Some Topics in Error Recognition

Jim Braatz (NRAO)

Thanks to Alison Peck for Error Analysis slides

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

Issues: Radio Frequency Interference (RFI)

Culprits:

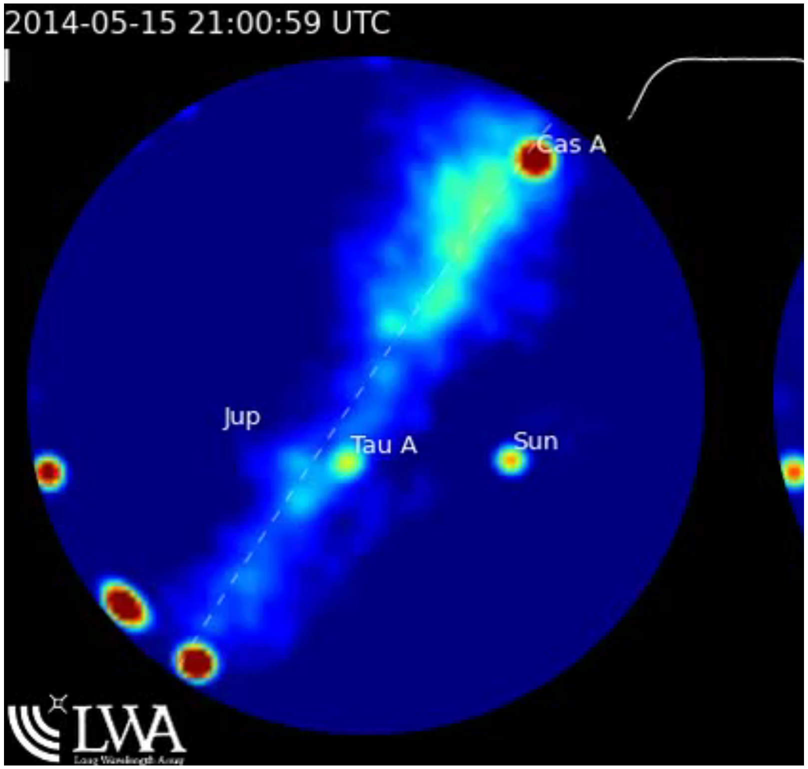
Wireless devices at low frequencies
Television/radio signals
Aircraft, Radar
Car radars

Problematic regions:

1215 – 1300 MHz mobile comm.
1675 – 1710 MHz mobile comm.
1755 – 1850 MHz mobile comm.
2155 – 2200 MHz mobile comm
4200 – 4220 MHz altimeters
4380 – 4440 MHz altimeters
5925 – 7250 level-probing-radar
14000 – 14500 air to ground
15400 – 15700 radar
76000 – 77000 automobile radar (and harmonics)

GBT
VLA
VLBA
(bracketing 1215 – 15700 MHz)

ALMA (76000 – 77000 automobile radar)



Error Recognition and Data Inspection

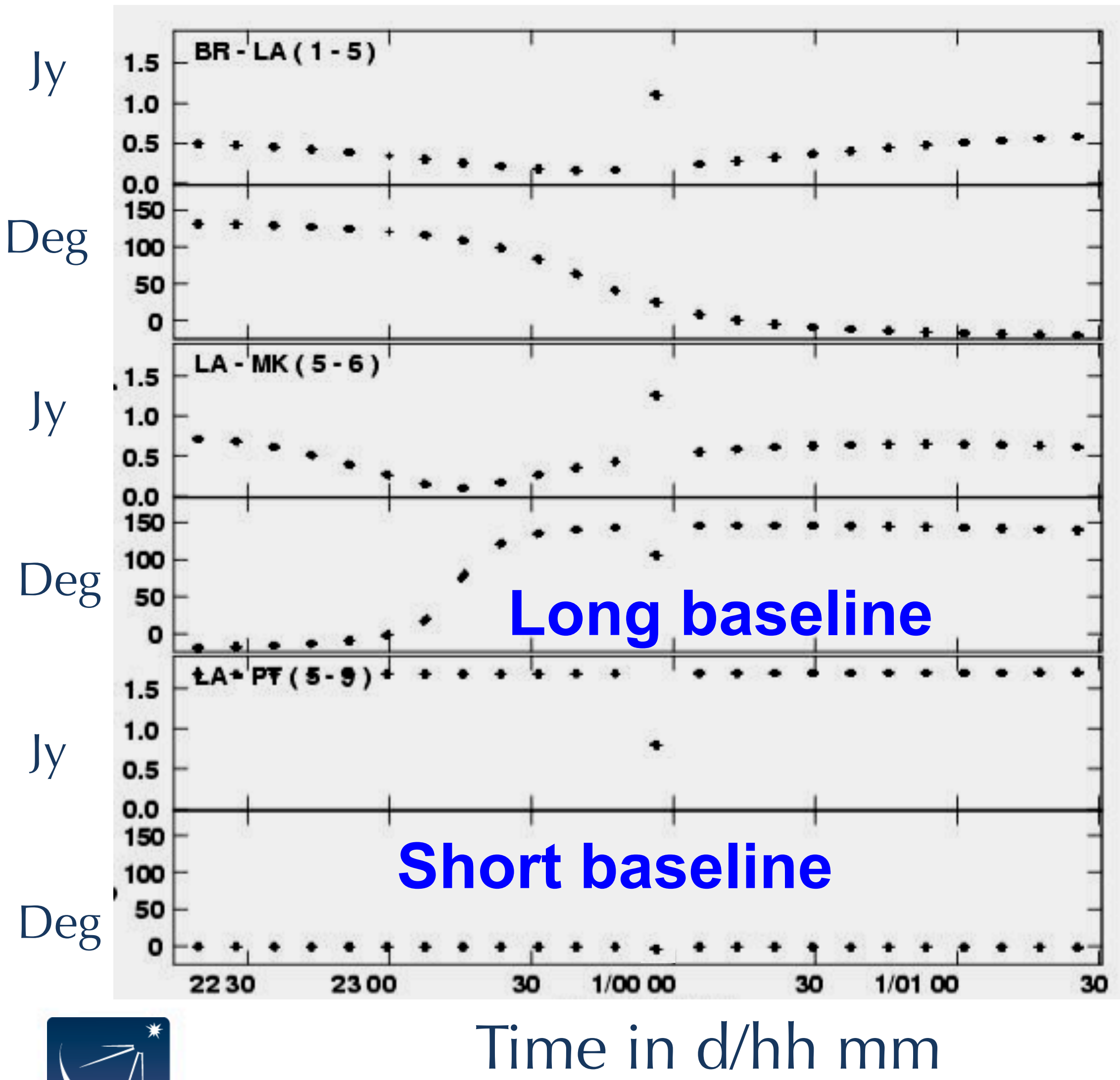
Start with the data have been edited and calibrated

Inspect the data!

- Calibration tables
- UV data
- Image data

- If calibration sources show serious problems, it may be necessary to edit (flag) the calibration sources, re-calibrate, and re-image

Examine calibration tables



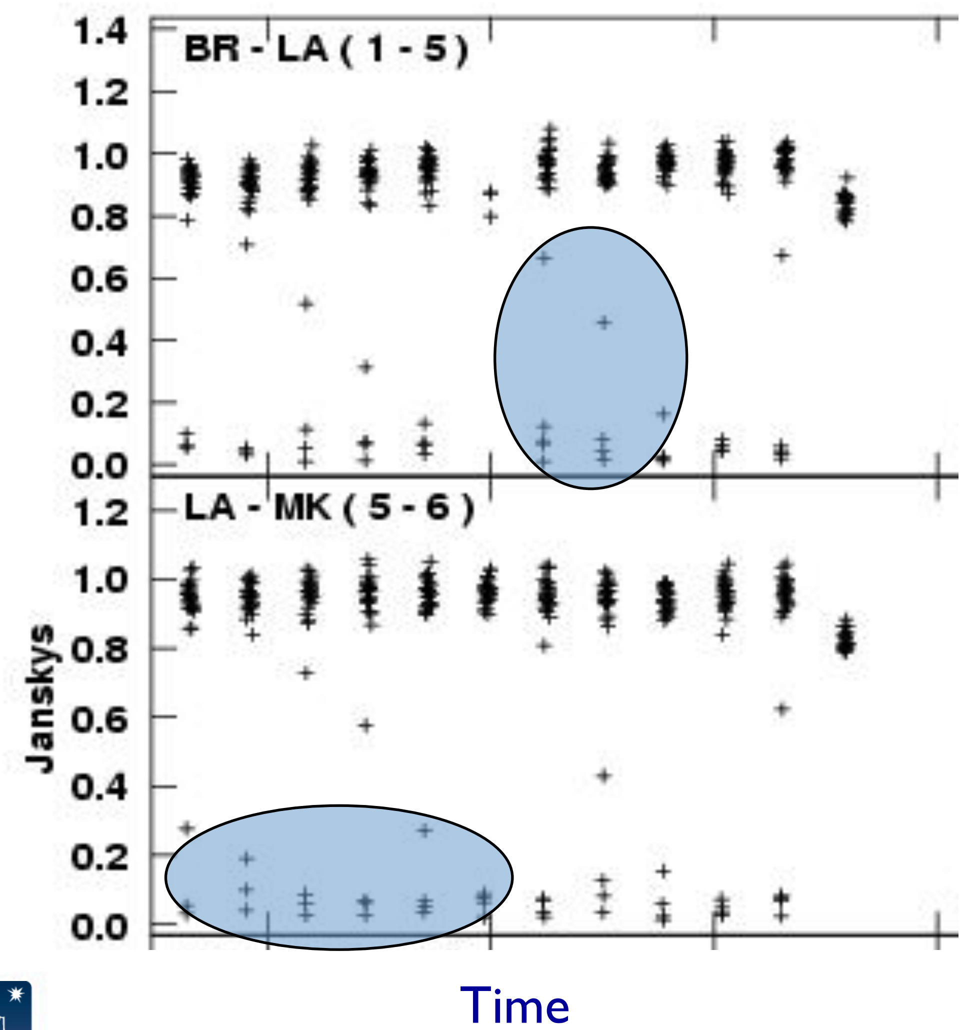
Visibility amplitude and phase versus time for various baselines

Good for determining the continuity of the data

Should be relatively smooth with time

Outliers are obvious.

Drop-outs at Scan Beginnings

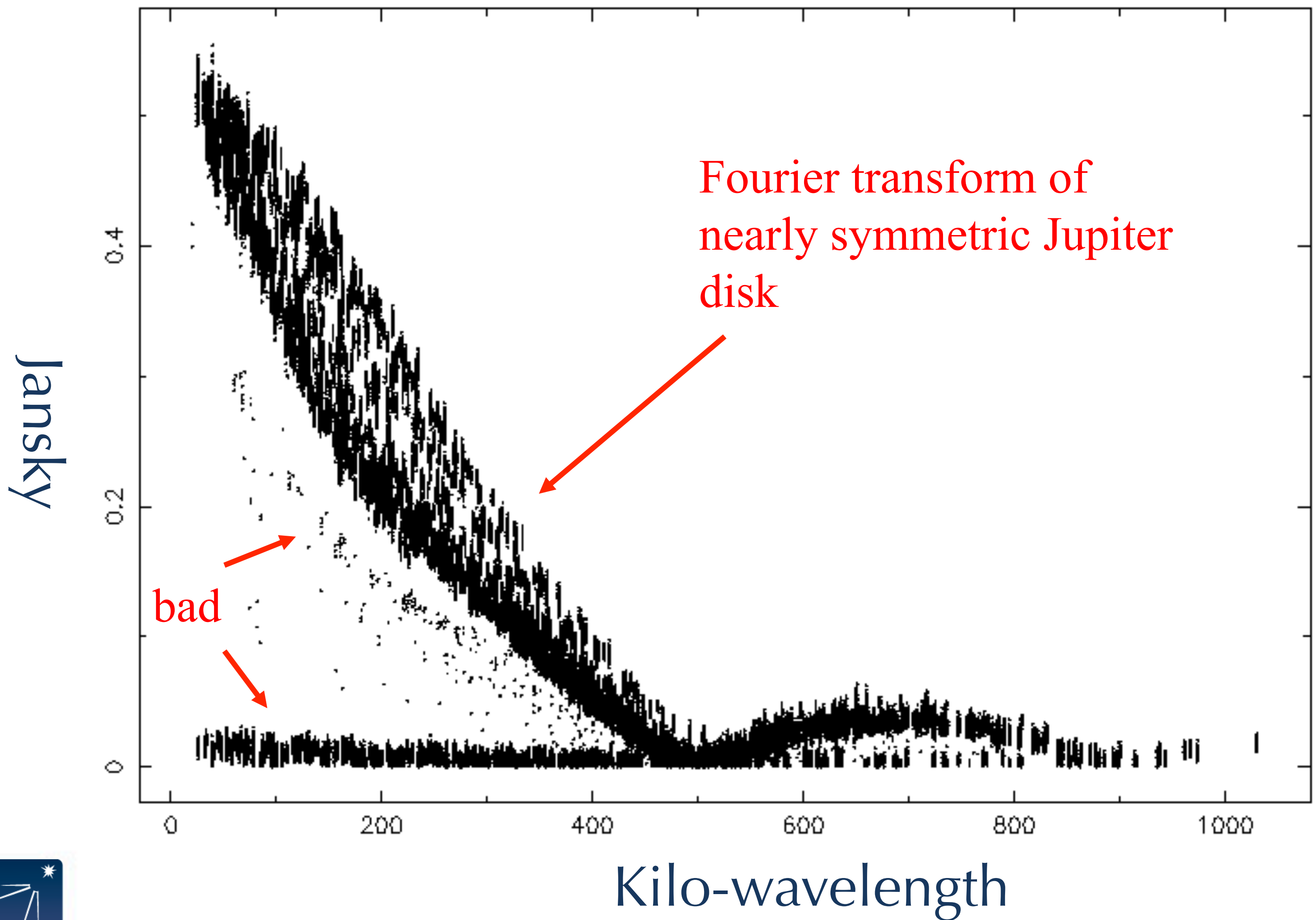


Often the first few points of a scan have low amplitude. E.g. antenna not on source.

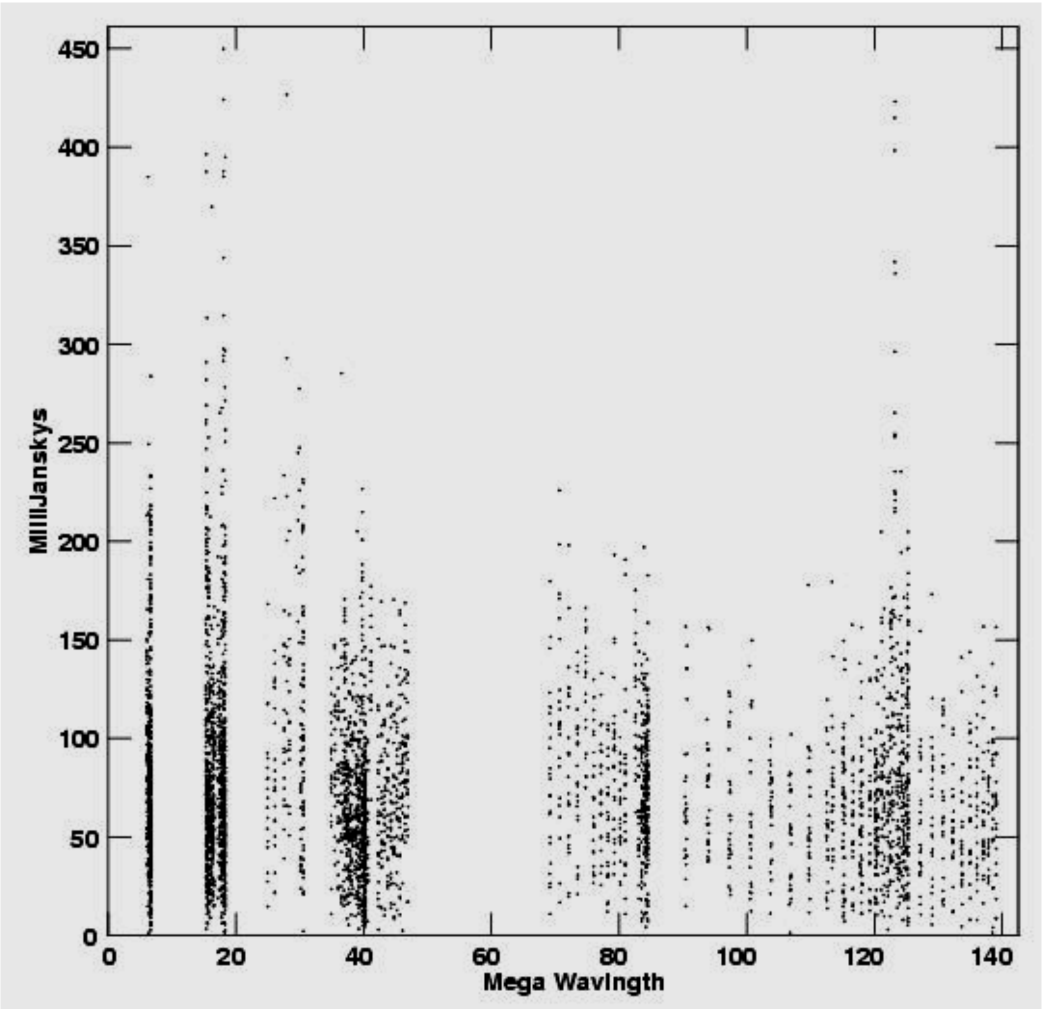
Use CASA 'quack' to flag

Flag extension:
Should flag all sources in the same manner even though you cannot see dropout for weak sources

UV data – plotms



Editing Noise-dominated Sources



No source structure information is detected. Noise dominated.

All you can do is quack and remove outlier points. Precise level not important as long as large outliers are removed.

It is a bad idea to flag based on phase. Only flag discrepant amplitudes in noise-dominated sources.

Error Recognition in the Image Plane

Some Questions to ask:

Noise properties of image:

- Is the rms noise about that expected from integration time?
- Is the rms noise much larger near bright sources?
- Are there non-random noise components (faint waves and ripples)?

Funny looking structure:

- Non-physical features; stripes, rings, symmetric or anti-symmetric
- Negative features well-below 4xrms noise
- Does the image have characteristics that look like the dirty beam?

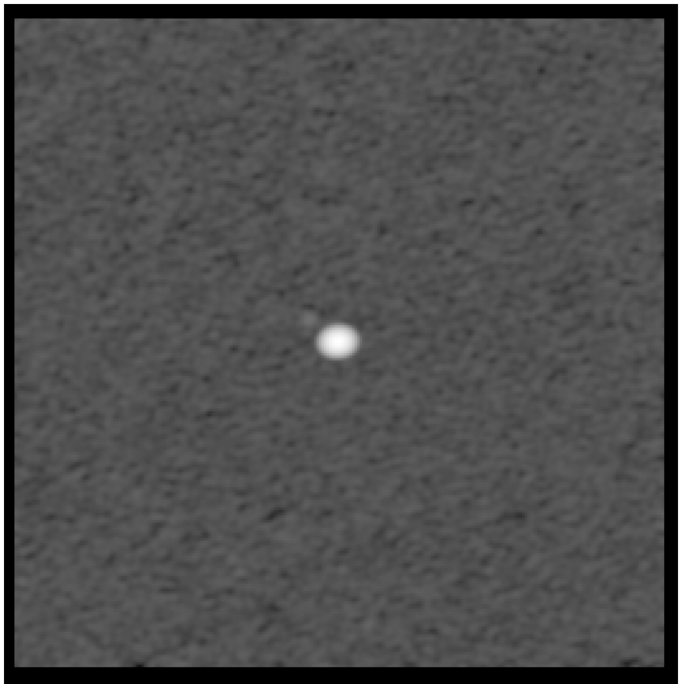
Image-making parameters:

- Is the image big enough to cover all significant emission?
- Is cell size too large or too small? ~4 points per beam okay
- Is the resolution too high to detect most of the emission?

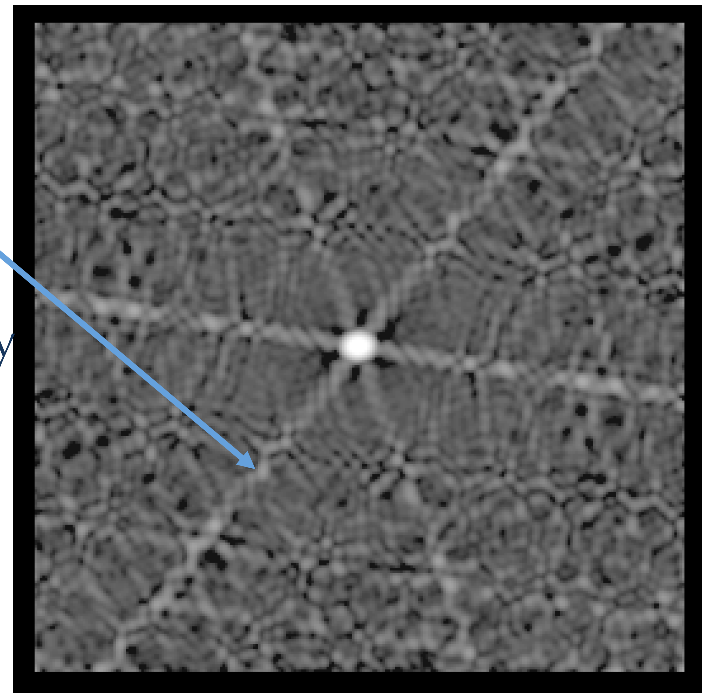
EXAMPLE 1: Data bad over a short period of time

Results for a point source using VLA.   13 x 5min observation over 10 hr.
Images shown after editing, calibration and deconvolution.

no errors:
max 3.24 Jy
rms 0.11 mJy



10% amp error for all antennas for 1 time period
rms 2.0 mJy



6-fold symmetric pattern due to VLA “Y”.
Image has properties of dirty beam.

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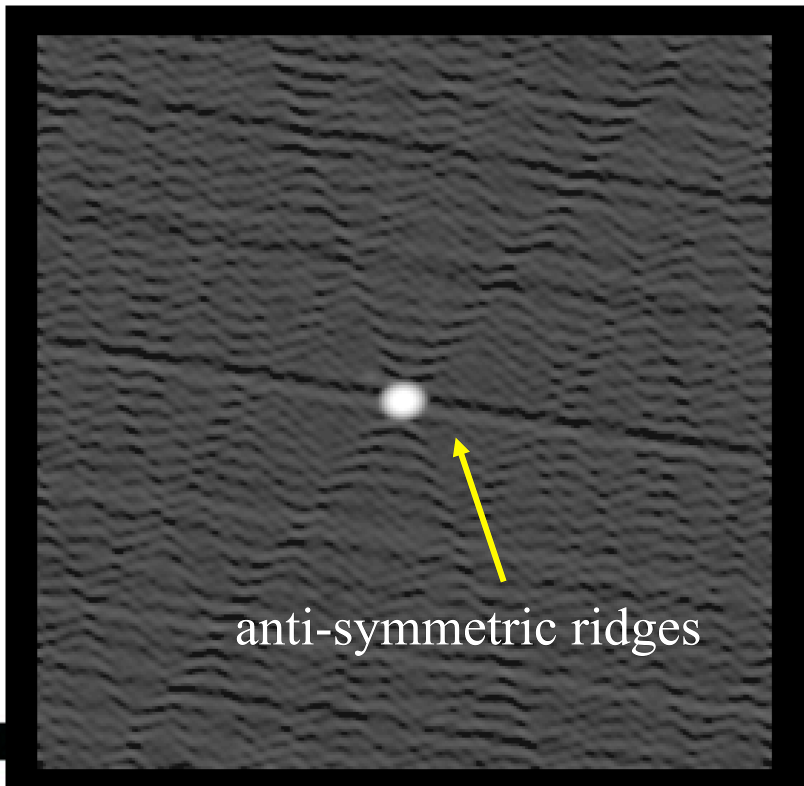
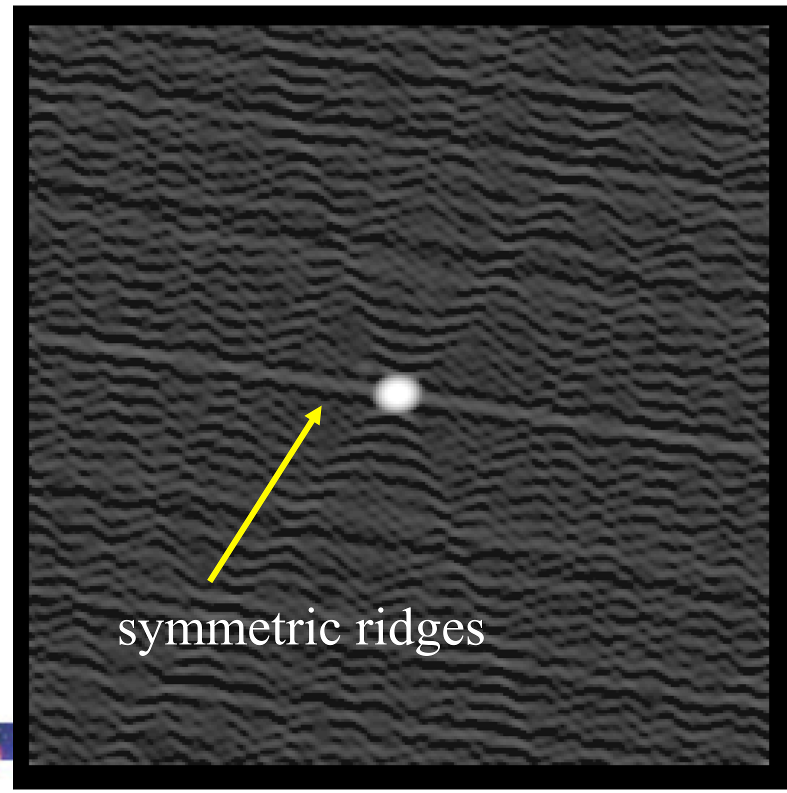
EXAMPLE 2: Short burst of bad data

Typical effect from one bad antenna

10 deg phase error for
one antenna at one time
rms 0.49 mJy



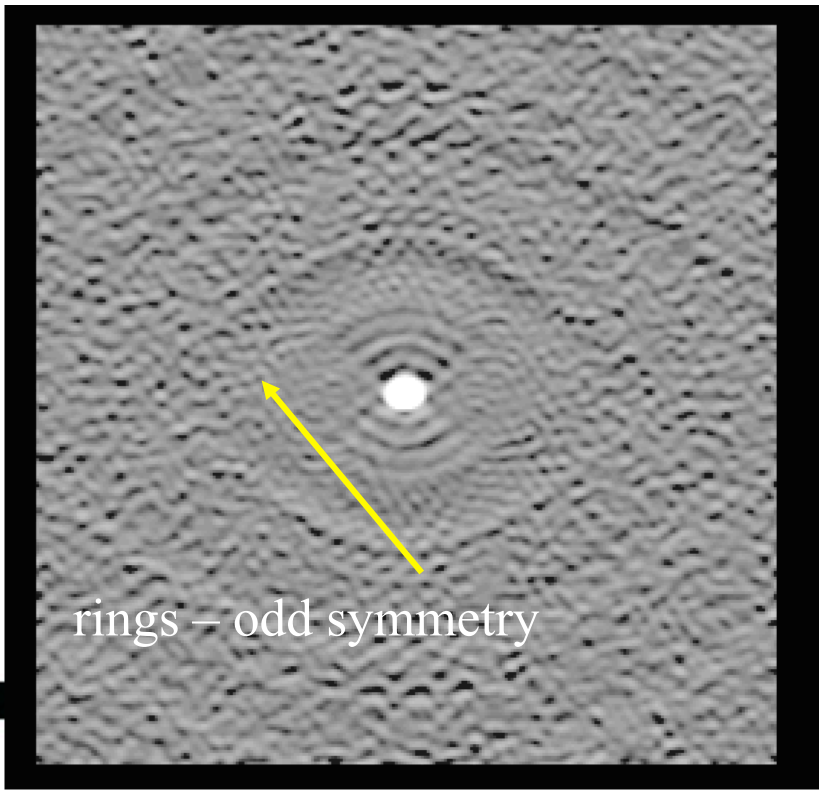
20% amplitude error for
one antenna at one time
rms 0.56 mJy (self-cal)



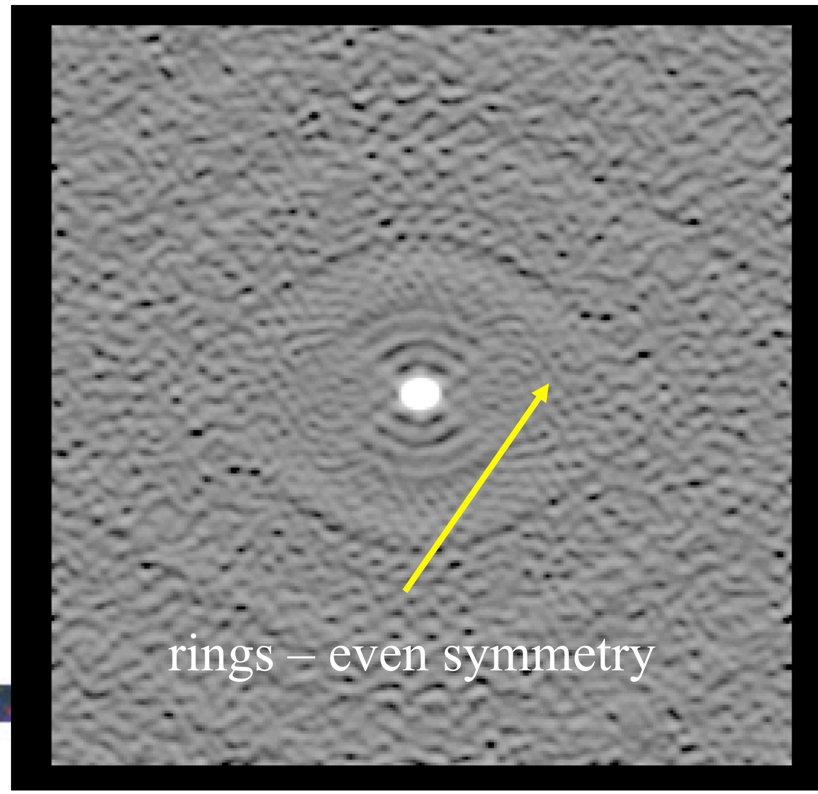
EXAMPLE 3: Persistent errors over most of observations

NOTE: 10 deg phase error to 20% amplitude error
cause similar sized artifacts

10 deg phase error for
one antenna all times
rms 2.0 mJy



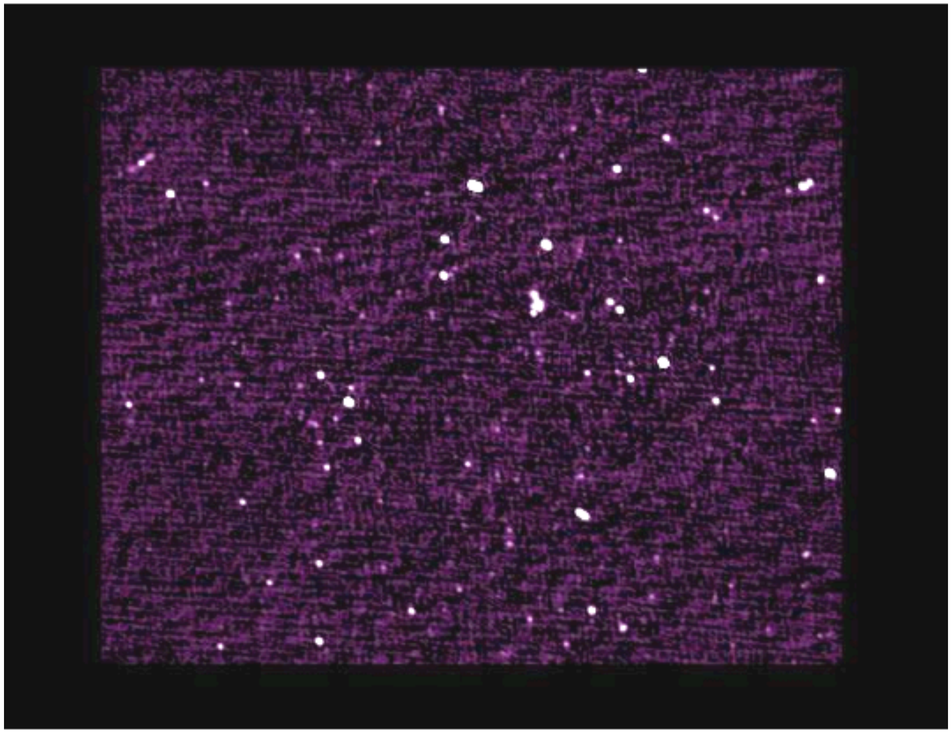
20% amp error for one
antenna all times
rms 2.3 mJy



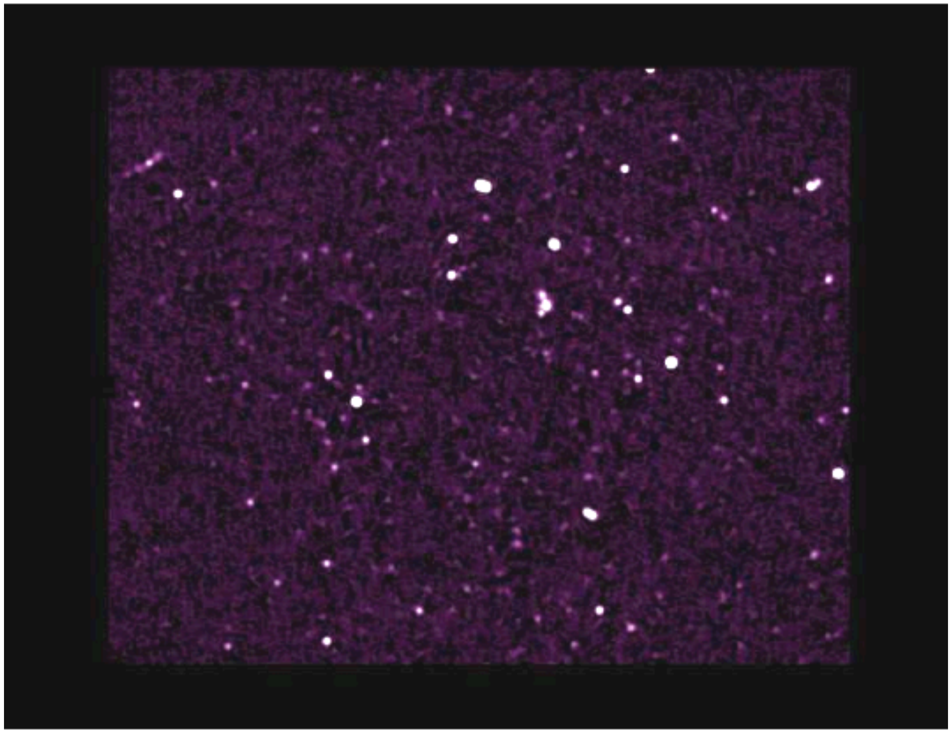
Improvement of Image

Removal of low level ripple improves detectability of faint sources

Before editing



After editing



Some Topics in Spectral Line Observing and Data Analysis

Jim Braatz (NRAO)

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

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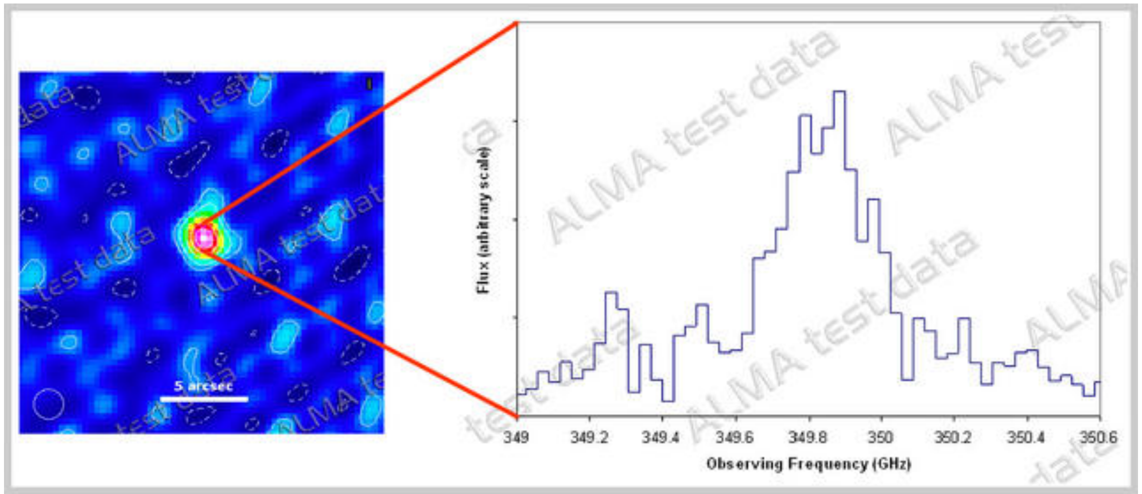
Outline

- Why spectroscopy?
- What do we observe?
- Some observational considerations
- Analyzing spectral line data

Why Spectroscopy?



- Probe physical conditions
  - Density – different transitions have different critical densities, also specific tracers of dense gas (optically thinner than CO) like HCN, CS, NH_3
  - Temperature – observe different energy transitions of the same species (e.g. Ammonia)
- Chemistry
- Dynamics

"Continuum"

- Even continuum observations are taken in spectroscopic correlator modes to reduce bandwidth smearing.

- Modern electronics allows for wide-band continuum observing

- Science does not depend sensitively on frequency, but using spectral line mode is favorable to correct for some frequency dependent issues:
  - Limitations of bandwidth smearing
  - Limitations of beam smearing
  - Problems due to atmospheric changes as a function of frequency
  - Problems due to signal transmission effects as a function of frequency
  - Opportunity to flag RFI

- Using a spectral line mode also allows editing for unwanted, narrow-band interference.

Effects of Broad Bandwidth:

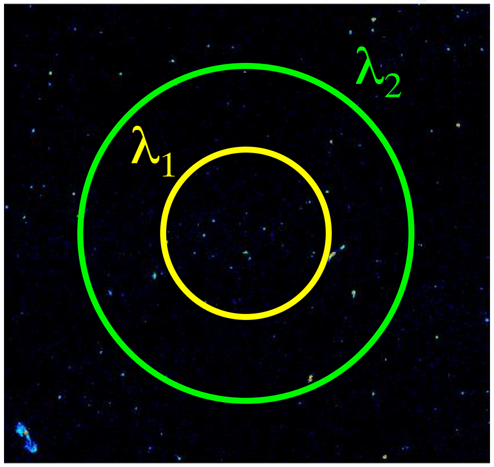
- Consider an observation covering the bandwidth (λ_1, λ_2)

- Changing Primary Beam ($\theta_{PB} = \lambda/D$)

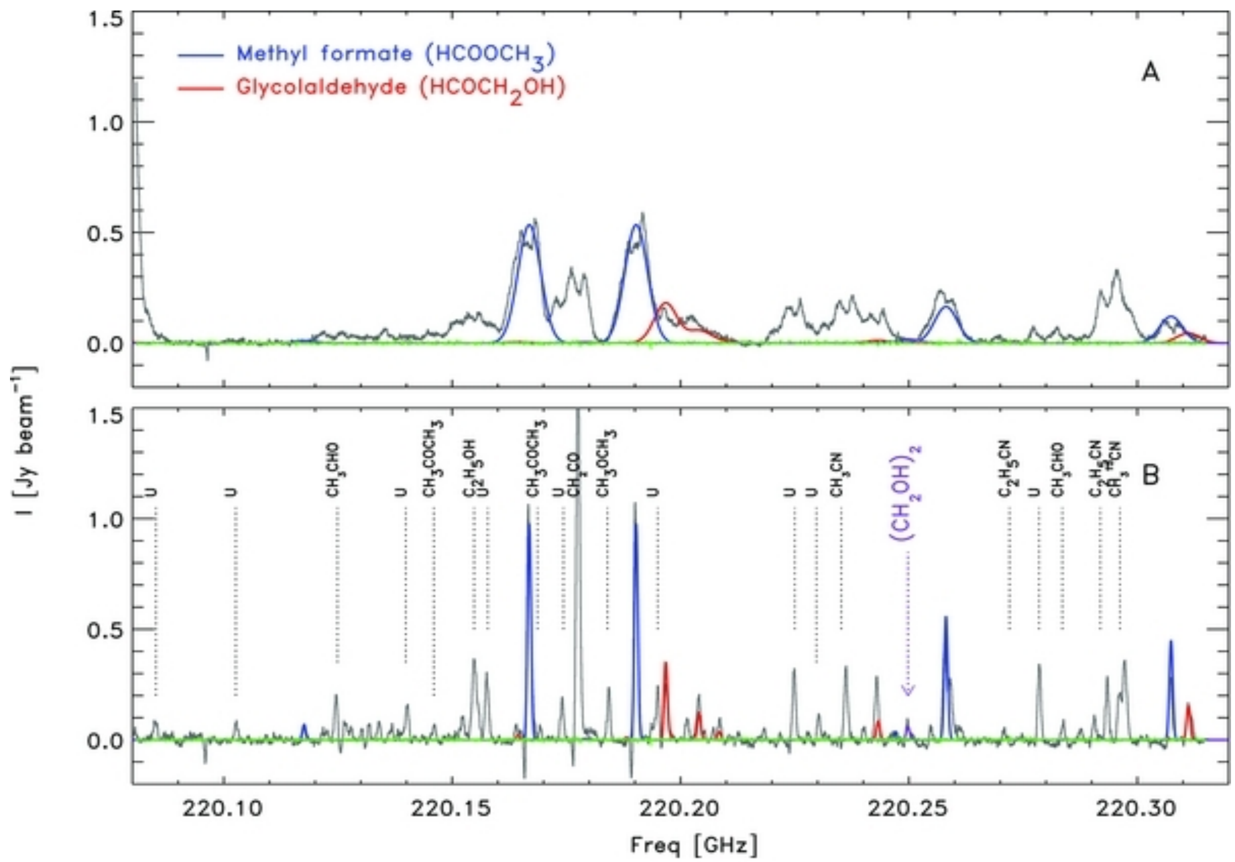
  $\Rightarrow$ θ_{PB} changes by λ_1/λ_2

- Dependent on fractional bandwidth observed, so more important at lower frequencies

- Bandwidth Smearing (chromatic aberration)
- Fringe spacing = λ/B
  - Fringe spacings change by λ_1/λ_2
  - *u,v* samples smeared radially
  - More important in larger configurations, and for lower frequencies
- Huge effects for VLA
- Multi-frequency synthesis



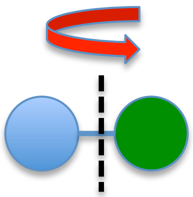
Example: complex molecules in protostars

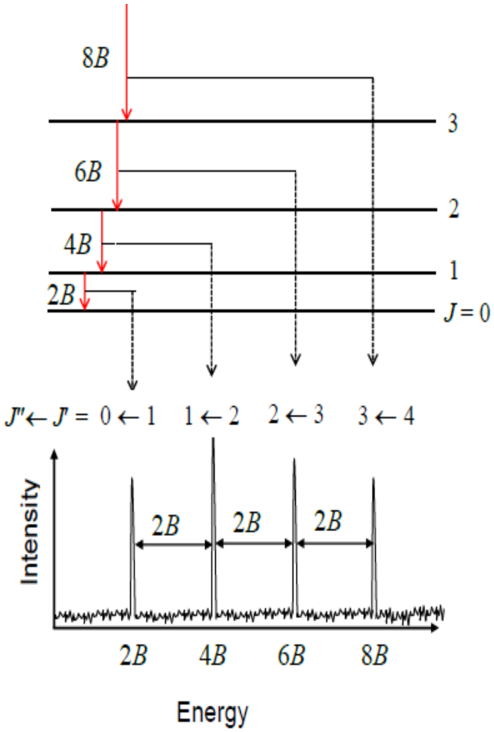


Detection of the Simplest Sugar, Glycolaldehyde, in a Solar-type Protostar with ALMA
Jørgensen et al. 2012

Molecular spectroscopy: linear molecules

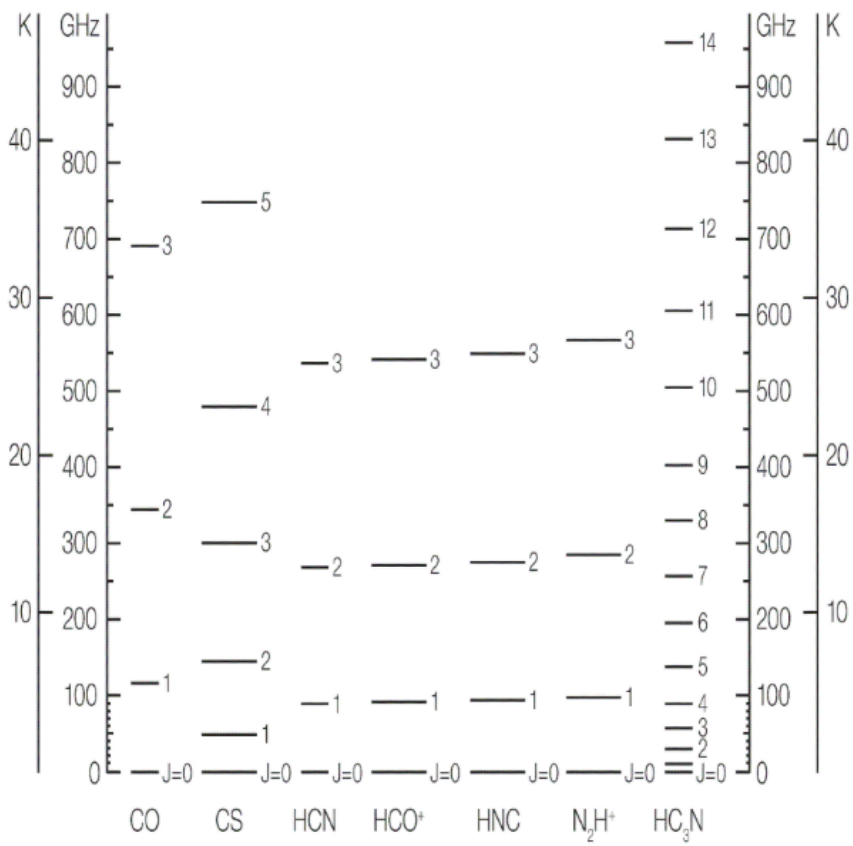
- The richness of a given molecule's spectrum depends on its shape.
- Molecules can have one, two or three rotation axes with dipoles.
- Linear molecules like CO have just one rotation axis, making a simple and evenly-spaced energy ladder
- Line intensity depends on, e.g., temperature and abundance of gas, optical thickness





CO: a Simple rigid rotor

Linear molecules: a rotation ladder

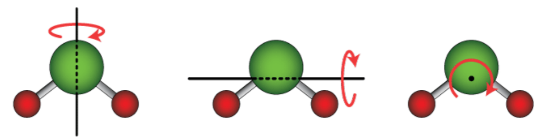


- States uniquely defined by total angular momentum quantum level J
- Selection rules: ΔJ = ± 1
- Successive transitions are evenly spaced, e.g.

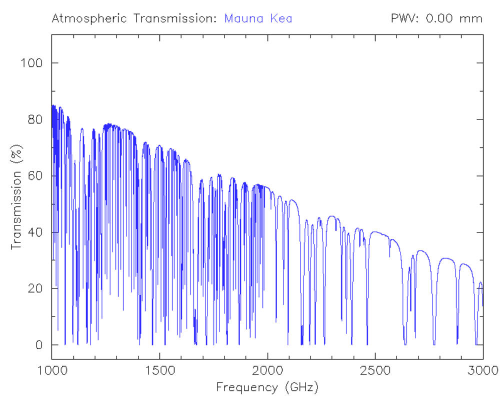
CO (1-0) at 115 GHz
CO (2-1) at 230 GHz
CO (3-2) at 345 GHz
Etc.

Molecular spectroscopy: More complex shapes

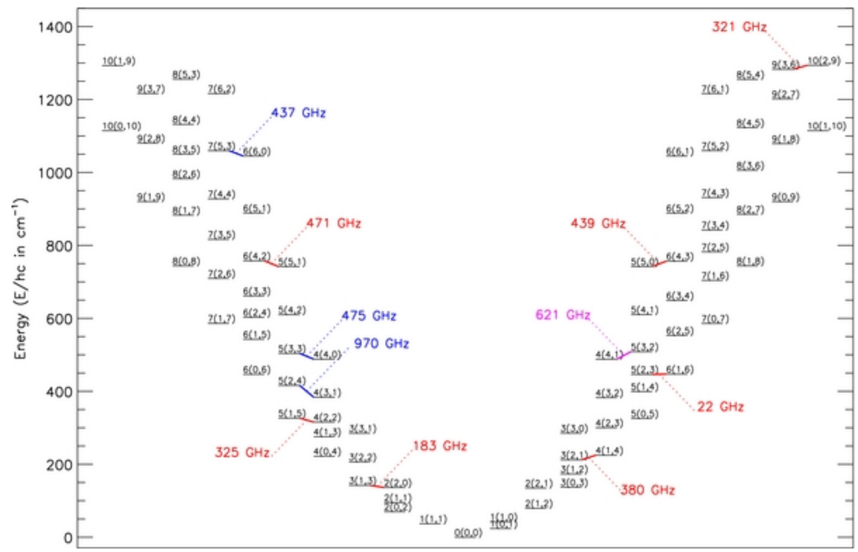
- Most molecules have more than one axis, and much more complex spectra.



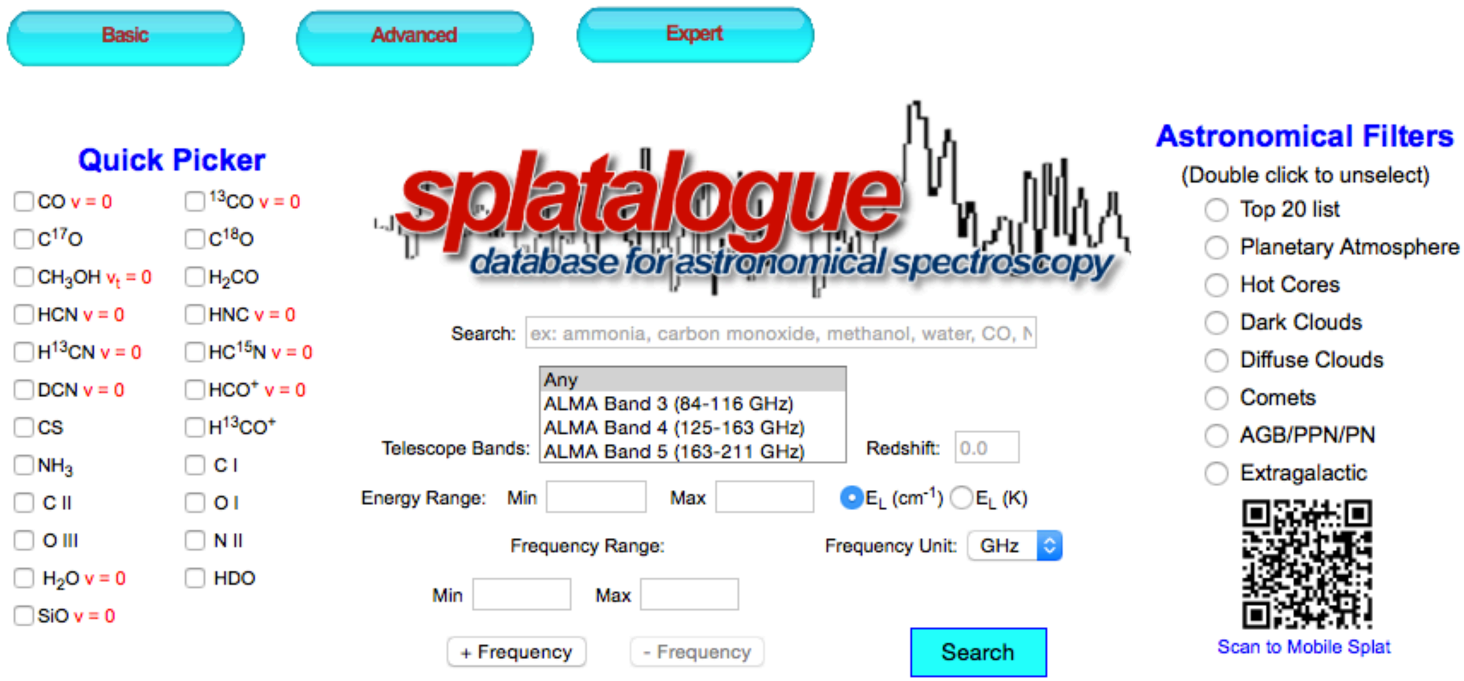
H_2O is an asymmetric top



Water (in absorption)



Splatalogue



Splatalogue

	Species	Chemical Name	Ordered Freq (GHz) (rest frame, redshifted)	Resolved QNs
1	CO v = 0	Carbon Monoxide	115.27120, 115.27120	1- 0
2	CO v = 0	Carbon Monoxide	230.53800, 230.53800	2- 1
3	CO v = 0	Carbon Monoxide	345.79599, 345.79599	3- 2
4	CO v = 0	Carbon Monoxide	461.04077, 461.04077	4- 3
5	CO v = 0	Carbon Monoxide	576.26793, 576.26793	5- 4
6	CO v = 0	Carbon Monoxide	691.47308, 691.47308	6- 5
7	CO v = 0	Carbon Monoxide	806.65180, 806.65180	7- 6
8	CO v = 0	Carbon Monoxide	921.79970, 921.79970	8- 7
9	CO v = 0	Carbon Monoxide	1036.91239, 1036.91239	9- 8

	Species	Chemical Name	Ordered Freq (GHz) (rest frame, redshifted)	Resolved QNs
1	SiO v = 0	Silicon Monoxide	43.42376, 43.42376	1- 0
2	SiO v = 0	Silicon Monoxide	86.84696, 86.84696	2- 1
3	SiO v = 0	Silicon Monoxide	130.26861, 130.26861	3- 2
4	SiO v = 0	Silicon Monoxide	173.68831, 173.68831	4- 3
5	SiO v = 0	Silicon Monoxide	217.10498, 217.10498	5- 4
6	SiO v = 0	Silicon Monoxide	260.51802, 260.51802	6- 5
7	SiO v = 0	Silicon Monoxide	303.92681, 303.92681	7- 6
8	SiO v = 0	Silicon Monoxide	347.33058, 347.33058	8- 7
9	SiO v = 0	Silicon Monoxide	390.72861, 390.72861	9- 8
10	SiO v = 0	Silicon Monoxide	434.12018, 434.12018	10- 9

	Species	Chemical Name	Ordered Freq (GHz) (rest frame, redshifted)	Resolved QNs
1	H_2O v=0	Water	22.23508, 22.23508	6(1, 6)- 5(2, 3)
2	H_2O v=0	Water	183.31009, 183.31009	3(1, 3)- 2(2, 0)
3	H_2O v=0	Water	321.22568, 321.22568	10(2, 9)- 9(3, 6)
4	H_2O v=0	Water	325.15290, 325.15290	5(1, 5)- 4(2, 2)
5	H_2O v=0	Water	380.19736, 380.19736	4(1, 4)- 3(2, 1)
6	H_2O v=0	Water	437.34666, 437.34666	7(5, 3)- 6(6, 0)
7	H_2O v=0	Water	439.15079, 439.15079	6(4, 3)- 5(5, 0)

Sensitivity

$$\sigma_{\mathrm{S}} = \frac{2\,k\,T_{\mathrm{sys}}}{\eta_{\mathrm{q}}\eta_{\mathrm{c}}A_{\mathrm{eff}}\sqrt{N(N-1)\,n_{\mathrm{p}}\,\Delta\nu\,t_{\mathrm{int}}}}.$$

Spectral line sensitivity is *not* improved with broader bandwidth. It requires:

– Adding antennas/collecting area
– Improving collecting efficiency
– Observing in better weather
– Long integrations

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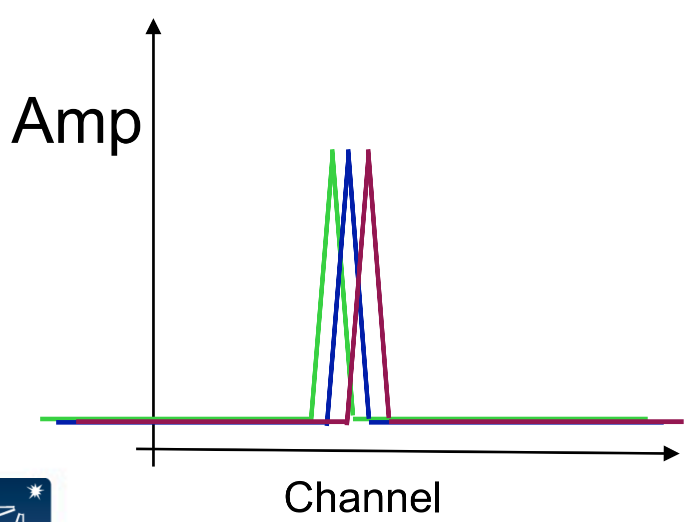
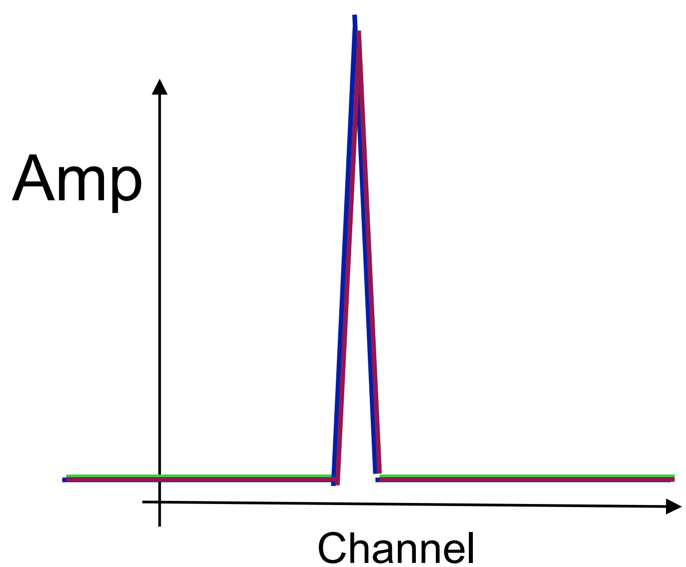
Some Observing considerations

Doppler Tracking

- Observing from the surface of the Earth, our velocity with respect to astronomical sources is not constant in time or direction.
- Note that the bandpass shape is really a function of *frequency*, not velocity!
  - Applying Doppler tracking will introduce a time-dependent and position dependent frequency shift.
  - If differences are large, apply corrections during post-processing instead.
  - With the wider bandwidths now common, online Doppler setting is done but not tracking.
- Doppler tracking is done in post-processing (AIPS: CVEL; CASA: CLEAN)





Velocity conventions

- $V_{rad} = c\ \Delta\nu/\nu_0$
- $V_{opt} = c\ \Delta\lambda/\lambda_0 = cz$

- Differences become large as redshift increases
- For the V_{opt} definition, constant frequency increment channels do not correspond to constant velocities increment channels

Velocity Reference Frames:

Correct for	Amplitude	Rest frame
Nothing	0 km/s	Topocentric
Earth rotation	< 0.5 km/s	Geocentric
Earth-Moon barycenter	< 0.013 km/s	E/M Barycentric
Earth around Sun	< 30 km/s	Heliocentric
Solar System barycenter	< 0.012 km/s	SS Barycentric (~Heliocentric)
Sun peculiar motion	< 20 km/s	Local Standard of Rest
Galactic rotation	< 300 km/s	Galactocentric

Transformations standardized by IAU.

See Frank Ghigo's Doppler Tracking web page for great details:

http://www.gb.nrao.edu/~fghigo/gbtdoc/doppler.html

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Spectroscopy with ALMA

- FDM : Frequency Division Mode
  - Used for high-res spectroscopy
  - Up to 32 Spectral Windows (spws) per baseband, each spw can be 60MHz-1875MHz wide.
  - Within a baseband, the total number of channels is fixed at $7680/N_{pol}$, and are distributed amongst the assigned spws. (N_{pol}=2 usually)
  - Highest resolution is 15kHz (Hanning smoothed, single polarization).

- TDM : Time Division Mode
  - Used for continuum, service observations (pointing), low-res spectroscopy

Data rates

- Modern correlators can produce more data than the storage and processing facilities can deal with.
- Data rates important for both VLA and ALMA.
- ~ 1 TB per day
- What to do?
  - Match spectral resolution to science.
  - Time average if possible (but beware of time smearing in wide fields).

- For the VLA, data rate, R:

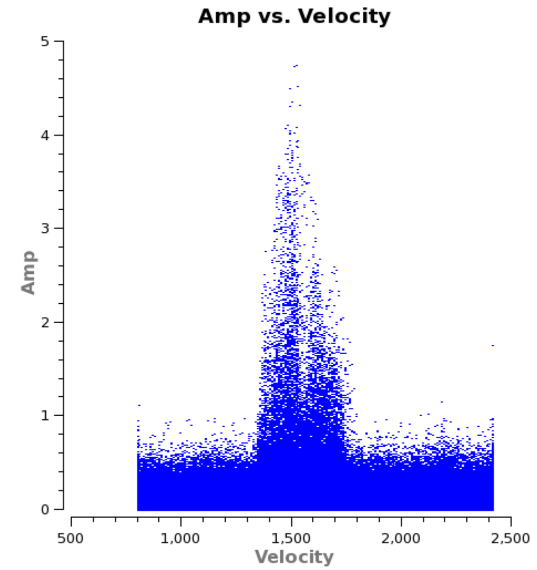
$$R = 160\mathrm{GB/hr}\frac{N_{chan}N_{pol}}{16384}\frac{N_{ant}(N_{ant}-1)}{26\times 27}\frac{1\mathrm{s}}{\Delta t}$$

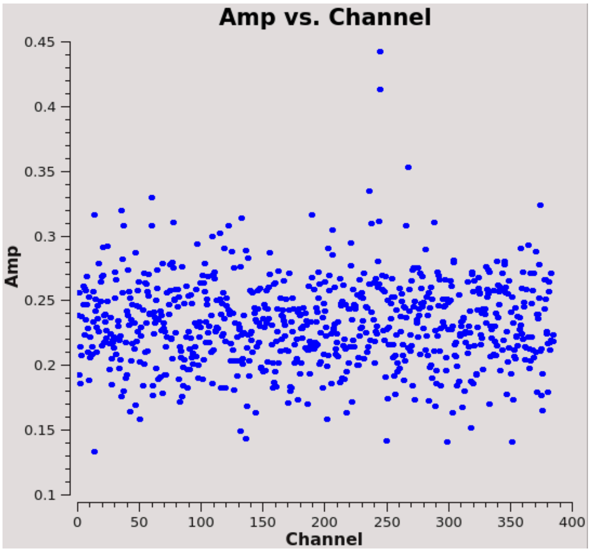
- ~32 bits/visibility
- Proportional to $\sim N_{ant}^2$
- ALMA in full resolution mode is similar (but more antennas; calculation is done for you in the ALMA Observing Tool).
- Because of high data volumes, nothing comes "for free"

The ALMA correlator – world's highest supercomputer

Continuum Subtraction:

- Spectral line data often contains continuum emission from the target.
  - This emission complicates the detection and analysis of lines
  - Easier to analyze line emission with continuum removed.
- Use channels with no line features to model the continuum; low-order polynomial fit
  - Subtract this continuum model from all channels
- Always bandpass calibrate before continuum subtracting
- Can be done before imaging (uvcontsub) or after imaging (imcontsub)
- Check results carefully!





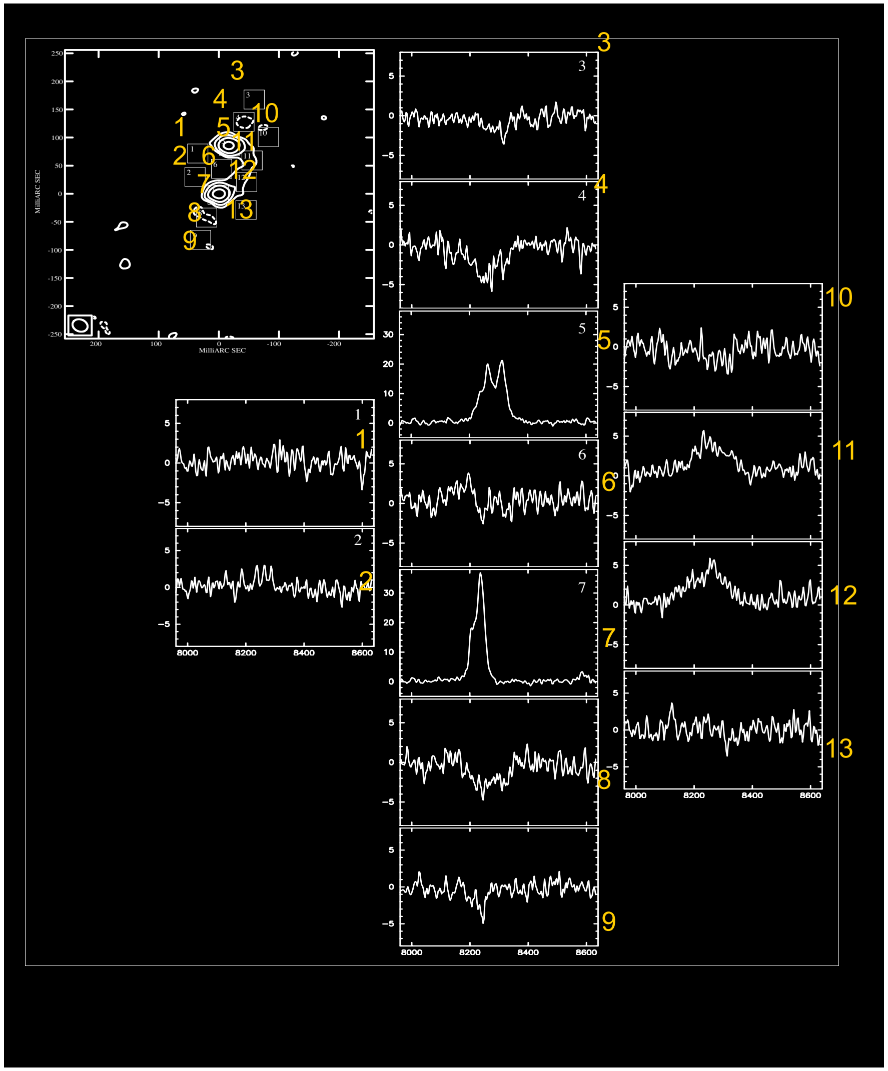
Visualizing and analyzing spectral line data

- Imaging will create a spectral line *cube*, which is 3-dimensional: RA, Dec and Velocity.

- With the cube, we usually visualize the information by making 1-D or 2-D projections:
  - Line profiles (1-D slices along velocity axis)
  - Channel maps (2-D slices along velocity axis)
  - Position-velocity plots (slices along spatial dimension)
  - Moment maps (integration along the velocity axis)

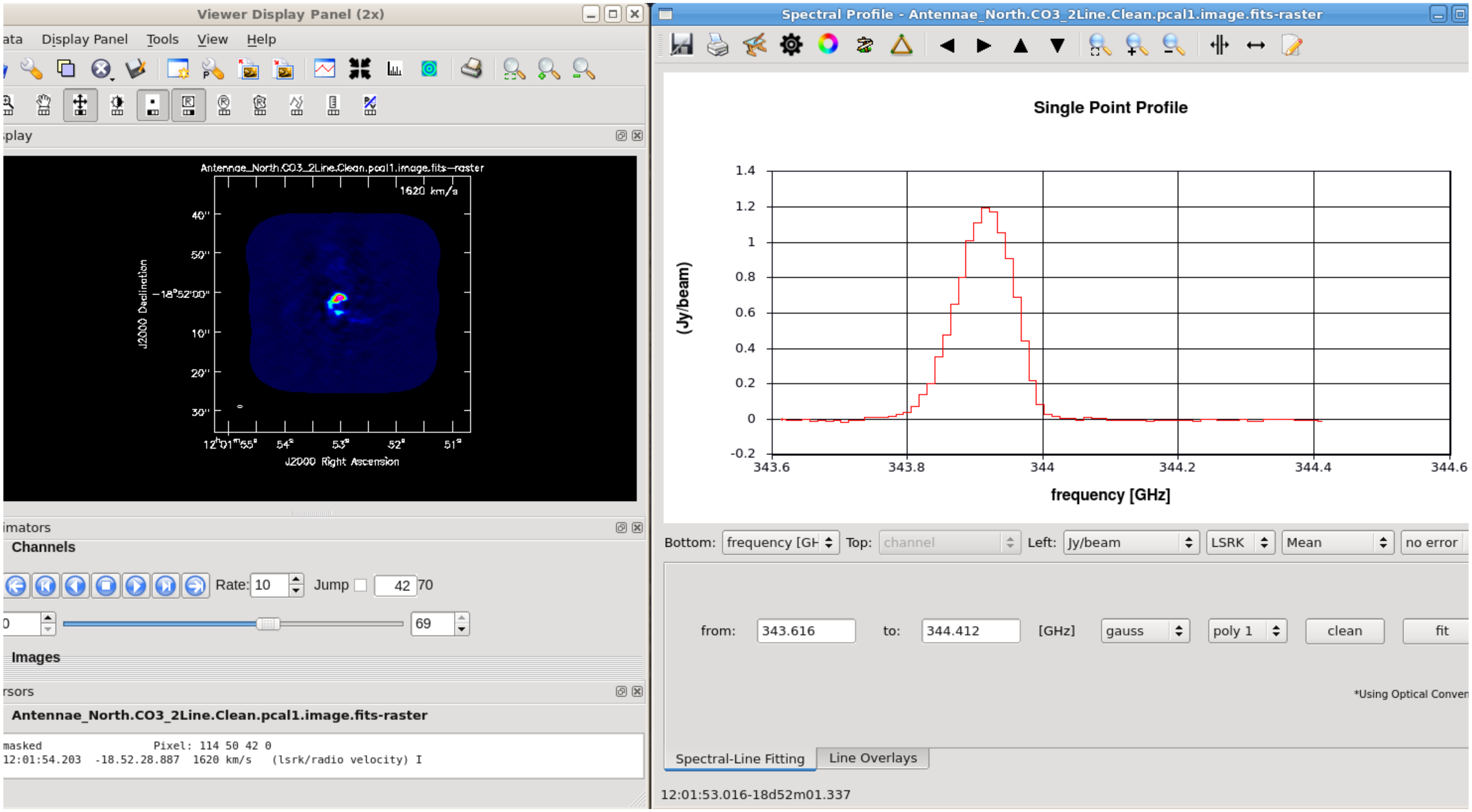
Example: line profiles

- Line profiles show changes in line shape, width and depth as a function of position.



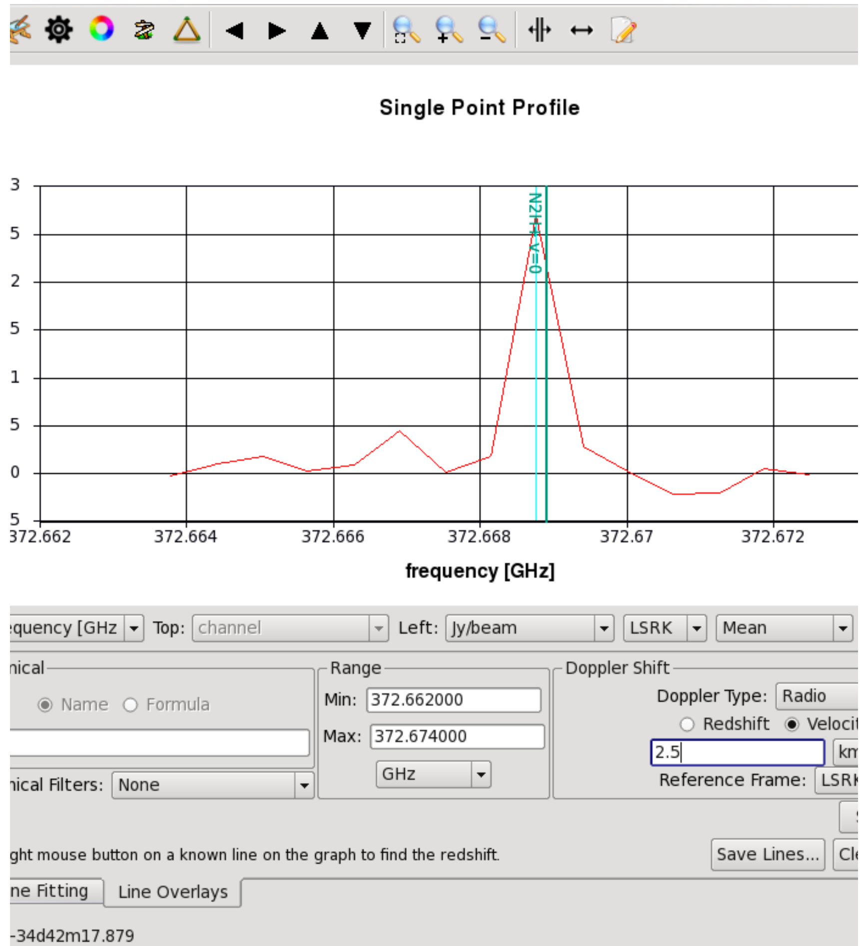
EVN+MERLIN 1667 MHz OH maser emission and absorption spectra in a luminous infrared galaxy (IIIZw35).

Spectral Profiles in CASA



Spectral extraction and line identification

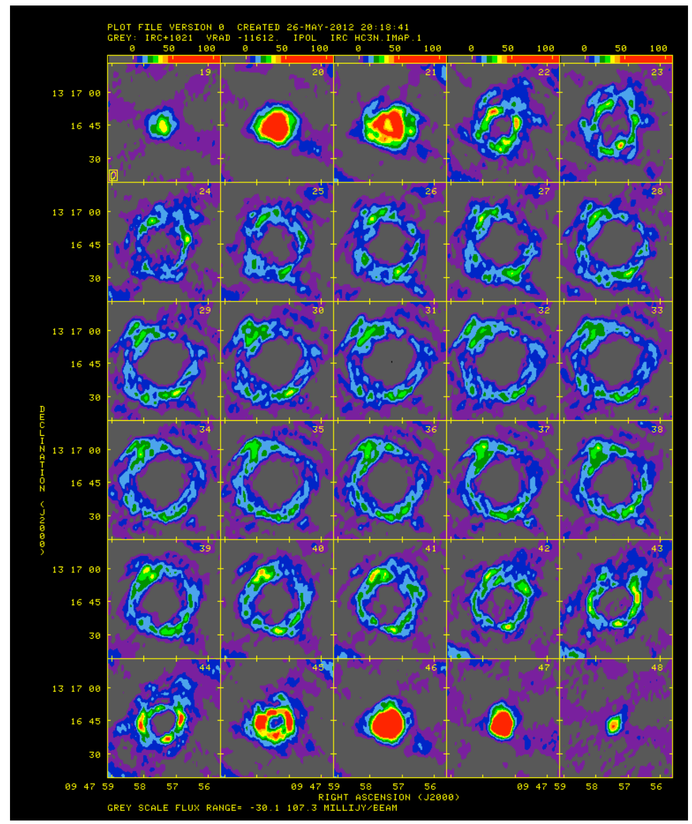
- Can use e.g. the CASA Viewer for line identification with the aid of Splatalogue.
- Can filter by species or common astrophysical lines to avoid getting too many results.
- Often, transitions of interest are in the ground vibrational state (v=0). E.g. CO (1-0) v=0 is the usual 115 GHz line.



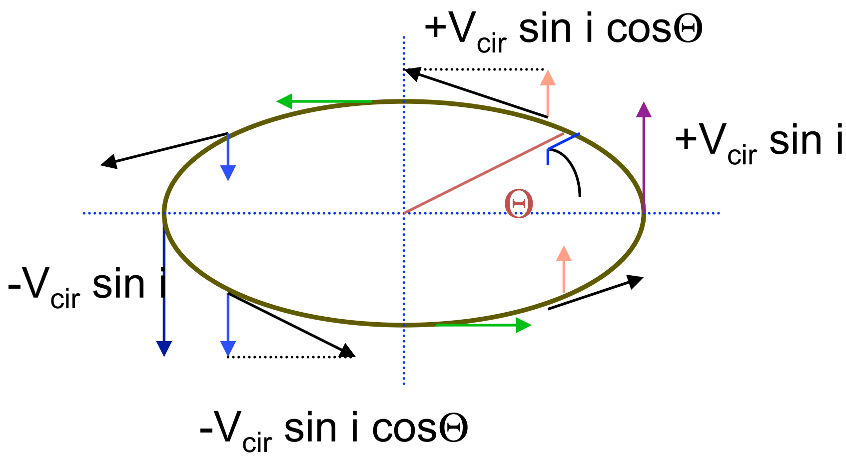
Channel maps give dynamical information

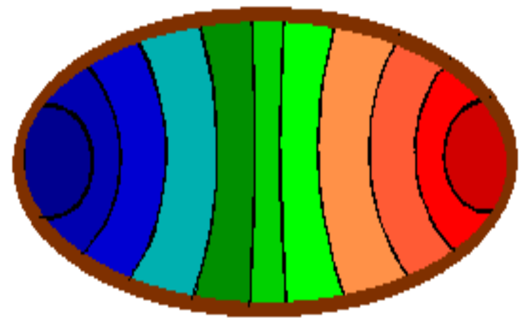
- IRC 10216 is a 16th mag AGB star but brightest star at 5 µm
- Expanding shell is clearly delineated in channel maps showing emission from the linear molecule HC_3N

HC_3N – IRC 10216



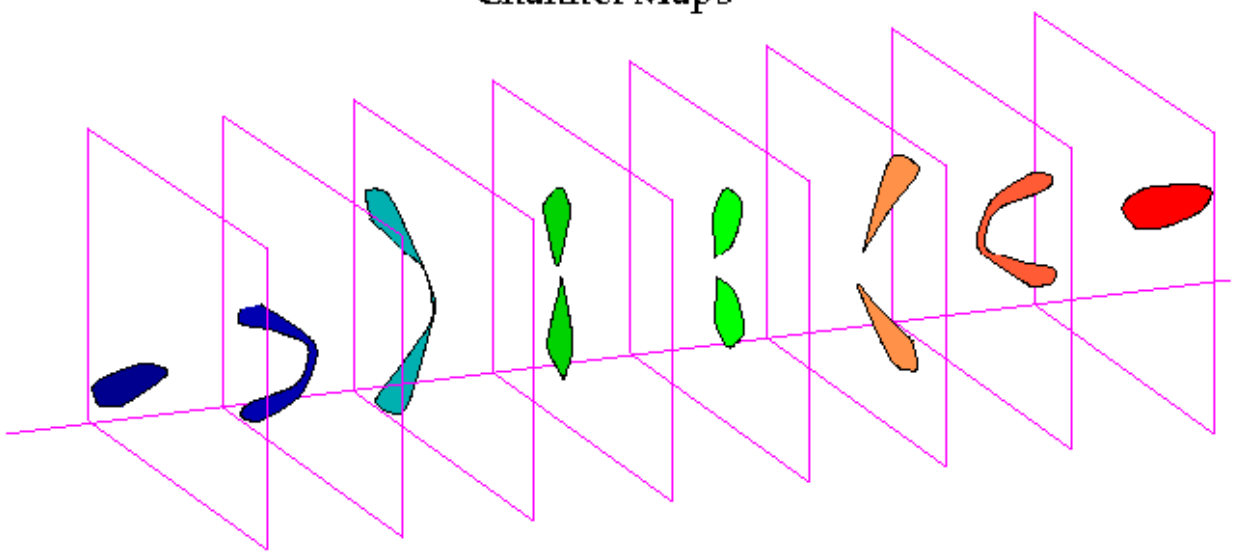
Example: A thin, tilted rotating disk





Mean Velocity Field

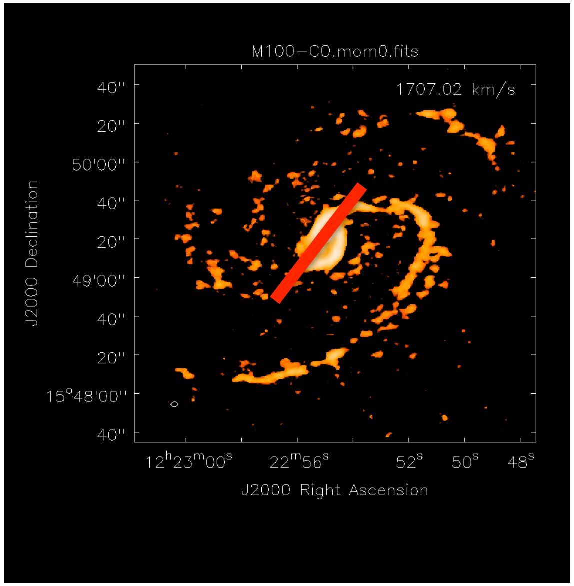
Channel Maps

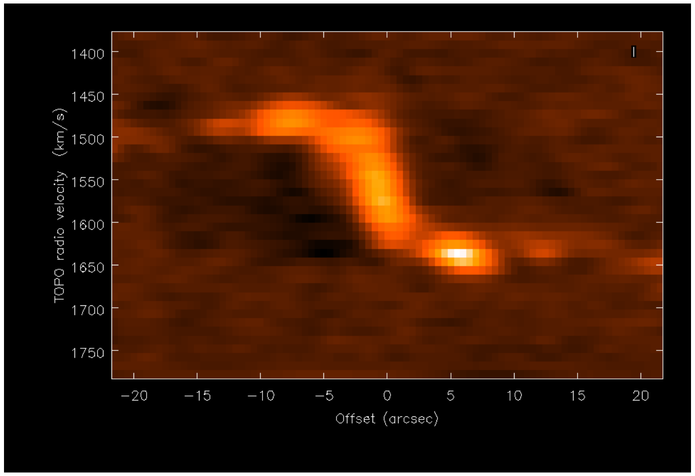


Position-velocity diagrams

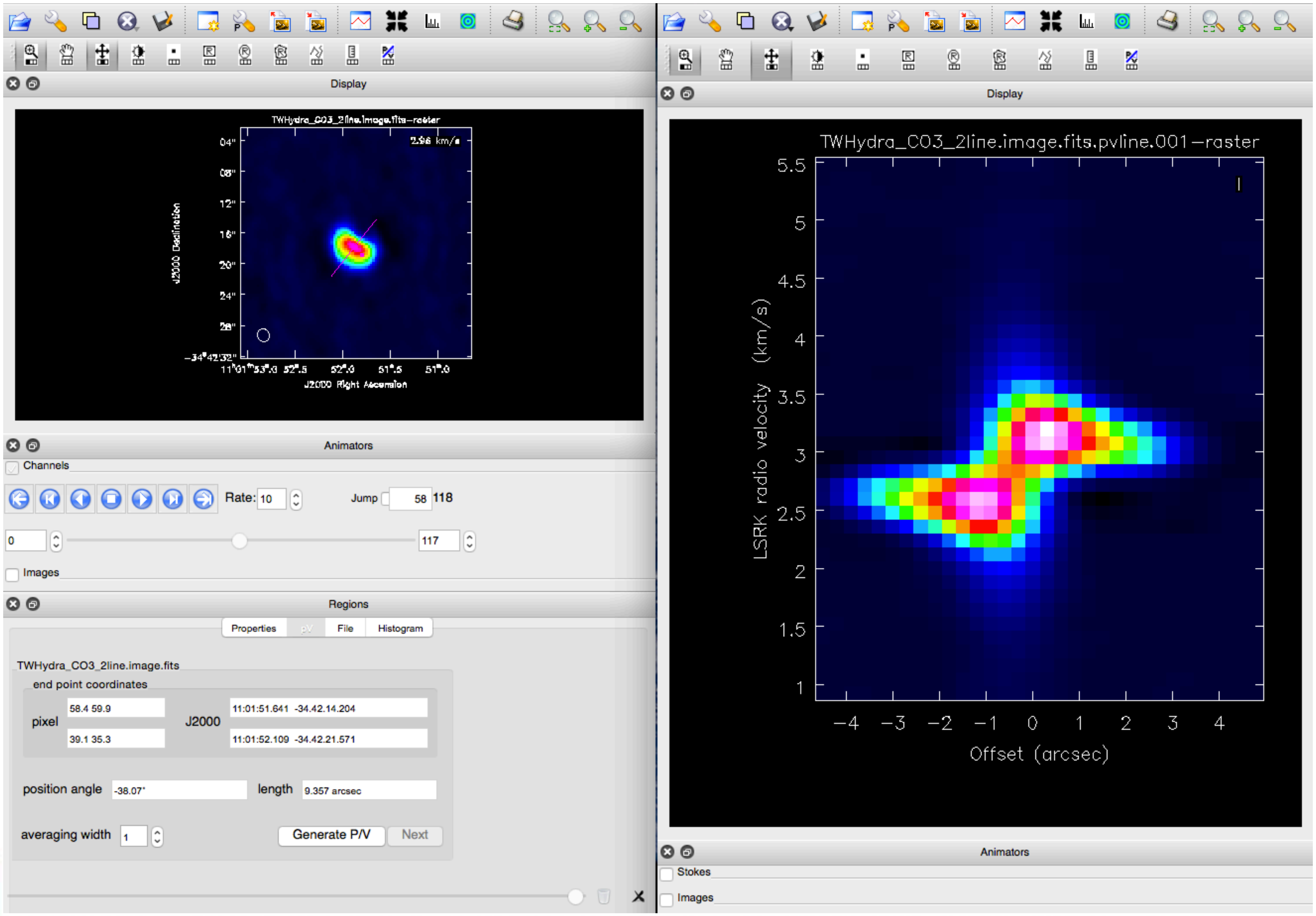
- PV-diagrams show, for example, the line emission velocity as a function of radius.
  - Here along a line through the dynamical center of the galaxy

- CASA task impv, or use the viewer





PV diagrams with the CASA viewer



3D (volume-rendered) visualization

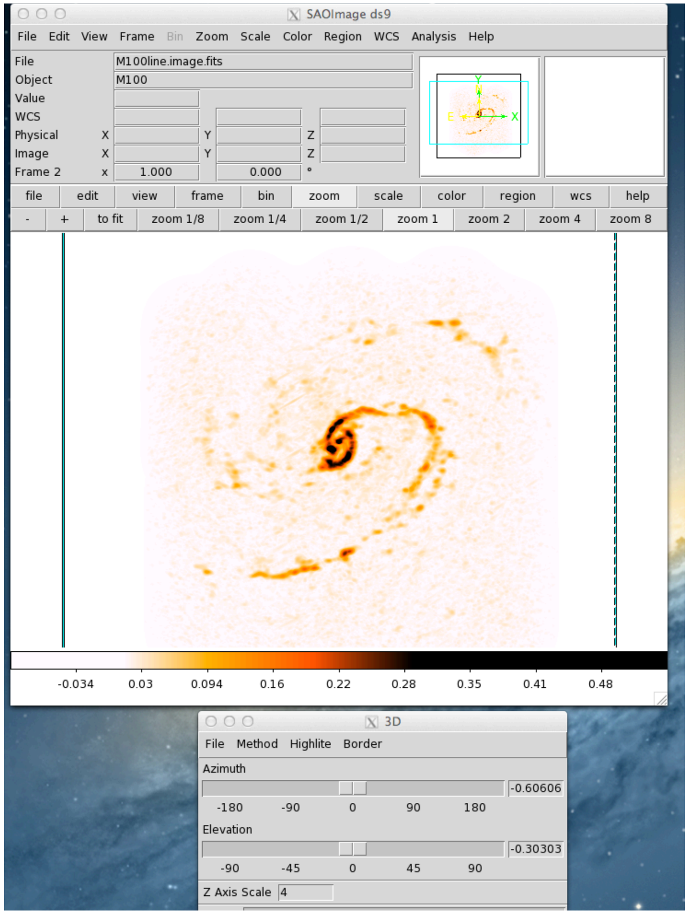
- Some software allows 3D visualization of image cubes.
- Can be useful for inspection of cube, and to find features that conventional moment analyses would miss.
- Can be hard to interpret though – velocity/frequency axis is not a spatial axis.

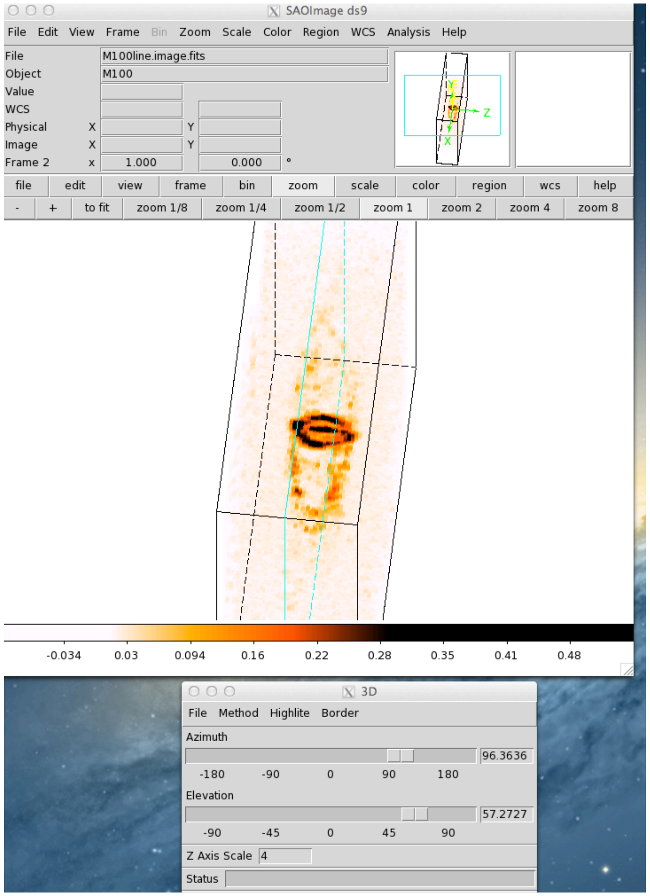
3D display software

- SAOimage ds9 is available from http://ds9.si.edu
- GAIA is available from star-www.dur.ac.uk/~pdraper/gaia/gaia.html (long-term support unclear)
- Karma kvis is available (though no longer updated) from http://www.atnf.csiro.au/computing/software/karma/
- Other, not observational astronomy specific 3D rendering packages are also available (ParaView, VisIt, yt….). Drawback is lack of understanding of astronomical coordinate systems.

SAOimage ds9 renderings of M100

ds9 -3d my_image_cube.fits





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Moment maps

- A popular way of reducing a 3D line to 2D
- Moment 0 : line map
- Moment 1 : velocity map
- Moment 2 : velocity dispersion

- Each higher moment requires better S/N; mask the low S/N
- Higher order moments (skew, kurtosis…) are also defined, but not usually useful

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- Moment 0 (integration of flux density *S* is carried out over the full width of the line profile):

$$\int S \mathrm{d}v$$

- Moment 1 = <v>:

$$\frac{\int vS\mathrm{d}v}{\int S\mathrm{d}v}$$

- Moment 2:

$$\frac{\int (v - <v>)^2 S\mathrm{d}v}{\int S\mathrm{d}v}$$

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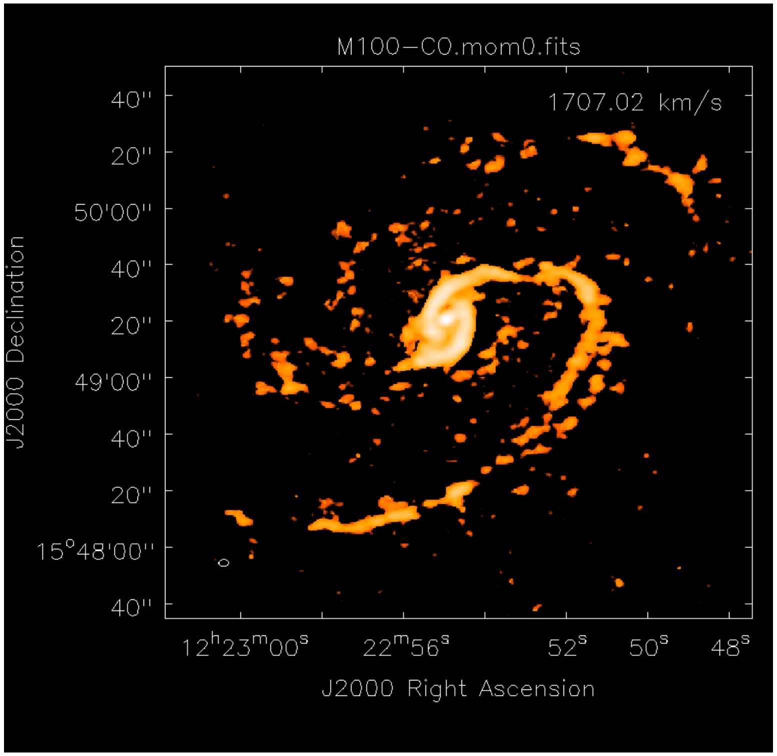
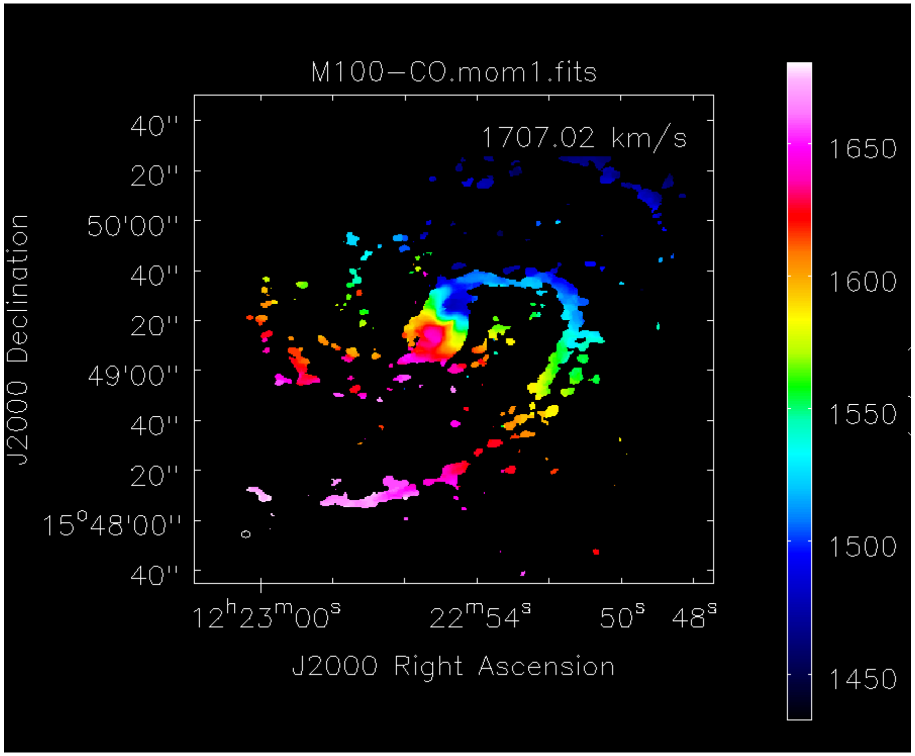
Example moment maps (CO in M100)

Moment 0

Moment 1





Moment maps: caution

- Moment maps should be just one component to an analysis strategy. Use them as a guide for investigating spectral features, or comparing with other λ.

- Moments sensitive to noise so clipping is required
  - Higher order moments depend on lower ones so progressively noisier.
- Hard to interpret correctly:
  - Both emission and absorption may be present, emission may be double peaked.
  - Biased towards regions of high intensity.
  - Complicated error estimates: number or channels with real emission used in moment computation will greatly change across the image.

The End