DYNAMICS AND STRUCTURE OF GALAXIES

GALACTIC ASTRONOMY

2.4 Large Scale Galaxy Structure

OVERVIEW

- Large scale distribution of gas & dust
- Large scale distribution of stars

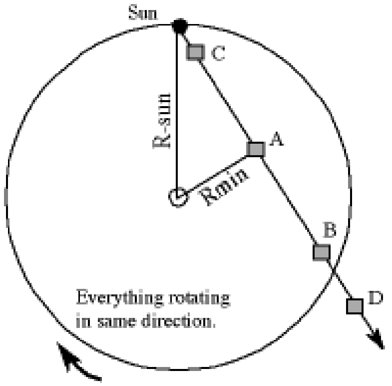
1 – DISTRIBUTION OF GAS - HI

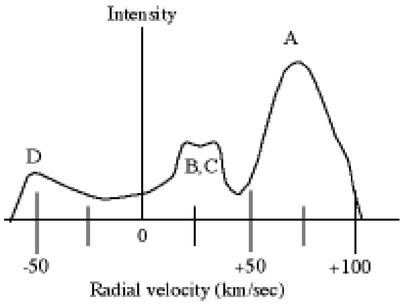
- Most of gas is in the form of atomic (HI) or molecular (H_2)
  (ionized H is only ~1%)

- HI is generally *optically thin*, unabsorbed by dust
  → *Intensity of 21cm line proportional to column density*

$$N(HI) = 1.82 \times 10^{18} \int_{linea} T_{HI} .dv \qquad cm^{-2}$$

- T_{HI} [°K] = line intensity
- dv = line width [km/sec]





NOTE: integrate only the dv corresponding to desired cloud along LOS

H_2 AND CO

- H_2 and other molecules live in cold (~10 K) environments
- Molecular clouds are associated to star formation because gas need to be cold enough in order to collapse

- Unfortunately, H_2 does not produce emission lines at low T

  … but …

  we can use CO radio emission lines (2.6 and 1.3 mm)

- CO molecules are excited by collisions with H_2

  → direct correlation between CO and H_2

  - problem 1: density of H_2 ↔ CO emission

  - problem 2: CO optically *thick* → emission depends on T, ρ

  → calibrated using nearby clouds

DISTRIBUTION OF GAS - H_2

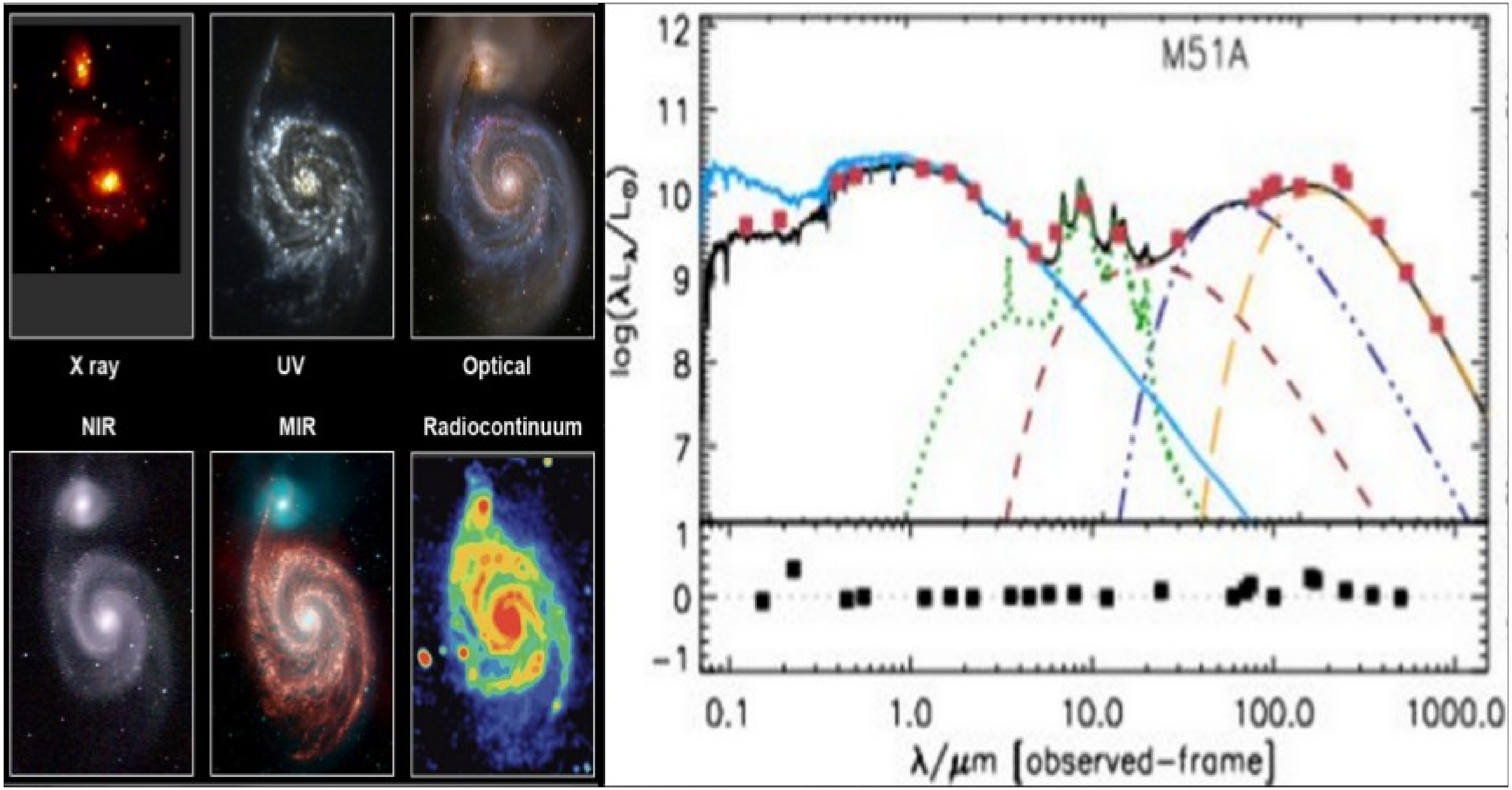
- Calibrated relation:

$$N(H_2) = 1.9 \times 10^{20} \int_{linea} T_{CO}.dv \qquad cm^{-2}$$

- Final remarks:
  - HI is more trustworthy than the H_2 ↔ CO
  - CO can be mapped with smaller-dish telescopes (21cm VS. 2.6 and 1.3mm)

DISTRIBUTION OF DUST

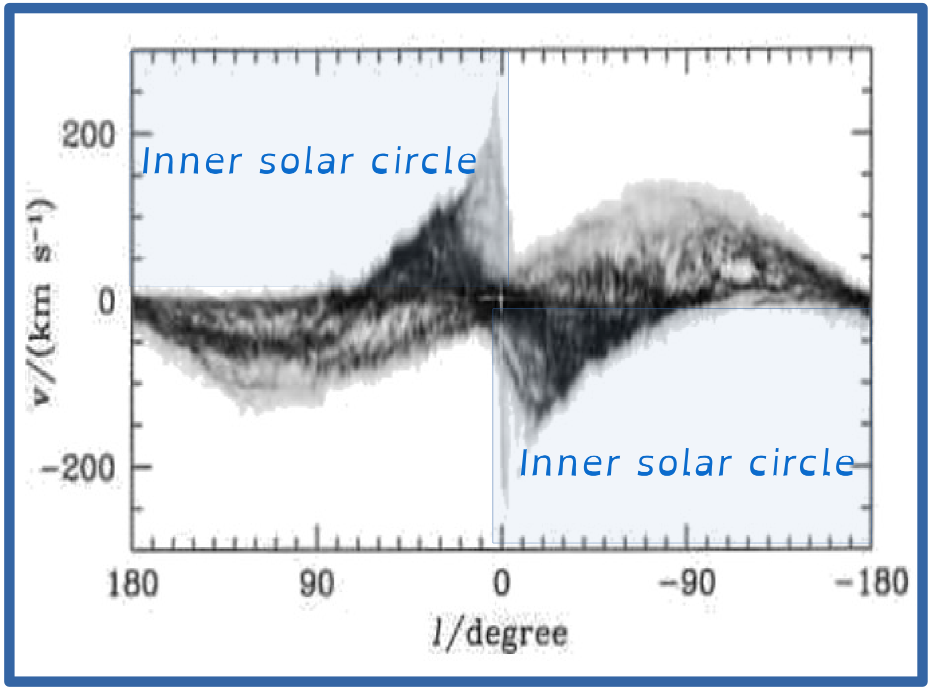
- Dust emission: 10 – 250 μm (dominates for λ > 20 μm)
- Observation of continuum → cannot map accurately

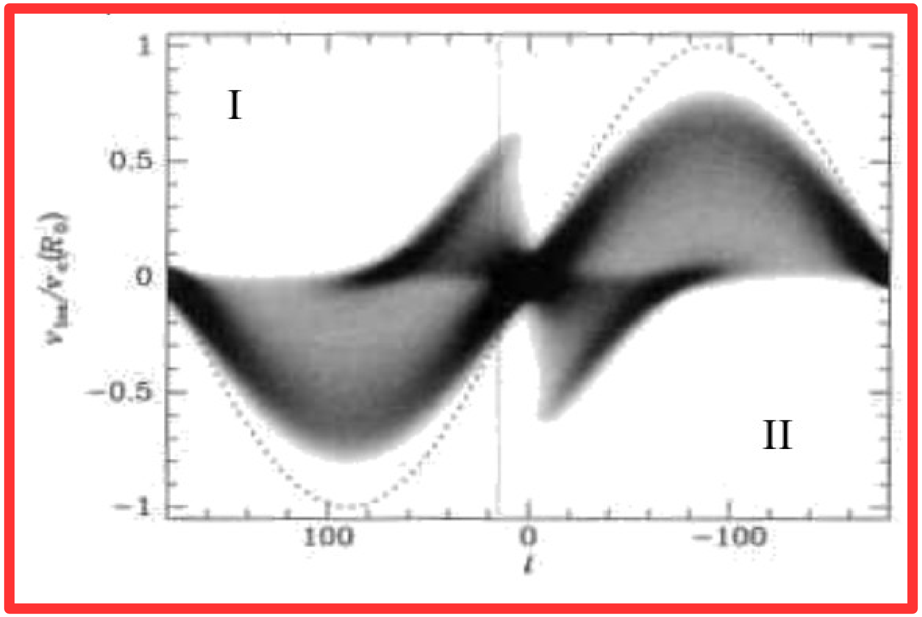


[Lanz et al. (2013)]

RADIAL DISTRIBUTION - HI

- Let's compare the observed position-velocity (v,l) planes for:
  - observed data
  - simulated thin disk with circular orbits

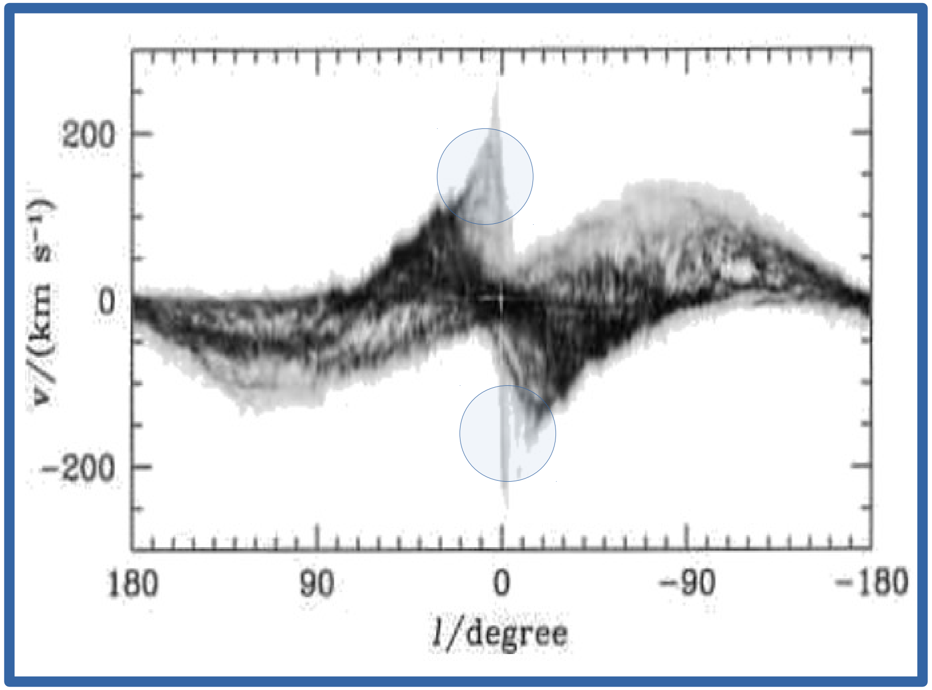


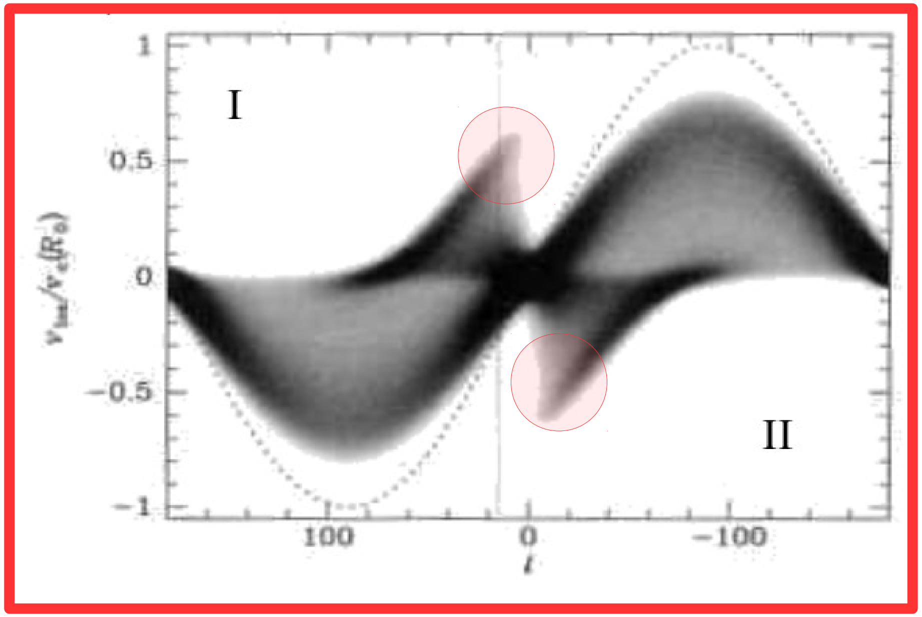


RADIAL DISTRIBUTION -
HI INNER LIMIT

- Starting at | l | ~ 20, lack of inner emission w/r to prediction
- Seen from d ~ 8kpc → | l |~ 20 ↔ 3kpc

  → there's a "hole" of HI gas of radius ~3 kpc



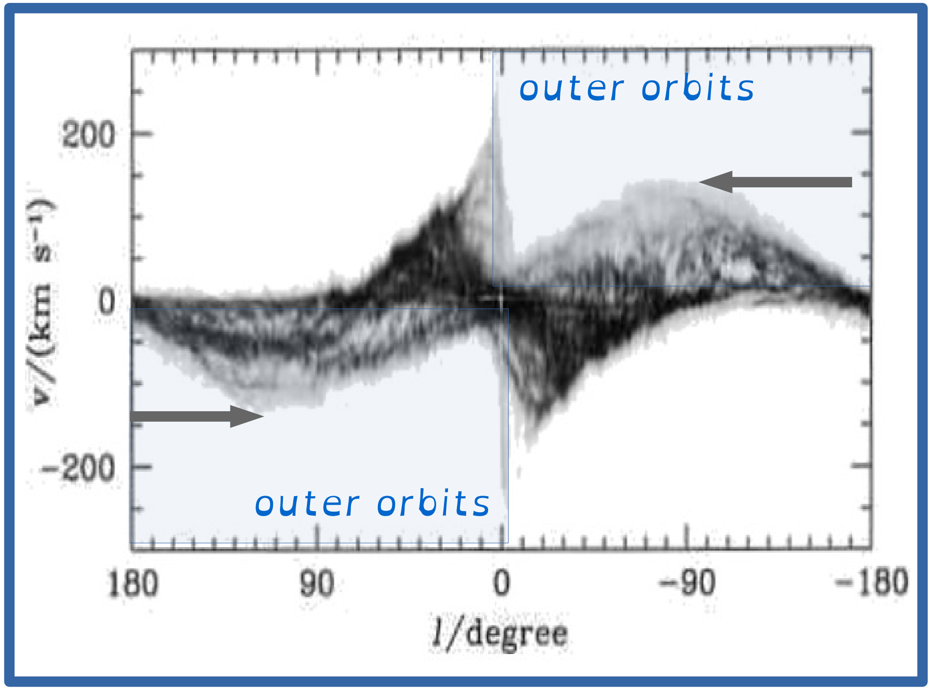


RADIAL DISTRIBUTION -
HI OUTER LIMIT

- Moving to outer orbits: MAX rotation velocity is ~130 km/sec

  NOTE: this happens at | *l* | ~ 90, as expected by:

$$v_{LOS} = (\omega - \omega_0) R_0 \sin l$$



- Assuming the outer velocity curve is CONST ~ Θ_0:

$$v_{LOS} = \left(\frac{\Theta_0}{R} - \frac{\Theta_0}{R_0} \right) R_0 \sin l$$

→ R ~ 21 kpc

(limit of the HI disk)

HI: 3 kpc ↔ 21 kpc

GAS MASS DISTRIBUTION - METHOD

- By measuring $T_{HI}(v,l)$ we can retrieve a cloud's column density:

$$N(HI) = 1.82 \times 10^{18} \int_{linea} T_{HI} .dv \qquad cm^{-2}$$

- From the rotation curve → R at (v,l)

- We can then plot the surface density ($T_{HI}(v,l)$ → N) VS. R

  (we will actually plot the surface brightness instead of N)

RADIAL MASS DISTRIBUTION FUNCTION

- By repeating ad different radii:

  - HI : 3 – 21 kpc

  - H_2 : 4 – 14 kpc (*molecular ring*)

  Total mass obtained integrating:

$$M(r)=\int_0^r \Sigma(r)dS=\int_0^r \Sigma(r).2\pi r.dr$$

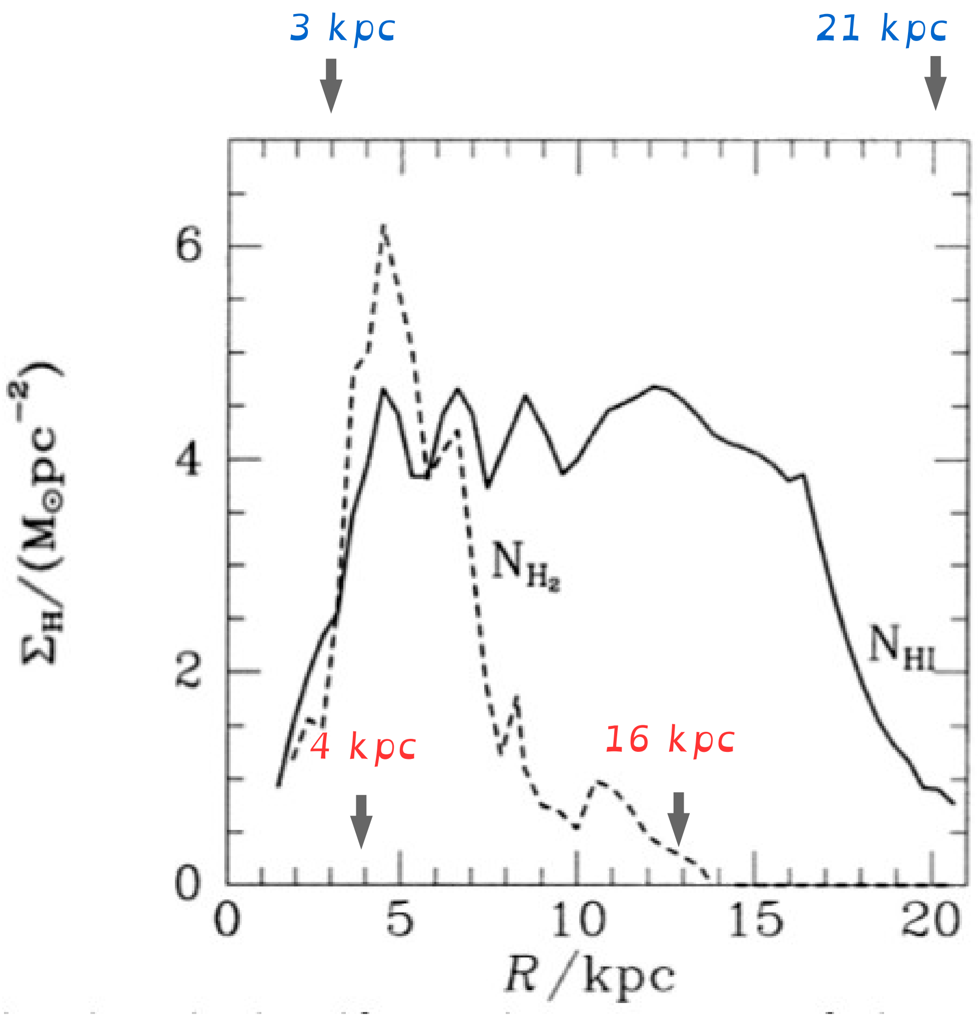
→ HI ~ 4 x 10^9 M_{SUN}

→ H_2 ~ 1 x 10^9 M_{SUN}

NOTE: The integral is performed on circular annulus

→ most of HI (80%) is outside R_0

→ most of H_2 (80%) is inside R_0



VERTICAL GAS DISTRIBUTION

- The rotational velocity of disk at $|z| > 0$ is very similar to $z = 0$

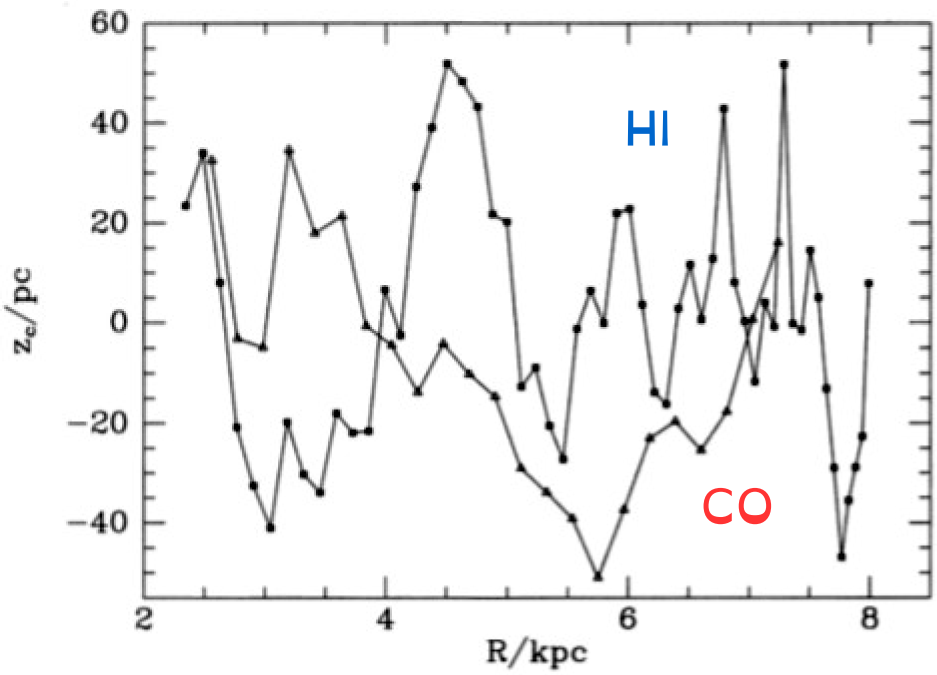
  → it's like a series of concentric cylinders
- We define:

  - z_C =disk height corresponding to MAX emission for given R
  - $z_{1/2}$ =disk height at which the intensity falls to half z_C

- We will consider $R > 3$ kpc (inside the disk is influenced by bar)

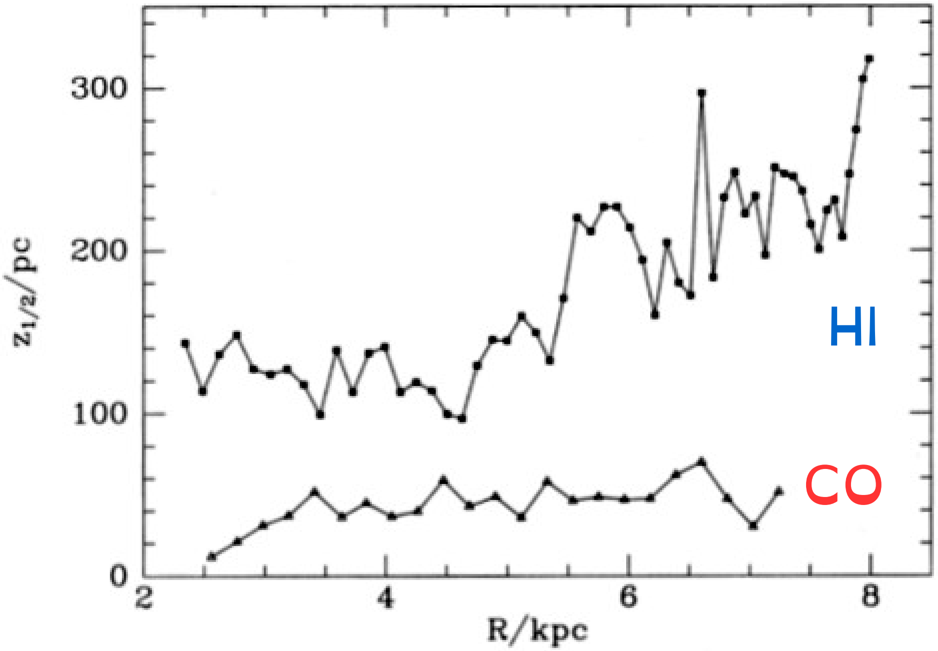
VERTICAL GAS DISTRIBUTION - EMISSION PEAK

- Both HI & CO oscillate around $z_C = 0$ → defines a plane
- Oscillation ~30pc (<1% R_0) → gas disks are *extremely* planar
- Oscillations of HI & CO correlate → dynamical process [unclear]



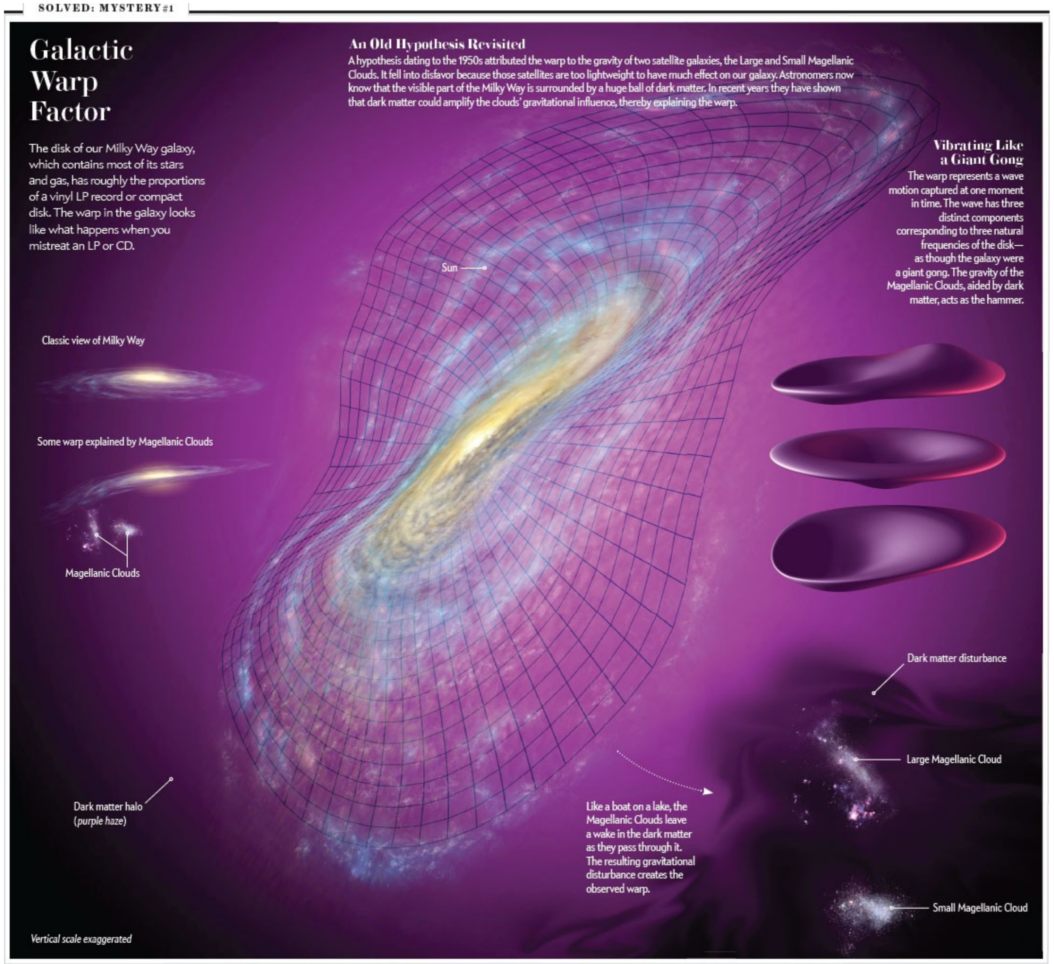
VERTICAL GAS DISTRIBUTION - VERTICAL SCALE LENGTH

- Thickness $z_{1/2}$ increases monotonically
- For $R < R_0$ gas disk is *extremely* thin (HI: ~150 pc / 8 kpc ~ 2%)
- Thickness is due to: vel. dispersion, magnetic fields, cosmic rays



VERTICAL GAS DISTRIBUTION - OUTER DISK

- Outer disk is characterized by a *warp*



SOLVED: MYSTERY #1

Galactic Warp Factor

The disk of our Milky Way galaxy, which contains most of its stars and gas, has roughly the proportions of a vinyl LP record or compact disk. The warp in the galaxy looks like what happens when you mistreat an LP or CD.

An Old Hypothesis Revisited

A hypothesis dating to the 1950s attributed the warp to the gravity of two satellite galaxies, the Large and Small Magellanic Clouds. It fell into disfavor because those satellites are too lightweight to have much effect on our galaxy. Astronomers now know that the visible part of the Milky Way is surrounded by a huge ball of dark matter. In recent years they have shown that dark matter could amplify the clouds' gravitational influence, thereby explaining the warp.

Vibrating Like a Giant Gong

The warp represents a wave motion captured at one moment in time. The wave has three distinct components corresponding to three natural frequencies of the disk—as though the galaxy were a giant gong. The gravity of the Magellanic Clouds, aided by dark matter, acts as the hammer.

Like a boat on a lake, the Magellanic Clouds leave a wake in the dark matter as they pass through it. The resulting gravitational disturbance creates the observed warp.

Vertical scale exaggerated

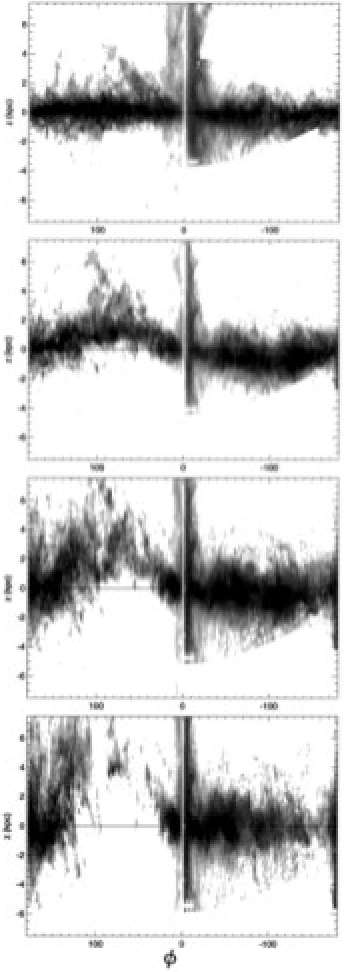
WARP – OBSERVATIONAL EVIDENCE

- We can separate the concentric "cylinders" along galactic R:

- Observationally, from the galactic center:
  - Increasing sinusoidal amplitude
  - Functional approximation:

    (sinusoidal expansion)

$$z_c = \frac{(R/\mathrm{kpc}) - 11}{6} \sin\phi + 0{,}3\left(\frac{(R/\mathrm{kpc}) - 11}{6}\right)^2 (1 - \cos 2\phi)$$



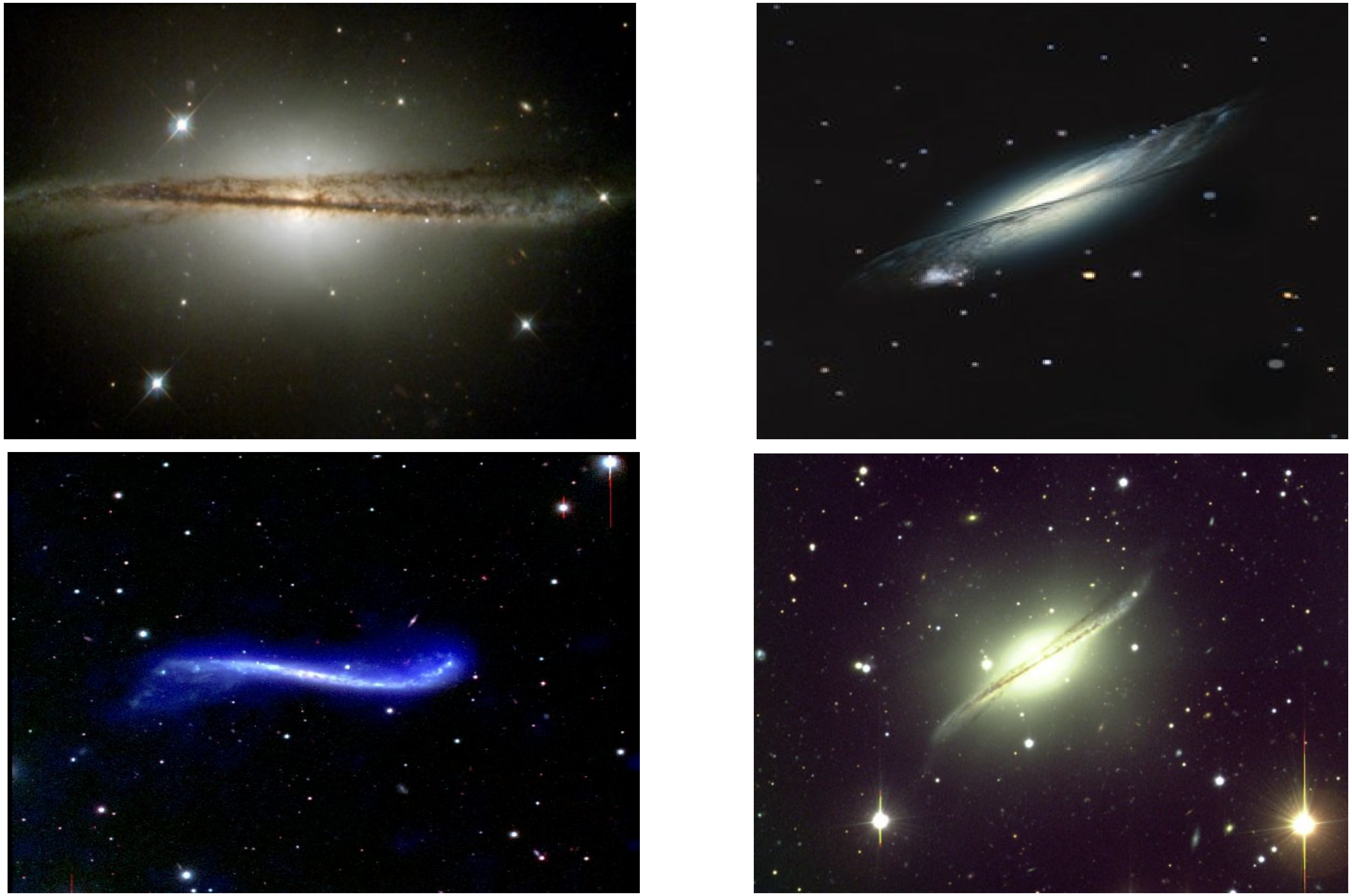
12 kpc

24 kpc

Increasing galactocentric distance of cylinder

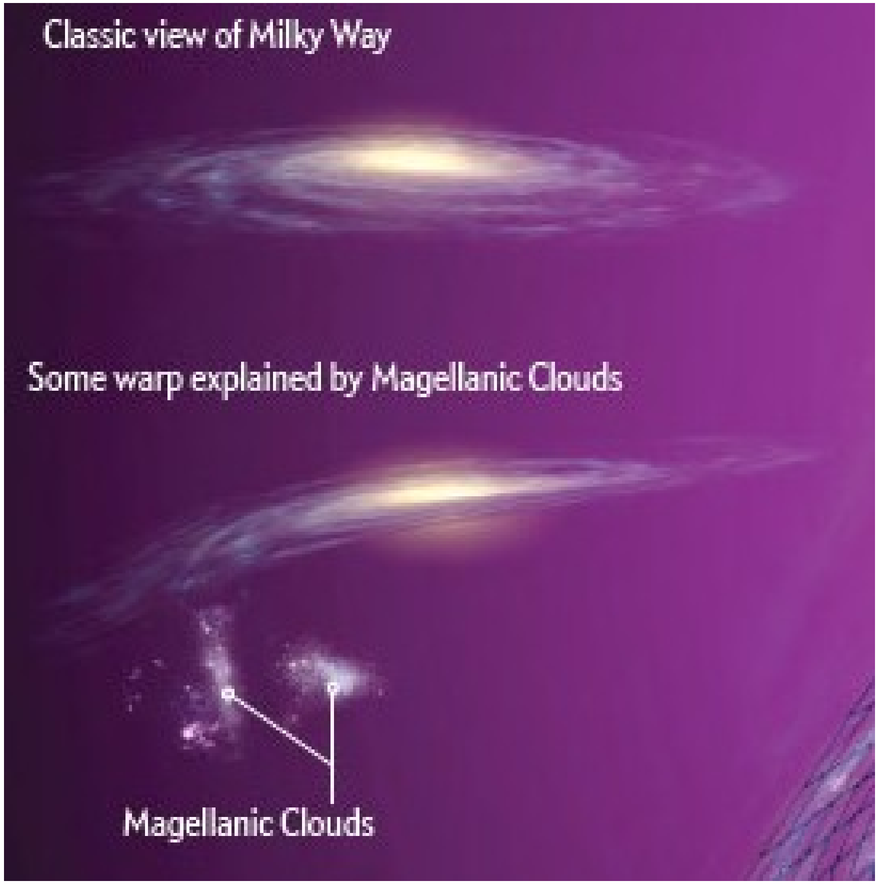
WARPED DISK GALAXIES

- Warped disks are common in disk galaxies



WARP - ORIGIN

- Favored hypothesis is tidal perturbation by nearby dwarf galaxy



→ LMC + SMC *[Levine 2006]*

→ Sgr dSph *[Bailin 2004]*

NOTE: LMC: ~10^{10} M_{SUN}

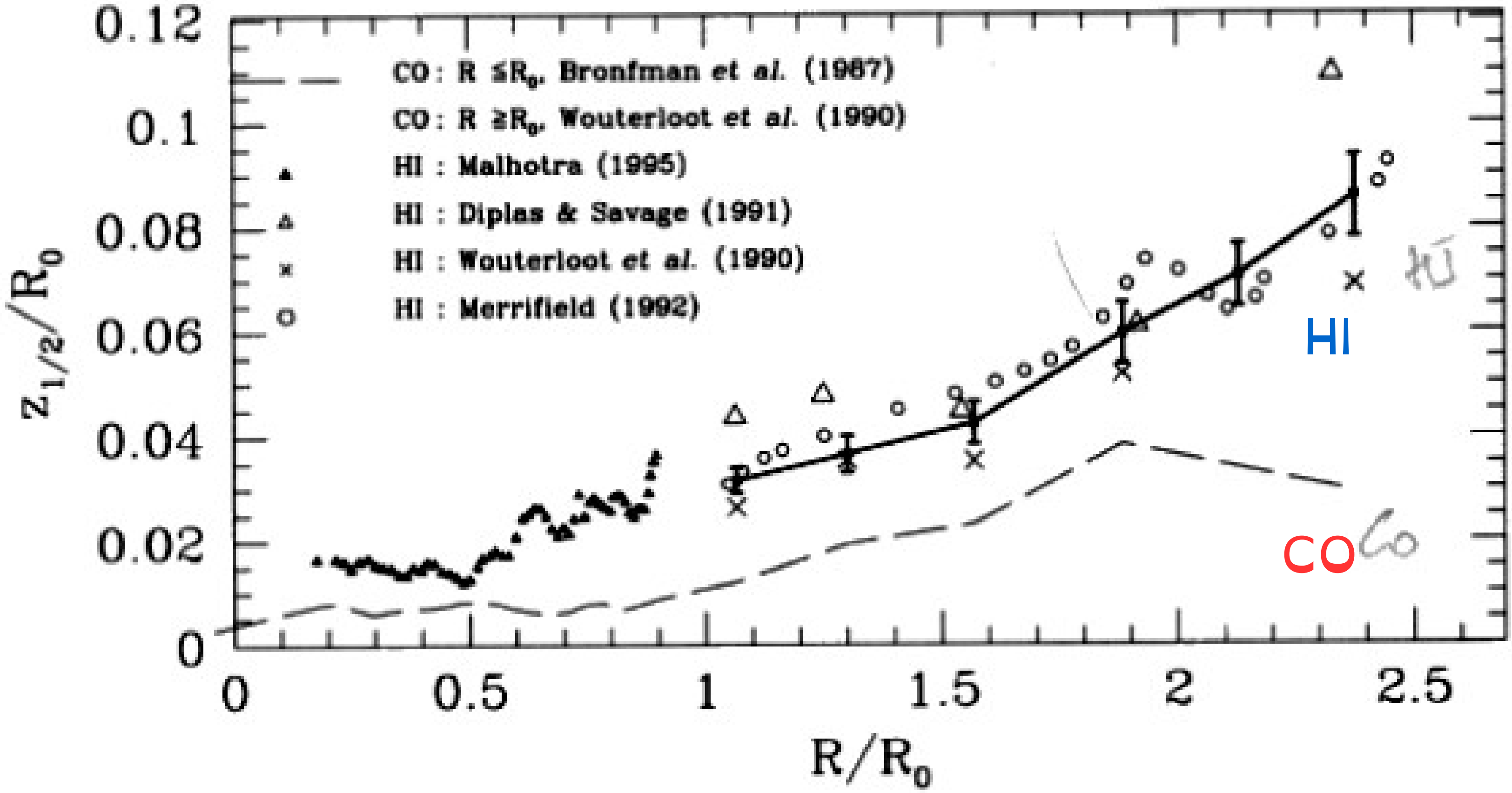
HI: ~10^9 M_sun

... but there's dark matter

- LMC may excite a wave in the Galactic dark matter halo
- Same effect for inner oscillations?

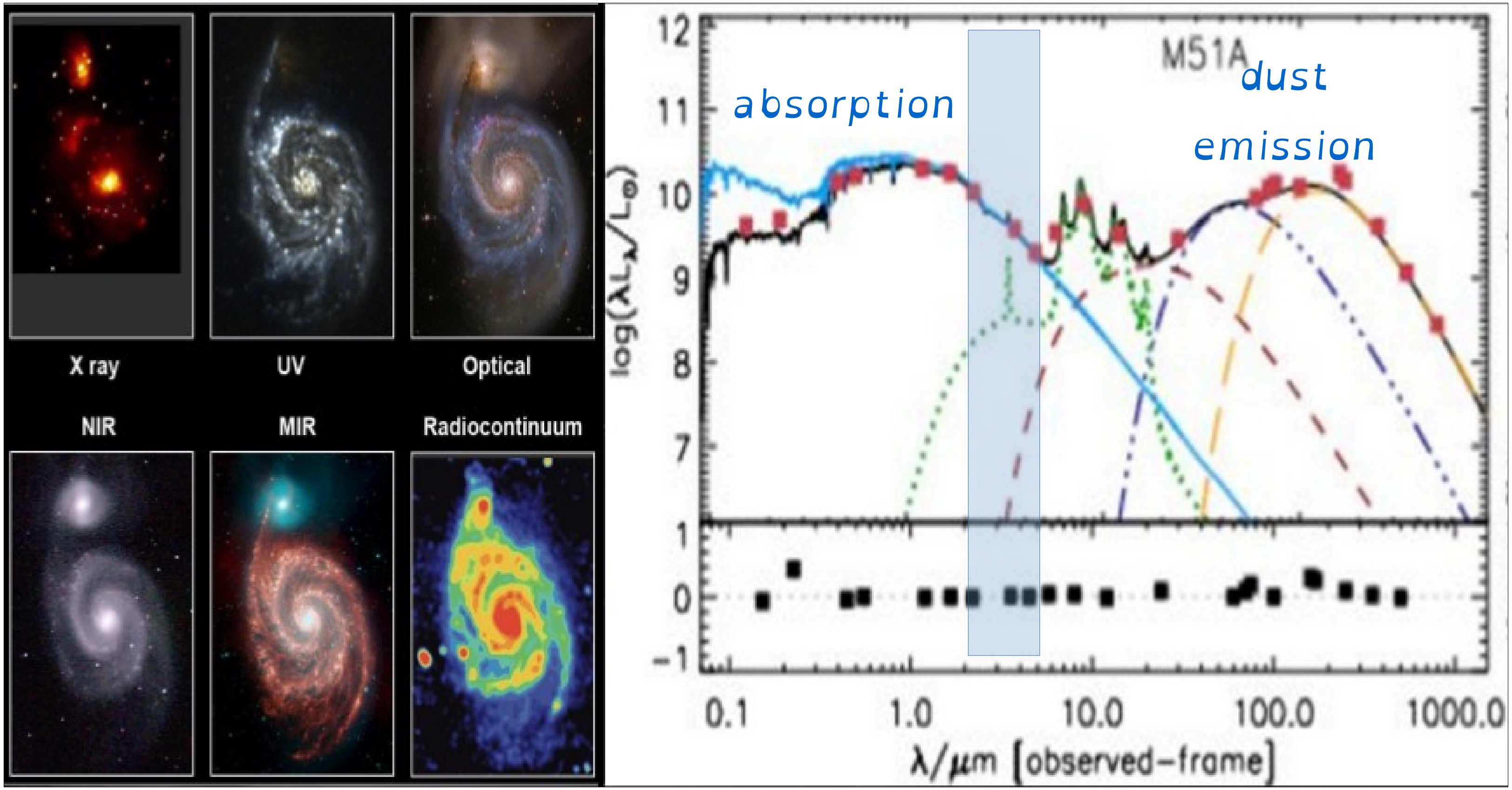
OUTERMOST DISK

- At its outskirts, the disk keeps getting thicker (*flaring*)
  → gravitational pull is weaker there, internal “pressure” prevails



2 – LARGE SCALE DISTRIBUTION OF STARS

- Stellar emission is heavily absorbed by dust
- The ideal “window” to study stars is 2-5 µm



[Lanz et al. (2013)]

GROUND-BASED OBSERVATIONS OF STARS

- Dust absorption is significant in Milky Way because along L.O.S.
- Additional issue: atmosphere

  $T_{PEAK} \sim 300$ K → 10μm

  (but the emission tail contaminates 2-5 μm)

- Noteworthy ground-base all-sky survey: 2MASS (K-band ~ 2-5 μm)
- Removing sky in near-IR requires specific observation strategy:

  (sky varies on time scales << 1 min)

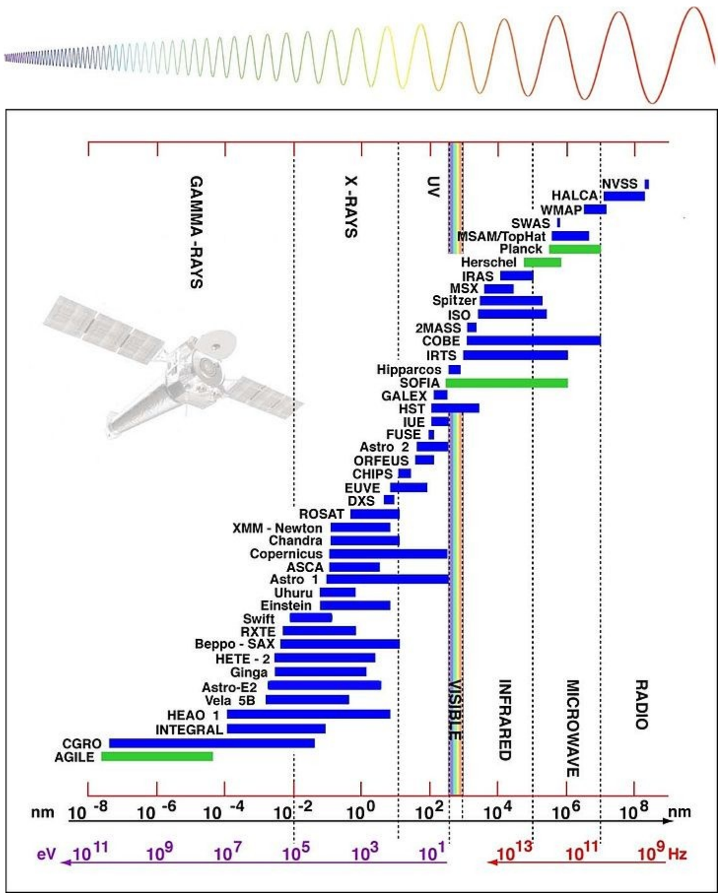
  → sequence of on-off exposures (1 on target, 1 on nearby sky, etc.)

SPACE-BASED OBSERVATIONS OF STARS

- Even better: space telescopes!

- Noteworthy space observatories:
  - COBE (NASA: 1989 - 1993)
  - Herschel (ESA: 2009 - 2013)
  - Spitzer (NASA: 2003 – 2009, cold mission)
    (NASA: 2009 – now , warm mission)

  NOTE: IR instruments must be kept cool to minimize noise → life depend on duration of cooling material

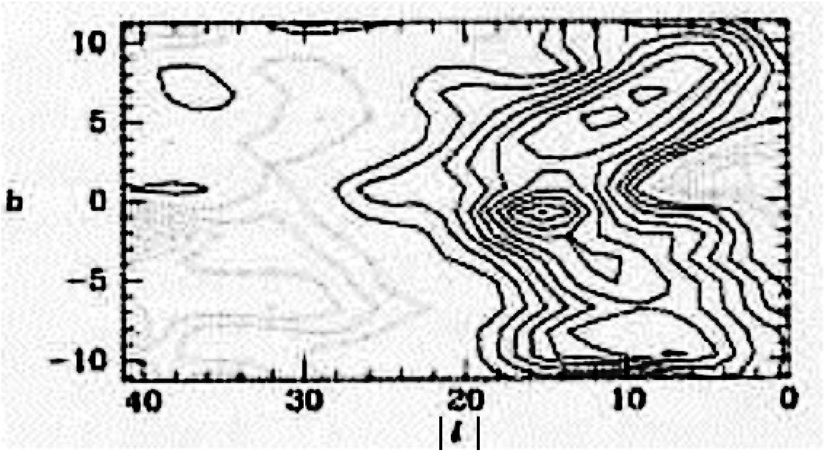


- 90% of observed stars are red clump giants (horizontal branch)

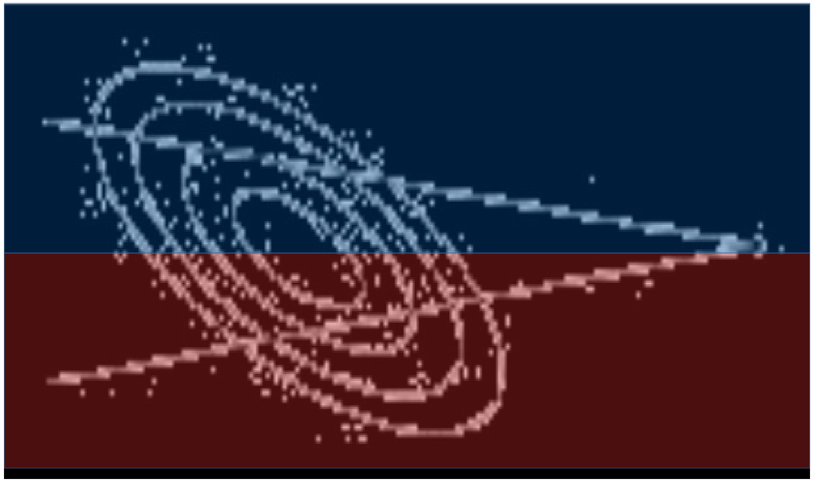
  luminosity ~ CONST ~ 100 L_{SUN} → ideal to measure distances

CENTRAL BAR

- The bulge has the shape of an elongated ellipsoid (bar)



← Ratio between quadrant I and IV

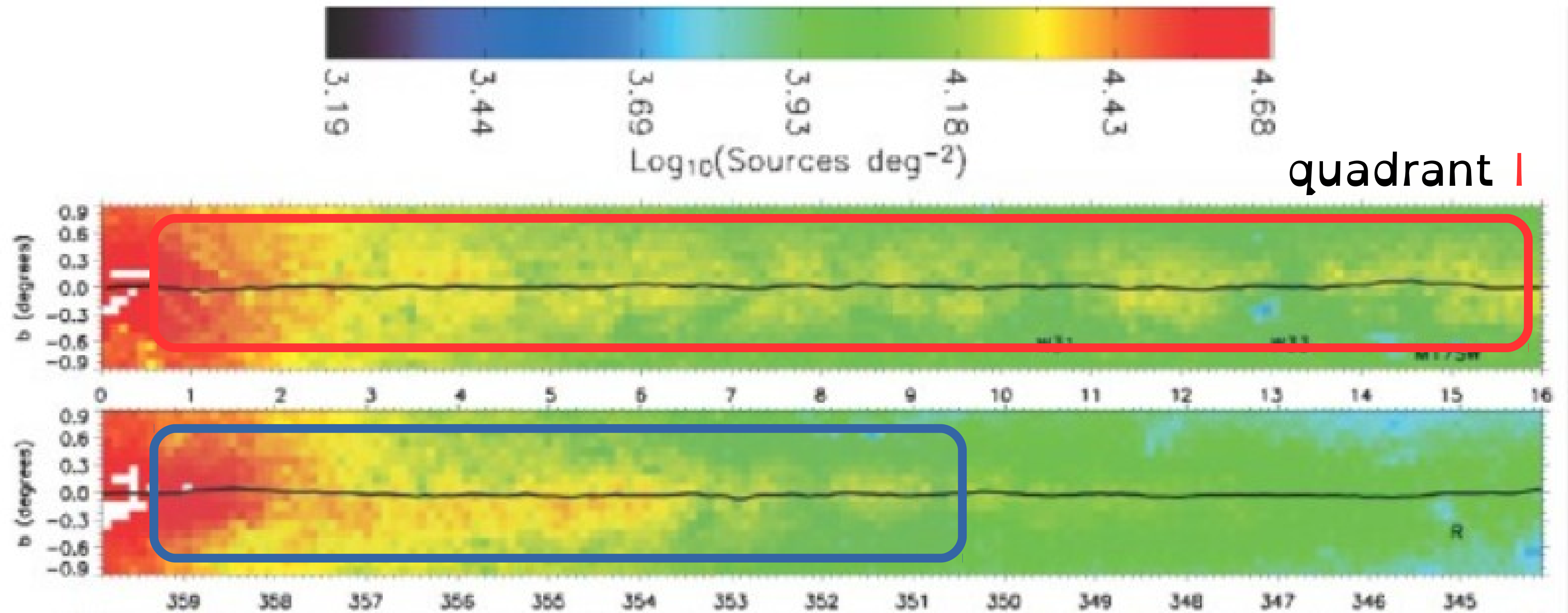


CENTRAL BAR – STELLAR COUNTS

- From stellar counts → density map of #stars/deg^2

  (Spitzer 4.5 μm)

  → emission is more extended in one quadrant → bar



quadrant I

quadrant IV

CENTRAL BAR – STELLAR COUNTS

- Alternative view: apparent magnitude function at different *l*
- Indications for bar:

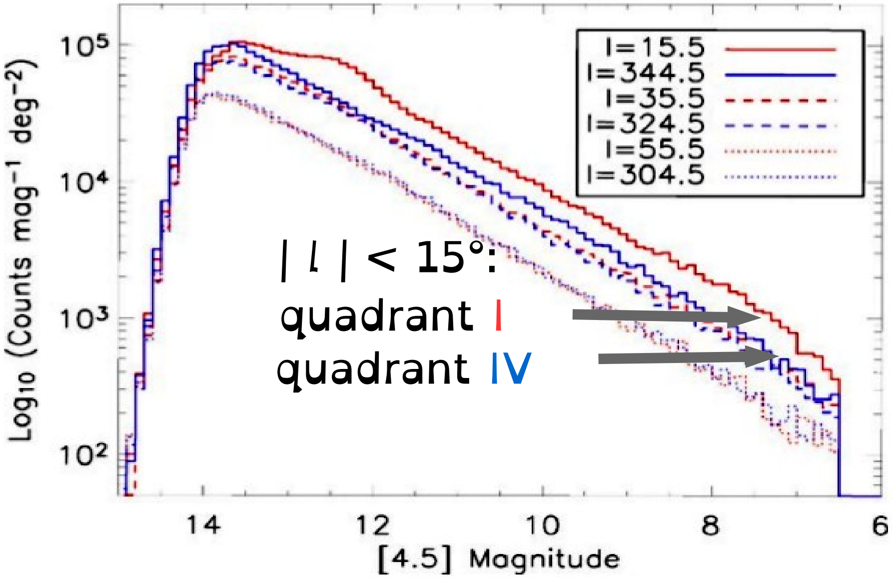
  - | *l* | < 15°: asymmetric stellar counts (+ bump)

  - | *l* | > 15°: symmetric stellar counts

  → quadrant I has brighter magnitude stars → most of stars are closer

NOTE: Difference is <u>not</u> due to the fact that we miss far away stars

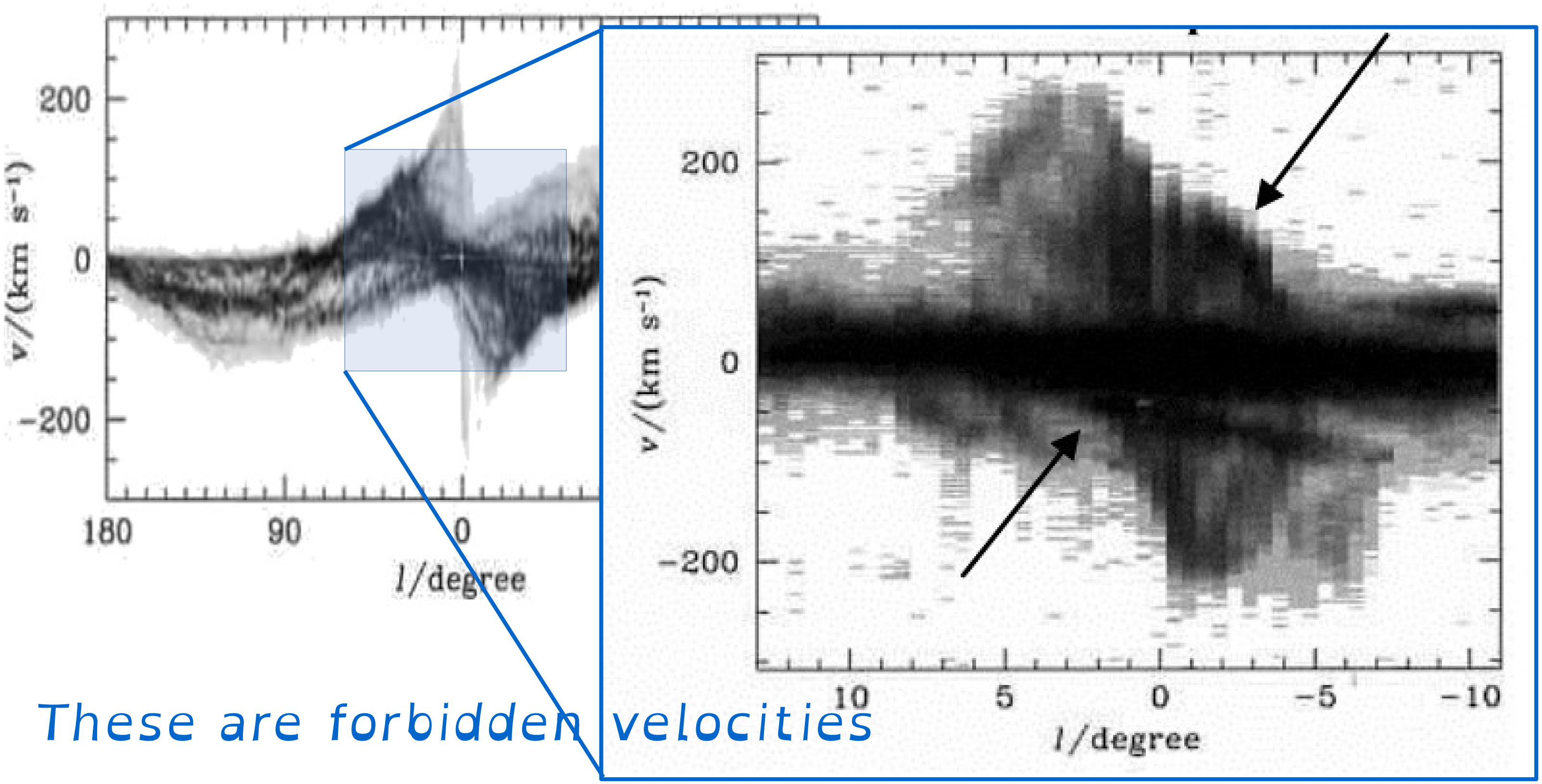
In fact we know the luminosity of red clump giants → we can calculate: completeness limit ~14 mag



| *l* | < 15°:
quadrant I
quadrant IV

CENTRAL BAR – COMPARISON WITH HI

- Spitzer: $R_{BAR} \sim 4.4$ kpc, inclination ~ 44° (w/r to $l = 0$)
- How does it compare to HI ?

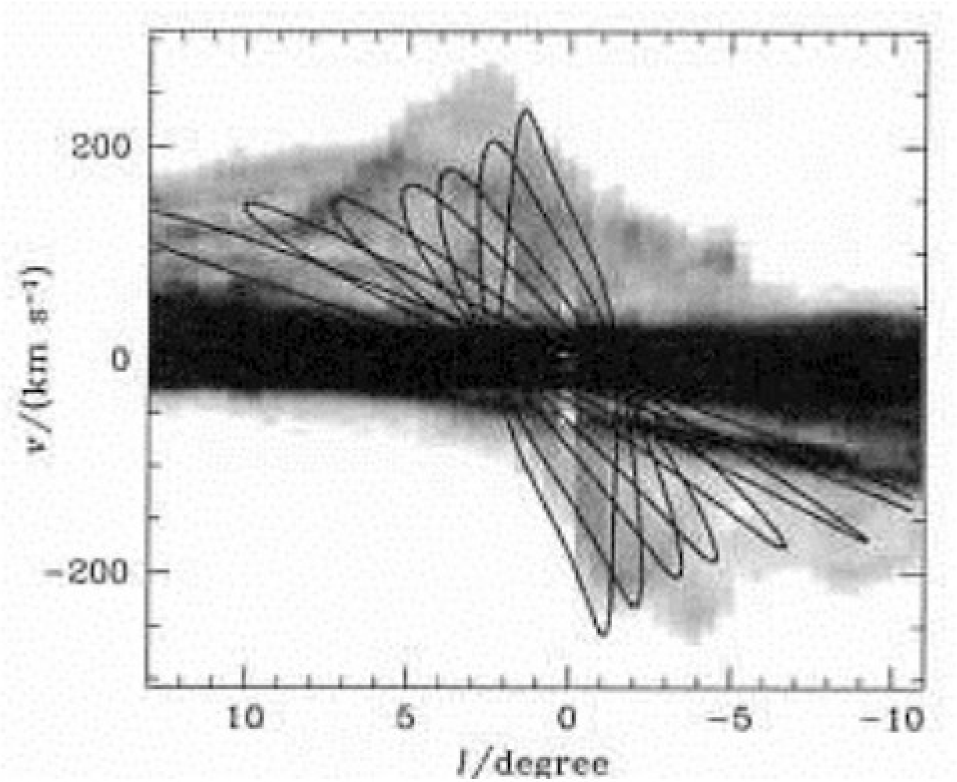


These are forbidden velocities

(should not be in this quadrant in case of circular orbits)

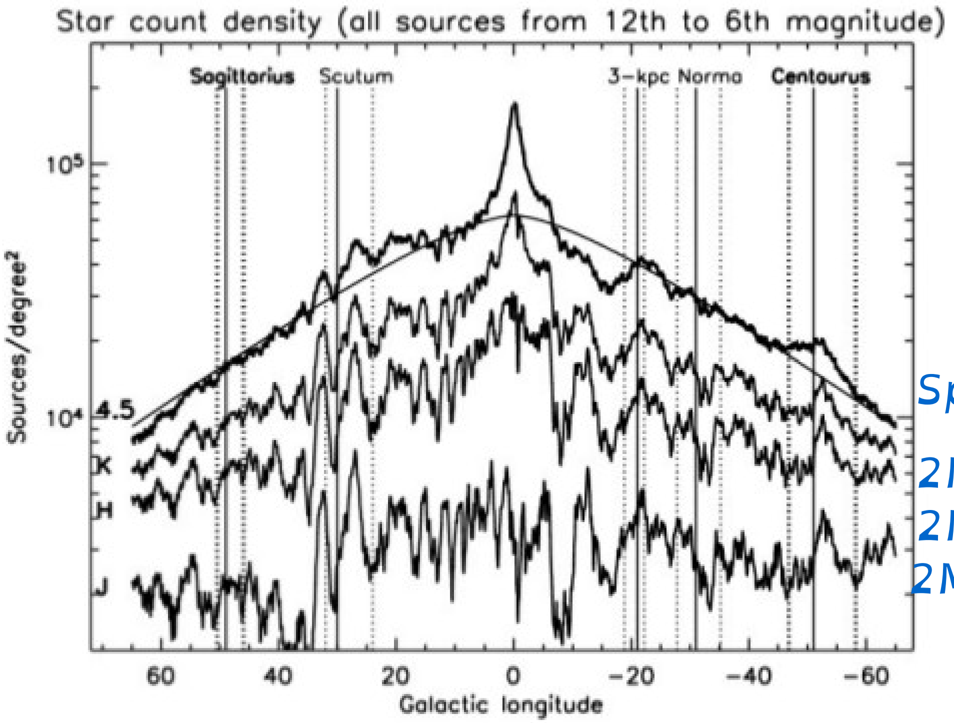
CENTRAL BAR – COMPARISON WITH HI

- Forbidden vel. → non-circular orbits / non-axisymmetric potential
- Consistent with orbits in a triaxial potential (bar):



RADIAL STRUCTURE

- Radial stellar count:



Spitzer 4.5 μm

2MASS K

2MASS H

2MASS J

- Fit compatible with an exponential profile:

$$I_d \;\alpha\; \exp\left(-\frac{r}{3.9kpc}\right)$$

RADIAL STRUCTURE – SPIRAL ARMS

- The spiral arms are visible in the star counts as well

  NOTE: Sun lies on a "short" arm, probably a "spur" of an other arm