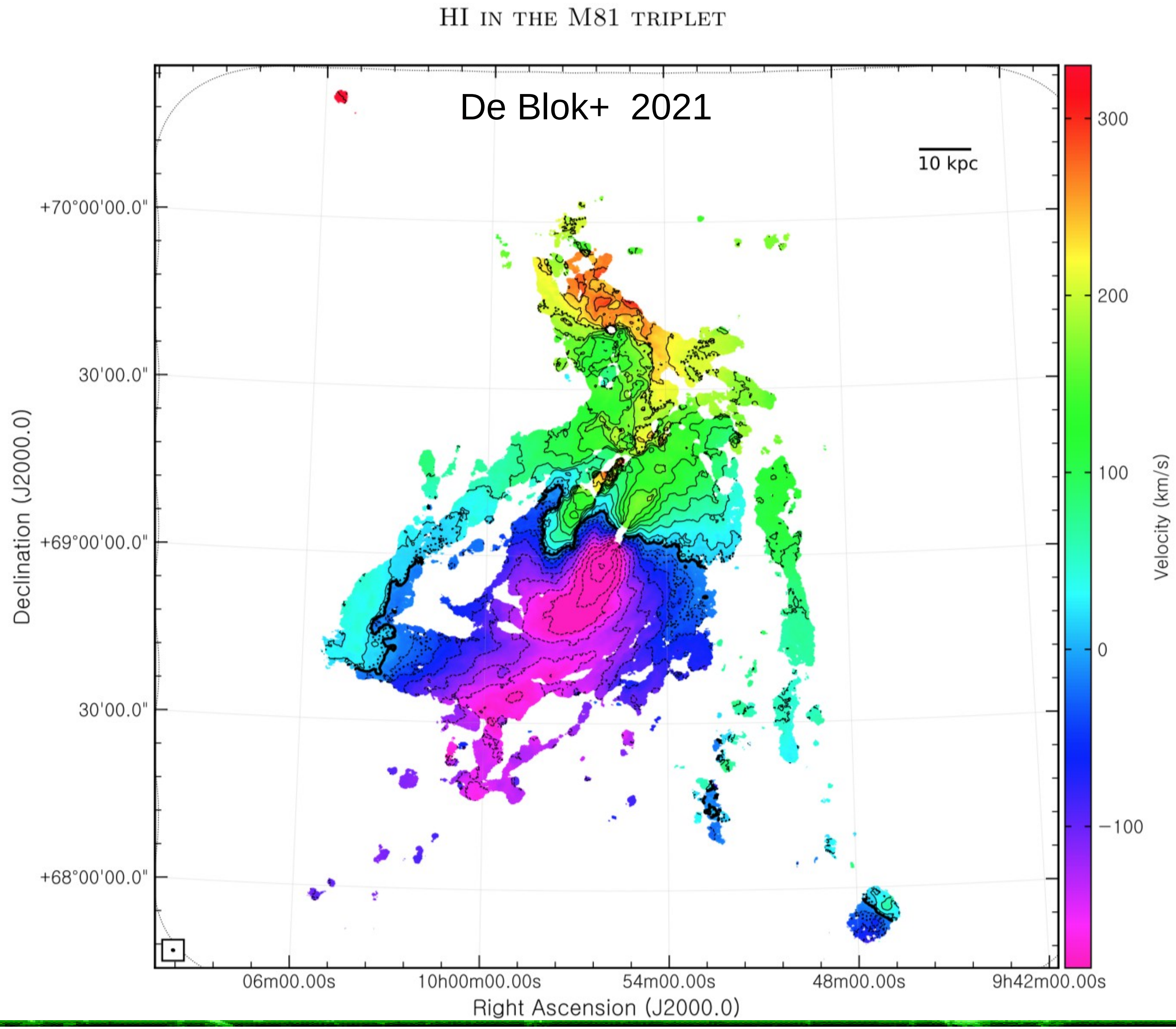
The Interstellar Medium (ISM)



The Interstellar Medium (ISM): outline

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)

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, absorbption & IR Emission

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

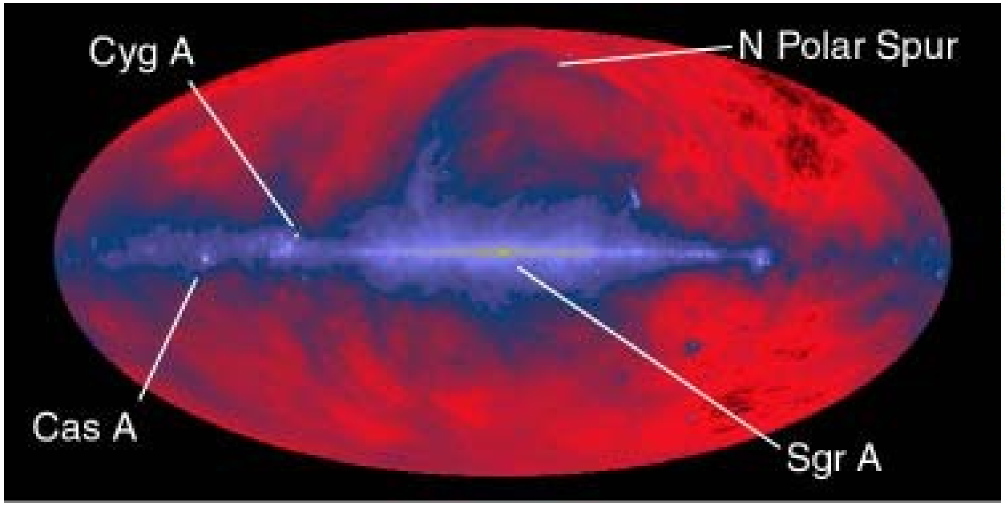
Hyperfine transition at 1.42 GHz

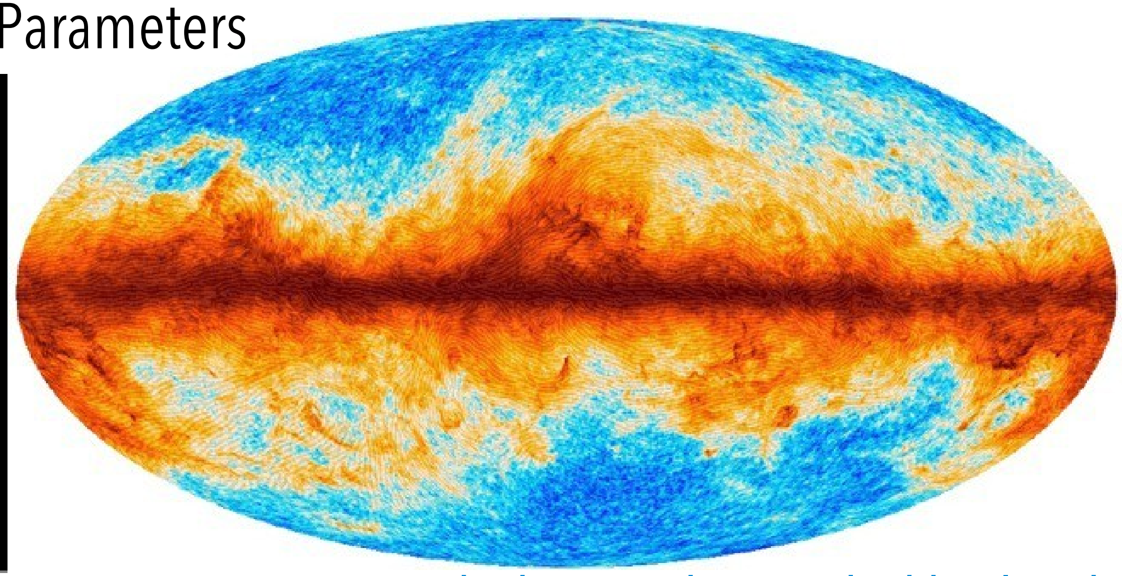
Bremsstrahlung from thermal plasma (WIM & HIM) +

Synchrotron (electrons in cosmic rays + individual objects)

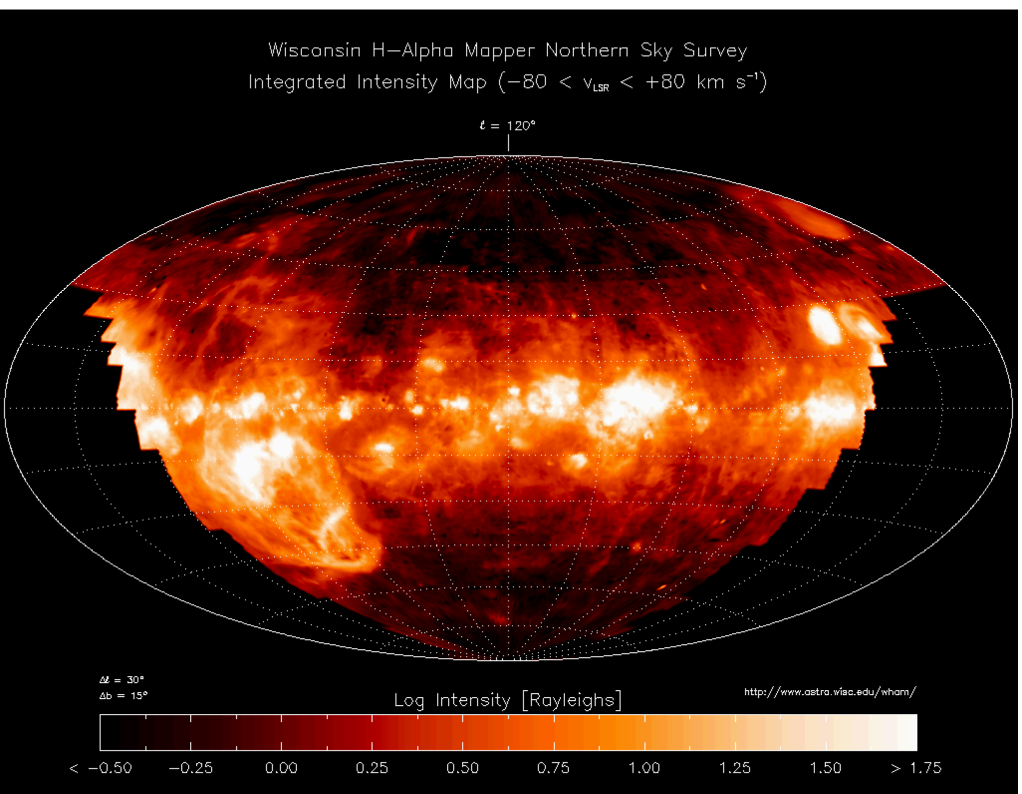
Gamma rays from CR-partner collisions

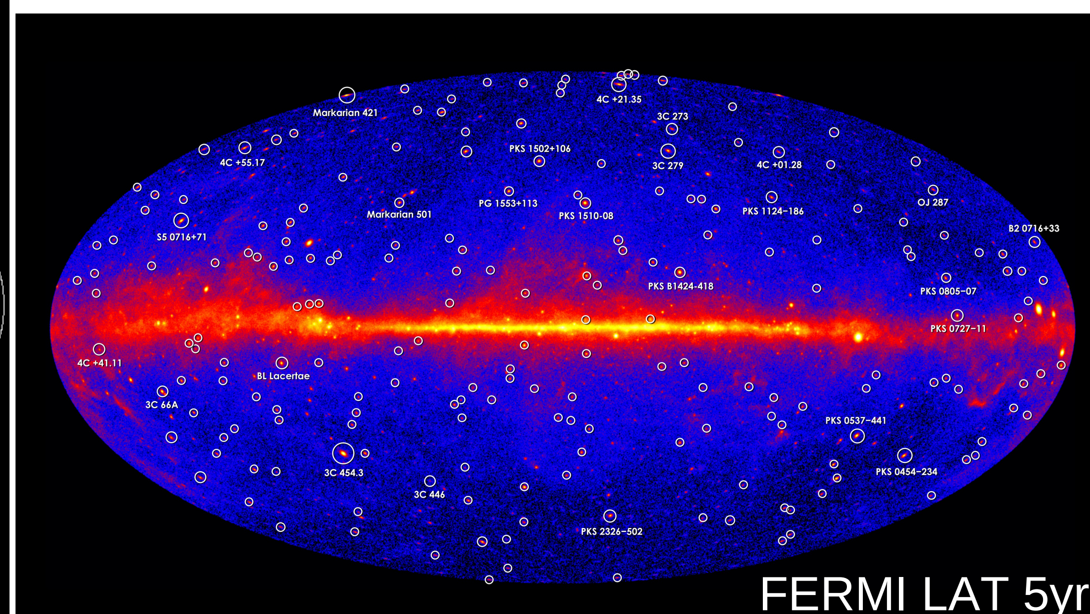
What is it? Composition, Observations, Parameters





Dust emission as observed with Planck





What is it? Composition, Observations, Parameters

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

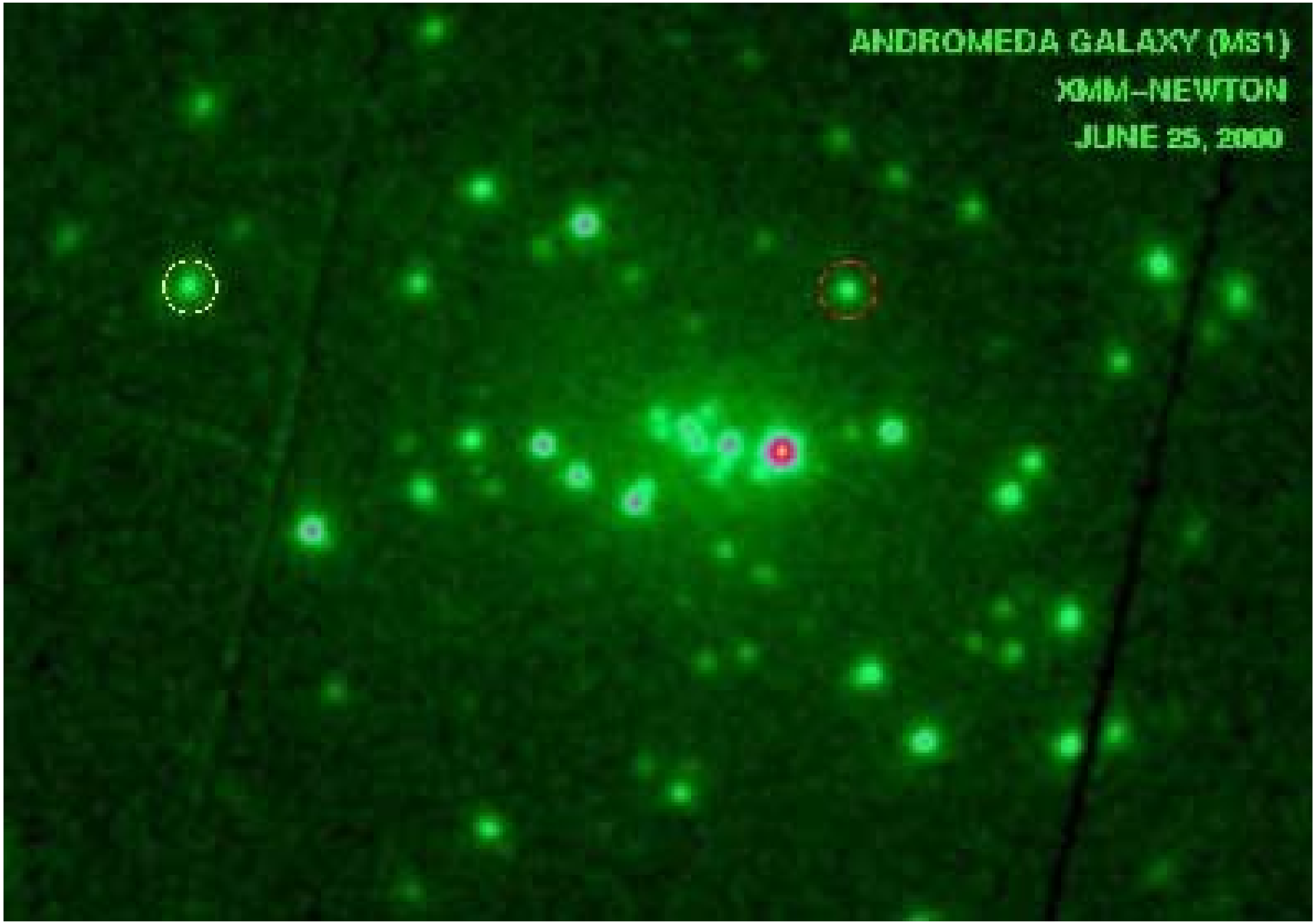
Name	N (cm^{-3})	T (K)	M ($10^9 M_{sun}$)	Fraction of Total Volume
molecular	$> 10^2$	*10*	*2*	*1%*
CNM	50	$< 10^2$	3	4%
WNM	0.5	10^3	4	30%
WIM	0.3	10^4	1	15%
HIM	0.003	$>10^6$	0.1	50%

Typical values for a spiral galaxy

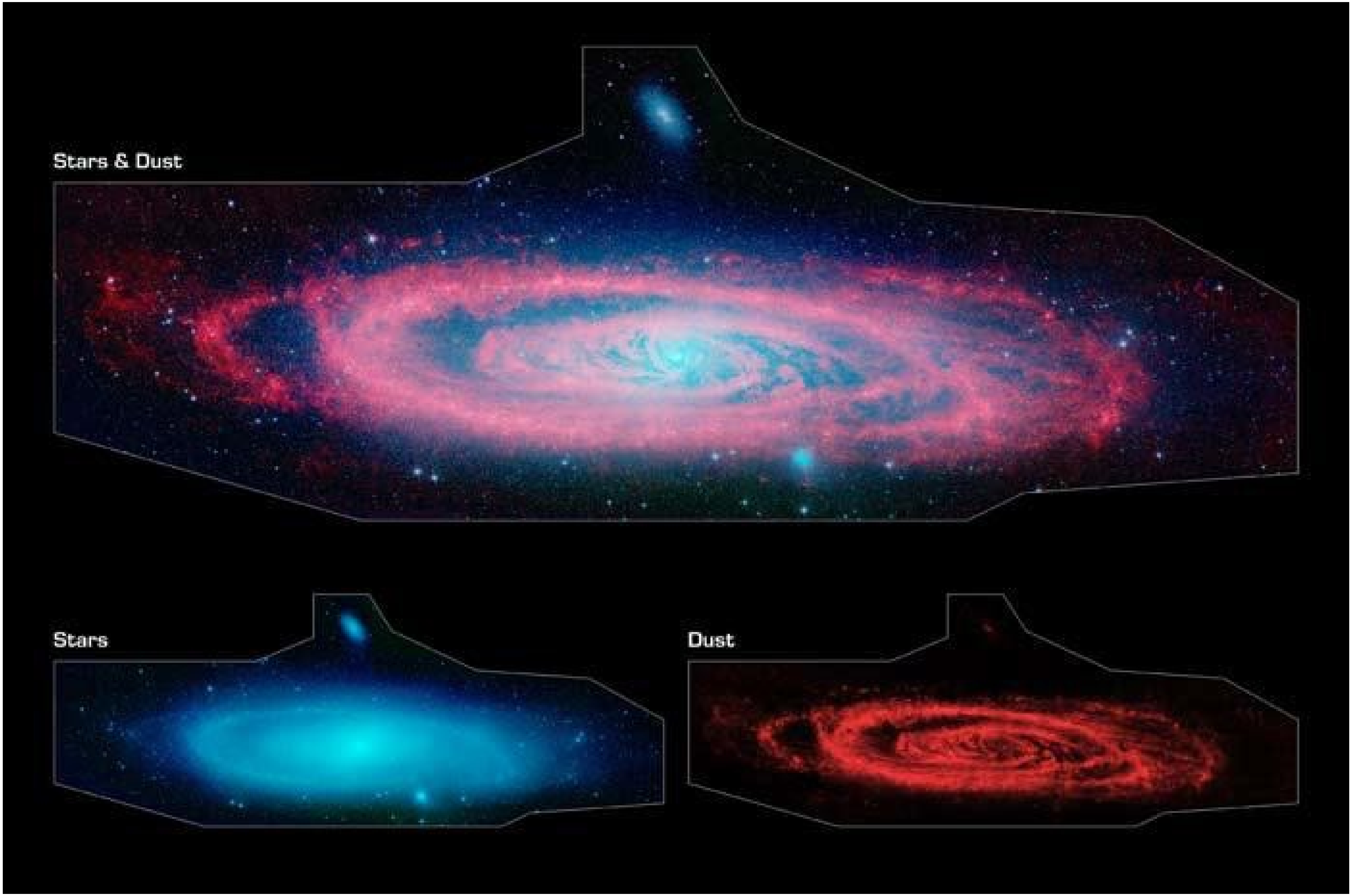
Dust is generally associated with CNM, i.e. dense and cold environments

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

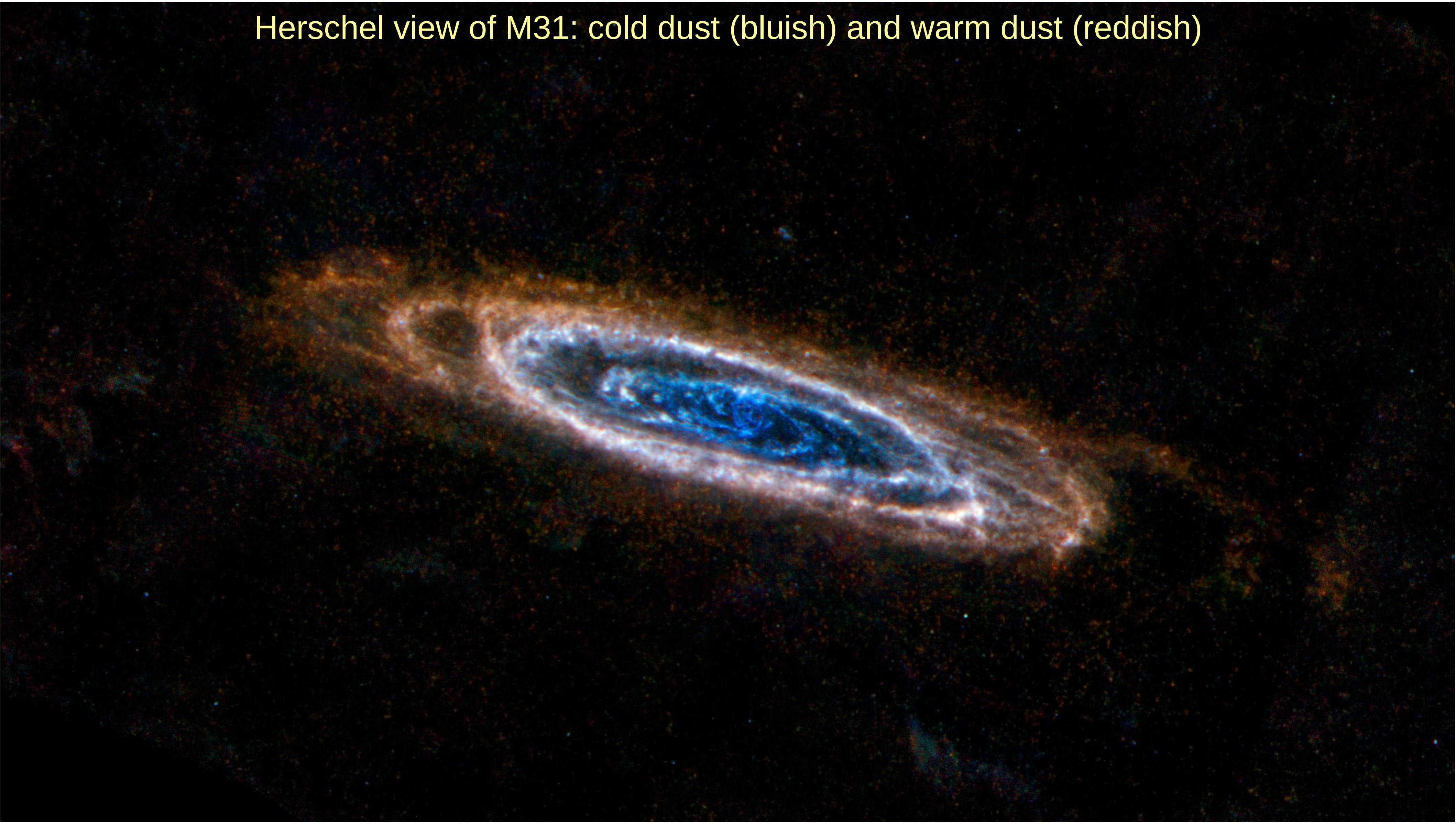
Learning from other spirals: X – rays captured by XMM – Newton (30' FoV)



Learning from other spirals:



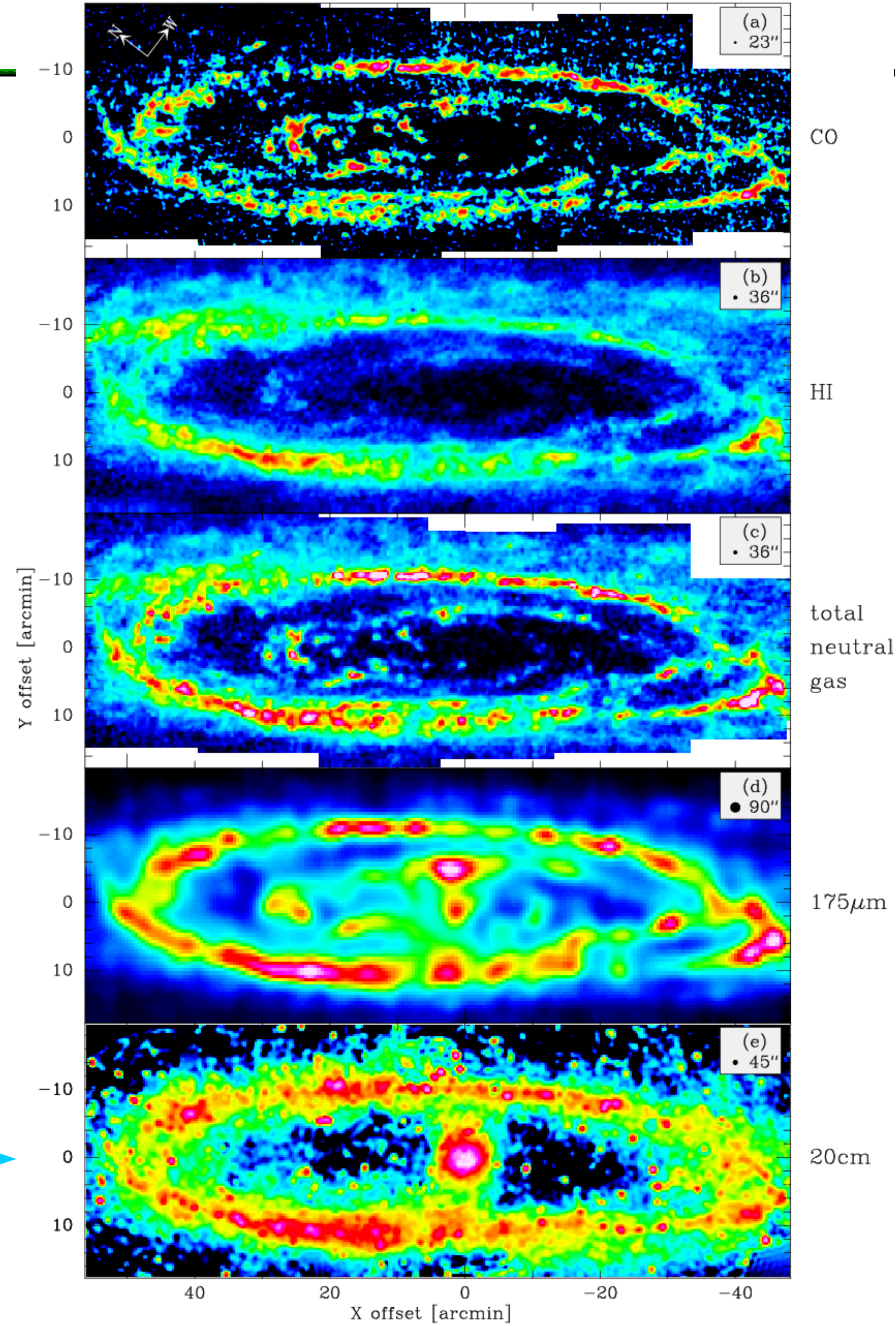
Learning from other spirals:



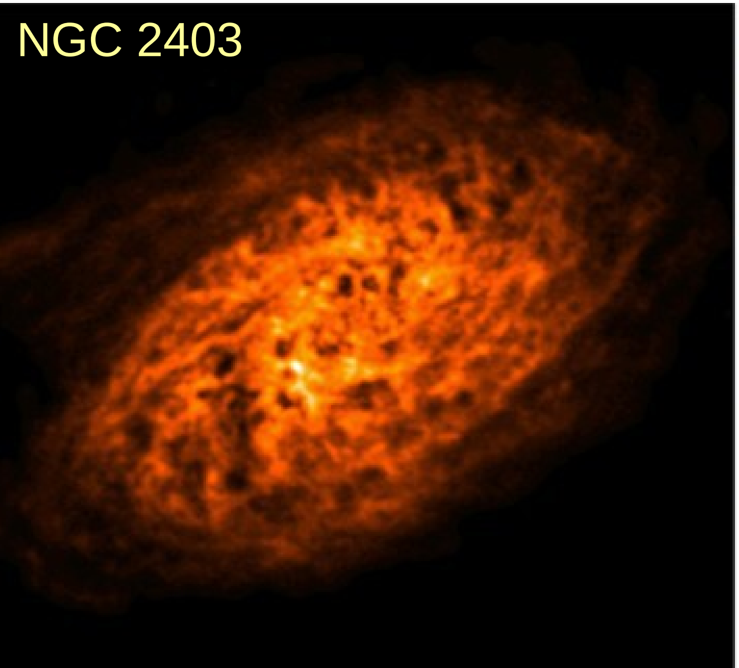
Learning from other spirals:

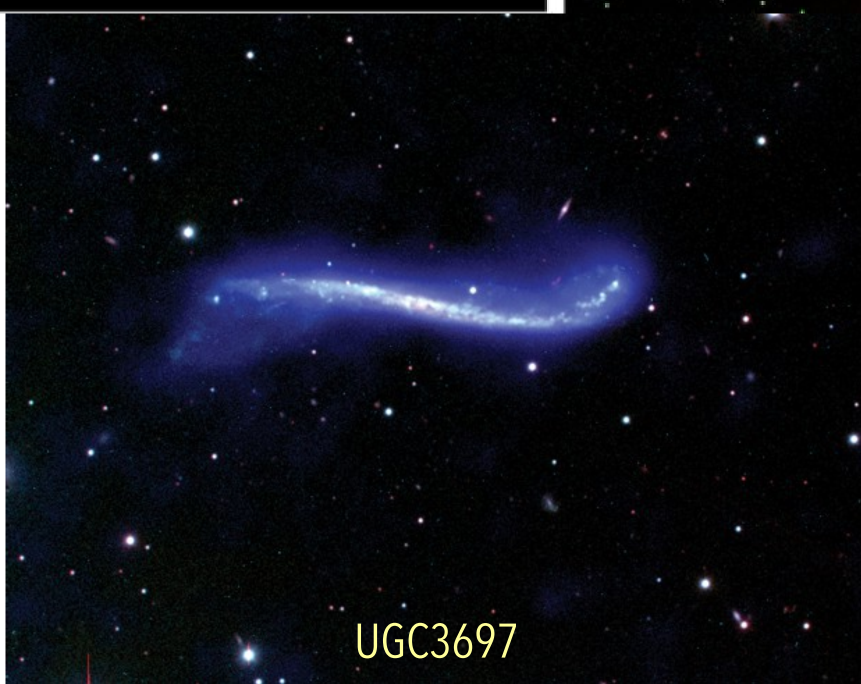
Comparison of emission observed at different wavelenghts

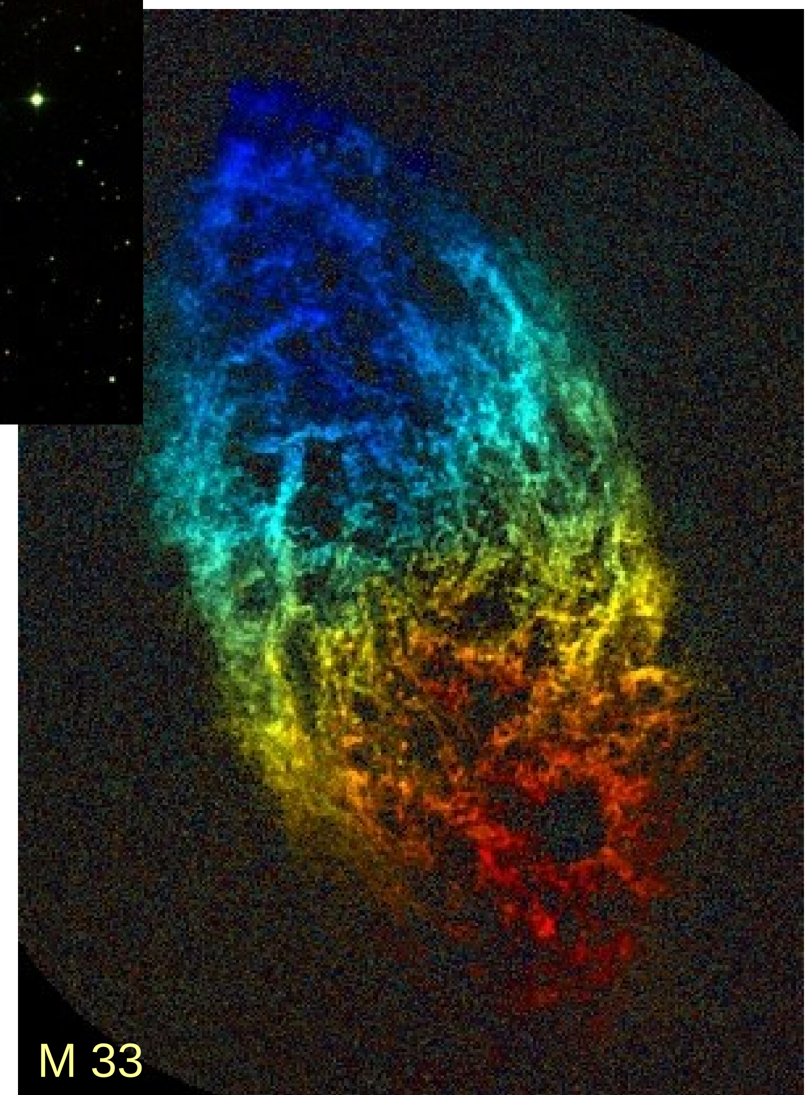
HI & Synchrotron



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 ~ 10^{-16} m/s

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

The brightness temperature derived from line photons:

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

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

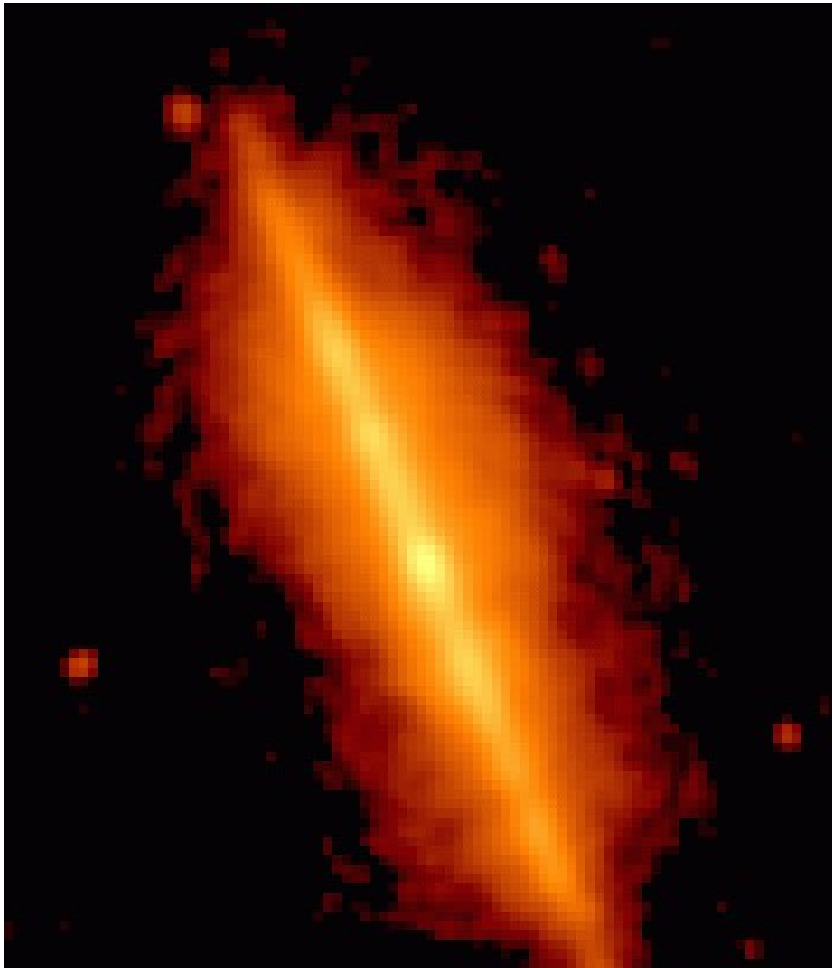
$T_{B(H)}$ is in K if N_H is in cm^{-2}

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

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

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

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



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).

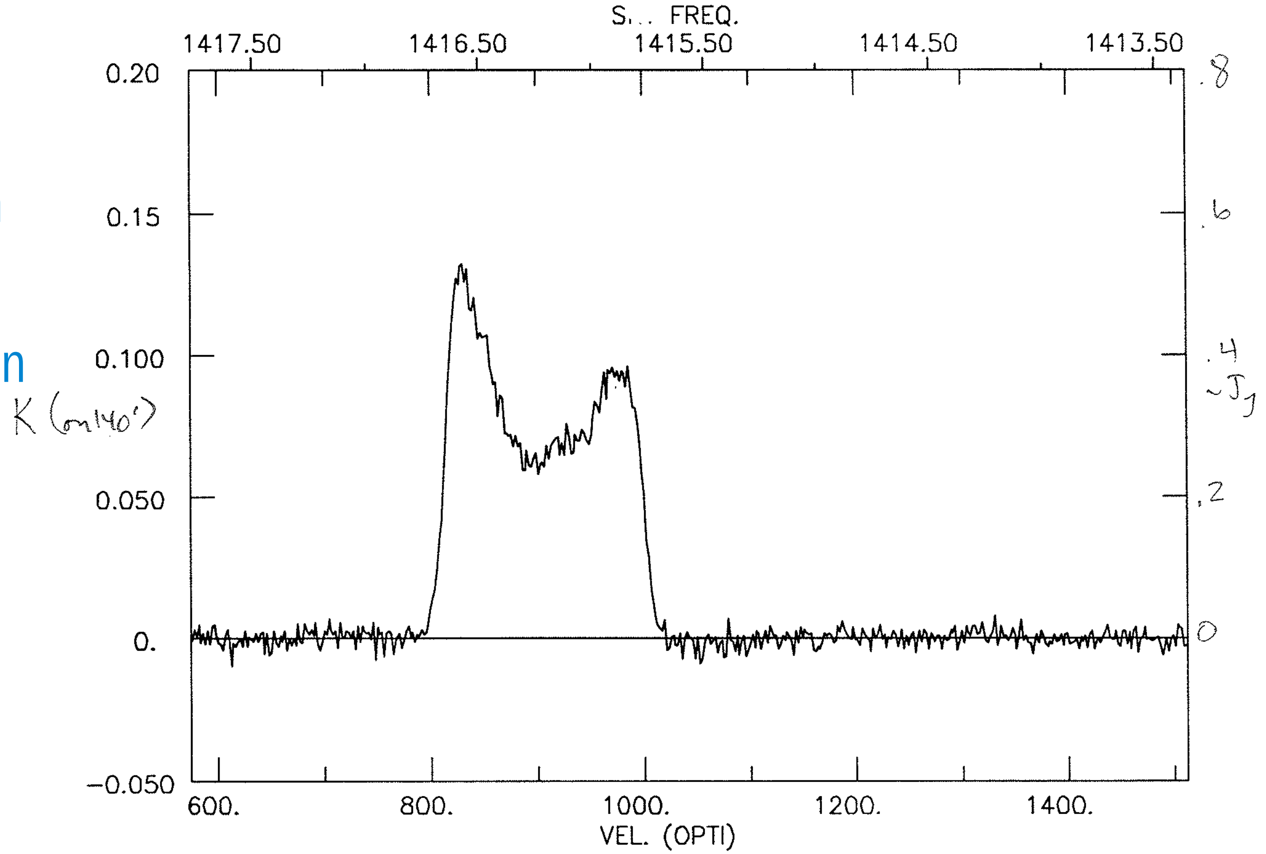
- Hyperfine structure: $\Delta E \sim 5.9\ \mu eV$
- Natural width of 21 cm line ~ 10^{-16} m/s

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

a) Broadening due to the thermal motions of the gas

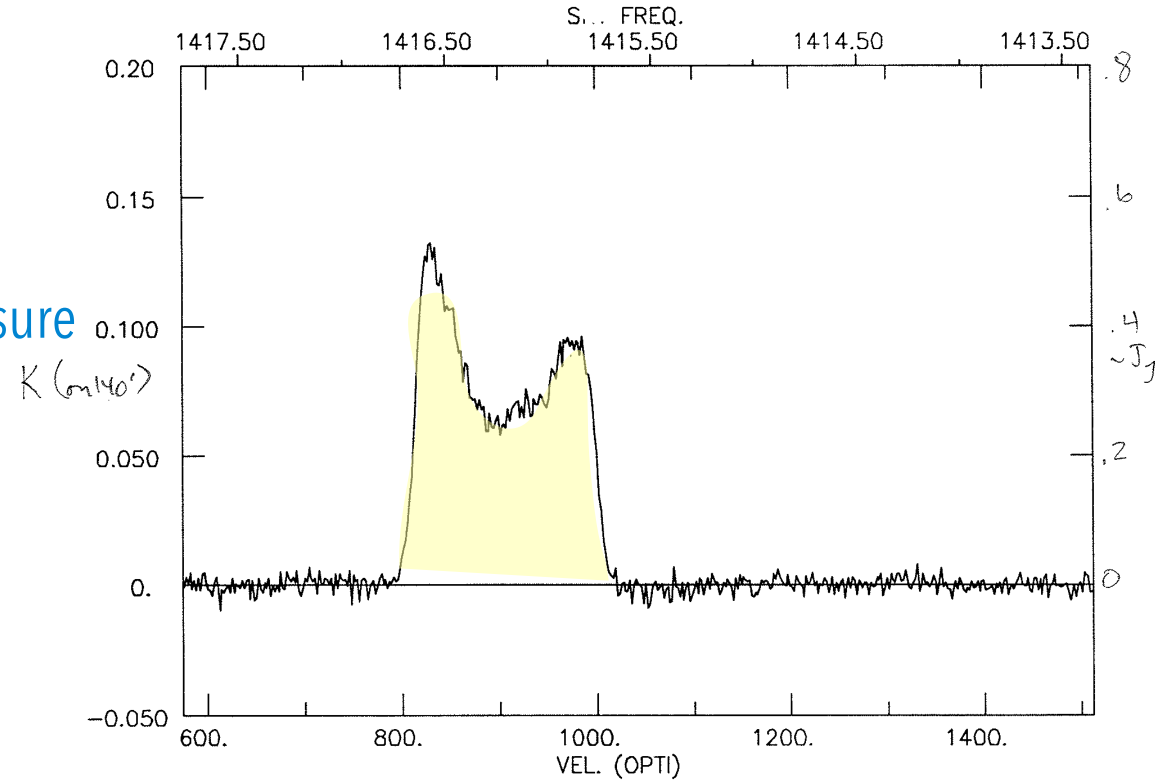
b) Systematic shift due to radial velocity along the l.o.s:

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 and a distribution of radial velocities)



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

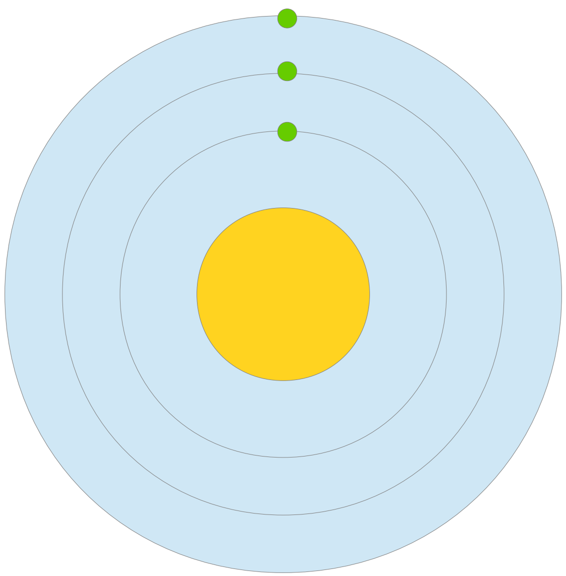
- The photons of the line are a direct measure of the total amount of HI in the volume explored by the radio telescope



- In case of an optically thin emission

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

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)

Alternative options:

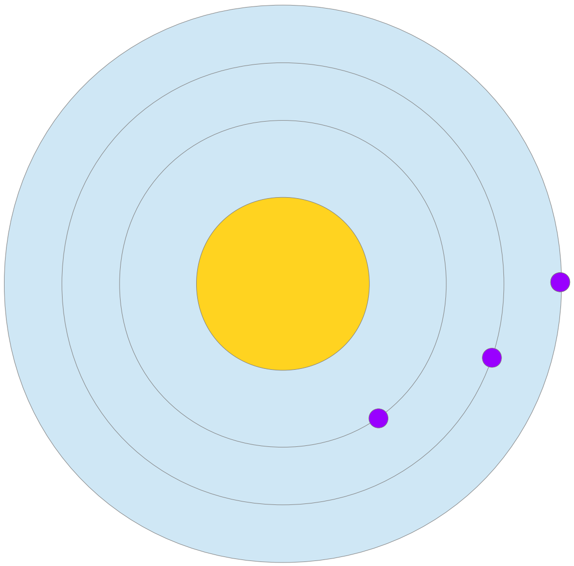
- **Solid body rotation**: constant angular velocity
- **Keplerian decrease**: once the mass of the galaxy increases marginally with radius, such circular velocity should go with $r^{-0.5}$.

Where is it? Distribution, Kinematics, Origin and Fate

Differential rotation

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

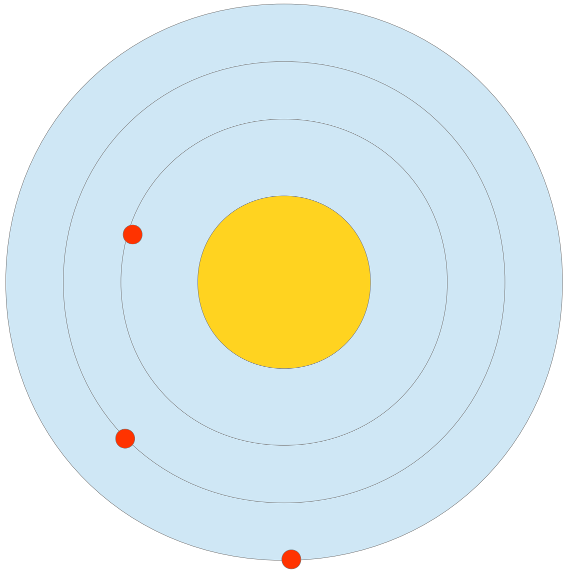
(each point has the same constant speed, but orbits with different lengths)



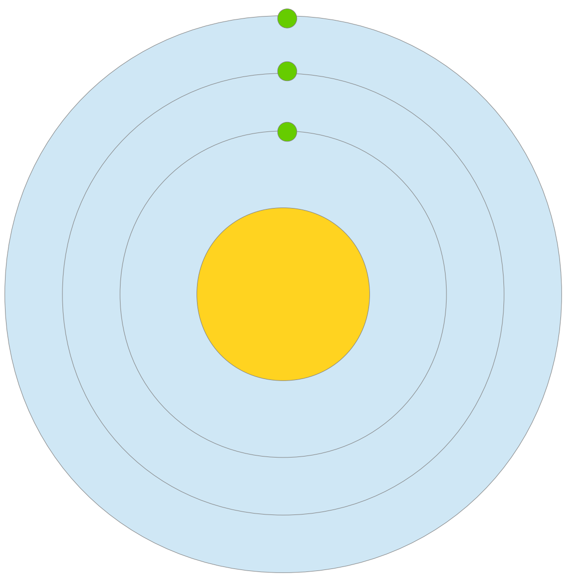
Where is it? Distribution, Kinematics, Origin and Fate

Differential rotation

Time lapse 2: red dots now appear uncorrelated



Where is it? Distribution, Kinematics, Origin and Fate

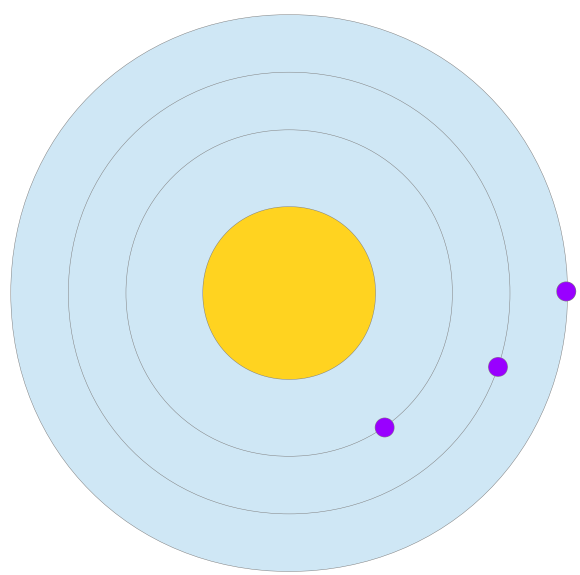


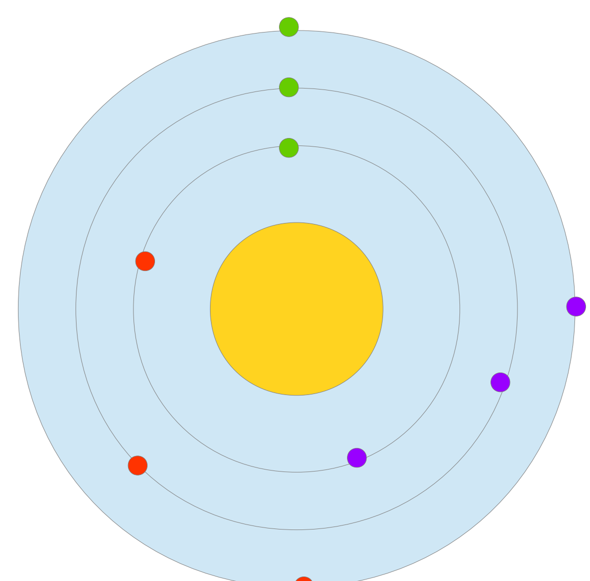
Differential rotation: **summary**

Green = stage 0, start

Purple = time lapse 1

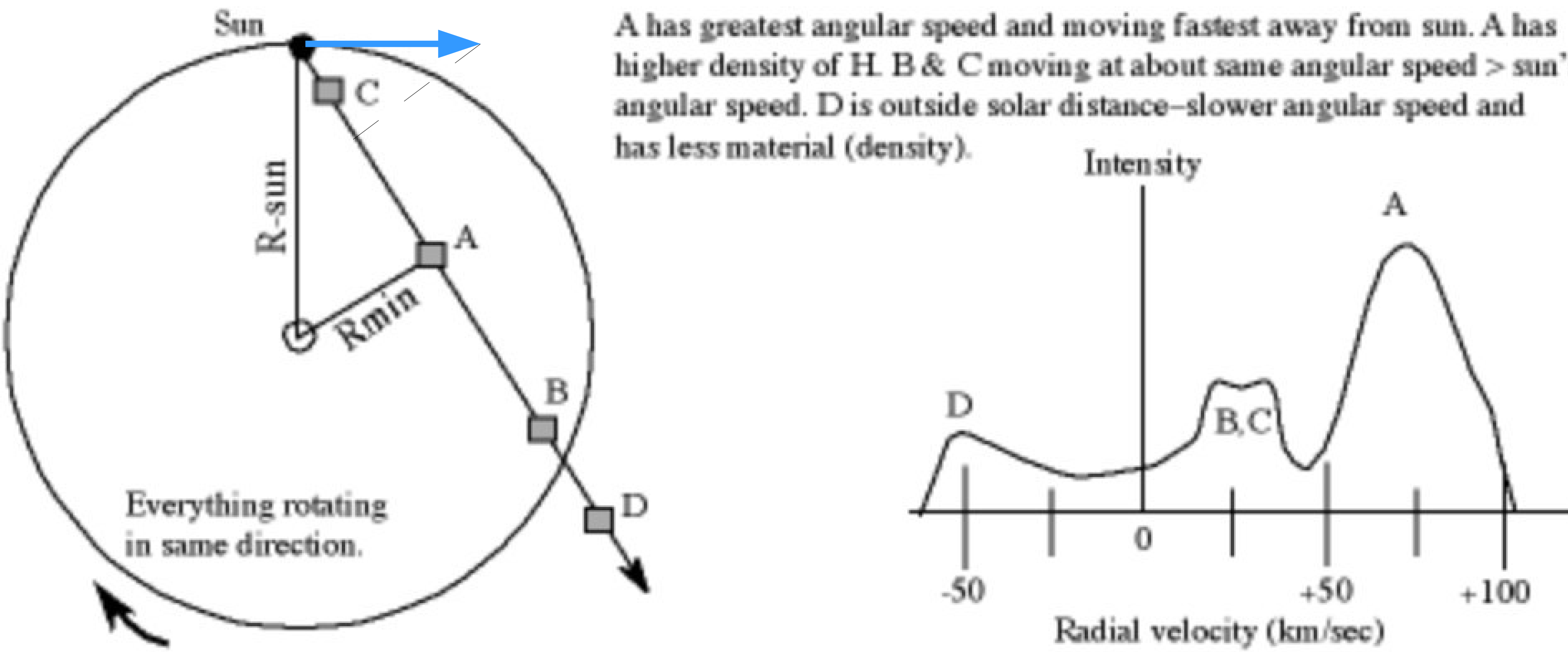
Red = time lapse 2





Motions within the MW

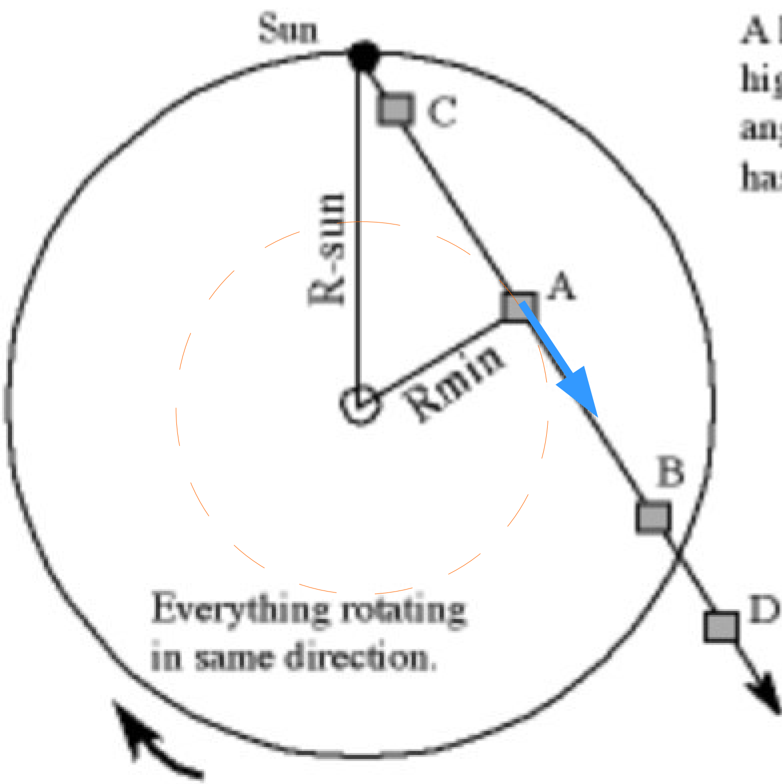
Hypothesis: any given point moves on a circular orbit with its own circular velocity



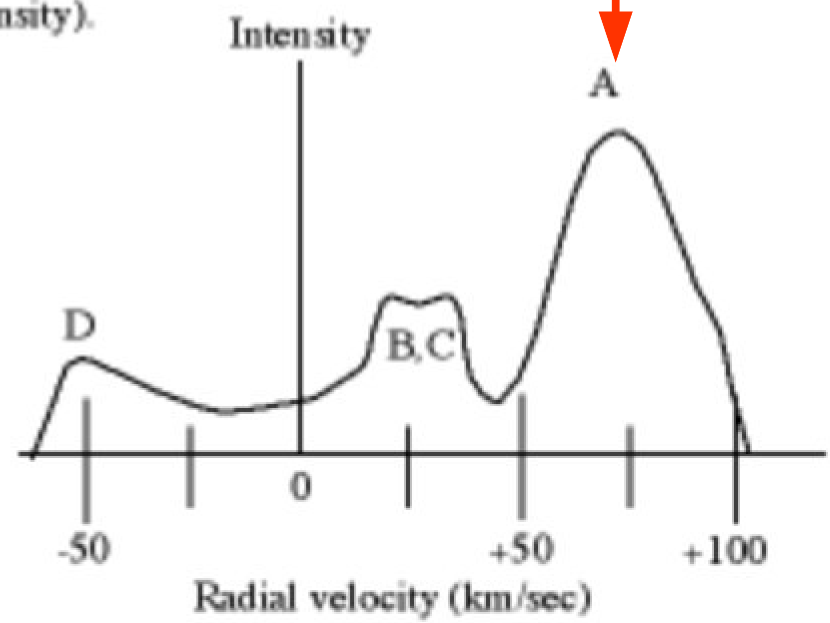
Four clouds all in the same direction. Use doppler shifts to distinguish one cloud from the other. Use the rotation curve to convert the doppler shifts of each cloud to distances from the center of the Galaxy. Do this for other directions to build up a map of the Galaxy strip by strip.

Motions within the MW

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

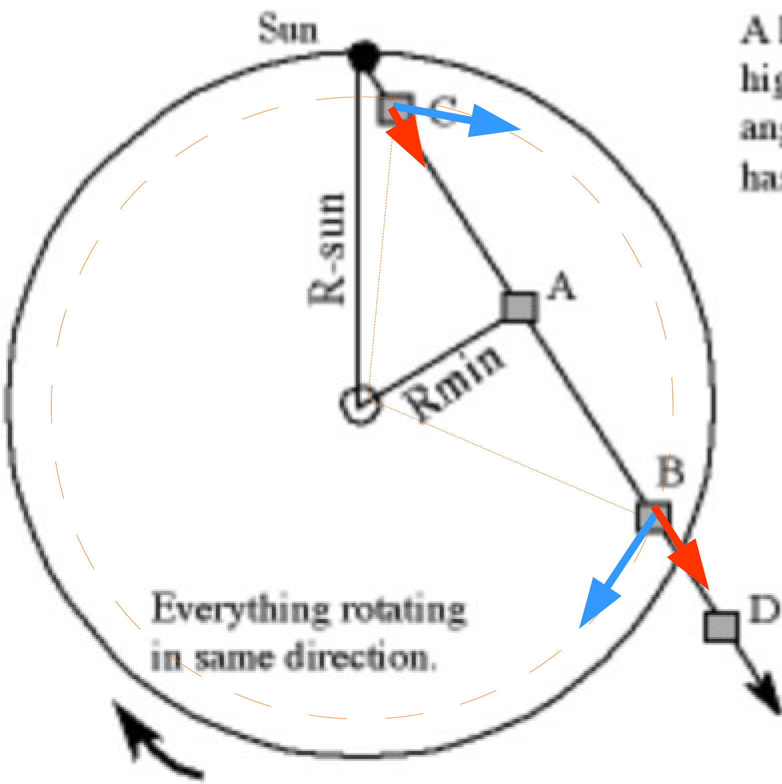


A has greatest angular speed and moving fastest away from sun. A has higher density of H. B & C moving at about same angular speed > sun's angular speed. D is outside solar distance–slower angular speed and has less material (density).

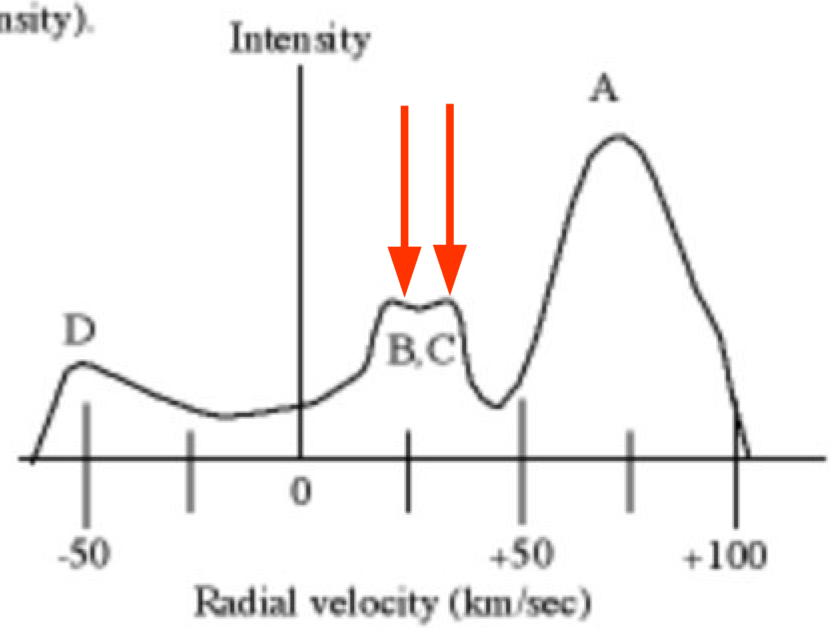


Four clouds all in the same direction. Use doppler shifts to distinguish one cloud from the other. Use the rotation curve to convert the doppler shifts of each cloud to distances from the center of the Galaxy. Do this for other directions to build up a map of the Galaxy strip by strip.

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



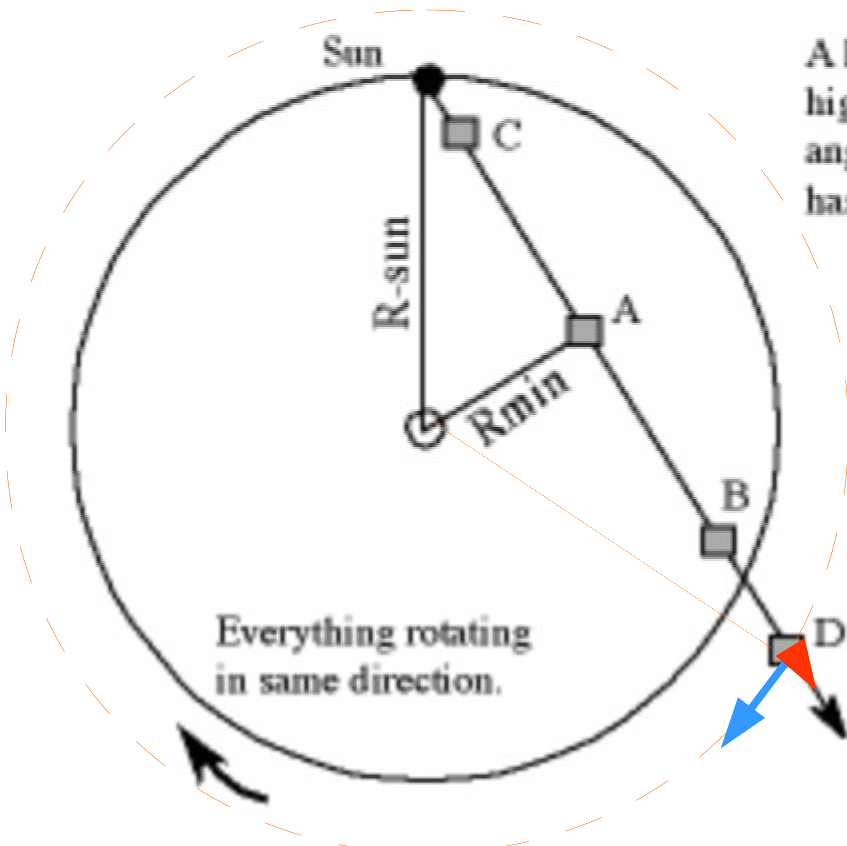
A has greatest angular speed and moving fastest away from sun. A has higher density of H. B & C moving at about same angular speed > sun's angular speed. D is outside solar distance–slower angular speed and has less material (density).



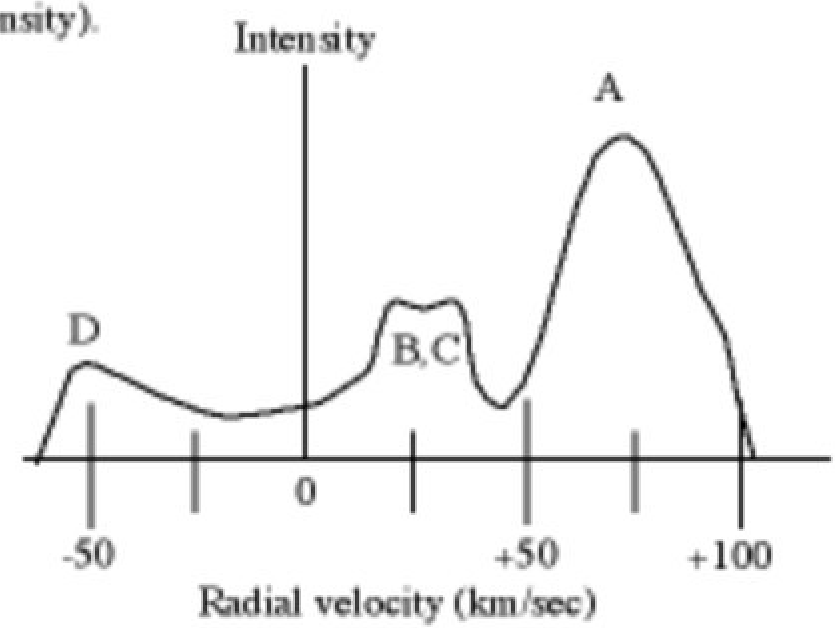
Four clouds all in the same direction. Use doppler shifts to distinguish one cloud from the other. Use the rotation curve to convert the doppler shifts of each cloud to distances from the center of the Galaxy. Do this for other directions to build up a map of the Galaxy strip by strip.

Motions within the MW

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

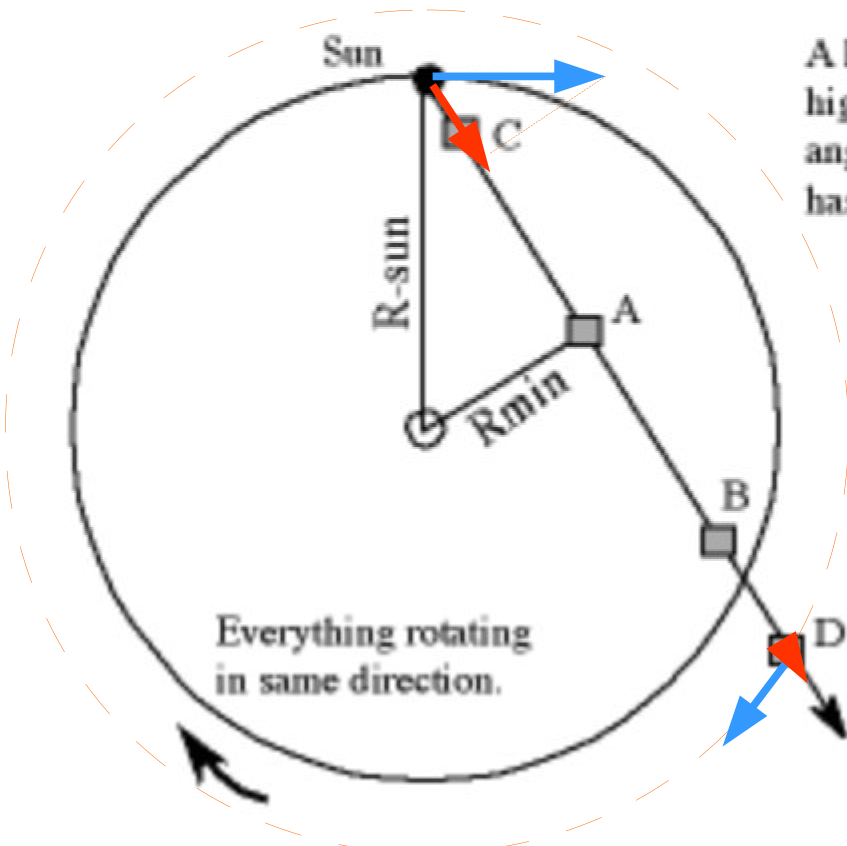


A has greatest angular speed and moving fastest away from sun. A has higher density of H. B & C moving at about same angular speed > sun's angular speed. D is outside solar distance–slower angular speed and has less material (density).

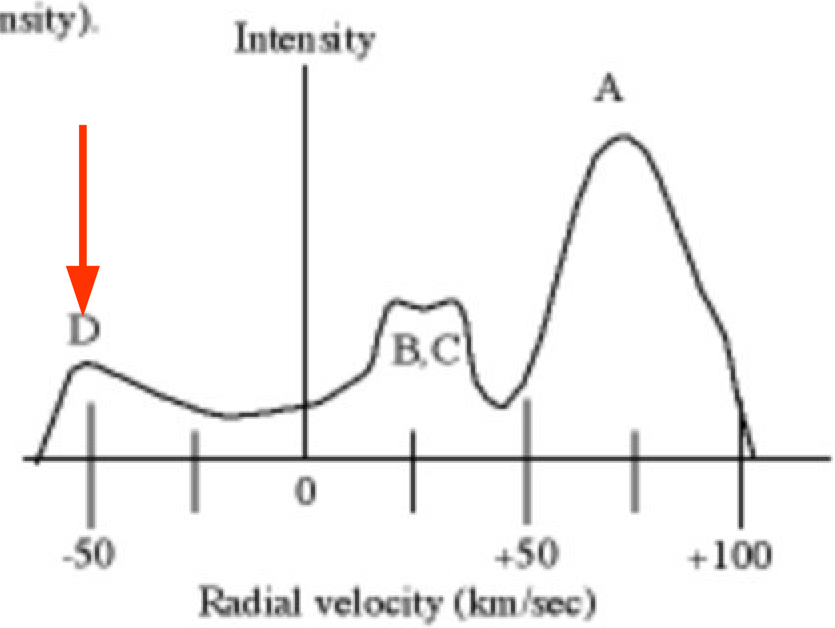


Four clouds all in the same direction. Use doppler shifts to distinguish one cloud from the other. Use the rotation curve to convert the doppler shifts of each cloud to distances from the center of the Galaxy. Do this for other directions to build up a map of the Galaxy strip by strip.

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



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.

Oort constants

Velocities within the MW

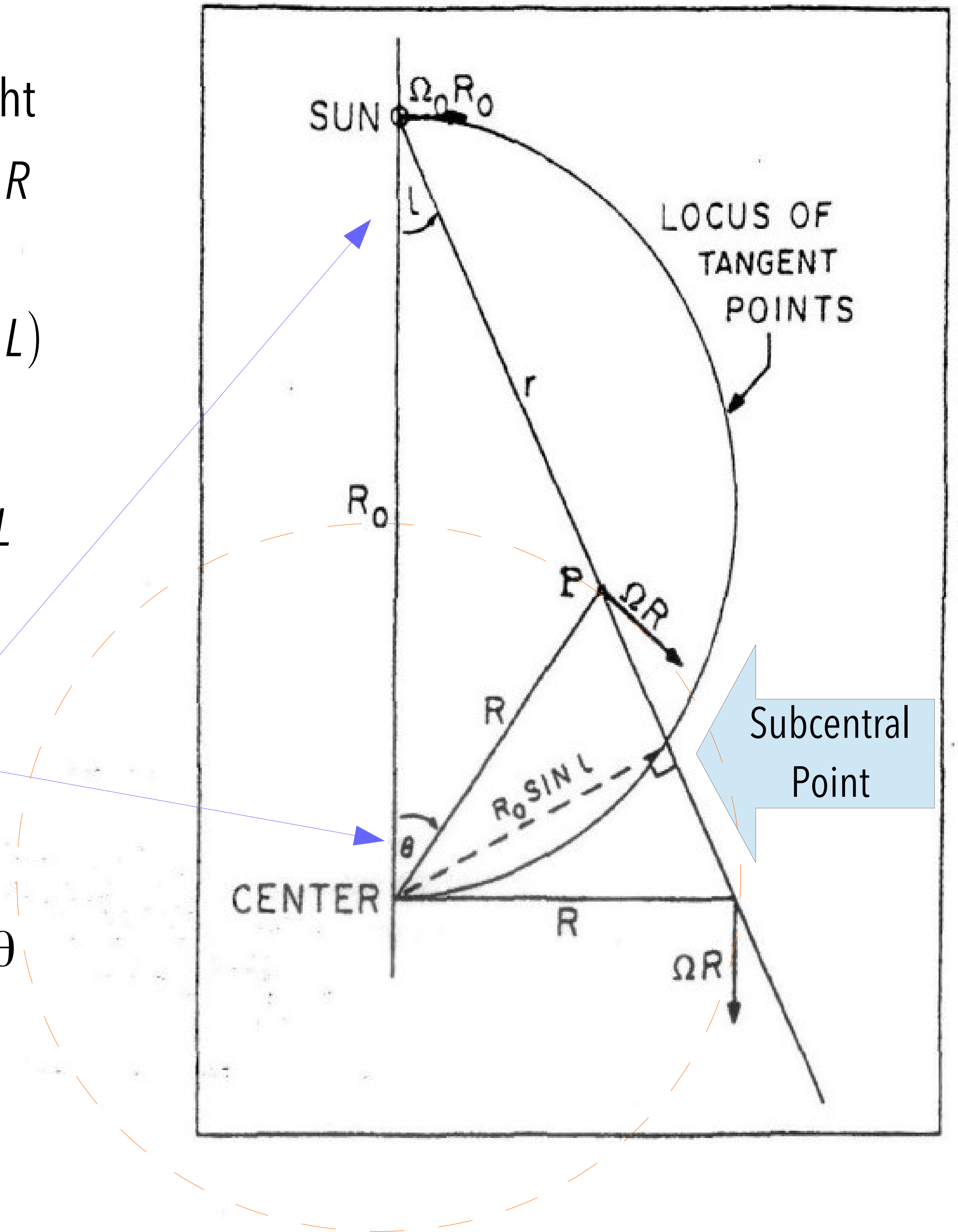
v_r must be computed along a given line of sight and has components from both $\Omega_o R_o$ and ΩR

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

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

L is the galactic longitude (b is taken 0)

θ is the galactocentric azimut



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

$$R\cos\theta = R_o - r\cos L$$

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

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

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

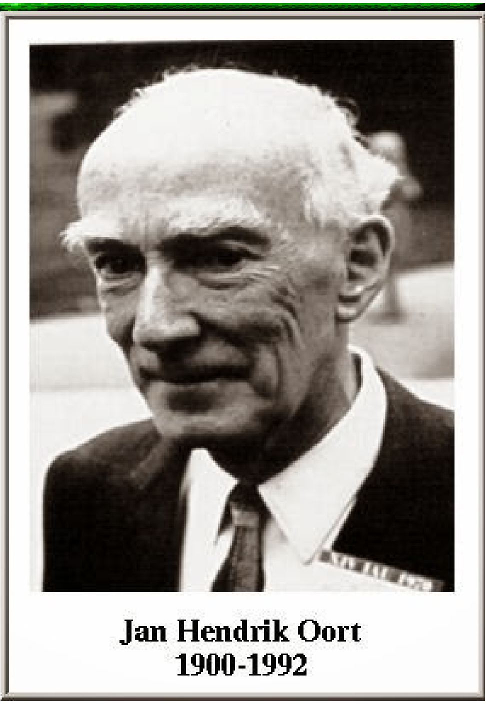
$$v(R,L)_t = R_o\left(\Omega(R)-\Omega_o\right)\cos L - r\,\Omega(R) \qquad \text{tangential velocity}$$

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: $(\Omega(R) - \Omega_o)$

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

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

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

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)

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

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

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, $v_0 \sim 220\ km\ s^{-1}$

- In case of a solid body rotation: A = 0, B = - Ω_0

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

$$A = \frac{1}{2}\left[\frac{v_0}{R_0} - (\Omega)_{R_0}\right] = \frac{1}{2}\left[\frac{\Omega_0 R_0}{R_0} - (\Omega)_{R_0}\right] = 0$$

$$B = -\frac{1}{2}\left[\frac{v_0}{R_0} + (\Omega)_{R_0}\right] = -\frac{1}{2}\left[\frac{\Omega_0 R_0}{R_0} + (\Omega)_{R_0}\right] = -\Omega_0$$

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

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

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

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

Oort constants

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

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

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

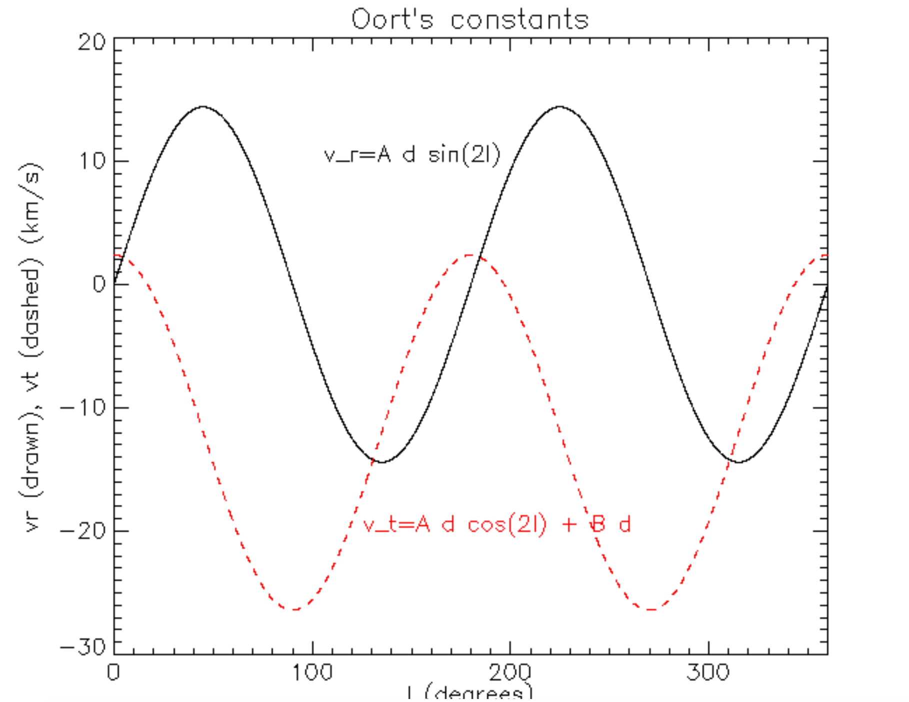
$$B = -\frac{1}{2}\left[\frac{v_0}{R_0} + (0)_{R_0}\right] = -\frac{1}{2}\frac{v_0}{R_0}$$

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

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

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

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



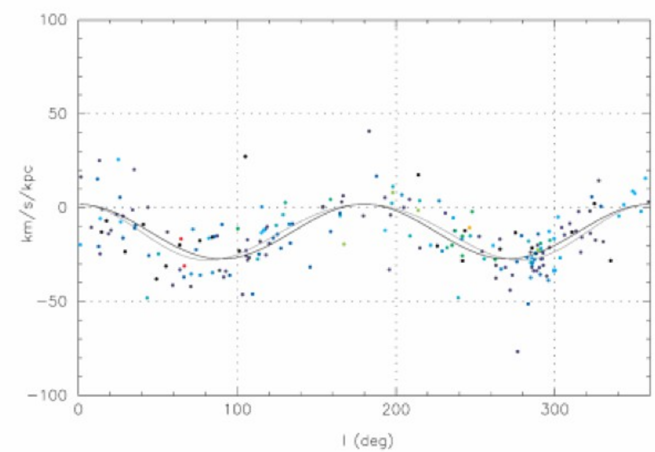
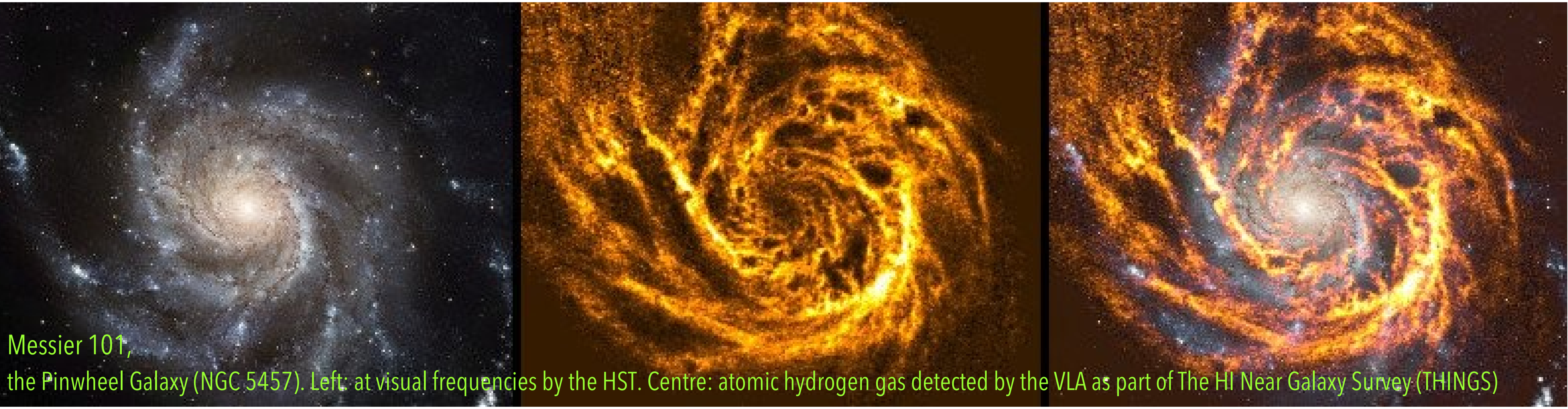
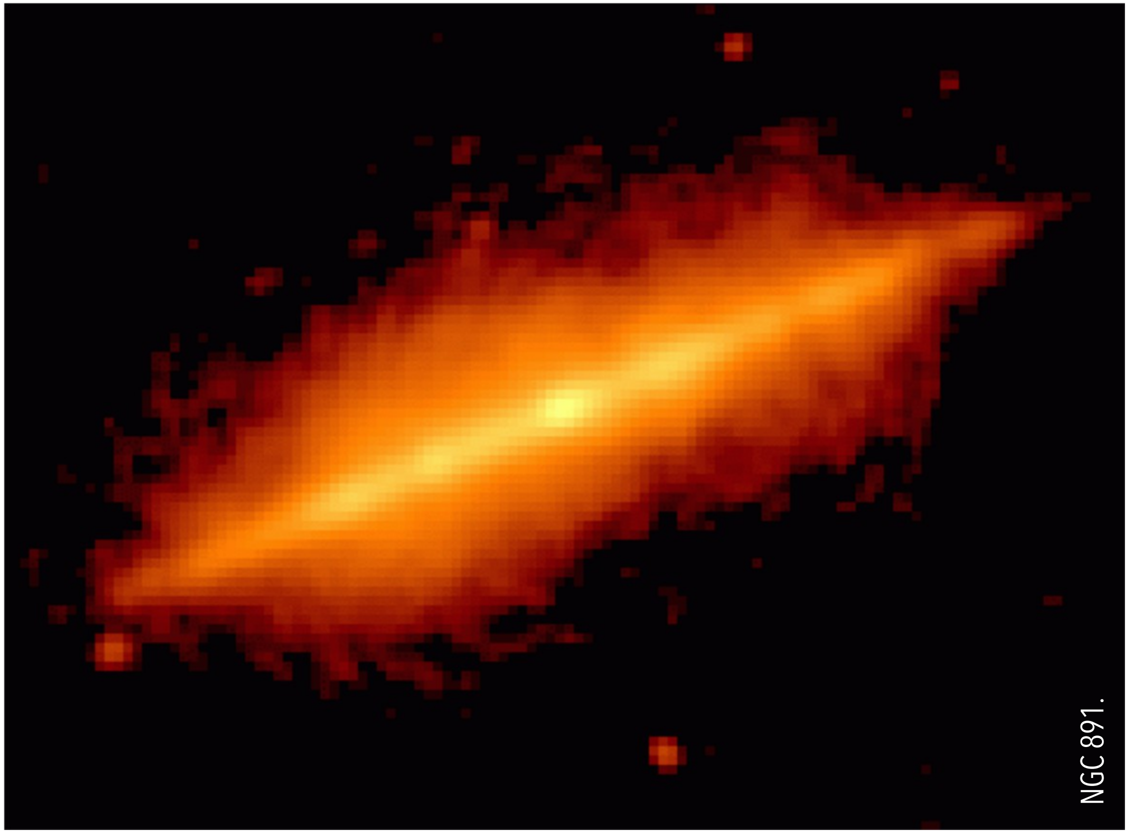


Figure 6.6. The quantity $\kappa\mu_l$, corrected for solar motion, as a function of galactic longitude, showing the effect of galactic rotation. The solid curve shows the fitting of the data for stars within 1 kpc from the Sun, the grey curve shows the same for stars with a projected distance of 5 kpc.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

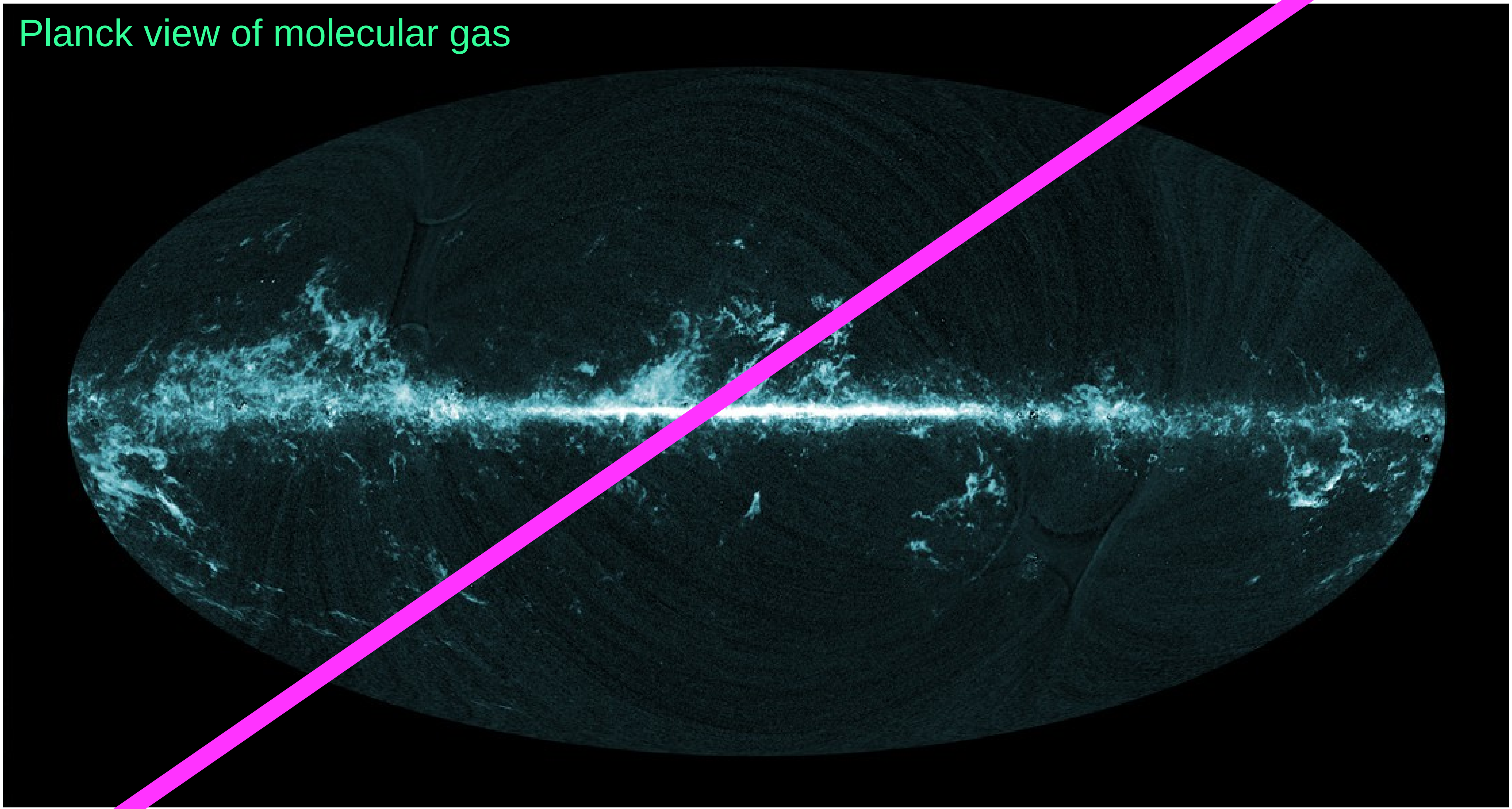
Rotation curve: going out to external galaxies



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)



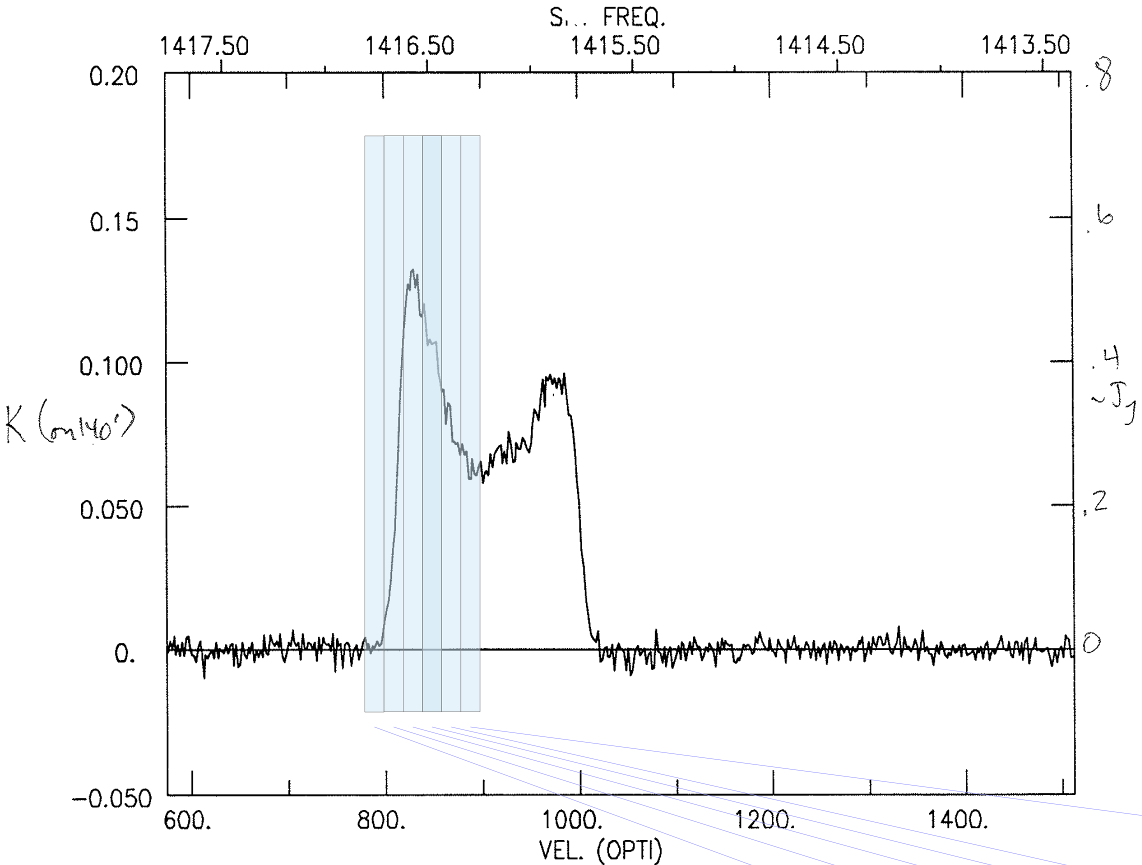
CO: also the molecular gas can be used to trace both distribution and dynamics

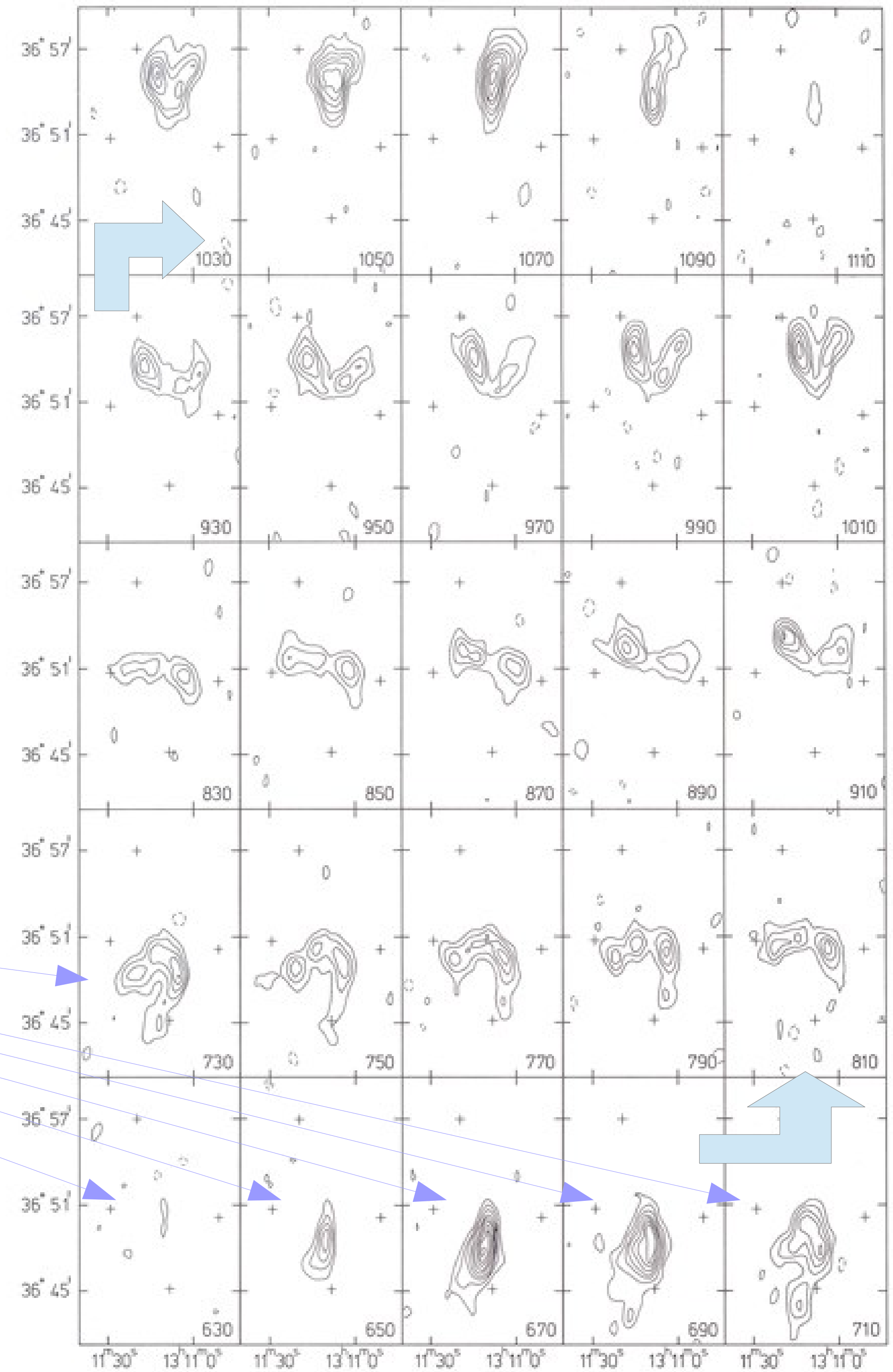


Located in different regions, is an independent tracer of the galactic dynamics

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

Different regions contribute to different portions of the spectrum





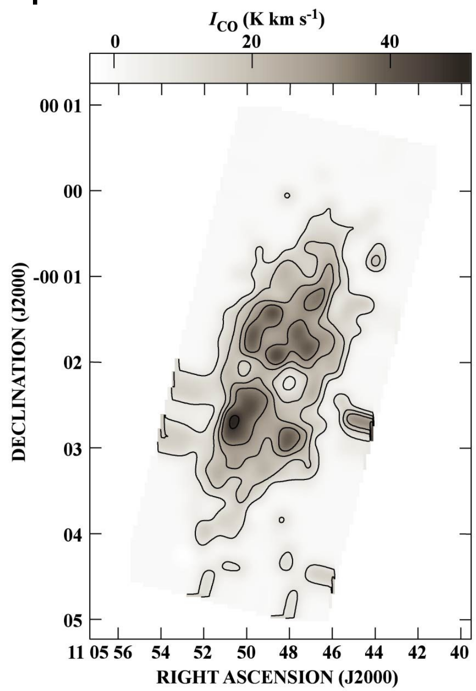
Images are 2D and organized as a DATACUBE

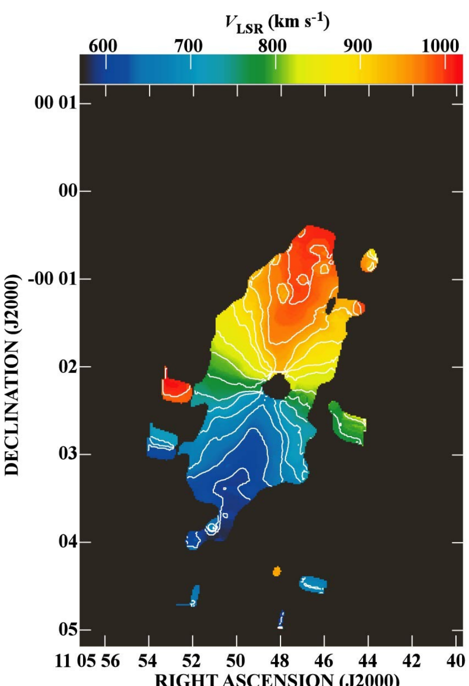
Moment 0 – total intensity

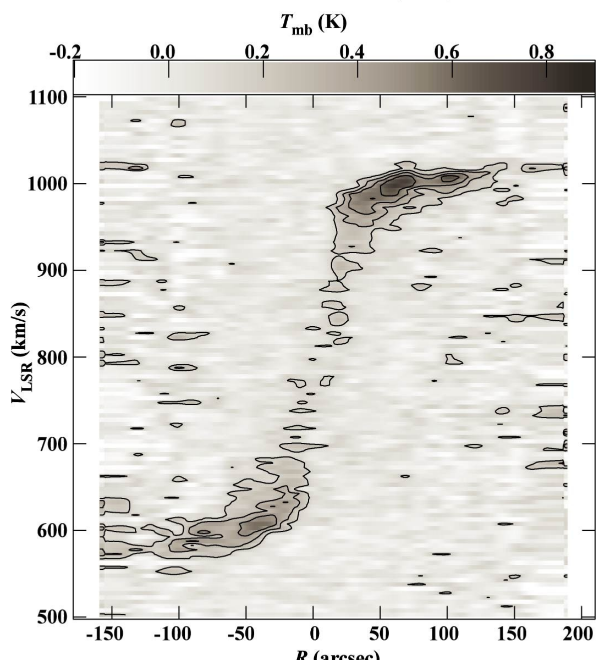
Moment 1 – relative (radial) velocity

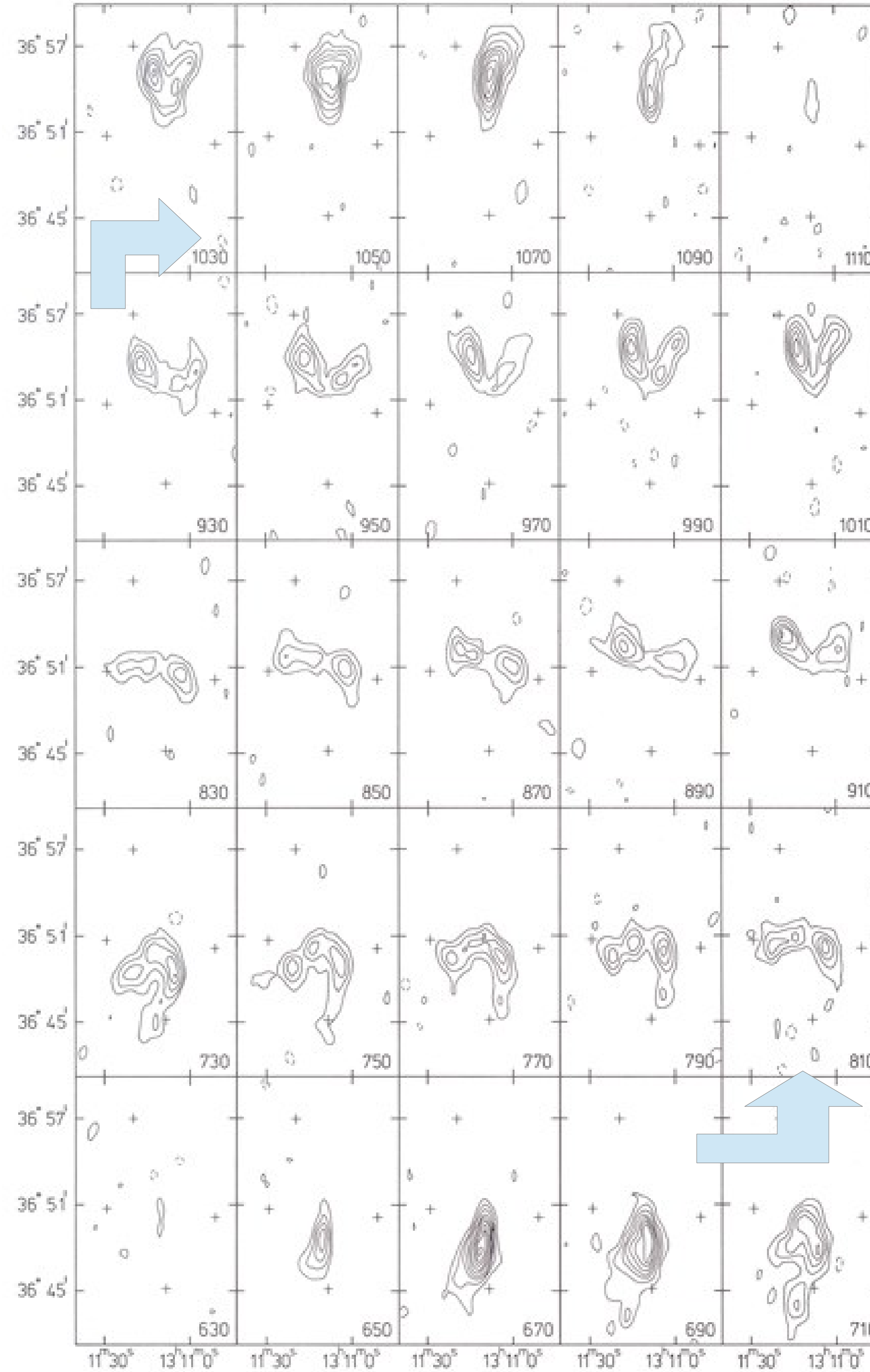
Moment 2 – velocity dispersion

Learning from other spirals:



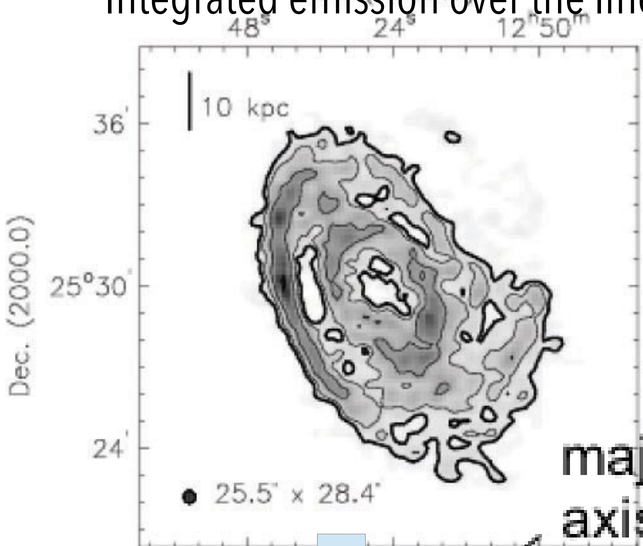


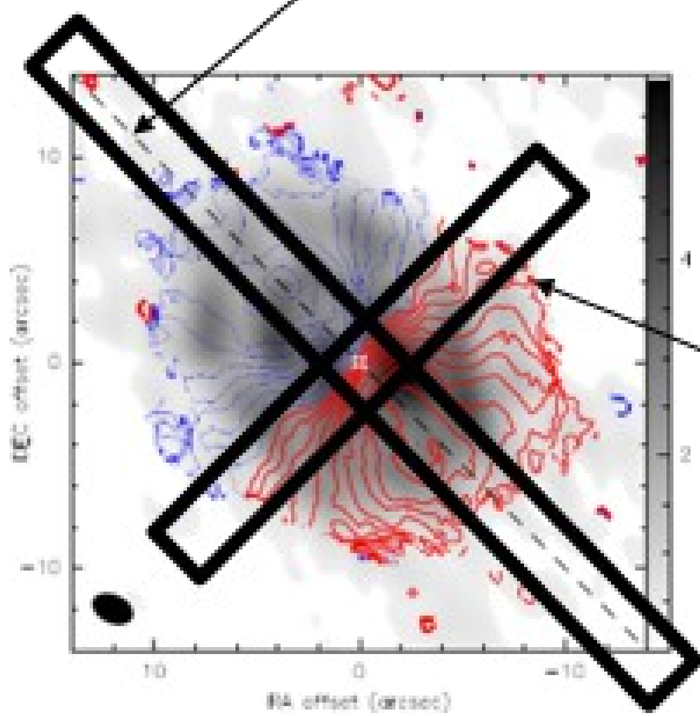




Neutral Hydrogen: the extraction of the Position – Velocity (PV) diagrams

Integrated emission over the line

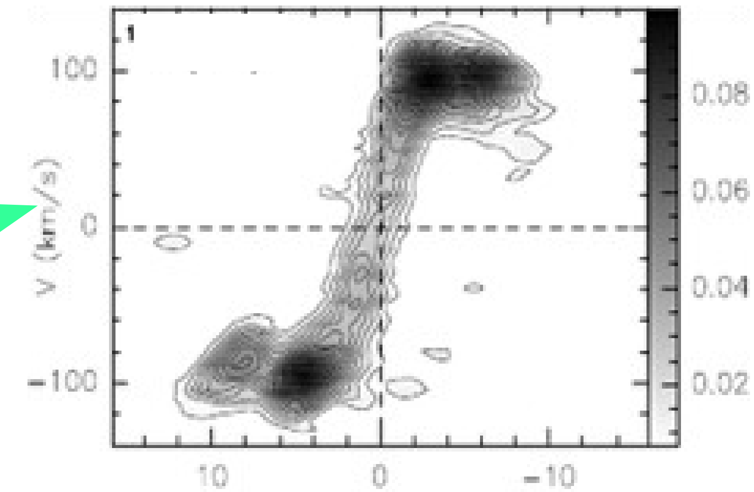


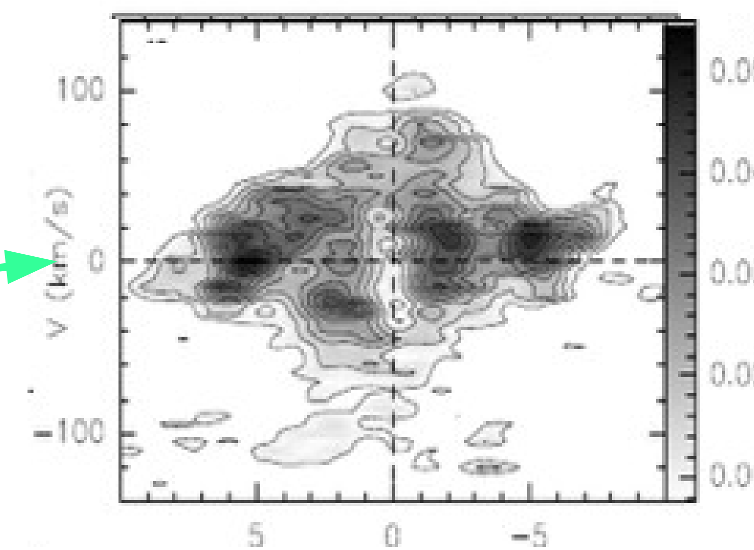


major axis (line of nodes)

minor axis (rotation axis)

NGC 5953





Distance in arcsec along major (top) minor (bottom)

Casasola +, 2009

- PV diagram

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

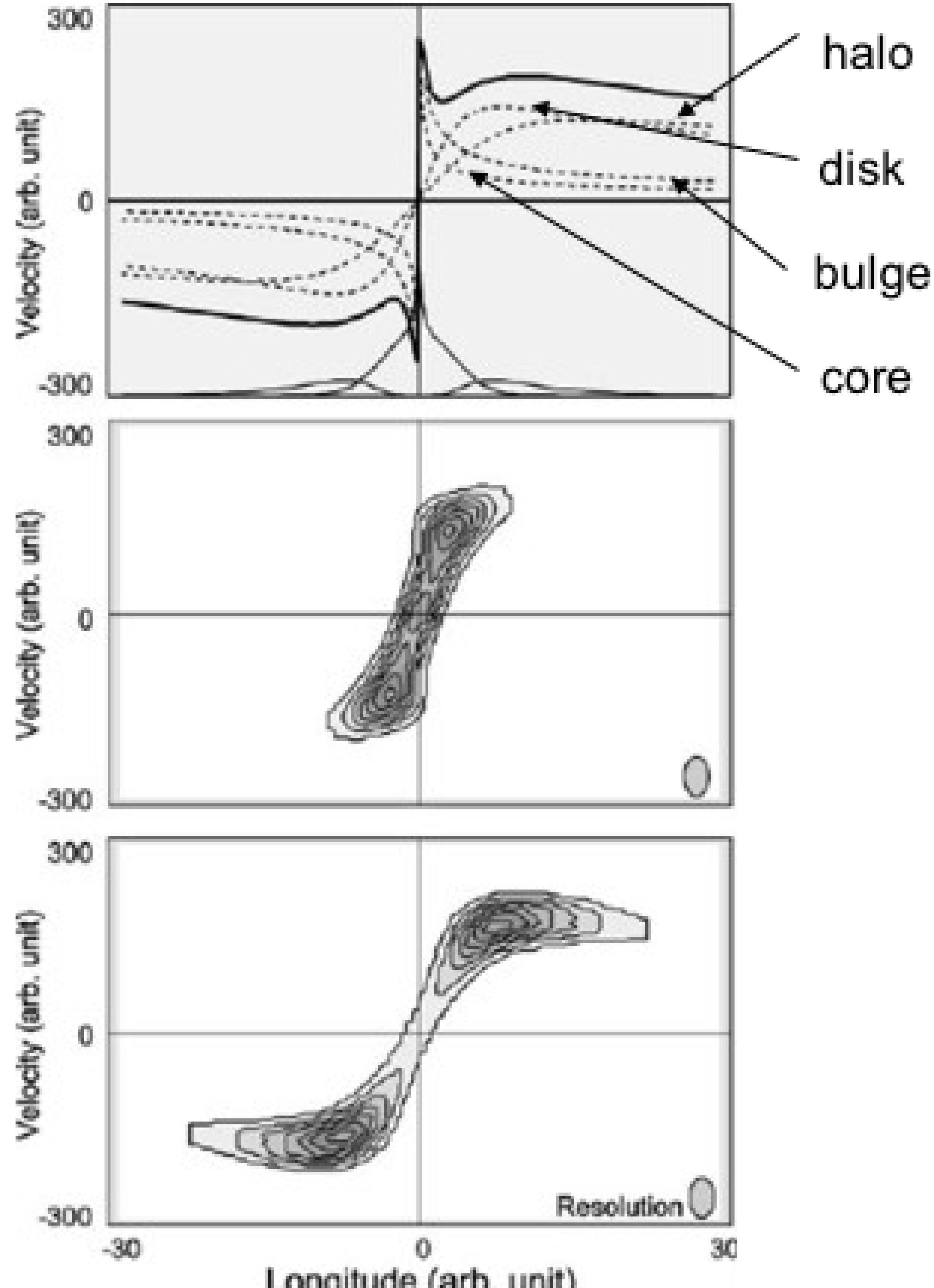
Top: Assumed "true" rotation curve (thick) with a central core, bulge, disk, and halo

Middle: "Observed" CO PV diagram

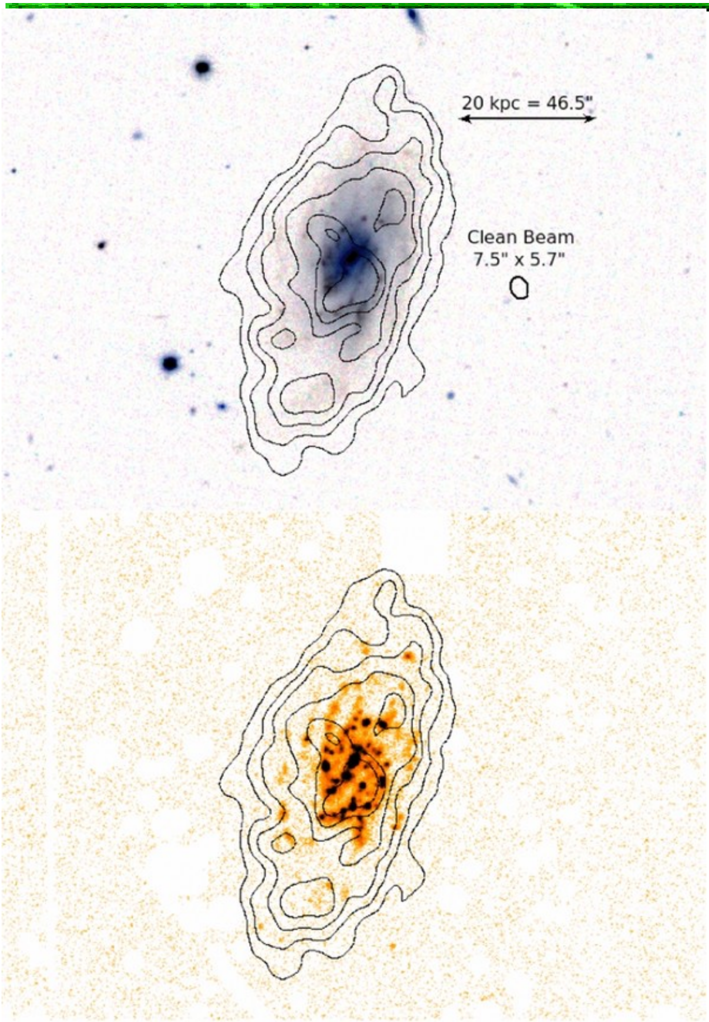
Bottom: "Observed" HI PV diagram

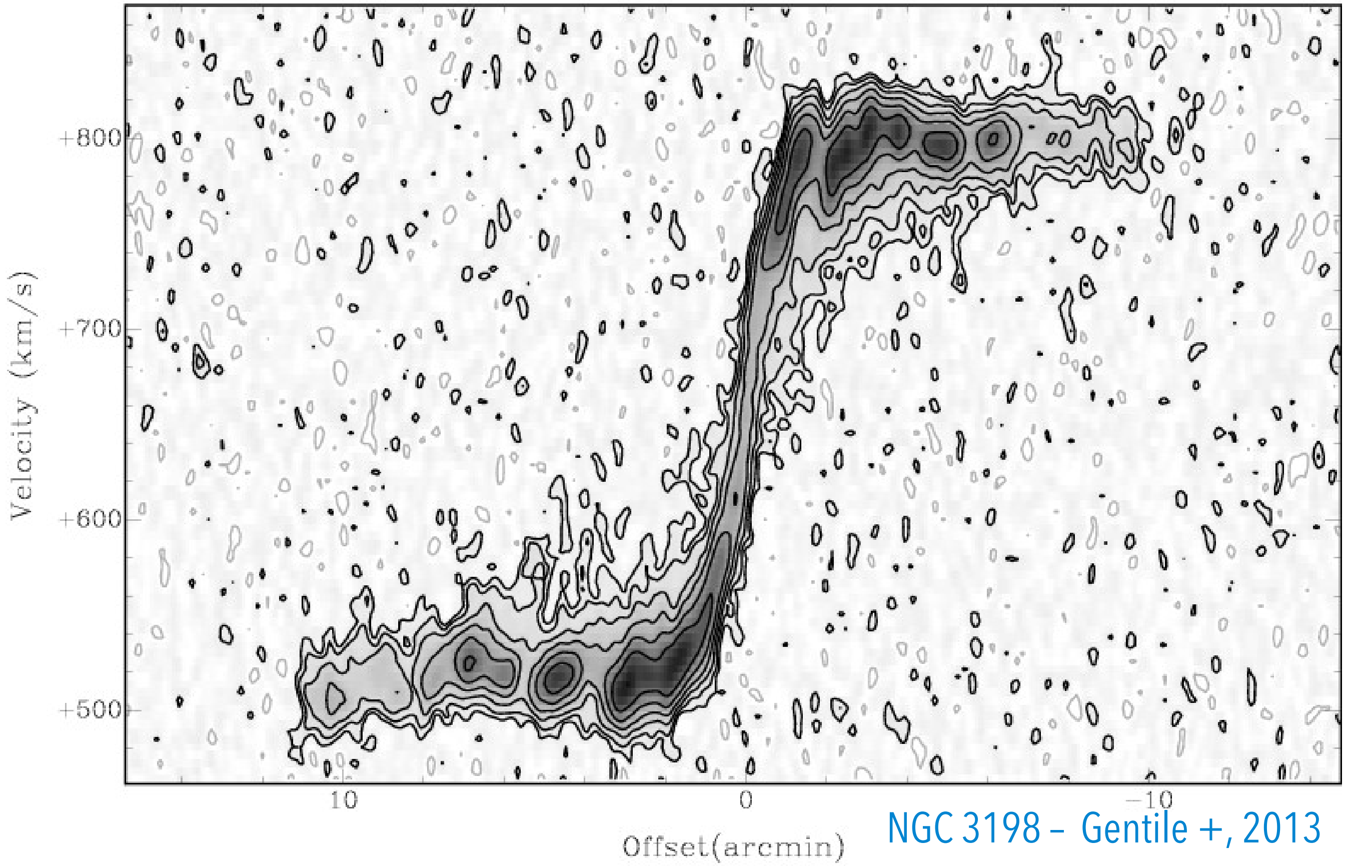
High resolution & high sensitivity necessary to detect central high velocities and steep rise

(Sofue & Rubin 2001)

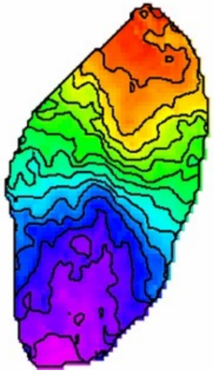


HI in external galaxies Galaxies ==> ricollocare

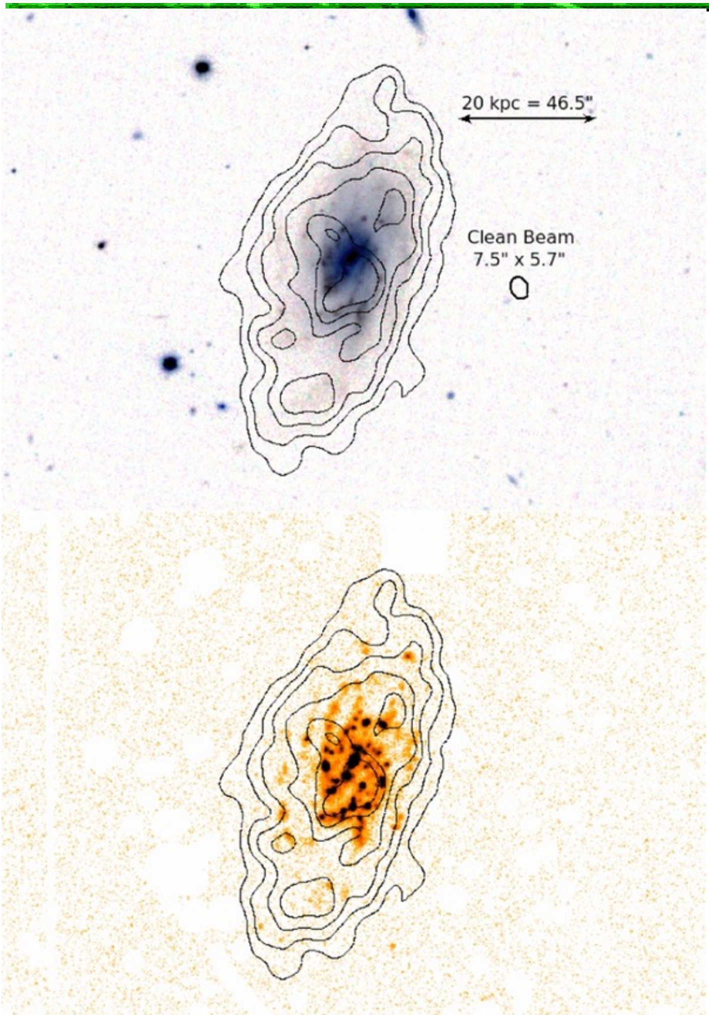


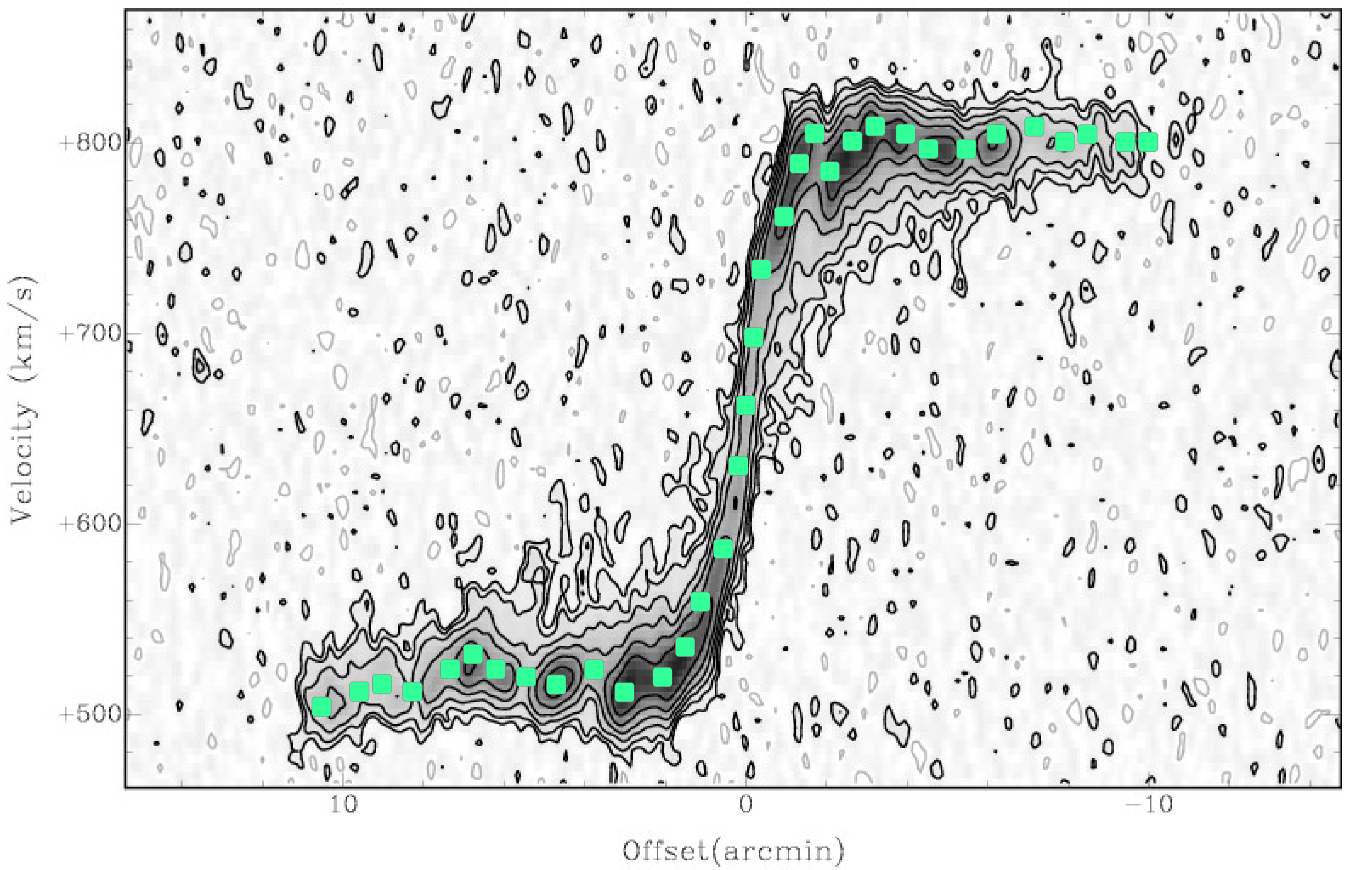


NGC 3198 – Gentile +, 2013

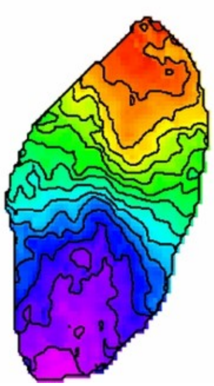


Contours: total HI emission;
Top: optical from SDSS
Middle: Hα, from Huang+, 2014
Bottom: HI velocity field from ALFAALFA
Hallenbeck +, 2014



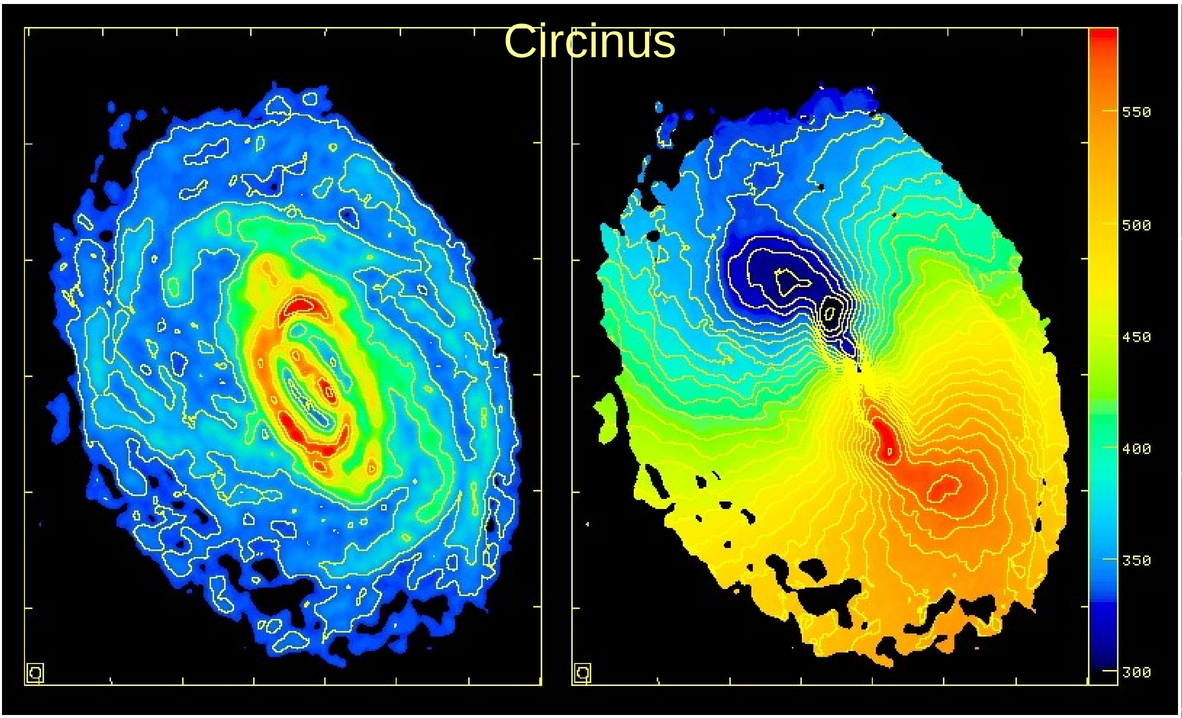


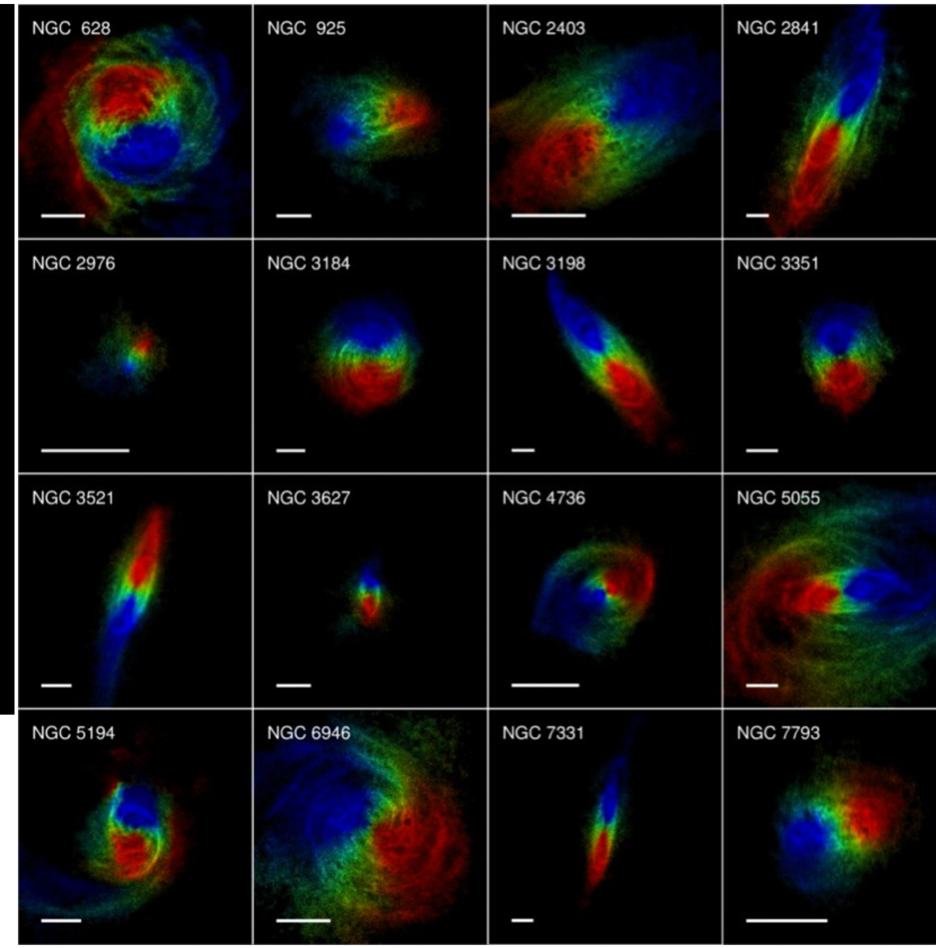
Turquoise points define the rotation curve (on both sides!)



Contours: total HI emission;
Top: optical from SDSS
Middle: Hα, from Huang+ 2014
Bottom: HI velocity field from ALFAALFA
Hallenbeck +, 2014

Learning from other spirals:

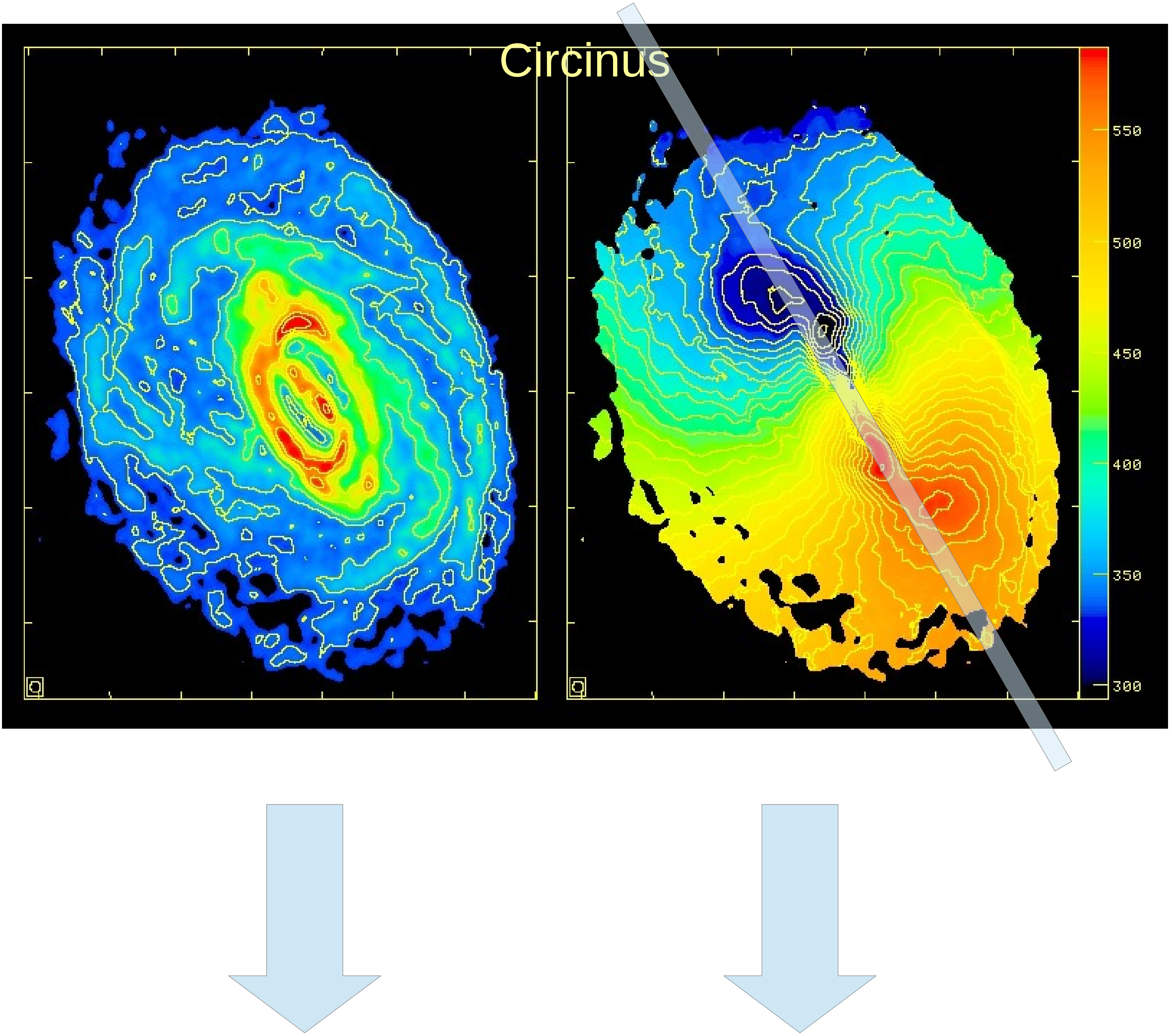




Total Intensity

Relative velocity

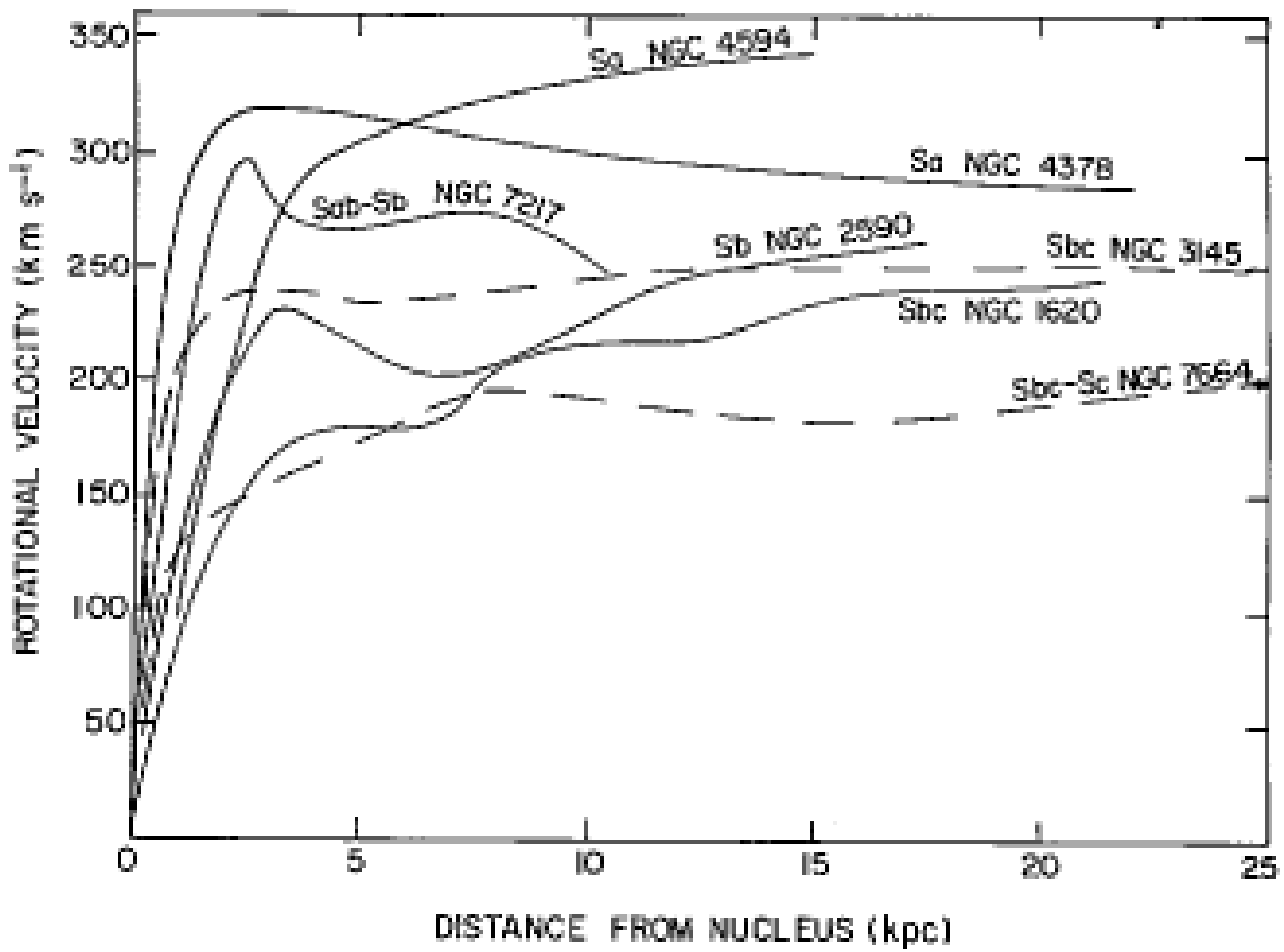
Learning from other spirals:



Total Intensity

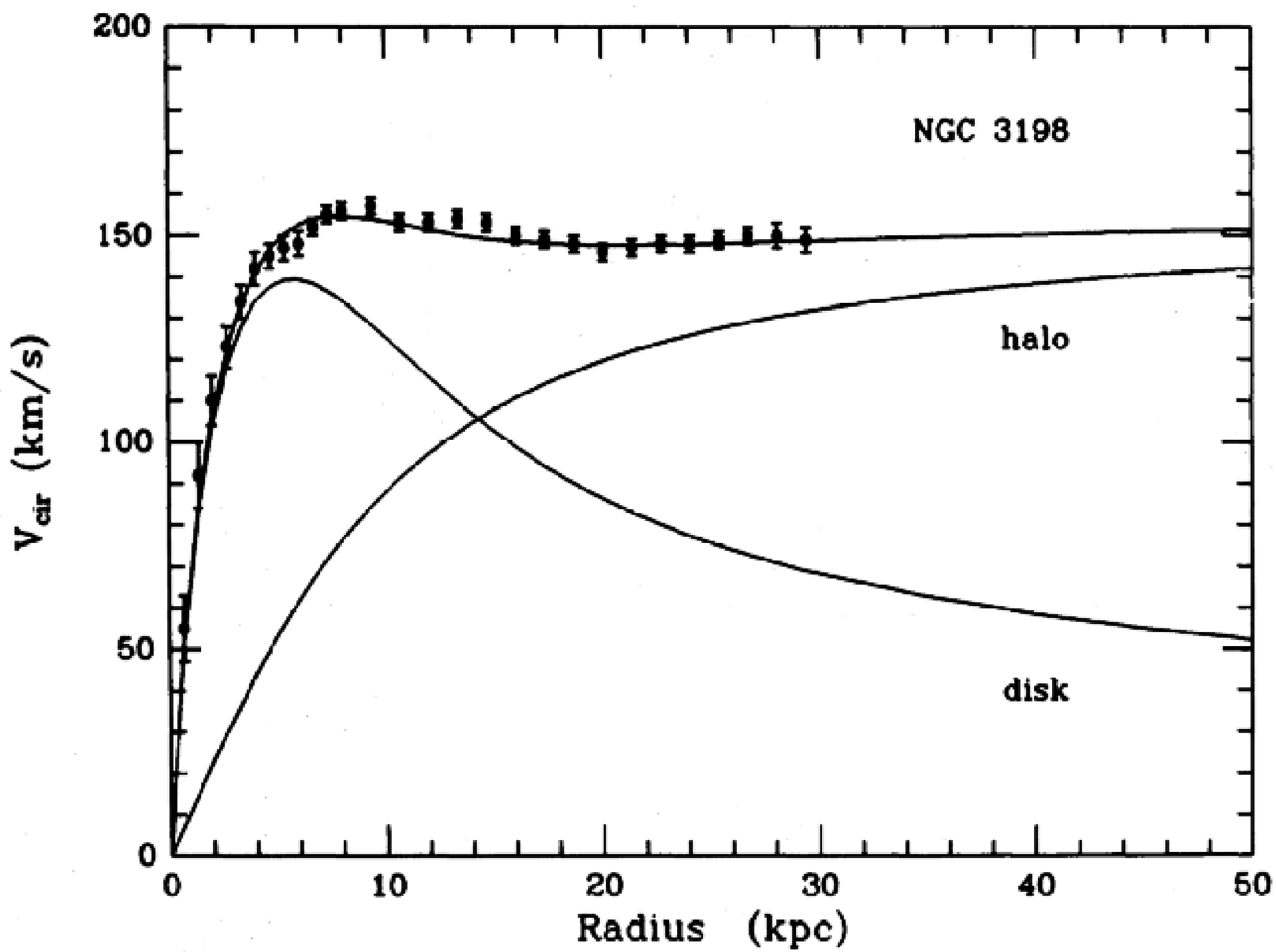
Relative velocity

Observations:

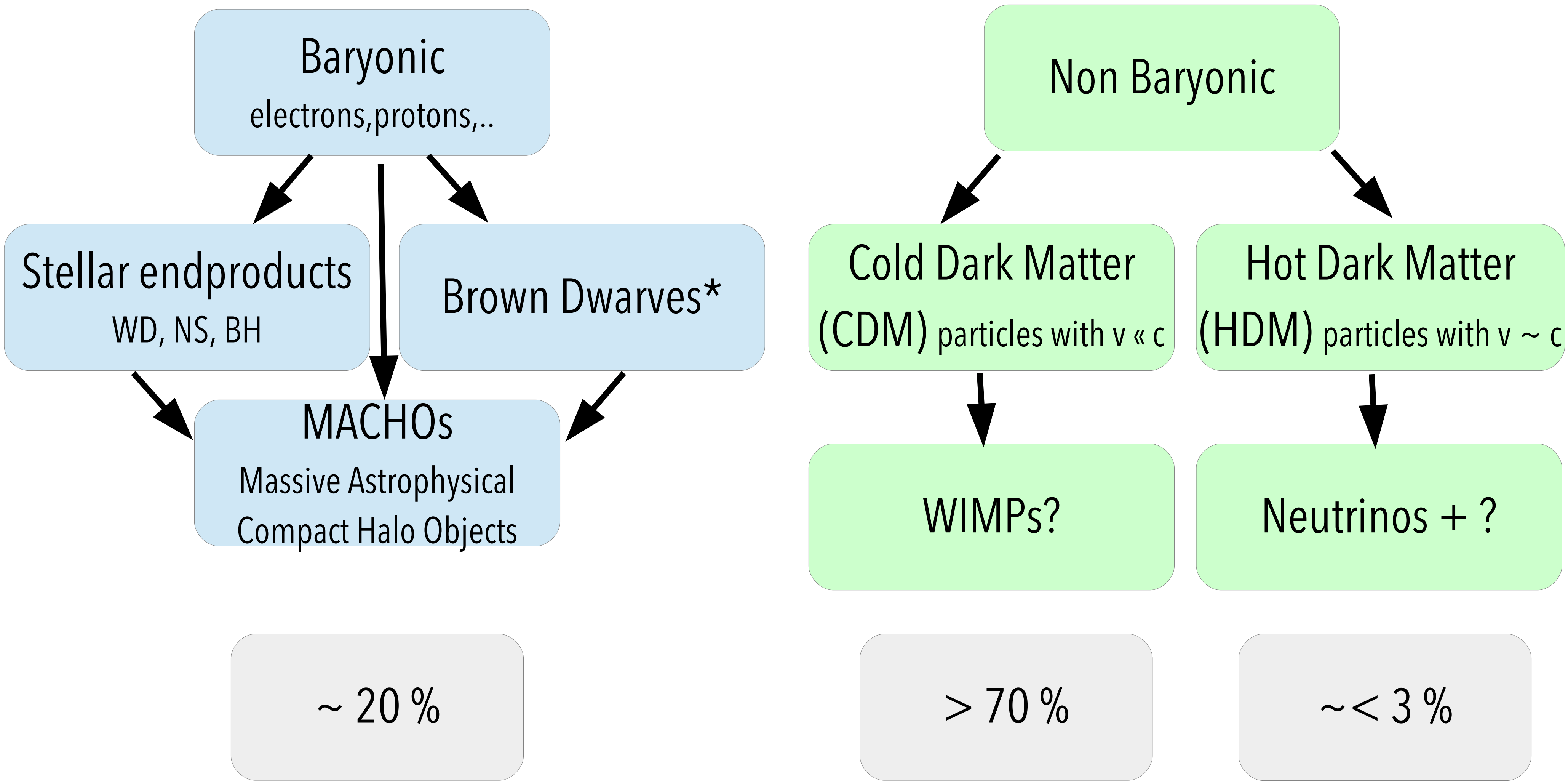


Observations: the "keplerian" decay of the radial velocity is never observed: **Dark MATTER!**

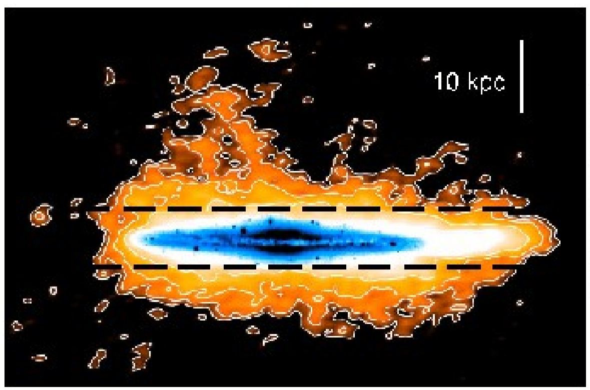
DISTRIBUTION OF DARK MATTER IN NGC 3198

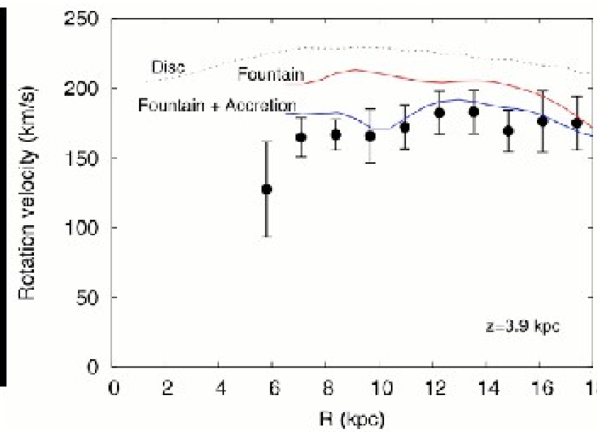


Constraints on Dark Matter:

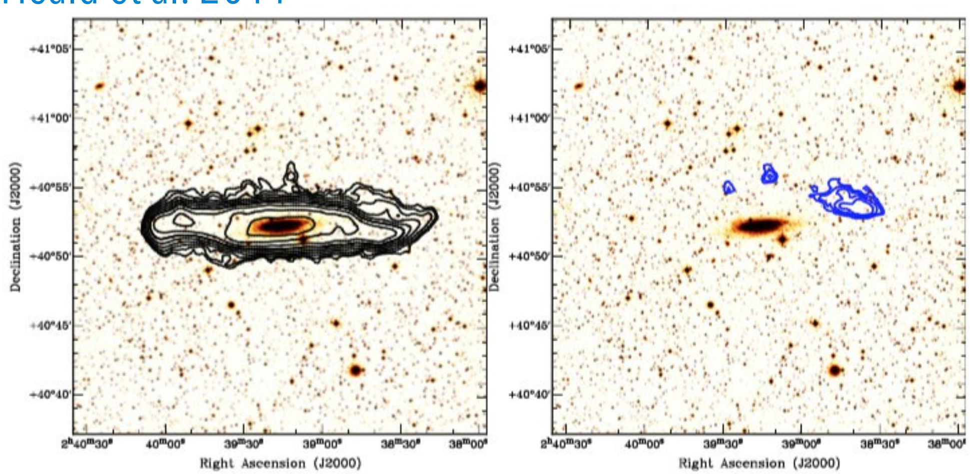


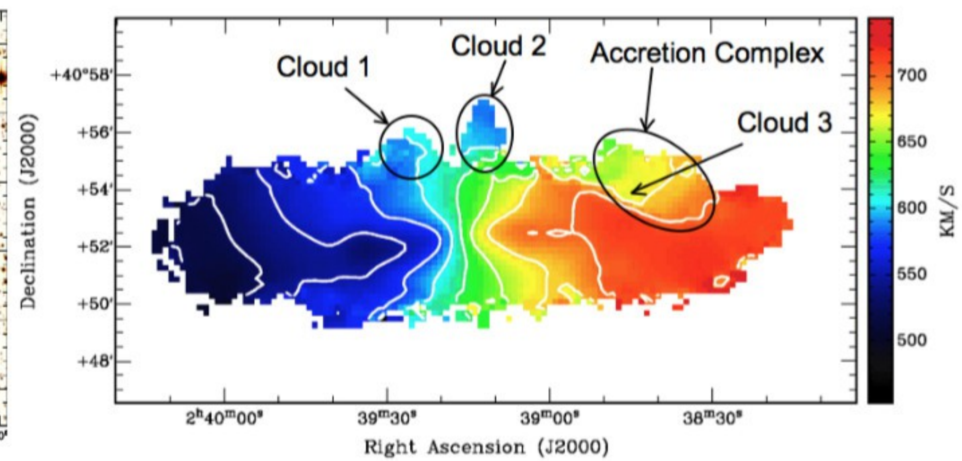
The story is not over… **extra-planar clouds**



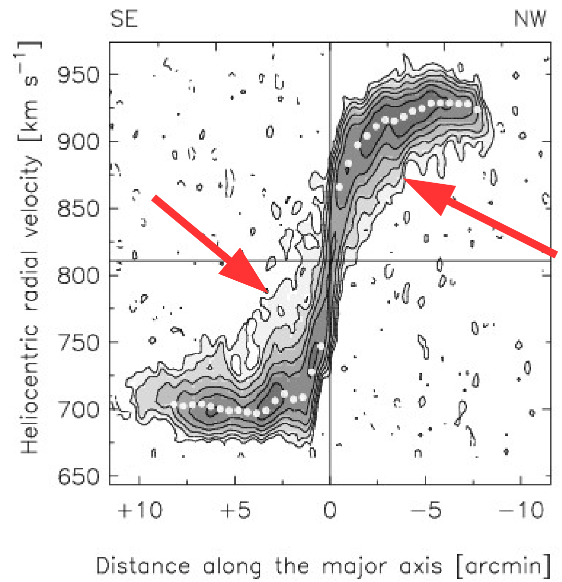


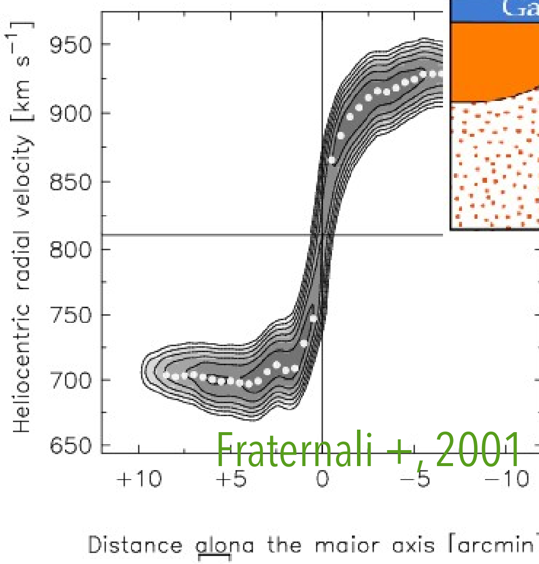
Heald et al. 2011

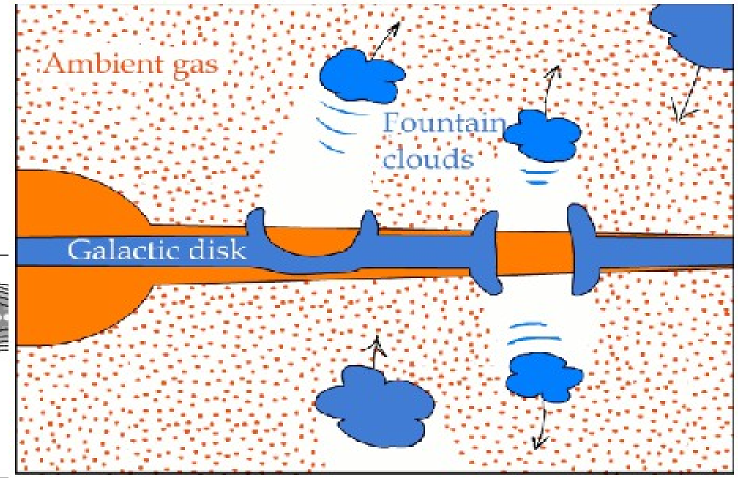




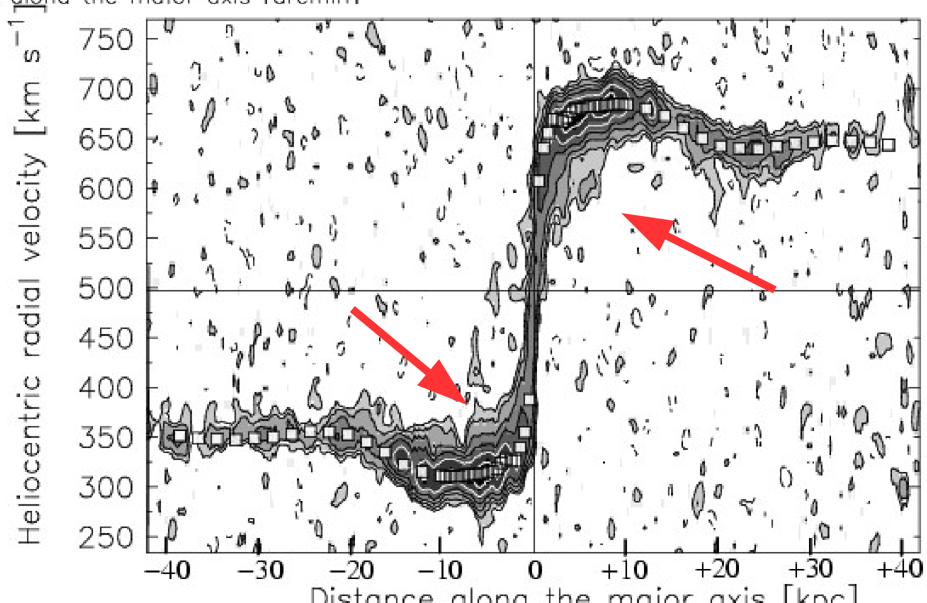
The story is not over…

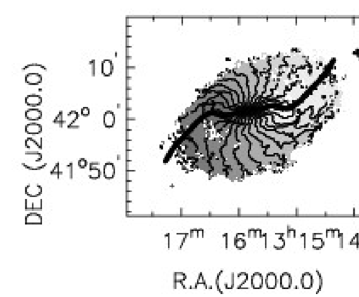






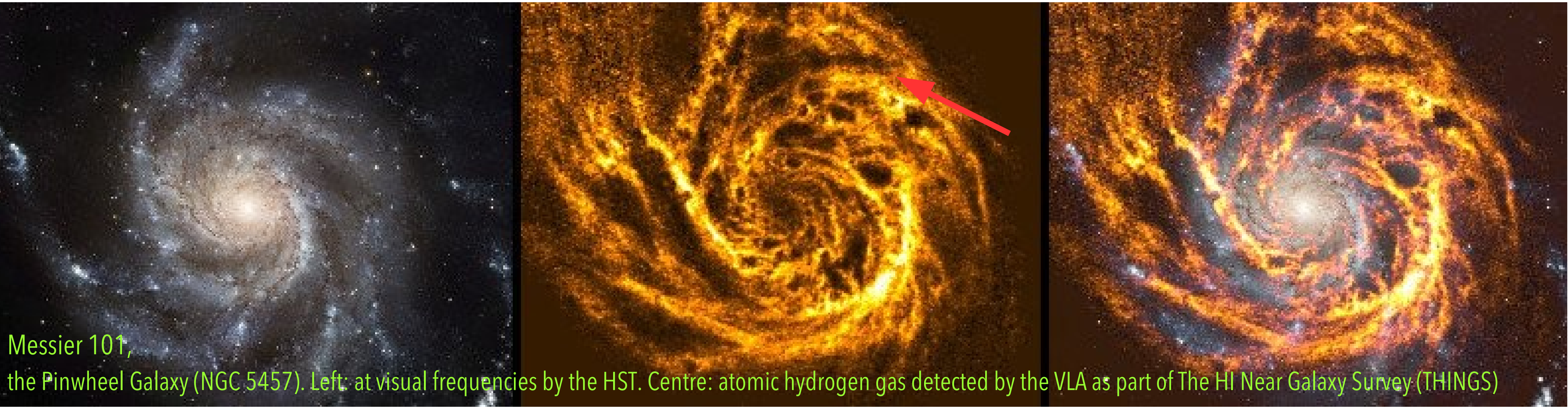
Fraternali +, 2001





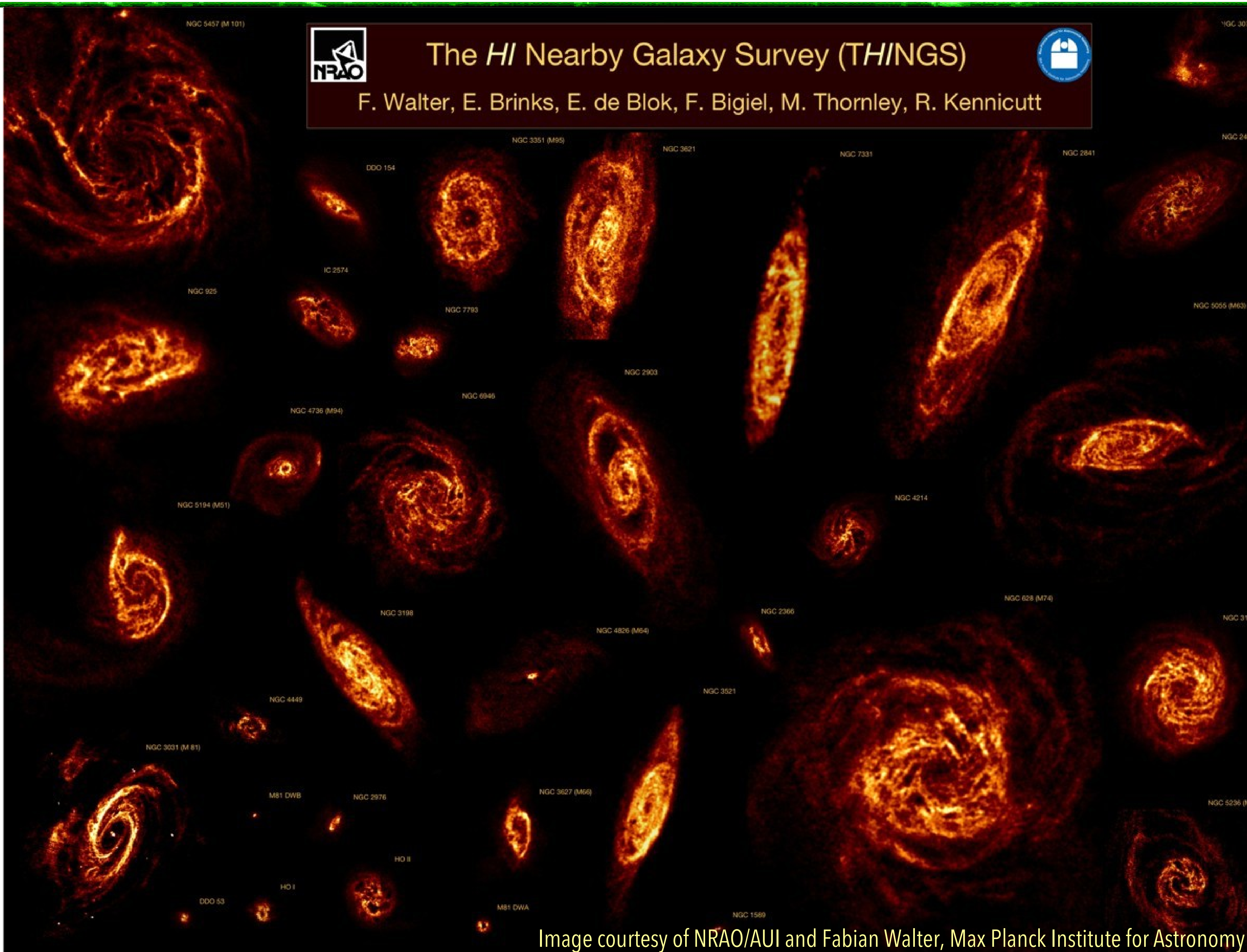
Battaglia +, 2006

Bubbles (holes) in HI distribution



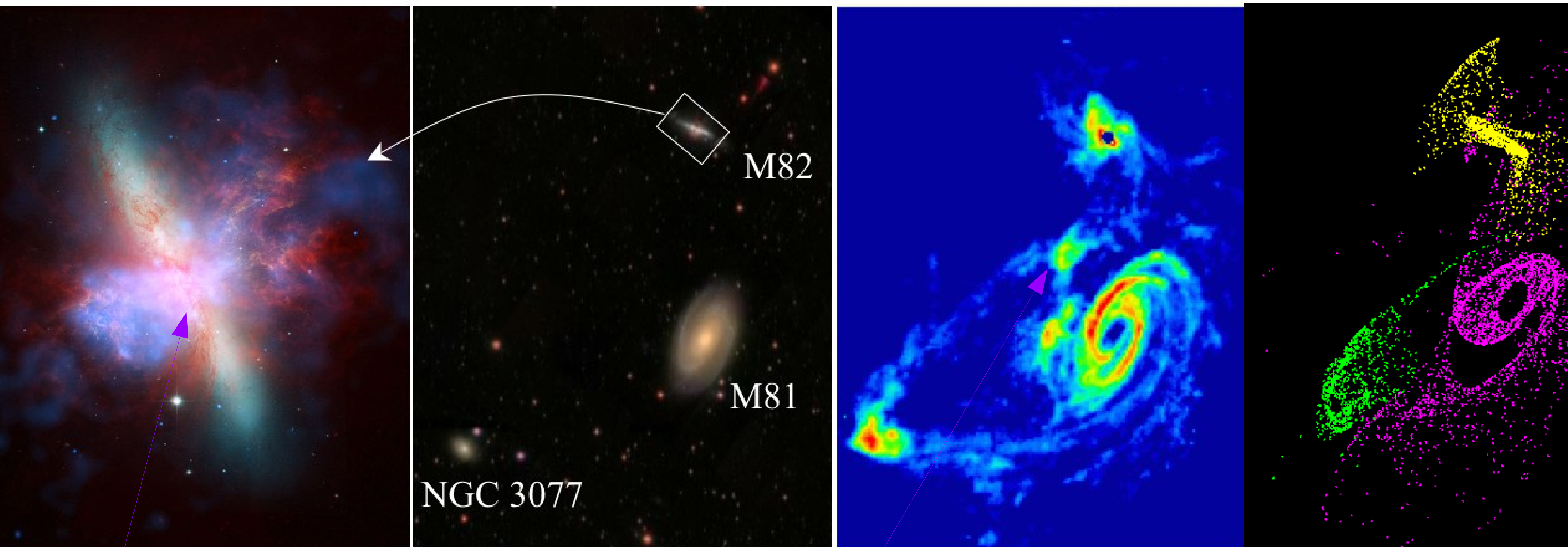
Messier 101, the Pinwheel Galaxy (NGC 5457). Left: at visual frequencies by the HST. Centre: atomic hydrogen gas detected by the VLA as part of The HI Near Galaxy Survey (THINGS)

The Interstellar Medium (ISM): HI emission



Groups

Interaction triggers starburst and outflow in M82



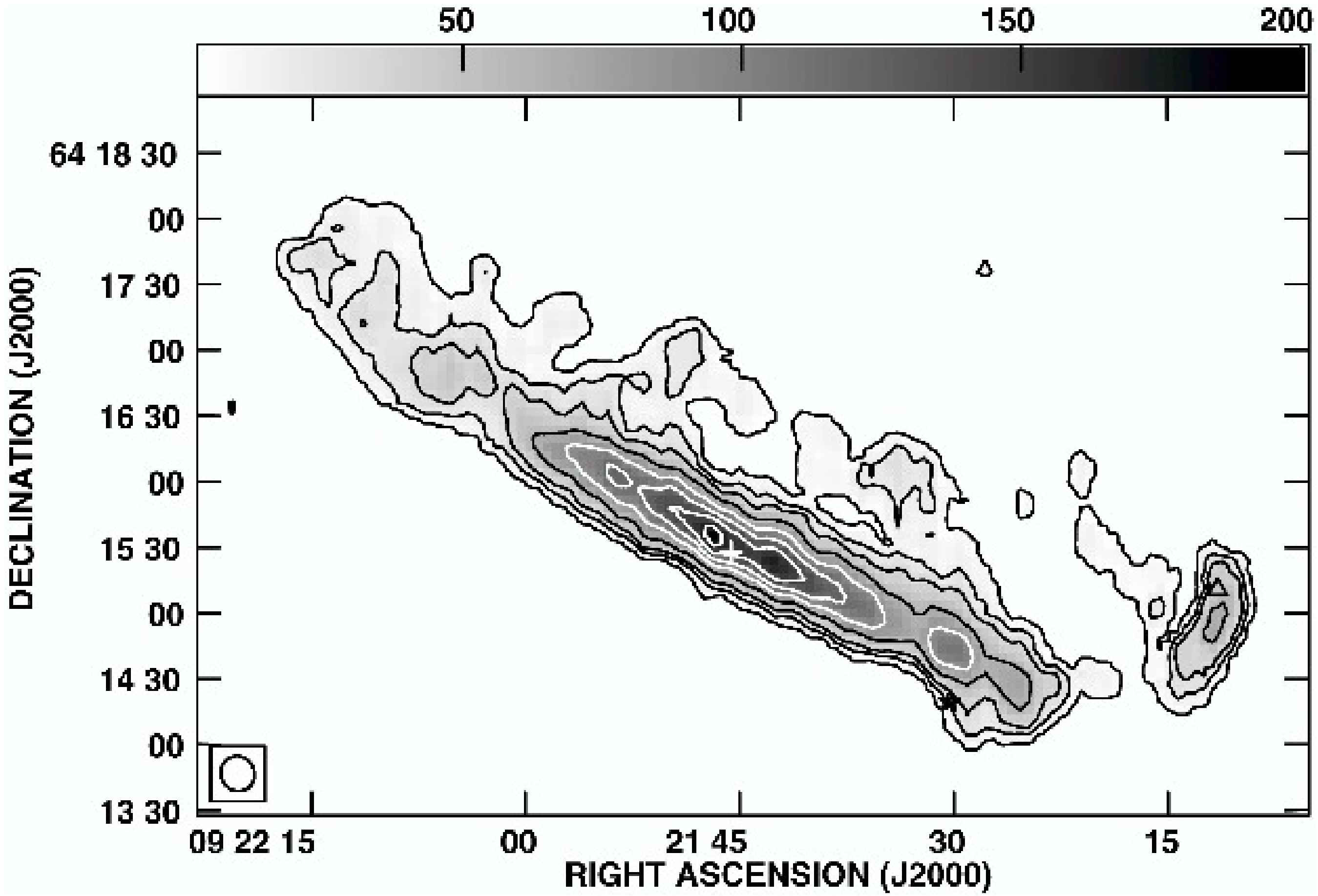
M82: with starburst driven outflowing wind

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

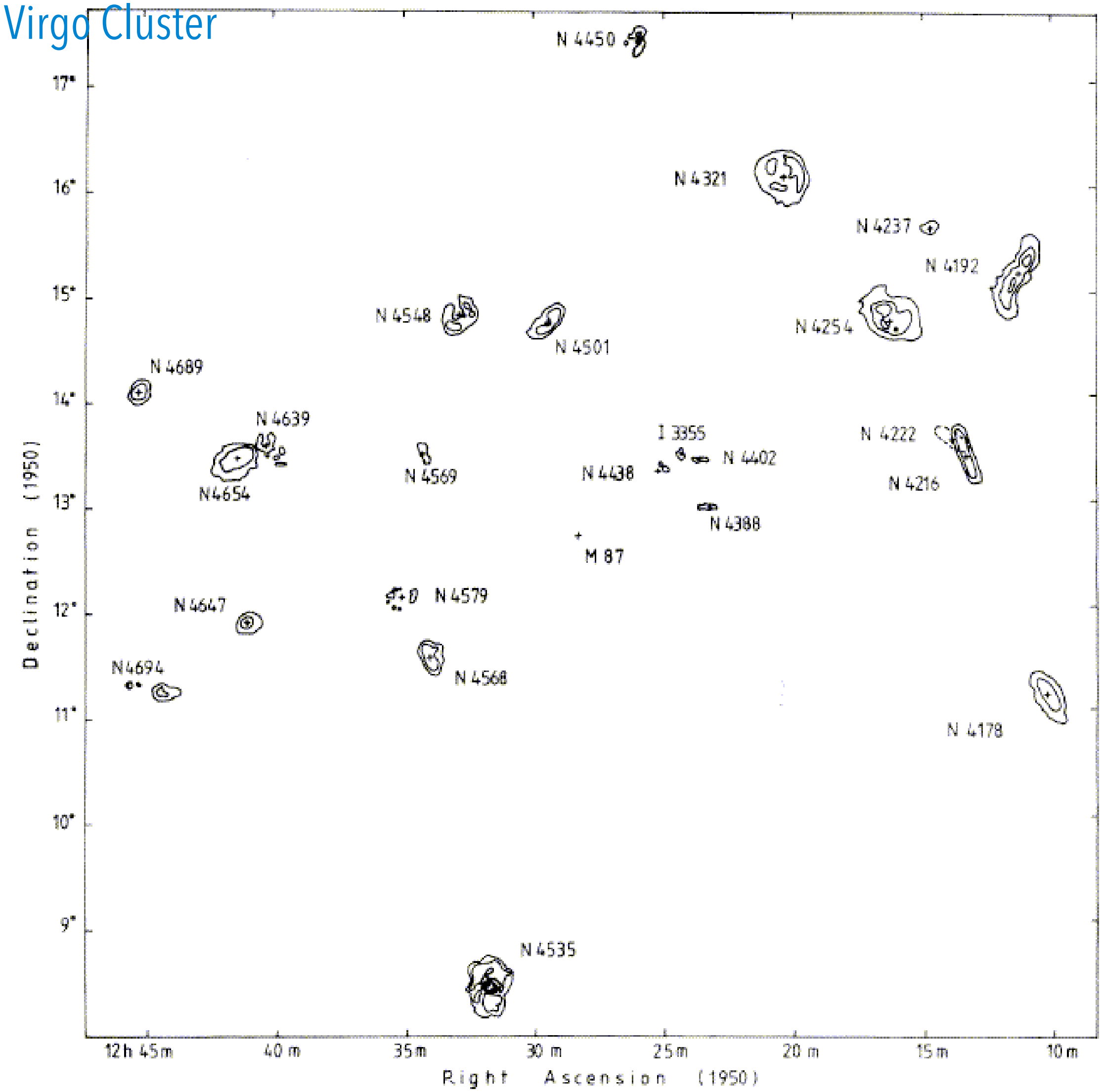
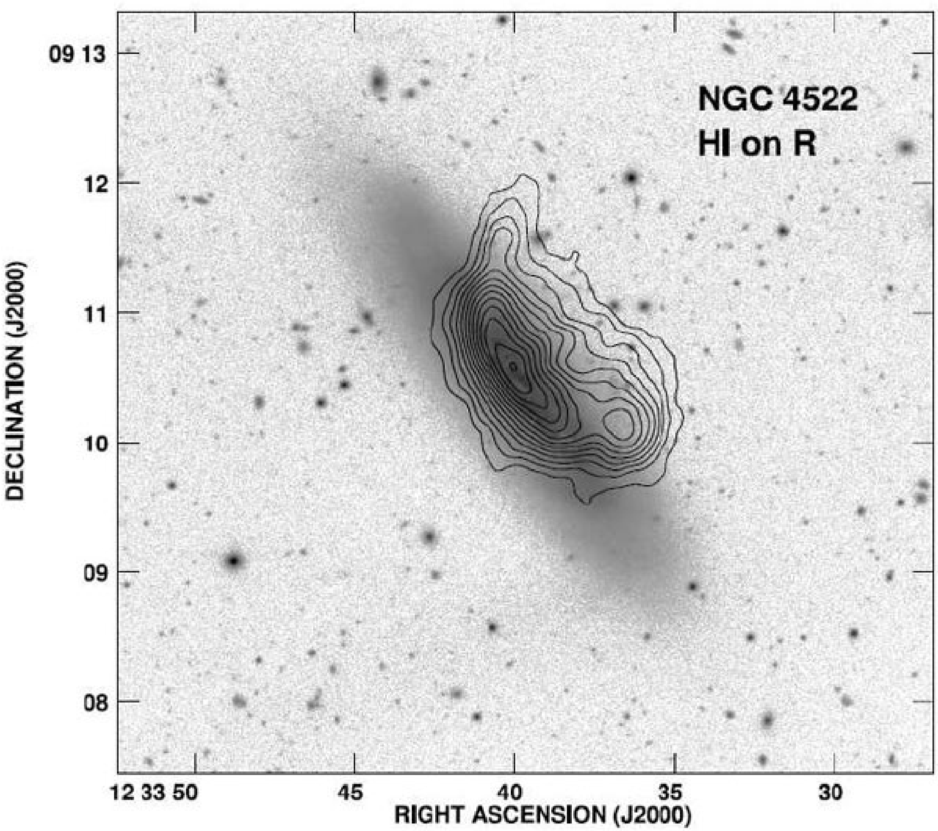


FIG. 23. Integrated neutral hydrogen maps of the brightest spirals in the Virgo Cluster center. Each map has been drawn at the galaxy position indicated by a cross and magnified by a factor of 5 compared with the scale in right ascension and declination. The first contour in each map corresponds approximately 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
- Tools of Radio Astronomy, , § 13

Galactic and Extragalactic Magnetic Fields

- Stars
- Pulsars
- SNR
- Microquasars
- ISM
- The GC, SgrA*

- Normal Galaxies
  - Elliptical, Spirals
- AGN &Radio sources
  - Compact/Extended, core, jets, lobes/tails
- IGM
  - Clusters of galaxies, filaments, etc.

Probes for astrophysical H field

- Synchrotron emission

- Polarization

- Faraday Rotation

- Zeeman Effect

- Cosmic Rays in the Milky Way

- Starlight polarization & polarized Dust emission

- Circular polarization in Masers

Importance of astrophysical H fields

- flux freezing in plasma

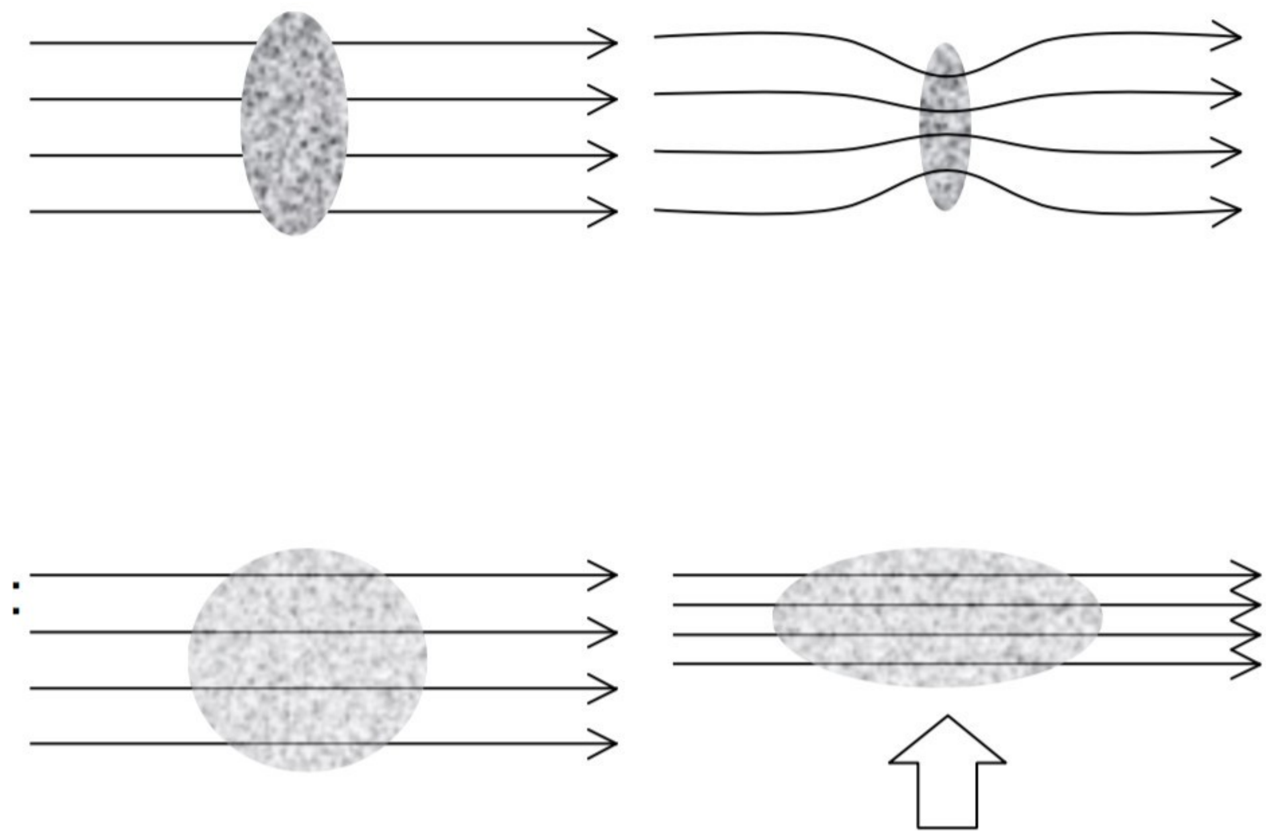
- energy budget in the ISM

- strong influence on star formation

- confinement and acceleration of cosmic rays

Importance of astrophysical H fields

- flux freezing in plasma (amplification)



Importance of astrophysical H fields - energy budget in the ISM

Thermal gas pressure $P_{therm} \approx 0.3 \; 10^{-12}$ dyn cm^{-2}

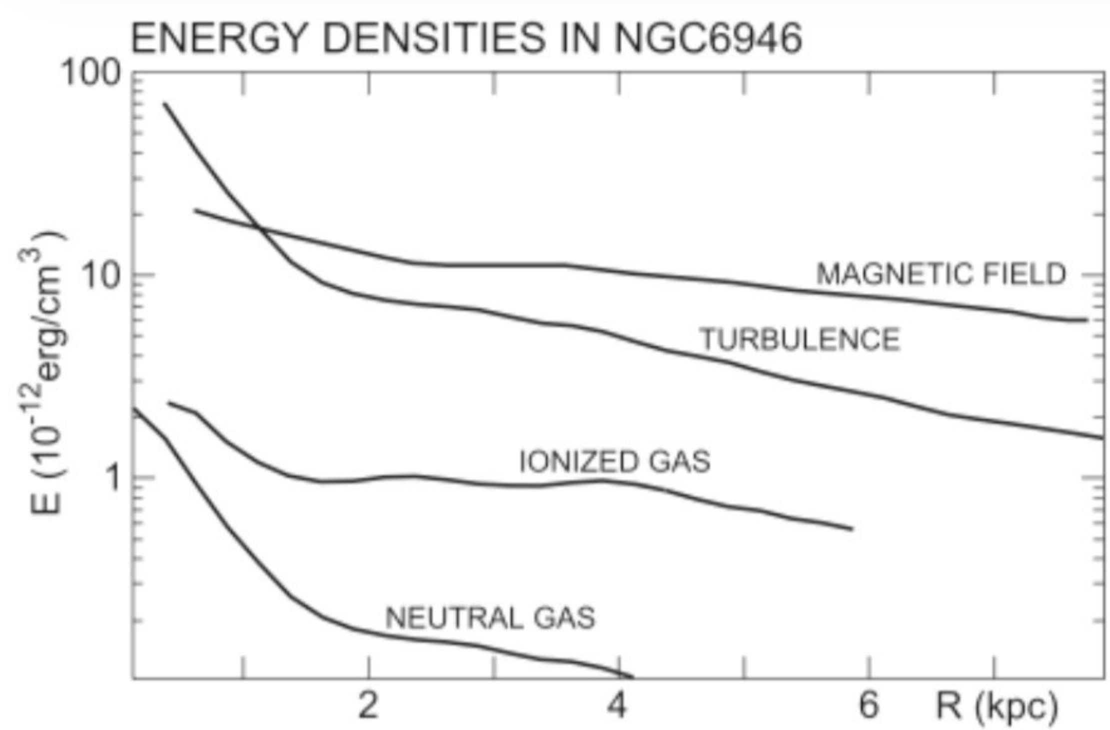
Magnetic pressure $P_H = H^2/8\pi \approx (0.4 - 1.4) \; 10^{-12}$ dyn cm^{-2}

Cosmic ray pressure $P_{CR} \approx (0.8 - 1.6) \; 10^{-12}$ dyn cm^{-2}

Turbulent gas pressure $P_{turb} \approx \rho\sigma^2 \approx (1.0 - 1.5) \; 10^{-12}$ dyn cm^{-2}

Boulares & Cox 1990

Energy densities in magnetic fields, cosmic rays, and turbulent gas are comparable in the ISM, on large scales



Beck 2004

Importance of astrophysical H fields

- strong influence on star formation

H:

- provides support against gravitational collapse through flux freezing
  ṳ delays collapse

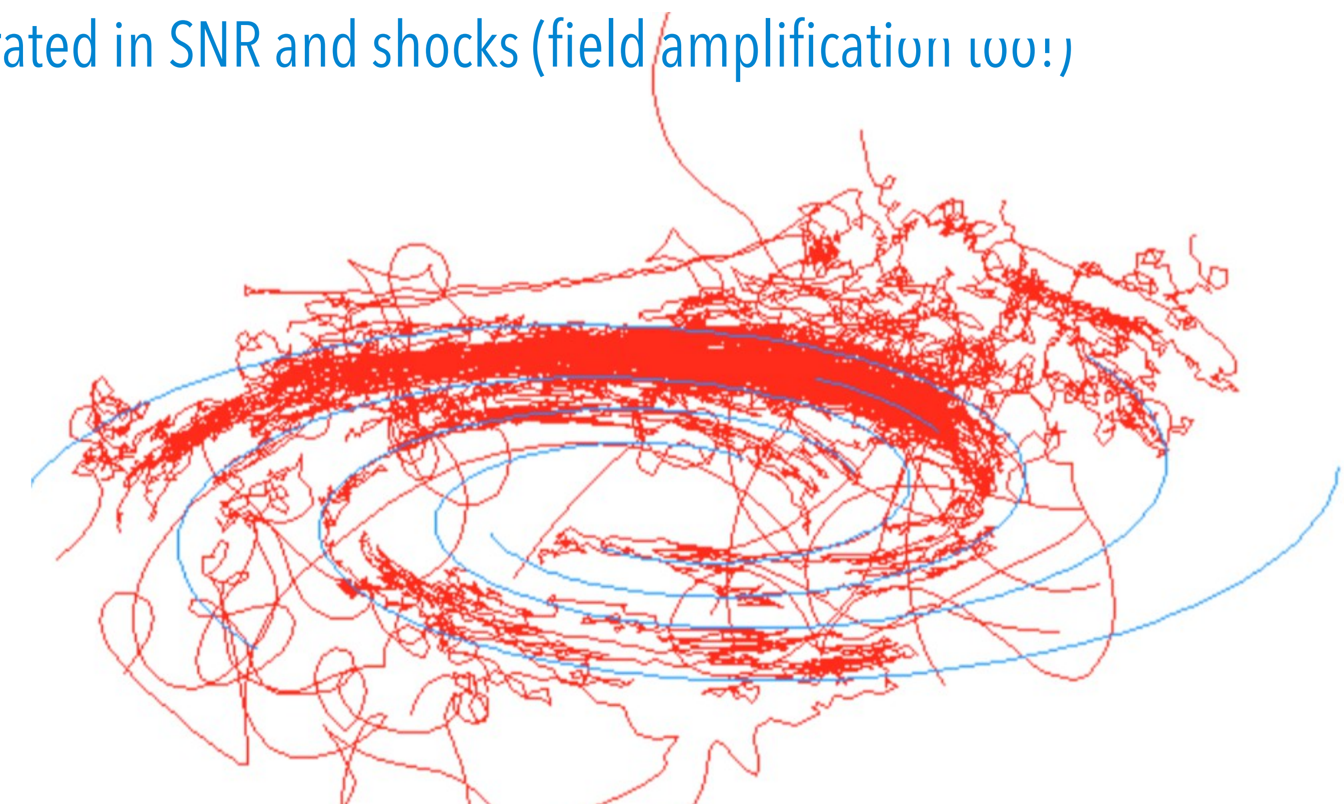
- transport angular momentum away from collapsing protostellar cores
  ("magnetic braking") ṳ enhances collapse

- reduces heat conduction significantly ṳ cloud evaporates much slower,
  and can be further compressed ṳ enhances collapse

Importance of astrophysical H fields

- confinement and acceleration of cosmic rays

- CRs are deflected by galactic H, directions are randomized
- Confinement for about 10 Myr
- Generated/accelerated in SNR and shocks (field amplification too!)



Prouza & Smida 2003

Probes for astrophysical H field

- Synchrotron emission

- Polarization

- Faraday Rotation

- Zeeman Effect

- Cosmic Rays in the Milky Way

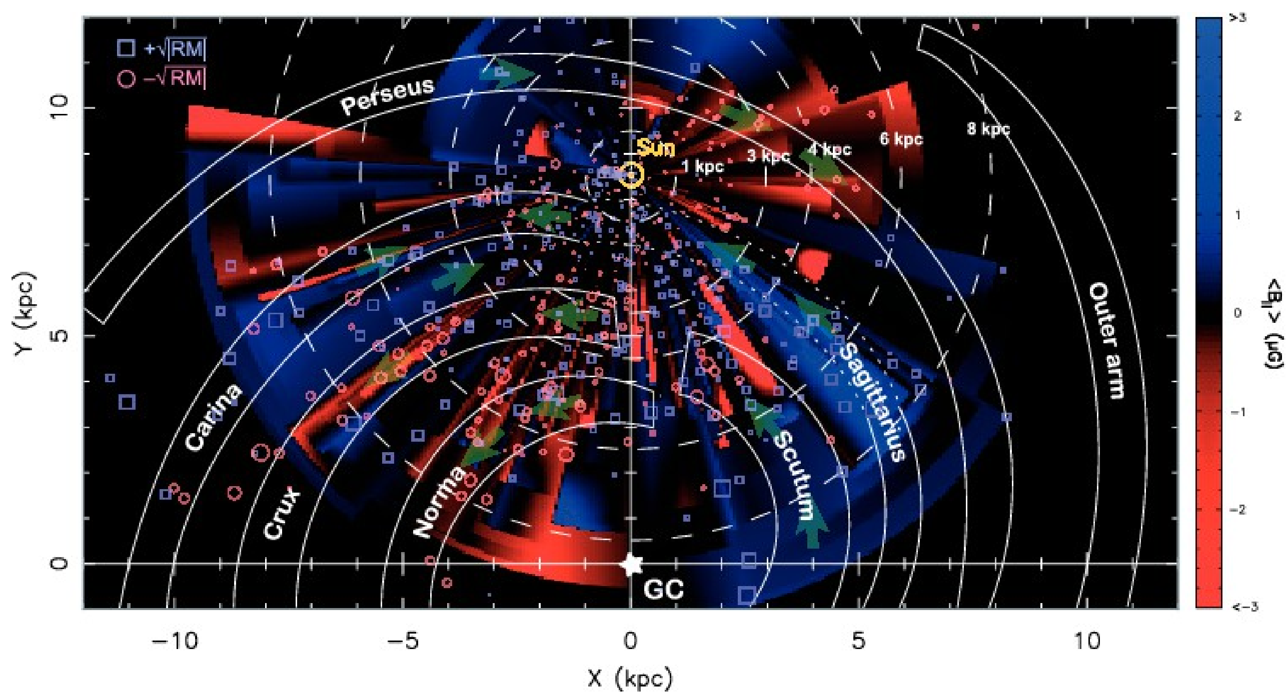
Probes for astrophysical H fields

- From synchrotron emission

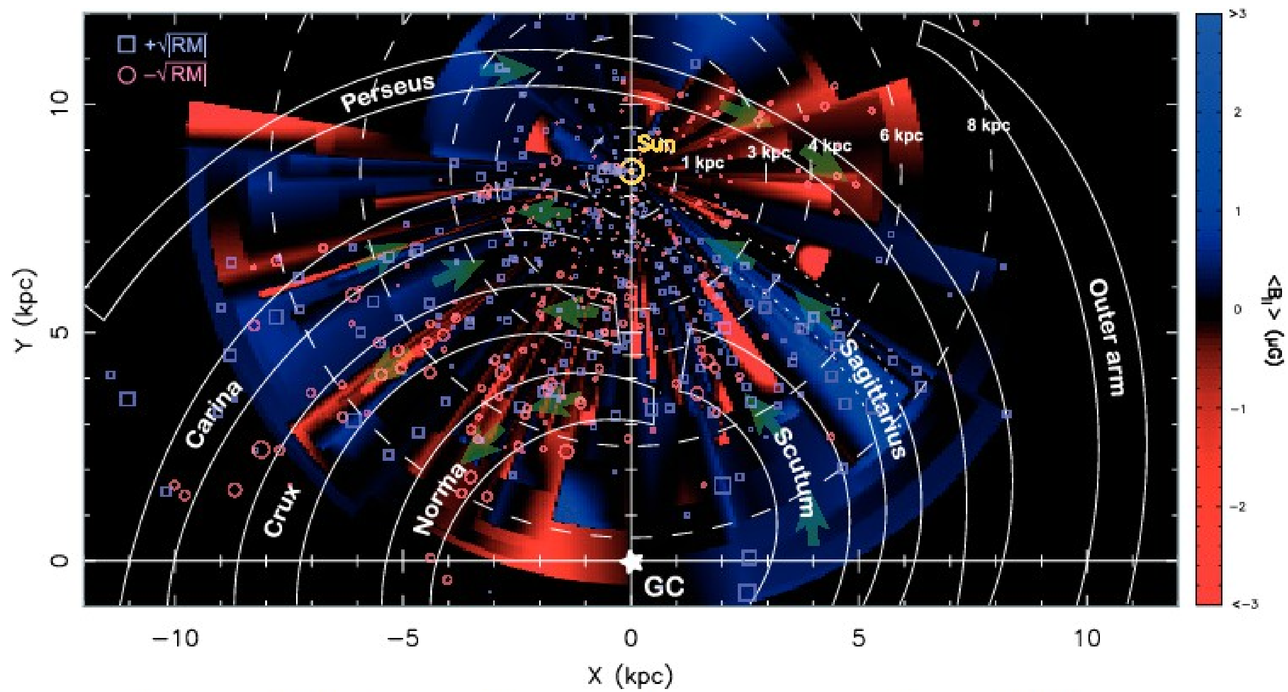
l is the depth of the source $B(\nu) \simeq N H^{(\delta+1)/2} l$ where $N = N_o \varepsilon^{-\delta}$

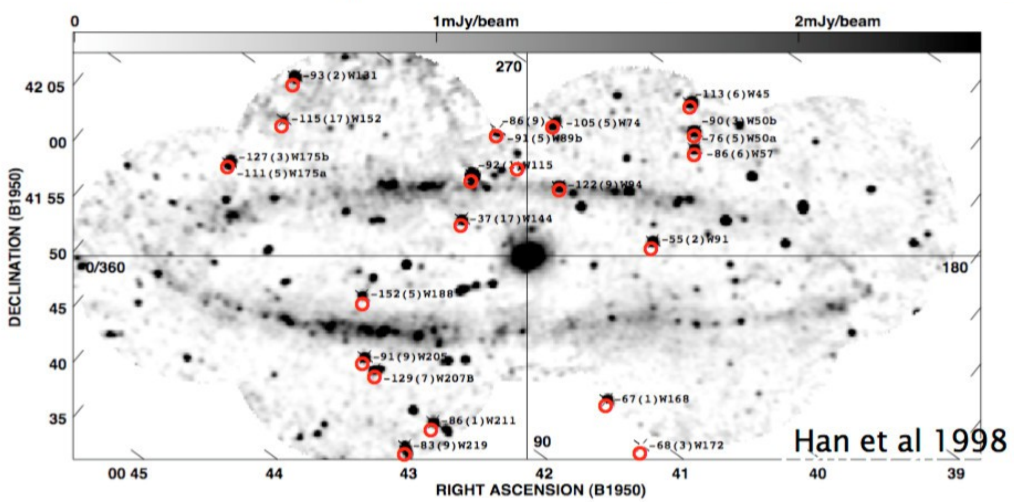
Our galaxy:

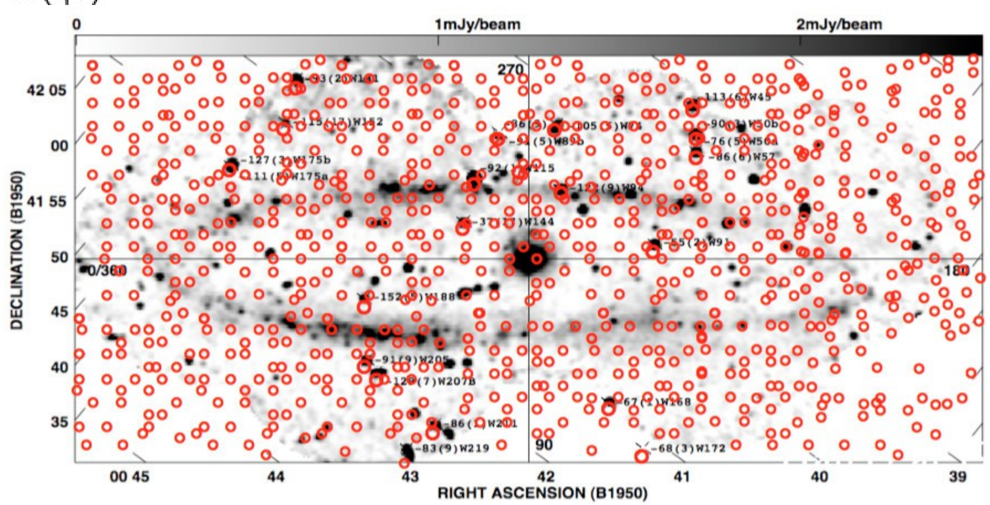
- if $N_0 \sim 0.01\ cm^{-3}$ as found in the solar neighborhood $\Rightarrow$ $H \sim 10\mu G$
- Pulsar <RM> / <DM> $\Rightarrow$ $H_{\parallel} \sim 5\text{-}6\ \mu G$



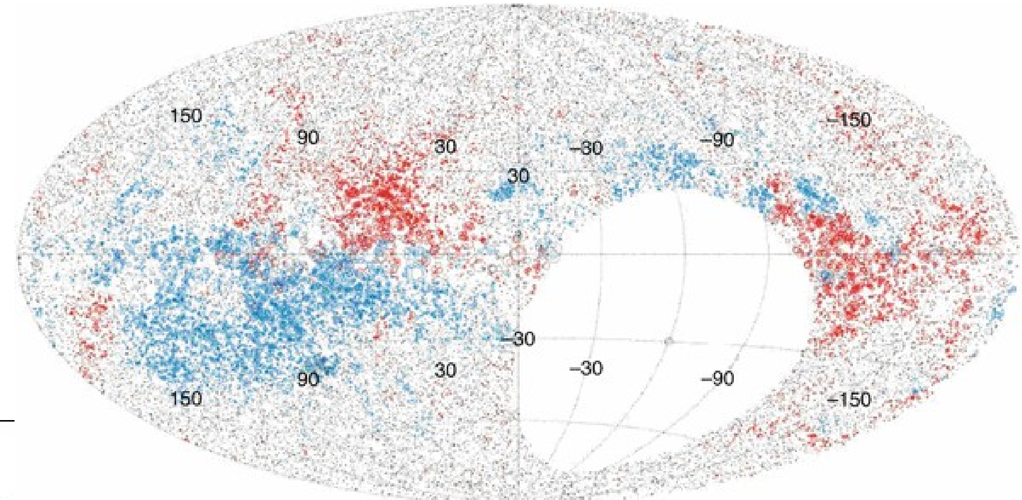
Probes of the H field in the MW - Polarization & Faraday Rotation



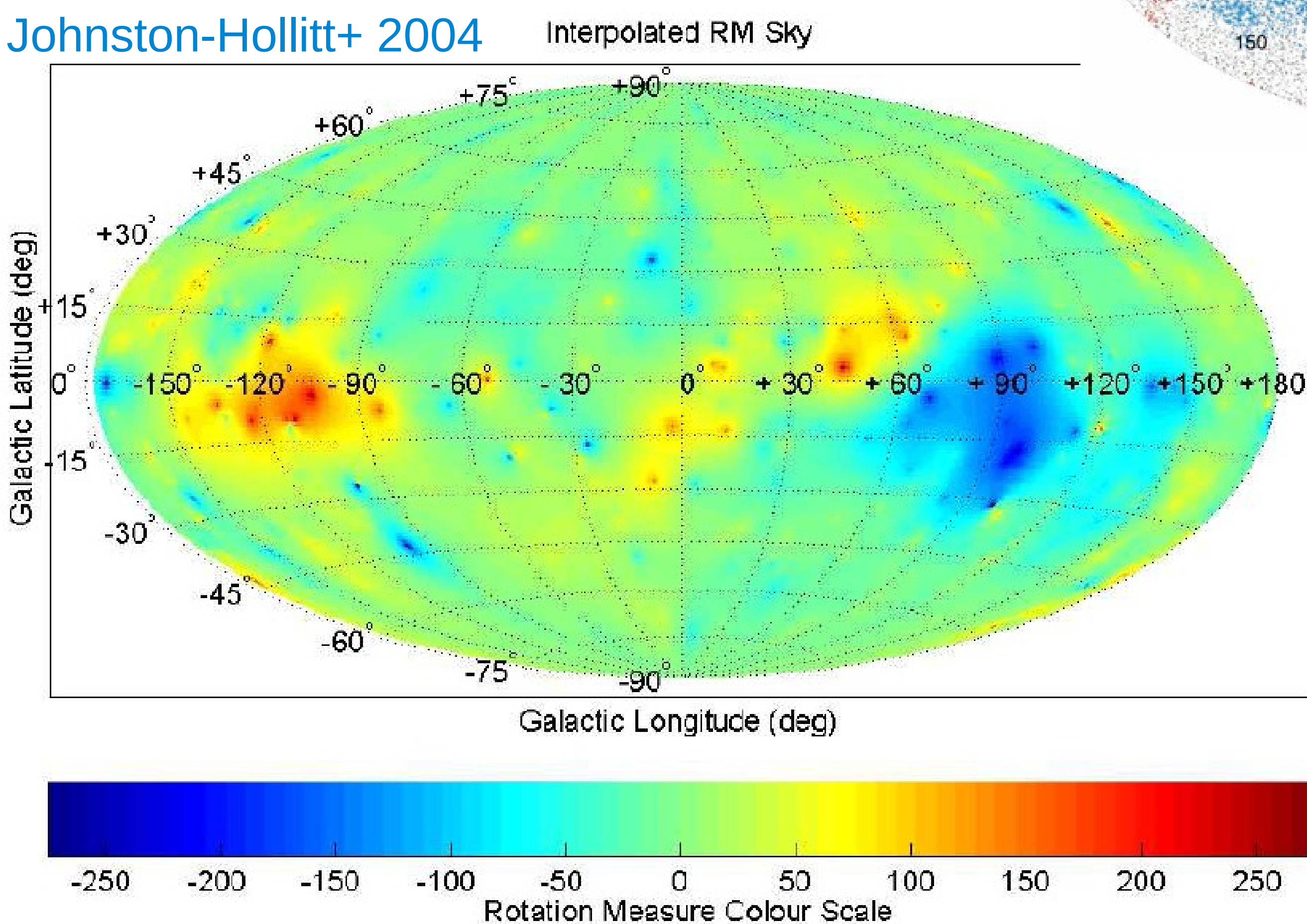




Probes of the H field in the MW - Polarization & Faraday Rotation

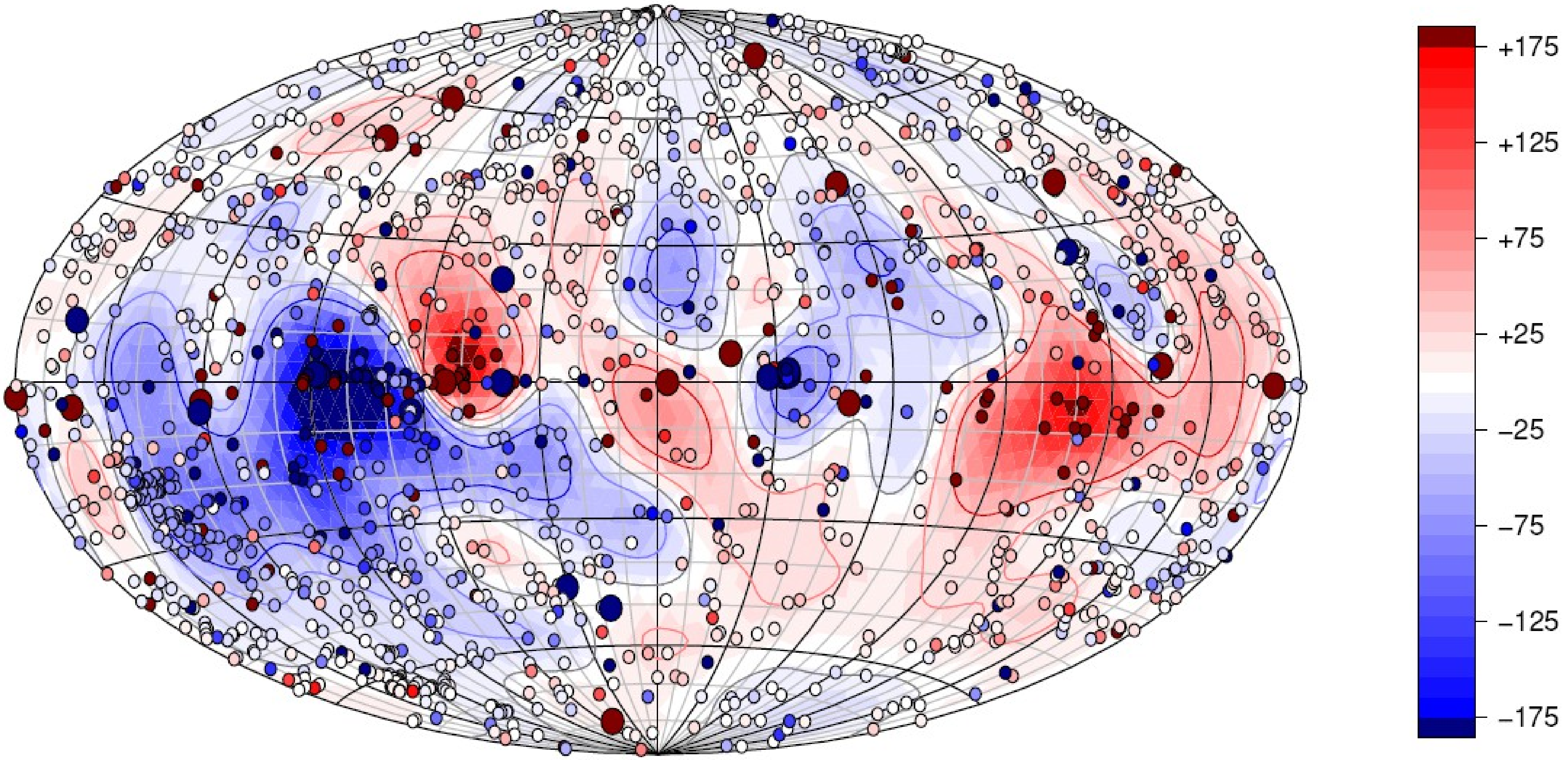


Johnston-Hollitt+ 2004



E-W are flipped!

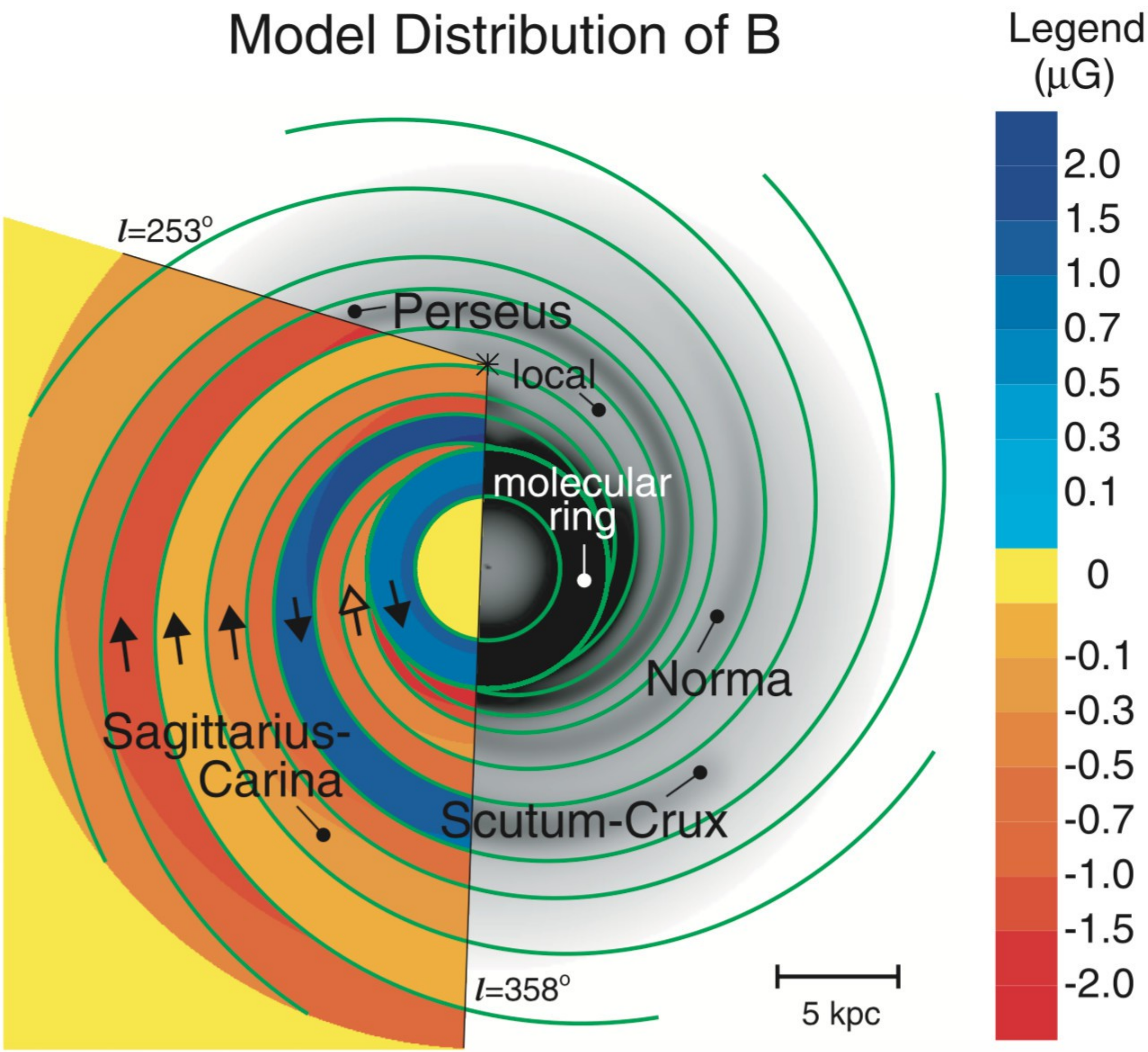
Probes of the H field in the MW - Polarization & Faraday Rotation

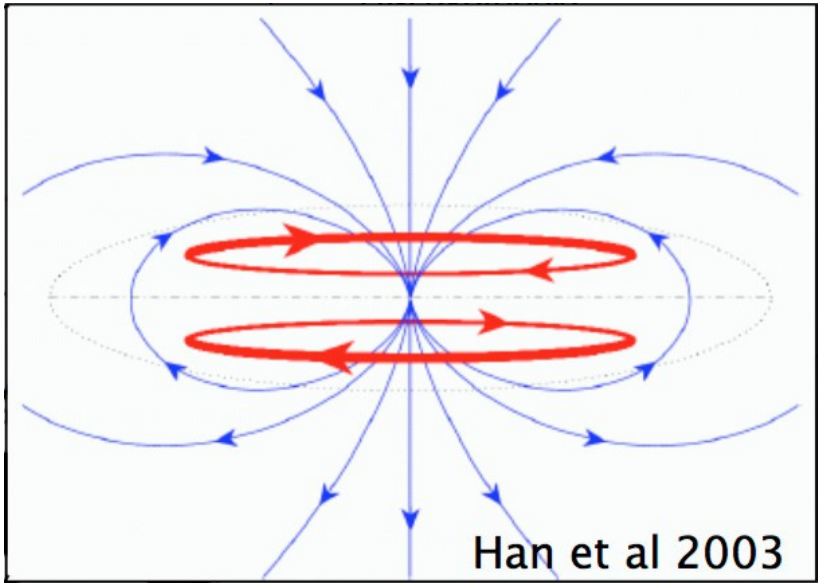


Probes of the H field in the MW - Polarization & Faraday Rotation

Model(s) for the field in the Milky Way Field Reversals

Brown+ 2007



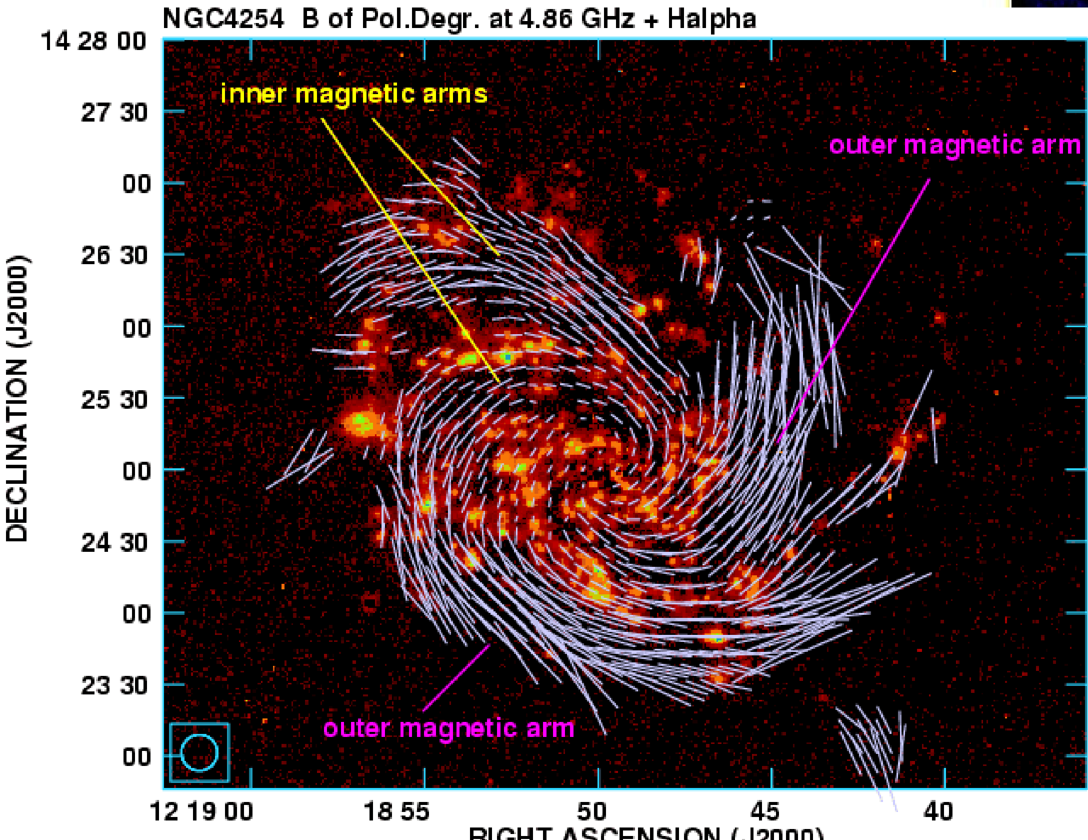


Nearby external galaxies

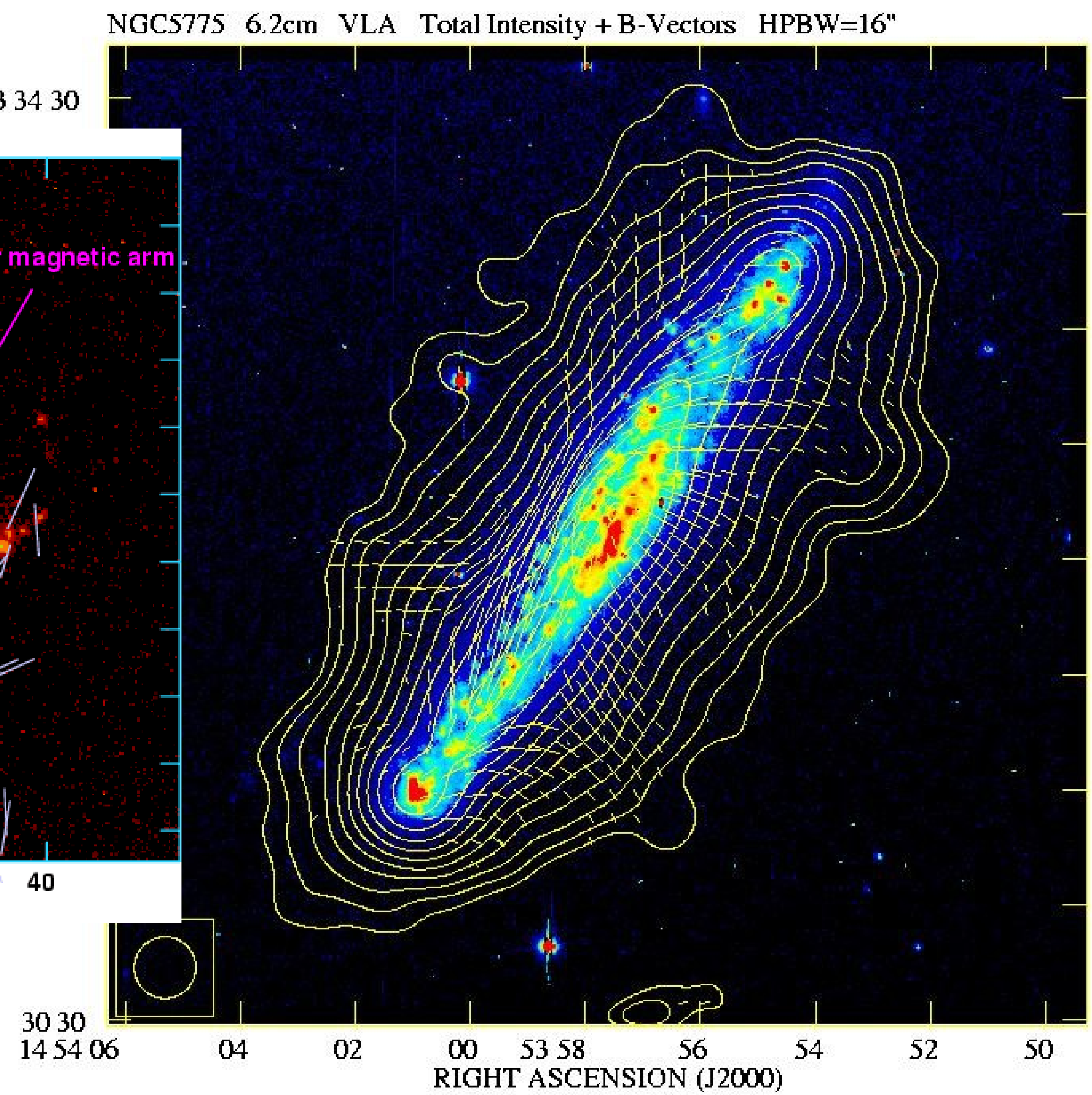
- Halos are seen around disks of many edge-on spirals.
- Radio intensity and halo extent vary greatly
- There is a rough correlation with HÁ and X-rays :
  star formation in the disk is an energy source for halo formation

Probes for astrophysical H field - Polarization & Faraday Rotation

In spiral galaxies



Chyzy+ 2008, projected ordered field vectors



Tullmann + 2000, projected ordered field vectors

Probes for astrophysical H field

Spirals:

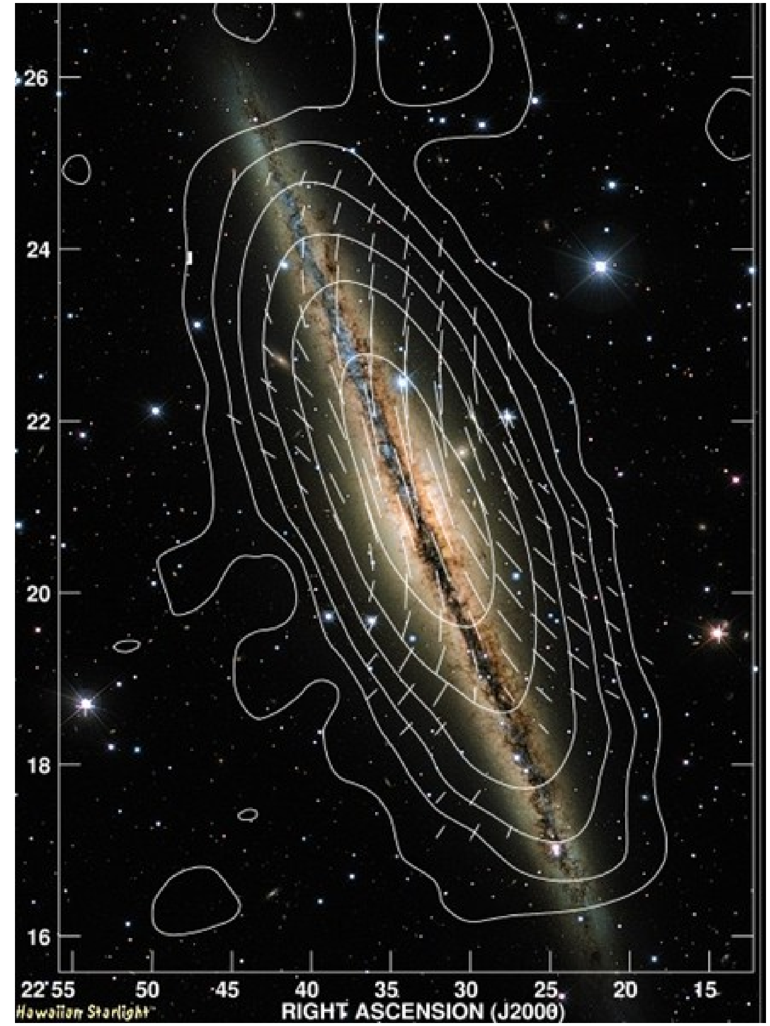
B ≈ 10 ÕG in typical spirals (M31, M33);

B ≈ 15 ÕG for high-star forming galaxies (M51)

B ≈ 30 ÕG for starburst galaxies (M82, Antennae)

$B_{uniform}$ is usually the strongest in the inter-arm regions

Spiral magnetic field exists in almost all galaxies, even the ringed and flocculent ones! This is a strong indication of dynamo action in these galaxies, that maintains a (spiral) magnetic field in these galaxies



Intergalactic magnetic fields

- "Empty" space (VOIDs) may be magnetized.

It may provide a seed field for galaxy and cluster magnetic fields.

What role do intergalactic magnetic fields have in structure formation in the early Universe?

$\Longrightarrow$ Upper limit from Faraday rotation observations: $B_{IGM} \leq 10^{-8} - 10^{-9}$ Gauss

Similar to upper limits from many theoretical studies

- In Galaxy Clusters

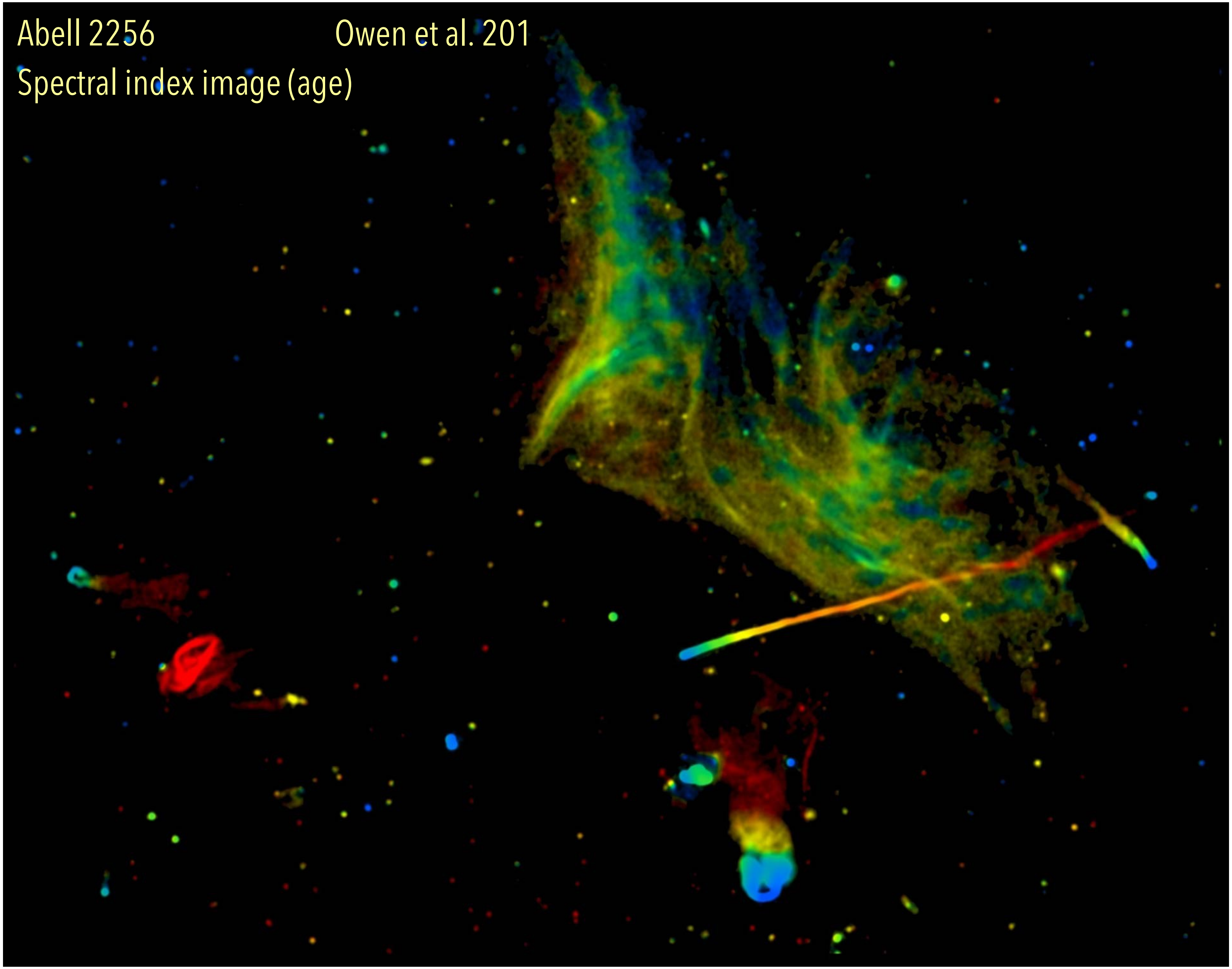
$B_{IGM} \sim 10^{-6} - 10^{-7}$ Gauss (from RM of background sources, and extended radio sources within the cluster)

Some fraction (mostly the X-ray bright & most massive ones, morphologically disturbed) have diffuse radio emission.

- Origin of cluster magnetic fields:

outflows from AGNs, turbulent wakes, cluster mergers etc.

Cluster scale intergalactic magnetic fields

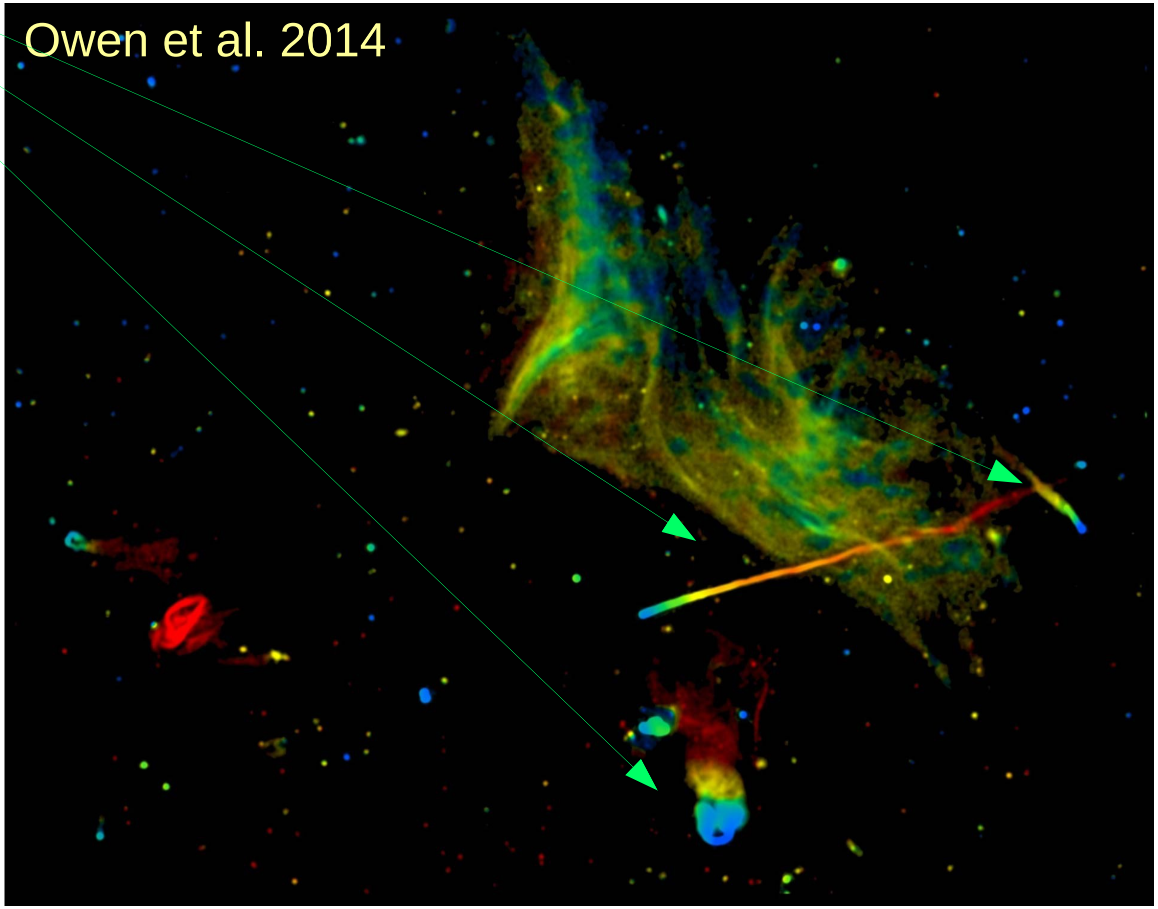


- Synchrotron emission (relativistic electrons, H)

- Spectral ageing in tailed radio galaxies (2D speed, evolution of H & γ in the tails, pressure equilibrium with the IGM)

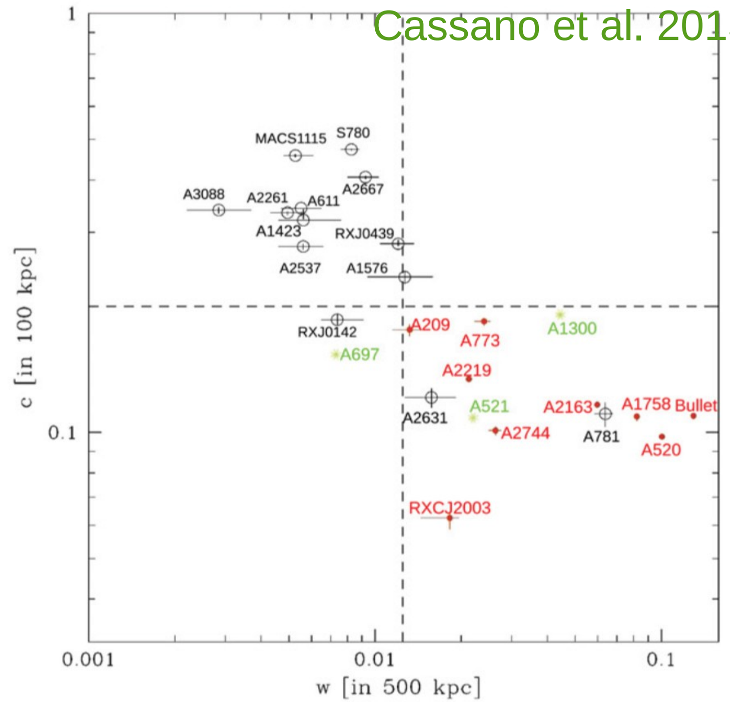
- RM in extended emission (2D tomography of the H field and n_e along various LOS)

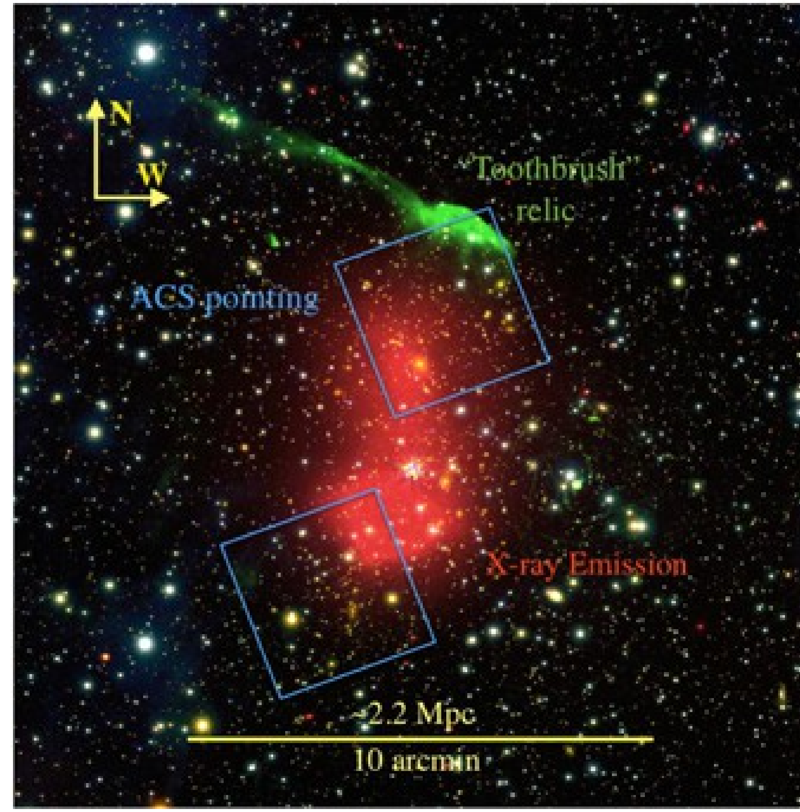
- Energy content in relativistic plasma & energy budget of the ICM

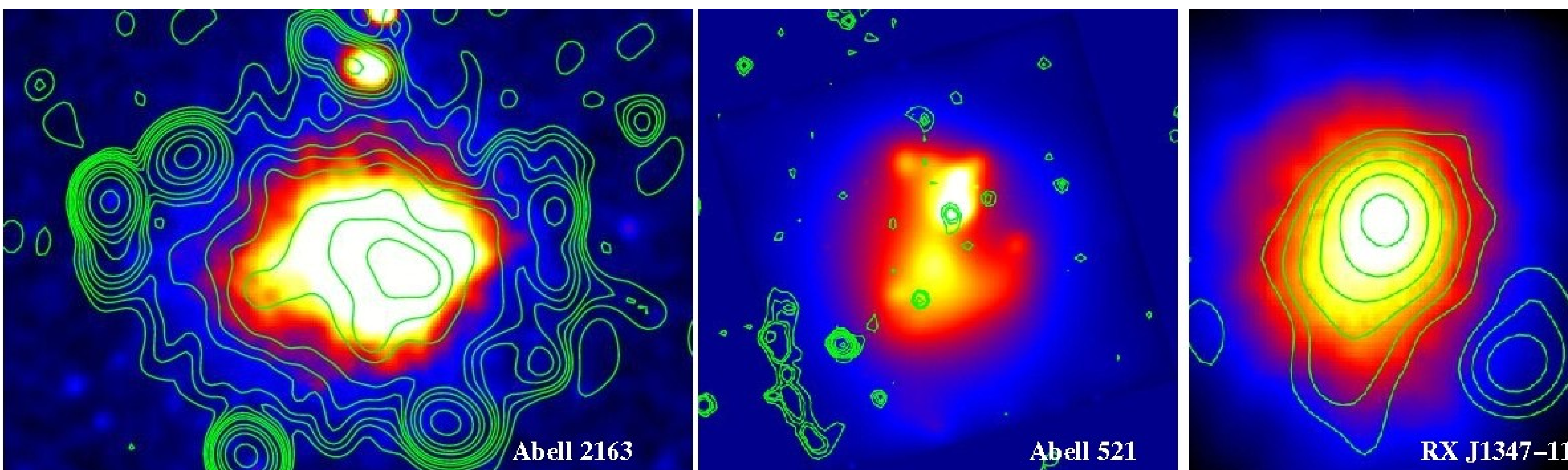


Cluster scale intergalactic magnetic fields

Cassano et al. 2013







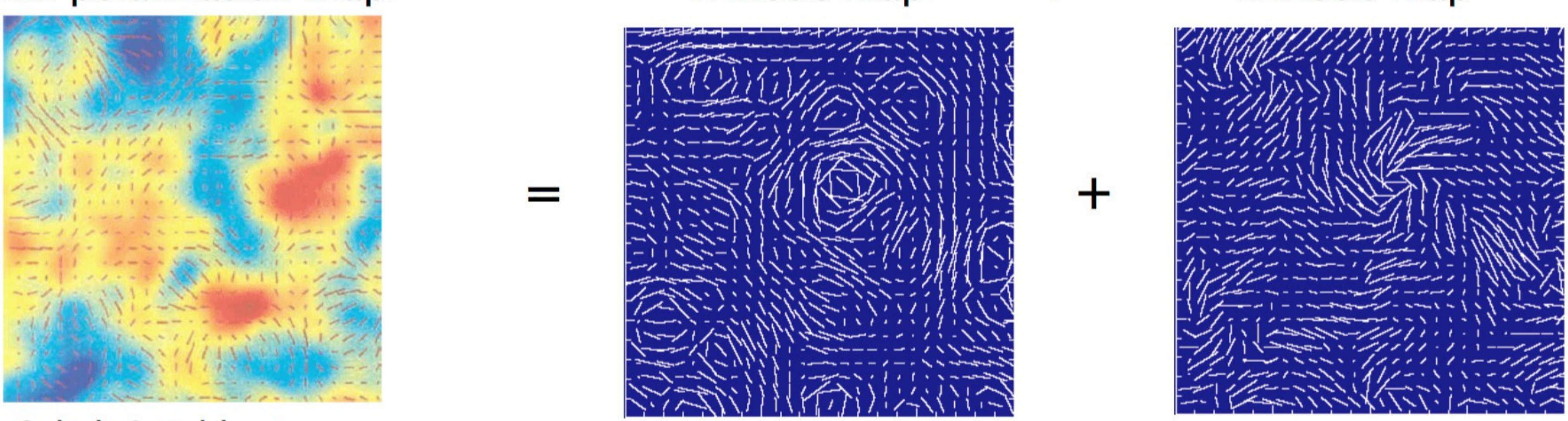
CMB linear polarisation can be decomposed into E-modes and B- modes

-- similar to decomposition in Stokes Q, U but without a preferred coordinate system.

(In effect the E-mode is a curl-free mode, while the B-mode is divergence-free.)

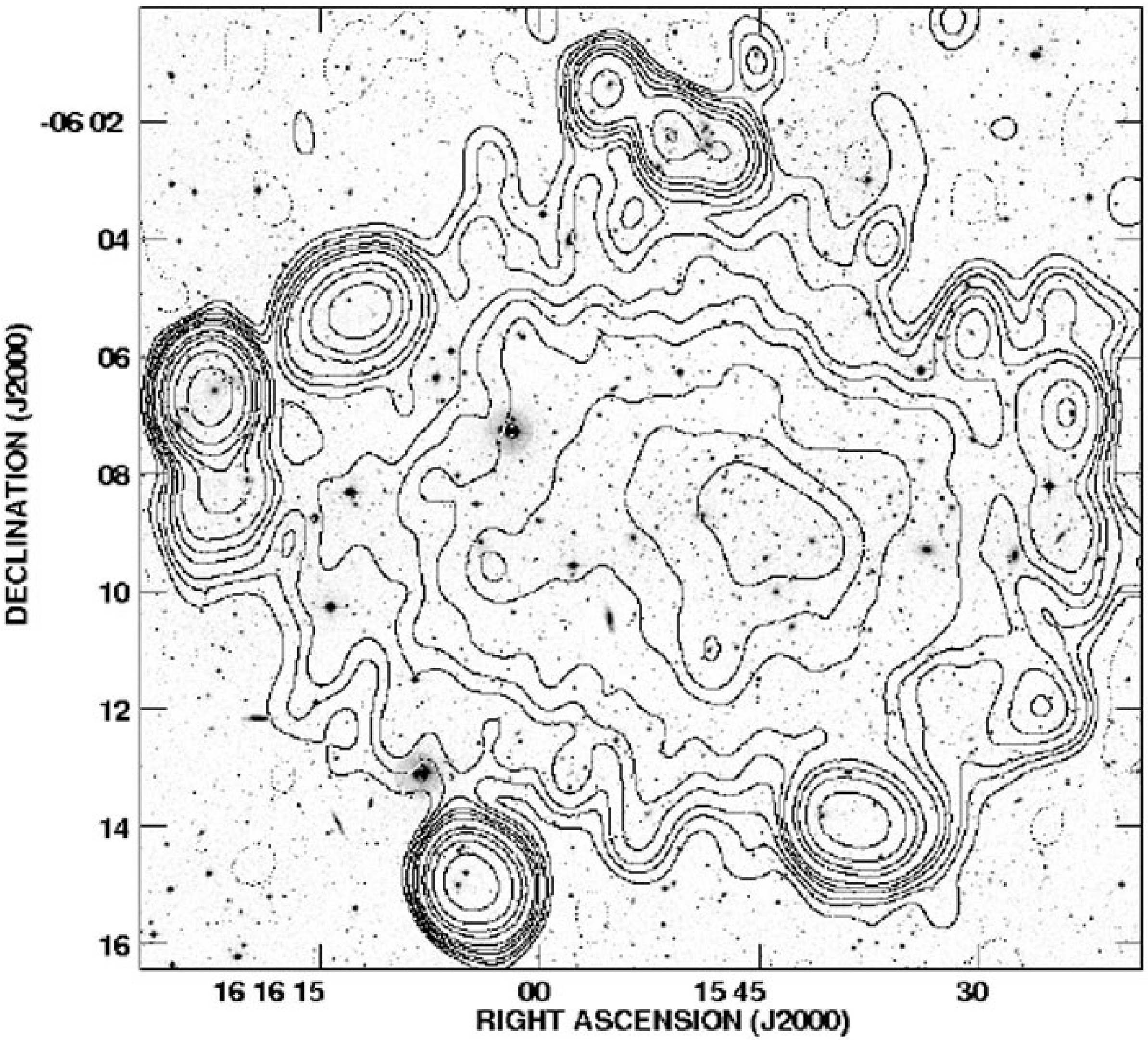
⟹ E-modes arise from Thomson scattering in an inhomogeneous plasma

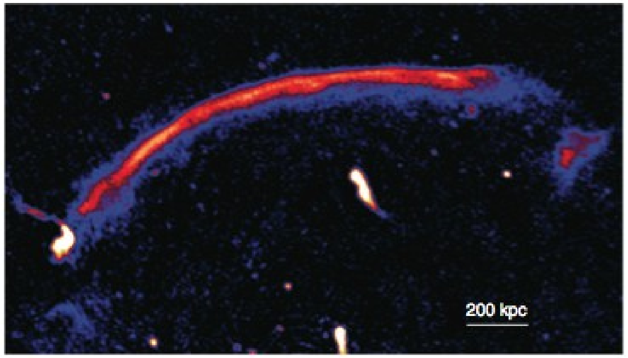
⟹ B-modes determined by primordial gravitational wave density t signal from inflation era!

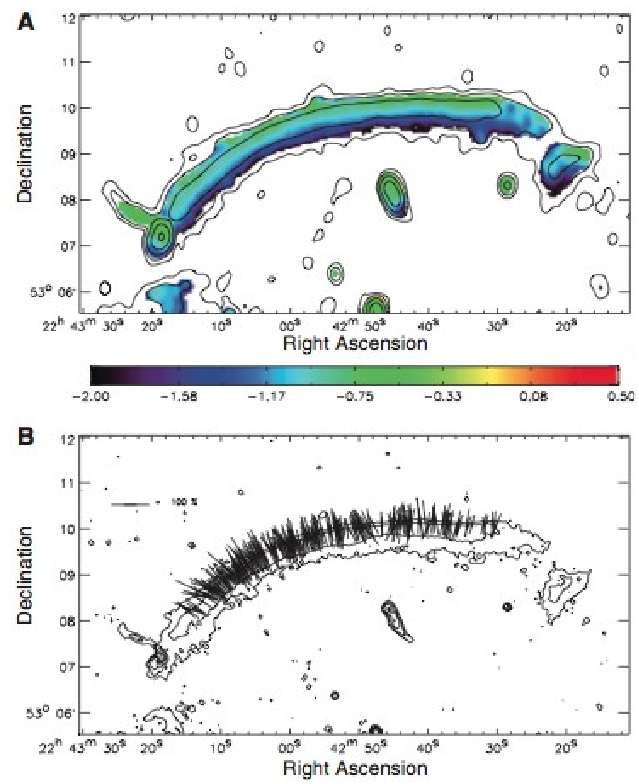


Seljak & Zaldarriaga

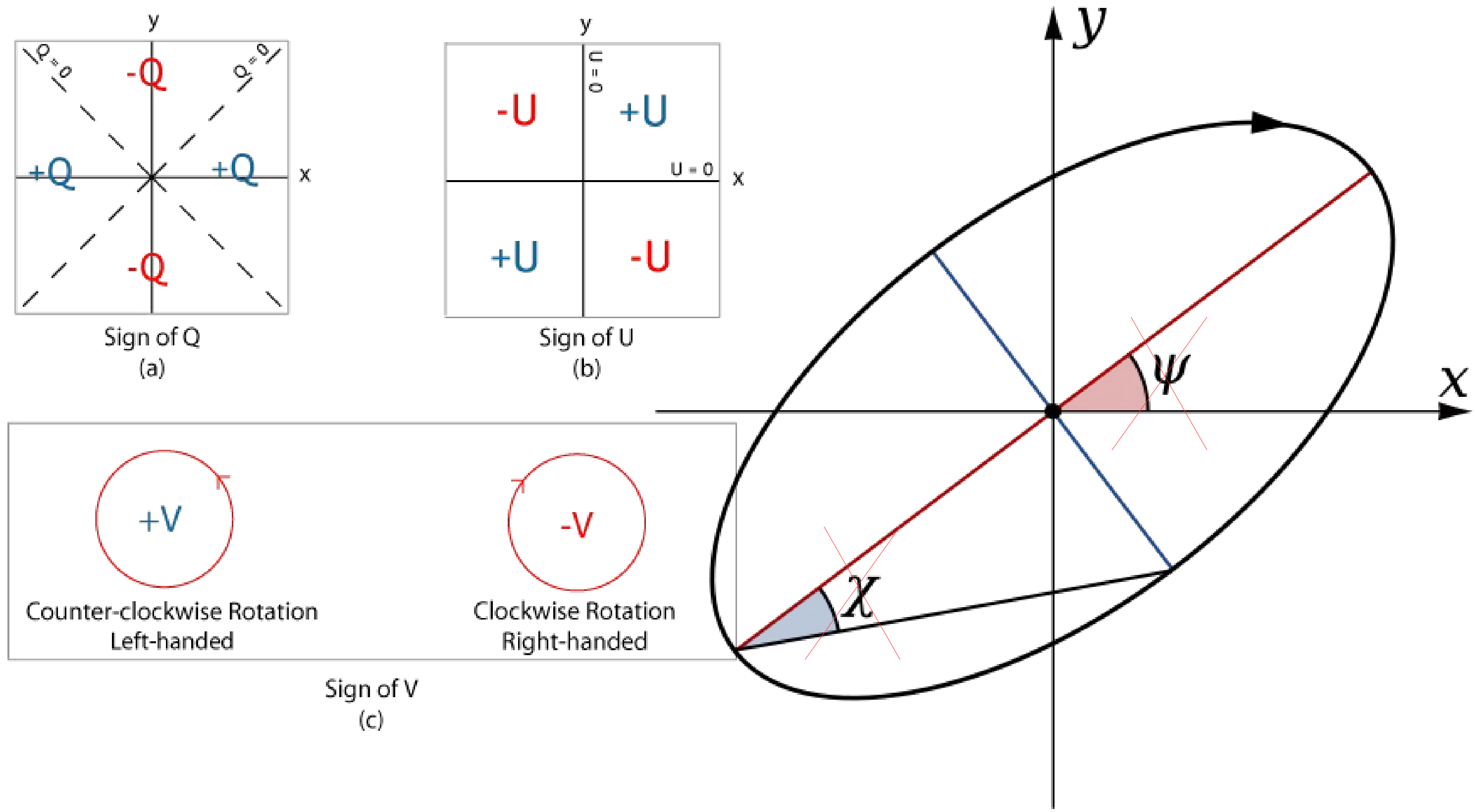
Much more in the "AMMASSI DI GALASSIE" lectures

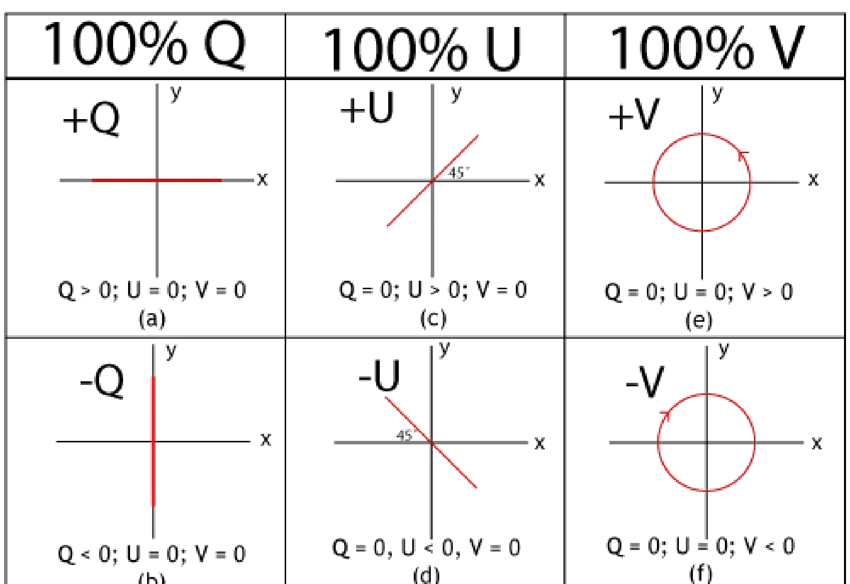




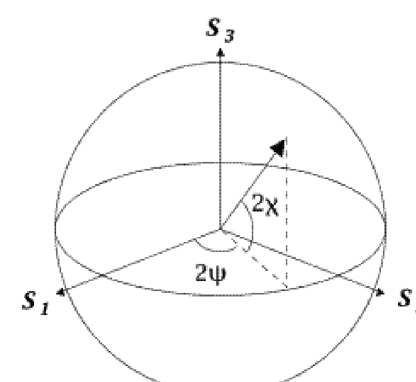


Appendix: linear, circular polarization and the Stokes' Parameters





$$S_0 = I$$
$$S_1 = Ip\cos 2\psi \cos 2\chi$$
$$S_2 = Ip\sin 2\psi \cos 2\chi$$
$$S_3 = Ip\sin 2\chi$$



2. Parametrization of the linear (and circular) polarization: Stokes' Parameters

Each radio telescope reveals two orthogonal components of the radiation

a. linear feeds E_X, E_Y

b. circular feeds E_R, E_L

Both interferometers and single dishes cross (auto) correlate these signals

$$< E_X^2 > + < E_Y^2 > = I$$

$$< E_X^2 > - < E_Y^2 > = Q$$

$$2 < \mathrm{Re}(E_X E_Y^*) > = 2 < \mathrm{Re}(E_X E_Y) \cos\delta_{XY} > = U$$

$$2 < \mathrm{Im}(E_X E_Y^*) > = 2 < \mathrm{Im}(E_X E_Y) \sin\delta_{XY} > = V$$

$$I = < E_R^2 > + < E_L^2 >$$

$$Q = 2 < \mathrm{Re}(E_R E_L^*) > = 2 < \mathrm{Re}(E_R E_L) \cos\delta_{RL} >$$

$$U = 2 < \mathrm{Im}(E_R E_L^*) > = 2 < \mathrm{Im}(E_R E_L) \sin\delta_{RL} >$$

$$V = < E_R^2 > - < E_L^2 >$$

2. Relationships for an interferometer: given two antennas i- and j- with circular feeds:

$$I = \frac{\left(E_R^i E_R^j + E_L^i E_L^i\right)}{2}$$

$$Q = \frac{\left(E_R^i E_L^j + E_L^i E_R^j\right)}{2}$$

$$U = \frac{\left(E_R^i E_L^j - E_L^i E_R^j\right)}{2i}$$

$$V = \frac{\left(E_R^i E_R^j - E_L^i E_L^i\right)}{2}$$

for linearly polarized radiation:

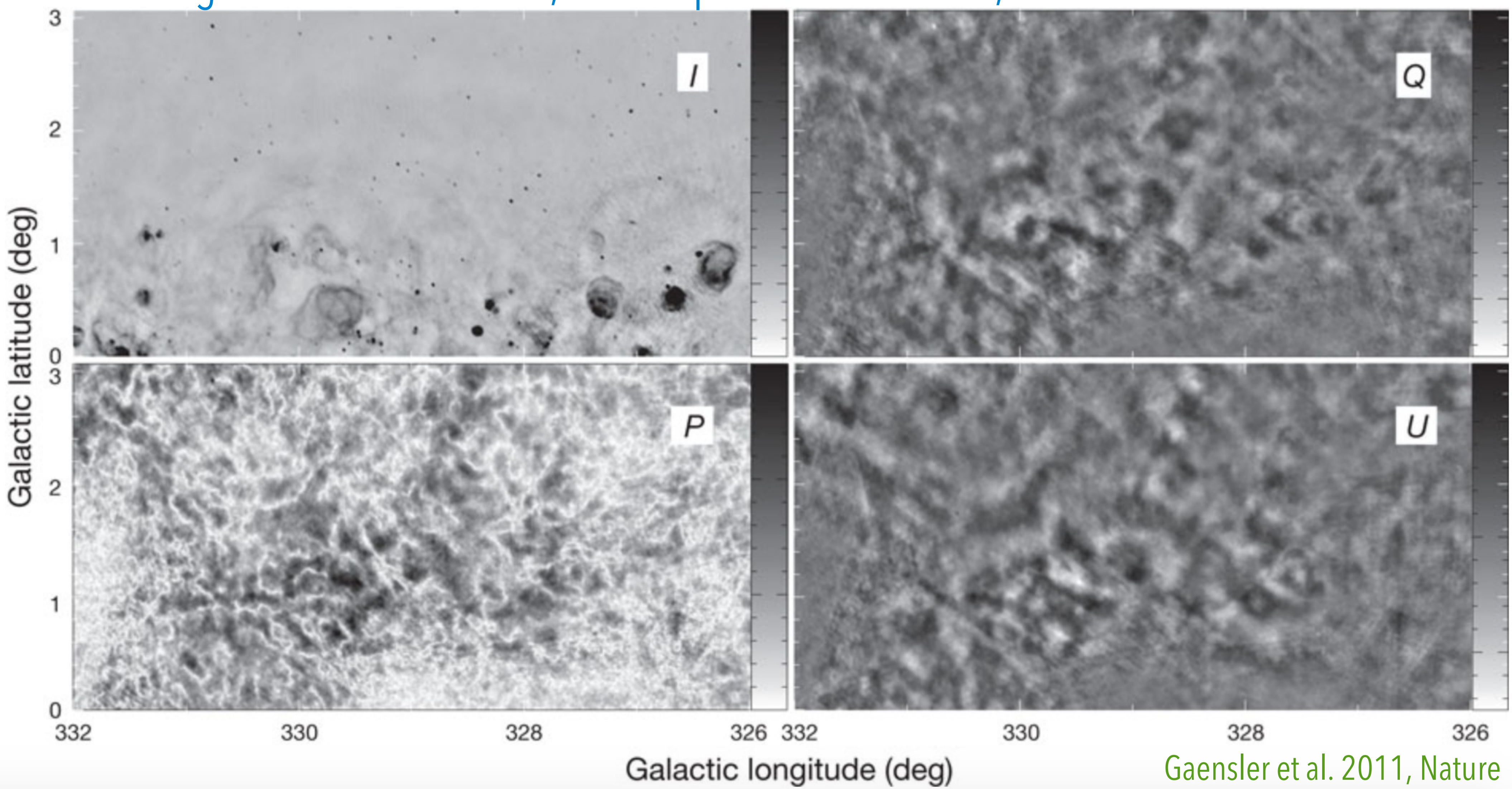
$$P = \sqrt{Q^2 + U^2}$$

$$\chi = 0.5 \times \mathrm{atan2}(U, Q)$$

$$f_{pol} = \frac{P}{I}$$

Images can be created in all Stokes parameters: I, U, Q, V, P, χ, f

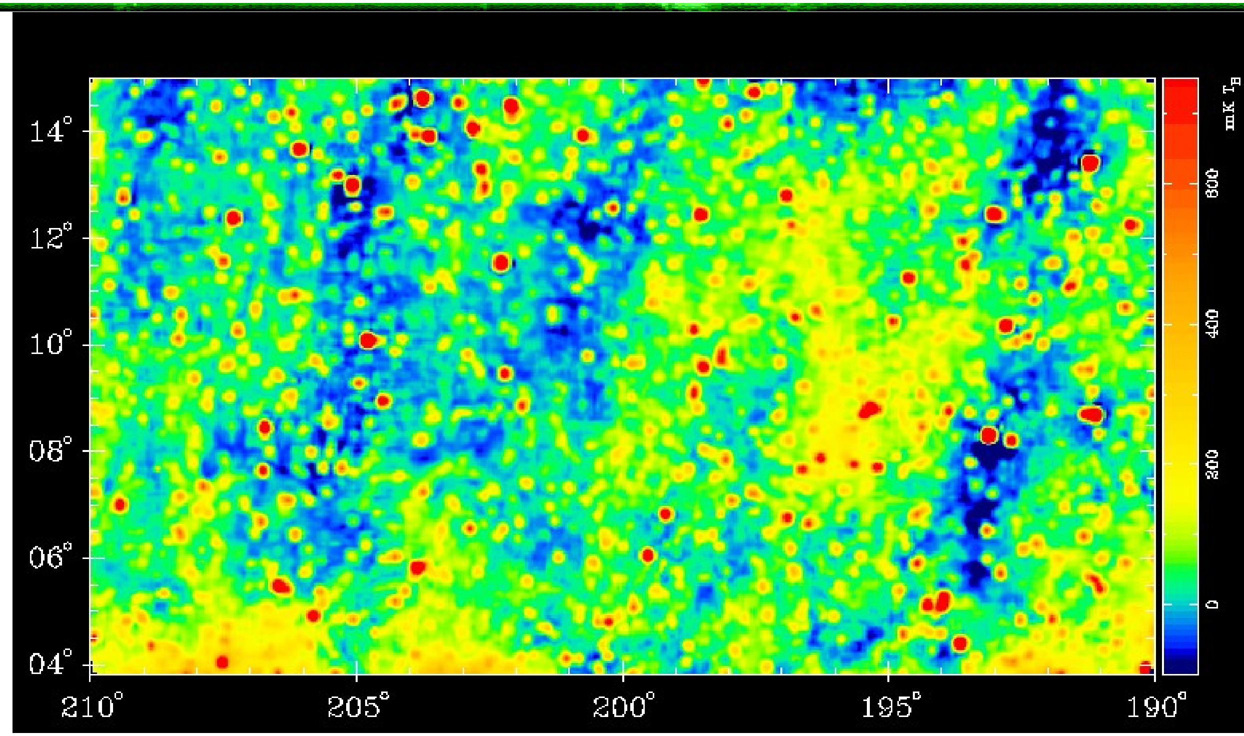
The magnetic field in the MW, seen in polarized emission, where no I is detected!

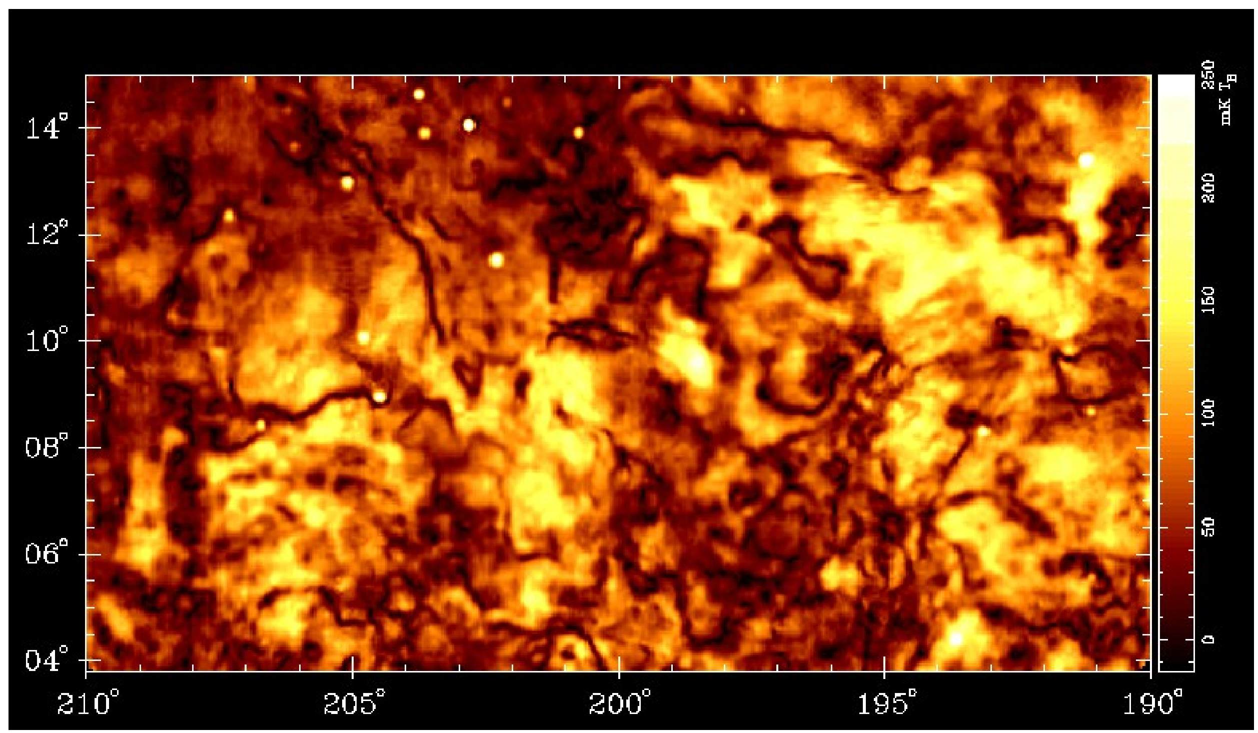


Gaensler et al. 2011, Nature

Images generated from a set of ATCA observations (1997 April – 1998 April, $\Delta\nu$= 96-MHz, centred on 1,384 MHz). Mosaic of 190 pointings (~ 20 min each), ~ uniform sensitivity of 0.8 mJy/beam (Stokes *I*) , 0.55 mJy/beam (Stokes *Q* and *U*), HPBW= 75″. ATCA is an interferometer: it is not sensitive to structure on angular scales > 35 arcmin. Faint wisps can be seen, corresponding to the sharp edges of large-scale structures. However, the bulk of the smooth radio emission from Galactic cosmic rays is not detected. Imaging artifacts (grating rings & radial streaks) can be seen around a few very bright sources. Almost none of the structures seen in *Q*, *U* and *P* has any correspondence with any emission in Stokes *I*; mottled structure = spatial fluctuations in Faraday rotation in the ISM.

The magnetic field in the MW, seen in polarized emission, where no I is detected!





Uyaniker et al. (1999)
Astron. Astrophys. Suppl. Ser. 138, 31-45
Images from Effelsberg single dish observations at 1.4 GHz. Total intensity map of the small-scale emission (at top) and the polarized intensity map in the direction of the Galactic anticentre.