The Cosmic Abundance of ^3He: Green Bank Telescope Observations

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Institute for Astrophysical Research
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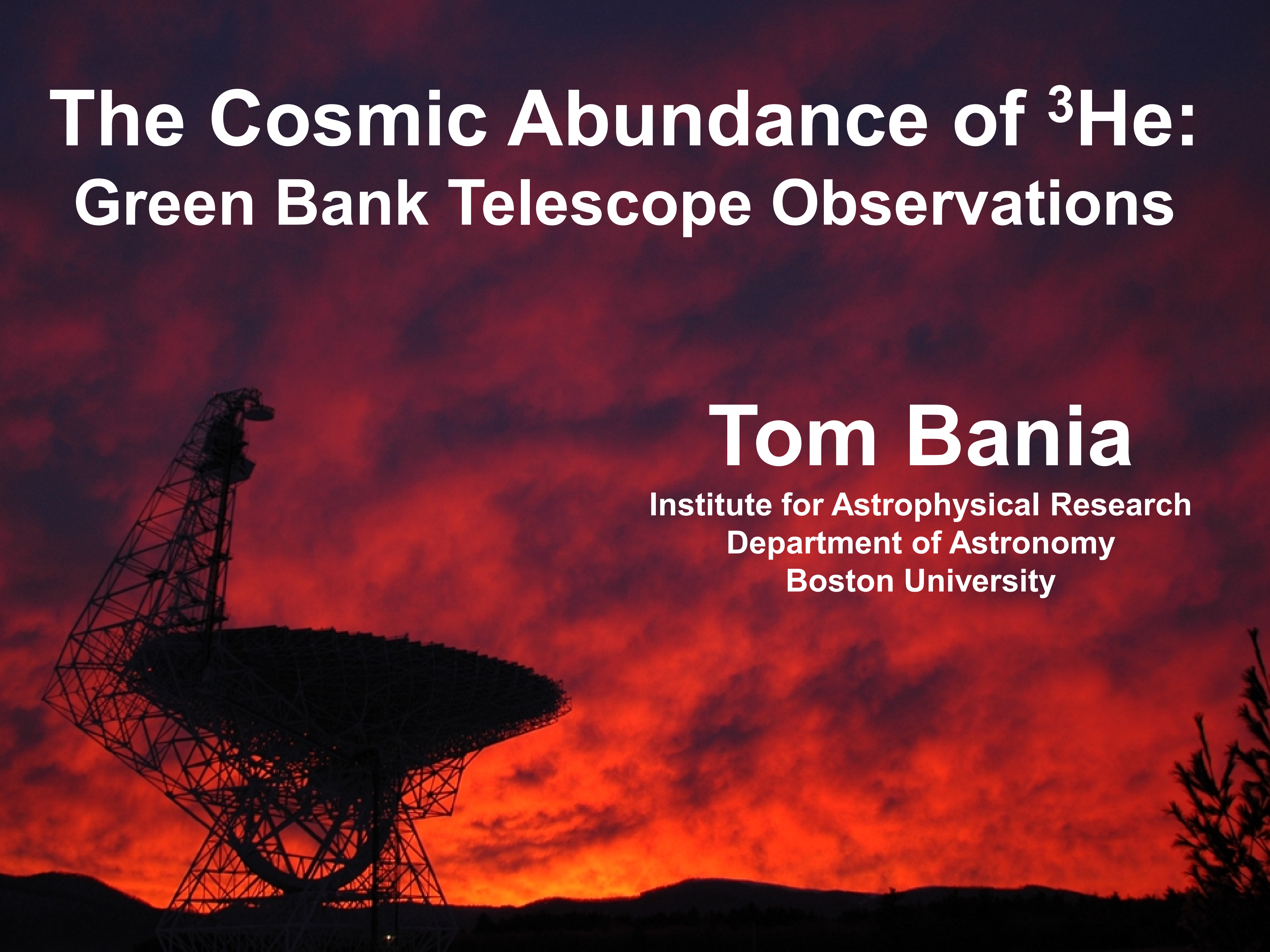
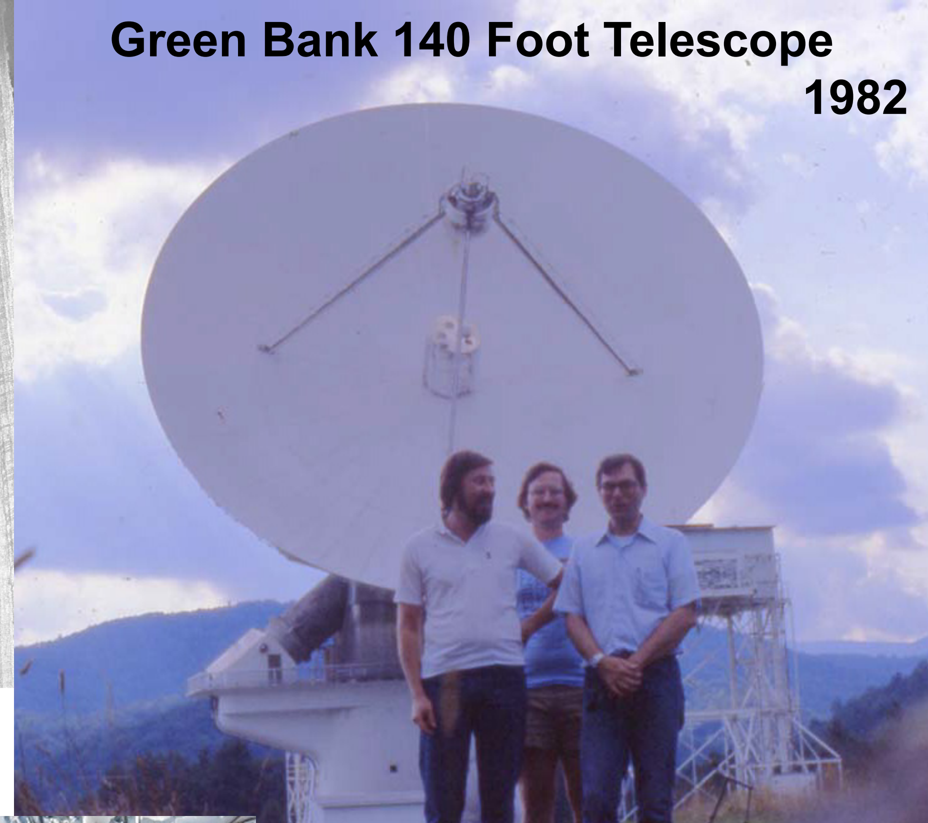
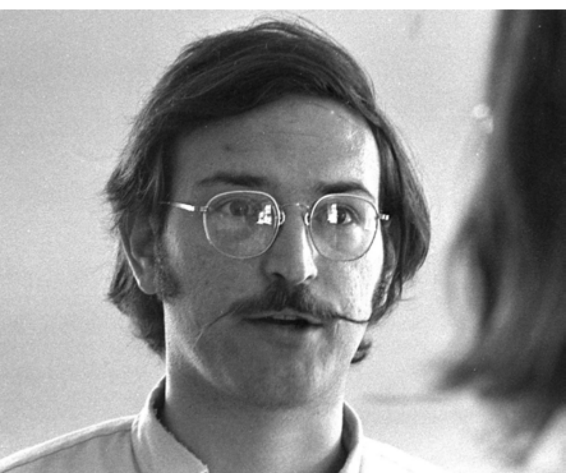


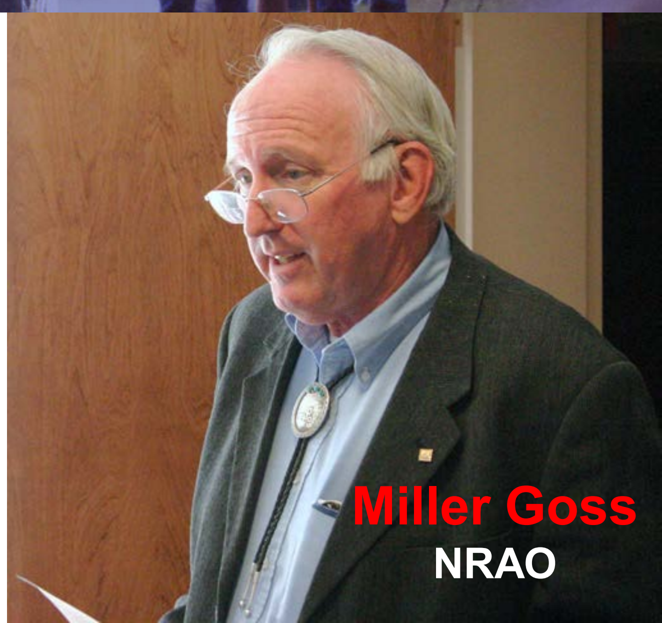
Bob Rood
University of Virginia
1942 – 2011

Tom Wilson
MPIfR





Dana Balser
NRAO



Radio Astronomy Holy Grails

H I

1420 MHz

D I

327 MHz

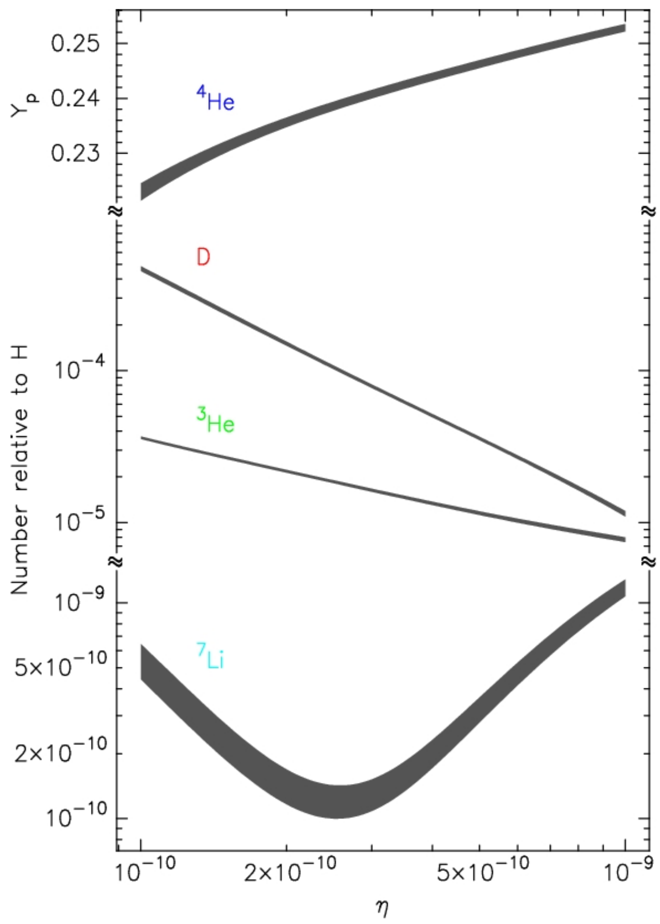
$^3He^+$

8665 MHz

Hyperfine “Spin Flip” Transitions

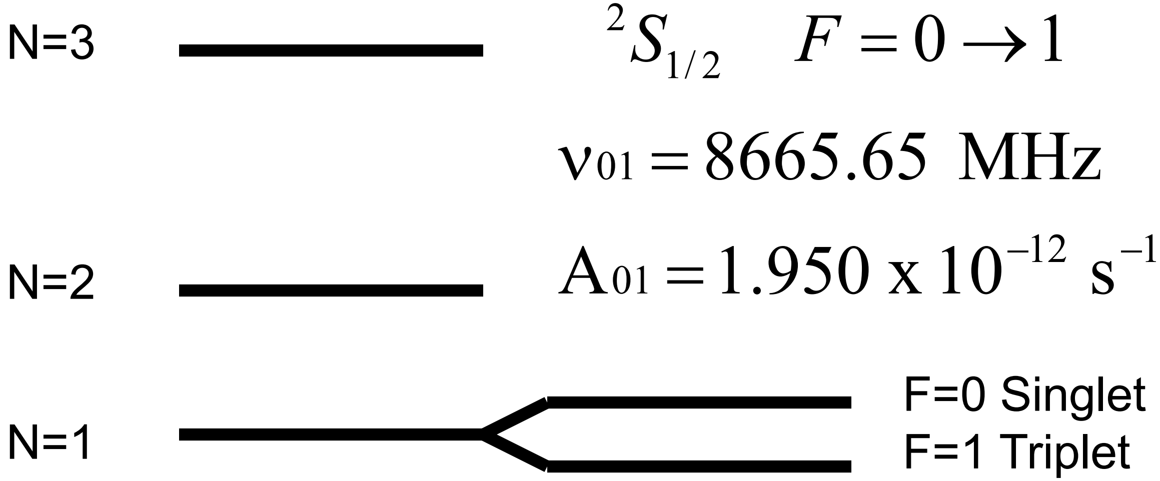
Primordial Nucleosynthesis BBNS

D
^{3}He
^{4}He
^{7}LI



Burles et al. (2001)

$^3He^+$ Hyperfine Transition



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

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

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

MICROWAVE RADIATION OF SINGLY CHARGED HELIUM 3 FROM H II REGIONS

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Department of Space Science, Rice University, Houston, Texas
and
W. Miller Goss
Radio Astronomy Laboratory, University of California, Berkeley
Received December 19, 1966; revised January 24, 1967

Goldwire & Goss 1967, ApJ, **149**,15

ABSTRACT

The hyperfine structure of the ground state of He^3 II is discussed. The lifetime of the upper hyperfine state against spontaneous emission of 3.46-cm radiation is determined to be about 16000 years. The spin temperature of He^3 II in H II regions is shown to be equal to the kinetic temperature of the regions. The expected intensity of the ground-state hyperfine transition radiation received from certain H II regions is shown to be near the limits of detectability by present techniques. It is shown that the microwave method can lead to the setting of an upper limit of 10^{-4}–10^{-5} for the He^3 to H abundance; this is contrasted with the current 10^{-2} upper limit established by optical means. We also delineate some of the important questions that may hinge upon the interstellar abundance of He^3.

Rood, Steigman & Tinsley 1976, ApJ, 207, L57

STELLAR PRODUCTION AS A SOURCE OF ^{3}He IN THE INTERSTELLAR MEDIUM*

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AND

BEATRICE M. TINSLEY‡
Astronomy Department, Yale University
Received 1976 February 9; revised 1976 April 5

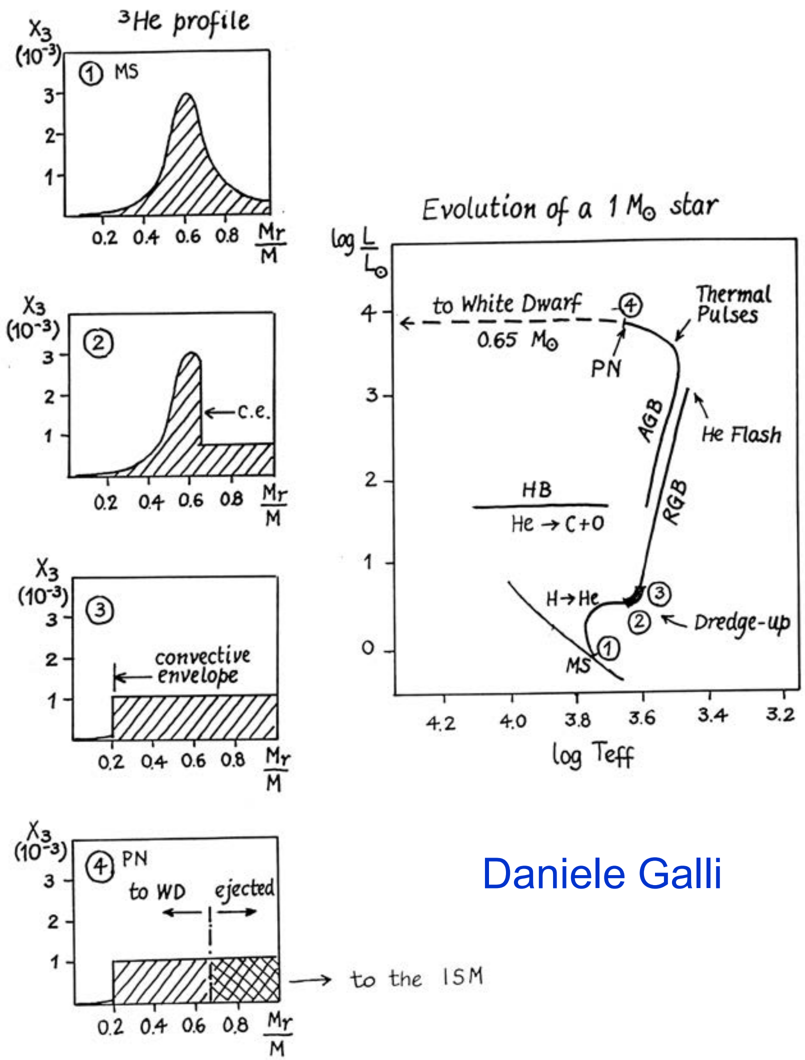
ABSTRACT

Low-mass stars produce substantial amounts of ^{3}He which is mixed into the convective envelope when the stars become giants. There is strong evidence that a large fraction of this envelope is lost from these stars, thus enriching the interstellar medium (ISM) in ^{3}He.

Analytic formulae are presented for the production of ^{3}He as a function of stellar mass so that our results can be incorporated into numerical models of galactic evolution. Simple estimates suggest that the present interstellar ^{3}He abundance could be much greater than the quoted protosolar value, perhaps in conflict with the observations.

It seems unlikely that ^{3}He can be used to supplement the cosmological information available from deuterium. Badly needed new observations of interstellar ^{3}He could provide a valuable check on the theory of the evolution of loss-mass stars.

Stellar Nucleosynthesis



Daniele Galli

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

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

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

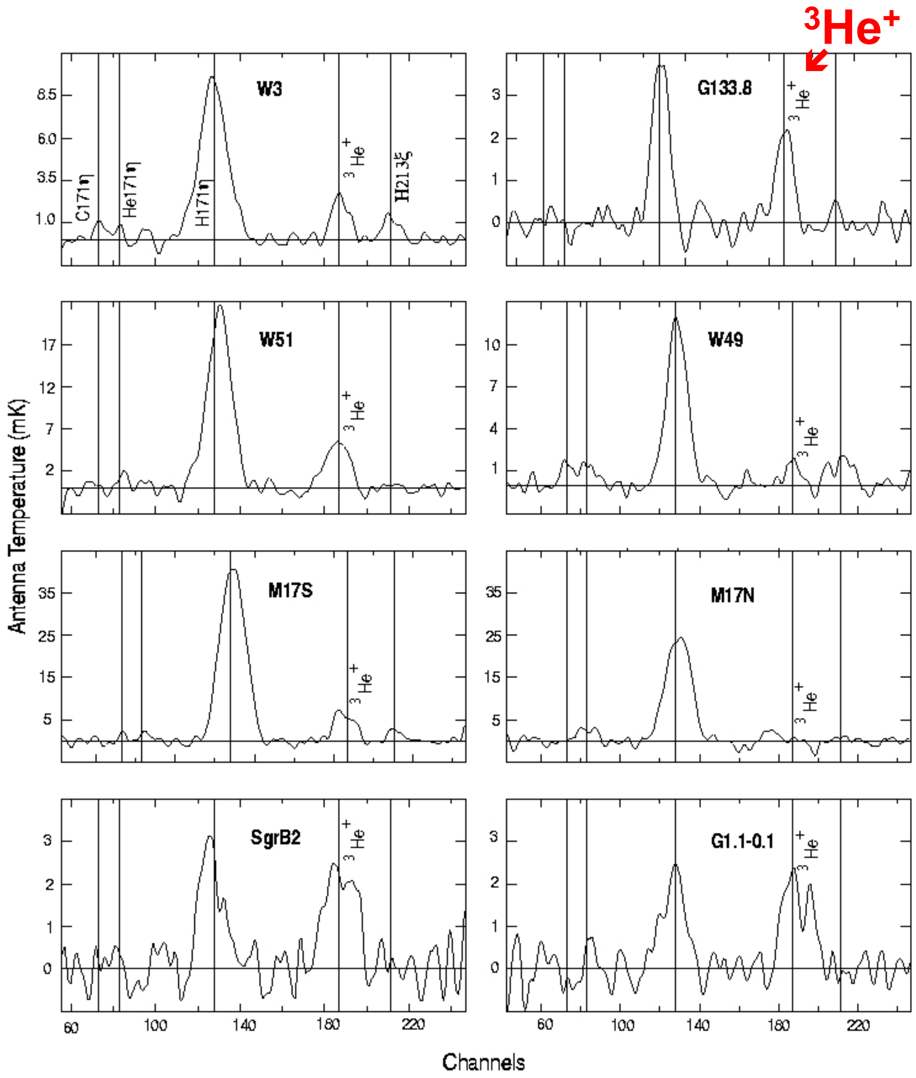
$$^3He + {}^4He \rightarrow {}^7Be + \gamma \qquad T > 7 \times 10^6\ K$$

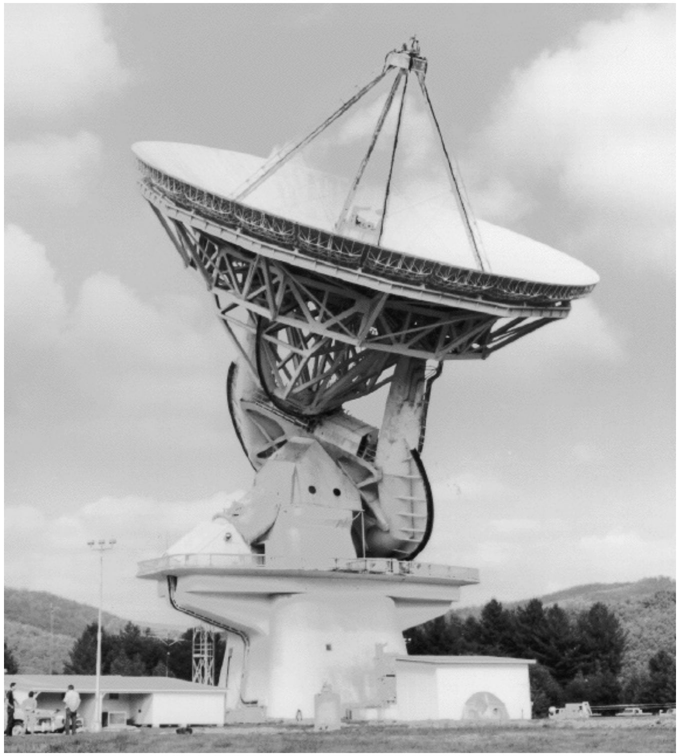
"The present interstellar ^{3}He is more of stellar than primordial origin."

Rood, Steigman & Tinsley (1976)

HII Region $^3He^+$ Spectra

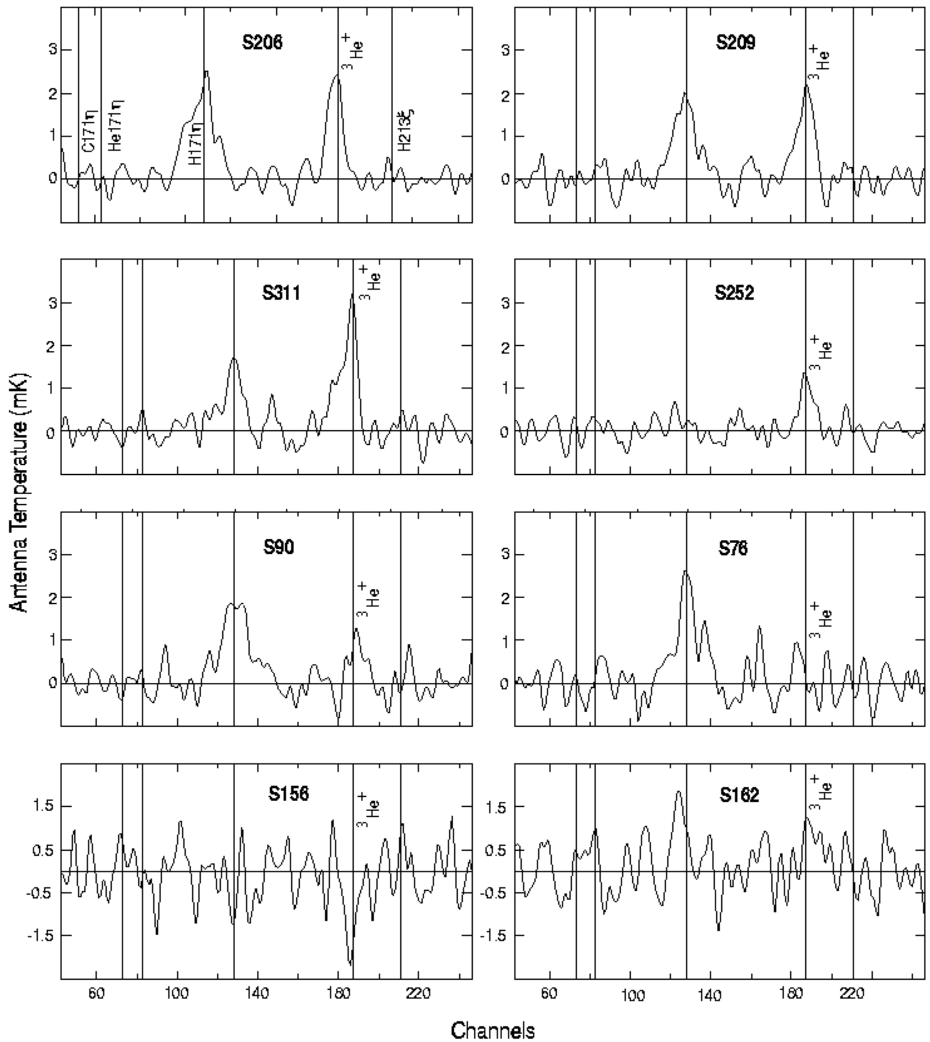
Bania et al. (1997)





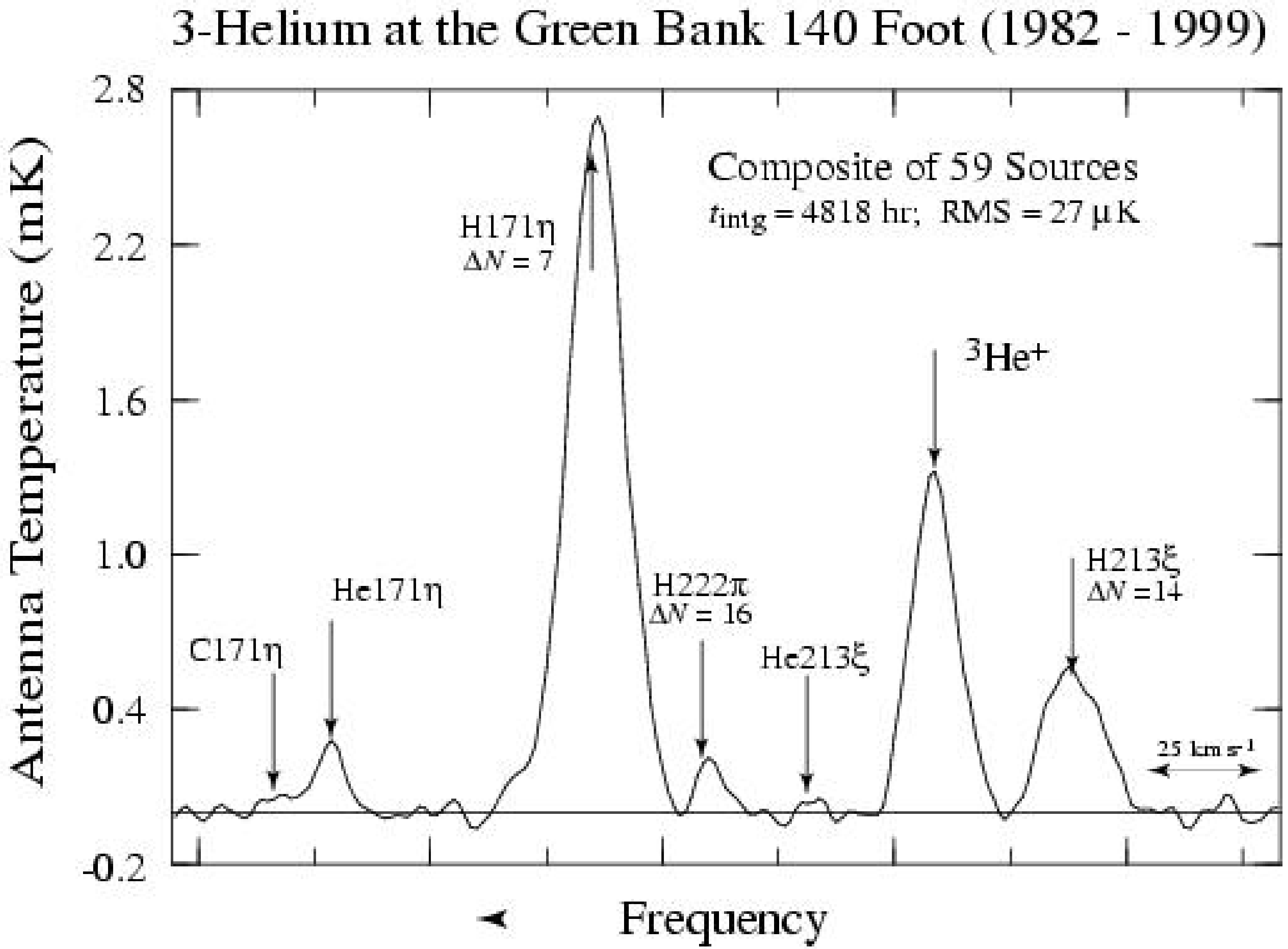
NRAO 140 Foot

HII Region $^3He^+$ Spectra



3-Helium Experiment

200 day integration 27 μK rms



^{3}He Abundance Determination

MEASURE the Equivalent Width of the spectral line
DERIVE the abundance

For a uniform, isothermal, ionized nebula composed solely of hydrogen and helium the ($^3He^+/H^+$) column density ratio is

$$\frac{N(^3\mathrm{He}^+)}{N(\mathrm{H}^+)} = 3.873 \times 10^{-3}\, \frac{T_{\mathrm{L}}^{\mathrm{A}}(^3\mathrm{He}^+)\Delta v(^3\mathrm{He}^+)[\ln(5.717\times 10^{-3} T_{\mathrm{e}}^{3/2})]^{1/2}\,\theta_{\mathrm{obs}}}{A\,(\eta_{\mathrm{b}} T_{\mathrm{C}}^{\mathrm{A}} D)^{1/2}\, T_{\mathrm{e}}^{1/4}\,(\theta_{\mathrm{obs}}^2 - \theta_{\mathrm{a}}^2)^{3/4}} \qquad (1)$$

where

$$A^2 = \left\{\left(1 + \frac{n(\mathrm{He}^+)}{n(H^+)} + 2\frac{n(\mathrm{He}^{++})}{n(\mathrm{H}^+)}\right)\left(1 + \frac{n(\mathrm{He}^+)}{n(H^+)} + 4\frac{n(\mathrm{He}^{++})}{n(\mathrm{H}^+)}\left[1 - \frac{\ln(2)}{\ln(5.717\times 10^{-3} T_{\mathrm{e}}^{3/2})}\right]\right)\right\}^{-1}. \qquad (2)$$

HII Region Models

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

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

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

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

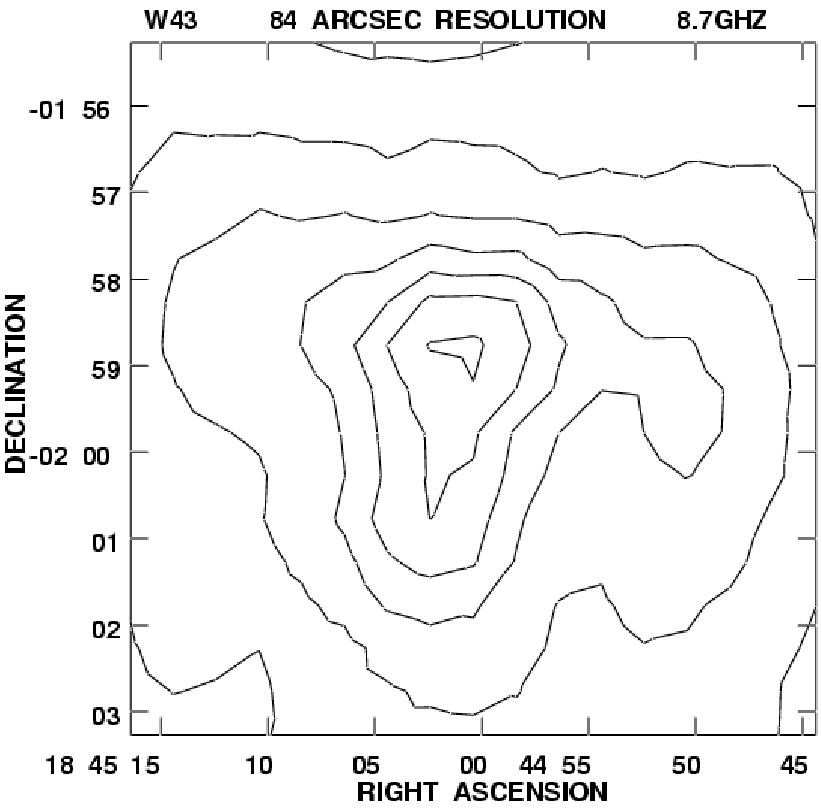
Dana Balser 1995 PhD Boston University

NEBULA

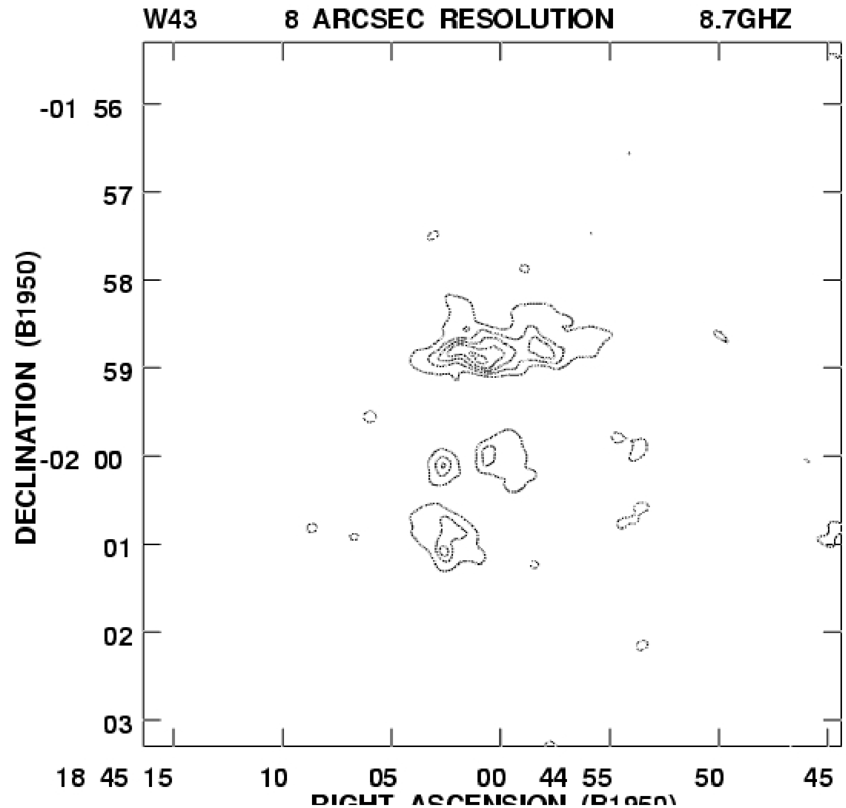
CLOUDY

HII Region Radio Continuum

MPIfR 100m Telescope



NRAO Very Large Array

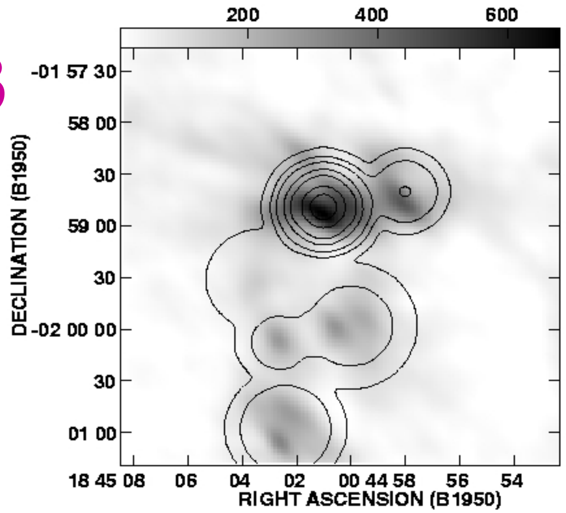


DSB et al. (1995)

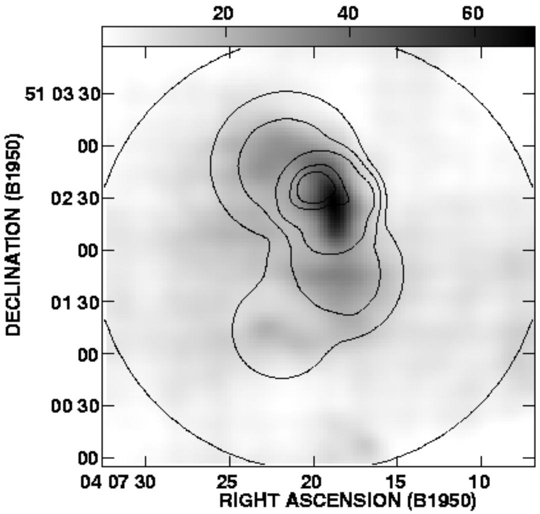
HII Region Models

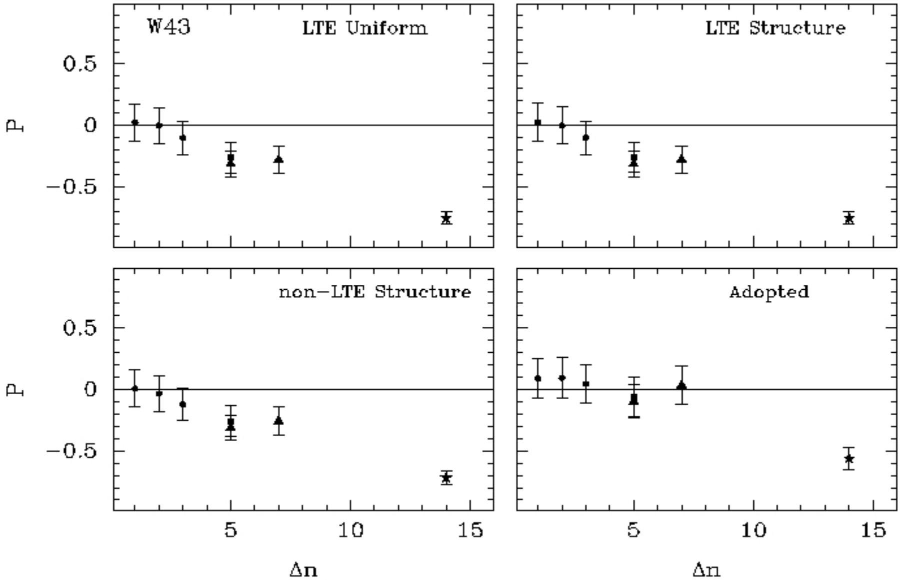
Balser et al. 1999

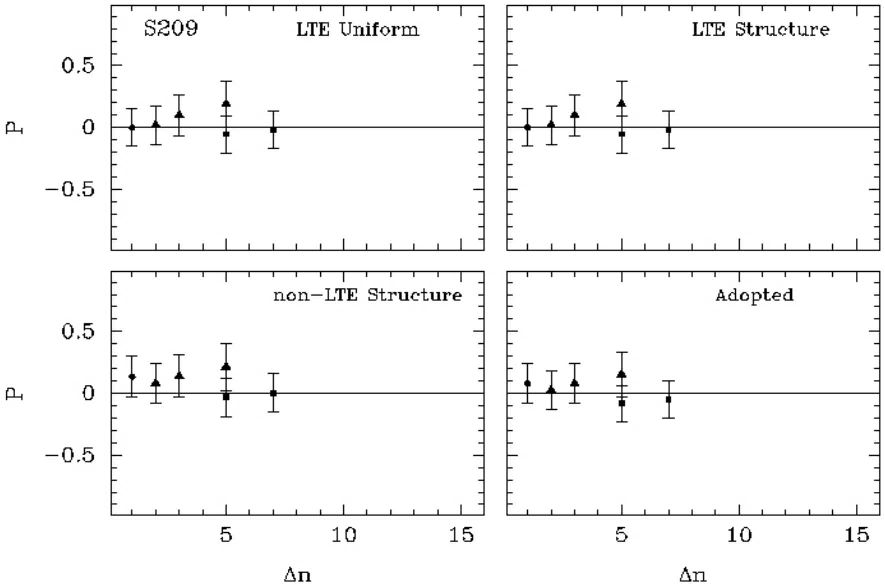
W43



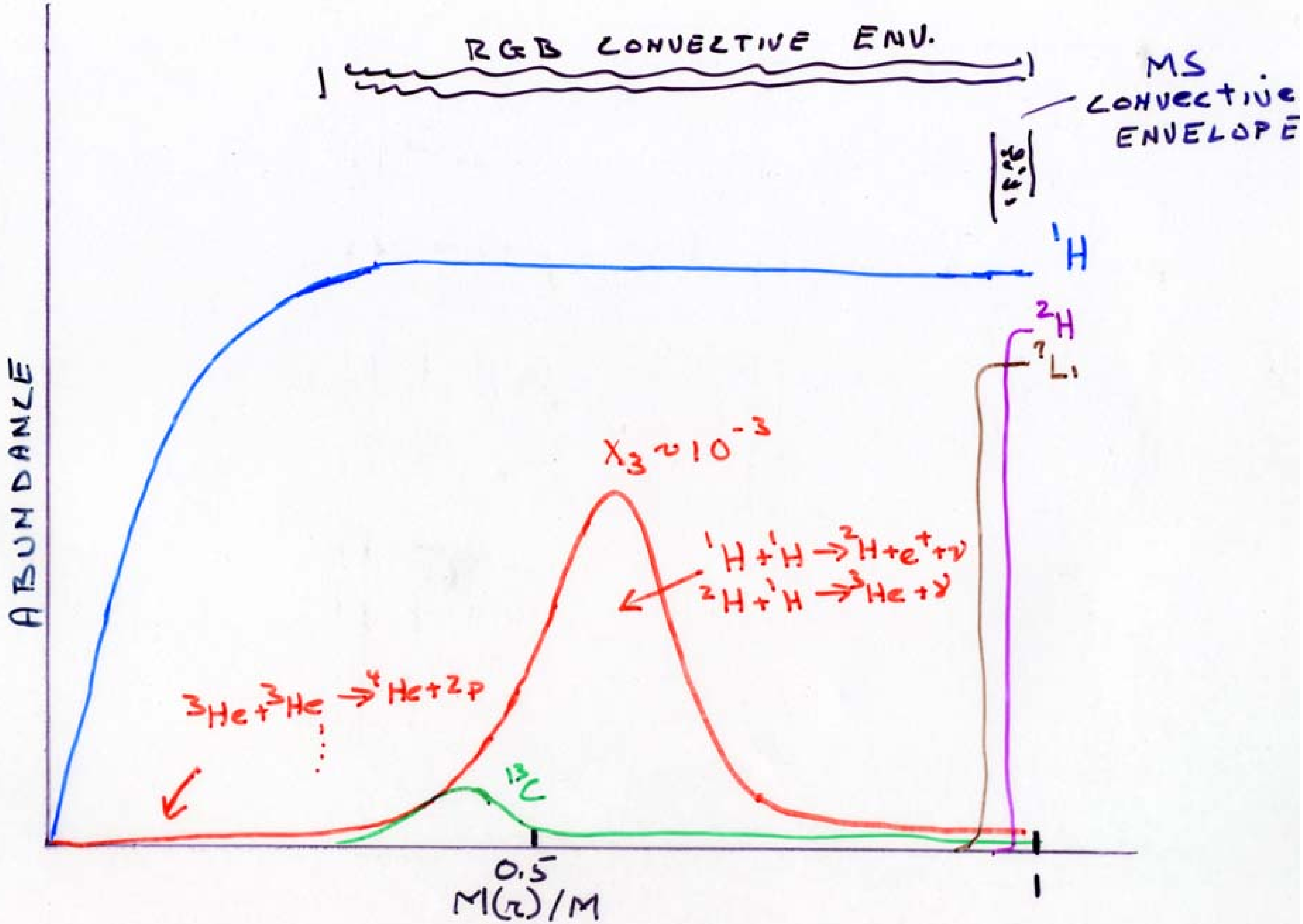
S209



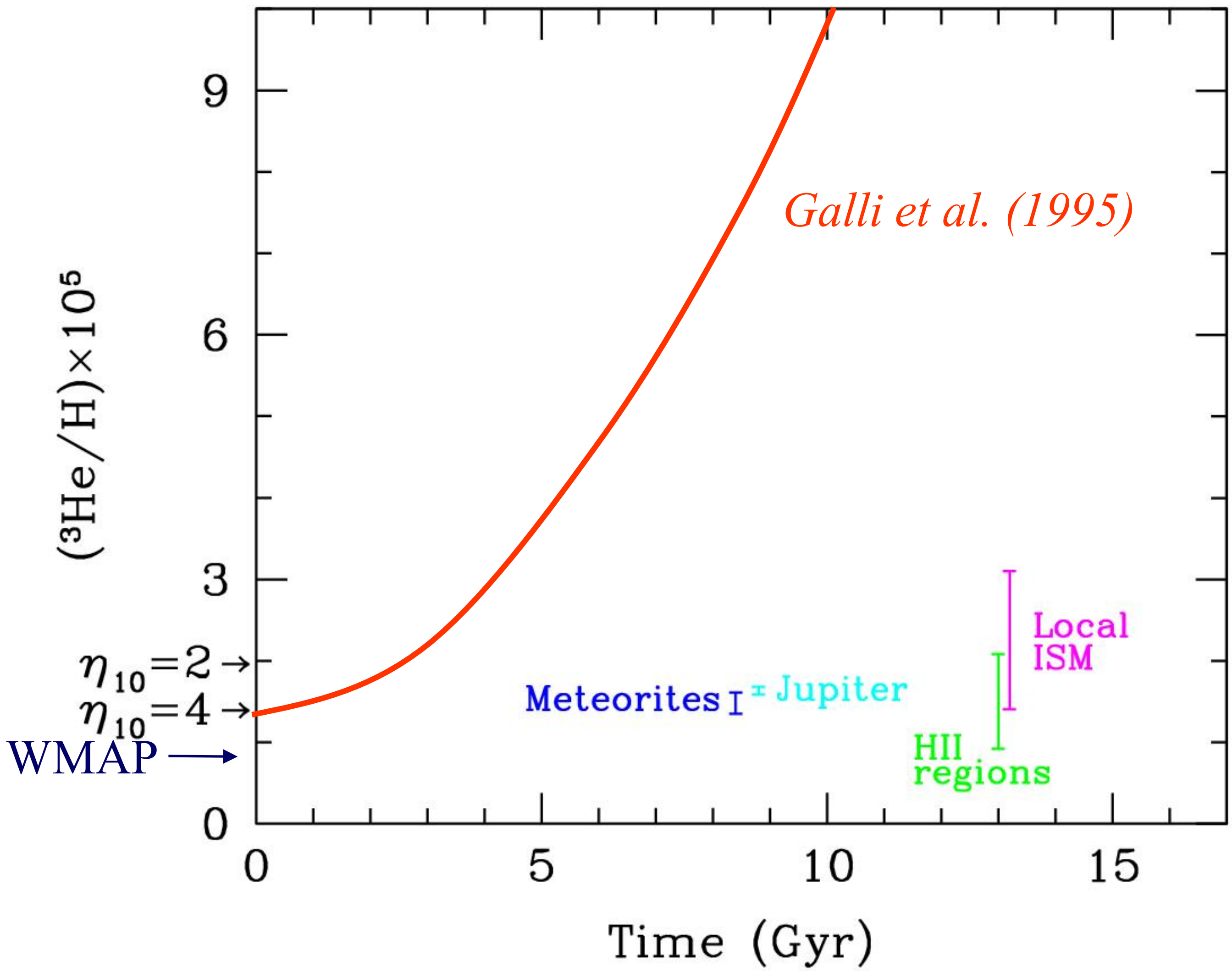




0.8 – 2 $M_\odot$ AT TURNOFF

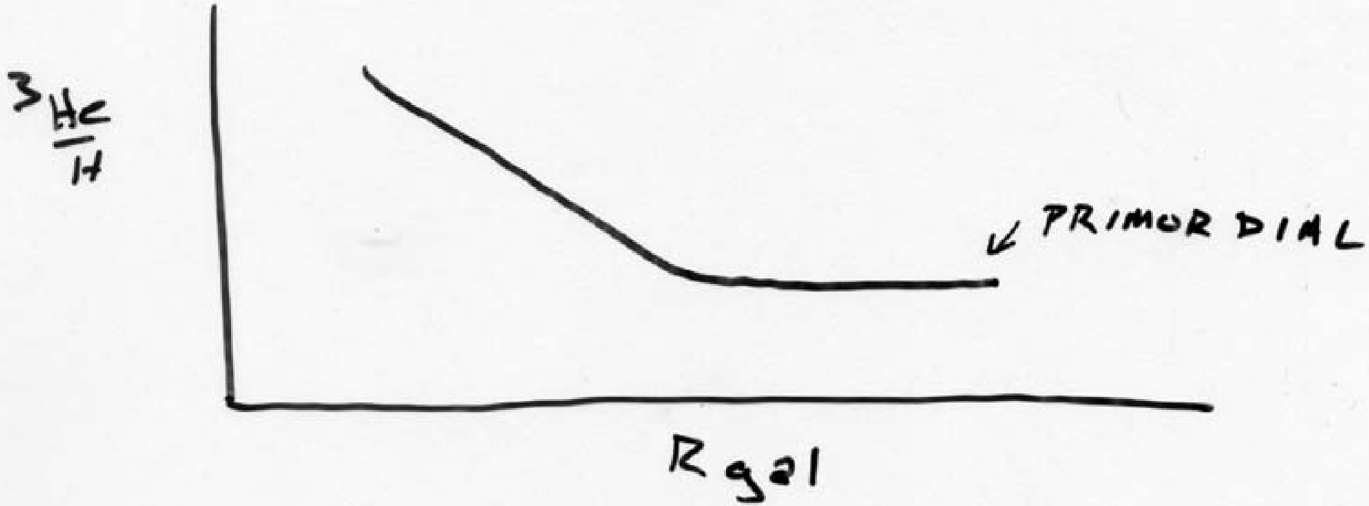


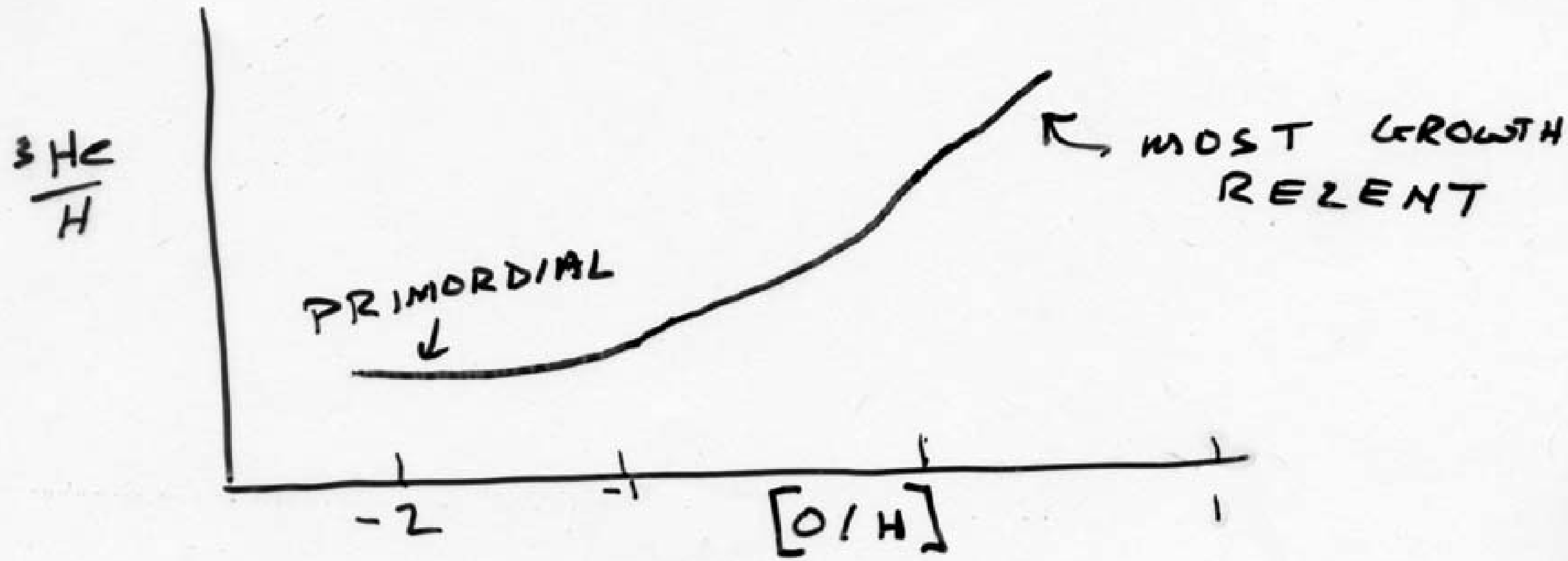
"The ^{3}He Problem"



Meteorites: Geiss (1993)
Jupiter: Mahaffy et al. (1998)
HII regions: Bania, Rood & Balser (2000)
Local ISM: Gloecker & Geiss (1998)

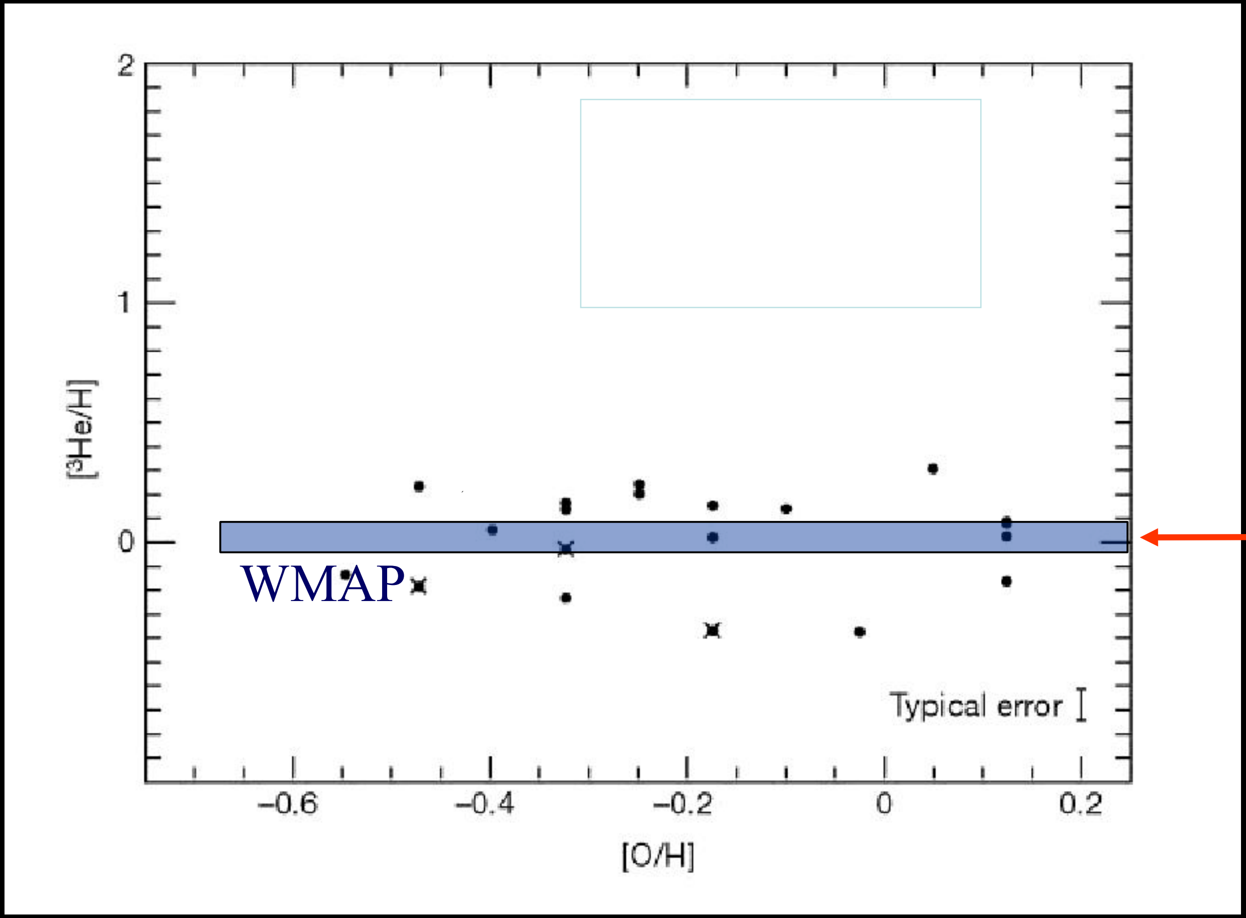
NAIVE EXPECTATIONS





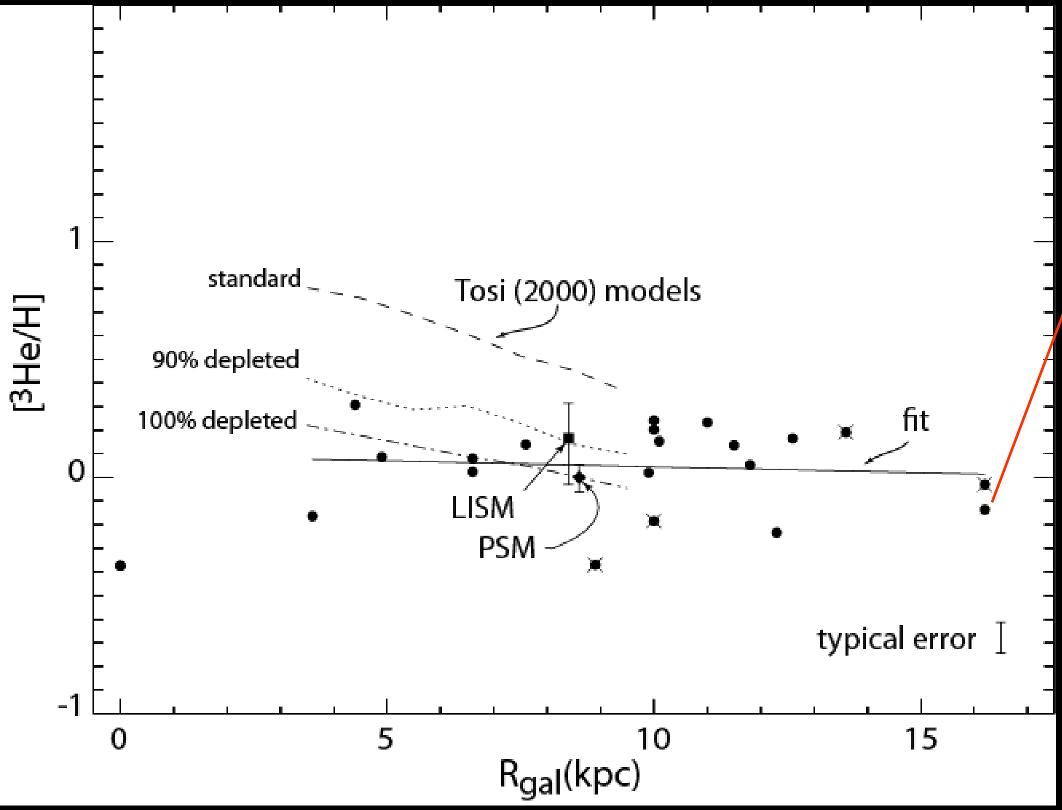
^{3}He Abundance in H II Regions

"The ^{3}He Plateau"



$(^3He/H)_p = 1.1 \times 10^{-5}$

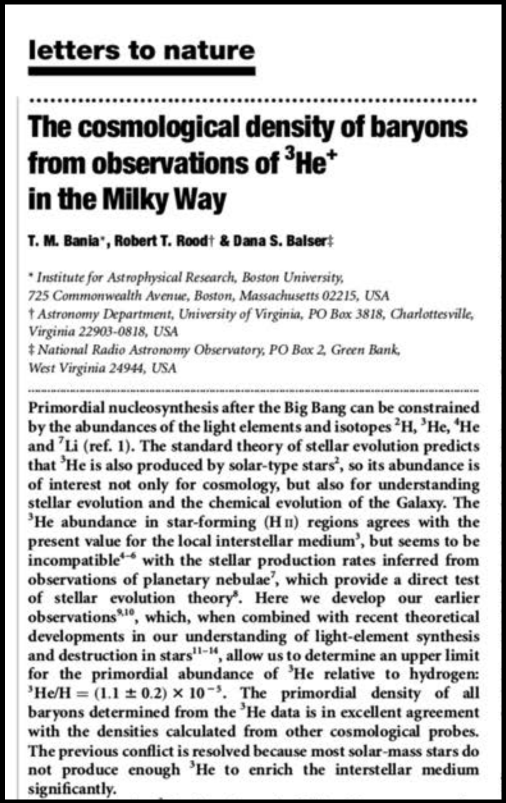
Bania, Rood & Balser 2002



Bania, Rood, & Balser
2002 Nature, 415, 54

$\Omega_B = 0.04$

$\eta_{10} = 5.4^{+2.2}_{-1.2}$



letters to nature

The cosmological density of baryons from observations of $^3He^+$ in the Milky Way

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* Institute for Astrophysical Research, Boston University, 725 Commonwealth Avenue, Boston, Massachusetts 02215, USA
† Astronomy Department, University of Virginia, PO Box 3818, Charlottesville, Virginia 22903-0818, USA
‡ National Radio Astronomy Observatory, PO Box 2, Green Bank, West Virginia 24944, USA

Primordial nucleosynthesis after the Big Bang can be constrained by the abundances of the light elements and isotopes ^2H, ^3He, ^4He and ^7Li (ref. 1). The standard theory of stellar evolution predicts that ^3He is also produced by solar-type stars[2], so its abundance is of interest not only for cosmology, but also for understanding stellar evolution and the chemical evolution of the Galaxy. The ^3He abundance in star-forming (H II) regions agrees with the present value for the local interstellar medium[3], but seems to be incompatible[4–6] with the stellar production rates inferred from observations of planetary nebulae[7], which provide a direct test of stellar evolution theory[8]. Here we develop our earlier observations[9,10], which, when combined with recent theoretical developments in our understanding of light-element synthesis and destruction in stars[11–14], allow us to determine an upper limit for the primordial abundance of ^3He relative to hydrogen: $^3He/H = (1.1 \pm 0.2) \times 10^{-5}$. The primordial density of all baryons determined from the ^3He data is in excellent agreement with the densities calculated from other cosmological probes. The previous conflict is resolved because most solar-mass stars do not produce enough ^3He to enrich the interstellar medium significantly.

For D highest observed value is a lower limit for cosmological D

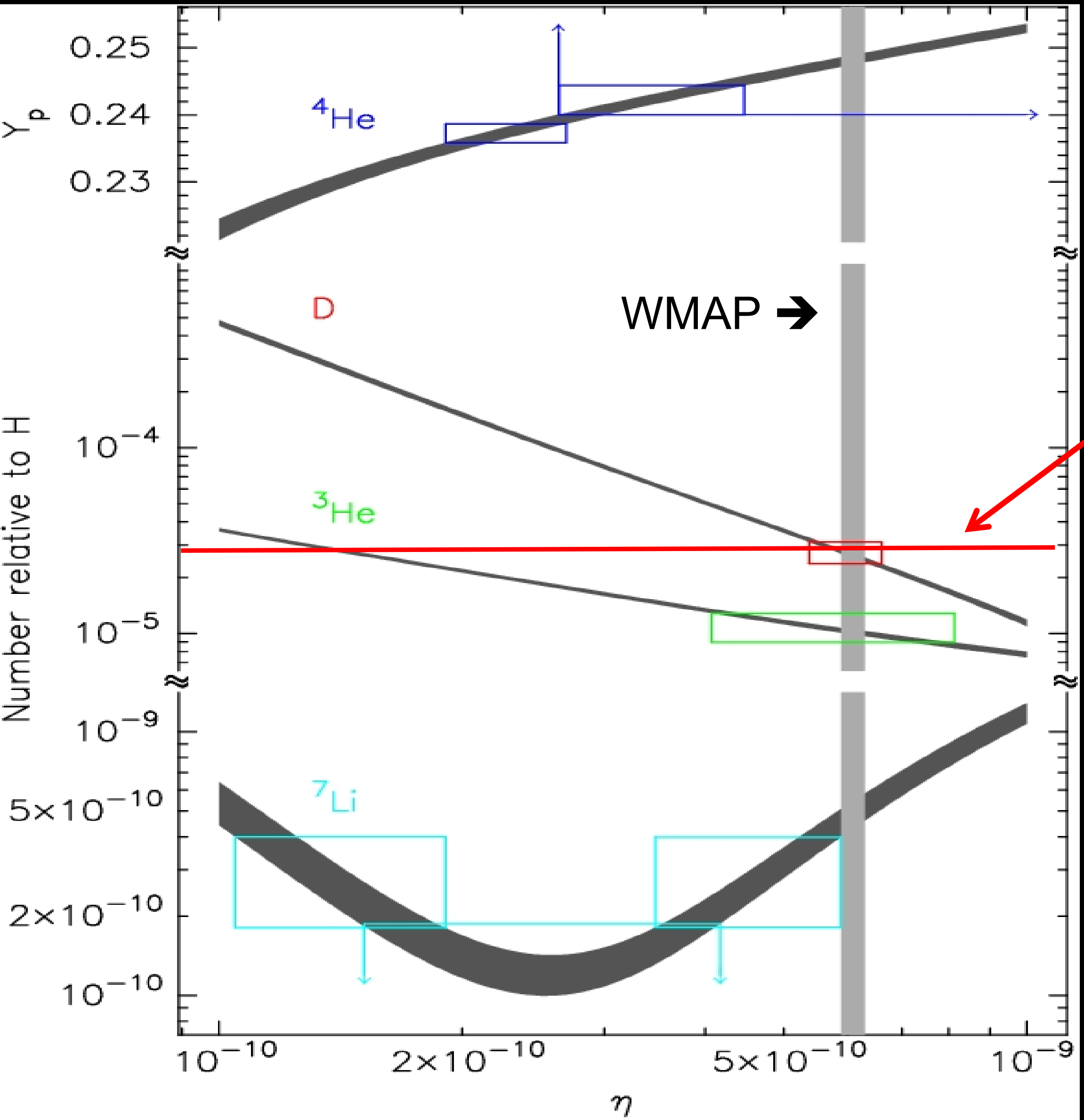
For ^3He lowest observed $^3He/H$ is an upper limit for cosmological ^3He

Spergel et al. 2003, WMAP

$\eta_{10} = 6.5^{+0.4}_{-0.3}$

$\Omega_B = 0.047 \pm 0.006$

BBNS Constraints



Izotov & Thuan (2004)
Peimbert & Peimbert (2002)
Olive & Skillman (2004)

Kirkman et al. (2003)

Alan Rogers D/H = 2.1 +/- 0.7 x 10^{-5}

Bania, Rood, & Balser (2002)

Ryan et al. (2003)
Boesgaard et al. (2006)

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

Robert C. Byrd

Green Bank Telescope

Conventional

Blocked

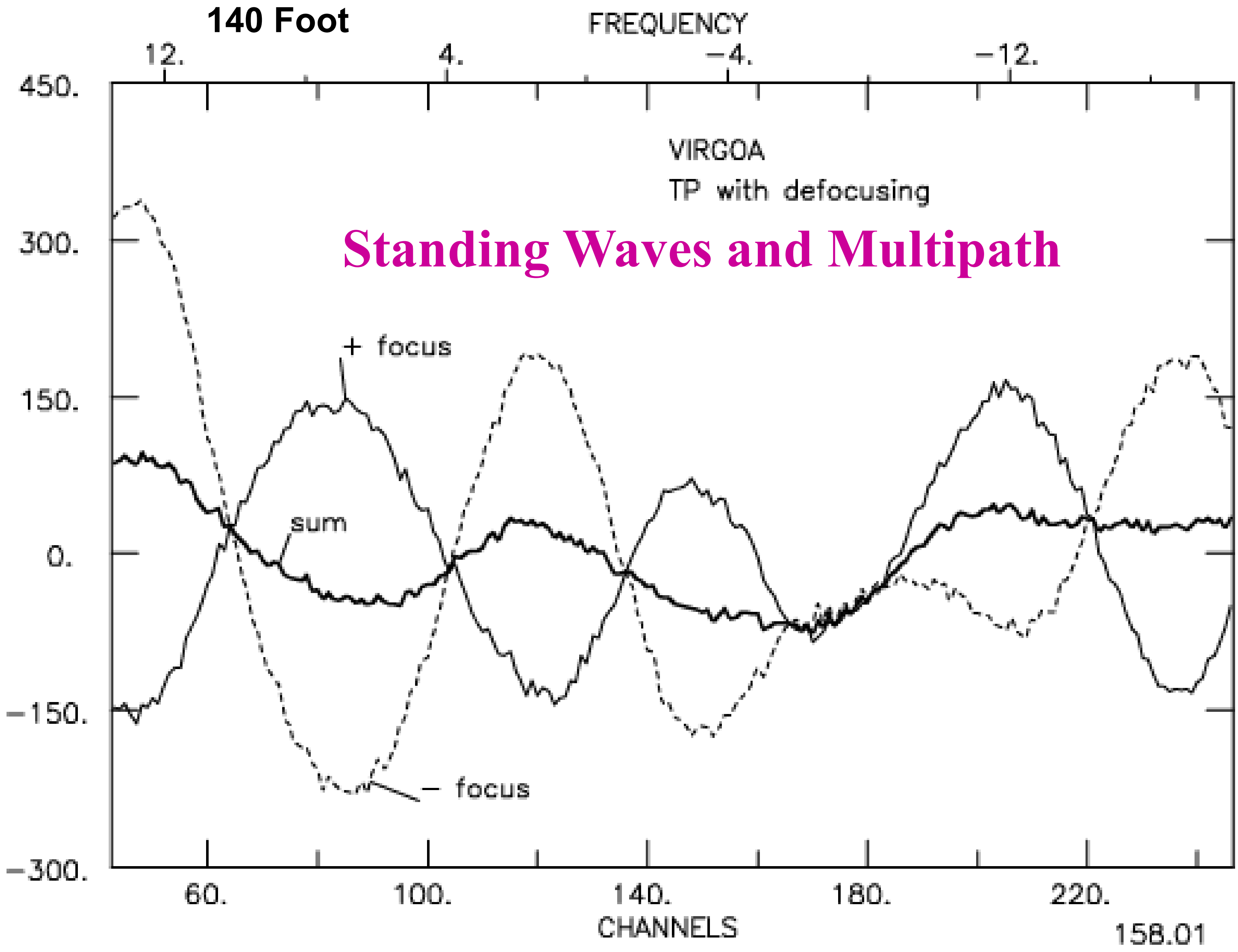
Aperture

Is a very

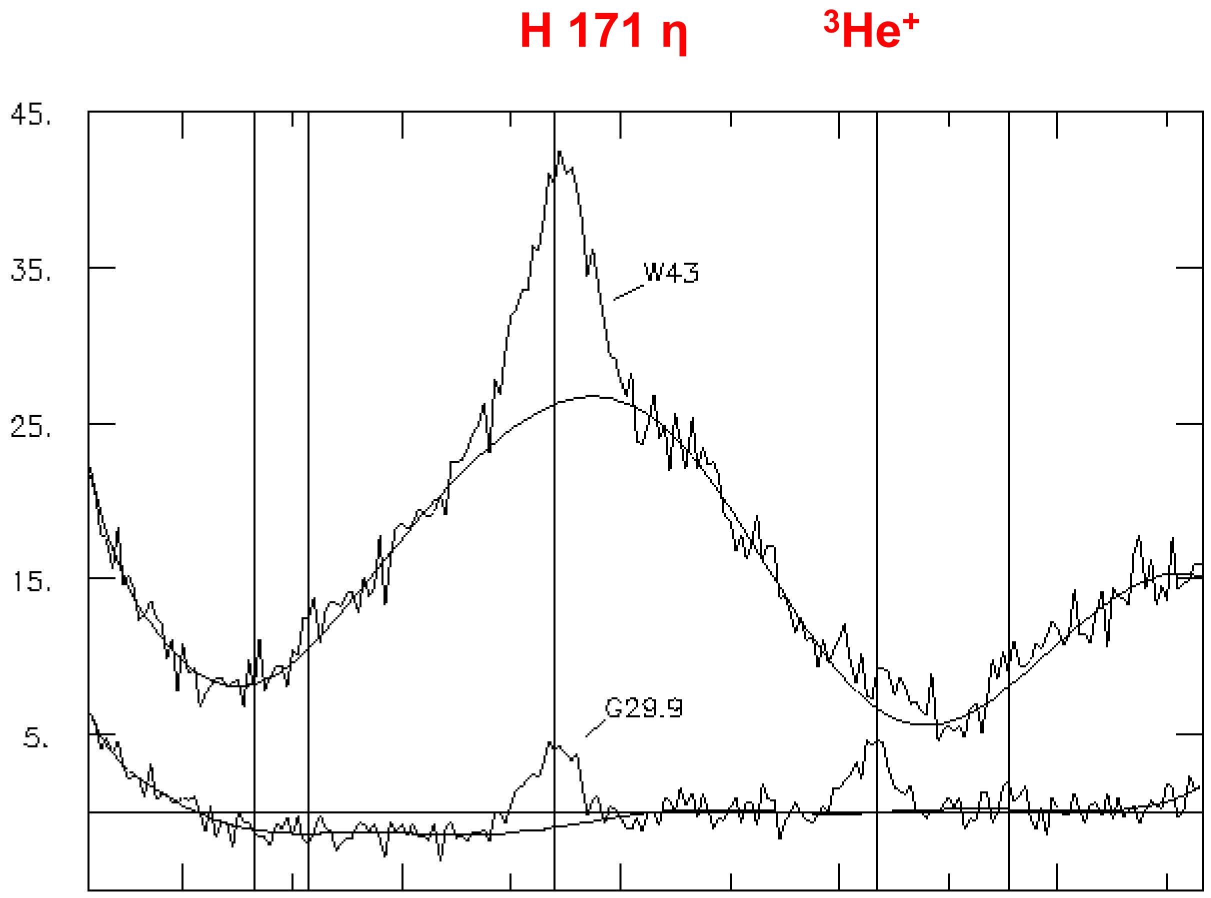
Bad

Design

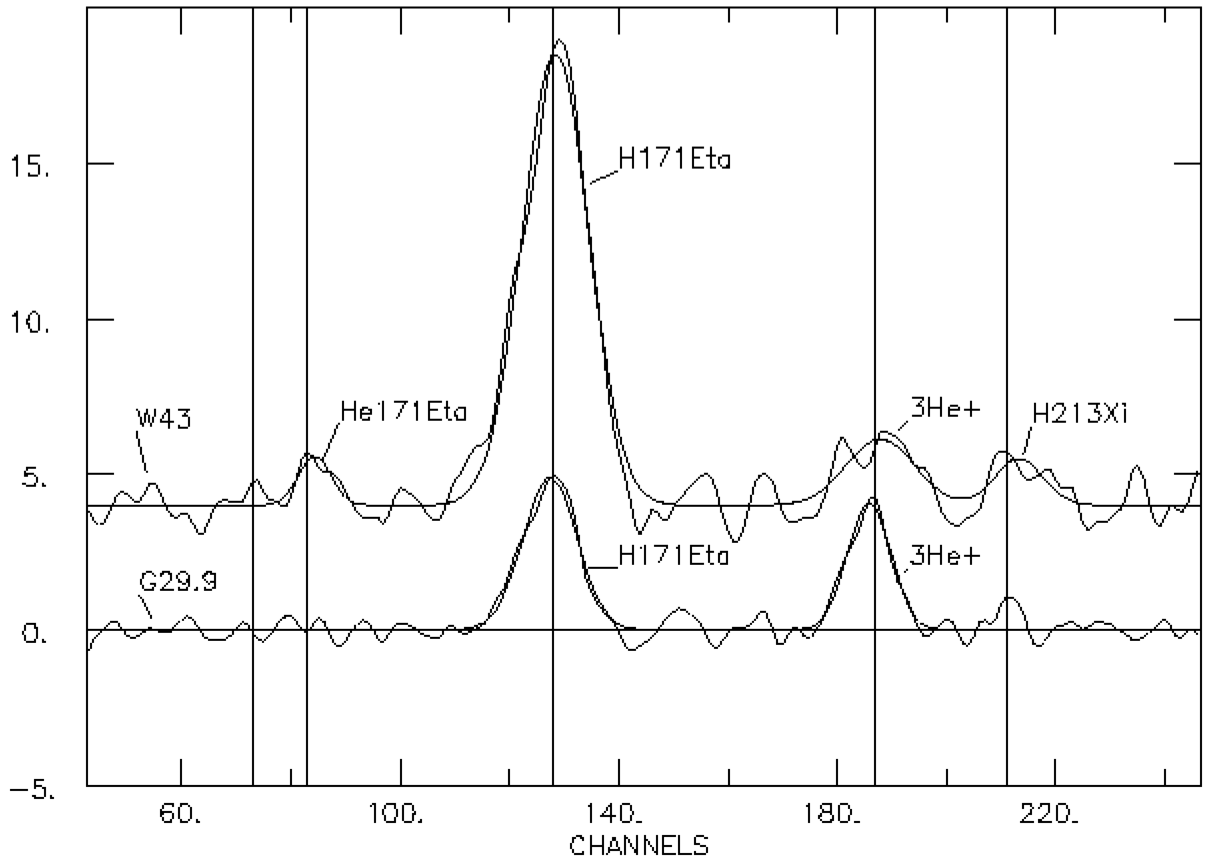
Standing Waves and Multipath



140 Foot



Baseline Model Subtracted

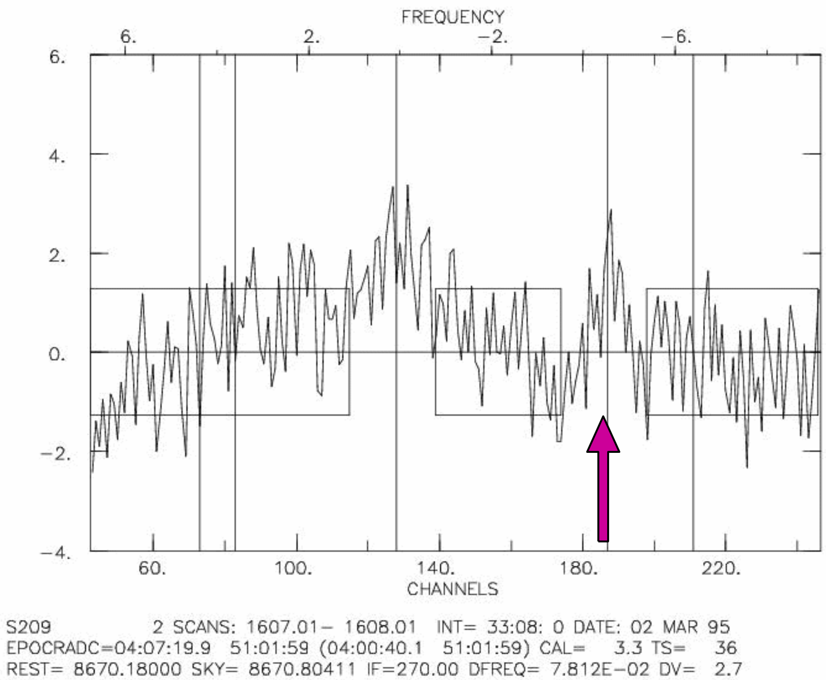


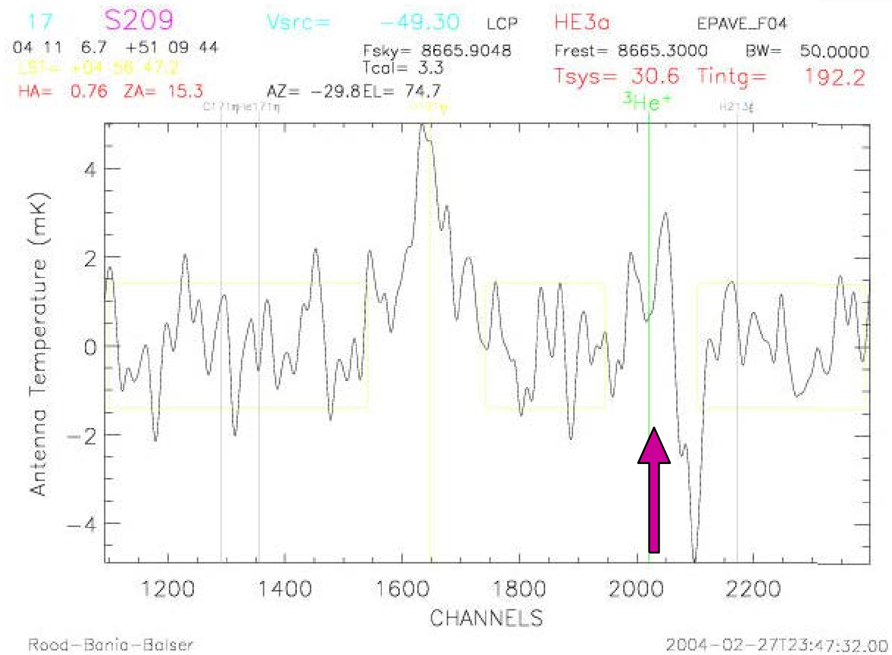
GBT: Clear Aperture Optics

S 209 HII Region

140 ft March 1995

GBT June 2004





33.1 hr

3.2 hr

Higher Order Radio Recombination Lines
GBT ACS Spectrometer

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

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

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

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

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

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

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

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

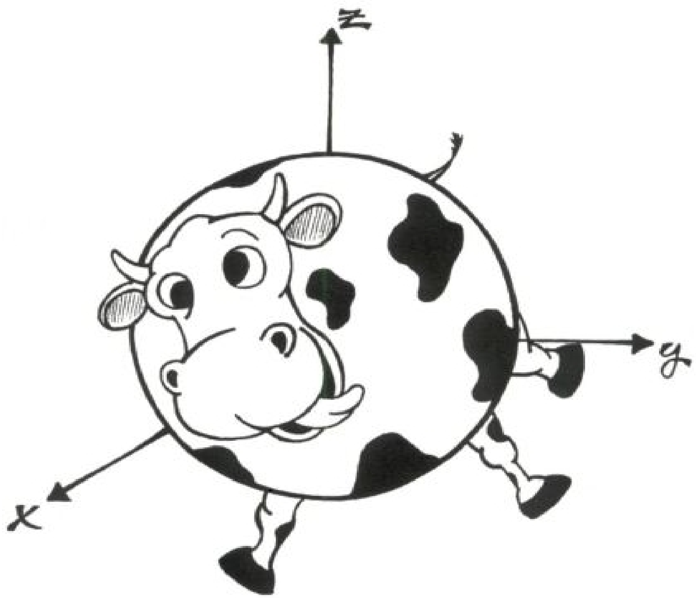
$\Delta n = 9:\ 186\iota, 187\iota, 188\iota$

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

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

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


HII Region
S206
NGC 1491



S206 Model

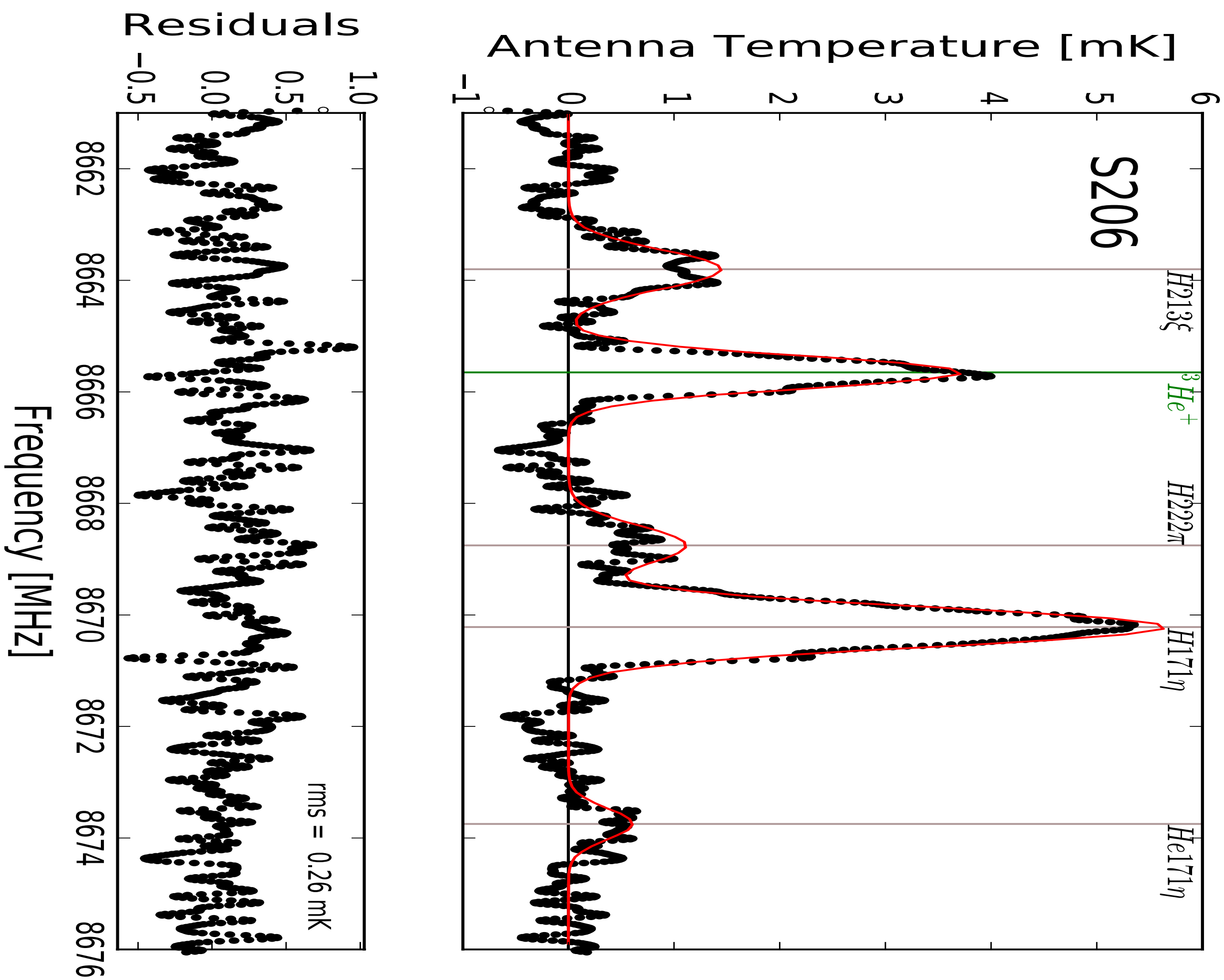
NEBULA

6 density components
LTE
No Pressure Broadening

$^4He^+/H^+ = 0.085$

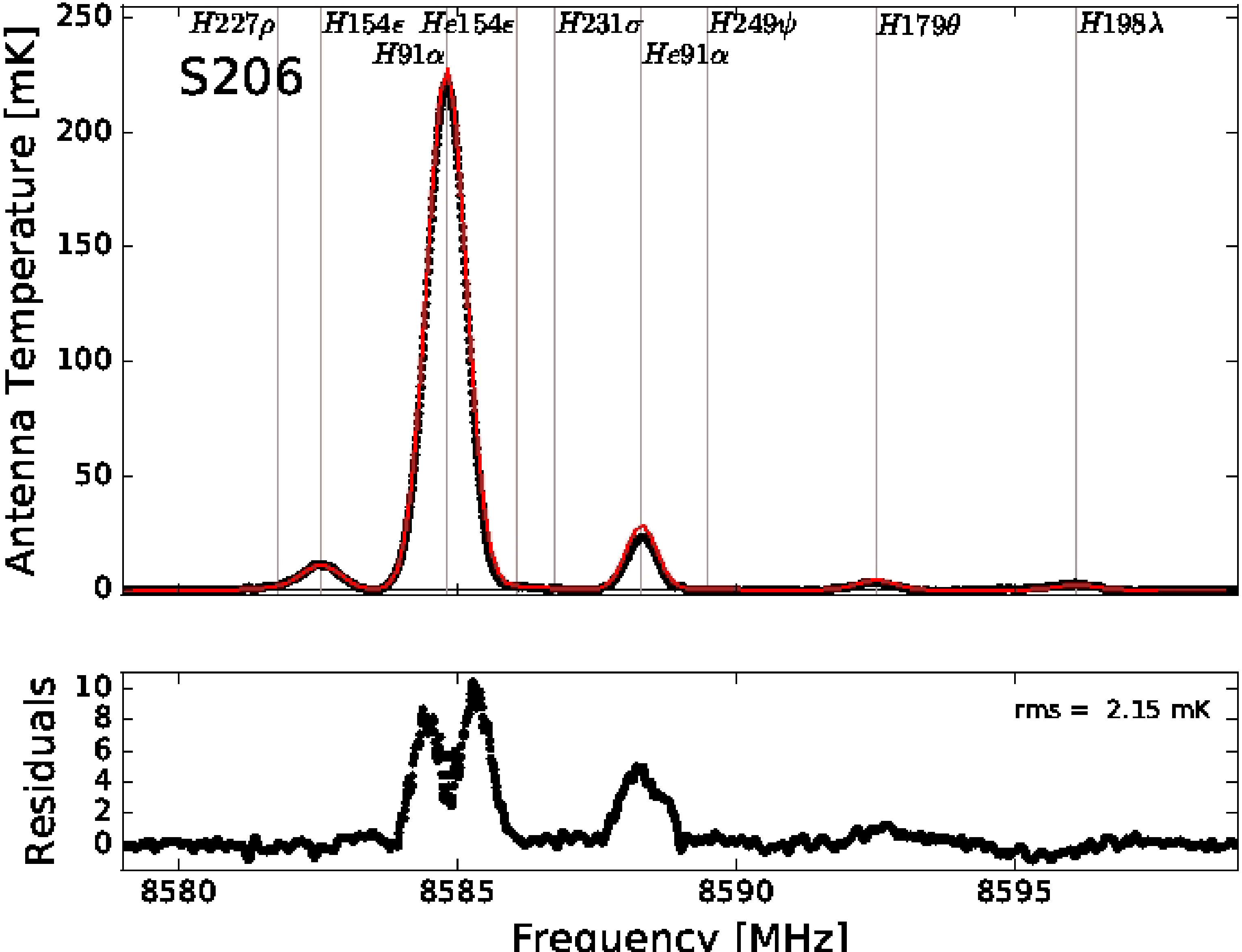
$^3He^+/H^+ = 1.89 \times 10^{-5}$

GBT $^3He^+$



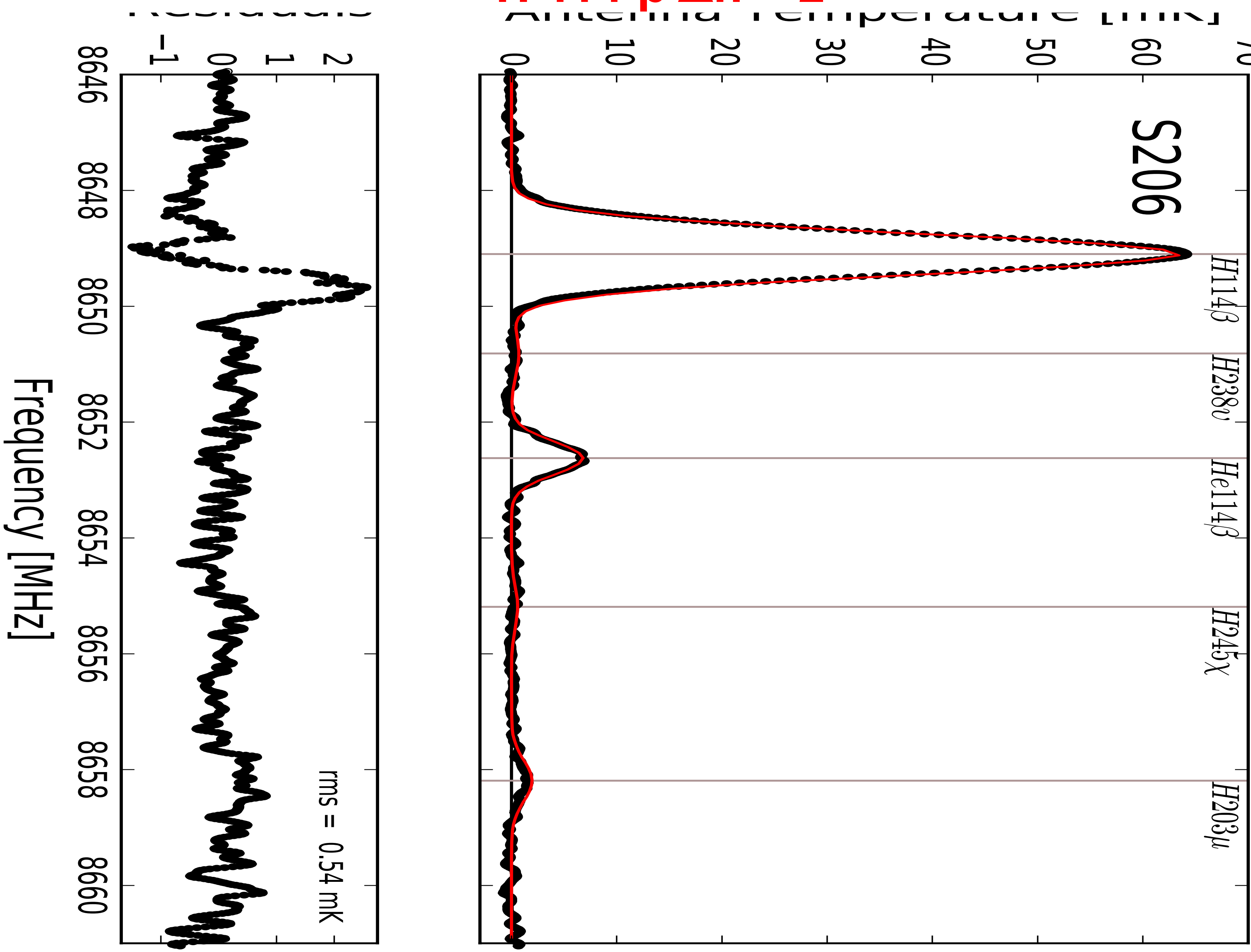
91 hour integration

H 91 α Δn = 1



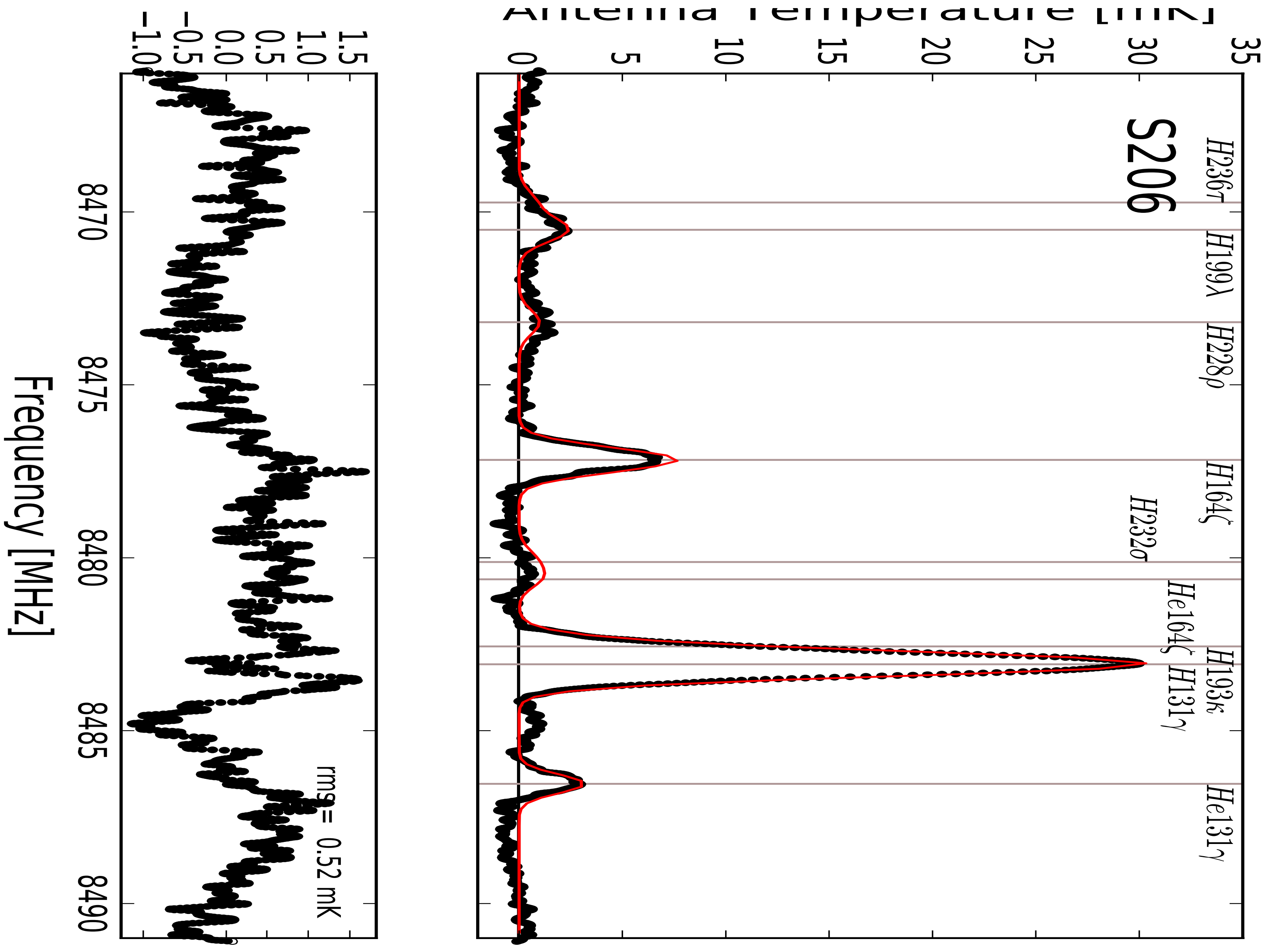
S206
H227ρ
H154ε
He154ε
H91α
H231σ
He91α
H249ψ
H179θ
H198λ
Antenna Temperature [mK]
250
200
150
100
50
0
Residuals
10
8
6
4
2
0
rms = 2.15 mK
8580
8585
8590
8595
Frequency [MHz]

H 114 β Δn = 2

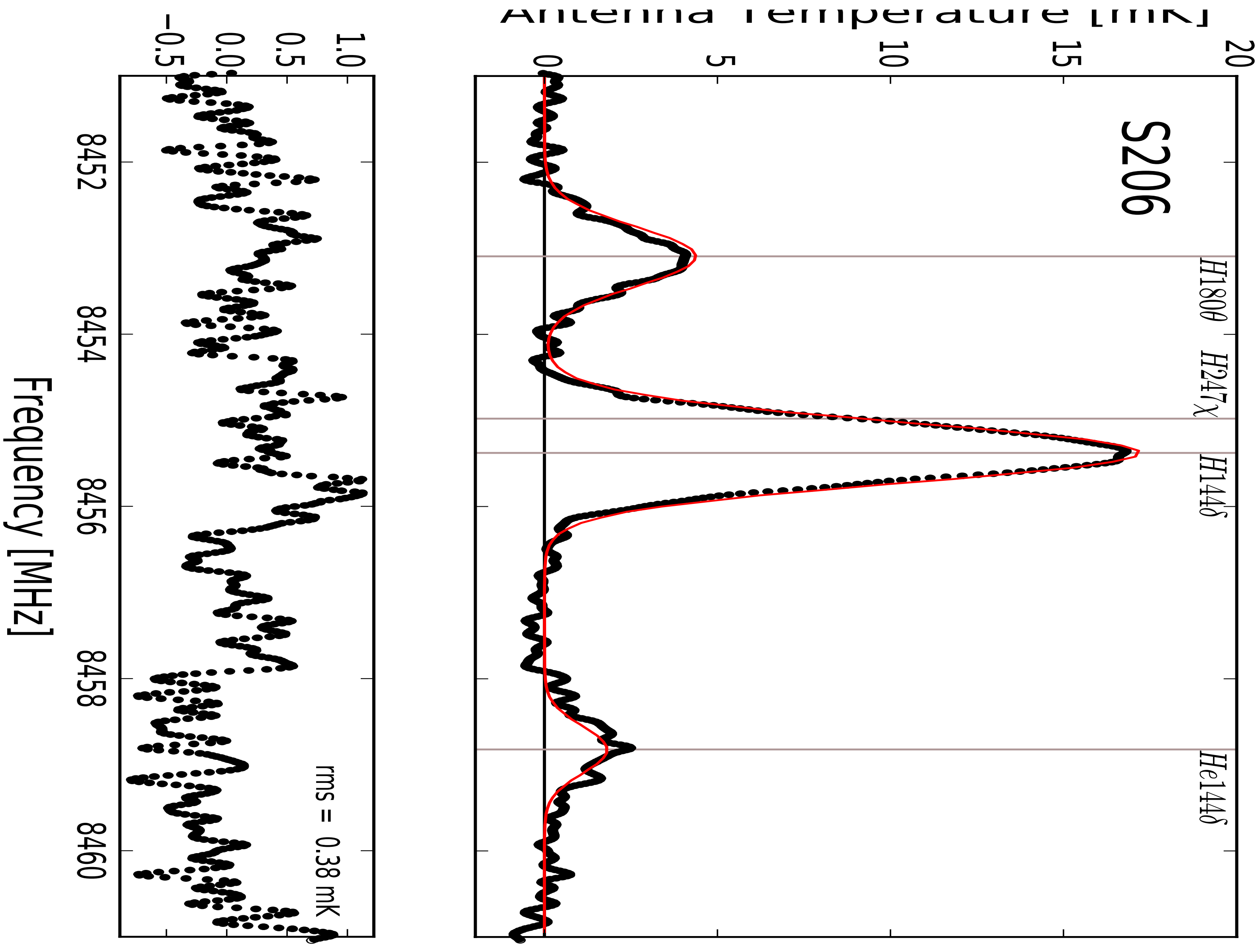


S206
Antenna Temperature [mK]
Residuals
Frequency [MHz]
rms = 0.54 mK
H114β
H238υ
He114β
H245χ
H203μ

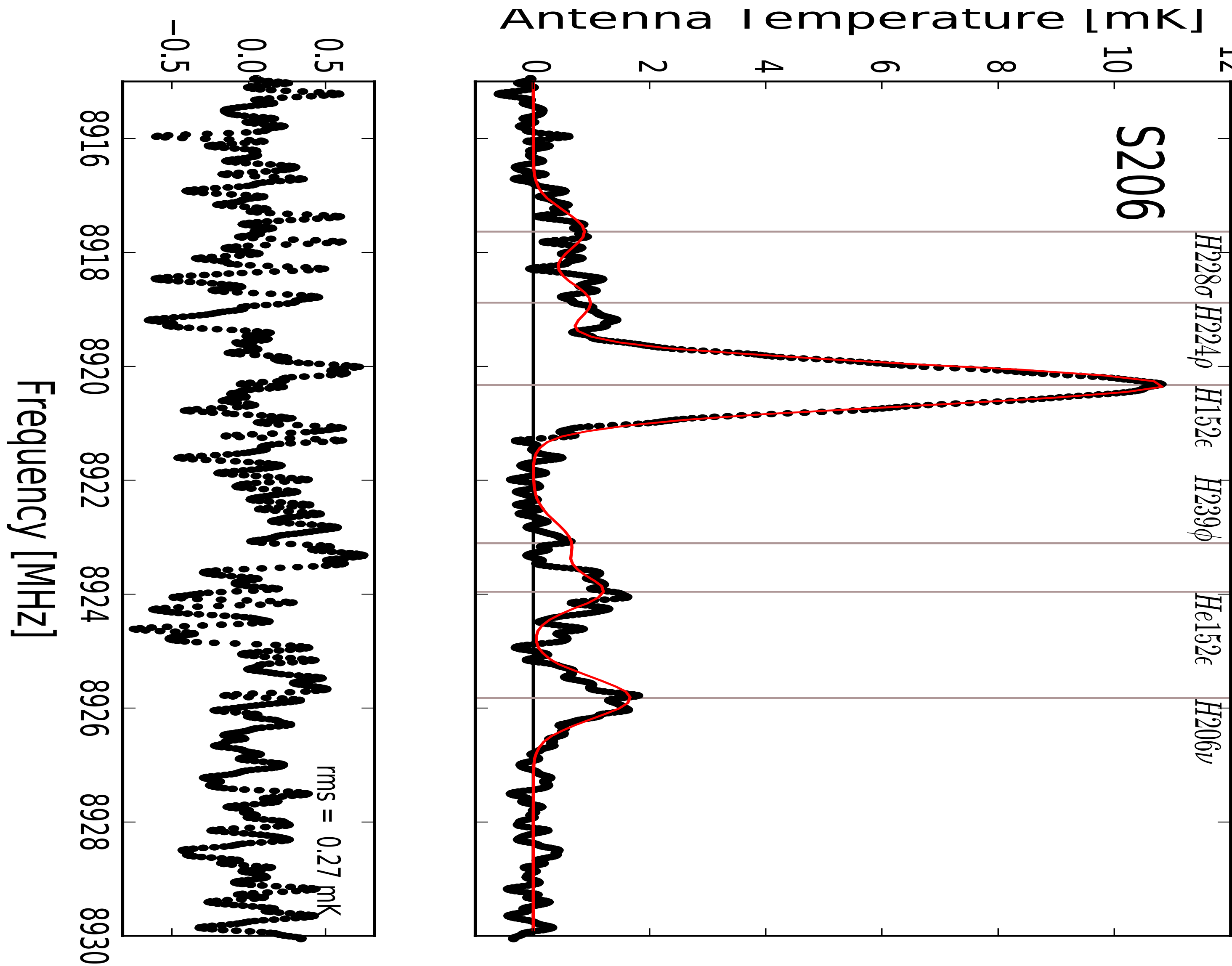
H 131 γ Δn = 3


Antenna Temperature [mK]
S206
H236τ
H199λ
H228ρ
H164ζ
H232σ
He164ζ
H193κ
H131γ
He131γ
rms = 0.52 mK
Frequency [MHz]

H 144 δ Δn =4


S206
Antenna Temperature [mK]
$H180\theta$
$H247\chi$
$H144\delta$
$He144\delta$
rms = 0.38 mK
Frequency [MHz]
8452
8454
8456
8458
8460
0
5
10
15
20
−0.5
0.0
0.5
1.0

H 152 ε Δn = 5


S206
Antenna Temperature [mK]
Frequency [MHz]
rms = 0.27 mK
H228σ
H224ρ
H152ε
H239φ
He152ε
H206ν
0
2
4
6
8
10
12
−0.5
0.0
0.5
8916
8918
8920
8922
8924
8926
8928
8930

GBT should have been a contender

Alas.
There is ~ 2 km between the GBT X-band receiver and the control room where the Spectrometer is located.
We find that the IF system produces instrumental baseline frequency structure at the ~ 0.5 mK level.
We are working on characterizing this and trying to mitigate its effects.