Theory of Spectral Line Radio Interferometry

- Some science, some theory & some practice

Rob Beswick [JBCA/Manchester]

Outline

- Why do spectral line (multi-channel) observations?
  - Potential science goals
- What do we have to consider?
  - Proposals & planning
  - Potential problems & solutions
- The observations
- Data reduction
- Presentation of the results

Spectral-line (=) multi-channel

- Spectral line observations were originally observations of spectral lines
  - i.e. Radio Spectroscopy
- But now it is also common to observe even continuum in "spectral-line mode"
  - Enables imaging of wide-fields of view (see Tom Muxlow's lecture on Tuesday)

➔ **i.e. Multi-channel Observations**

- In the future,

  all observations will be taken in this mode!

Why spectral line-mode?

First and foremost Science driven

Spectral Line Science – This lecture

and

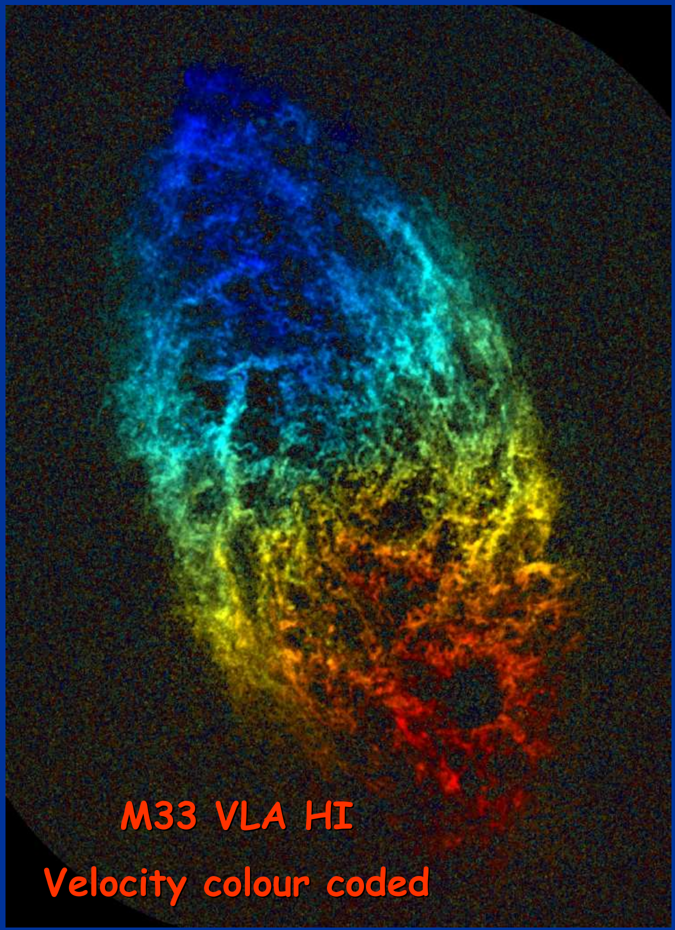
Wide-field imaging – Lecture on tuesday

Some spectral line science

- With Radio interferometry we can observe various radio lines both in emission (inc Masers) and absorption
- Providing PHYSICAL information
  - Gas composition, column densities, temperature tracers, density tracers, velocity fields etc..
    - Basically physics.
- Gas is important as it is the fuel that makes the stars & feeds accretion

Giving you a 3rd axis

- Sample the frequency axis
  - Gets you velocity information
  - Estimate the amount of gas
  - And some handle on excitation condition
  - And even the chemical history
- Result is not a map, but a cube
  - In: α,δ,ν or α,δ,v
  - A challenge to handle
    - Often VERY large data-sets
      - Recent EVN experiments >100GB
  - A challenge to visualize
    - Channel maps and movies
    - Moment maps: intensity, velocity, width
      - 3D rendering and visualization software…
  - A challenge to analyze…
    - Model for structure & kinematics
    - Optical depth effects
    - Excitation: collisions vs radiation
      - Masers amplify these in a non-linear way



Thilker, Braun, & Walterbos

Important radio lines

Radio spectral lines below 1THz designated as ‘important’ by the IAU

1. Deuterium (DI) 327.384 MHz
2. Hydrogen (HI) 1420.406 MHz
3. Hydroxyl radical (OH) 1612.231 MHz
4. Hydroxyl radical (OH) 1665.402 MHz
5. Hydroxyl radical (OH) 1667.359 MHz
6. Hydroxyl radical (OH) 1720.530 MHz
7. Methyladyne (CH) 3263.794 MHz
8. Methyladyne (CH) 3335.481 MHz
9. Methyladyne (CH) 3349.193 MH
10. Formaldehyde (H2CO) 4829.660 MHz
11. Methanol (CH2OH) 6668.518 MHz
12. Ionized Helium Isotope (3HeII) 8665.650 MHz
13. Methanol (CH3OH) 12.178 GHz
14. Formaldehyde (H2CO) 14.488 GHz
15. Cyclopropenylidene (C3H2) 18.343 GHz
16. Water Vapour (H2O) 22.235 GHz
17. Ammonia (NH3) 23.694 GHz
18. Ammonia (NH3) 23.723 GHz
19. Ammonia (NH3) 23.870 GHz
20. Silicon monoxide (SiO) 42.519 GHz
21. Silicon monoxide (SiO) 42.821 GHz
22. Silicon monoxide (SiO) 42.880 GHz
23. Silicon monoxide (SiO) 43.122 GHz
24. Silicon monoxide (SiO) 43.424 GHz
25. Carbon monosulphide (CS) 48.991 GHz
26. Deuterated formylium (DCO+) 72.039 GHz
27. Silicon monoxide (SiO) 86.243 GHz
28. Formylium (H13CO+) 86.754 GHz
29. Silicon monoxide (SiO) 86.847 GHz
30. Ethynyl radical (C2H) 87.300 GHz
31. Hydrogen cyanide (HCN) 88.632 GHz
32. Formylium (HCO+) 89.189 GHz
33. Hydrogen isocyanide (HNC) 90.664 GHz
34. Diazenylium (N2H) 93.174 GHz
35. Carbon monosulphide (CS) 97.981 GHz
36. Carbon monoxide (C18O) 109.782 GHz
37. Carbon monoxide (13CO) 110.201 GHz
41. Carbon monoxide (C17O) 112.359 GHz
42. Carbon monoxide (CO) 115.271 GHz
43. Formaldehyde (H213CO) 137.450 GHz
44. Formaldehyde (H2CO) 140.840 GHz
45. Carbon monosulphide (CS) 146.969 GHz
46. Water vapour (H2O) 183.310 GHz
47. Carbon monoxide (C18O) 219.560 GHz
48. Carbon monoxide (13CO) 220.399 GHz
49. Carbon monoxide (CO) 230.538 GHz
50. Carbon monosulphide (CS) 244.953 GHz
51. Hydrogen cyanide (HCN) 265.886 GHz
52. Formylium (HCO+) 267.557 GHz
53. Hydrogen isocyanide (HNC) 271.981 GHz
54. Dyazenulium (N2H+) 279.511 GHz
55. Carbon monoxide (C18O) 312.330 GHz
56. Carbon monoxide (13CO) 330.587 GHz
57. Carbon monosulphide (CS) 342.883 GHz
58. Carbon monoxide (CO) 345.796 GHz
59. Hydrogen cyanide (HCN) 354.484 GHz
60. Formylium (HCO+) 356.734 GHz
61. Dyazenulium (N2H+) 372.672 GHz
62. Water vapour (H2O) 380.197 GHz
63. Carbon monoxide (C18O) 439.088 GHz
64. Carbon monoxide (13CO) 440.765 GHz
65. Carbon monoxide (CO) 461.041 GHz
66. Heavy water (HDO) 464.925 GHz
67. Carbon (CI) 492.162 GHz
68. Water vapour (H218O) 547.676 GHz
69. Water vapour (H2O) 556.936 GHz
70. Ammonia (15NH3) 572.113 GHz
71. Ammonia (NH3) 572.498 GHz
72. Carbon monoxide (CO) 691.473 GHz
73. Hydrogen cyanide (HCN) 797.433 GHz
74. Formylium (HCO+) 802.653 GHz
75. Carbon monoxide (CO) 806.652 GHz
76. Carbon (CI) 809.350 GHz

Plus various others (e.g. Radio Recombination lines etc)

Important radio lines

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Centimetre/decimetre line

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13. **Methanol (CH2OH) 6668.518 MHz**
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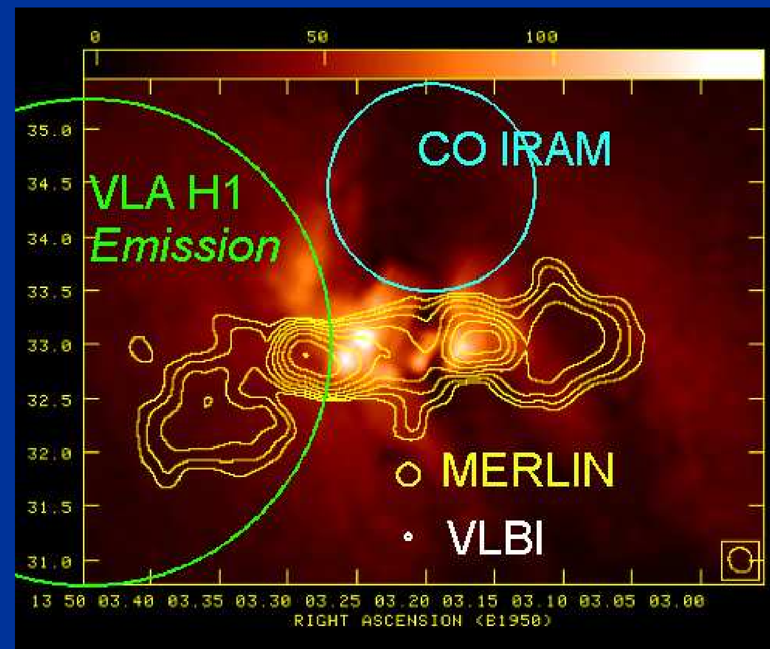
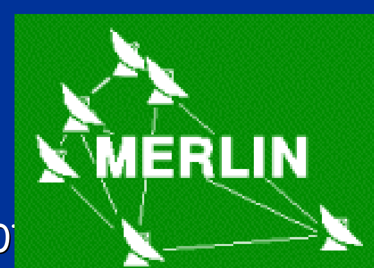
Plus various others (e.g. Radio Recombination lines etc)

Observing gas – resolution achievable with interferometer

- H1 emission gives ~>5" (VLA, WSRT etc)
- mm synthesis (CO) gives ~>0.5-1"
  - IRAM, KARMA, SMA
- Via Absorption (H1, OH etc)
  up to arcsec-to-mas
  - WSRT, VLA, MERLIN, VLBI etc
- Masers (e.g. OH, H2O, SiO)
  up to arcsec-to-<mas
  - VLBI, MERLIN etc



- FUTURE instruments such as SKA & ALMA will add more..



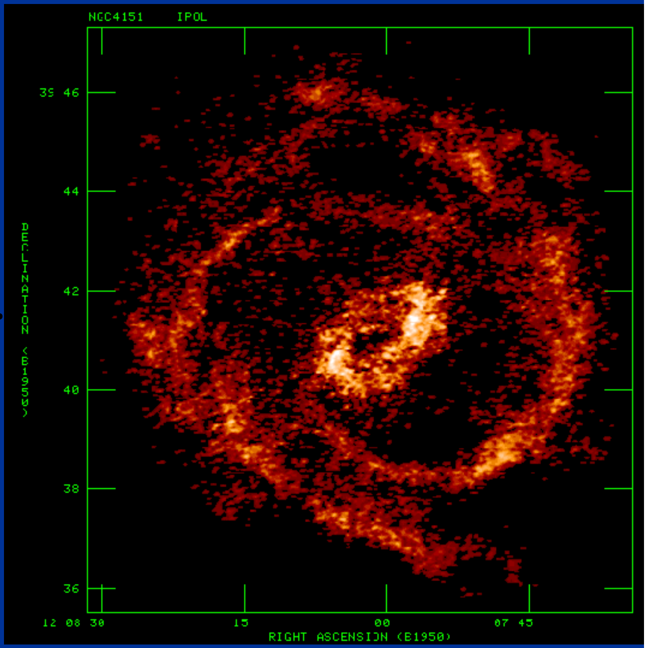
Types of spectral line observations

- Emission experiments (non-stimulated)
  - E. g. H1 emission, CO etc
    - Low T_B implies lower resolution (for H1)
- Absorption experiments
  - Various lines (e.g. H1, OH etc)
    - Requires a Background source
    - T_B is that of the background source implies can be observed at high resolution (VLBI, MERLIN etc)
- Maser experiments (Stimulated emission)
  - E.g. OH, methanol, water, SiO
    - Stimulated emission requires certain physical conditions
    - Can be very high T_B implies VLBI sources

Radio observations of HI at high resolution

$$S = \frac{2kT_b\Omega_b}{\lambda^2}$$

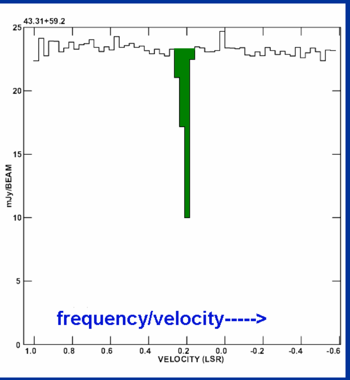
- Small brightness temperature T_b~100K
- Small beam
- Large wavelength
- Narrow bandwidth (line width)
- Rayleigh-Jeans equation implies that
  - HI Emission studies are limited to resolutions ~few arcseconds at best.



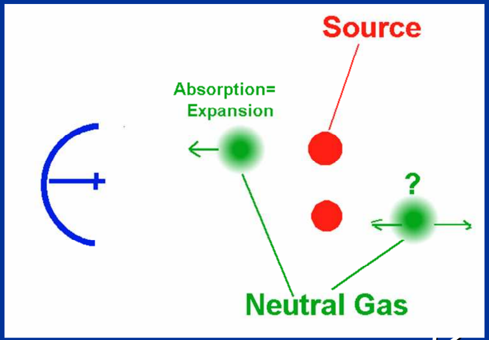
H1 emission in NGC4151 (Mundell et al '99)

The advantages of *absorption* studies

- **Absorption line strength**
  - Determined by the brightness temperature of the background
  - Many Active Galaxies emit Synchrotron $T_b > 10^5$ K
    - (compare with 100K excitation temperature for H1)



- **Angular resolution**
  - arcsecs- few mas 100pc- <1pc
  - Limited by the detectability of the background
- **Geometry -** Absorber must be in front!
  - ie Blueshift must = expansion
  - & Redshift=infall

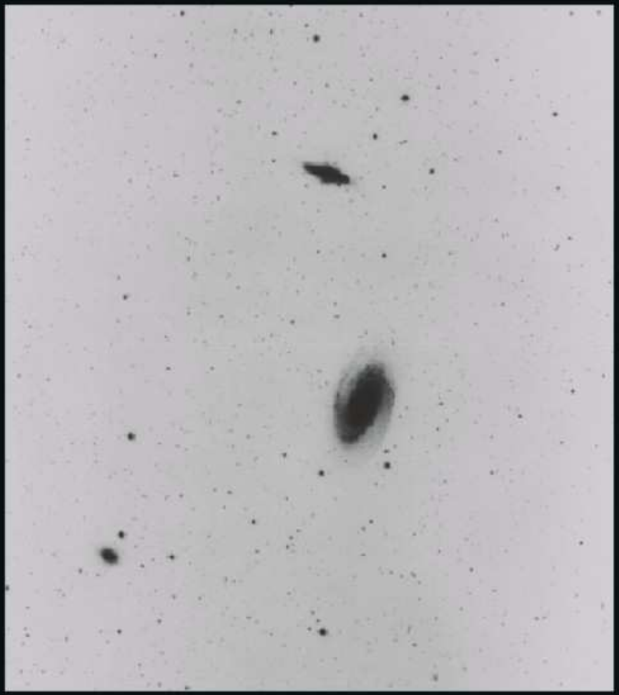


Science examples

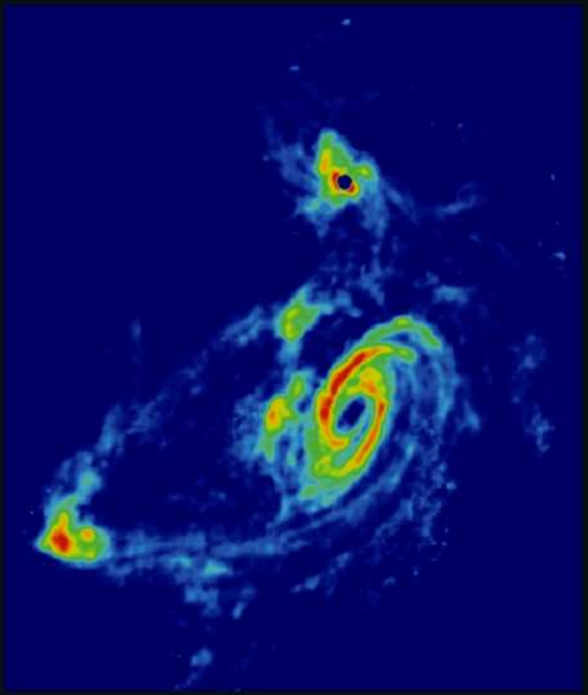
Large scale gas distribution

TIDAL INTERACTIONS IN M81 GROUP

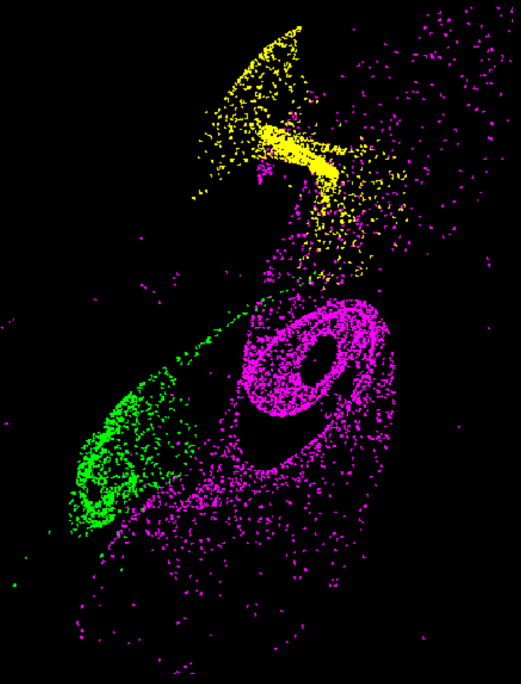
Stellar Light Distribution



21 cm HI Distribution

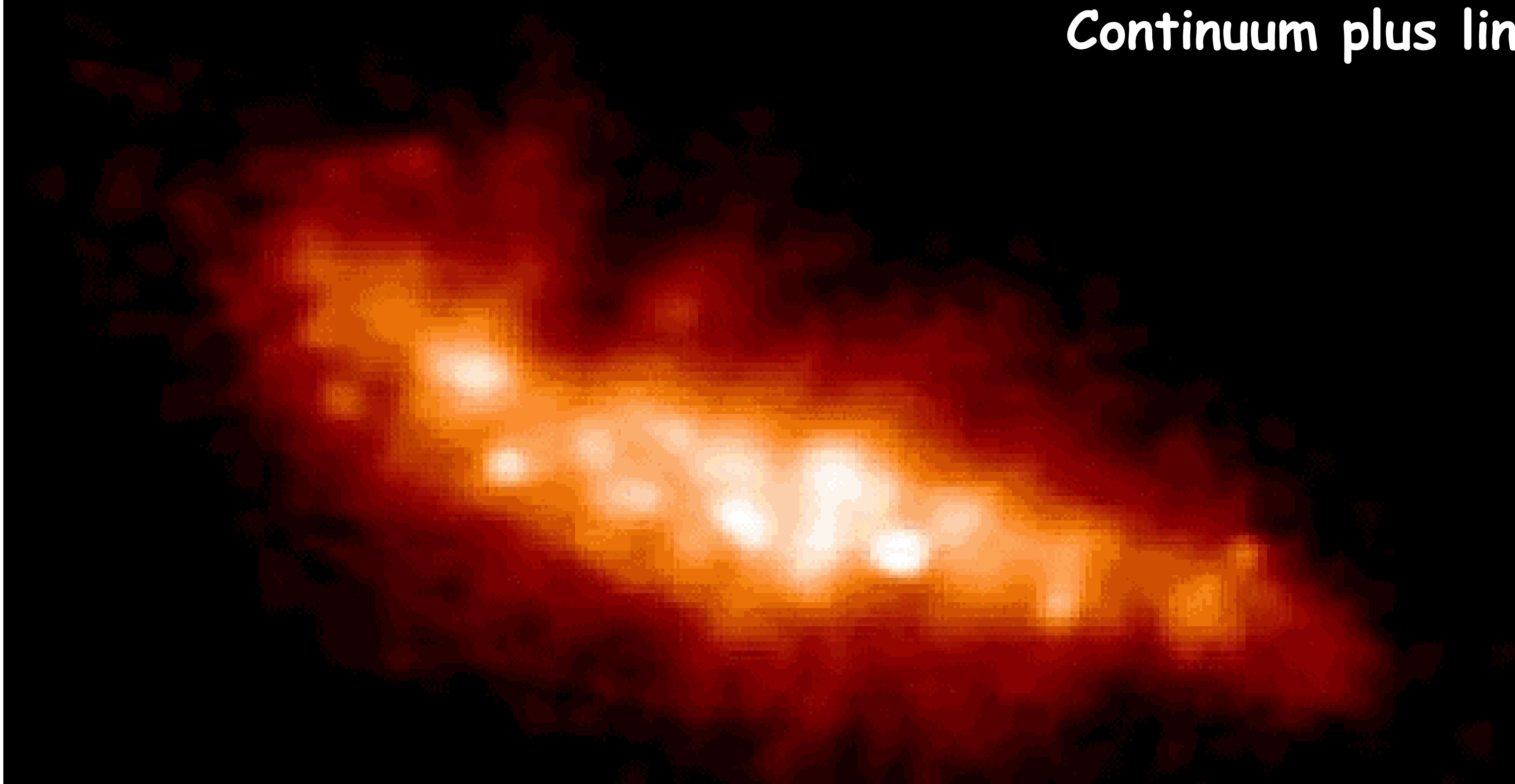


Numerical simulations



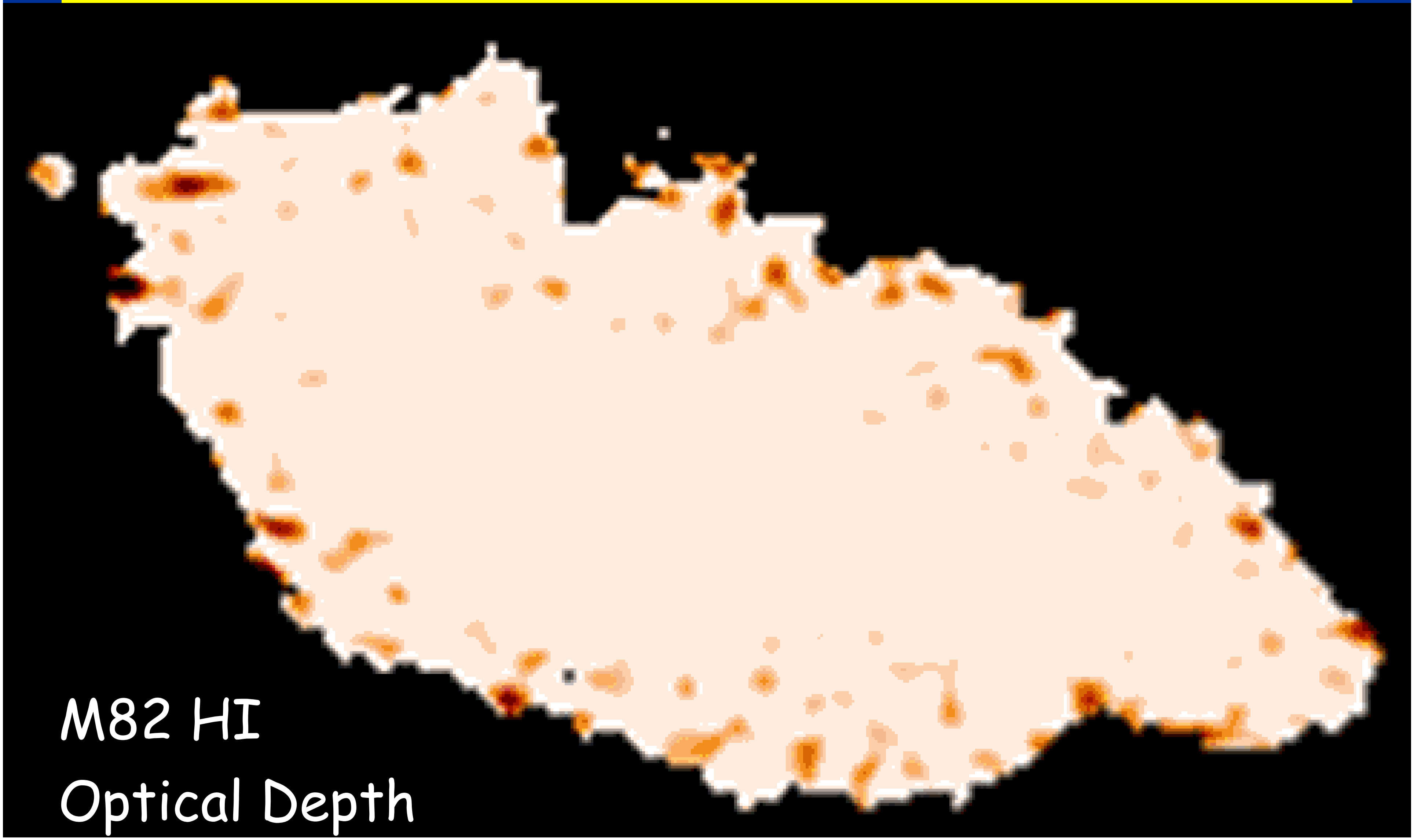
M82 H1 absorption

Continuum plus line

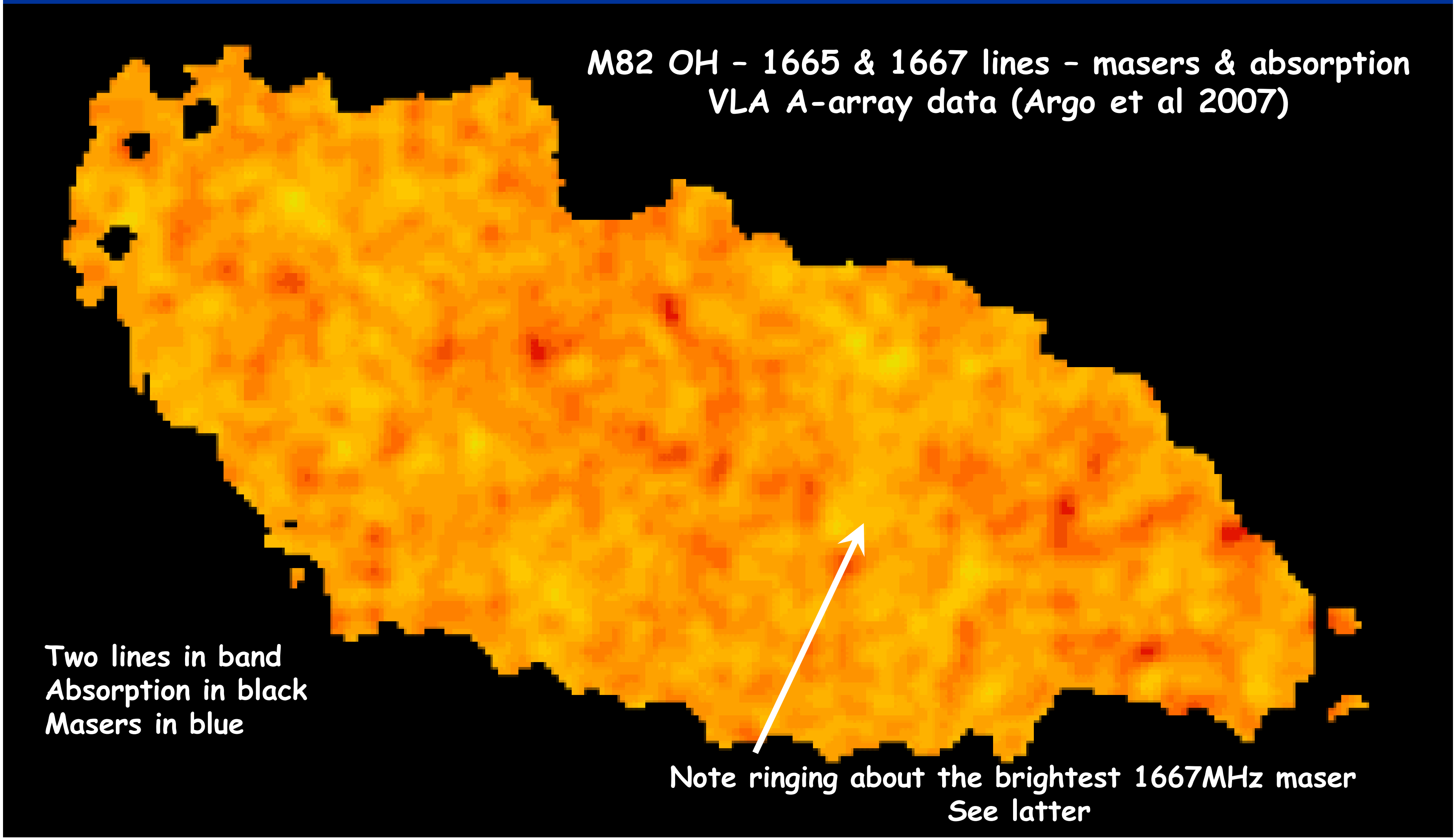


M82 HI (Wills, Pedlar et al)

M82 H1 Optical depth

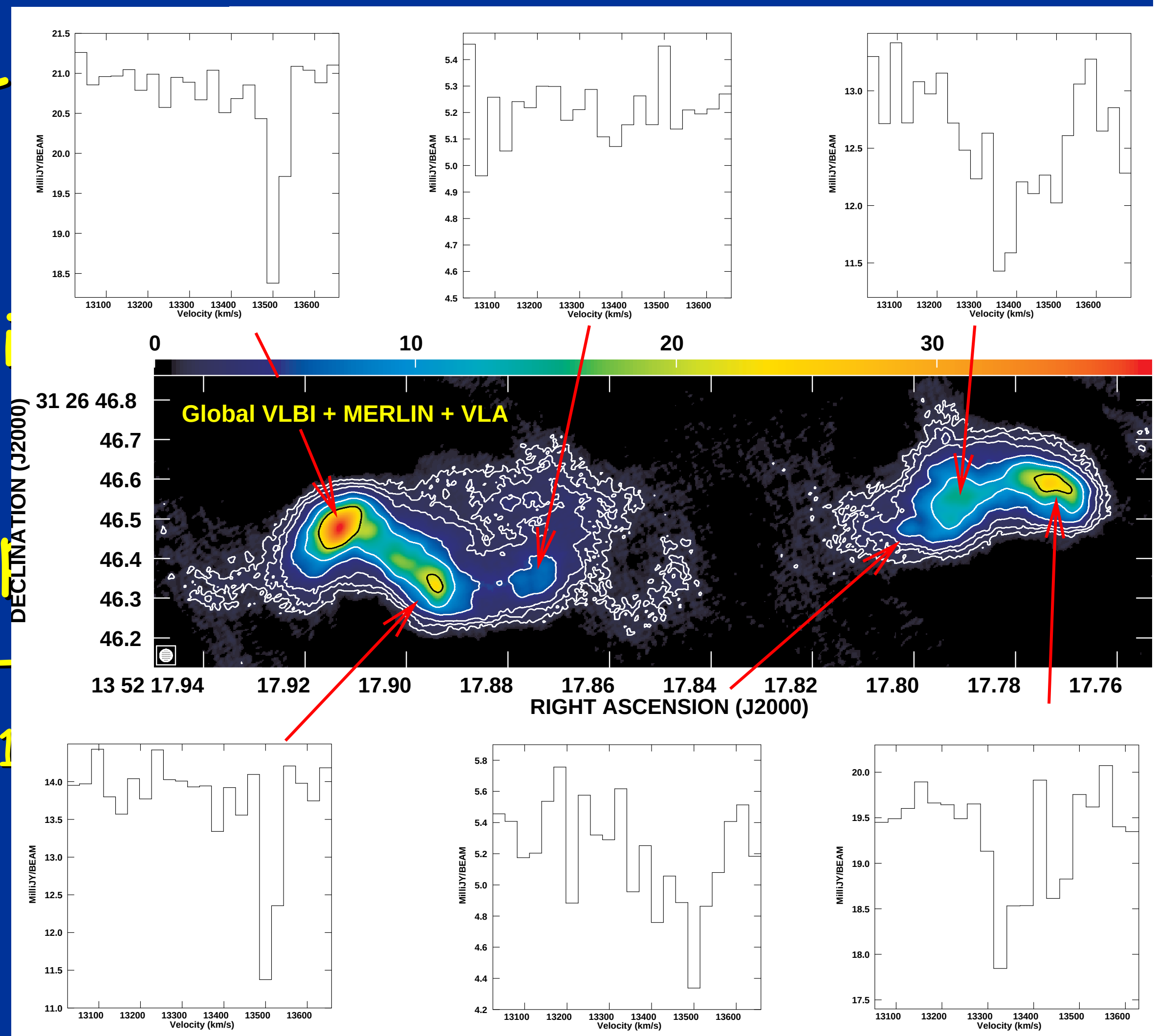


Continuum subtracted cube



Example 1: HI Absorption in 3C293

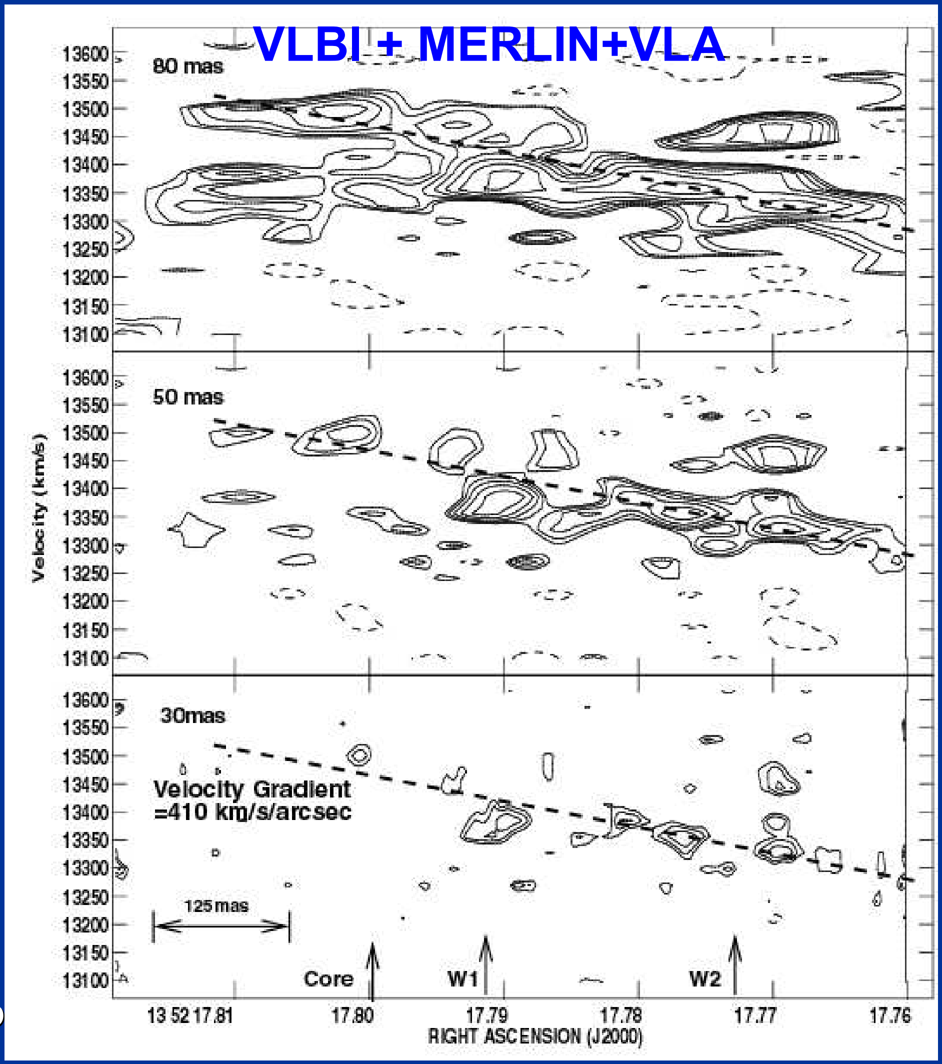
- Extensive MERL
  HI absorption
- Eastern side :-
  Narrow absorpti
- Western side :-
  broad(er) absor
- Opacities ~0.01-
- $N_H \sim 10^{21}$ atoms^{-1}



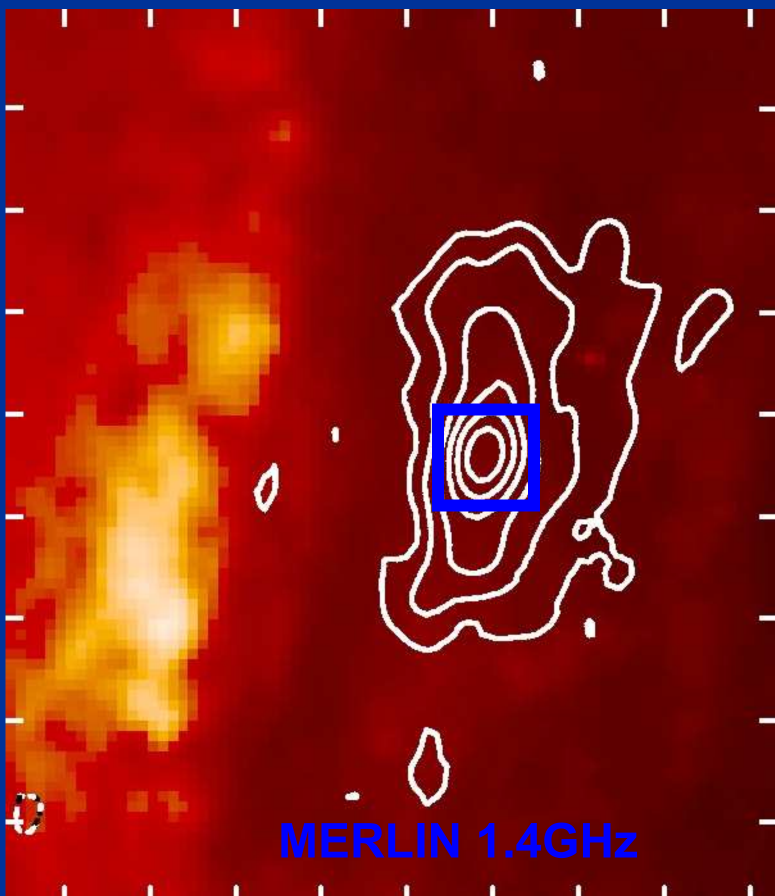
3C293 H1 rotating gas ring??

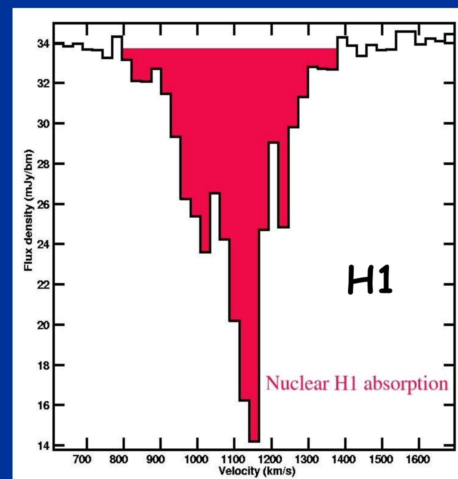
- On ~200mas angular scales. Velocity gradient centred upon the core(?)
  - Multi component (0.5 kpc ring/disk?)

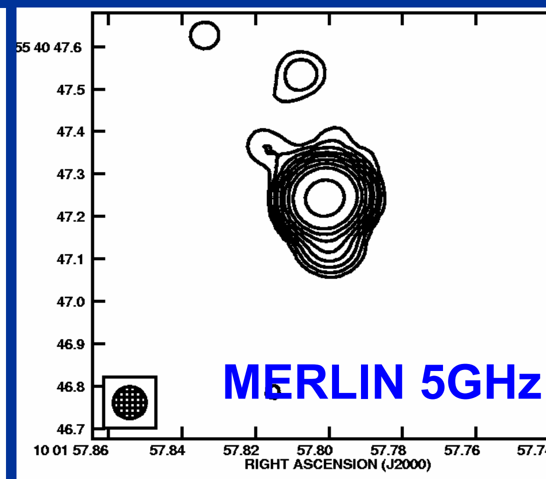
• However stepping up the resolution the absorption breaks up many composite components.
• Lack of illuminating background continuum.

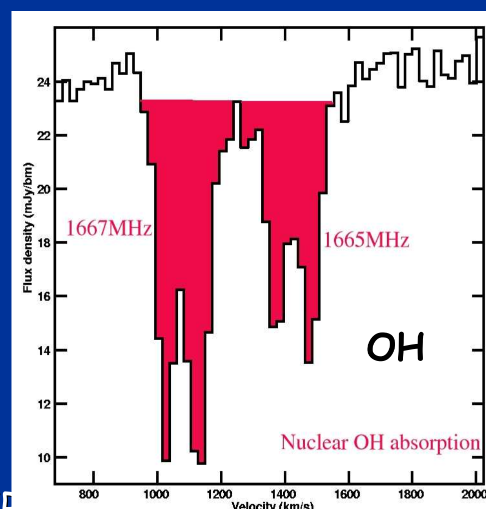


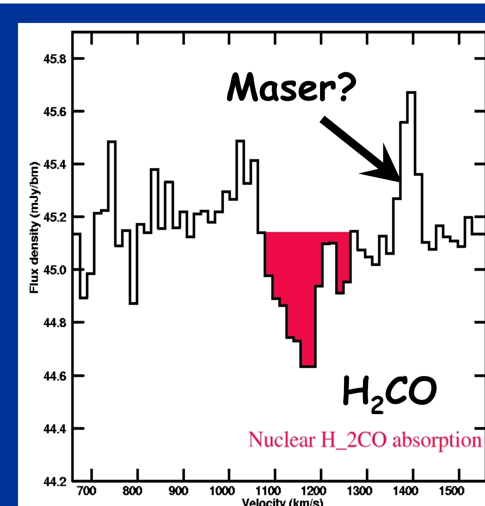
Example of multiple lines: NGC3079 – Seyfert 2 +(nuclear starburst?)



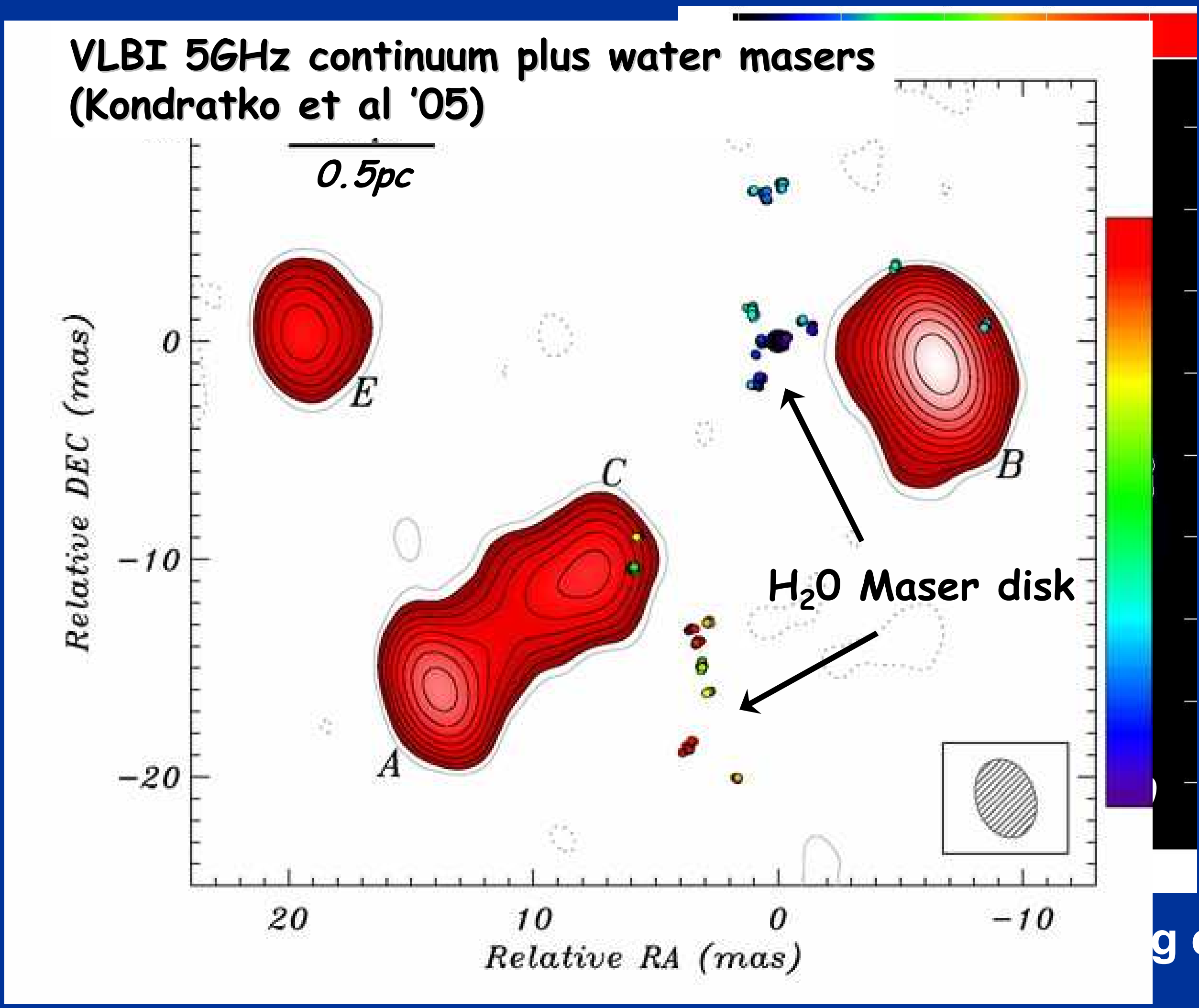


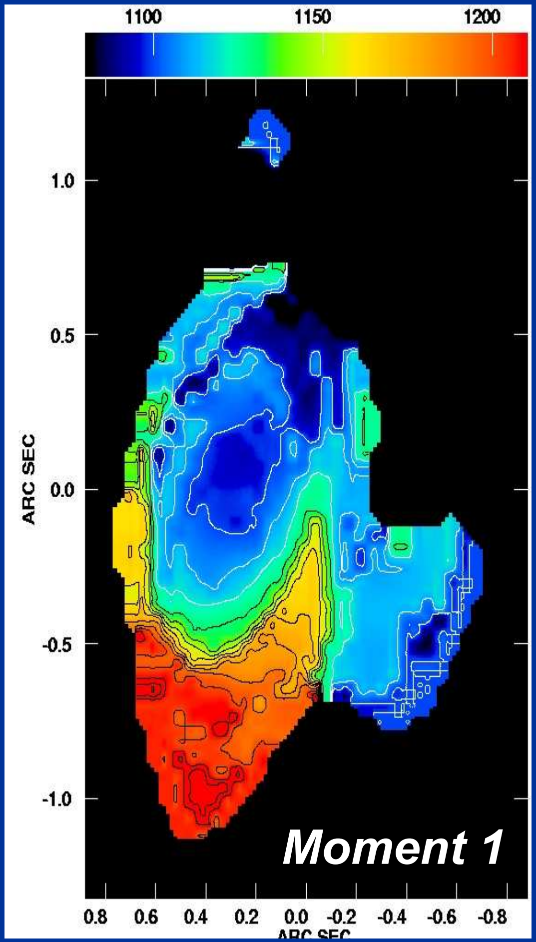






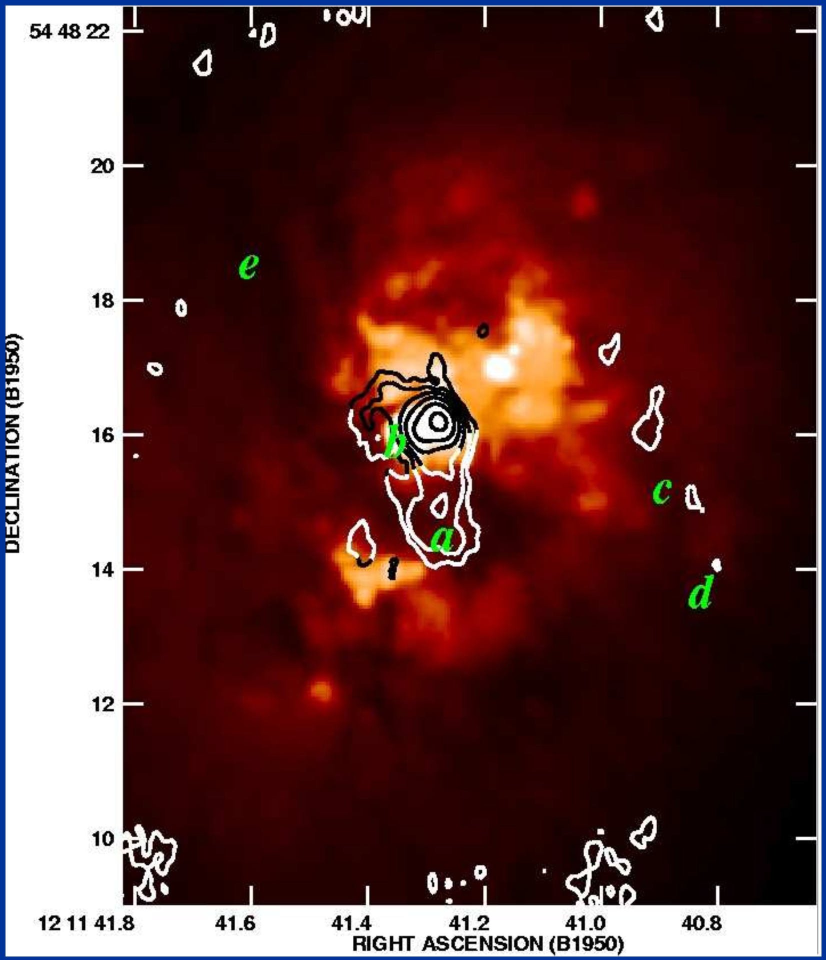
NGC3079 (Sy2): MERLIN H1 absorption





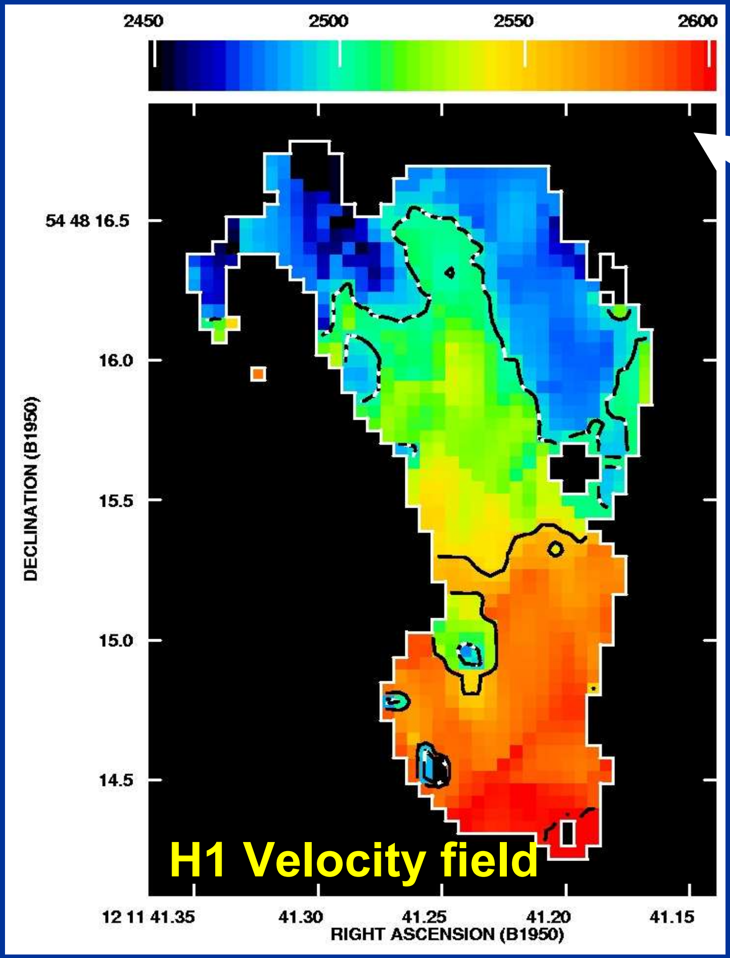
g et al. in Prep)

Medusa Merger: Dust Lane in CO & H1

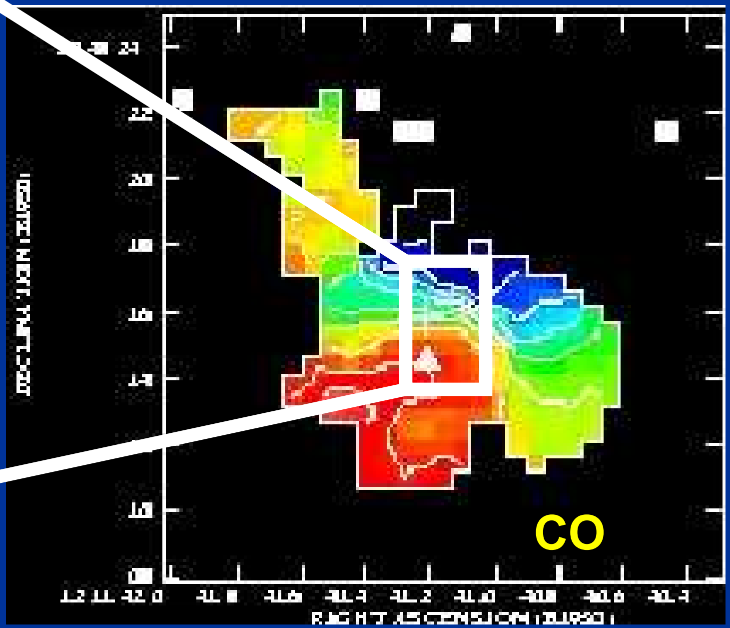


- Note also that the dust lane is co-spatial with the CO emission (Aalto & Huttemeiser '00)
- Implies probable association of dust lane, CO, and H1.
- And all are probably in front of the radio cont.

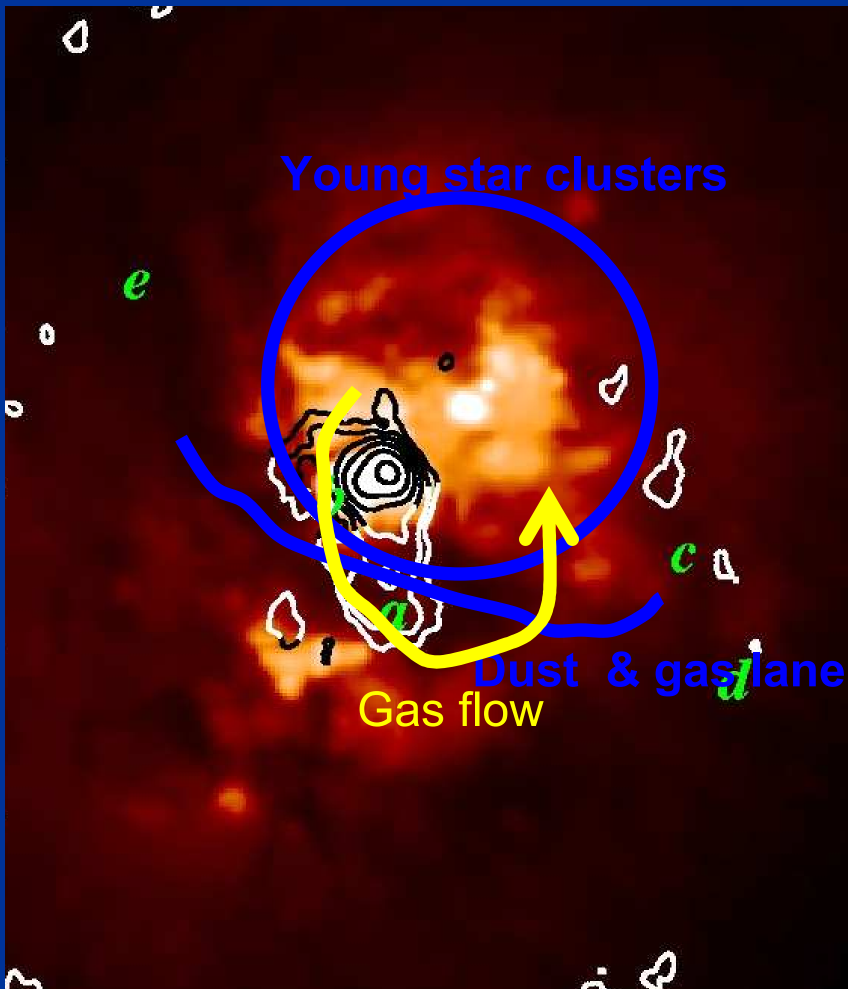
CO & H1 Velocity fields



- Sub arcsecond H1 velocity field
  - ~ north-south vel. grad.
  - Some twisting and detail now visible in the H1 velocity field.



Fuelling of the Starburst?



- Most of the gas & dust resides toward south of the source.
- Whereas the majority of the star formation is to the N & NW.
- Gas circulation from the dust lane to the SF regions.
- & Lowest H1 absorption columns toward north of radio source.
  - Gas & dust in reservoir in dust lane region.
  - Less gas in front of the northern radio source.
- i.e. gas being circulated with some being converted to stars.

Planning an experiment

- Know your science Goals
- Lines to be observed
  - What is the observing frequency (redshifted)
- Instruments
  - Which observe the correct frequency?
  - Resolution required?
  - Sensitivity required?

Aside : Velocity/distance conventions & Doppler tracking

- The redshifted/blueshifted velocity of a source is a crucial number as this dictates what sky frequency a line is observed.
  - Getting it wrong by a small amount means you can miss your line completely and waste all that precious telescope time! (believe me I know!)

Aside: Velocity/distance conventions & Doppler tracking

- Red or blue-shifted velocities are usually quoted in either the 'Radio' or 'Optical' conventions. These are approximations of the relativistic Doppler equation.
  - Relativistic ->

$$v = c\frac{\nu_0^2 - \nu^2}{\nu_0^2 - \nu^2}$$

  - Optical approx ->

$$v_{Optical} = c(\frac{\nu_0}{\nu} - 1) = c(1 - \frac{\lambda_0}{\lambda}) = cz$$

  - Radio approx ->

$$v_{Radio} = c(1 - \frac{\nu}{\nu_0})$$

These are not the same and diverge as redshift increases

Rest Frames

Correct for	Amplitude	Rest frame
Nothing	0 km/s	Topocentric
Earth rotation	< 0.5 km/s	Geocentric
Earth around Sun (inc barycenter earth-moon)	< 30 km/s	Heliocentric ≈ barycentric
Sun peculiar motion (inc planets barycenter)	< 20 km/s	Local Standard of Rest
Galactic rotation	< 300 km/s	Galactocentric

- Correcting these motions done in array model
  - Usually part of fringe stopping in connected elements
  - But VLBI done with fixed frequency
    - Alignment must be done later, even off-line
      - Taking into account details of the correlator model
    - Otherwise narrow (maser) lines may be 'blurred'

Aside: Velocity/distance conventions

- These velocities then need to be corrected relative to a rest frame:
  - Earth surface is not a good rest frame because of diurnal (rotation) and annual (orbit about the sun) motions. Up to ~0.5km/s & 30km/s respectively
  - Common rest frames used in Astronomy are
    - Local Standard of Rest
      - **Various definitions used. E.g. the solar system barycentre is moving at 20 km/s in the direction of (RA,DEC) = 18 hours,+30 degrees (B1900) (this is called ``kinematic'' definition of the LSR)**
      - **Mainly used in Galactic work**
    - **Barycentric**
    - **Heliocentric (very close but slightly different to Barycentric)**
      - **Most extragalactic work uses these solar system based rest frames.**

Aside: Velocity/distance conventions

- Summary:
  - Know what your source velocity is and what convention is used.

    - Radio-LSR -- Mainly Galactic work

    or

    - Optical-heliocentric – Mainly extrgalactic work

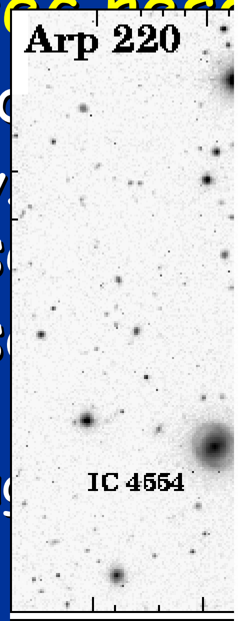
An example 1 - experiment

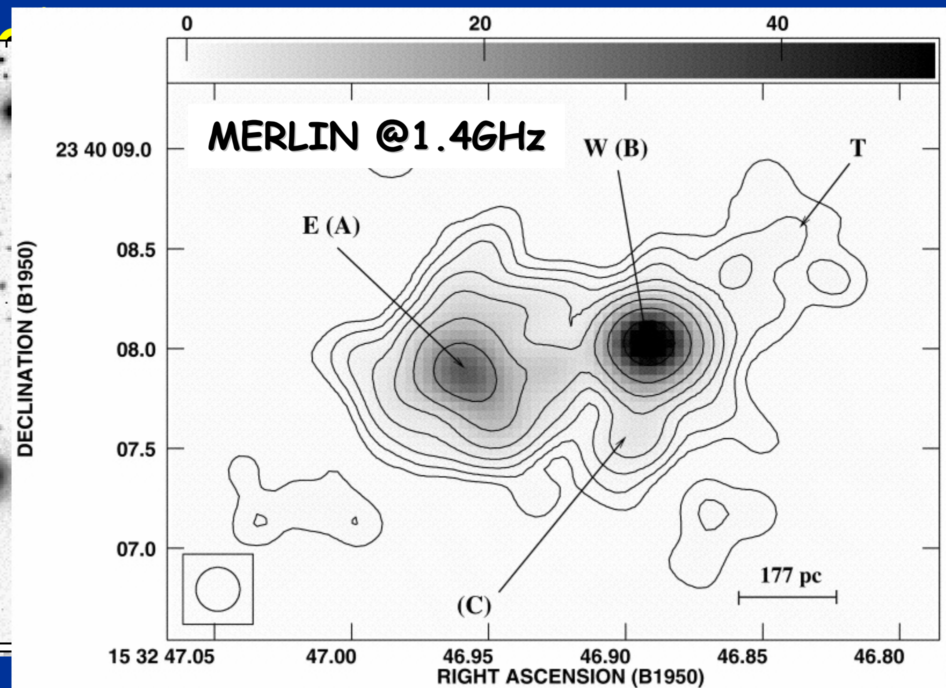
- I want to observe cold neutral gas (H1) in a merging galaxy (say Arp220) at the sub-arcseond resolution, in order to separate the two merging nuclei

1. Observing frequency?
   - observe H1 line, rest-freq=1420.406MHz
   - Arp220 is at a distance of 78Mpc
   - ➔ $V_{opt\text{-}hel}$=5434km/s → sky freq =1395.0..MHz

Choose an interferometer

- Need sub-arcsec reso
  - → VLBI or/and
  - → these arrays
    temperature s
  - -> is there abs
    - YES!
    - Is there enoug
    - Yes!





  - THEN LETS OBSERVE H1 IN ABSORPTION….
    With MERLIN or VLBI?

Configuration: e.g. MERLIN correlator

Table 4.4: Relationship between the number and the width of frequency channels for 1 polarization (LL or RR), 2 polarizations (LL and RR) or all 4 polarizations (LL, RR, LR, RL).

B'width	Max No. channels			Channel width			Velocity resolution		
(MHz)	per correlator card			(kHz)			at 1420 MHz (km s^{-1})		
	1	2	4	1	2	4	1	2	4
0.25	1024	512	256	0.24	0.48	0.96	0.052	0.104	0.21
0.5	1024	1024	512	0.24	0.48	0.96	0.052	0.104	0.21
1	1024	512	256	0.96	1.92	3.91	0.21	0.42	0.83
2	512	256	128	3.91	7.81	15.63	0.83	1.66	3.32
4	256	128	64	15.63	31.25	62.50	3.32	6.64	13.3
8	128	64	32	62.50	125.00	500.00	13.3	26.6	53.2
16	64	32	16	250.00	500.00	1000.00	53.2	106.4	212.8

Notes: (1) If there are ≤ 5 antennas in use e.g. at 22 GHz then twice the number of channels per bandwidth are available.

Bandwidth/spectral resolution

- Choose Band- & channel- width
  - to fully cover line and provide some additional non-line channels for continuum
  - Enough channels → Higher enough spectral resolution to sample the line.
  - Sensitivity??
    - sensitivity per channel *not* for the whole bandwidth to line.
    - If observing Continuum at same time need to bare in mind how much 'line-free' continuum bandwidth

Configuration: MERLIN correlator

Table 4.4: Relationship between the number and the width of frequency channels for 1 polarization (LL or RR), 2 polarizations (LL and RR) or all 4 polarizations (LL, RR, LR, RL).

B'width	Max No. channels			Channel width			Velocity resolution		
(MHz)	per correlator card			(kHz)			at 1420 MHz (km s^{-1})		
	1	2	4	1	2	4	1	2	4
0.25	1024	512	256	0.24	0.48	0.96	0.052	0.104	0.21
0.5	1024	1024	512	0.24	0.48	0.96	0.052	0.104	0.21
1	1024	512	256	0.96	1.92	3.91	0.21	0.42	0.83
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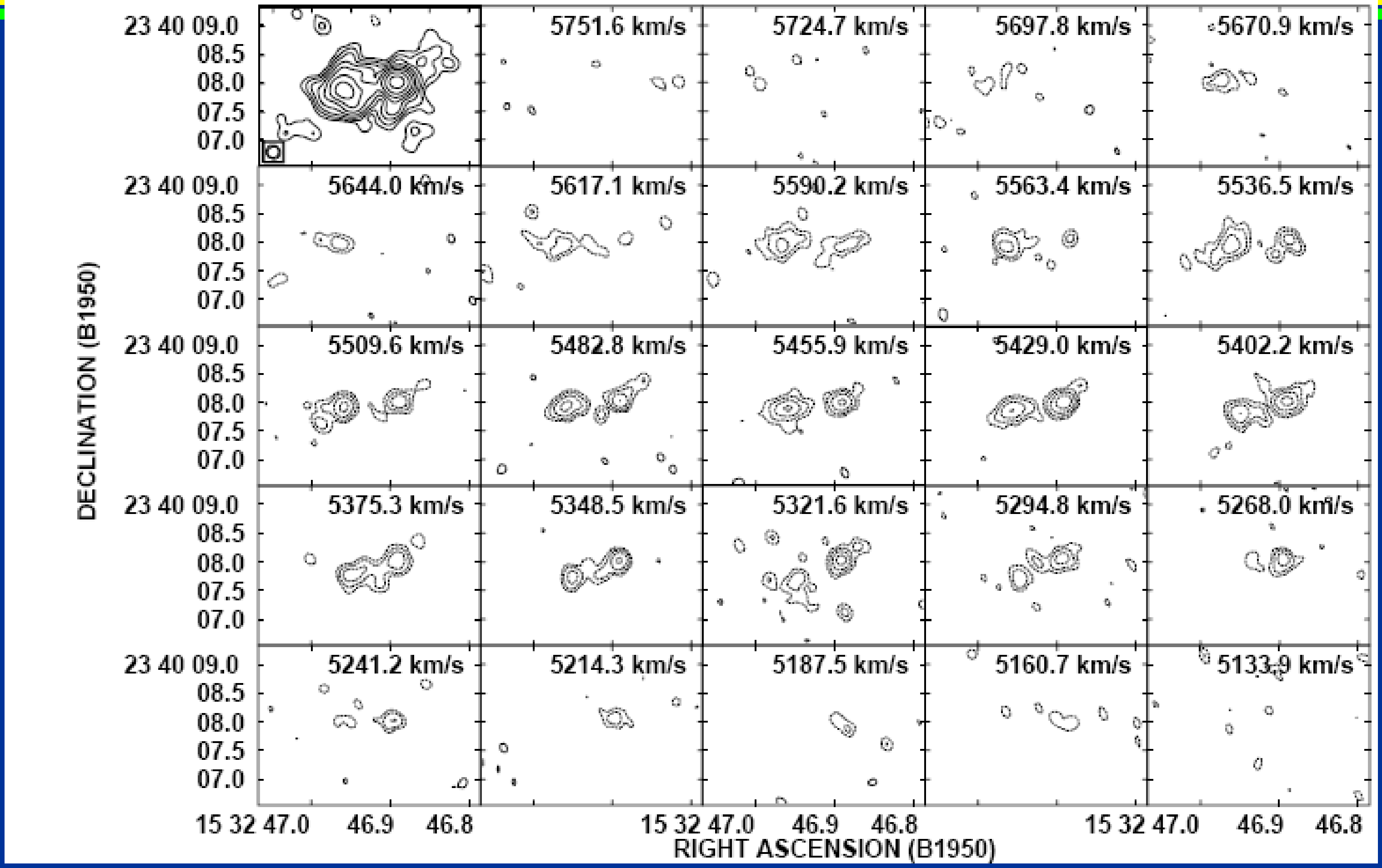
16	64	32	16	250.00	500.00	1000.00	53.2	106.4	212.8

Notes: (1) If there are ≤ 5 antennas in use e.g. at 22 GHz then twice the number of channels per bandwidth are available.

Then results!



Resolution, Brightness & Sensitivity

- What an interferometer can do
  - Give you resolution (spatial & spectral)
  - Sensitivity to brightness regime
    - No sensitivity for smooth structures
    - Lower limit for unresolved source
    - Filter for certain radiative processes
      - VLBI looks at high energy universe
      - At mm waves one can study cold universe with sub-arcsecond resolution

$$T_b = \frac{c^2}{2\upsilon^2 k}\frac{S_\nu}{\Delta\Omega}$$

- Express the sensitivity of interferometer: T_b
  - Array with N identical dishes of size A is given by:

$$\Delta S_\upsilon = \frac{\sqrt{2 k_b T_{sys}}}{\eta_a \eta_c A \sqrt{\Delta t \Delta \upsilon}\sqrt{\frac{1}{2}N(N-1)}}.$$

$$\Delta T_\nu \approx \frac{A_{synth} T_{sys}}{\sum A_{tel}\eta_a \eta_c \sqrt{\Delta t \Delta \nu}}$$

The observations & prepare observing schedules

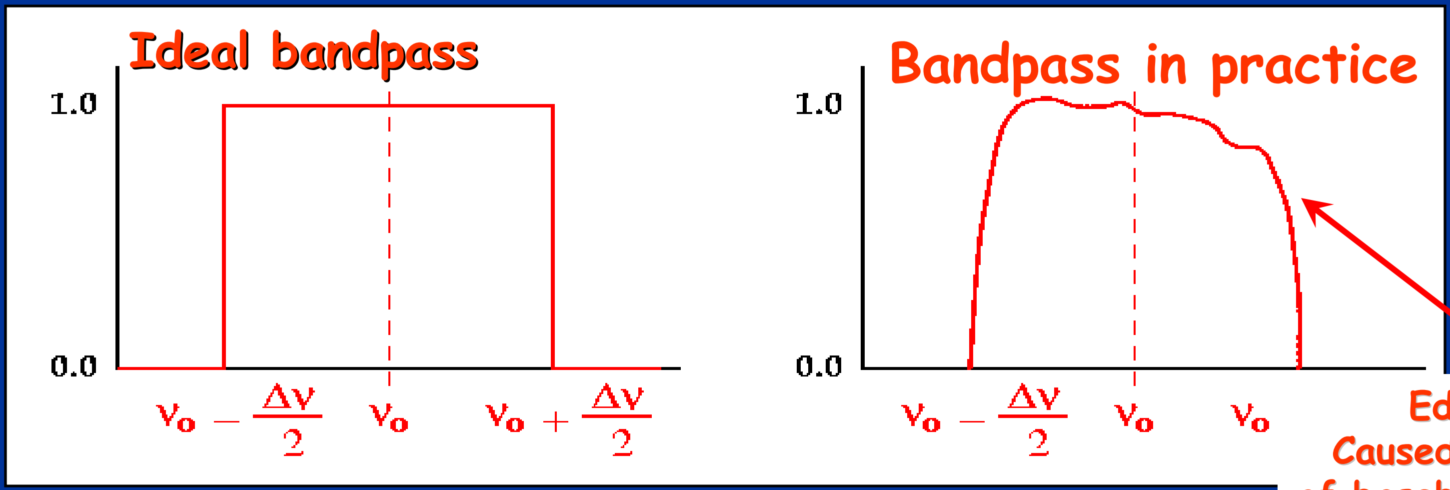
1. Check observing frequency/velocity
2. Include bandpass calibrators (need good SNR)
    1. Multiple scans through the run
    2. Bandpass calibrator
        - flux on all baselines
        - Simple structure
        - May be able to use flux cal sources for low res arrays
    3. Phase & flux cals etc

Data calibration & analysis

- Bandpass
- Continuum subtraction (see also demo)
- Visualisation & analysis (more in demo)

Spectral Bandpass:

- Spectral frequency response of antenna to a spectrally flat source of unit amplitude



Edge roll-off
Caused by shape
of baseband filters

- Shape due primarily to individual antenna electronics/transmission systems
- Different for each antenna
- Varies with time, but much more slowly than atmospheric gain or phase terms

Bandpass calibration

- In general, the goal of calibration is to find the relationship between the observed visibilities, *V*obs, and the true visibilities, *V*:

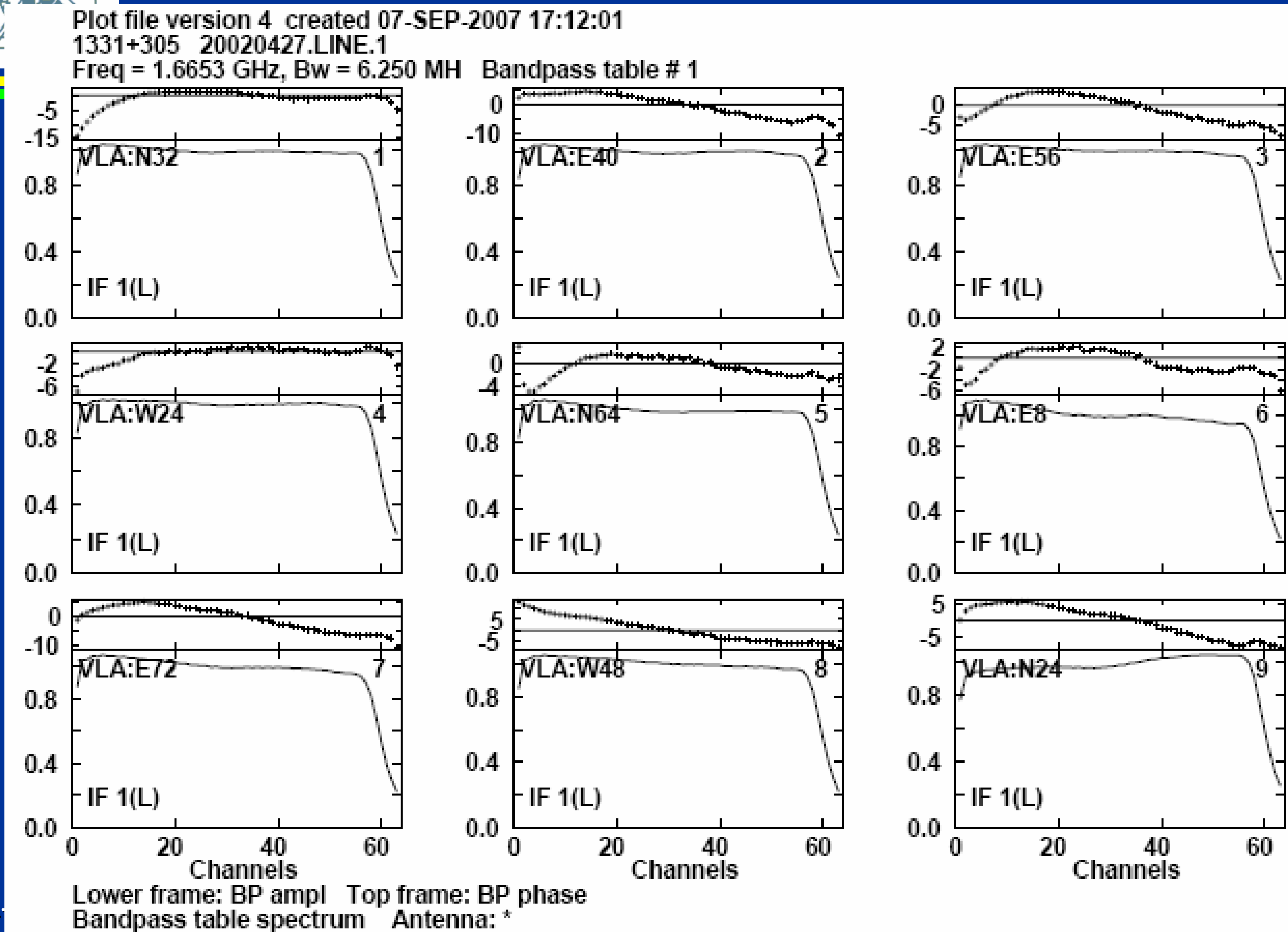
$$V_{ij}(t,\nu)^{obs} = V_{ij}(t,\nu)G_{ij}(t)B_{ij}(t,\nu)$$

- where t is time, ν is frequency, *i* and *j* refer to a pair of antennas *(i,j)* (i.e., one baseline), *G* is the complex "continuum" gain, and *B* is the complex frequency-dependent gain (the "bandpass").
- **Bandpass calibration** is the process of deriving the *frequency-dependent* part of the gains, $B_{ij}(t,\nu)$ (i.e., the spectral response function).
- B_{ij} may be constant over the length of an observation, or it may have a slow time dependence.
- **Bandpass calibration attempts to correct for the deviations of the observed bandpass from the "ideal" one.**

Flux scale/BPass & autocorrelations

- Initial flux scale determination as for continuum
  - EVN using T_{sys}; MERLIN using 3C286
- Edit Radio Freq. Interference (SPFLG, IBLED)
  - Inspect XCs (local interference decorrelates)
    - If very bad consider editing ACs (VLBI)
      - → Terrestrial interference antenna-based
- Use of AC template for bandpass amp cal. (VLBI)
  - Select short good period, average ACs all antennas
    - Advantage: no danger of resolving-out flux
    - Problems: much worse effects of RFI on ACs
    - T_{sys} errors exacerbated in heterogenous array
      - → not recommended for EVN, MERLIN & similar?
- Retain scale from initial calibration
  - If poss. also use point/mappable source of known flux

Example bandpasses



Bandpass Calibration: Why is it important?

The quality of the bandpass calibration is a key limiting factor in the ability to detect and analysis of spectral features.

- Bandpass amplitude errors may mimic changes in line structure with ν
- ν-dependent phase errors may lead to spurious positional offsets of spectral features as a function of frequency, mimicking doppler motions of the emitting/absorbing material.
- ν-dependent amplitude errors limit ability to detect/measure weak line emission superposed on a continuum source (simply subtracting off the continuum does not fully alleviate this problem).
- For continuum experiments performed in spectral line mode, dynamic range of final images is limited by quality of bandpass calibration.

Bandpass Calibration: Some Guidelines

- Bandpass calibration is typically performed using observations of a strong continuum source.

Within the frequency range of interest, bandpass calibration source(s) should have:

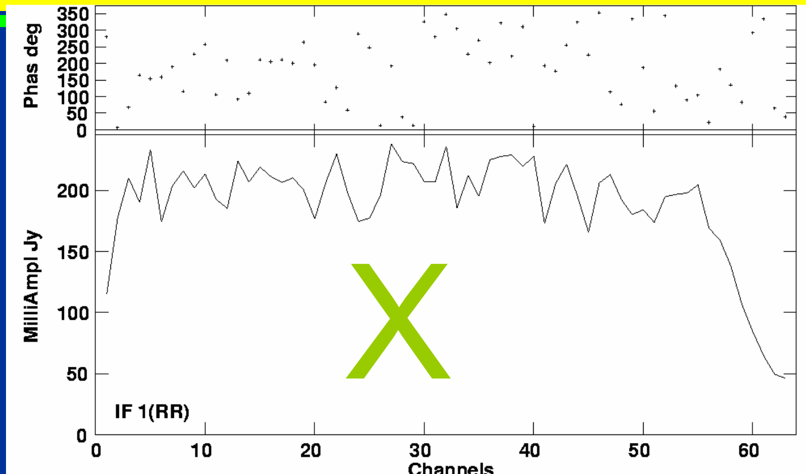
(1) high S/N in each spectral channel
(2) an intrinsically flat spectrum
(3) no spectral features
(4) no changes in structure across the band

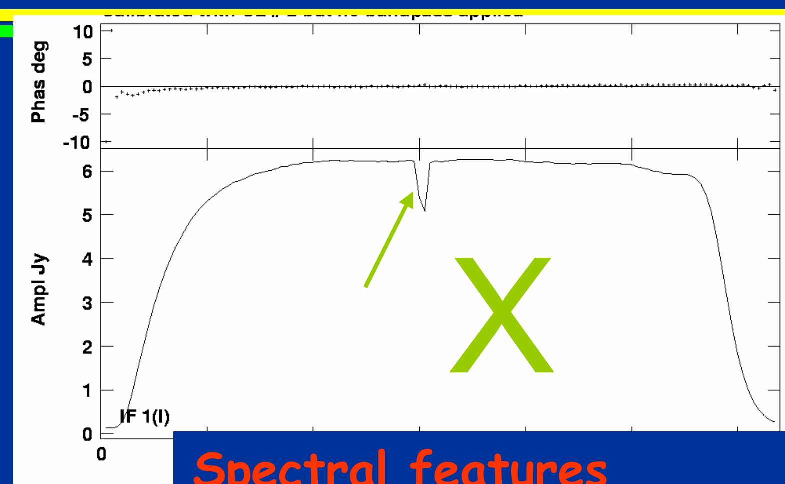
Rule of thumb:

BP calibrator should have sufficient S/N *per channel* so as not to degrade the target spectrum by more than ~10%; i.e.,

$$(S/N)_{BP} > 2\times(S/N)_{target}$$

Bandpass Calibration: Some Guidelines

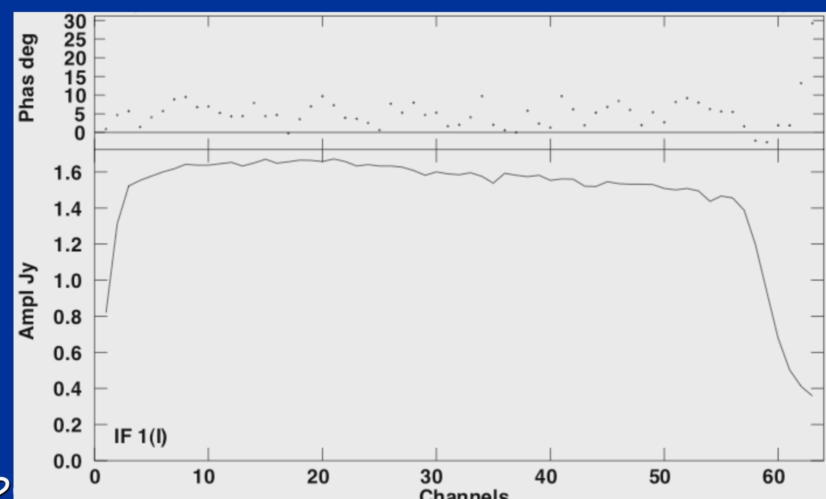




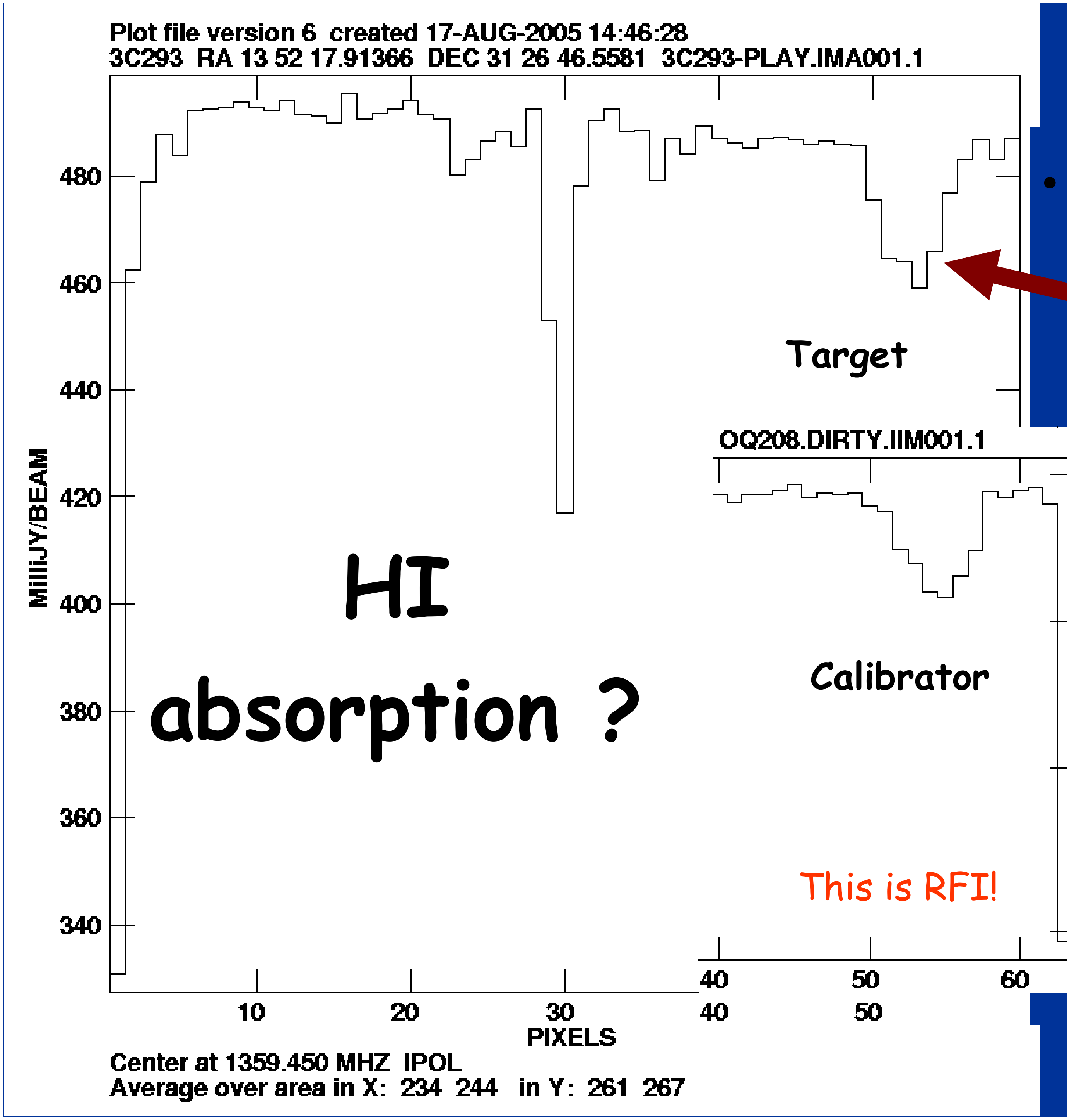
Spectral features (e.g. spec lines. RFI etc)

Signal-to-noise per channel too low.

Cross-power spectra of three potential bandpass calibrators.



Good S/N; no spectral features



- If BP cal source has a spike
  - BP table makes a dip
- If it's there when you apply BP table to cal source
  - Edit the BP cal
  - Re-make BP table

Computing the Bandpass Calibration

In theory, the frequency spectrum of the visibilities of a flat-spectrum calibration source should yield a direct estimate of the bandpass for each baseline : $B_{i\,j}(t,\nu) = B_{i\,j}(t,\nu)_{obs} / S_{cal}$
BUT: this requires very high S/N.

Most corruption of the bandpass occurs before correlation, and is linked to individual antennas.

$\Rightarrow$*solve for antenna-based gains*: $B_{i\,j}(t,\nu) \approx B_i(t,\nu)\ B_j(t,\nu)^*$

$$= b_i(t,\nu) b_j(t,\nu)\ \exp[i\,(\phi_i(t,\nu)\phi_j(t,\nu))]$$

- Given N antennas, now only N complex gains to solve for compared with $N(N - 1)/2$ for a baseline-based solution.
  - $\Rightarrow$ less computationally intensive
  - $\Rightarrow$ improvement in S/N of ~ sqrt[$(N$-1) /2]
- Calibration can be obtained for all antennas, even if some baselines are missing.

Computing the Bandpass Calibration

The method commonly used for solving for the bandpass calibration is analogous to channel-by-channel *self-calibration*:

- Calibrator data are either divided by a source model or Channel 0 (this effectively removes any source structure and any uncalibrated continuum gain changes).

- Antenna-based gains are solved for as free parameters.

Note: This approach may require modification if S/N per channel is low, no strong calibrators are available, etc.

Bandpass Calibration: Modified Approaches May Be Required in Some Circumstances

Signal-to-noise too low to fit channel-by-channel?⇒ try polynomial fit across the band (e.g., AIPS task CPASS).

For VLBI, compact continuum sources strong enough to detect with high S/N on all baselines are rare. ⇒ use autocorrelation spectra to calibrate the amplitude part of the bandpass.

At mm wavelengths, strong continuum sources are rare. ⇒ use artificial noise source to calibrate the bandpass.

Line emission present toward all suitable BP calibrators? ⇒ use a modest frequency offset during the BP calibrator observations.

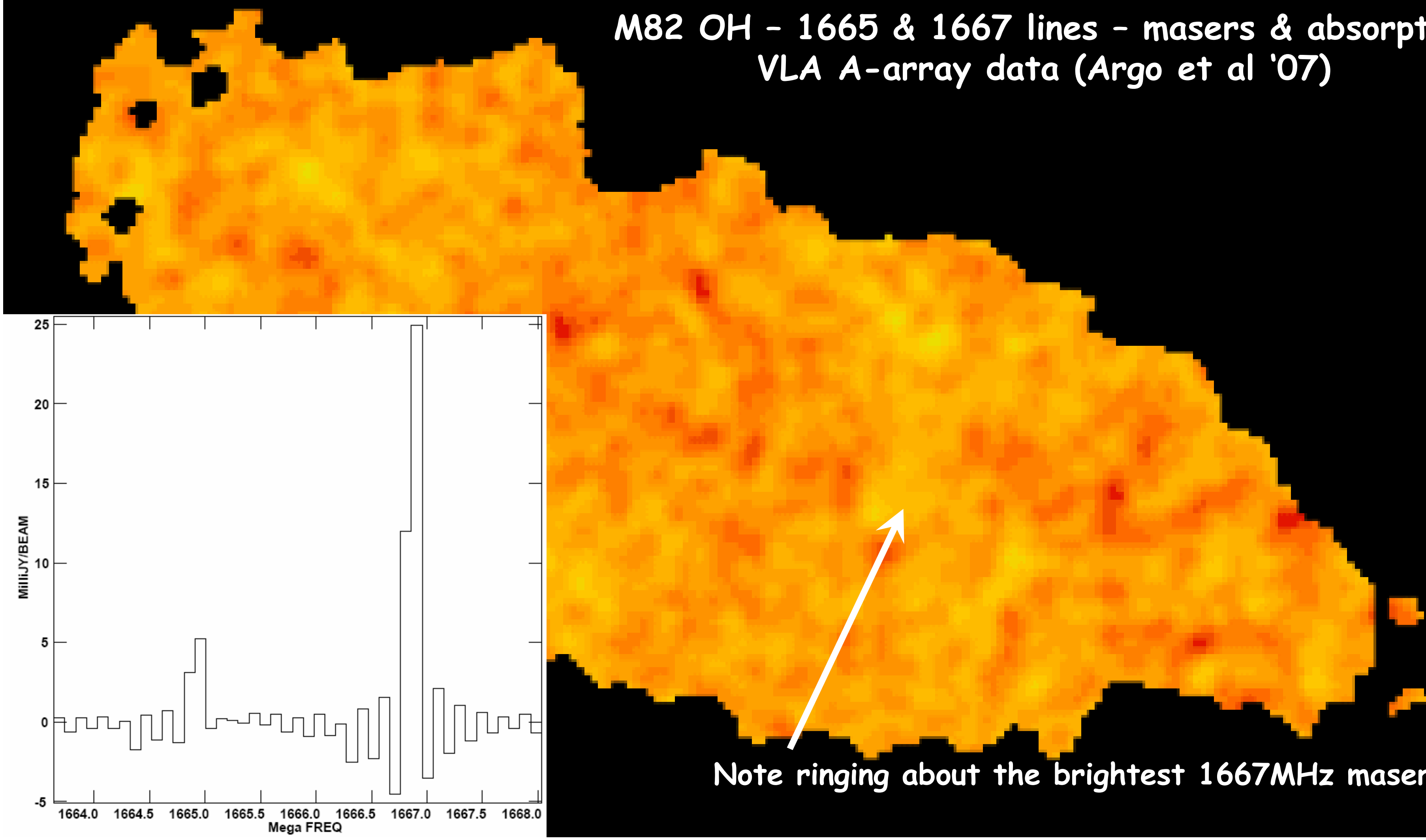
Ripple across the band? ⇒ smooth the solution in frequency (but note: you then should also smooth the target data, as smoothing will affect the shape of real ripples, and the slope of the bandpass edges)

Ringing

- Bright-sharp spectral features in your spectra can cause ringing and ghost emission/absorption features.
  - Solution – Smooth data
    - Can be done in the online systems at some array (eg current VLA) or offline in AIPS
    - Beware that you will loose velocity resolution

Example of ringing

M82 OH – 1665 & 1667 lines – masers & absorption
VLA A-array data (Argo et al '07)



Note ringing about the brightest 1667MHz maser

Smoothing Spectral Line Data

Spatially:

Smoothing data spatially (through convolution in the image plane or tapering in the *u-v* domain) can help to emphasize faint, extended emission.

Caveats:

This only works for *extended* emission.

This cannot recover emission on spatial scales larger than the largest angular scale to which the interferometer is sensitive.

Smoothing effectively downweights the longer baselines, leaving fewer data points in the resulting image; this tempers gains in S/N.

Smoothing Spectral Line Data

In frequency:

Smoothing in frequency can improve S/N in a line if the smoothing kernel matches the line width ("matched filter").

Caveats:

In general, channel width, spectral resolution, and noise equivalent bandwidth are all different: $\Delta\nu_c \neq \Delta\nu_R \neq \Delta\nu_N$

$\Rightarrow$ Smoothing in frequency does not 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.

$\Rightarrow$ *further smoothing or averaging in frequency does not lower noise by sqrt(n_{chan})*

Continuum subtraction & cleaning

- Spectral-line data often contain continuum sources (no change with frequency) as well as line data.
  - Note this continuum also contains valuable science!
- If your spectral-line data set has continuum emission in addition to line emission this should be subtracted before deconvolution and cleaned separately.
  - Clean line data & Continuum data separately. Recombine latter if needed.

Less cleaning needed and most channels are just noise

- less cleaning = reduced computing
- Less cleaning = reduced errors

Continuum Subtraction

Continuum emission and its sidelobes complicate the detection and analysis of the spectral line features:

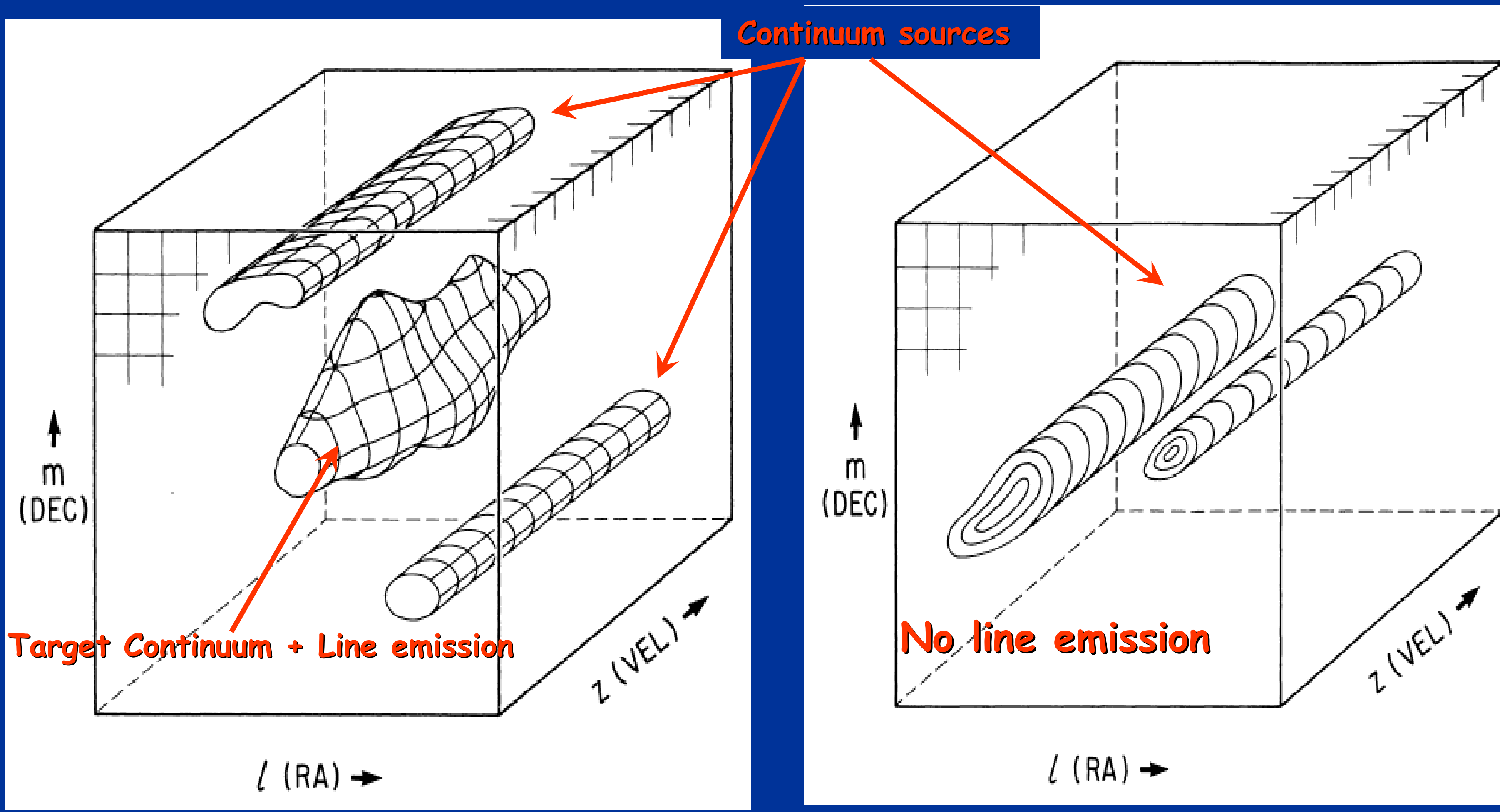
- weak line signals may be difficult to disentangle from a complex continuum background; complicates measurements of the line signal

- multiplicative errors scale with the peak continuum emission
  $\Rightarrow$*limits the achievable spectral dynamic range*

- deconvolution is a non-linear process; results often improved if one does not have to deconvolve continuum and line emission simultaneously

- if continuum sources are far from the phase center, will need to image large field of view/multiple fields to properly deconvolve their sidelobes

Structure of cube



(Roelfsema '85)

Continuum subtraction methods (see also demo)

1. In the uv-plane

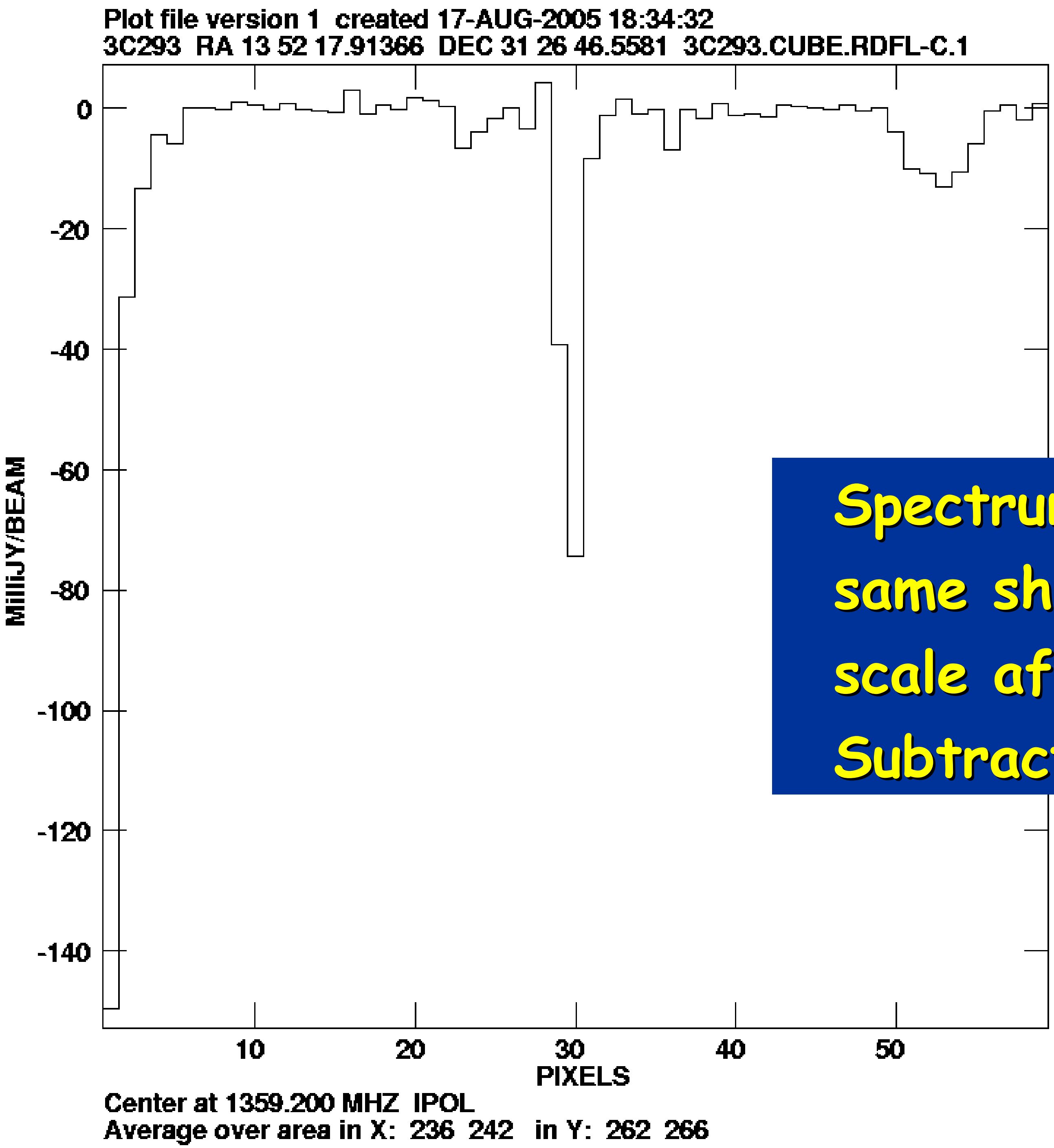
   Subtract continuum → clean line & cont separately → recombine if needed

   - Use AIPS task such as uvlin, uvlsf, uvsub

2. In the map-plane

   FT data → subtract continuum from 'dirty' cube → clean both cont. & line (with appropriate beam) → recombine if needed

   - AIPS task – imlin, (sqash & comb)



Spectrum should have same shape, different scale after continuum Subtraction.

Analysis of line data

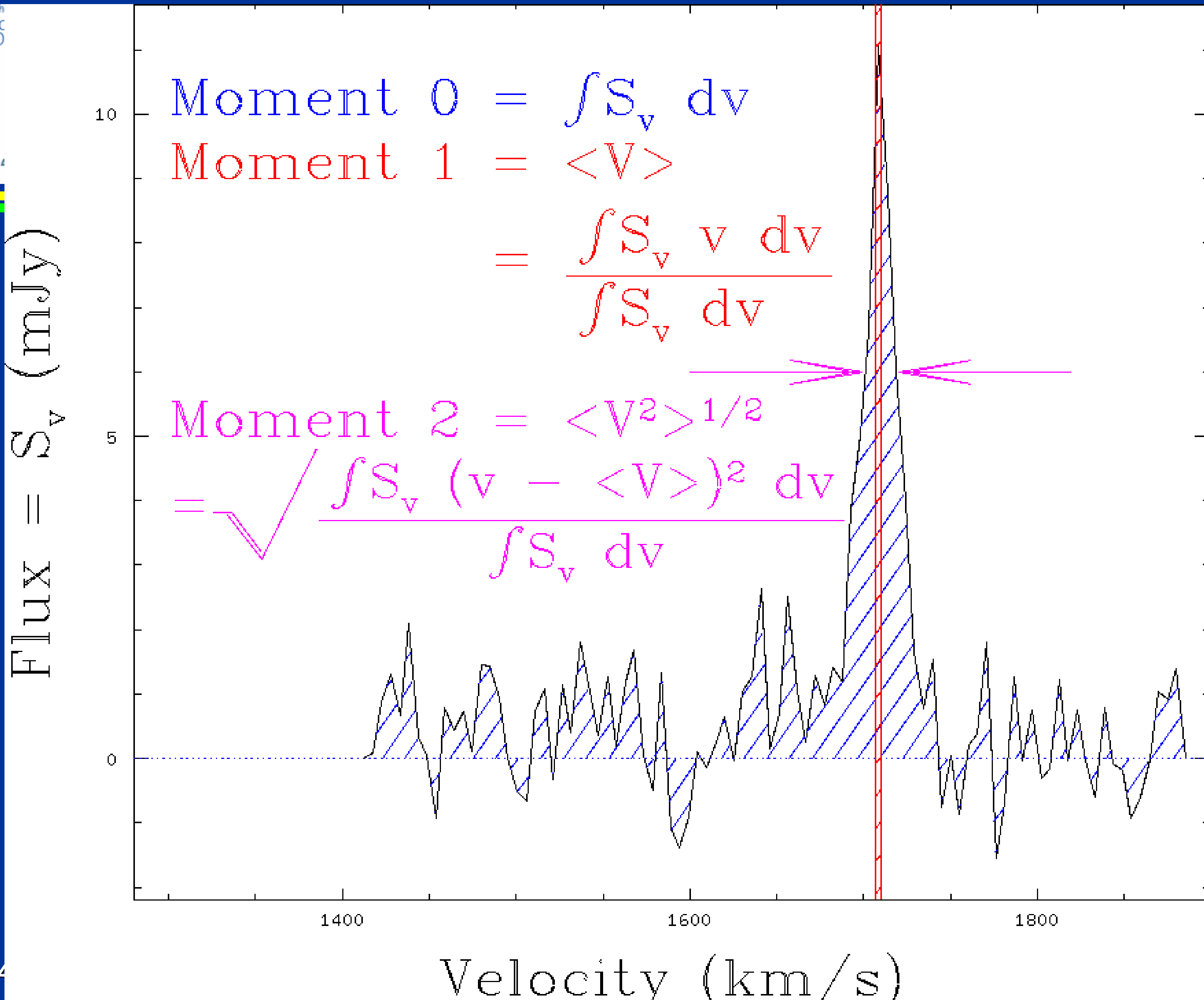
- Numerous visualisation/analysis methods
  - Spectra to contour maps to pv-plots to movies etc.

One example:

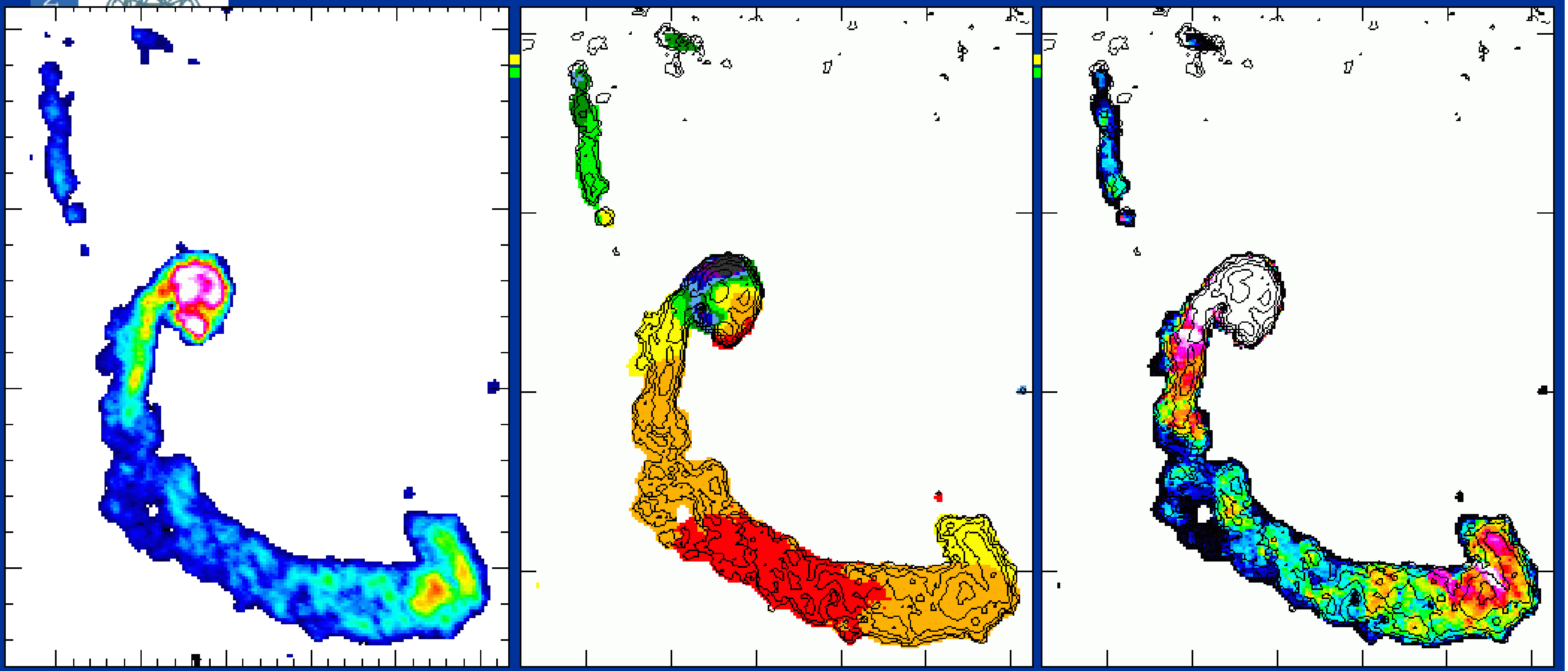
  - Moment maps

“Moment” Analysis

- Integrals over velocity
- 0th moment = total flux
- 1st moment = intensity weighted (IW) velocity
- 2nd moment = IW velocity dispersion
- 3rd moment = skewness or line asymmetry
- 4th moment = curtosis


Moment 0 = $\int S_v \, dv$
Moment 1 = $\langle V \rangle$
$= \dfrac{\int S_v \, v \, dv}{\int S_v \, dv}$
Moment 2 = $\langle V^2 \rangle^{1/2}$
$= \sqrt{\dfrac{\int S_v \, (v - \langle V \rangle)^2 \, dv}{\int S_v \, dv}}$
Flux = S_v (mJy)
Velocity (km/s)
10
5
0
1400
1600
1800

Moment Maps



Zeroth Moment	First Moment	Second Moment
Integrated flux	mean velocity	velocity dispersion

Concluding remarks

- Spectral line imaging – gives YOU THE ASTRONOMER more information & hence more science
  - 3-D+ (RA, DEC, vel, + gas physics!) rather than just 2-D images
- Techniques applied here can (should) be applied to continuum too → better images (dynamic range etc), wider fields..

NOW DEMO!!

- Demonstration (hopefully) including –
  - Imaging
  - Continuum subtraction
  - Deconvolution
  - Smoothing
  - Analysis & presentation

Extra offline demo…

- MERLIN H1 absorption in 3C293
    - Data & Notes available at

http://www.jb.man.ac.uk/~rbeswick/ERIS/H1_demo.html