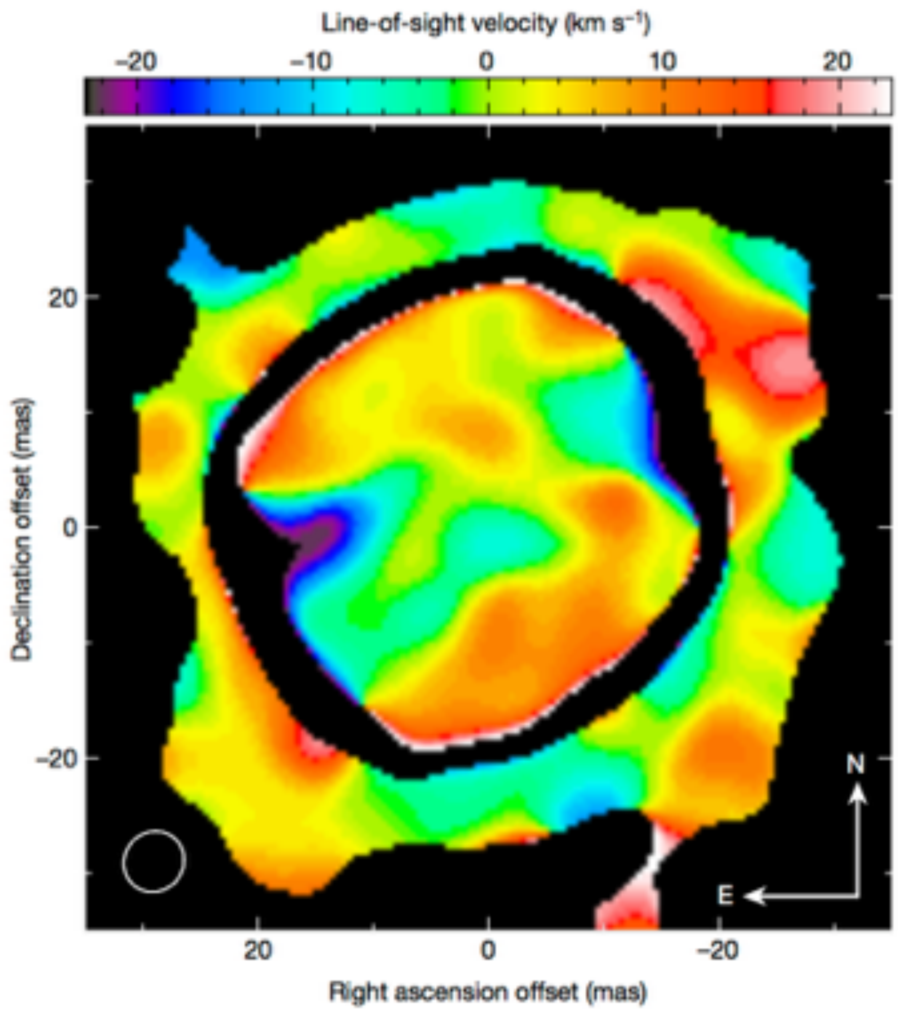


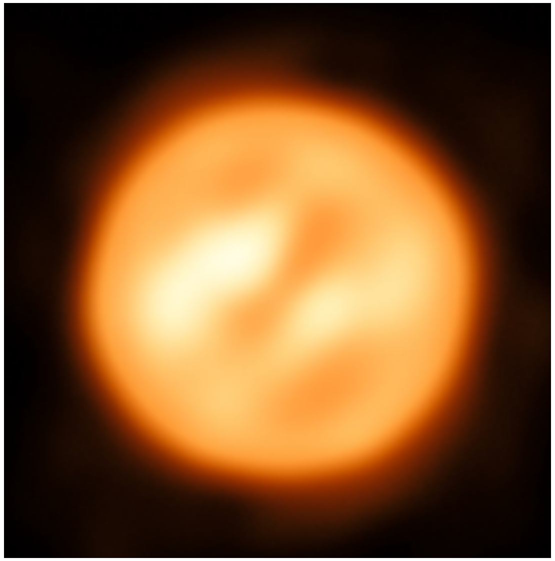
Haubois et al. (2009)

Interferometric observations resolve structure on Betelgeuse:
hot spots, 'plumes'
cold gas, a few giant convective cells

Observations: interferometry

Red supergiant Antares



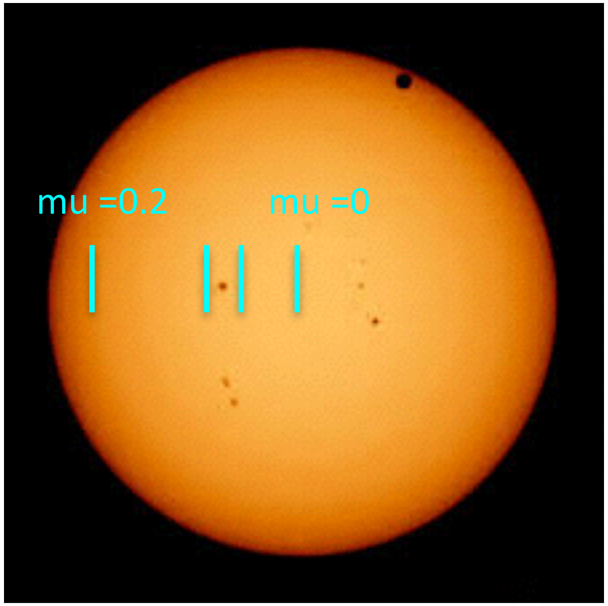


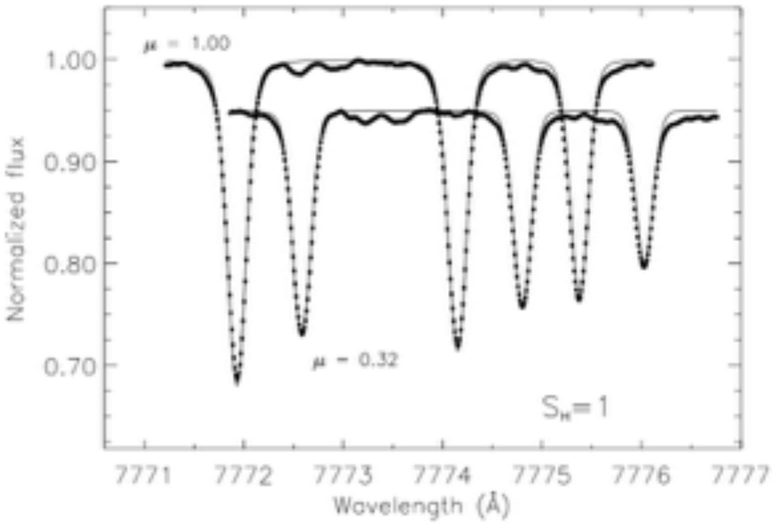
ESO VLTI / AMBER
Ohnaka et al. 2017 Nature

Spectro-interferometric imaging

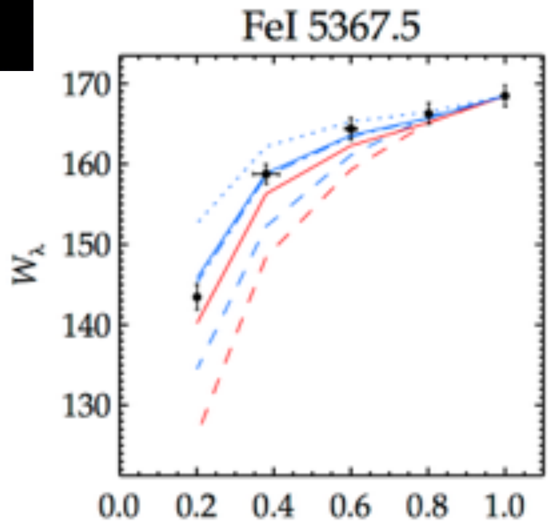
upwelling and downdrafting motions of gas in the atmosphere with V ± 20 km/s

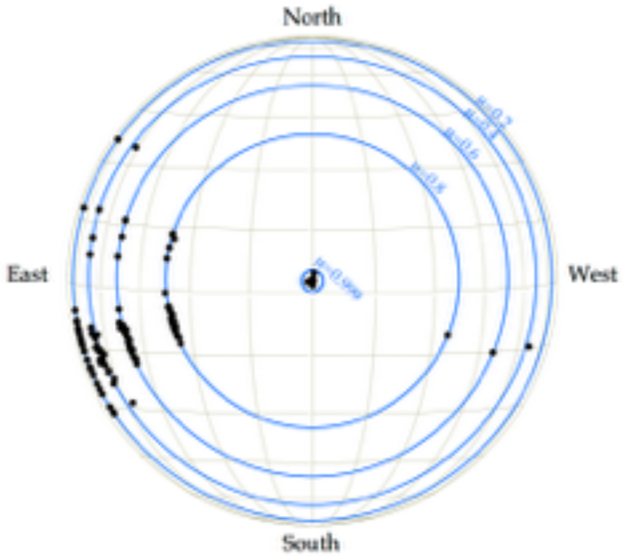
Observations: center-to-limb variation





The strengths and shapes of spectral lines vary greatly over the solar surface



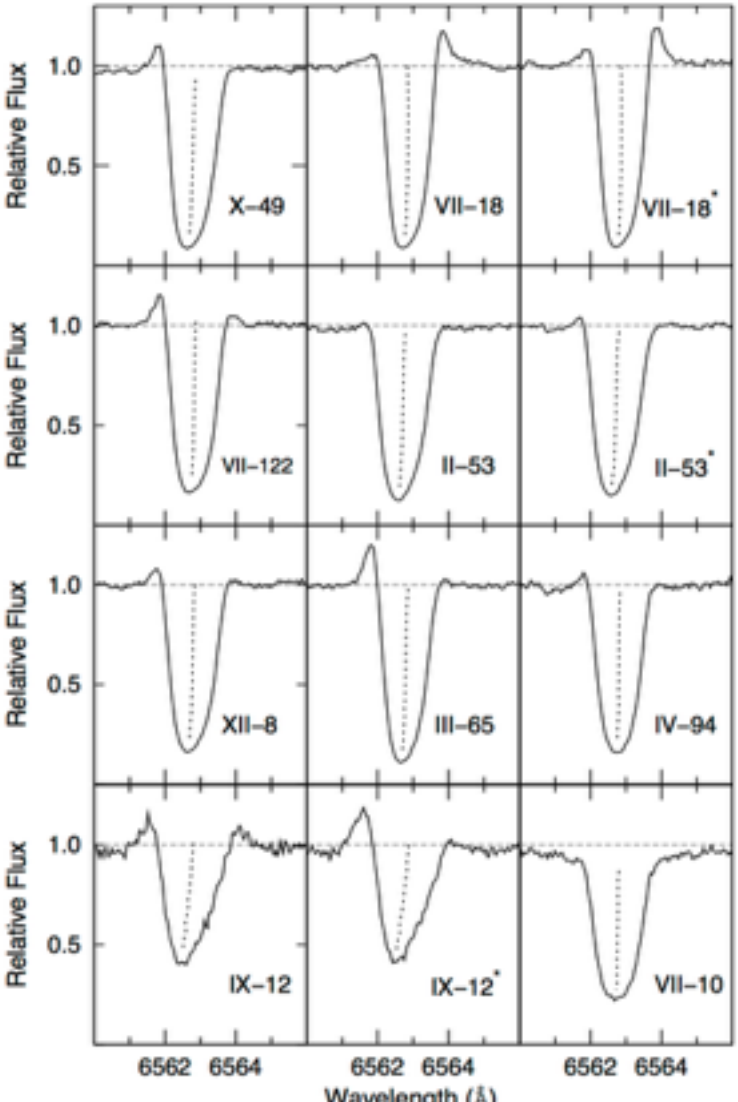


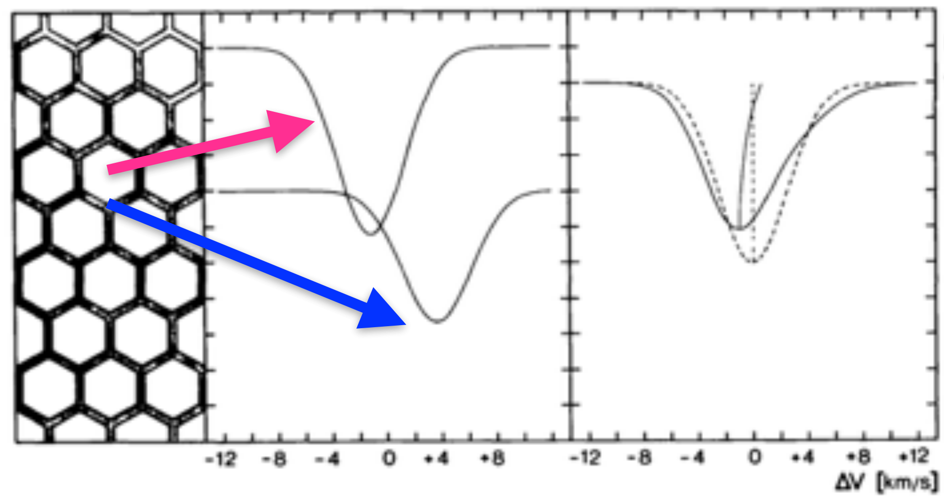
Allende Prieto et al. (2004)

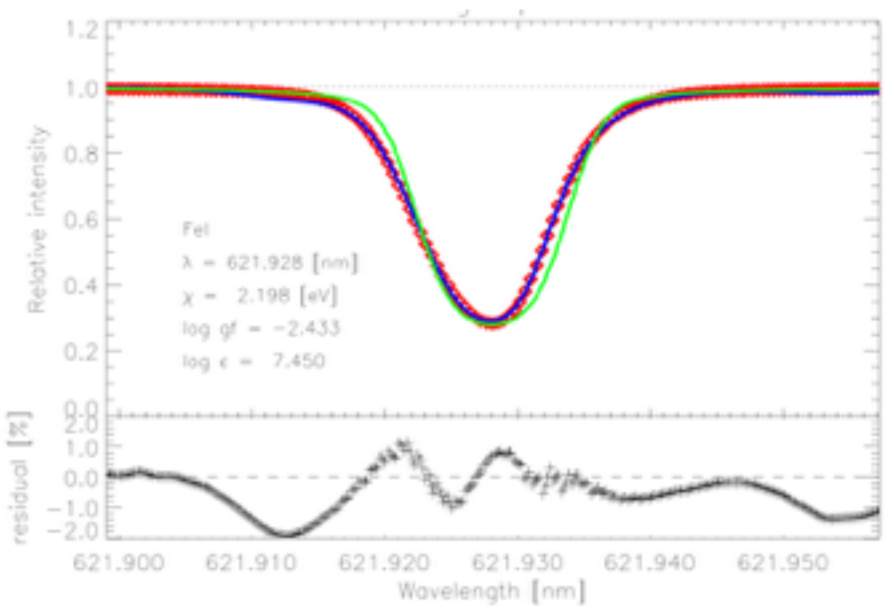
Lind et al. (2017)

Observations: line profiles

RGB stars in globular clusters

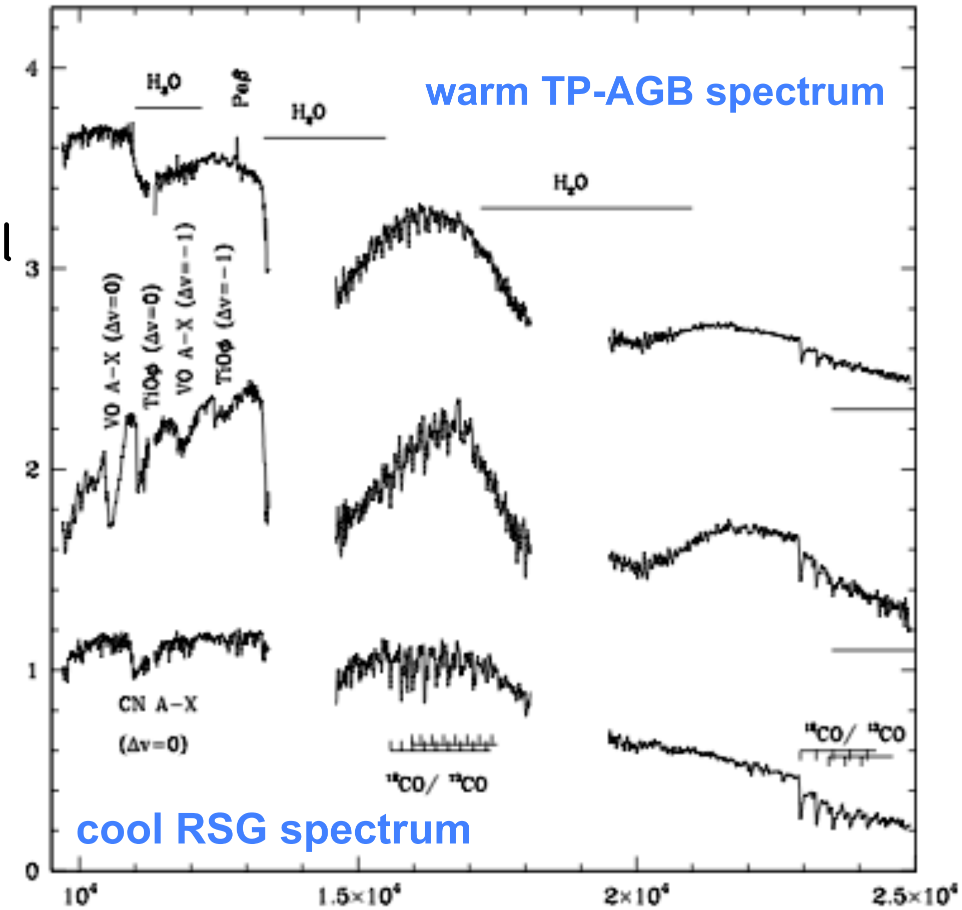






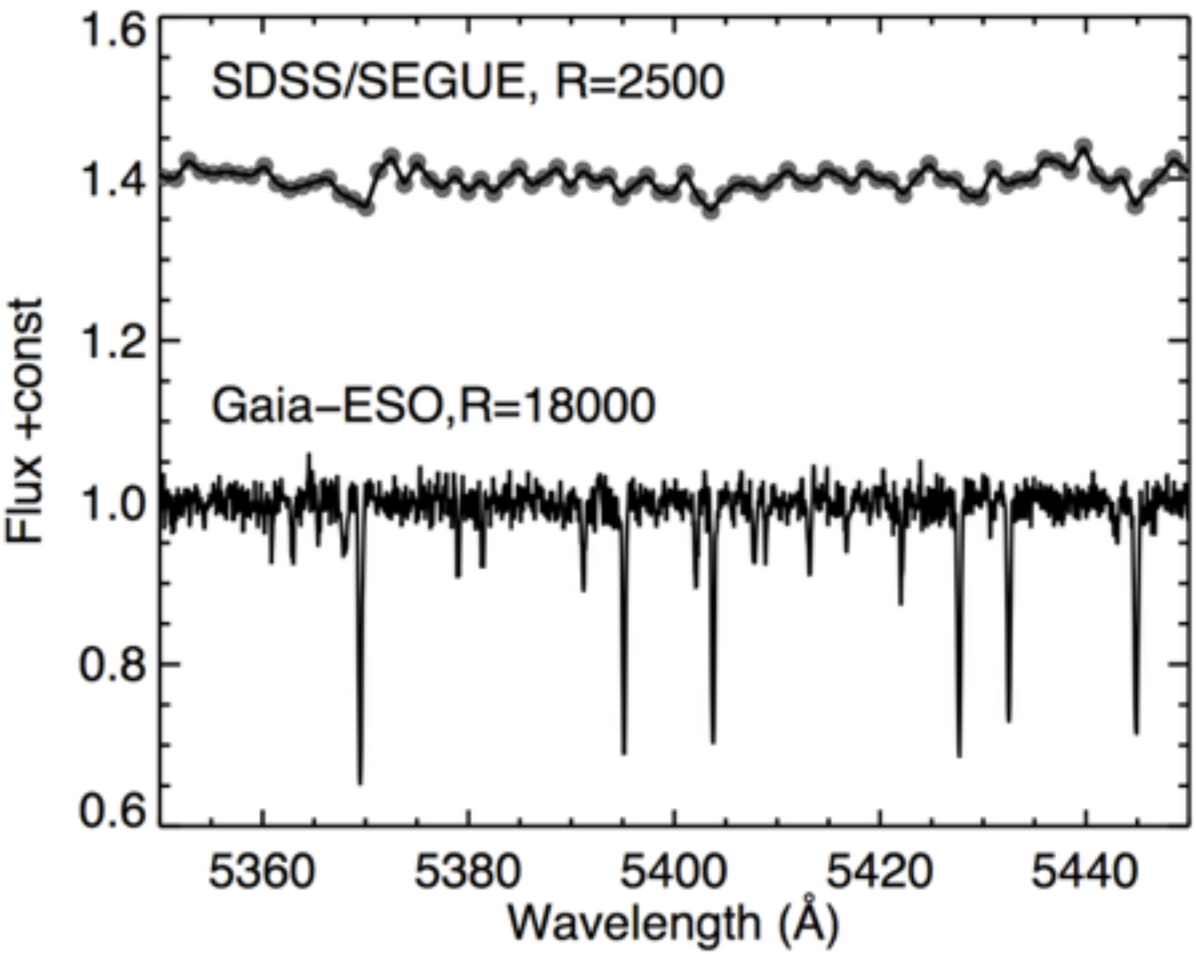
Observations: spectroscopy

- Basic surface parameters
  - effective temperature, surface gravity, abundances > 70 chemical elements: Li … U
  - rotation velocity
  - activity
  - radial velocity
- Fundamental parameters
  - mass, age
- Distances



Observations: spectroscopy

enormous progress over the past decades
large spectroscopic stellar surveys on 8-m, 10-m telescopes



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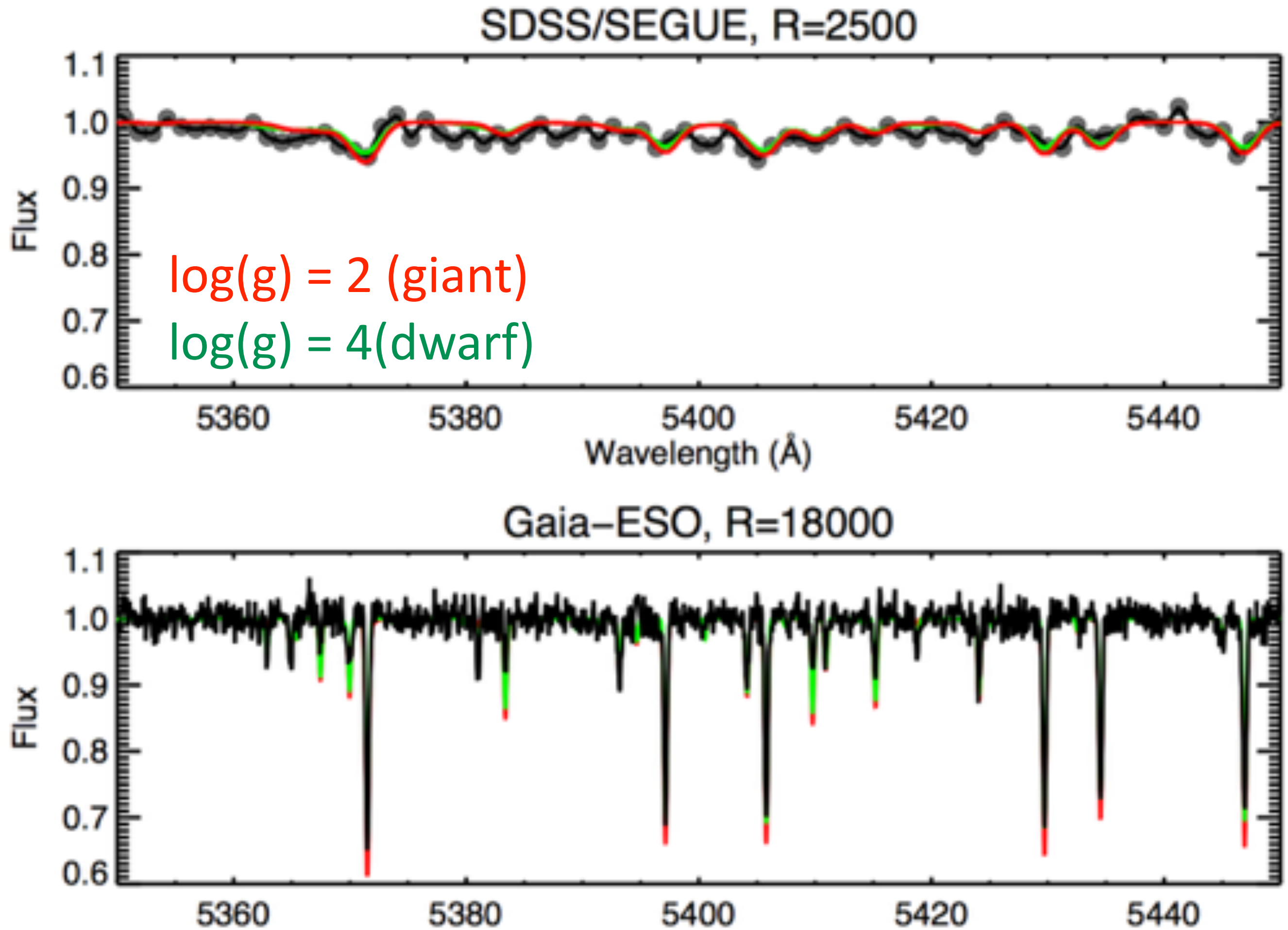
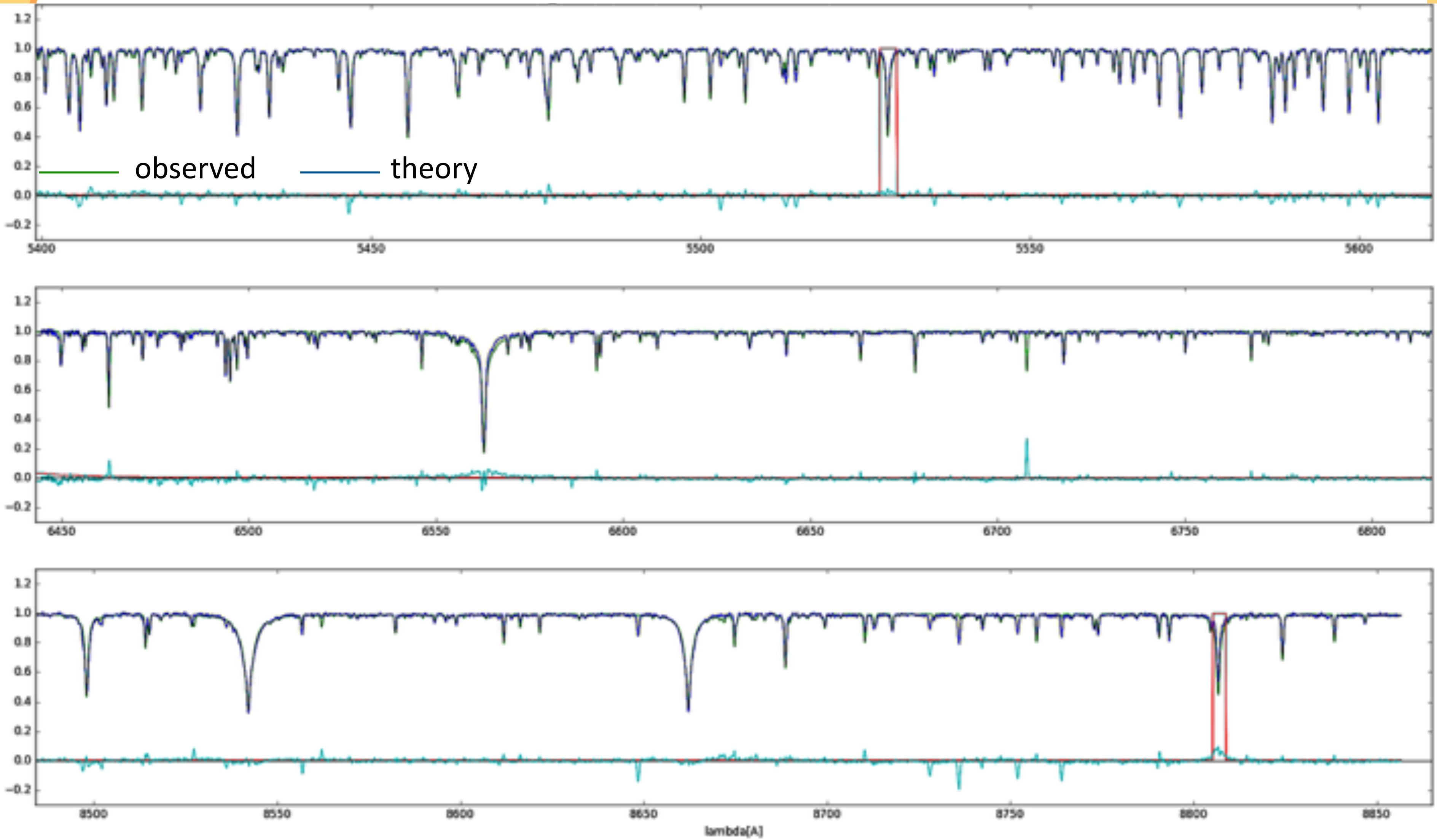
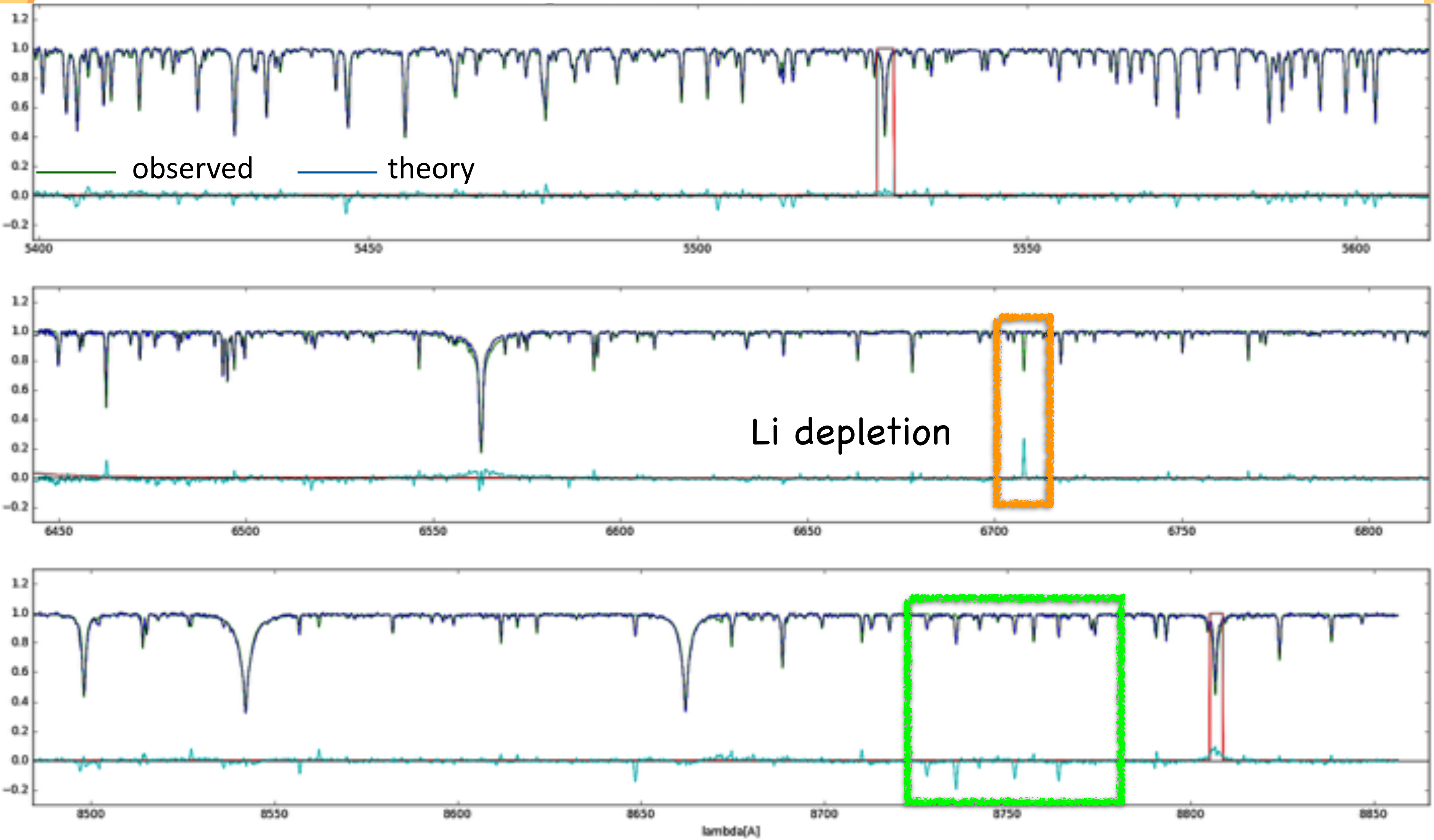


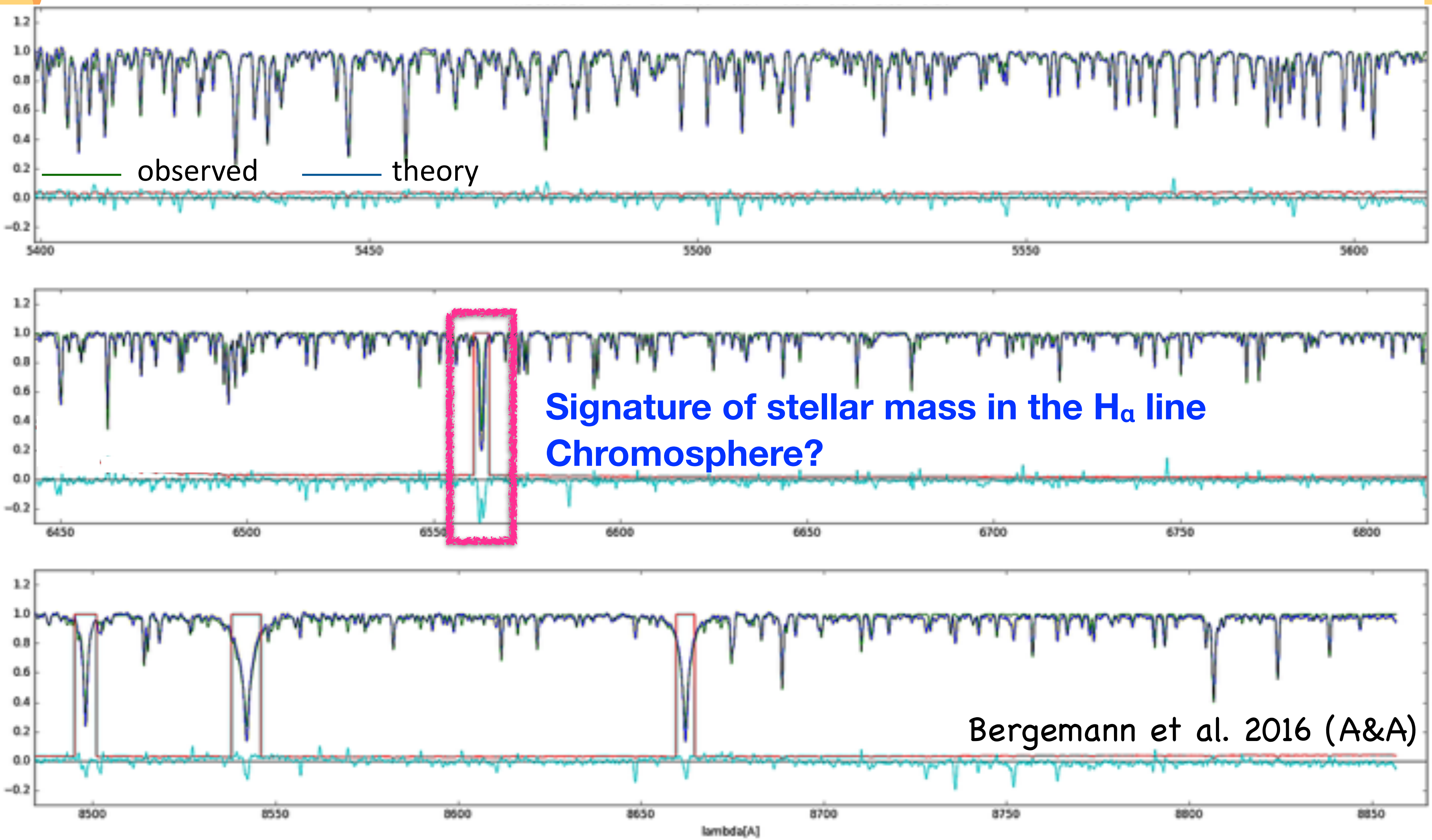
Observations: high-res spectroscopy



Observations: high-res spectroscopy



New physics from the residuals



compute model spectra LTE and NLTE nlte.mpia.de

Spectrum Synthesis

Home Spectrum Synthesis NLTE abundance correction References Contact

console output: hide show

Atmosphere model

plane-parallel 1D (MAFAGS-OS) spherical 1D (MARCS) coverage

Stellar parameters from a file? (please use the same format)

Star_name Teff log(g) [Fe/H] Vmic (Vmac Vrot : optional)

```
Star1 5777 4.44 0.00 1.0
```

Input from a file ? select file: Browse... No file selected.

Spectral interval : from 6542 to 6582 NLTE spectral lines

compute only molecular lines (below 12700 angstroms)

R:[λ/dλ] 50000