The Interstellar Medium (ISM)

The radio view, what radio astronomy can measure

Main research fields

A number of open questions

- Fanti & Fanti   § 13
- Tools of Radio Astronomy § 13

- What is it? Composition, Observations, Parameters

➢ HII

➢ HI

➢ Masers & Stars (circum – stellar envelopes)

➢ H_2 (CO & al.)

- Where is it? Distribution, kinematics, origin and fate

Spirals .vs. Ellipticals (& Irregulars)

The Interstellar Medium (ISM)

Composition: ~99% gas 90% H, 10% other elements (mostly He)

Molecules, Atoms, Ions (including cosmic rays)

1% dust (grains, sub- um size)

\+ Magnetic Field

Extinction, absorption & IR Emission

Roto–vibrational transitions in mm, sub-mm (mostly CO) and infrared bands

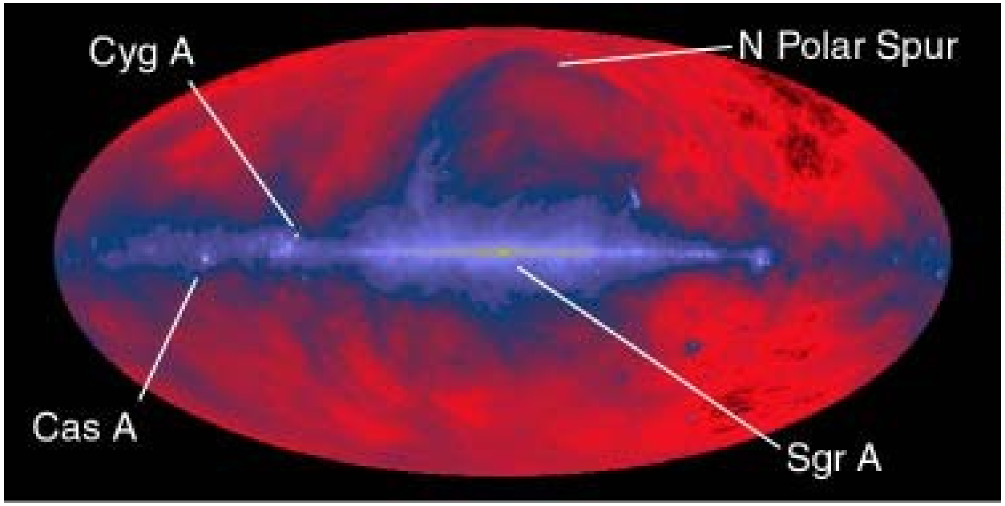
Hyperfine transition at 1.42 GHz

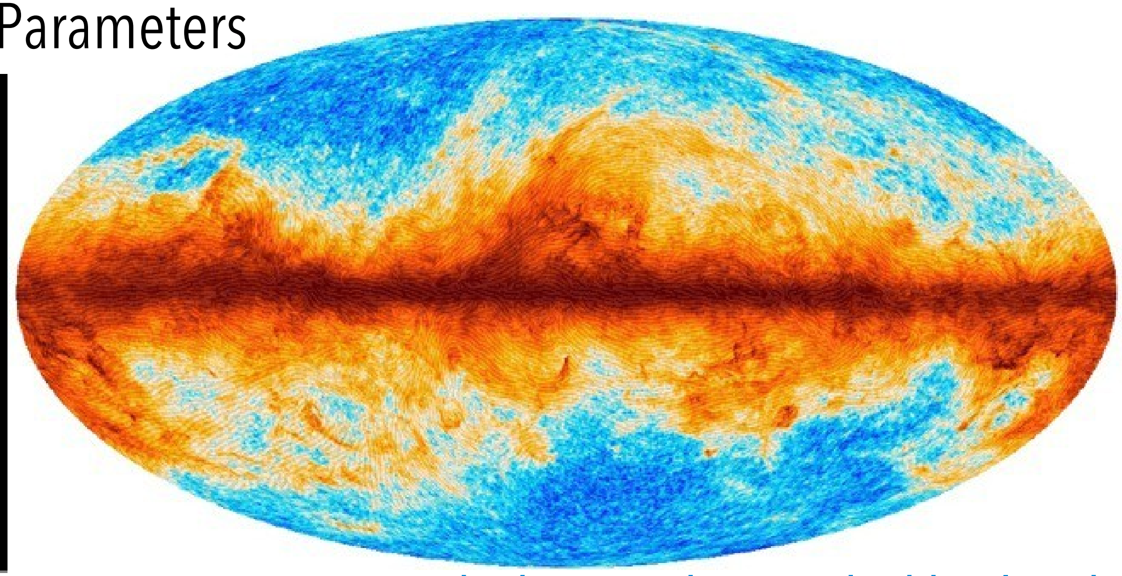
Bremsstrahlung from thermal plasma (WIM & HIM) +

Synchrotron (electrons in cosmic rays + individual objects)

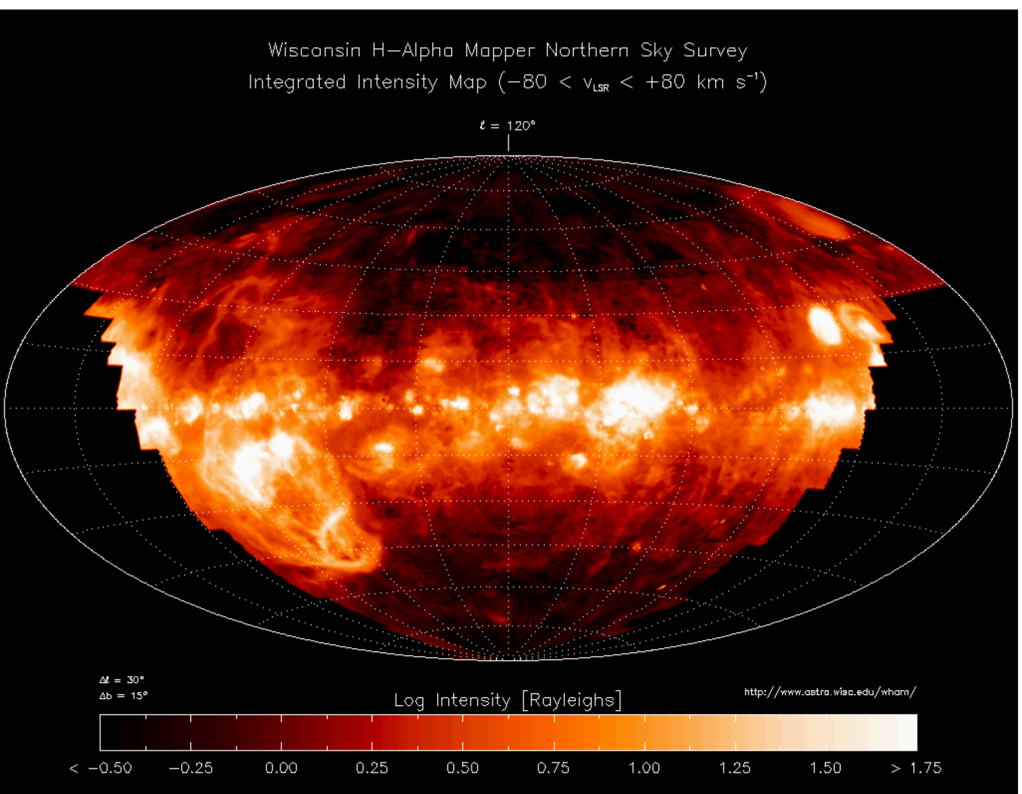
Gamma rays from CR-partner collisions

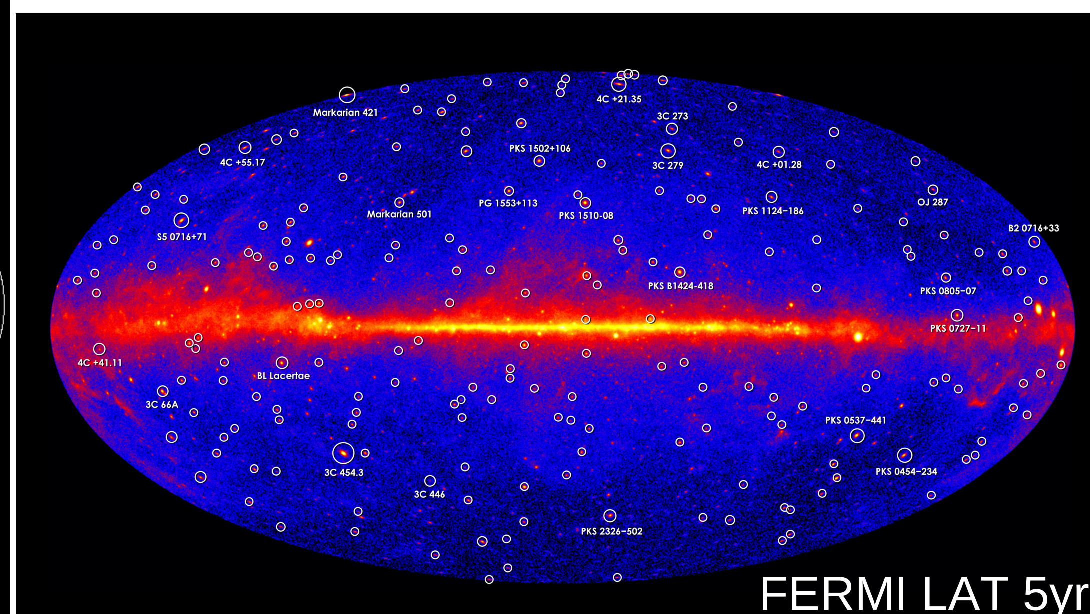
What is it? Composition, Observations, Parameters





Dust emission as observed with Planck





What is it? Composition, Observations, Parameters

Average density 0.1-1 cm $^{-3}$, inhomogeneous distribution

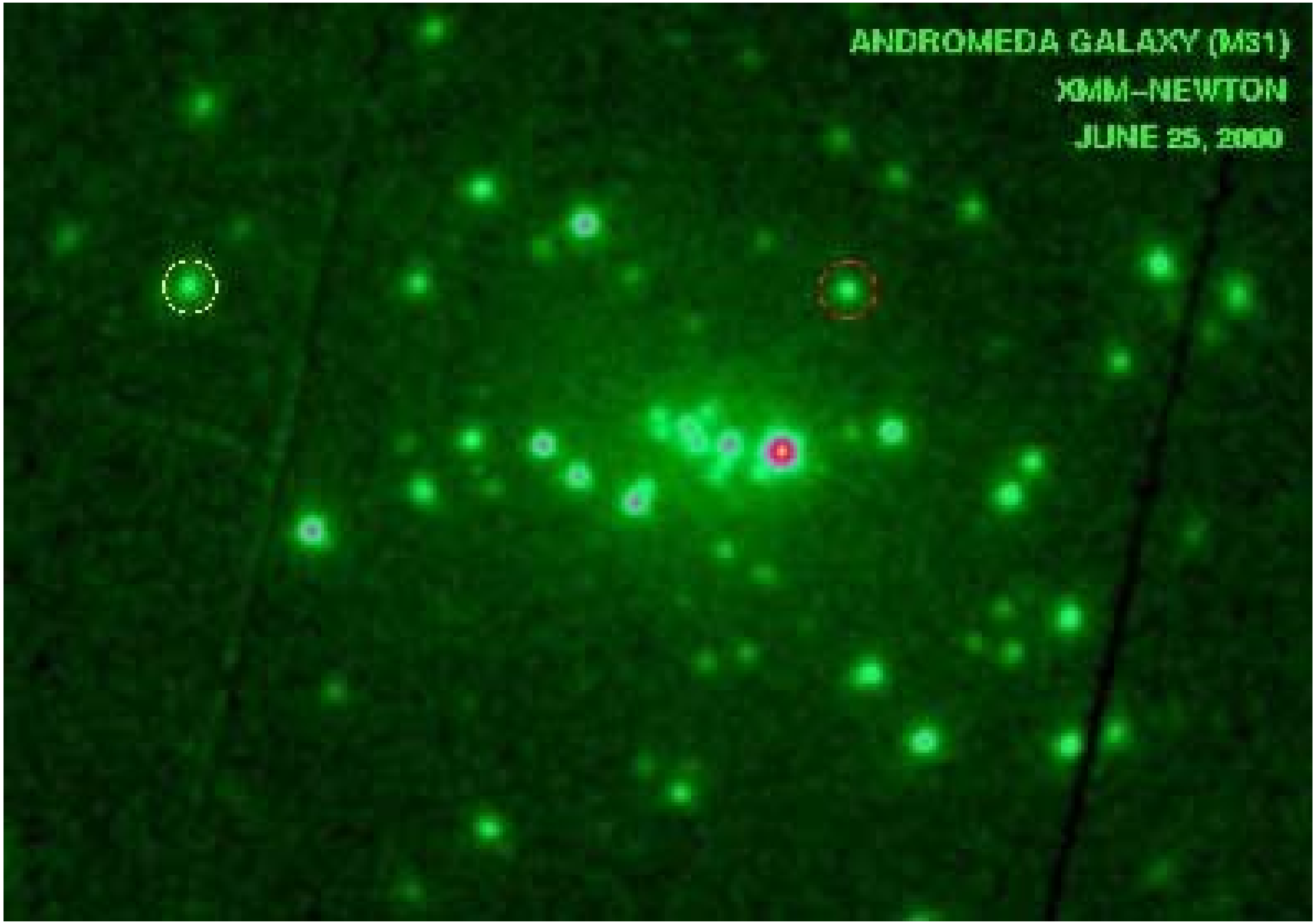
Name	N (cm^{-3})	T (K)	M (10^9 M_{sun})	Fraction of Total Volume
molecular	> 10^2	*10*	*2*	*1%*
CNM	50	< 10^2	3	4%
WNM	0.5	10^3	4	30%
WIM	0.3	10^4	1	15%
HIM	0.003	>10^6	0.1	50%

Typical values for a spiral galaxy

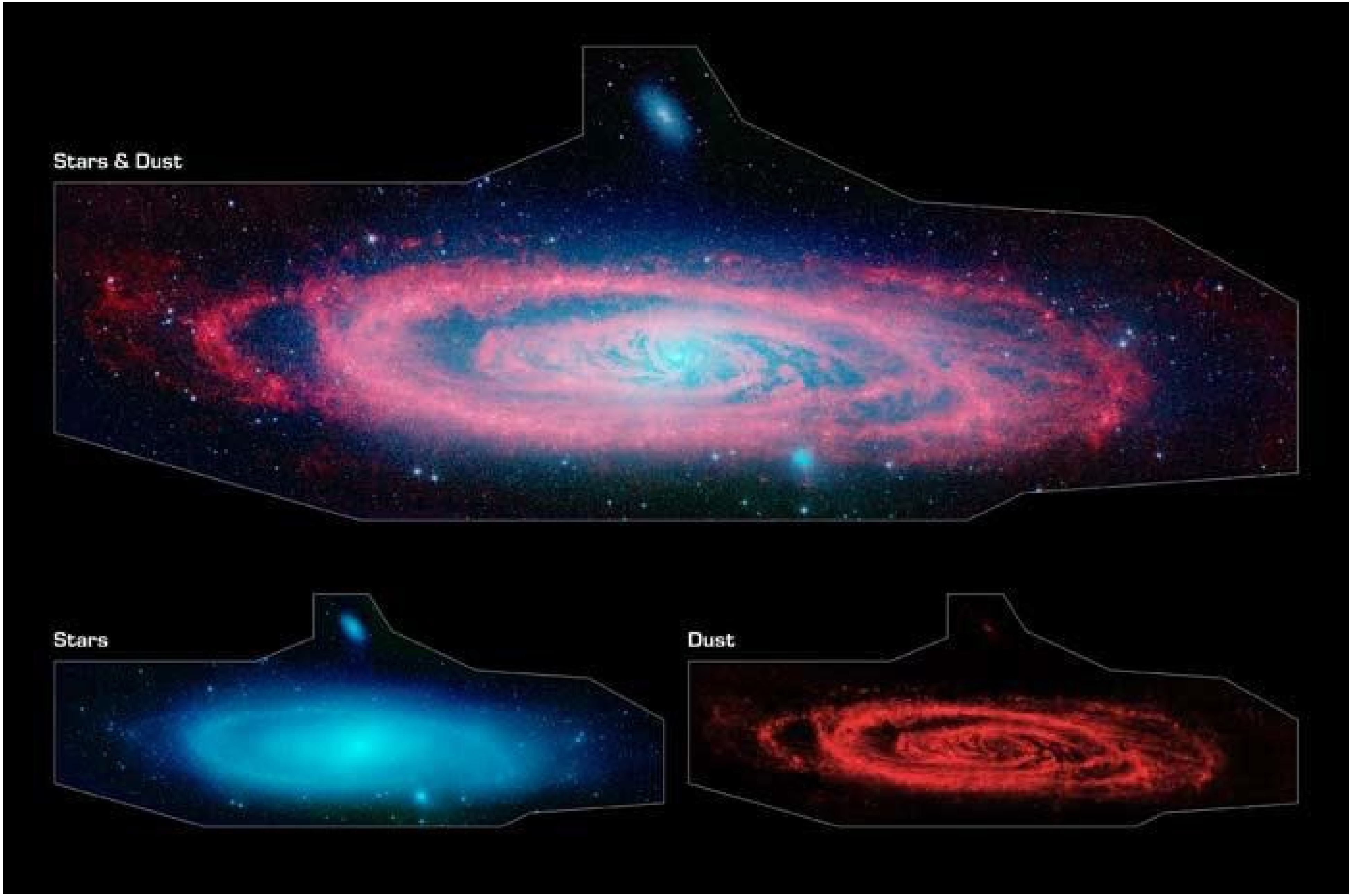
Dust is generally associated with CNM, i.e. dense and cold environments

Learning from other spirals: M 31 aka Andromeda Galaxy, ~3.2° x 1.0° in size

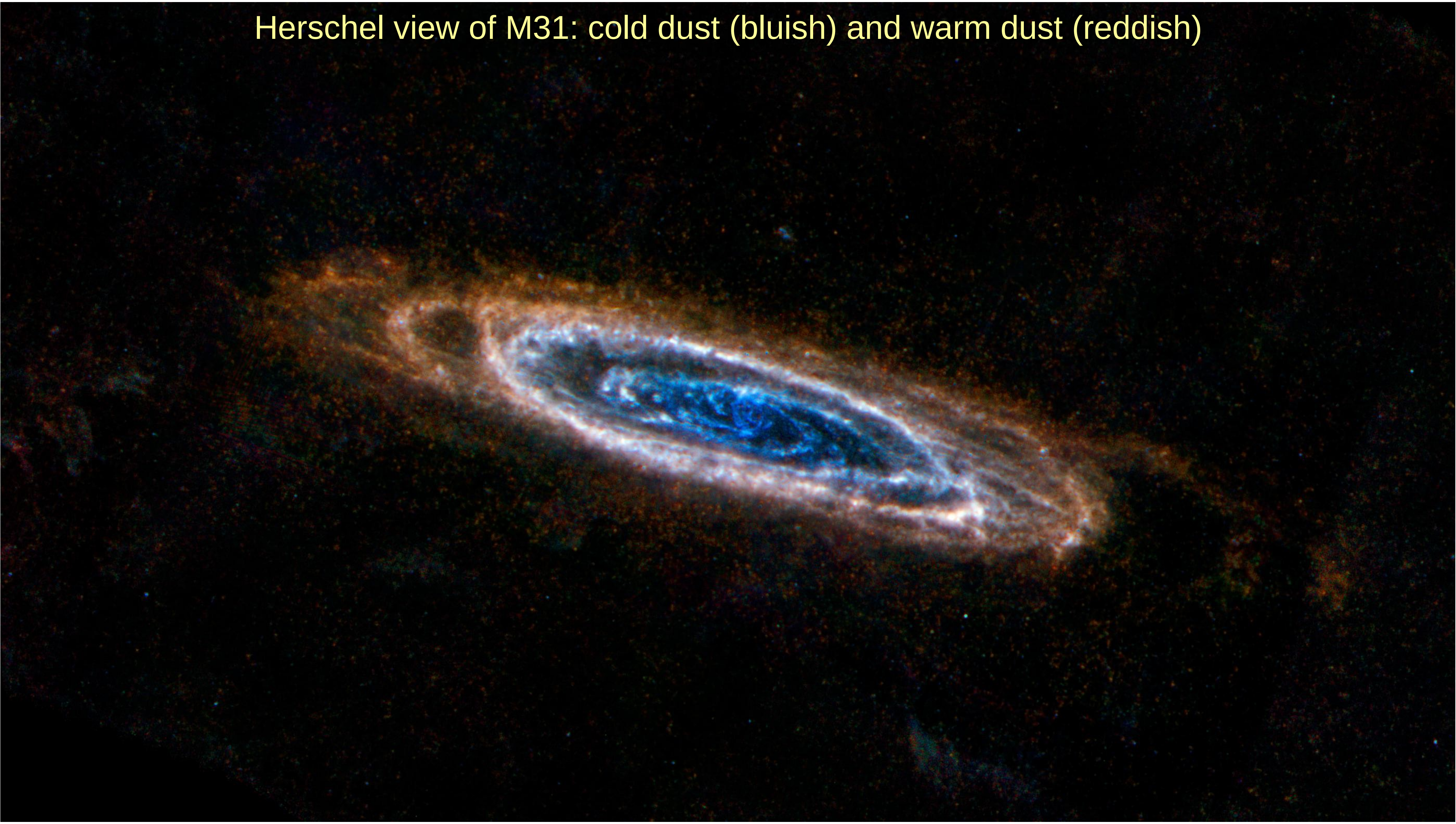
Learning from other spirals: X – rays captured by XMM – Newton (30' FoV)



Learning from other spirals:

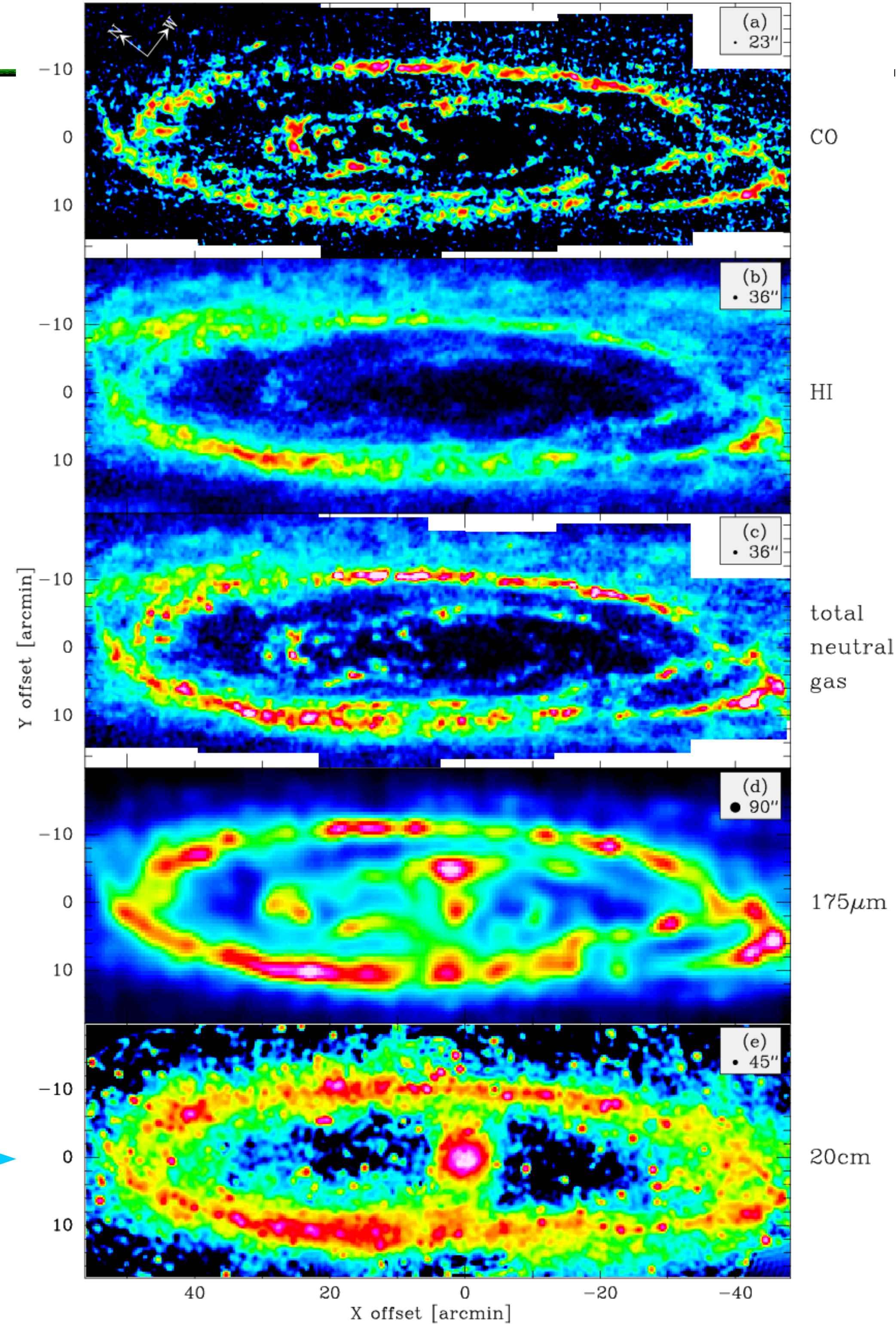


Learning from other spirals:



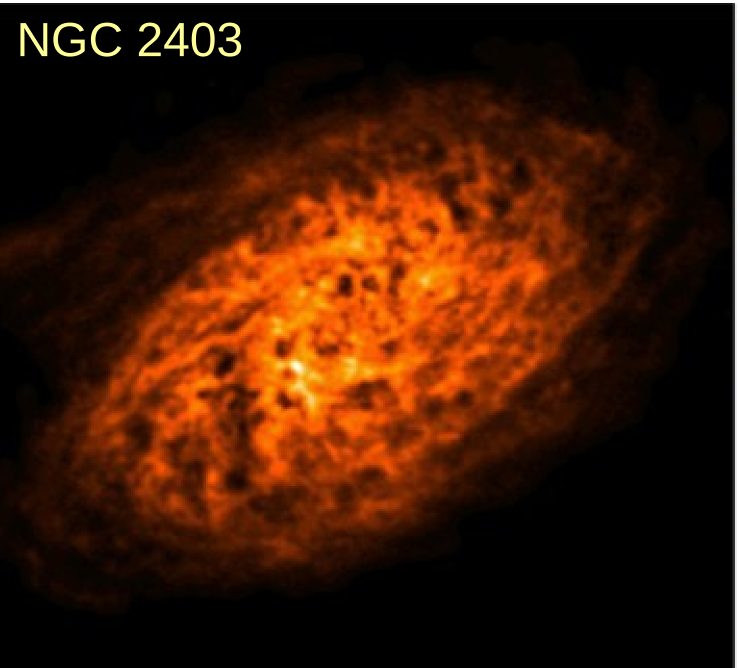
Learning from other spirals:

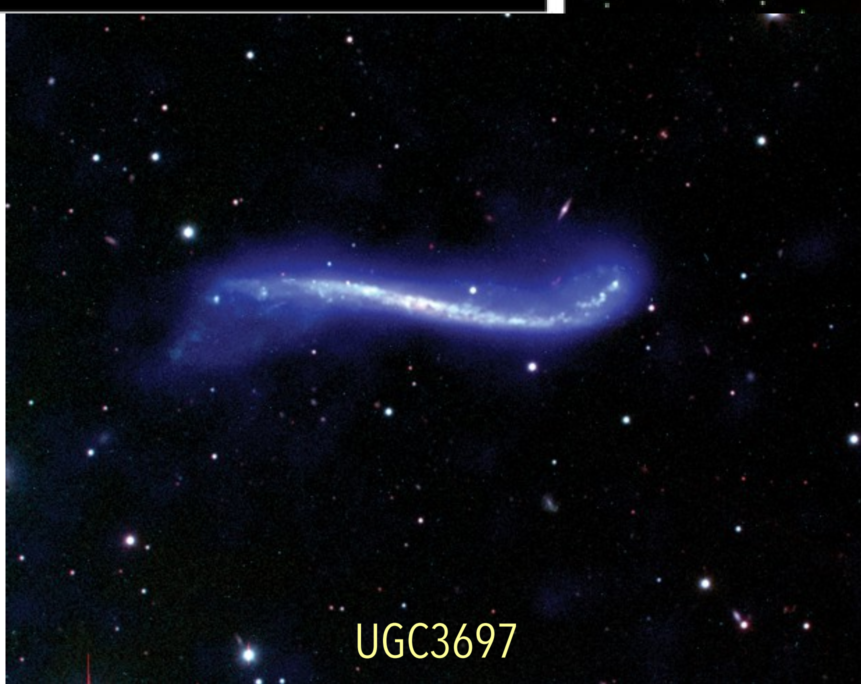
Comparison of emission observed at different wavelenghts

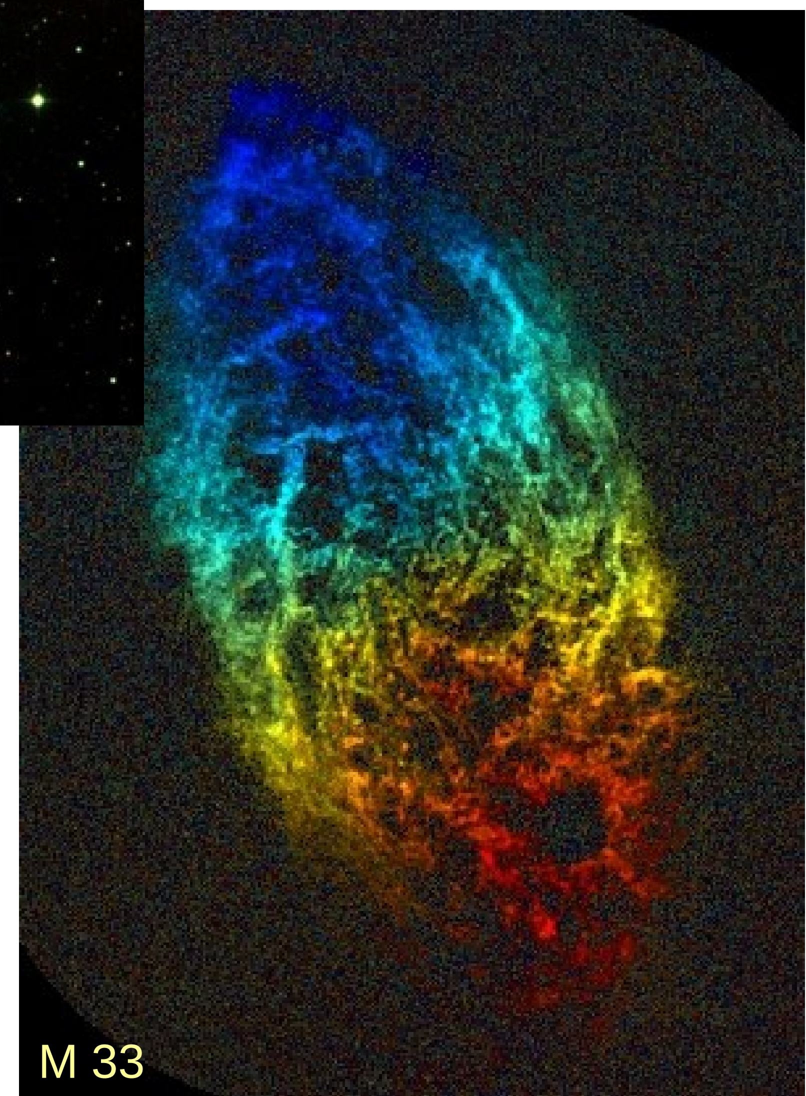


HI & Synchrotron

Learning from other spirals: Neutral H emission .vs. Stellar distribution







Learning from other spirals:

Purple: VLA

Red: Spitzer

Yellow: DSS

Blue: Chandra

- Hyperfine structure: $\Delta E \sim 5.9\ \mu eV$
- Natural width of 21 cm line $\sim 10^{-16}$ m/s

- Collisions $\sim 10^4$ times more frequent than radiative transitions, then thermal equilibrium
- Excited level : Ground level = 3 : 1

The brightness temperature derived from line photons:

$$T_{B(H)} = T_s\left(1 - e^{-\tau_H}\right) \text{ where } \tau_H \text{ is the optical depth}$$

$$\text{If} \quad \tau_H \ll 1 \quad \rightarrow \quad T_{B(H)} = T_s \tau_H$$

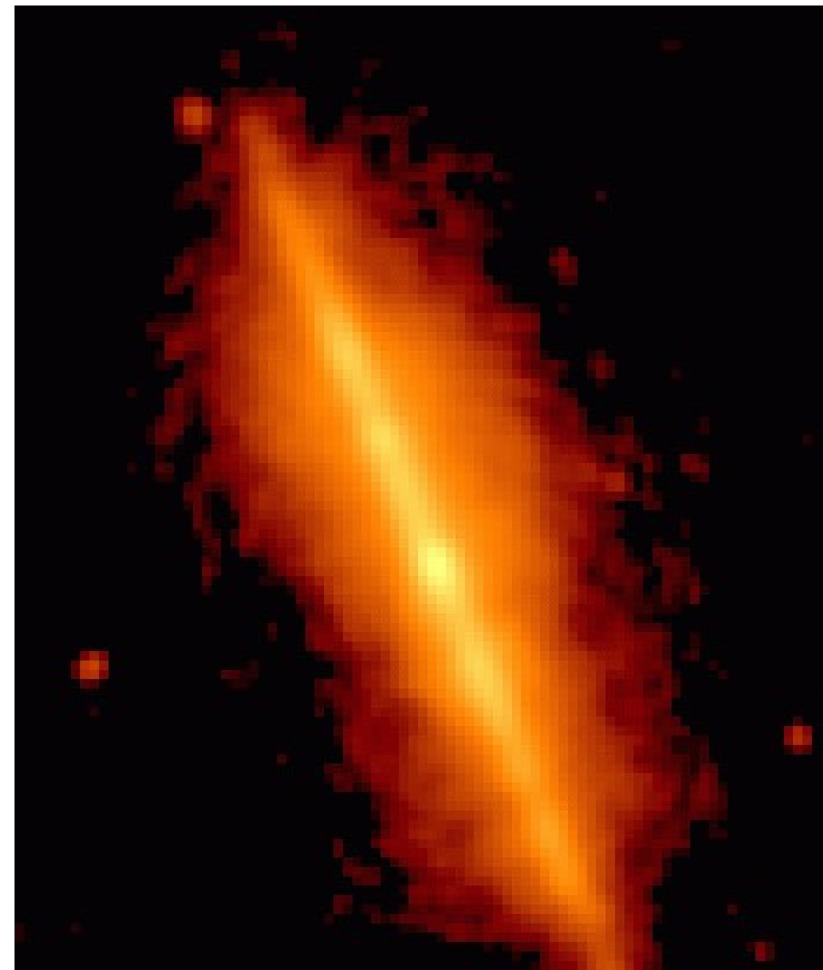
$T_{B(H)}$ is in K if N_H is in cm^{-2}

$$n_H l = N_H \quad \text{column density}$$

$$T_{B(H)} = \int_{line} T_{B(H)}(\nu) d\nu = \int_{line} T_S \tau_H(\nu) d\nu =$$

$$= 2.58 \cdot 10^{-15} N_H = T_s \tau_H$$

$$\tau_H = 2.58 \cdot 10^{-15} \frac{n_H l}{T_s} = 2.58 \cdot 10^{-15} \frac{N_H}{T_s}$$



Observed 1.4 GHz radio image of the edge-on spiral galaxy NGC 891. All the continuum emission seen in the image comes from relativistic electrons (synchrotron continuum emission).

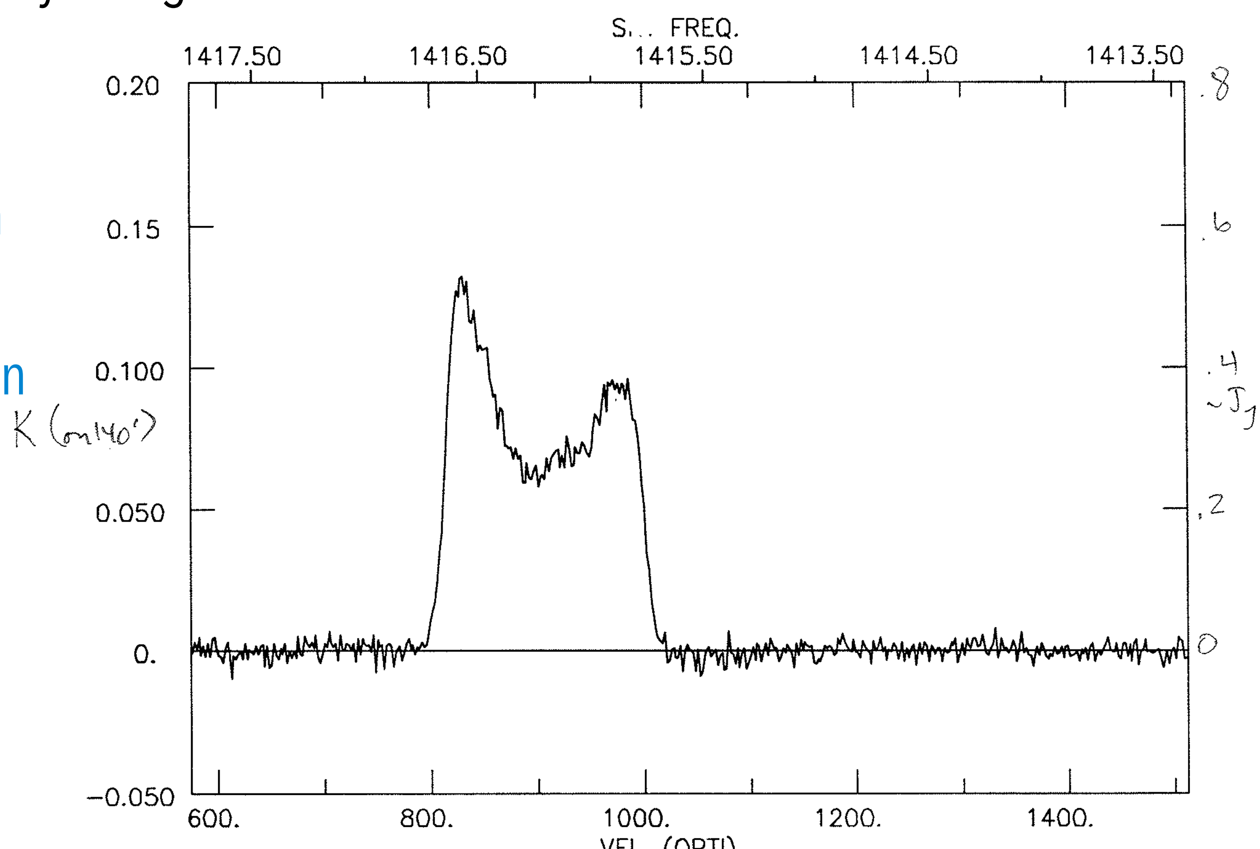
- Hyperfine structure: $\Delta E \sim 5.9\ \mu eV$
- Natural width of 21 cm line ~ 10^{-16} m/s

- Observed width ~100 km/s, up to 500 km/s in the Galactic centre

a) Broadening due to the thermal motions of the gas

b) Systematic shift due to radial velocity along the l.o.s:

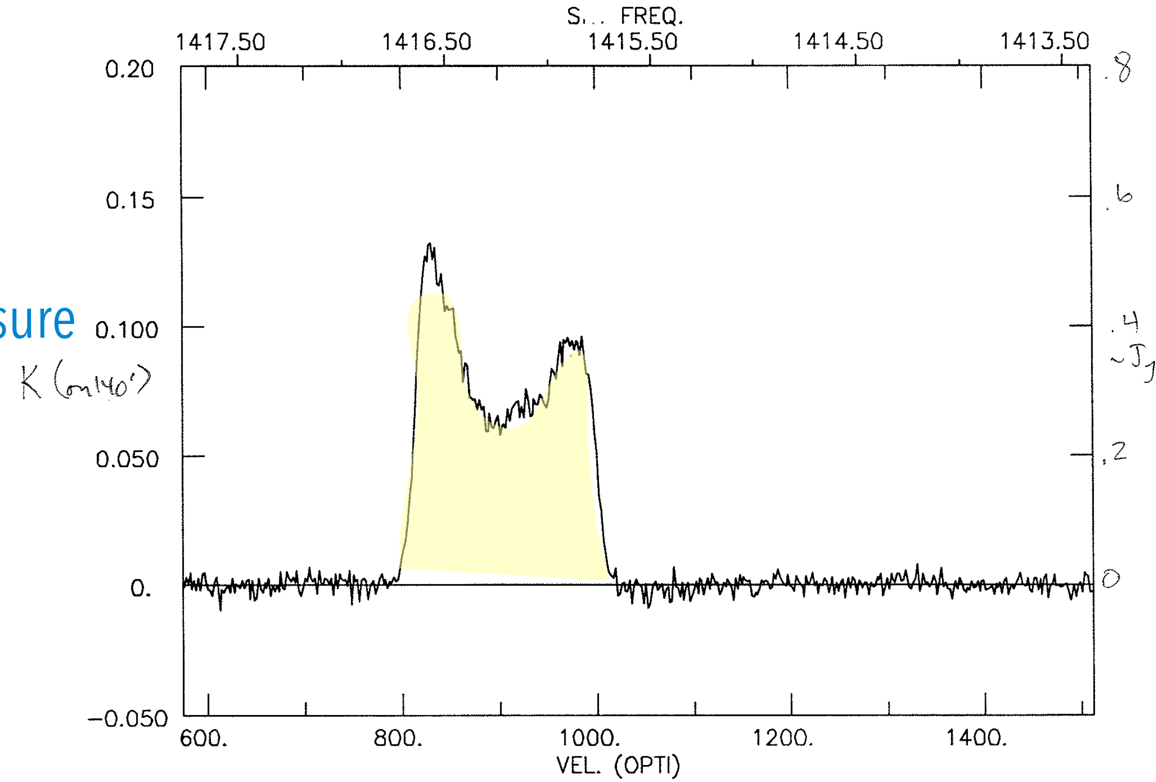
Thermal/turbulent and/or systematic motions are studied using the 21 cm line, which has a gaussian profile (or superposition of clouds with Gaussian profiles)



- Hyperfine structure: $\Delta E \sim 5.9\ \mu eV$
- Natural width of 21 cm line ~ 10^{-16} m/s

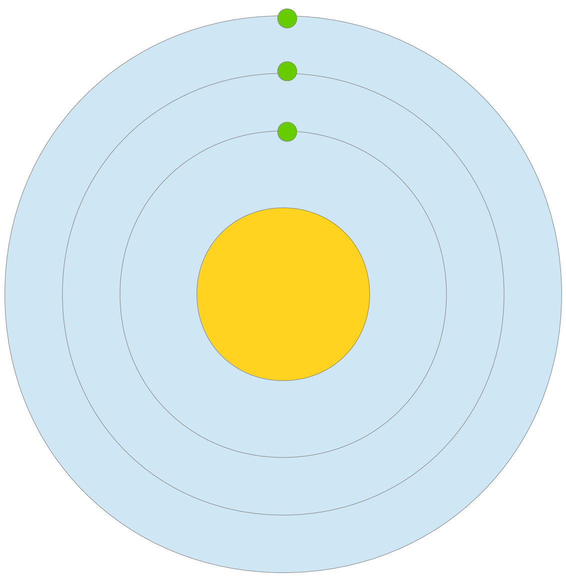
- The photons of the line are a direct measure of the total amount of HI in the volume explored by the radio telescope

- In case of an optically thin emission



$$\frac{M}{M_{sun}} \approx 2.36 \cdot 10^5 \left(\frac{D}{\mathrm{Mpc}}\right)^2 \int_{\mathrm{line}} \left(\frac{S(\nu)}{\mathrm{Jy}}\right)\left(\frac{dv}{\mathrm{km\ s^{-1}}}\right)$$

Where is it? Distribution, Kinematics, Origin and Fate



Differential rotation?

◊ Let's assume circular orbits & same velocity

Inner regions have higher angular velocity (faster mix)

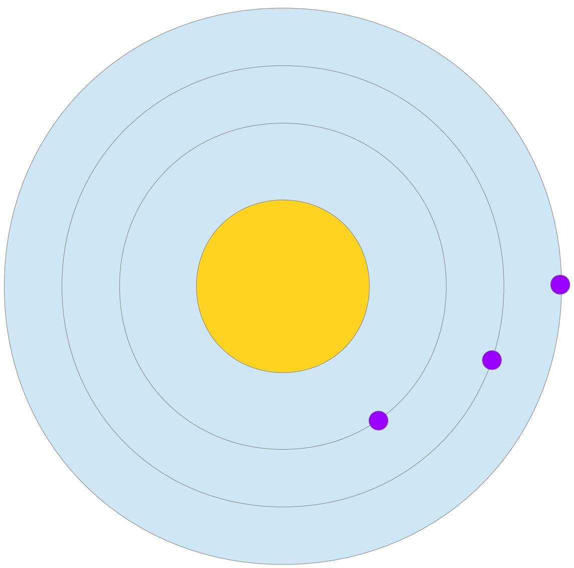
Other options:

- Solid body rotation: constant angular velocity
- Keplerian view: once the mass of the galaxy increases marginally with radius, such circular velocity should go with $r^{-0.5}$.

Where is it? Distribution, Kinematics, Origin and Fate

Differential rotation

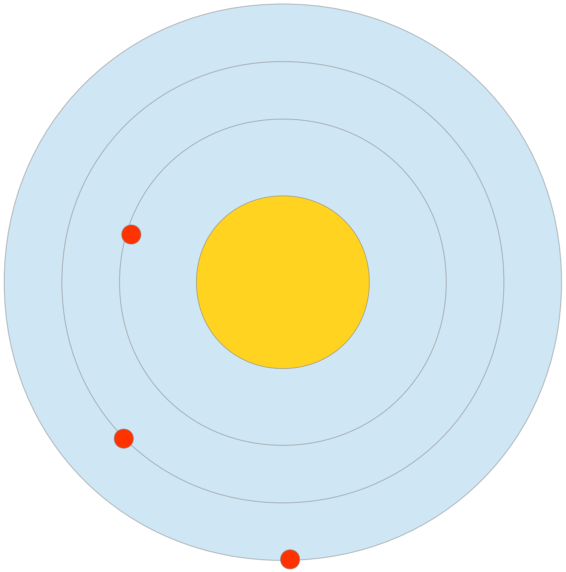
Time lapse 1: green points were aligned, purple points are not aligned anymore



Where is it? Distribution, Kinematics, Origin and Fate

Differential rotation

Time lapse 2: red dots appear uncorrelated



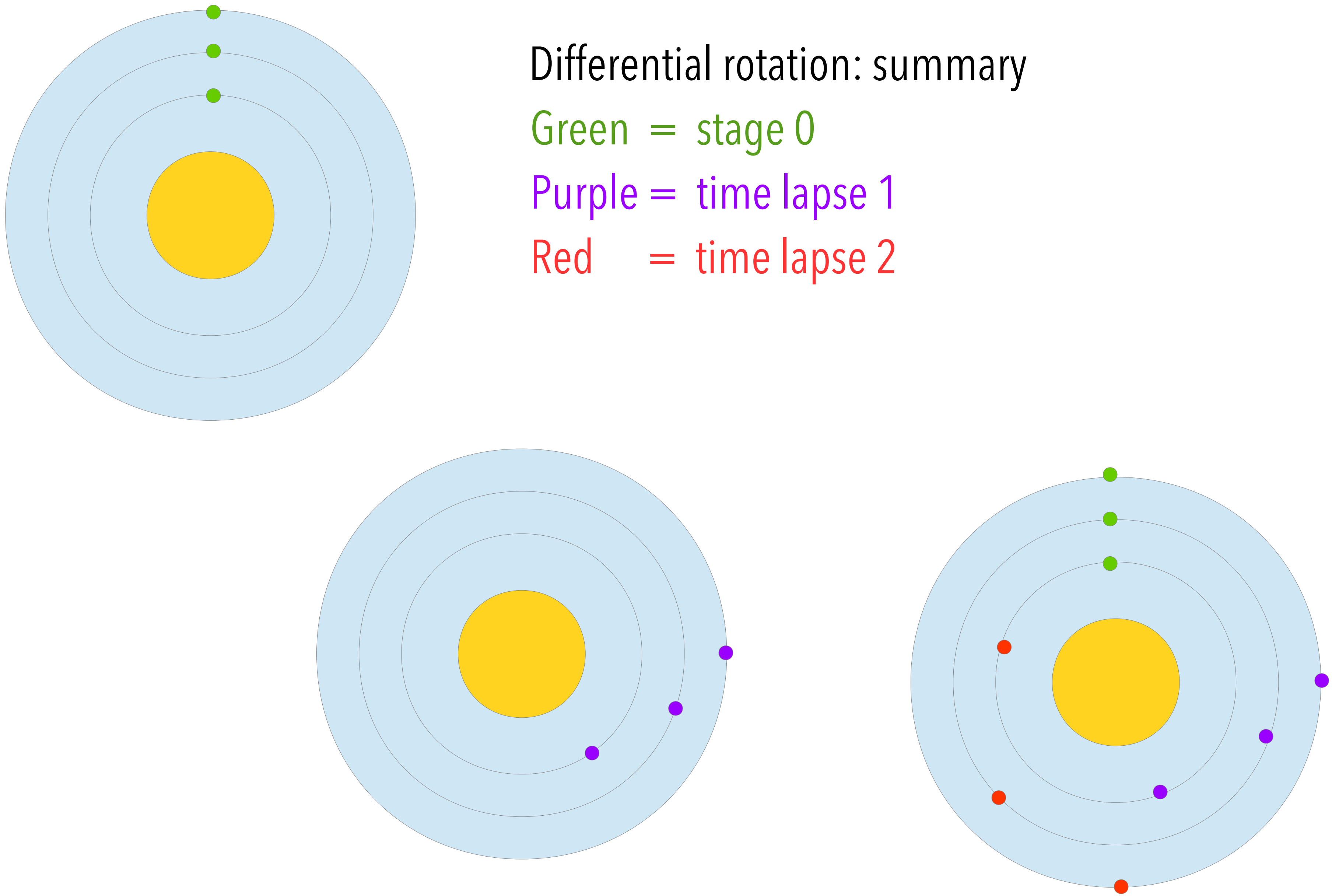
Where is it? Distribution, Kinematics, Origin and Fate

Differential rotation: summary

Green = stage 0

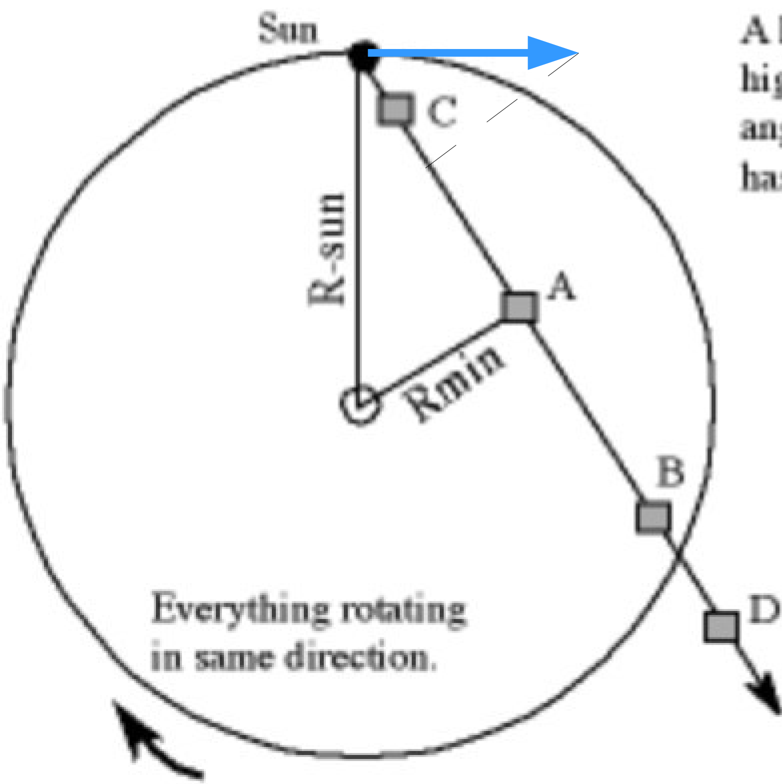
Purple = time lapse 1

Red = time lapse 2

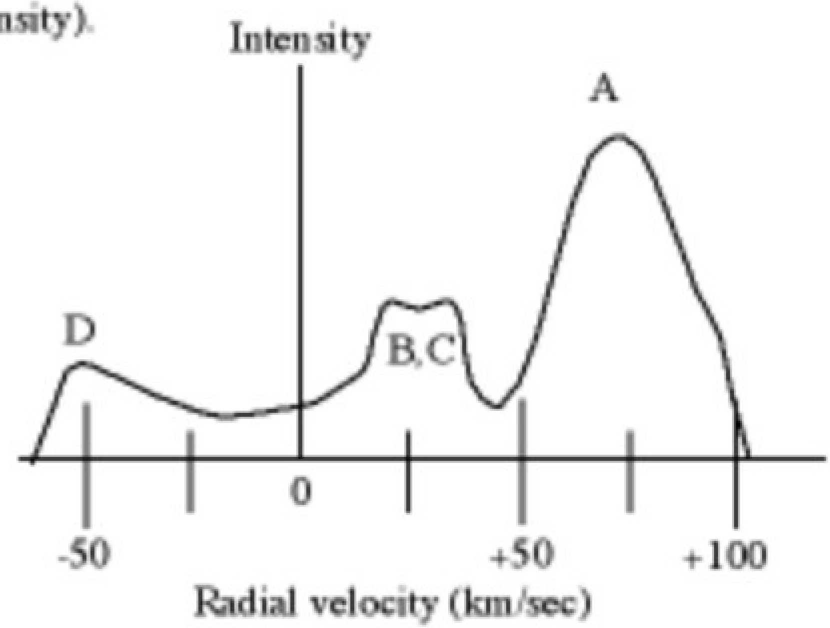


Motions within the MW

Hyp: any given point moves on a circular orbit with its own circular velocity



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).



Four clouds all in the same direction. Use doppler shifts to distinguish one cloud from the other. Use the rotation curve to convert the doppler shifts of each cloud to distances from the center of the Galaxy. Do this for other directions to build up a map of the Galaxy strip by strip.

Motions within the MW

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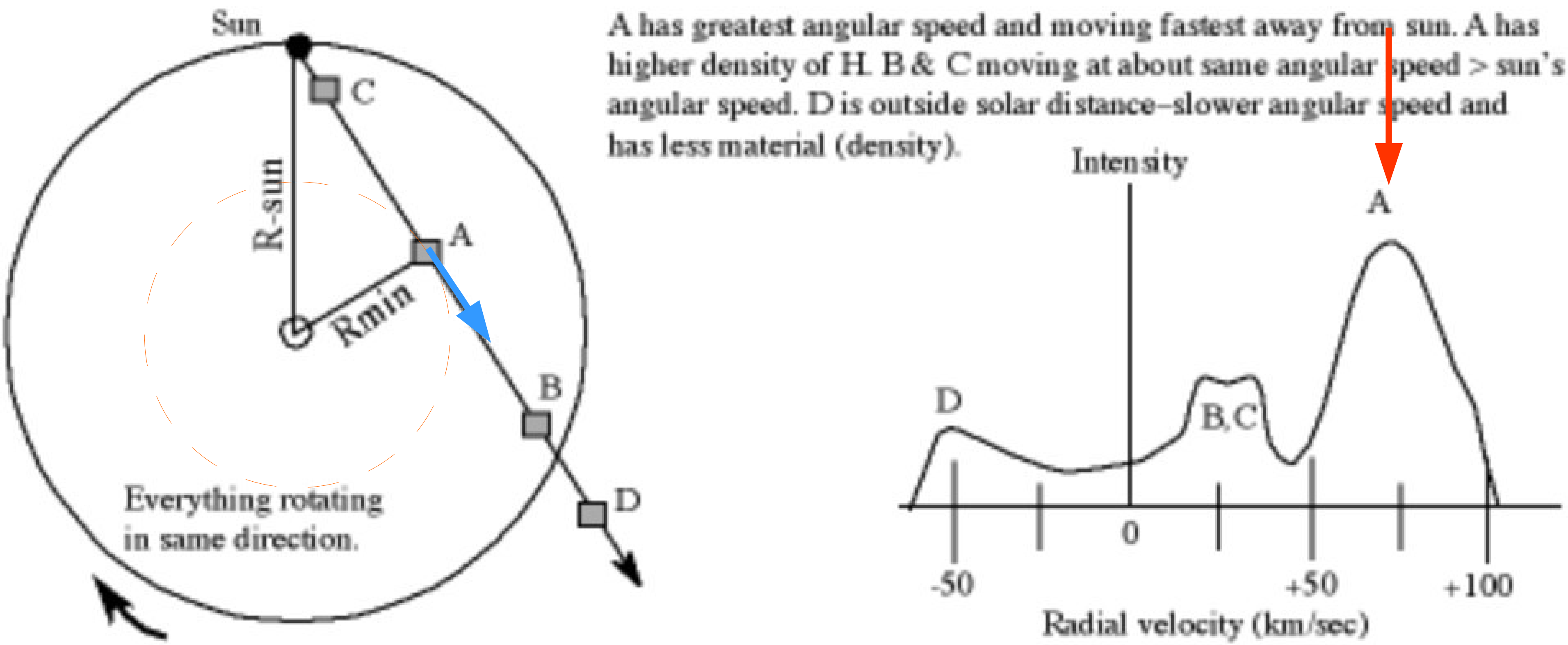

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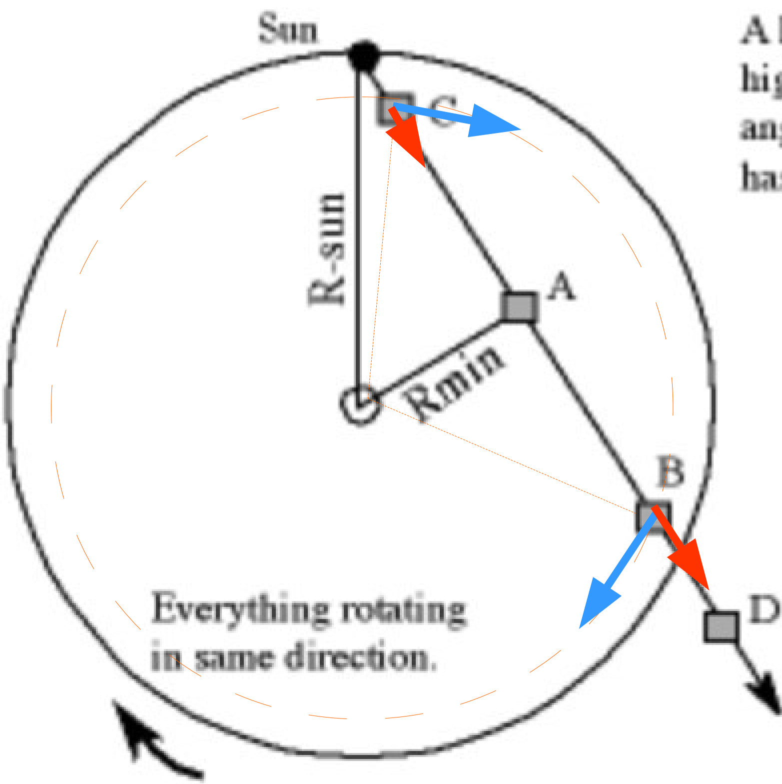

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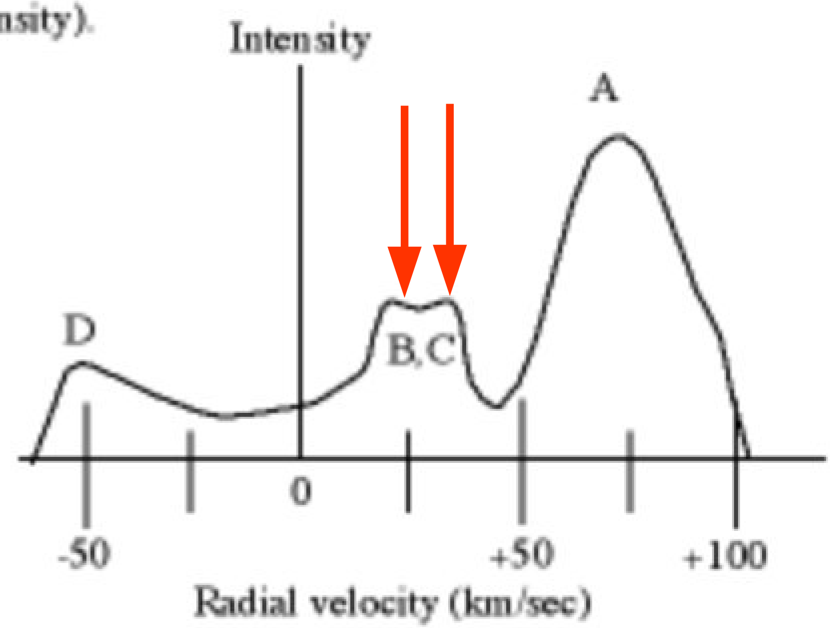

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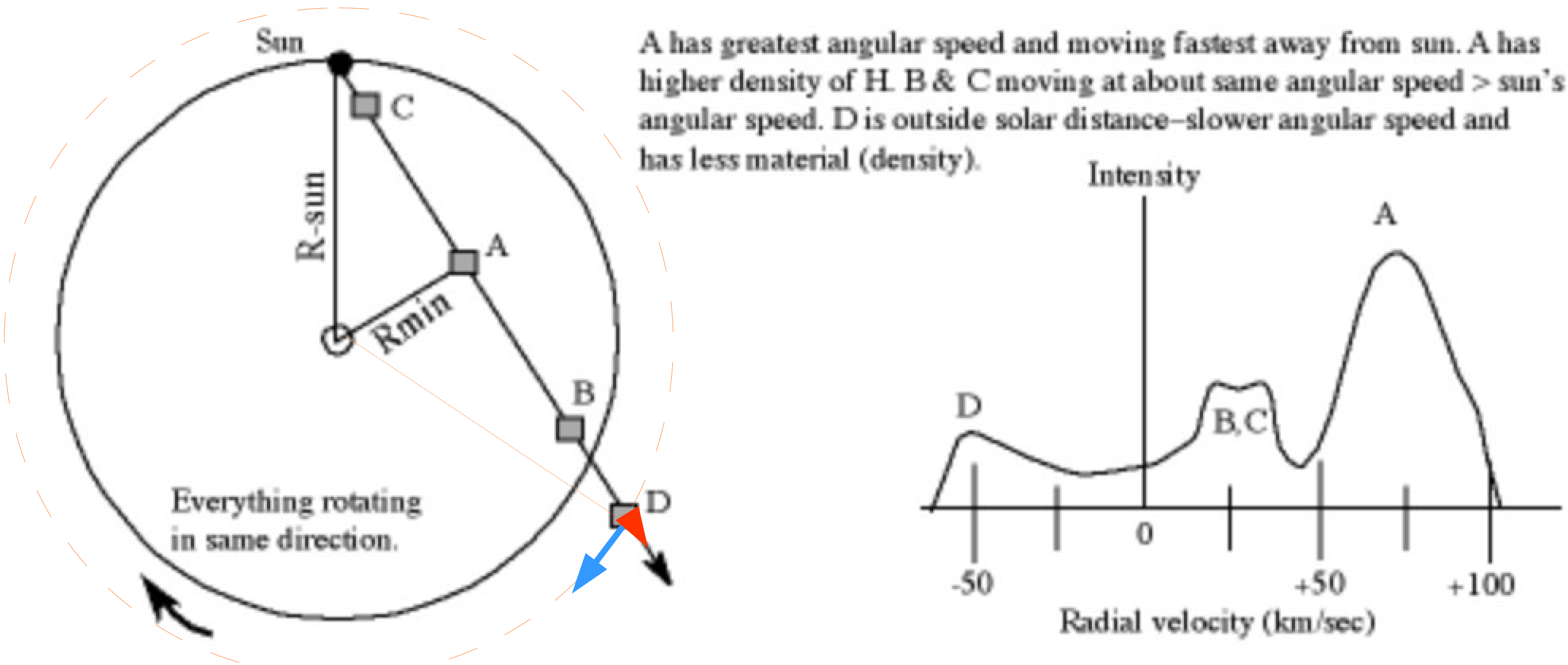

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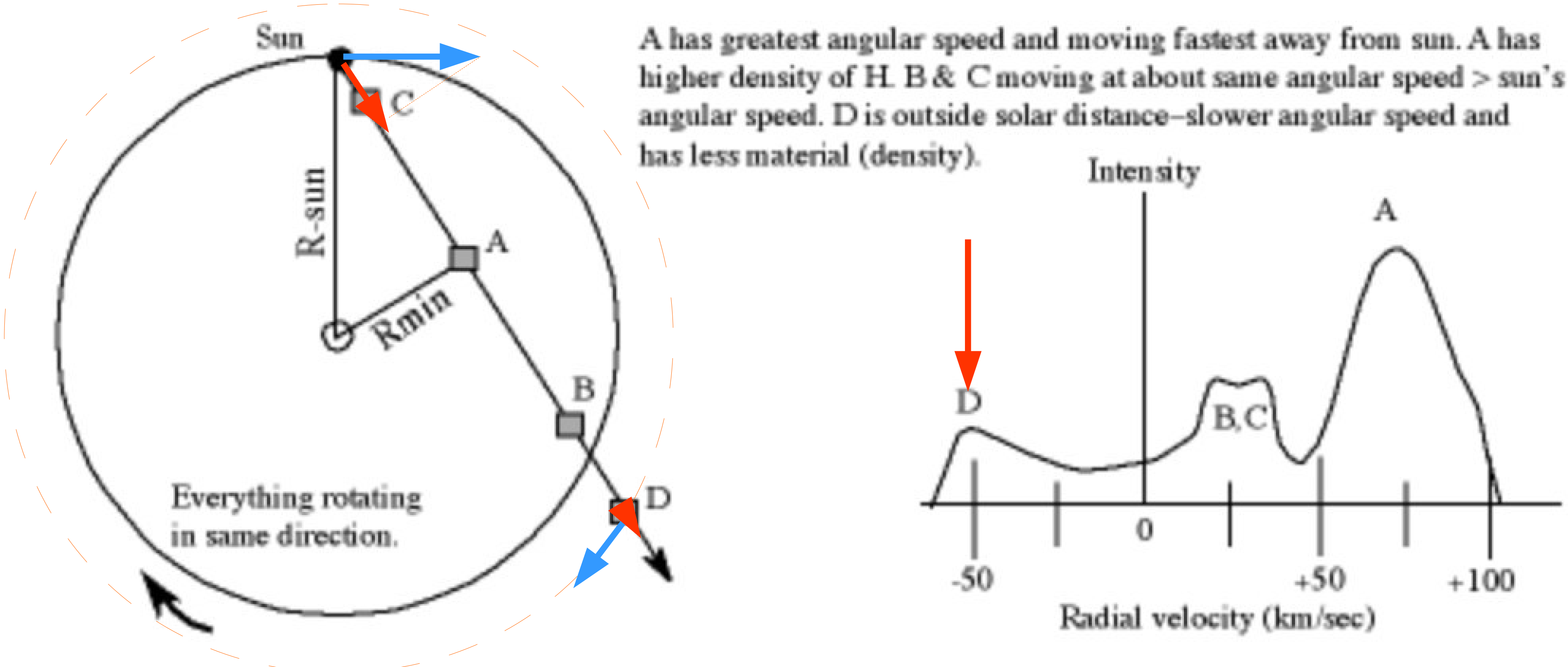
Motions within the MW

Also the Sun moves, and has a component of the velocity along the line of sight!



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Velocities in the MW

v_r must be computed along a given line of sight and has components from both $\Omega_o R_o$ and ΩR

$$v_r = \Omega R \cos\left(\frac{\pi}{2} - L - \theta\right) - \Omega_o R_o \cos\left(\frac{\pi}{2} - L\right)$$

$$= \Omega R \left(\sin\theta \cos L + \cos\theta \sin L\right) - \Omega_o R_o \sin L$$

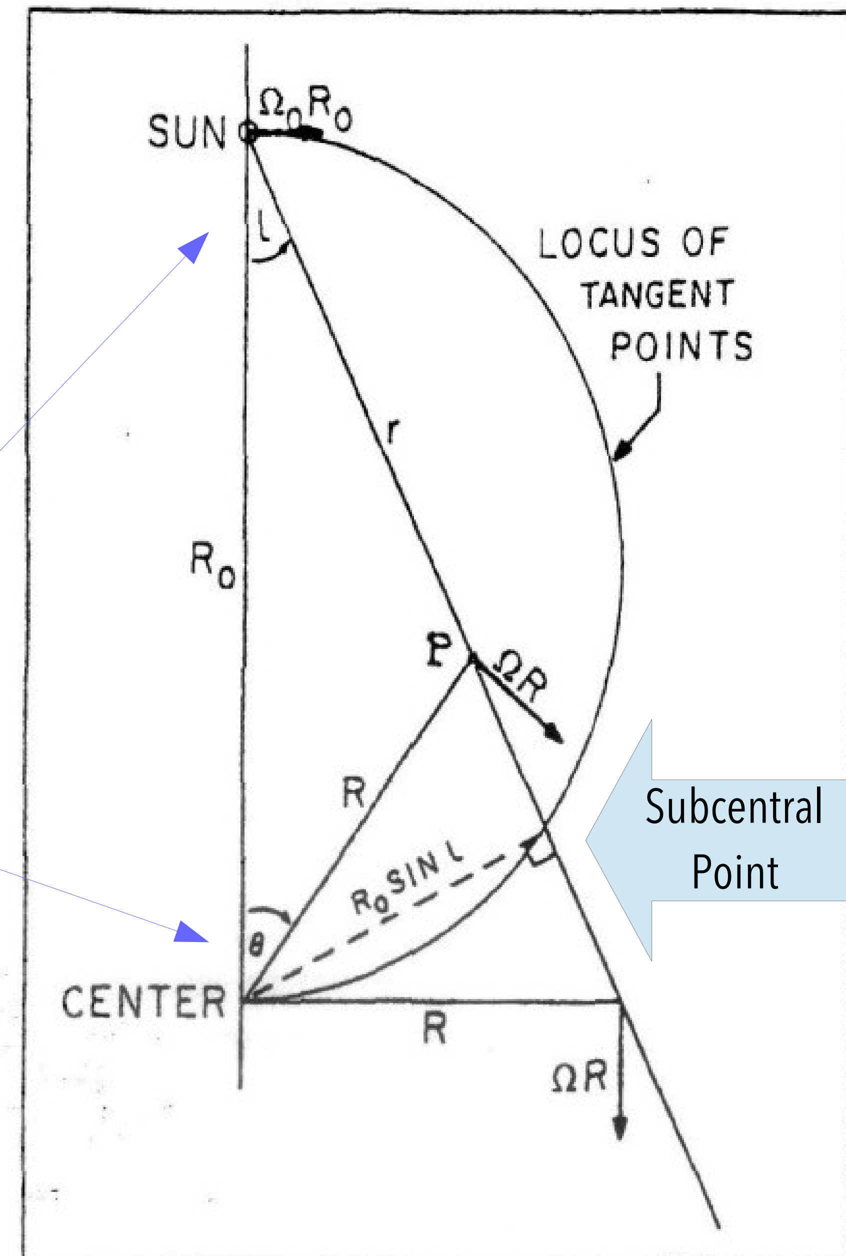
L is the galactic longitude (b is taken 0)

θ is the galactocentric azimut

$$\frac{r}{\sin\theta} = \frac{R}{\sin L} \quad \text{i.e.} \quad r \sin L = R \sin\theta$$

$$\boxed{R\cos\theta = R_o - r\cos L}$$

$$v_r = R_o \left(\Omega(R) - \Omega_o\right) \sin L$$



Fundamental equation to determine the rotation curve (measuring the radial velocity)

$$v(R,L)_r = R_o\left(\Omega(R)-\Omega_o\right)\sin L \qquad \text{radial velocity}$$
$$v(R,L)_t = R_o\left(\Omega(R)-\Omega_o\right)\cos L - r\,\Omega(R) \qquad \text{tangential velocity}$$

For a measured v_r in a given direction L, we can obtain Ω(R), from which the local circular velocity can be derived: $v(R) = \Omega(R) \cdot R$

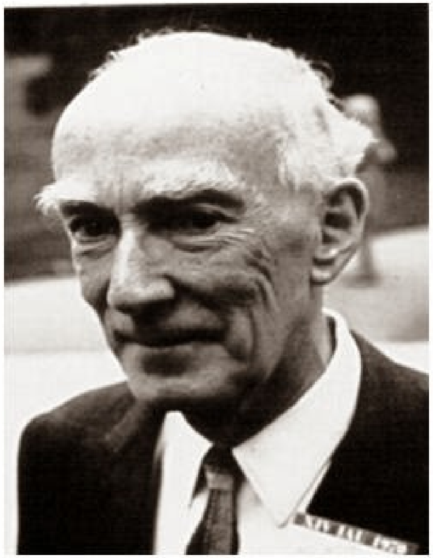
How to measure R: stars, HII regions, PN, ...? any distance indicator

In case R is not known and motions are axially symmetric to the GC

differential rotation

Velocity has a maximum at the “sub-central” / “tangential” point

Oort constants: $\left(\Omega(R)-\Omega_o\right)$



Jan Hendrik Oort
1900-1992

Can be expanded in Taylor series to the first order and at the end we get

$$\left(\Omega(R)-\Omega_o\right) = \left(\frac{d\,\Omega}{dR}\right)_{R_o}(R-R_o)+\ldots \quad \text{where } (R-R_o) \text{ is small}$$

$$\frac{d\,\Omega(R)}{dR} = \frac{d\,(v/R)}{dR} = \frac{1}{R}\frac{d\,v}{dR} - \frac{v}{R^2}$$

The radial velocity can be rewritten as

$$v_r = \left[\left(\frac{dv}{dR}\right)_{R_o} - \frac{v_o}{R_o}\right](R-R_o)\sin L = \left[\frac{v_o}{R_o} - \left(\frac{dv}{dR}\right)_{R_o}\right] r\cos L \sin L$$

since in the solar neighborhood $(R - R_o) \simeq r\cos L$

Oort constants

$$v_r = \frac{1}{2}\left[\frac{v_o}{R_o} - \left(\frac{dv}{dR}\right)_{R_o}\right] r \sin 2L$$

first Oort constant: $A = \frac{1}{2}\left[\frac{v_o}{R_o} - \left(\frac{dv}{dR}\right)_{R_o}\right]$ allowing to write $v_r = A r \sin 2L$

The tangential velocity is $v_t = \frac{v}{R}\left(R\cos L - r\right) - v_o \cos L = [\Omega(R) - \Omega_o] R\cos L - \Omega(R) r$

using the same Taylor expansion

$$v_t = \left[\frac{v_o}{R_o} - \left(\frac{dv}{dR}\right)_{R_o}\right] r\cos^2 L - \frac{v_o}{R_o} r = \left[\frac{v_o}{R_o} - \left(\frac{dv}{dR}\right)_{R_o}\right]\frac{r}{2}(1 \cos 2L) - \frac{v_o}{R_o} r$$

$$v_t = A r\cos 2L - \left[\frac{v_o}{R_o} + \left(\frac{dv}{dR}\right)_{R_o}\right]\frac{r}{2}$$

defining the second Oort constant $$B = -\frac{1}{2}\left[\frac{v_o}{R_o} + \left(\frac{dv}{dR}\right)_{R_o}\right]$$

The velocity of a given point at a distance r can be written as

$$v_r = A \cdot r \cdot \sin(2L)$$
$$v_t = A \cdot r \cdot \cos(2L) + B \cdot r$$

with

$$A = \frac{1}{2}\left[\frac{v_o}{R_o} - \left(\frac{dv}{dR}\right)_{R_o}\right]$$

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

A and B are two coefficients dependent on R_0 and $(d\Omega / dR)_0$, known as Oort constants (1927)

$$A = \frac{1}{2}\left[\frac{v_o}{R_o} - \left(\frac{dv}{dR}\right)_{R_o}\right]$$

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

they can be computed by observations in the solar neighborhood.

- In case of a solid body rotation: $A = 0$, $B = -\Omega_0$
- In case of a Keplerian regime: $A = 3/4\, v_0/R_0$, $B = -1/4\, v_0/R_0$
- Observed values

$$A = 14.82 \pm 0.84 \quad km\, s^{-1}\, kpc^{-1}$$

$$B = -12.37 \pm 0.64 \quad km\, s^{-1}\, kpc^{-1}$$

Once known $R_0 \sim 8.5$ kpc, the two constants allow to determine the velocity of the sun wrt the Galactic centre, $v_0 \sim 220$ km s^{-1}

Oort constants

- In case of a flat rotation curve: $A = 1/2\, v_0/R_0$, $B = -1/2\, v_0/R_0$

$$\rightarrow \quad \frac{dv}{dr} = 0$$

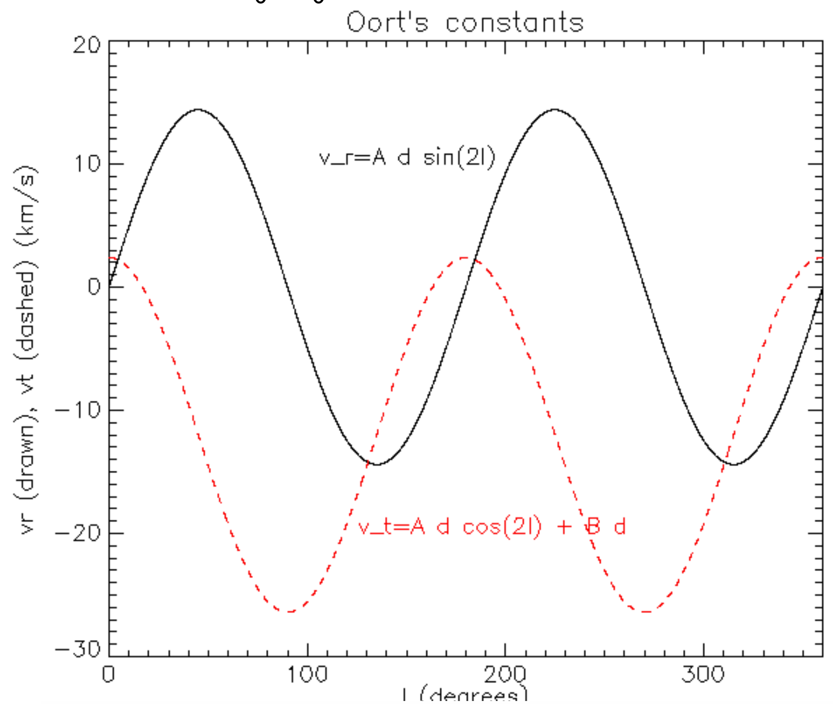
$$A = \frac{1}{2}\left[\frac{v_0}{R_0} - (0)_{R_0}\right] = \frac{1}{2}\frac{v_0}{R_0}$$

$$B = -\frac{1}{2}\left[\frac{v_0}{R_0} + (0)_{R_0}\right] = -\frac{1}{2}\frac{v_0}{R_0}$$

$$\left(\frac{dv}{dr}\right)_{R_0} = -A - B = -3.4\, km\, s^{-1}$$

$$\frac{V_0}{R_0} = \Omega = A - B = 27.2\, km\, s^{-1}\, kpc^{-1}$$

$$A = 14.82 \pm 0.84 \quad km\, s^{-1}\, kpc^{-1}$$
$$B = -12.37 \pm 0.64 \quad km\, s^{-1}\, kpc^{-1}$$



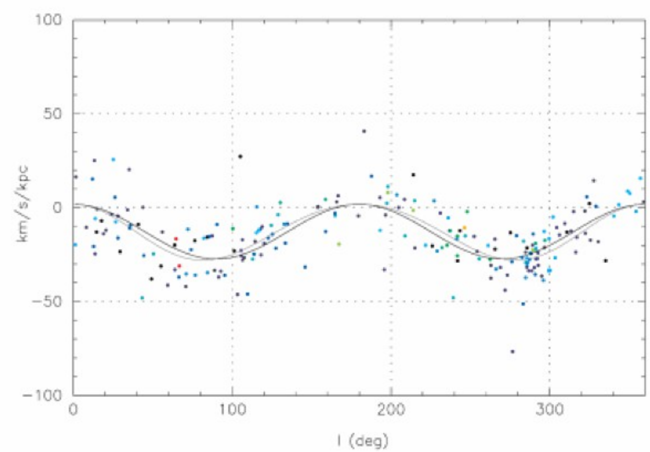


Figure 6.6. The quantity $\kappa\mu_l$, corrected for solar motion, as a function of galactic longitude, showing the effect of galactic rotation. The solid curve shows the fitting of the data for stars within 1 kpc from the Sun, the grey curve shows the same for stars with a projected distance of 5 kpc. Only stars with projected distances beyond 1.2 kpc are shown and used in the solution for the curves shown here

- In case of a solid body rotation: $A = 0$, $B = -\Omega_0$

$$\frac{dv}{dR} = \frac{v}{r} = \Omega$$

$$A = \frac{1}{2}\left[\frac{v_o}{R_o} - (\Omega)_{R_o}\right] = \frac{1}{2}\left[\frac{\Omega_o R_o}{R_o} - (\Omega)_{R_o}\right] = 0$$

$$B = -\frac{1}{2}\left[\frac{v_o}{R_o} + (\Omega)_{R_o}\right] = -\frac{1}{2}\left[\frac{\Omega_o R_o}{R_o} + (\Omega)_{R_o}\right] = -\Omega_o$$

- In case of a Keplerian regime: A=3/4 v_0/R_0, B= – 1/4 v_0/R_0

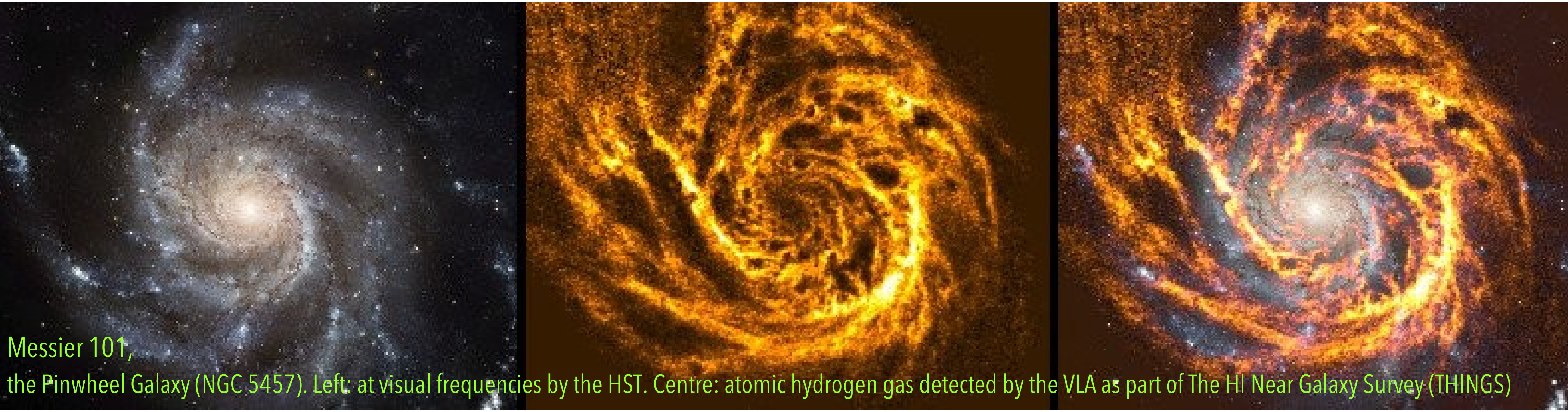
$$v = \sqrt{\frac{GM}{r}} \quad \rightarrow \quad \frac{dv}{dr} = -\frac{1}{2}\sqrt{\frac{GM}{r^3}} = -\frac{1}{2}\frac{v}{r}$$

$$A = \frac{1}{2}\left[\frac{v_o}{R_o} - \left(-\frac{v}{2r}\right)_{R_o}\right] = \frac{3}{4}\frac{v_o}{R_o}$$

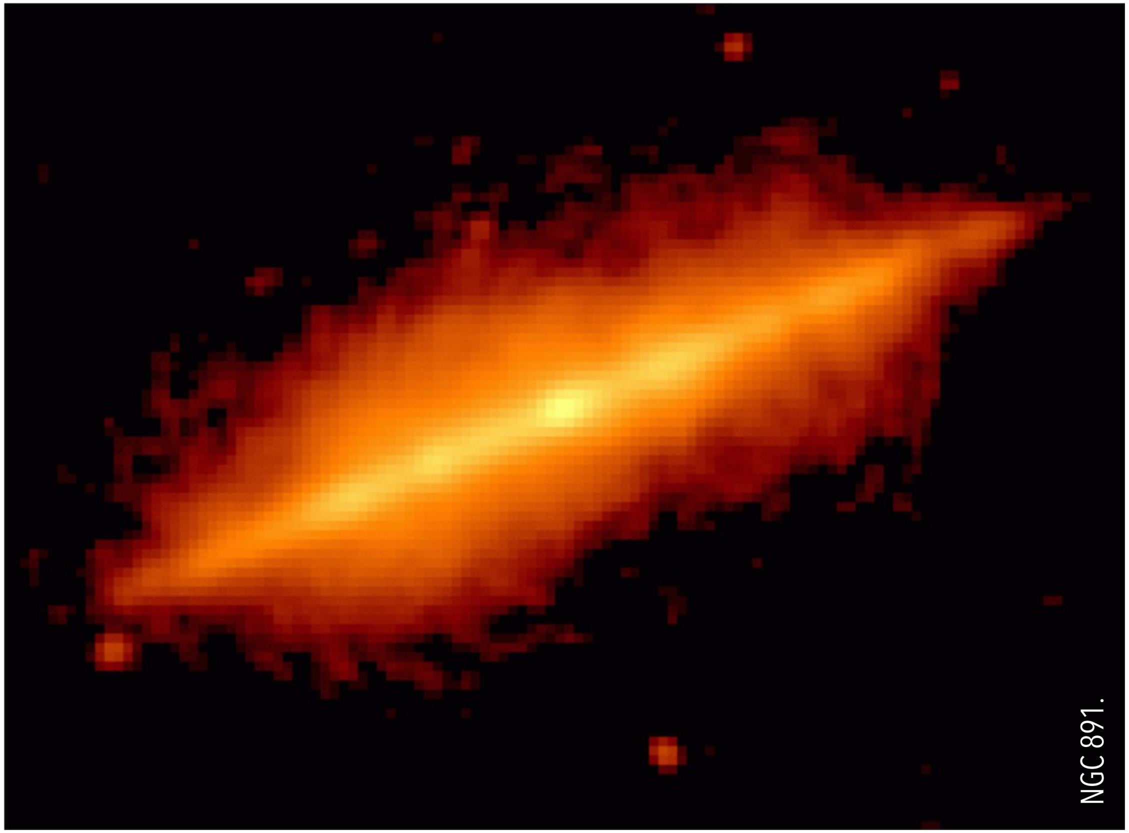
$$B = -\frac{1}{2}\left[\frac{v_o}{R_o} + \left(-\frac{v}{2r}\right)_{R_o}\right] = -\frac{1}{4}\frac{v_o}{R_o}$$

Since A ~ – B, the rotation curve derived for out galaxy is ~ flat

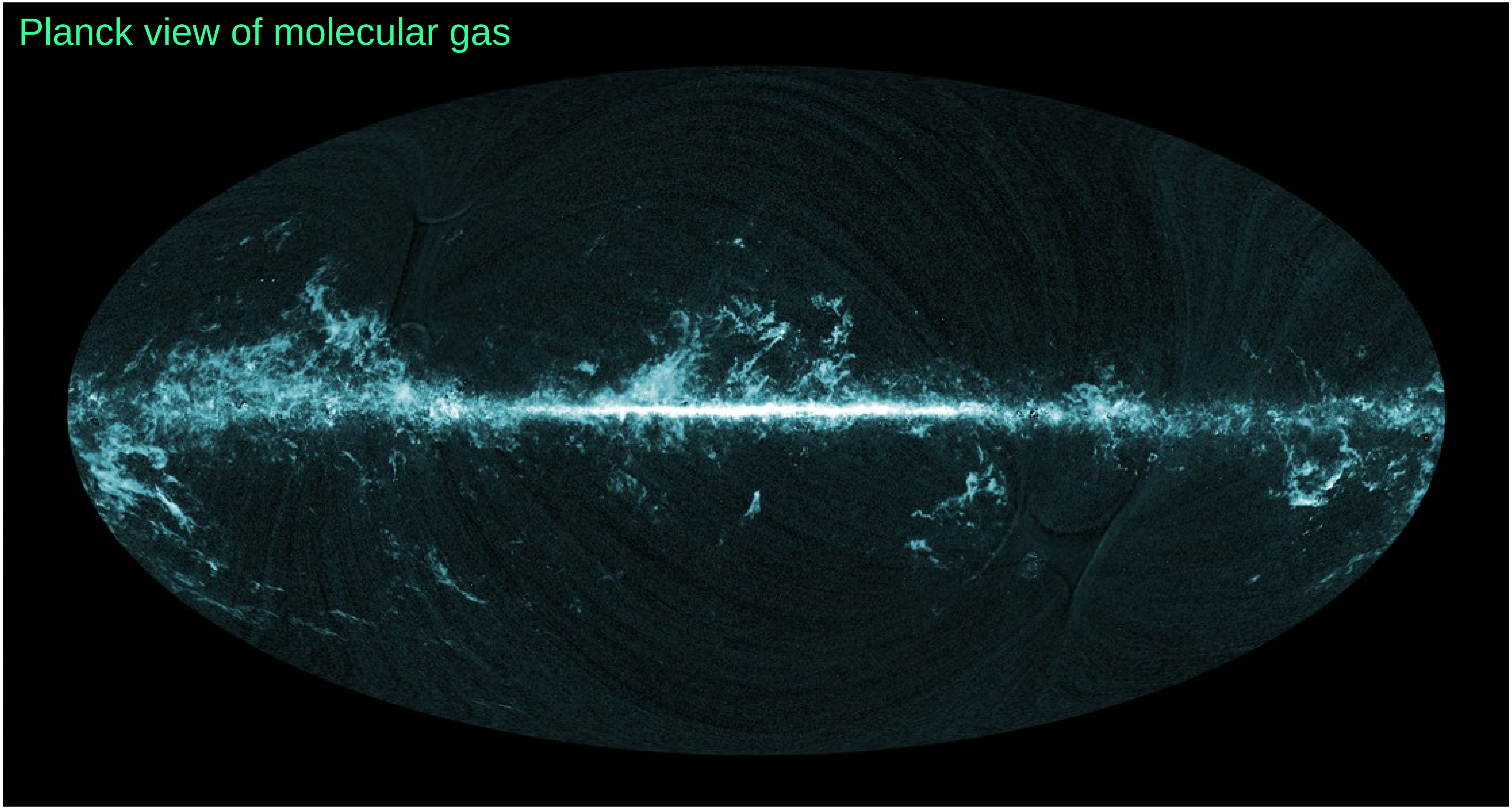
Rotation curve: going out to external galaxies



Messier 101,
the Pinwheel Galaxy (NGC 5457). Left: at visual frequencies by the HST. Centre: atomic hydrogen gas detected by the VLA as part of The HI Near Galaxy Survey (THINGS)



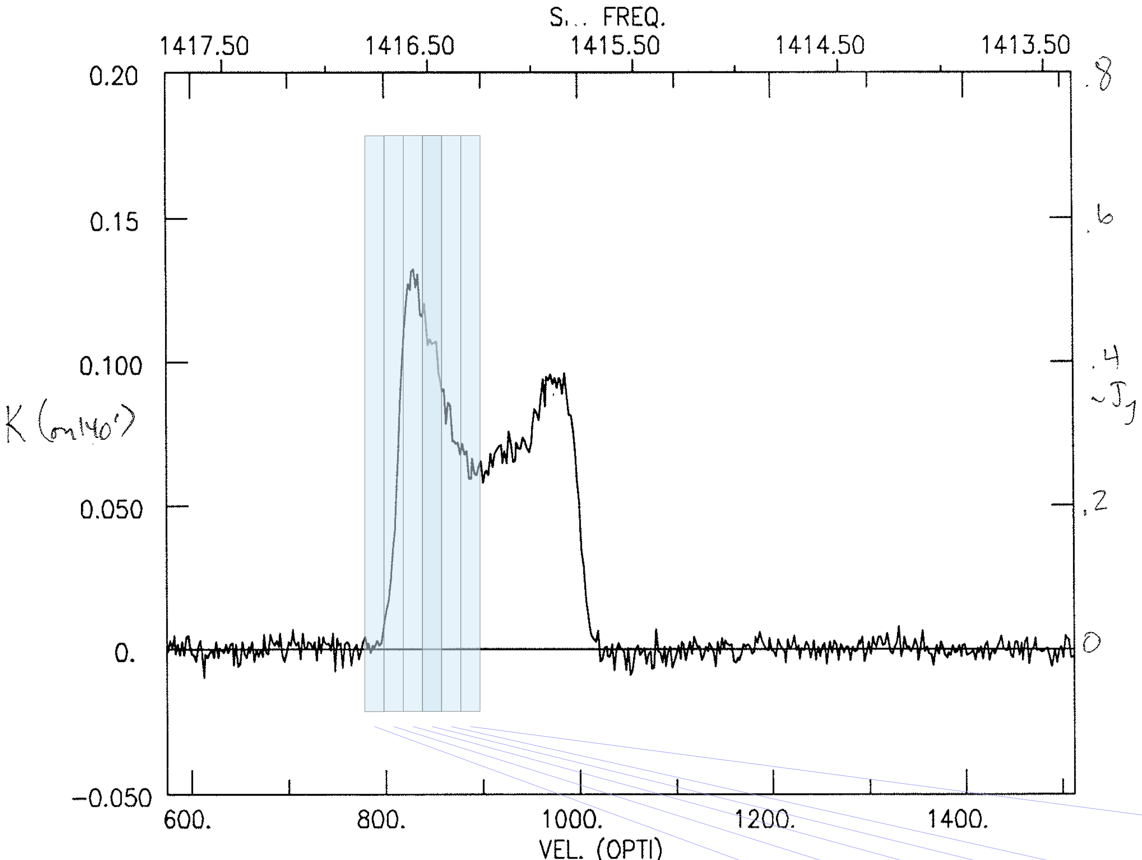
CO: also the molecular gas can be used to trace both distribution and dynamics

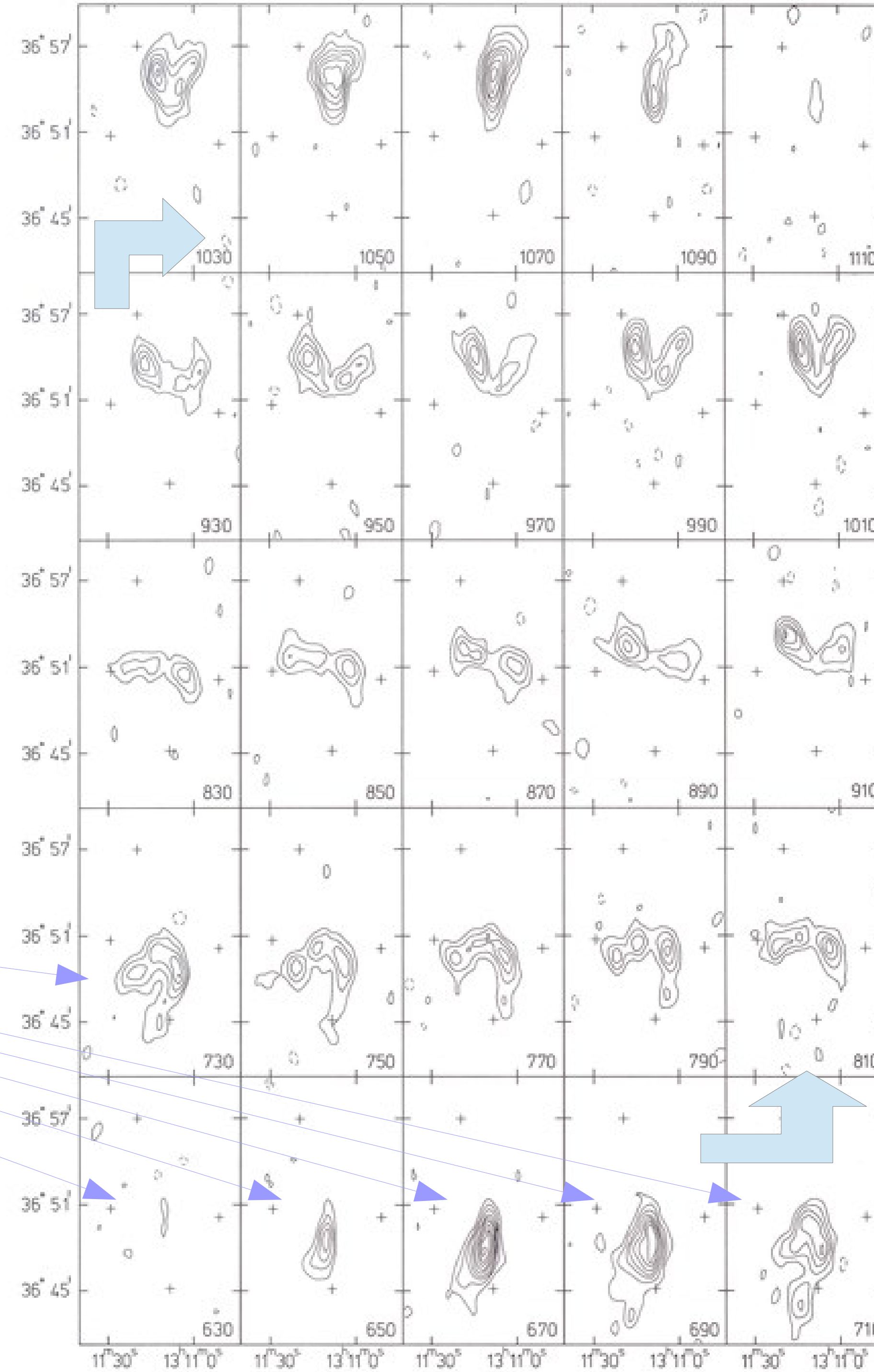


Located in different regions, is an independent tracer of the galactic dynamics

In particular, very important in SFG and SBG. Complete analogy to HI line analysis

Different regions contribute to different portions of the spectrum





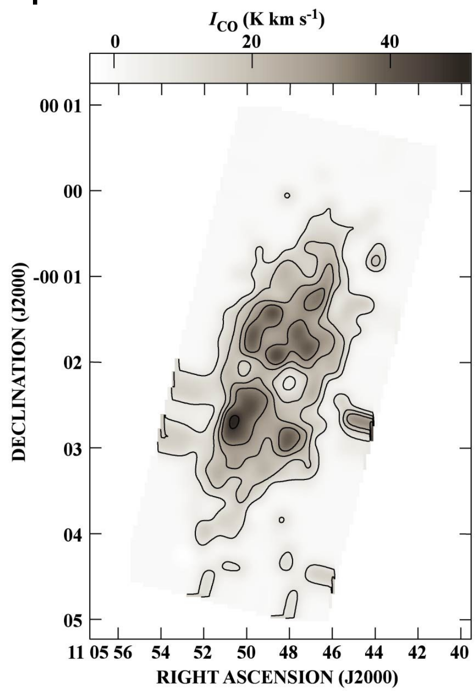
Images are 2D and organized as a DATACUBE

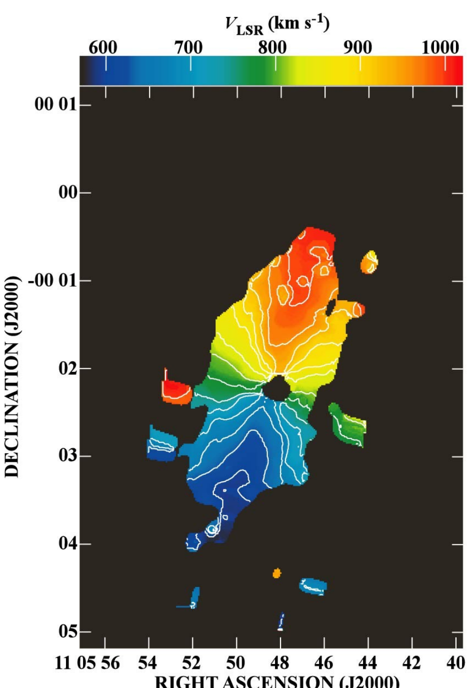
Moment 0 – total intensity

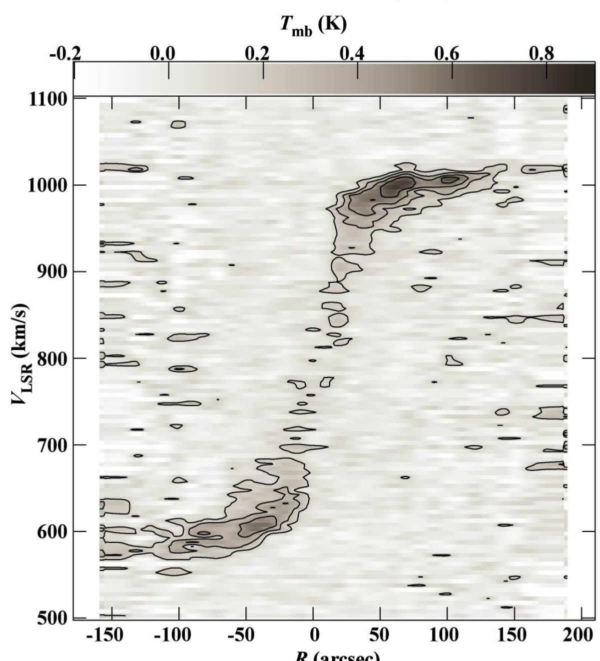
Moment 1 – relative (radial) velocity

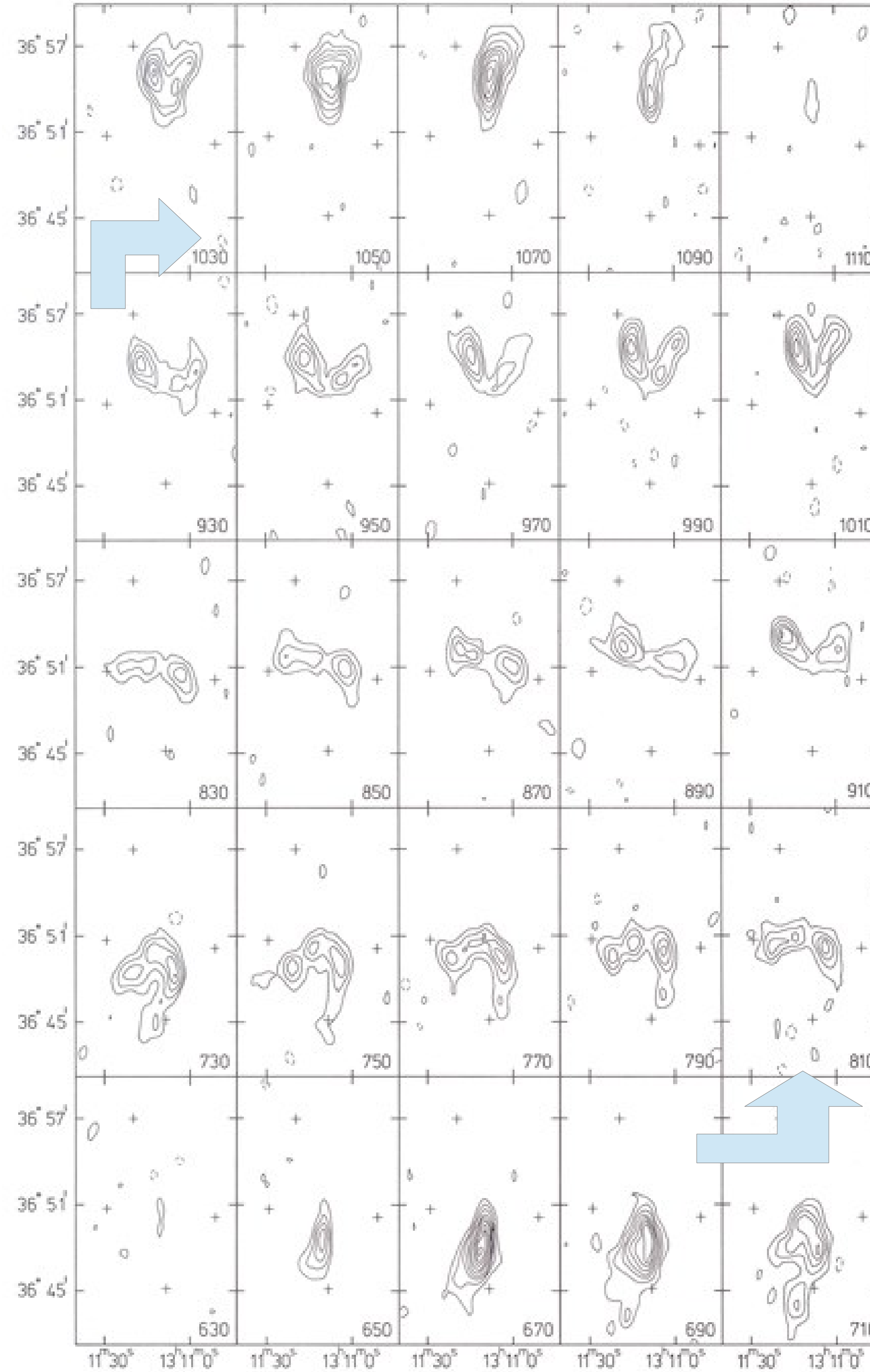
Moment 2 – velocity dispersion

Learning from other spirals:

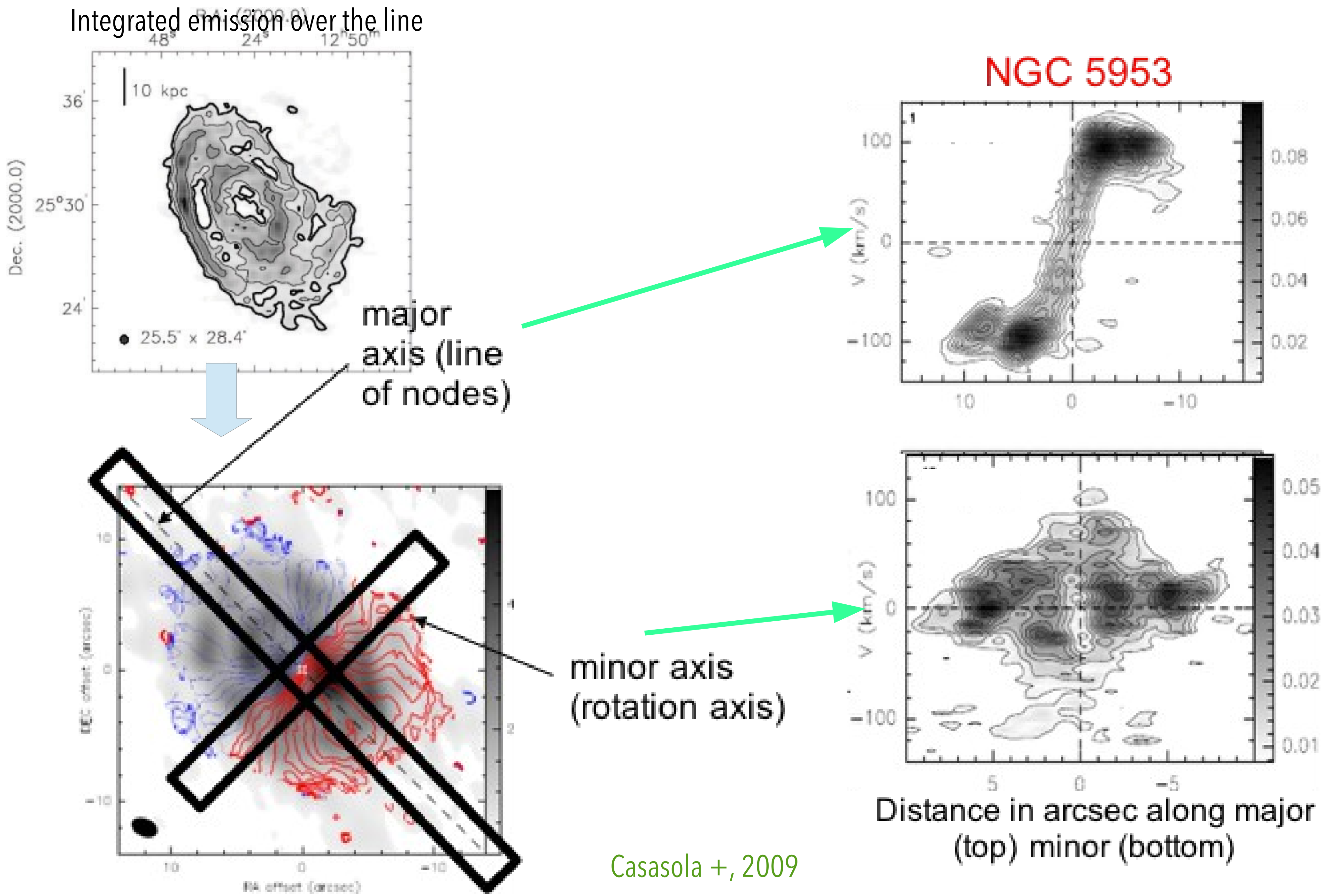








Neutral Hydrogen: the extraction of the Position – Velocity (PV) diagrams



- PV diagram

Simulations of beam-smearing on a major-axis PV diagram.

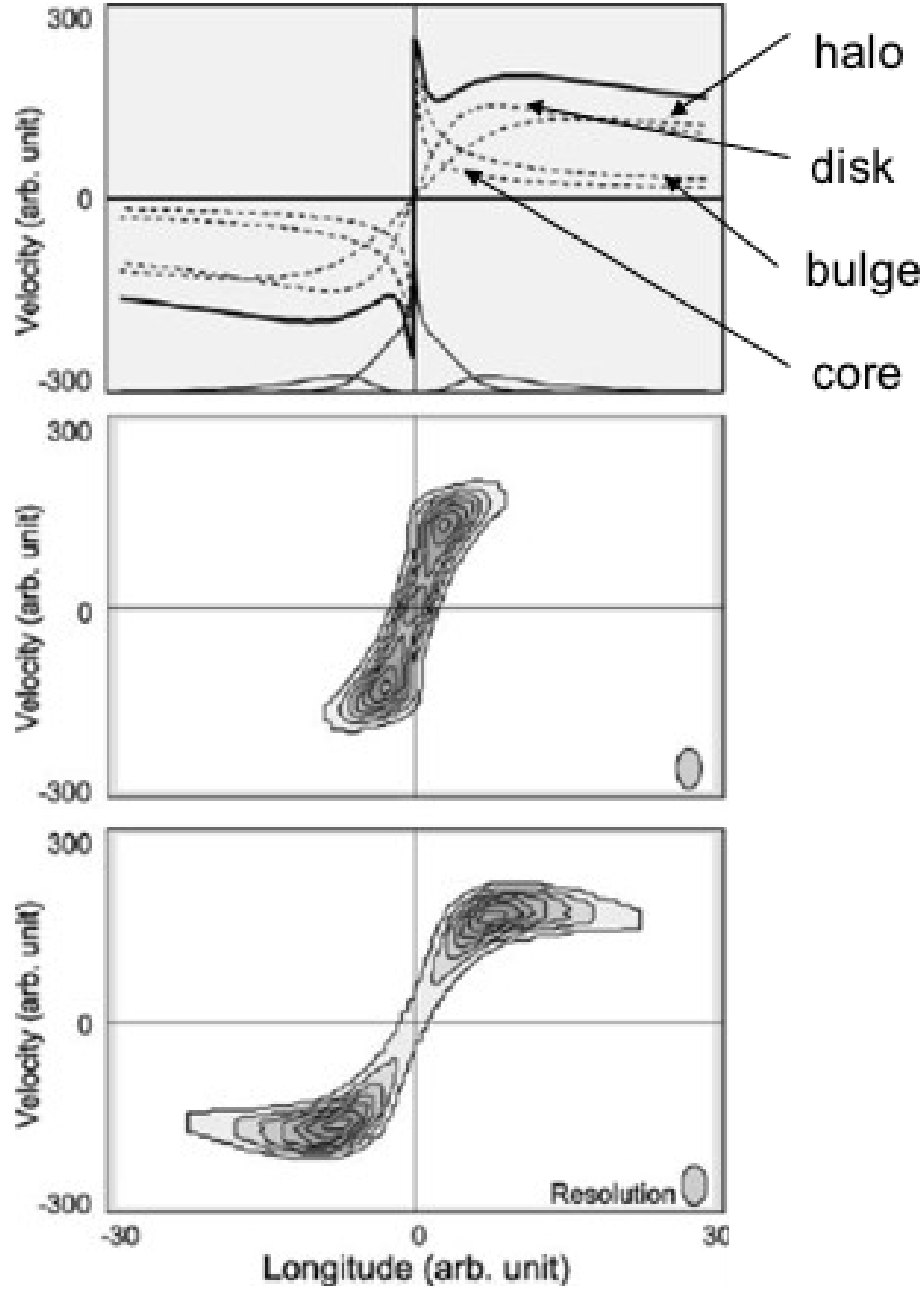
Top: Assumed "true" rotation curve (thick) with a central core, bulge, disk, and halo

Middle: "Observed" CO PV diagram

Bottom: "Observed" HI PV diagram

High resolution & high sensitivity necessary to detect central high velocities and steep rise

(Sofue & Rubin 2001)



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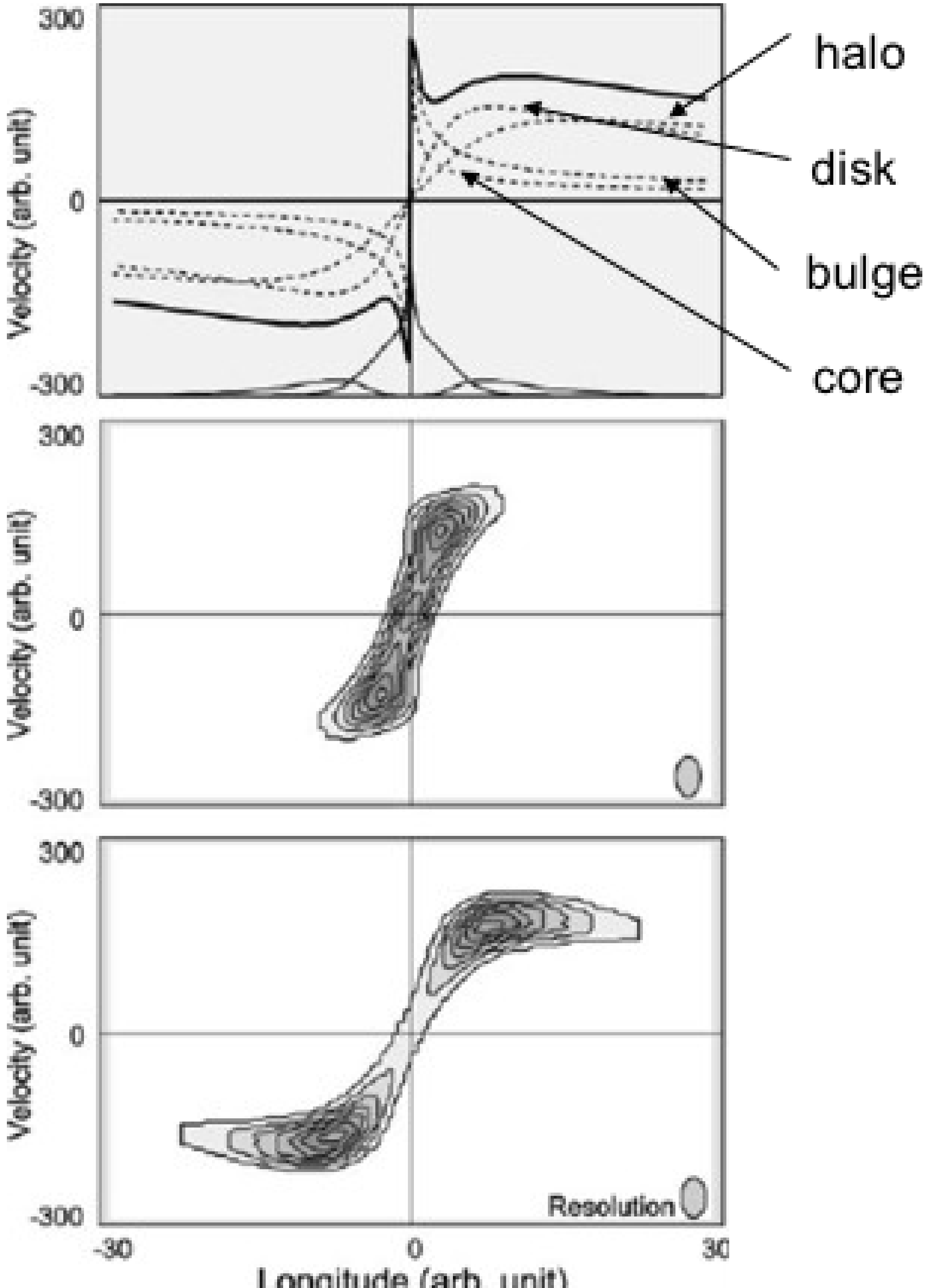
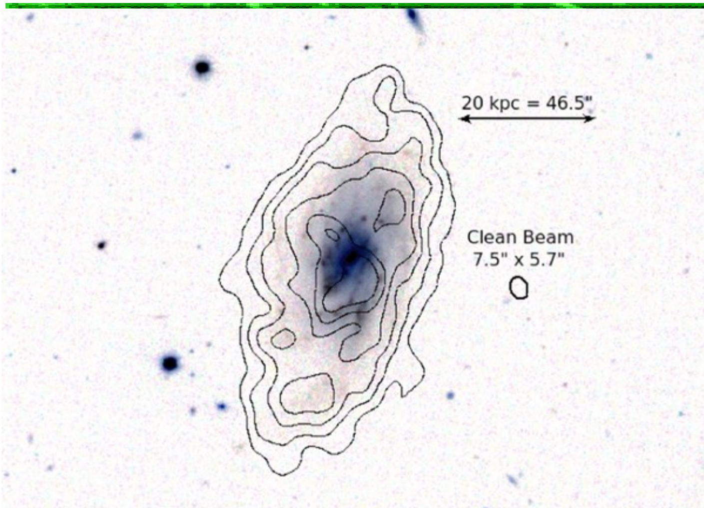
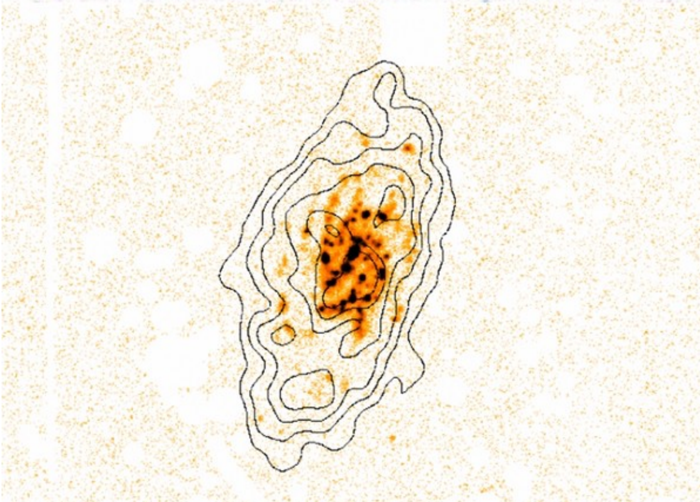
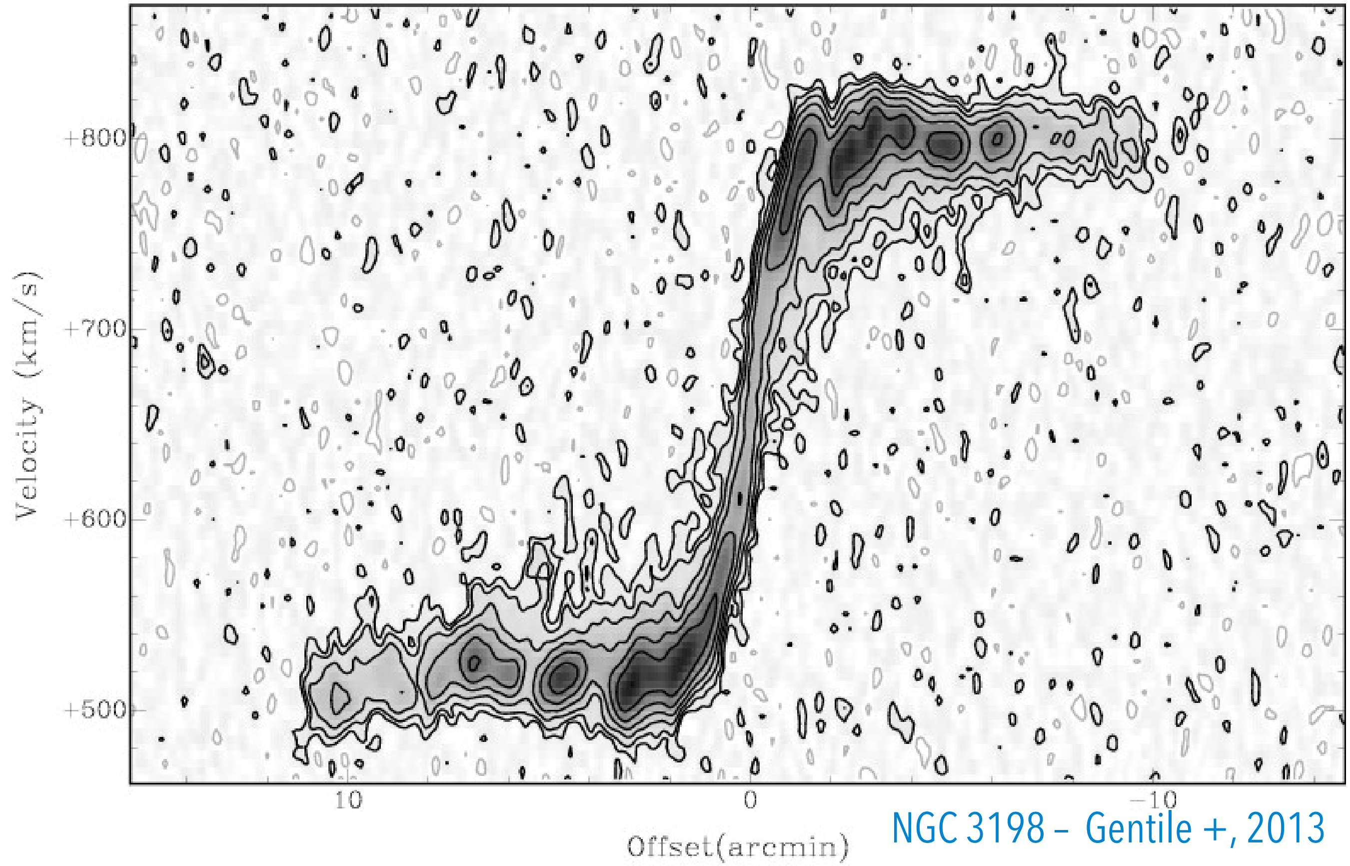


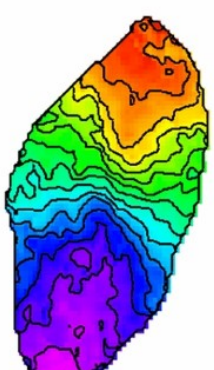
HI in external galaxies Galaxies ==> ricollocare







NGC 3198 – Gentile +, 2013



Contours: total HI emission;

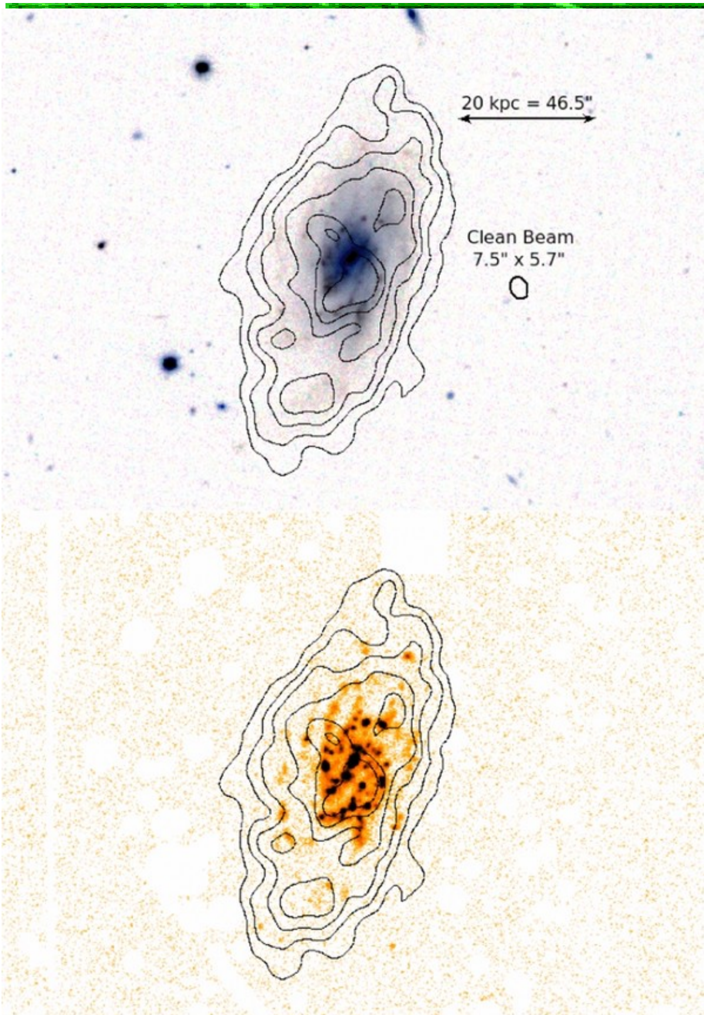
Top: optical from SDSS

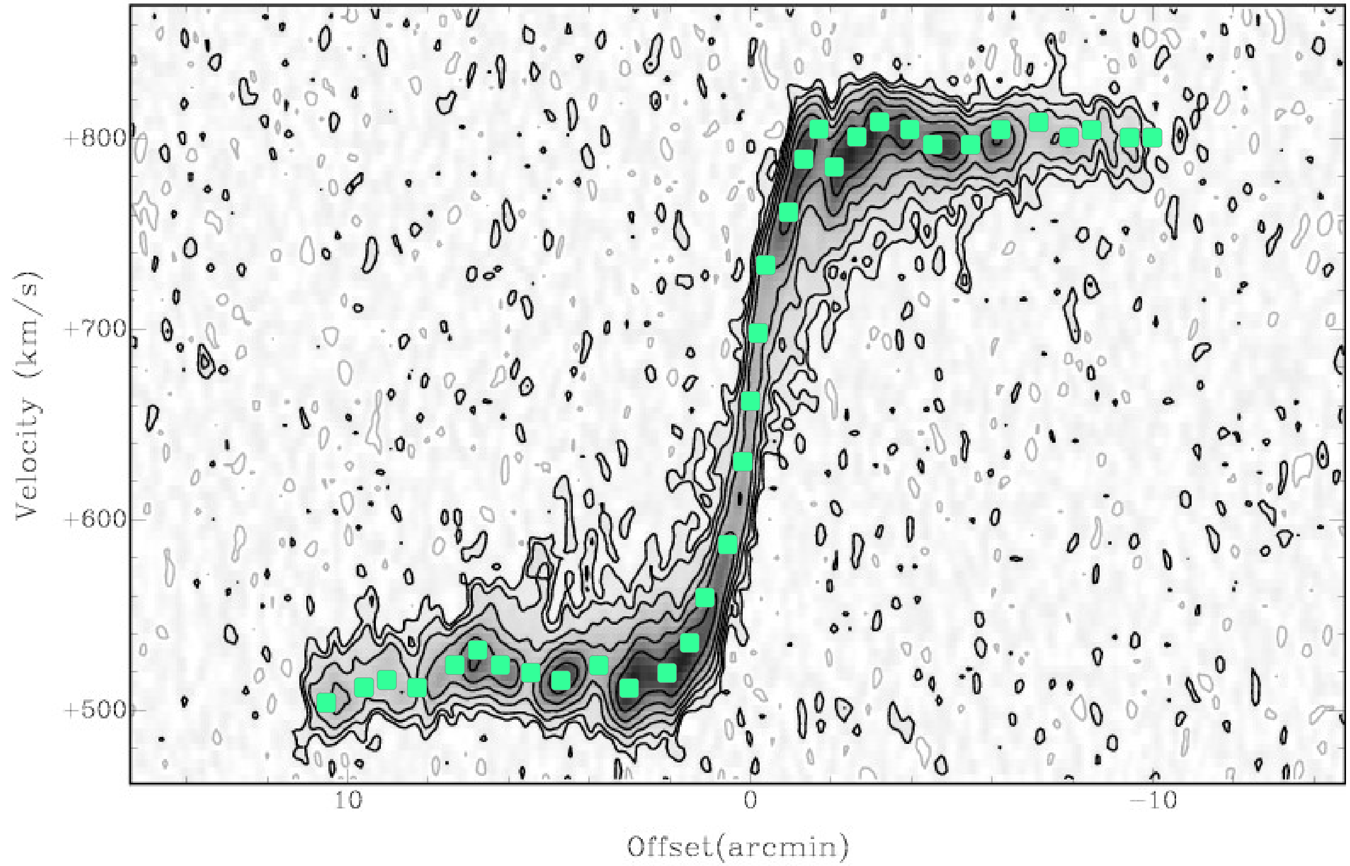
Middle: Hα, from Huang+, 2014

Bottom: HI velocity field from ALFAALFA

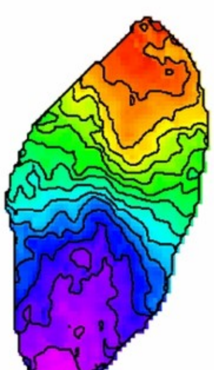
Hallenbeck +, 2014

HI in external galaxies Galaxies





Turquoise points define the rotation curve (on both sides!)



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Hallenbeck +, 2014

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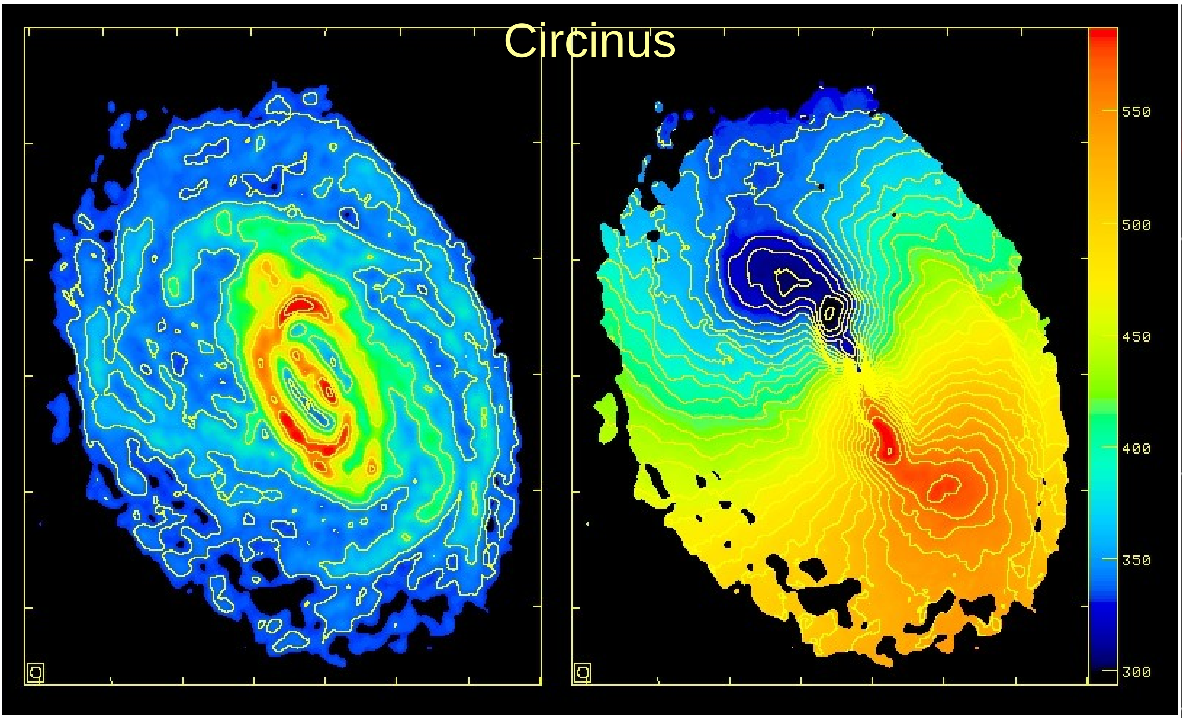
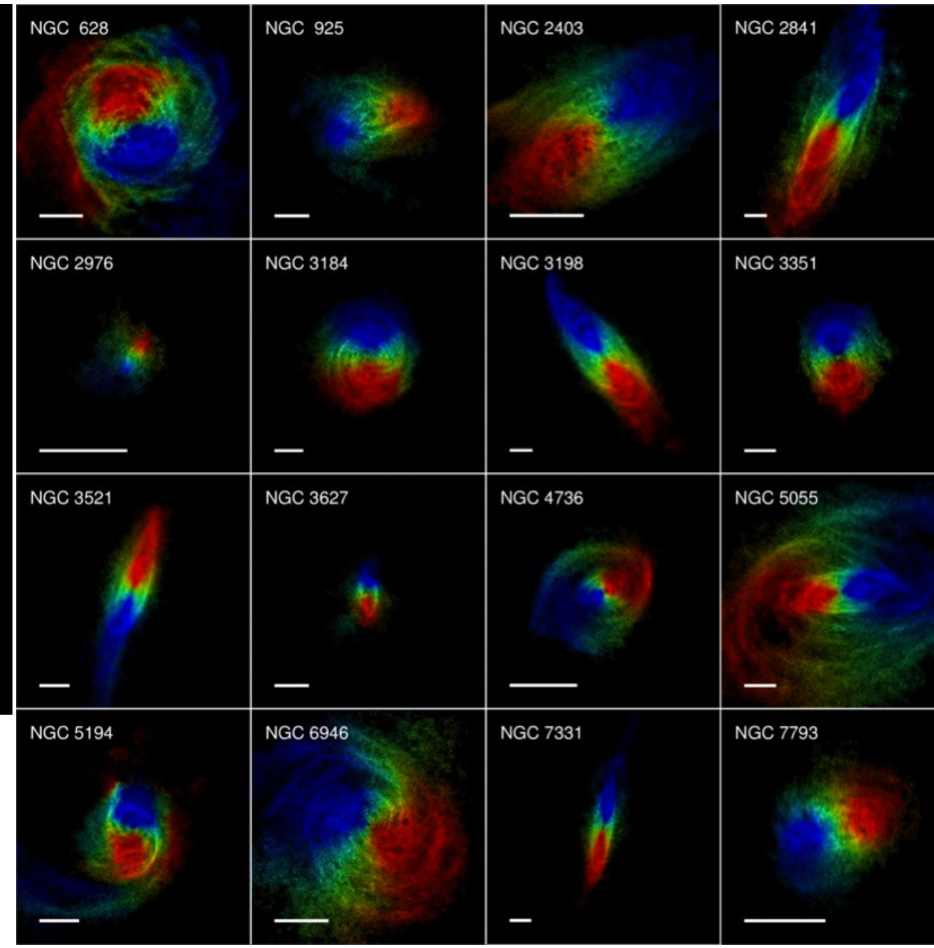
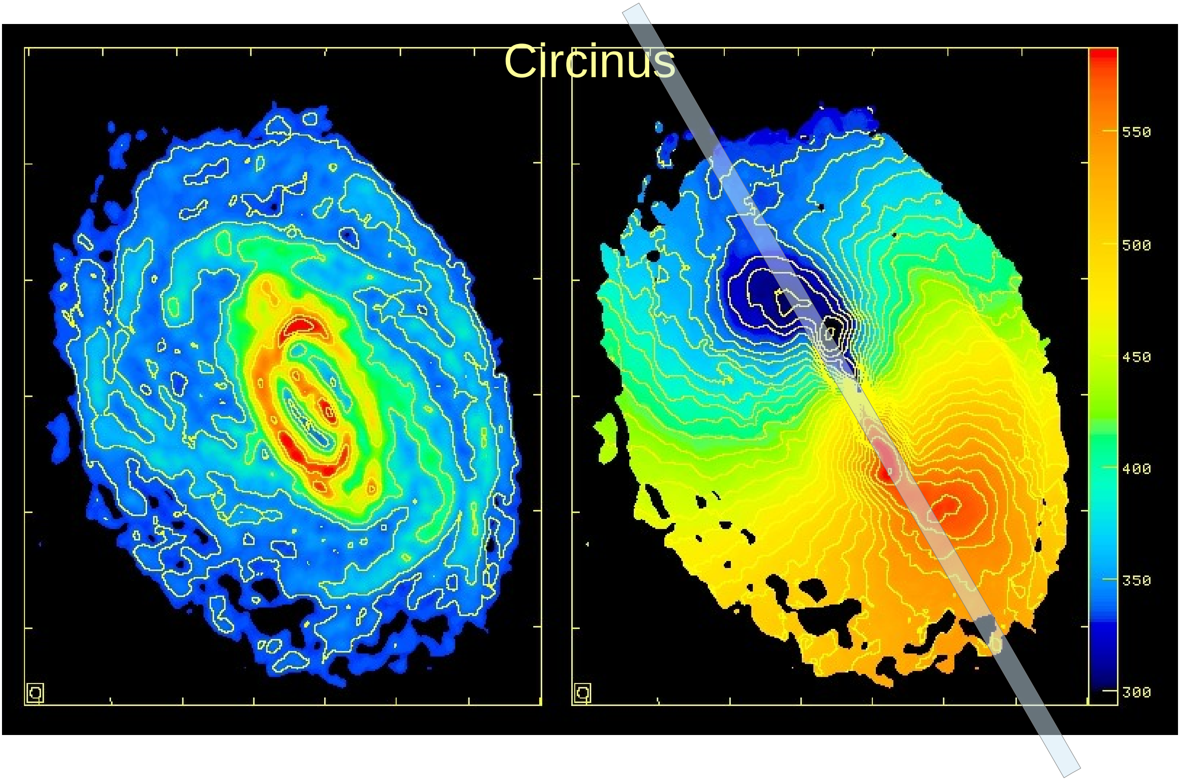




Total Intensity

Relative velocity

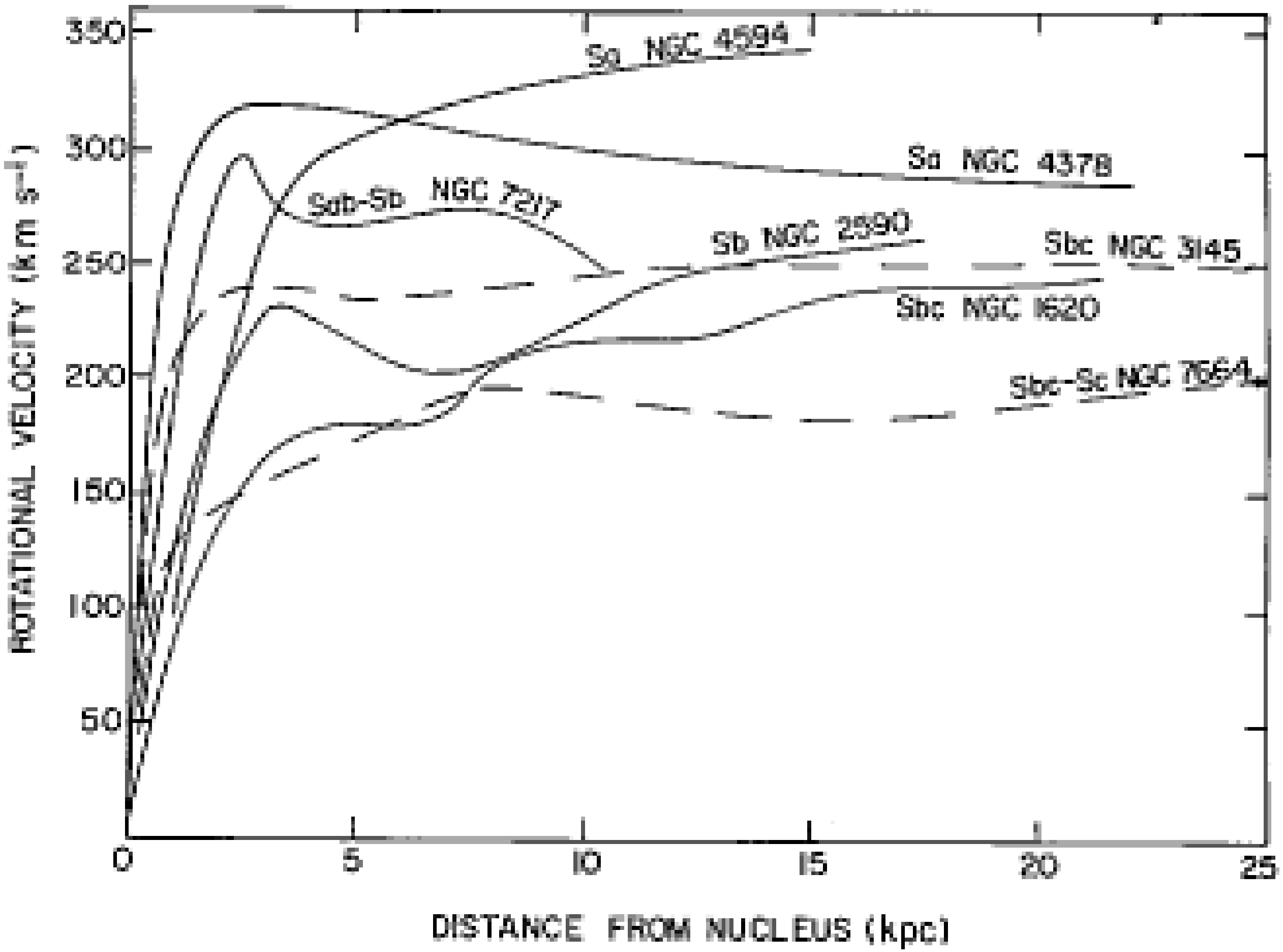
Learning from other spirals:



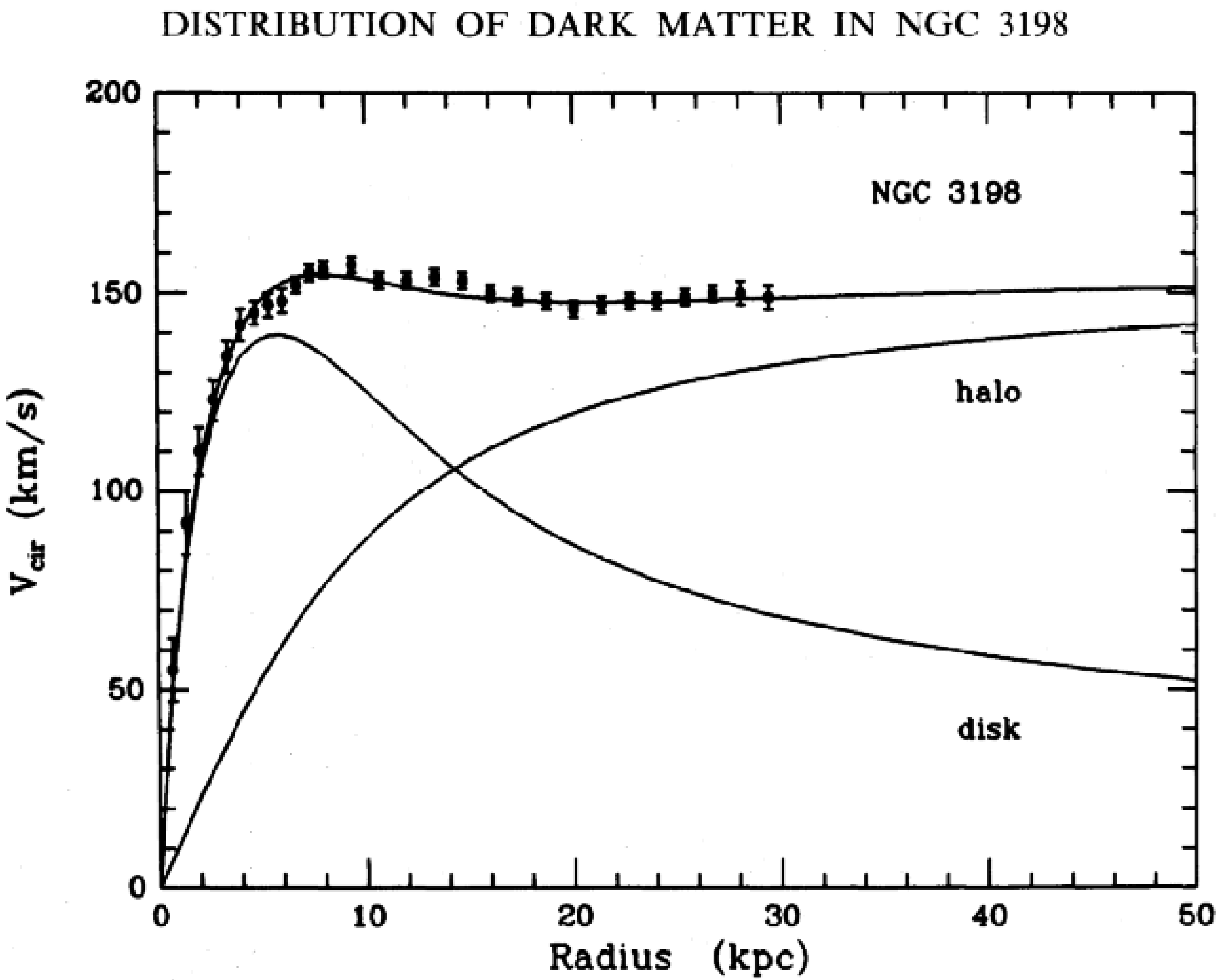
Total Intensity

Relative velocity

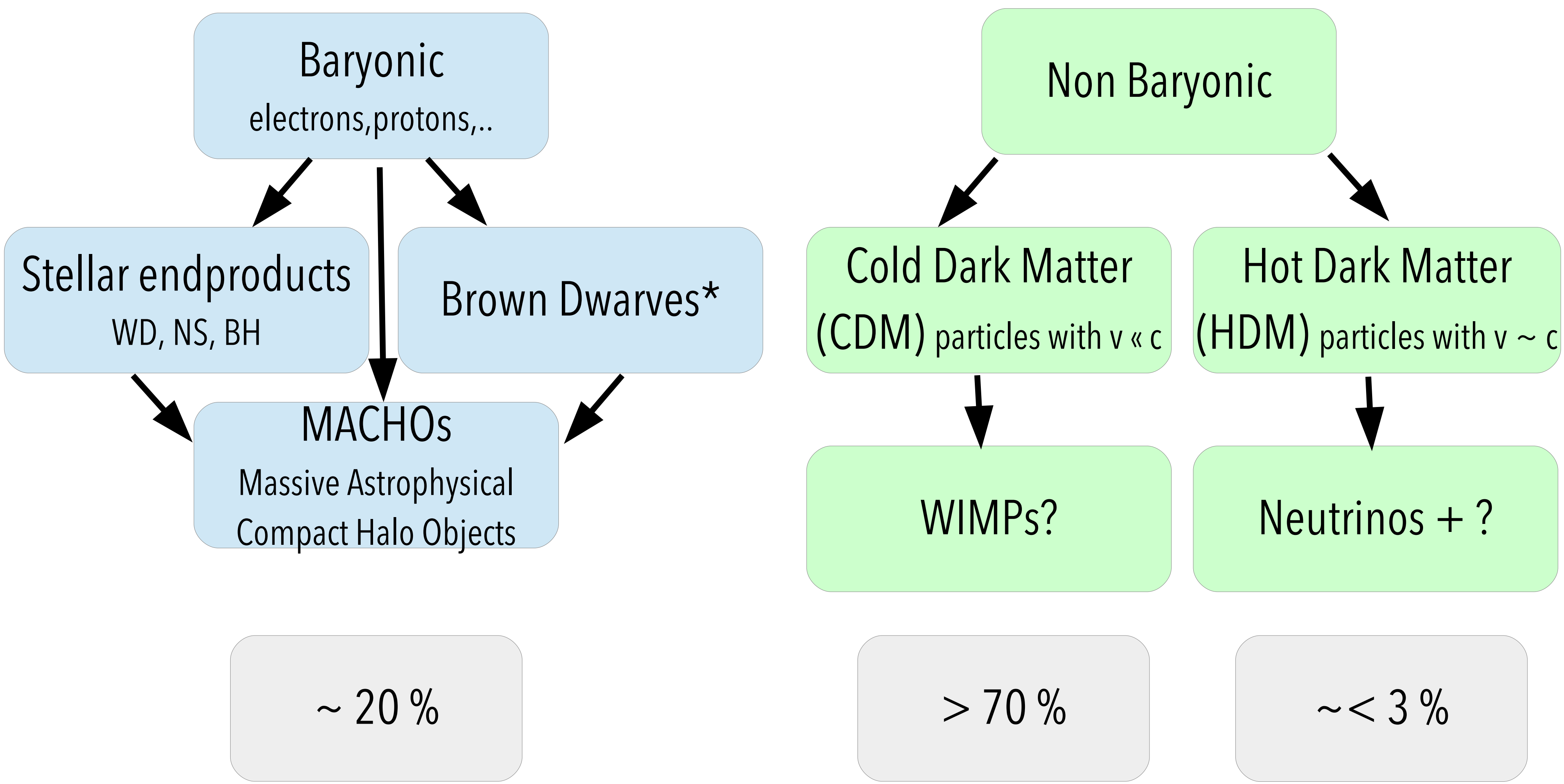
Observations:



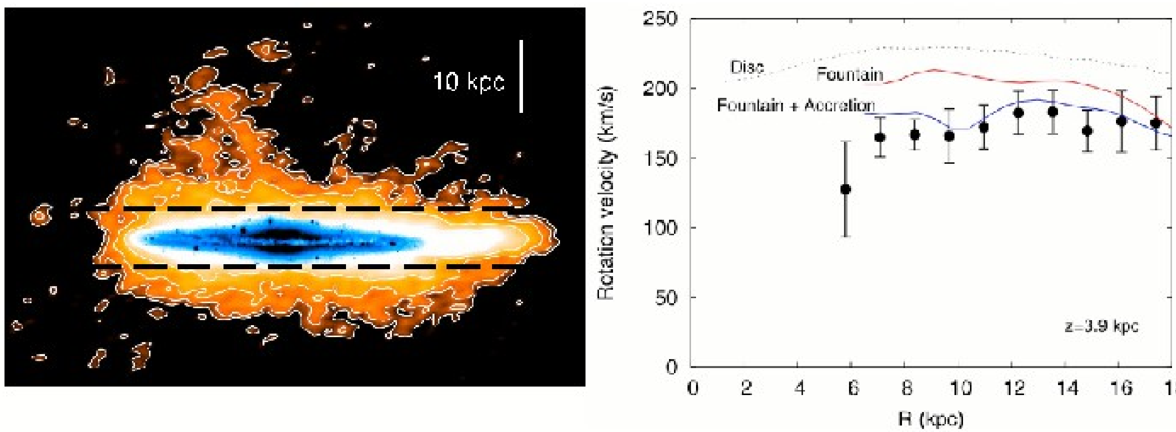
Observations:



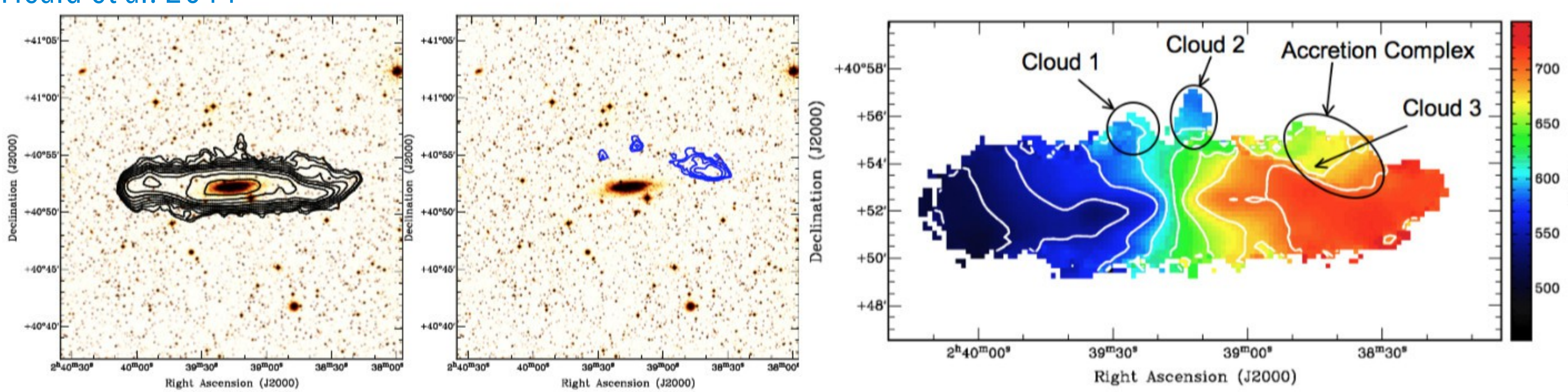
Constraints on Dark Matter:



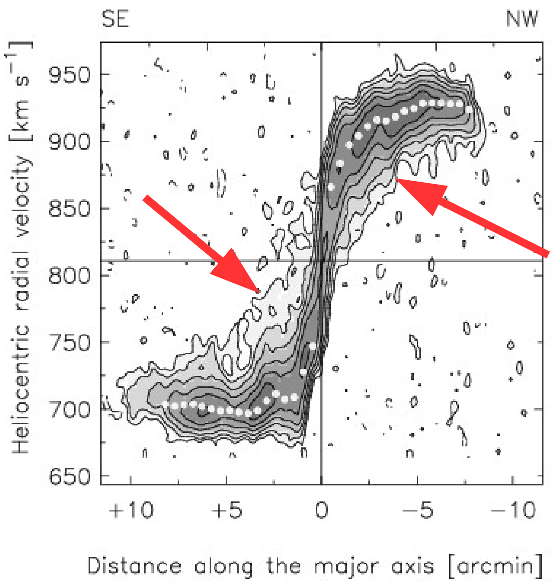
The story is not over... extra-planar clouds

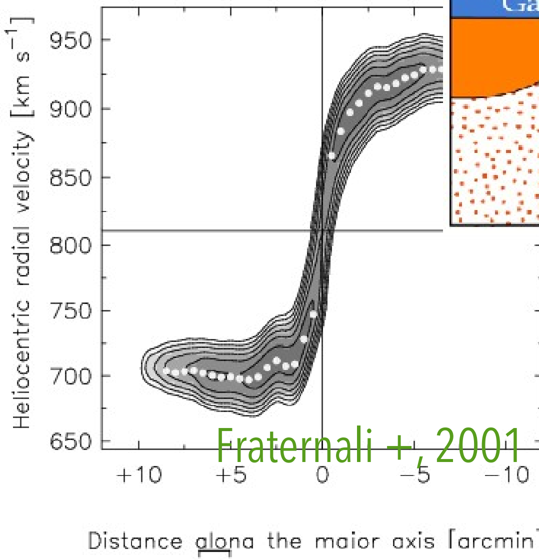


Heald et al. 2011

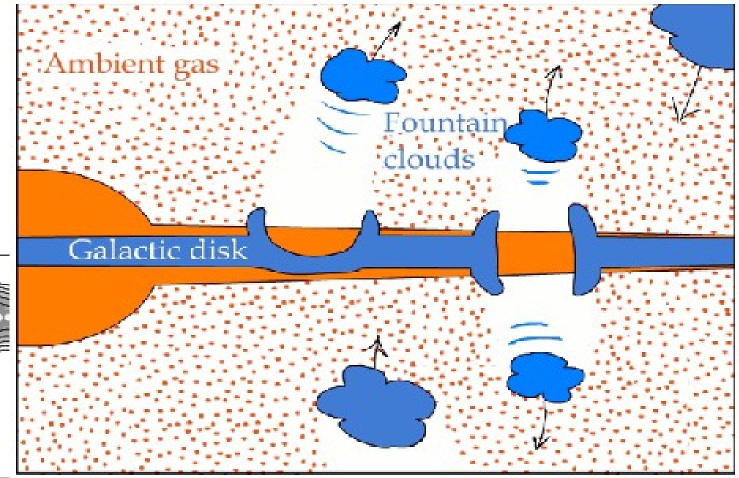


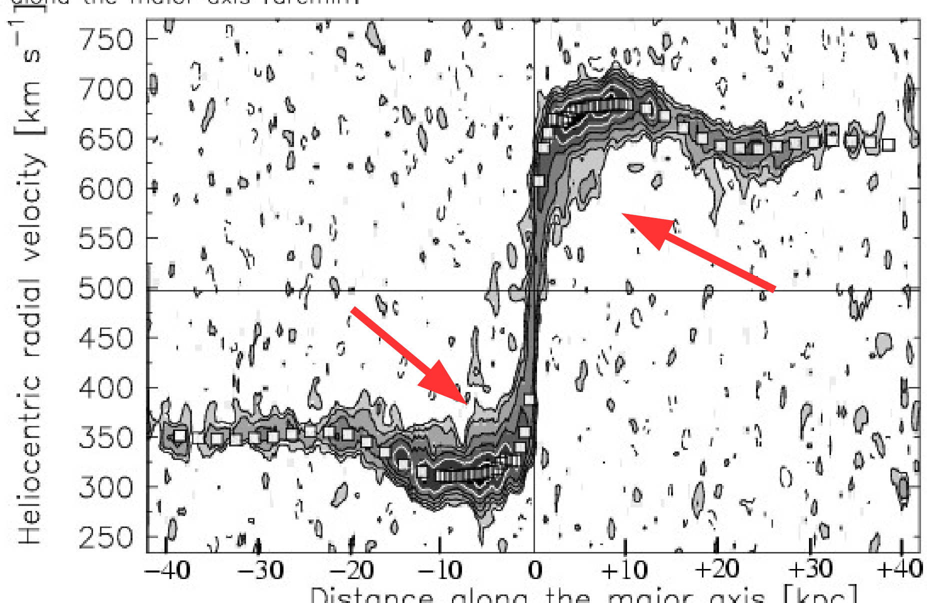
The story is not over…

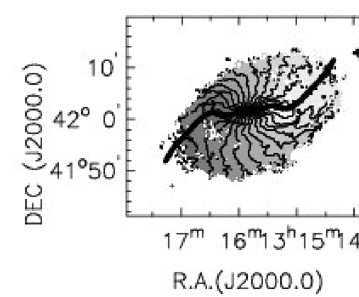




Fraternali +, 2001

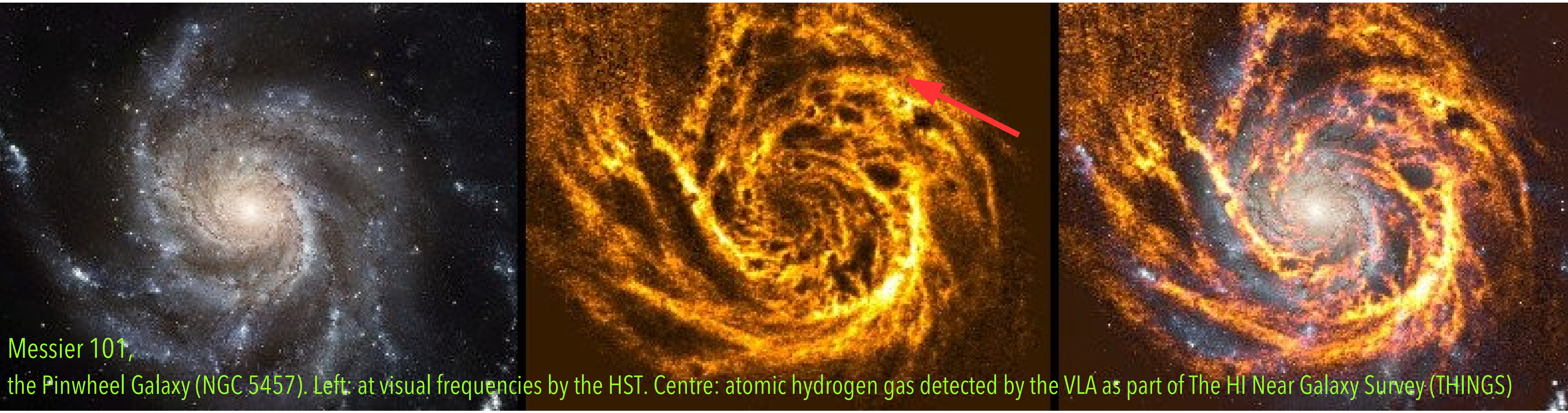




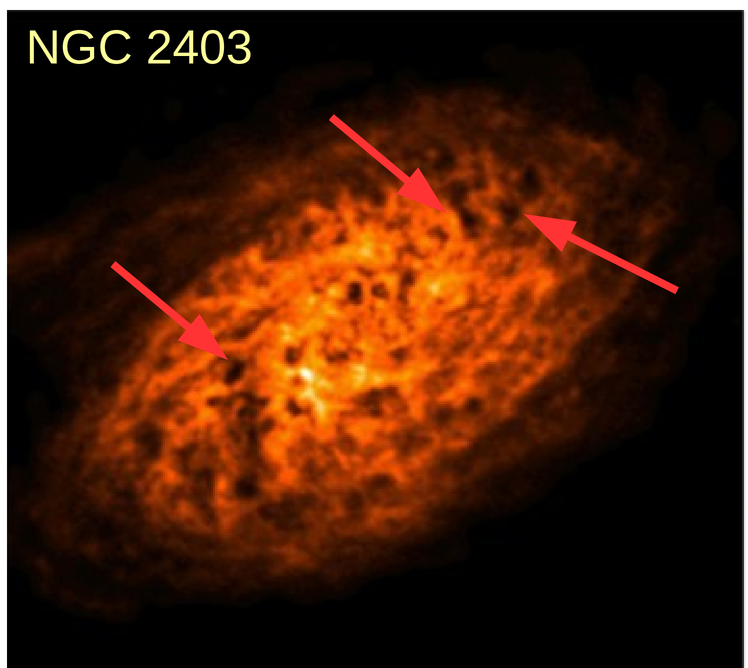


Battaglia +, 2006

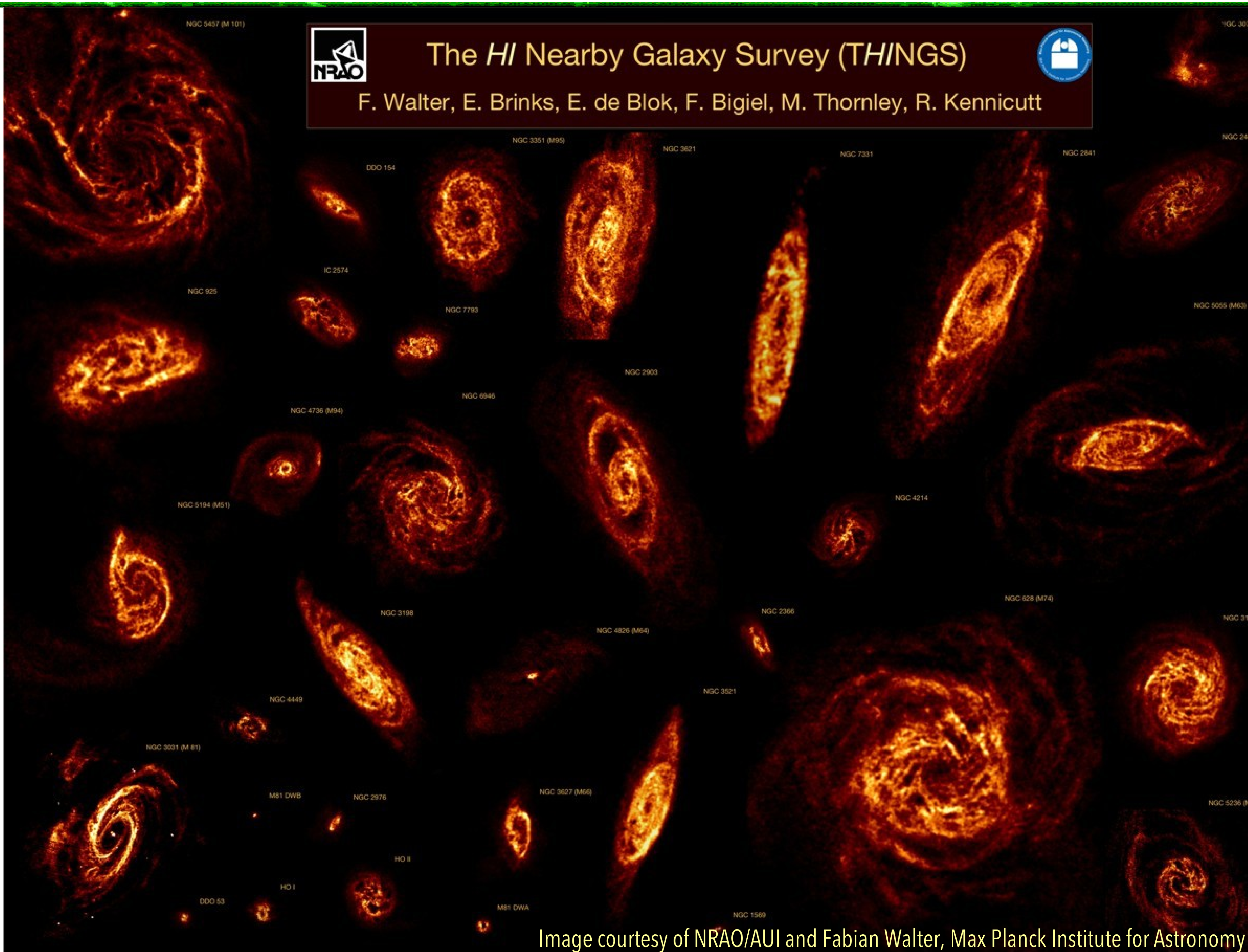
Bubbles (holes) in HI distribution



Messier 101,
the Pinwheel Galaxy (NGC 5457). Left: at visual frequencies by the HST. Centre: atomic hydrogen gas detected by the VLA as part of The HI Near Galaxy Survey (THINGS)

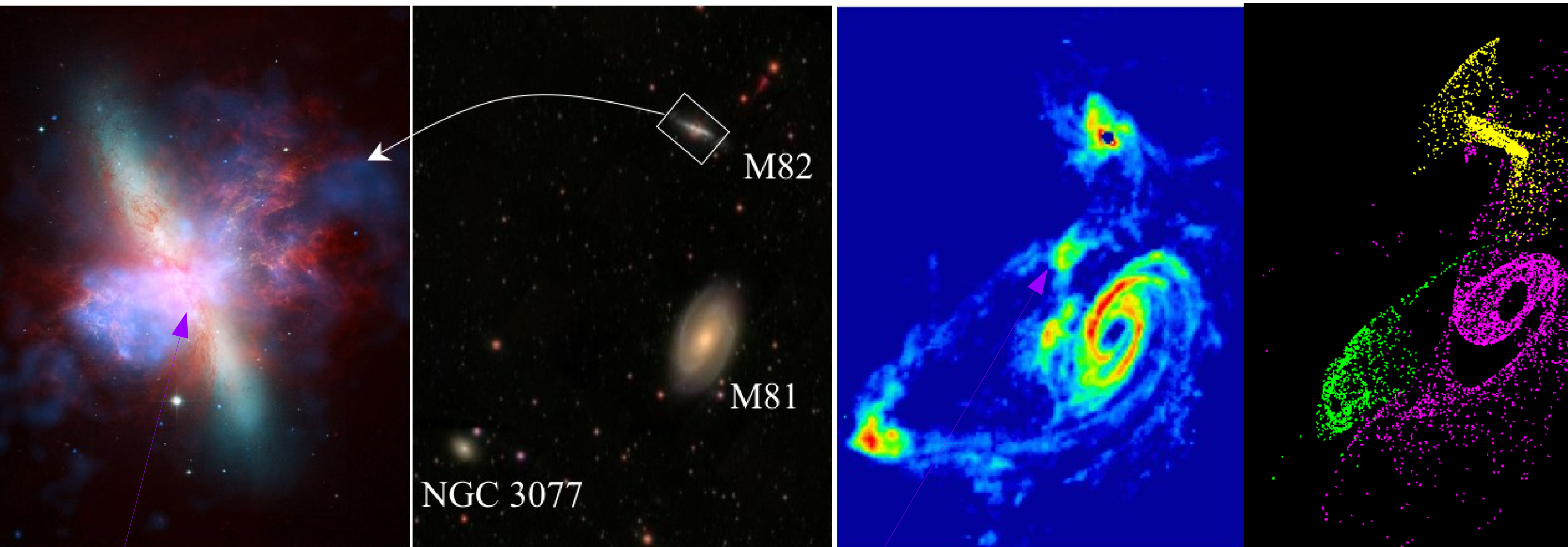


The Interstellar Medium (ISM)



Groups

Interaction triggers starburst and outflow in M82



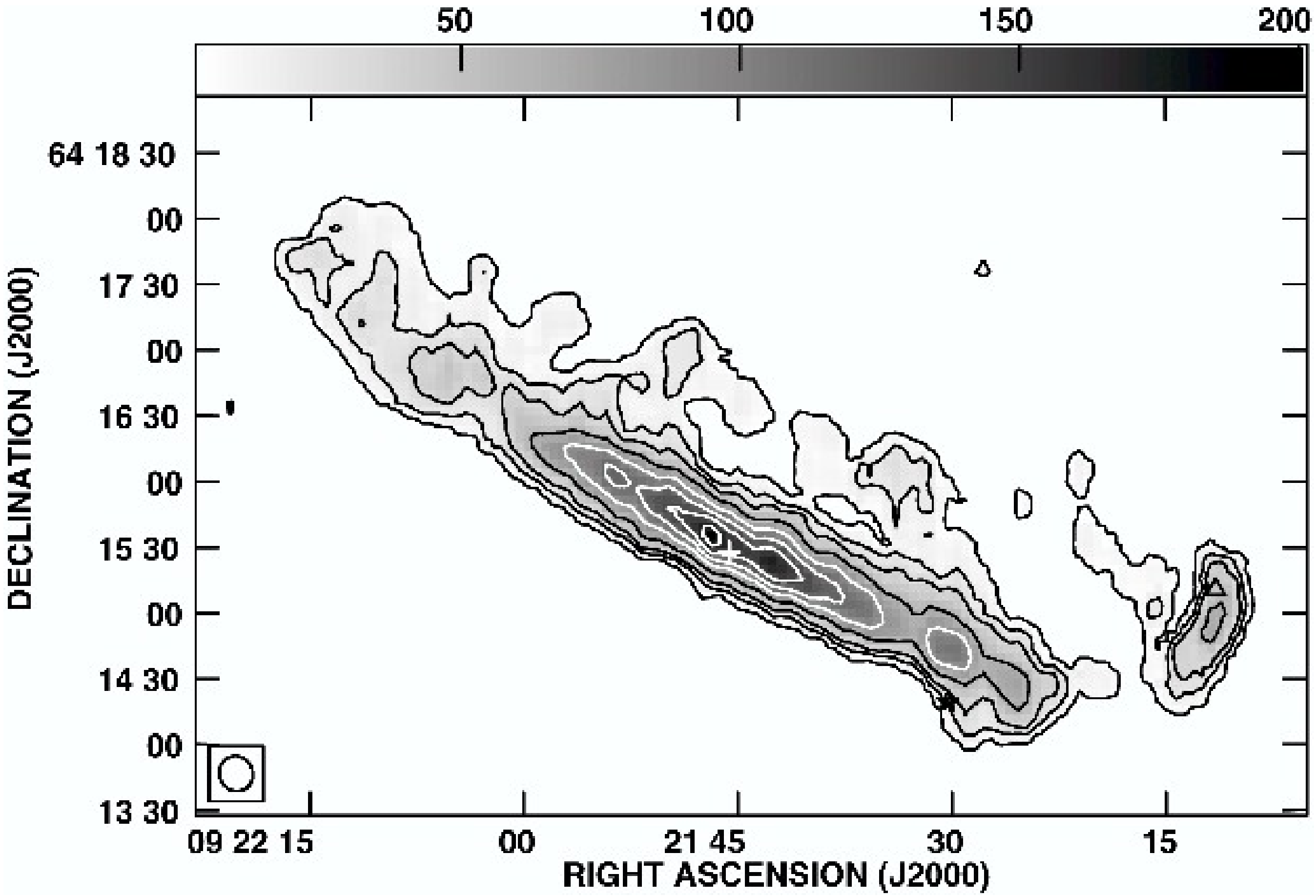
M82: with starburst driven outflowing wind

Optical image (starlight)

Radio image (hydrogen gas)

- Tidal interaction (physical link)
- Different dynamical times: gas/stars
- Induced star formation
- Gas concentrations also in "empty parts of the sky"

Lopesidedness



- Environment weather
- Galaxy motion

Galaxy clusters

- HI deficiency
- Morphological segregation

Virgo Cluster

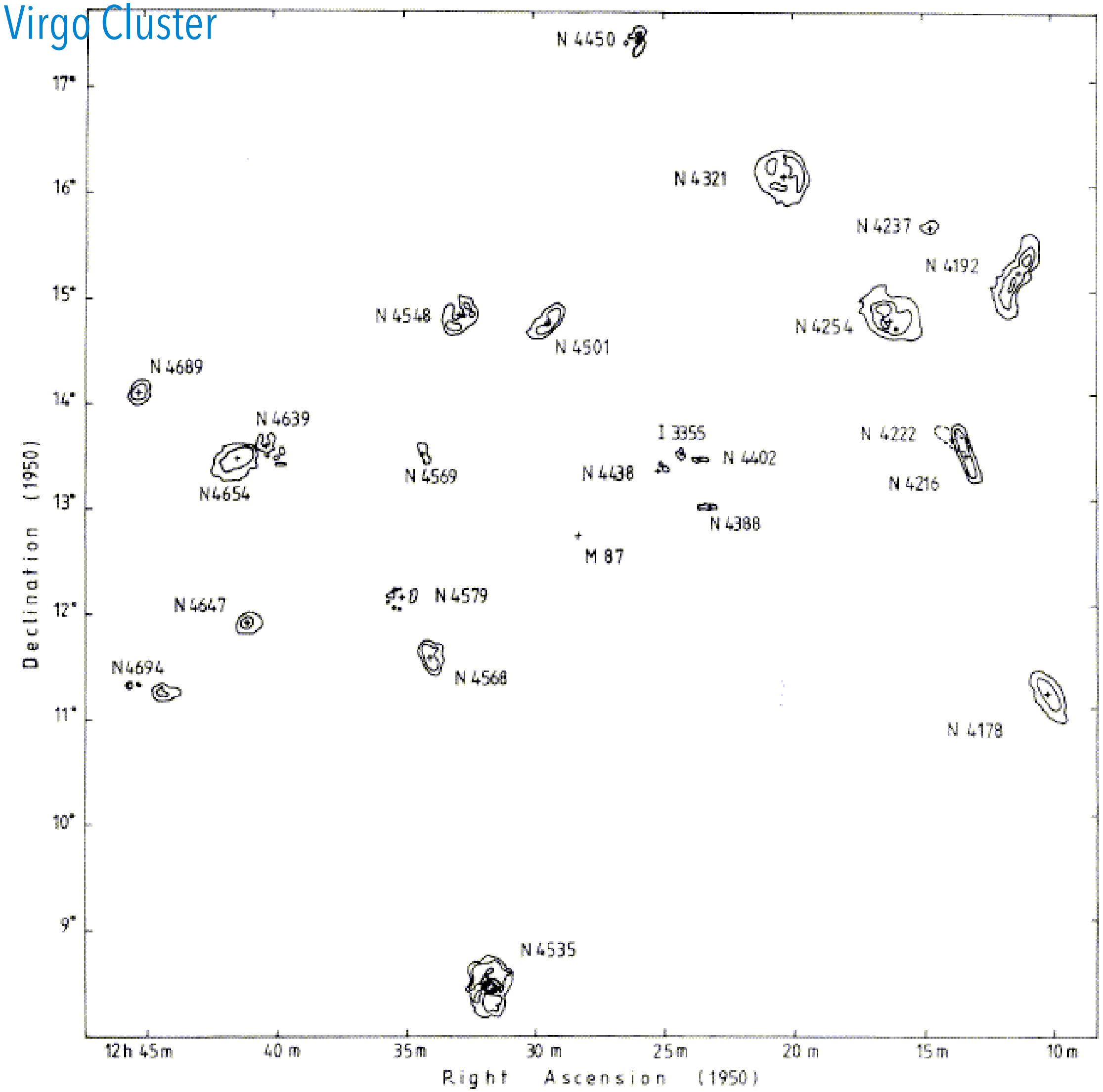
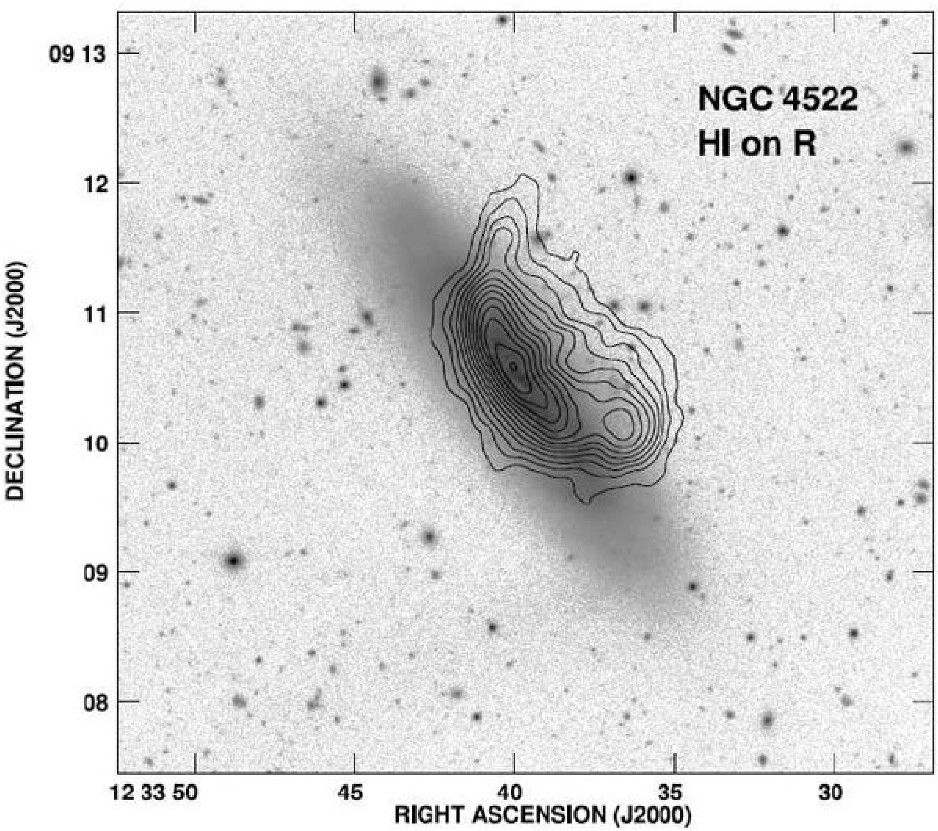


FIG. 23. Integrated neutral hydrogen maps of the brightest spirals in the Virgo Cluster center. Each map has been drawn at the galaxy position indicated by a cross and magnified by a factor of 5 compared with the scale in right ascension and declination. The first contour in each map corresponds approximately to a column density of 10^{20} atoms cm^{-2} (even if it is not the case in the maps published in Figs. 1–22 especially for NGC 4388, 4450, 4569, 4694).



Ram pressure stripping

Summary

- In spirals HI is distributed on a large fraction of the volume
- HI traces the neutral & warm ISM
- Line emission (absorption) very effective kinematic tool

- Rotation curve & Oort constants
- Dark matter
- External spirals
- Neutral gas effects (e.g. Lopesidedness, extra-planar gas, bubbles, etc)

- Suggested readings:
- Fanti & Fanti , § 13