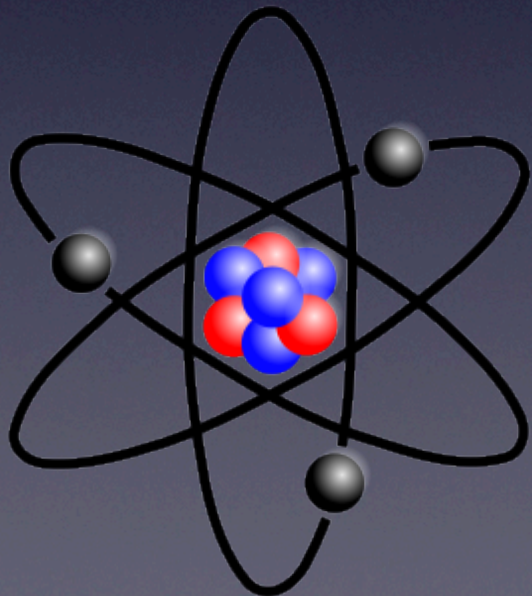
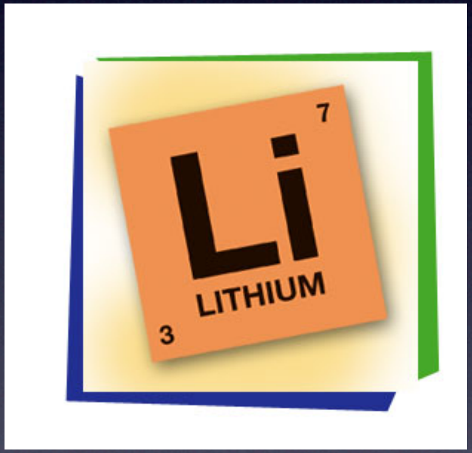
Lithium in the Cosmos

Greg Ruchti



Outline

- Why is lithium Interesting?
- The cosmic lithium problem.
- The lithium problem in giants.



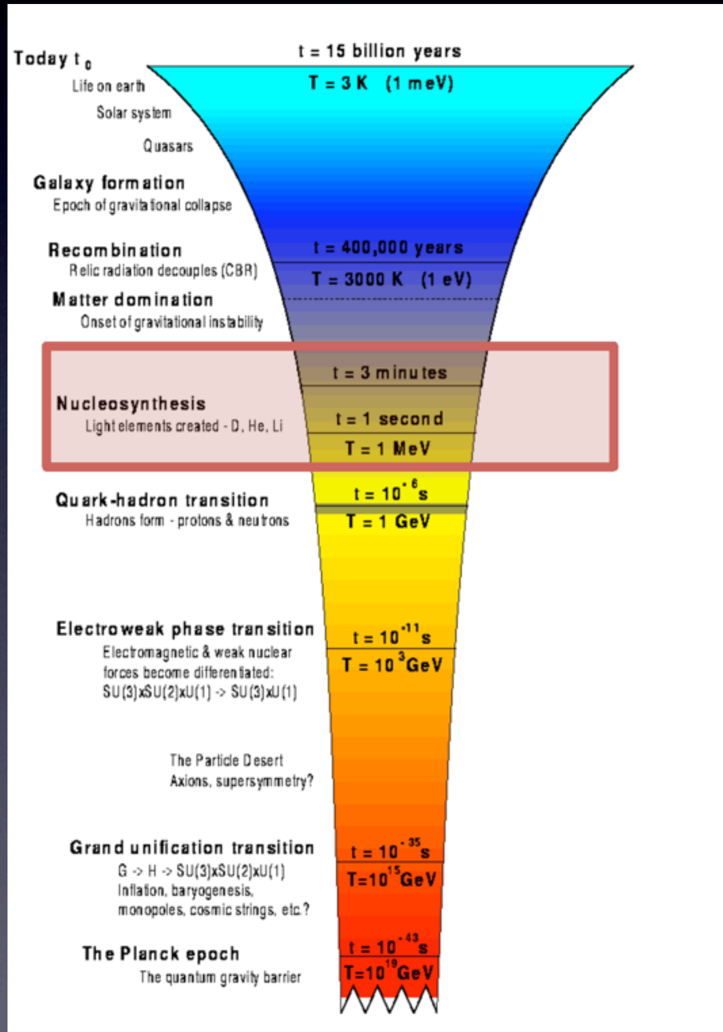
Why is lithium interesting?

- Important for our understanding of the universe.
  - ^{7}Li is one of four isotopes synthesized immediately after the big bang.
  - A primordial abundance can be predicted using measurements of the cosmic microwave background.
- Important for our understanding of stellar interiors.
  - ^{7}Li is produced during nuclear burning inside a star.
  - The abundance of Li can be used to constrain the processes that take place inside a star.
- However, lithium is a problem...

The Cosmic Lithium Problem

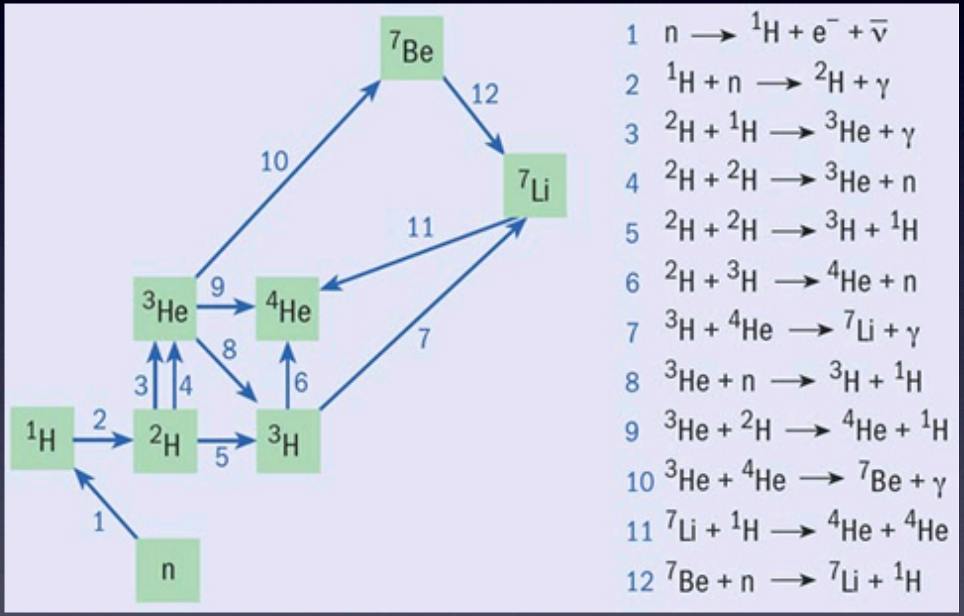
Big Bang Nucleosynthesis

- BBN describes the production of the lightest elements - D, ^{3}He, ^{4}He, and ^{7}Li - about 1 second to 3 minutes after the big bang.
- The “Standard BBN” refers to the marriage of the Standard Model of particle physics with ΛCDM cosmology in that:
    - Gravity is governed by General Relativity.
    - The universe is homogeneous and isotropic.
    - The microphysics is that of the Standard Model of particle physics.
    - The Standard Model particle content is supplemented with dark matter and dark energy.

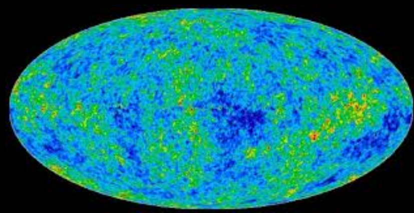


Light Element Production

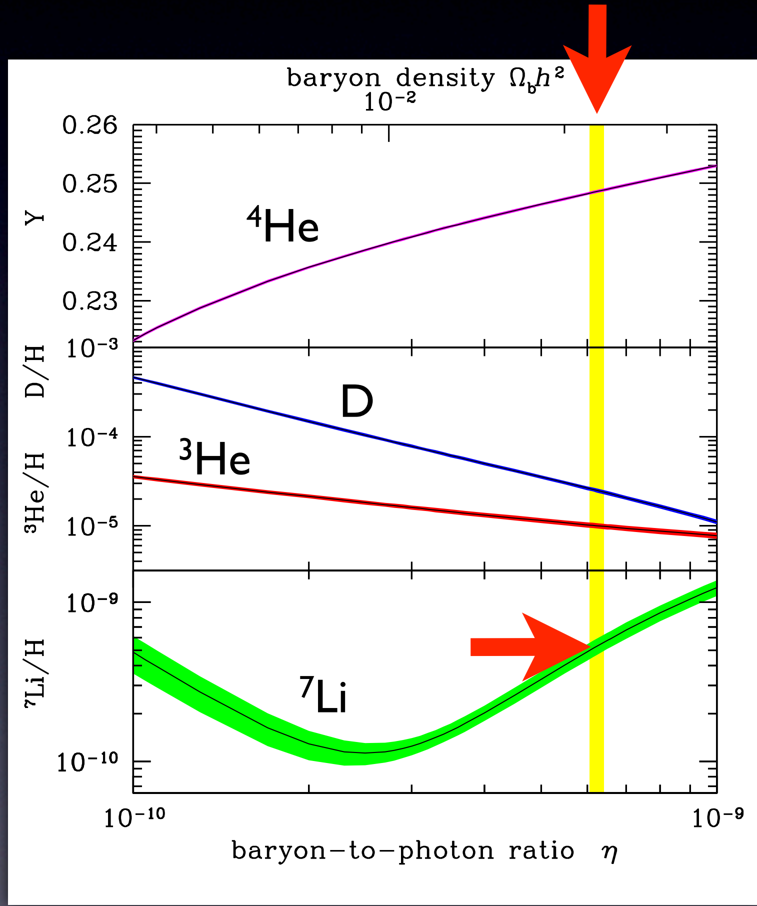
- Number of key reactions in BBN much smaller as compared to stellar nucleosynthesis.
- All important reactions have been measured in the laboratory.
- Light element formation depends crucially on the relative amounts of baryons and radiation.
- In standard Big Bang theory, the only free parameter controlling primordial nucleosynthesis is the baryon-to-photon ratio, η.



The Advent of WMAP



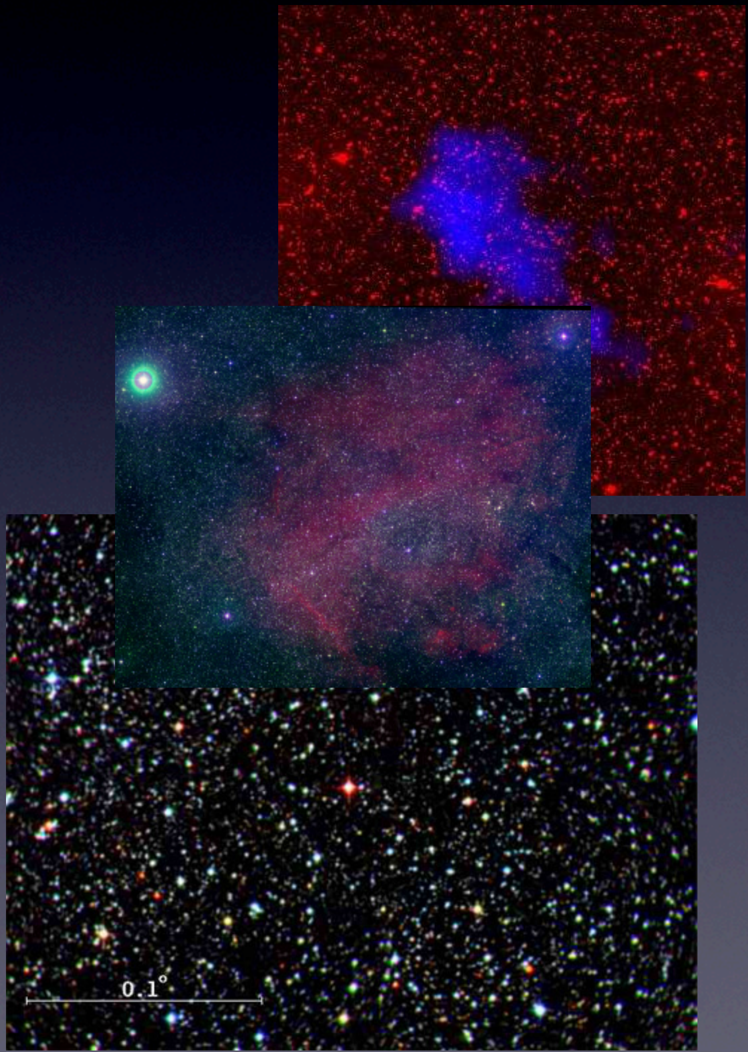
- The Wilkinson Microwave Anisotropy Probe (WMAP) makes ultra-precise measurements of the anisotropies of the cosmic microwave background.
- One of the most robust measurements is that of the cosmic baryon density, $\Omega_b h^2 = 2.258\times10^{-2}$ (Larson et al. 2011).
- This corresponds to $\eta = 6.19\times10^{-10}$ with an uncertainty of only 2.4%.
- Can then predict the primordial abundances of D, ^{4}He, ^{3}He, and ^{7}Li.
- $A(^7Li) = 2.7$ for $\log A(H) = 12$.



Cybert et al. (2008)

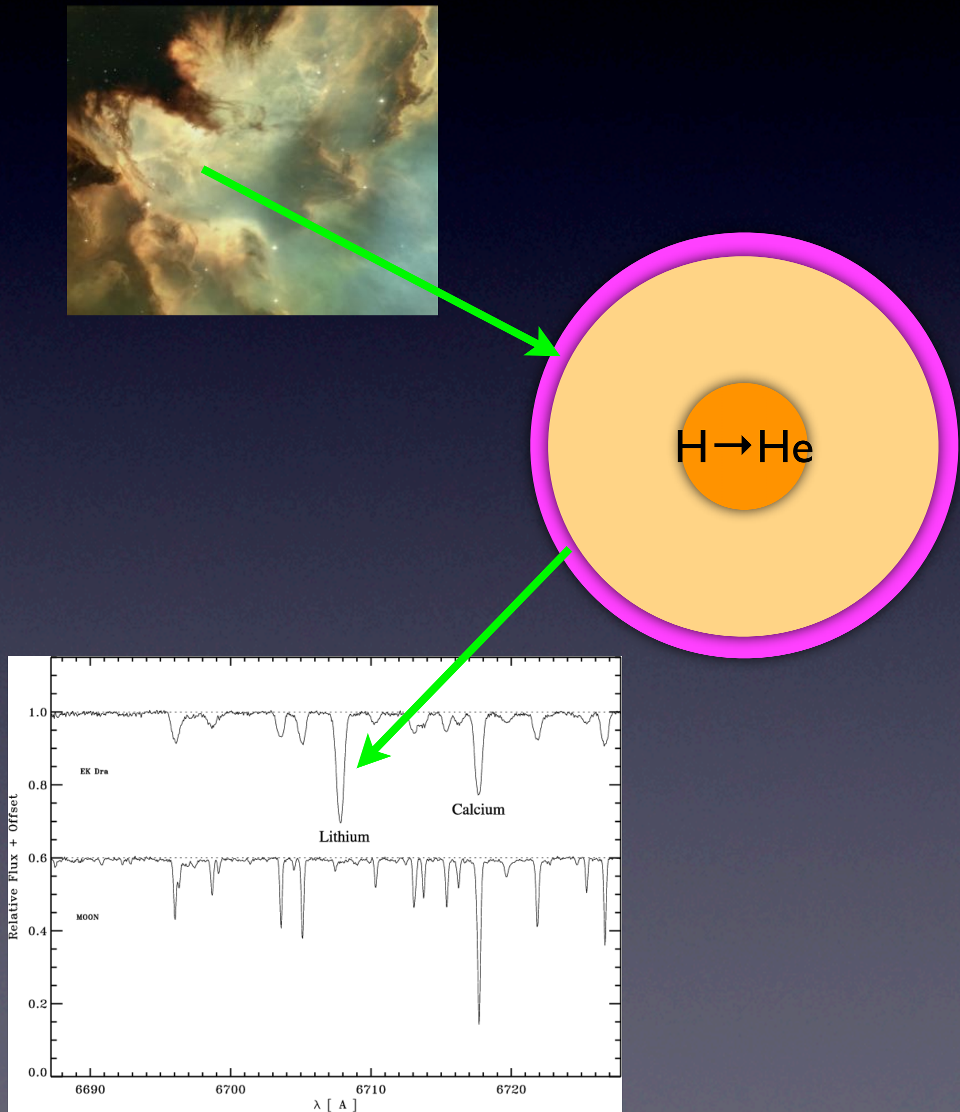
Measuring the Primordial Abundances

- Deuterium can be measured at high redshift in neutral hydrogen gas clouds seen in absorption along sight-lines to distant quasars.
- ^{4}He can be measured in emission from H II regions in nearby metal-poor galaxies.
- ^{3}He can only be measured in the Milky Way interstellar medium -- not primordial!
- ^{7}Li is measured in stars.



Measuring Primordial Li

- Low-mass stars can be as old as the Universe.
- The chemical composition of the atmosphere of a dwarf star is a good witness of the matter which formed the star.
- In other words, the chemical composition of the atmosphere does not "change" with time.
- Can measure the abundance of Li using absorption lines in the spectrum of the star.



Lithium is fragile!

- Ok, I lied...
- Lithium is readily destroyed in stars like the Sun.
- If mixing between the atmosphere and inner hot layers, Li destroyed.

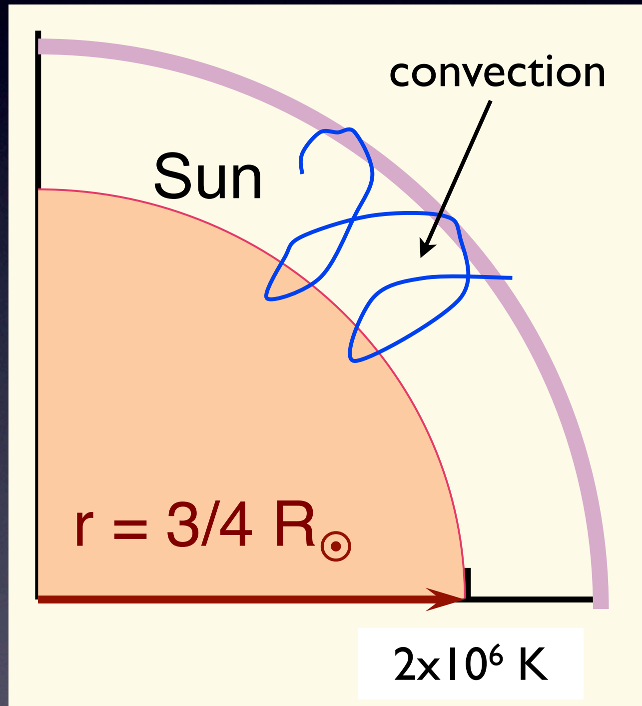
^{7}Li: $T > 2.5 \times 10^{6}$ K

$^{7}Li + p \rightarrow {}^{4}He + {}^{4}He$

^{6}Li: $T > 2.0 \times 10^{6}$ K

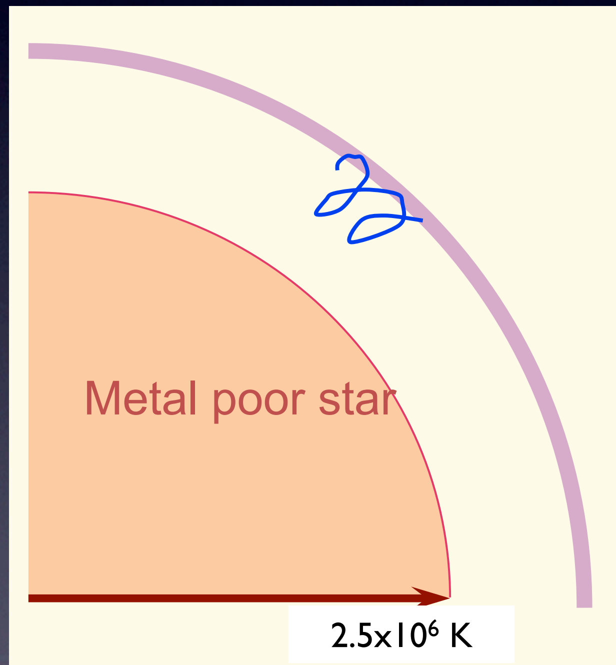
$^{6}Li + D \rightarrow {}^{4}He + {}^{4}He$

$^{6}Li + p \rightarrow {}^{4}He + {}^{3}He$



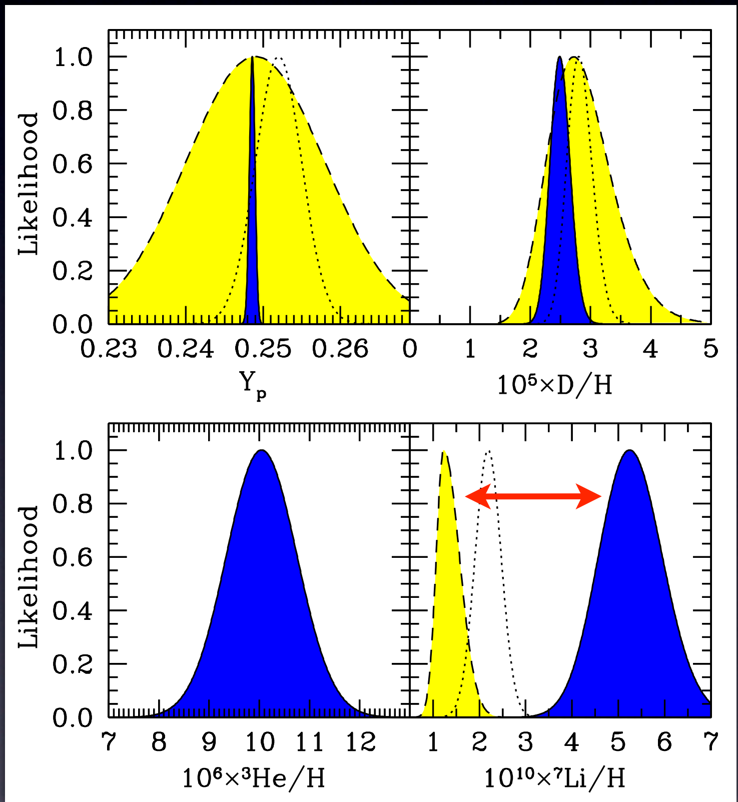
Metal-poor stars the answer

- Warm, metal-poor stars (turn-off stars: T>5900 K) mixing is not as deep as the Sun.
- Convection does not reach temperatures at which Lithium is burned.
- Lithium is preserved (temporarily).
- So, a priori, abundance of Li in old metal-poor turnoff stars = abundance of Li in primitive Galactic matter.

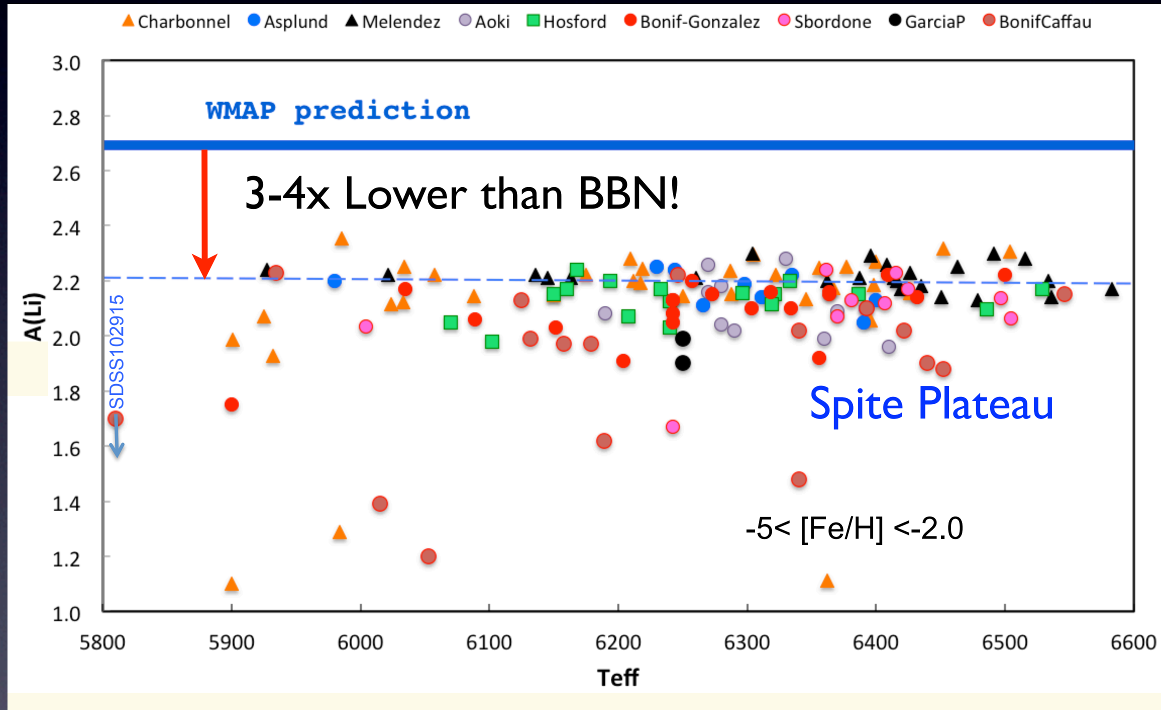


And here lies the problem...

Cybert et al. (2008)



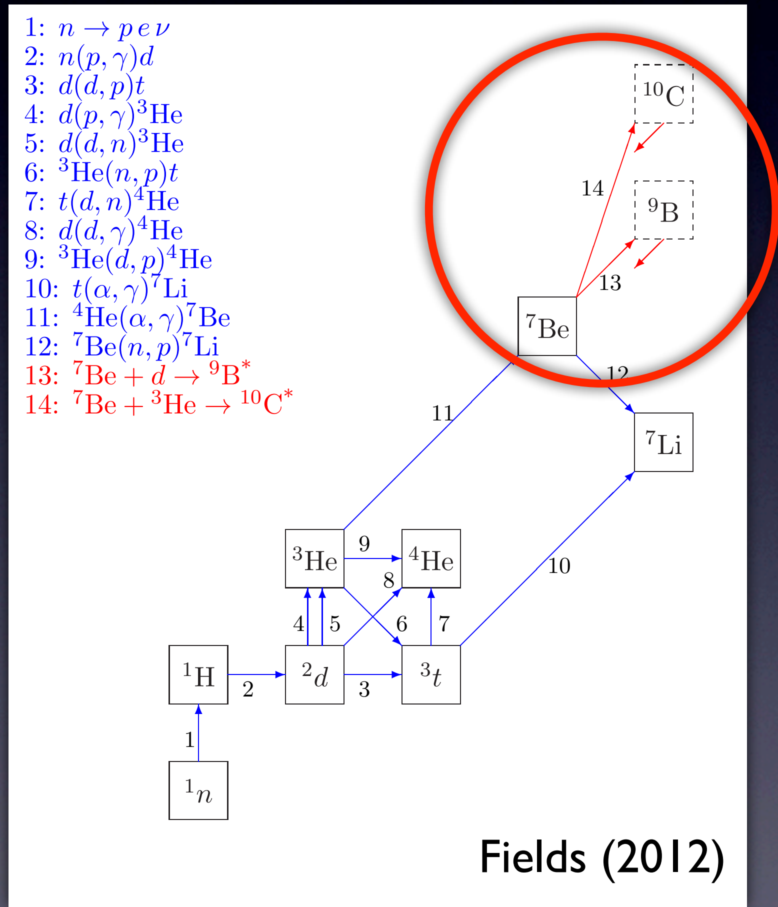
Blue: Prediction Likelihood
Yellow: Observational Likelihoods
Dotted: Observational likelihoods for different abundance analyses.



Excellent agreement for D/H, but ^{7}Li/H way off!!

Could predictions be wrong?

- BBN theory predictions have sharpened due to new nuclear data.
    - Uncertainty on $^3He(\alpha,\gamma)^7Be$ reduced to ~7% (Cyburt et al. 2008).
    - Resonances which have evaded experimental detection -- important or no? (e.g., Cybert & Pospelov 2009)
- WMAP now has 7 years of data.
    - Uncertainty in cosmic baryon density reduced to 2.4% (Larson et al. 2011).

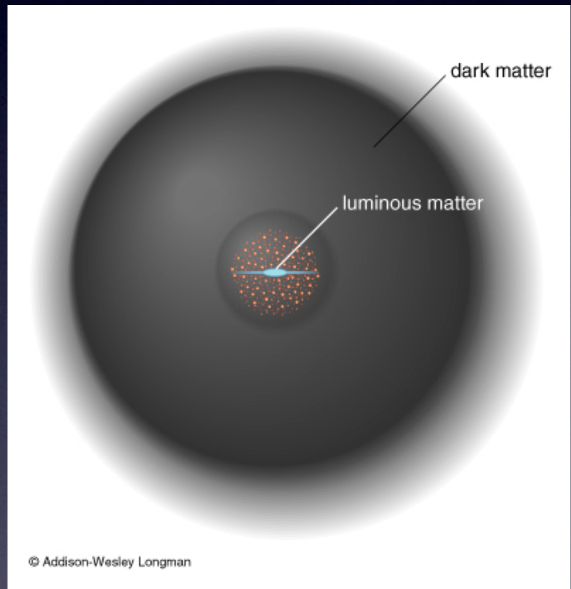


Two solutions...

- Lithium destroyed *before* the formation of the old metal-poor stars.
- Lithium destroyed *during* the lifetime of old metal-poor stars.

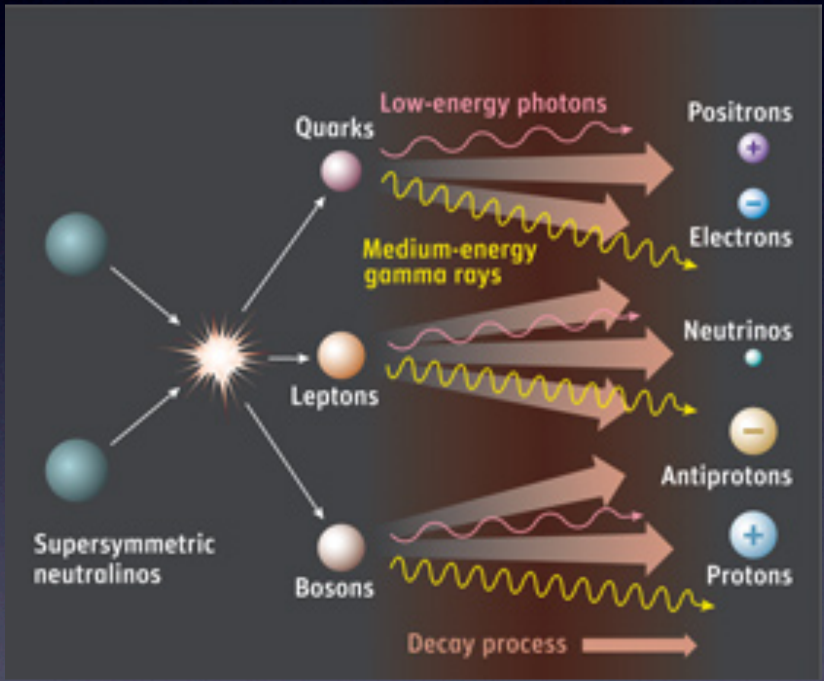
Dark Matter Decay

- Standard BBN is very robust, which implies need to go beyond the Standard Model.
- If dark matter is a relic particle created in the early universe, it must be non-baryonic and demands physics beyond the Standard Model.
- Dark matter present during BBN, but non-relativistic and weakly interacting → weakly interacting massive particles (WIMPS).
- WIMPs today are likely the stable endpoints of a decay cascade.
- Decays are model-dependent, but produce Standard Model particles which interact with surroundings.
- If decays occur during (or after) BBN, the interactions can change light element abundances.



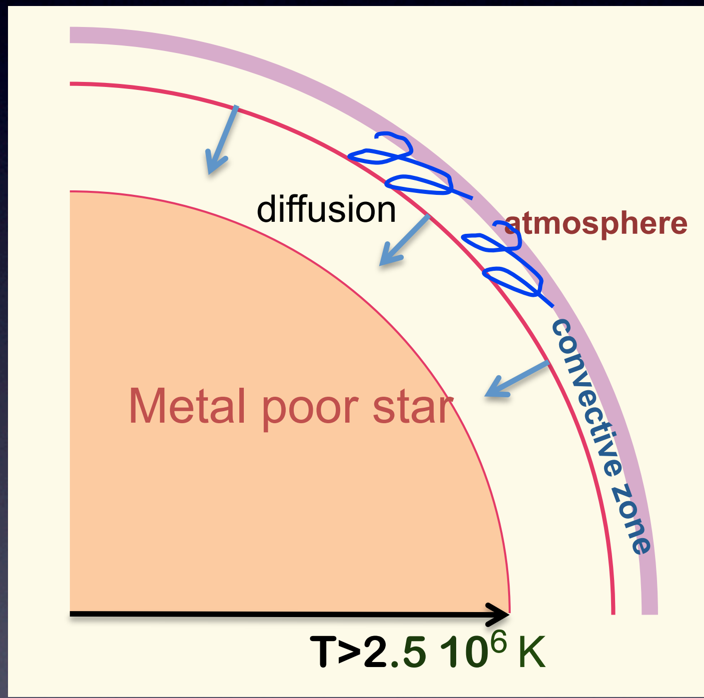
Supersymmetric Dark Matter

- Supersymmetry provides well-motivated candidates for decaying dark matter.
- Supersymmetry requires opposite-statistics partners for every known particle.
- The lightest supersymmetric partner (LSP) is the stable end product of the decays of higher-mass supersymmetric particles.
- Thus, the LSP is a candidate for dark matter.
- Supersymmetric scenarios *demand* that particle decays occur.
- These decays could lead to the depletion of the primordial ^{7}Li.
- Some models have been found, which appear to work if the gravitino is the LSP (Feng et al. 2004, Jedamzik et al. 2006)



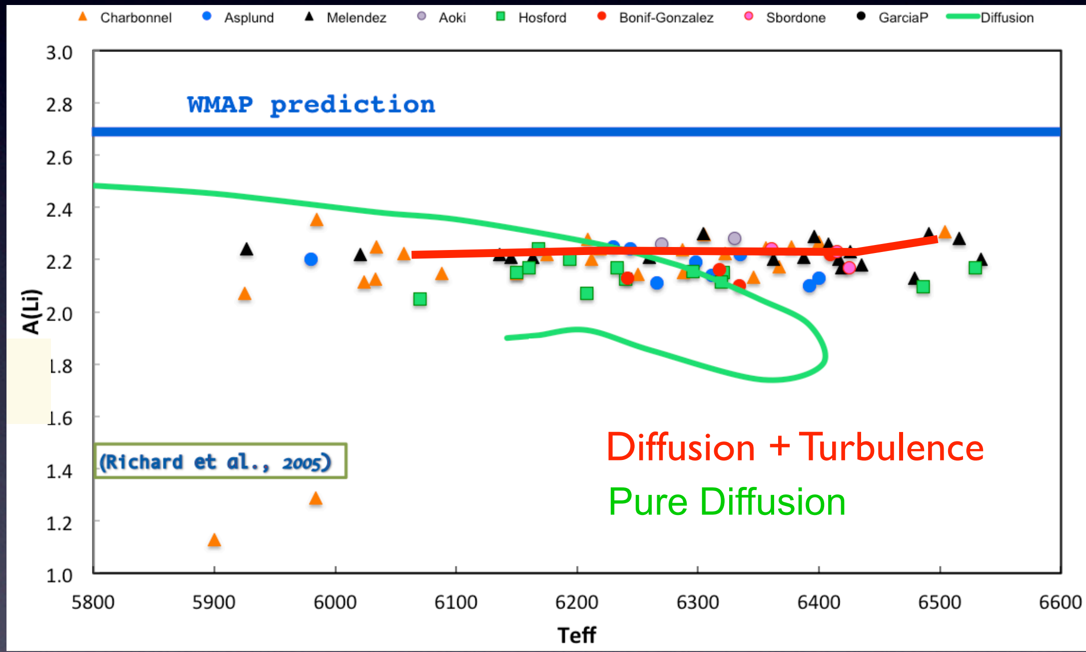
Stellar Li Depletion

- Atomic Diffusion: a one-way ticket to the destruction of Li.
  - Slow gravitational settling of elements below the convective zone.
  - However, diffusion too efficient.



Atomic Diffusion

- Li depletes too quickly.
- Needs an additional *ad hoc* turbulence parameter (Richard et al. 2005, Korn et al. 2006).
- Work still being done to constrain the turbulence parameter using stellar clusters.



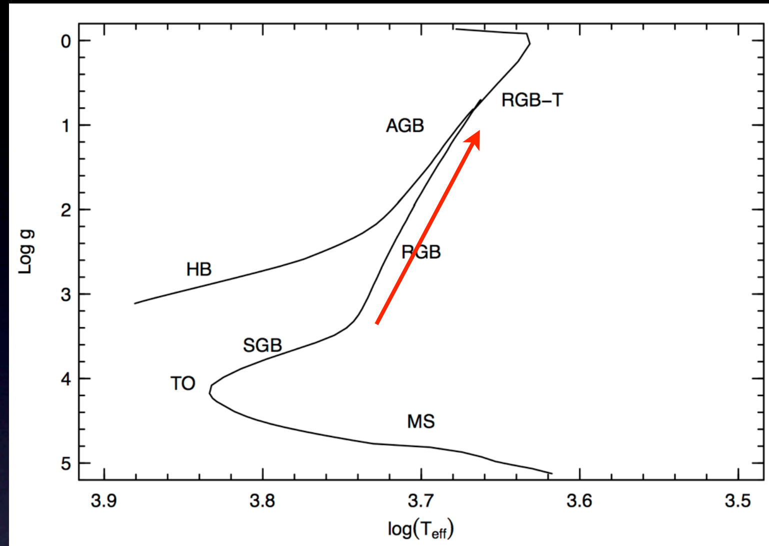
To Summarize...

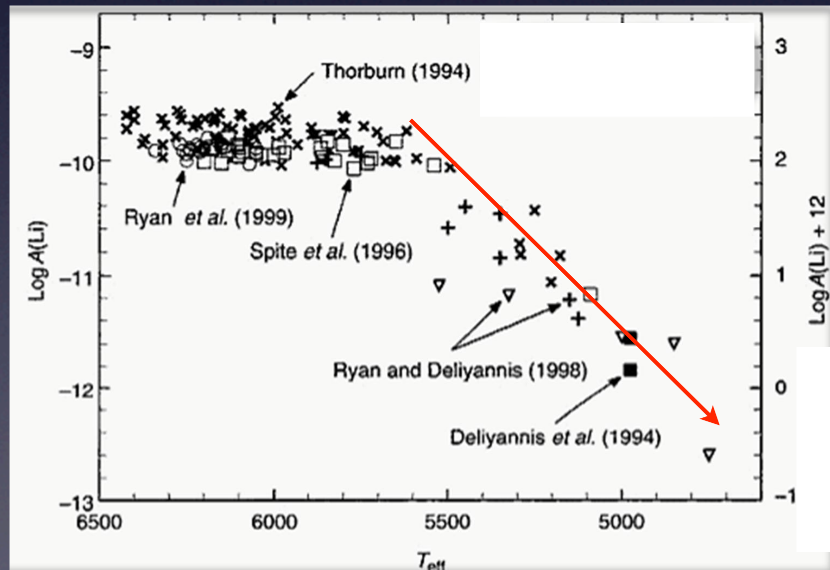
- The discrepancy between the WMAP predictions for the primordial Li abundance and that measured in stars still unexplained.
- New theories perhaps closing the gap.
- Supersymmetric dark matter could decay, which depleted the primordial ^{7}Li in the galactic matter.
  - The large hadron collider will be able to probe supersymmetry and may give indications for the existence of the LSP.
  - Stay tuned for results from full LHC 2011/2012 data sets!
- Stars are depleting Li in their atmospheres (diffusion).
  - More modeling and tests using globular cluster stars are needed to constrain the turbulence parameter for atomic diffusion.
  - Other possibilities: e.g., internal gravity waves.
- Measure Li in low-metallicity gas (e.g., in the SMC; Howk et al. 2012).

The Lithium Problem in Giants

Li beyond the subgiant branch

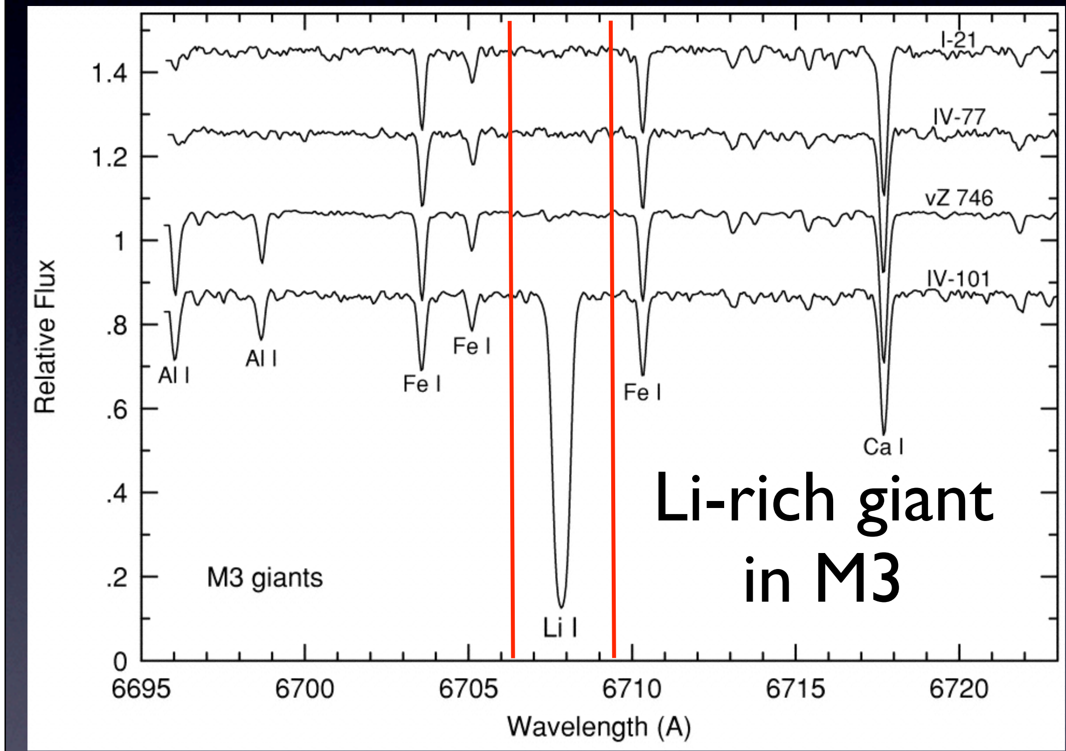
- As a star moves beyond the SGB, convective depletion brings A(Li) down by more than one order of magnitude.
- Li produced in interior, but immediately destroyed.
- Li in surface layers burned away by convective dilution.



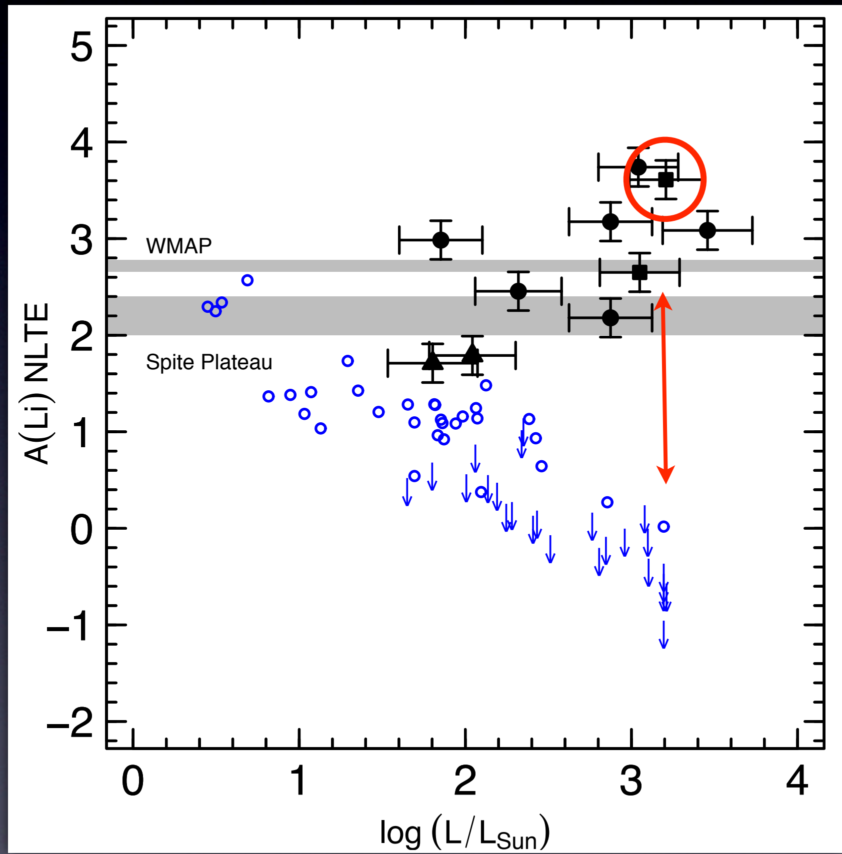


Gray (2005)

But, Li-rich giants exist!



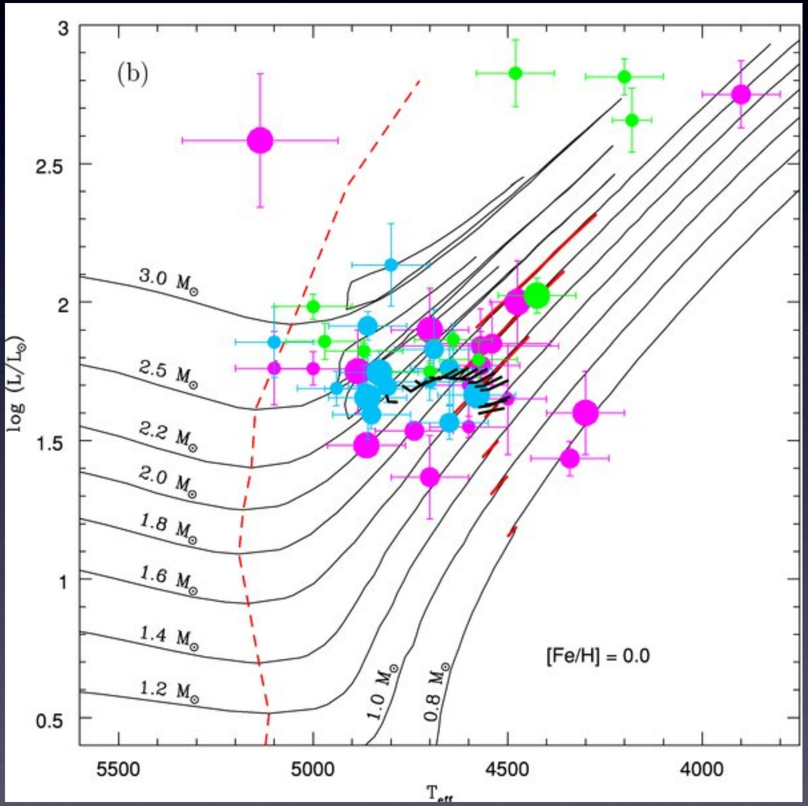
Kraft et al. (1999)



Ruchti et al. (2011)

And so, we have another Li problem...

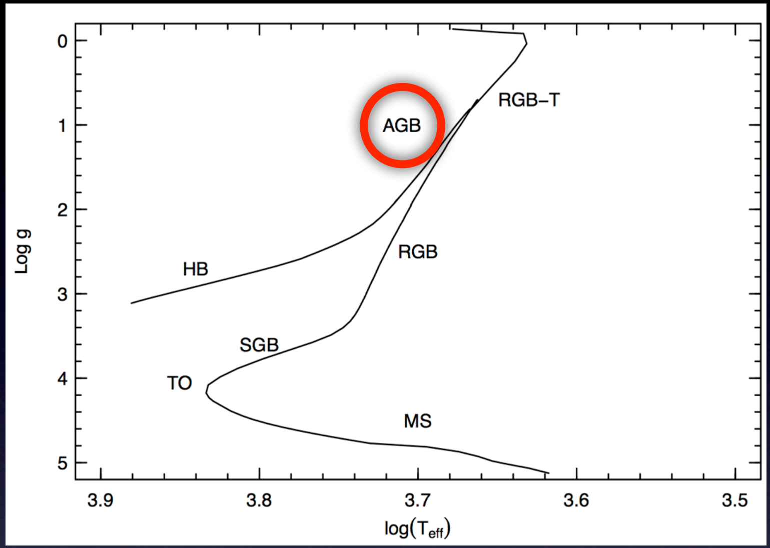
- Li-rich giants have been discovered in both the field and in clusters (e.g., Kraft et al. 99, Charbonnel & Balachandran 2000, Monaco et al. 2011, Ruchti et al. 2011).
- New discoveries in the dwarf spheroidal galaxies in the Local Group (Kirby et al. 2012).
- They appear to represent about 1% of all giants (Brown et al. 1989) ⇒ short-lived phase??
- Stars can produce Li in their late-stages of evolution via the Cameron & Fowler (1971) mechanism

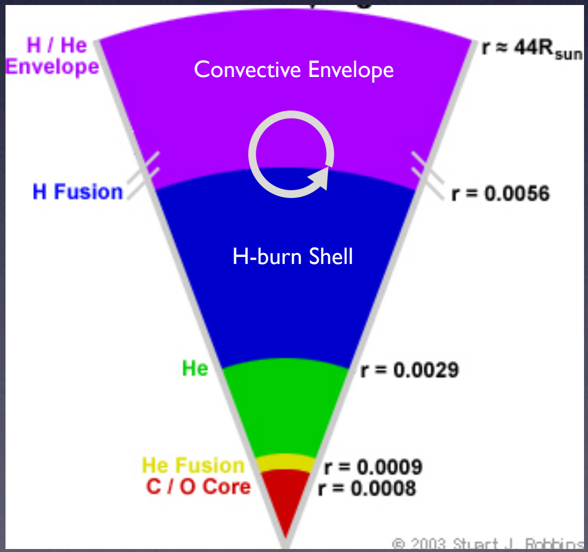


Kumar et al. (2011)

Cameron-Fowler Mechanism

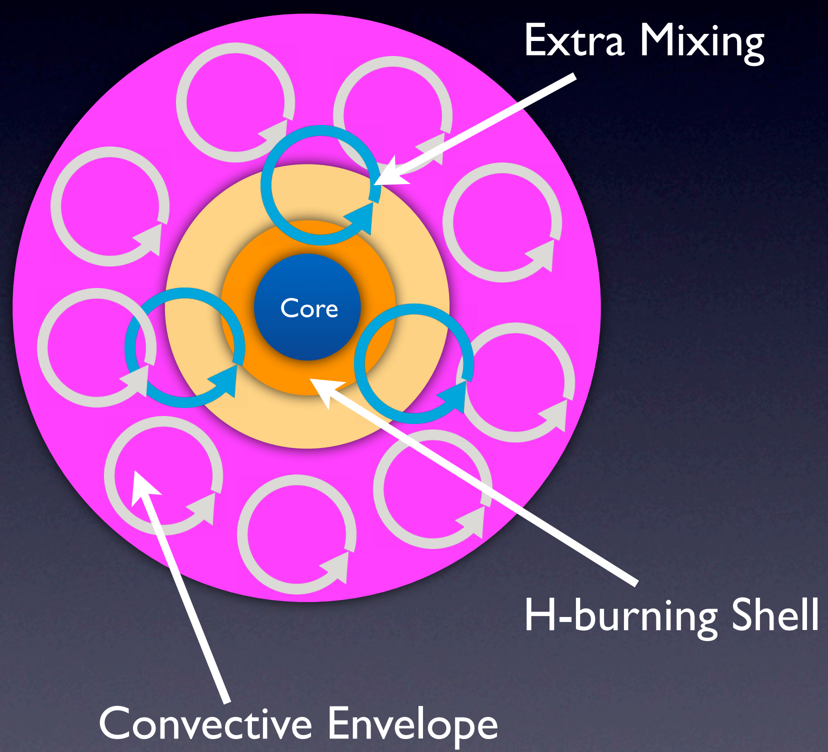
- Takes place in intermediate-mass AGB stars.
- At this stage, outer convective envelope is in contact with the H-burning shell where ^3He is being produced by proton-proton reactions.
- The ^3He is burned to ^7Be via $^3He(\alpha,\gamma)^7Be$ under convective conditions.
- The ^7Be is then swept up to the stellar surface and decays to ^7Li by electron capture.
- ^7Li will then survive for a short period.
- However, some Li-rich giants are *low-mass* and *not* evolving on the AGB!!





Li-production in low-mass stars

- The convective envelope and H-burning shell are not in contact in low-mass stars.
- Standard mixing not enough.
- Non-canonical "extra mixing" mechanism needed to connect the two zones.
- Physical mechanism not understood -- many theories for induced "extra mixing".



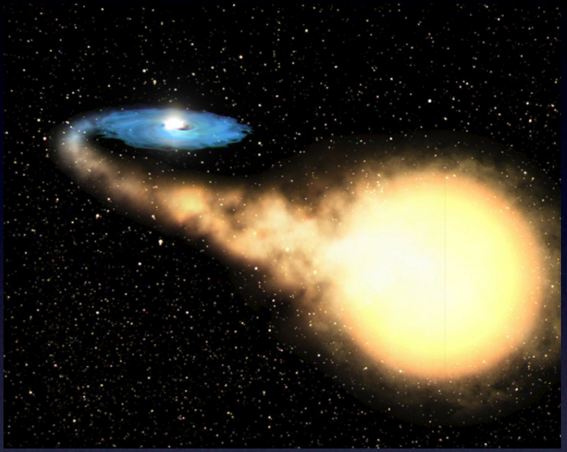
Extra Mixing

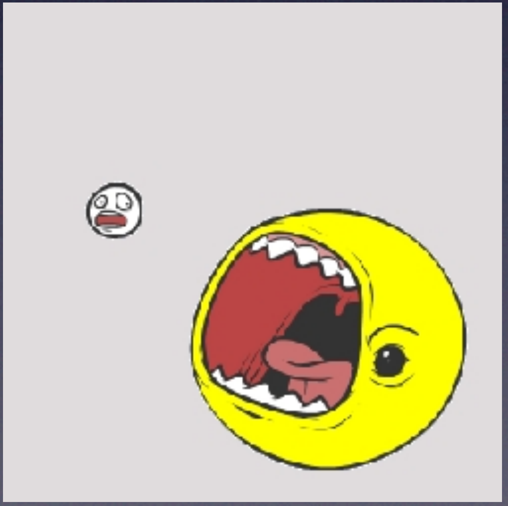
- Efficient extra mixing postulated to occur at the luminosity bump of the red giant branch (Gratton et al. 2004, Charbonnel & Balachandran 2000).
- Thermohaline mixing (Charbonnel & Zahn 2007).
- Magneto-thermohaline mixing -- magnetic buoyancy (Denissenkov et al. 2009).
- Rotation induced mixing -- 50% of Li-rich giants may be rapid rotators (vsini > 8km/s) (Drake et al. 2002).
- Cool Bottom Processing (Sackmann & Boothroyd 1999).
- Mass loss (de La Reza et al. 1996,97).

Other Possibilities

- Giant star in a close binary system with more massive AGB star.
    - AGB star has undergone the Cameron-Fowler Mechanism.
    - Li-rich material is transferred to the low-mass giant.
    - Scenario is certainly feasible, however, recent studies have shown that not all Li-rich giants are in close binary systems.
- Ingestion of planet or brown dwarf.
    - Angular momentum may induce extra mixing which could drive the Cameron-Fowler mechanism (Denissenkov & Weiss 2000).
    - Metal-poor giants less likely to host planets (Fischer & Valenti 2005).
    - Lack of enriched Be (Melo et al. 2005) ⇒

      unlikely to be main driver of Li-production in the Li-rich giants.

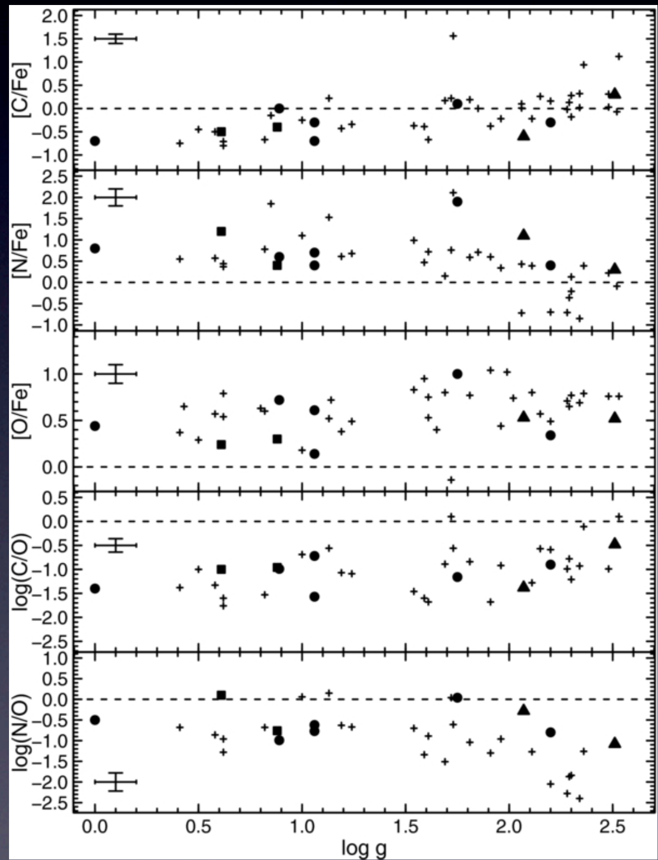




A Caveat

Ruchti et al. (2011)

- Some mixing mechanisms are accompanied by the mixture of other elements to the surface (e.g, C, N, O).
- Li-rich giants appear to show similar abundance ratios to other "Li-normal" giants.
- Implies that extra mixing event cannot affect the other elements.
- Or, mixing event is short-lived and occurs in *all* giants? (de La Reza et al. 1996, Gonzalez et al. 2009)



Large points: Li-rich
Small pluses: Li-normal

To Summarize...

- Lithium is expected to be destroyed as a star evolves beyond the subgiant branch.
- However, Li-rich giants exist.
- Require non-canonical extra mixing (internally or externally driven) to produce lithium on the stellar surface.
- The next step: asteroseismology.

“- It looks like grandma’s mood is so much better today!”
“- ‘course son...Lithium never fails.”