^{6}Li detection in metal-poor stars: Can 3D model atmospheres solve the second lithium problem?

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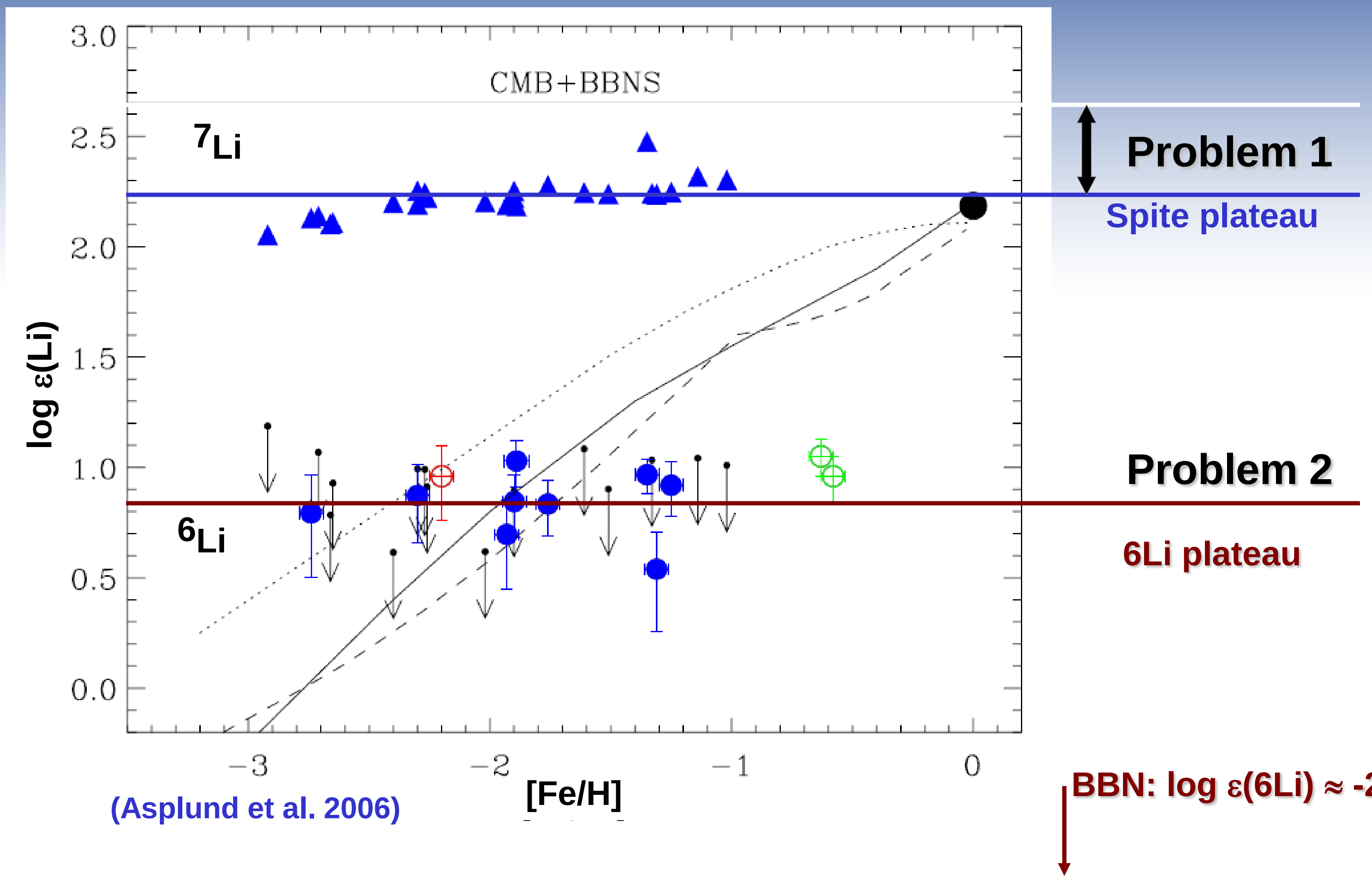
Can 3D model atmospheres solve the second lithium problem?

M. Steffen, R. Cayrel, P. Bonifacio, E. Caffau, H.-G. Ludwig, et al.

- **Introduction:**
  Line asymmetry due to stellar granulation and ^{6}Li
- **Method of analysis:**
  3D NLTE line formation calculations for lithium
- **Results:**
  - 1D→3D correction of the Asplund et al. (2006) ^{6}Li abundances
  - 3D NLTE analysis of real stars:
    G020-024, G271-162, HD 160617, HD 74000, G275-4, HD 84937
- **Conclusions**

The second lithium problem



A radical solution of the 2nd lithium problem

Line shift, line asymmetry, and the ^{6}Li/^{7}Li isotopic ratio determination ★

Roger Cayrel[1], Matthias Steffen[2], Hum Chand[3], Piercarlo Bonifacio[4,5,6], Monique Spite[4], François Spite[4], Patrick Petitjean[3], Hans-Günter Ludwig[4,5], and Elisabetta Caffau[4]

A&A 473, L37 (2007)

Instead of invoking new physics,
we considered the possibility that …

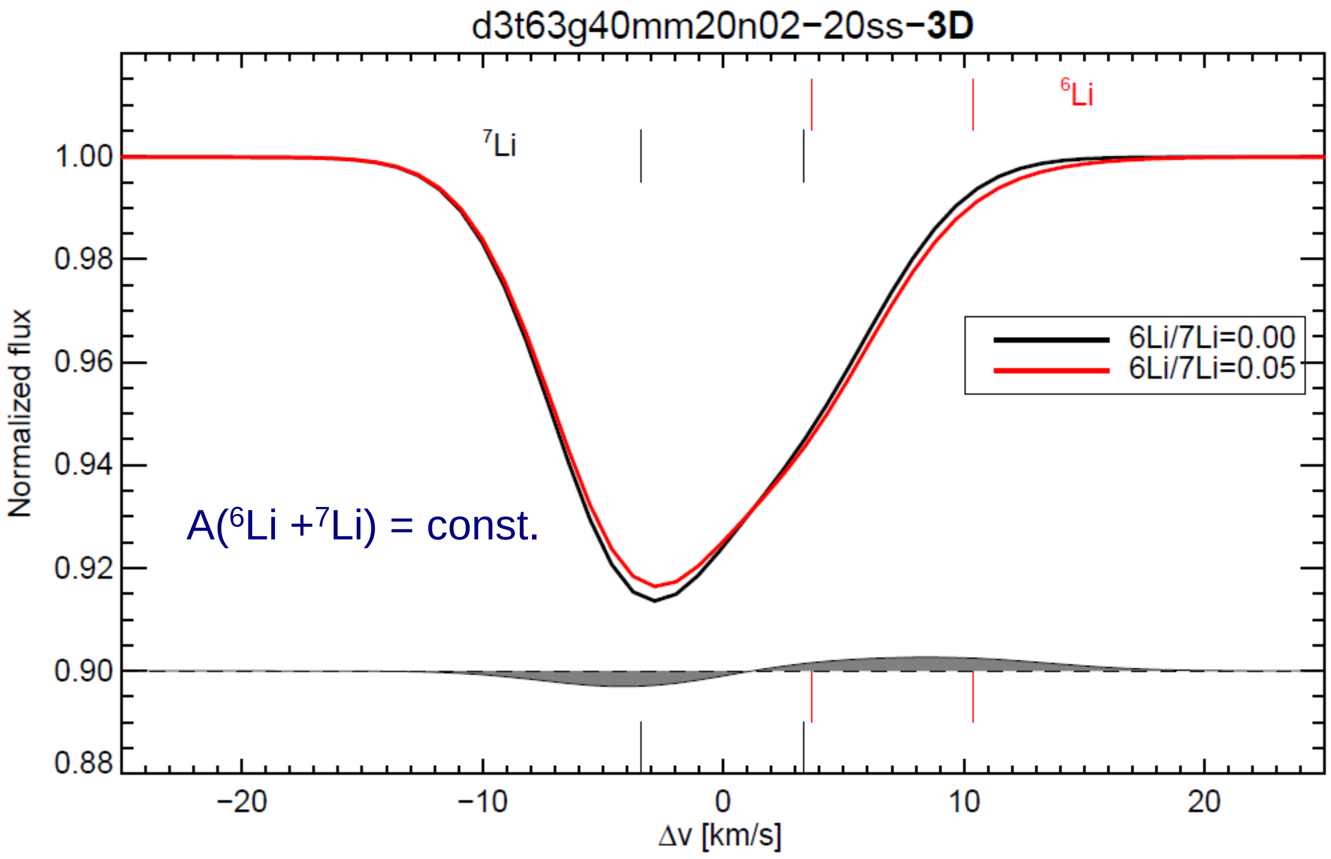
- Previous ^{6}Li detections are only upper limits

  ignoring the intrinsic, convection-induced line asymmetry results in a systematic overestimation of the ^{6}Li abundance

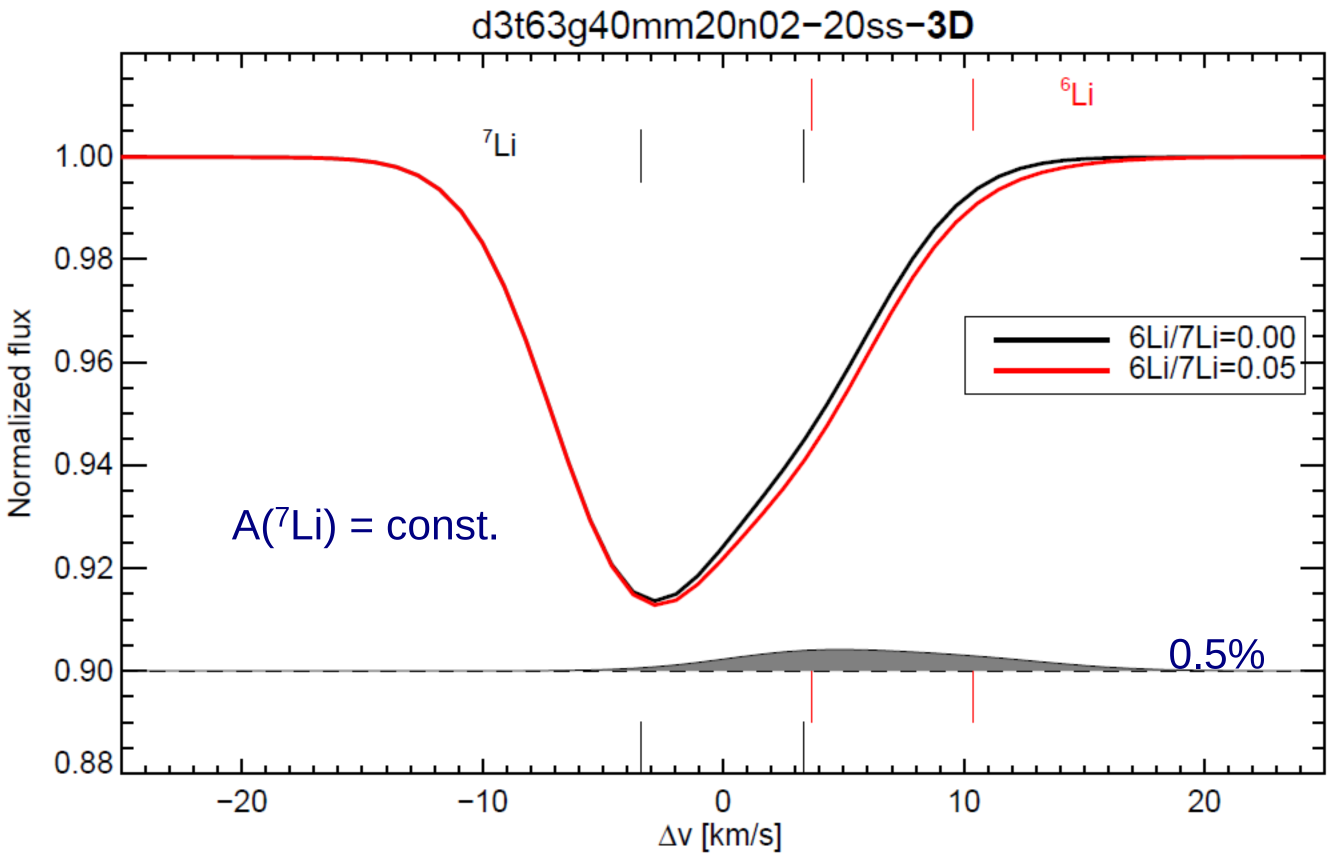
- A systematic reappraisal of former determinations of ^{6}Li abundances in halo stars is needed

  requires spectra of the highest possible quality

Spectroscopic signature of ^{6}Li



Spectroscopic signature of ^{6}Li

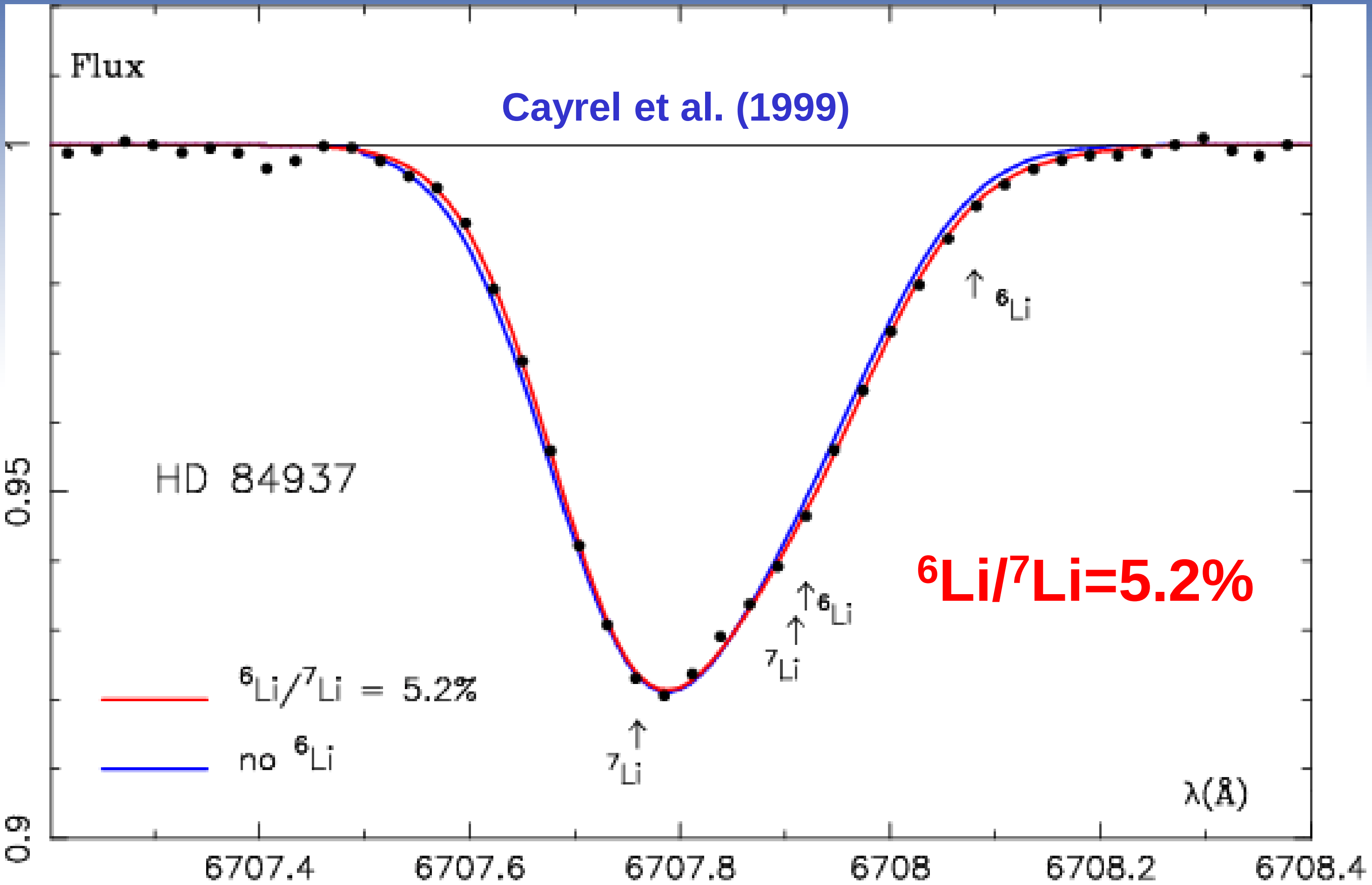


High-quality spectra needed (*R* ≥ 100 000, *S/N* ≥ 500)

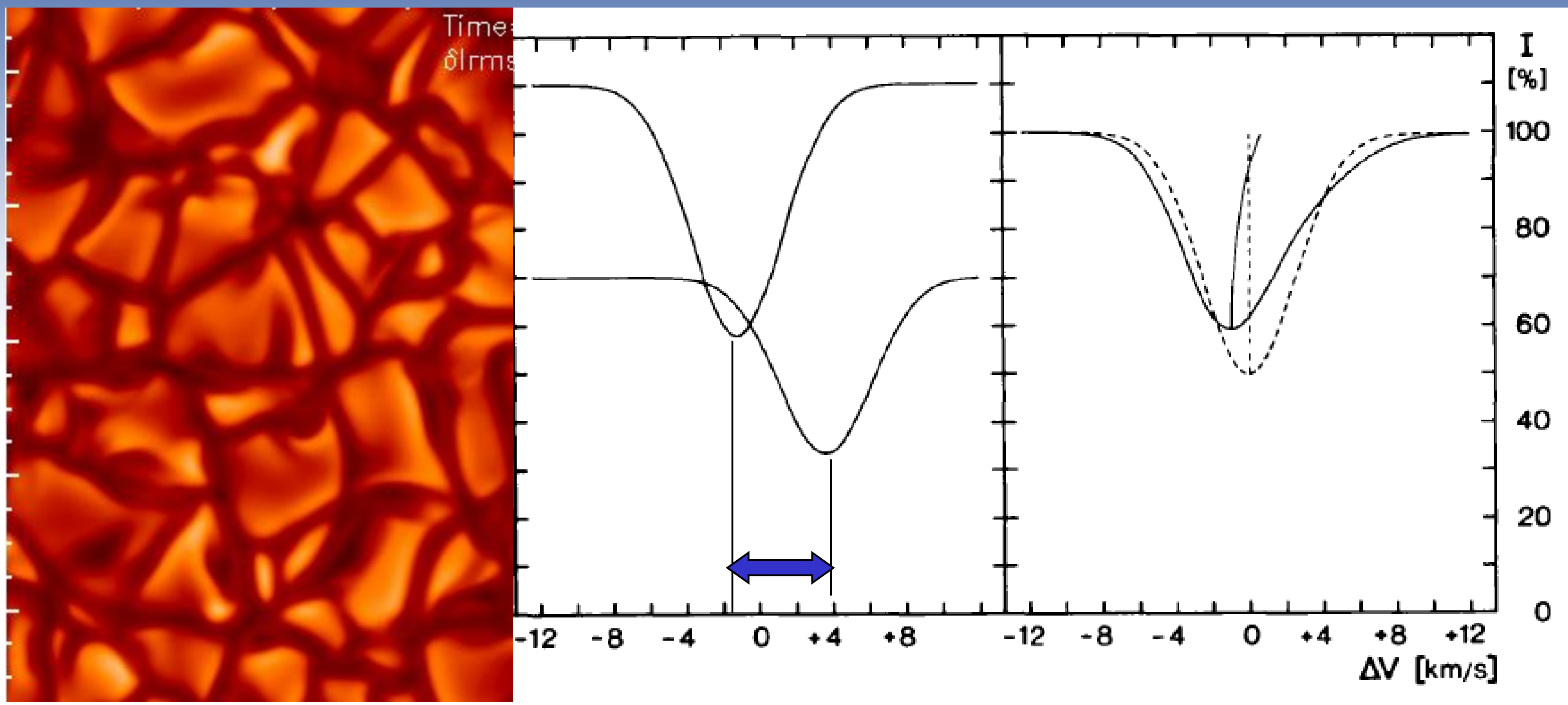
Determination of the ^{6}Li / ^{7}Li isotopic ratio

- Fitting of **observed spectrum** with **grid of synthetic line profiles**
- Fixed: ξ_{mic}, v sin i, FWHM (instrumental)
- **4 free fitting parameters:**
  - ➔ Lithium abundance: A(^{6}Li + ^{7}Li)
  - ➔ Isotopic ratio: ^{6}Li / ^{7}Li
  - ➔ Residual line broadening: ξ_{mac}
  - ➔ Global Doppler shift: Δv

^{6}Li detection in HD84937



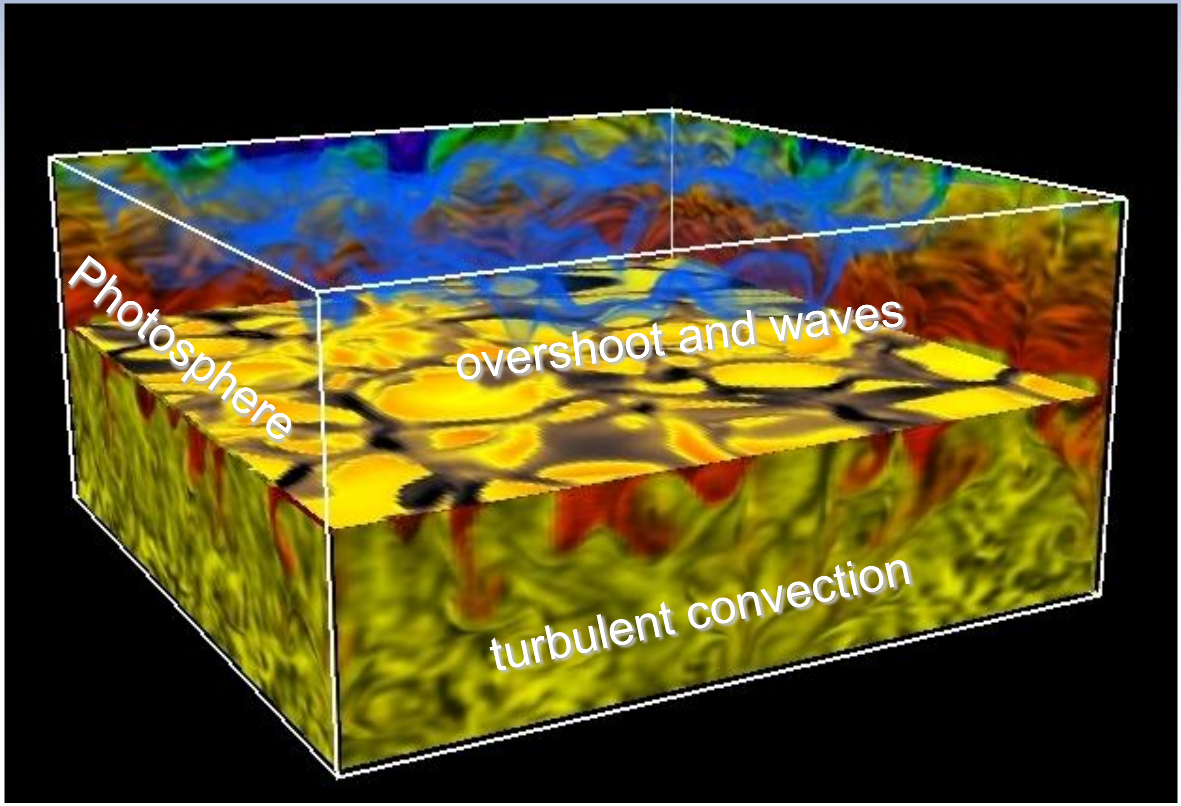
Stellar granulation and convective line asymmetry



Strong blue-shifted + weak red-shifted profile ➔ asymmetry

After Dravins et al. (1981)

CO⁵BOLD 3D hydrodynamical simulations of surface convection in metal-poor stars



$\leftarrow$ $\log \tau_{Ross} \approx -8$

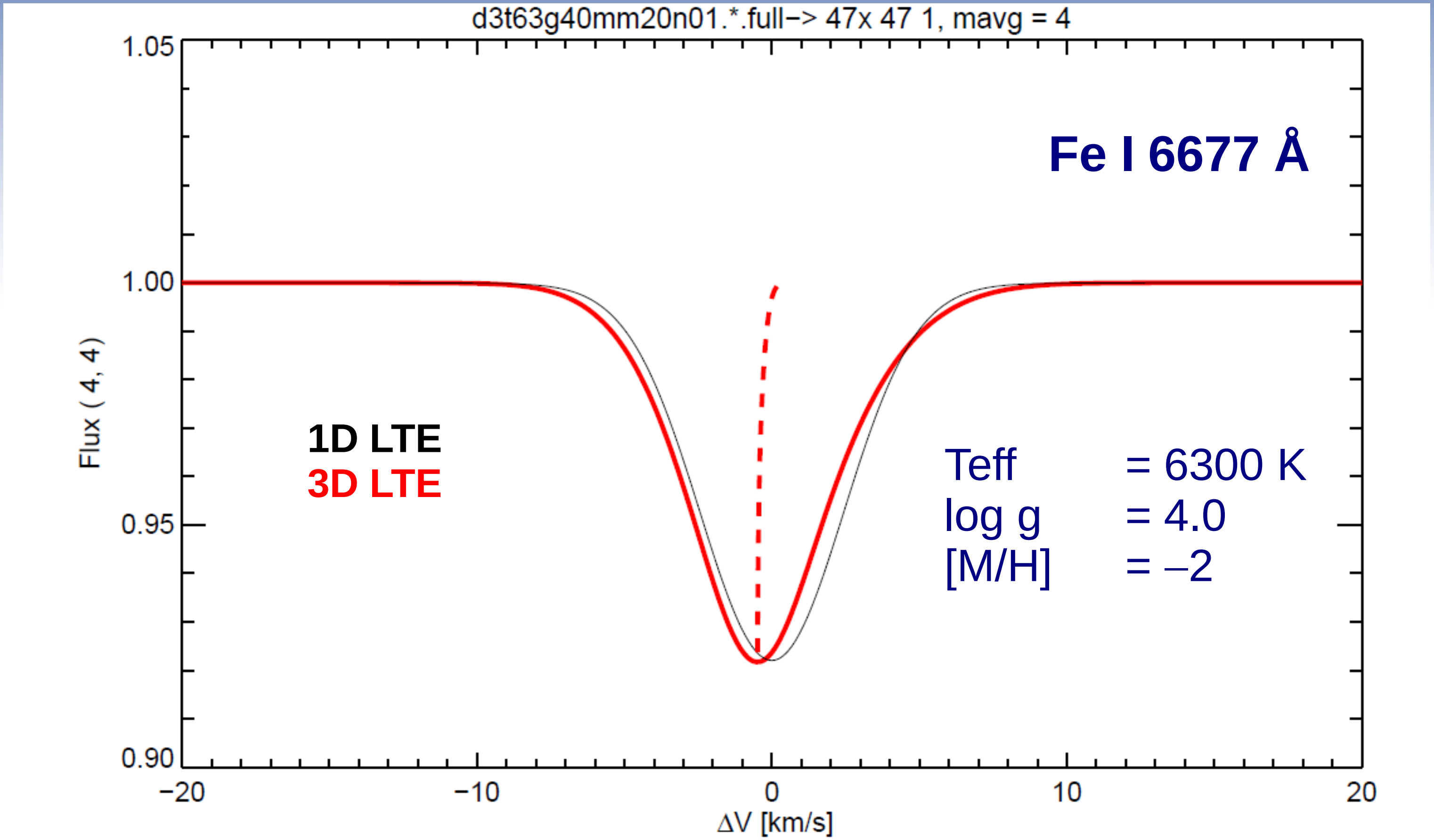
$\leftarrow$ $\log \tau_{Ross} \approx 0$

$\leftarrow$ $\log \tau_{Ross} \approx +7.5$

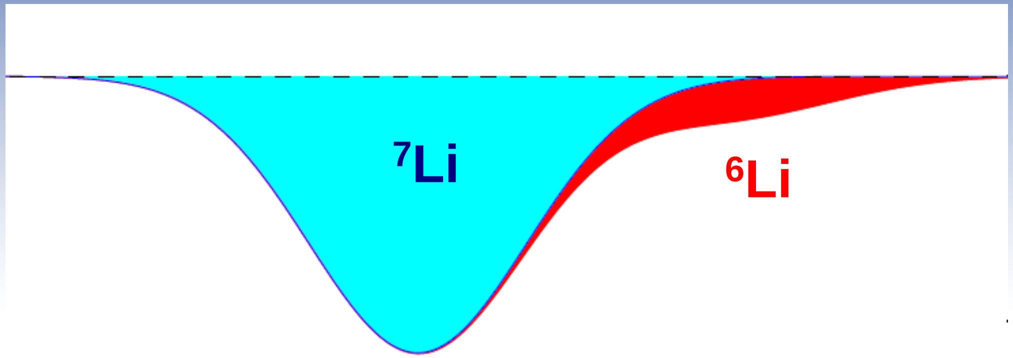
Teff = 6300 K, log g = 4.0, [M/H] = –2

- **typically 140x140x150 cells**
- **realistic MARCS opacities**
- **RT in 6 or 12 opacity bins**

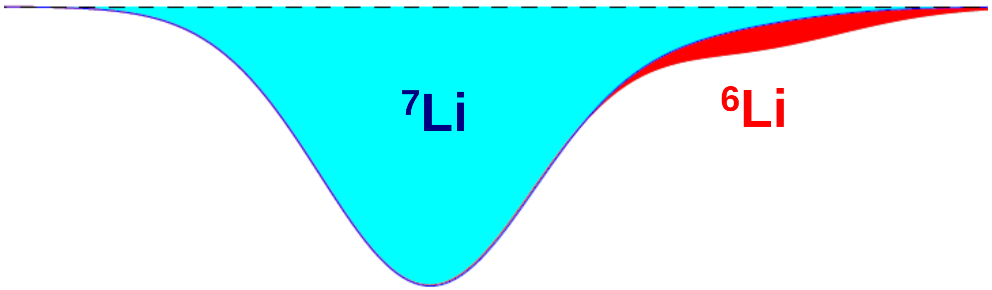
Spectroscopic signature of convection in the atmospheres of metal-poor stars



Fitting procedure: 1D versus 3D



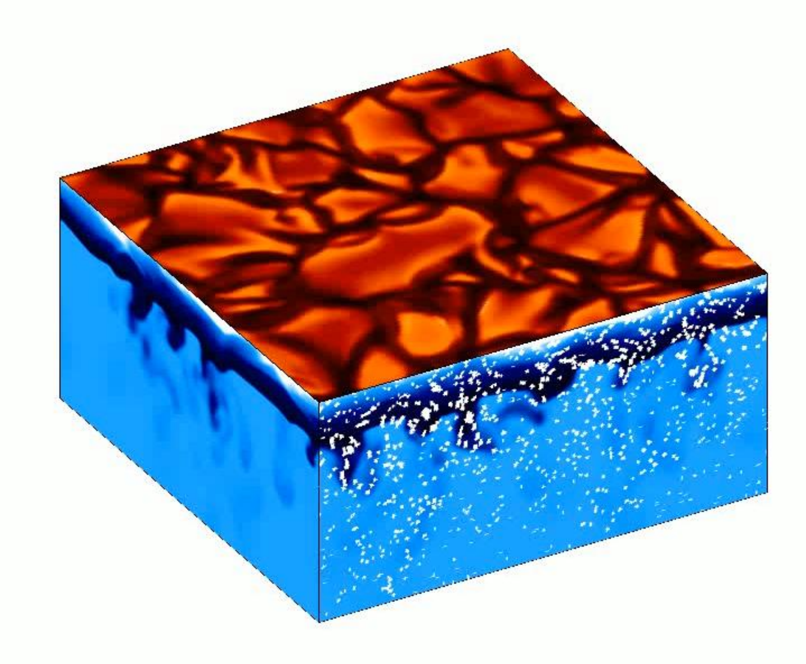
1D fitting: symmetric ^{7}**Li** profile



3D fitting: *asymmetric* ^{7}**Li** profile

3D analysis expected to yield higher ^{6}Li / ^{7}Li isotopic ratio

3D-NLTE line formation in metal-poor stars

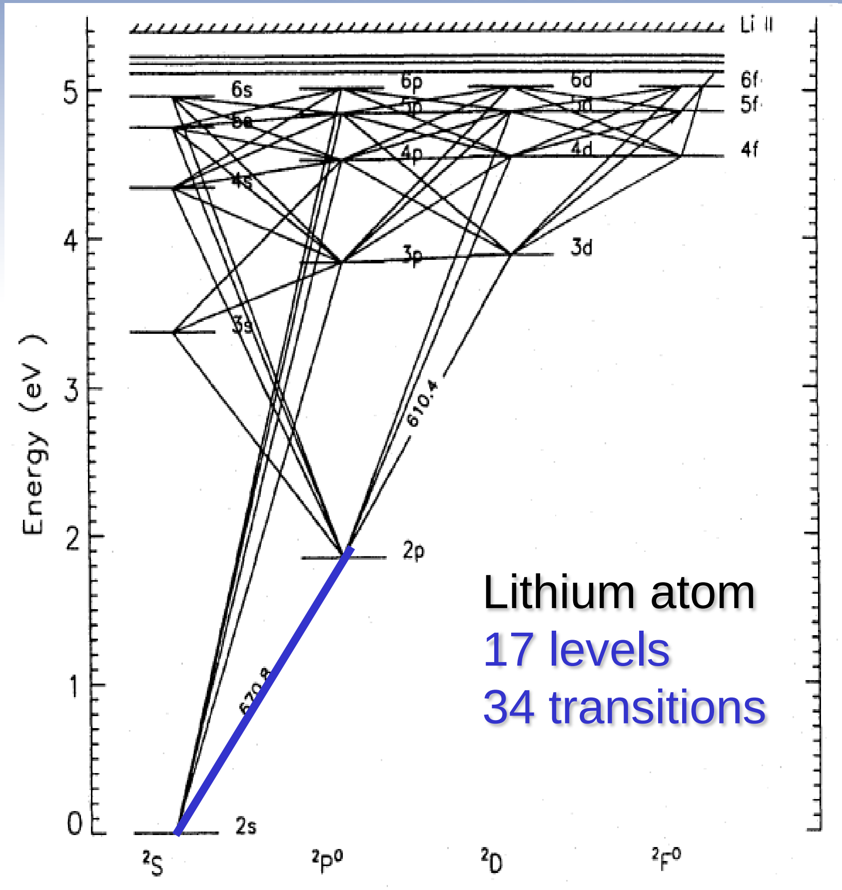


1. Radiation field $J\nu(x,y,z)$, ν : UV .. IR
2. Photo-ionization rates for all levels *i*
3. Statistical equilibrium equations

➔ departure coefficients *bi*(x,y,z)

Cayrel, Steffen, et al. (2009)

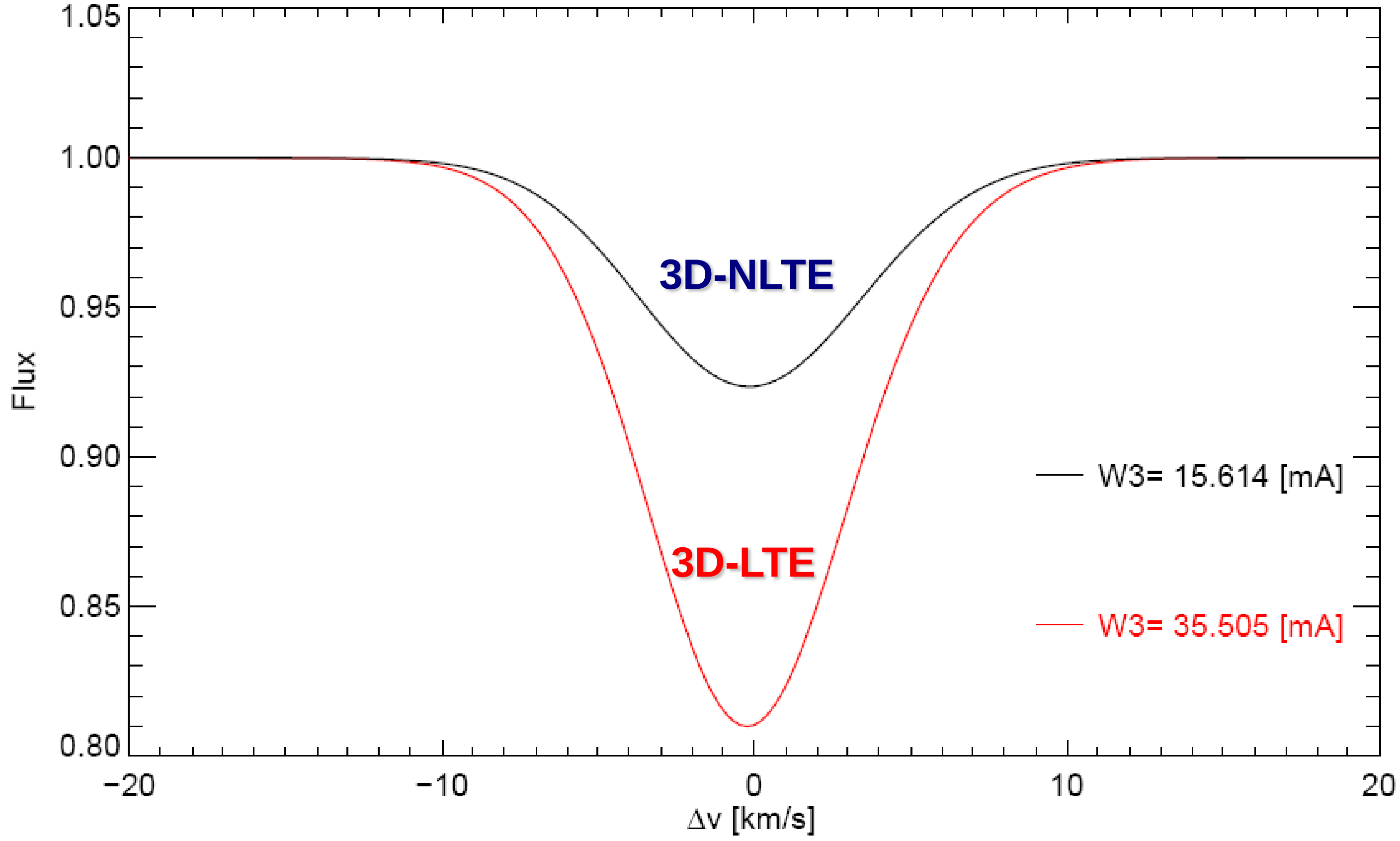
Lithium model atom



Lithium atom
17 levels
34 transitions

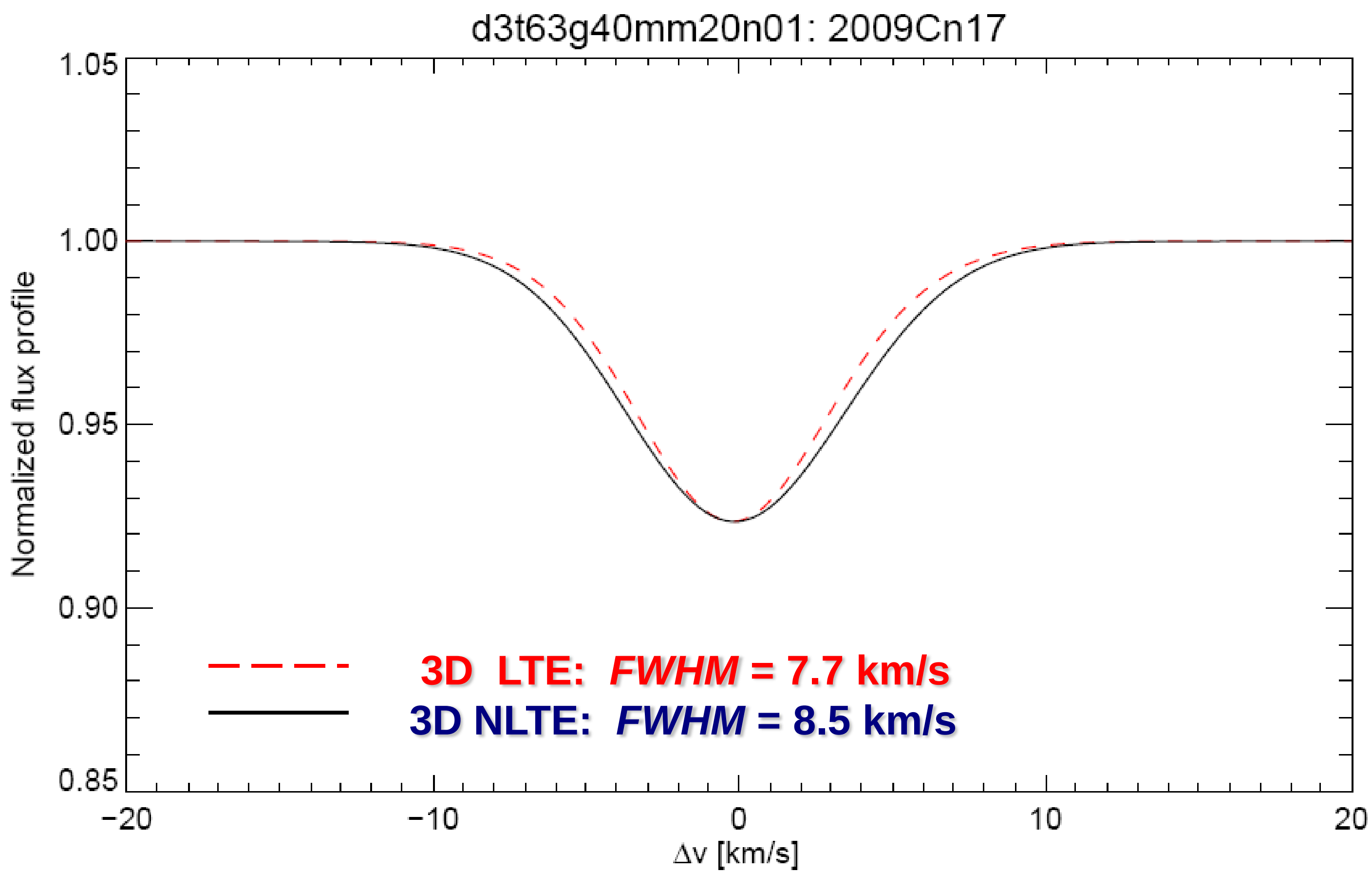
H + Li ⇔ H^- + Li^+: Barklem et al. 2003

Li 6707: 3D line formation in LTE / NLTE

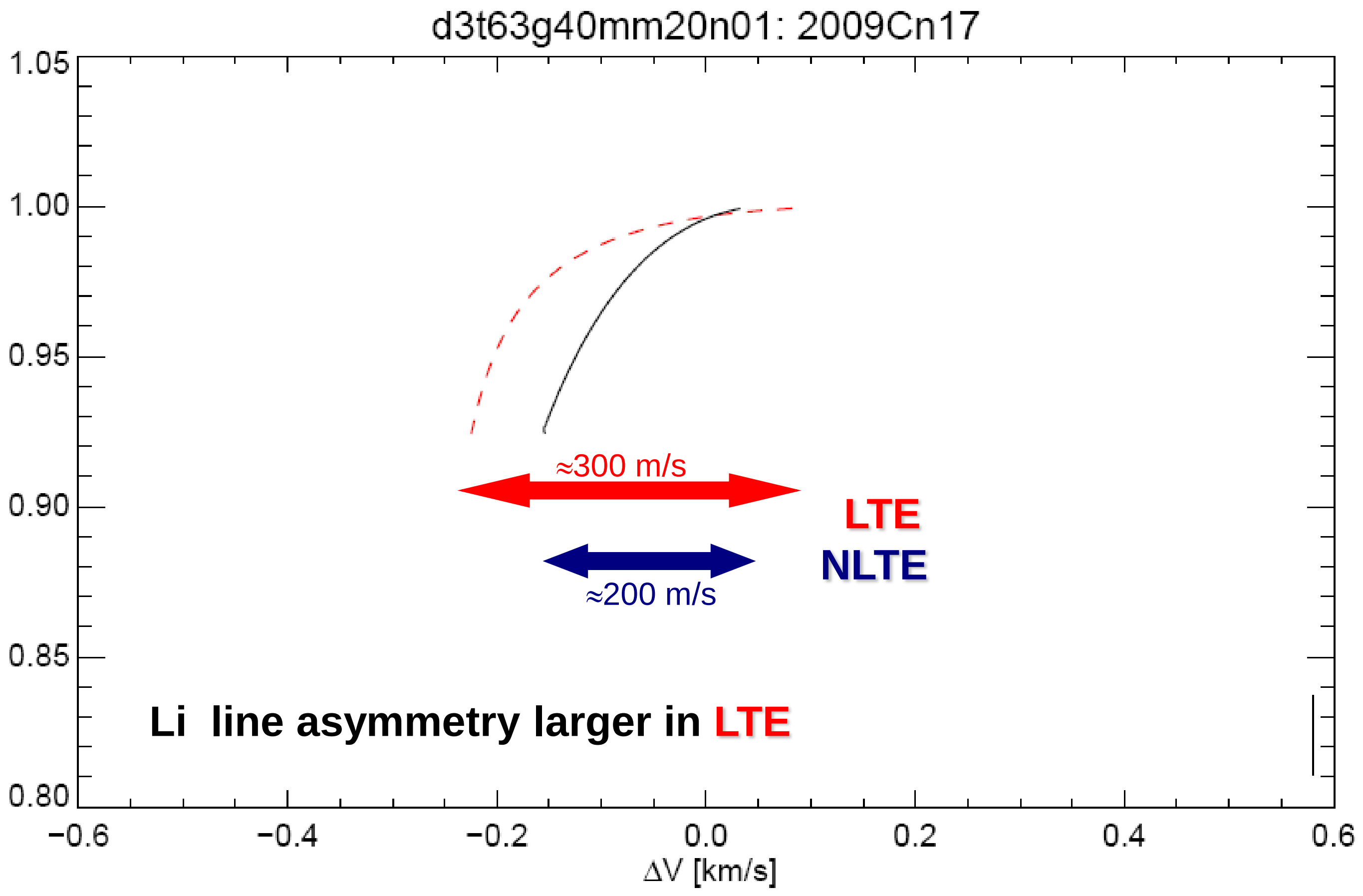


Li line strength smaller by factor ≈ 2 in NLTE

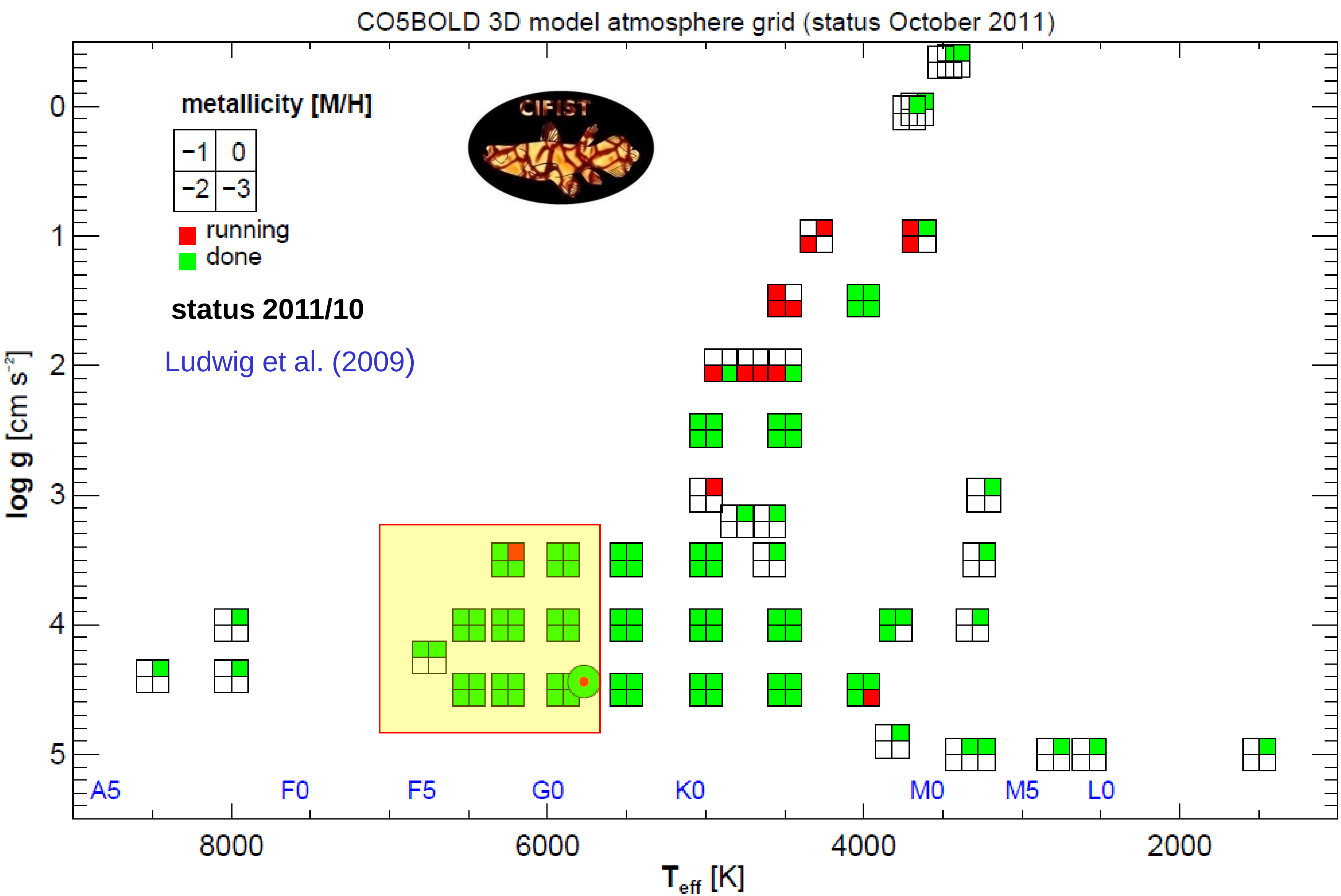
Li 6707: 3D line formation in LTE / NLTE



Li 6707: 3D line formation in LTE / NLTE



The CO5BOLD 3D model atmosphere grid



3D NLTE corrections of ^{6}Li / ^{7}Li derived with 1D LTE

Purely theoretical method based on synthetic line profiles:

- Fitting the same Li 6707 profile with **1D LTE** and **3D NLTE**

  4 free fitting parameters:

  Lithium abundance: $A(^{6}Li + ^{7}Li)$

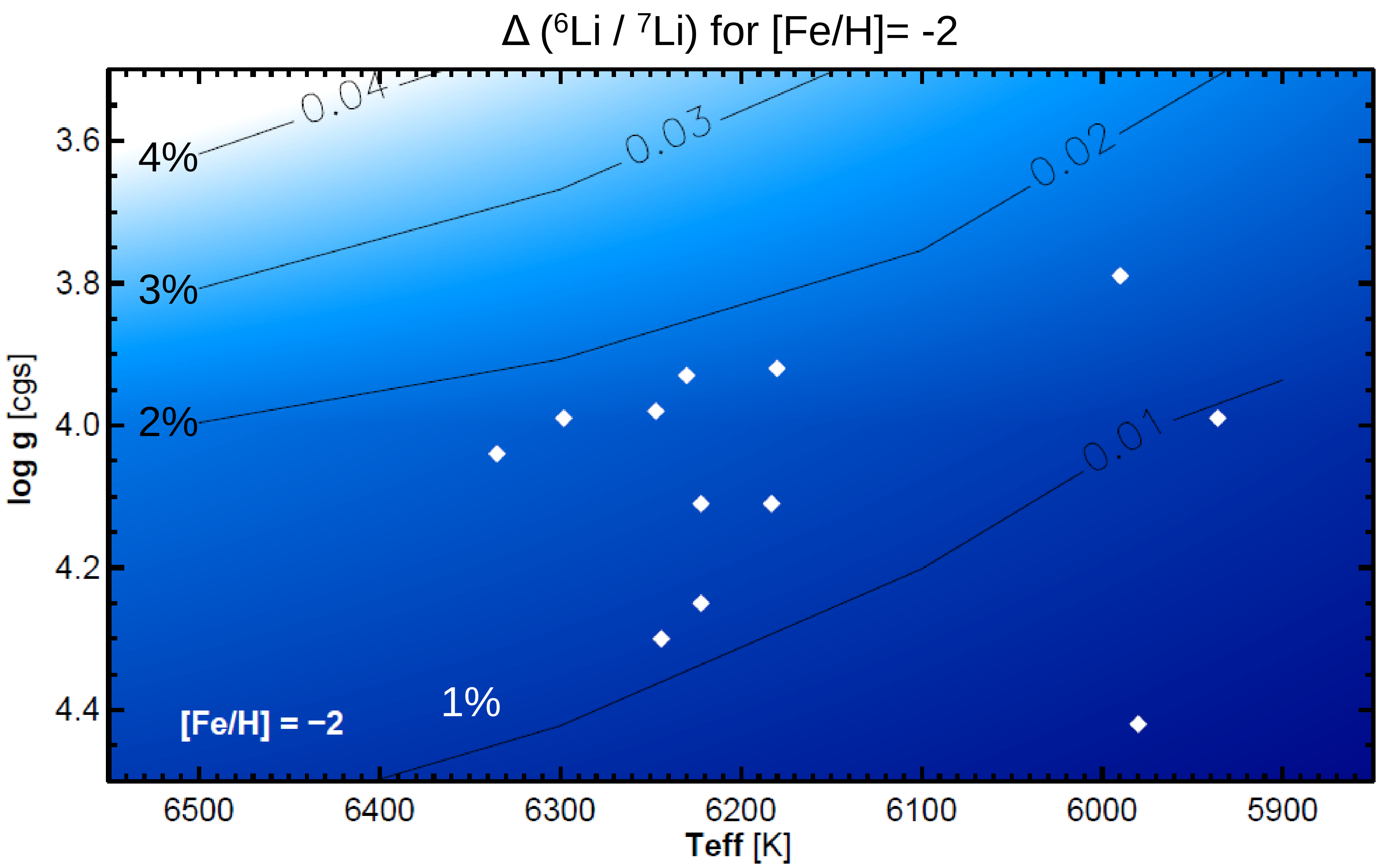
  Isotopic ratio: **$^{6}Li / ^{7}Li$**

  Residual line broadening: ξ_{mac}

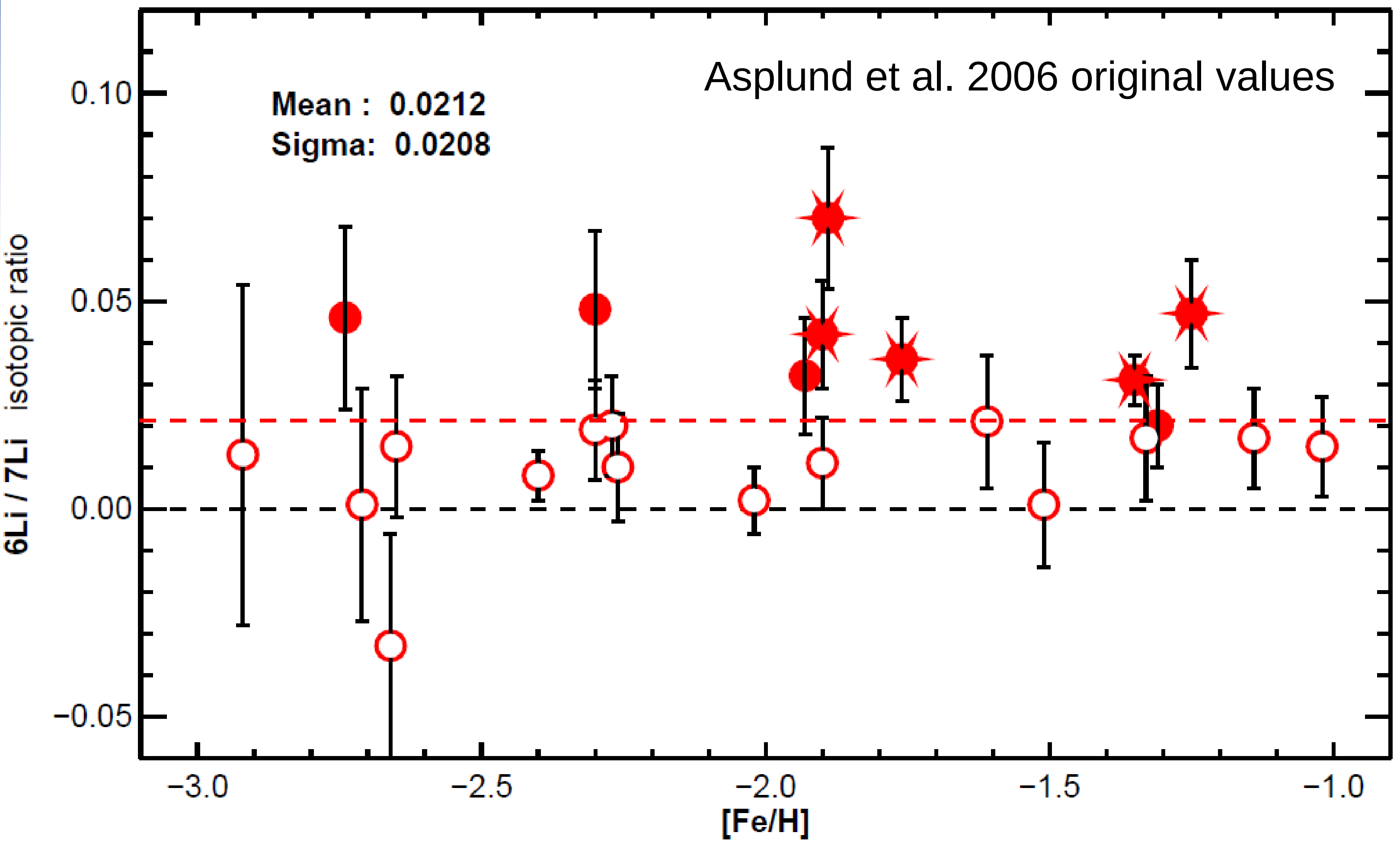
  Global Doppler shift: Δv

- Fixed: ξ_{mic}, v sin i, FWHM (instrumental)
- Result: **$\Delta (^{6}Li / ^{7}Li)$**
  = correction for intrinsic line asymmetry (T_{eff}, log g, [Fe/H])

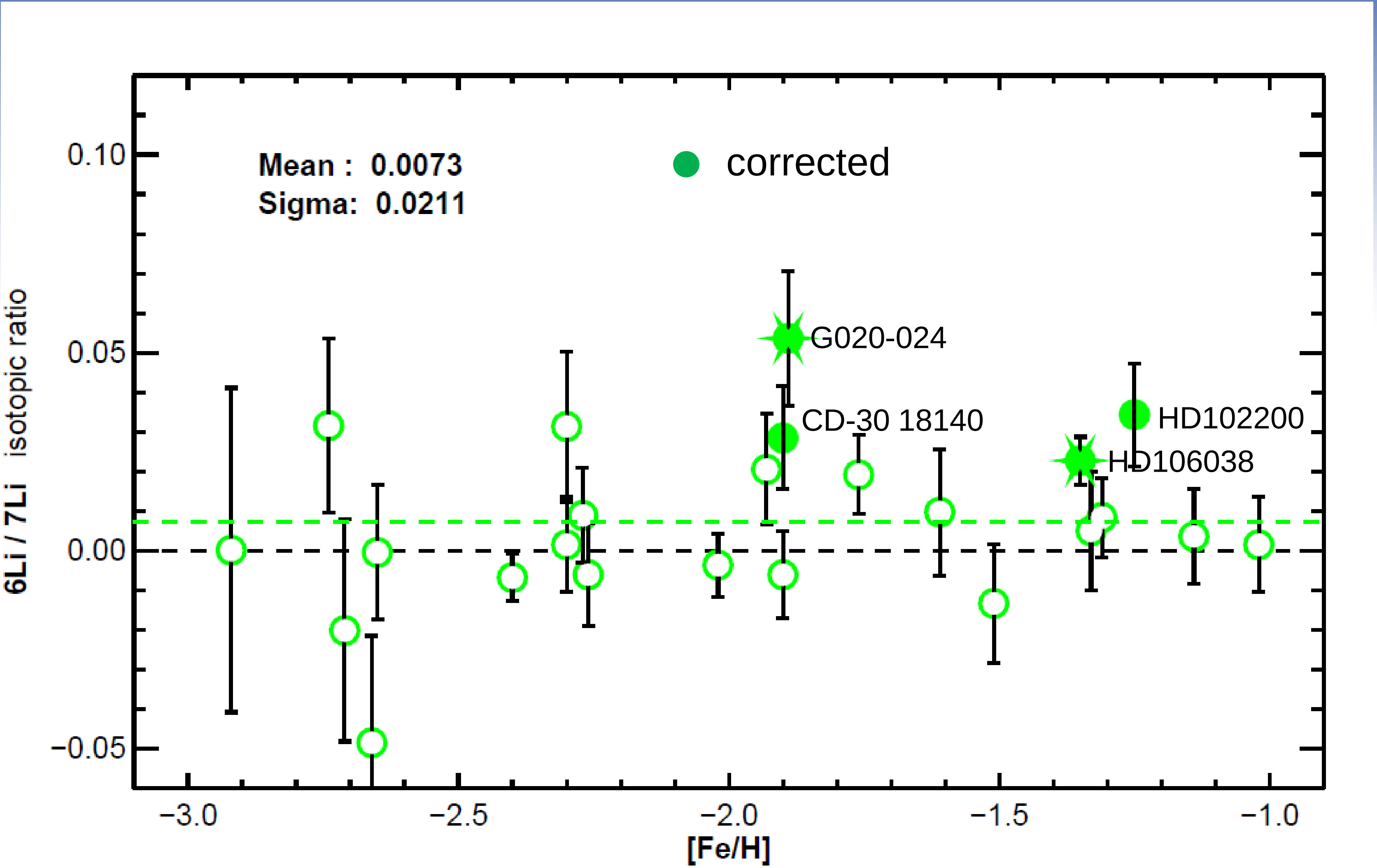
^{6}Li correction for intrinsic line asymmetry



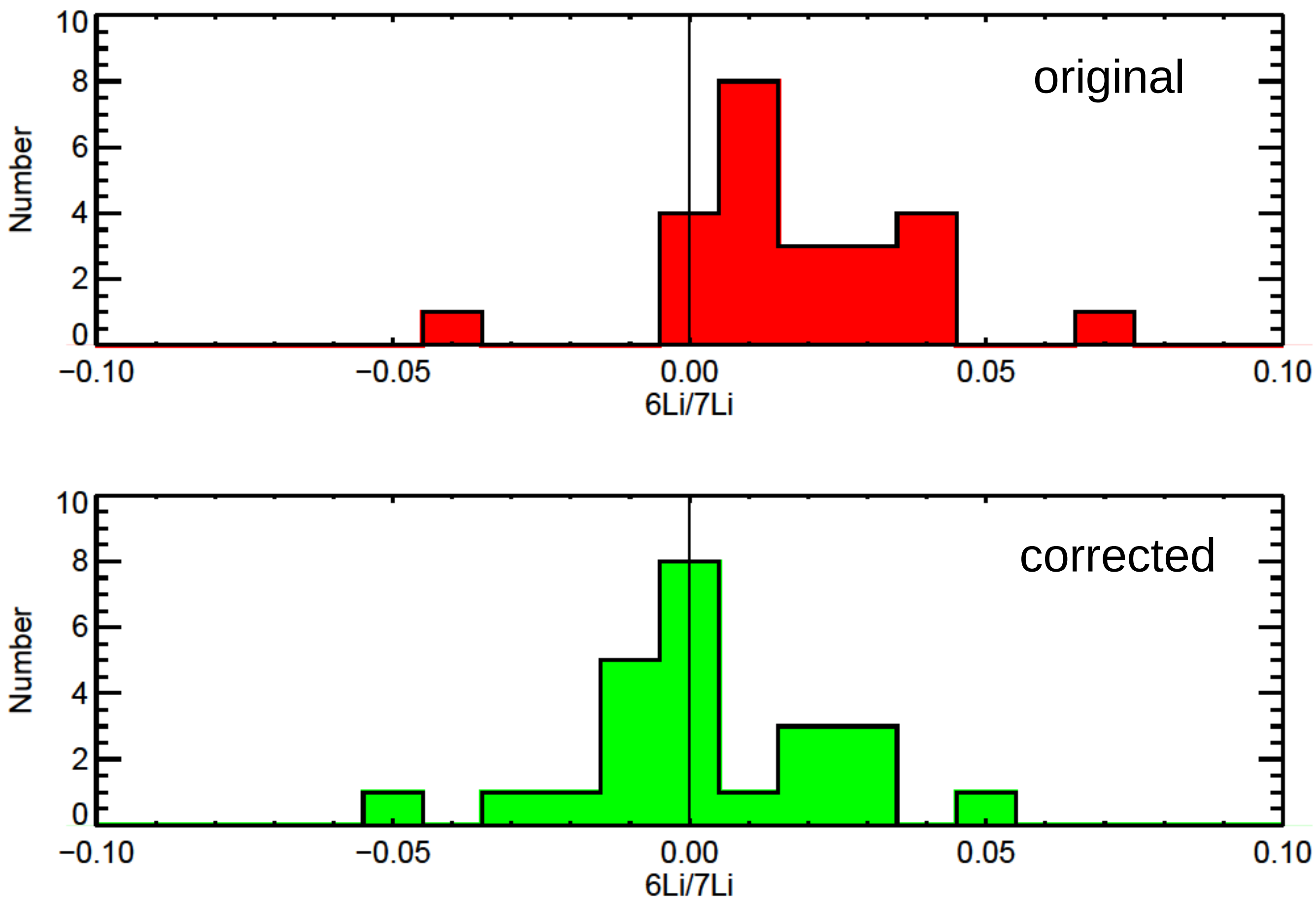
^{6}Li detection by Asplund et al. (2006)



^{6}Li detection by Asplund et al. (2006) corrected



^{6}Li / ^{7}Li distribution before and after correction



Preliminary ^{6}Li / ^{7}Li results for six real stars

Star	Teff [K]	log g	[Fe/H]	1D LTE (A2006)	1D LTE *)	3D NLTE *)	Spectr *)	
G020-024	6247	3.98	-1.89	**7.0**	**11.7**	**9.5**	UVES	?
HD 160617	5990	3.79	-1.76	**3.6**	**0 .. 8**	**-1 .. 7**	HARPS	?
G271-162	6230	3.93	-2.30	**1.9**	**2.1**	**0.4**	UVES	👎
HD 74000	6203	4.03	-2.05	---	**0.6**	**-1.1**	HARPS	👎
HD 84937	6310	4.10	-2.40	---	**6.5**	**4.8**	GECKO	👍
G275-4	6338	4.32	-3.21	---	**4.5**	**3.5**	UVES	👍

^{6}Li / ^{7}Li insensitive to assumed *v* sin *i*

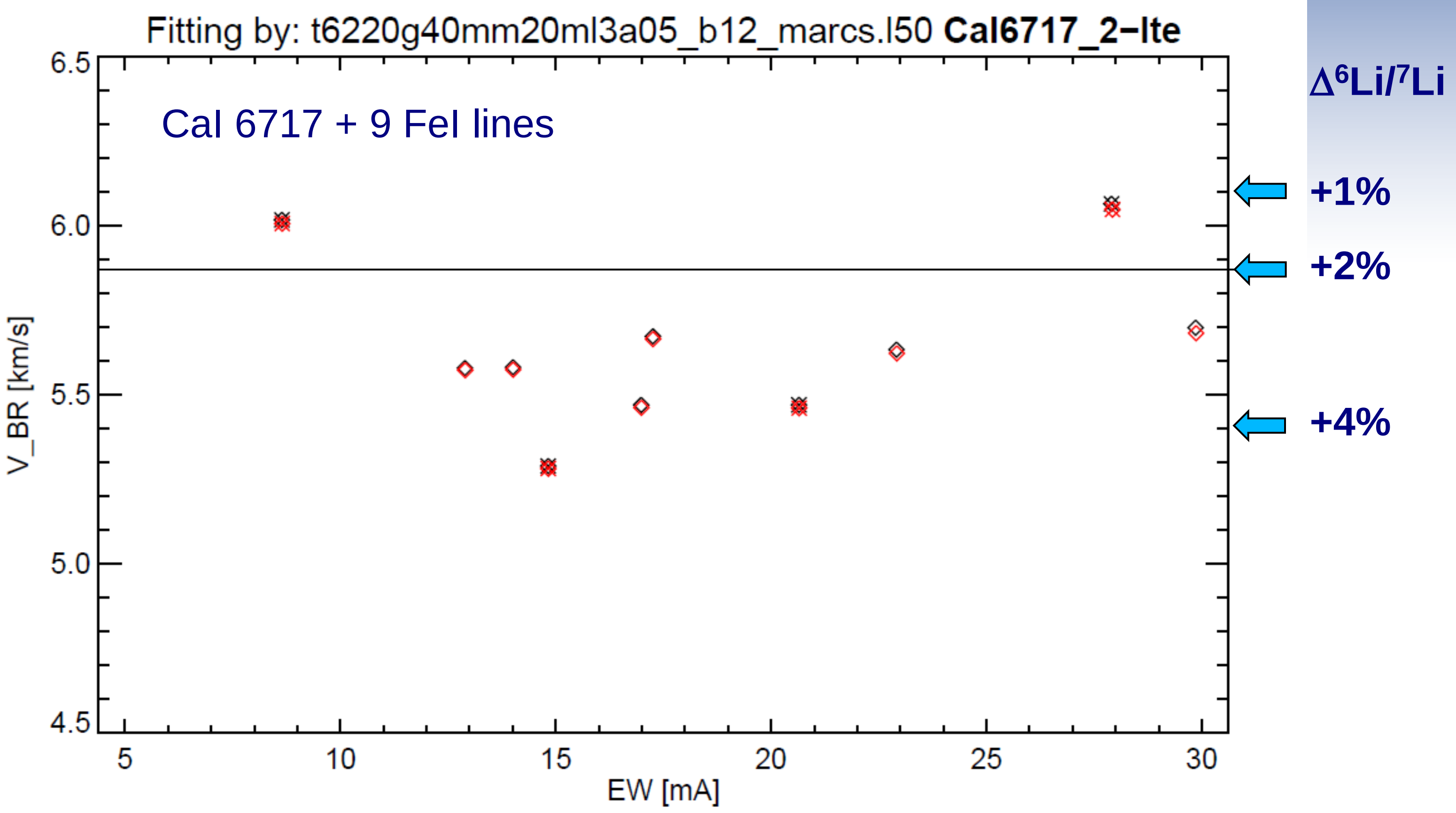
Using additional "calibration lines"

- Fixed: ξ_{mic}, v sin i, FWHM (instrumental)
- Fixed: ξ_{mac}, (macroturbulence) from **calibration lines**

- Fitting of **observed Li 6707** with **grid of synthetic line profiles**
- **3 free fitting parameters:**
  ➔ Lithium abundance: $A(^6Li + ^7Li)$
  ➔ Isotopic ratio: $^6Li / ^7Li$
  ➔ Global Doppler shift: Δv

1D LTE fitting of HD 74000 calibration lines

Anti-correlation between line broadening and ^{6}Li abundance



Conclusions

- Taking intrinsic line asymmetry into account in 3D NLTE reduces the ^{6}Li / ^{7}Li ratio by ≈ 2%
- Correcting the Asplund et al. (2006) sample reduces the number of 2σ detections from 9 to 2
  (G020-024, HD 102200)
- Remaining detections under 3D NLTE
  HD 84937: ^{6}Li / ^{7}Li ≈ 4.8% (2σ detection)
  G275-4: ^{6}Li / ^{7}Li ≈ 3.5% (?)
- Fixing the broadening of Li from other lines is problematic (choice of lines) ➔ overestimation of ^{6}Li / ^{7}Li
- Further investigations necessary
  Spectra of even higher quality