Rotational Mixing and Lithium Depletion

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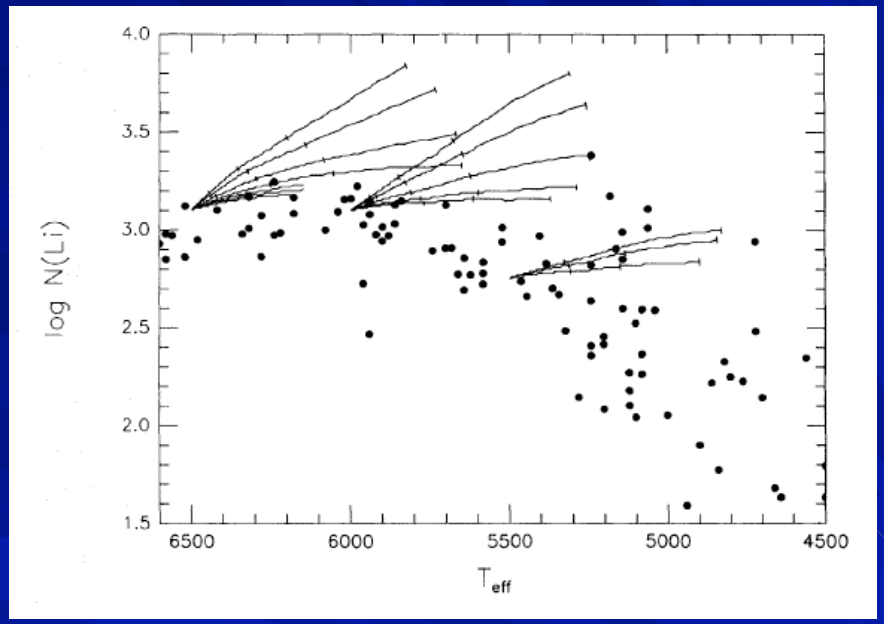
Pre-MS Lithium Depletion

- Mass and composition trend predicted (Iben 1965)
- Long-standing problem: lithium dispersion in cool stars
  - Dispersion is real, not induced by activity (King et al. 2009)
  - Not from mixing

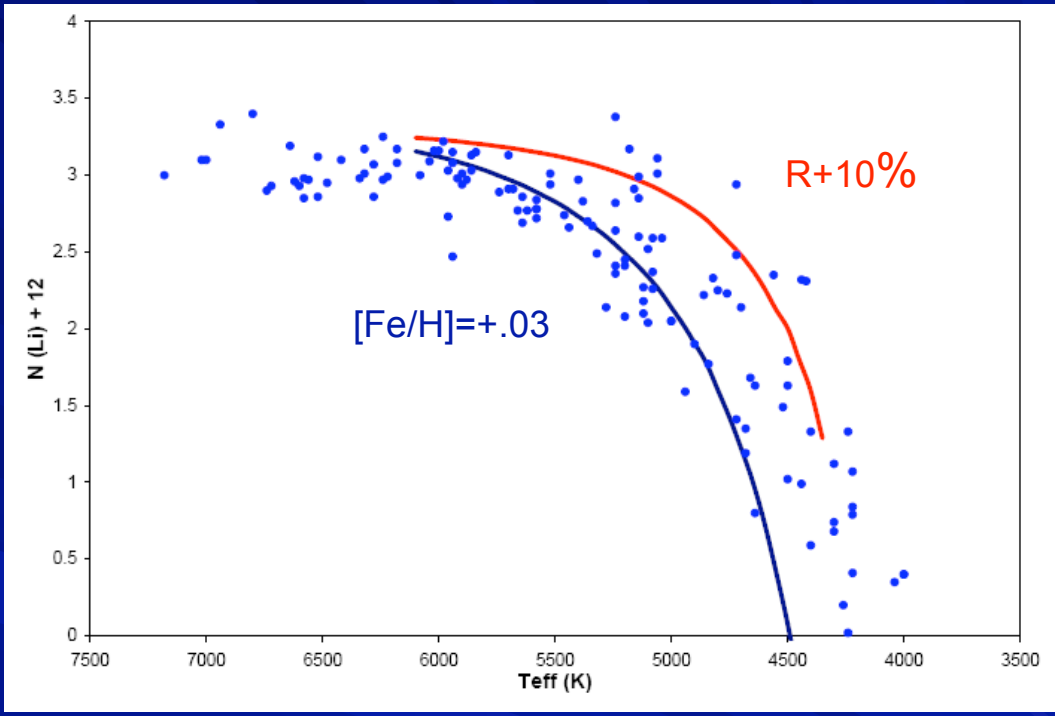


Lithium in the Pleiades (Soderblom et al. 1993) with varying spot covering factors

Culprit: Starspots

- New evidence: radius anomalies in active stars
  - Spotted stars are ~10% larger
- Implication: range of radii in pre-MS stars will cause a range of depletion rates
  - Anomaly tied to pre-MS activity and rotation

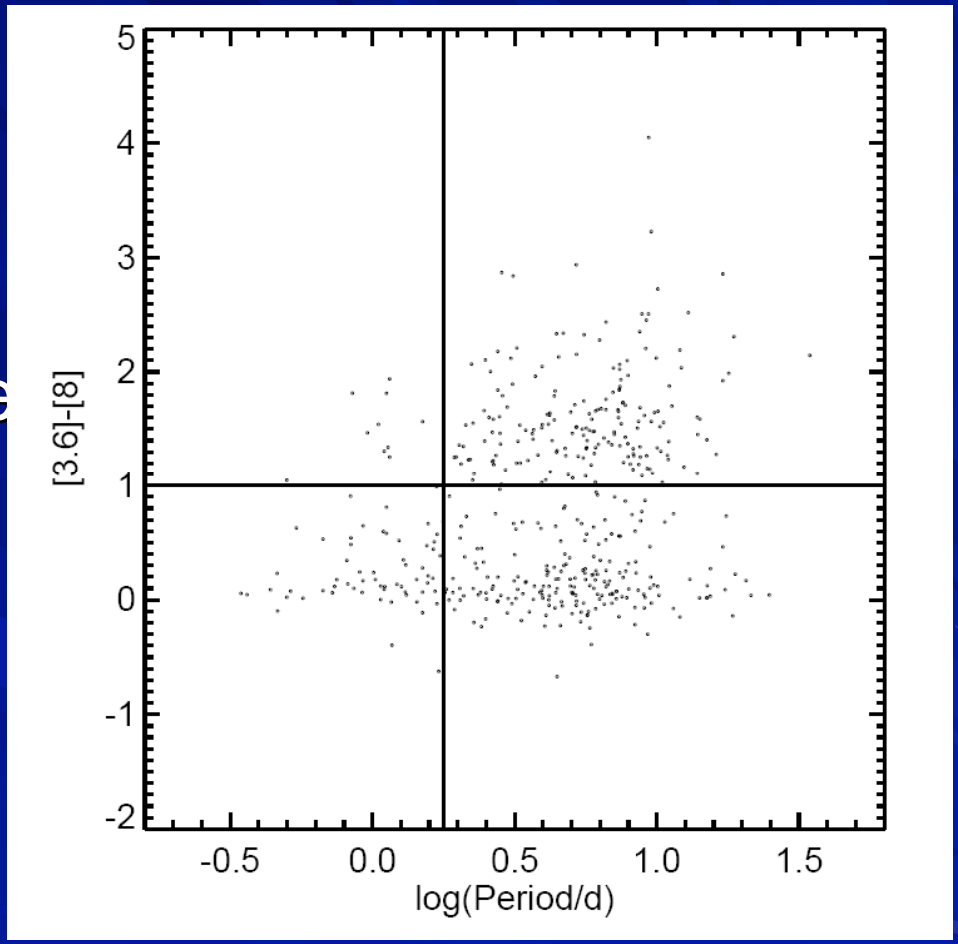
Pleiades Lithium Revisited



Teff (K)

Where does rotation come from?

- Initial Angular Momentum
  - Mass assembly rate
  - Interactions with accretion disk
- Impacted by
  - Environment
  - Planet formation



Rebull et al. 2006: Correlation of IR excess with rotation period in ONC

Angular Momentum Evolution

Tinker et al. 2002: ONC->Pleiades->Hyades

- Magnetized solar-like winds
  - more efficient for rapid rotation
  - Saturate at mass-dependent threshold
- Angular Momentum Transport and Mixing
  - Core eventually coupled to surface; three classes of mechanisms competitive

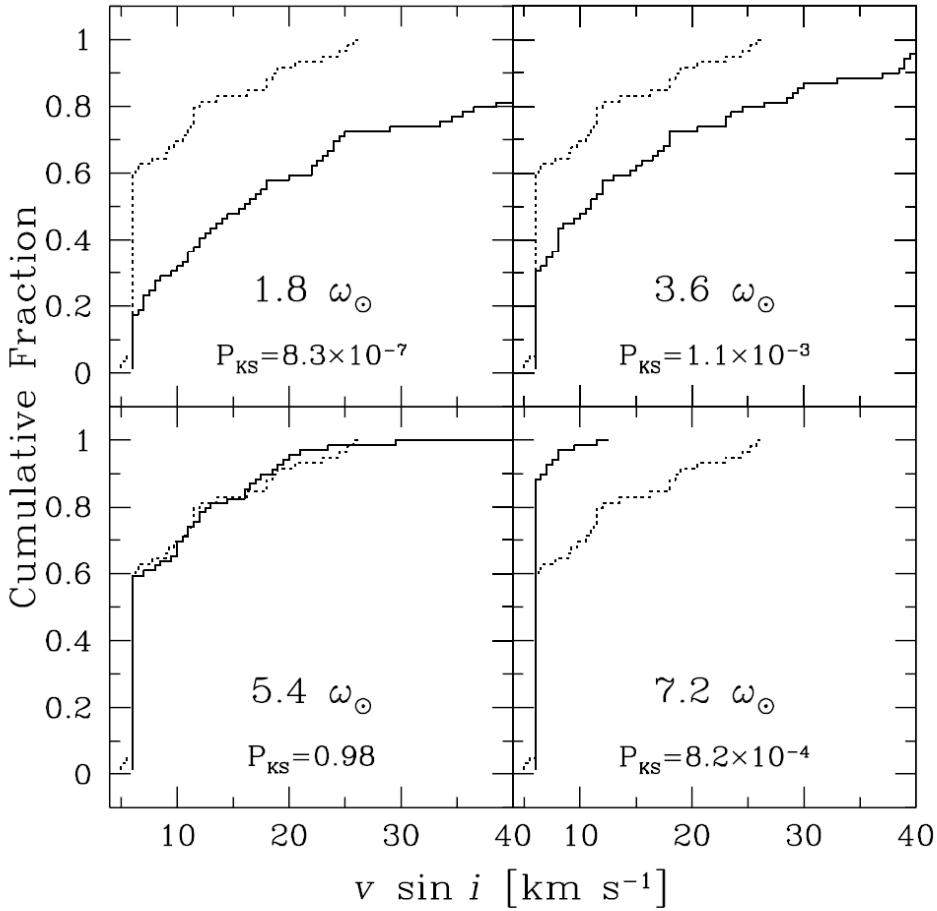


Fig. 1.— The cumulative distribution of $v \sin i$ for the projected sample of Pleiades stars is shown for 4 different saturation thresholds. The projected Pleiades is the solid line and the observed Hyades distribution is the dotted line.

Rotational Mixing and Lithium

- Two mechanisms for inducing:
  - Shears
  - Meridional circulation
- Inhibited by mu gradients
  - Can interact with diffusion
- Key predictions:
  - Rate of depletion declines as stars spin down
  - Different rotation histories

  -> Different depletion histories

Strong Arguments for Rotational Mixing: Timing and Dispersion

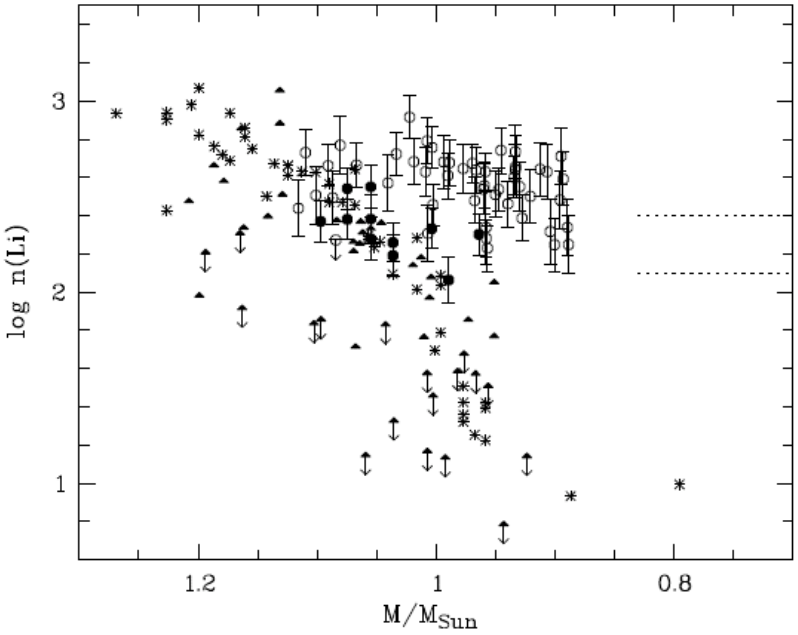
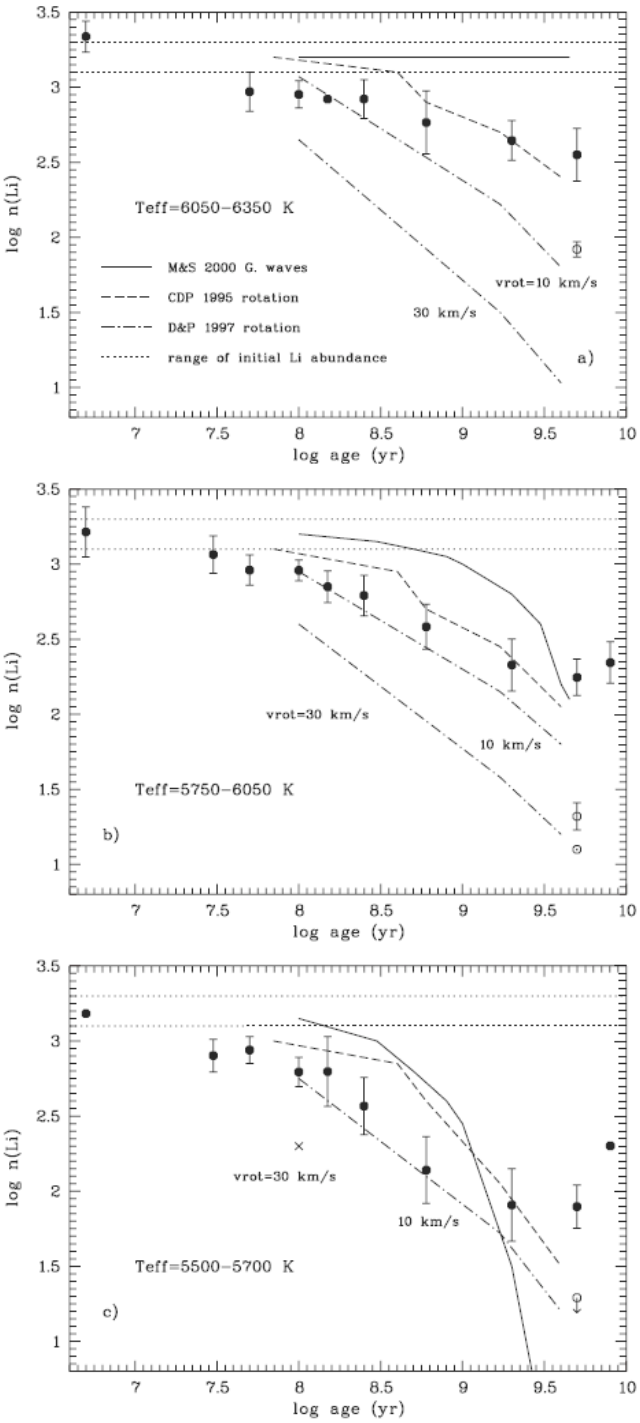


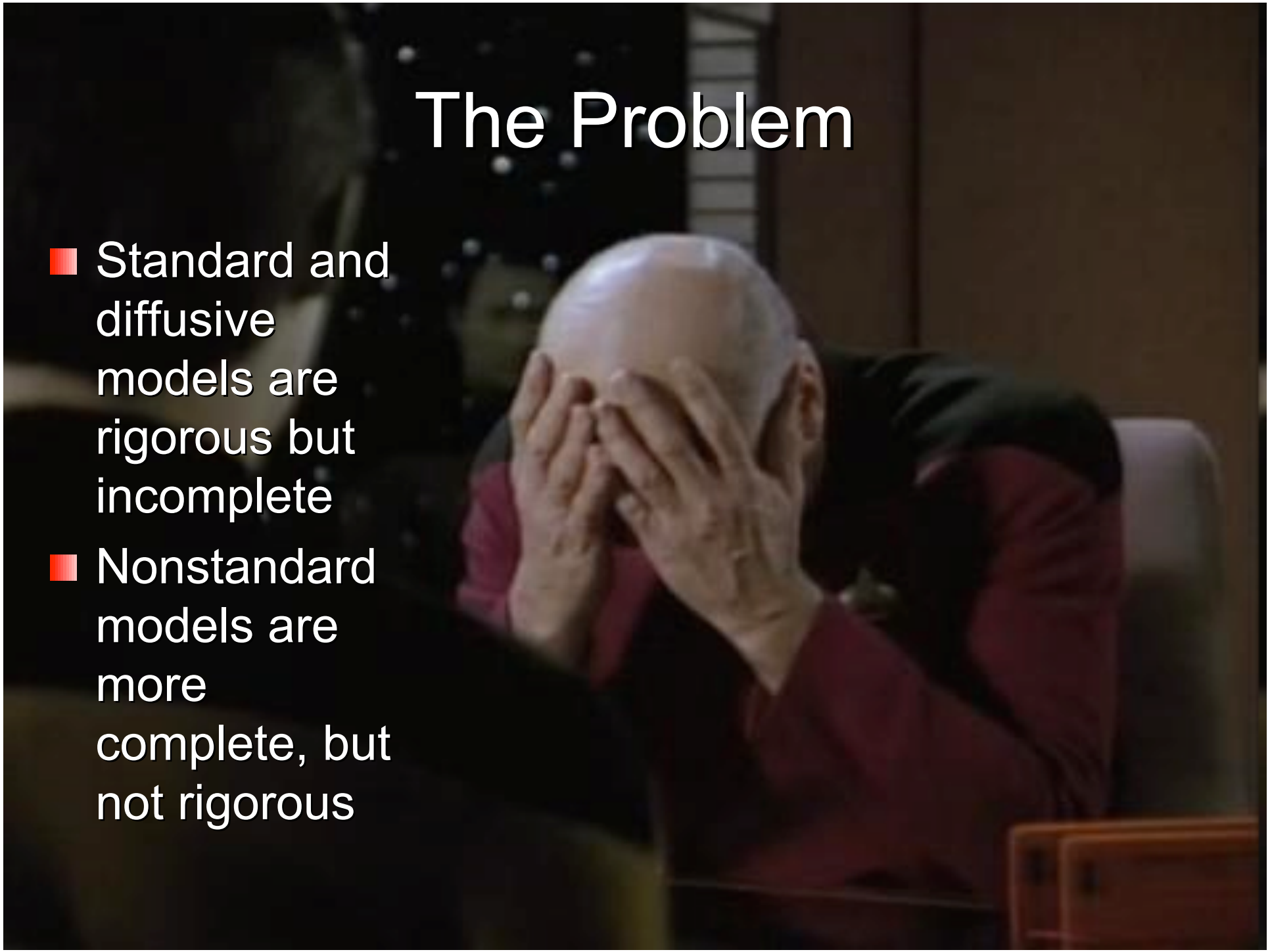
Fig. 8. log n(Li) as a function of mass for Be 32 (open circles), the Hyades (asterisks), M 67 (filled triangles), and NGC 188 (filled circles). The horizontal lines delimits the range covered by Pop. II stars considering the lowest and highest values of the plateau.

Randich et al. 2009: Be 32

Sestito & Randich 2005

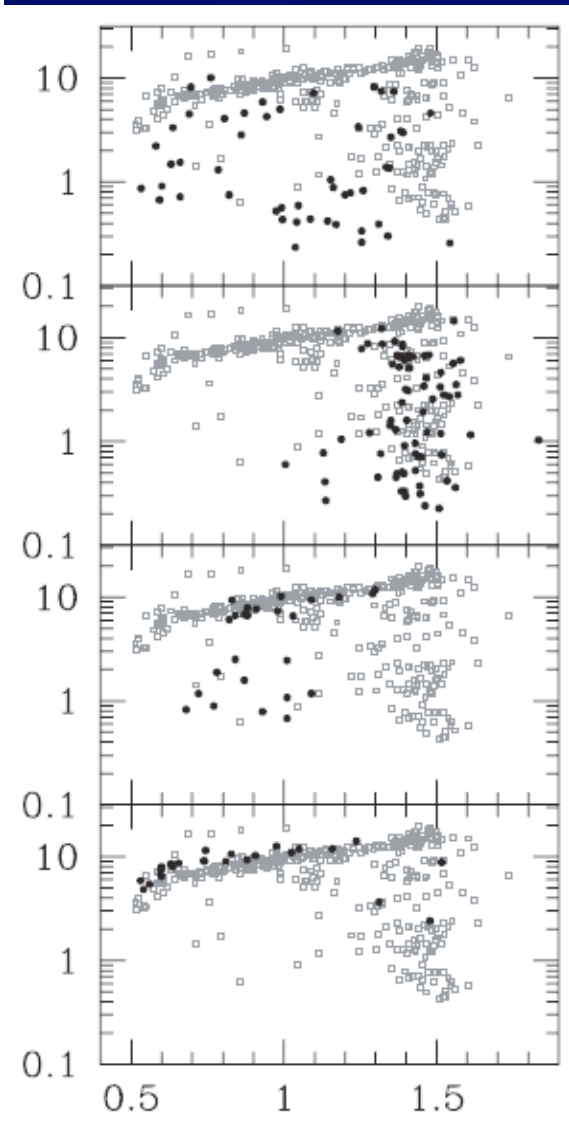


The Problem



- Standard and diffusive models are rigorous but incomplete
- Nonstandard models are more complete, but not rigorous

Convergence in Rotation Rates of Solar Analogs is Clearly Seen



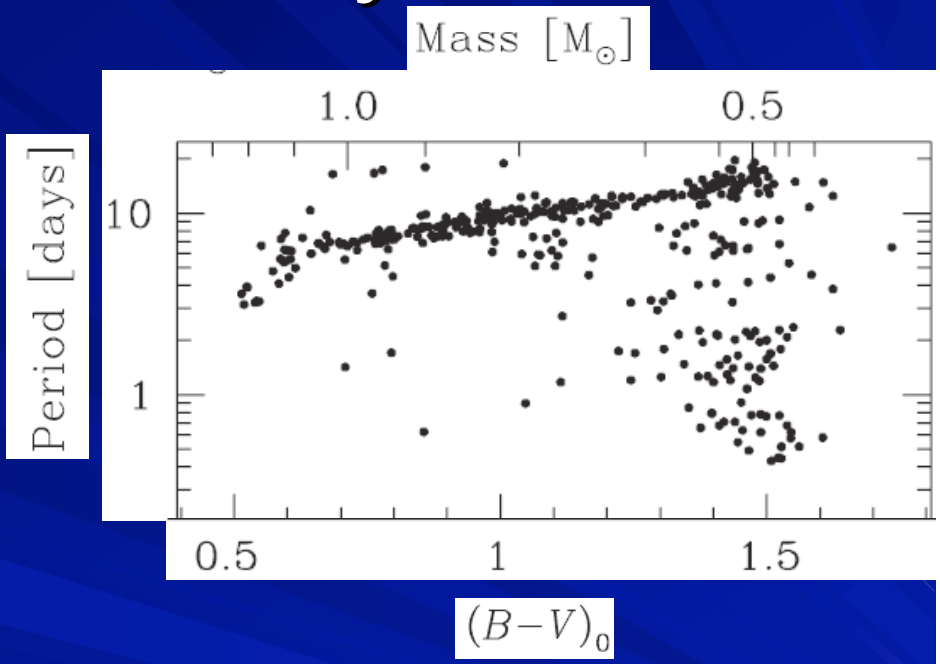
Pleiades
120 Myr

NGC 2516
140 Myr

M34
200 Myr

Hyades
625 Myr

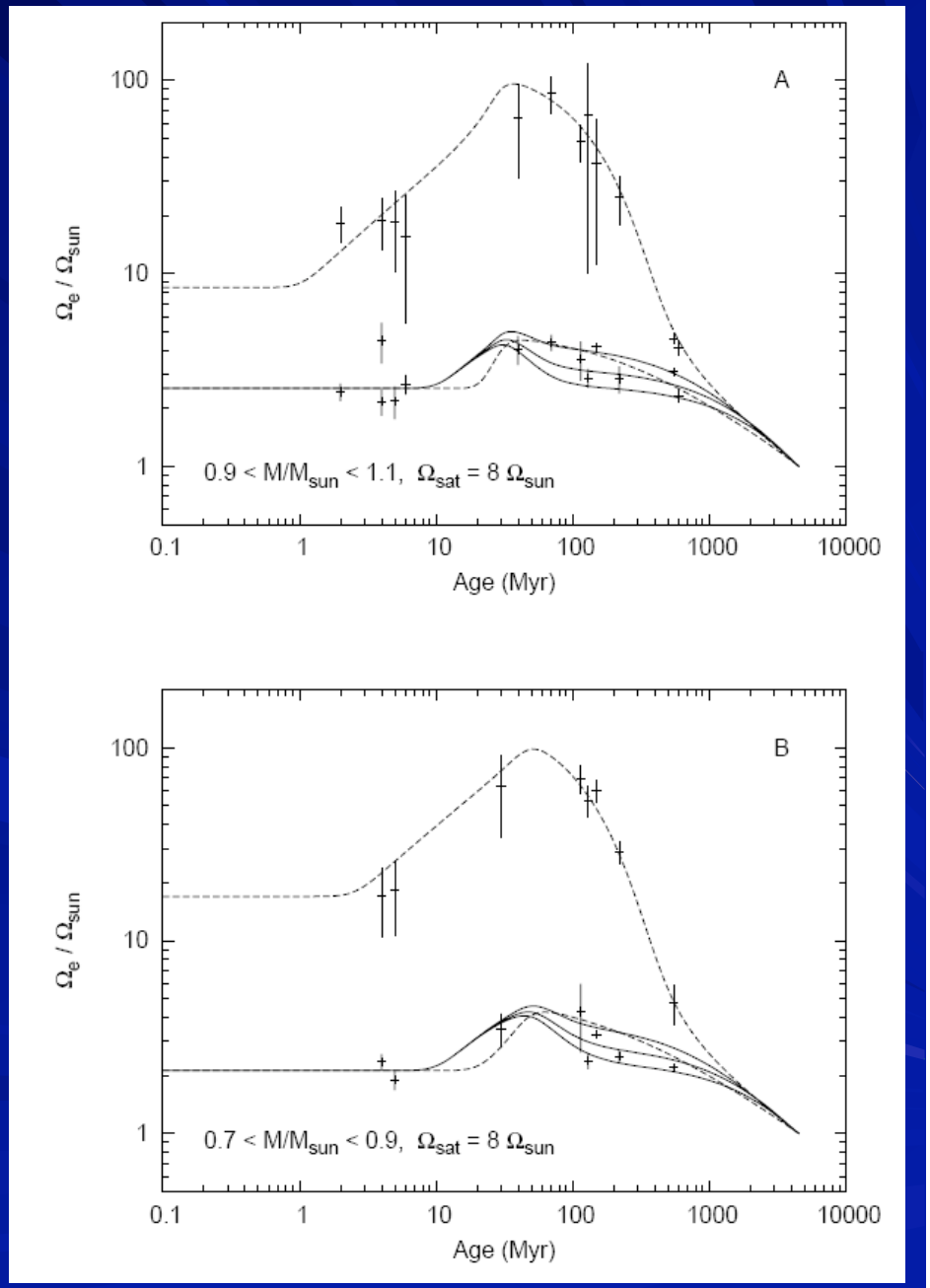
Rotation Periods in M37 (550 Myr)
Hartman et al. 2009



Interesting Coupling Timescale

- Rapid rotators are strongly coupled
- Slow rotator spindown is strongly inconsistent with SB rotation
  - $\tau \sim 50$ Myr

Denissenkov et al. 2009
(astro-ph/0911.1121)

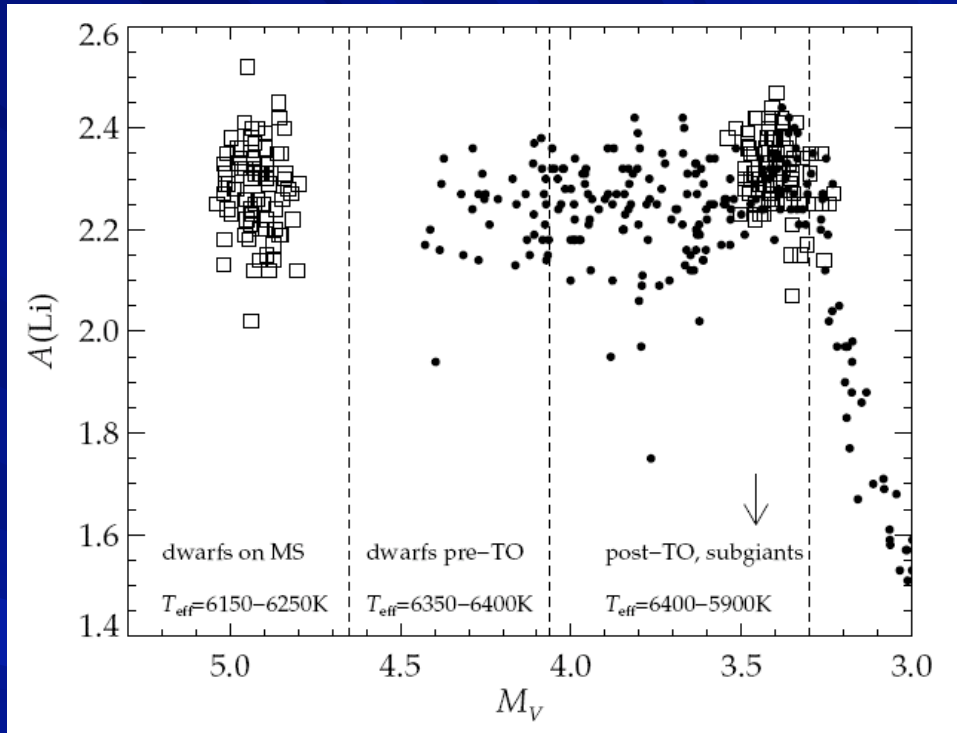


Implications for Lithium Depletion

- Internal rotation convergences on a timescale comparable to that for surface rotation
  - Dispersion is generated early in the lifetime of a star
- Predicted magnitude of dispersion is therefore sensitive to
  - Angular momentum loss
  - Accretion disk properties

Interaction of Rotation and Settling

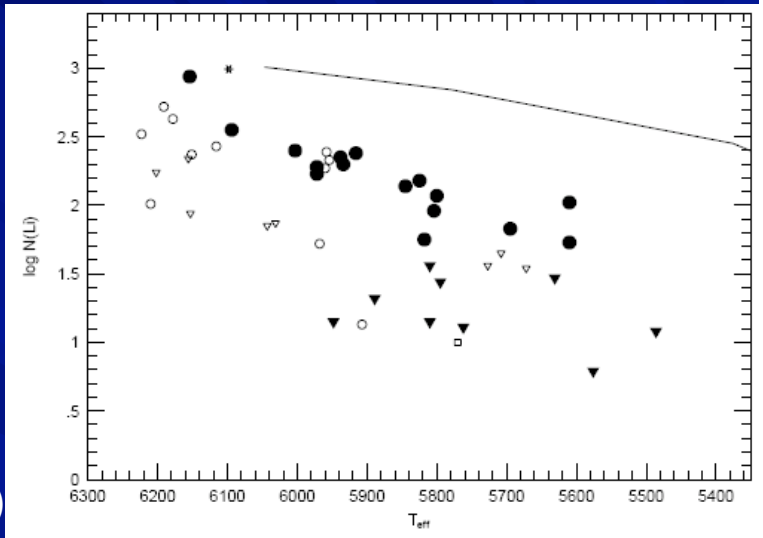
- Required to understand helioseismology (Richard et al. 1988)
- Stalling of lithium depletion in old open clusters (Randich & Sestito 2005)
- Much recent evidence for settling in globular cluster stars (Korn et al. 2007)
- Diffusion expected late, rotational mixing expected early



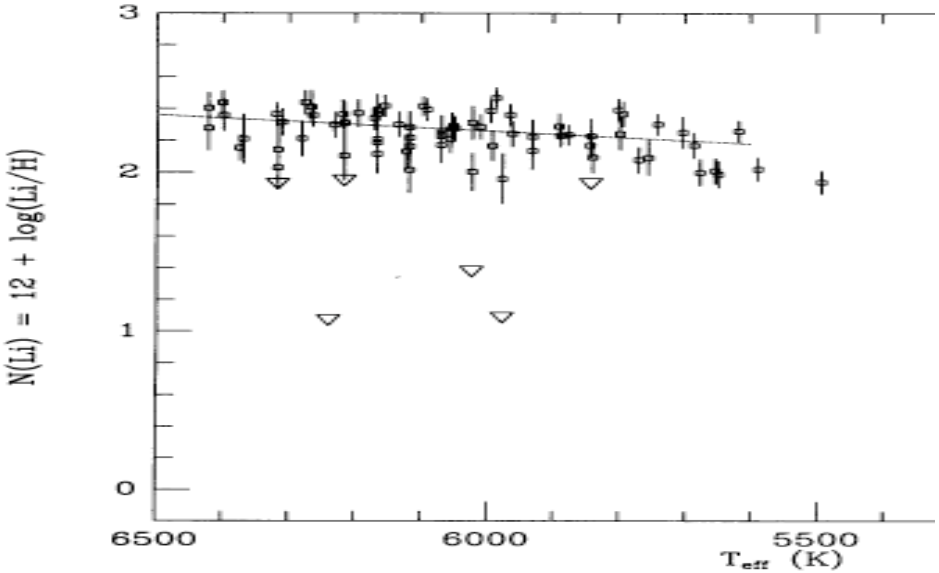
On Halo Lithium Depletion

- Basic issue: Pop II pattern does not look like the Pop I pattern
- Taken as evidence that the Pop II stars are undepleted
  - Very difficult to understand from stellar interiors point of view
- Diffusion (late ages) can add to mixing (early)
- Major uncertainty: rotational properties of halo stars (dispersion/depletion) relationship
- Testable in halo tidally synchronized binaries

M67 (Jones et al. 1999)

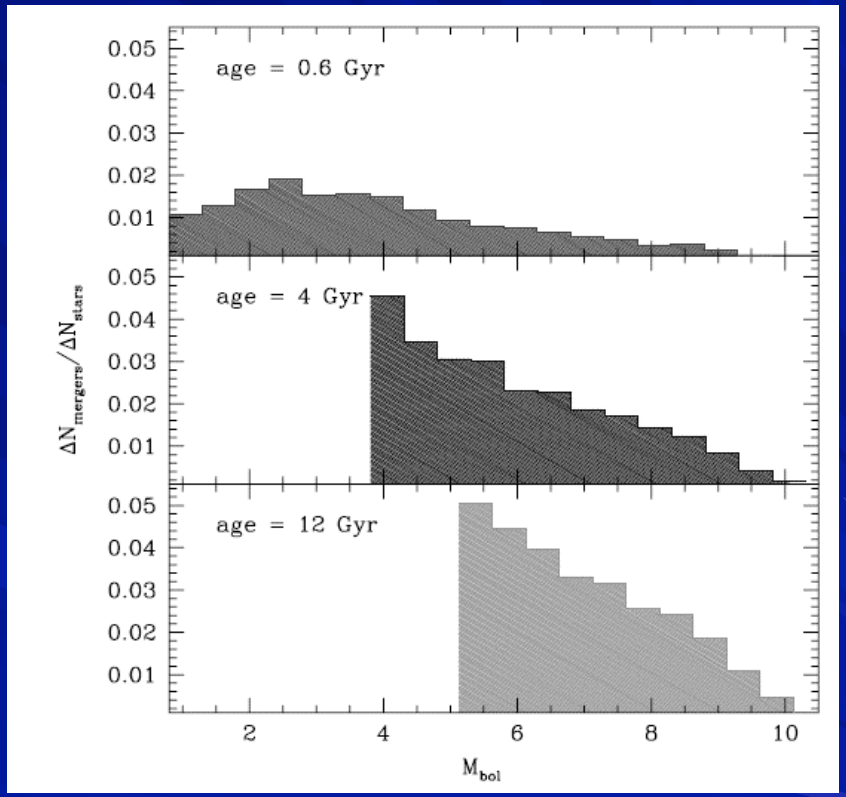


Halo field
(Thorburn 1994)



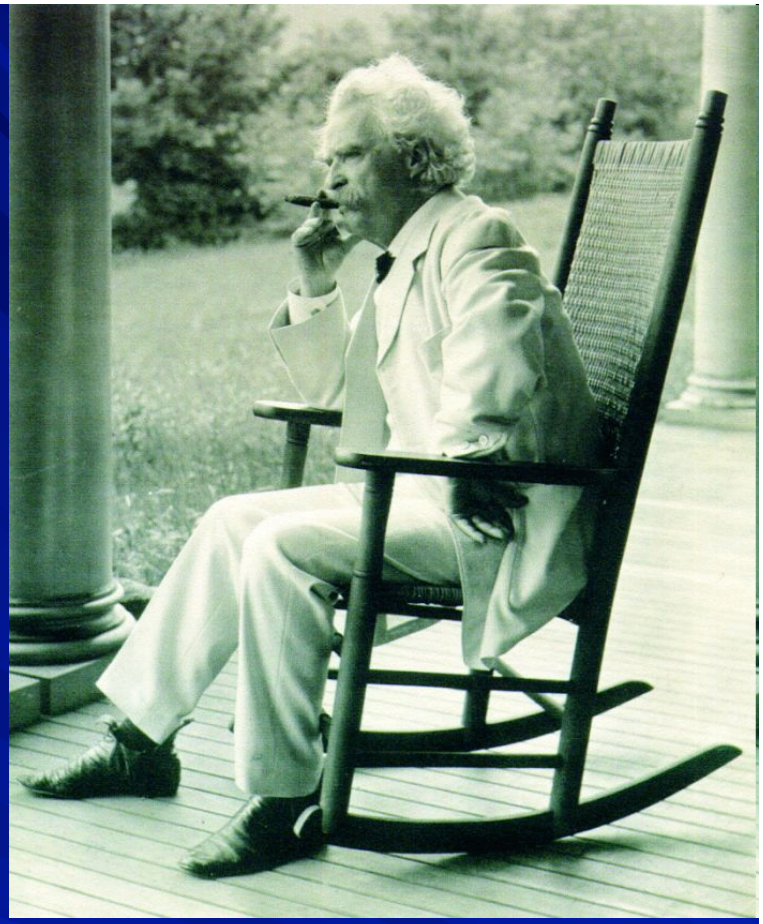
Binary Interactions & Ultra-Depleted Stars

- Persistent population of highly Li depleted halo stars (e.g. Thorburn 1994)
- Blue stragglers are highly depleted (Ryan et al. 2002)
- Fraction is consistent with predictions from blue straggler counts (Andronov et al. 2006)



Fraction of sub-turnoff merger products (Andronov, Pinsonneault & Terndrup 2006)

There is something fascinating about *science*. One gets *such wholesale returns* of conjecture out of *such* a trifling investment of fact



- Cluster vs. field: differences in disk lifetimes?
- Planet host vs. no planet host: planet formation impacts disk evolution?