

Single Dish Spectral Line Observing

Dr Andrew Walsh
James Cook University



Image Courtesy: Cormac Purcell

Outline

- Introduction to Spectral Lines
- Examples of Spectral Line Features
- Data Cubes and Moment Maps
- Column Density and Rotation Diagrams
- Atoms, Molecules, Ions and Radicals in Space

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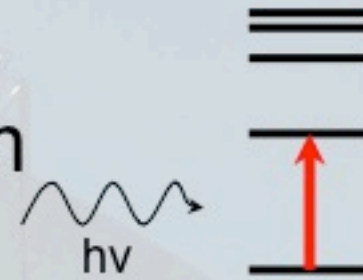
- Mention talking about the outline
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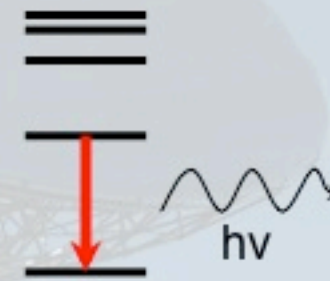
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Three basic processes:

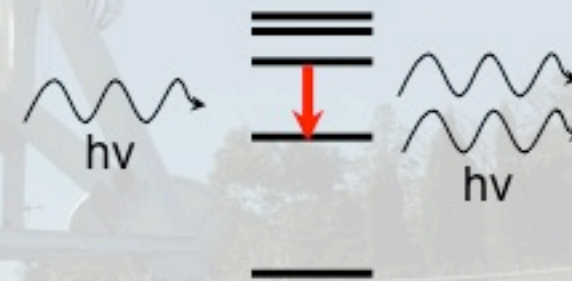
- Absorption against continuum



- Spontaneous emission



- Stimulated emission
(maser)



Energy levels

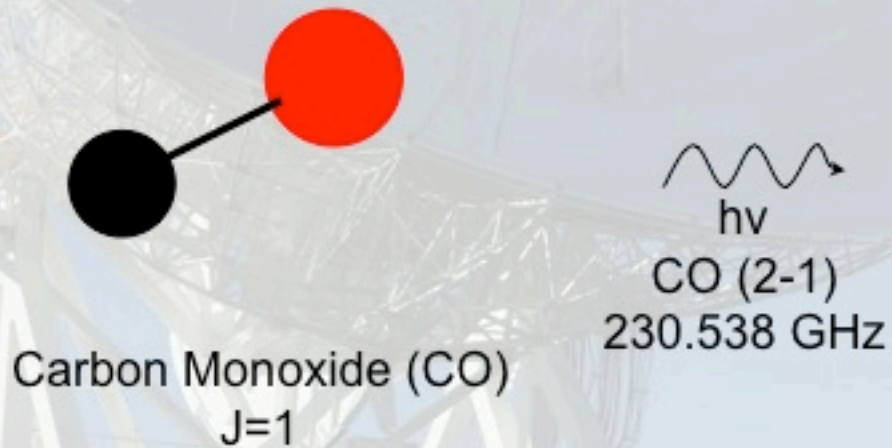
- Rotation



Carbon Monoxide (CO)
J=2

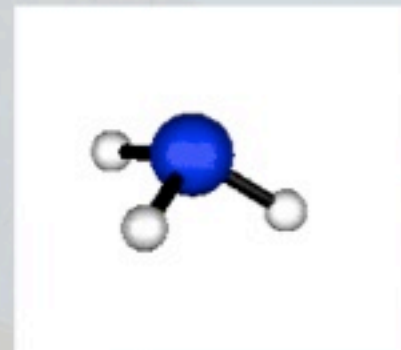
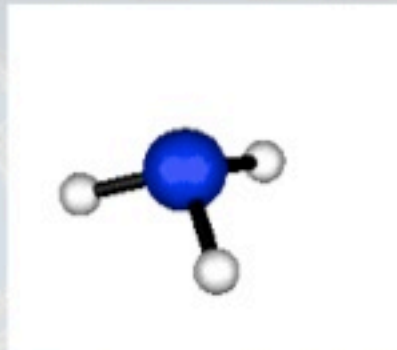
Energy levels

- Rotation



Energy levels

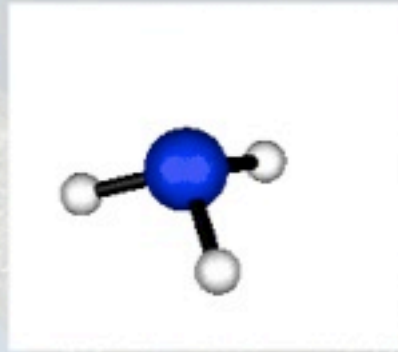
- Rotation
- Vibration



Ammonia (NH₃)

Energy levels

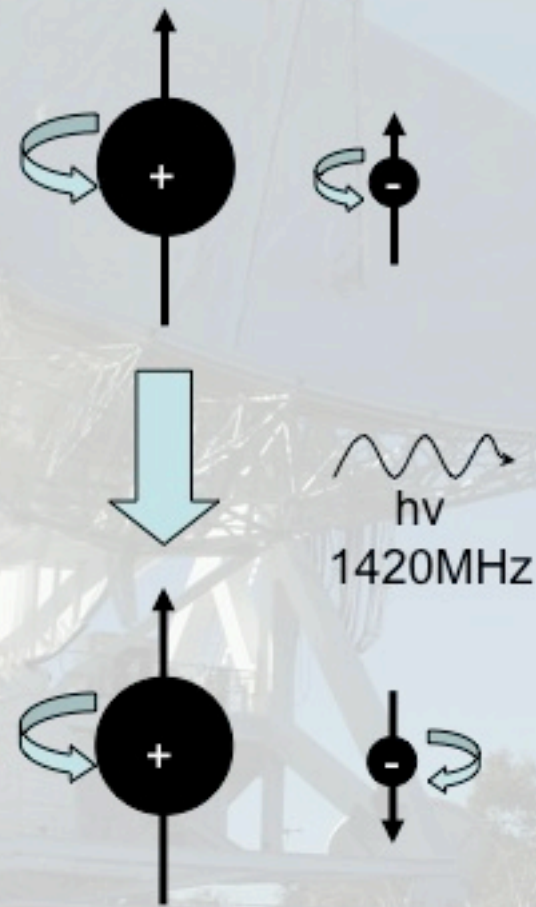
- Rotation
- Vibration
- Inversion



Ammonia (NH₃)

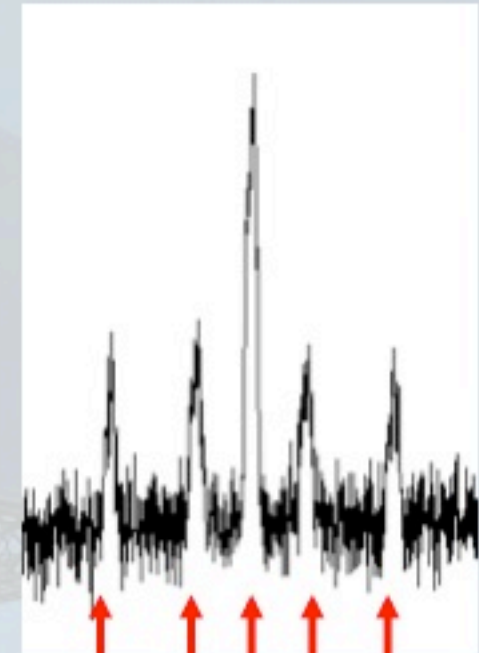
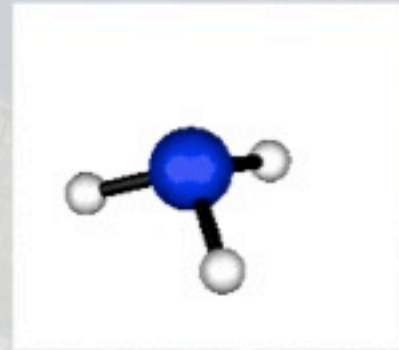
Energy levels

- Rotation
- Vibration
- Inversion
- Hyperfine/spin-flip



Energy levels

- Rotation
- Vibration
- Inversion
- Hyperfine/spin-flip

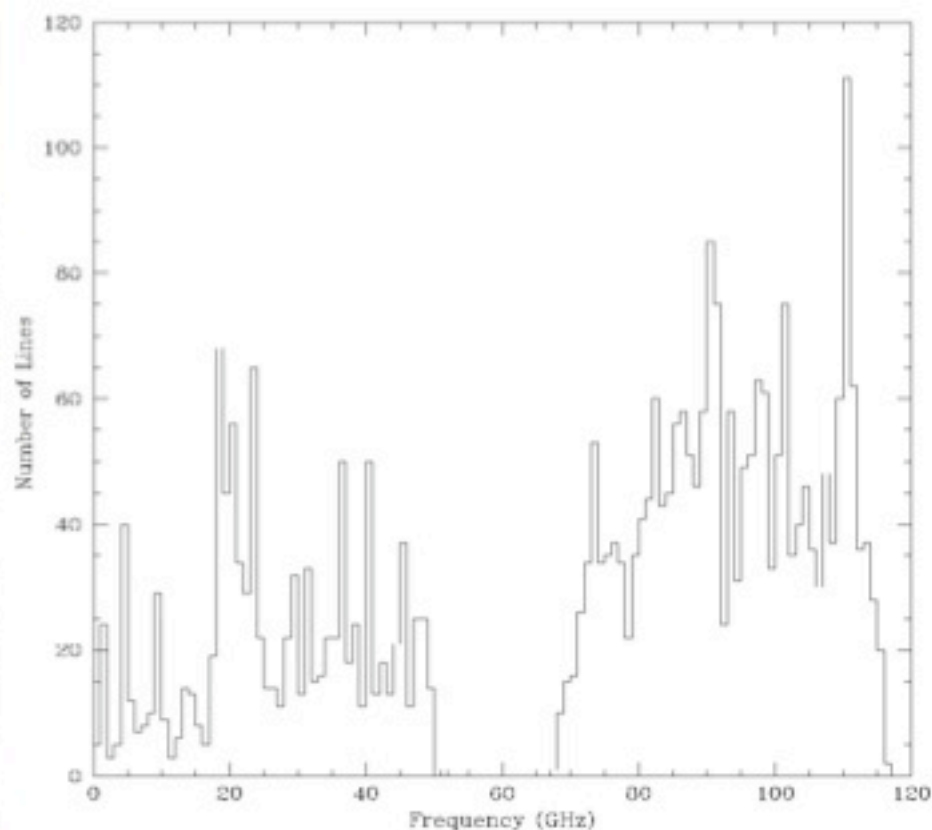


Ammonia hyperfine structure

Spectral Line Observing Across the Frequencies

Available Frequency range (GHz):

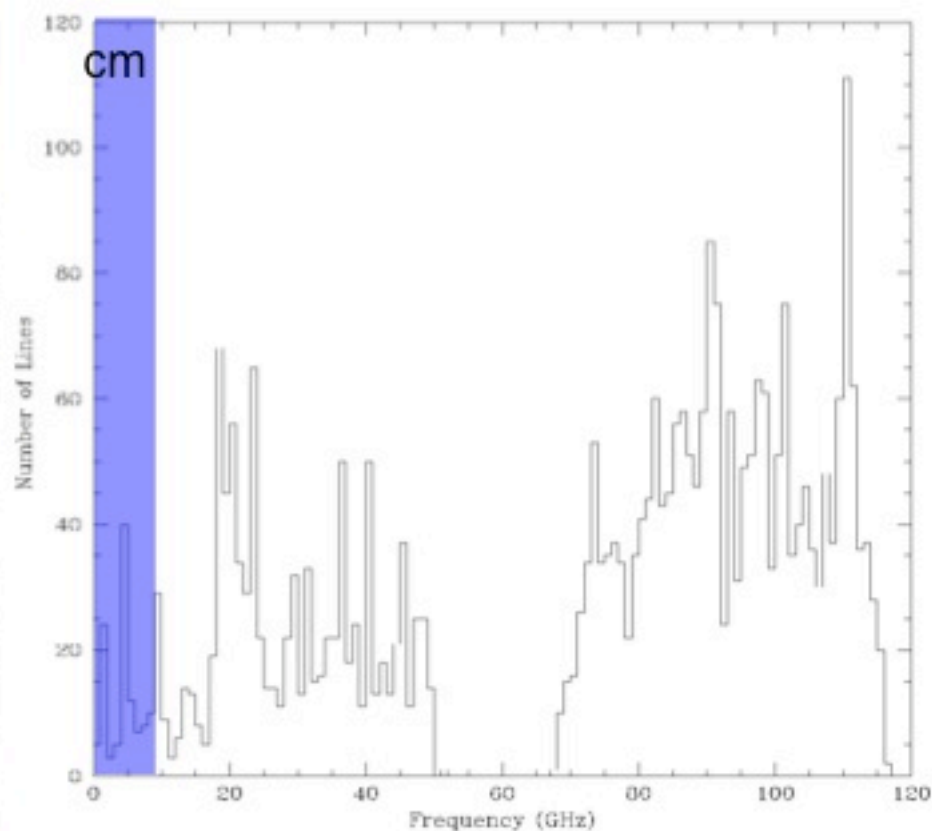
1.25-1.78	16-28
2.2-2.5	30-50
4.4-6.7	80-116
8.0-9.2	



Spectral Line Observing Across the Frequencies

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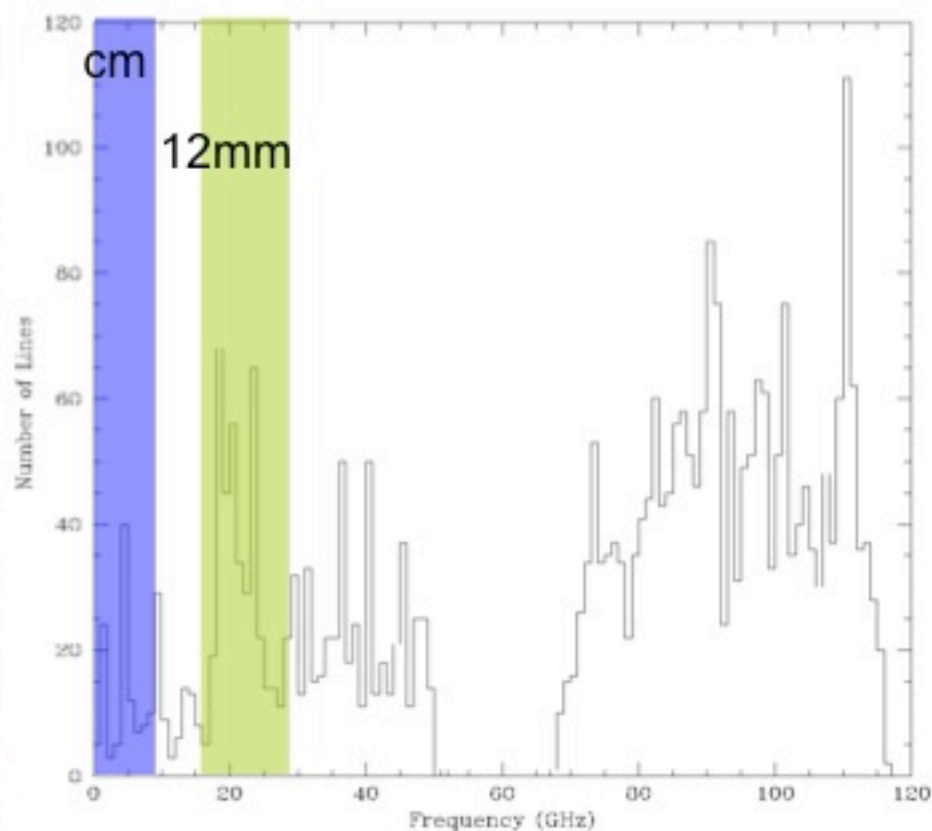
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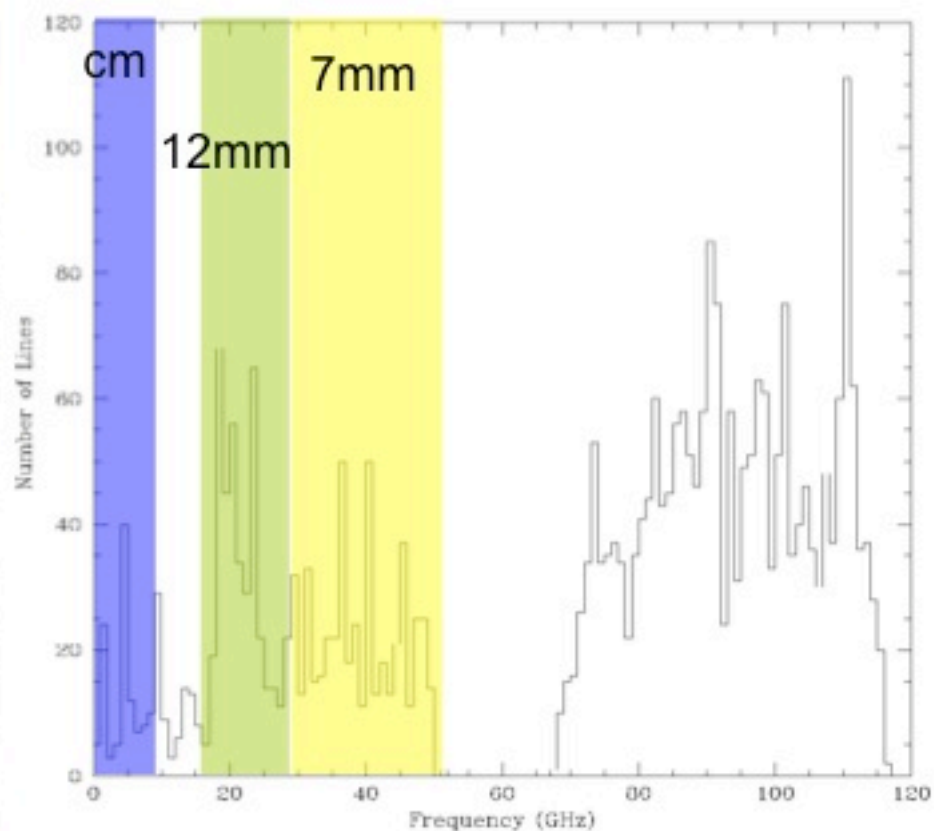
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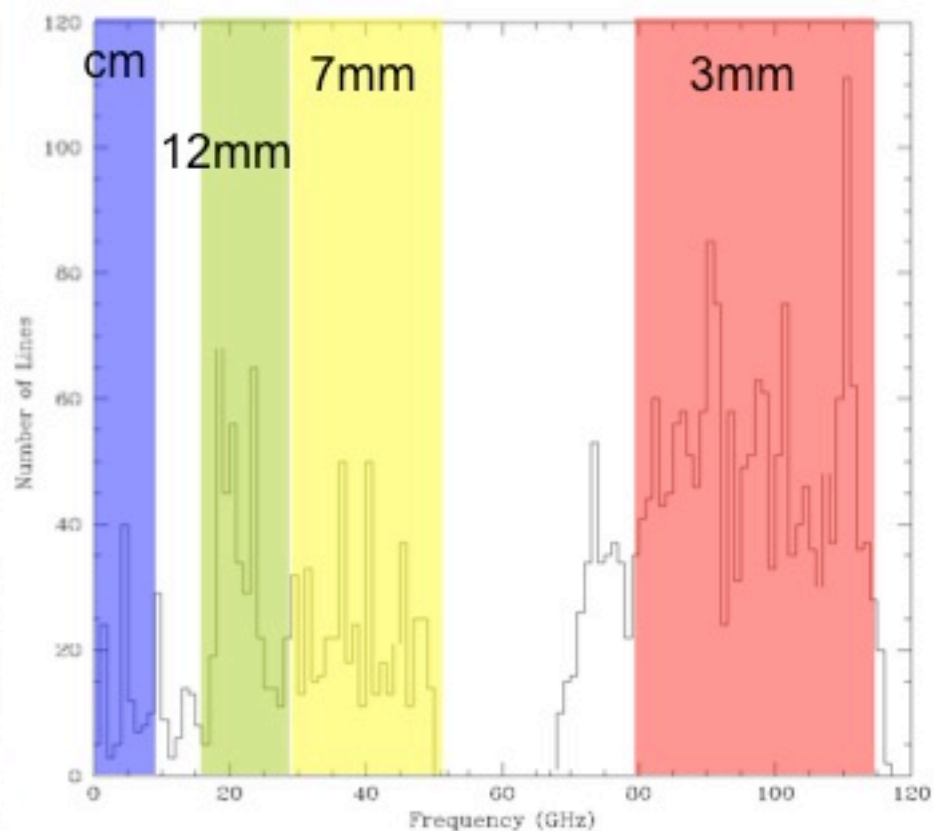
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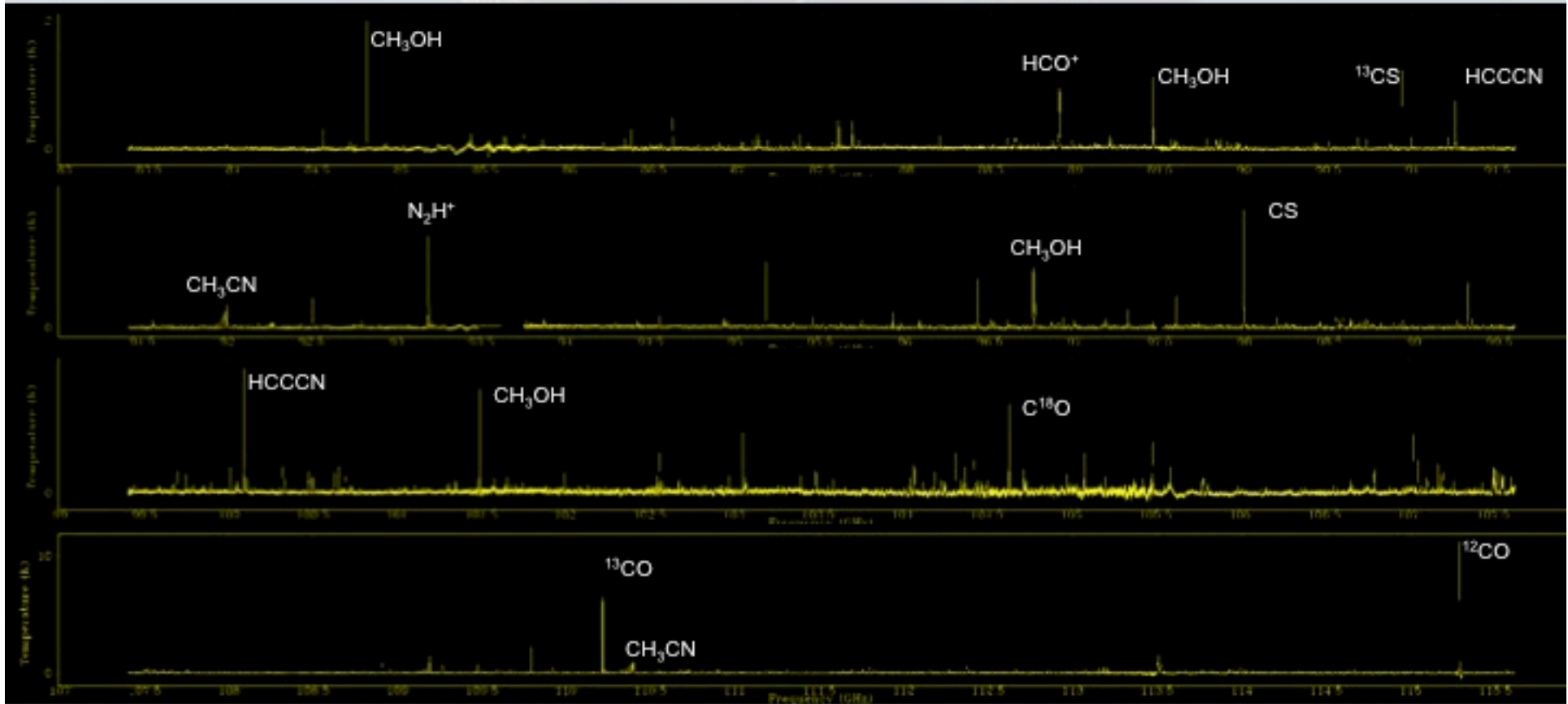
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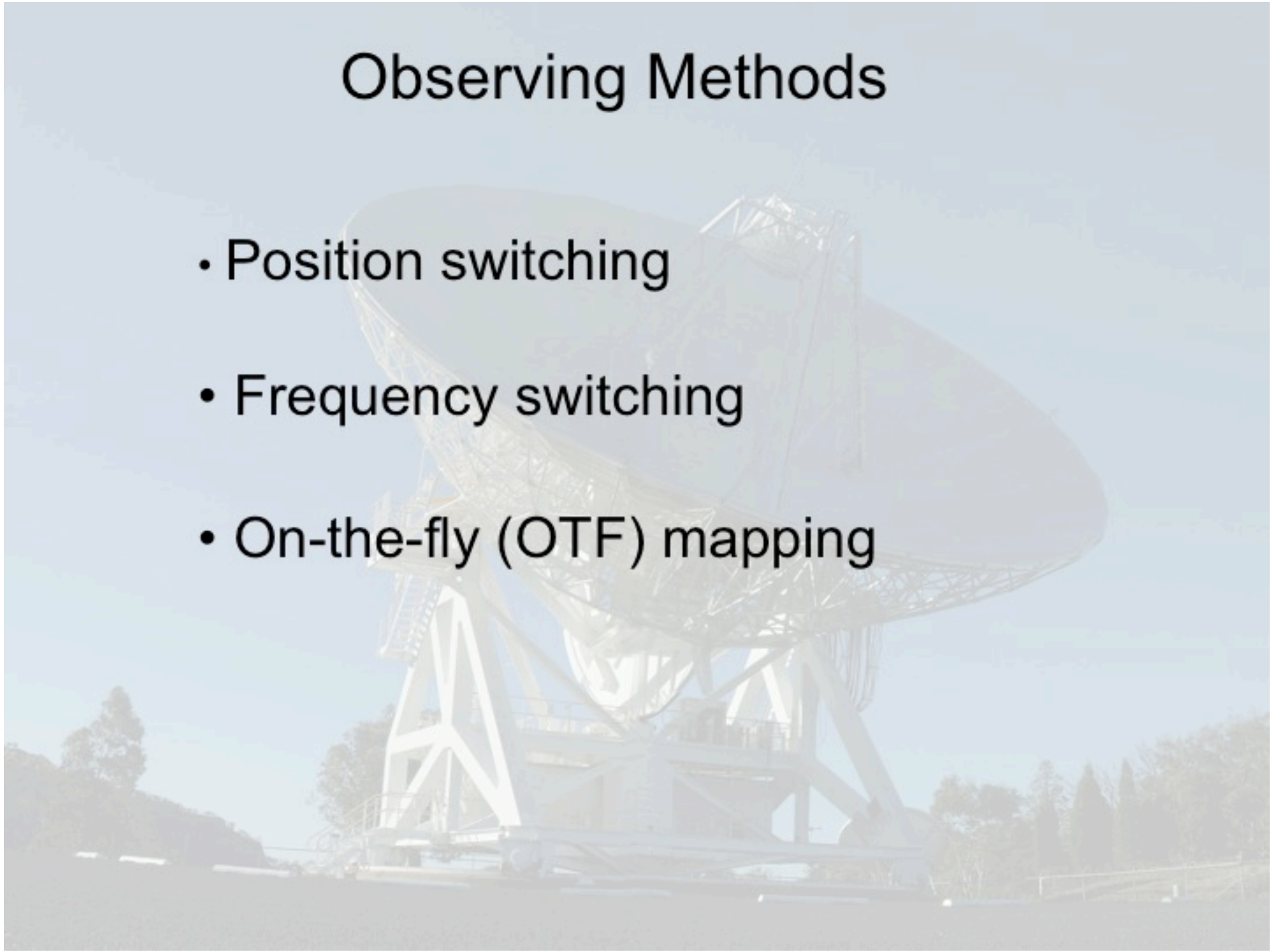


3mm band ~ 800 lines
12mm band ~ 120 lines

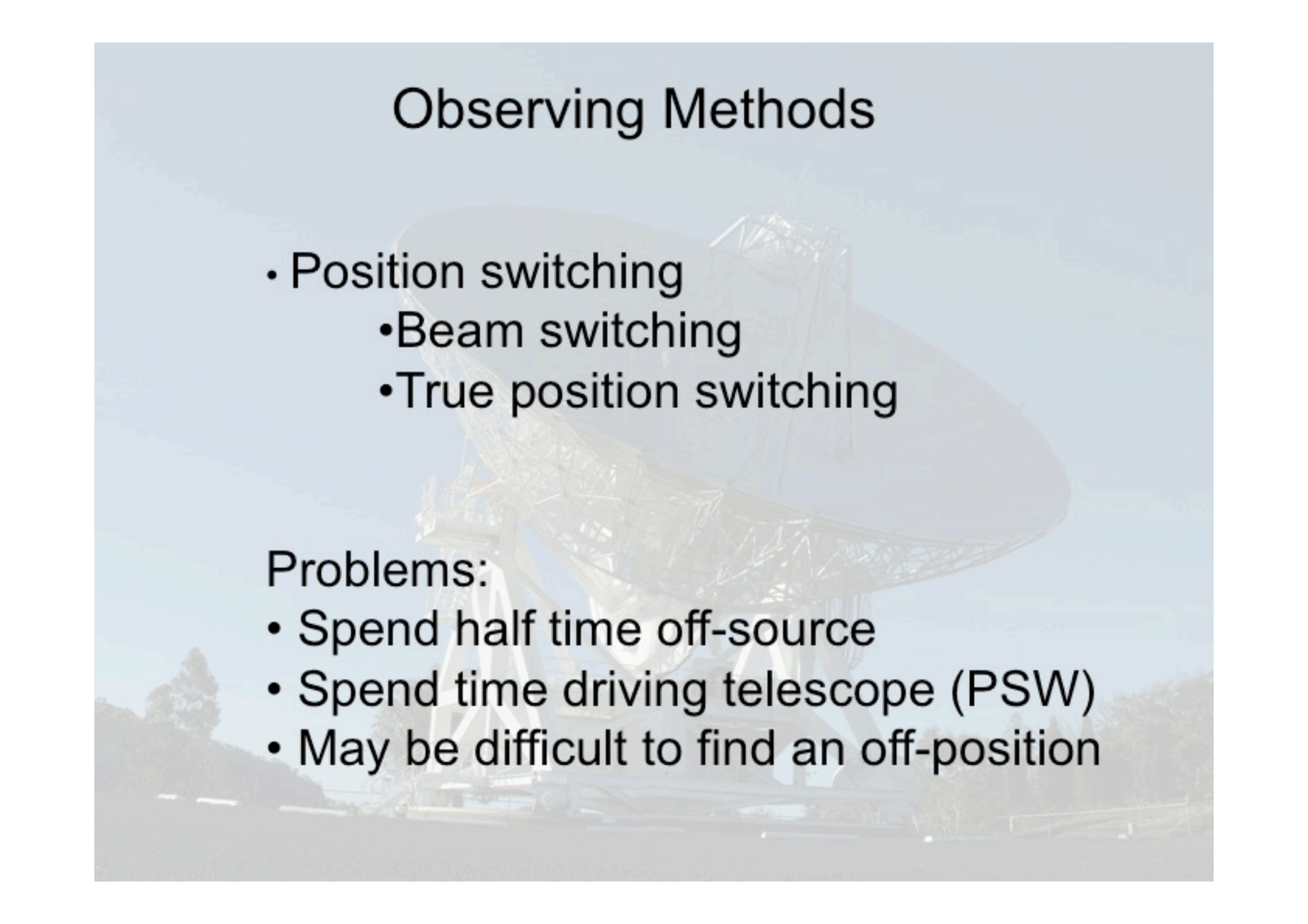


Observing Methods

- Position switching
- Frequency switching
- On-the-fly (OTF) mapping



Observing Methods

A large, white, parabolic radio telescope dish is mounted on a complex metal structure. The dish is positioned on a grassy hillside under a clear blue sky. The background shows some trees and a fence line.

- Position switching
 - Beam switching
 - True position switching

Problems:

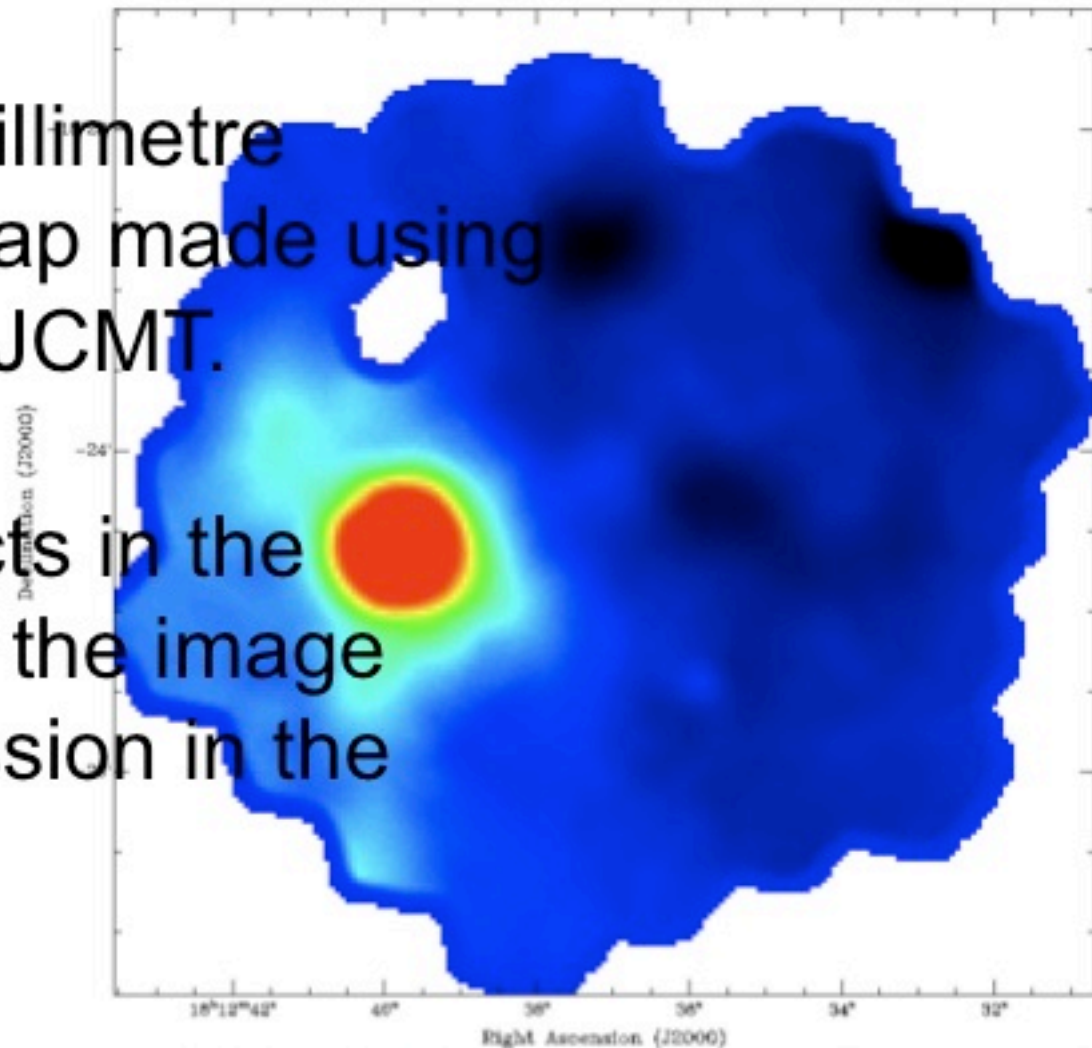
- Spend half time off-source
- Spend time driving telescope (PSW)
- May be difficult to find an off-position

Observing Methods

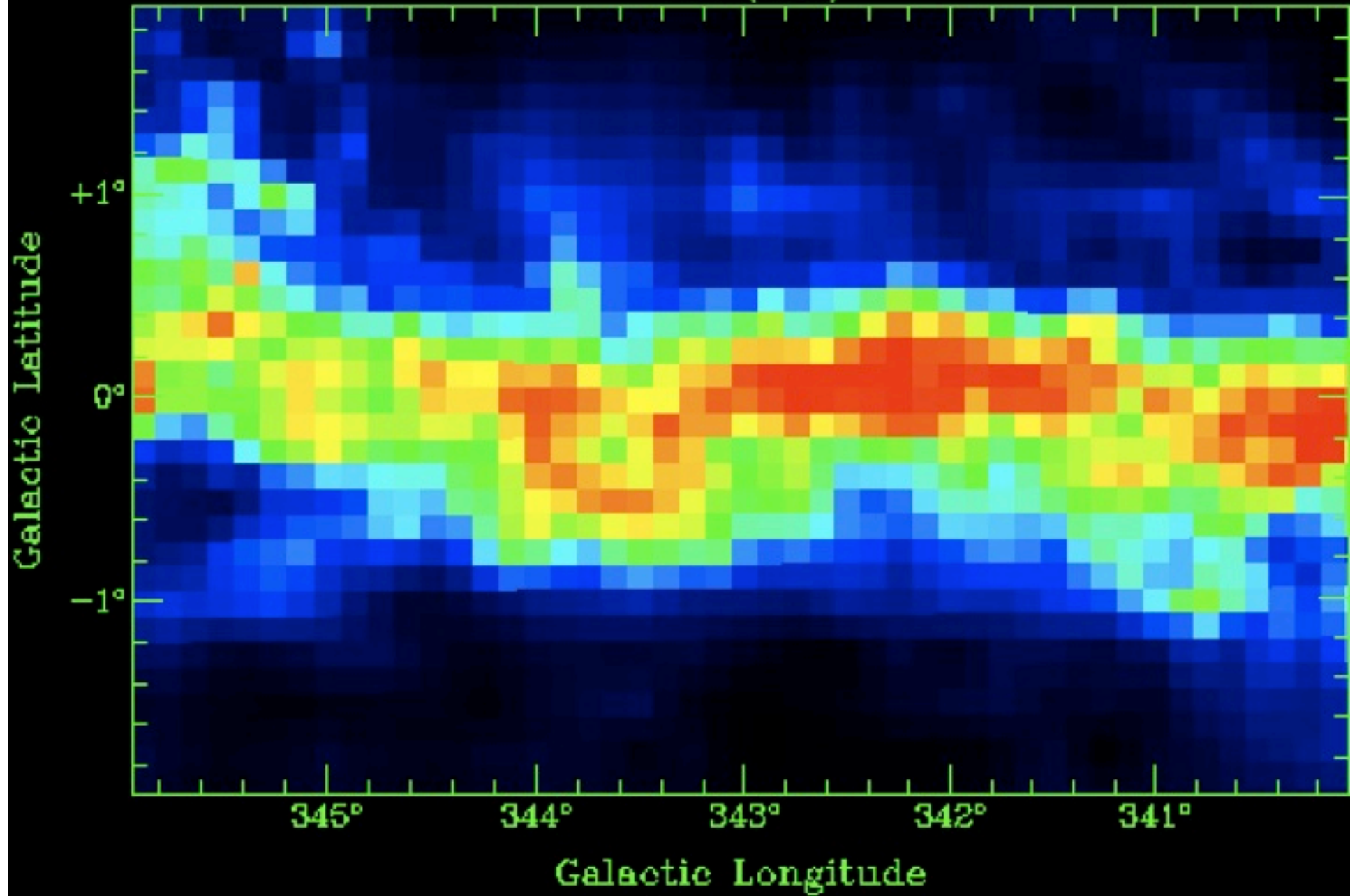
Beam switching

This is a sub-millimetre (850 micron) map made using SCUBA on the JCMT.

Negative artifacts in the northern half of the image are due to emission in the off-position.

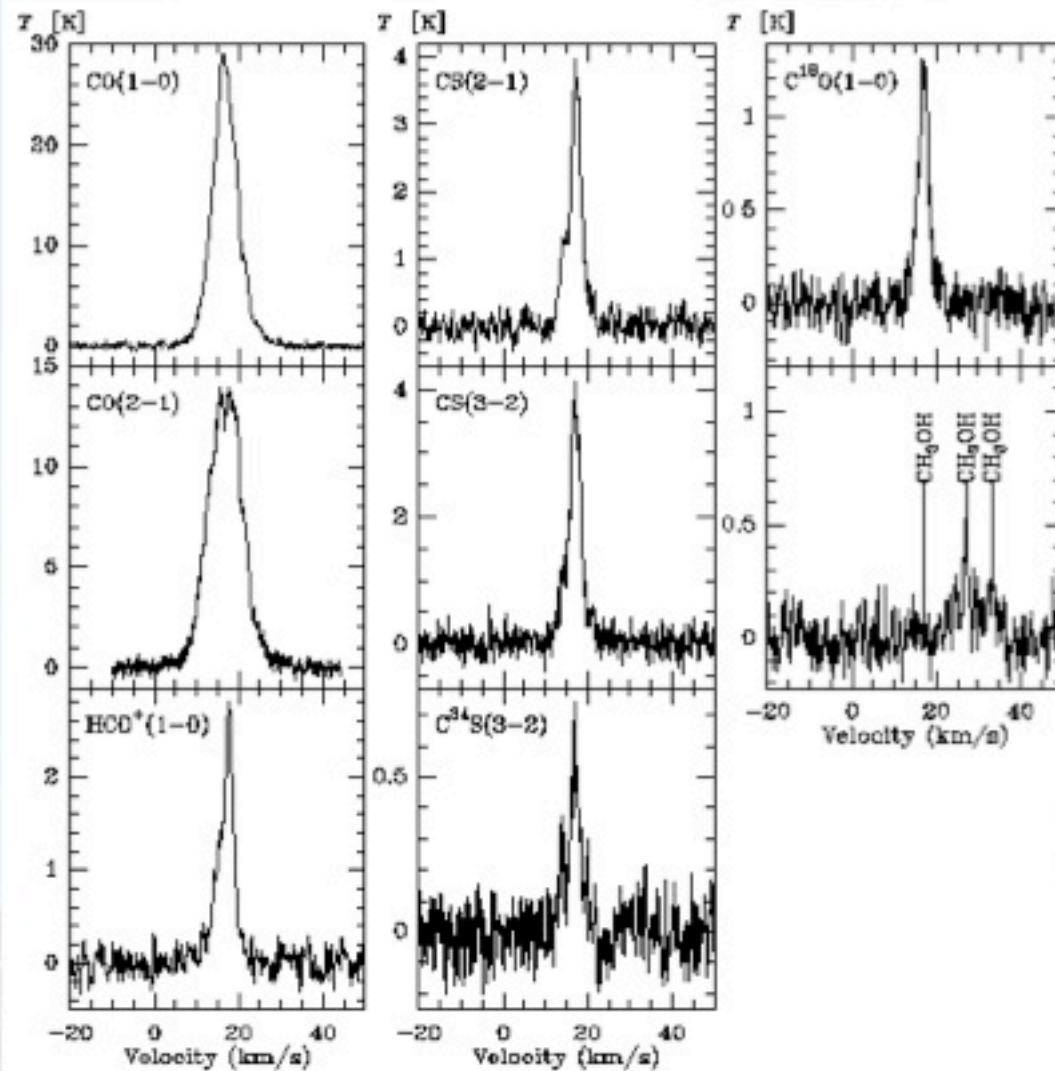


$^{12}\text{CO} (1-0)$



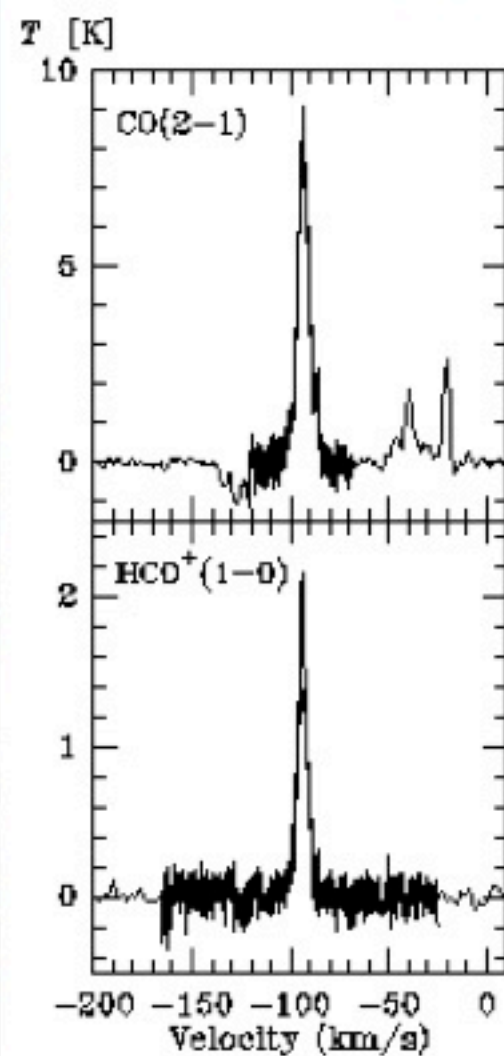
Position Switching

SEST spectra of G232.62+1.01



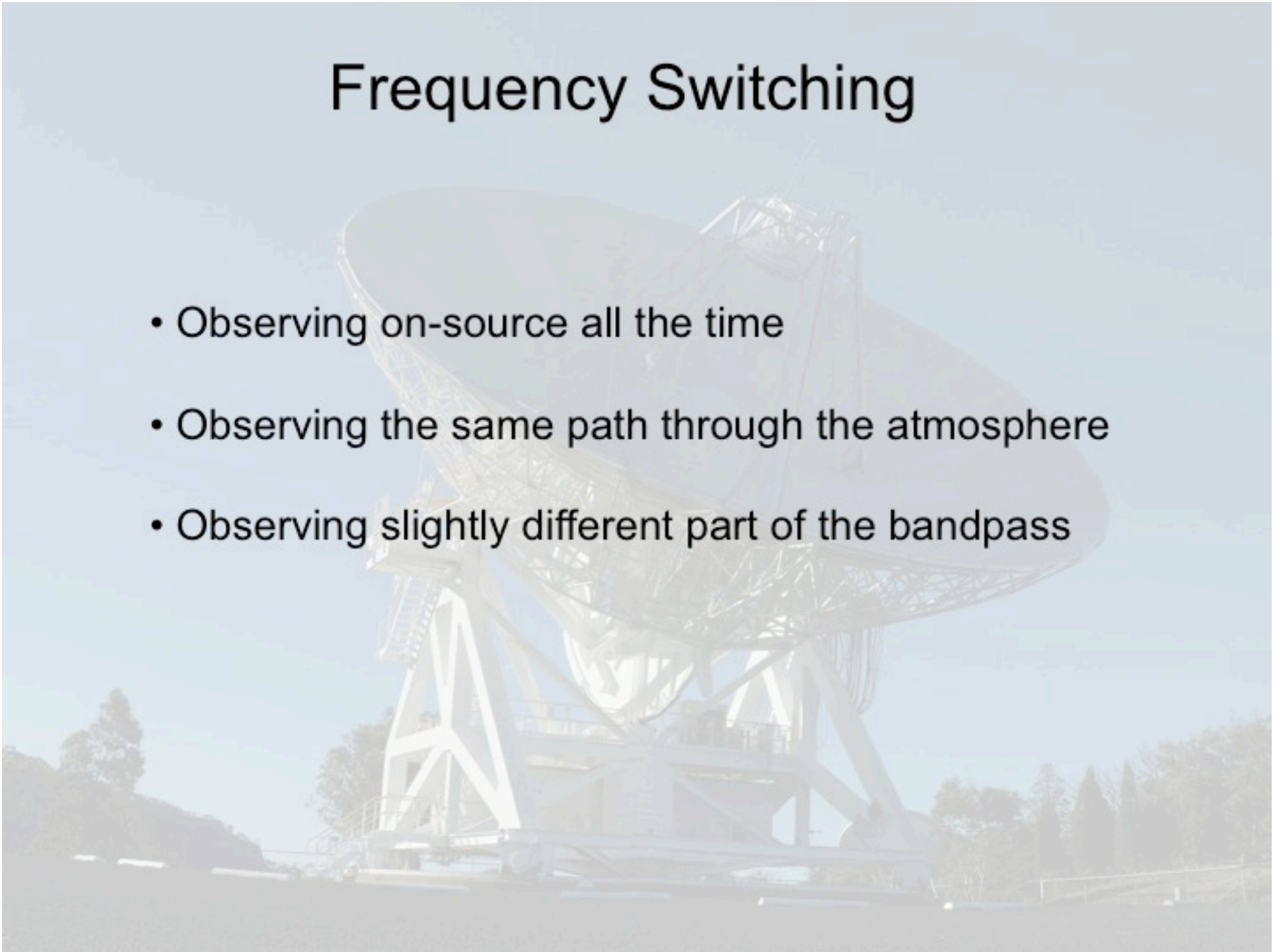
Position Switching

SEST spectra of G339.97-0.52

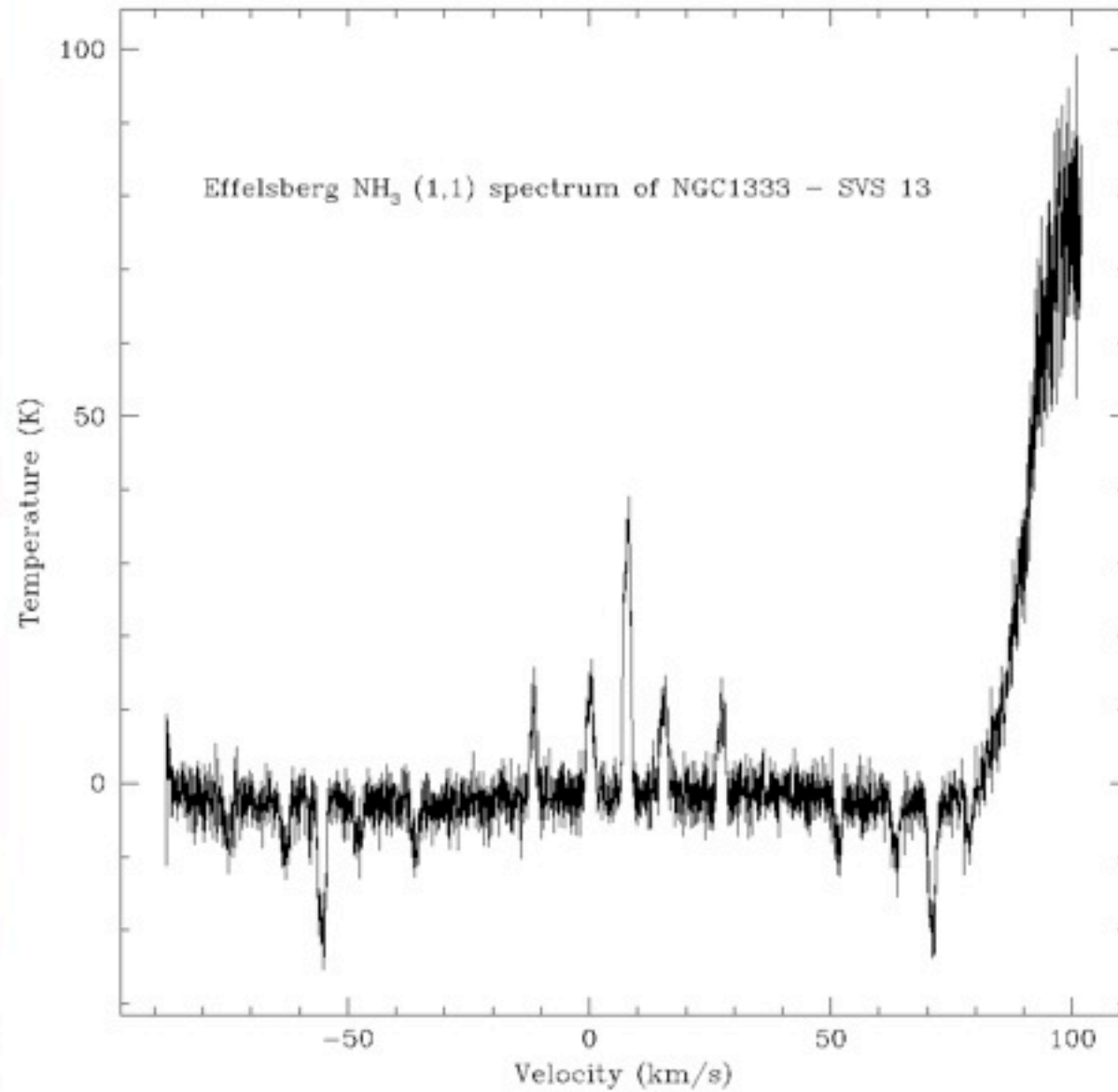


Frequency Switching

- Observing on-source all the time
- Observing the same path through the atmosphere
- Observing slightly different part of the bandpass

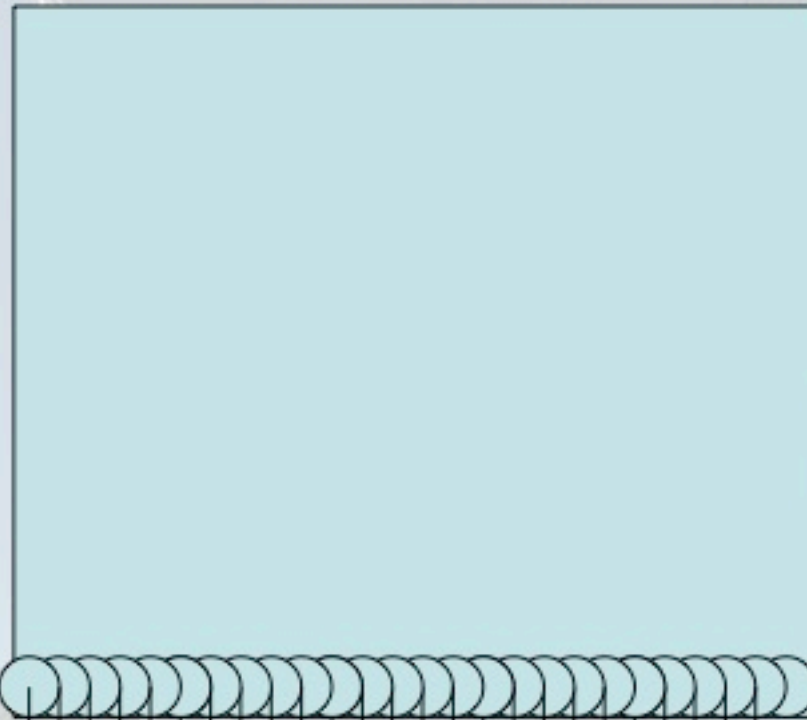


Frequency Switching



On-the-fly Mapping

Reference
Position

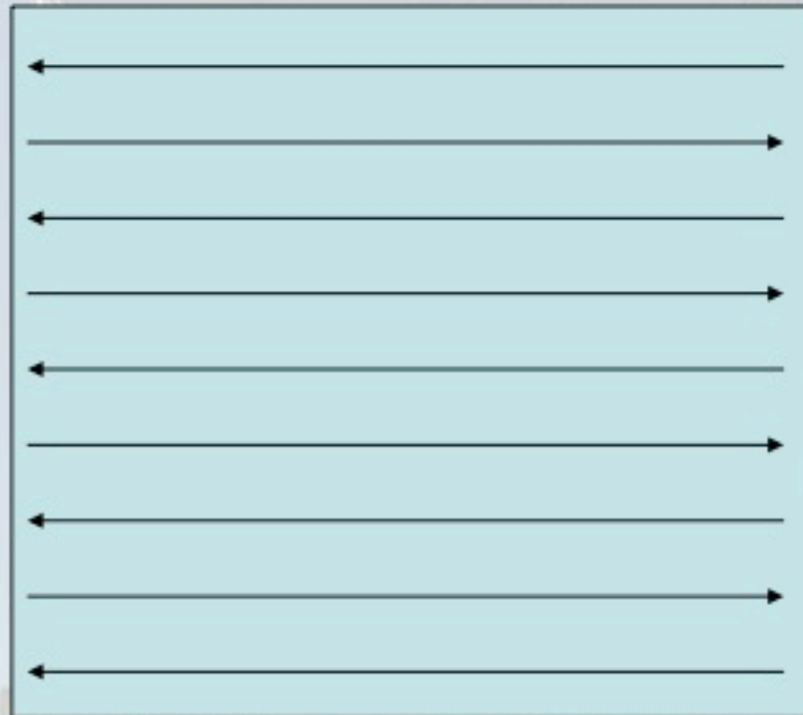


Beam Shape



On-the-fly Mapping

Reference
Position



Data Reduction

A large radio telescope dish is shown in the background, mounted on a complex metal structure. The dish is white and has a large, curved surface. It is situated on a hillside with some trees and a clear blue sky in the background.

Data reduction considerations:

- For Mopra/Parkes OTF maps, use livedata and gridzilla
- Livedata does initial bandpass calibration and splits data into IF components

LiveData - Parkes Multibeam Data Reduction

SCHEDULER
 Configuration MOPRA **START** Pause Stop after this STOP NOW DGT CSIRO

Read directory: Write directory:
 File wildcard(s): *.rpf MULTIBEAM WRITER Output format: SDFFTS

Raw files: Queue selection Update Queued files Auto-Queue Dequeue Processed files Clear

2006-10-20_0002-M168.rpf 2006-10-20_2333-M168.rpf 2006-10-20_0002-M168.rpf

DATA REDUCTION CONTROL unspecified Gridder...

Reader: Bandpass calibration Monitor output Statistics Write data
 IDLE IDLE inactive inactive IDLE

13:15:10: 2007/06/26 EST (Tue) Livedata logger

MULTIBEAM READER

Format:
 Max retries: 0

Input data selection

13	6	12
7	1	5
2	3	4
9	10	

IFs

1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16

Channel range
 1 - 8192
 Read X-pol

Interpolate
 Calibrate...

BANDPASS CALIBRATION

Configuration: MOPRA

Pre-bandpass calibration options
 Spectral smoothing: NONE Spectral pre-scaling: NONE

Bandpass calibration parameters
 Method: REFERENCED Cross-beam
 Estimator: MEAN
 STATISTIC OF RATIOS

Post-bandpass calibration options
 Spectral baseline fit: 1 Preserve continuum
 Mask: 1 159 0 0 0 0 0 0 0000 0132
 Doppler frame: LSRK Rescale frequency axis

Validity checking
 Check field name Time Position
 jump: 0 second 1 arcmin

Data Reduction



Data reduction considerations:

- For Mopra OTF maps, use livedata and gridzilla
- Livedata does initial bandpass calibration and splits data into IF components
- Gridzilla regrids data and selects which data to include based on Tsys or pixel range. Combines data using mean, median etc.

INPUT DATA SELECTION



Frequency range 19500 - 27500 MHz

Line rest frequency 23500 MHz Spectral ContinuumPolarization Baseline

IFs 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

A&B

GRIDZILLA

Parameter set

MOPRA

PROCESSING OPTIONS

Output image geometry

Projection SIN P1: 0 Reference point EQUATORIAL

P2: 0

LONPOLE 999

LATPOLE 999

Image centre and extent Autosize

x-scale: 0.5 arcmin / pixel

y-scale: 0.5 arcmin / pixel

Data validation

Tsys range 0 - 70

Data range -10000 - 10000

Doppler registration 0.1 channel

Gridding parameters

Statistic MEDIAN Beam weighting 0 Smoothing kernel GAUSSIAN

Clip fraction 0 % Beam FWHM 0.77 arcmin Kernel FWHM 0.55 arcmin

 Tsys weighting Beam normalization Cutoff radius 0.55 arcmin

Blanking level 0 Processor host localhost Use 25 % of 2069MByte

FITS spectral type FREQ FITS numerical format IEEE floating

Output FITS directory /Users/andrew/Work/2007/1204_MOPRA/RF1/2007_1204/04/10F111

Output FITS file name gridzilla_*.fits

GO

ABORT

EXIT

Search path

File wildcard(s) *

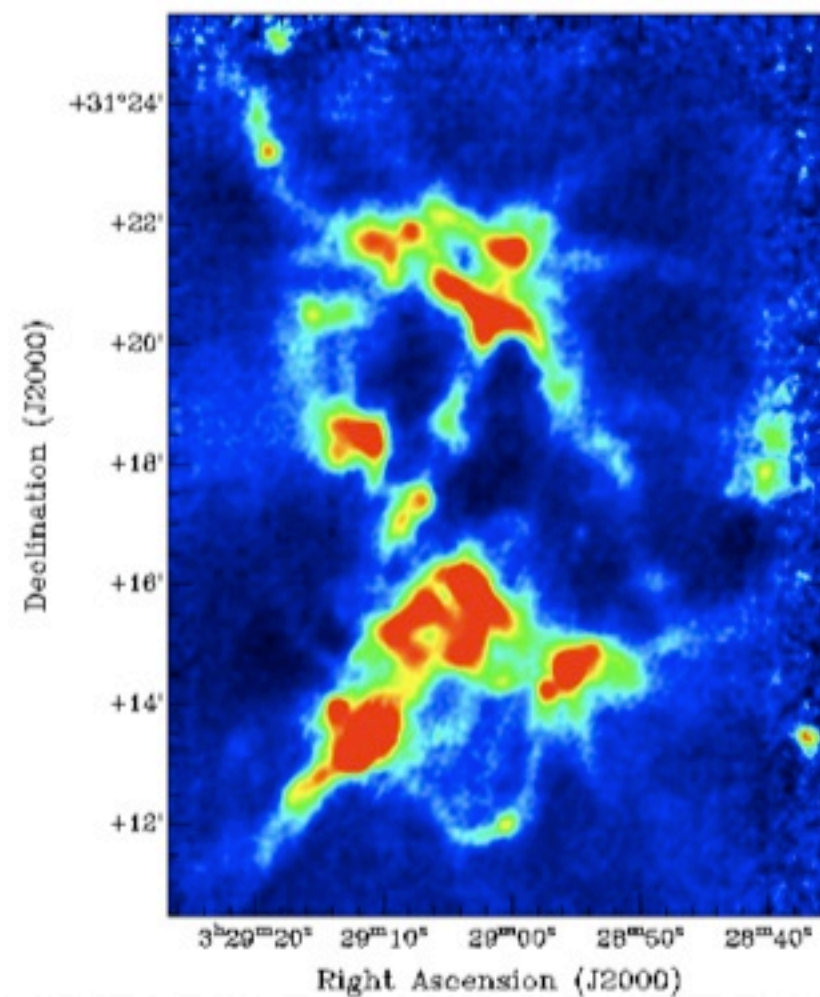
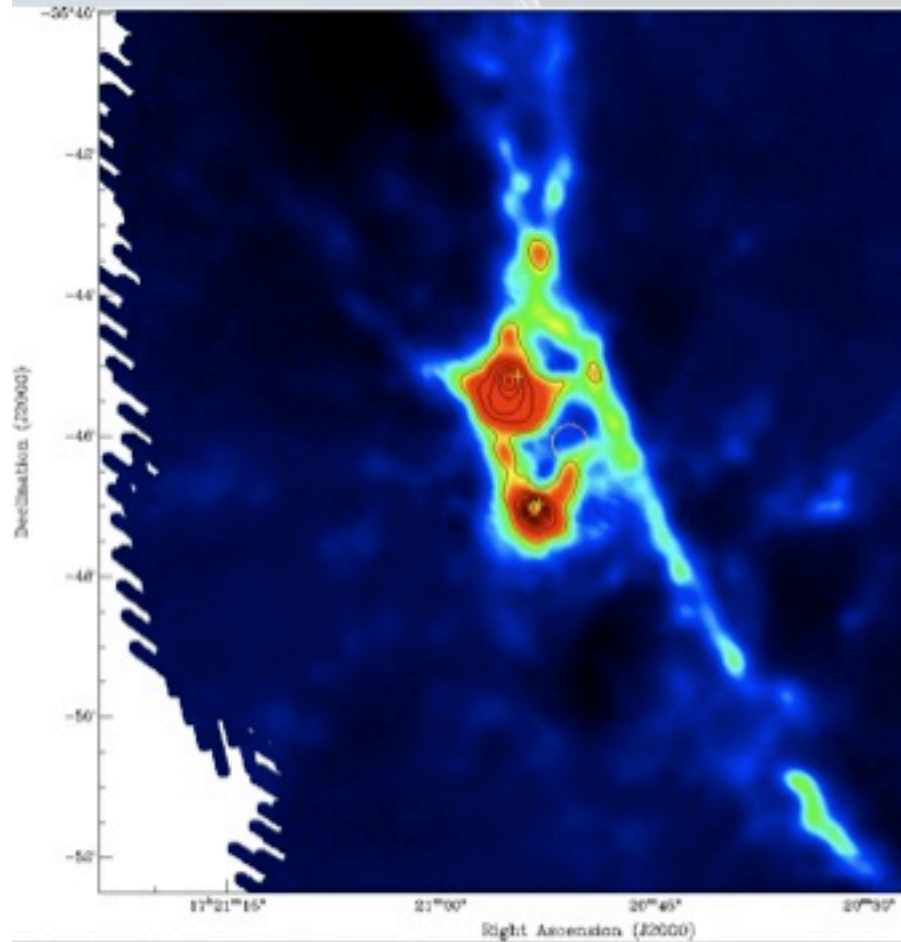
Search

0700-0000-11-07_0000-0000-F112_000000_165_0
 0700-0000-11-07_0000-0000-F112_000000_165_0
 0700-0000-11-07_0000-0000-F112_000000_165_0
 0700-0000-11-07_0000-0000-F112_000000_165_0
 0700-0000-11-07_0000-0000-F112_000000_165_0
 0700-0000-11-07_0000-0000-F112_000000_165_0
 0700-0000-11-07_0000-0000-F112_000000_165_0
 0700-0000-11-07_0000-0000-F112_000000_165_0
 0700-0000-11-07_0000-0000-F112_000000_165_0
 0700-0000-11-07_0000-0000-F112_000000_165_0
 0700-0000-11-07_0000-0000-F112_000000_165_0

13:21:04: 2007/06/26 EST (Tue) Multibeam logger

Observing Methods

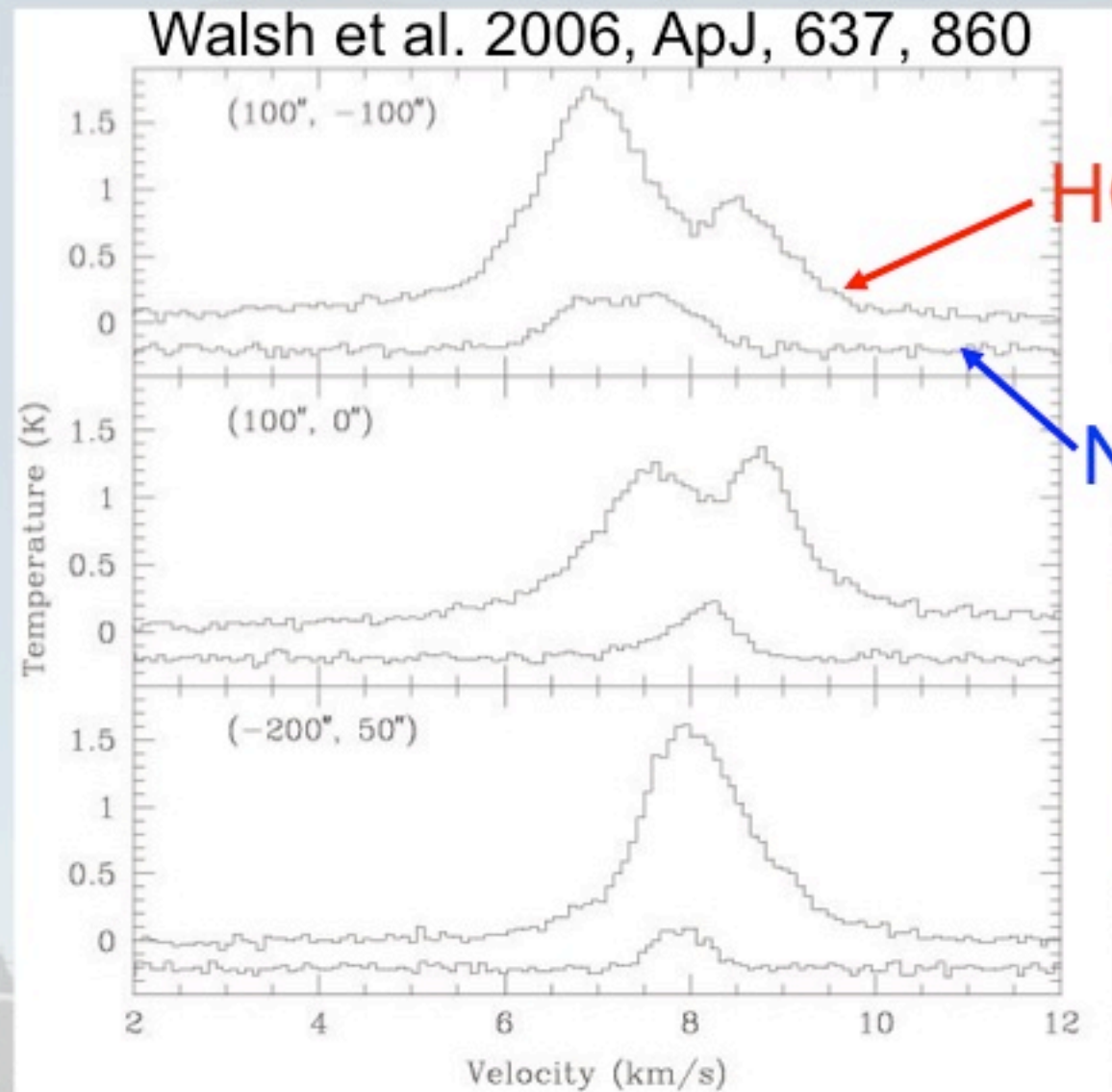
Mapping with SCUBA



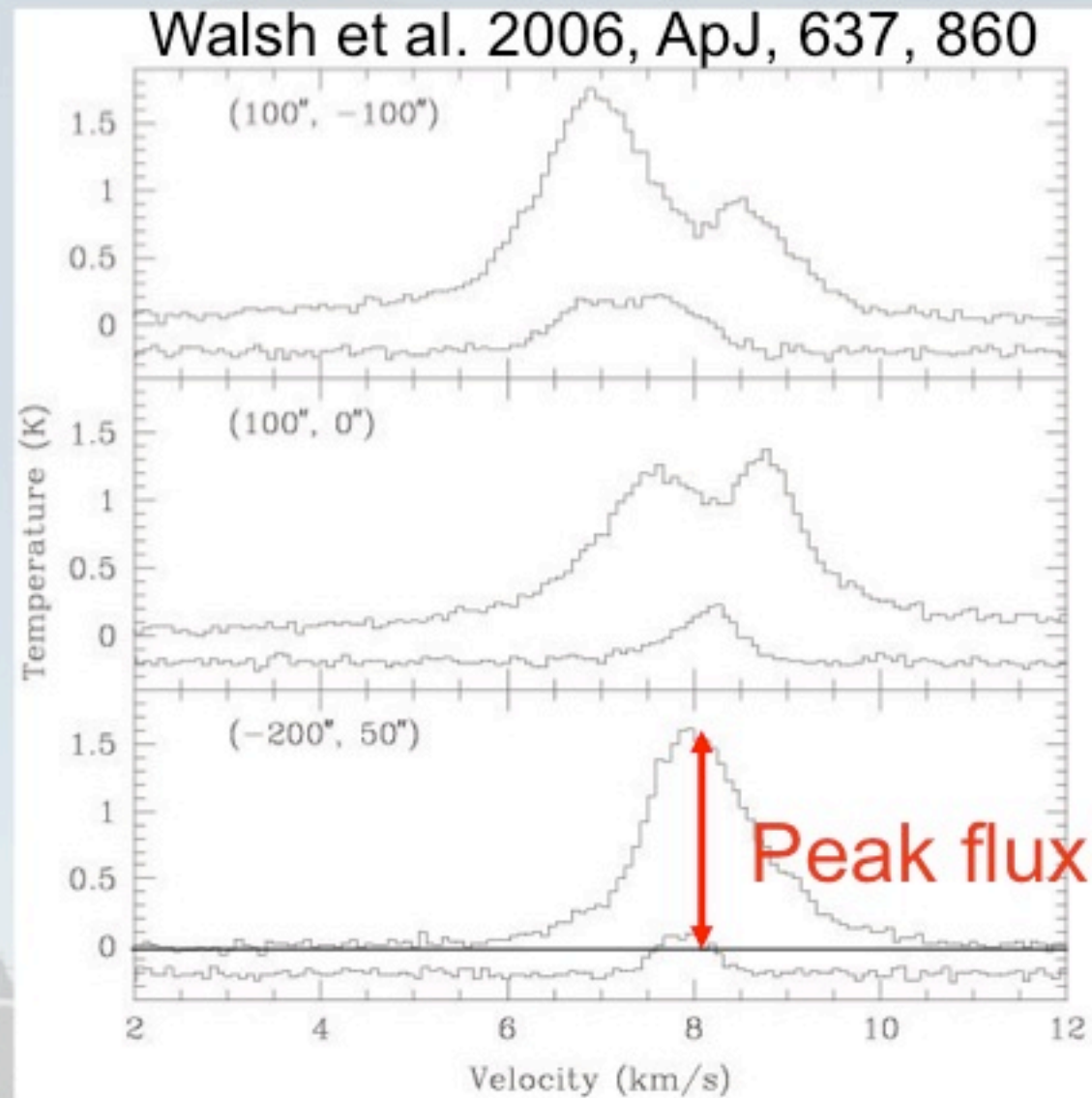
Examples of Spectral Lines



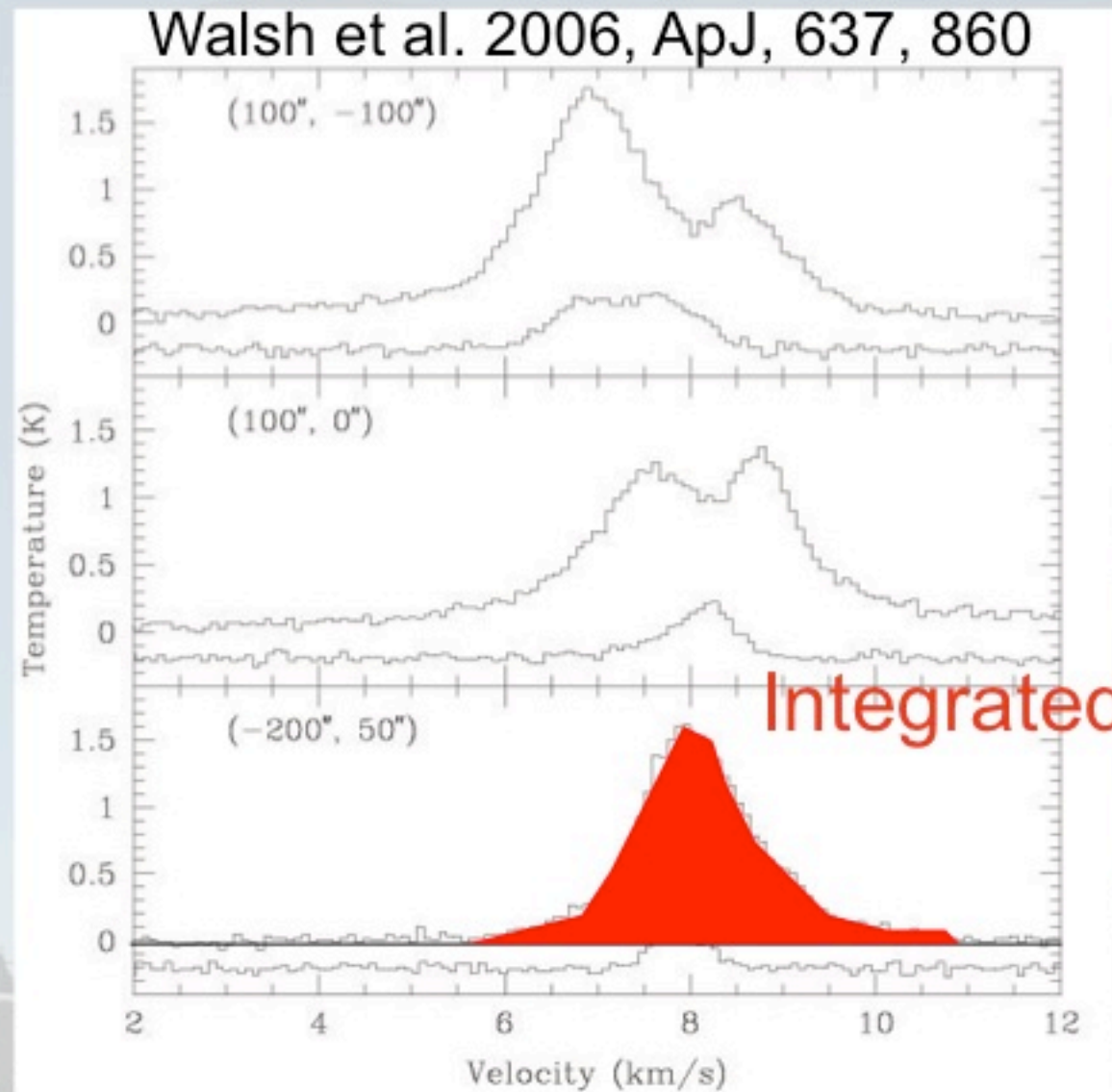
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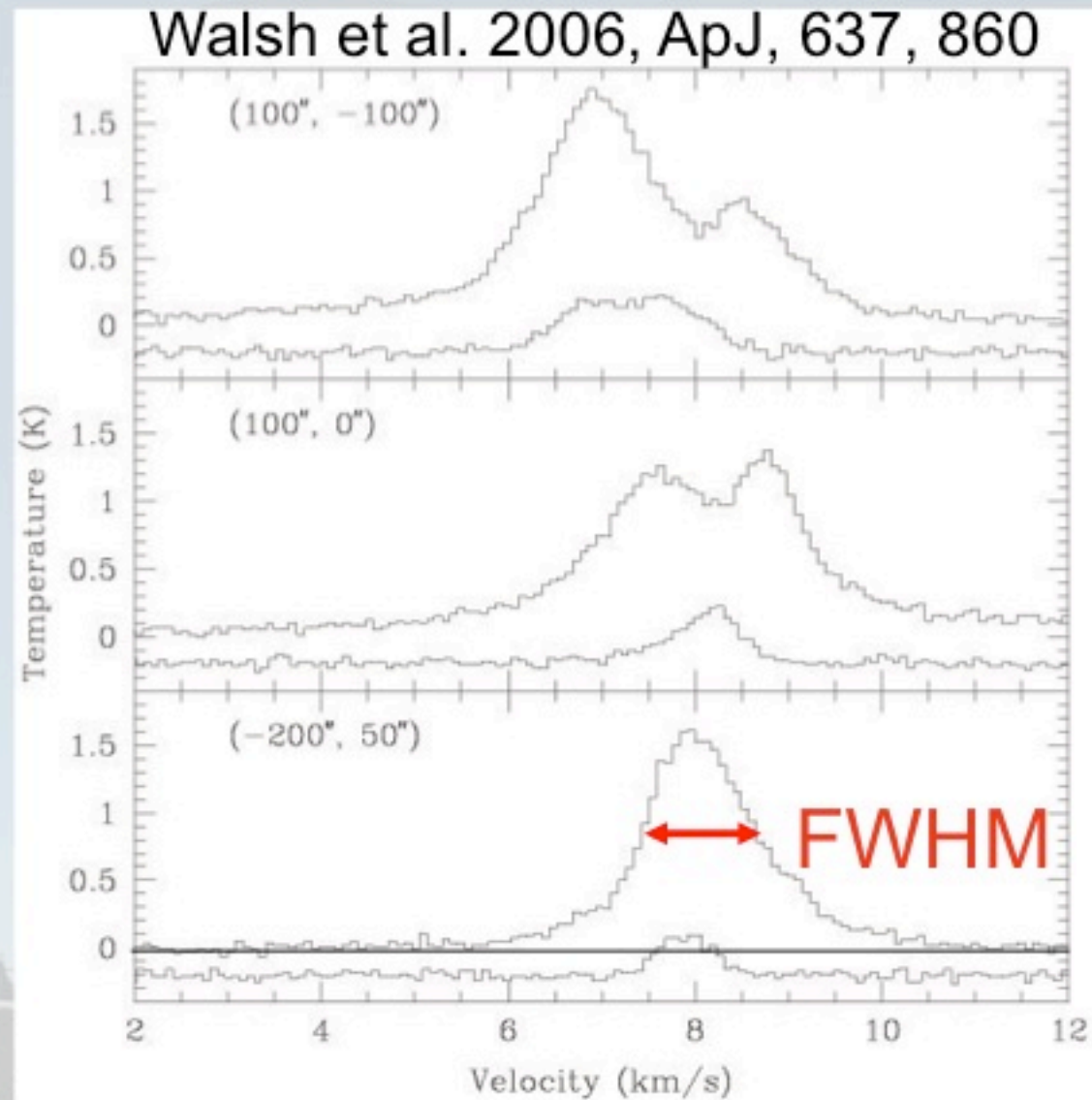
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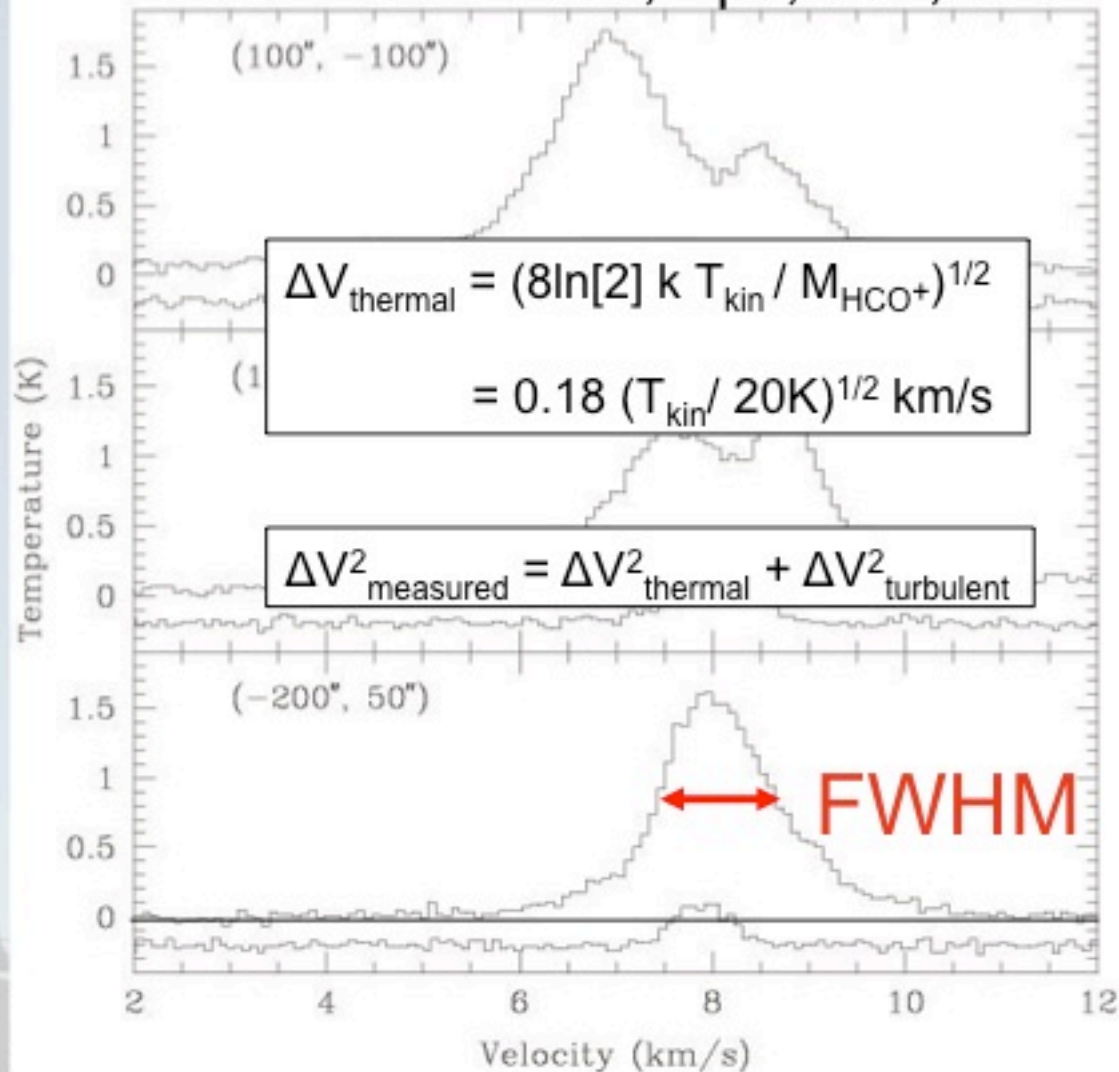


Examples of Spectral Lines

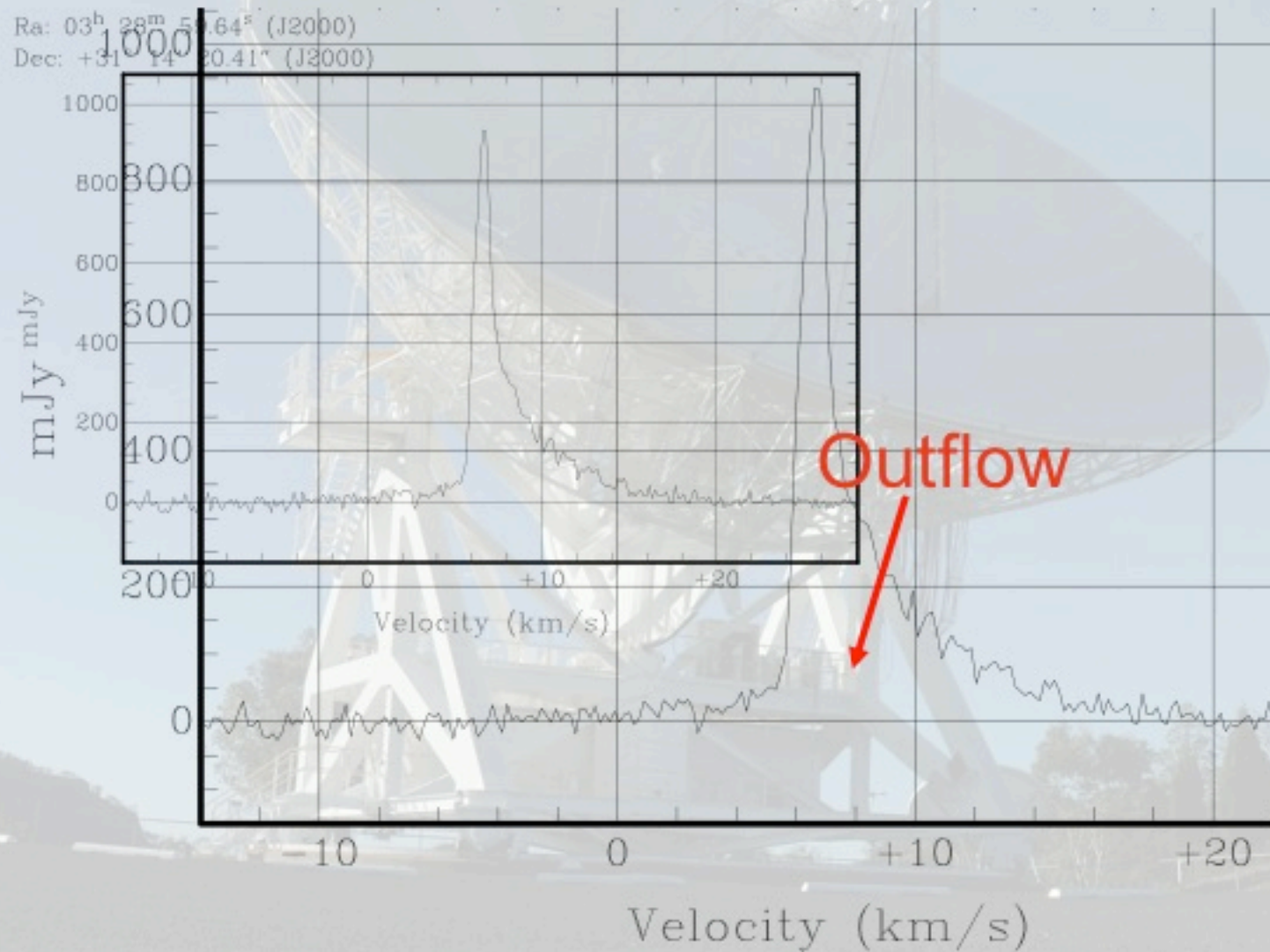


Examples of Spectral Lines

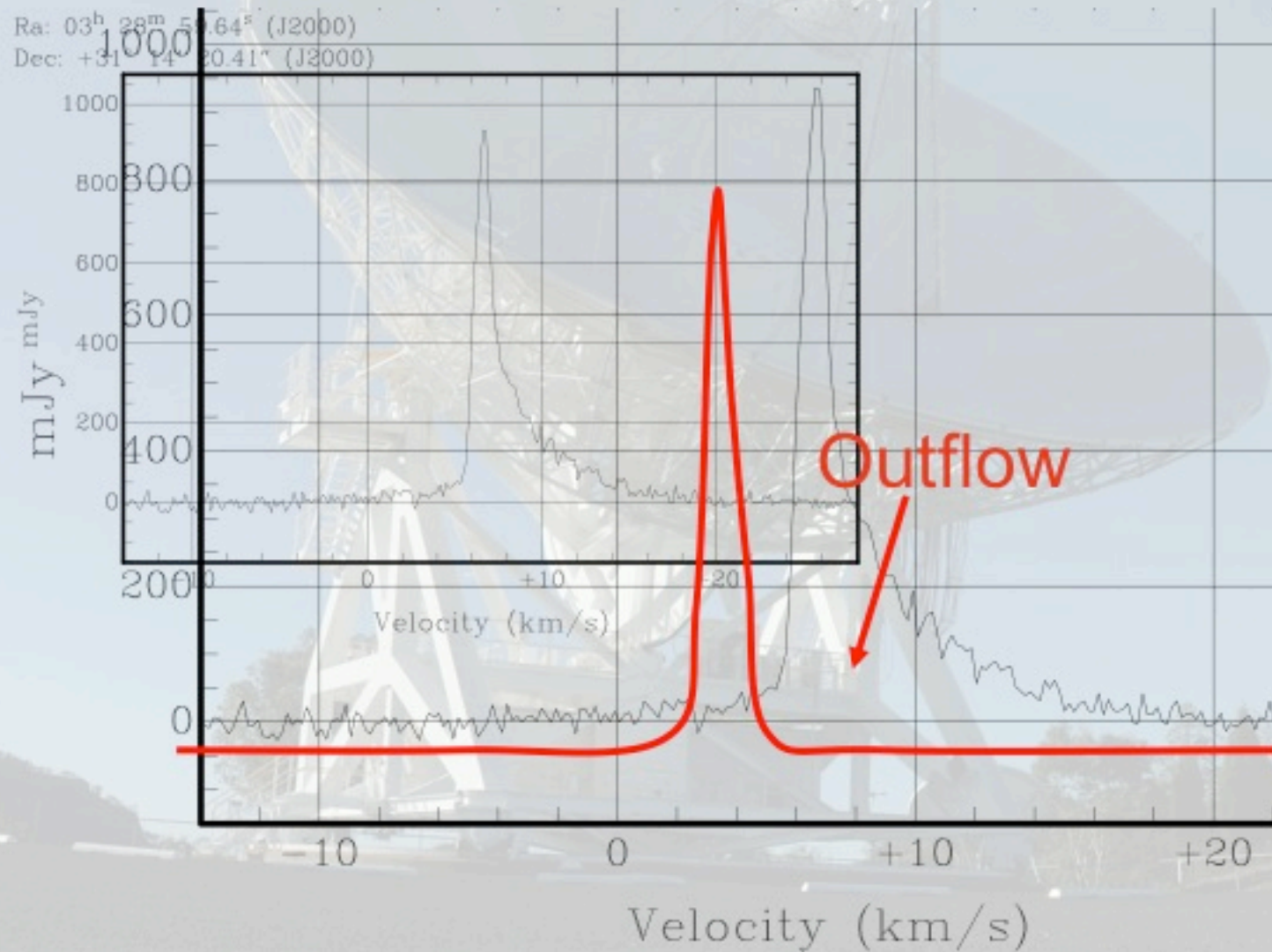
Walsh et al. 2006, ApJ, 637, 860



Examples of Spectral Lines



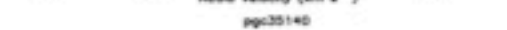
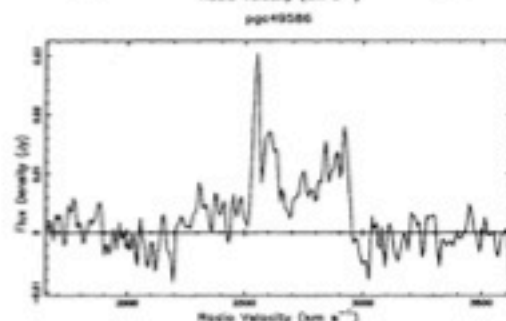
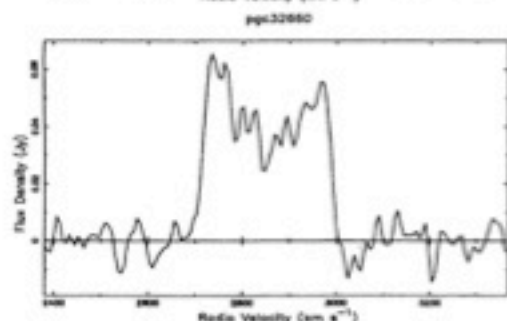
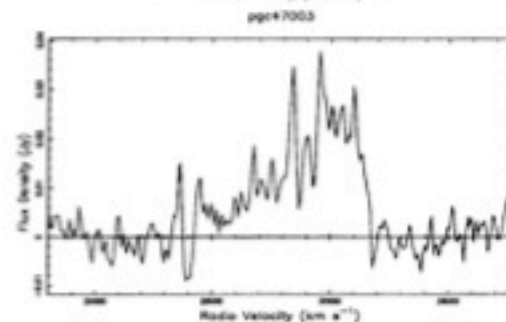
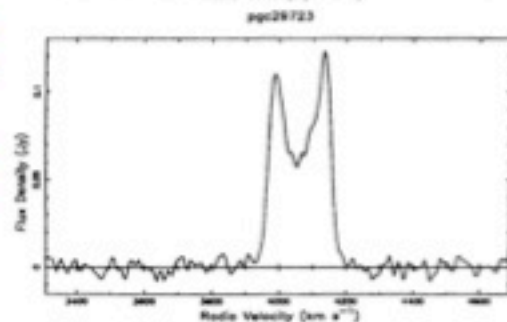
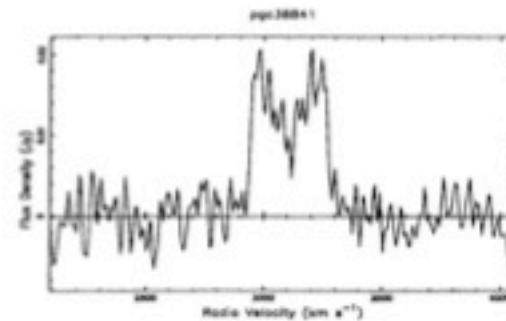
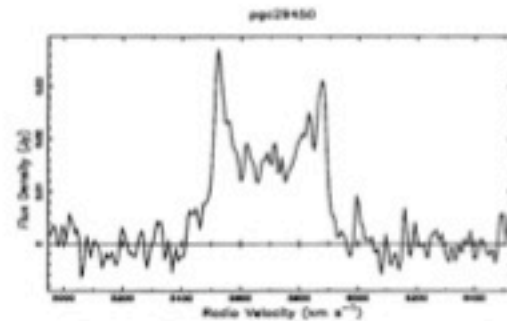
Examples of Spectral Lines



Examples of Spectral Lines

Di Nella et al. 1996 A&AS, 116, 331

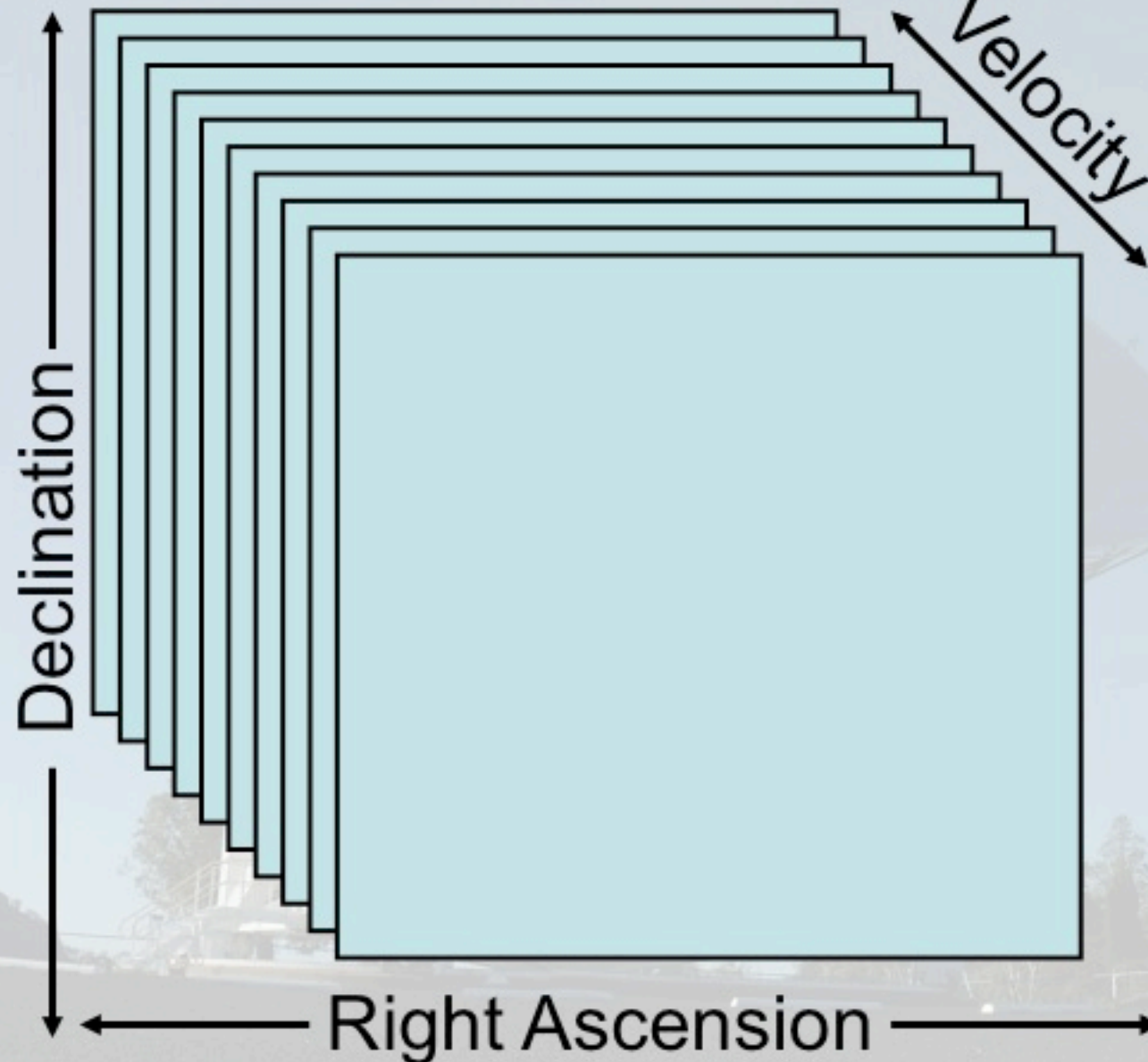
HI emission
in galaxies



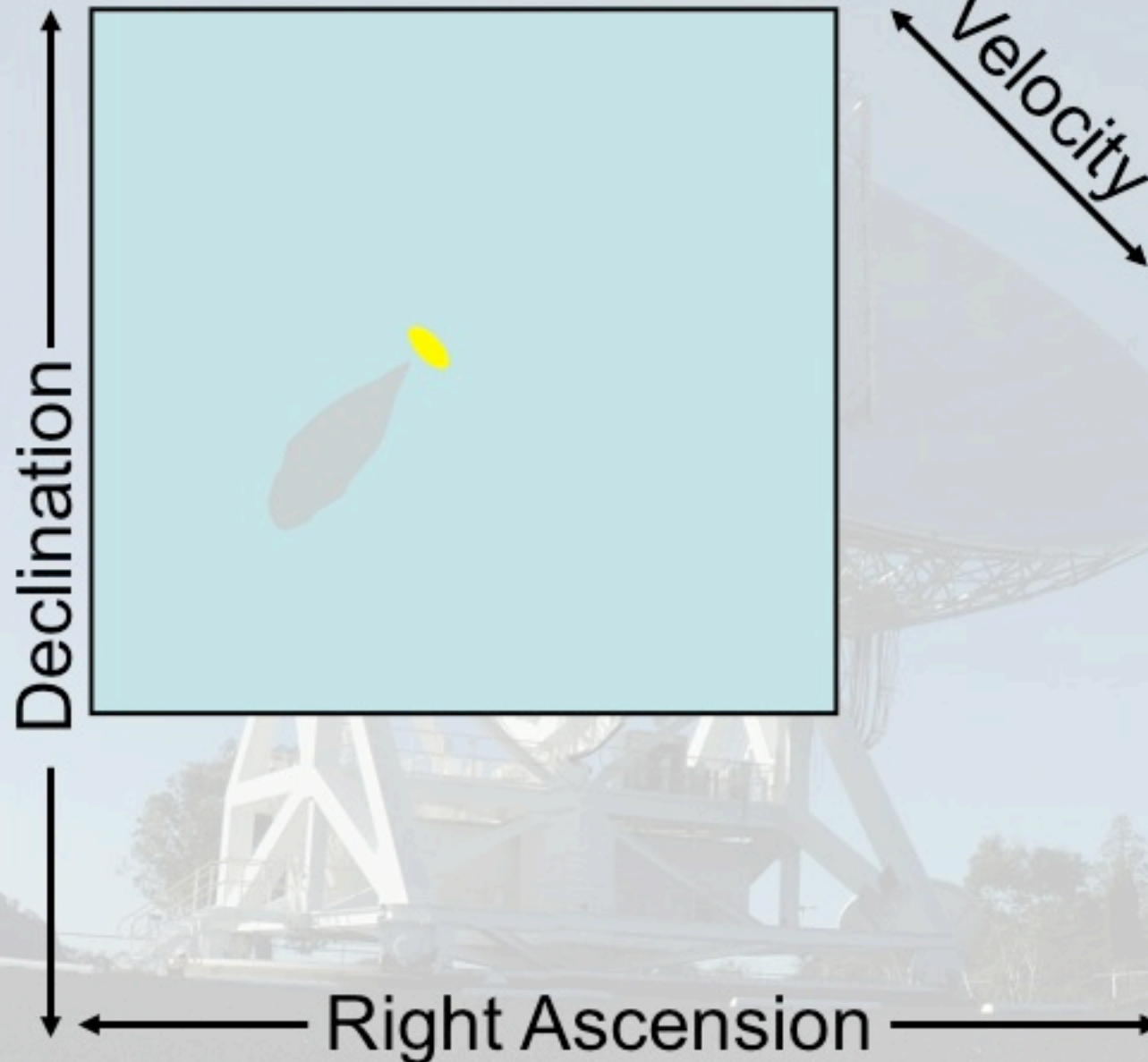
Data cubes and moment maps



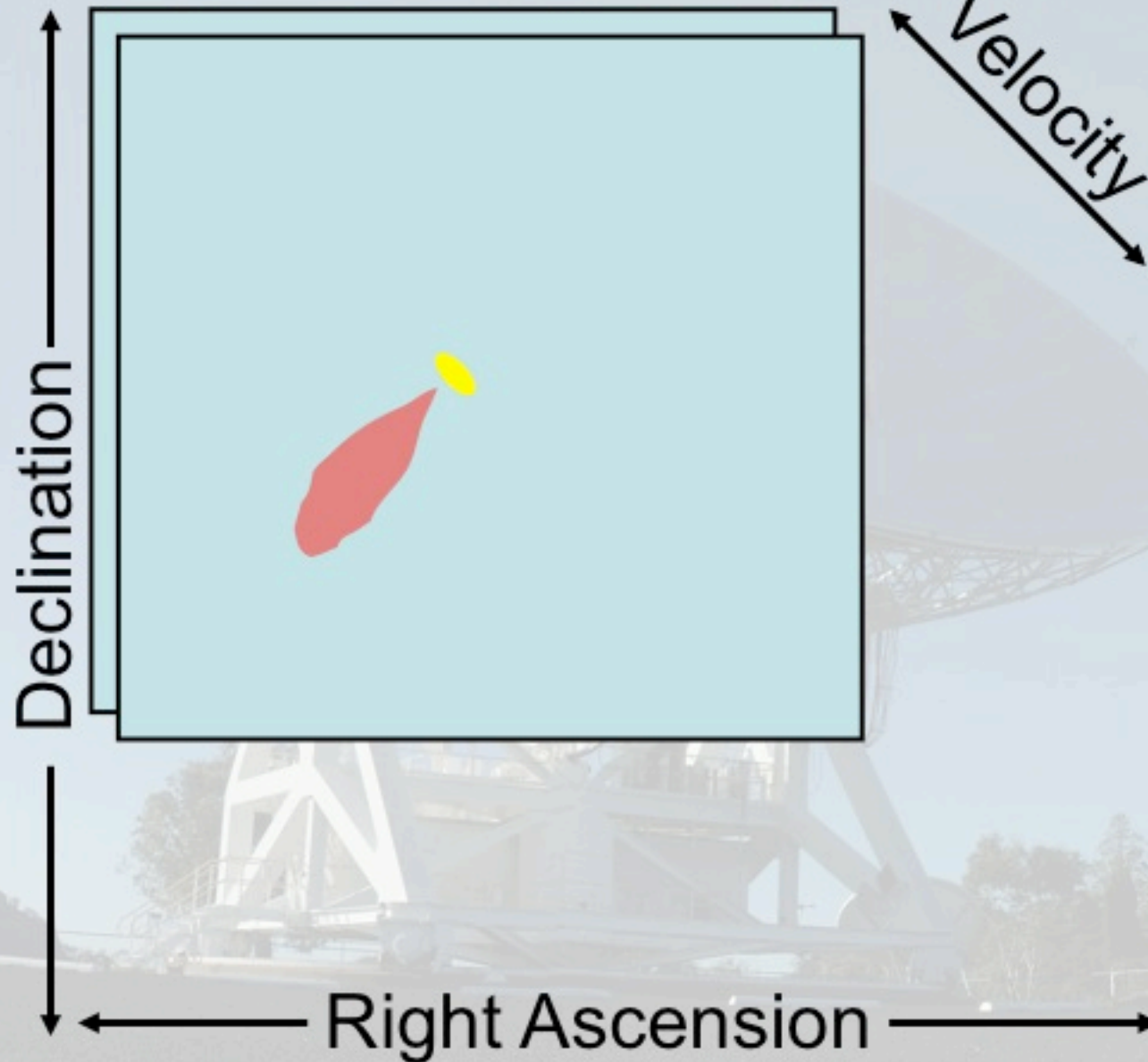
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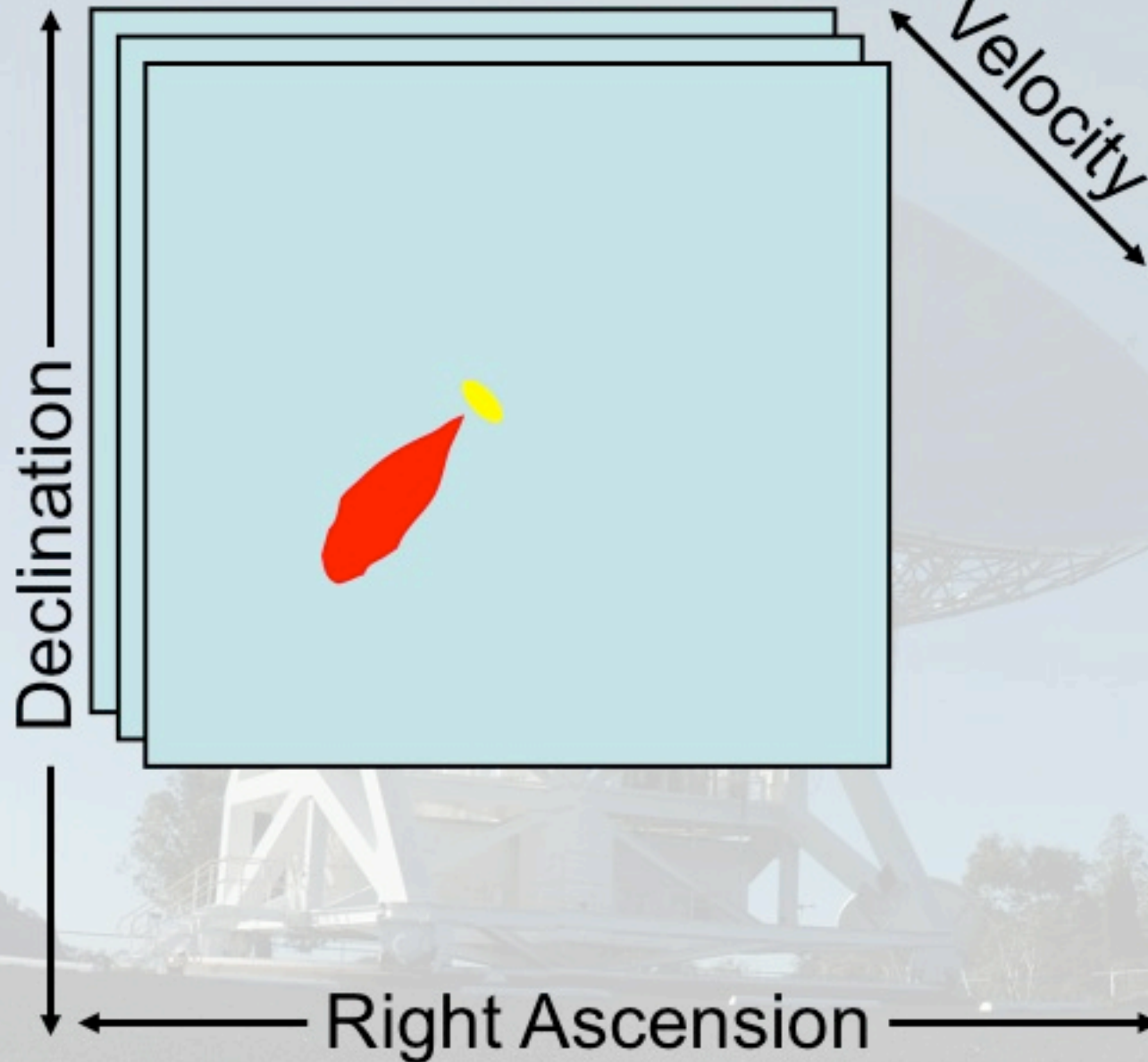
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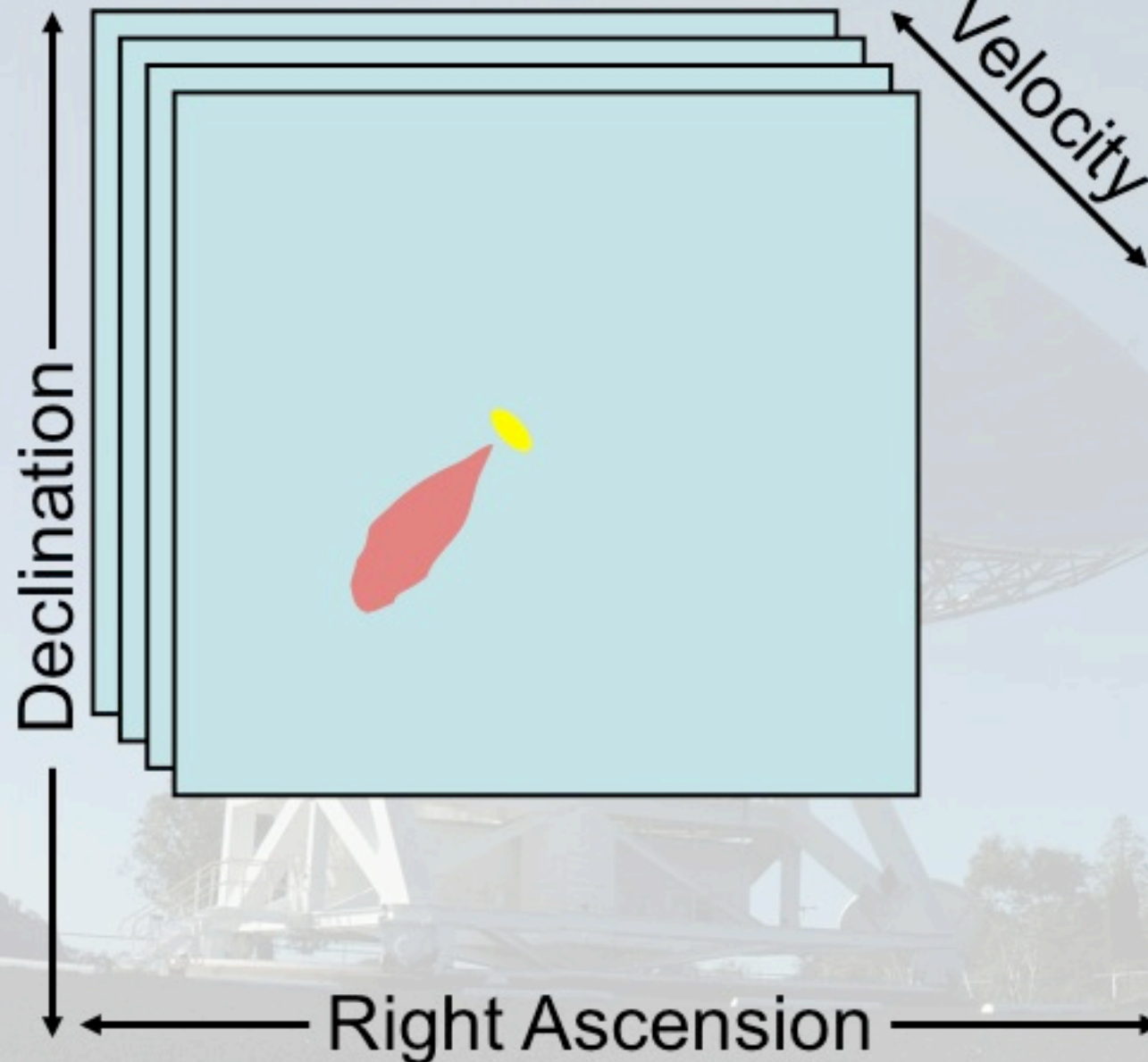
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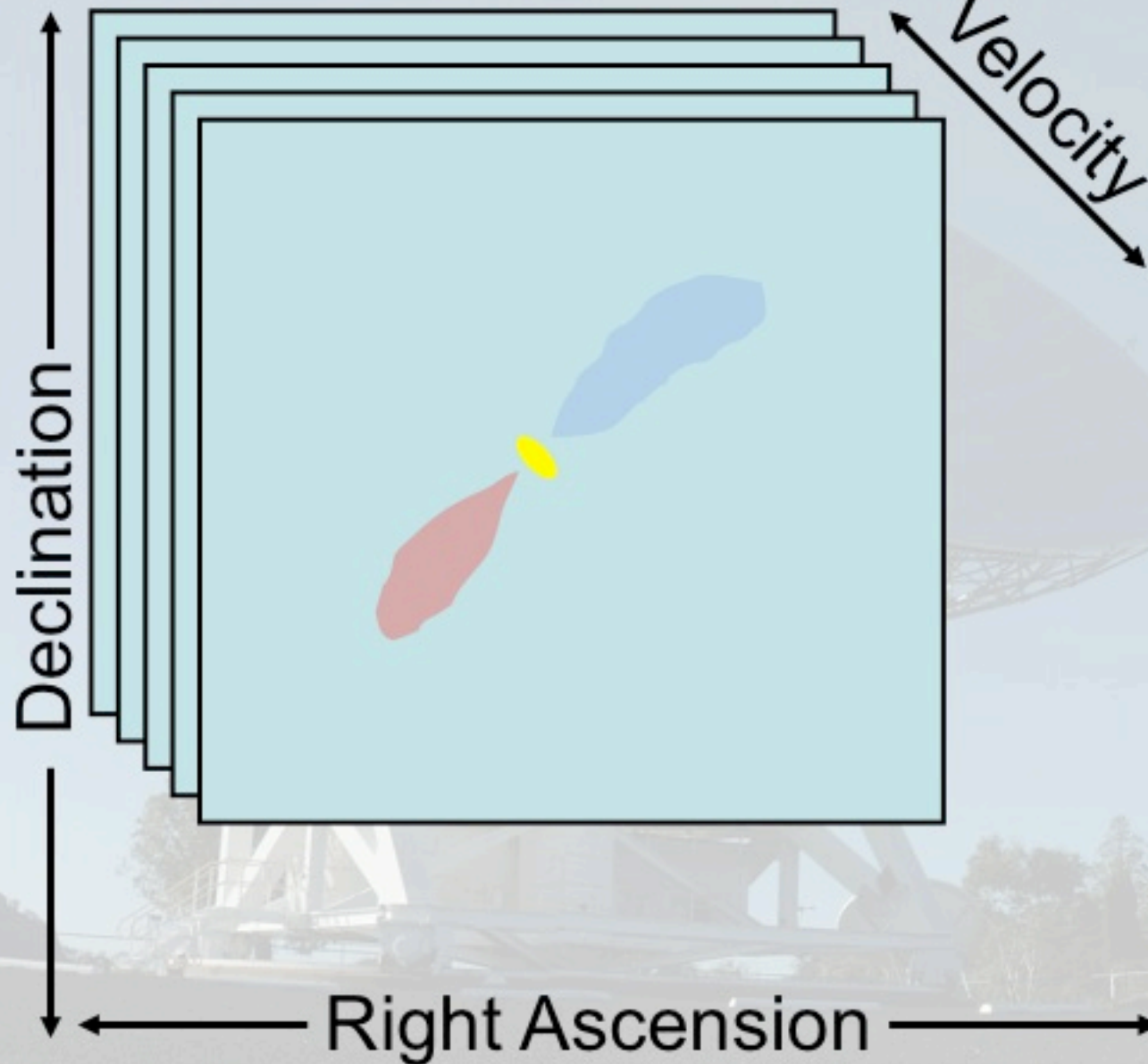
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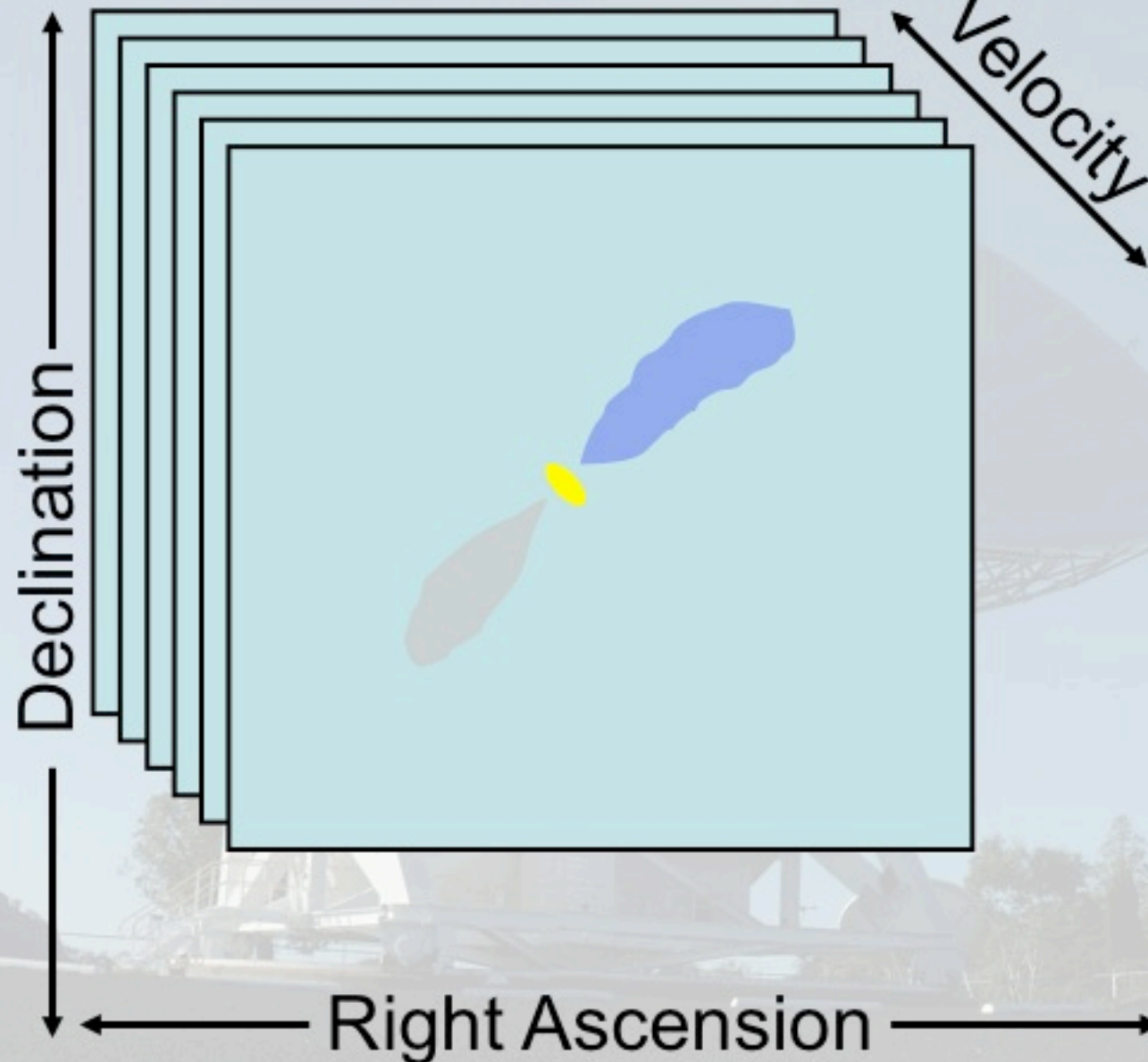
Data cubes and moment maps



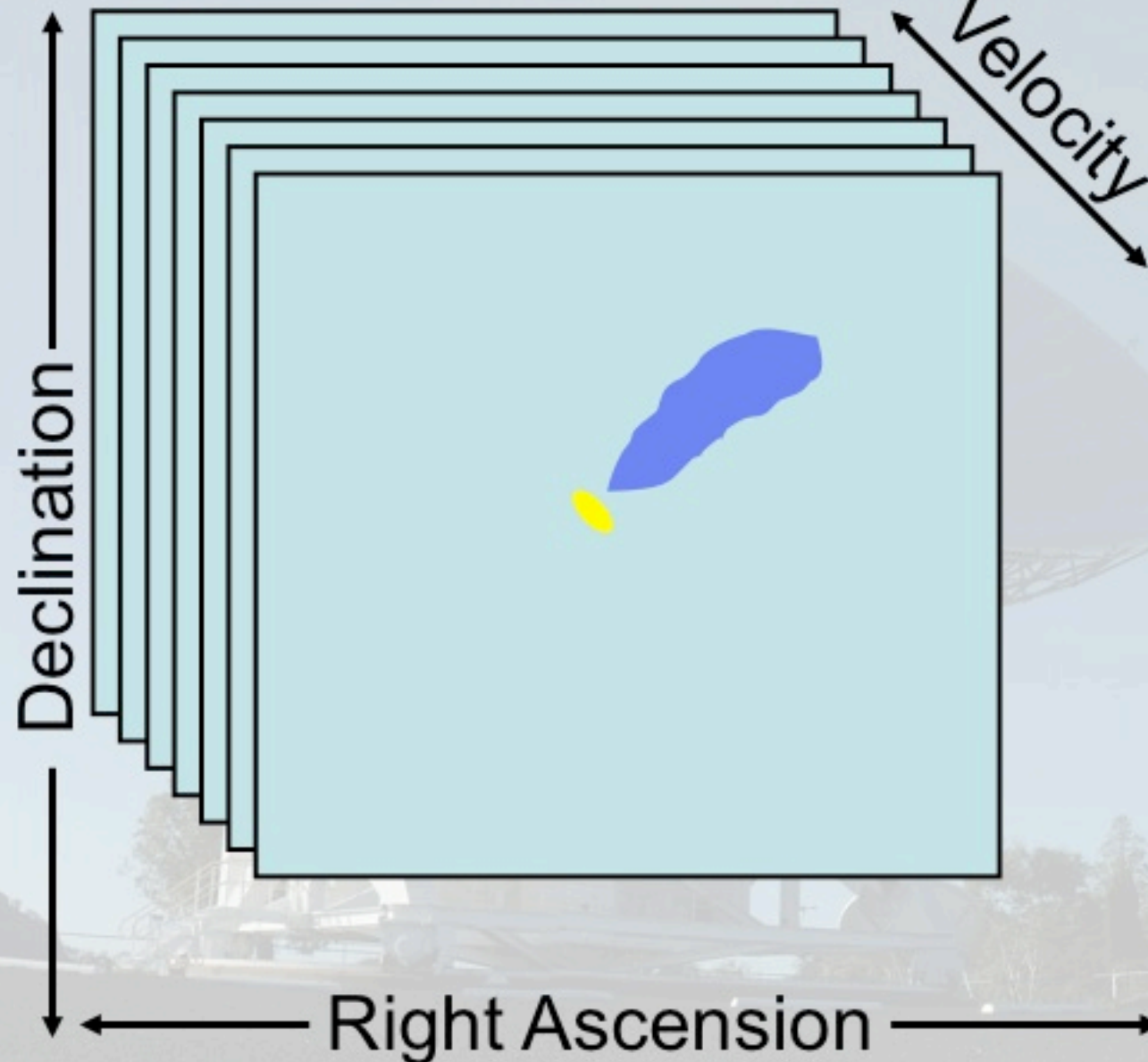
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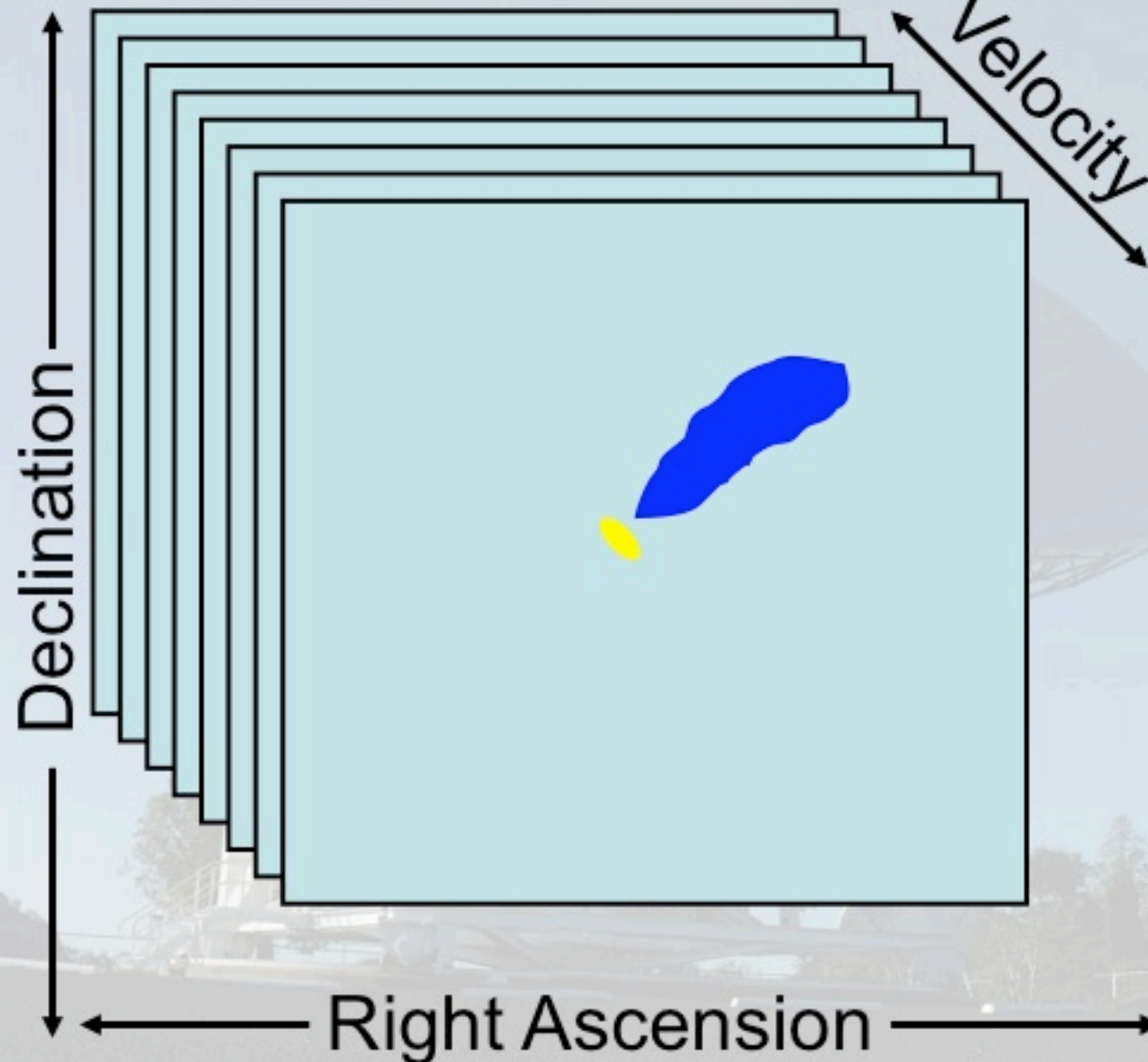
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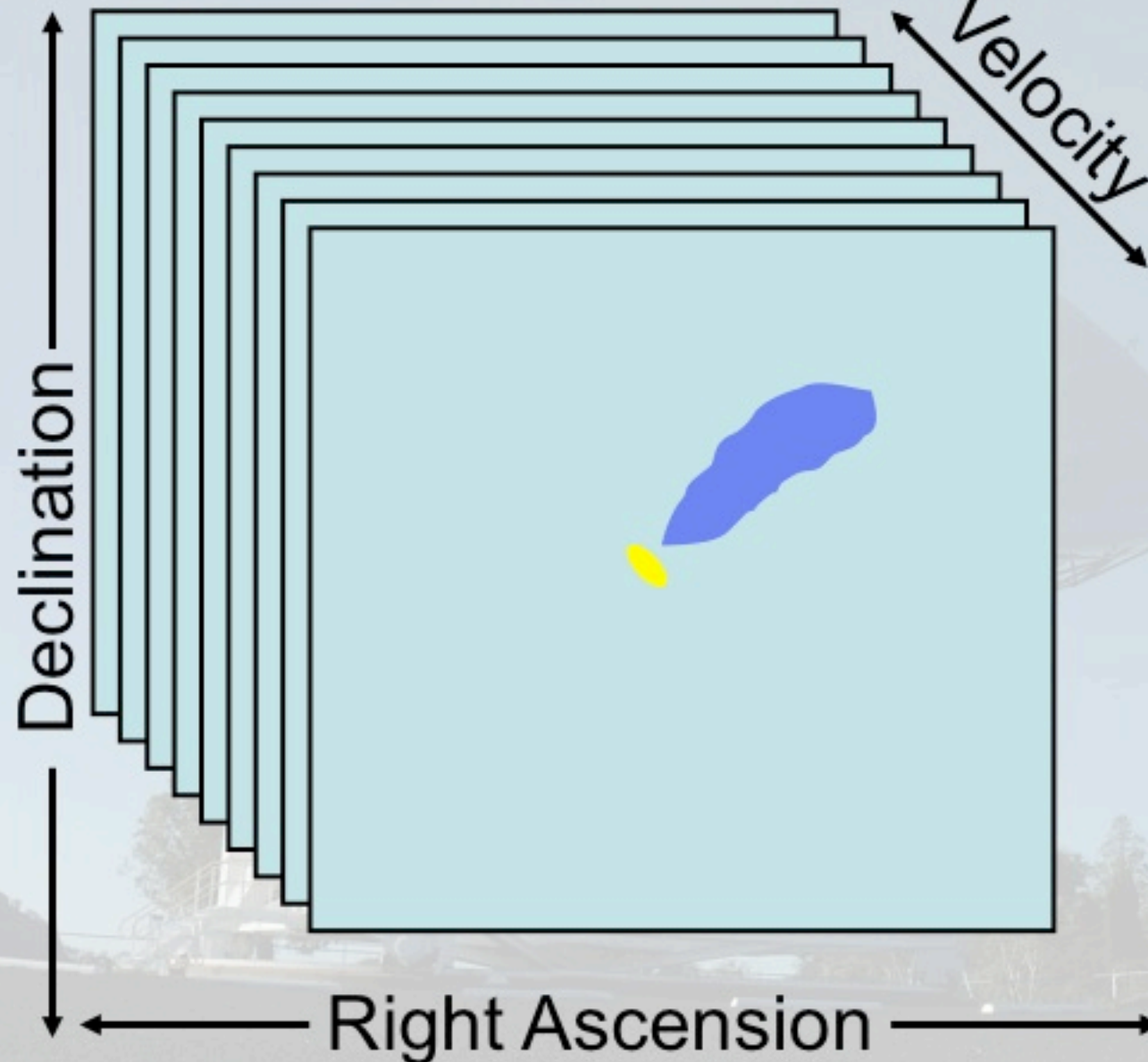
Data cubes and moment maps



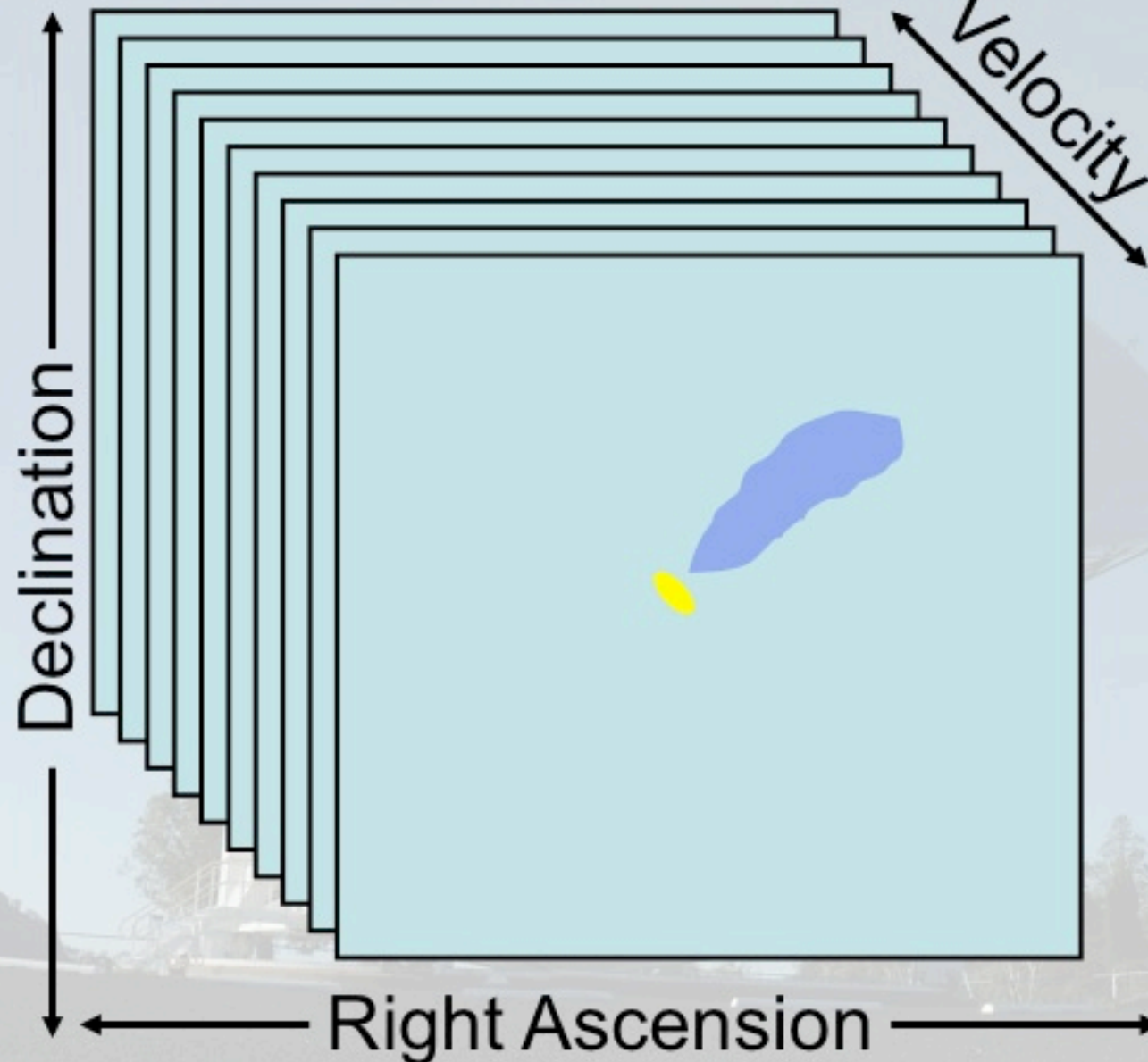
Data cubes and moment maps



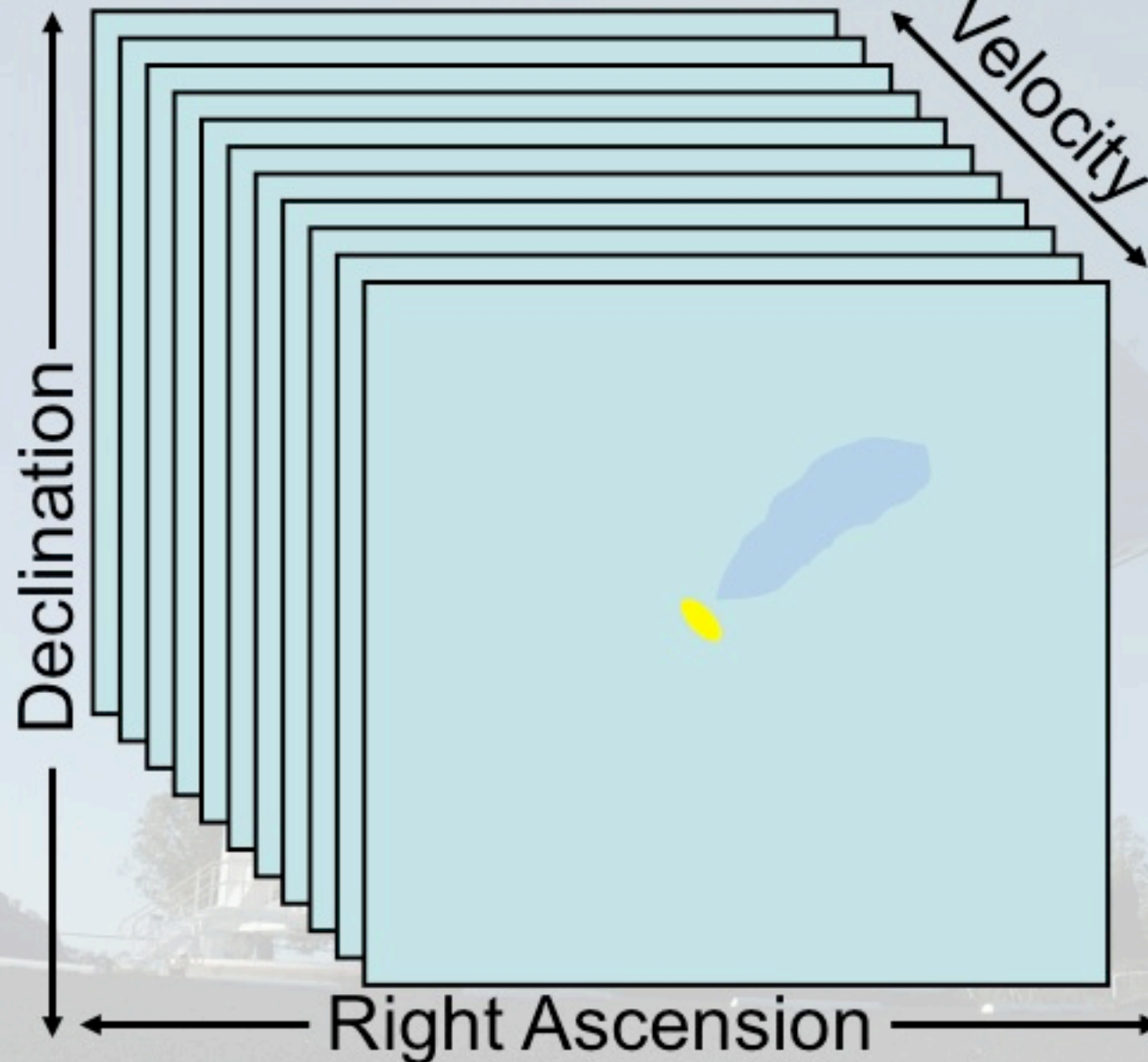
Data cubes and moment maps



Data cubes and moment maps

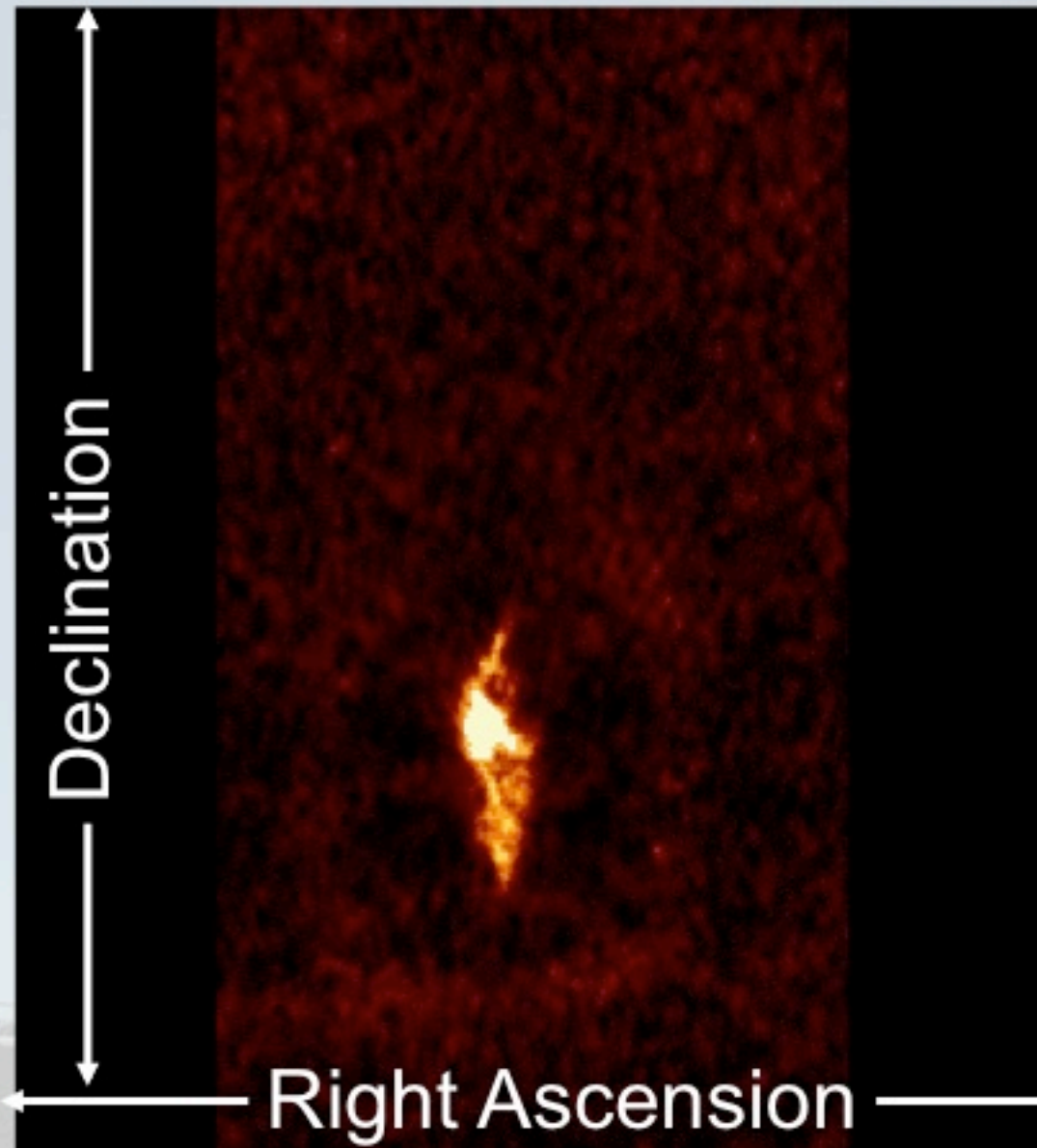


Data cubes and moment maps



Data cubes and moment maps

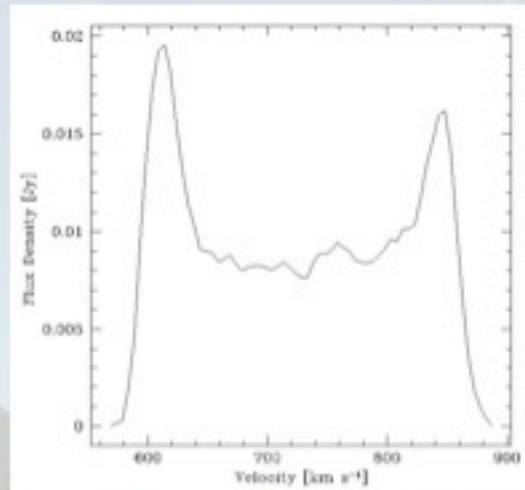
Thanks
Juergen
Ott!



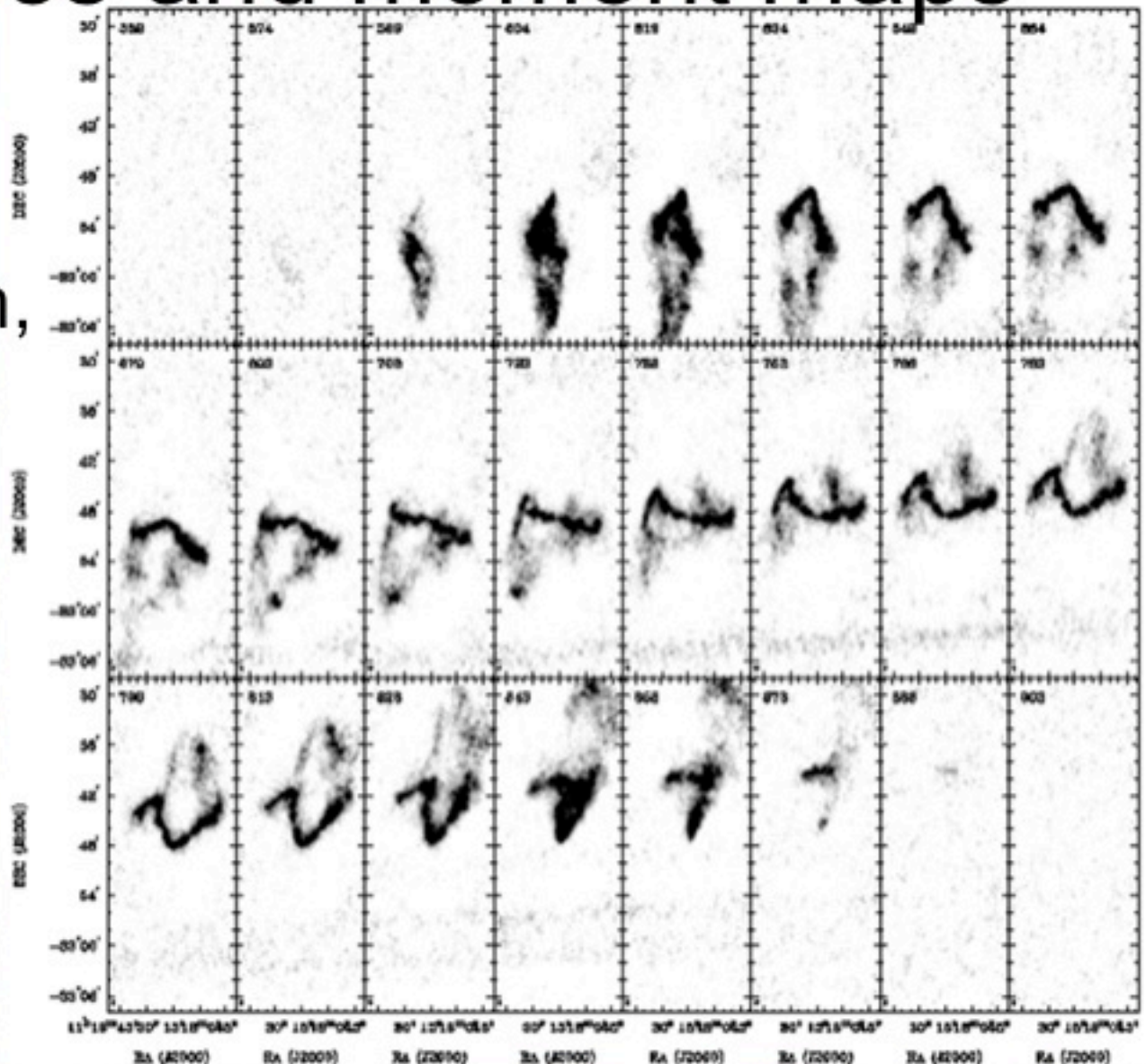
Data cubes and moment maps

Channel
Maps

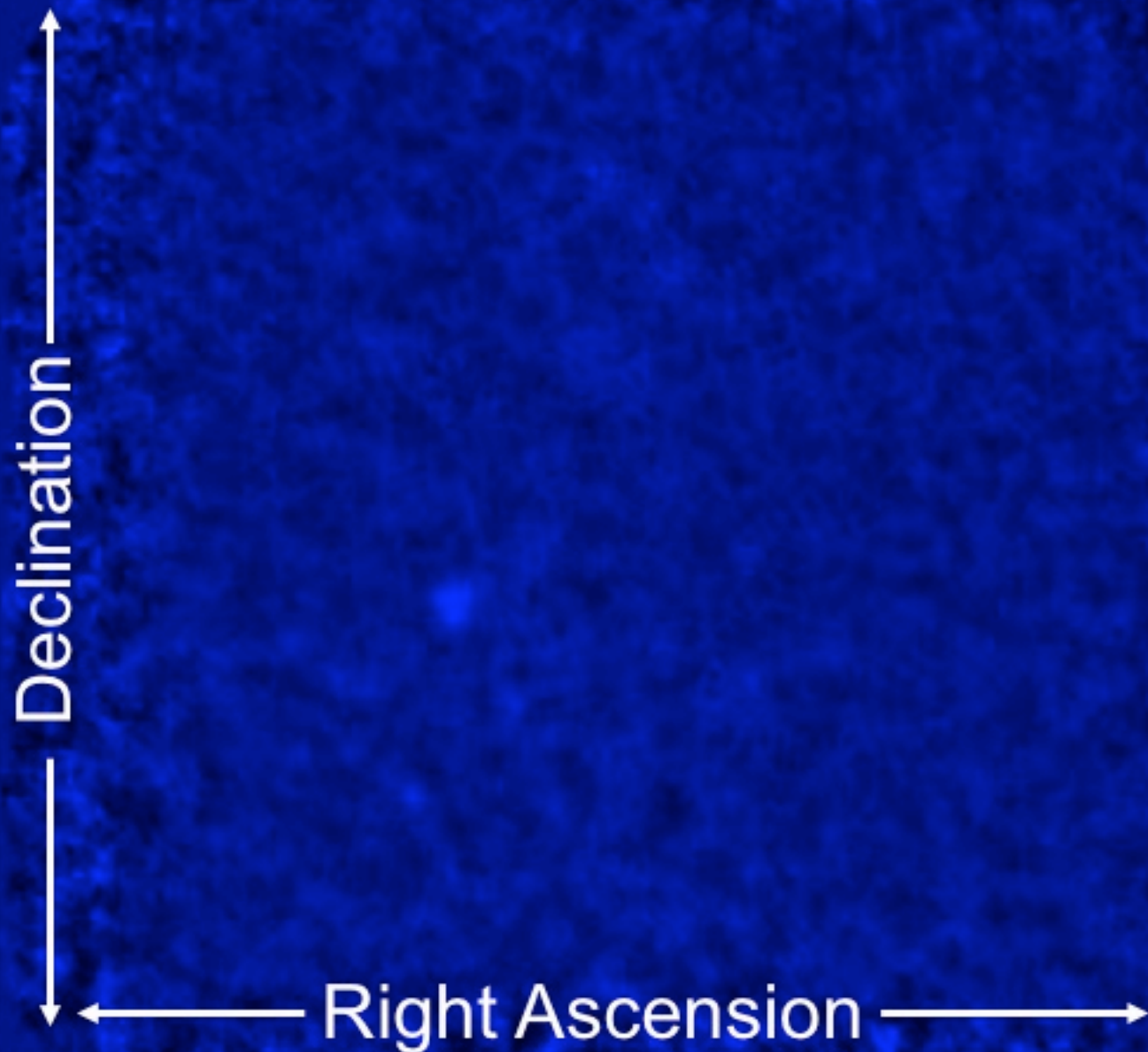
You're the man,
Ottmeister!



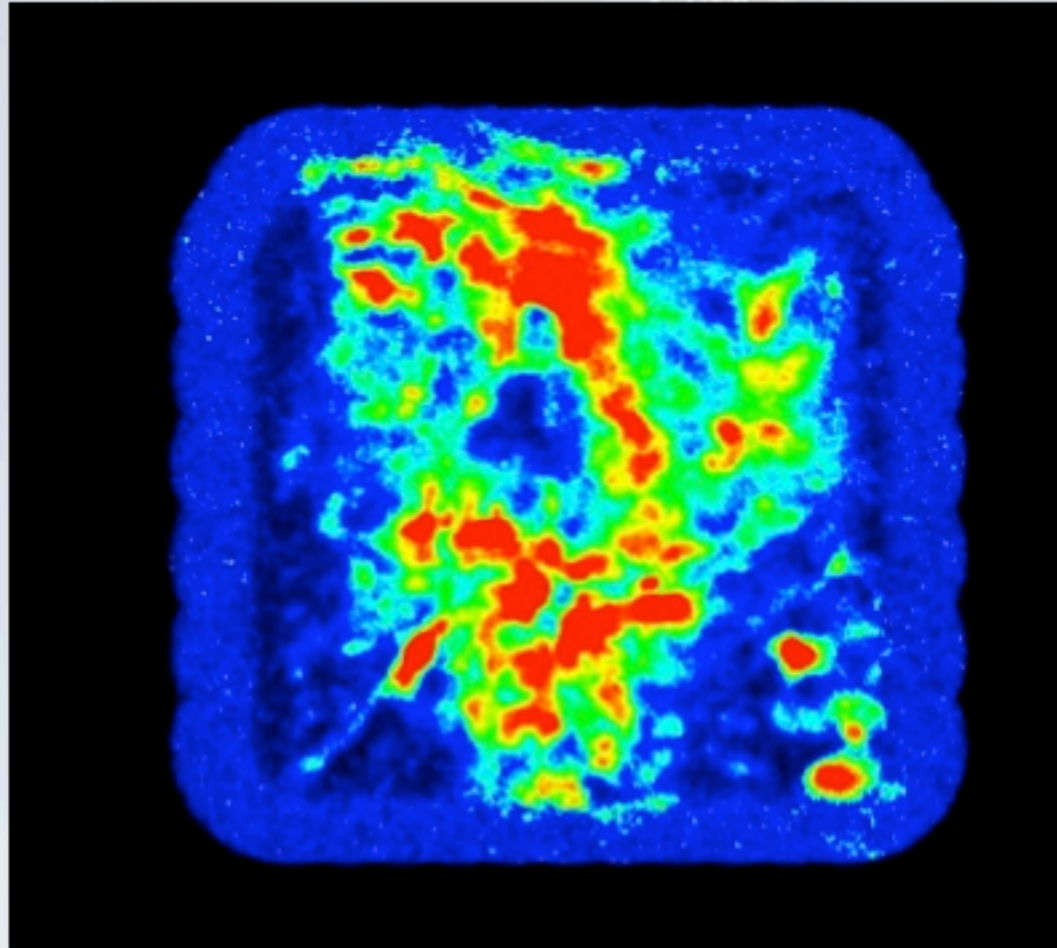
Spectrum



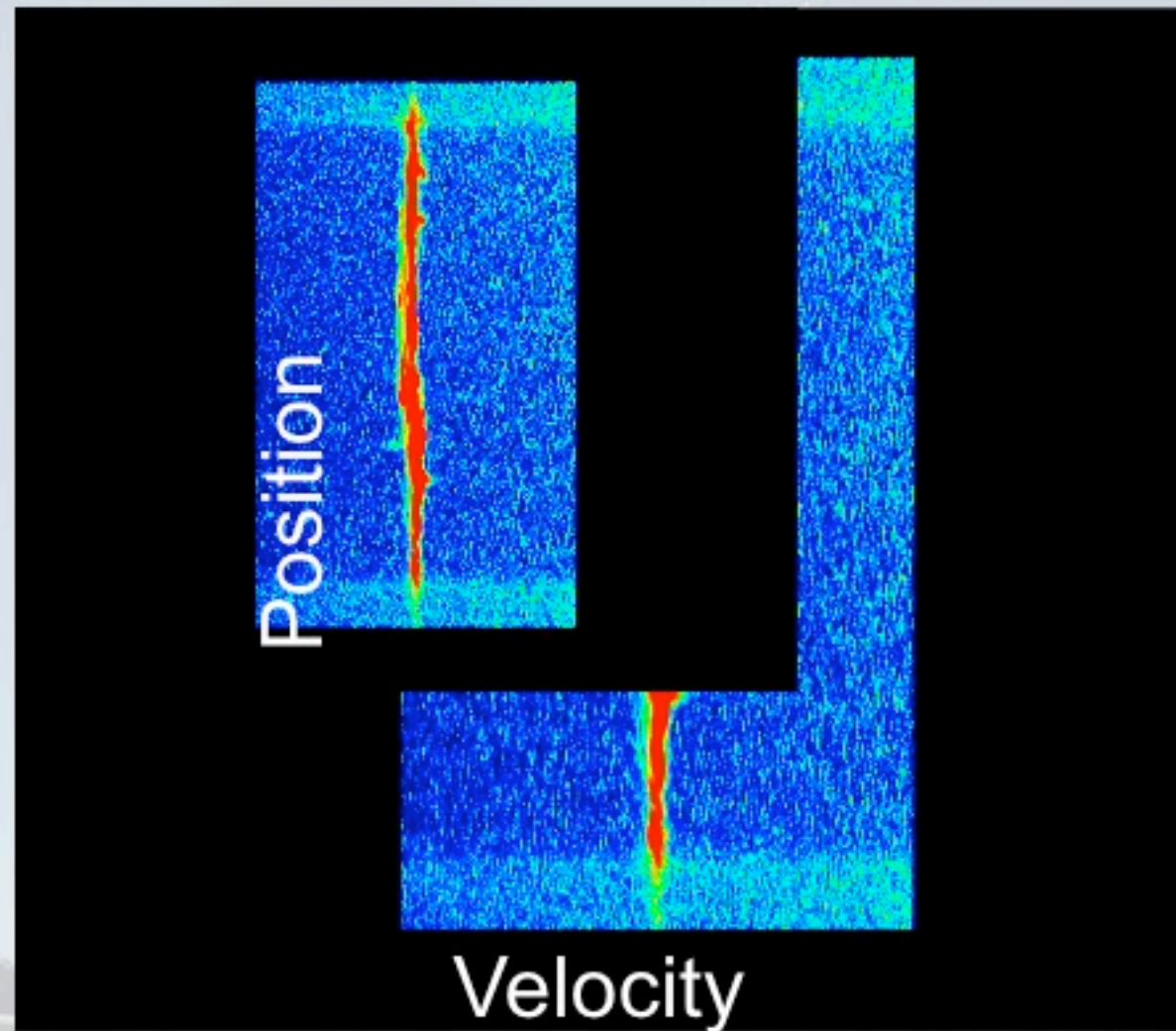
Data cubes and moment maps



Data cubes and moment maps



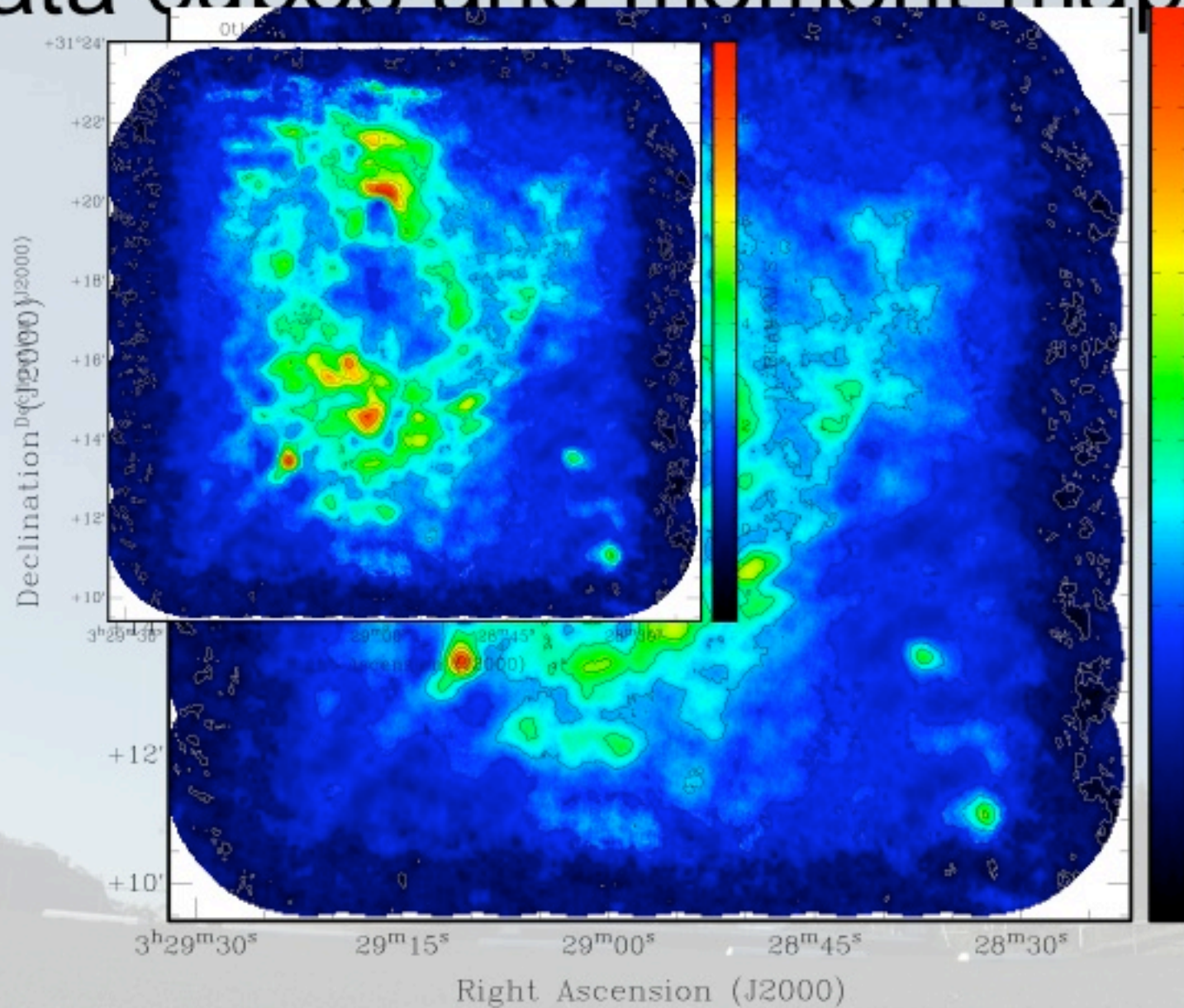
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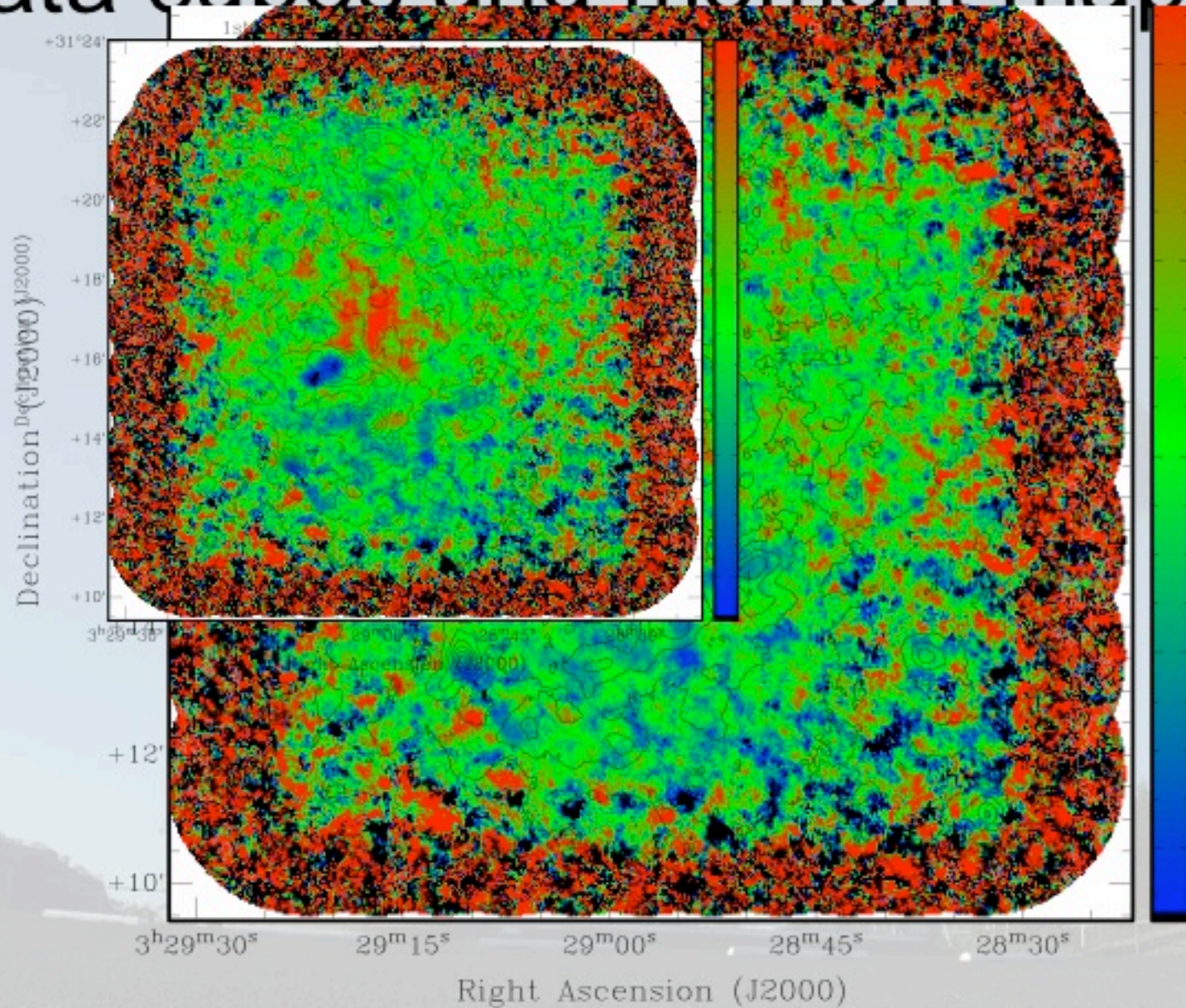
Data cubes and moment maps

- **0th moment** = integrated intensity map [Jy km s^{-1}]
= $\sum I(v) \delta v$
- **1st moment** = intensity weighted velocity map [km s^{-1}]
= $\sum I(v) v / \sum I(v)$
- **2nd moment** = 1 σ velocity dispersion [km s^{-1}]
= $\sqrt{\sum [I(v) (v-M1)^2] / \sum I(v)}$

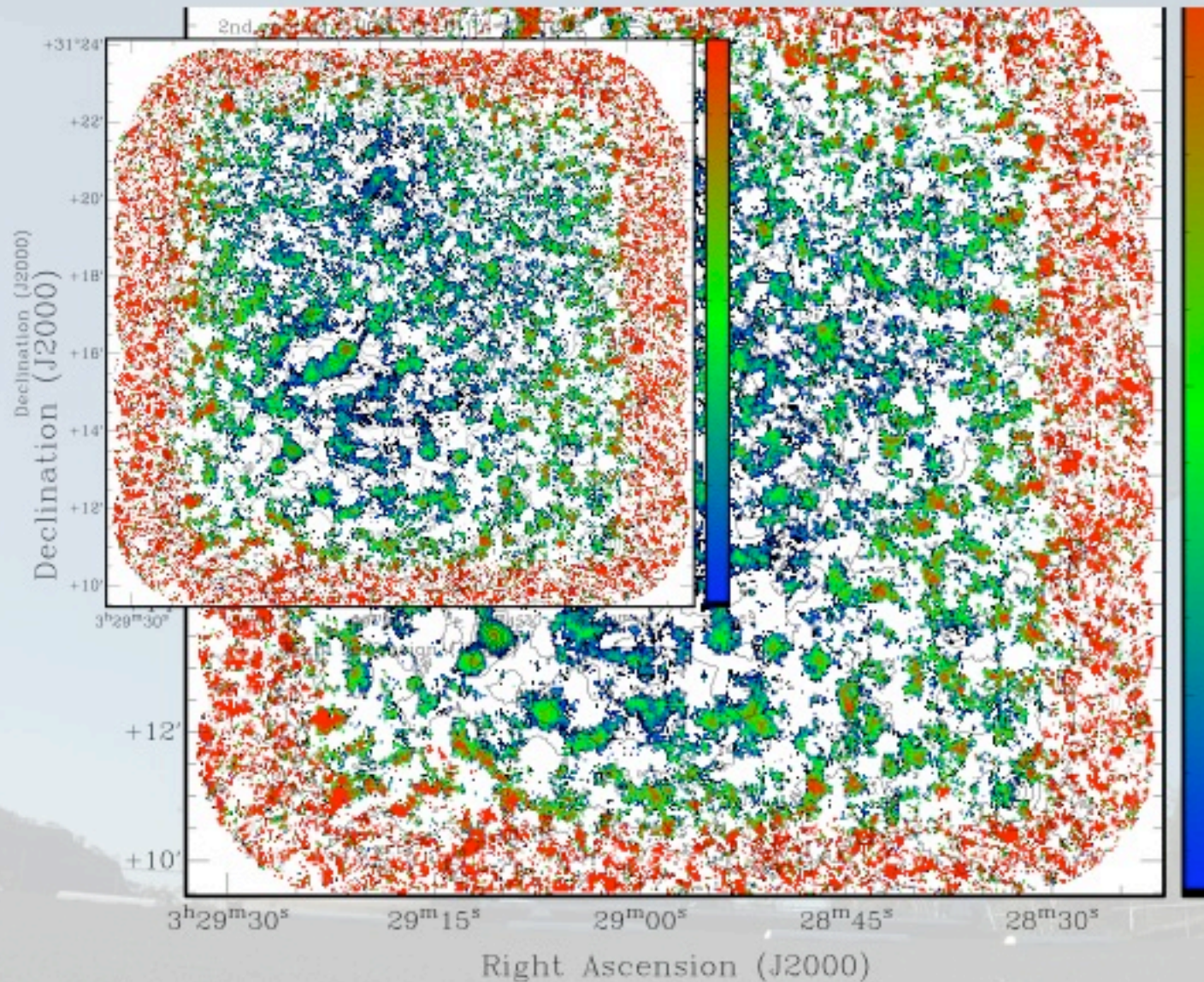
Data cubes and moment maps



Data cubes and moment maps



Data cubes and moment maps

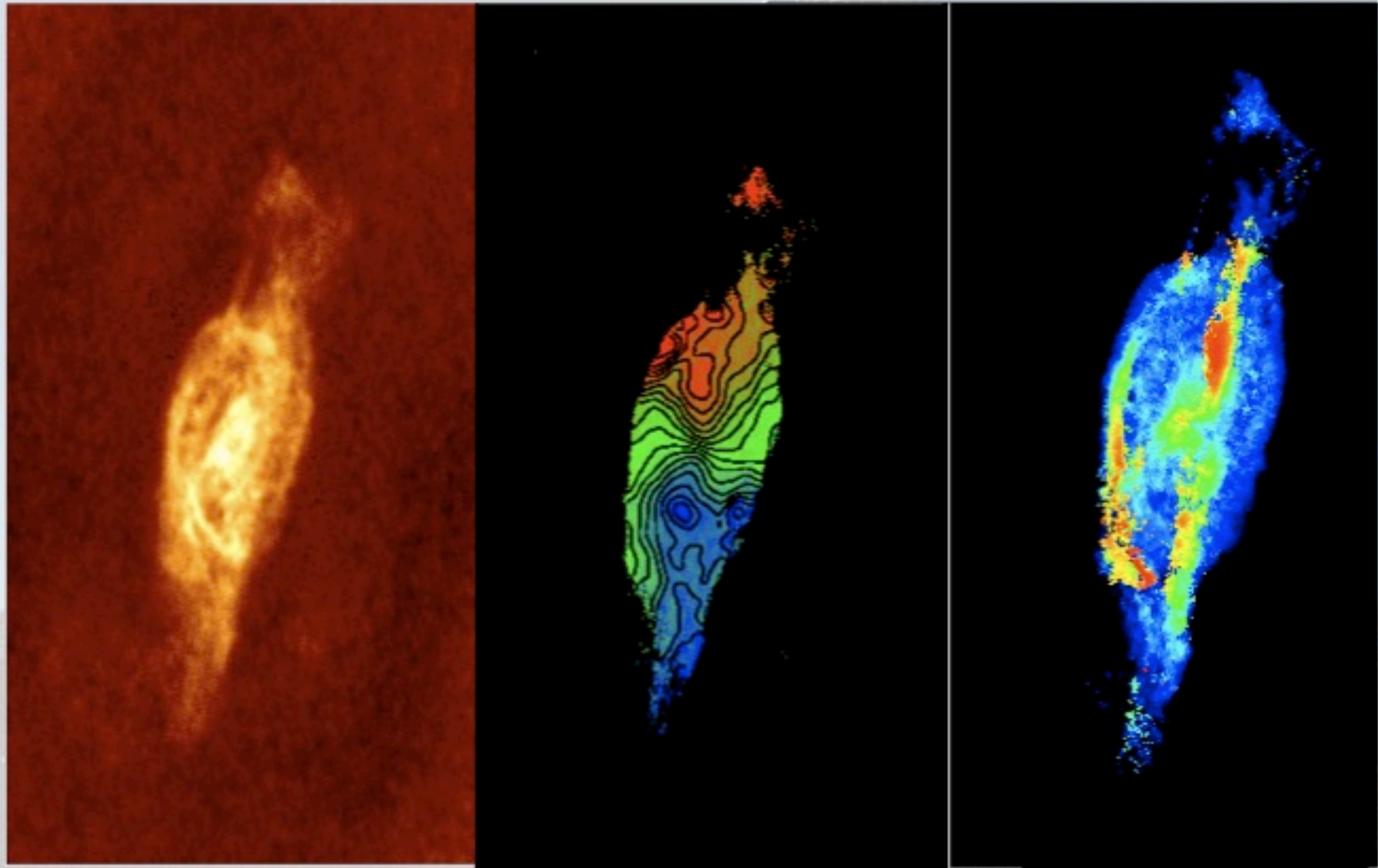


Data cubes and moment maps

Moment 0

Moment 1

Moment 2

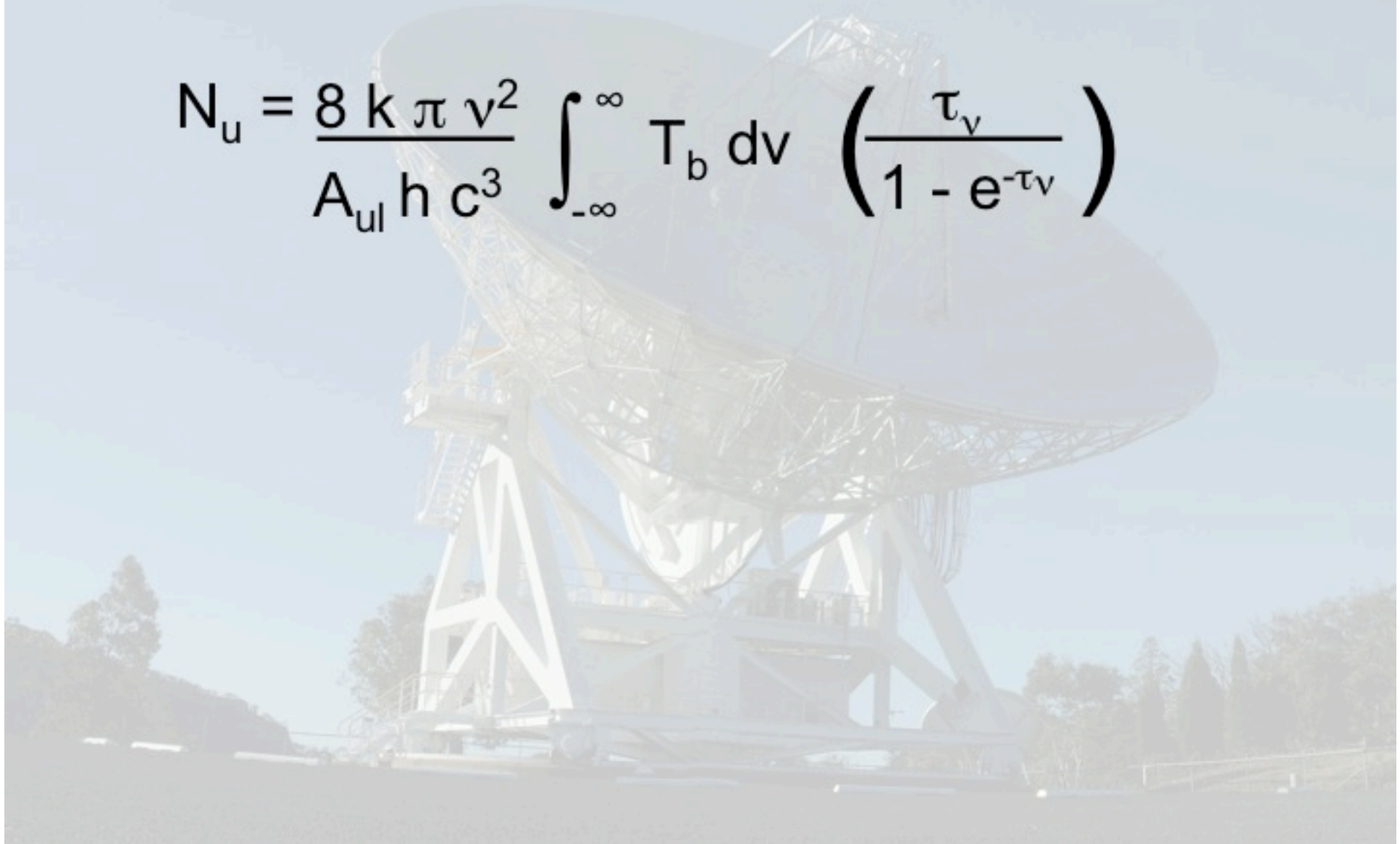


Calculating Column Densities



Calculating Column Densities

$$N_u = \frac{8 k \pi \nu^2}{A_{ul} h c^3} \int_{-\infty}^{\infty} T_b d\nu \left(\frac{\tau_\nu}{1 - e^{-\tau_\nu}} \right)$$



Calculating Column Densities

$$N_u = \frac{8 k \pi \nu^2}{A_{ul} h c^3} \int_{-\infty}^{\infty} T_b d\nu \left(\frac{\tau_\nu}{1 - e^{-\tau_\nu}} \right)$$

N_u = Column density in upper energy level

Calculating Column Densities

$$N_u = \frac{8 k \pi \nu^2}{A_{ul} h c^3} \int_{-\infty}^{\infty} T_b d\nu \left(\frac{\tau_\nu}{1 - e^{-\tau_\nu}} \right)$$

k = Boltzmann's constant
= $1.38 \times 10^{-23} \text{ m}^2 \text{ kg s}^{-2} \text{ K}^{-1}$

Calculating Column Densities

$$N_u = \frac{8 k \pi \nu^2}{A_{ul} h c^3} \int_{-\infty}^{\infty} T_b dv \left(\frac{\tau_\nu}{1 - e^{-\tau_\nu}} \right)$$

ν = frequency of line transition
(eg. 115.271 GHz for CO(1-0))

Calculating Column Densities

$$N_u = \frac{8 \kappa \pi \nu^2}{A_{ul} h c^3} \int_{-\infty}^{\infty} T_b \, d\nu \left(\frac{\tau_\nu}{1 - e^{-\tau_\nu}} \right)$$

A_{ul} = Einstein A coefficient for transition

$$= \frac{16\pi^3 \nu^3}{3\epsilon_0 h c^3} |\mu^2|$$

Calculating Column Densities

$$N_u = \frac{8 \kappa \pi \nu^2}{A_{ul} h c^3} \int_{-\infty}^{\infty} T_b \, d\nu \left(\frac{\tau_\nu}{1 - e^{-\tau_\nu}} \right)$$

A_{ul} = Einstein A coefficient for transition

$$= \frac{16\pi^3 \nu^3}{3\epsilon_0 h c^3} |\mu^2|$$

ϵ_0 = permittivity of free space

$$= 8.854 \times 10^{-12} \text{ m}^{-3} \text{ kg}^{-1} \text{ s}^4 \text{ A}^2$$

Calculating Column Densities

$$N_u = \frac{8 \kappa \pi \nu^2}{A_{ul} h c^3} \int_{-\infty}^{\infty} T_b \, d\nu \left(\frac{\tau_\nu}{1 - e^{-\tau_\nu}} \right)$$

$$\begin{aligned} A_{ul} &= \text{Einstein A coefficient for transition} \\ &= \frac{16\pi^3 \nu^3}{3\epsilon_0 h c^3} |\mu^2| \end{aligned}$$

μ = magnetic dipole moment
(eg, for N_2H^+ =

Calculating Column Densities

$$N_u = \frac{8 \kappa \pi \nu^2}{A_{ul} h c^3} \int_{-\infty}^{\infty} T_b d\nu \left(\frac{\tau_\nu}{1 - e^{-\tau_\nu}} \right)$$

$$A_{ul} = \text{Einstein A coefficient for transition} \\ = \frac{16\pi^3 \nu^3}{3\epsilon_0 h c^3} |\mu^2|$$

μ = magnetic dipole moment
(eg, for N_2H^+ = 3.4 Debye)

Calculating Column Densities

$$N_u = \frac{8 \kappa \pi \nu^2}{A_{ul} h c^3} \int_{-\infty}^{\infty} T_b \, d\nu \left(\frac{\tau_\nu}{1 - e^{-\tau_\nu}} \right)$$

$$\begin{aligned} A_{ul} &= \text{Einstein A coefficient for transition} \\ &= \frac{16\pi^3 \nu^3}{3\epsilon_0 h c^3} |\mu^2| \end{aligned}$$

μ = magnetic dipole moment

(eg, for N_2H^+ = 3.4 Debye = 1.13×10^{-29} C m)

Calculating Column Densities

$$N_u = \frac{8 \pi \nu^2}{A_{ul} h c^3} \int_{-\infty}^{\infty} T_b dv \left(\frac{\tau_\nu}{1 - e^{-\tau_\nu}} \right)$$

Integrated Intensity
(area under the curve)

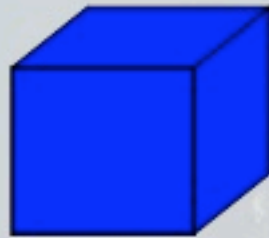
Calculating Column Densities

$$N_u = \frac{8 k \pi \nu^2}{A_{ul} h c^3} \int_{-\infty}^{\infty} T_b d\nu \left(\frac{\tau_\nu}{1 - e^{-\tau_\nu}} \right)$$

$\tau_\nu =$ optical depth

Optical Depth

Optically thick



$$\tau \gg 1 \quad T_B = T_B(B_\nu)$$

→ Temperature probe

Optically thin



$$\tau \ll 1 \quad T_B = \tau_\nu T_B(B_\nu)$$

→ Column density probe

Calculating Column Densities

$$N_u = \frac{8 \pi \nu^2}{A_{ul} h c^3} \int_{-\infty}^{\infty} T_b \, d\nu \left(\frac{\tau_\nu}{1 - e^{-\tau_\nu}} \right)$$

$$N = \frac{N_u}{g_u} e^{E_u/kT} Q(T_{ex})$$

Calculating Column Densities

$$N_u = \frac{8 \pi \nu^2}{A_{ul} h c^3} \int_{-\infty}^{\infty} T_b dv \left(\frac{\tau_\nu}{1 - e^{-\tau_\nu}} \right)$$

$$N = \frac{N_u}{g_u} e^{E_u/kT} Q(T_{ex})$$

g_u = upper energy level degeneracy
= $2J+1$

Calculating Column Densities

$$N_u = \frac{8 \pi \nu^2}{A_{ul} h c^3} \int_{-\infty}^{\infty} T_b \, d\nu \left(\frac{\tau_\nu}{1 - e^{-\tau_\nu}} \right)$$

$$N = \frac{N_u}{g_u} e^{E_u/kT} Q(T_{ex})$$

E_u = upper energy level (K)

Calculating Column Densities

$$N_u = \frac{8 \pi \nu^2}{A_{ul} h c^3} \int_{-\infty}^{\infty} T_b dv \left(\frac{\tau_\nu}{1 - e^{-\tau_\nu}} \right)$$

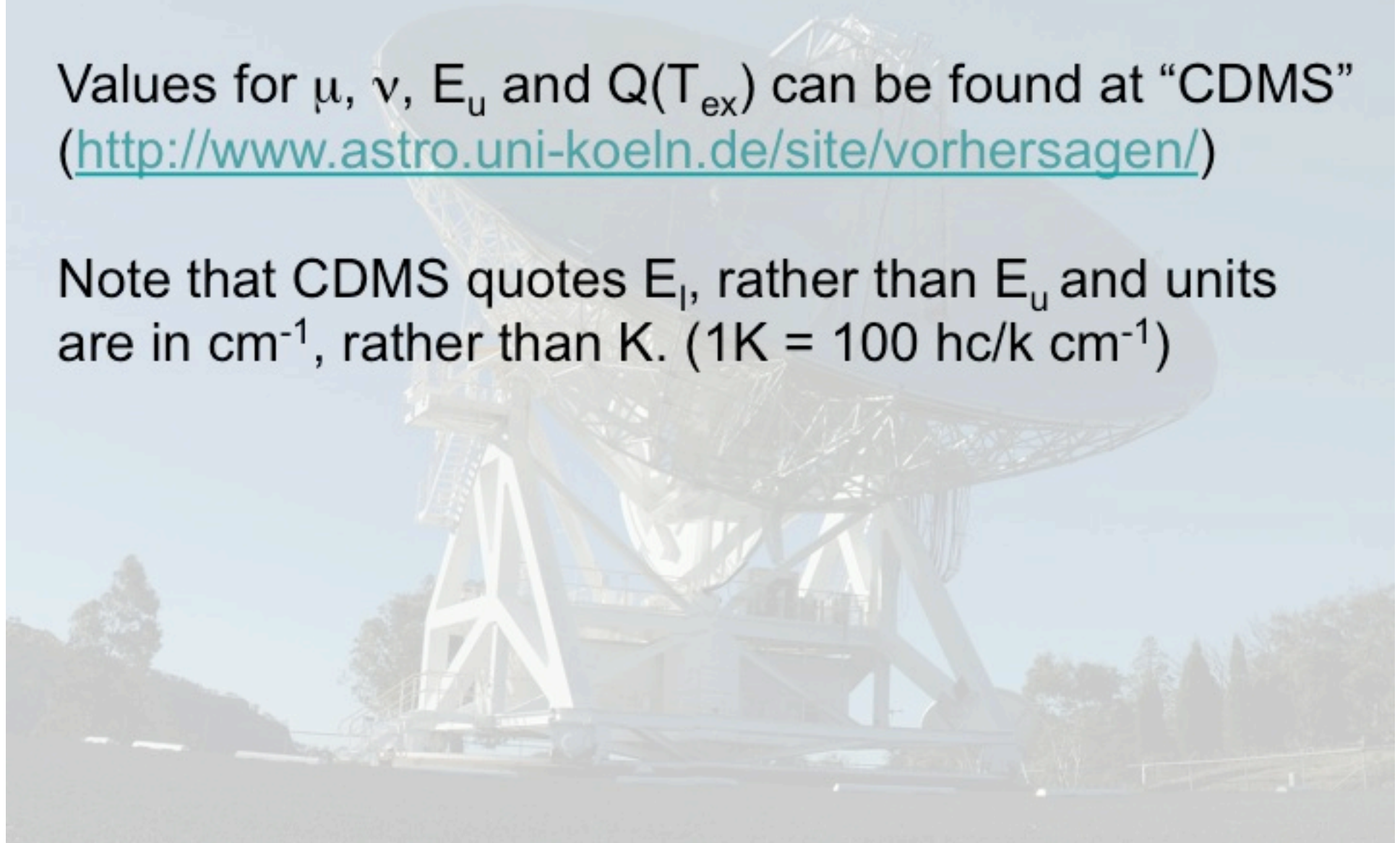
$$N = \frac{N_u}{g_u} e^{E_u/kT} Q(T_{ex})$$

$Q(T_{ex})$ = partition function (a sum over all energy states) at a given temperature, T_{ex}

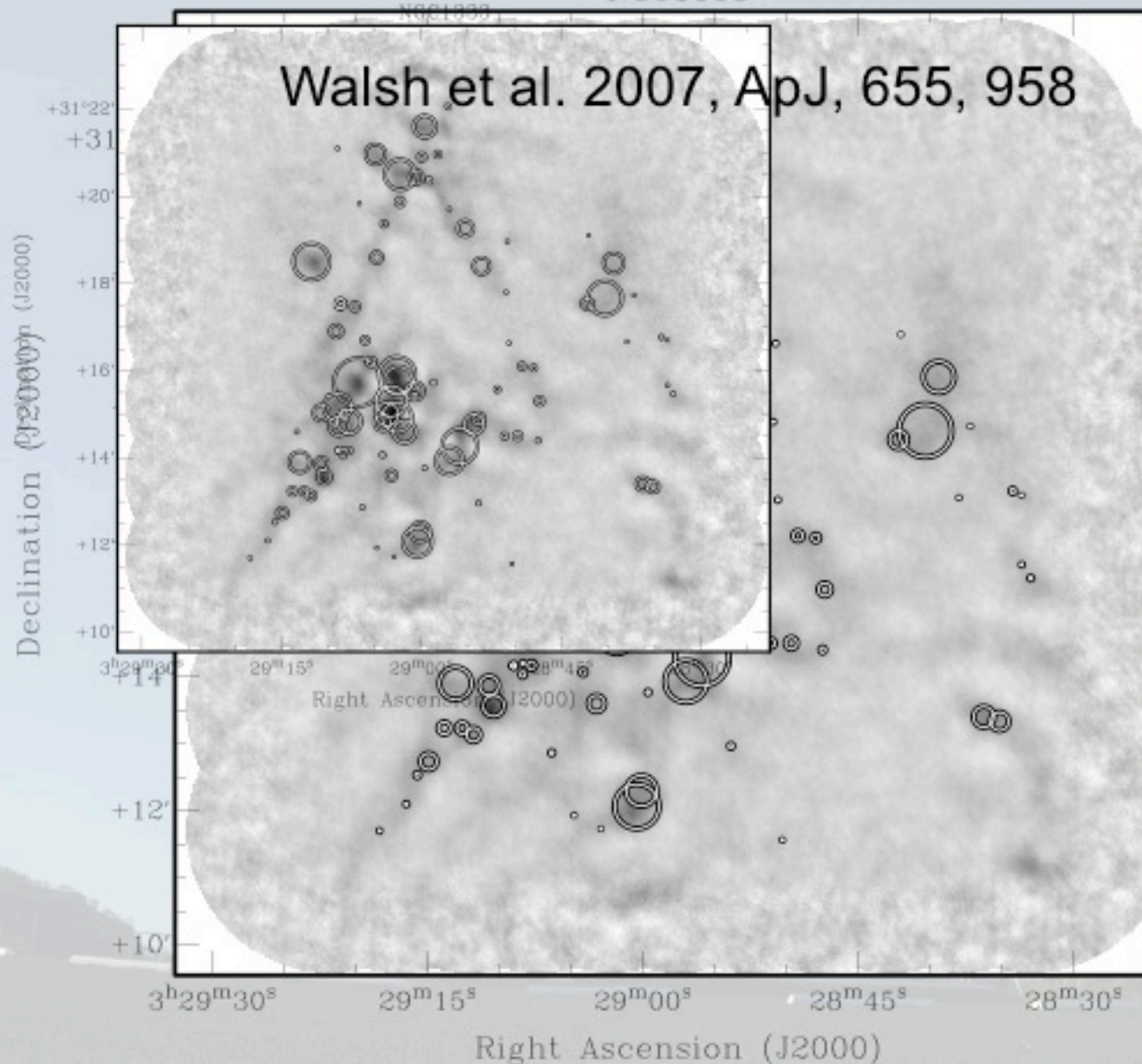
Calculating Column Densities

Values for μ , ν , E_u and $Q(T_{ex})$ can be found at “CDMS” (<http://www.astro.uni-koeln.de/site/vorhersagen/>)

Note that CDMS quotes E_l , rather than E_u and units are in cm^{-1} , rather than K. ($1\text{K} = 100 \text{ hc/k cm}^{-1}$)



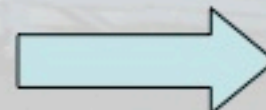
Applying Column Densities



Applying Column Densities

Given column density of N_2H^+ clump in NGC1333:

- Assume LTE
- Assume size of clump
- Assume relative abundance of N_2H^+ to H_2
($\sim 1.8 \times 10^{-10}$)
- Assume mean molecular weight 2.3

 Mass of clump

Applying Column Densities

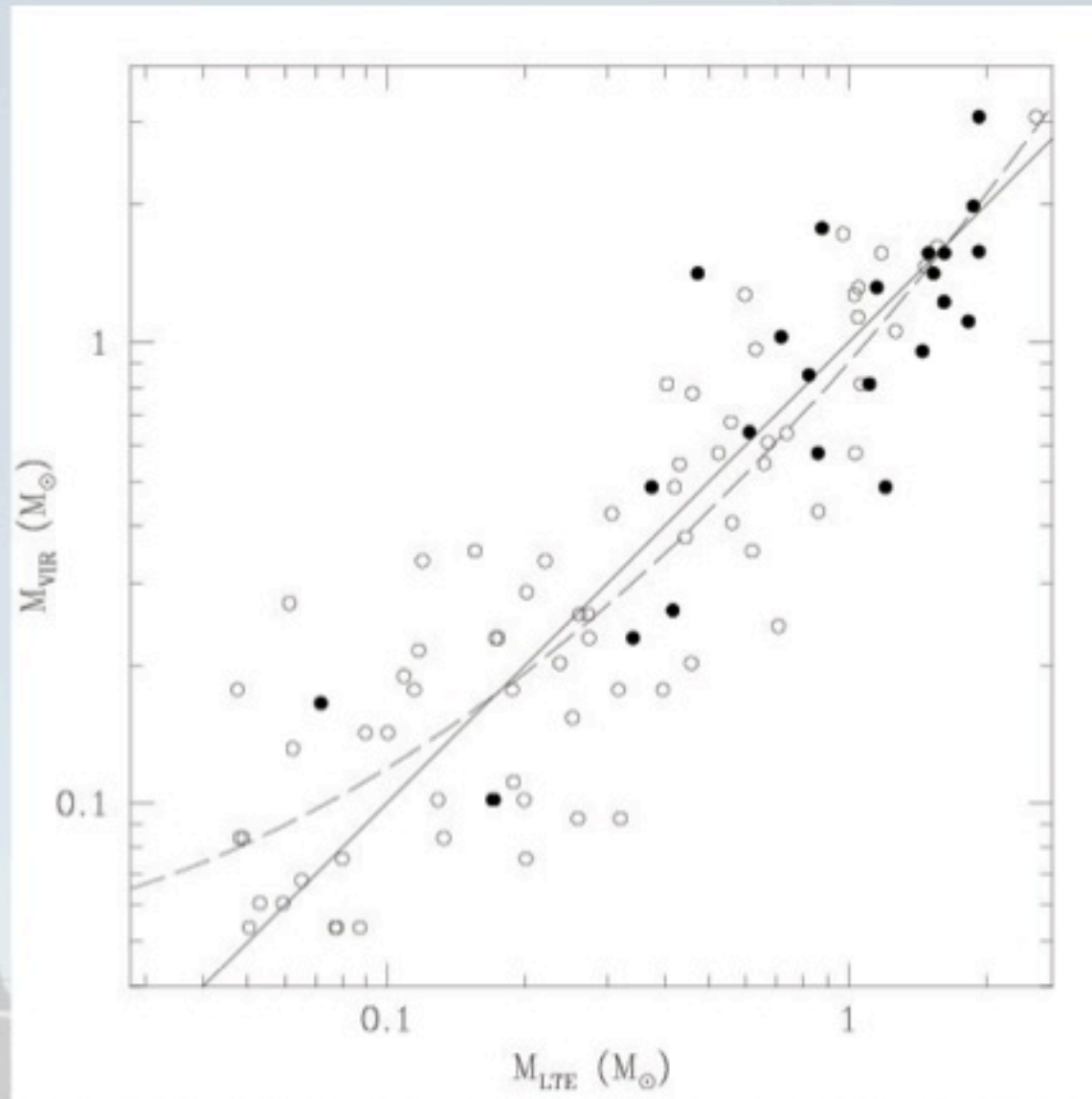
Compare to Virial Mass:

$$\frac{M_{\text{VIR}}}{M_{\odot}} = 210 \frac{\delta v^2}{\text{km/s}} \frac{r}{\text{pc}}$$

Assumes uniform density profile

If density falls off as r^{-2} ,
210 changes to 126.

Applying Column Densities



Applying Column Densities

$$N = \frac{N_u}{g_u} e^{E_u/kT} Q(T_{ex})$$



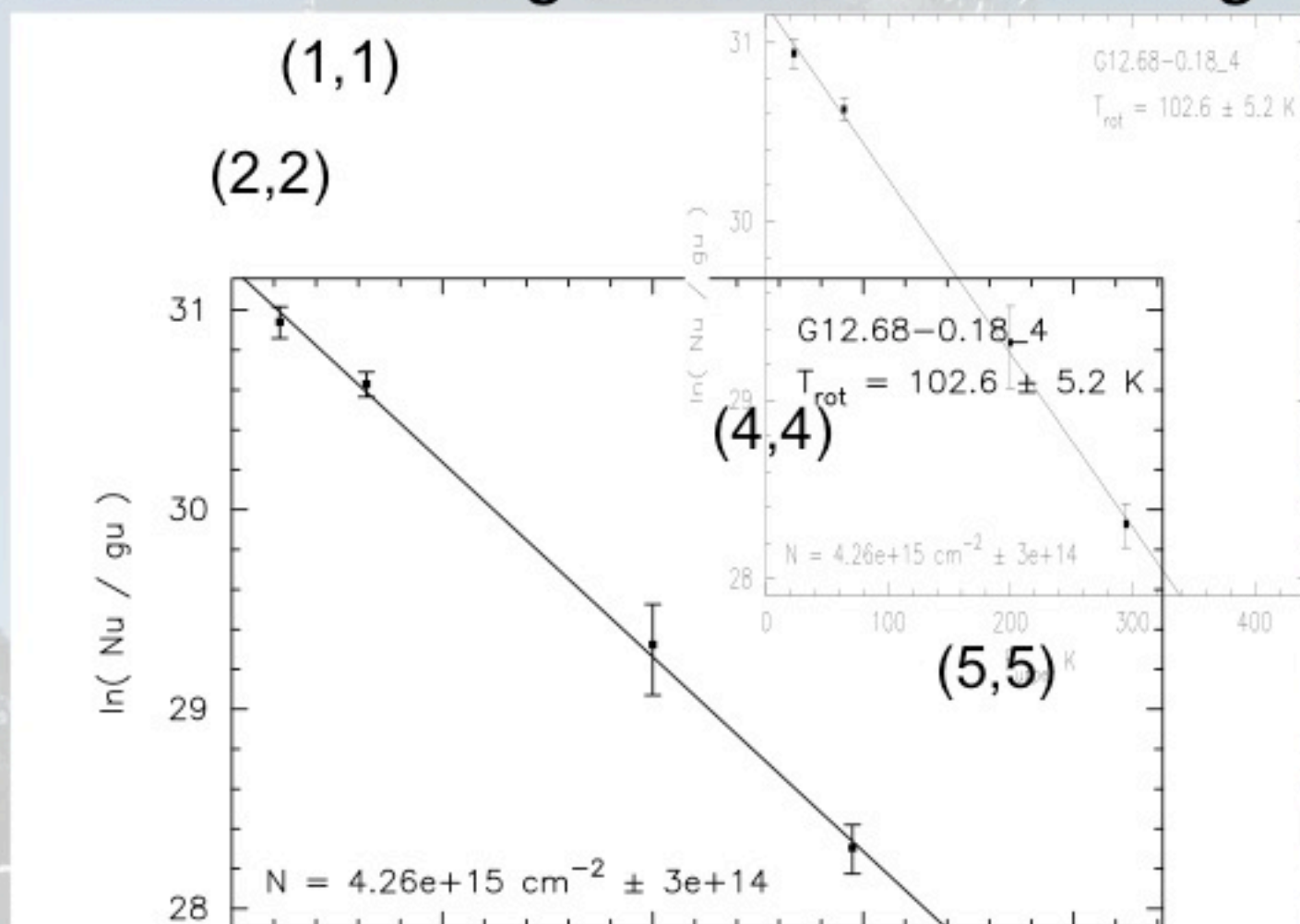
Rotation Diagrams

$$\ln \left(\frac{N_u}{g_u} \right) = \ln \left(\frac{N}{Q(T)} \right) - \frac{E_u}{kT_{\text{ex}}}$$

- Plot $\ln (N_u/g_u)$ vs. E_u/k
- Slope = $1/T$
- Y-intercept = $\ln (N/Q(T))$

Rotation Diagrams

Ammonia in a high mass star forming region



(Longmore et al. 2007, MNRAS, 379, 535)

Atoms, Molecules, Ions and Radicals in Space



Atoms, Molecules, Ions and Radicals in Space

AlCl	C ₂ S	C ₃ N	HNCCC	CO	C
AlF	C ₃ S	C ₅ N	HNCO	CO ⁺	C ₂
AlNC	CH ₃ SH	CH ₂ CHCN	HNCO ⁻	CO ₂	C ₂ H
FeO	CS	CH ₂ CN	HNO	CO ₂ ⁺	C ₂ H ₂
HCl	H ₂ CS	CH ₂ NH	N ₂ H ⁺	H ₂ CCO	C ₂ H ₄
HF	H ₂ S	CH ₃ C ₃ N	N ₂ ⁺	H ₂ CO	C ₃
KCl	H ₂ S ⁺	CH ₃ CH ₂ CN	N ₂ O	H ₂ O	c-C ₃ H
MgCN	HCS ⁺	CH ₃ CN	NH	H ₂ O ⁺	I-C ₃ H
MgNC	HNCS	CH ₃ NC	NH ₂	H ₃ CO ⁺	c-C ₃ H ₂
NaCl	HS	CH ₃ NH ₂	NH ₃	H ₃ O ⁺	C ₄ H
NaCN	HS ⁺	CN	NH ₄ ⁺	HC ₂ CHO	C ₅
PN	OCS	CN ⁺	NH ₂ CN	HCO	C ₅ H
CP	S ₂	H ₂ C ₃ N ⁺	NH ₂ CHO	HCO ⁺	C ₆ H
	NS	H ₂ CN	NO	HCOOCH ₃	C ₆ H ₂
SiC	SO	HCN	c-C ₂ H ₄ O	HCOOH	C ₆ H ₆
c-SiC ₂	SO ⁺	HNC	CH ₃ CH ₂ OH	HOC ⁺	C ₇ H
SiC ₂	SO ₂	HCCN	C ₂ O	HOCH ₂ CH ₂ OH	C ₈ H
SiC ₃		HC ₃ N	C ₃ H ₄ O	HOCO ⁺	CH
SiC ₄		HC ₄ N	C ₃ O	OH	CH ⁺
SiCN		HC ₅ N	CH ₂ OHCHO	OH ⁺	CH ₂
SiH	H	HC ₇ N	CH ₃ CH ₂ CHO		CH ₃
SiH ₄	H ₂	HC ₉ N	CH ₃ CHO		CH ₃ CCH
SiN	H ₃ ⁺	HC ₁₁ N	CH ₃ COCH ₃		CH ₃ C ₄ H
SiNC		HCCNC	CH ₃ COOH		CH ₃ CH ₃
SiO		HCNH ⁺	CH ₃ OCH ₃		CH ₄
SiS			CH ₃ OH		H ₂ CCC
					H ₂ CCCC
					HCCCCCH
					HCCCCCCH

Some of the more important lines

H OH NH₃ H₂O HCN CO HCO⁺ N₂H⁺ CH₃OH CH₃CN SiO CS HCCCN



Some of the more important lines

H OH NH₃ H₂O HCN CO HCO⁺ N₂H⁺ CH₃OH CH₃CN SiO CS HCCCN

H I - atomic hydrogen

Ubiquitous low density gas tracer

Critical density $\sim 10^1 \text{ cm}^{-3}$

Frequency (GHz)

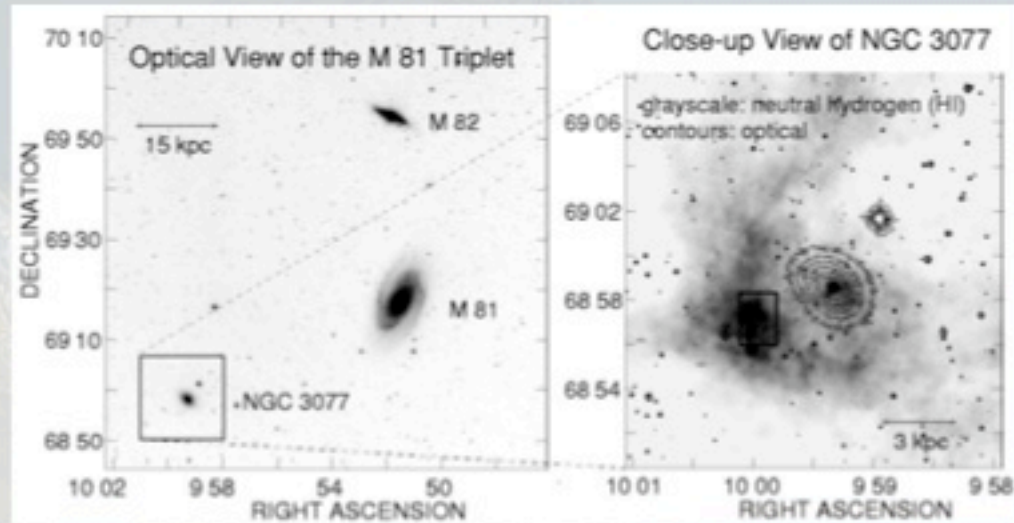
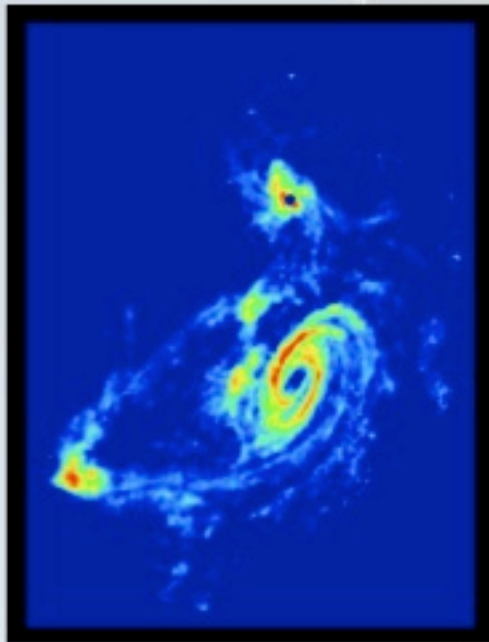
1.420

Strong enough to be easily
detected in other galaxies
– traces outer edges

Tully-Fisher relation

Some of the more important lines

H OH NH₃ H₂O HCN CO HCO⁺ N₂H⁺ CH₃OH CH₃CN SiO CS HCCCN



(Walter & Heithausen 1999)

Some of the more important lines

H **OH** NH₃ H₂O HCN CO HCO⁺ N₂H⁺ CH₃OH CH₃CN SiO CS HCCCN

OH - Hydroxyl Radical

Maser and thermal emission

Found towards star forming regions,
Evolved stars (post-AGB), SNRs,
Extragalactic sources

Frequency (GHz)
1.612
1.665
1.667
1.720
4.765
6.035

Some of the more important lines

H OH **NH₃** H₂O HCN CO HCO⁺ N₂H⁺ CH₃OH CH₃CN SiO CS HCCCN

NH₃ - Ammonia

Maser and thermal emission

Ubiquitous medium to high density
Gas tracer $> 10^3 \text{ cm}^{-3}$

Closely traces density structure

Frequency (GHz)

23.694

23.722

23.870

24.139

24.532

25.056

etc

Some of the more important lines

H OH **NH₃** H₂O HCN CO HCO⁺ N₂H⁺ CH₃OH CH₃CN SiO CS HCCCN

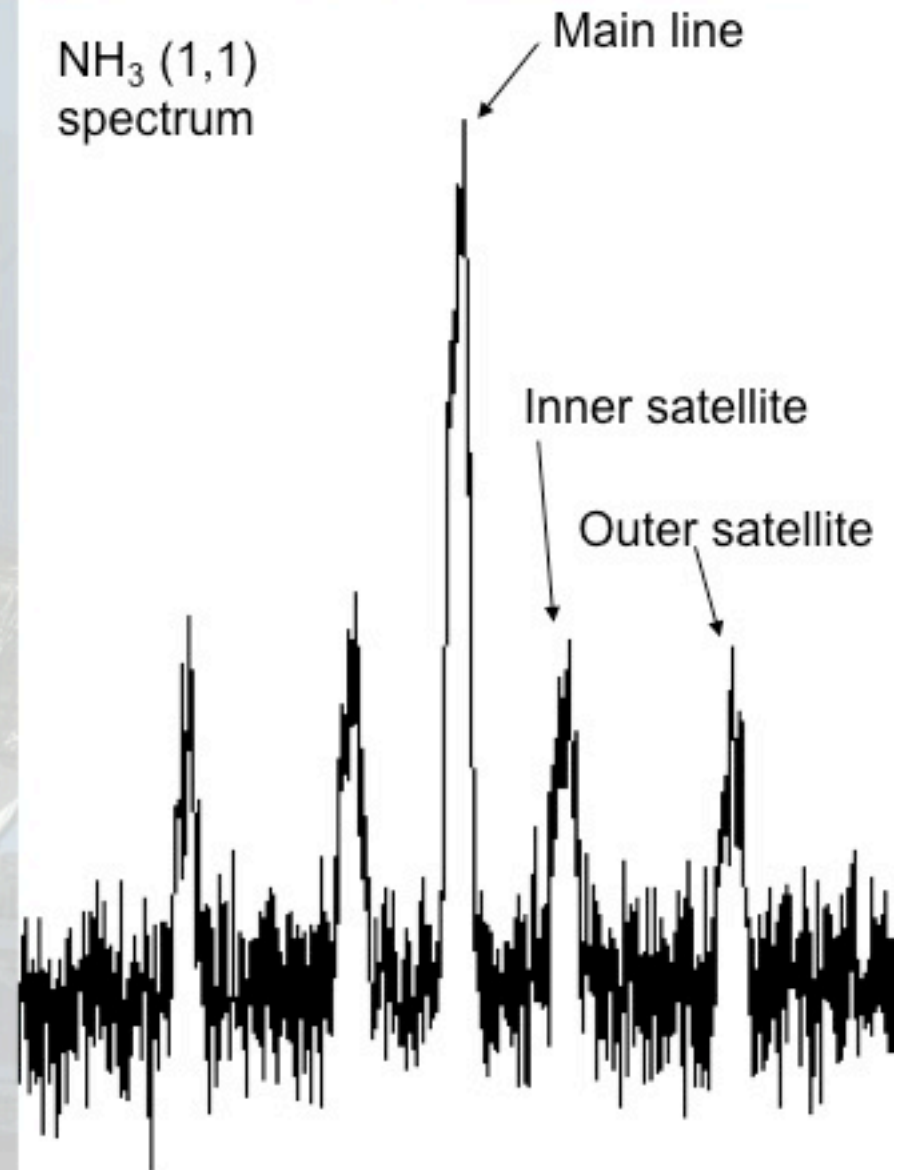
Optical Depth:

$$\frac{T_{\text{main}}}{T_{\text{sat}}} = \frac{(1 - e^{-\tau})}{(1 - e^{-a\tau})}$$

$$a = 0.28 \text{ (inner)}$$

$$a = 0.22 \text{ (outer)}$$

$$\therefore \tau = 0.5$$



Some of the more important lines

H OH NH₃ **H₂O** HCN CO HCO⁺ N₂H⁺ CH₃OH CH₃CN SiO CS HCCCN

H₂O - Water

Maser only

Frequency (GHz)

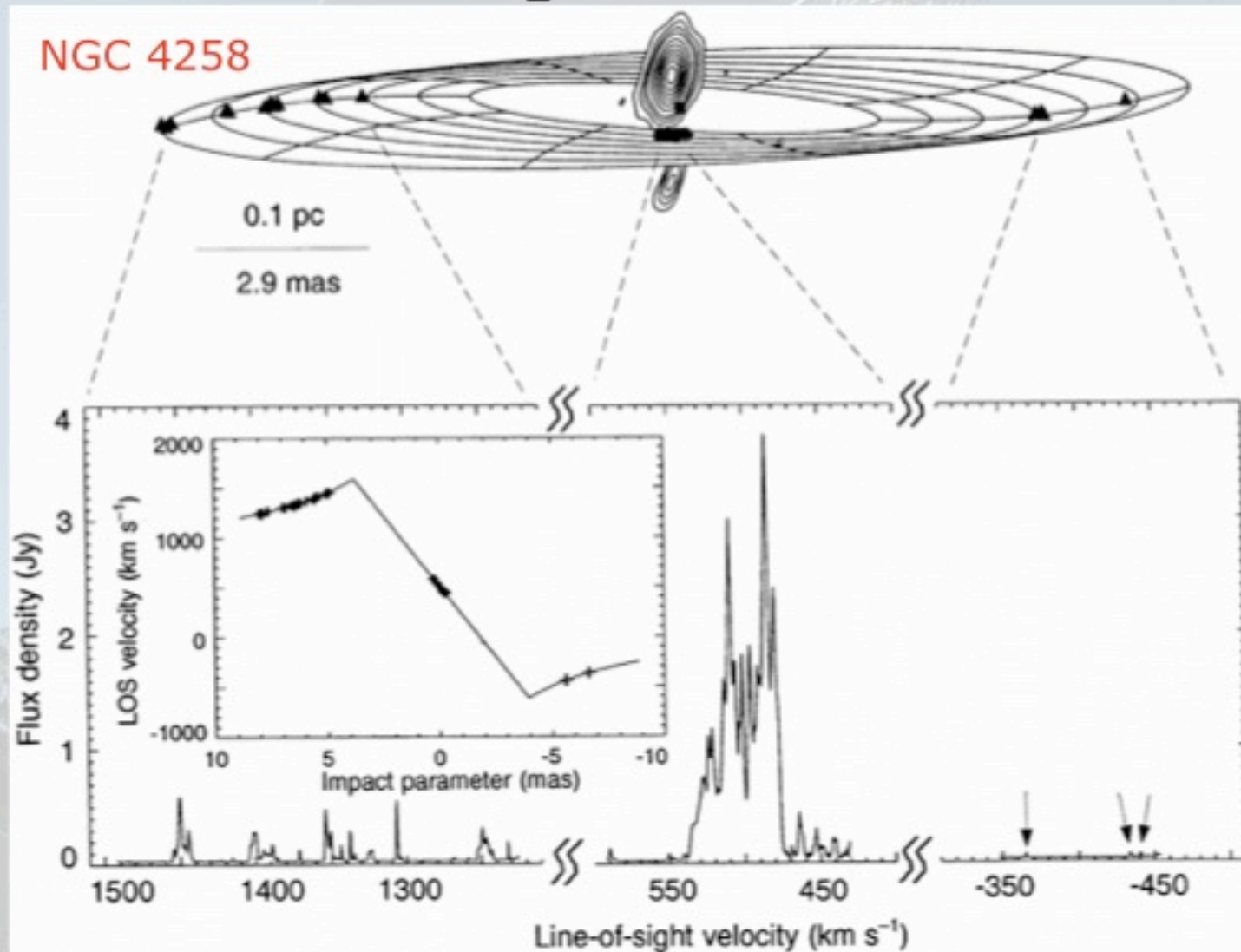
22.235

Most common maser known
(star forming regions, evolved stars,
Circumnuclear disks)

Some of the more important lines

H OH NH₃ **H₂O** HCN CO HCO⁺ N₂H⁺ CH₃OH CH₃CN SiO CS HCCCN

H₂O - Water



Herrnstein et al. 1999

Some of the more important lines

H OH NH₃ H₂O **HCN** CO HCO⁺ N₂H⁺ CH₃OH CH₃CN SiO CS HCCCN

HCN - Hydrogen Cyanide

Ubiquitous high density gas tracer

Frequency (GHz)

88.632

Hyperfine structure

Bright enough to be seen in the centres of other galaxies

Some of the more important lines

H OH NH₃ H₂O HCN **CO** HCO⁺ N₂H⁺ CH₃OH CH₃CN SiO CS HCCCN

CO - Carbon Monoxide

Ubiquitous low density gas tracer

Critical density $\sim 10^2 \text{ cm}^{-3}$

Strongly influenced by outflows in our Galaxy

Found in the cores of galaxies

Can be traced right across the universe

	Frequency (GHz)
	115.271
¹³ CO	110.201
C ¹⁸ O	109.978
C ¹⁷ O	112.358

Some of the more important lines

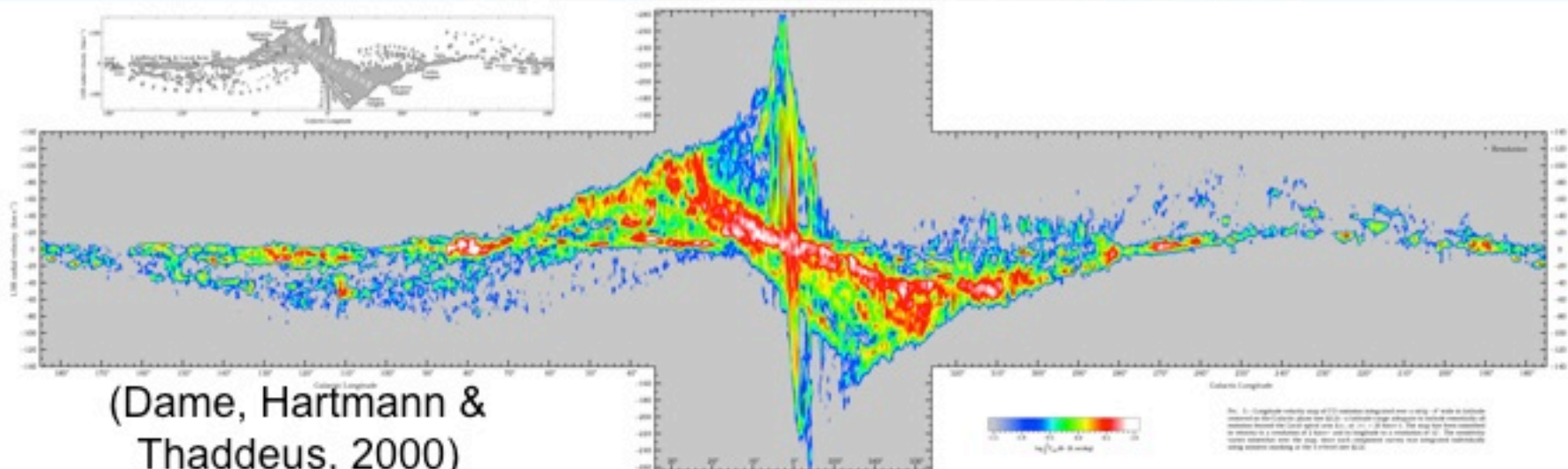
H OH NH₃ H₂O HCN **CO** HCO⁺ N₂H⁺ CH₃OH CH₃CN SiO CS HCCCN

CO - Carbon Monoxide

Second most abundant molecule

$$X \sim 10^{-4} \times H_2$$

CO (1-0) one of the brightest lines

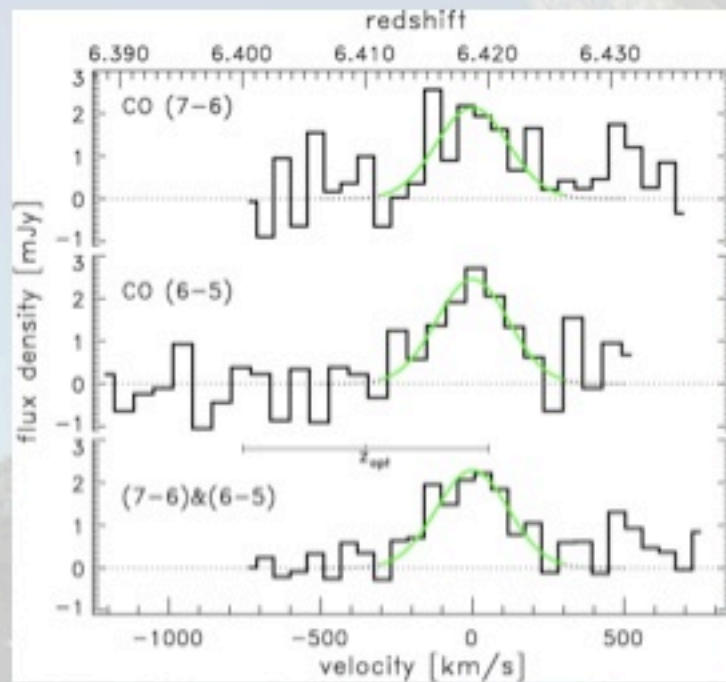


Some of the more important lines

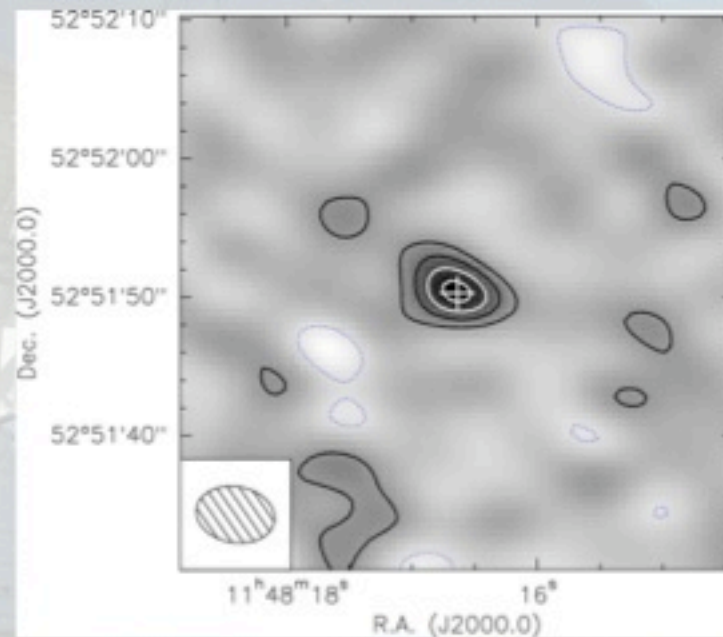
H OH NH₃ H₂O HCN **CO** HCO⁺ N₂H⁺ CH₃OH CH₃CN SiO CS HCCCN

CO - Carbon Monoxide On the other side of the universe!

Quasar at $z=6.4$
Universe $\sim 10^9$ yr old



Bertoldi et al. 2003



Some of the more important lines

H OH NH₃ H₂O HCN CO **HCO⁺** N₂H⁺ CH₃OH CH₃CN SiO CS HCCCN

HCO⁺ - Oxomethylium

Occurs in similar regions to CO

Higher critical density

$\sim 2 \times 10^5 \text{ cm}^{-3}$

Like CO enhanced in outflows and suffers from freeze-out onto dust grains in cold, dense regions

	Frequency (GHz)
	89.188
H ¹³ CO ⁺	86.754
HC ¹⁸ O ⁺	85.162

Some of the more important lines

H OH NH₃ H₂O HCN CO HCO⁺ **N₂H⁺** CH₃OH CH₃CN SiO CS HCCCN

N₂H⁺ - Diazenylium

Reliable high density gas tracer

Frequency (GHz)

93.173

Hyperfine structure gives optical depth

Critical density $\sim 2 \times 10^5 \text{ cm}^{-3}$

Does not show up in outflows

Less prone to freeze-out/depletion

Some of the more important lines

H OH NH₃ H₂O HCN CO HCO⁺ N₂H⁺ CH₃OH CH₃CN SiO CS HCCCN

CH₃OH - Methanol

Both thermal and maser

MANY spectral lines (asymmetric rotor)

Frequency (GHz)

6.669

12.179

24.933

44.069

96.741

etc

Some of the more important lines

H OH NH₃ H₂O HCN CO HCO⁺ N₂H⁺ CH₃OH CH₃CN SiO CS HCCCN

Thermal Methanol

Lines in 12mm and 3mm bands

→ rotation diagram

12mm ladder:

24.928 CH₃OH (3_{2,1}-3_{1,2}) E Energy = 35K

24.933 CH₃OH (4_{2,2}-4_{1,3}) E Energy = 44K

24.959 CH₃OH (5_{2,3}-5_{1,4}) E Energy = 56K

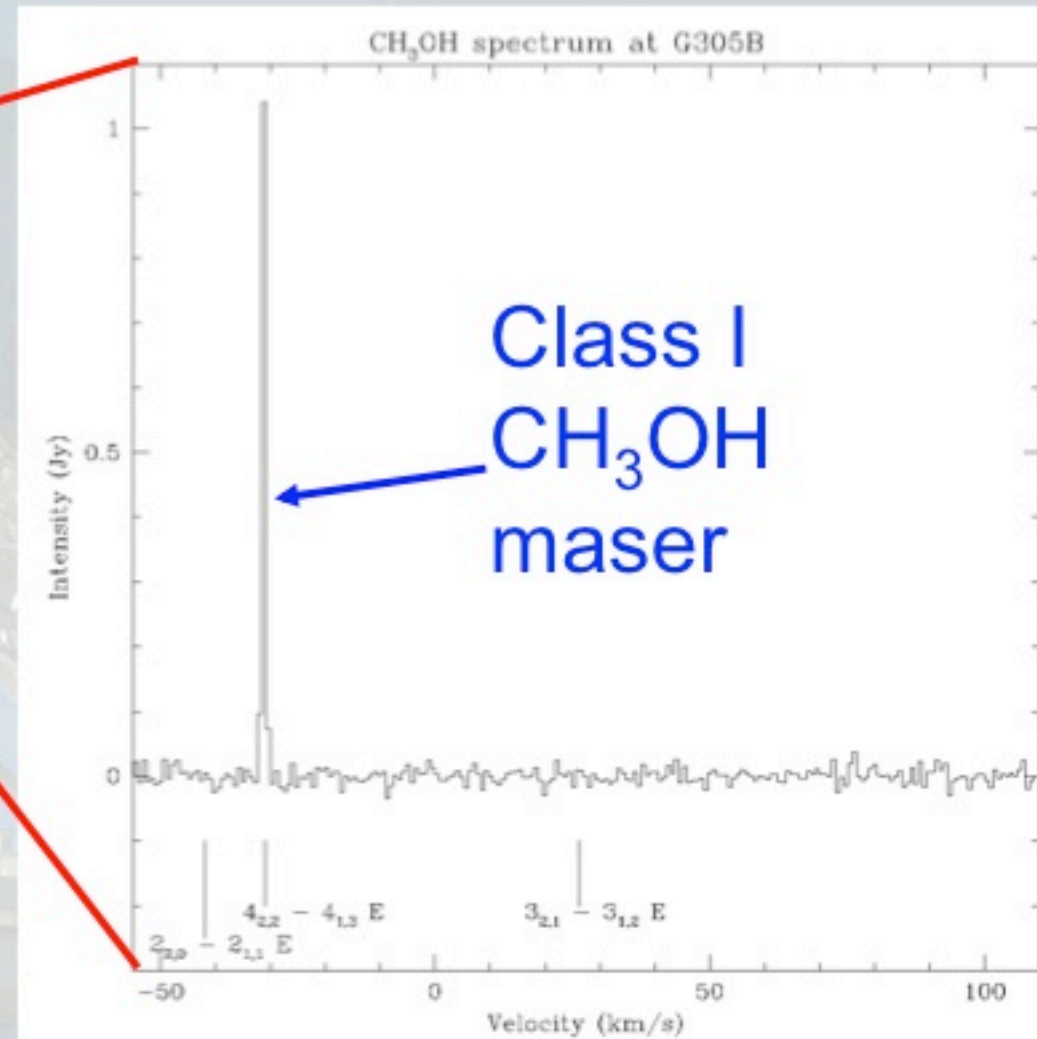
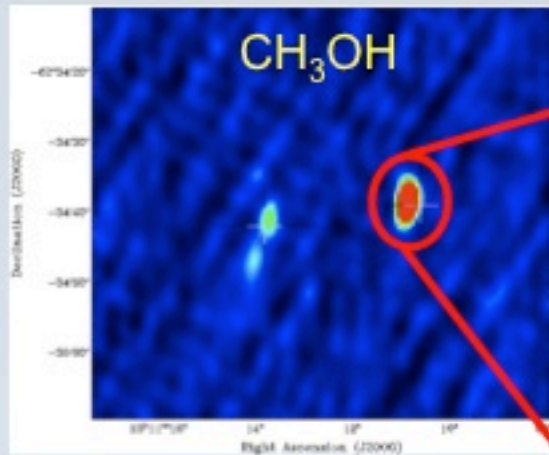
25.018 CH₃OH (6_{2,4}-6_{1,5}) E Energy = 70K

...

27.472 CH₃OH (13_{2,11}-13_{1,12}) E Energy = 232K

Some of the more important lines

H OH NH₃ H₂O HCN CO HCO⁺ N₂H⁺ **CH₃OH** CH₃CN SiO CS HCCCN

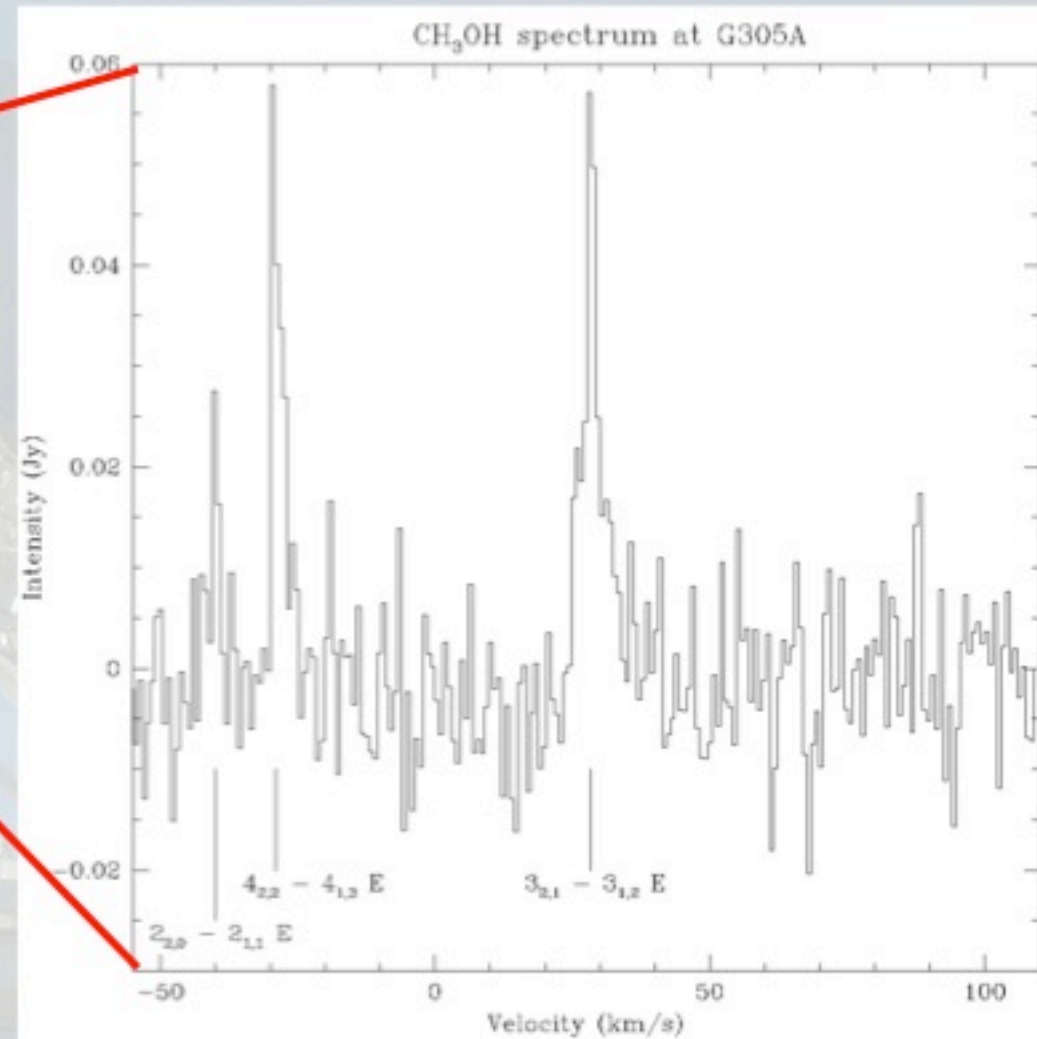
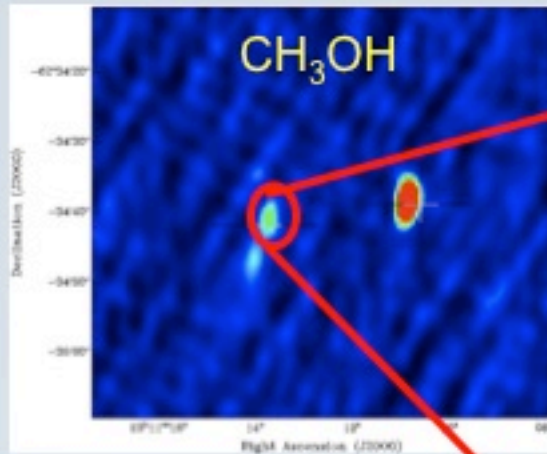


G305.2+0.2
High-mass star
forming region

(Walsh et al. 2007,
MNRAS, 380, 1703)

Some of the more important lines

H OH NH₃ H₂O HCN CO HCO⁺ N₂H⁺ CH₃OH CH₃CN SiO CS HCCCN



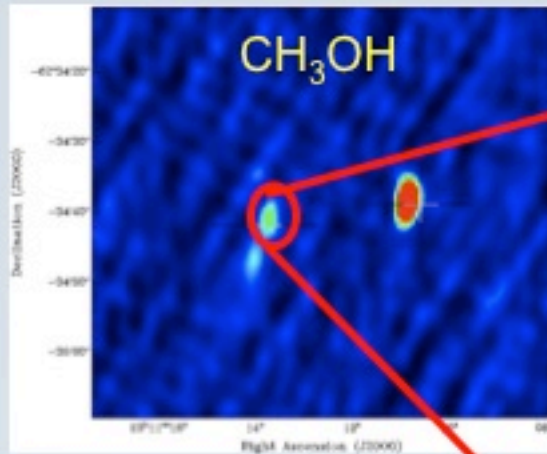
G305.2+0.2
High-mass star
forming region

(Walsh et al. 2007,
MNRAS, 380, 1703)

Thermal CH₃OH spectrum

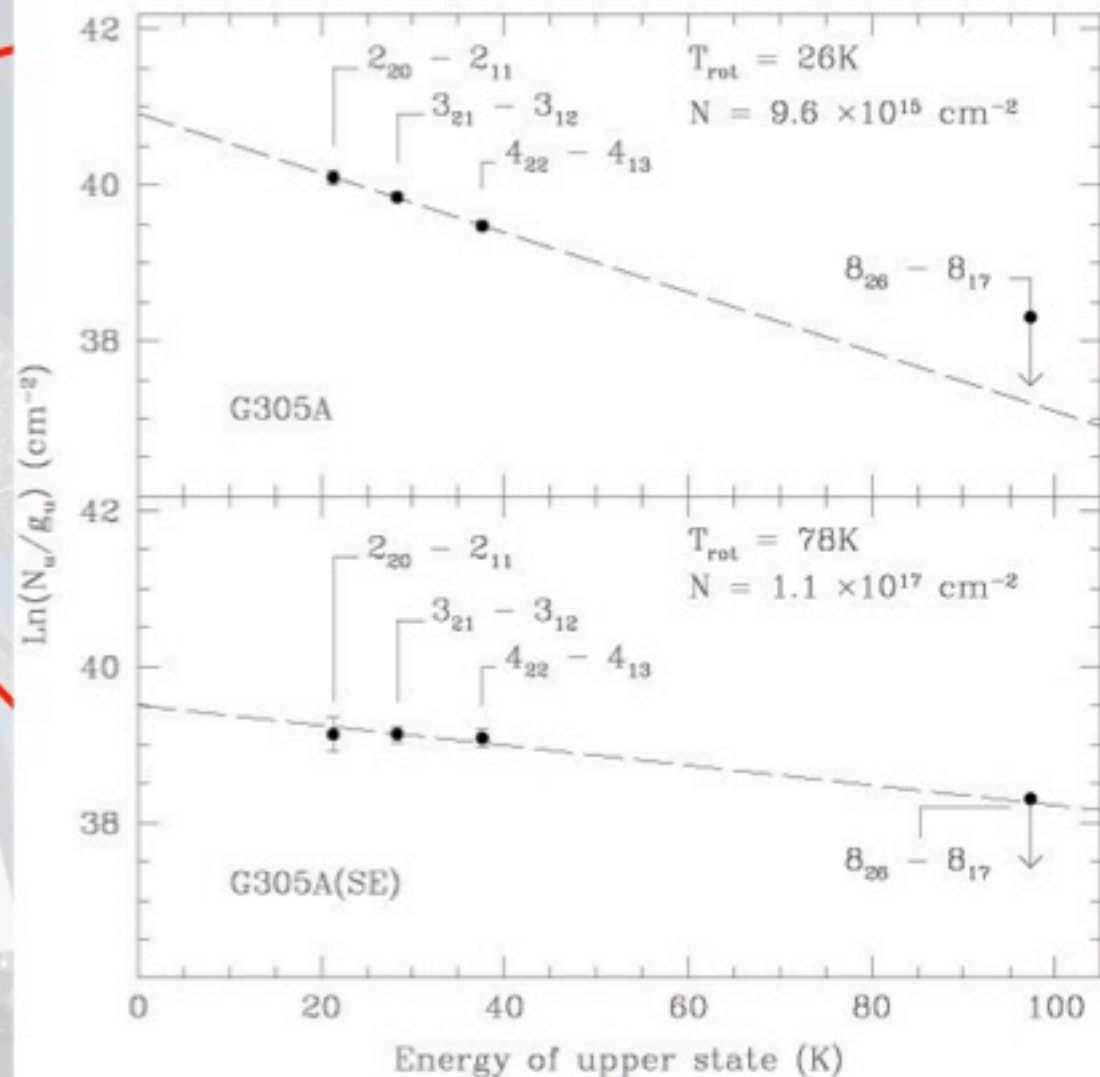
Some of the more important lines

H OH NH₃ H₂O HCN CO HCO⁺ N₂H⁺ **CH₃OH** CH₃CN SiO CS HCCCN



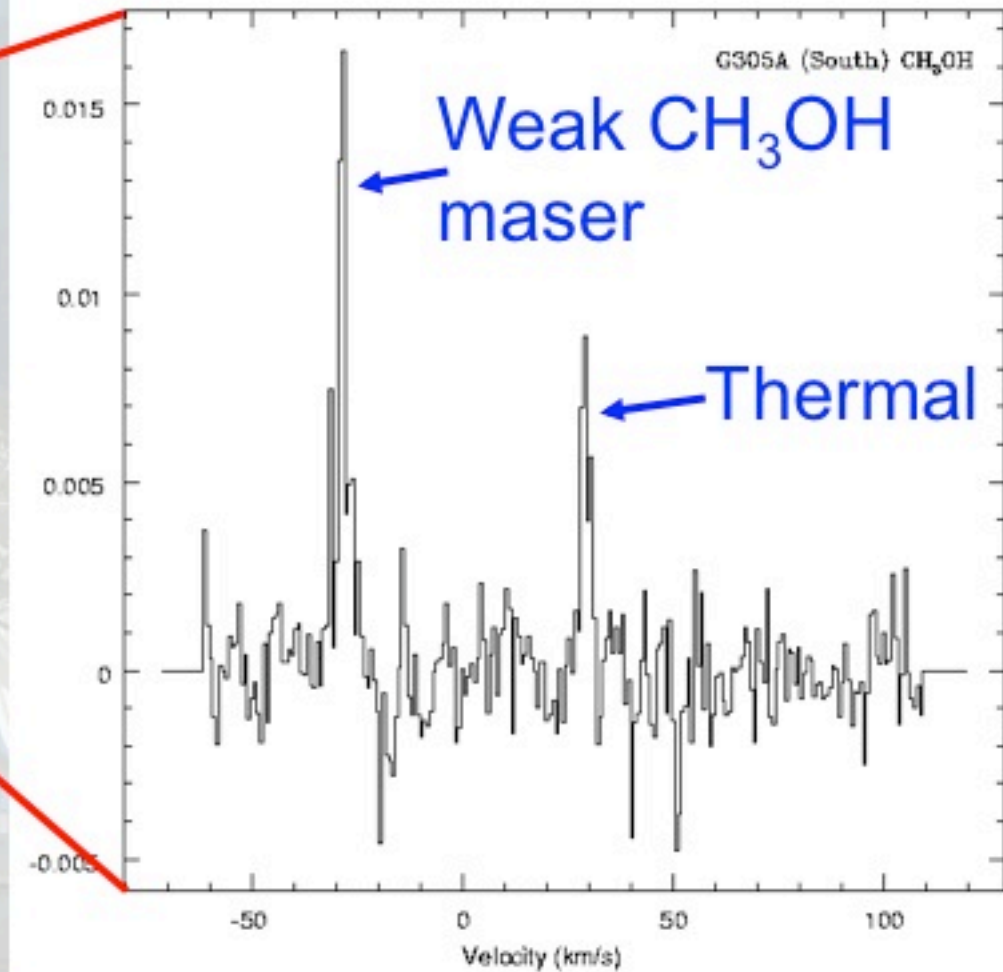
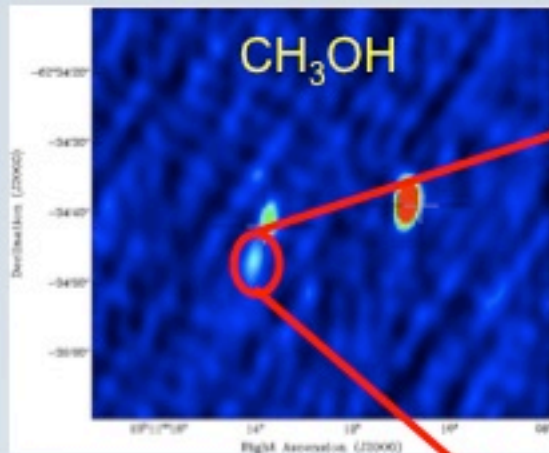
G305.2+0.2
High-mass star
forming region

(Walsh et al. 2007,
MNRAS, 380, 1703)



Some of the more important lines

H OH NH₃ H₂O HCN CO HCO⁺ N₂H⁺ CH₃OH CH₃CN SiO CS HCCCN



G305.2+0.2
High-mass star
forming region

(Walsh et al. 2007,
MNRAS, 380, 1703)

Some of the more important lines

H OH NH₃ H₂O HCN CO HCO⁺ N₂H⁺ CH₃OH CH₃CN SiO CS HCCCN

Methanol Masers

Class I masers collisionally excited

Class II masers radiatively excited

Class I usually found offset from star
Formation sites

Class II closely associated with sites
Of high-mass star formation
(and nothing else)

Some of the more important lines

H OH NH₃ H₂O HCN CO HCO⁺ N₂H⁺ CH₃OH CH₃CN SiO CS HCCCN

Methanol Masers

Methanol masers tracing high-mass
Circumstellar disks?

Use methanol masers to determine
Distances to Galactic sources through
VLBI

Some of the more important lines

H OH NH₃ H₂O HCN CO HCO⁺ N₂H⁺ CH₃OH **CH₃CN** SiO CS HCCCN

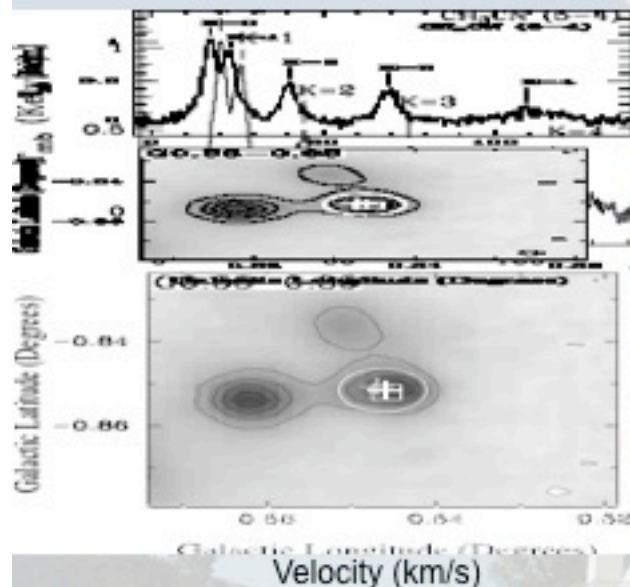
CH₃CN – Methyl Cyanide

Useful rotational ladders
(close together)

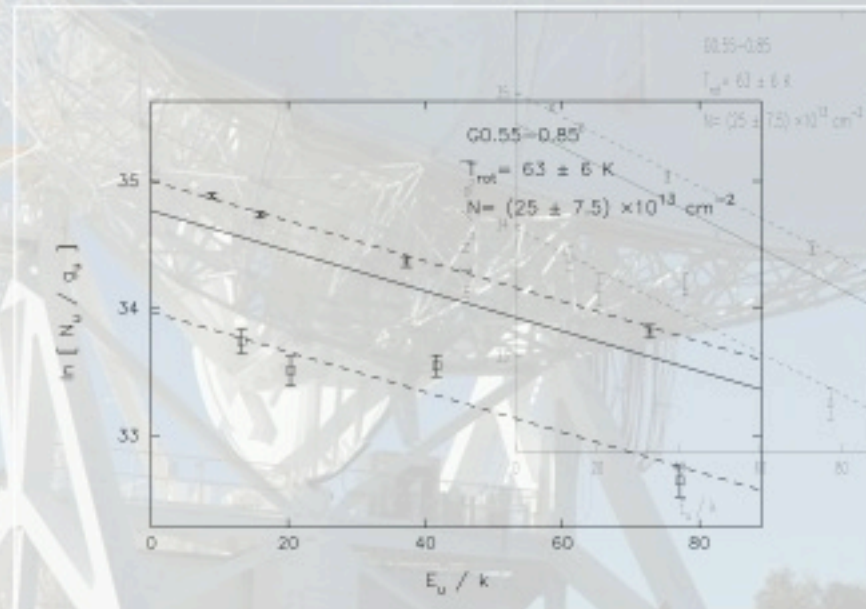
Frequency
(GHz)

91.987

110.353



CH₃CN Spectrum



Rotation diagram using the $J=(5-4)$ & $J=(6-5)$ transitions.

(Purcell et al. 2006, MNRAS, 367, 553)

Some of the more important lines

H OH NH₃ H₂O HCN CO HCO⁺ N₂H⁺ CH₃OH CH₃CN **SiO** CS HCCCN

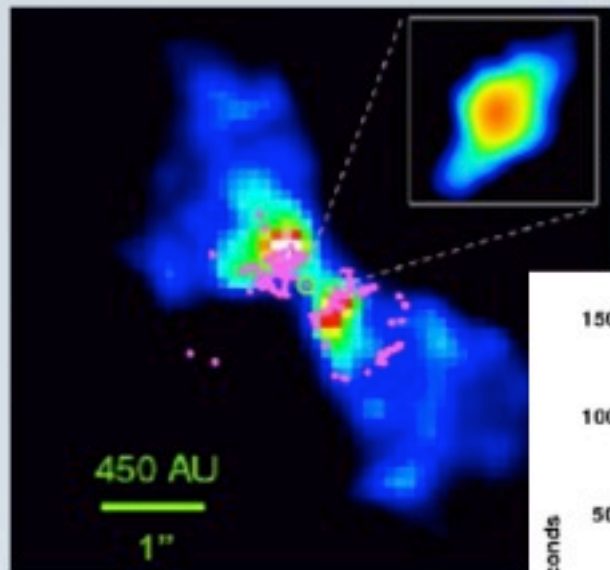
SiO – Silicon Monoxide

Both maser and thermal emission

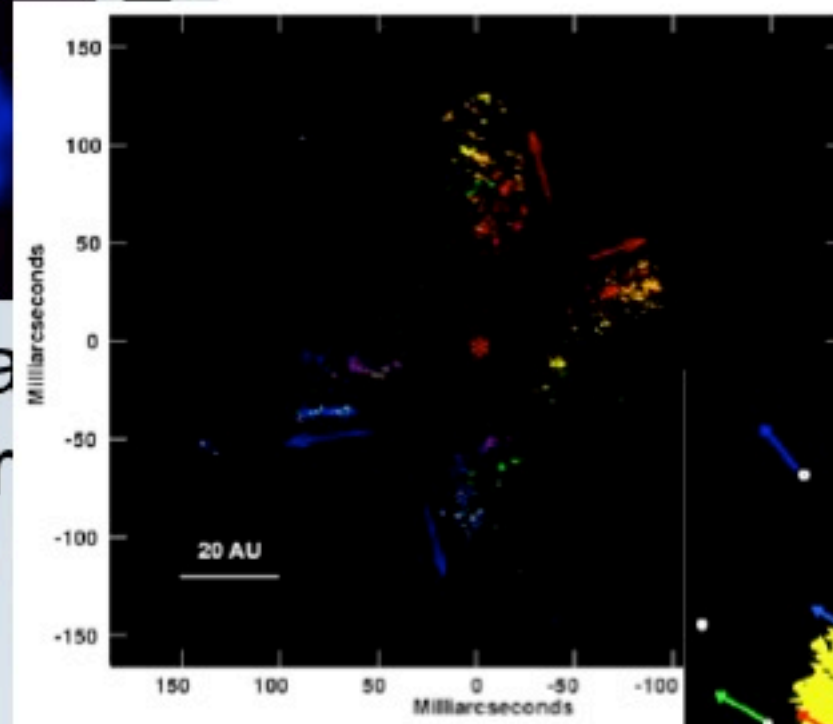
Maser emission in vibrationally excited states only seen towards 2 or 3 SF regions. But results very productive in Orion.

Frequency (GHz)
43.423
86.243
86.847

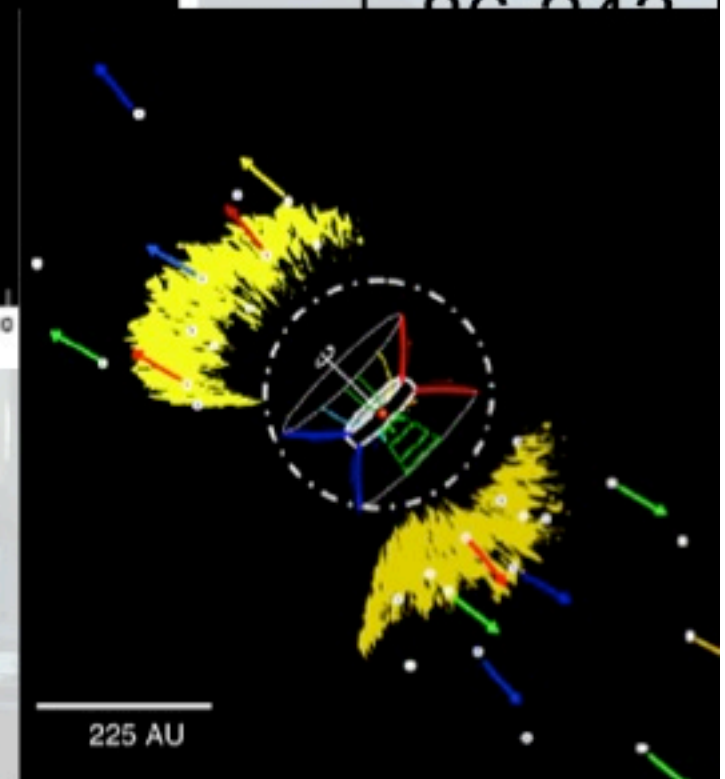
Matthews et al. 2007



Excited state
2 or 3 sources
productive



Frequency (GHz)
43.423
86.846



Some of the more important lines

H OH NH₃ H₂O HCN CO HCO⁺ N₂H⁺ CH₃OH CH₃CN **SiO** CS HCCCN

SiO – Silicon Monoxide

Both maser and thermal emission
Maser emission in vibrationally
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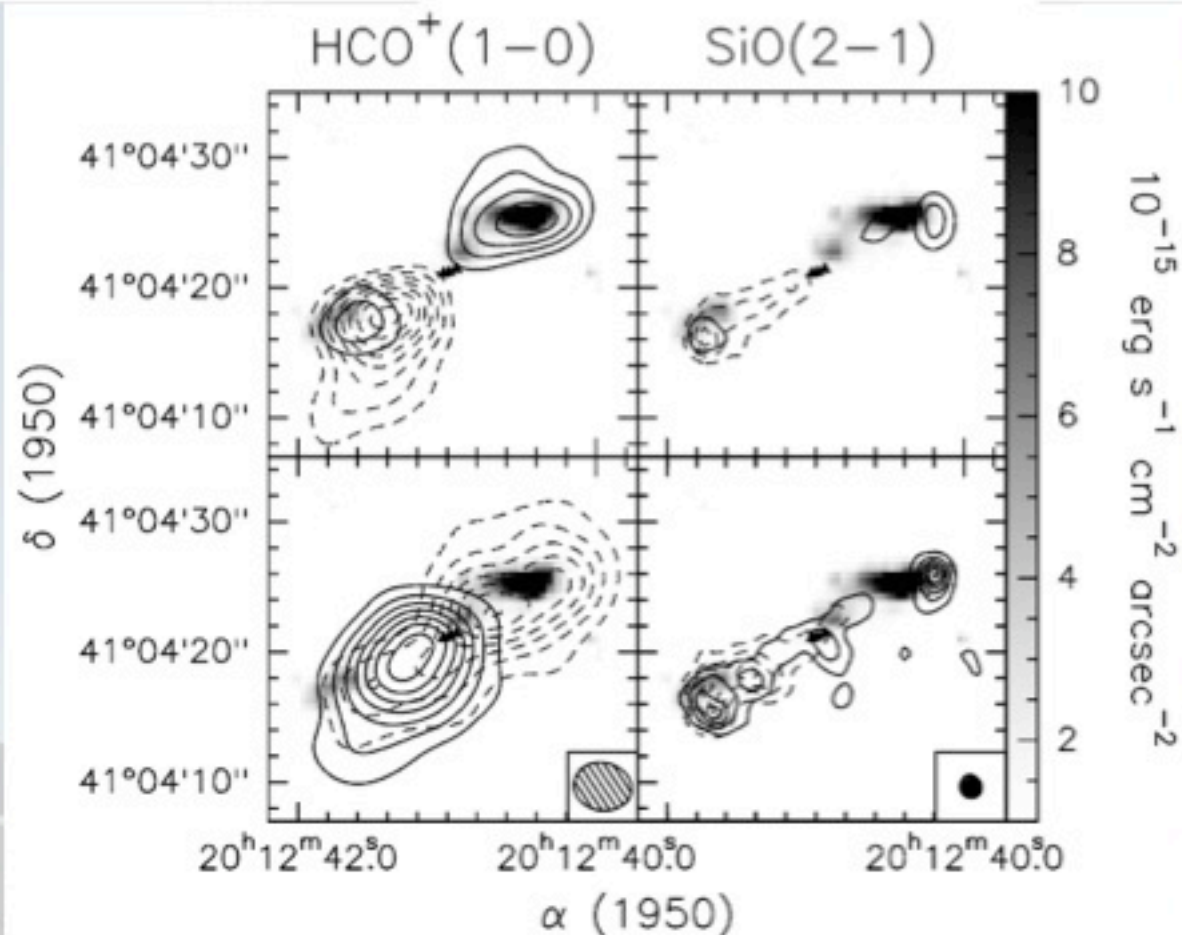
Thermal SiO closely associated with
Outflows in star forming regions

Some of the more important lines

H OH NH₃ H₂O HCN CO HCO⁺ N₂H⁺ CH₃OH CH₃CN SiO CS HCCCN

SiO – Silicon Monoxide

Cesaroni et al. 1999 IRAS 20126+4104



Some of the more important lines

H OH NH₃ H₂O HCN CO HCO⁺ N₂H⁺ CH₃OH CH₃CN SiO **CS** HCCCN

CS – Carbon Sulfide

Ubiquitous tracer of high density gas

Critical density $\sim 2 \times 10^6 \text{ cm}^{-3}$

Suffers from freeze-out onto dust grains (depletion)

Frequency (GHz)

48.991

97.981

Some of the more important lines

H OH NH₃ H₂O HCN CO HCO⁺ N₂H⁺ CH₃OH CH₃CN SiO CS **HCCCN**

HCCCN - Cyanoacetylene

Hot core molecule
(tracer of high mass star formation)

Frequency (GHz)
18.196
27.294
36.392
90.980
100.078

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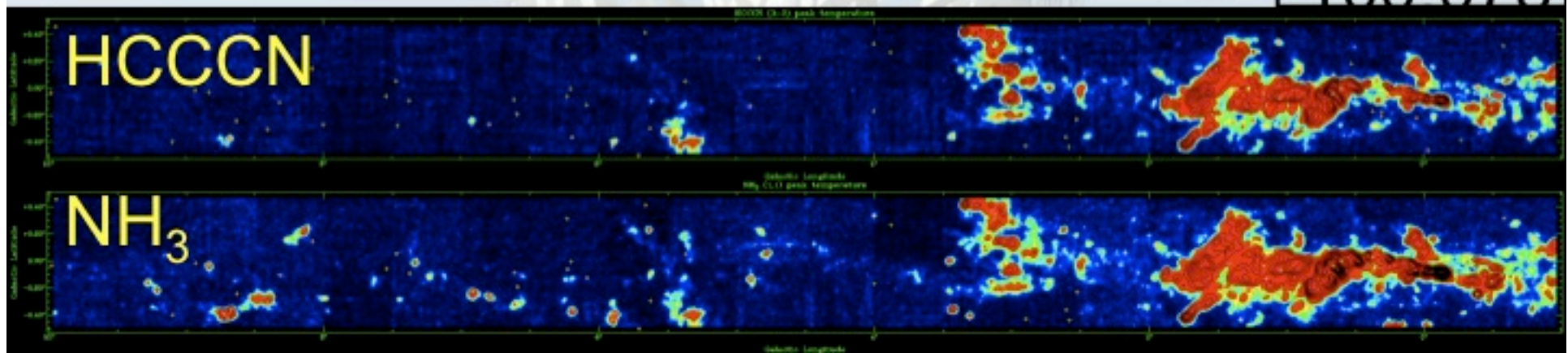
27.294

36.392

90.980

100.078

HOPS results



Summary

- Spectral lines give a wealth of information
- Useful to all scales of astronomy
- Data cubes and moment maps important diagnostics
- Many different spectral lines tell us about a wide variety of physical conditions
- NH_3 and H_2O are vitally important to SKA