Interstellar Constraints on the Cosmic Evolution of Lithium

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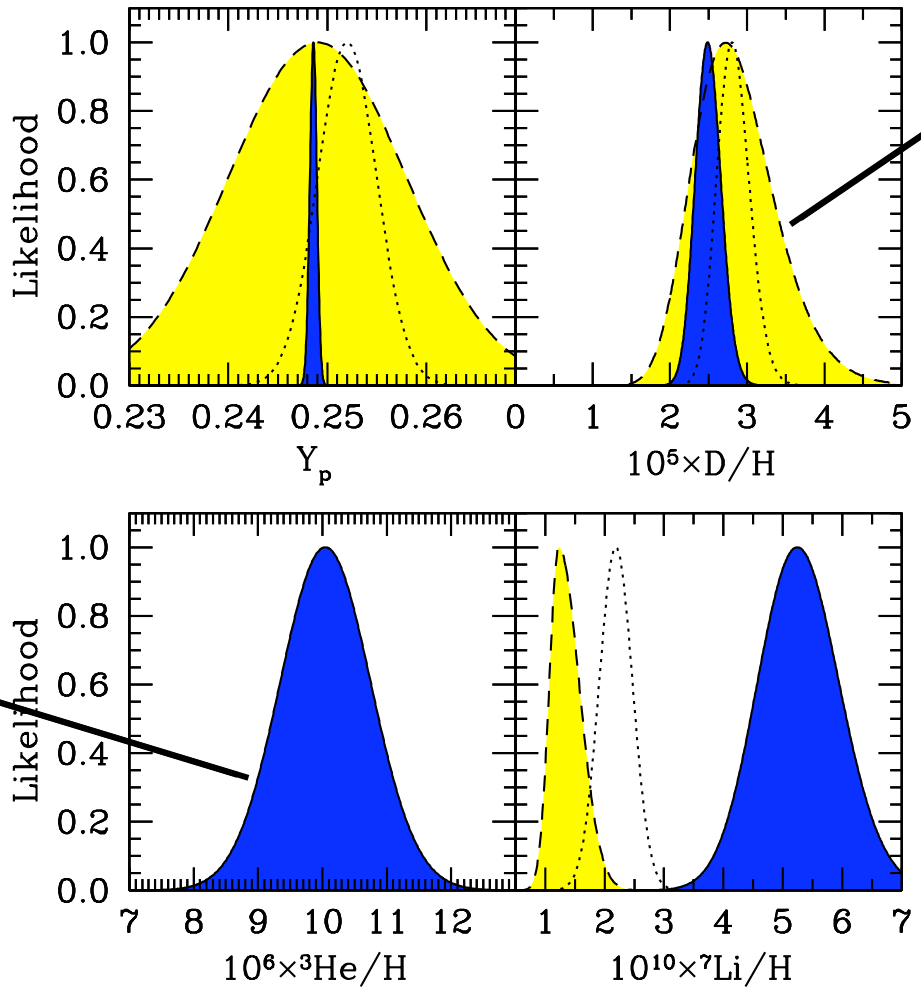
The ISM as a probe of the cosmic evolution of lithium

Motivation
Observational probes
Systematic uncertainties

The lithium problem: Pop II abundances inconsistent with SBBN.



Observational Constraints

SBBN+WMAP

Hard to reconcile these estimates of the "primordial" ^{7}Li abundance.

Cyburt+ (2008)

Interstellar Li to Probe Pre-Galactic Li Production

The idea:

Use *interstellar* Li in low metallicity environments as a probe of the contemporary Li abundance.

While the chemical evolution of Li will be complex, there is no worry about time-dependent *in situ* destruction modifying the abundance of Li over time.

Significant systematic uncertainties associated with (photo)ionization and incorporation of Li into dust grains are *completely independent* of those affecting stellar measurements.

Interstellar Li to Probe Pre-Galactic Li Production

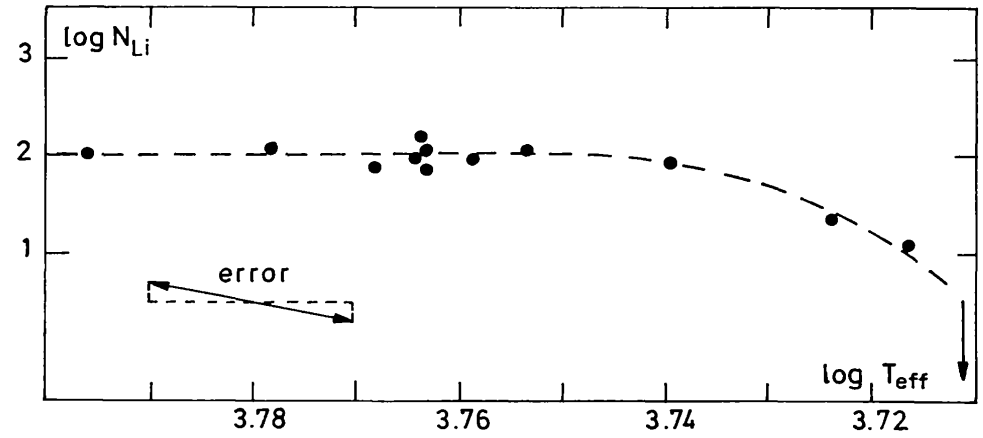


Fig. 5. N_{Li} versus $\log T_{eff}$ for old halo stars

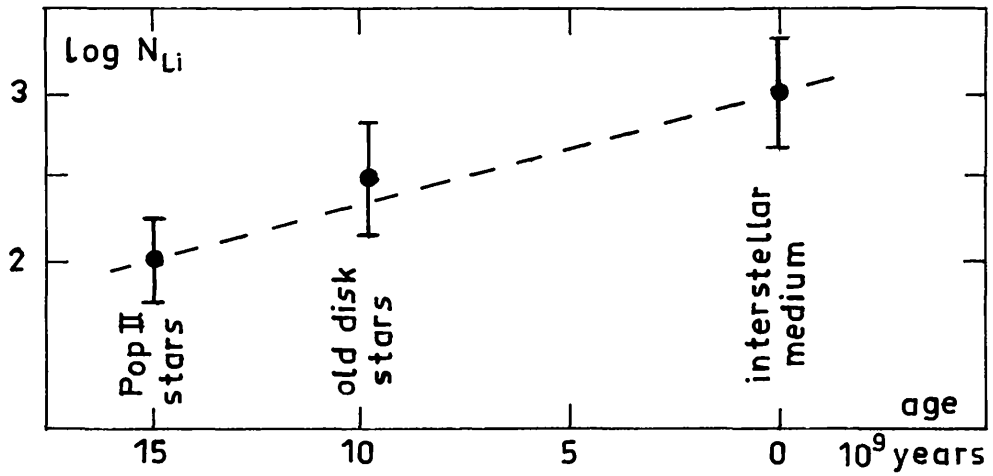


Fig. 6. Evolution of the Li abundance during the life of the Galaxy

Spite & Spite (1982)

Interstellar Li to Probe Pre-Galactic Li Production

Astron. Astrophys. 177, L17–L20 (1987)

ASTRONOMY AND ASTROPHYSICS

Letter to the Editor

The interstellar spectrum toward SN 1987 A ⋆

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[4] Osservatorio Astronomico di Trieste, Via G.B. Tiepolo 11, Trieste, Italy

Astron. Astrophys. 207, L1–L4 (1988)

ASTRONOMY AND ASTROPHYSICS

Letter to the Editor

Search for primordial lithium in the interstellar medium towards SN 1987 A⋆

K. C. Sahu [1], M. Sahu [2], and S. R. Pottasch [1]

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[2] LAT du Collège de France, Institut d'Astrophysique, 9

Astron. Astrophys. 251, 253–258 (1991)

ASTRON AN ASTROP

Reduced upper limits on the equivalent width of interstellar Li I 670.8 towards SN 1987 A⋆

D. Baade [1], S. Cristiani [2], T. Lanz [3], R.A. Malaney [4], K.C. Sahu [5], and G. Vladilo [6]

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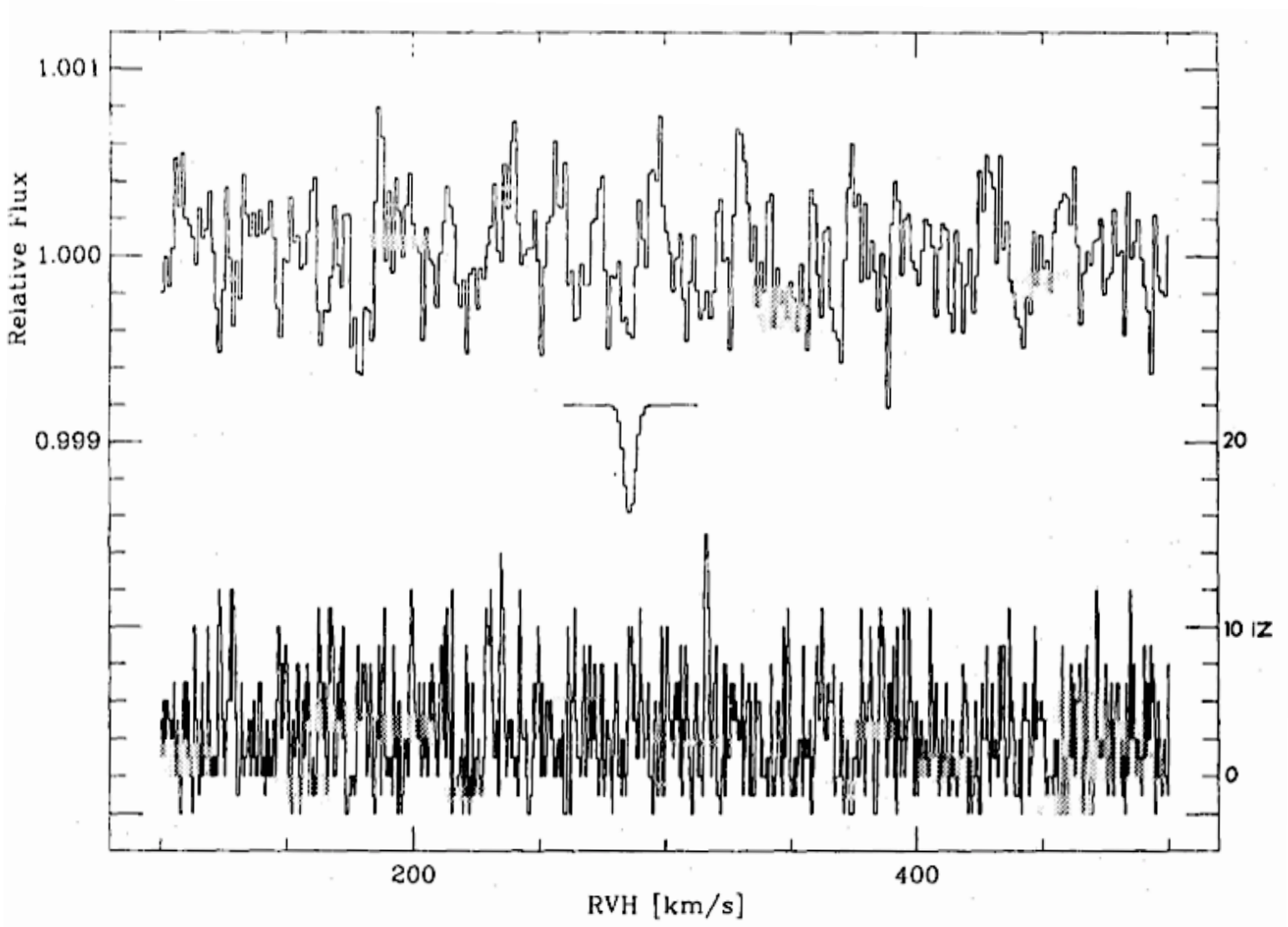
[6] Osservatorio Astronomico di Trieste, Via G.B. Tiepolo 11, I-34131 Trieste, Italy

Interstellar Li to Probe Pre-Galactic Li Production



Motivation

Prodanovic & Fields (2004)

PROBING PRIMORDIAL AND PRE-GALACTIC LITHIUM WITH HIGH-VELOCITY CLOUDS

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Received 2004 September 20; accepted 2004 October 18; published 2004 October 27

ABSTRACT

The pre-Galactic abundance of lithium offers a unique window into nonthermal cosmological processes. The primordial Li abundance is guaranteed to be present and probes big bang nucleosynthesis (BBN), while an additional Li component is likely to have been produced by cosmic rays accelerated in large-scale structure formation. Pre-Galactic Li currently can only be observed in low-metallicity Galactic halo stars, but abundance measurements are plagued with systematic uncertainties due to modeling of stellar atmospheres and convection. We propose a new site for measuring pre-Galactic Li: low-metallicity, high-velocity clouds (HVCs), which are likely to be extragalactic gas accreted onto the Milky Way and which already have been found to have deuterium abundances consistent with primordial. An Li observation in such an HVC would provide the first extragalactic Li measurement and could shed new light on the apparent discrepancy between BBN predictions and halo star Li abundance determinations. Furthermore, HVC Li could at the same time test for the presence of nonprimordial Li due to cosmic rays. The observability of elemental and isotopic Li abundances is discussed, and candidate sites are identified.

Subject headings: cosmic rays — cosmology: observations — nuclear reactions, nucleosynthesis, abundances

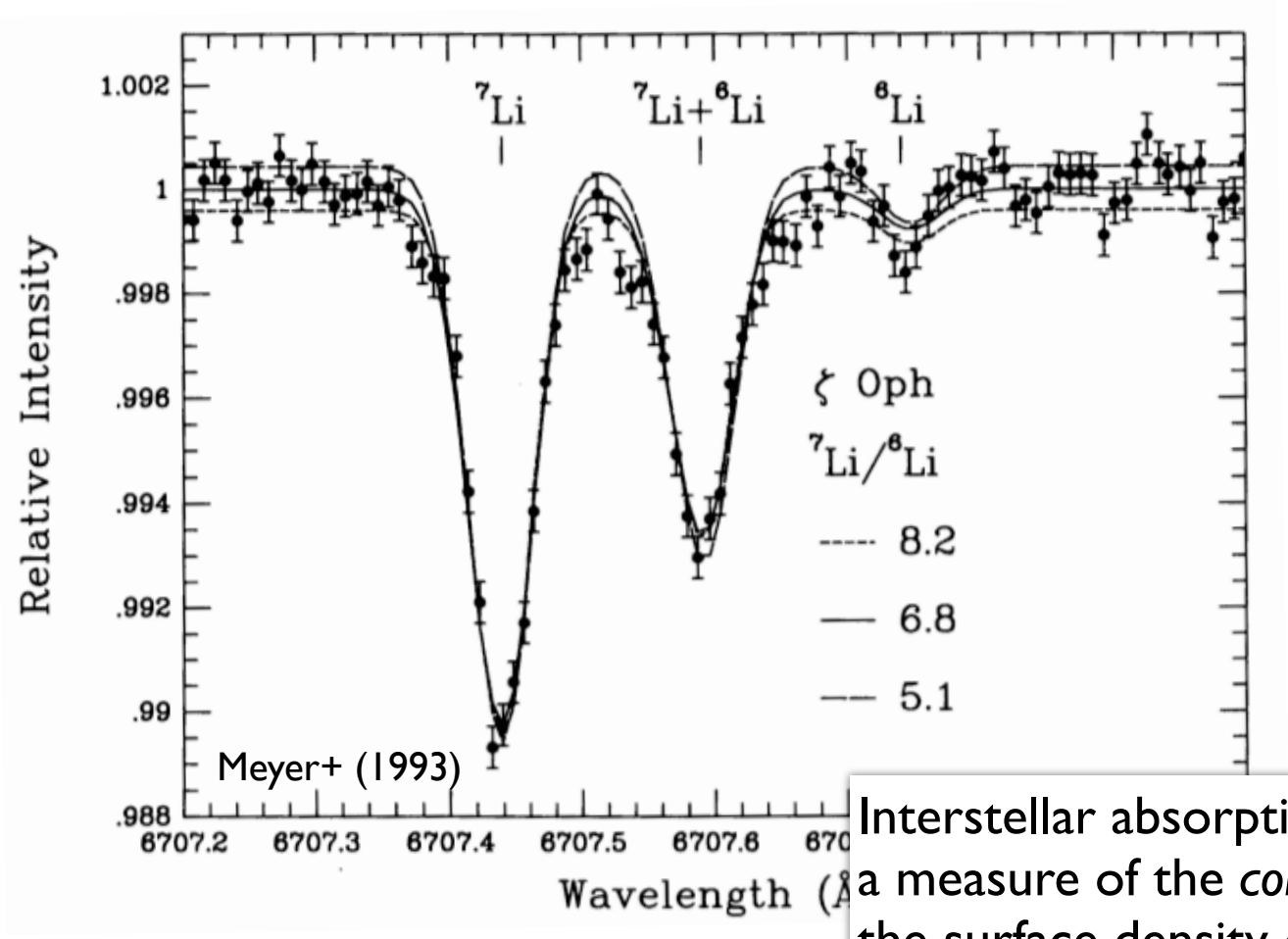
$$\mathrm{Li_{HVC}} \sim \mathrm{Li_p} + \frac{\mathrm{Fe_{HVC}}}{\mathrm{Fe_\odot}} \left[\mathrm{Li_\odot} - \mathrm{Li_p}\right]$$

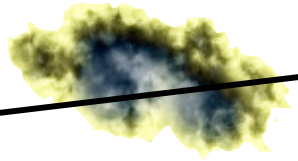
BEWARE!

The predictions for Li absorption in HVCs are ~10x too generous.
*Ionization of Li I to higher ionization states was underestimated significantly.

Also, quasars needed to probe HVCs are faint!

Interstellar Li to Probe Pre-Galactic Li Production





Interstellar absorption lines give a measure of the *column density*, the surface density of atoms projected onto the star:

$$N(\mathrm{Li\ I}) = \int n(\mathrm{Li}^0) ds$$

Interstellar Li as a probe of pre-galactic production

Interstellar Systematics

$$(\mathrm{Li/H}) = N(\mathrm{Li\ I})N(\mathrm{H\ I})^{-1}x(\mathrm{Li}^0)^{-1}\delta_{\mathrm{Li}}^{-1}$$

- x(Li^0) -- Ionization fraction of Li^0.

  Constrained by observations of other neutral and singly ionized species.

- δ_{Li} -- Depletion factor for Li.

  Adapt Jenkins (2008) F* parameterization of dust depletion effects to estimate this.

- N(H I) -- H I column

  From HST/IUE Lyman-α observations and/or ATCA H I 21-cm observations.

Interstellar Li as a probe of pre-galactic production

Interstellar Systematics

$$(\mathrm{Li/H}) = N(\mathrm{Li\ I})N(\mathrm{H\ I})^{-1}x(\mathrm{Li^0})^{-1}\delta_{\mathrm{Li}}^{-1}$$

- x(Li^0) -- Ionization fraction of Li^0.

The ionization correction is by far the largest correction and may be dictated by non-equilibrium physics, perhaps with unknown recombination pathways.

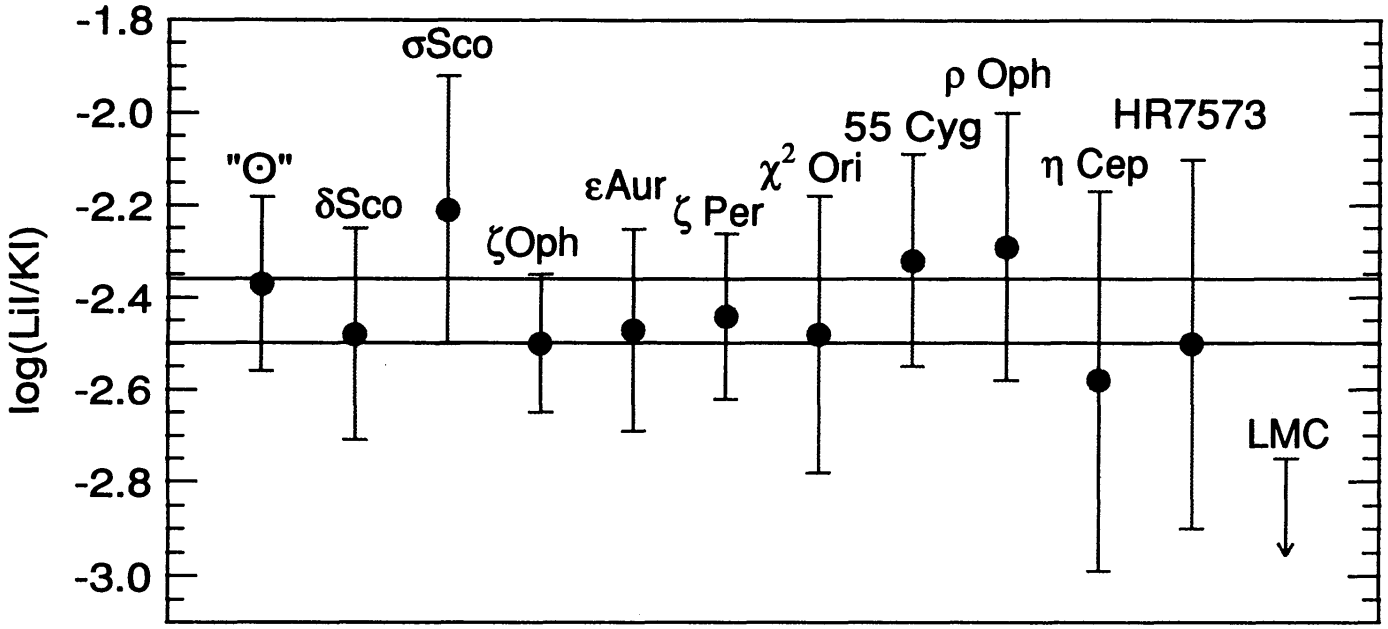
In equilibrium: $$\frac{N(\mathrm{Li\ I})}{N(\mathrm{Li\ II})} = n_e \frac{\alpha_{rec}(\mathrm{Li^+},T)}{\Gamma(\mathrm{Li^0})}$$

Where the precise value of the electron density n_e is not crucial:

$$\frac{N(\mathrm{Li\ I})}{N(\mathrm{Li\ II})} = \frac{N(\mathrm{Ca\ I})}{N(\mathrm{Ca\ II})} \frac{\Gamma(\mathrm{Ca^0})}{\Gamma(\mathrm{Li^0})} \frac{\alpha_{rec}(\mathrm{Li^+},T)}{\alpha_{rec}(\mathrm{Ca^+},T)}$$

Interstellar Li as a probe of pre-galactic production

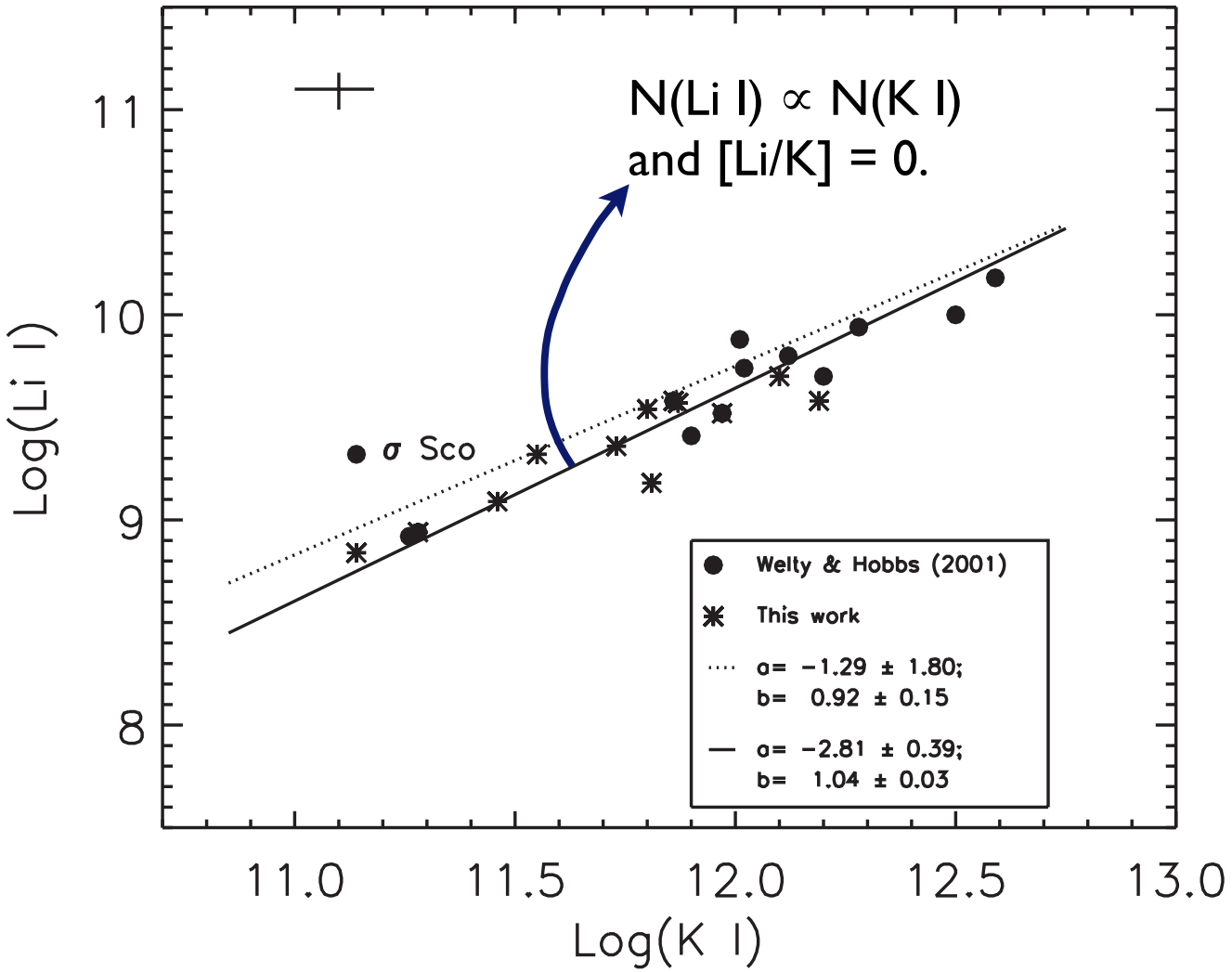
Interstellar Systematics



Steigman (1996)
Milky Way data from Hobbs (1984) & White (1986)

Interstellar Li as a probe of pre-galactic production

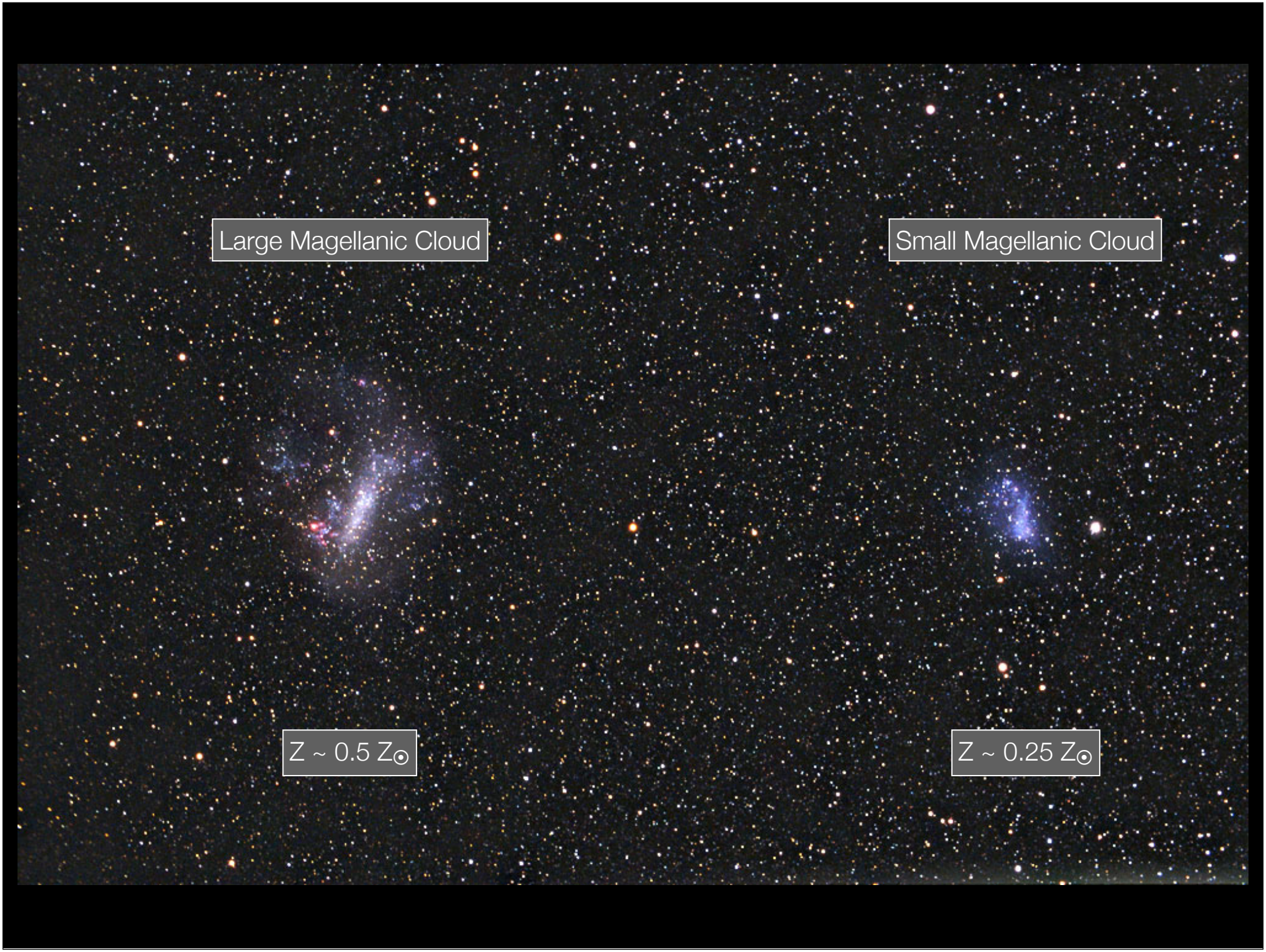
Interstellar Systematics

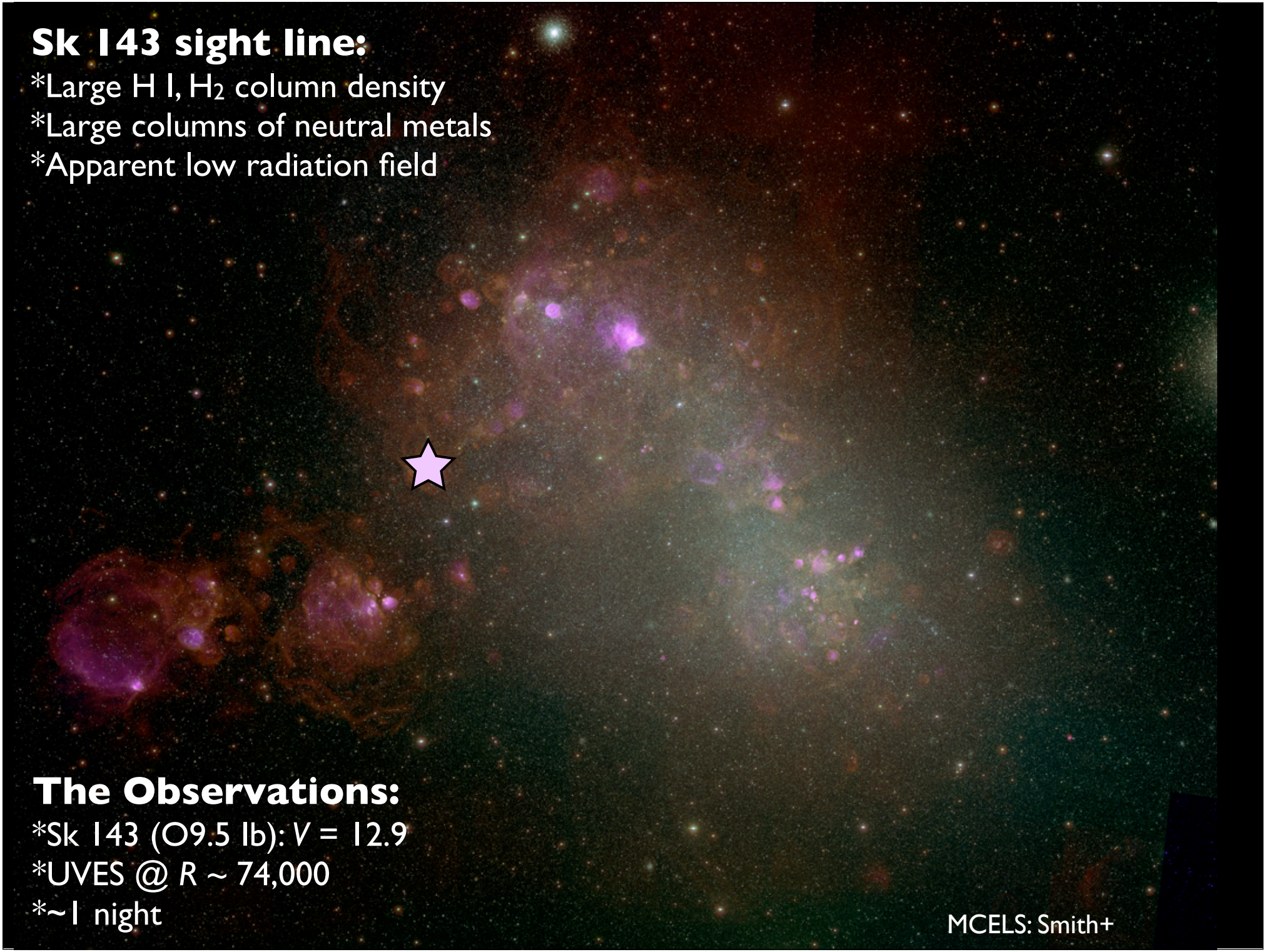


Knauth et al. (2003)

The first measurement of interstellar lithium beyond the Milky Way

Small Magellanic Cloud lithium
Absolute Li abundances
Li-to-metal abundances

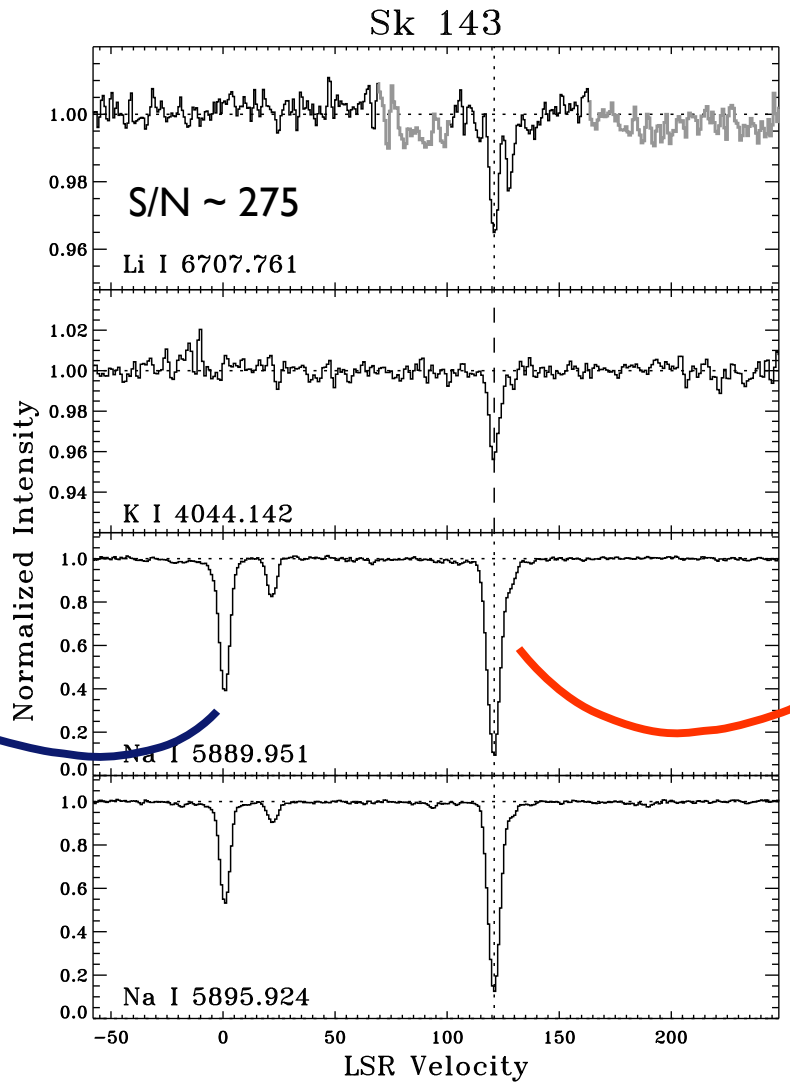

Large Magellanic Cloud
Small Magellanic Cloud
Z ~ 0.5 Z⊙
Z ~ 0.25 Z⊙


Sk 143 sight line:
*Large H I, H_2 column density
*Large columns of neutral metals
*Apparent low radiation field
The Observations:
*Sk 143 (O9.5 Ib): *V* = 12.9
*UVES @ *R* ~ 74,000
*~1 night
MCELS: Smith+

Interstellar Li as a probe of pre-galactic production

The Small Magellanic Cloud as probe of pre-galactic Li

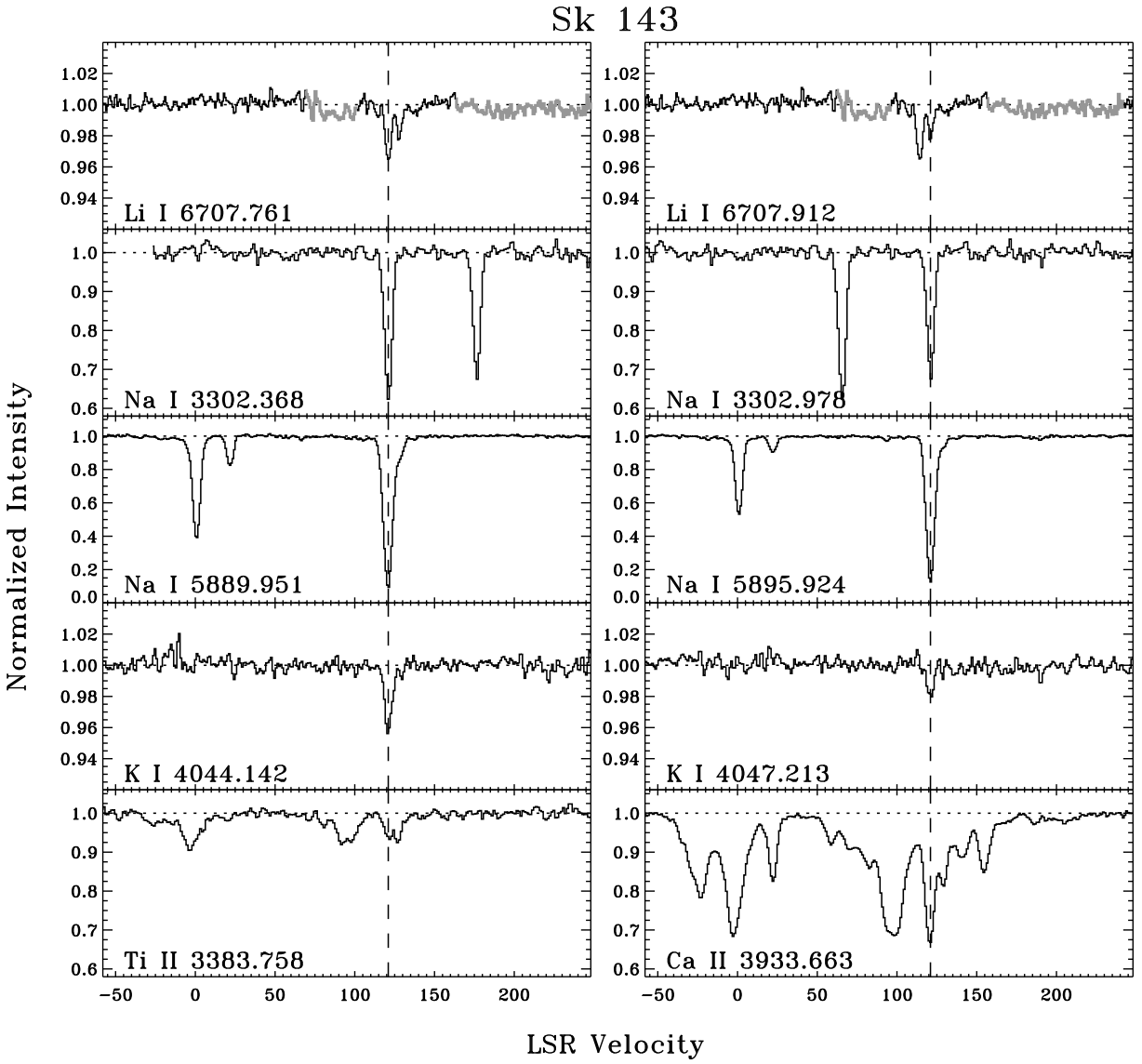
Absorption from the MW at v ~ +0 to +50 km/s



Absorption from the SMC at v ~ +120 km/s

Interstellar Li as a probe of pre-galactic production

The Small Magellanic Cloud as probe of pre-galactic Li



Also detected:

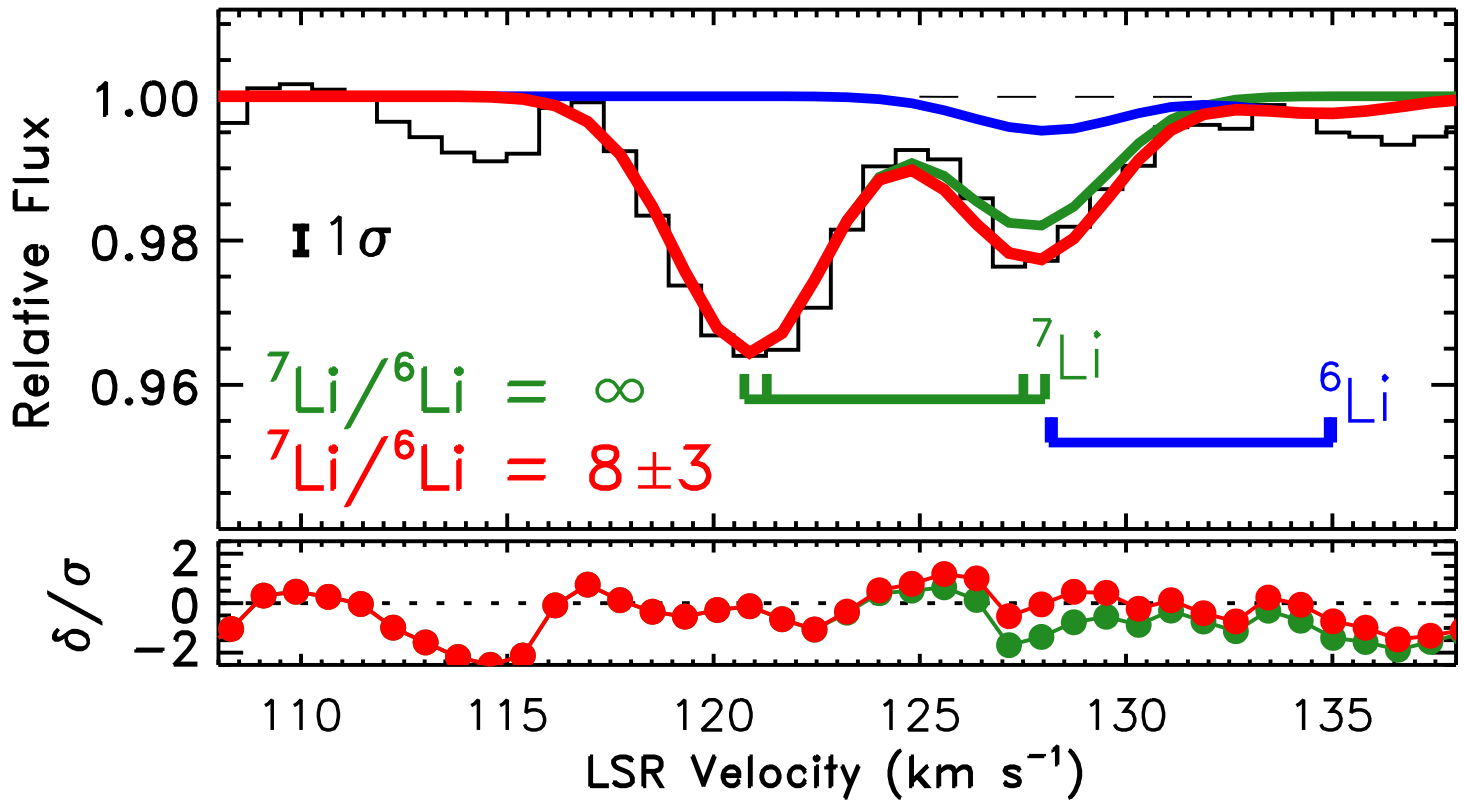
Ca I, Fe I, Rb I

CH, CH^+, C_2, C_3, CN

H I, H_2

Interstellar Li as a probe of pre-galactic production

The Small Magellanic Cloud as probe of pre-galactic Li

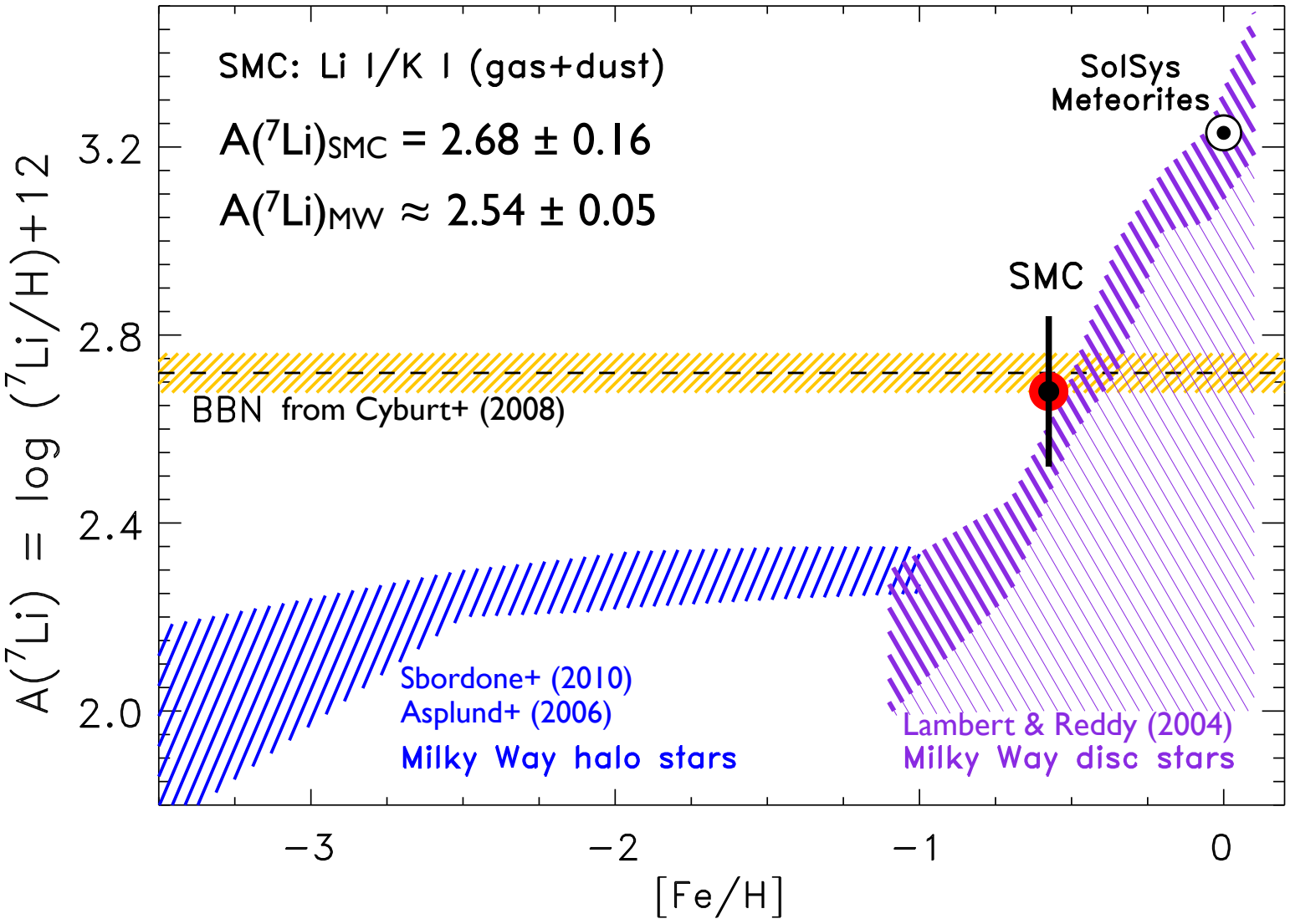


$b \equiv 2^{1/2}\,\sigma \sim 0.8$ km/s

$T \lesssim 270$ K

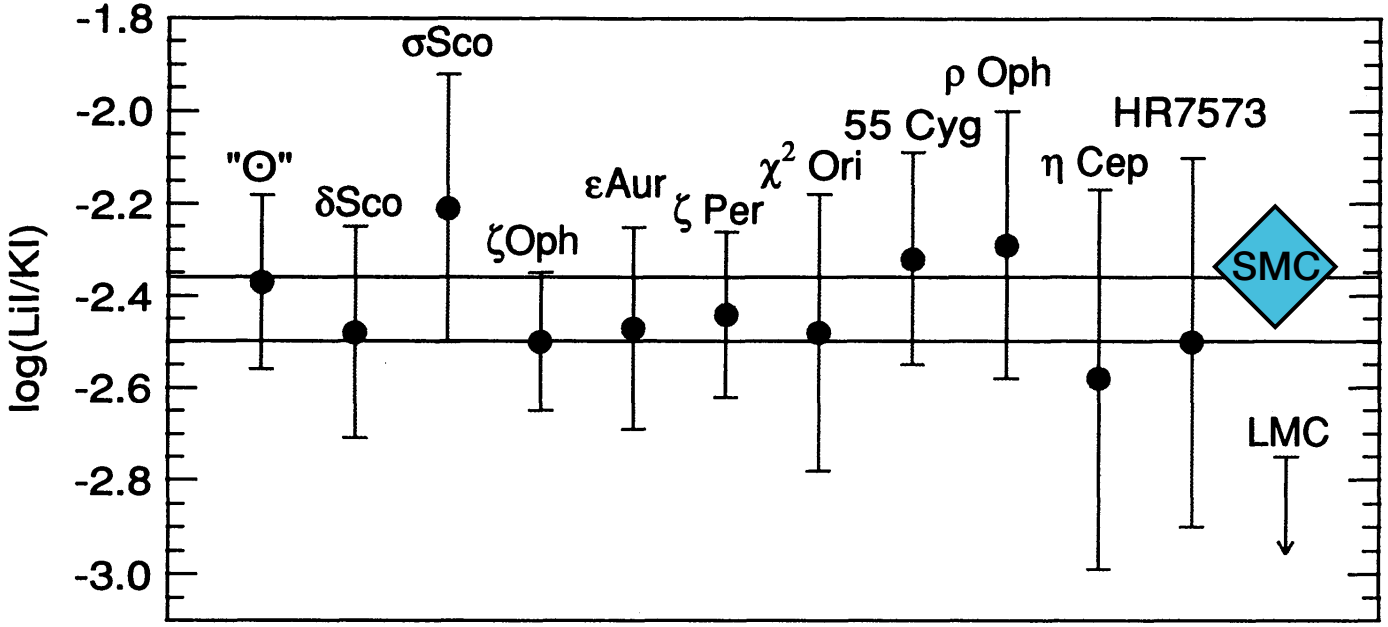
Interstellar Li as a probe of pre-galactic production

The Small Magellanic Cloud as probe of pre-galactic Li



Interstellar Li as a probe of pre-galactic production

The Small Magellanic Cloud as probe of pre-galactic Li

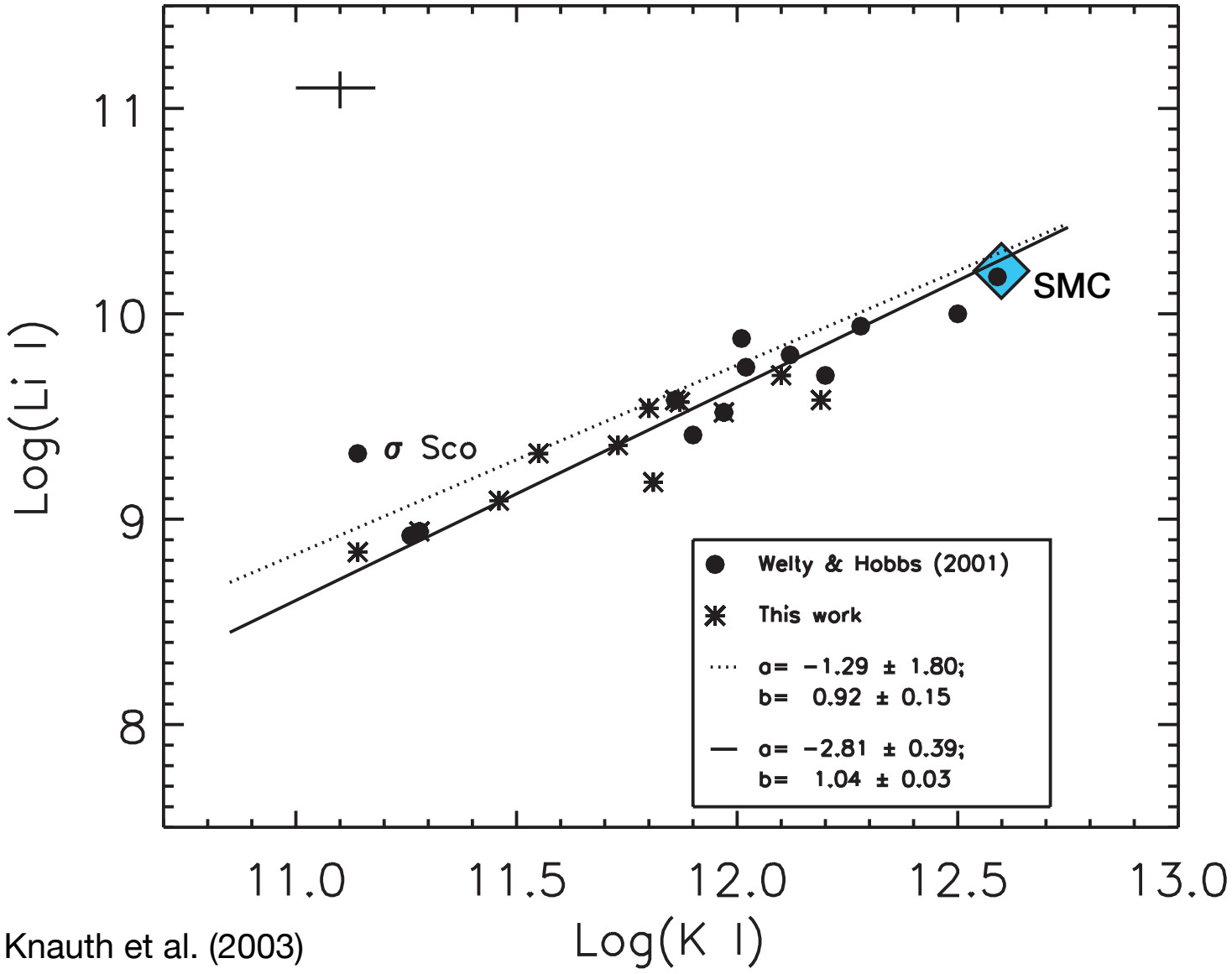


Steigman (1996)

$$[Li/K]_{SMC} = +0.04 \pm 0.10$$

Interstellar Li as a probe of pre-galactic production

The Small Magellanic Cloud as probe of pre-galactic Li



Knauth et al. (2003)

Interstellar Li as a probe of pre-galactic production

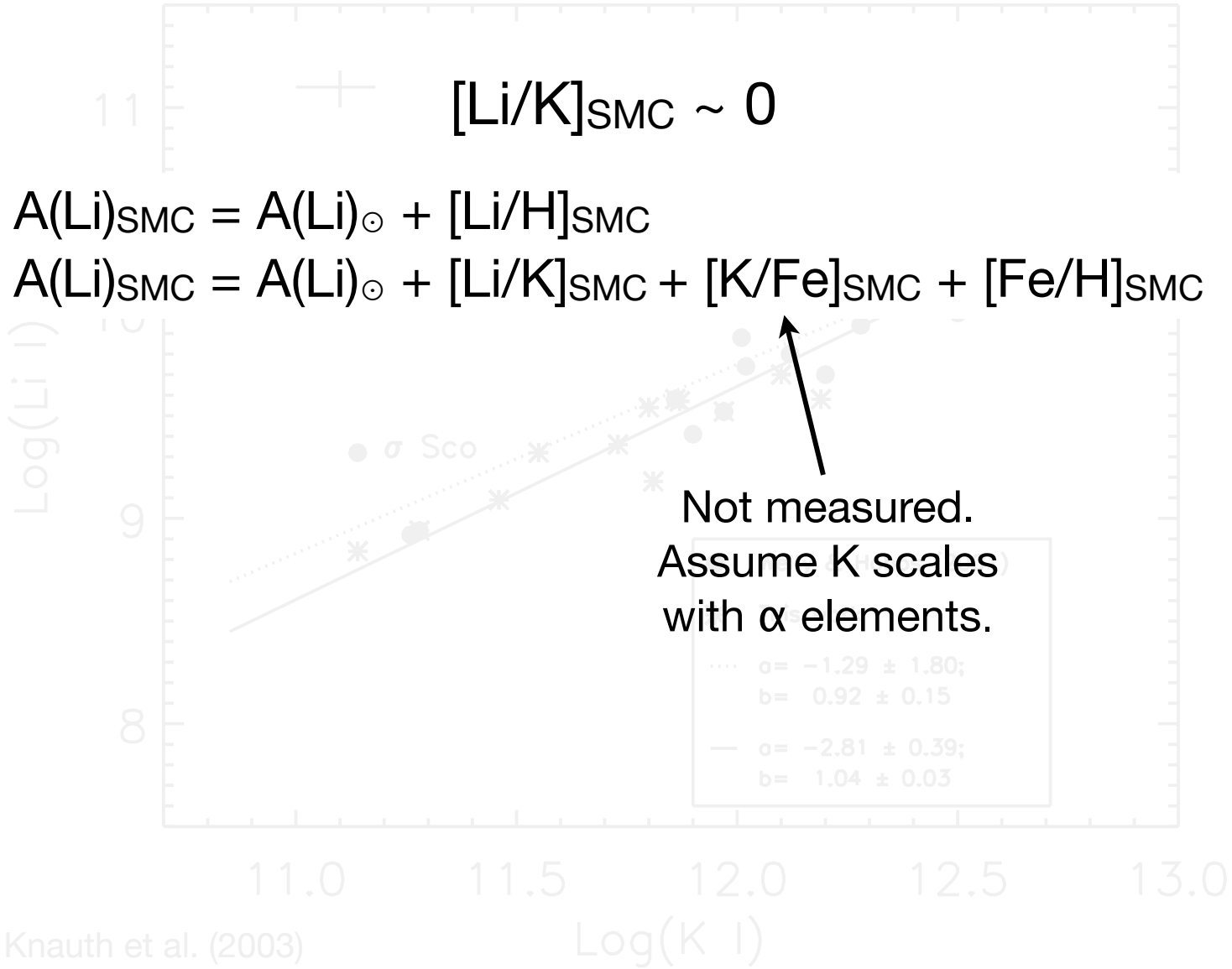
The Small Magellanic Cloud as probe of pre-galactic Li

$$[Li/K]_{SMC} \sim 0$$

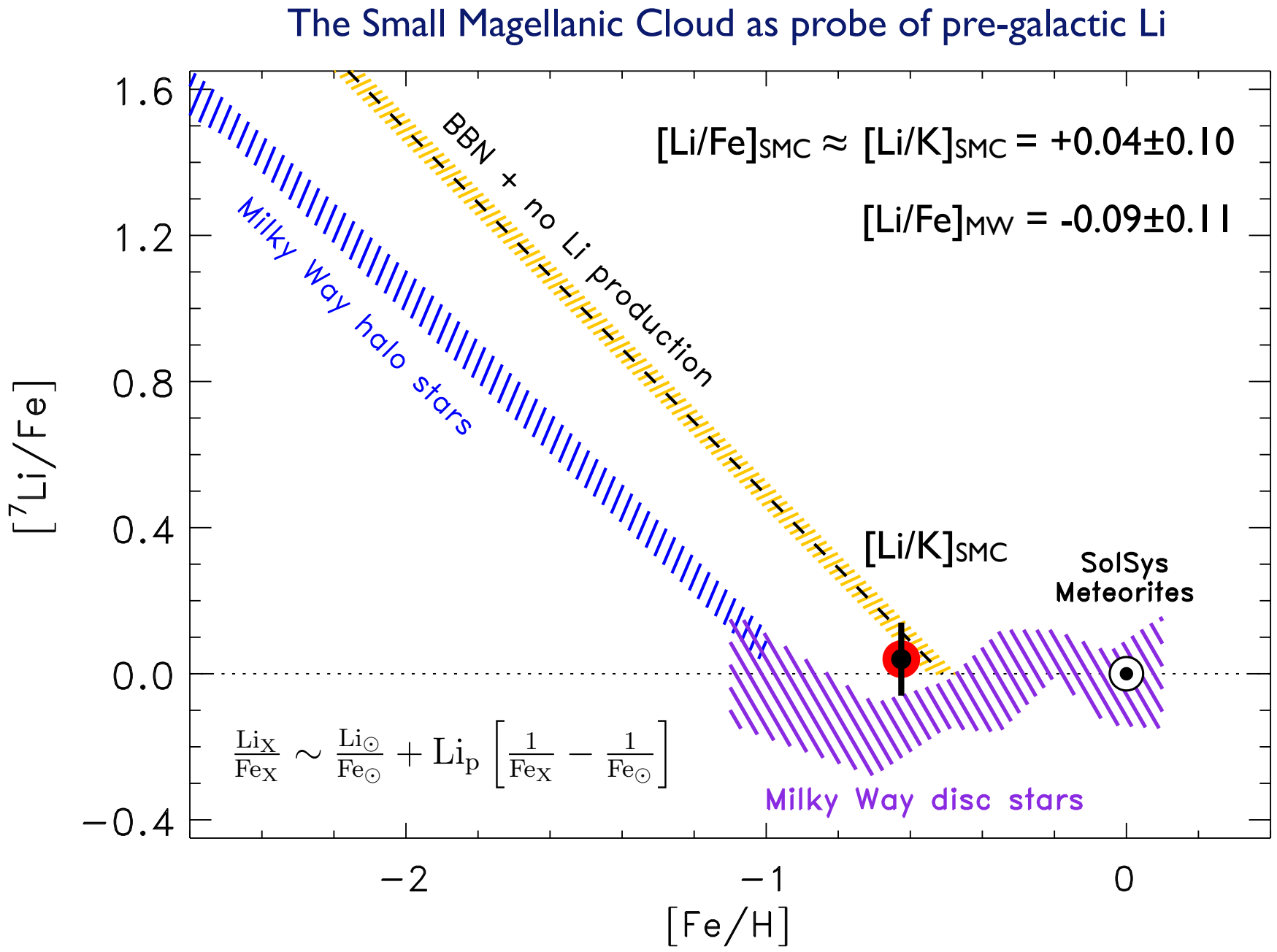
$$A(Li)_{SMC} = A(Li)_{\odot} + [Li/H]_{SMC}$$

$$A(Li)_{SMC} = A(Li)_{\odot} + [Li/K]_{SMC} + [K/Fe]_{SMC} + [Fe/H]_{SMC}$$

Not measured.
Assume K scales
with α elements.



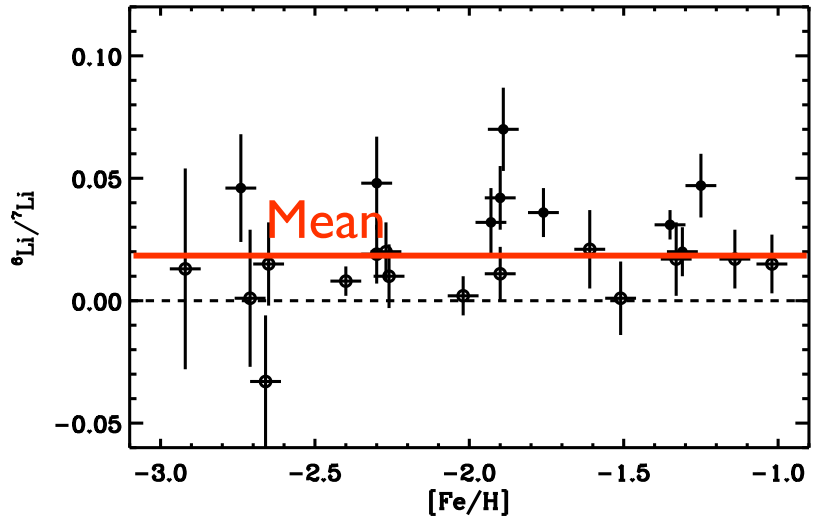
Interstellar Li as a probe of pre-galactic production

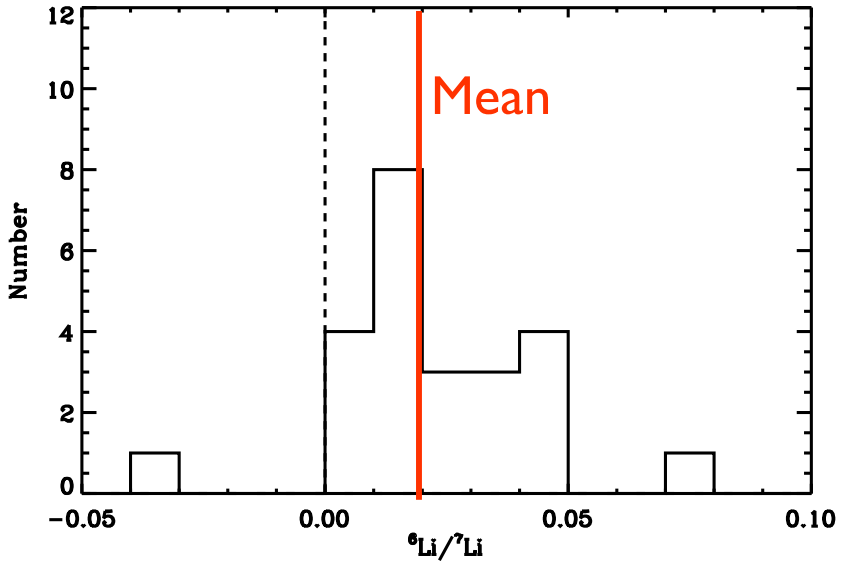


The ISM as a probe of the cosmic evolution of lithium: future prospects

New approaches to systematics
Lithium isotopic ratio as a probe of nucleosynthesis
Lithium isotopic ratio as a probe of non-standard BBN
Lithium in the ISM of the LMC
Prospects for ELT?

The lithium problem in Pop II stars may extend to ^{6}Li.

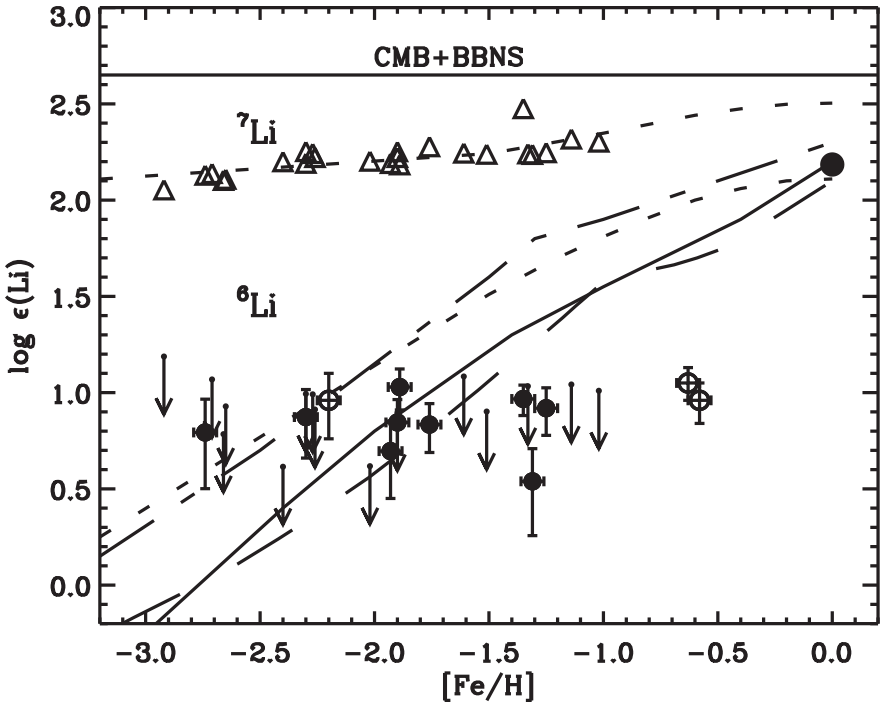




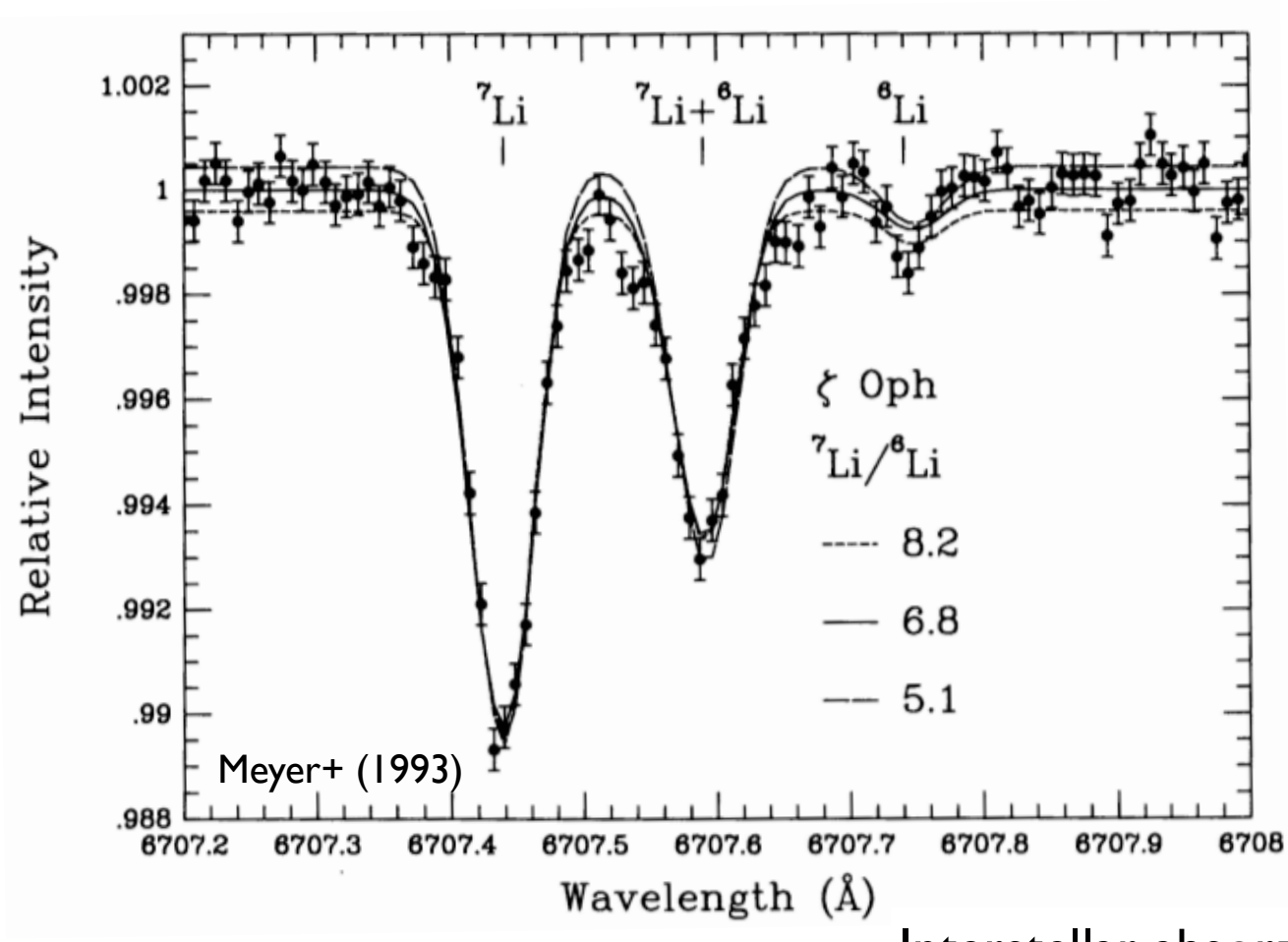
Asplund+ (2006)

A ^{6}Li Plateau?

SBBN predicts ^{6}Li/H ~ 10^{-14}.



Interstellar Li as a probe of pre-galactic production

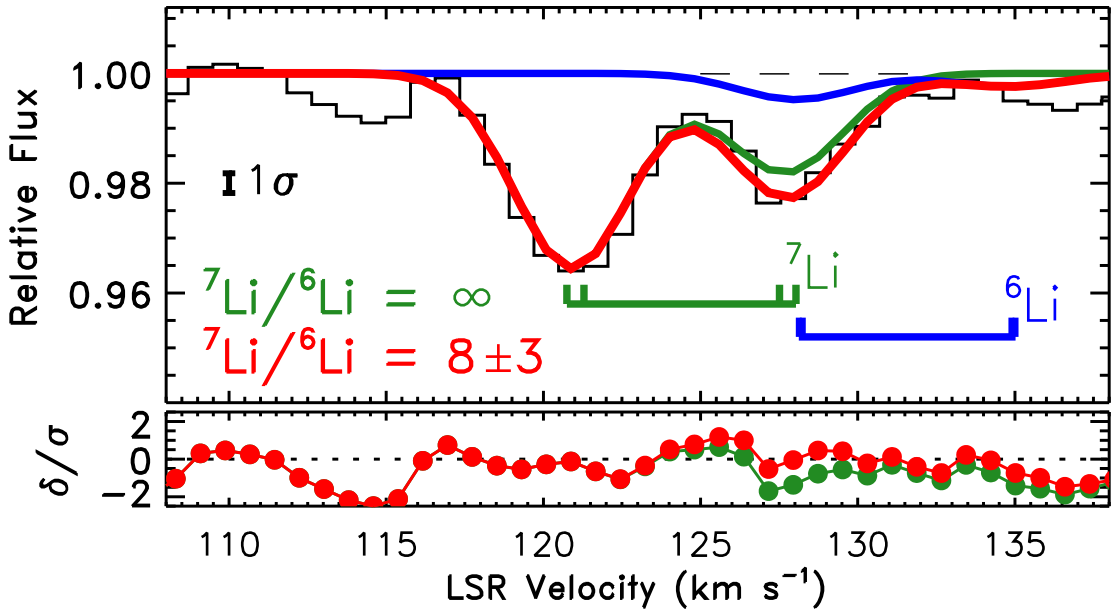


Interstellar absorption lines give a measure of the *column density*, the surface density of atoms projected onto the star:

$$N(\mathrm{Li\ I}) = \int n(\mathrm{Li}^0) ds$$

Interstellar Li as a probe of pre-galactic production

The Small Magellanic Cloud as probe of pre-galactic Li



A good constraint on ^{7}Li/^{6}Li will require S/N ~ 500 (preferably at higher resolution).

We measure

$(^7\text{Li}/^6\text{Li})_{\text{SMC}} \geq 3.6$ *or*
$(^6\text{Li}/^7\text{Li})_{\text{SMC}} \leq 0.28$ (3σ).

Our limits imply ≤40% of the ^{7}Li has been produced by cosmic rays.

*See *posters by Adam Ritchey, Tijana Prodanovich*

For comparison:

$(^7\text{Li}/^6\text{Li})_{\odot} \sim 12$

$\langle ^7\text{Li}/^6\text{Li}\rangle_{\text{MW}} \sim 7.6$

$(^7\text{Li}/^6\text{Li})_{\text{CR}} \sim 1.6$

*MW = ISM from Kawanomoto+ (2009), Knauth+ (2003)

Cosmic ray synthesis of ^{7}Li, ^{6}Li

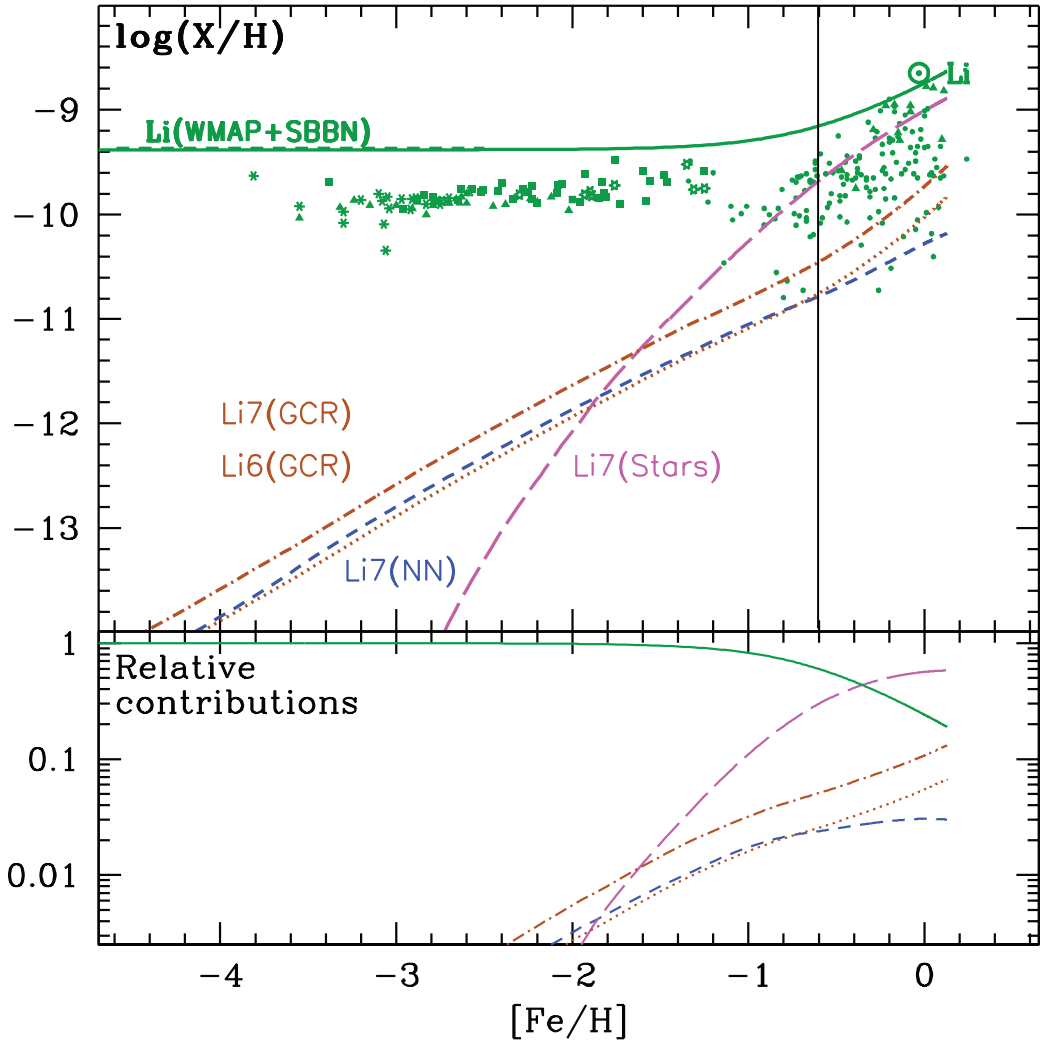
$p,\alpha + C,N,O \rightarrow LiBeB$

$C,N,O + p,\alpha \rightarrow LiBeB$

$\alpha + \alpha \rightarrow {}^{6,7}Li$

These processes largely produce:
$(^{7}Li/^{6}Li)_{CR} \sim 1.6 \pm 0.3$

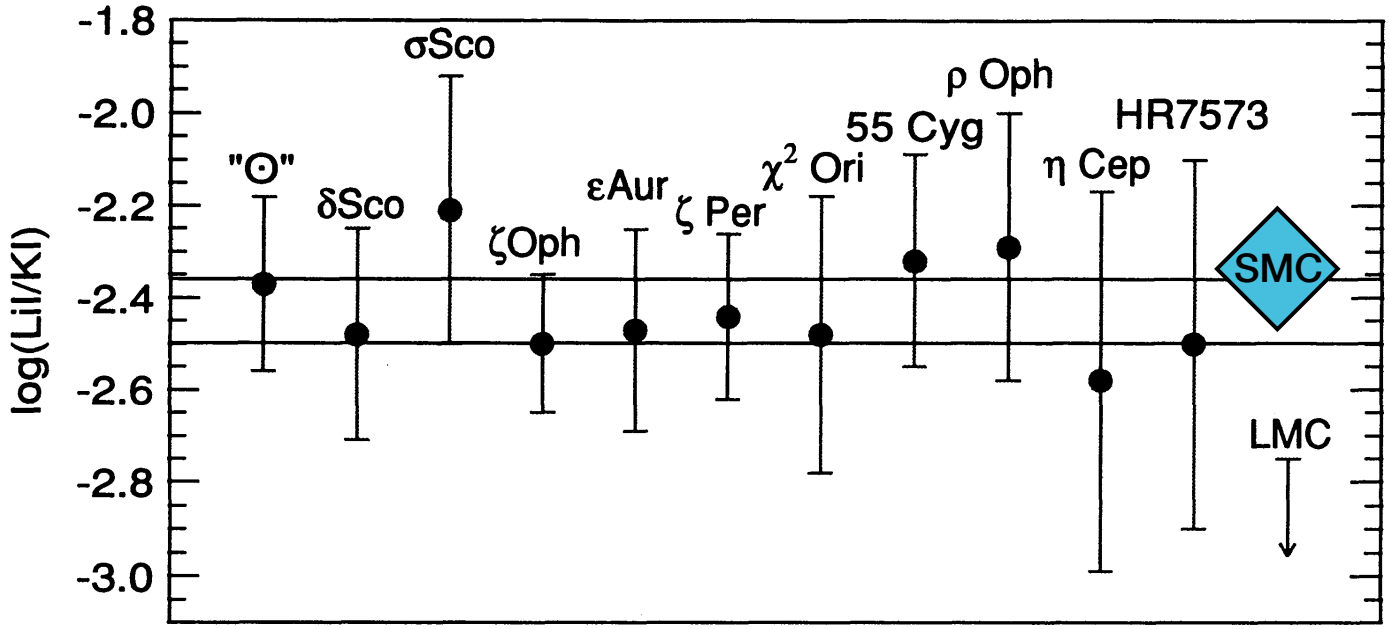
The CRs need not be galactic CRs...



Prantzos (2010)

Interstellar Li as a probe of pre-galactic production

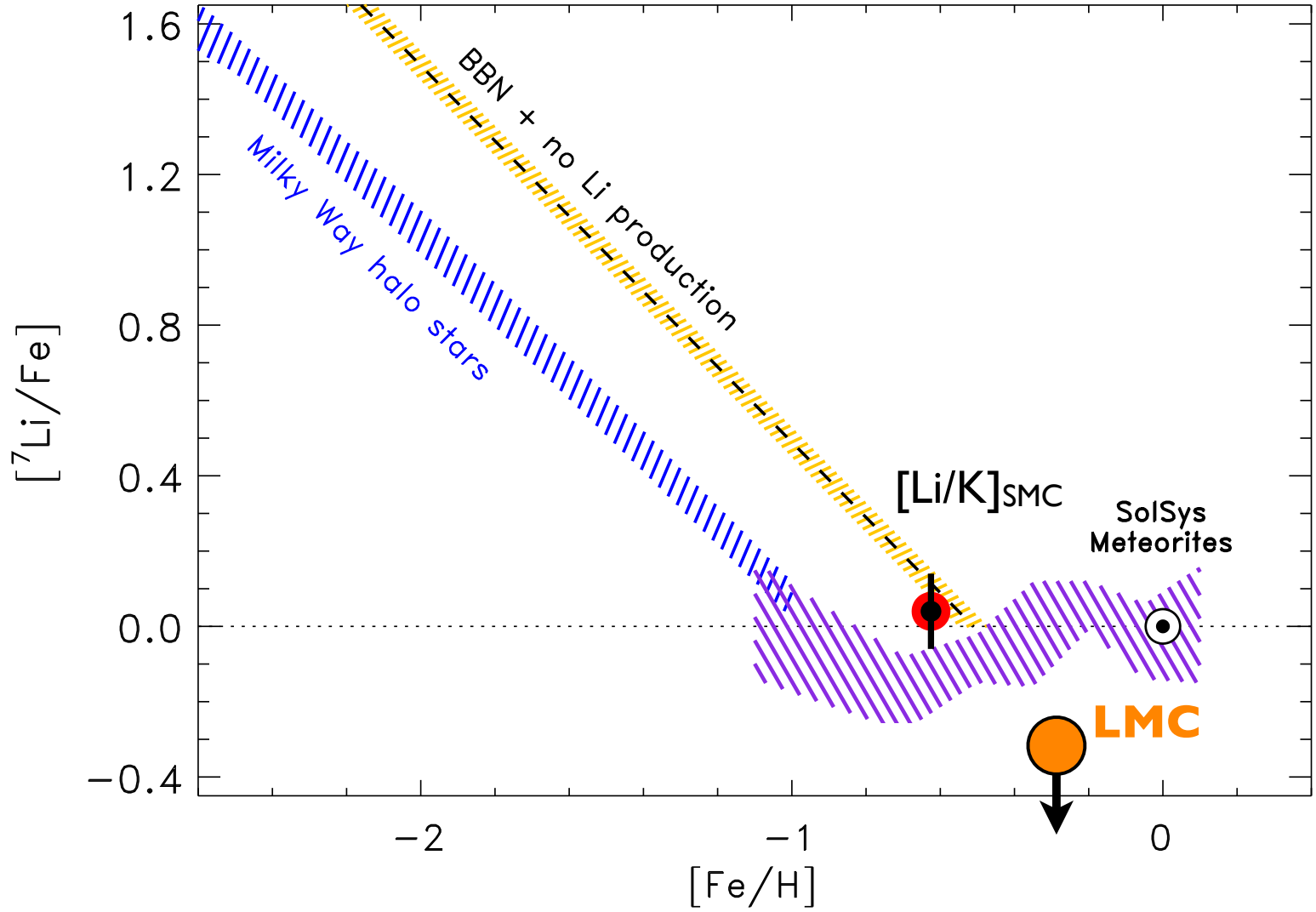
The Small Magellanic Cloud as probe of pre-galactic Li



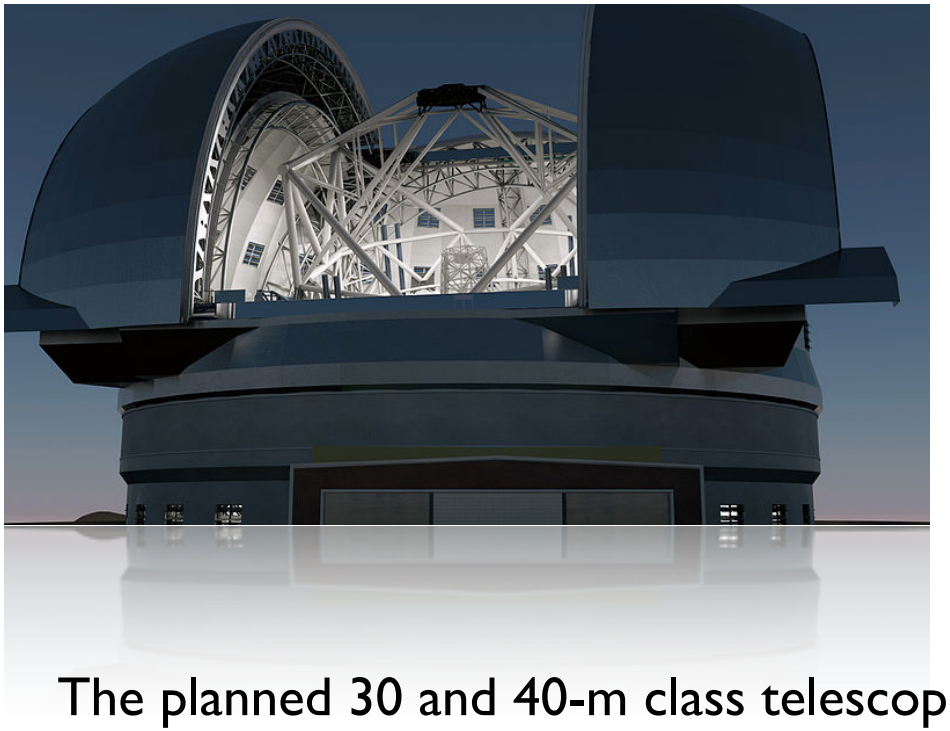
Steigman (1996)

Interstellar Li as a probe of pre-galactic production

The Small Magellanic Cloud as probe of pre-galactic Li



Interstellar Li in the ELT era



With 10-m class telescopes, this approach is limited to the SMC, LMC, and a single low-redshift damped Lyman-α (DLA) absorber *with LMC-like metallicity*.

The planned 30 and 40-m class telescopes have the *grasp* to extend the search for interstellar Li to more DLAs. However, there are several issues:

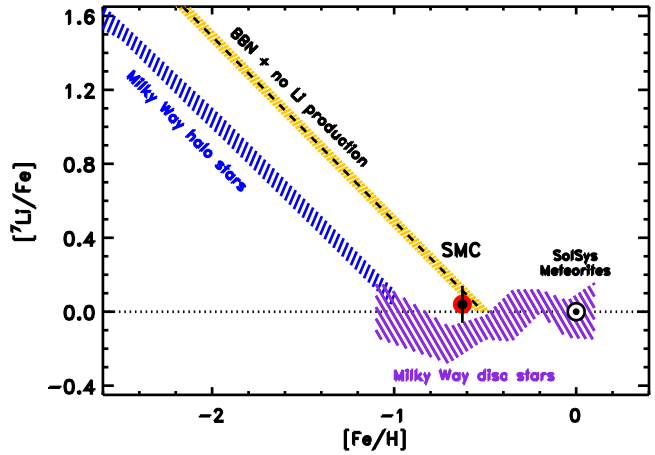
1) Li will be redshifted quickly into the NIR.
2) The number of bright QSOs with quite low metal DLAs is limited.
3) The number of DLAs bearing neutral gas and/or H_2 is *VERY* limited.

More work will be doable in the SMC/LMC on isotopic abundances.

High velocity clouds will largely still be out of reach.

Summary

- Measurements of interstellar Li I in low metallicity galaxies will allow us to probe primordial and pre-galactic production of Li (including the $^7Li/^6Li$ ratio) in a way that is *independent of the systematics associated with stellar determinations*.



- The first measurement of gas-phase Li in the SMC suggests a current abundance consistent with the BBN value, leaving little room for chemical enrichment. This may favor a low primordial abundance.

- The first marginal measurement of the isotopic ratio in the SMC implies that <40% of the ^7Li had been produced since the era of Big Bang nucleosynthesis. The ratio may represent the best test on non-standard BBN from the ISM.