Spectral Line Techniques

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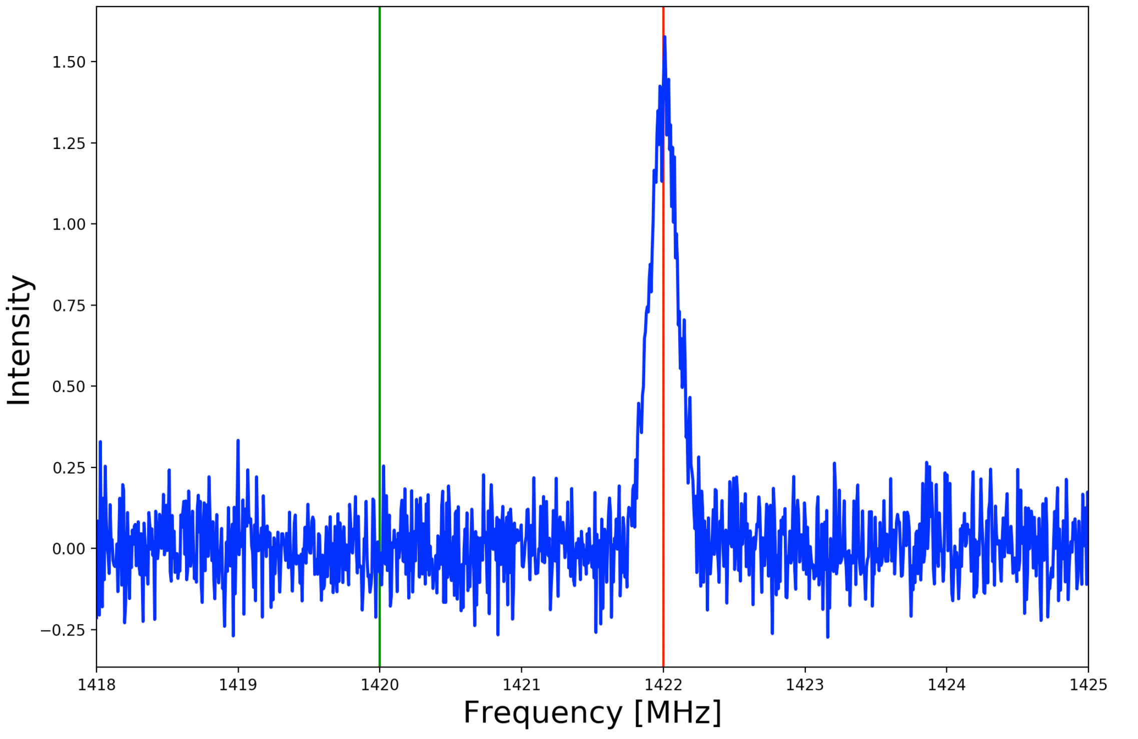
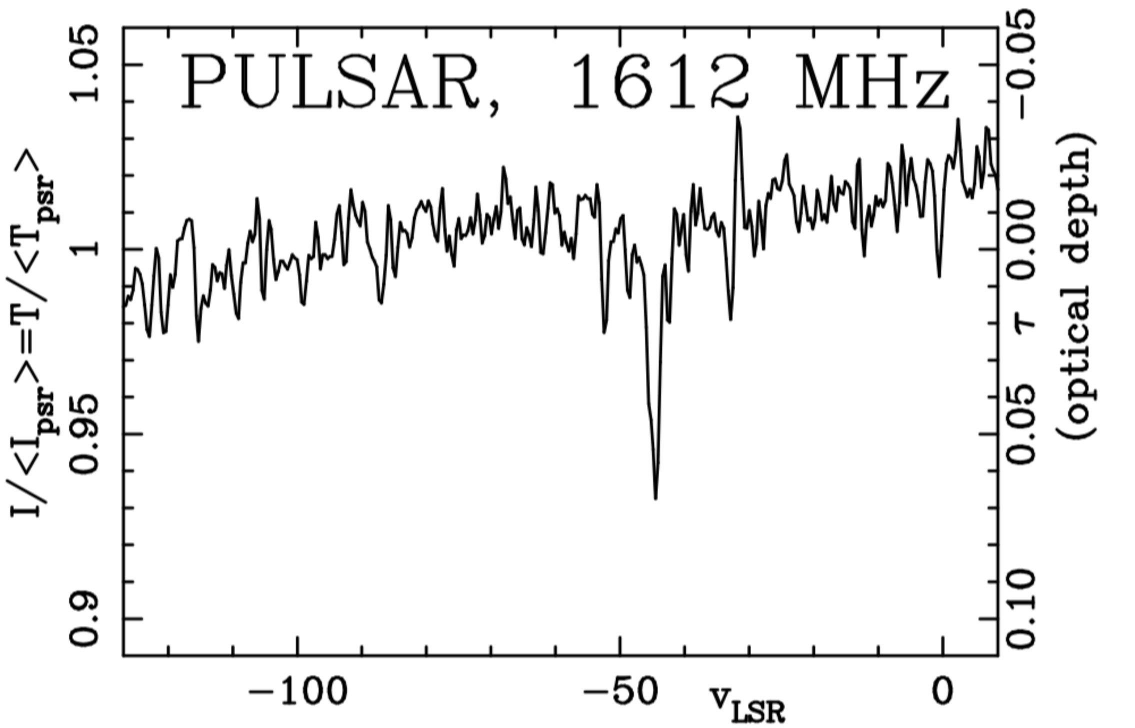
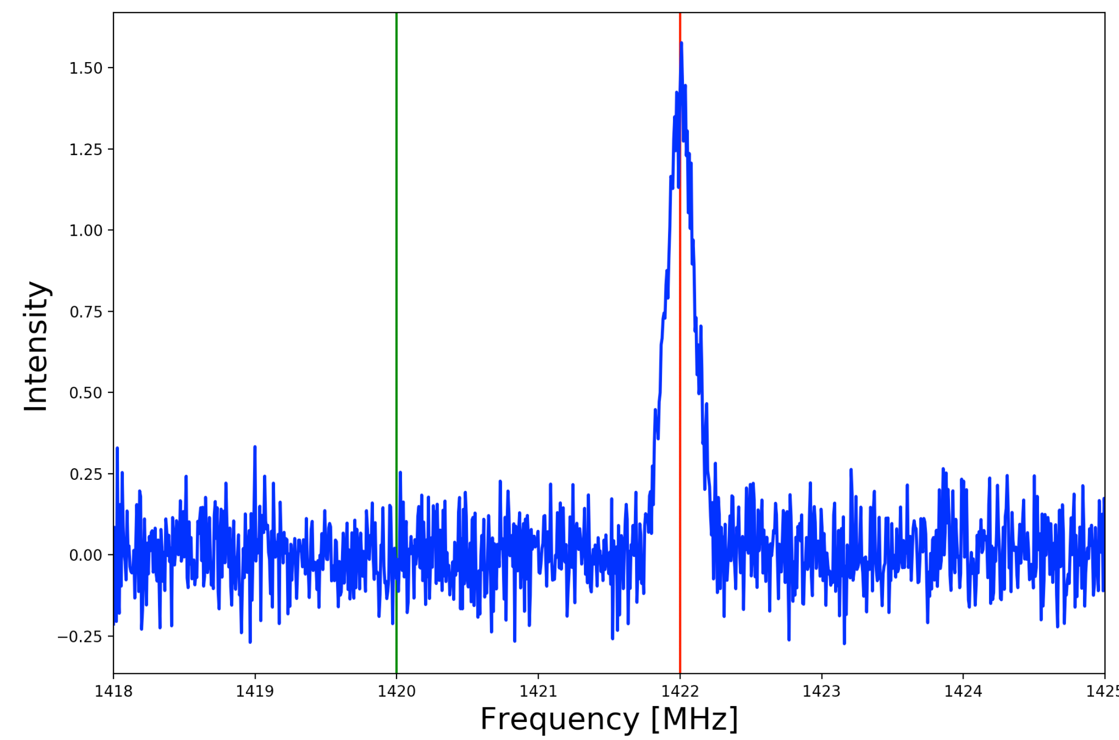


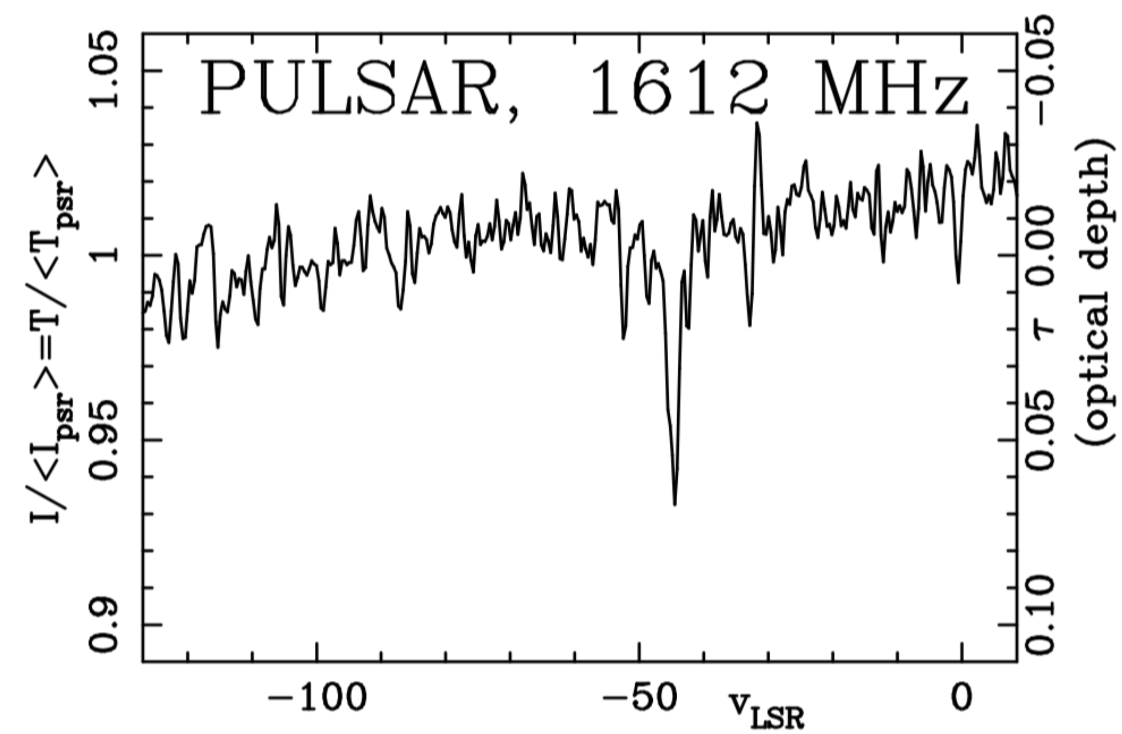


Weisberg, J. M., Rankin, J., & Boriakoff, V. 1980, A&A, 88, 84

Spectral Line Techniques

- Most of the emission is restricted to a narrow frequency range
- The transitions are well known from atomic/molecular physics
- Emission and Absorption *
- Almost always have associated continuum emission
- Emission/Absorption can be from extended sources, high resolution image/map making requires to do interferometry.





Weisberg, J. M., Rankin, J., & Boriakoff, V. 1980, A&A, 88, 84

Importance to learn spectral line analysis (for continuum studies!)

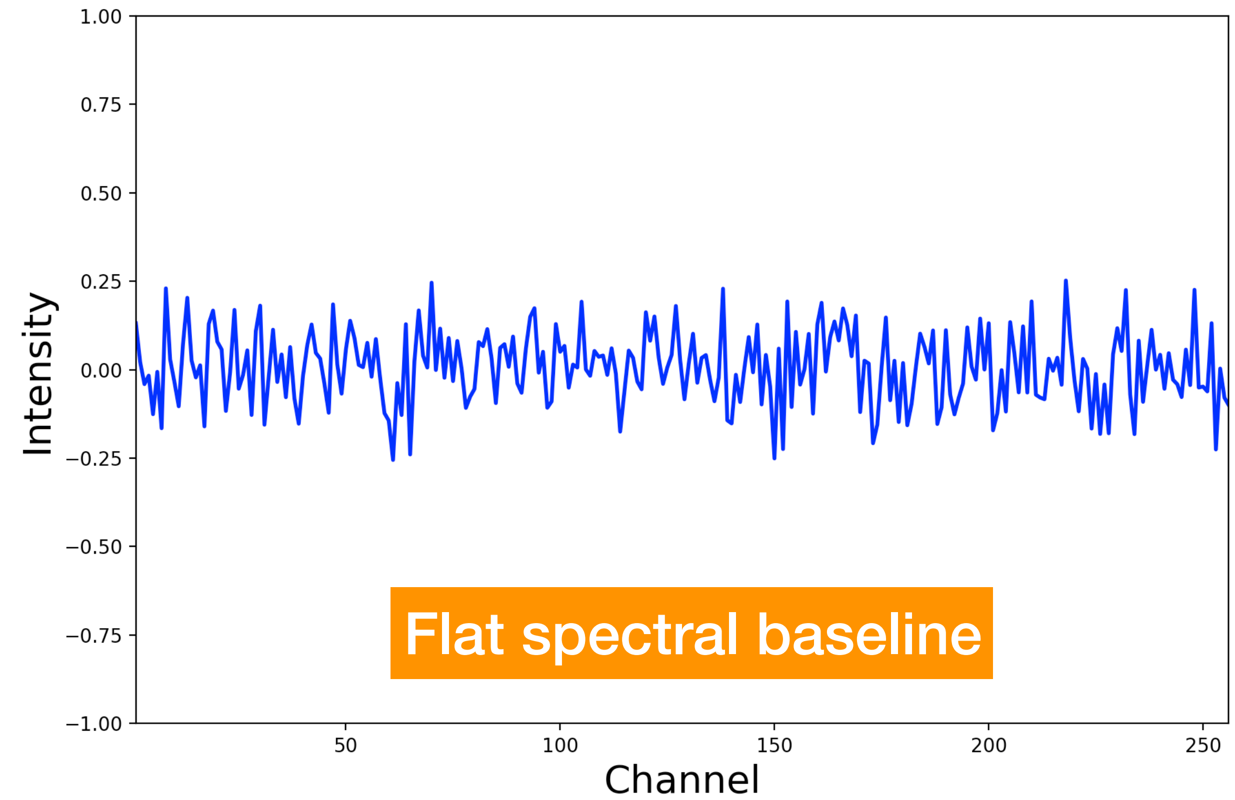
Single channel noise

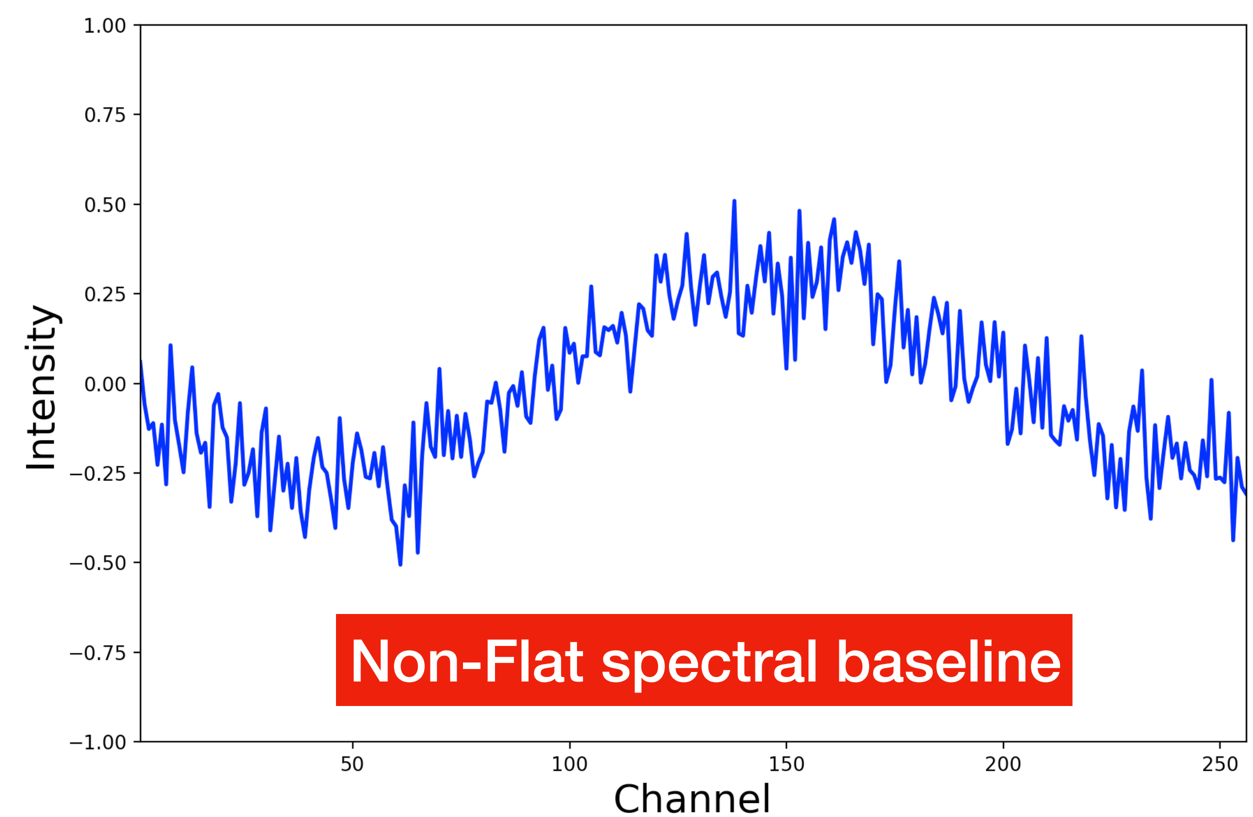
$$\sigma_N = \frac{\sigma_1}{\sqrt{N}}$$

Averaged over channels

No of Channels

Also continuum subtraction from continuum gives a good way of checking residual RFI!





Timeline

- Observation and Techniques with interferometers
    - Observation Preparation [Nissim again!]
    - Calibration
    - Doppler correction
    - Continuum Subtraction
    - Map making
- Science

Takeaways for the science case

- What is the line frequency? Cosmological/Doppler redshift. Which frequency band to observe?
- Compact or extended source ? If extended do the interferometer see it all? Choose antenna configuration wisely.
- What velocity/spectral resolution is required?
- What bandwidth is required?
- Galactic/extragalactic line?

Doppler correction I

Line of sight velocity

$$\nu = \nu_0 \sqrt{\frac{c - v_{los}}{c + v_{los}}}$$

Sky frequency **Rest Frequency**

$$z_{rad} = \frac{\nu - \nu_0}{\nu_0}$$

$$z_{opt} = \frac{\nu - \nu_0}{\nu}$$

Topocentric

Frame Name	Correction	Velocity (km/sec)	
Geocentric	Earth Spin	0.5	**Varies with time !**
Heliocentric	Earth revolution	30	**Varies across dates!**
LSR	Sun Motion	20	**For Galactic observations**
Galactocenric	Galaxy rotation	230	**For Extragalactic**
Local Group	LG motion	100	**For high redshift**

Choice of channel width, bandwidth and NChan

- First select the channel width required. (say 8.0 KHz)
- Guess the width of the spectral line/feature and keep enough spectral baselines in both sides. That decides the bandwidth. (say 3.8 MHz)
- Bandwidth/Channel width gives you number of spectral channel = NChan (~180)
- Choose these parameters now from one of the available sets.
- Should check the data rate!

			Bandwidth	**Channels**	**Integ. Time**
Interferometry : Spectral Line	Total Intensity (16 MHz and lower BW modes)	16,6	16 / N (N=4,8,16..128) (viz. 4, 2, 1, 0.5,0.25 & 0.125 MHz)	512, 256	2,4,8..(sec)

Check the GWB setups and figure out what you will do.

Choosing Bandpass calibrator(s)

- *Need to choose phase and flux calibrators (Ishwar)
- Bandpass Calibration: Calibration for the spectral response of Interferometer.
- A calibrator source is used, the source need not be a point source.
- If the phase calibrator has enough flux then that can be used. Calibrator spectra need to be flat!

$$SNR = \frac{I\ G}{T_{sys}} \sqrt{\Delta\nu\ T\ N(N-1)}$$

- **Signal to noise ratio** → SNR
- **Source Intensity** → I
- **Antenna gain** → G
- **Integration time** → T
- **System temperature (???)** → T_{sys}
- **Channel width** → $\Delta\nu$
- **No of baselines** → $N(N-1)$

$$SNR_{BP} >> SNR_{TS}$$

$$T_{BP} = \left[\frac{I_{TS}}{I_{BP}}\right]^2 T_{TS}$$

Remember bandpass slowly changes with time!

Choosing Bandpass Methods(s)

- Main spectral response come from the baseband filter
- **Position Switching:** By observing a strong calibrator source near to the target source. Almost all observation not involving spectral line from our galaxy uses this method.
- **Frequency Switching:** Shift the sky frequency. This does not change the response of the bandpass filter. Almost all observations involving spectral line from our galaxy uses this method.
  - **Frequency switching (In band):** If a large bandwidth is available, one can switch the frequency inside the band itself. This improve the signal to noise.
- Choosing calibrator with low optical depth.

Source	Coordinates (l, b)	$S^{a}_{1.4}$ Jy	$\tau_{\rm rms}$ ^{b} $\times 10^{-3}$	$\tau_{\rm peak}$
GMRT targets:				
B0316+162	166.6,−33.6	7.8	0.75	0.496
B0438−436	248.4,−41.6	5.0	1.46	< 0.0009
B0531+194	186.8, −7.1	6.8	0.99	0.631
B0834−196[g]	243.3,+12.6	5.0	1.08	0.187
B1151−348	289.9,+26.3	5.0	1.05	0.120
B1245−197	302.0,+42.9	5.3	1.23	0.032
B1345+125	347.2,+70.2	5.2	1.07	0.086
B1827−360	358.3,−11.8	6.9	0.89	0.227
B1921−293	9.3,−19.6	6.0	1.02	0.377
B2223−052	59.0,−48.8	5.7	0.79	0.148
WSRT targets:				
B0023−263	42.3,−84.2	7.5	1.04	0.0037
B0114−211	167.1,−81.5	3.7	1.58	0.044
B0117−155	154.2,−76.4	4.2	1.51	0.0067
B0134+329[g]	134.0,−28.7	16.5	0.53	0.058
B0202+149	147.9,−44.0	3.5	0.98	0.084
B0237−233	209.8,−65.1	5.7	1.19	0.116
B0316+413	150.6,−13.3	23.9	0.49	0.230
B0355+508	150.4, −1.6	5.3	2.12	6.438
B0404+768	133.4,+18.3	5.8	1.16	0.424
B0429+415	161.0, −4.3	8.6	0.90	0.716
B0518+165	187.4,−11.3	8.5	1.08	1.130
B0538+498	161.7,+10.3	22.5	0.49	0.912
B0831+557	162.2,+36.6	8.8	1.15	0.089
B0906+430	178.3,+42.8	3.9	0.82	0.0059
B1328+254	22.5,+81.0	6.8	0.33	0.0016
B1328+307	56.5,+80.7	14.7	0.30	0.0082
B1611+343	55.2,+46.4	4.8	0.72	0.0033
B1641+399	63.5,+40.9	8.9	0.49	0.0014

Roy et al. MnRAS, 436, 3, (2013), 2352

Bandpass Calibration

$$V_{AB}^{sky}(\nu) = \langle E_A^* E_B \rangle$$

Measured **Unknown**

$$V_{AB}^{obs}(t,\nu) = \mathcal{G}_{AB}(t,\nu) V_{AB}^{sky}(\nu)$$

Calibration is to know this.

$$\mathcal{G}_{AB}(t,\nu) = g_{AB}(t) B_{AB}(t,\nu)$$

Baseline based

Fast variation In time

Slow variation In time

- The spectral variation of bandpass is weak.
- If single channel does not have enough signal to noise, some channels can be averaged to gain in sensitivity for temporal calibration (g_AB).
- The temporal variation in g_AB may not be weak, but the temporal variation in B_AB is weak.

Bandpass Calibration

Measured **Unknown** **Known**

$$V_{AB}^{band}(t,\nu) = g_{AB}(t)B_{AB}(t,\nu)V_{AB}^{sky}$$

$$V_{AB}^{band}(t,\nu_0) = g_{AB}(t)B_{AB}(t,\nu_0)V_{AB}^{sky}$$

Amplitude and Phase Calibration

- We first do calibration for a given channel (nu_0) and find the stronger temporal variations in gain, g_A(t).

Bandpass Calibration

Measured **Unknown** **Known**

$$V_{AB}^{band}(t,\nu) = g_{AB}(t)B_{AB}(t,\nu) V_{AB}^{sky}$$

$$V_{AB}^{band}(t,\nu_0) = g_{AB}(t)B_{AB}(t,\nu_0) V_{AB}^{sky}$$

$$\frac{V_{AB}^{band}(t,\nu)}{V_{AB}^{band}(t,\nu_0)} = \frac{B_{AB}(t,\nu)}{B_{AB}(t,\nu_0)} = B'_{AB}(t,\nu)$$

AIPS: BPASS, BPASSPRM(5) = 1, BPASSPRM(10) = 3

$$B'_{AB}(t,\nu) = b_A^*(t,\nu) b_B^*(t,\nu)$$

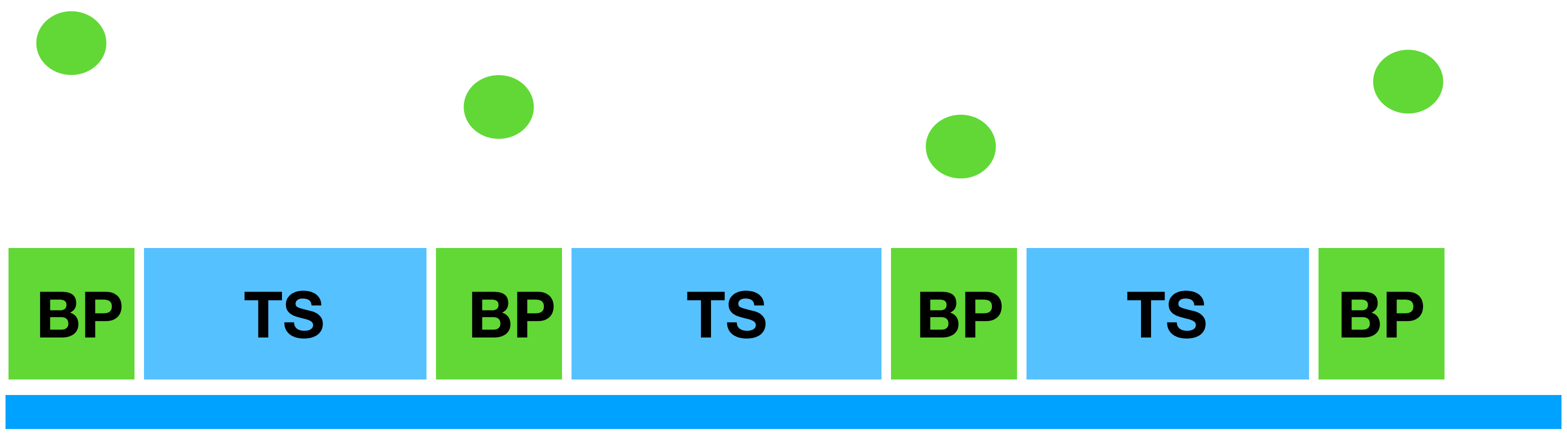
N antenna -> N(N-1)/2 measurements

- We first do calibration for a given channel (nu_0) and find the stronger temporal variations in gain, g_A(t).
- If the bandpass calibrator is not a point source, then the visibilities at different baselines can be different. Do not worry, the variation with baseline is taken care of when you do the (complex) division.
- Gains are antenna based

Bandpass Calibration

$$B'_{AB}(t,\nu) = b^*_A(t,\nu)b^*_B(t,\nu)$$

N antenna -> N(N-1)/2 measurements



Single Baseline, Time →

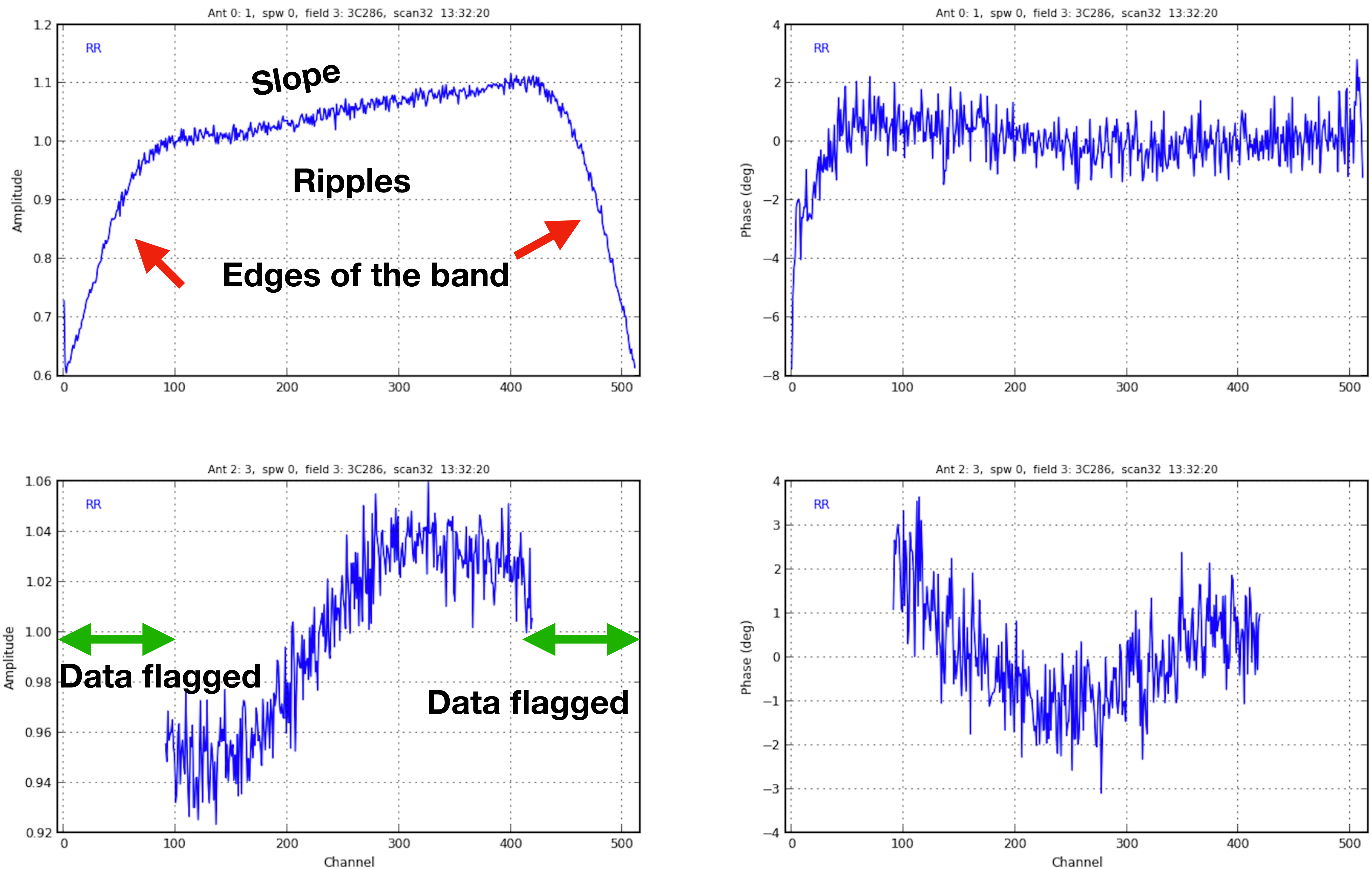
- In case you have many observations of bandpass, interpolate in time/use nearest bandpass in time.
- If you happened to have only one… or two bandpass separated over large time, then just average all entries.
- Polynomial fit across time/frequency also can be tried.

AIPS: DOBAND

= 1 : Average everything — *When only one observation*

= 2 : Nearest in time
= 3 : Interpolate in time
} *Check which gives better result*

Bandpass Calibration



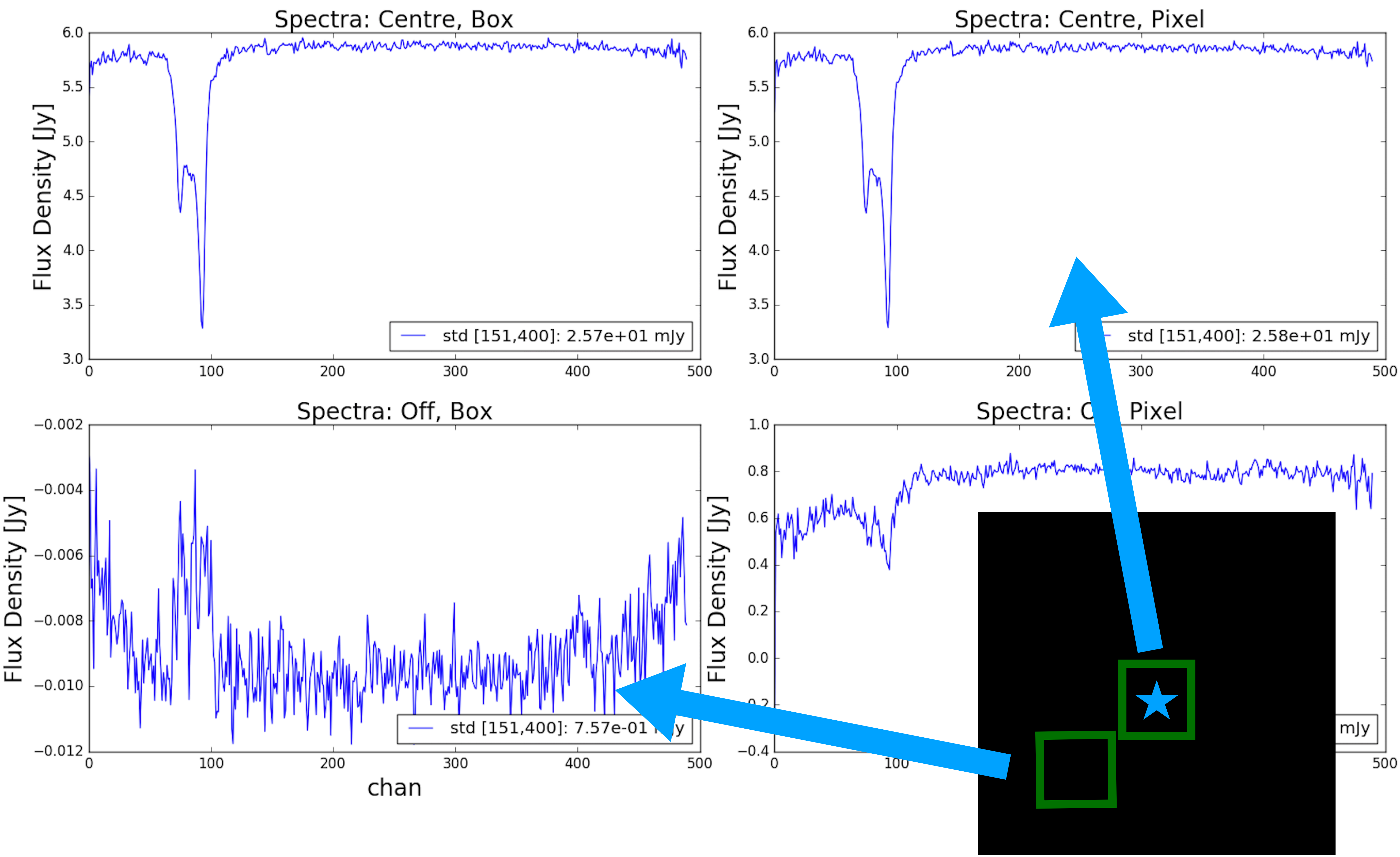
Bandpass Calibration

- Data need to be FLAGGED for different spectral lines too.
- Bandpass solutions for bad antennas are often completely different from the good ones… easy identifications.
- Do Scalar averaged cross power spectra and look for spikes (positive or negative) and inspect those channels.
- Do FLAGGING and BANDPASS calibration iteratively.

Scalar Average: *Average amplitudes and phases separately*

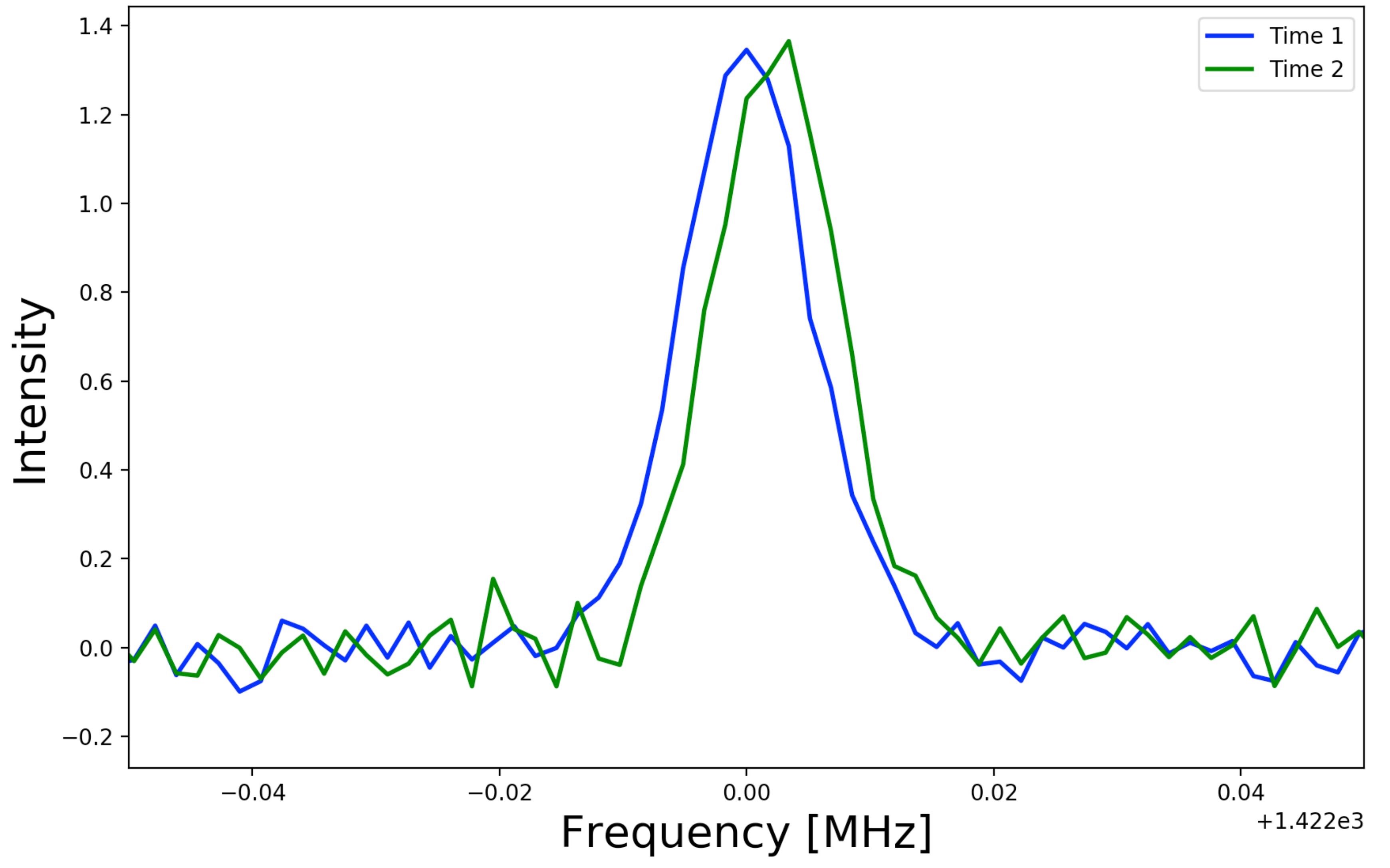
Vector Average: *Average Real and Imaginary separately*

Bandpass Calibration

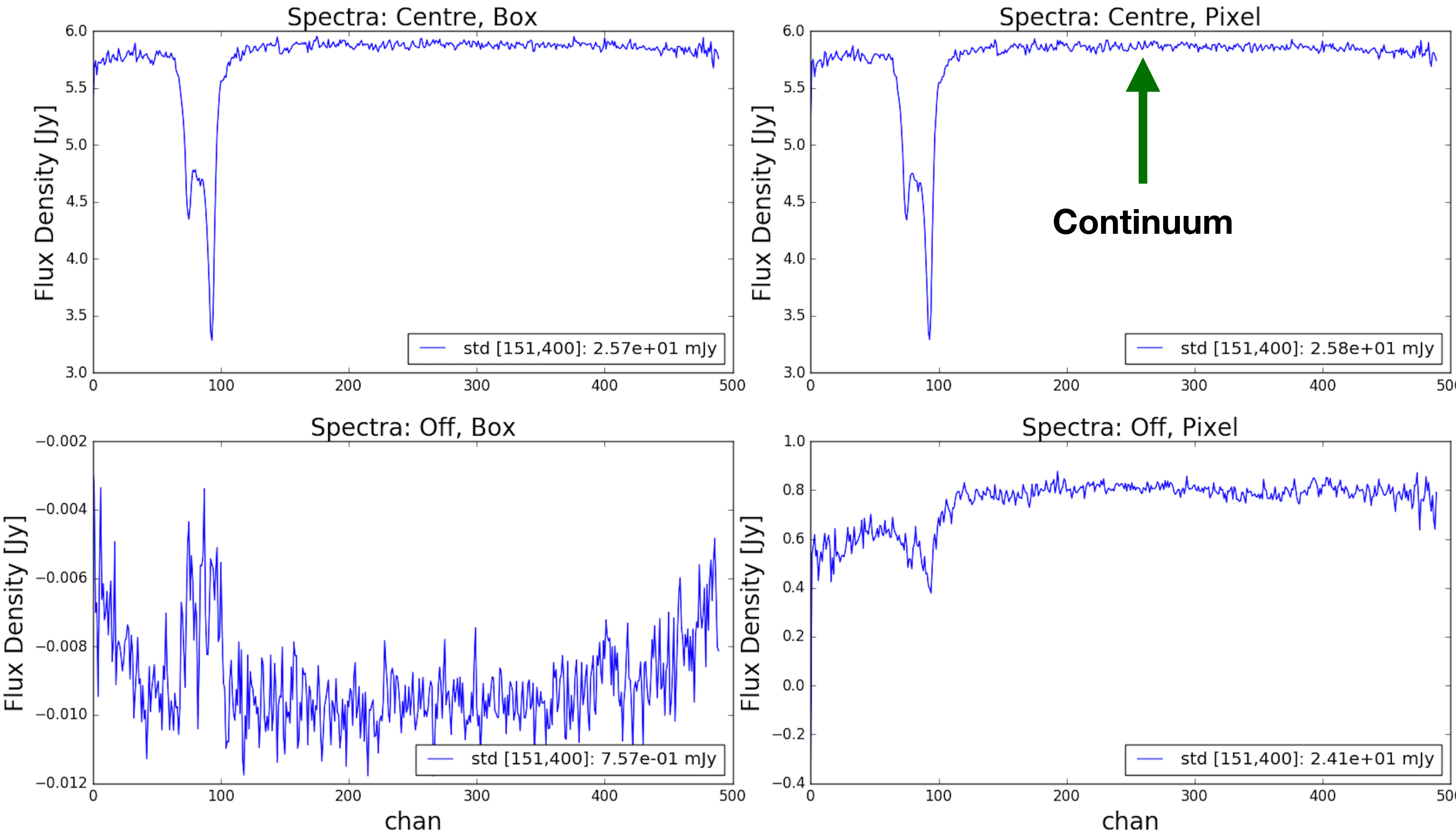


Doppler correction II

- Necessary if you need spectral resolution > 1.2 km /sec.
- This correction is for the earth's rotation during the observation.
- Task used is CVEL



Continuum Subtraction



Continuum Subtraction

$$V_{AB}(\nu) = V_{AB}^{cont}(\nu) \quad + \quad V_{AB}^{line}(\nu)$$

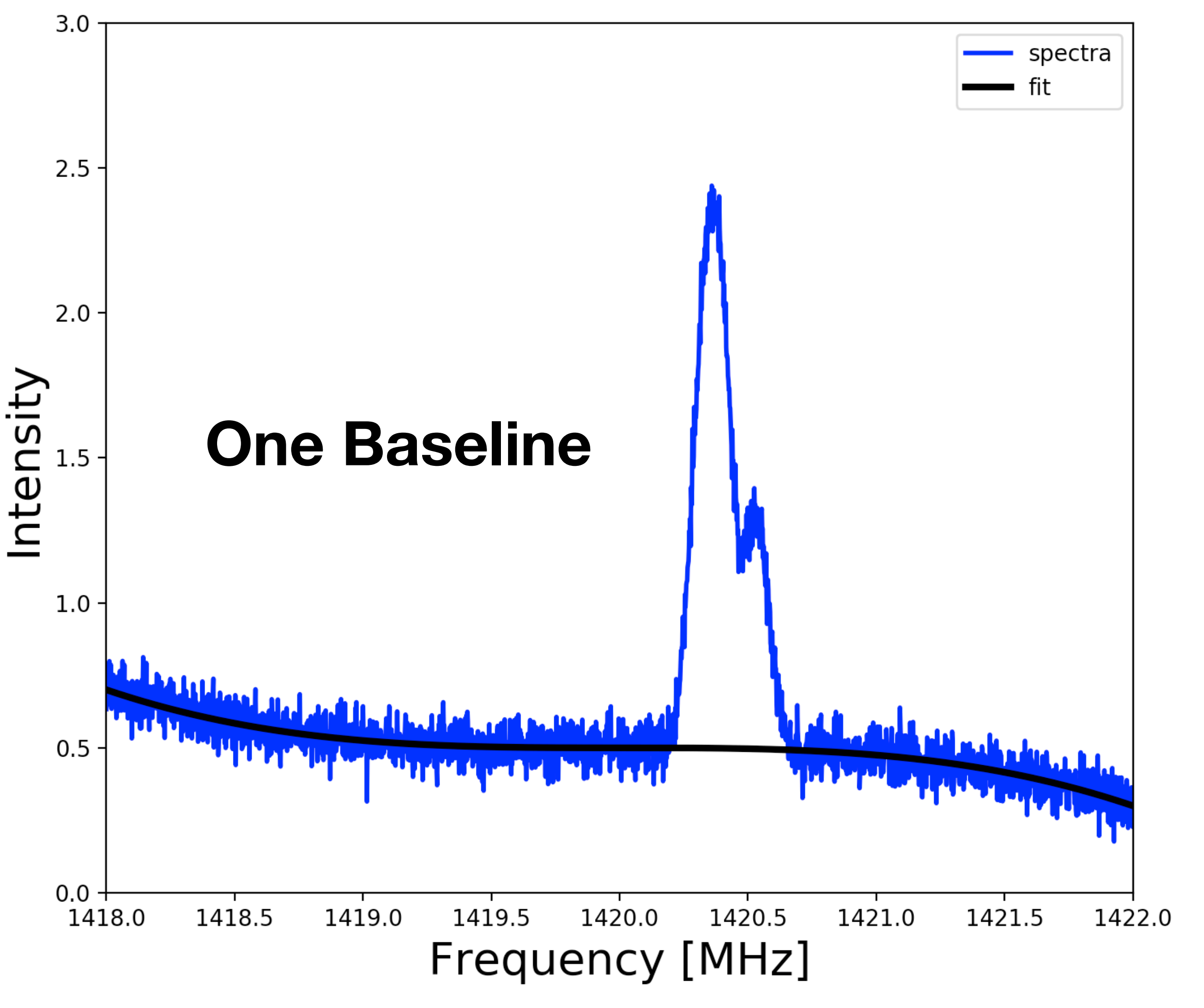
$$I(l,m,\nu) = I^{cont}(l,m,\nu) \quad + \quad I^{line}(l,m,\nu)$$

Both baseline based [UVSUB, UVLIN]
and
Image based [IMLIN] algorithms exists

Continuum Subtraction [UVLIN]

$$V_{AB}(\nu) = V_{AB}^{cont}(\nu) \quad + \quad V_{AB}^{line}(\nu)$$

- Works on each baseline separately.
- Choose line free channels in the band and fit a low order polynomial.
- Identify outliers compared to the fit and FLAG those!
- Subtract the polynomial from all channels.



Continuum Subtraction [UVLIN]

Advantages

- No need to make an image!
- Fast algorithm.
- Automated flagging.
- Statistics of continuum is estimated.

Disadvantages

- Assumes uniform uv coverage across frequencies
- Field of view over which works is restricted
- More residual flux away from phase centre

Continuum Subtraction [UVLIN]

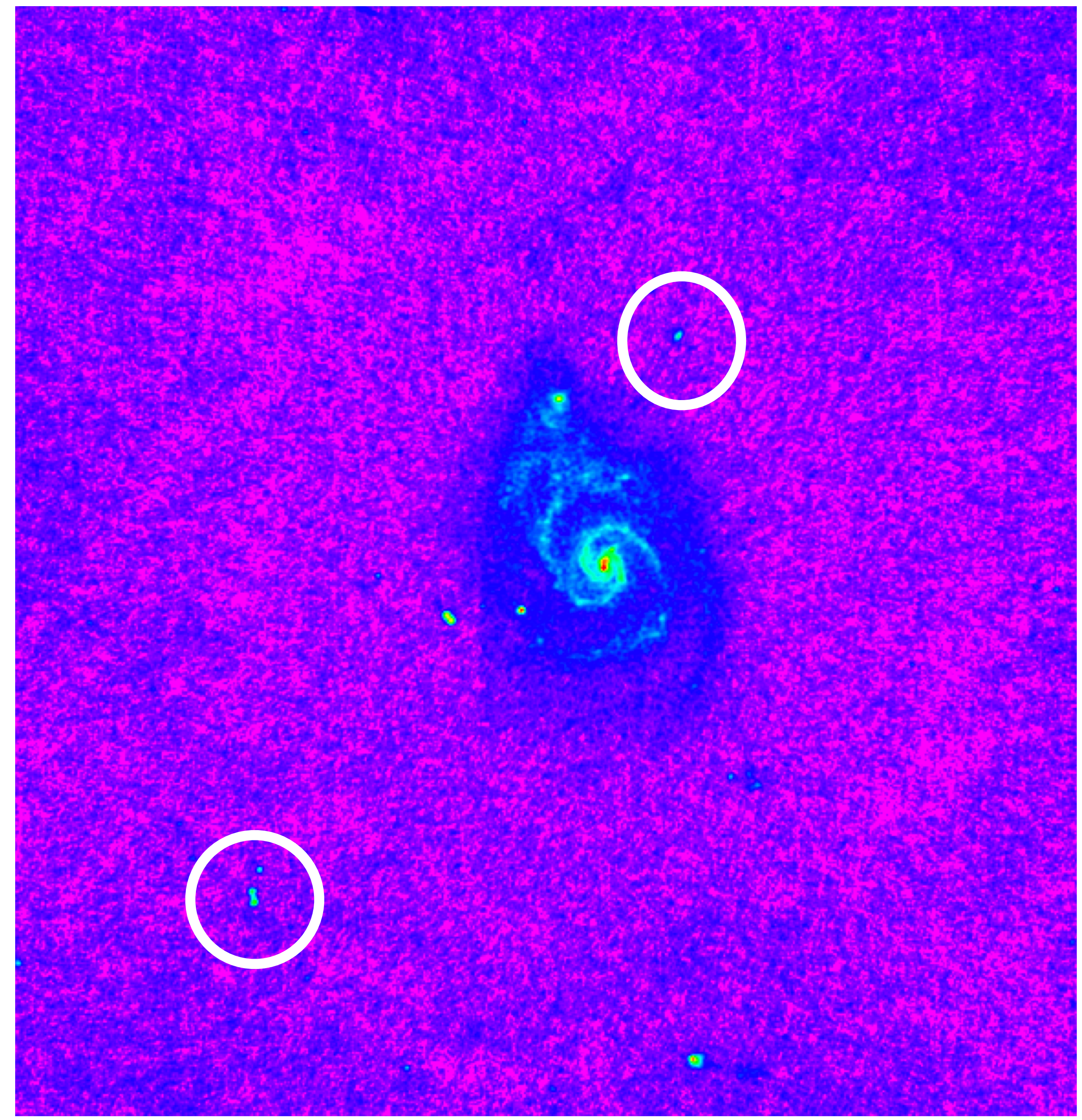
$$V(u,v,\nu) = I_0 \left[cos\left(\frac{2\pi\ \nu}{c}[b_x l_0 + b_y m_0]\right) + isin\left(\frac{2\pi\ \nu}{c}[b_x l_0 + b_y m_0]\right)\right]$$

$$\theta_S << \frac{\nu_0}{\Delta\nu}\theta_{beam}$$

$$\Delta S \sim S\frac{\pi^2}{36}\left(\frac{\Delta\nu}{\nu_0}\right)^2 \frac{\theta_S^2}{\theta_{beam}^2}$$

Disadvantages

- Assumes uniform uv coverage across frequencies
- Field of view over which works is restricted
- More residual flux away from phase centre



Cornwell, Holdaway and Uson (1993) A&A 271, 697, Sault (1994) A&A 107, 55

Continuum Subtraction [IMLIN]

- Make image for each channel (a data cube) by deconvolving the dirty beam
- For each pixel fit a lower order polynomial across the channels and subtract the polynomial values from the same pixel at all channels
- Assumes point spread function and noise to be same across the band

$$\Delta S \sim S \frac{\pi^2}{36} \left(\frac{\Delta \nu}{\nu_0} \right)^2 \frac{(\theta - \theta_S)^2}{\theta_{beam}^2}$$

Advantages

- Fast algorithm.
- Removes continuum at even large distance from the phase centre
- Statistics of continuum is estimated.

Disadvantages

- Imaging problems
- Residuals scales as distance from the source
- Do not work well for extended source and not good uv-coverage

Cornwell, Uson, Haddad, (1992), A&A, 258, 583

Continuum Subtraction [UVSUB]

- Make image combining all the line free channels.
- Calculate the visibility model for the continuum image
- Subtract this model from all the channels

$$\sigma_{Line} = \sigma_0 \sqrt{1 + \frac{1}{N}}$$

Dynamic Range

$$D = \frac{I_{Cont}^{peak}}{\sigma_{Line}}$$

Advantages

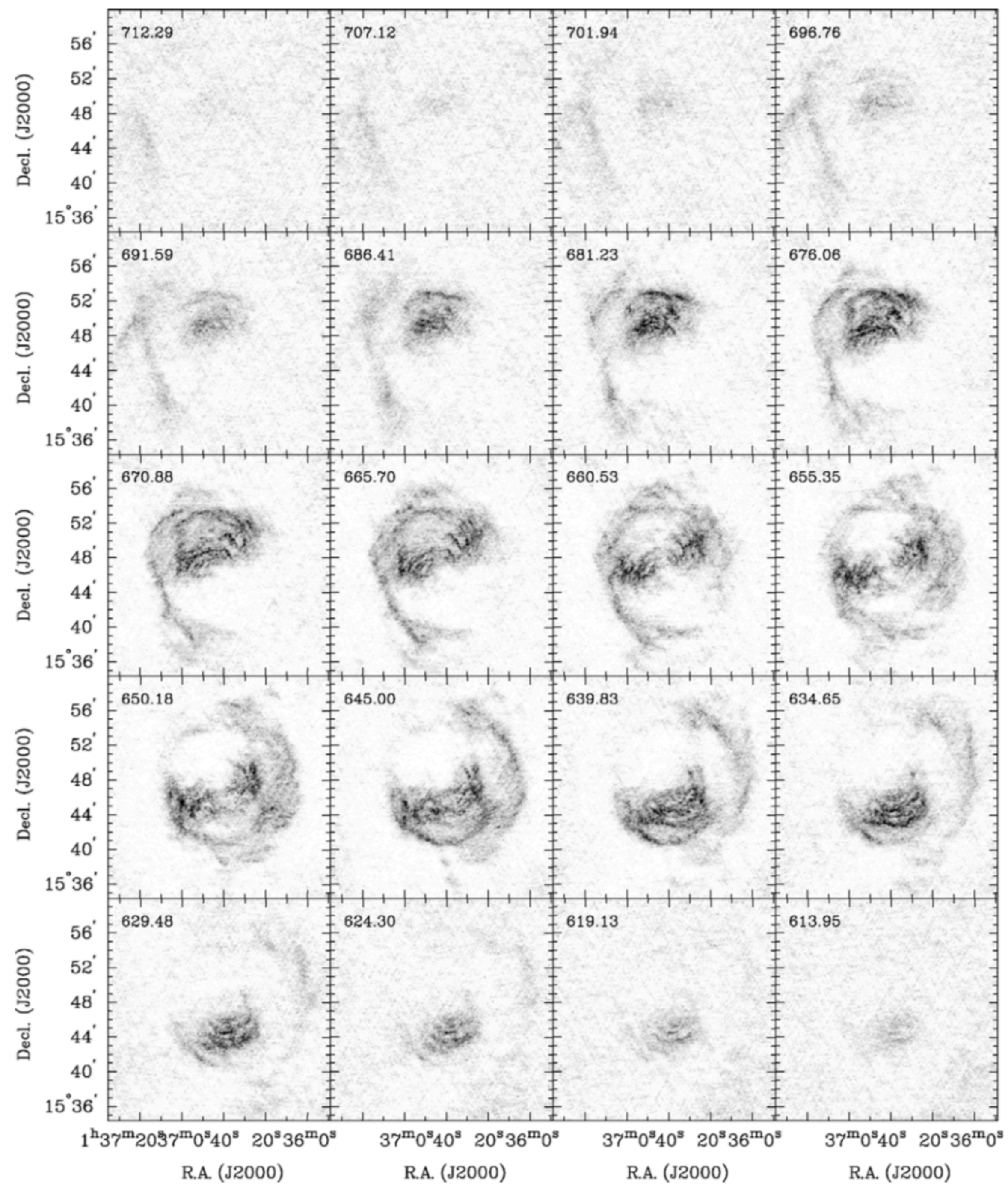
- Removes continuum at even large distance from the phase centre, residuals in the line free channels are practically zero!
- Gets robust continuum maps

Disadvantages

- Very slow!
- Requires good continuum image/model

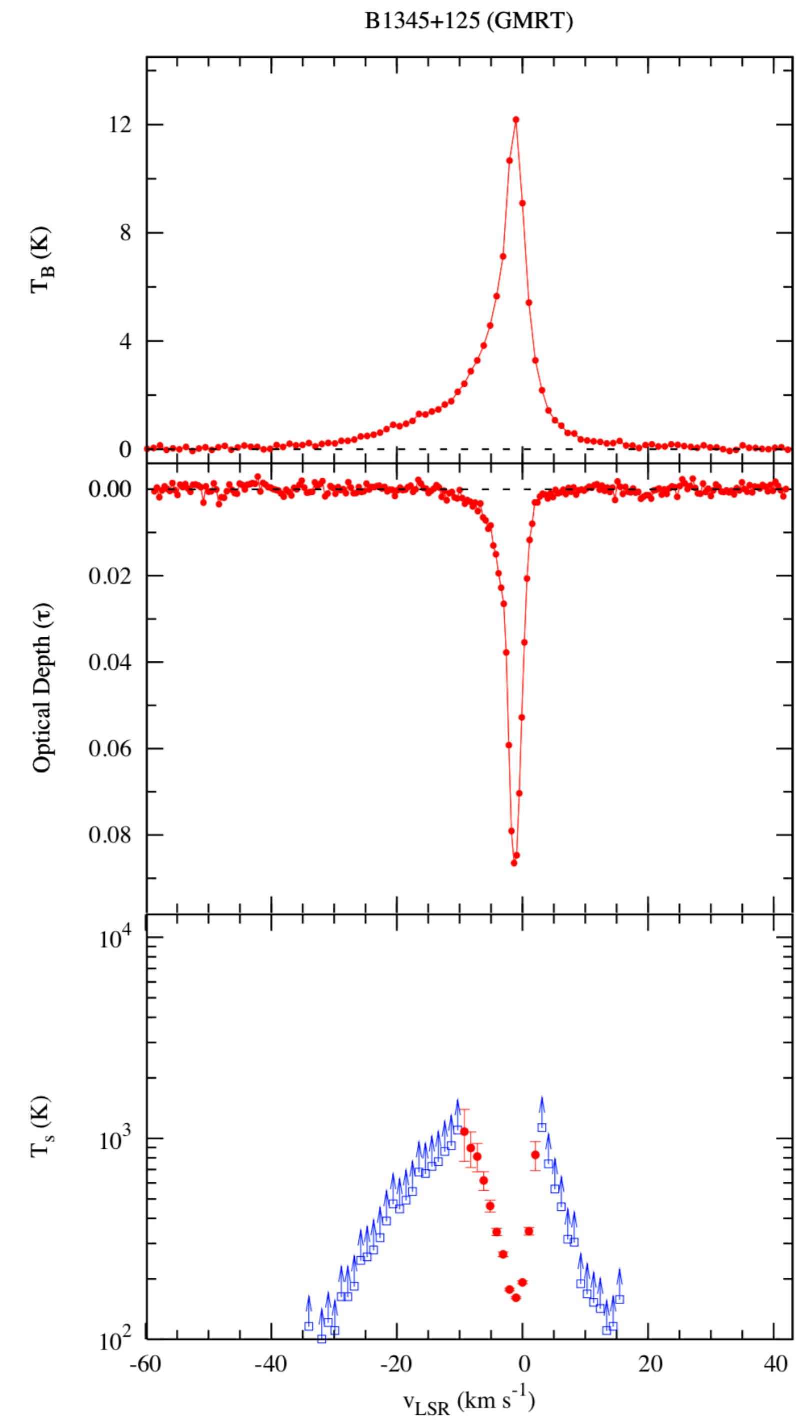
Science Cases: Data Cube

Extended Source: HI in Galaxy



Walter et al. (2008) ApJ, V-136, P- 2563

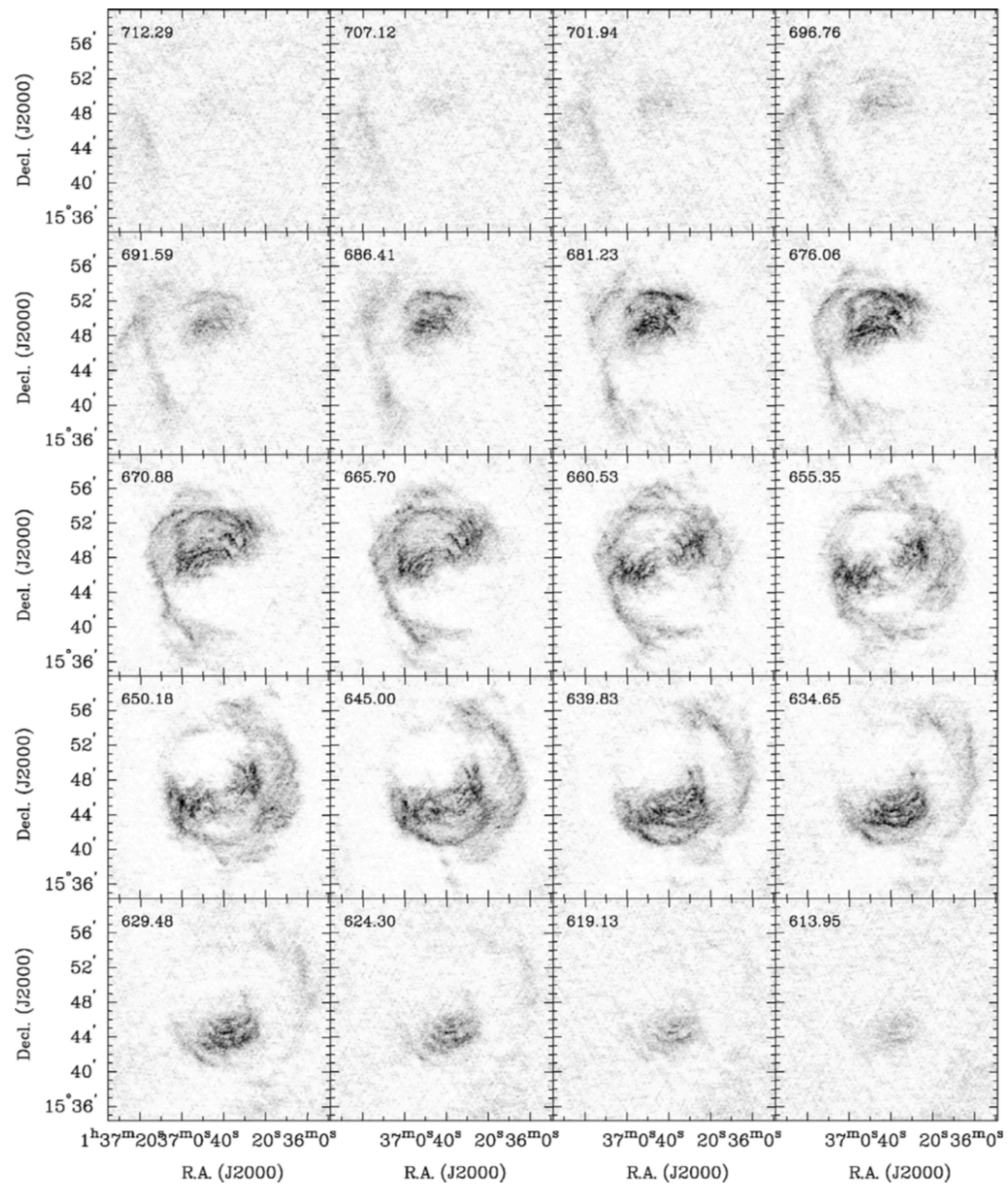
Point Source: Galactic HI absorption



Roy et al. MnRAS, 436, 3, (2013), 2352

Science Cases: HI in Galaxy

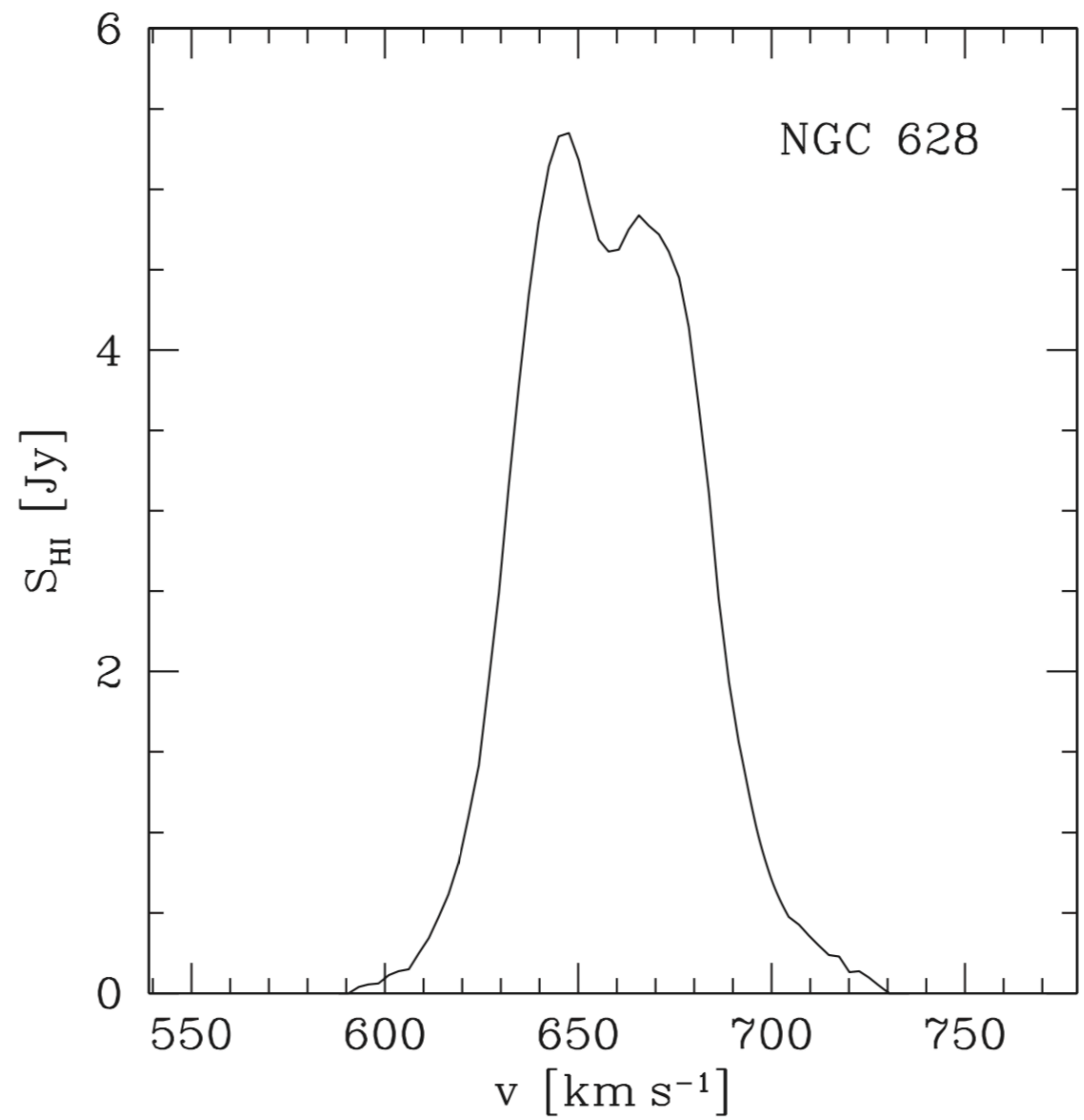
Extended Source: HI in Galaxy



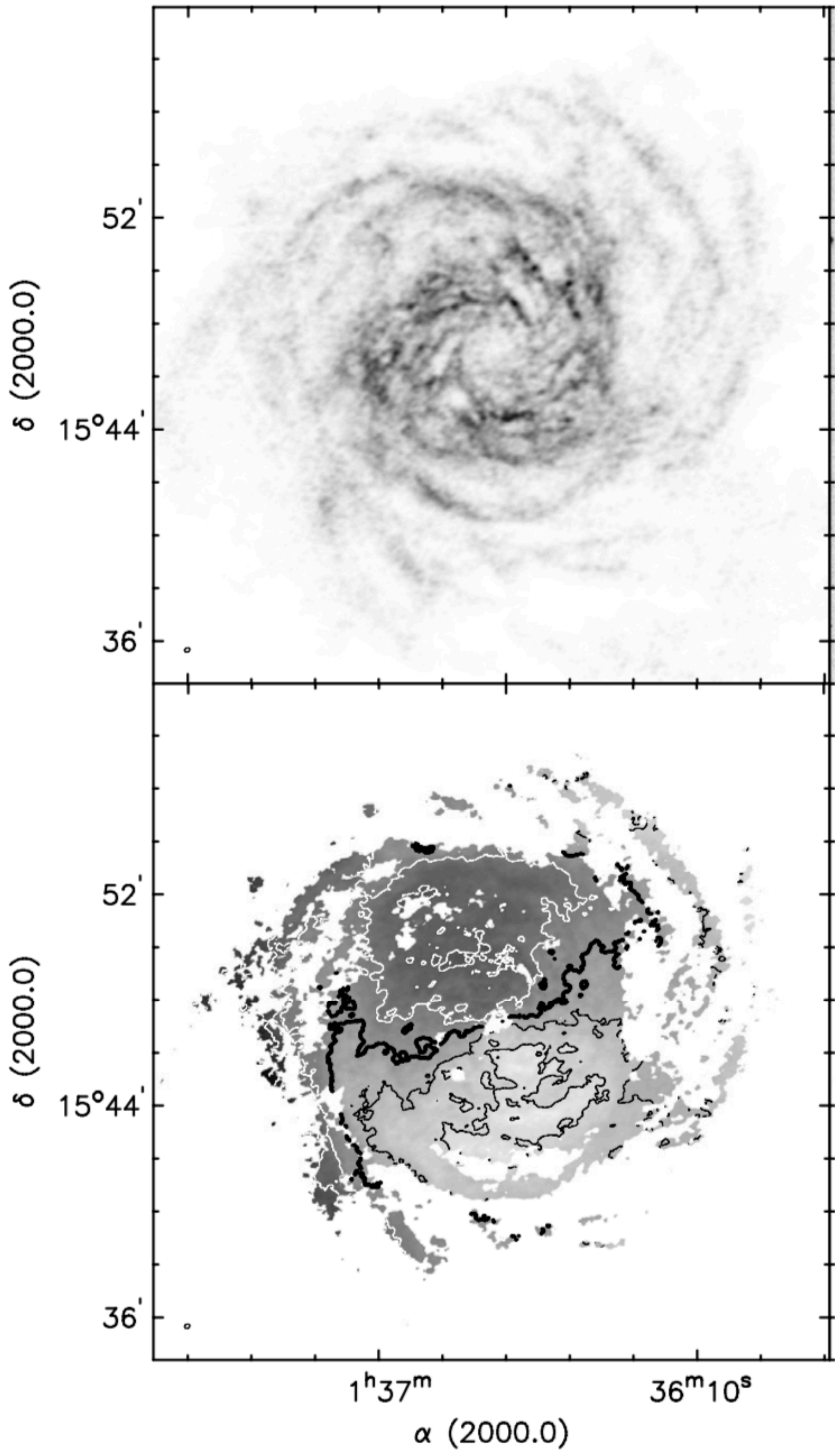
Walter et al. (2008) ApJ, V-136, P- 2563

Integrated Spectra

$$S(\nu) = \sum_{l,m} I(l,m,\nu)$$



Science Cases: HI in Galaxy

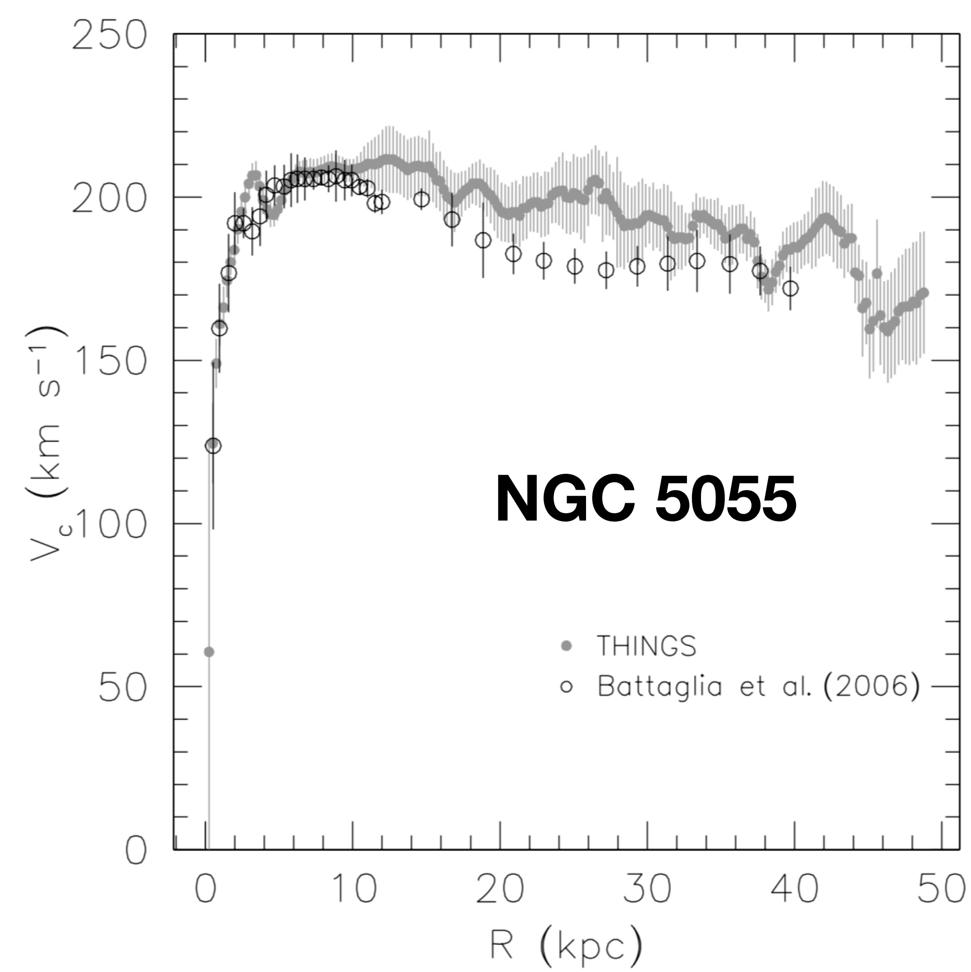


Walter et al. (2008) ApJ, V-136, P- 2563

Moment Maps

$$M_0(l,m) = \Delta\nu \sum_{i=1}^{NChan} I(l,m,\nu_i)$$

$$M_1(l,m) = \frac{\sum_{i=1}^{NChan} I(l,m,\nu)\nu_i}{\sum_{i=1}^{NChan} I(l,m,\nu_i)}$$

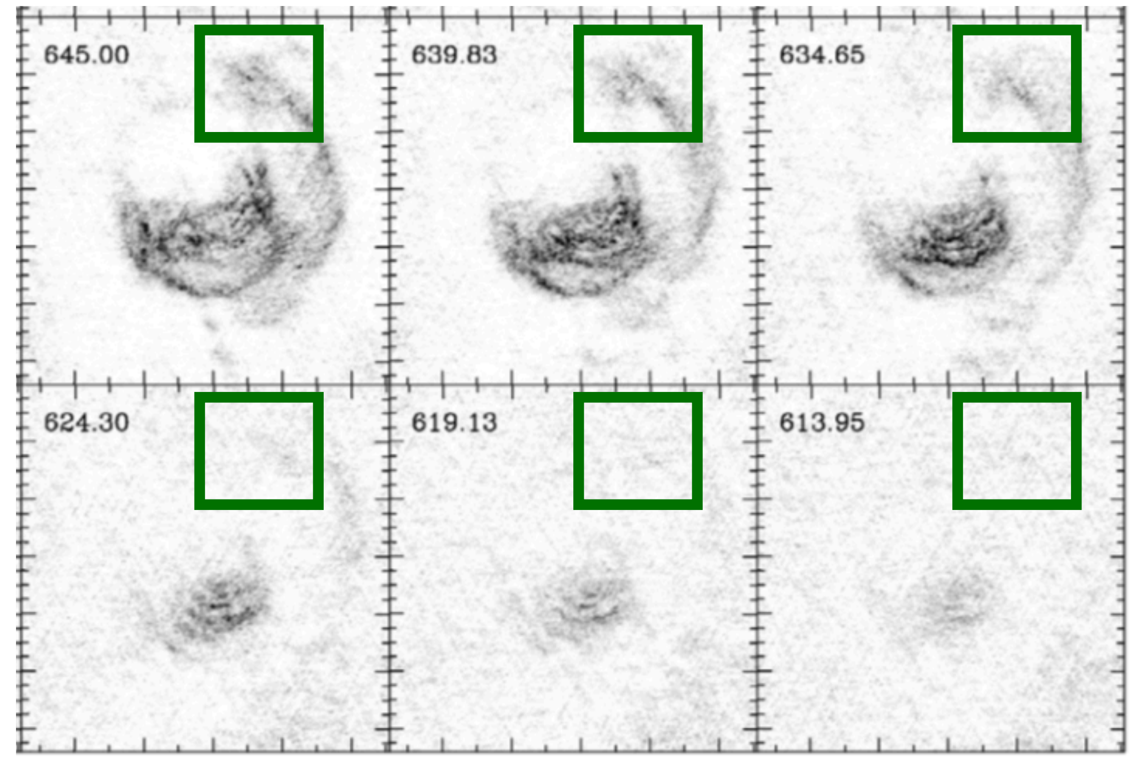


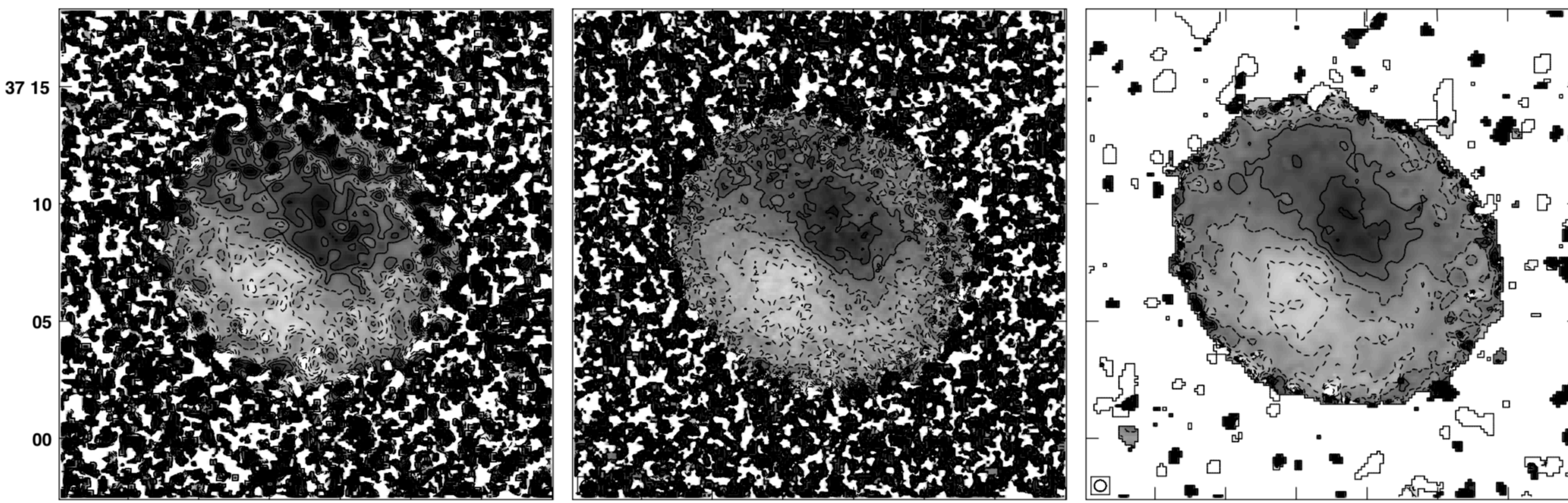
Rotation Curve

de Blok et al. (2008) ApJ V-136, P- 2648

Science Cases: HI Moments

- Use a cutoff to choose channels for moment maps.
- Average over channels and space first
- Spill over to nearby channels (from the good channels) even if the value is lower than cutoff





Spectral Line analysis II (M. P. Rupen), Synthesis Imaging in Radio Astronomy II

What we learned ?

- Observation and Techniques with interferometers
  - Observation Preparation [Nissim again!]
  - Calibration **[AIPS: POSSM, BPASS, UVFLG]**
  - Doppler correction **[AIPS: CVEL]**
  - Continuum Subtraction **[AIPS: UVSUB, UVLIN, IMLIN]**
  - Map making **[AIPS: IMAGR]**
- Science **[AIPS: ISPEC, MOMNT]**