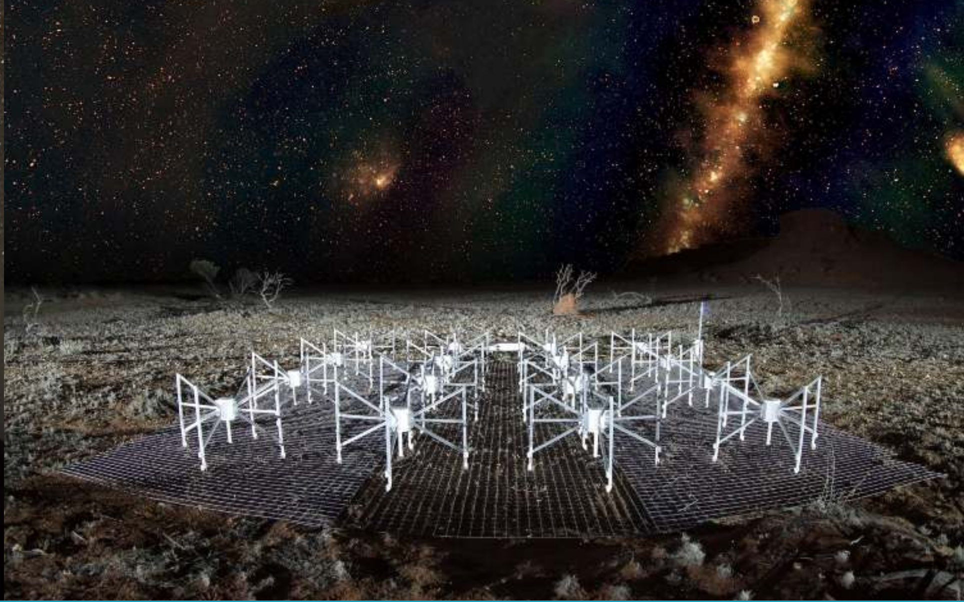


Spectral Line Processing

Karen Lee-Waddell | Research+ Postdoctoral Fellow
ICRAR/CASS Radio School 2018

Outline

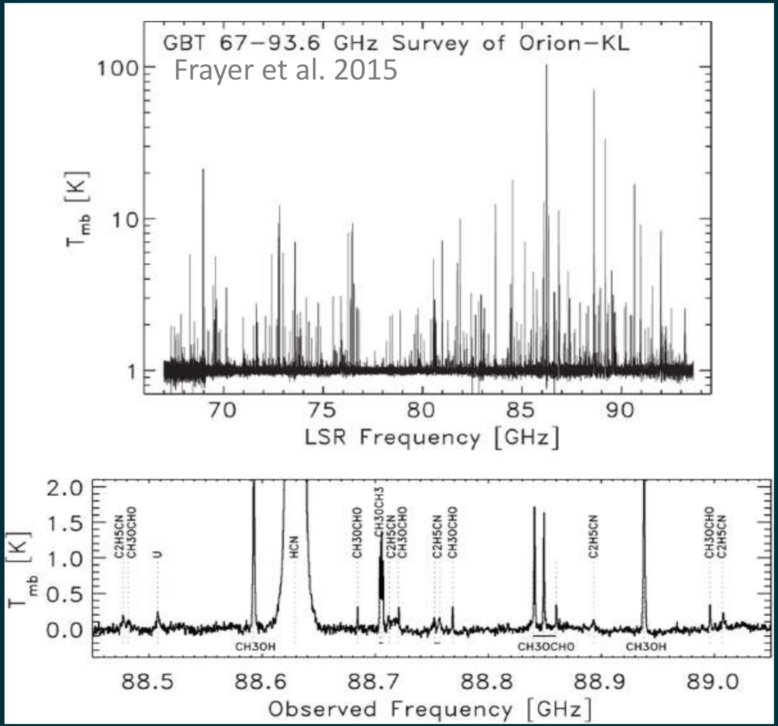
- Motivation
  - What can spectral lines tell us?
- What are spectral lines
  - How do they form, types: masers, recombination, molecular, atomic
- Data processing
  - Doppler correction, continuum subtraction
- Data products

Radio spectral lines

Spectral lines

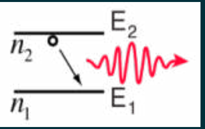
- narrow emission or absorption features in the spectra of **gaseous** and **ionized sources**

- enable us to probe the **physical, chemical** and **dynamical properties** of the interstellar medium (ISM) in galaxies



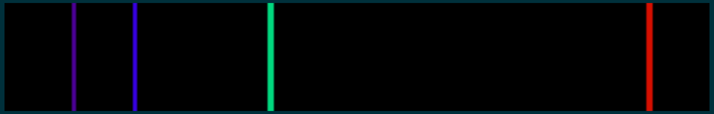
Formation of spectral lines

- spectral lines are **quantum phenomena**
- quantum systems (atoms or molecules) change their state in **discrete** amounts of **energy** (E)
- transition between states caused by **emission** or **absorption** of a photon at a **specific frequency** ($f_o = E_{photon}/h$)



Continuous spectrum

Emission lines (discrete spectrum)

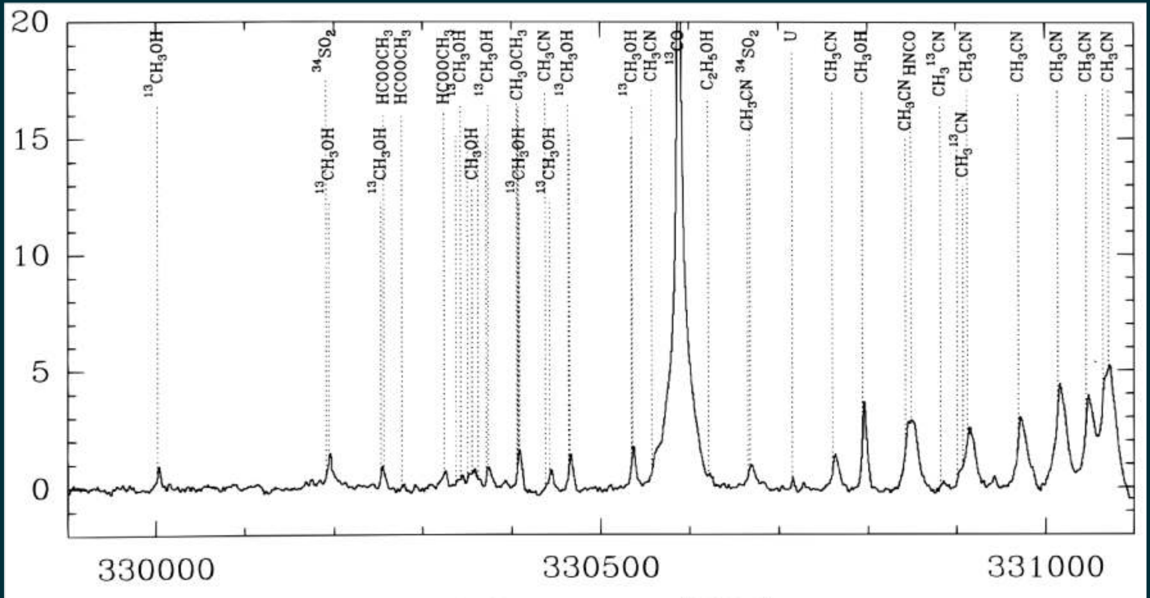


Absorption lines (discrete spectrum)

Information from spectral lines

- rest frequencies identify specific **atoms** and **molecules**

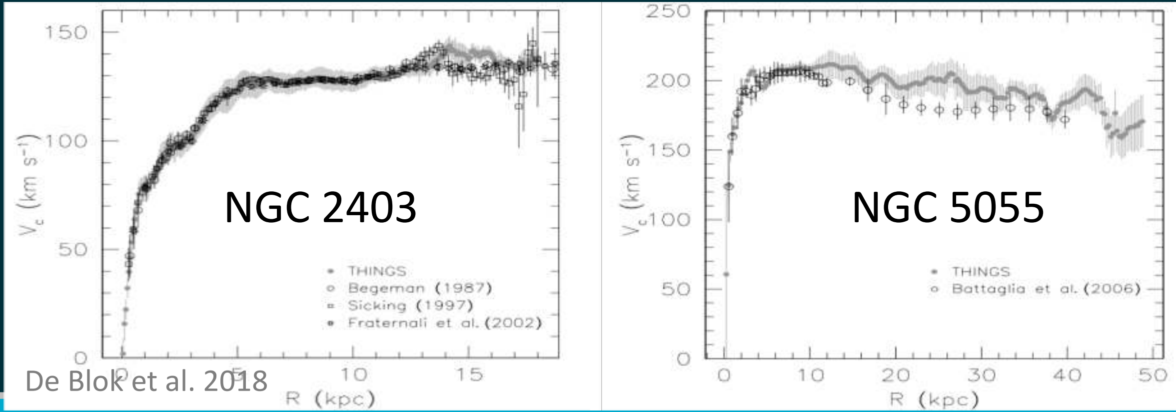
	Rest frequency (GHz)
^{13}CO	110.201
$C^{18}O$	109.782
C^3H^2	18.343
CH^3OH	6.669, 12.179
CO	115.271
CS	48.991, 97.981
DCO^+	72.039
$H^{13}CO^+$	86.754
H^2O	22.235
H^2CO	4.83, 14.488
HC^3N	9.098
HCN	88.632
HCO^+	89.189
HI	1.420
HNC	90.664
N^2H^+	93.174
NH^3	23.695, 23.723, 23.870
OH	1.612, 1.665, 1.667, 1.721
SiO	42.821, 43.122, 43.424, 85.64, 86.243, 86.847



Schilke et al. 1997

Information from spectral lines

- rest frequencies identify specific **atoms** and **molecules**
- Doppler shifts provide radial velocities
  - redshifts and Hubble **distances** of extragalactic sources
  - **rotation curves** and radial **mass distribution**



De Blok et al. 2018

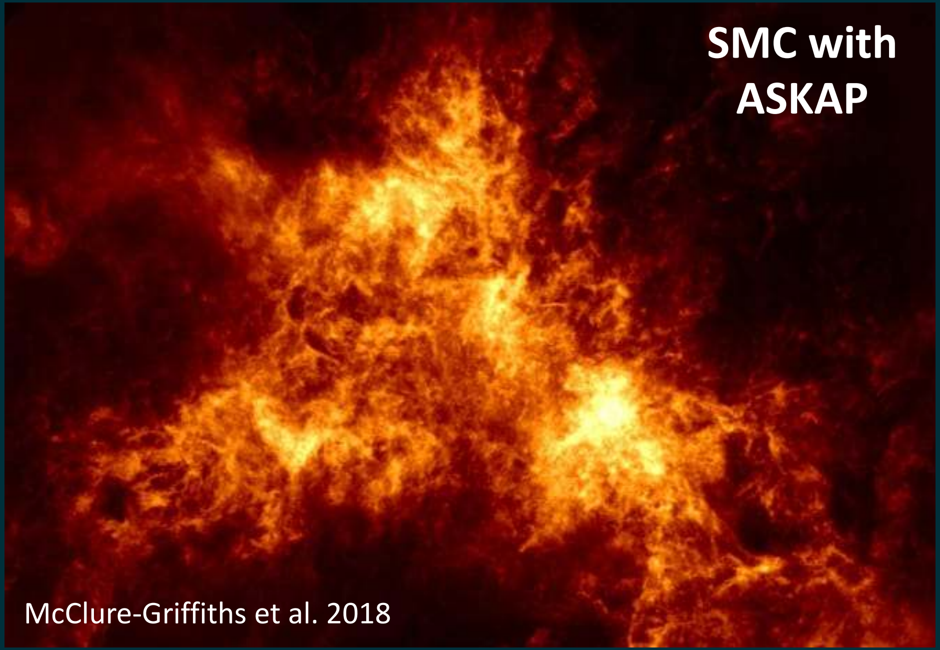
Information from spectral lines

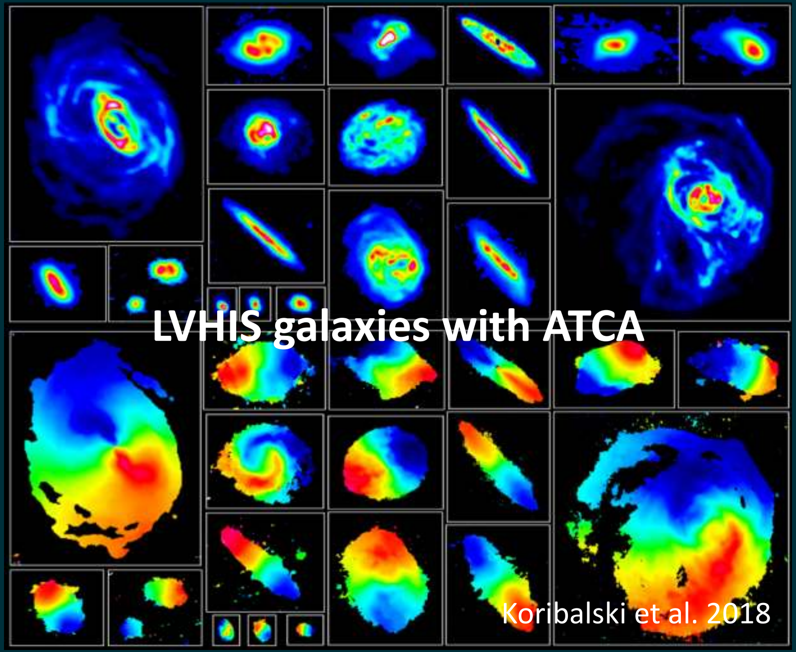
- rest frequencies identify specific **atoms** and **molecules**
- Doppler shifts measure radial velocities
  - redshifts and Hubble **distances** of extragalactic sources
  - **rotation curves** and radial **mass distribution**
- line broadening can indicate **collapse speeds**, **turbulent velocities** and **thermal motions**
- line intensities can constrain **temperatures**, **densities** and **chemical compositions**

Unique characteristics of radio spectral lines

- line widths are smaller than Doppler-broadened → measure **gas temperatures** and small changes in **radial velocity**
- stimulated emission → formation of natural **masers**
- radio waves can **penetrate dust** → detection of line emission from molecular clouds, protostars and disks around AGNs
- frequency can be measured with very **high precision** → detect small changes in fundamental physical constants over cosmic timescales

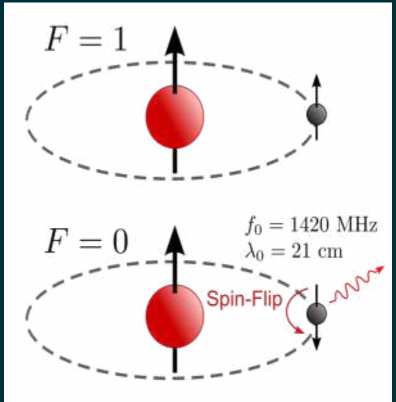
Neutral atomic hydrogen (HI)

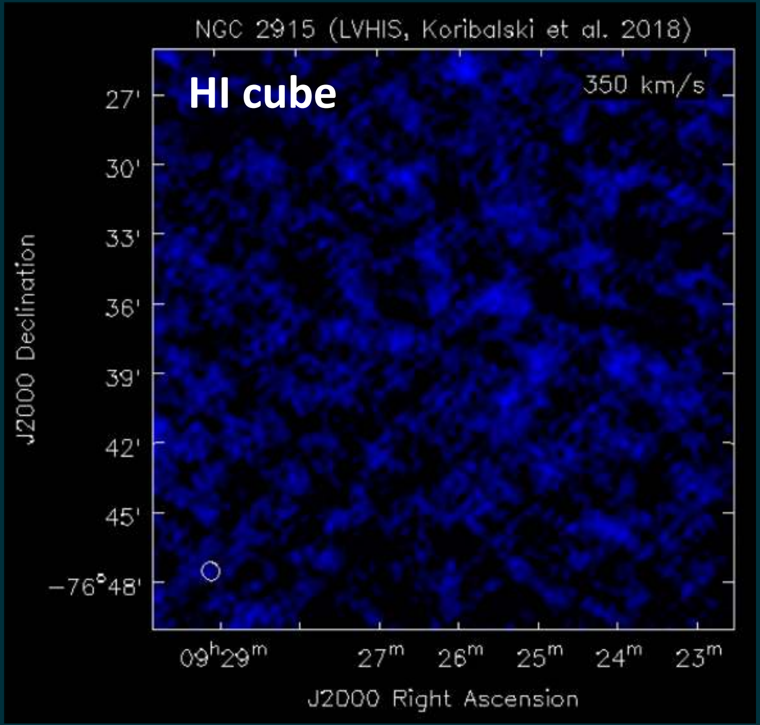




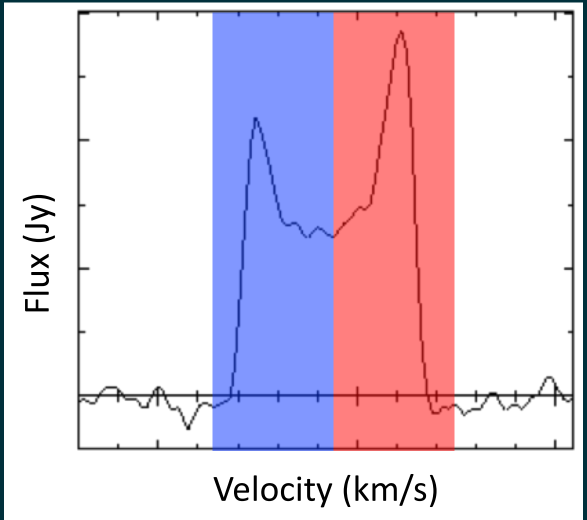
Neutral atomic hydrogen (HI)

hyperfine splitting

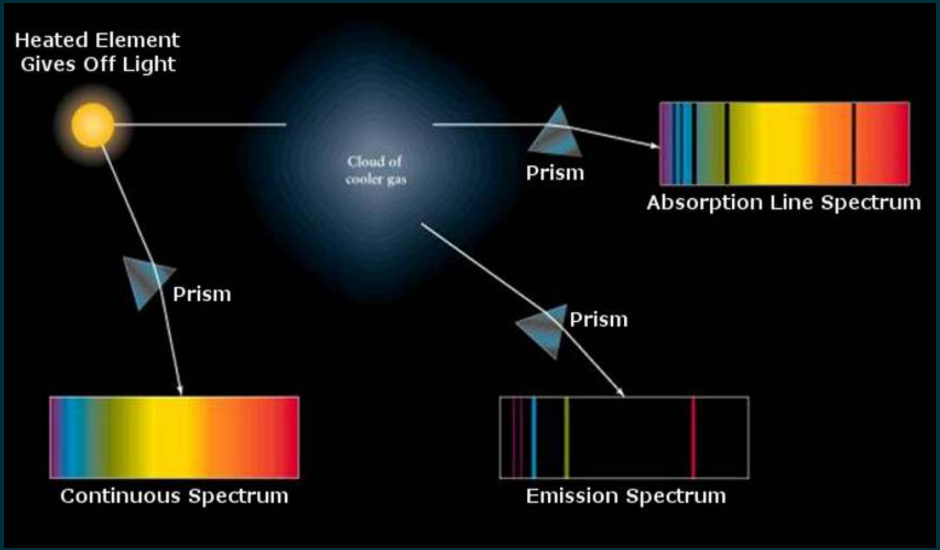


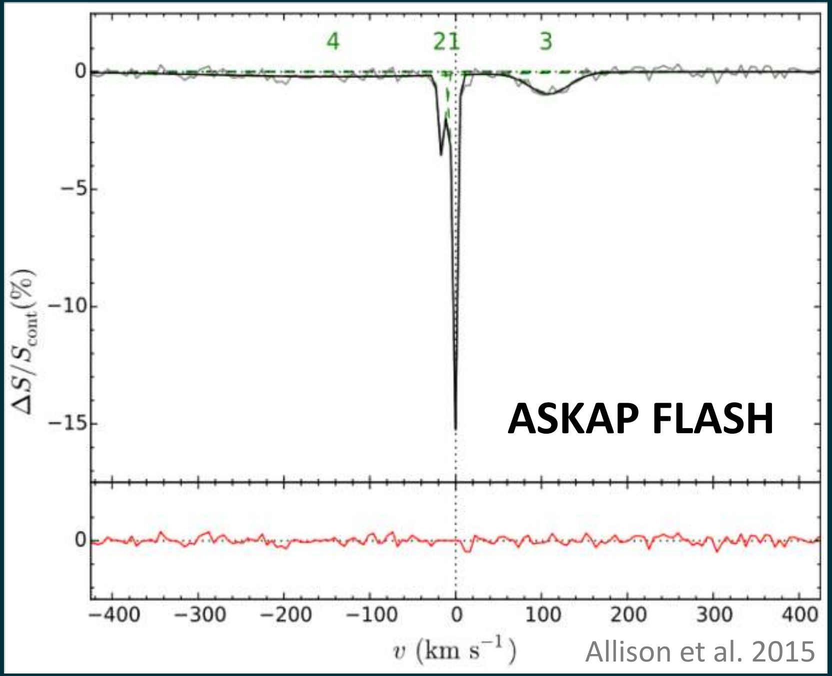


emission spectrum

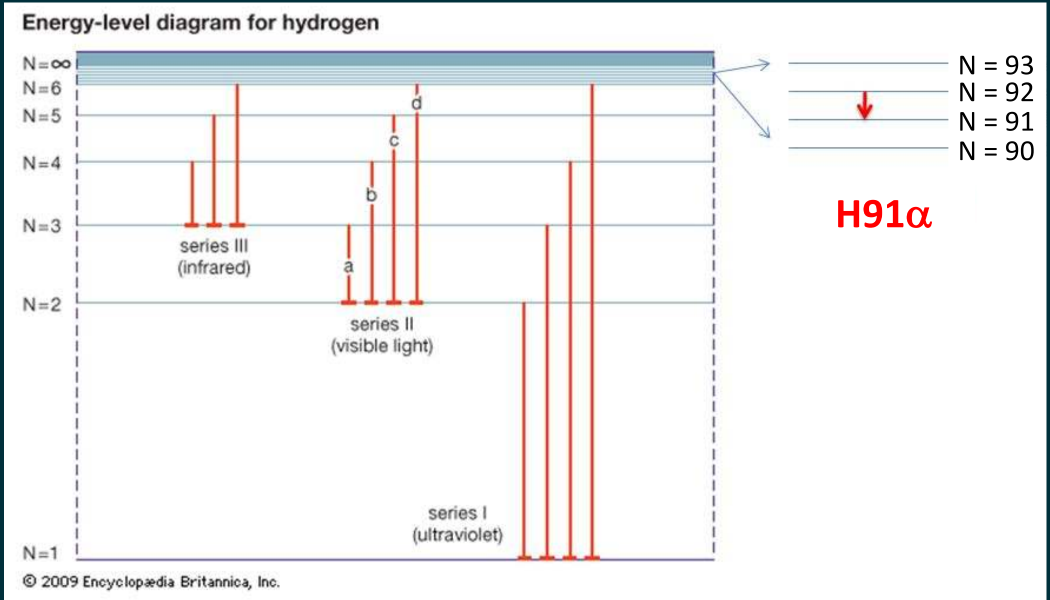


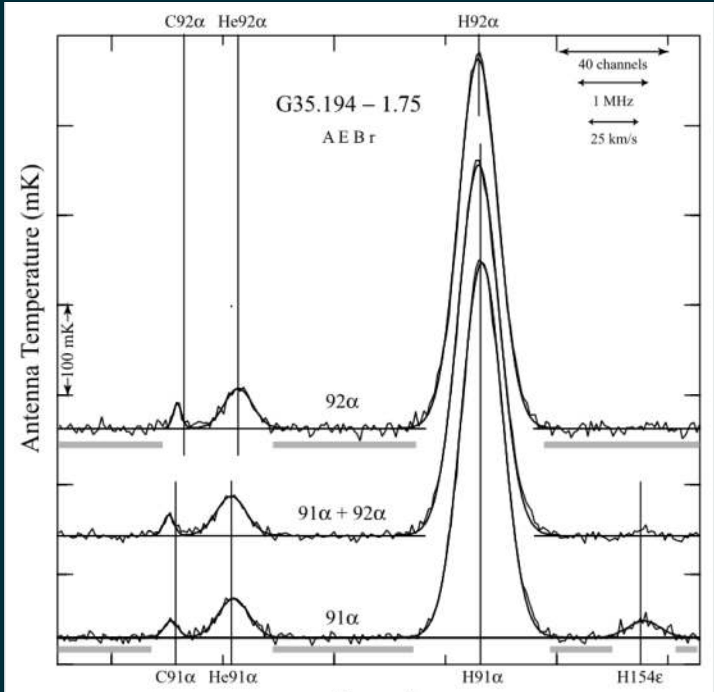
HI in absorption





Recombination lines

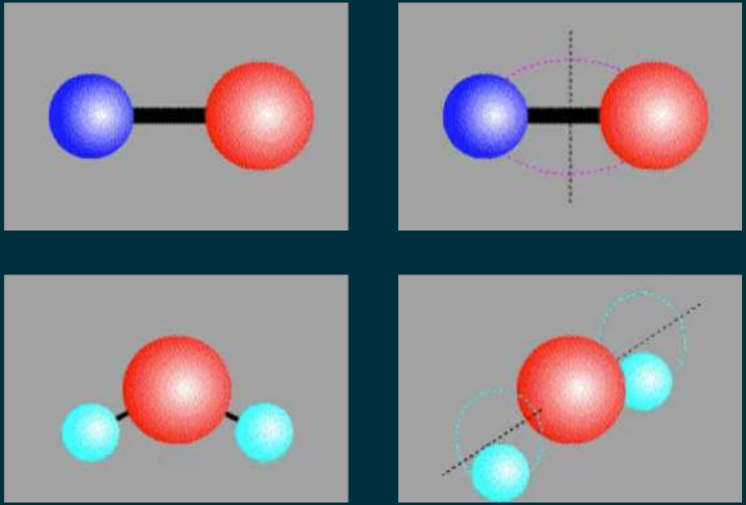




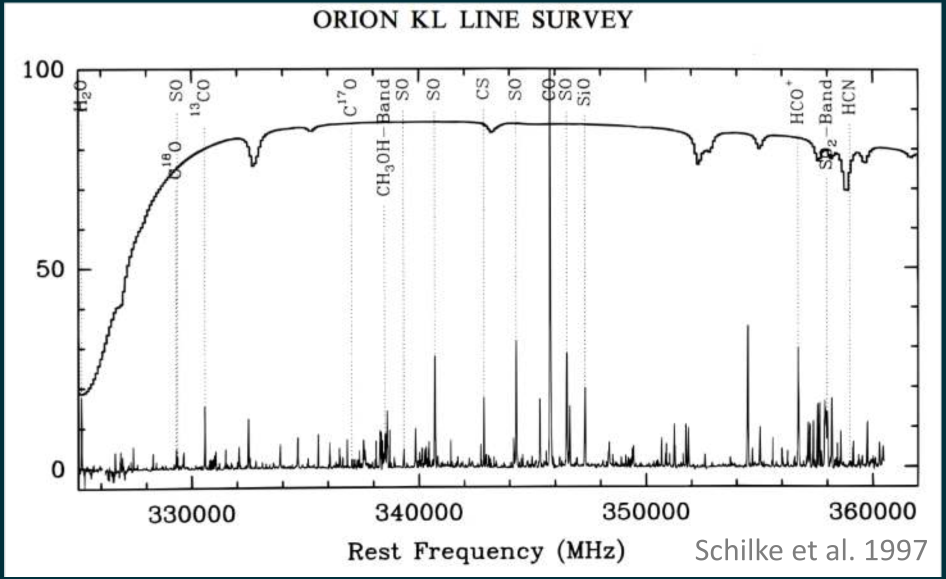
Quireza et al. 2006

Molecular lines

- molecules can **vibrate** or **rotate** around an axis and emit or absorb line radiation



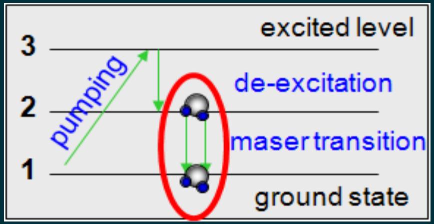
(www.shokabo.co.jp/sp_e/optical/labo/opt_line/opt_line.htm)



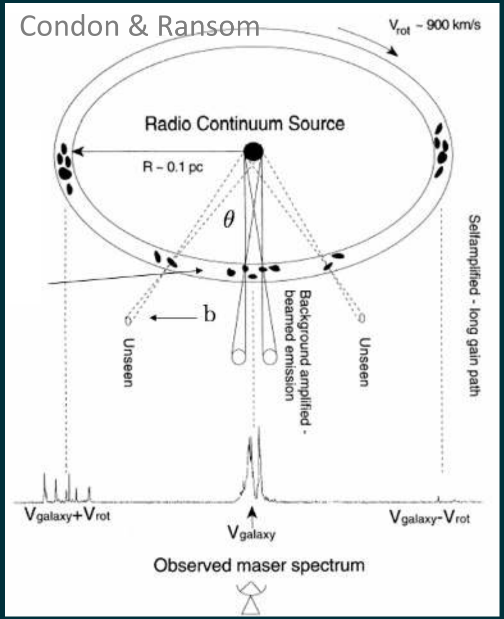
Schilke et al. 1997

Masers

- microwave amplification by **stimulated emission** of radiation
- requires **pumping** mechanism for **population inversion**
- incident photon causes atom/molecule to emit two coherent photons in a **beam of emission**



Molecule	Name	Frequency (GHz)
OH	hydroxyl	1.612
OH	hydroxyl	1.667
OH	hydroxyl	1.72
H_2CO	formaldehyde	4.829
CH_3OH	methanol	12.178
SiS	silicon sulphide	18.155
H_2O	water	22.235
NH_3	ammonia	23.87
SiO	silicon oxide	43.122
SiO	silicon oxide	86.243
HCN	hydrogen cyanide	89.087



Spectral line data

Telescope properties

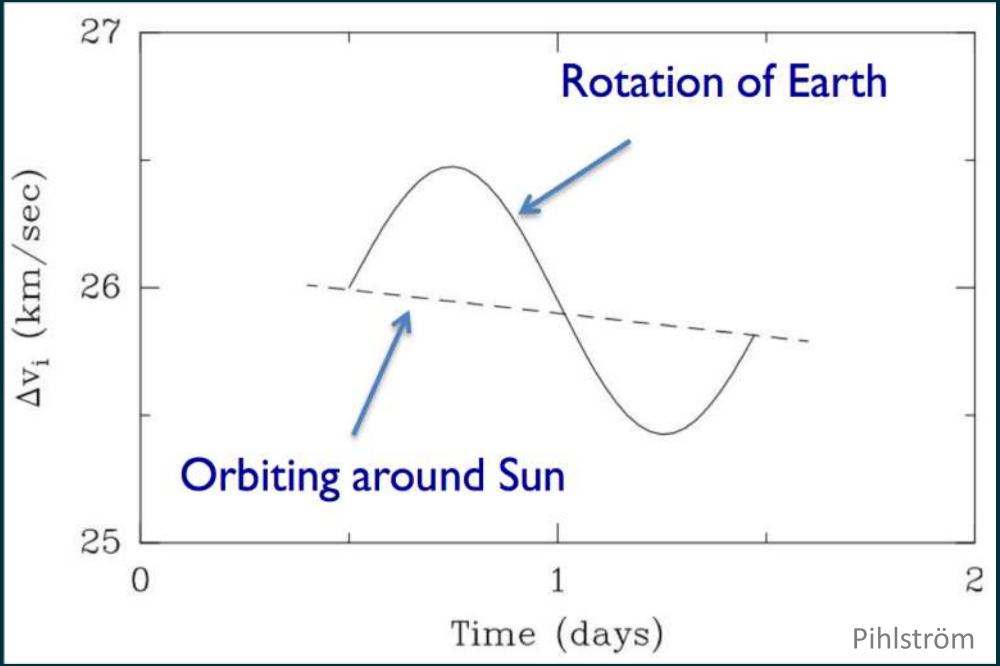
	ASKAP	MWA
Frequency range (MHz)	**700 – 1800**	**80 – 300**
Wavelength range (m)	0.17 – 0.43	1 – 3.7
Instantaneous bandwidth (MHz)	300	30.72
Number of channels	16k	3k
Spectral resolution (kHz)	**18.5**	**30**
Field of view (deg^2)	30	200 – 2500

Data Processing

- Splitting, flagging/editing
- Calibration
- Continuum imaging & validation
- Doppler correction / velocity considerations
- Subtract continuum
- Spectral line imaging & validation

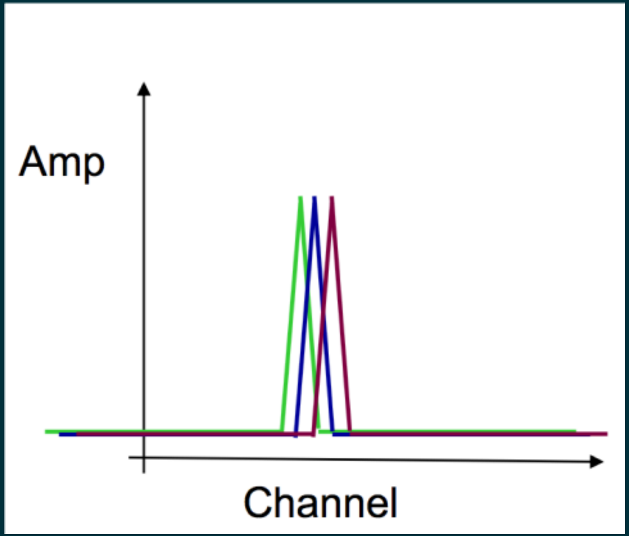
Doppler correction

- due to Earth's motion, our velocity with respect to astronomical sources is **not constant** in time or direction
- if not corrected, the spectral line will **slowly drift** through spectrum

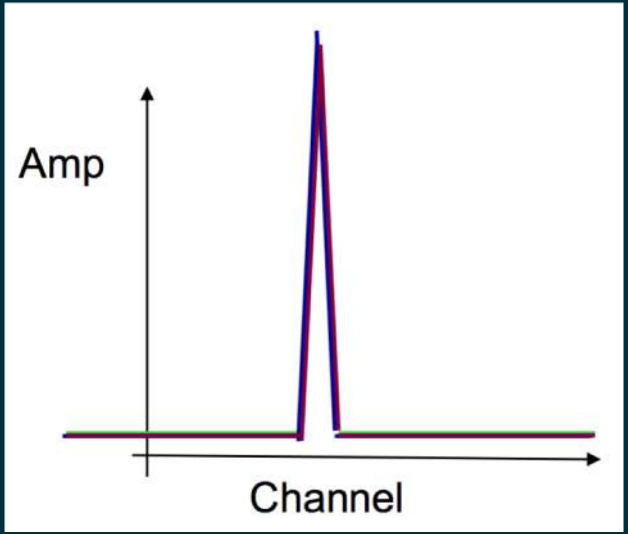


Doppler correction

- Doppler track during observations or apply correction during post-processing



Doppler correction



Velocity convention

- relativistic expression:

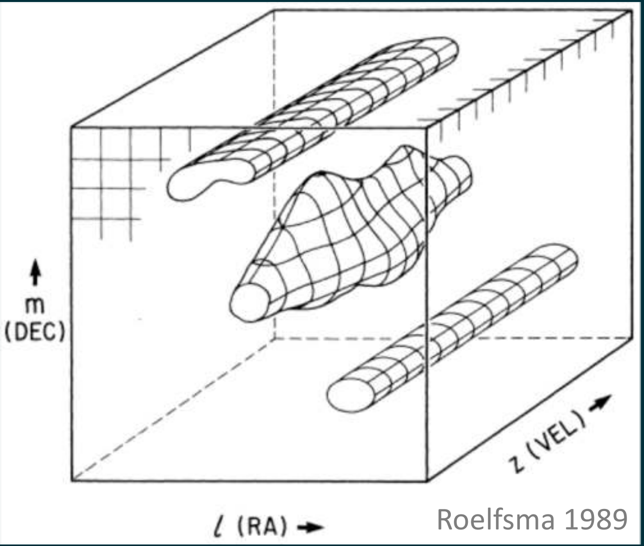
$$v_{radial} = c \frac{f_o^2 - f^2}{f_o^2 + f^2}$$

- two approximations:

$$v_{radio} = c \left(1 - \frac{f}{f_o} \right)$$ ← depreciated by IAU

$$v_{optical} = c \left(\frac{f}{f_o} - 1 \right)$$

Continuum subtraction



Spectral line cube with two continuum sources – structure independent of frequency – and one spectral line source

- continuum emission **complicates the detection and analysis** of spectral line data
- can affect **image quality** of the spectral cube (e.g. deconvolution differences, sidelobes of bright continuum sources)

Continuum subtraction - visibility based

- low order polynomial, fit to **line free channels** in each visibility spectrum, then subtracted from whole spectrum
  - works well for **small field of view**

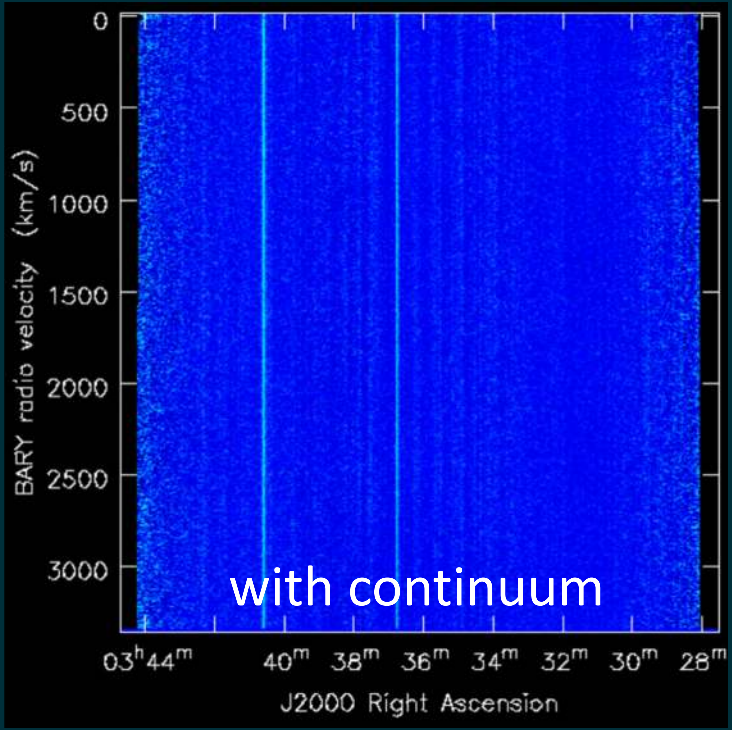
- continuum model (clean model or source catalogue) subtracted from the visibility cube

Continuum subtraction - image based

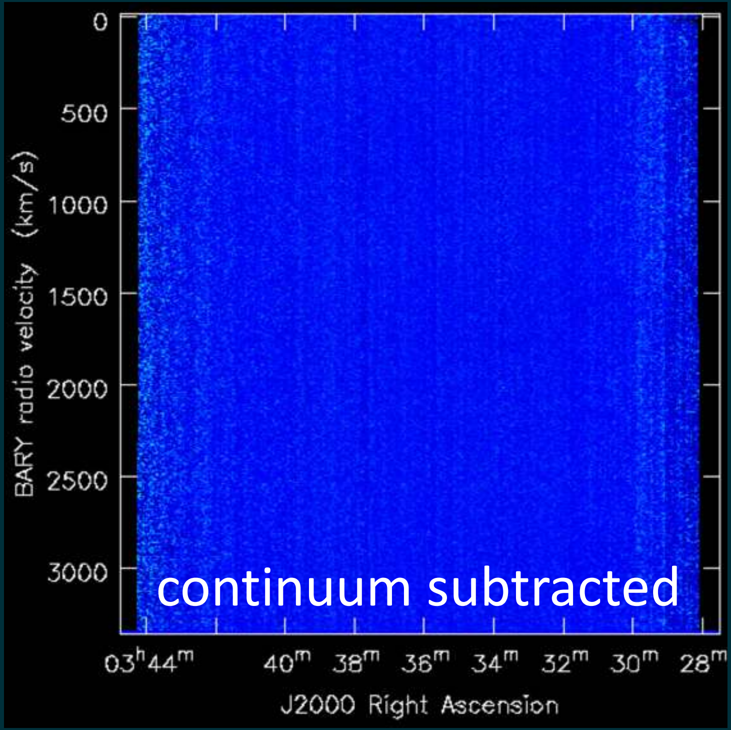
- low order polynomial fitted to and subtracted from each spectrum in the cube
  - better at removing point **sources far away** from phase centre

- ASKAPsoft option: Savitzky-Golay filter fits and then removes the spectral baseline in each spectrum

Continuum subtraction



← frequency / velocity axis →



Spectral line imaging

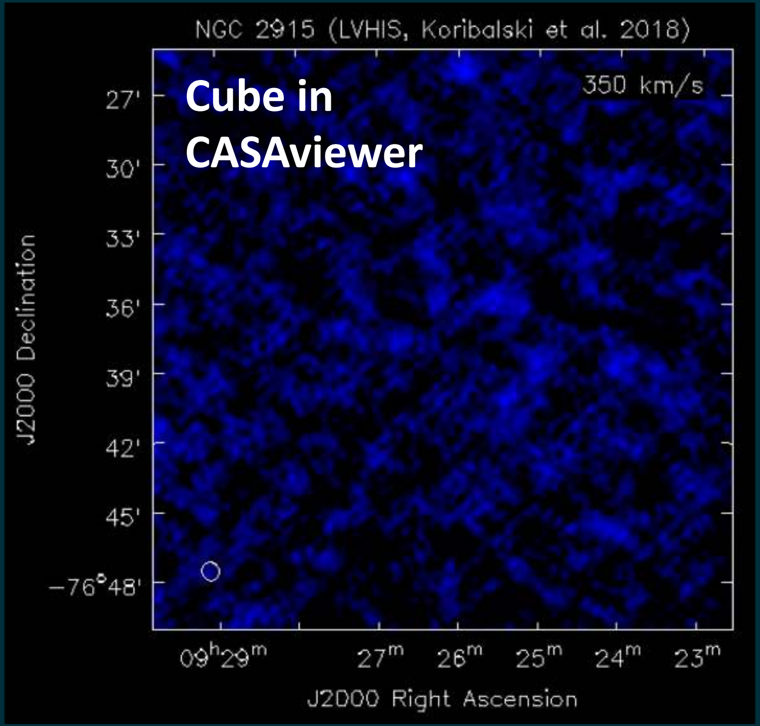
- spatially distributed spectra are interpolated onto a grid to make 3D data cubes with two spatial and one spectral axis
- similar to deconvolution of continuum maps; however, emission structures vary across channels
  - try to keep deconvolution as similar as possible for all channels (same restoring beam, clean to same depth)

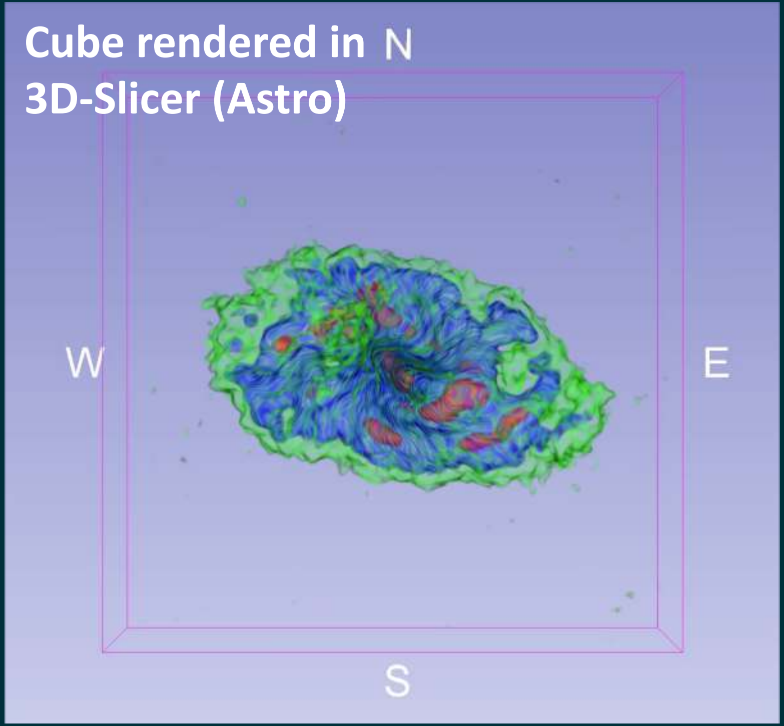
Smoothing

- bring out fainter features
- useful for comparing to other data (different beam sizes & resolution)
- reduce data size

- **spatial smoothing** (by uv tapering or convolution in image domain) → emphasize extended structures
- **spectral smoothing** → emphasize low signal-to-noise lines

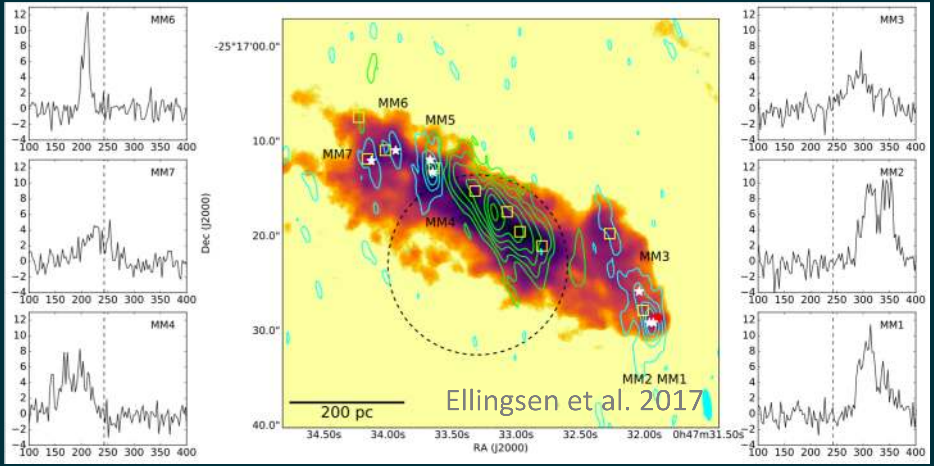
Data products – image cubes



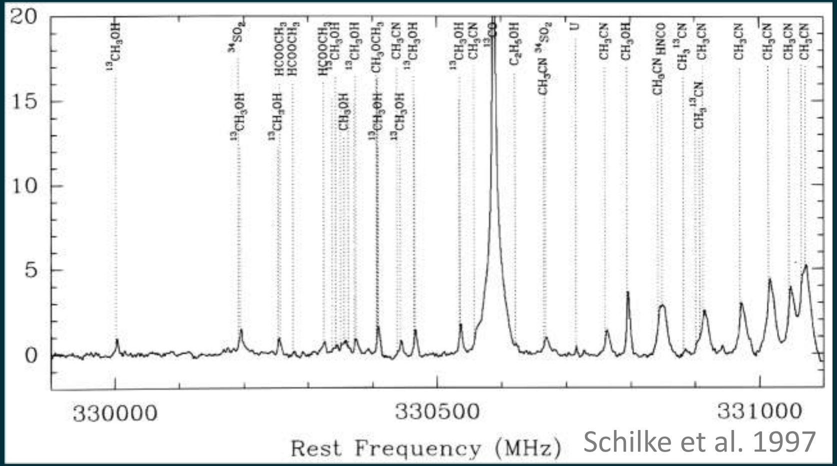


Data products – spectra

Methanol maser in NGC 253



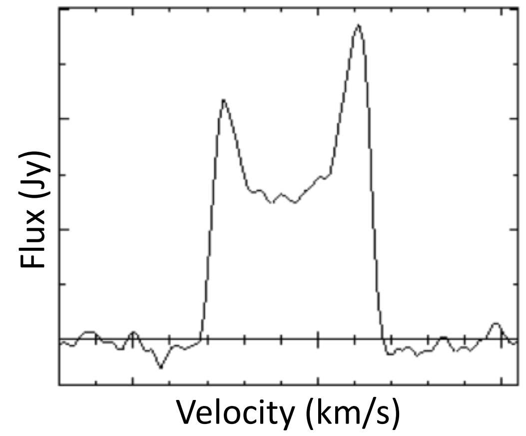
Molecular lines in Orion KL



Data products – HI spectra

- integral of HI profile → flux density (F_{HI})
- HI in galaxies is optically thin → HI mass

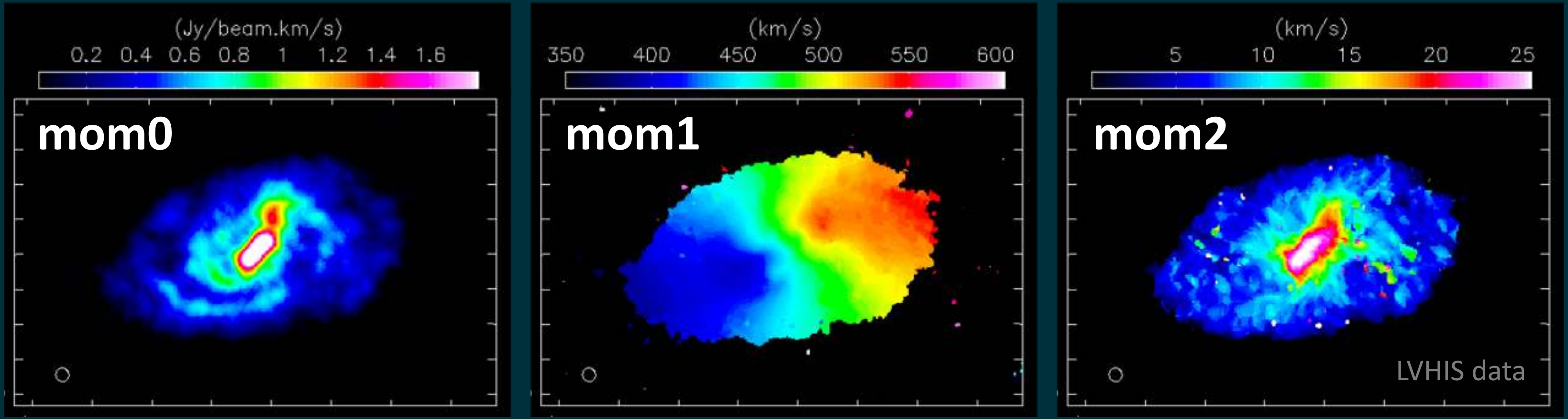
$$\frac{M_{HI}}{M_\odot} = 2.356 \times 10^5 \frac{F_{HI}}{\text{Jy km/s}} \left(\frac{d}{\text{Mpc}}\right)^2$$



- dynamical mass → total contained mass

$$M_r = \frac{r v_r^2}{G} \rightarrow M_{dyn} = 3.39 \times 10^4 \frac{a_{HI}}{\text{arcmin}} \frac{d}{\text{Mpc}} \left(\frac{½\, W_{50}}{\text{km/s}}\right)^2$$

Data products – moment maps



"moment 0" = total intensity (integrated spectrum)

"moment 1" = intensity weighted velocity field

"moment 2" = intensity weighted velocity dispersion

References and inspiration

- Essential Radio Astronomy ~ J. Condon & S. Ransom

Various online lecture slides from previous radio schools, including but not limited to:

- Spectral Line Observing, ESSEA ~ D. Muders
- Spectral Line Data Analysis, NRAO Workshop ~ Y. Pihlström
- Spectral Line Science, ATNF Radio School ~ O.I. Wong

Thank you!

Karen Lee-Waddell
Research+ Postdoctoral Fellow

t +61 2 9372 4129
e karen.lee-waddell@csiro.au
@KarenLeeWaddell