The Formation of Molecular Clouds in our Galaxy

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University of New South Wales

John Storey, Nick Tothill (UNSW)

David Hollenbach, Craig Kulesa, Chris Walker, Chris Martin (USA)

Jüergen Stutzki, Robert Simon (Germany) + many more….

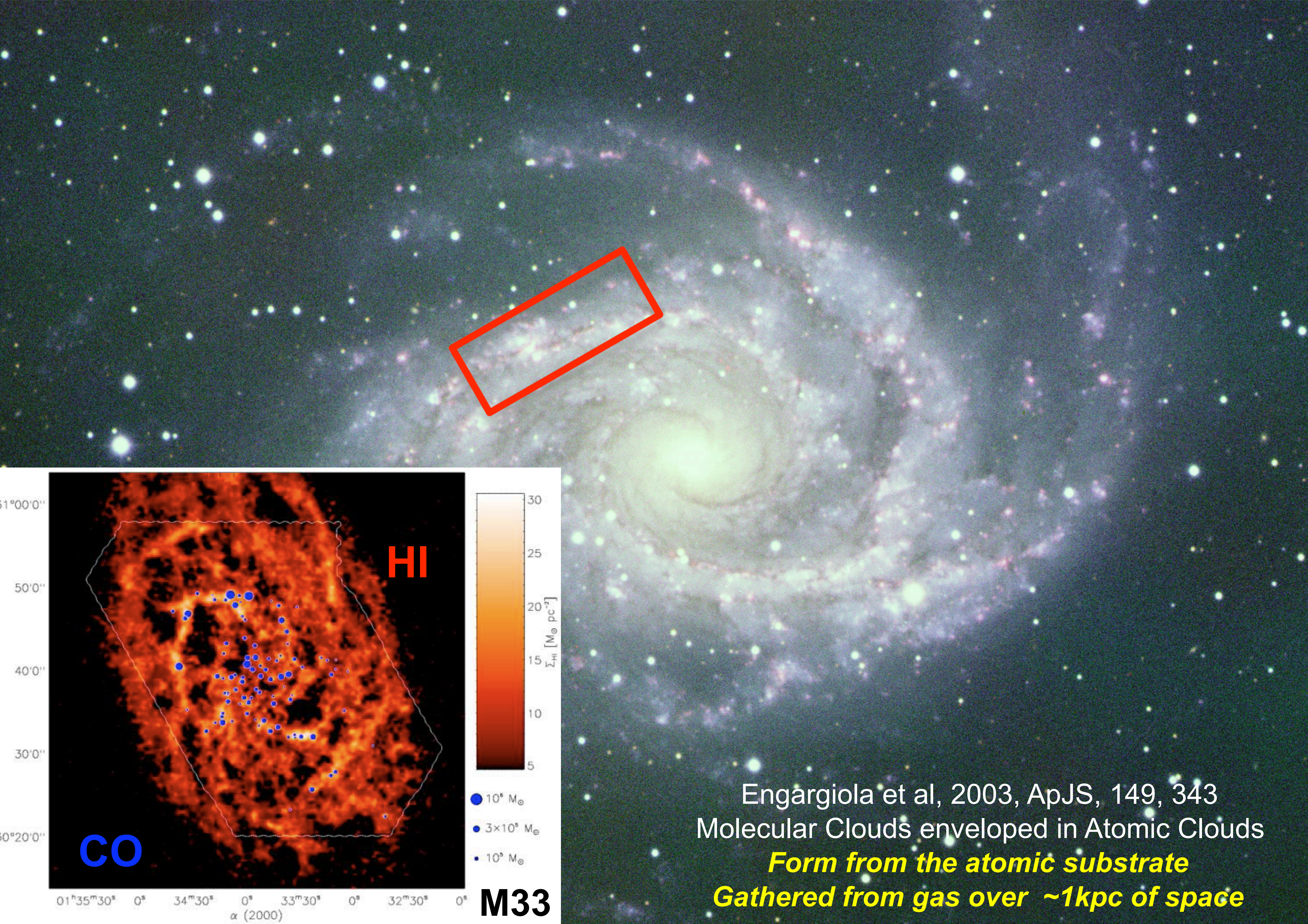
STO, Antarctica
0.8m Terahertz

NANTEN2, Chile
4m Sub-millimetre

Mopra, Australia
22m Millimetre

Outline

* The formation of molecular clouds?
  * "Dark" H_2
  * Spectral diagnostics of the molecular medium
* Three Telescopes
  * Stratospheric Telescope Observatory (STO) - Antarctica (THz)
  * NANTEN2 - Chile (sub-mm)
  * Mopra - Australia (mm)
    * Long-wavelength mm astronomy: *ATCA* + *Mopra* + *Parkes*
* Mapping the fourth quadrant of the Galaxy
  * "Fast-mapping"



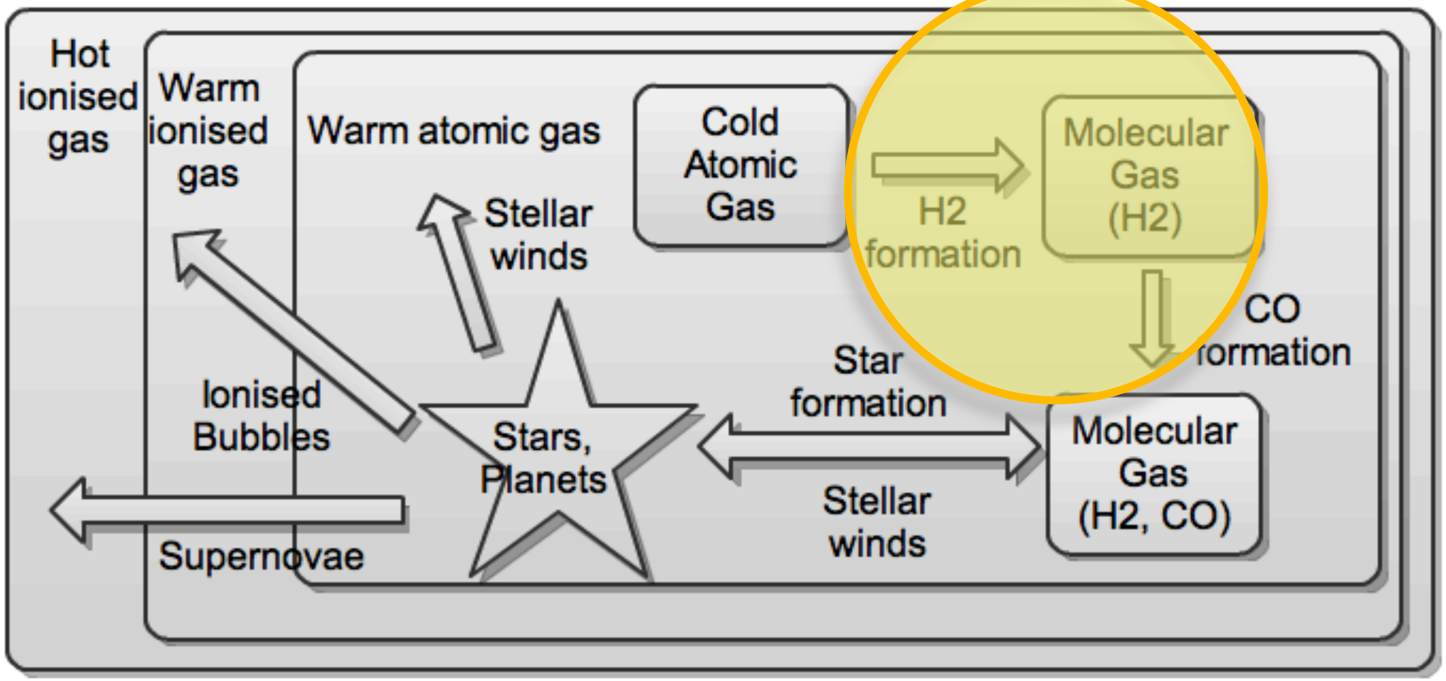
Engargiola et al, 2003, ApJS, 149, 343

Molecular Clouds enveloped in Atomic Clouds

Form from the atomic substrate

Gathered from gas over ~1kpc of space

The Star-Gas Cycle



Stars form once molecular clouds form.
The formation of molecular clouds is its rate-determining step.

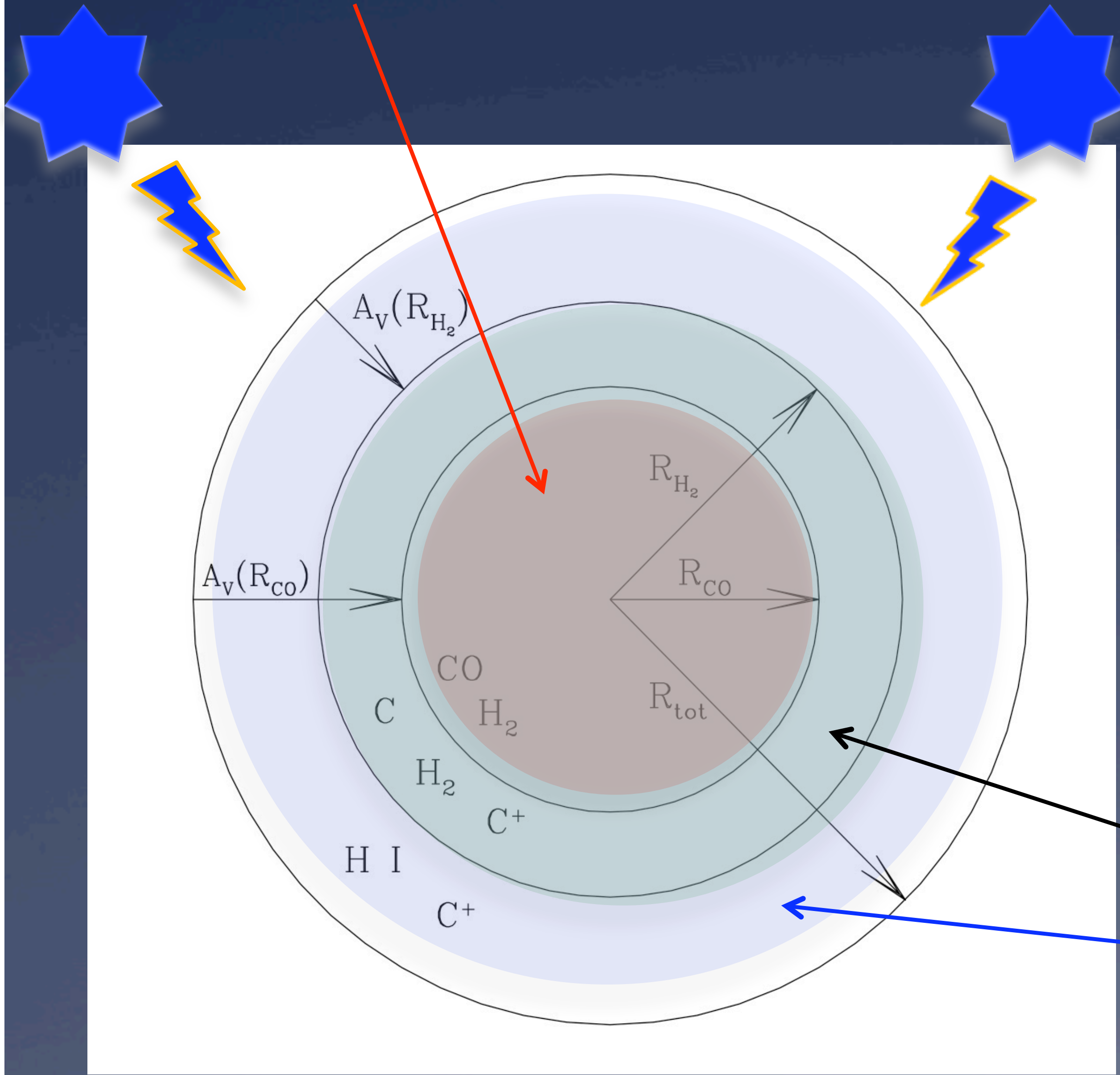
Gathering Atomic Gas in Molecular Clouds?

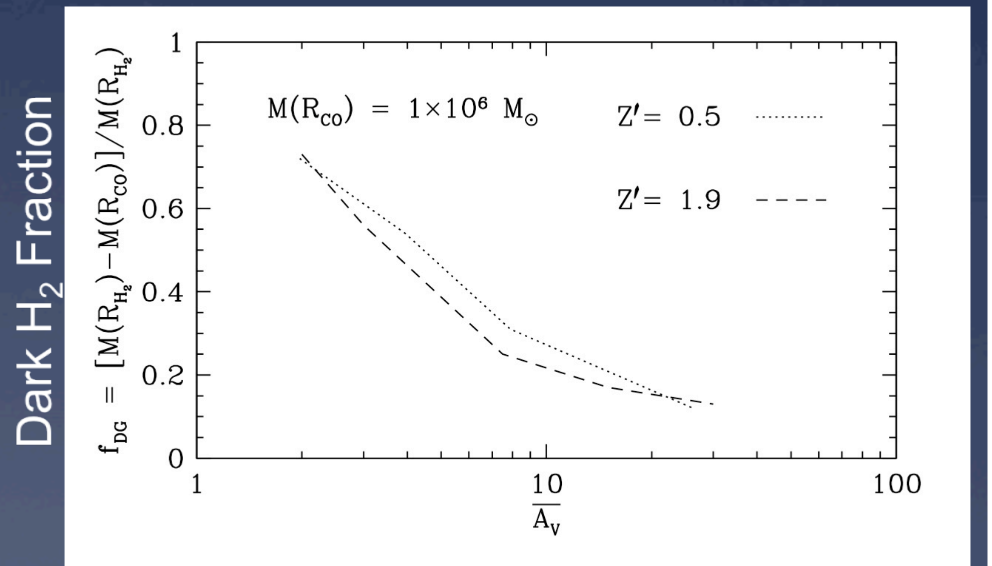
1. Self-gravitational collapse of ensemble of small atomic clouds
   - Clouds long-lived & stable. Gravity vs. turbulence & mag fields.
   - Spherical cluster small clouds; velocity field showing collapse.
2. Random collisional agglomeration of small clouds
   - Irregular-shaped cluster of clouds with random velocities.
3. Accumulation of material within high-pressure environments (e.g. winds from massive stars, SNRs)
   - Shells centred on previous regions of star formation.
4. Compression & coalescence of gas in converging flows in a turbulent medium
   - Clouds are transient; gravity plays little role.
   - Large diffuse features; evidence for compression where flows shock

“Dark” H_2

‘Normal’ Molecular Gas

Perhaps one-third of the molecular gas is “dark”?!





Column Density of Cloud

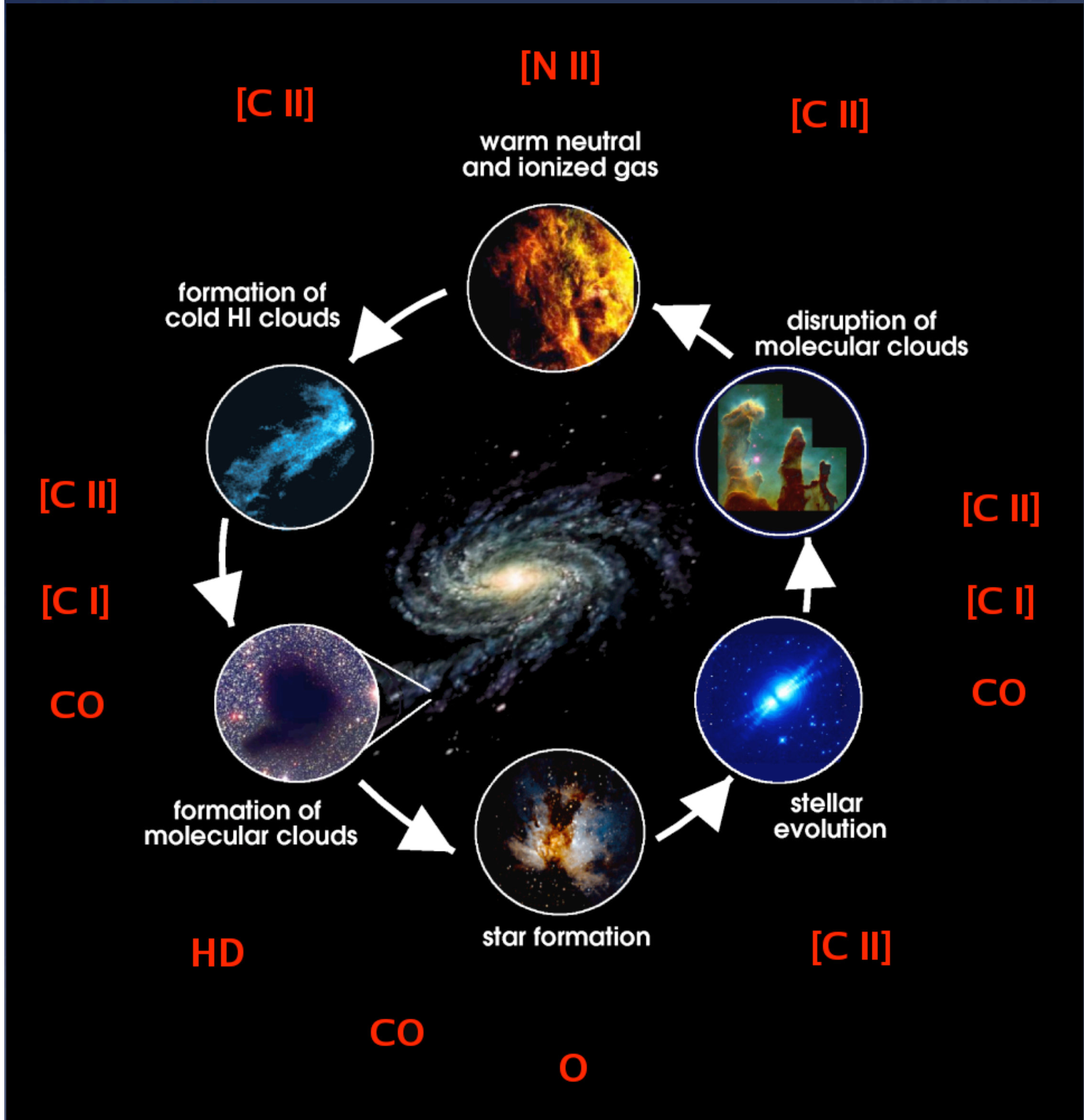
Purely Molecular Hydrogen – Dark H_2

Atomic Gas

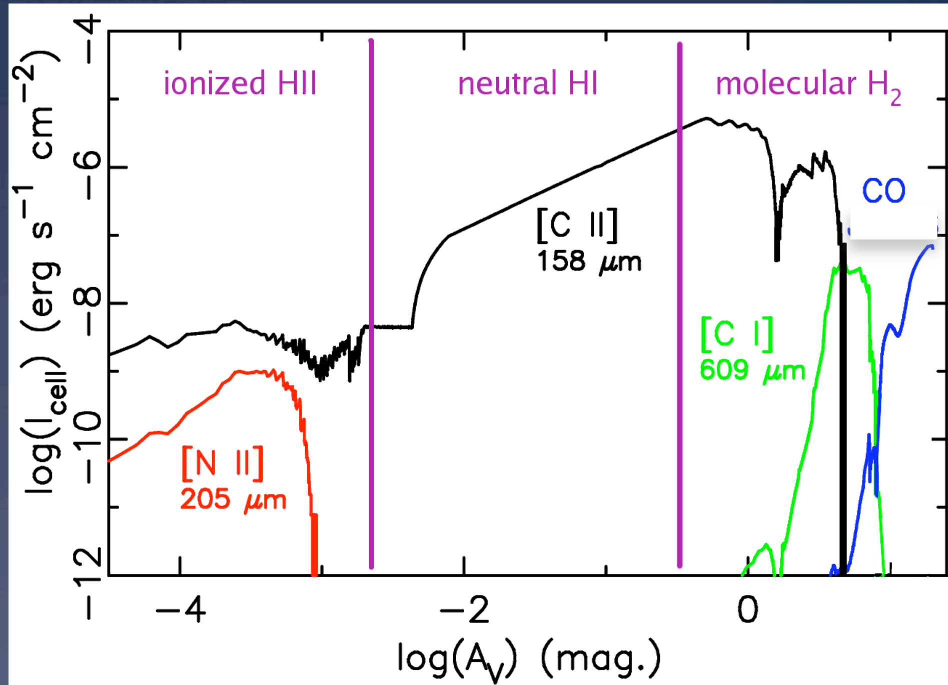
“The dark molecular gas”, Wolfire, Hollenbach & McKee, 2010, Astrophysical Journal, 716, 1191

Emission Signatures

H_2 cannot be seen directly

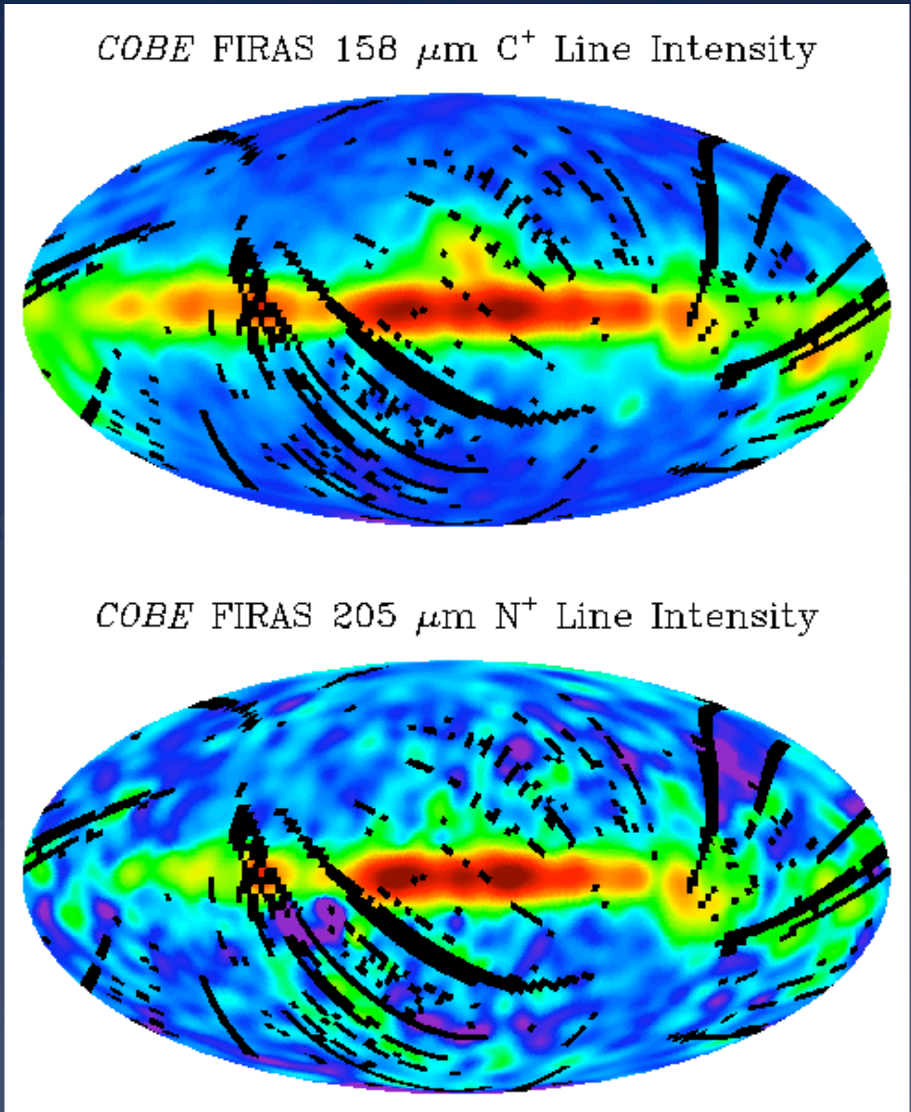


Cut through surface of a molecular cloud



THz	[CII] [NII]	158μm 205μm
Sub-mm	[CI]	609μm
MM	CO	2.6mm
CM	HI	21cm

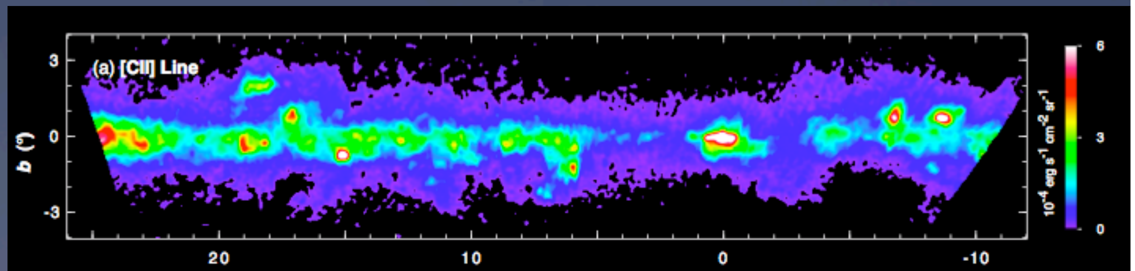
Only low resolution maps exist



Only Galactic Plane survey in [CII] and [NII] by FIRAS on COBE. 7° degree + R=100.

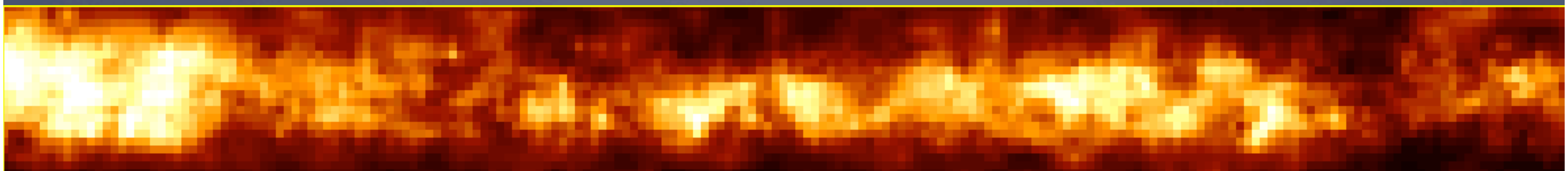
Balloon-borne BICE experiment measured [C II] over 200° with 15' resolution and R=1500.

In CO 1-0, the Colombia/CfA survey mapped the Galactic Plane at 8' resolution.



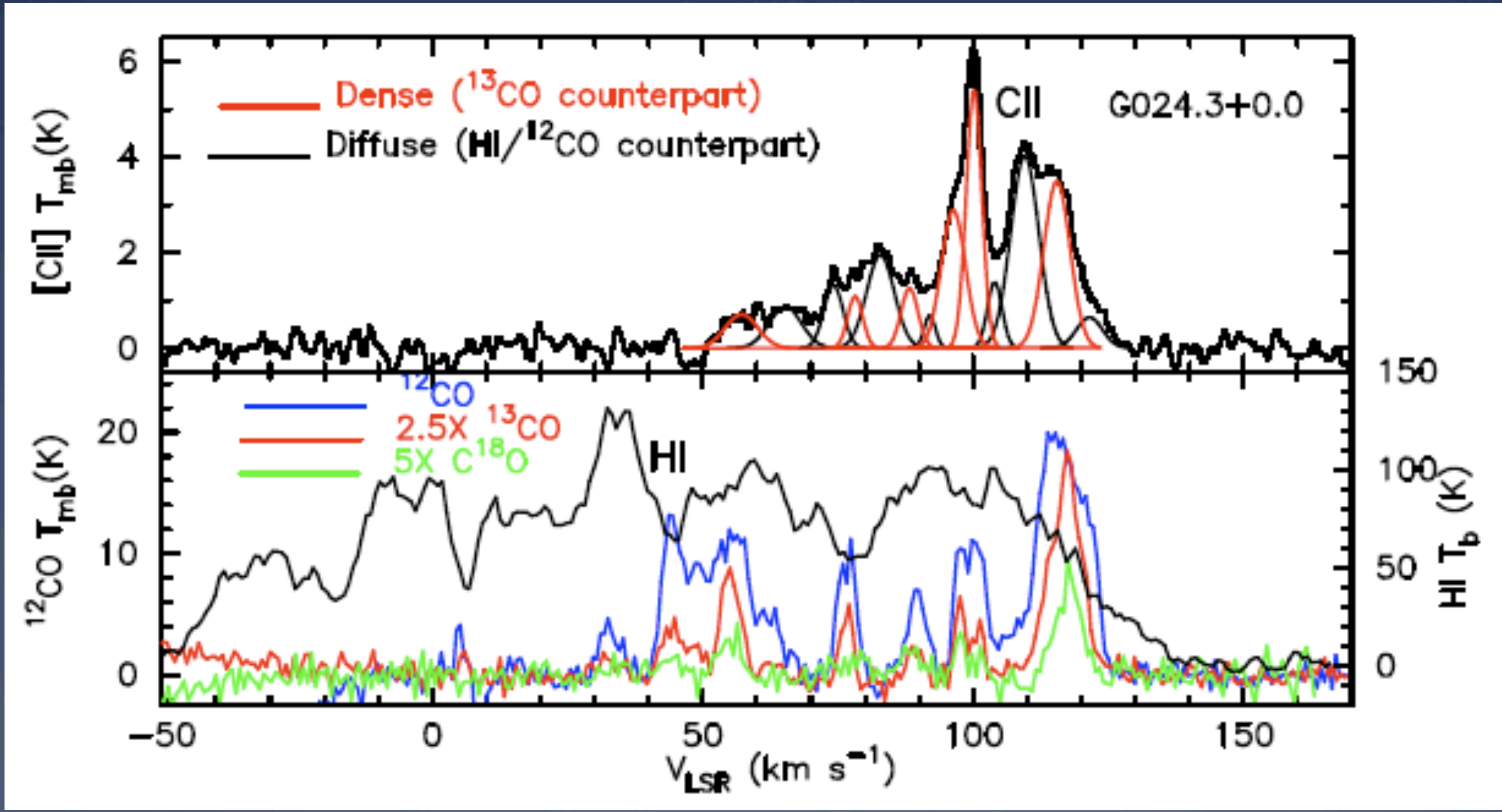
BICE [C II] balloon map

Columbia/CfA CO J=1-0



Herschel/HIFI GOT C+

Pencil beams through the Galactic plane



Velusamy et al (2010) A&A, 521, L18

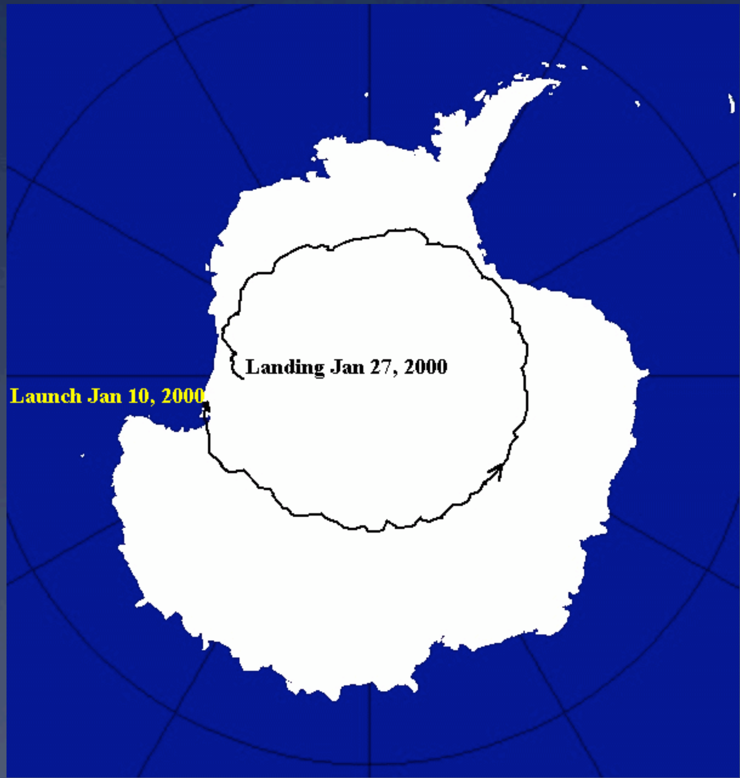
Diagnostic Species

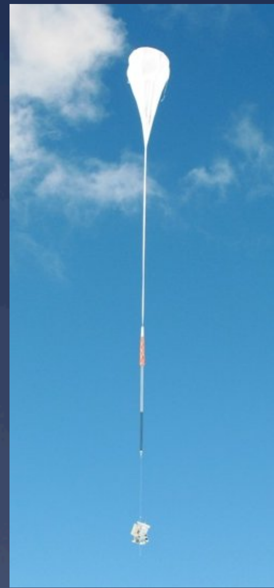
Table 1: Diagnostic Species and their Spectral Lines to be Observed

Species & Spectral Transition	**Frequency (GHz)**	**Telescope**	**Spatial & Spectral Resolution**	**Diagnostic Value**
CO J=1-0	115.3	Mopra (mm-band)	30″ & 0.1 km/s	Principal tracer of molecular clouds.
^{13}CO J=1-0	110.2			Isotopologues provide optical depths (hence column densities), line centres and line widths for saturated CO lines.
C^{18}O J=1-0	109.8			
[C$^+$] $^2P_{1/2}$-$^2P_{3/2}$	1901	STO (THz band)	60″ & 0.2 km/s	Major coolant of the dense ISM. Can arise in molecular, atomic and ionized gas.
[N$^+$] $^3P_1$-$^3P_0$	1461		90″ & 0.2 km/s	Major coolant from warm ionized medium.
[C] $^3P_1$-$^3P_0$ [C] $^3P_2$-$^3P_1$	492.2 809.3	Nanten2 (sub-mm band)	40″ & 0.3 km/s 25″ & 0.2 km/s	Surfaces of molecular clouds. Temperature and density probe.
CO 4-3 CO 7-6	461.0 806.7		45″ & 0.3 km/s 25″ & 0.2 km/s	Warm molecular gas. With Mopra J=1-0 lines provides temperature.
H 21cm	1.420	Parkes /ATCA (cm-band)	120″ & 0.8 km/s	Atomic gas clouds. Available from the Southern Galactic Plane Survey.

STO

Stratospheric Terahertz Observatory





- 80 cm telescope & gondola from Flare Genesis Experiment (solar)
- 2x4-pixel multibeam receiver
- 1.45 THz (NII) + 1.9 THz (CII)
- 0.2 km/s,1–1.5’ resolution

- Launched from McMurdo LDBF
- Long duration balloons
- 35 km altitude, 4 week mission
- Scheduled to fly Dec 2011
- 1 day US test flight in Sep 2009

- Can be refurbished new receivers & flown again
- Four missions planned.

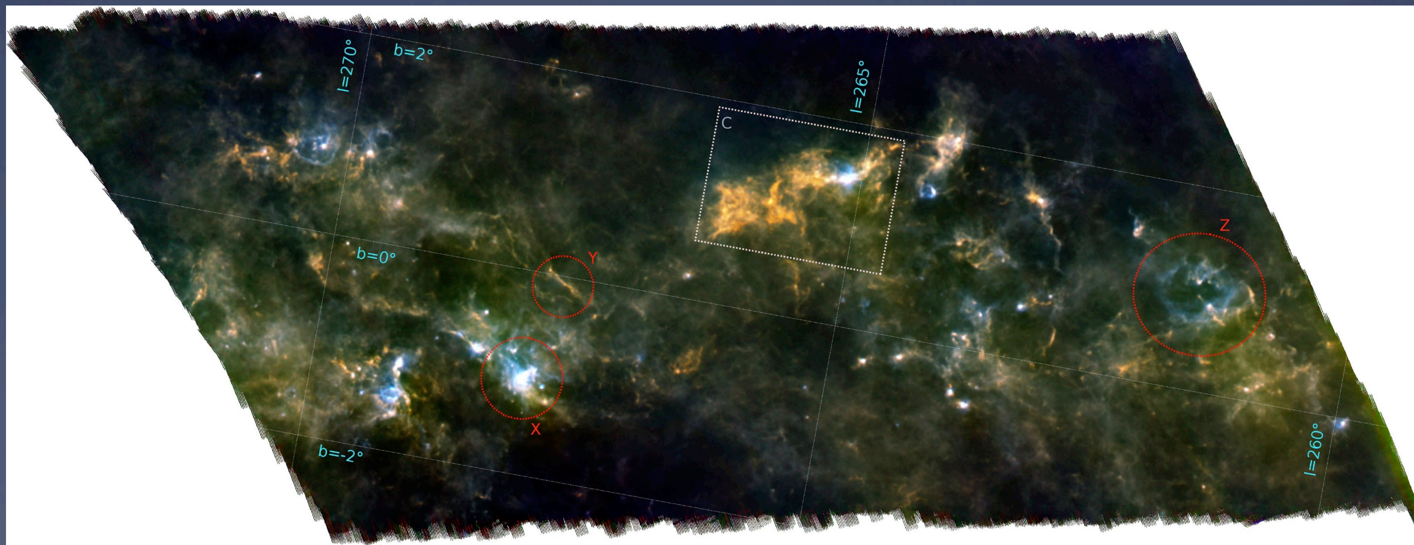
University of Arizona: Chris Walker & Craig Kulesa

BLAST

shows it can be done!

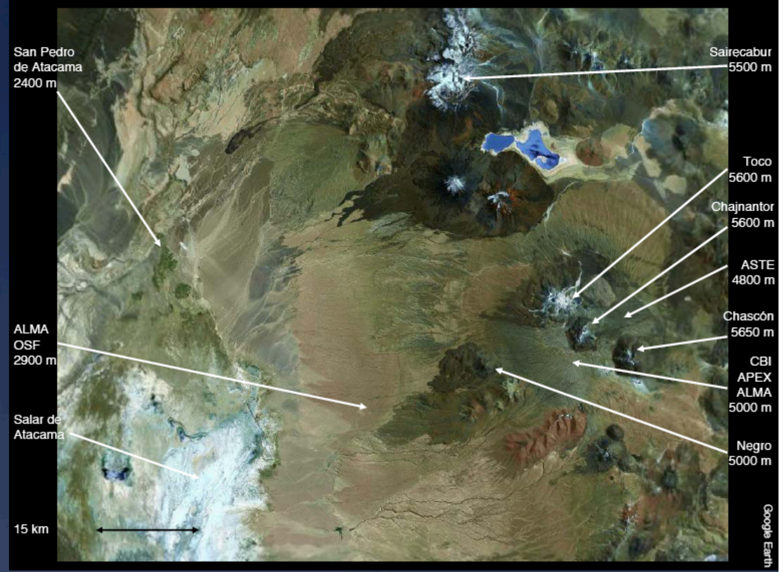
Balloon Large Aperture Sub-millimetre Telescope
2m Telescope, 11 day flight

10°x5° Vela Molecular Ridge
250μm, 350μm, 500μm

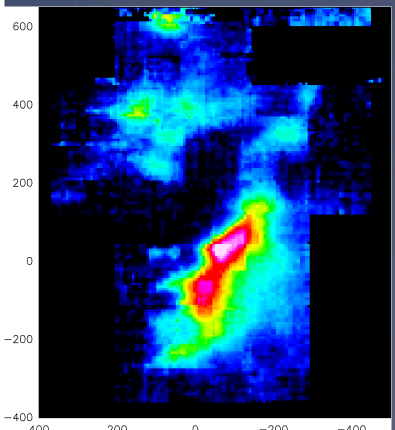


Netterfield CB *et al. (27 authors) (2009) BLAST: the mass function, lifetimes and properties of intermediate mass cores from a 50 square degree sub-millimetre galactic plane survey in Vela at l~265°.* ApJ 707, 1824

NANTEN2



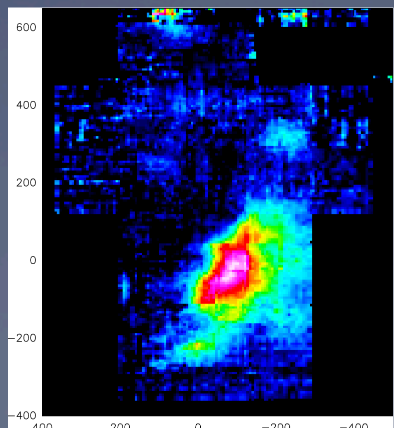
- 4m sub-mm Telescope
  - Pampa la Bola (4,800m; ALMA site)
  - 115/230/345 (Nagoya) + 460/810 (SMART) GHz receivers
- University of Nagoya (Japan) + Cologne (Germany)
- + Universities from Chile, Korea, Switzerland, Australia
  - UNSW, Sydney, Macquarie + Adelaide, JCU, Swinburne



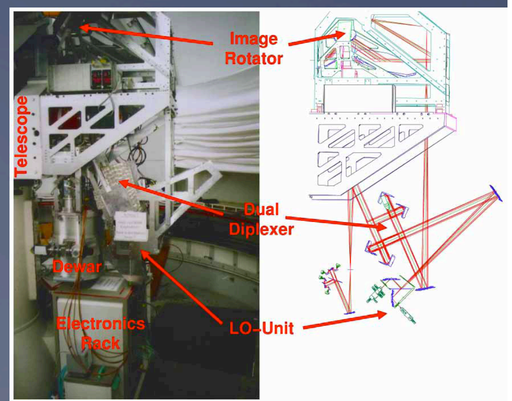
M17 @ 810GHz
~15'x20'

←CO 7-6

[CI] →



SMART
2x8 channel
multibeam
460 + 810 GHz



Millimetre Astronomy in Australia

CSIRO Australia Telescope

Australia Telescope Compact Array

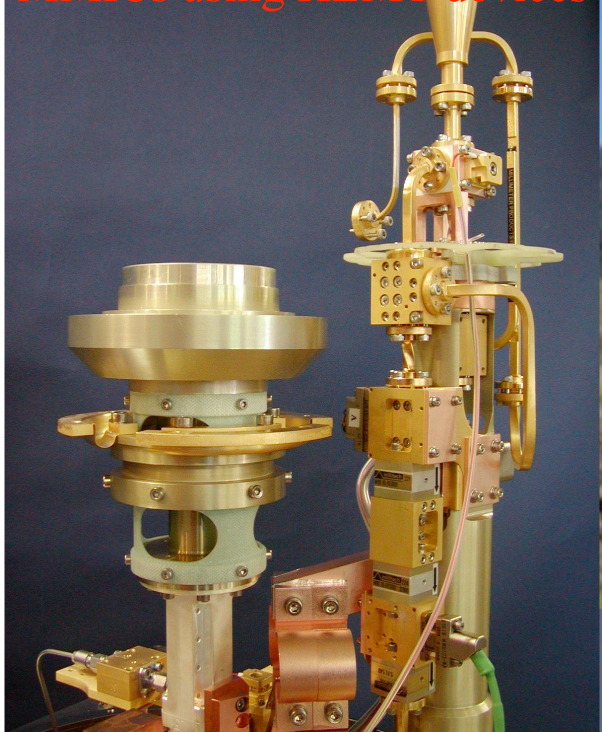
- Millimetre-capable
  - 3 mm (85-105 GHz)
    - 5 x 22m antennas
  - 7mm (30-50 GHz)
    - 6 x 22m antennas
  - 12 mm (18-26 GHz)
    - 6 x 22m antennas
- 4 GHz bandwidth
  - The CABB…..
- Water Vapour Radiometers
  - 22 GHz under development

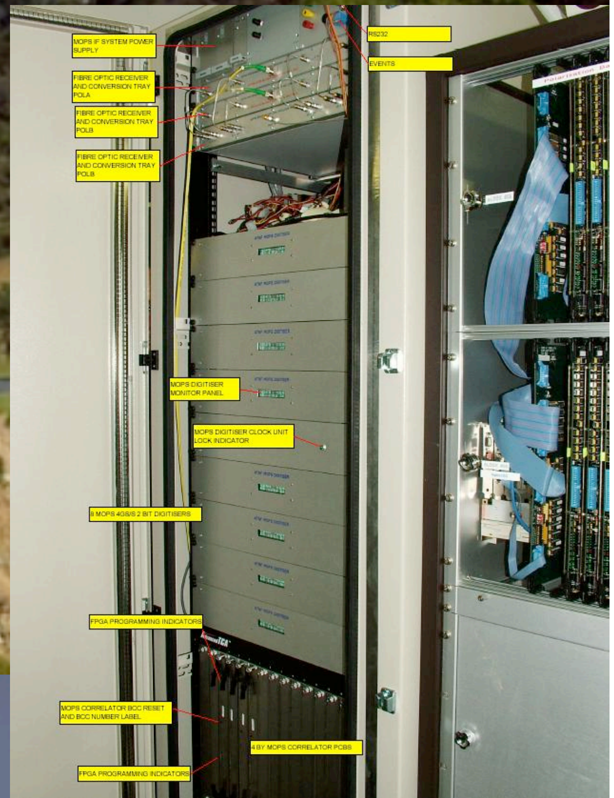
Mopra Radio Telescope

SEEKING THE BIRTHPLACE OF THE STARS

OTF Mapping with 22m dish

MMICs using HEMT devices





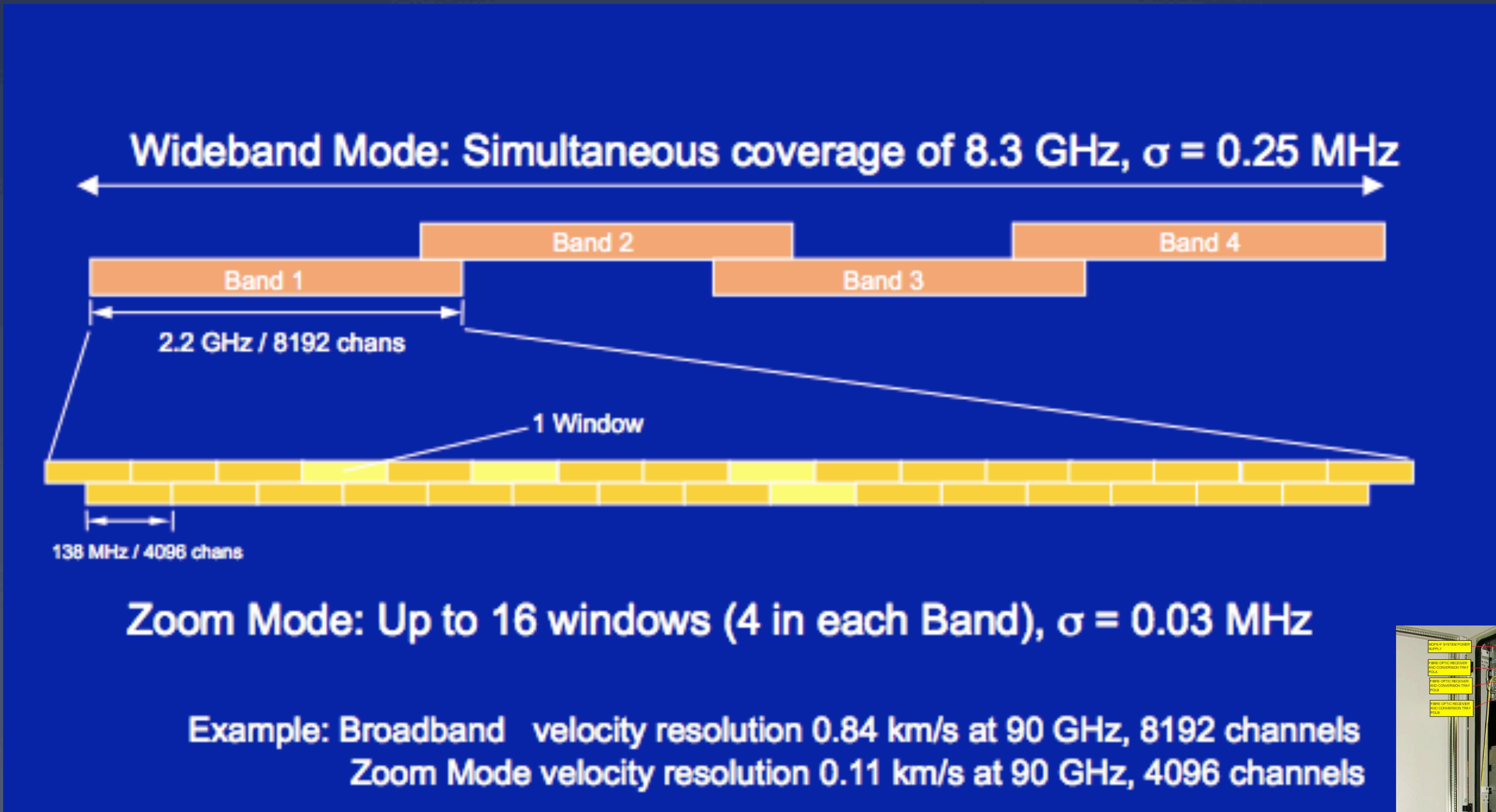
UNSW-MOPS 8 GHz DFB

Mopra Telescope MM Capabilities

- 22-m Telescope for long-wave mm astronomy
  - 3mm + 7mm + 12mm
- 77–116 GHz MMIC receiver (2.5-4 mm)
  - T_{sys} ~ 150K (@85GHz) – 300K (@115GHz)
  - 35" beam
  - η_{mb} (86 GHz) = 0.49, η_{mb} (115 GHz) = 0.42
  - η_{xb} (86 GHz) = 0.65, η_{xb} (115 GHz) = 0.55
- 30-50 GHz receiver (5-10mm)
  - T_{sys} ~ 65K, 75" beam
- 16-25 GHz receiver (12-18mm)
  - T_{sys} ~ 45K, η_{mb} ~ 0.7, 150" beam
- Bandwidth 8 GHz: UNSW-MOPS correlator
  - Broad Band 32,000 channels, 0.8 km/s resn.
  - 16 Zooms modes over 137 MHz
    - 4 per band, 4096 channels/zoom, 0.1 km/s
- 2 Polarizations (i.e. 64,000 channels)
- "On-the-Fly" (OTF) Mapping

THE UNIVERSITY OF NEW SOUTH WALES

Mopra Spectrometer: UNSW-MOPS



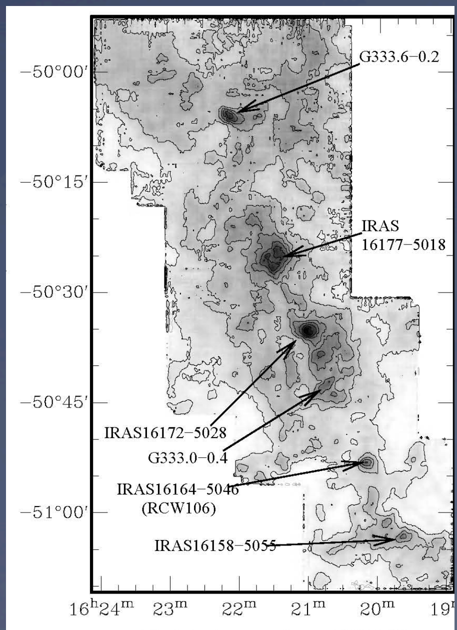
Built by CSIRO for UNSW, U. Sydney and Monash U. with ARC support

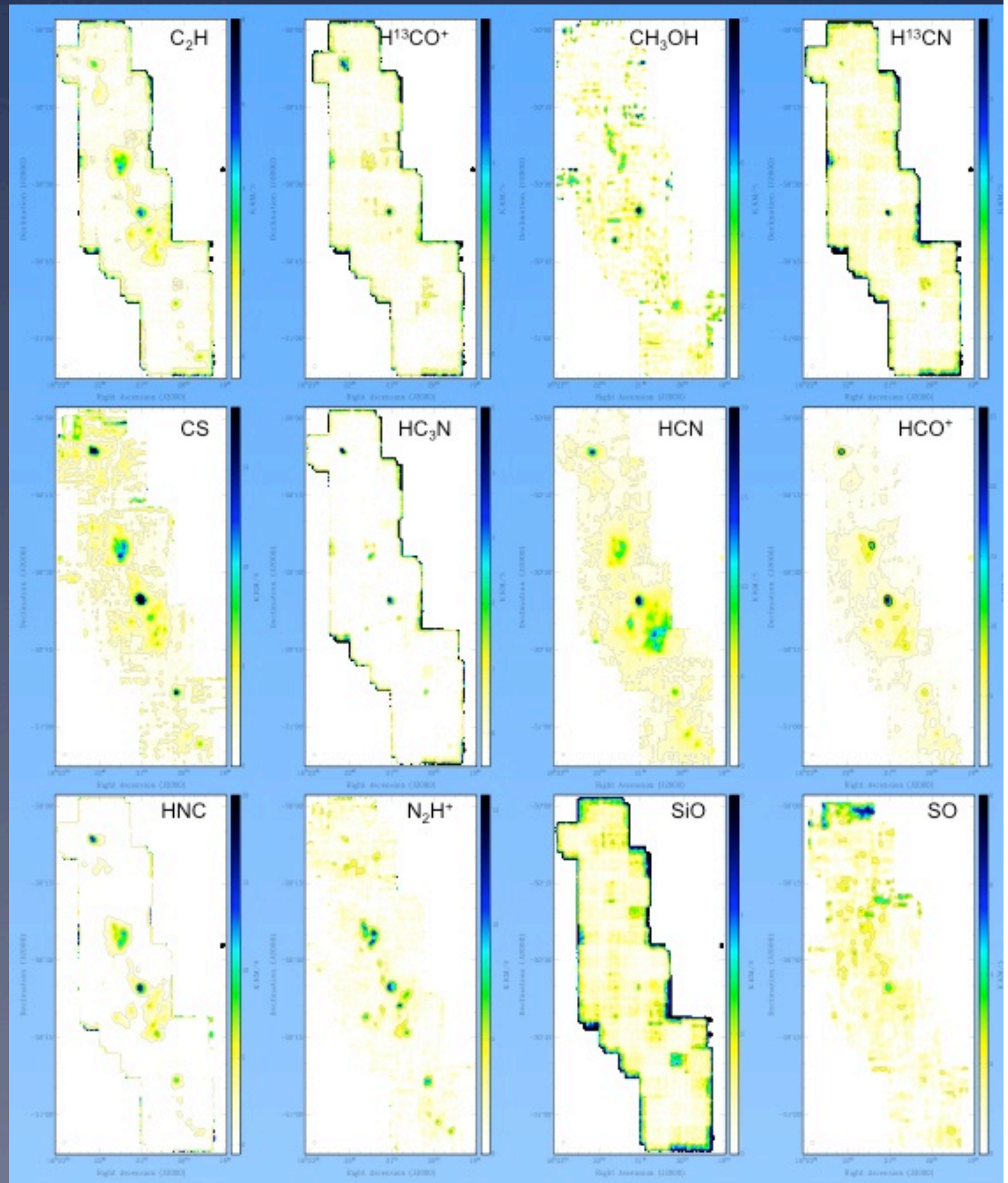
Bains et al, MNRAS 2006; Wong et al MNRAS 2008; Lo et al, MNRAS 2009.

Mapping Projects I: The DQS

Maria Cunningham, Indra Bains, Tony Wong, Nadia Lo

- 1□° multi-molecular line mapping at 3mm
- 35" + 0.1 km/s
  - Zoom-mode
- GMC-complex

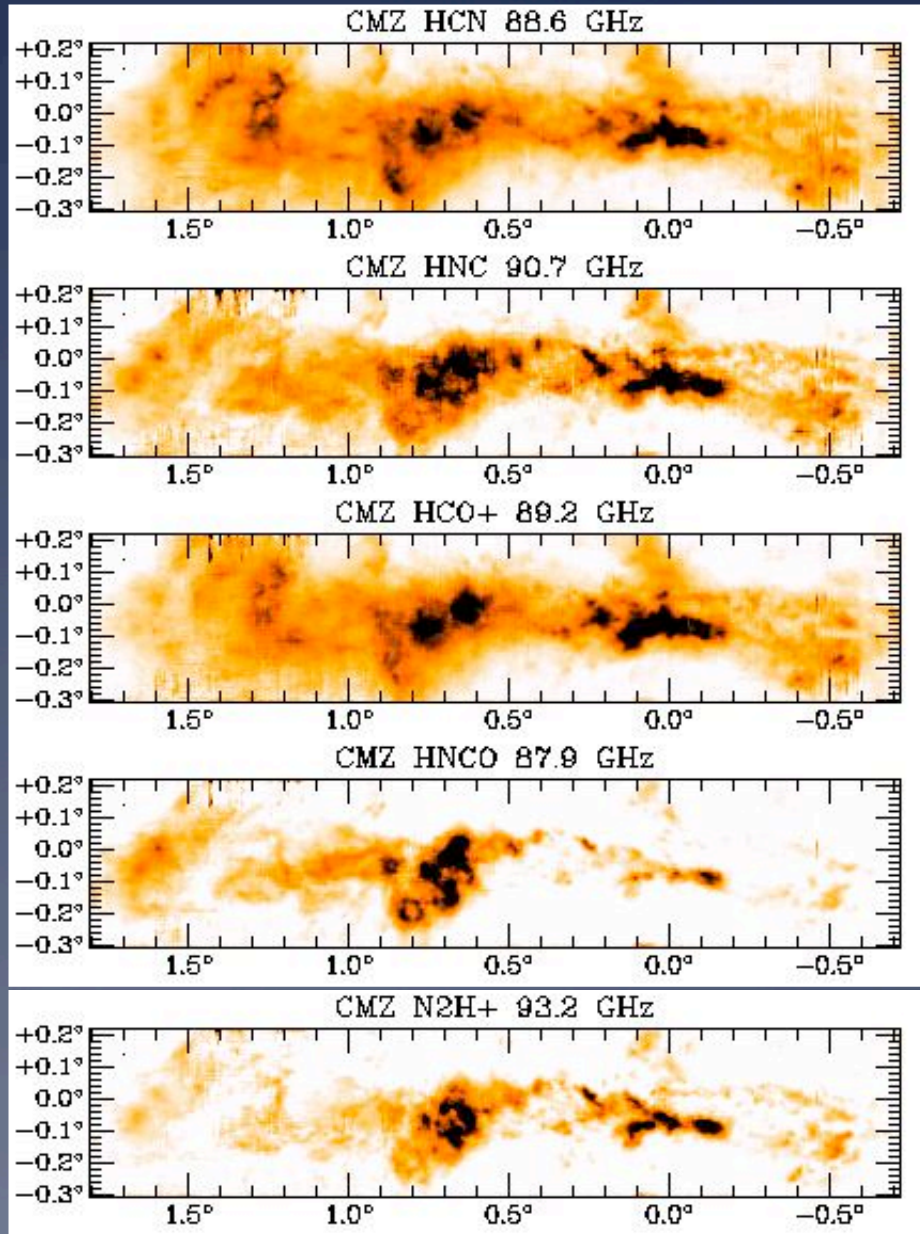




Mapping Projects II: The CMZ

Michael Burton, Paul Jones

* 18 lines over 8 GHz band
  * 85-93 GHz
* 35" resn + 1 km/s
  * Broad-band
* Inner 3° of the Galaxy
* 3 seasons (@3 wks/yr)



collab.phys.unsw.edu.au/CMZ/

Jones et al, 2008 & 2010

Molecular Lines Mapped in the CMZ

3mm Band (30'' + 1km/s)		**7mm Band** (60'' + 2km/s)		**12mm Band** (150'' + 0.5 km/s)	
C_3H_2	85.34	NH_2CHO	42.39	**H_2O Maser**	**22.24**
CH_3CCH	85.46	HC_5N 16-15	42.60	**NH_3 (1,1)**	**23.69**
$HOCO^+$ 4-3	85.53	HCS^+	42.67	**NH_3 (2,2)**	**23.72**
SO	86.09	$HOCO^+$ 2-1	42.77	**NH_3 (3,3)**	**23.87**
SiO 2-1	**86.85**	^{29}SiO 1-0	42.88	CH_3OH	24.9
$H^{13}CN$	86.34	**SiO 1-0**	**43.42**	**NH_3 (6,6)**	**25.06**
$H^{13}CO^+$	86.76	**HNCO 2-1**	**43.96**	HC_5N 10-9	26.63
$HN^{13}C$	87.09	**CH_3OH–I**	**44.07**	**HC_3N 3-2**	**27.29**
CCH	87.3	$H^{13}CCCN$	44.08	NH_3 (9,9)	27.48
HNCO 4-3	**87.93**	HC_5N 17-16	45.26		
HCN	**88.63**	$HC^{13}CCN$	45.30		
HCO^+	**89.18**	$HCC^{13}CN$	45.30		
HNC	**90.66**	CCS	45.38		
HC_3N 10-9	**90.98**	**HC_3N 5-4**	**45.49**		
CH_3CN	**91.99**	^{13}CS	46.25		
^{13}CS 2-1	92.49	HC_5N 18-17	47.93		
N_2H^+	**93.17**	^{13}CS	48.21		
		CH_3OH	48.37		
		OCS	48.65		
		CS 1-0	**48.99**		

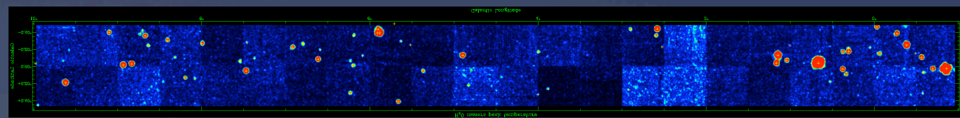
Mapping Projects III: HOPS

Andrew Walsh

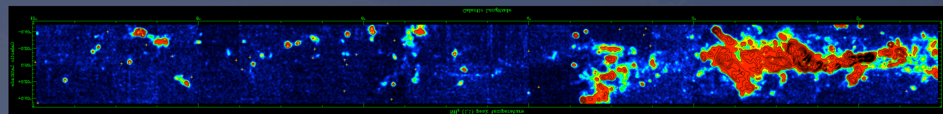
Walsh et al, 2008, MNRAS

- ~12 lines at 12 mm
- Zoom mode
- 2.5' beam, 0.5 km/s
- 100°x1°
- 3 seasons (@ 6 wks/yr)
- Summer observing!
- Galactic Plane

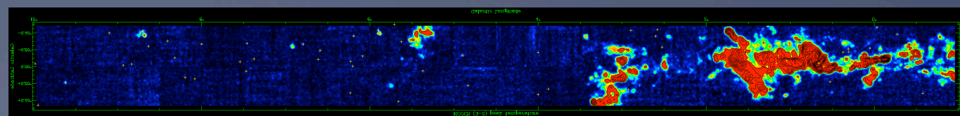
H_2O Masers



NH_3 (1,1)



HC_3N



10° x 1°

www.jcu.edu.au/school/mathphys/astronomy/awalsh/HOPS/

Parkes 64m Telescope

- 12mm receiver
- 55m effective aperture at 22 GHz

Band 0 NH_3 at 1 arcmin resolution?!

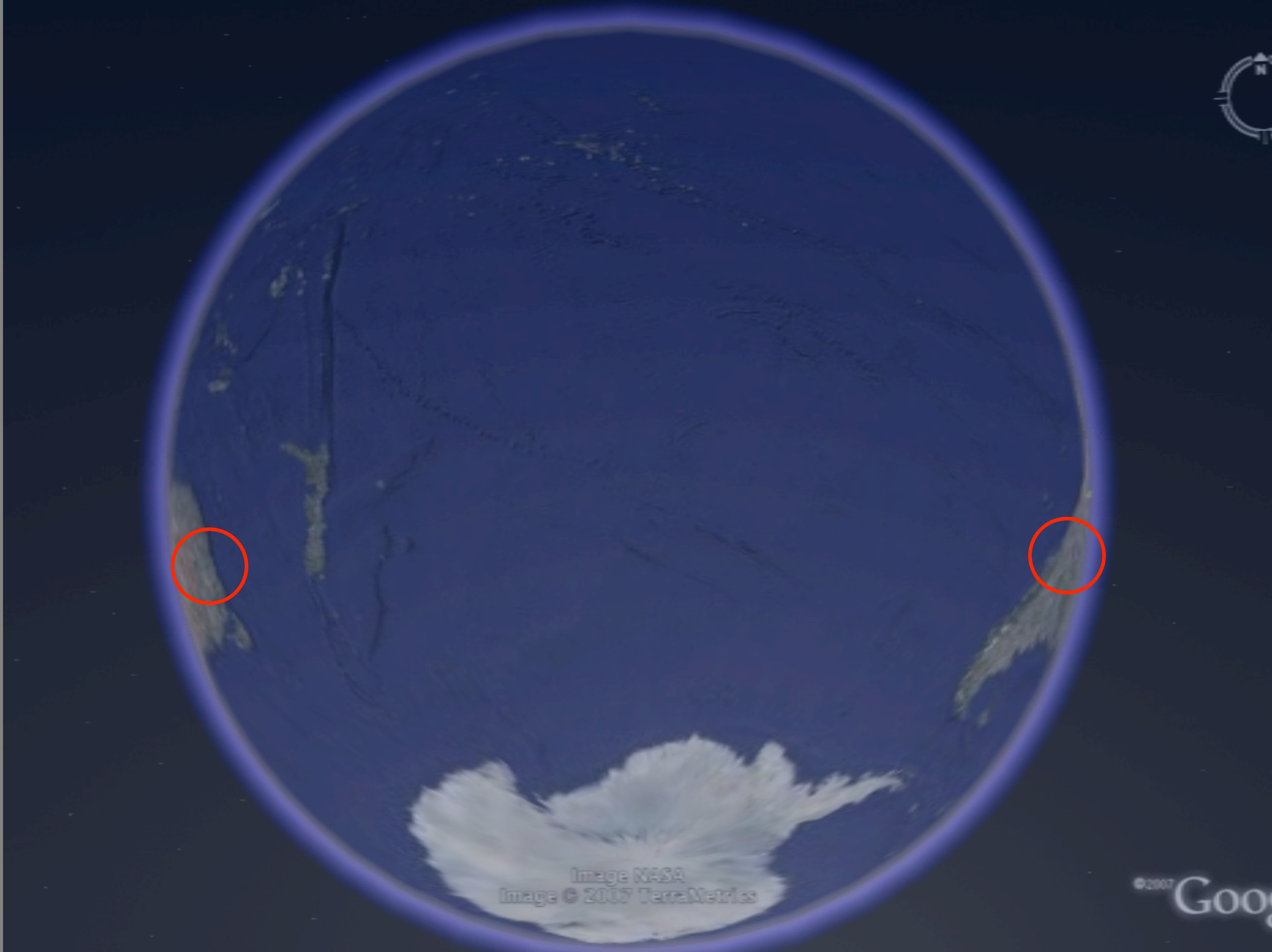


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Image NASA
Image © 2007 TerraMetrics
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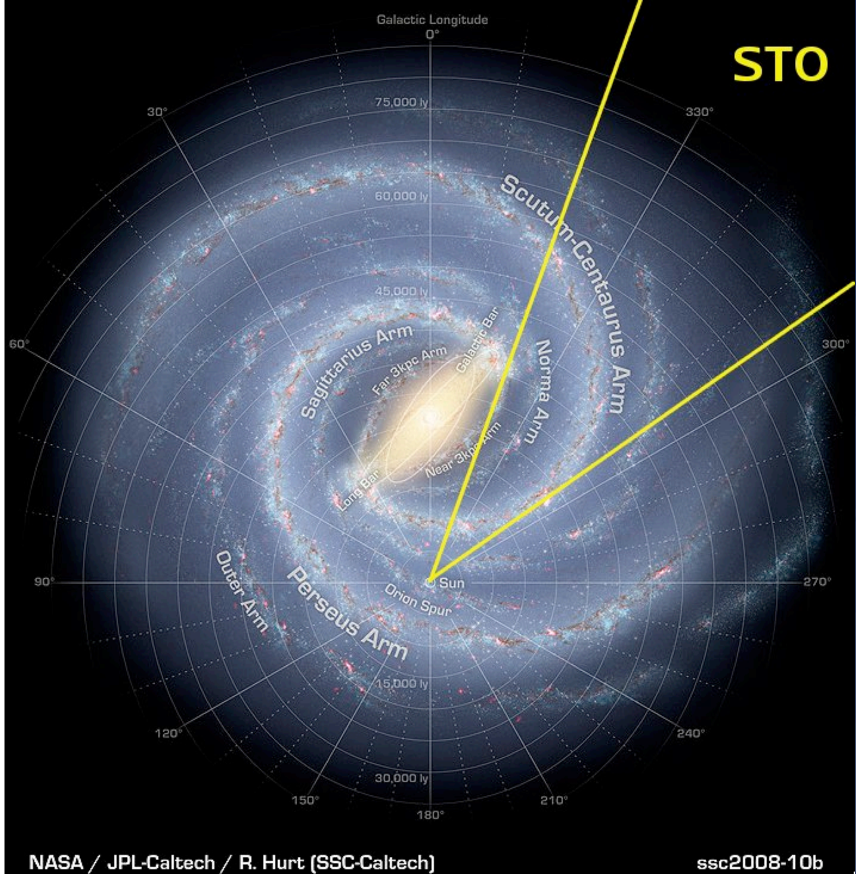
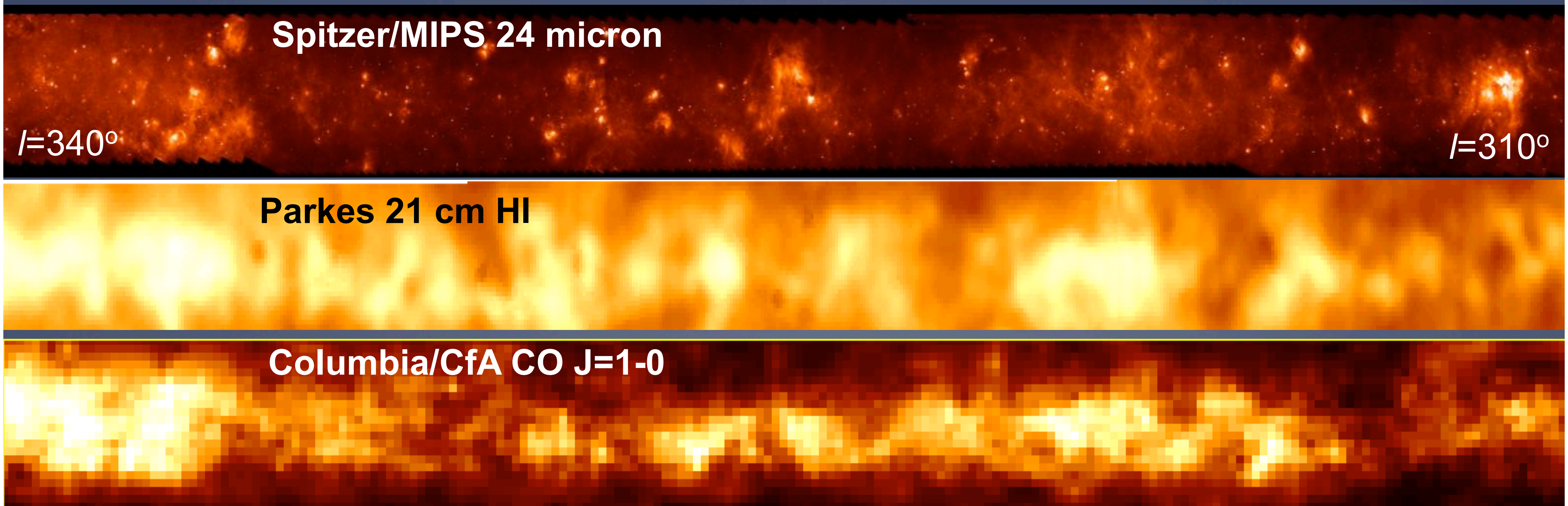


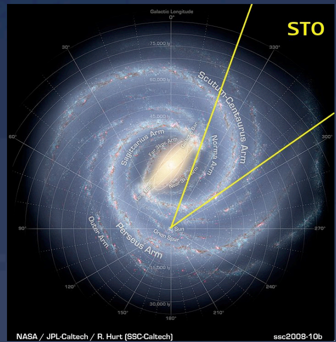
The STO Survey

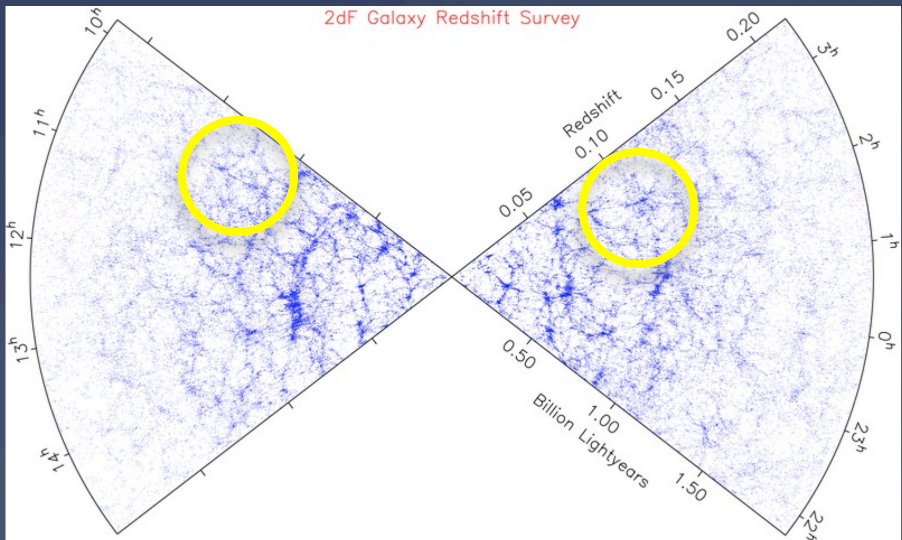
Stratospheric Terahertz Observatory

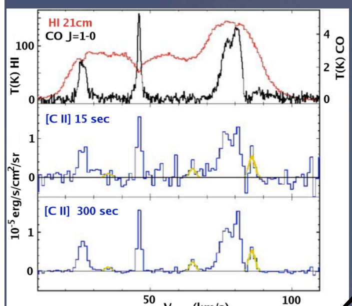
STO will perform a midplane Galactic survey from *l*=-20° to *l*=-55°, and |*b*|<1° spanning the Molecular Ring through the Scutum-Centaurus spiral arm and two inter-arm regions.

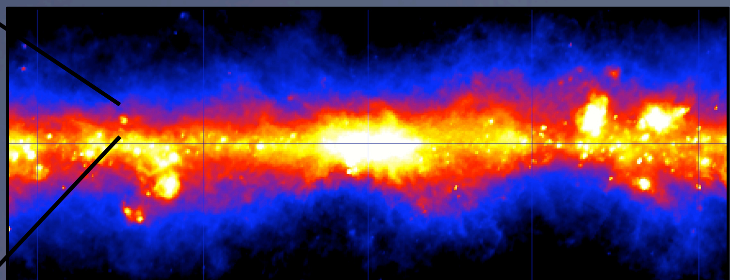


Identifying Forming Molecular Clouds from the Atomic Substrate





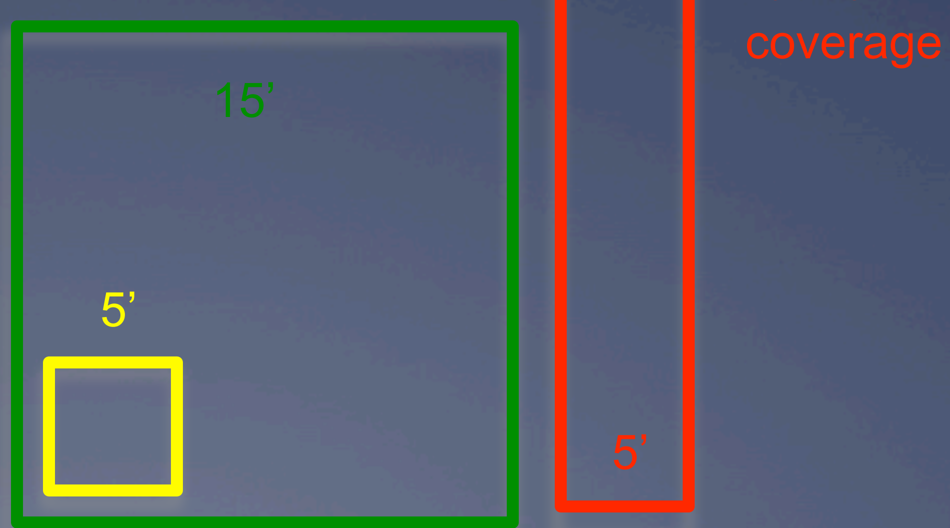




* Identify molecular, dark, atomic clouds from [CII], [CI], CO, [NII], HI emission
  * GMC initially spread over ~1 kpc
* Cover arm + inter-arm region
* Velocity structures akin to "fingers-of-God" in Galaxy redshift surveys, but on km/s scales.
* Galactic rotation curve for distance + "peculiar" velocities around a cloud complex
* Infall or Disruption?
  * Look for past tracers of SF; e.g. clusters, SN: disruption
  * If none: molecular cloud forming

Fast Mapping with Mopra

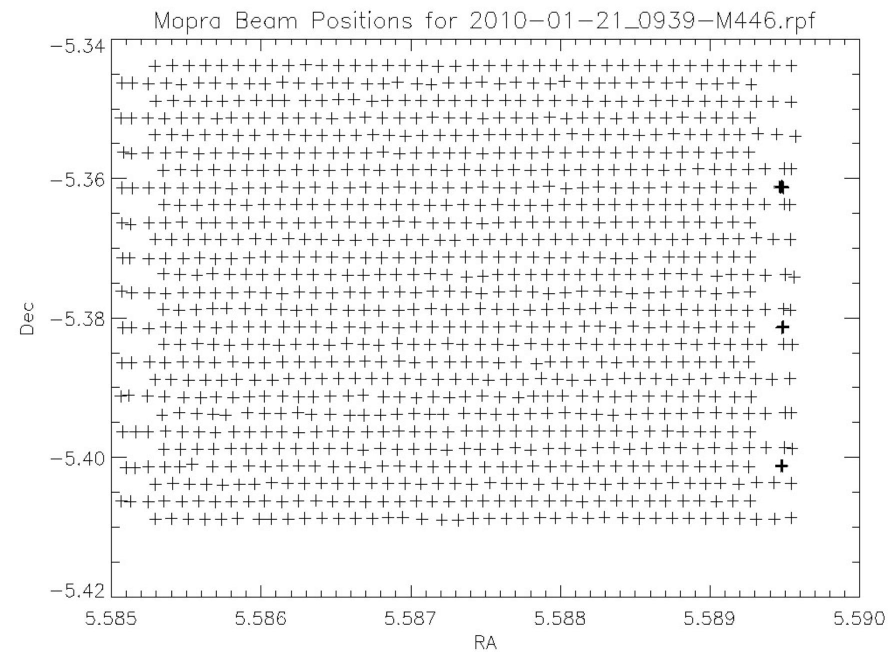
* Binning mode in 2s cycles
  * 8 x 256ms samples
* i.e. 8 x faster for $1/3^{rd}$ the sensitivity
  * Only suitable for CO lines
* Scan at 36"/s with 12" row spacing
  * c.f. 3"/s with 9" spacing
* 36 hours/sq deg c.f. 350 hours
* 4 zoom modes, not 16
  * ^{12}CO, ^{13}CO, $C^{18}O$, $C^{17}O$



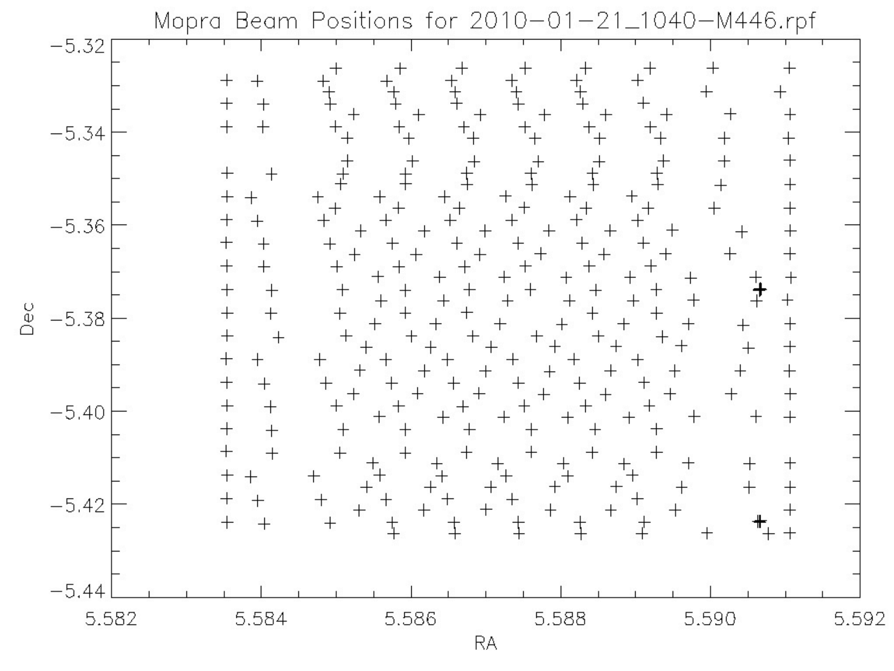
Thanks to Nick Tothill, Warwick Wilson, Dick Ferris, Balt Indermuehle, James Urquhart!

Beware uneven beam coverage with Fast OTF

Standard OTF

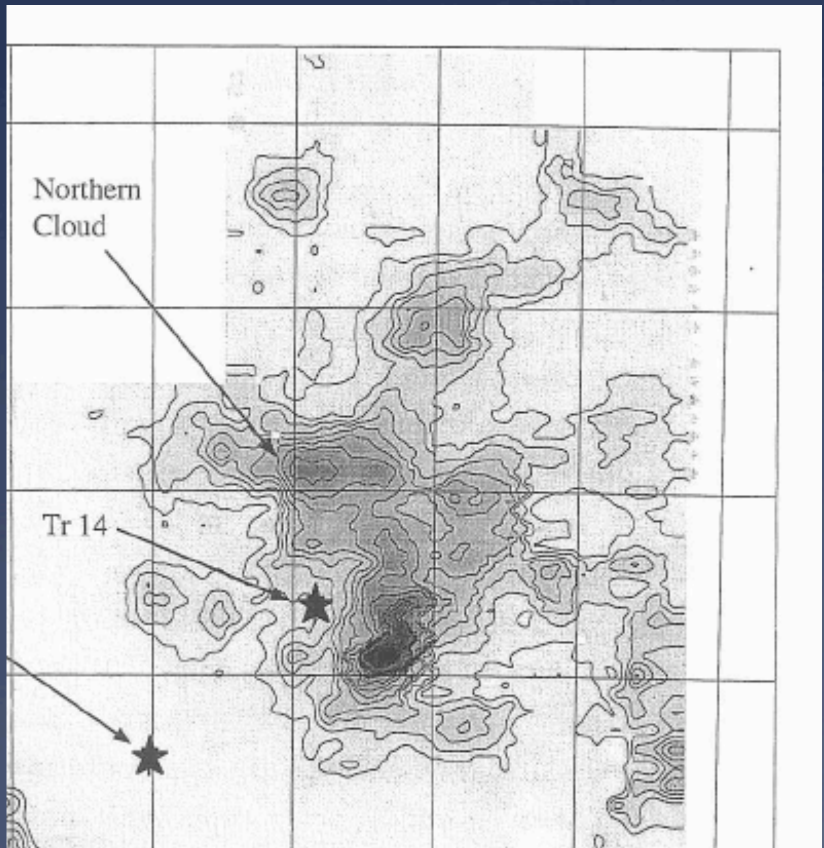


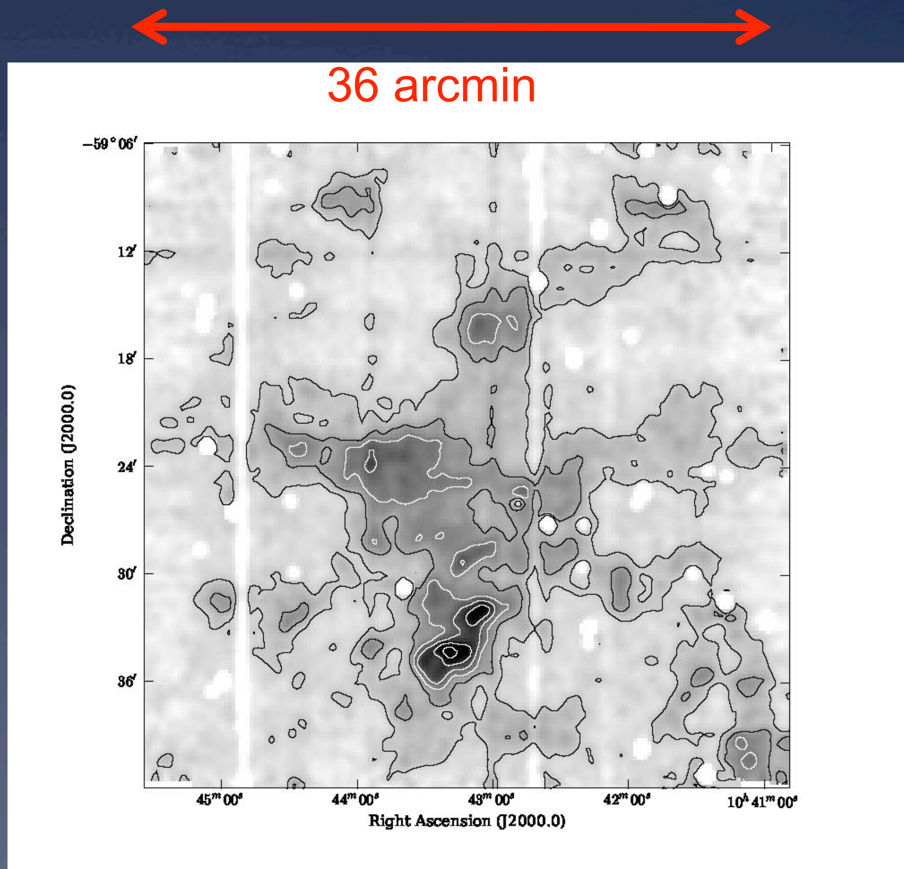
Fast OTF



Two Views of Carina in CO with Mopra

Point-by-Point *Fast–OTF*





1996-7: Several months, at site.
45" beam, 1line, 1 poln, 64 MHz, 0.2 km/s
Clear skies!

Kate Brooks, PhD Thesis

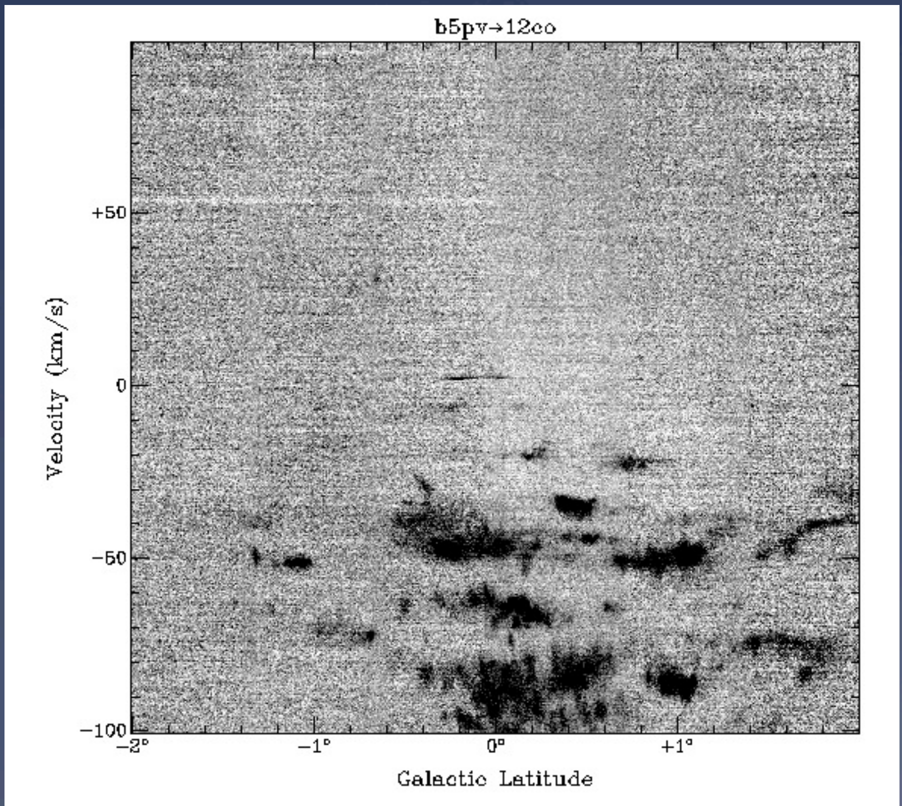
2010: 6 hours, in-between teaching from my office
30" beam, 4 lines, 2 poln, 137 MHz, 0.1 km/s
Extensive cloud!

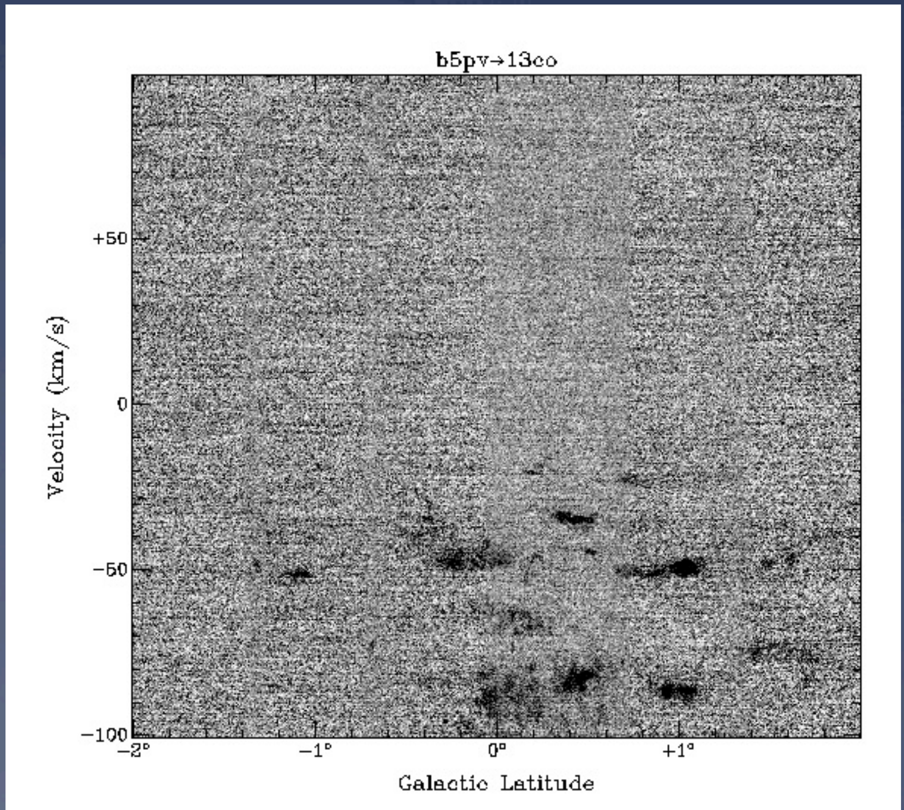
Fast Mapping Strip Scans
l=330° x 6', b=-2° – +2°, ΔV=+250 km/s

^{12}CO (115.3 GHz)

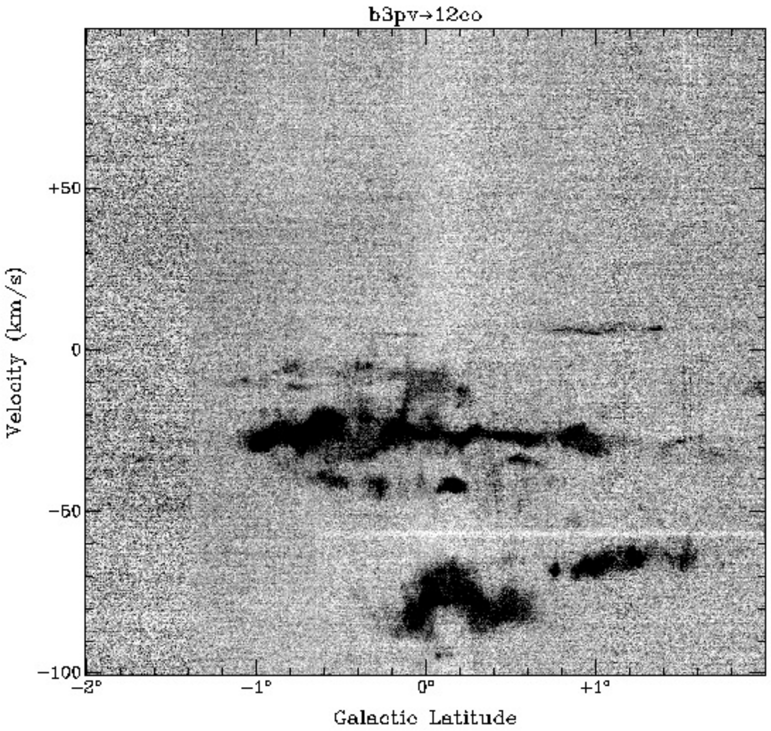
^{13}CO (110.2 GHz)

Velocity

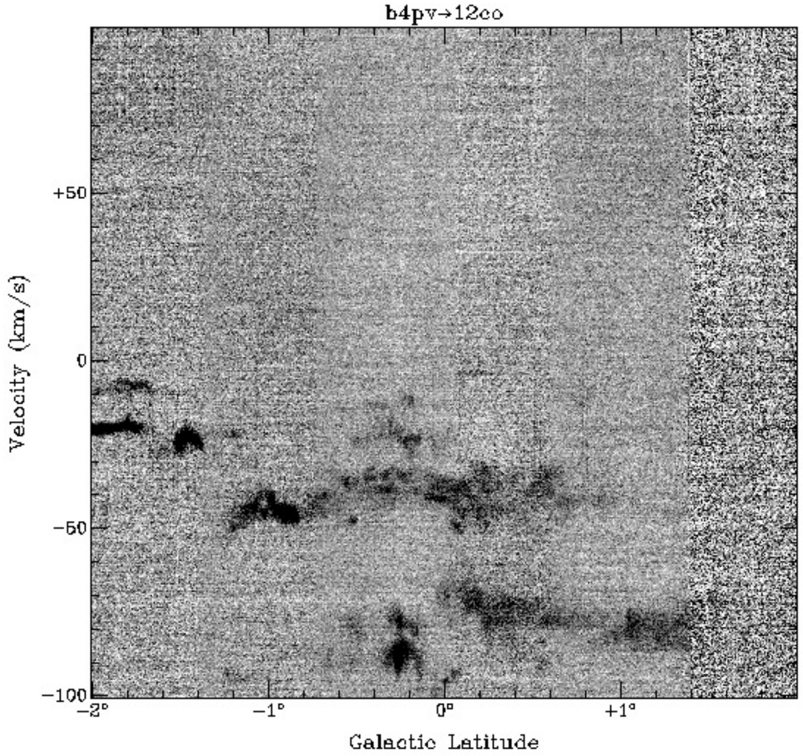




Latitude

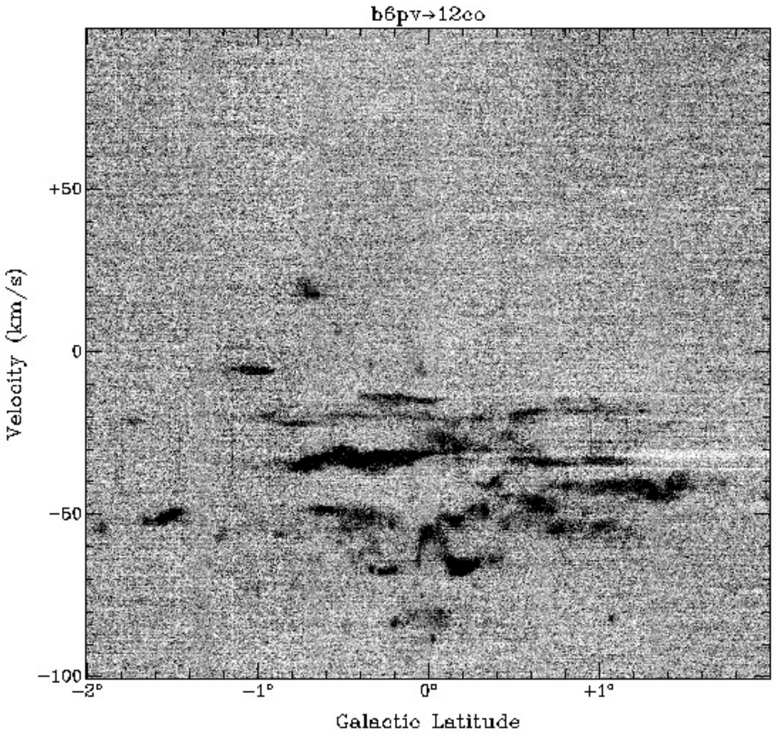


l=332°

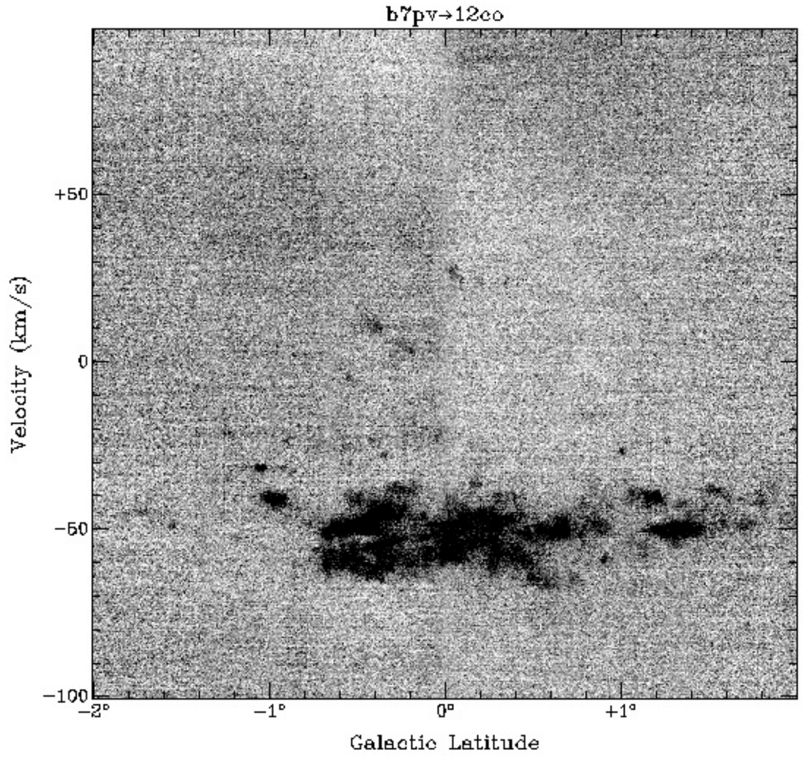


l=336°

Velocity



l=323°



l=316°

Latitude

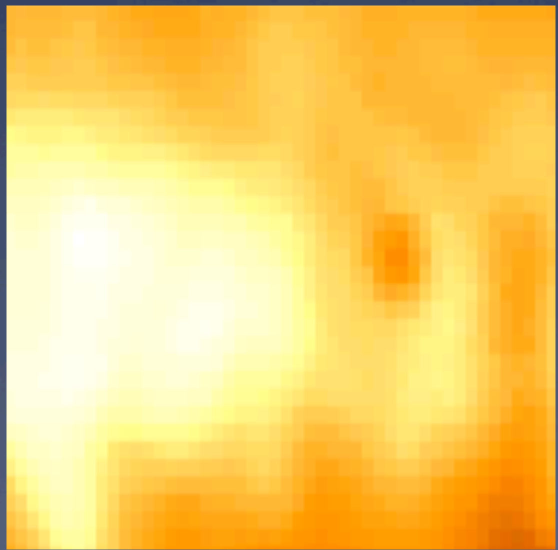
The First Segment for Mopra

Edge of spiral arm to inter-arm region

l=325.25°–327.25°, b=+/-1°

2 x 2°

Spitzer / MIPSGAL
3.6µm+8µm+24µm



Parkes 21cm HI