

1. Diffuse matter in the Universe
2. Properties of the InterStellar Medium (ISM)
3. The ISM in galaxies

Fanti & Fanti – chap 13

Tools of Radio Astronomy – chap 13

Longair – chap 12

Purple: VLA  
Red: Spitzer  
Yellow: DSS  
Blue: Chandra

Composite image of spiral galaxy M106 (NGC 4258):  
optical data from the Digitized Sky Survey is shown as yellow  
radio data from the Very Large Array appears as purple  
X-ray data from Chandra is coded blue,  
infrared data from the Spitzer Space Telescope appears red.



1. The **Universe** has a **very low density** (average density of the Universe  $\sim 0.5\text{--}1.0 \times 10^{-5} \text{ cm}^{-3}$ ). **Most of the volume is made of gas**
2. On the large scale, the **densest regions are the clusters of Galaxies**, then the **filaments** connecting clusters, the remaining volume is made of **voids** (average density  $\sim 0.5\text{--}1.0 \times 10^{-6} \text{ cm}^{-3}$ )
3. On galactic scale, **spiral/irregular galaxies have very rich ISM** in various conditions, while **ellipticals/lenticulars have a limited amount of very hot tenuous thermal plasma**
4. The Medium often (may) contain also a significant **magnetic field**.
5. This **diffuse gas is in general found through observations**: e.g. bremsstrahlung and line emission for the "thermal gas", synchrotron (and IC) radiation for a "non-thermal" relativistic plasma in a magnetic field.
6. **Observations in the radio** can provide **line emission photons** (HI, molecules), **continuum** from **bremsstrahlung** of  $10^4 \text{ K}$  plasma and **synchrotron** from a magnetised ultra relativistic "non-thermal" plasma.
7. In other bands, it is worth to mention the thermal bremsstrahlung emission in the **X-rays** from bulges, and individual objects (e.g. supernovae), where temperatures reach  $10^6\text{--}10^8 \text{ K}$
8. In the **Infra-Red (IR)**, there are many molecular lines and the continuum from the **dust**, which is in association with molecular gas, at temperatures in the range 10s to 100s K.

# Radioastronomy - 3 - **Interstellar medium**

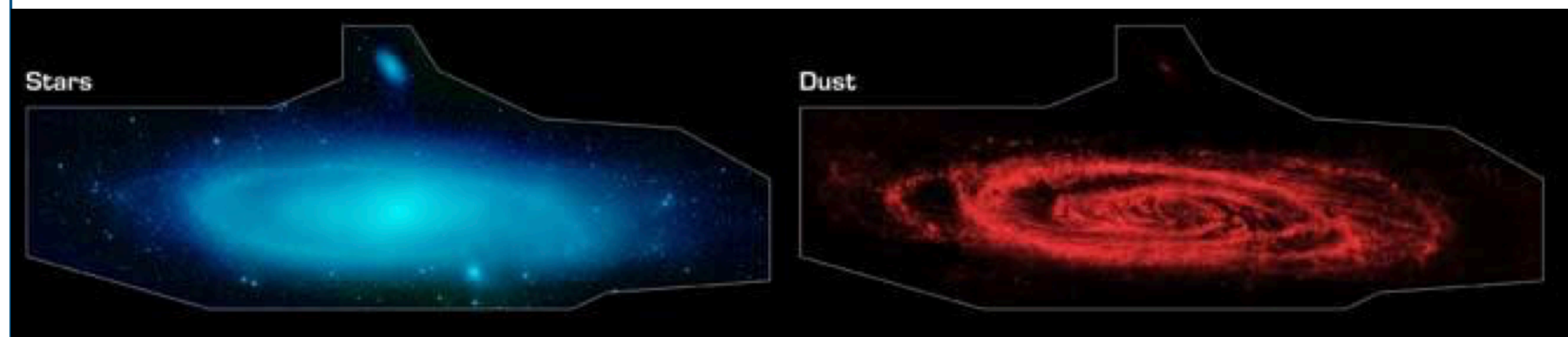
Galaxies have different ingredients of the ISM: The fraction of gas mass versus the total baryonic mass of the galaxy ranges from 0.01 in ellipticals to 0.1+ in spirals and even more in irregulars.

The table shows the four phases of the ISM: Hot Ionised Medium (**HIM**), Warm Ionised Medium (**WIM**), Warm Neutral Medium (**WNM**) and Cold Neutral Medium (**CNM**)

We will see that WIM and CNM are connected, bound to star formation (and evolution).

A galaxy might have a significantly different aspect at various wavelengths, depending on what phase is tested by the observation.

Gas phase	Spirals (& Irregulars)	Ellipticals & Lenticulars	Mass ( $10^9 M_{\text{SUN}}$ ) Typical Spiral
<b>HIM</b> $T \sim 10^{6-7} \text{ K}$ $n_{\text{H}} \sim 0.01 - 0.001 \text{ cm}^{-3}$	Bulge	Whole galaxy	0.1
<b>WIM</b> $T \sim 10^4 \text{ K}$ $n_{\text{H}} \sim 100 - 1000 \text{ cm}^{-3}$	Spiral arms	–	1
<b>WNM</b> $T \sim 100\text{s} - 1000\text{s} \text{ K}$ $n_{\text{H}} \sim 0.1 - 1 \text{ cm}^{-3}$	Disk	–	4
<b>CNM</b> (Molecules & Dust) $T \sim 10 - 100\text{s} \text{ K}$ $n_{\text{H}} \sim 100 - 1000 \text{ cm}^{-3}$	Spiral arms	(Dust lanes in lenticular)	3 (2 in molecules)



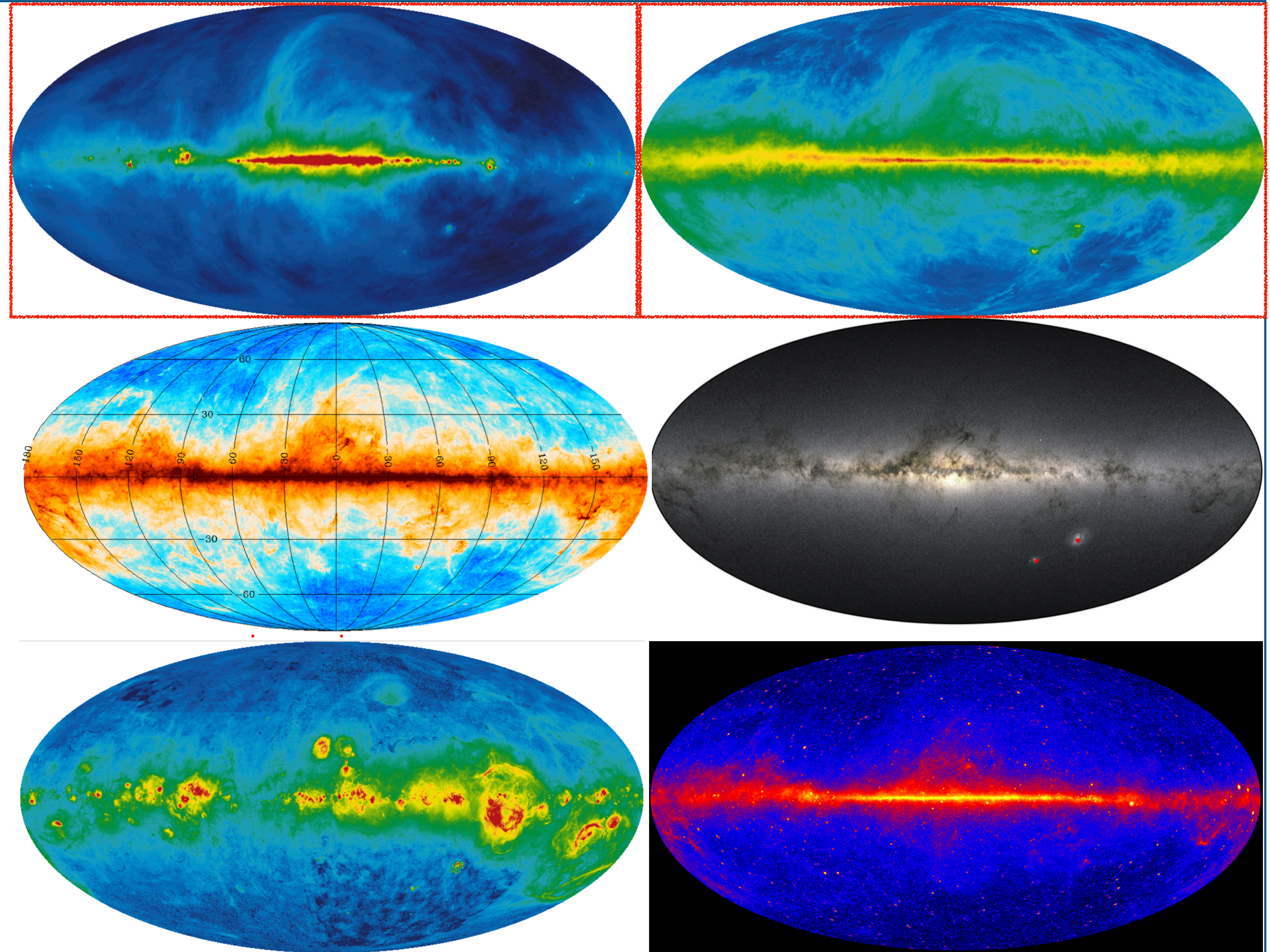
# Radioastronomy - 3 - **Interstellar medium** – The **Milky Way** (MW) at various wavelengths

The MW and its components of the ISM:  
from left to right and from top to bottom:

1. @ 408 MHz (continuum, synchrotron)
2. @ 1420 MHz (line emission, HI)
3. Planck image of the dust emission (IR)
4. Optical (visible) continuum image
5. H $\alpha$  line emission
6. Gamma ray from FERMI satellite

Composite images (sometimes obtained  
with a combination of instruments – if  
ground based)

Other examples could be found  
(e.g. CO image From ground; IR, UV and  
X-rays from satellites)



**HIM** is detected through its thermal bremsstrahlung emission:

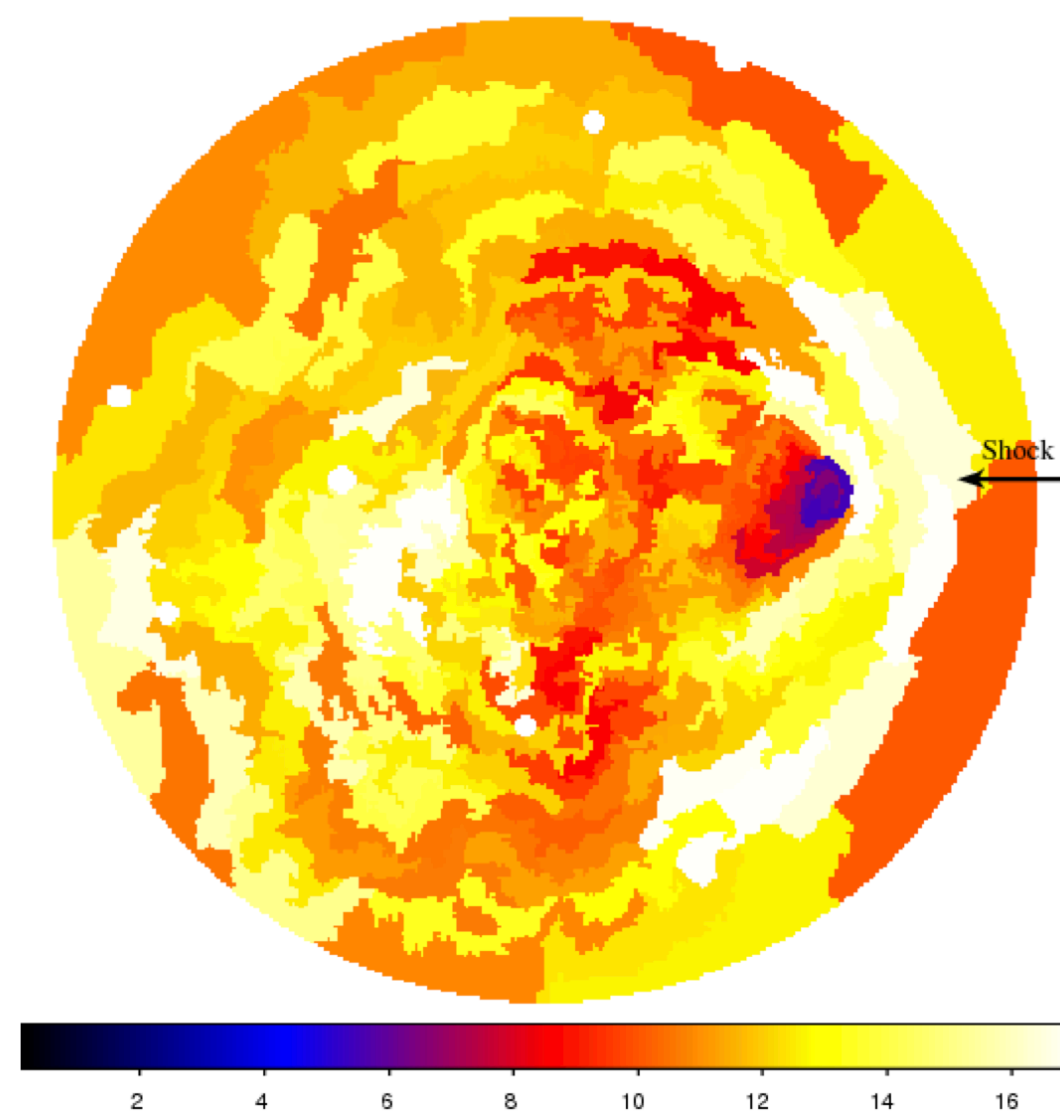
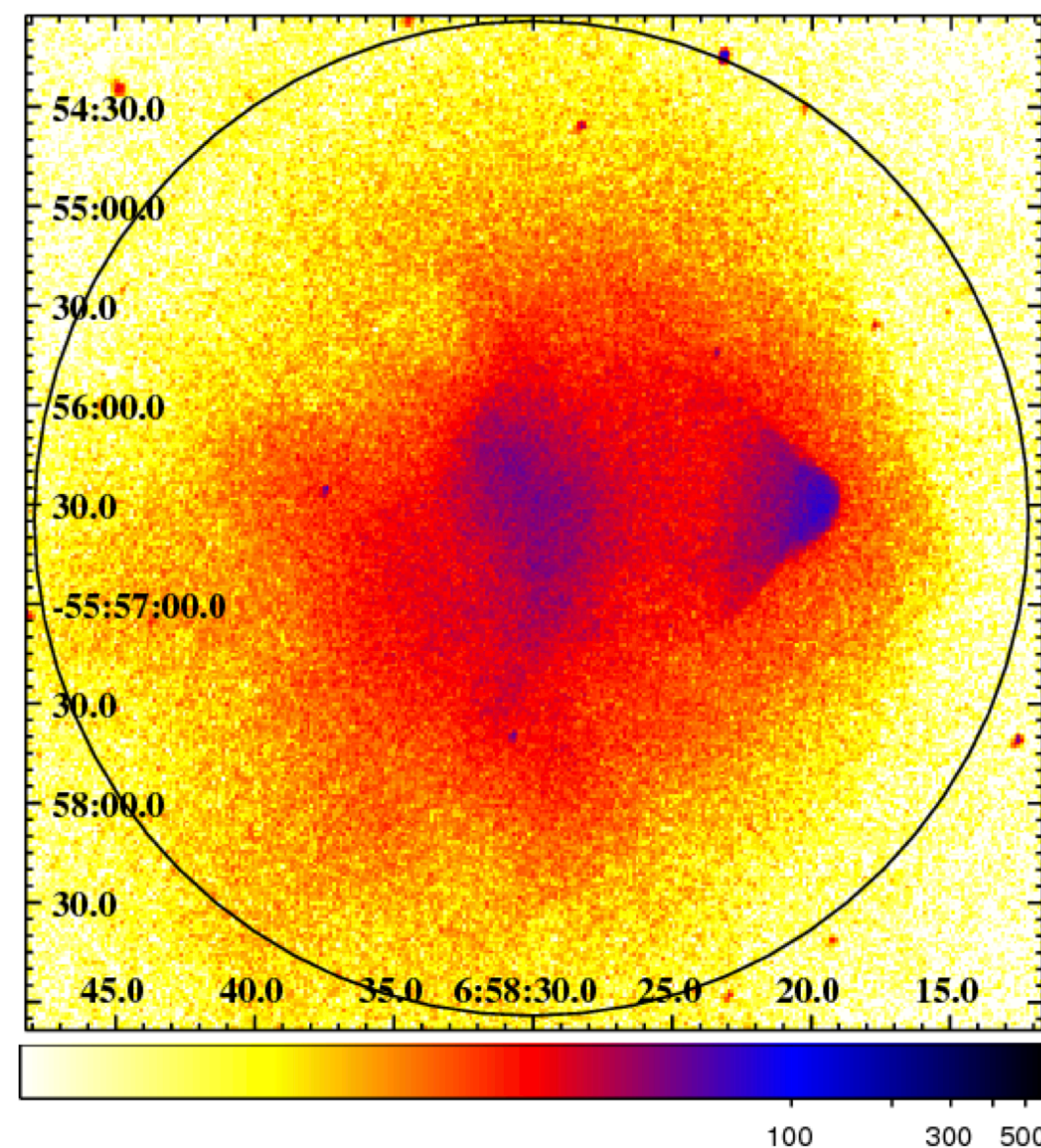
The cut-off frequency determines the temperature, then well below the cut-off, the emissivity (Flux density over Volume) determines the free electron density.

**Not directly relevant to radio astronomy**, since its emission is in the far-UV and X-rays.

It may become relevant in case of interaction with non-thermal plasma.

Worked examples: **Top-right**: a cD elliptical galaxy. **Bottom right**: the radiogalaxy CygA.

**Below**: the Bullet cluster – the intensity of X-ray emission measuring the density (**left panel**) the temperature of the plasma determined along the LoS in different regions of the cluster (**right panel**).



The Bullet cluster: left X-ray emission, right: temperature map (Million & Allen 2009)



The Elliptical galaxy **NGC1399** in the Fornax cluster, with a large number of globular clusters.



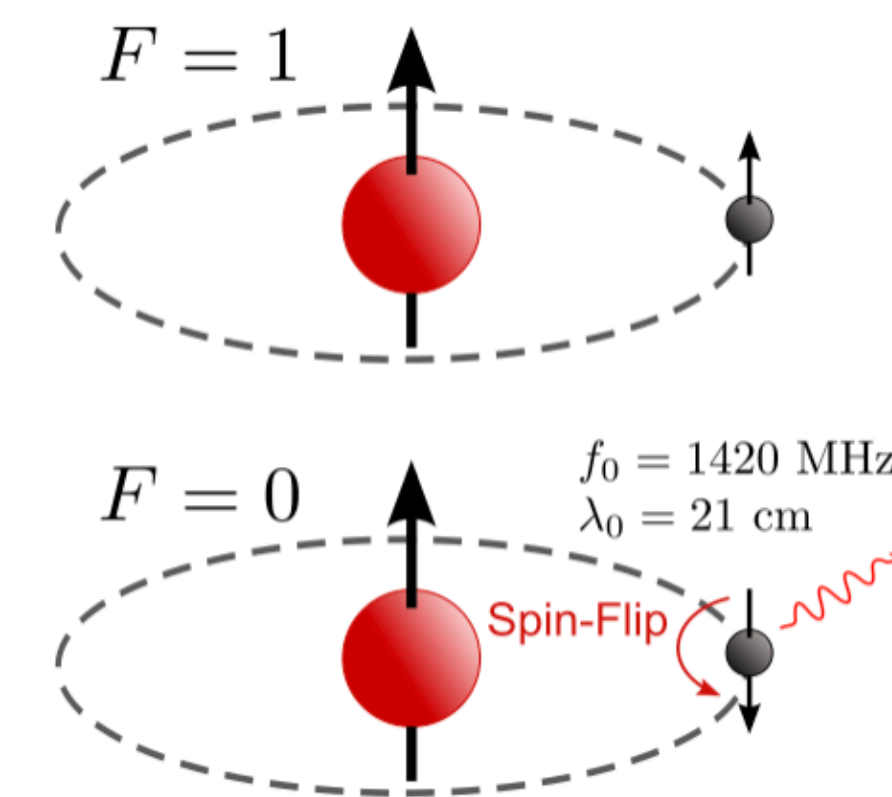
CygA: **blue** bremsstrahlung emission, **yellow** stars, **red** synchrotron (radio) emission

**WNM** is made mainly of atomic Hydrogen distributed in most of the disk of spiral galaxies. It is detected through its line emission at  $\sim 1420$  MHz.

Predicted by van de Hulst in 1944, discovered by Ewan & Purcell in 1951.

The energy difference between the two states is very small  $5.87 \times 10^{-6}$  eV.

It refers to a "**forbidden transition**", since  $A_{UL}$  is very small ( $2.87 \times 10^{-15} \text{ s}^{-1}$ ), consequently, the excited state is very stable (10 million years). In the disk, the average density is in the range 0.1–1, and collisions are about  $10^4$  more frequent than radiative decays, granting **thermal equilibrium** and then **the upper level is the more populated**:



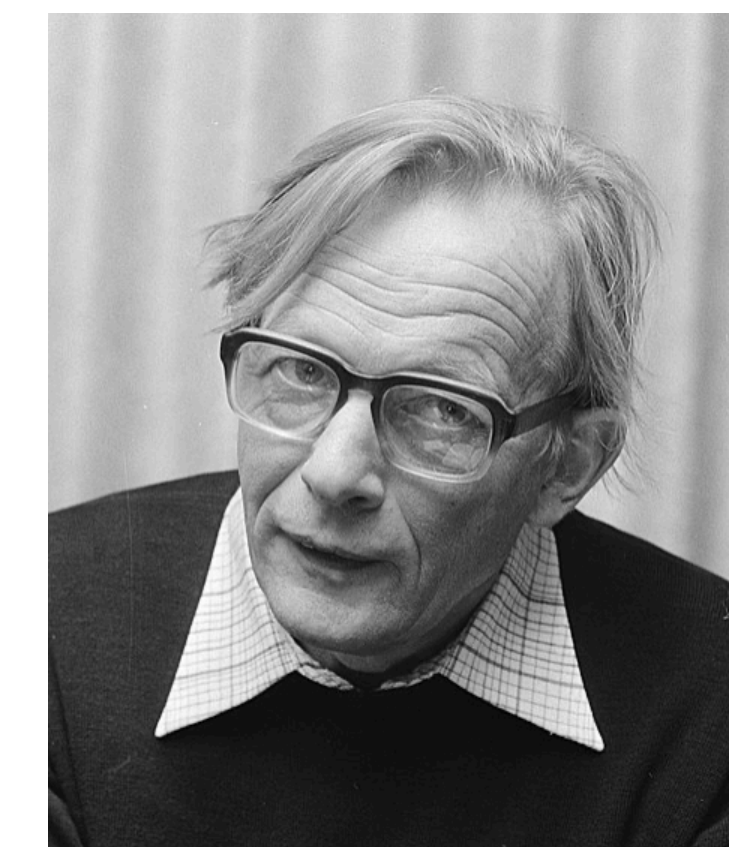
$$\frac{N_U}{N_L} = \frac{g_U}{g_L} e^{-\frac{\Delta E}{kT}}$$

the statistical weights are  $2F+1$  and then **the ratio is 3:1** ( $\Delta E \ll kT$ )

The **natural width is very small**.

The broadening of the line profile is from Doppler effects:

- **thermal motions within the cloud** (just broadening related to T)
- composition of **relative velocities of various clouds along the LoS** (centroid shift of each cloud)



From Left to Right: Purcell (1952 Nobel prize) & Ewan

H. van de Hulst

# Radioastronomy - 3 - **Interstellar medium – WMN**

The radiation can cross the ISM without absorption.

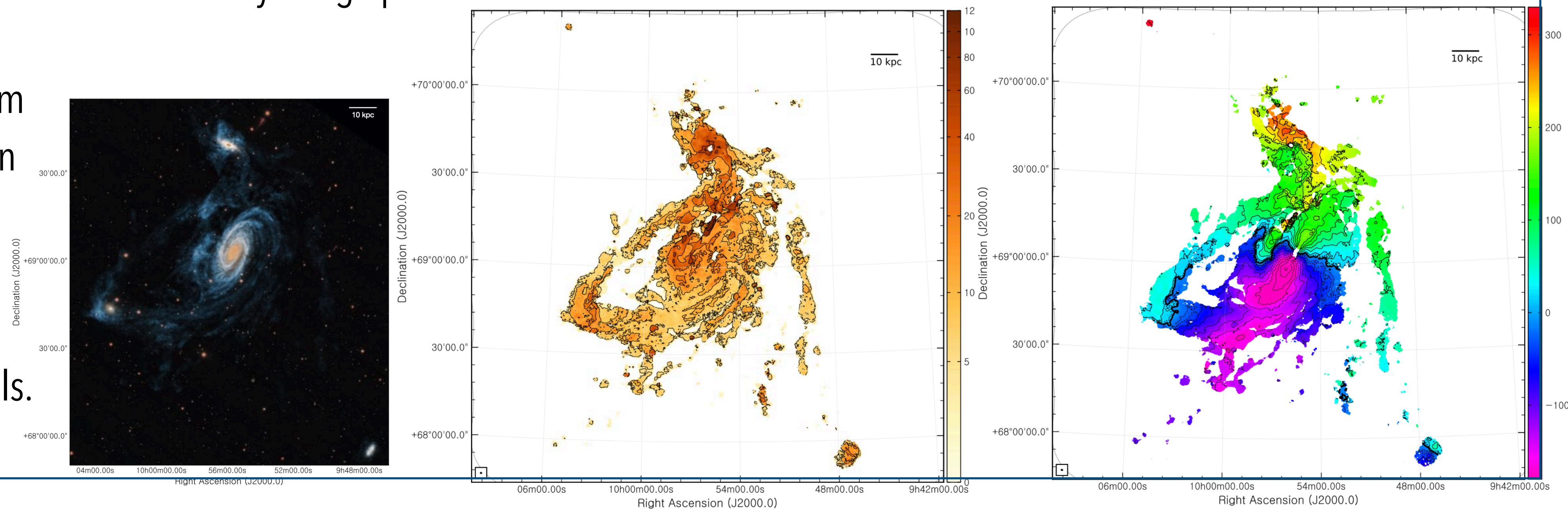
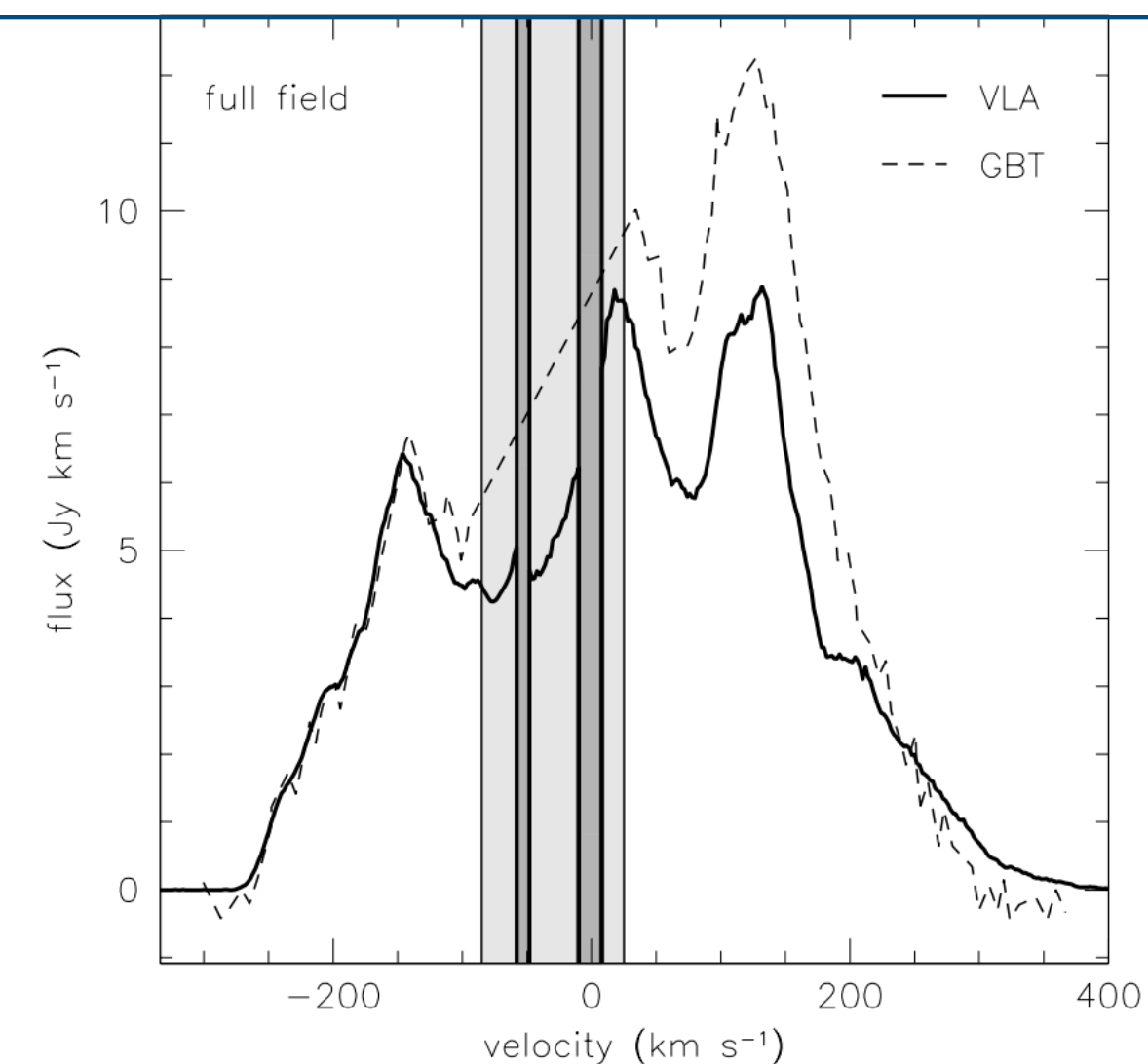
Worked example: the **M81 group** (from de Blok et al. 2018) [M81, M82, NGC3077, NGC2976]:

The **observed spectrum** (continuum subtracted) is shown on the top right panel (shaded areas exclude galactic emission).

The bottom panels show the optical image, the total intensity of the line, the "Doppler" image.

HI emission comes from wider areas wrt to the optical emission, there are tails/wakes connecting the galaxies in the system. The total intensity image provides information on the total HI mass.

The Doppler image (bottom right) provides information on the gas dynamics, with clear indications of systematic motions, both in M81 and in the tidal tails.

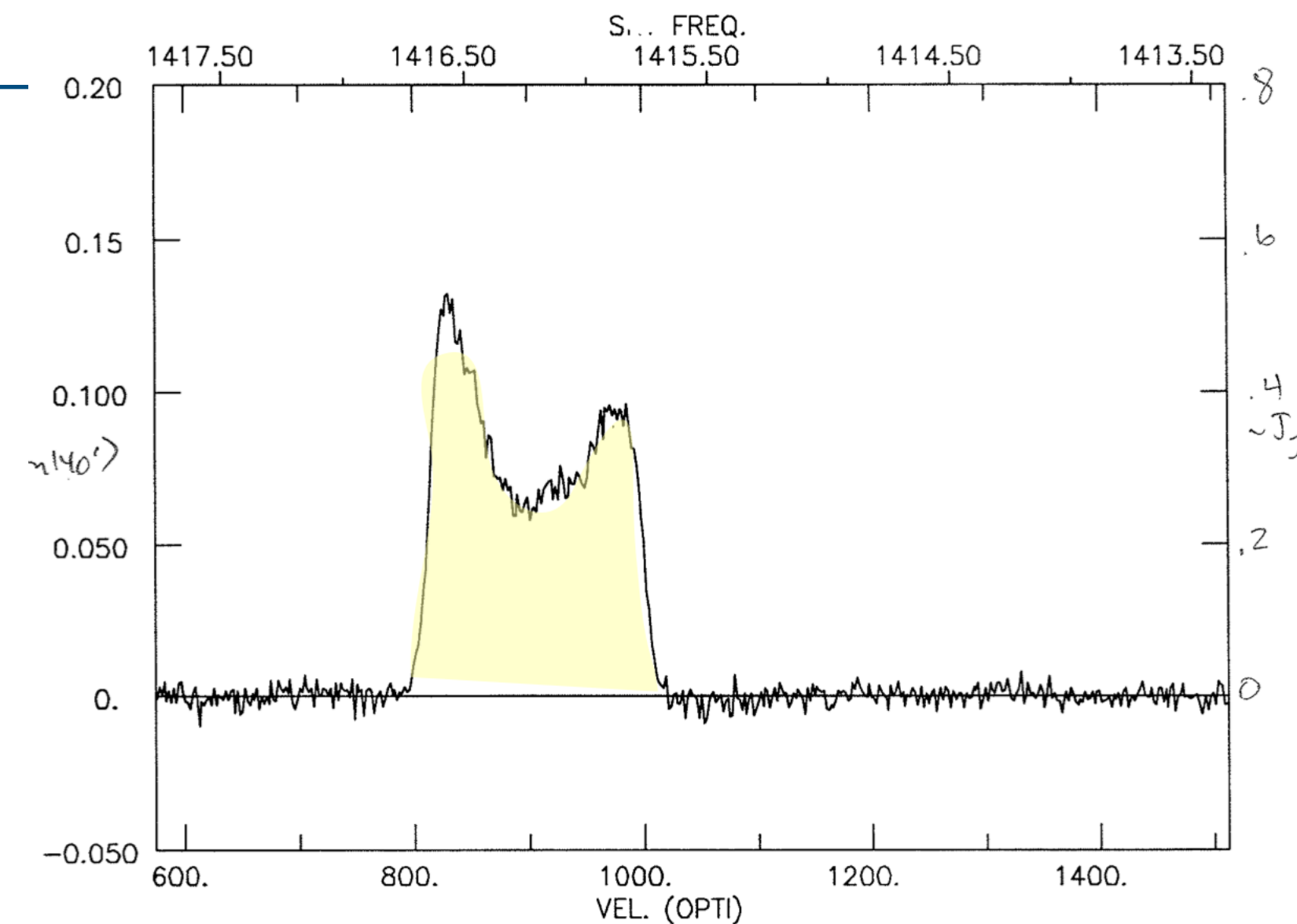


The integral over the spectral profile provides a measure of the mass:

Using reference values, the following relation is used to determine the HI mass:

$$M_{HI} \simeq 2.36 \cdot 10^5 \left( \frac{D}{\text{Mpc}} \right)^2 \int_{line} \left( \frac{S(\nu)}{\text{Jy}} \right) \left( \frac{dv}{\text{kms}^{-1}} \right) \text{ in } M_{\odot} \text{ units}$$

On the basis of the distance (squared), the number of photons are a proxy of the total amount of gas in that galaxy.

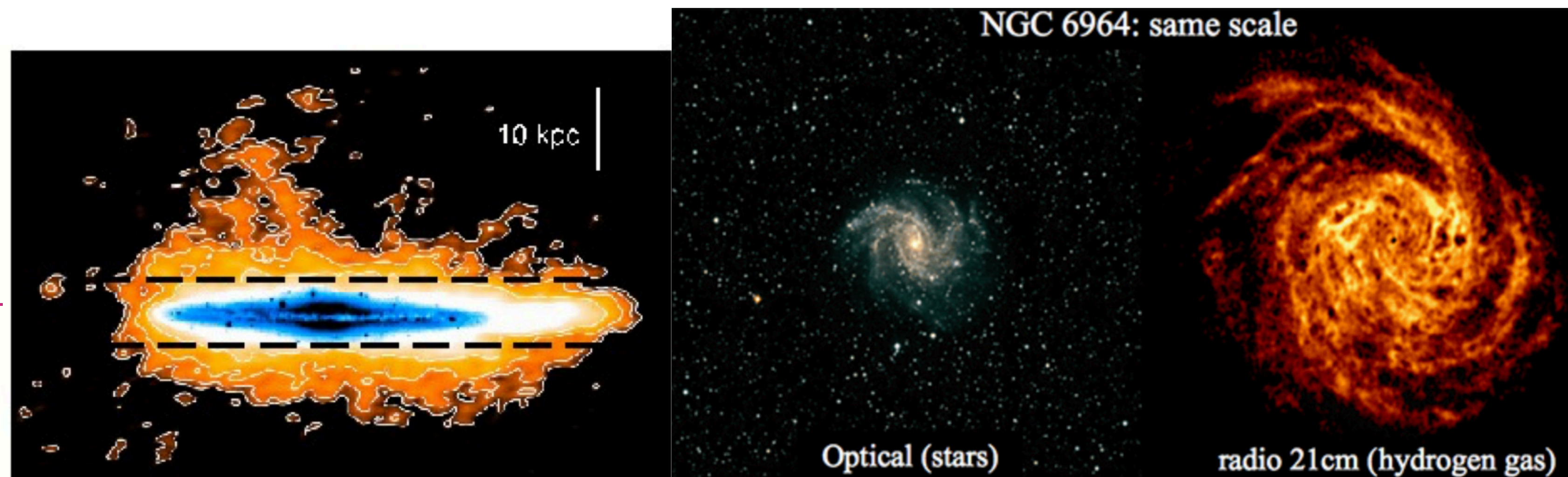


Often, the emission from the CNM largely exceeds the area covered by the stellar emission.

The displacement between gas and stars can be used to infer dynamical conditions of the galaxy.

Side on the left: lopsidedness and extra-planar gas.

Side on the right: optical and radio extensions are significantly different.



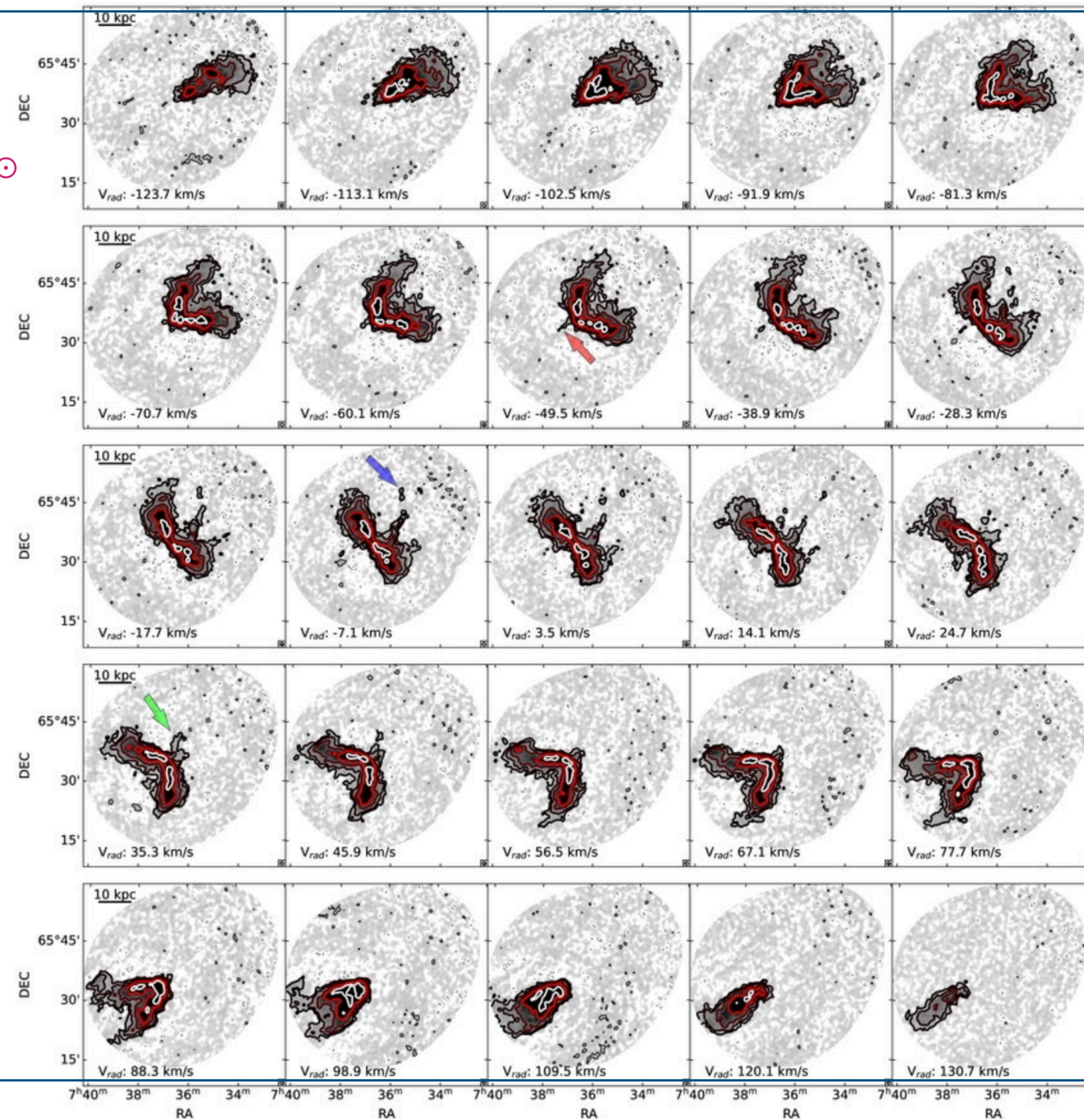
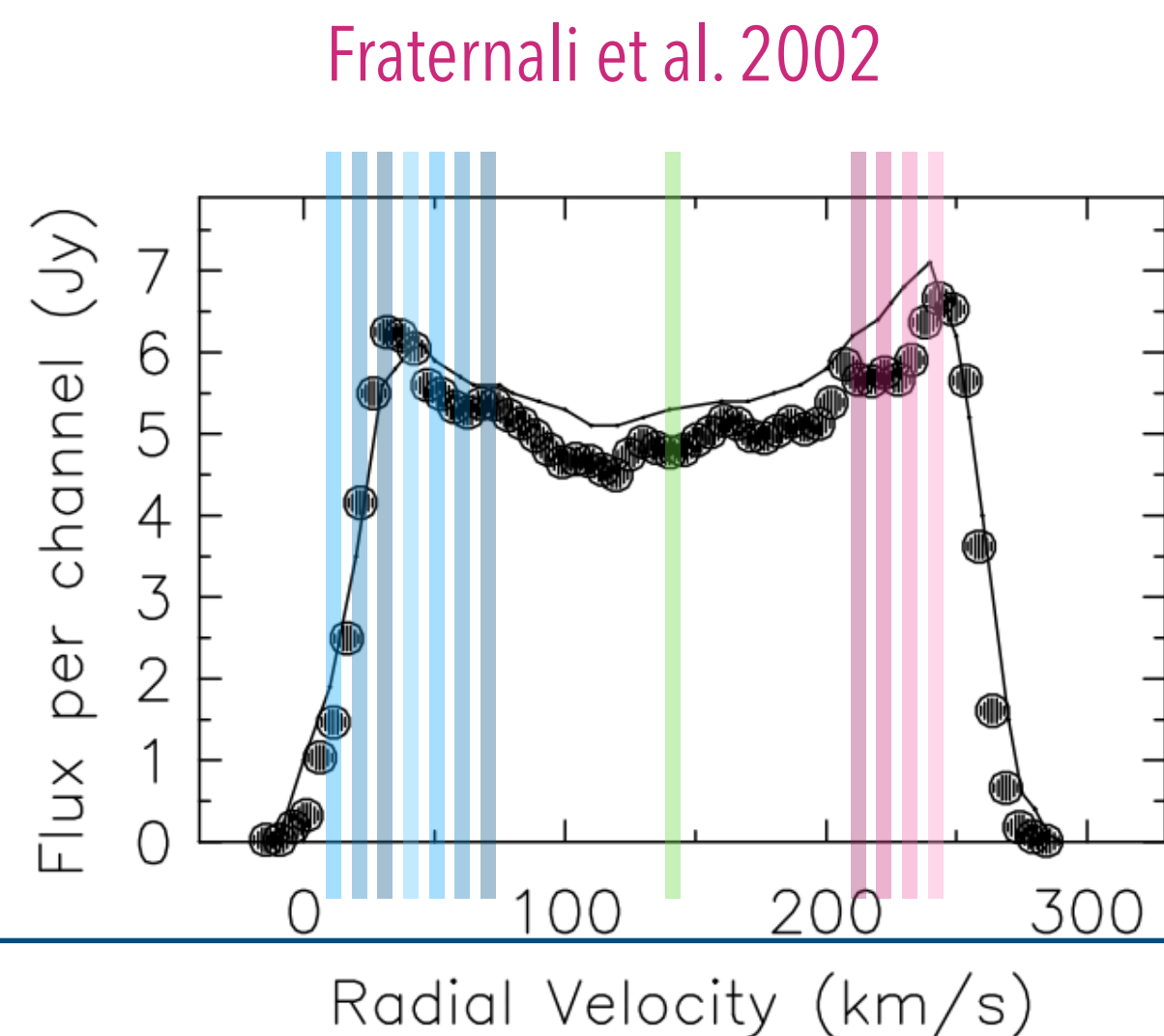
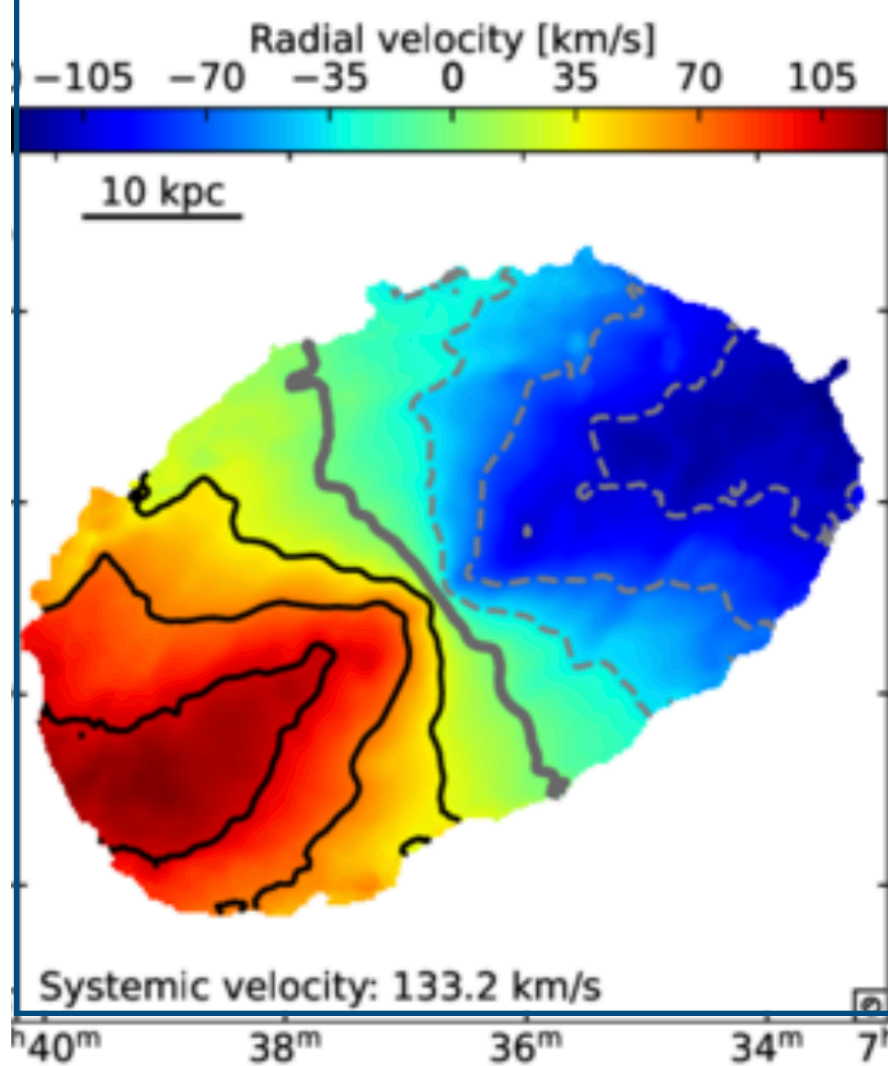
Blue = optical emission, White/Orange = radio emission

The **rotation curve** in spiral galaxies:

The integral of the line provides a **total HI mass of  $\sim 3.5 \times 10^9 M_{\odot}$**

It is possible to select portions of the emission line spectrum (center bottom) and determine which region of the sky/source has originated the selected photons (right panel).

Following the Doppler convention the whole emission is represented in the bottom left panel (**blue=approaching; red=receding**).



The **rotation curve** in spiral galaxies:

Along the grey rectangle the doppler velocity is evaluated and the **rotation curve** is determined, through the position–velocity (PV) diagram (bottom panel). **Radiation at 21 cm can cross the galaxy.**

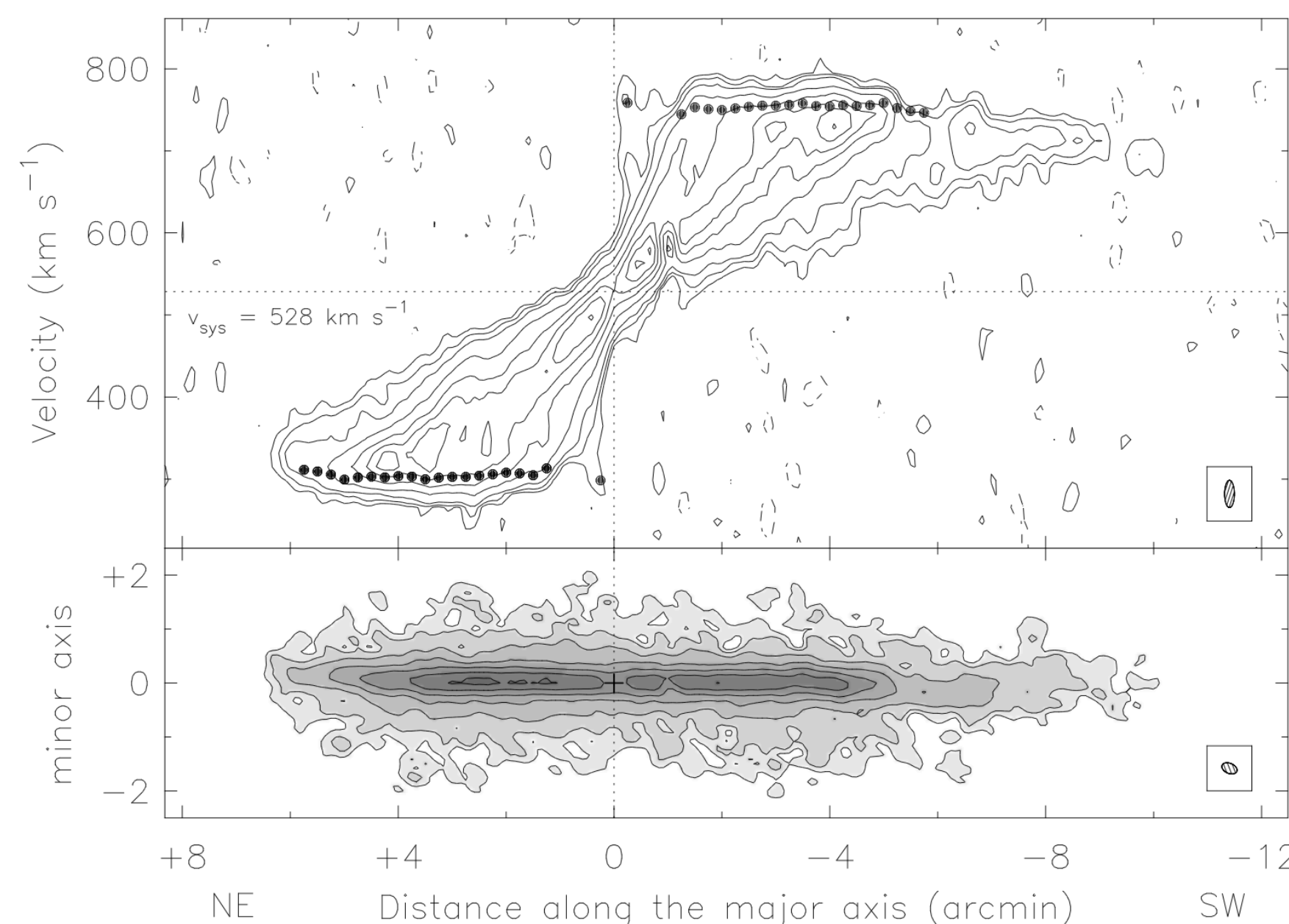
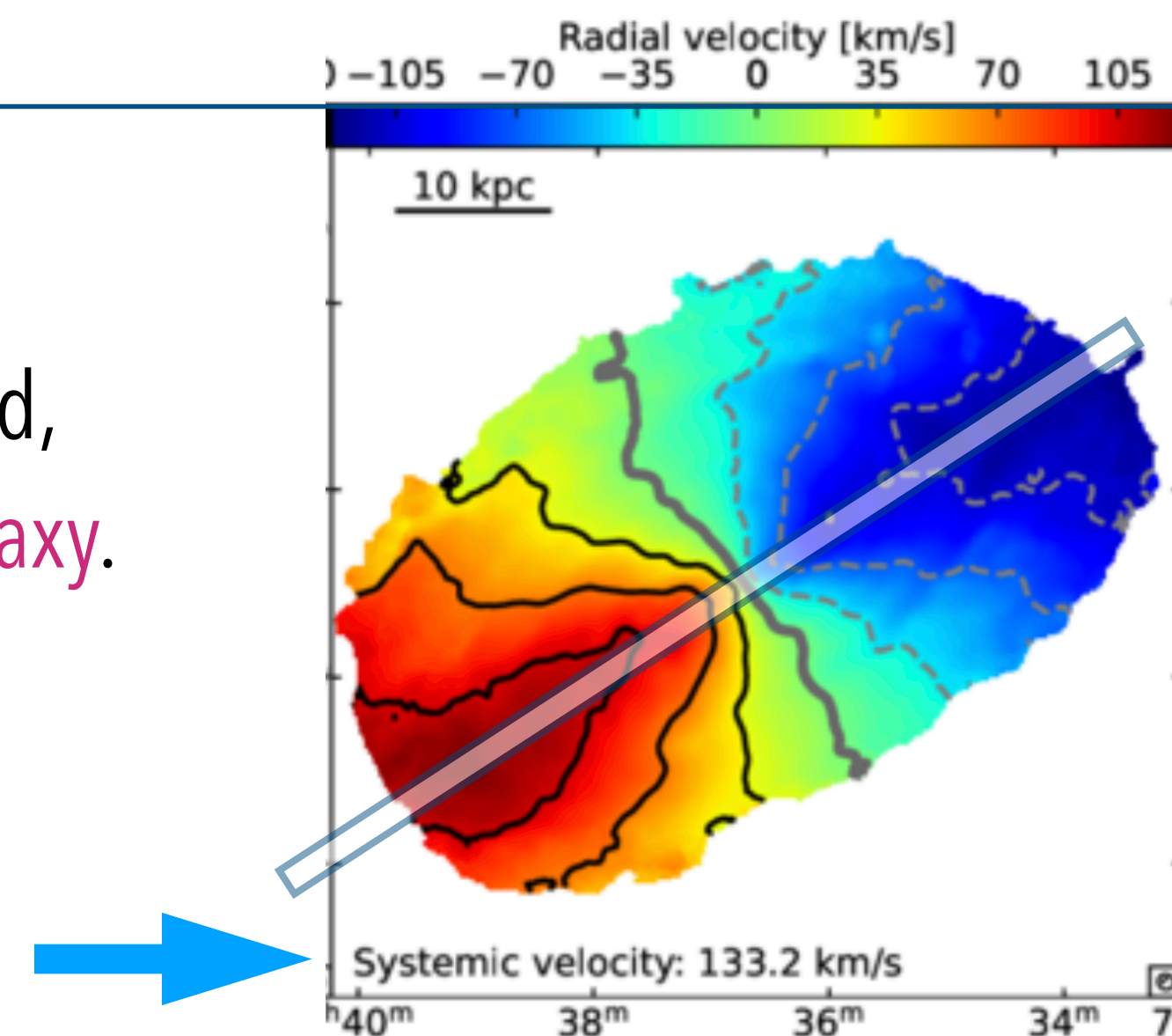
The projection of the radial component of the circular velocity is displayed as a function of the distance from the center of the galaxy.

- **Edge-on** galaxies show the full radial component, and then measure the intrinsic value.

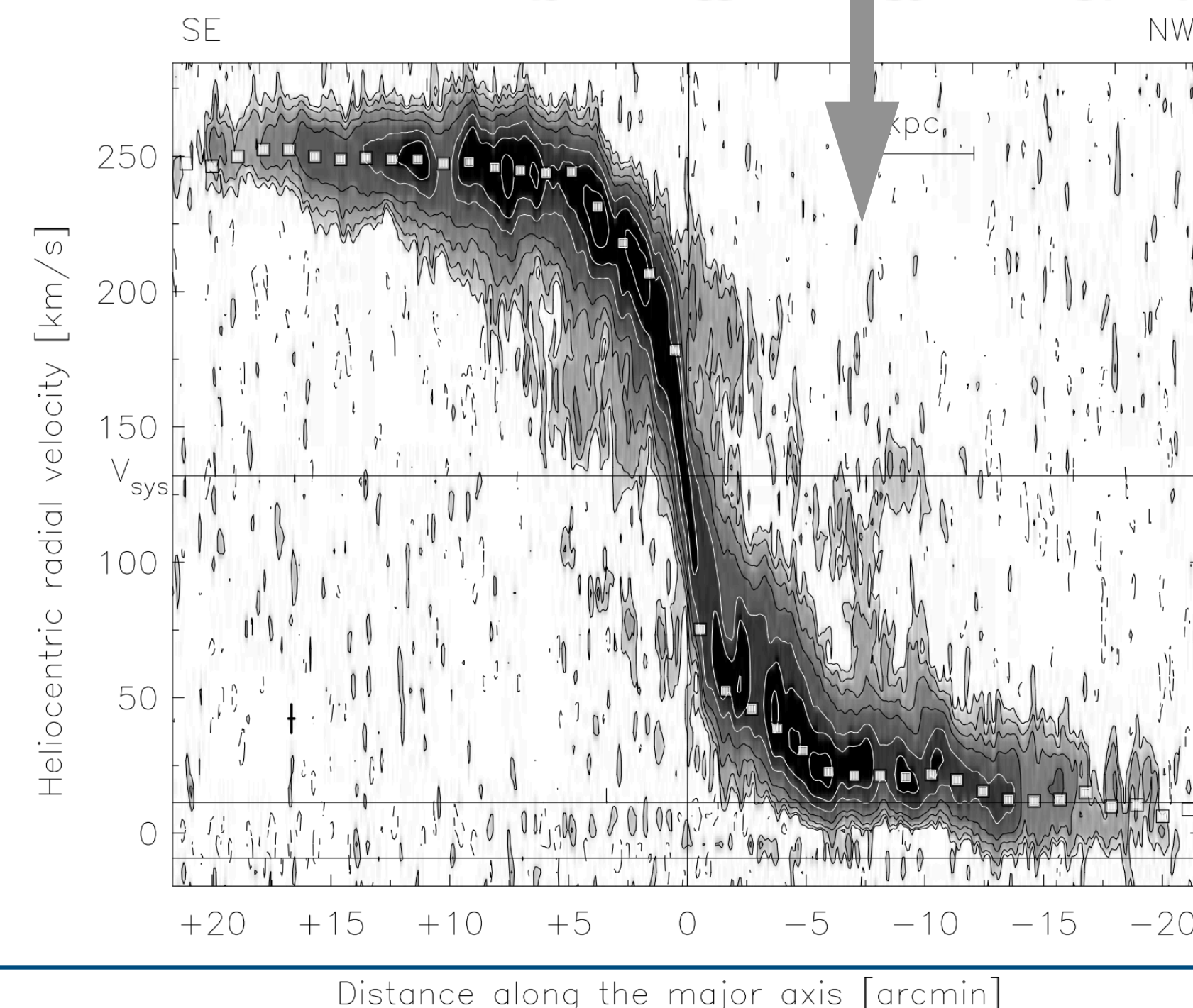
The **circular velocity** appears to be **roughly constant with radius**

Implications will be discussed later on

- What about the **face-on** galaxies?



NGC891 – Swaters, Sancisi & vdHulst 1997



Fraternali et al. 2002

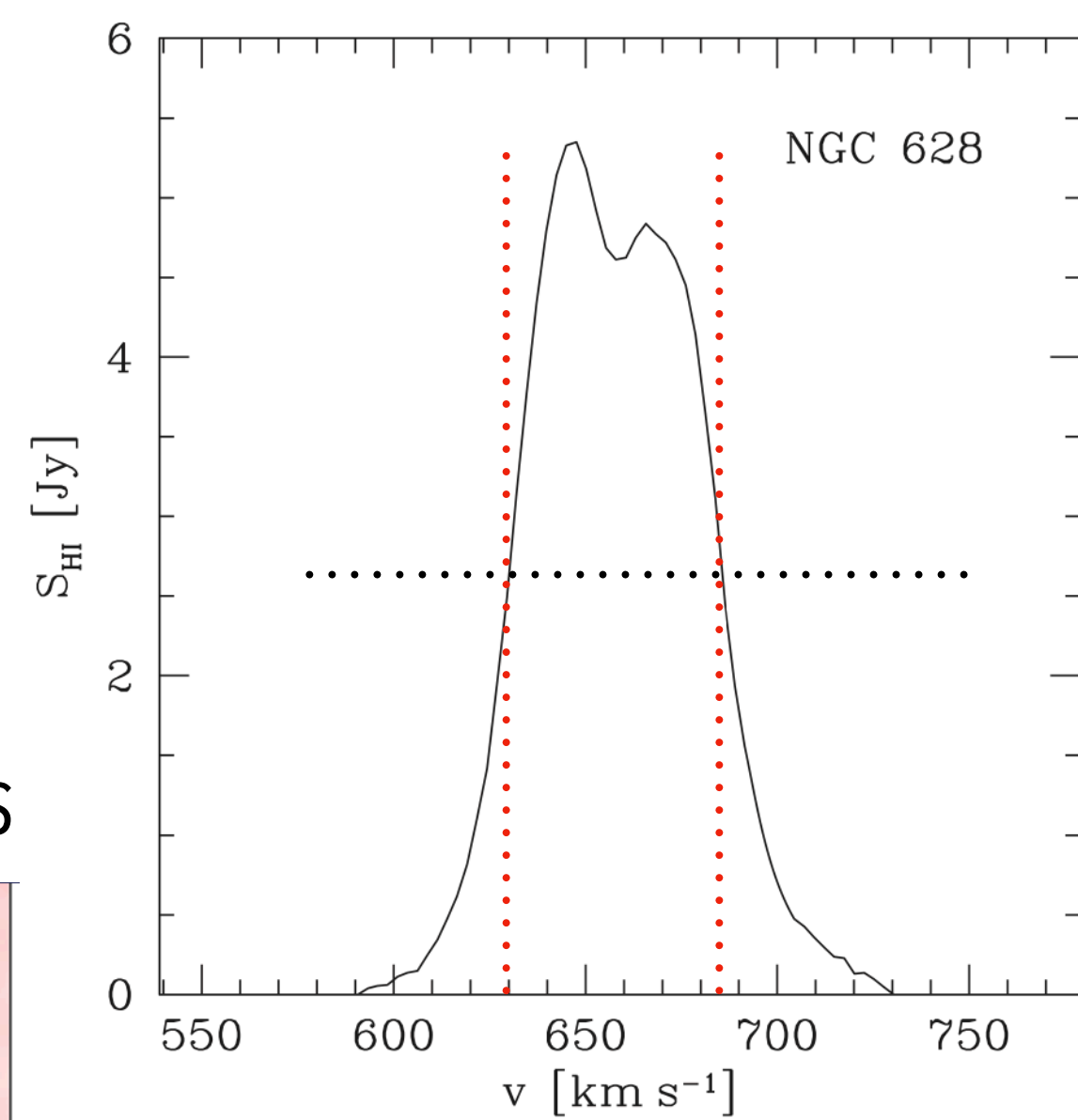
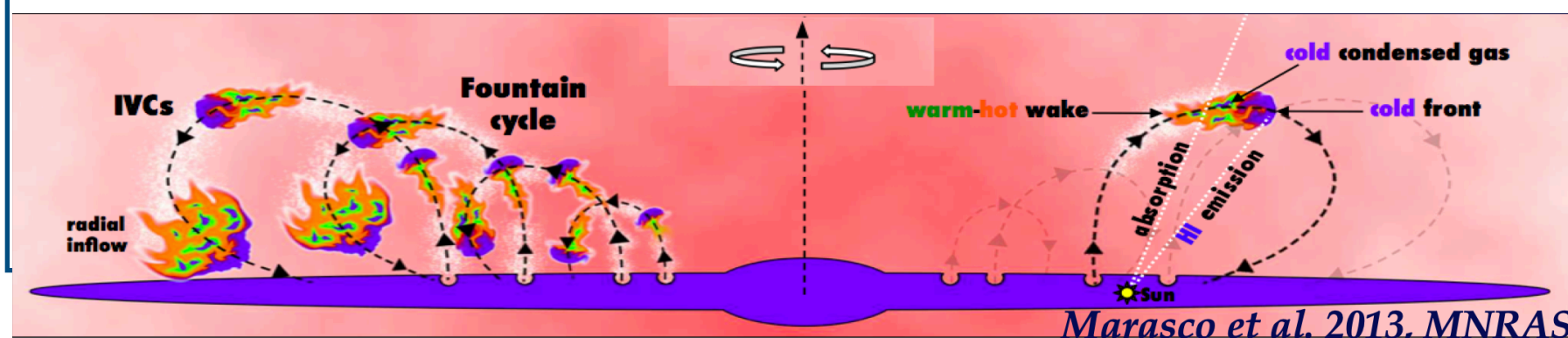
The **rotation curve** in face-on spiral galaxies measures the **velocity dispersion of the HI clouds perpendicularly to the disk**.

In NGC 628 (with an inclination angle  $\sim 10^\circ$ ) the line-width ( $\sim 55$  km/s) is much smaller than in edge-on objects (100–500 km/s, twice the local circular velocity), but much larger than the thermal broadening ( $\sim 3$  km/s for  $T \sim 10^3$  K)

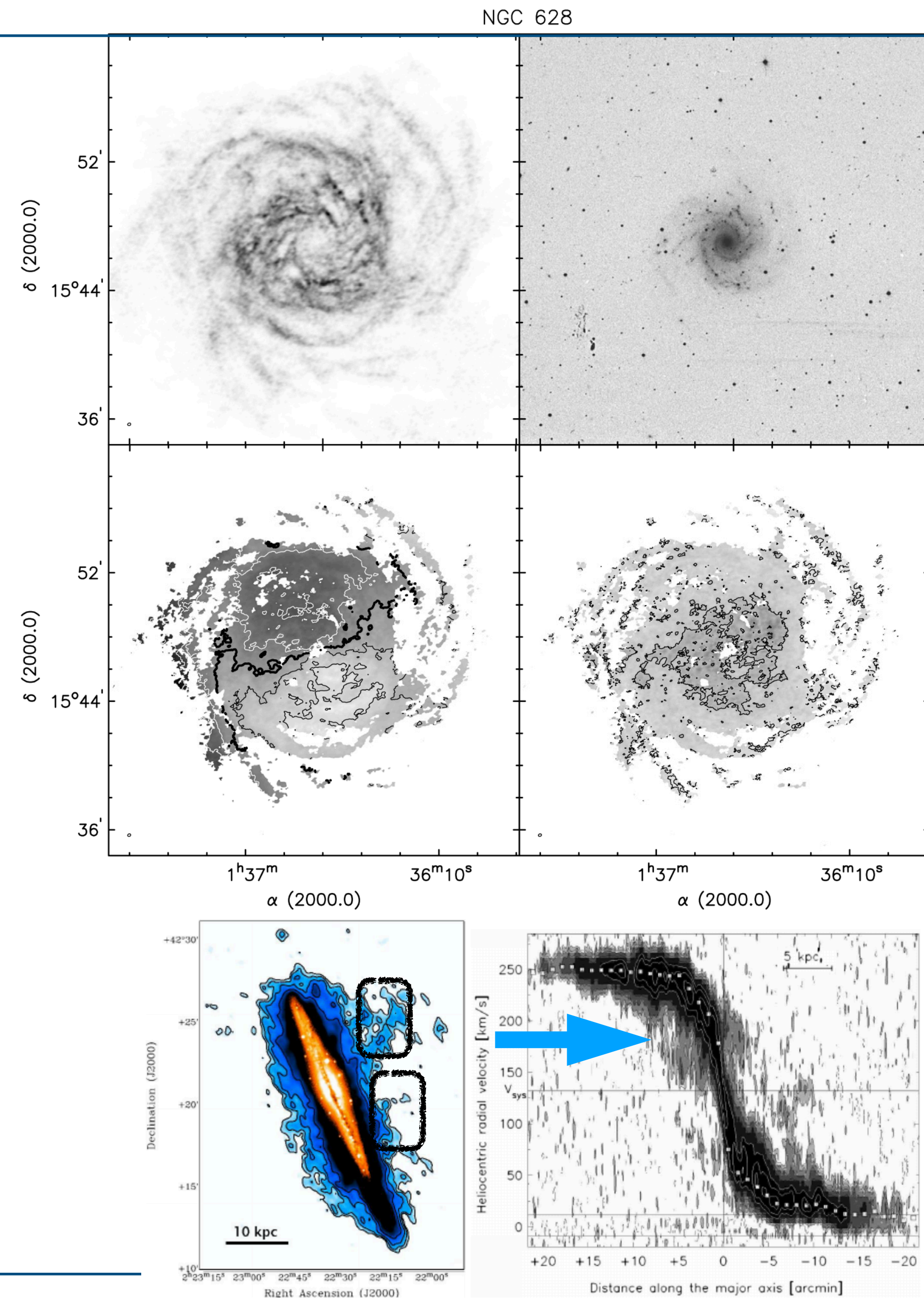
The only viable explanation is that the HI clouds have also a component of their velocity which is perpendicular to the disk.

The distribution of the gas in on a thicker disk wrt the one of stars.

Furthermore, there is evidence of clouds with anomalous velocities (extraplanar gas), associated to phenomena like galactic fountains



Walter et al. 2008 (THINGS)



Other effects of the environment:

**HI deficiency:** in spiral galaxies in dense environment, the amount of gas is significantly smaller than in similar galaxies (e.g. in the optical) in lower-density regions (e.g. isolated).

$$DEF = \log[M_{HI_{exp}}] - \log[M_{HI_{obs}}]$$

– if  $DEF > 0.3$  (less than half compared to normal) Deficient

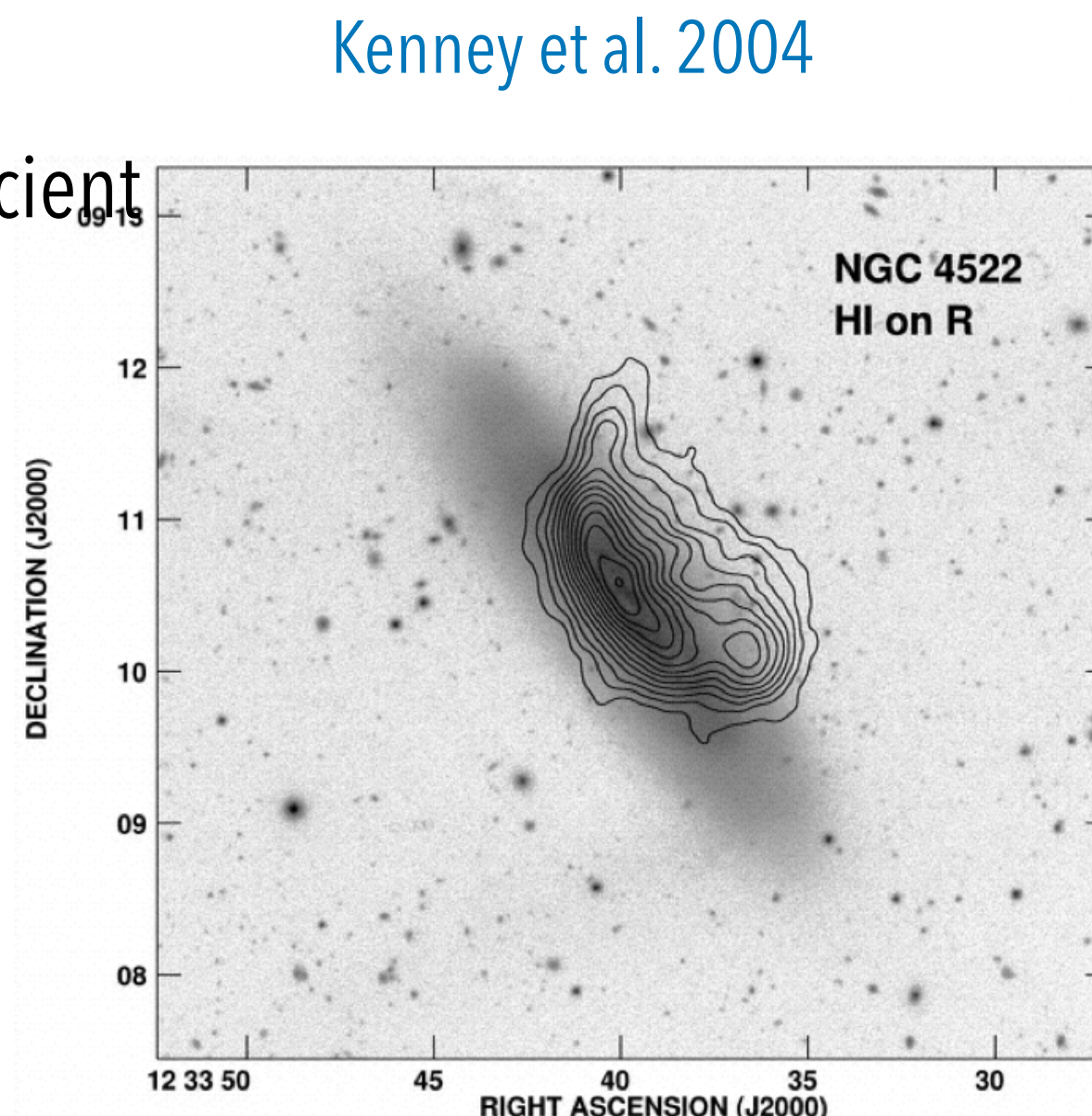
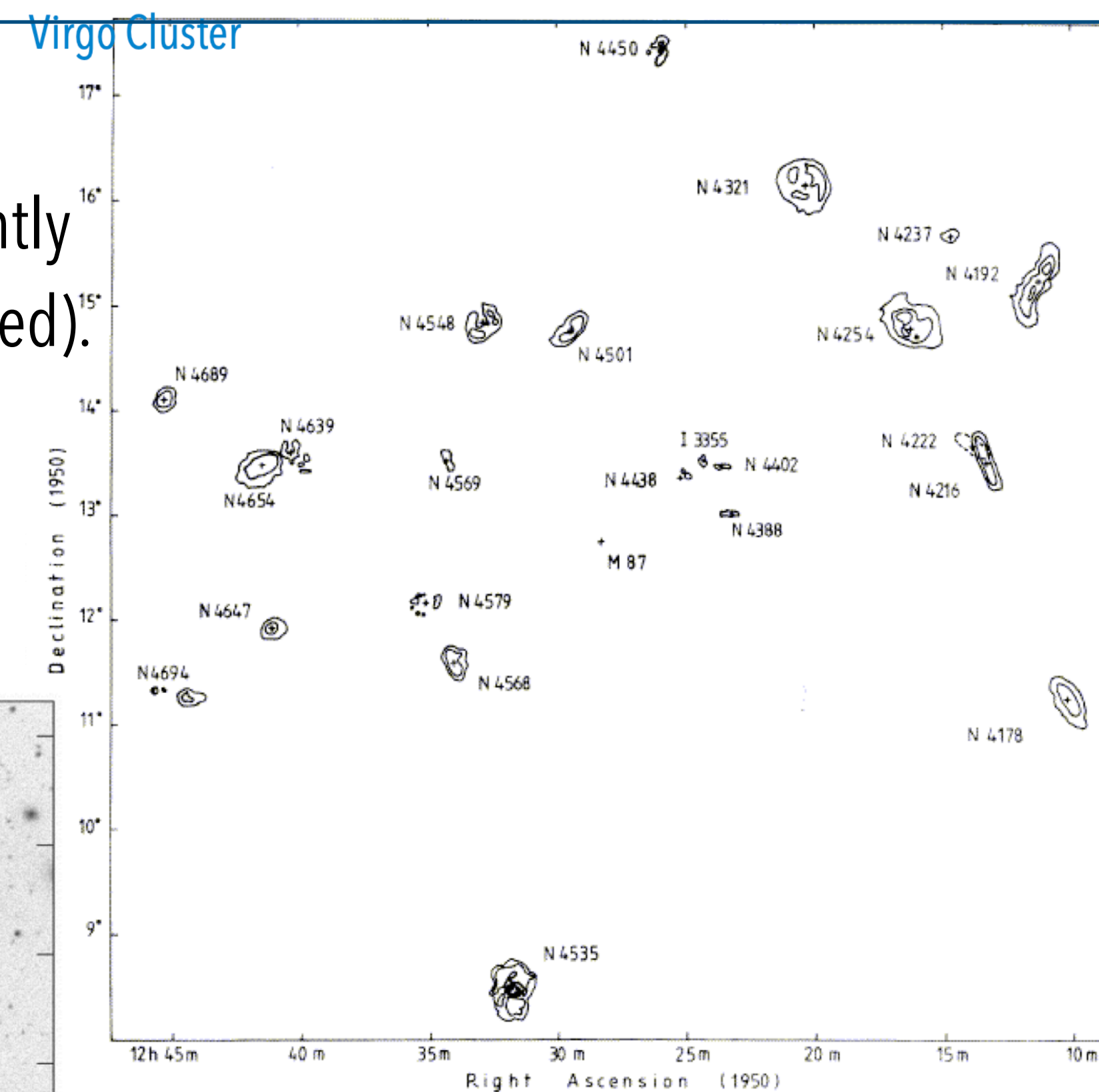
– if  $DEF > 0.6$  (less than 1/4 compared to normal) Strongly Deficient

We observe:

- A. Truncated disks
- B. Reduced/quenched star formation
- C. Loss of atomic/molecular gas (and dust)

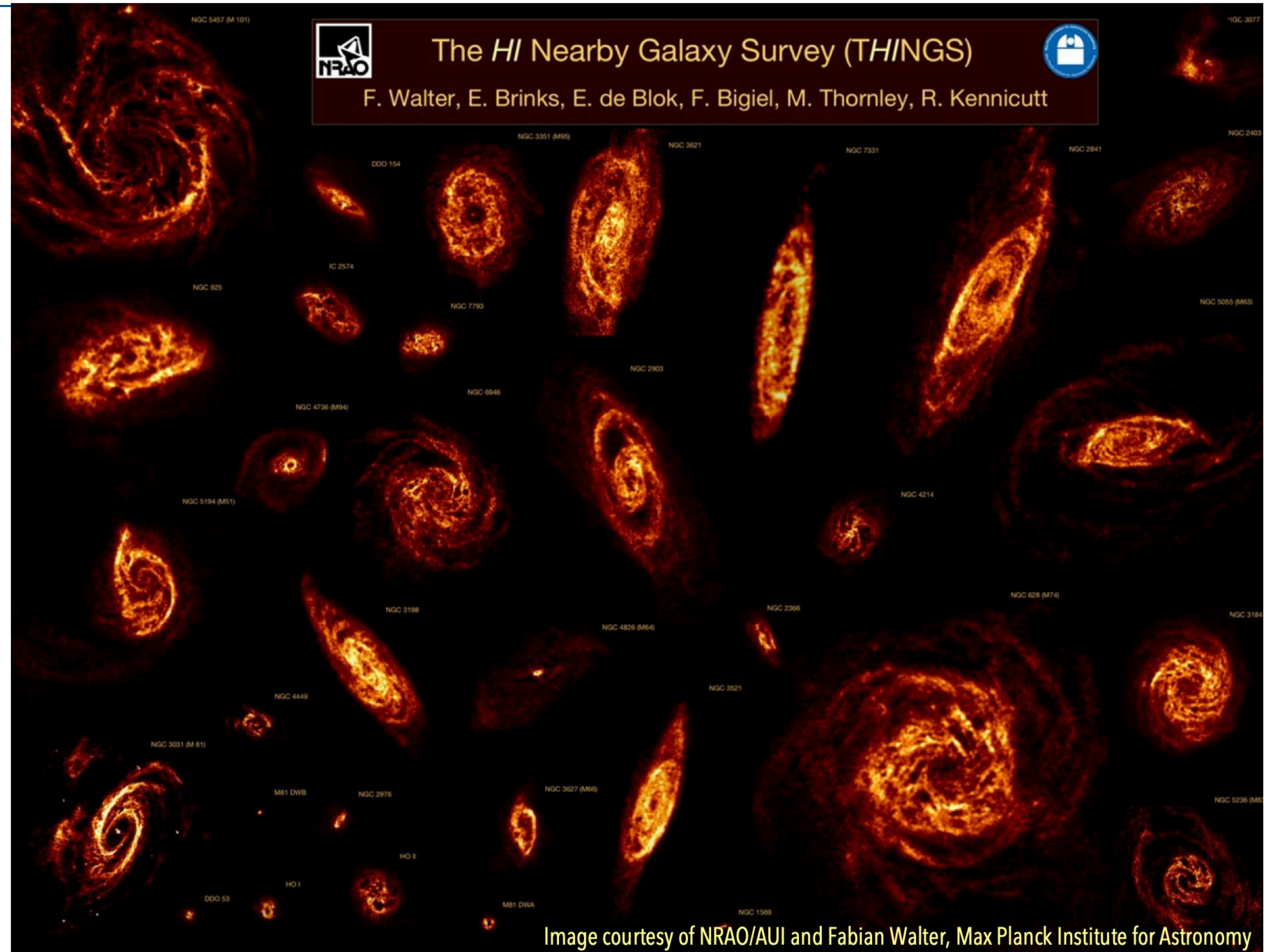
Motivation:

- Ram pressure stripping (more efficient in high density environments, and with high velocity galaxies)
- Orbital path (trajectories with small distance from the cluster center are more effective in stripping)
- High galaxy density provides gravitations interaction with neighbours (e.g. tidal tails)



Warning!

The amount, distribution, aspect  
Of the HI may be very different  
Among the various galaxies



# Radioastronomy - 3 - Interstellar medium – Oort (Constants) Parameters

Rotation within our own galaxy has been studied through the Doppler effect on spectral line emission.

## Assumption:

all the bodies have circular orbits wrt the galactic centre.

→ all velocities are identical, the change of relative positions (top panel) is a consequence of different angular velocities.

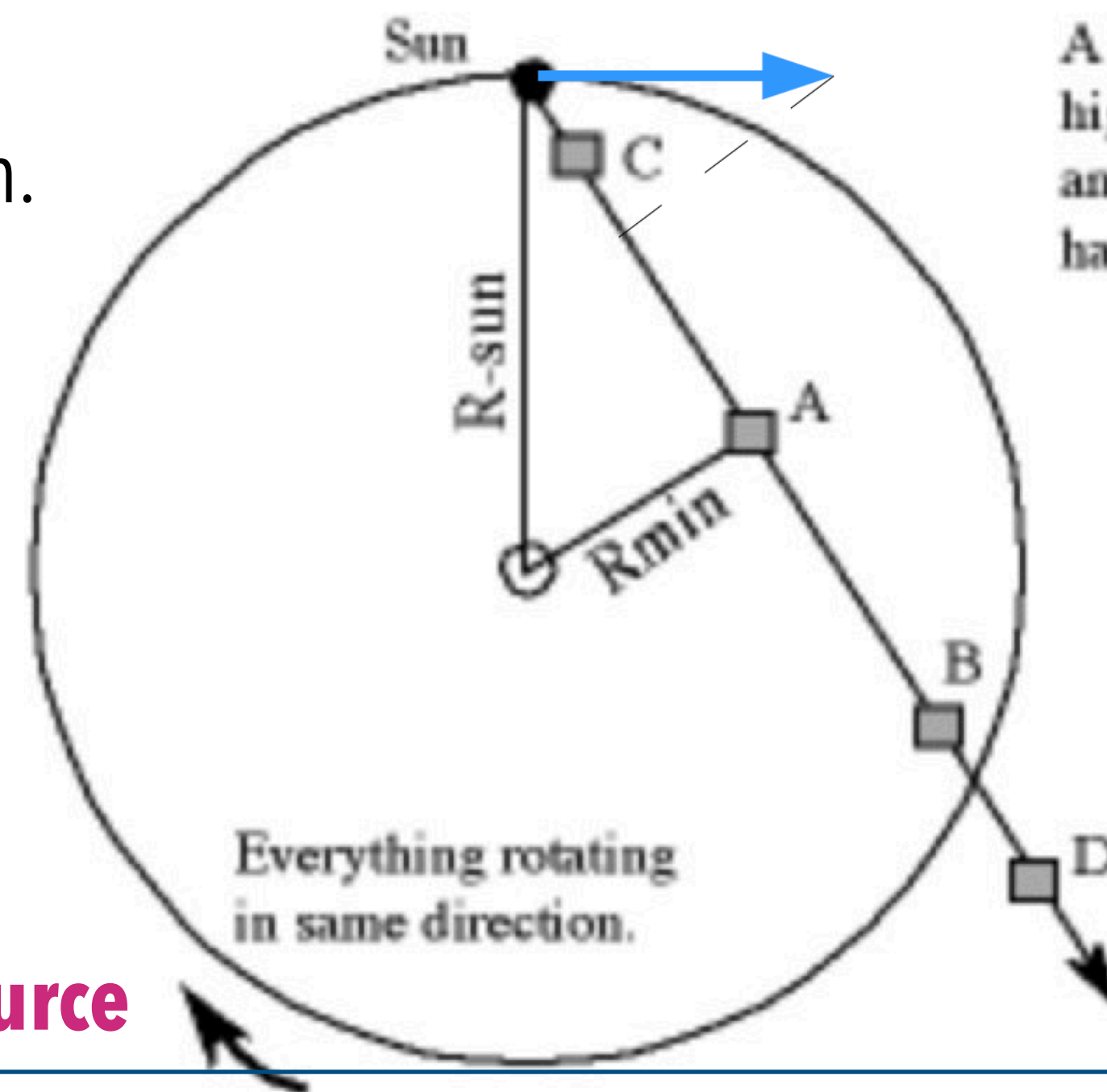
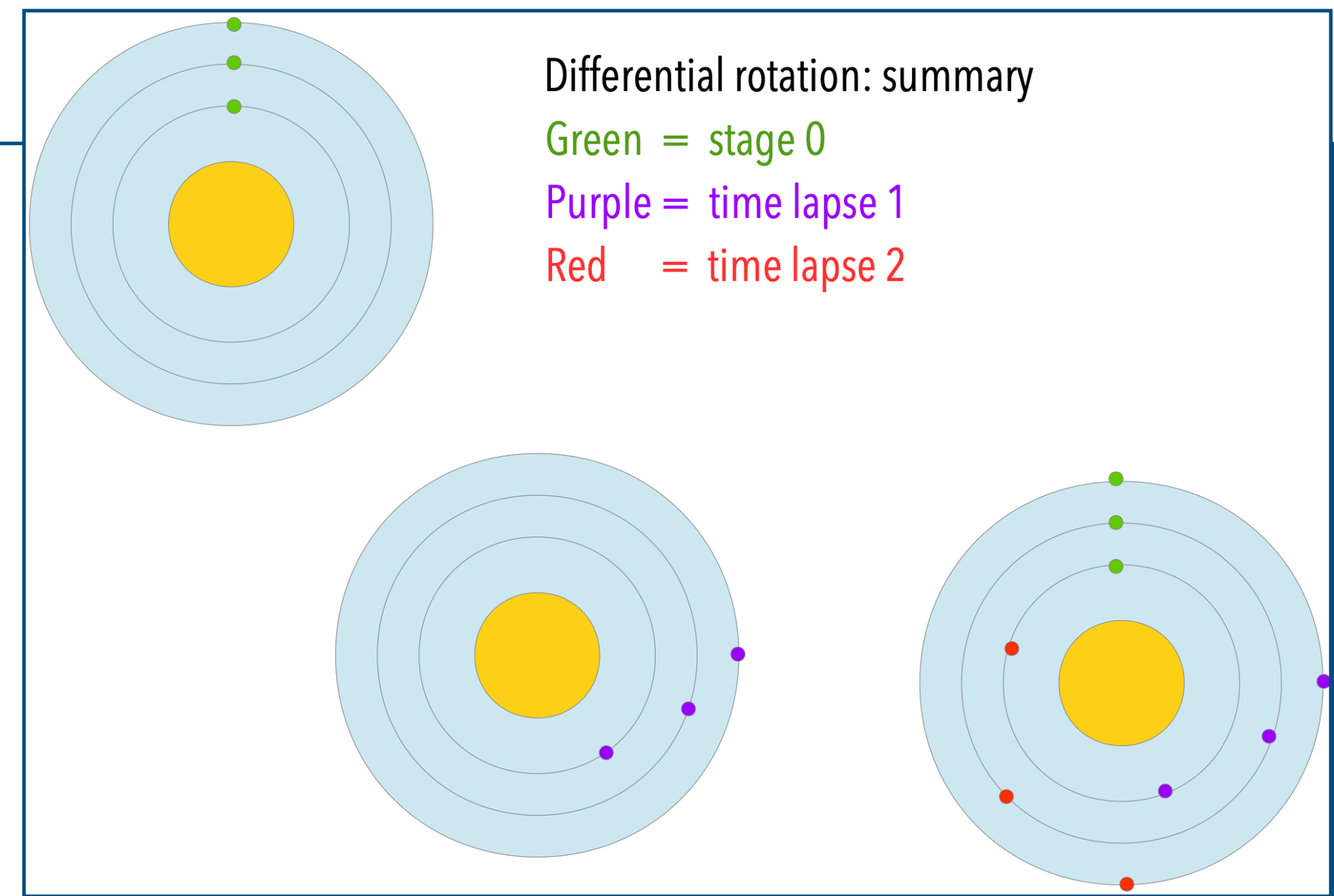
## Observational test:

let's consider 4 bodies in a given direction.

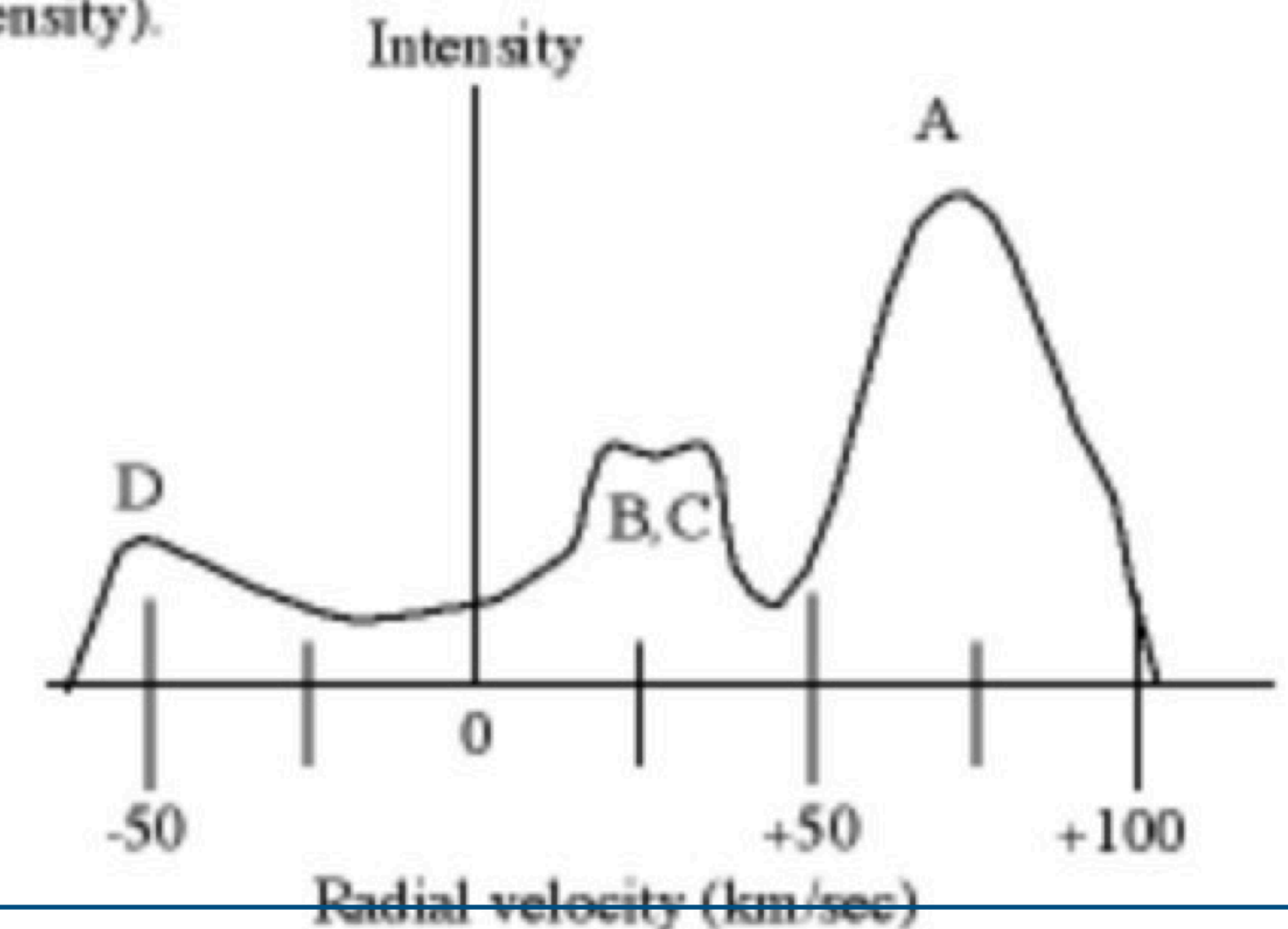
All of them follow circular orbits, but also the motion of the sun must be taken into account (bottom panel).

What is relevant is the projection of its velocity along the given direction.

**Need to know the distance to the source**



A has greatest angular speed and moving fastest away from sun. A has higher density of H. B & C moving at about same angular speed > sun's angular speed. D is outside solar distance—slower angular speed and has less material (density).



# Radioastronomy - 3 - Interstellar medium – Oort (Constants) Parameters

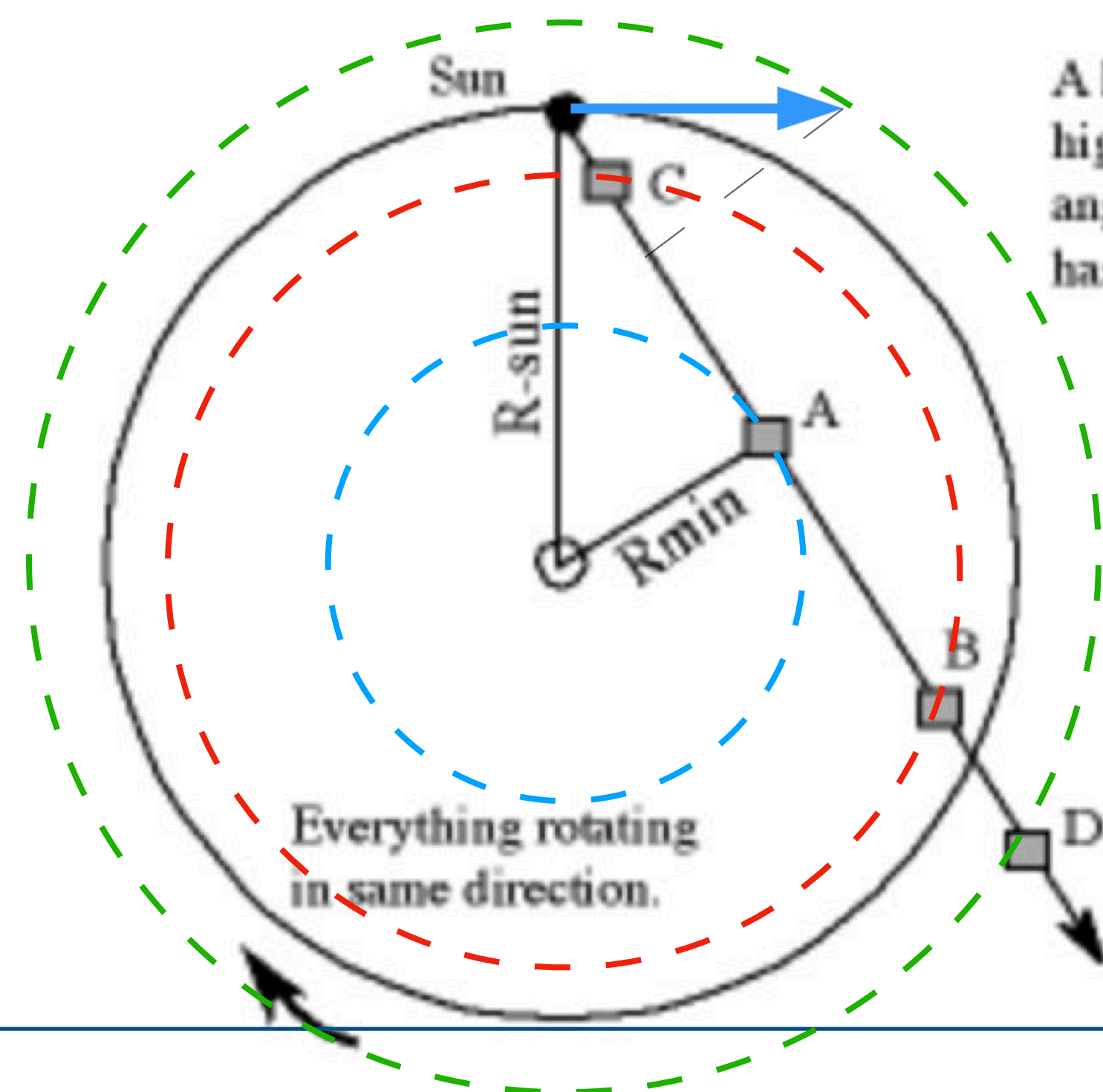
If we assume to know the positions of the various bodies, we can assess that, along the direction of A, B, C and D the **projection** of their velocity is determined by the **distance to the centre** of the Milky Way

- The velocity of A is aligned to its line of sight, then the Doppler effect is maximum.
- B and C are at the same distance to the galactic centre and have ~ the same velocity component along the LoS.
- D is at a larger radius, and its component is minimum, even smaller than the projection of the velocity of the sun along the LoS. Therefore its Doppler component will be negative (the sun is approaching D)

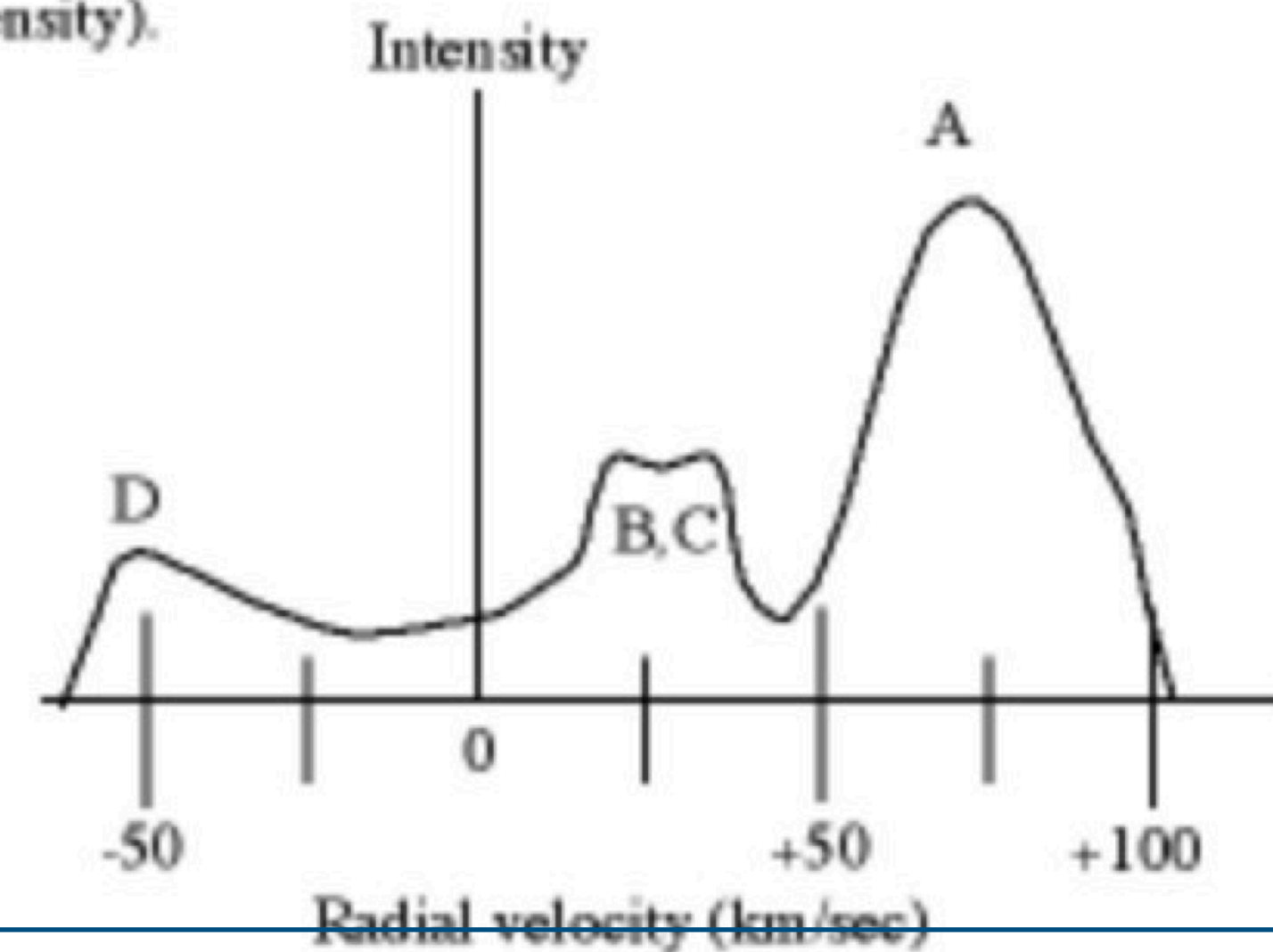
The observed spectrum of the same line would appear like shown on the right panel.

What kind of objects/lines can be used in the determination of the relative motions of the various parts of the MW?

– suggestions are welcome –



A has greatest angular speed and moving fastest away from sun. A has higher density of H. B & C moving at about same angular speed > sun's angular speed. D is outside solar distance—slower angular speed and has less material (density).



The problem can be restricted to a (simple) geometric system and worked out by Oort in 1927, using local stars (within a few kpc at most)

$l$  = galactic longitude ;  $\theta$  = galactocentric azimuth ;  $r$  = distance (assumed small)

$\Omega_{\odot}, R_{\odot}$  = solar angular velocity and distance to the galactic centre

$\Omega_R, R$  = angular velocity and distance of the body to the galactic centre

The **radial velocity** of a given body at P at distance  $r$  is given by:

$$v_r = \Omega_R R \cos\left(\frac{\pi}{2} - l - \theta\right) - \Omega_{\odot} R_{\odot} \cos\left(\frac{\pi}{2} - l\right) = \Omega_R R (\sin \theta \cos l + \cos \theta \sin l) - \Omega_{\odot} R_{\odot} \sin L$$

$$\frac{r}{\sin \theta} = \frac{R}{\sin l} \rightarrow r \sin l = R \sin \theta \text{ and } R \cos \theta = R_{\odot} - r \cos l$$

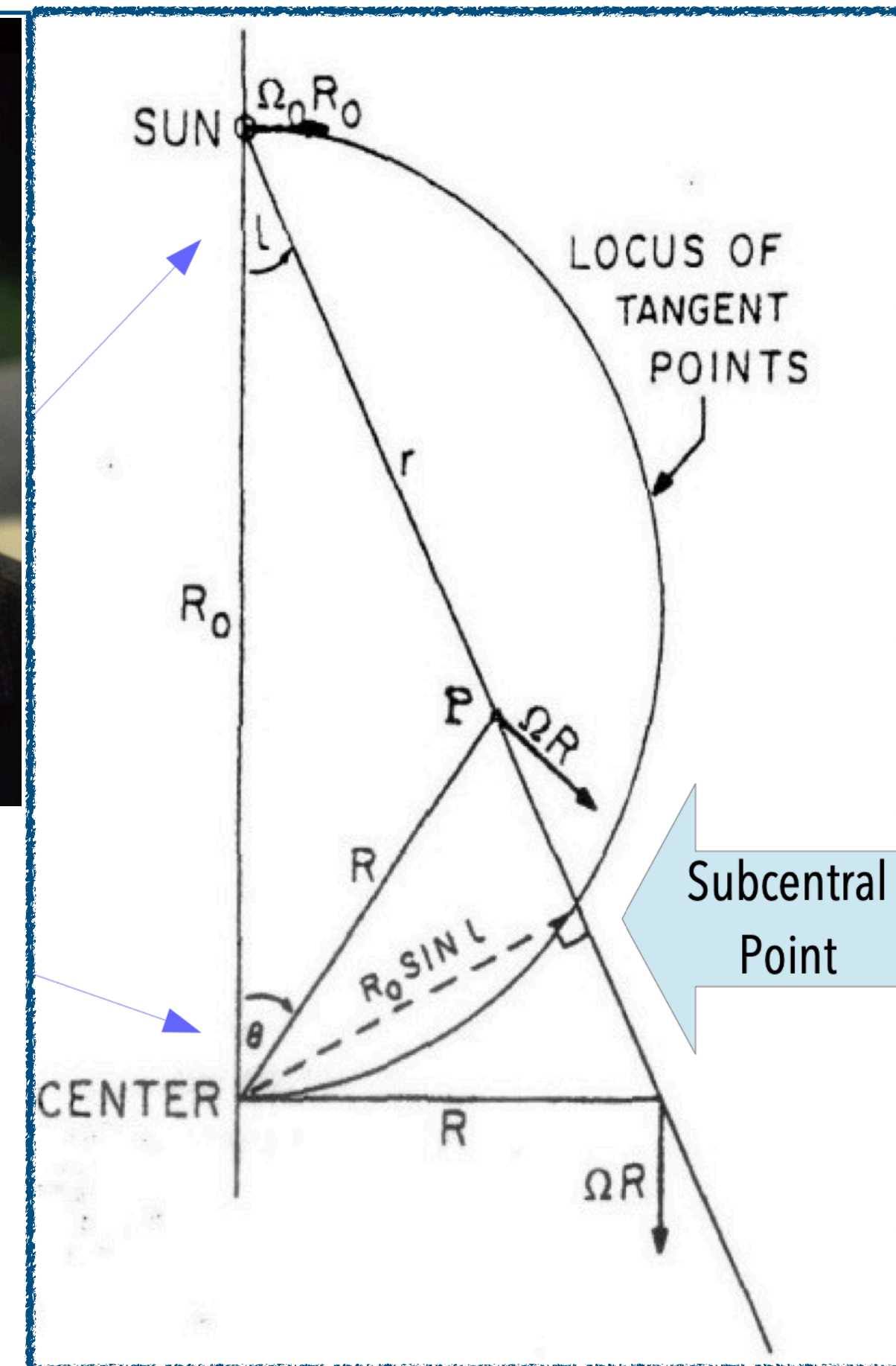
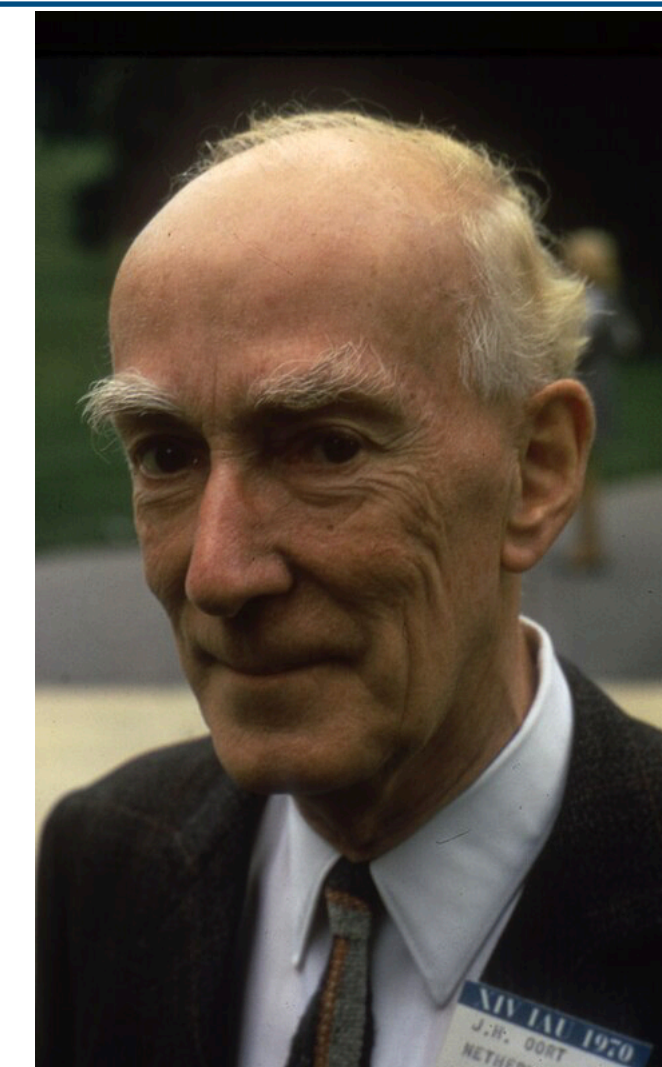
then the radial velocity can be written as

$$v_r = R_{\odot} [\Omega_R - \Omega_{\odot}] \sin l$$

Similarly, the **tangential** component of the velocity can be written and then we end with the following expressions

$$v(R, l)_r = R_{\odot} [\Omega_R - \Omega_{\odot}] \sin l$$

$$v(R, l)_t = R_{\odot} [\Omega_R - \Omega_{\odot}] \cos l - r \Omega_R$$



# Radioastronomy - 3 - Interstellar medium – Oort (Constants) Parameters

$v(R, l)_r$  has a maximum at the sub-central point.

From the measurement of the radial velocity for objects at distance  $r$  in a given direction  $l$ ,  $\Omega_R$  can be obtained and the local circular velocity can be determined  $v(R) = \Omega_R \cdot R$ .

If  $(\Omega_R - \Omega_{\odot})$  is small, we can use its Taylor expansion, remembering that, in the solar neighbourhood, also  $(R - R_{\odot})$  is small and it can be written as  $\simeq -r \cos l$

$$[\Omega_R - \Omega_{\odot}] = \left(\frac{d\Omega}{dR}\right)(R - R_{\odot}) \longrightarrow \frac{d\Omega_R}{dR} = \frac{d(v/R)}{dR} = \frac{1}{R} \frac{dv}{dR} - \frac{v}{R^2}$$

The radial velocity can be rewritten as.

$$v(R, l)_r = \left[\left(\frac{dv}{dR}\right)_{R_{\odot}} - \frac{v_{\odot}}{R_{\odot}}\right](R - R_{\odot}) \sin l = \left[\left(\frac{v_{\odot}}{R_{\odot}} - \frac{dv}{dR}\right)_{R_{\odot}}\right] r \cos l \sin l = Ar \sin 2l$$

The first Oort constant  $A$  has been defines as  $A = \frac{1}{2} \left[ \frac{v_{\odot}}{R_{\odot}} - \left(\frac{dv}{dR}\right)_{R_{\odot}} \right]$

The tangential velocity is  $v(R, l)_t = \frac{v}{R}(R \cos l - r) - v_{\odot} \cos l = [\Omega_R - \Omega_{\odot}]R \cos l - \Omega_R r$  and using the same Taylor expansion set

$$v(R, l)_t = \left[\left(\frac{v_{\odot}}{R_{\odot}} - \frac{dv}{dR}\right)_{R_{\odot}}\right] r \cos^2 l - \frac{v_{\odot}}{R_{\odot}} r = \left[\left(\frac{v_{\odot}}{R_{\odot}} - \frac{dv}{dR}\right)_{R_{\odot}}\right] r \left(\frac{1 + \cos 2l}{2}\right) - \frac{v_{\odot}}{R_{\odot}} r = \left[\left(\frac{v_{\odot}}{R_{\odot}} - \frac{dv}{dR}\right)_{R_{\odot}}\right] \frac{r}{2} + \left[\left(\frac{v_{\odot}}{R_{\odot}} - \frac{dv}{dR}\right)_{R_{\odot}}\right] r \cos 2l - \frac{v_{\odot}}{R_{\odot}} r$$

$$\left[\left(\frac{v_{\odot}}{R_{\odot}} - \frac{dv}{dR}\right)_{R_{\odot}}\right] r \cos 2l - \left[\left(\frac{v_{\odot}}{R_{\odot}} + \frac{dv}{dR}\right)_{R_{\odot}}\right] \frac{r}{2} = Ar \cos 2l - \left[\left(\frac{v_{\odot}}{R_{\odot}} + \frac{dv}{dR}\right)_{R_{\odot}}\right] \frac{r}{2}$$

And the second Oort constant has been defined as  $B = -\frac{1}{2} \left[ \left(\frac{v_{\odot}}{R_{\odot}} + \frac{dv}{dR}\right)_{R_{\odot}} \right]$

# Radioastronomy - 3 - Interstellar medium – Oort (Constants) Parameters

For any point, its velocity components can be written as:  $v_r = Ar \sin 2l$      $v_t = Ar \cos 2l + Br$

A and B are two coefficients dependent on  $R_\odot$  and  $\left(\frac{dv}{dR}\right)_{R_\odot}$  known as **Oort constants**. From the analysis of the Oort constants, it is possible to determine the properties of the motions of the bodies in the Milky Way:

The first Oort constant A has been defined as.

$$A = \frac{1}{2} \left[ \frac{v_\odot}{R_\odot} - \left( \frac{dv}{dR} \right)_{R_\odot} \right]$$

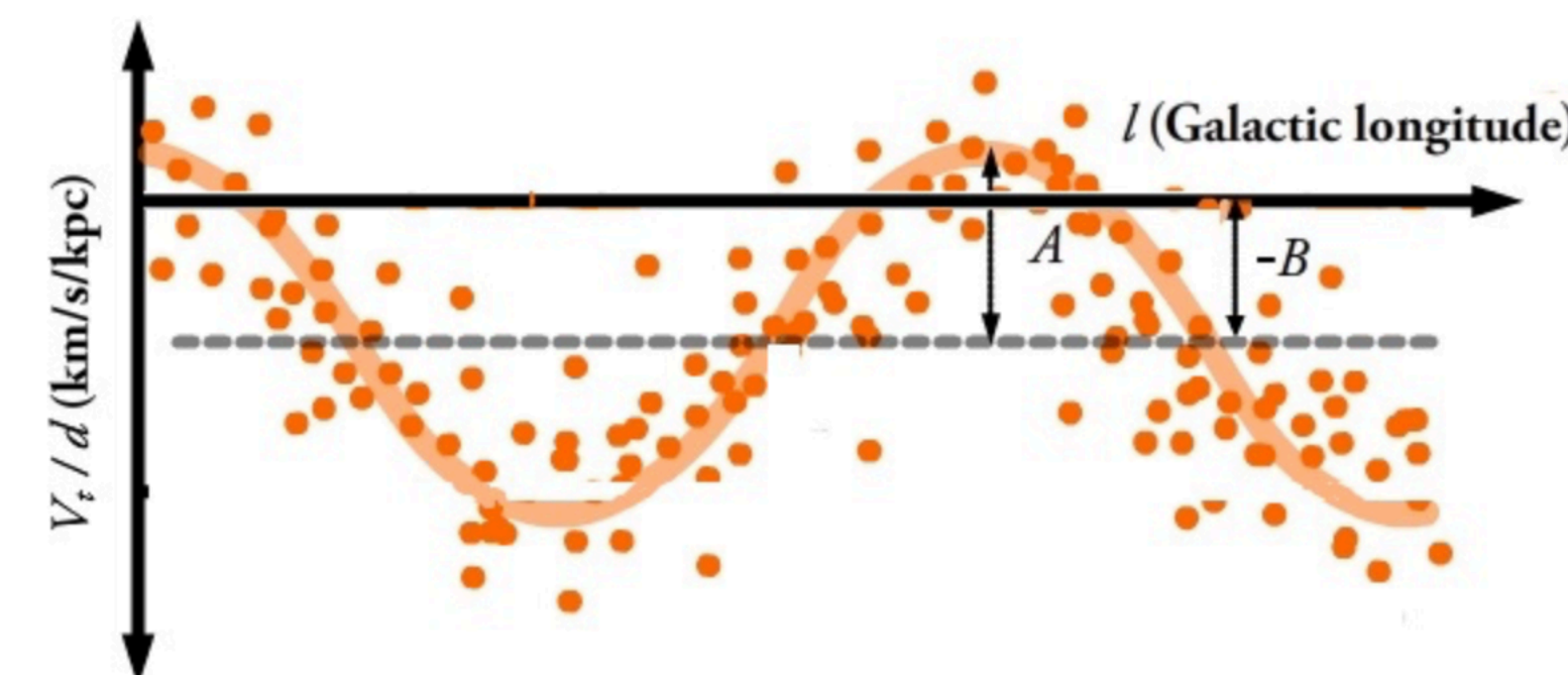
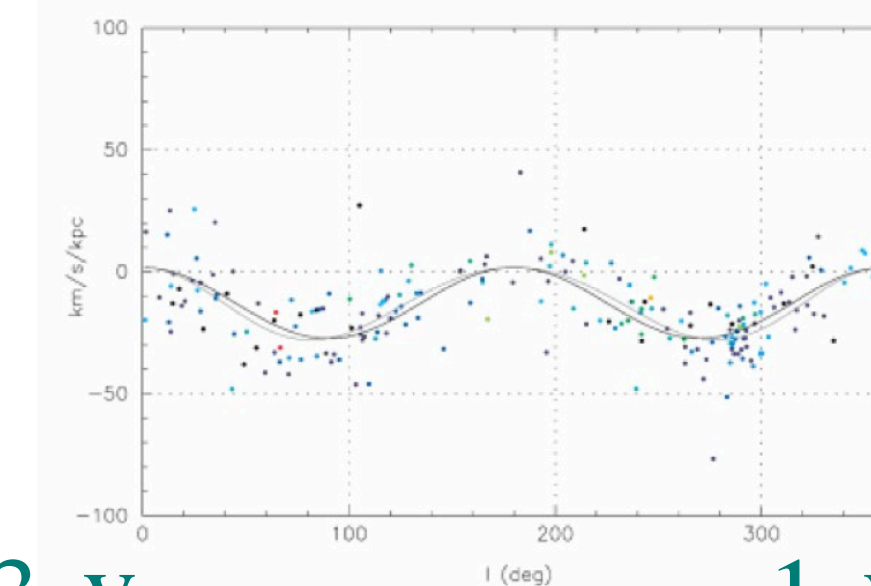
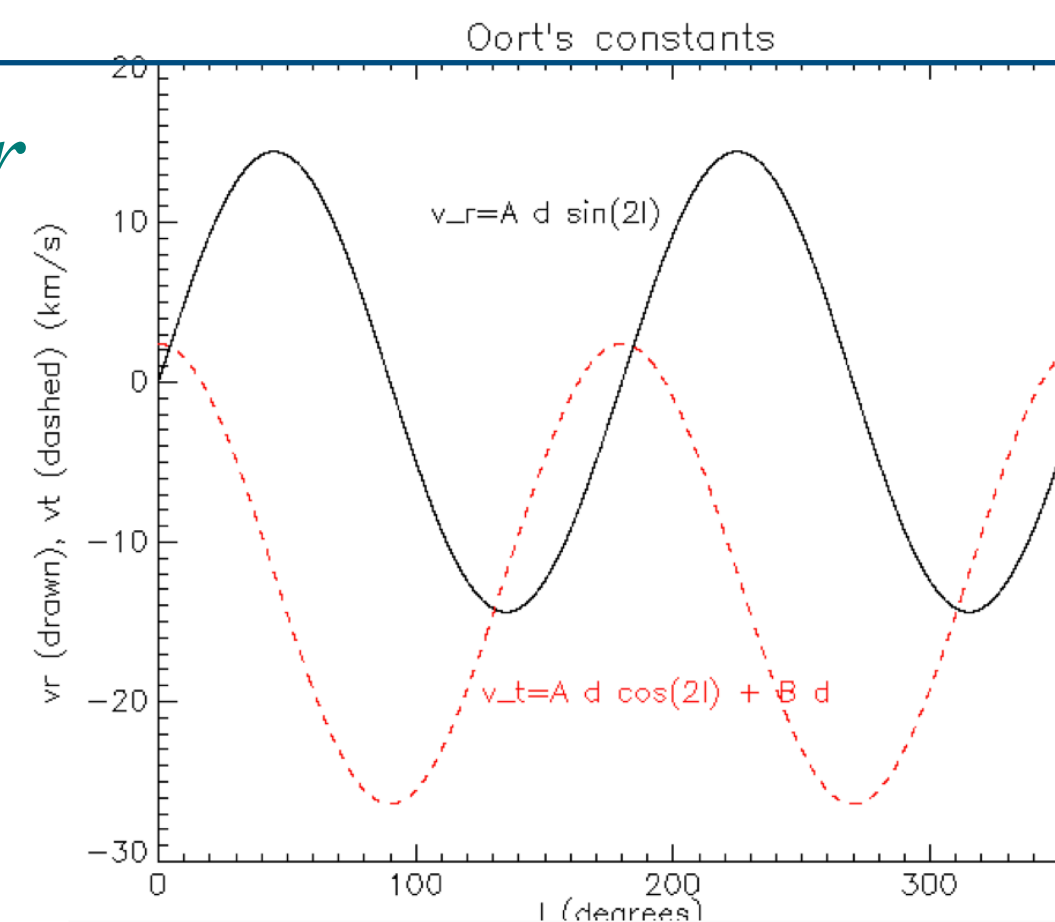
And the second Oort constant has been defined as

$$B = -\frac{1}{2} \left[ \left( \frac{v_\odot}{R_\odot} + \frac{dv}{dR} \right)_{R_\odot} \right]$$

● **Solid body:**  $\frac{dv}{dR} = \frac{v}{R} = \Omega \quad \longrightarrow \quad A = 0 \quad B = -\Omega_\odot$

● **Keplerian regime:**  $v = \sqrt{\frac{GM}{R}} \quad \longrightarrow \quad \frac{dv}{dR} = -\frac{1}{2} \sqrt{\frac{GM}{R^3}} = -\frac{1}{2} \frac{v}{R} \quad \longrightarrow \quad A = \frac{3}{4} \frac{v_\odot}{R_\odot} \quad B = -\frac{1}{4} \frac{v_\odot}{R_\odot}$

● **Flat rotation curve:**  $\frac{dv}{dR} = 0 \quad \longrightarrow \quad A = \frac{1}{2} \frac{v_\odot}{R_\odot} \quad B = -\frac{1}{2} \frac{v_\odot}{R_\odot}$



Observations provide

$$A = 14.82 \pm 0.84 \text{ kms}^{-1}\text{kpc}^{-1}$$

$$B = -12.37 \pm 0.64 \text{ kms}^{-1}\text{kpc}^{-1}$$

# Radioastronomy - 3 - Interstellar medium – Oort (Constants) Parameters

$$A = 14.82 \pm 0.84 \text{ kms}^{-1}\text{kpc}^{-1}$$

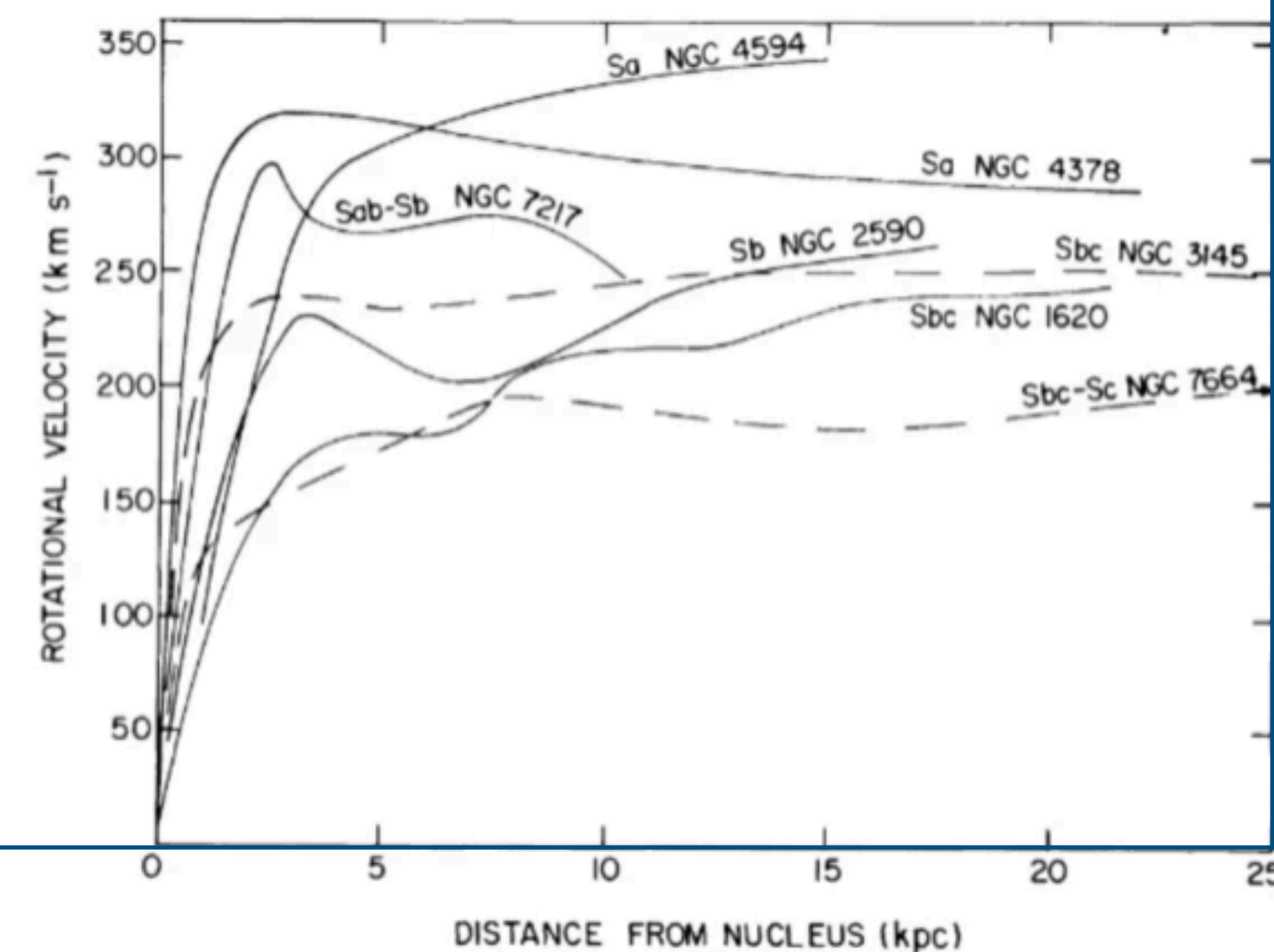
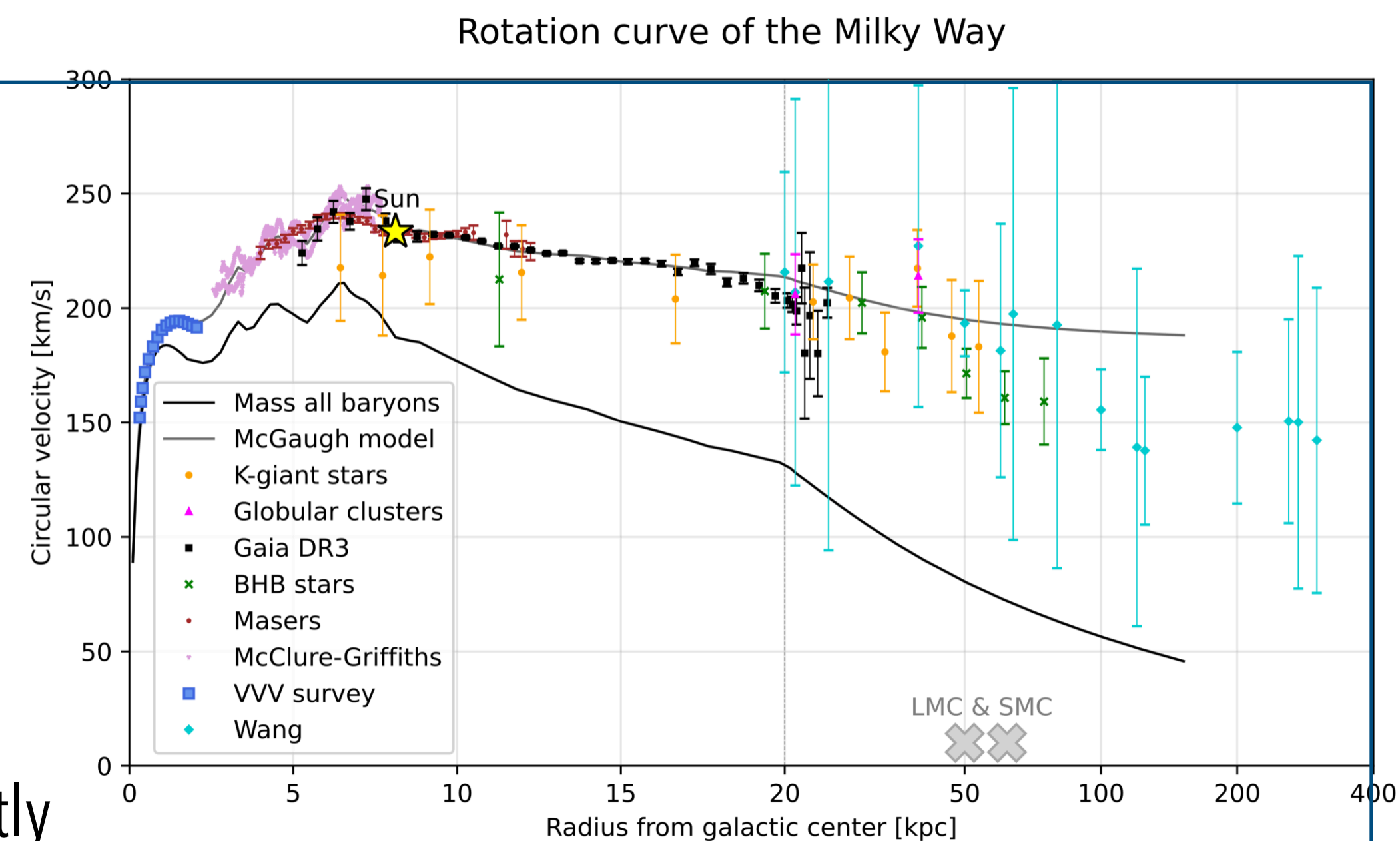
$$B = -12.37 \pm 0.64 \text{ kms}^{-1}\text{kpc}^{-1}$$

The rotation curve is nearly flat, and the Keplerian regime is never observed. This is consistent with the observations of the rotation curve in external spiral galaxies. All of them have similar trends (bottom panel).

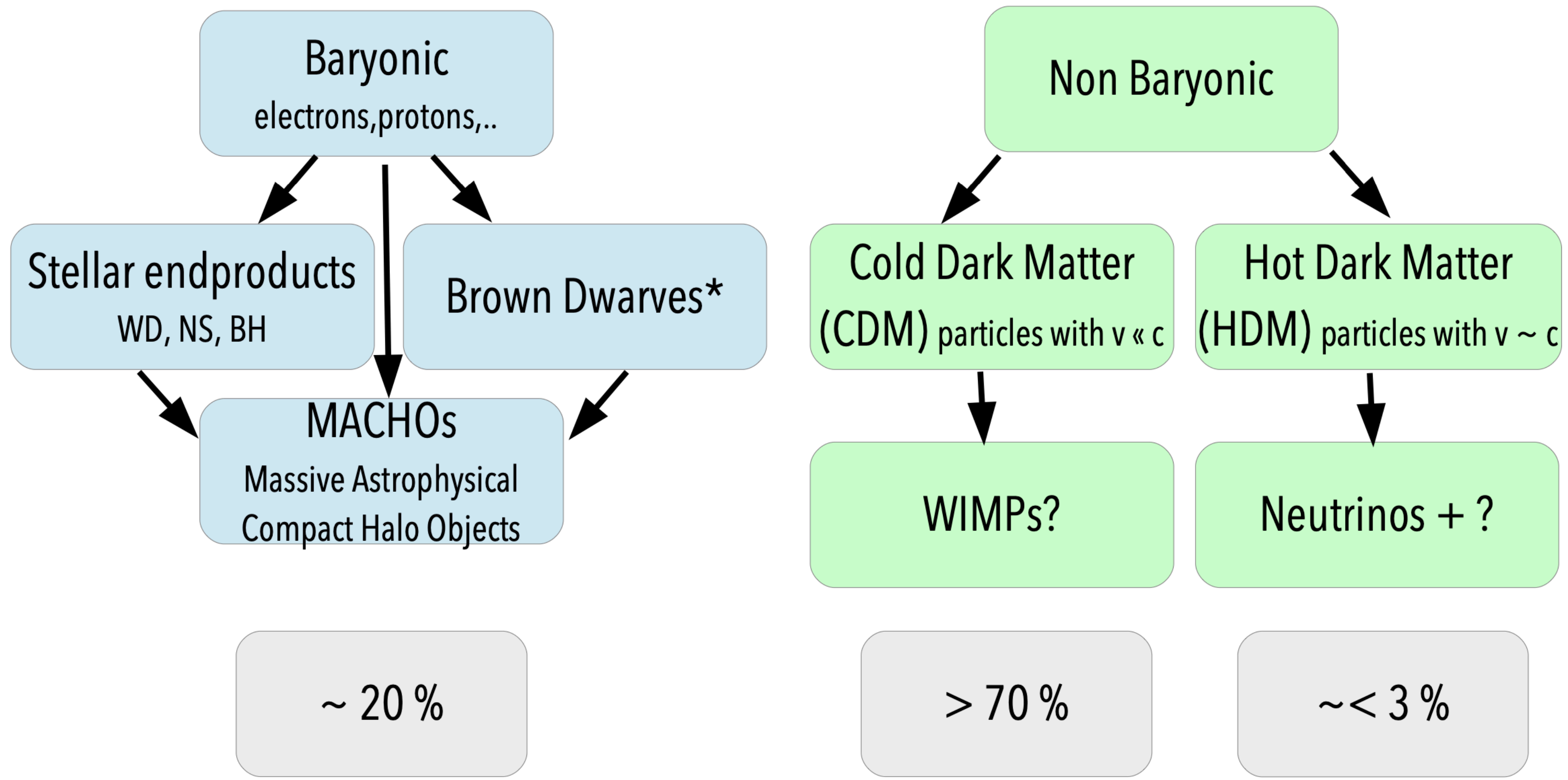
In order to have nearly constant circular velocities, the mass has to significantly increase with the distance from the center of the galaxy.

Dark matter would be necessary to keep the velocity at high values at large distances, even where the stars are not visible anymore and HI emission only is visible.

Other possibilities have also been explored (e.g. MOND), but none of them has turned out satisfactory



Constraints on Dark Matter:



e.g. MOND)