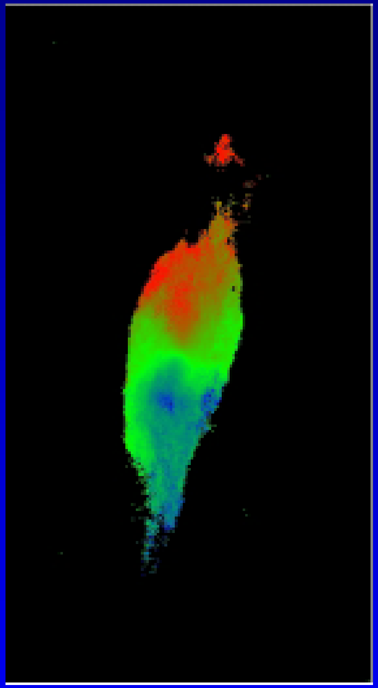
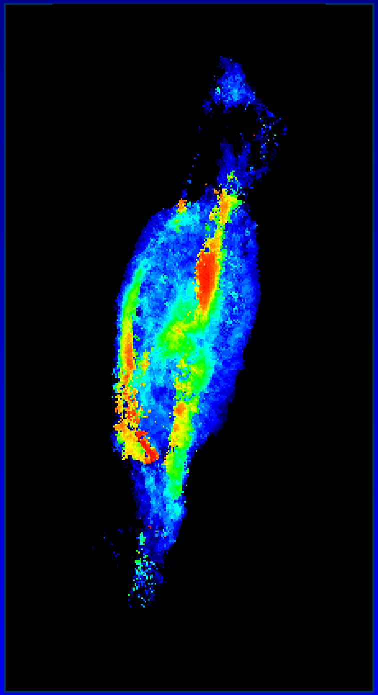
Spectral Line Imaging





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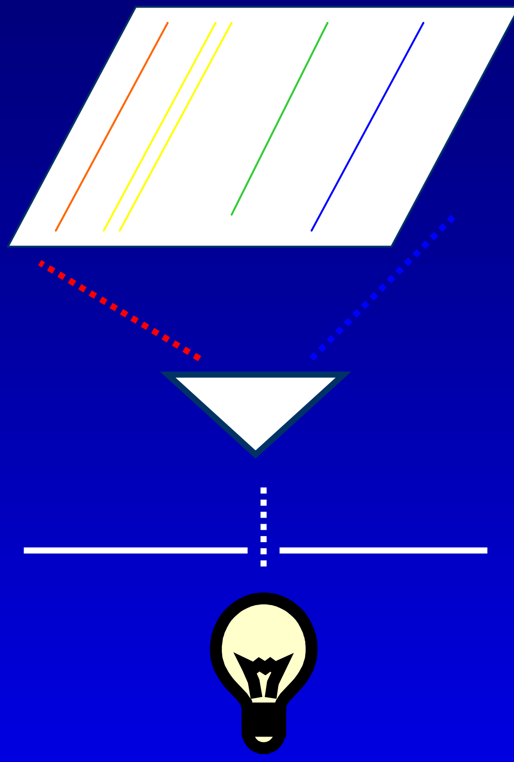
Topics

- Introduction to Spectral Lines
- Velocity Reference Frames
- Bandpass Calibration
- Continuum Subtraction
- Gibbs Phenomenon & Hanning Smoothing
- Data Cubes & Moment Maps

Literature:
Synthesis Imaging in Radio Astronomy II, Chapters 11 & 12
Synthesis Imaging in Radio Astronomy,   Chapter 17

What is a spectral line ?

Origin: Light dispersion (prisma, slit)
sharp intensity maxima on screen



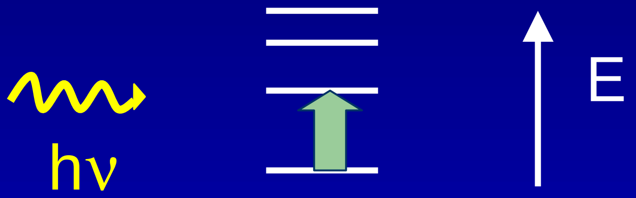
"extent in frequency much less than central frequency of feature"

$$S(\nu, \nu_0, A, \Delta\nu, t)$$

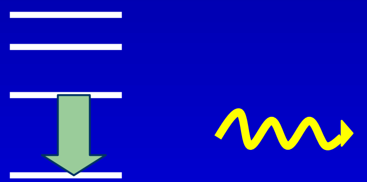
atomic/molecular origin

Basic photon–matter interactions to produce spectral lines:

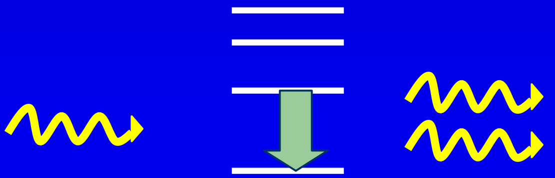
Absorption
(e.g., towards quasars)



Spontaneous emission
(e.g., HI, molecular lines, cascading recombination lines)



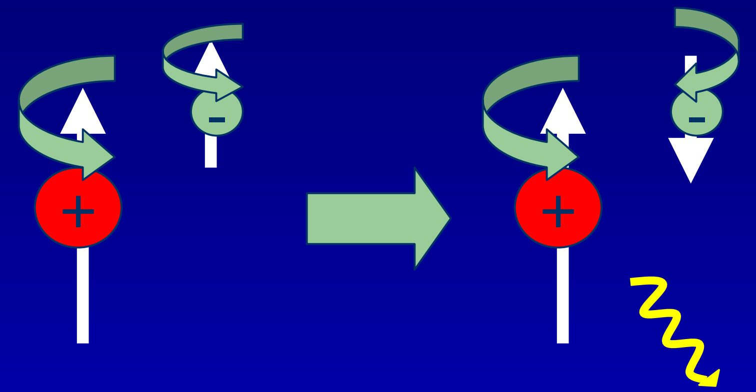
Induced emission
(Maser/Laser)



Continuum: free-free, free-bound recombination
(e.g., synchrotron emission, thermal bremsstrahlung)

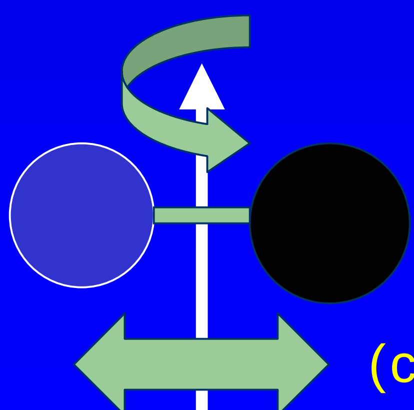
Energy levels can be:

- Atoms: electron orbits,
  hyperfine states
  (UV, optical, IR, radio)

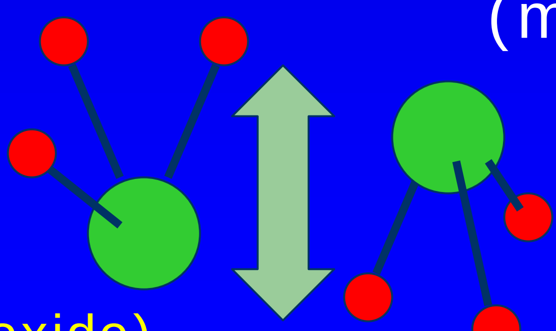


HI 21cm

- Nuclei: excitations (shell model), γ radiation
- Solid states: bands (IR, opt), lattice modes (phonons)
- Molecules: (electronic+) rotation, vibration, bending
  (mm, submm, IR)



CO
(carbon monoxide)



NH_3 (ammonia)

What can we learn from spectral lines?

Observables: frequency, shape (width), amplitude, (time)

- Parameters of the Gas

(density, temperature, pressure, column density, ...)

- Parameters of the Environment

(radiation field, maser conditions, chemistry, magnetic field)

- Kinematics

(expansion/contraction, infall/outflow, rotation curves, galaxy clusters, turbulence, virialization theorem)

- Distance (Hubble Law v=H r)

Velocity Reference Frames

Relativistic Doppler Effect:

$$v_{radial} = \frac{\nu_0^2 - \nu^2}{\nu_0^2 + \nu^2}$$

approximations for $v_{radial} << c$

$$v^{opt} = c\,\frac{\lambda_0 - \lambda}{\lambda_0} = c\,z$$

$$v^{radio} = c\,\frac{\nu_0 - \nu}{\nu_0} = c\,\frac{\lambda_0 - \lambda}{\lambda}$$

$$v^{opt} \neq v^{radio}$$

Velocity Reference Frames

Rest Frame	Correct for	Max Amplitude [km s^{-1}]
Topocentric	Nothing	0
Geocentric	Earth rotation	0.5
Earth-Moon Barycentric	Earth-Moon center of mass	0.013
Heliocentric	Earth's orbital motion	30
Barycentric	Sun-Earth center of mass	0.012
Local Standard of Rest (LSR)	Solar motion relative to nearby stars	20
Galactocentric	Milky Way rotation	230
Local Group Barycentric	Milky Way motion	100
Virgocentric	Local Group motion	300
Microwave Background	Local Supercluster motion	600

Correlator Configurations:

- Bandwidth
- Channel Separation (# Channels)
- # Blocks (simultaneous observations of different frequencies)
- # polarization products

Cold molecular gas: linewidth ~ few km s^{-1}
Rotation curves: Amplitude ~200 km s^{-1}

	Full_16_512-128	ANT234AC_64_128_2P-2F
1.4 GHz (HI)	BW 3200 km s^{-1} Channel sep 6 km s^{-1}	BW 12800 km s^{-1} Channel sep 100 km s^{-1}
90 GHz (mol. lines, e.g., HCO+, HCN, ...)	BW 50 km s^{-1} Channel sep 0.1 km s^{-1}	BW 200 km s^{-1} Channel sep 1.7 km s^{-1}
	2nd frequency: BW: 128 MHz, 32 ch continuum	2nd frequency: As 1st frequency Other line of interest

Gibbs Phenomenon, Hanning Smoothing

BUT...

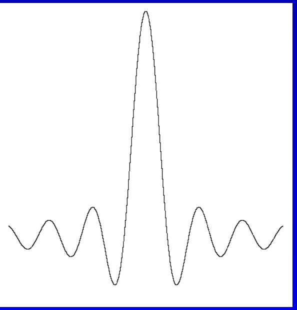
Ideal: Lag (cross-correlation) spectrum R(τ) measured from -∞ to ∞

But: Digital cross-correlation spectrometer

➡ Truncation of time lag spectrum R(τ)

R(τ) *

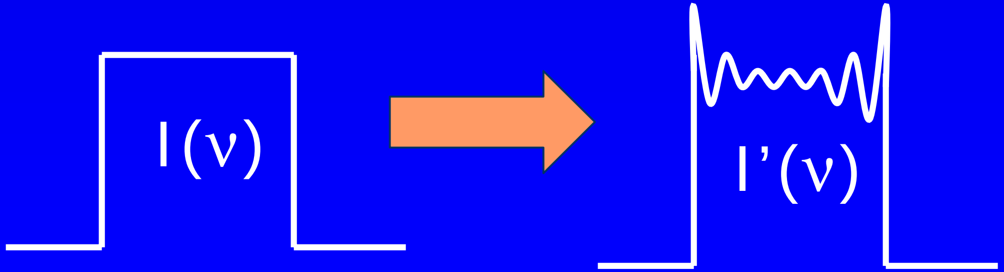

FT ➡

I(ν) ⊗


sinc (x) = sin(x) / x

Gibbs phenomenon
or Gibbs ringing

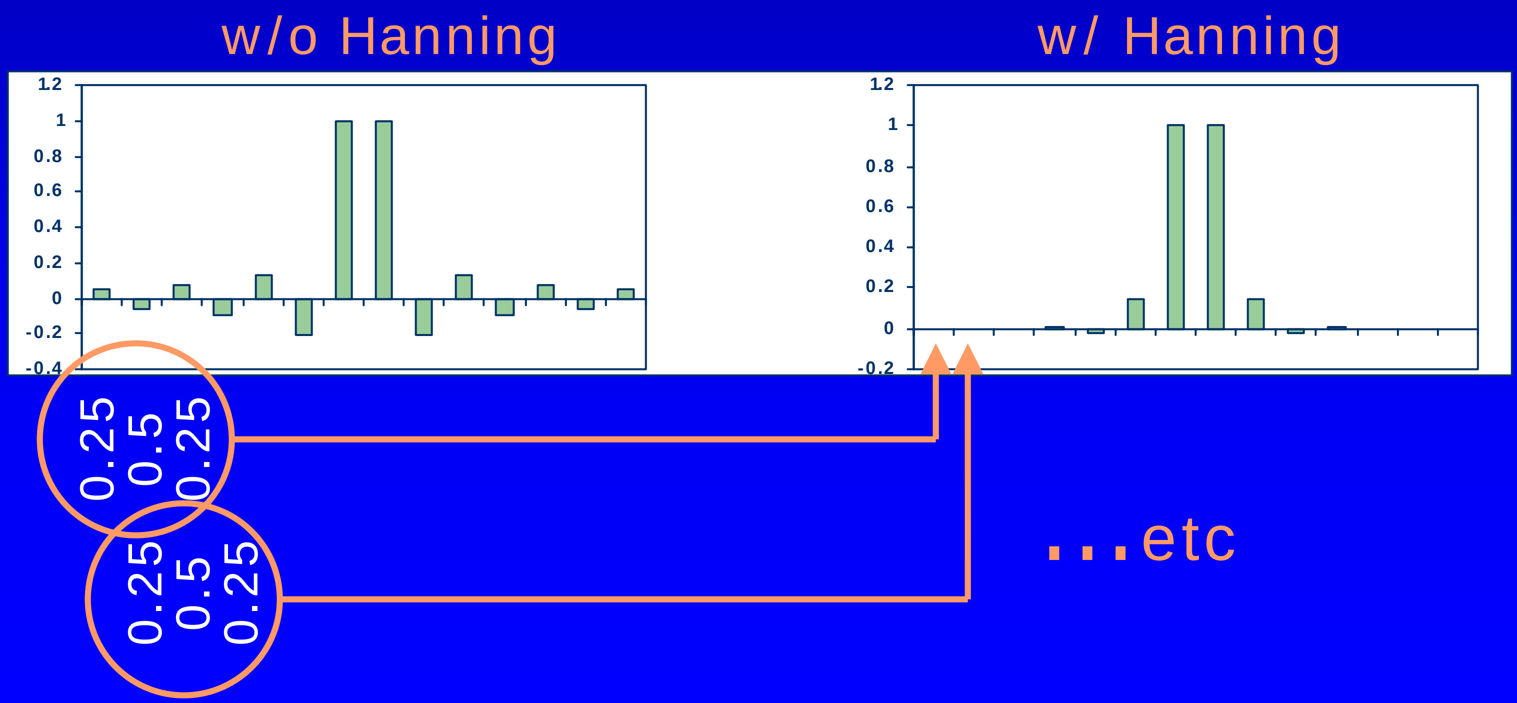
Nulls spaced by
channel separation



Gibbs Phenomenon, Hanning Smoothing

Solution

- Observe with more channels than necessary
- Tapering sharp end of lag spectrum R(τ)
- Hanning smoothing: f(τ)=0.5+0.5 cos (πτ/T)
- In frequency space: multiply channels with 0.25, 0.5, 0.25 → half velocity resolution



Calibration: Bandpass

$$\tilde{V}_{ij}(\nu,t) = G_{ij}(\nu,t)\;V_{ij}(\nu,t)$$

complex measured visibility — Gain — calibrated visibility

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

$$B_{ij}(\nu,t) \approx b_i(\nu,t)\;b_j^*(\nu,t)$$

baseline Bandpass

antenna

Measurement: Strong point source with flat (known) spectrum:

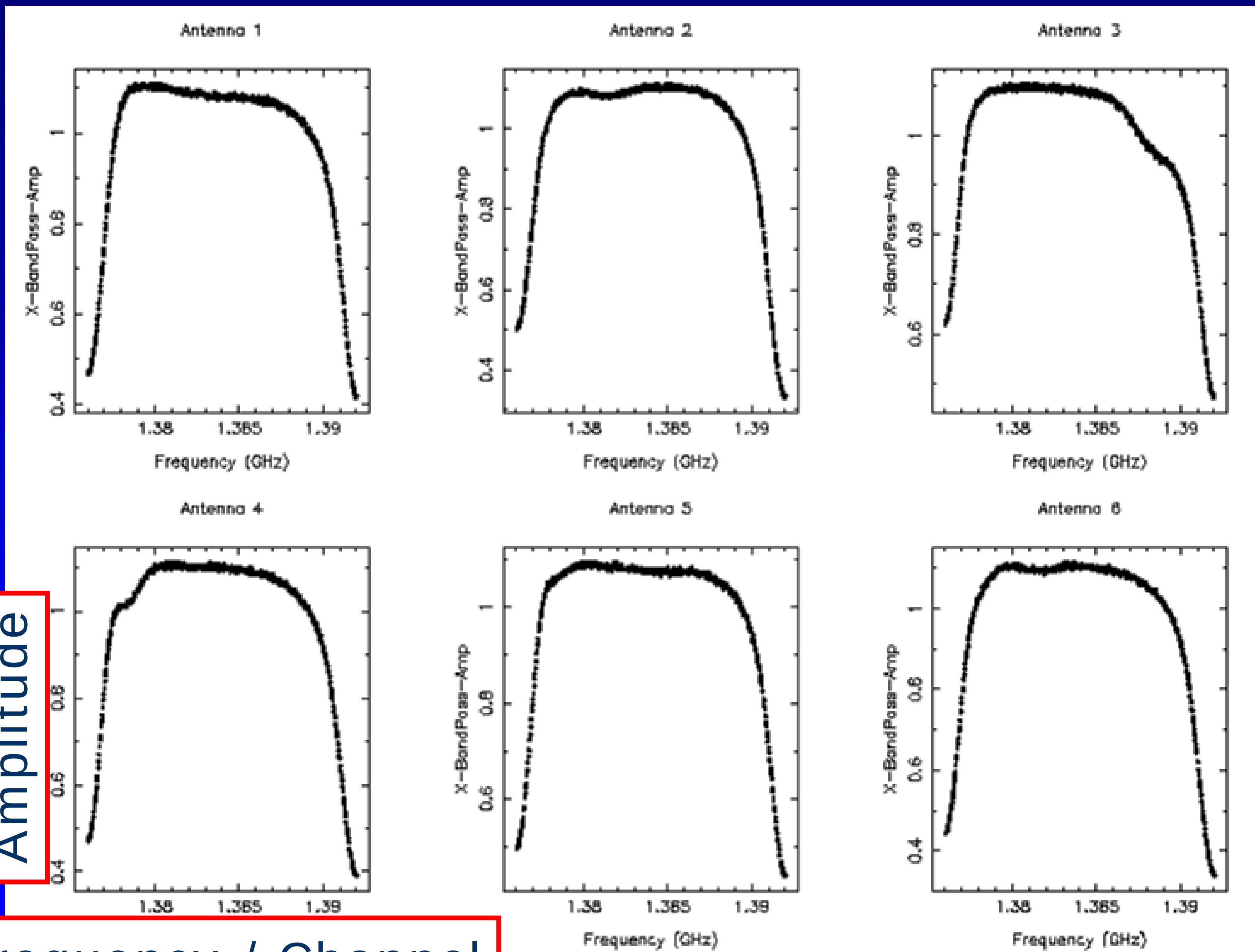
Bandpass Calibrator, noise source

@ source frequency & correlator setup, maybe several times

Strong enough for high S/N per individual channel!

Solve from N(N-1)/2 baselines for N antennas

Bandpass Calibration



Amplitude

Frequency / Channel

Continuum Subtraction

Data: continuum + spectral line emission
(several sources with different sizes)

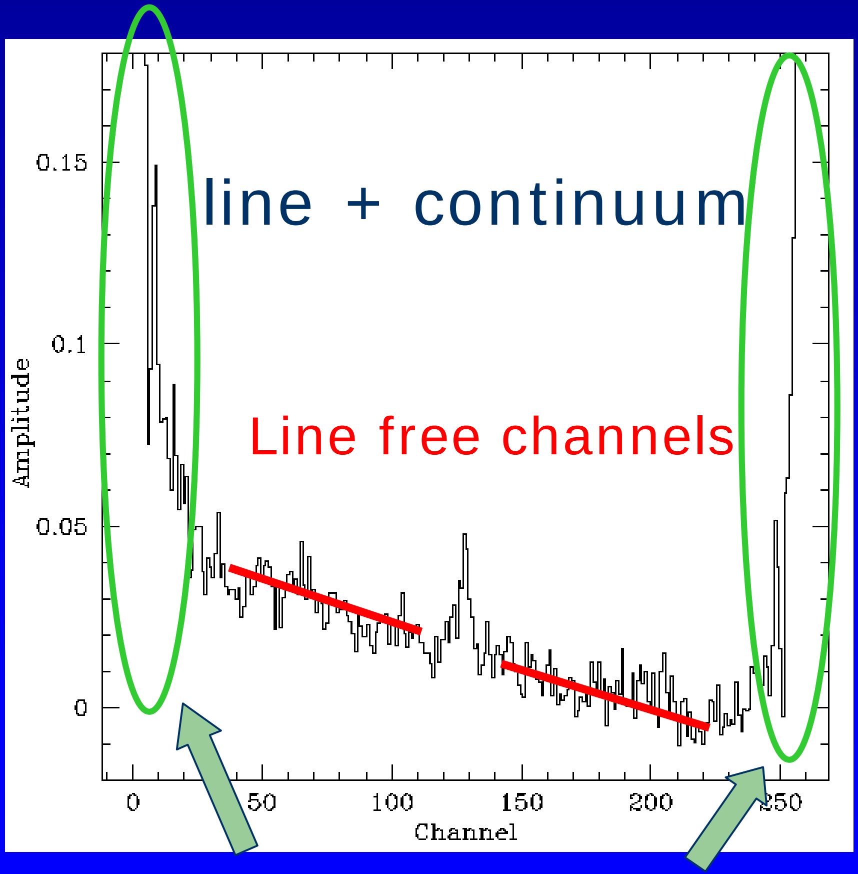
Continuum subtraction

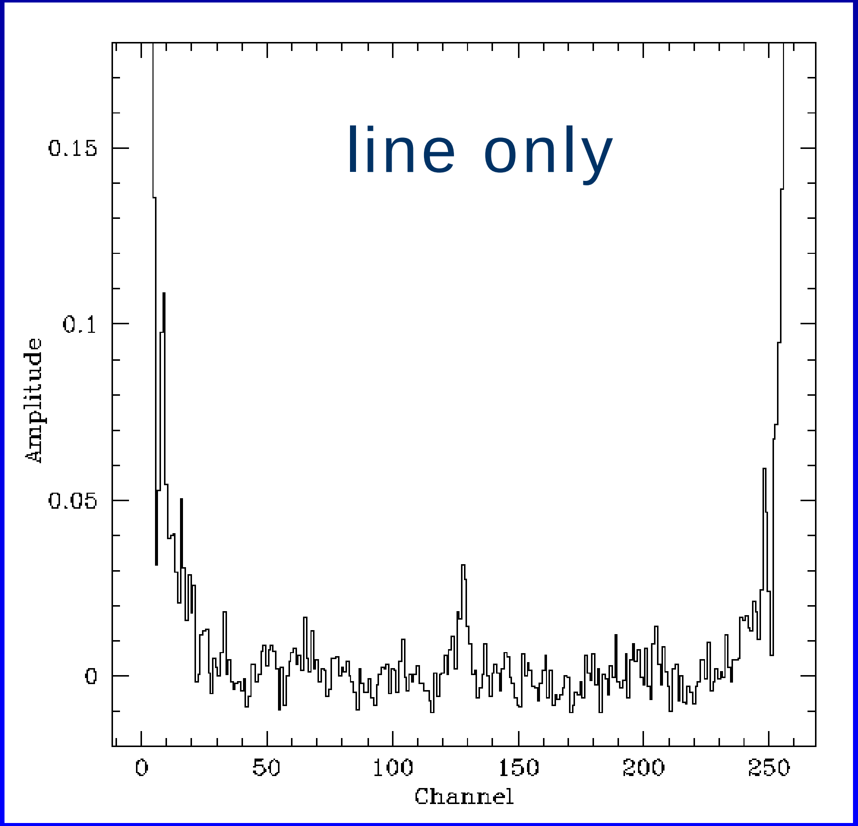
uv plane		image plane
uvlin	(MIRIAD tasks)	**contsub**
Visibilities (real & imaginary)	Spectra	Pixel

- Additional flagging can be applied
- Better continuum map
- Allows shifting of reference center on string source, then back
- no deconvolution which is non-linear

Continuum Subtraction

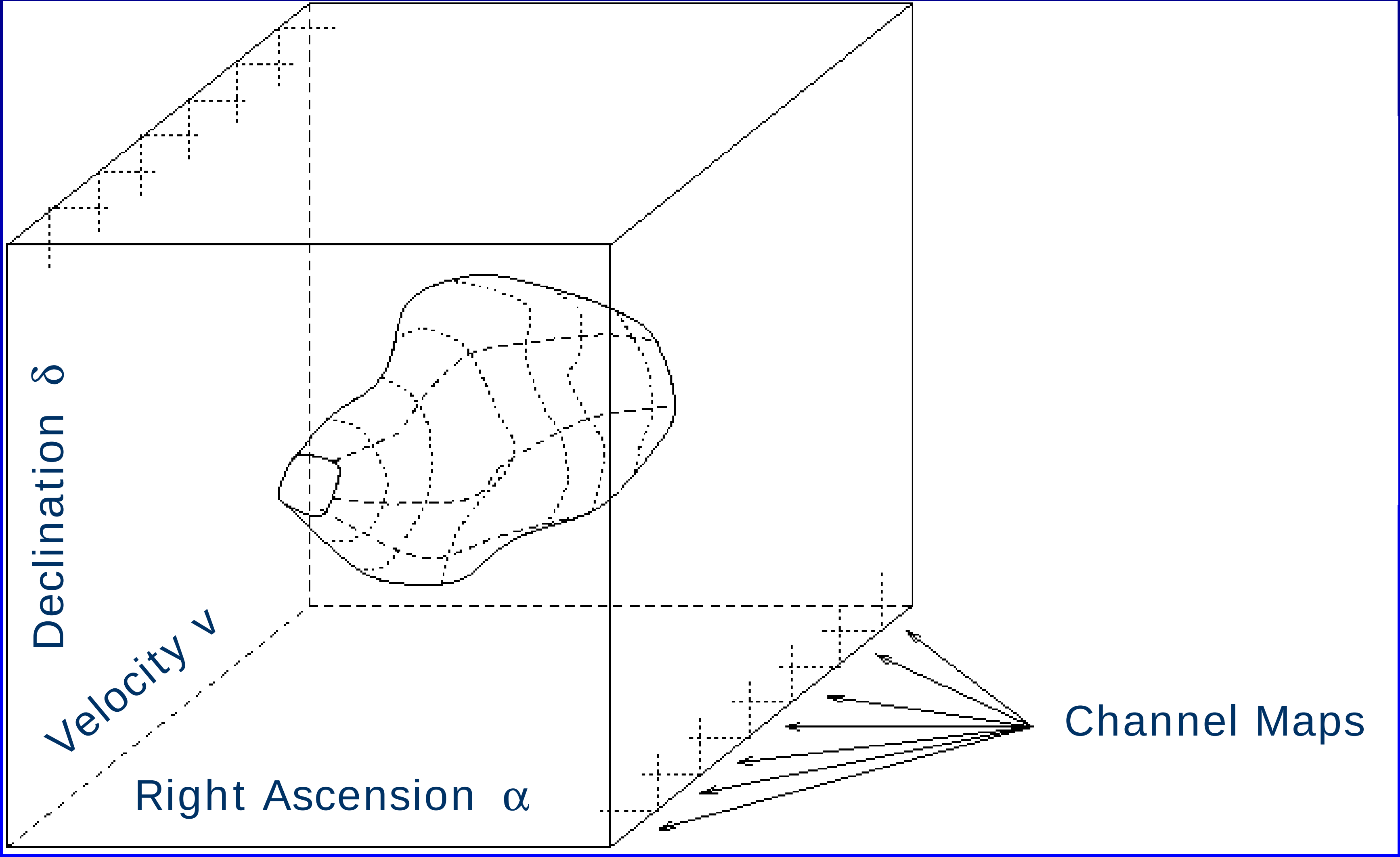
- select line free channels
- low order polynomial fit for each visibility (real & imaginary)
- subtract fit from spectrum





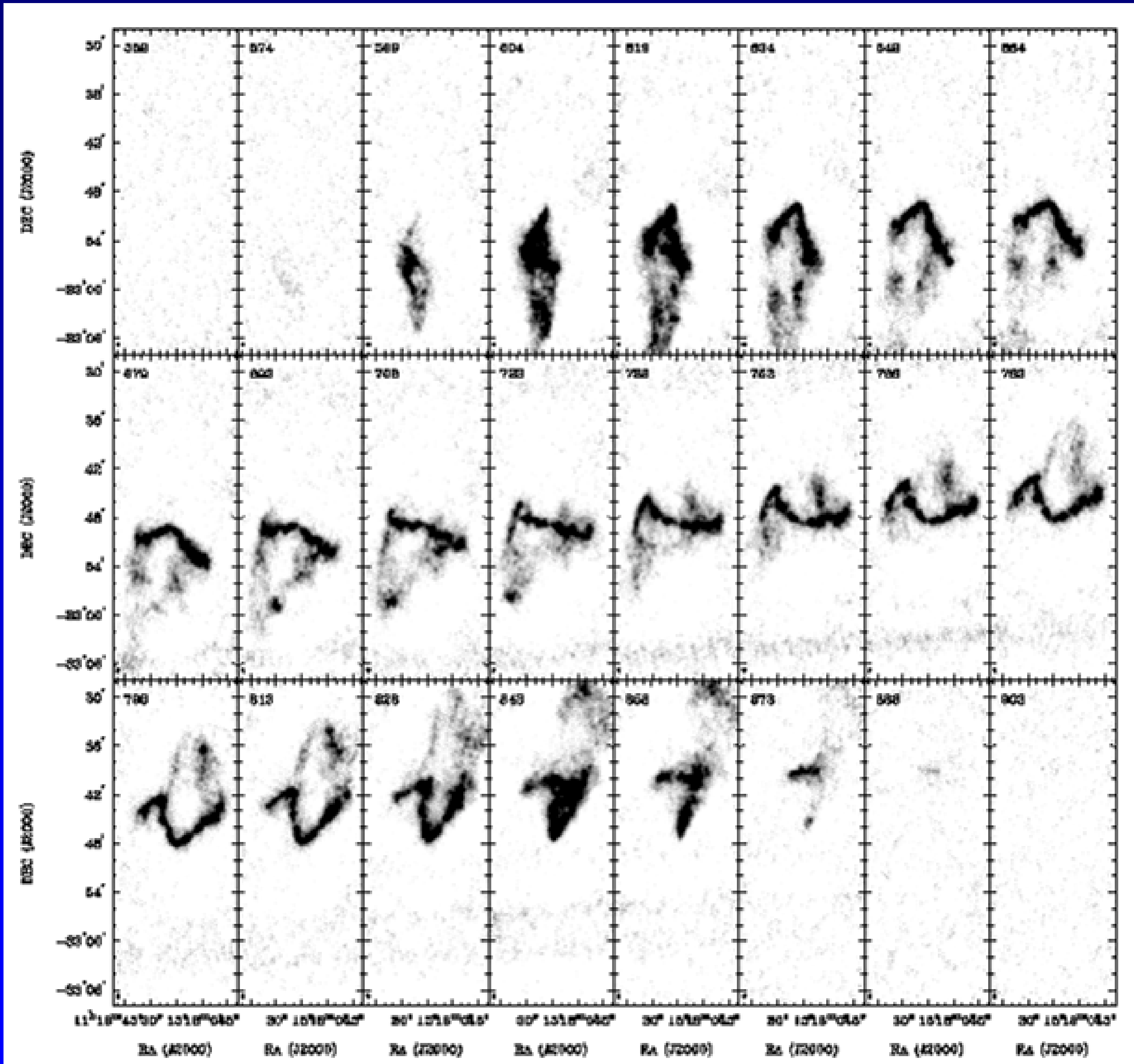
result of bandpass correction: flag it!

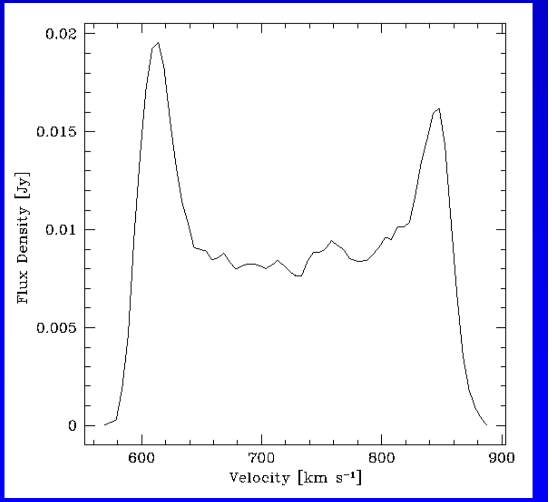
Data Cubes



Data Cubes

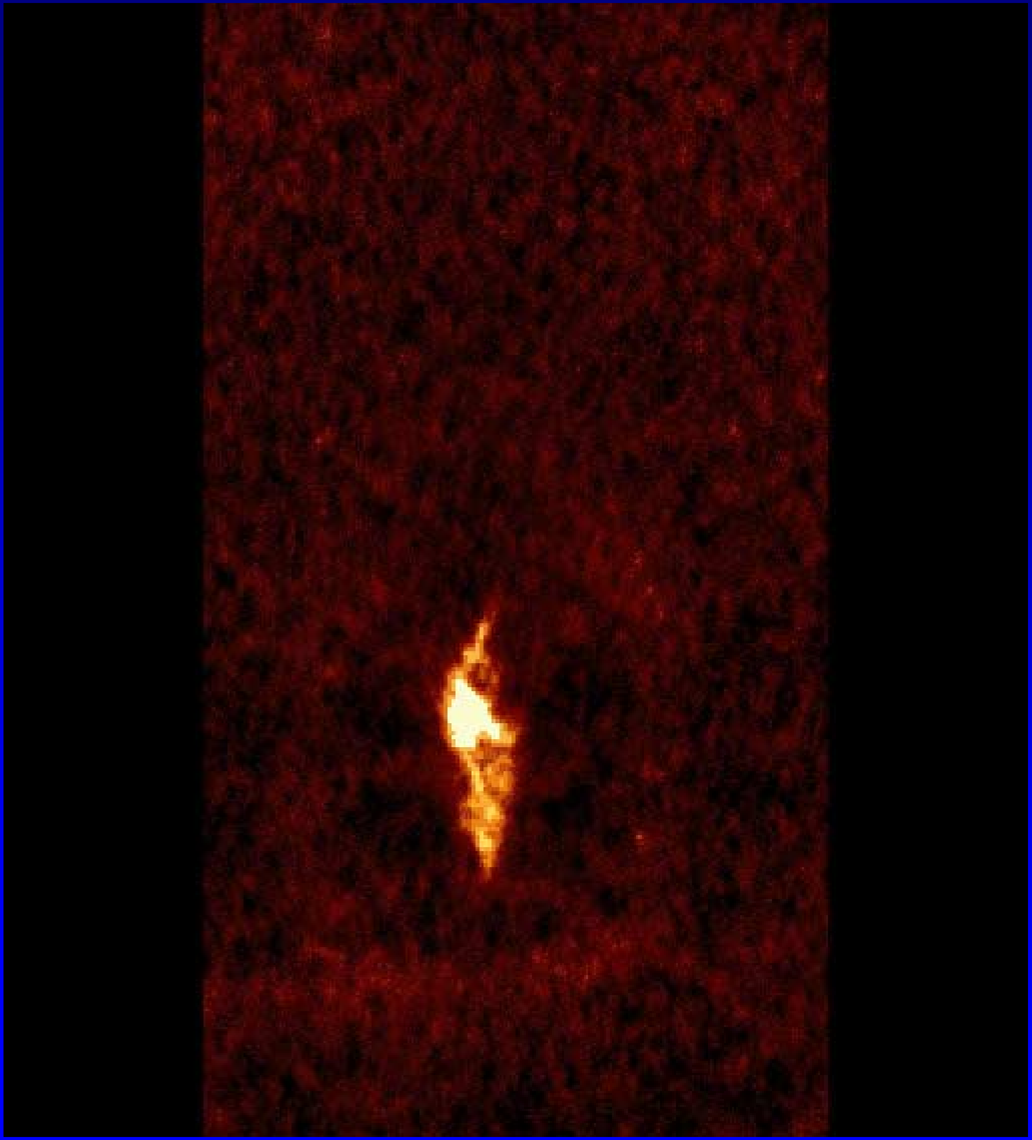
Channel Maps





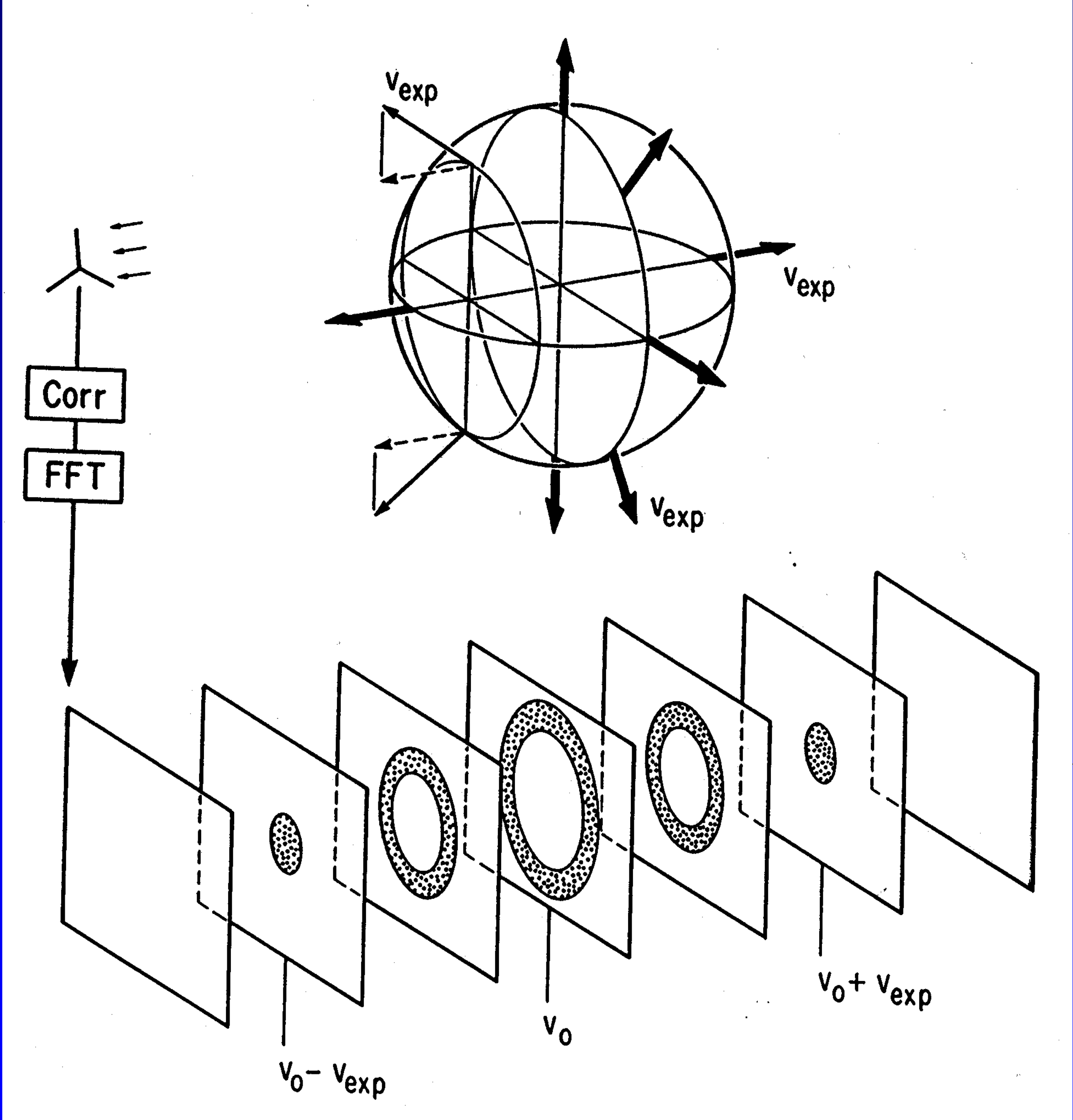
Spectrum

Data Cubes

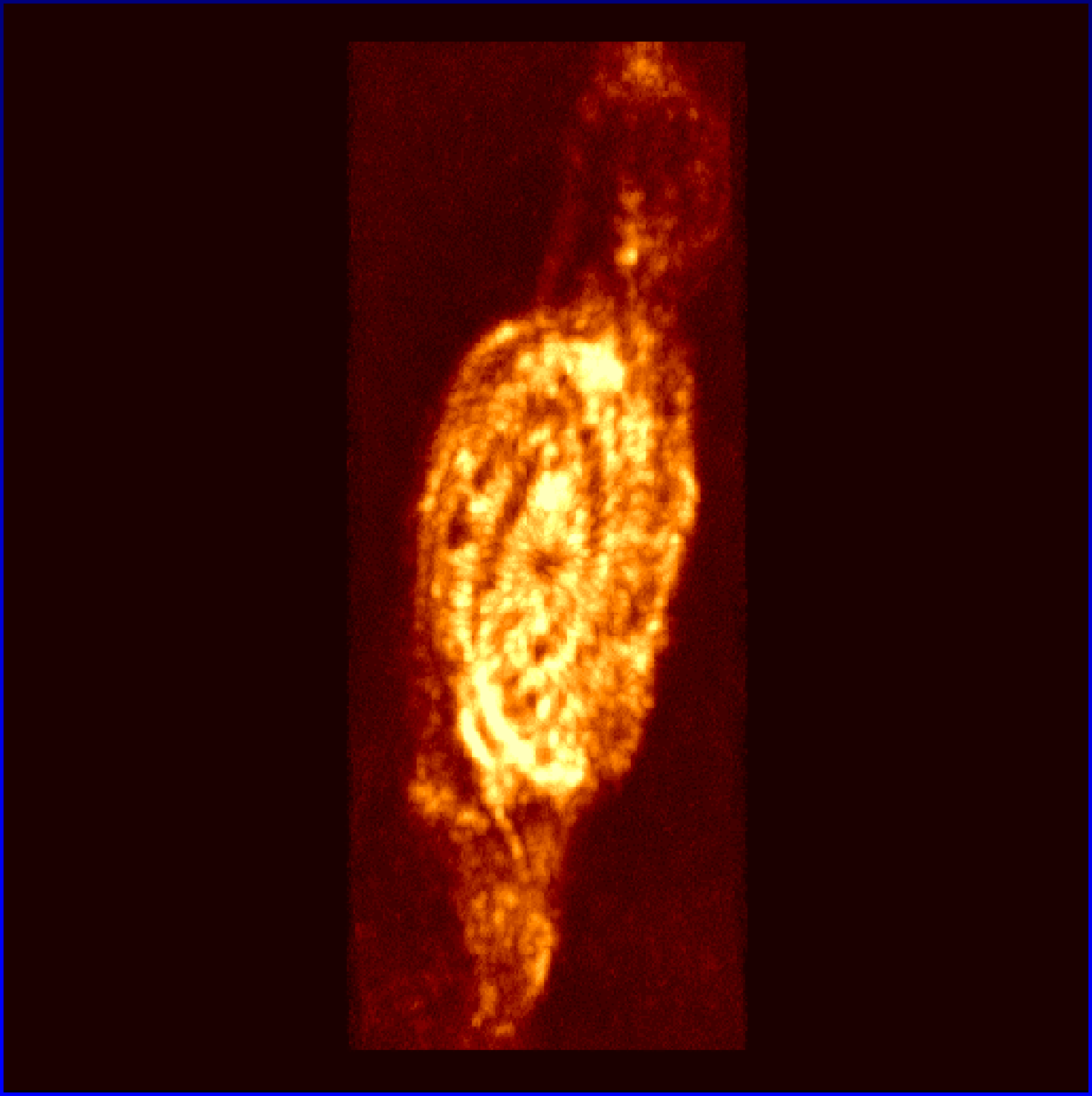


Data Cubes

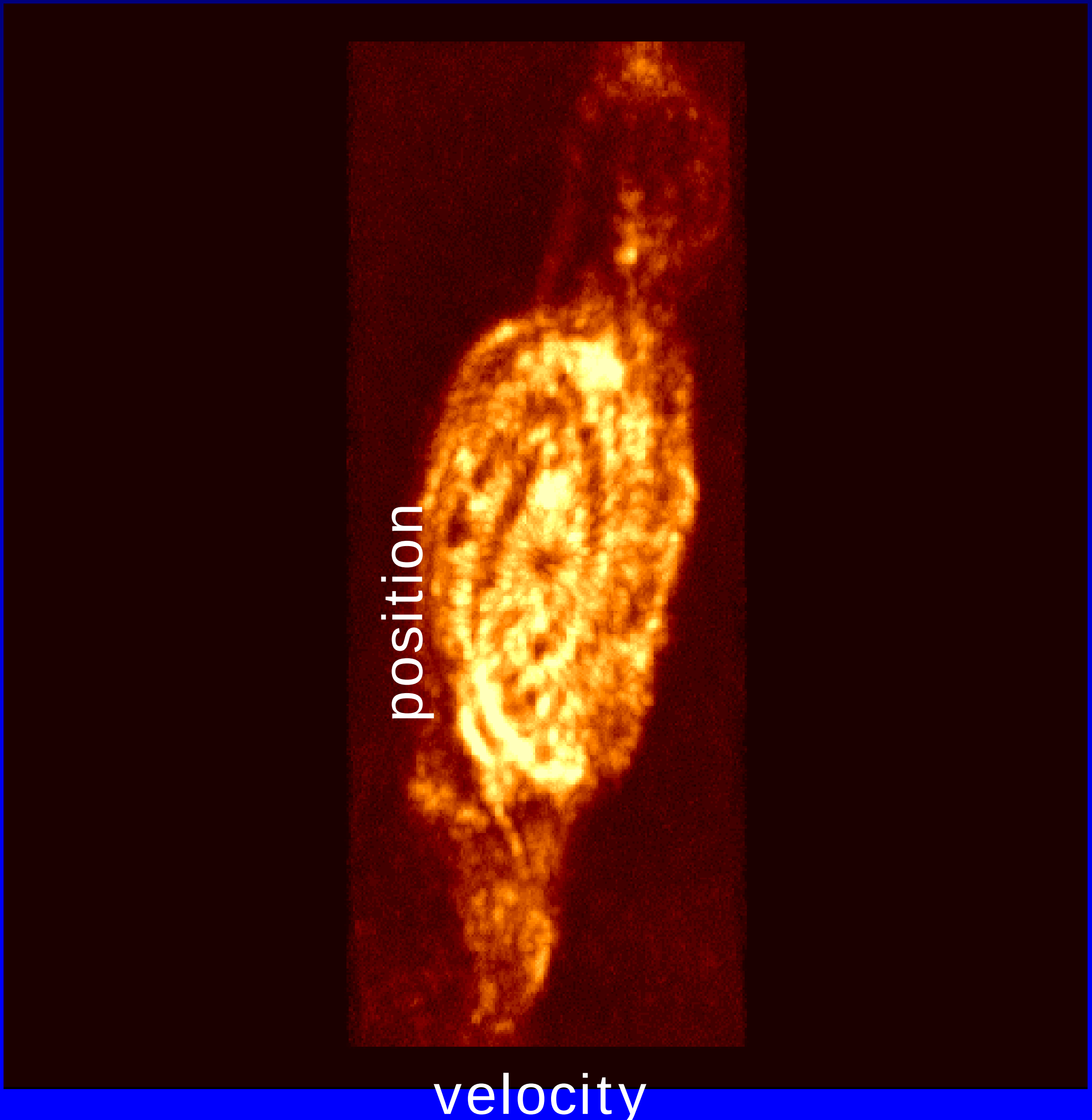
Expanding Shell



Data Cubes

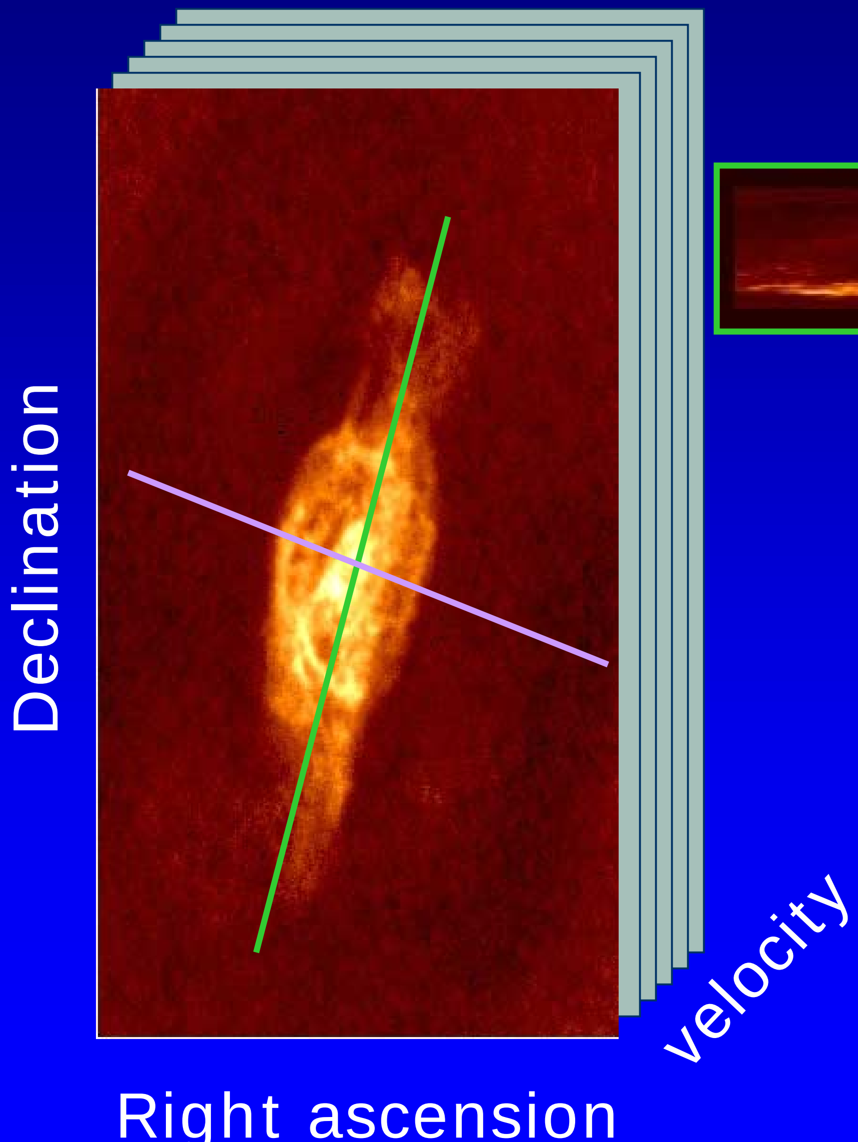


Data Cubes



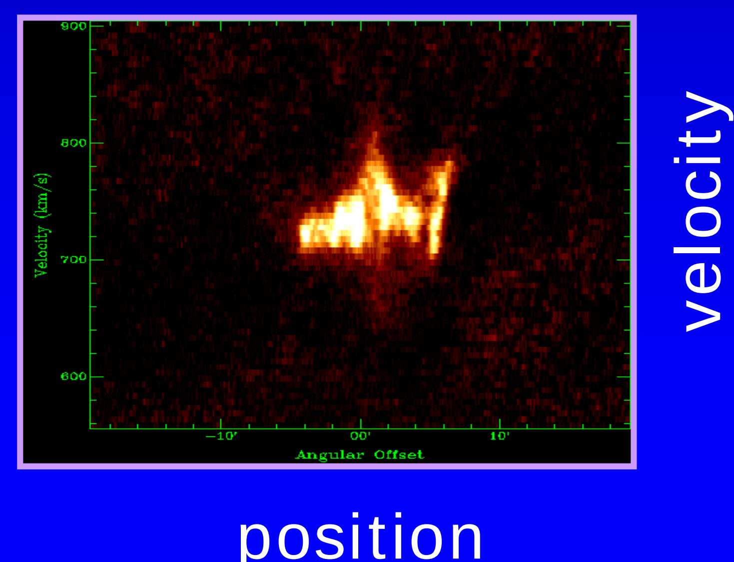
Data Cubes

position – velocity cuts



Major axis cut

Minor axis cut



Moment maps

Mathematical definition of central i-th moment (statistics):

$$\mu_i := \int_{-\infty}^{\infty} (x-\alpha)^i \, f(x)\, dx$$

f(x): probability distribution
α: center of mass of f(x)

$$\alpha := \int_{-\infty}^{\infty} v \, f(v)\, dv$$

Important Moments

(as actually calculated, Σ over all spectral channels for each pixel):

0^{th} moment: integrated intensity map [Jy km s^{-1}]

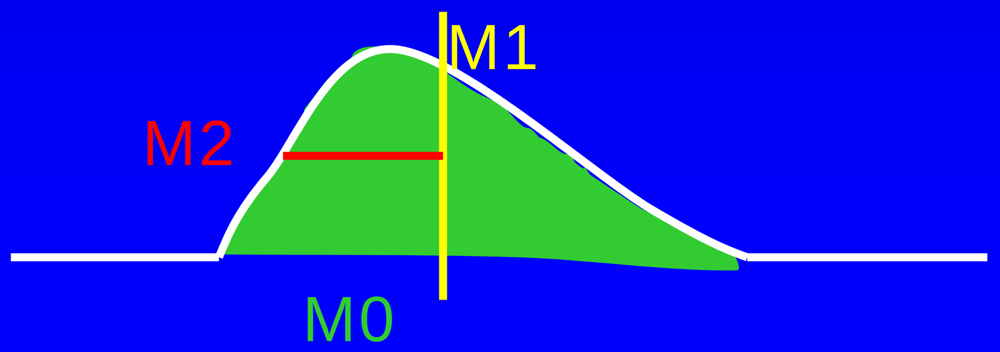
$$M0 = \Sigma\, I(v)\ \Delta v$$

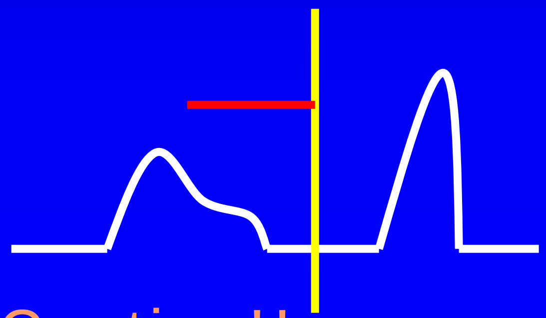
1^{st} moment: intensity weighted velocity map [km s^{-1}]

$$M1 = \Sigma\, I(v)\, v \,/\, \Sigma\, I(v)$$

i=2, 2^{nd} moment: 1σ velocity dispersion [km s^{-1}]

$$M2 = \sqrt{\Sigma\, [I(v)\ (v-M1)^2] \,/\, \Sigma\, I(v)}$$

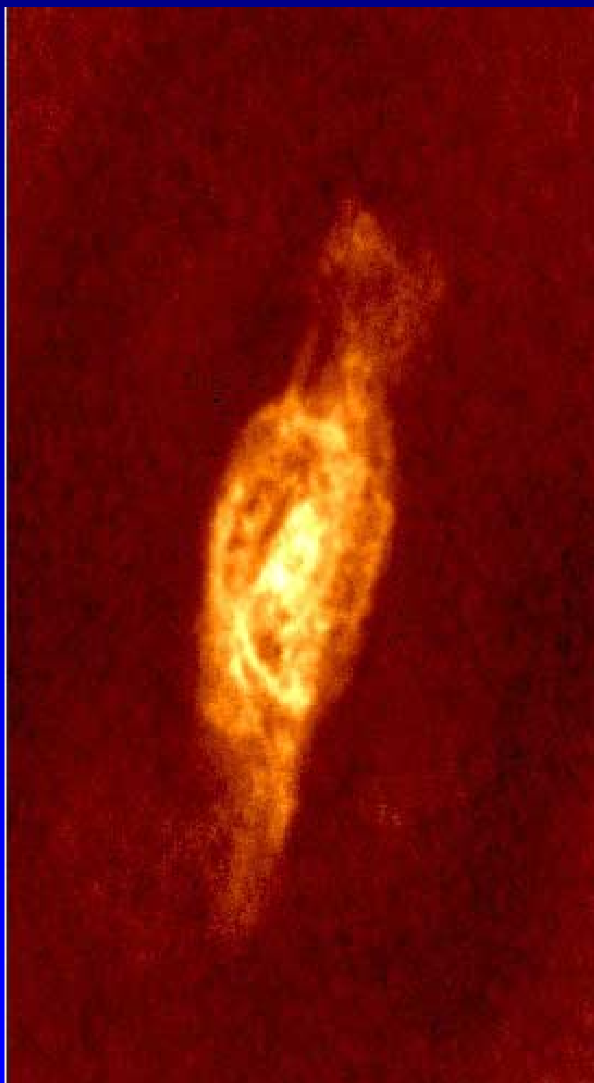




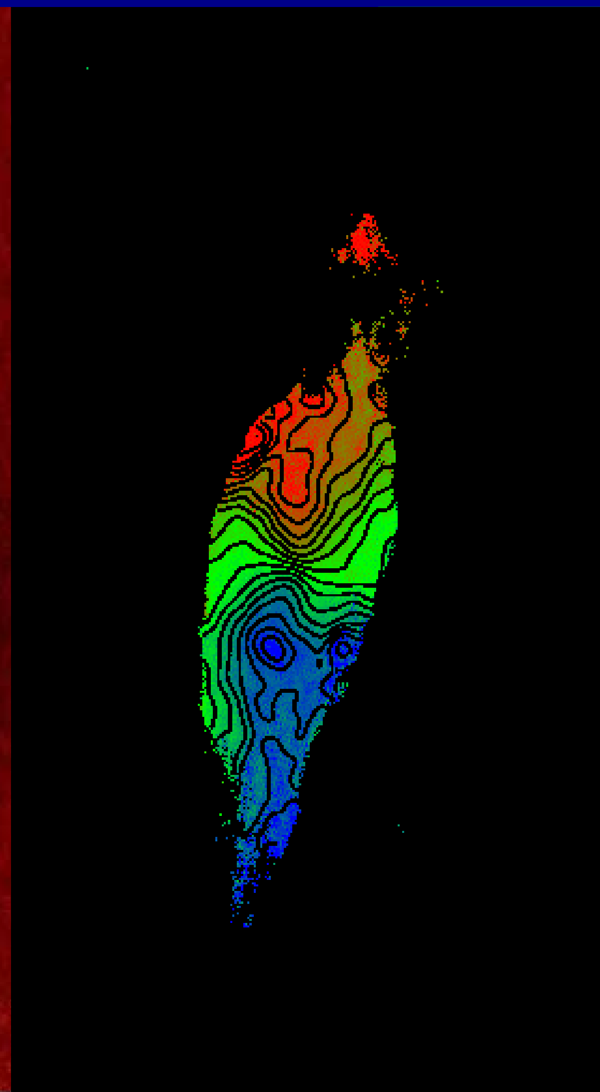
Caution!!

Data Cubes – Moment Maps

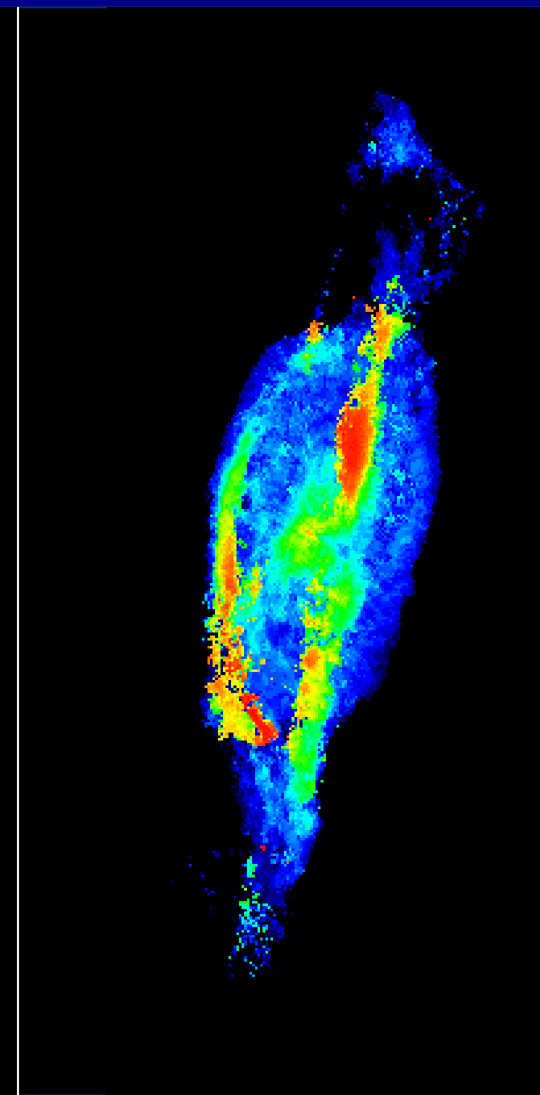
Moment 0



Moment 1

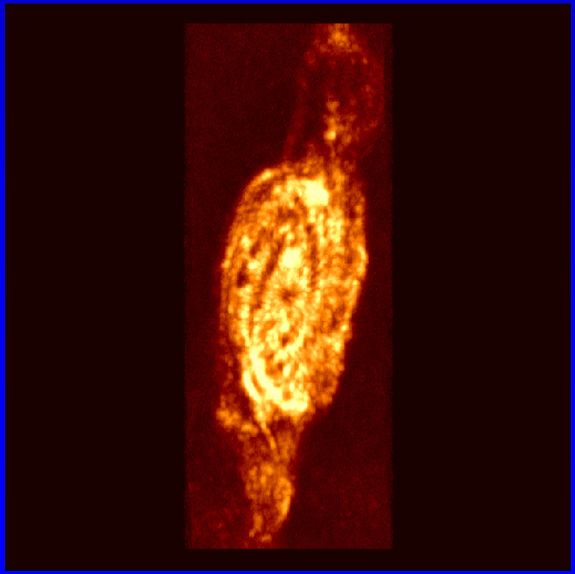


Moment 2



Conclusion:

Spectral line imaging is...



powerful, versatile, fun!!!