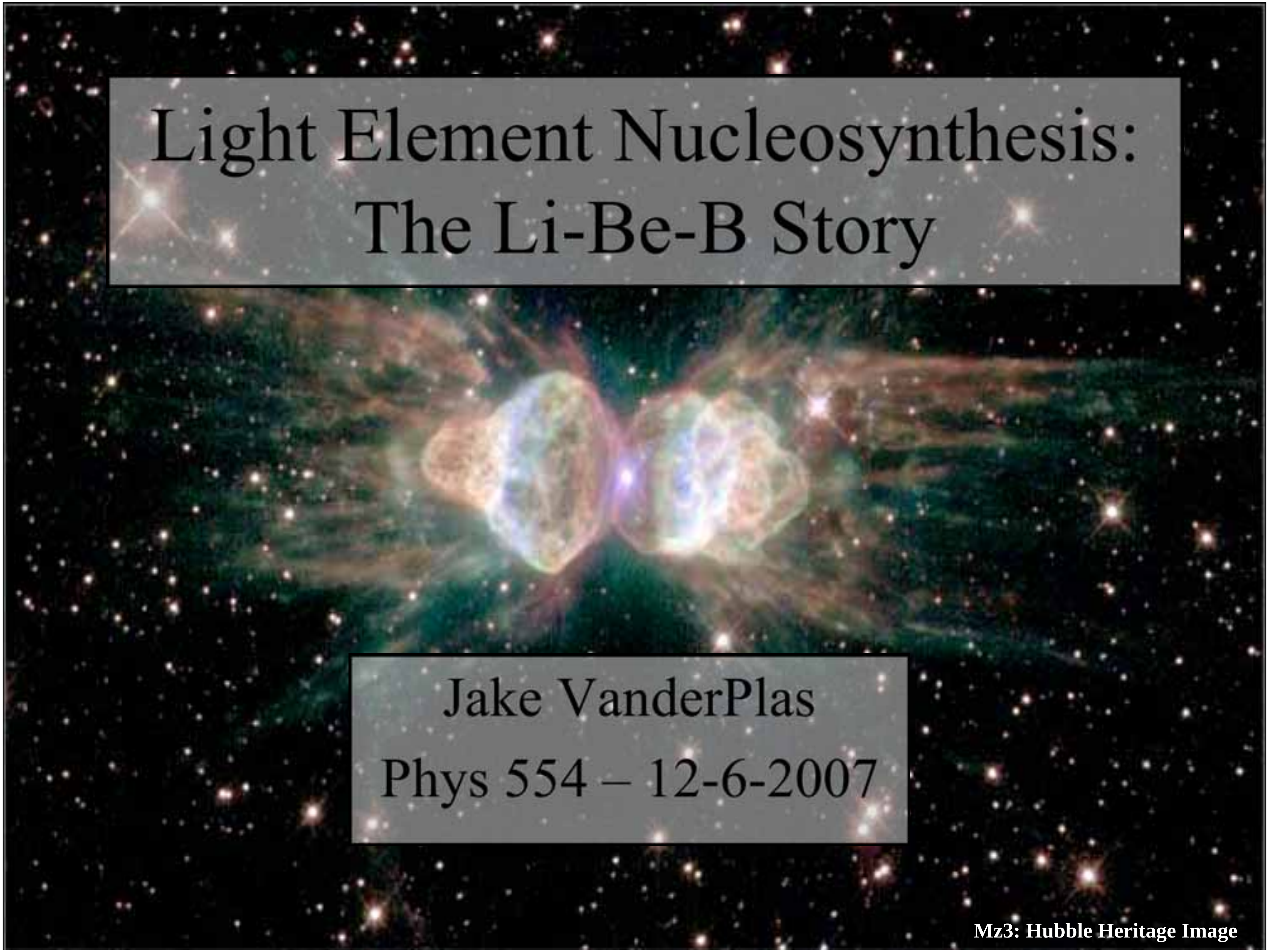
Light Element Nucleosynthesis: The Li-Be-B Story



Jake VanderPlas

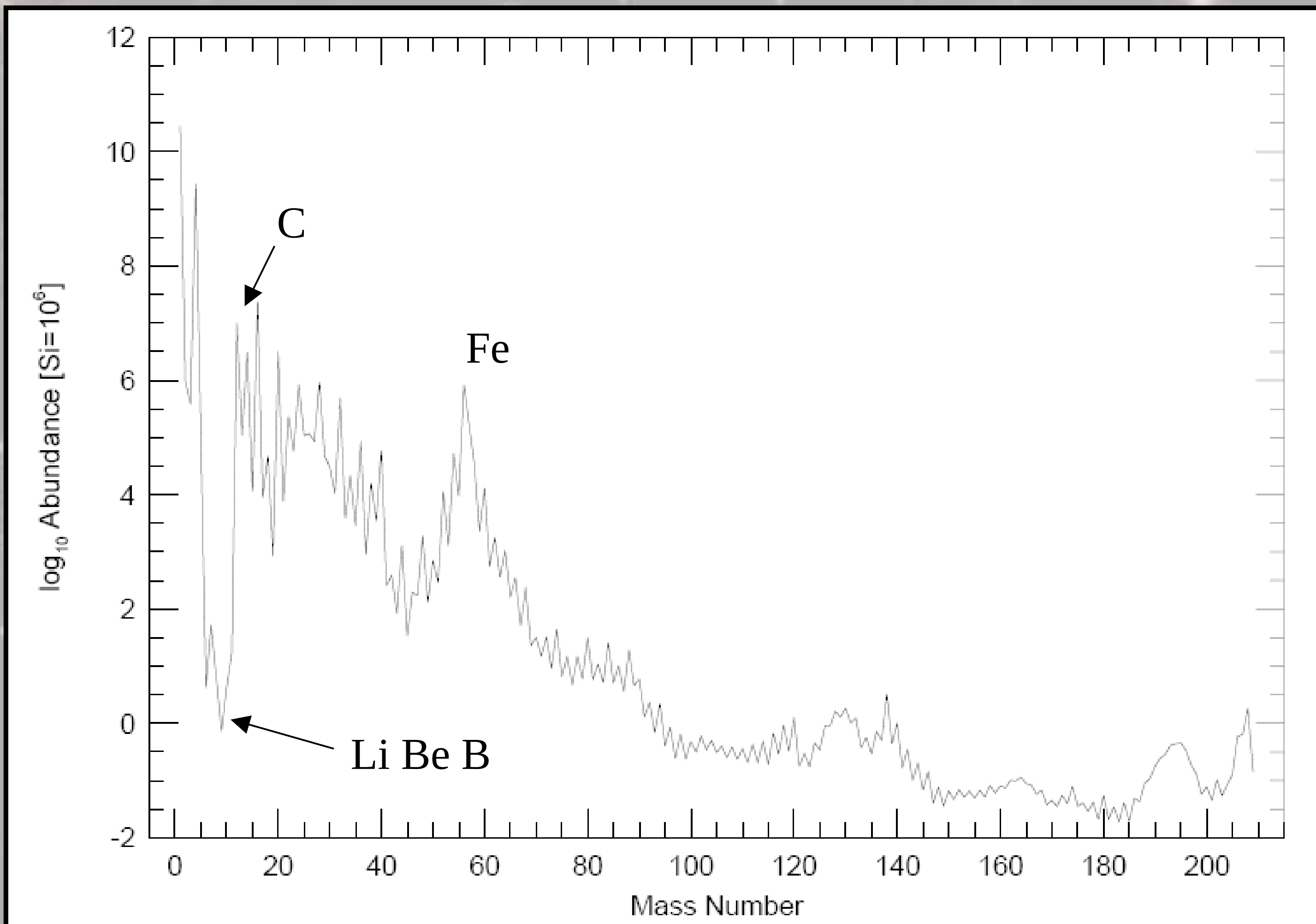
Phys 554 – 12-6-2007

Mz3: Hubble Heritage Image

Presentation Summary

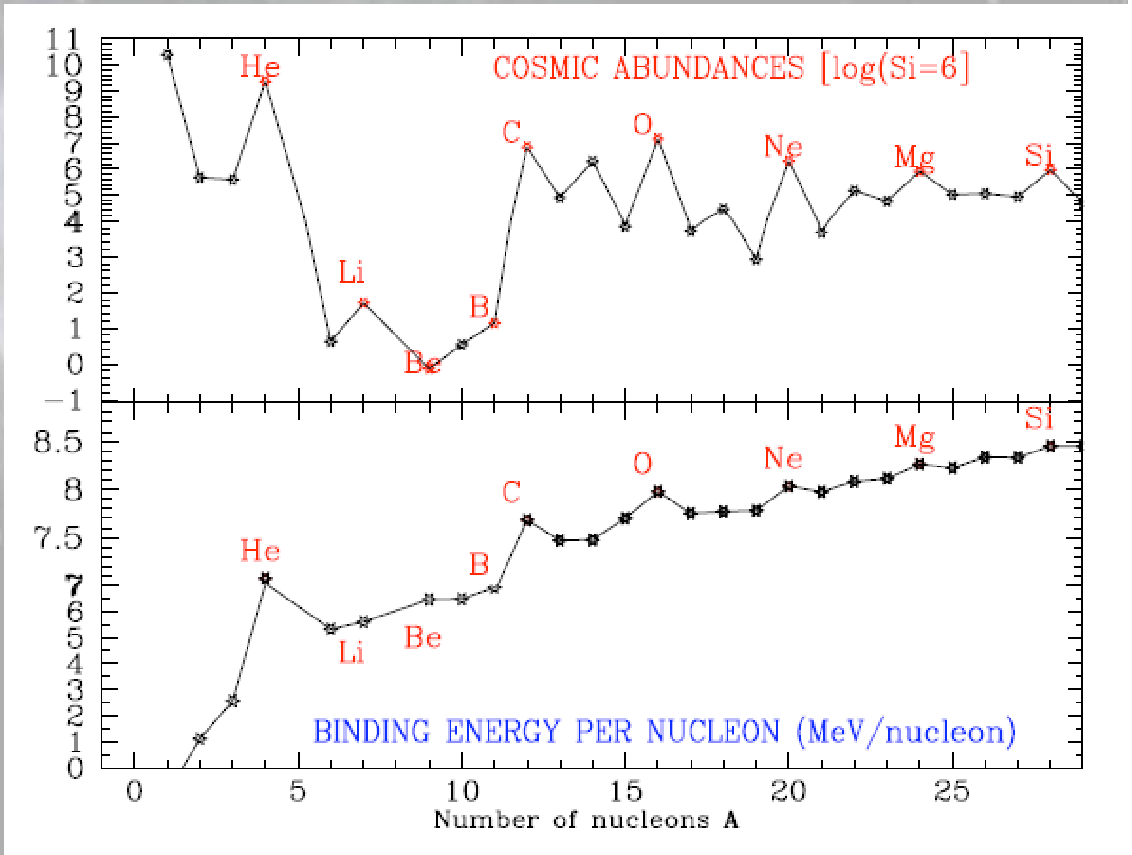
- The Problem of Light Elements
- Big Bang Nucleosynthesis
- Cosmic Ray Nucleosynthesis
- Supernova Nucleosynthesis
- The Field Now

Elemental Abundances



Where are the light elements?
(Burbidge et al 1957)

- Noted that D, ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B are fragile enough to be destroyed in stellar interiors
- Posited "x-process" – a low-density, low-temperature nucleosynthetic process



Prantzos 2007

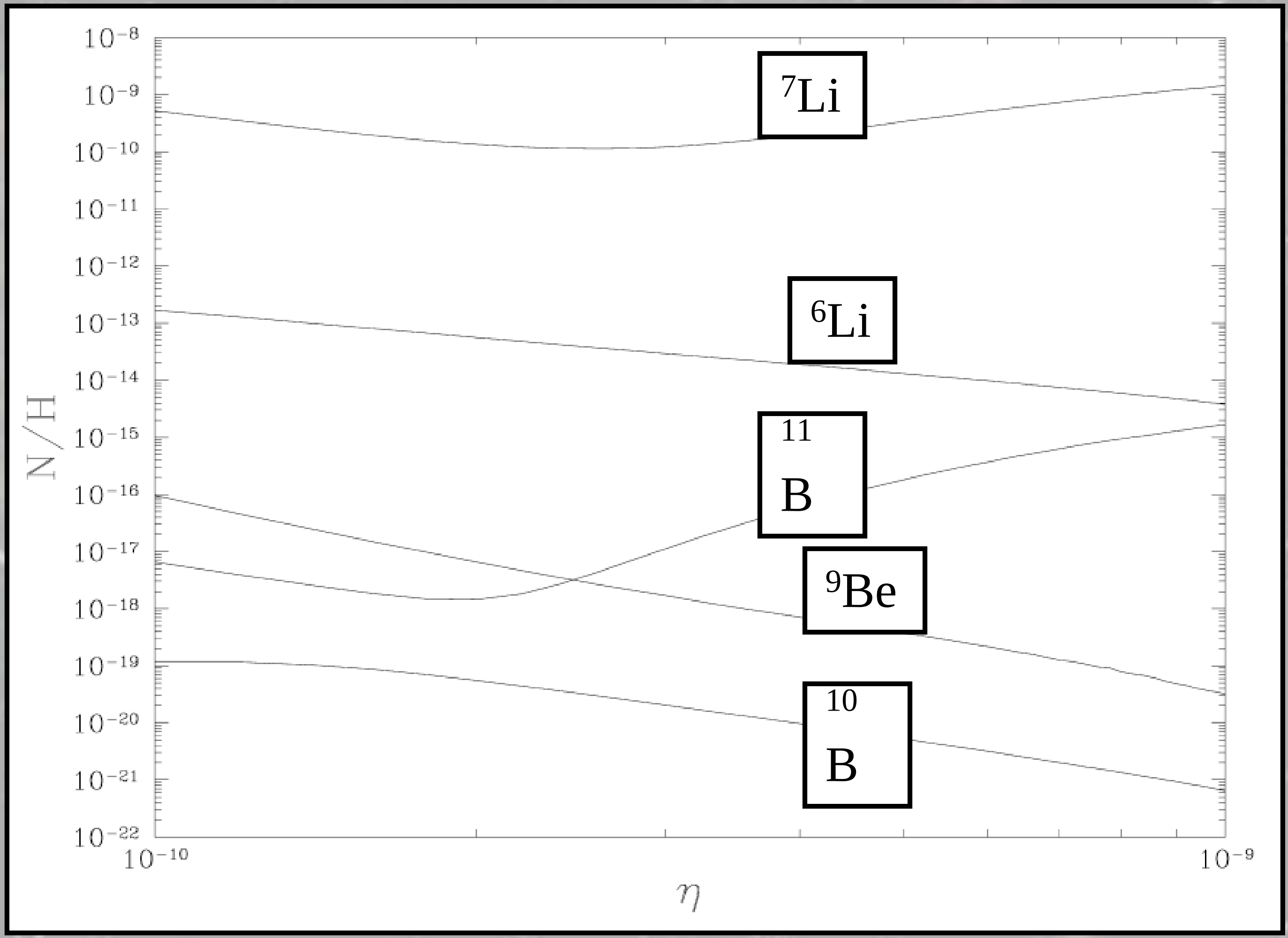
Stellar Processes?

- Stellar burning bypasses LiBeB with triple-α process
- Conditions in stellar interior favor *destruction* of LiBeB

Big Bang Nucleosynthesis

From standard BBN model…

10 orders of magnitude!

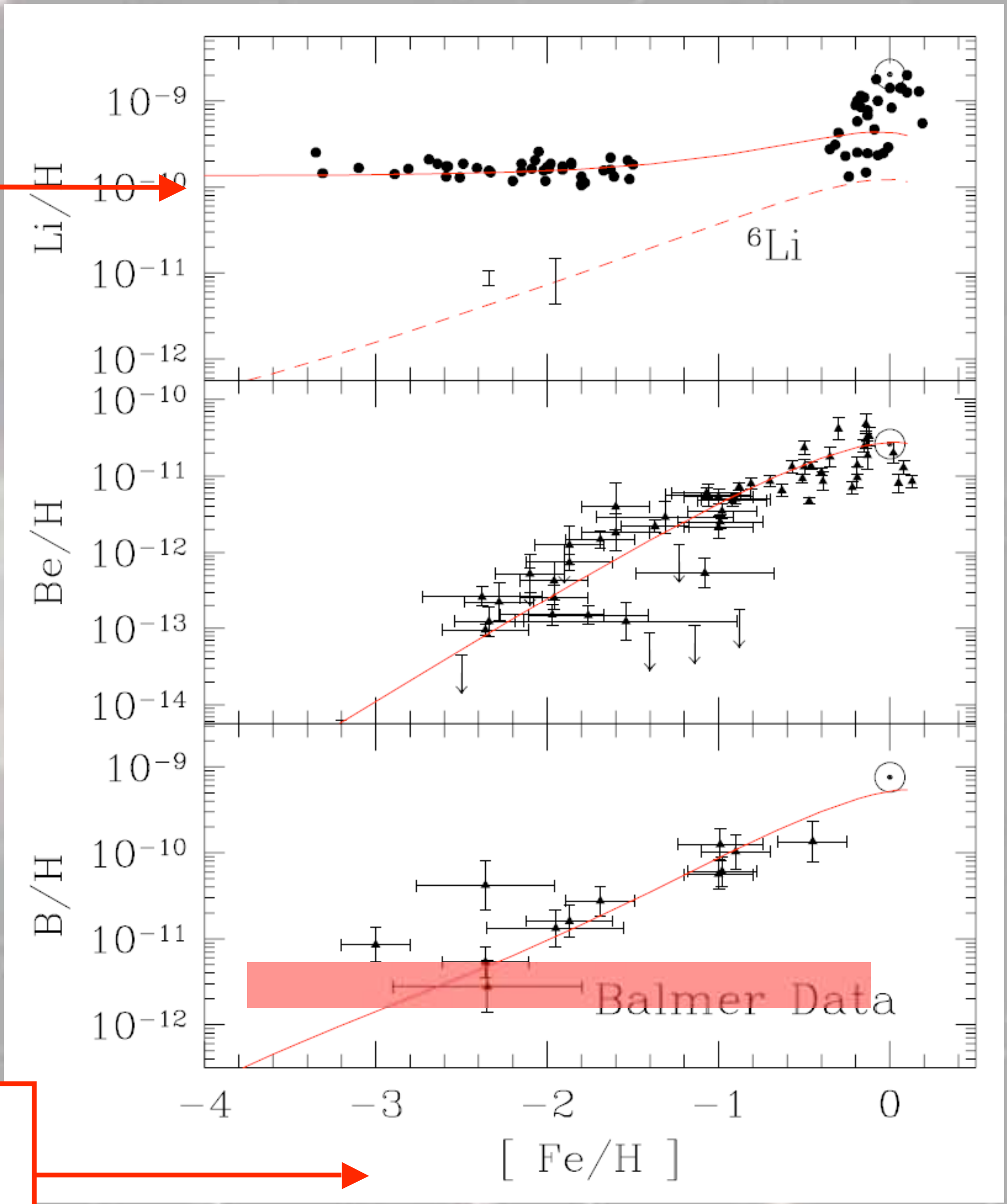


Vangioni-Flam 1999

Spite Plateau:

Evidence of primordial origins of ^{7}Li

No Primordial Abundance



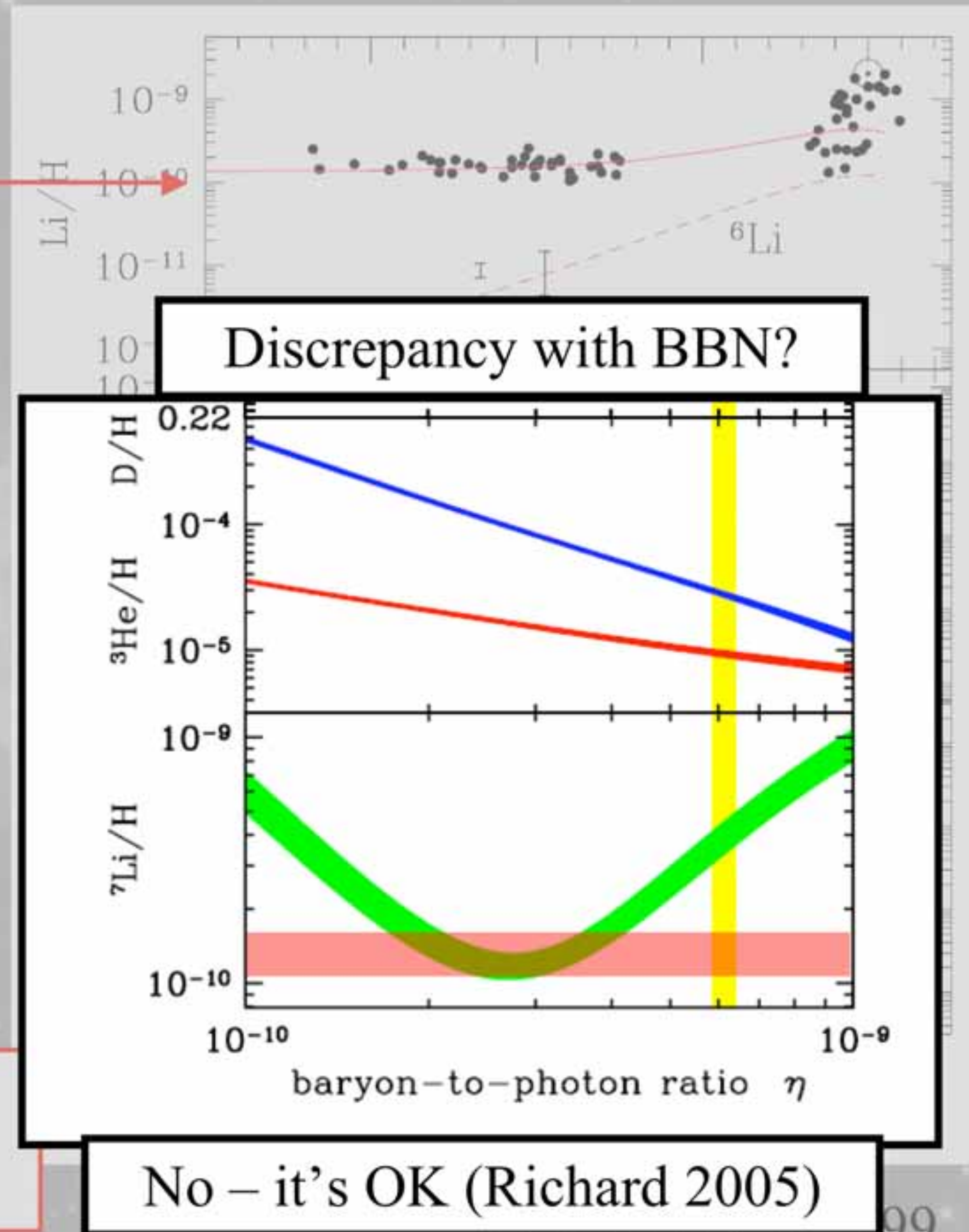
Metallicity is a tracer of age:

$$[Fe/H] = \log(Fe/H) - \log(Fe/H)_{solar}$$

Fields&Olive 1999

Spite Plateau:

Evidence of primordial origins of ^{7}Li



No Primordial Abundance

Metallicity is a tracer of age:

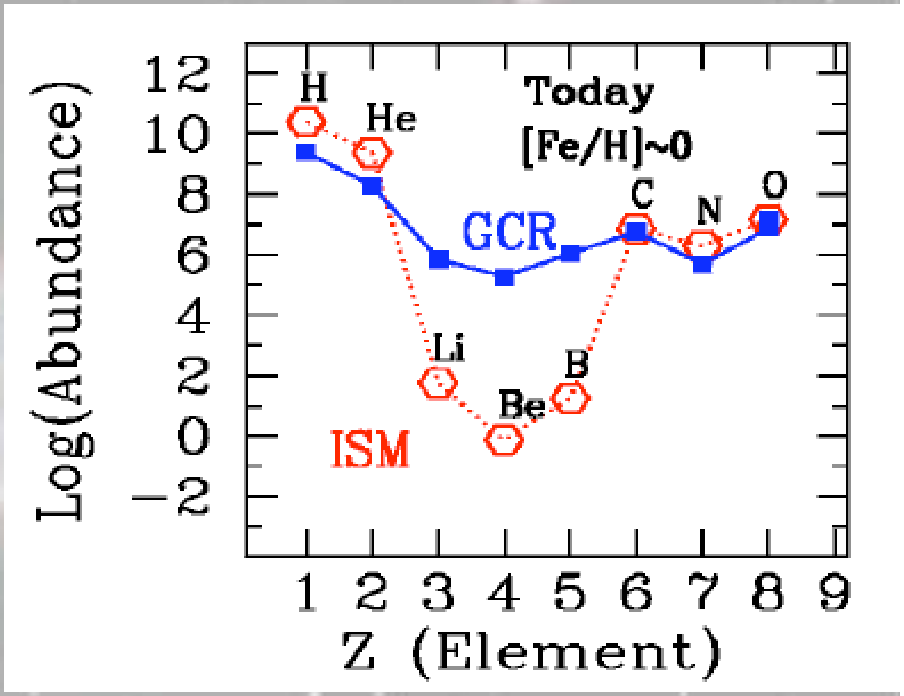
$[Fe/H] = \log(Fe/H) - \log(Fe/H)_{solar}$

What is the x-process?

- Light elements not from BBN (except ^{7}Li)
- Light elements not from stellar burning
- So they must come from galactic processes
  - Cosmic Rays
  - Supernovae
  - Neutrino processes

Cosmic Ray Nucleosynthesis

- Cosmic rays are enriched with Li-Be-B
- ~5 orders of magnitude more enriched than ISM

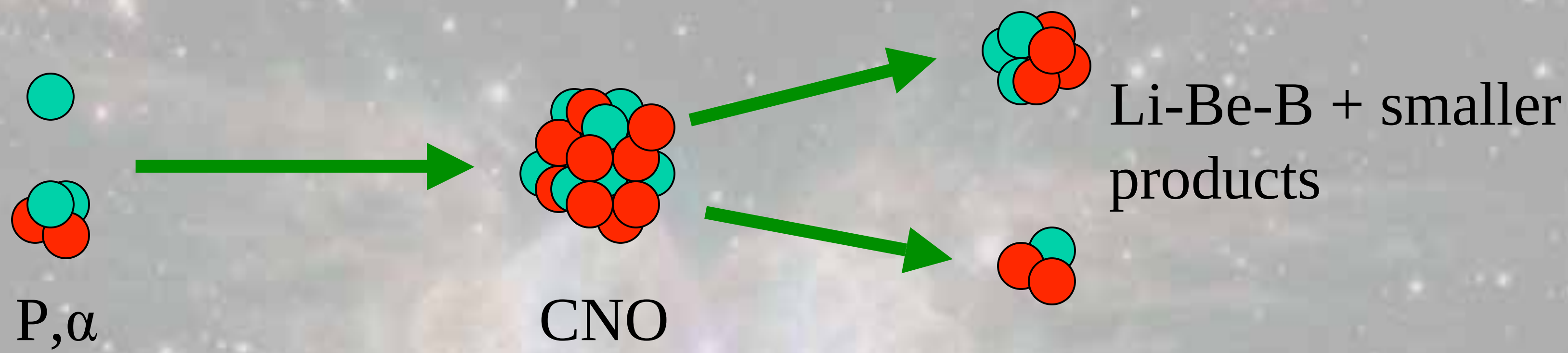


Prantzos 2007

Possible Sources of this Abundance

- Supernovae
  - more on this in a bit
- Cosmic ray interaction with ISM
  - Spallation
  - Inverse Spallation

Cosmic ray Spallation

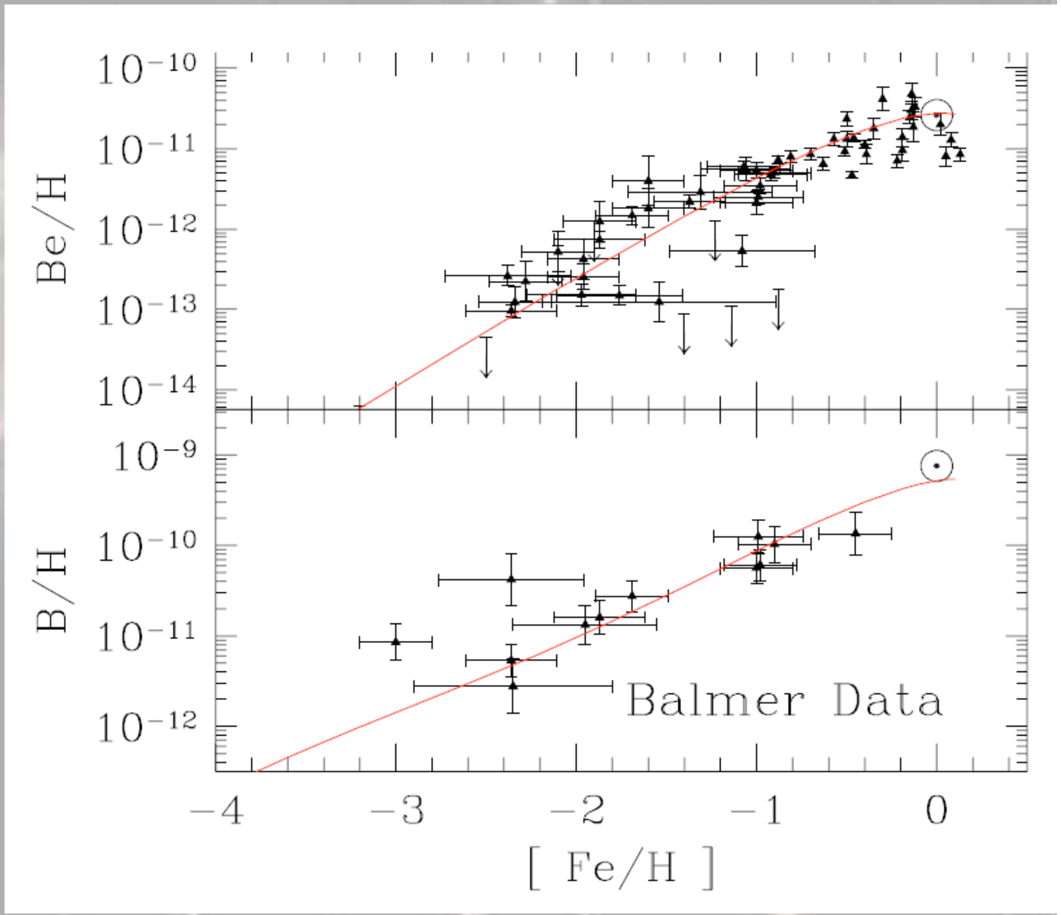


- Cosmic ray particles interact with CNO in ISM to produce light elements
- This is a *metallicity dependent* "secondary" process – it depends on the amount of CNO in the ISM

Secondary Process?

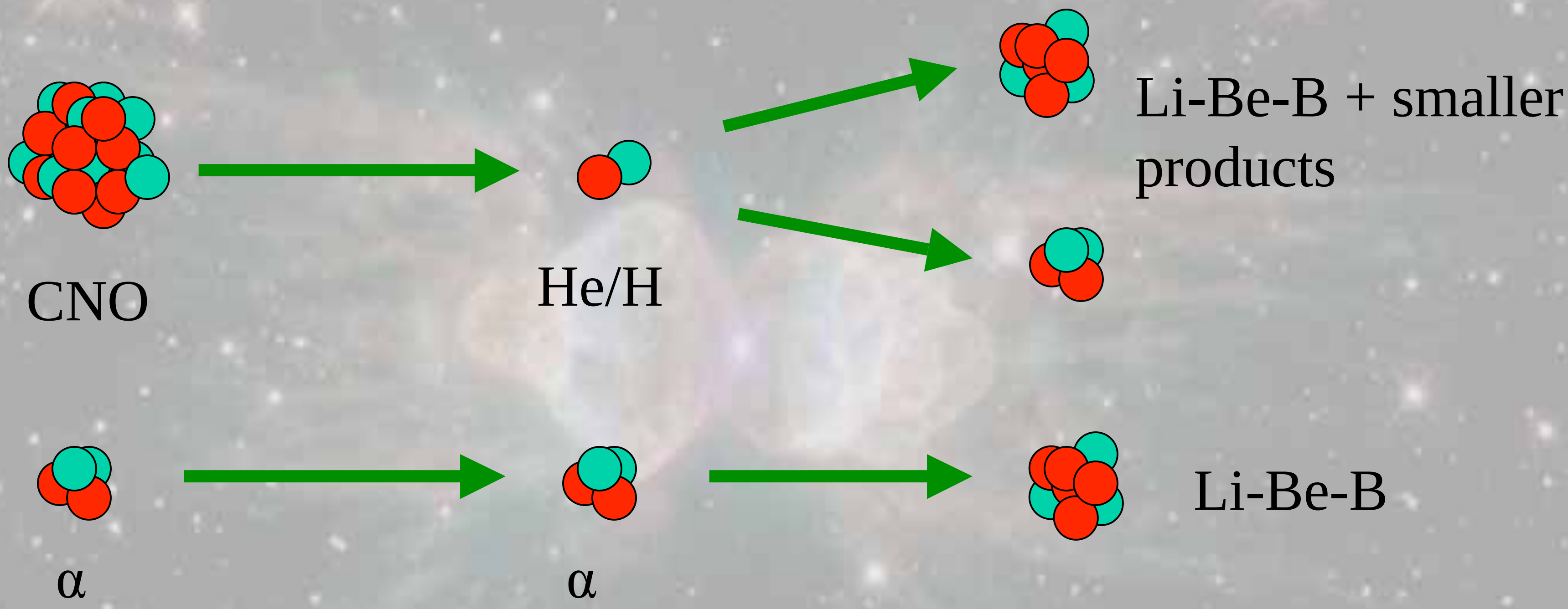
$$\frac{d(LiBeB)}{dt} \propto E_{GCR} \times N[C,N,O]$$

- Be/H and Be/H appear roughly linear with Fe/H, which doesn't match predictions
- GCR more energetic in past? Probably not (Ramaty et al 1997)
- Galaxy more "leaky" now than in the past? Probably not (Prantzos et al 1993)
- CNO/Fe higher in the past? Very Possible (Boesgaard et al 1999, Fields et al 1999)
- Stellar primary source? Possibly for B, not for Be (Woosley et al 1990)



Fields&Olive 1999

Inverse Spallation



- C,N,O,H accelerated by supernovae reacts with interstellar H & He, breaks apart

Inverse Spallation

- Primary source if CNO abundance in GCR is constant with time

Questions:

Is this a good assumption?

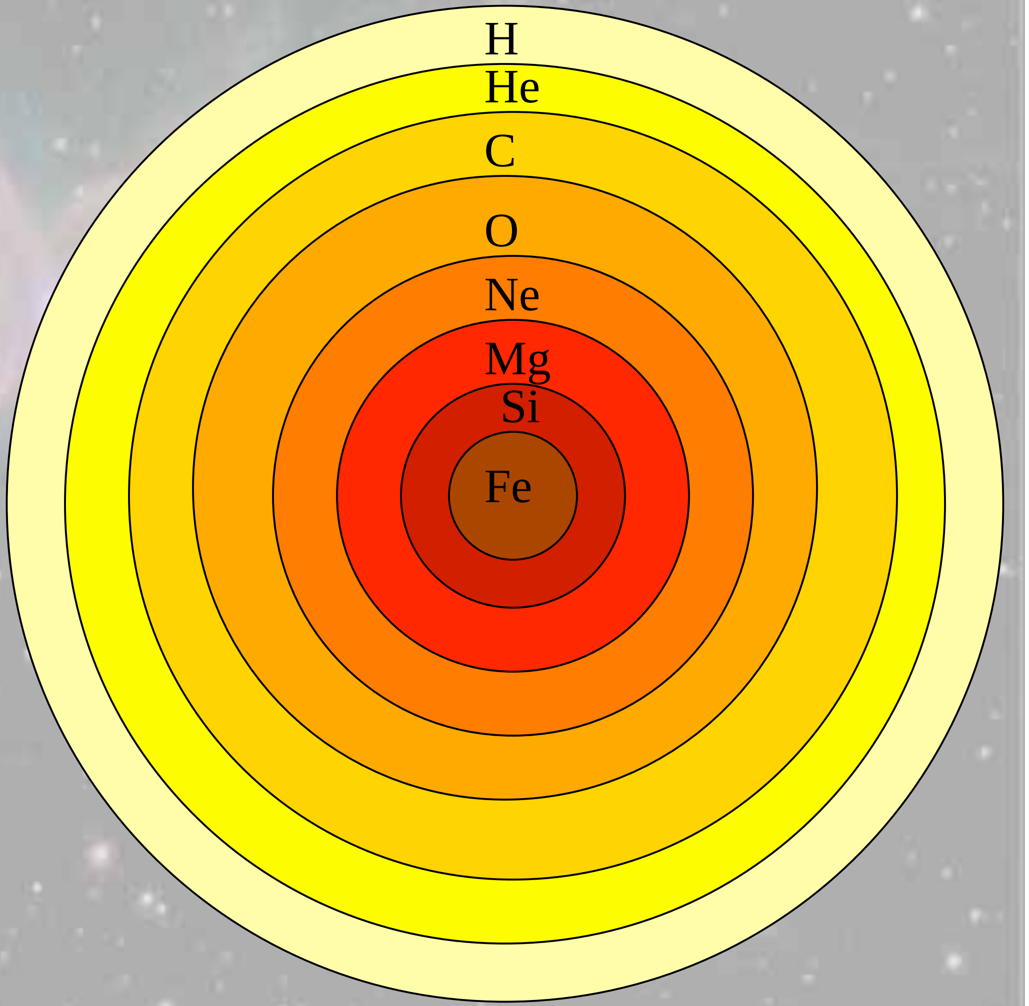
Where do these energetic CNO come from?

“Superbubbles”

- GCRs contain no ^{59}Ni (half life ~ 10^5 years)
  - Secondary acceleration? Timescale between supernovae is ~ 10^5 years (Prantzos 2007)
  - Supermassive stars? Quick evolution means less heavy elements end up in stellar winds

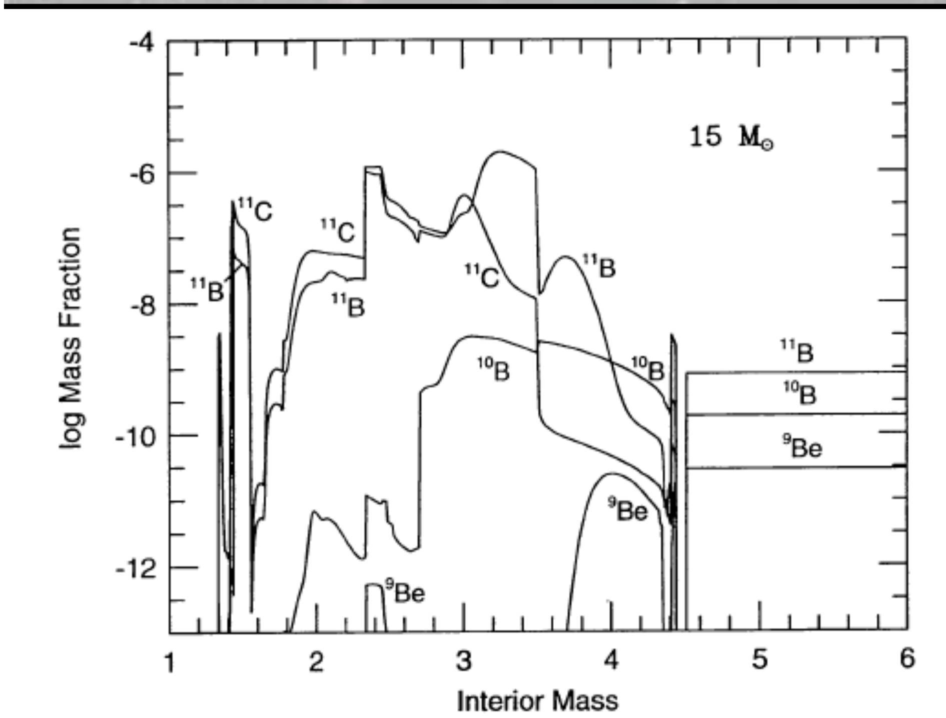
Supernova Nucleosynthesis

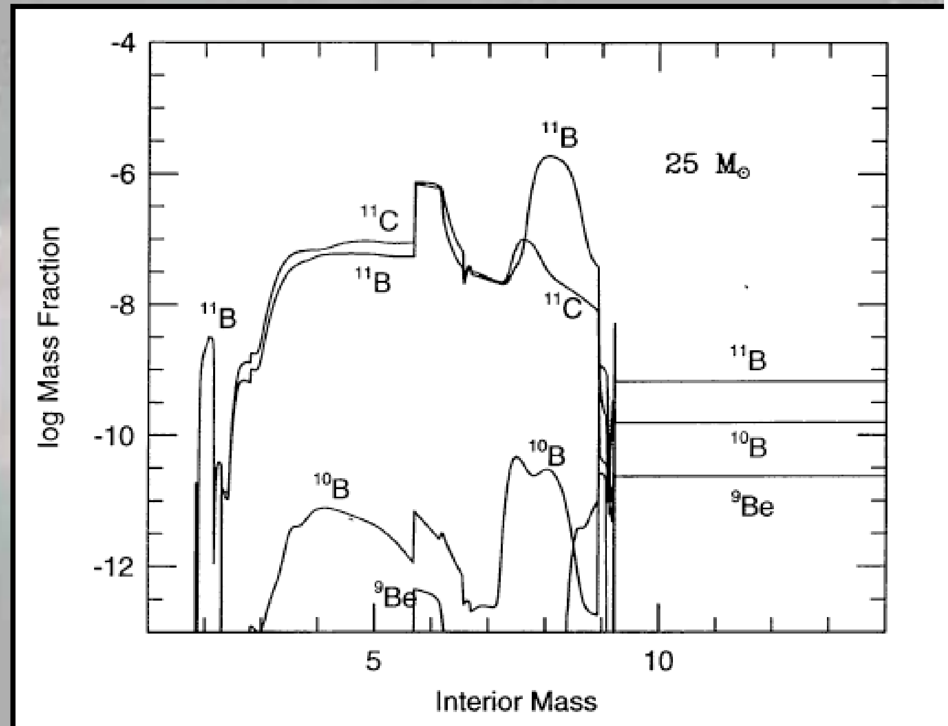
- ^{11}B had been thought to have been produced by $^{12}C(\alpha,\gamma)$ at supernova shock fronts (Dearborn 1989).
- Neutrinos produced in core-collapse supernovae could be sufficient to break apart nuclei in the Carbon shell (Woosley et al 1990)
- Process described in detail in class notes – I won’t elaborate here



Explosion Models

^{11}B/Be ~ 4 for ISM (Olive et al 1994)



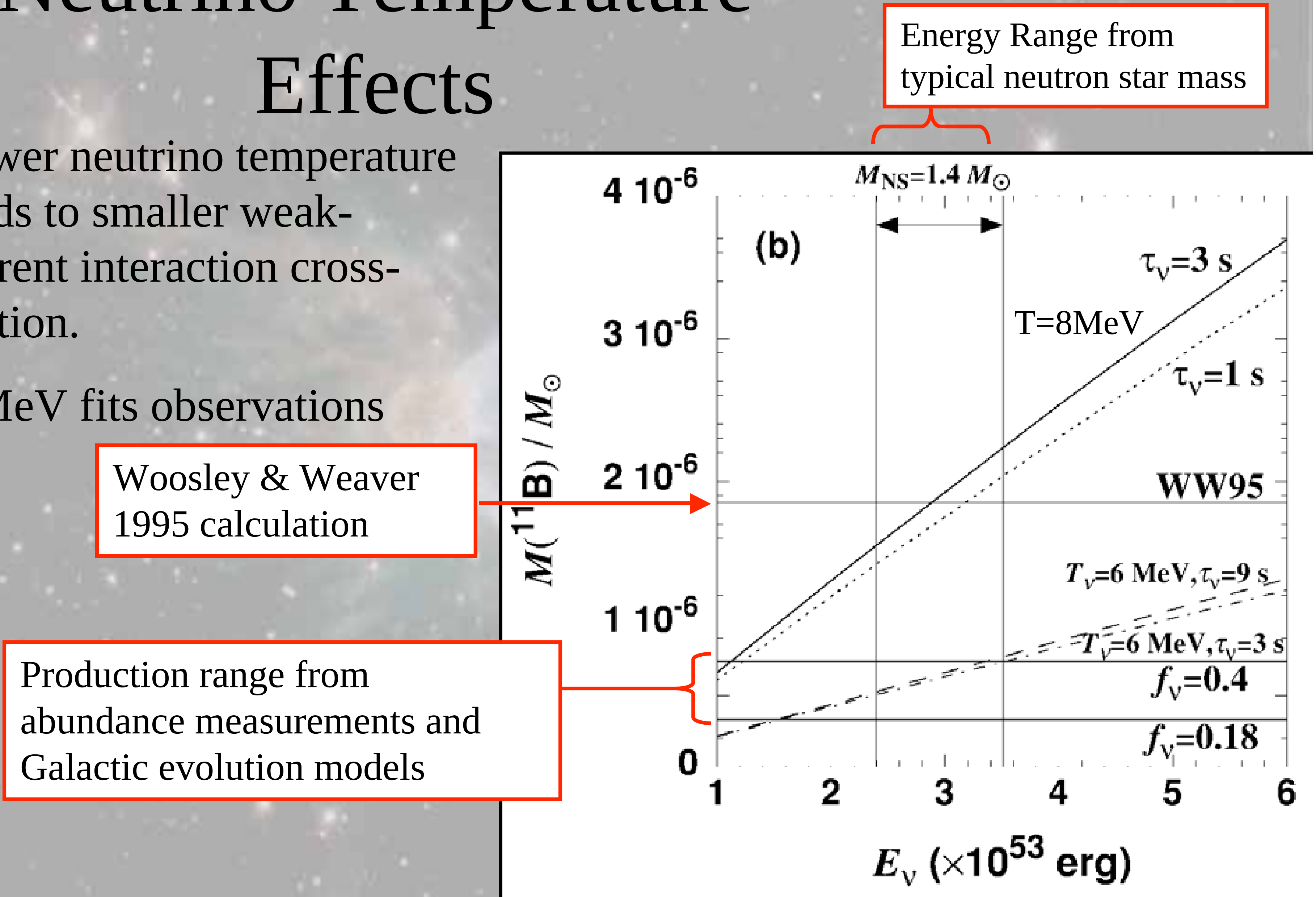


Woosley & Weaver 1995 – incorporated neutrino processes in detailed explosion models – found Be overproduced by a factor of 2. Other models predict as much as a factor of 5.

Neutrino Temperature Effects

Lower neutrino temperature leads to smaller weak-current interaction cross-section.

6 MeV fits observations



Yoshida et al 2004

Sources of Li-Be-B

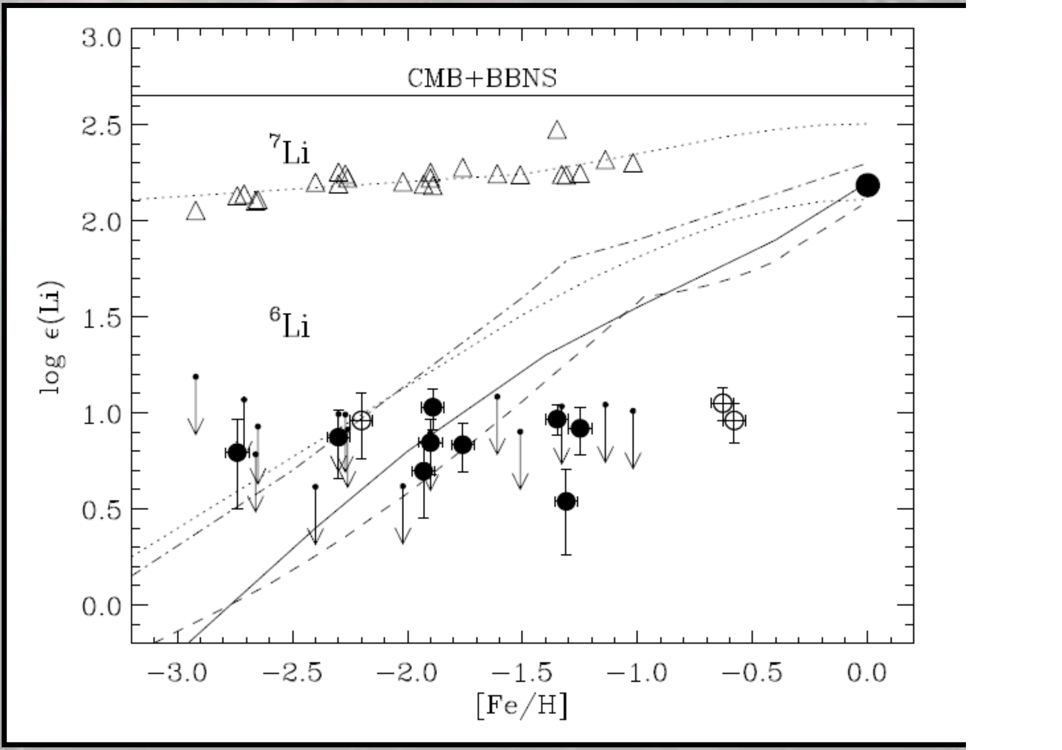
- Big Bang Nucleosynthesis — ^{7}Li (trace of others)
- Stellar Nucleosynthesis — ^{7}Li?
- Supernova Nucleosynthesis — ^{11}B ^{7}Li
  - "Normal" processes: ✓ (^{11}B)
  - Neutrino effects: ✓ (^{11}B) ✓ (^{7}Li)
- Cosmic ray Nucleosynthesis — $^{6,7}Li$ $^{10,11}B$ ^{9}Be
  - Spallation
  - Inverse Spallation

What we can learn from Li-Be-B Abundances

- Ω_B from measurements of ^{7}Li in low-metallicity halo stars (Fields et al 2005)
- Spite plateau + BBN models are evidence for of Big Bang (Spite & Spite 1982)
- Mixing lengths in stellar atmospheres (^{7}Li discrepancies)
- Asplund plateau – ^{6}Li from exotic heavy particle decay? (Jedamzik 2004) Pop III star ages? (Prantzos 2007)
- Neutrino spectrum in core-collapse supernovae (Yoshida et al 2004)
- Constraints on neutrino oscillations (Yoshida et al 2006)

Remaining Mysteries/Disagreements

- "Asplund plateau" of ^{6}Li in metal-poor stars challenges standard BBN
- O/Fe~1?: Primary vs. secondary slope
- Source of heavy GCRs
- Correct mixture of processes?



Asplund et al 2006

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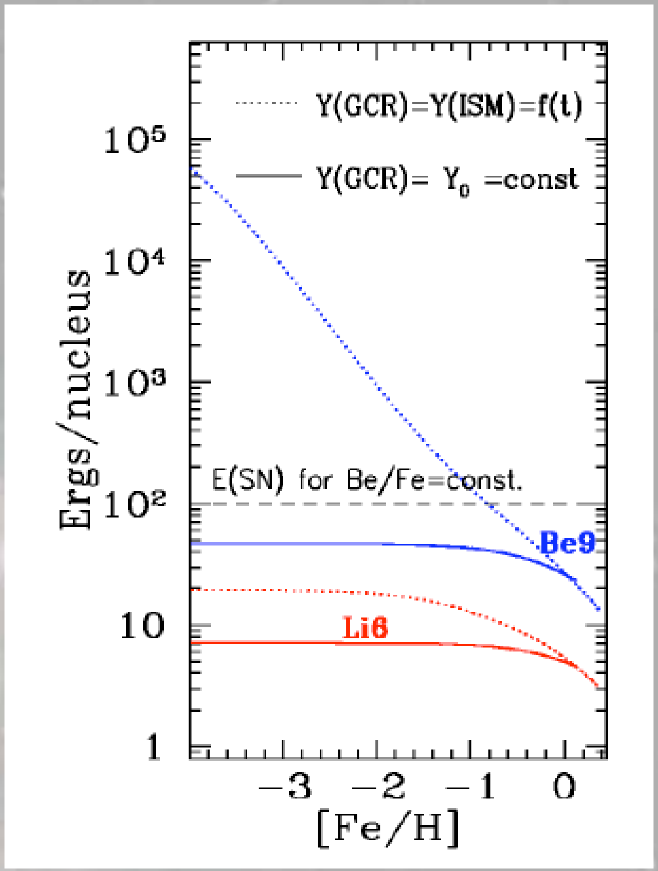

Prantzos 2007 (based on Ramaty 1997) – necessary GCR energy increase to change Be/Fe and Li/Fe slopes