Stalking the Cosmic ^{3}He Abundance

Tom Bania (BU)

Bob Rood (UVa)

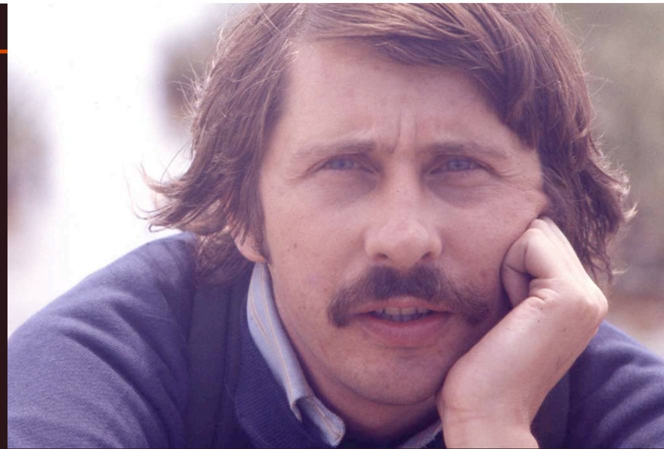
Dana Balser (NRAO)

Miller Goss (NRAO)

Cintia Quireza (ON, Brazil)

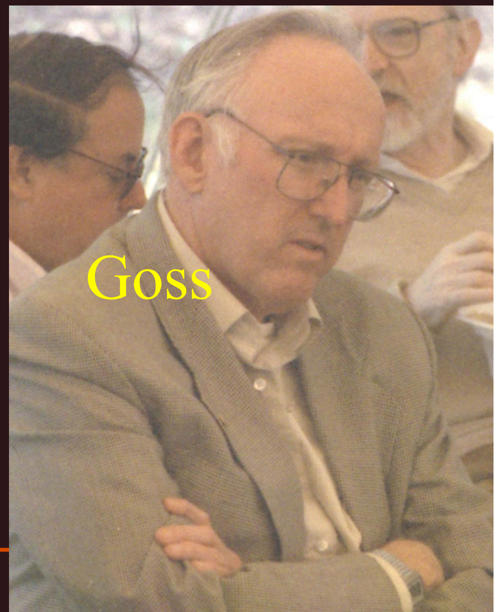
Tom Wilson (MPIfR)

The Saga of


Steigman


Wilson

Bania

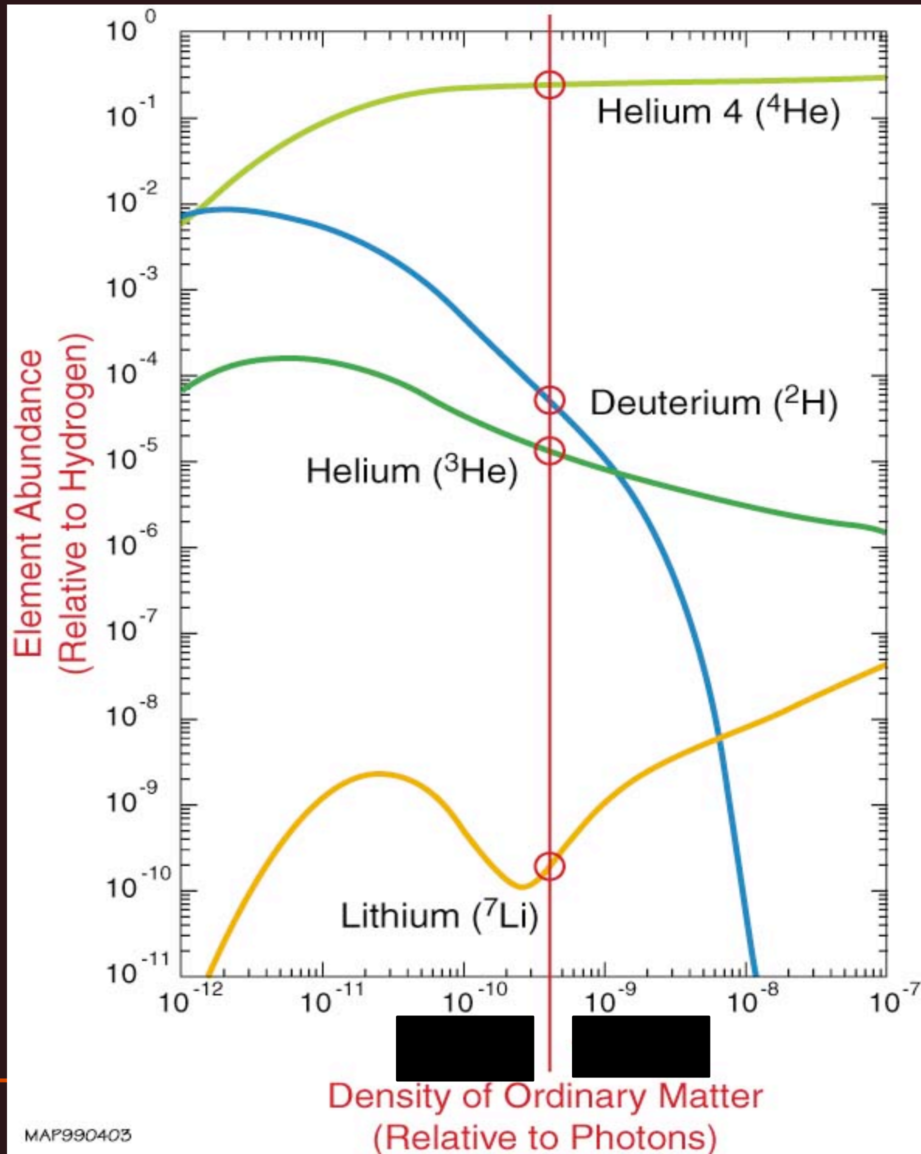
Balser

Goss

Quireza

^{3}He is one of the four BBN isotopes

It has become the Rodney Dangerfield isotope

Light Elements as Baryometers



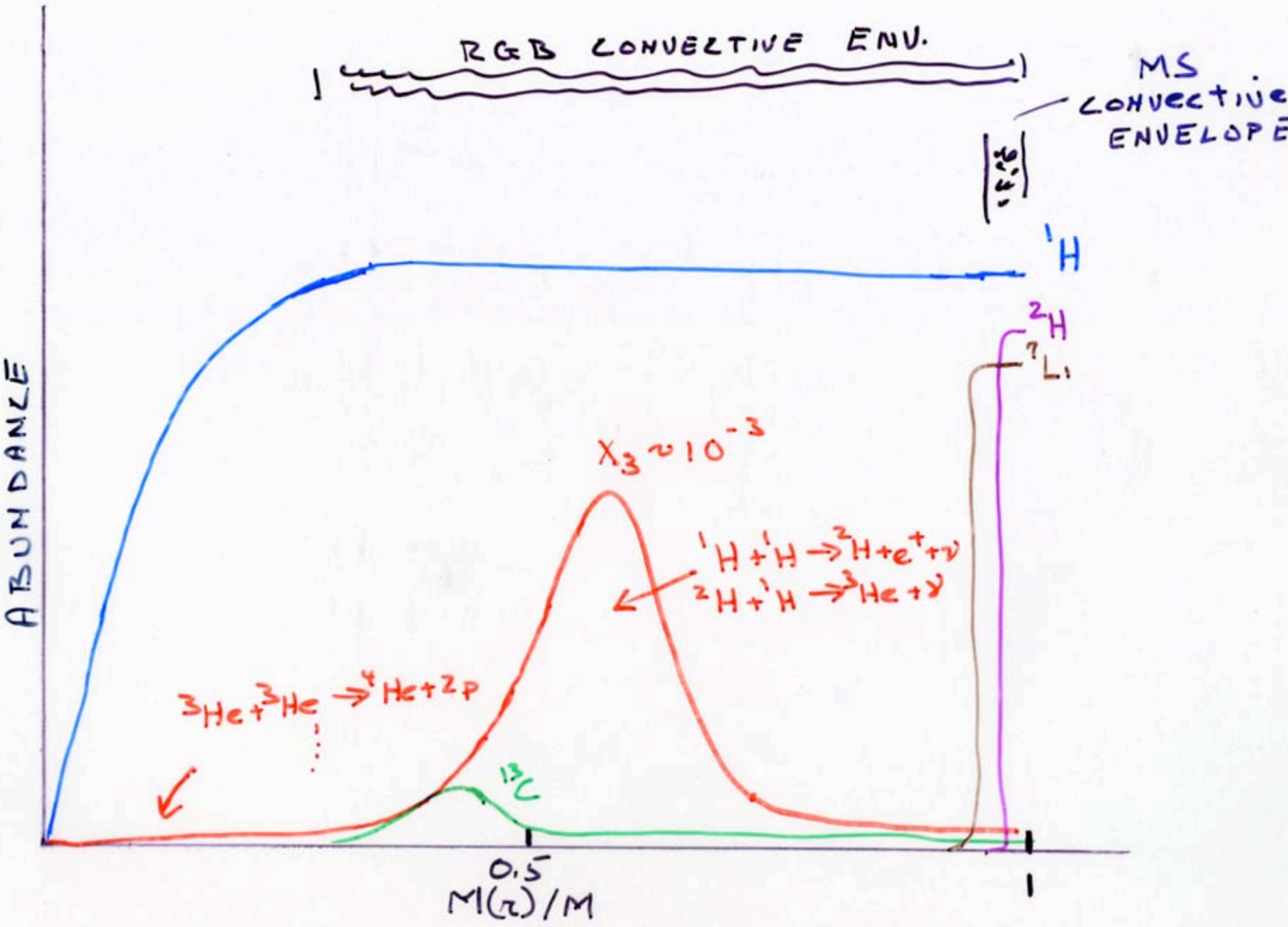
3-Helium is also made ~~in stars.~~ standard stellar models

It reaches the surface on the lower RGB

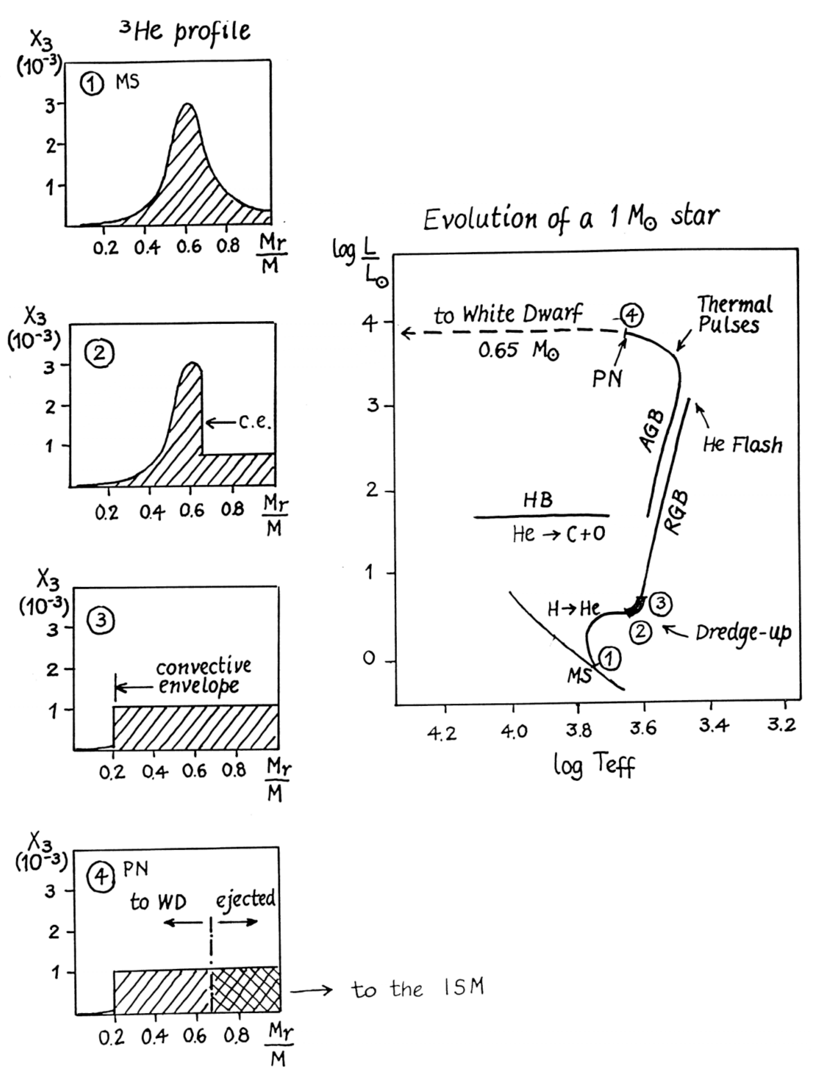
RGB & AGB winds and PNe should be enriched in ^{3}He

many 10's primordial or protosolar value

0.8 – 2 M⊙ AT TURNOFF



^{3}He: Stellar Evolution



$^1H + ^1H \rightarrow ^2H + e^+ + \nu$ 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

Daniele Galli

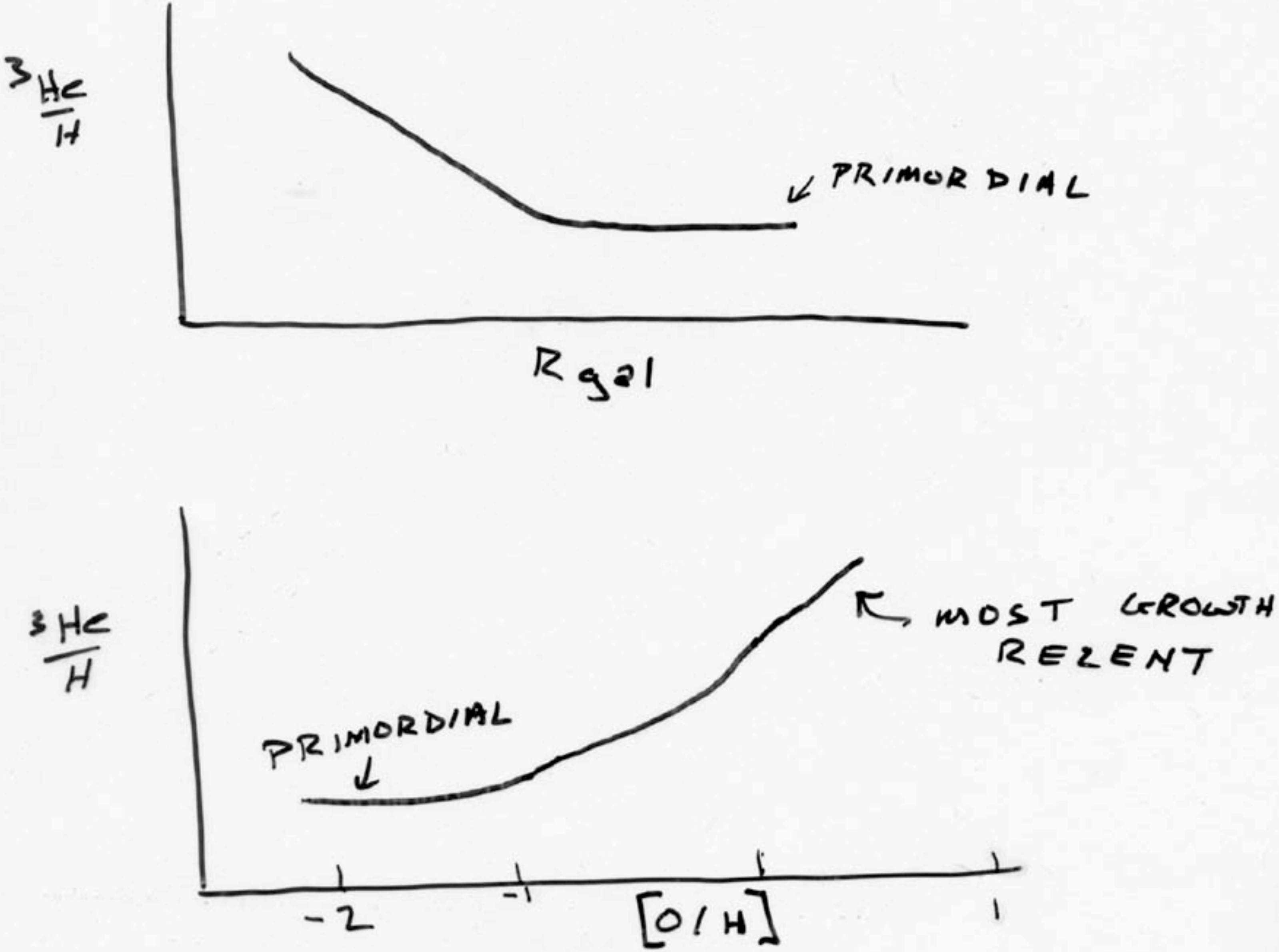
^{3}He Factinos – ^{3}He/^{4}He

Solar wind	3.75×10^{-4}
Jupiter	1.66×10^{-4}
Terrestrial	10^{-8}

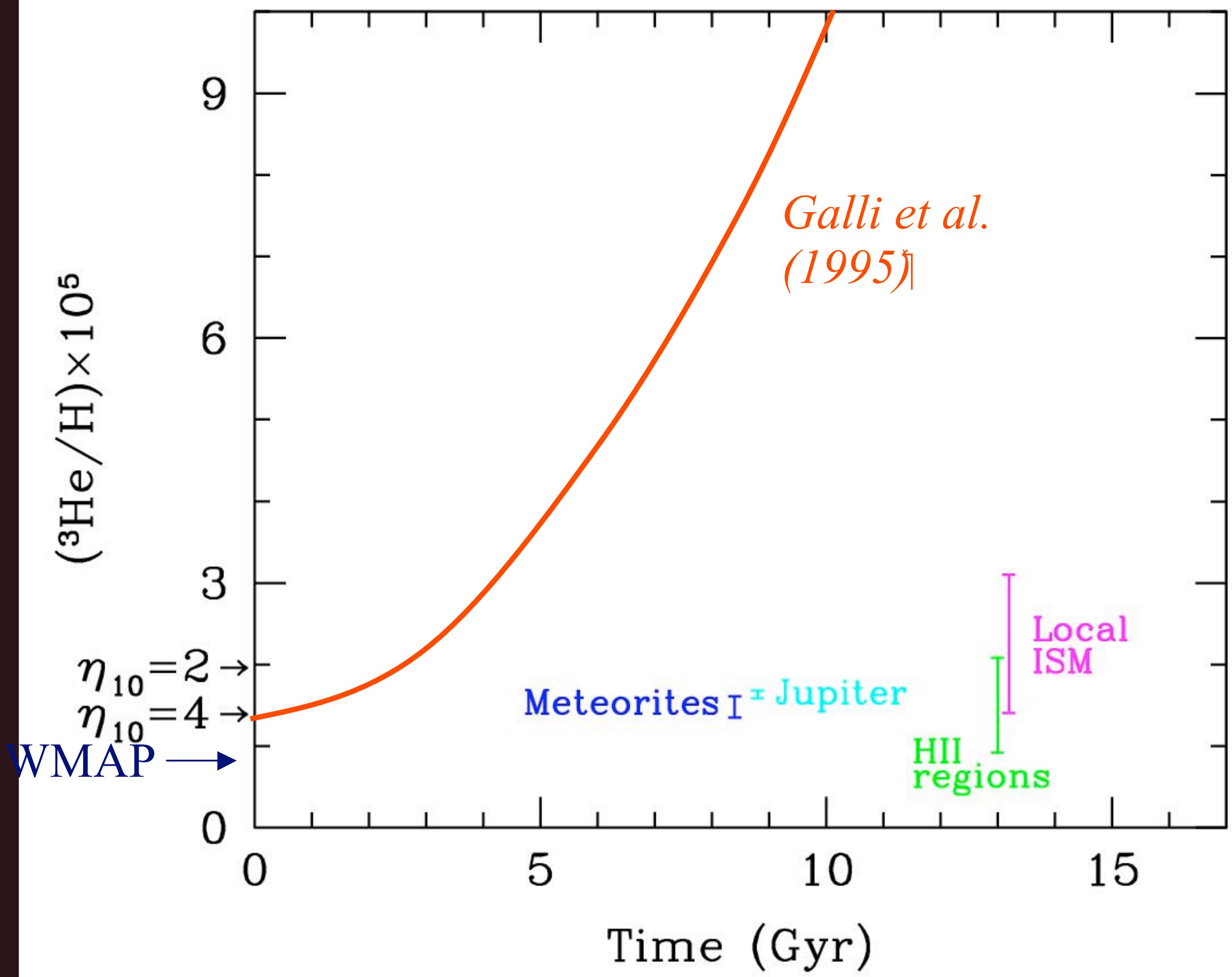
A clue

on the Earth Ar is 99.6% the stable isotope 40Ar,
on the Sun Ar is 84% 36Ar and 14% 38Ar

NAIVE EXPEZTATIONS



“The ^{3}He Problem”



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

^{3}He Factinos

In production of terrestrial ^{3}He, atmospheric spallation has regained the lead from nuclear weapons

Interplanetary ^{3}He can be sampled from gas trapped in infalling Buckyballs.

^{3}He is the 11th most abundant isotope

^{3}He: Observations

Solar System:

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

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

Local Interstellar Medium (LISM):

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

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

Galactic:

^{3}He Recombination Lines?

^{3}He$^+$ Hyperfine Line?

Radio Astronomy Holy Grails

H I

1420 MHz

D I

327 MHz

$^{3}He^{+}$

8665 MHz

Hyperfine "Spin Flip" Transitions

$^{3}He^{+}$ Hyperfine Transition

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

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

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

Observe ^3He using the hyperfine (spin-flip) line of $^3He^+$

Analog of the 21 cm line of H

ν = 8665.65 MHz λ = 3.36 cm

$$\frac{N(^3\mathrm{He}^+)}{N(\mathrm{H}^+)} = 1.5 \times 10^{-3} \frac{T_L \Delta v [N(^4\mathrm{He}^+)/N(\mathrm{H}^+) + 1]\theta_{\mathrm{obs}}}{(\beta T_c)^{0.5}(\theta_{\mathrm{obs}}{}^2 - \theta_A{}^2)^{0.75} R^{0.5}} \times \left[\frac{T_e}{8000\ \mathrm{K}}\right]^{-0.175}$$

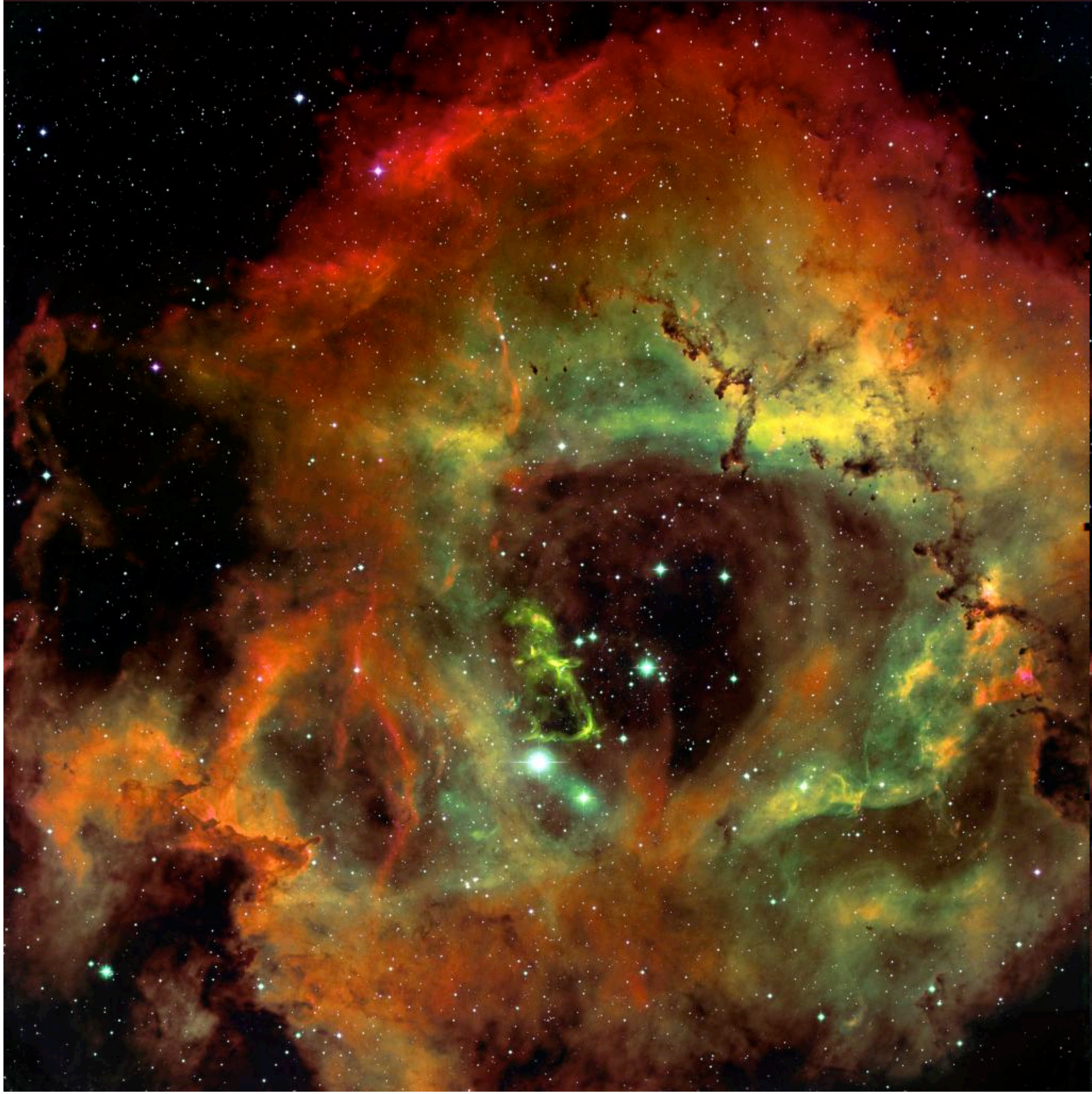
NRAO 140 ft

H II Regions

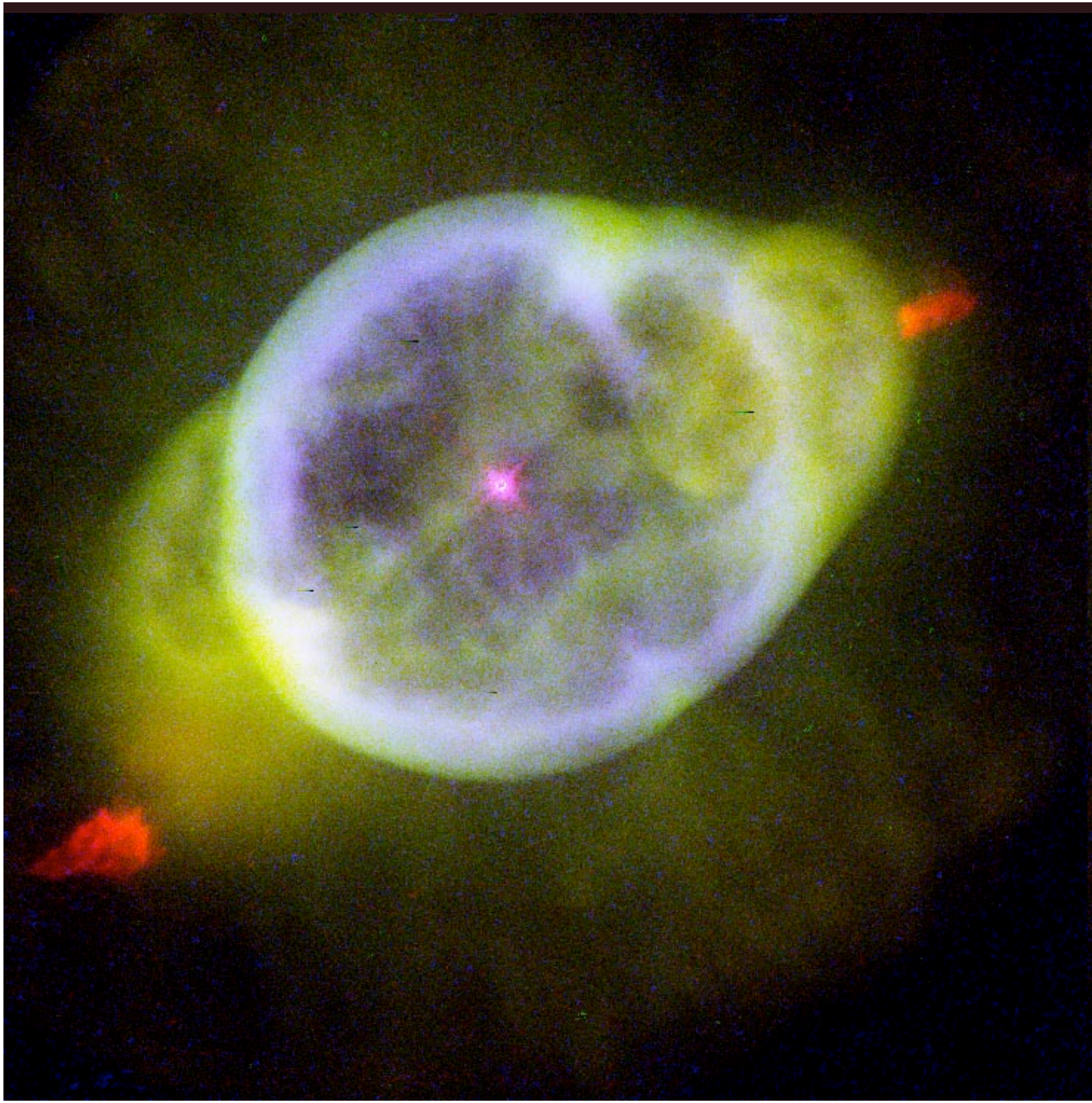
MPIfR 100 m

Planetary Nebulae (PNe)

Observes giant clouds of ionized gas (H II regions) like the Orion Nebula



Even better are distant versions of the Rosette Nebula



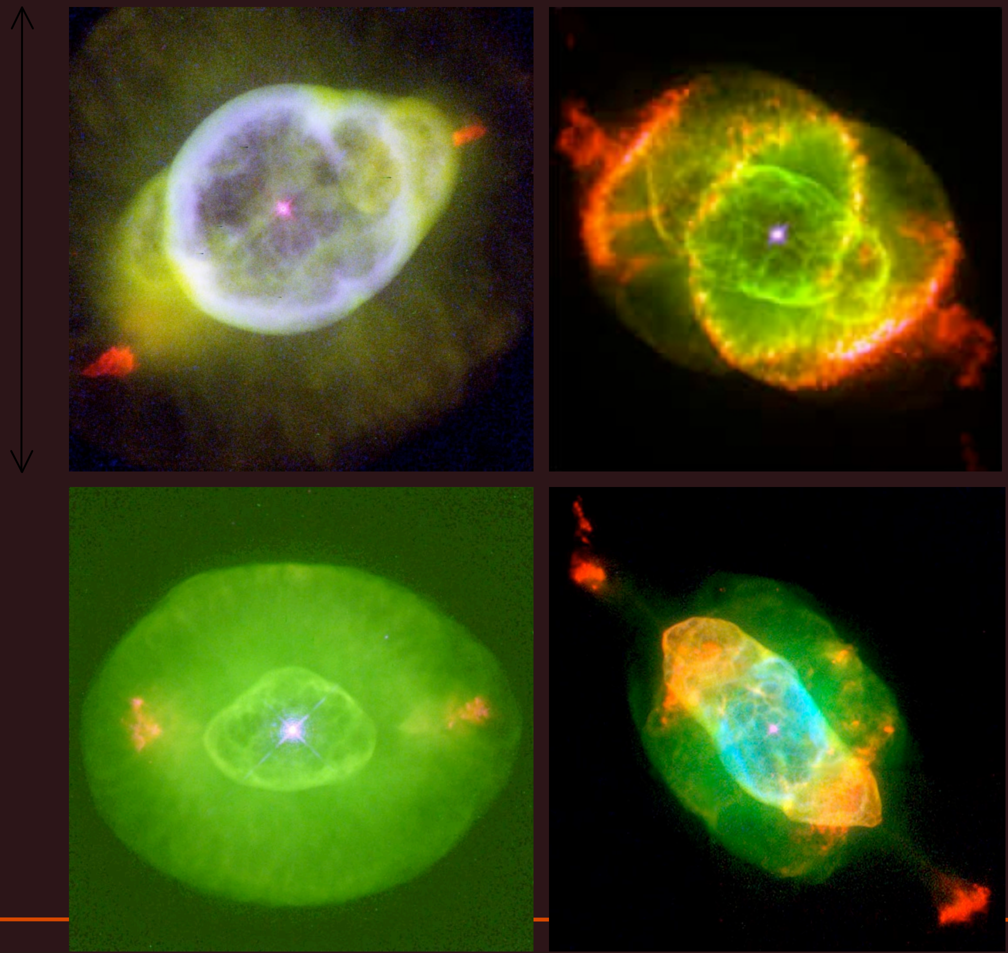
Or observe the ejecta of solar-type stars, planetary nebulae.

Less ionized gas, but perhaps much higher $^{3}He/H$.

Planetary Nebulae

NGC 3242 NGC 6543

50”



NGC 6826 NGC 7009

Balick et al.

NRAO 140 Foot: HII Regions

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

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

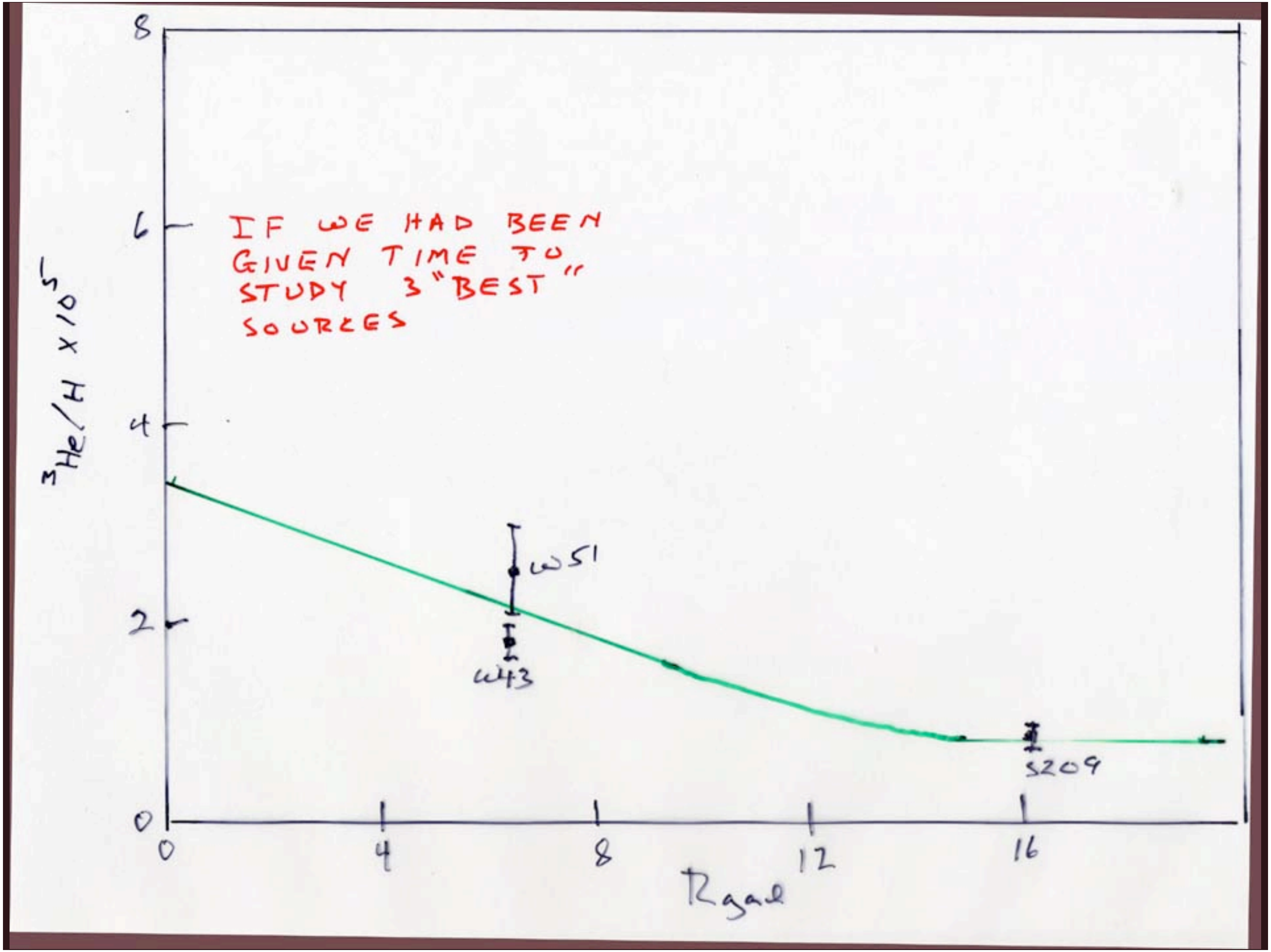
HPBW = 3.5 arcmin

The 140ft was designed to be rigid but to still operate at wavelengths of 1 cm.

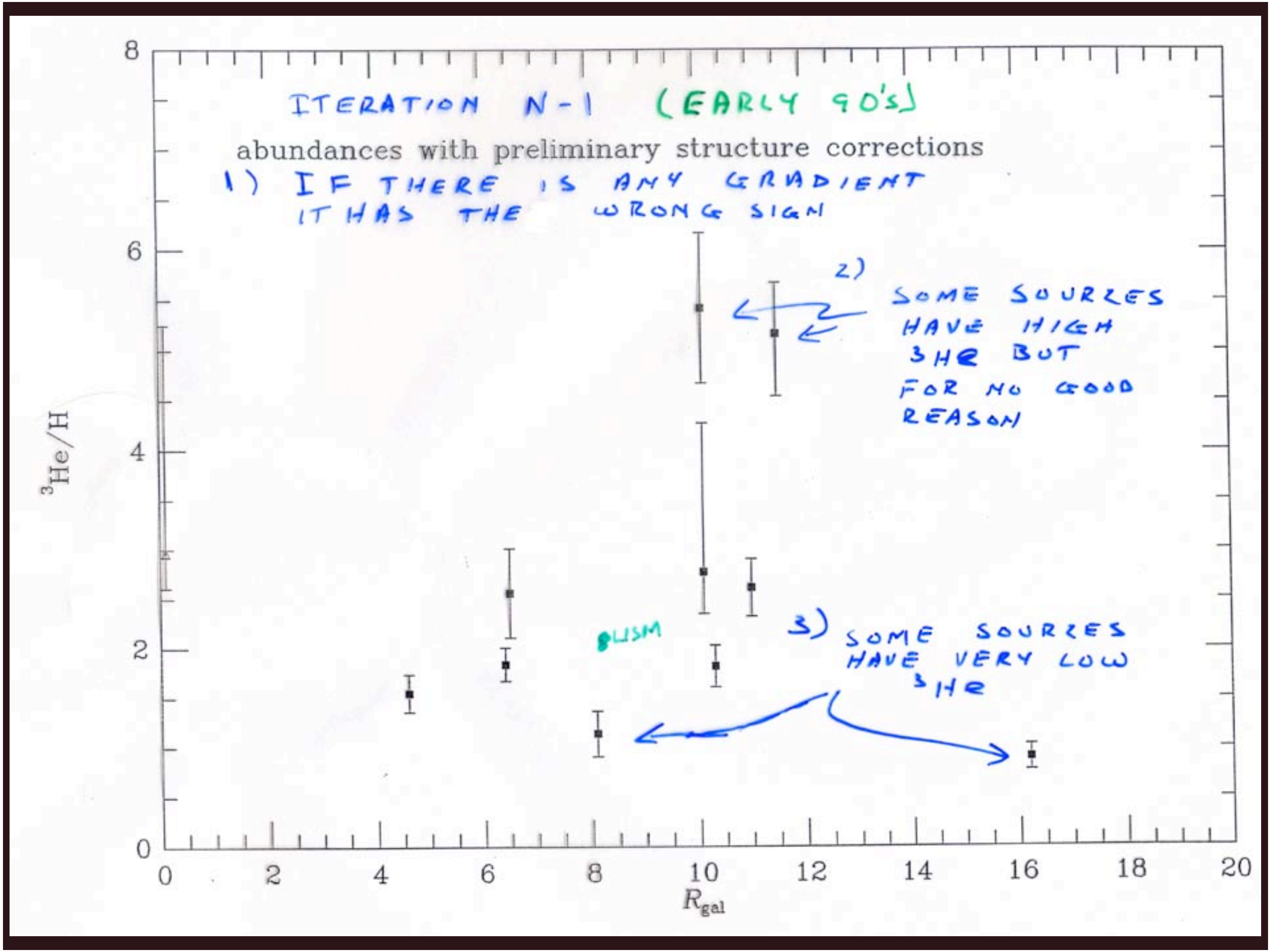
It still sagged which sometimes gave it double vision.

Sebastian von Hoerner designed a <u>deformable secondary mirror</u> which basically functioned as eye glasses.

It also had a polar mount---one axis parallel to the Earth's axis so it could have a "clock drive" like 19th century optical telescopes.



IF WE HAD BEEN GIVEN TIME TO STUDY 3 "BEST" SOURCES
$^3He/H \times 10^5$
W51
W43
S209
Rgal
0
2
4
6
8
12
16


ITERATION N-1 (EARLY 90's)
abundances with preliminary structure corrections
1) IF THERE IS ANY GRADIENT IT HAS THE WRONG SIGN
2) SOME SOURCES HAVE HIGH 3HE BUT FOR NO GOOD REASON
3) SOME SOURCES HAVE VERY LOW 3HE
LISM
^{3}He/H
R_{gal}
0
2
4
6
8
10
12
14
16
18
20

Conventional

Blocked

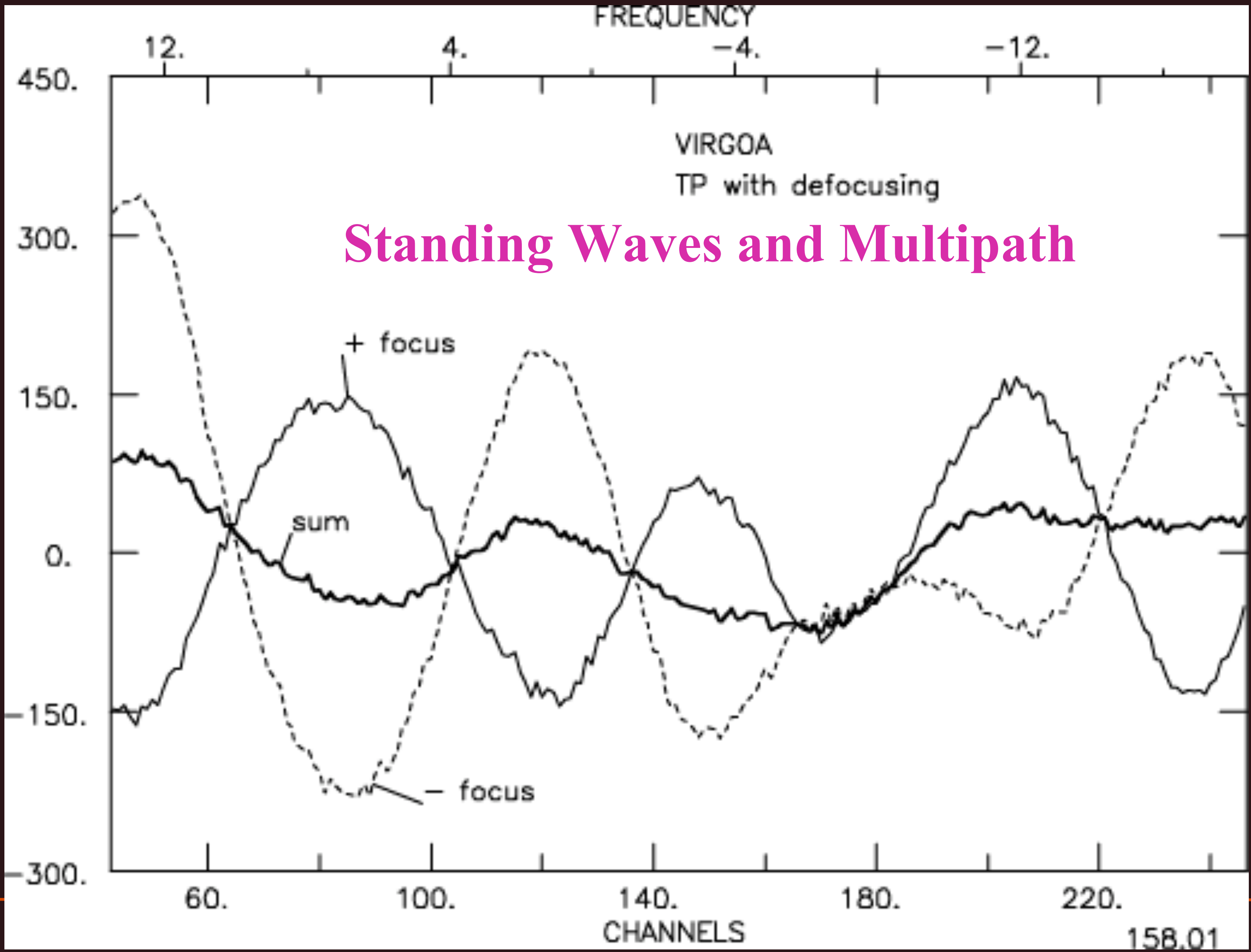
Aperture

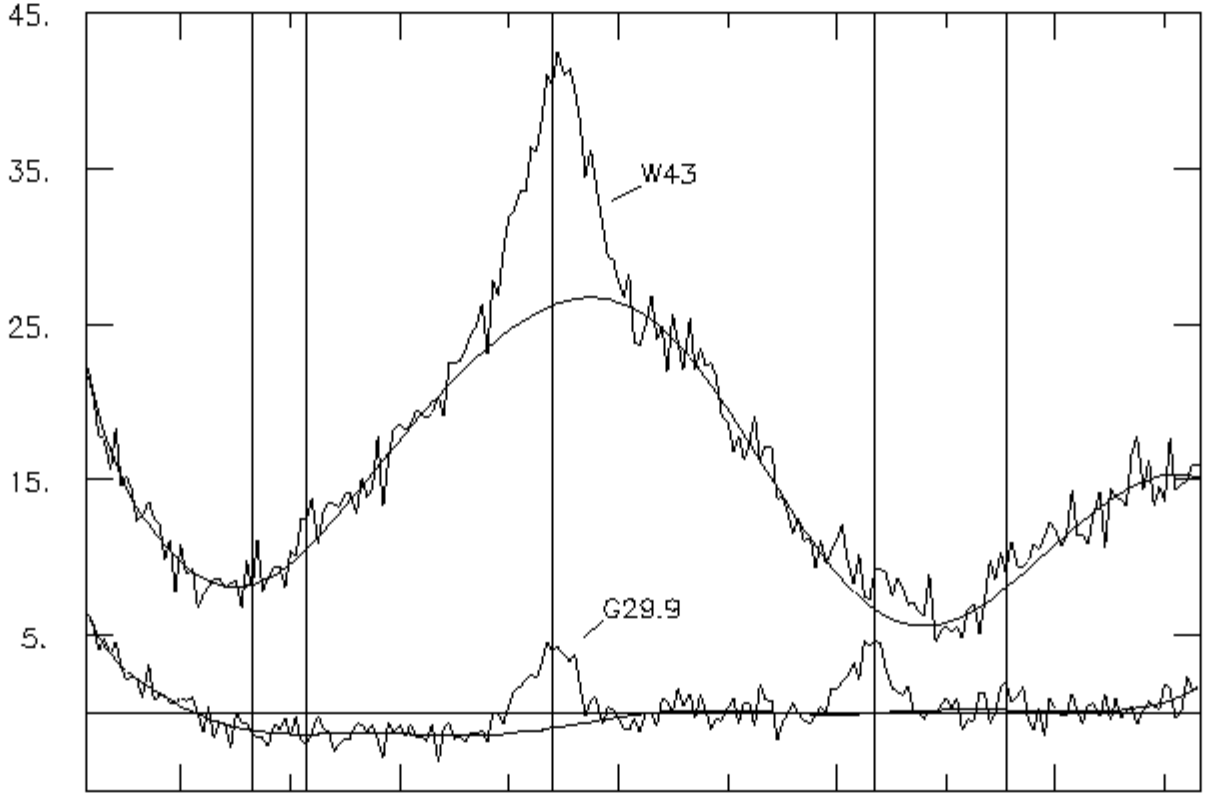
Is a very

Bad

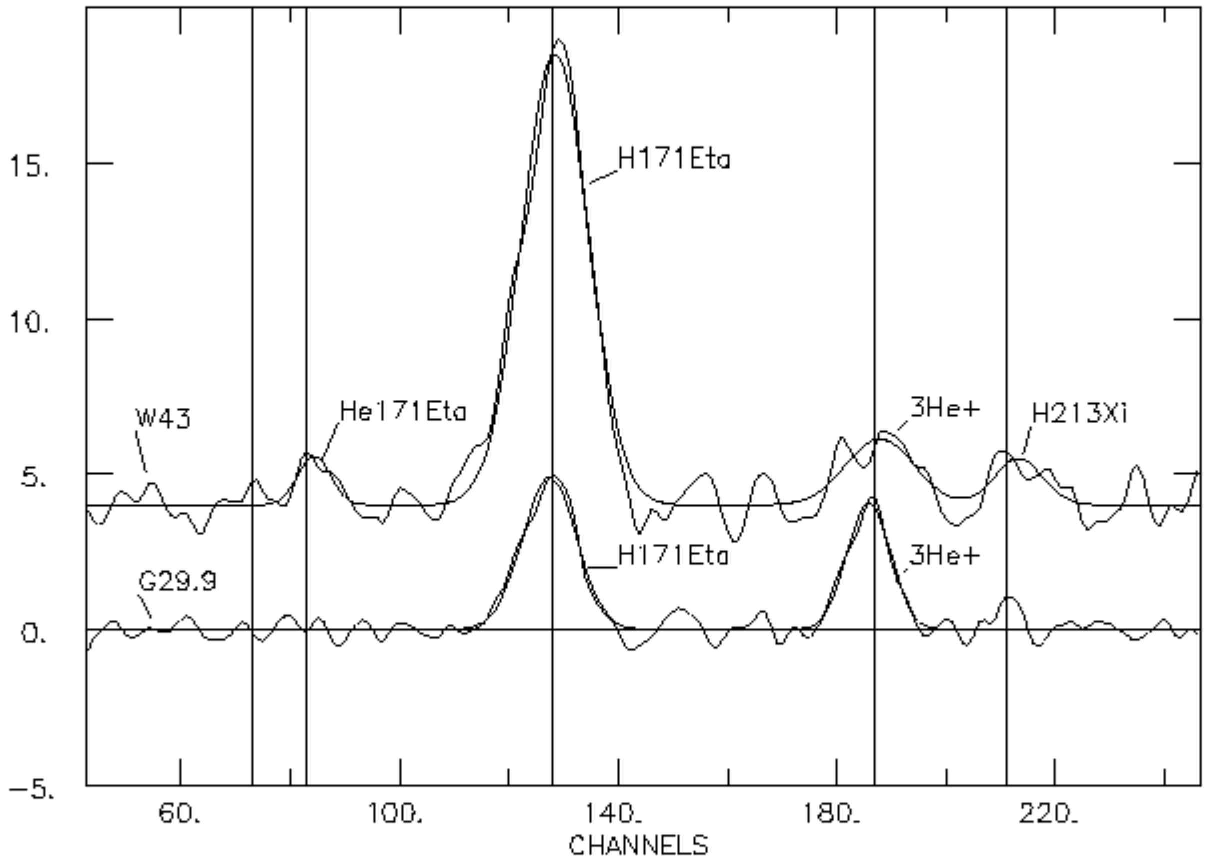
Design

Standing Waves and Multipath





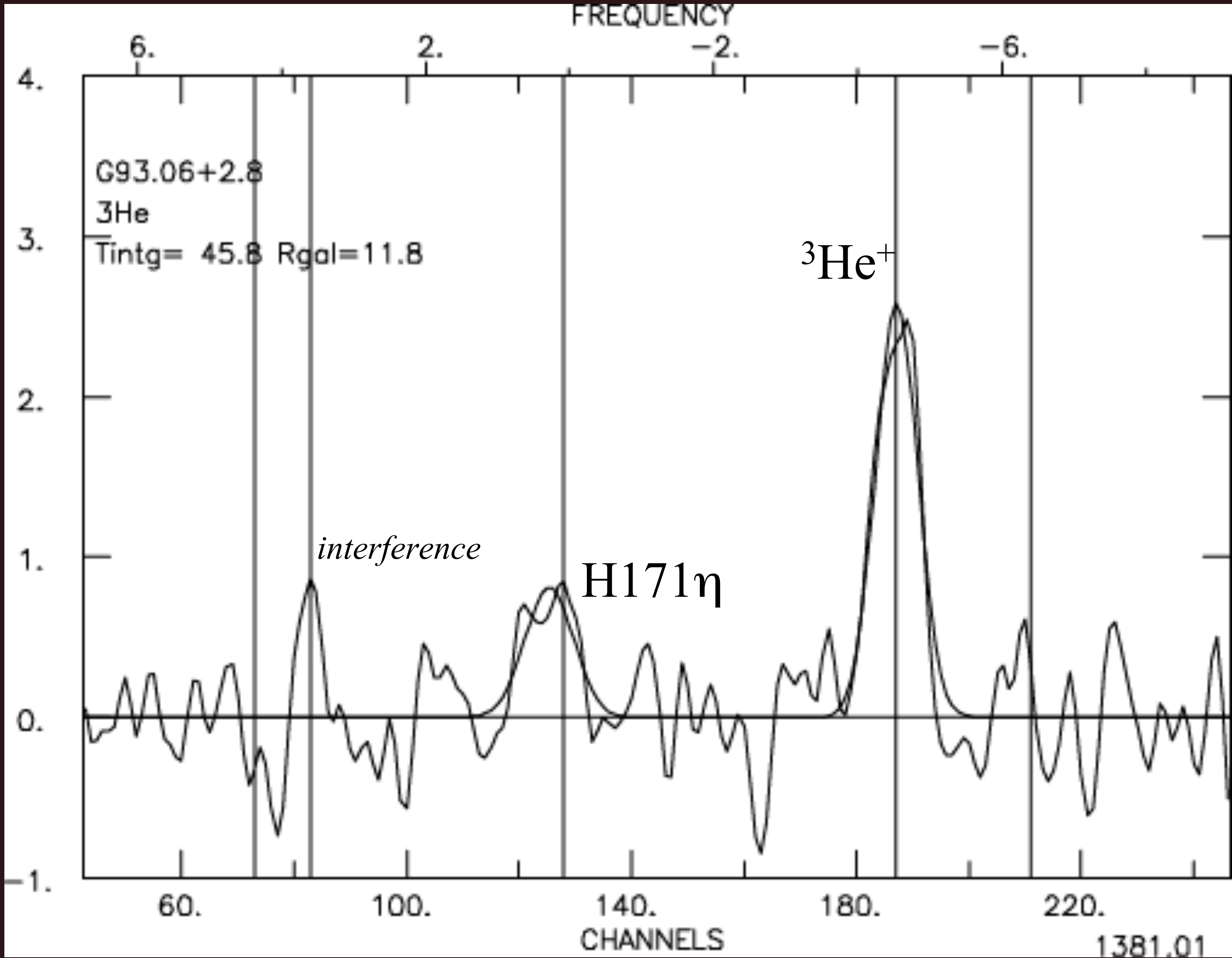
45.
35.
25.
15.
5.
W43
G29.9



15.
10.
5.
0.
−5.
60.
100.
140.
180.
220.
CHANNELS
W43
G29.9
He171Eta
H171Eta
H171Eta
3He+
3He+
H213Xi

Duh…

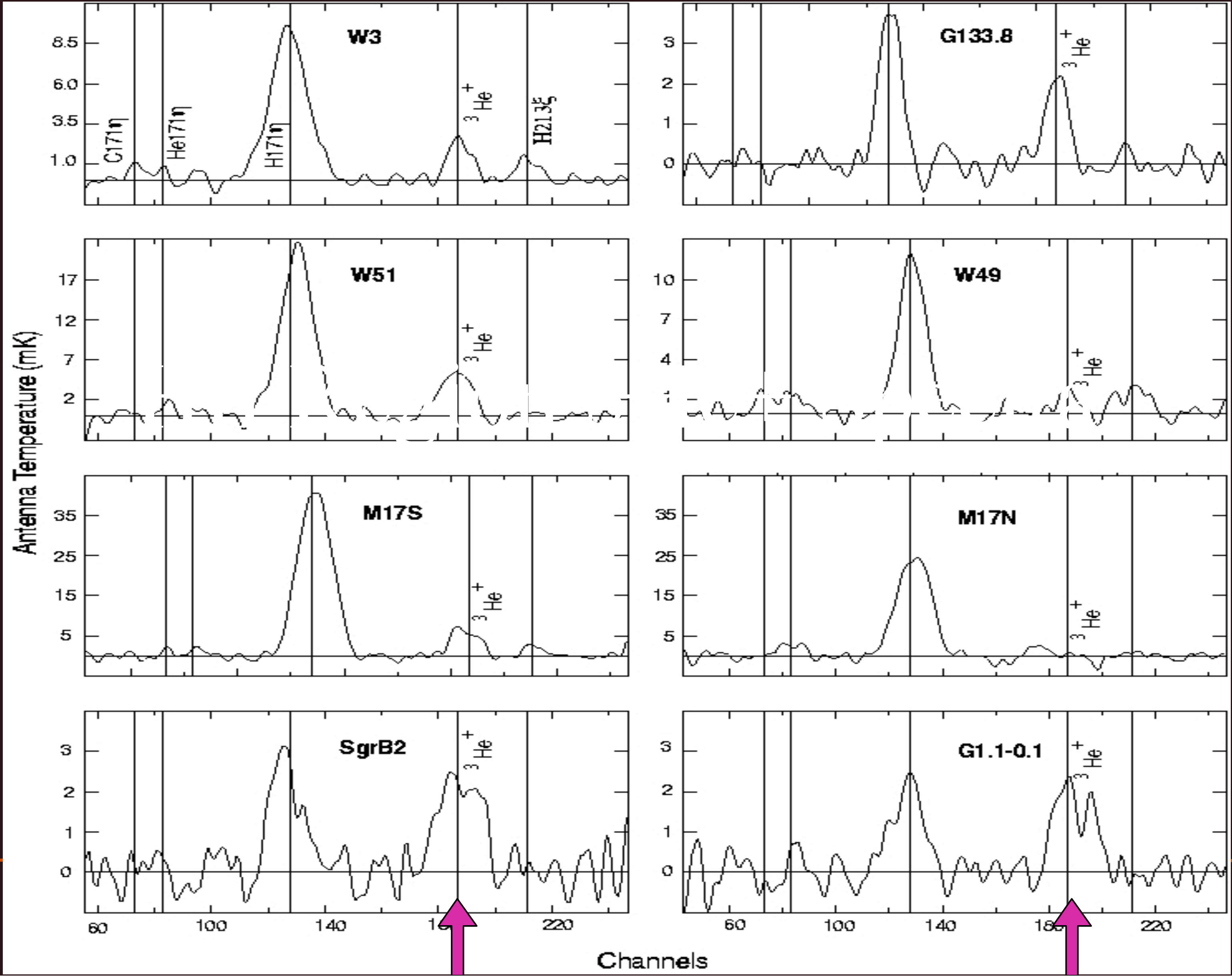
The famous HII regions are not the best ^3He targets



G93.06+2.8 45.8 hr integration

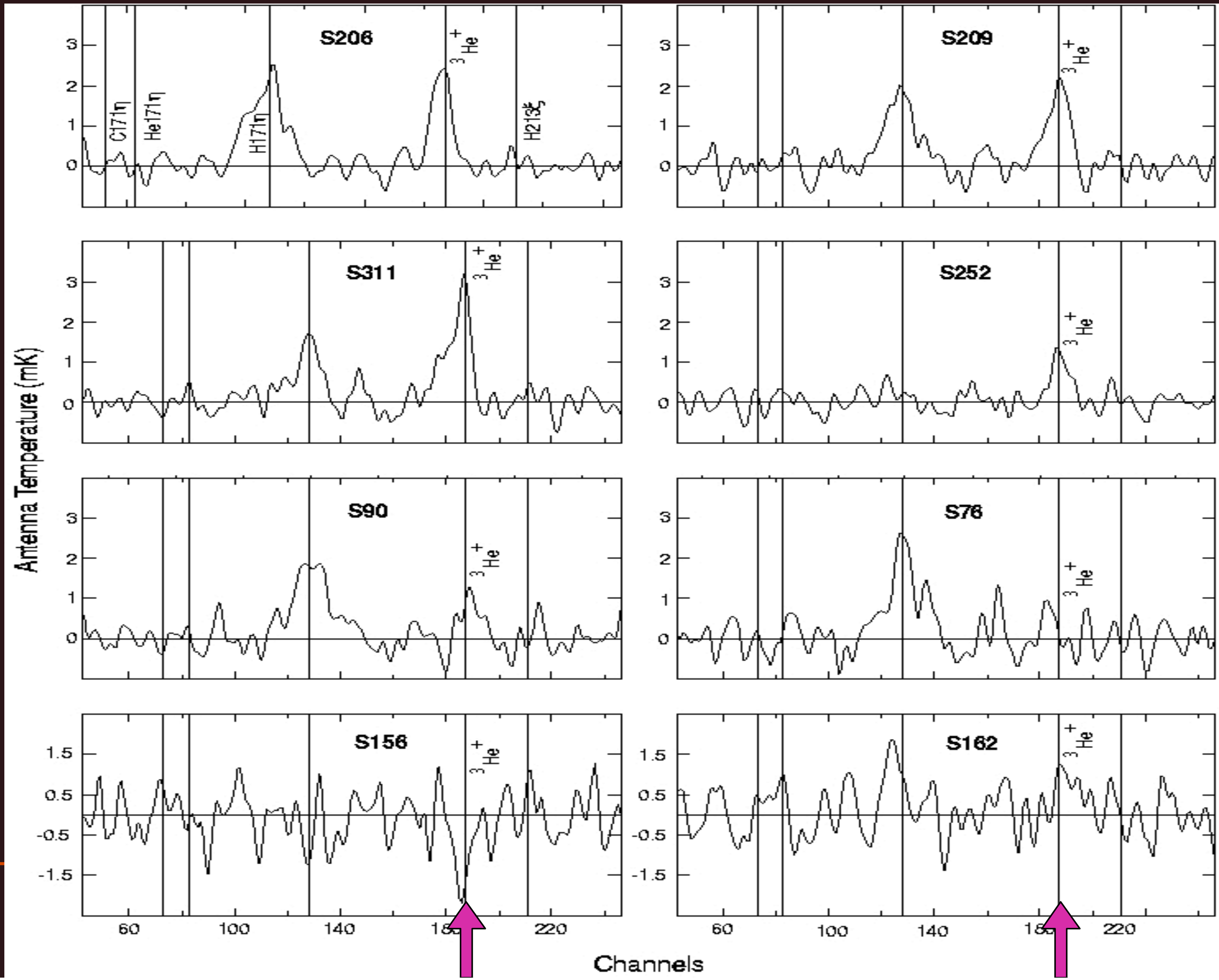
HII Region $^3He^+$ Spectra

Bania et al. (1997)



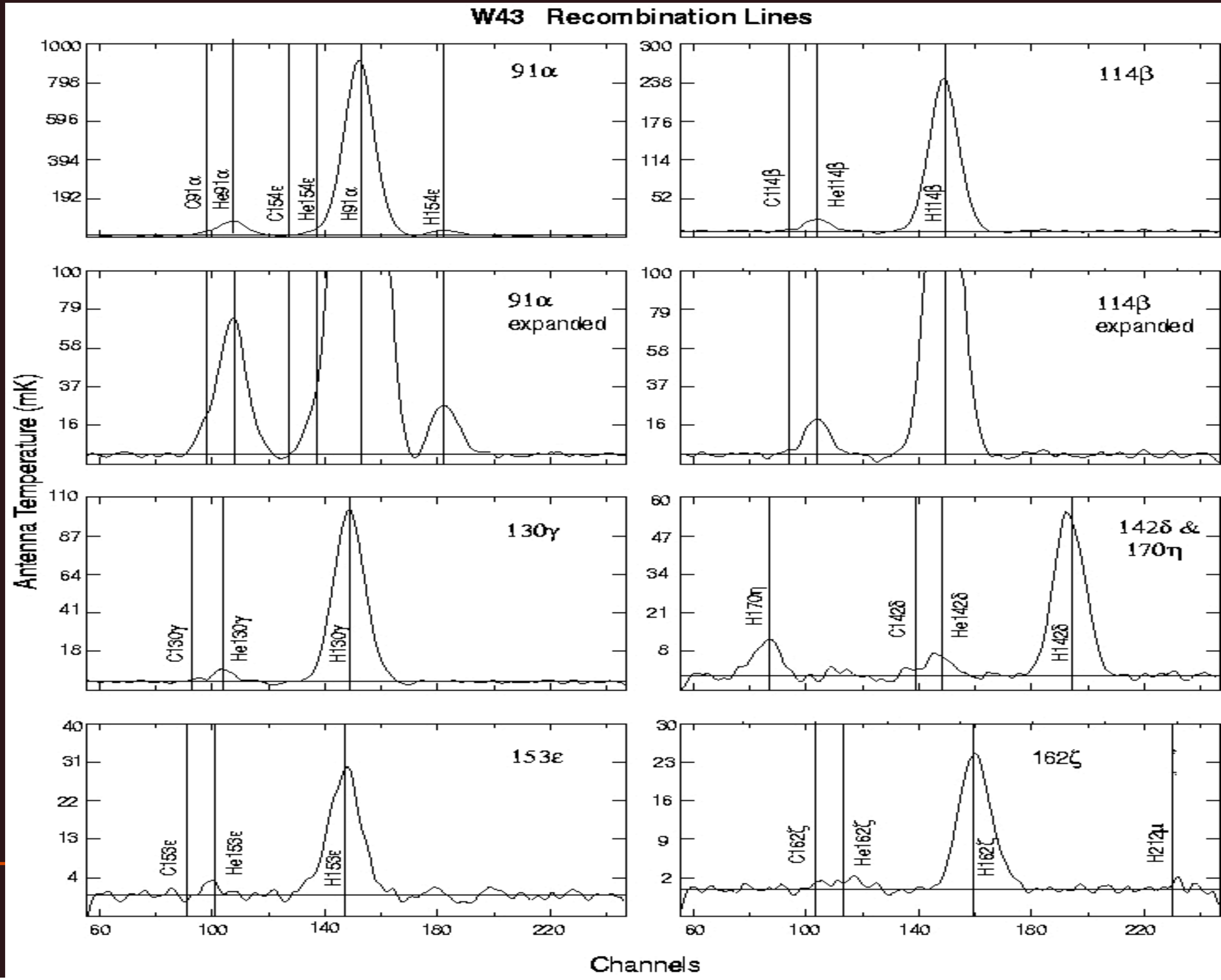
Sharpless HII Regions

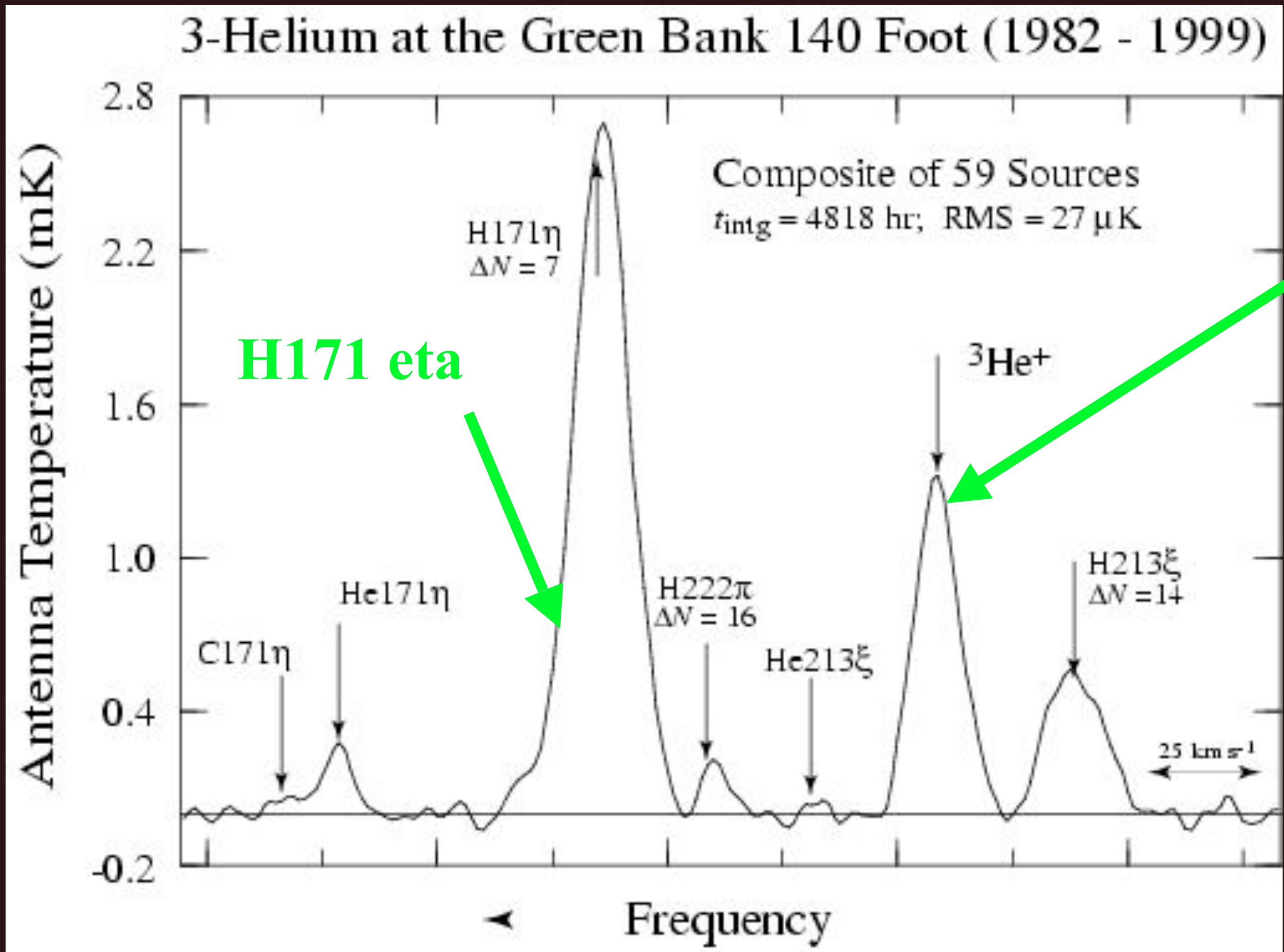
Bania et al. (1997)



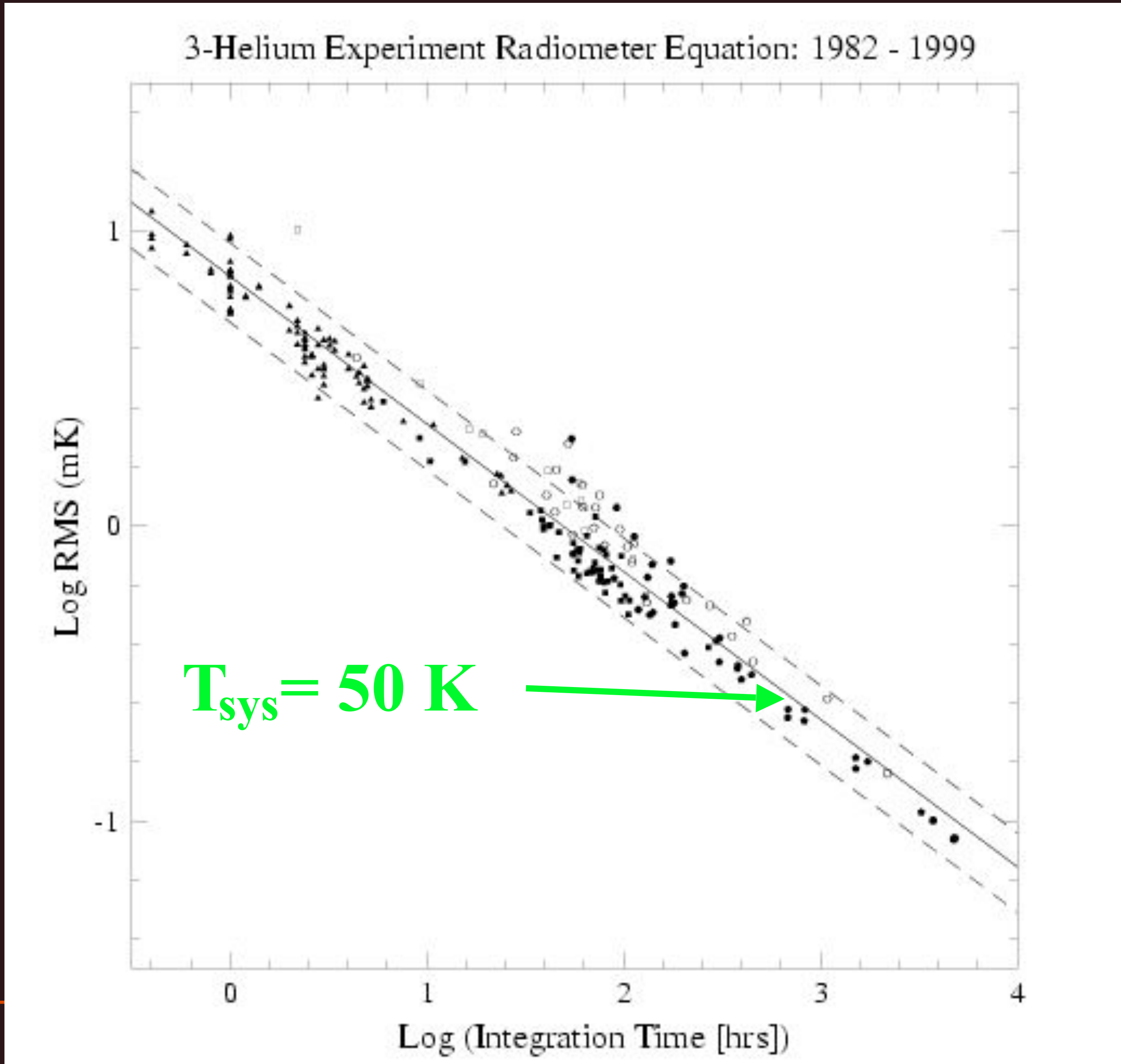
Radio Recombination Lines

Bania et al. (1997)





200 Day Integration: 27 microKelvin RMS



3-Helium Experiment Radiometer Equation: 1982 - 1999
Log RMS (mK)
1
0
-1
0
1
2
3
4
Log (Integration Time [hrs])
Tsys= 50 K

^{3}He Abundance Determination

OBSERVE THE EQUIVALENT WIDTH DERIVE THE ABUNDANCE

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

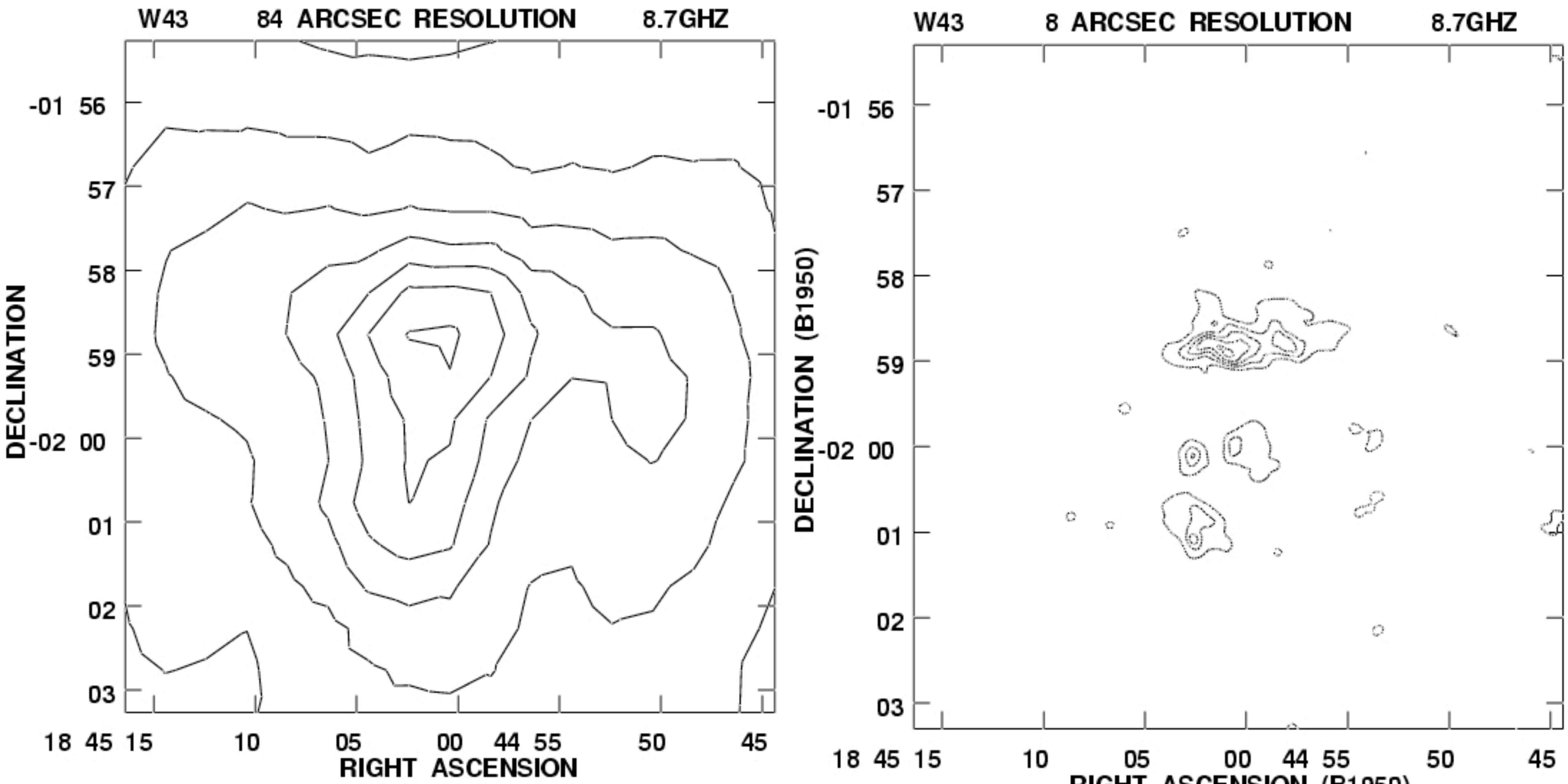
$$\frac{N(^3\mathrm{He}^+)}{N(\mathrm{H}^+)} = 3.873 \times 10^{-3} \, \frac{T_{\mathrm{L}}^{\mathrm{A}}(^3\mathrm{He}^+)\Delta v(^3\mathrm{He}^+)[\ln(5.717 \times 10^{-3} T_{\mathrm{e}}^{3/2})]^{1/2} \, \theta_{\mathrm{obs}}}{A \, (\eta_{\mathrm{b}} T_{\mathrm{C}}^{\mathrm{A}} D)^{1/2} \, T_{\mathrm{e}}^{1/4}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

where

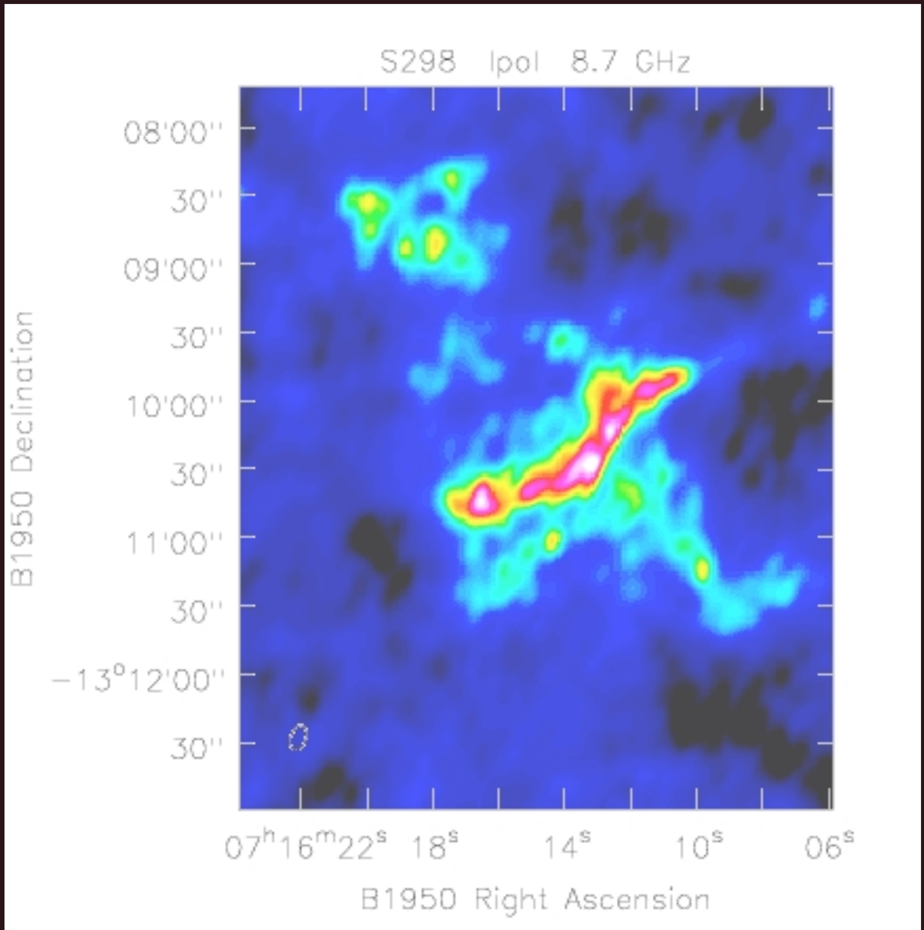
$$A^2 = \left\{ \left(1 + \frac{n(\mathrm{He}^+)}{n(H^+)} + 2\frac{n(\mathrm{He}^{++})}{n(\mathrm{H}^+)}\right) \left(1 + \frac{n(\mathrm{He}^+)}{n(H^+)} + 4\frac{n(\mathrm{He}^{++})}{n(\mathrm{H}^+)}\left[1 - \frac{\ln(2)}{\ln(5.717 \times 10^{-3} T_{\mathrm{e}}^{3/2})}\right]\right)\right\}^{-1} .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

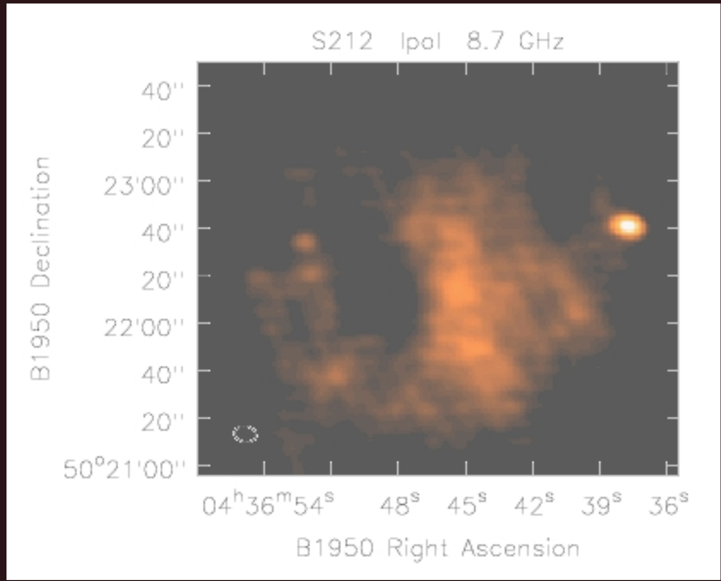
H II Region Continuum

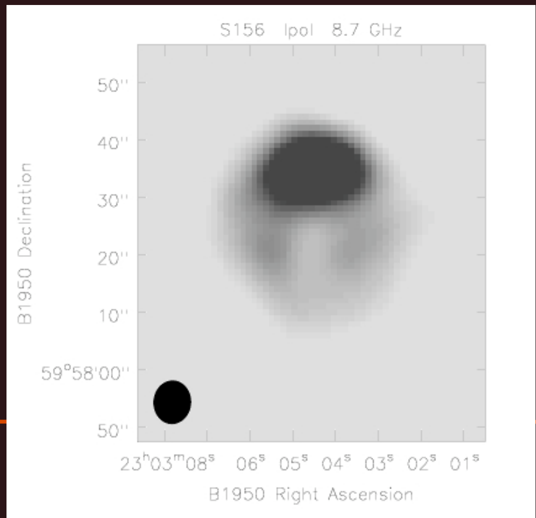
Balser et al. (1995)



H II Region Continuum



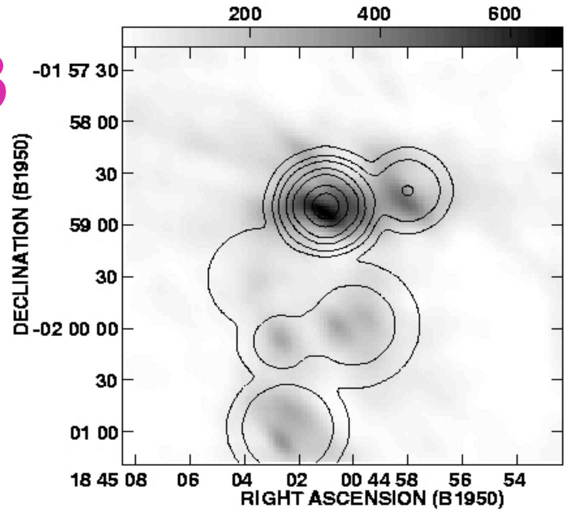




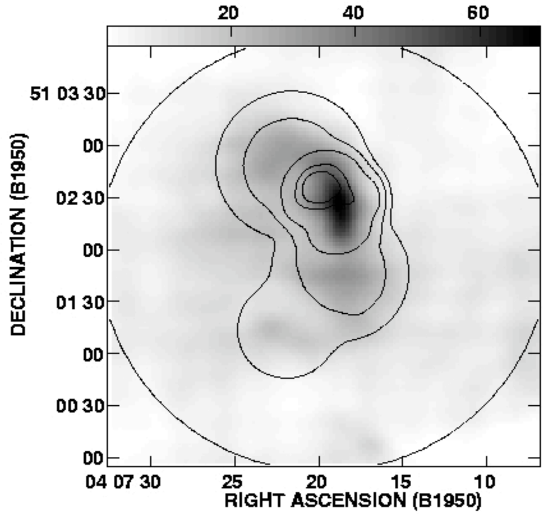
H II Region Models

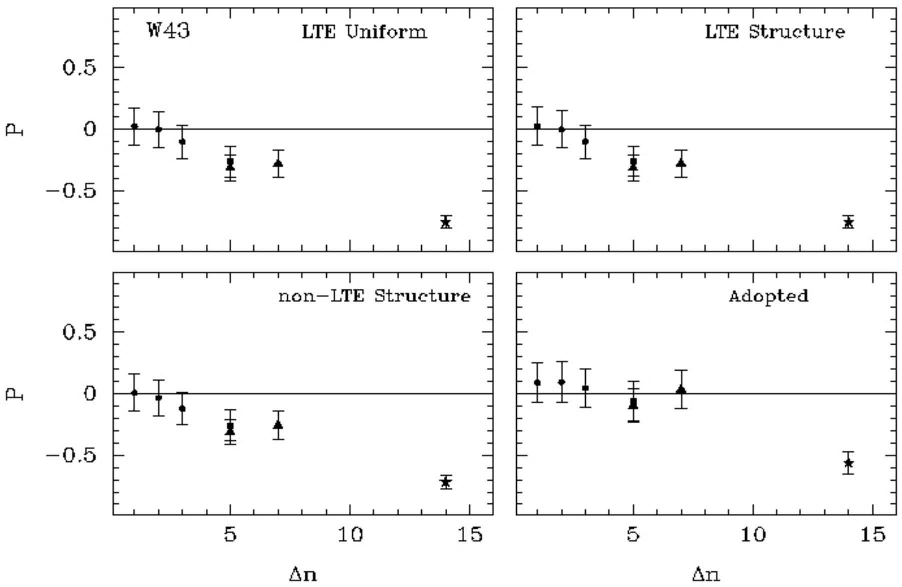
Balser et al. (1999)

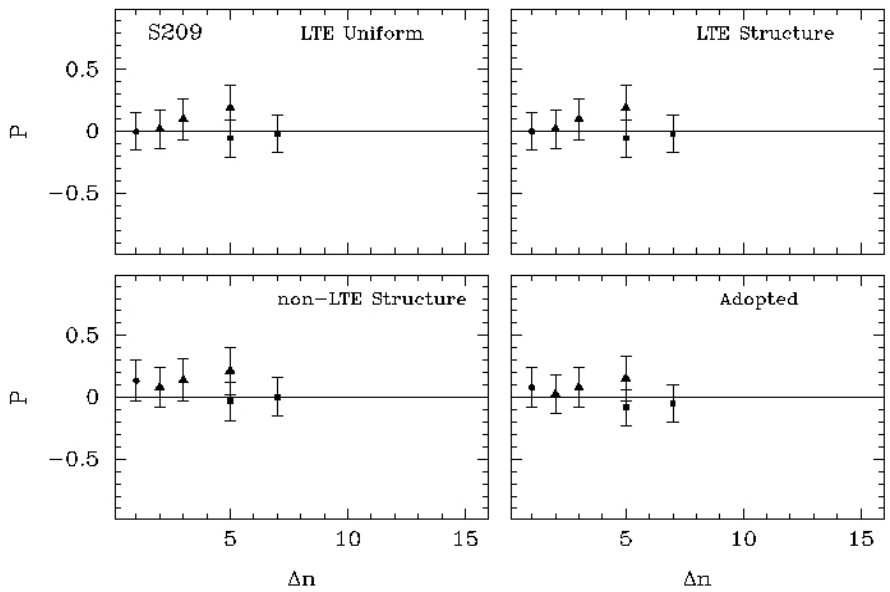
W43



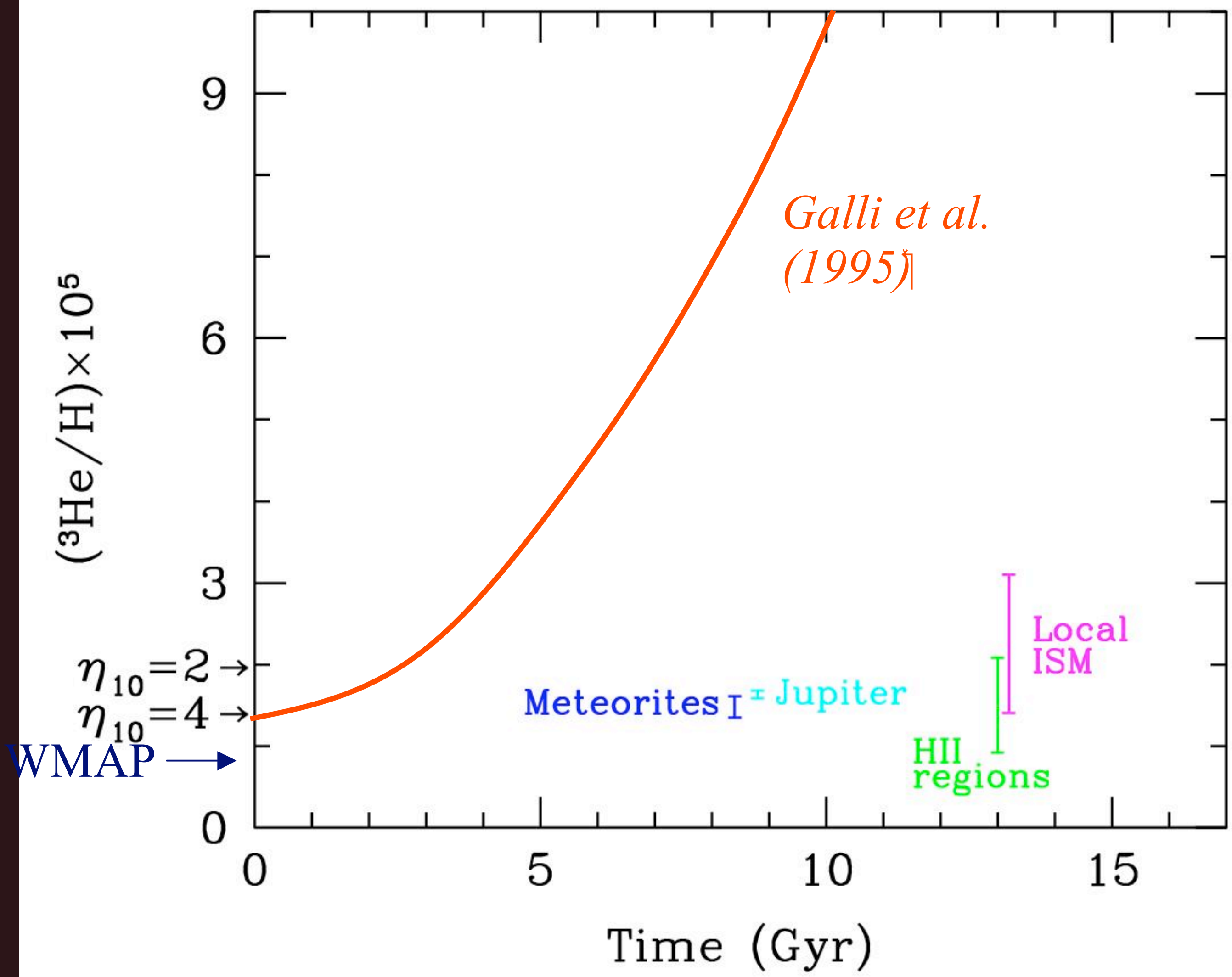
S209







"The ^{3}He Problem"



Meteorites: Geiss (1993)
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HII regions: Bania, Rood & Balser (2000)
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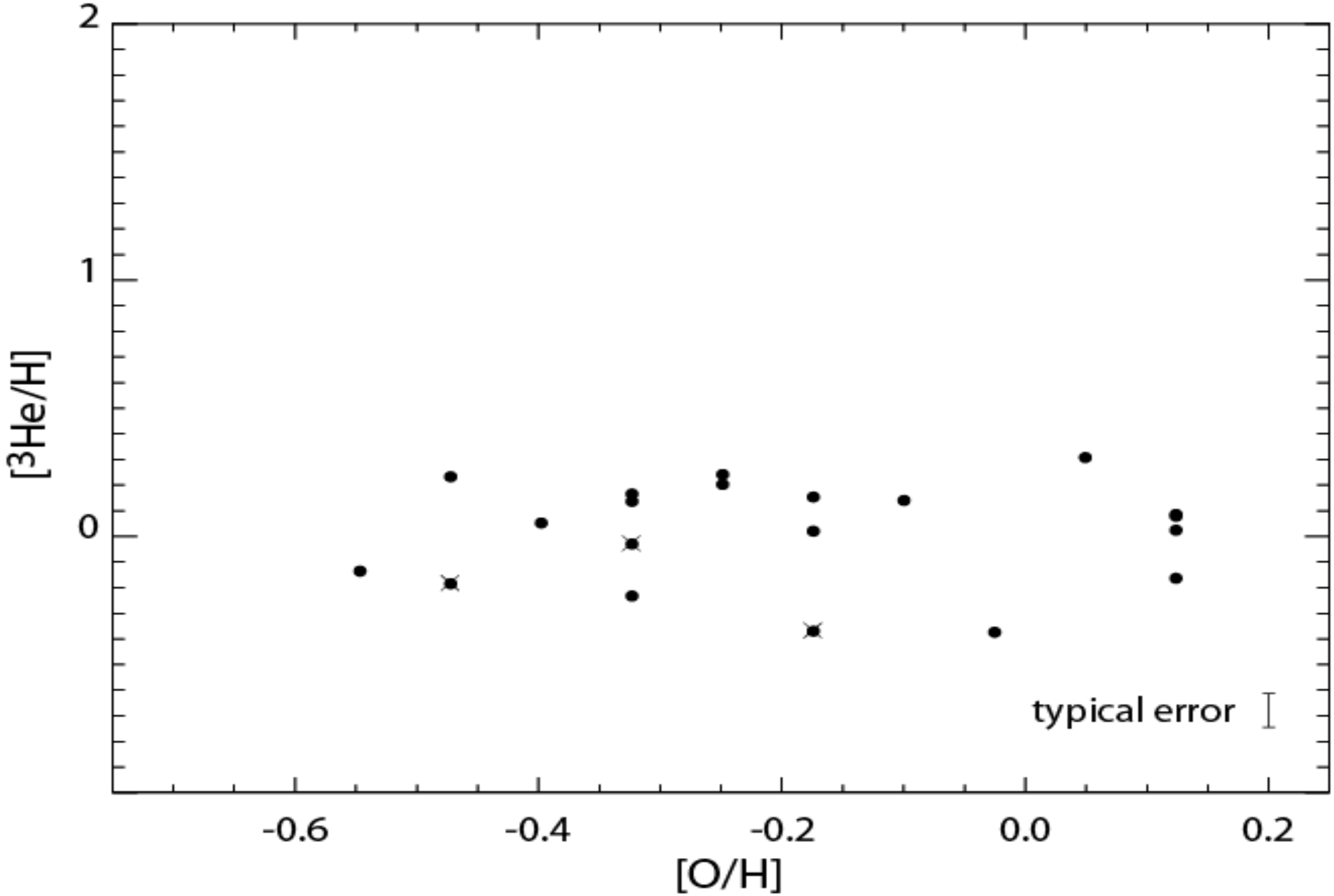
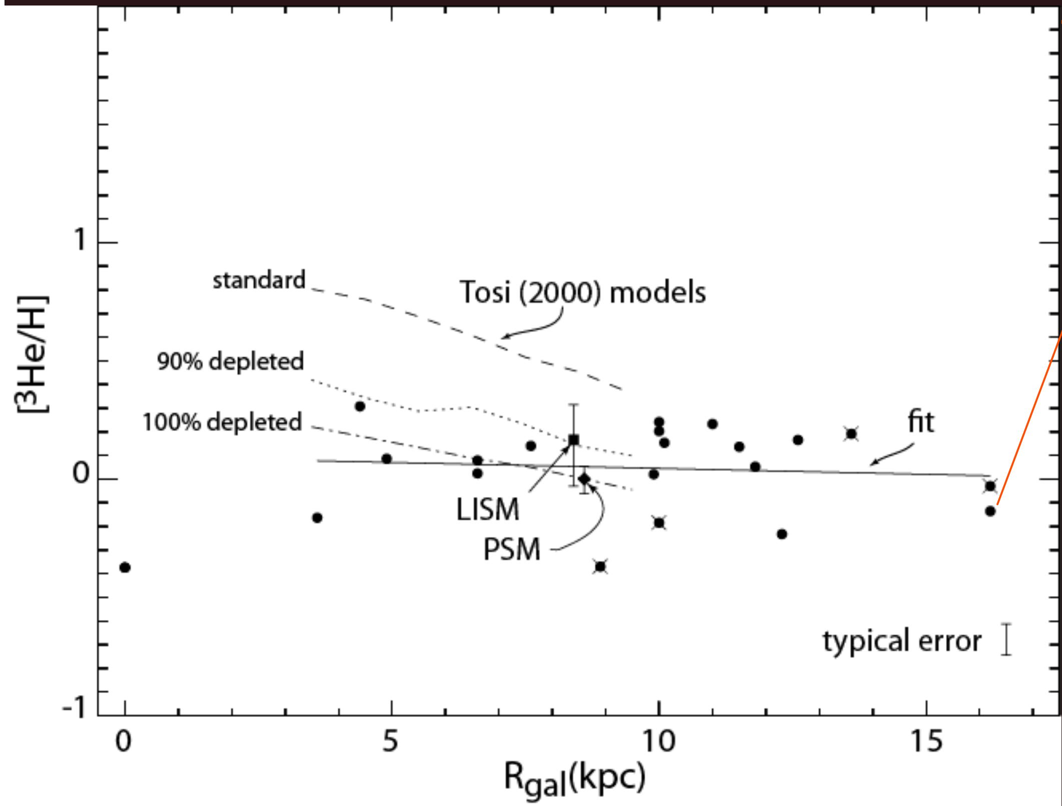


“Simple” H II Regions



Bania, Rood, & Balser 2002

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

$\Omega_B = 0.04$

Spergel et al. 2003, WMAP

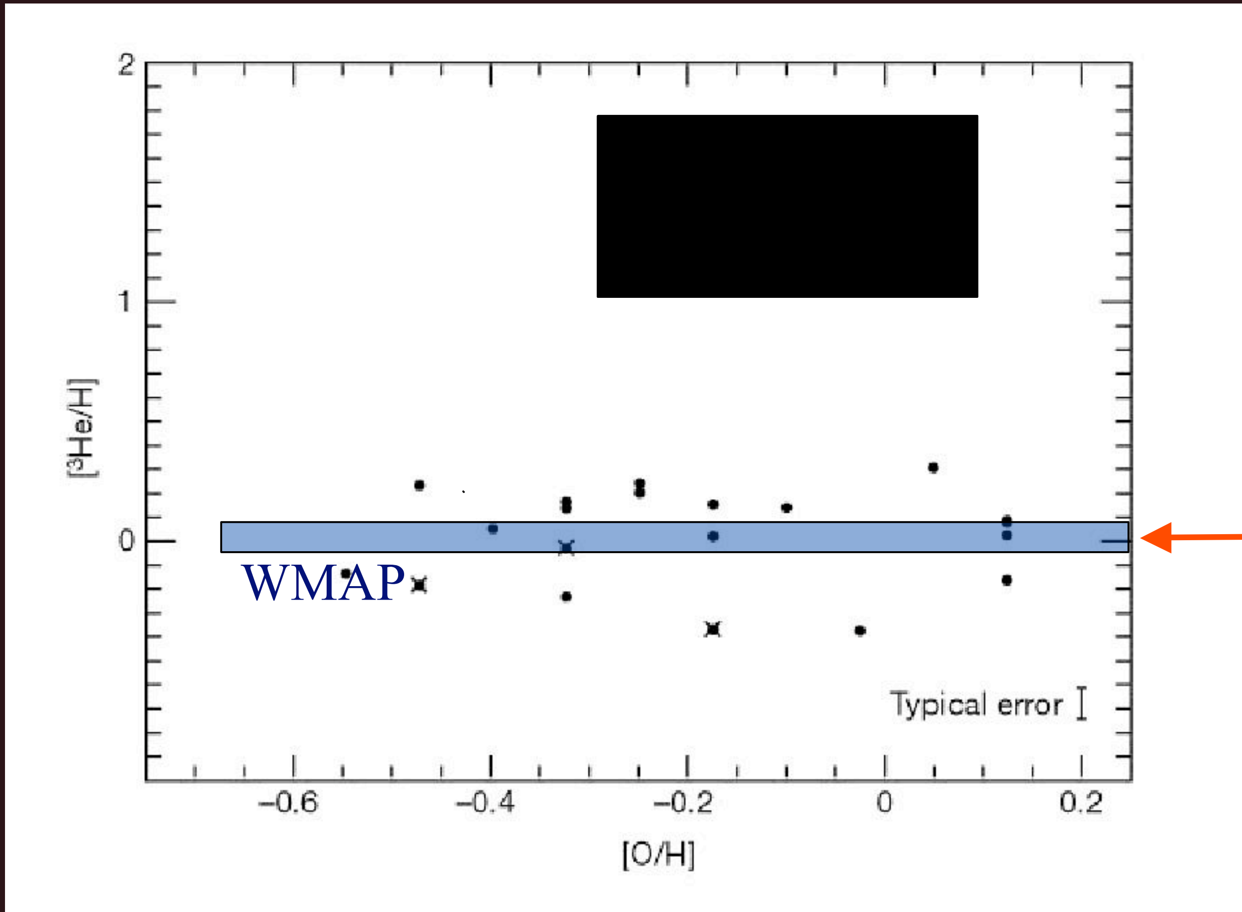
$\eta_{10} = 6.5^{+0.4}_{-0.3}$

$\Omega_B = 0.047 \pm 0.006$

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

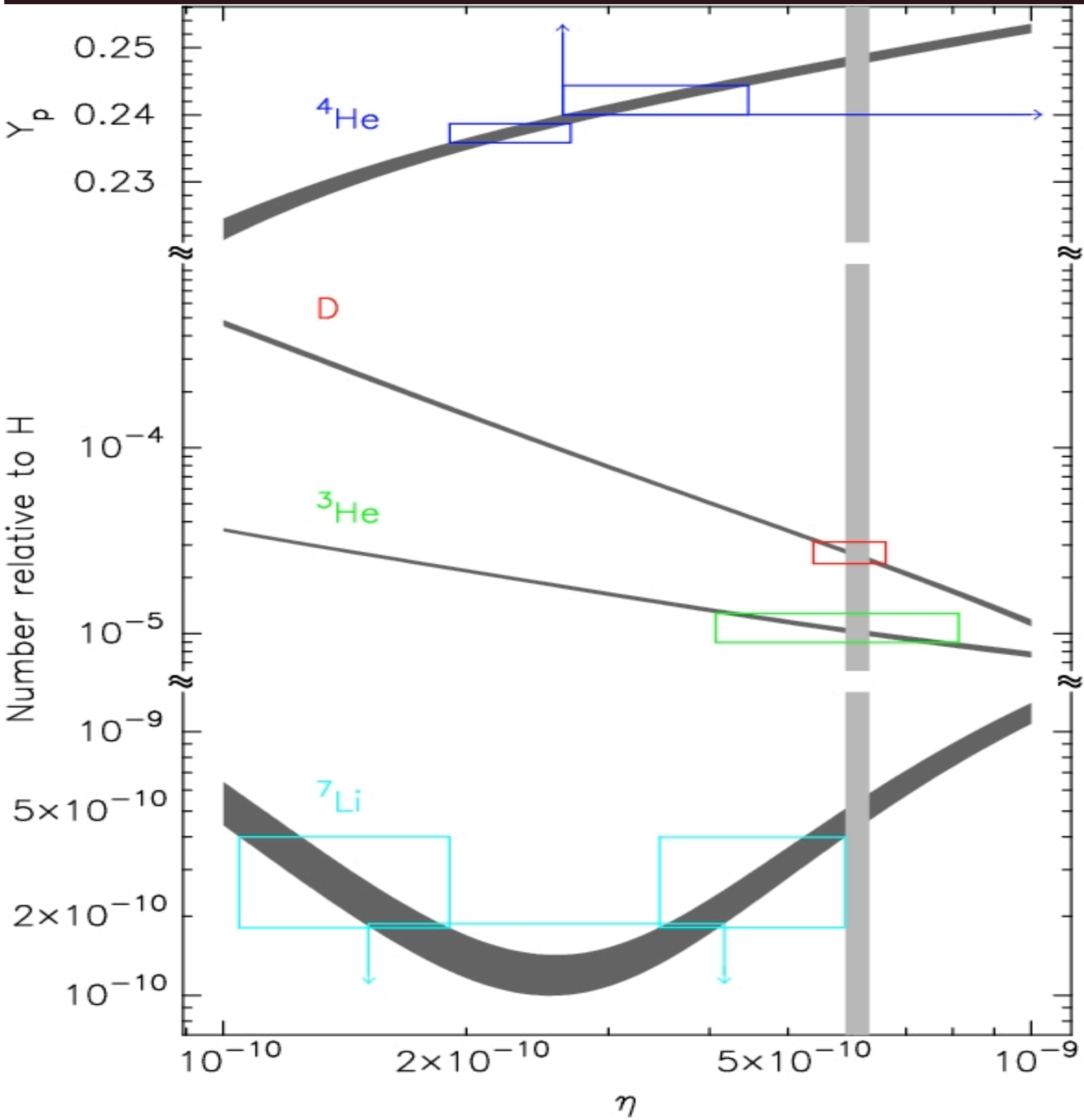
^{3}He Abundance in H II Regions --
"The ^{3}He Plateau"



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

Bania, Rood & Balser (2002)

BBNS CONSTRAINTS



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

Kirkman et al. (2003)

Bania, Rood, & Balser (2002)

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

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

Life is complicated

Despite the fact that HII regions suggest that stars produce little ^{3}He, we "found" ^{3}He in the planetary nebula NGC3242.

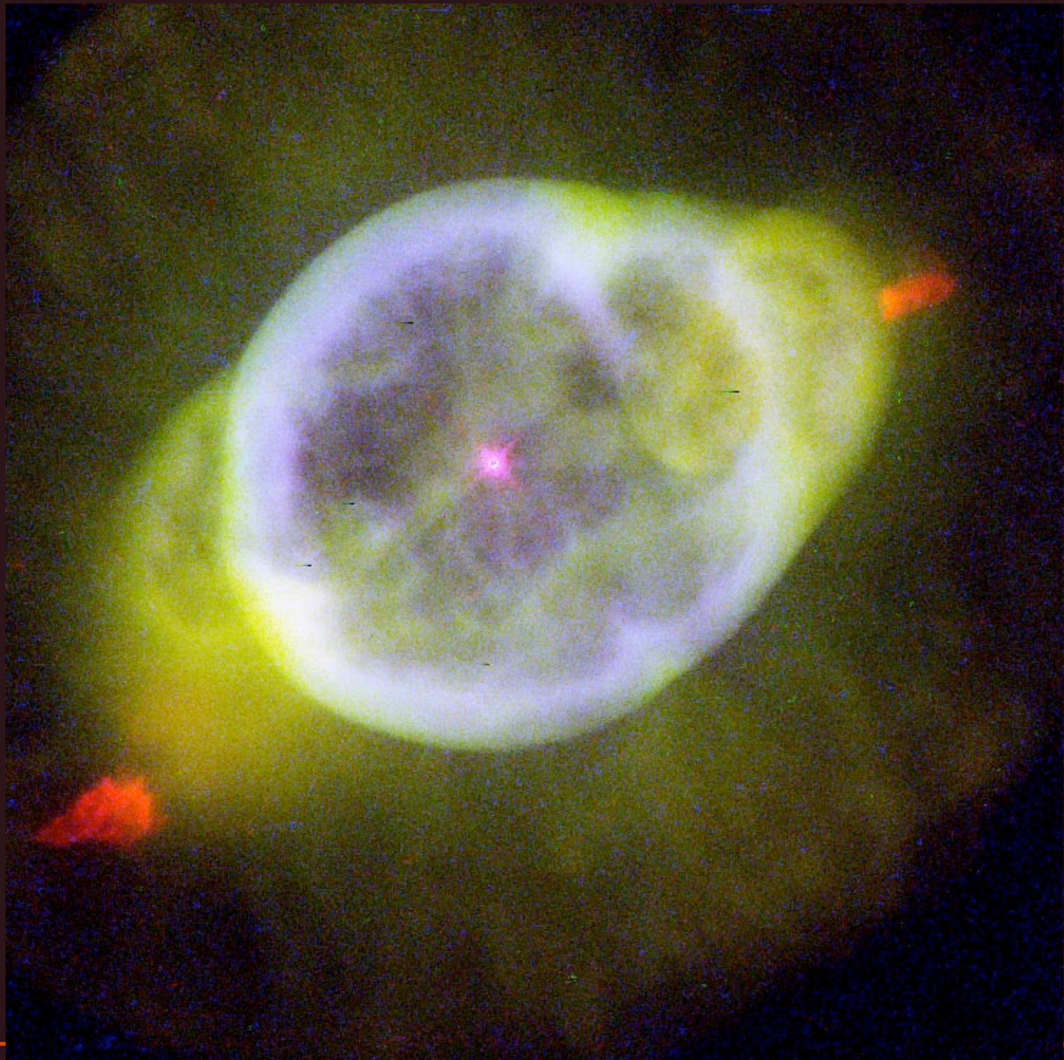
MPIfR 100 m: PNe

Galactic Planetary Nebulae
(1991 – 1995)

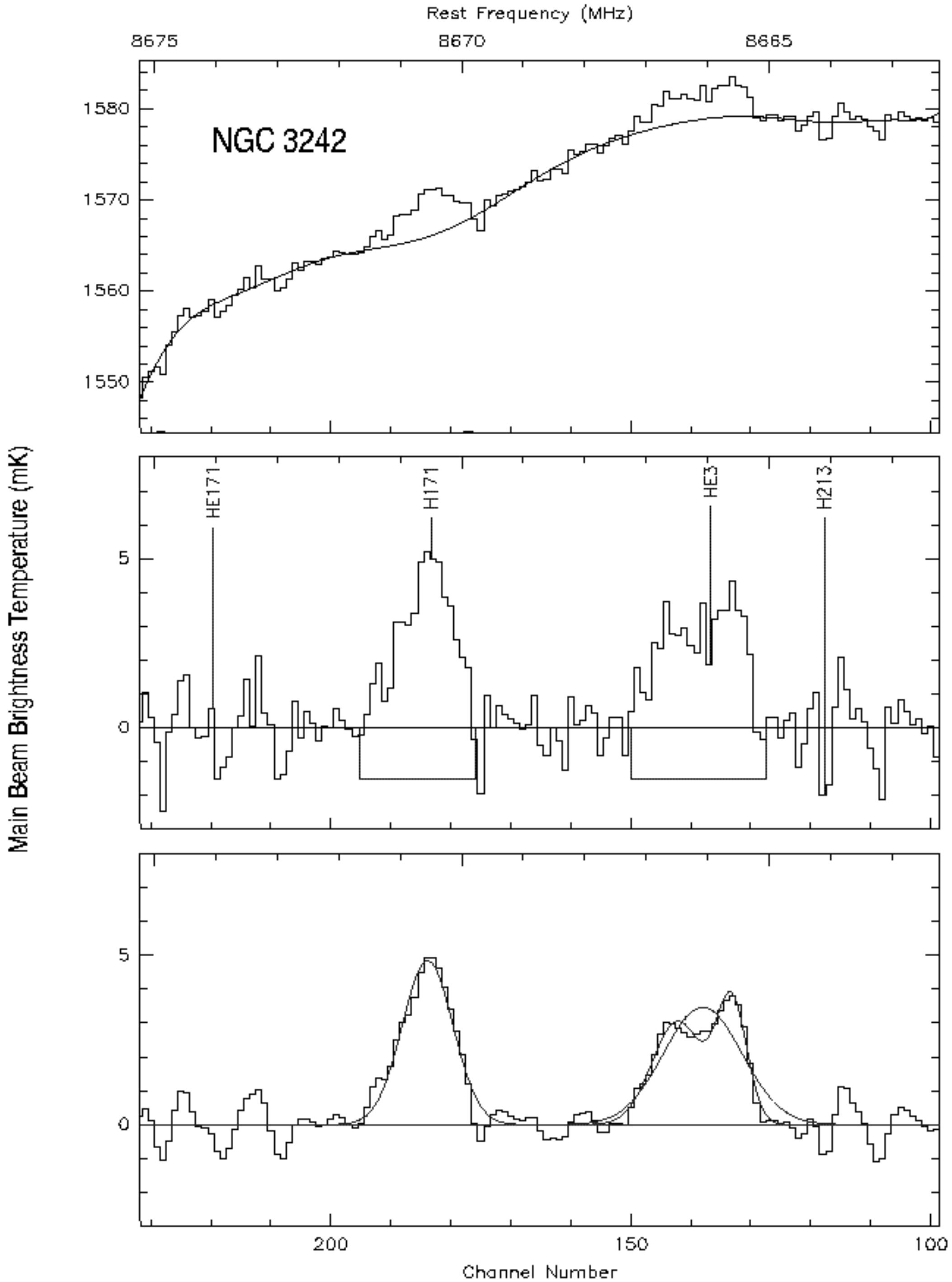
NGC 3242 (Eye)
NGC 6543 (Cat's Eye)
NGC 6720 (Ring)
NGC 7009 (Saturn)
NGC 7662 (Blue Snowball)

HPBW = 80 arcsec

NGC 3242: Eye Nebula



Balick et al.



MPIfR observations of 3He in the PN NGC3242.

Results from 6 observing sessions combined

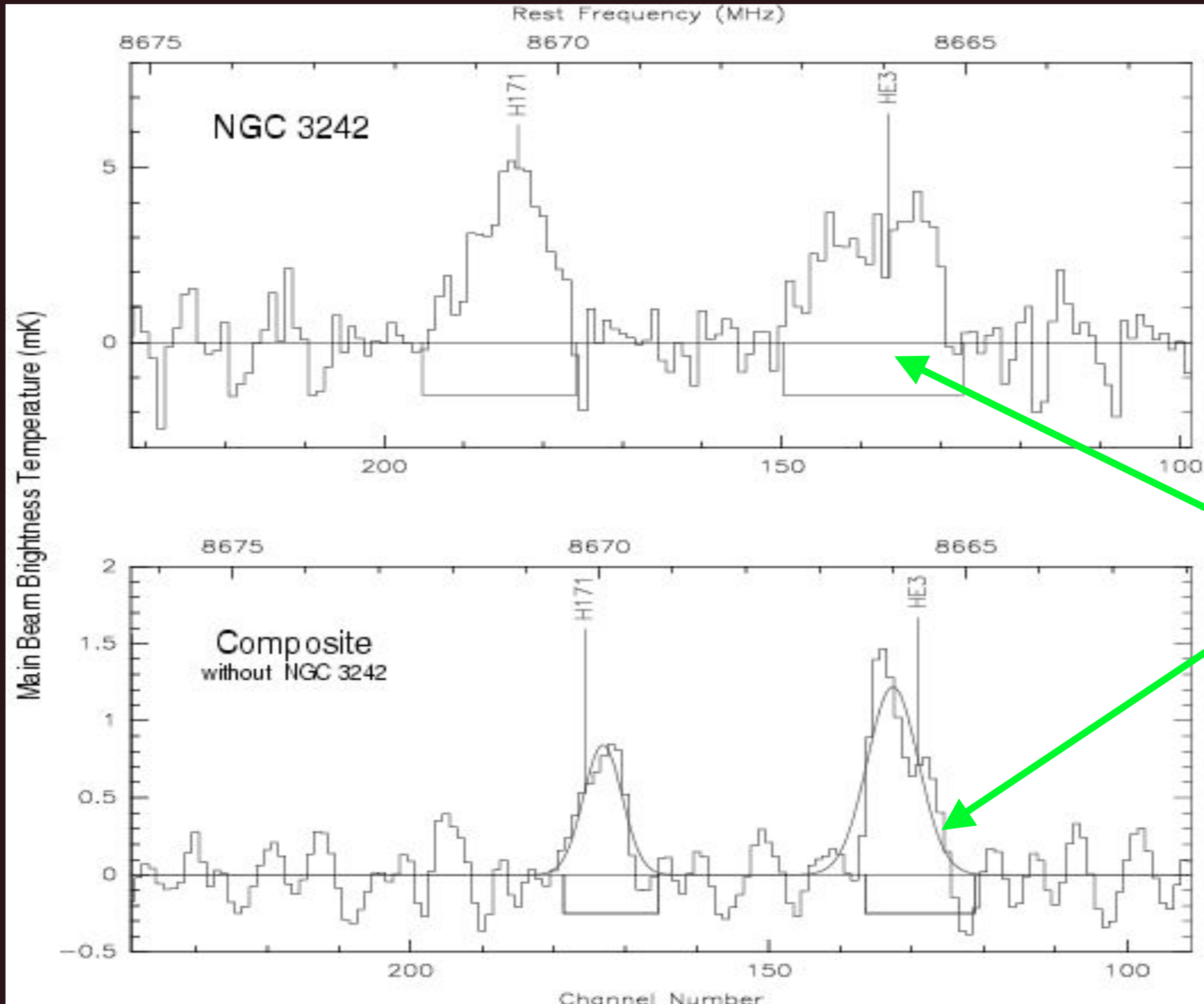
MPIfR 100 m PNe Survey

Balser, et al. 1997, ApJ 483, 320

106 hr

443 hr

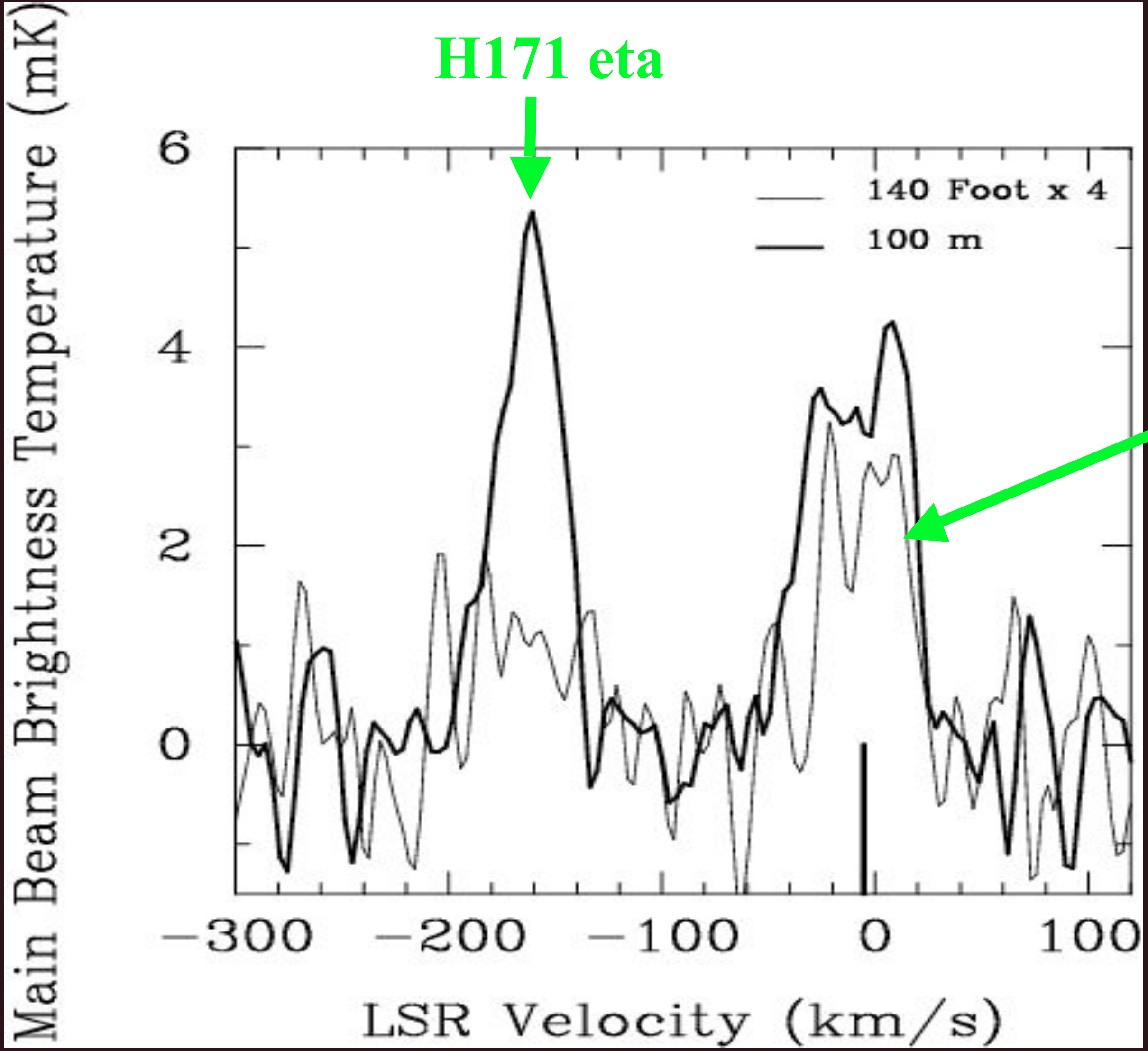
1987-1997



$^3He^+$

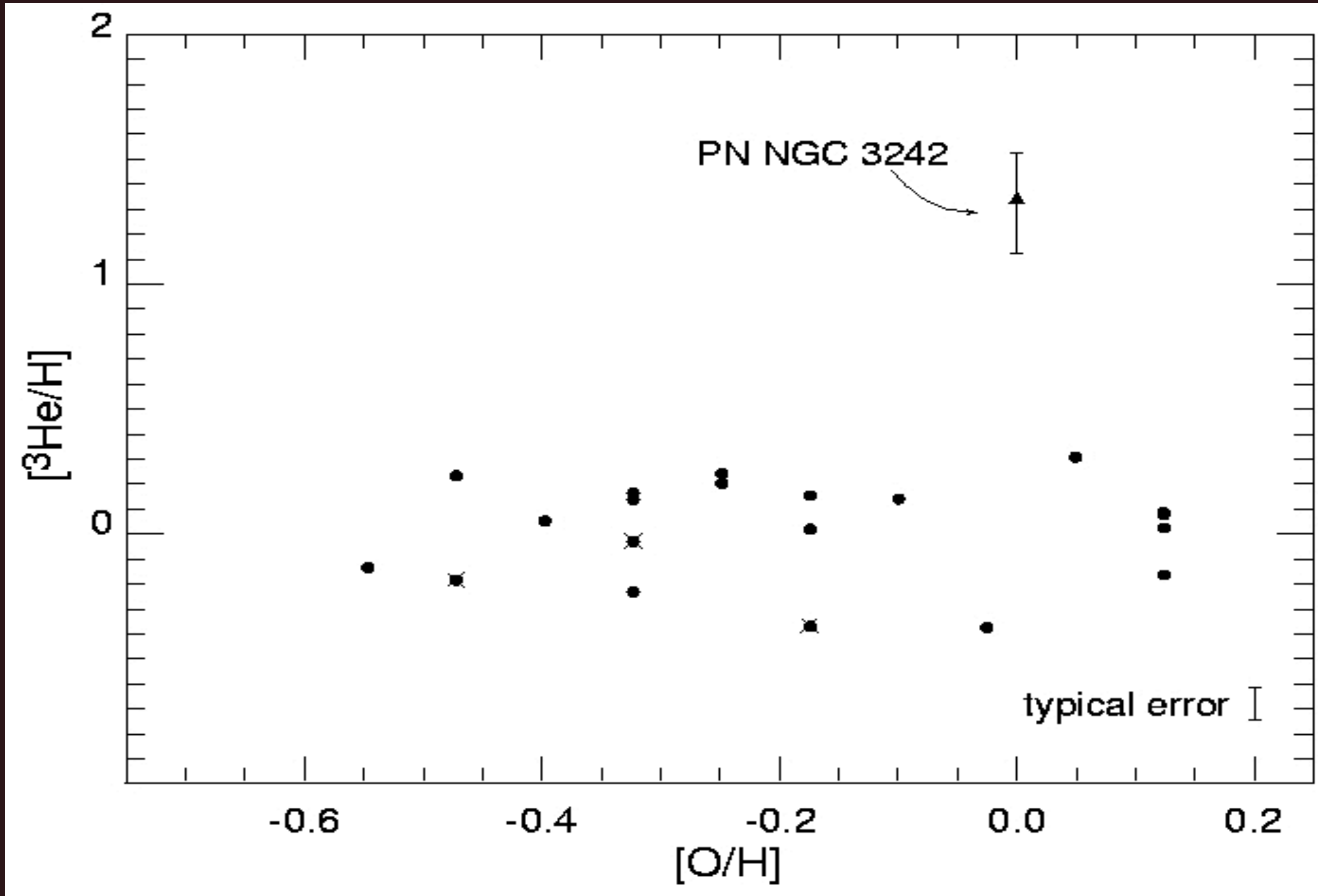
Composite: NGC 6543 + NGC 6720 + NGC 7009 + NGC 7662 + IC 289

NGC 3242 Confirmation Balser, et al. 1999 ApJ 522, L73



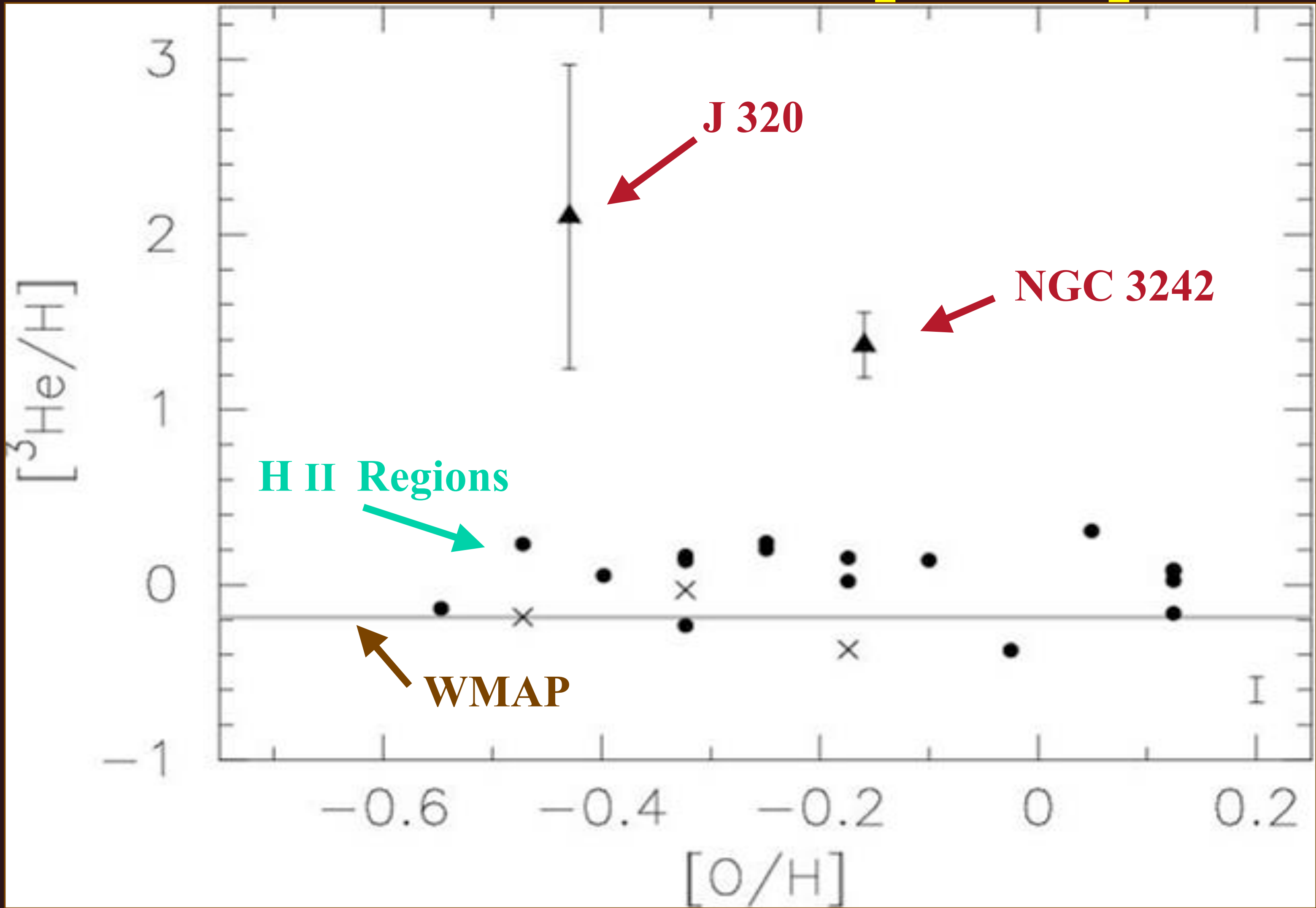
NRAO 140 ft spectrum is a 270 hour integration

Abundance versus [O/H]



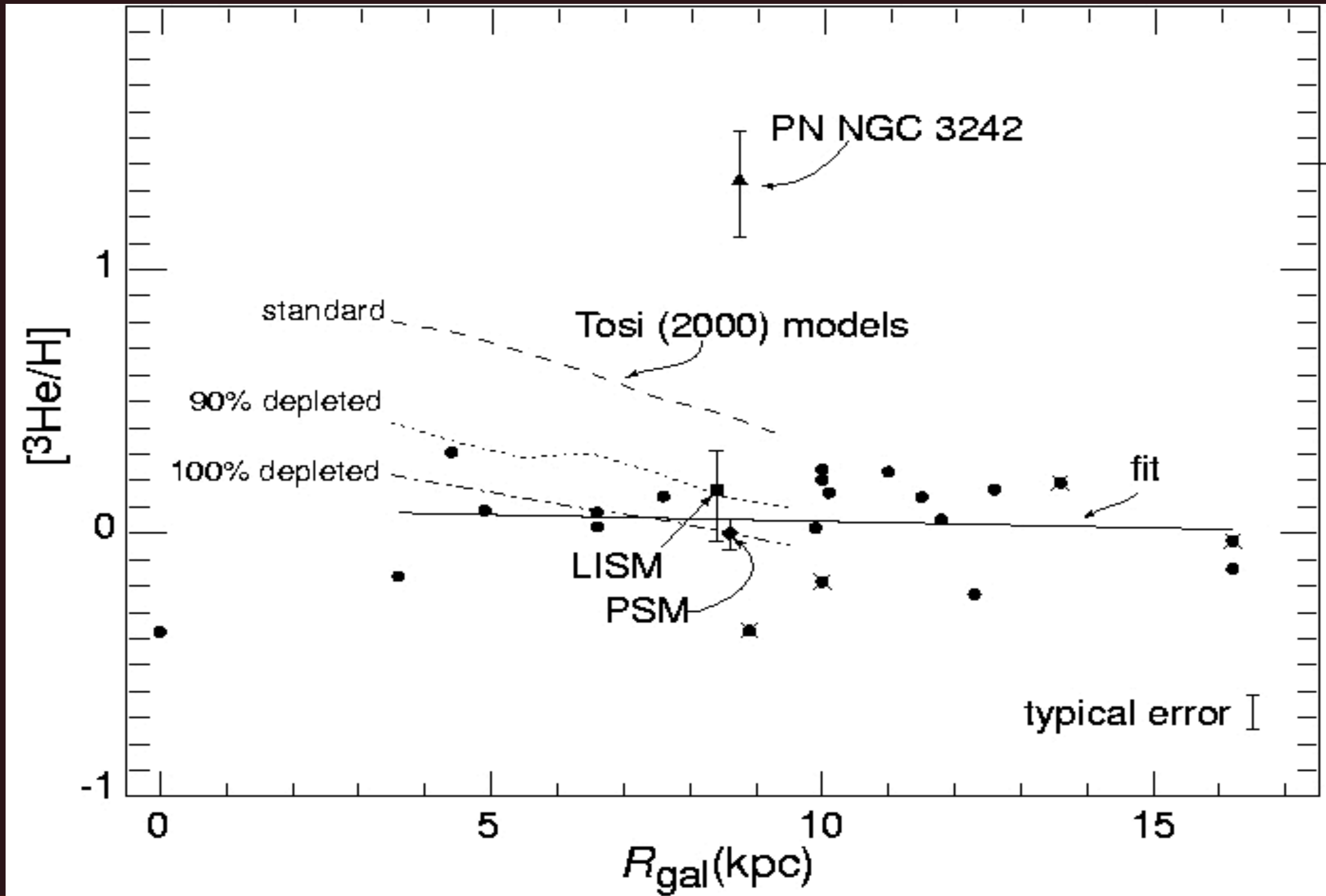
Bania, Rood & Balser (2002)

Abundance versus [O/H]



Bania, Rood & Balser (2006)

Abundance versus Rgal



Bania, Rood & Balser (2002)

One is not enough!

Except in cosmology

The PN sample:

PNe progenitor stars with no extra mixing:

$^{4}He / H < 0.125$

[N / O] < -0.3

$^{13}C / ^{12}C$ as low as possible

Oldest possible stellar population has highest 3-He:

Peimbert Class IIb, III, and IV

Helium is singly ionized

PNe Sample

PNe progenitor stars with no extra mixing:

$^{4}He/H \leq 0.125$

$[N/O] \leq -0.3$

$^{13}C/^{12}C$ as low as possible

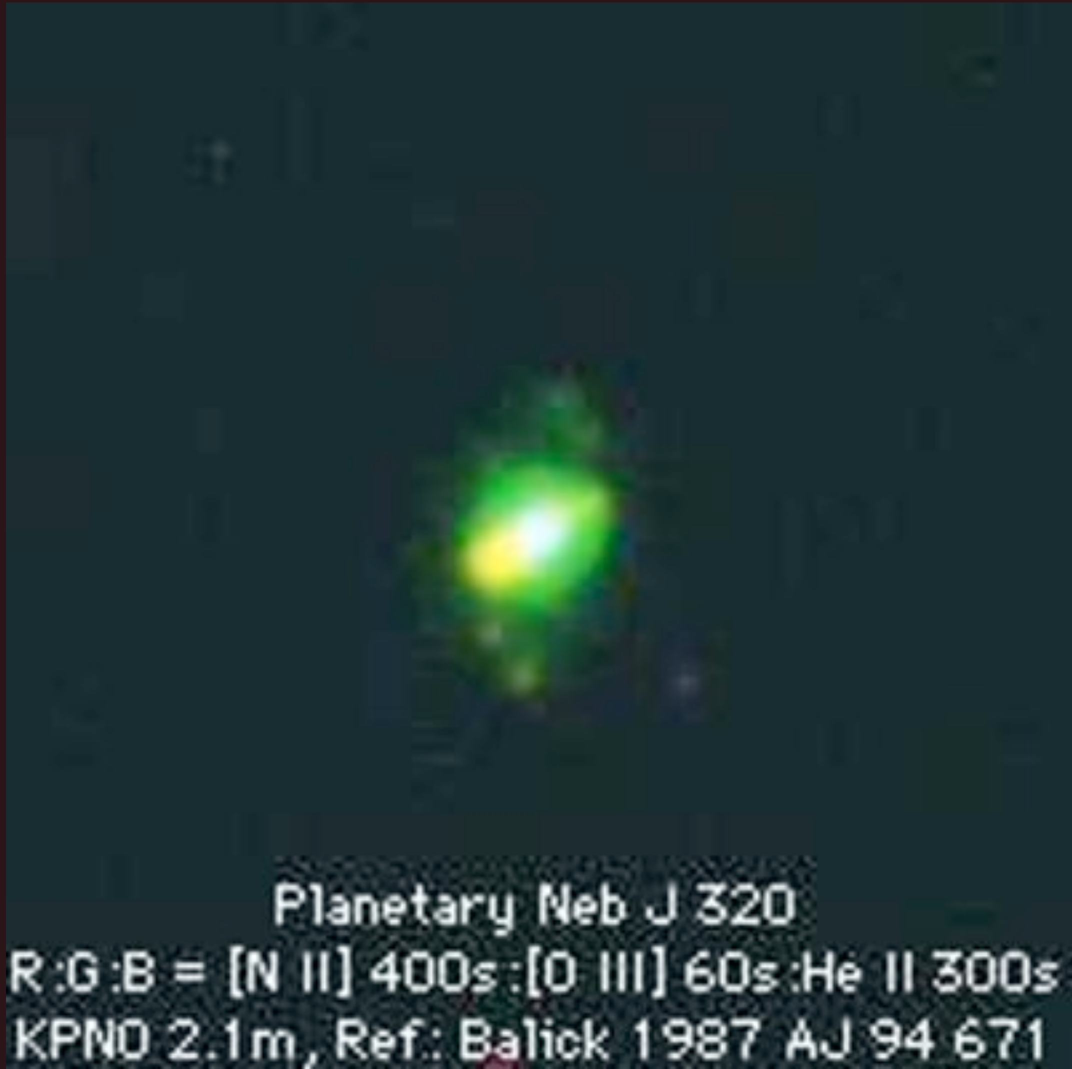
Peimbert Class: IIb, III, IV (old population)

Helium is singly ionized

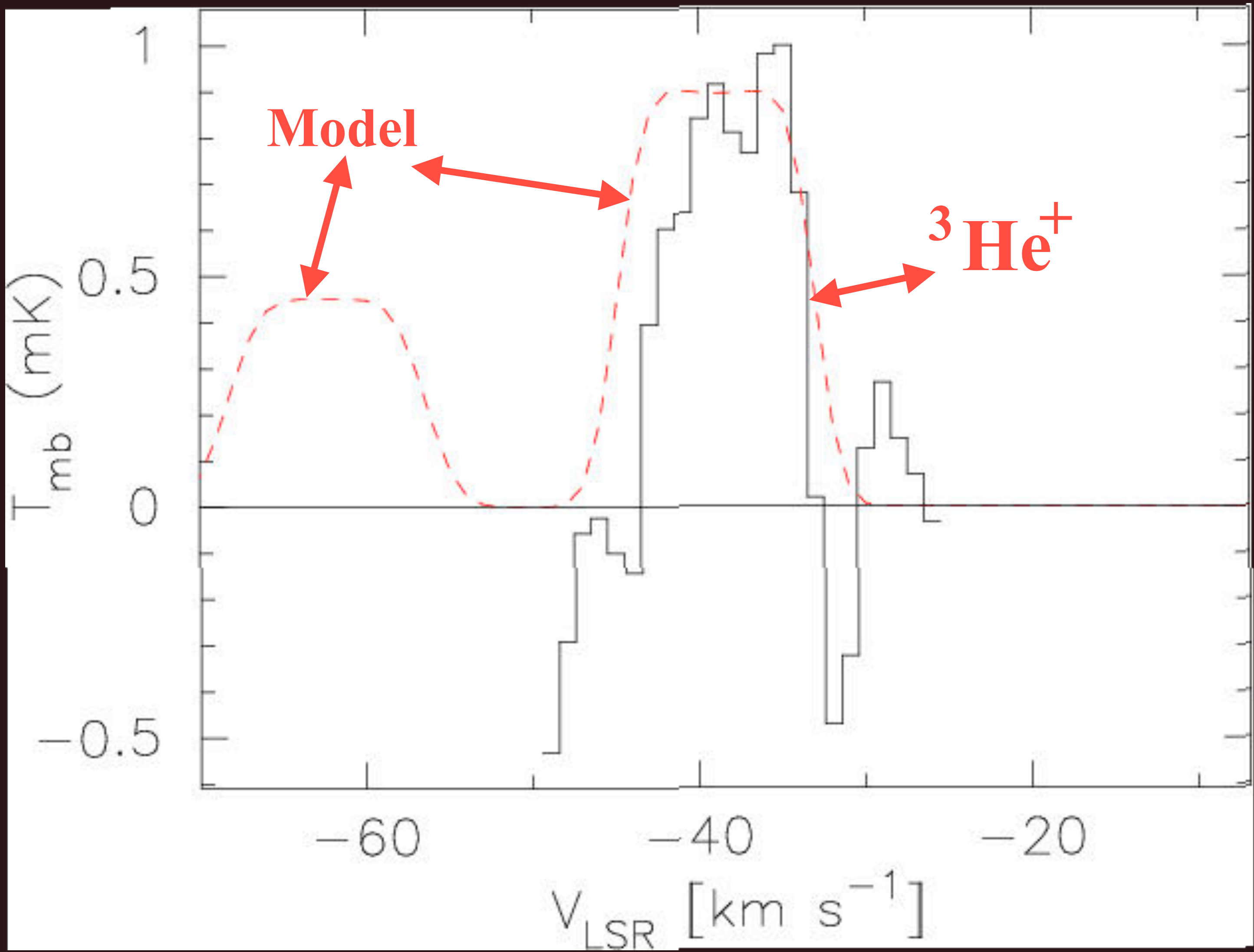
Balser, Goss, Bania, Rood (2005)

Jonckheere 320 – PN G190.3-17.7

J320

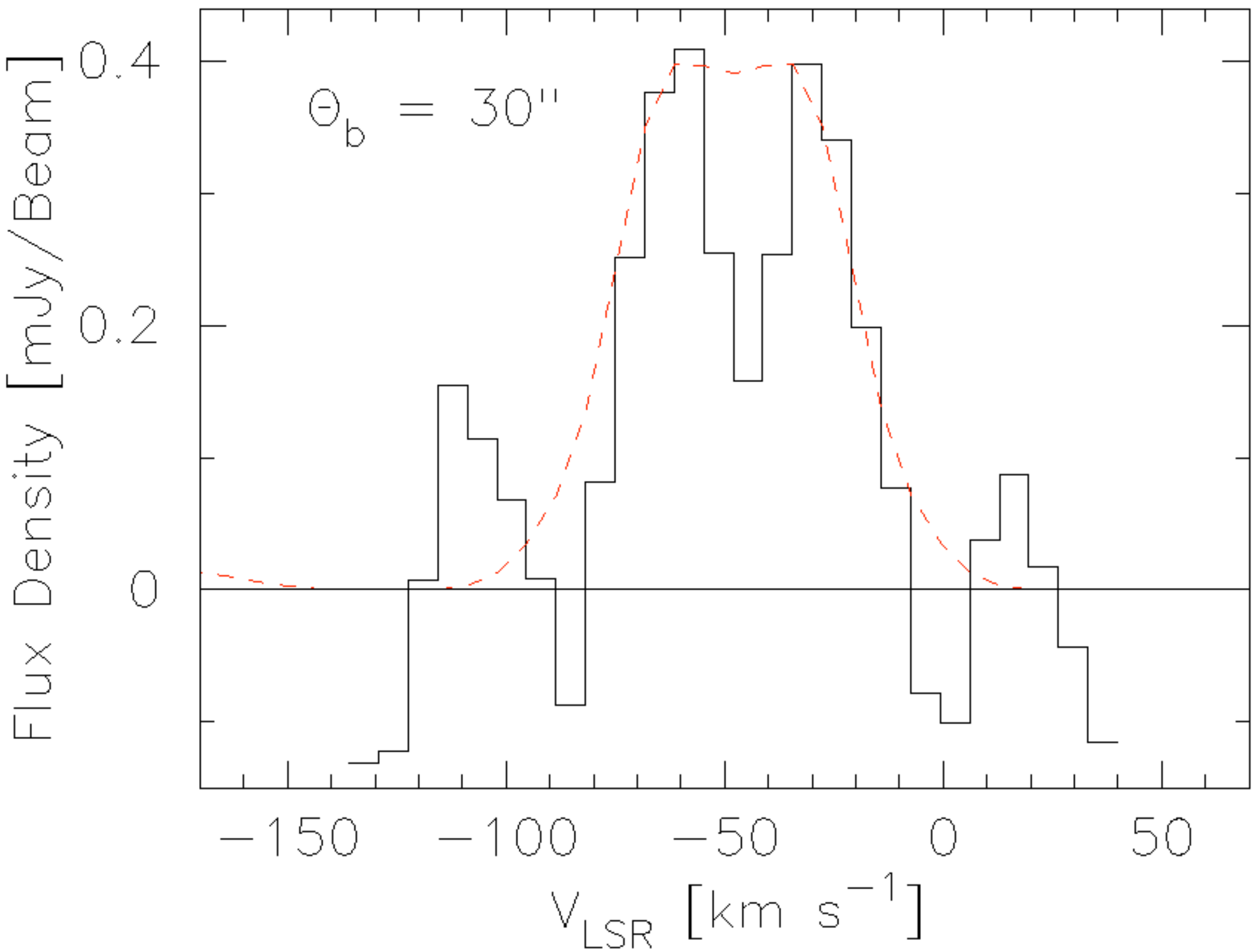


VLA Planetary Nebula J320

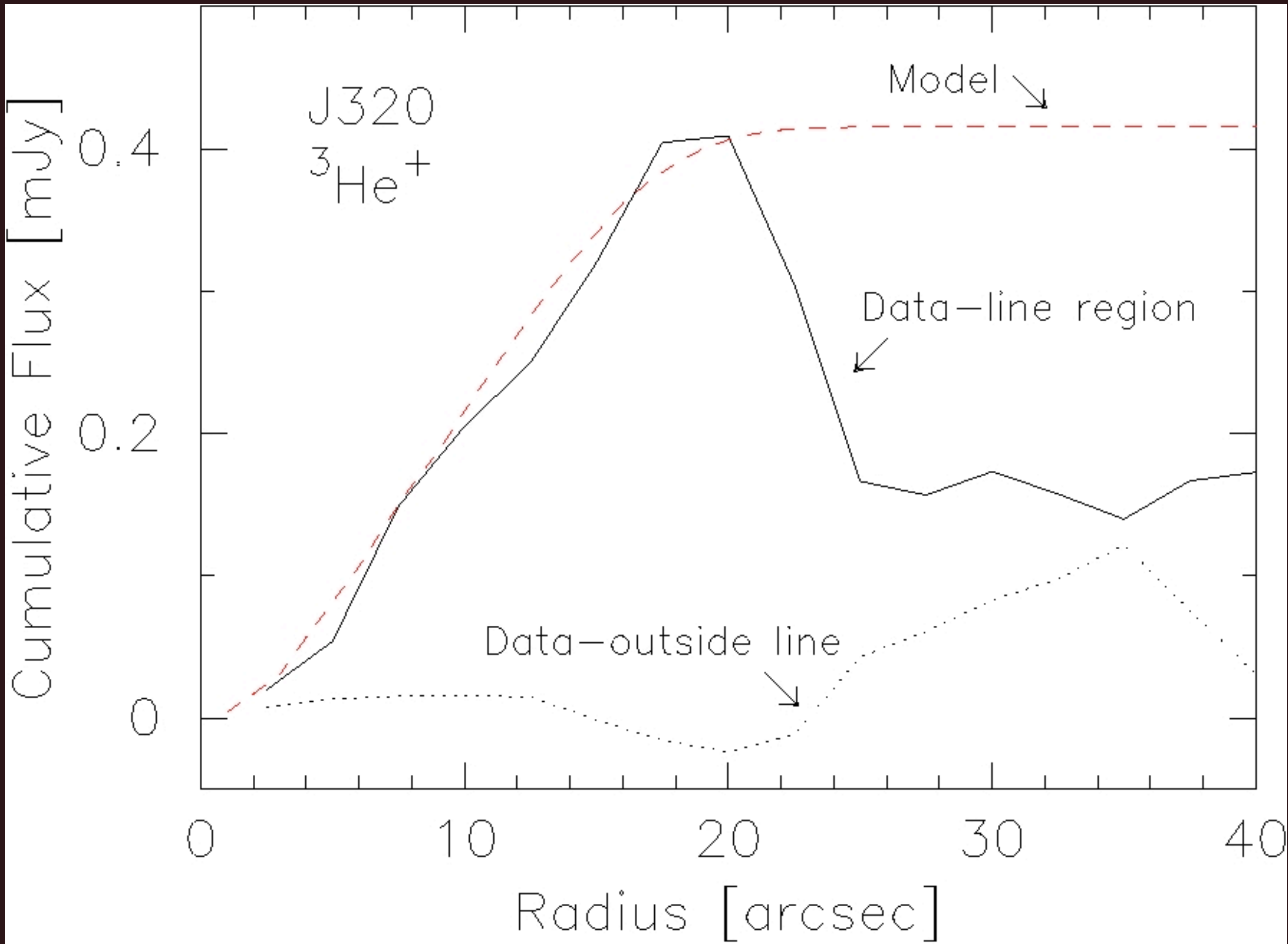


^3He / H abundance = 1.9 x 10^{-3} by number

J320 $^{3}He^{+}$

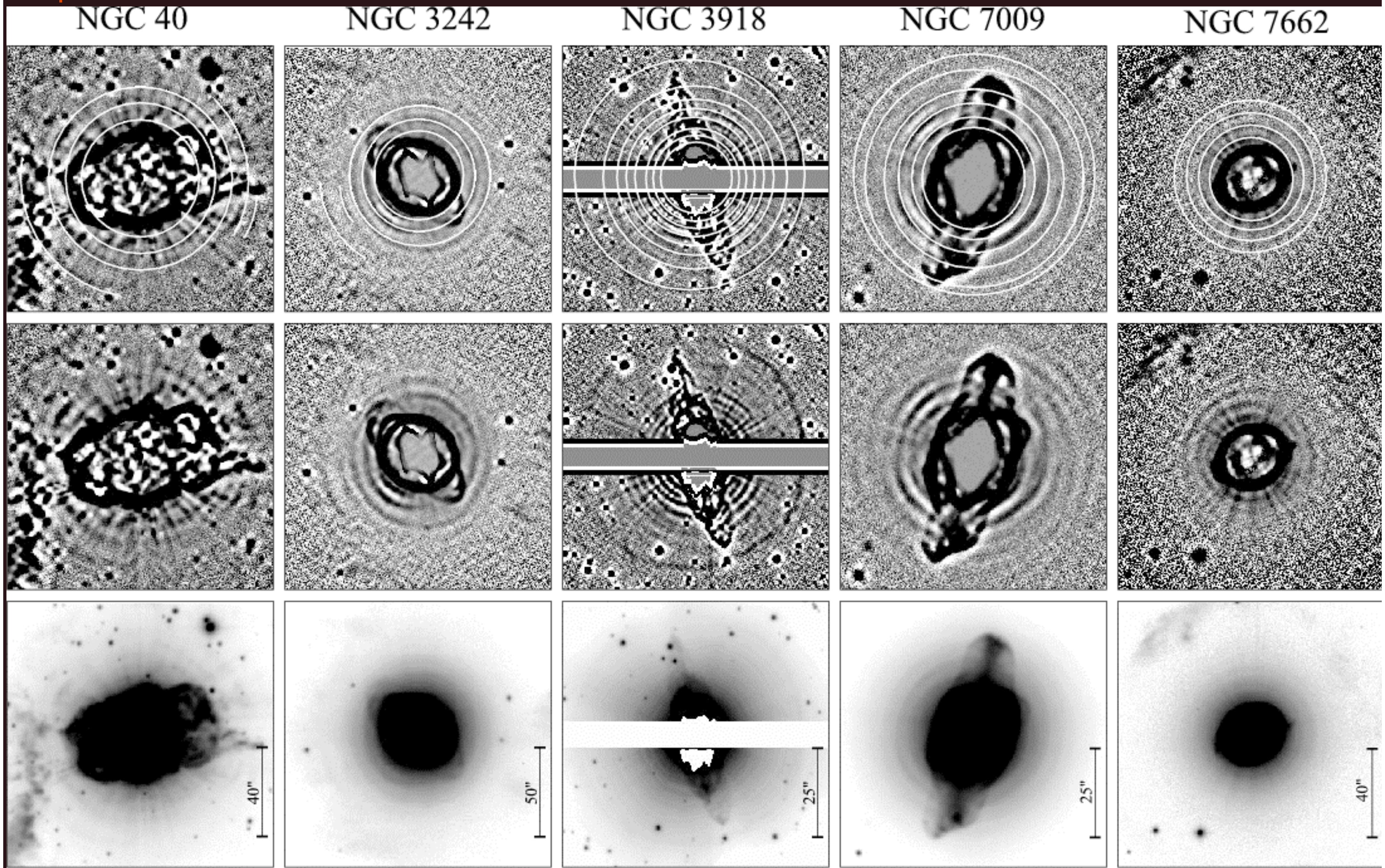


J320 Halo: 30 arcsec



Balser et al. (2006)

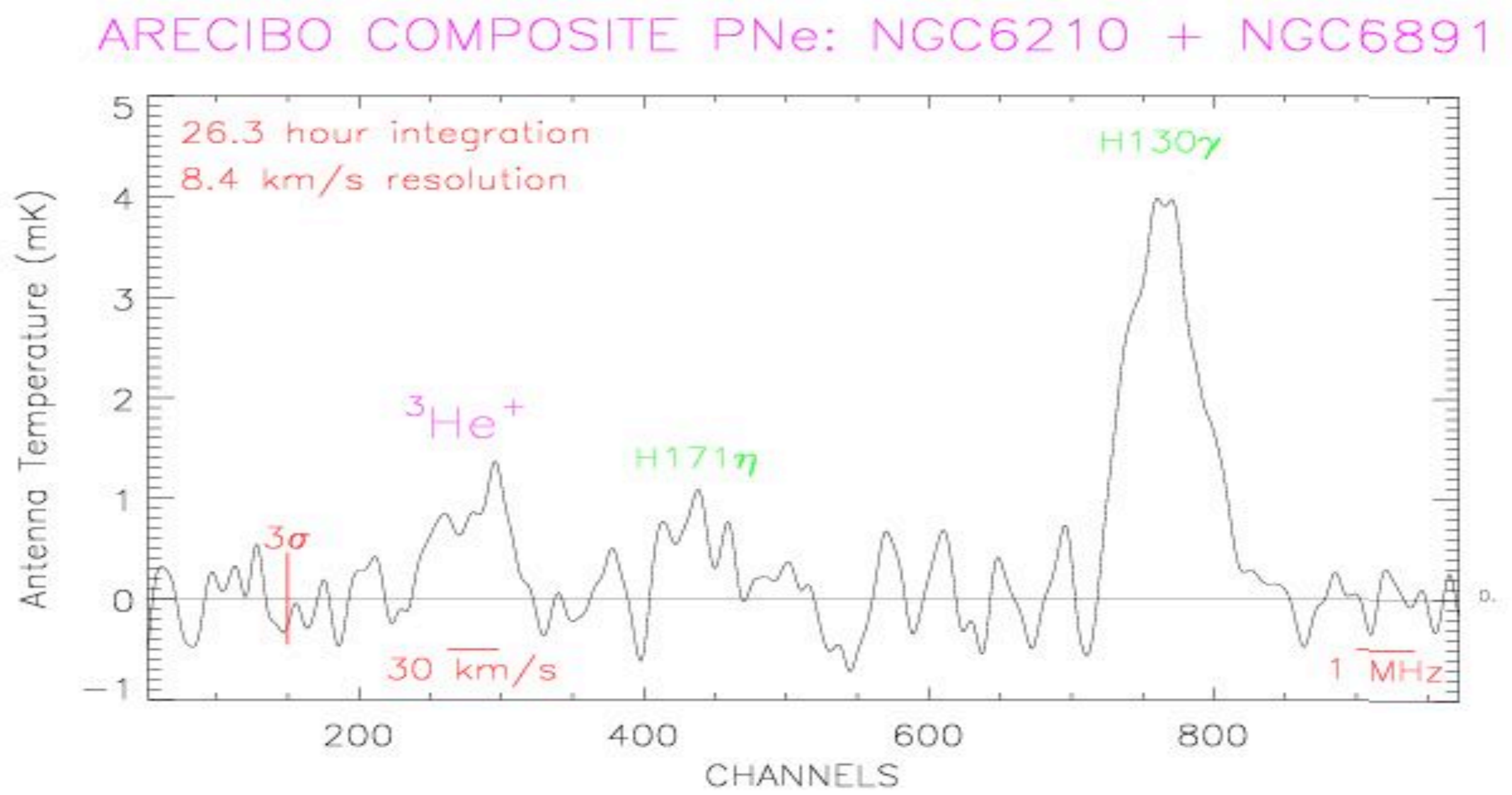
Rings in the Haloes of Planetary Nebulae



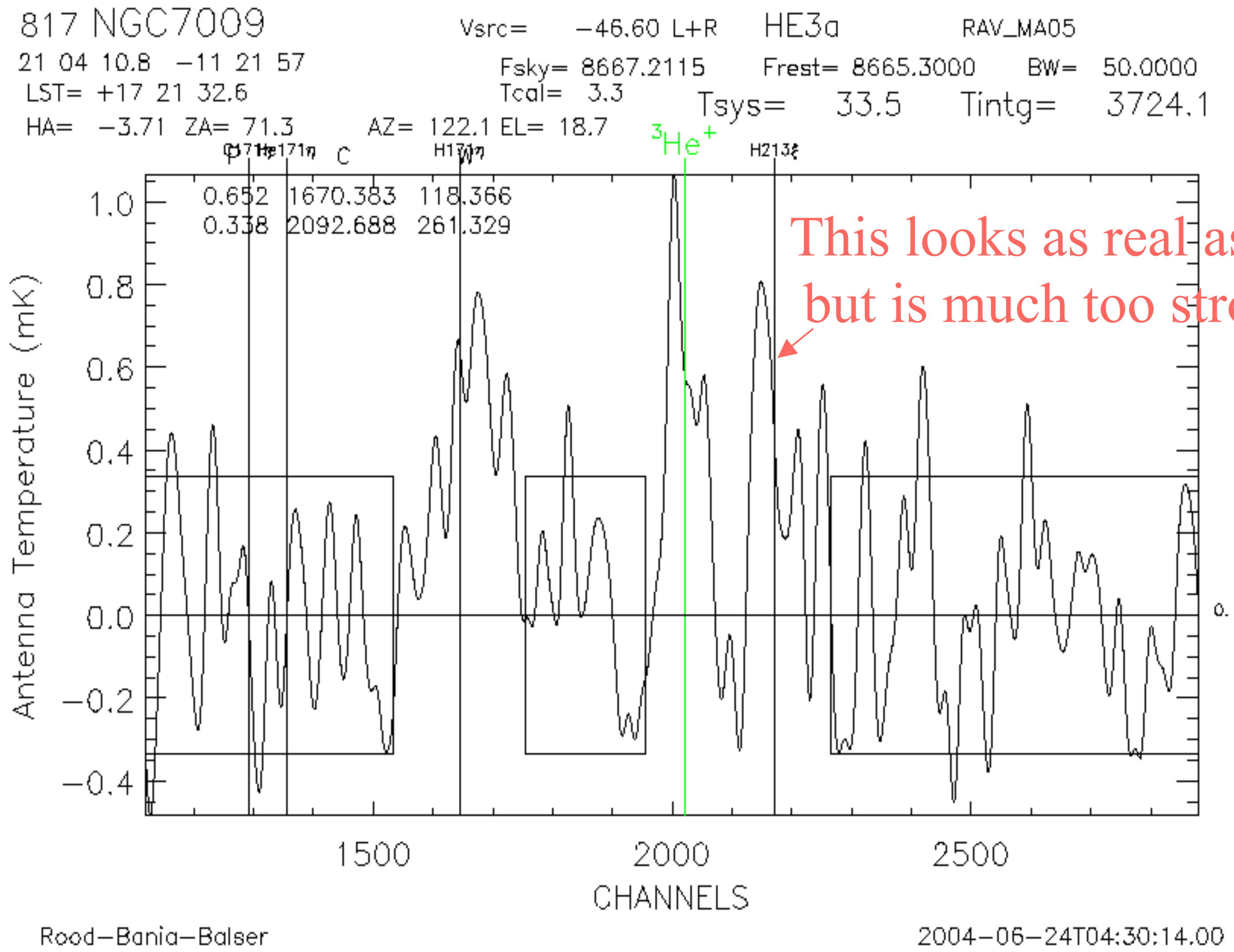
Corradi et al. (2004) A&A,417, 637

NAIC Arecibo Observatory 305 m

First Epoch Arecibo Observations



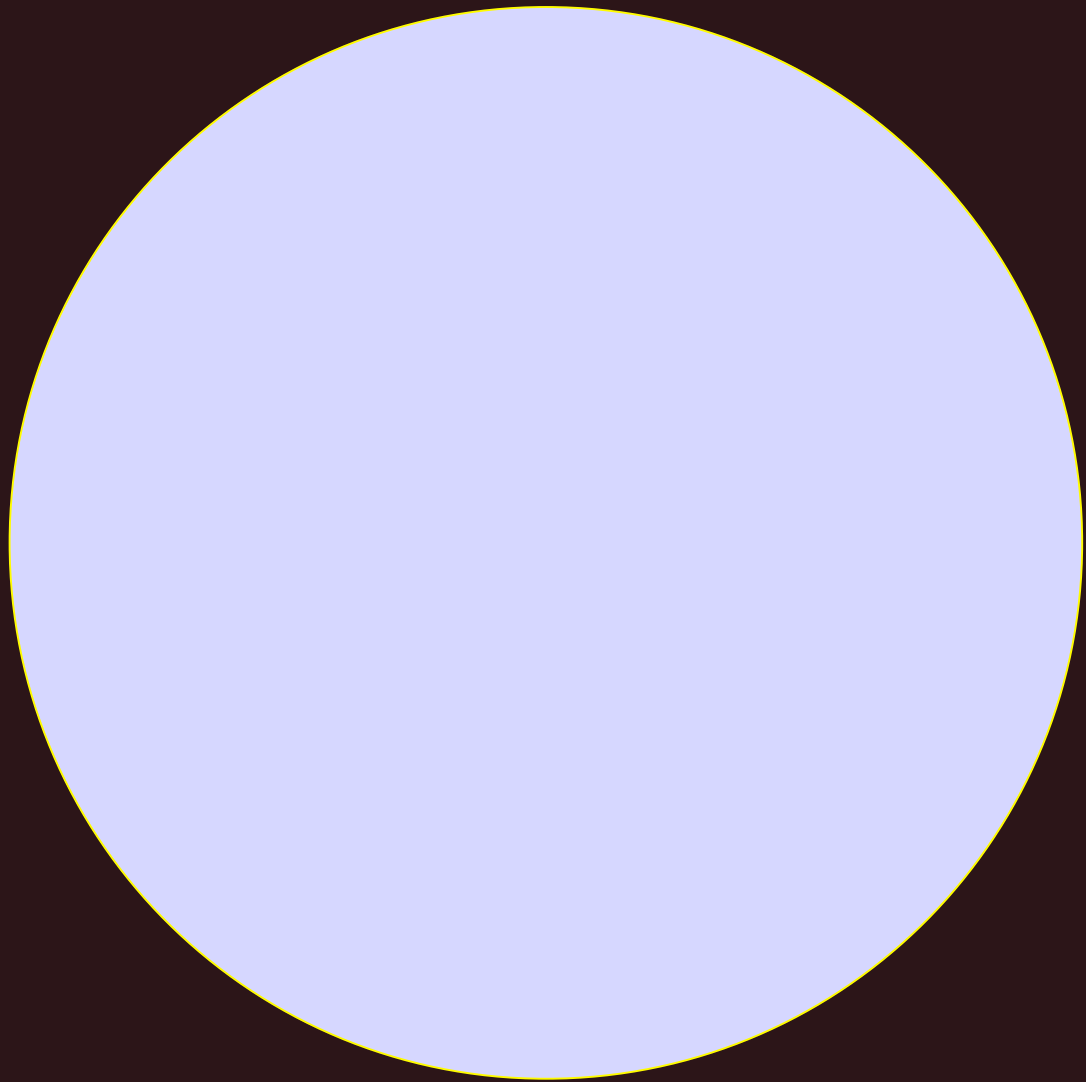
NGC 7009 H 171eta 3-He 62.1 hrs



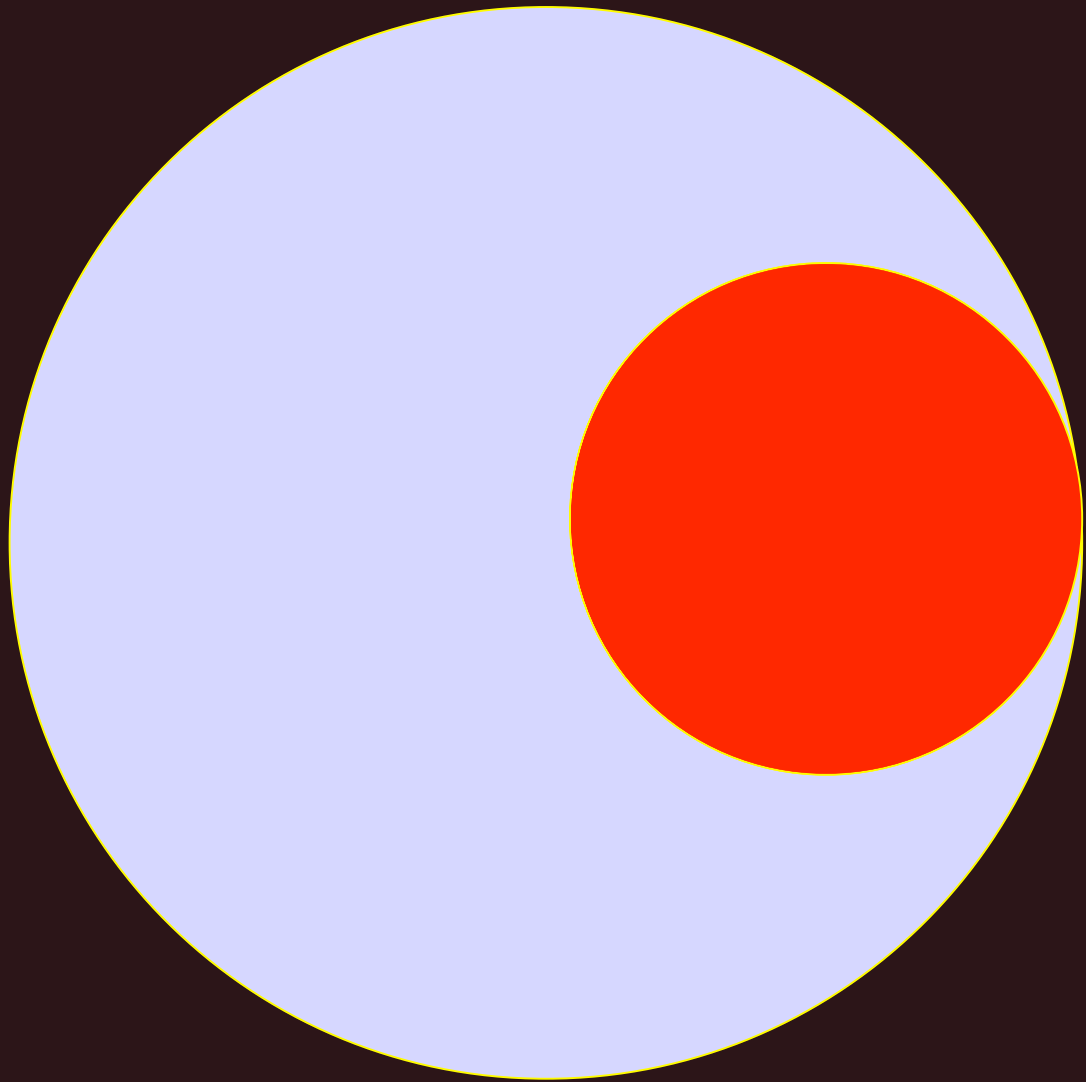
The Robert C. Byrd

GREEN BANK TELESCOPE

To avoid this and other problems the replacement for the collapsed 300ft RT was designed as an off-axis system.

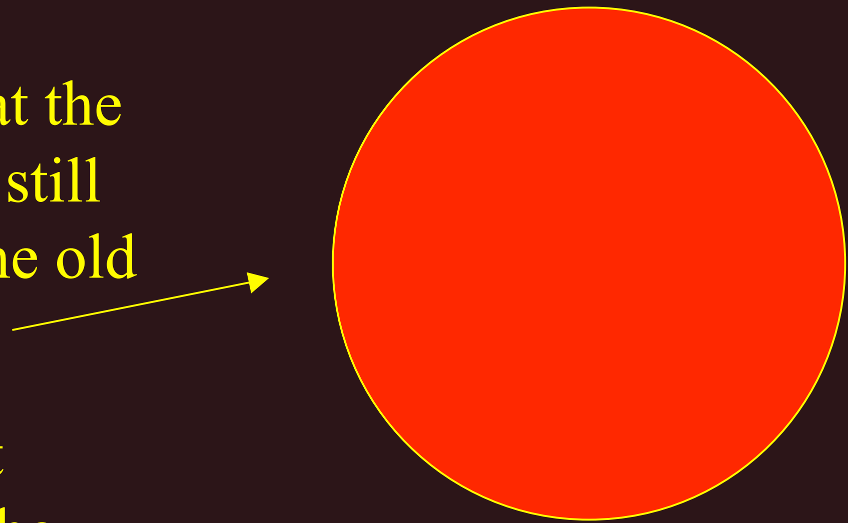


Imagine building a 220m paraboloid.



Take a giant cookie cutter and cut a 100m chunk out of one side.

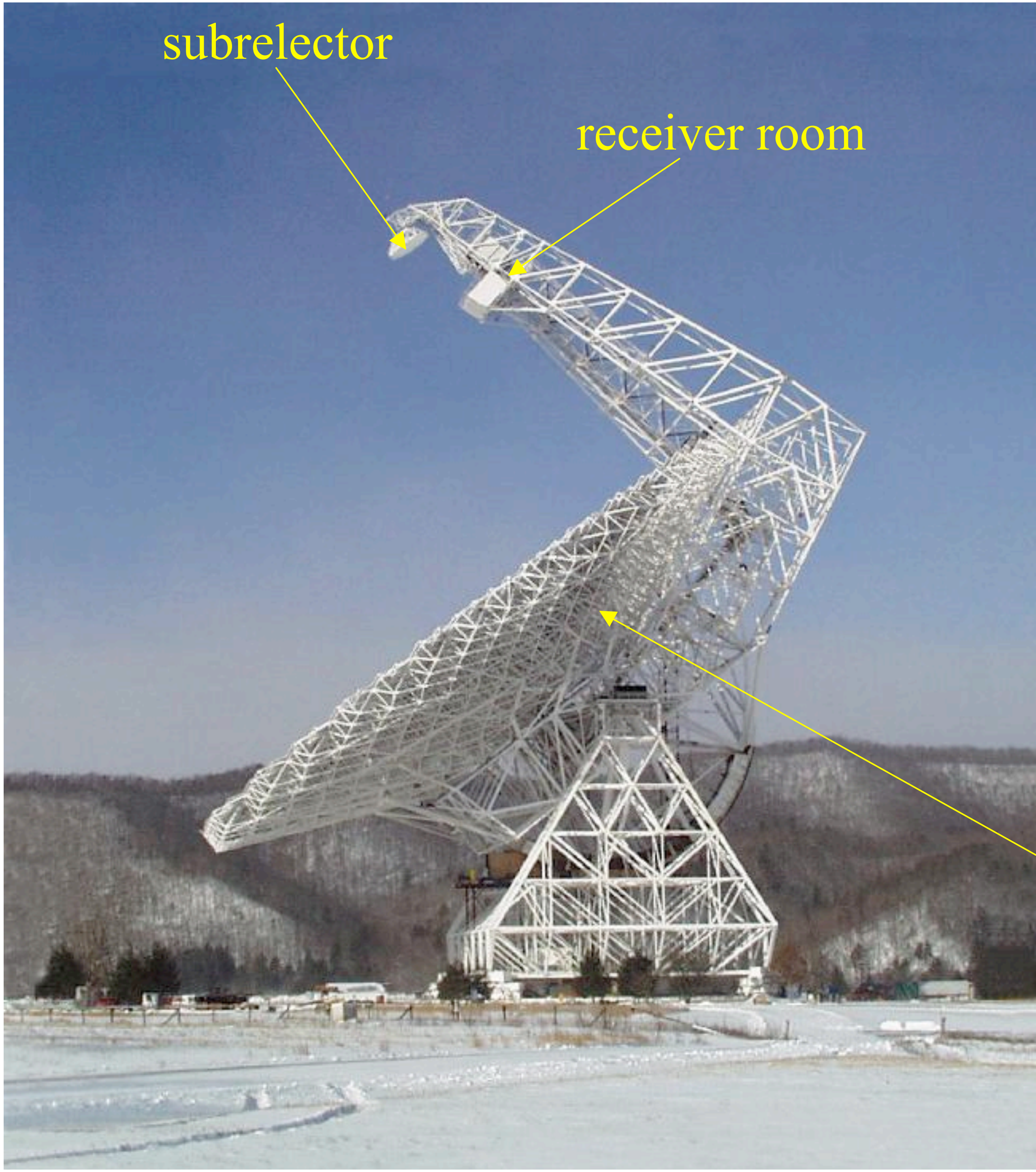
Note that the focus is still above the old center.



It is not above the dish.

Don’t build the rest.

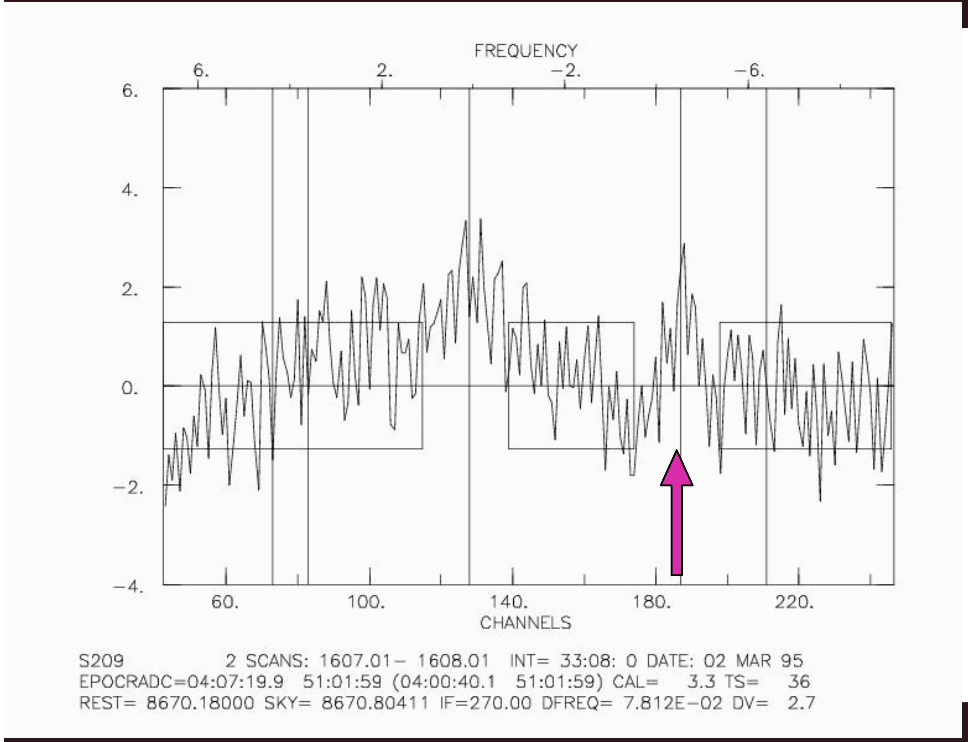
GBT: Clear Aperture Optics

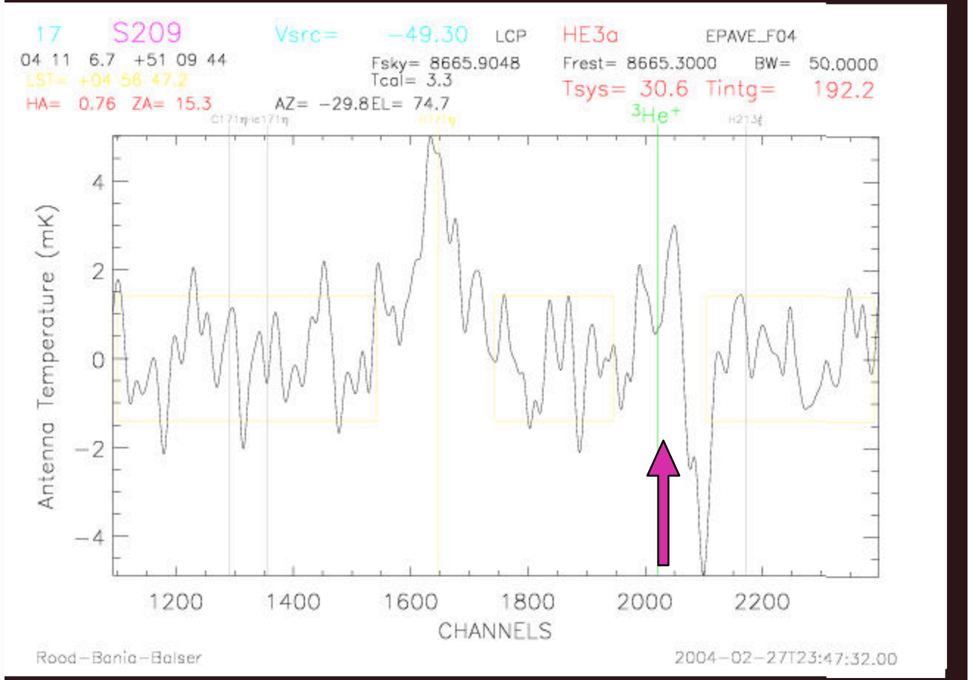


Like the German 100m the GBT is a deformable RT. Hence the complex backup structure.

S 209 H II Region

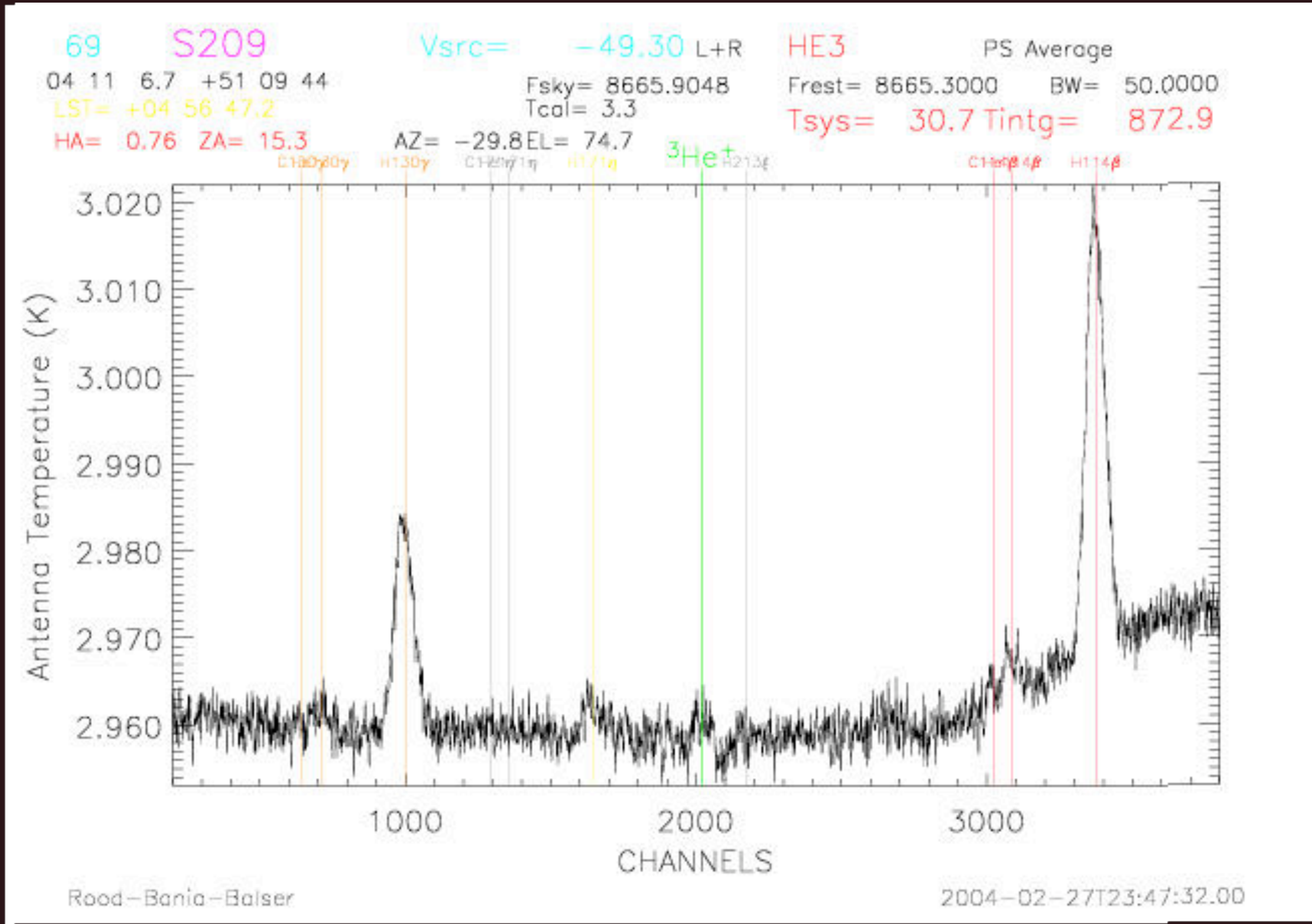
140 ft March 1995	GBT June 2004



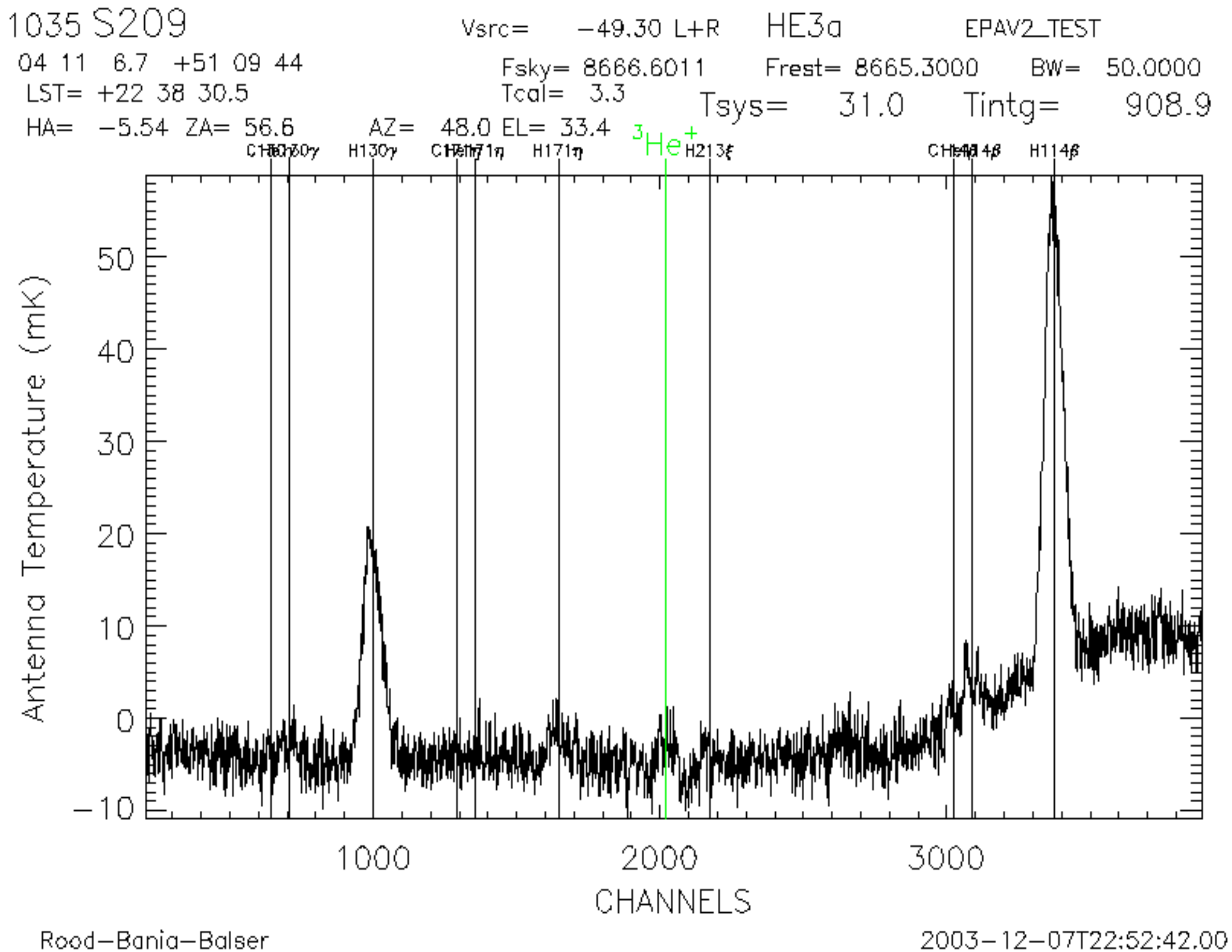


33.1 hr	3.2 hr

GBT S 209 H II Region

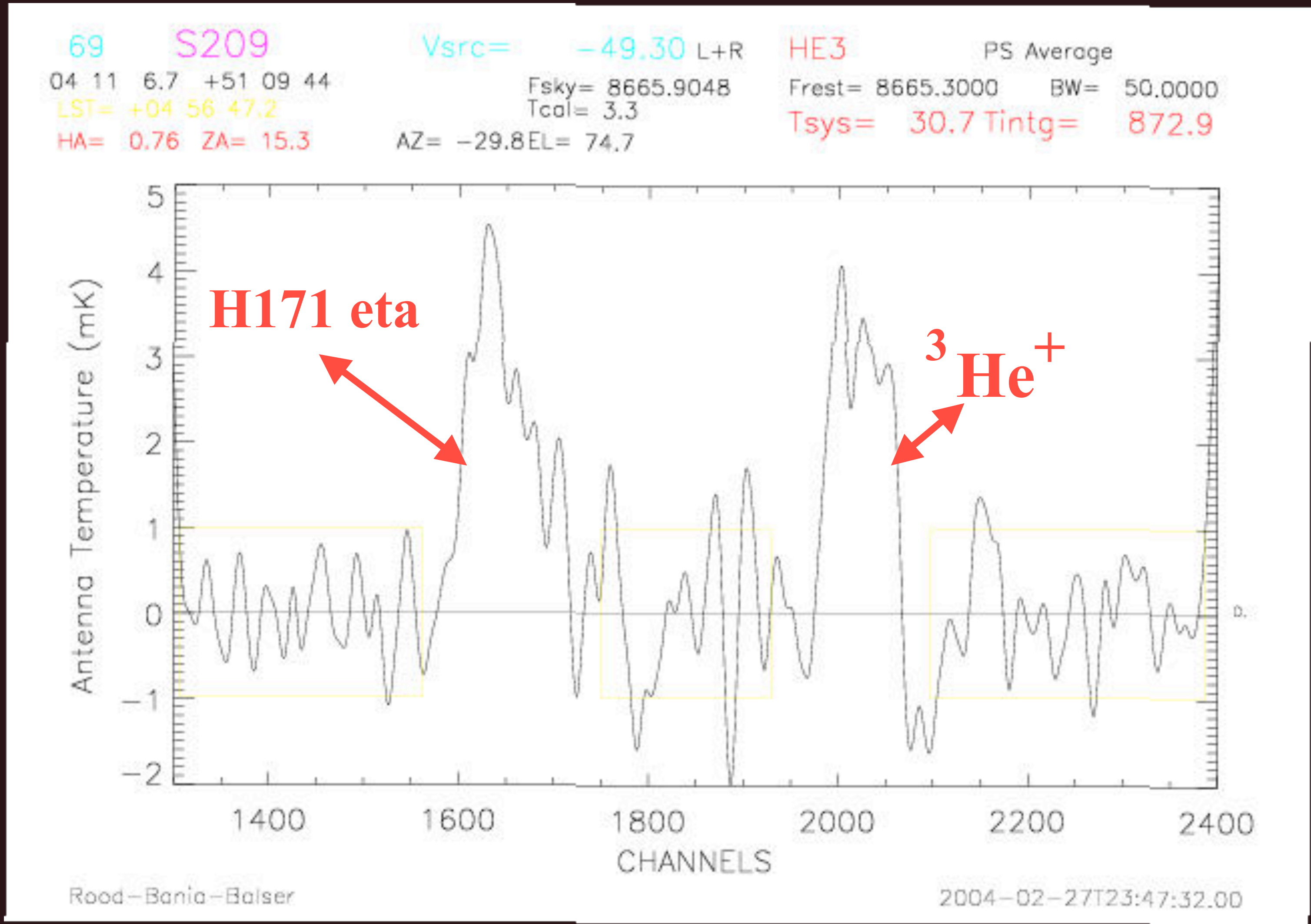


Calibrated Raw Spectrum 14.5 hour integration

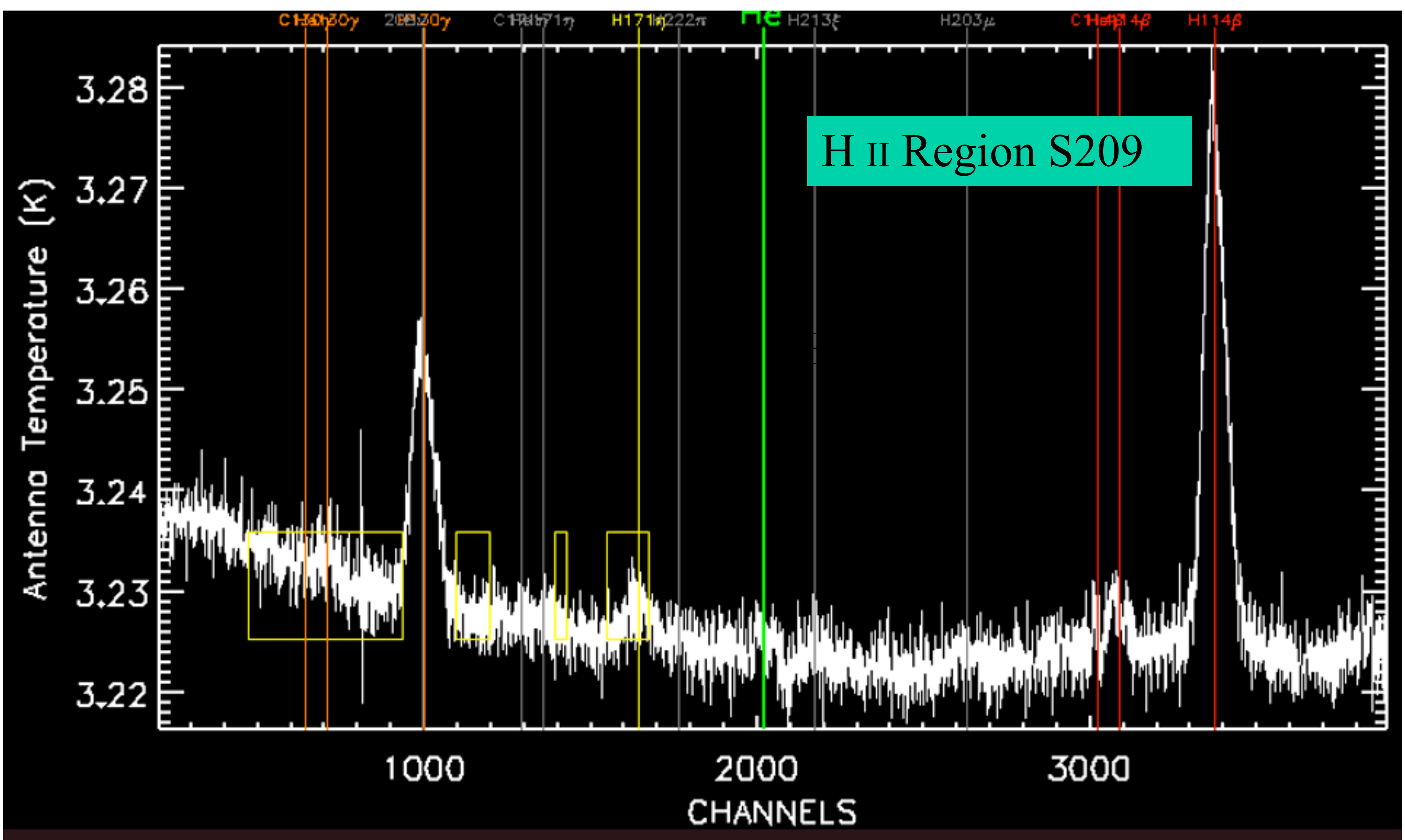


DC Level Subtracted **15.1 hr integration**

S 209 H II Region



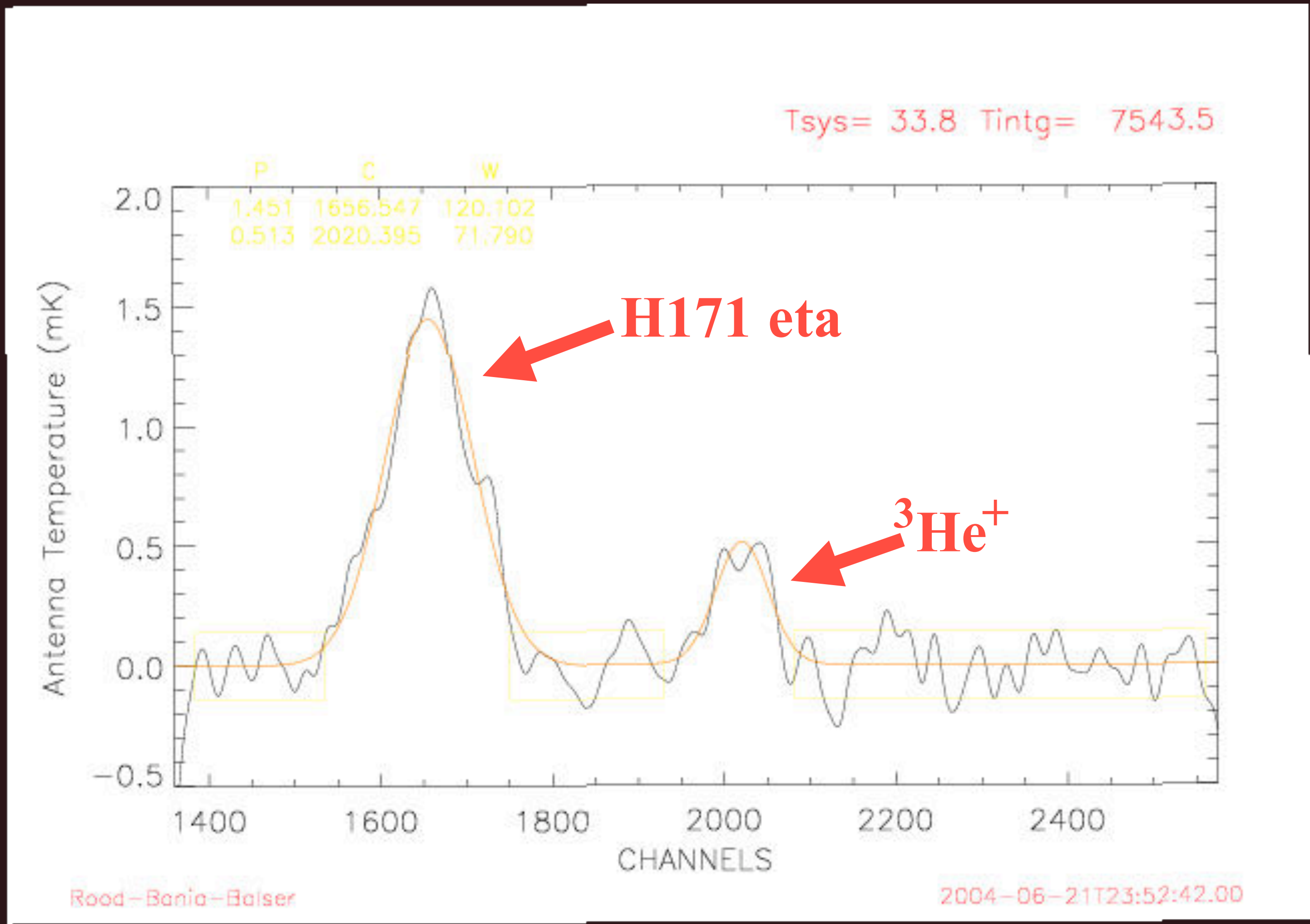
14.5 hour integration **5 km/sec resolution**



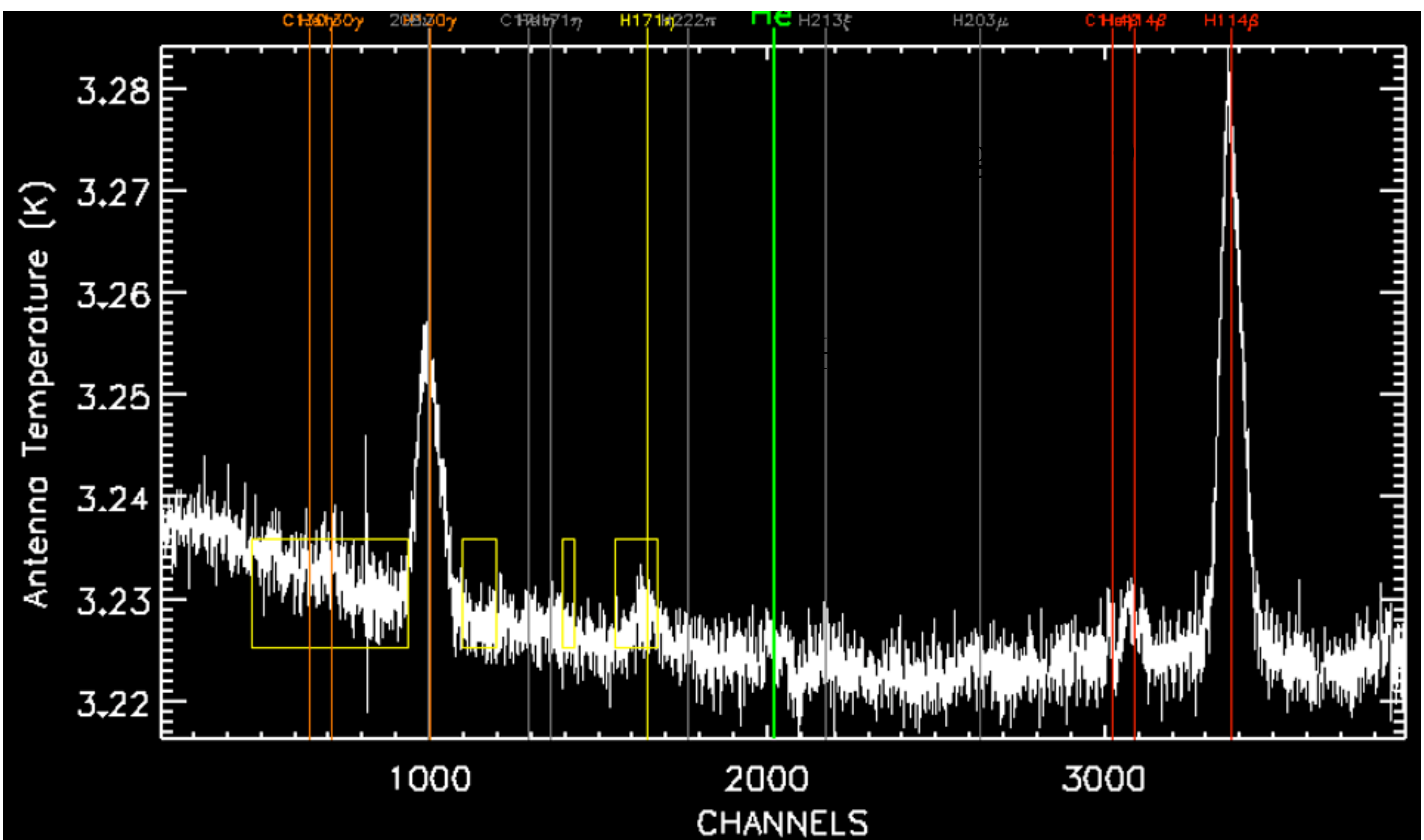
Indeed, a 50MHz band containing the $^{3}He^{+}$ line is devoid of standing waves.

GBT PNe Composite Spectrum

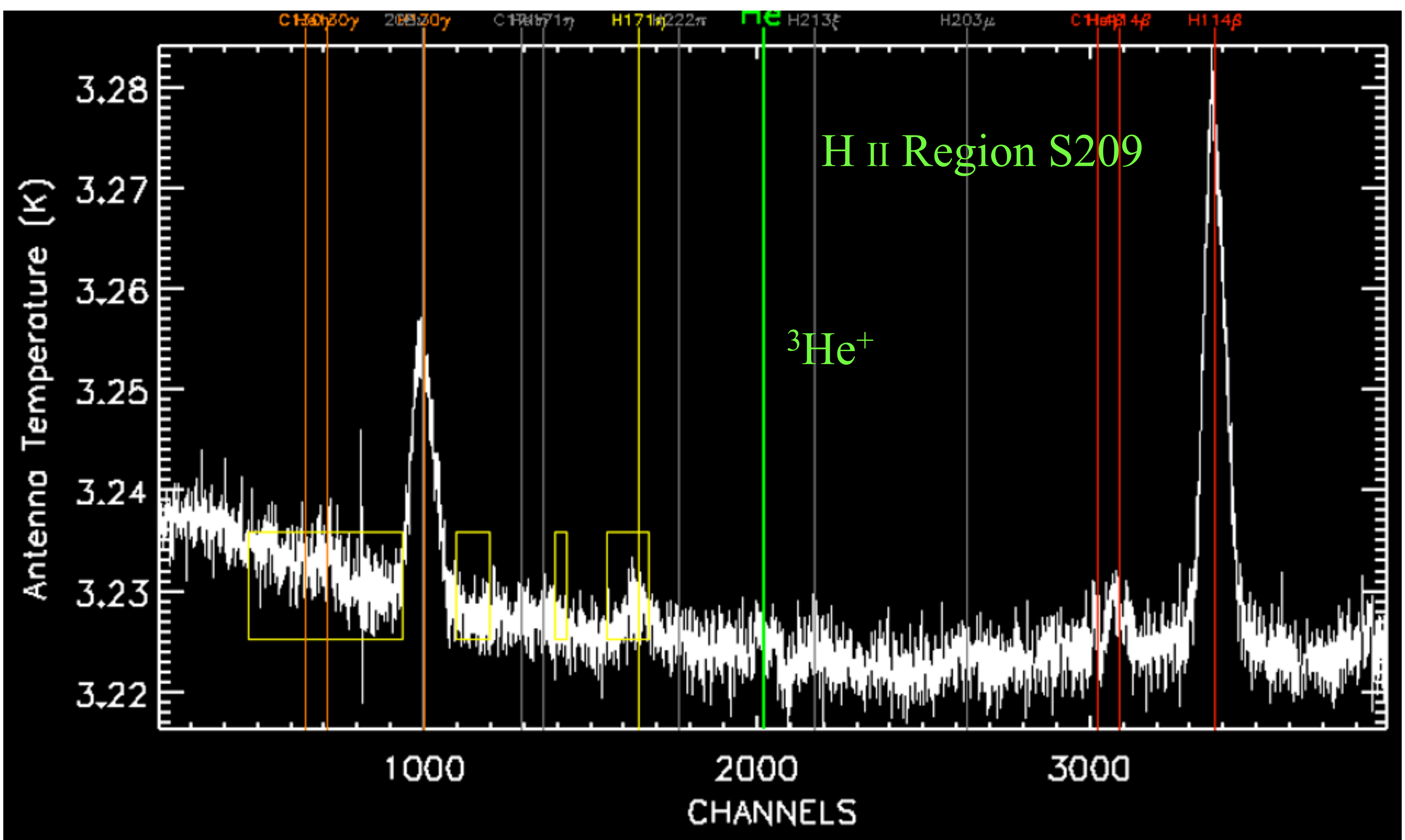
NGC 3242 + NGC 6543 + NGC 6826 + NGC 7009



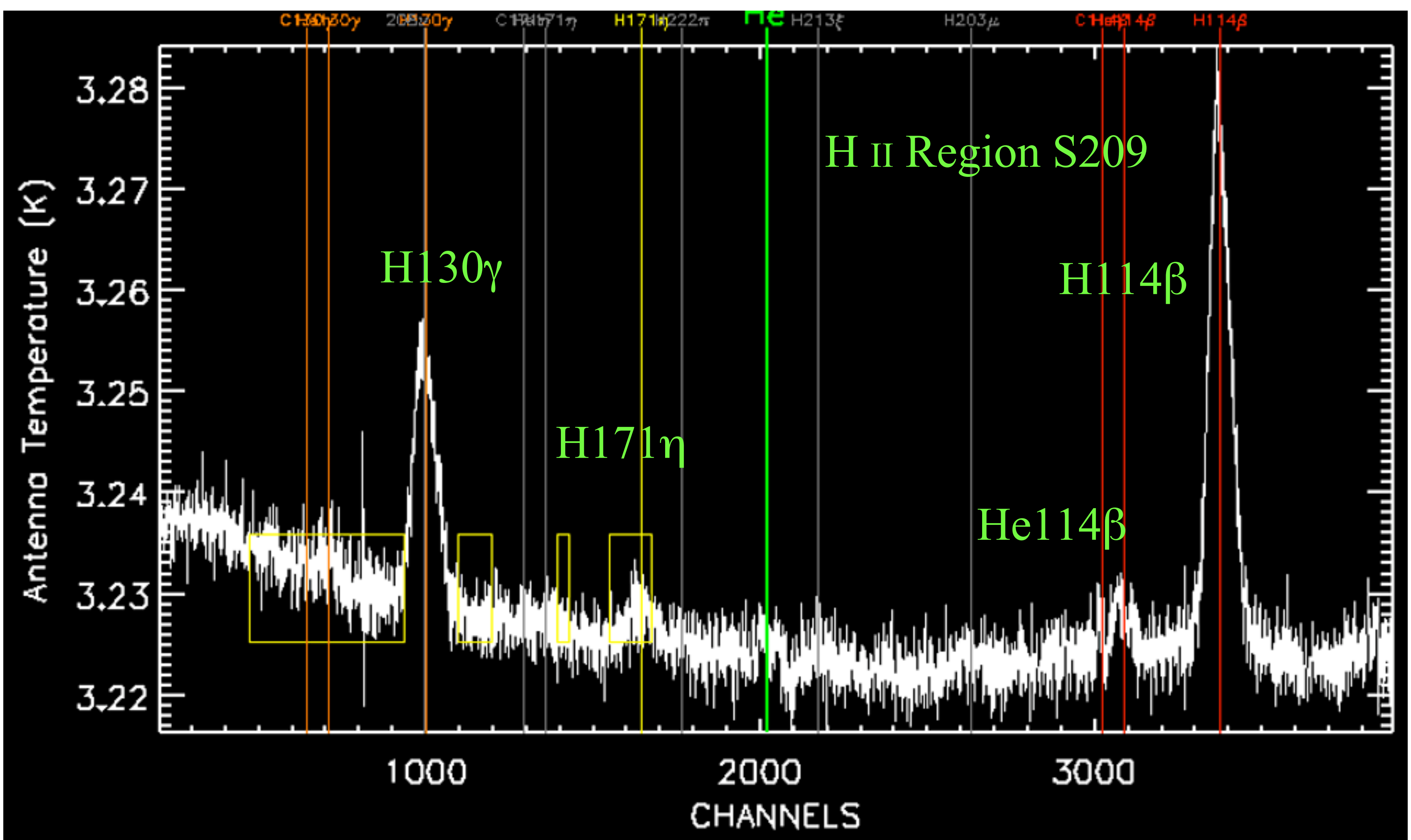
125.7 hour integration



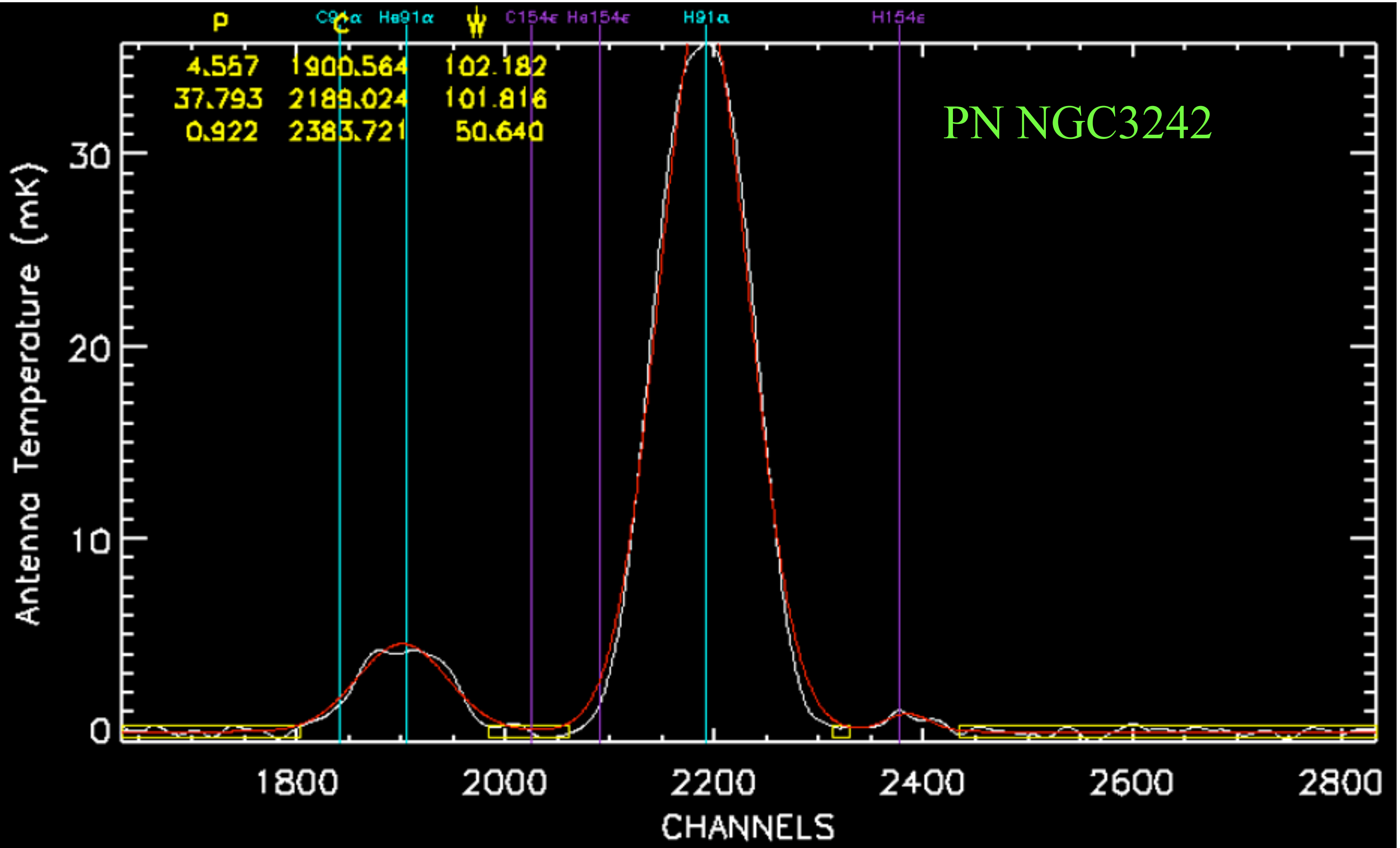
Indeed, a 50MHz band containing the $^{3}He^{+}$ line is devoid of standing waves.



Indeed, a 50MHz band containing the $^3He^+$ line is devoid of standing waves.

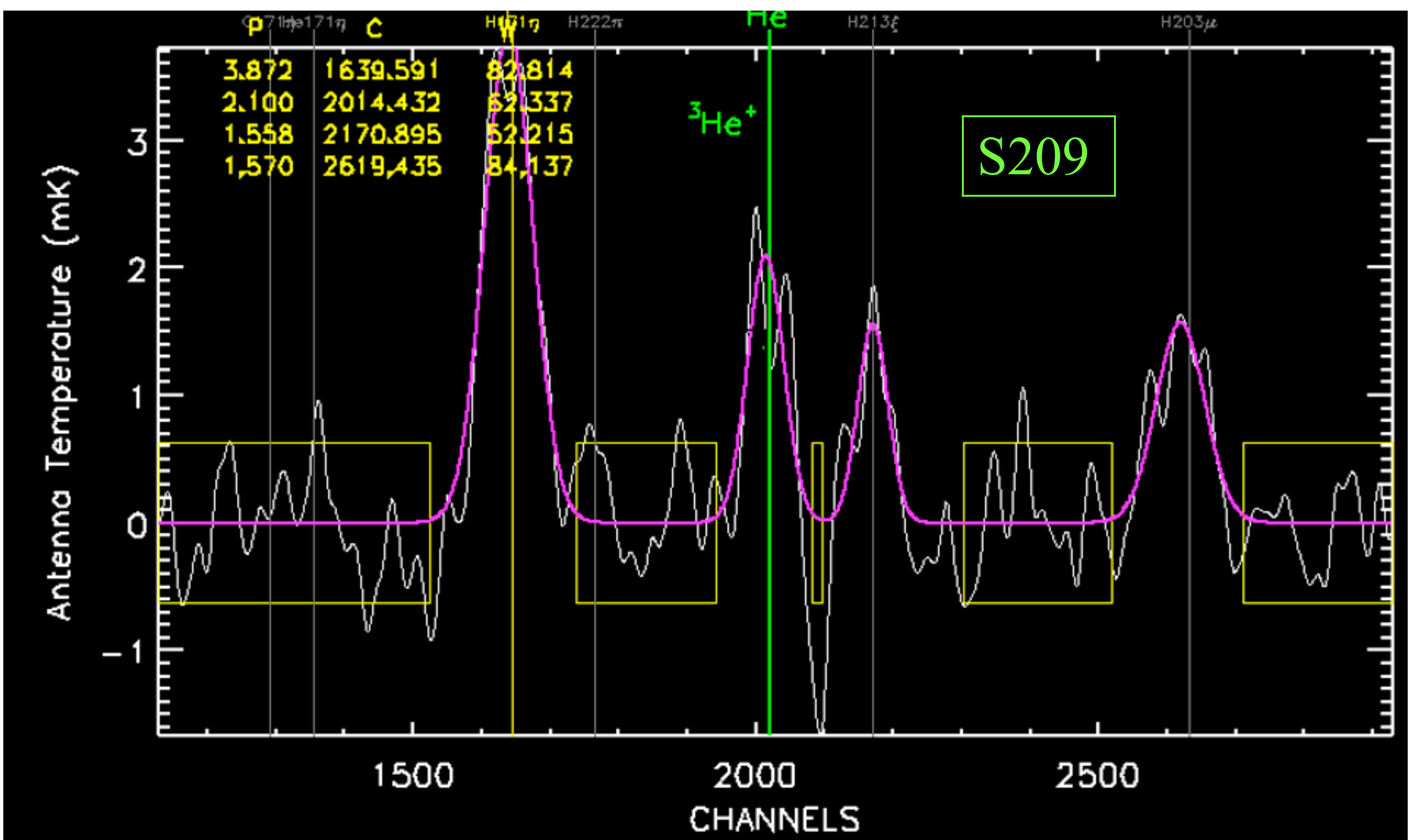


There are many radio recombination lines (RRL) in our spectra.

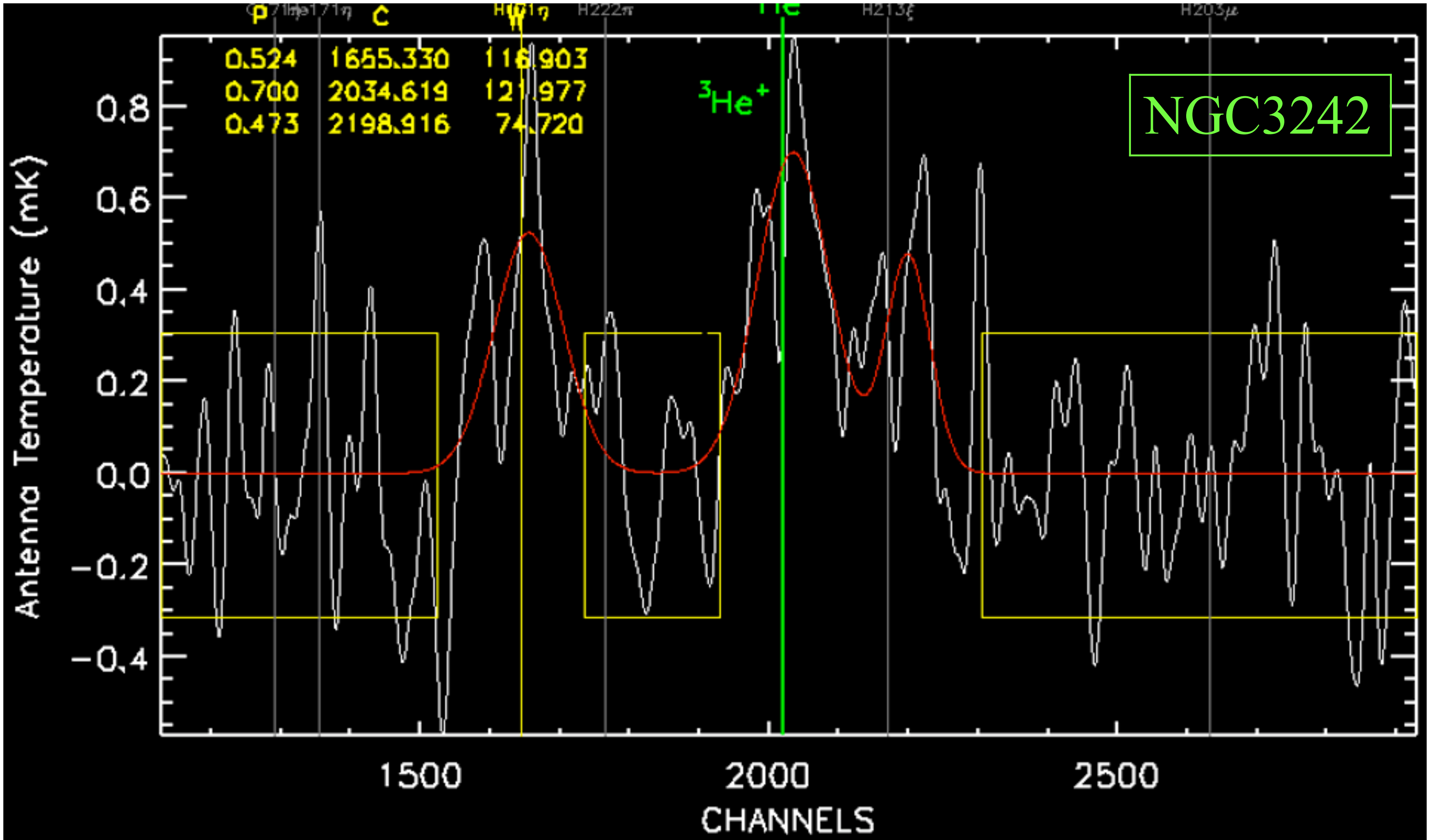


He/H ratio should be independent of order ~ 1/10

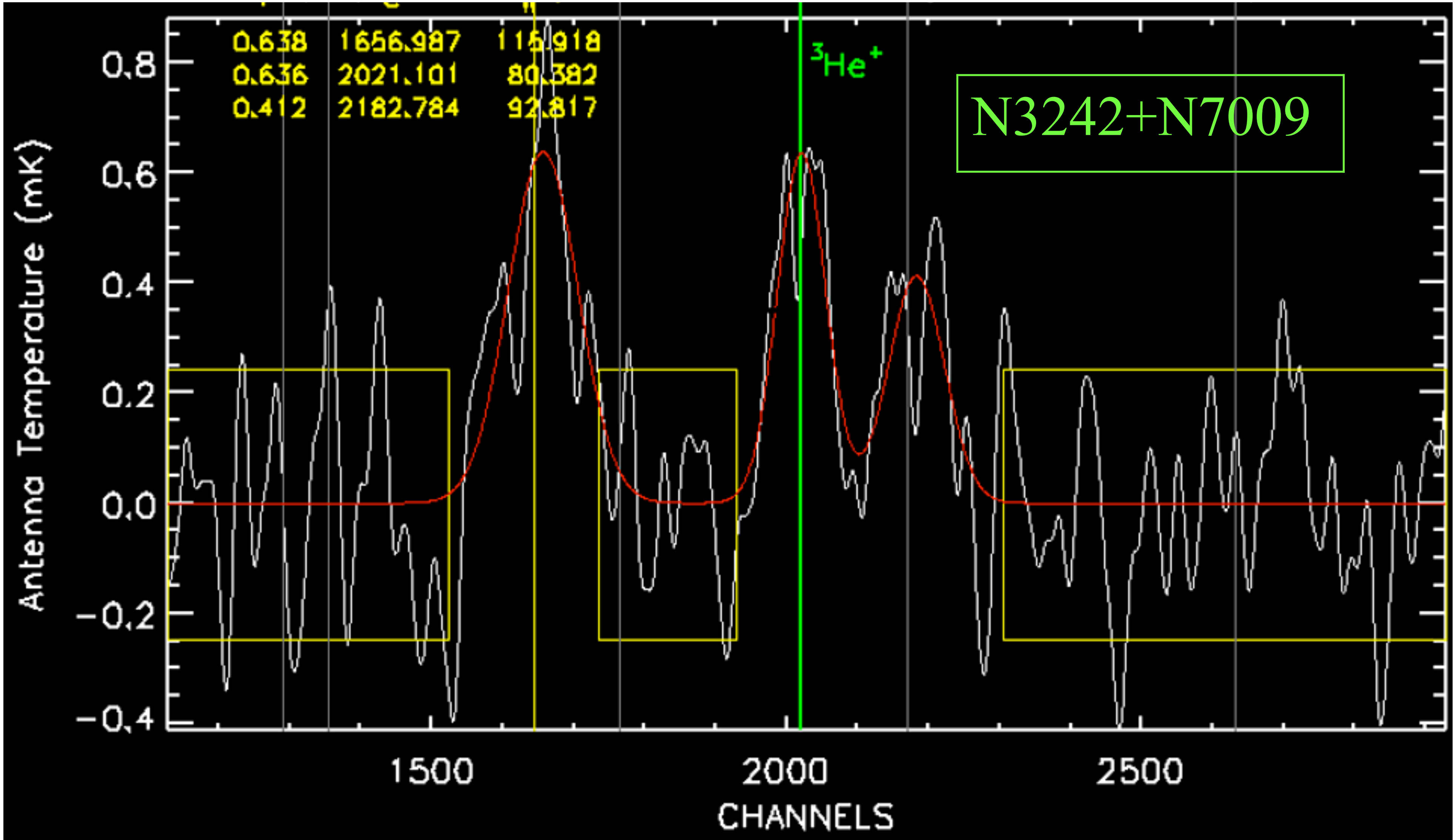
Set this ratio with 91α



The He3b path does give a better result for S209. The $^3He^+$ line is separable from the 213ξ feature/line and consistent with our 140ft result.



$^3He^+$ line in PN should be much wider and will blend with 213ξ feature. This is a more appropriate baseline fit.



Can increase S/N by making a composite spectrum. This is the best composite: NGC3242+NGC7009.

GBT Results

- Really unlucky to have an instrumental feature right next to the 3He+ line. We find only these 2 features in the 350 MHz we sample. The features are weak and thus hard to study.
- GBT PN NGC3242 result is inconsistent with MPIfR. We find 3-He in GBT 2 PN composite but they are weaker than MPIfR and are at limit of detectability.

GBT Results

- GBT results for S209, important for both cosmology and chemical evolution, are consistent with our earlier results.
- GBT results for PNe are inconsistent with those from 100m.
- $^3He^+$ lines may still be present in 2 PNe but they are much weaker, and the lines are at the limit of detectability.

Helium-3 PNe Conclusions

• We have found helium-3 in another PN, J320, using the VLA

• GBT results suggest our earlier detection in NGC3242 is wrong. This is a very preliminary result and requires careful assessment of possible errors

• Roughly 25% of PNe meet our selection criteria. To avoid conflict with Monica and Gary we should detect 3He in only 1/5

• The scheduling mode and proposal pressure on the GBT may not allow us to solidify these results in the near future.

• The EVLA (10 x more sensitive than the VLA) has great potential

3-Helium in Planetary Nebulae

- VLA 3-He 4-sigma detection for PN J320
- Arecibo J320 observations underway
- Arecibo composite PN spectrum consistent with MPIfR composite result
- GBT NGC3242 intensity inconsistent with MPIfR result
- GBT composite PN spectrum marginally consistent with MPIfR composite result

3-Helium in Planetary Nebulae

- **25% of all planetary nebulae meet our selection criteria. To be consistent with Galactic Chemical Evolution models, only 1/5 of these should show detectible ^{3}He.**

- **The EVLA has great potential: 10 times more sensitive than the VLA.**

3-Helium in H II Regions

``THE 3-HELIUM PLATEAU'' result, important for primordial nucleosynthesis and Galactic chemical evolution stands.

GBT S209 results consistent with ALL previous measurements.

Deep Mixing of ^{3}He:

Reconciling Big Bang and Stellar Nucleosynthesis

Eggleton, Dearborn & Lattanzio 2006 SCIENCExpress 10.1126/science.1133065

Announces solution of "The He Problem"

- **Claim numerical discovery with red giant 3D modelling**
- **Find extra-mixing due to Rayleigh-Taylor instability just above the H-burning shell at convective envelope base that burns all the ^{3}He produced on main sequence**

Mechanism should occur in ALL stars:

there should be NO ^{3}He produced by ANY PNe

Systematic Error

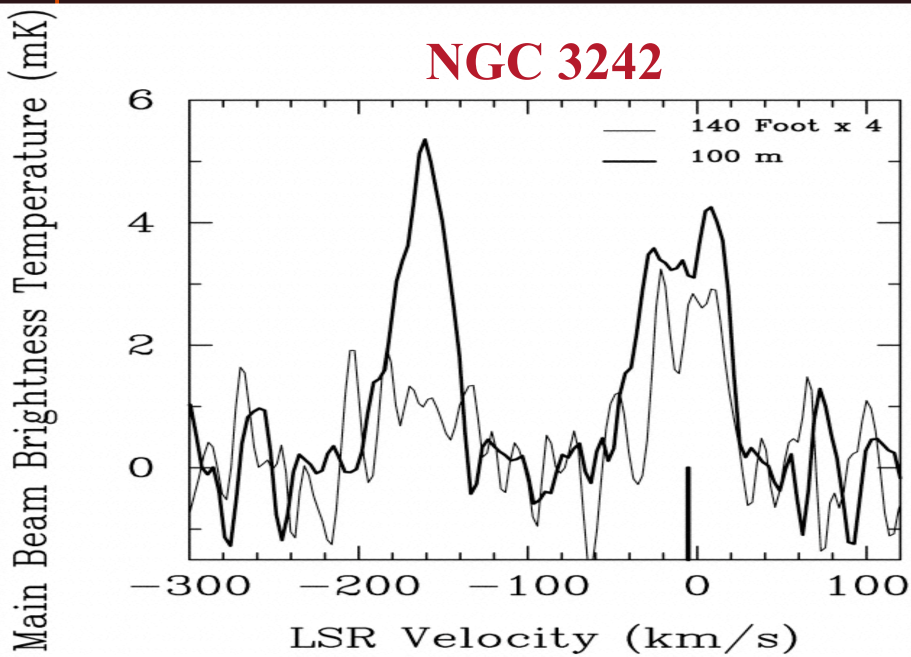
Like other BBN isotopes ^3He abundance errors are dominated by systematics

Systematic error bars are an oxymoron

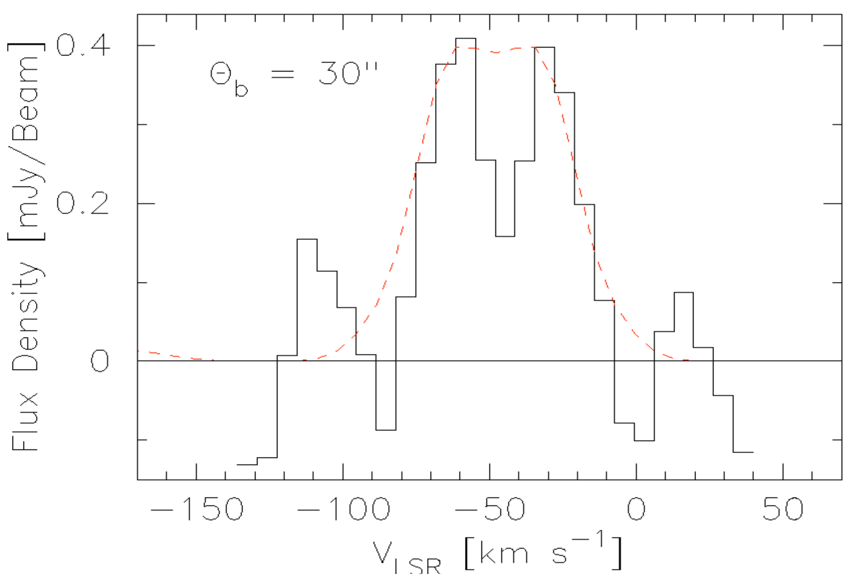
The real problem with systematic error estimates arises from those errors that we don’t know that we don’t know

7 PNe with Standard 3-He Yields

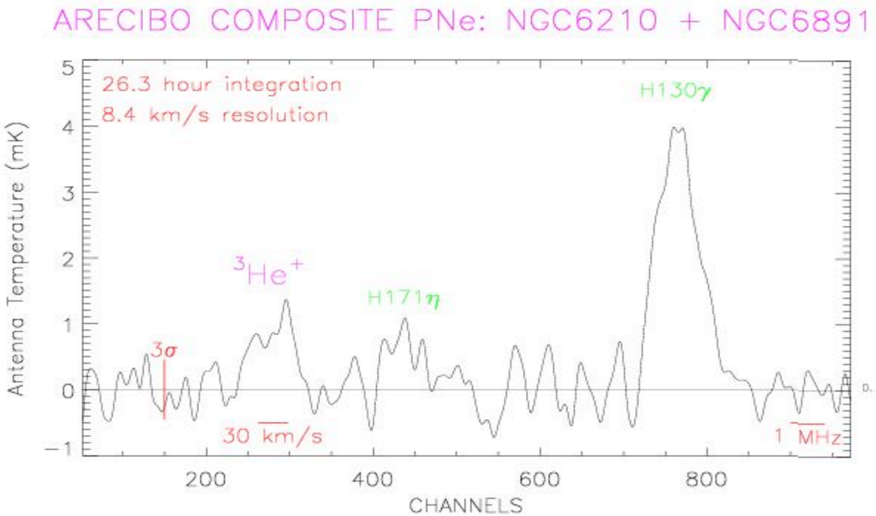
NGC 3242



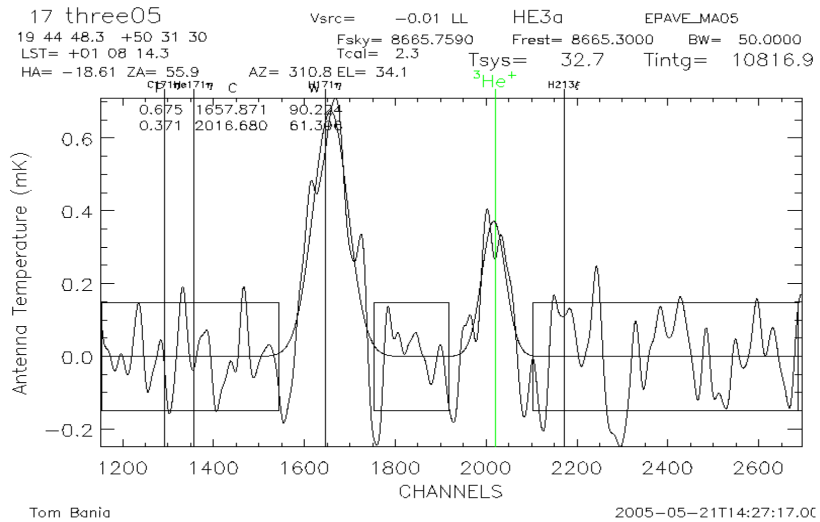
J 320



Arecibo: NGC 6210 + NGC 6891

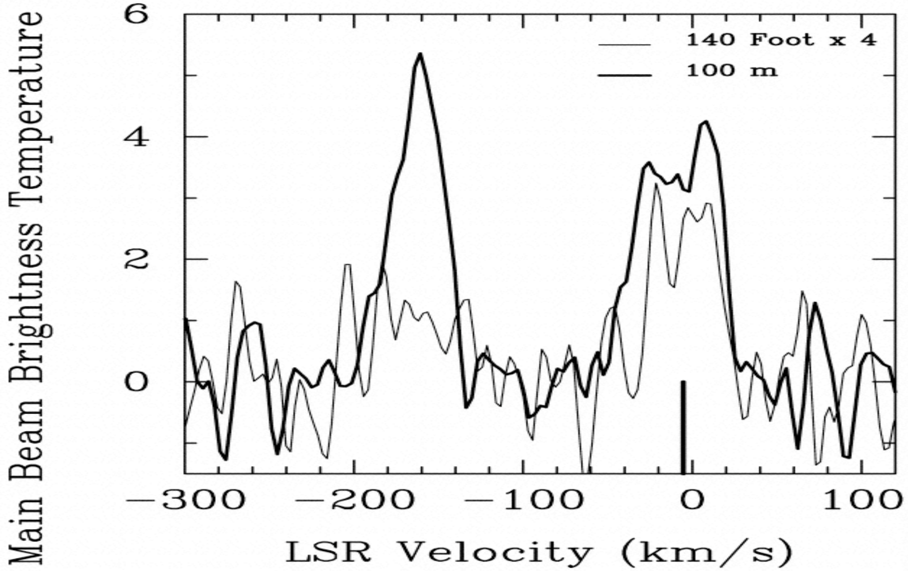


GBT: NGC6543 + NGC6826 + NGC7009

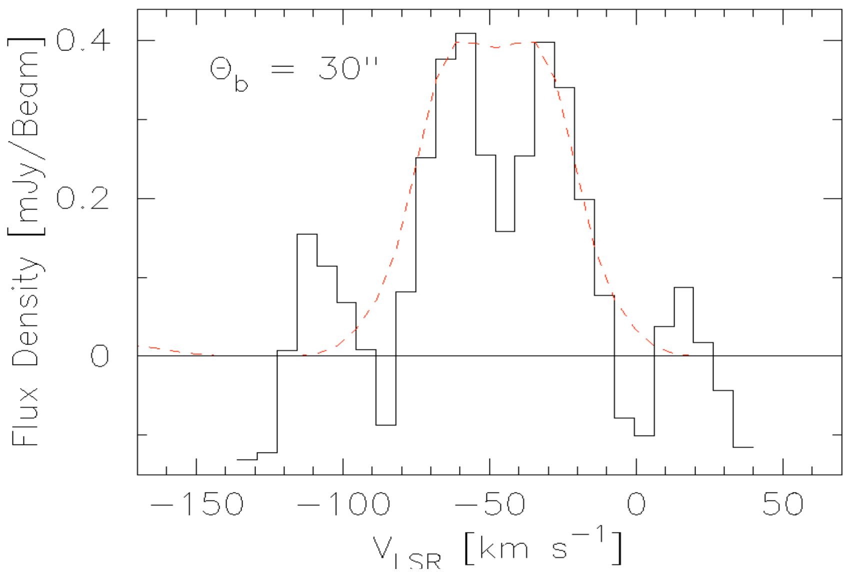


7 PNe with Standard 3-He Yields

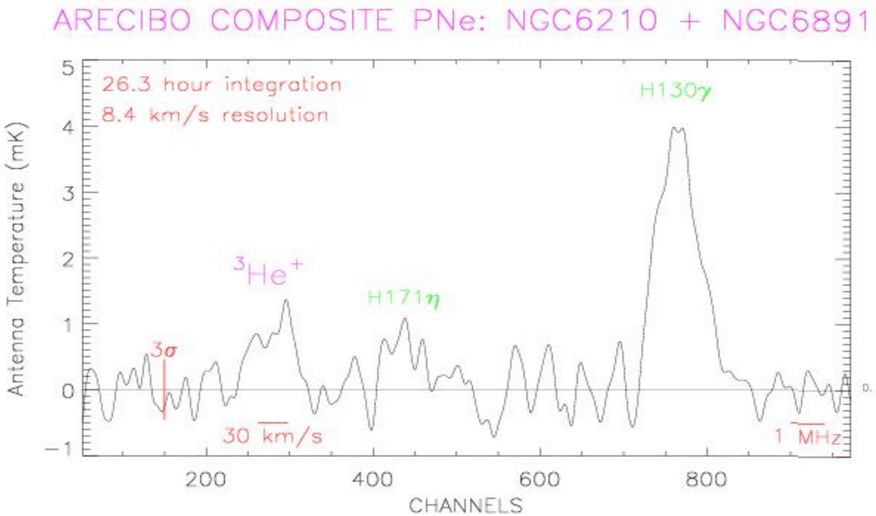
NGC 3242



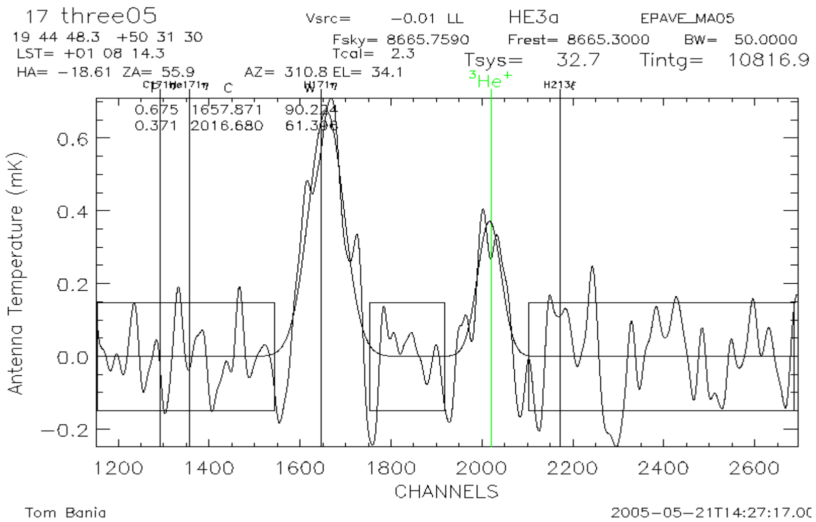
J 320

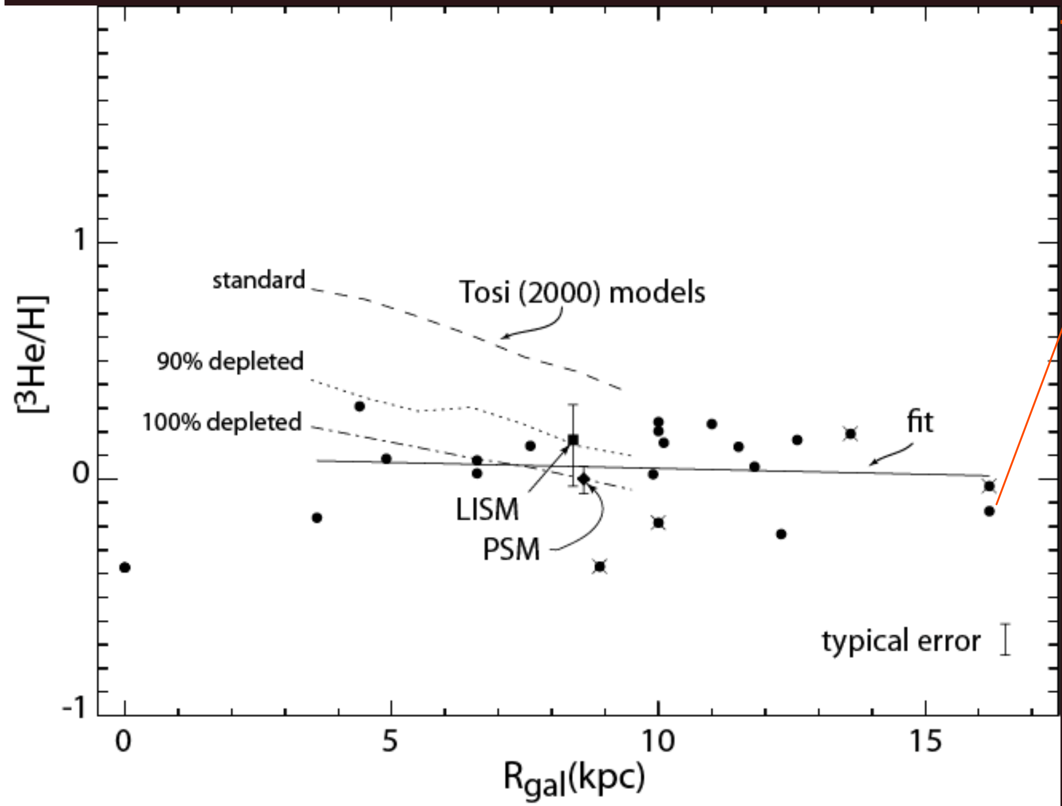


Arecibo: NGC 6210 + NGC 6891



GBT: NGC6543 + NGC6826 + NGC7009





Bania, Rood, & Balser 2002

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

$\Omega_B = 0.04$

Spergel et al. 2003, WMAP

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

$\Omega_B = 0.047 \pm 0.006$

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

GBT Conclusions

- Standing waves are not a problem
- There is still baseline structure (BS) probably resulting from the broadband feed, the polarizer, and or mismatches in the IF system.
    - BS varies with frequency sometimes almost invisible other times very problematic
    - BS amplitude is proportional to source continuum and moves with sky frequency
- At the mK level there are pseudo-lines
- In some AC bands there are short duration spikes in the ACF at seemingly random times, lags, and amplitudes

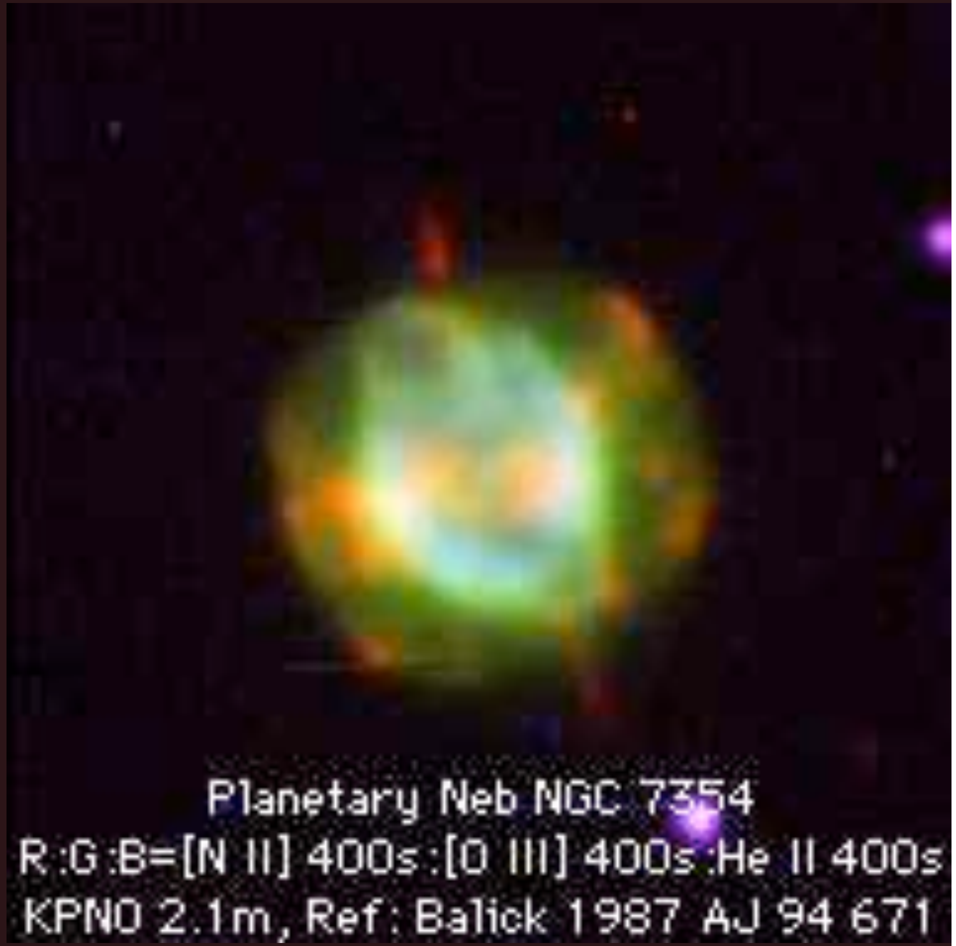
Helium-3 Conclusions

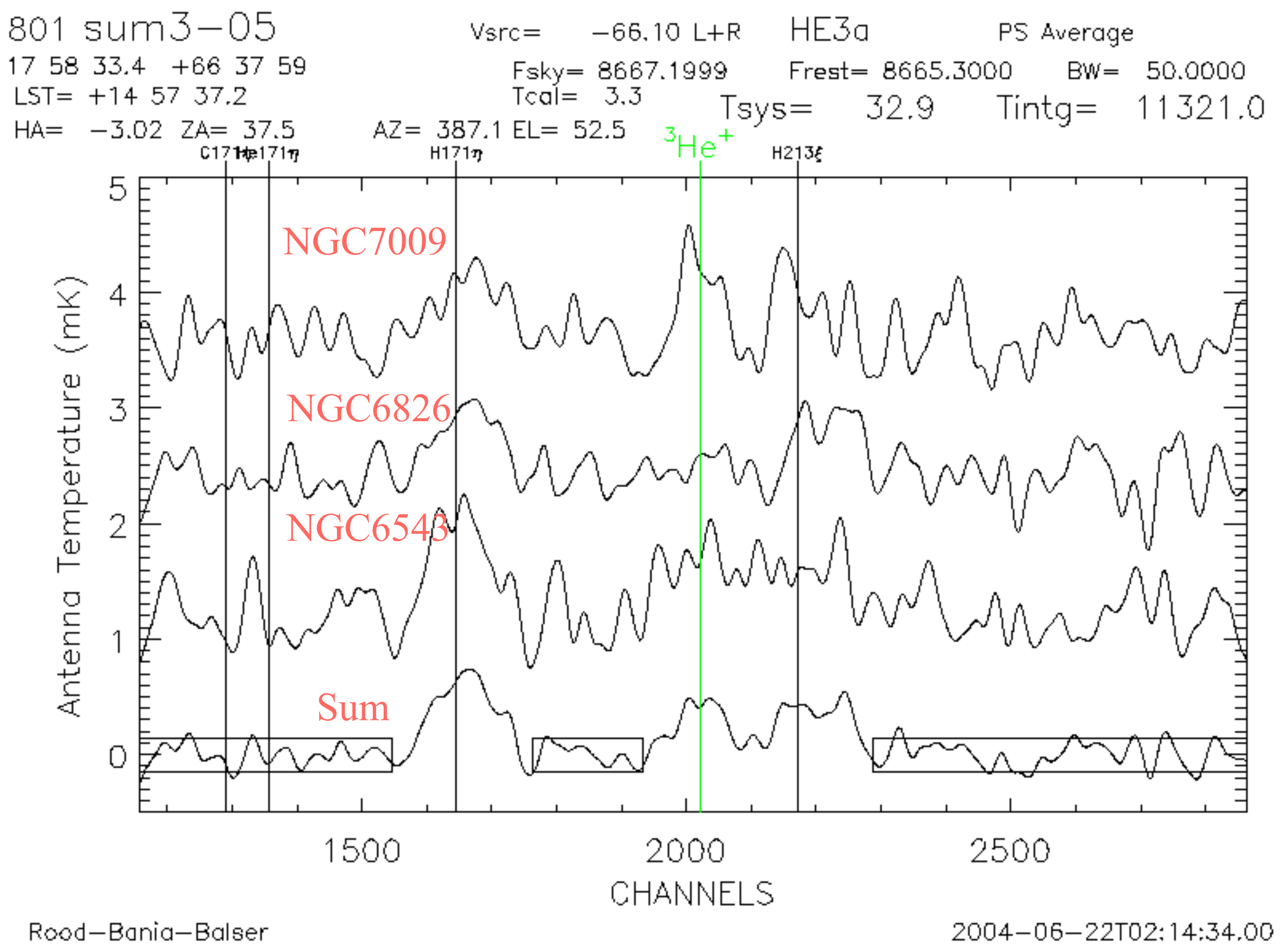
- We have found helium-3 in another PN, J320, using the VLA
- We probably have found helium-3 in NGC7009 using the GBT and may have a second detection in NGC6543
- Roughly 25% of PNe meet our selection criteria. To avoid conflict with Monica we should detect 3He in only 1/5
- The scheduling mode and proposal pressure on the GBT may not allow us to solidify these results in the near future.
- The EVLA (10 x more sensitive than the VLA) has great potential

3-Helium Experiment Status

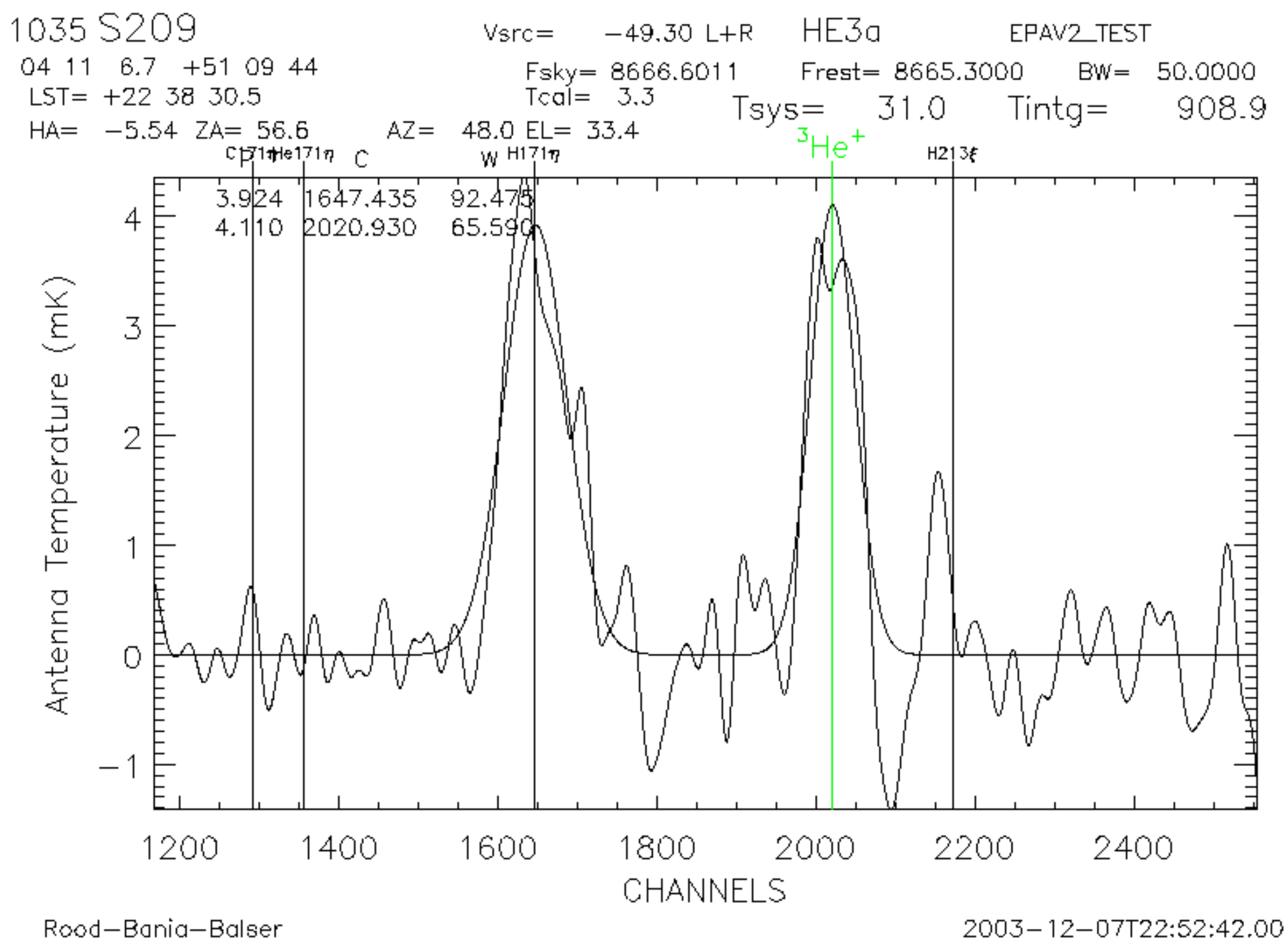
- VLA ^{3}He detection for PN J 320. It has a substantial halo, just as NGC 3242 does.
- Composite GBT PNe spectrum consistent with MPIfR 100 m survey result.
- Probable GBT ^{3}He detection for NGC 7009 A second detection in NGC 6543 is likely.
- Composite Arecibo PNe spectrum consistent with MPIfR 100 m survey result.

NGC 7009 NGC 7354





801 sum3–05
17 58 33.4 +66 37 59
LST= +14 57 37.2
HA= –3.02 ZA= 37.5
Vsrc= –66.10 L+R
HE3a
PS Average
Fsky= 8667.1999
Frest= 8665.3000
BW= 50.0000
Tcal= 3.3
Tsys= 32.9
Tintg= 11321.0
AZ= 387.1 EL= 52.5
C171η
He171η
H171η
3He+
H213ξ
NGC7009
NGC6826
NGC6543
Sum
Antenna Temperature (mK)
CHANNELS
Rood–Bania–Balser
2004–06–22T02:14:34.00

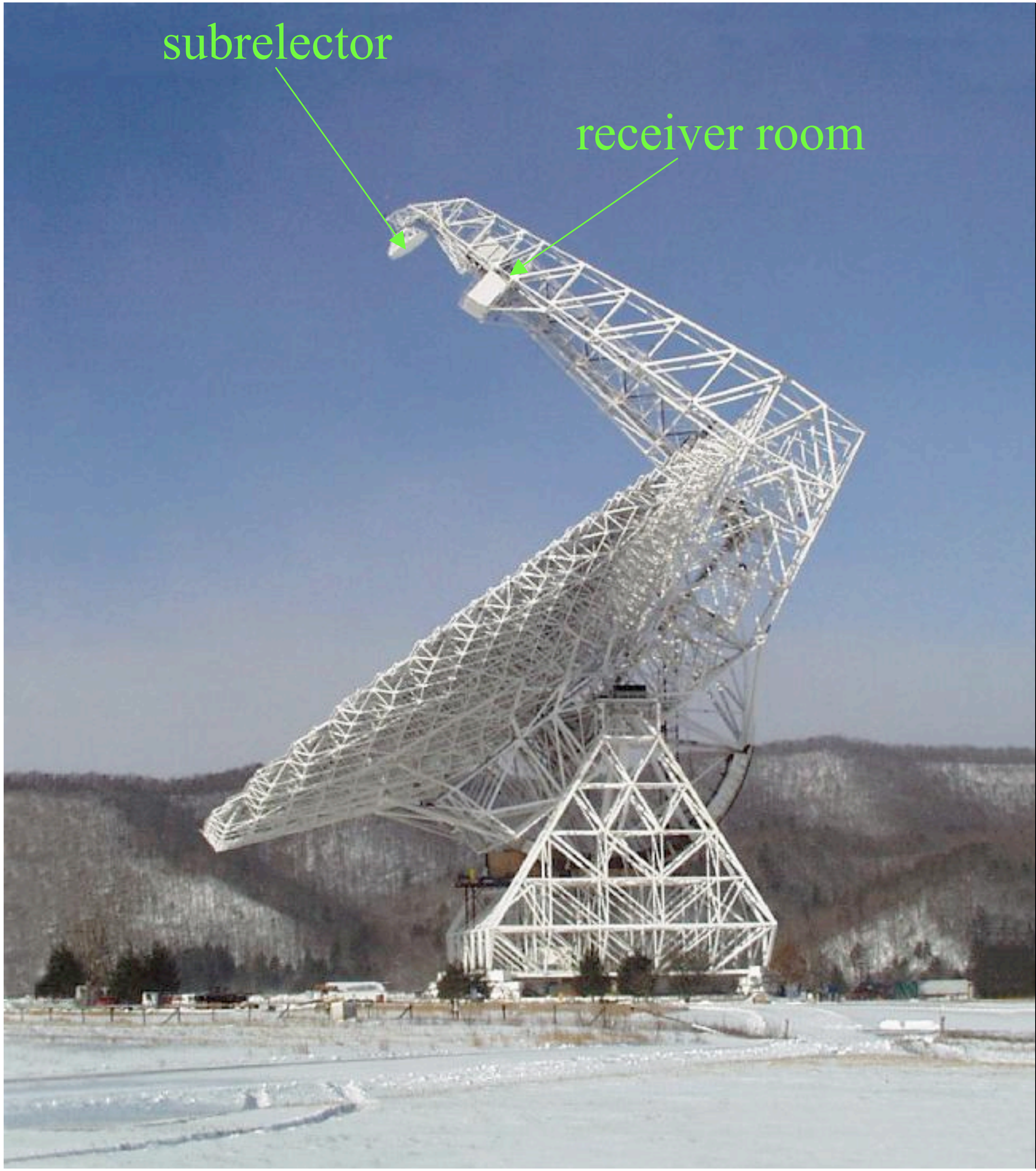

1035 S209
04 11 6.7 +51 09 44
LST= +22 38 30.5
HA= −5.54 ZA= 56.6
AZ= 48.0 EL= 33.4
Vsrc= −49.30 L+R
HE3a
EPAV2_TEST
Fsky= 8666.6011
Frest= 8665.3000
BW= 50.0000
Tcal= 3.3
Tsys= 31.0
Tintg= 908.9
C
W
H171η
³He⁺
H213ξ
3.924 1647.435 92.475
4.110 2020.930 65.590
Antenna Temperature (mK)
CHANNELS
Rood−Bania−Balser
2003−12−07T22:52:42.00

GBT Results

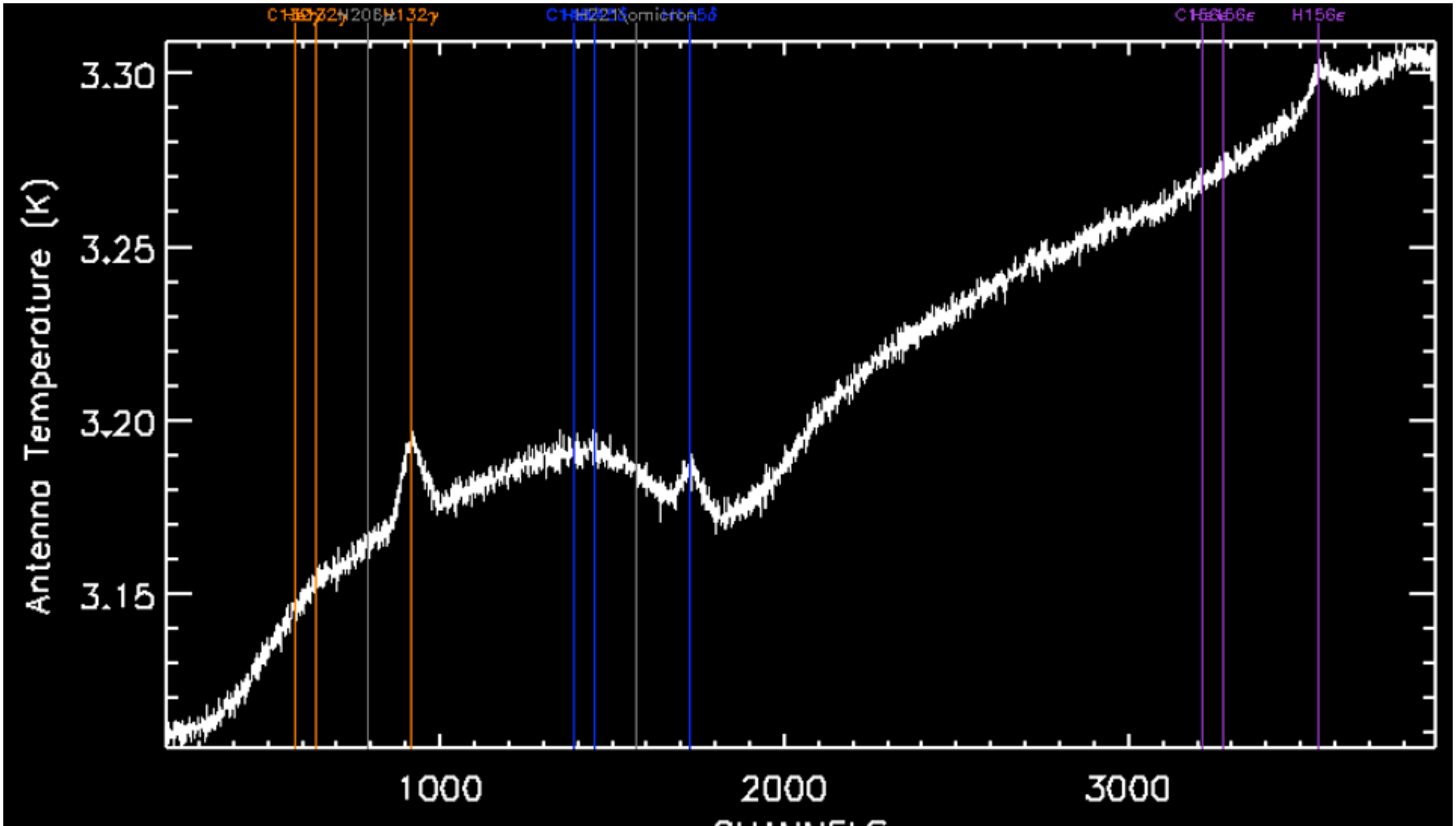
The feedlegs and other structures in the optical path of conventional radio telescopes cause some problems.

Among these are standing waves in spectral baselines.

This was a problem with the NRAO 140ft radio telescope and was especially bad with the MPIfR 100m, where techniques to minimize the standing waves did not work.



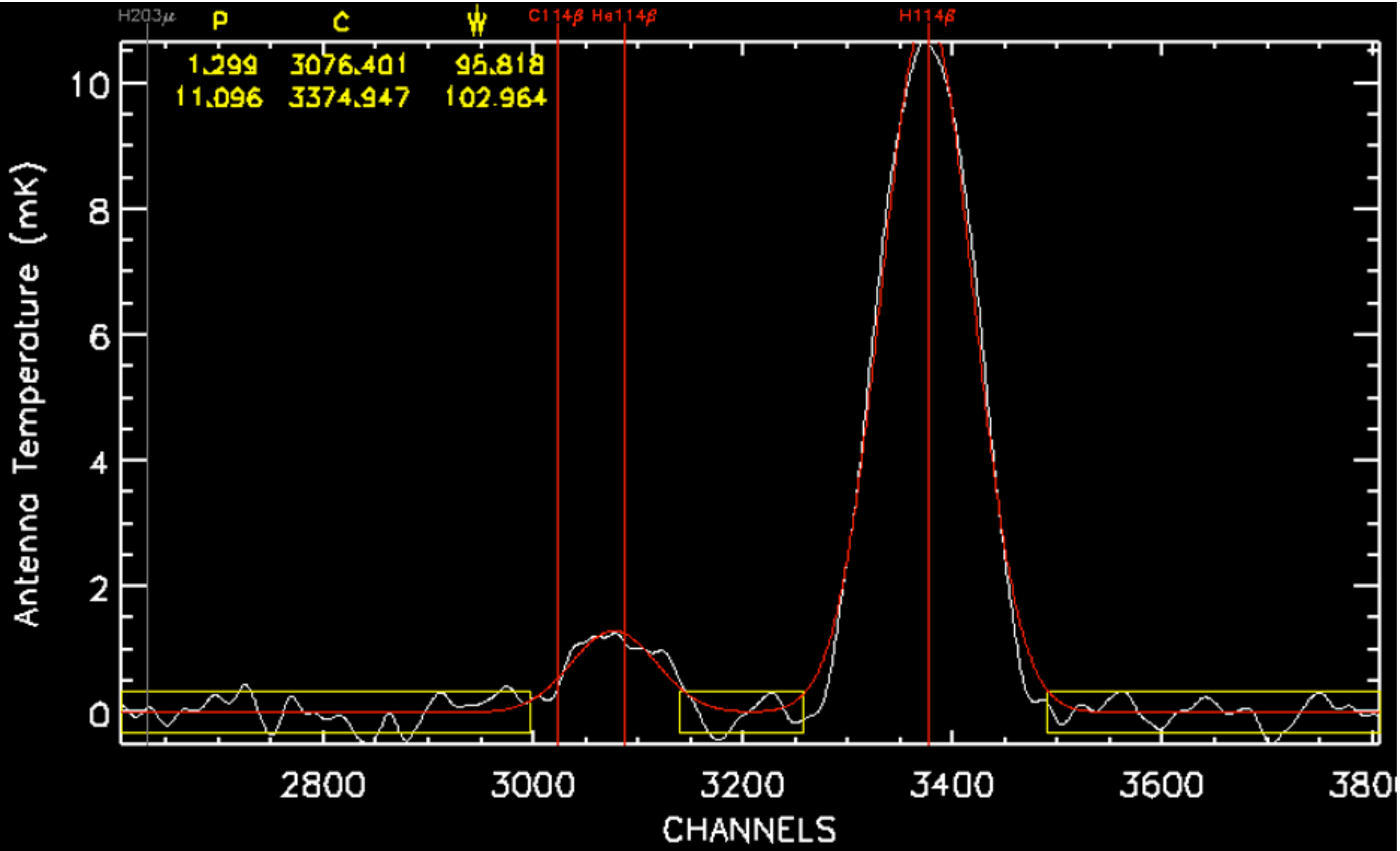
The off-axis design of the NRAO 100m Green Bank Telescope has a clean beam and standing waves are no longer a problem.



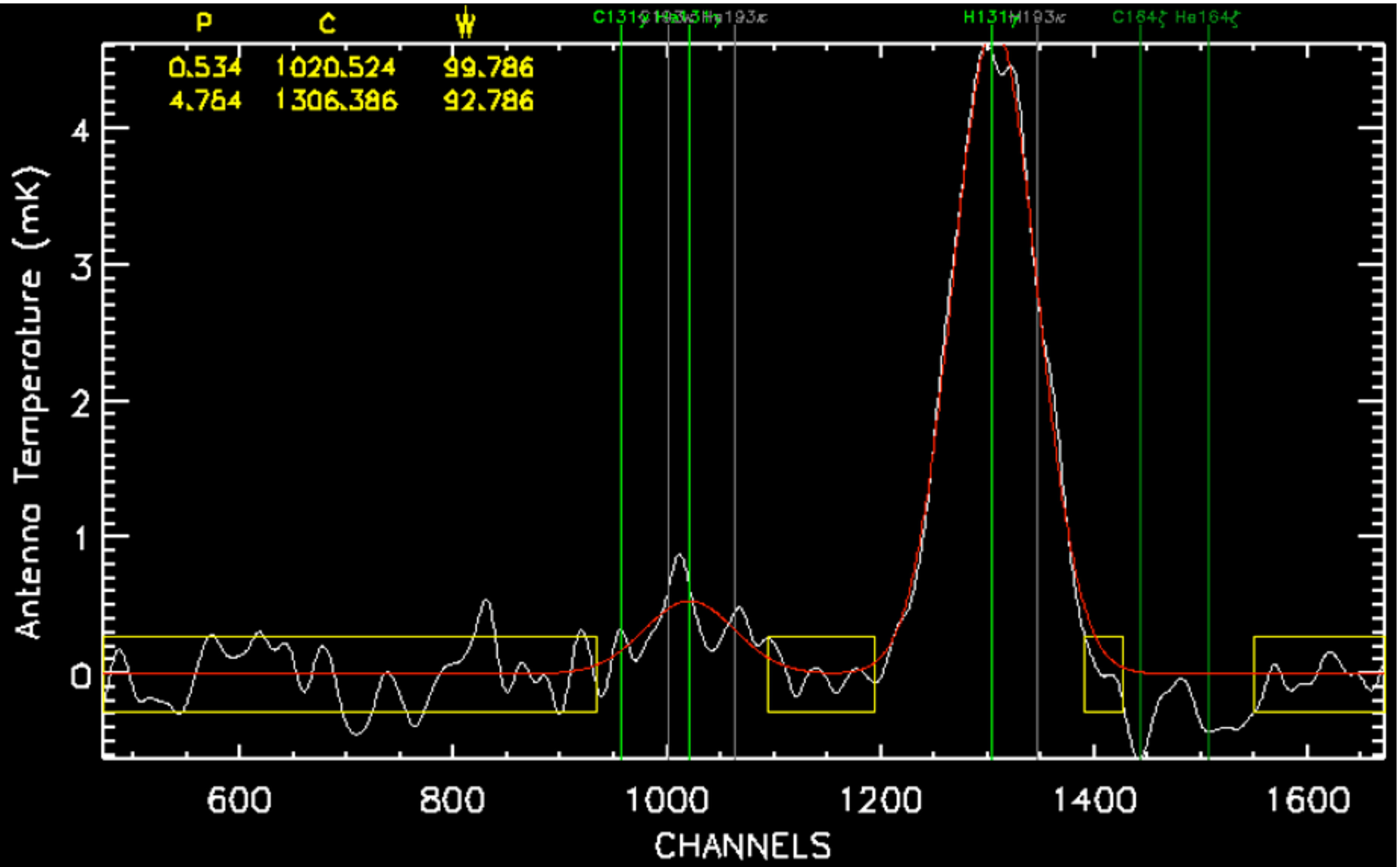
The GBT spectrometer does have instrumental "features," some like this suck out, obvious.

If we were studying 144δ we would be in deep doodoo, but the $^3He^+$ band seems clean.

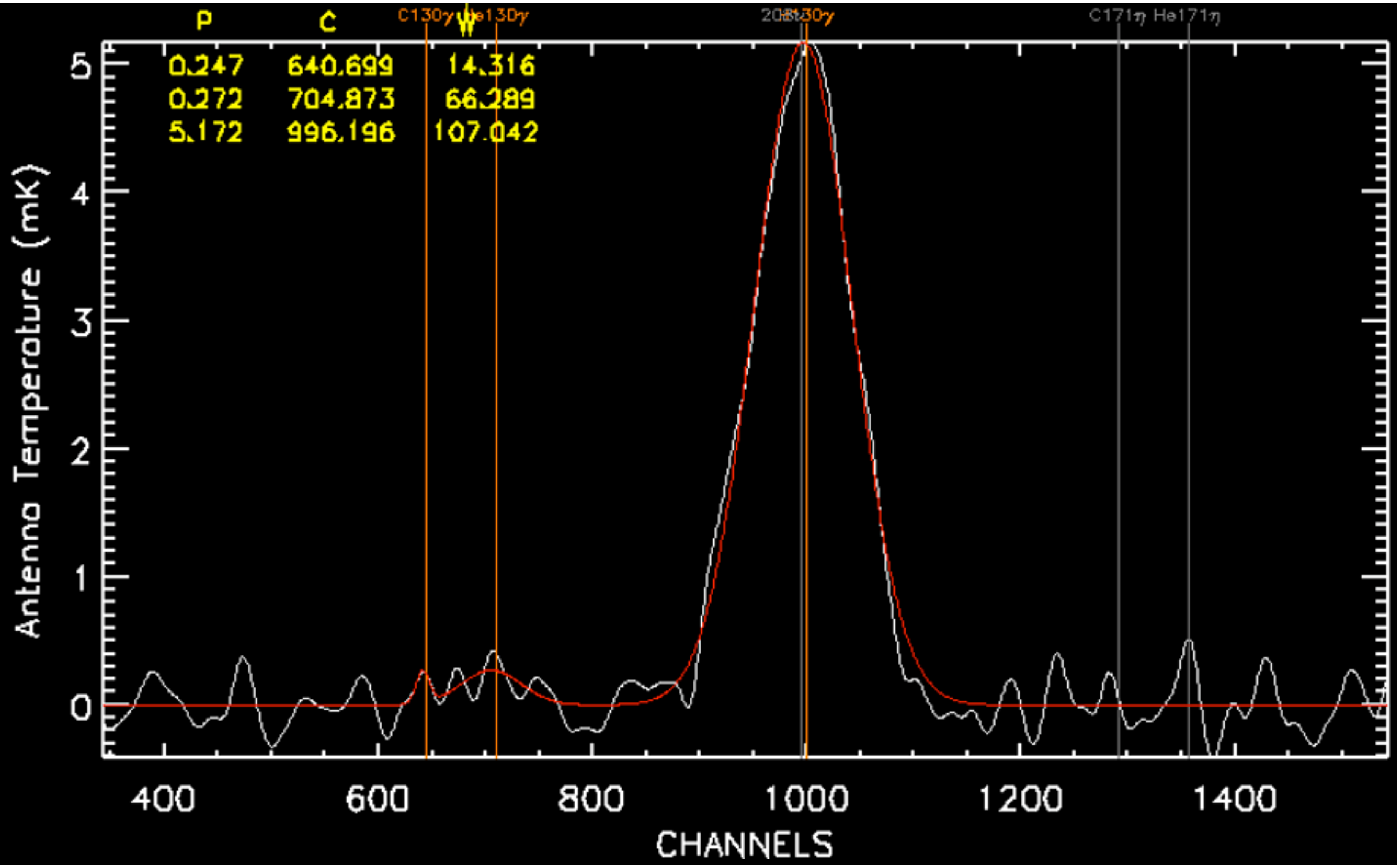
- Given the presence of obvious instrumental features we must be alert to the possible existence of less obvious features.
- Fortunately the GBT spectrometer allows for many quality checks using RRL.
- We observe in 8 separate 50 MHz frequency bands, each in two polarizations.
- We have set these to observe lines of order 1 (α) to order 16 (π)



114β ⇛ good 1 mK He line



131γ ⇛ good 0.5 mK He line



130γ do not recover 0.5 mK He line

There is additional information in the H RRL's, which should decrease in intensity smoothly as order increases.

Conclude:

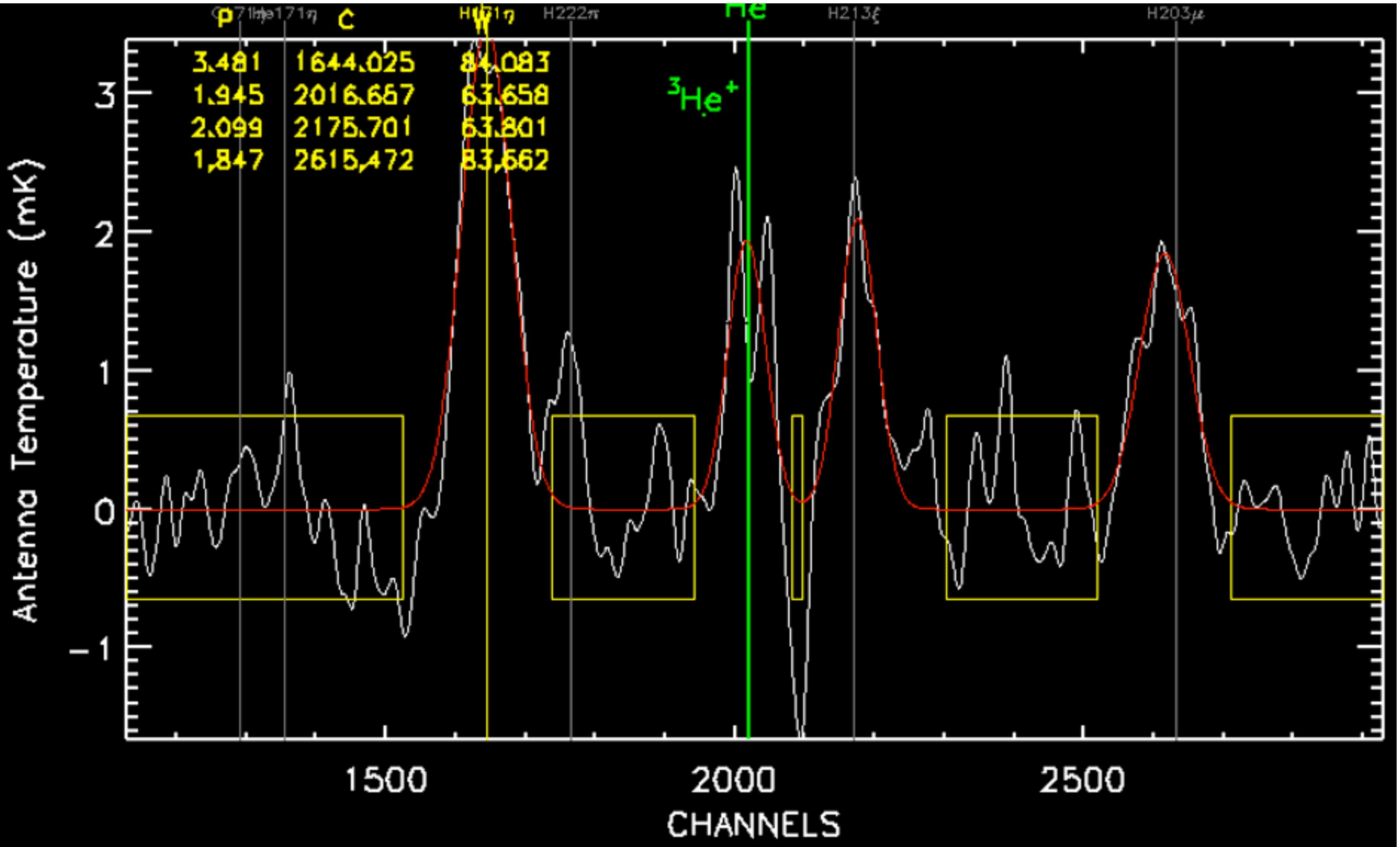
For NGC3242: 1 mK lines are robust

usually detect 0.5 mK lines, but occasionally miss

For S209, which we're still observing

2—3 mK lines robust

trouble starts < 1mK



S209: We detect $^3He^+$. Trouble is the H213ξ and 203μ lines are much too strong.

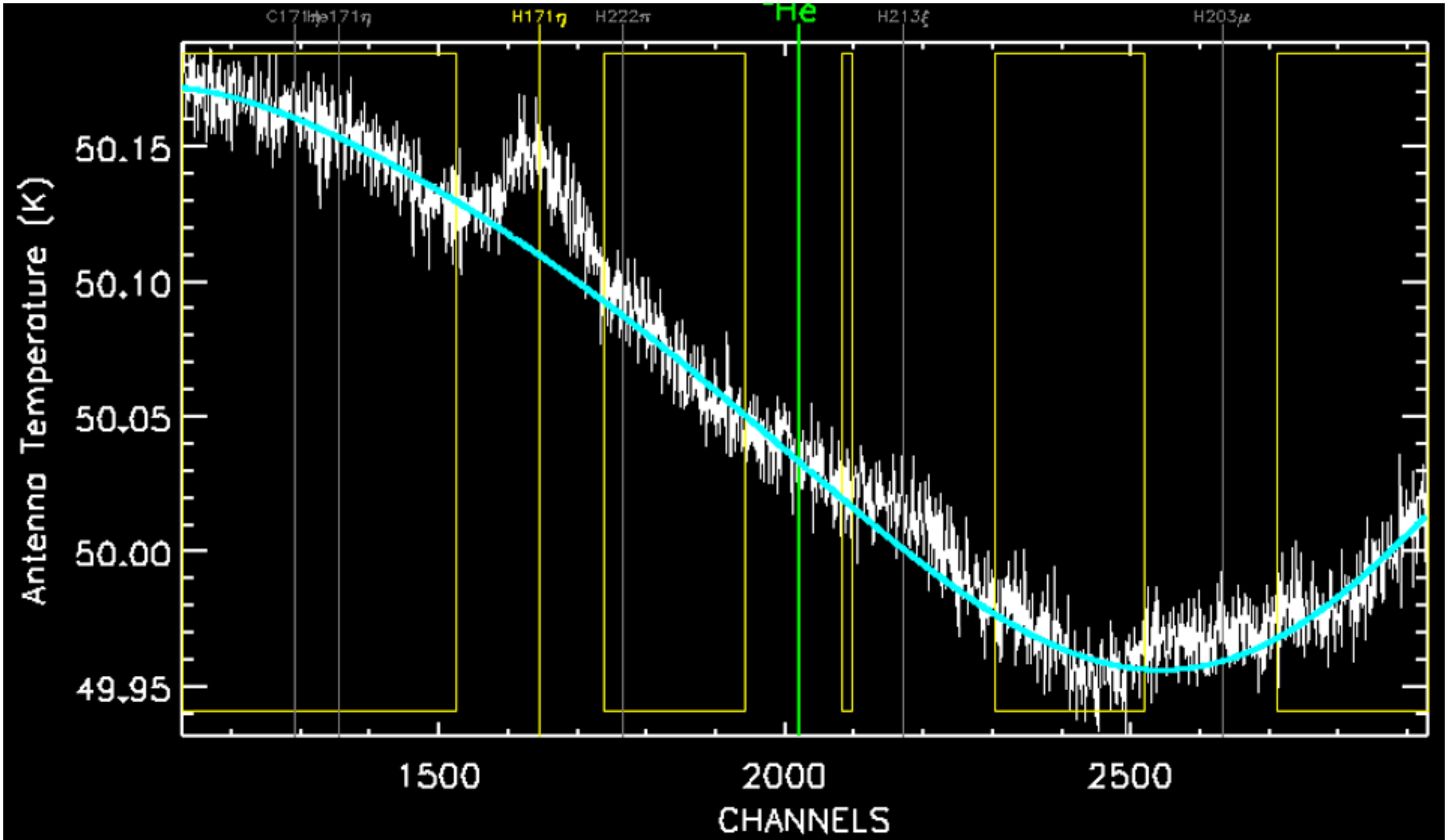
- For a low density HII region like S209 H213ξ should be about ¼ H171η or 0.8 mK
- This is what we got with the 140ft
- < 1 mK would be consistent our detections of

  179,180,181θ,

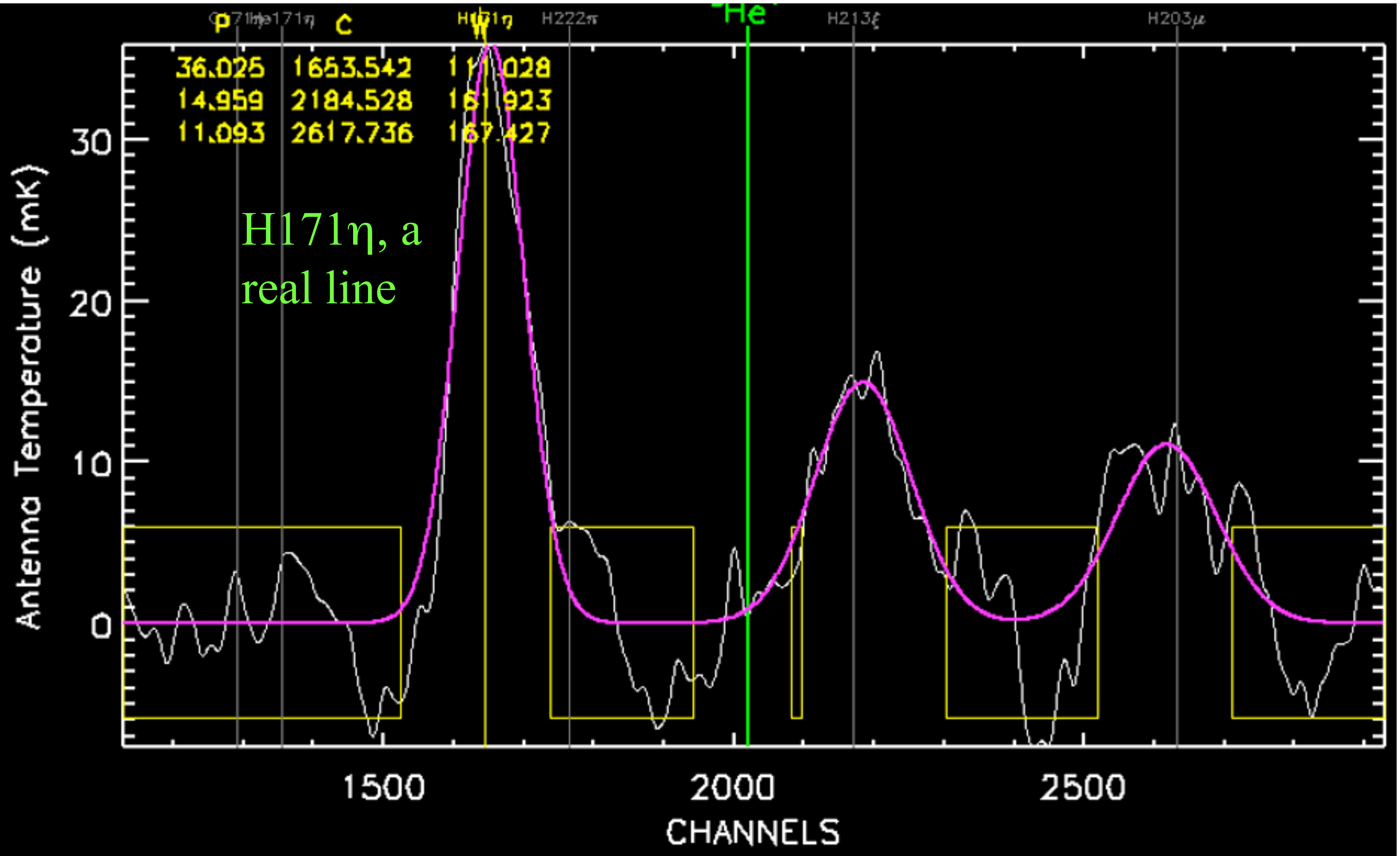
  187,188ι,

  197,199λ,

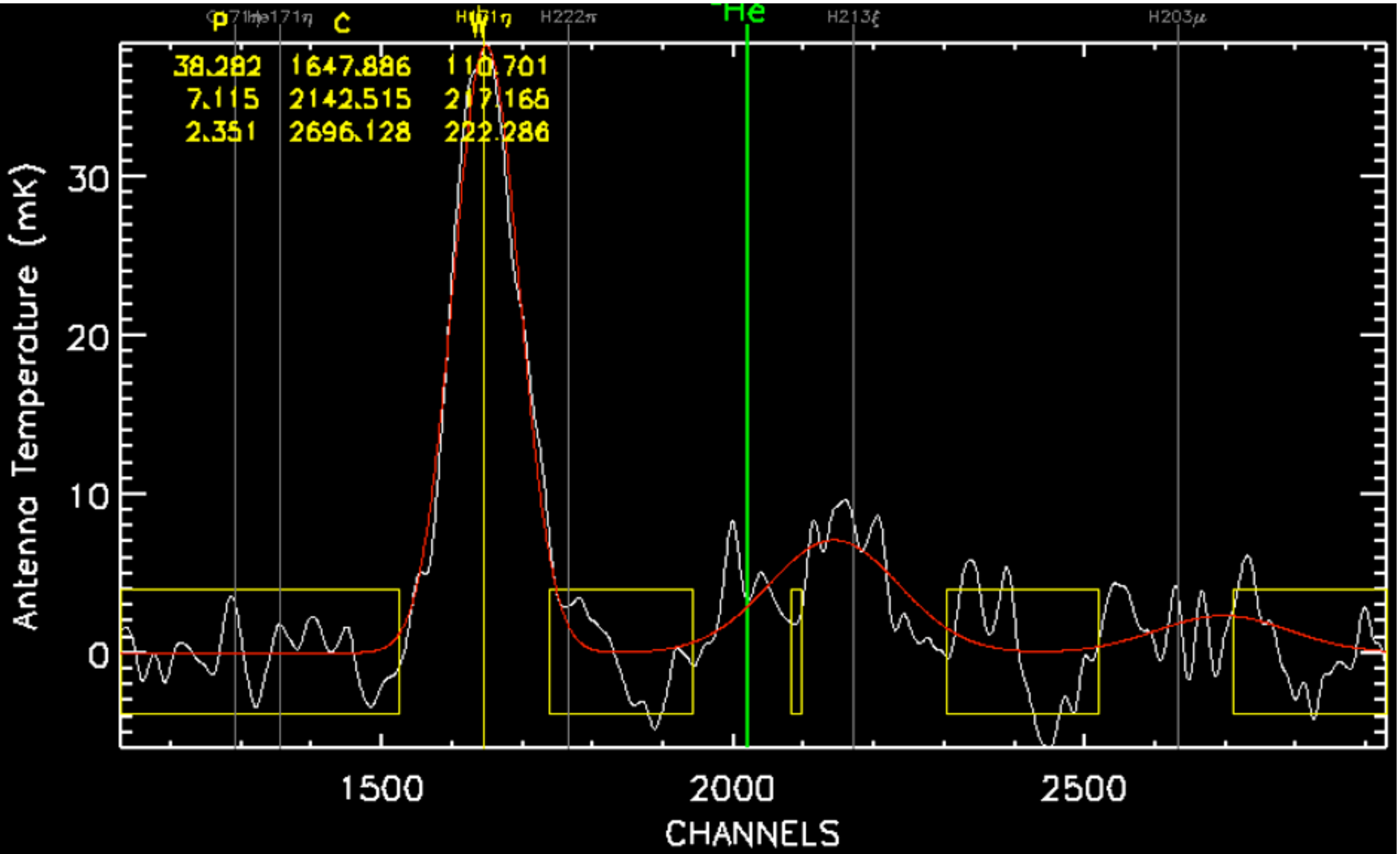
  213ν
- Conclude that H213ξ is part instrumental, part real



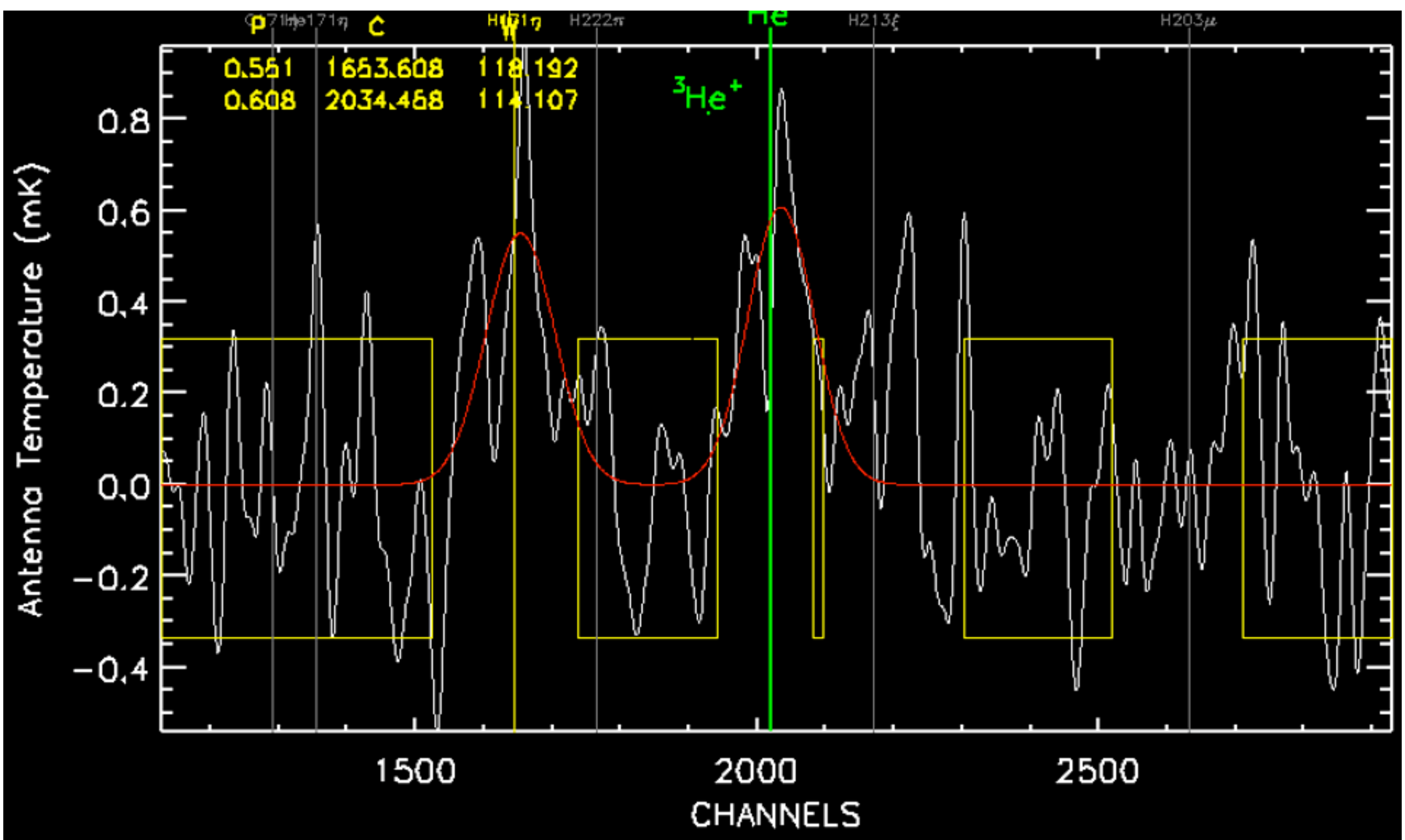
Since instrumental features usually scale up with source brightness, check the bright HII region W3 which we observe as a calibrator. 213ξ and 203μ features are there!



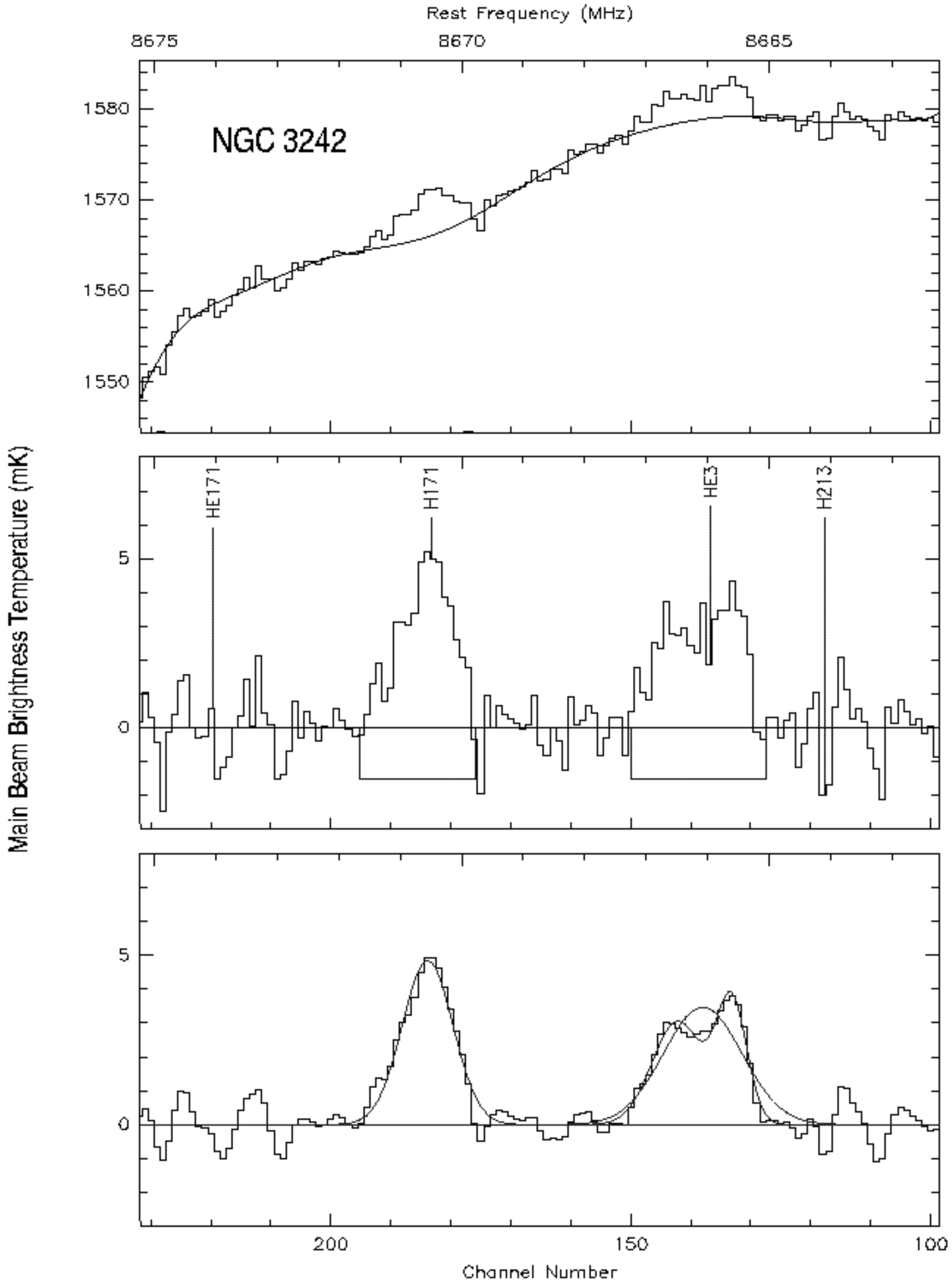
H213ξ and H203μ should be very weak in a dense HII region like W3. These features are almost certainly instrumental.



We send the $^3He^+$ signal through two independent paths to and inside the spectrometer. The 213ξ feature is weaker and the 203μ feature may be gone.



NGC3242 He3b path. $^3He^+$ line maybe there; probably some remnant 213ξ as well.



MPIfR observations of 3He in the PN NGC3242.

Results from 6 observing sessions combined

Lines are more than 4 times stronger than our GBT results.