The millimetre regime

Jill Rathborne

Parkes Radio School - September 2011

CSIRO

www.csiro.au

Outline

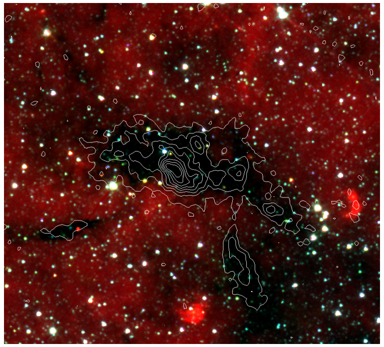
- Motivation for millimetre astronomy
- Millimetre telescopes
  - Mopra, ATCA, Parkes
- Special considerations for mm observations
  - Atmospheric opacity
  - Pointing accuracy
- Typical observing modes
- Derived properties from mm observations
  - Molecular lines
  - Dust continuum
- Science from mm observations
  - Galactic structure
  - Early stages of star-formation
- Questions along the way

Motivation for millimetre astronomy

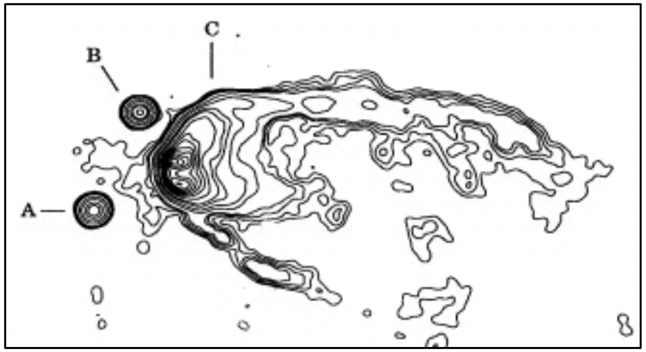
Motivation for mm astronomy

- Thermal emission from (cold) dust
  - UV Photons absorbed by dust grains, energy is re-emitted as thermal radiation at sub-mm/mm/FIR/IR wavelengths
- Free-free emission
  - Thermal Bremsstrahlung from electrons (HII regions)
- Molecular line emission
  - Low order rotational transitions of many molecules fall in the mm regime

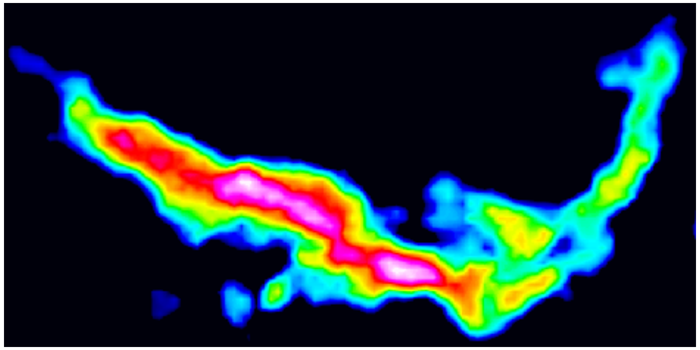
Dust continuum



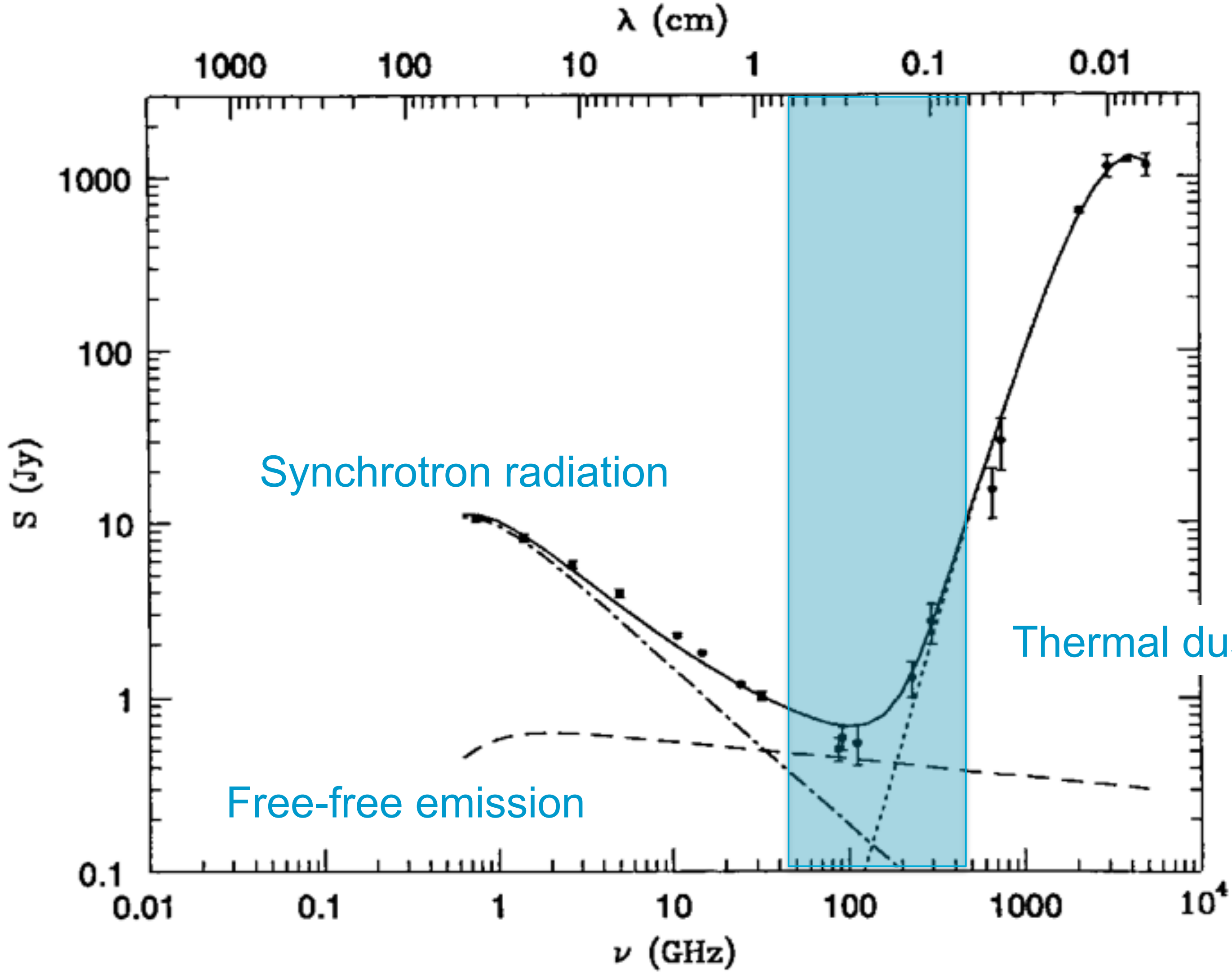
Radio continuum



Molecular lines



Motivation for mm astronomy



The radio to far-infrared spectrum of the nearby starburst galaxy M82

Motivation for mm astronomy

- Cosmic microwave background (CMB) peaks at ~1mm
- Rayleigh-Jeans regime, $h\nu \ll kT$

Flux density:

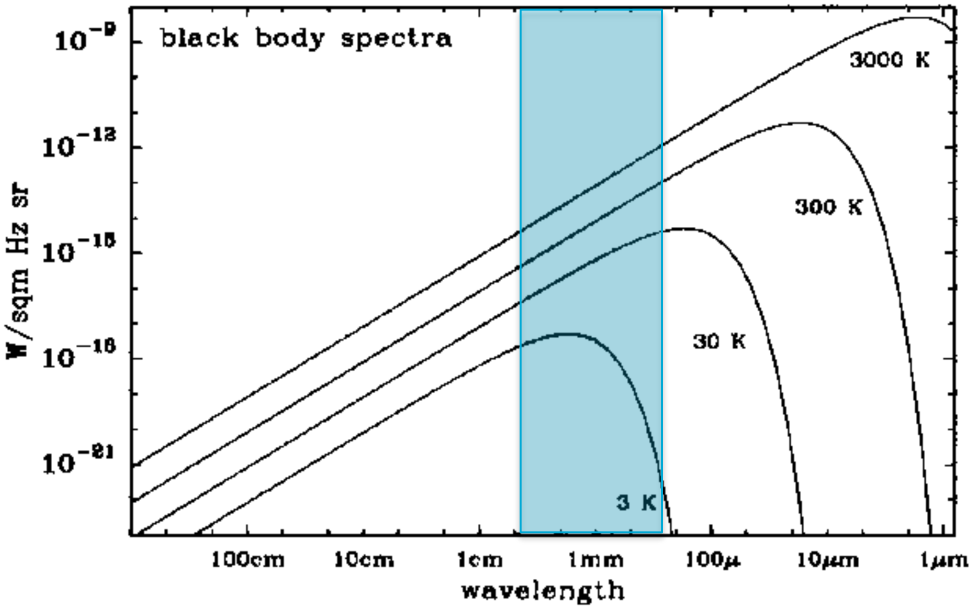
$$S_\nu = \frac{2\,kT\,\nu^2\,\tau_\nu\,\Omega}{c^2} \quad Wm^{-2}\,Hz^{-1}$$

Dust opacity:

$$\tau_\nu \propto \nu^2$$

For optically-thin emission:

$$S_\nu \propto \nu^4$$



Thermal emission is brighter at higher frequencies

Motivation for mm astronomy

- Molecular line spectroscopy
  - Low order rotational transitions of abundant molecules fall in the mm regime
  - Critical densities of ~10^2 – 10^5 cm^{-3}
  - Kinetic temperature ~ few to a few 10's K
    - Dense, cold regions of the ISM
    - Early stages of star-formation
  - Dust obscured these regions at optical and IR wavelengths
  - Detailed studies are done exclusively in mm regime

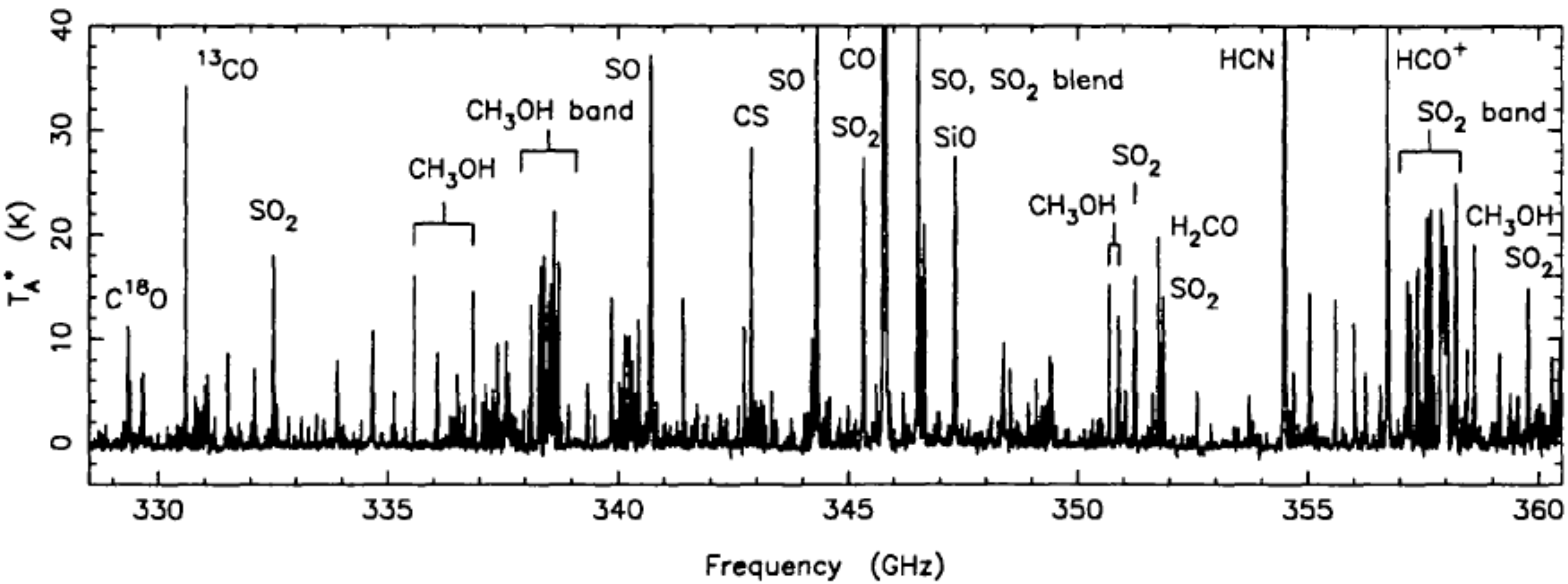
Table 28–1. Low Order Rotational Transitions of Simple Heavy Molecules

Molecule	J(1-0) GHz	J(2-1) GHz	J(3-2) GHz	n_{crit}[J(1-0)] cm^{-3}
CO	115.271	230.538	345.795	10^2 - 10^3
CS	48.991	97.981	146.969	10^3 - 10^4
HCN	88.631	177.260	265.886	10^5
HCO^+	89.188	178.375	267.557	10^5
SiO	43.122	86.243	130.268	10^3 - 10^4

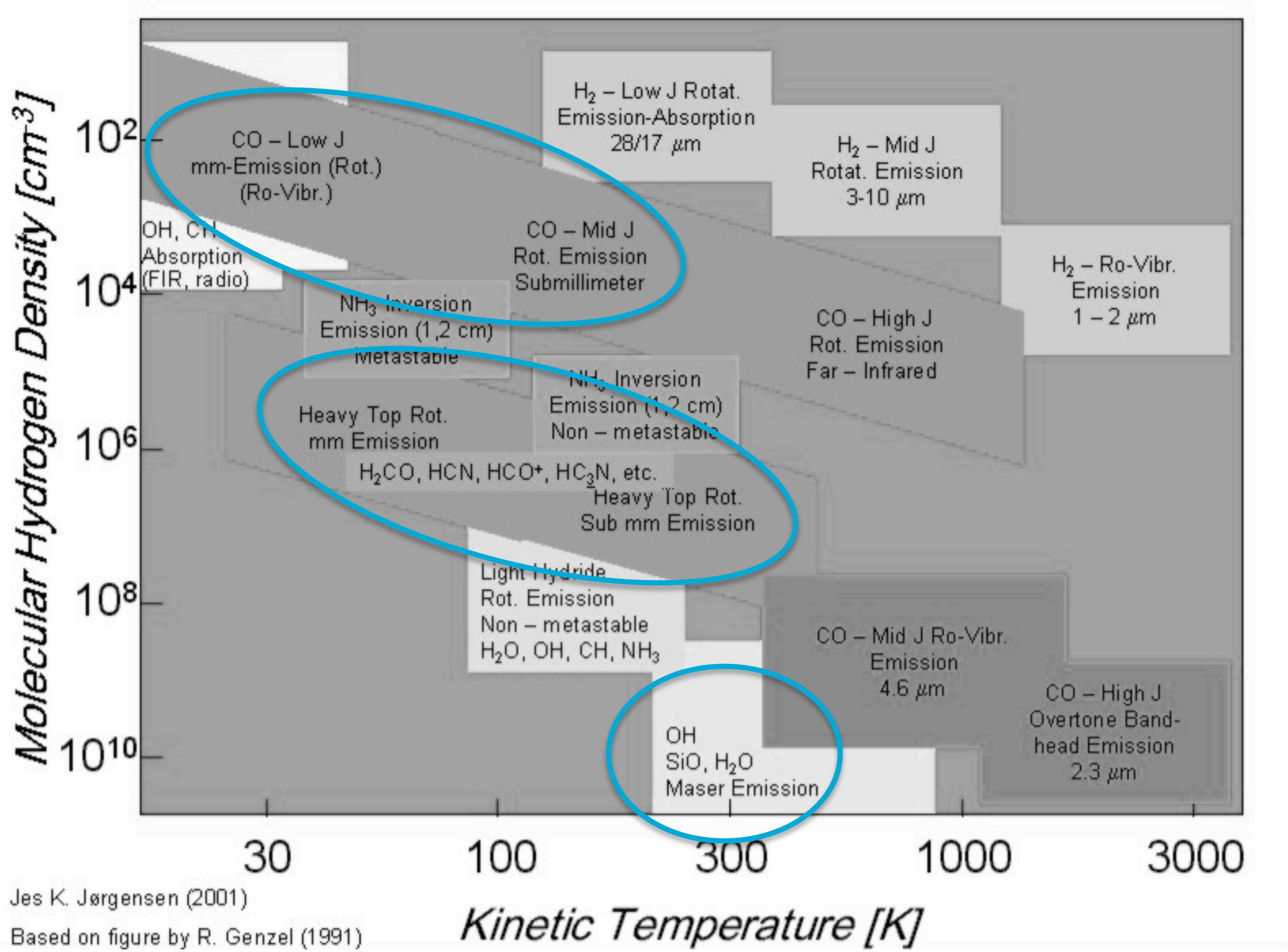
List of currently known interstellar molecules

H_2	HD	H_3+	H_2D+				
CH	CH^+	C_2	CH_2	C_2H	*C_3		
CH_3	C_2H_2	C_3H(lin)	c-C_3H	*CH_4	C_4		
c-C_3H_2	H_2CCC(lin)		C_4H	*C_5	*C_2H_4	C_5H	
H_2C_4(lin)	*HC_4H	CH_3C_2H	C_6H	*HC_6H	H_2C_6		
*C_7H	CH_3C_4H	C_8H	*C_6H_6				
OH	CO	CO+	H_2O	HCO	HCO+		
HOC+	C_2O	CO_2	H_3O+	HOCO+	H_2CO		
C_3O	CH_2CO	HCOOH	H_2COH+	CH_3OH	CH_2CHO		
CH_2CHOH	CH_2CHCHO		HC_2CHO	C_5O	CH_3CHO	c-C_2H_4O	
CH_3OCHO	CH_2OHCHO		CH_3COOH	CH_3OCH_3	CH_3CH_2OH	CH_3CH_2CHO	
$(CH_3)_2CO$	$HOCH_2CH_2OH$		$C_2H_5OCH_3$				
NH	CN	N_2	NH_2	HCN	HNC		
N_2H^+	NH_3	$HCNH^+$	H_2CN	HCCN	C_3N		
CH_2CN	CH_2NH	HC_2CN	HC_2NC	NH_2CN	C_3NH		
CH_3CN	CH_3NC	HC_3NH^+	*HC_4N	C_5N	CH_3NH_2		
CH_2CHCN	HC_5N	CH_3C_3N	CH_3CH_2CN	HC_7N	CH_3C_5N	HC_9N	$HC_{11}N$
NO	HNO	N2O	HNCO	NH2CHO			
SH	CS	SO	SO+	NS	SiH		
*SiC	SiN	SiO	SiS	HCl	*NaCl		
*AlCl	*KCl	HF	*AlF	*CP	PN		
H_2S	C_2S	SO_2	OCS	HCS+	c-SiC_2		
*SiCN	*SiNC	*NaCN	*MgCN	*MgNC	*AlNC		
H_2CS	HNCS	C_3S	c-SiC_3	*SiH_4	*SiC_4		
CH_3SH	C_5S	FeO					

Spectrum toward Orion



Probes of distinct physical conditions



Questions

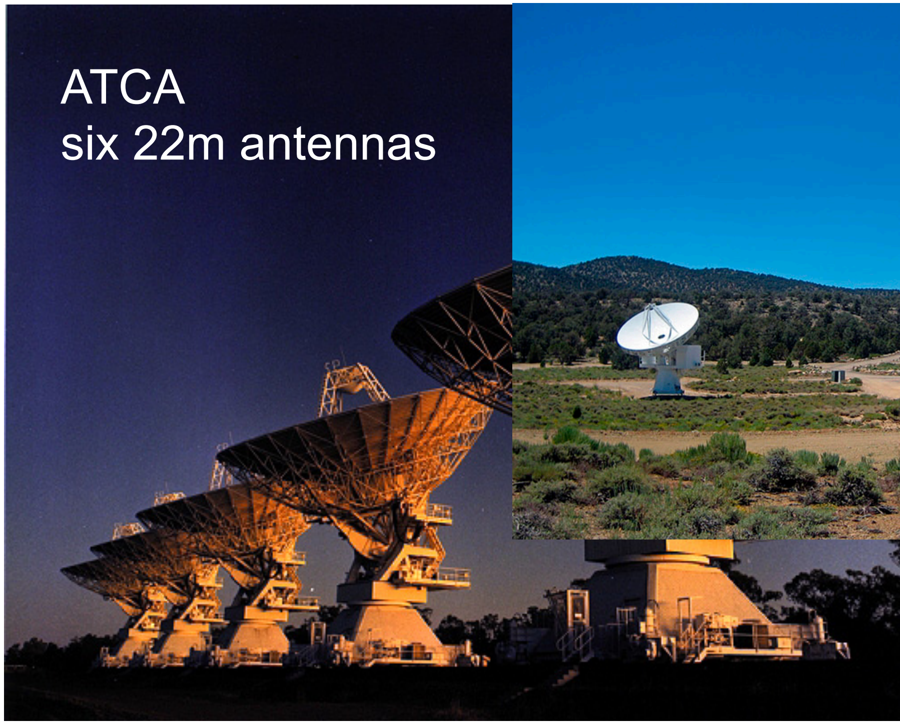
What is the dominant type of emission in the millimetre regime?

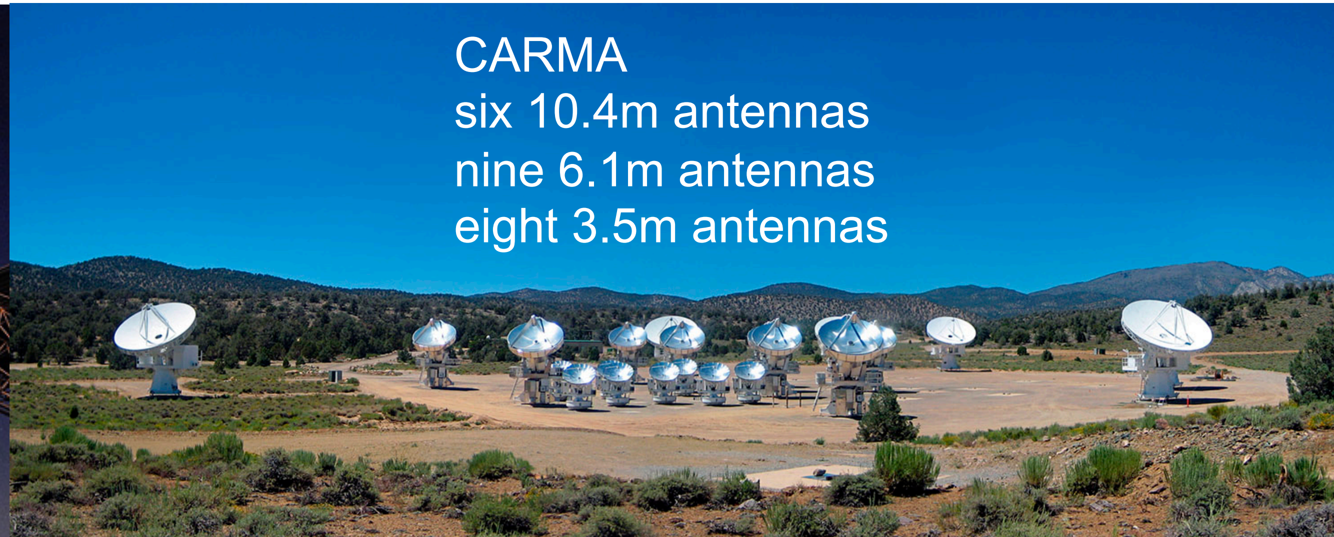
Name one molecule that emits in the millimetre regime

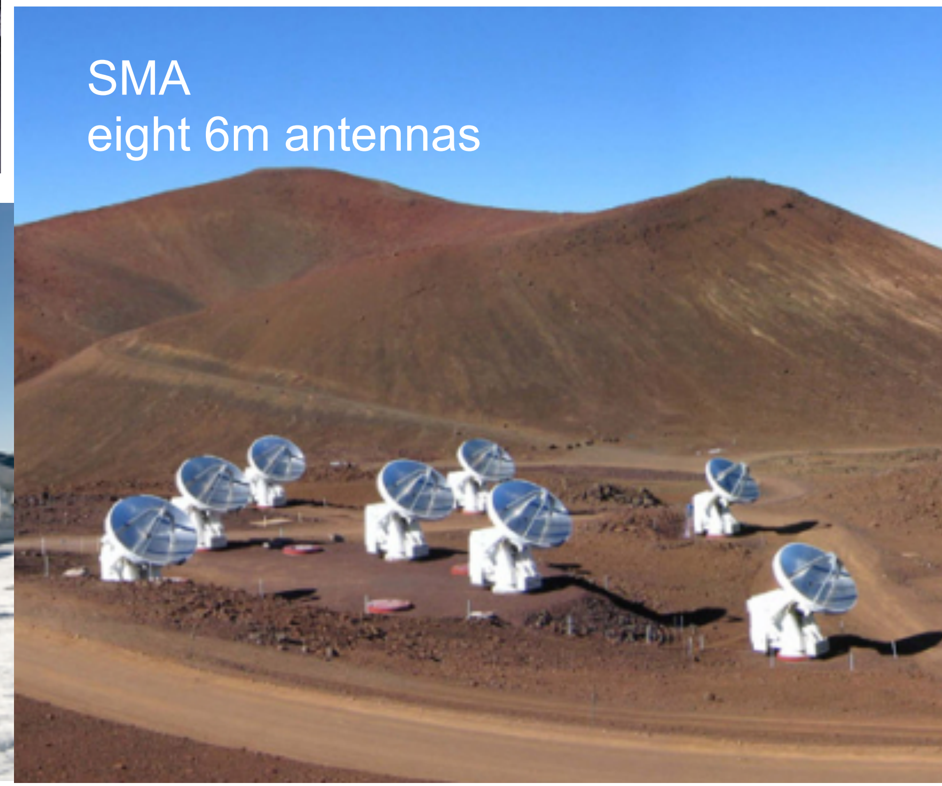
CSIRO

Millimetre telescopes

Mopra Australia 22m
CSO Hawaii 10.4m
NANTEN2 Chile 4m
Onsala Sweden 20m
JCMT Hawaii 15m
ASTE Chile 10m
GBT West Virginia 100m
SMT Arizona 10m
IRAM 30m Spain
LMT Mexico 50m
ARO Arizona 12m
Nobeyama Japan 45m
APEX Chile 12m


ATCA
six 22m antennas


CARMA
six 10.4m antennas
nine 6.1m antennas
eight 3.5m antennas


SMA
eight 6m antennas


IRAM Plateau de Bure
six 15m antennas

Atacama Large Millimetre Array (ALMA)

- 5000m, Chajnantor plateau, Chile
- 66 antennas
  - Main array, fifty 12-m antennas
  - Atacama Compact Array (ACA), twelve 7-m and four 12-m antennas
- 0.4mm - 4mm (84 GHz -720 GHz)
- Movable antennas, baselines from 125m to 16 km
  - Compact configurations : 0.7" at 675 GHz to 4.8" at 110 GHz
  - Extended configuration: 6 mas at 675 GHz to 37 mas at 110 GHz
- Early science starts Sept 30, Cycle 1 starts July 2012

Mopra : mm specifications

- 22 m telescope
- 3mm, 7mm, 12mm receivers
- MOPS: flexible, 8 GHz bandwidth
- Single spectrum at 115 GHz
  - 30 mins (on+off) with $T_A^* \sim 0.3$ K
- Map 3'x 3' area in 16 different lines (90 GHz)
  - ~30 mins with $T_A^* \sim 0.2$ K
- Routine remote observing
- Fully automated observing mode

	Wideband Mode		Zoom Mode	
Receiver	Bandwidth	Resolution	Bandwidth	Resolution
12-mm (22GHz)	112 050 km/s	3.38 km/s	1 863 km/s	0.41 km/s
7-mm (44 GHz)	56 025 km/s	1.69 km/s	932 km/s	0.21 km/s
3-mm (90 GHz)	30 378 km/s	0.915 km/s	505 km/s	0.11 km/s

CSIRO

ATCA: mm specifications

Frequency	16 - 26 GHz (12 mm)	30 - 50 GHz (7 mm)	85 - 105 GHz (3 mm)
T_{sys}	~ 60 K	~ 90 K	200 - 500 K
Primary Beam	2′ at 22 GHz	1′ at 45 GHz	33″ at 88 GHz
Synthesized Beam (H214)	10″	5″	2.4″
8 GHz Bandwidth (Δv)	110 km / s 0.2 km / s	53 km / s 0.1 km / s	28 km / s 0.05 km / s
6 hr rms noise (continuum)	0.05 mJy / beam 0.002 K	0.1 mJy / beam 0.003 K	0.7 mJy / beam 0.02 K

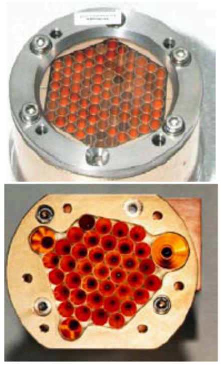
Parkes: mm specifications

Receiver	Band	Range	Diameter	FWHM	T_{sys}	Sens	Pol	Bandwidth
K-band	12 mm	21–24 GHz	55 m	1.5’	105 K	3.5 Jy/K	2 circ	500 MHz

Receivers

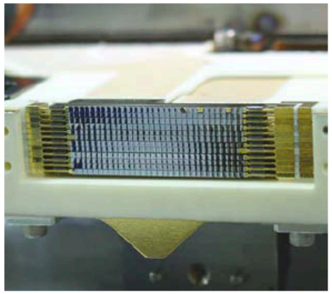
- Hetrodyne receivers
  - Molecular line observations
  - Bandwidths of few MHz (spectroscopy), 1-8 GHz (continuum)
- Bolometer receivers
  - Dust continuum emission
  - Sensitivity through bandwidth (~100 GHz)

JCMT-SCUBA 450/850μm



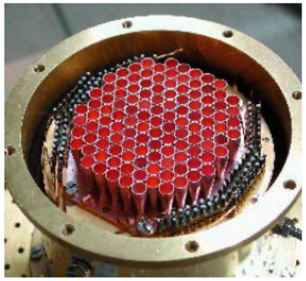
91/37 pixels

CSO-SHARCII 350μm



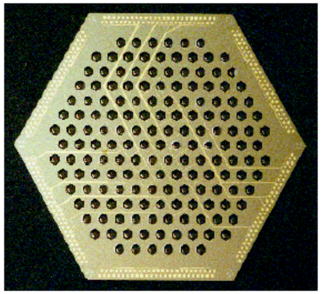
384 pixels

IRAM-MAMBO-2 1.2mm



117 pixels

CSO-BOLOCAM 1.4mm



151 pixels

Questions

Name a millimetre telescope

Name a millimetre array

How many mm receivers are there on Mopra, ATCA, Parkes?

Special considerations for millimetre observations

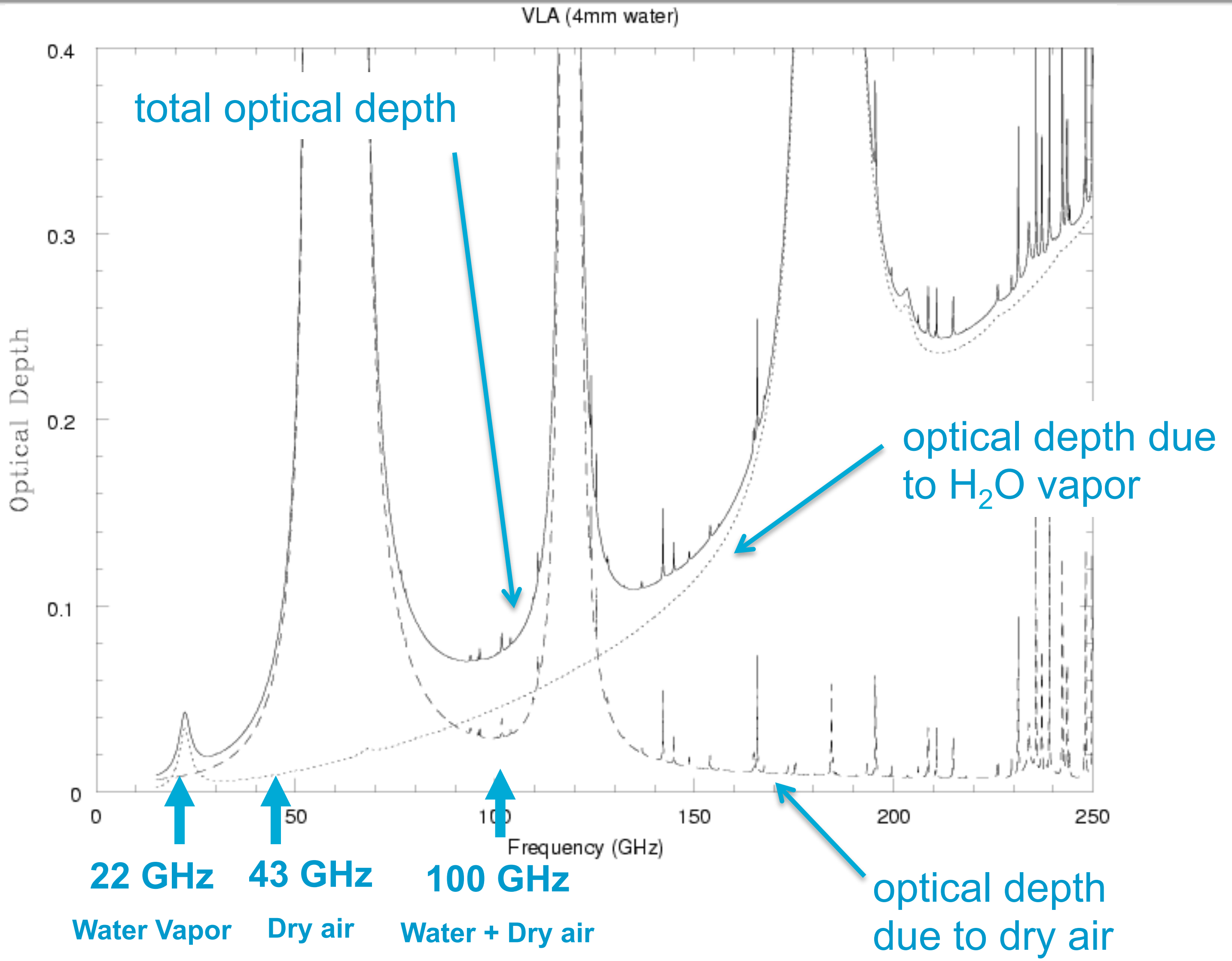
Special considerations for mm observations

Observing is more difficult at higher frequencies

- Atmospheric opacity increases T_{sys} and attenuates the signal
  - Opacity varies with frequency, altitude, and weather conditions
  - Observatory sites need to be high, dry, cold

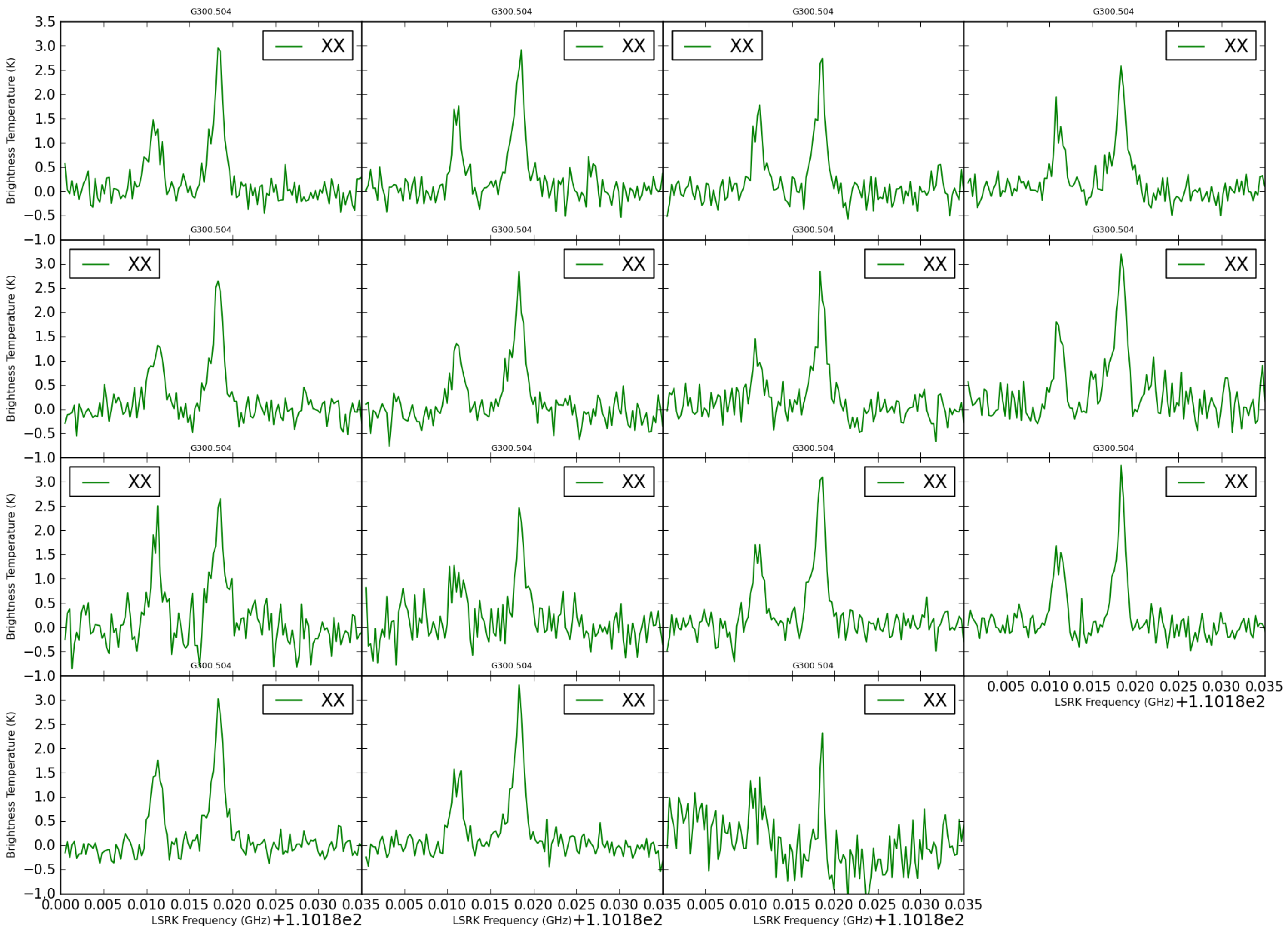
- Field of view (antenna primary beam) is smaller
  - Pointing accuracy needs to be monitored
  - Pointing checked every hour
  - Telescope moved to different part of sky

The atmosphere is very important in mm regime



CSIRO

Atmosphere adds noise and reduces signal



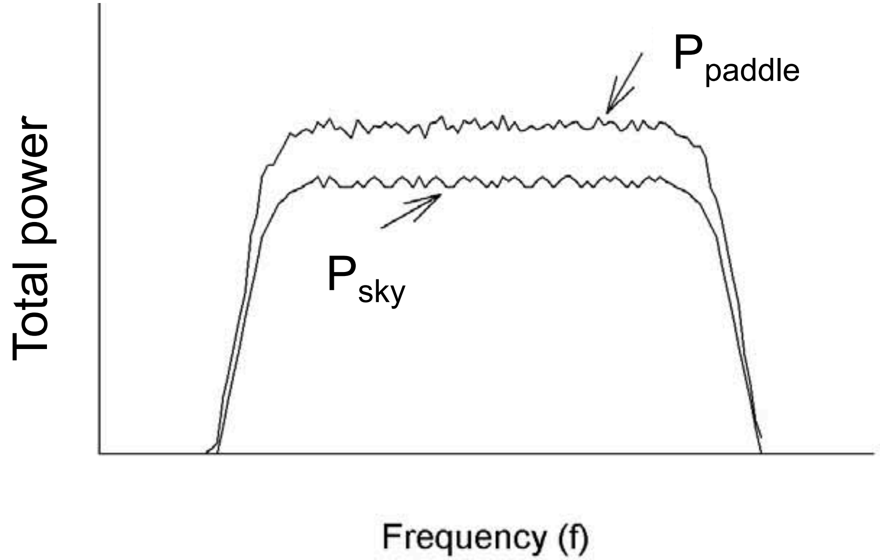
CSIRO

Accounting for atmospheric effects

- At 3mm, T_{sys} and atmospheric attenuation is measured using the "paddle" method
  - Placing an ambient load (paddle) in front of the receiver horn for 30 sec
  - Gives a T_{sys} corrected for the current atmospheric conditions

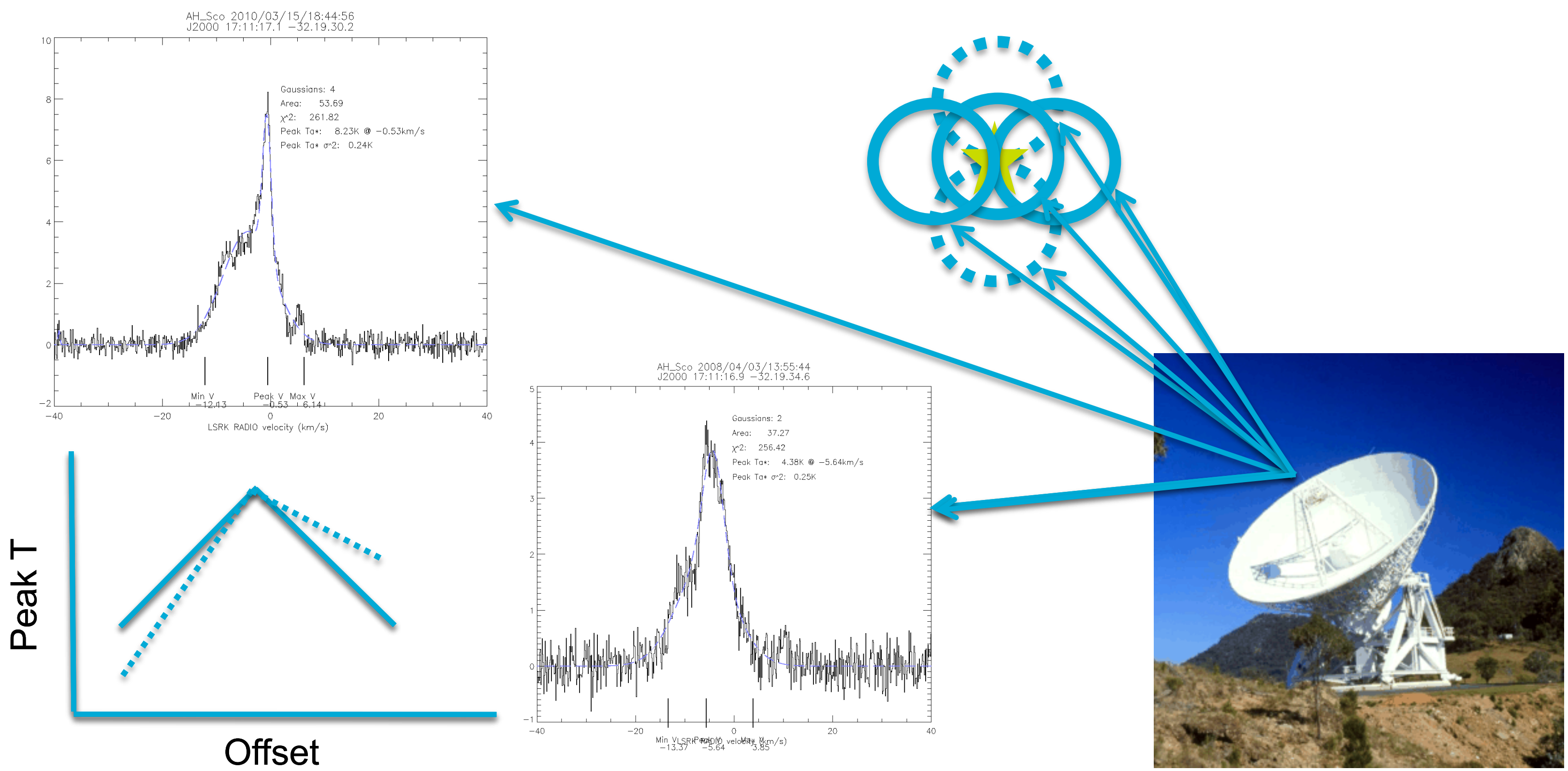
$$T_{sys}^{eff} = (300\text{ K}) \frac{P_{sky}}{P_{paddle} - P_{sky}}$$

- Frequent measurements (every ~15 mins)



Accounting for the small beam

- Frequent pointing checks
  - SiO masers (at 7mm and 3mm) and H_2O masers (at 12mm) for Morpa
  - Bright continuum sources (> 0.5 – 1 Jy) for ATCA
  - Choose one that is close to the science target



Questions

What is the major concern for mm observations?

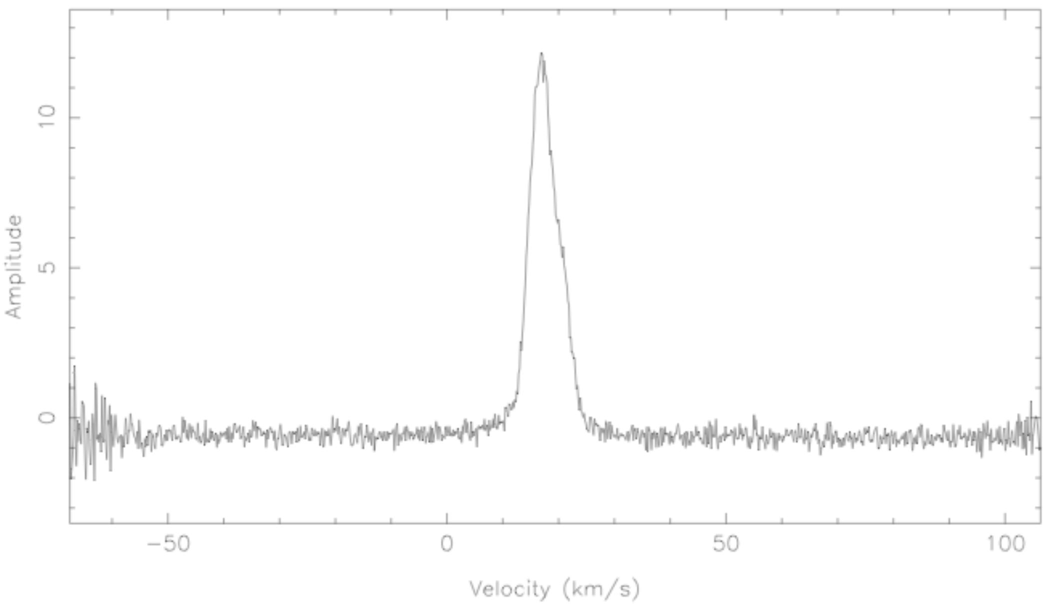
How do we correct for atmospheric opacity?

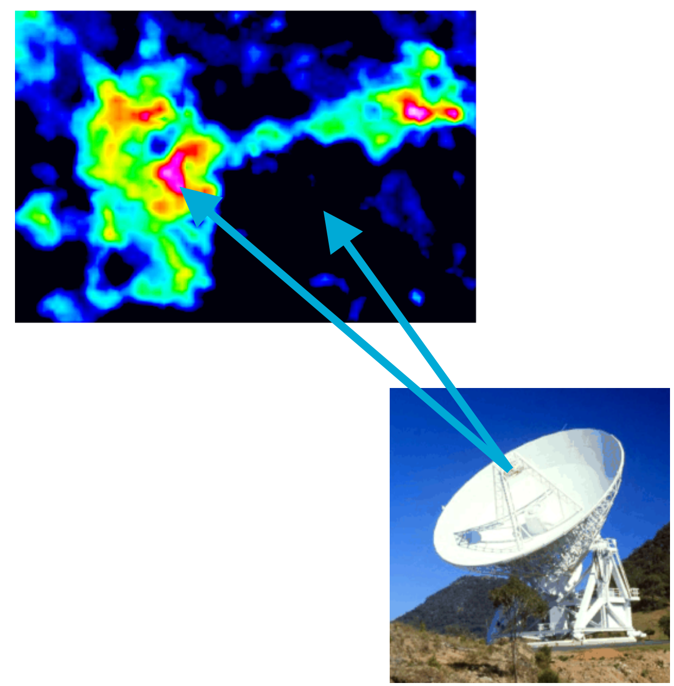
Typical observing modes

Typical observing modes : line observations

- Position switching
  - Telescope moves between an on source position and a “reference” (signal free) position
  - Deep integrations, single position, half of the time spent off source
  - Flat baselines

$T_{ON} - T_{OFF} / T_{OFF}$ = Quotient Spectrum

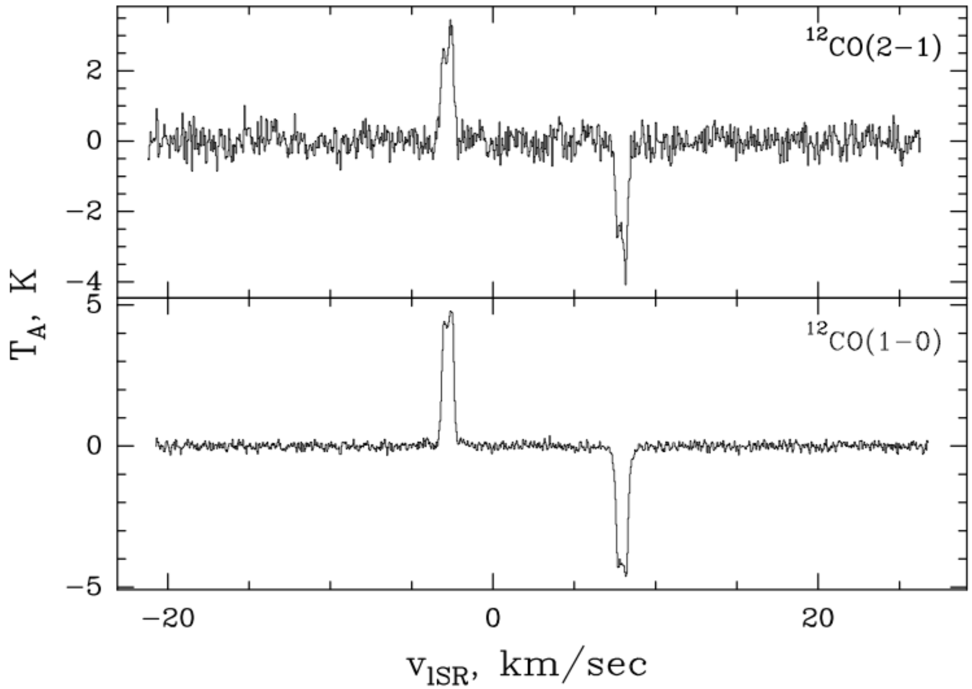


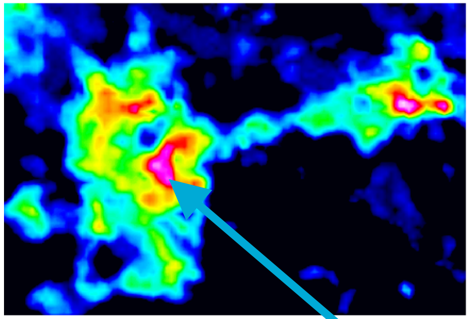


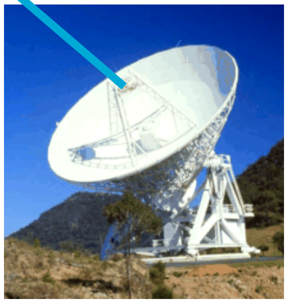
Typical observing modes : line observations

- Frequency switching
  - Software switches between two frequencies
  - All time spent on source
  - Simple, narrow line profile, at known V_{LSR}
  - Bad baselines

$T_{ON} – T_{OFF} / T_{OFF}$ = Quotient Spectrum

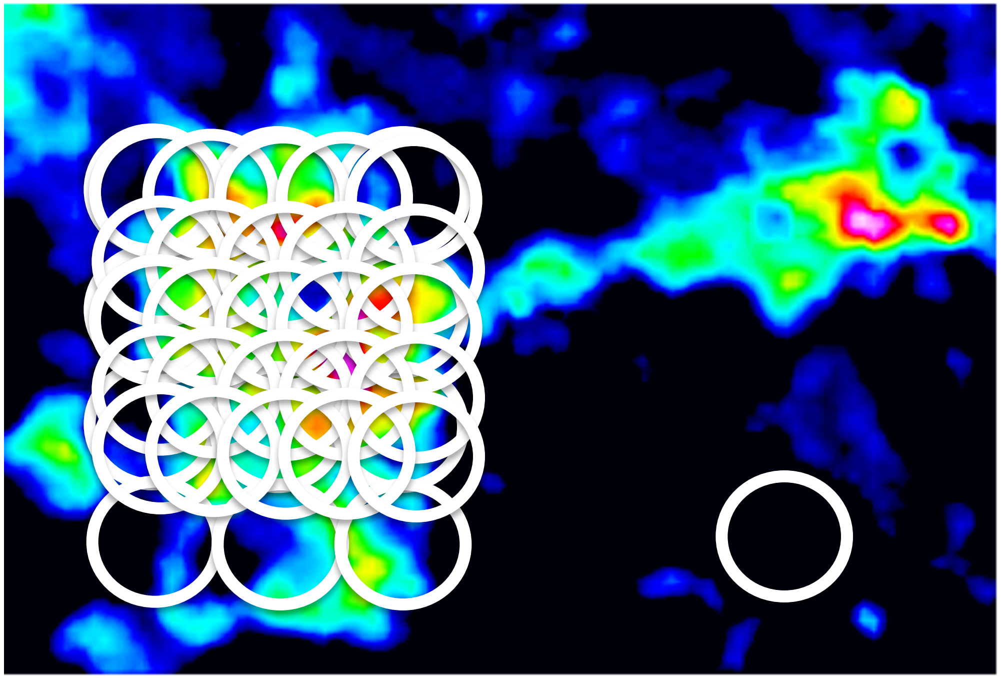






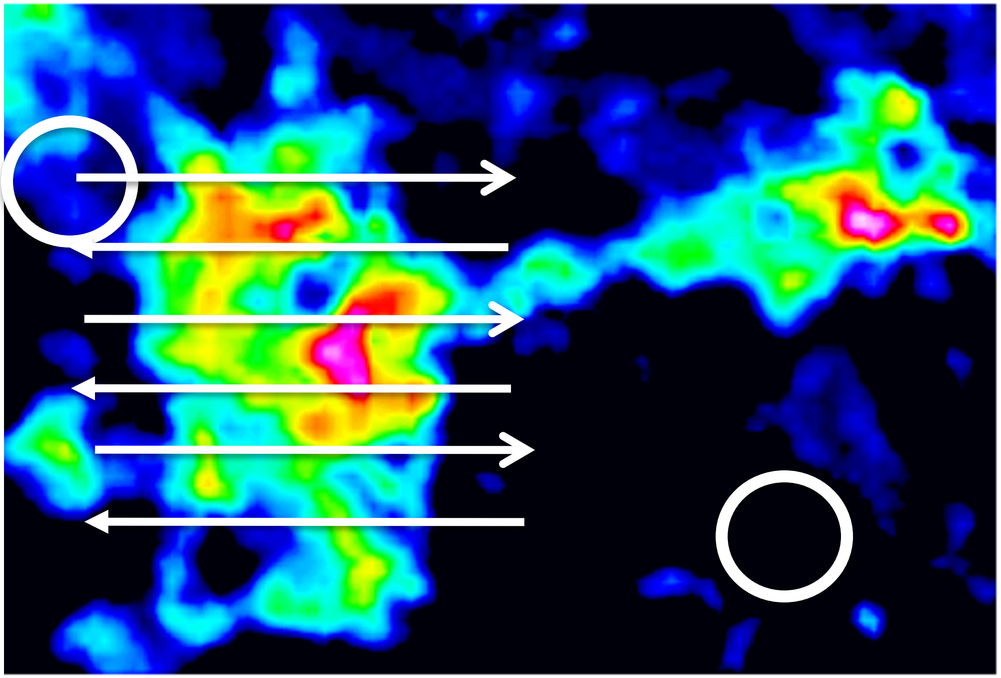
Typical observing modes : line observations

- Mapping
  - Specified grid, position switch observations at each point
  - Choose sampling: Beam, Nyquist
  - Deep observations at all points
  - Extended (few arcmin) sources



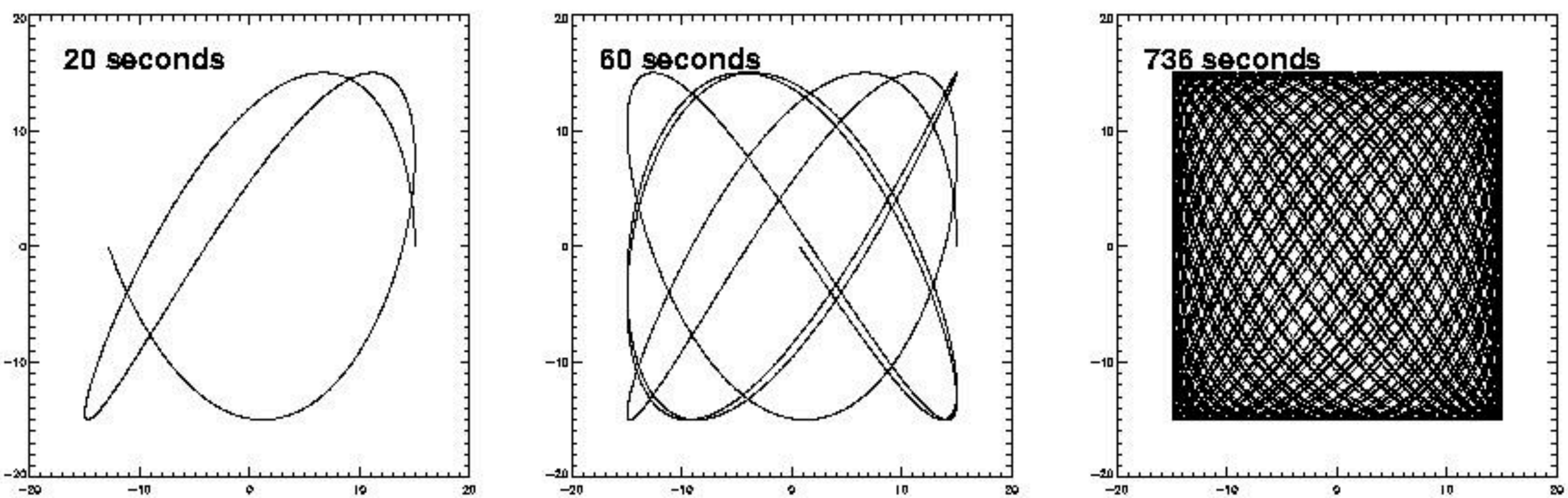
Typical observing modes : line observations

- On-The-Fly (OTF) mapping
  - Scan telescope across a region, continuously takes data
  - Re-sampled to a regular grid in data reduction
  - More efficient, cover large areas quickly
  - Lines need to be bright



Typical observing modes : continuum observations

- Bolometer arrays
  - OTF mapping
    - Sensitive to weather variations → stripes in map
    - Orthogonal scans and average
  - More complex patterns
    - Jiggle maps, Lissajous scan



CSIRO

Questions

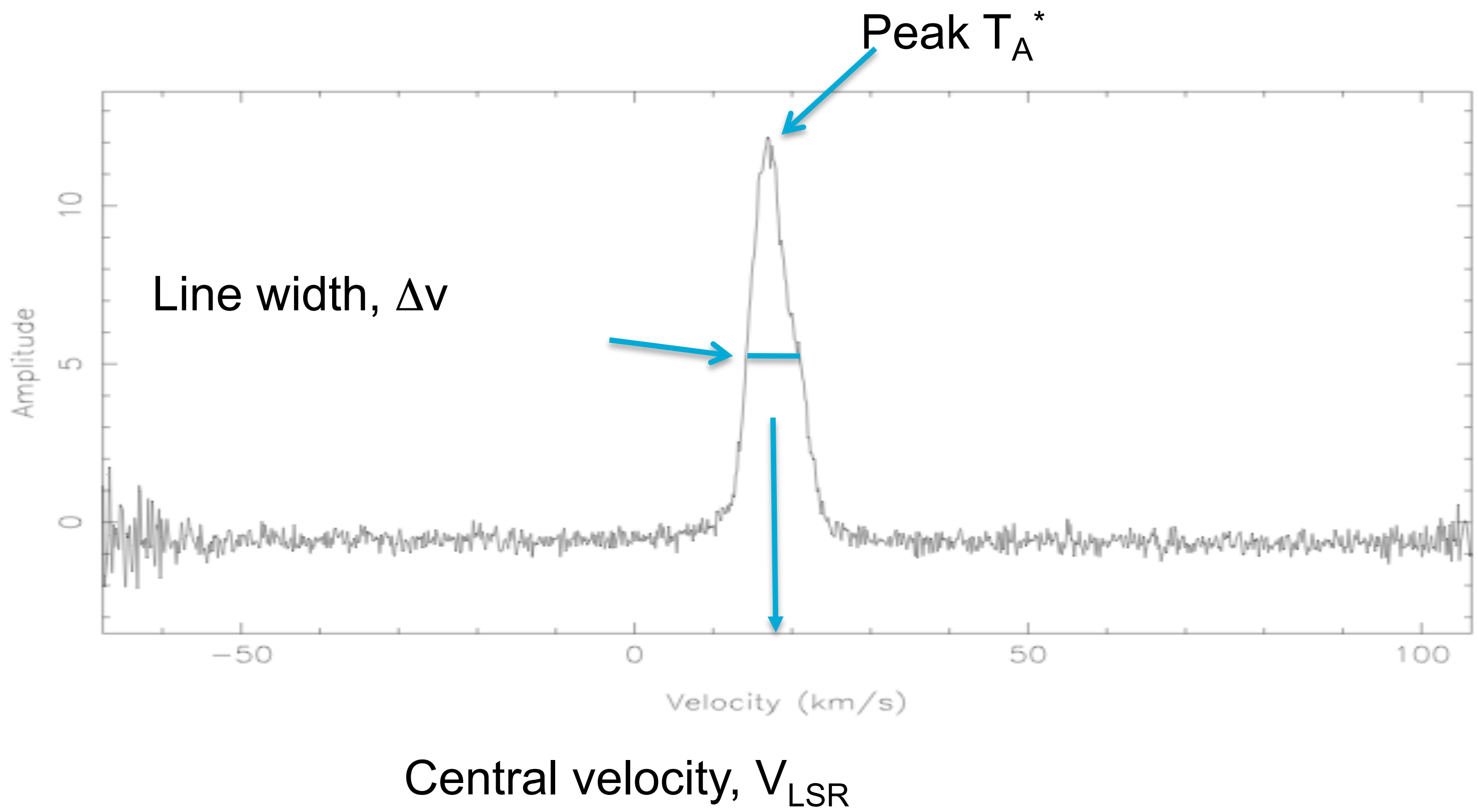
What observing mode should I use if I want to obtain a deep, spectrum of a compact source?

What does OTF stand for?

Physical properties derived from mm observations

Derived properties : line observations

- Measure directly from the emission lines
  - $V_{LSR,}$ line width, peak T_A^*



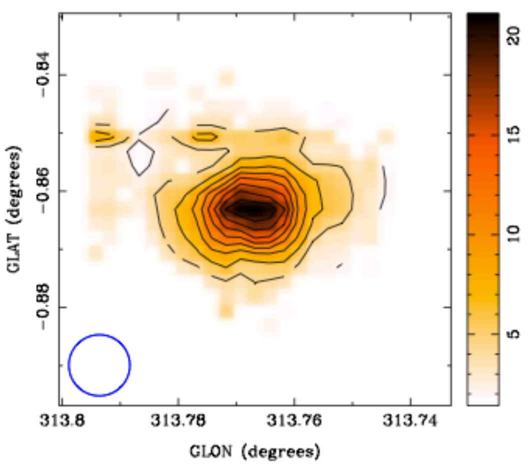
CSIRO

Derived properties : line observations

- Line emission at many points within a grid
  - Moment maps

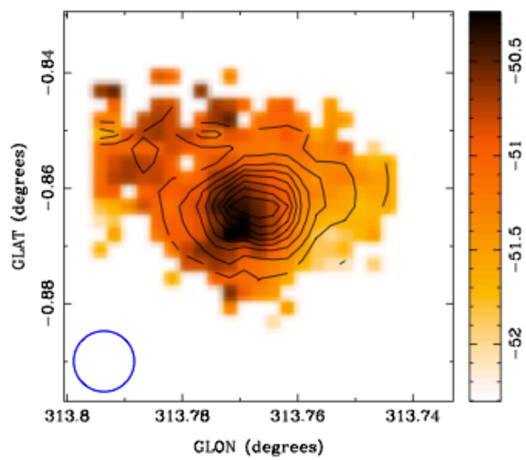
Integrated intensity

$$M_0 = \int I(\nu)\ d\nu$$



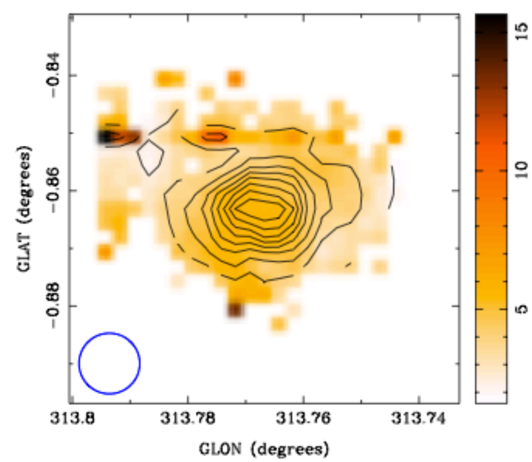
Intensity-weighted velocity

$$M_1 = \frac{1}{M_0}\int I(\nu)\nu\ d\nu$$



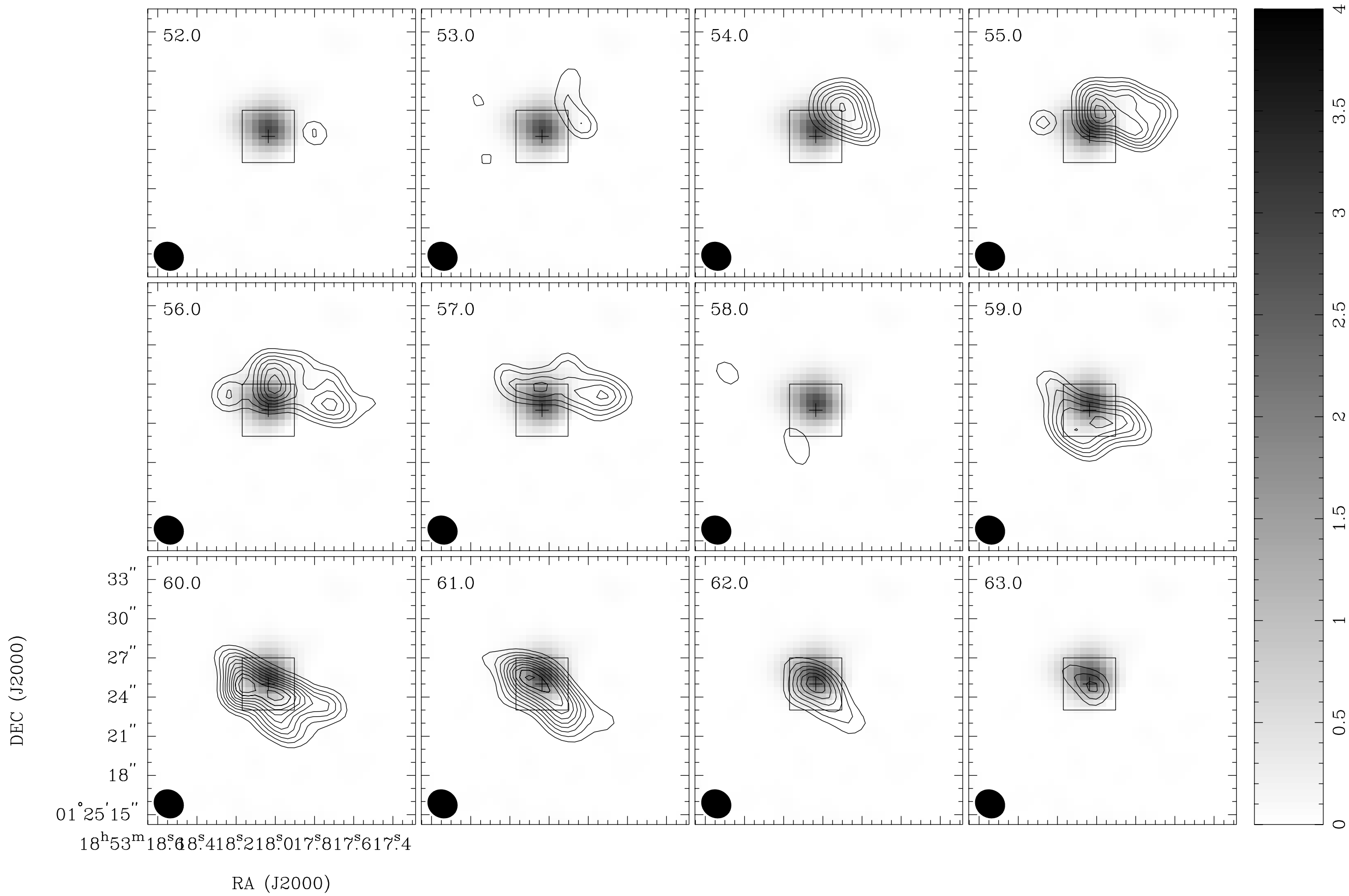
Intensity-weighted line width

$$M_2 = \sqrt{\frac{1}{M_0}\int I(\nu)(\nu - M_1)^2\ d\nu}$$

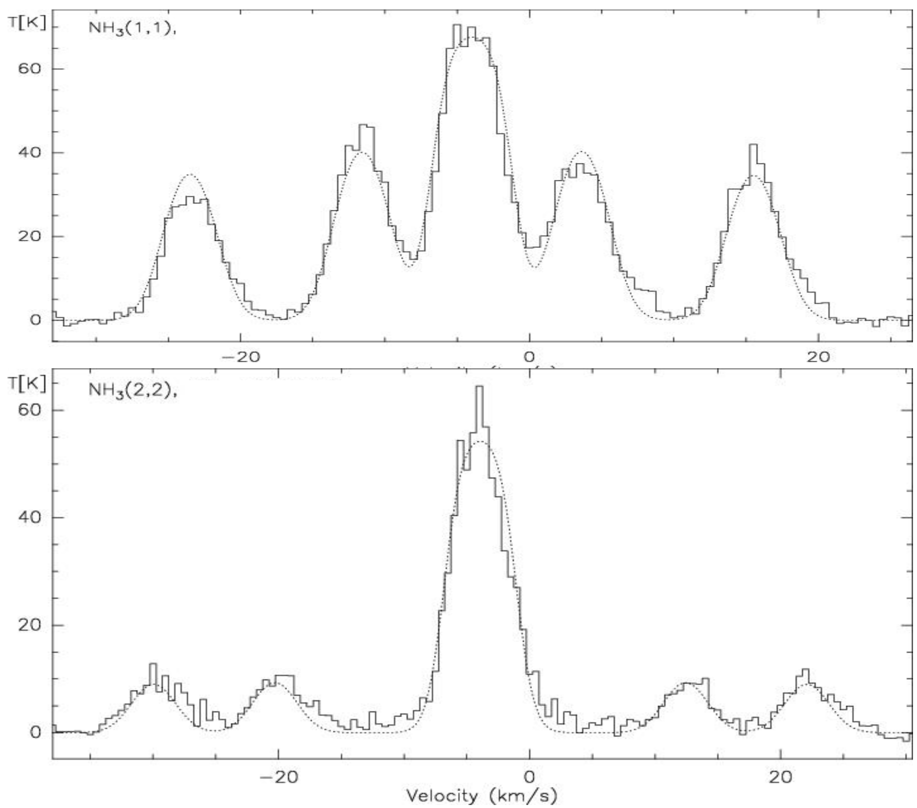


Derived properties : line observations

- Line emission at many points within a grid
  - Channel maps



Ammonia as a cloud thermometer



NH_3 (1,1) at 23.69 GHz
NH_3 (2,2) at 13.93 GHz

- NH_3 is an excellent diagnostic of kinematic temperature over a wide range of densities

- NH_3 (1,1) inversion transition
  - 18 hyperfine components
  - Optical depth, τ
  - Column density, $N(H_2)$

- Ratios of the NH3 (1,1) and (2,2)
  - Kinetic temperature, T_K
  - Density of the cores, $n(H_2)$

CO as a measure of H_2 density, mass

- CO mass

$$\left[\frac{M}{M_{sun}}\right] = 6.6\times10^{-24}\left[\frac{N(H_2)}{cm^{-2}}\right]\left[\frac{D}{pc}\right]^2\left[\frac{A}{\deg^2}\right] \qquad X_{CO} = \frac{I(CO)}{N(H_2)}$$

  - Galactic value: $X_{CO} \approx 2.8 \times 10^{20}$ cm^{-2} K (km s^{-1})$^{-1}$, uncertain (factors of 2-5)
  - To determine X_{co} we need an independent measure of the mass of the cloud and the distance in order to measure $N(H_2)$
    - dust extinction, dust emission, Virial mass
  - CO is usually optically thick

- Virial mass
  - Cloud's kinetic energy stabilizes it against gravitational collapse
  - Width of an emission line reflects the motion of the gas and ultimately the underlying mass

$$\left[\frac{M_{vir}}{M_{sun}}\right] = 1145\left[\frac{\Delta V}{km\,s^{-1}}\right]\left[\frac{D}{pc}\right]\left[\frac{A}{\deg^2}\right]^{0.5}$$

Derived properties : continuum observations

- Thermal emission from dust
  - Optically thin emission at (sub)mm wavelengths
  - Column density, mass

Assumes
- Dust temperature
- Dust emissivity
- Gas-to-dust ratio
- Distance

$$N_{\mathrm{H}} = \frac{S_\lambda}{\Omega B_\lambda(T_d)\kappa_\lambda \mu m_{\mathrm{H}}}$$

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{\exp(hc/\lambda kT) - 1}$$

$$\kappa_\lambda = \kappa_{1300}\left(\frac{\lambda}{1300\ \mu\mathrm{m}}\right)^{-\beta}$$

$$M = \frac{S_\lambda d^2}{\kappa_\lambda B_\lambda(T_d)}$$

Questions

What is the zeroth, first, and second moments of a spectral line?

What can ammonia be used as?

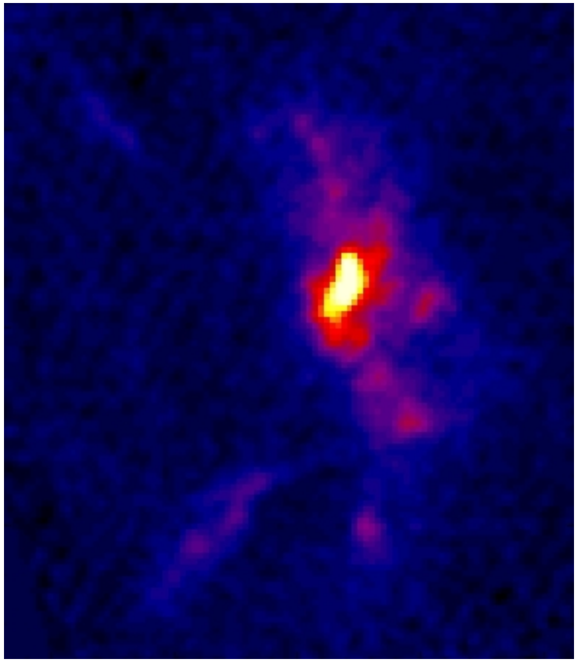
What is an assumption that needs to be made to calculate the dust mass?

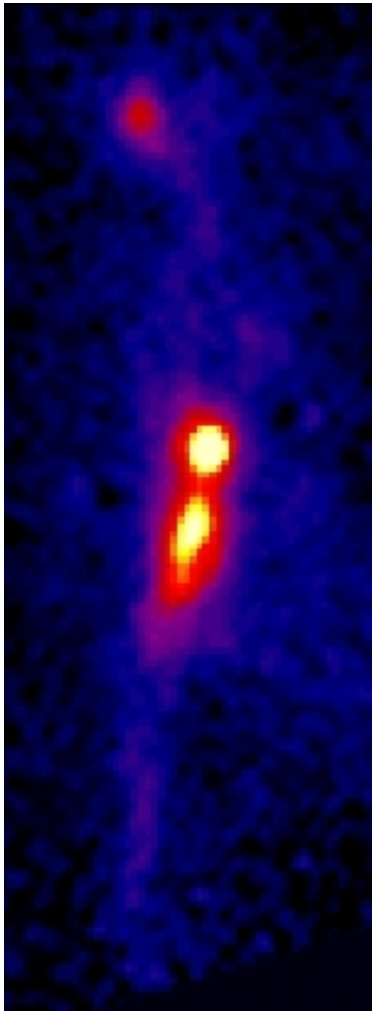
CSIRO

Science from millimetre observations

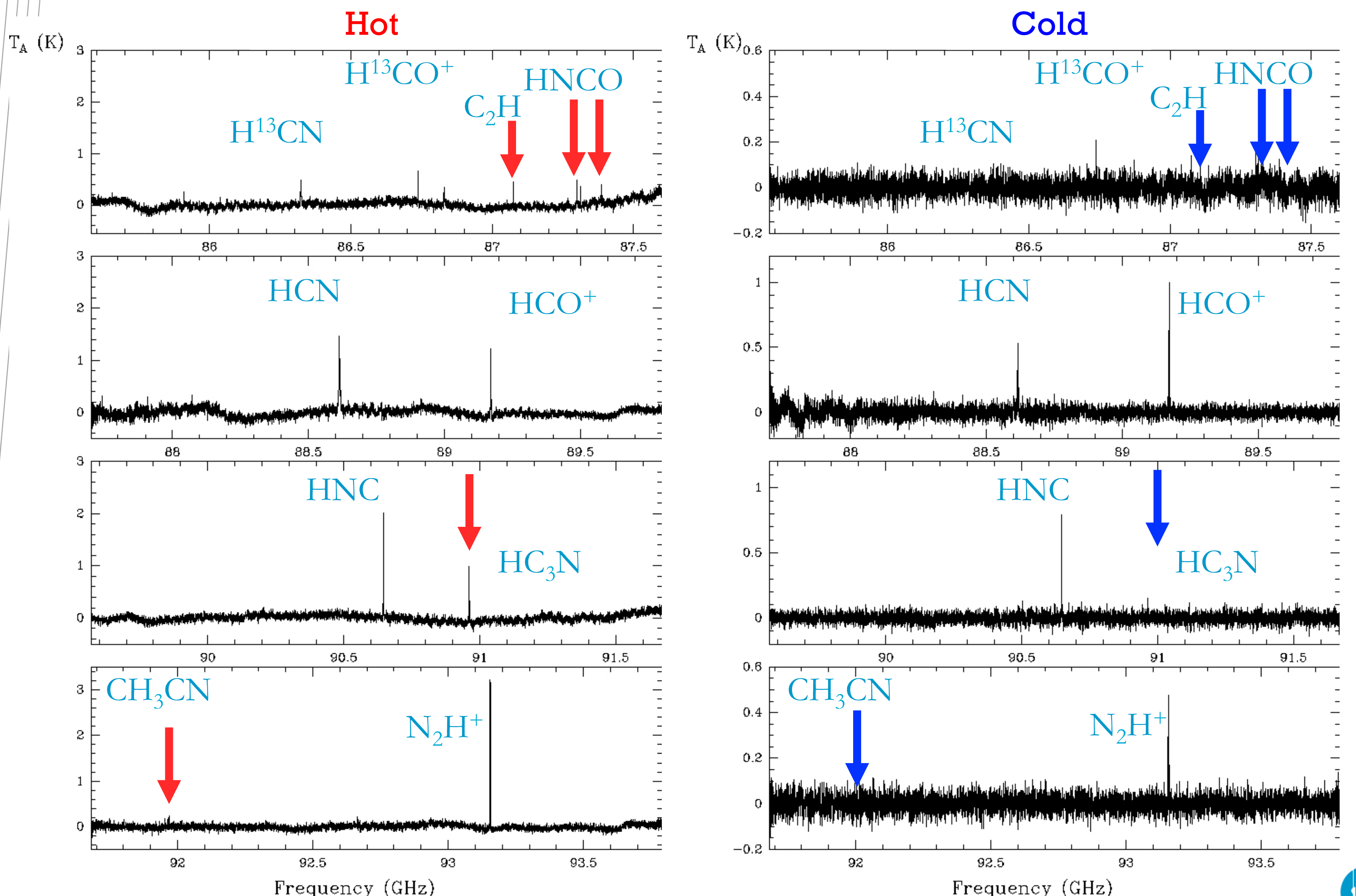
Dust continuum surveys

- ATLASGAL, Bolocam
- Continuum emission across the galaxy
  - Filaments are ubiquitous
  - Derive masses, sizes of cores
  - Core formation
  - CMF → IMF
  - High-mass star-formation
  - Cluster formation



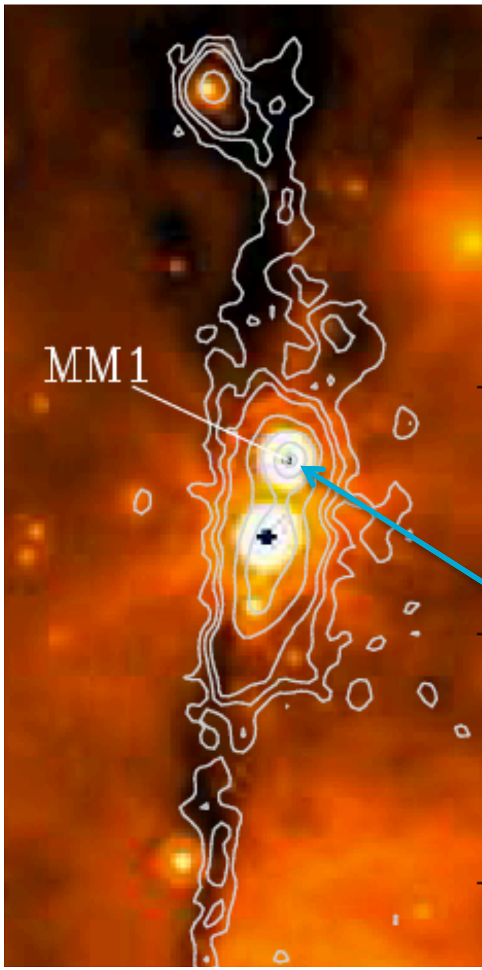


Star forming cores : hot vs cold gas

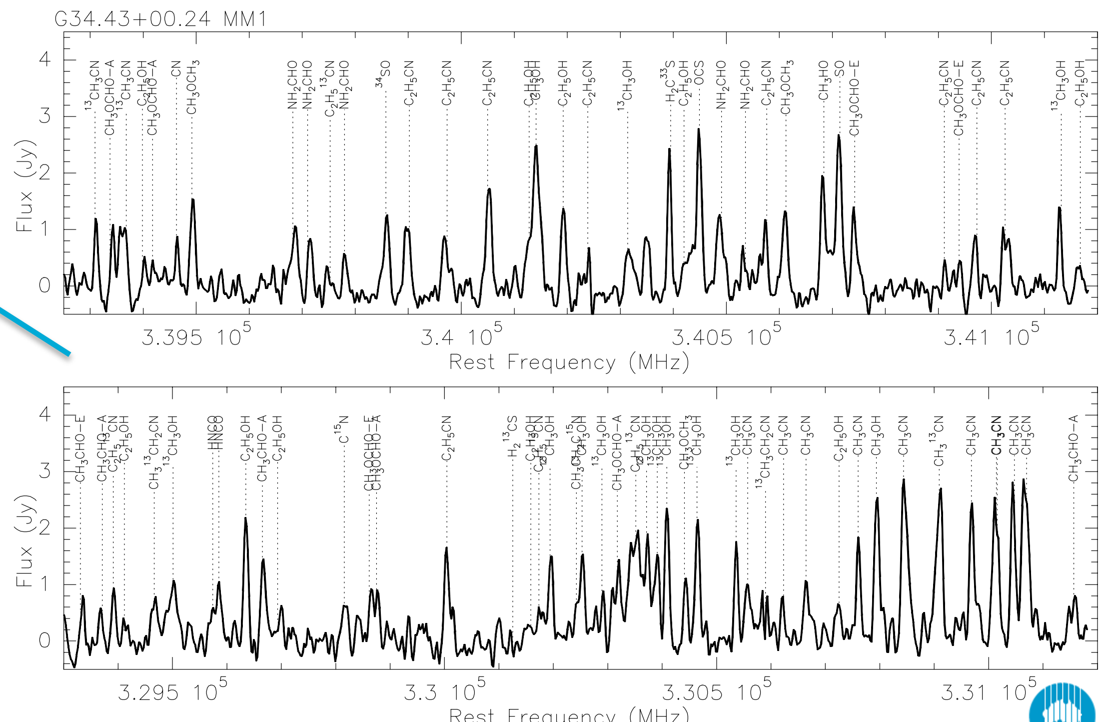


CSIRO

Early stages of high-mass star-formation



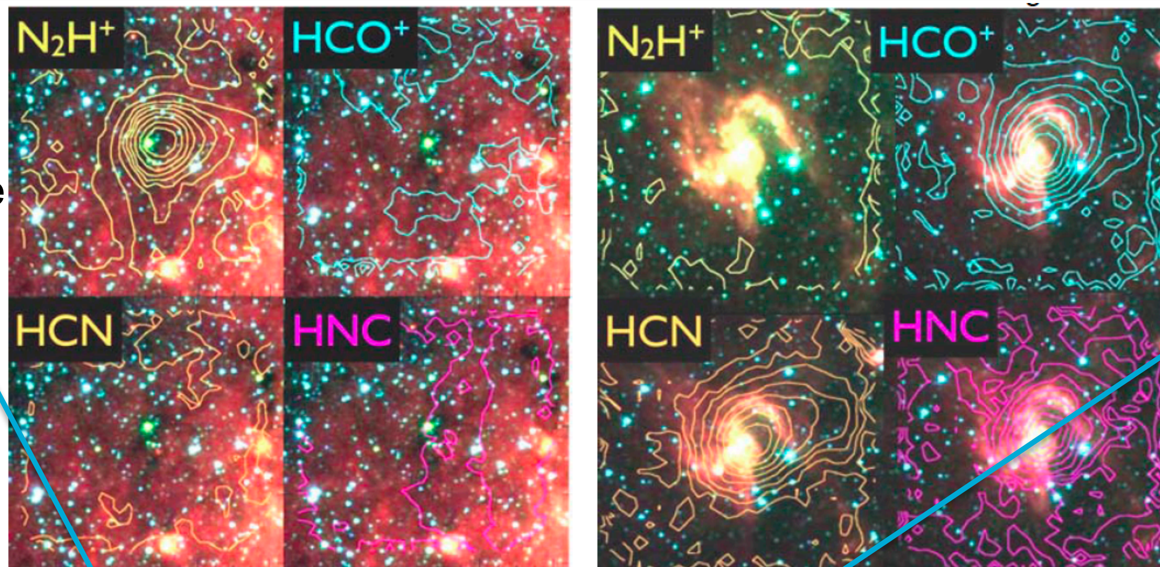
- Bright 24μm emission → protostar
- Emission from many complex molecules
  - Excited by UV radiation from a high-mass star
  - Trace regions in the immediate vicinity of a recently formed, high-mass star



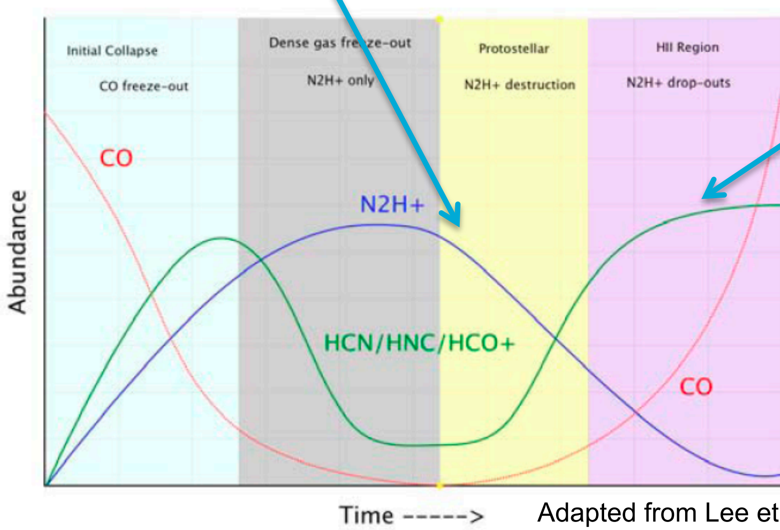
Chemistry, core evolution

High N_2H^+ abundance

Low N_2H^+ abundance



Spitzer/IRAC images (3, 4.5, 8μm) with contours of molecular line integrated emission from MALT90



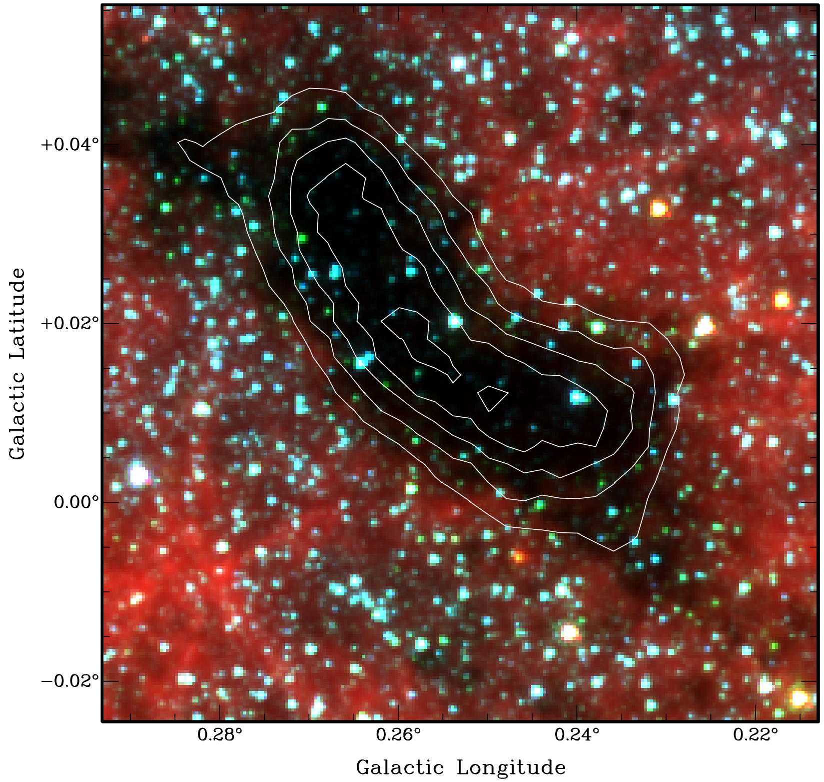
Adapted from Lee et al. (2004)

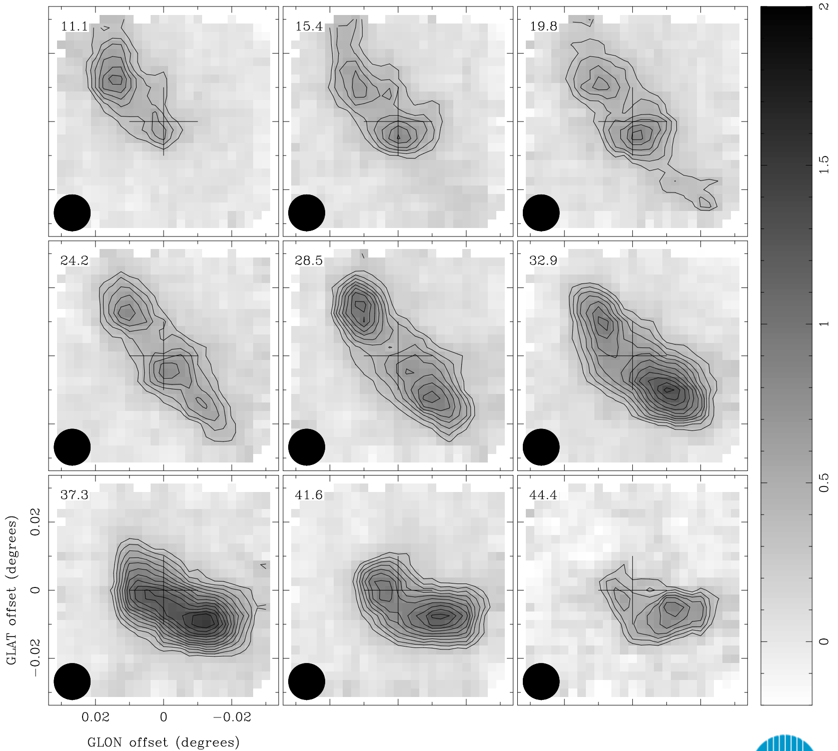
These chemical variations likely indicate special phases in a core's chemical evolution

CSIRO

Cluster formation : cold dust, dense gas

- Early stages of high-mass star and cluster formation
  - Cold, dense molecular clouds
  - Seen as extinction features against the bright mid-IR background
  - Very bright in mm dust continuum and in dense molecular gas tracers





CSIRO

Summary

- Millimetre astronomy is great!

- Probe of cool gas and dust in the nearby and distant universe

- Emission is brighter at higher frequencies
- Forest of molecular lines
- Observing is more difficult

Learning to use millimetre facilities will give you the skills to best utilize next-generation telescopes like ALMA

Postdoctoral fellowships at CSIRO

- Bolton Fellowship
  - *Australia's longest standing fellowship and provides an outstanding opportunity for post-doctoral astronomy research in Australia. The Bolton Fellowship is designed to help young scientists establish their research careers by undertaking independent research and/or development projects in any area relevant to the Australia Telescope National Facility (ATNF) observational capabilities.*
  - Deadline : November 15, 2011
- OCE postdoctoral fellow (MALT90)
  - *We are seeking a motivated postdoctoral researcher to join CSIRO to drive scientific output and follow-up projects that fully exploit the MALT90 dataset. The post-doc will also have an opportunity to pursue a strong independent research program in high-mass star formation studies.*
  - Deadline : November 15, 2011
- Australis Fellow
  - *Joint post-doctoral research position in the field of star formation collaborating with Dr Kate Brooks, Dr Jill Rathborne (CSIRO), and Prof. Guido Garay (UChile). The Australis Fellow is expected to spend half of the time between Chile and Australia.*
  - *For the duration of the Fellowship the appointee will have access to the 10% observing time reserved for Chilean astronomers on all astronomical facilities in Chile.*
  - Deadline : December 1, 2011

www.csiro.au

Thank you

Jill Rathborne

Parkes Radio School - September 2011

CSIRO