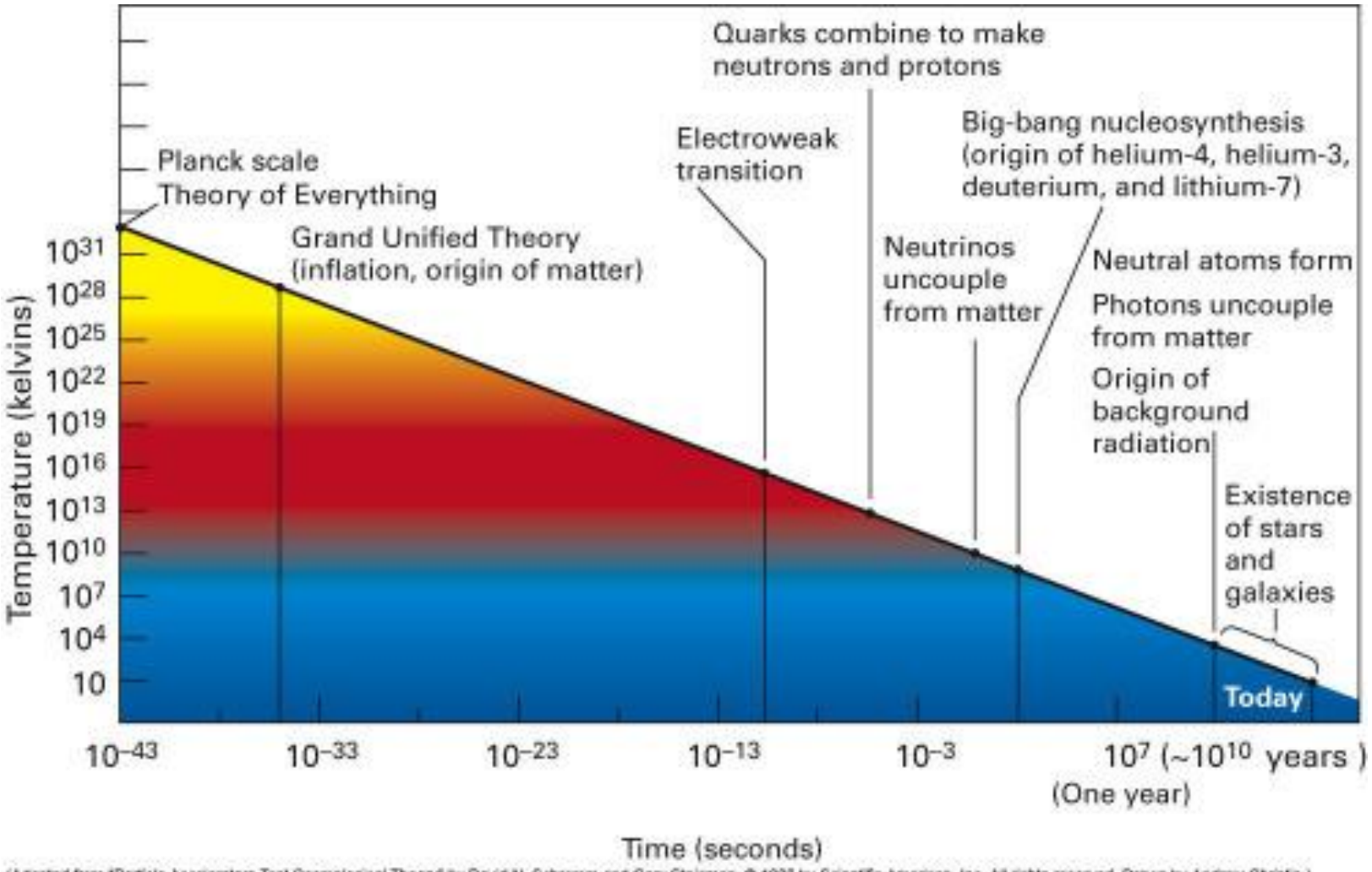
Evolution of the Elements
(Primordial and Stellar Nucleosynthesis)
Dana S. Balser

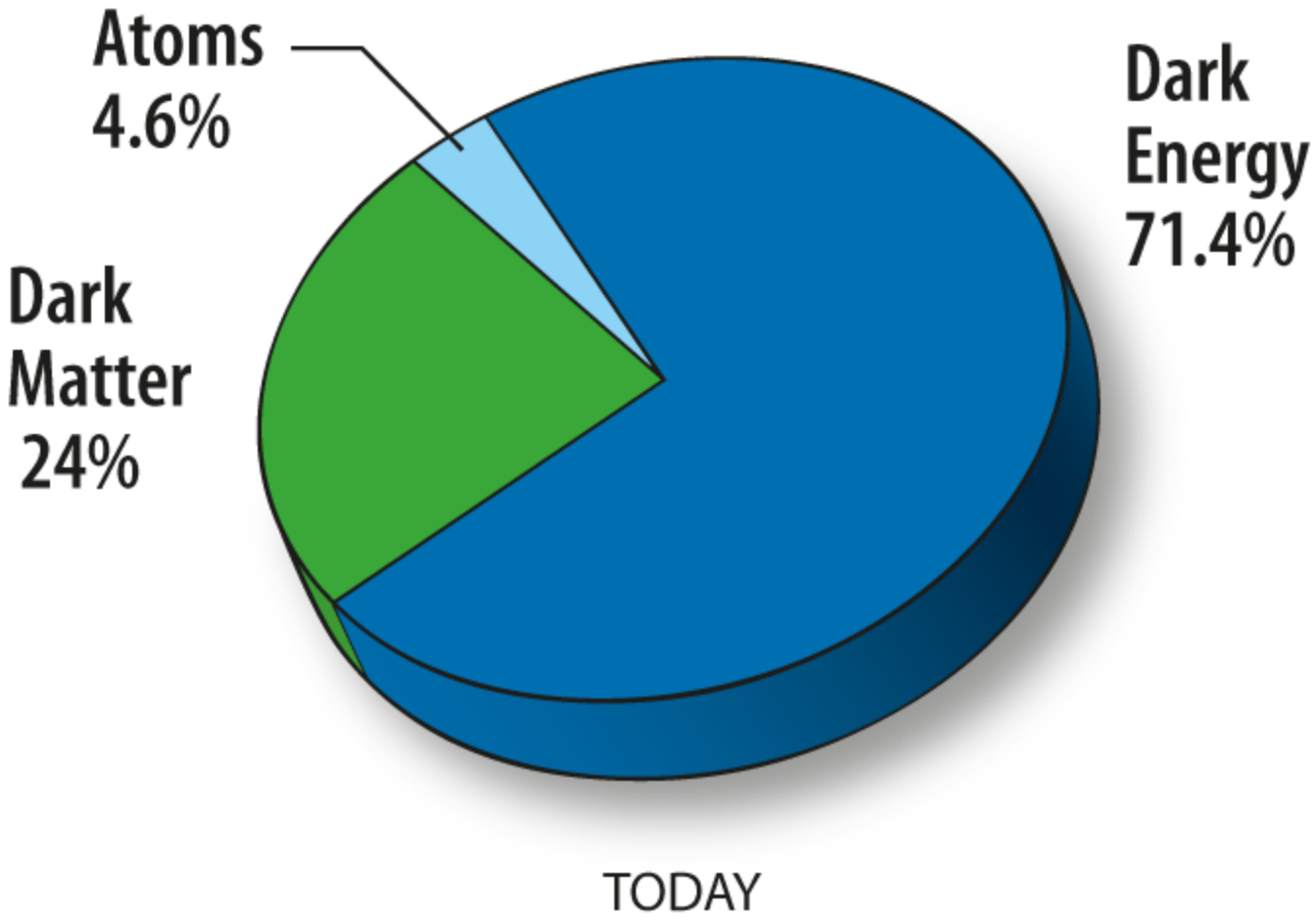
Corradi &
Tsvetanov

Cosmic Evolution

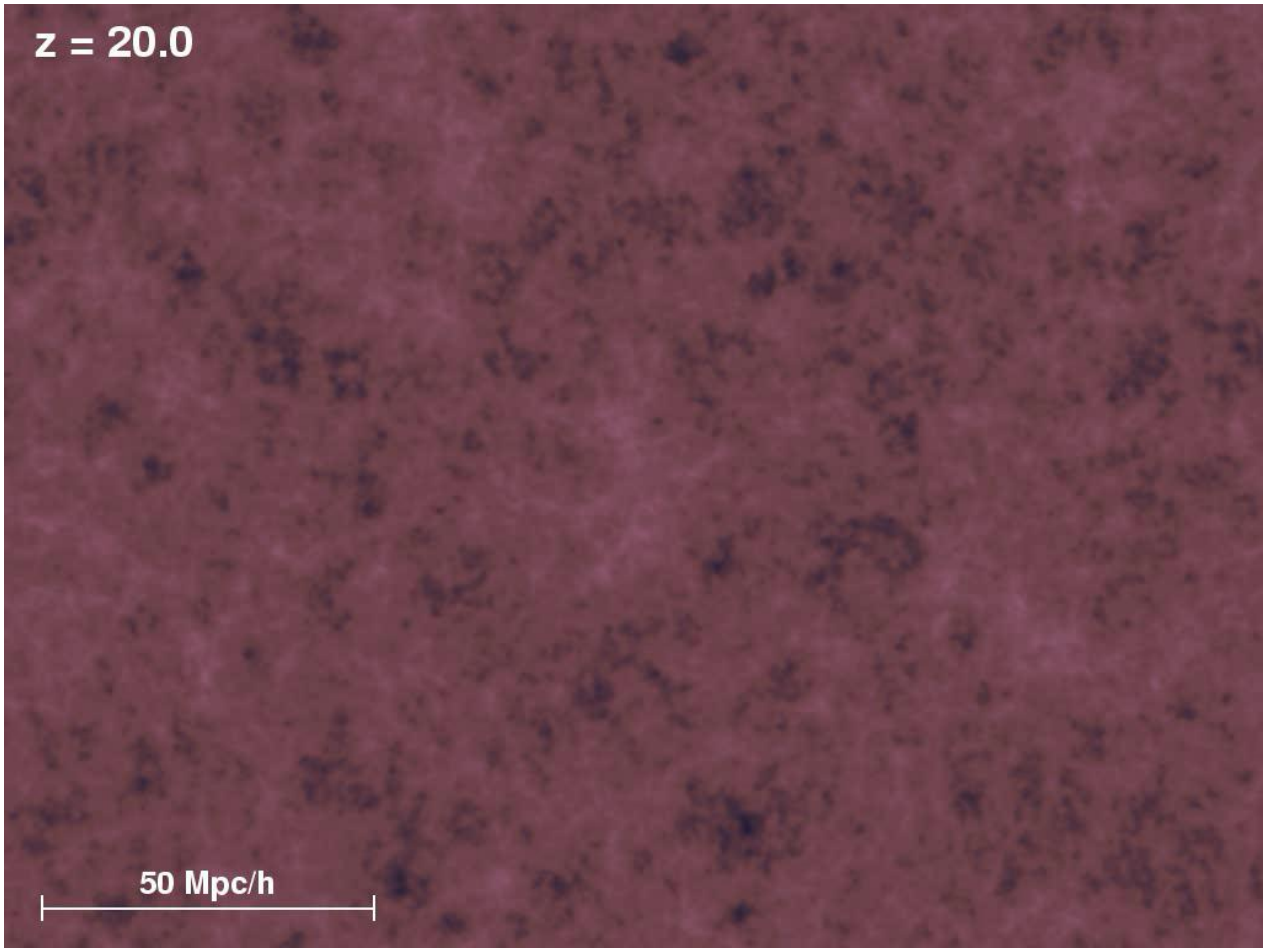


(Adapted from "Particle Accelerators Test Cosmological Theory" by David N. Schramm and Gary Steigman. © 1988 by Scientific American, Inc. All rights reserved. Drawn by Andrew Christie.)

Contents of the Universe

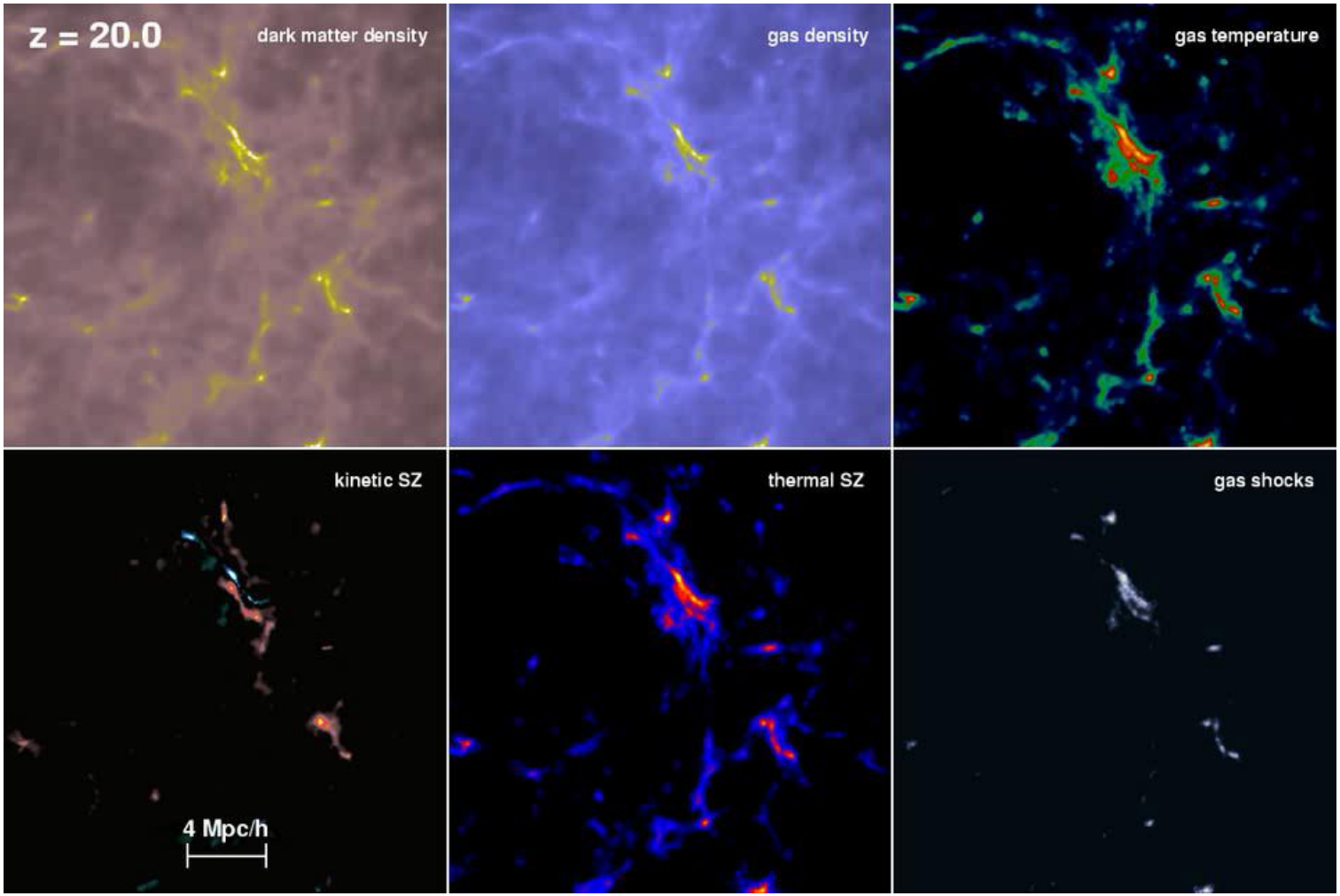


Simulation: Large Scale Structure



Volker Springel

Simulation: Galaxy Cluster



Volker Springel

Primordial Nucleosynthesis

Deuterium bottleneck

$$n + p \leftrightarrow {}^{2}H + \gamma$$

Tritium production

$${}^{2}H + n \rightarrow {}^{3}H + \gamma$$

$${}^{2}H + {}^{2}H \rightarrow {}^{3}H + p$$

$${}^{3}He$$ production

$${}^{2}H + p \rightarrow {}^{3}He + \gamma$$

$${}^{2}H + {}^{2}H + {}^{3}He + n$$

$${}^{4}He$$ production

$${}^{3}H + p \rightarrow {}^{4}He + \gamma$$

$${}^{3}H + {}^{2}H \rightarrow {}^{4}He + n$$

$${}^{3}He + n \rightarrow {}^{4}He + \gamma$$

$${}^{3}He + {}^{2}H \rightarrow {}^{4}He + p$$

$${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$$

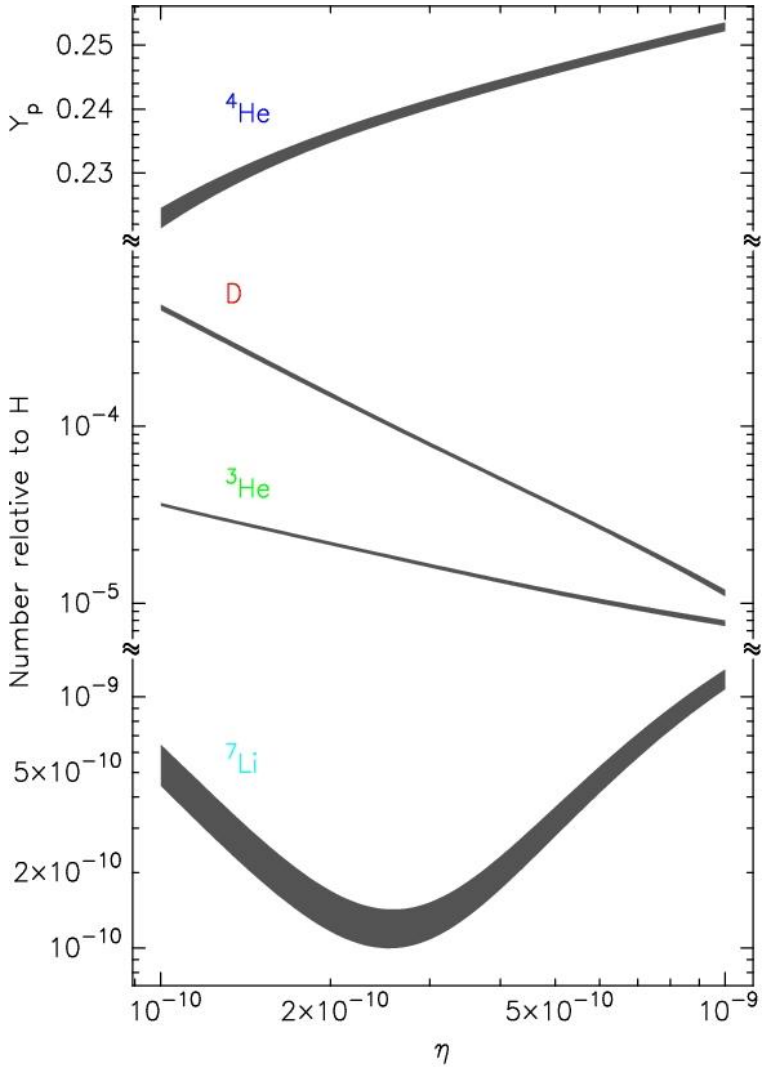
$${}^{7}Li$$ production

$${}^{4}He + {}^{3}H \rightarrow {}^{7}Li + \gamma$$

$${}^{7}Be$$ production

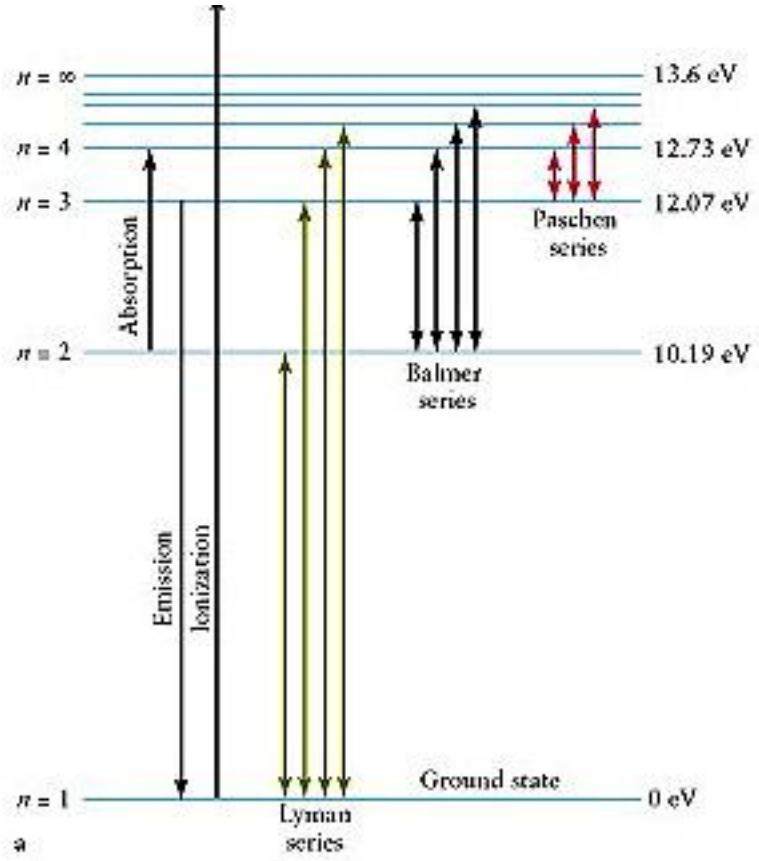
$${}^{4}He + {}^{3}He \rightarrow {}^{7}Be + \gamma$$

Primordial Nucleosynthesis



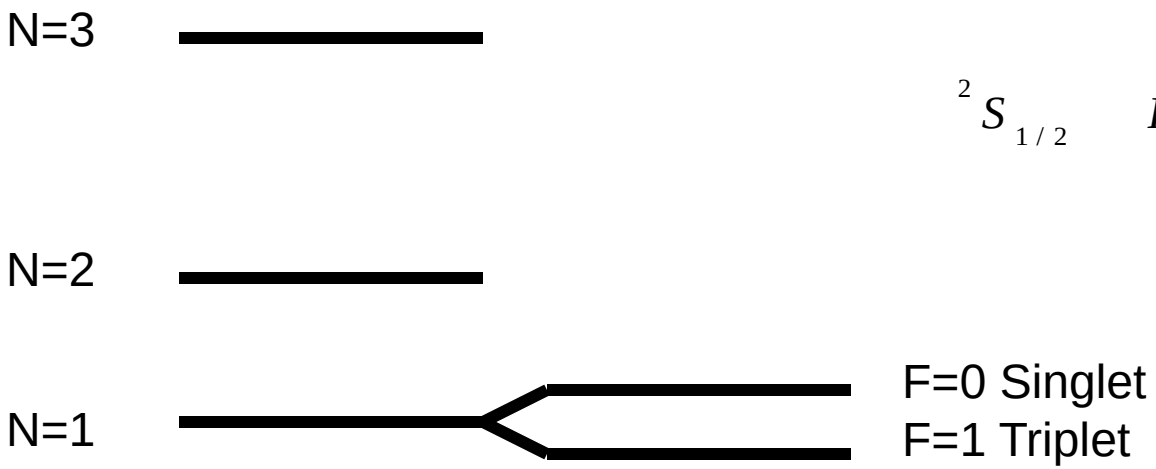
Burles et al. (2001)

Lyman, Balmer, … Series



Hydrogen

3He+ Hyperfine Transition

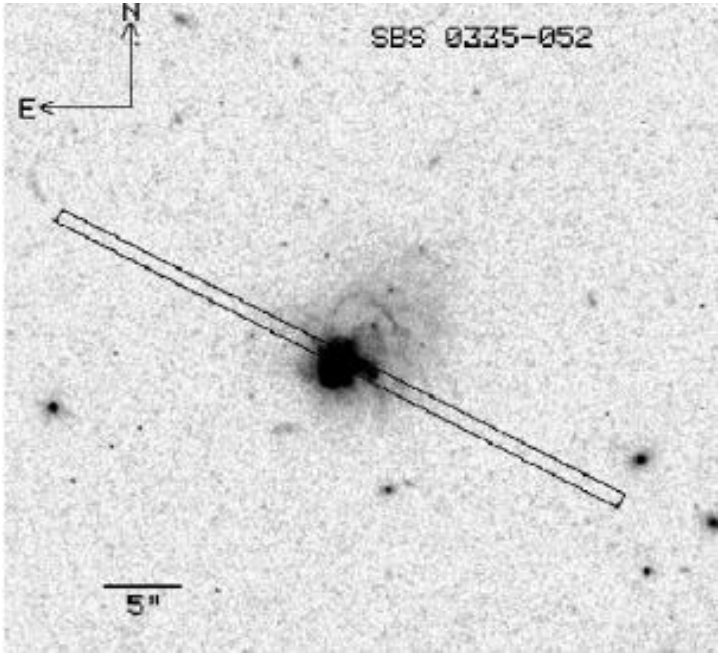


$$^{2}S_{1/2} \qquad F = 0 \rightarrow 1$$

$$\nu_{01} = 8665.65 \text{ MHz} \quad (3.46 \text{ cm})$$

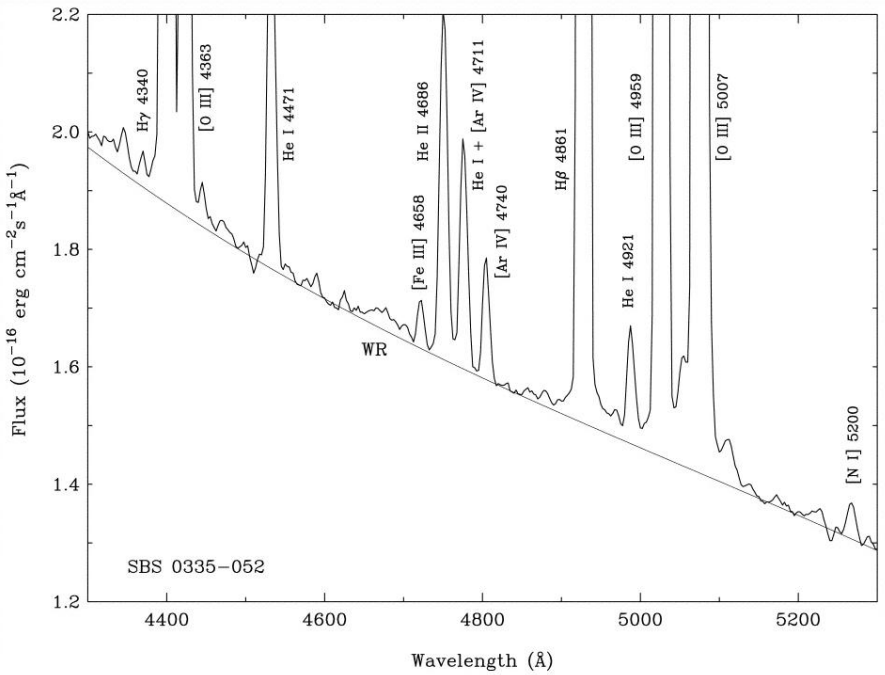
$$A_{01} = 1.950 \times 10^{-12} \text{ s}^{-1} \quad (16{,}300 \text{ years})$$

4He Observations: Optical Recombination Lines

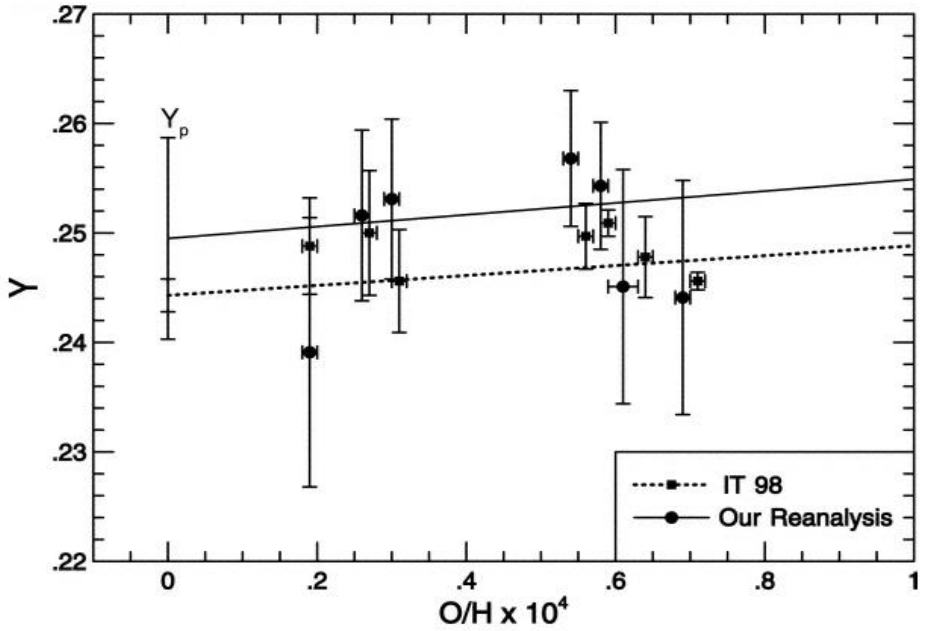


Izotov et al. (1999)

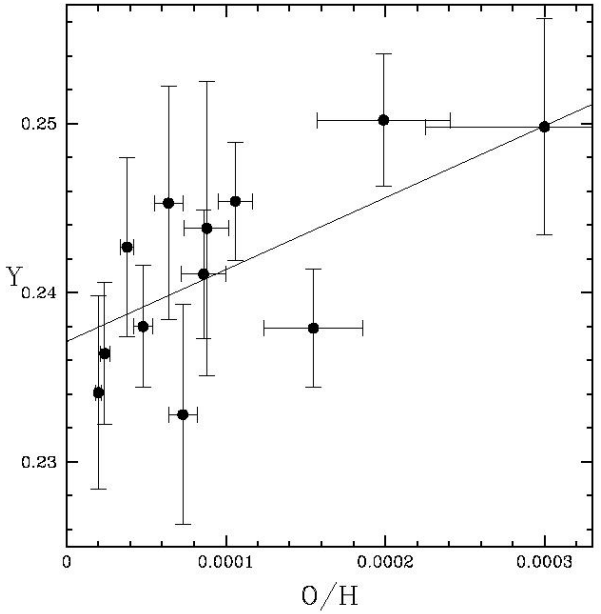
HII regions in metal poor blue compact galaxies



4He Results



Olive & Skillman (2004)

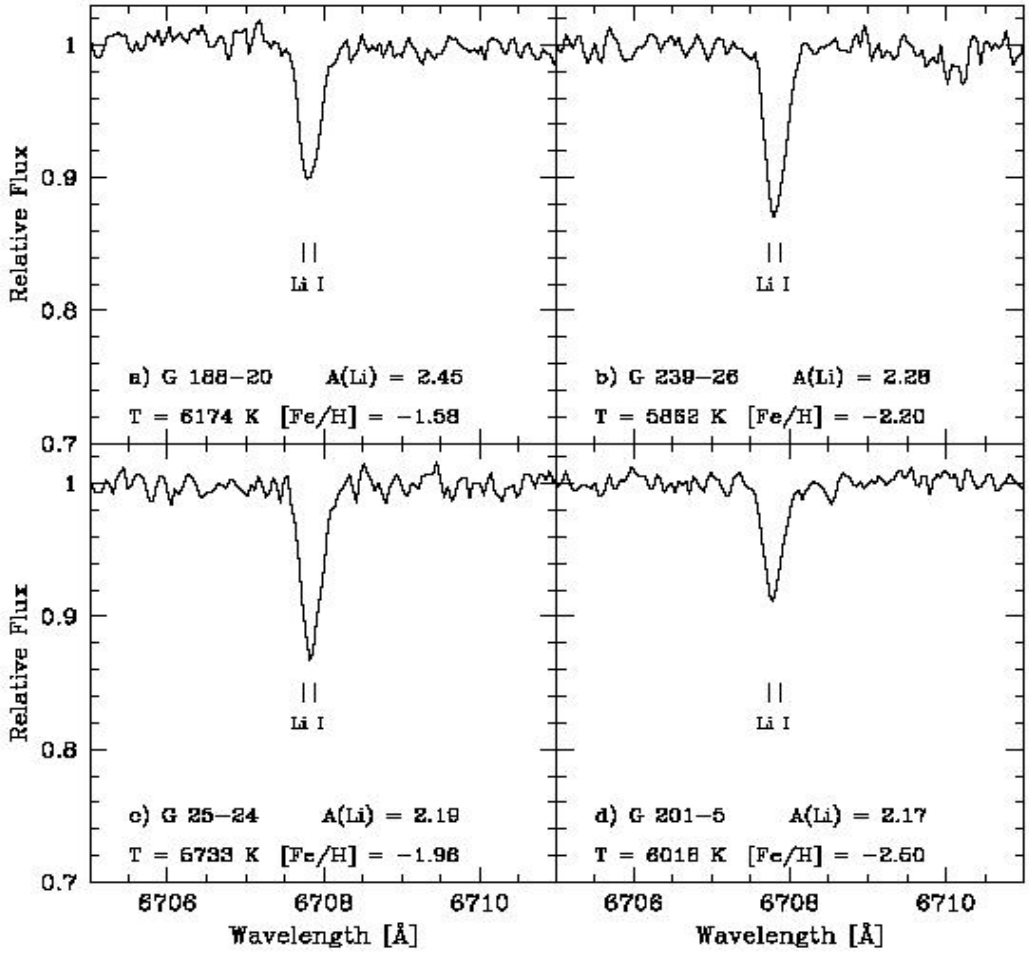


Peimbert & Peimbert (2002)

Yp [mass]	Reference
0.2472 (0.0012)	Izotov et al. (2007)
0.2474 (0.0028)	Peimbert et al. (2007)
0.249 (0.009)	Olive & Skillman (2004)

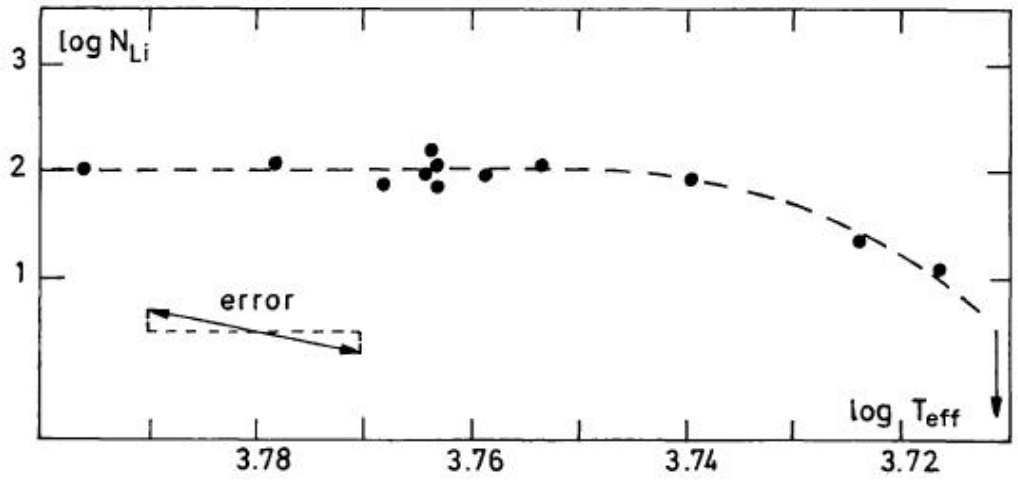
7Li Observations: Resonance Line

Metal poor
Halo stars



Boesgaard et al. (2005)

7Li Results: The Spite Plateau

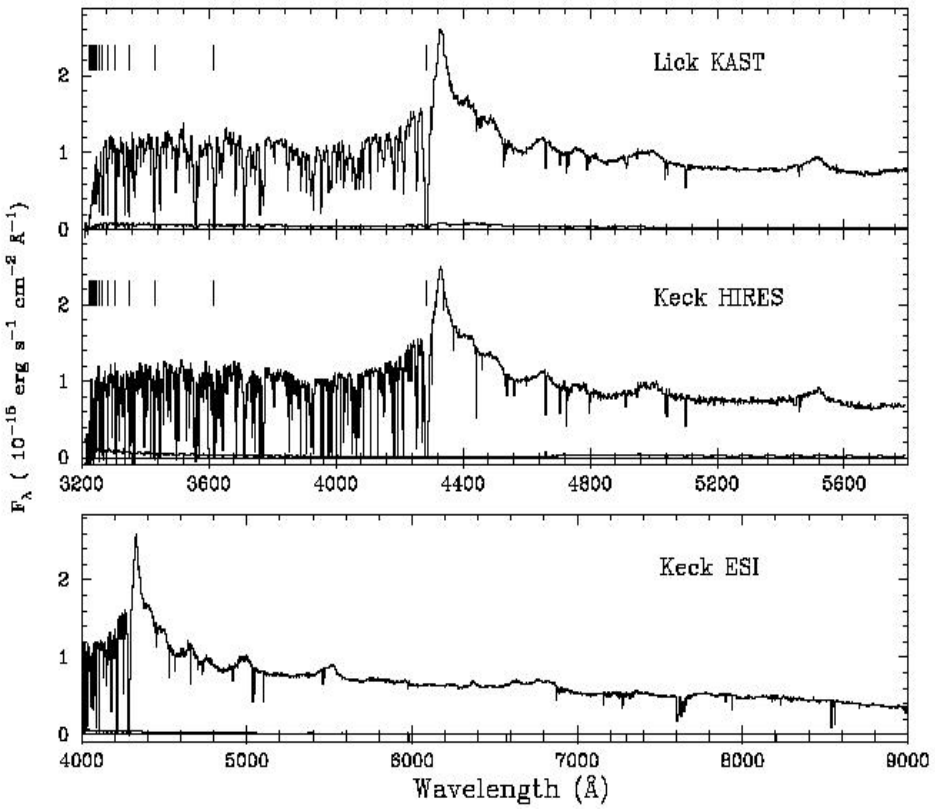


Spite & Spite (1982)

Log(7Li/H) + 12	Reference
2.09 (+0.19,-0.13)	Ryan et al. (2000)
2.37 (0.1)	Melendez & Ramirez (2004)
2.44 (0.18)	Boesgaard et al. (2005)

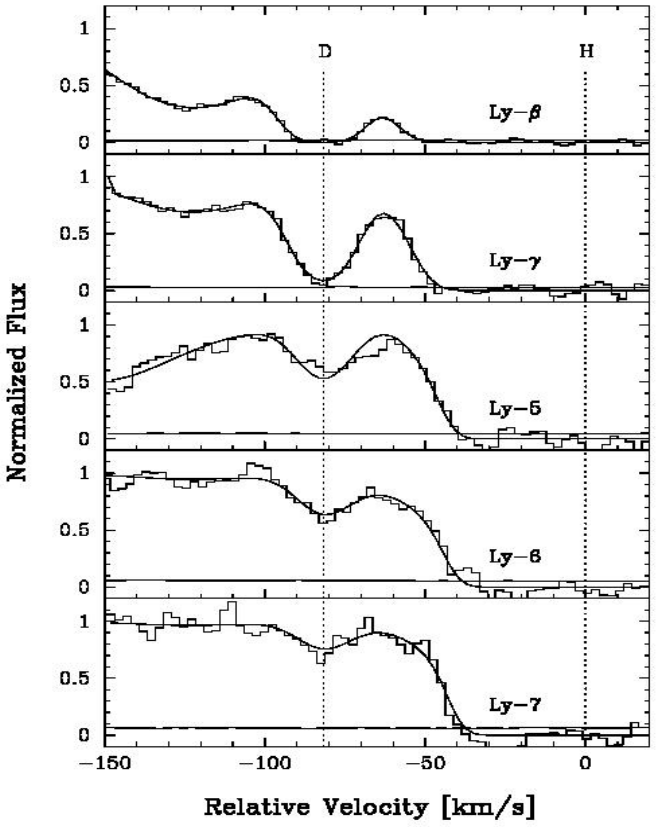
Deuterium Observations: Lyman Series

Q1243+3047



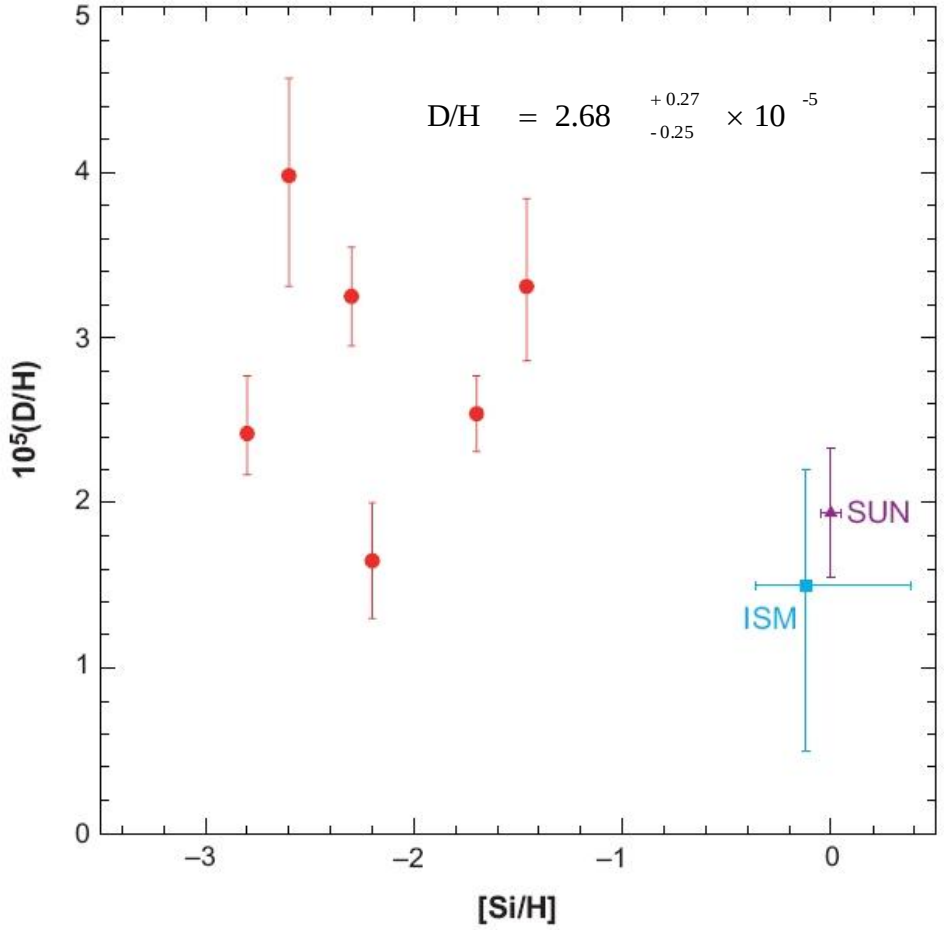
Kirkman et al. (2003)

HS 0105+1619



O'Meara et al. (2001)

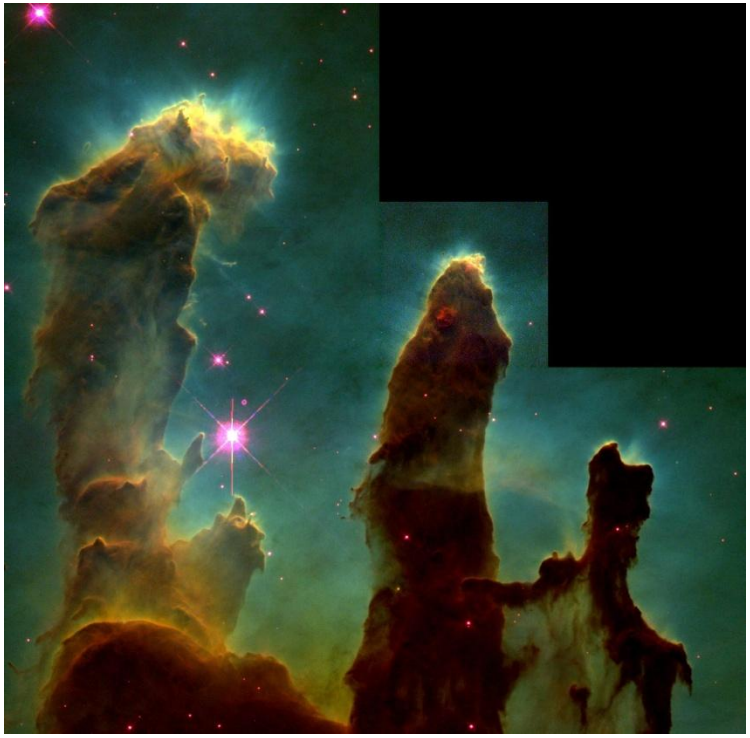
Deuterium Results

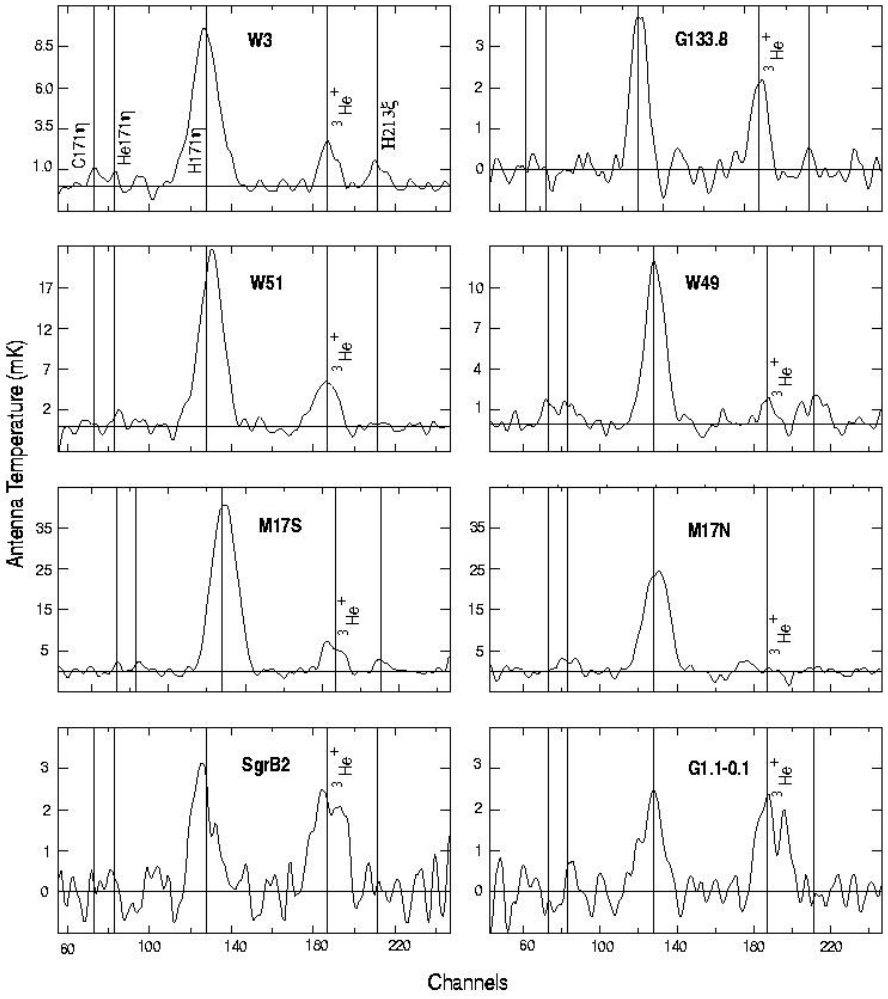


Steigman (2007)

3He+ Observations: HII Regions

HII Regions: M16

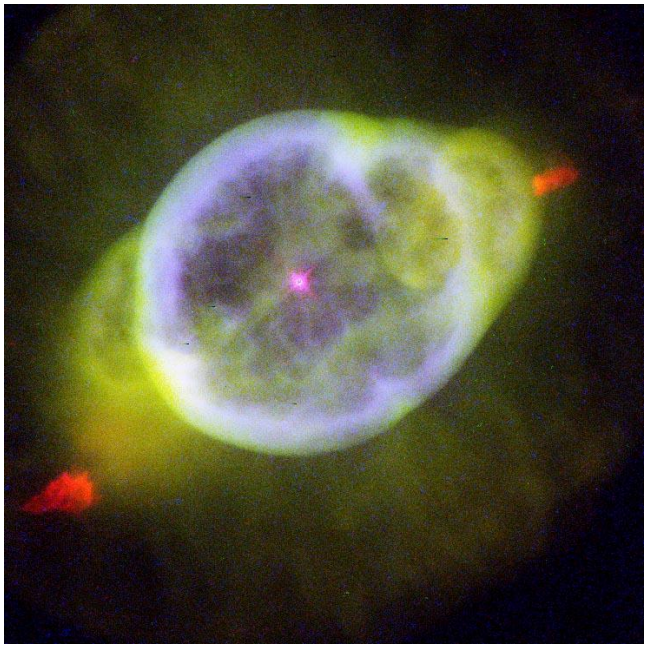


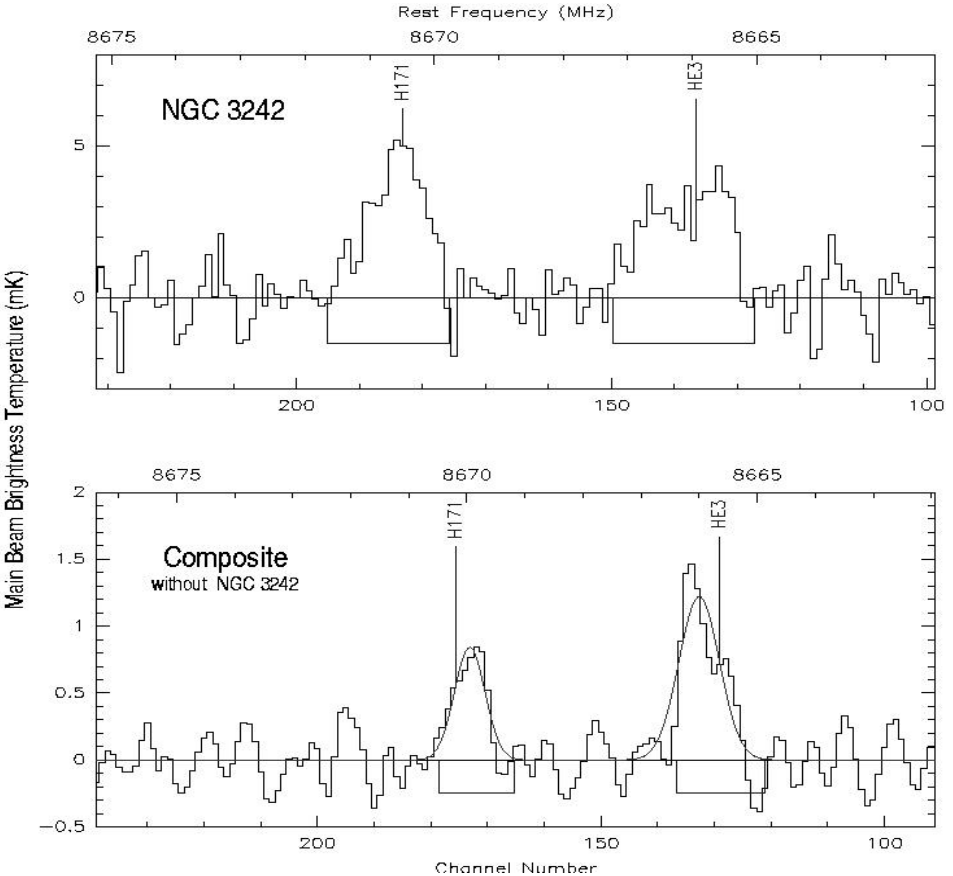


Bania et al. (1997)

3He+ Observations: PNe

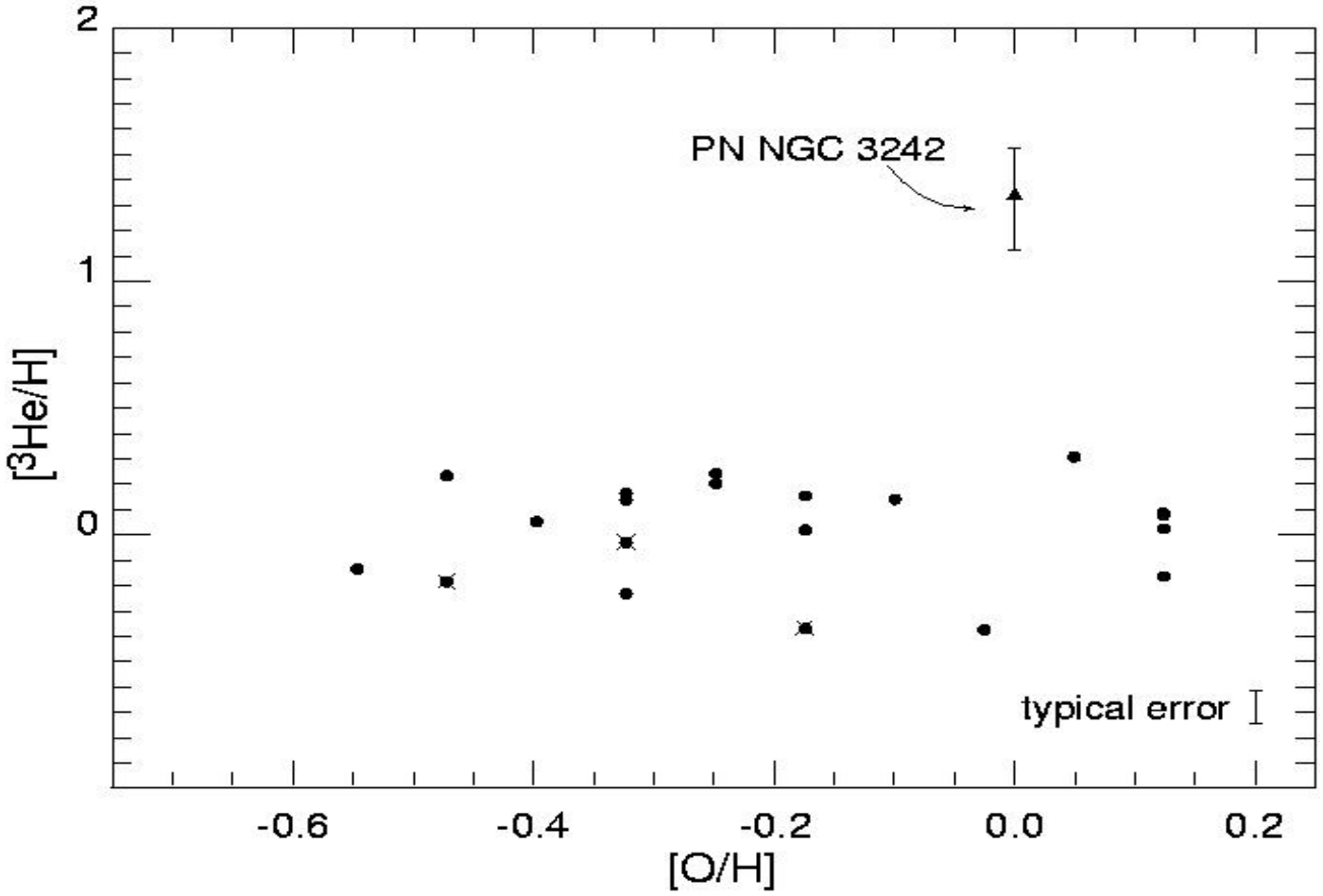
PNe: NGC 3242





Balser et al. (1997)

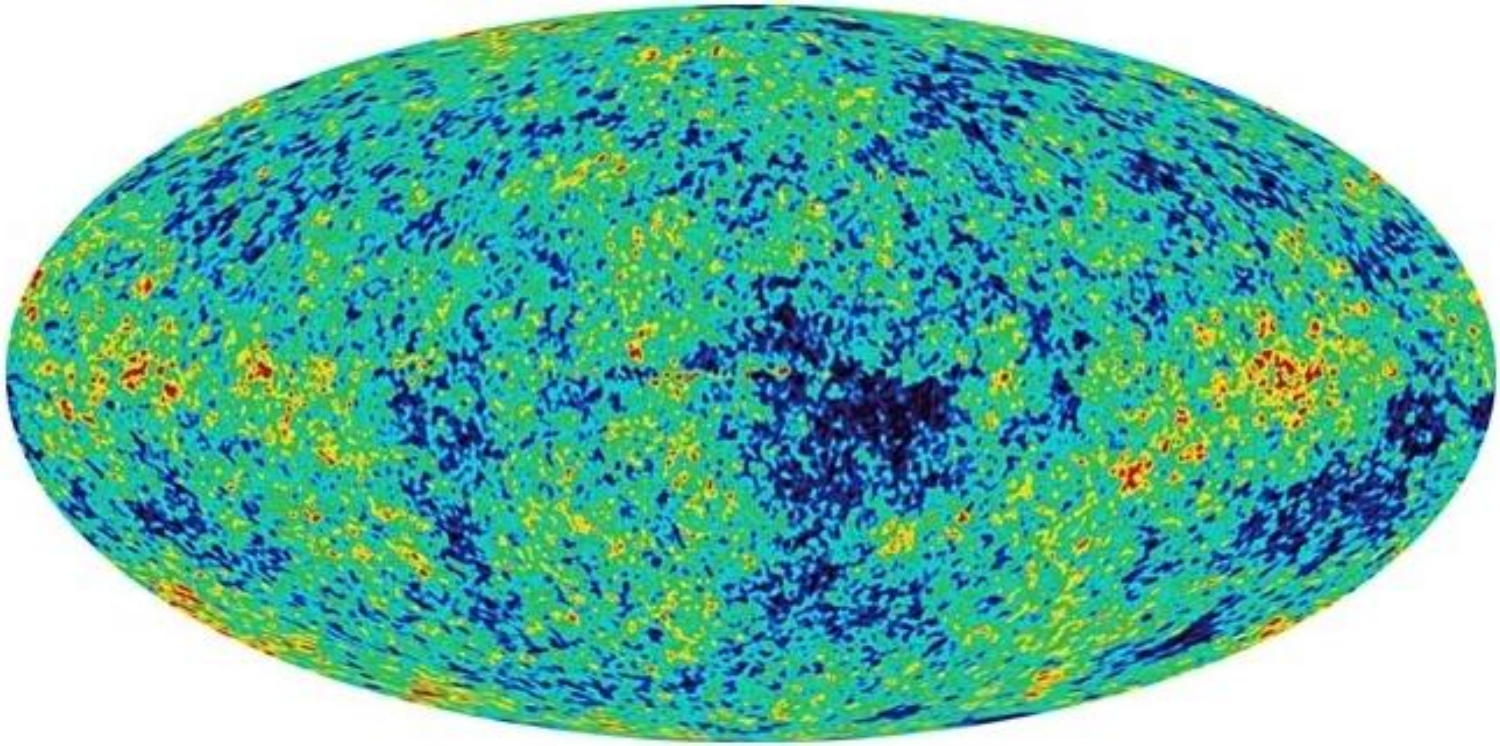
3He Results: The 3He Plateau



$$\left(^{3}\mathrm{He/H}\right)_{primordial} = 1.1 \pm 0.2 \times 10^{-5}$$

Bania, Rood, & Balser (2002)

Cosmic Microwave Background (WMAP)

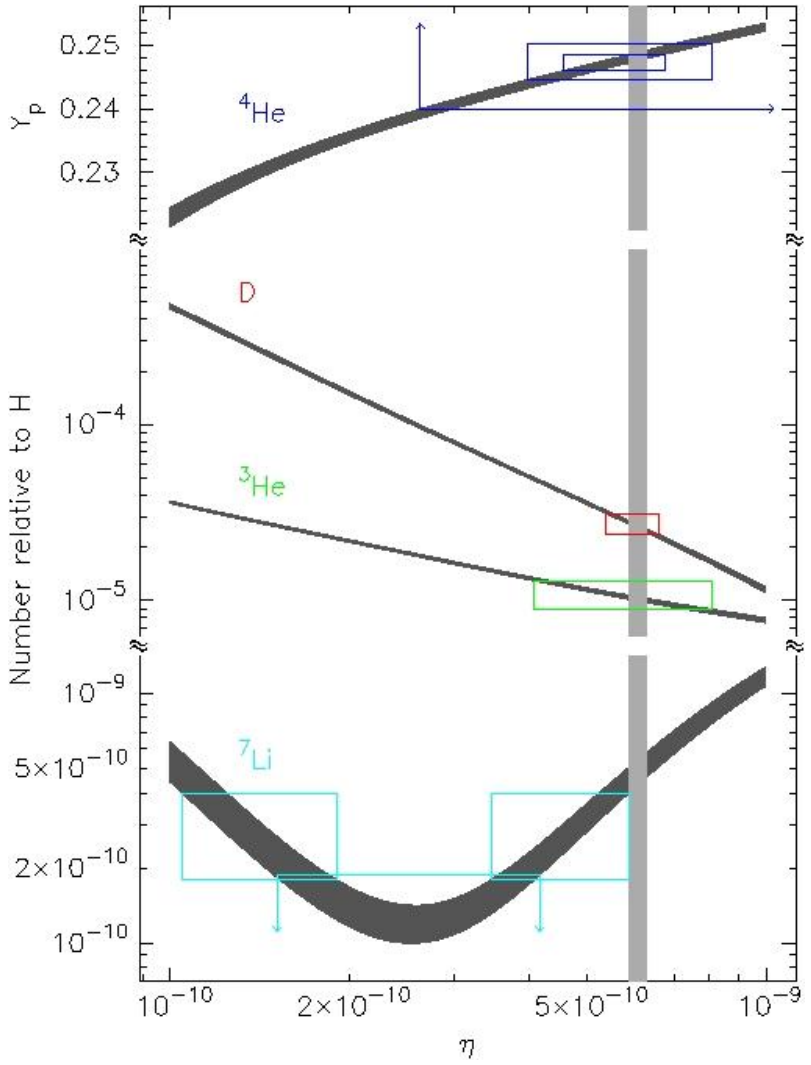


$$\Omega_b h^2 = 0.0223 \; {}^{+0.0007}_{-0.0009}$$

$$\eta = 6.0965 \pm 0.2055 \; x \; 10^{-10}$$

Spergel et al. (2006)

Primordial Abundances



Izotov et al. (2007)
Peimbert et al. (2007)
Olive & Skillman (2004)

Kirkman et al. (2003)

Bania, Rood & Balser (2002)

Ryan et al. (2000)
Boesgaard et al. (2005)

Burles et al. (2001)
Spergel et al. (2006)

Stellar Nucleosynthesis

$$p + p \rightarrow {}^{2}H + e^{+} + \nu$$

$${}^{2}H + p \rightarrow {}^{3}He + \gamma \qquad T > 6 \times 10^{5} K$$

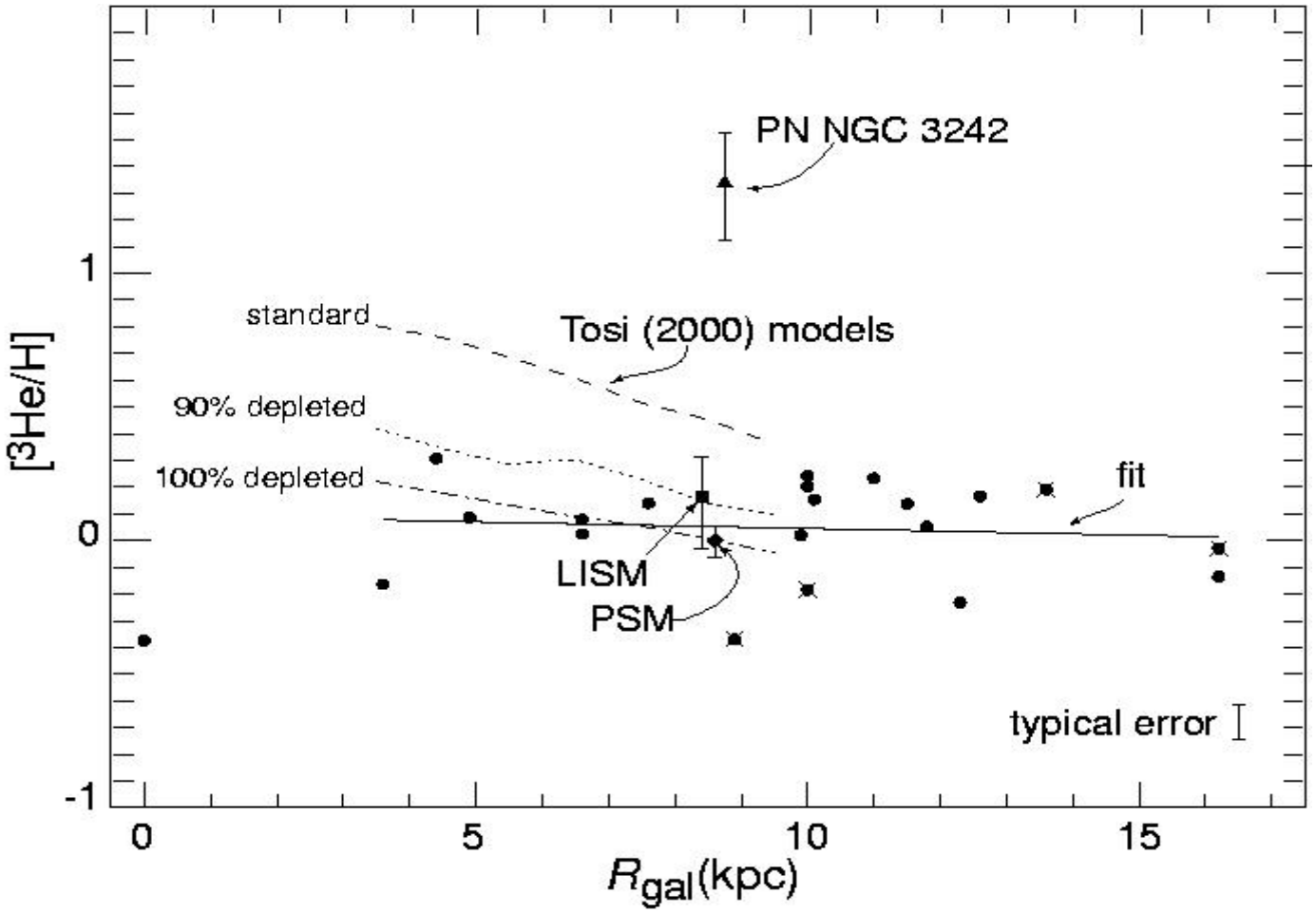
$${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$$

$${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma \qquad T > 7 \times 10^{6} K$$

$${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu$$

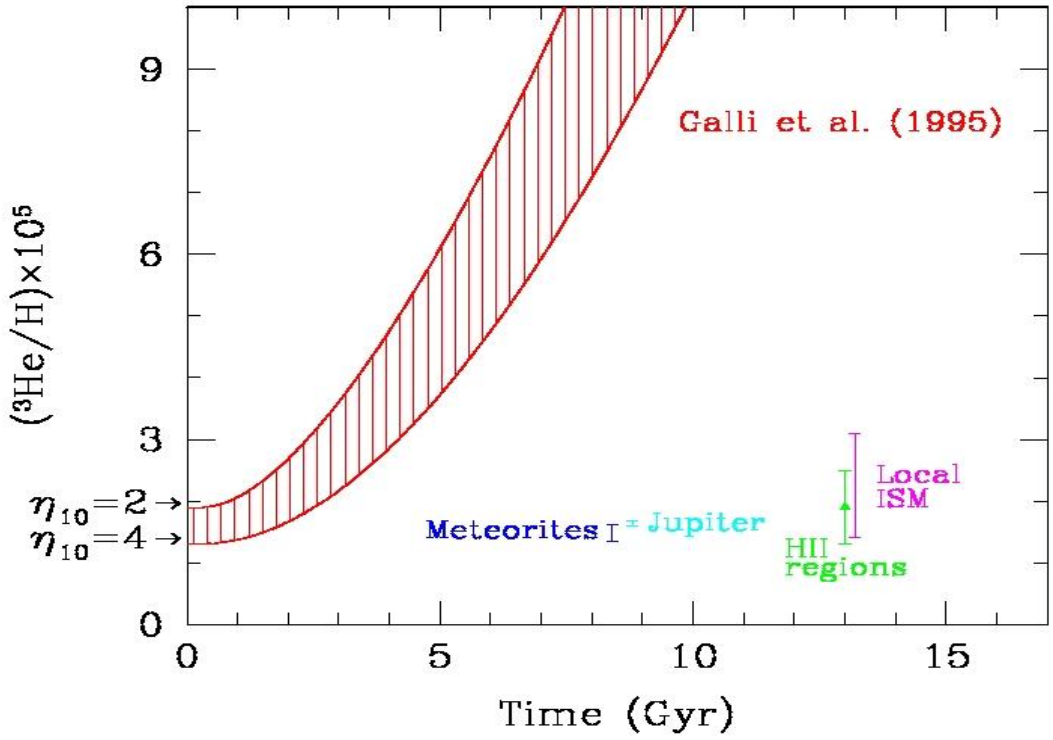
$${}^{7}Li + p \rightarrow {}^{4}He + \alpha$$

Evolution of 3He



Bania, Rood & Balser (2002)

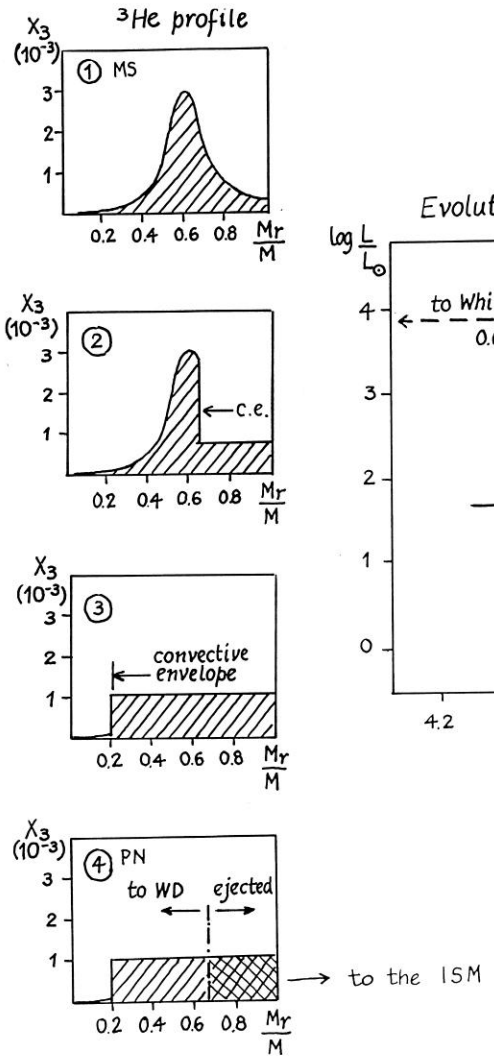
“The 3He Problem”

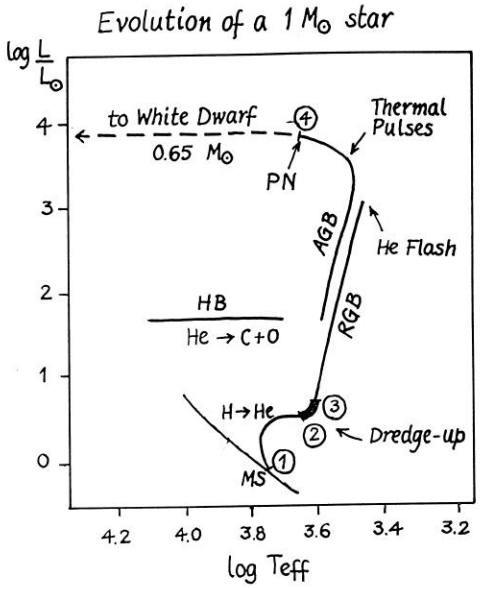


Meteorites: Geiss (1993)
Jupiter: Mahaffy et al. (1998)
HII regions: Bania, Rood & Balser (2002)
Local ISM: Gloecker & Geiss (1998)

Daniele Galli

Stellar Evolution of 3He: Theory

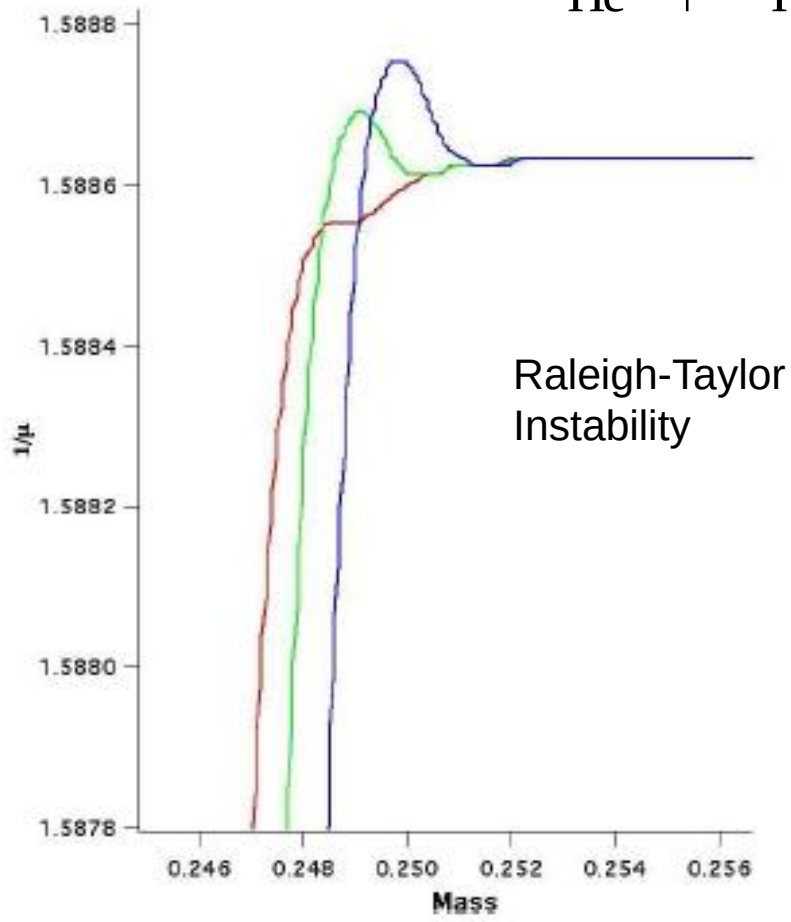




Daniele Galli

3-D Hydrodynamical and Nucleosynthetic Network

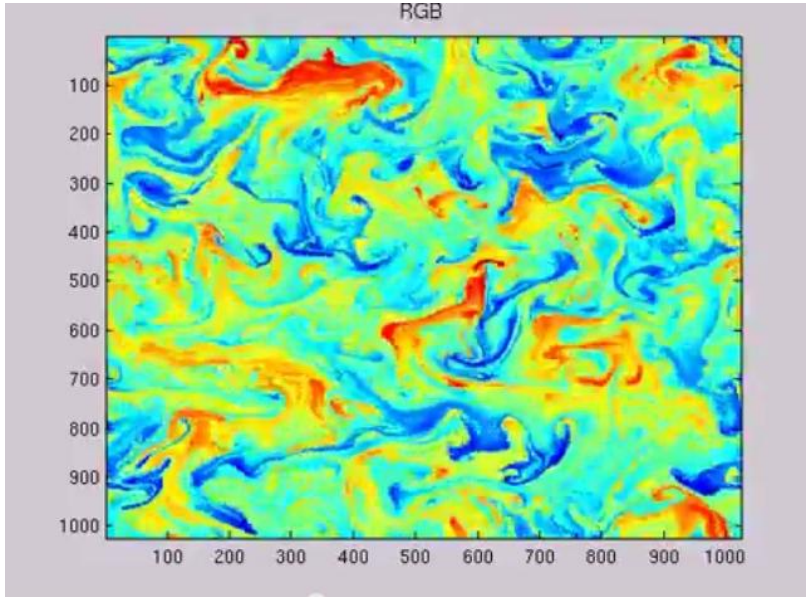
$$^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + 2\,\mathrm{p}$$



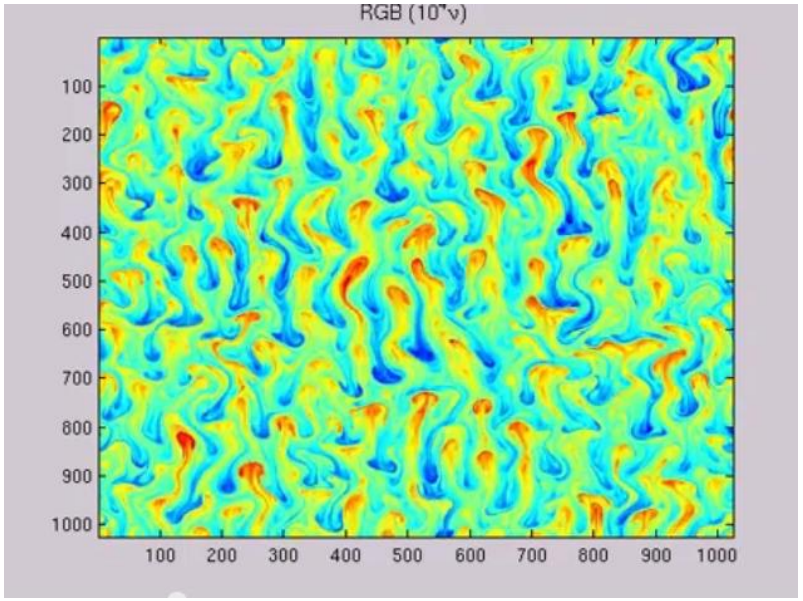
Raleigh-Taylor Instability

Eggleton et al. (2006)

Thermohaline Mixing



Low Viscosity



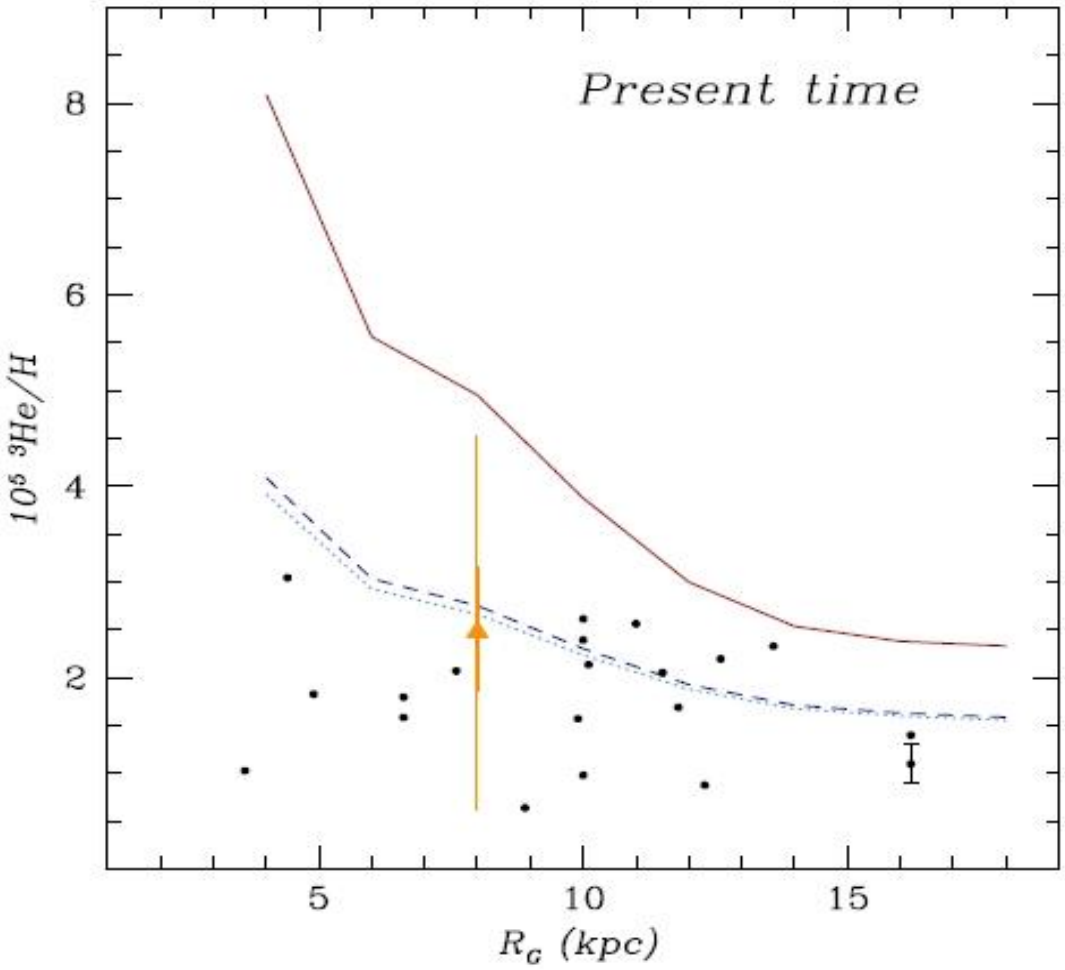
High Viscosity

Red (lower salinity) → Blue (higher salinity)

$$^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + 2\,\mathrm{p}$$

Denissenkov

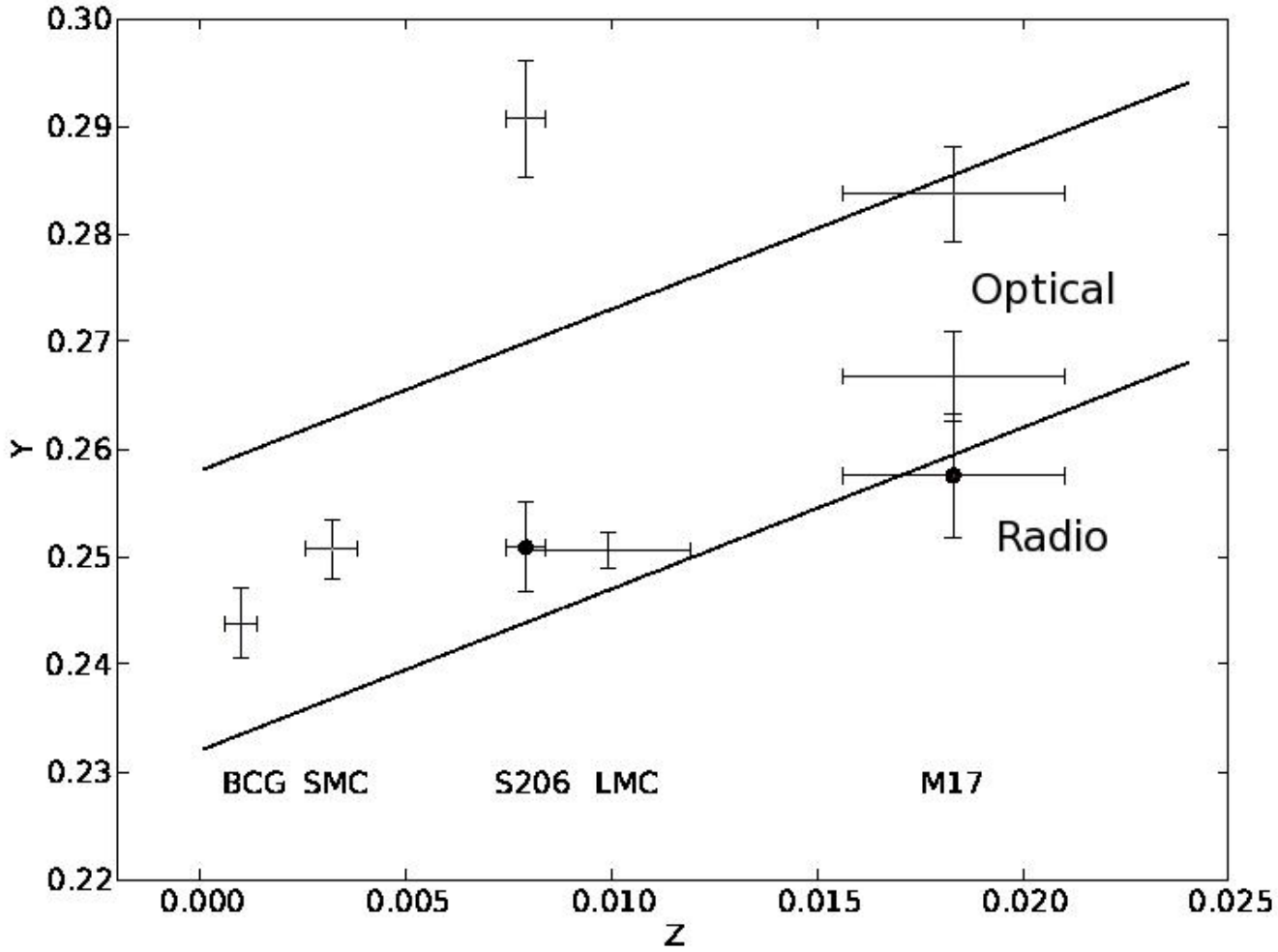
Evolution of 3He



Lagarde et al. 2012

Fini

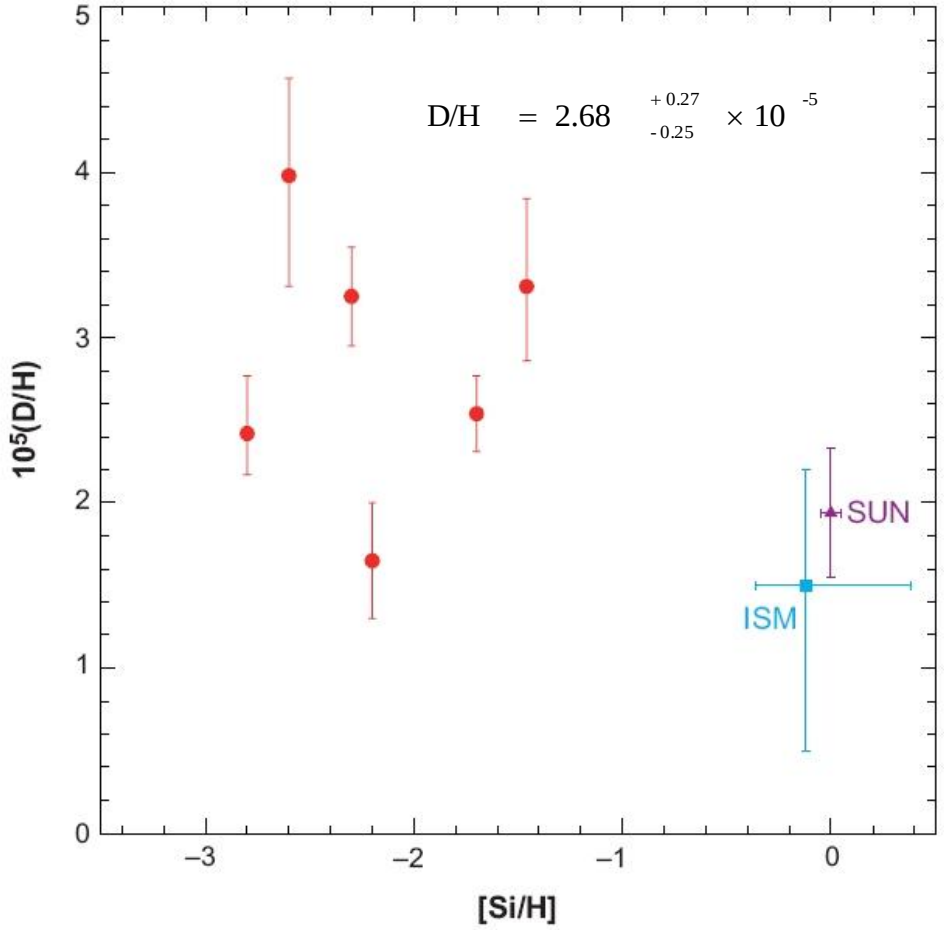
Evolution of 4He



dY/dZ = 1.5

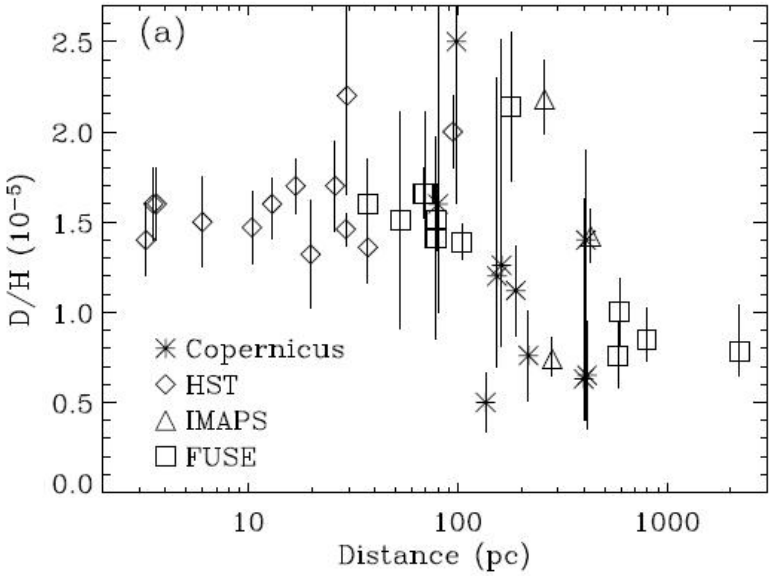
Balser et al. (2010)

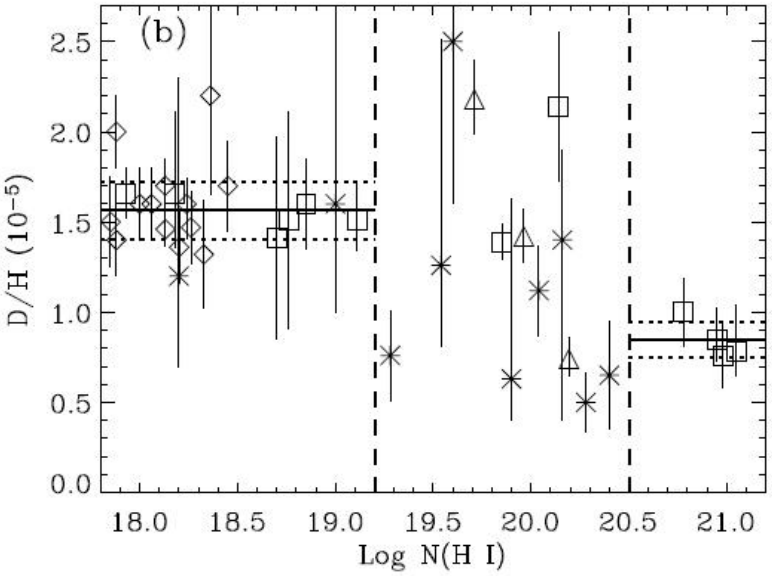
Evolution of Deuterium



Steigman (2007)

Evolution of Deuterium

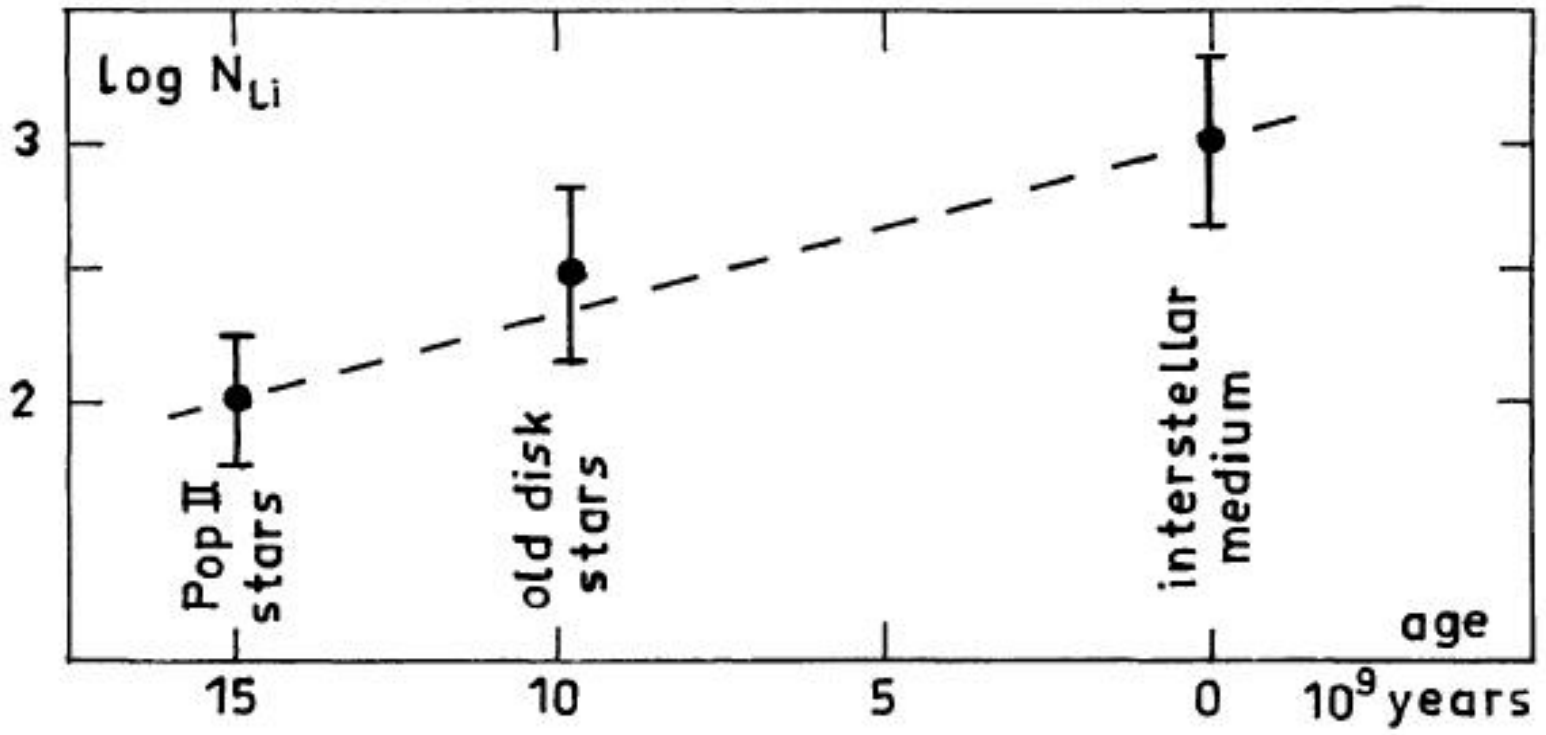




$$\frac{(D/H)_{primordial}}{(D/H)_{Galactic}} \leq 1.19^{+0.16}_{-0.15}$$

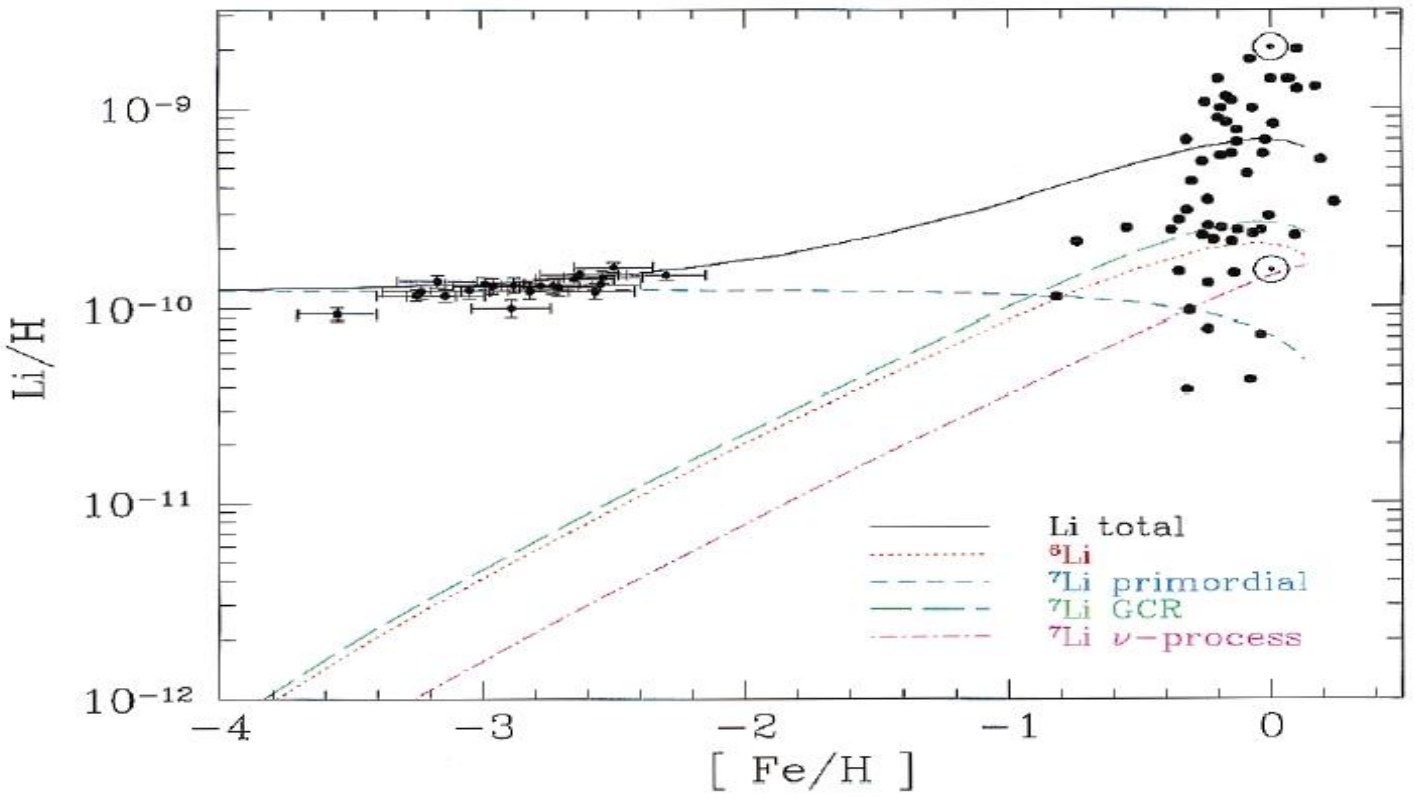
Wood et al. (2004)
Linsky et al. (2008)

Evolution of 7Li



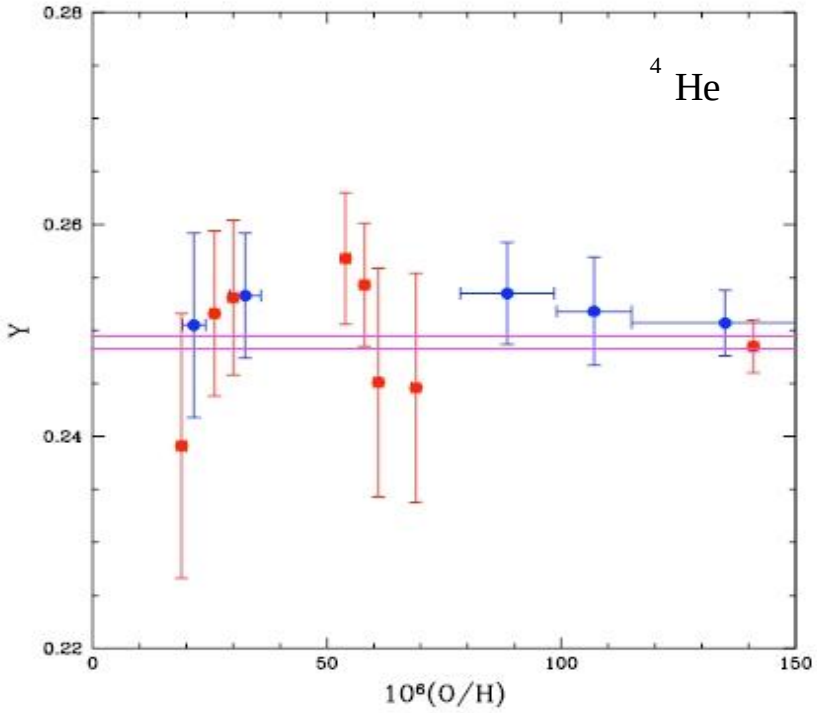
Spite & Spite (1982)

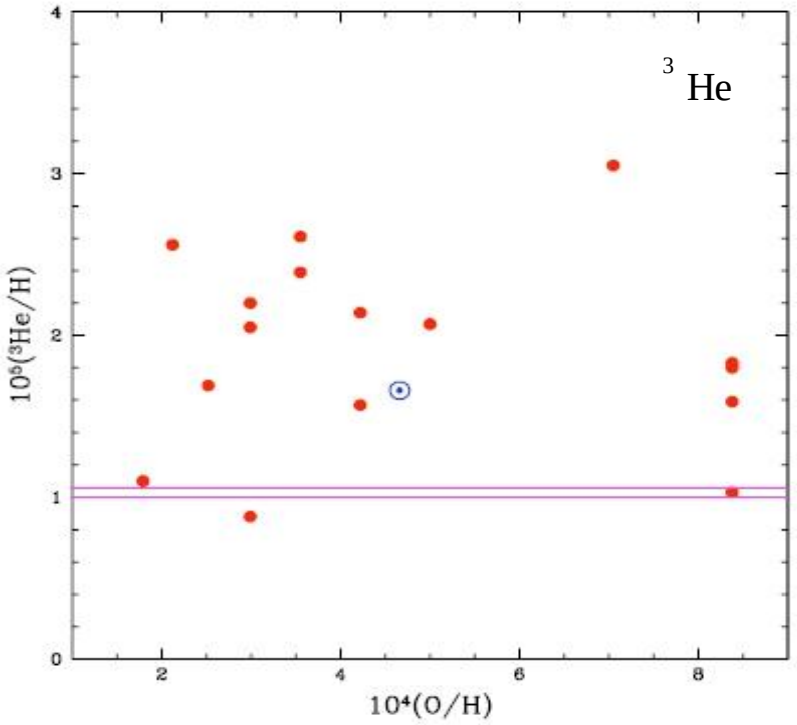
Evolution of 7Li



Ryan et al. (2000)

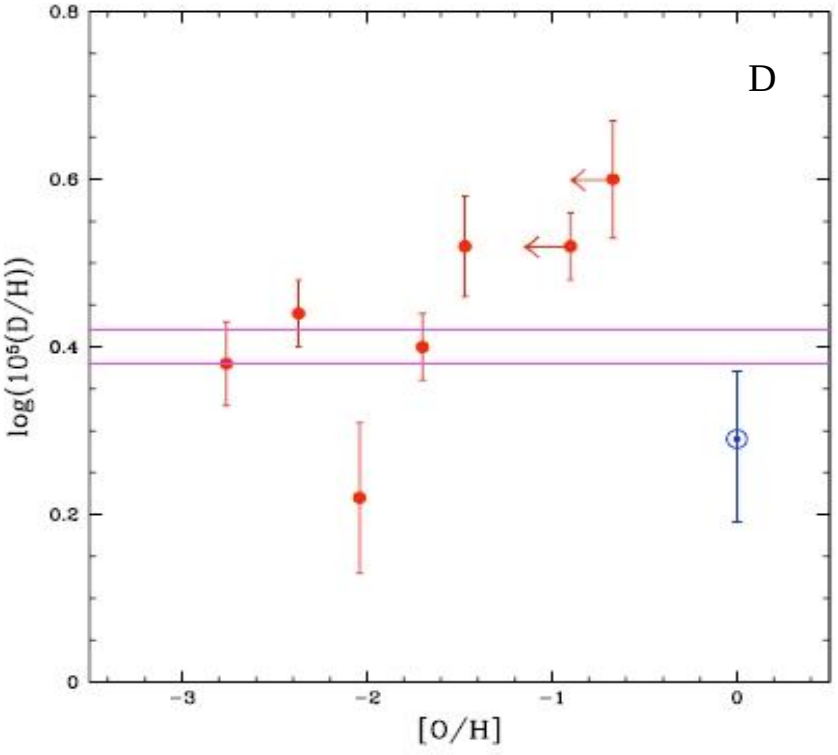
Primordial Abundances

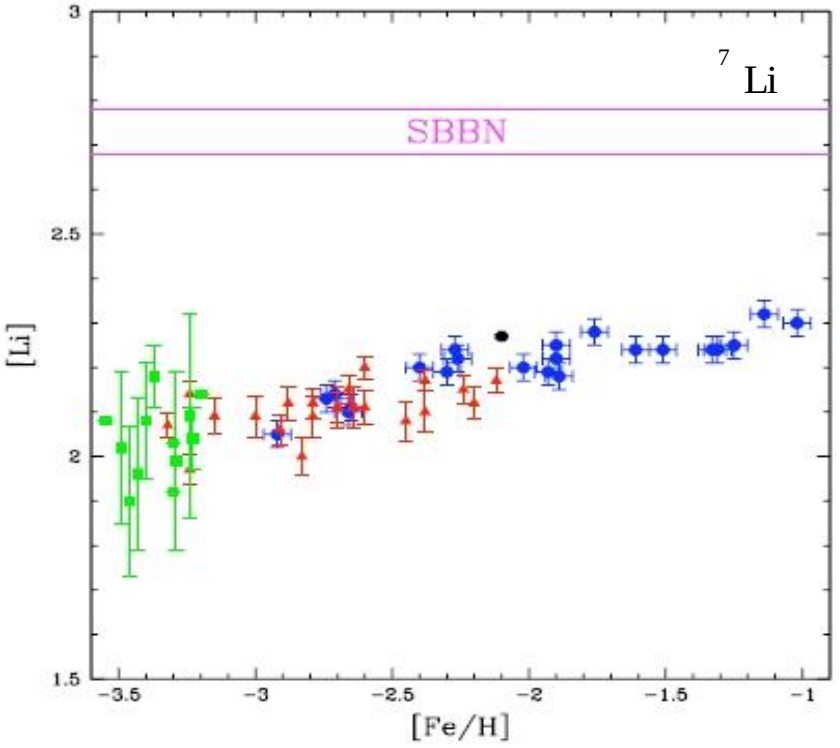




Steigman (2010)

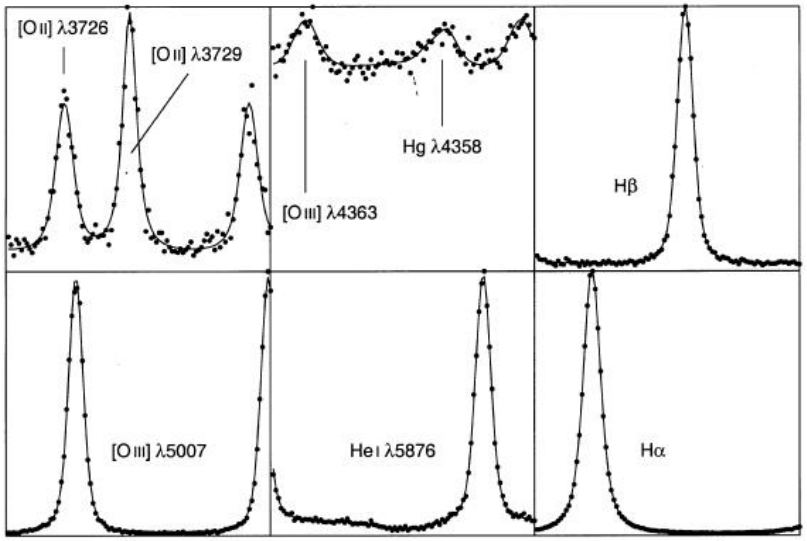
Primordial Abundances





Steigman (2010)

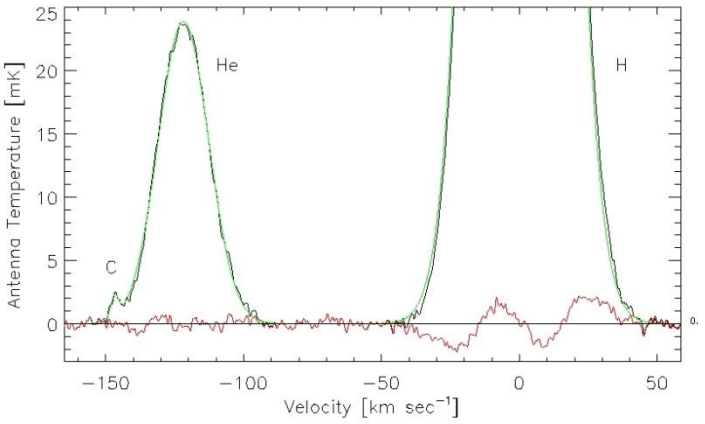
4He: Galactic HII Regions



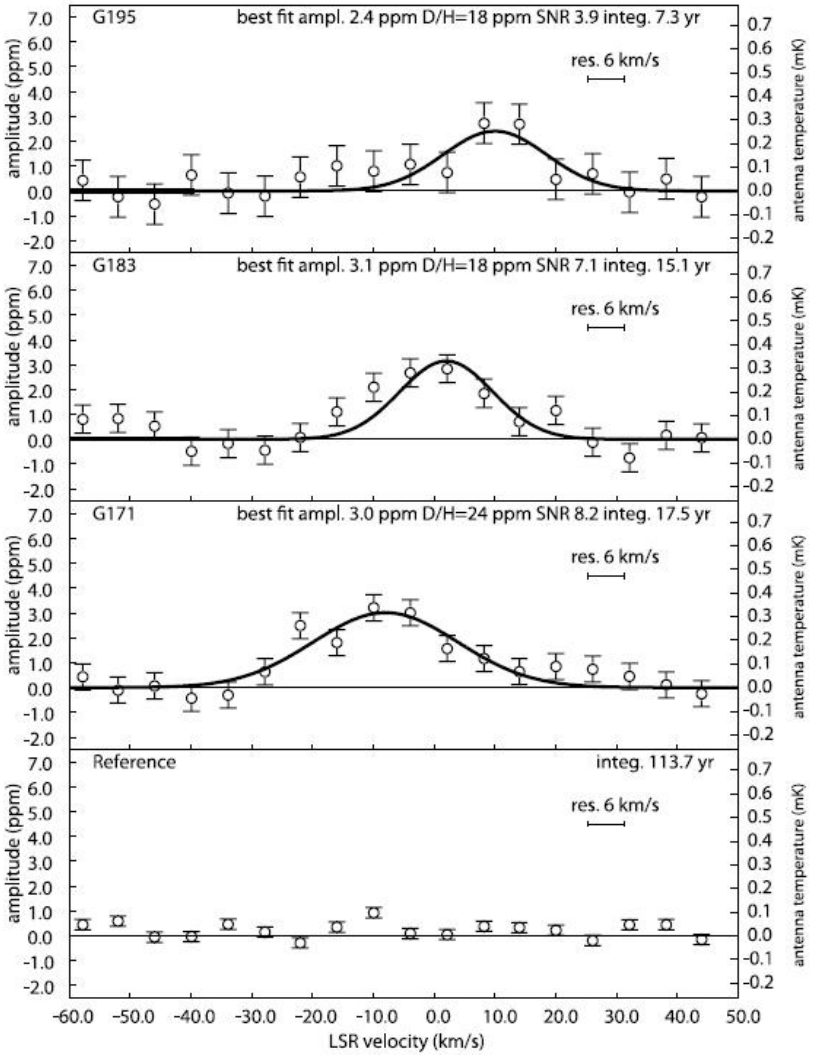
Caplan et al. (2000)

HII Region: S206

Balser (2006)



Deuterium: Galactic Anticenter

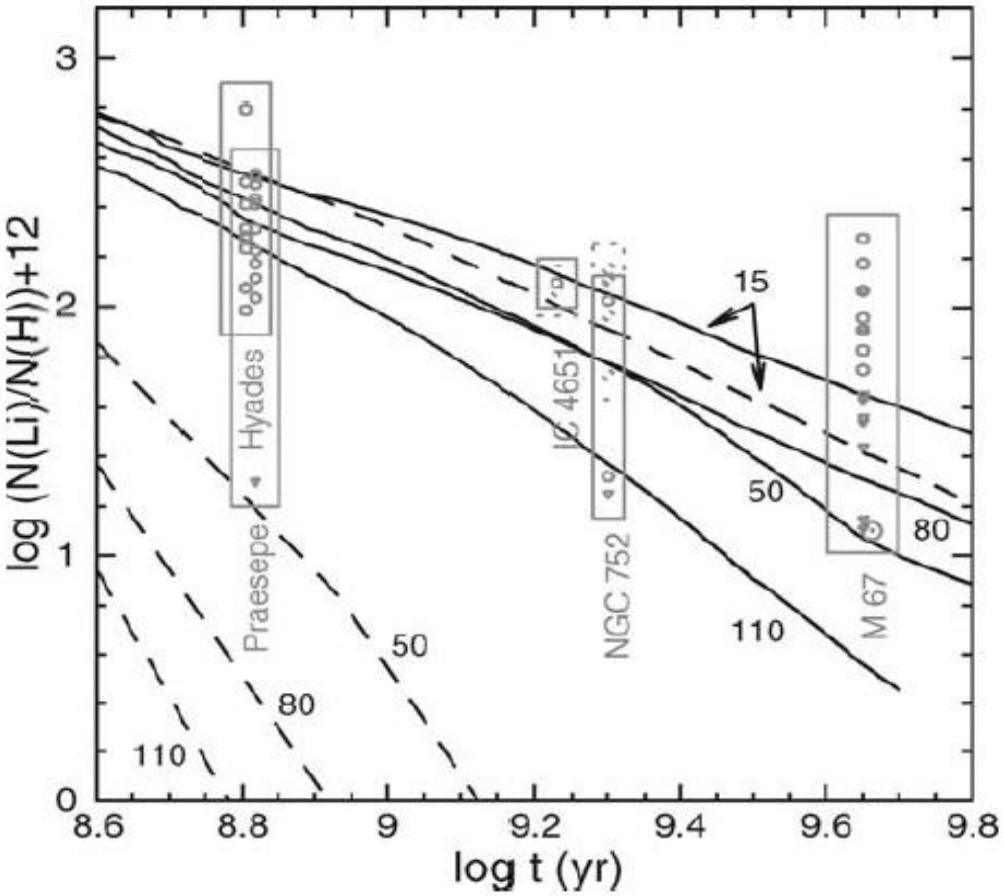


Deuterium 327 MHz
Hyperfine Transition

$$D / H = 2.1 \pm 0.7 \, x 10^{-5}$$

Rogers et al. 2007

Internal Gravity Waves



Charbonnel & Talon (2005)

3-D Hydrodynamical and Nucleosynthetic Network

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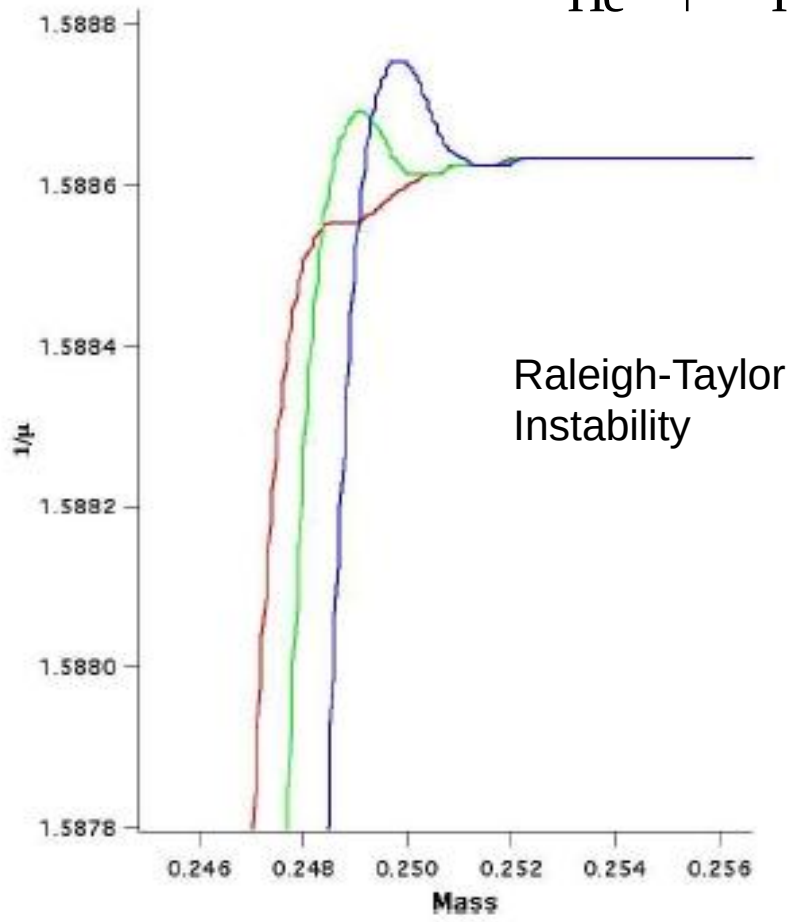

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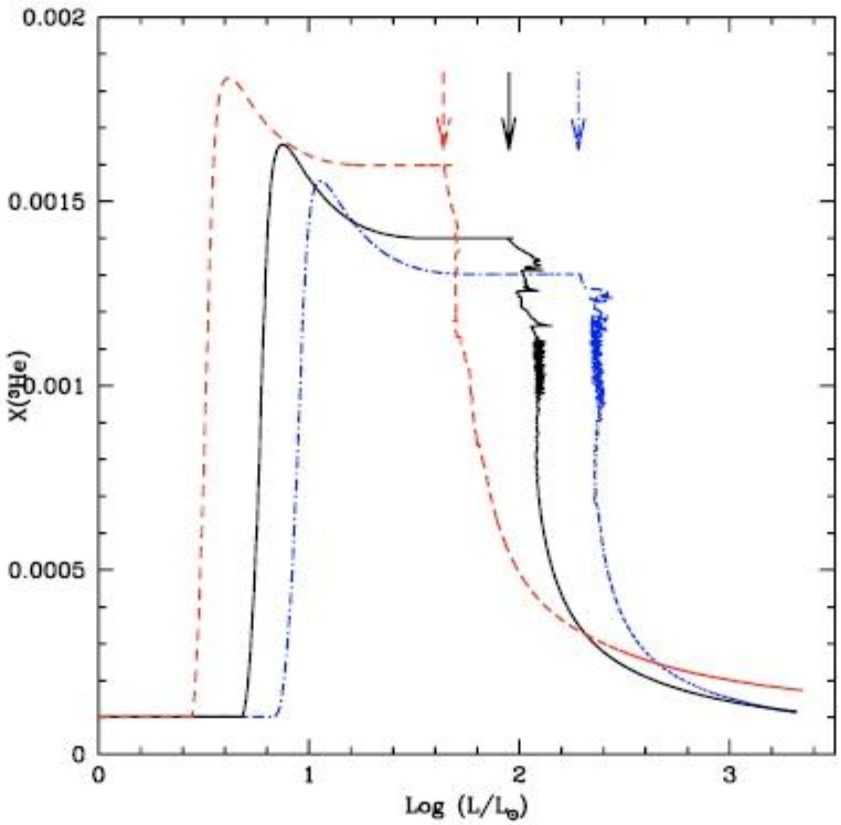


Charbonnel & Zahn (2007)

Search for 3He in Planetary Nebulae

NRAO Green Bank Telescope

NGC 3242
NGC 6543
NGC 7009
NGC 6826

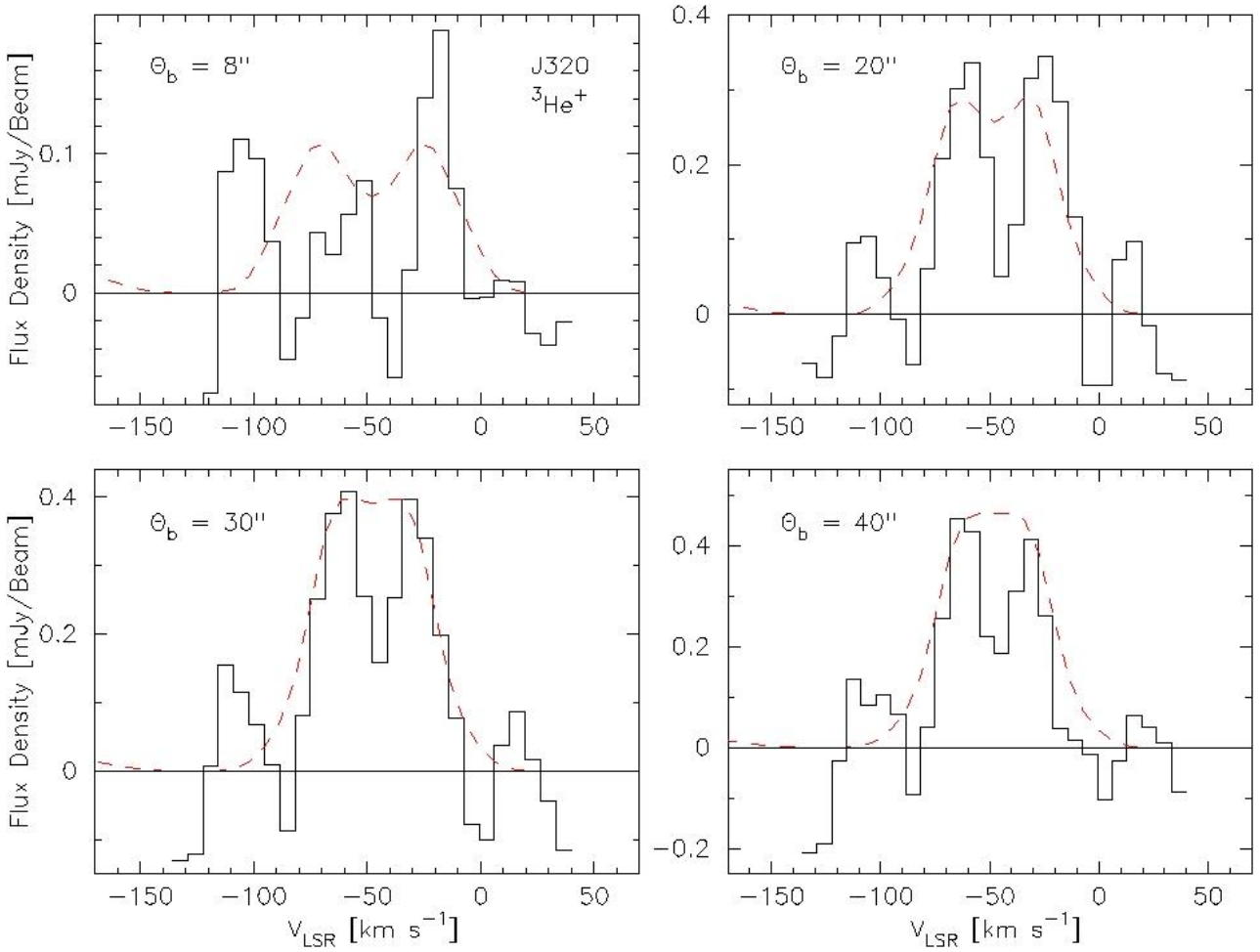
NRAO Very Large Array

NGC 6572
J320

NAIC Arecibo Telescope

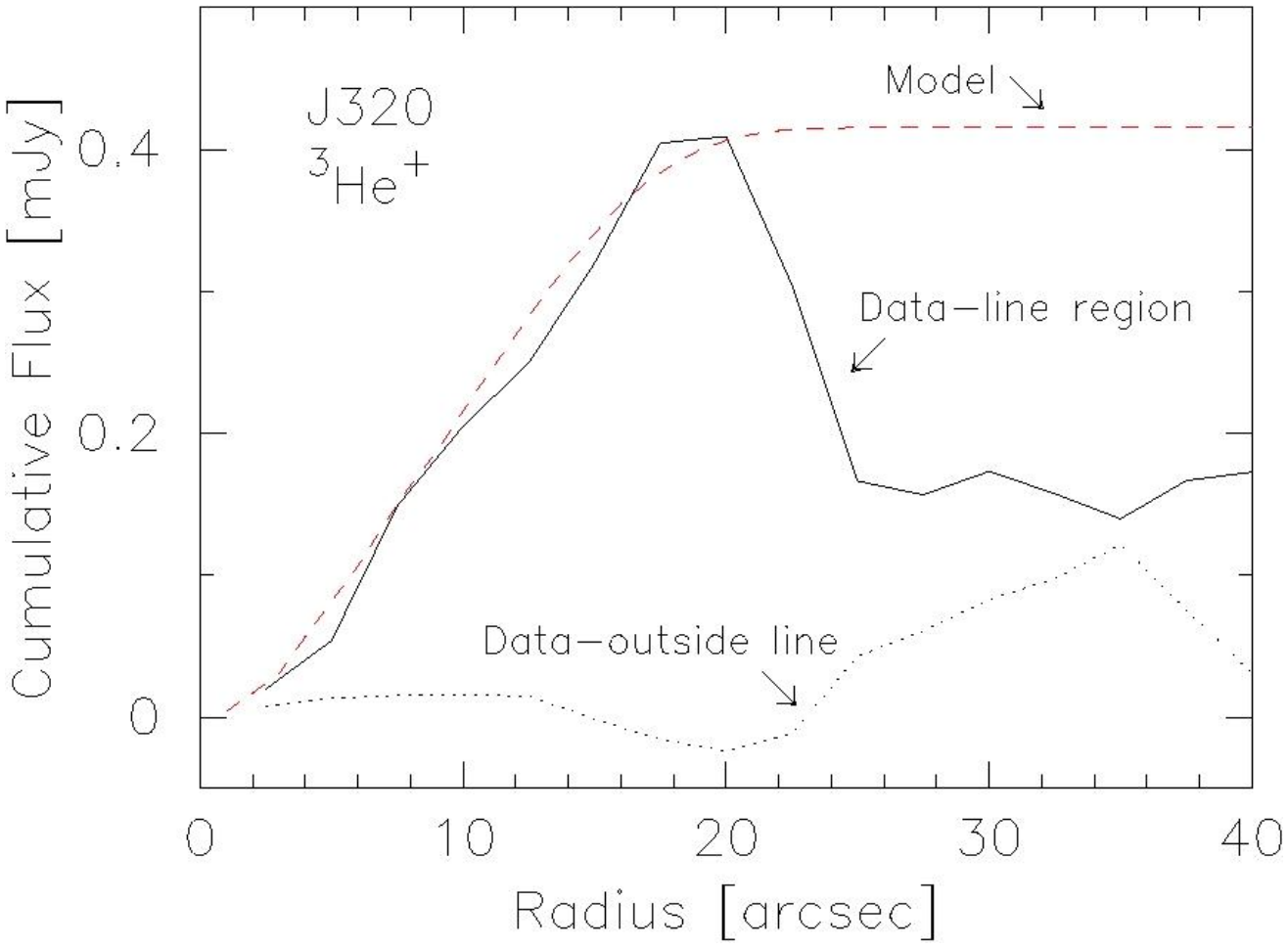
NGC 6210
NGC 6891

VLA J320 3He+ Spectra



Balser et al. (2006)

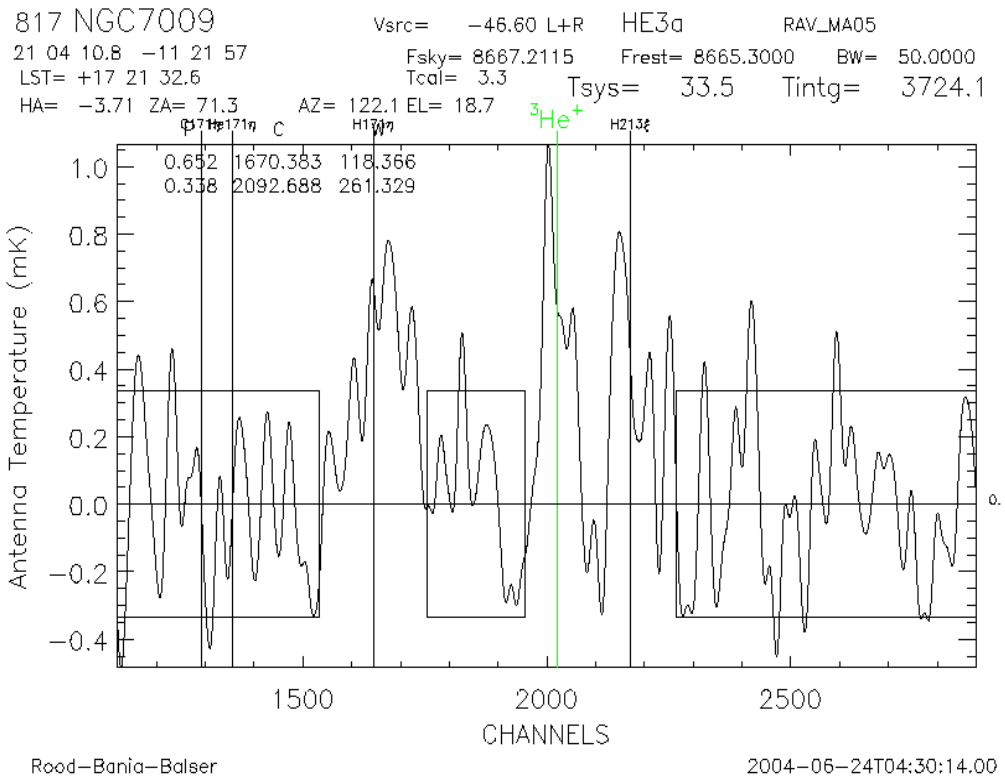
VLA J320 Model



^{3} He/H $\approx 2 \times 10^{-3}$

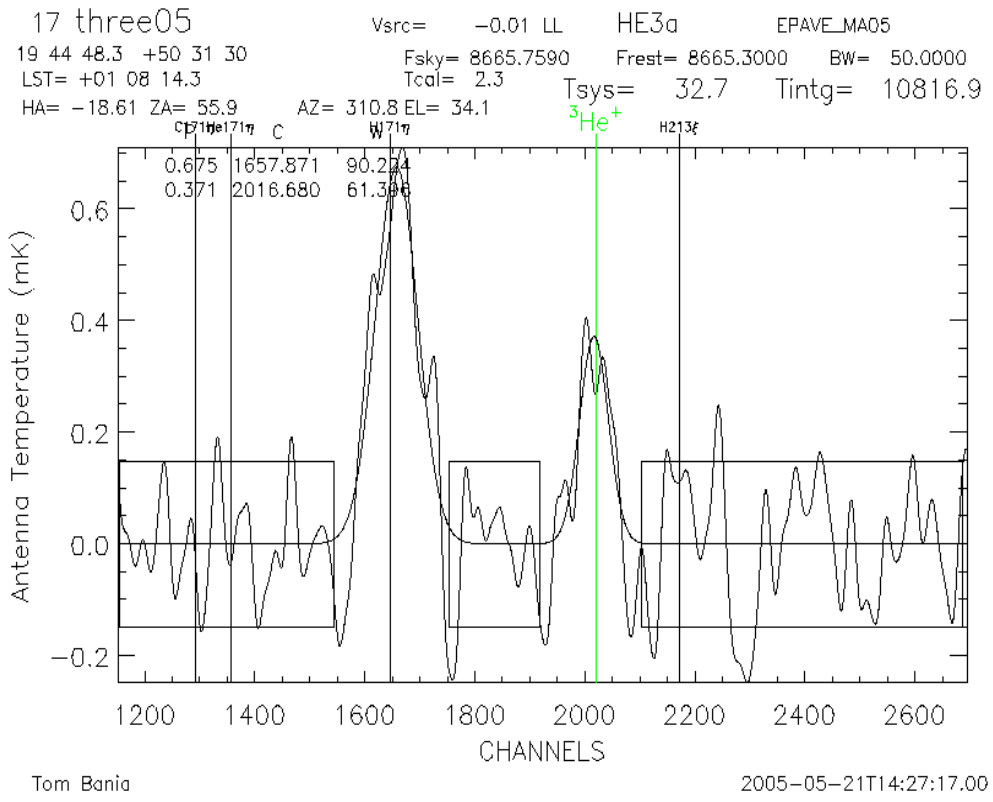
Balser et al. (2006)

GBT NGC 7009



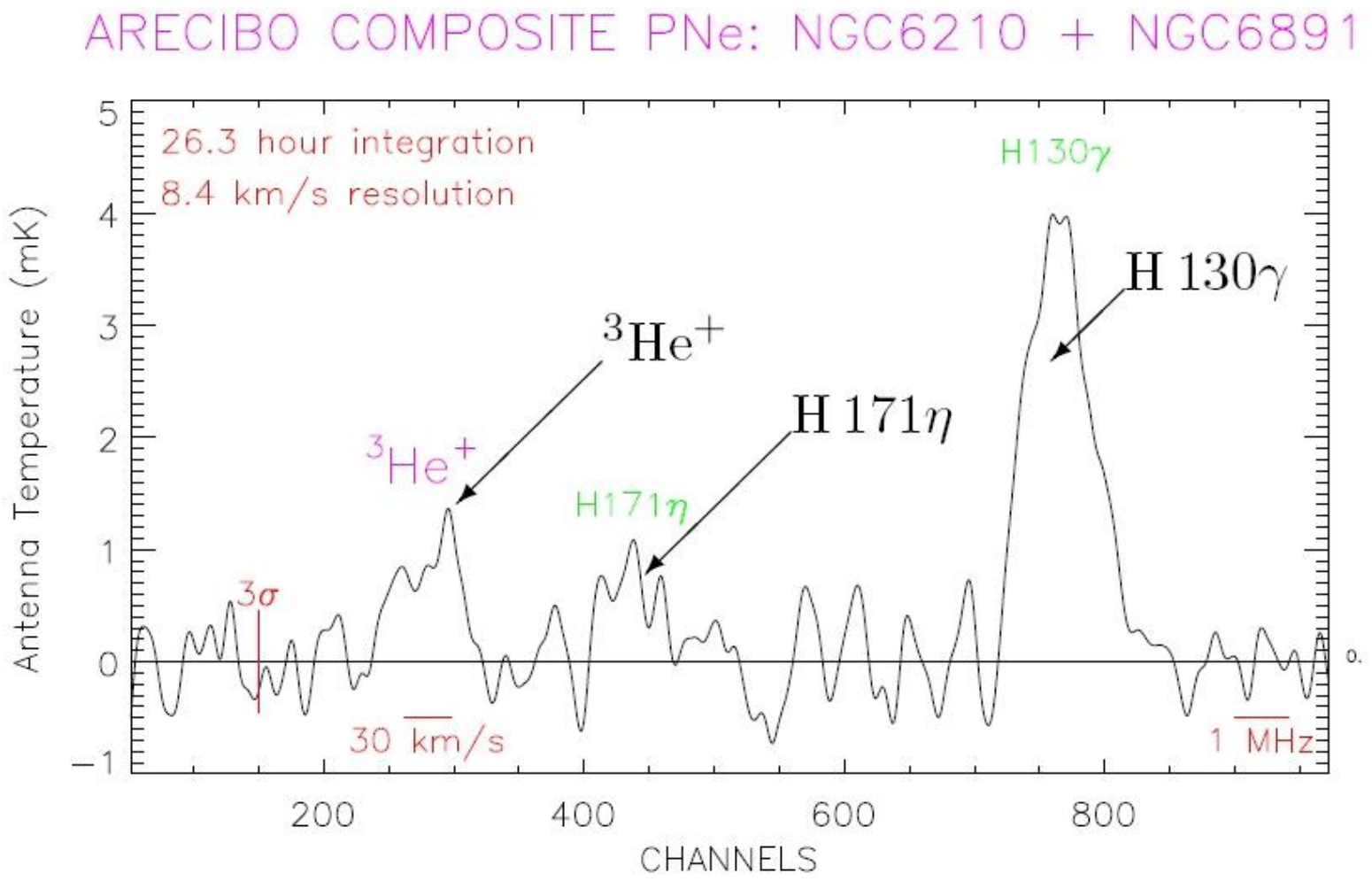
62.1 hr integration

GBT (NGC7009 + NGC6543 + NGC6826)



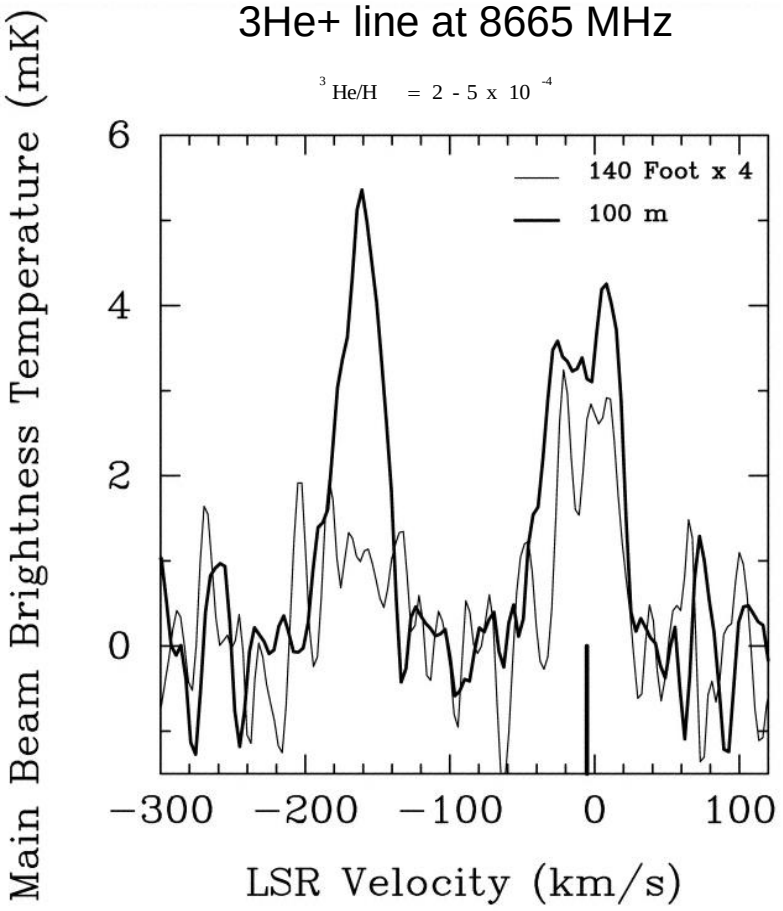
180.3 hr integration

Arecibo (NGC6210 + NGC6891)



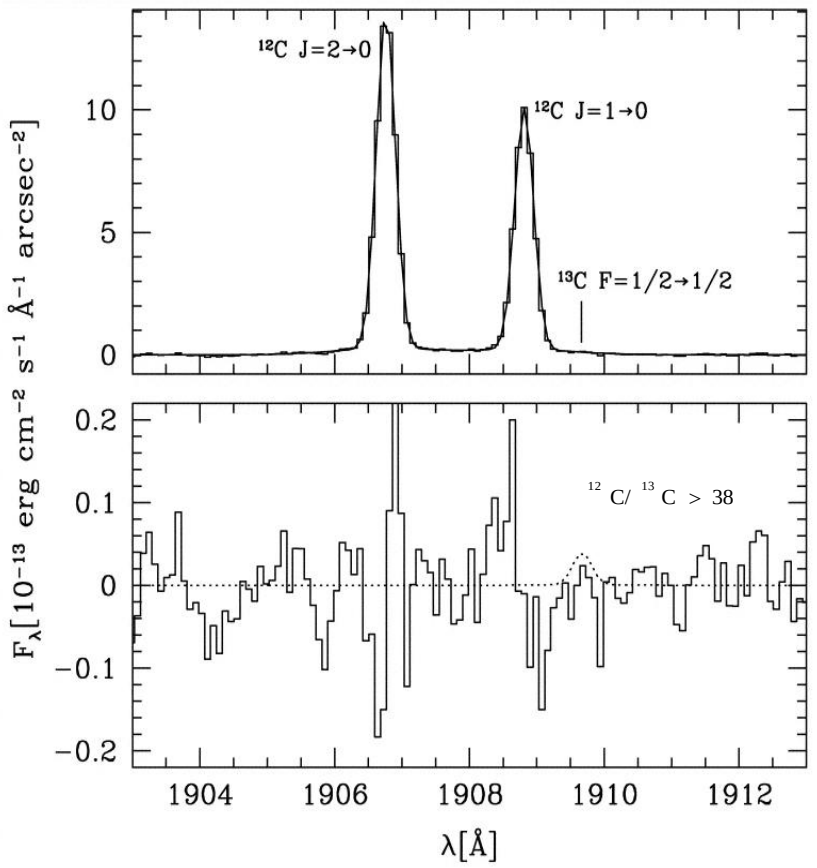
No Mixing in NGC3242

3He+ line at 8665 MHz



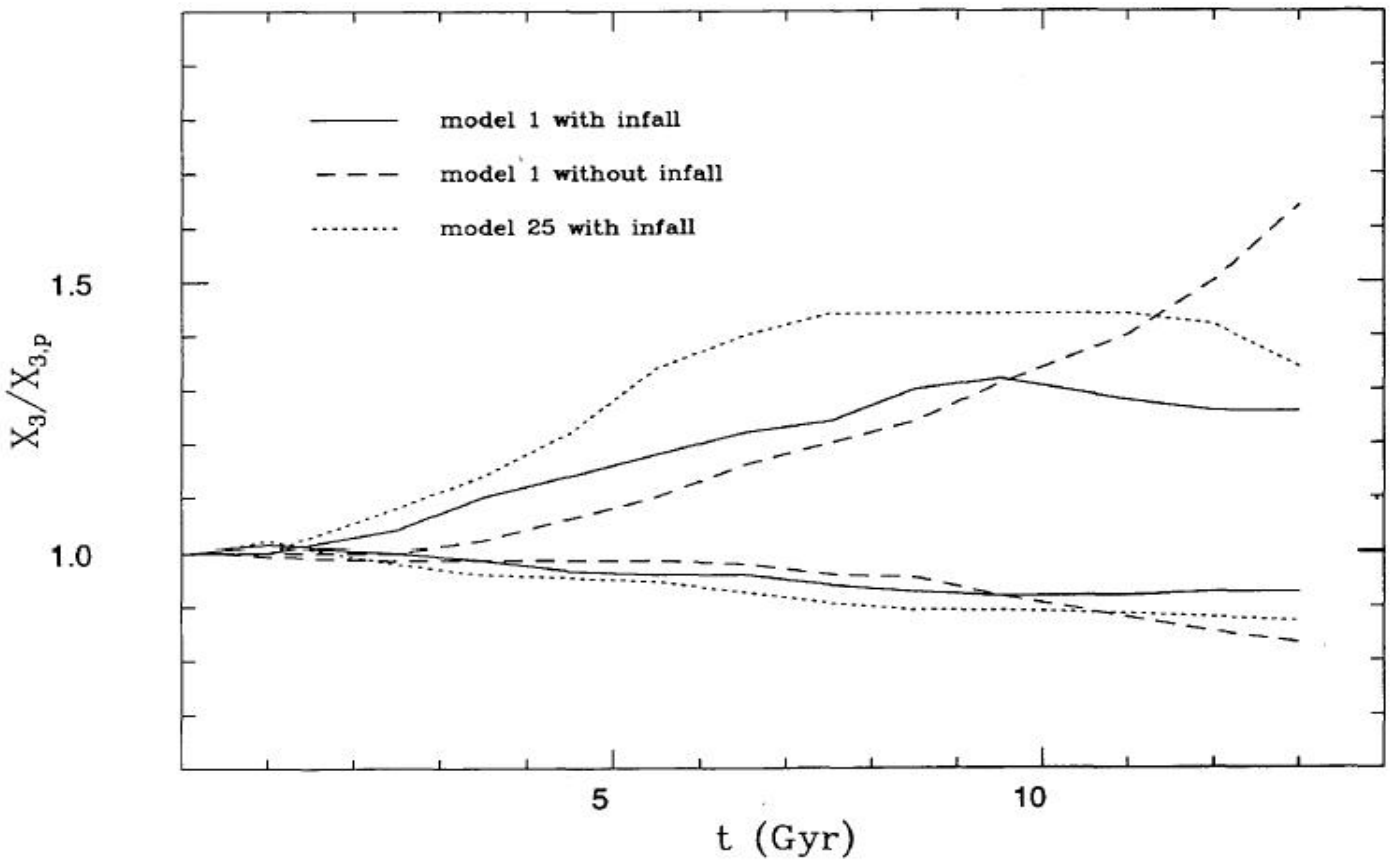
Balser et al. (1999)

C III] multiplet near 1908 A



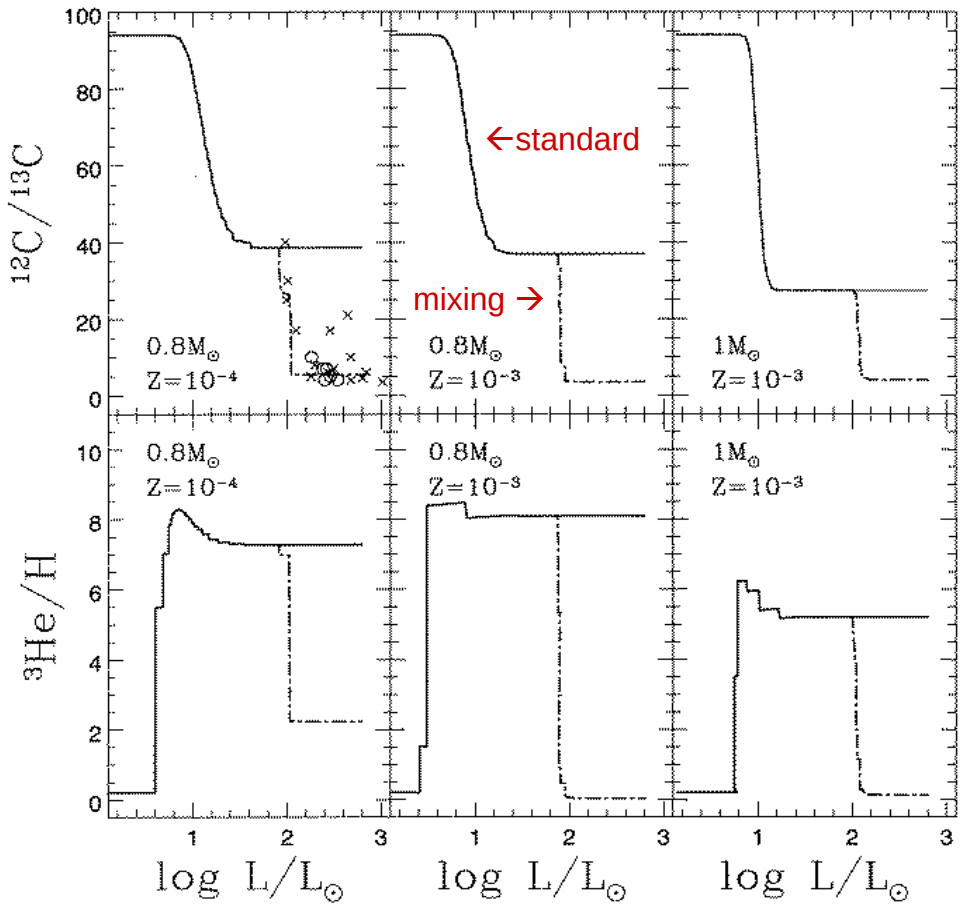
Palla et al. (2002)

Galactic Evolution of 3He: Theory



Steigman & Tosi (1992)

Rotational Mixing in Stars



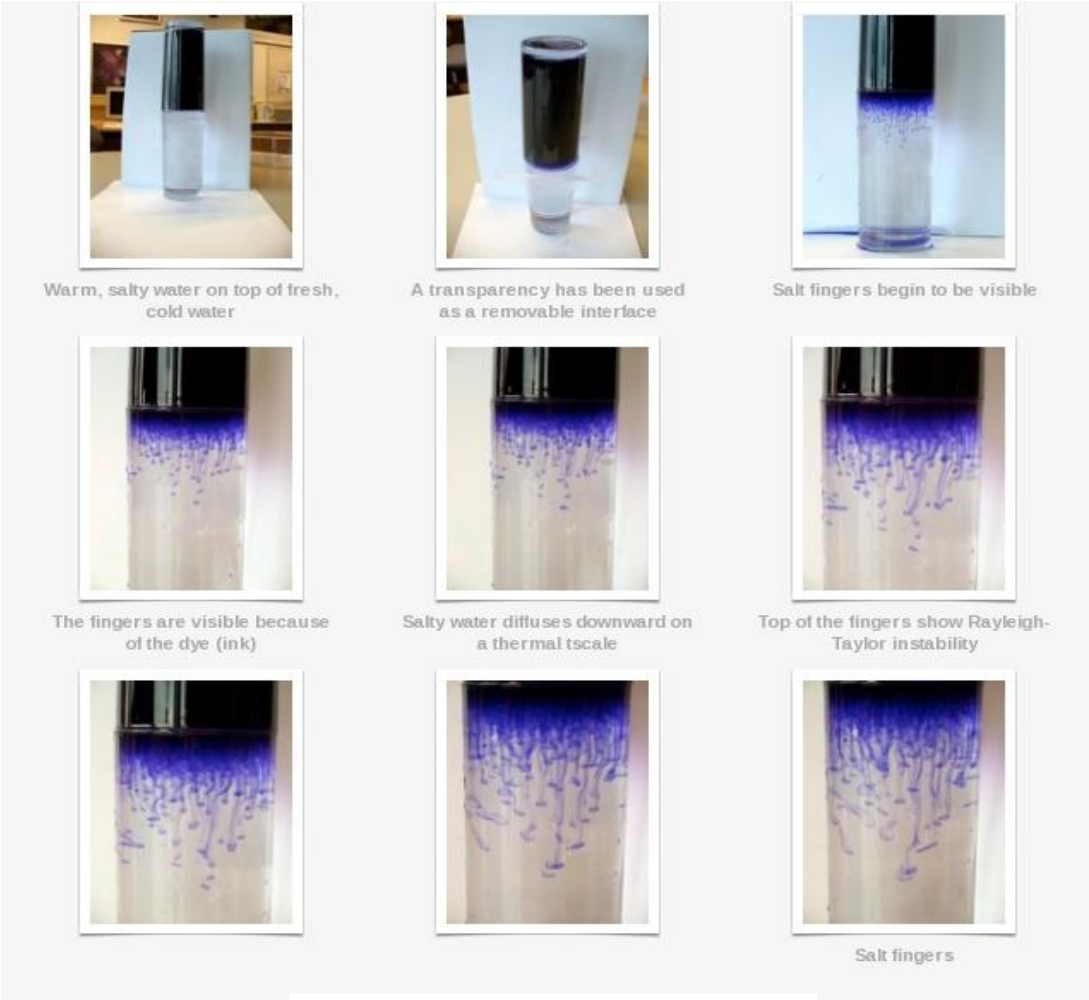
Charbonnel (1995)

"…meridional circulation driven by internal rotation might lead to the mixing of CNO-processed material …of a red giant star."
Sweigart & Mengel (1979)

"…96% of low-mass stars do experience an extra-mixing process on the RGB…"
Charbonnel & do Nascimento (1998)

"…meridional circulation…does not lead to enough mixing…to explain the abundance anomalies…"
Palacios et al. (2006)

Thermohaline Mixing



$$^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + 2\,\mathrm{p}$$

Cantiello