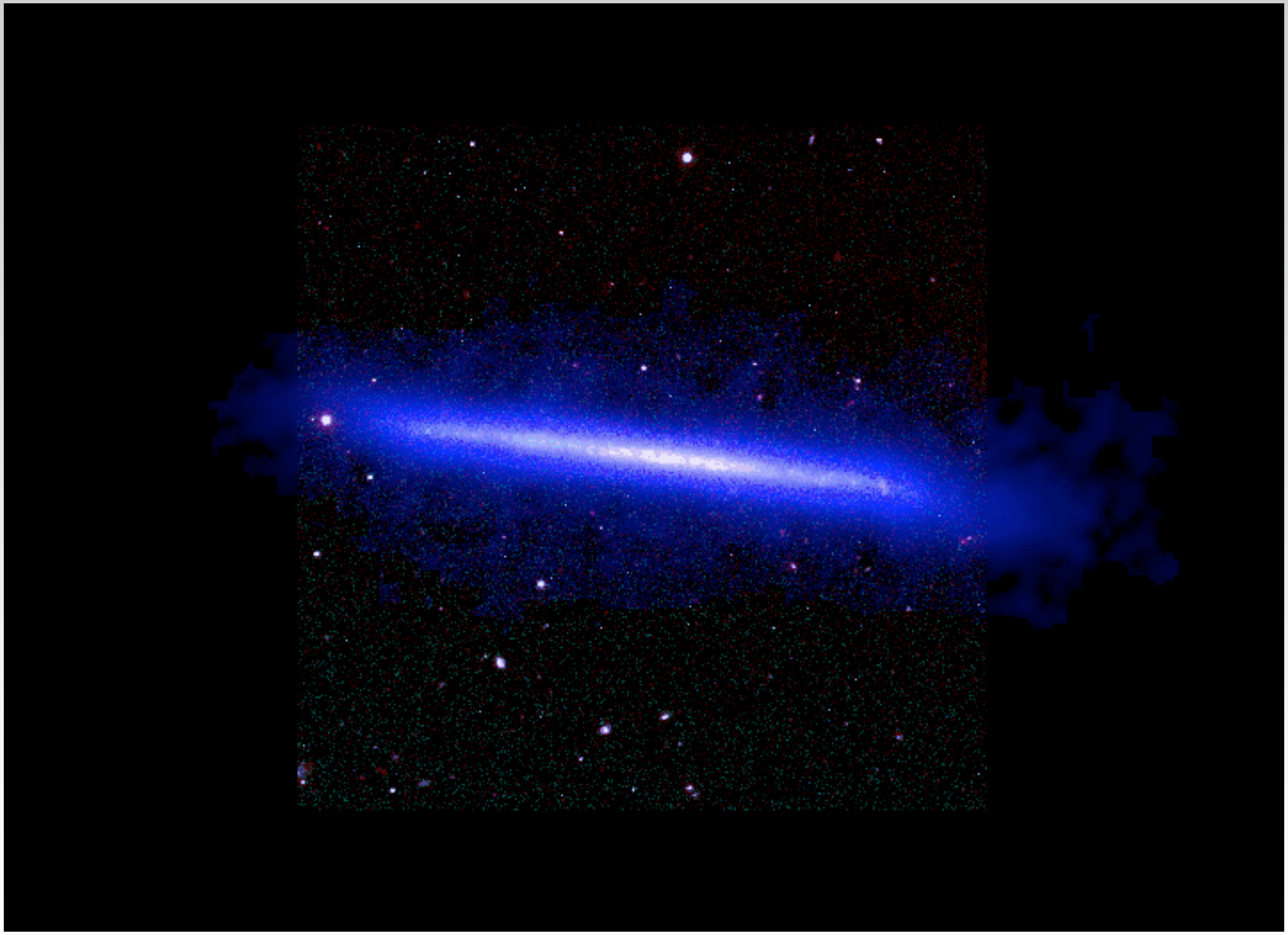
Spectral Imaging



Juan M. Usón (NRAO) 12/07/06

Revelaciones y utopías

Habrá un día en el que
se verán las imágenes
de todas las revelaciones que trajeron
los poetas al mundo.

de Pavel Oyarzún

Revelations and utopias

A day will come when
we will see the images
of all the revelations brought
by poets to the world.

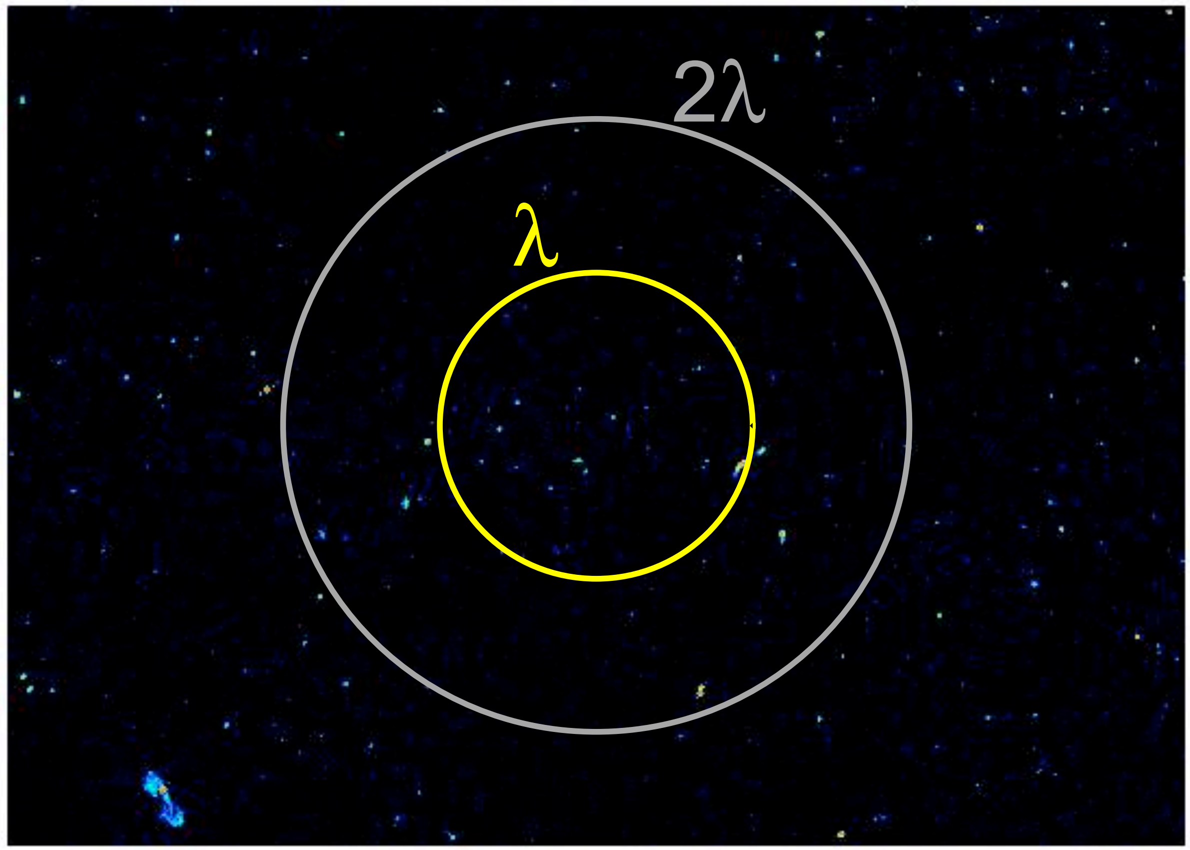
by Pavel Oyarzún

Spectral line observations

- Spectral line observations were once observations of spectral lines.
- ALMA and the EVLA will always observe in spectral mode.
- Key points:
  - Arrays suffer from chromatic aberration
  - Calibration is channel dependent: Bandpass calibration is necessary
  - There are ghost sources at the band edges
  - Small errors in the continuum emission can mask spectral line emission
  - Choosing the right weighting can bring out weak emission
- What can we learn?
  - Analysis tools
  - Examples

Arrays suffer from chromatic aberration

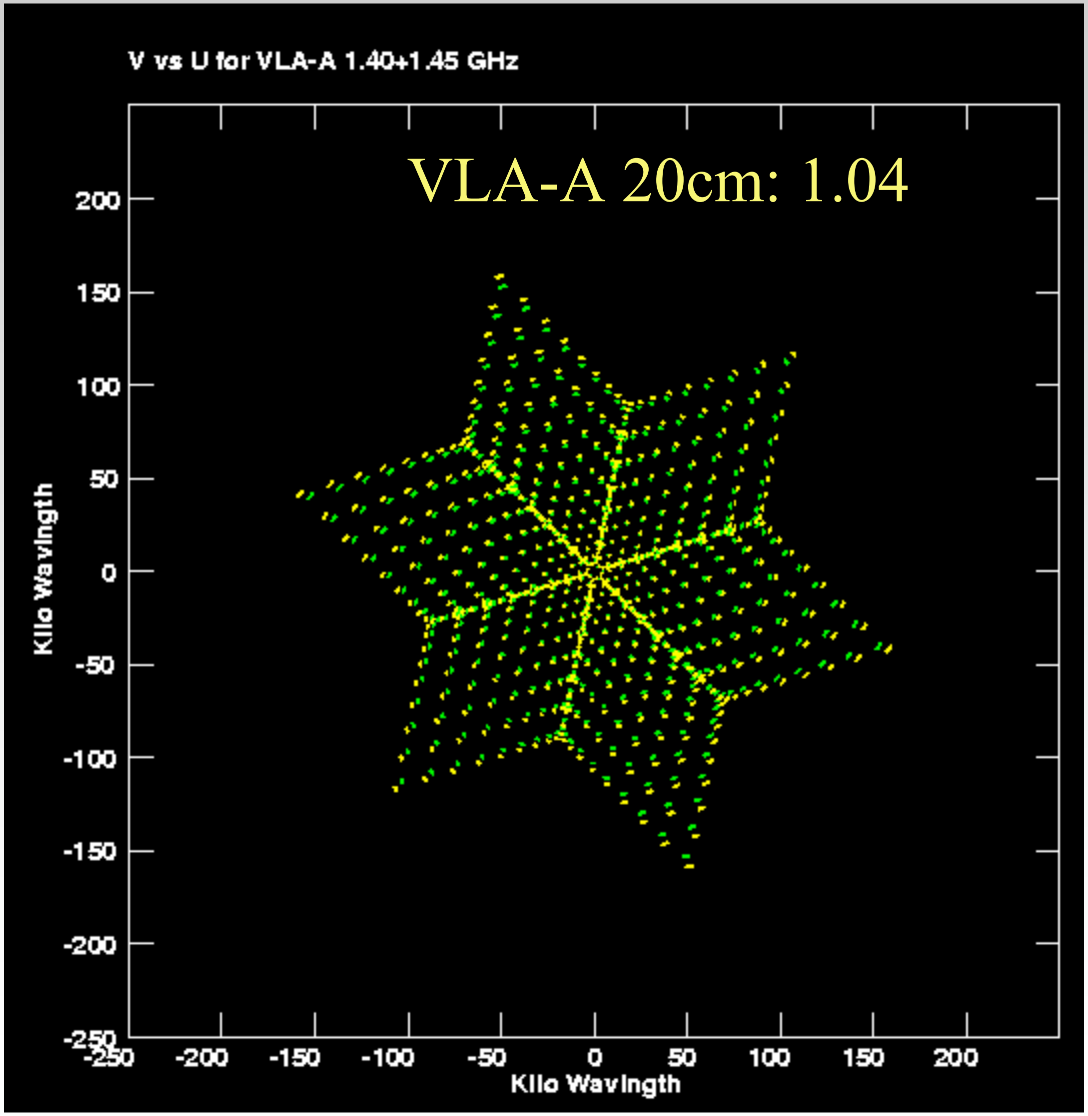
- Primary beam: λ/D
- Band covers λ_1 - λ_2
  - → PB changes by
    $\boldsymbol{\lambda_1/\lambda_2}$
- More important at longer wavelengths
  (also more sources)
  - VLA 20cm: 1.4 (1.04)
  - VLA   2cm: 1.05
  - EVLA 20-6cm: 2.0
  - ALMA 1mm: 1.35 (1.03)
- Sidelobes scale with λ too!



Background: 1.4GHz wide-field image courtesy of F. Owen

Chromatic aberration: (u,v) scale with λ

- Interferometric baselines:
  B/λ
- Band covers λ_1 - λ_2
  - → baseline changes by
    λ_1 / λ_2
  - → u, v scale radially
  - → more important in larger configurations



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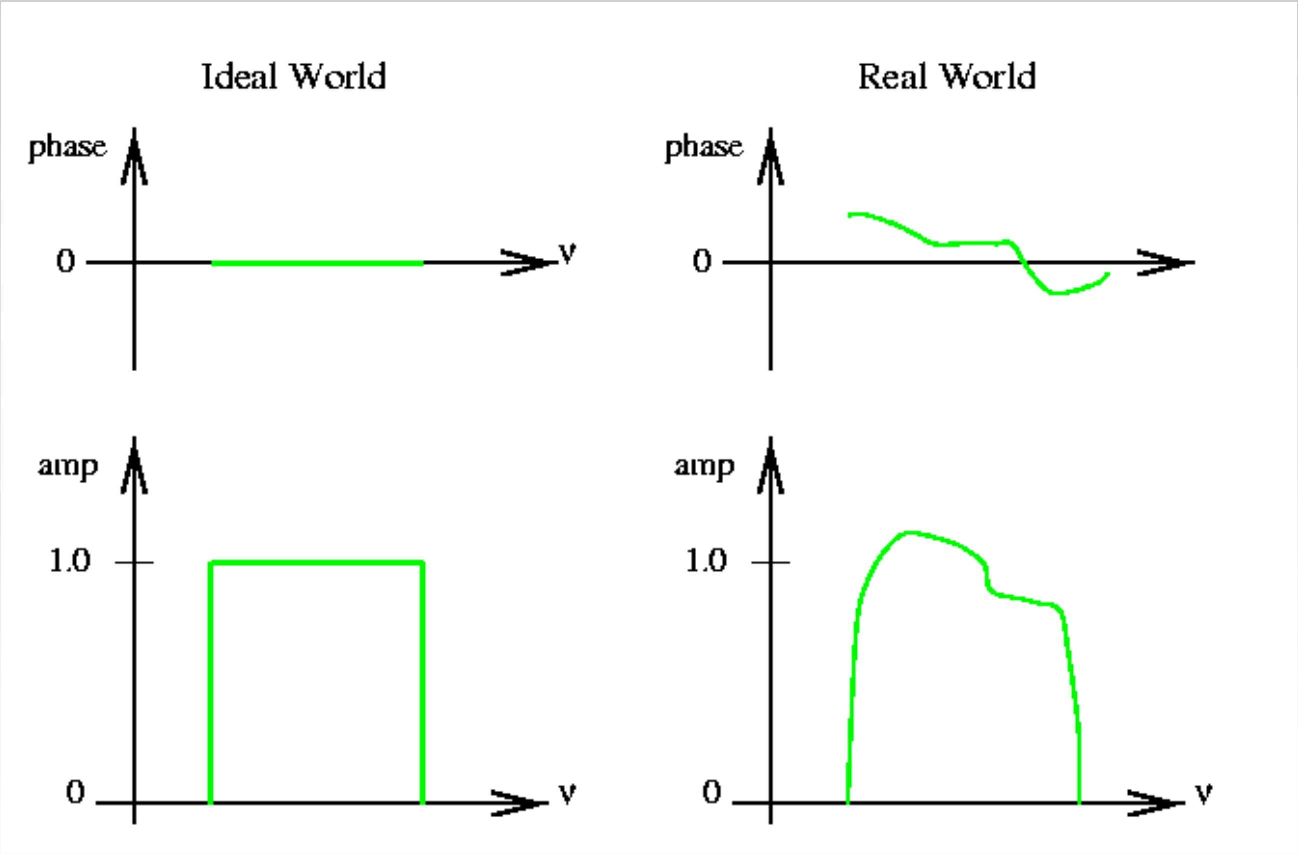
Bandpass calibration is necessary

Calibration is somewhat different for each channel.

Response to a point source of unit amplitude at the phase center

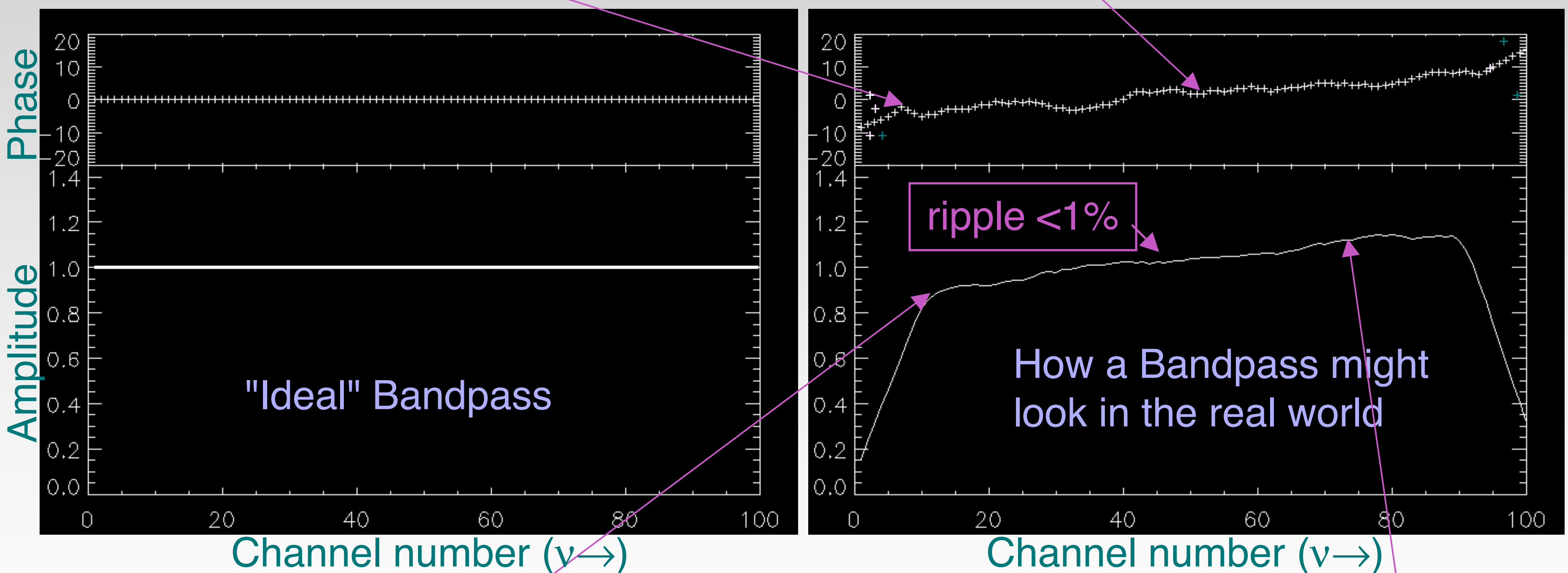


- Shape due primarily to individual antenna electronics/transmission systems
- Different for each antenna
- Varies with time, but much slower than atmospheric gain or phase terms

What does a typical bandpass look like?

Higher phase noise at band edges caused by ghost sources (Bos 1985, JU 2006)

Phase slope of a few degrees across band from delay errors



Edge roll-off caused by shape of baseband filters

nearly flat over inner ~75% of band

Bandpass calibration attempts to correct for the deviations of the observed bandpass from the "ideal" one.

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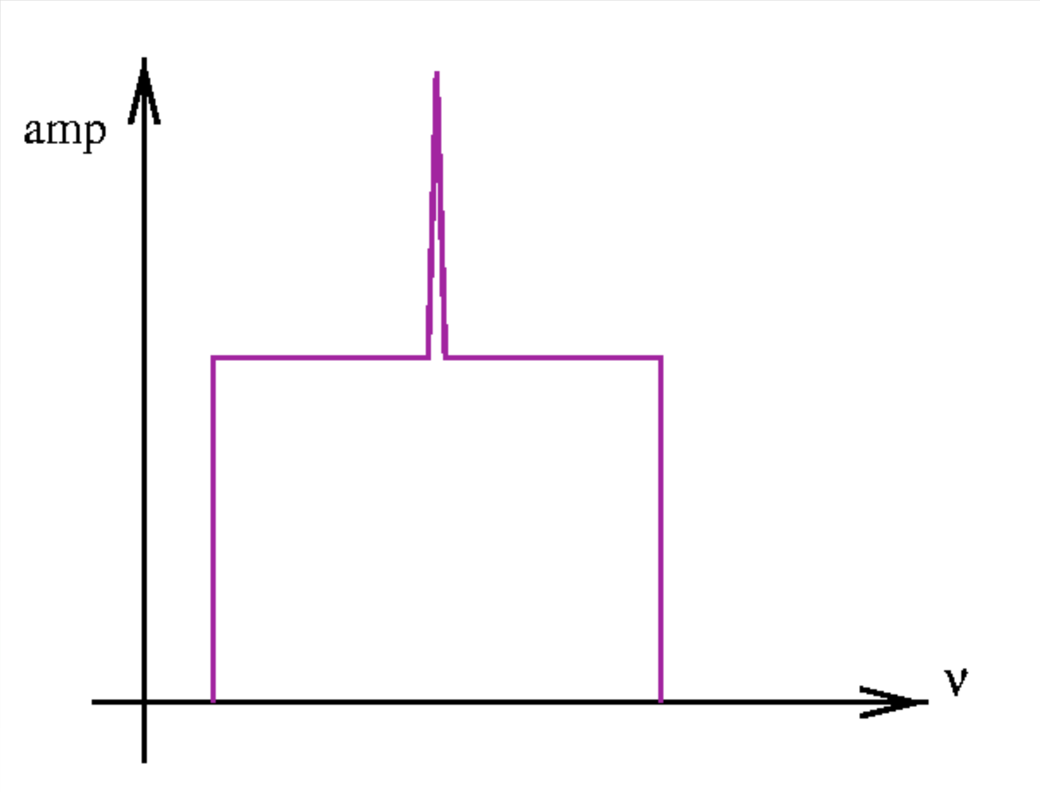
The Gibbs Phenomenon: spectral ringing



Consider a source with strong continuum and a strong, narrow spectral line.

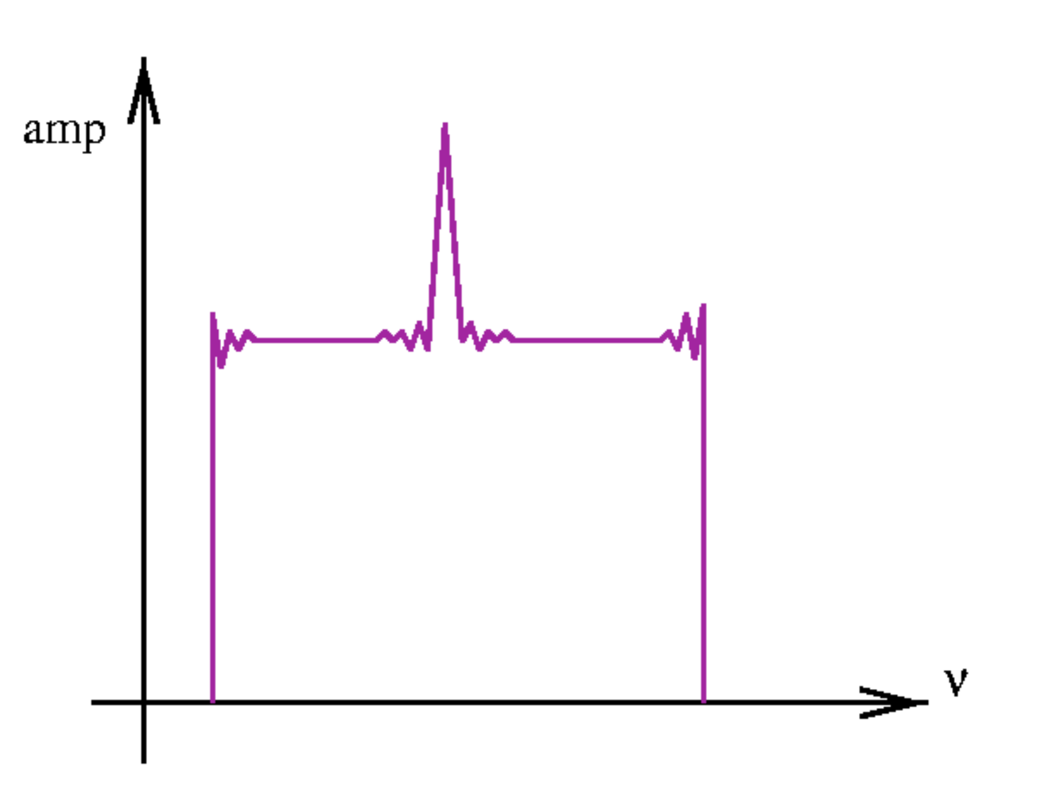
The spectral correlations are obtained through yet another set of Fourier transforms (with respect to time)

Synthesizing very sharp edges requires an infinite number of Fourier components. We do not have enough!

So, instead of this sharp spectrum, we get…

The Gibbs Phenomenon: spectral ringing

The result of synthesizing sharp edges with a finite number of lags/time



Remedies to alleviate ringing:

1. Hanning smoothing (online or offline); spectral resolution gets worse by x2
2. Ignore it. If the continuum is not strong and your line is not strong/sharp, it may not be an issue.

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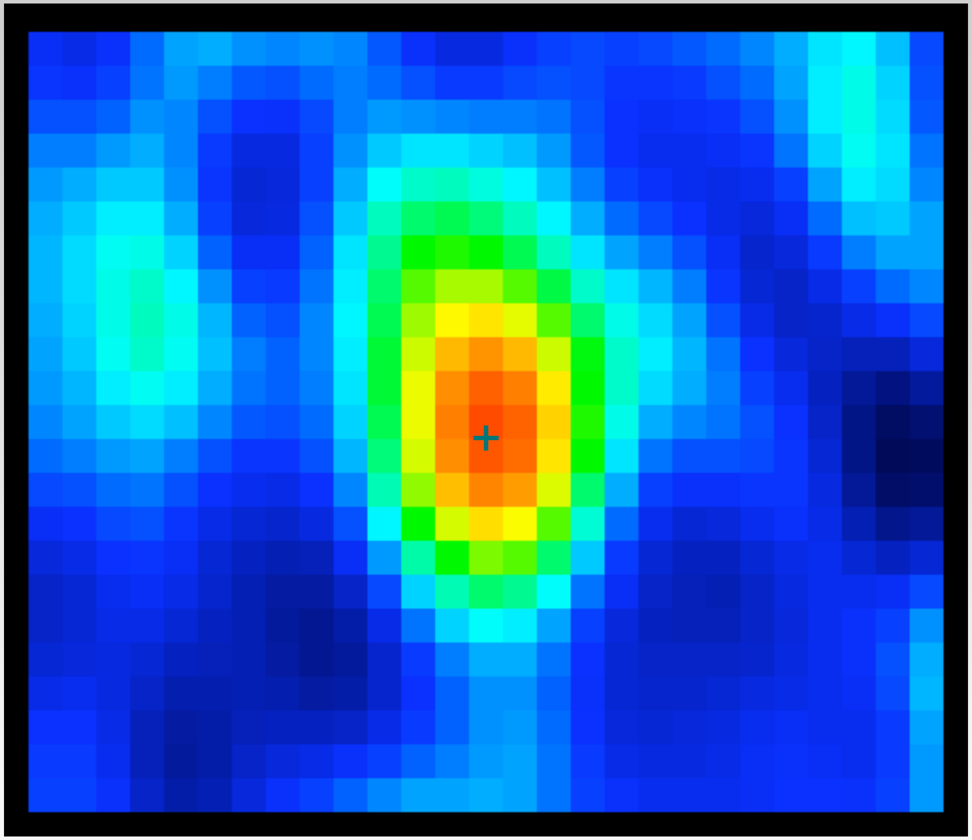
Phase errors can lead to shifts in the position (and morphology) of a source from channel to channel:

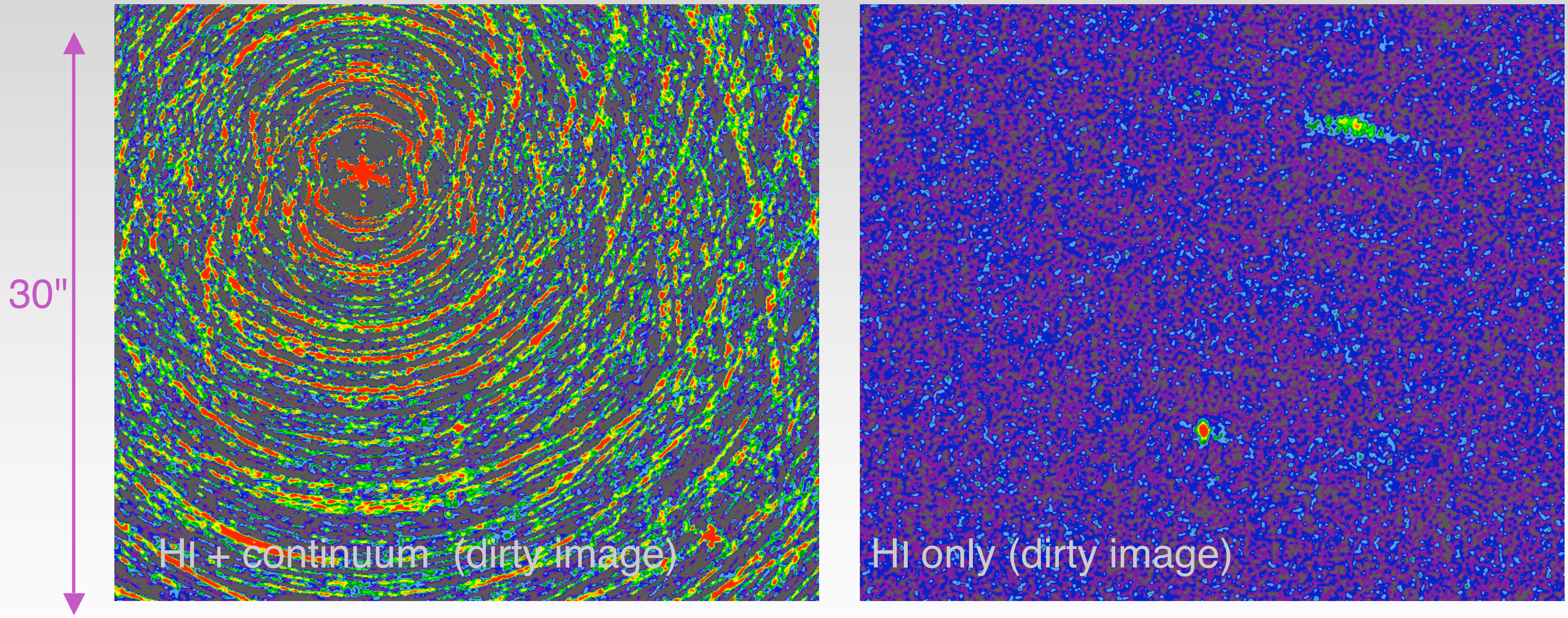


Rule of thumb:

Relative positional accuracy in channel images: $\Delta\theta / \theta_B = \Delta\phi / 360$
where θ_B is the synthesized beam and $\Delta\phi$ is the scatter in the phases.

Continuum subtraction (continued)

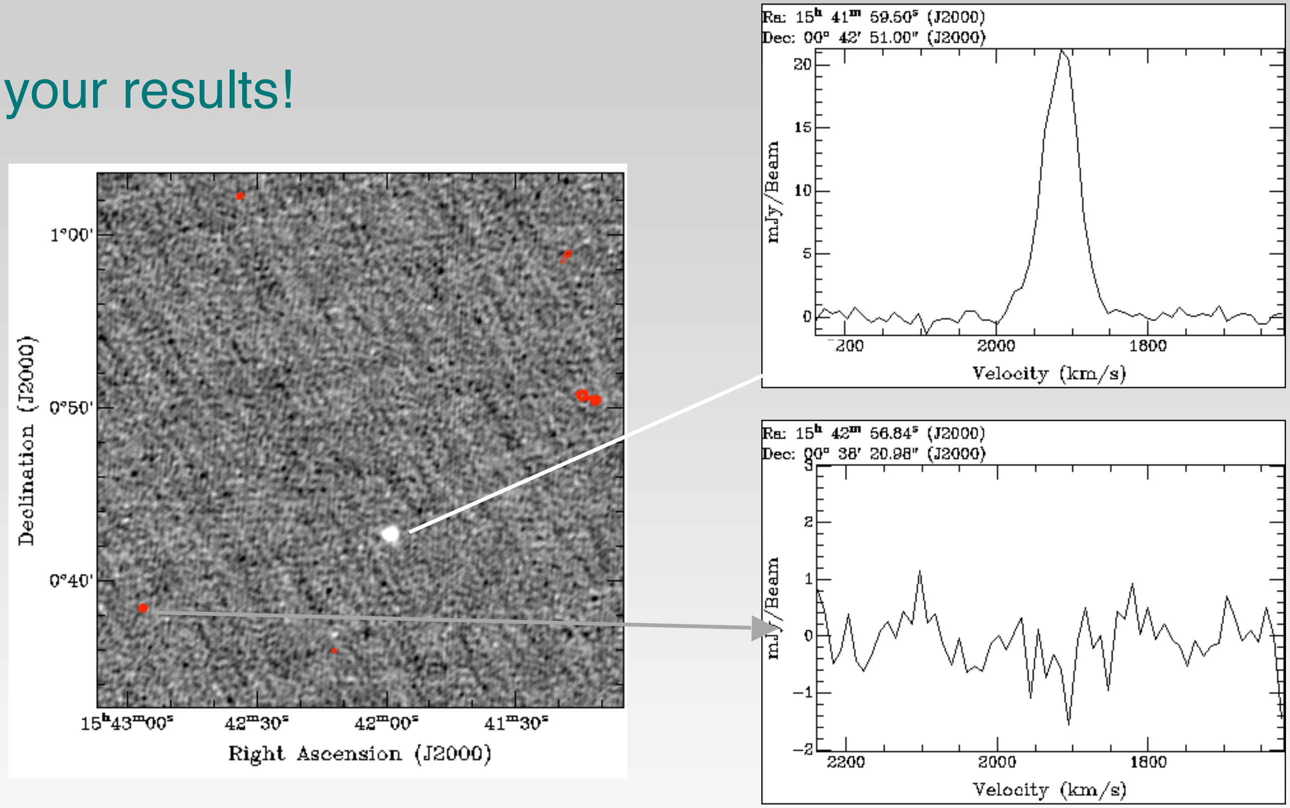
Dirty images of a field containing HI line emission from two galaxies, before and after continuum subtraction.



Peak continuum emission in field: ~1 Jy; peak line emission: ~13 mJy

Continuum Subtraction: Additional Notes

- Check your results!



- Always perform bandpass calibration before subtracting the continuum.

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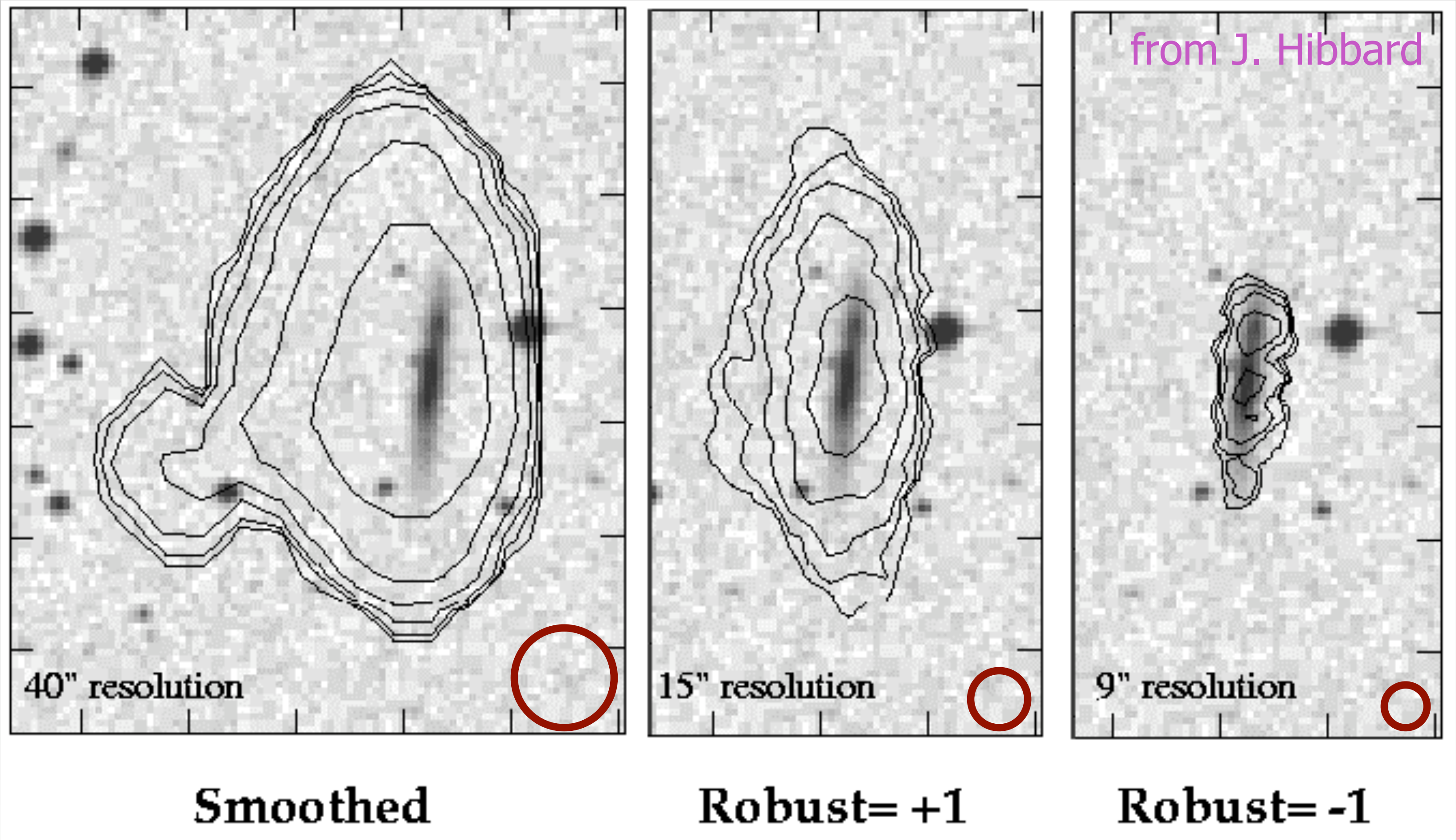
Imaging with different weighting



- Figure: HI contours overlaid on optical images of an edge-on galaxy
- Choose the weighting that matches your signal optimally, vary it.

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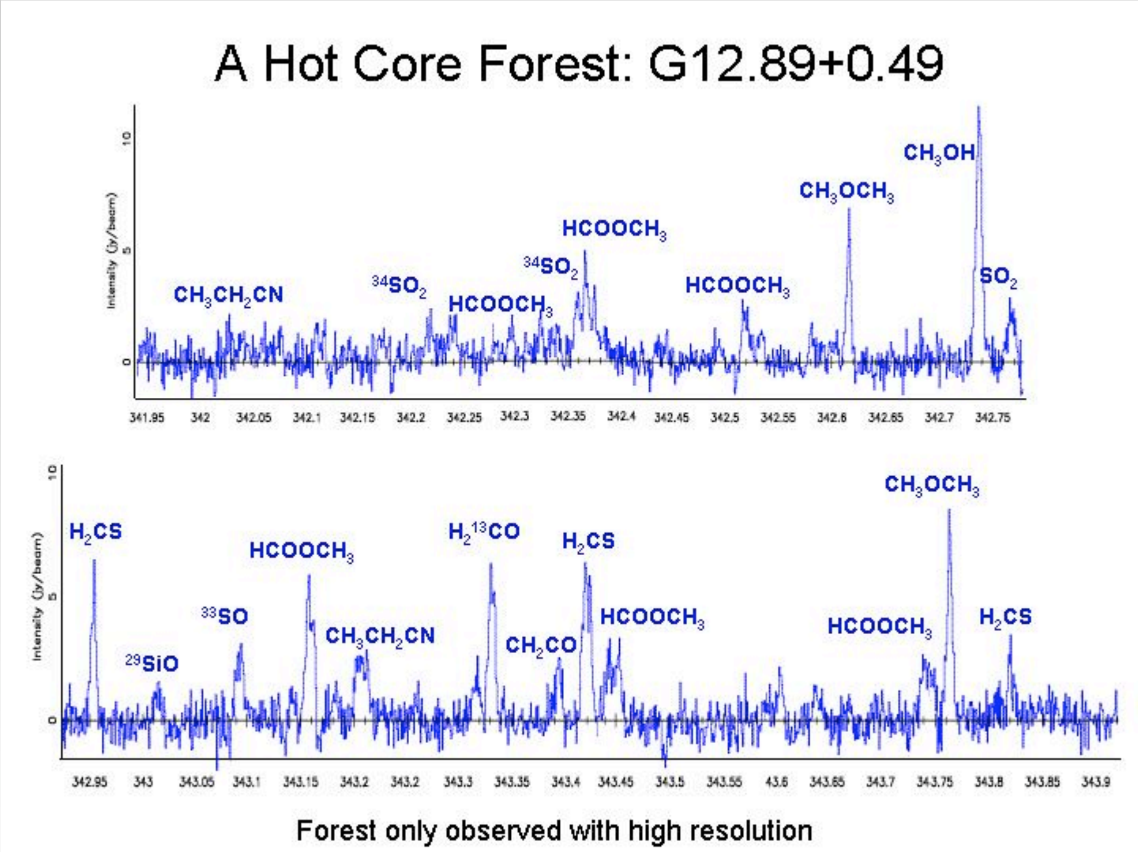
What can we learn from spectral imaging?



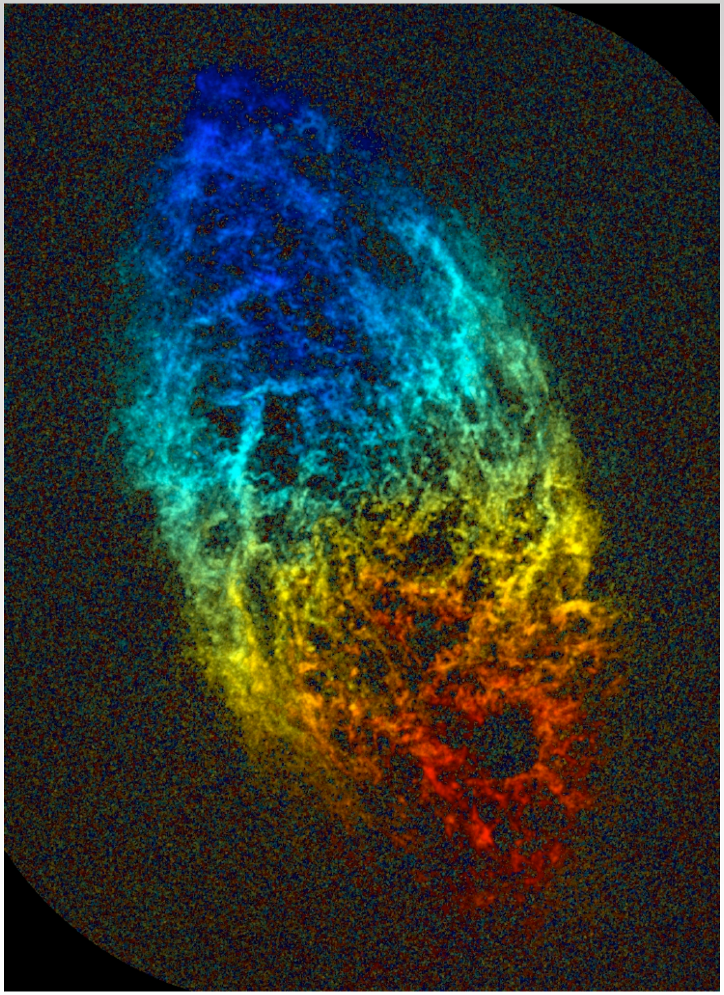
Observations from 342 to 344 GHz with the SMA by Brogan and Shirley (2004)

What can we learn from spectral imaging?

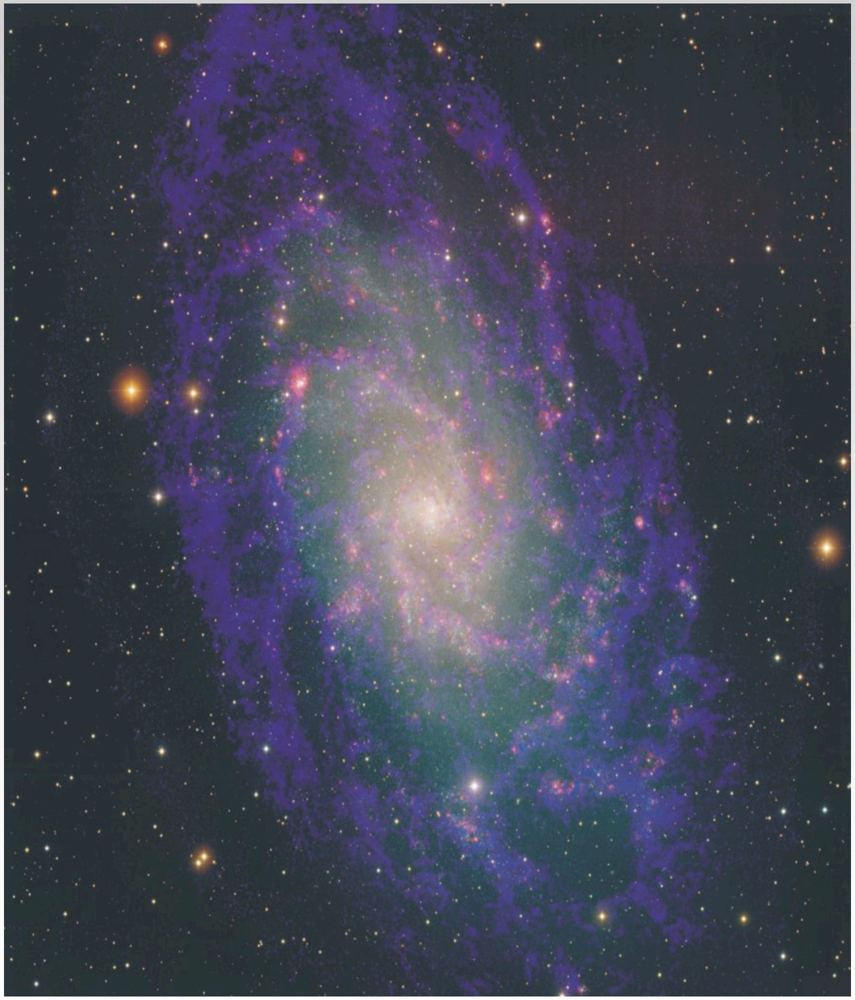
- Narrow spectral features
  - spectral lines: spin-flip (HI), recombination lines, rotational/vibrational lines (CO, NH_3, SO, …), masers
    - particularly important in mm/submm (PdBI, SMA, ALMA)

What can we learn from spectral imaging?

HI gas content, kinematics



M33 HI (VLA observations)



Thilker, Braun, & Walterbos, 2001

What can we learn from spectral imaging?

HH211 PdBI CO

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  - spectral lines: spin-flip (HI), recombination lines, rotational/vibrational lines (CO, NH_3, SO, …), masers
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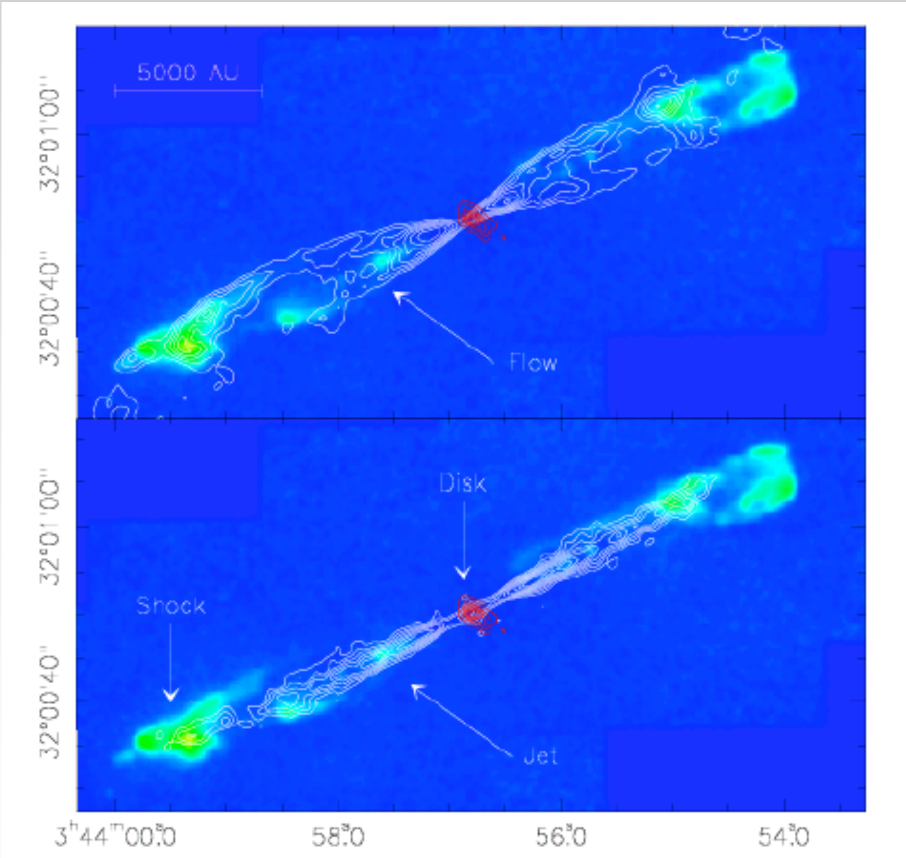

Gueth & Guilloteau 1999

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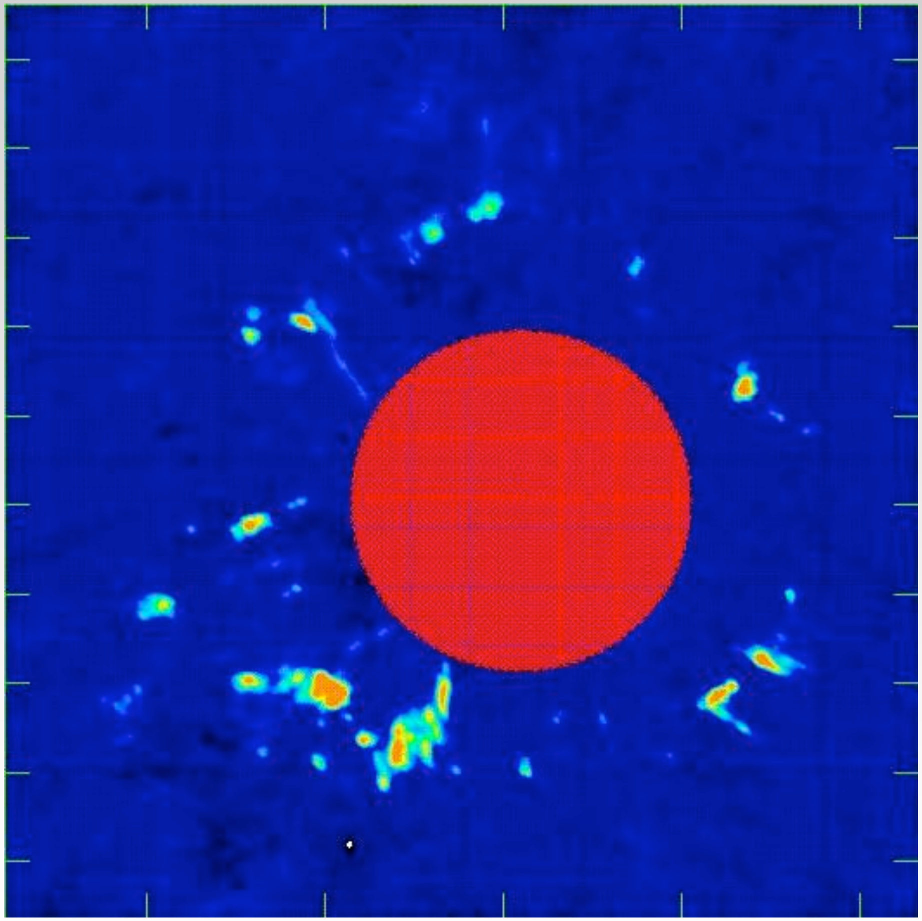
TX Cam VLBA SiO

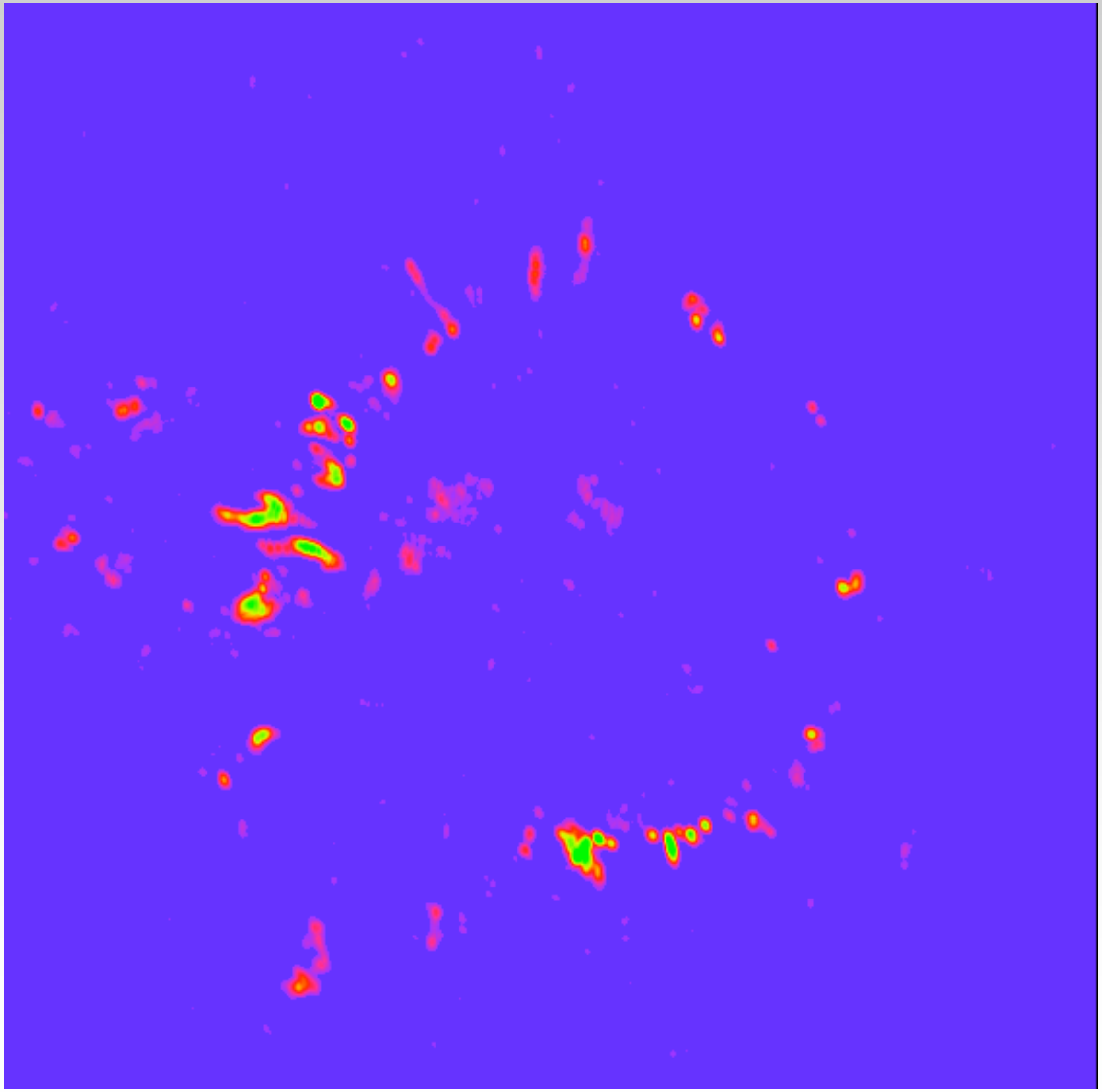


Kemball & Diamond 1997

VLBA: Time-lapse imaging

Observations of SiO masers in TX-CAM by Kemball and Diamond

Nearly two years with VLBA (twice weekly)



Analyzing spectral images: 2-D representations

The information content of 3-D data cubes can be conveyed using a variety of 1-D or 2-D displays:

- 2-D slices at one point on velocity axis = channel images
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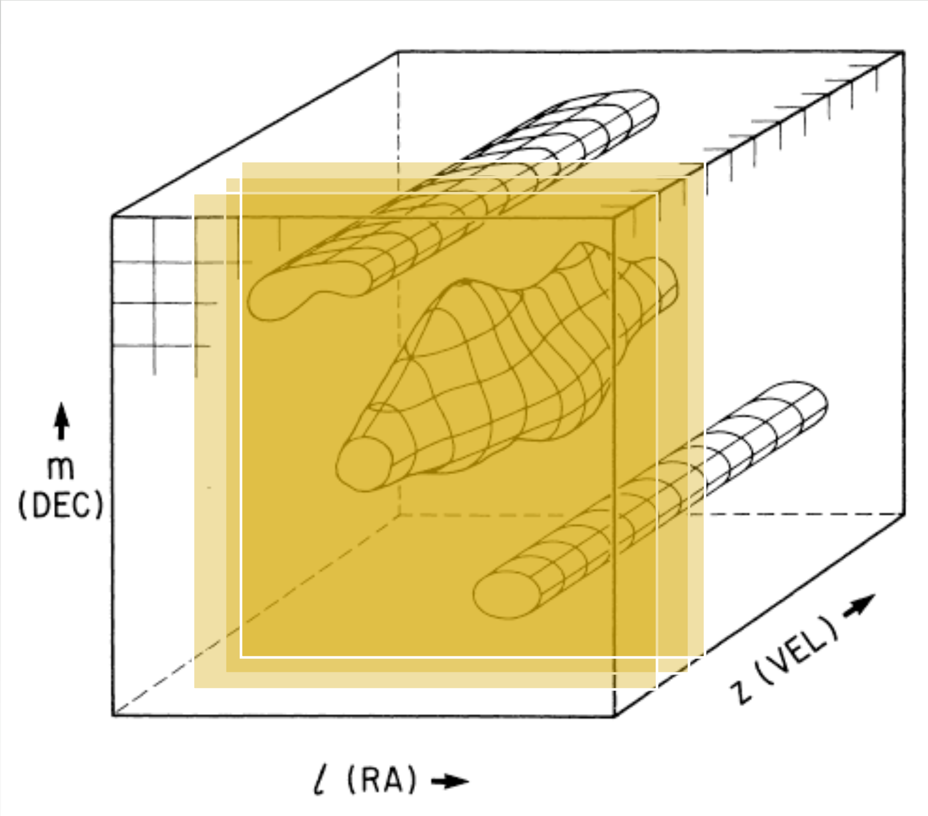
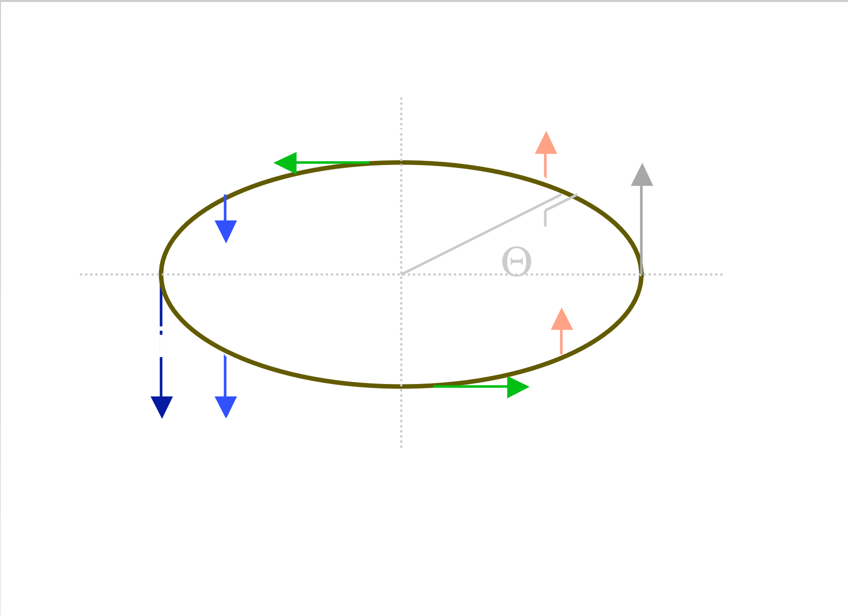
- 2-D slices integrated along the velocity axis = moment maps

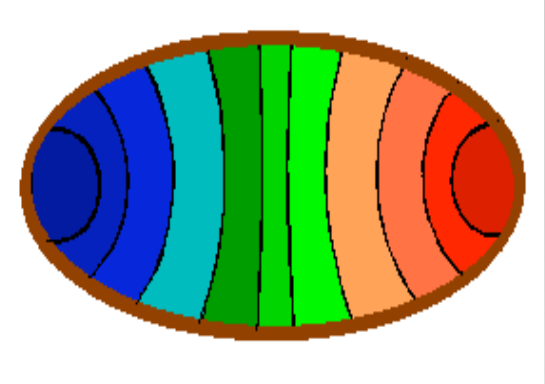
Analyzing spectral images: channel images



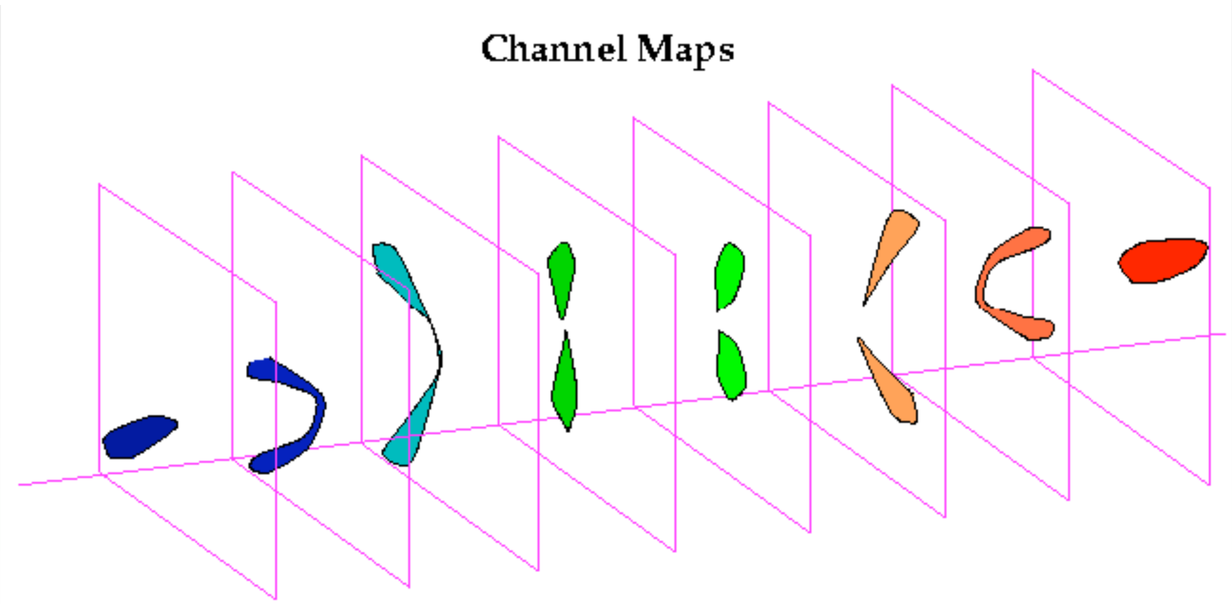
After editing, calibrating, and deconvolving, we are left with an inherently 3-D data set comprising a series of 2-D spatial images of each of our frequency (velocity) channels.

Schematic data cube for a rotating galaxy disk



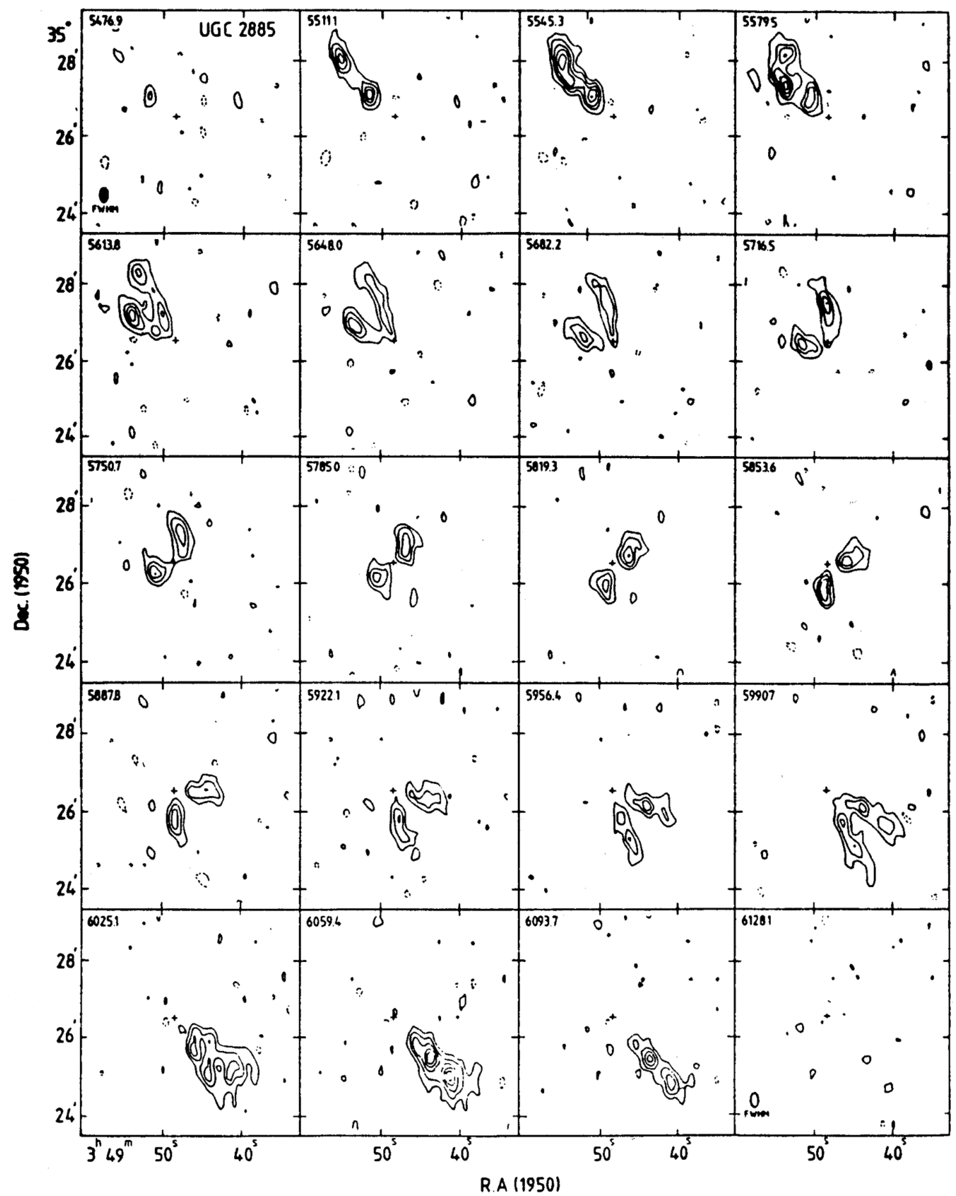


Mean Velocity Field

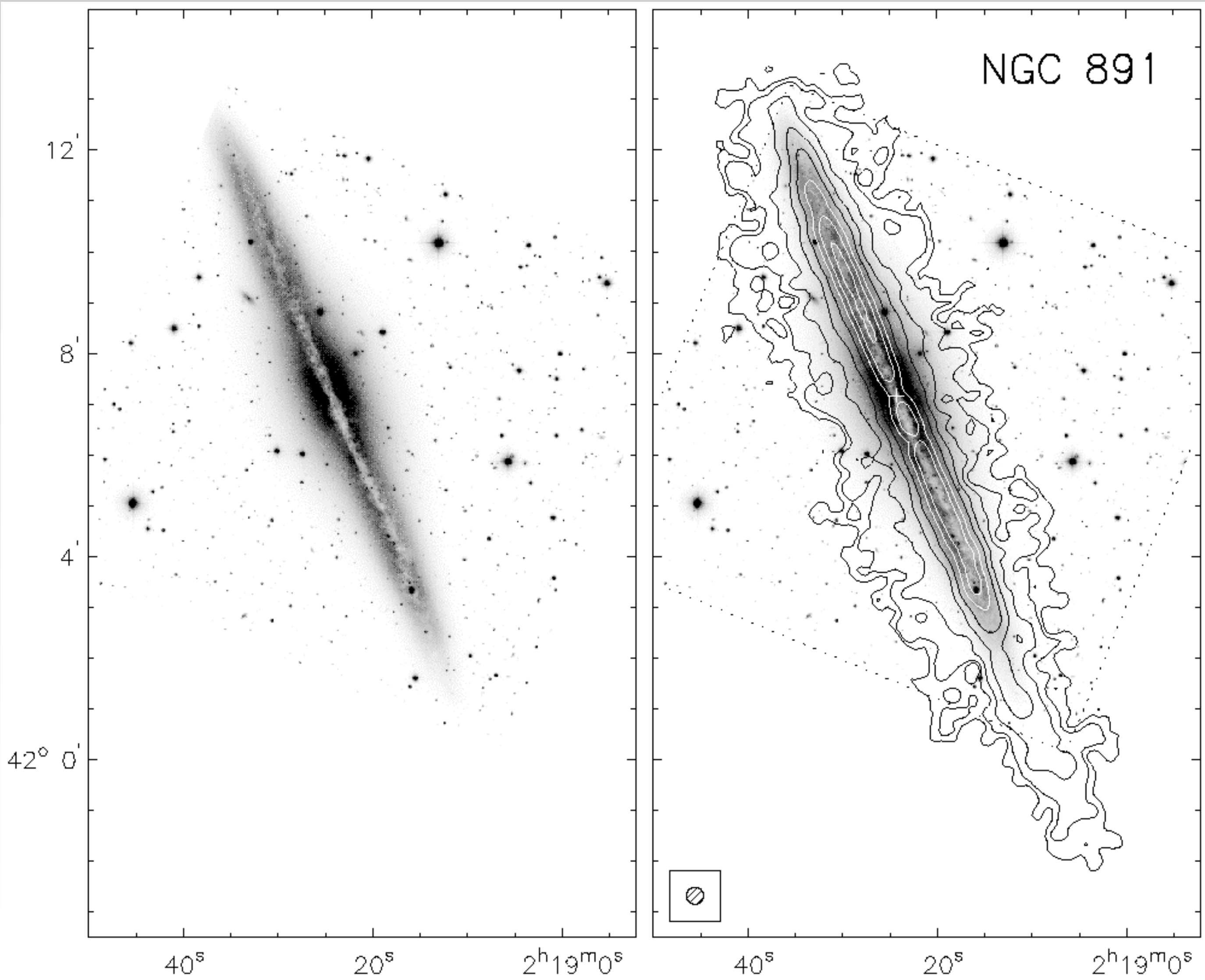


Example:

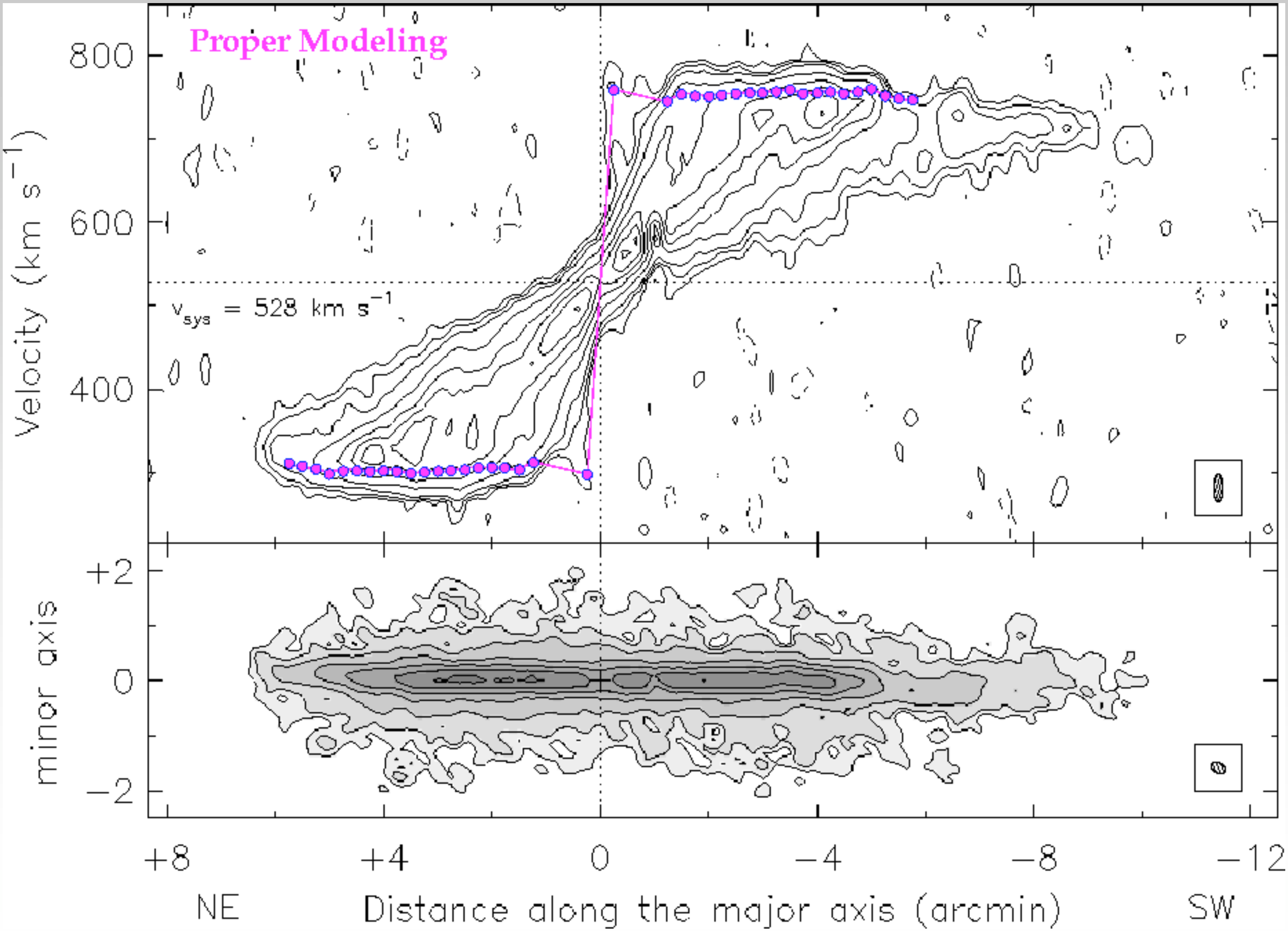
Channel images from a rotating disk



Matching Data in 3-dimensions: Rotation Curve Modeling



Swaters et al., 1997, ApJ, 491, 140



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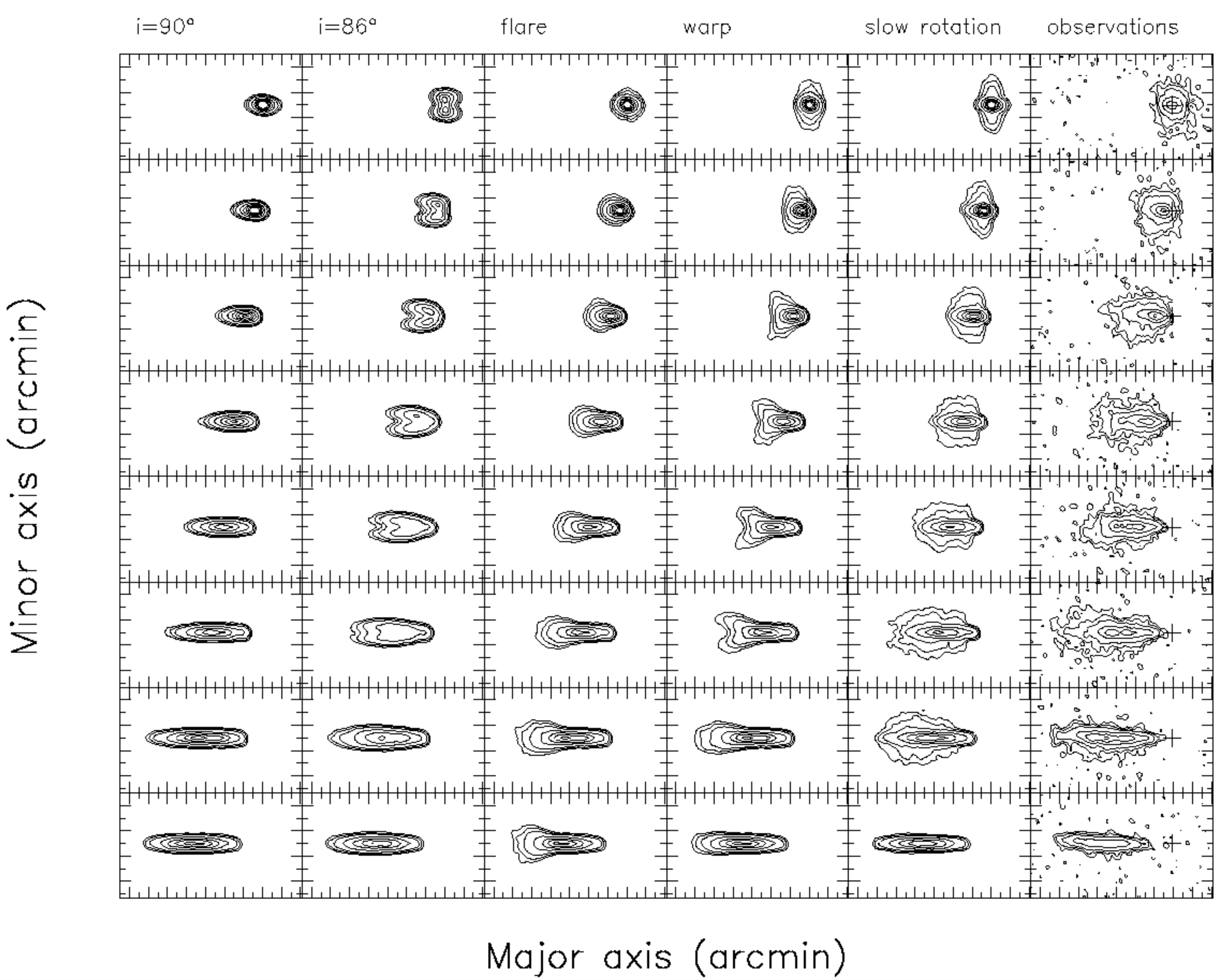
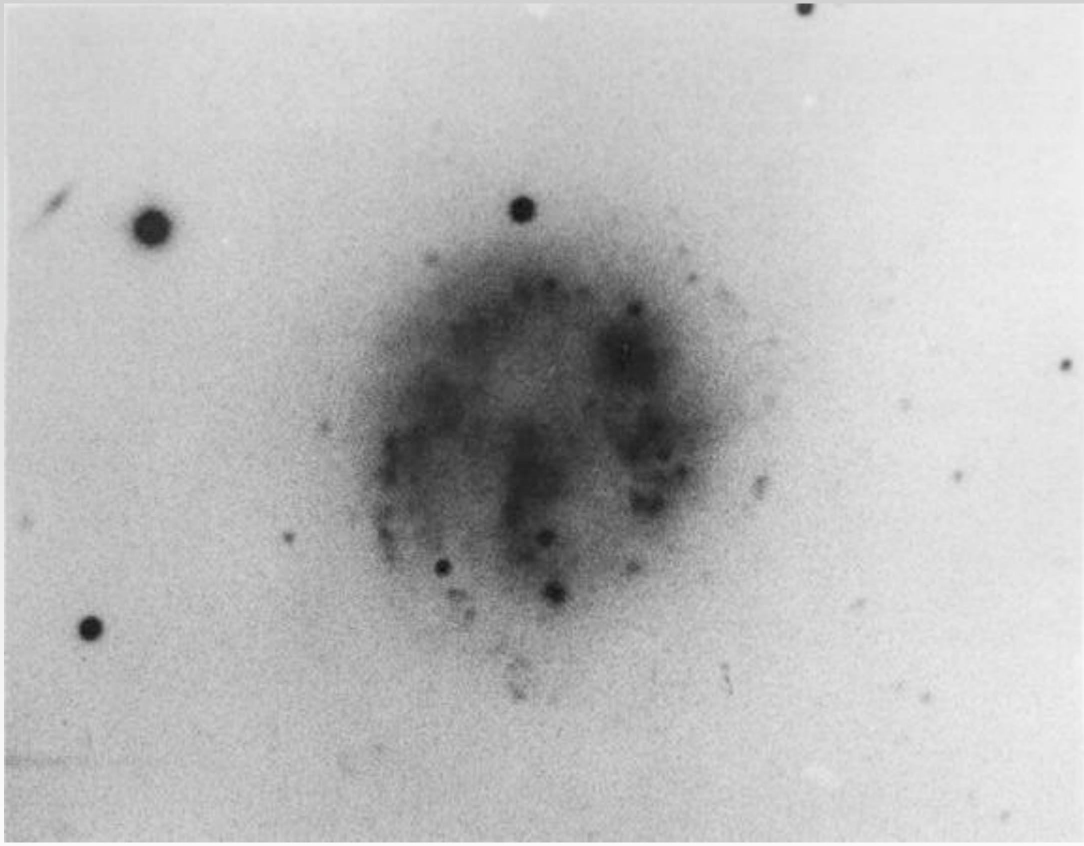


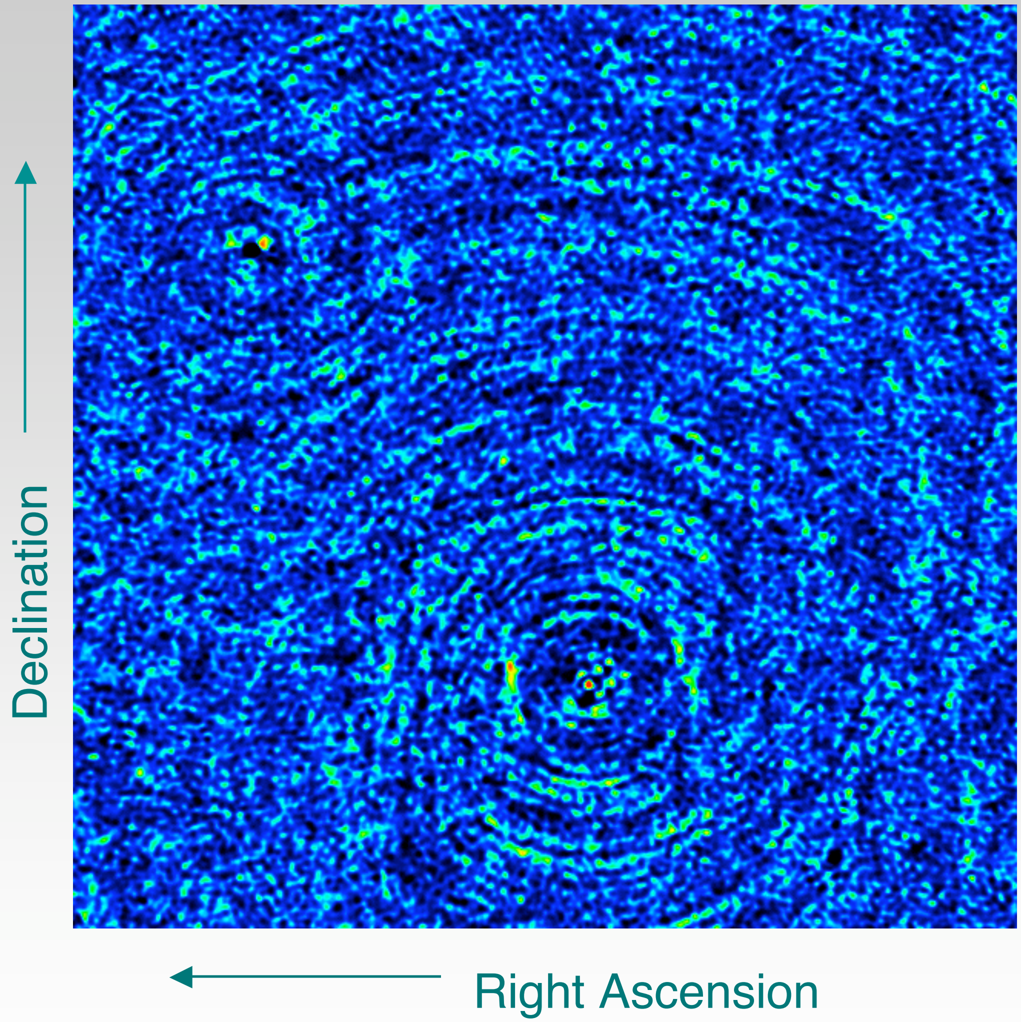
Swaters et al., 1997, ApJ, 491, 140

Example: HI observations of Mk86



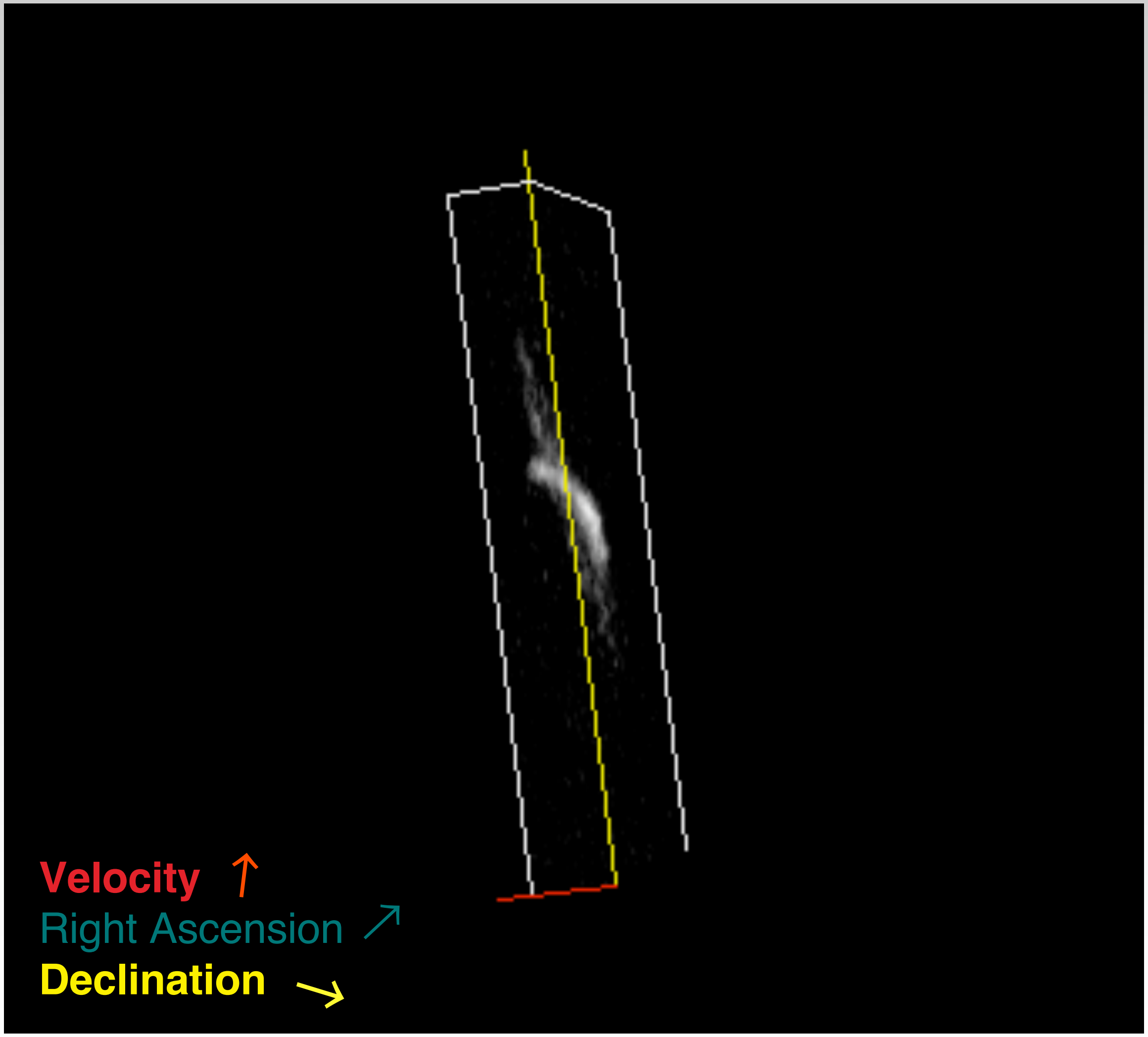
Optical image of peculiar face-on galaxy from Arp (1966)

Visualizing spectral image cubes: Movies



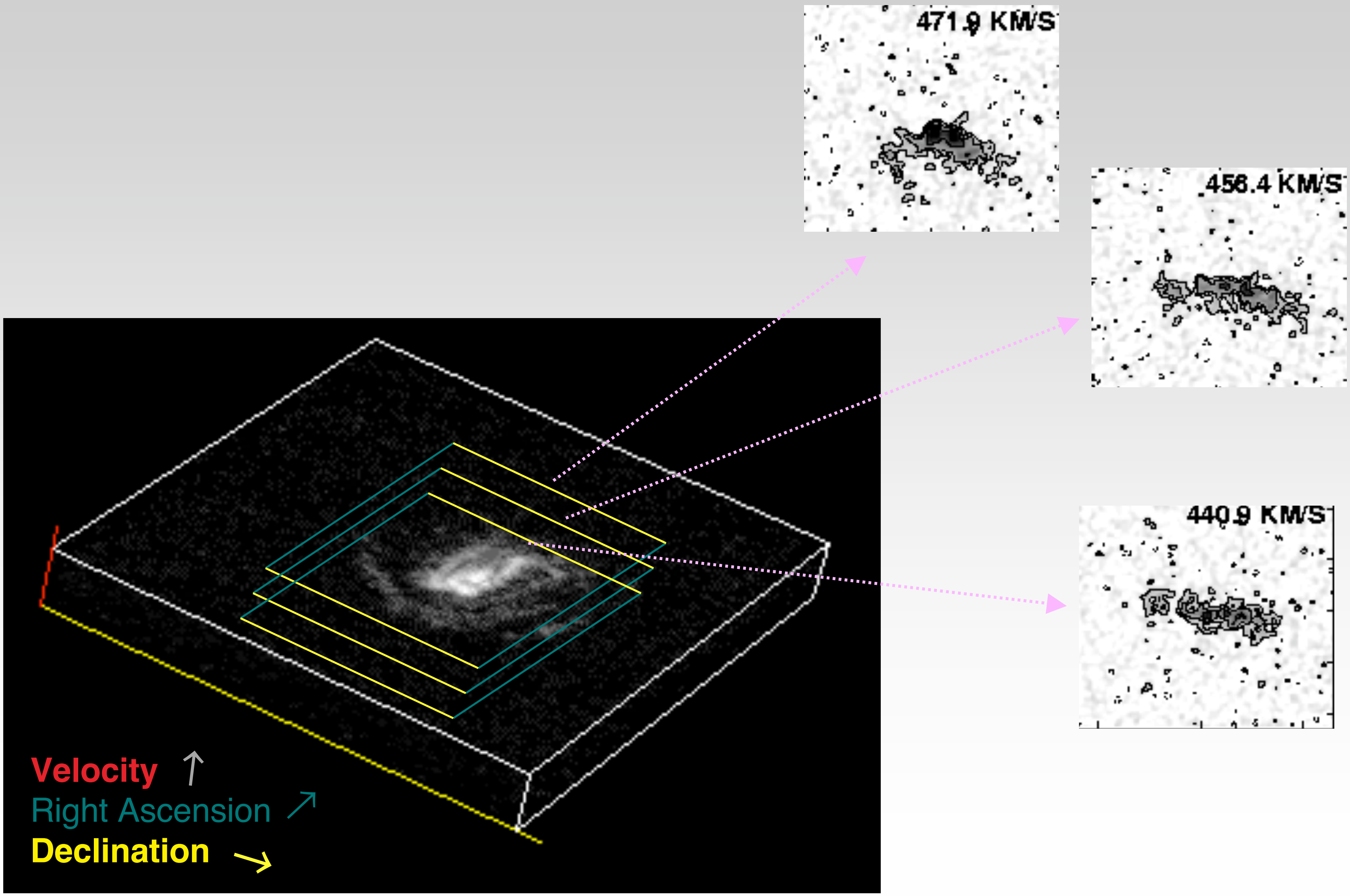
"Movie" showing a consecutive series of channel images from a data cube.
This cube contains HI emission from two rotating disk galaxies (IC2233, Mk86).

Visualizing spectral image cubes: 3-D rendering

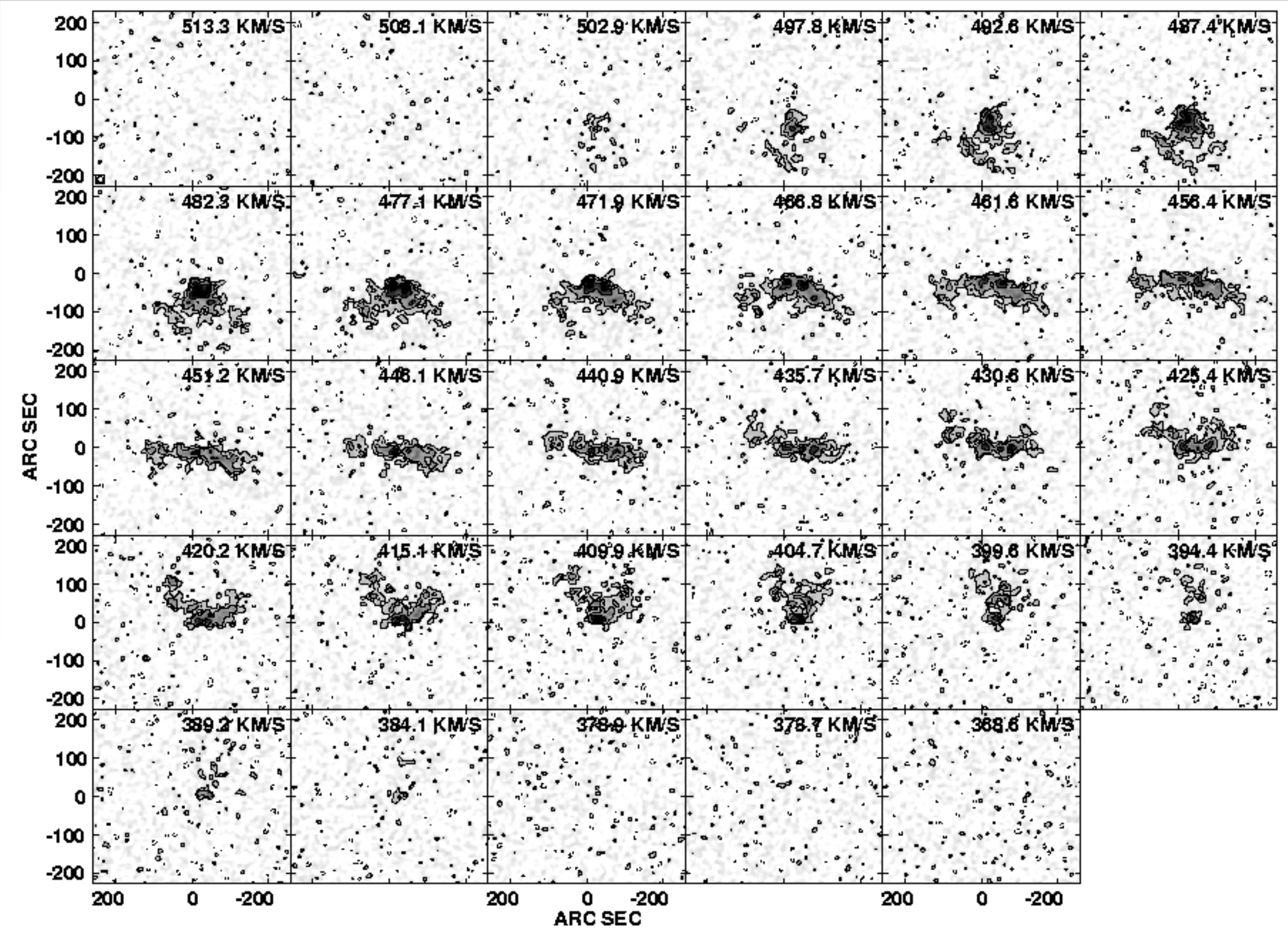


Display produced using the 'xray' program in the karma software package (http://www.atnf.csiro.au/software/karma/)

Visualizing spectral image cubes: Channel images

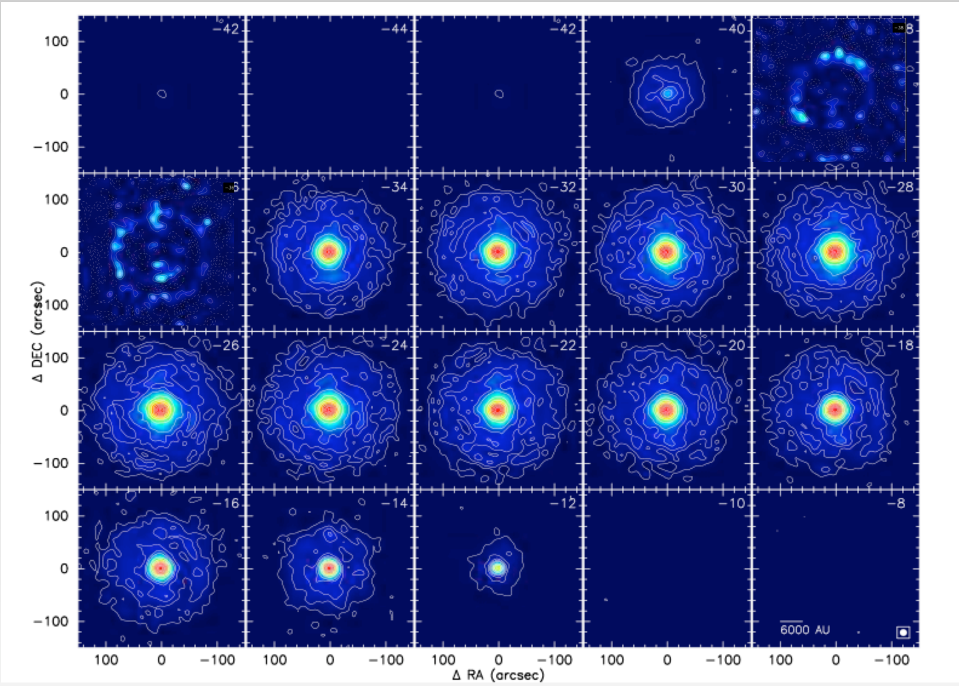


Visualizing spectral image cubes: Channel images

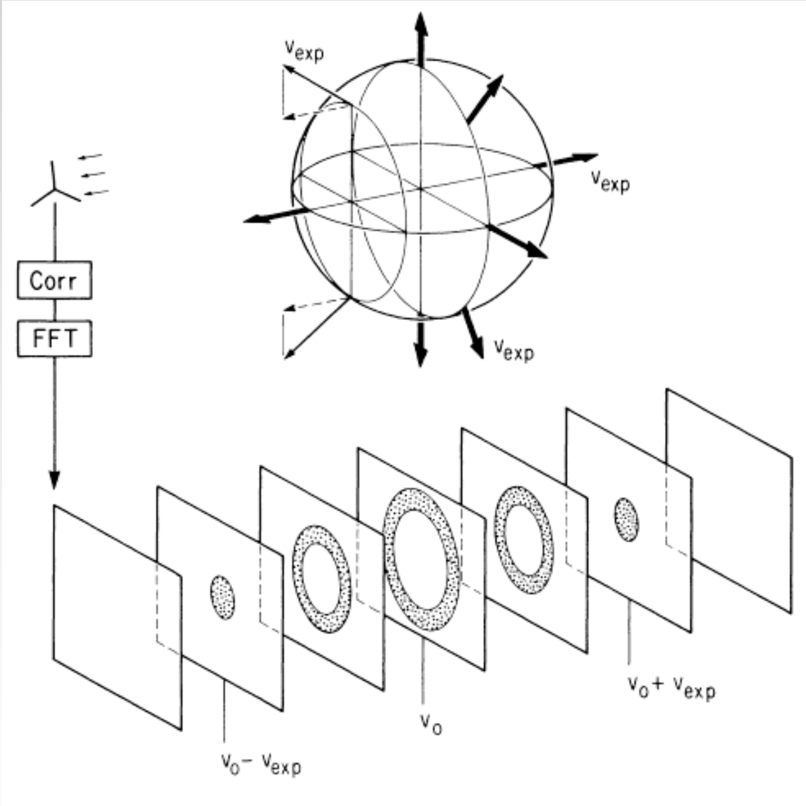


Greyscale+contour representations of individual channel images

Sample Application of Channel Map Analysis: An Expanding Circumstellar Envelope



Model of a uniformly expanding shell (from Roelfsema 1989)



Channel maps of $^{12}CO(J=1\text{-}0)$ emission in the circumstellar envelope of the asymptotic giant branch star IRC+10216, obtained with BIMA+ NRAO 12-m (from Fong et al. 2003).

$$v_{rad}(r) = \pm\, |\boldsymbol{v}_{exp}|\,[1 - (r^2/R^2)]^{0.5}$$

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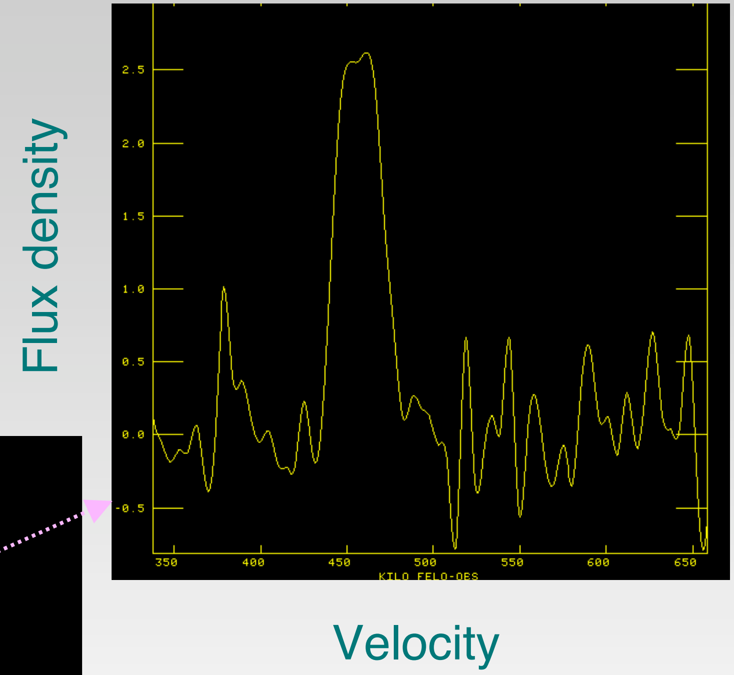
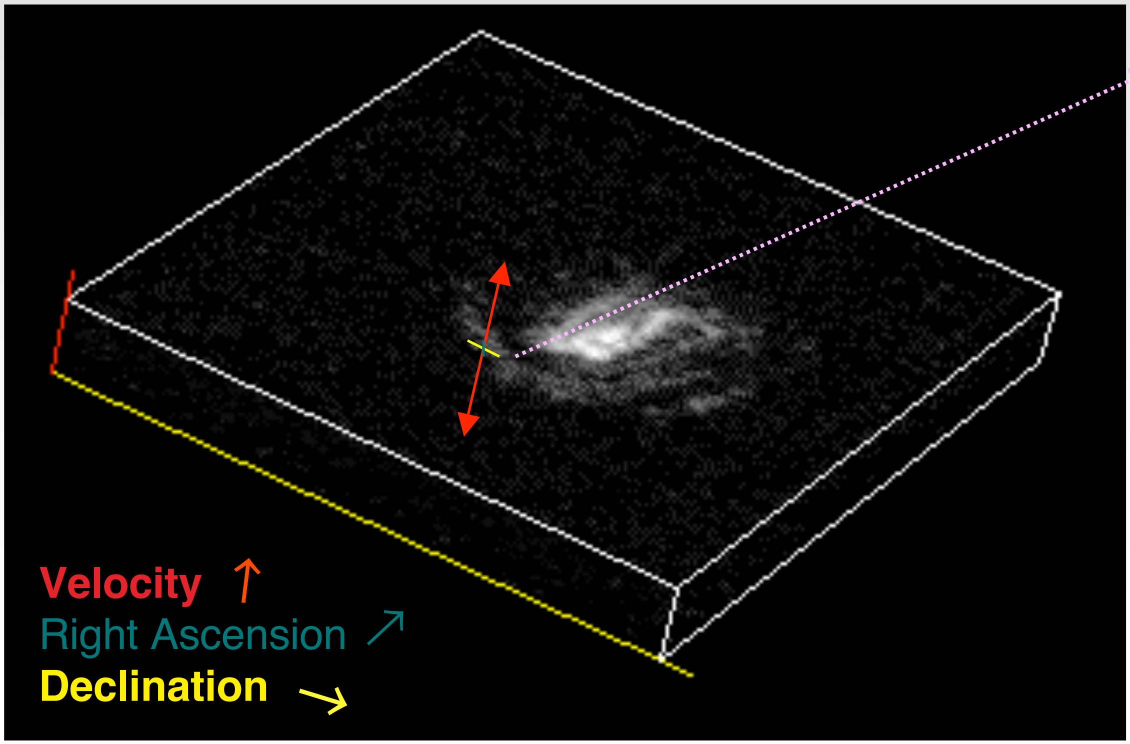
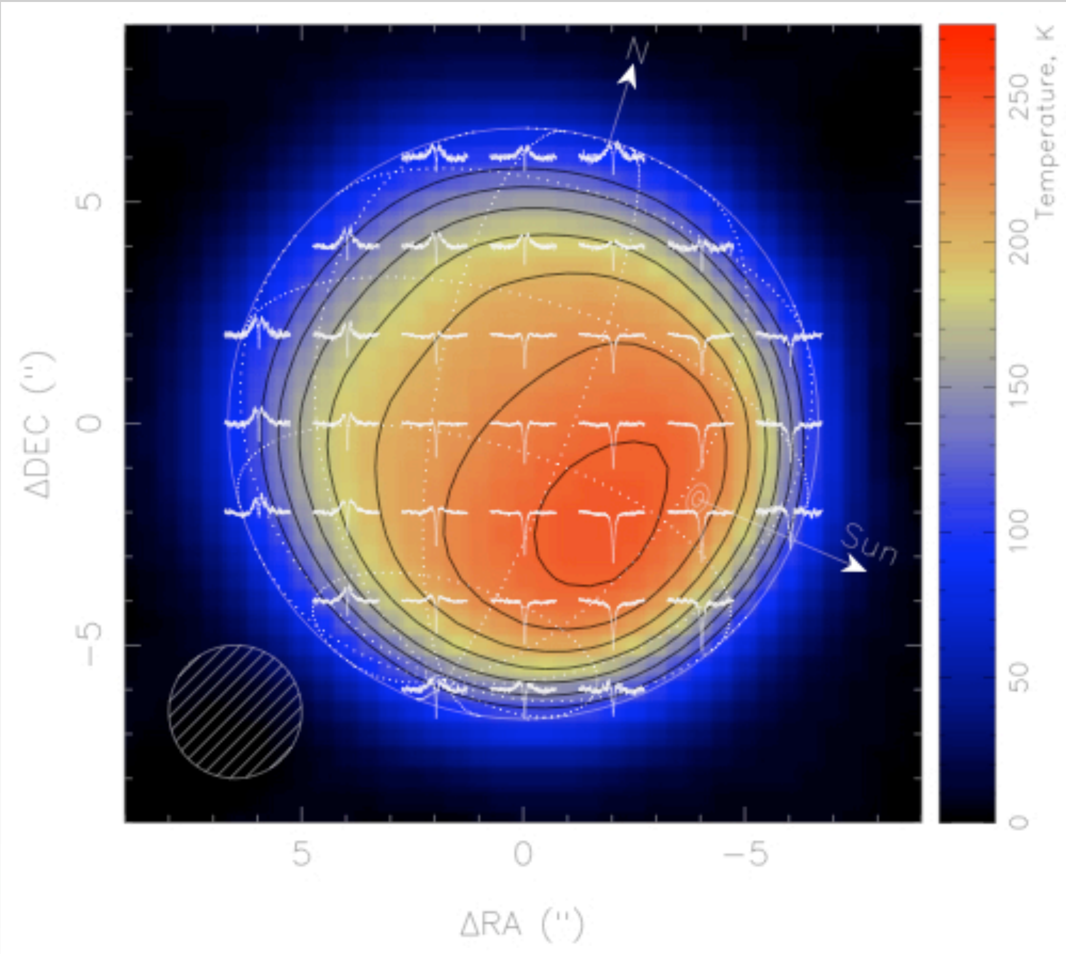
Analyzing spectral images: Spectral profiles





Analyzing spectral images: Spectral profiles



SMA CO(2-1) line profiles across the disk of Mars, overplotted on 1.3mm continuum image.

Credit: M. Gurwell (see Ho et al. 2004)

Changes in line shape, width, and depth probe the physical conditions of the Martian atmosphere.

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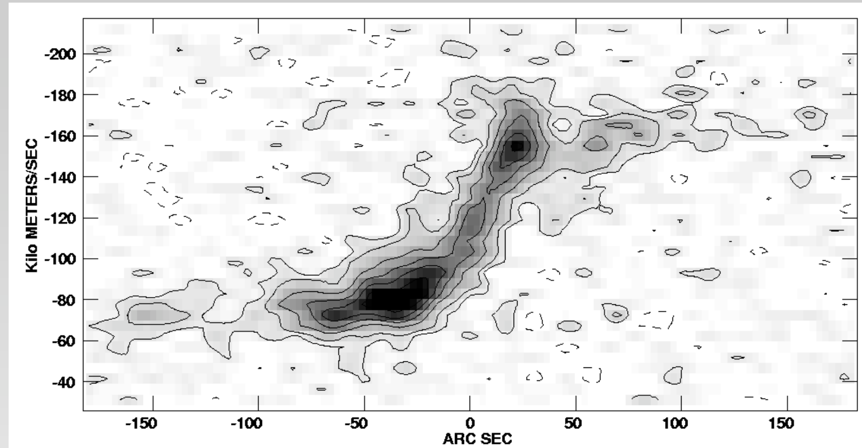
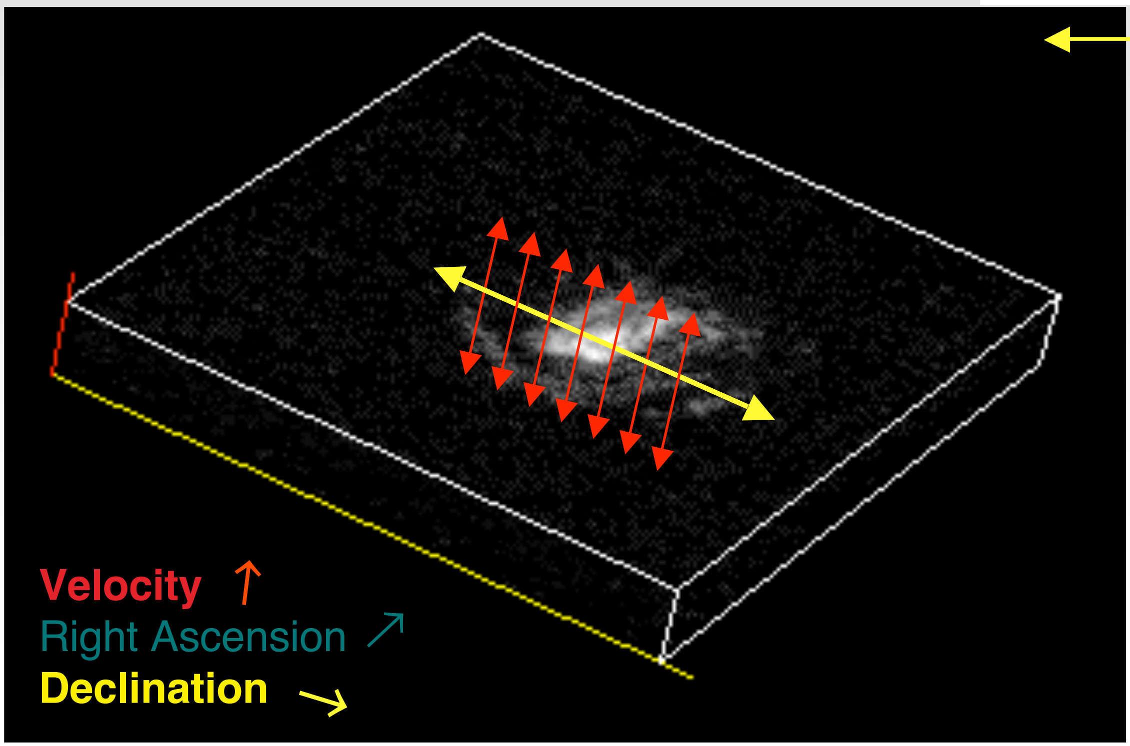
Visualizing spectral images: Position-velocity plots

Velocity profile

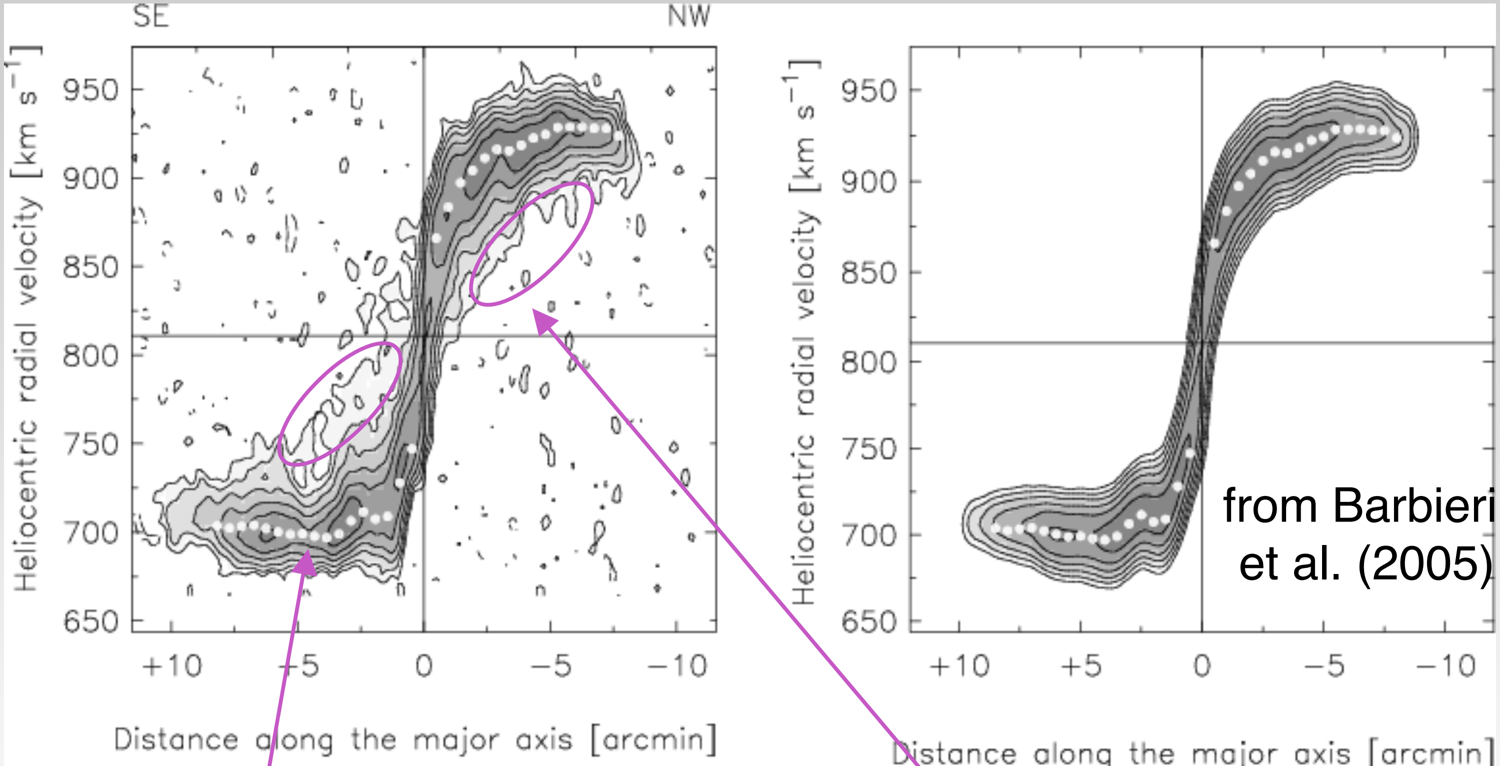


Distance along slice



Greyscale & contours convey intensity of the emission.

Sample application of P-V plots: Identifying an anomalous gas component in a rotating galaxy



Fitting of line profiles along a P-V curve can yield the **rotation curve** of a galaxy disk (white dots).

Comparison of model to observed P-V diagram reveals gas at unexpected velocities: rotationally lagging HI "thick disk"

Models computed using GIPSY (www.astro.rug.nl/~gipsy.html)

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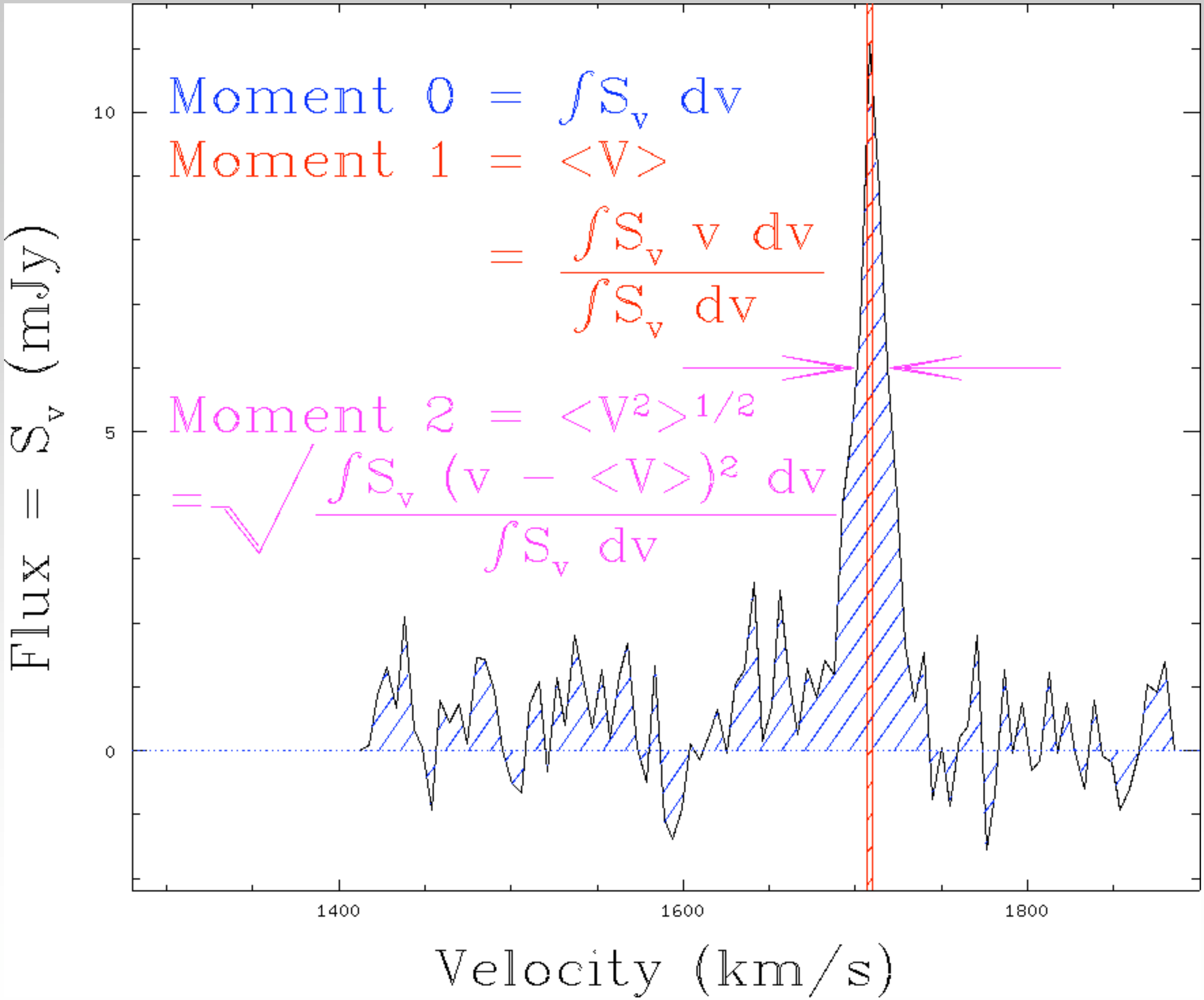
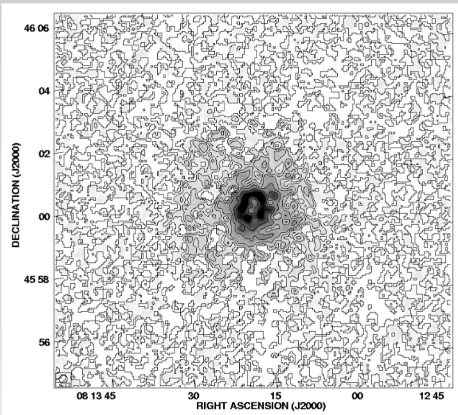
“Moment” maps

- Are integrals over the velocity dimension
- 0th moment = total flux
- 1st moment = intensity weighted (IW) velocity
- 2nd moment = IW velocity dispersion
- 3rd moment = skewness or line asymmetry
- 4th moment = kurtosis

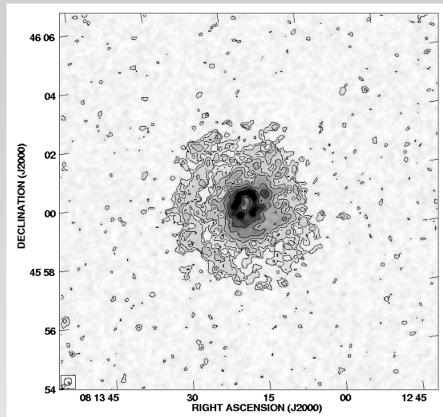


Moment 0 = $\int S_v \, dv$
Moment 1 = $\langle V \rangle$
$= \frac{\int S_v \, v \, dv}{\int S_v \, dv}$
Moment 2 = $\langle V^2 \rangle^{1/2}$
$= \sqrt{\frac{\int S_v \, (v - \langle V \rangle)^2 \, dv}{\int S_v \, dv}}$
Flux = S_v (mJy)
Velocity (km/s)
10
5
0
1400
1600
1800

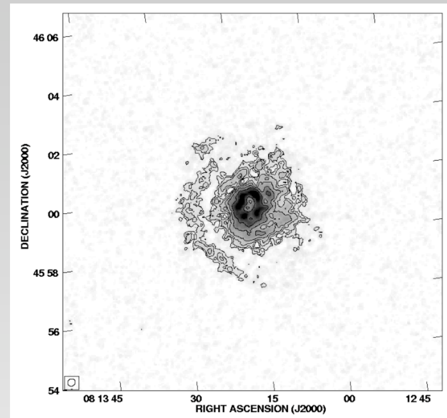
Computing Moment Maps: cutoffs matter!



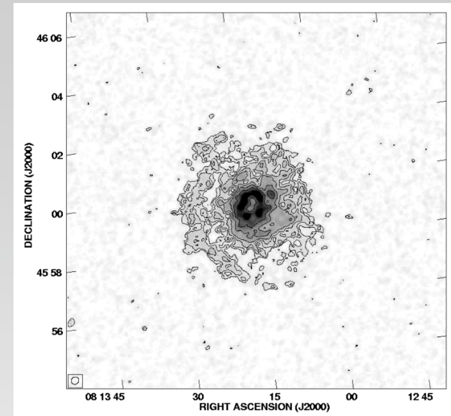
Straight sum of all channels containing line emission



Summed after clipping below 1σ



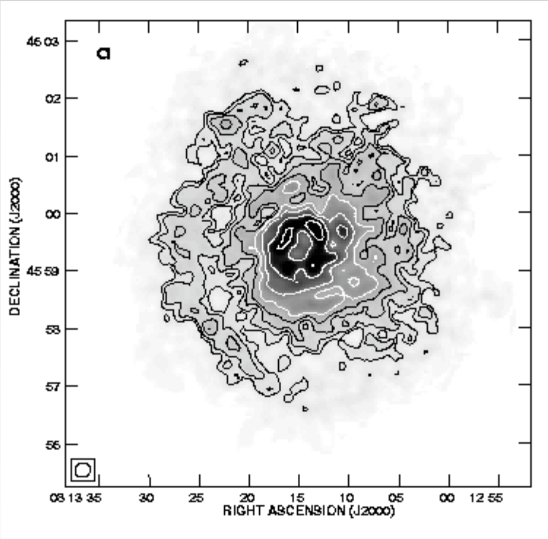
Summed after clipping below 2σ



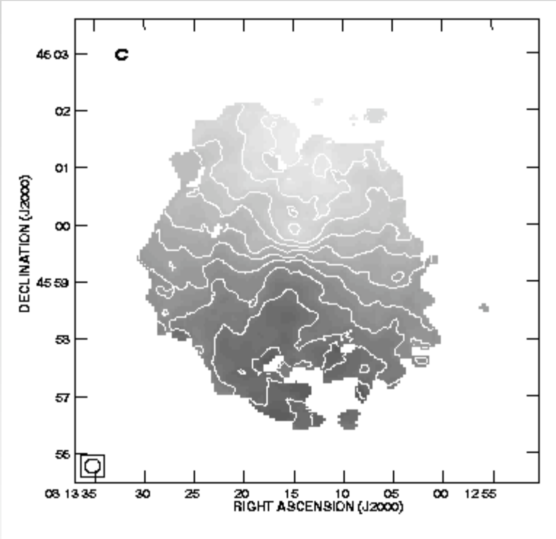
Summed after clipping below 1 σ, but clipping is based on a version of the cube smoothed by factor of 2 in space and freq.

Four versions of a moment 0 (total intensity) map computed from the same data cube.

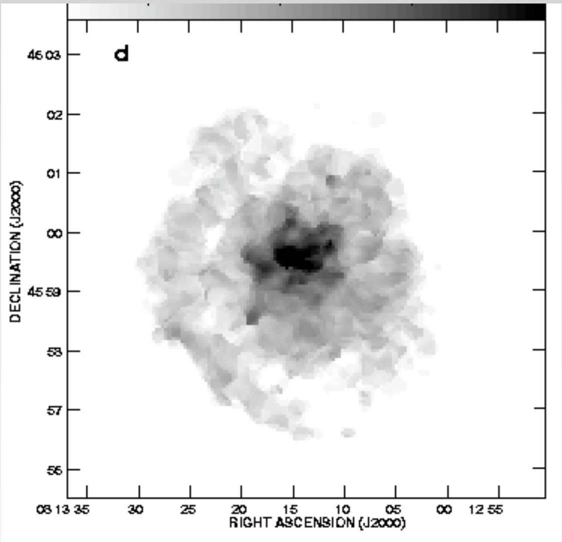
Analyzing Spectral Line Data: Moment Maps



Moment 0
(Total Intensity)

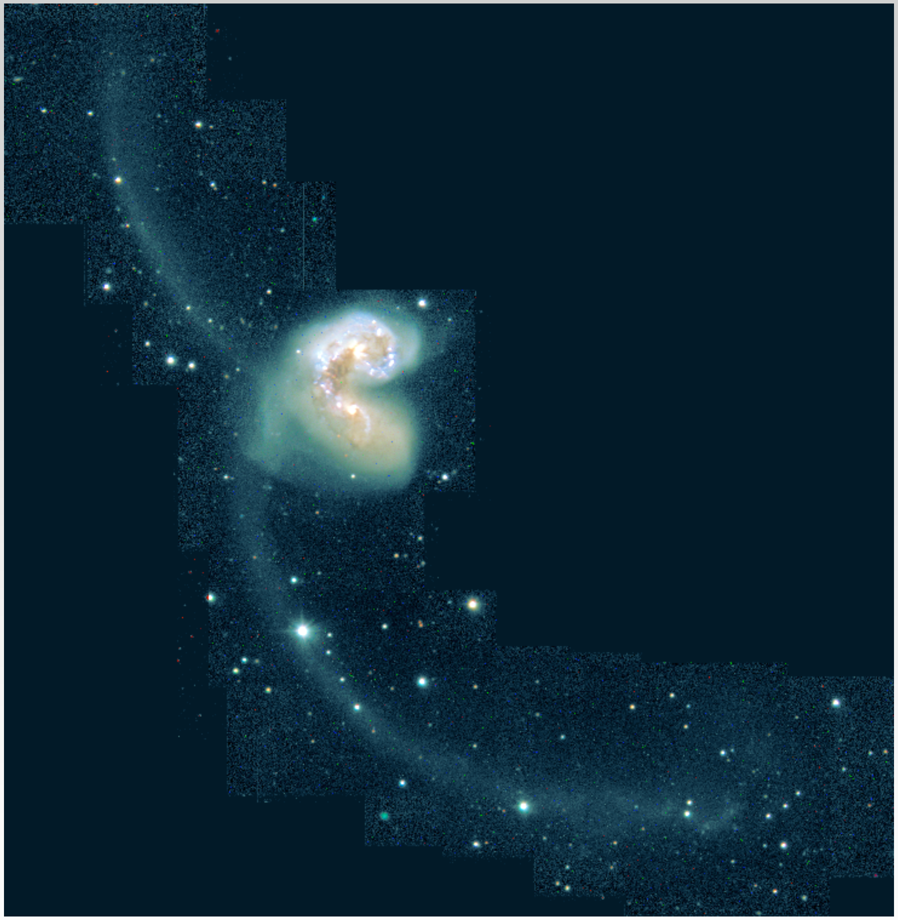


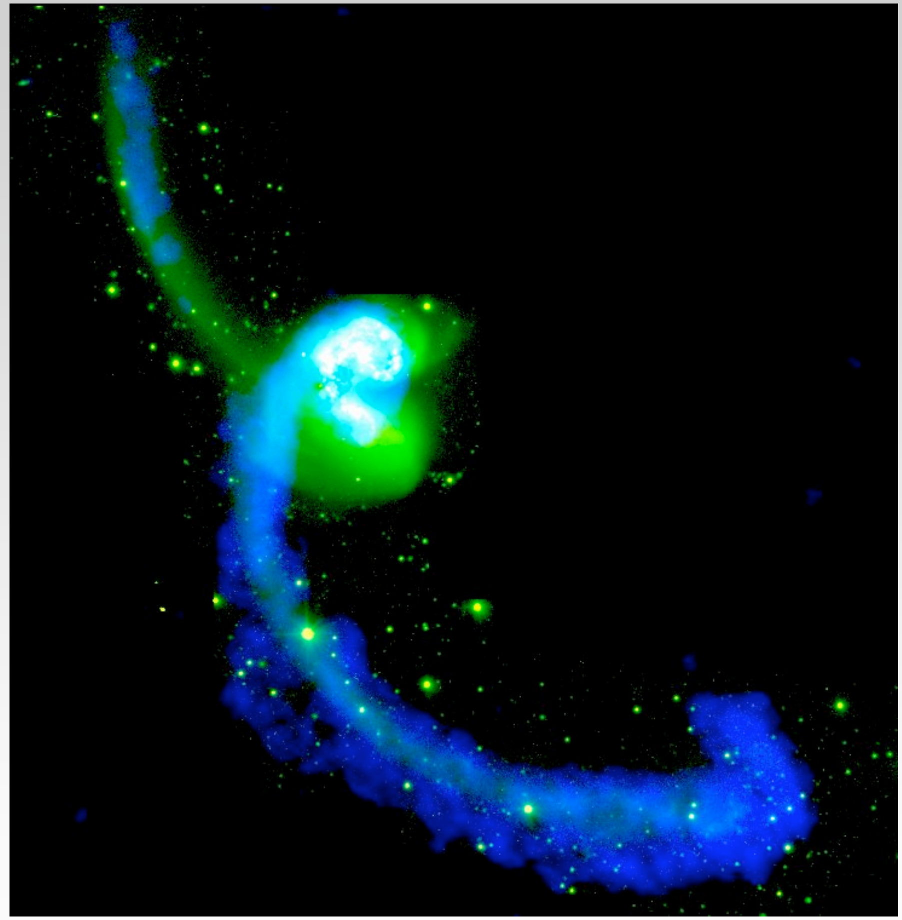
Moment 1
(Velocity Field)



Moment 2
(Velocity Dispersion)

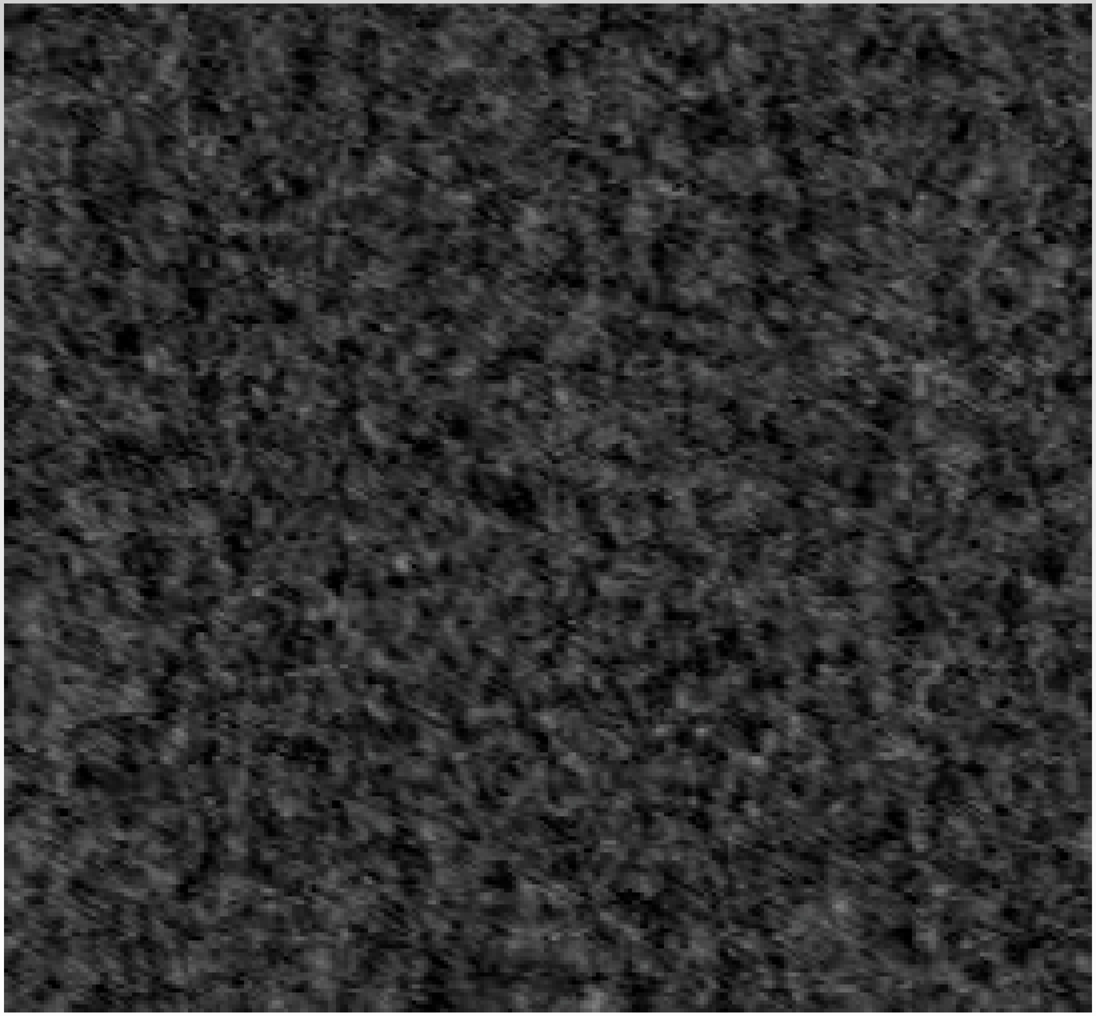
VLA C+D-array observations of NGC 4038/9



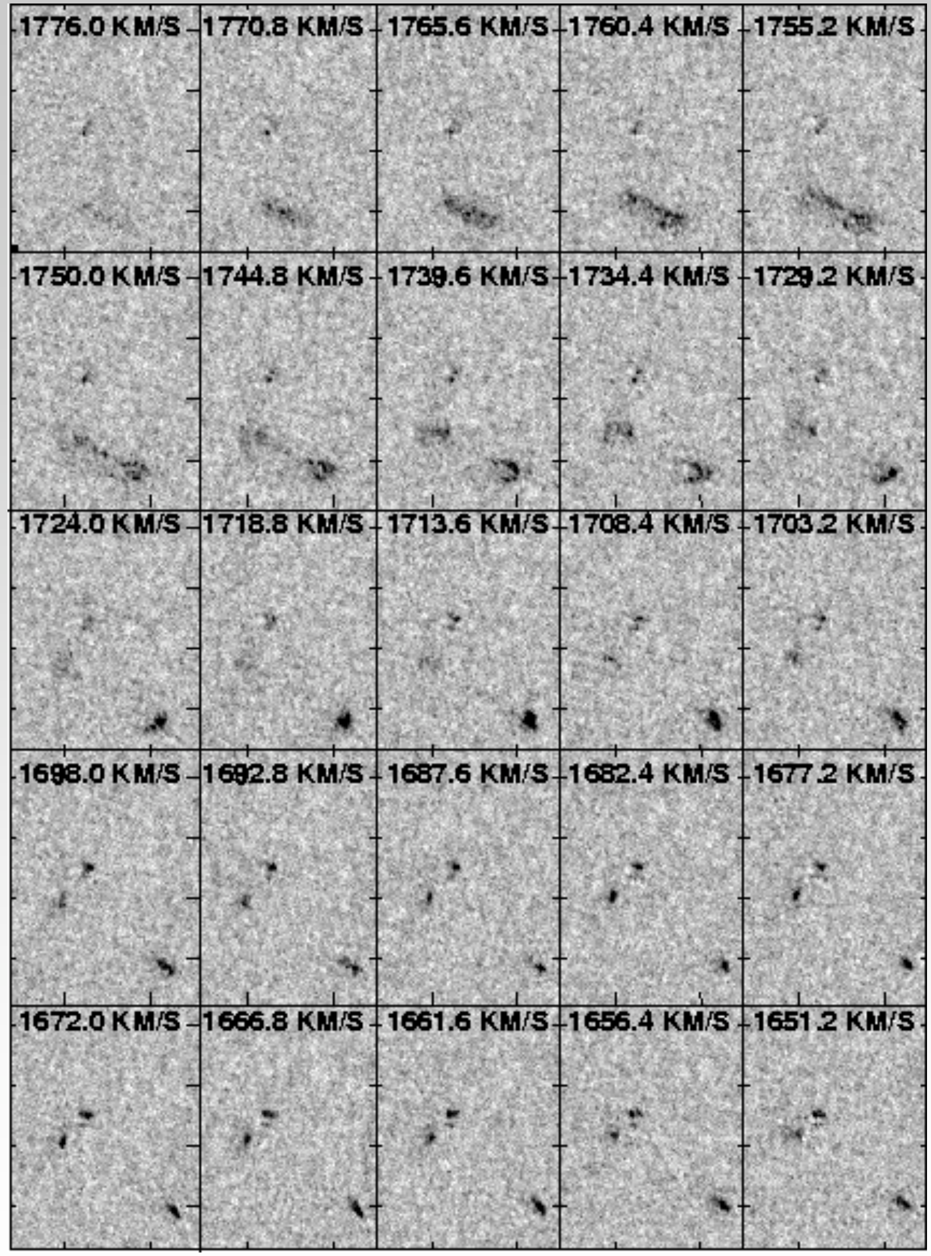


Better known as "The Antennae"   (courtesy of John Hibbard)

“Channel Maps”: spatial distribution of line flux at each successive velocity setting

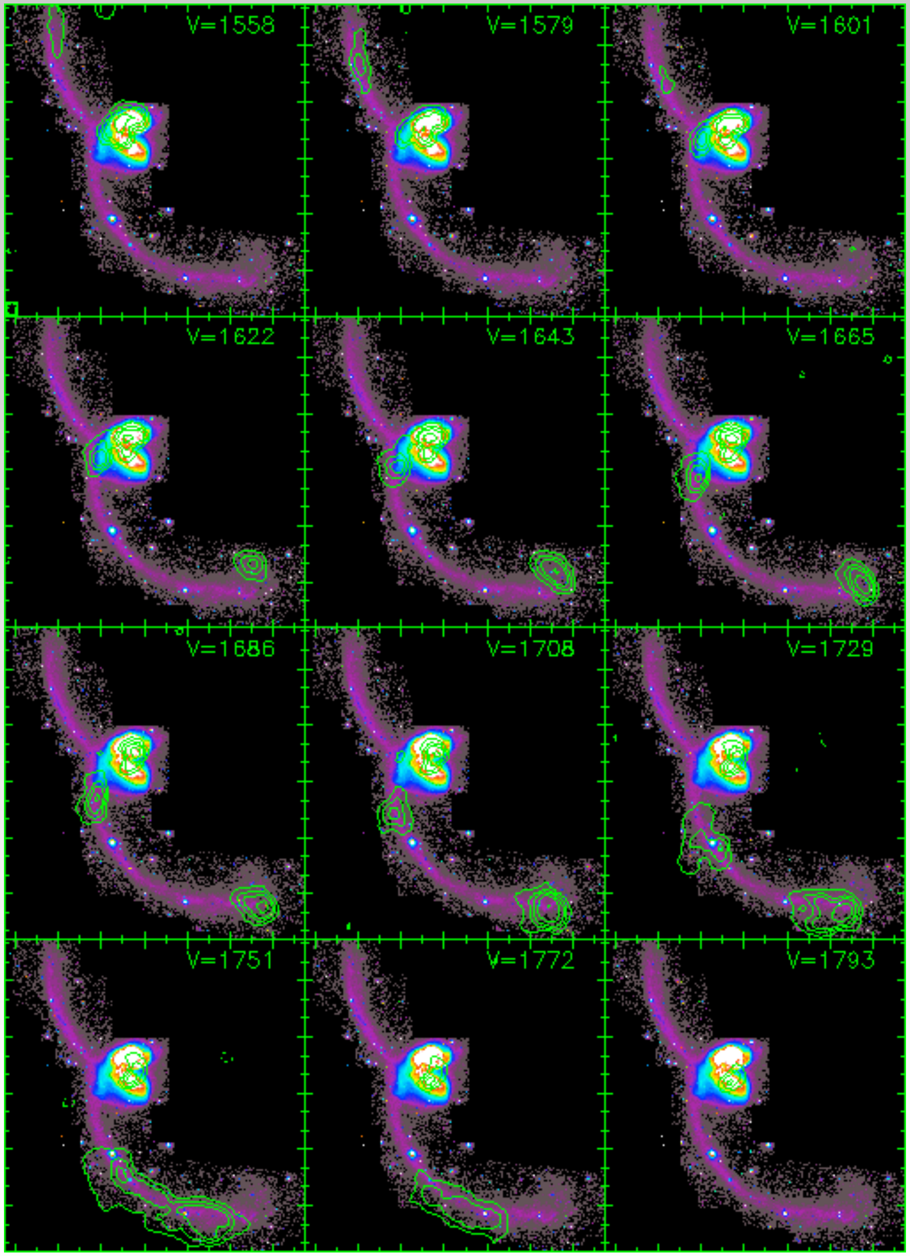


The Antennae:



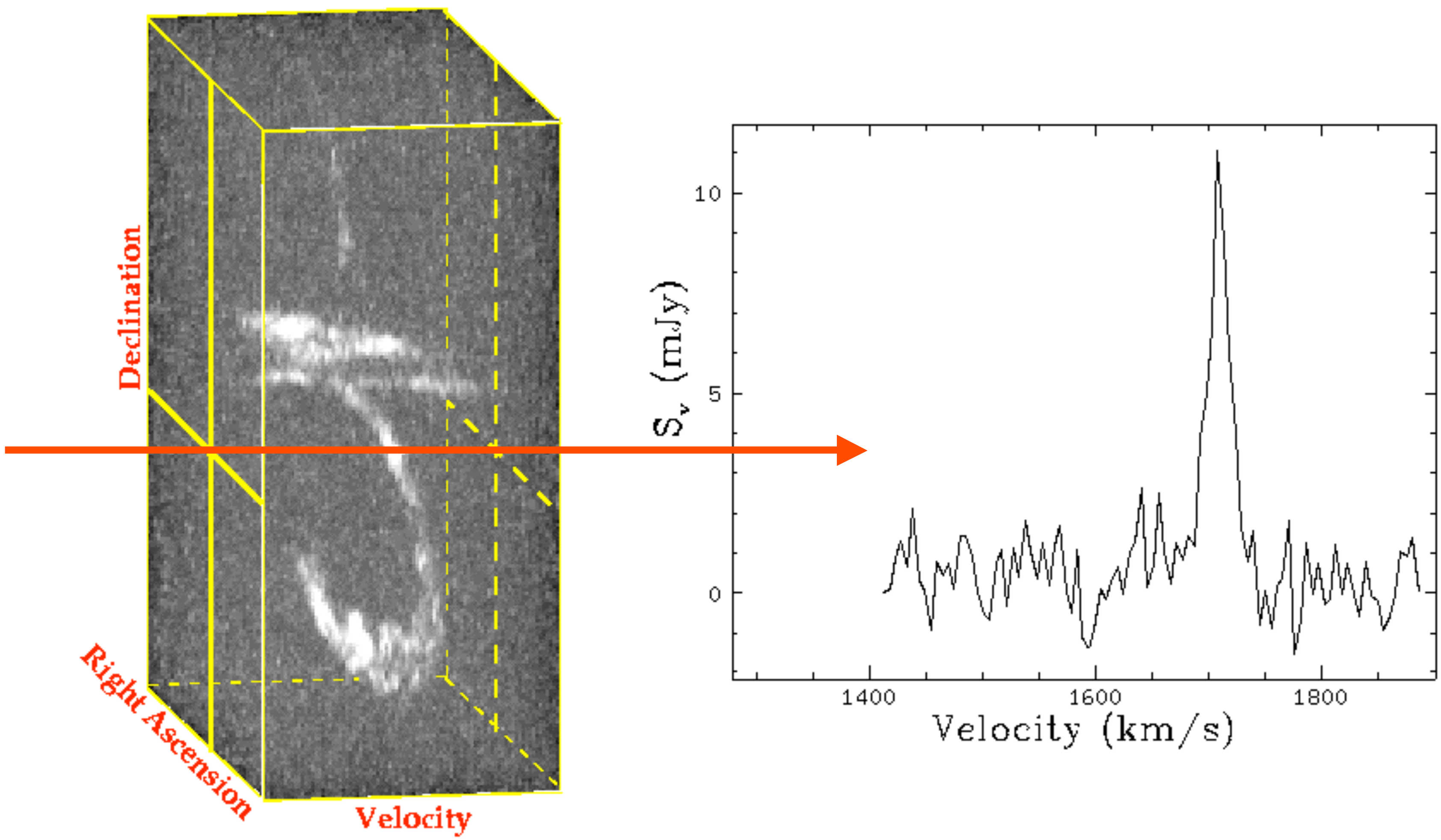
Greyscale representation of a set of channel maps

The Antennae:



Emission from channel maps displayed as contours overlaid upon an optical image

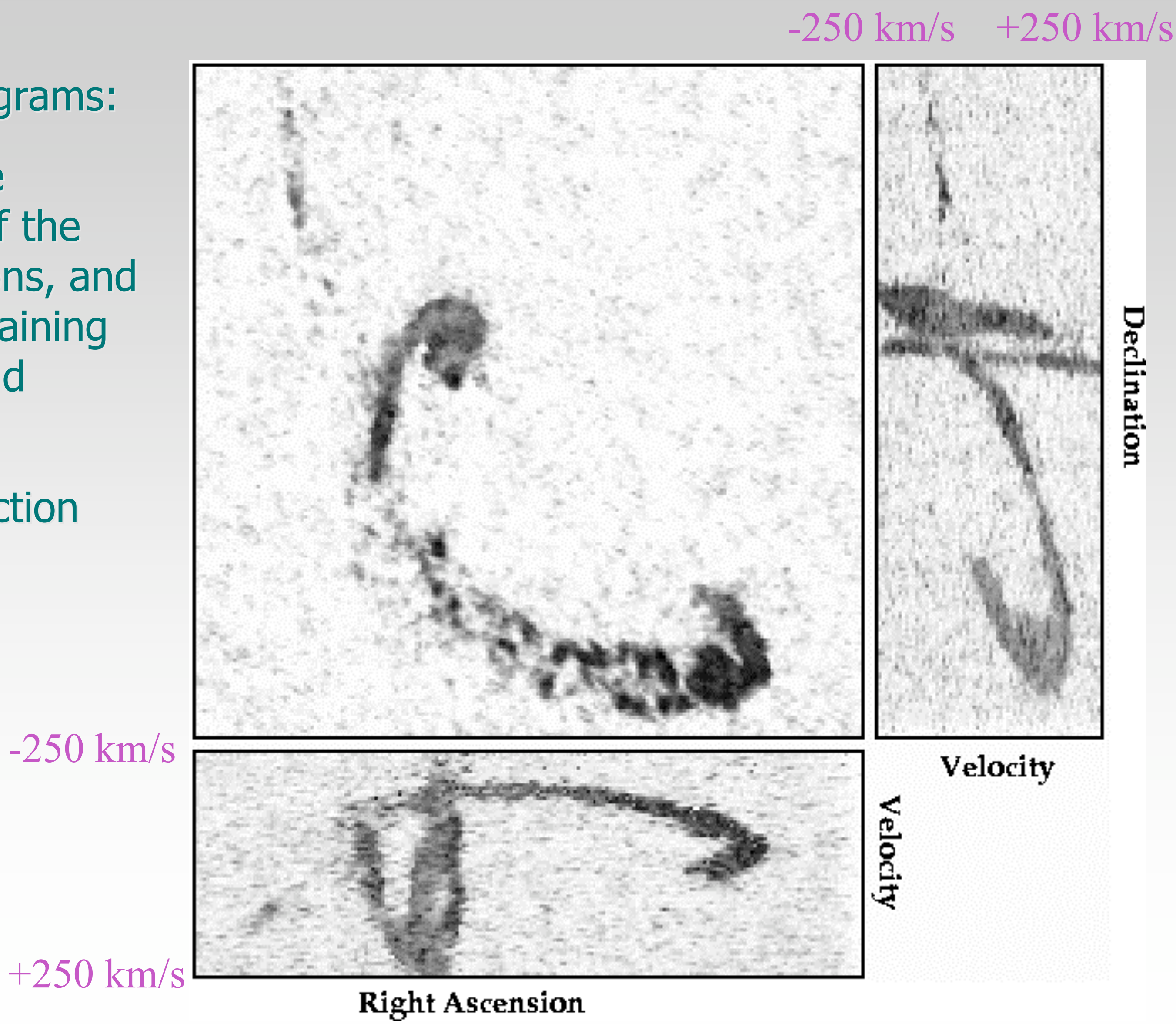
The Antennae:



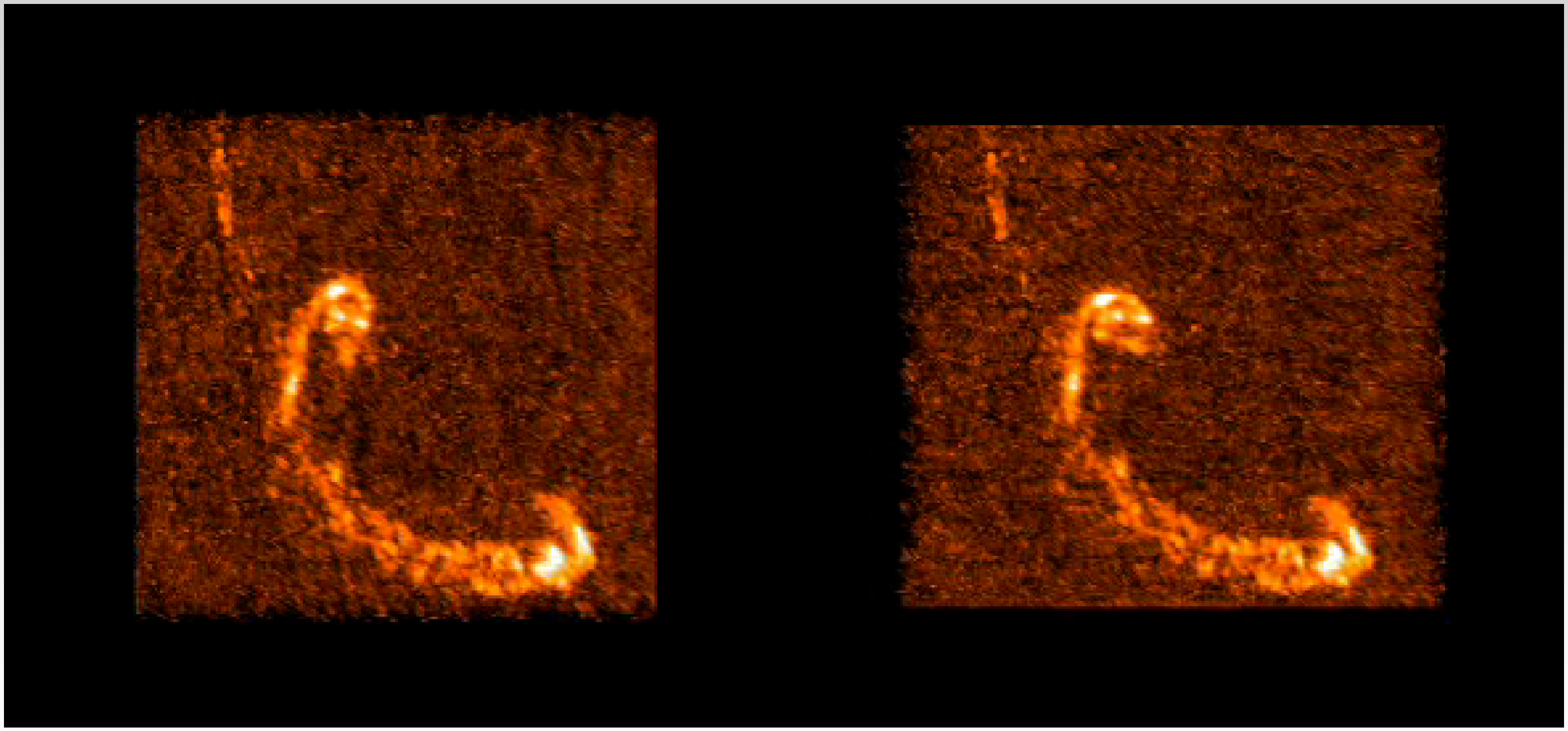
Line profiles

The Antennae:

- Position-velocity diagrams:
- Slice or Sum the line emission over one of the two spatial dimensions, and plot against the remaining spatial dimension and velocity
- Susceptible to projection effects

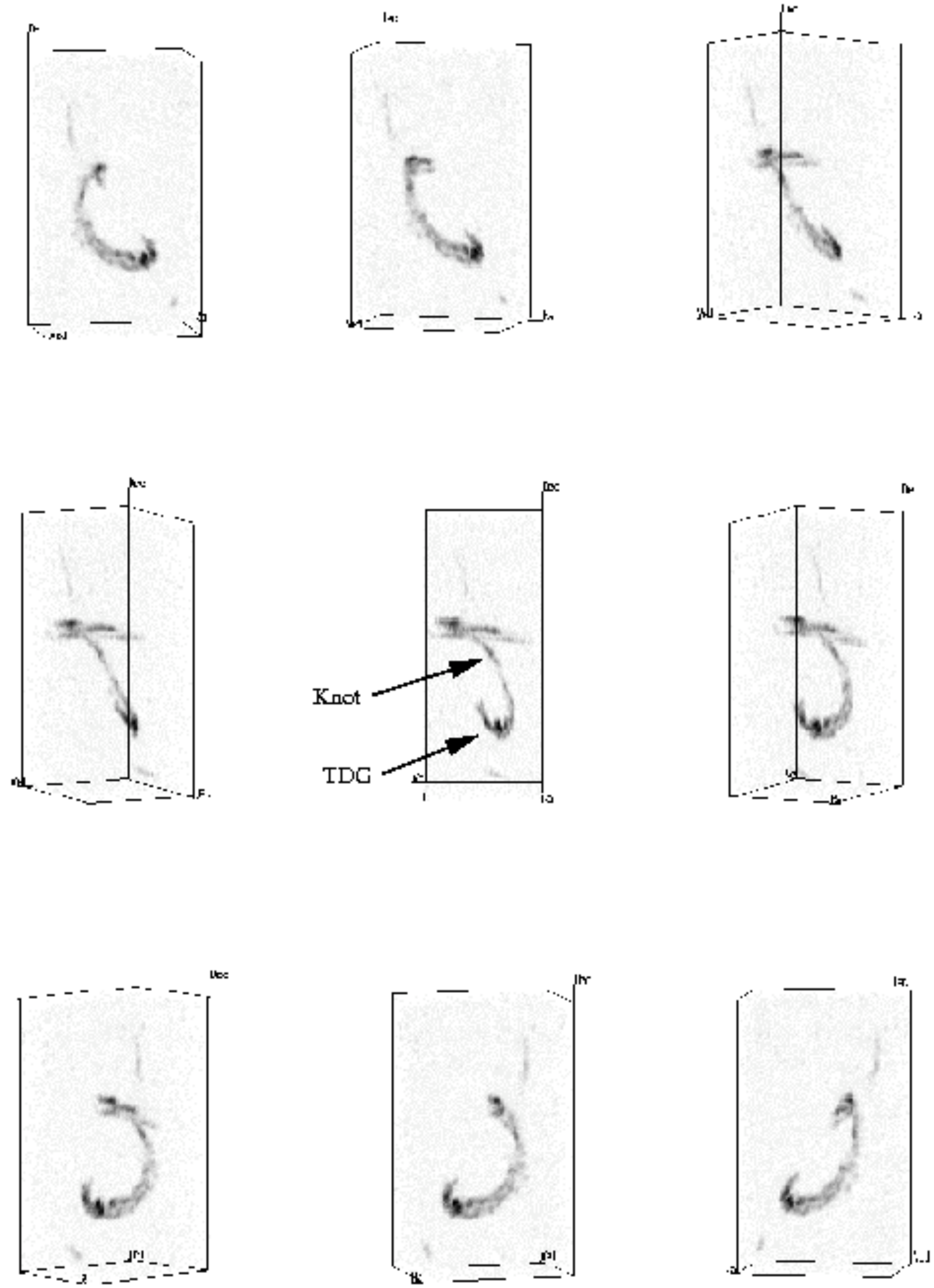


Rotating data cubes gives a complete picture of data, noise, and remaining systematic effects

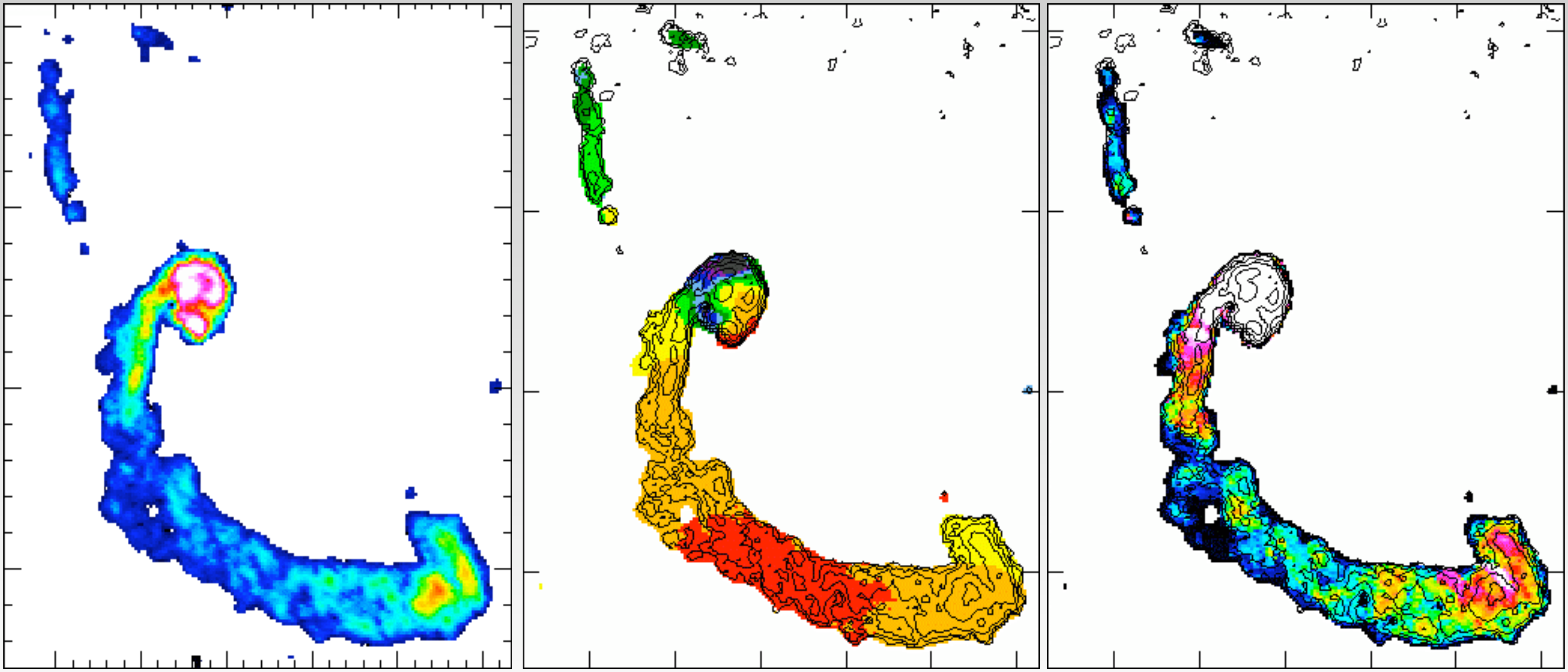


The Antennae:

- Rotations emphasize kinematic continuity and help untangle projection effects
- However, they are not really intuitive, so the interpretation can still be difficult!



The Antennae: Moment maps

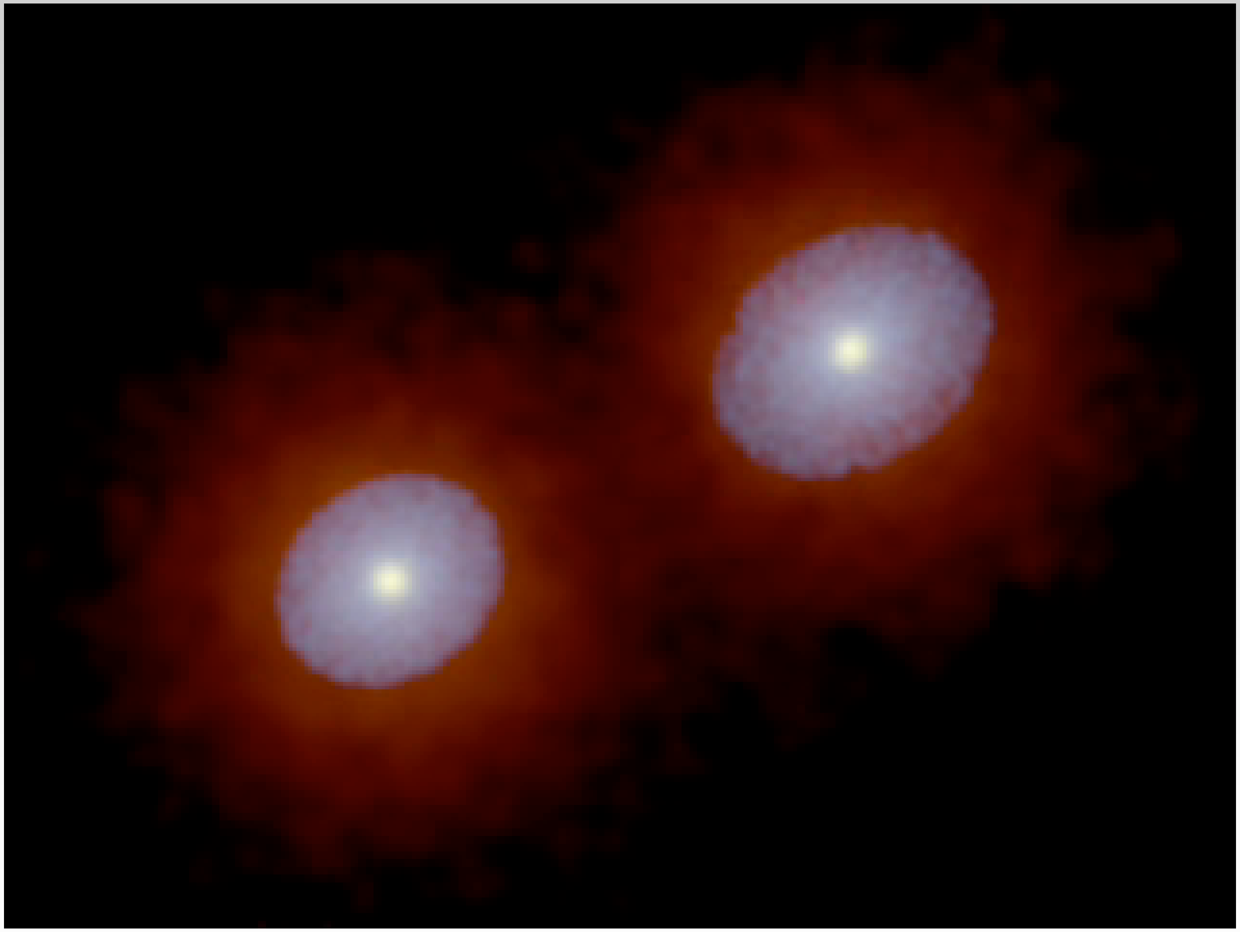


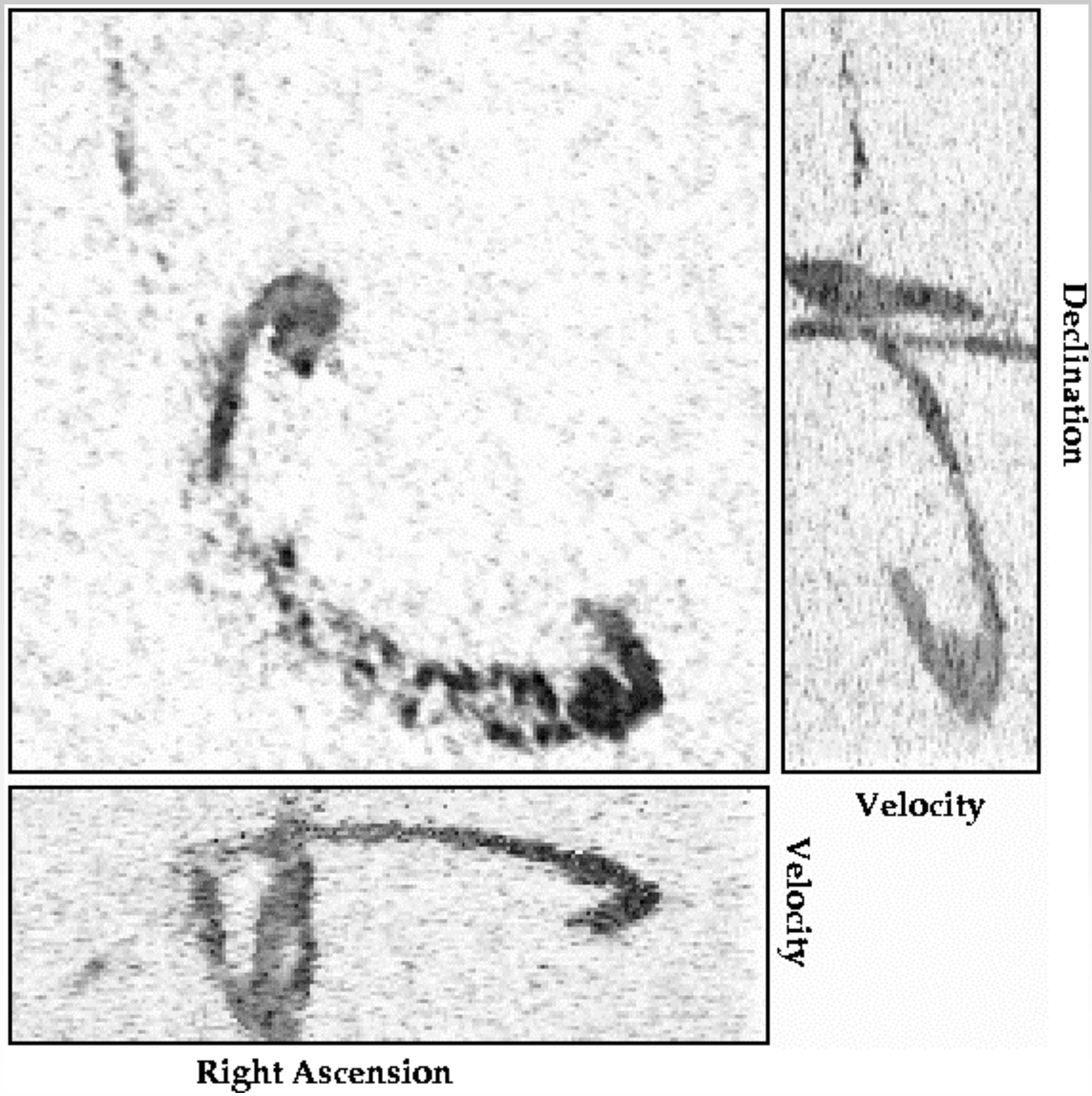
Zeroth Moment
Integrated flux

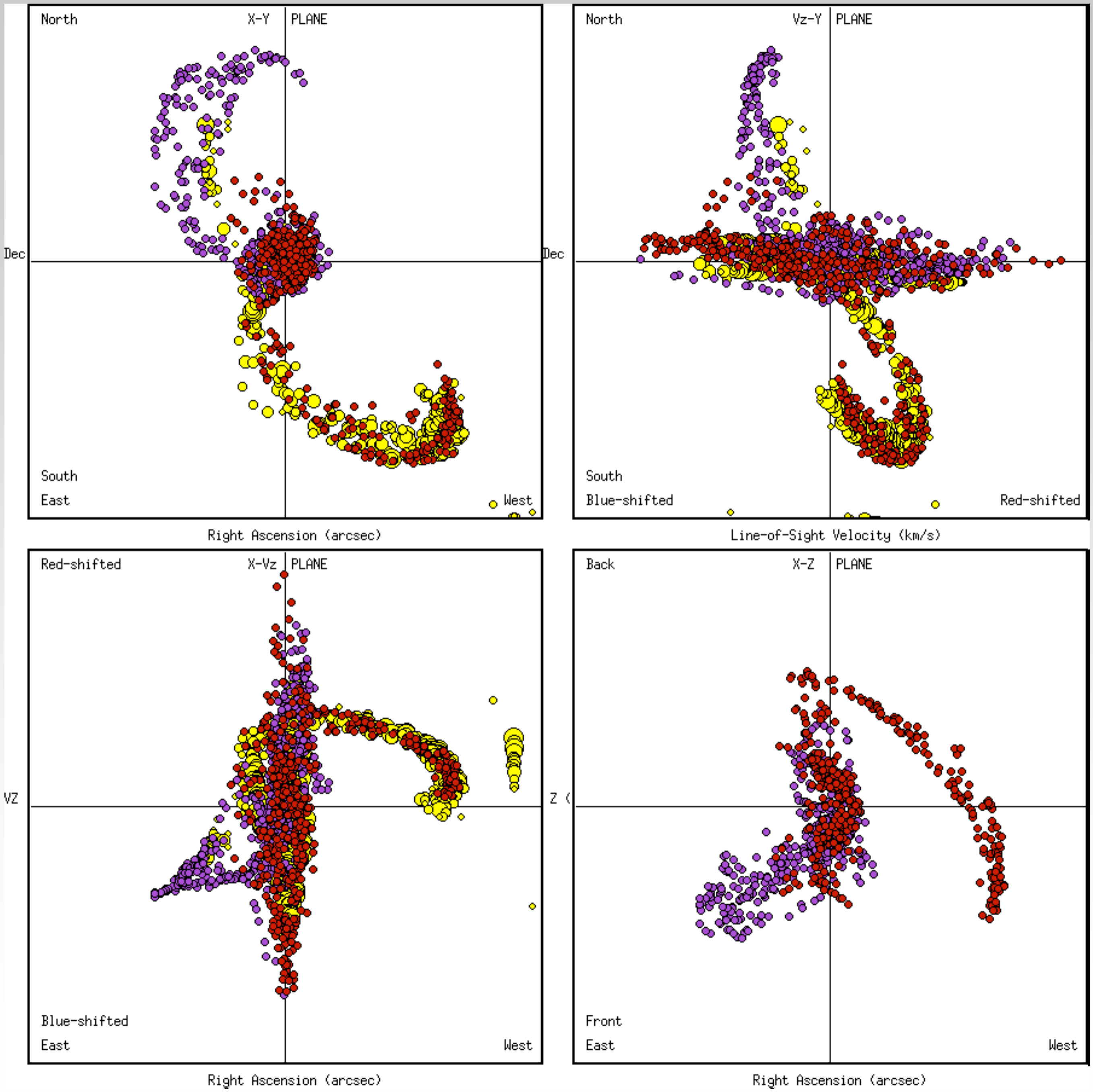
First Moment
mean velocity

Second Moment
velocity dispersion

Matching Data in 3-dimensions: N-body simulations




Declination
Velocity
Velocity
Right Ascension


North
X-Y
PLANE
Dec
South
East
West
Right Ascension (arcsec)
North
Vz-Y
PLANE
Dec
South
Blue-shifted
Red-shifted
Line-of-Sight Velocity (km/s)
Red-shifted
X-Vz
PLANE
VZ
Blue-shifted
East
West
Right Ascension (arcsec)
Back
X-Z
PLANE
Z (
Front
East
West
Right Ascension (arcsec)

Acknowledgements and references

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References:

Interferometry and Synthesis in Radio Astronomy (2nd Edition) by A. R. Thompson, J. M. Moran & G. W. Swenson, Wiley (2001)

Synthesis Imaging in Radio Astronomy II. Eds. G. B. Taylor, C. L. Carilli & R. A. Perley, ASP Conference Series vol. 180 (1999)

Lectures of the 10th Synthesis Imaging Summer School (2006): http://www.aoc.nrao.edu/events/synthesis/2006/lectures/

Los Enigmas.

Anduve como vosotros escarbando la estrella interminable,
y en mi red, en la noche, me desperté desnudo,
única presa, pez encerrado en el viento.

(de “Canto General” de Pablo Neruda)

Enigmas.

I walked around as you do investigating the endless star,
and in my net, during the night, I awoke naked,
the only catch, a fish trapped in the wind.

(from “General Chant” by Pablo Neruda)