Dark Matter
and the
Galactic Rotation Curve
a.k.a
The Radio Telescope Lab

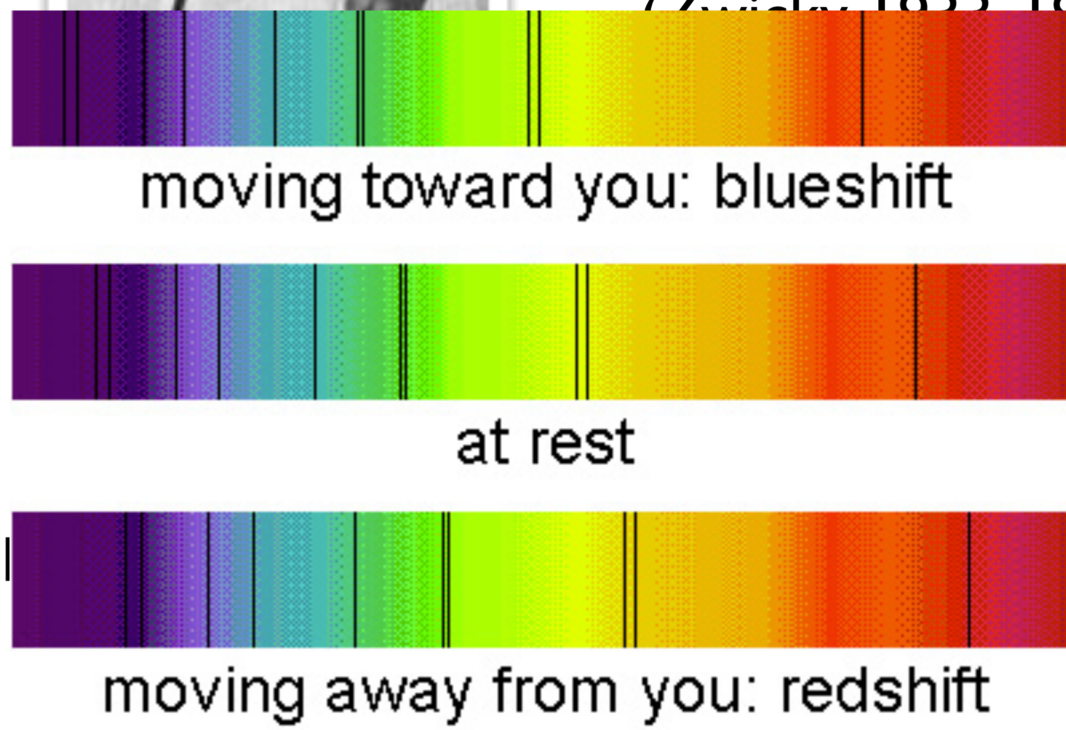
JHU Advanced Lab

Andromeda (M31)

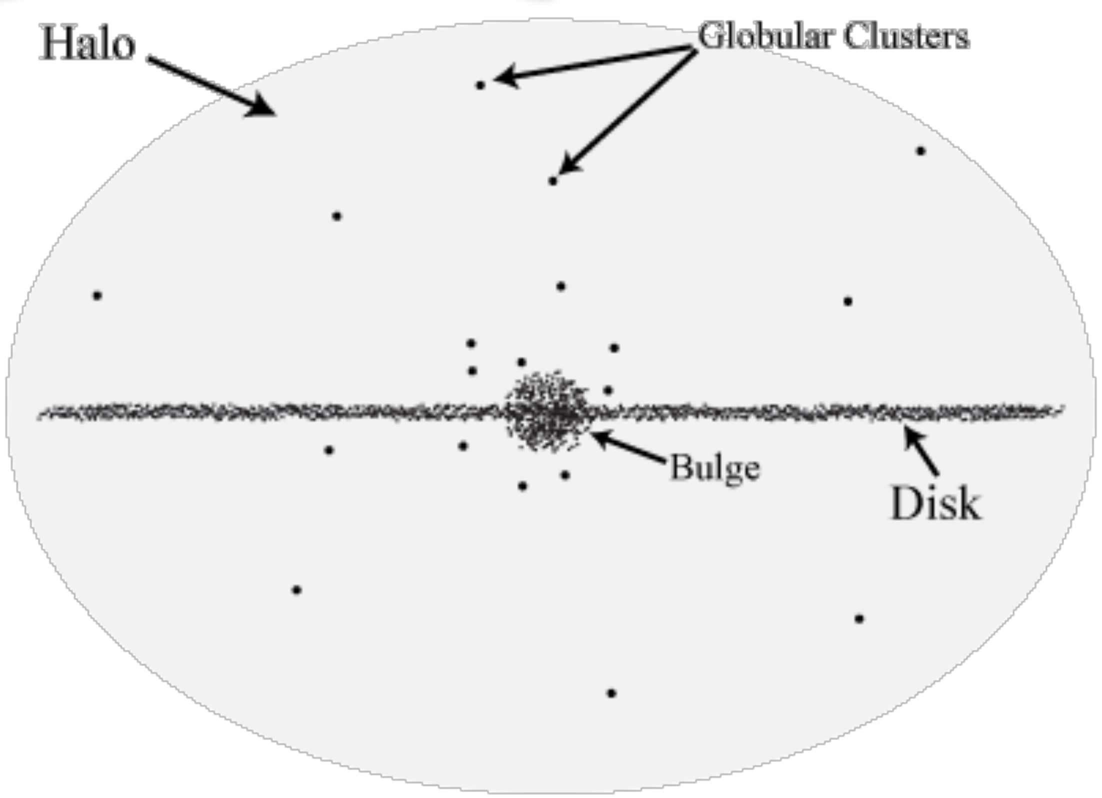
Science progresses best when observations force us to alter our preconceptions. -V. Rubin

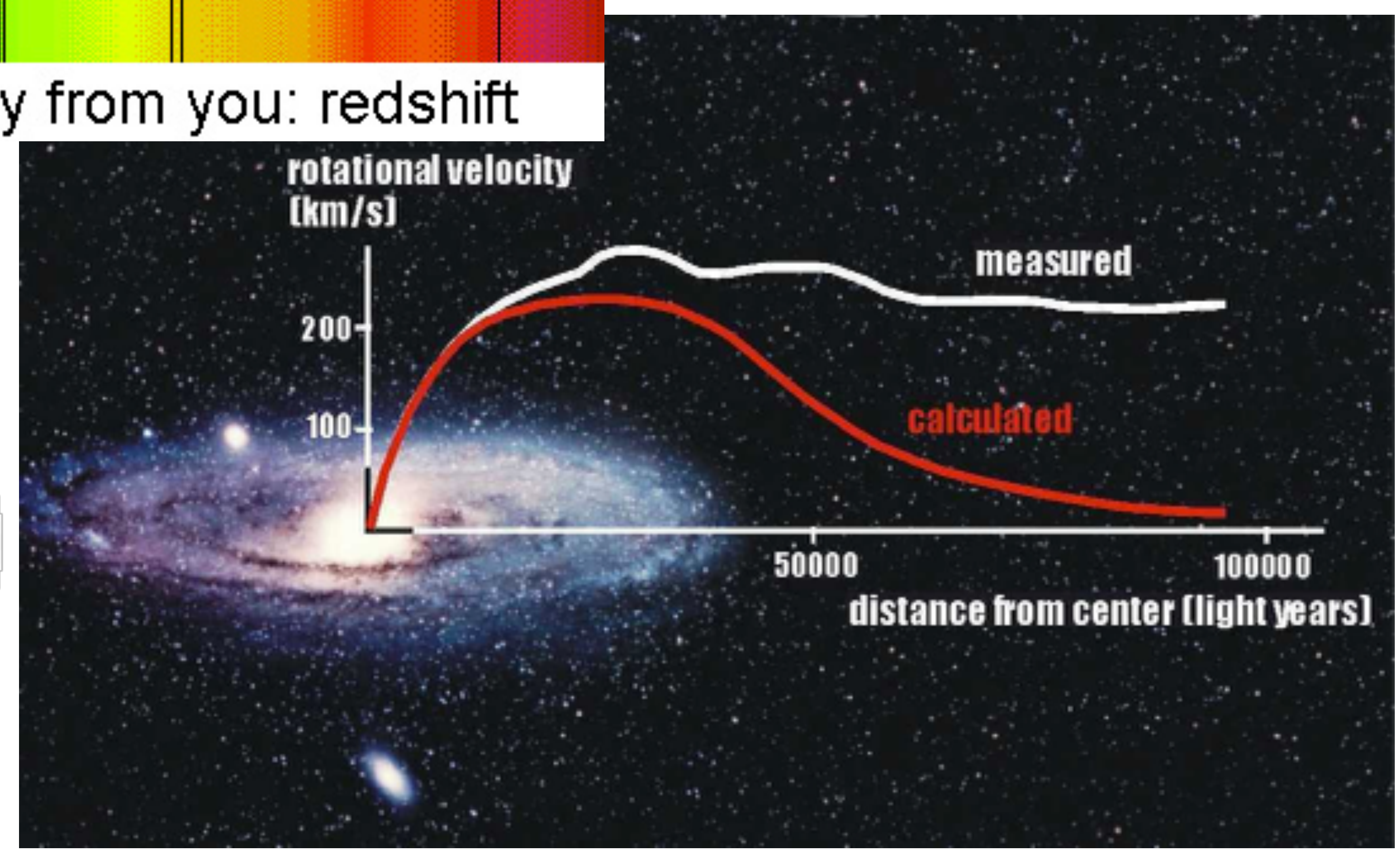
Discovering Dark Matter with Orbits

Fritz Zwicky found that velocities of galaxies in the Coma galaxy cluster imply more gravitating mass than seen in luminous matter. (Zwicky 1933-1937)



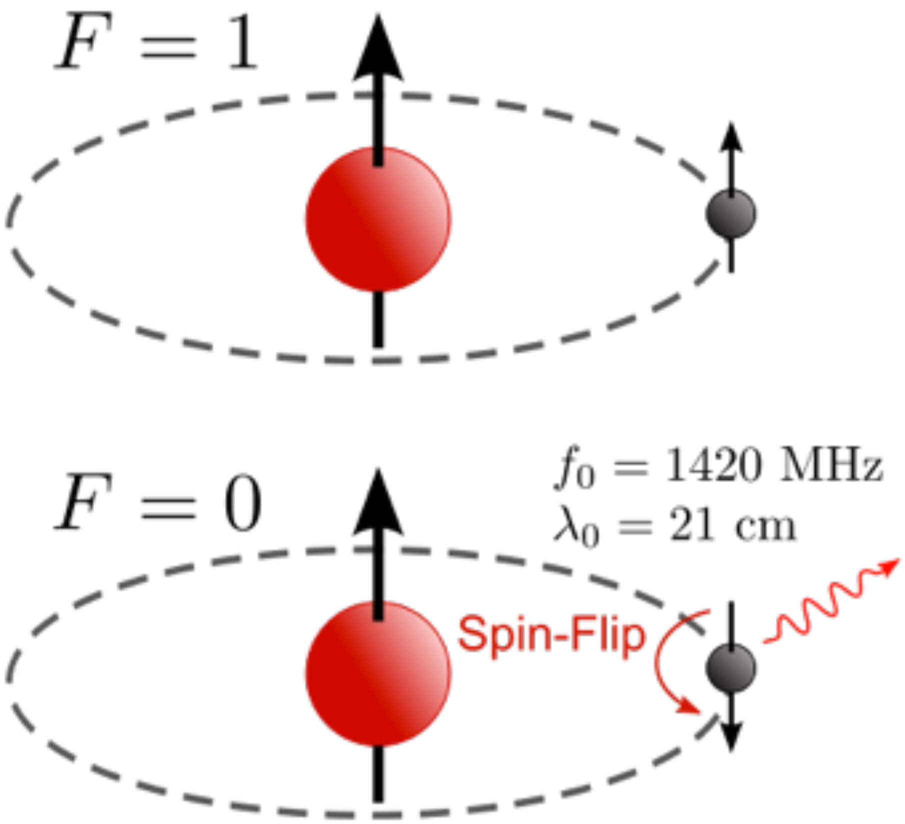
t of optical spectral lines,
orbital velocities of hot HII
galaxies (Andromeda etc).
concentrated in a central
distance in the predicted
non-luminous "dark" matter.





http://www.universetoday.com/91520/astronomy-without-a-telescope-could-dark-matter-not-matter/
Credit Queens University

Radio-wave Measurements of Rotation Curves



Spin-flip transition in neutral hydrogen produces 21-cm wavelength radiation.*

Due to long wavelength, these radio waves pass through dust in the interstellar medium of galaxies unlike visible.

Measure velocities of hydrogen clouds through doppler shift of 21-cm line.

* ("Forbidden" transition with 10 Myr lifetime, but there are many atoms in low density environments in space.)

"Old" Greenbank 300 ft Telescope; West Virginia

Westerbork Synthesis Radio Telescope; Netherlands

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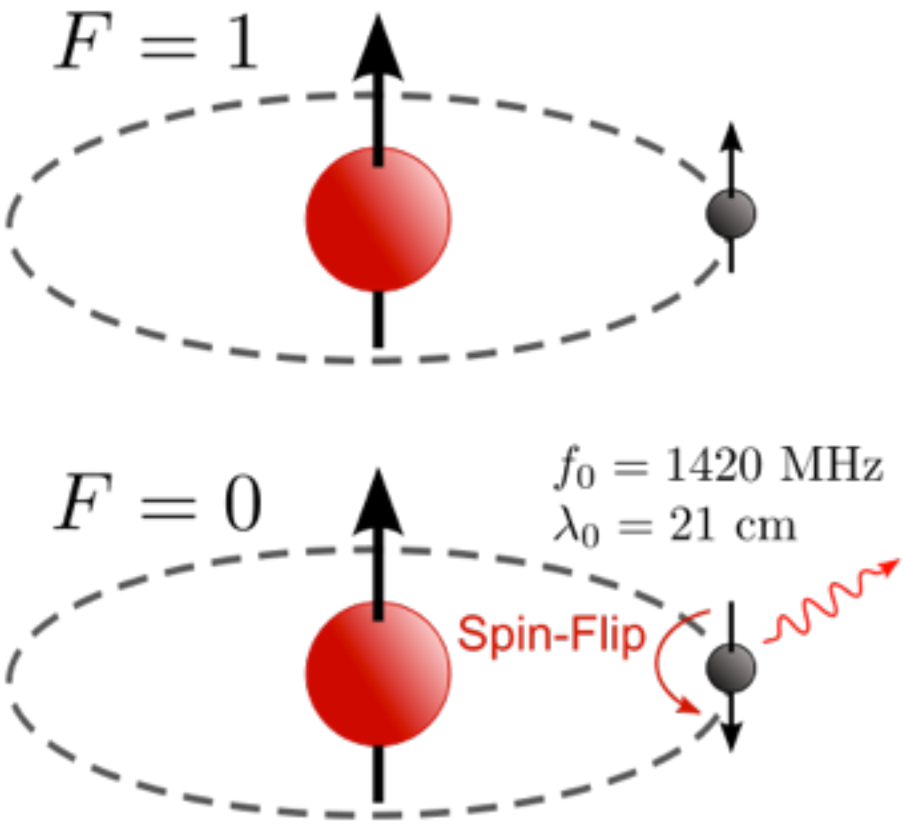

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1988 Collapse

Westerbork Synthesis Radio Telescope; Netherlands

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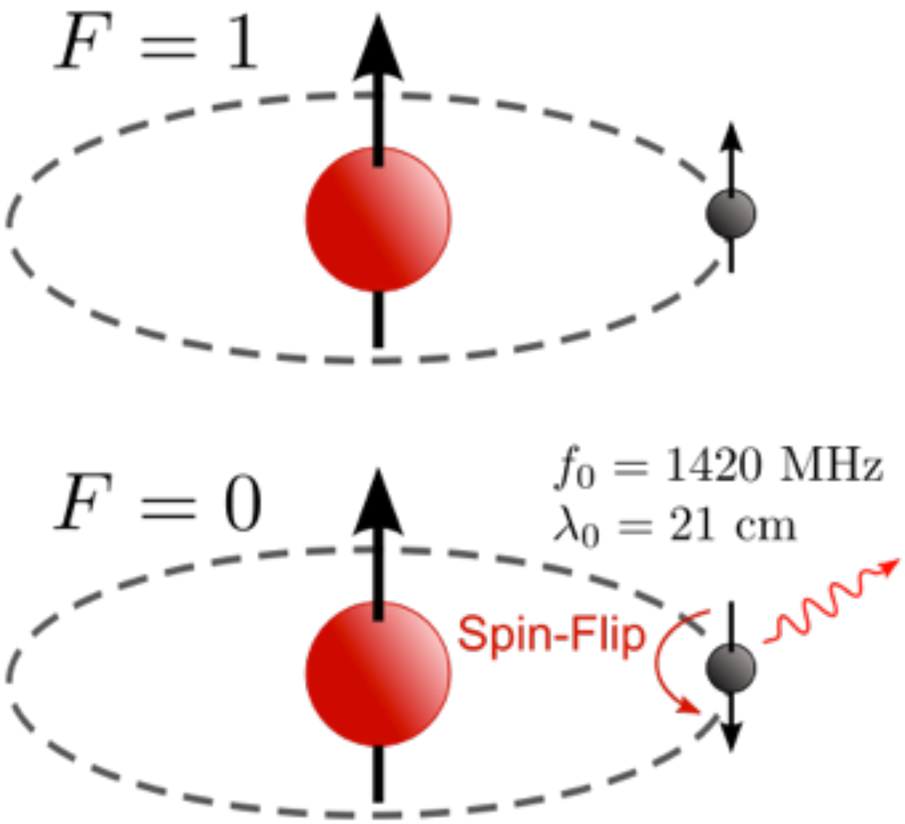

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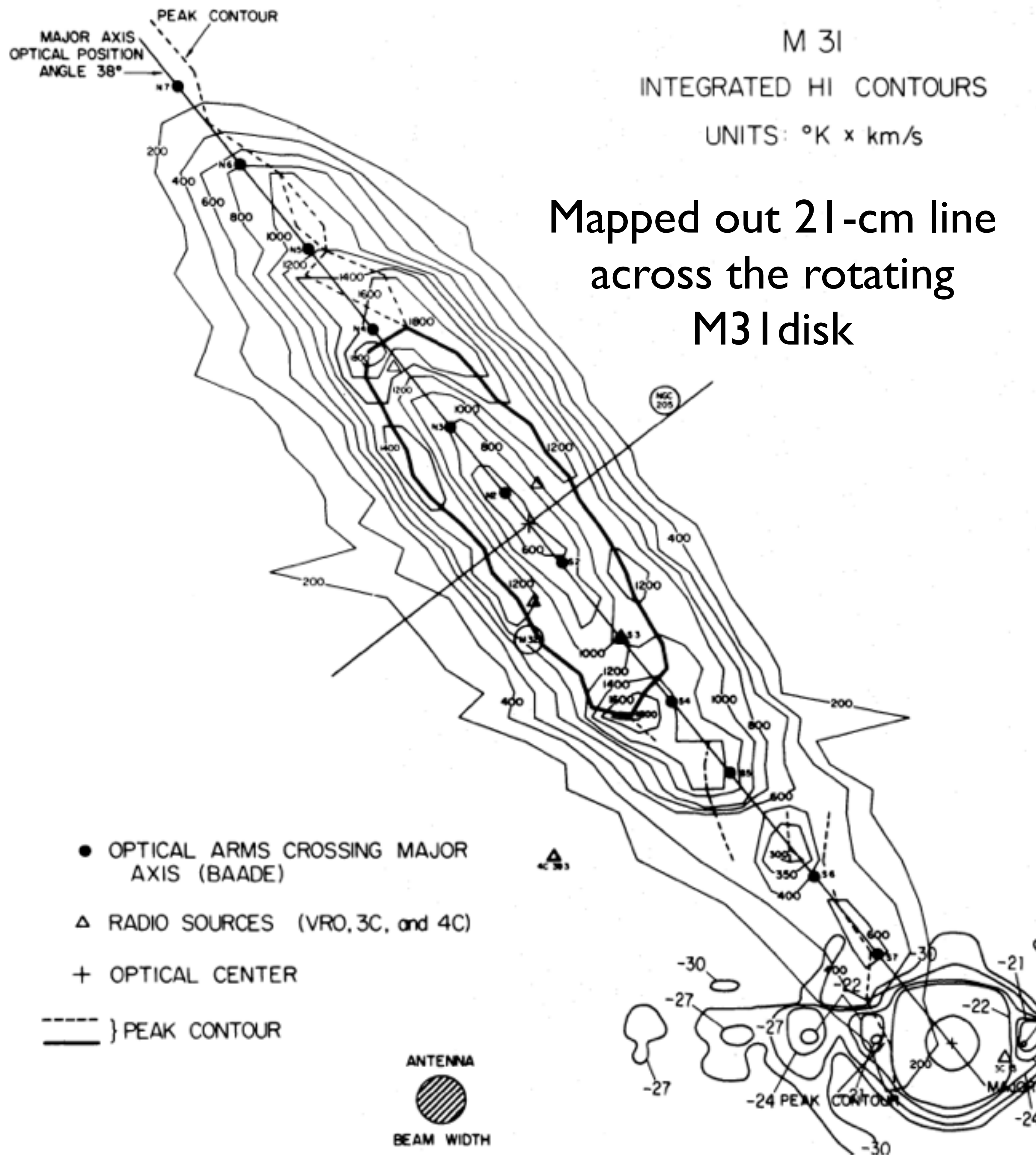
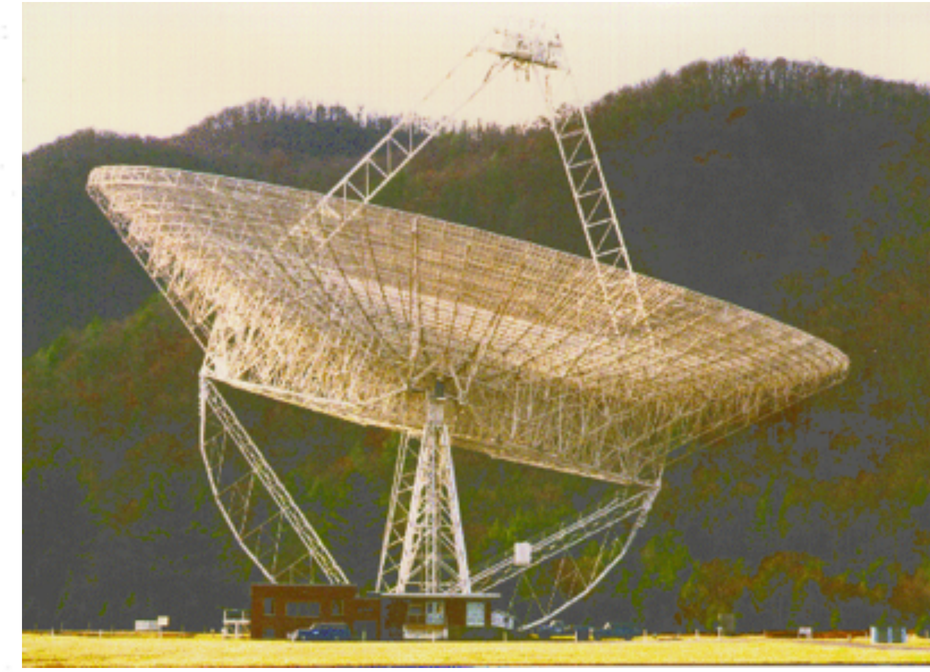
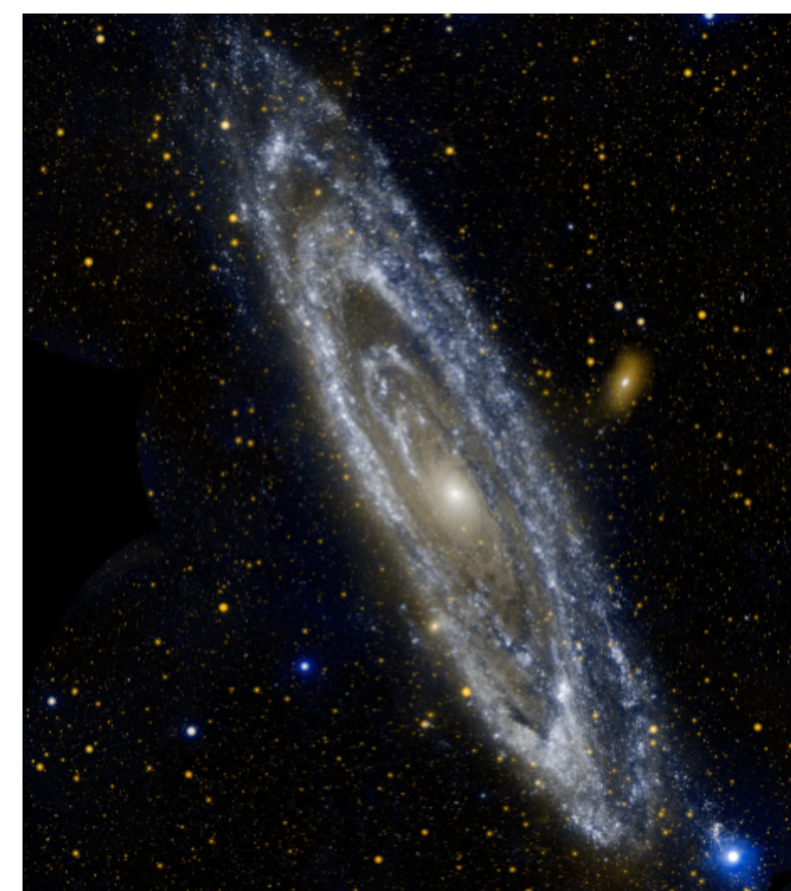


Mapped out 21-cm line across the rotating M31disk



21-cm Study of Andromeda

(Roberts & Whitehurst 1975)



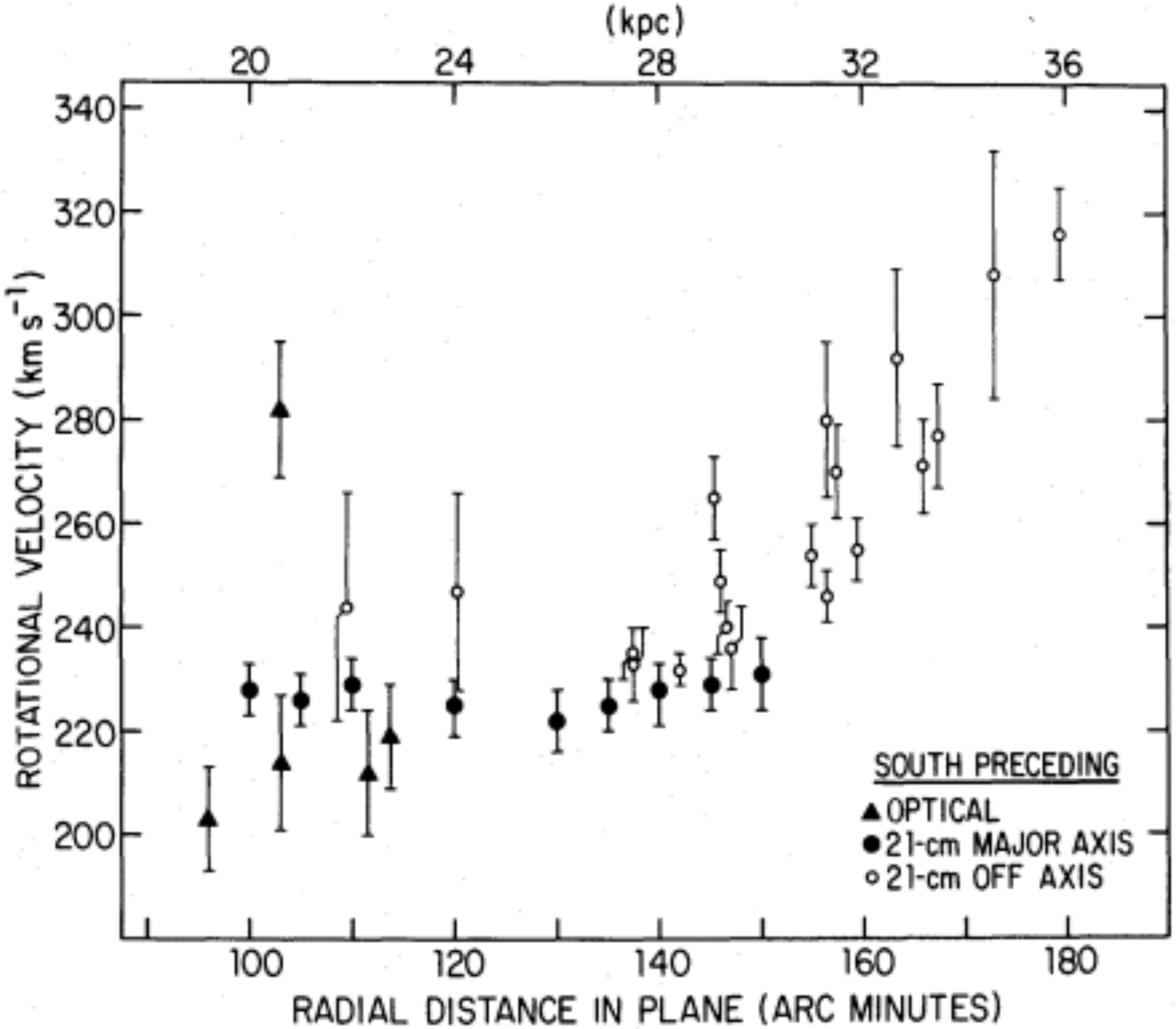
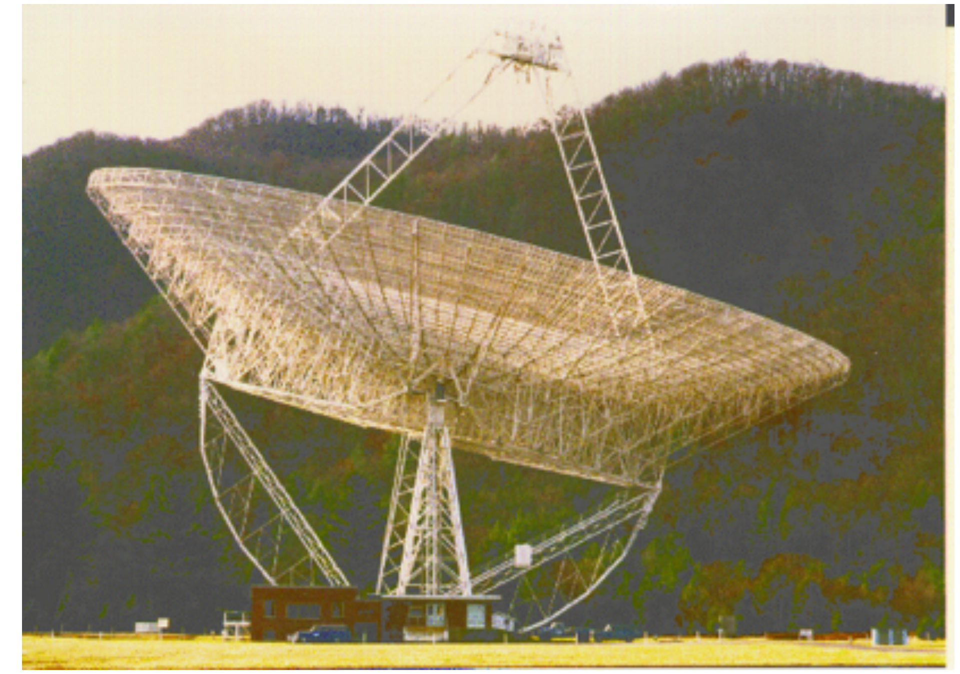


FIG. 10.—Rotational velocities derived from optical observations (Rubin and Ford 1970), 21-cm major axis positions, and 21-cm off-axis positions. The increase in rotational velocity at large radii as well as the differences between axis and off-axis velocities at similar radii are artificial and are attributed to a nonplanar H I distribution.

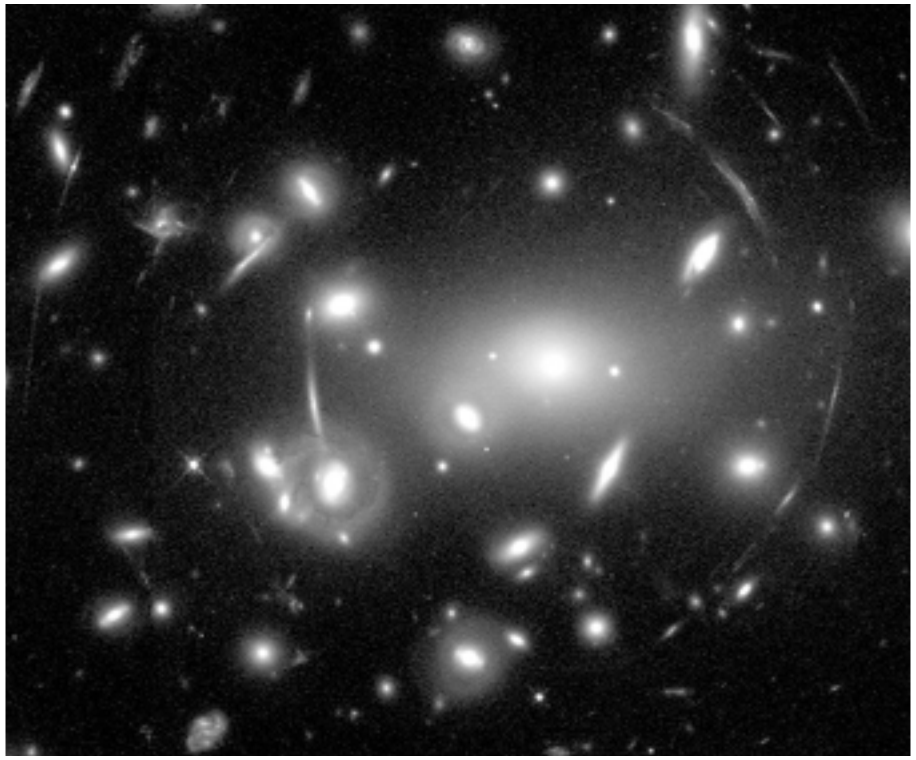


21-cm Study of Andromeda

(Roberts & Whitehurst 1975)

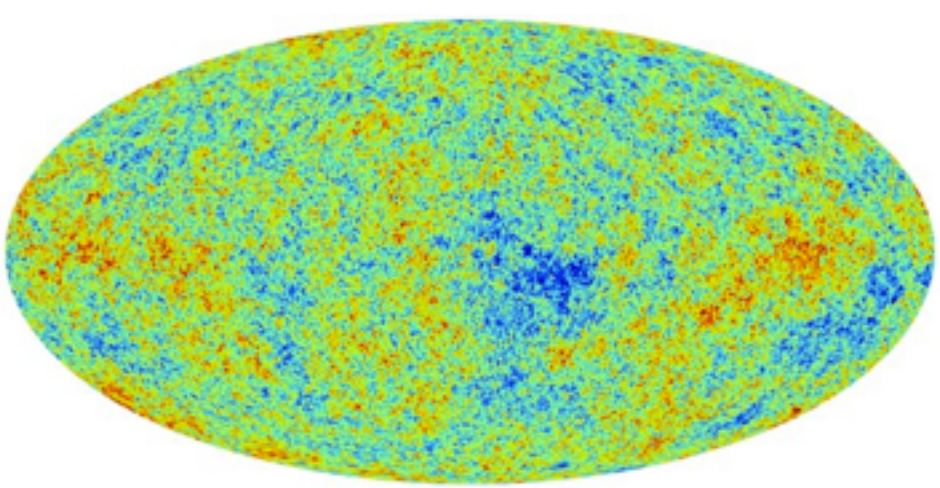
Also Rogstad & Shostak 1972, Roberts & Rots 1973, etc

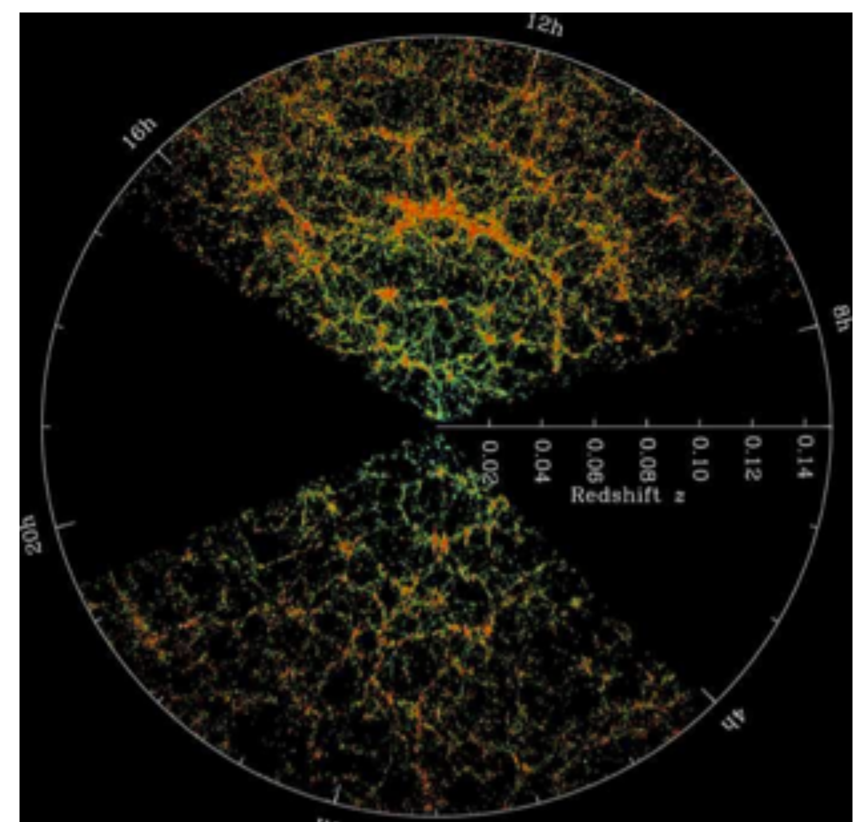
Other Evidence for Dark Matter



Gravitational lensing of background galaxies indicates there must be much more mass than is present in the observable “baryonic” components

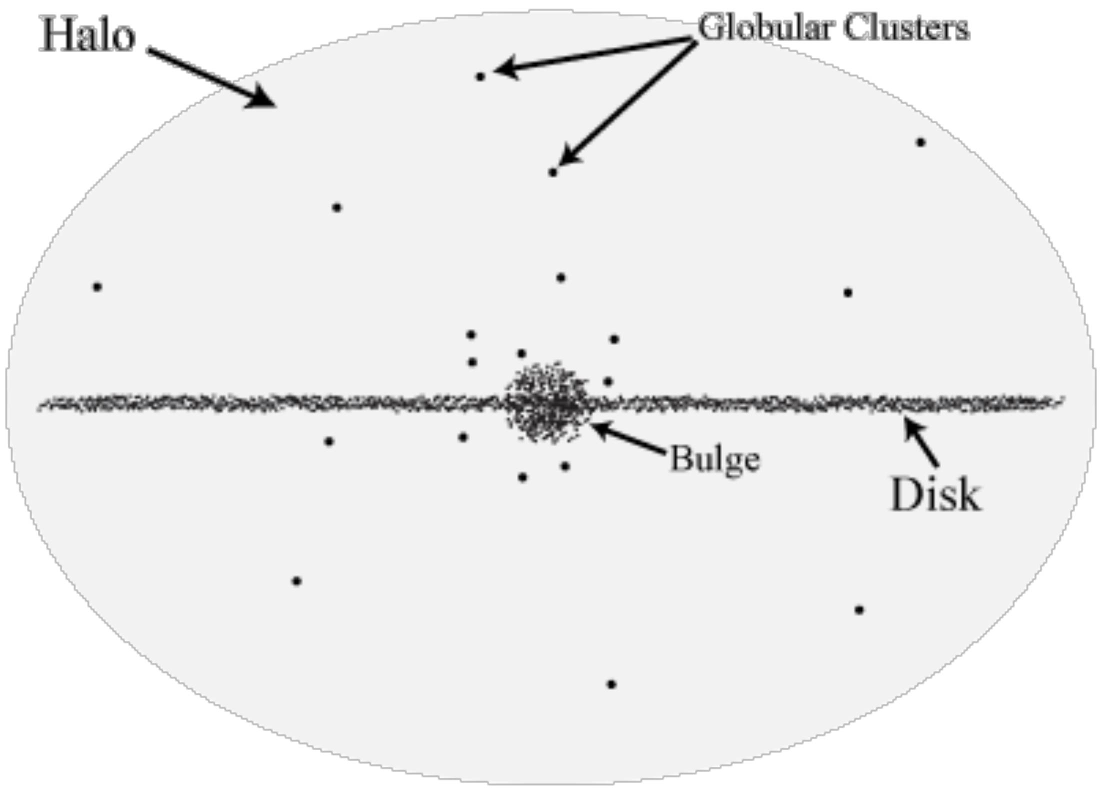
Extra dark matter is needed to gravitationally collapse the tiny (1 part in 10^5) fluctuations seen in the CMB to the present web of galaxies.





Bulge Dominated Keplerian Orbits

Theory



If most mass resides in central bulge.

$$\frac{v^2(r)}{r} = \frac{GM_b}{r^2}$$

$$v(r) = \frac{(GM_b)^{1/2}}{r^{1/2}}$$

Singular Isothermal Sphere

Dark Matter as an ideal gas at a constant temperature.

$v^2 \propto T$ = constant (Equipartition Theorem)

Density: $\rho(r) = \frac{\sigma_V^2}{2\pi G r^2}$

Orbital velocities constant essentially by construction

Non-thermal Singular "Isothermal" Sphere

$$\rho_{\rm iso}(r) = \frac{\rho_0}{1 + (r/r_c)^2}.$$

$$V_{\rm iso}(r) = 4\pi G \rho_0 r_c^2 [1 - (r/r_c) \arctan(r/r_c)].$$

Navarro, Frenk and White (NFW) Profile

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1 + r/r_s)^2},$$

Derived from "N-body" Simulations

$$\left(\frac{V_c(r)}{V_{200}}\right)^2 = \frac{1}{x} \frac{\ln(1 + cx) - (cx)/(1 + cx)}{\ln(1 + c) - c/(1 + c)},$$

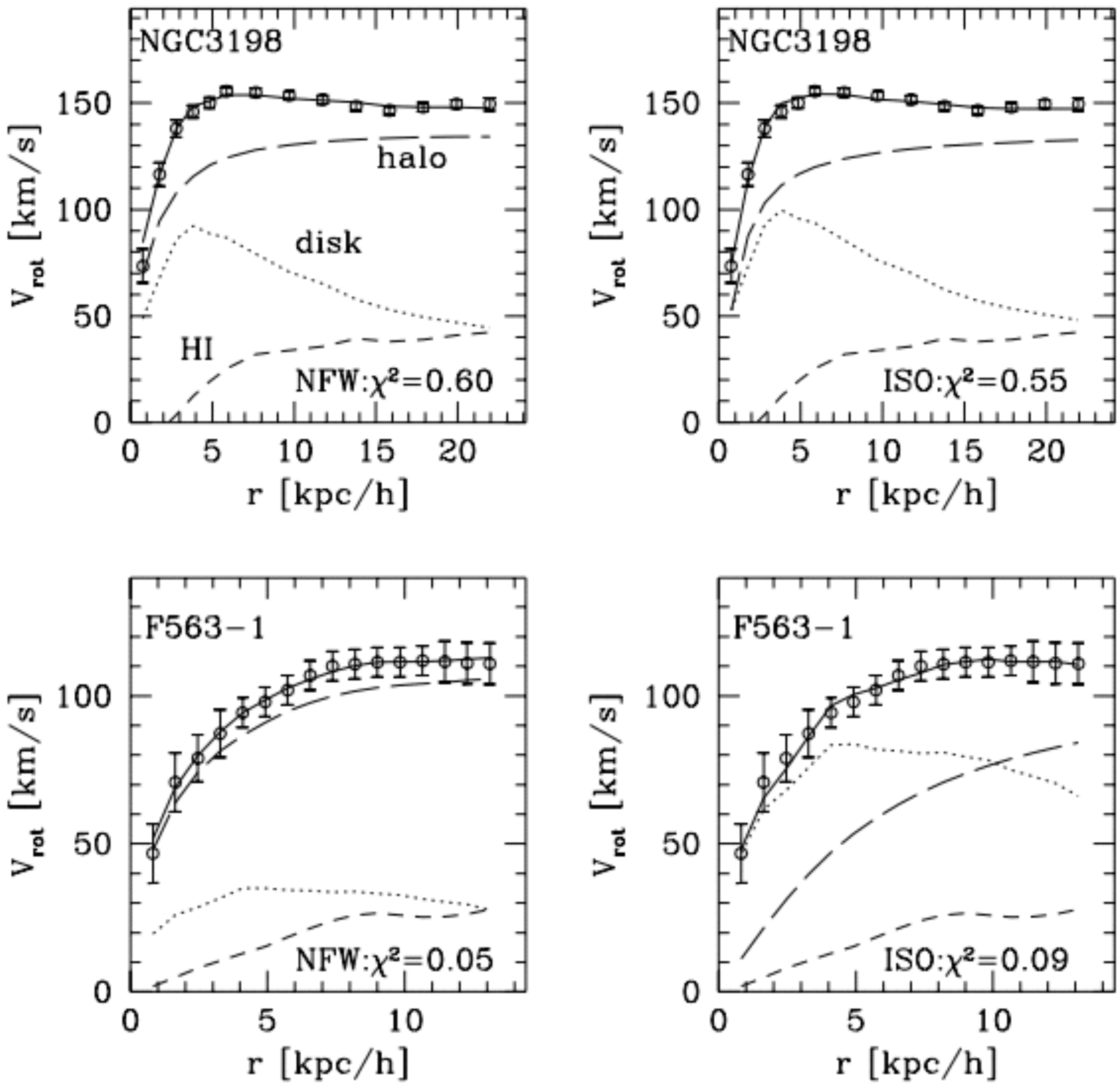
$x = r/r_{200}$

$c = r_{200}/r_s$

(c~10 for Milky Way)

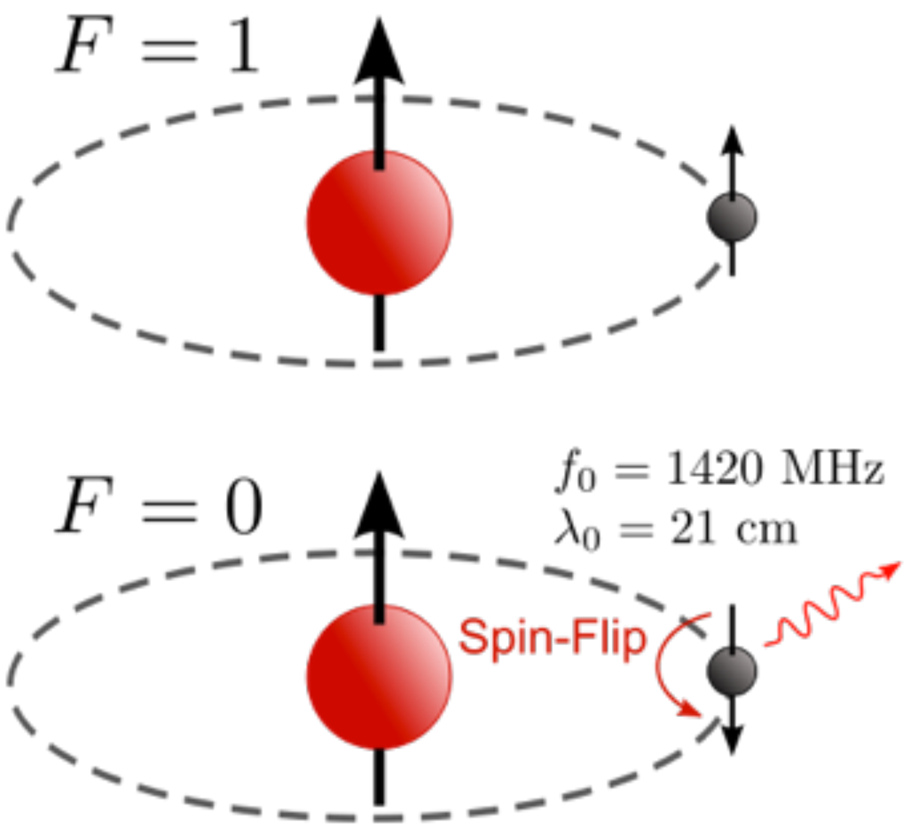
NFW

Non singular "Isothermal"



from Navarro 1998

Experiment and Data



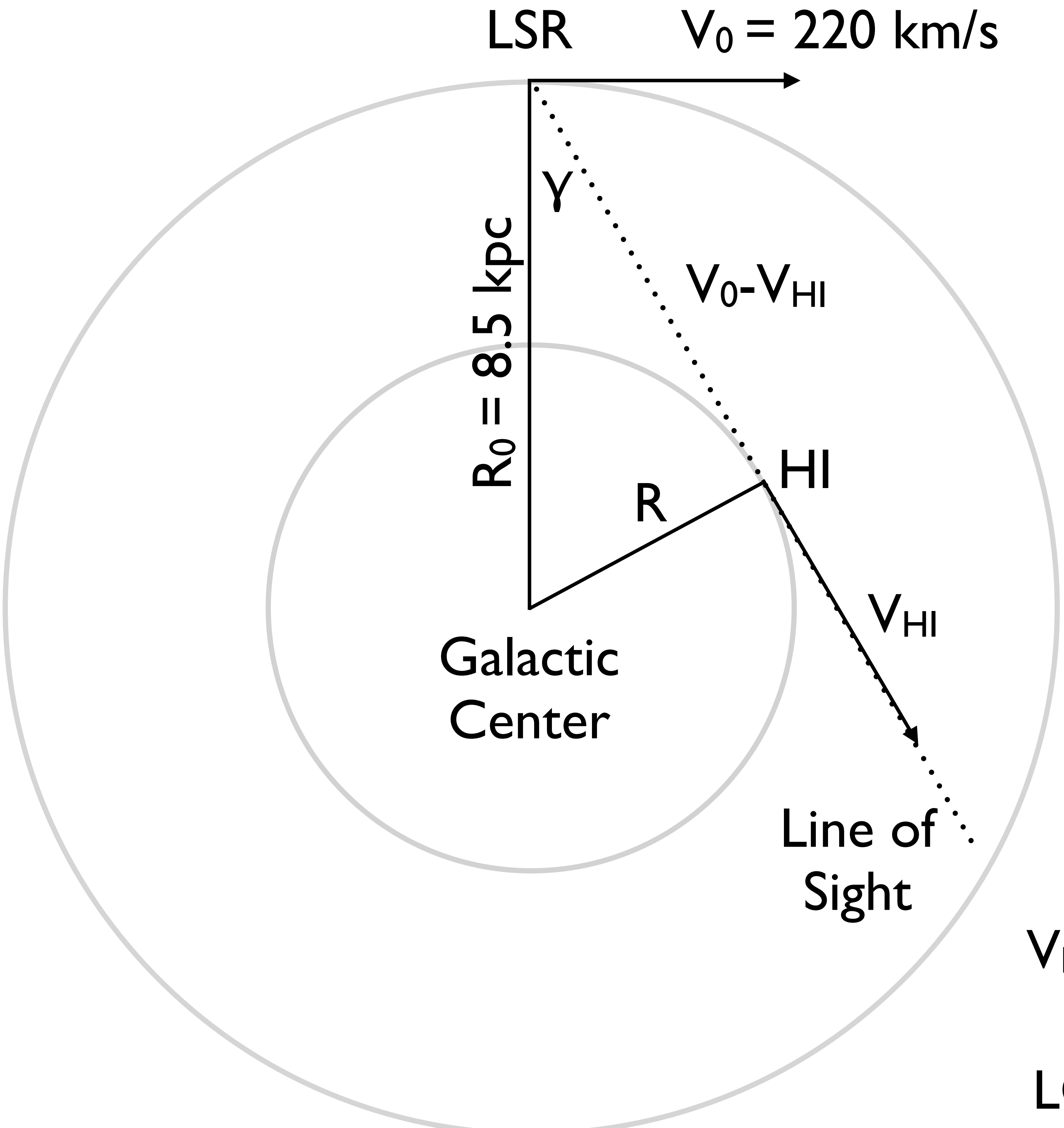
Measure velocity through Doppler shift of 21-cm line

$$(V_{HI} - V_{Earth})_{LOS} = c\,(f_0 - f)/\,f_0$$

LOS: Line of Sight Projected Velocities

f_0 = 1420.4 MHz
f : observed frequency

JHU Small Radio Telescope



γ: Galactic Longitude

LSR: Local Standard of Rest

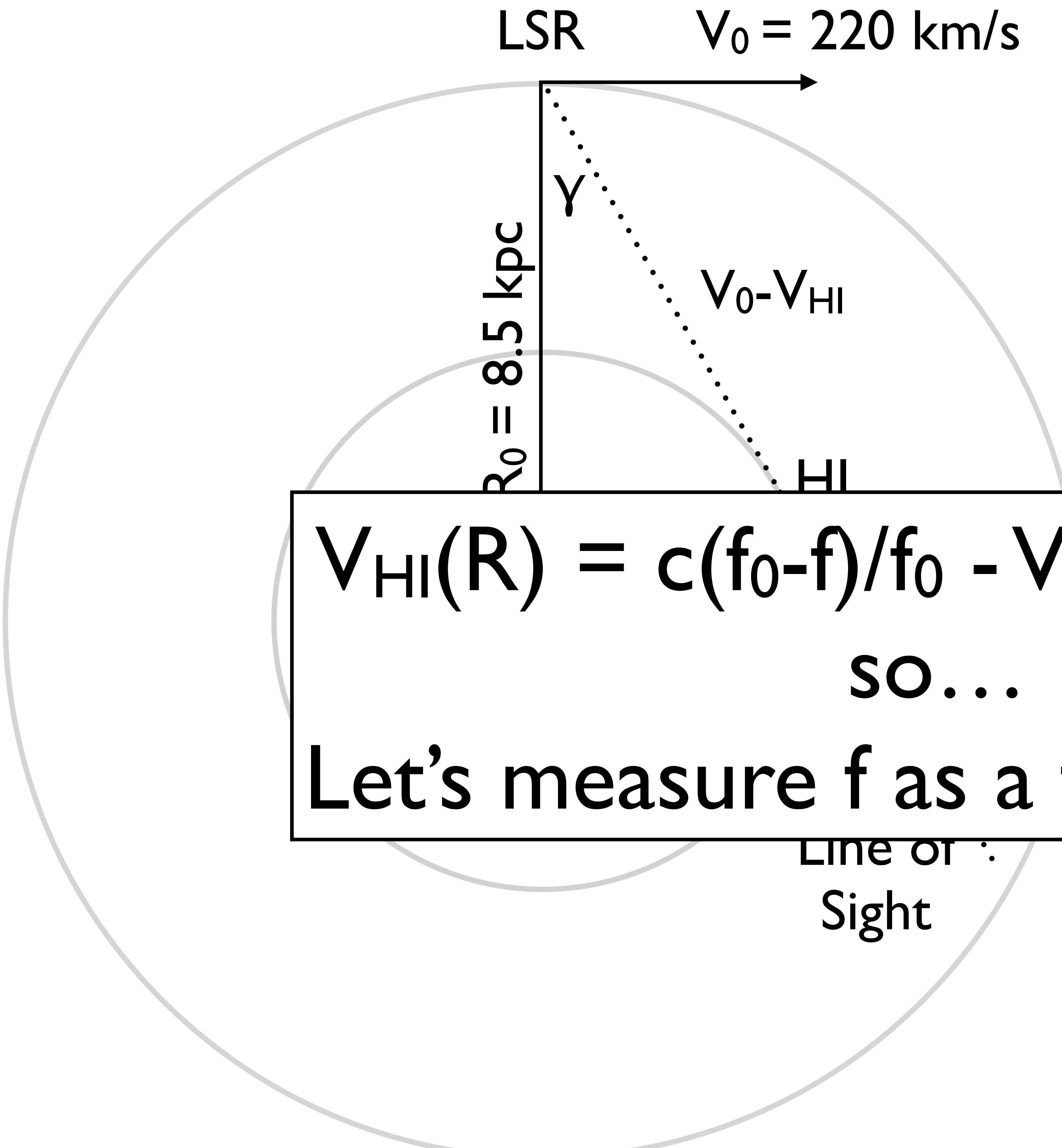
If angular velocity V/R is a monotonically decreasing function of R, then can show highest relative LOS velocity is at tangent point where $R = R_0 \sin(\gamma)$.

Rotation Curve:

$$V_{HI}(R) = (V_0 \sin(\gamma) - V_{HI}) + V_0 \sin(\gamma)$$

↑

LOS relative velocity Measured from H1 redshift (almost)



$$V_{HI}(R) = c(f_0-f)/f_0 - V_{LSR} + V_0\sin(\gamma)$$

so…

Let's measure f as a function of γ!

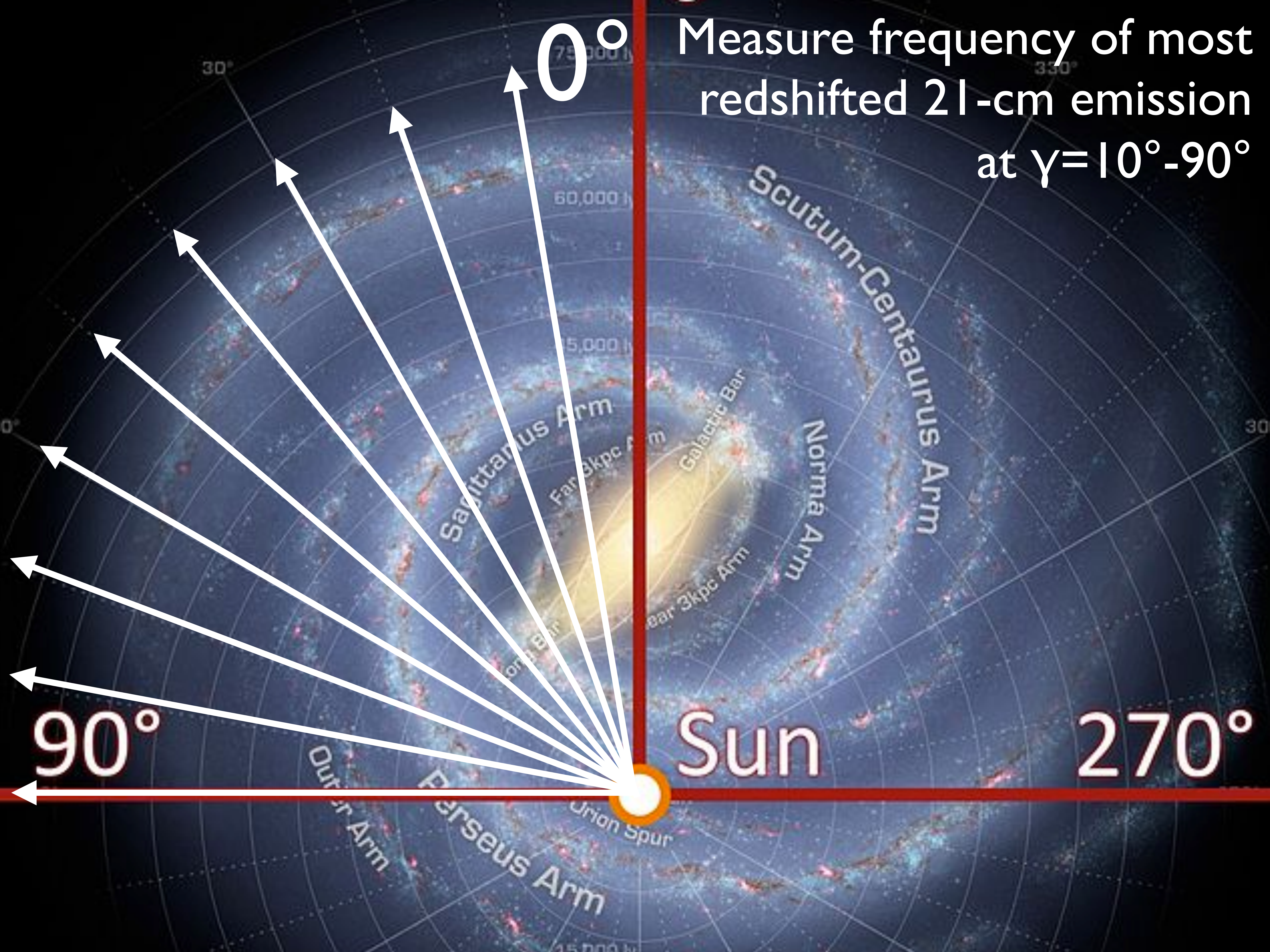
The LSR is anchored to a group of stars around the sun, and V_0 and R_0 are associated with this group.

The velocity of the Earth … LSR … ccount.

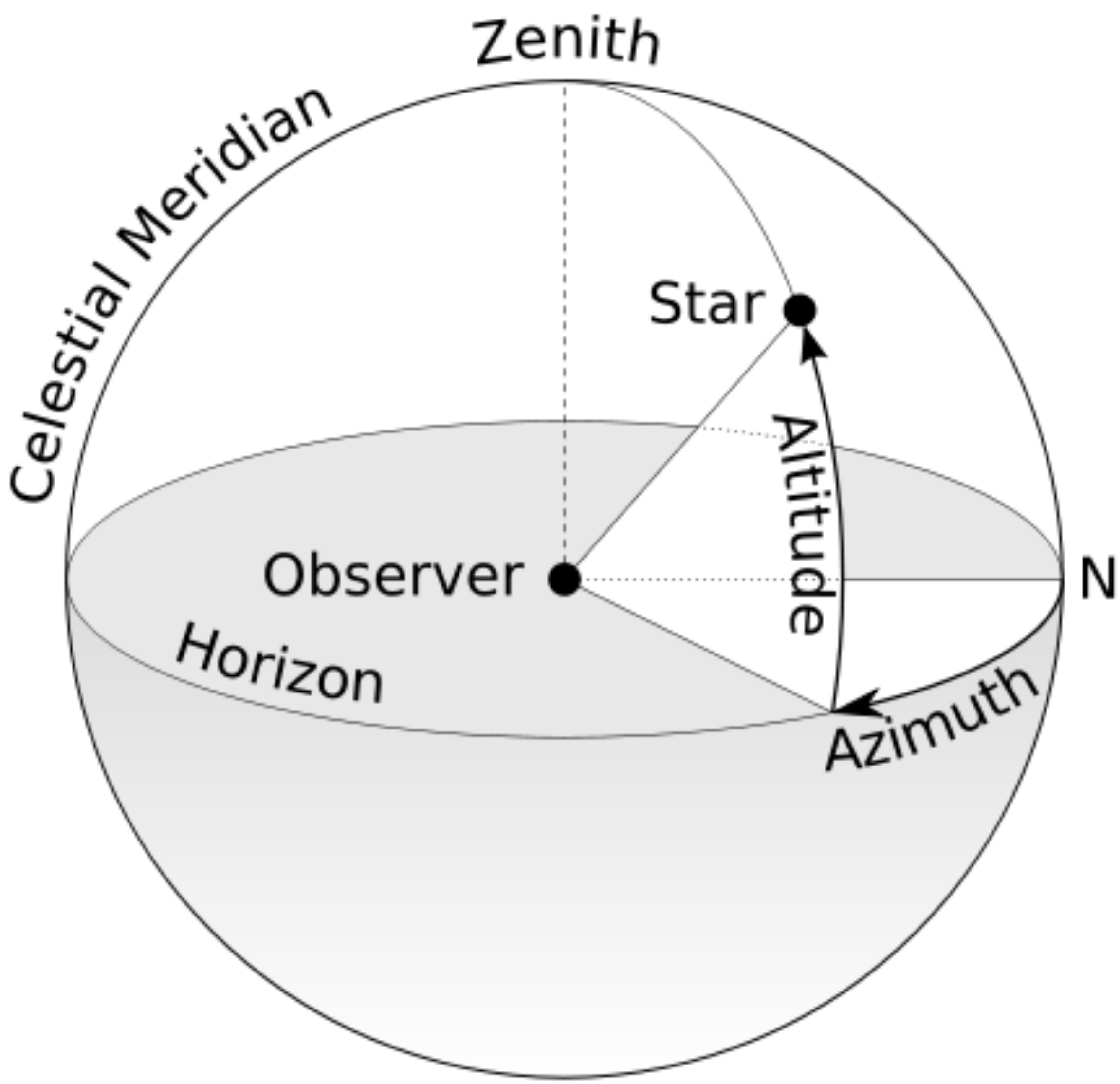
…$_{er}$-V_{LSR}

V_{LSR}: Earth's velocity with respect to the LSR along the LOS

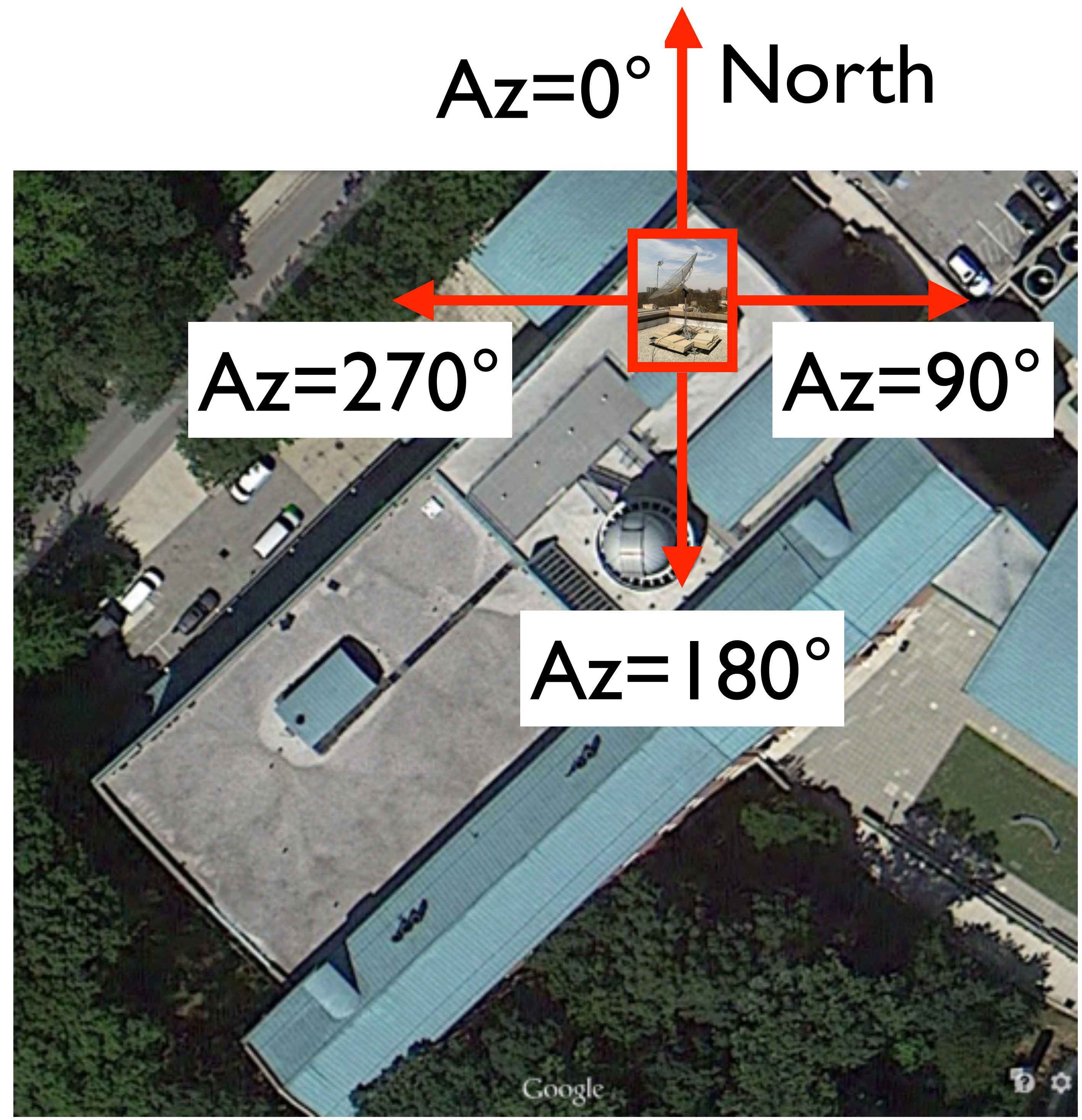
$V_{Doppler} = c\ (f_0-f)/\ f_0$


Measure frequency of most
redshifted 21-cm emission
at γ=10°-90°
0°
90°
270°
Sun
Scutum-Centaurus Arm
Sagittarius Arm
Norma Arm
Galactic Bar
Perseus Arm
Orion Spur
60,000 ly
30°
330°

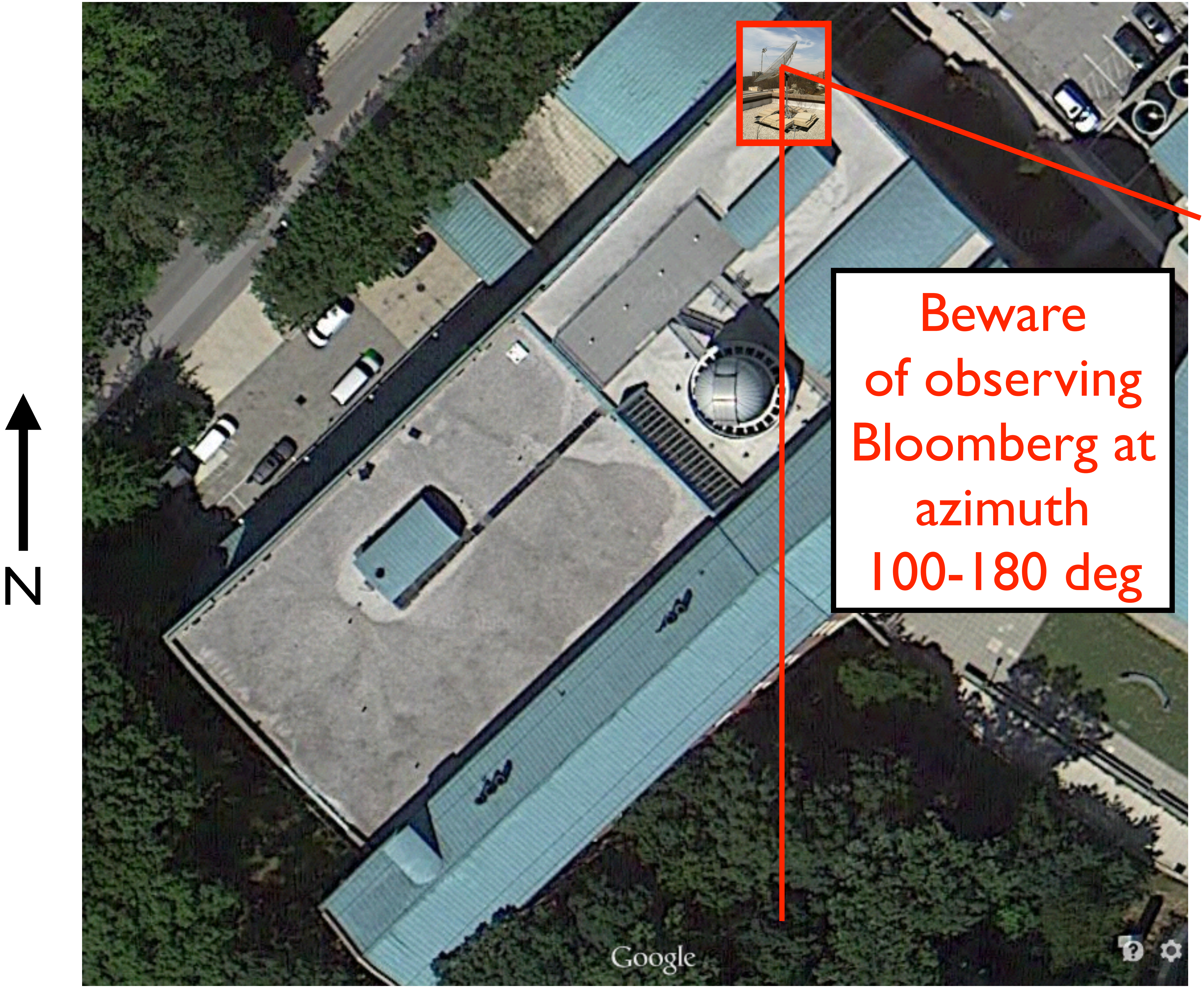
Horizon Coordinates: Azimuth and Elevation



Altitude is also called Elevation



Galactic targets rising (Elevation > 30°) in late night/ early morning, setting by afternoon.


Beware of observing Bloomberg at azimuth 100-180 deg
N
Google

For Next Week:

Each group is assigned one night/morning of the week.

Using a command file:

1) Obtain a reference spectrum off the plane of the galaxy. This will be used to model/remove the systematic signal not associated with the galactic emission.
2) Record at least 10 minutes of data at γ=10°-90° in increments of 10°.

Then:

3) Make a composite plot of the average of all spectra and post to shared drive for discussion next Monday.
4) Write up Intro, Theory and Experiment/Data for next Monday.

References

[Rubin & Ford(1970)] Rubin, V. C., & Ford, W. K., Jr. 1970, ApJ, 159, 379

[Rubin et al.(1980)] Rubin, V. C., Ford, W. K. J., & . Thonnard, N. 1980, ApJ, 238, 471

[Rogstad & Shostak(1972)] Rogstad, D. H., & Shostak, G. S. 1972, ApJ, 176, 315

[Roberts & Rots(1973)] Roberts, M. S., & Rots, A. H. 1973, A&A, 26, 483

[Roberts & Whitehurst(1975)] Roberts, M. S., & Whitehurst, R. N. 1975, ApJ, 201, 327

[Navarro(1998)] Navarro, J. F. 1998, arXiv:astro-ph/9807084

[Navarro et al.(1996)] Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, ApJ, 462, 563

[Navarro et al.(1996)] Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, ApJ, 462, 563