Studying Small Scale (Filamentary) Structure in Molecular Clouds using the ARGUS Focal Plane Array on the GBT

Paul F. Goldsmith (JPL, California Institute of Technology)
on behalf of the ARGUS team

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Stanford University, Kavli Institute Calif. Inst. Technology, JPL, Univ. Maryland, Univ. Miami, Univ. de Concepción, Chile

This work was carried out in part at the Jet Propulsion Laboratory, which is operated by the California Institute of Technology for NASA. The *Argus* instrument is funded by NSF ATI grant 1207825 and preliminary technology development was supported by NSF ATI grant 0905855.

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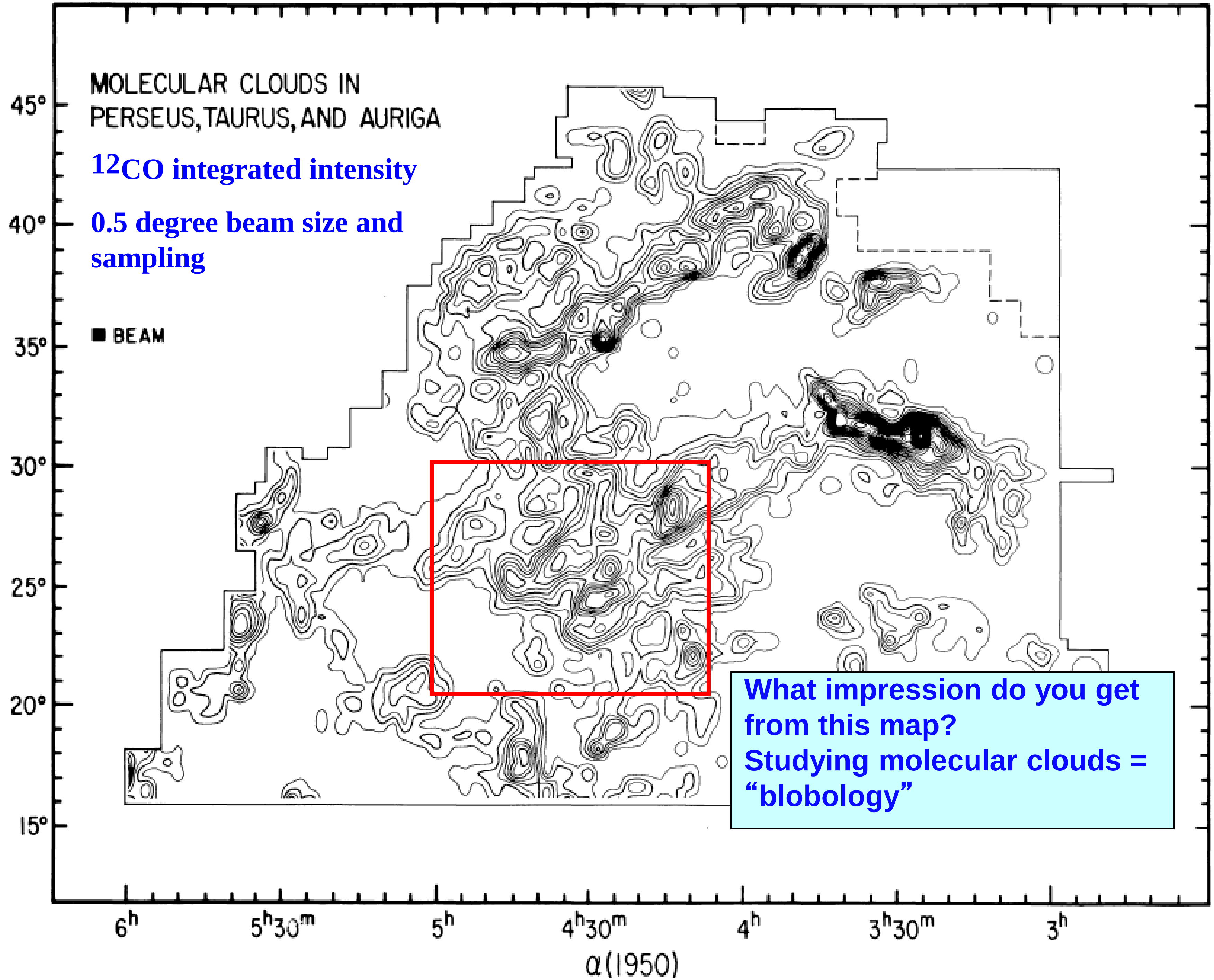
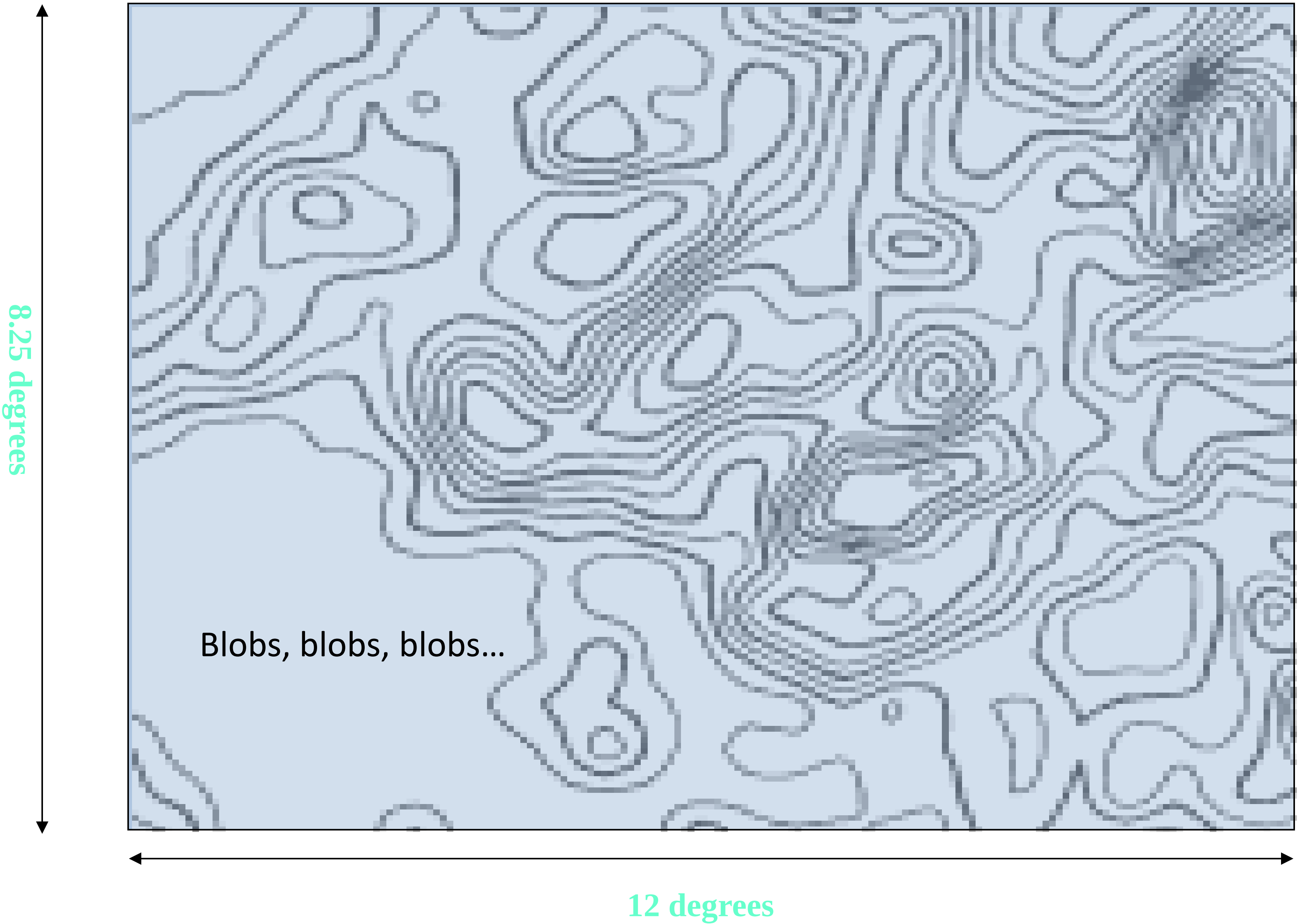
Responsibility for modifications and any errors that result is mine and mine alone!



MOLECULAR CLOUDS IN
PERSEUS, TAURUS, AND AURIGA
12CO integrated intensity
0.5 degree beam size and sampling
BEAM
45°
40°
35°
30°
25°
20°
15°
6h
5h30m
5h
4h30m
4h
3h30m
3h
α(1950)
What impression do you get from this map?
Studying molecular clouds = "blobology"


Blobs, blobs, blobs…
8.25 degrees
12 degrees


Spatial Dynamic Range
= Image Size / Nyquist
Interval ~ 1500 to 2000

Requirements for Studying Fine Structure in Molecular Emission

1. Adequate angular resolution

Dist. (pc)	0.1 pc size	5 pixels across = 0.02 pc	
140	7.1e-04 = 150"	1.4e-04 = 30"	(Taurus)
440	2.5e-04 = 47"	2.8e-05 = 6"	(Orion)
3000	3.3e-05 = 7"	6.7e-06= 1.4"	(DR21)

For GBT @ 110 GHz (2.7mm) Θ_{FWHM} = 6.7"

2. Sufficient mapping speed to cover area of interest

Quick Review of Mapping Speed

T_{sys}	system noise temperature
δT	required rms noise per pixel
B	RF bandwidth = f*(v/c)
Ω_{im}	solid angle of image
Ω_{mb}	antenna main beam solid angle
F	multiplicative time factor for reference, calibration, etc.

$$T_{map} = [\Omega_{im} / \Omega_{mb}]\ (F/B)(T_{sys}/\delta T)^2$$

For GBT, $\Omega_{mb} = 51''^2$ so for map of 10' x 10' region, $\Omega_{im} / \Omega_{mb} = 7073$
To get $\delta T = 0.1$ K in 0.1 km/s channel with $T_{sys} = 100$ K and F = 1

$$T_{map} = 1.9 \times 10^5 \text{ s} = 53 \text{ hr}$$

The only way to speed this up is with a FOCAL PLANE ARRAY
The time required is reduced by N, the number of pixels (for same T_{sys})
For N = 16, above image would take only 3.3 hr
This is the goal of ARGUS

Focal Plane Arrays – Some Considerations

- For large-field mapping, the spacing and arrangement of the beams on the sky is not critical.
- Observing each sky pixel with many (all) beams is highly advantageous in terms of reducing systematics and increasing immunity from deficient or dead pixel(s).
- It is critical not to sacrifice sensitivity either noise temperature or source-beam coupling efficiency or advantage of array can be dissipated.

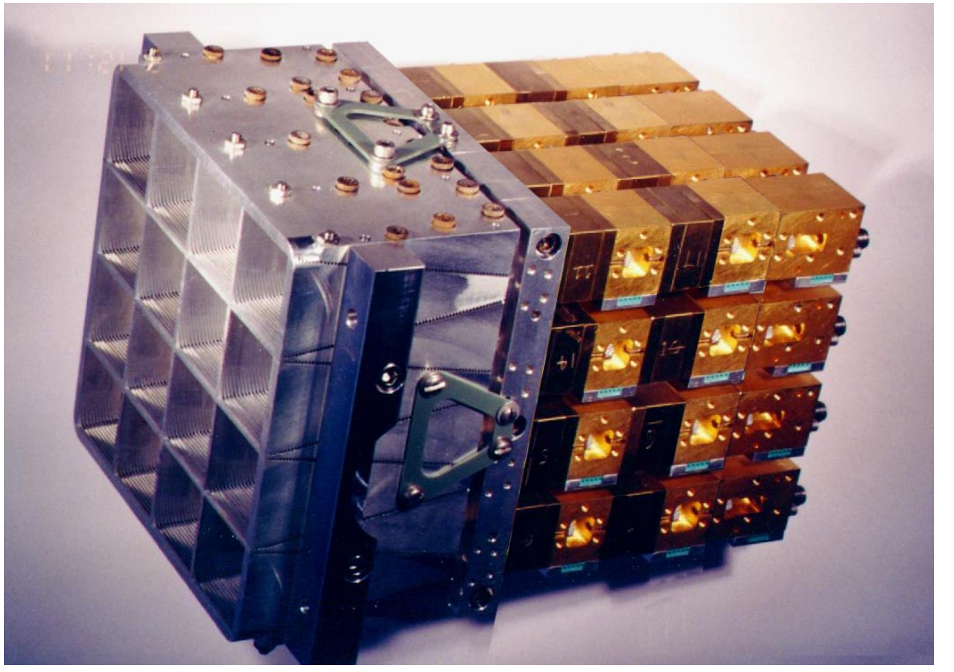
High quality feeds are appropriate even if loose beam packing results

- Successful MM-wavelength focal plane arrays include 3mm QUARRY (15 pix Schottky) and SEQUOIA (32 pix SIS) on FCRAO 14m telescope, 1.3mm HERA (9 pix x 2 pol SIS) on IRAM 30m, 3mm BEARS (25 pix SIS) on Nobeyama 45m

SEQUOIA 3mm MMIC Array Module

First mm-λ array using MMICs

Erickson, Grosslein, Erickson, & Weinreb 1999



Other mm-λ arrays under construction:

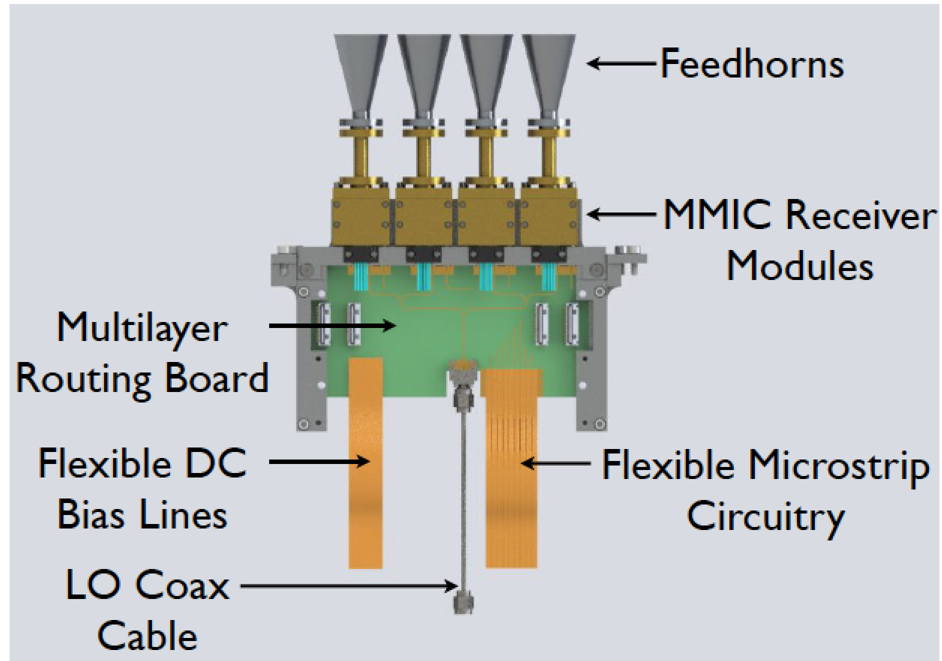
7x7 pixel **SHERA** array for IRAM 30m telescope
17 element 33-50 GHz array for Sardinia Radio Telescope
4 element x 2 pol. x 2SB **FOREST** array for Nobeyama Radio Telescope

Focal plane arrays have operated at **longer wavelengths** (e.g. 21 cm, K-band GBT)

Heterodyne focal plane arrays for **submillimeter wavelengths** are also being actively developed: 64 pixel 345 GHz Supercam array for SMT and APEX; 7pixel x 2 pol. 1900 GHz array for SOFIA (review by Groppi & Kawamura IEEE Trans. THz Science Tech. 2011)

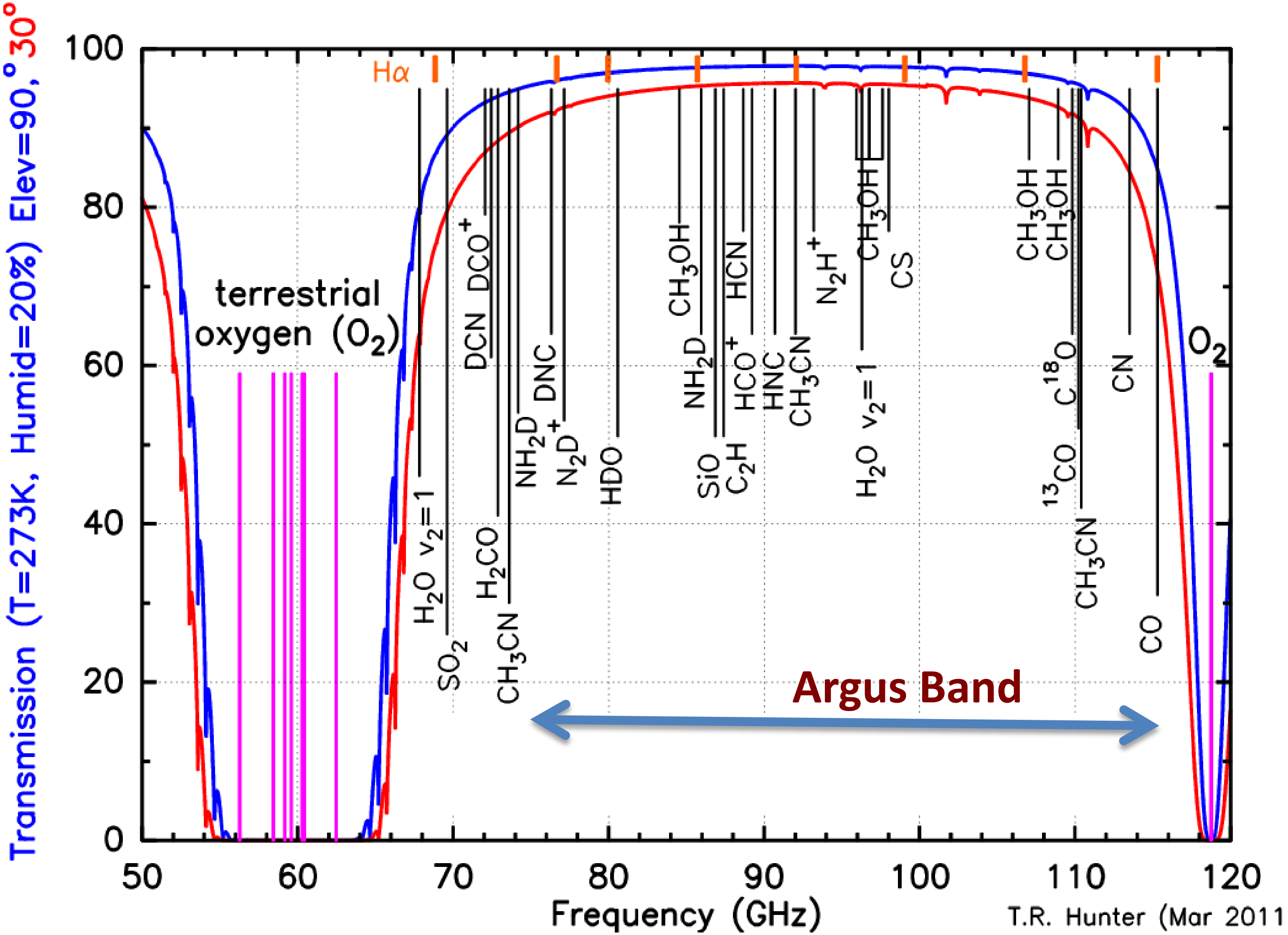
ARGUS Design

Sieth et al. Proc. SPIE 2014
See also poster this conference

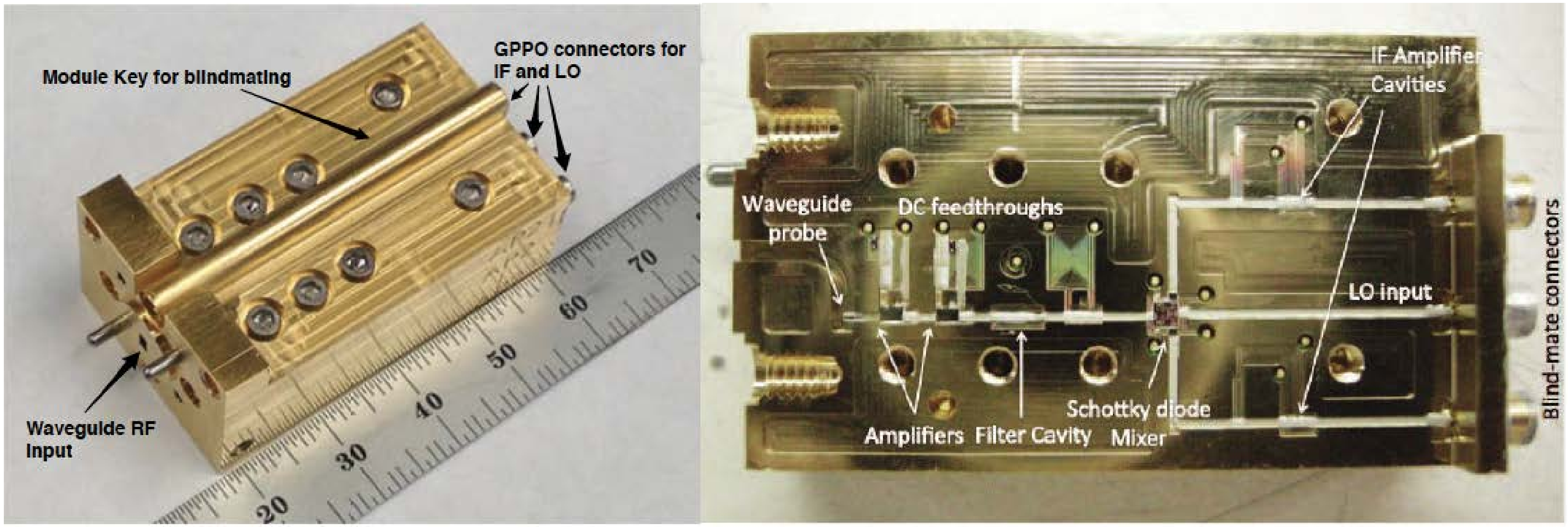


- **16 pixels** covering **75-115 GHz (**IF bandwidth is limited to 1.25 GHz to mate with the VEGAS spectrometer input bandwidth)
- Smooth-walled feeds performance comparable to scalar feed horns but at far lower cost

Frequency Coverage

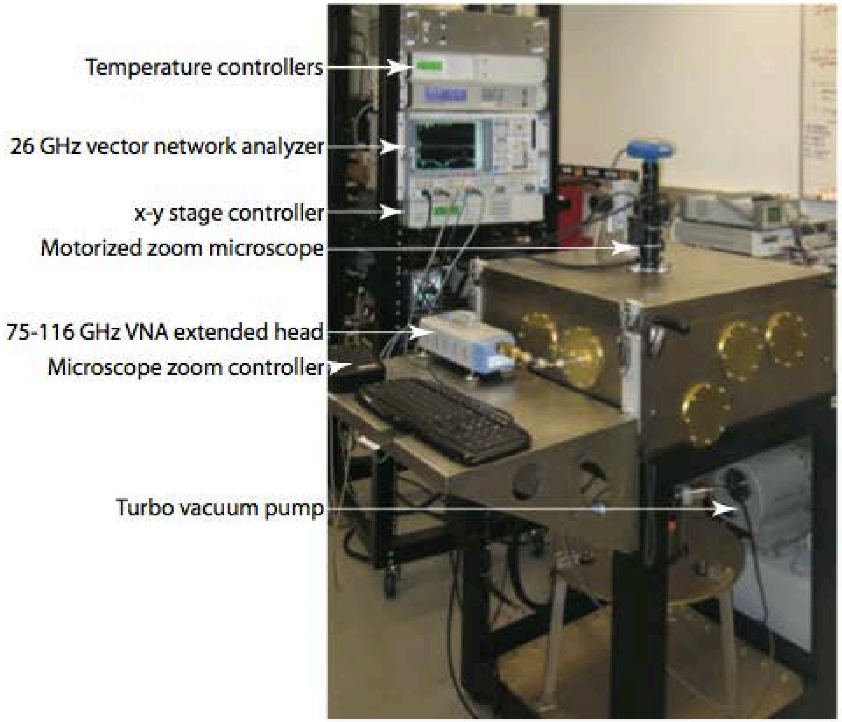


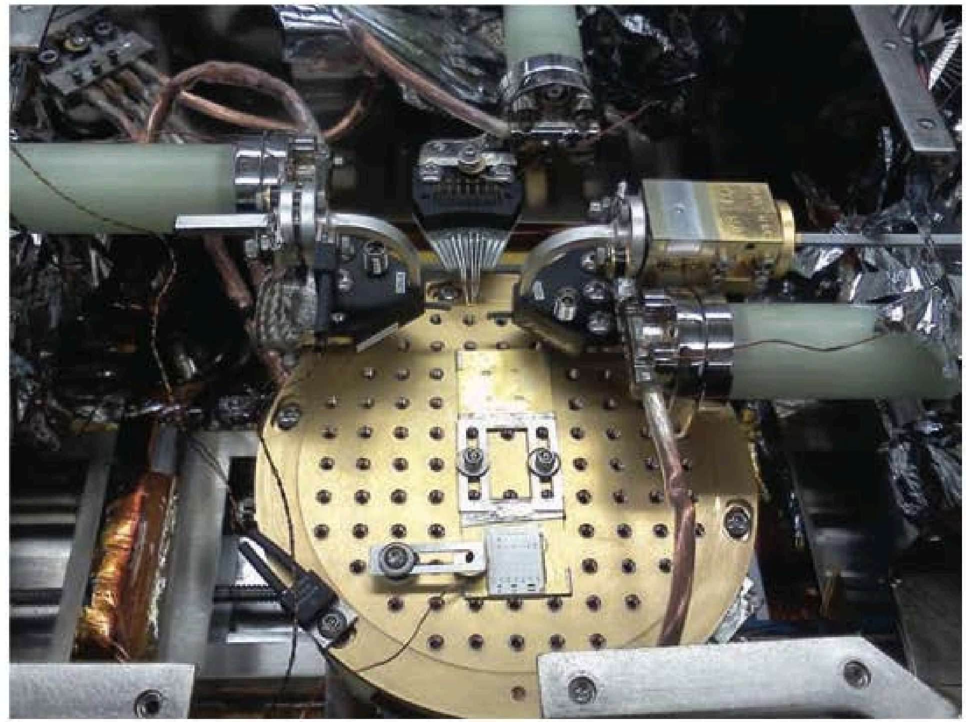
ARGUS MMIC Module



- LNA chips use 35 nm gate length InP MMICs
  - First stage MMIC selected for minimum noise
  - second to maximize bandwidth
- MMIC amplifier modules provide 25-30 dB gain. Followed by IQ downconverter using subharmonic mixers
- Modules have IF and LO with blind-mate connectors from rear
- An individual pixel module can be removed along with its feedhorn if needed

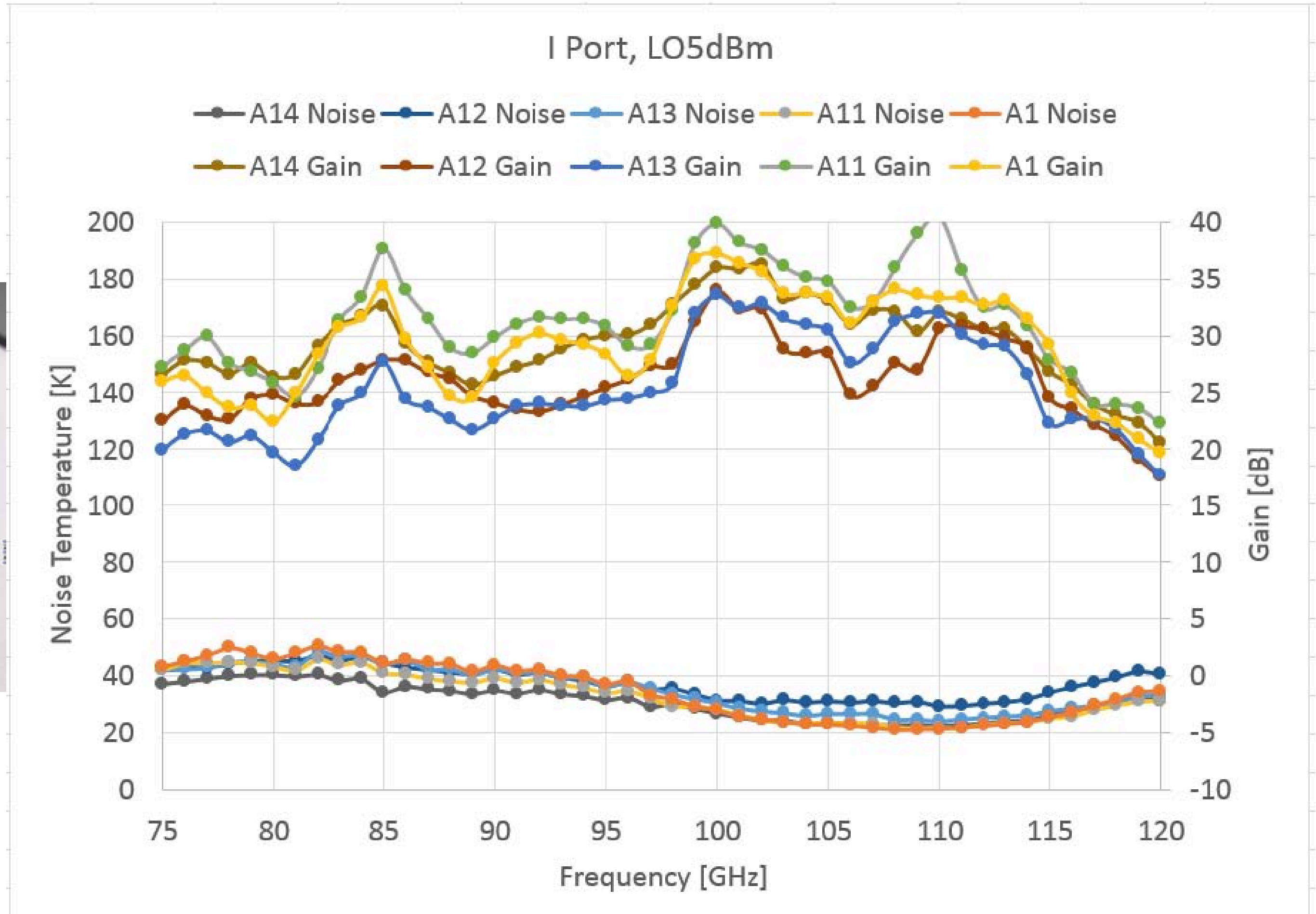
Caltech facility to characterize large numbers of chips has been a game-changer





Caltech W-band cryogenic probe station used to screen chips for *Argus* so that the best devices can be incorporated into the modules as the first stage amplifiers

Measurements of Performance of ARGUS Modules

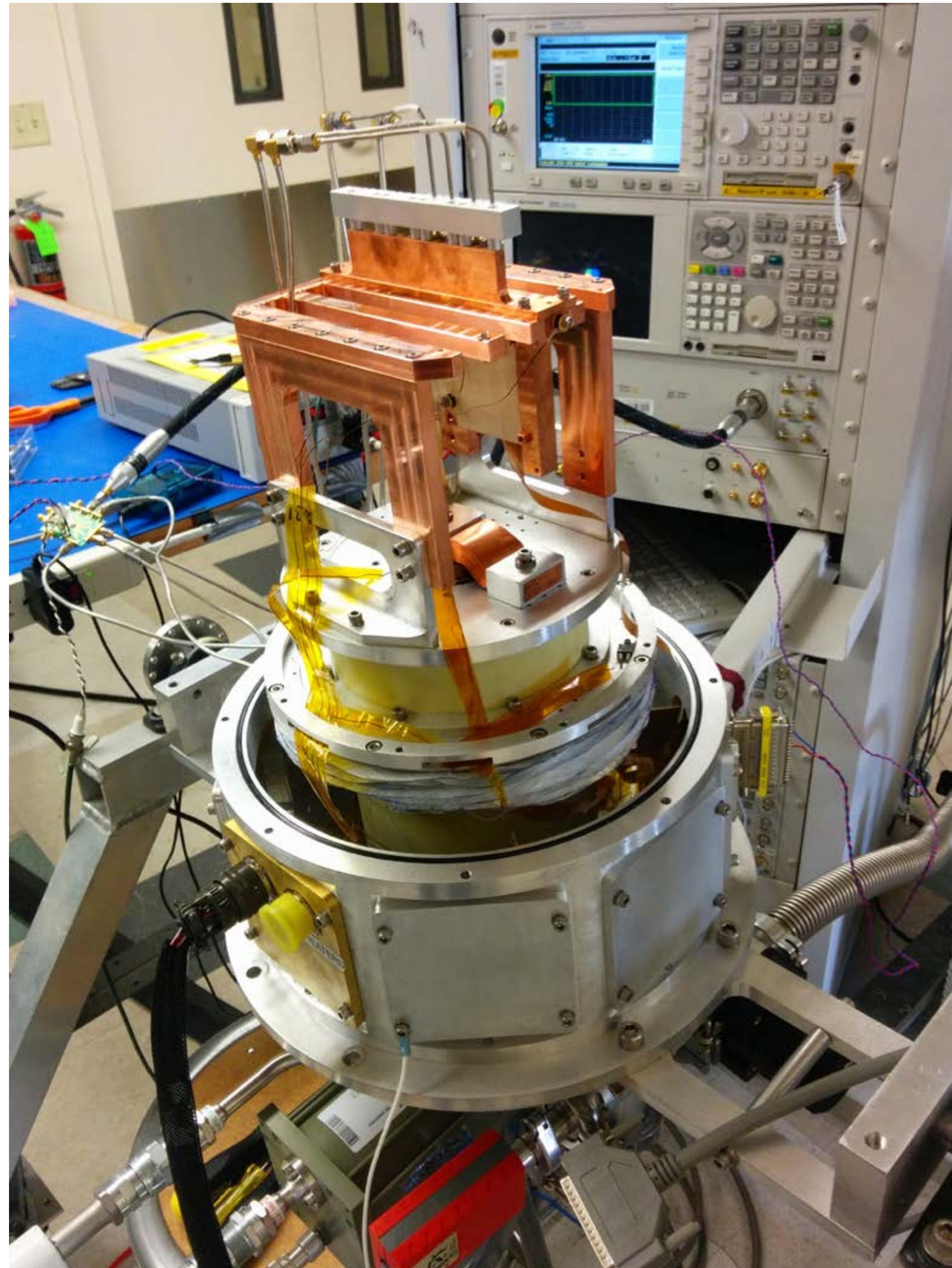


ARGUS Receiver

- UHMWPE (ultra high molecular weight polyethylene) dewar window; machined holes (~12000) form broadband artificial dielectric matching layer
- **No** field derotator – this component is complex, unreliable, and can harm data quality compared to doing OTF mapping with every pixel on sky being observed multiple times by many receiver pixels

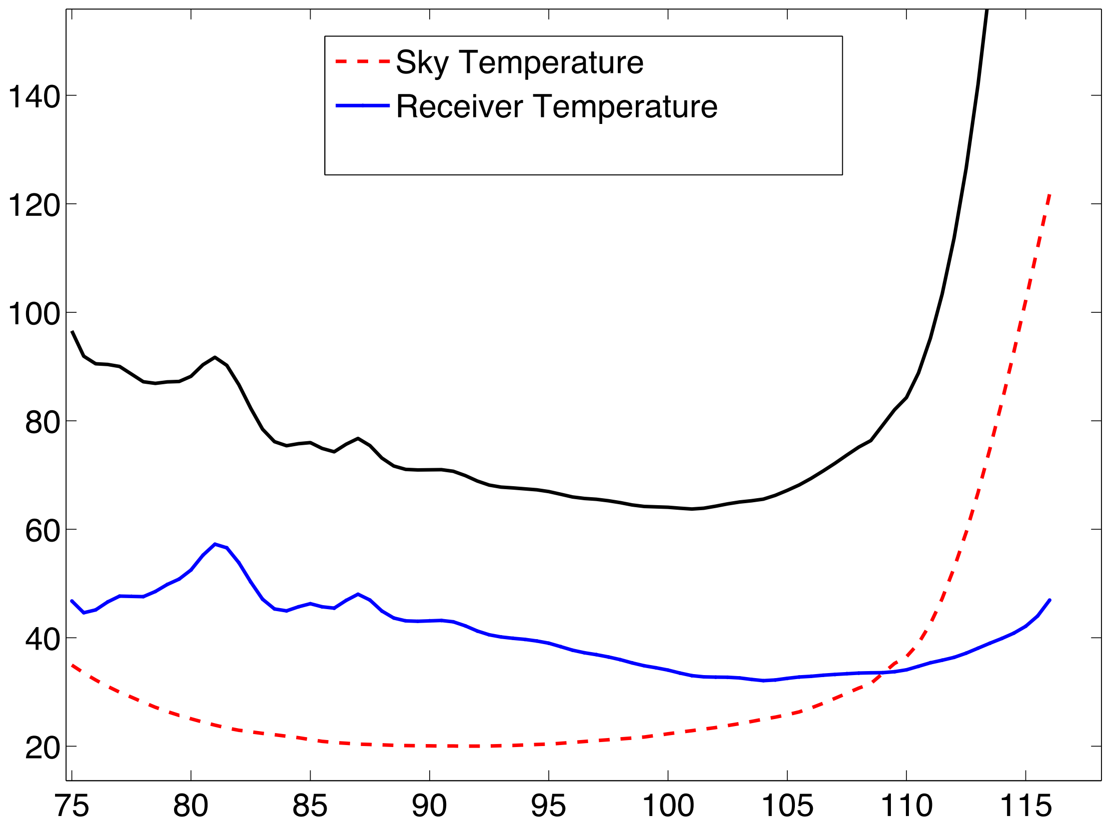
Status of Argus

- Assembly underway at Stanford
- Delivery to GBT late Nov/early Dec
- First light expected Feb 2015



Projected Performance

- Calibration vane being built -- standard mm-style calibration yielding T_{sys} referred to above the atmosphere
- Beam efficiency not well known at this time
- Aperture efficiency ≅ 0.25 and beam efficiency should be greater



Using ARGUS on the GBT

- Vegas operation permits 8 separate windows anywhere within 1.25 GHz range
  - Observe ^{13}CO and $C^{18}O$ simultaneously
  - Or HCN and C_2H
  - Or ^{13}CS and N_2H^+
  - Maximum coverage per window is then 23.44 MHz or 60 km/s, with resolution of 0.15 km/s or better
- Overhead factor F ≅ 1.5 for OTF mapping (per D. Frayer)
- Allen time needed to define detailed OTF strategy – likely short integrations and multiple repeats

Mode	Spectral Windows per Spectrometer	Bandwidth per Spectrometer (MHz)	Number of Channels per Spectrometer	Approximate Spectral Resolution (kHz)
1	1	1500[a]	1024	1465
2	1	1500[a]	16384	92
3	1	1080[b]	16384	66
4	1	187.5	32768	5.7
5	1	187.5	65536	2.9
6	1	187.5	131072	1.4
7	1	100	32768	3.1
8	1	100	65536	1.5
9	1	100	131072	0.8
10	1	23.44	32768	0.7
11	1	23.44	65536	0.4
12	1	23.44	131072	0.2
13	1	23.44	262144	0.1
14	1	23.44	524288	0.05
15	1	11.72	32768	0.4
16	1	11.72	65536	0.2
17	1	11.72	131072	0.1
18	1	11.72	262144	0.05
19	1	11.72	524288	0.02
20	8[c]	23.44	4096	5.7
21	8[c]	23.44	8192	2.9
22	8[c]	23.44	16384	1.4
23	8[c]	23.44	32768	0.7
24	8[c]	23.44	65536	0.4
25	8[c]	16.875	4096	4.1
26	8[c]	16.875	8192	2.0
27	8[c]	16.875	16384	1.0
28	8[c]	16.875	32768	0.5
29	8[c]	16.875	65536	0.26

[a] The useable bandwidth for this mode is 1250 MHz.
[b] The useable bandwidth for this mode is 850 MHz.
[c] For modes 20-24, the spectral windows must be placed within 1500 MHz with a useable frequency range of 150 to 1400 MHz. For modes 25-29, the spectral windows must be placed within 1000 MHz with a useable frequency range of 150 to 950 MHz.

1 kHz = 0.027 km/s @ ^{13}CO

ARGUS Upgrades

Ongoing - Expand instantaneous bandwidth of 2 pixels

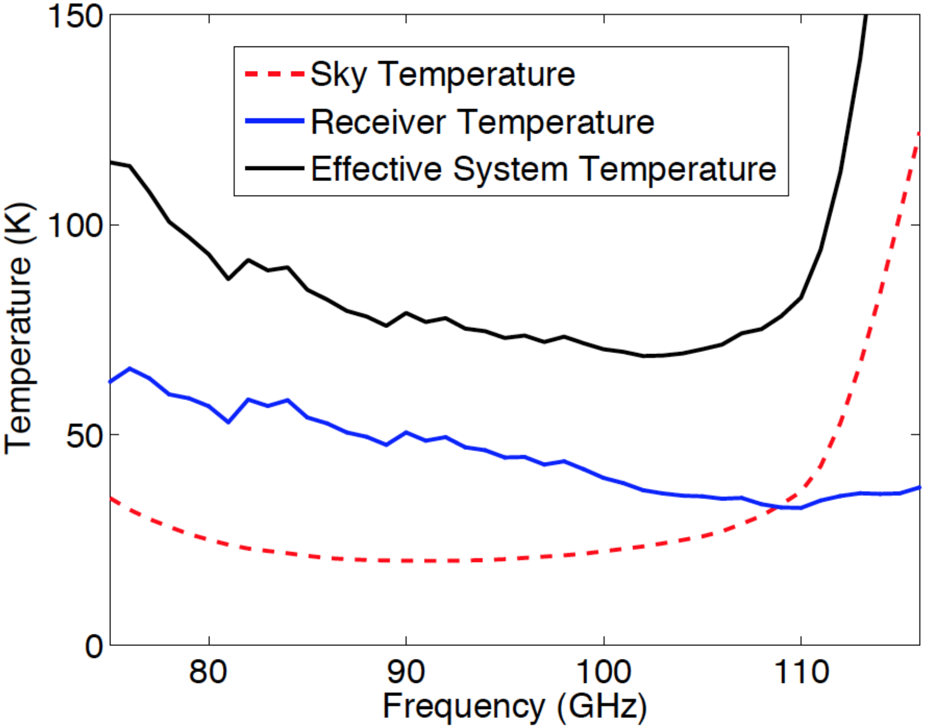
- Currently limited by IF processing and transmission
- Modify 2 pixels so that 10 GHz bandwidth is brought to VEGAS spectrometer which can analyze these at 92 kHz (0.24 km/s) resolution (VEGAS Mode 2)
- Useful for extragalactic absorption spectroscopy or line survey of pointlike source (e.g. galaxy)

Future - Expand array format

- Add more pixels, possibly second polarization

Conclusions

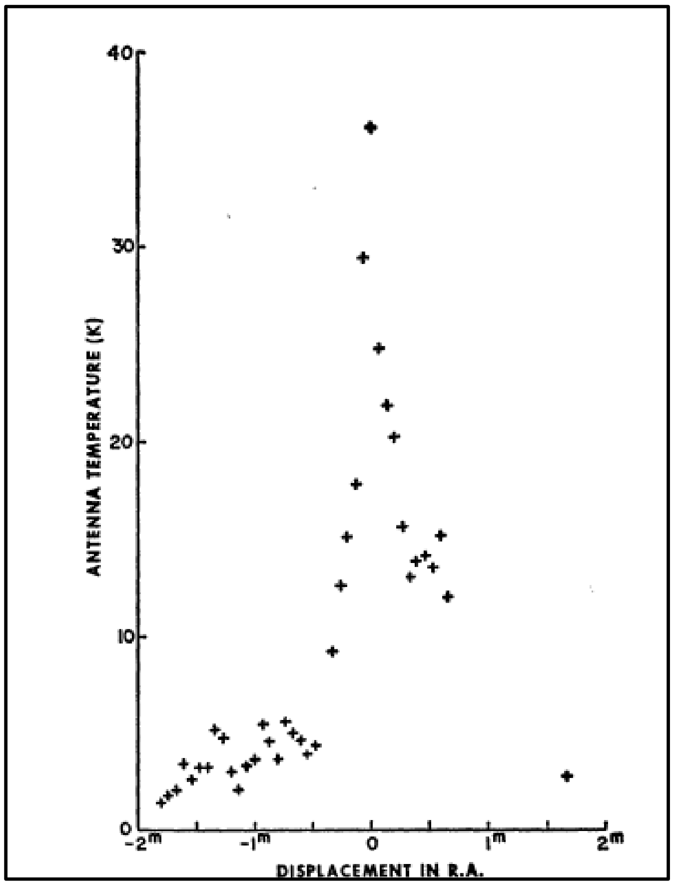
- The **ARGUS** 16 element focal plane array covering 85 – 115 GHz will be available on the GBT; test observations starting in February 2015
- State of the art noise temperature & broad bandwidth allow sensitive multi-line spectral imaging
- Nominal mapping speed for **high-sensitivity high-resolution** imaging (F = 1.5) is 180 hr/sq degree
- Large-scale imaging projects will require significant commitment of time but will yield important information about filamentary and other molecular cloud structure
- ARGUS **is expandable** and even more capable focal plane array receivers can be envisioned

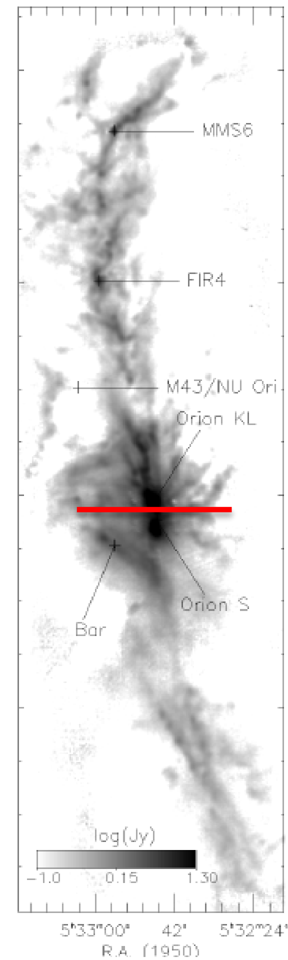


Latest Noise Data and Estimated T_{sys}

Goldsmith slides not used

The Original Detection of CO in ISM (Wilson, Penzias, & Penzias 1970) Included Cut Through a Filament





Johnstone & Bally 1999

Filaments Identified From Their Optical Extinction

“A catalog of dark globular filaments”

Schneider & Elmegreen 1979

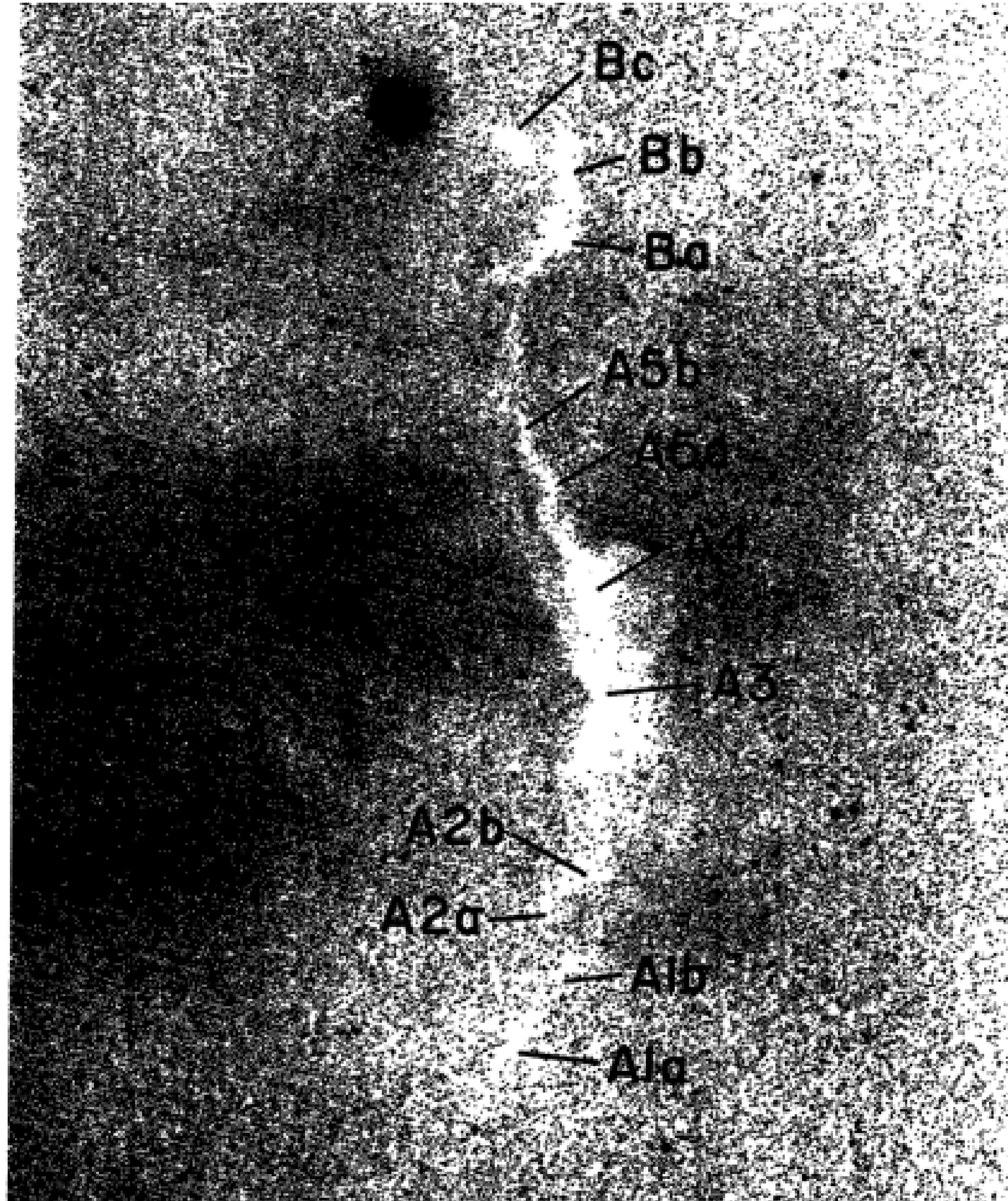
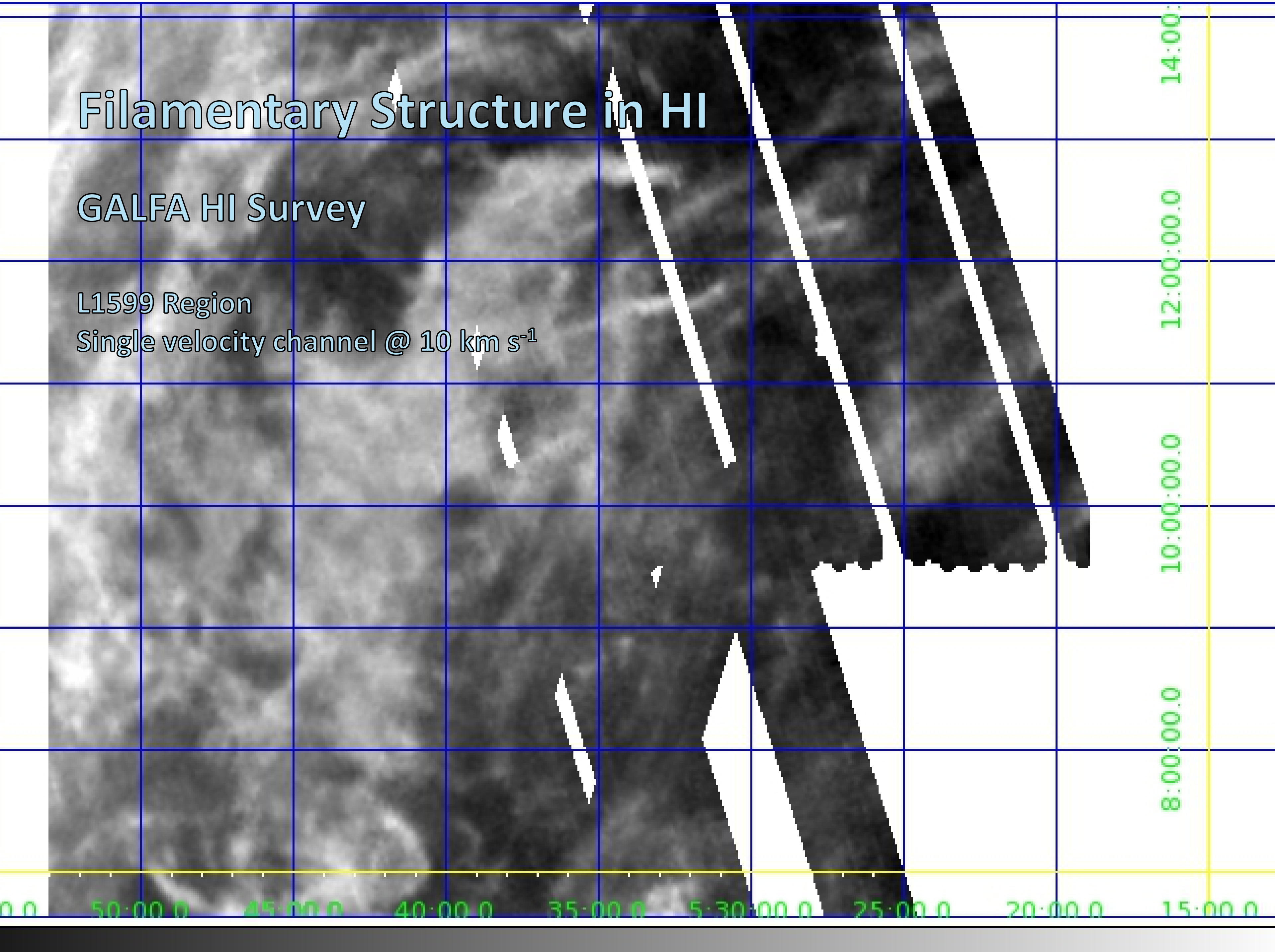


FIG. 3.—GF 3; (16^h48^m, $-12°$)

Filamentary Structure in HI

GALFA HI Survey

L1599 Region
Single velocity channel @ 10 km s^{-1}



Need to Consider “Anti-Filaments” (a.k.a. troughs) in HI When Looking for Association with Molecular Clouds