HI in the Universe (STHIU-09)

Lecture outline

Week 1: basic physics, determination of HI properties of galaxies, overview of HI properties of galaxies in relation to other global galaxy properties

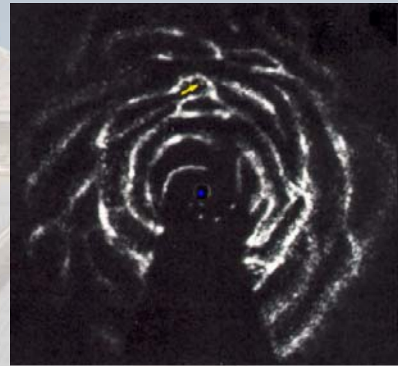
Week 2: HI as a tracer of galaxy dynamics, galaxy evolution, galaxy structure, star formation

Week 3: HI surveys: HI properties, HI Mass Function, HI properties as a function of environment

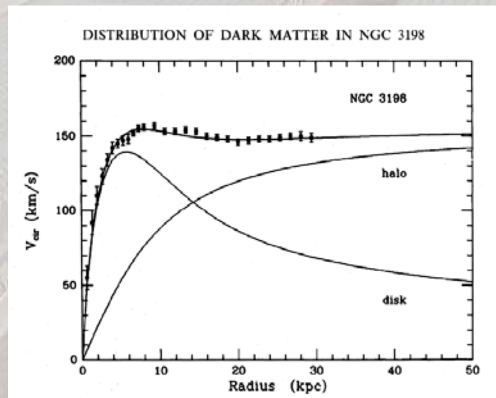
Week 4: relevance for galaxy formation and evolution, the cosmic picture, future observational capabilities

Neutral Hydrogen Studies:

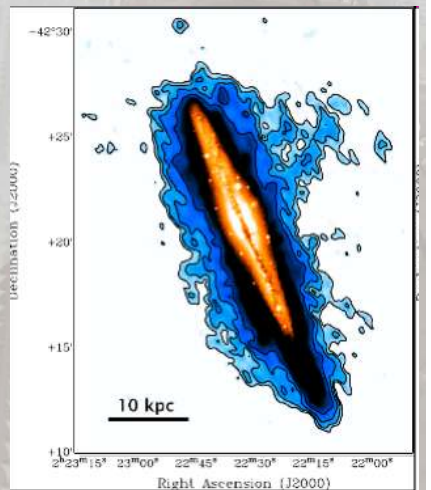
- Spiral structure and warp of the Milky Way



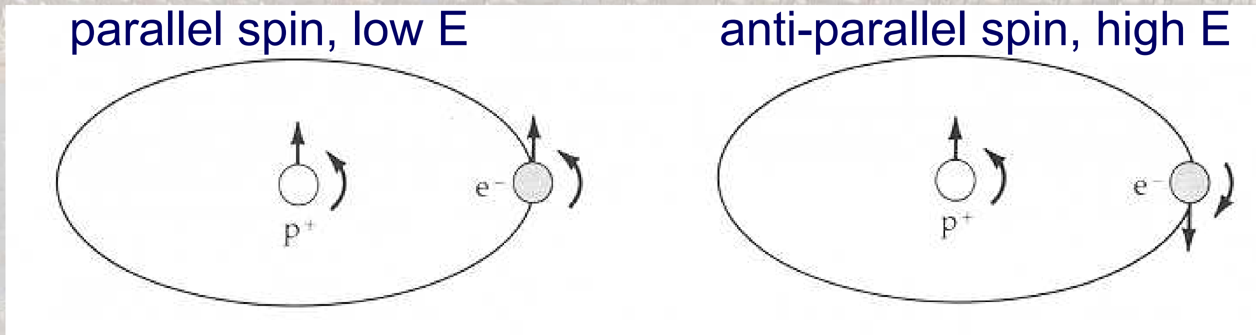
- Rotation curves of galaxies: Dark Matter

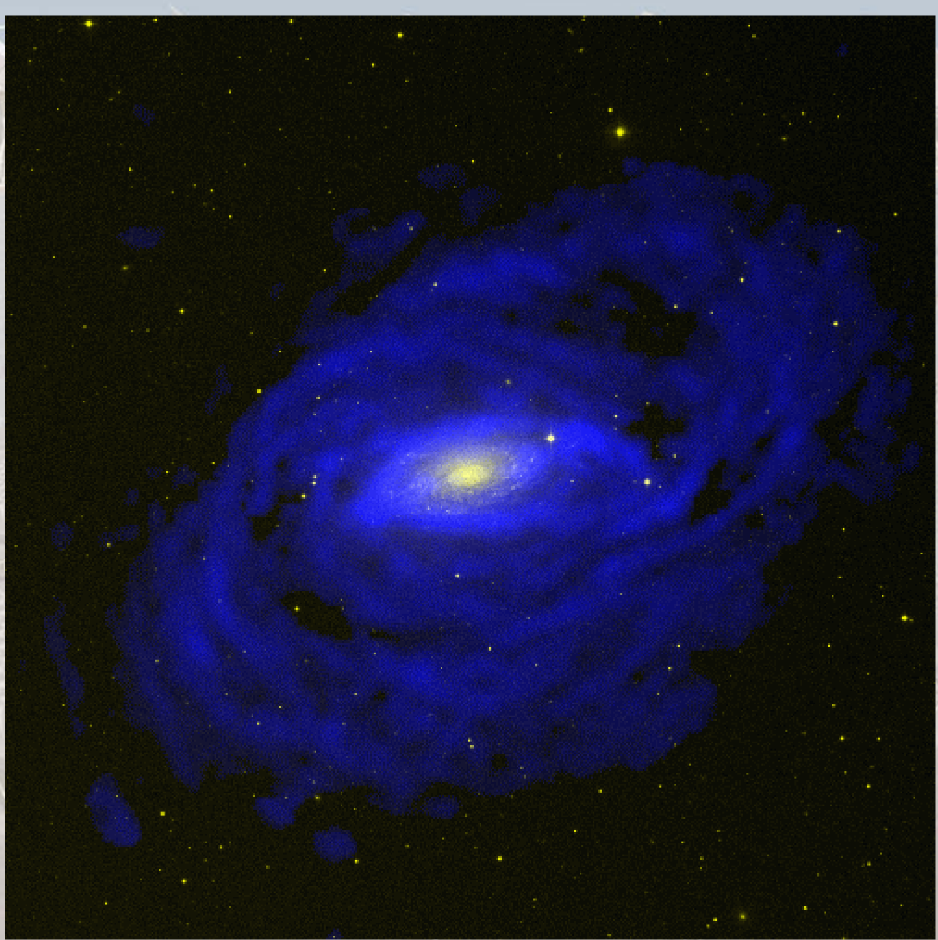
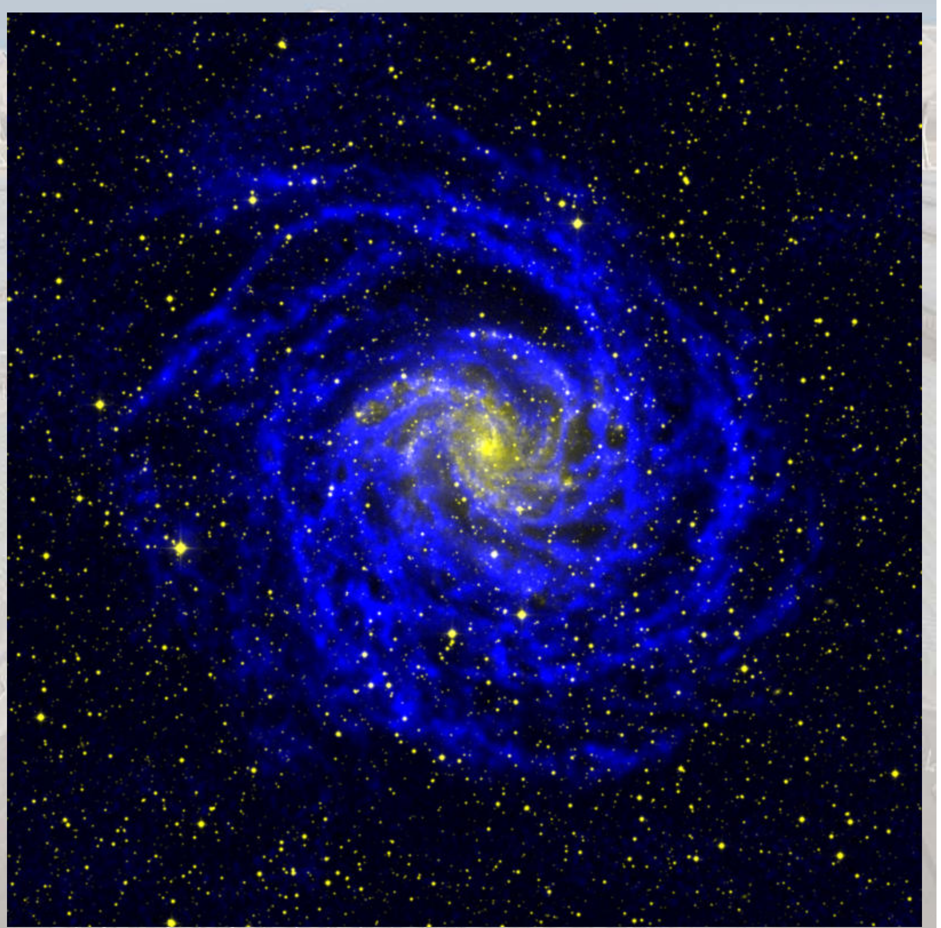


- Faint outer parts of galaxies: Nature or Nurture?



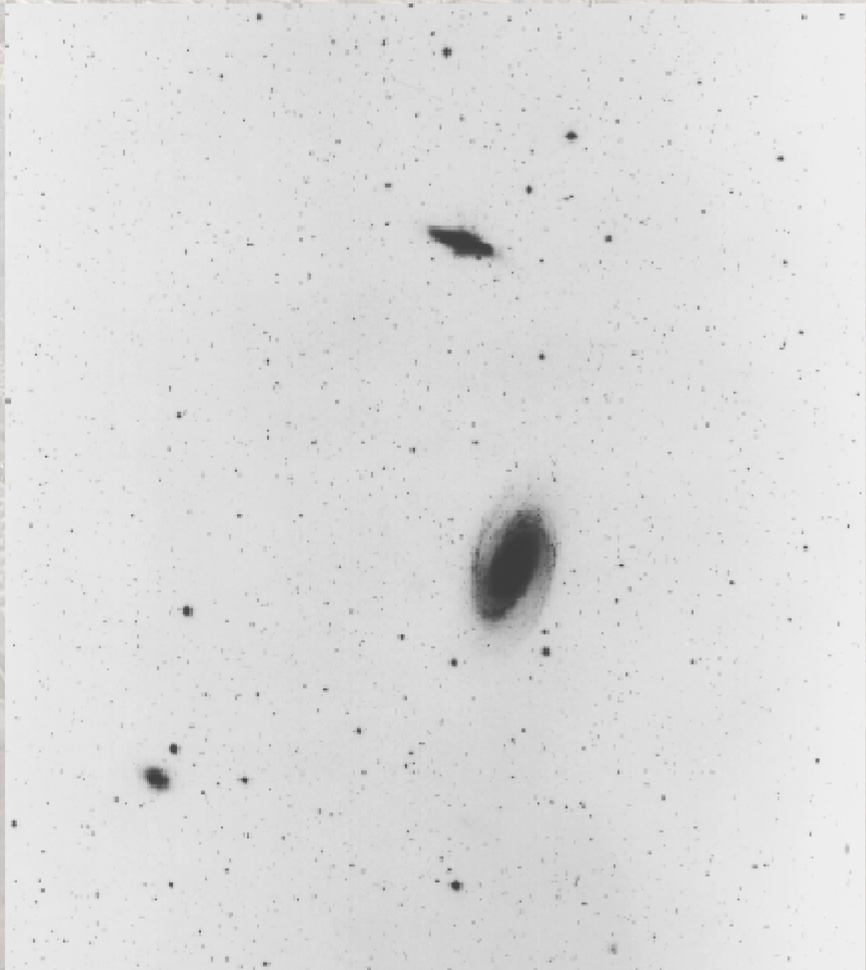
Henk van de Hulst discussed the 21-cm line at Leiden Observatory



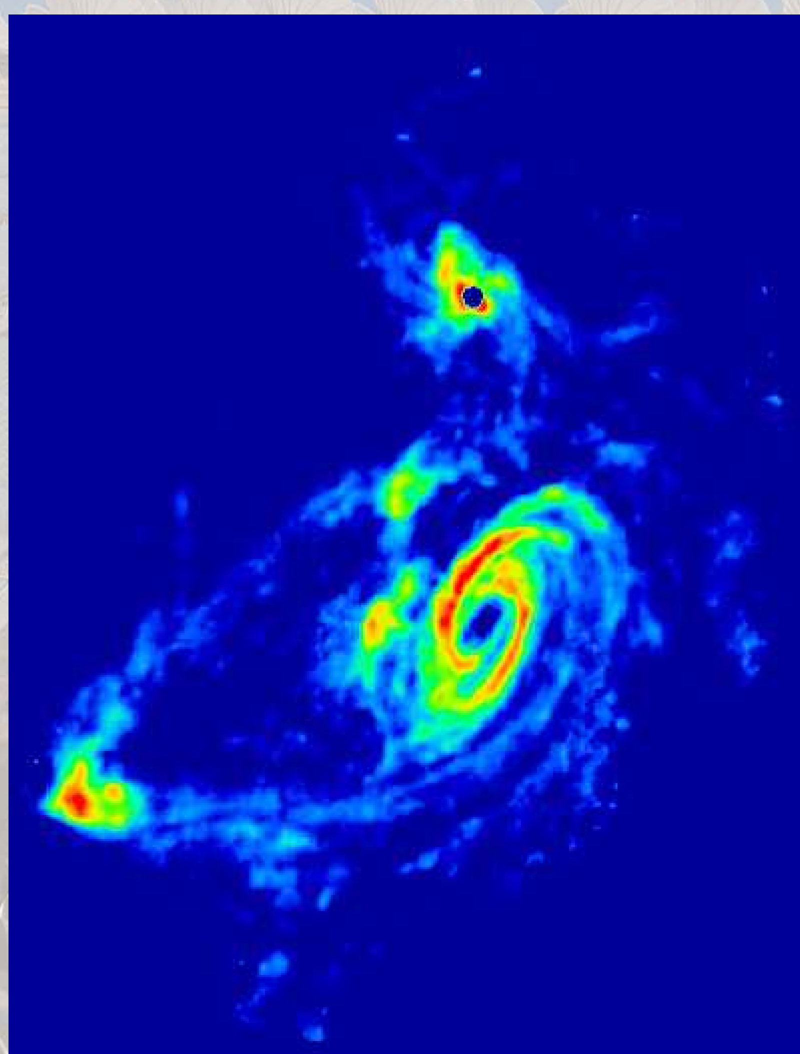
NGC 5055	NGC 6946
	
Battaglia, Fraternali, Oosterloo and Sancisi 2006 A&A, 447, 49	Boomsma, Oosterloo, Sancisi and van der Hulst, 2008 A&A, 490, 555

Messier 81

Optical



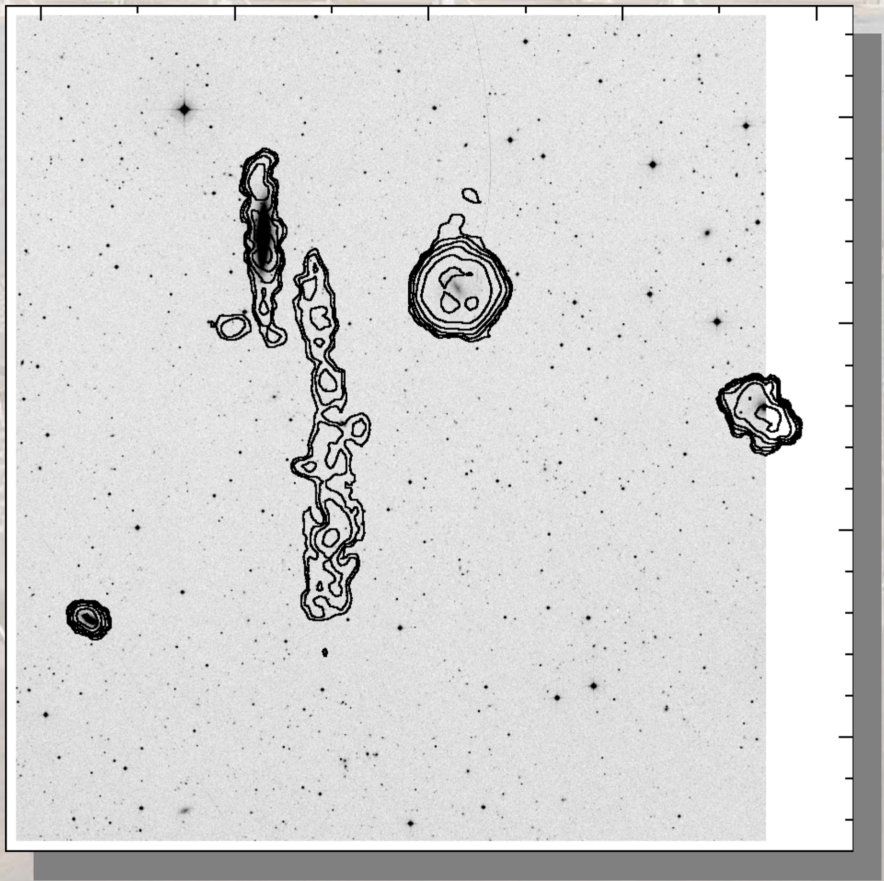
Neutral Hydrogen



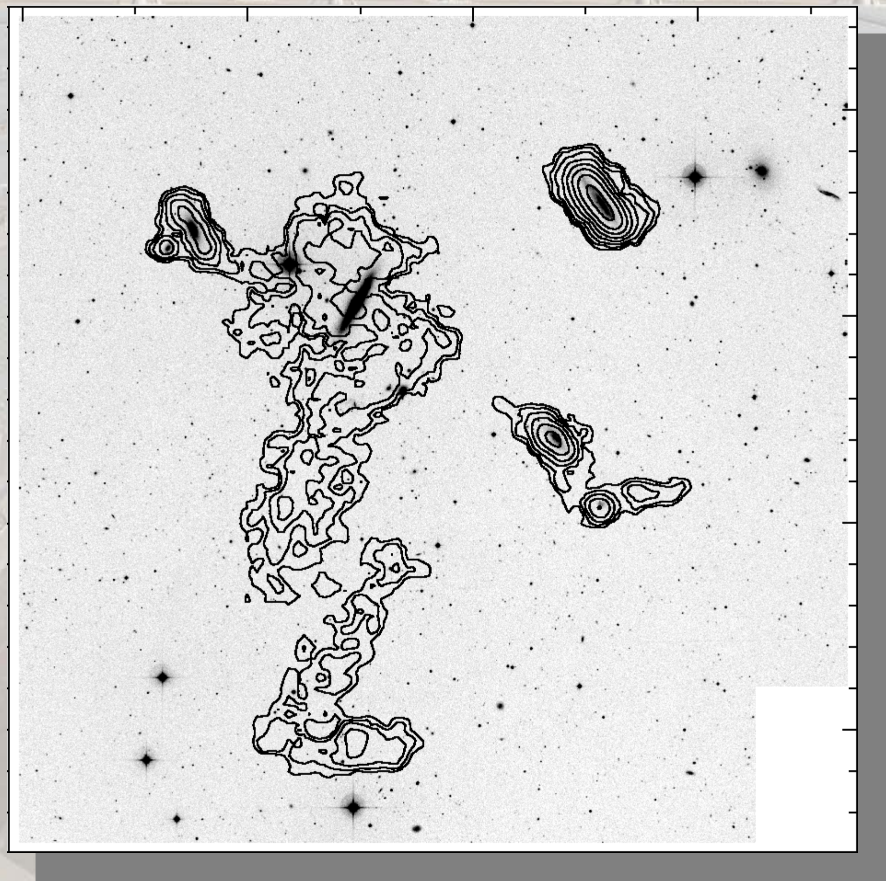
The brightest lenticulars in Ursa Major

Verheijen et al, 2001

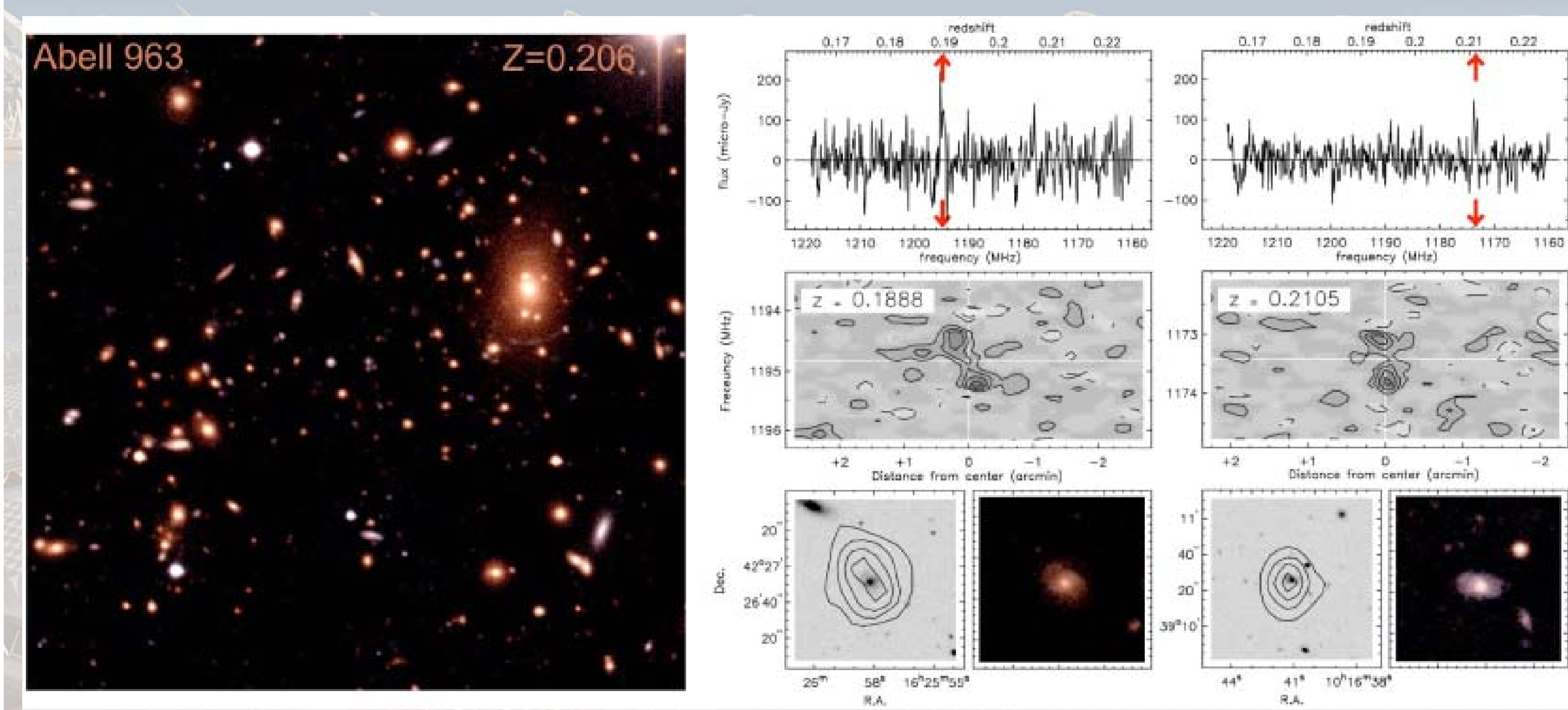
NGC 4026



NGC 4111



Present state of the art: imaging HI emission out to z = 0.2

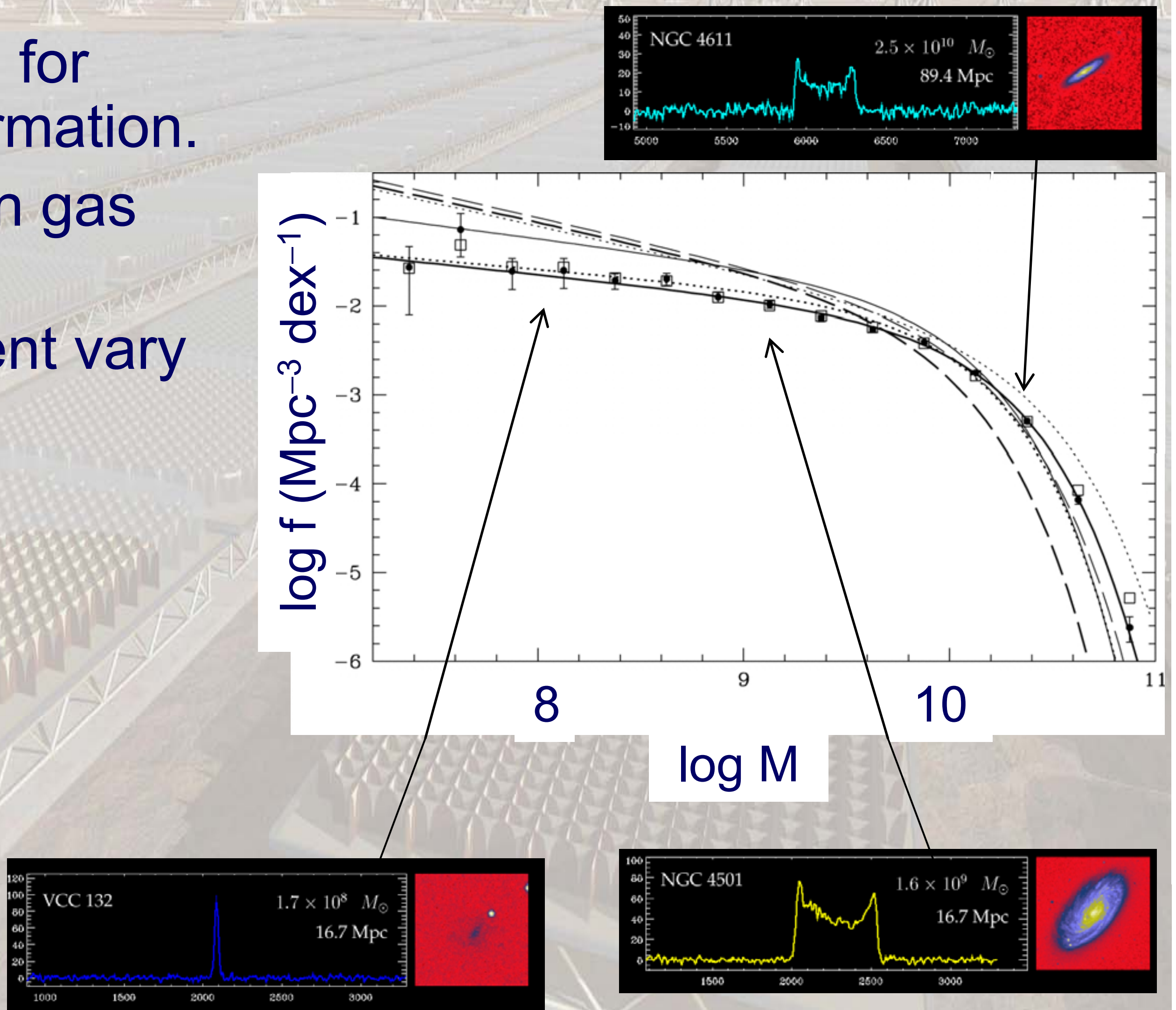


Verheijen et al. ApJ, 668, L9, 2007

Galaxy Assembly & Evolution

H I is the raw material for galaxies and star formation.

- How do galaxies turn gas into stars?
- How does gas content vary with
  - Morphology;
  - Redshift;
  - Environment;
  - Mergers;
  - Feedback;
  - …

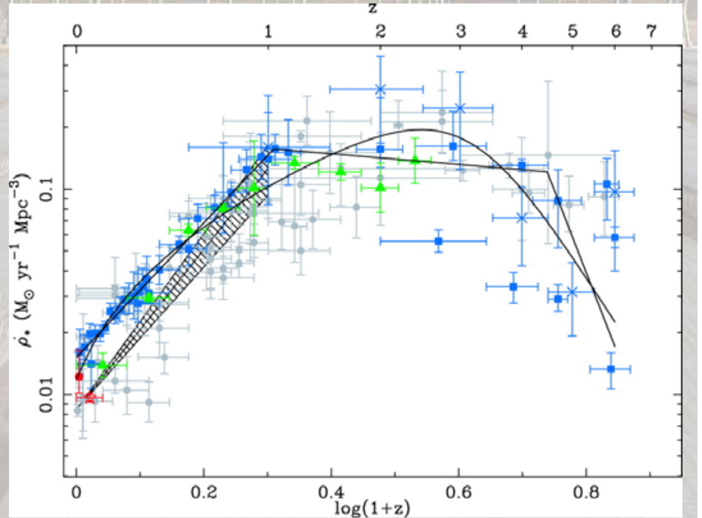


Origins
First Light
Galaxy Evolution

Galaxy Assembly
Stars *and* Gas

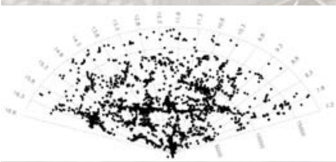
- Stellar "downsizing" since *z* ~ 1
- … but gas content unchanging!
- Gas content and dynamics becoming critical part of simulations.

stars →

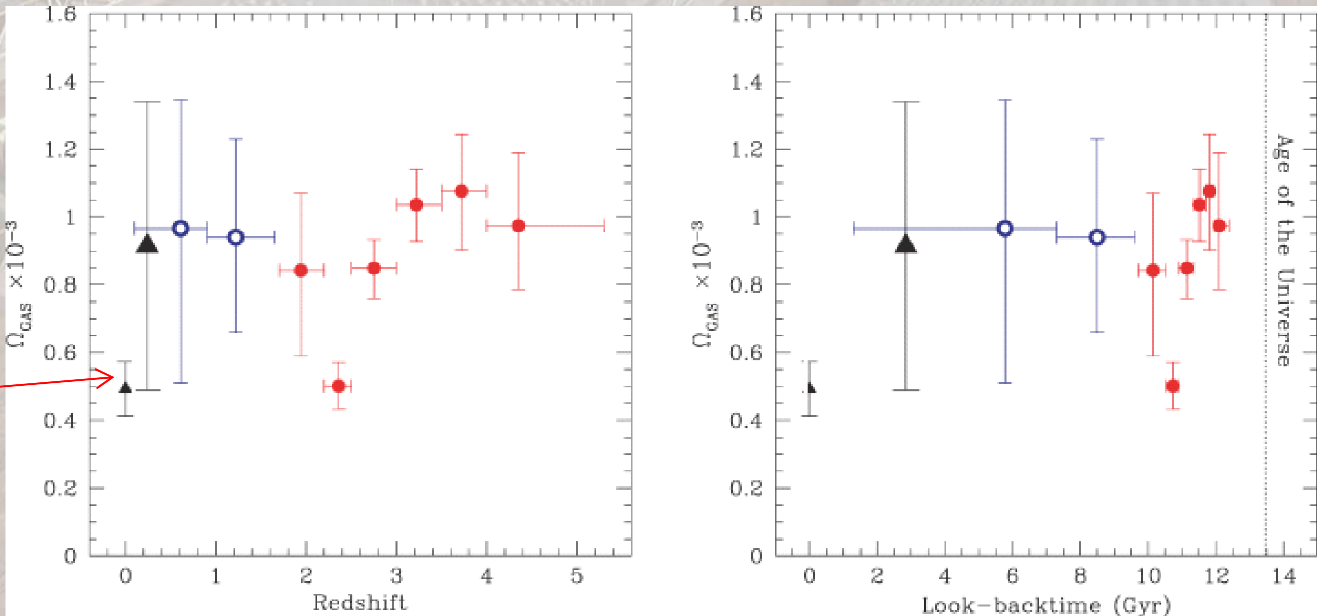


gas ↓

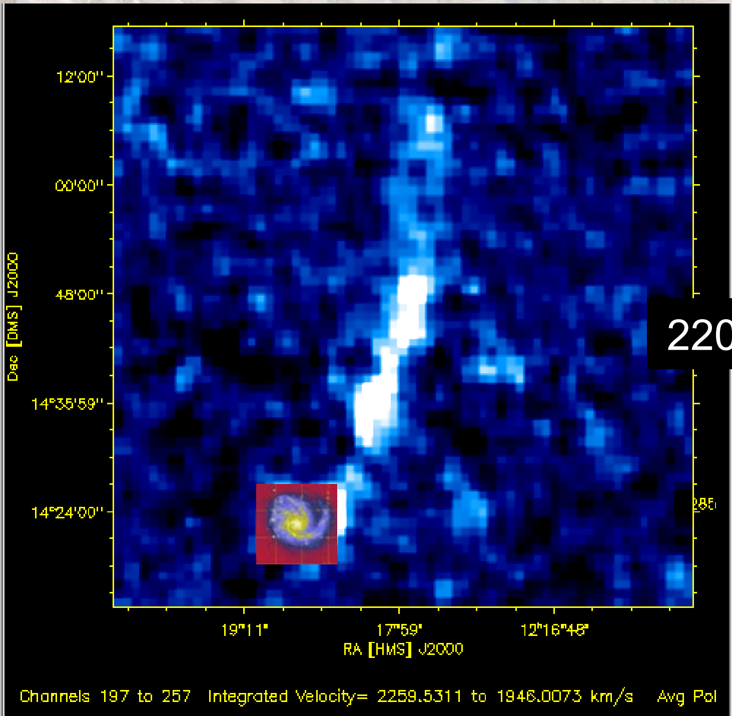
Hopkins & Beacom



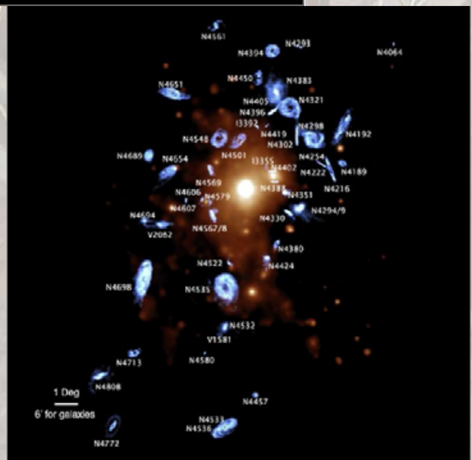
HIPASS (Parkes), ALFALFA (Arecibo)



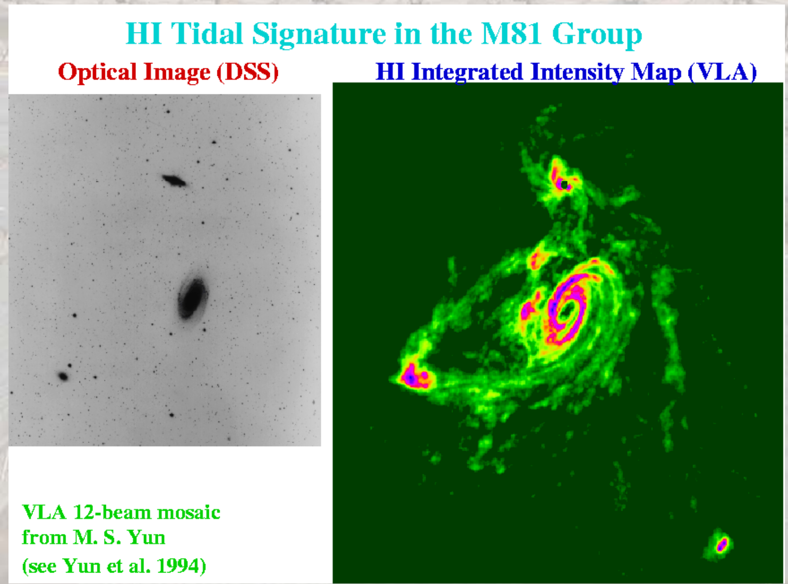
Evolution and Environment



NGC 4254 in
Virgo (ALFALFA)



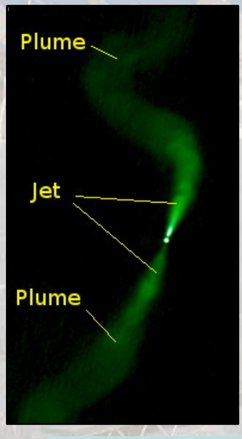
VIVA



- How do galaxies gain and lose gas?
- Infall vs. removal processes
- Gas serves as a tracer of interactions.

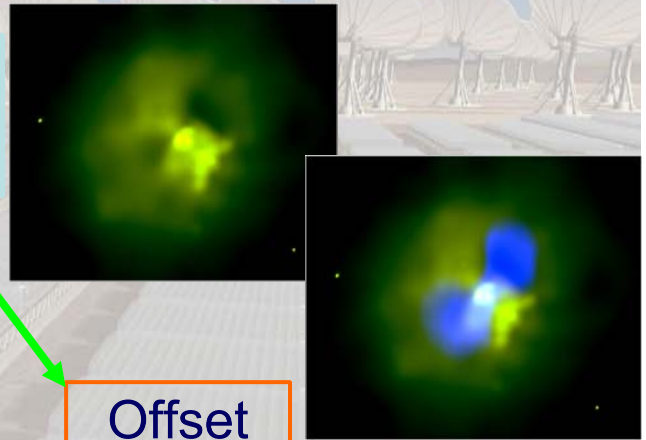
Origins
First Light
Galaxy Evolution

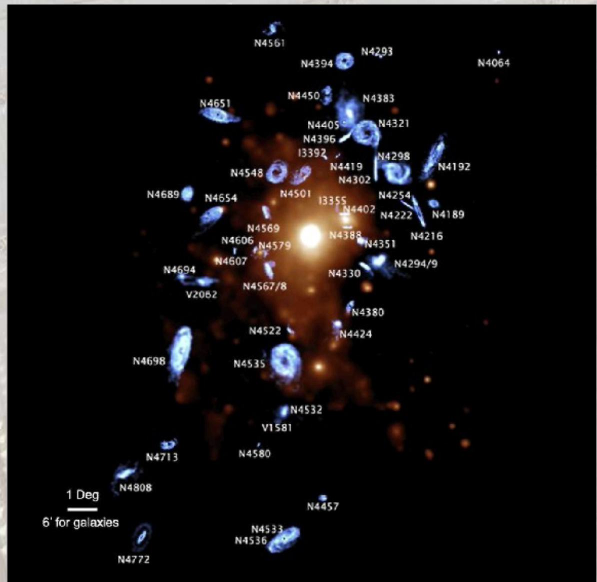
… and Feedback



Radio Jet activates

Heats X-ray gas





BH accretion

Offset X-ray cooling

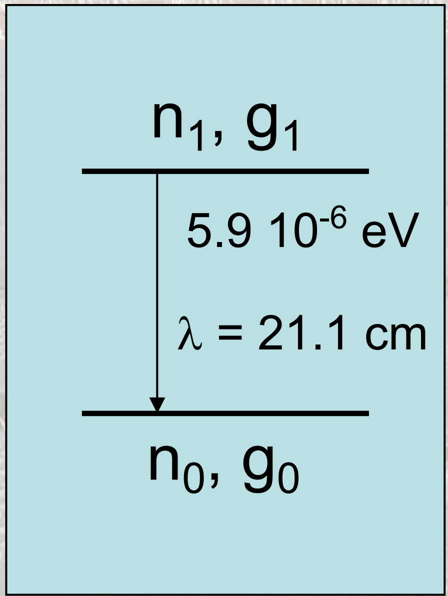
X-ray cooling

BH stops accreting

RG is quiescent

Clarke, Feretti

The 21 cm transition (Field 1958, ApJ 129, 536)



- The 21 cm hyperfine transition is a forbidden transition between the two $1^2s_{1/2}$ ground level states of hydrogen.

- The relative population of the two states is given, $n_1/n_0=g_1/g_0 \exp(-T_*/T_s)$, with T_s (the spin temperature) and $T_* = 0.068$ k

- The value of the T_s is given by:

$$T_s = \frac{T_c + y_\alpha T_k + y_c T_k}{1 + y_\alpha + y_c}$$

Basic radiative transfer

- Basic function of radiative transfer
  - Expressed in temperature equivalent

$$T_b = T_{ex}(1 - e^{-\tau_\nu}) + T_{bg} e^{-\tau_\nu}$$

- Where optical depth is given:

$$\tau_\nu = \int \frac{h\upsilon}{4\pi}(n_1 B_{12} - n_2 B_{21})\phi(\upsilon)ds = \int \frac{h\upsilon}{4\pi} n_1 B_{12}(1 - \exp(\frac{-h\nu}{kT_{ex}}))\phi(\upsilon)ds \approx \frac{N(v)}{CT_{ex}}$$

  - For HI the T_{ex} is usually called T_{spin}
    - local thermal equilibrium: $T_{spin} \approx T_{kin}$

- Thin emission (no background)
  - Measure the total column density

$$T_b(v) = N(v)/C$$

- Thick emission
  - Measure the temperature

$$T_b(v) = T_{ex} \approx T_{kin}$$

Radiation transport in an HI cloud

The increase in intensity through a layer of radiating material will the sum of the emission (given by the emission coefficient j_ν) and the radiation absorbed in the layer (given by the absorption coefficient κ_ν):

$$dI_\nu(r) = + j_\nu(r)\rho dr - \kappa_\nu(r)\rho I_\nu(r)dr$$

using the definition for optical depth: $\int_{r=0}^{r=s} \kappa_\nu(r)\rho dr = \tau_\nu$

We can rewrite this as: $-\frac{1}{\kappa_\nu(r)\rho}\frac{dI_\nu(r)}{dr} = I_\nu(r) - \frac{j_\nu(r)}{\kappa_\nu(r)}$

so for an HI layer or cloud seen against a background radiation field of intensity I_o we can write this as:

$$I_\nu(s) = I_\nu(0)e^{-\tau_\nu} + S_\nu(1 - e^{-\tau_\nu})$$

S_ν is the so called source function describing the radiation field of the plasma.

For a gas in thermodynamic equilibrium this is the *Planck function*.

In radio astronomy it is customary to describe thw radiation in terms of a temperature. This temparature is coupled to the physical temperature of the gas

The radiation transport equation then becomes:

$$\boxed{T_{obs} = e^{-\tau_\nu} T_{cont} + (1 - e^{-\tau_\nu}) T_{spin}}$$

Where T_{obs} is the observed intensity, T_{cont} the intensity of the background radiation and T_{spin} the radiation from the HI gas

In the absence of background radiation this simplifies into:

$T_{obs} = (1 - e^{-\tau_\nu}) T_{spin}$ which can be simplified further:

$\boxed{T_{obs} = T_{spin}}$ for $\tau_\nu >> 1$

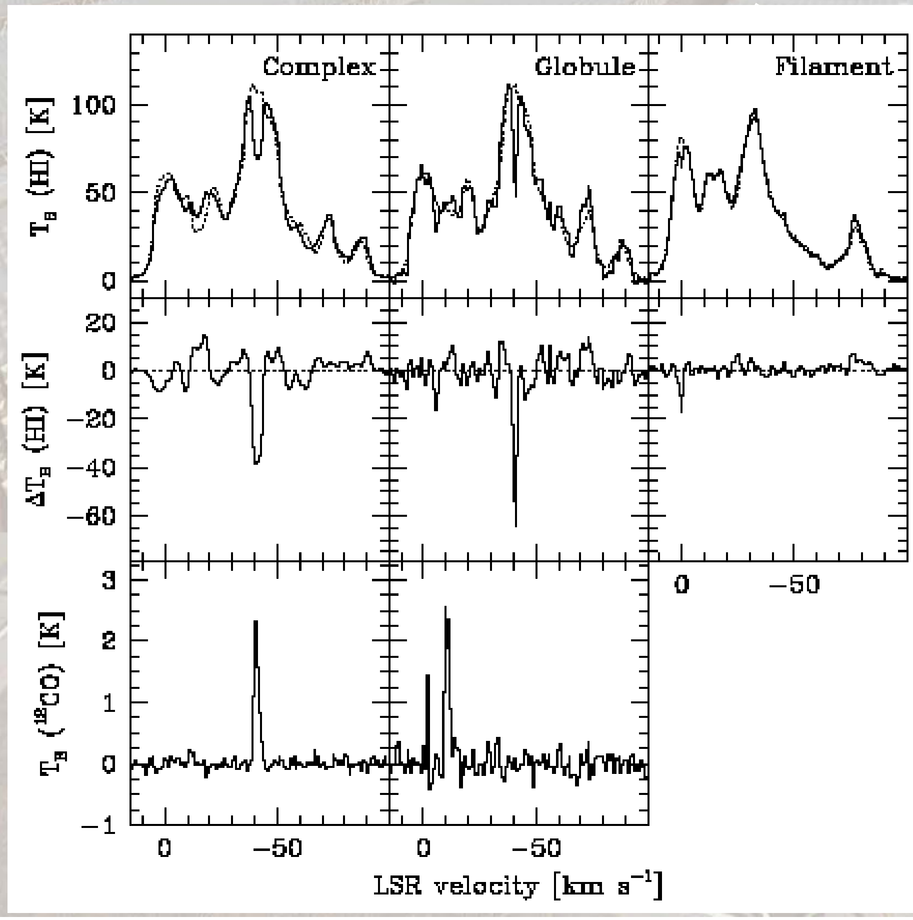
$\boxed{T_{obs} = \tau_\nu T_{spin}}$ for $\tau_\nu << 1$

If we rewrite this in terms of the difference between the observed emission and the background continuum emission the radiative transfer equation becomes:

$$T_{line} = T_{obs} - T_{cont} = (1 - e^{-\tau_\nu})(T_{spin} - T_{cont})$$

We can se immediately that the line emission becomes negative (absorption) if $T_{spin} < T_{cont}$.

Example profiles (emission and absorption):



A few basic relations

Typical sensitivities in synthesis images (VLA, WSRT) with ~4 km/s velocity resolution and 6 - 12 hours integration time: ~ 1 mJy/beam or 1 K brightness temperature for an angular resolution of 25’’ x 25’’

conversions:

$$T_b\,(\mathrm{K}) = 1.36\ \lambda\ (\mathrm{cm})^2\ S\ (\mathrm{mJy})\ /\ \theta_{min}(\mathrm{arcsec})\theta_{maj}(\mathrm{arcsec})$$

column density:

$$N_{HI} = 1.82 \times 10^{18} \int T_b(v)\ (\mathrm{K})\ dv\ (\mathrm{km/s})$$

HI mass:

$$M_{HI}\,(\mathrm{M}_\odot) = 2.36 \times 10^5\, D^2\ (\mathrm{Mpc}) \int S(v)\ (\mathrm{mJy})\ dv\ (\mathrm{km/s})$$

In addition to emission – absortpion measurements we can also derive the spin temperature T_{spin} from the width of HI emission profiles if the width is determined by thermal broadening.

For a gas cloud with temperature *T* consisting of particles with mass *m* we can wite the average kinetic energy per particle as:

$E_{kin} = \frac{1}{2} m v^2$ were v the average velocity per particel is

According to the kinetic gas theory he average energy per particle is also equal to:

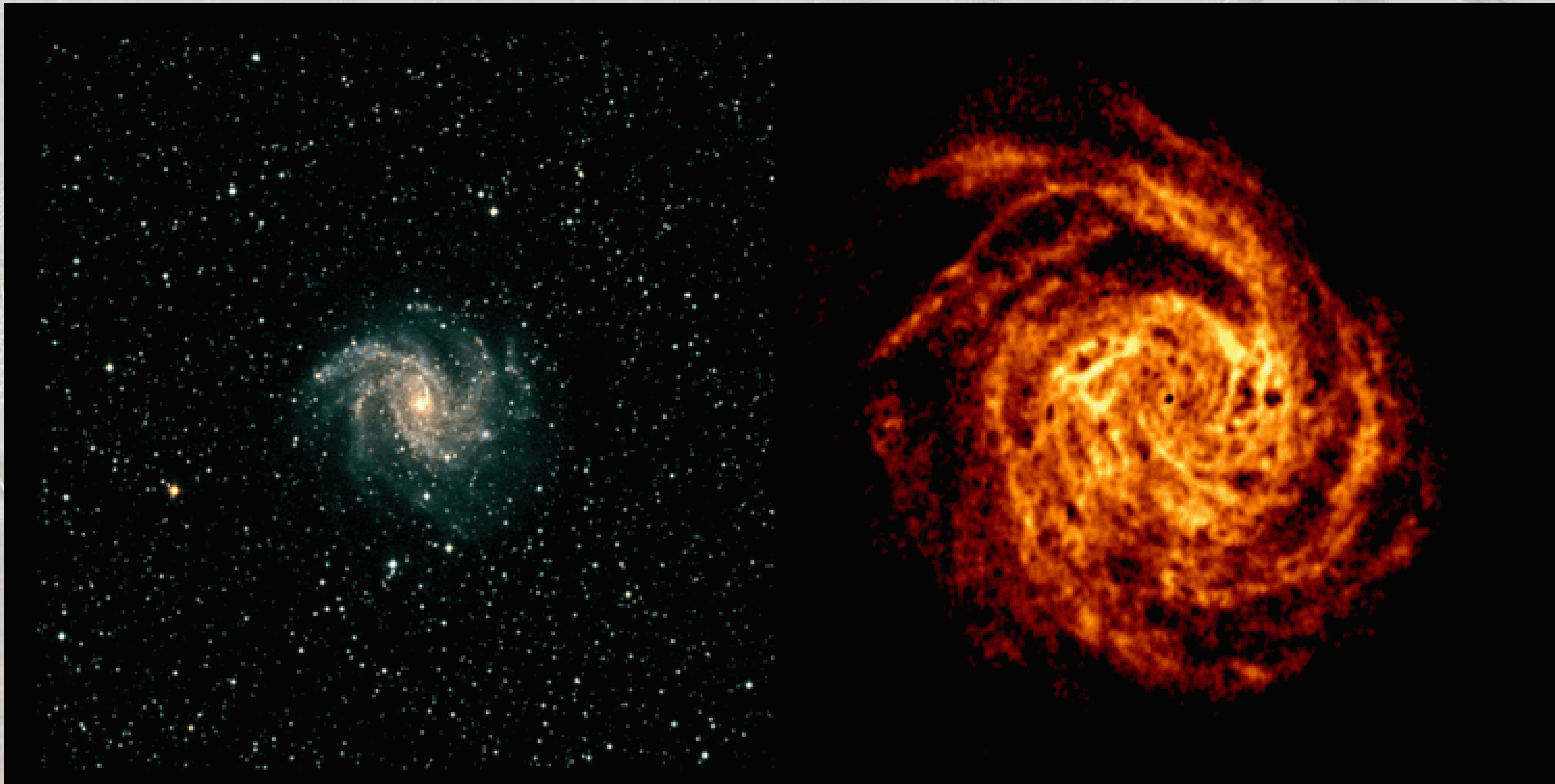
$$E_{kin} = \frac{3}{2} kT = \frac{1}{2} m v^2 \rightarrow v = \sqrt{\frac{3kT}{m}}$$

So there is a direct relation between the kinetic temperature of the gas and the average velocity of the particles. If the profile width we observe is determined solely by the temperature motion of the particles we can use this a a measure of the kinetic temperature.

Hoe zou de melkweg er “van buiten” uitzien ?

Voorbeeld:

Het melkwegstelsel NGC 6946: een optisch en HI beeld

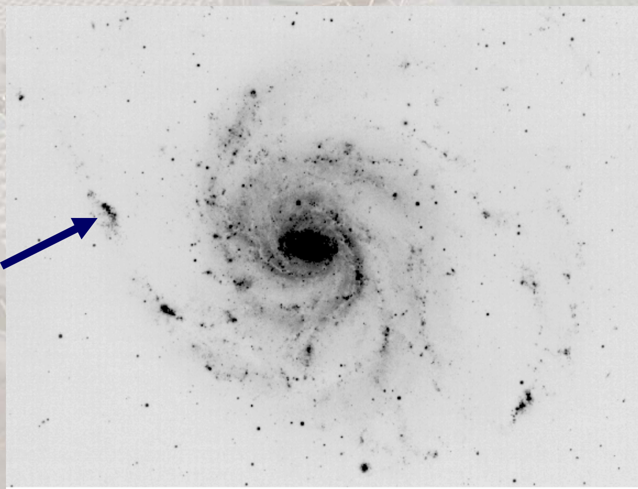


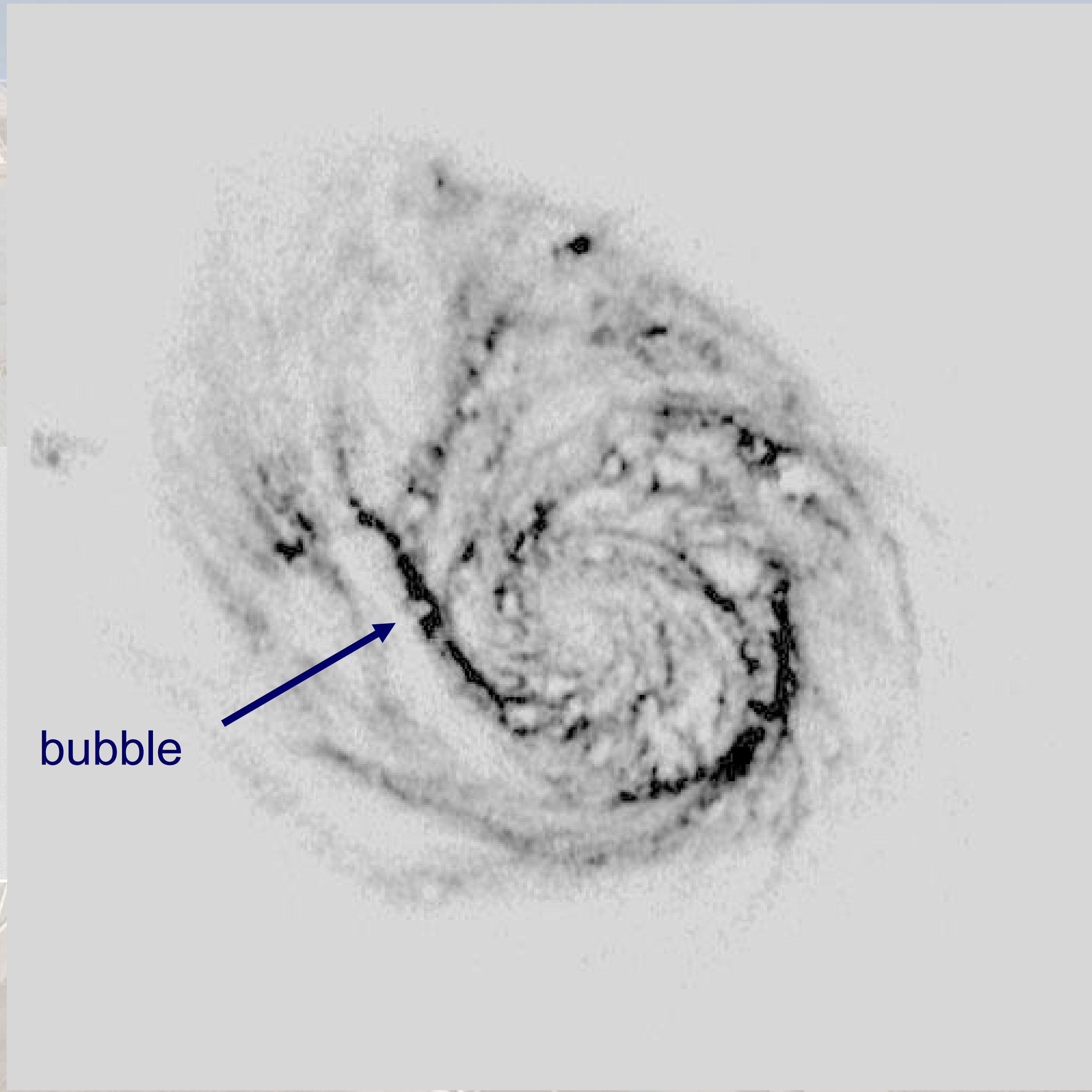
sterlicht HI verdeling

Messier 101

HI

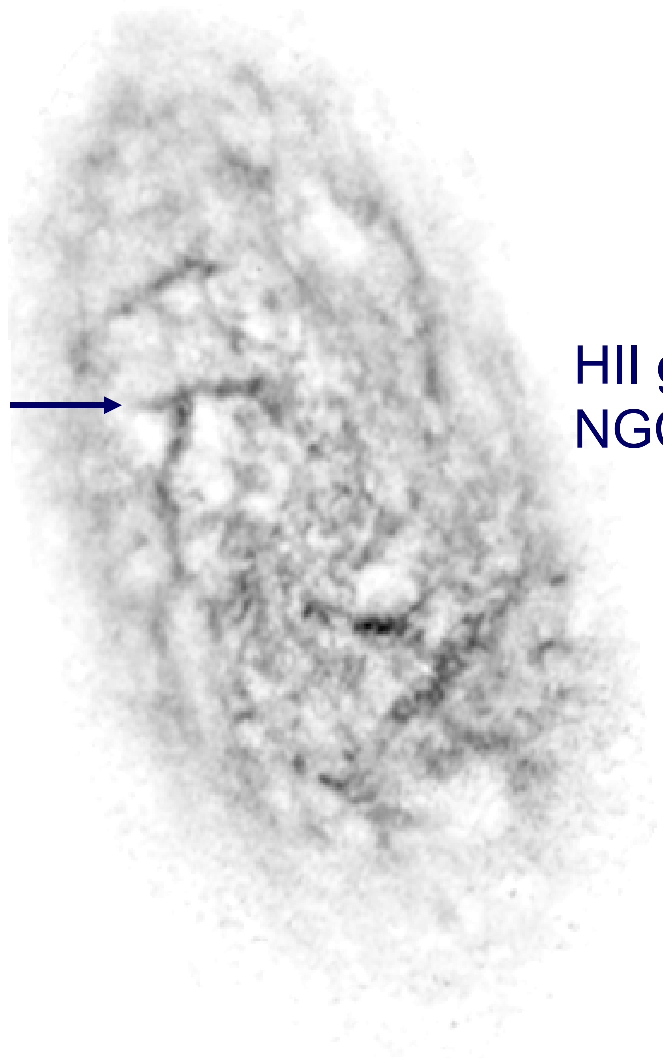
optisch





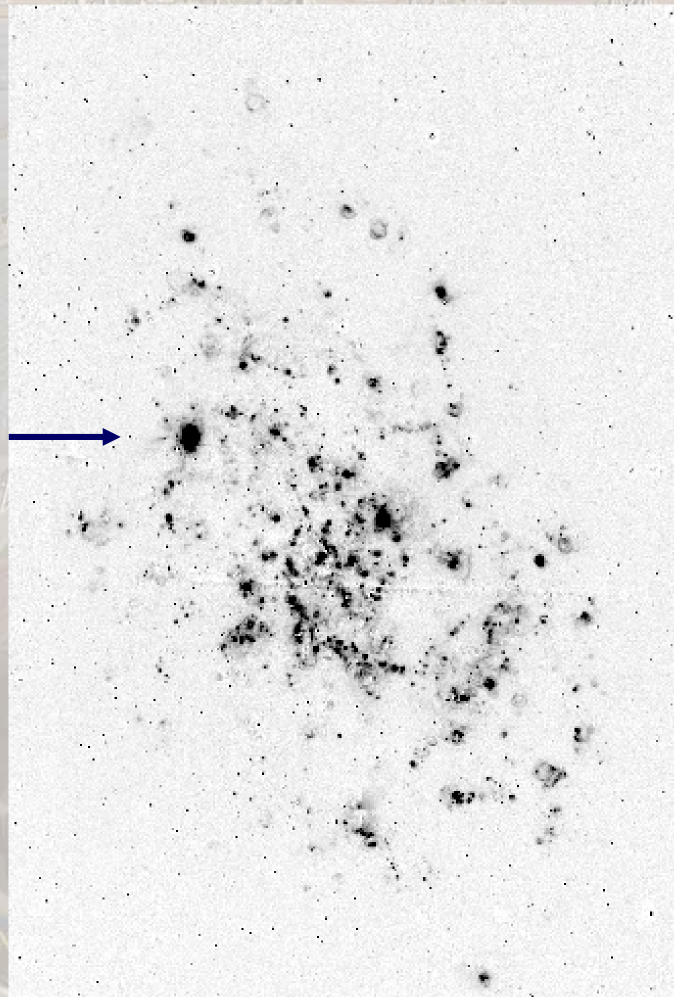
Messier 33 (NGC 598)

HI neutraal waterstof



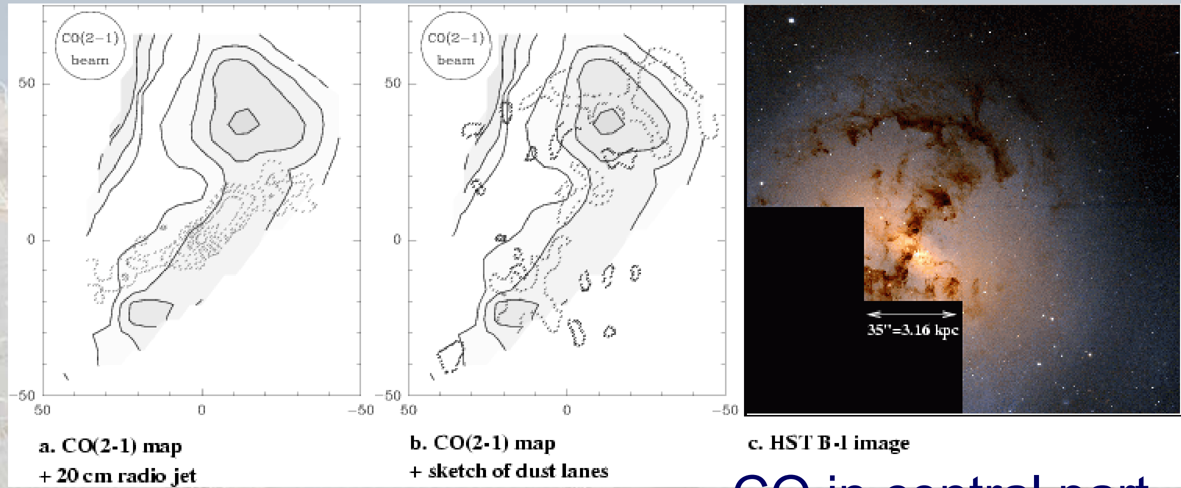
HII gebied
NGC 604

HII geioniseerd waterstof

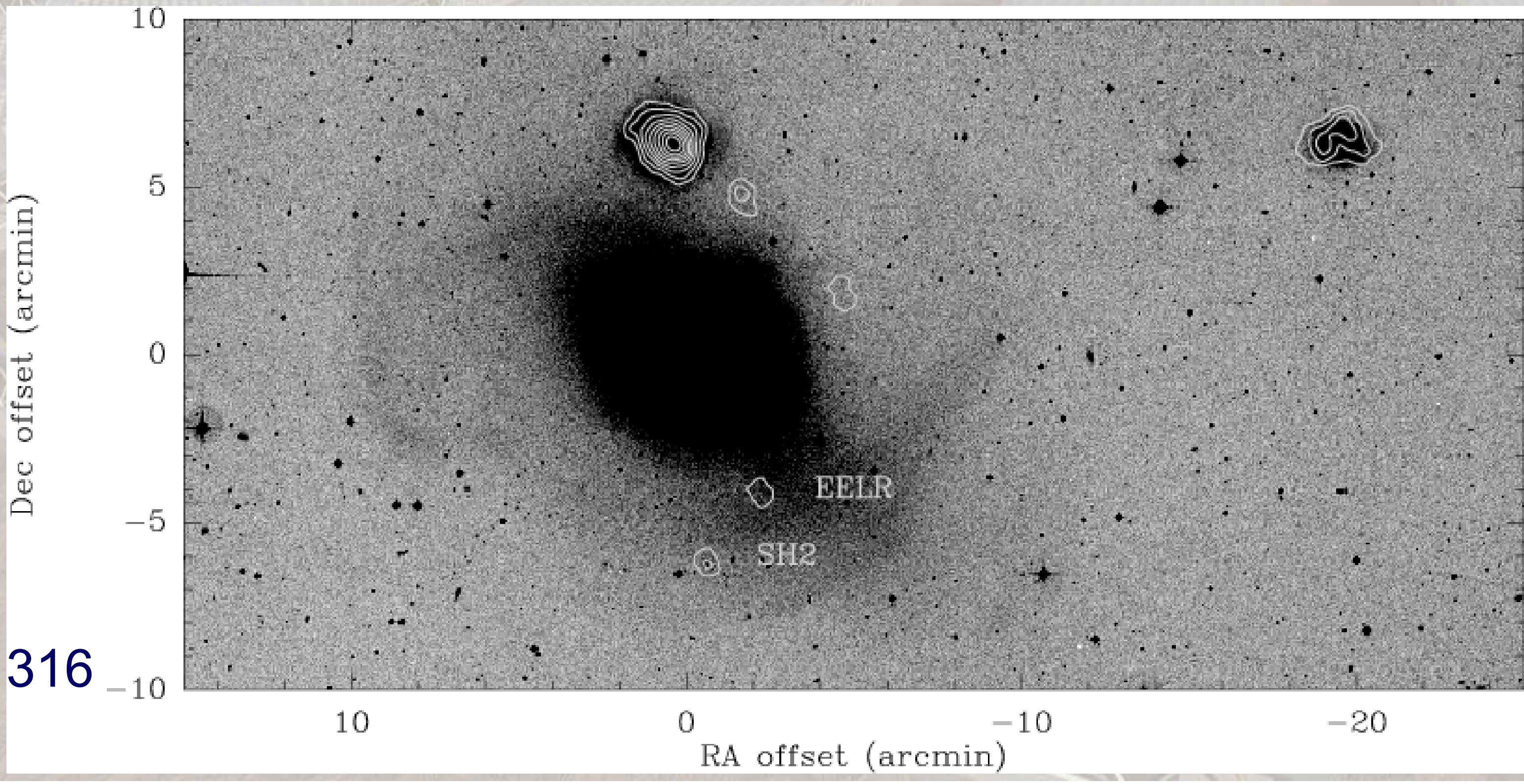


Elliptical galaxy NGC 1316 (Fornax A)

optical



CO in central part

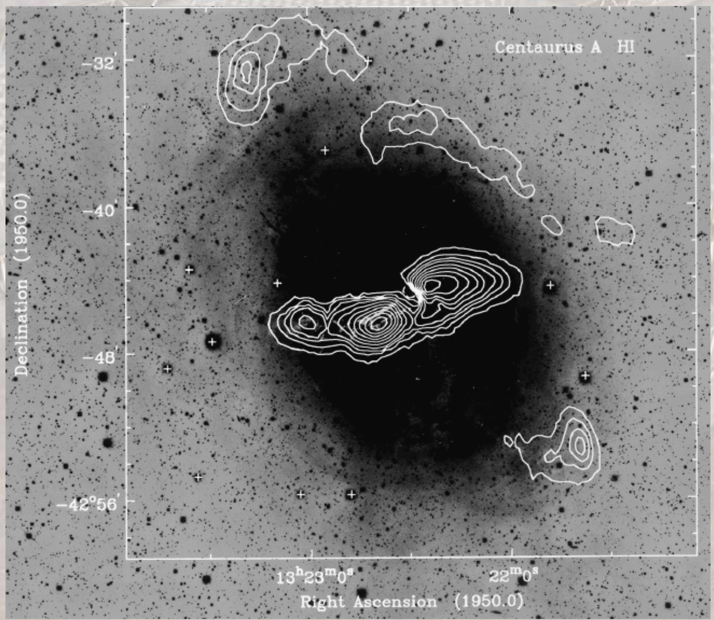


HI in NGC 1316

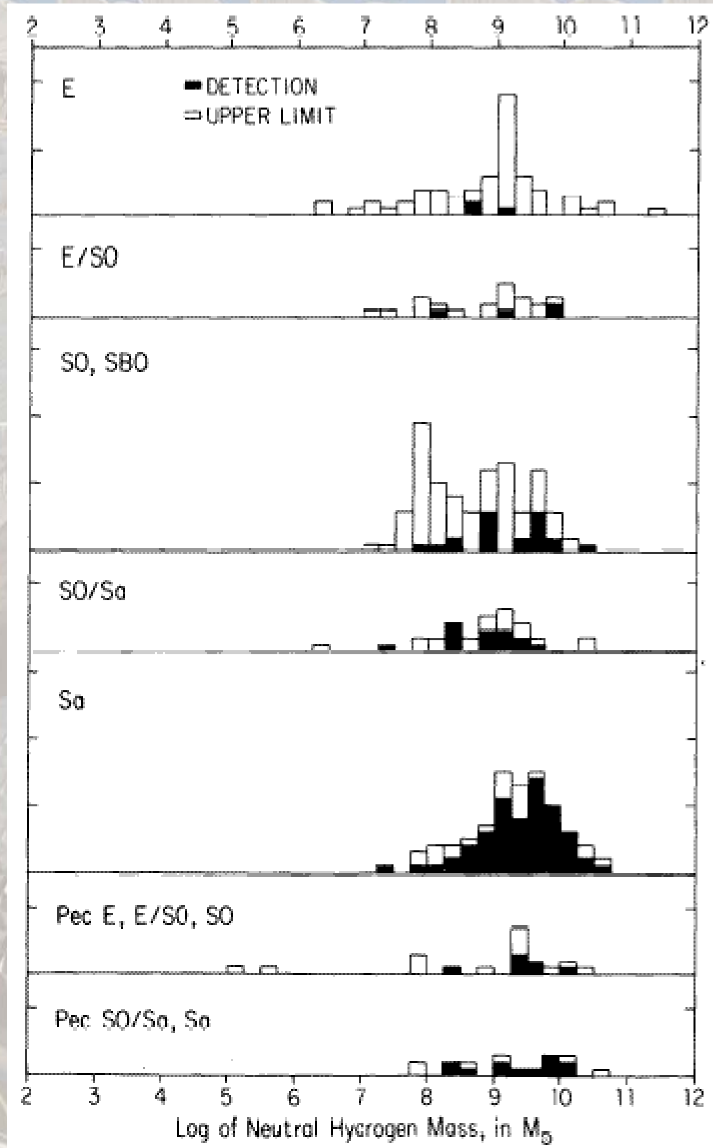
HI massa van E – S0 stelsels

De meeste E stelsels worden niet in HI gedetecteerd.

E/S0 stelsels die gedetecteerd worden blijken vaak optische structuur te vertonen meestal opgevat als een teken van interactie en merging.



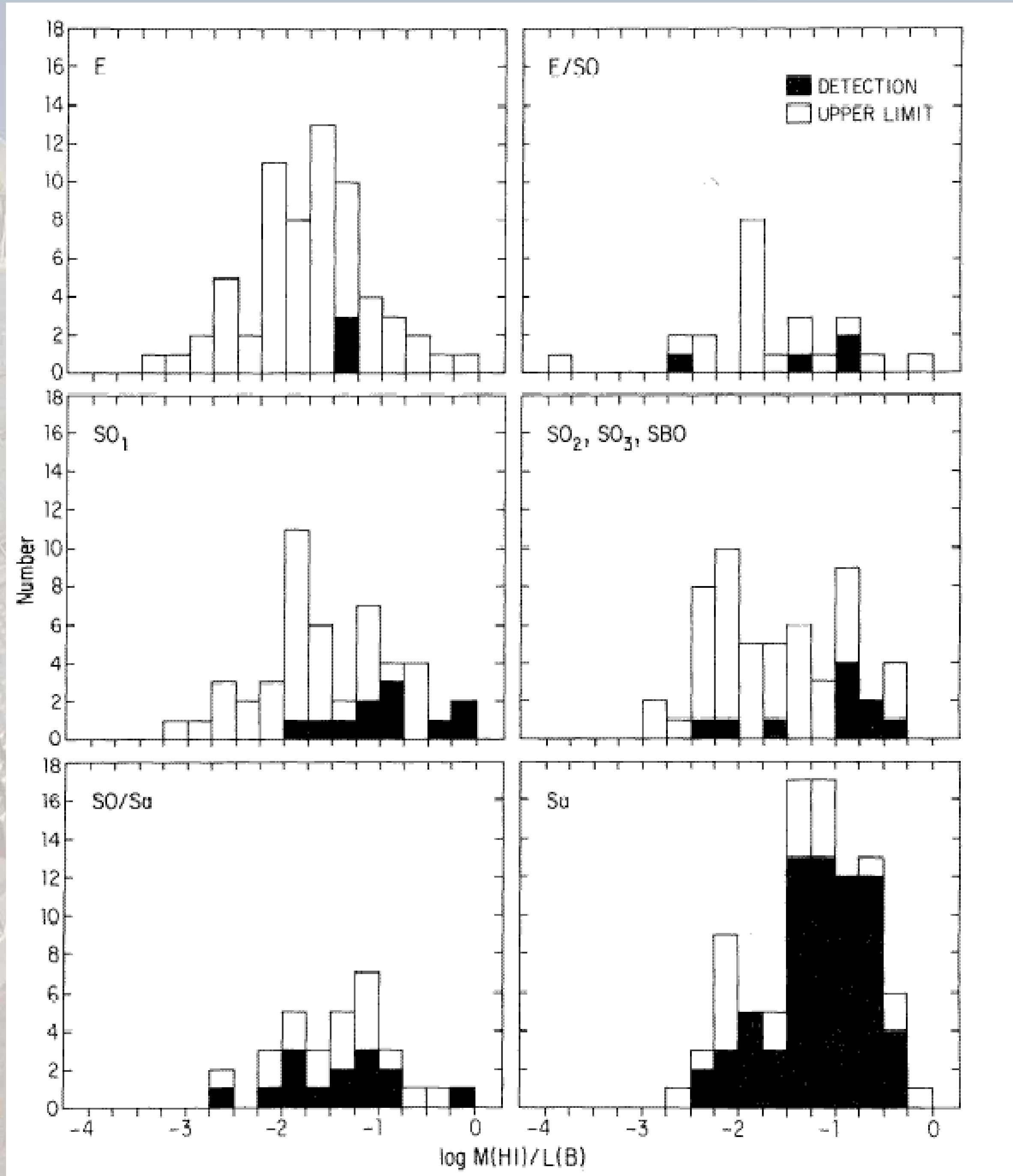
HI in NGC 5128 (Centaurus A)



Log HI massa

M_{HI}/L_B

HI mass – luminosity ratio of E – Sa galaxies

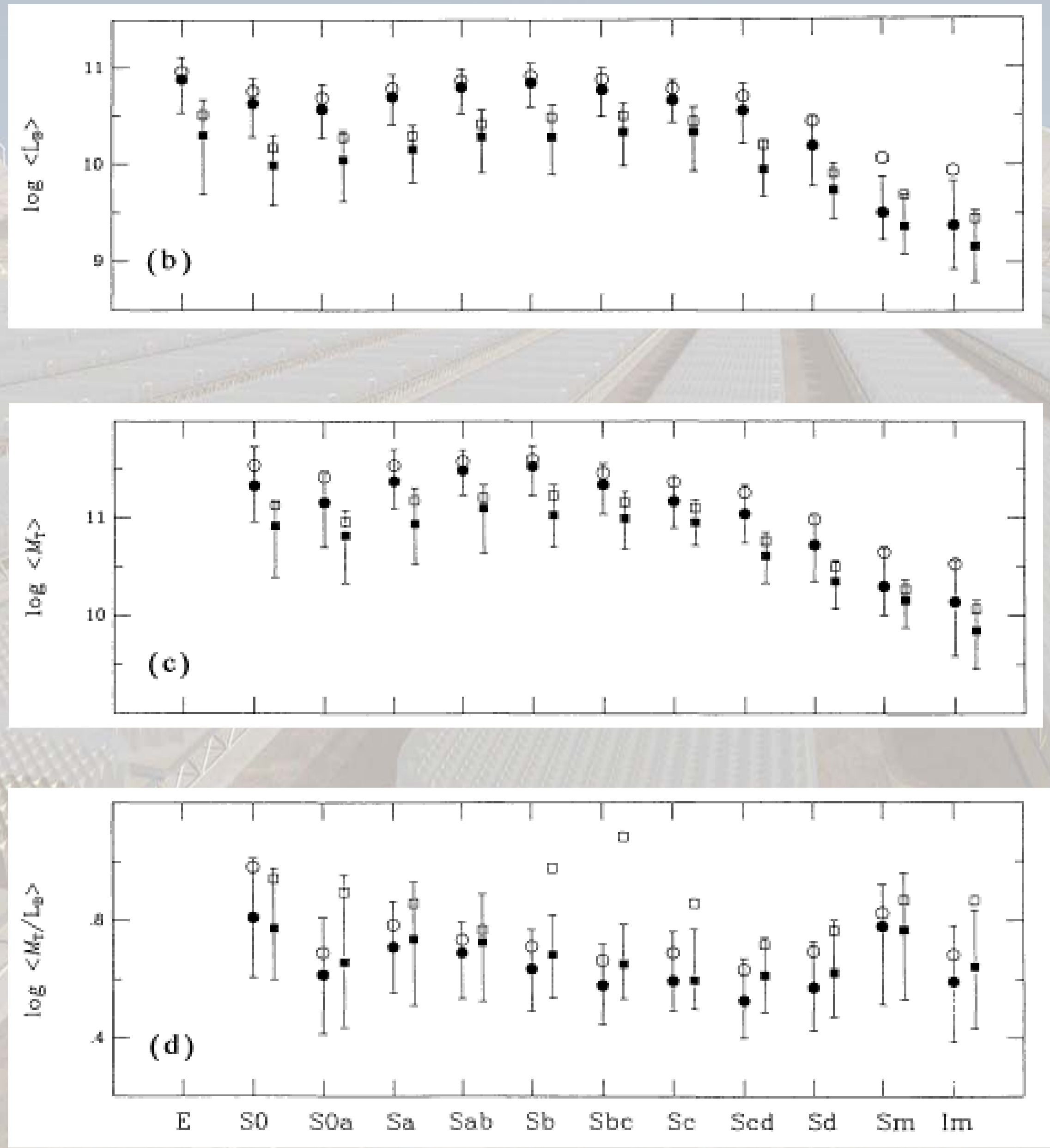


Variation of properties
with morphological type

L_B

M_T

L_B / M_T



Morphological type

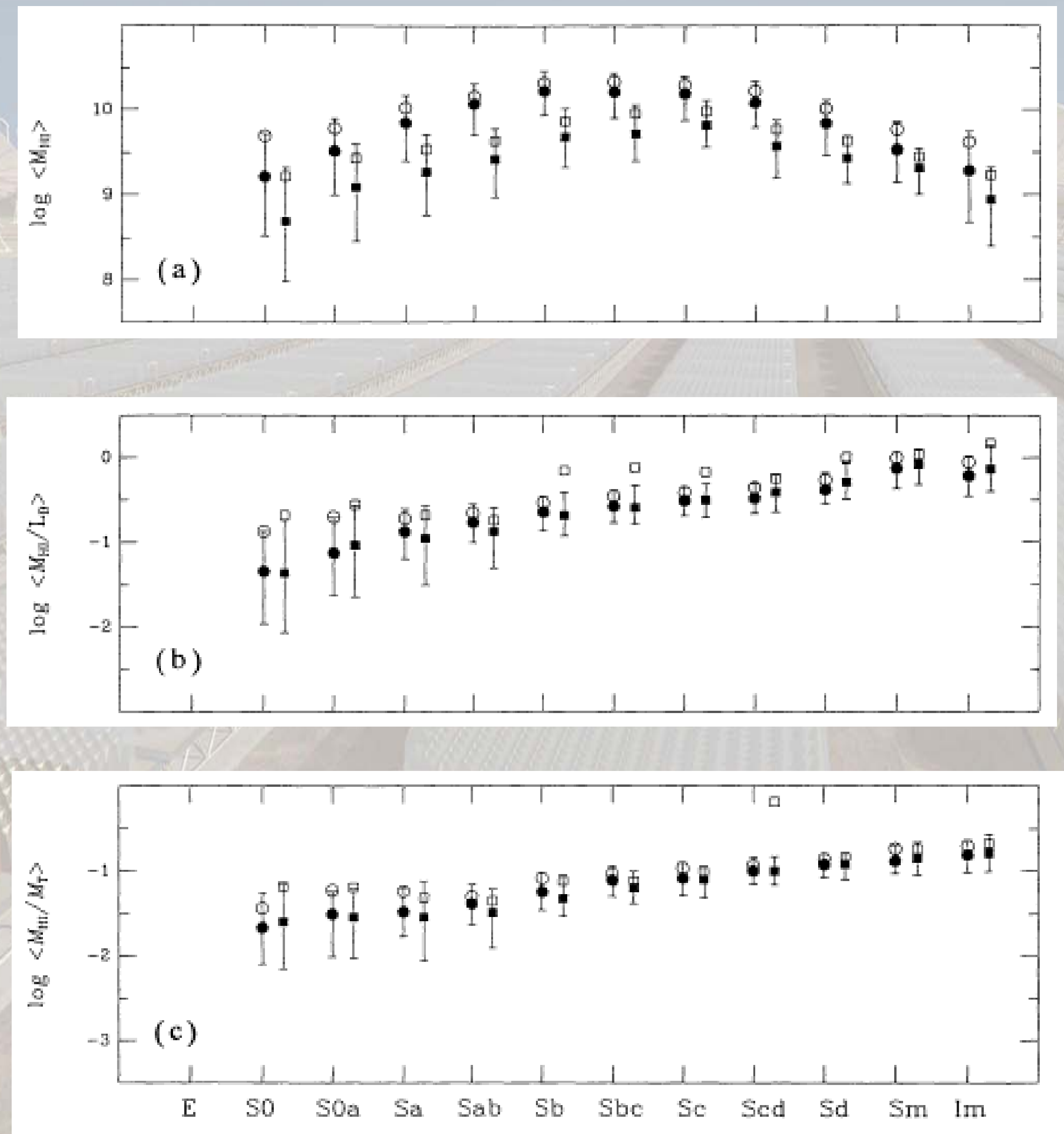
Haynes & Roberts, 1992
Ann. Rev. Astron & Astrophys.
32, 115

Variation of properties
with morphological type

M_{HI}

M_{HI}/L_B

M_{HI}/M_T

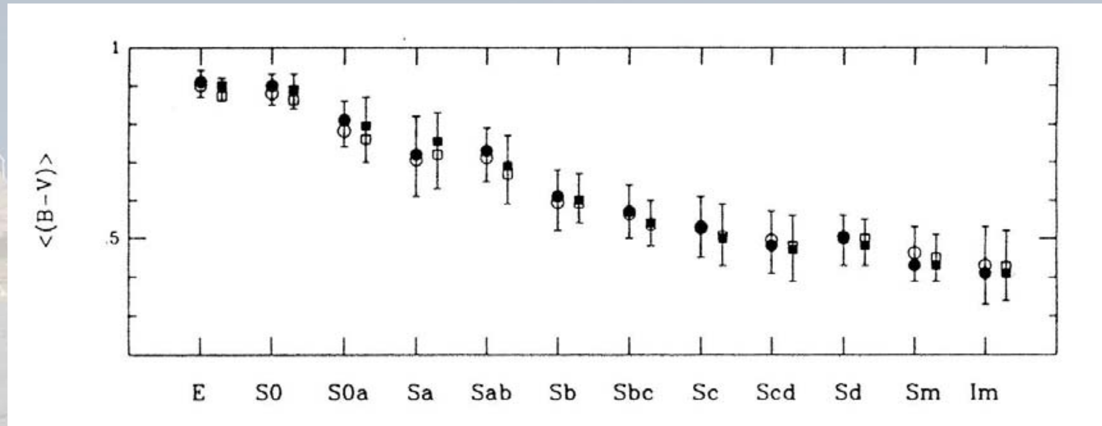


Morphological type

Haynes & Roberts, 1992
Ann. Rev. Astron & Astrophys.
32, 115

Variation of properties
with morphological type

<B – V> color



Morphological type

E (early type galaxies)

---

gas poor
red color
luminous & massive

Sm/I (late type galaxies)

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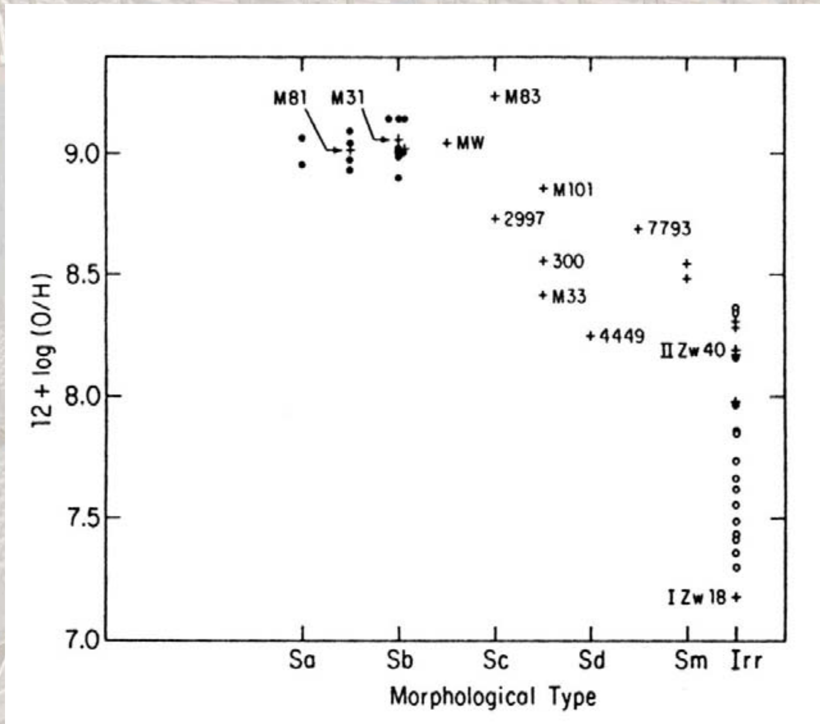
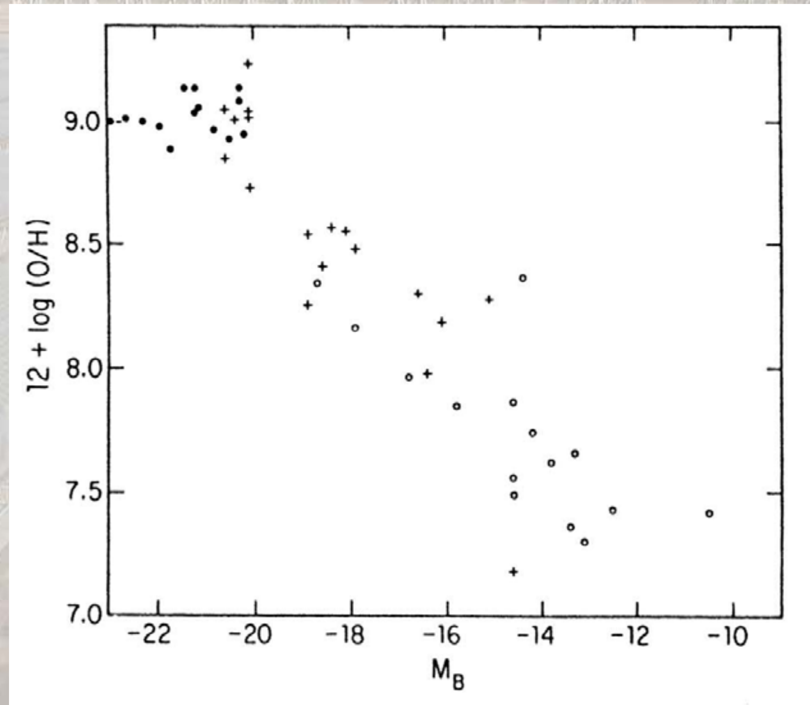
gas rich
blue color
faint and small

Haynes & Roberts, 1992
Ann. Rev. Astron & Astrophys.
32, 115

Variation of properties
with morphological type

O abundance as a measure of
chemical enrichment





Morphological type

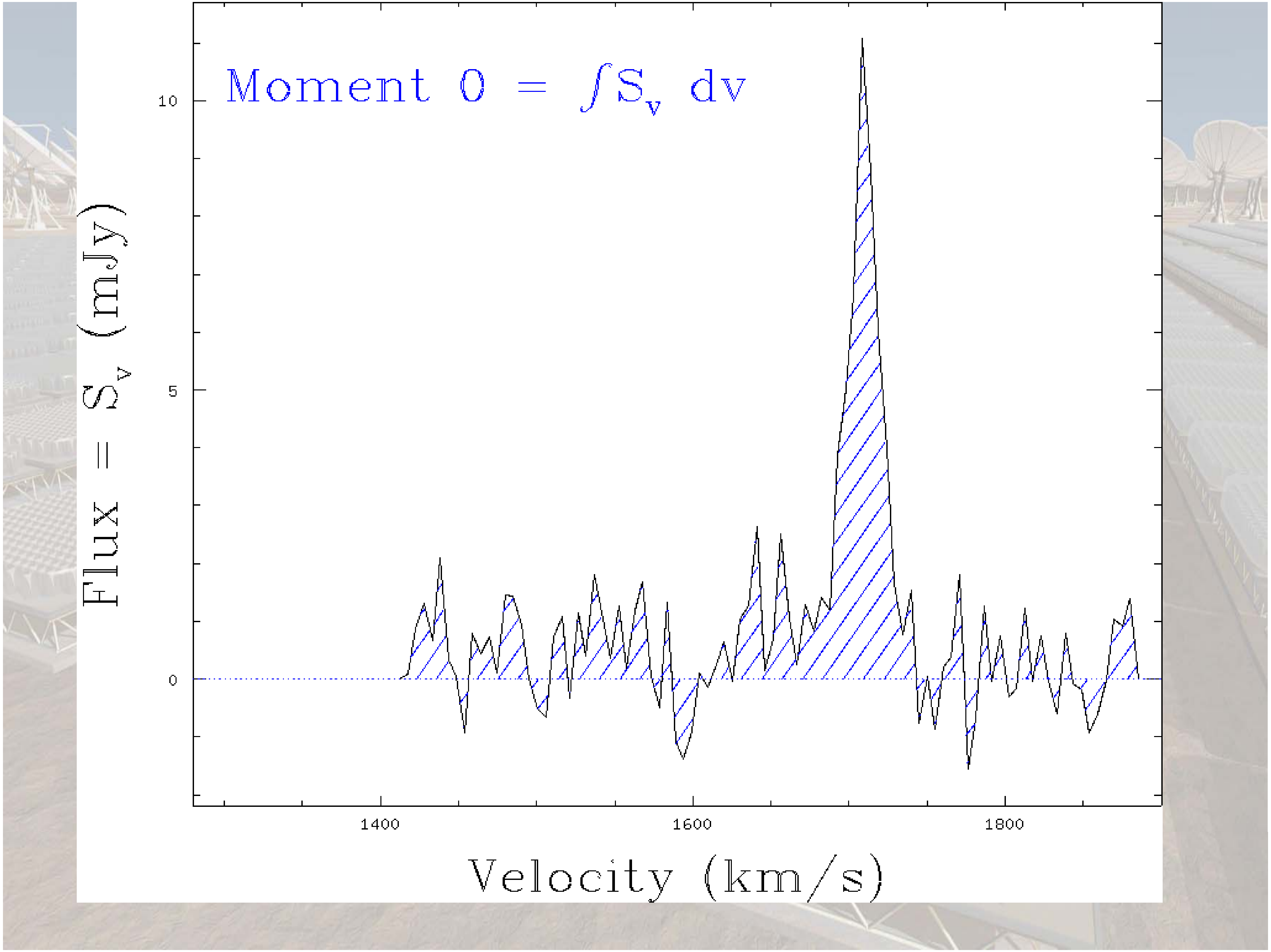
Absolute magnitude

Haynes & Roberts, 1992
Ann. Rev. Astron & Astrophys.
32, 115

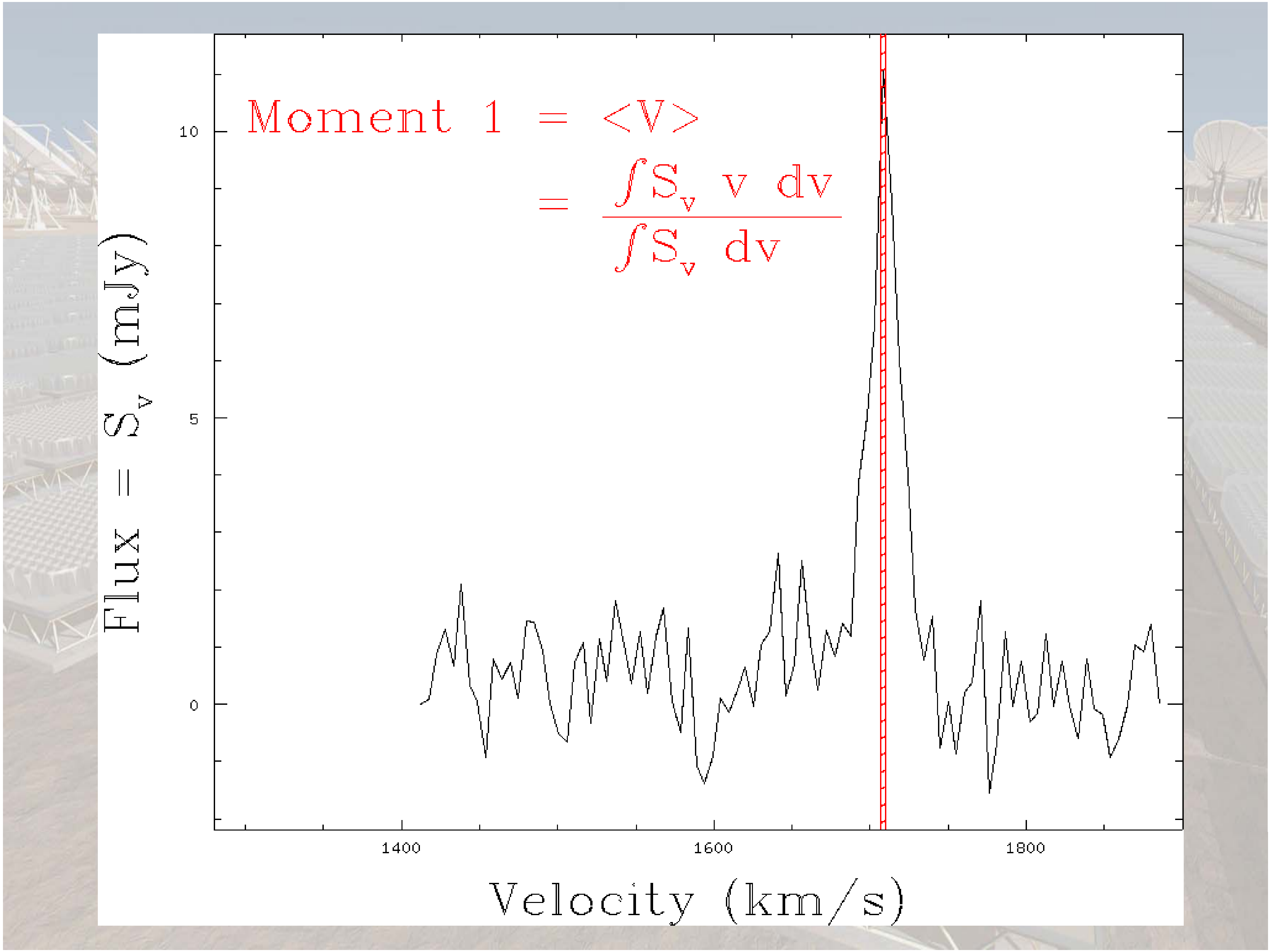
Fundamentel characteristics of galaxies

	Ellipticals	**Spirals**	**Irregulars**
Mass (M_o)	$10^5 \rightarrow 10^{13}$	10^9 - 4 x 10^{11}	$10^8 \rightarrow 3 \times 10^{10}$
Absolute Mag.	$-9 \rightarrow -23$	$-15 \rightarrow -21$	$-13 \rightarrow -18$
Luminosity (L_o)	$3 \times 10^5 \rightarrow 10^{11}$	$10^8 \rightarrow 2 \times 10^{10}$	$10^7 \rightarrow 10^9$
M/L (M_o/L_o=1)	100	$2 \rightarrow 20$	1
Diameter (kpc)	$1 \rightarrow 200$	$5 \rightarrow 50$	$1 \rightarrow 10$
Stellar population	II en old I	arms I; II and old I	mostly I, some II
Dust	very little	yes	yes

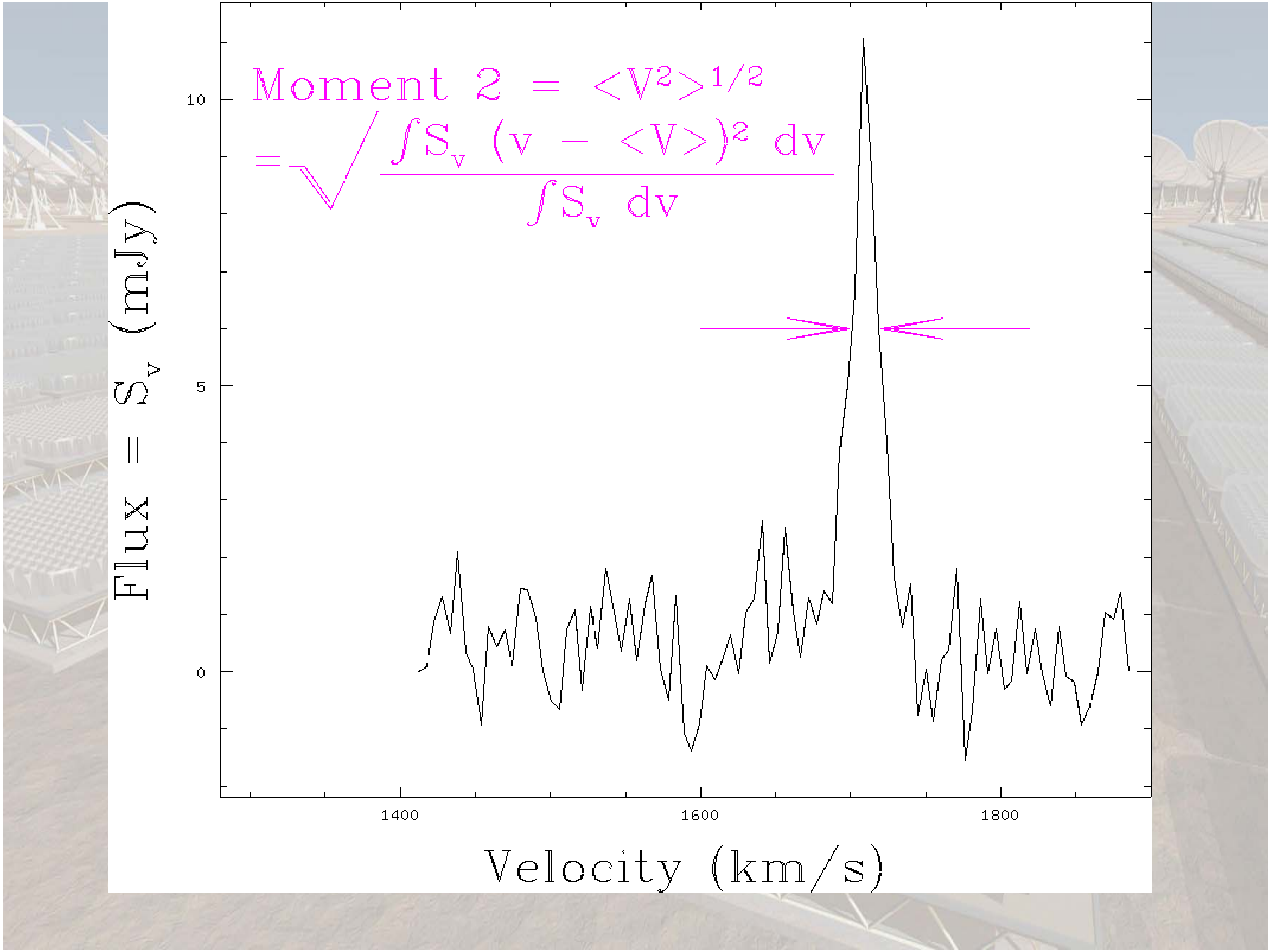
	E	**Sa**	**Sb**	**Sc,Sd**	**I**
Color index (B-V)	+1.0	+0.9	$+0.4 \rightarrow +0.8$	$+0.4 \rightarrow +0.6$	$+0.3 \rightarrow +0.4$
M_{HI}/M_T (%)	~ 0	2 +/- 2	5 +/- 2	10 +/- 2	22 +/- 4
Spectral type	K	K	$F \rightarrow K$	$A \rightarrow F$	$A \rightarrow F$



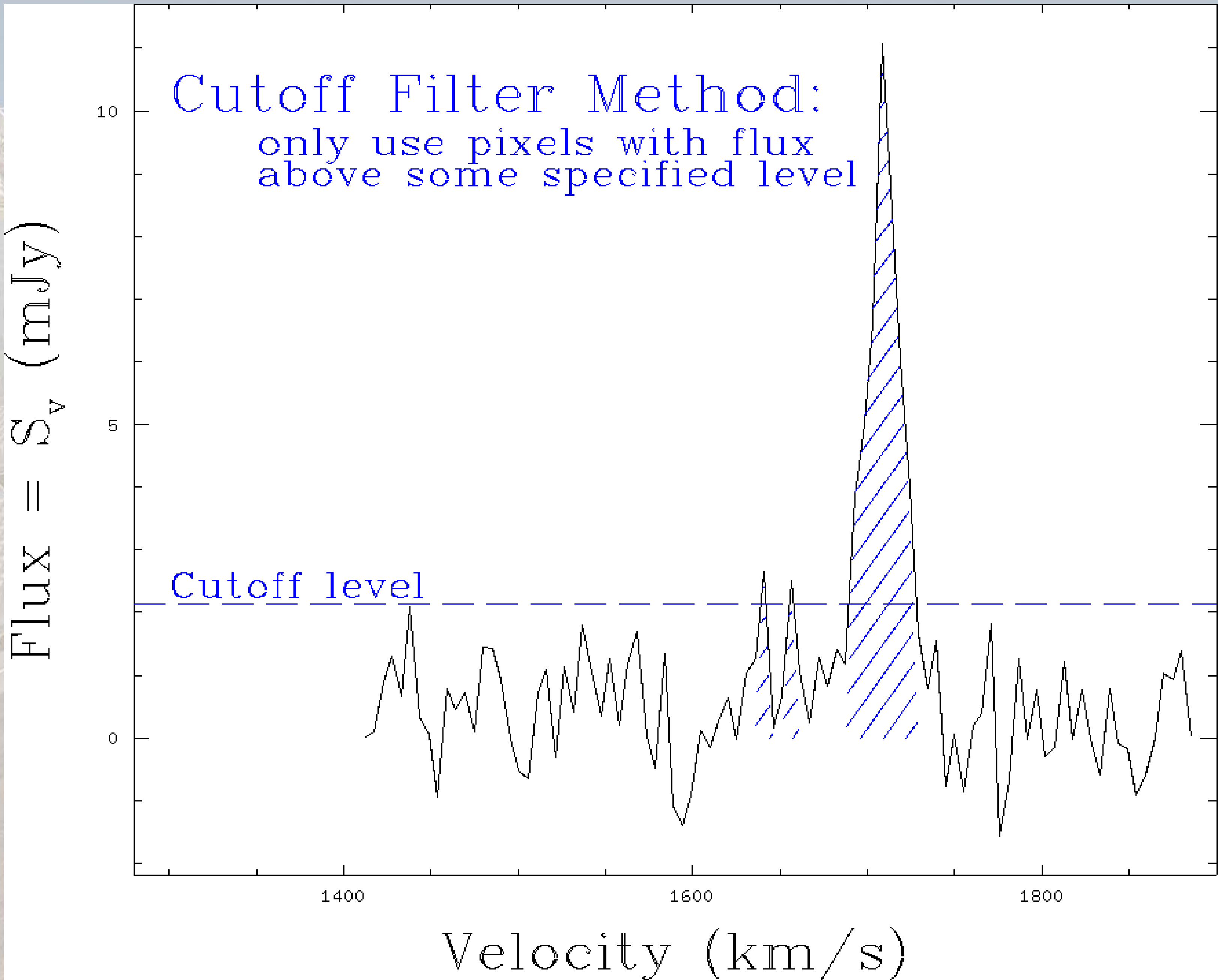
Moment 0 = ∫S_v dv
Flux = S_v (mJy)
Velocity (km/s)
10
5
0
1400
1600
1800

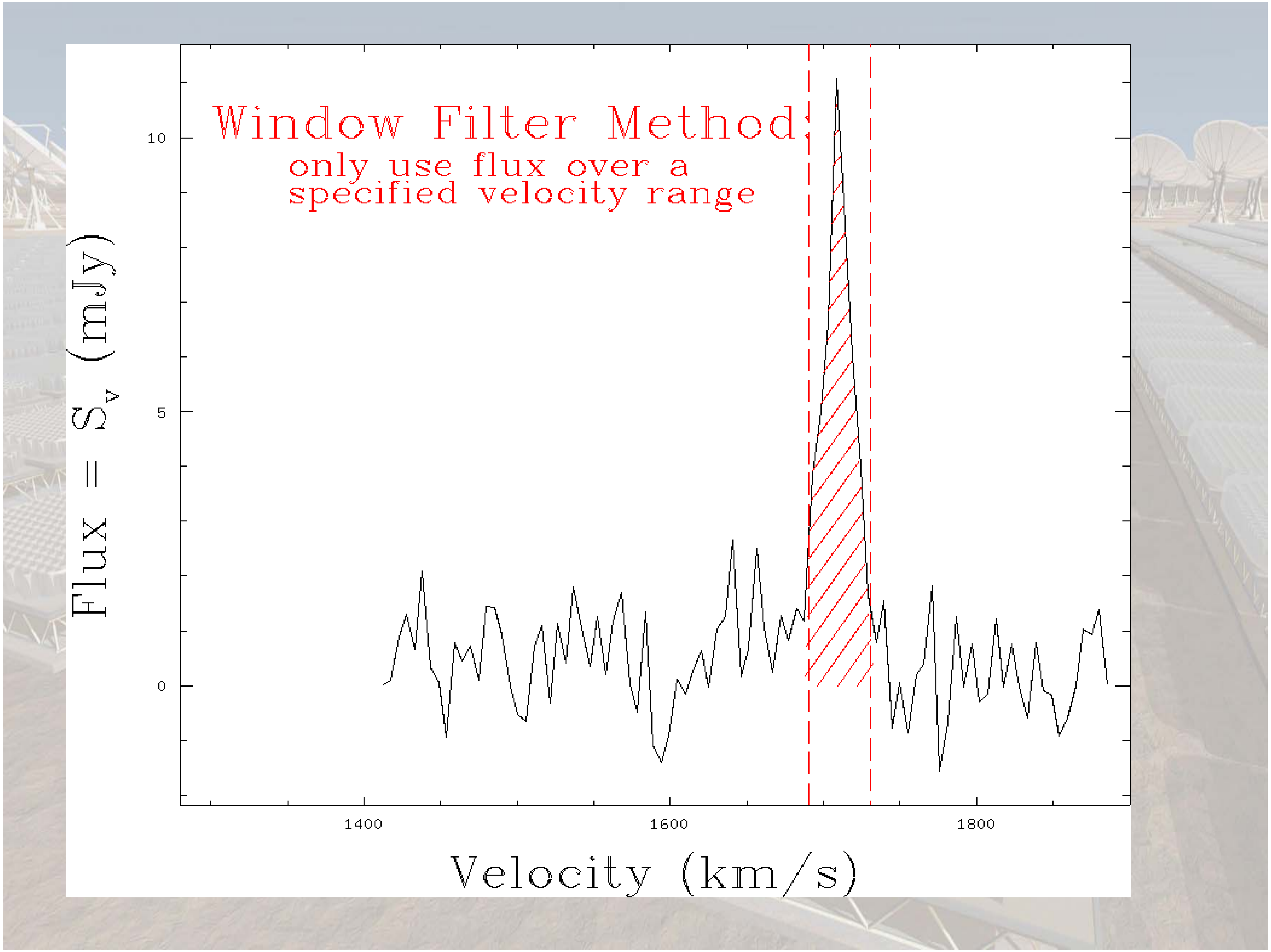


Moment 1 = <V>
$= \frac{\int S_v \, v \, dv}{\int S_v \, dv}$
Flux = S_v (mJy)
Velocity (km/s)
0
5
10
1400
1600
1800

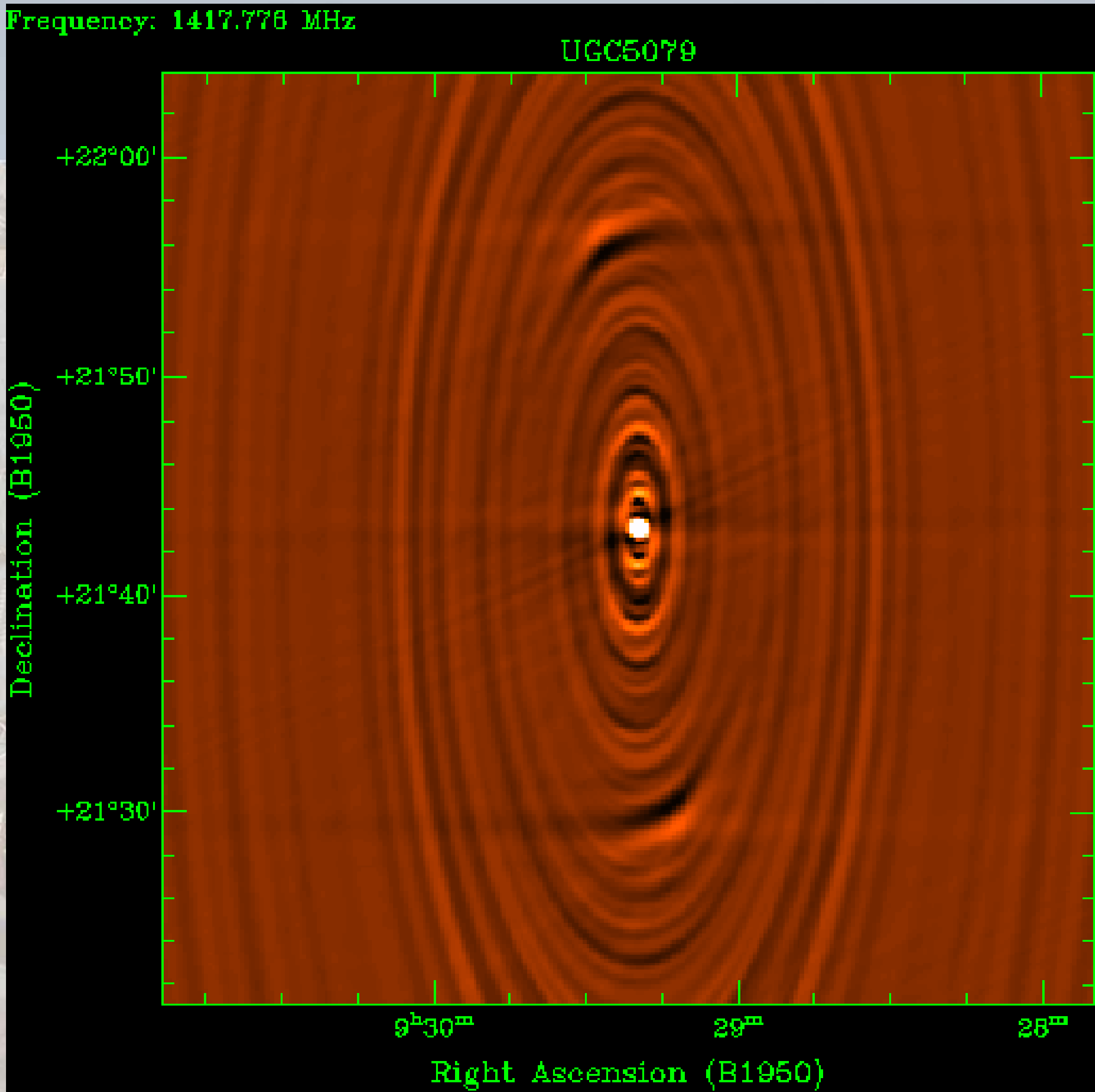


Moment 2 = <V²>^1/2
= √(∫S_v (v − <V>)² dv / ∫S_v dv)
Flux = S_v (mJy)
10
5
0
1400
1600
1800
Velocity (km/s)


Cutoff Filter Method:
only use pixels with flux
above some specified level
Cutoff level
Flux = S_ν (mJy)
10
5
0
1400
1600
1800
Velocity (km/s)

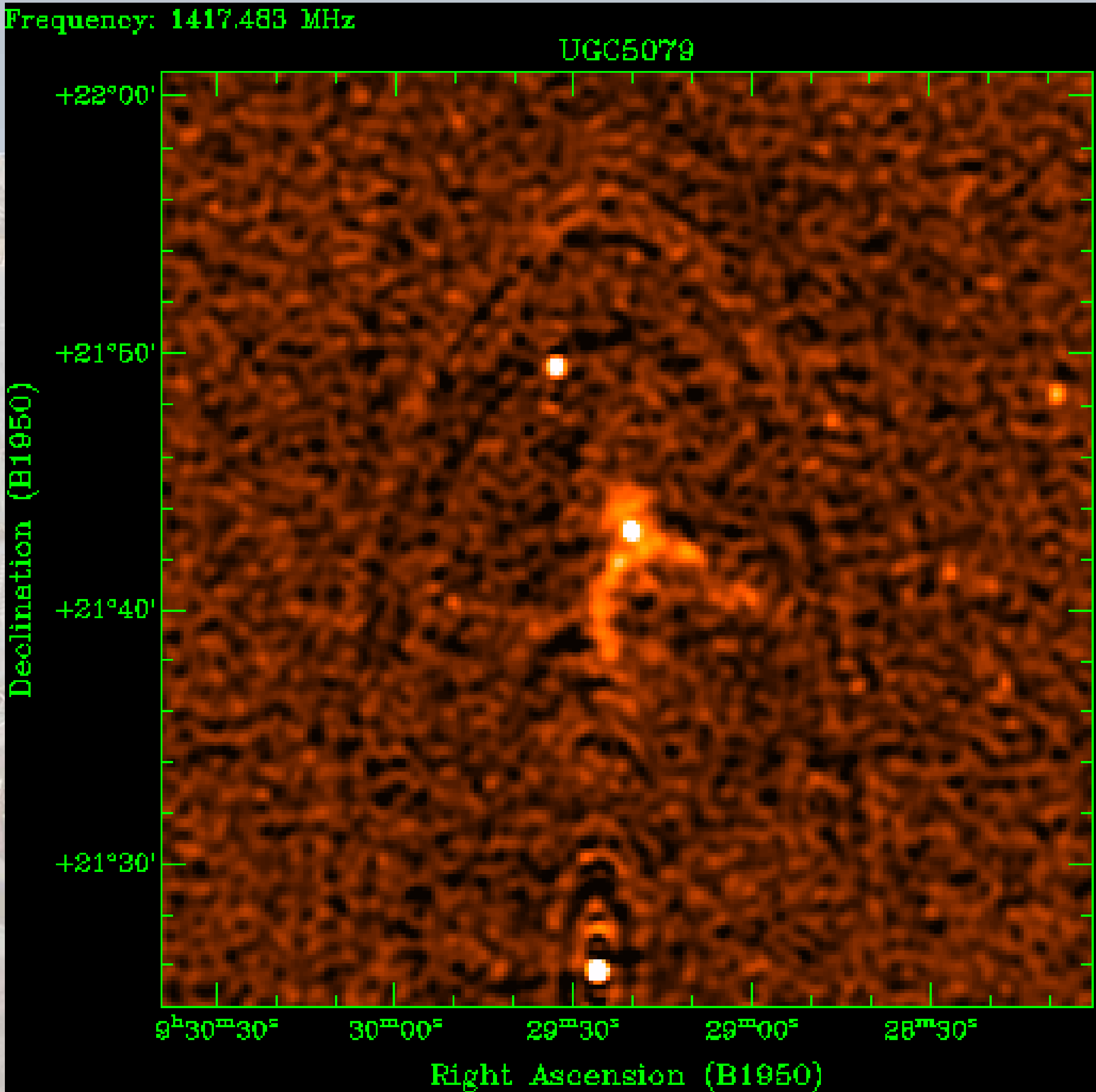

Window Filter Method:
only use flux over a
specified velocity range
Flux = S_ν (mJy)
Velocity (km/s)
10
5
0
1400
1600
1800

dirty beam

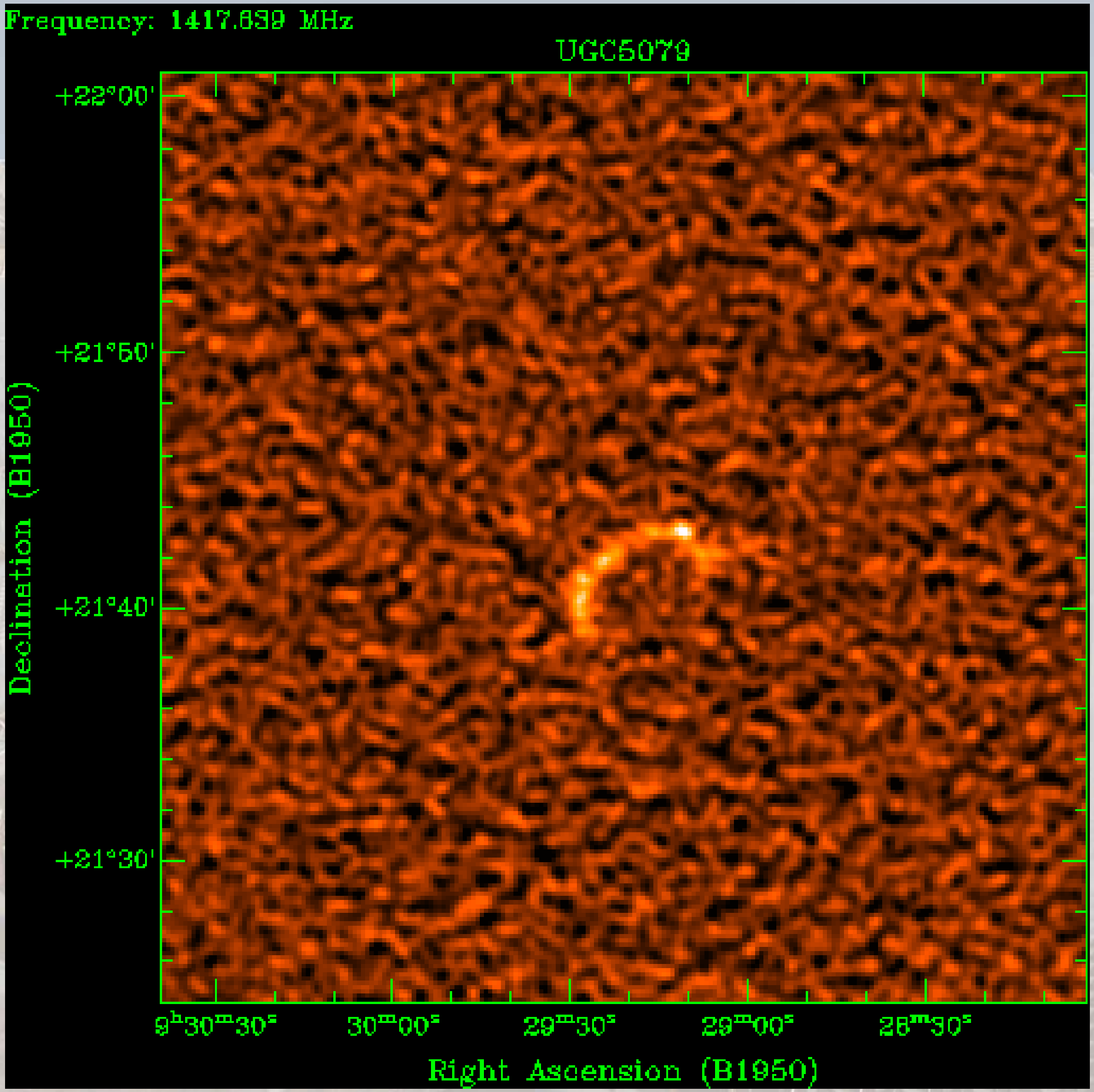


Frequency: 1417.778 MHz
UGC5079
+22°00'
+21°50'
+21°40'
+21°30'
Declination (B1950)
9h30m
29m
28m
Right Ascension (B1950)

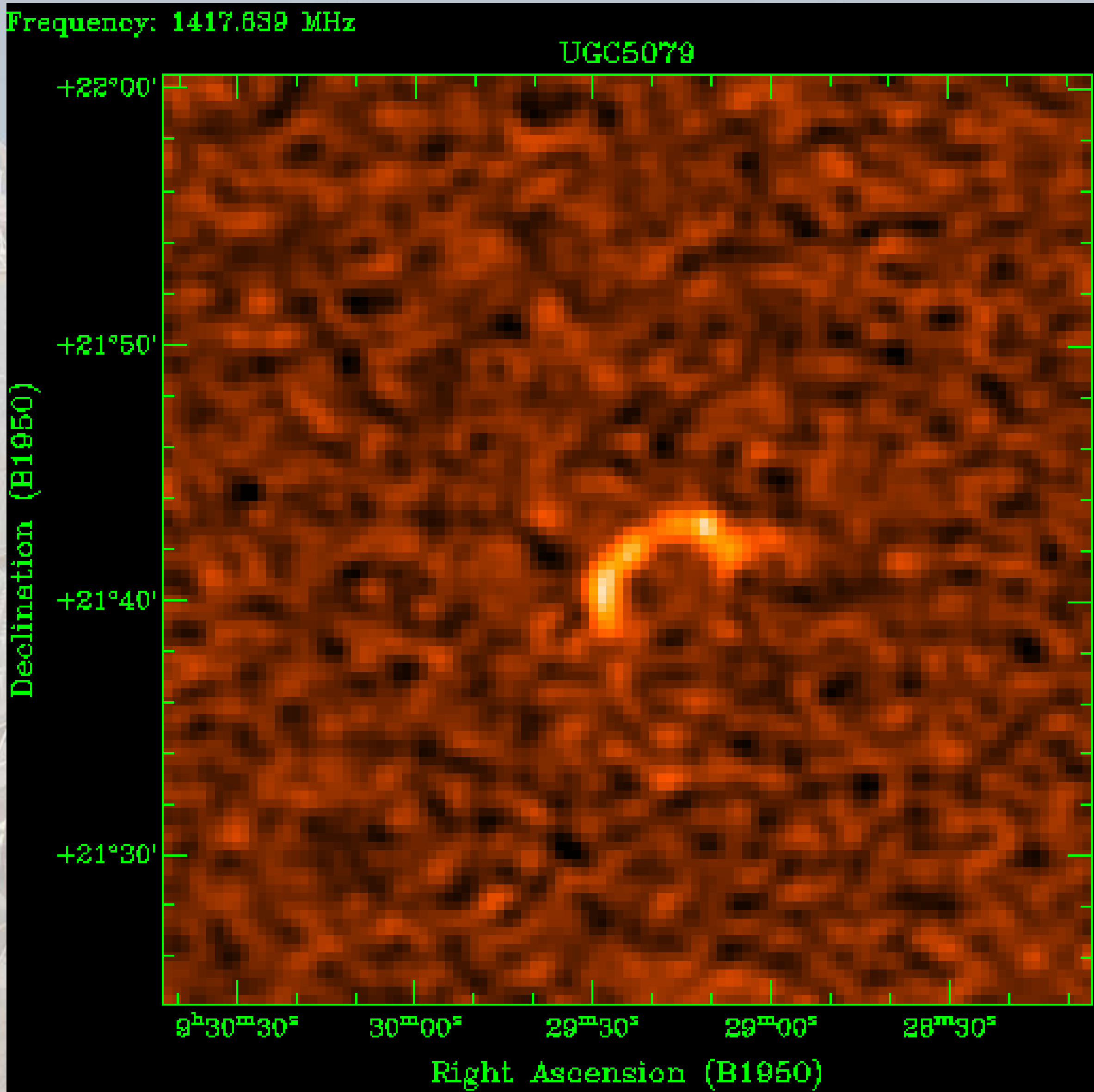
dirty map


Frequency: 1417.483 MHz
UGC5079
+22°00'
+21°50'
+21°40'
+21°30'
Declination (B1950)
9h30m30s
30m00s
29m30s
29m00s
28m30s
Right Ascension (B1950)

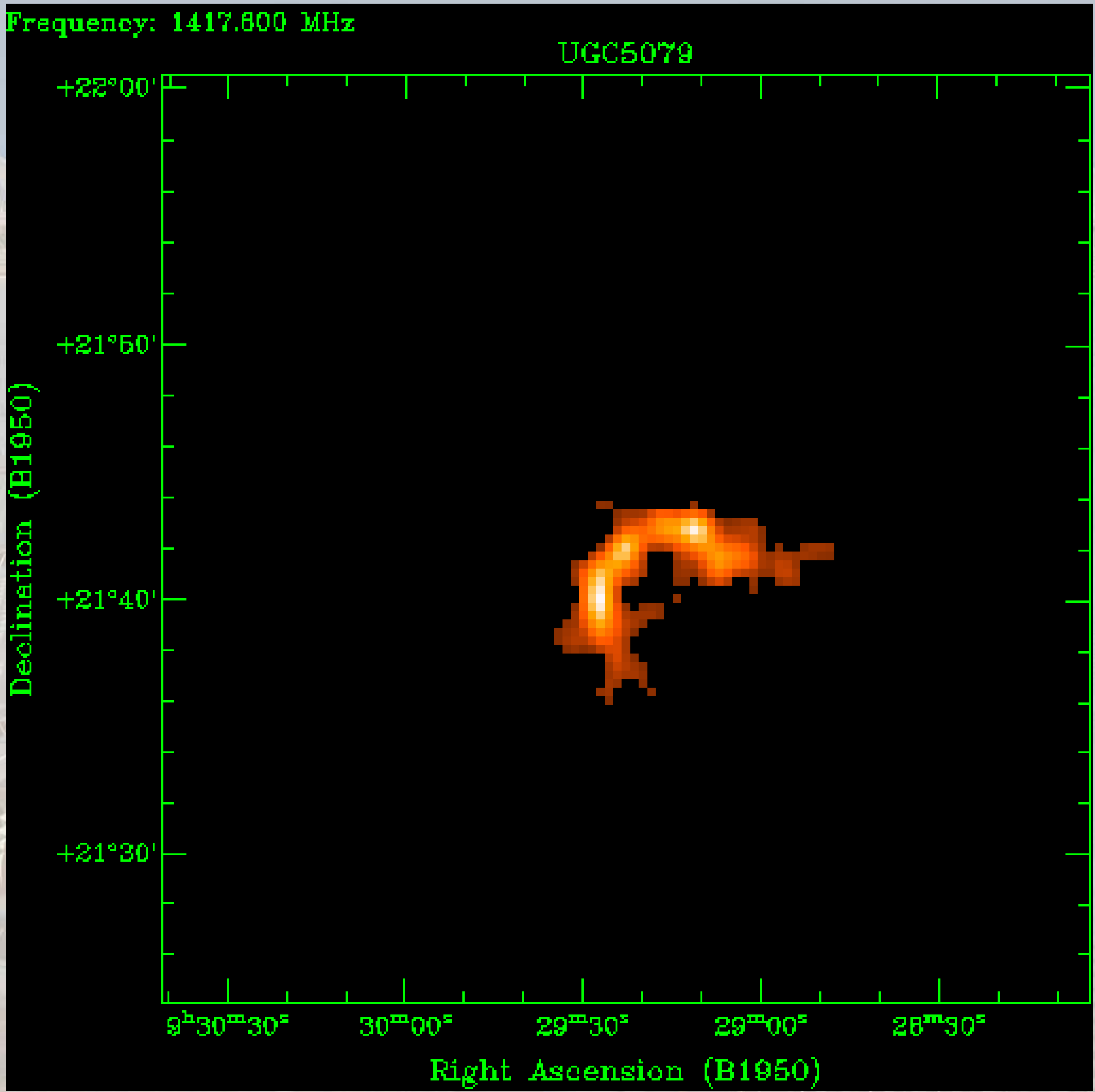
cleaned line map



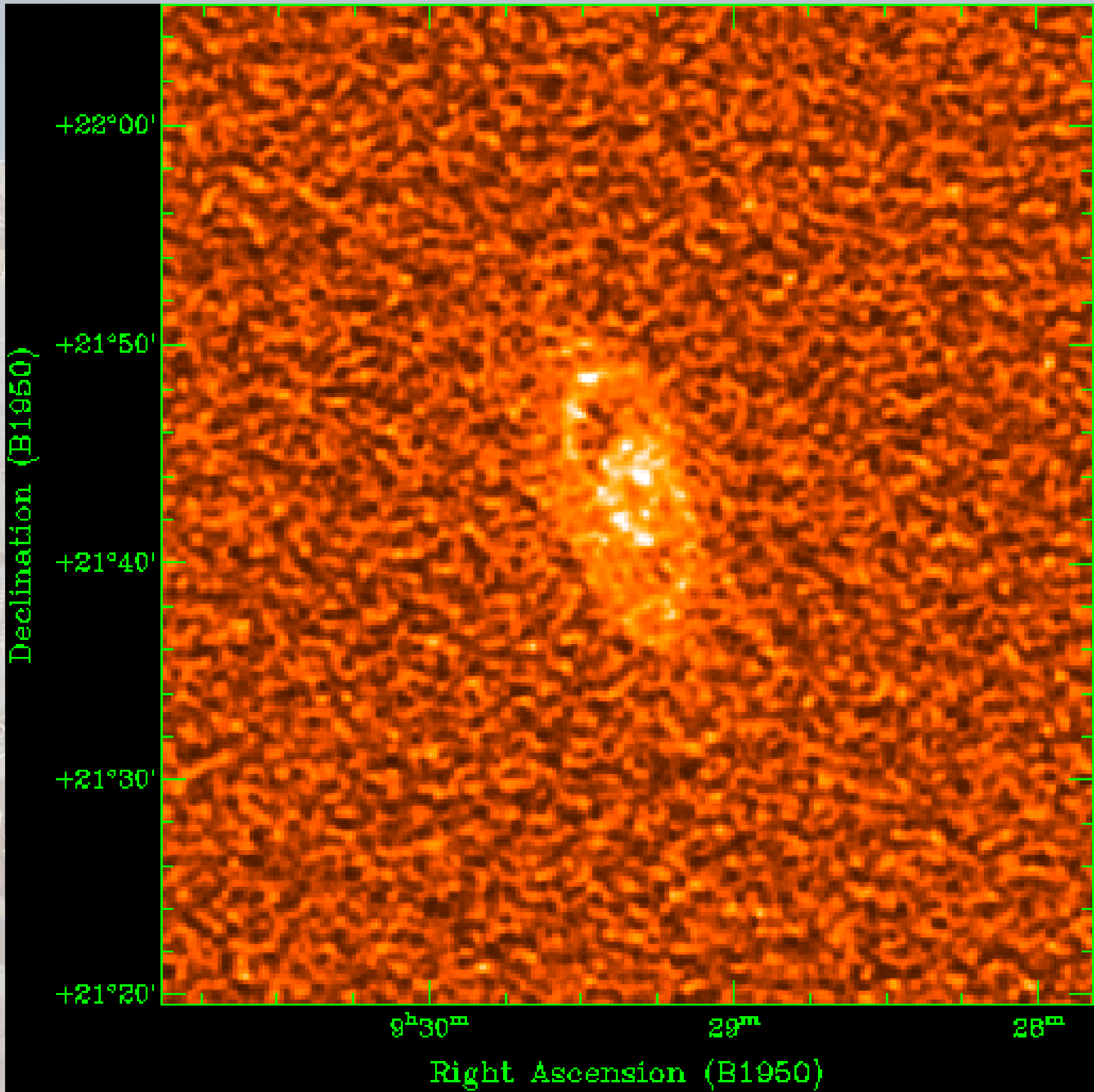
smoothed line map



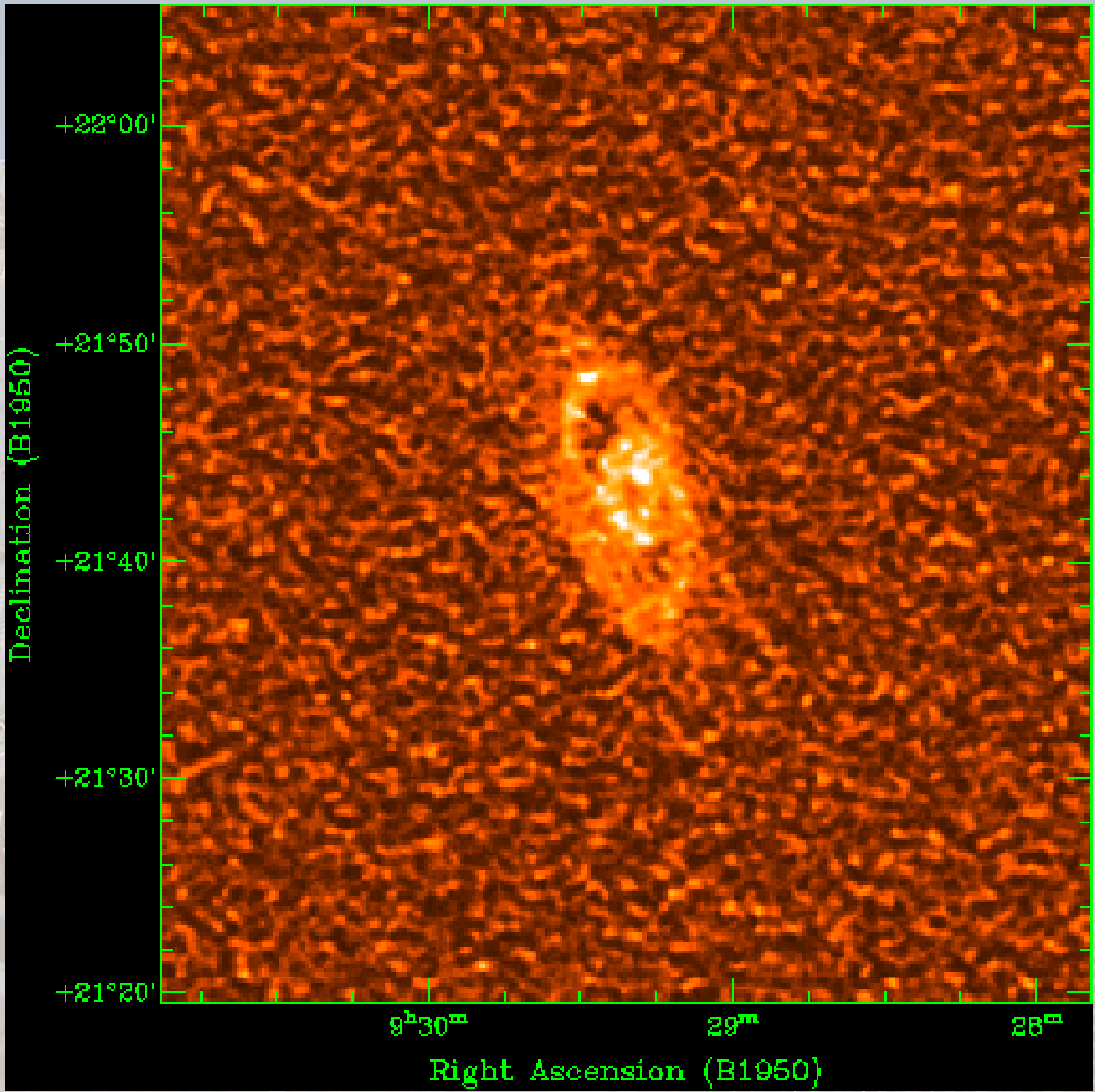
mask from smoothed map



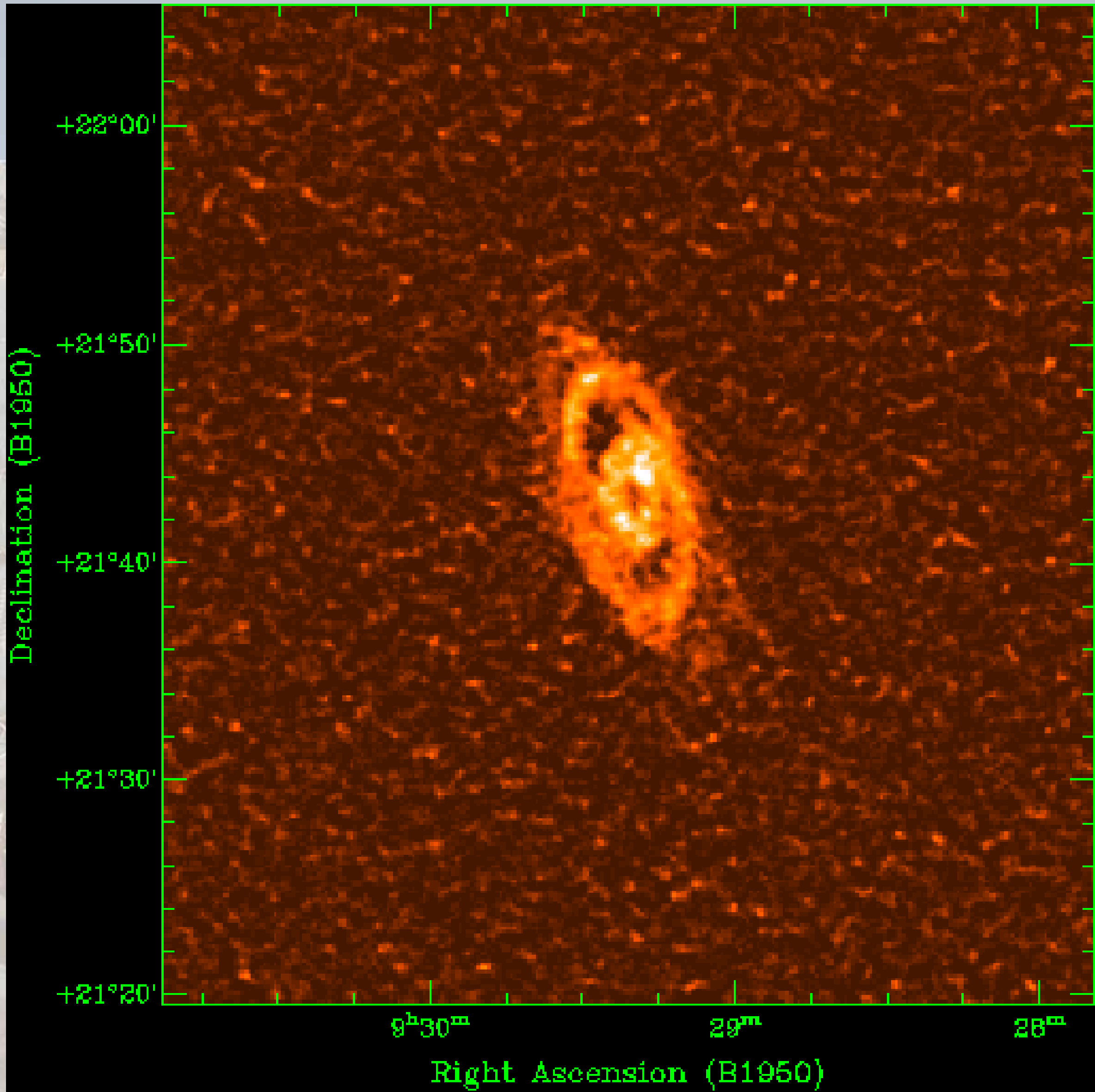
cut-off
1σ



cut-off
2σ

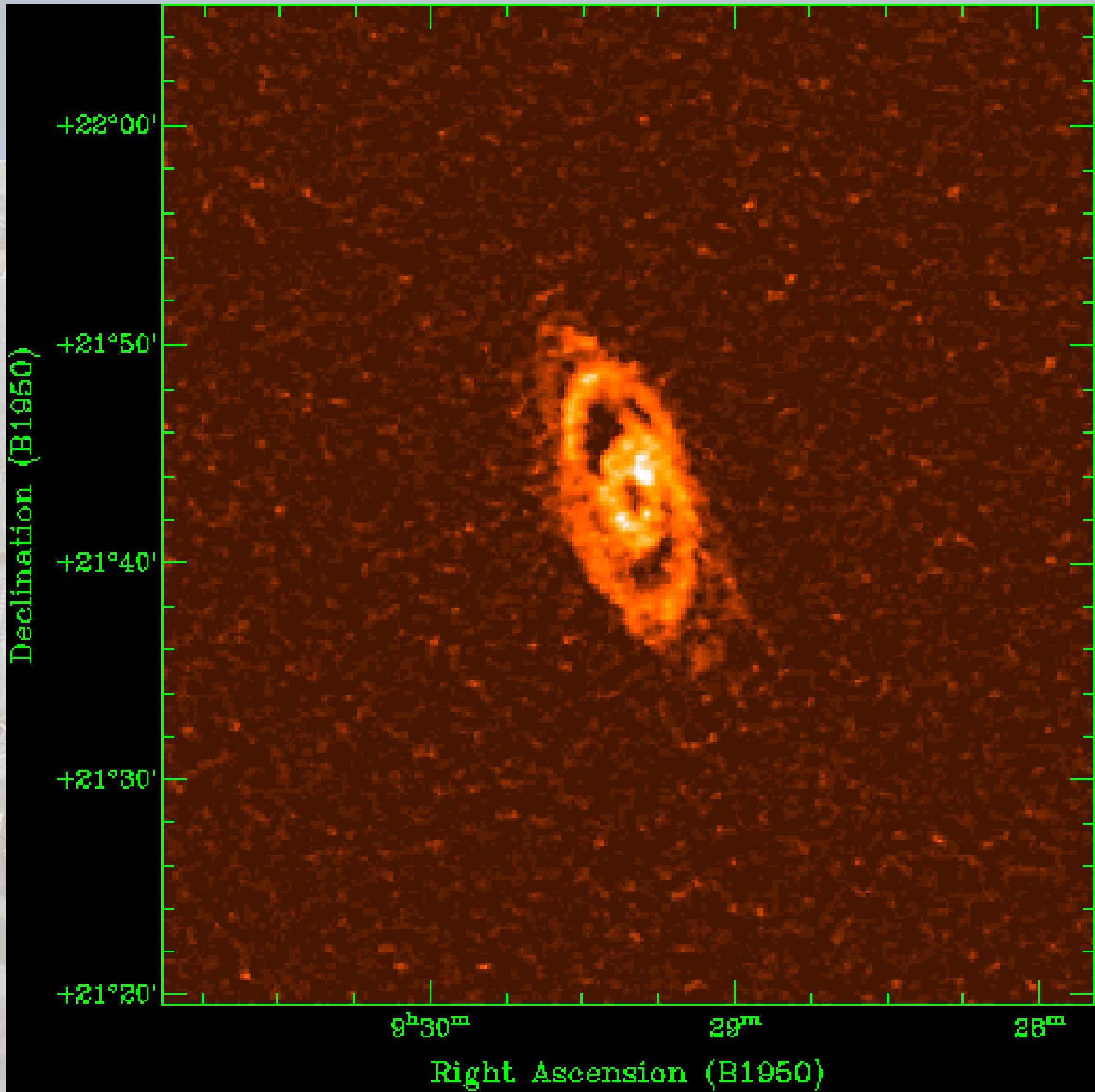


cut-off
3σ

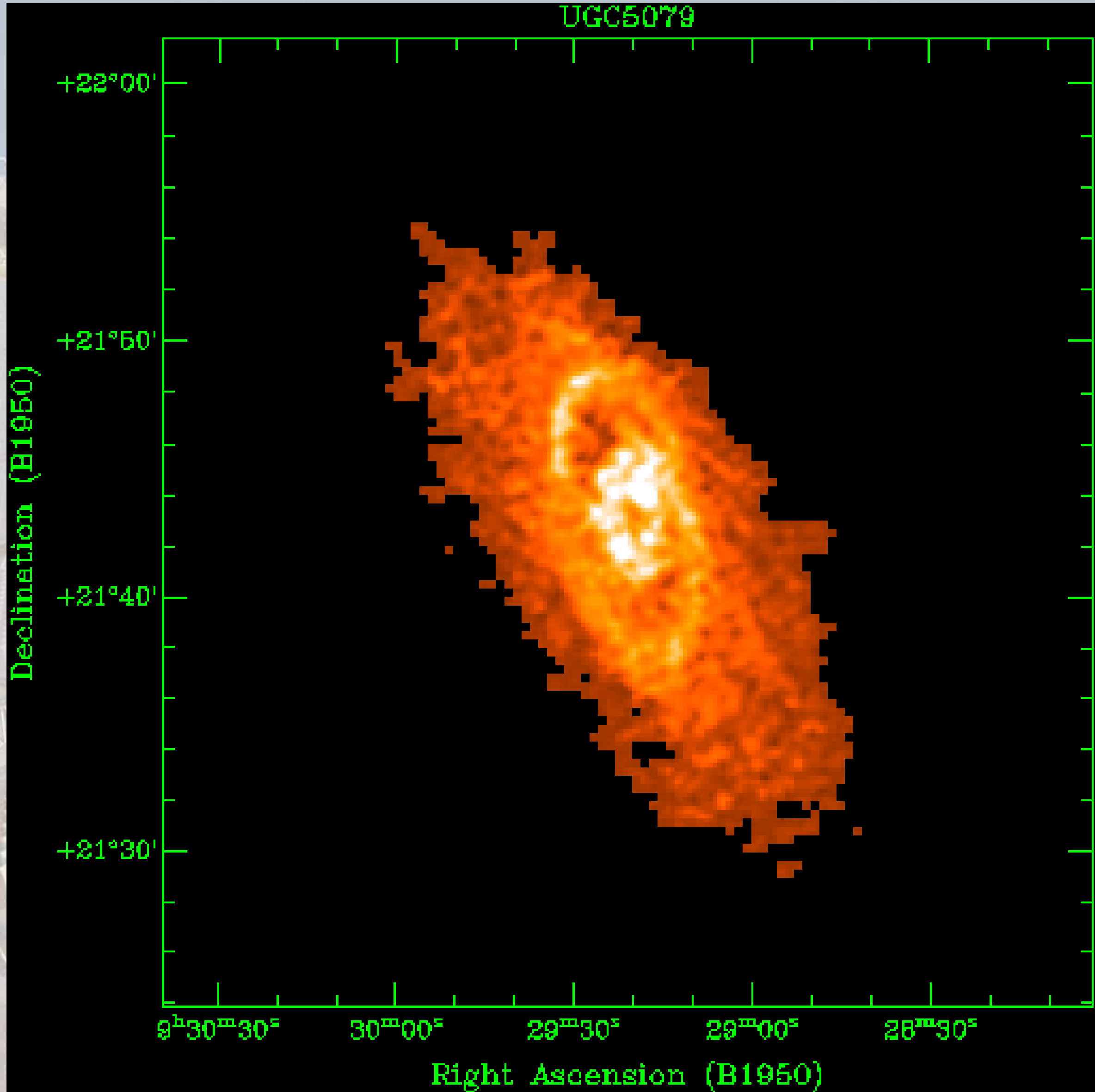

+22°00'
+21°50'
+21°40'
+21°30'
+21°20'
Declination (B1950)
9h30m
29m
28m
Right Ascension (B1950)

cut-off

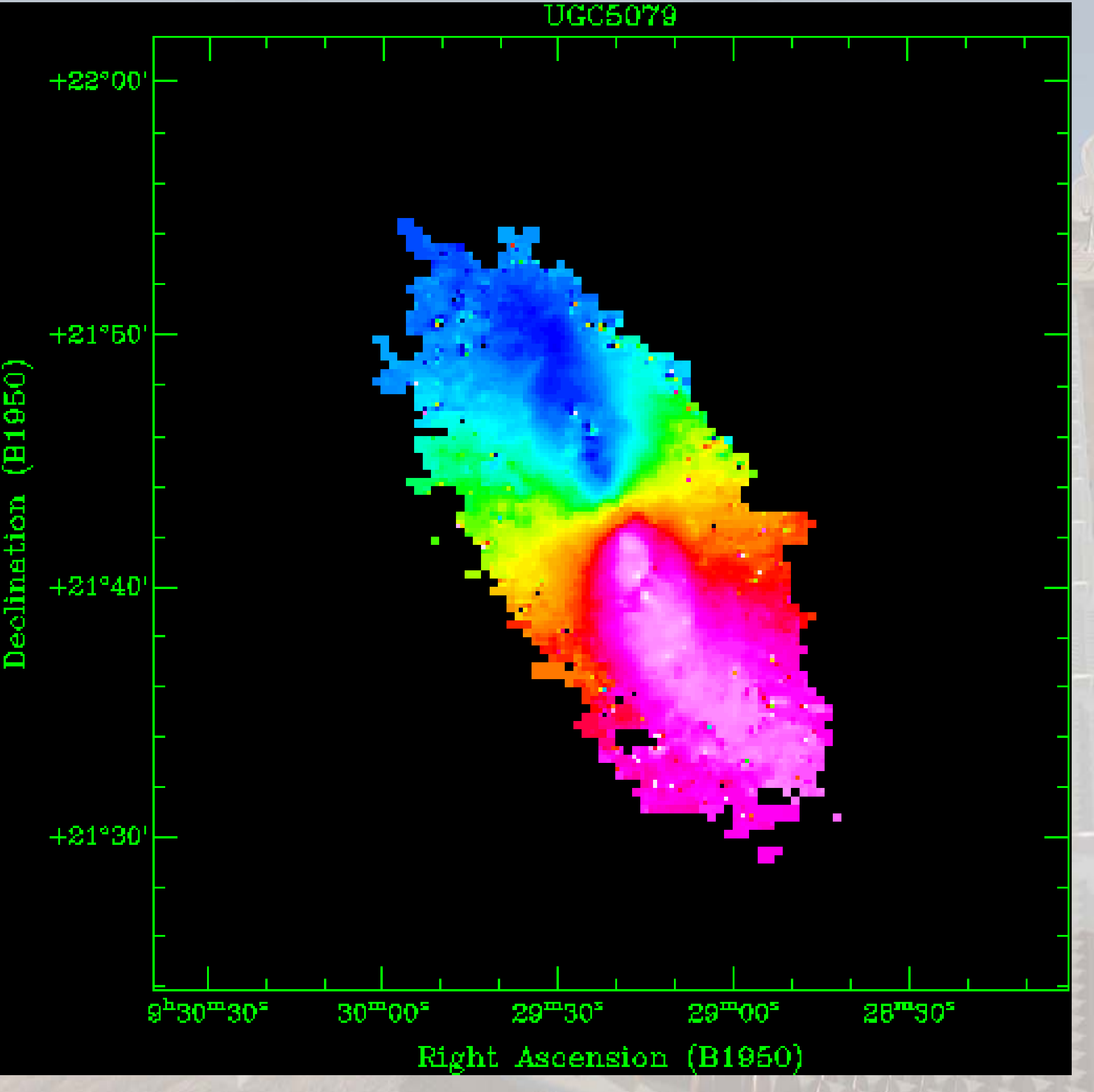
4σ


+22°00'
+21°50'
+21°40'
+21°30'
+21°20'
Declination (B1950)
9h30m
29m
28m
Right Ascension (B1950)

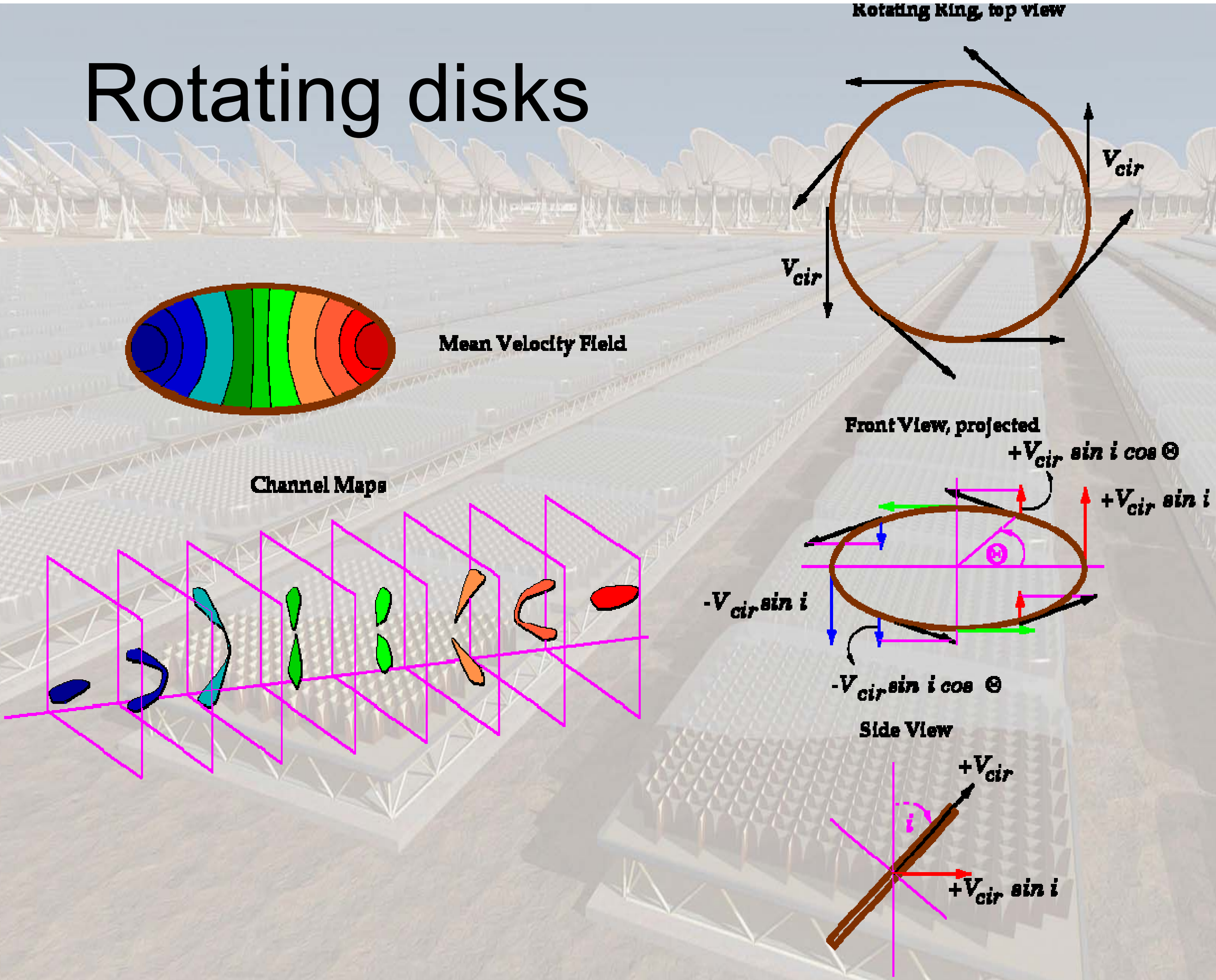
0th moment + masking



1st moment + masking

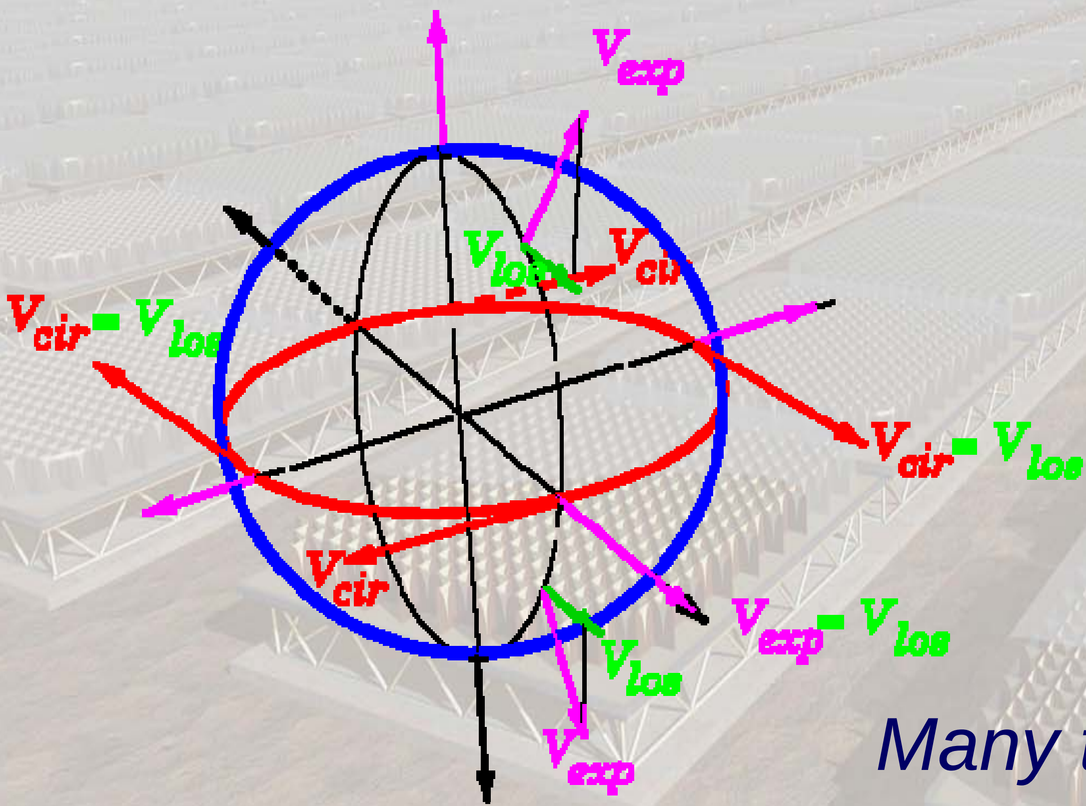


Rotating disks



Modelling Your Data:

$$v_{los} = v_{sys} + v_{circ}(R)\sin i\ \cos\vartheta + v_{exp}(R)\sin i\ \sin\vartheta$$



- Rotation Curves
- Disk Structure
- Expanding Shells
- Bipolar Outflows
- N-body Simulations
- etc, etc.

Many tools available in Gipsy, some in Aips, Miriad

But the moment analysis is restrictive.

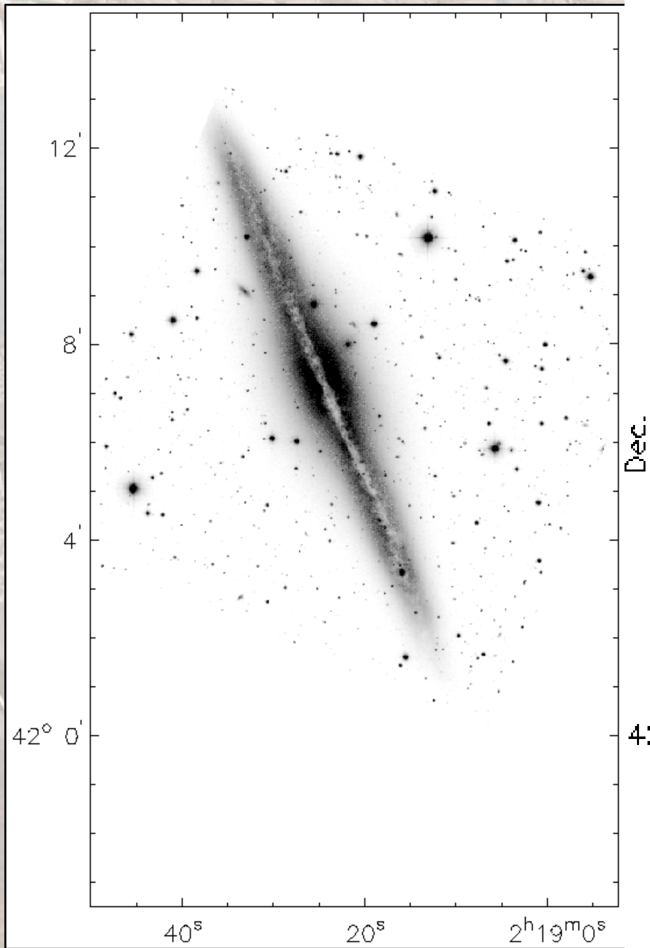
- It does not describe complex profiles
  (asymmetries, double profiles)
- it does not always define mean velocities well
  (especially when S/N ratio is low,
  when beam-smearing is important,
  and in case of edge-on galaxies)

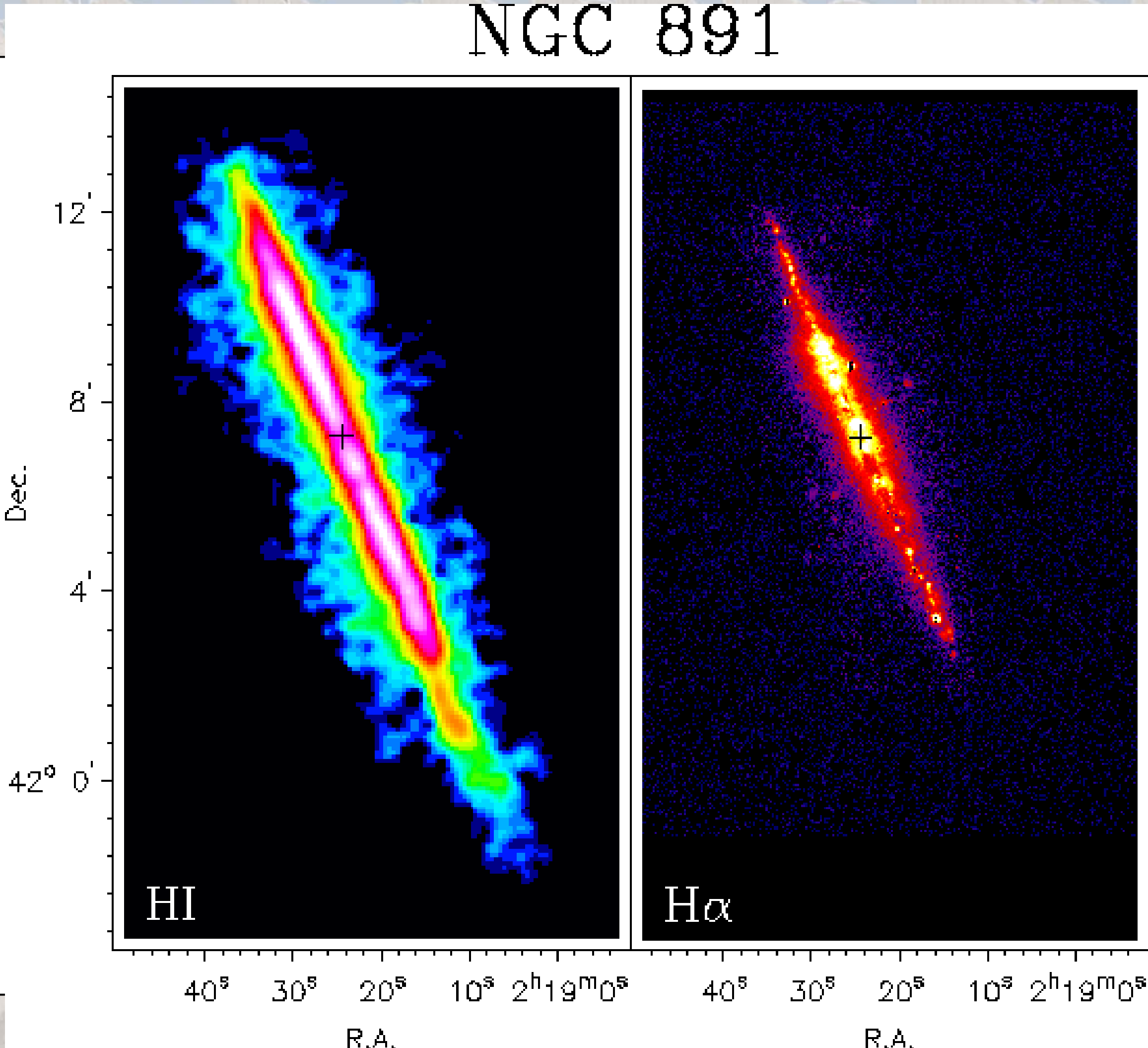
Alternatives:

- multiple Gauss fitting, fitting of Hermitian functions
- special visualisation and treatment of the 3D data

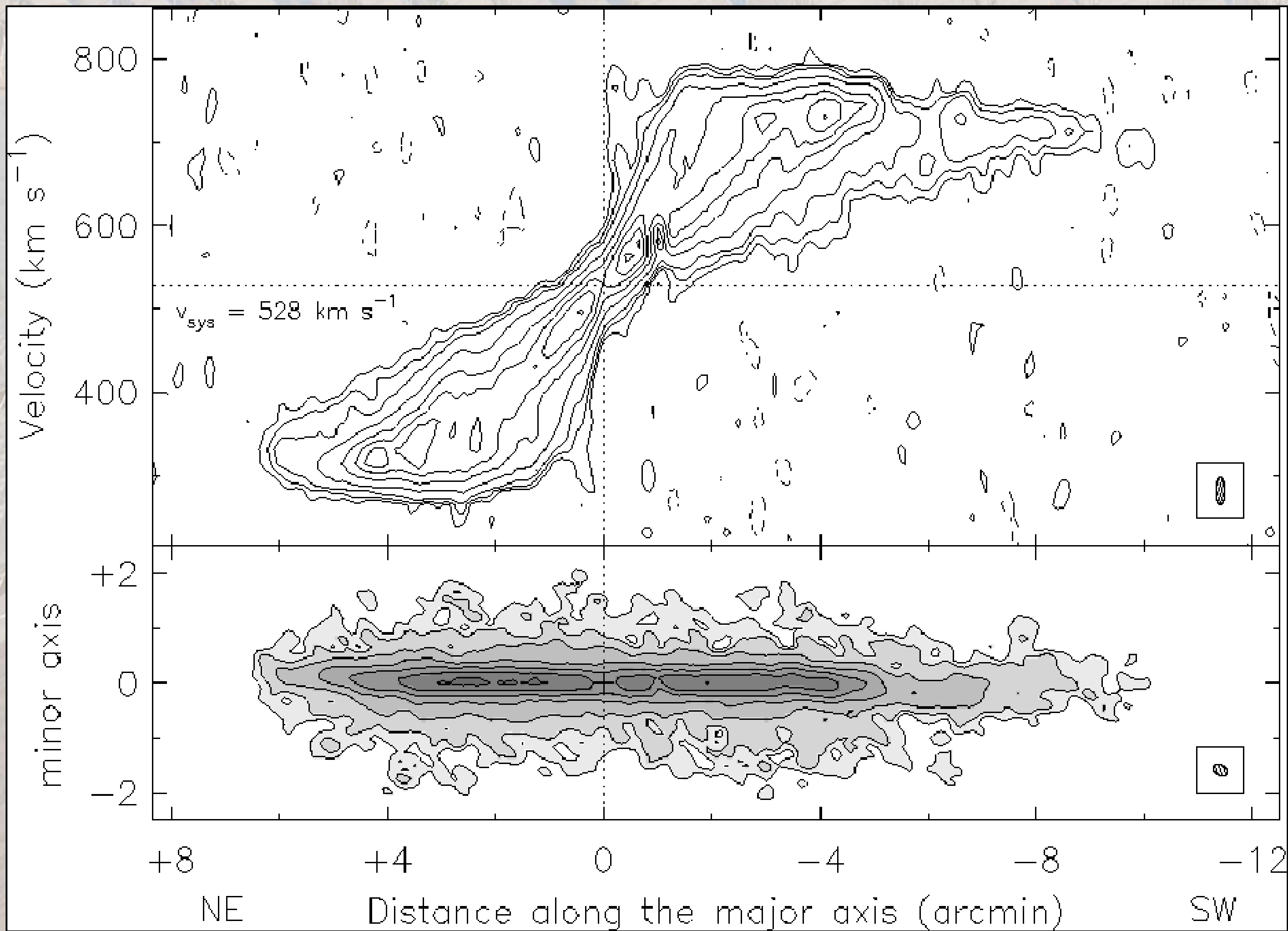
examples: derotation, position – velocity
diagrams along well chosen directions

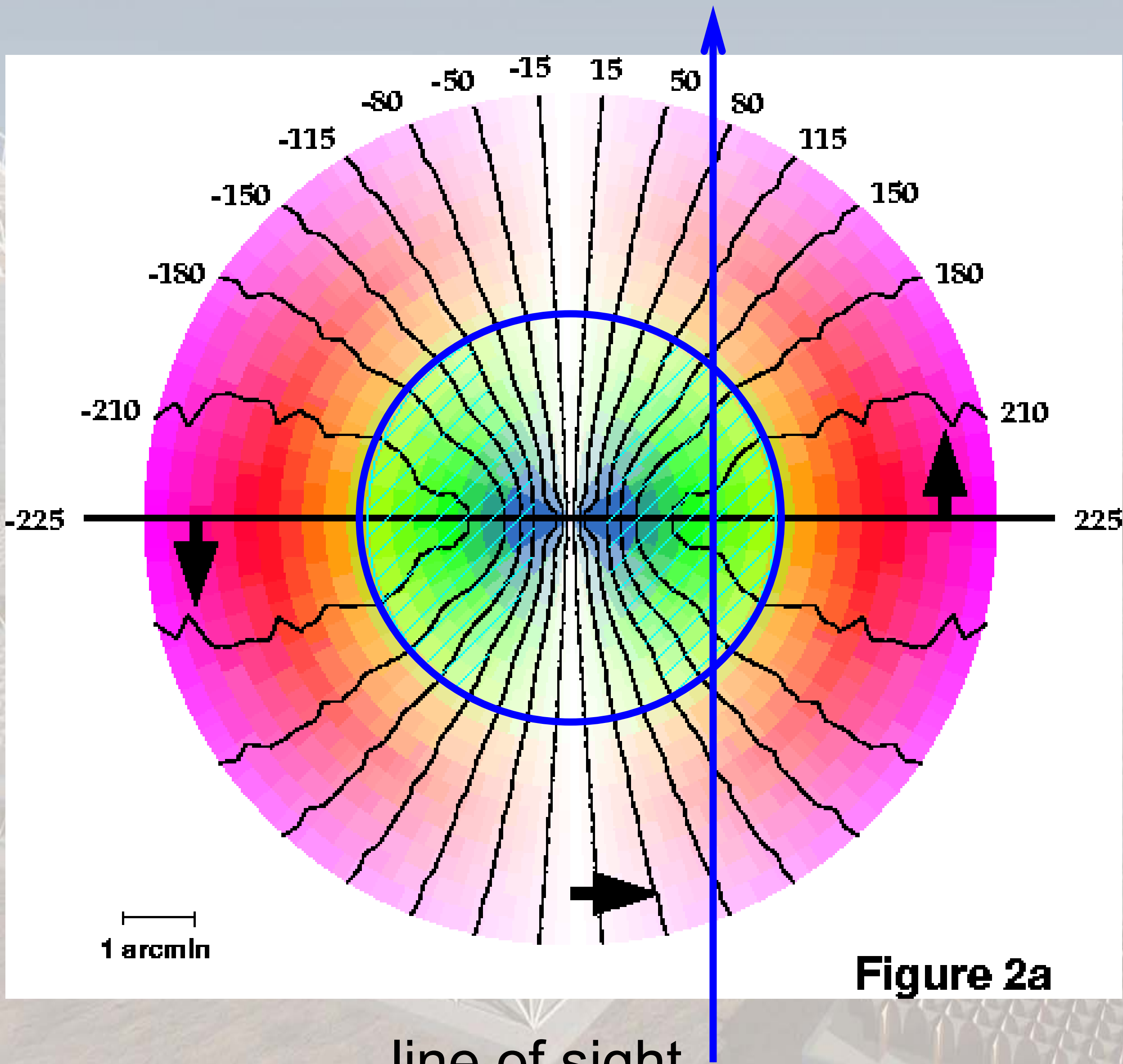
Use of position -velocity diagrams





position - velocity diagram

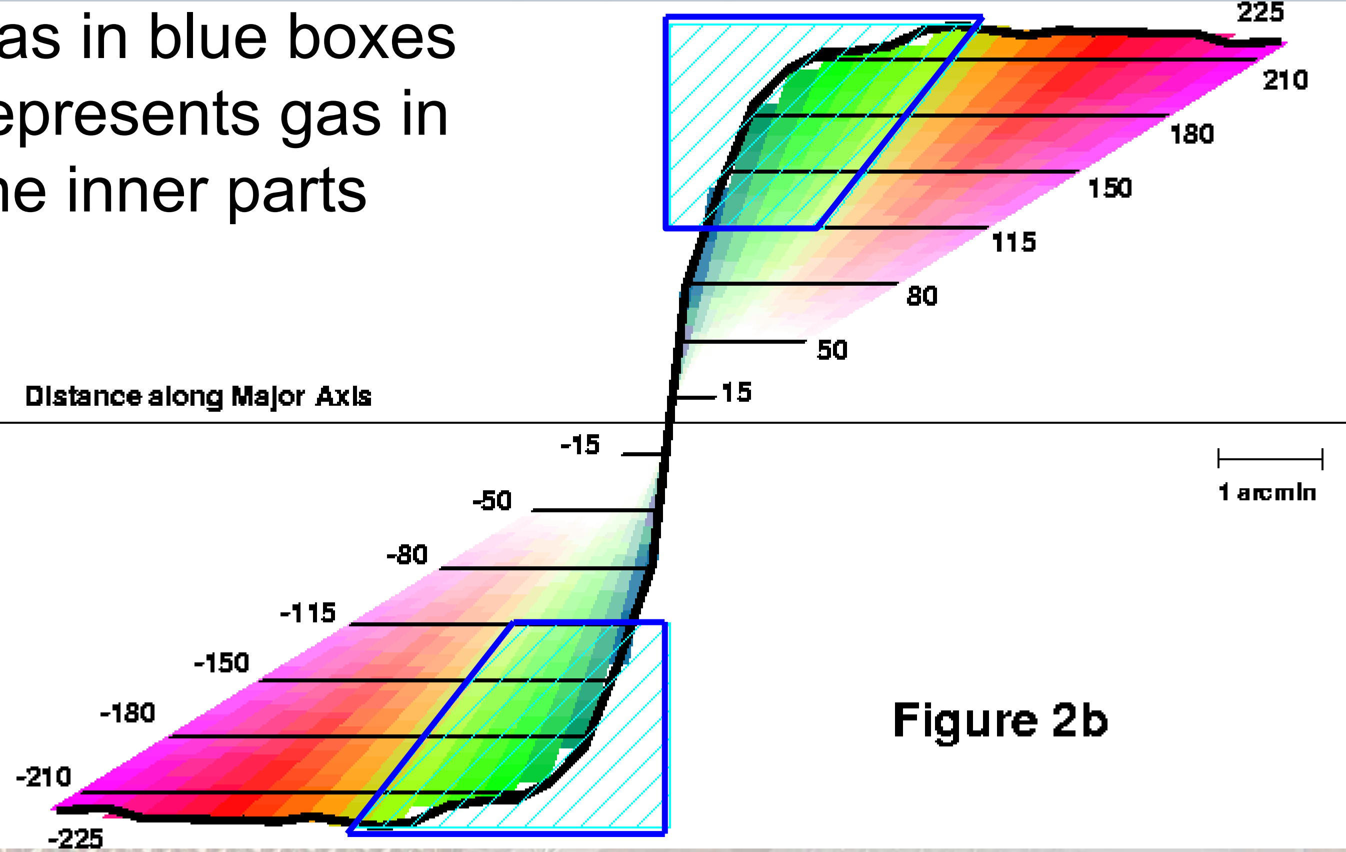


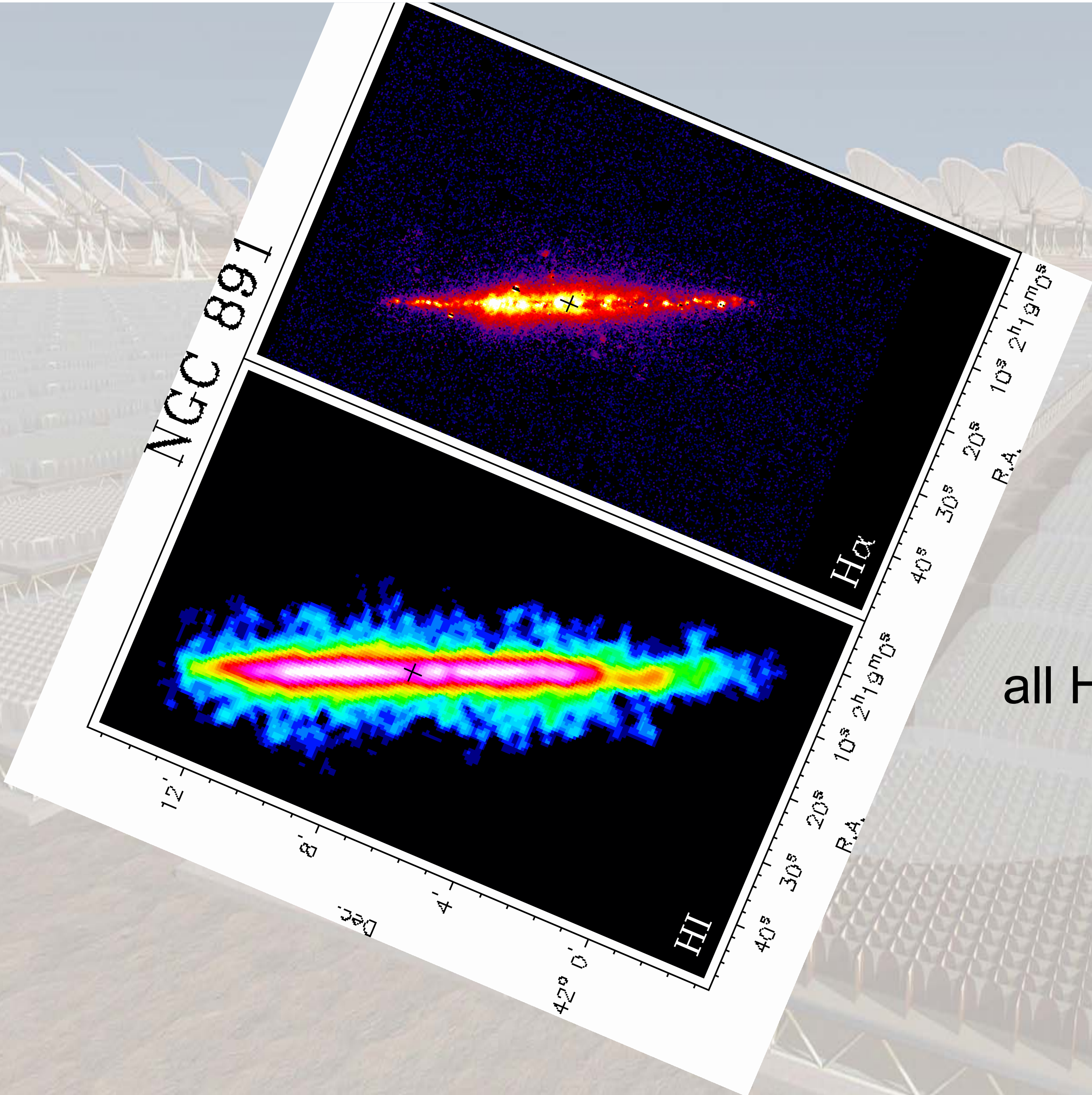


line of sight

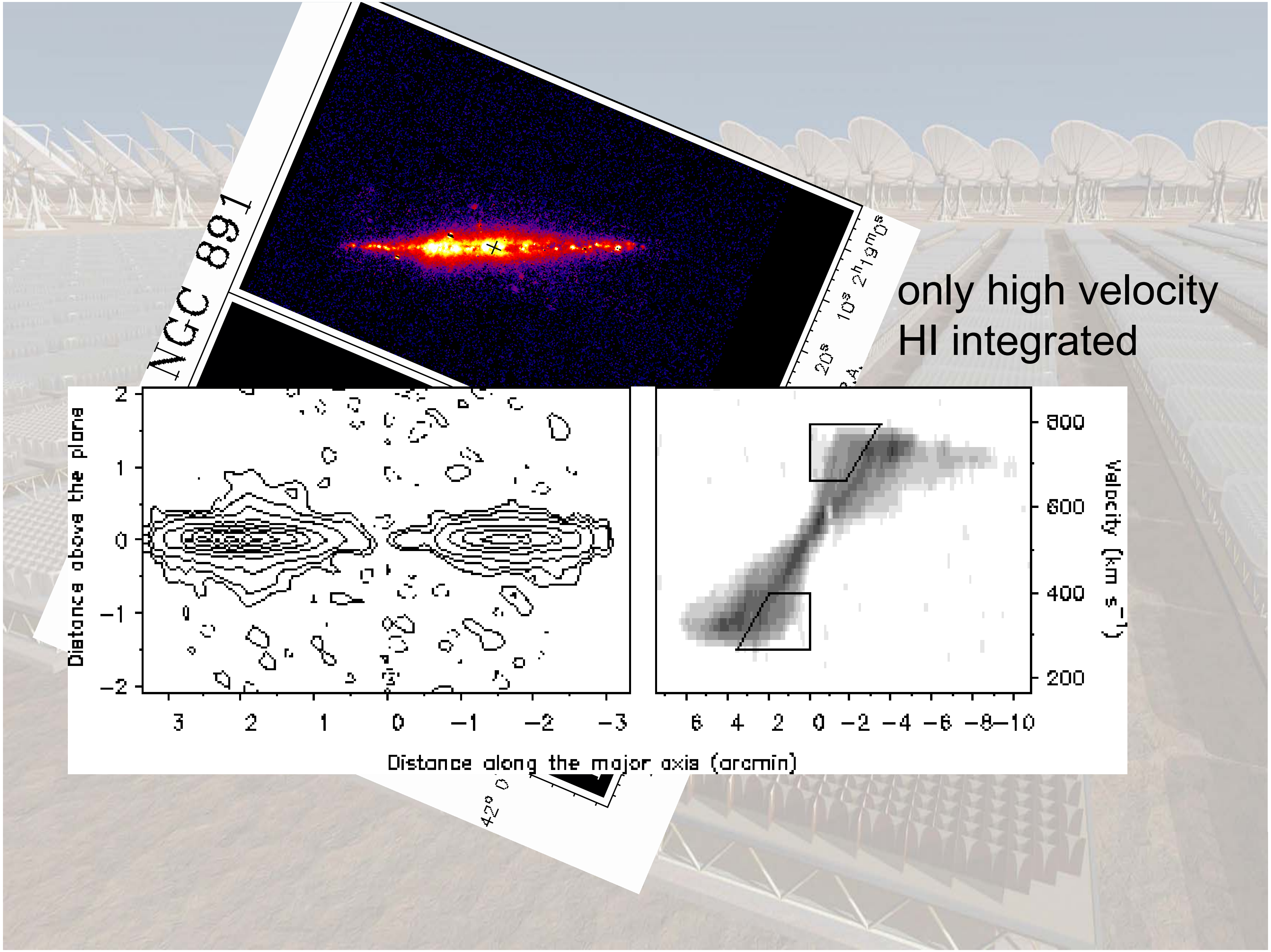
Velocity Field:

velocities in inner region are all higher than in the outer parts along a single line of sight gas in blue boxes represents gas in the inner parts



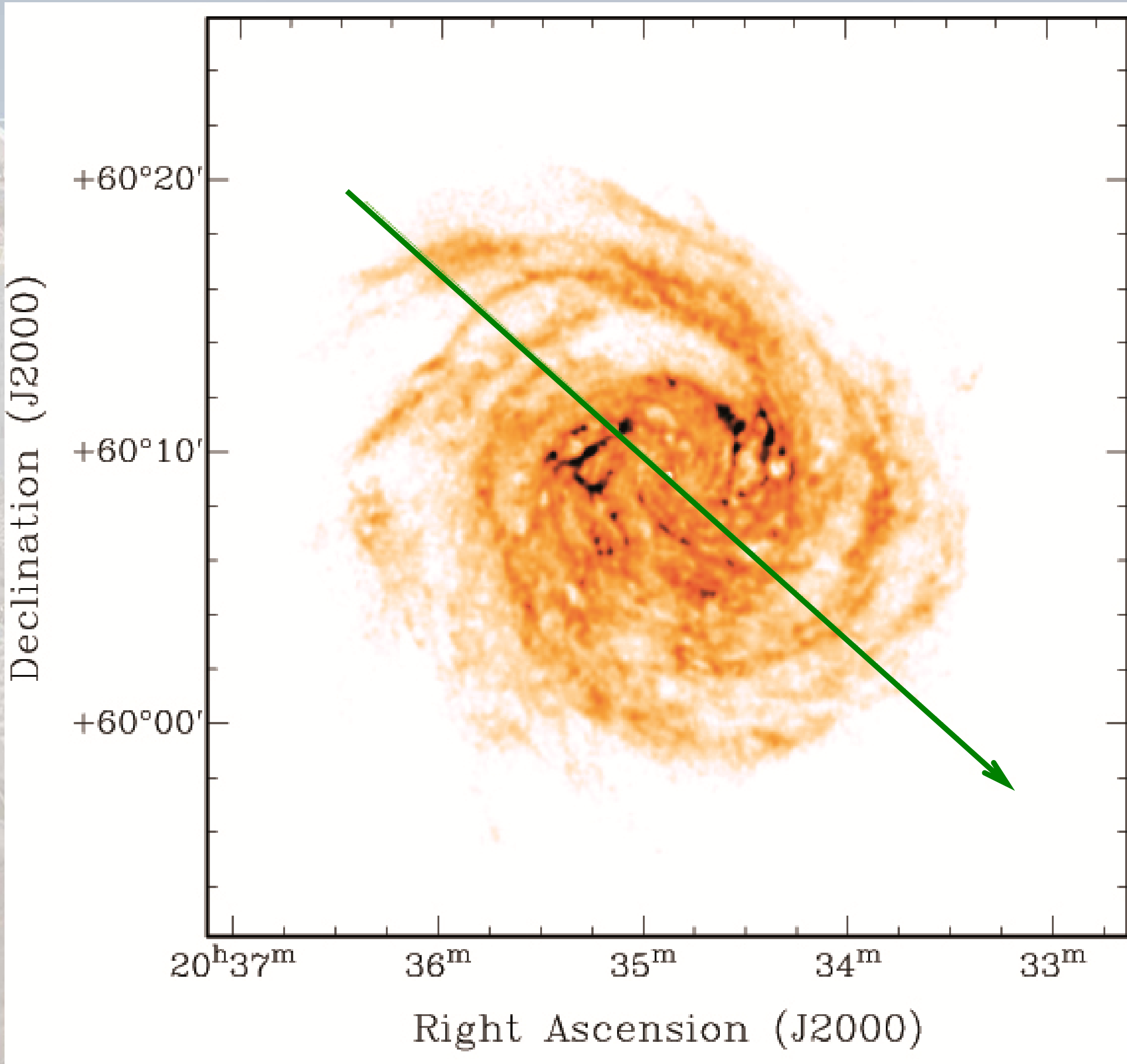


all HI integrated



only high velocity
HI integrated

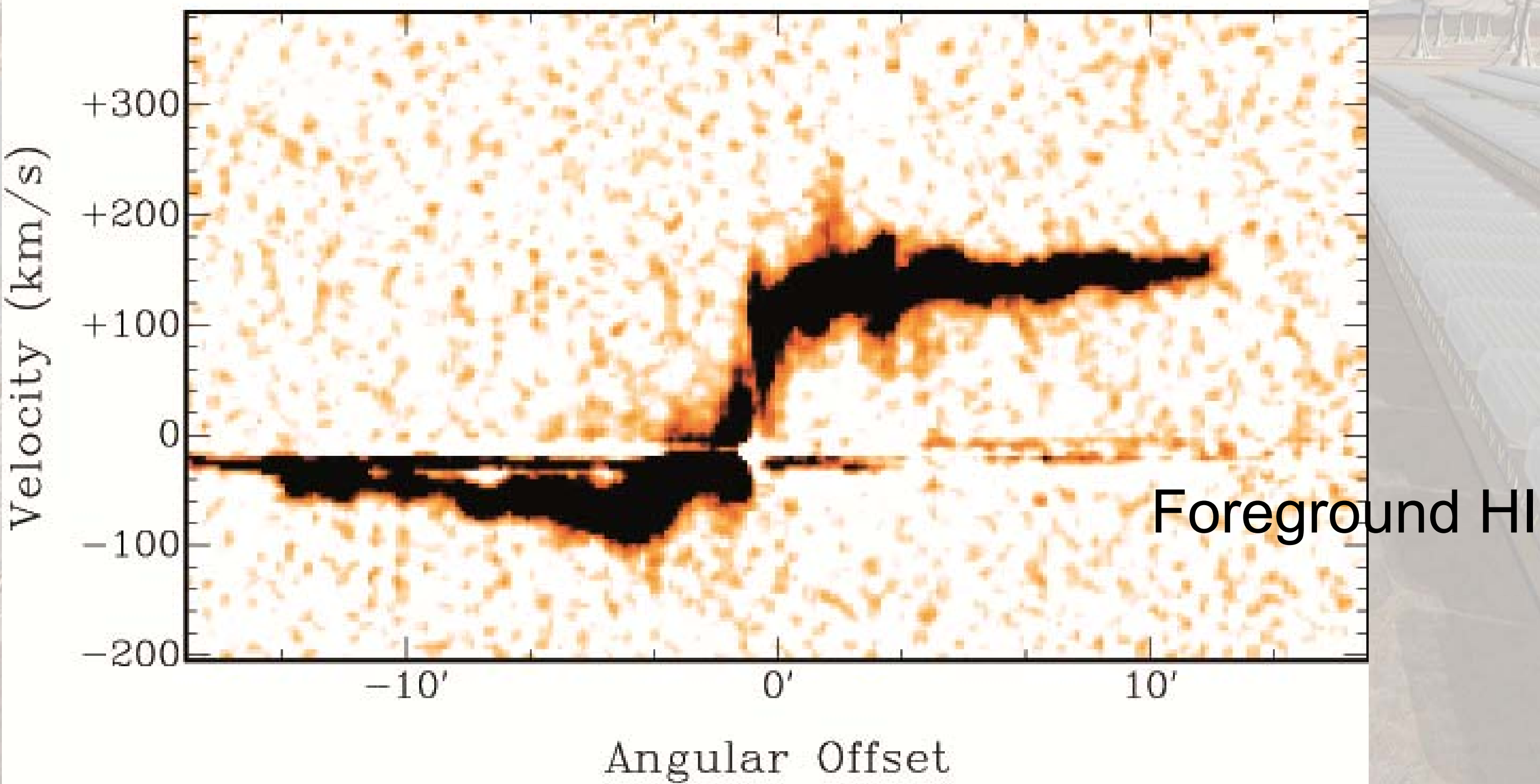
NGC 6946



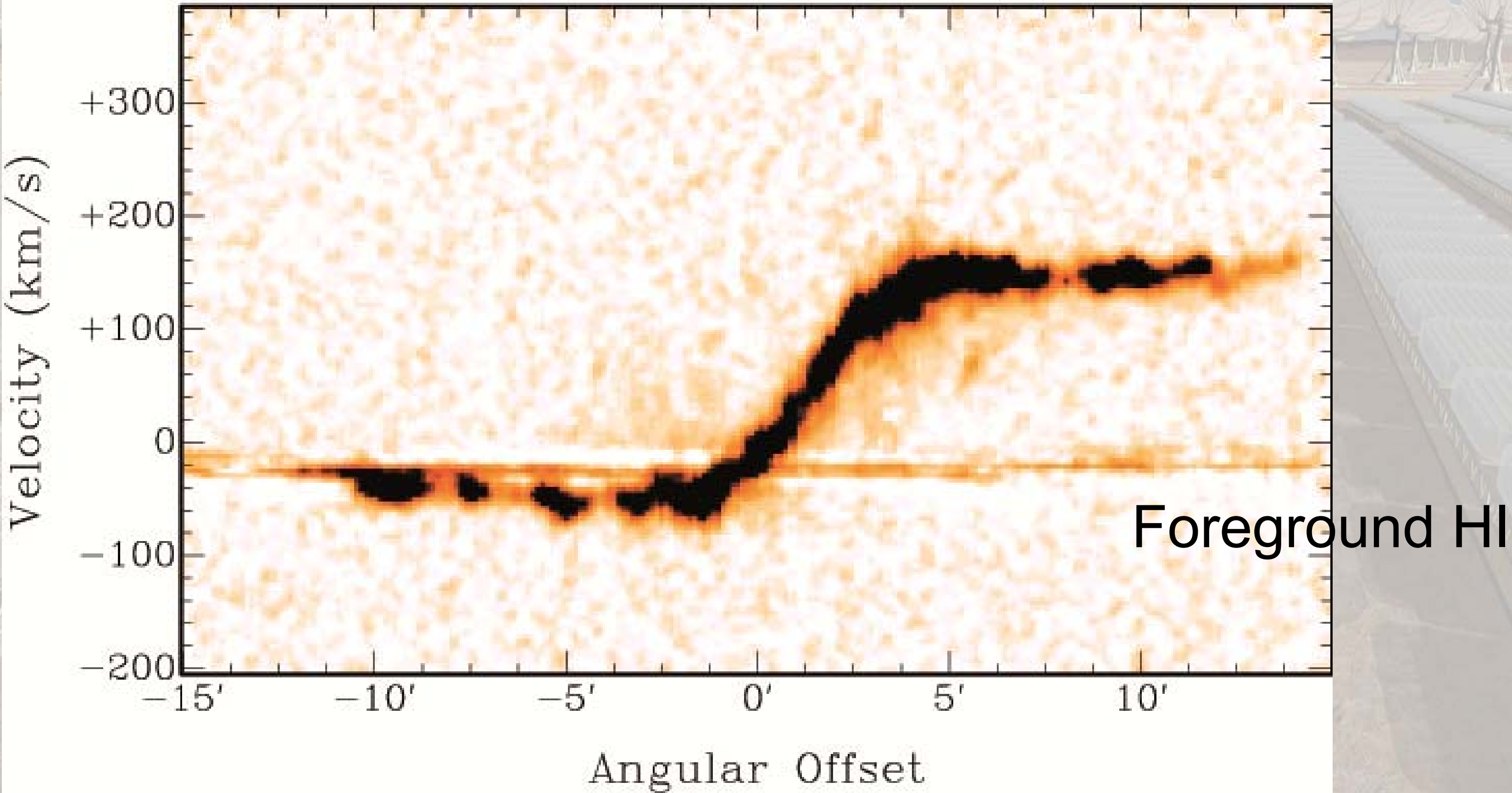
To inspect the data:

make a position velocity slice along the green arrow

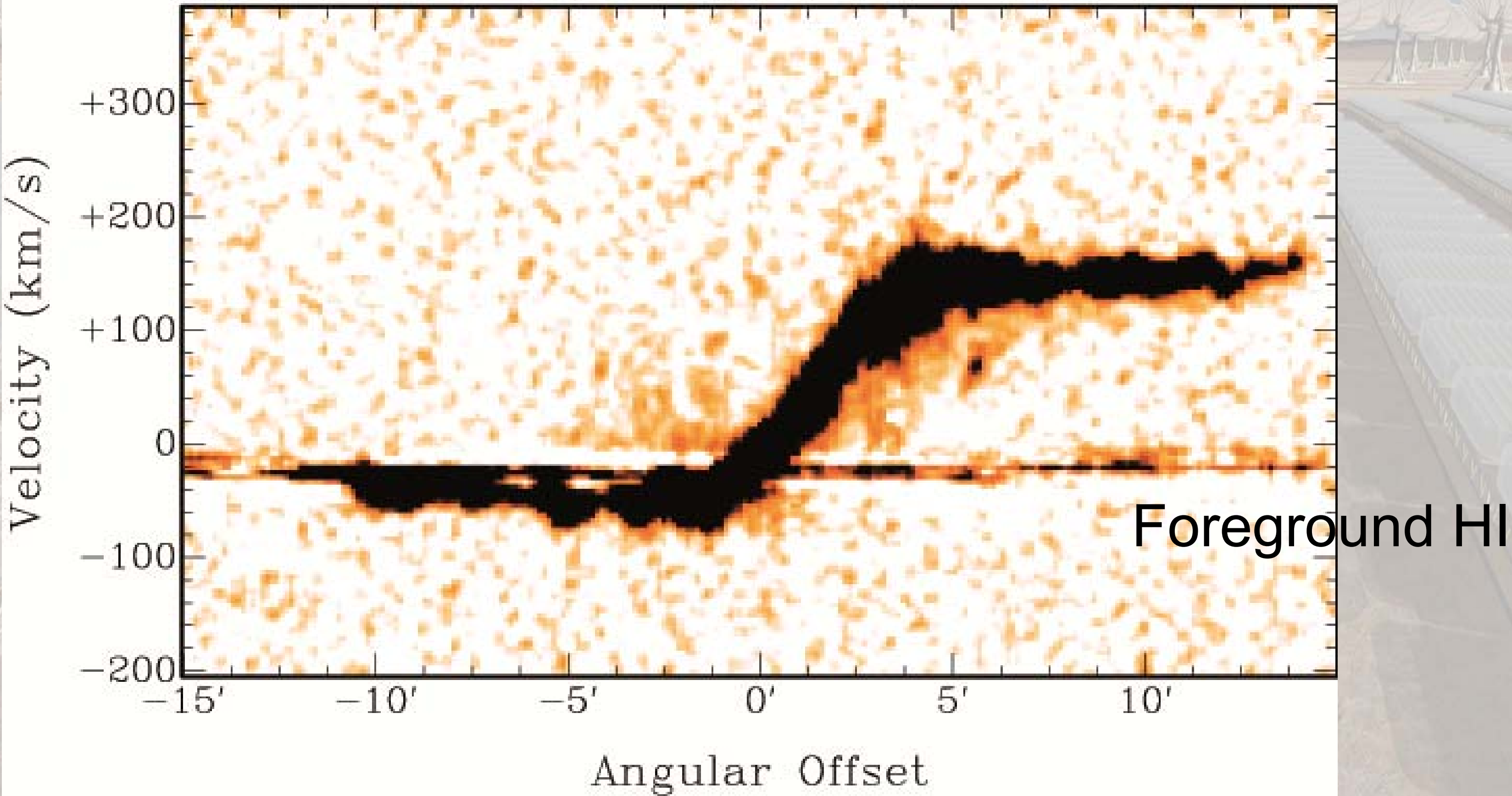
Result: rotating gas disk plus gas at anomalous velocities



Result: rotating gas disk plus gas at anomalous velocities
Another slice:



Result: rotating gas disk plus gas at anomalous velocities



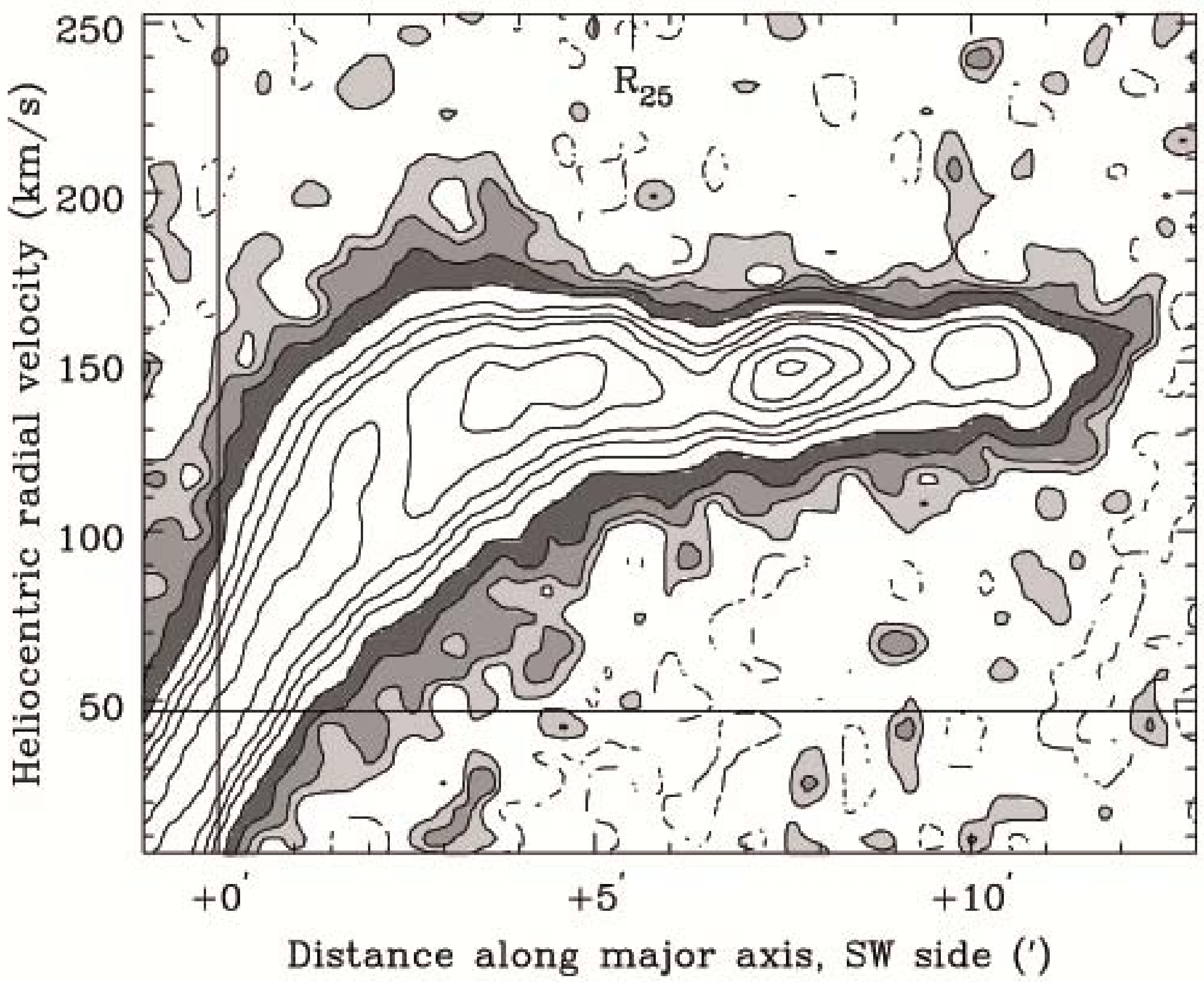
To isolate this anomalous velocity gas we can transform the cube into one without rotation:

shift every profile in velocity so that all mean velocities end up in one channel (*SHUFFLE in Gipsy*)

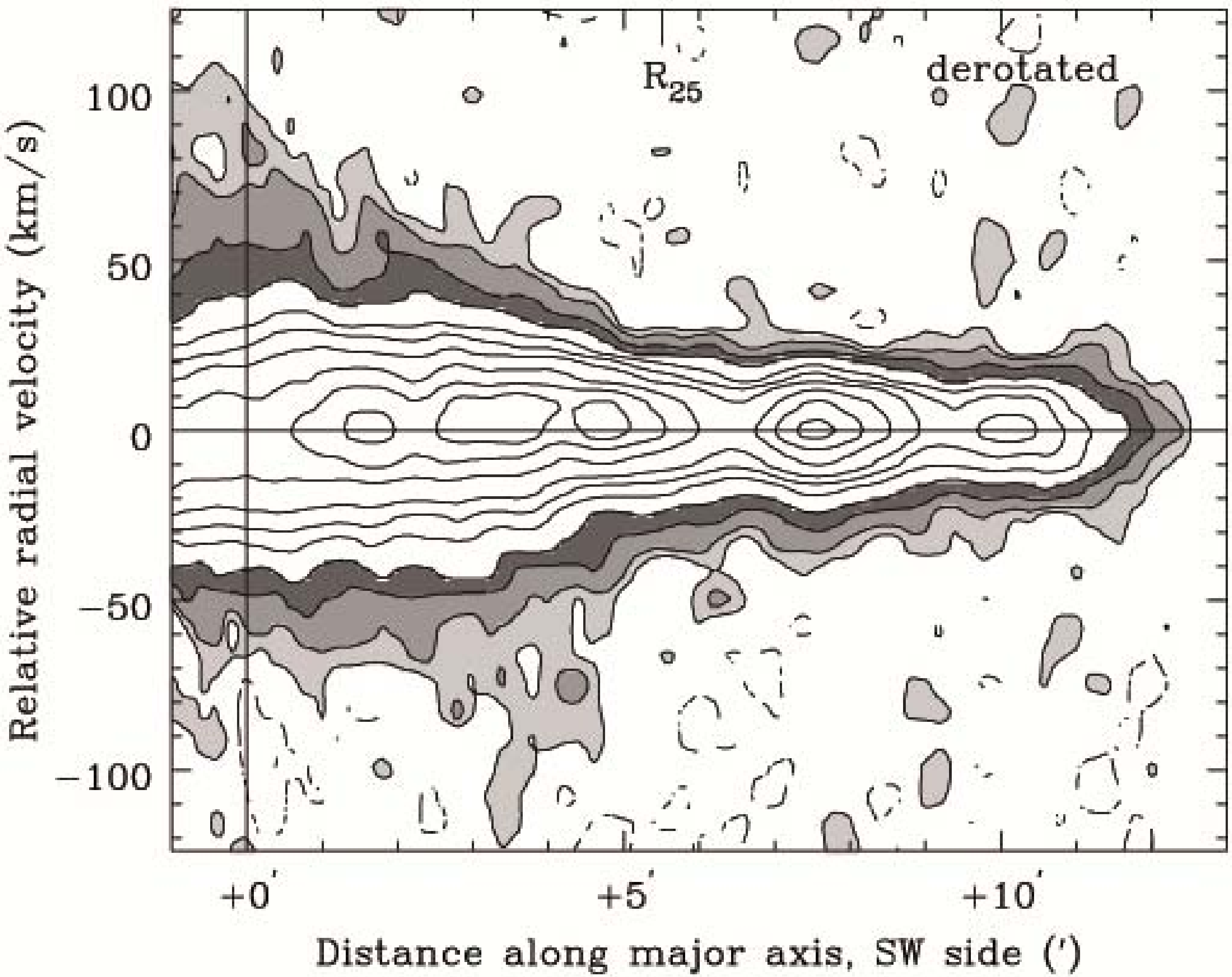
use the velocity field to guide this operation

The result: a data cube with axes α, δ, anomalous vel

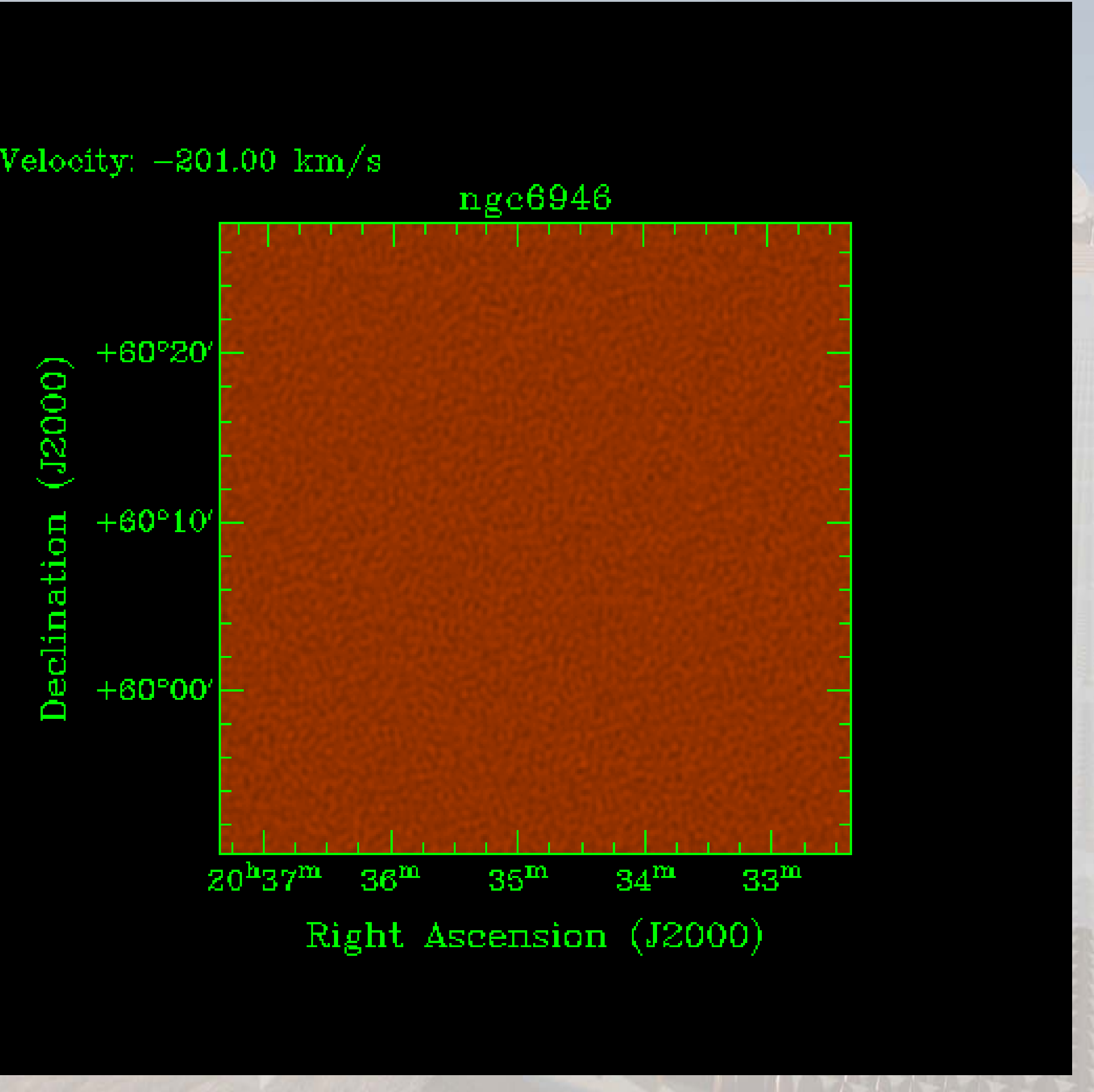
NGC 6946 XV slice along the major axis



NGC 6946 XV slice along the major axis, rotation removed



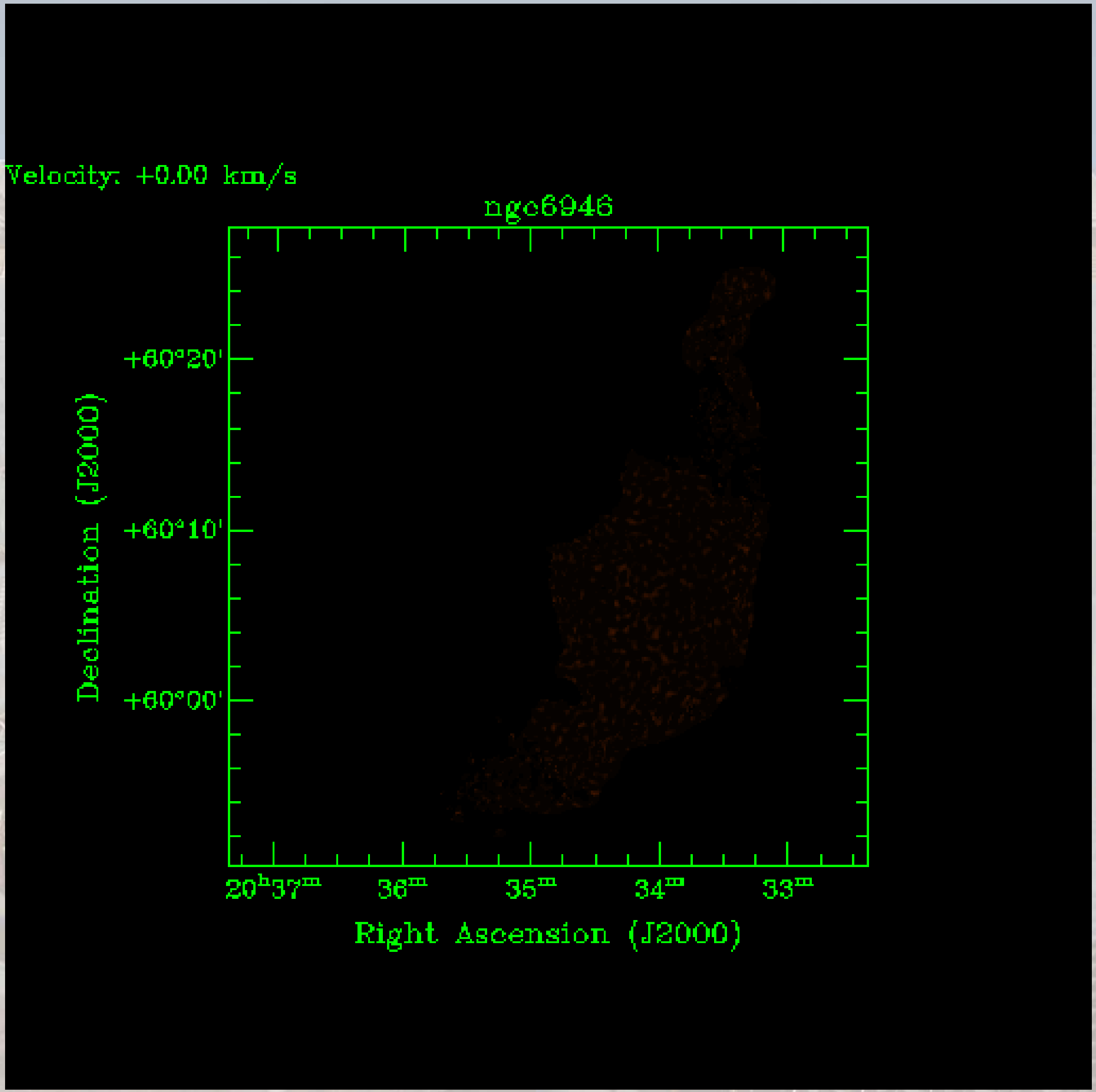
NGC 6946



original cube

NGC 6946

shuffled cube



NGC 6946 extraplanar gas

Boomsma, PhD Thesis 2007