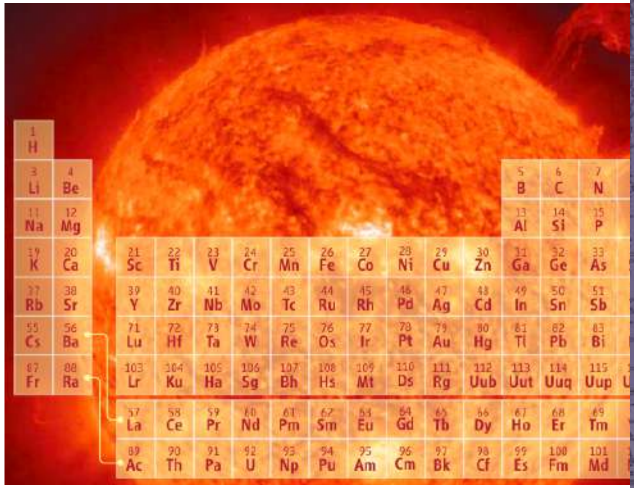
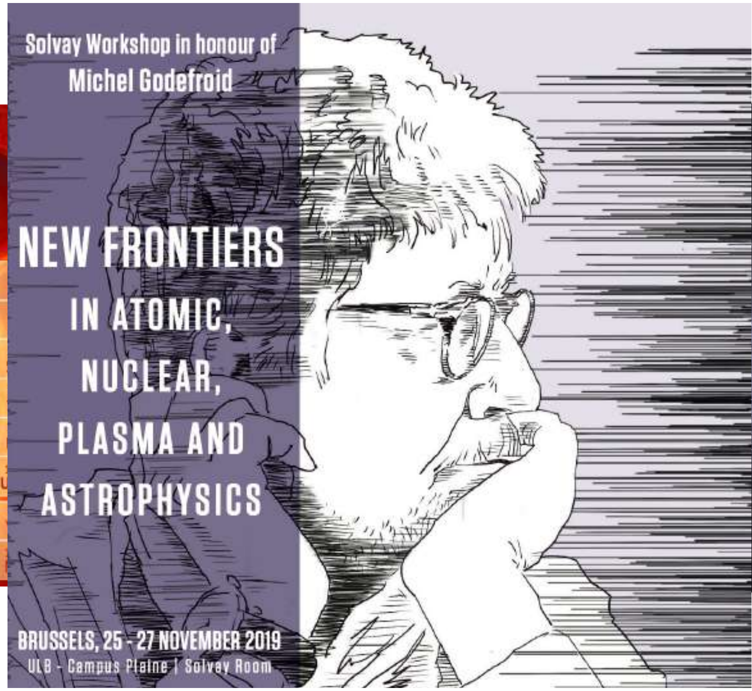
Precision stellar spectroscopy





Martin Asplund

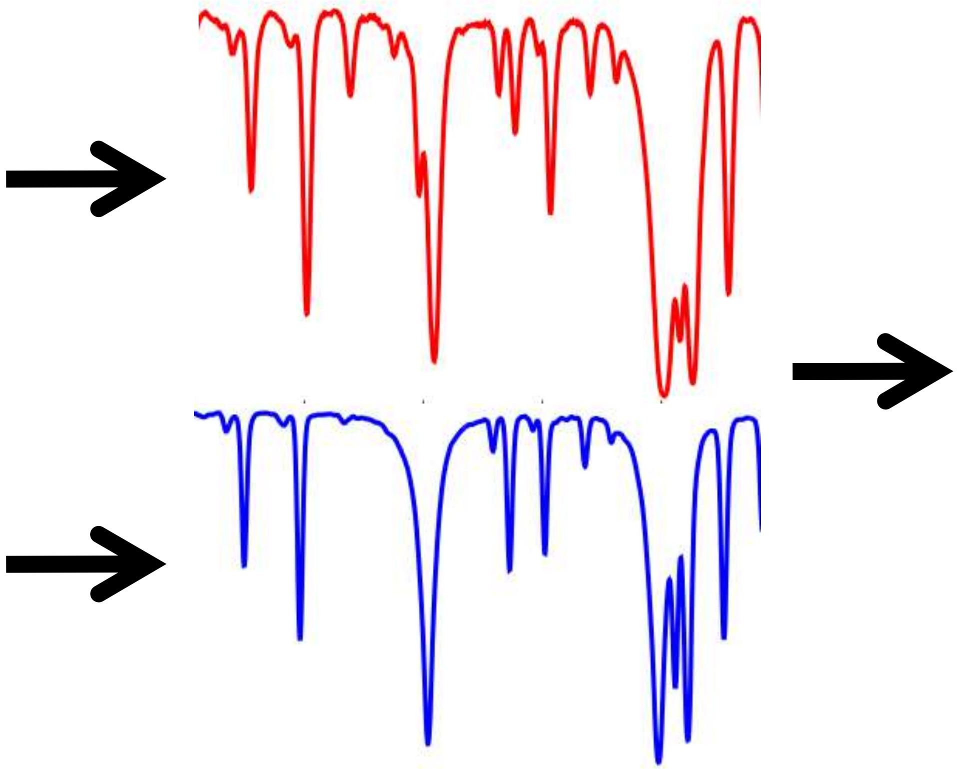
ANU
THE AUSTRALIAN NATIONAL UNIVERSITY

Australian Government
Australian Research Council

ASTRO 3D

Stellar spectroscopy

λ, λ/Δλ, S/N

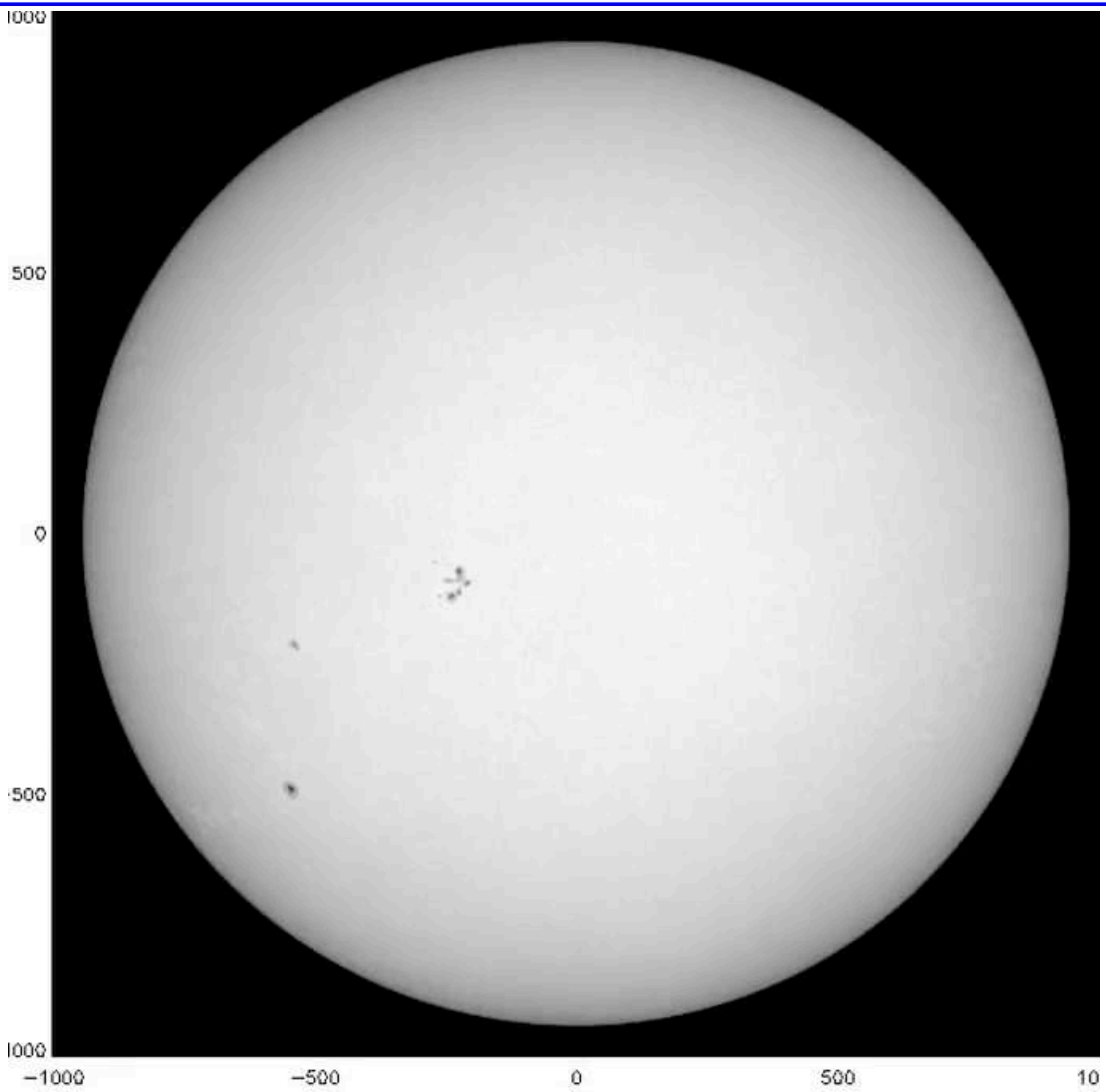


Temperature
Gravity
Radius
Mass
Chemistry
Age
Rotation
Magnetic fields
etc

Stellar Atmosphere
Radiative transfer
Atomic data

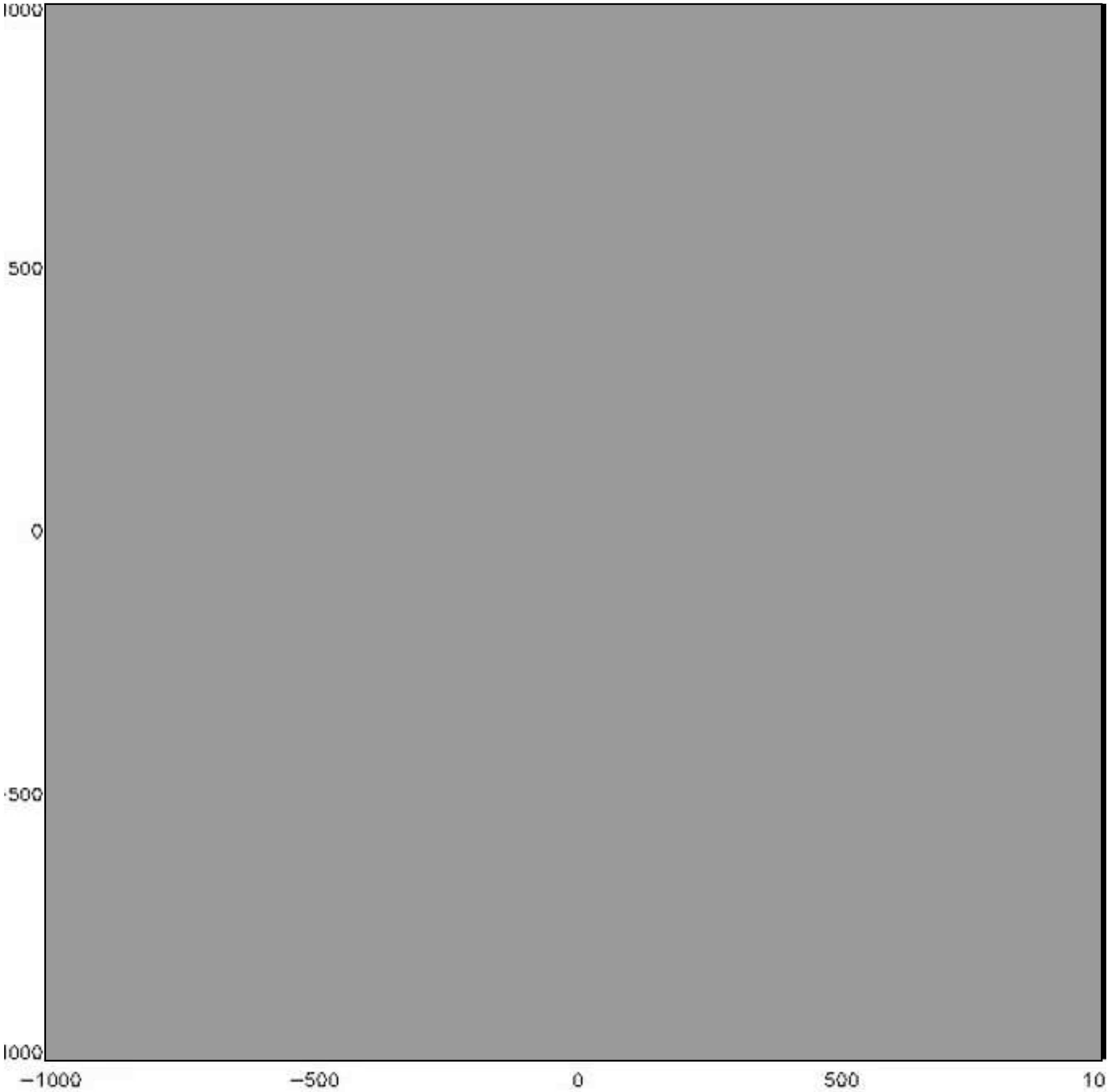
Optimal solution
Speed
Robustness

Stellar surface convection



© Mats Carlsson (Oslo)

Stellar surface convection

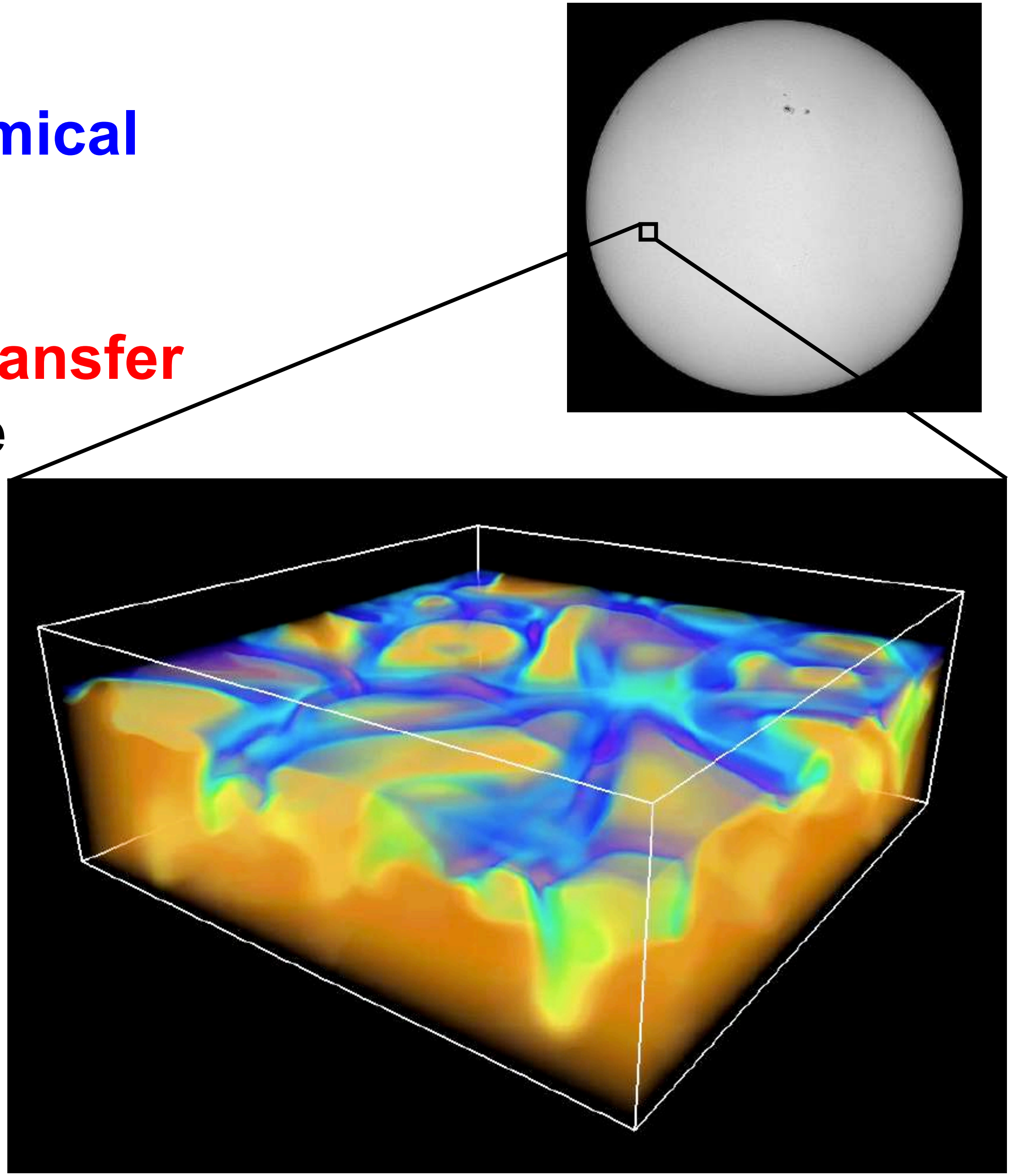


3D stellar atmosphere models

Ingredients:

- Radiative-hydrodynamical
- Time-dependent
- 3-dimensional
- Simplified radiative transfer

Essentially parameter free



For the aficionados:

Stagger-code (Nordlund et al.)
MHD EoS (Mihalas et al.)
Opacities (Gustafsson et al.)
Opacity binning

Non-LTE radiative transfer

~~LTE: Boltzmann, Saha & Planck distributions (local T only)~~

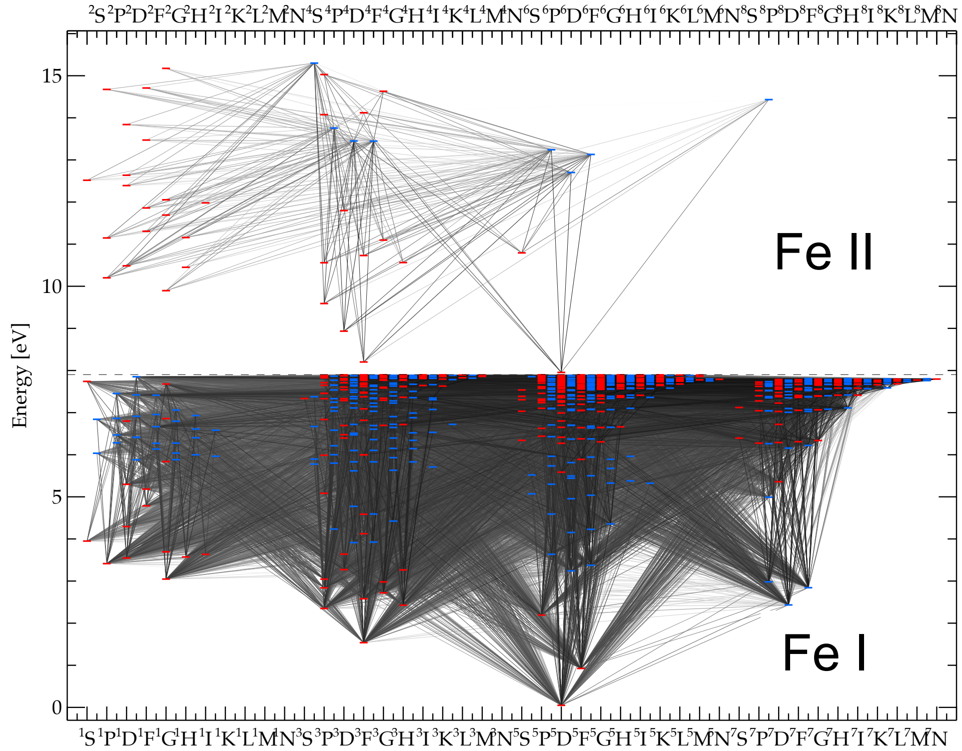
Non-LTE: Rate equations simultaneous w/ radiative transfer equation

$$\frac{\mathrm{d}n_i(\vec{r})}{\mathrm{d}t} = \sum_{j \neq i}^{N} n_j(\vec{r}) P_{ji}(\vec{r}) - n_i(\vec{r}) \sum_{j \neq i}^{N} P_{ij}(\vec{r}) = 0 \qquad \frac{\mathrm{d}I_\nu}{\alpha_\nu \mathrm{d}s} = S_\nu - I_\nu$$

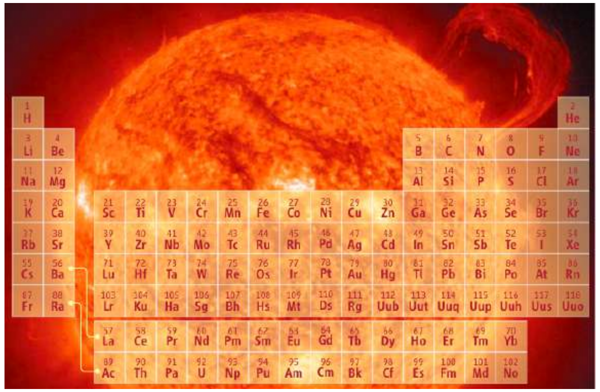
Huge amount of atomic data needed

(opacity, gf, photo-ionisation, H & e- collisions, broadening, HFS, charge transfer, etc)

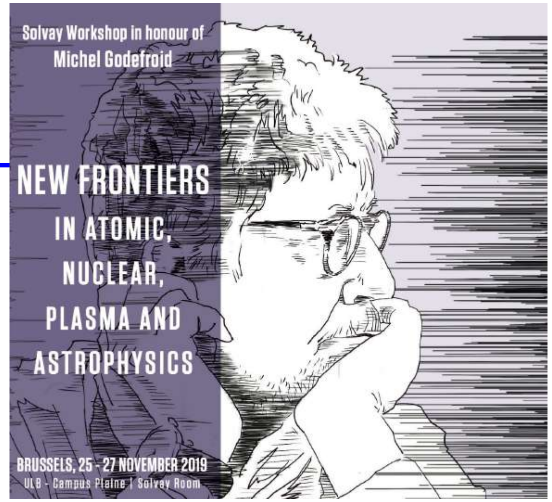
Merci Michel et collègues!

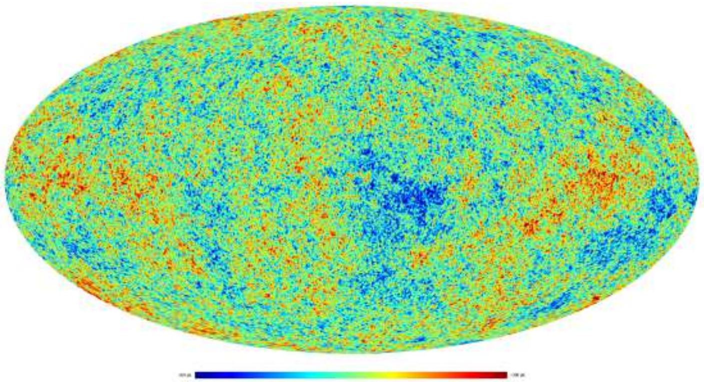


Precision spectroscopy

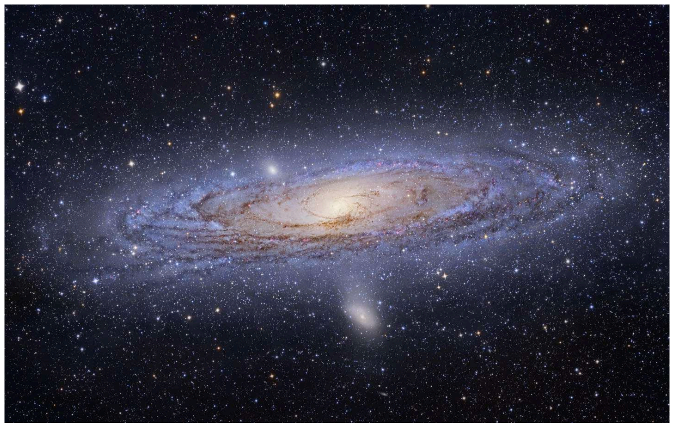


Does the Sun have a subsolar metallicity?





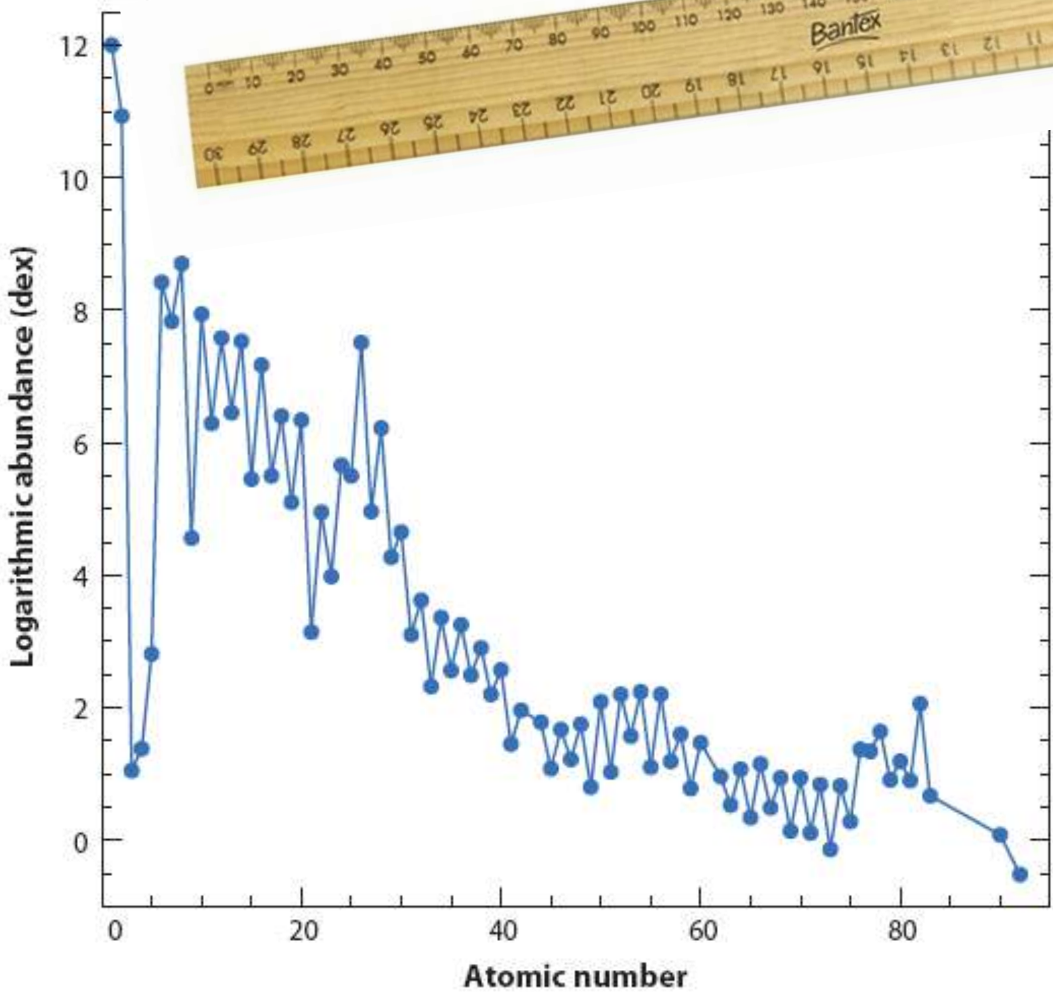
Cosmological Li problems



Galactic archaeology

Solar chemical composition

Fundamental yardstick for all astronomy



Main partners in crime

Nicolas Grevesse

Pat Scott

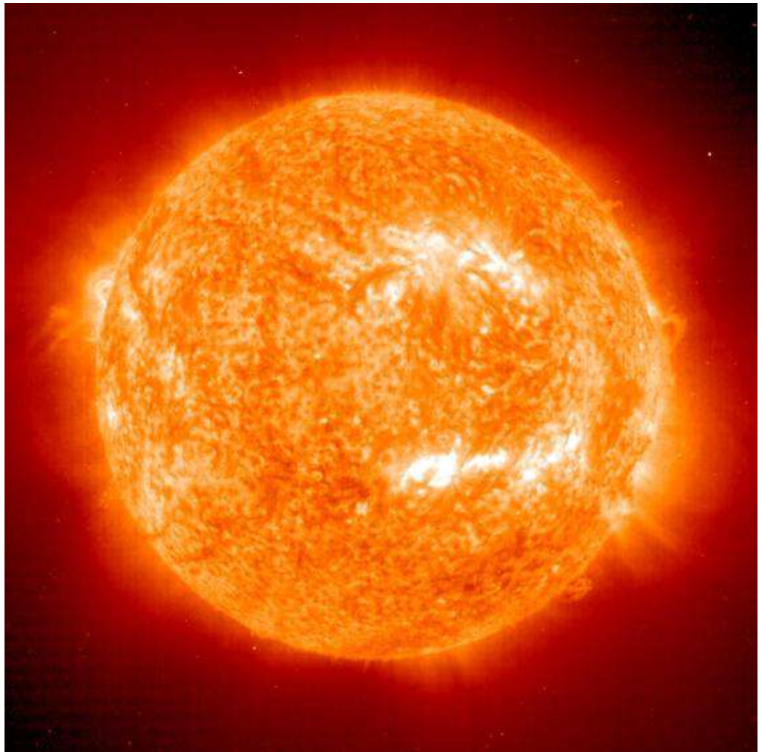
(+ many collaborators)

Past and present PhD students + postdocs:
Anish Amarsi, Maria Bergemann, Remo Collet, Wolfgang Hayek, Karin Lind, Zazralt Magic, Jorge Melendez, Thomas Nordlander, Tiago Pereira, Aldo Serenelli, Regner Trampedach

Solar system abundances

Meteorites
Mass spectroscopy
Very high accuracy
Element depletion

Solar atmosphere
Solar spectroscopy
Modelling-dependent
Very little depletion



Solar abundances revisited

- Asplund et al., 2009, ARAA, 47, 481
- Realistic 3D model for the solar atmosphere
- 3D/non-LTE spectrum formation calculations
- Improved atomic and molecular input data
- Careful selection of lines
- Updated: Scott et al. 2015ab, Grevesse et al. 2015ab, Amarsi et al. 2015, 2018, 2019

Element	Anders & Grevesse (1989)	Asplund et al. (2009)	Difference
Carbon	8.56+/-0.06	8.43+/-0.05	-26%
Nitrogen	8.05+/-0.04	7.83+/-0.05	-40%
Oxygen	8.93+/-0.03	8.69+/-0.05	-42%

Note: logarithmic scale with H defined to have 12.00

Oxygen diagnostics

- Discordant results in 1D: log O~8.6-8.9
- Excellent agreement in 3D: log O=8.70±0.05
- Asplund et al. (2009), Amarsi et al. (2018)

Lines	MARCS (1D)	Holweger-Mueller (1D)	3D
[O I]	8.69+/-0.05	8.73+/-0.05	8.70+/-0.05
O I	8.62+/-0.05	8.69+/-0.05	8.70+/-0.05
OH, dv=0	8.78+/-0.03	8.83+/-0.03	8.71+/-0.03
OH, dv=1	8.75+/-0.03	8.86+/-0.03	8.71+/-0.02

Two often-used 1D model atmospheres

[O I]: blends

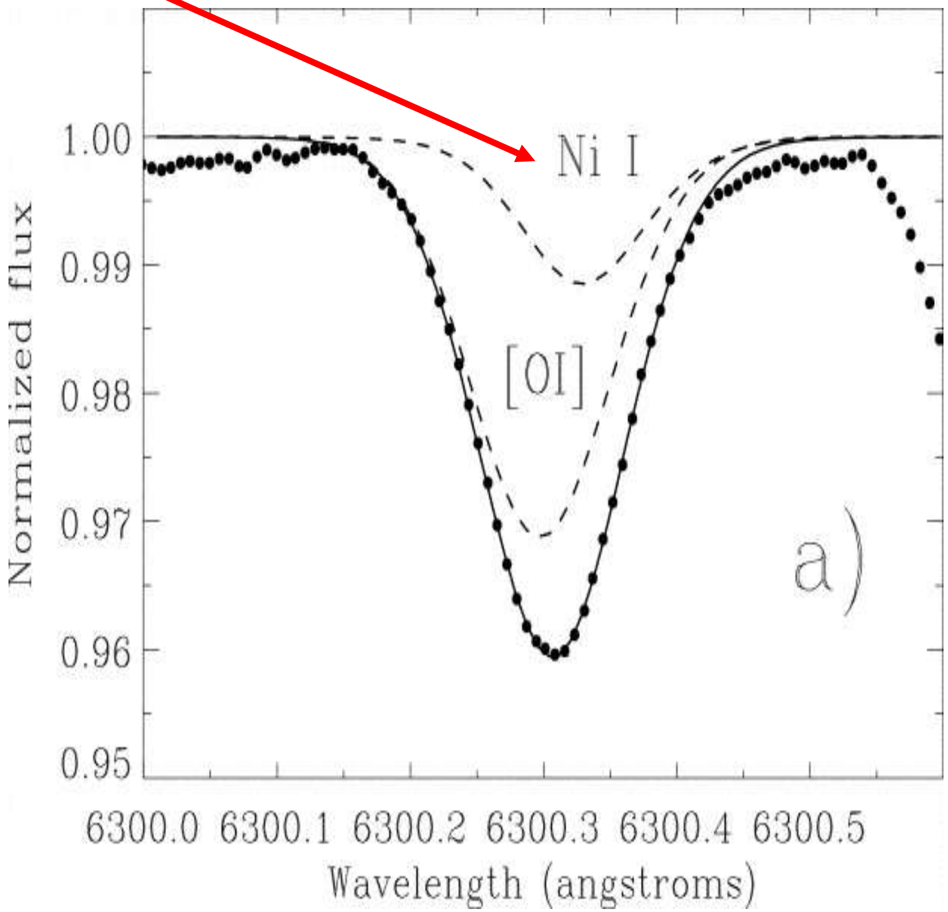
Allende Prieto et al. 2001:
Blend with Ni: -0.19 dex

Johansson et al. 2003:
gf-value of Ni I blend measured experimentally

Scott et al. 2009, 2015:
New solar Ni abundance

↓

Asplund et al. 2009,
Amarsi et al. 2018:
log O = 8.70±0.05



O I: non-LTE effects

High-excitation O I lines are sensitive to non-LTE

Non-LTE - LTE≈-0.2 dex

Pereira et al. 2009:

Use observed center-to-limb variations and full 3D non-LTE to determine poorly known H collisions

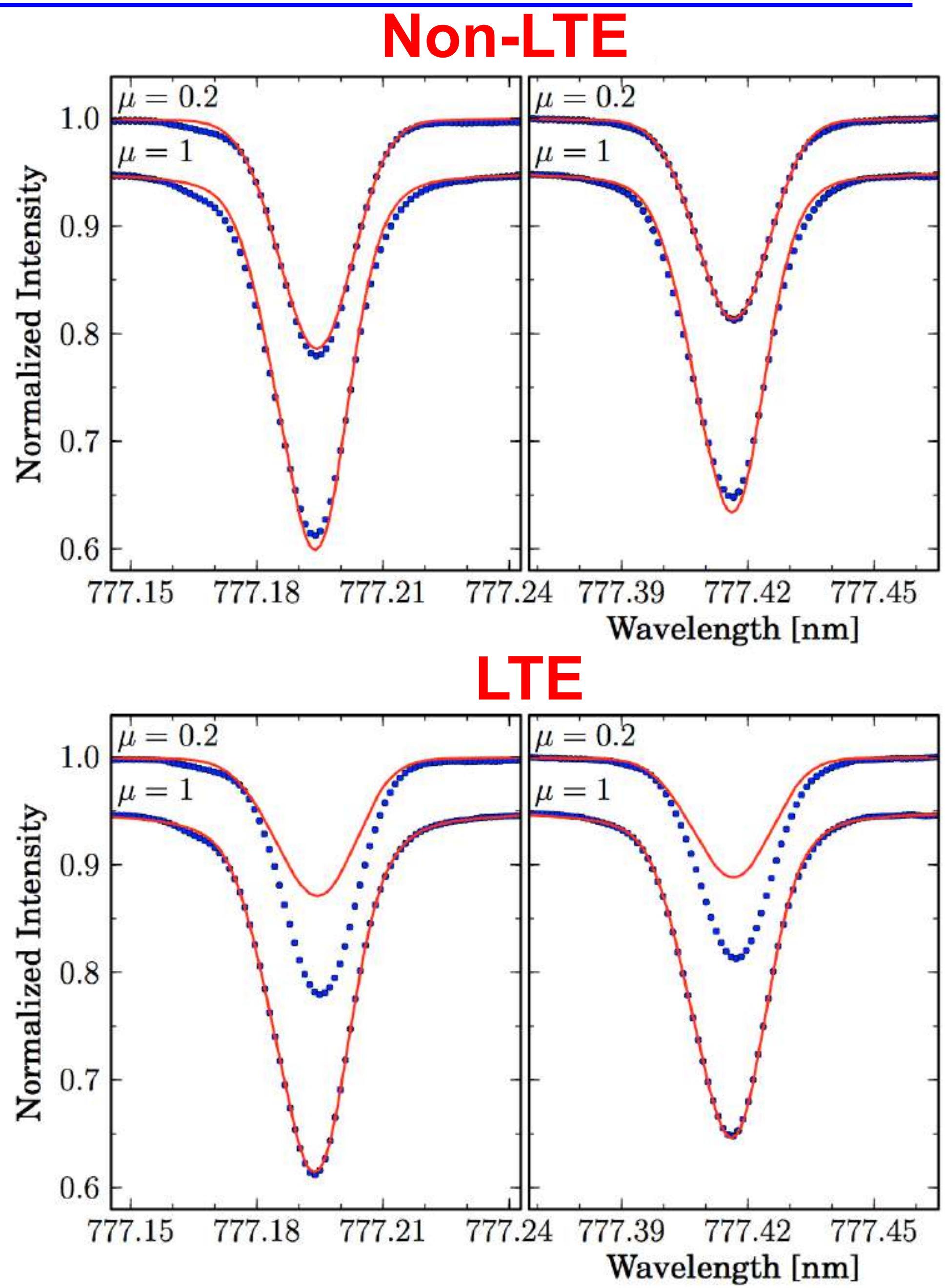
↓

Asplund et al. 2009:

log O=8.68±0.05

Amarsi et al. 2018:

log O=8.69±0.03



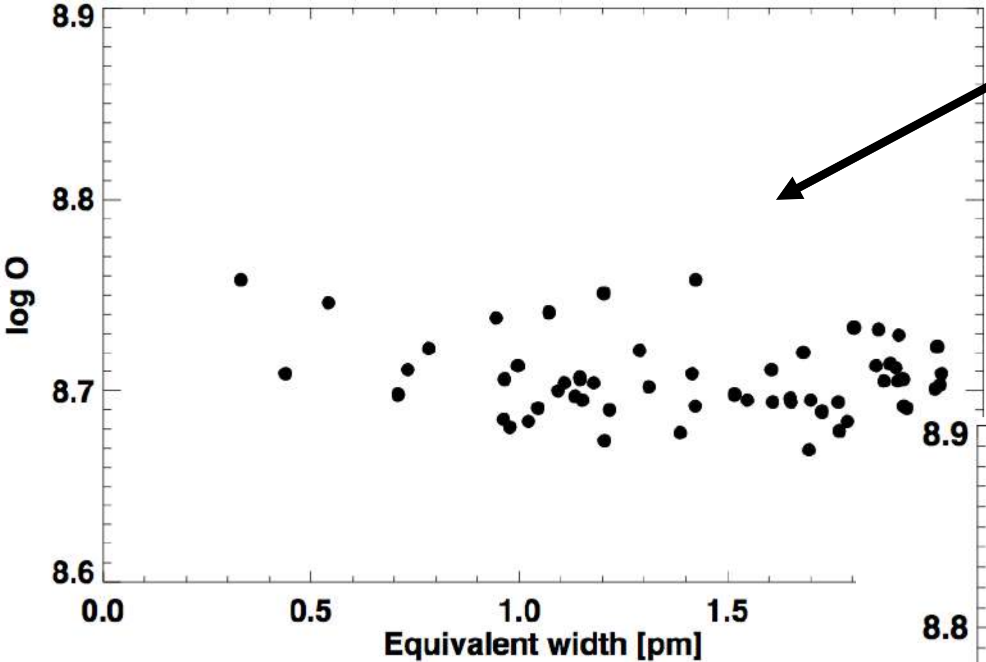
OH lines: 3D effects

Molecular lines are very temperature sensitive

3D model: different mean T(τ) and T inhomogenities

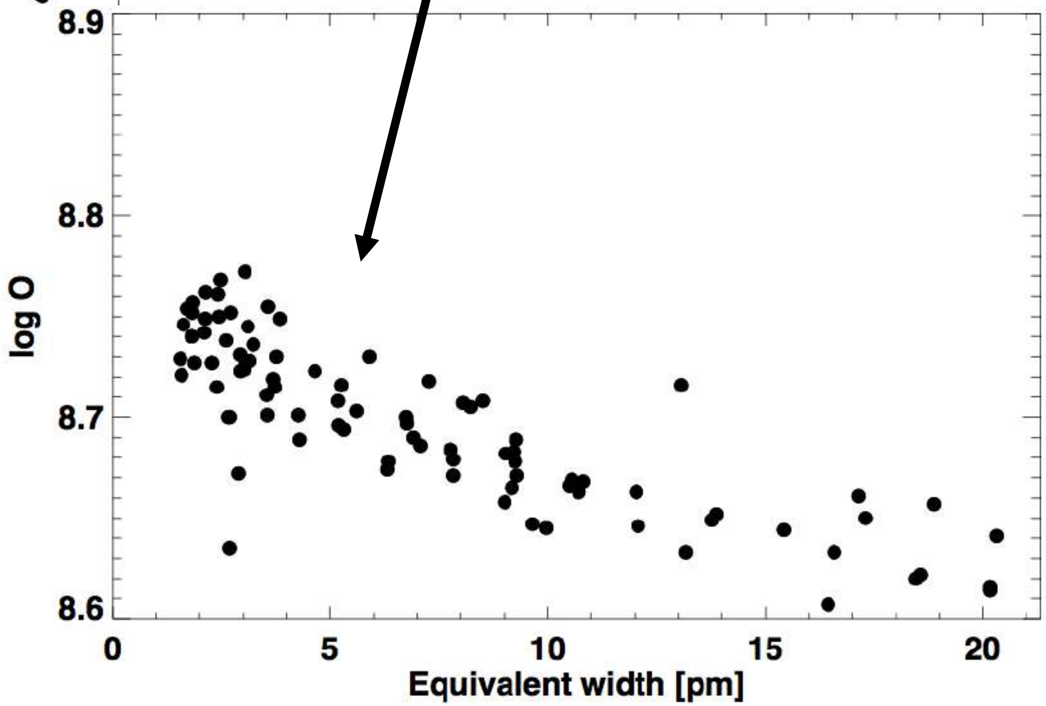
Vibration-rotation lines:

log O=8.71±0.02



Pure rotation lines:

log O=8.71±0.03



Complete solar inventory

Table 1 Element abundances in the present-day solar photosphere. Also given are the corresponding values for CI carbonaceous chondrites (Lodders, Palme & Gail 2009). Indirect photospheric estimates have been used for the noble gases (Section 3.9)

Z	Element	Photosphere	Meteorites	Z	Element	Photosphere	Meteorites
1	H	12.00	8.22 ± 0.04	44	Ru	1.75 ± 0.08	1.76 ± 0.03
2	He	[10.93 ± 0.01]	1.29	45	Rh	0.91 ± 0.10	1.06 ± 0.04
3	Li	1.05 ± 0.10	3.26 ± 0.05	46	Pd	1.57 ± 0.10	1.65 ± 0.02
4	Be	1.38 ± 0.09	1.30 ± 0.03	47	Ag	0.94 ± 0.10	1.20 ± 0.02
5	B	2.70 ± 0.20	2.79 ± 0.04	48	Cd		1.71 ± 0.03
6	C	8.43 ± 0.05	7.39 ± 0.04	49	In	0.80 ± 0.20	0.76 ± 0.03
7	N	7.83 ± 0.05	6.26 ± 0.06	50	Sn	2.04 ± 0.10	2.07 ± 0.06
8	O	8.69 ± 0.05	8.40 ± 0.04	51	Sb		1.01 ± 0.06
9	F	4.56 ± 0.30	4.42 ± 0.06	52	Te		2.18 ± 0.03
32	Ge	3.65 ± 0.10	3.58 ± 0.04	76	Os	1.40 ± 0.08	1.35 ± 0.03
33	As		2.30 ± 0.04	77	Ir	1.38 ± 0.07	1.32 ± 0.02
34	Se		3.34 ± 0.03	78	Pt		1.62 ± 0.03
35	Br		2.54 ± 0.06	79	Au	0.92 ± 0.10	0.80 ± 0.04
36	Kr	[3.25 ± 0.06]	−2.27	80	Hg		1.17 ± 0.08
37	Rb	2.52 ± 0.10	2.36 ± 0.03	81	Tl	0.90 ± 0.20	0.77 ± 0.03
38	Sr	2.87 ± 0.07	2.88 ± 0.03	82	Pb	1.75 ± 0.10	2.04 ± 0.03
39	Y	2.21 ± 0.05	2.17 ± 0.04	83	Bi		0.65 ± 0.04
40	Zr	2.58 ± 0.04	2.53 ± 0.04	90	Th	0.02 ± 0.10	0.06 ± 0.03
41	Nb	1.46 ± 0.04	1.41 ± 0.04	92	U		−0.54 ± 0.03
42	Mo	1.88 ± 0.08	1.94 ± 0.04				

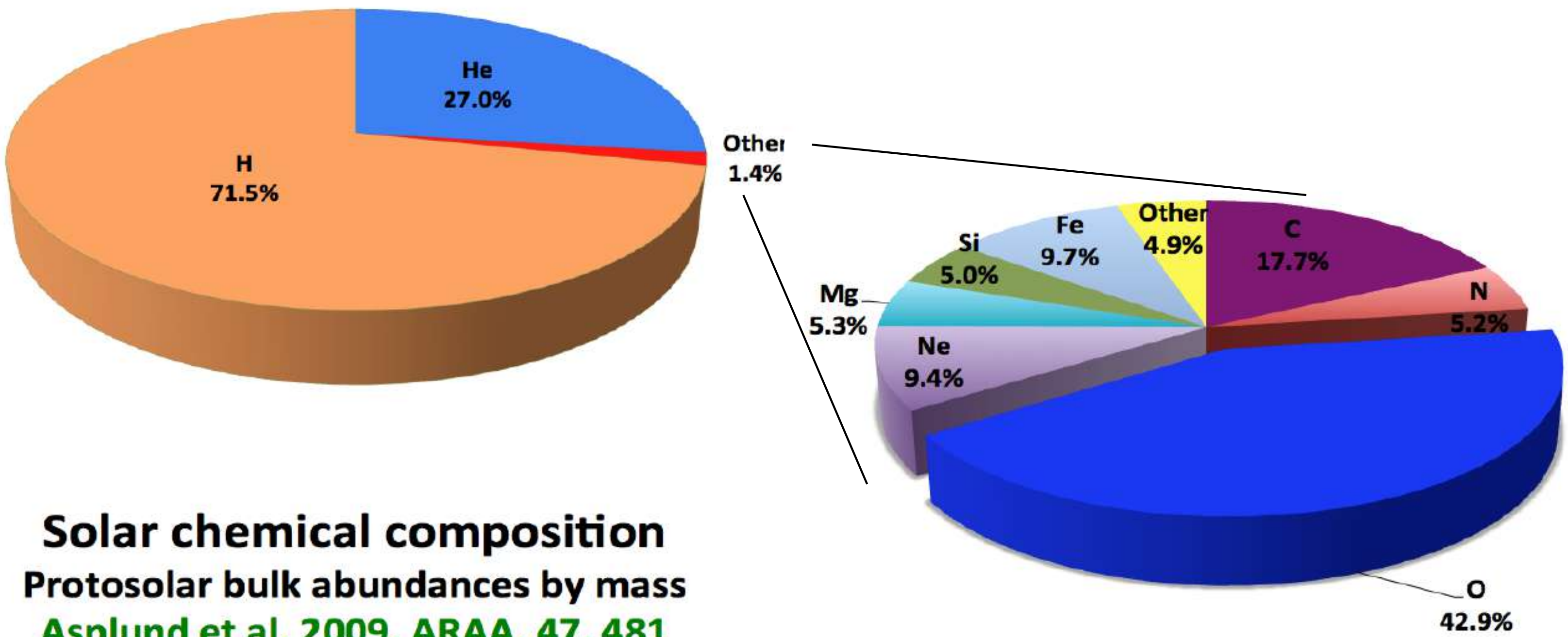
Asplund et al. 2009, ARAA, 47, 481;
Scott et al. 2015ab; Grevesse et al. 2015:
3D-based analysis of all elements
Statistical and systematic errors
included in total uncertainties

Sun has a subsolar metallicity

~~Z=0.021~~ (Anders & Grevesse 1989)

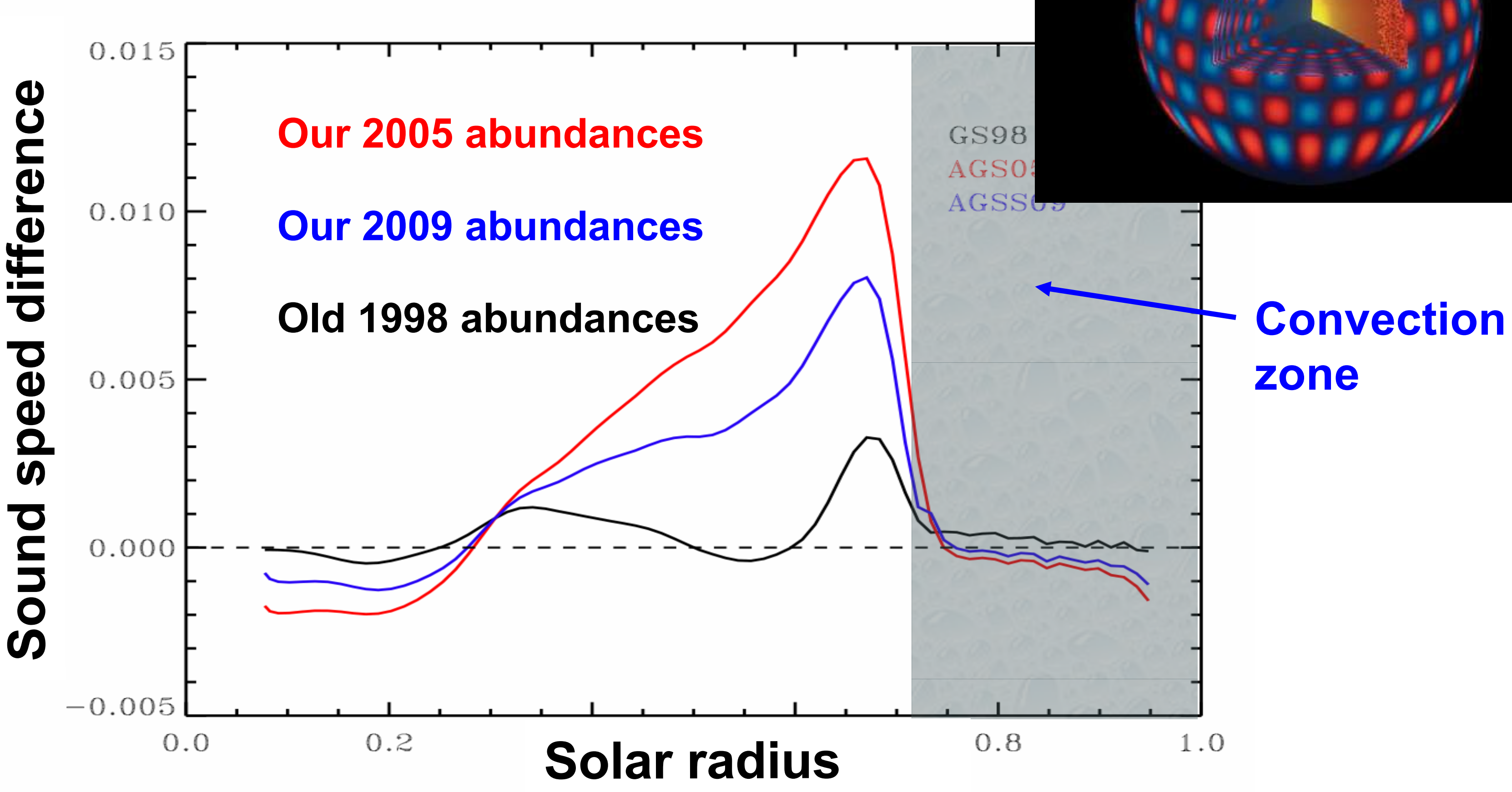
↓

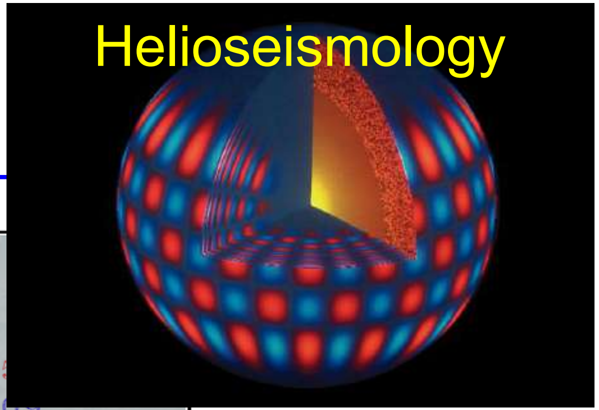
Z=0.014±0.002 (Asplund et al. 2009)



Solar chemical composition
Protosolar bulk abundances by mass
Asplund et al. 2009, ARAA, 47, 481

Trouble in paradise



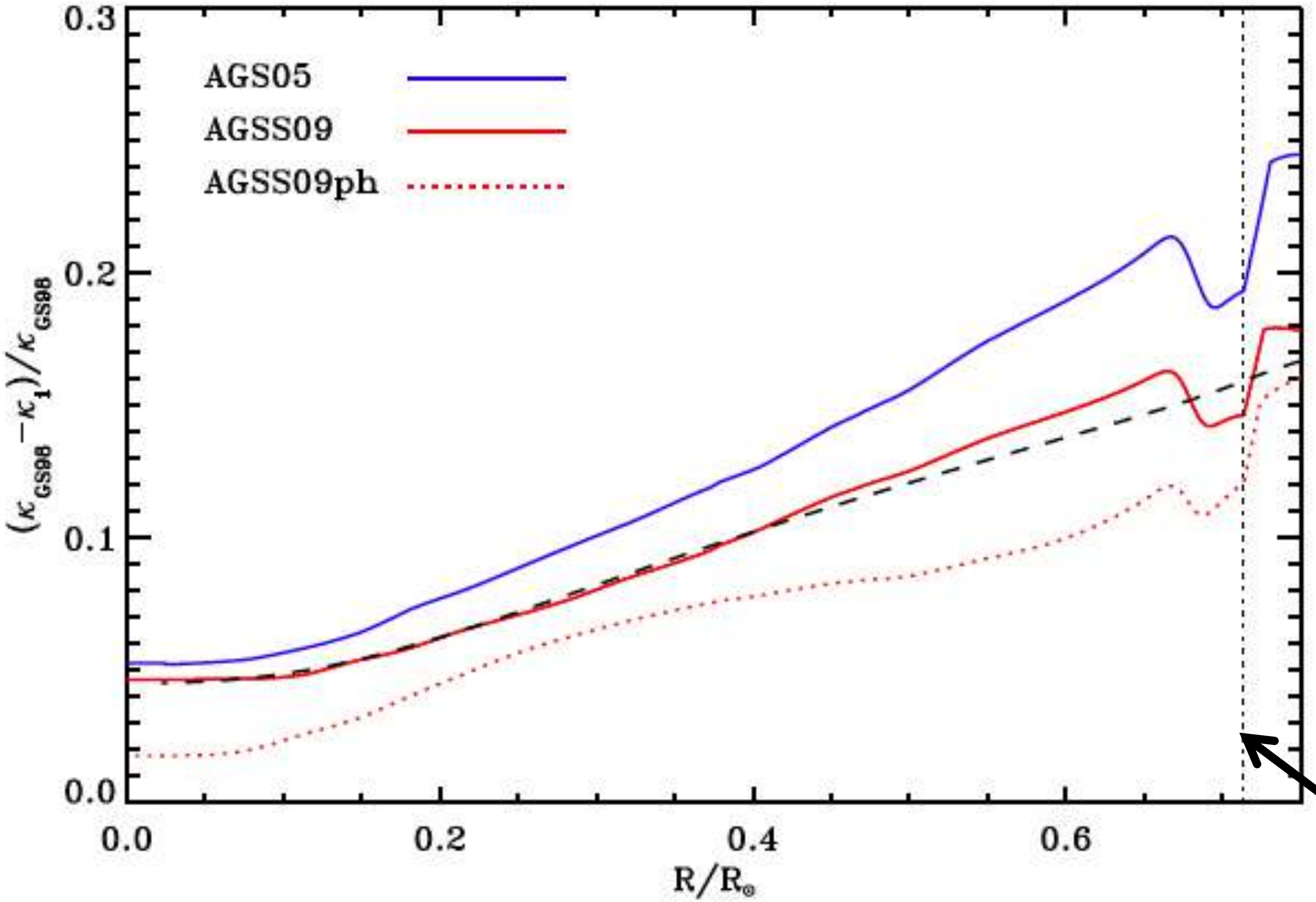


Solar interior models with new abundances are in conflict with helioseismology

- Wrong sound speed
- Wrong depth of convection zone: R=0.723 vs 0.713±0.001
- Wrong surface helium abundance: Y=0.235 vs 0.248±0.004

Missing opacity?

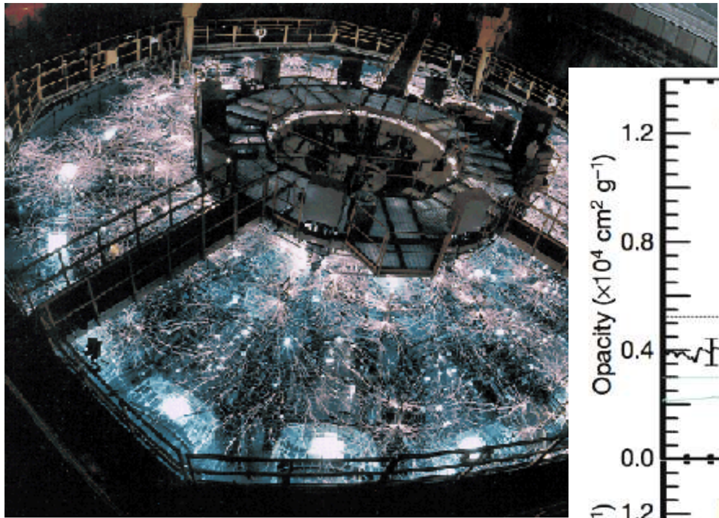
Serenelli (2009): Higher opacities by ~10-15% below the convection zone would restore agreement

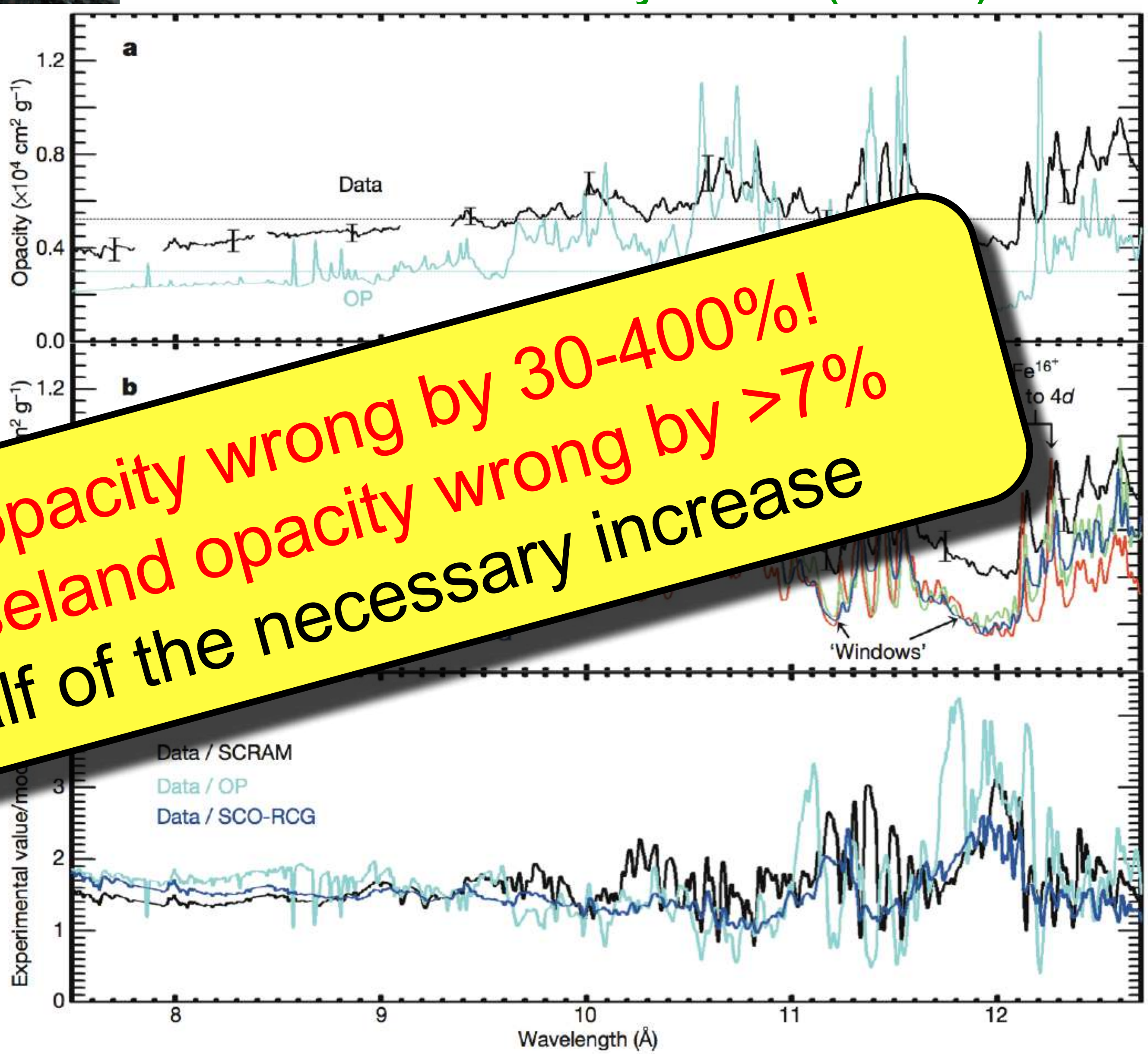


Bottom of CZ

Missing opacity

Bailey et al. (2014)





Measurements of opacities at conditions bottom of convection using Sand Pinch facility

Fe opacity wrong by 30-400%!

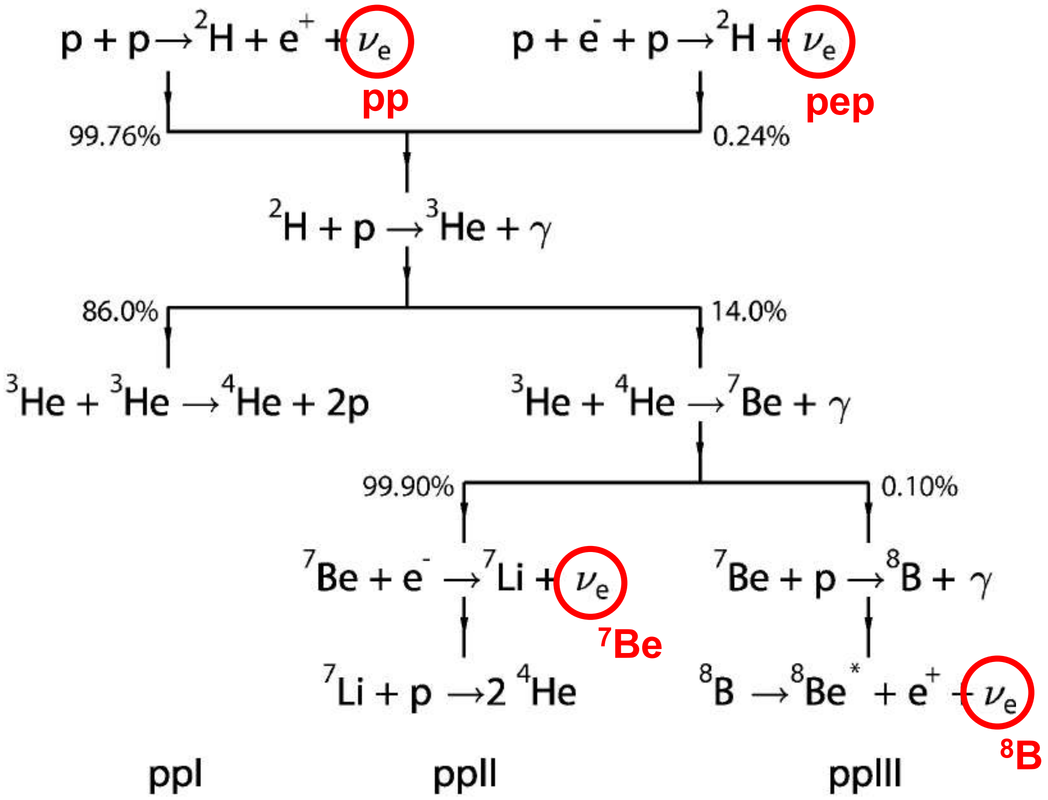
Rosseland opacity wrong by >7%

Half of the necessary increase

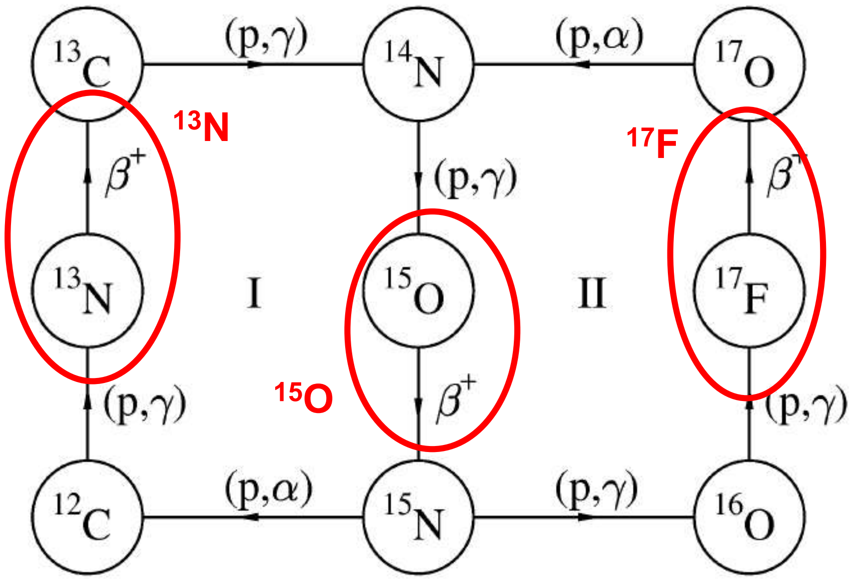
Solar composition: neutrinos

Solar hydrogen burning

pp chains



CNO cycle



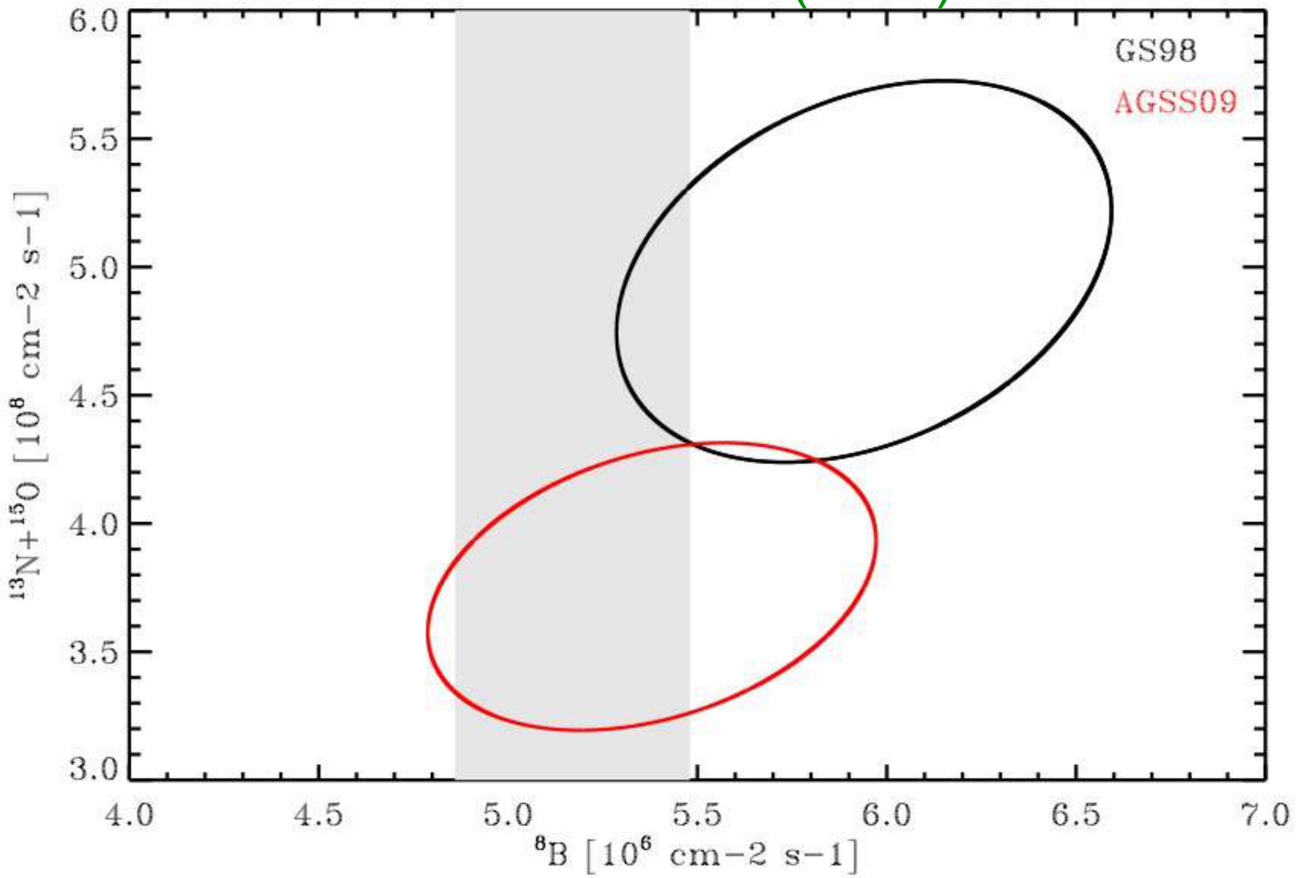
^{8}B vs $^{13}N+^{15}O$ neutrinos

Prospect of discriminating between solar chemical compositions with ^{13}N and ^{15}O neutrinos

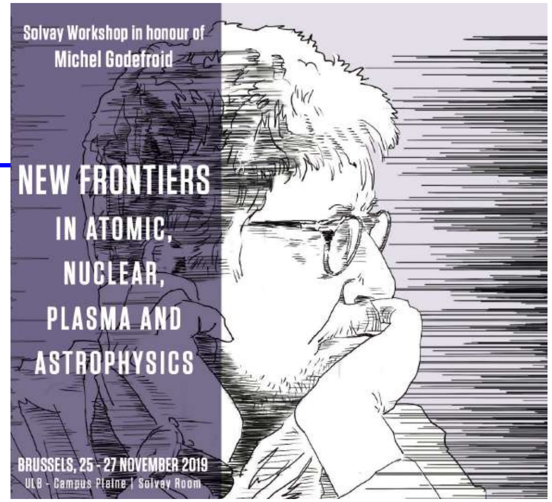
Borexino: expect 10% uncertainty $\Rightarrow$ 3σ result

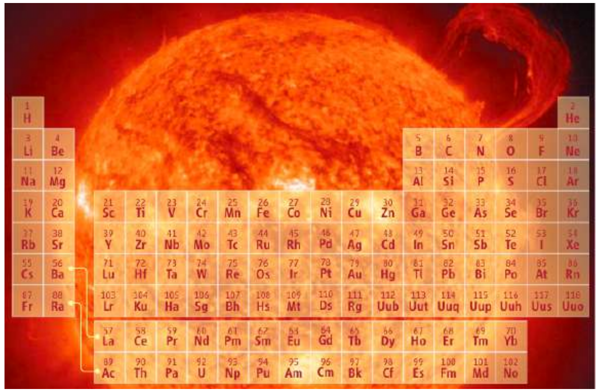
(Improved p+^{14}N cross-section from LUNA experiment will also help)

Serenelli et al. (2009):

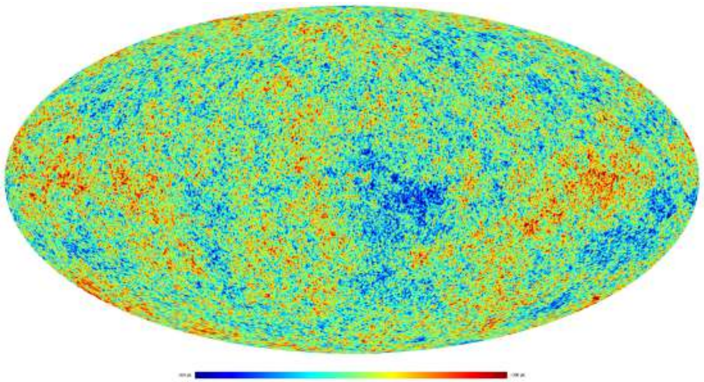


Precision spectroscopy

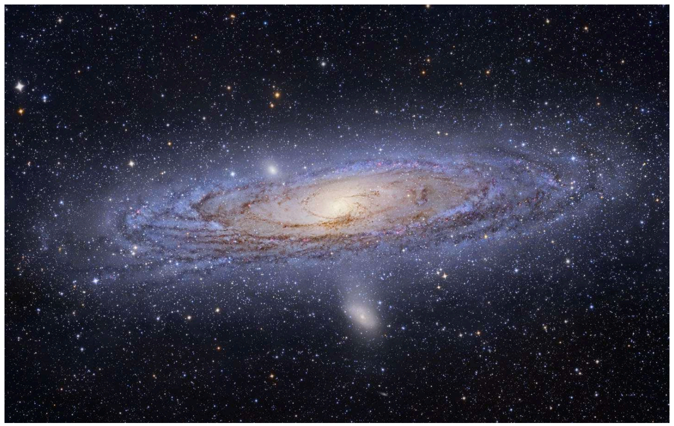




Does the Sun have a subsolar metallicity?

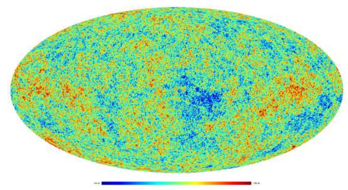


Cosmological Li problems

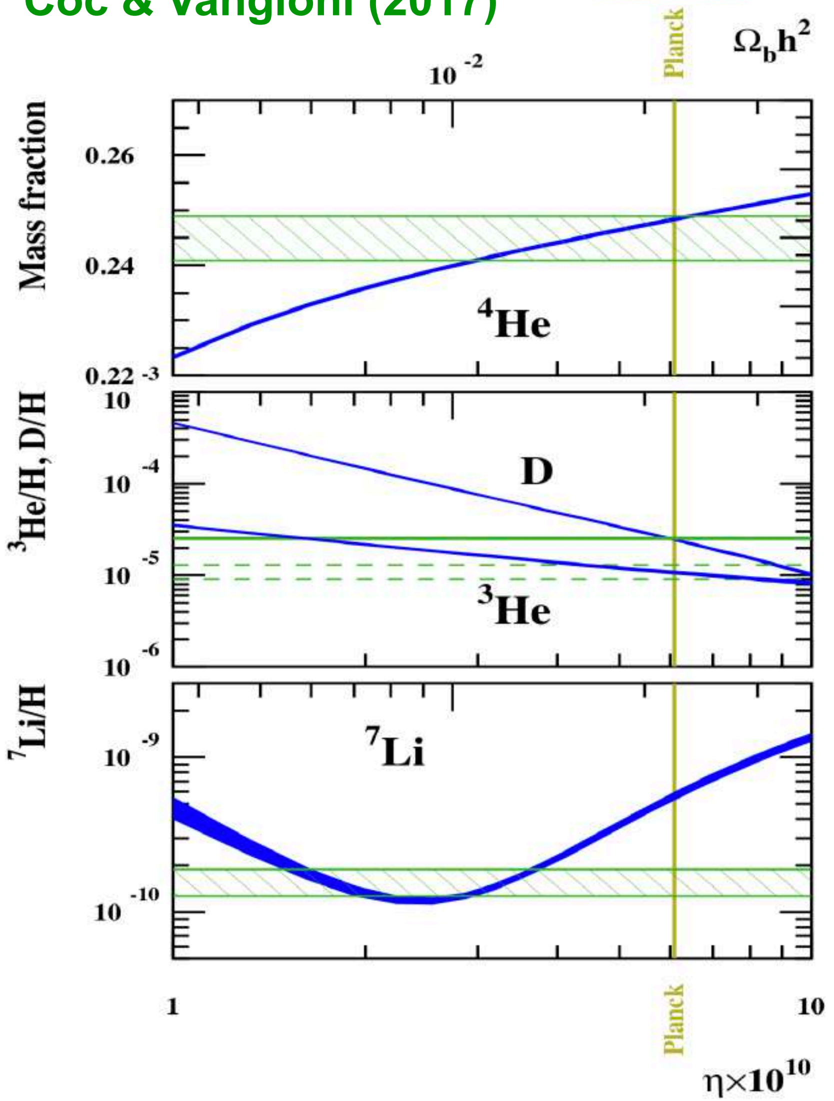


Galactic archaeology

Big Bang nucleosynthesis



Coc & Vangioni (2017)



Abundances of D, ^{3}He, ^{4}He, ^{7}Li determined by baryon-to-photon density η

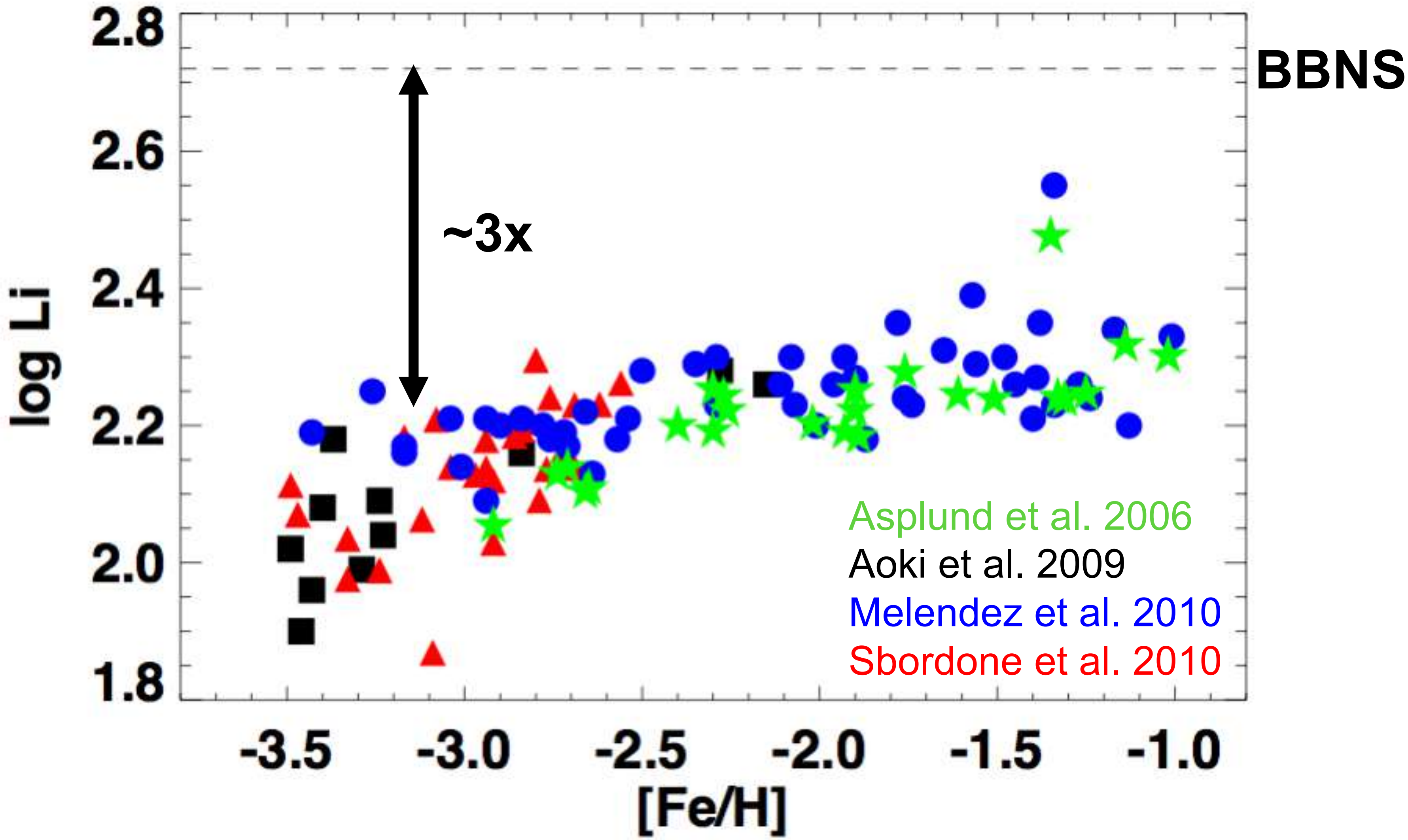
Coc & Vangioni (2017):

$^7Li/H=(5.61\pm0.24)\times10^{-10}$

$\Rightarrow \log \varepsilon_{Li} = 2.75\pm0.04$

Cosmological ^{7}Li problem

Spite & Spite 1982: Primordial Li in metal-poor stars?

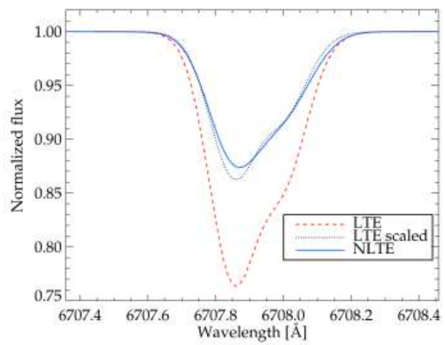


Plateau? Slope? Scatter? Li-deficient stars?

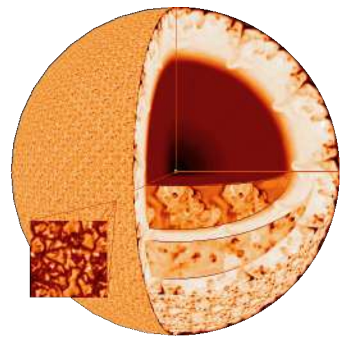
Something wrong with…

- Big Bang nucleosynthesis?

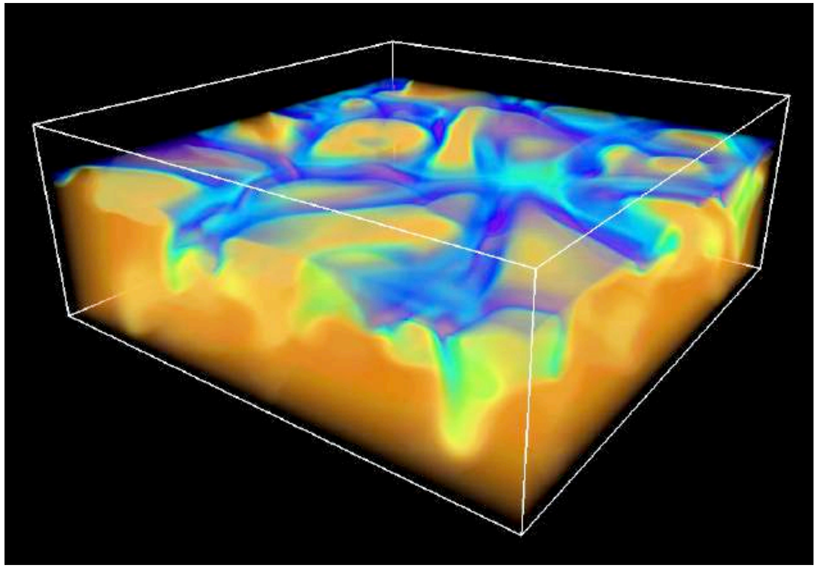
- Spectroscopic analysis?

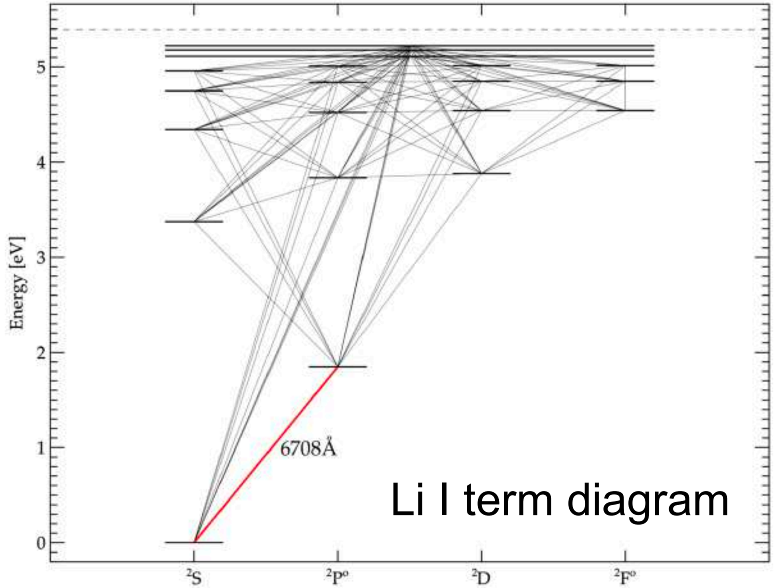


- Stellar Li destruction?



Problems with observed Li?





3D stellar atmospheres & 3D NLTE radiative transfer

&

Improved stellar parameters (e.g. T_{eff}-scale)

Same old results!

Asplund et al. 2003, 2006
Melendez et al. 2010
Sbordone et al. 2010
Wang et al. 2019a
Reggiani et al. 2019

Li destroyed in stars?

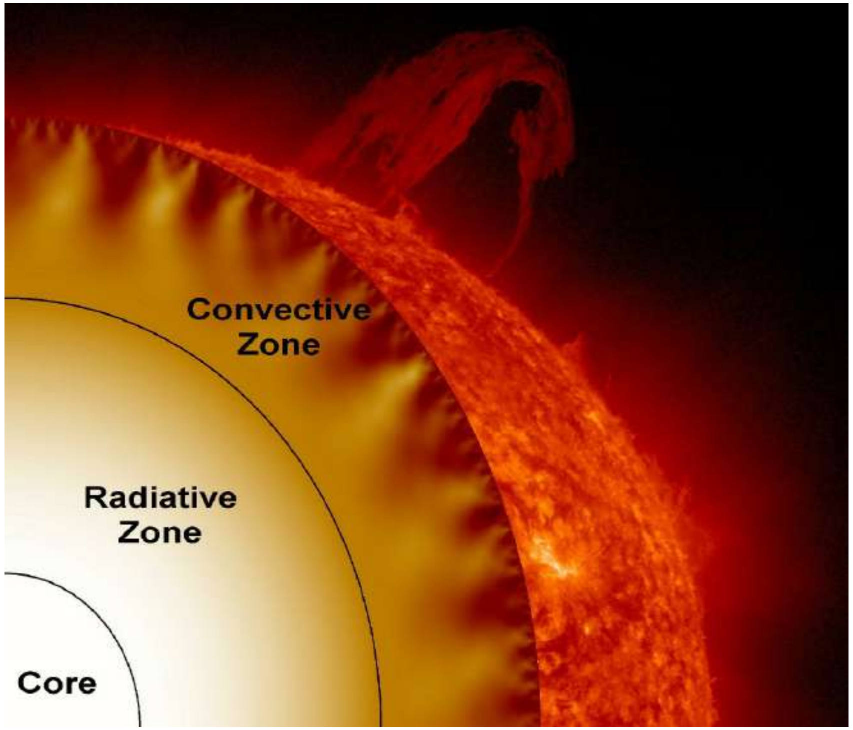
Standard stellar evolution models metal-poor stars do not predict appreciable surface Li depletion

Extra mixing?

Convection

Buffer

Li destruction
($T>2.5\times10^{6}$ K)



Extra mixing to bring Li-depleted gas back into convection zone?
Rotation? Diffusion + turbulence? Gravity waves?

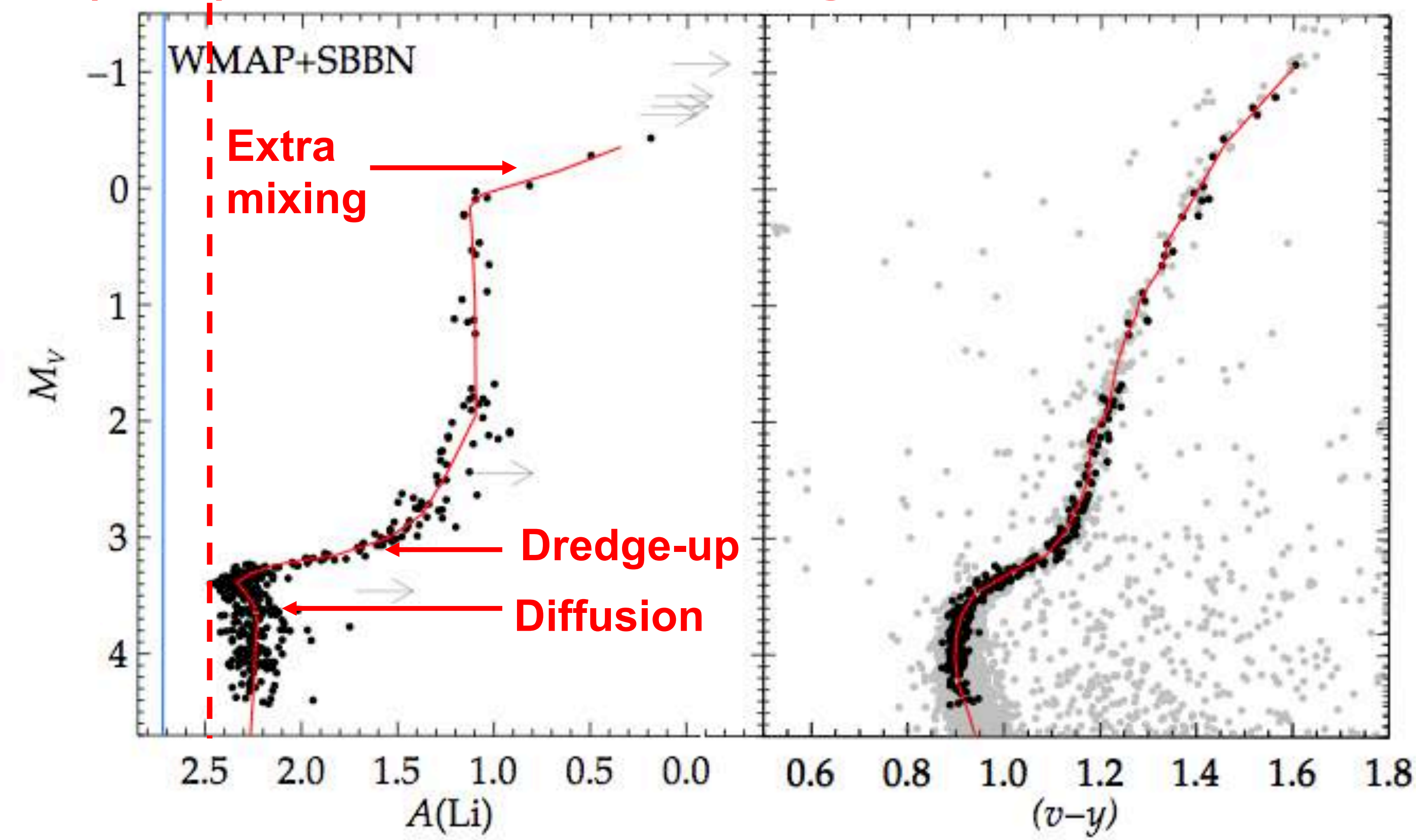
Li in globular clusters

Korn et al. 2006; Lind et al. 2009; Nordlander et al. 2016:

Li depleted in turn-off stars in NGC6397:

Signature of atomic diffusion + turbulent mixing?

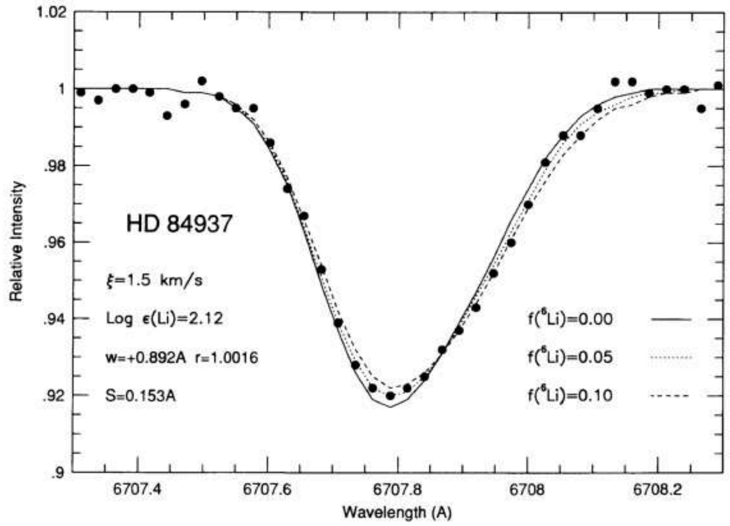
⇒ (Part) Solution to cosmological ^{7}Li problem?



Lind et al. (2009)

Lithium isotopes

If ^{7}Li is depleted by 3x in metal-poor stars then ^{6}Li is depleted by much more but…



THE ASTROPHYSICAL JOURNAL, 408:262–276, 1993 May 1

THE ^{6}Li/^{7}Li RATIO IN THE METAL-POOR HALO DWARFS HD 19445 AND HD 84937

VERNE V. SMITH,[1] DAVID L. LAMBERT,[1] AND POUL E. NISSEN[1,2]

Received 1992 September 2; accepted 1992 October 26

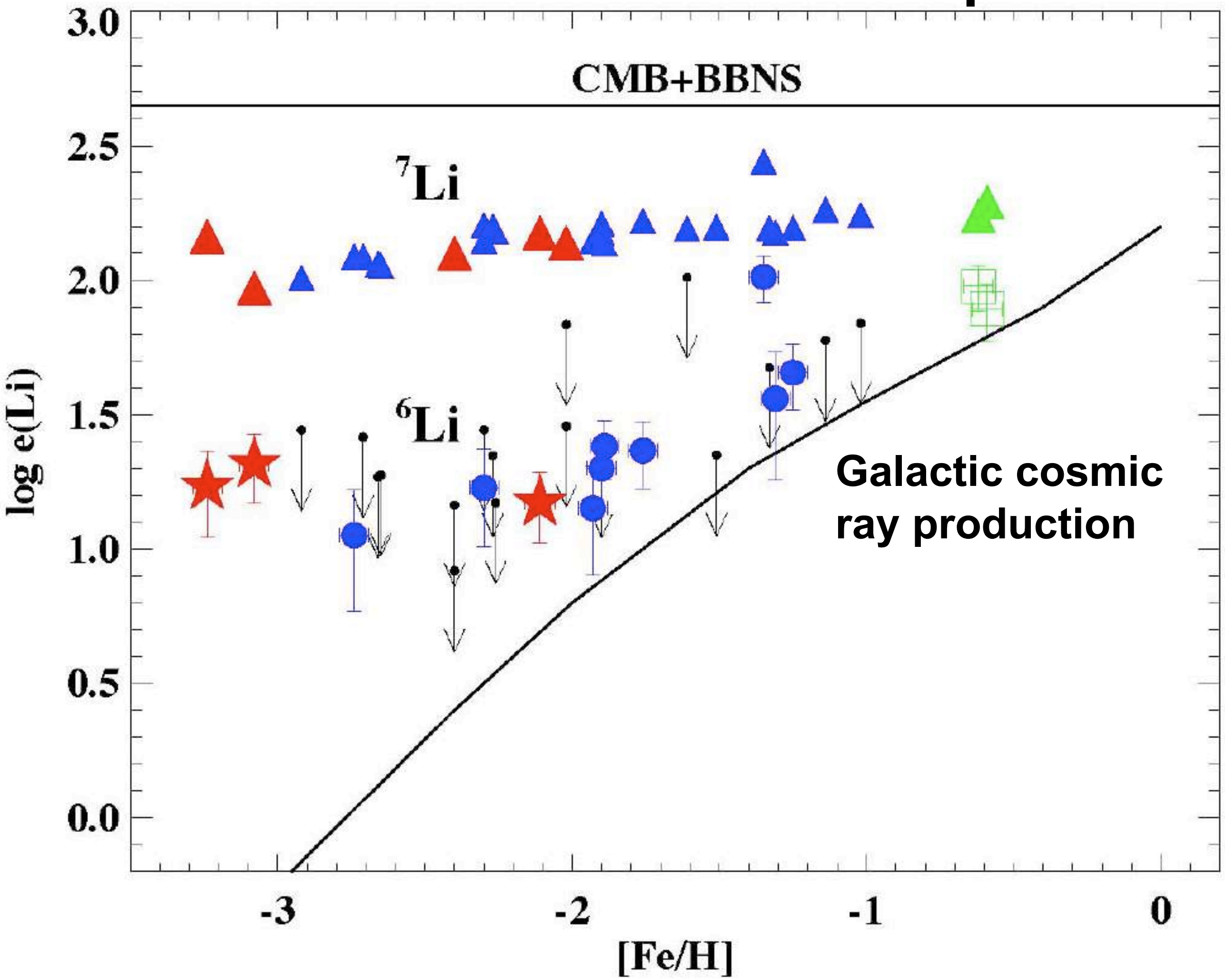
ABSTRACT

High-resolution high signal-to-noise spectra of the Li I 6707 Å line in the subdwarfs HD 19445 and HD 84937 have been analyzed for the presence of ^{6}Li. By measurement of the Li I lines's wavelength and analysis of its profile, the atmosphere of HD 84937 is shown to have a small amount of ^{6}Li: $R = {}^6\text{Li/Li} = 0.05 \pm 0.02$. For HD 19445, an upper limit is set of $R < 0.02$. The presence of ^{6}Li in HD 84937 is consistent with the mild depletion of ^{6}Li predicted by standard (nonrotating) models and the initial presence of ^{6}Li in the halo produced by (principally) α-on-α fusion reactions involving the cosmic rays that are required to account for the Be and B observed in subdwarfs. Depletion of ^{6}Li in the lower mass star HD 19445 is expected to remove the initial ^{6}Li content and, hence, the absence of ^{6}Li is expected. If Yale models of rotating subdwarfs are adopted, the predicted severe depletion of ^{6}Li and the observed survival of ^{6}Li in HD 84937 have to be reconciled. Four suggestions are made: the rotating models are inapplicable to halo dwarfs, production of ^{6}Li by cosmic rays has been underestimated, the required high initial ^{6}Li abundance of the halo was produced prior to the formation of the Galaxy, or the ^{6}Li was produced in stellar flares.

Two cosmological Li problems?

Asplund et al. 2006, 2012:
^{6}Li detected (>2σ) in
12 metal-poor stars
Beware: difficult!

With standard stellar Li depletion

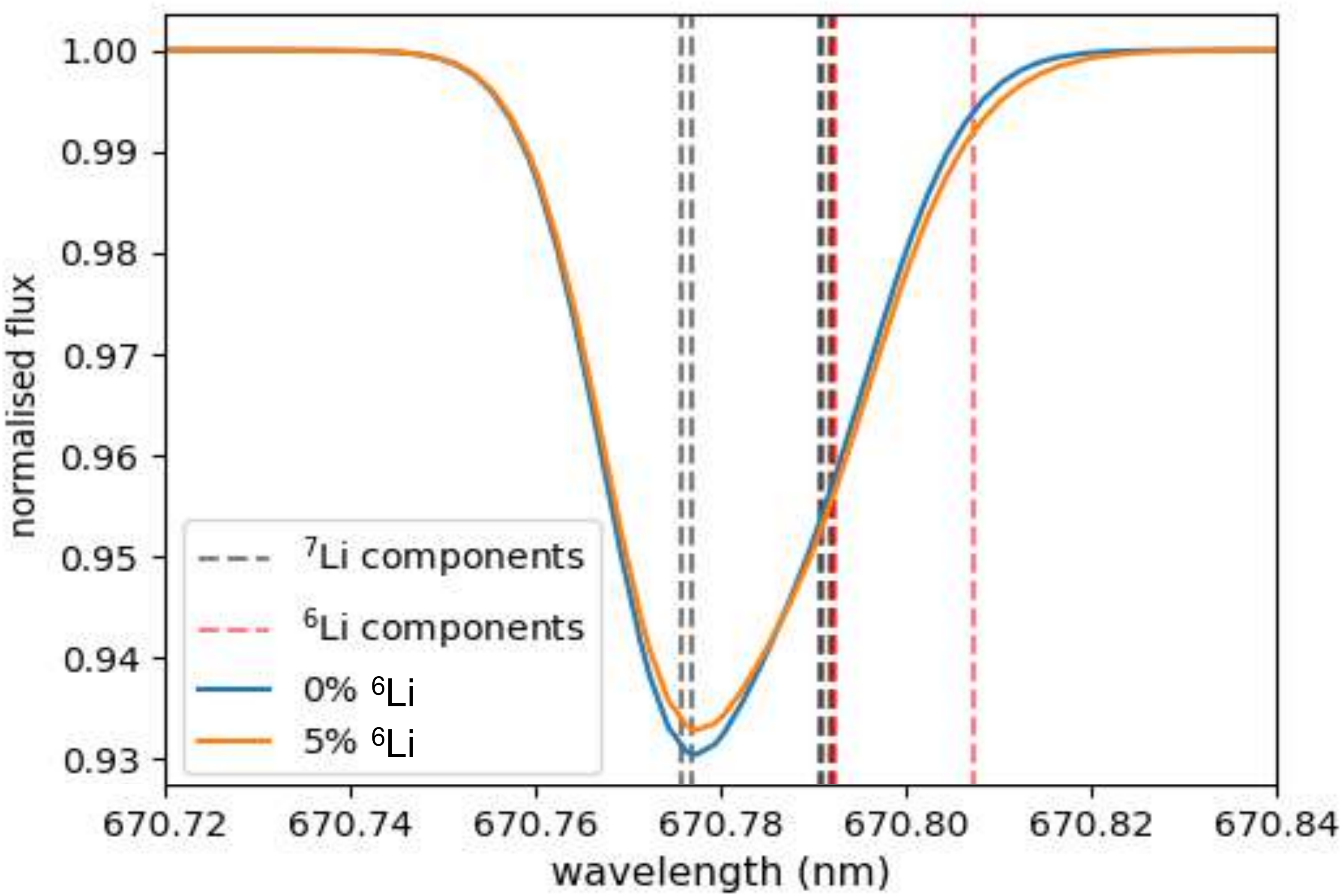


**Problem with Big Bang…?
…or stars?
…or us?**

Lithium isotope determination

Utilise isotopic shift in Li I 670.8nm resonance line

Exceptionally challenging measurement

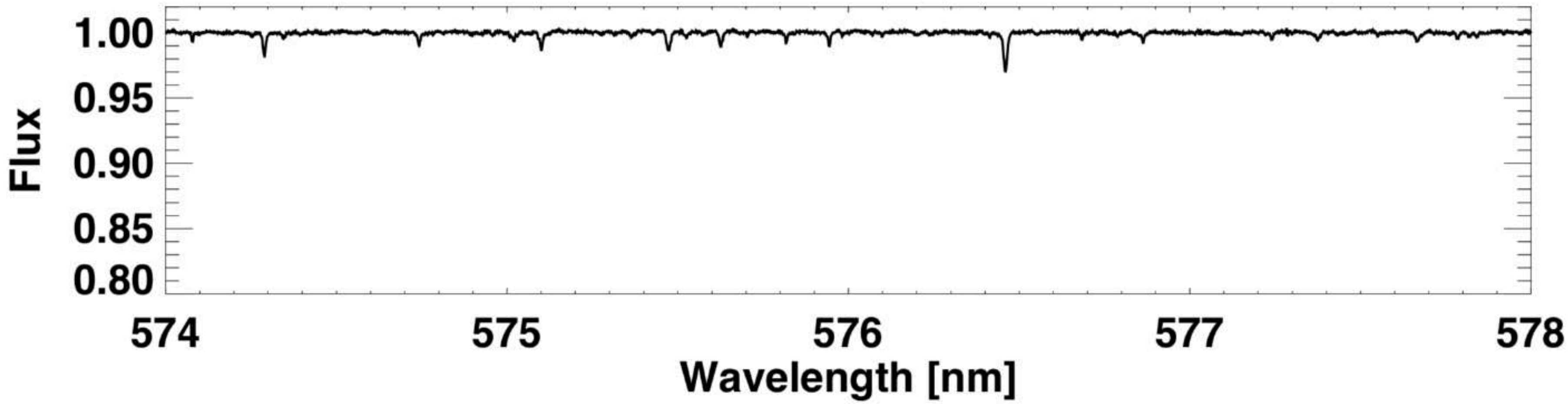


New observations

ESPRESSO spectra of HD84937 & HD140283

- S/N=1800 per pixel, R=$\lambda/\Delta\lambda$=140,000, 4 pixels/r.e.
- Extreme wavelength precision
- 3D non-LTE for Fe ⇒ vsini and v_{rad}
- 3D non-LTE for Li ⇒ convective line asymmetry

⇒ **Improved ^{6}Li/^{7}Li determination**



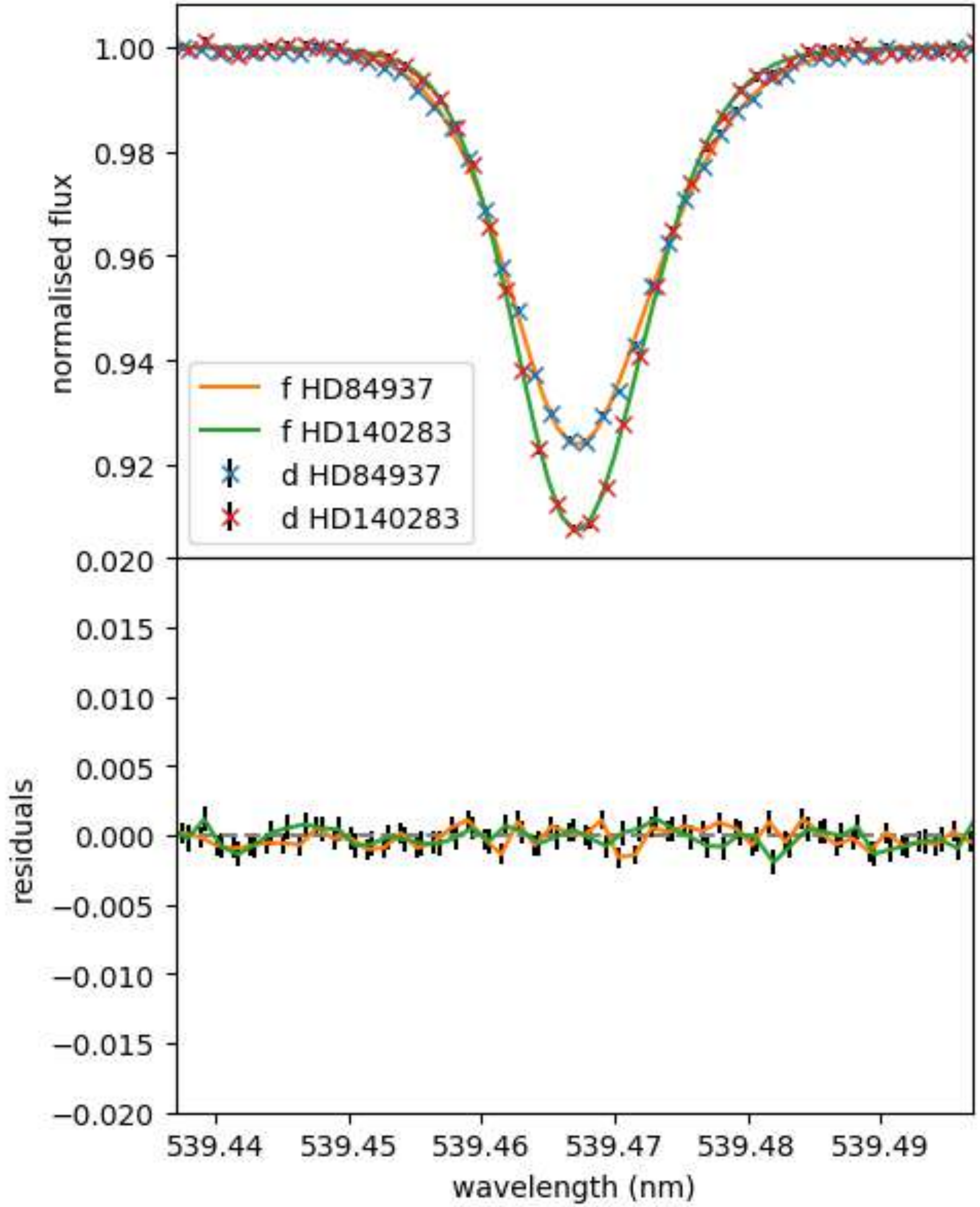
3D non-LTE for Fe

Large Fe model atom:
463 levels, 3000 transitions,
16000 frequencies

Rotational broadening (vsini) and wavelength shift (v_{rad}) determined from ~50 Fe lines ⇒ apply to Li

No macroturbulence or microturbulence needed in 3D

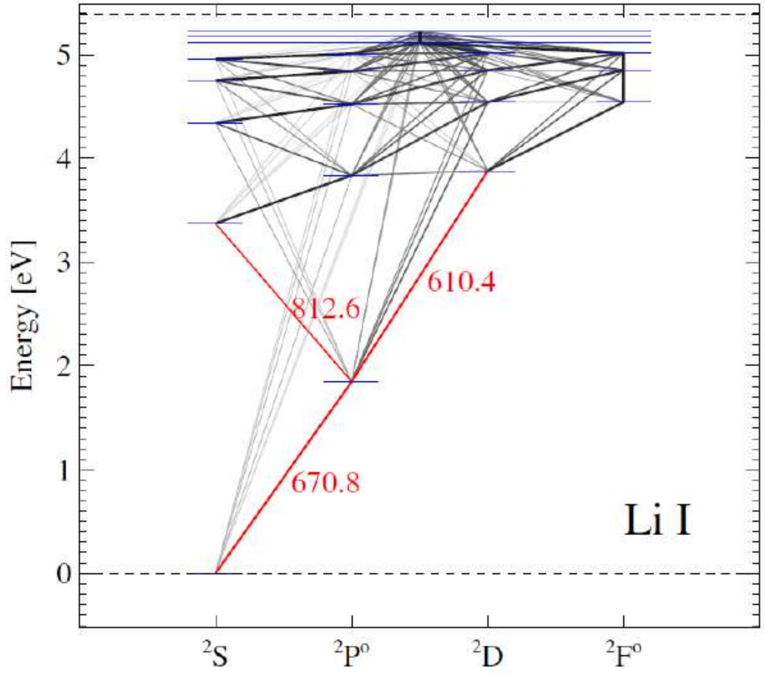
Convective line asymmetries accurately predicted by 3D model



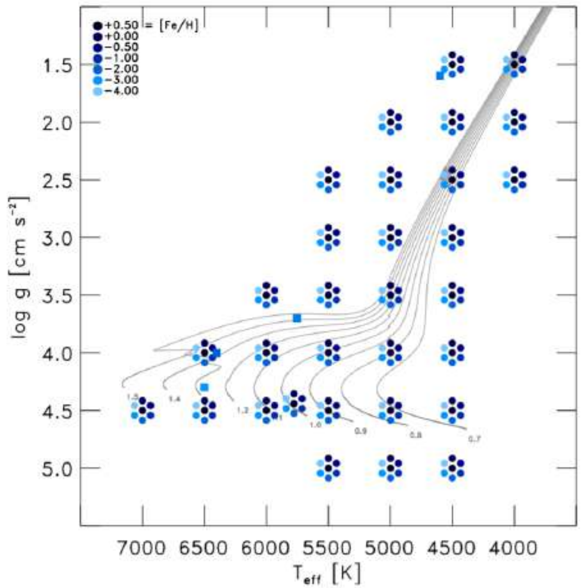
3D non-LTE for Li

Li model atom with accurate radiative + collisional cross-sections

5 snapshots of 3D stellar models,
5 Li abundances, and 5 ^{6}Li/^{7}Li ratios



Wang et al. 2019a:
3D non-LTE calculations for Li lines for FGK dwarfs/giants and many Li abundances publicly available:
https://github.com/ellawang44/Breidablik



Li in HD84937

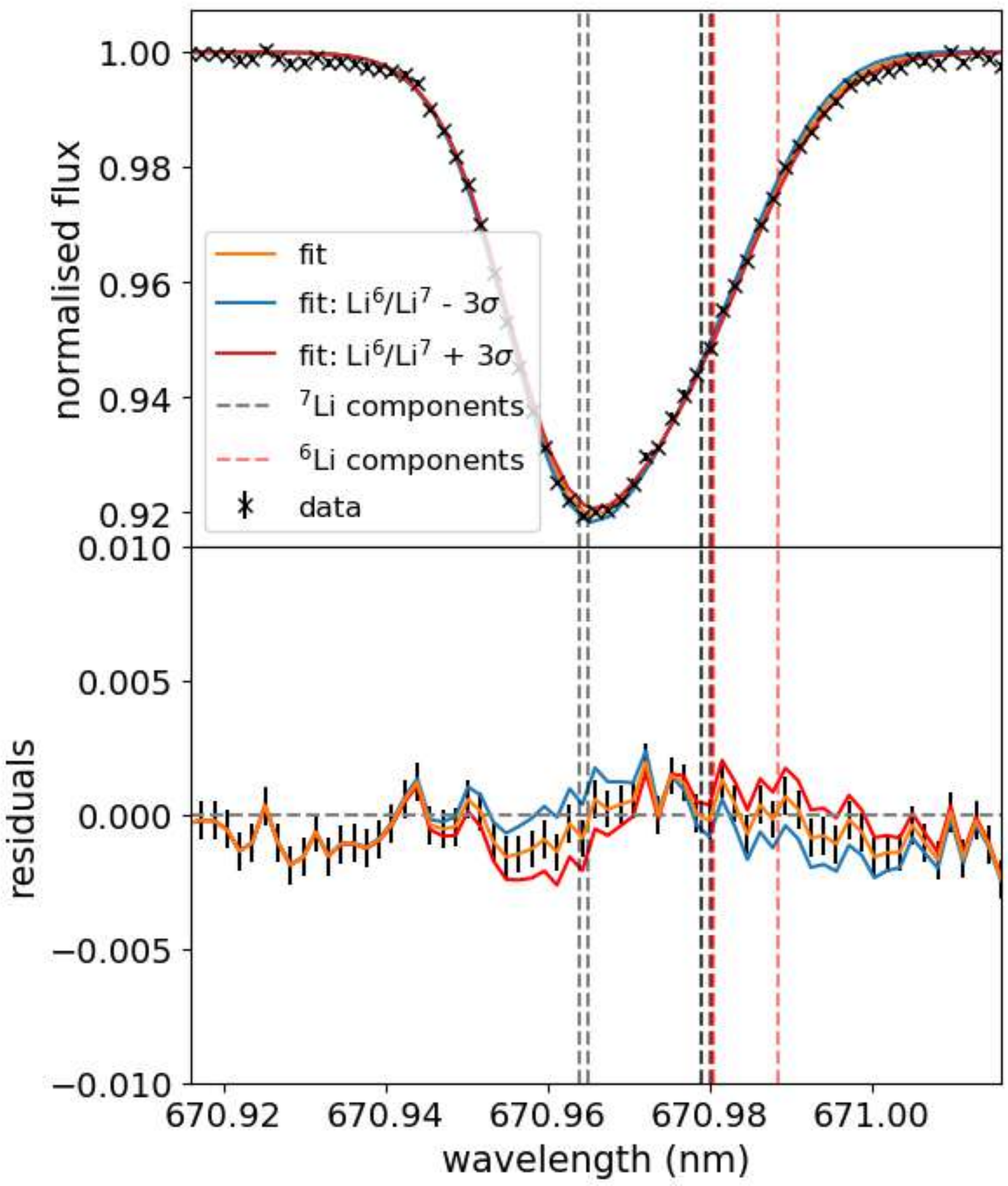
Fixed: vsini & v_{rad} (Fe lines)

vsini=0.91±0.30km/s

vrad=1.349±0.050km/s

Free: ^{7}Li, ^{6}Li, continuum

MCMC analysis to determine ^{7}Li and ^{6}Li abundances



^{6}Li/^{7}Li in HD84937

Wang et al. 2019b:

HD84937:

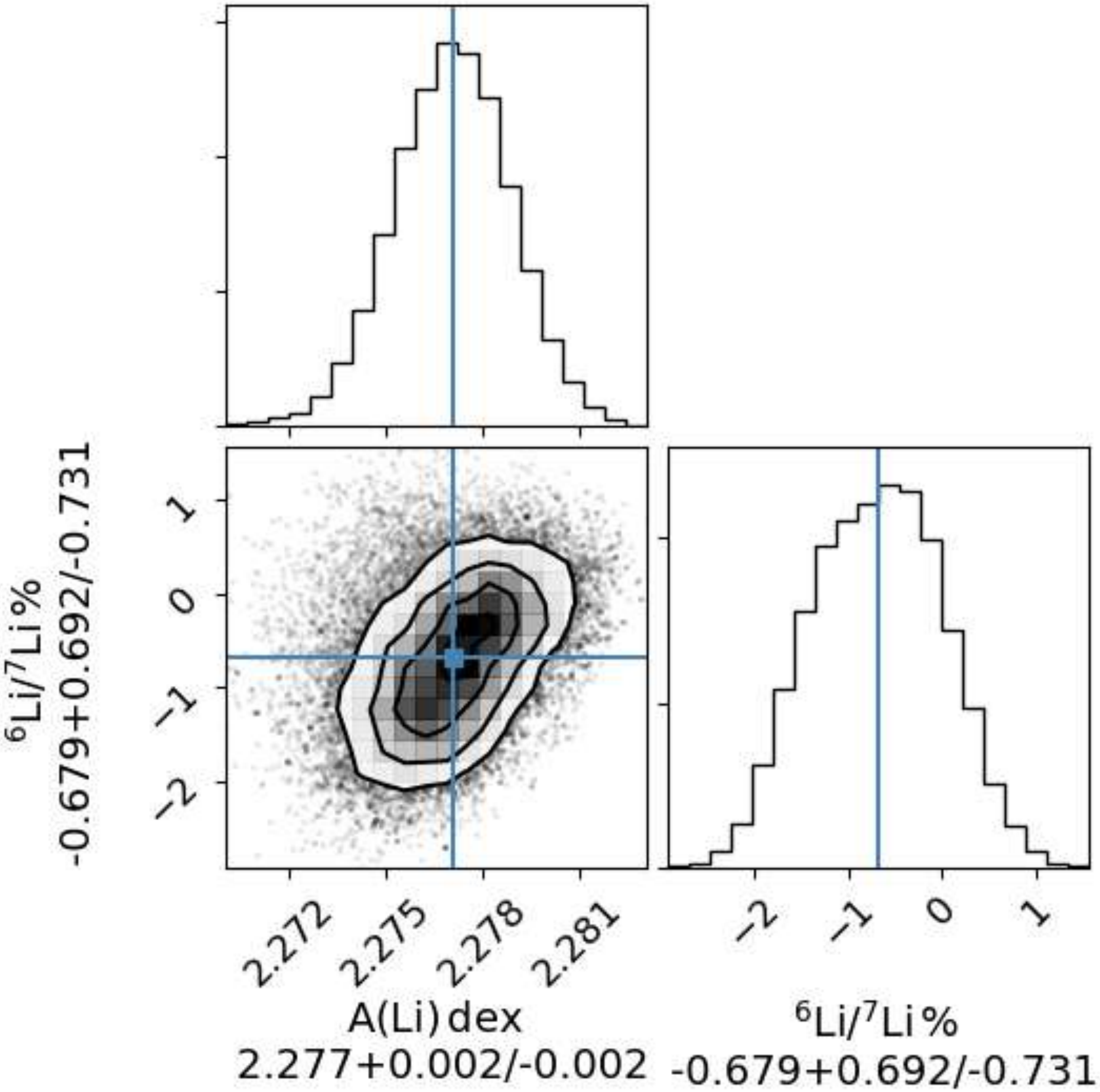
^{6}Li/^{7}Li=-0.7±0.7%

(1D: ^{6}Li/^{7}Li=5±2%)

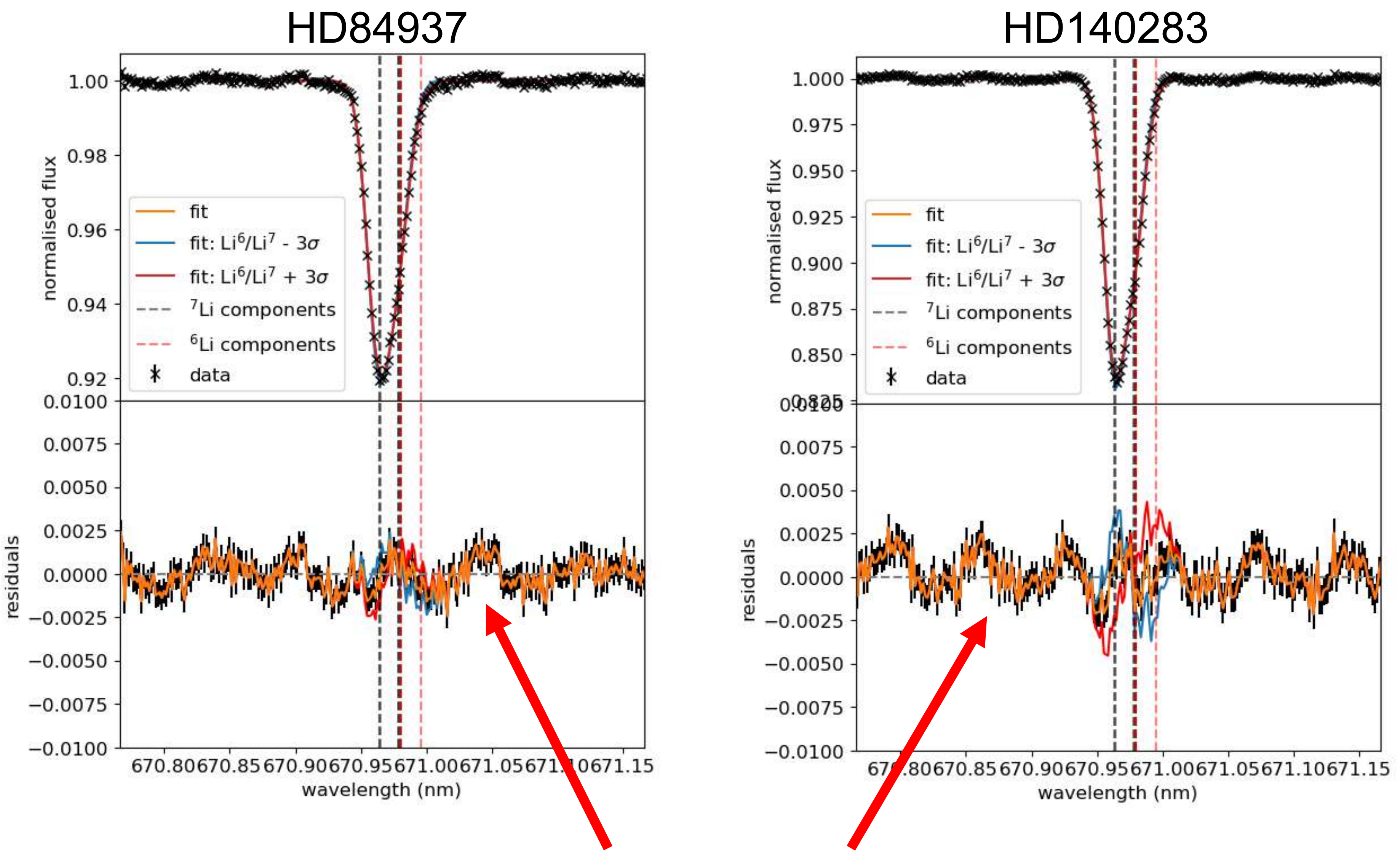
HD140283:

^{6}Li/^{7}Li=-1.1±0.9%

Negative ^{6}Li/^{7}Li formally allowed by treating ^{6}Li components as emission



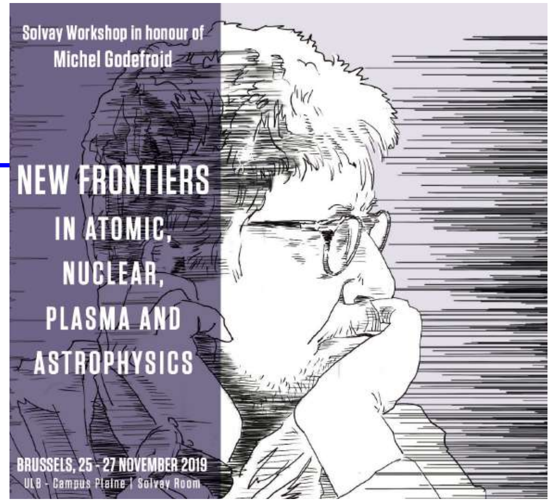
Not quite final word

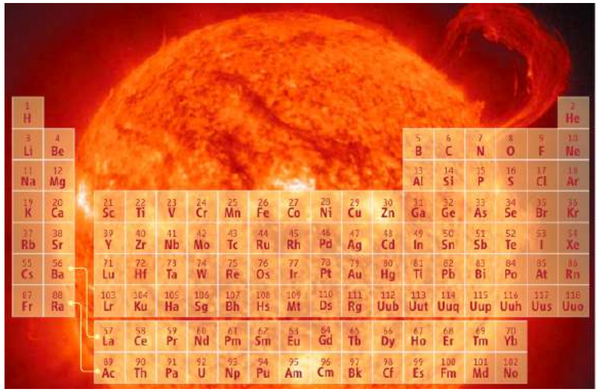


Residual fringing pattern

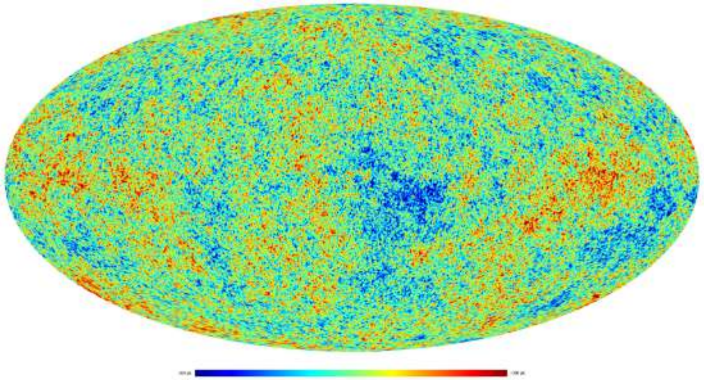
S/N>1000 is extremely challenging

Precision spectroscopy

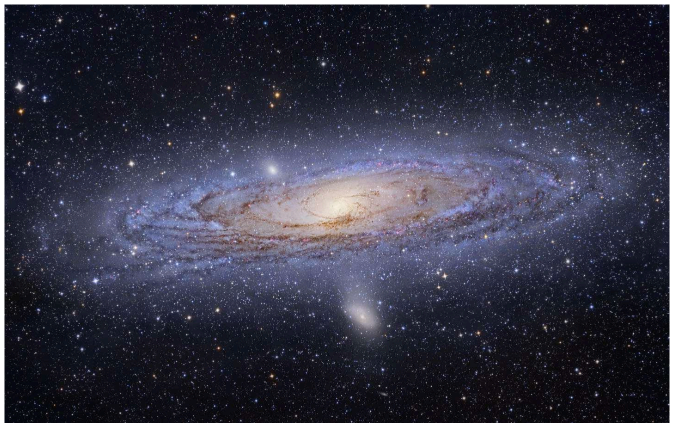




Does the Sun have a subsolar metallicity?



Cosmological Li problems



Galactic archaeology

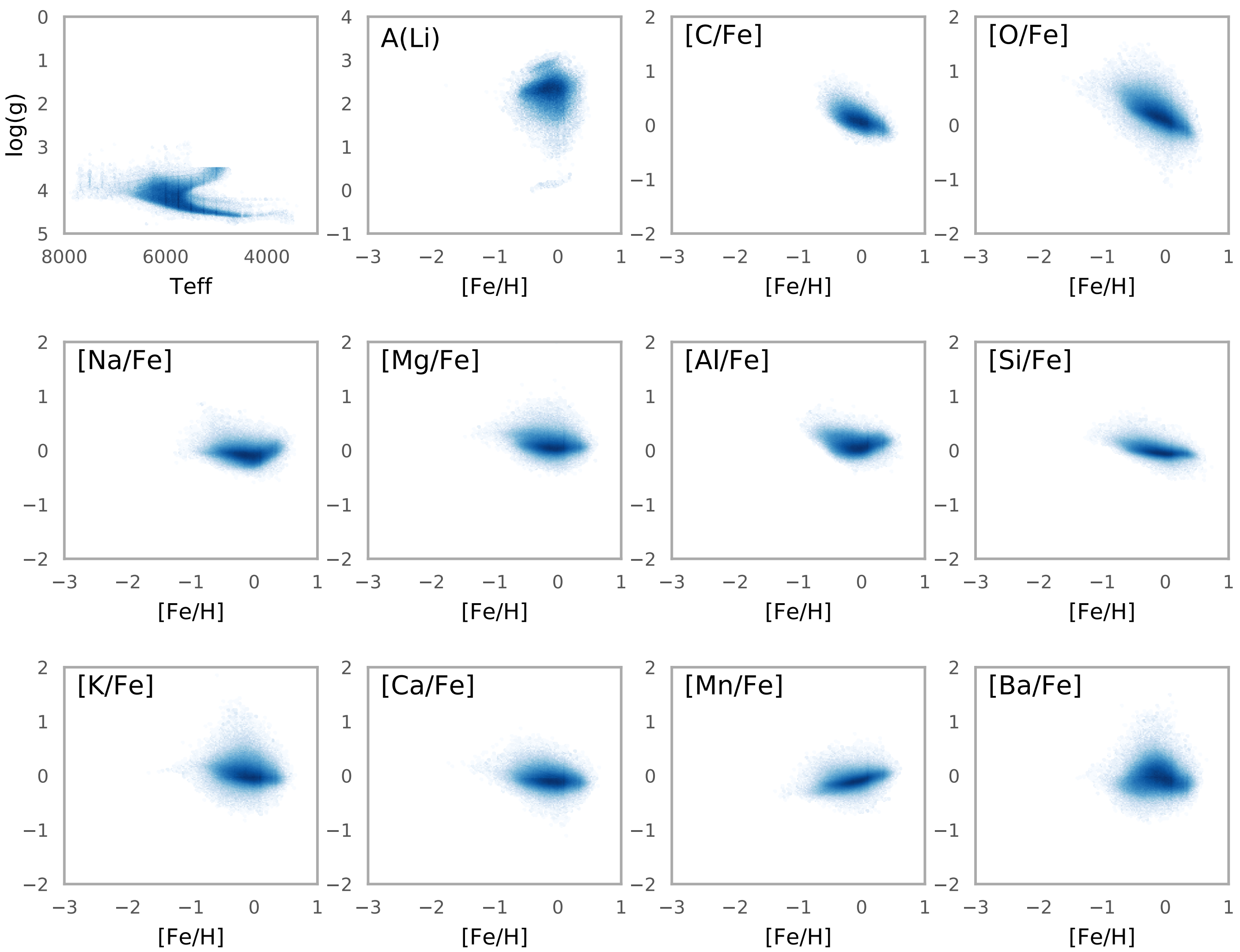
Galactic archaeology

How to analyse millions of stars?

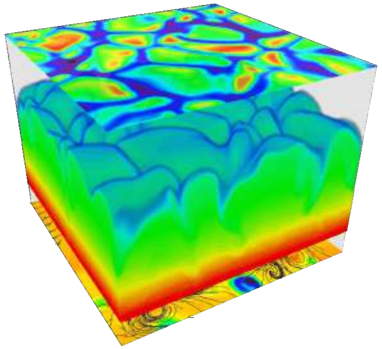
- Automated
- Fast
- Accurate
- Precise
- Reliable
- Reproducible

GALAH survey

1D non-LTE for 11 elements in >500,000 stars

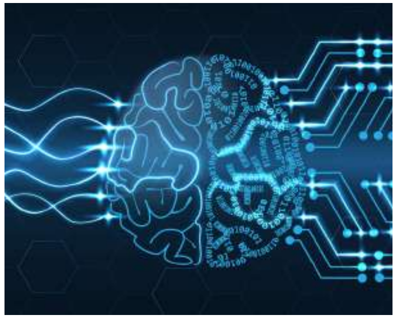


What's next?



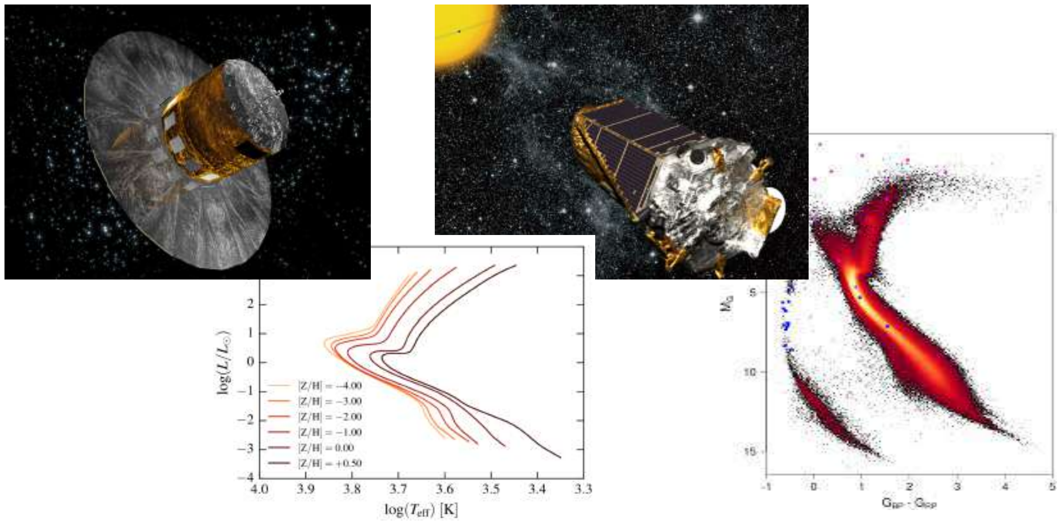
3D non-LTE stellar spectra

Training set & input spectra



Machine learning

Mapping spectrum ⇔ labels



Bayesian inference

Use <u>all</u> information available: parallax, photometry, asteroseismology, stellar evolution models, reddening etc