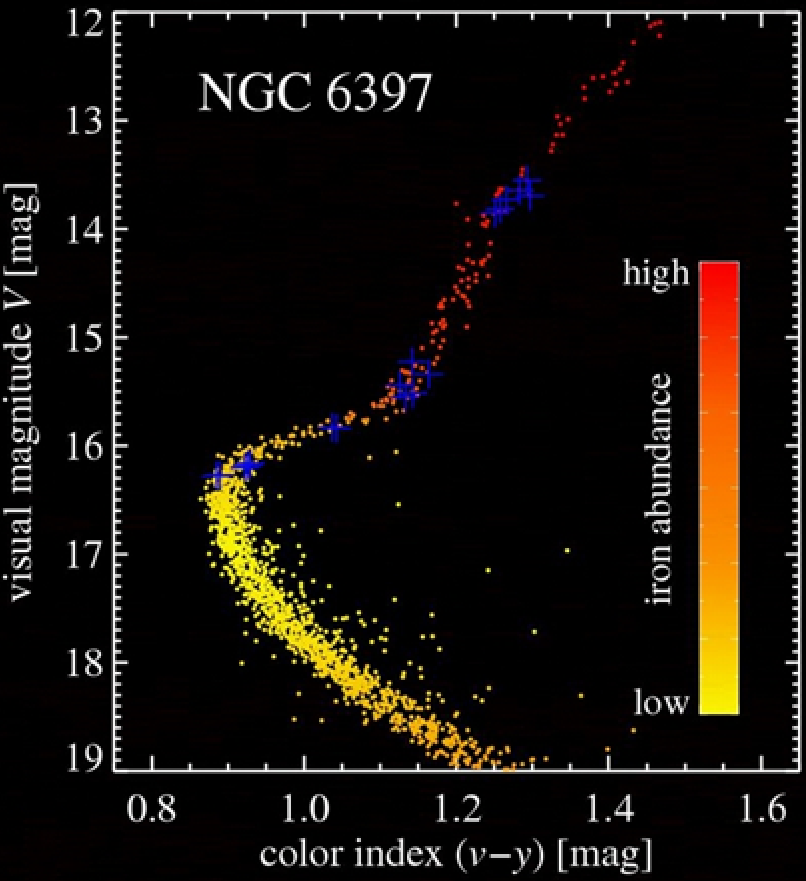
Diffusion in old stars

(c) European Southern Observatory



Andreas Korn

Uppsala **A**stronomical **O**bservatory

Overview

- The cosmological lithium discrepancy
- Atomic diffusion: theory vs. observation
- Observational difficulties
- Results for NGC 6397
- Implications
- Outlook

collaborators:
Frank Grundahl,
Olivier Richard,
Lyudmila Mashonkina,
Paul Barklem,
Remo Collet,
Nikolai Piskunov &
Bengt Gustafsson

lithium: BBN and the Spite plateau

historically (1982 – 2003):

use the uniform atmospheric lithium abundance of warm halo stars (Spite & Spite 1982) to constrain Ω_b

1984: Michaud *et al.* predict stellar depletion of lithium in warm halo stars by a factor of 10

(mid-1990s: use $\log \varepsilon(\mathrm{D})_{\text{high-z}}$ to constrain Ω_b)

1999: Ryan *et al.* find slope in $\log \varepsilon(\mathrm{Li})$ vs. [Fe/H]

now: use CMB+BBN to predict $\log \varepsilon(\mathrm{Li})_p$

result: **stellar abundances are systematically below primordial one (2.2 ± 0.1 vs. 2.64 ± 0.03)**

possible solutions

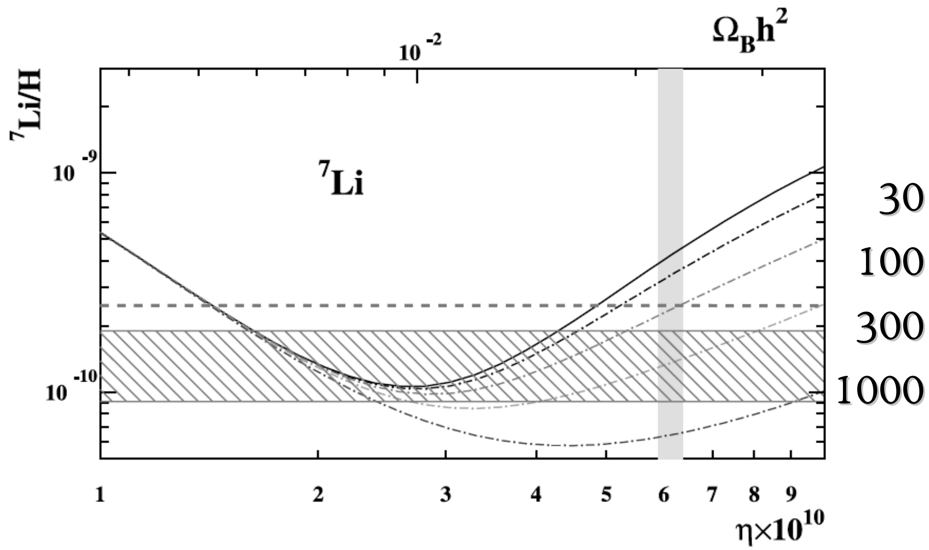
- BBN wrong: assumed ^{7}Be (d,p) 2 ^{4}He reaction rate **too small?** (Coc *et al.* 2004)

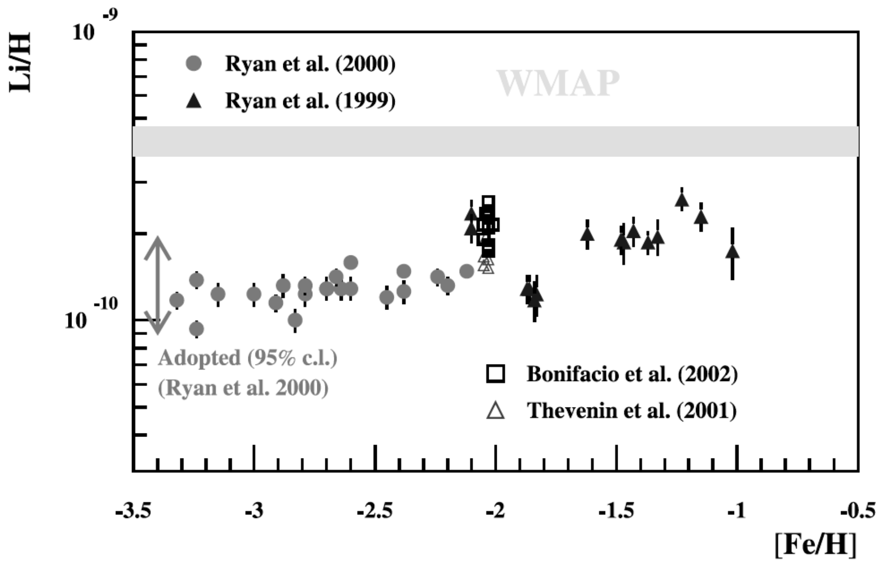
Angulo *et al.* (2005):
  (X-section)$_{exp}$ slightly ***smaller***

- stellar depletion à la Michaud:
  Can such models meet all observational constraints in connection with lithium?

Richard *et al.* (2005): ***yes***

- new physics: decaying super-symmetric particle? (Jedamzik *et al.* 2006)





What is atomic diffusion?

Atoms/ions are subject to a number of forces in stellar atmospheres:

- gravity (⇓, *gravitational settling*)
- gas pressure gradient (⇑)
- thermal gradient (⇓)
- radiative acceleration (⇑, *levitation)*
- macroscopic flows: primarily *convection*
- e-m forces, shocks, …

***atomic diffusion*: the net effect of all processes**

convection + small diffusion constants ⇨ long timescales are required to produce sizable effects in cool stars

current model predictions

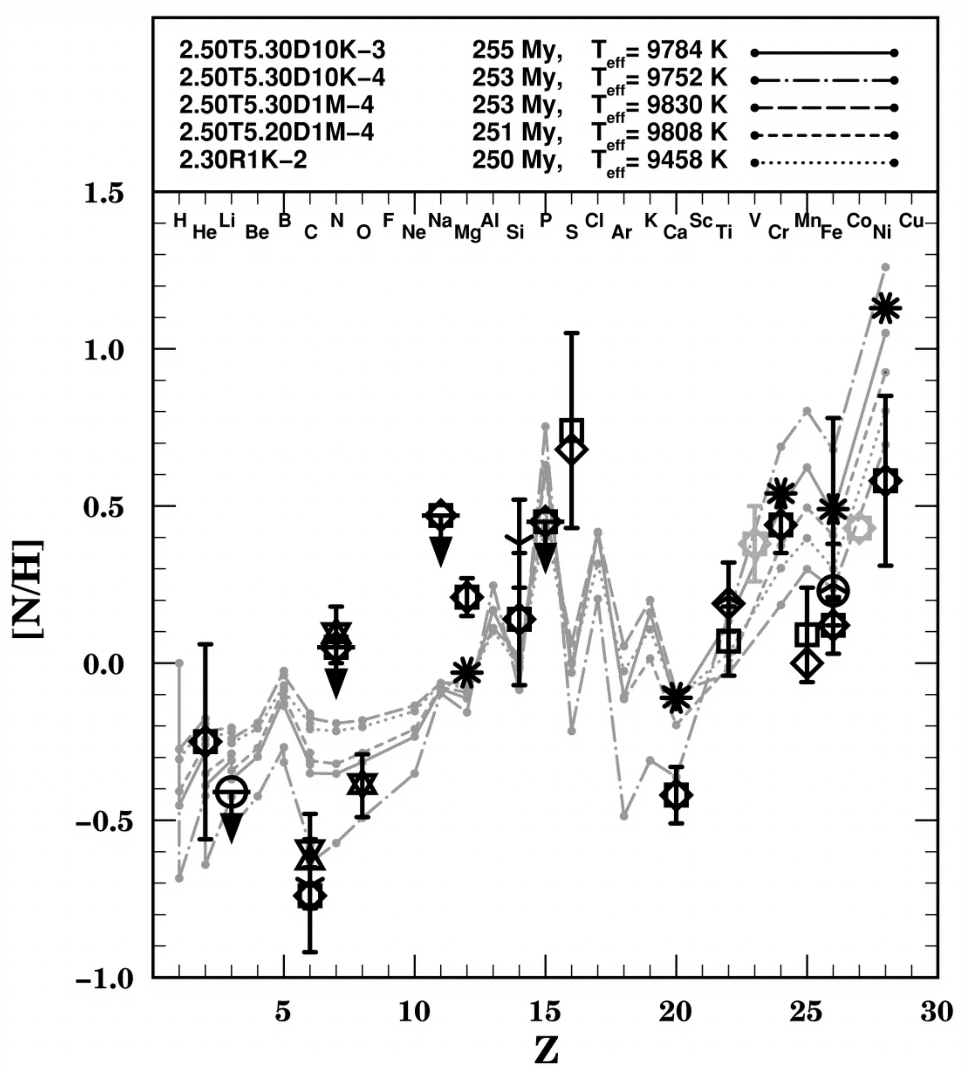
theory vs. observations of Sirius A for various efficiencies of turbulent mixing (Richer *et al.* 2000)

this mixing is needed to keep a certain fraction of the star mixed, otherwise effects become too large to reconcile with observations

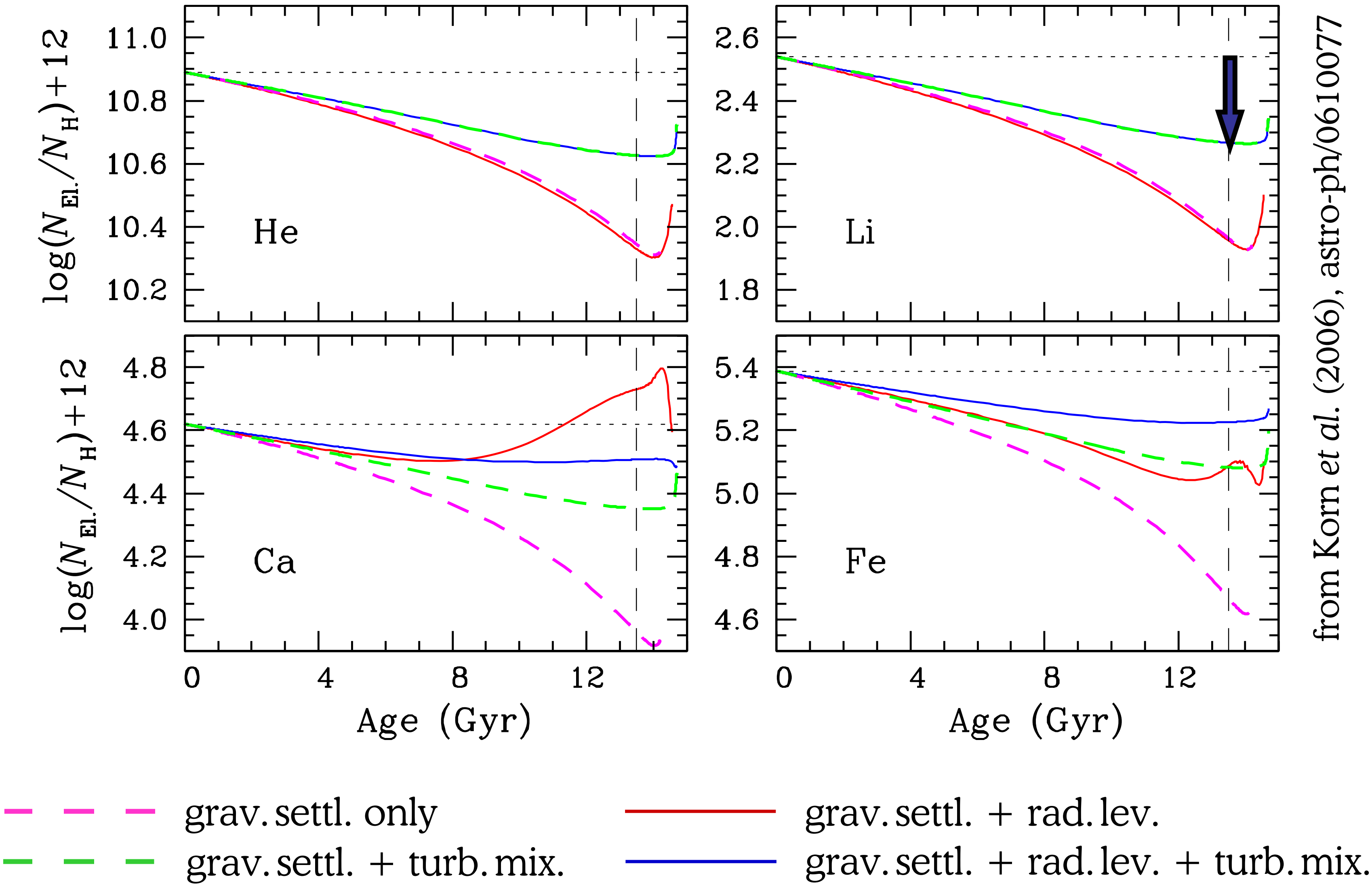
turbulent mixing parametrized as an additional term in diffusion equation (*ad hoc*):

$$D_T \propto D(\mathrm{He})_0 \, (\rho_0 / \rho)^3$$

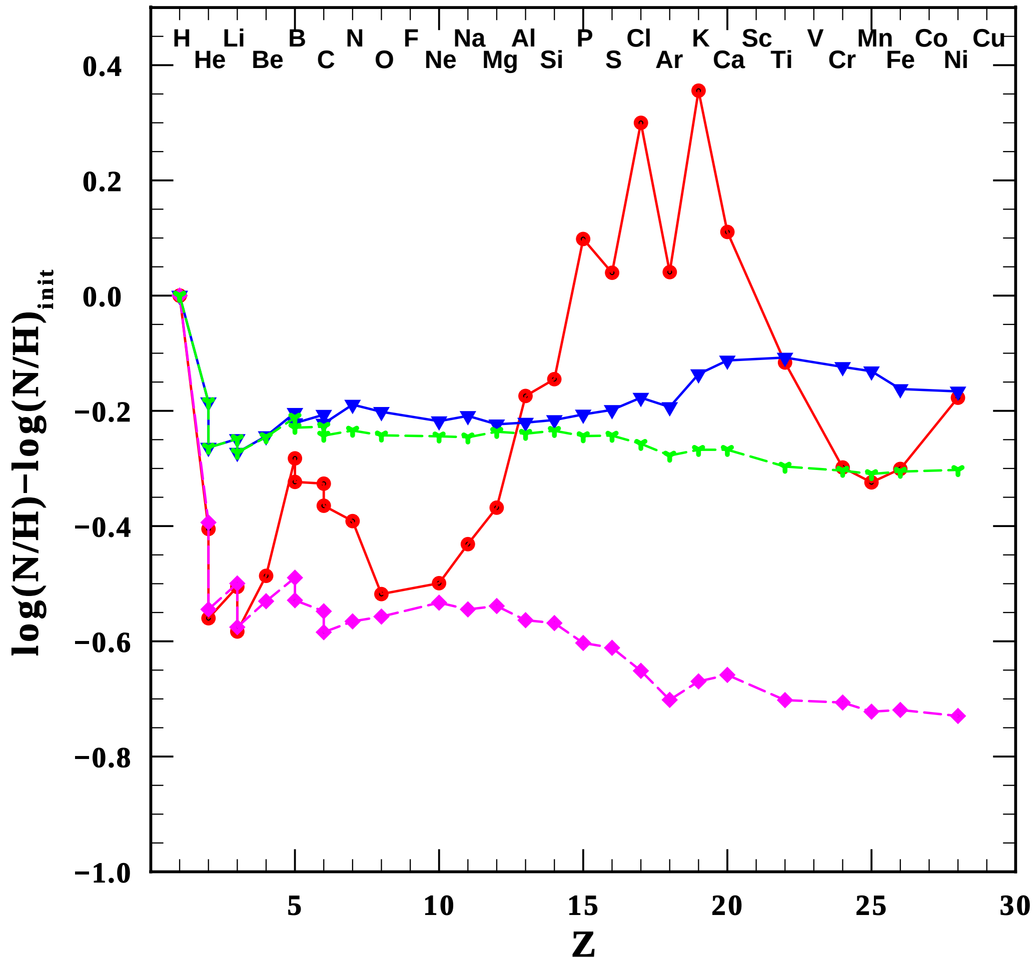
ρ^{-3} dependence constrained by the solar Be abundance (Proffit & Michaud 1991)



current model predictions (cont'd)



current model predictions (cont'd)



abundance variations for a TOP star ([Fe/H] = −2) after 13.5 Gyr **with respect to the original abundances**

from Korn *et al.* (2006), astro-ph/0610077

grav. settl. only — grav. settl. + rad. lev.

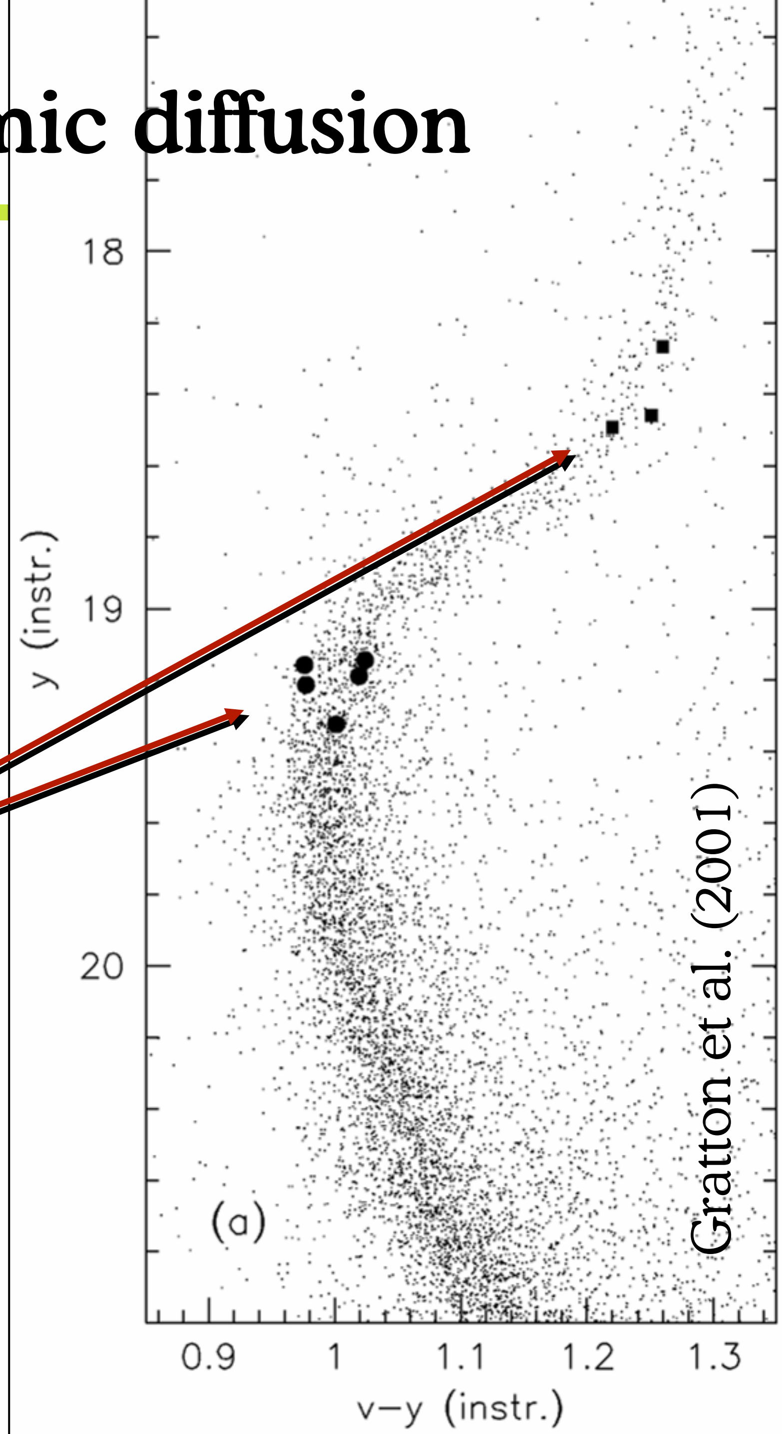
grav. settl. + turb. mix. — grav. settl. + rad. lev. + turb. mix.

How to observe atomic diffusion

compare abundances in TOP stars
to those in stars at the base of the RGB,
all drawn from a single population
⇨ **GCs are ideal objects for this purpose**

$\Delta\, T_{\mathrm{eff}} \simeq 1000$ K
$\Delta \log g \simeq 0.7$ dex

How can one distinguish between ***atomic diffusion*** and ***modelling deficits***?



Methods and results so far

King *et al.* (1998): M92 @ [Fe/H] ≈ −2.4
"We note possible evidence for [Fe/H] differences within M92."

Gratton *et al.* (2001): NGC 6397 @ [Fe/H] ≈ −2.1
no indication of significant abundance differences

Gratton *et al.* (2001): NGC 6752 @ [Fe/H] ≈ −1.6
no indication of significant abundance differences

Cohen & Meléndez (2005): M13 @ [Fe/H] ≈ −1.5
only one/two unevolved (subgiant) stars

Ramírez & Cohen (2003): M5 @ [Fe/H] ≈ −1.3
no indication of significant abundance differences

Ramírez *et al.* (2001): M71 @ [Fe/H] ≈ −0.8)
no indication of significant abundance differences

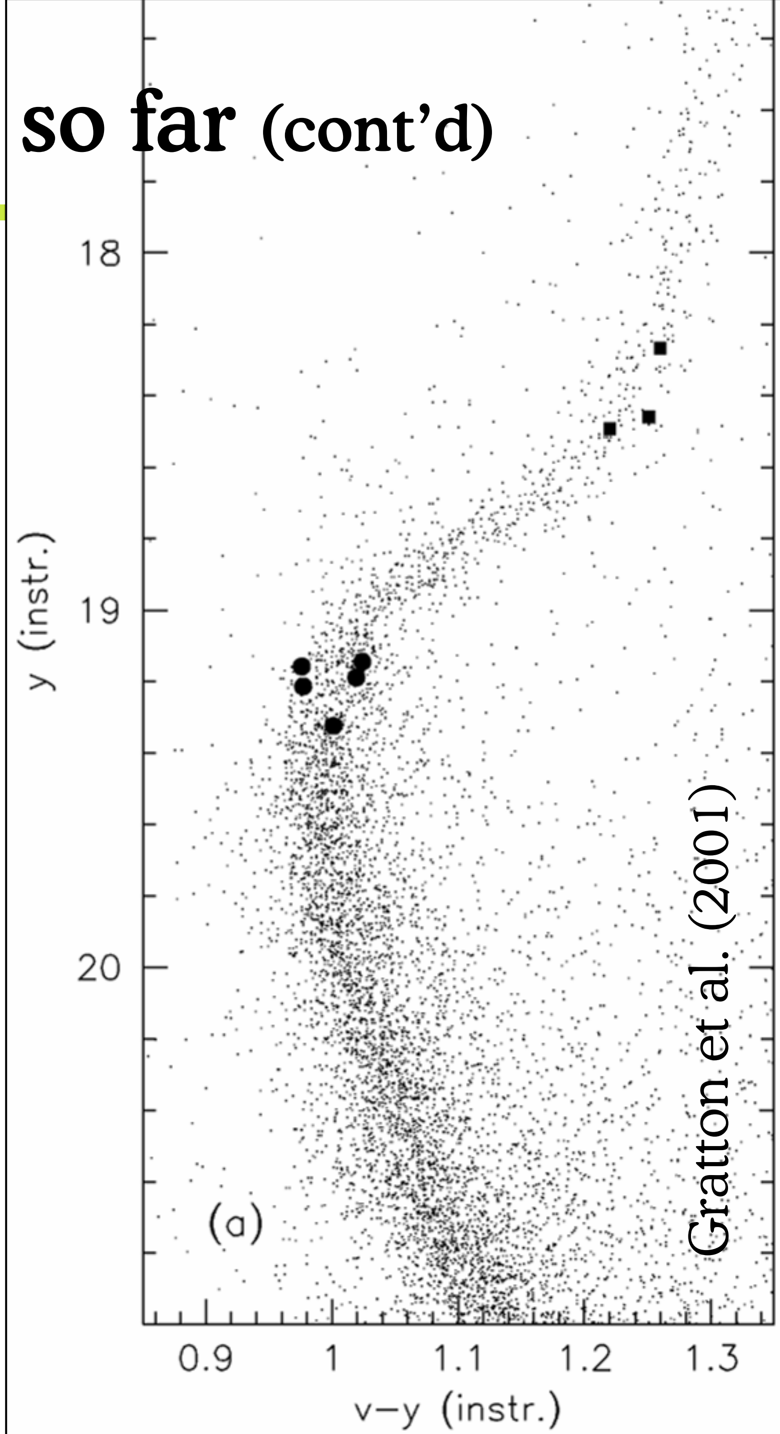
Methods and results so far (cont'd)

Gratton *et al.* (2001):

1. want to avoid reddening
   - ⇨ use a spectroscopic temperature scale
   - ⇨ Balmer profile temperatures
2. use gravity estimate from isochrone
3. derive [Fe/H] from Fe I

Results:

1. $T_{\rm eff}$ (TOP) = 6480 K
   $T_{\rm eff}$ (bRGB) = 5480 K
2. $\log g$ (TOP) = 4.1
   $\log g$ (bRGB) = 3.4
3. $[{\rm Fe/H}]_{\rm TOP} = [{\rm Fe/H}]_{\rm bRGB} = -2.03 \pm 0.02$
   assuming LTE



Problems in the Gratton *et al.* analysis

Gratton *et al.* (2001):

1. want to avoid reddening
   ⇨ use a spectroscopic temperature scale
   ⇨ Balmer profiles temperatures
2. use gravity estimate from isochrone
3. derive [Fe/H] from Fe I

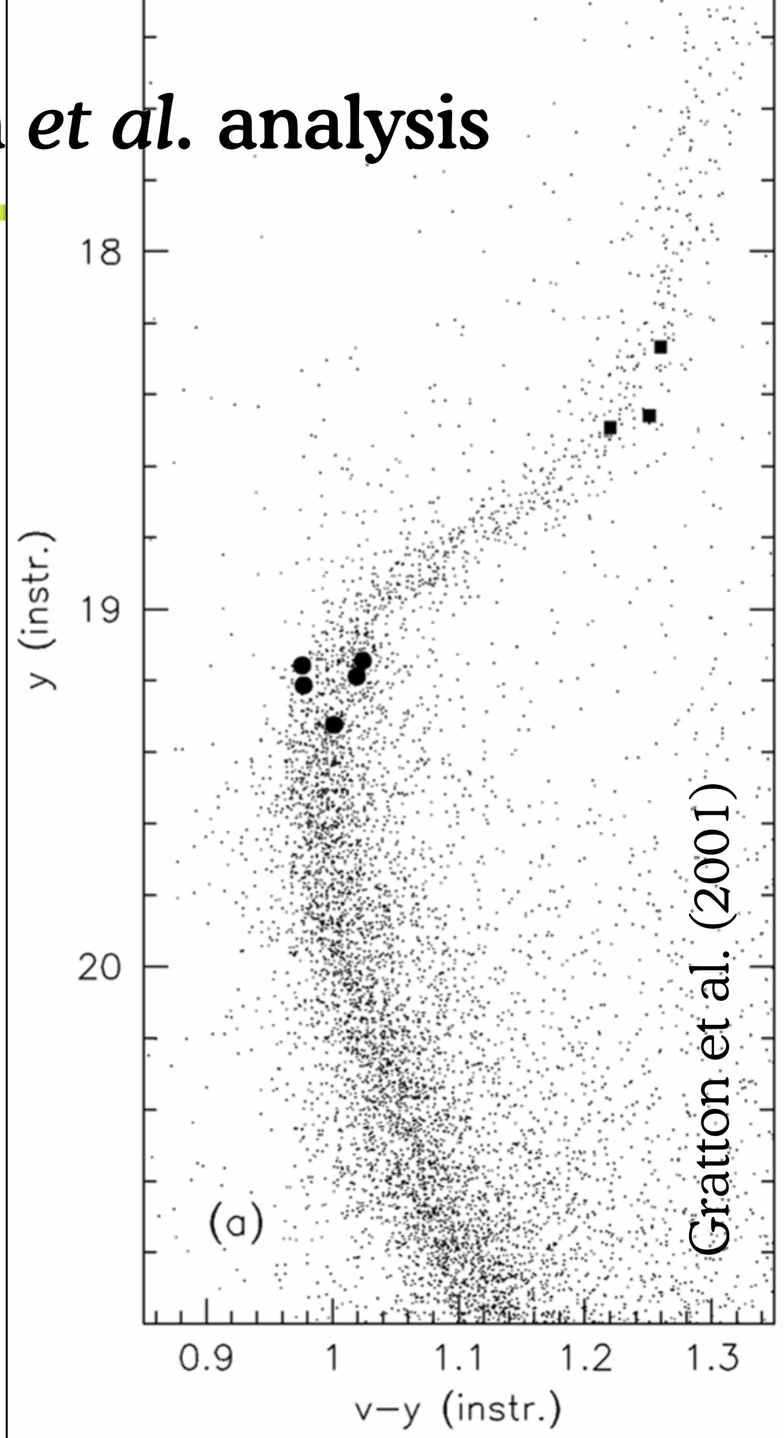
Problems:

1. UVES blaze correction is imperfect
   ⇨ $\Delta T_{\rm eff}$ misestimated?

Not checked by independent means!

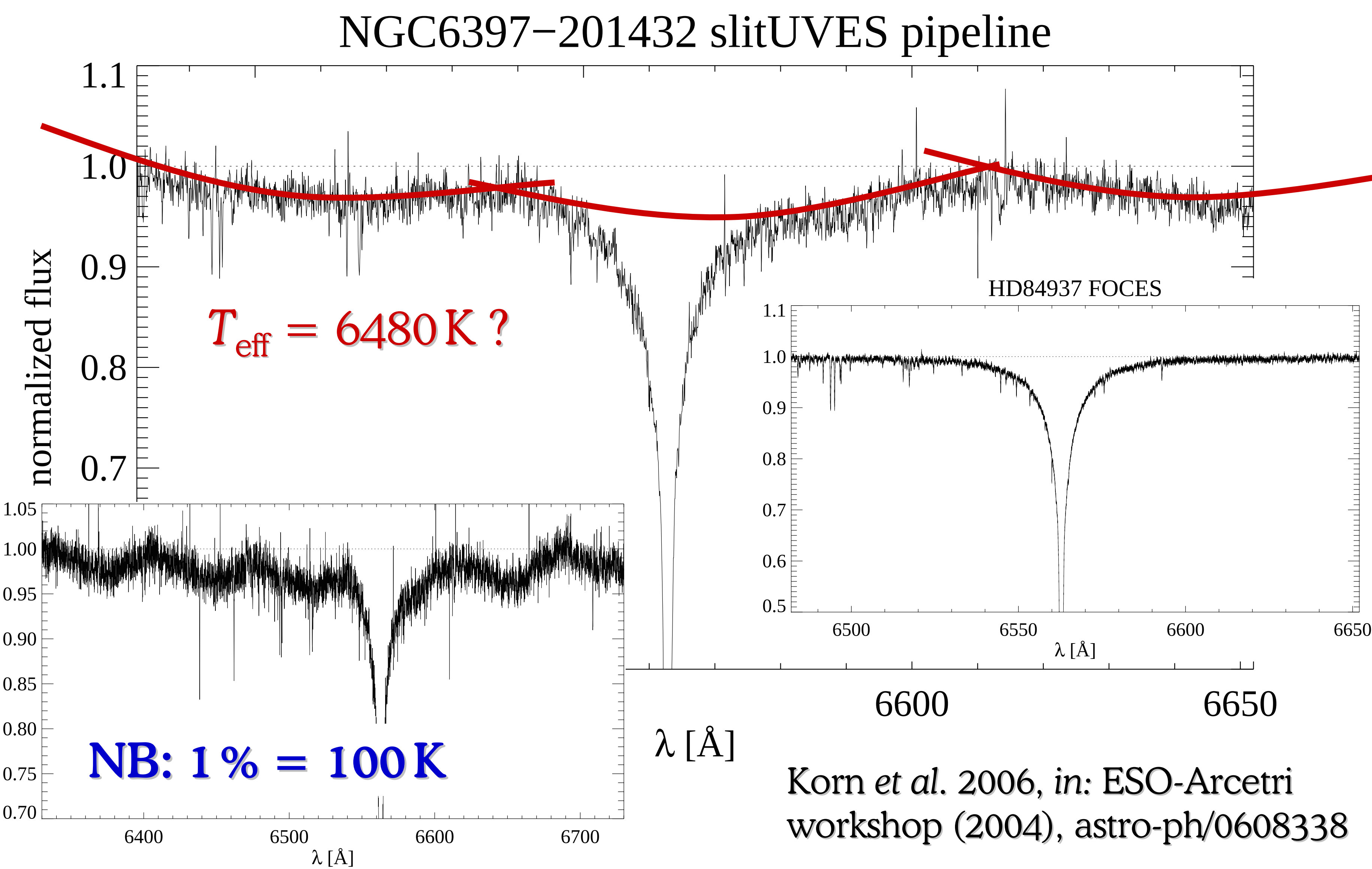
2. & 3. Ionization equilibrium of Fe not established (0.11 dex), LTE assumption valid?
   ⇨ $\Delta \log g$ misestimated?

Use of non-diffusive isochrones may lead to a circular argument!



Gratton et al. (2001)

Problems in the Gratton et al. analysis (cont'd)

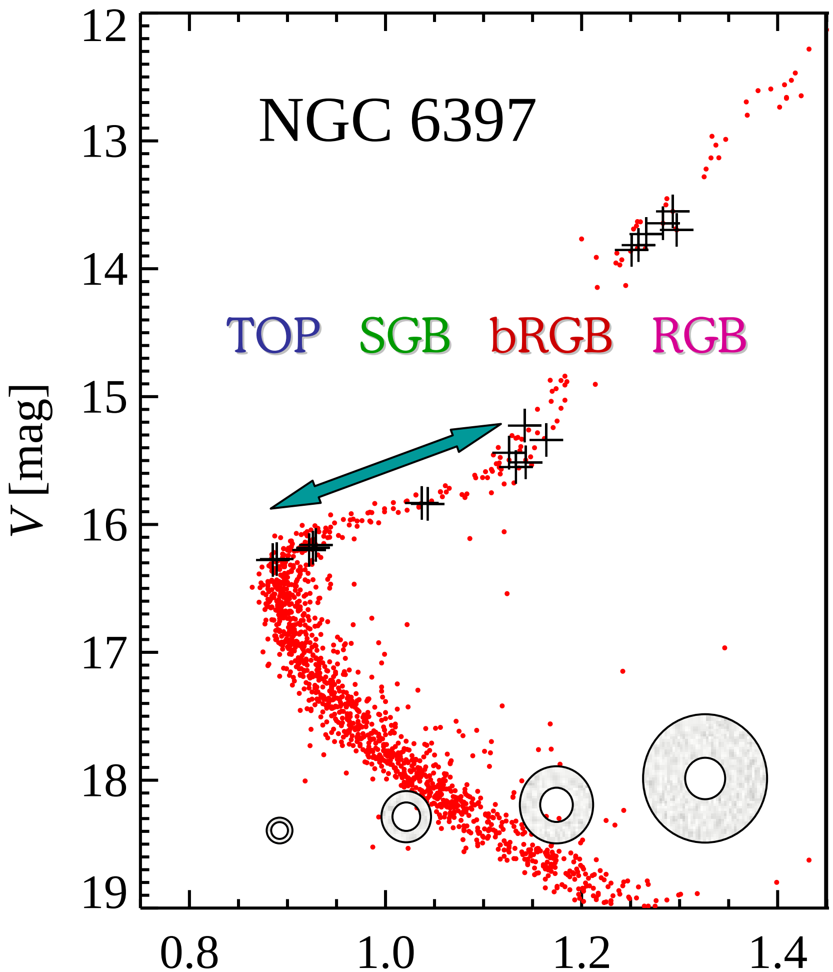


Korn *et al*. 2006, *in:* ESO-Arcetri workshop (2004), astro-ph/0608338

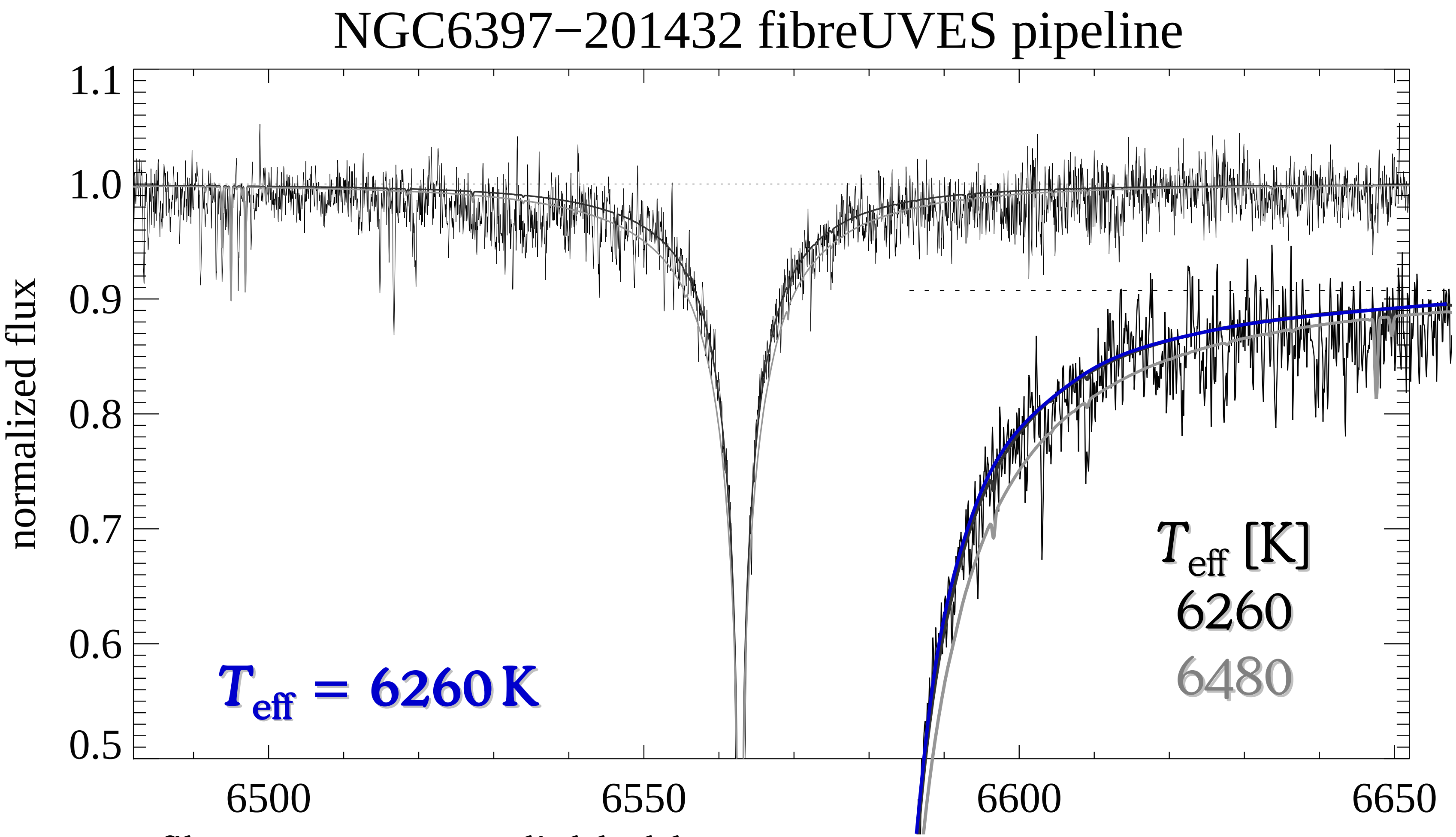
A re-examination of atomic diffusion in NGC 6397

observations with VLT UT2 and FLAMES+UVES (~~6/2004 (VM) &~~ 3/2005 (SM); Korn, Gustafsson, Piskunov, Barklem & Grundahl):

- re-observe some of Gratton's targets with FLAMES+UVES: 5 bRGB and 5 TOP stars;
- additionally, observe 2 SGB and 6 RGB stars;
- fill the 130 MEDUSA fibres with targets along the SGB to look for abundance trends at somewhat lower resolution



FLAMES+UVES: UVES goes fibres



fibres ⇒ more reliable blaze

⇒ more reliable order merging ⇒ more reliable $T_{\rm eff}$ values

homogeneous analysis of FLAMES+UVES targets

- T_{eff} of bRGB stars confirmed, but systematically lower T_{eff} values for TOP stars, by 220 K; baseline extended to RGB stars
- log g values determined from Fe I/II ionization equilibrium in non-LTE (Korn *et al*. 2003)
- new stellar parameters not in conflict with a 13.5 Gyr diffusive isochrone
- independent support for lower $\Delta T_{\mathrm{eff}} / \Delta \log g$ (TOP−RGB) values from broad-band and Strömgren photometry:

ΔT_{eff} (spec) = 1124 K vs.

$\Delta T_{\mathrm{eff}}(V-I)$ = 1070 K and $\Delta T_{\mathrm{eff}}(v-y)$ = 1108 K

$\Delta \log g$ (spec) = 1.33 (+0.05 for He) vs. $\Delta \log g$ (ΔV) = 1.38

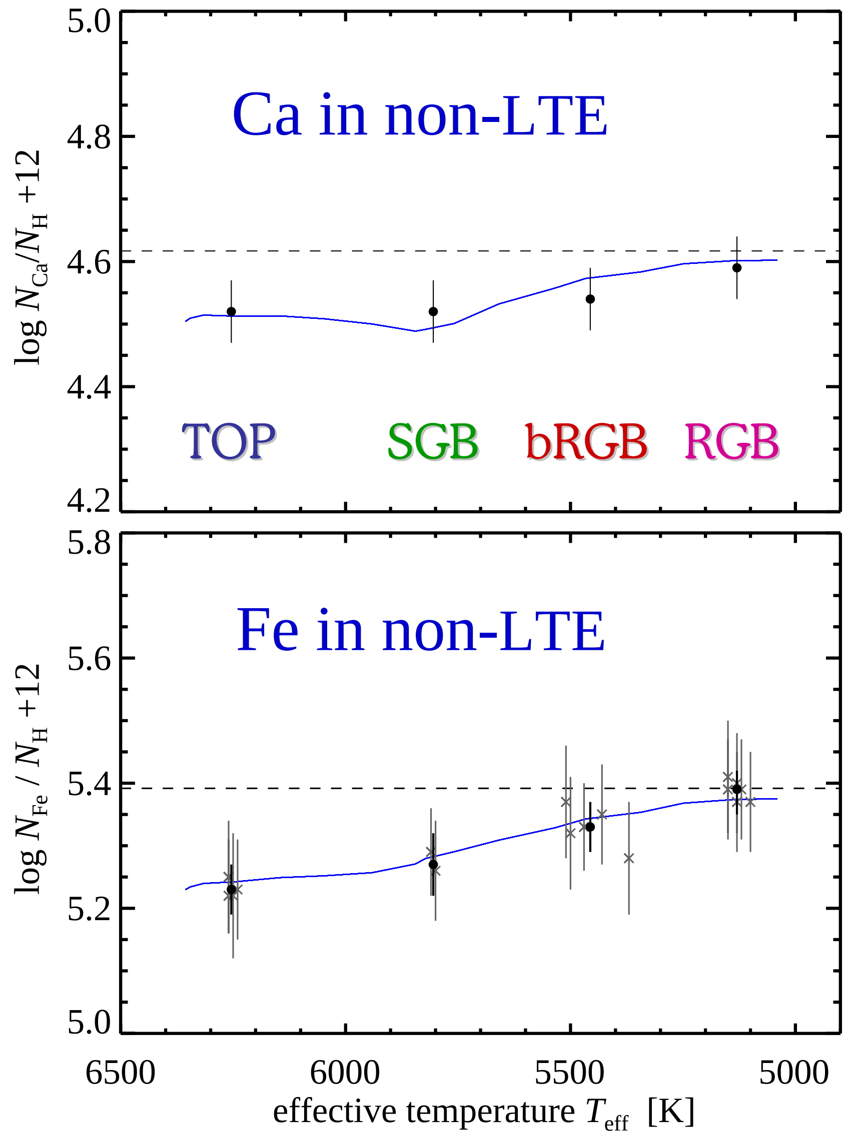
main results

atomic diffusion is at work at the level predicted by current models including turbulent mixing (T6.0)

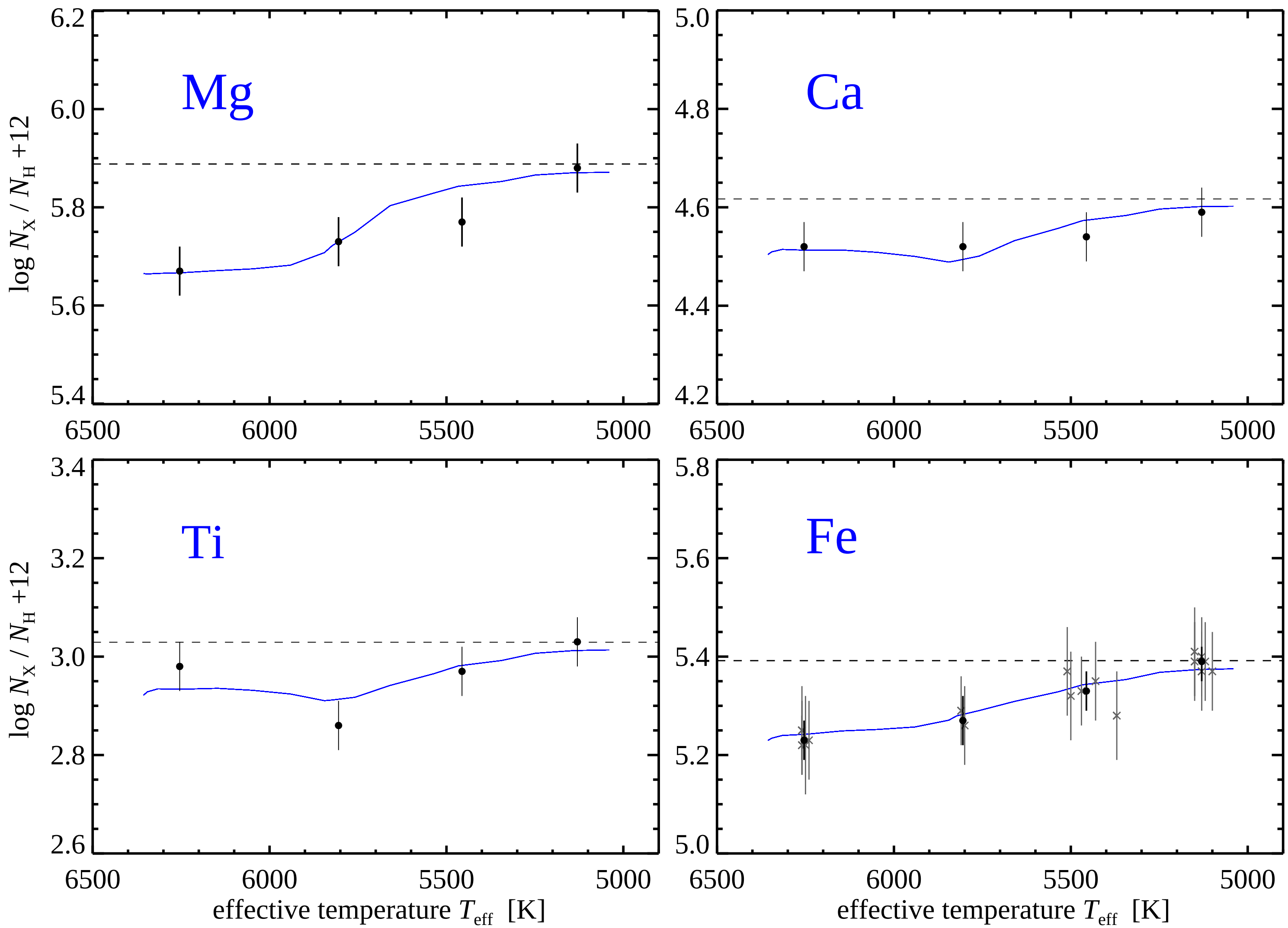
$\Delta\,[\mathrm{Fe/H}]_{\mathrm{TOP-RGB}} = 0.16 \pm 0.05$

(similar trend using a 3D MA)

other elements (Ca, Ti) show shallower trends, as predicted by the models



main results (cont'd)



Korn et al. 2007, *in:* Cool Stars 14 (2006)

main results (cont'd)

correcting for diffusion, the stellar lithium abundances can be reconciled with the CMB+BBN prediction (Korn *et al*. 2006, Nature 442, 657):

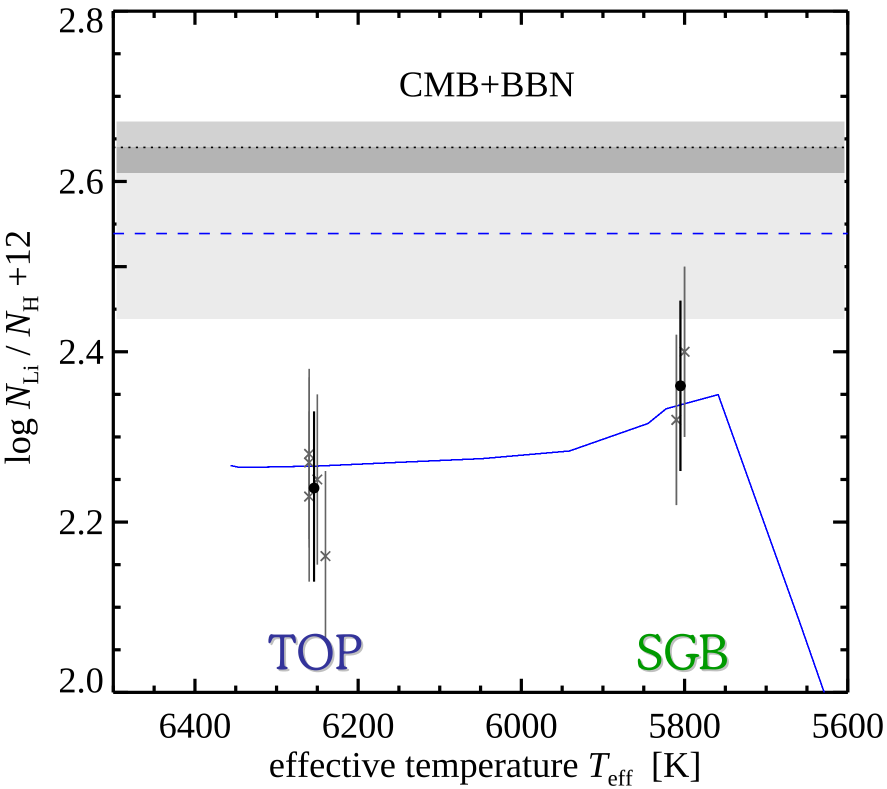
$\log \varepsilon\,(\mathrm{Li})_{\mathrm{NGC\ 6397}} = 2.54 \pm 0.10$

vs. $\log \varepsilon\,(\mathrm{Li})_{p} = 2.64 \pm 0.03$

(Spergel *et al*. 2007)

predicted by Michaud *et al*. (1984)

shown to be compatible with observations by Richard *et al*. (2005)



other implications

- unevoled metal-poor stars appear more metal-poor than they really are; abundance *ratios* are less affected.

  Can such models explain the absence of lithium in the ultra-metal-poor star HE 1327−2326 (Frebel *et al*. 2005)?

- together with helium diffusion, metal diffusion can likely explain the notoriously high ages of halo field TOP and SGB stars

- globular-cluster ages are hardly affected, as metallicity can be determined from giants and turbulent mixing does not affect the central helium diffusion

- integrated-light studies of extragalactic metal-poor stellar populations are possibly affected, if not properly calibrated

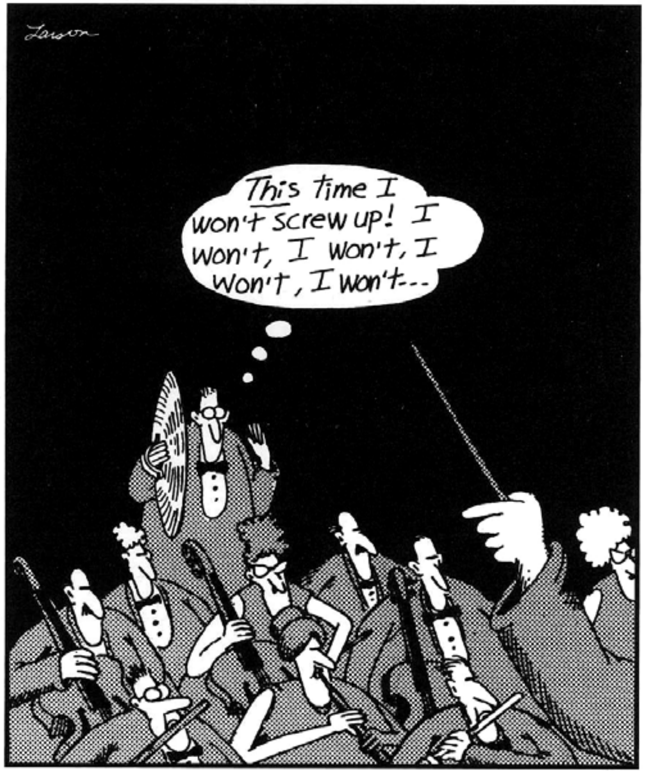
Lessons learned

important things should not be done "single-handedly"

don't rely on a single $T_{\rm eff}$ / log g indicator ("cross-check")

don't use non-diffusive evolutionary tracks to prove the non-existence of diffusion

differential analyses can be remarkably accurate



Outlook

"[…] Urknalltheorie ist gerettet. Zumindest momentan."

NyTeknik, August 2006

Focus has changed: from constraining Ω_b to understanding stellar physics. In particular, we would like to understand what gives rise to the turbulent mixing needed to make theory agree with observations.

One possible explanantion: rotation, angular-momentum transport & internal gravity waves (see, e.g., Talon & Charbonnel 2005)

To constrain atomic diffusion and turbulent mixing further, we will observe NGC 6752 @ [Fe/H] = −1.5 (46 h with FLAMES in P79)

Other challenges: ^{6}Li plateau well above BBN prediction (Asplund *et al*. 2006), a signature of new physics (Jedamzik *et al*. 2006)?

other works

King *et al.* (1998): M 92 @ [Fe/H] ≈ −2.4
"We note possible evidence for [Fe/H] differences within M92."

Gratton *et al.* (2001): NGC 6397 @ [Fe/H] ≈ −2.1
data-reduction problem ⇒ biased T_{eff} values for TOP stars
(see Korn *et al.*, astro-ph/0608338)

Gratton *et al.* (2001): NGC 6752 @ [Fe/H] ≈ −1.6
similar data-reduction problems? to be re-investigated…

Cohen & Meléndez (2005): M 13 @ [Fe/H] ≈ −1.5
only three unevolved (subgiant) stars: $\overline{\text{[Fe/H]}}$ lower by 0.13 dex

Ramírez & Cohen (2003): M 5 @ [Fe/H] ≈ −1.3
6 unevoled vs. 19 evolved stars: more efficient turbulent mixing?

Ramírez *et al.* (2001): M 71 @ [Fe/H] ≈ −0.8
likely too metal-rich (extended outer CZ, cooler TOP)

the hard limit: 13.5 Gyr

stellar parameters in good agreement with a 13.5 Gyr diffusive isochrone constructed from the turbulent-mixing model that describes the heavy-element abundance trends best