

Stellar Atmospheres & Abundance Determinations: $^{6,7}\text{Li}$ in Ancient Halo Stars?

Josipa Vujaklija

June 24th, 2009

Outline

1. Standard Big Bang Nucleosynthesis (SBBN)
2. Spite Plateau & ${}^6\text{Li}$ plateau?
3. Abundance Determinations
4. Solutions to Lithium Problems
 - Possible ${}^7\text{Li}$ explanation?
 - Possible ${}^6\text{Li}$ production?

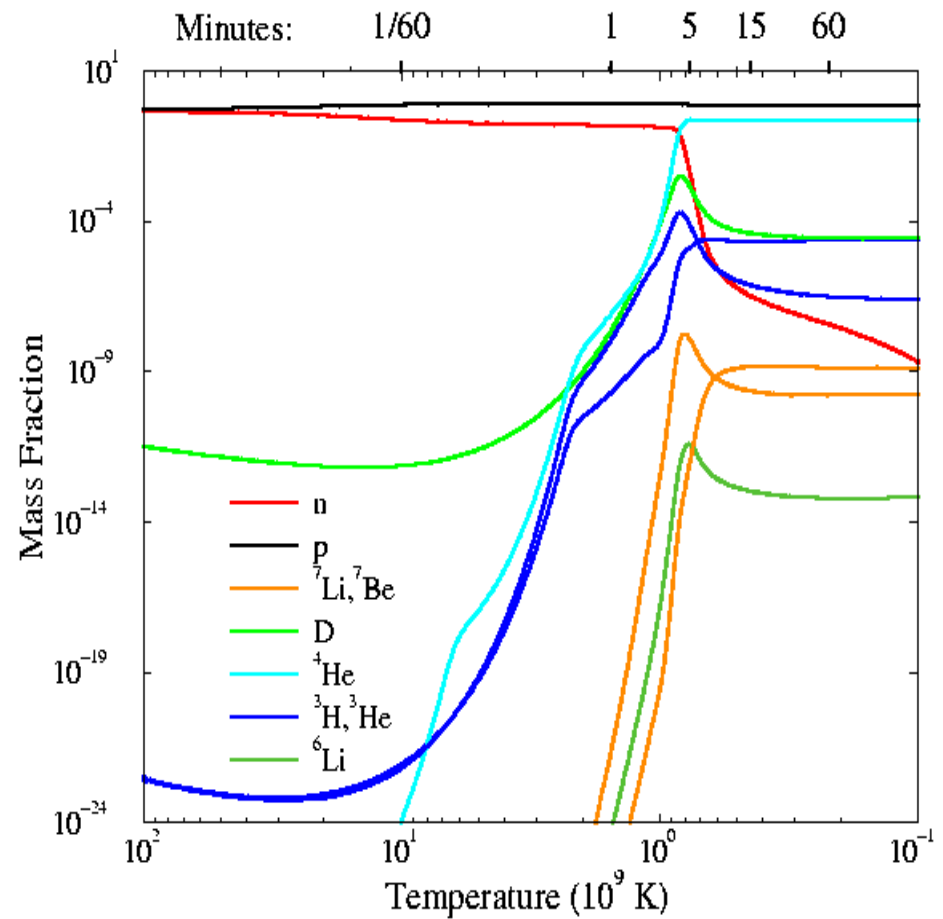
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Standard Big Bang Nucleosynthesis

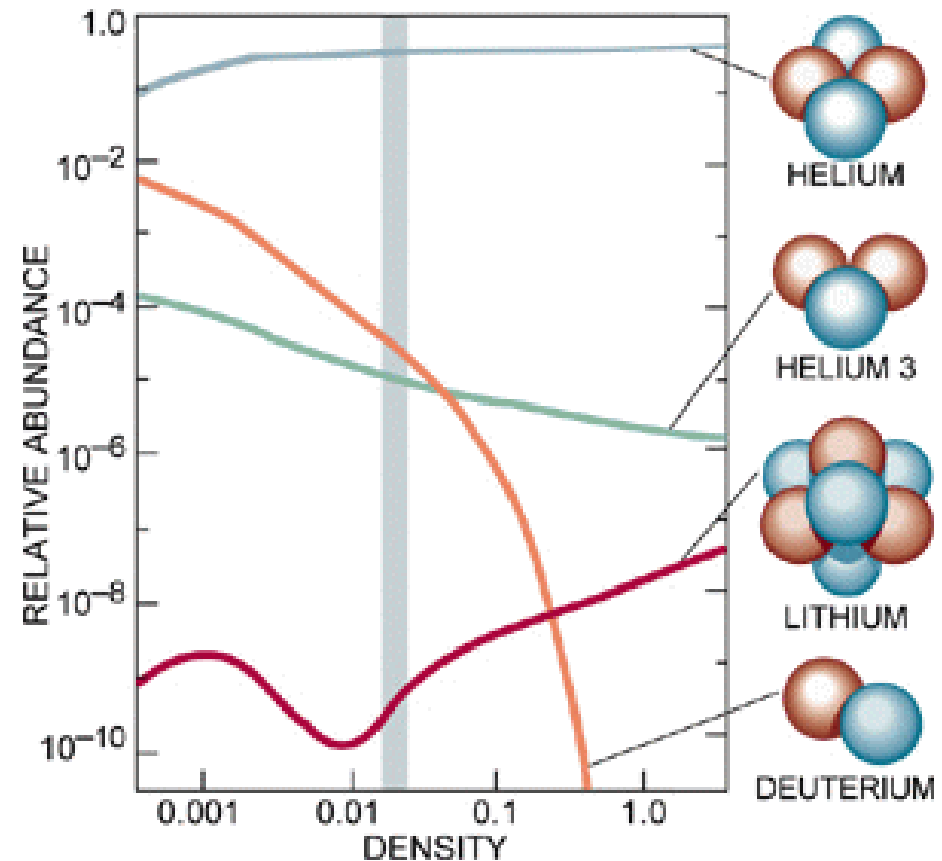
- Predicts primordial abundances of light elements
- D, ^3He , ^4He , ^7Li produced during first 15 minutes of Big Bang, $T \sim 10^9\text{K}$
- Heavier elements produced in stars and through supernovae

75% ^1H
25 % ^4He
0,001% D
traces of ^3He , ^7Li



Predicted abundances

- In SBBN abundances of light elements **only depend on baryon density η !**
- η from anisotropies in Cosmic Microwave Background:
 $\eta = n_b/n_\gamma = 0.0224 \pm 0.0009$
(WMAP)
- Perfect agreement with observed D, good agreement with He but
NO agreement with Lithium!



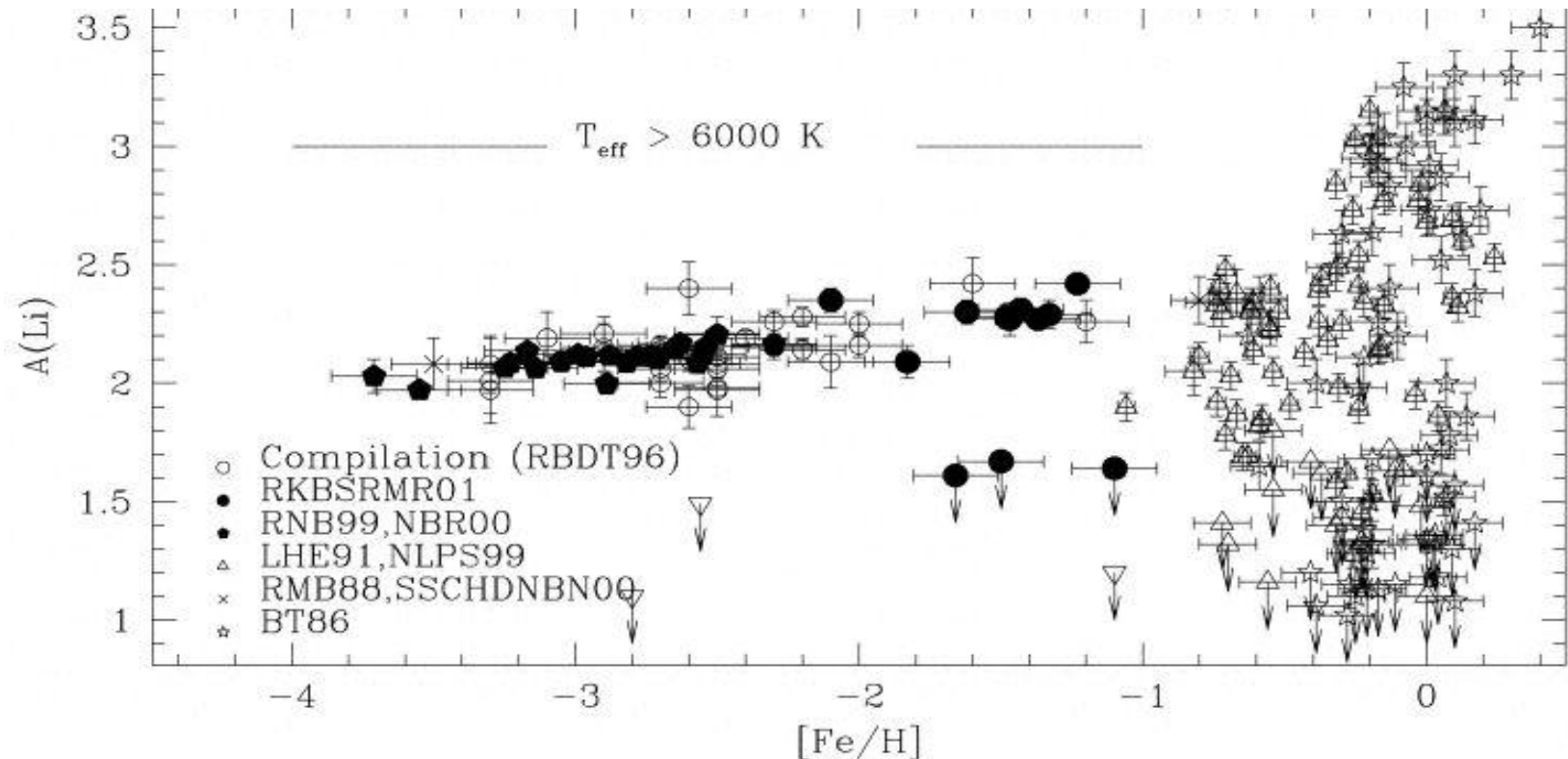
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Spite Plateau

- **F. Spite & M. Spite (1982):**

Li abundances in metal-poor halo dwarfs independent of metallicity ([Fe/H] < -1.5): „Spite Plateau“



Spite Plateau

- Li abundance with only small scatter
⇒ primordial origin?
- Trend with [Fe/H]?
- Derived abundance: $\log \epsilon_{7\text{Li}} = 2.05 \pm 0.15$
SBBN: $\log \epsilon_{7\text{Li}} = 2.72 \pm 0.10$
with $\log \epsilon_{Li} = \log \frac{N(Li)}{N(H)} + 12$
→ discrepancy for ${}^7\text{Li}$ of a factor of 4-5 (~ 0.7 dex)!

${}^6\text{Li}$ Plateau?

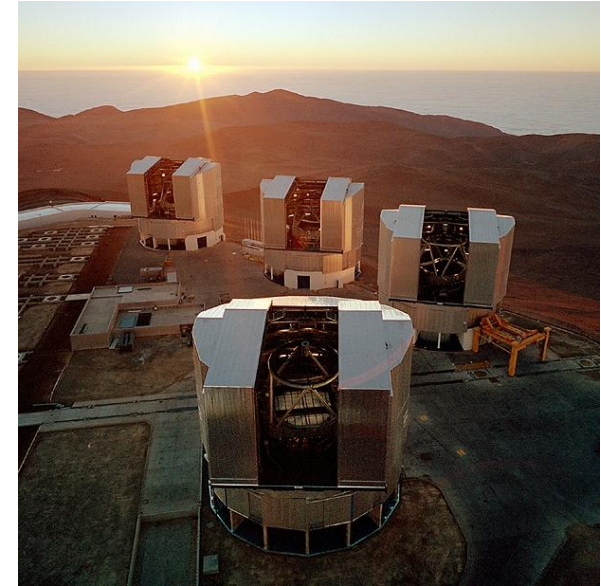
- Detection of ${}^6\text{Li}$ in several metal-poor stars (${}^6\text{Li}/{}^7\text{Li} < 0.1$)
 - ➔ ${}^6\text{Li}$ plateau parallel to Spite Plateau?
 - ➔ synthesis prior to star formation
- Measured abundance: $\log \epsilon_{6\text{Li}} = 0.82$ (Asplund et al, 2006)
- **BUT: ${}^6\text{Li}$ abundance of plateau exceeds SBBN abundance by large factor!**

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Data reduction & selection of stars

- Stars with range $-3.0 < [\text{Fe}/\text{H}] < -1.0$
- Spectra obtained with UVES (on the ESO VLT)
- High S/N ratio (~ 500)
- In turnoff region of Hertzsprung-Russell (H-R) diagram
 - ⇒ Thin upper convection zone
 - ⇒ Minimal proton destruction of Li



UVES (VLT)

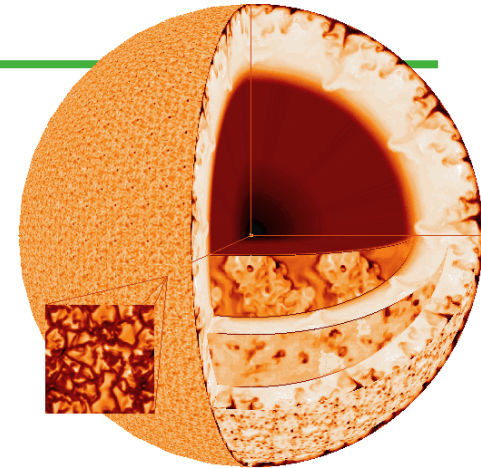
Stellar model atmospheres

1 D

- One dimensional
- **Hydrostatic**
- **Time independence**
- Convection treated by mixing-length theory
- LTE
- **3 free parameters:**
 $\alpha_{\text{MLT}}, \xi_{\text{turb}}, \zeta_{\text{macro}}$

3 D

- 3 dimensional
- **Hydrodynamical**
- **Time dependence**
- Hydrodynamical simulation predicts convection efficiency
- LTE
- **NO free parameters!**



LTE / non-LTE

LTE (Local Thermodynamic Equilibrium):

Assumption: only local temperature determines

populations of all atomic levels at a given place

- Boltzmann distribution: $\frac{N_i}{N} \propto \exp\left(-\frac{E_i}{kT}\right)$
- Saha distribution for ions: $\frac{N_{i+1}}{N_i} \propto \frac{1}{N_e} \cdot (kT)^{\frac{3}{2}} \cdot \exp\left(-\frac{E_{i+1}-E_i}{kT}\right)$

BUT:

Level populations also depend on radiation field and pressure

⇒ **non-LTE**: considering all possible energy level transitions

Computationally demanding!

Li spectral line formation

Assumption: (1D) LTE

Line broadening:

turbulence, rotation,
Doppler broadening...

Line asymmetries:

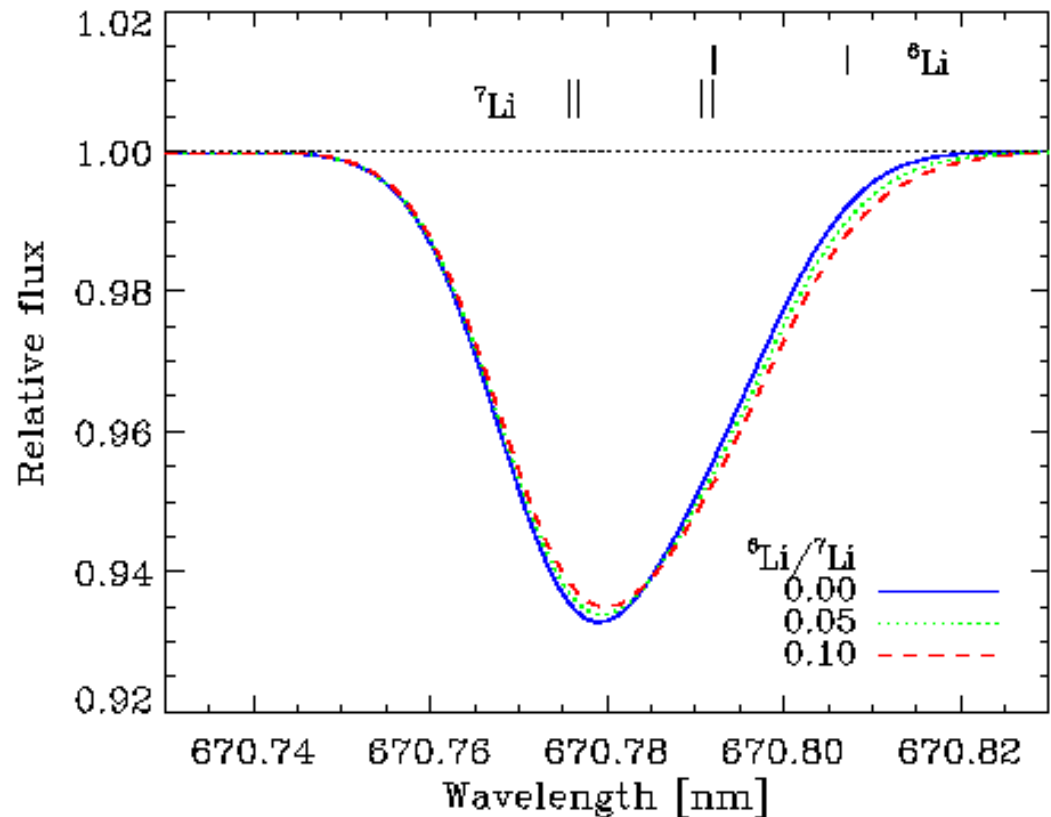
Doppler shift, convection

+

Additional asymmetry

from presence of ${}^6\text{Li}$

⇒ **Challenging analysis!**



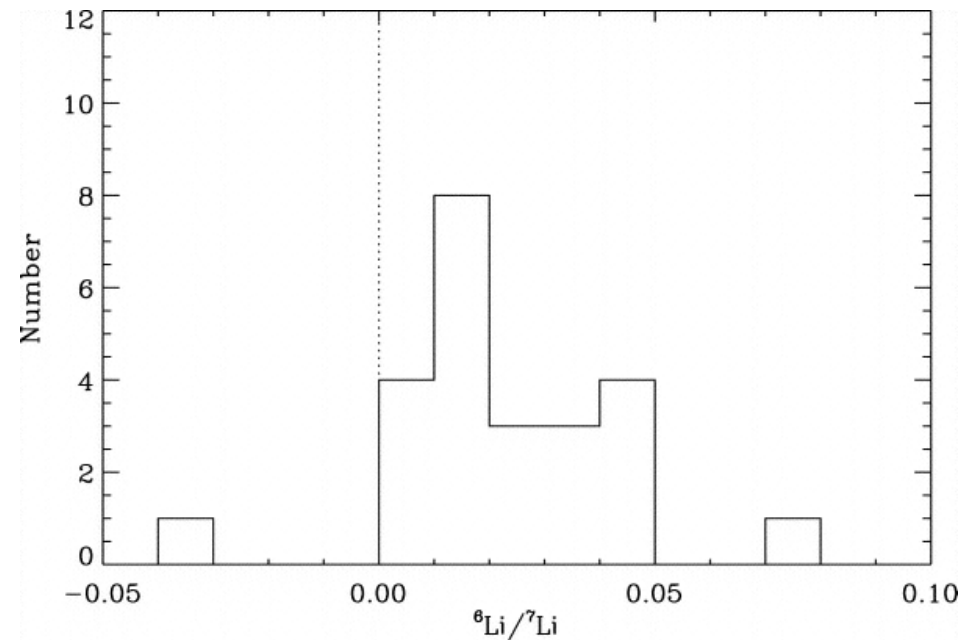
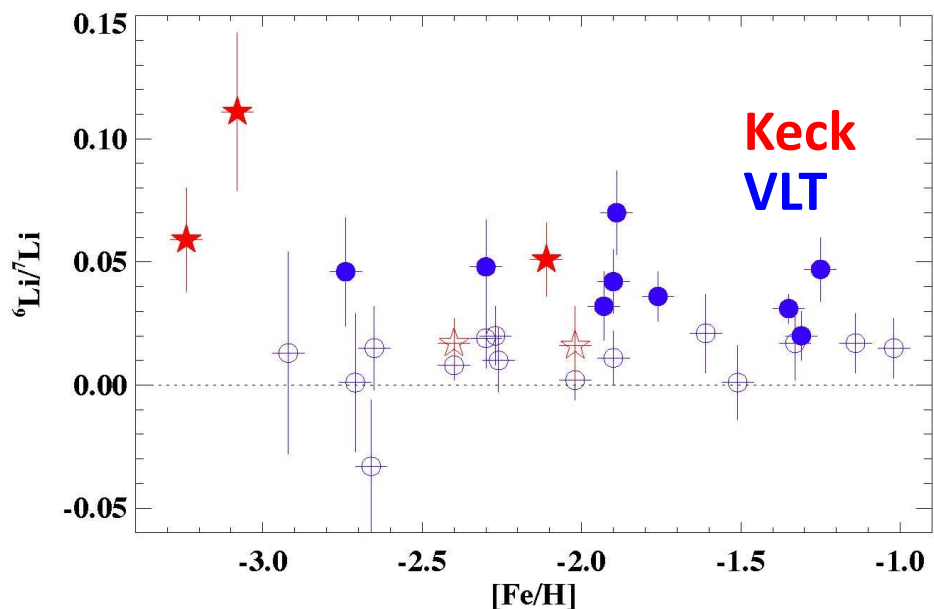
Li I 670.8 nm line

${}^6\text{Li}/{}^7\text{Li}$ ratio

SBBN: ${}^6\text{Li}/{}^7\text{Li} \sim 10^{-5}$

Nondetections cluster around ${}^6\text{Li}/{}^7\text{Li} \approx 0.01$ (1-2 σ)

\Rightarrow Systematic error?



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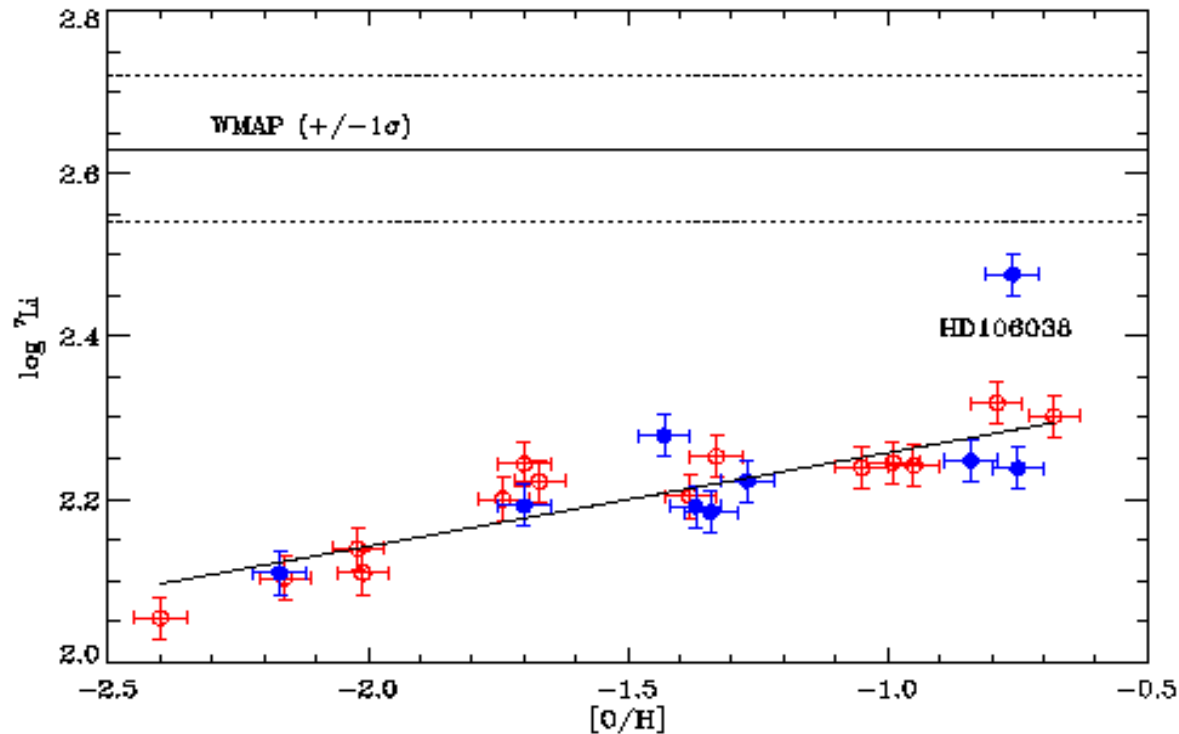
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${}^7\text{Li}$ abundance

Measured abundance: $\log \epsilon_{7\text{Li}} = 2.21 \pm 0.07$

VS

WMAP (BBN) : $\log \epsilon_{7\text{Li}} = \log \epsilon_{7\text{Li}} = 2.72 \pm 0.10$



Stellar parameters

Stellar parameters: T_{eff} , $\log g$,
[Fe/H]

Small errors in $\log g$, [Fe/H]

T_{eff} : from H_{α} line profile:
small relative uncertainties in
 T_{eff} but absolute temperature
scale uncertain!

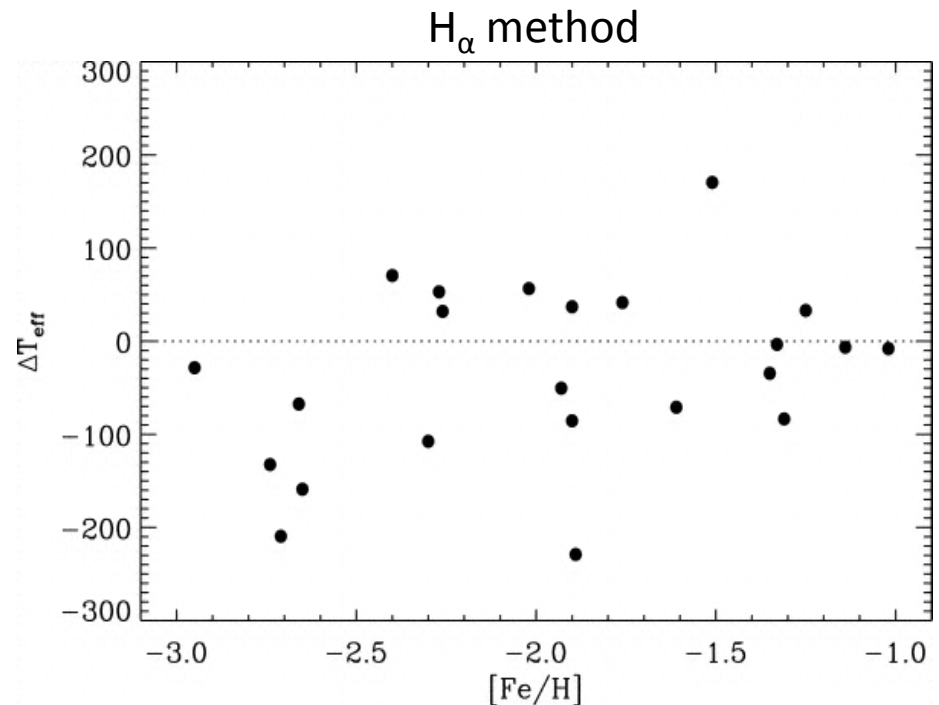
Higher T_{eff} in other methods

($\Delta T_{\text{eff}} \sim 400\text{K}$):

$\log \varepsilon(^7\text{Li}) = 2.1 \Rightarrow 2.3$



Not enough!



Nuclear reaction rates

- Well studied
- Uncertainties in relevant temperatures for BBN but cannot be responsible
- BBN:
$$\begin{array}{l} {}^7\text{Be} + n \rightarrow {}^7\text{Li} + p \\ {}^3\text{H} + \alpha \rightarrow {}^7\text{Li} \end{array}$$
- ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$: large errors in cross-section unlikely
- A lot more ${}^7\text{Be}$ than expected destroyed by ${}^7\text{Be}(d, p)2\alpha$?
-> NO! cross-section found out to be smaller than assumed...

Li depletion in stellar atmospheres?

- **Standard stellar models:**

depletion of ${}^7\text{Li}$ for metal-poor turnoff stars is negligible (< 0.02 dex)

⇒ Present-day abundance = primordial abundance

- **Nonstandard stellar models:**

1. Rotationally induced mixing
 2. Diffusion
- Requirement:
 ${}^7\text{Li}$ depletion of
 ~ 0.5 dex
- ⇒ Can lead to significant ${}^7\text{Li}$ depletion

1. Rotationally induced mixing

- Poorly known initial conditions and processes
⇒ Introduction of free parameters
- Calibrations using other stars required

Problems

- Causes dispersion (${}^7\text{Li}$ depletion of 0.5 dex implies $\sigma_{\text{RIM}} = 0.2 \text{ dex} \gg \sigma_{\text{obs}} = 0.029 \text{ dex}$)
- ${}^7\text{Li}$ depletion \Rightarrow ${}^6\text{Li}$ depletion!
($\log \varepsilon_{6\text{Li}} \approx 0.8 \text{ dex} \rightarrow \log \varepsilon_{6\text{Li}} \approx 2.0 \text{ dex}$)

Sharpens
discrepancy
for ${}^6\text{Li}$!

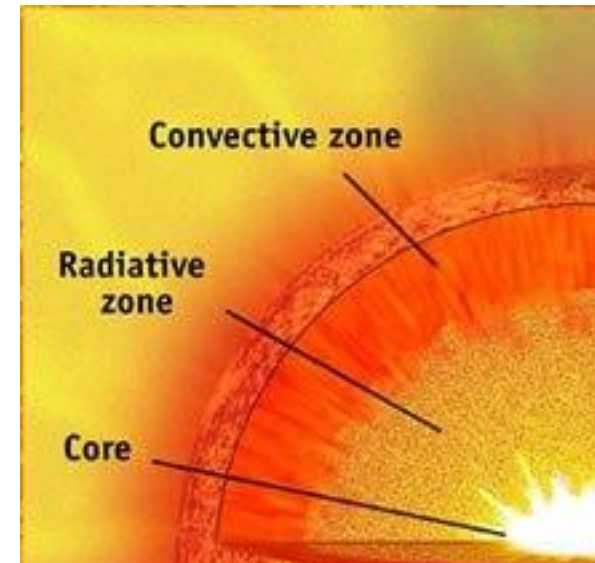
Diffusion

- Stars on Spite Plateau have thin convective envelope
- Li predicted to diffuse inward in radiative zone
⇒ Li surface abundance decreases
- Inward diffusion of Li can result in its destruction by protons

Again:

${}^7\text{Li}$ destruction \Rightarrow ${}^6\text{Li}$ depletion

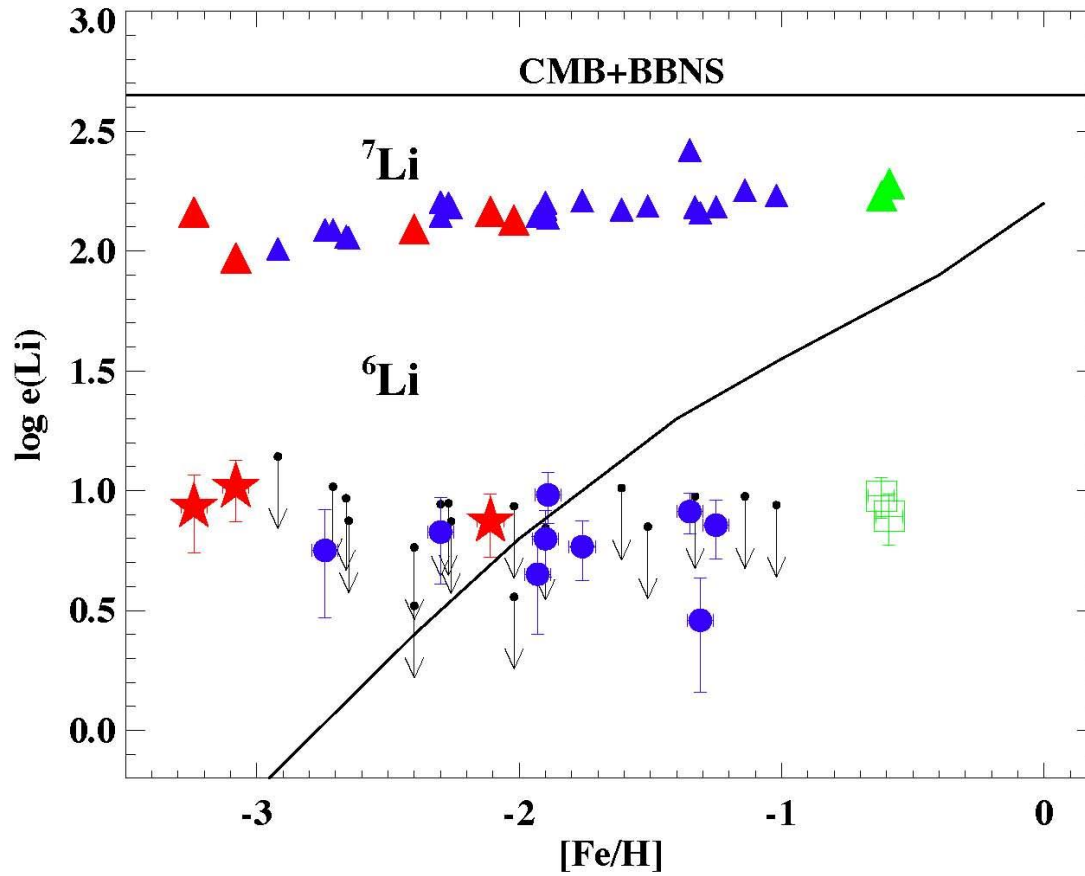
$\log \epsilon_{7\text{Li}} = 2.6 \Rightarrow \log \epsilon_{6\text{Li}} \approx 2.6$ too!



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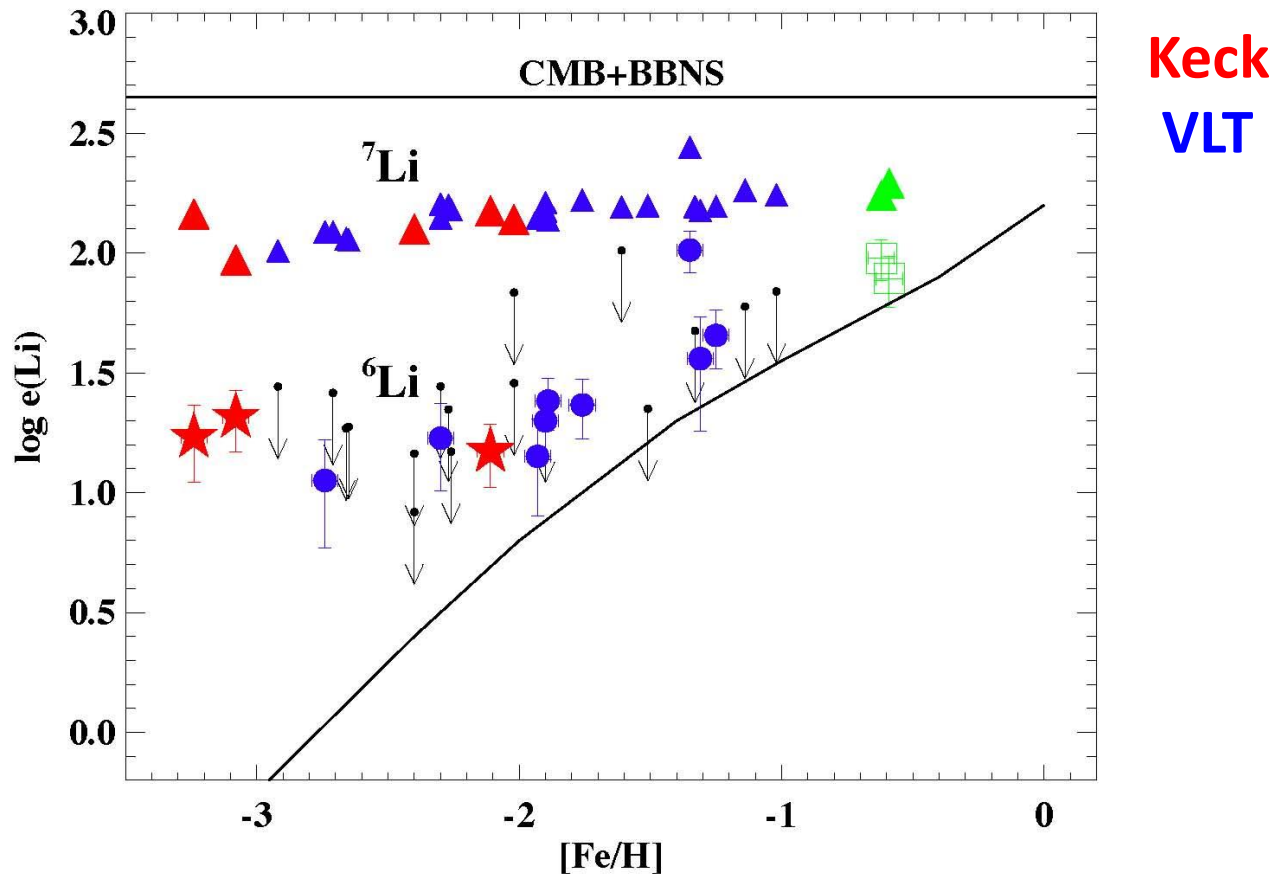
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${}^6\text{Li}$ abundance



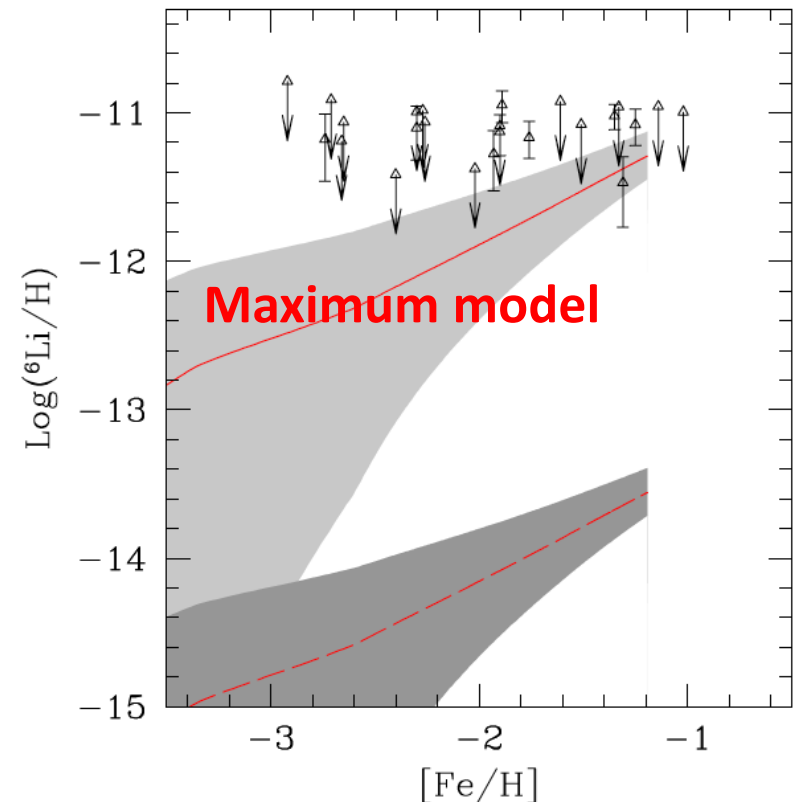
Keck
VLT

${}^6\text{Li}$ depletion during PMS



Pop III supernovae

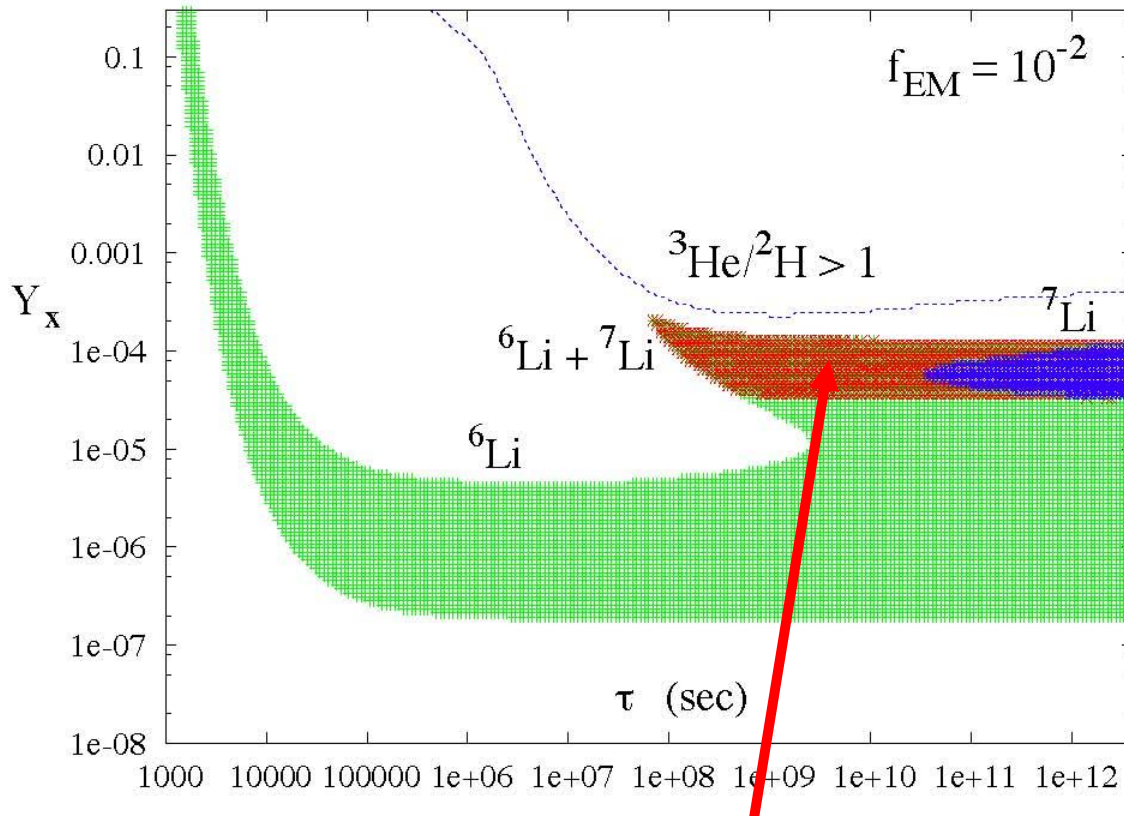
- ${}^6\text{Li}$ traditionally believed to originate in galactic cosmic ray (GCR) nucleosynthesis via
 1. Spallation reaction: $p, \alpha + \text{C} (/N/ \text{O}) \rightarrow \text{Li} (/Be /B)$
 2. Fusion reaction: $\alpha + \alpha \rightarrow \text{Li}$
- **Cosmic ray acceleration from early Pop III supernovae?**
-> favours $\alpha - \alpha$ fusion process



Nonstandard solution

- ${}^6\text{Li}$ production during BBN?
 - **Supersymmetry:**
 - existence of exotic particles (gravitino, axion, neutralino)
 - Decay/annihilation of these particles can alter primordial element abundances
 - Annihilation of neutralino can produce ${}^6\text{Li}$:
 ${}^3\text{H}(\alpha, n){}^6\text{Li}$ and ${}^3\text{He}(\alpha, p){}^6\text{Li}$ -> but doesn't resolve ${}^7\text{Li}$ dilemma!
 - Decay of gravitino:
observed ${}^6\text{Li}$ **and** ${}^7\text{Li}$ abundances can be obtained for appropriate choices of gravitino properties!
- PROBLEM: Unproven Physics!**

Nonstandard solution



**${}^6\text{Li}$ production +
 ${}^7\text{Li}$ destruction**

Summary

- Discrepancy between ${}^7\text{Li}$ on Spite Plateau and SBBN value
- ${}^6\text{Li}$ inconsistent with predictions of Galactic cosmic ray production

Both resist simple solutions!

Thank you for your
attention!

References

- Asplund et al, Lithium Isotopic abundances in metal-poor Halo stars, The Astrophysical Journal, 644:229-259, 2006 June 10
- Bonifacio et al, First stars VII – Lithium in extremely metal poor dwarfs, A&A, 851-864 (2007)
- New Scientist, July 5, 2008
- Karsten Jedamzik and Maxim Pospelov, Big Bang Nucleosynthesis and Particle Dark Matter, arXiv:0906.2087v1 [hep-ph] 11 Jun 2009

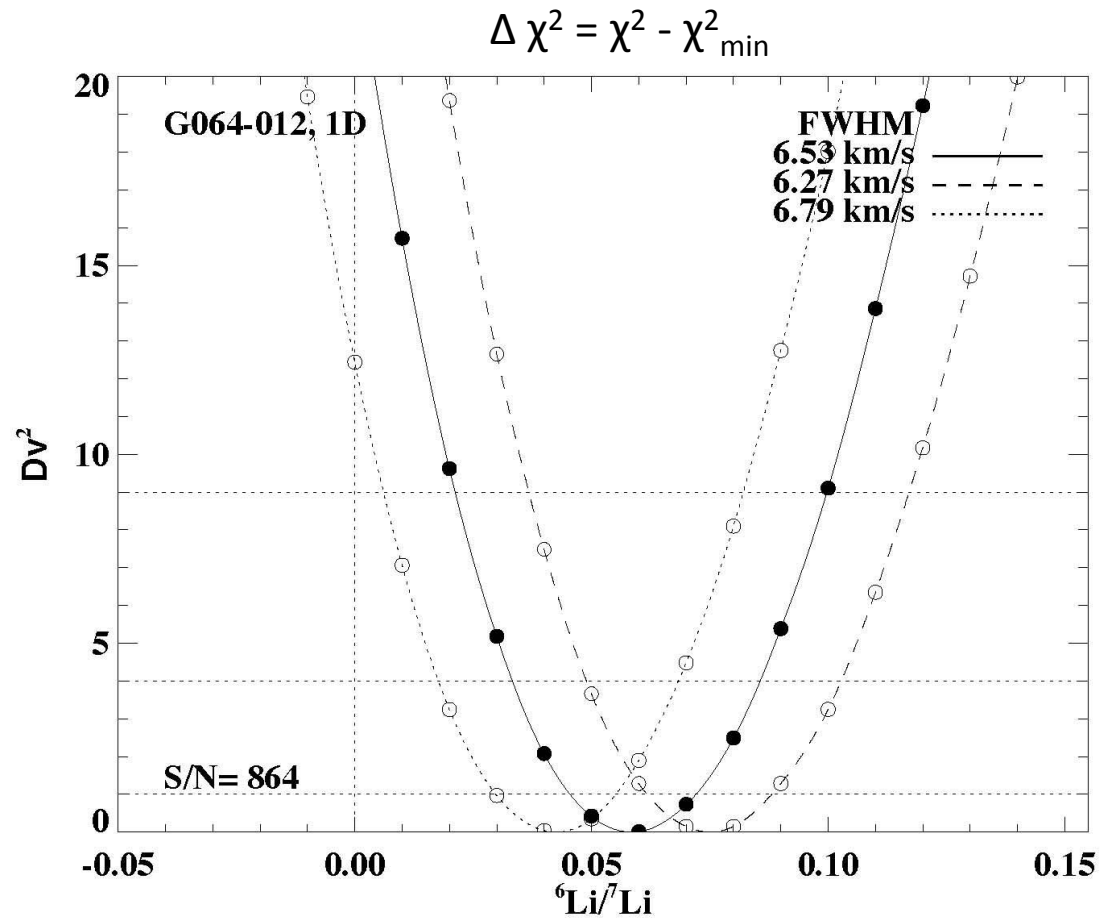
${}^6\text{Li}/{}^7\text{Li}$ ratio

Minimal deviation?

$\chi^2 \rightarrow \chi^2_{\min}$ determines
most probable value for
 ${}^6\text{Li}/{}^7\text{Li}$

S/N dominating error
term, errors in stellar
parameters minor

Criteria for significant
 ${}^6\text{Li}$ detection: $> 2\sigma$



Hertzsprung-Russell (H-R) diagram

