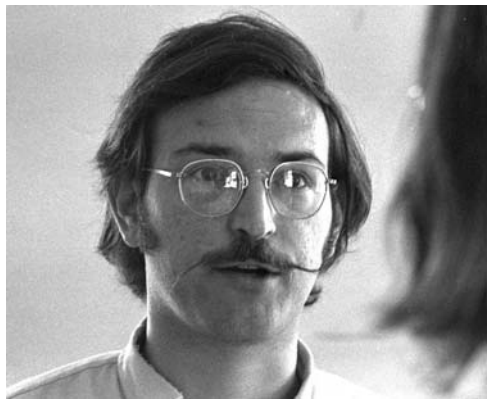
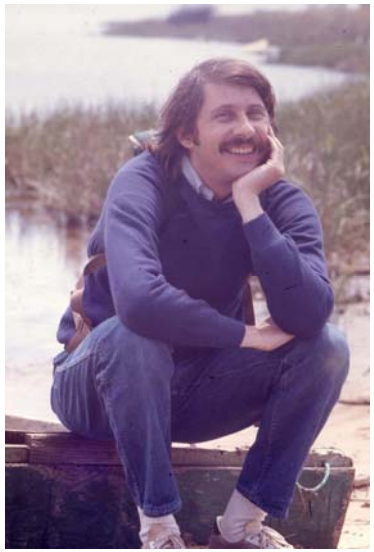
Stalking the Cosmic 3He Abundance

Dana S. Balser

Collaborators

Tom Bania



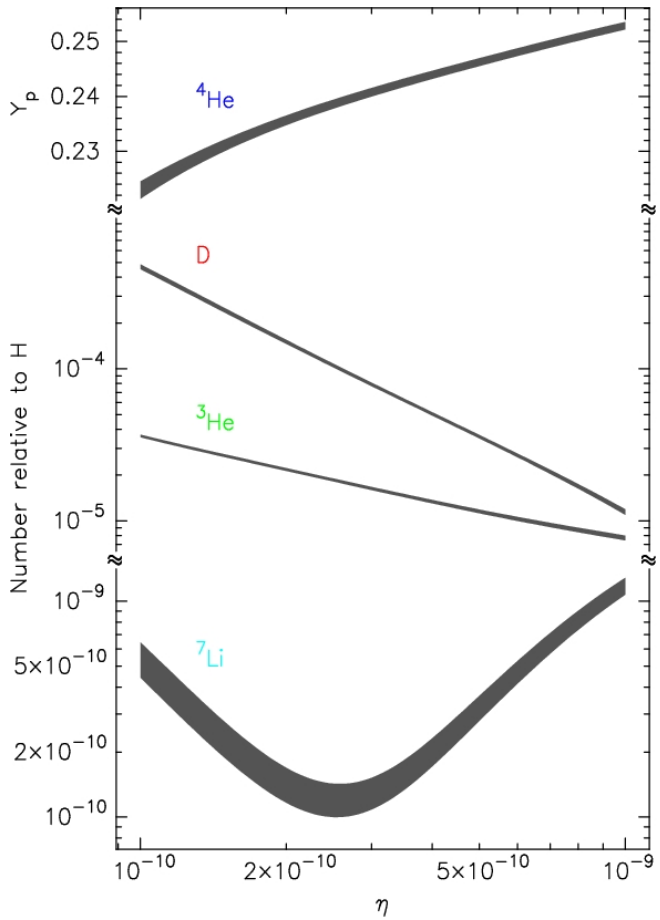


Bob Rood

Tom Wilson

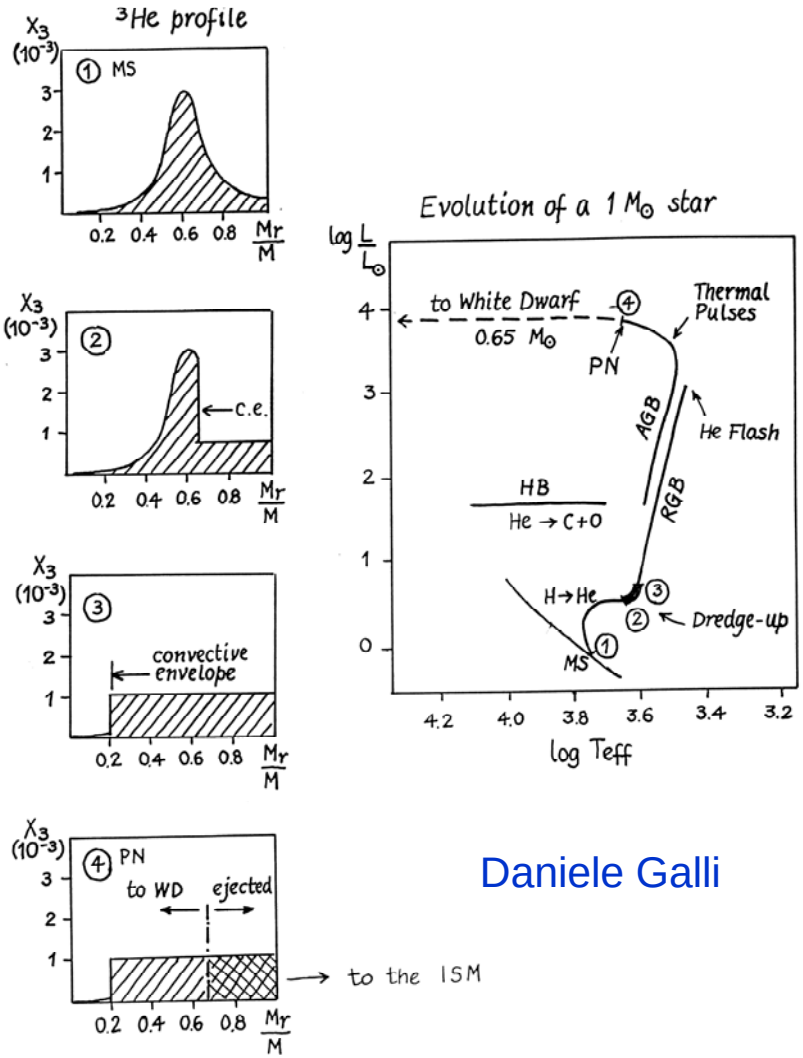
Miller Goss

Primordial Nucleosynthesis



Burles et al. (2001)

Stellar Nucleosynthesis



Daniele Galli

$^1H + {}^1H \rightarrow {}^2H + e^+ + \nu$ Production

$^2H + {}^1H \rightarrow {}^3He + \gamma$ $T > 6 \times 10^5$ K

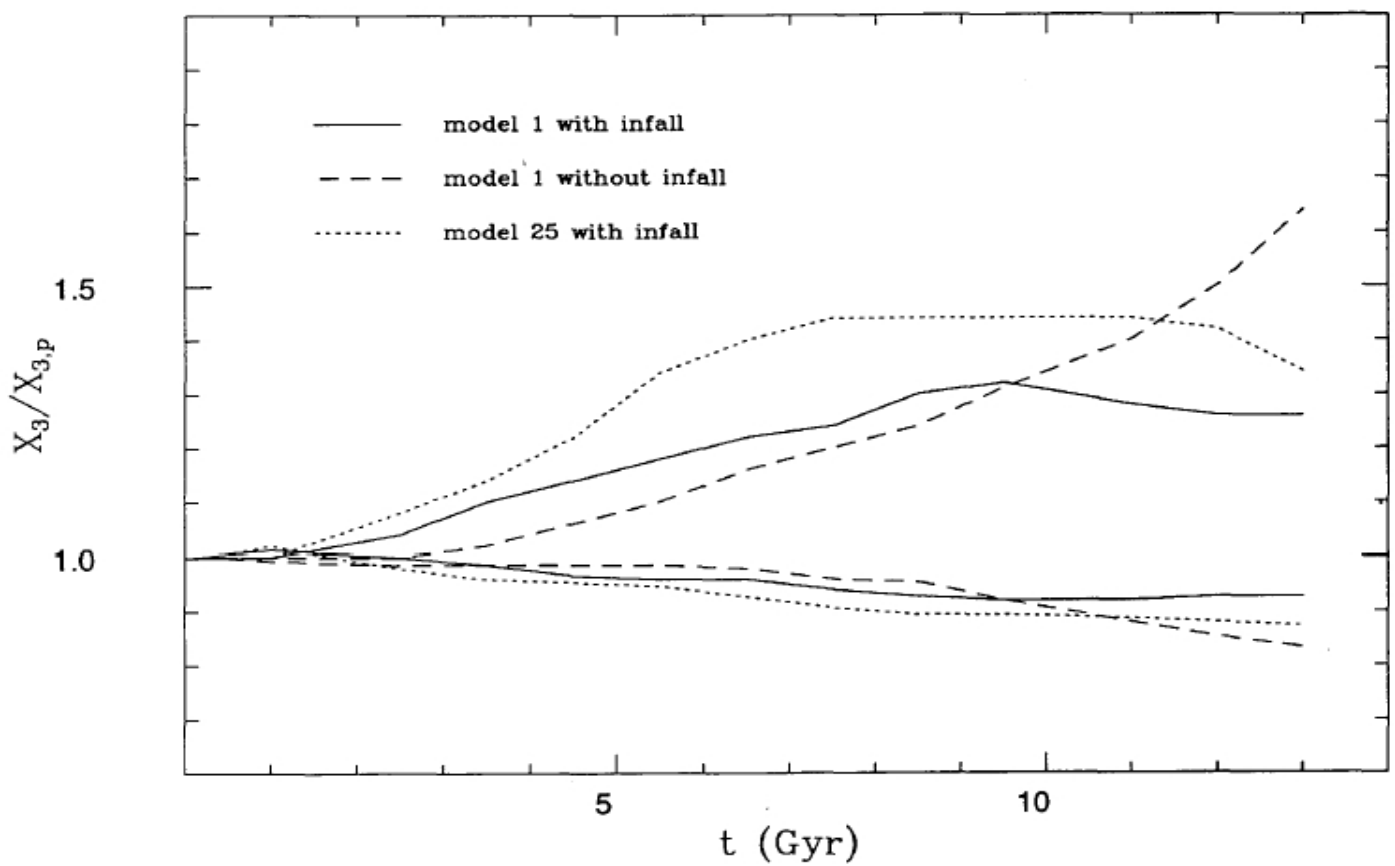
$^3He + {}^3He \rightarrow {}^4He + 2p$ Destruction

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

"The present interstellar 3He is more of stellar than primordial origin."

Rood, Steigman & Tinsley (1976)

Galactic Chemical Evolution



Steigman & Tosi (1992)

Observations of 3He

Solar System:

Meteorites (protosolar)— $^3He/H = 1.5 \pm 0.3 \times 10^{-5}$ (Bochsler & Geiss 1974)

Jupiter (Galileo Probe)— $^3He/^4He = 1.66 \pm 0.05 \times 10^{-4}$ (Mahaffy et al. 1998)

Local Interstellar Medium (LISM):

Ulysses Probe— $^3He/^4He = 2.2^{+0.7}_{-0.6}(stat) \pm 0.2(sys) \times 10^{-4}$ (Gloeckler & Geiss 1996)

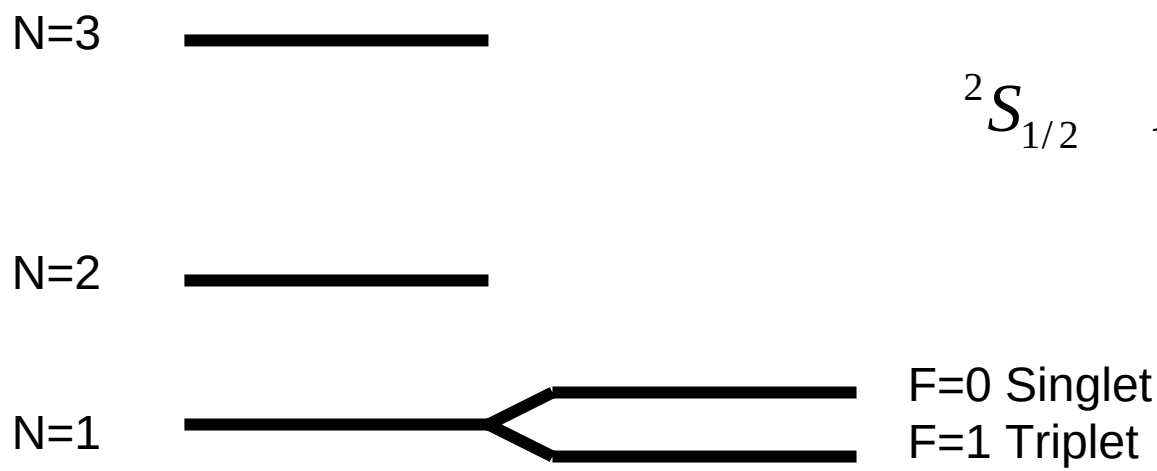
Mir— $^3He/^4He = 1.71^{+0.50}_{-0.42} \times 10^{-4}$ (Salerno et al. 2003)

Galactic:

^3He Recombination Lines?

$^3He^+$ Hyperfine Line?

3He+ Hyperfine Transition

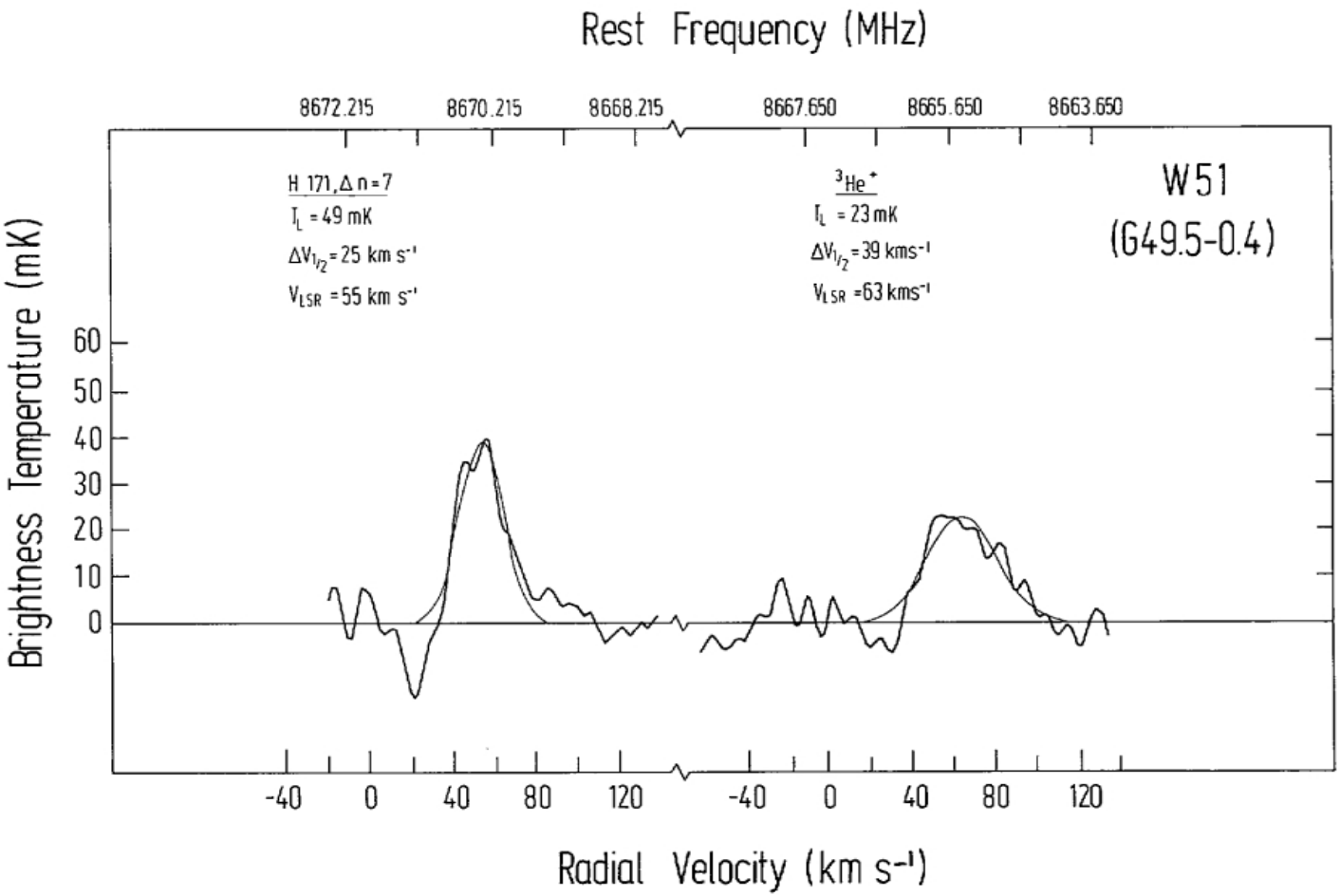


$^2S_{1/2} \quad F = 0 \rightarrow 1$

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

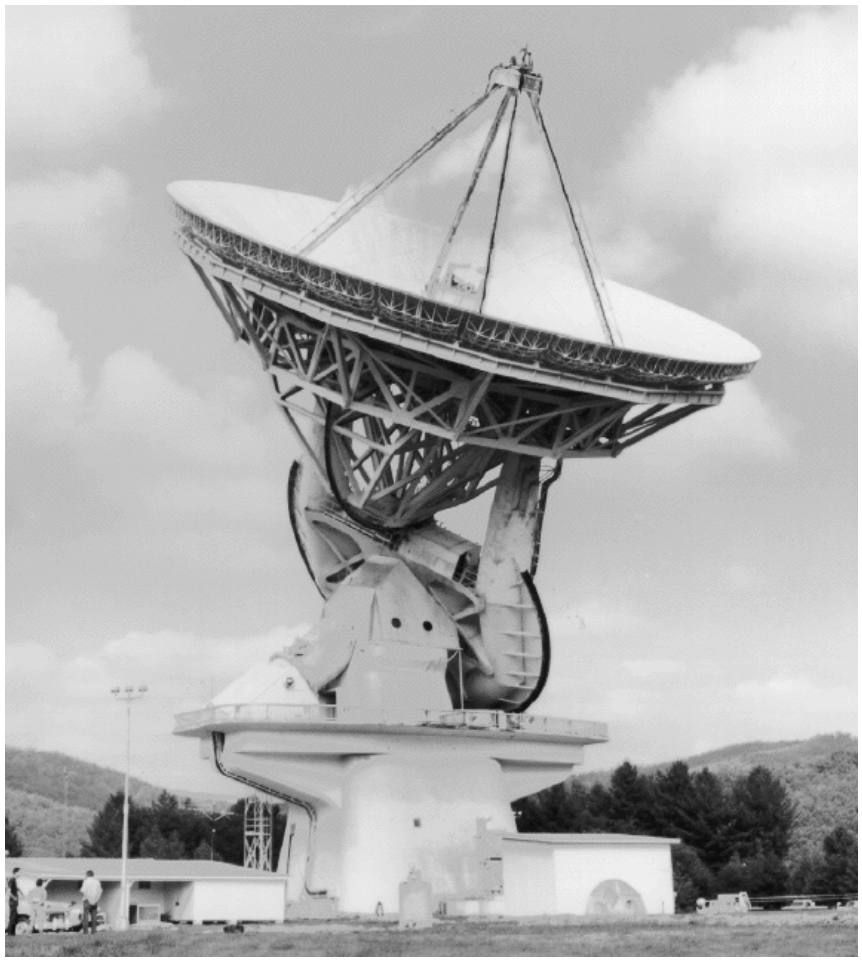
$A_{01} = 1.950 \text{ x } 10^{-12} \text{ s}^{-1} \quad (16{,}300 \text{ years})$

First 3He+ Hyperfine Detection



Rood et al. (1979)

NRAO 140 Foot Telescope (HII Regions)



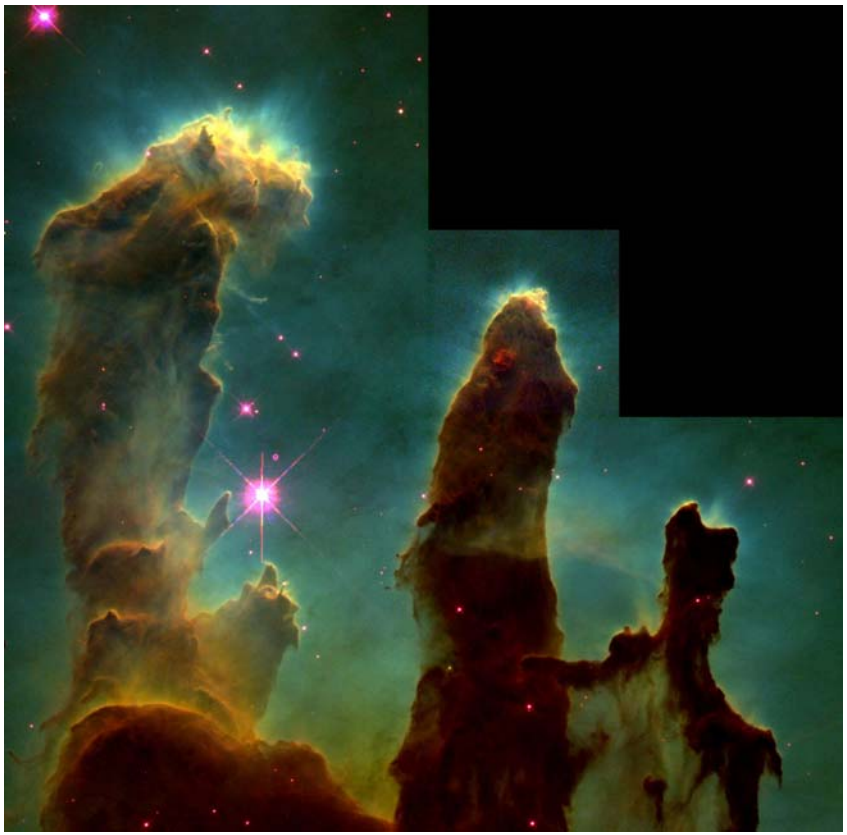
Galactic HII Regions
(1982 – 1999)
(~50)

Orion nebula (M42)
Eagle nebula (M16)
Rosette nebula
W49
S209
G0.60+0.32

HPBW = 3.5 arcmin

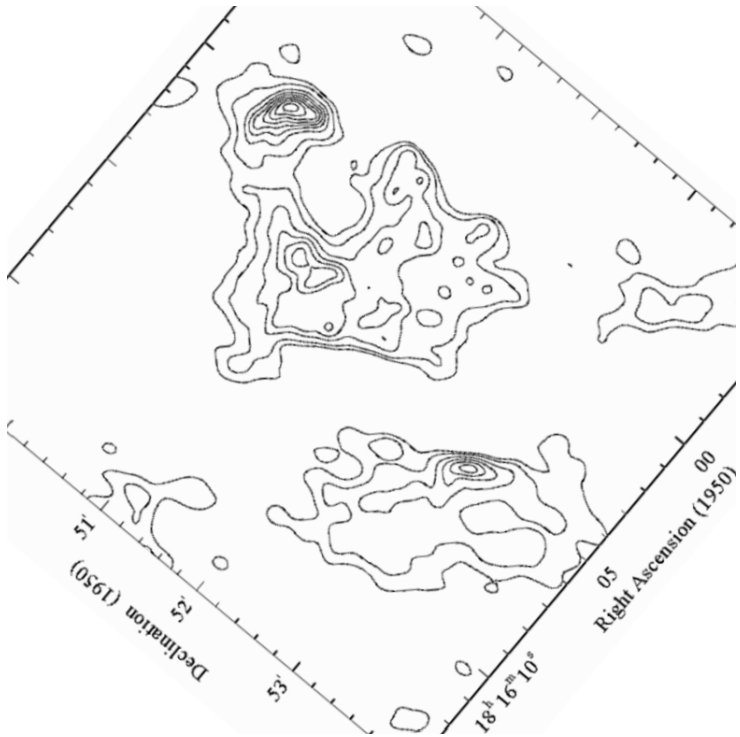
M16 (Eagle Nebula)

Hubble Space Telescope



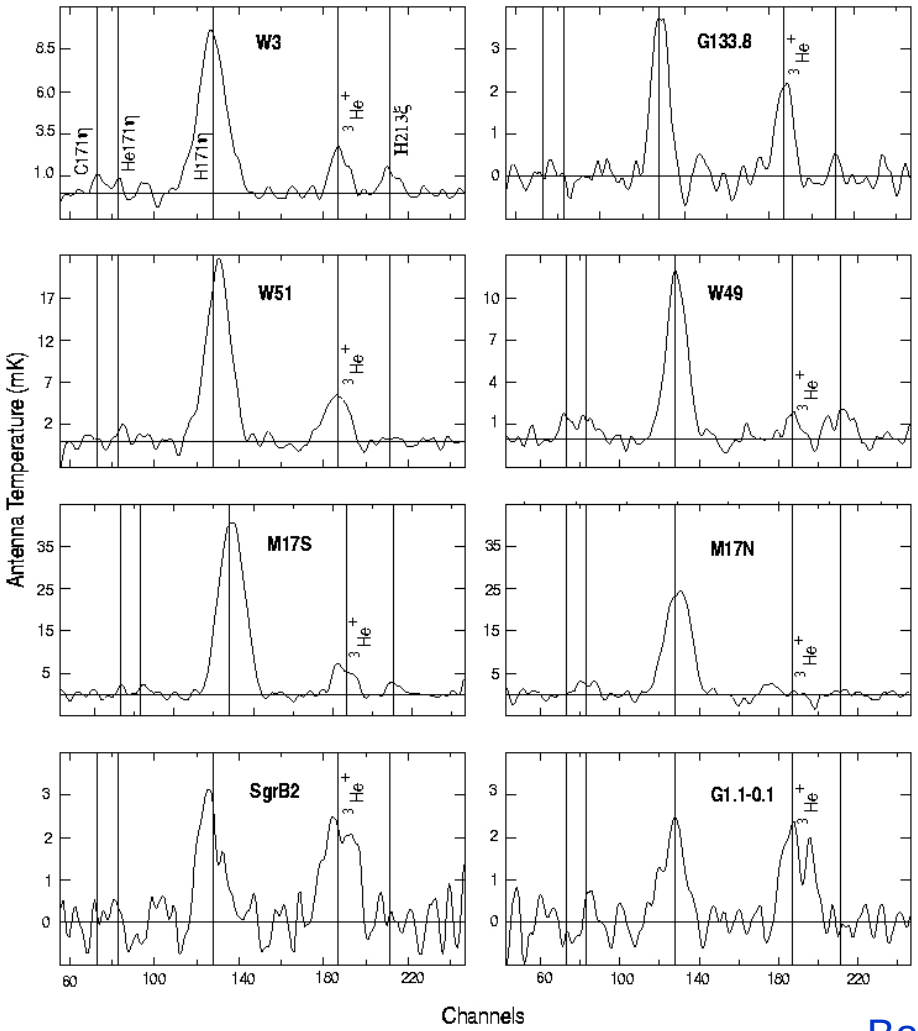
Hester & Scowen

NRAO Very Large Array



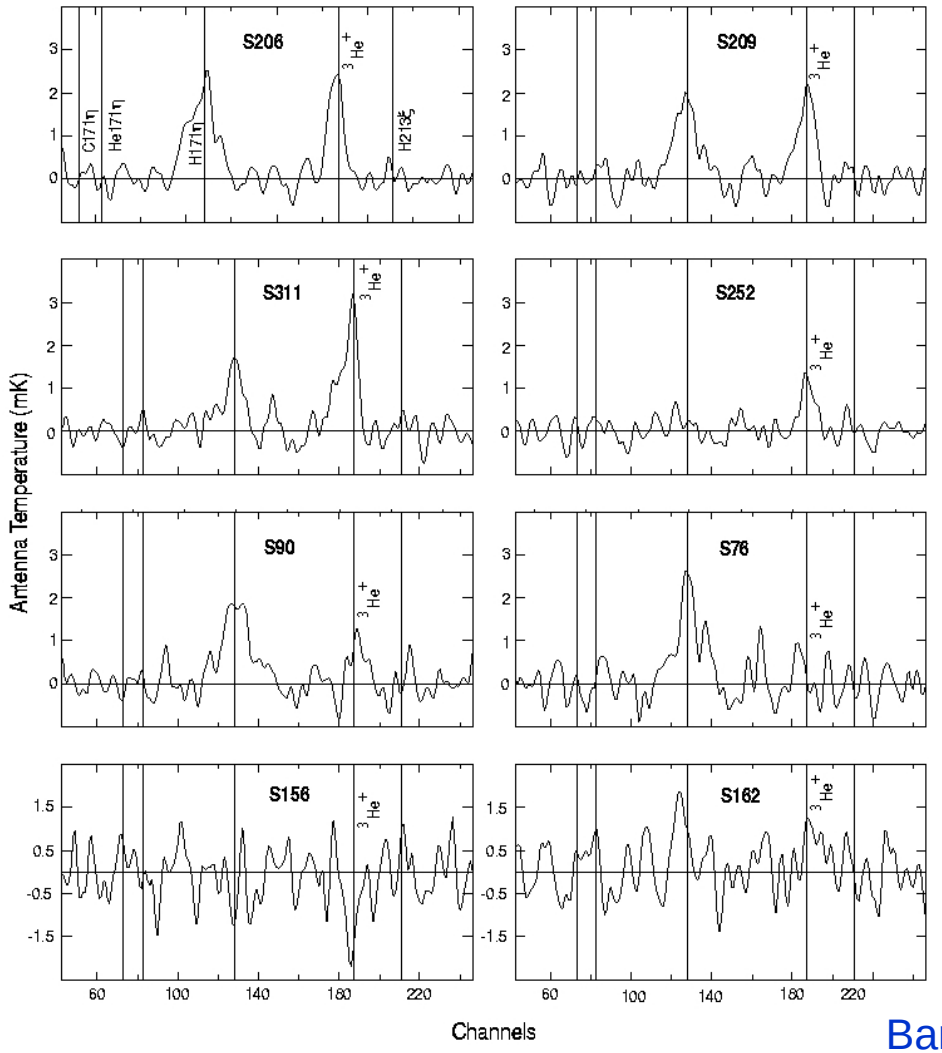
White [DSB] et al. (1999)

HII Region 3He+ Spectra



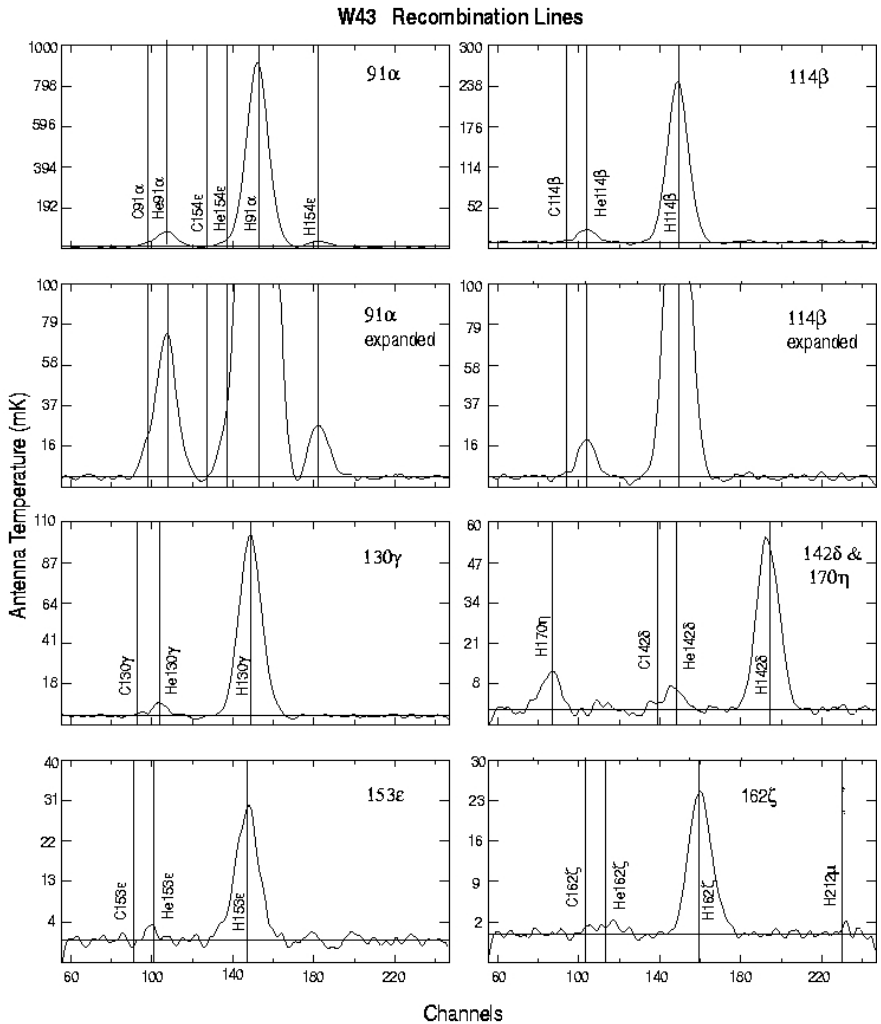
Bania [DSB] et al. (1997)

HII Region 3He+ Spectra – cont.



Bania [DSB] et al. (1997)

HII Region Radio Recombination Line Spectra



$H91\alpha \quad n = 92 \rightarrow 91$

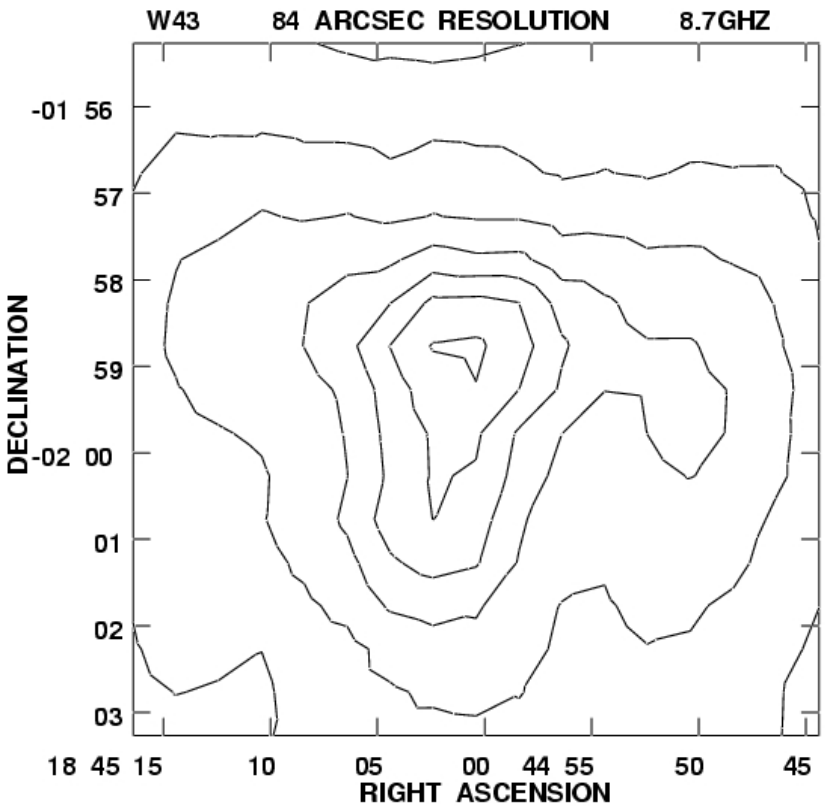
$H114\beta \quad n = 116 \rightarrow 114$

$H130\gamma \quad n = 133 \rightarrow 130$

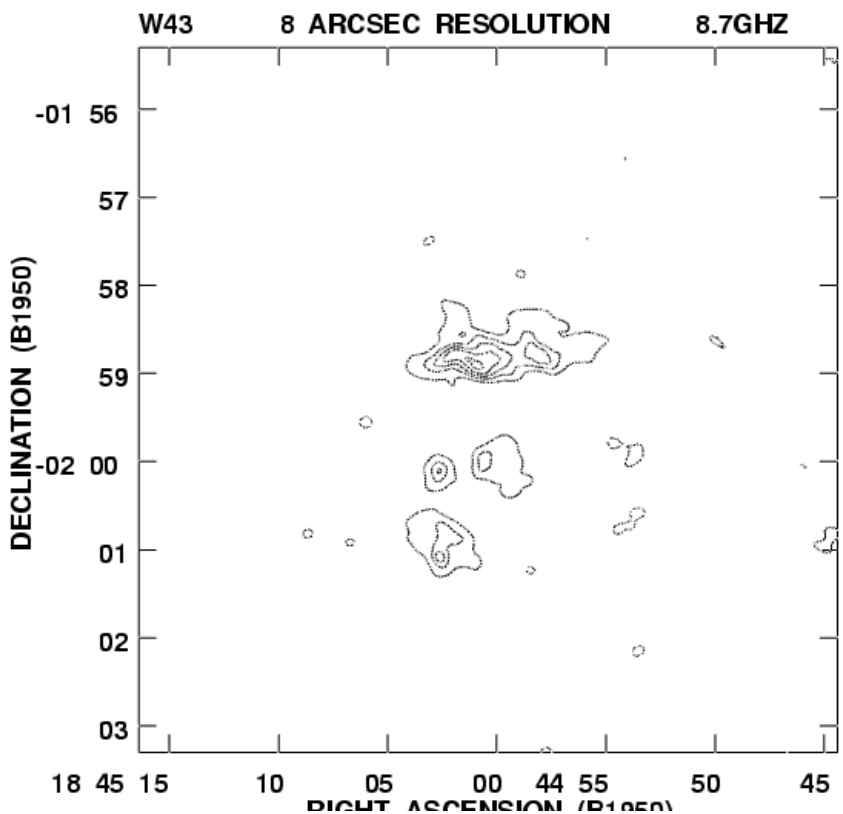
Bania [DSB] et al. (1997)

HII Region Radio Continuum

MPIfR 100m Telescope

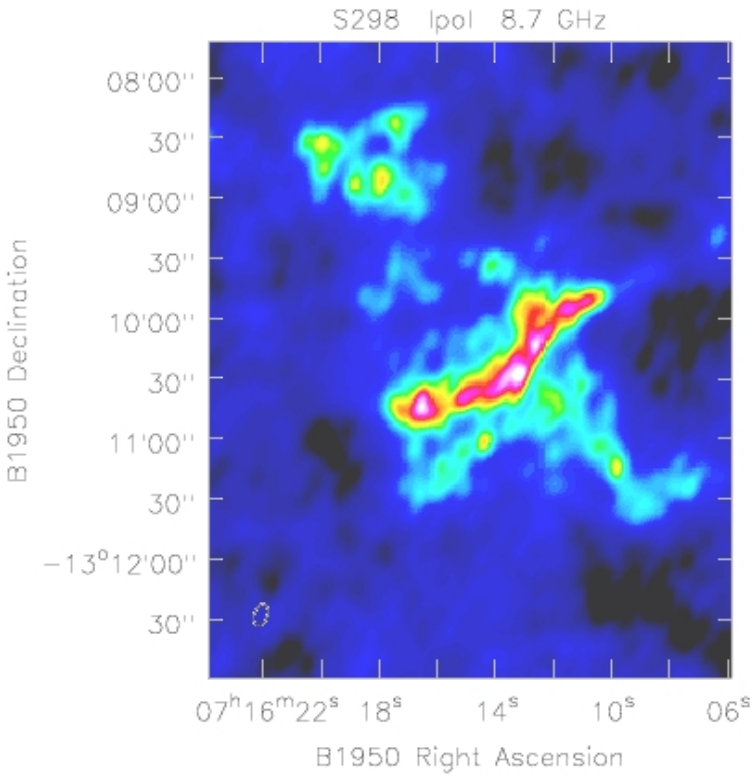


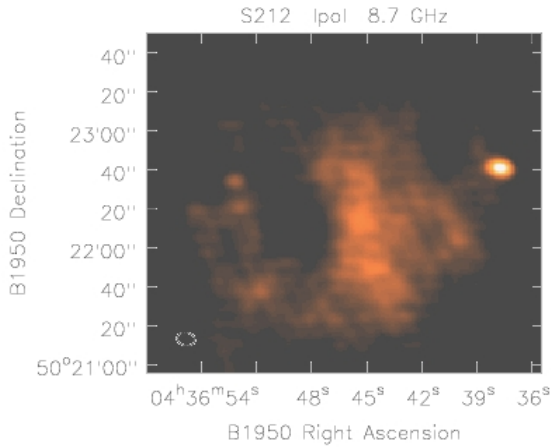
NRAO Very Large Array

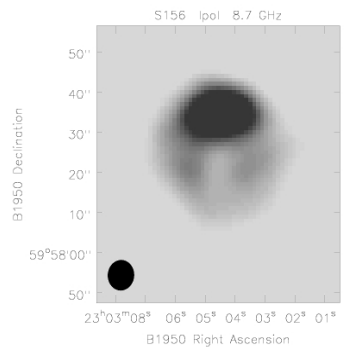


DSB et al. (1995)

HII Region Radio Continuum – cont.







MPIfR 100 meter Telescope (Planetary Nebulae)

Galactic Planetary Nebulae
(1991 – 1995)

NGC 3242 (Ghost of Jupiter)
NGC 6543 (Cat's Eye)
NGC 6720 (Ring)
NGC 7009 (Saturn)
NGC 7662 (Blue Snowball)

HPBW = 80 arcsec

NGC3242 (Ghost of Jupiter)

Hubble Space Telescope

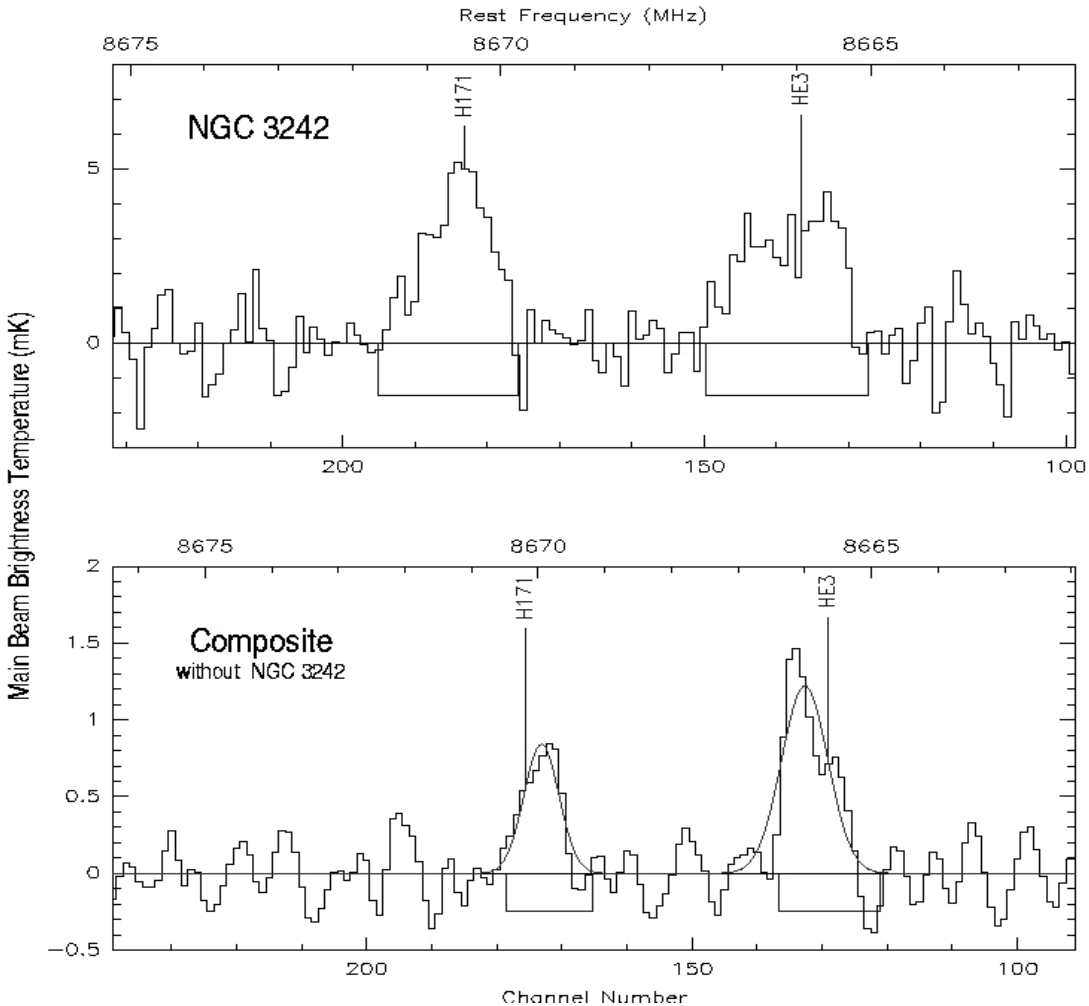
Balick et al.

NGC6543 (Cat's Eye)

Hubble Space Telescope

Corradi & Tsvetanov

Planetary Nebulae 3He+ Spectra



DSB et al. (1997)

HII Region Models

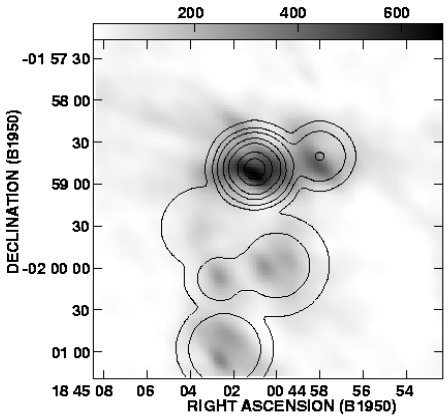
$$\text{Density Structure}: \quad {}^3\text{He}^+; \text{H}^+ \Rightarrow {}^3\text{He}^+ / \text{H}^+$$

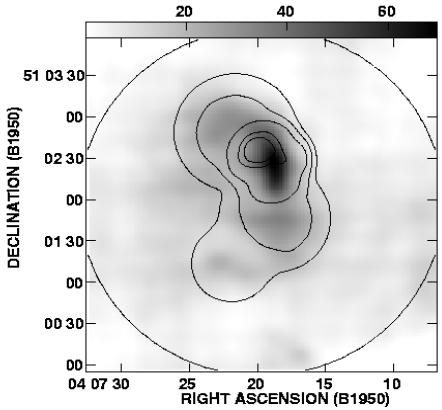
$$\text{Ionization Structure}: \quad {}^3\text{He}^+ / \text{H}^+ \Rightarrow {}^3\text{He} / \text{H}$$

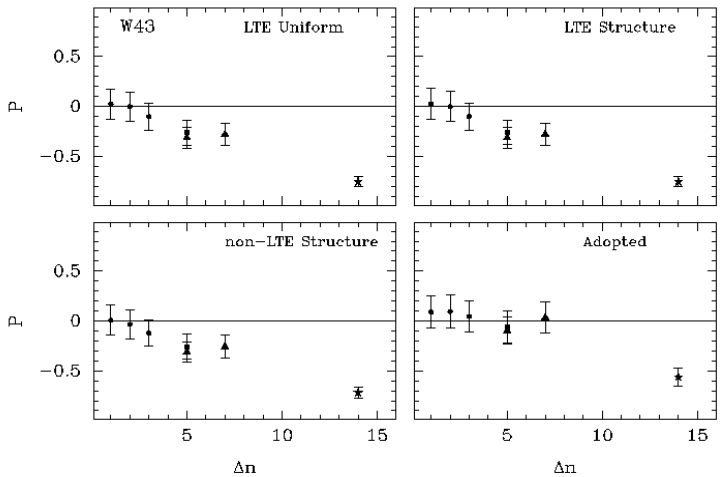
$${}^3\text{He}^+ \text{ Transition}: \int n_e dl$$

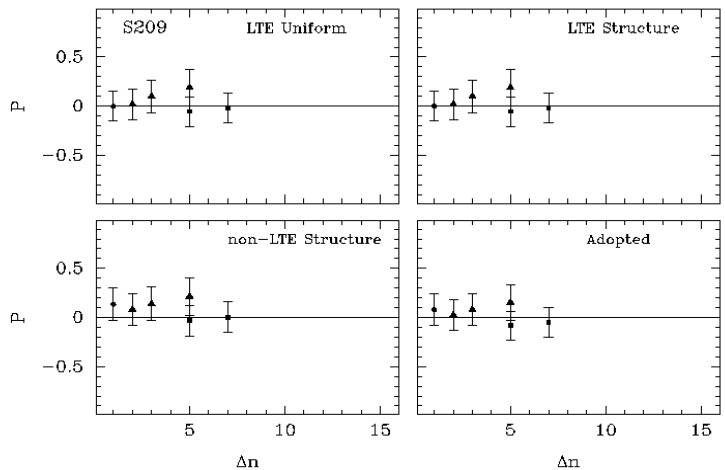
$$\text{RRL/Continuum}: \int n_e^2 dl$$

Density Structure Correction





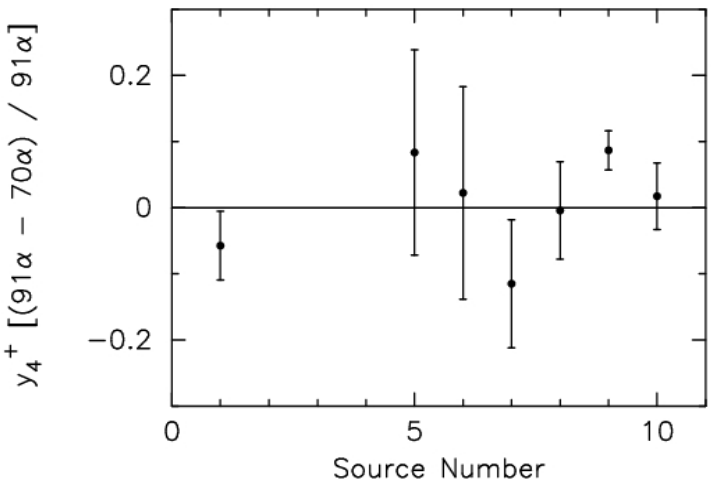




DSB et al. (1999)

Ionization Structure Correction

10 HII Regions

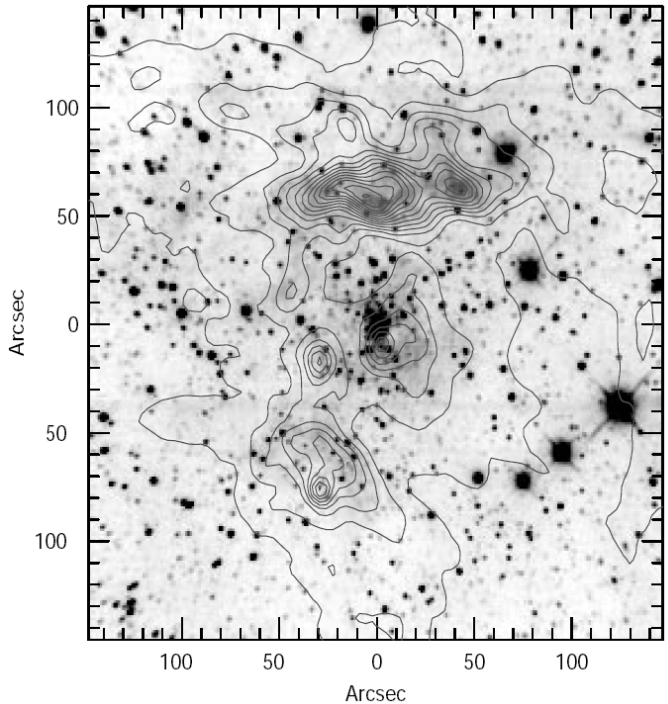


$\mathrm{H91}\alpha \quad \mathrm{HPBW} = 3.'5$

$\mathrm{H70}\alpha \quad \mathrm{HPBW} = 1.'5$

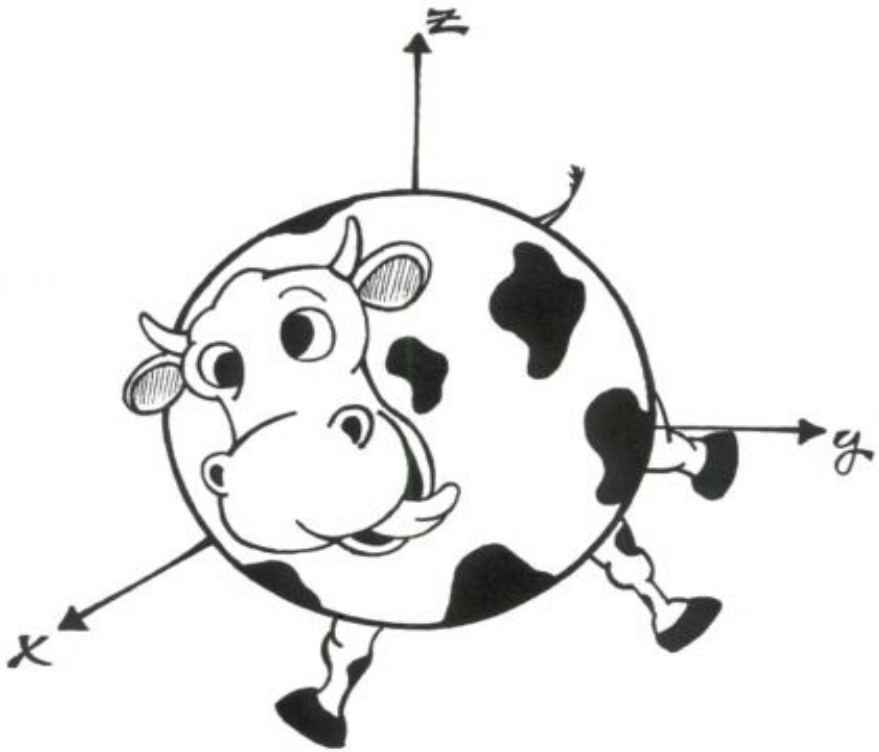
Bania [DSB] et al. (2007)

W43

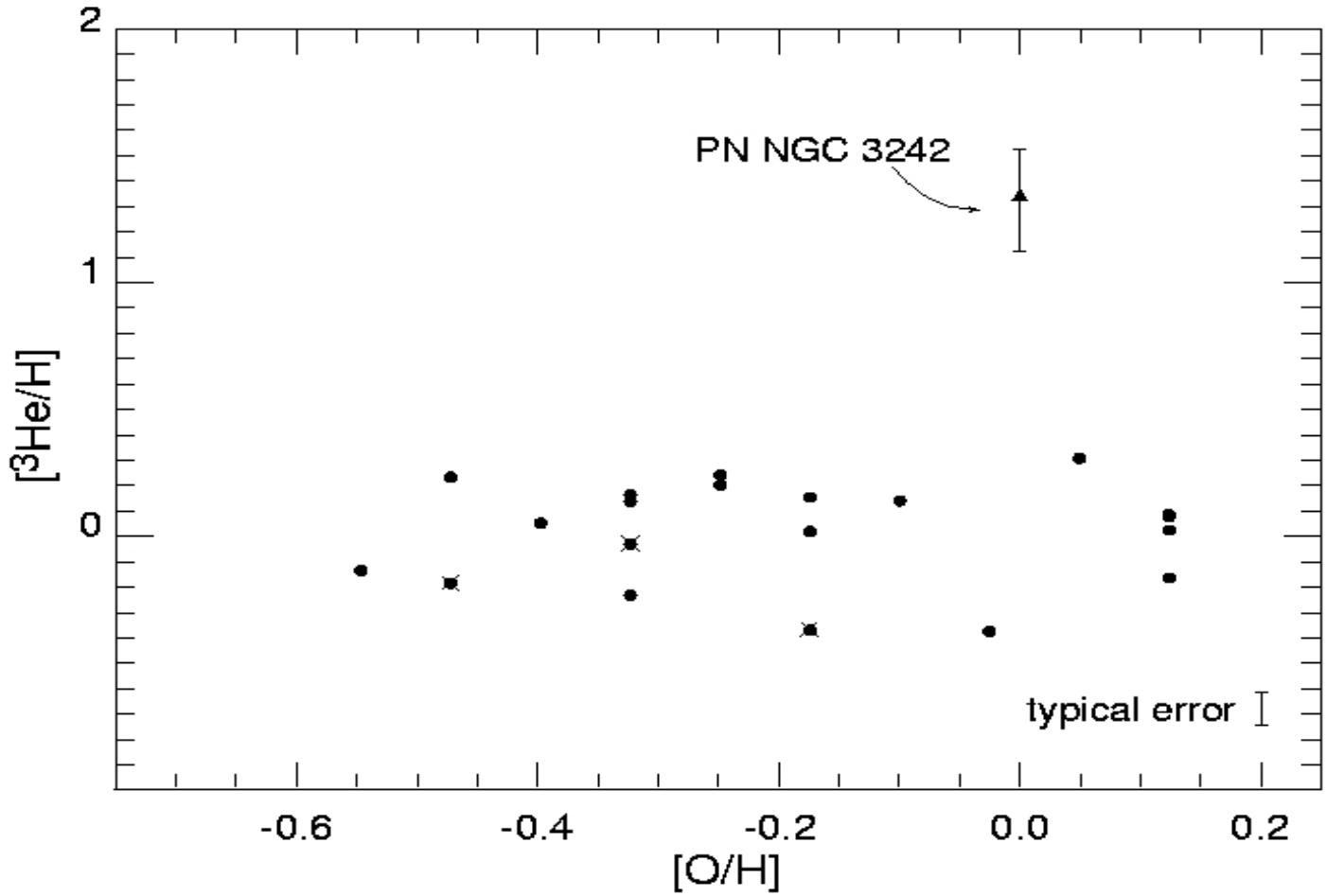


DSB, Goss, & De Pree (2001)
Blum et al. (1999)

Simple Sources

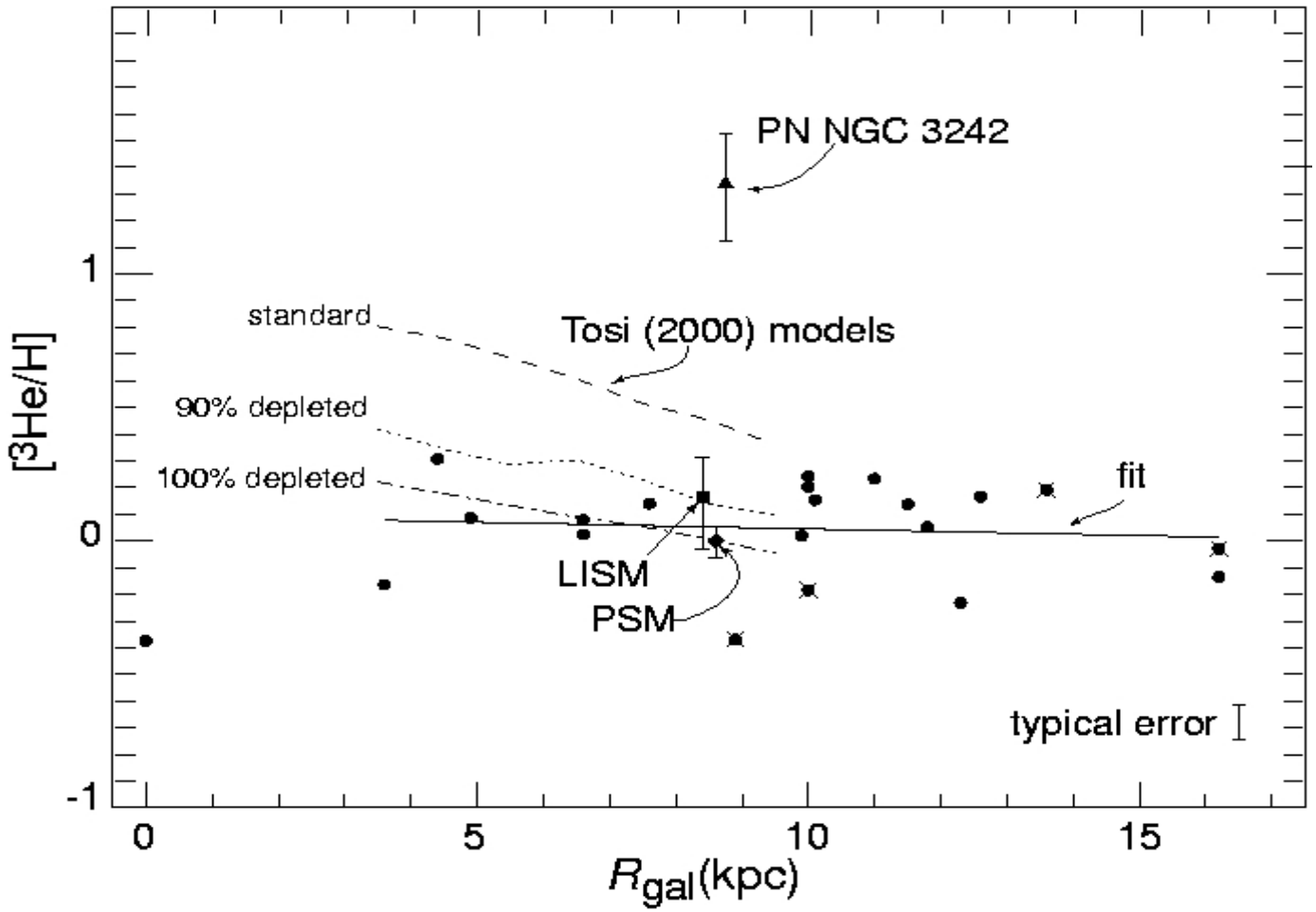


3He Abundance versus [O/H]



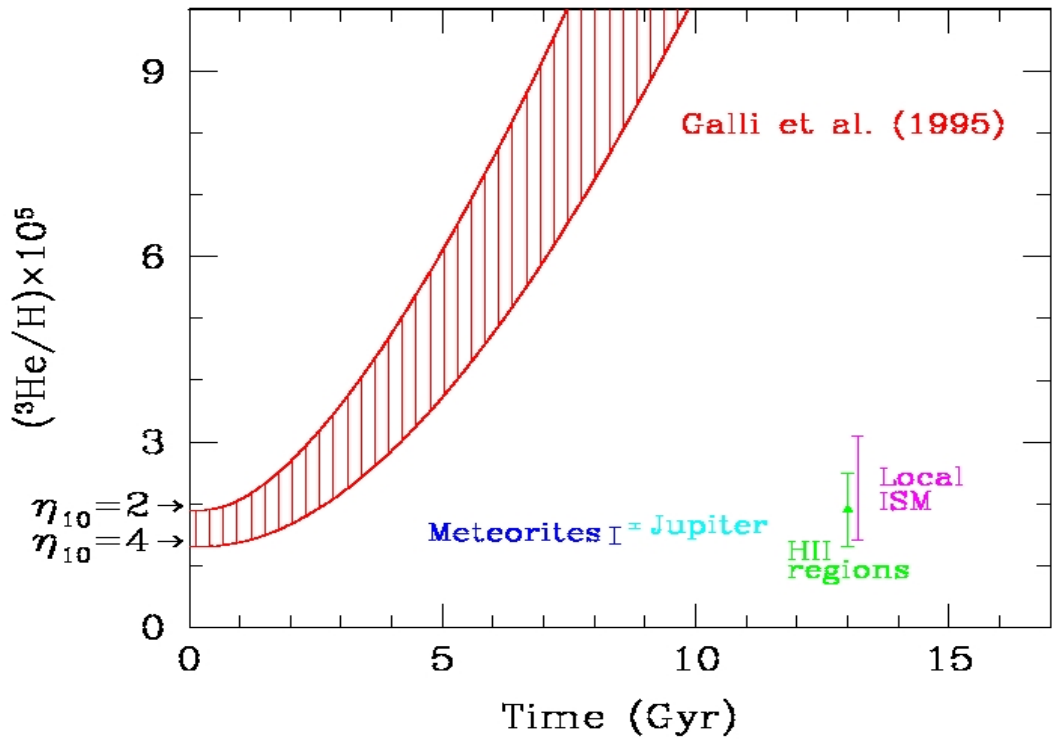
Bania, Rood & DSB (2002)

3He Abundance versus Rgal



Bania, Rood & DSB (2002)

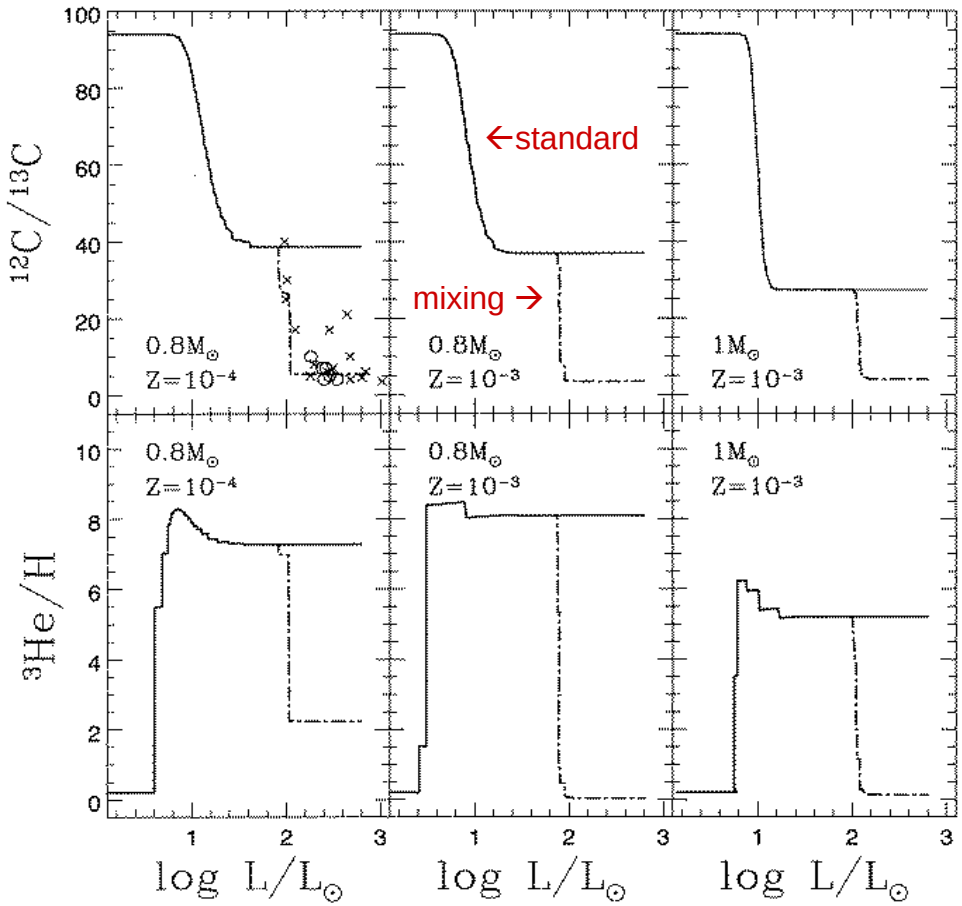
“The 3He Problem”



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

Daniele Galli

Rotational Mixing in Stars



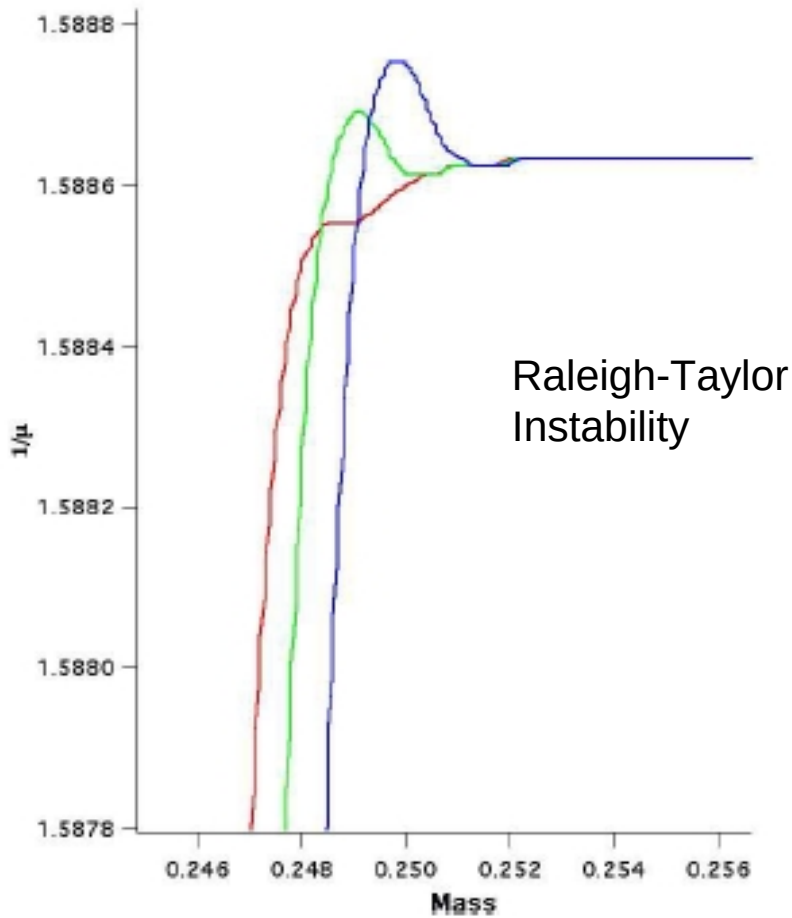
Charbonnel (1995)

"…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)

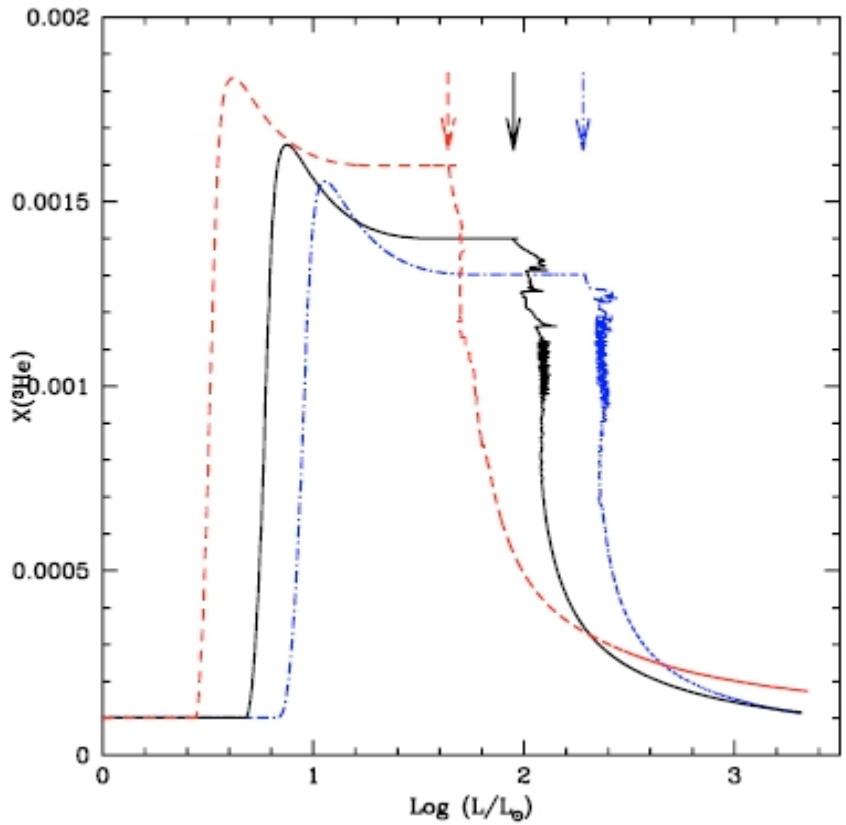
3-D Hydrodynamical and Nucleosynthetic Network



Raleigh-Taylor Instability

Eggleton et al. (2006)

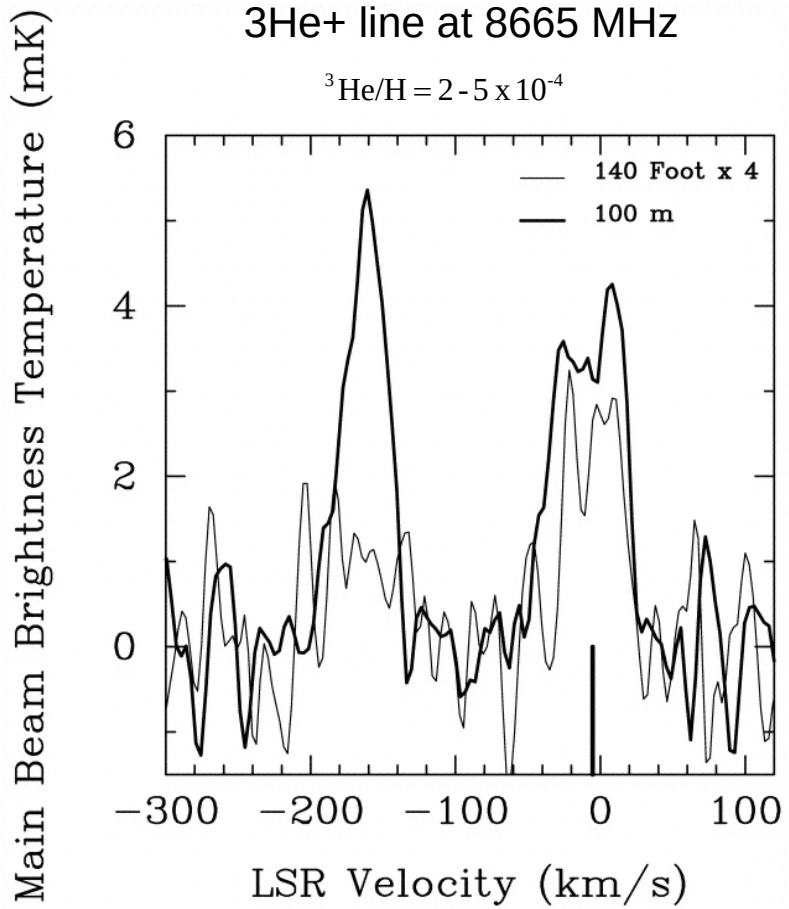
Thermohaline Mixing



Charbonnel & Zahn (2007)

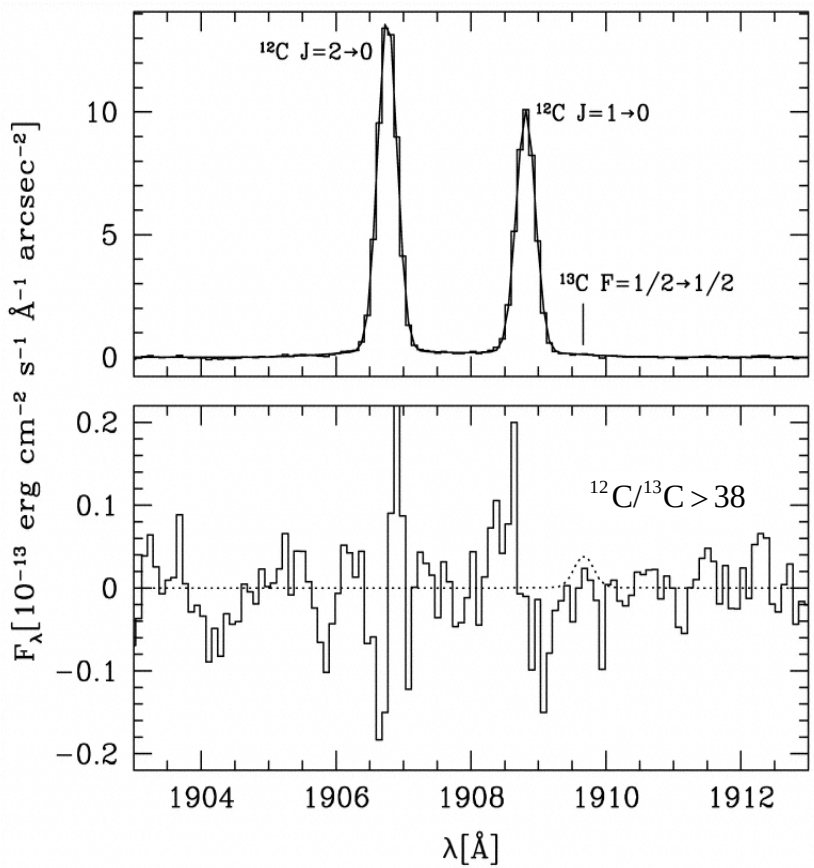
No Mixing in NGC3242

3He+ line at 8665 MHz



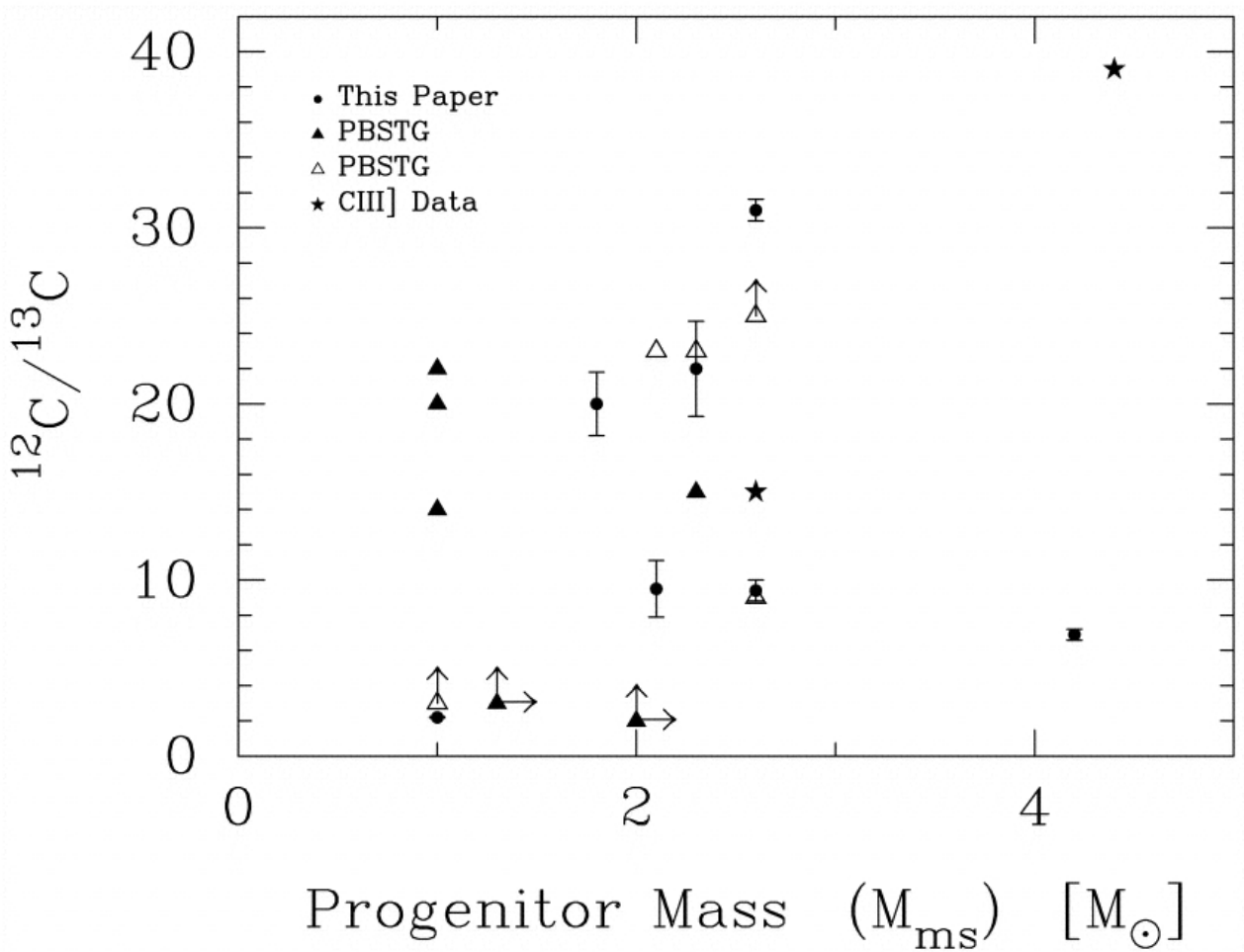
DSB et al. (1999)

C III] multiplet near 1908 A



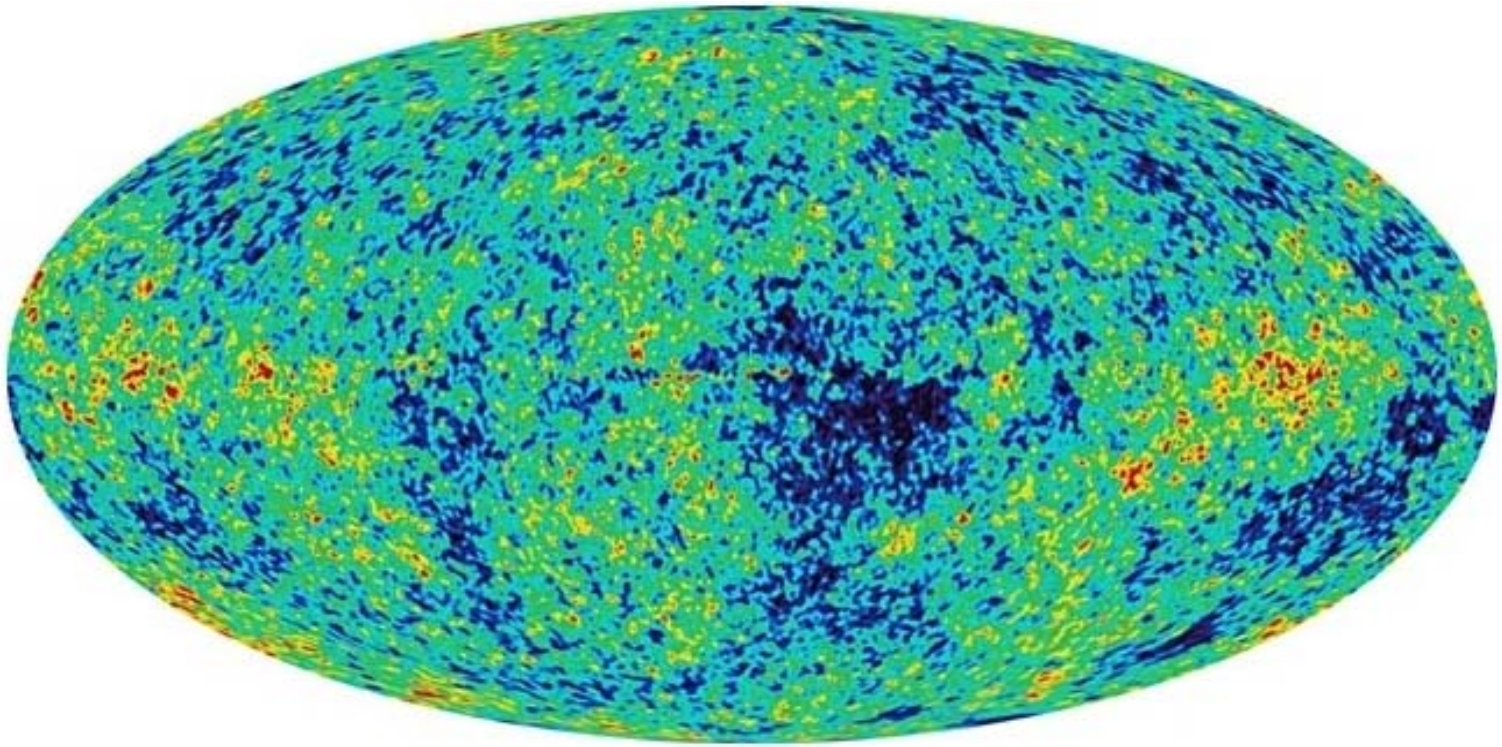
Palla et al. (2002)

12C/13C Ratios in Planetary Nebulae



DSB, McMullin & Wilson (2002)

Cosmic Microwave Background (WMAP)

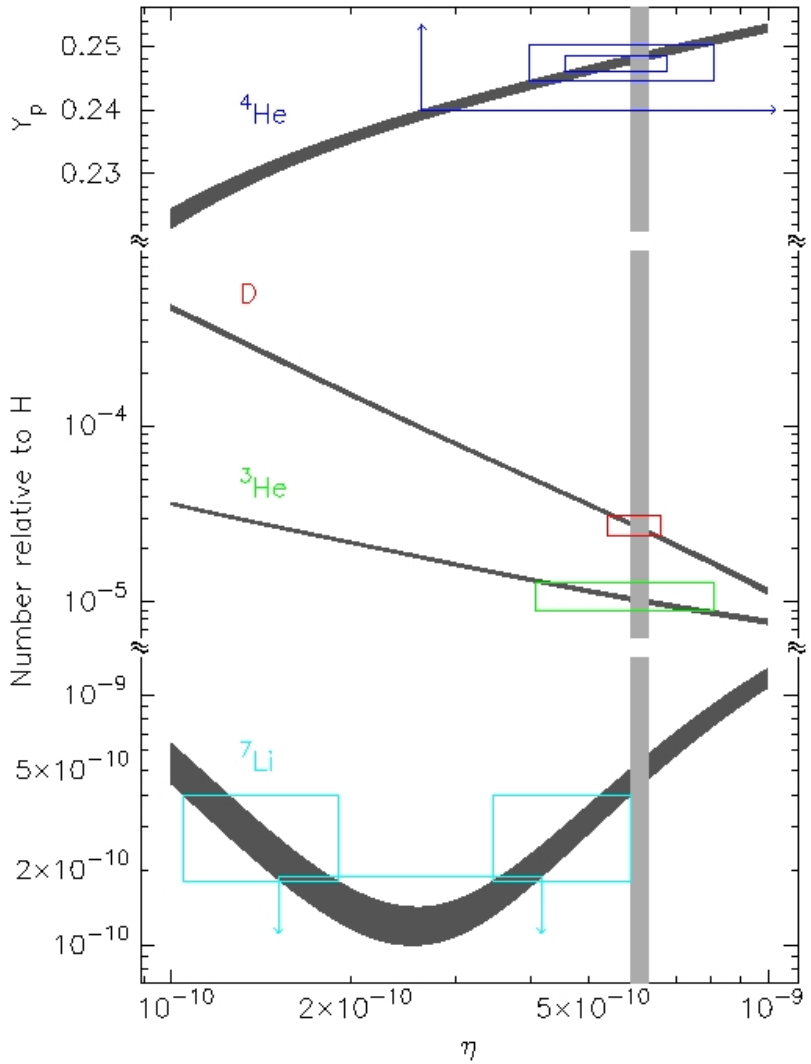


$$\Omega_b h^2 = 0.0223^{+0.0007}_{-0.0009}$$

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

Spergel et al. (2006)

Primordial Abundances



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

Kirkman et al. (2003)

Bania, Rood & DSB (2002)

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

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

Search for 3He in Planetary Nebulae

NRAO Very Large Array

NGC 6572
J320

NRAO Green Bank Telescope

NGC 3242
NGC 6543
NGC 7009
NGC 6826

NAIC Arecibo Telescope

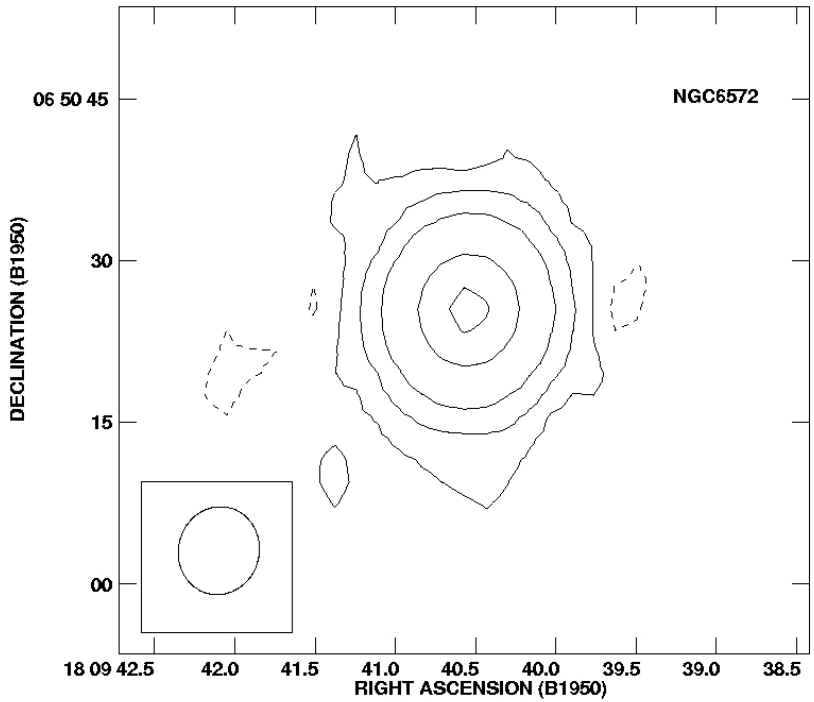
NGC 6210
NGC 6891

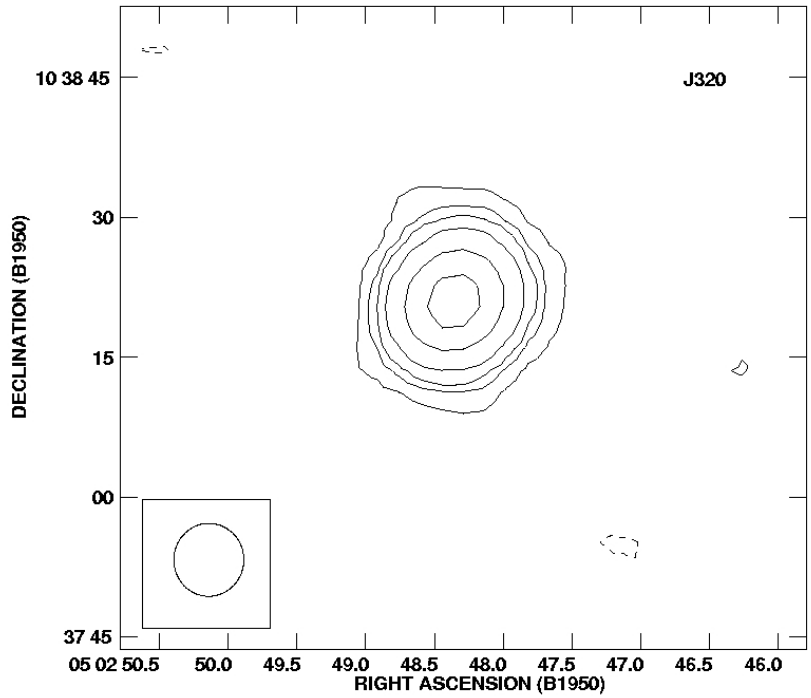
Planetary Nebulae Sample

PNe progenitor stars with NO extra mixing:

1. 4He/H < 0.125
2. [N/O] < -0.3
3. 13C/12C as low as possible
4. Peimbert Class: IIb, III, IV (old population)
5. Helium is singly ionized

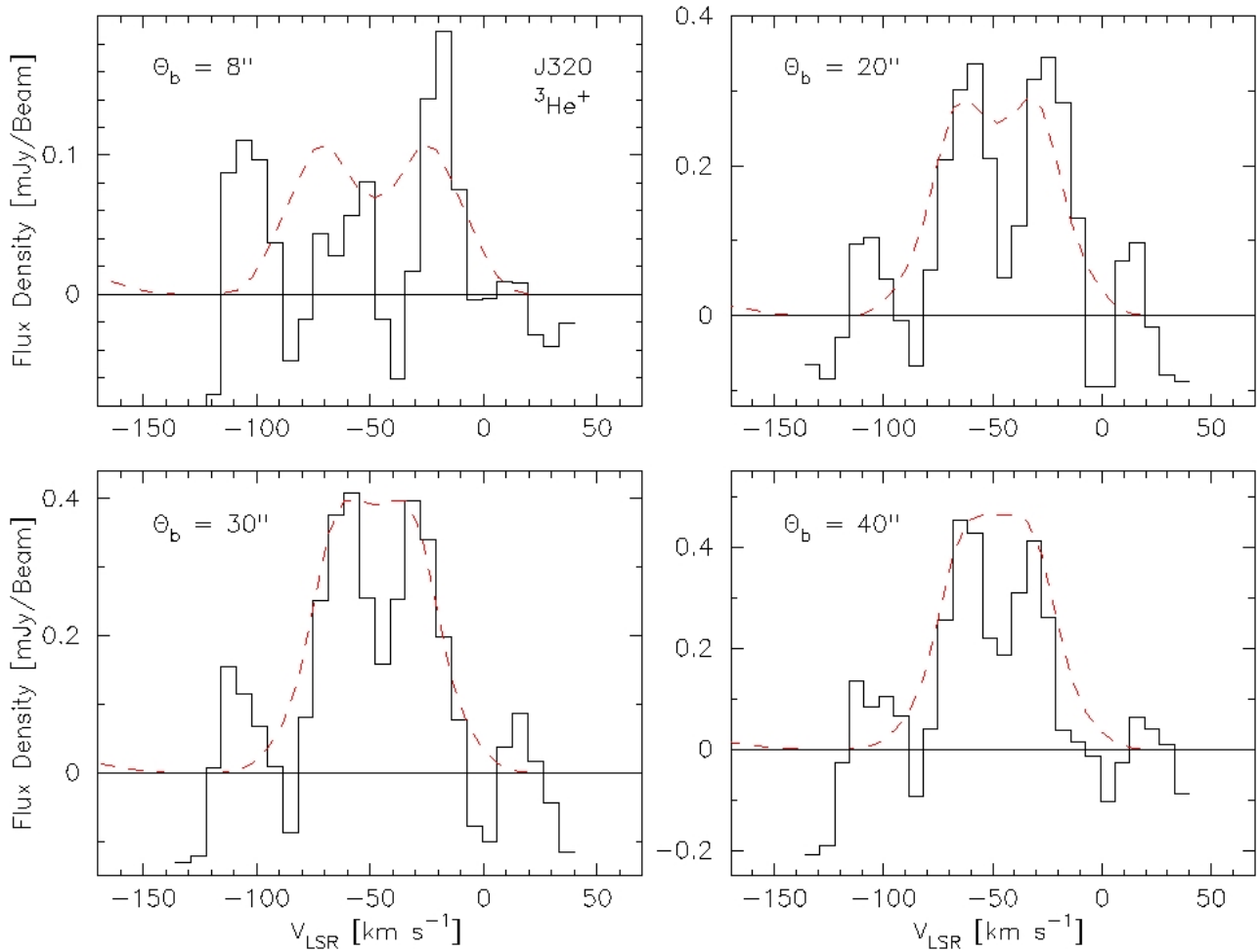
VLA PNe Continuum





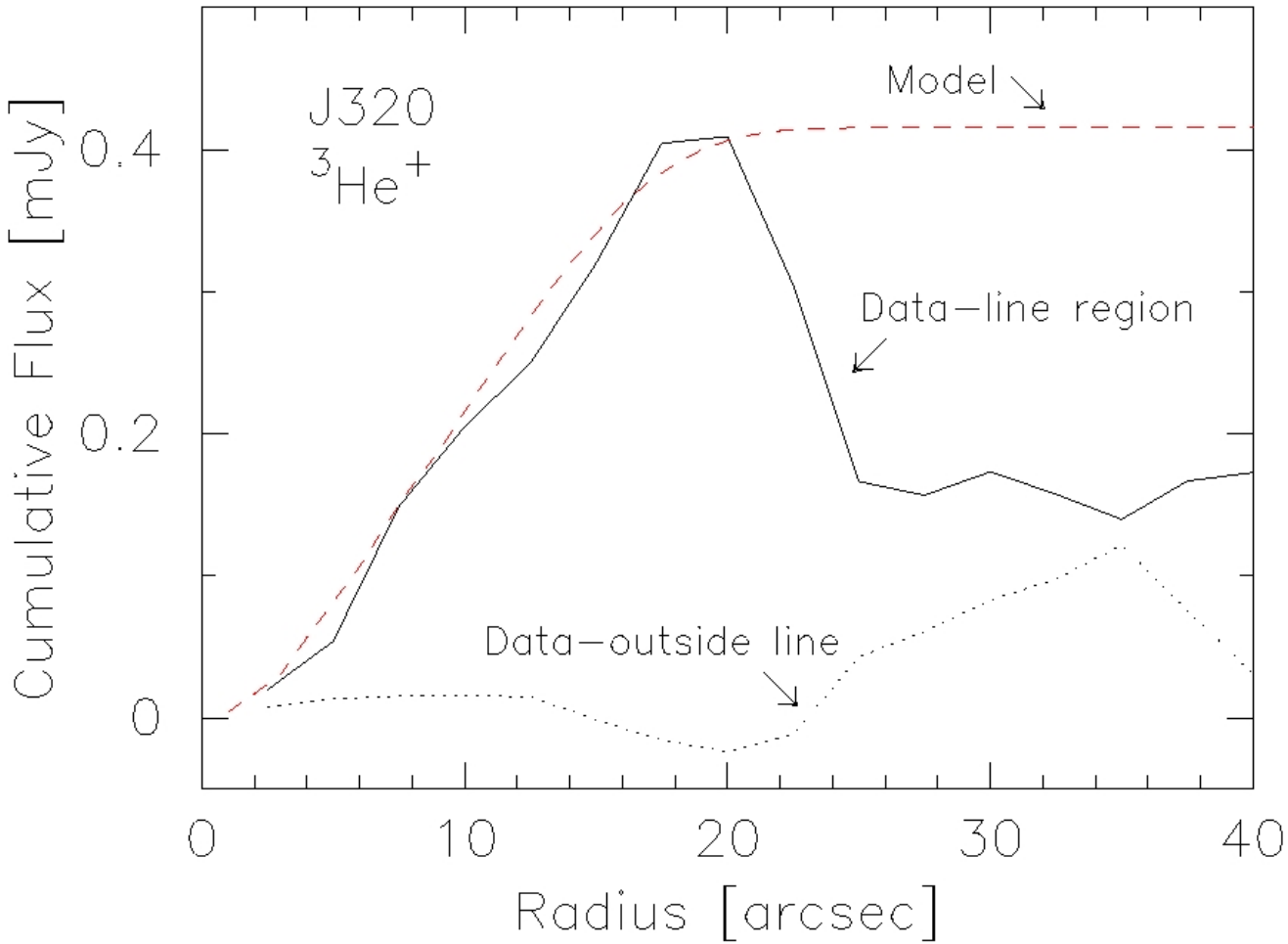
DSB et al. (2006)

VLA J320 3He+ Spectra



DSB et al. (2006)

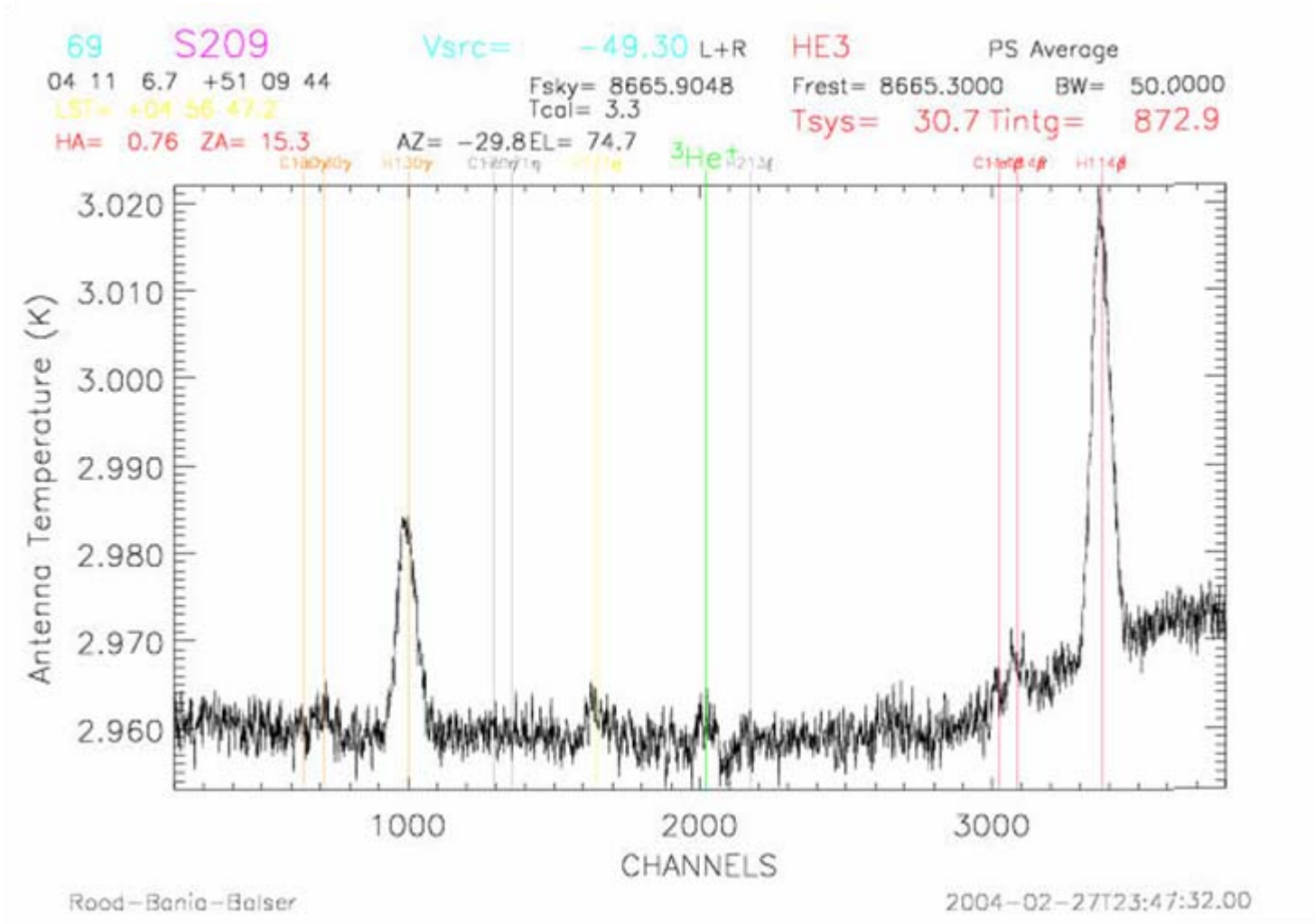
VLA J320 Model



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

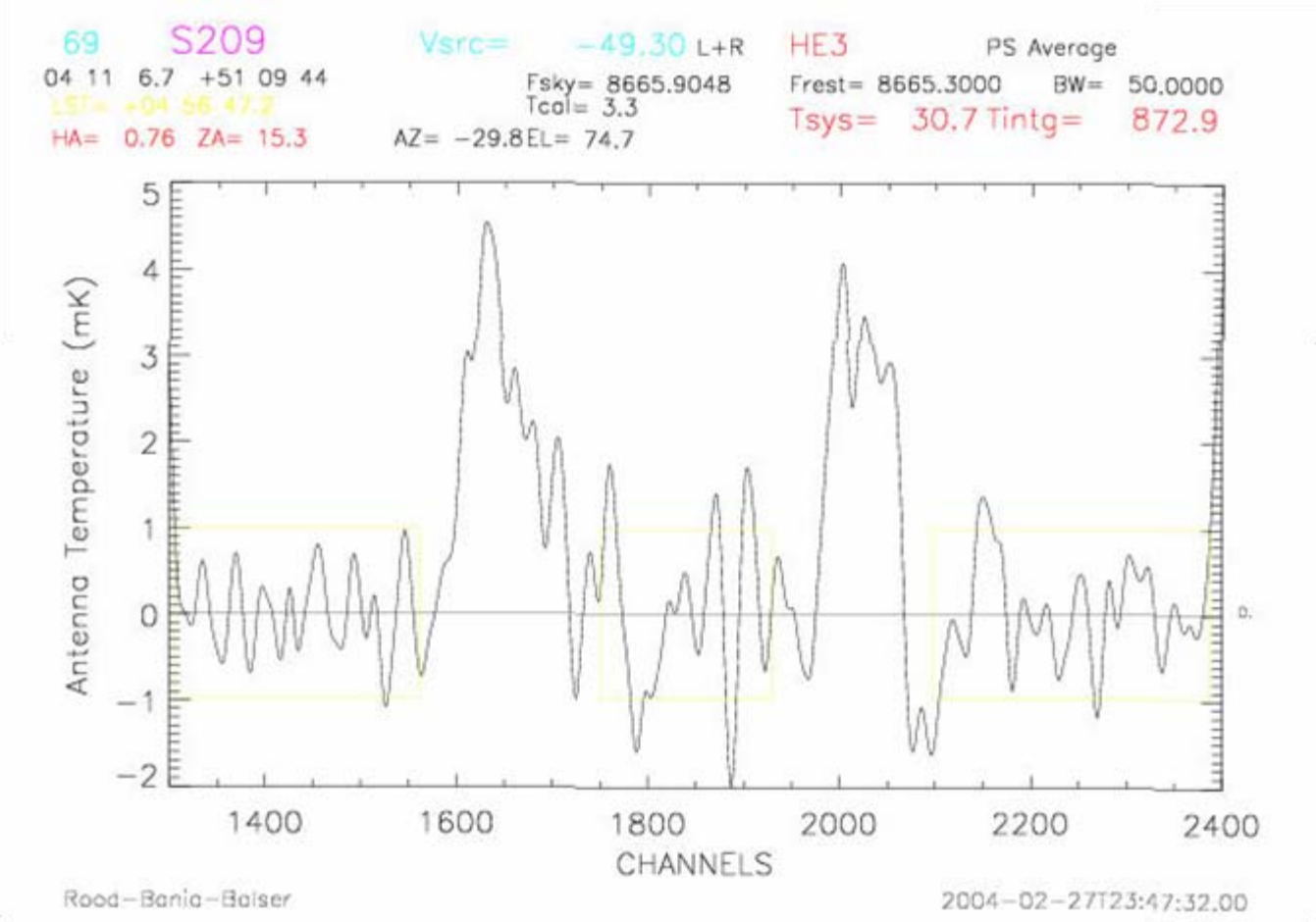
DSB et al. (2006)

GBT HII Region S206: calibrated raw spectrum



14.5 hr integration

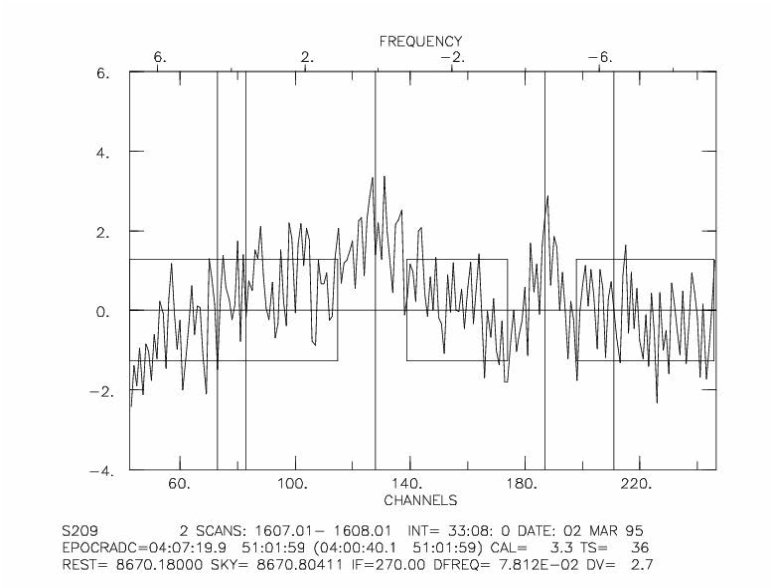
GBT HII Region S206: baseline removed and smoothed



14.5 hr integration 5 km/s resolution

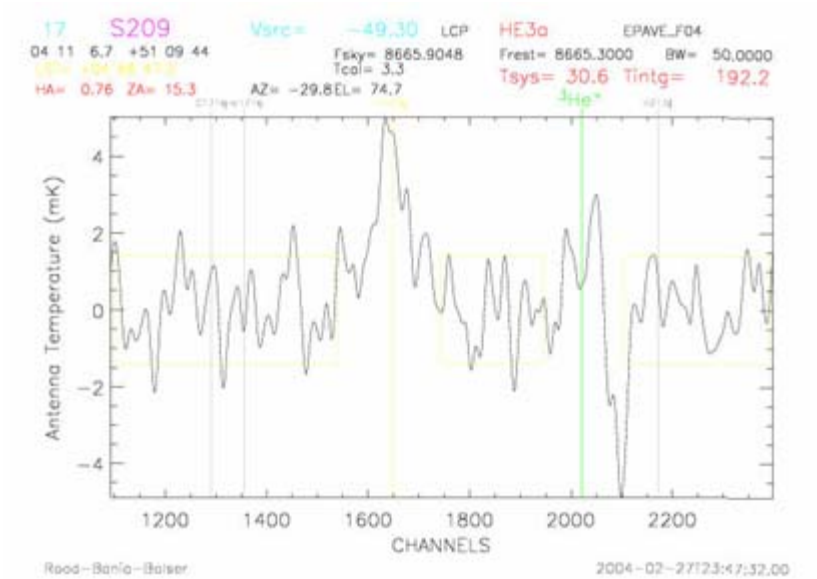
HII Region S209: 140 Foot versus GBT

140 Foot March 1995



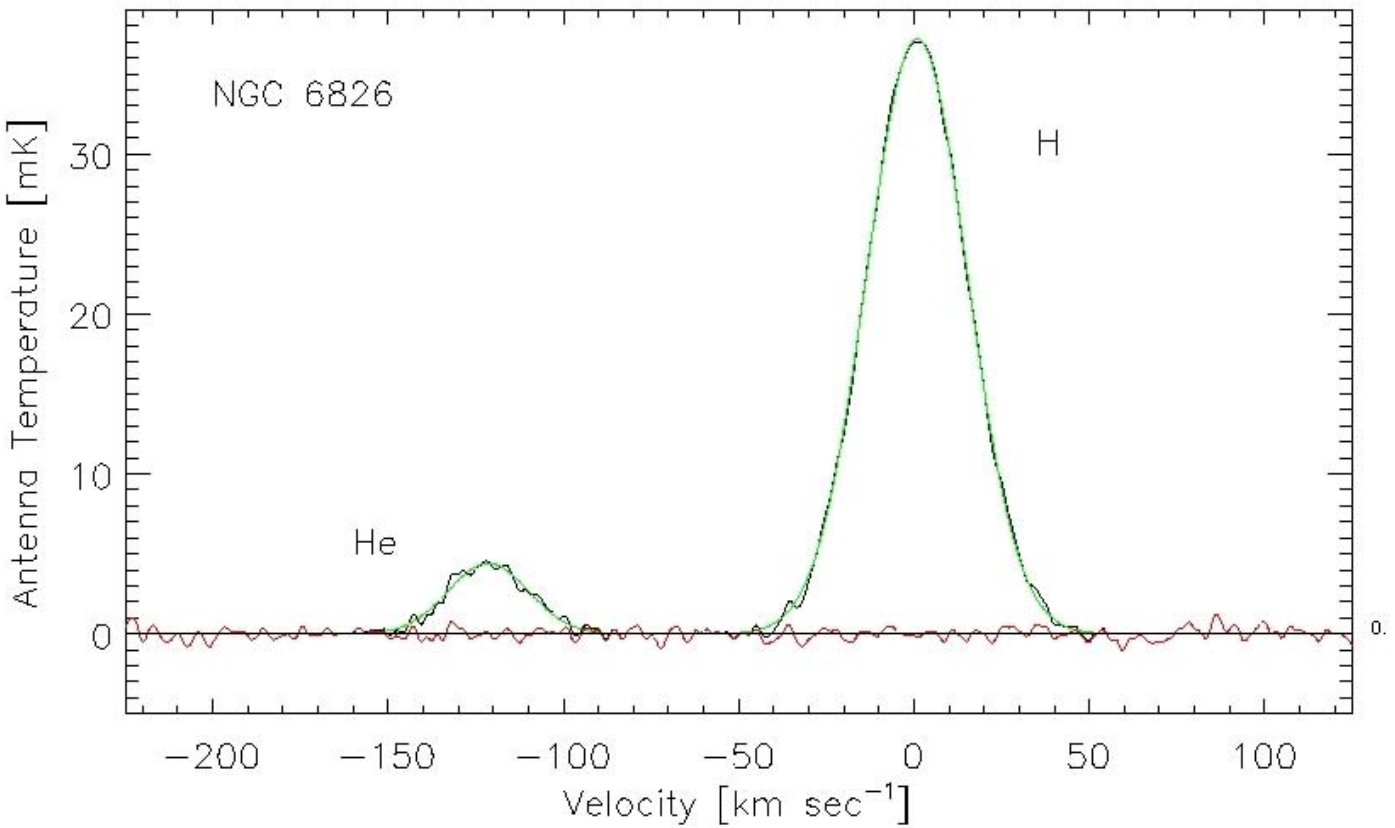
33.1 hr integration

GBT June 2004



3.2 hr integration

GBT PNe NGC 6826: (91+92) alpha lines



116.5 hr integration 2.1 km/s resolution

Higher Order Radio Recombination Lines

$\Delta n = 1: \; 91\alpha, 92\alpha$

$\Delta n = 2: \; 114\beta, 115\beta$

$\Delta n = 3: \; 130\gamma, 131\gamma, 132\gamma$

$\Delta n = 4: \; 144\delta, 145\delta$

$\Delta n = 5: \; 154\varepsilon, 155\varepsilon, 156\varepsilon$

$\Delta n = 6: \; 164\zeta, 165\zeta$

$\Delta n = 7: \; 171\eta, 173\eta$

$\Delta n = 8: \; 179\theta, 180\theta, 181\theta$

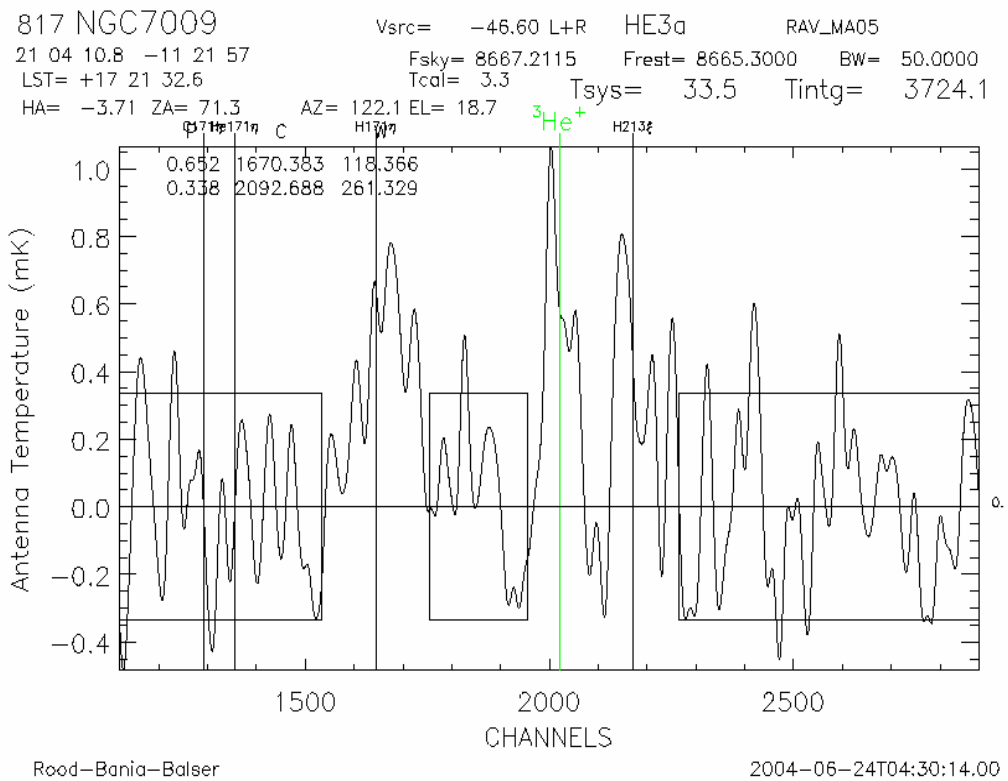
$\Delta n = 9: \; 186\iota, 187\iota, 188\iota$

$\Delta n = 10: \; 193\kappa, 194\kappa$

$\Delta n = 11: \; 211\lambda$

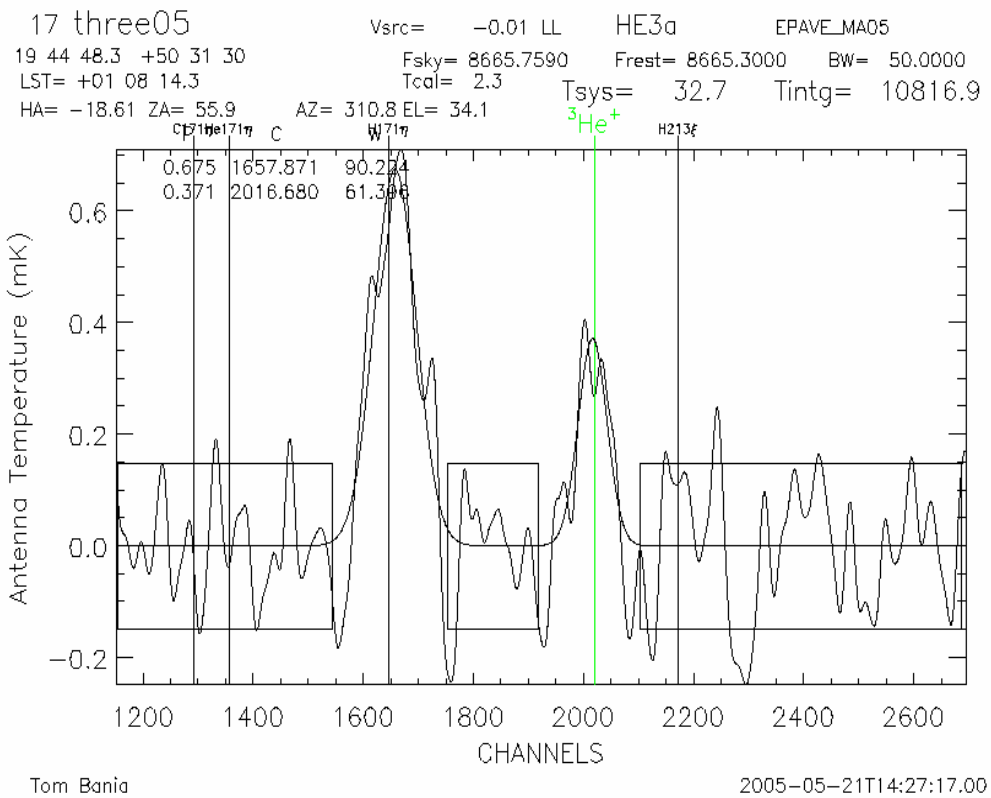
1. 4He/H abundances
2. Model physical properties
3. Reliability level of ~0.5 mK

GBT NGC 7009



62.1 hr integration

GBT (NGC7009 + NGC6543 + NGC6826)



180.3 hr integration

Summary

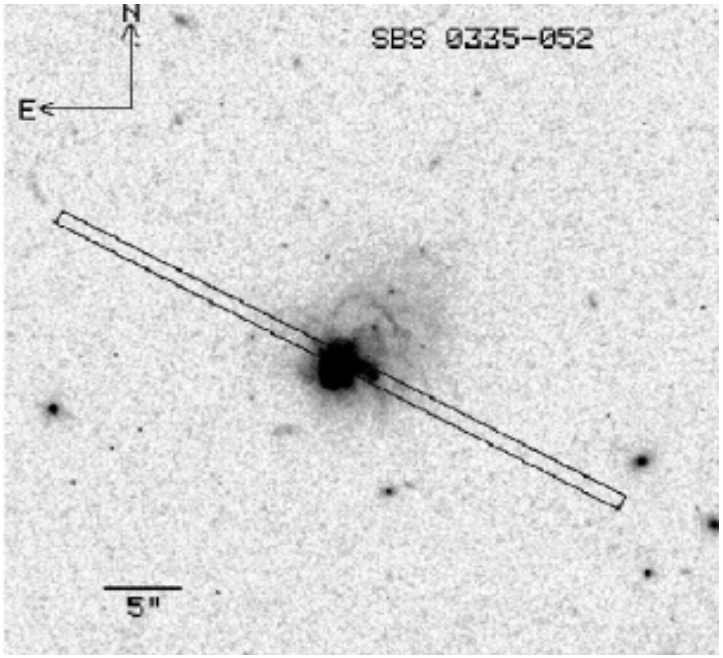
1. Primordial estimate of 3He/H consistent with WMAP and D observations.
2. Some stars appear to produce “high” values of 3He/H.
3. We still do not understand how stars process 3He but …

Future

1. Additional observations of 3He in PNe? (EVLA)
2. Observations of 12C/13C in PNe. (CARMA, ALMA)
3. Observations of 3He in select outer Galaxy HII regions. (GBT)
4. Observations of 3He in the low metallicity LMC/SMC. (Parkes)

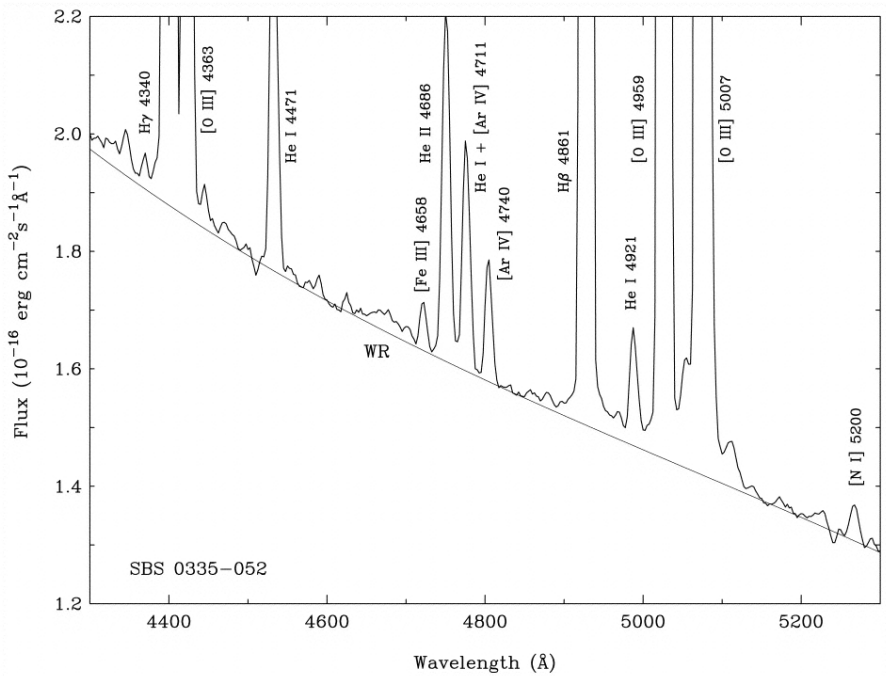
Done

4He Observations (optical recombination lines)

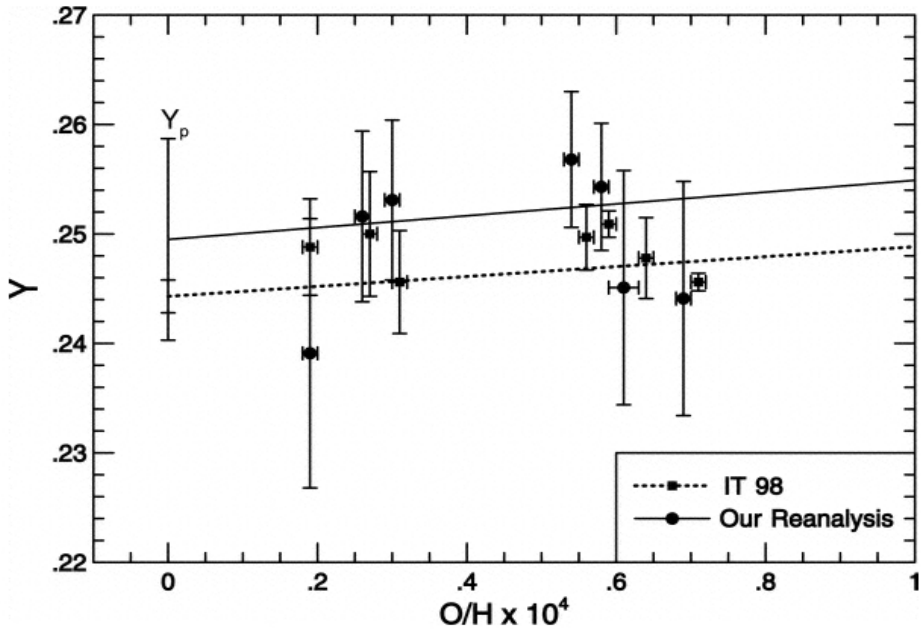


Izotov et al. (1999)

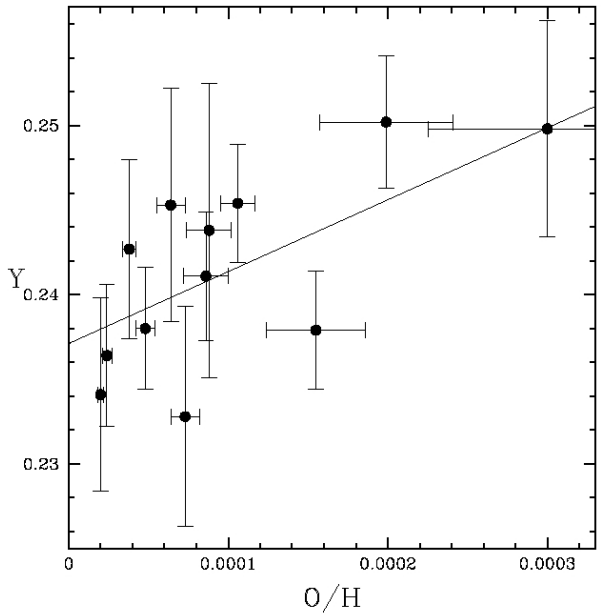
Metal poor blue compact galaxies



4He Results



Olive & Skillman (2004)

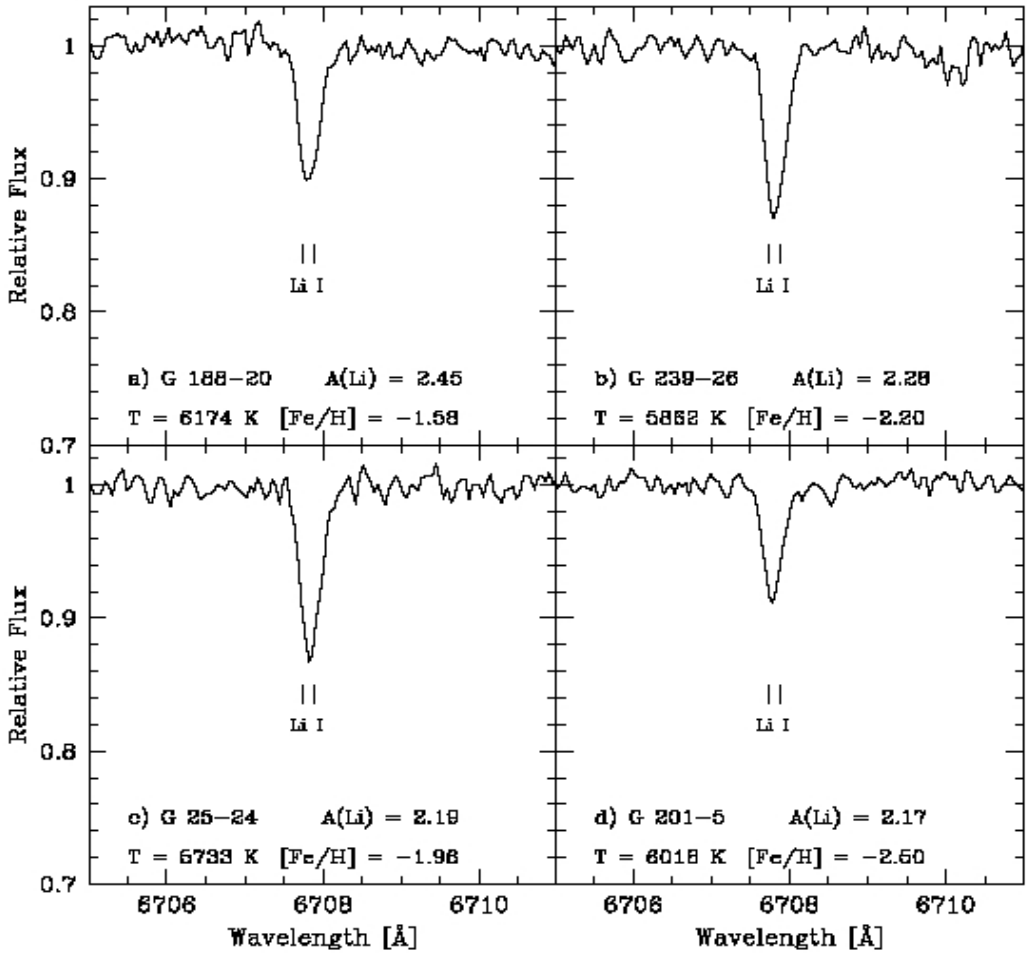


Peimbert & Peimbert (2002)

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)

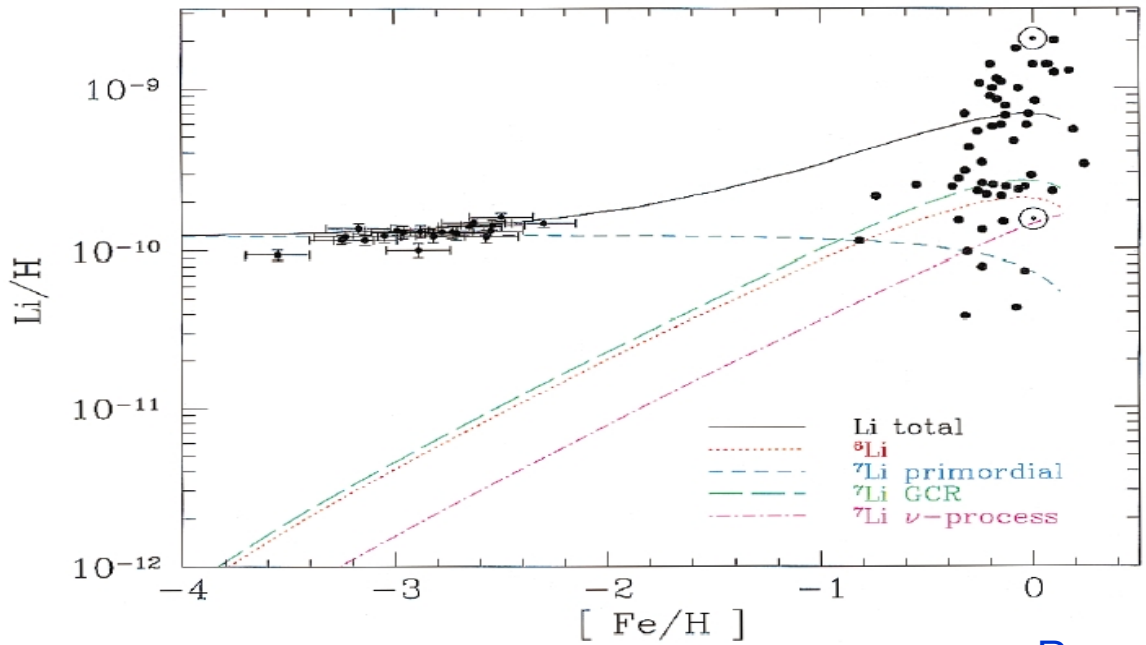
7Li Observations (resonance line)

Metal poor
Halo stars



Boesgaard et al. (2005)

7Li Results (The Spite Plateau)

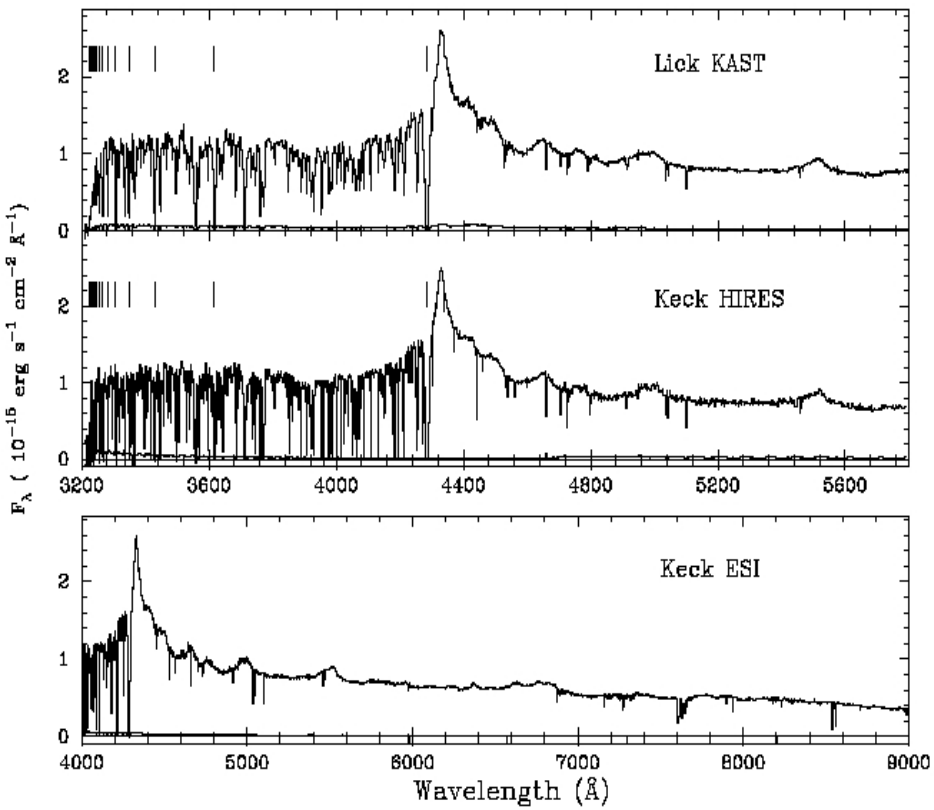


Ryan et al. (2000)

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)

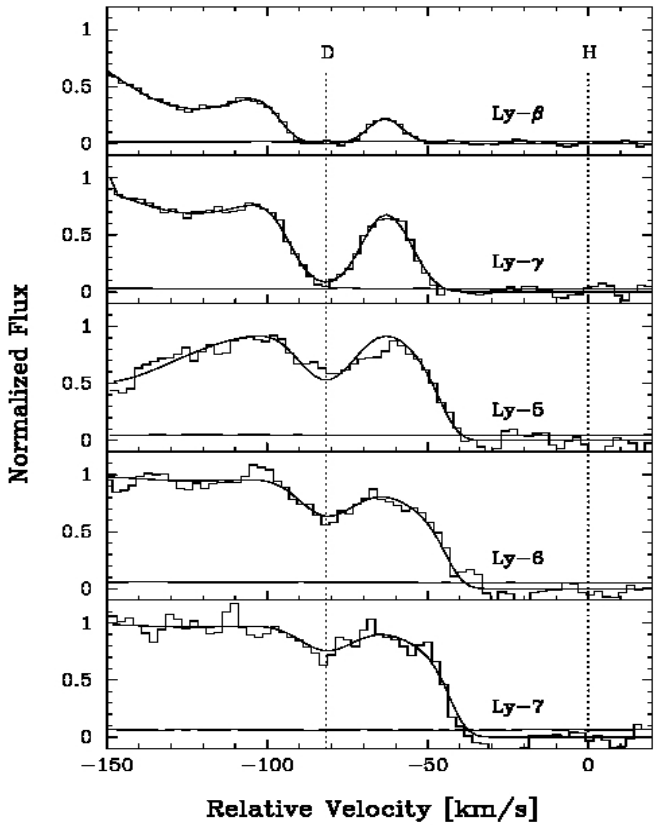
Deuterium Observations (Lyman Series)

Q1243+3047



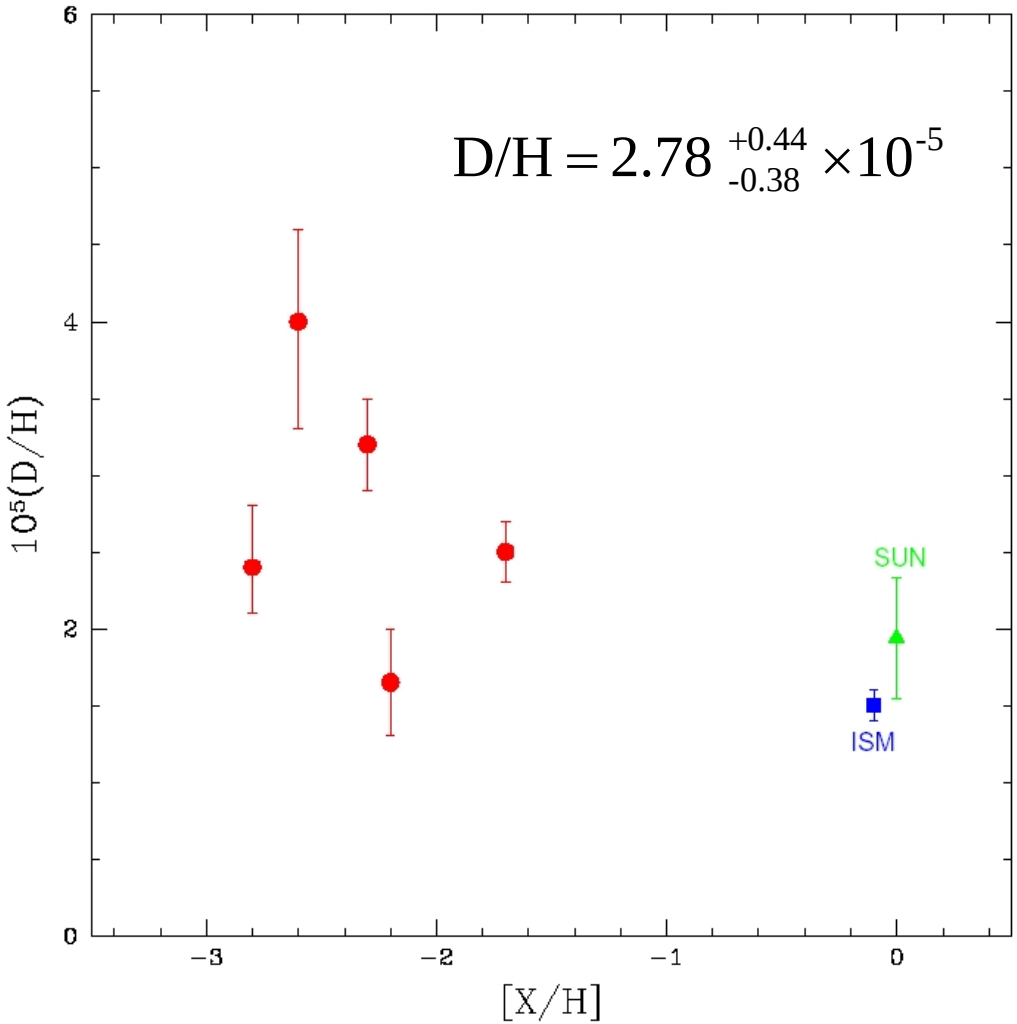
Kirkman et al. (2003)

HS 0105+1619



O'Meara et al. (2001)

Deuterium Results



Kirkman et al. (2003); Steigman (2005)