Analyzing Spectral Cubes

Calibration, Imaging and Analysis

Thirteenth Synthesis Imaging Workshop

2012 May 29– June 5

NRAO

Associated Universities, Inc.

New Mexico Tech
SCIENCE · ENGINEERING · RESEARCH · UNIVERSITY

The University of New Mexico

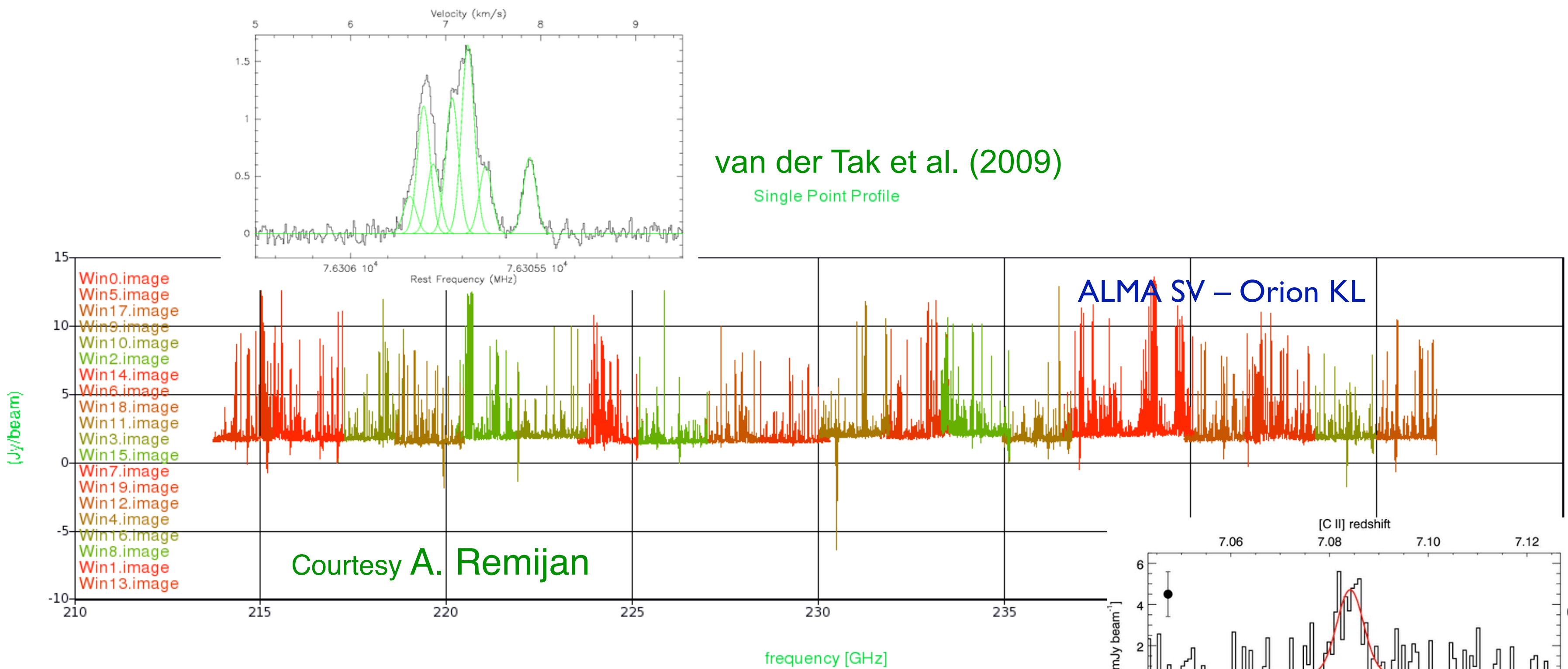
New Mexico CONSORTIUM

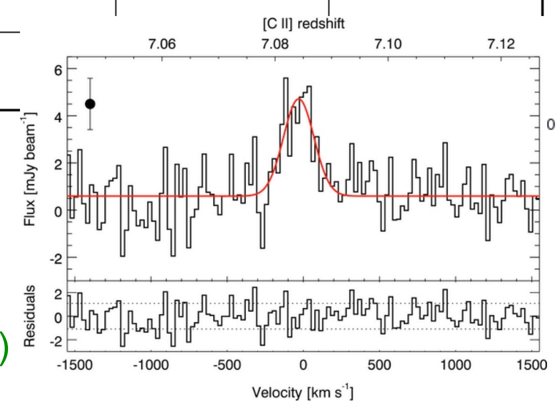
Outline:

- Why spectral line (multi-channel) observing?
  - Not only for spectral lines, but there are many advantages for continuum experiments as well
- Calibration specifics
  - Bandpass, flagging, continuum subtraction
- Imaging of spectral line data
- Visualizing and analyzing cubes

Radio Spectroscopy:

- There is a vast array of spectral lines available, covering a wide range of science.



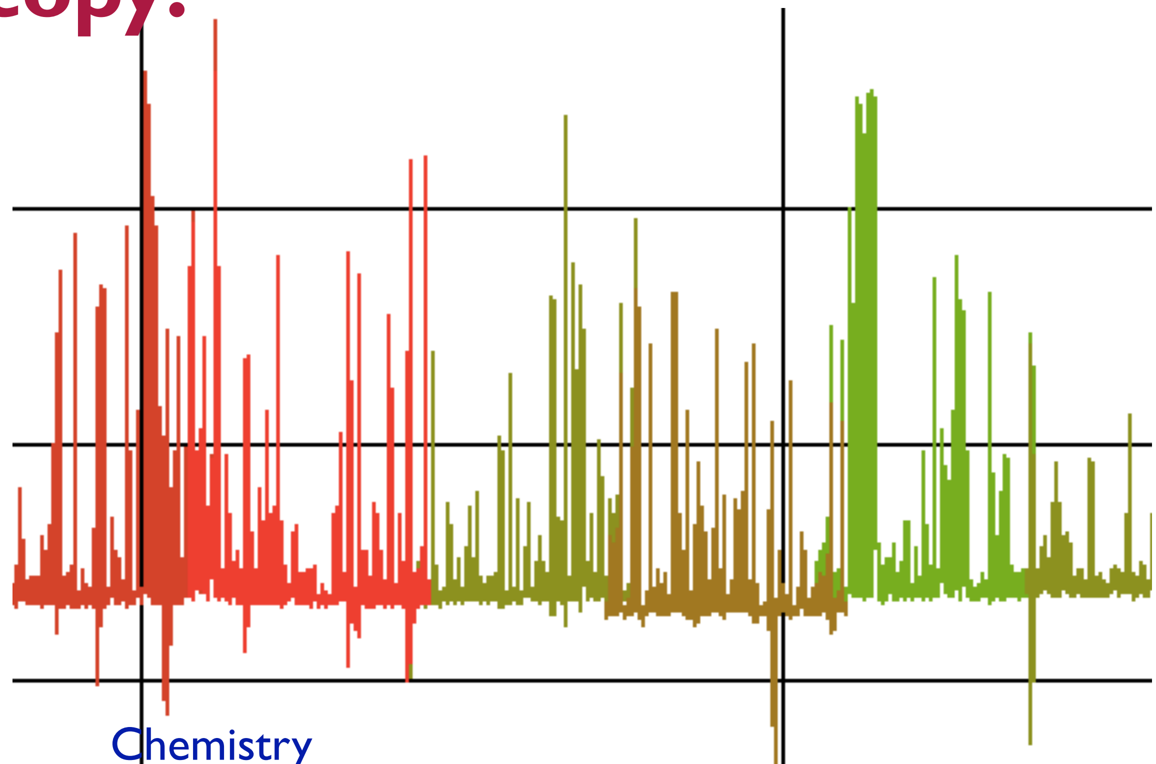


[CII] at a redshift of 7.1

Venemans et al. (2012)

Radio Spectroscopy:

CM lines **Both** **MM lines**



Chemistry

Morphology and Kinematics

Atomic: HI

Molecular: CO, ^{13}CO

Masers OH, H_2O, CH_3OH, SiO

Ionized: H186α – H50α

H42α – H22α

Dense Molecular Gas

HCN, HNC, HCO^+, CS, NH_3, HC_3N

PDRs

CH, CN, CCH, c-C_3H_2

Shocks & Outflows

SiO, CH_3OH, HNCO, H_2S

Hot Cores

CH_3CN, 'big floppy things'

- http://www.physics.nmt.edu/Department/homedirlinks/dmeier/echemprimer/

Introduction:

Spectral line observers use many channels of width $\delta\nu$, over a total bandwidth $\Delta\nu$. Why?

- Science driven: science depends on frequency (spectroscopy)
  - Emission and absorption lines, and their Doppler shifts
  - Ideally we would like $\delta v < 1$ km/s over bandwidths of several GHz which requires *thousand and thousands* of channels
    - ALMA multiple lines: over 8 GHz, < 1km/s resolution~1 MHz $\Rightarrow$ >8,000 channels
    - EVLA HI absorption: 1-1.4 GHz, < 1km/s resolution ~4 kHz $\Rightarrow$ >100,000 channels

Introduction:

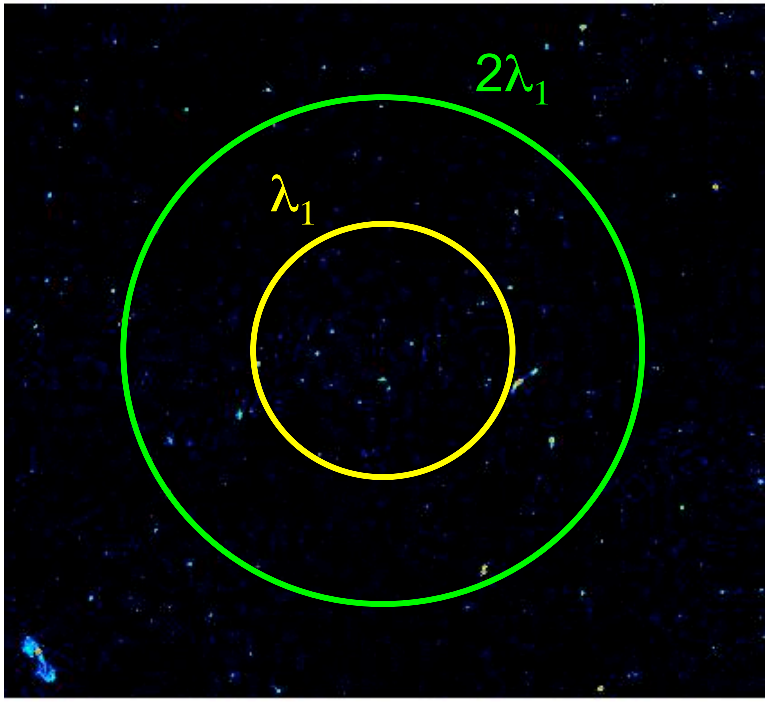
- Science driven: science depends on frequency (pseudo-continuum).
- Want maximum bandwidth for sensitivity [Thermal noise $\propto 1/\mathrm{sqrt}(\Delta\nu)$]
  - BUT achieving this sensitivity also requires high spectral resolution:
    - Source contains continuum emission with a significant spectral slope across $\Delta\nu$
    - Contaminating narrowband emission:
      - line emission from the source
      - RFI (radio frequency interference)
    - Changes in the instrument with frequency
    - Changes in the atmosphere with frequency
- Technical reasons: science does not depend on frequency (pseudo-continuum) – particularly in the era of wide-band datasets
  - Changing primary beam with frequency
  - Limitations of bandwidth smearing

Effects of Broad Bandwidth:

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

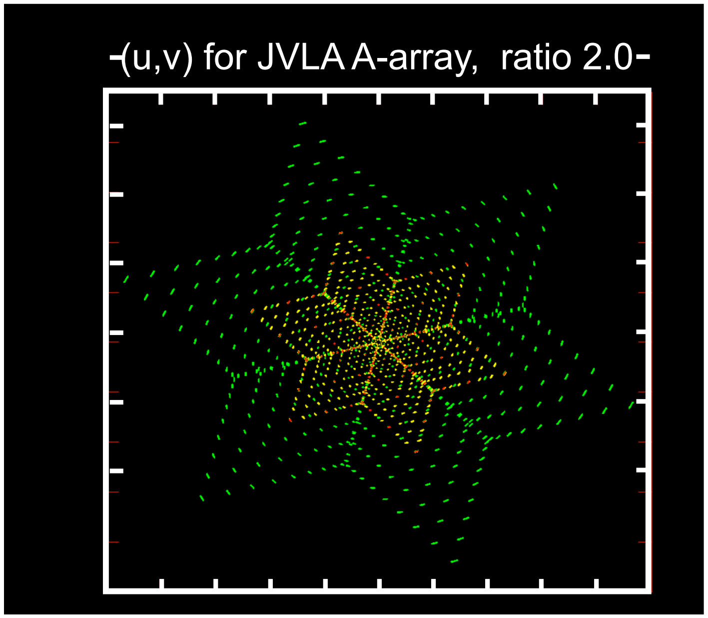
  $\Rightarrow$ θ_{PB} changes by λ_1/λ_2

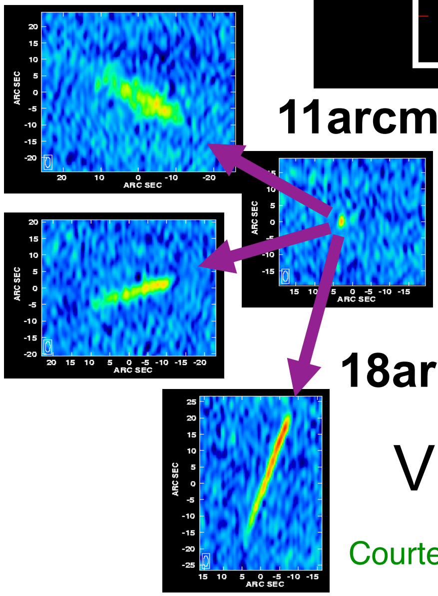
  - More important at longer wavelengths:
    - VLA 20 cm: 1.03 ; 2 cm: 1.003
    - JVLA 20 cm: 2.0 ; 2 cm: 1.5
    - ALMA 1mm: 1.03



Effects of Broad Bandwidth:

- 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 JVLA
  - Multi-frequency synthesis





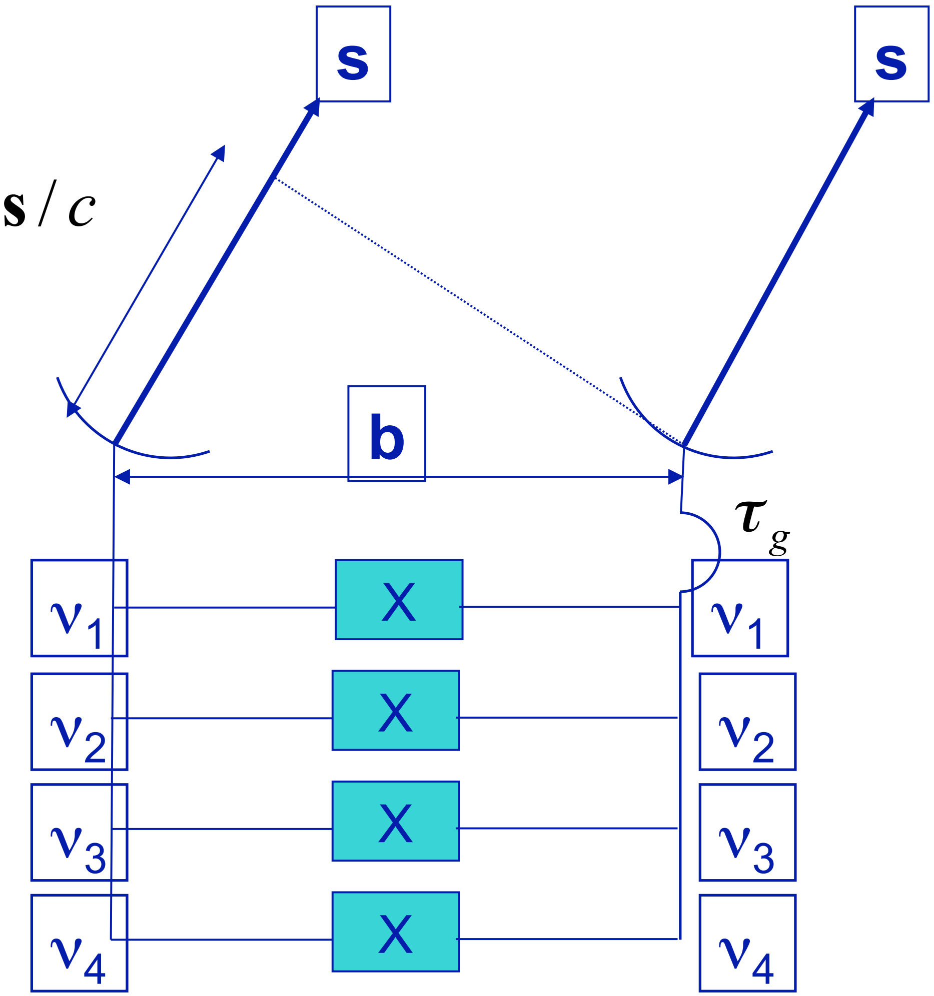
VLA-A 6cm: 1.01

Courtesy C. Chandler

Spectroscopy with Interferometers (Simple):

- Simplest concept: filter banks

$$\tau_g = \mathbf{b} \cdot \mathbf{s} / c$$



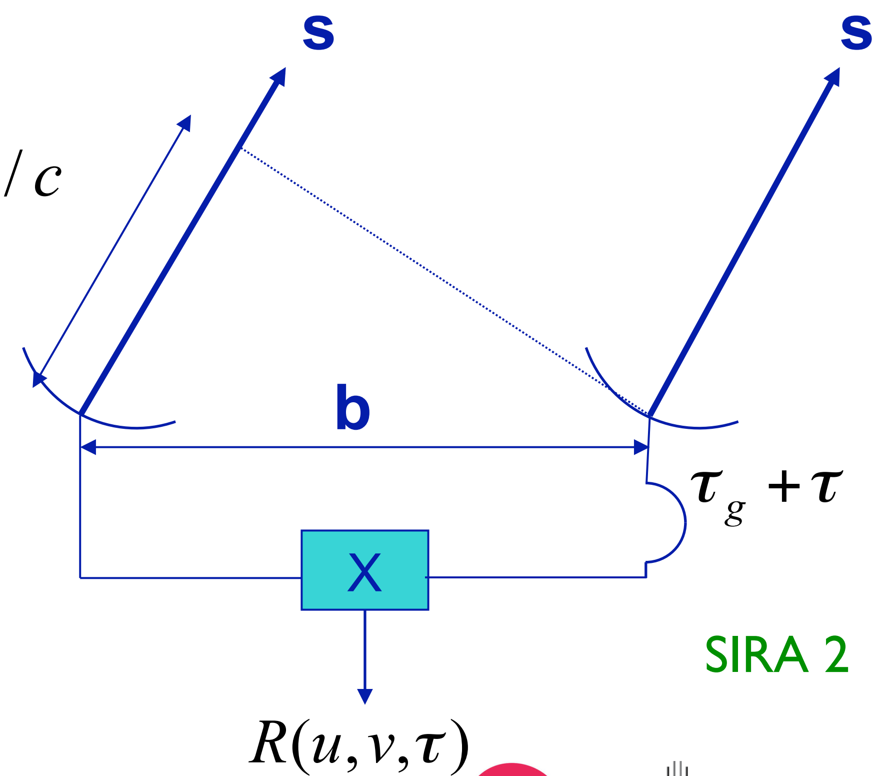
- Output from correlator is $r(u,v,\nu)$
- Very limited in its capabilities scientifically

Spectroscopy with Interferometers (Lag):

- Lag (XF) correlator: introduce extra lag τ and measure correlation function for many (positive and negative) lags; FT to give spectrum

$$\tau_g = \mathbf{b}\cdot\mathbf{s}/c$$

$$r(u,v,\nu) = \int_{-\infty}^{+\infty} R(u,v,\tau)\exp(-2\pi i\nu\tau)\,d\tau$$



SIRA 2

Spectroscopy with Interferometers (Lag):

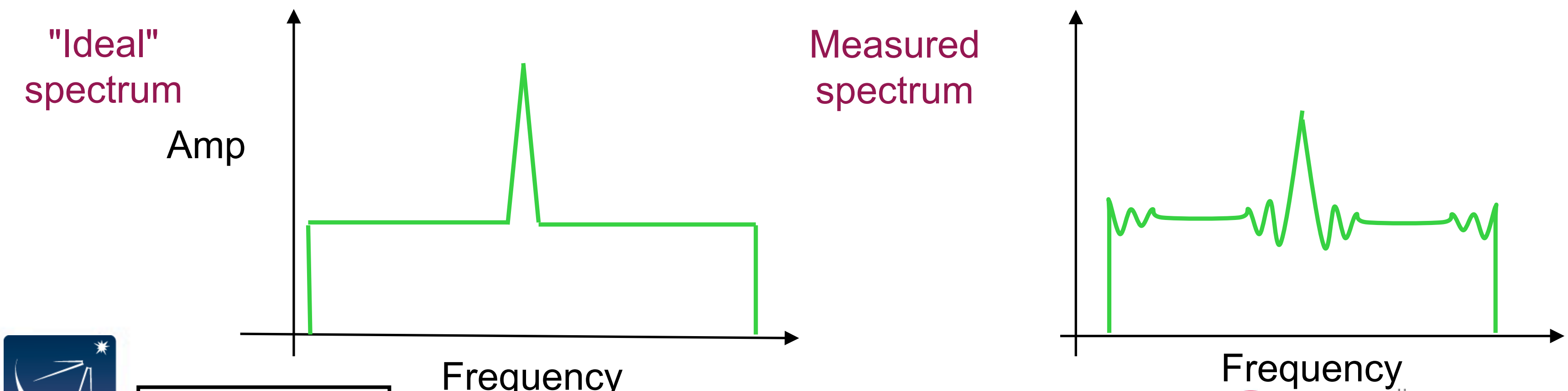
- In practice, measure a finite number of lags, at some fixed lag interval, $\Delta\tau$
- Total frequency bandwidth = $1/(2\Delta\tau)$
- For N spectral channels have to measure 2N lags (positive and negative), from $-N\Delta\tau$ to $+(N-1)\Delta\tau$ (zero lag included)
- Spectral resolution $\delta\nu = 1/(2N\Delta\tau)$ (Nyquist)
- Note: equal spacing in frequency, not velocity
- Very flexible: can adjust N and $\Delta\tau$ to suit your science

Gibbs Ringing:

- For spectroscopy in an XF correlator (EVLA) lags are introduced
  - The correlation function is measured for a large number of lags.
  - The FFT gives the spectrum.

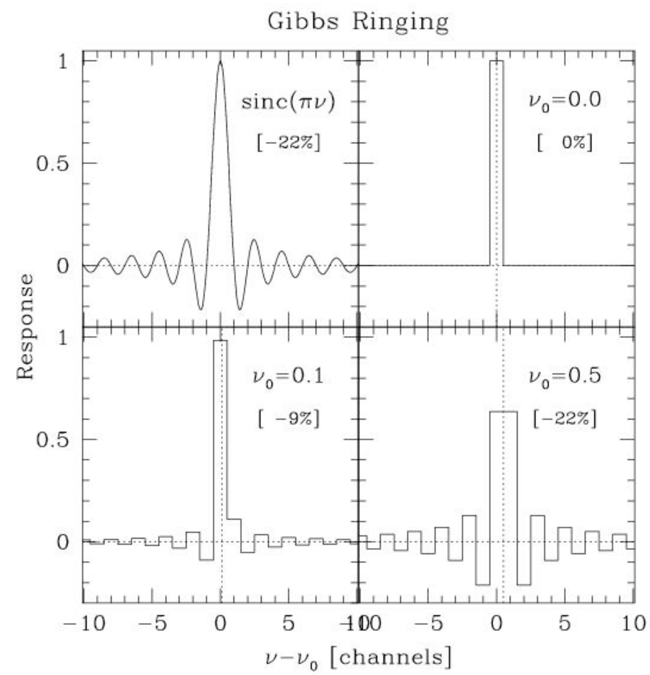
- We don't have an infinite amount of time, so we don't measure an infinite number of Fourier components.

- A finite number or lags means a truncated lag spectrum, which corresponds to multiplying the true spectrum by a box function.
  - The spectral response is the FT of the box, which for an XF correlator is a sinc(πx) function with nulls spaced by the channel separation: 22% sidelobes!



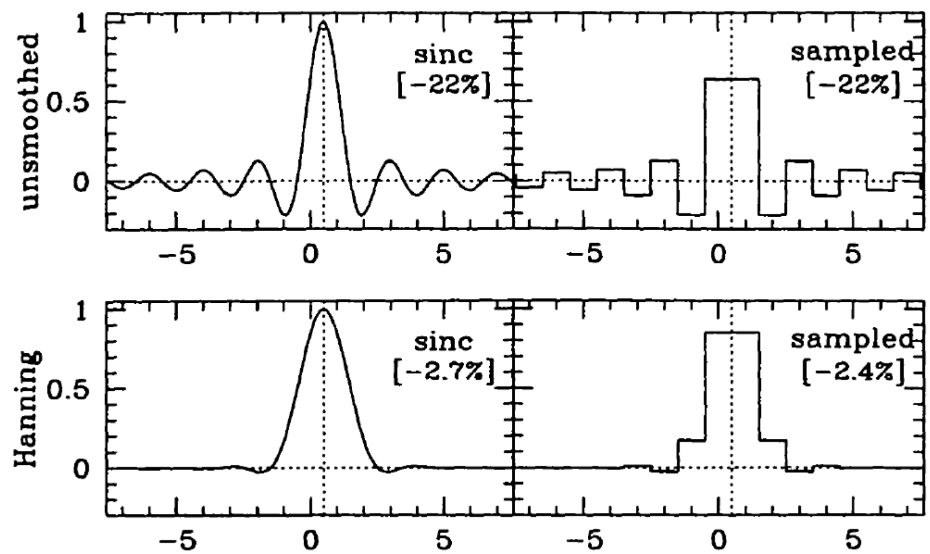
Gibbs Ringing (Cont.):

Sampled:



- Increase the number of lags, or channels.
  - Oscillations reduce to ~2% at channel 20, so discard affected channels.
  - Works for band-edges, but not for spectral features.
- Smooth the data in frequency (i.e., taper the lag spectrum)
  - Usually Hanning smoothing is applied, reducing sidelobes to <3%.

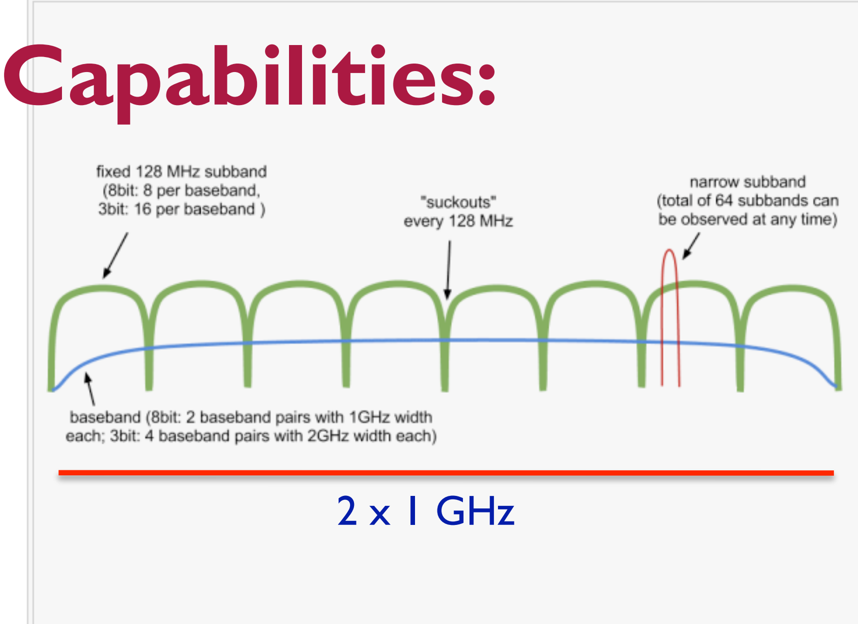
$$S_h(\nu_i) = \frac{S(\nu_{i-1}) + 2S(\nu_i) + S(\nu_{i+1})}{4}$$



SIRA 2

JVLA Spectral Line Capabilities:

- 2 x 1 GHz basebands
- 16 tunable subbands per baseband (except avoid suckouts) with between 0.03125 – 128 MHz
- Dual polarization: Up to 2000 channels per subband (up to 16,384 per baseband)
  - But data rate limitations



WIDAR correlator baseband with subbands

- Dual Polarization

Sub-band BW (MHz)	Number of channels/poln product	Channel width (kHz)	Channel width (km/s at 1 GHz)	Total velocity coverage (km/s at 1 GHz)
128	128	1000	300/ν(GHz)	38,400/ν(GHz)
64	128	500	150	19,200
32	128	250	75	9,600
16	128	125	37.5	4,800
8	128	62.5	19	2,400
4	128	31.25	9.4	1,200
2	128	15.625	4.7	600
1	128	7.813	2.3	300
0.5	128	3.906	1.2	150
0.25	128	1.953	0.59	75
0.125	128	0.977	0.29	37.5
0.0625	128	0.488	0.15	18.75
0.03125	128	0.244	0.073	9.375

Up to 2000

ALMA Spectral Line Capabilities:

- Summary (Cycle 0):
  - Band 3,7 (6): 2 x 4(5) GHz sidebands, separated by 8 (10) GHz
  - 4 x 2 GHz basebands, with 0,2,4 distributed per sideband
  - 1 Spectral Windows per baseband, for a total of up to 4
  - For dual polarization, bandwidths of each spectral window range from 0.0586 – 2 GHz
  - For dual polarization spectral resolution ranges from 0.0306 MHz – 0.976 MHz
  - Single polarization: you can get ~7.5 GHz simultaneously at ≤1.5 km/s

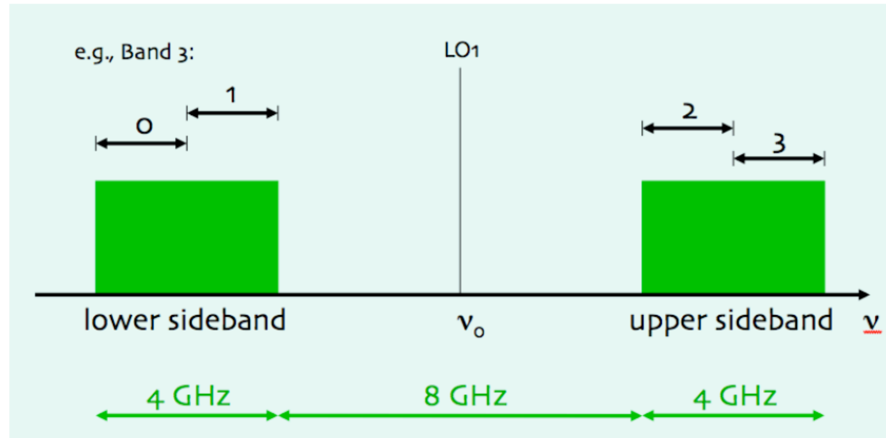


Figure 34: *A graphical view of basebands and sidebands.*

ALMA *Early Science* Correlator Modes

Mode	Polarization	Bandwidth per baseband (MHz)	Nchan	Spacing (MHz)	Mode	Polarization	Bandwidth per baseband (MHz)	Nchan	Spacing (MHz)
1	Single	1875	7680	0.244	7	Dual	1875	3840	0.488
2	Single	938	7680	0.122	8	Dual	938	3840	0.244
3	Single	469	7680	0.061	9	Dual	469	3840	0.122
4	Single	234	7680	0.0305	10	Dual	234	3840	0.061
5	Single	117	7680	0.0153	11	Dual	117	3840	0.0305
6	Single	58.6	7680	0.00763	12	Dual	58.6	3840	0.0153
71	Single	2000‡	256	7.8125	69	Dual	2000‡	128	15.625

Note that the velocity resolution will be 2 x spacing due to a default Hanning filter applied to the data. Up to 4 basebands will be available. Mixed band modes will not be possible during *Early Science*.

‡*Note: Because of an anti-aliasing filter, the useful (effective) bandwidth of this mode is 1.875GHz.*

Calibration:

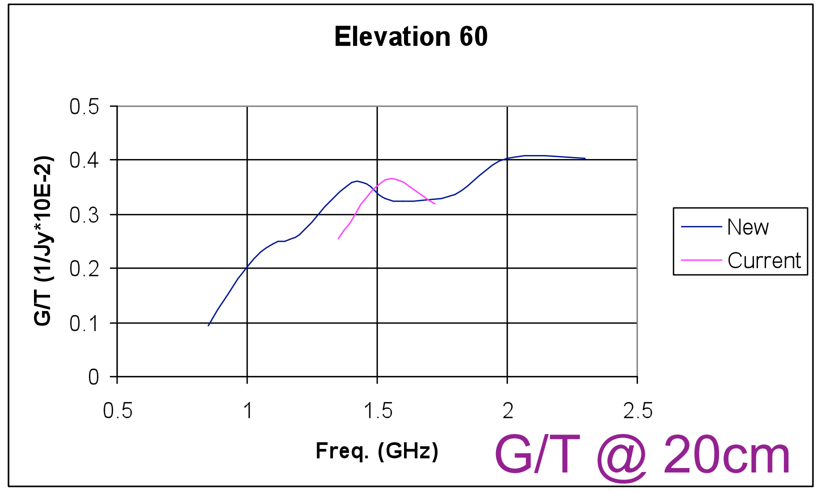
- Data editing and calibration is not fundamentally different from continuum observations, but a few additional items to consider:
  - Bandpass calibration
  - Presence of RFI (data flagging)
  - Doppler corrections

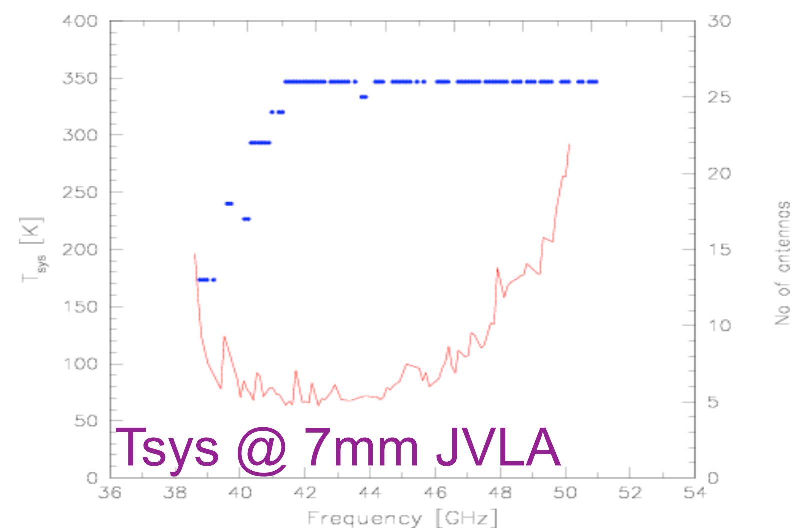
Calibration - Bandpass:

- We need the total response of the instrument to determine the true visibilities from the observed visibilities:

$$^{obs}V_{ij}(t,\nu) = G_{ij}(t,\nu)\, V_{ij}(t,\nu)$$

- The bandpass shape is a function of frequency, and is mostly due to electronics of individual antennas.
    - Atmosphere
    - Front end system
    - Cables
    - Inacurate clocks and antenna positions
    - Gibbs Phenomena
    - But typically not standing waves





Calibration - Bandpass (cont.):

- Usually varies slowly with time, so we can break the complex gain $G_{ij}(t)$ into a fast varying frequency independent part, $G'_{ij}(t)$ and a slowly varying frequency dependent part, $B_{ij}(t,\nu)$.

$$G_{ij}(t,\nu) = G'_{ij}(t)\, B_{ij}(t,\nu)$$

- The demands on $B_{ij}(t)$ are different from those of $G'_{ij}(t,\nu)$.
  - $G'_{ij}(t)$: point source, near science target
  - $B_{ij}(t,\nu)$: very bright source, no spectral structure, does not need to be a point source (though preferable).
- Observe a bright calibrator with the above properties at least once during an observation
  - Sometimes a noise source is used to BP, especially at high frequencies and when channels are very narrow
    - Still observe a BP calibrator
- Bij(t,ν) can often be solved on an antenna basis: $B_{ij}(t,\nu) = b_i(t,\nu)b_j^*(t,\nu)$
  - Computationally less expensive
  - Solutions can be found for antennas even with missing baselines

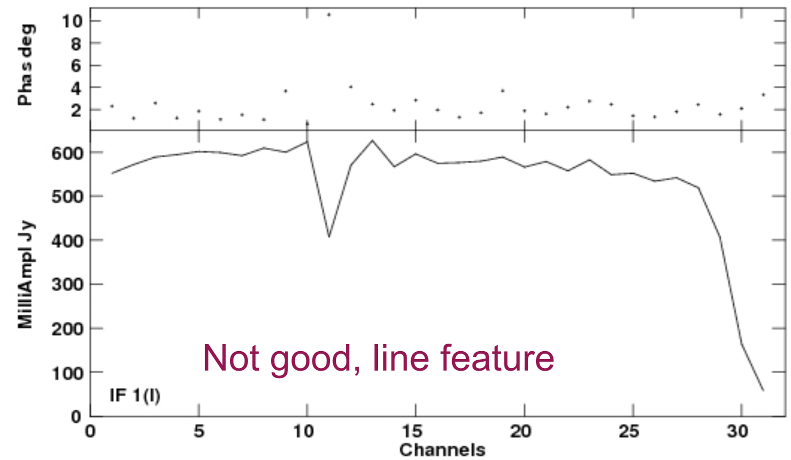
Calibration - Bandpass (Issues):

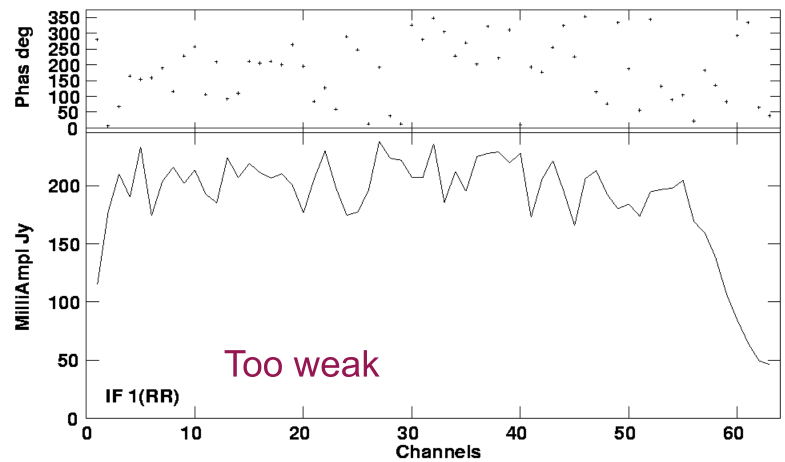
- Important to be able to detect and analyze spectral features:
  - Frequency dependent phase errors can lead to spatial offsets between spectral features, imitating Doppler motions.
    - *Rule of thumb*: $\theta/\theta_B \cong \Delta\phi/360°$
  - Frequency dependent amplitude errors can imitate changes in line structures.
    - Need to spend enough time on the BP calibrator so that $SNR_{BPcal} >> SNR_{target}$.
      - *Rule of thumb:* $t_{BPcal} > 9\times(S_{target}/S_{BPcal})^2\, t_{target}$
      - When observing faint lines superimposed on bright continuum more stringent bandpass calibration is needed.
        - » SNR on continuum limits the SNR achieved for the line

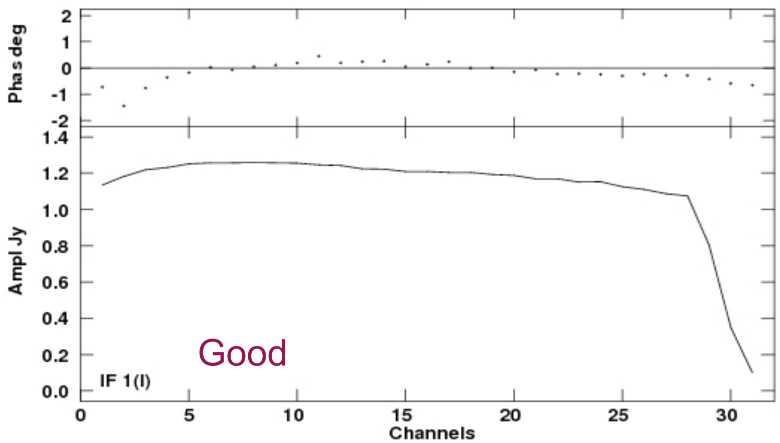
- For pseudo-continuum, the dynamic range of final image is limited by the bandpass quality.

Calibration - Bandpass:

- Solutions should look comparable for all antennas.
- Mean amplitude ~1 across useable portion of the band.
- No sharp variations in amplitude and phase; variations are not dominated by noise.

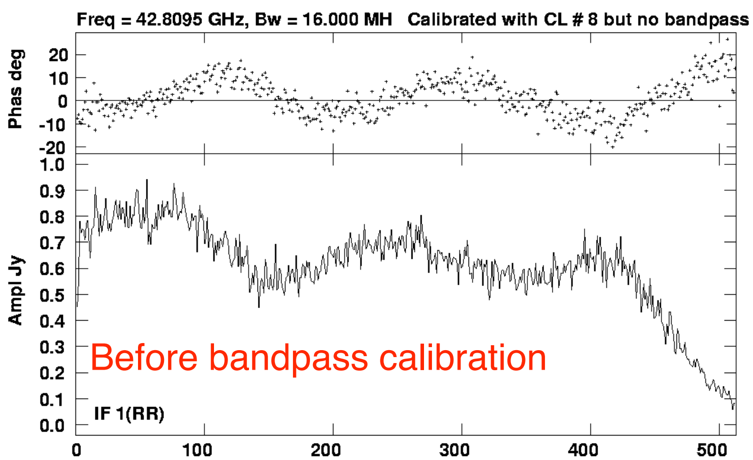


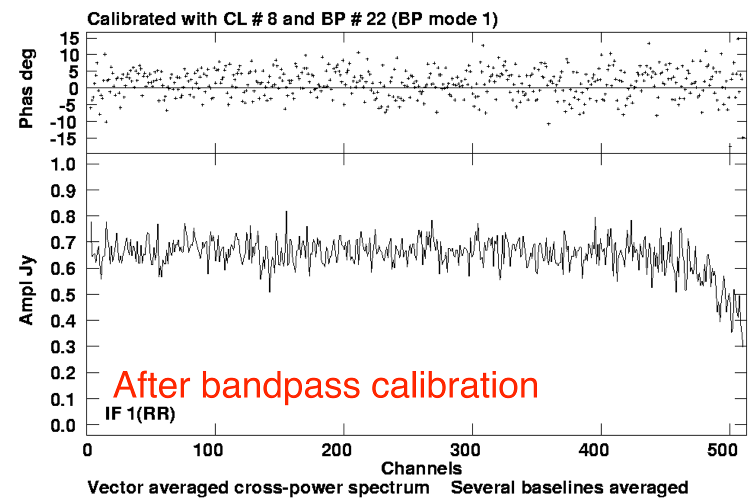




Calibration - Bandpass:

- Always check BP solutions: apply to a continuum source and use cross-correlation spectrum to check:
  - That phases are flat
  - That amplitudes are constant across band (continuum)
  - Absolute fluxes are reasonable
  - That the noise is not increased by applying the BP





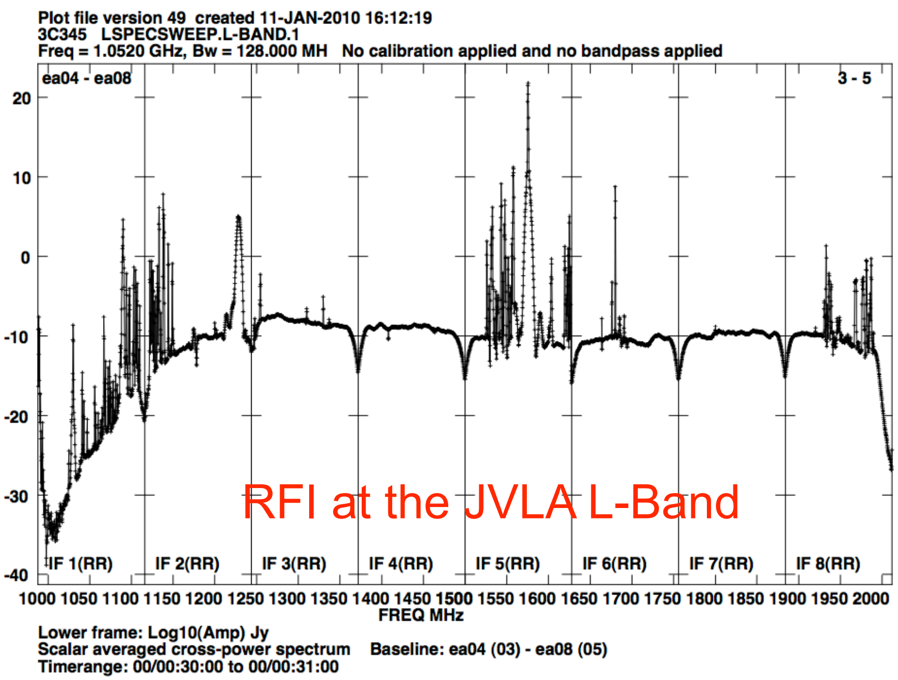
Courtesy L. Matthews

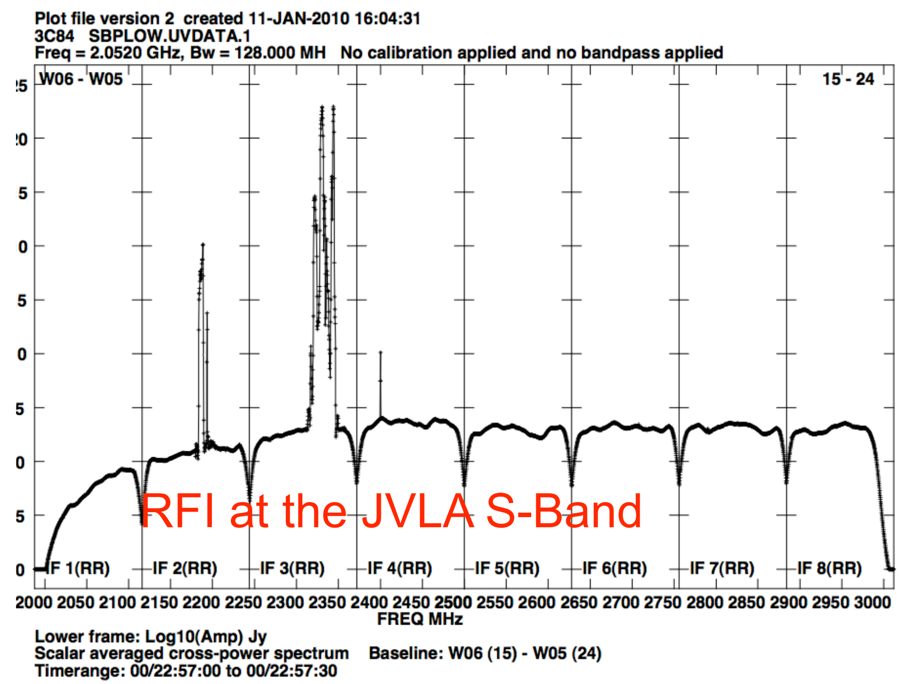
Calibration:

- Data editing and calibration is not fundamentally different from continuum observations, but a few additional items to consider:
  - Bandpass calibration
  - Presence of RFI (data flagging)
  - Doppler corrections
  - Correlator setup

Flagging Spectral Line Data (RFI):

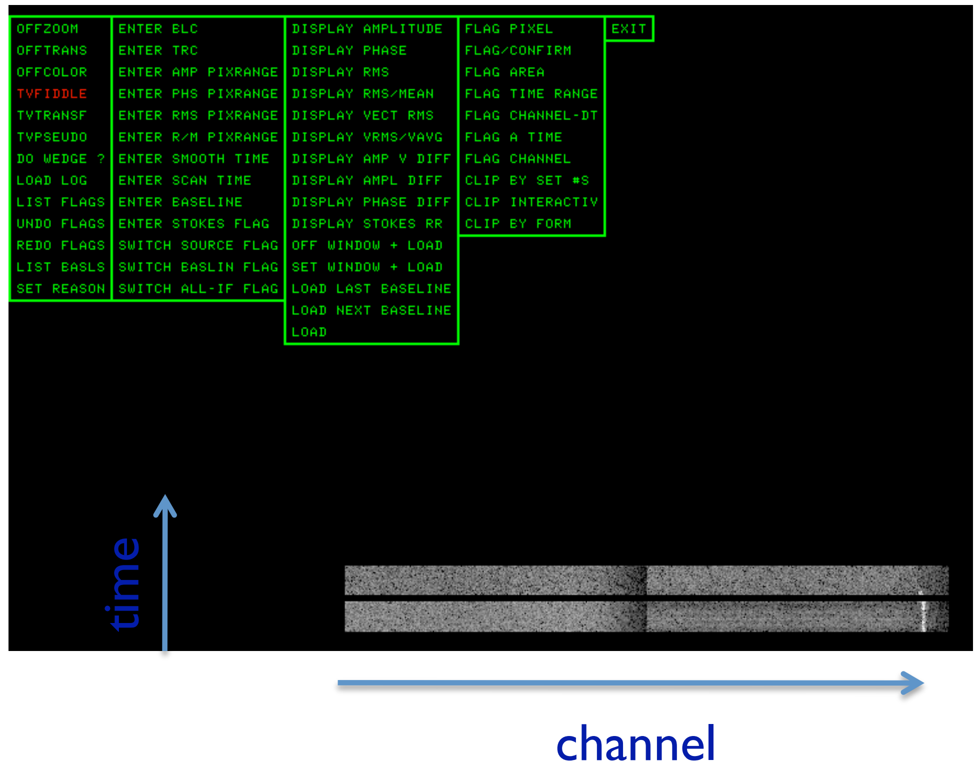
- Primarily a low frequency problem (for now)
- Avoid known RFI if possible, e.g. by constraining your bandwidth (if you can)
- Use RFI plots posted online for JVLA & VLBA





Flagging Spectral Line Data:

- Start with identifying problems affecting all channels, but using a frequency averaged 'channel 0' data set.
  - Has better signal-to-noise ratio (SNR)
  - Copy flag table to the line data
- Continue checking the line data for narrow-band RFI that may not show up in averaged data.
  - Channel by channel is very impractical, instead identify features by using cross- and total power spectra (POSSM)
  - Avoid extensive channel by channel editing because it introduces variable (u,v) coverage and noise properties between channels (AIPS: SPFLG, CASA:MSVIEW)



Calibration:

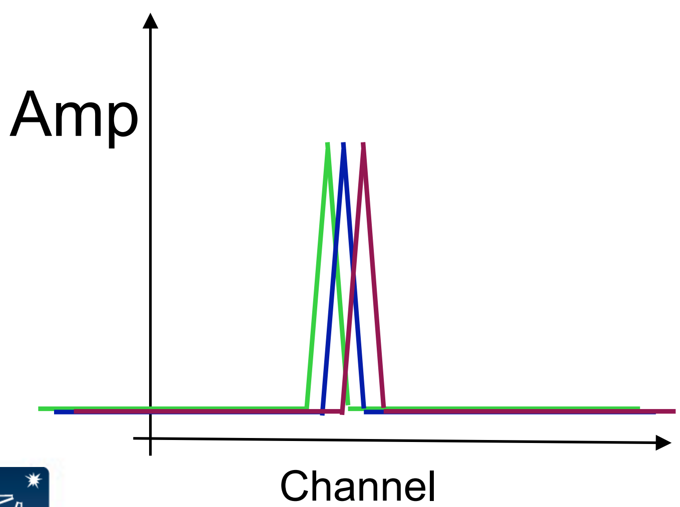
- Data editing and calibration is not fundamentally different from continuum observations, but a few additional items to consider:
  - Bandpass calibration
  - Presence of RFI (data flagging)
  - Doppler corrections

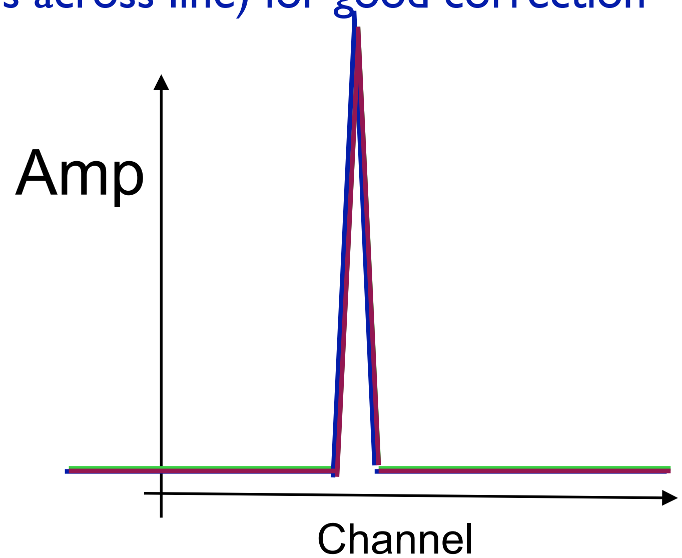
Doppler Tracking:

- Observing from the surface of the Earth, our velocity with respect to astronomical sources is not constant in time or direction.
- Doppler tracking can be applied in real time to track a spectral line in a given reference frame, and for a given velocity definition:
  - $V_{rad} = c\ (\nu_{rest} - \nu_{obs})/\nu_{rest}$ (approximations to relativistic formulas)
  - $V_{opt} = c\ (\nu_{rest} - \nu_{obs})/\nu_{obs} = cz$
    - Differences become large as redshift increases
    - For the V_{opt} definition, constant frequency increment channels do not correspond to constant velocities increment channels

Doppler Tracking:

- 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 large, apply corrections during post-processing instead.
  - With wider bandwidths are now common (JVLA, SMA, ALMA) online Doppler setting is done but not tracking (tracking only correct for a single frequency).
- Doppler tracking is done in post-processing (AIPS/CASA: CVEL/CLEAN)
  - Want well resolved lines (>4 channels across line) for good correction





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
Sun/planets barycenter	< 0.012 km/s	SS Barycentric (~Heliocentric)
Sun peculiar motion	< 20 km/s	Local Standard of Rest
Galactic rotation	< 300 km/s	Galactocentric

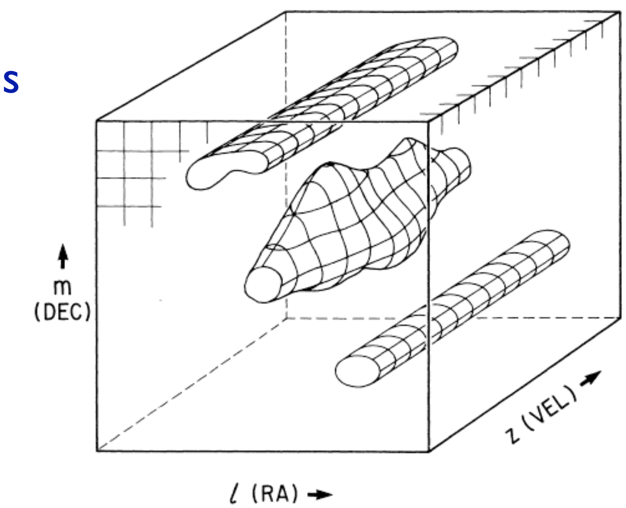
Start with the topocentric frame, the successively transform to other frames. Transformations standardized by IAU.

Imaging:

- We have edited the data, and performed bandpass calibration. Also, we have done Doppler corrections if necessary.
- Before imaging a few things can be done to improve the quality of your spectral line data
  - Image the continuum in the source, and perform a self-calibration. Apply to the line data:
    - Get good positions of line features relative to continuum
    - Can also use a bright spectral feature, like a maser
  - For line analysis we want to remove the continuum

Continuum Subtraction:

- Spectral line data often contains continuum emission, either from the target or from nearby sources in the field of view.
  - This emission complicates the detection and analysis of lines
    - Easier to compare the line emission between channels with continuum removed.
- Use channels with no line features to model the continuum
  - Subtract this continuum model from all channels
- Always bandpass calibrate before continuum subtracting
- Deconvolution is non-linear: can give different results for different channels since *u,v* - coverage and noise differs
  - results usually better if line is deconvolved separately
- Continuum subtraction changes the noise properties of the channels

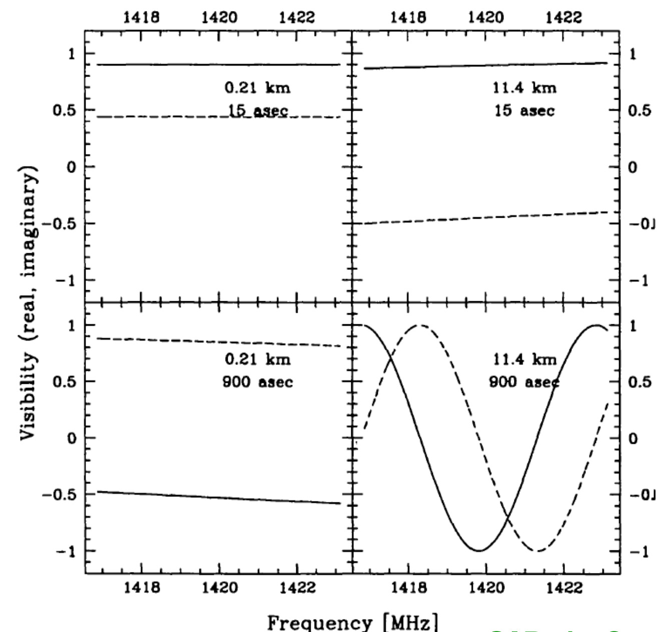


Roelfsma 1989

Spectral line cube with two continuum sources (structure independent of frequency) and one spectral line source.

Continuum Subtraction (UVLIN):

- A low order polynomial is fit to a group of line free channels in each visibility spectrum, the polynomial is then subtracted from whole spectrum.
- Advantages:
  - Fast, easy, robust
  - Corrects for spectral index across spectrum
  - Can do flagging automatically (based on residuals on baselines)
  - Can produce a continuum data set
- Restrictions:
  - Fitted channels should be line free (a visibility contains emission from all spatial scales)
  - Only works well over small field of view
    - $\theta << \theta_B \, \nu / \Delta\nu_{tot}$



SIRA 2

- For a source at distance ℓ from phase center observed on baseline *b:*

$$V = \cos(\frac{2\pi\nu bl}{c}) + i\sin(\frac{2\pi\nu bl}{c})$$

Continuum Subtraction (IMLIN):

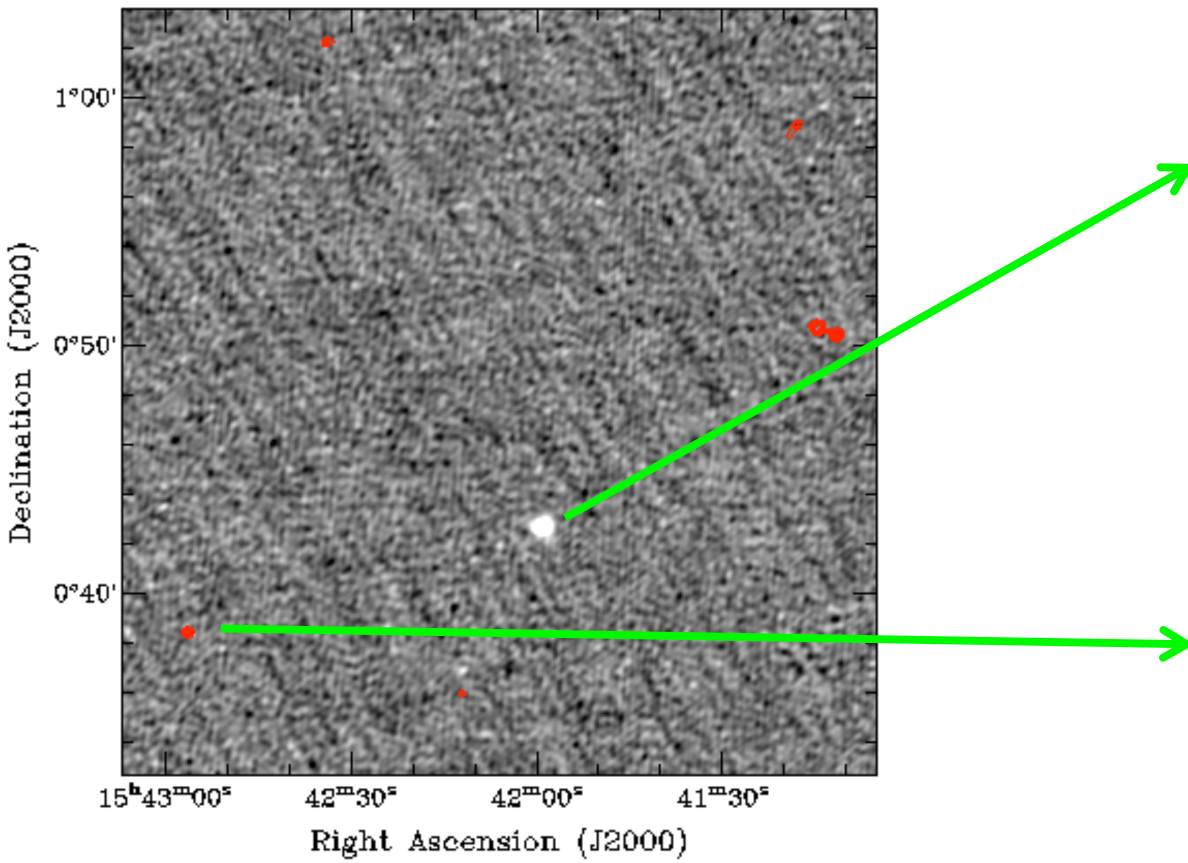
- Fit and subtract a low order polynomial fit to the line free part of the spectrum measured at each spatial pixel in cube.
- Advantages:
  – Fast, easy, robust to spectral index variations
  – Better at removing point sources far away from phase center (Cornwell et al. 1992).
  – Can be used with few line free channels.
- Restrictions:
  – Can't flag data since it works in the image plane.
  – Line and continuum must be simultaneously deconvolved.

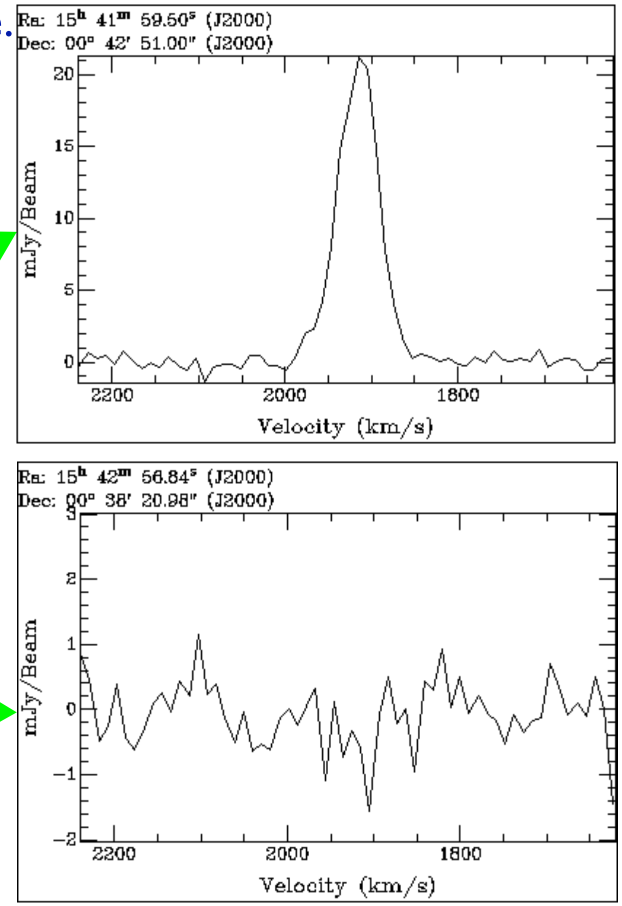
Continuum Subtraction (UVSUB):

- A visibility + imaging based method
  - Deconvolve the line-free channels to make a ‘model’ of the continuum
  - Fourier transform and subtract from the visibilities
- Advantages:
  - Accounts for chromatic aberration
  - Channel-based flagging possible
  - Can be effective at removing extended continuum over large fields of view
- Restrictions:
  - Computationally expensive
  - Errors in the ‘model’ (e.g. deconvolution errors) will introduce systematic errors in the line data

Continuum Subtraction:

- Again check results: Look at spectrum with POSSM, and later (after imaging) check with ISPEC: no continuum level, and a flat baseline.





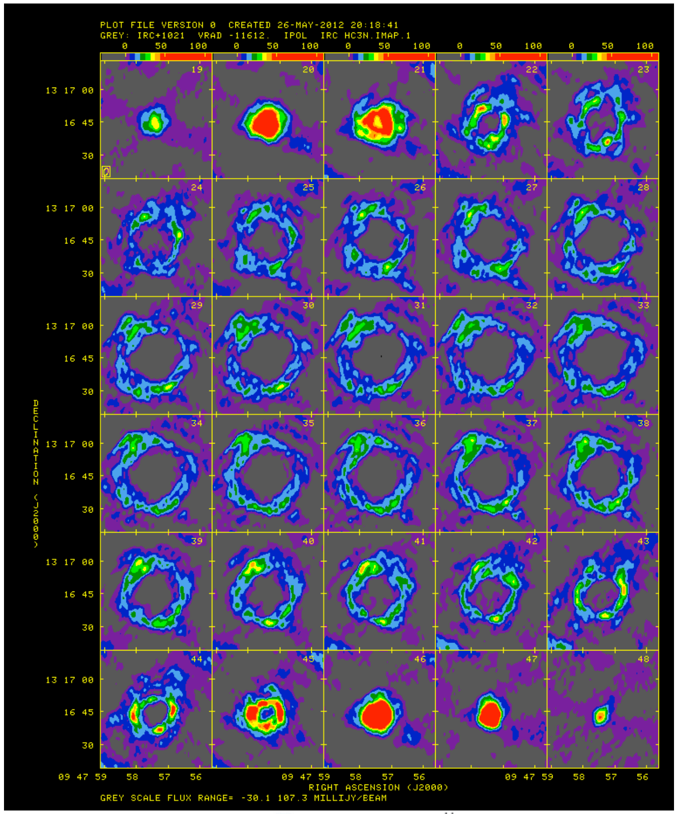
Courtesy L. Matthews

Deconvolution (Spectral Line):

- CLEANing:
  - Remove sidelobes that would obscure faint emission (masers, significant extended emission)
  - Interpolate to zero spacings to estimate flux
  -
- Deconvolution poses special challenges
  - Spectral line datasets are inherently detailed comparisons of the morphology of many maps
  - Emission structure can change radically from channel to channel
  - Large data volumes / computationally expensive

HC_3N – IRC 10216

EVLA spectral line tutorial



Deconvolution (Spectral Line):

- Spatial distribution of emission changes from channel to channel:
    - Try to keep channel-to-channel deconvolution as similar as possible (same restoring beam, same CLEANing depth, etc.)
    - May have to change cleaning boxes from channel to channel
  - Want both:
    - Sensitivity for faint features and full extent of emission
    - High spectral & spatial resolution for kinematics
      - Averaging channels will improve sensitivity but may limit spectral resolution
      - Choice of weighting function will affect sensitivity and spatial resolution
        - » Robust weighting with $-1<\mathcal{R}<1$ is often a good compromise
  - Interferometer response is sensitive to velocity structure of object
    - Response to continuum and spectral line is not necessarily the same

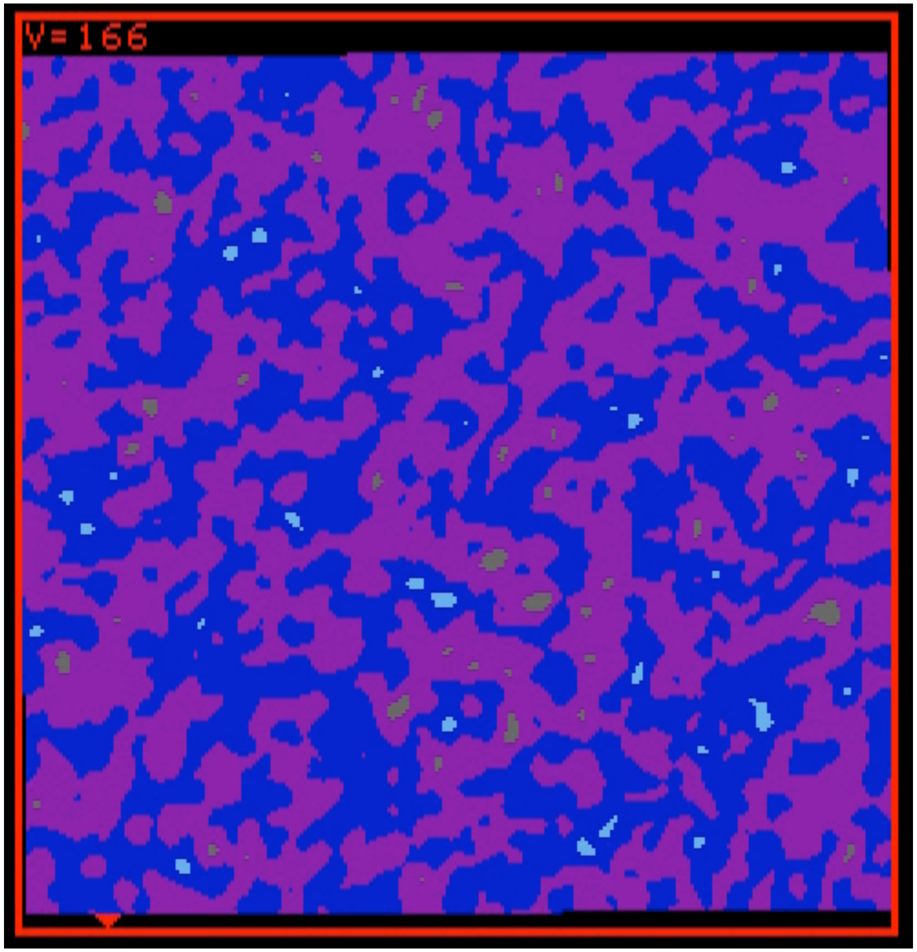
Smoothing (Spectral Line):

- *In frequency:*
- Smoothing in frequency can improve S/N in a line if the smoothing kernel matches the line width ("matched filter").
  - And reduce your data size (especially if you oversampled)
  - Smoothing doesn't propagate noise in a simple way
    - Example: data are Hanning smoothed to diminish Gibbs ringing
      - Spectral resolution will be reduced from $1.2\Delta\nu$ to $2.0\Delta\nu$
      - Noise equivalent bandwidth is now $2.67\Delta\nu$
      - Adjacent channels become correlated: ~16% between channels i and i+1; ~4% between channels i and i+2.
- *Spatially:*
- Smoothing data spatially (through convolution in the image plane or tapering in the *u-v* domain) can help to emphasize faint, extended emission.
  - This only works for *extended* emission.
  - Cannot recover flux you didn't sample

Visualizing Spectral data:

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

Movies:



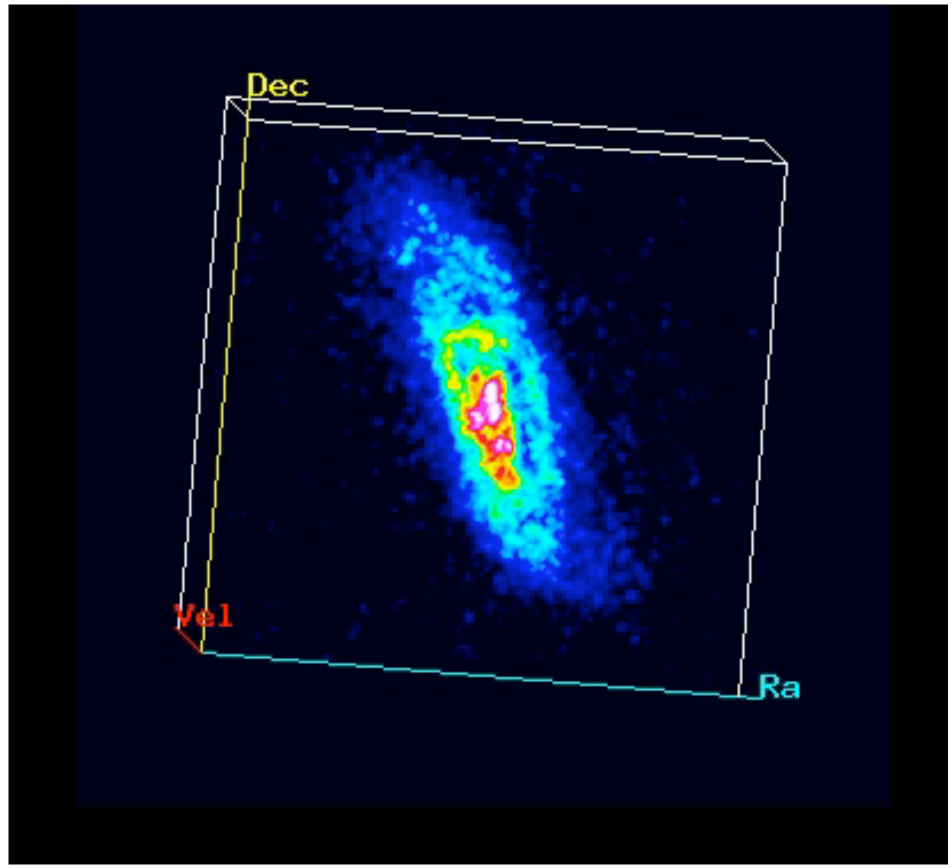
HI - NGC 3741

Courtesy J. Ott (VLA-ANGST)

Visualizing Spectral data:

- Imaging will create a spectral line *cube*, which is 3-dimensional: RA, Dec and Velocity.
  - 3rd axis not the same as the first two

HI – NGC 3741



3-D Rendering:

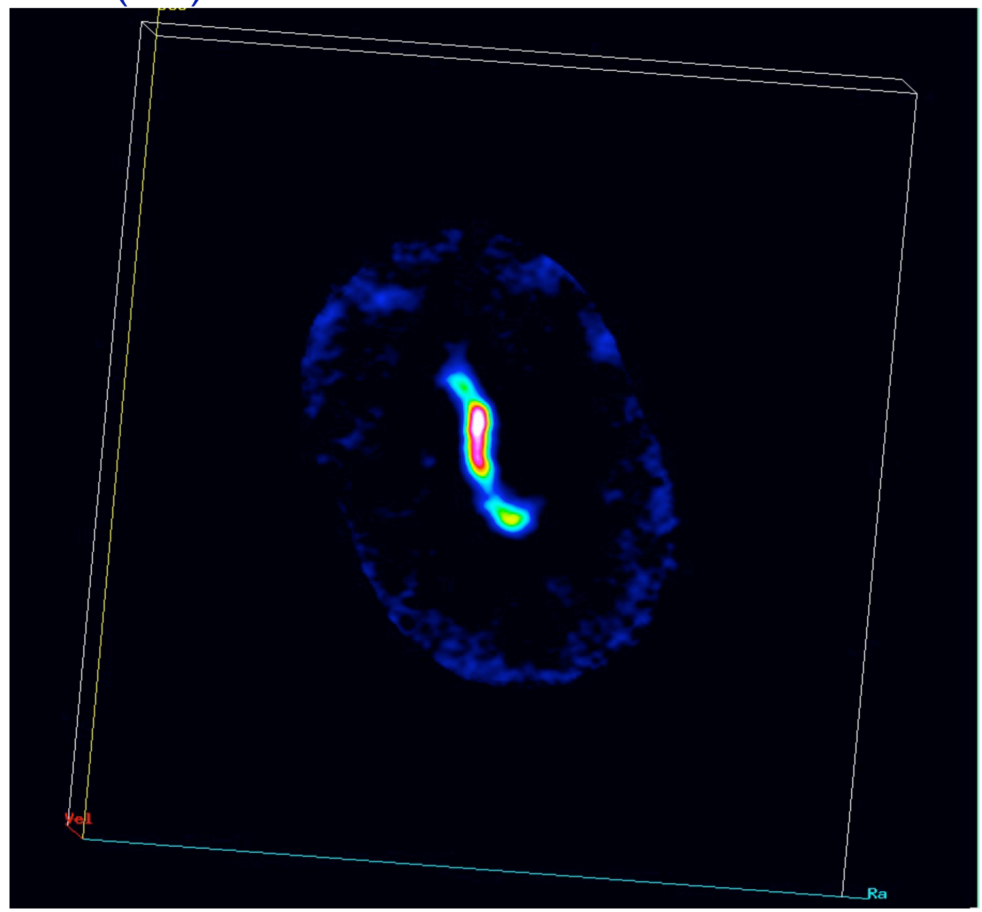
- Displayed with the 'xray' program in the visualization package 'Karma'

(http://www.atnf.csiro.au/computing/software/karma/)

Visualizing Spectral data:

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

$^{13}CO(1\text{-}0)$ – Maffei 2



Meier et al. (2008)

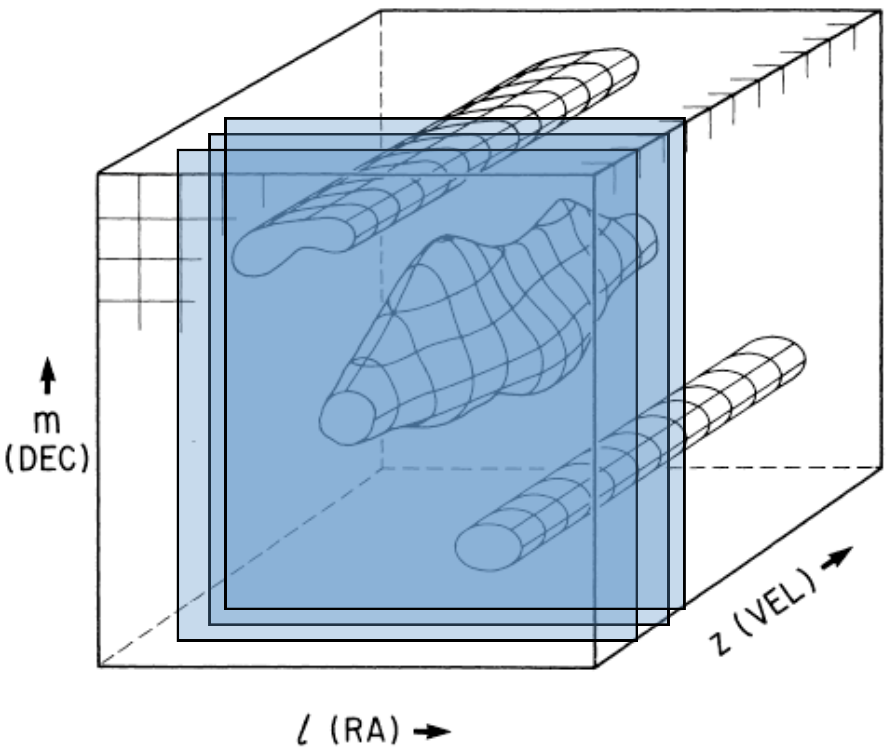
3-D Rendering:

- Displayed with the 'xray' program in the visualization package 'Karma'

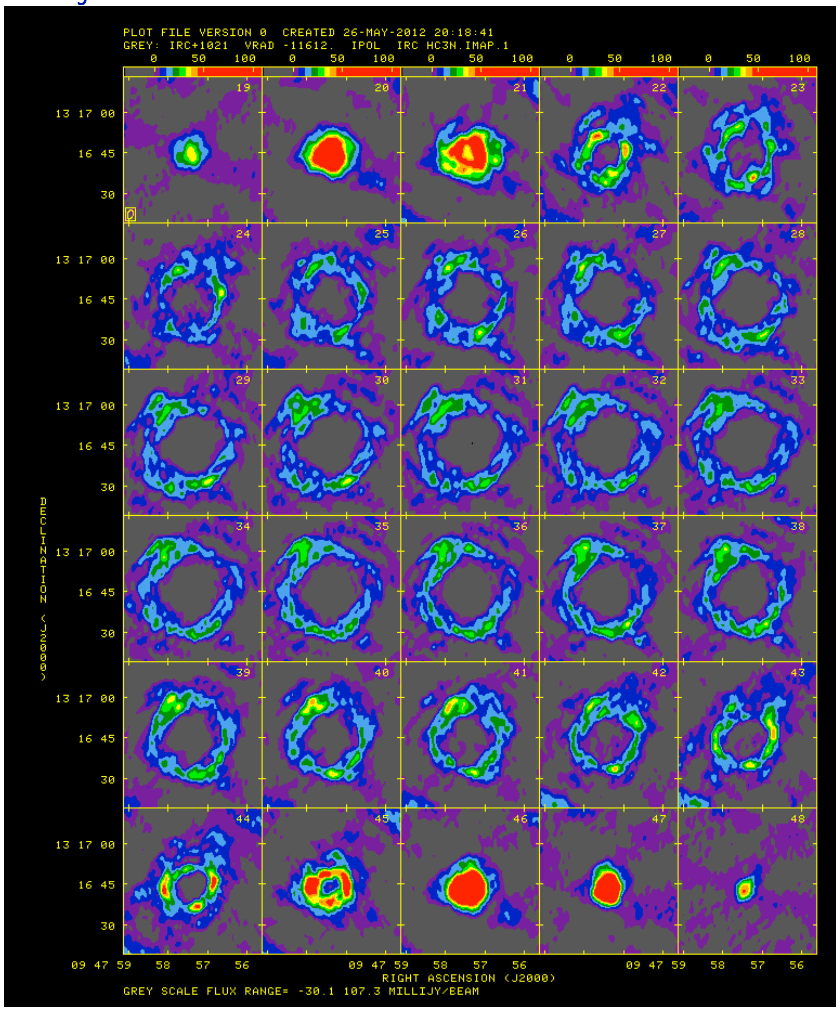
(http://www.atnf.csiro.au/computing/software/karma/)

Channel Maps:

- Channel maps show how the spatial distribution of the line feature changes with frequency/ velocity.



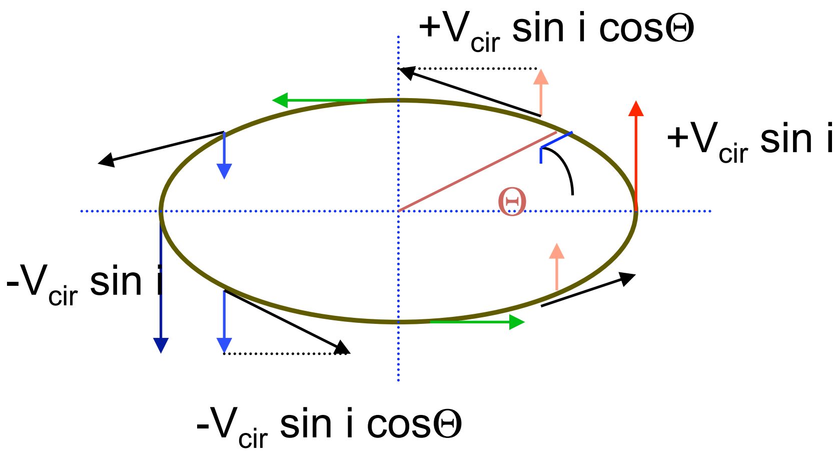
HC_3N – IRC 10216

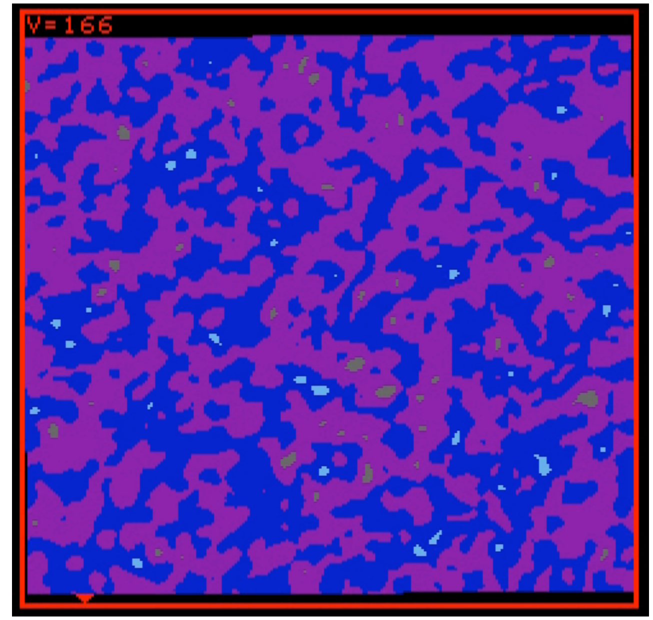


CASA spectral line tutorial

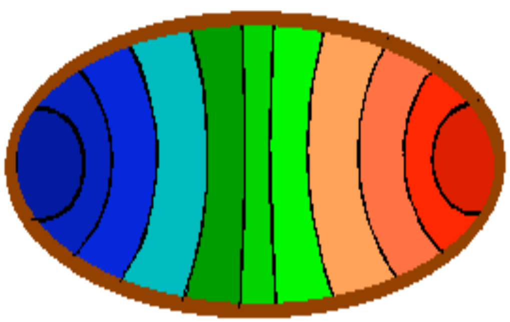
Inclined Disks:

'Butterfly Pattern':

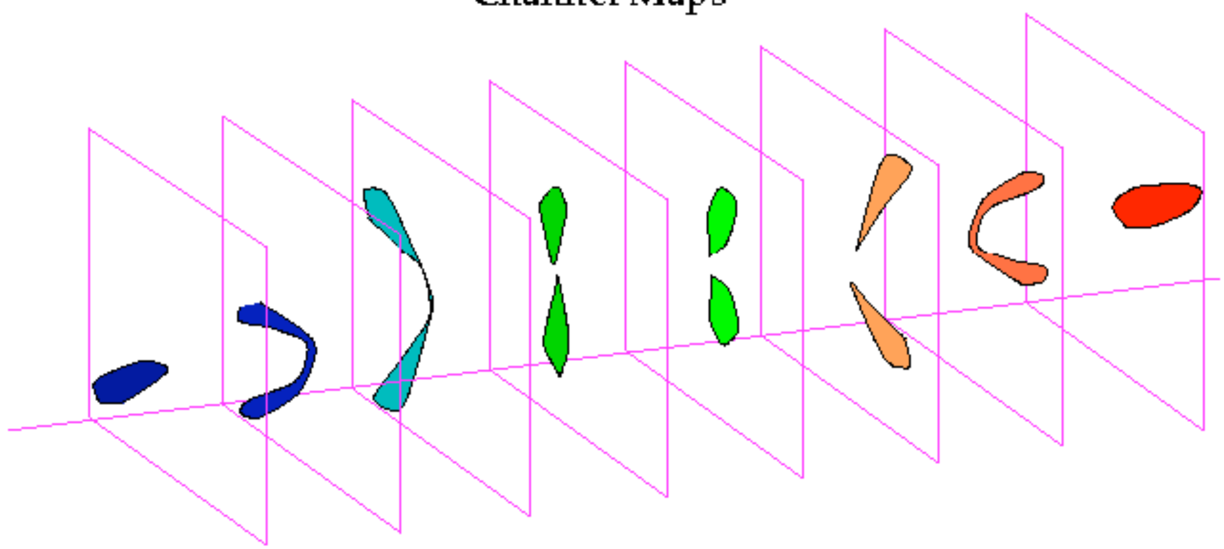




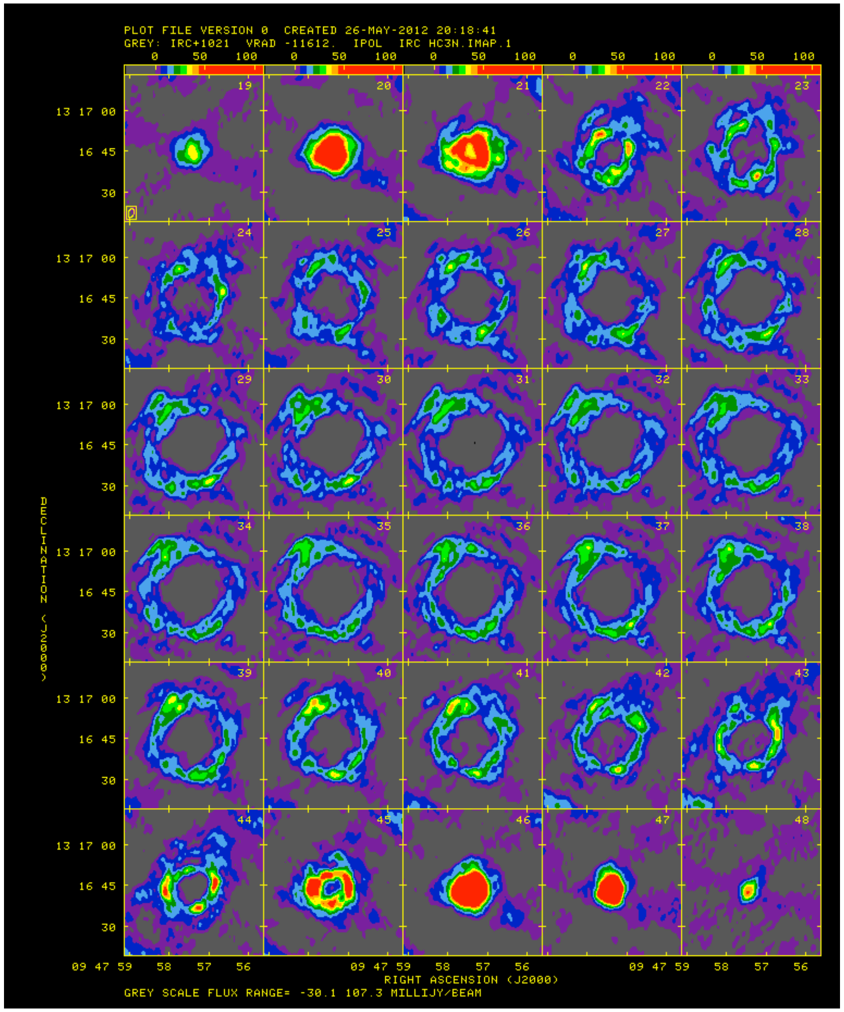
Mean Velocity Field



Channel Maps

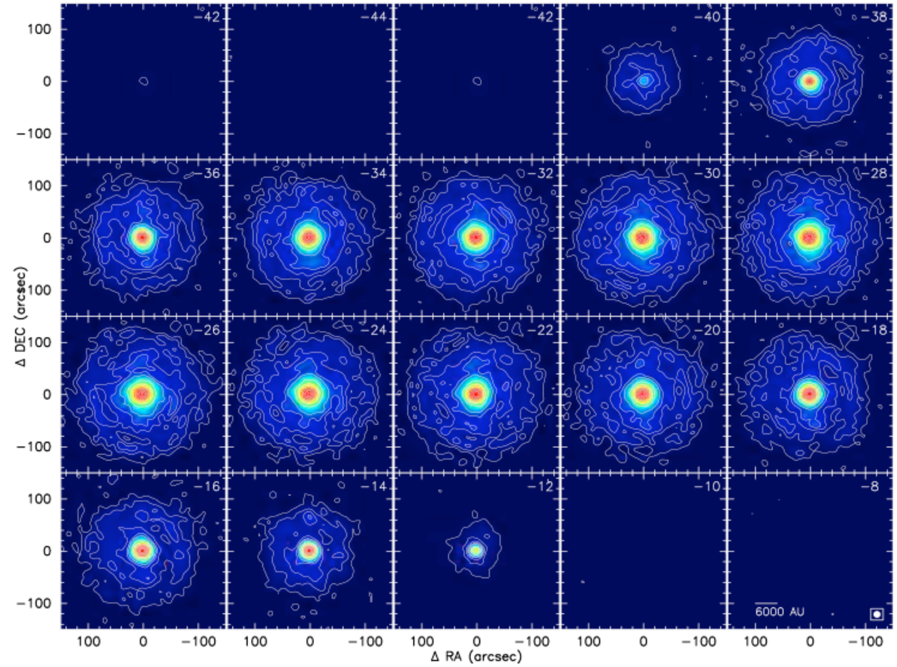


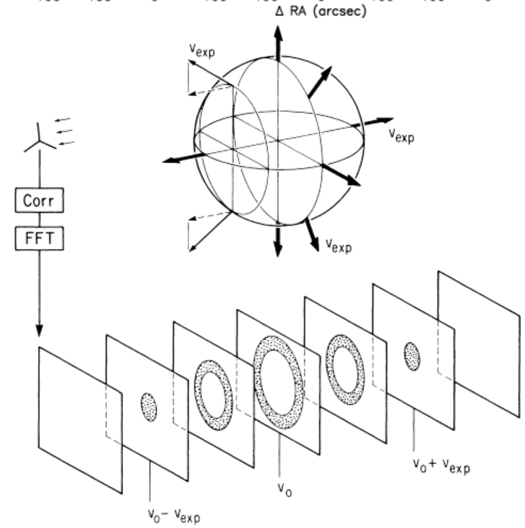
Spherical Shells:



CO(1-0) – IRC 10216

Fong et al. (2003)





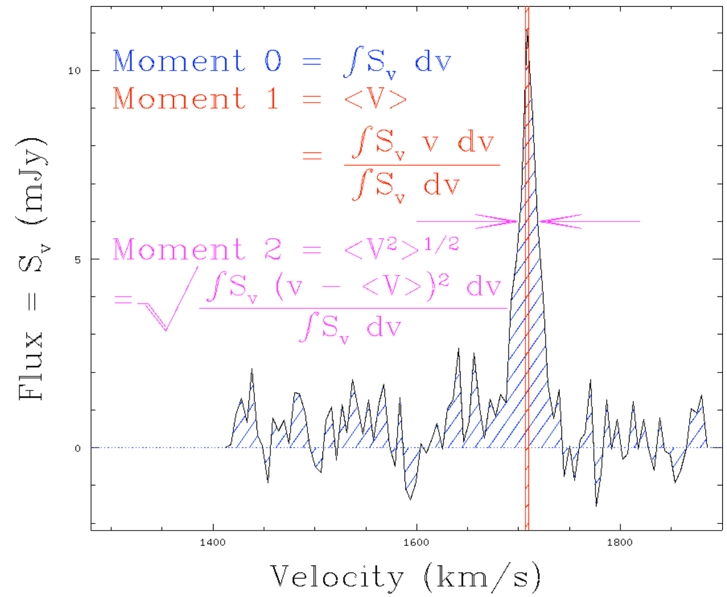
Visualizing Spectral data:

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

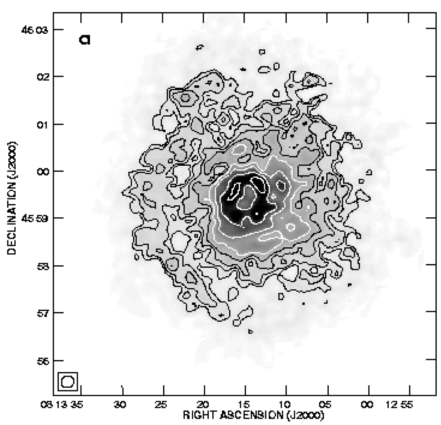
- With the cube, we usually visualize the information by making 1-D or 2-D projections:
  - Moment maps (integration along the velocity axis)
  - Line profiles (1-D slices along velocity axis)
  - Channel maps (2-D slices along velocity axis)
  - Position-velocity plots (slices along spatial dimension)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

Moment Maps:

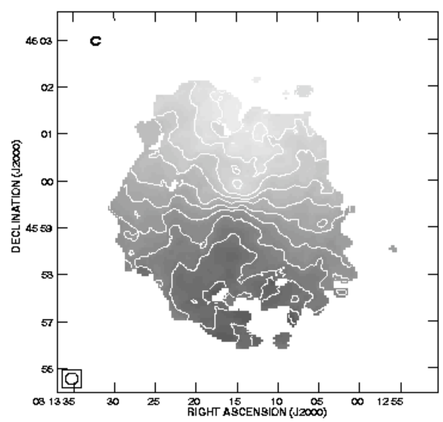
- You might want to derive parameters such as integrated line intensity, centroid velocity of components and line widths - all as functions of positions. Estimate using the *moments* of the line profile:



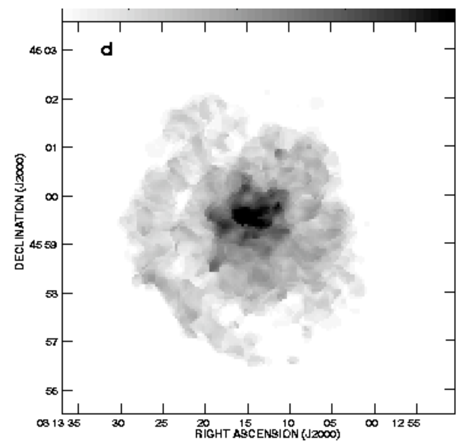
Courtesy L. Matthews



Moment 0
(Total Intensity)



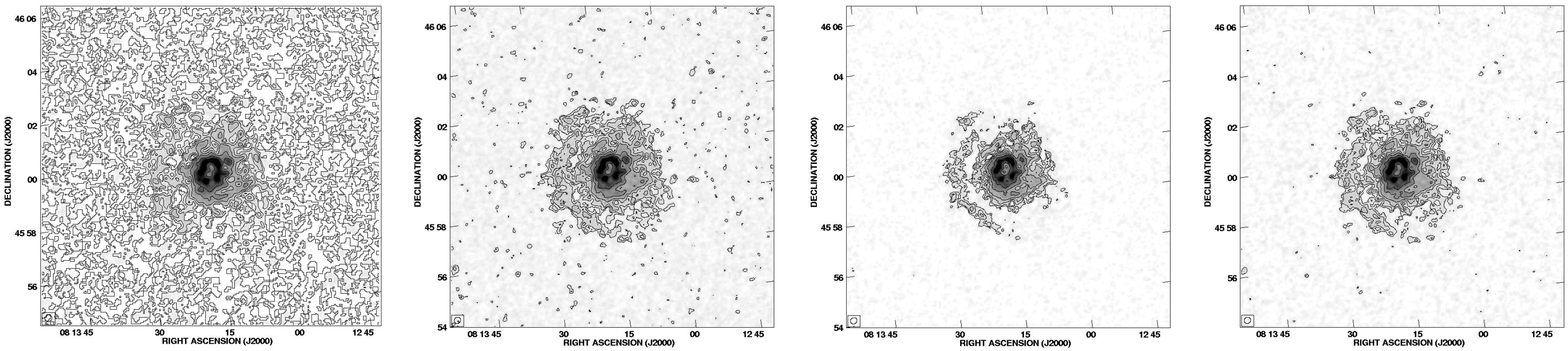
Moment 1
(Velocity Field)



Moment 2
(Velocity Dispersion)

Moment Map Issues:

- Moments sensitive to noise so clipping is required
  - Higher order moments depend on lower ones so progressively noisier.



Straight sum of all channels containing line emission

Summed after clipping below 1σ

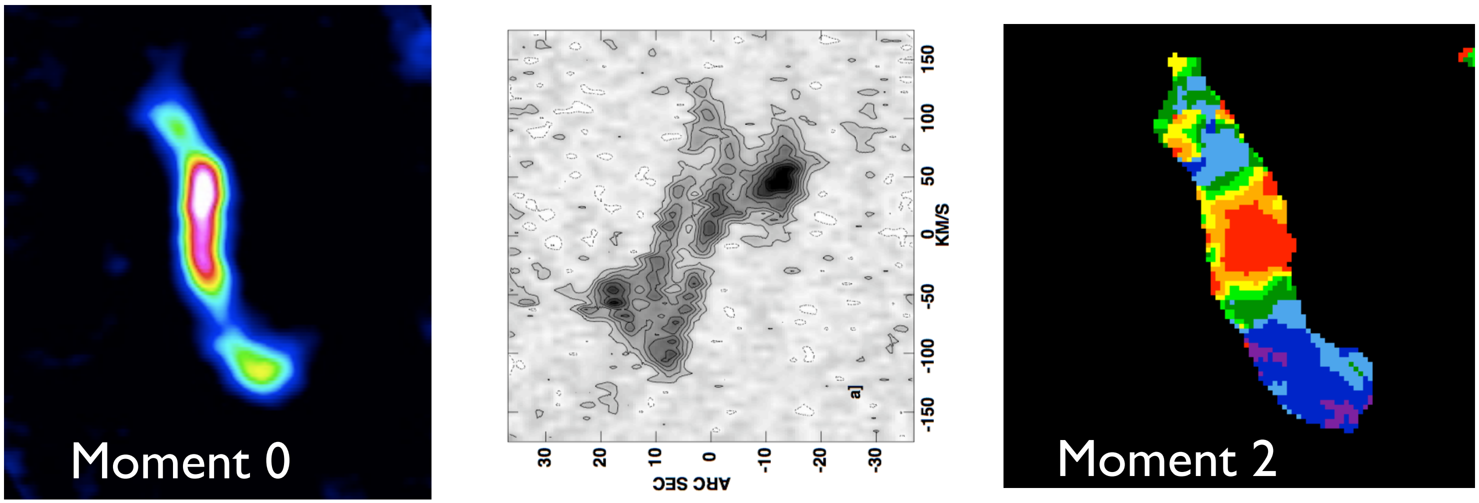
Summed after clipping below 2σ

Clipping below 1 σ, but based on masking with a cube smoothed x2 spatially and spectrally

Courtesy L. Matthews

Moment Map Issues (cont.):

- Hard to interpret correctly:
  - Non-monotomic emission/absorption or velocity patterns lead to misleading moment maps



Meier et al. (2008)

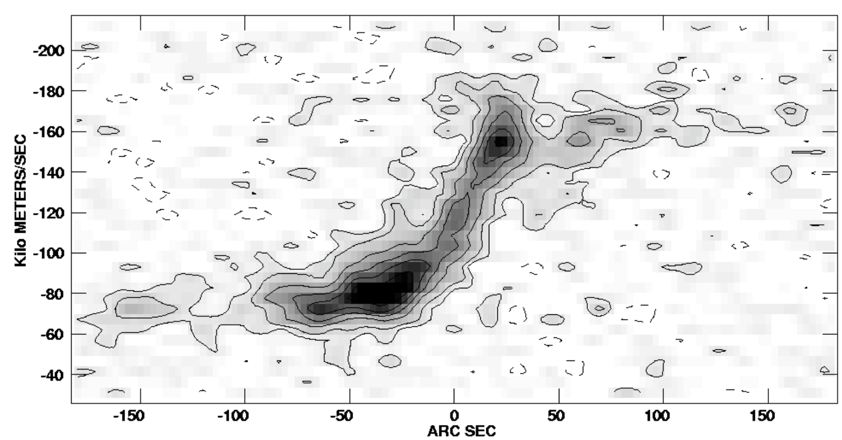
  - Biased towards regions of high intensity.
  - Complicated error estimates: number or channels with real emission used in moment computation will greatly change across the image.
- Use as guide for investigating features, or to compare with other λ.

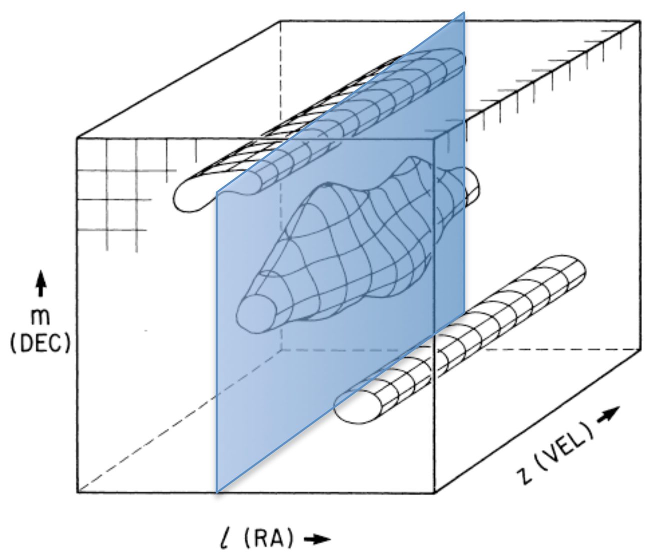
Position-Velocity diagrams:

- 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

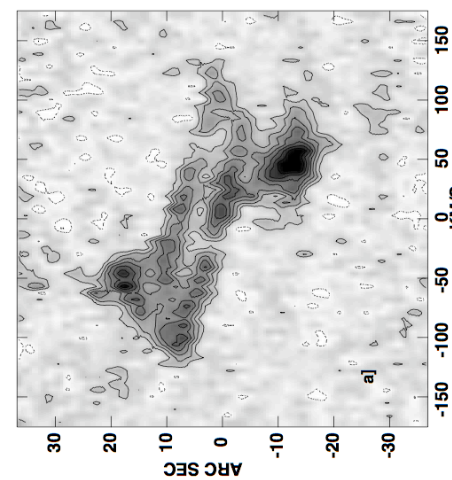
Velocity profile

Courtesy L. Matthews





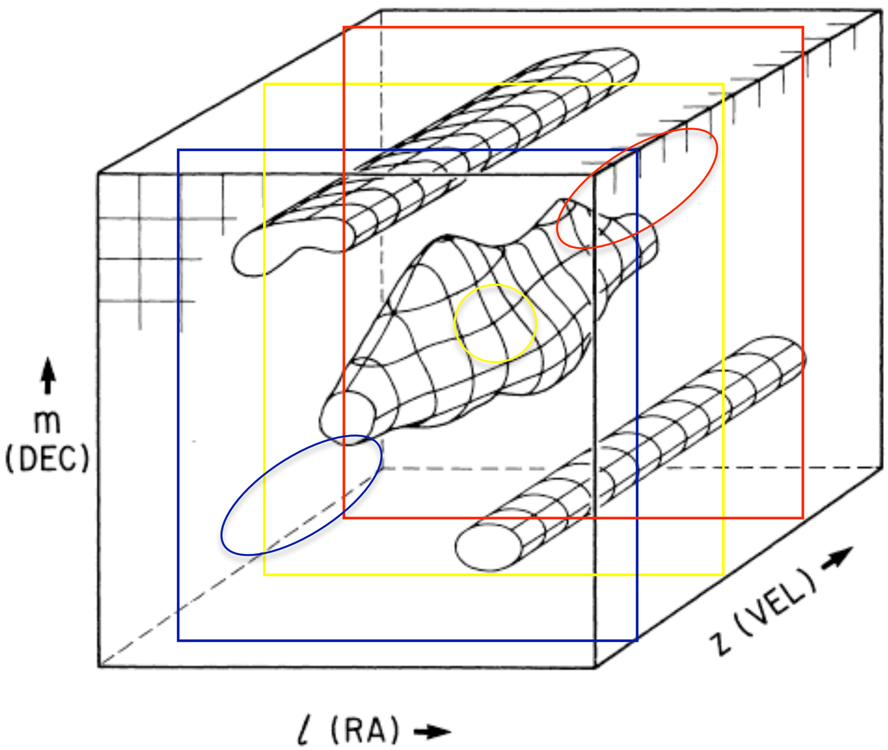
Meier et al. (2008)



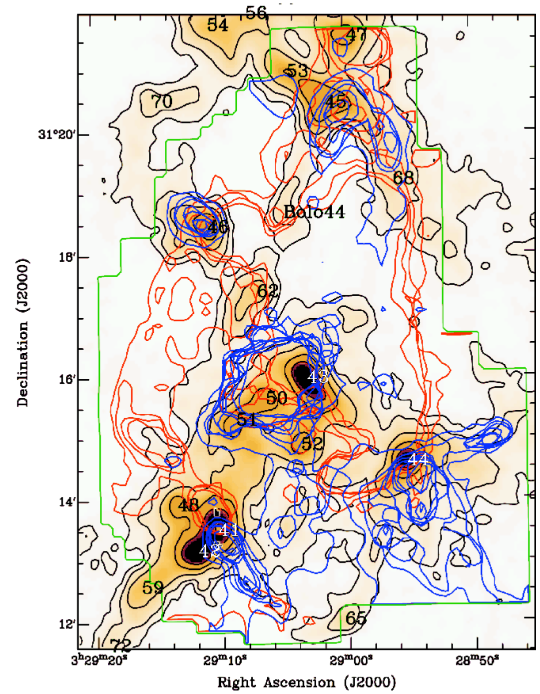
Distance along slice

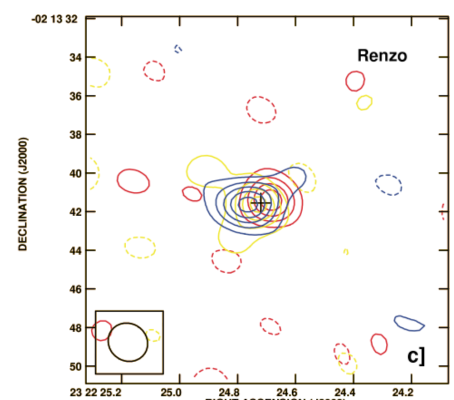
Renzograms:

- Contour selected planes (usually redshifted, systemic and blueshifted), and superpose onto one plane
  - Often done when velocity structure is very simple or very complex



Hatchell et al. (2007)

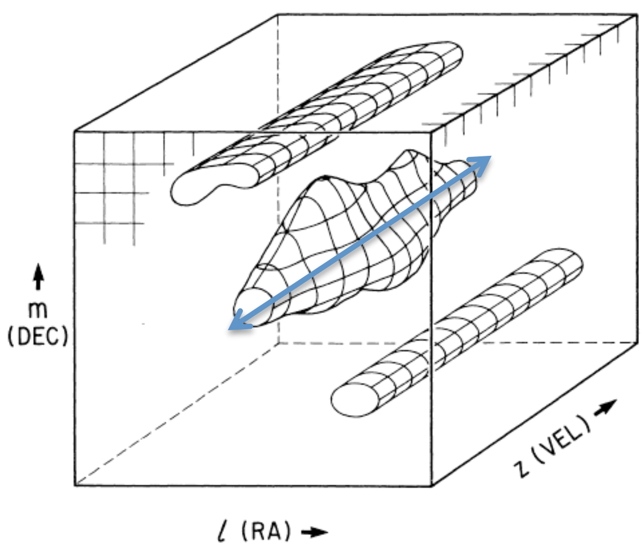


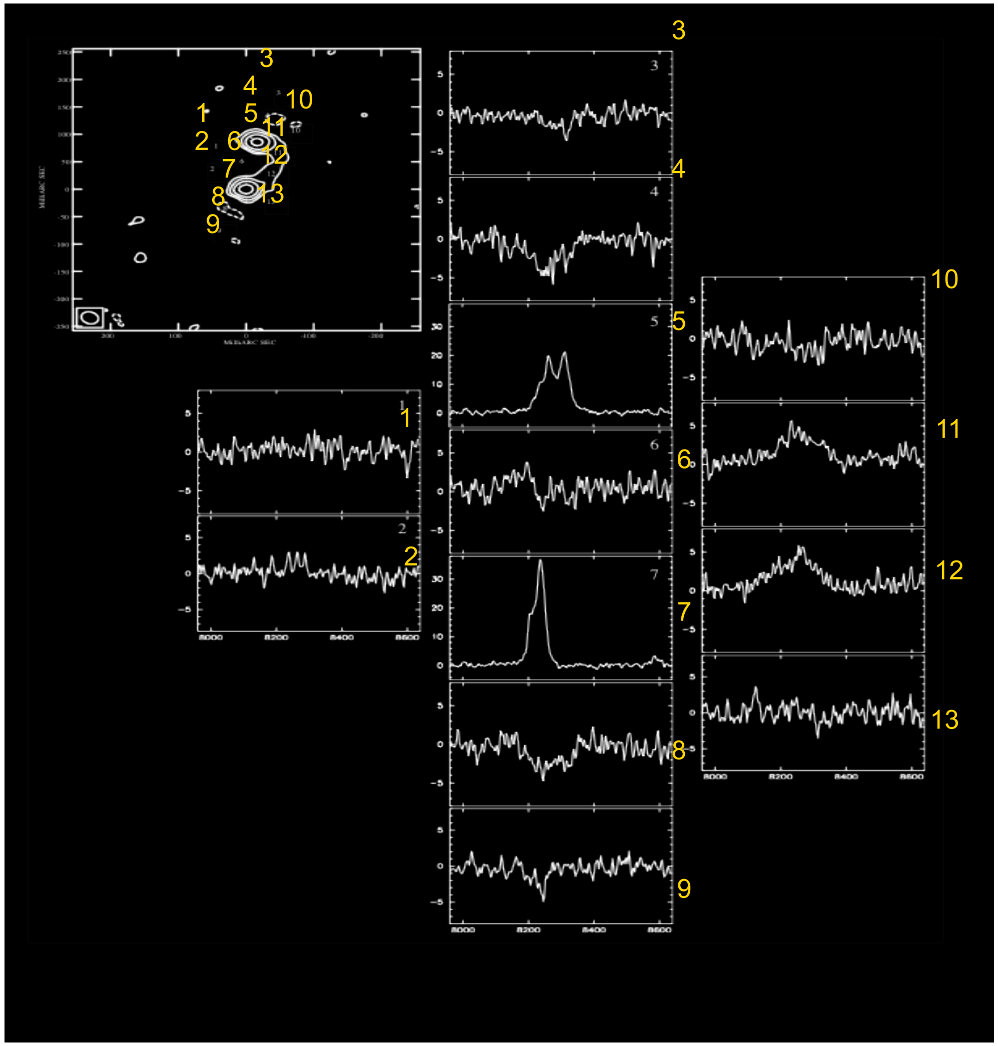


Zuckerman et al. (2008)

Line profiles (spectra):

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

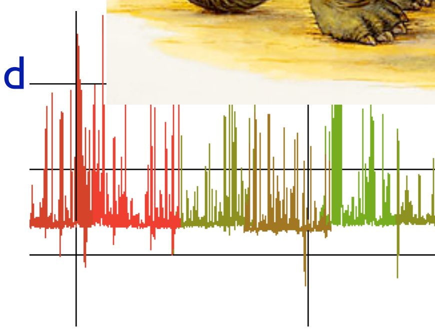




Courtesy Y. Pihlstrom

Going the Way of the

- Many (most?) of these techniques are likely to have to go the way of the dinosaur with the datasets on the horizon
  - A 16,000 channel cube played at 10 frames/sec will take *~30 min!*
  - Anyone interested in generating (and comparing) 4000 moment 0 maps?

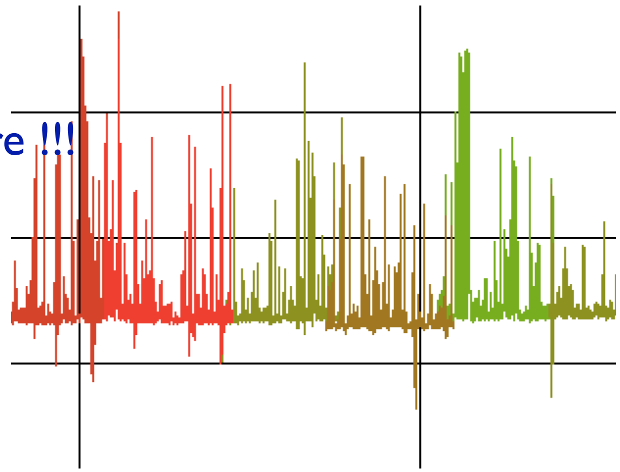


- We need new visualization tools
  - 3D slicers
  - Volume Rendering
  - Isosurface analysis
    - Clumpfind

- More sophisticated analysis tools:
  - Direct modeling of velocity fields
  - Principle Component Analysis
  - Fractal properties
  - Global spectrum fitting (line identification)

Summary:

- Most synthesis observations are now 'spectral line' observations
  - With most new instruments observing is in multi-channel mode:
  - Large bandwidths implying bandwidth smearing effects
  - RFI removal necessary (see talk later in the week)
  - Must correct for atmospheric and instrumental gain variations
- Better, it also implies:
  - Avoid line contamination
  - Much improved line searches
  - Multi-frequency synthesis enabled
- Have fun ---There are plenty of spectral lines out there !!!



References:

- Cornwell et al. 1992, A&A, 258, 583
- Fong et al. 2003, ApJL, 582, L39
- Hatchell et al. 2007, A&A, 472, 187
- Helfer et al. 2003, ApJS, 145, 259
- Meier et al. 2008, ApJ, 675, 281
- Roelfsma 1989, SIRA I
- SIRA 2 1998, Ed. Taylor, Carilli, Perley, chp. 11-12
- Van der Tak et al. 2009, A&A, 507, 347
- Venemans et al. 2012, ApJL, 751, L25
- Zuckerman et al. 2008, ApJ, 683, 1085