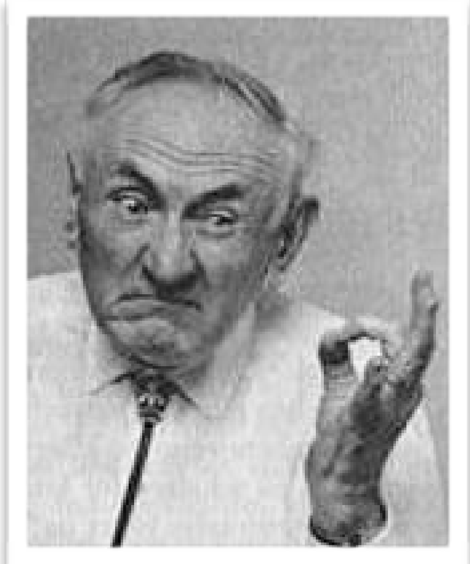
Dark Matter
and the
Galactic Rotation Curve
a.k.a
The Radio Telescope Lab

JHU Advanced Lab

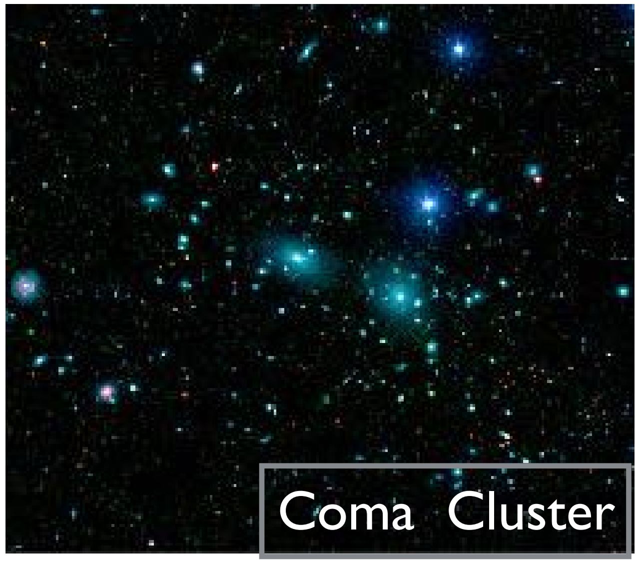
Andromeda (M31)

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

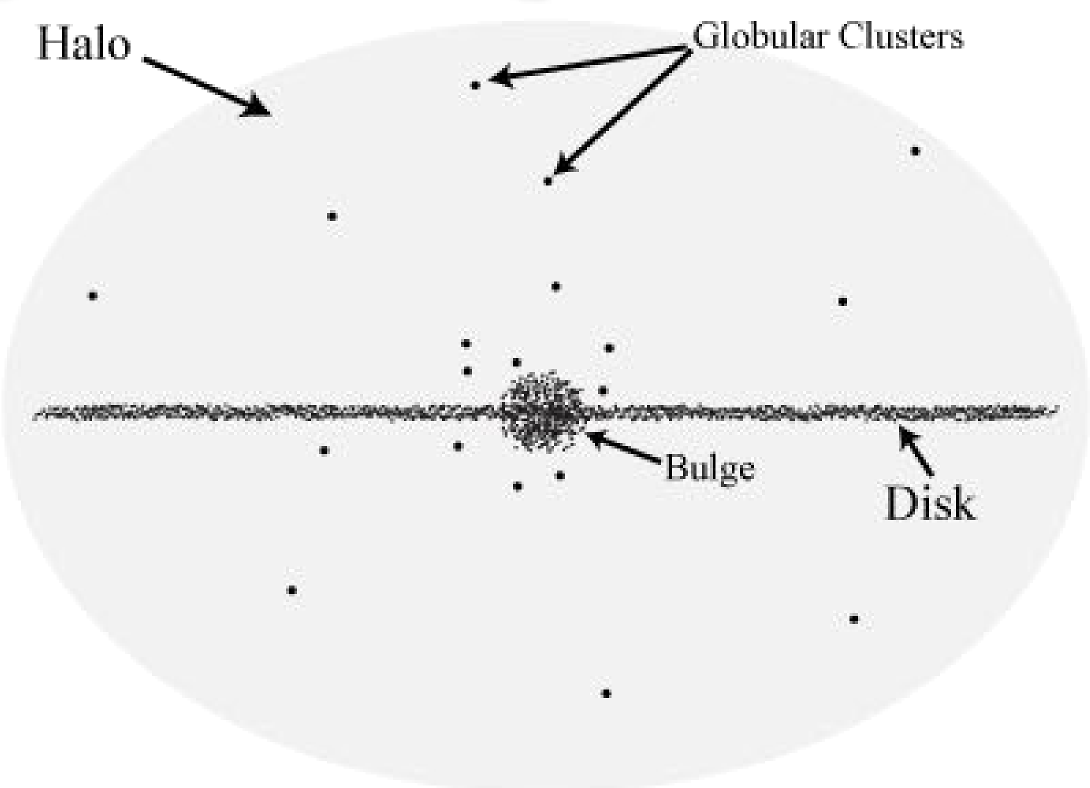
Discovering Dark Matter with Orbits



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

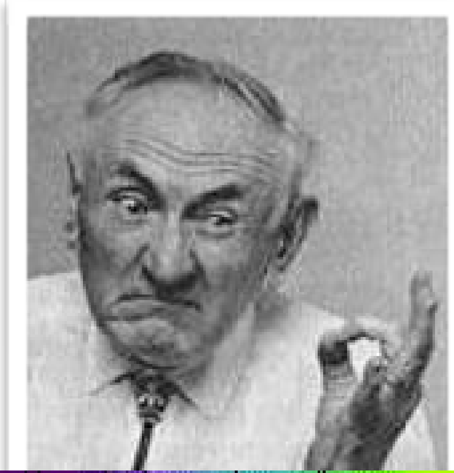


1970-80 By measuring the **Doppler shift of optical spectral lines**, Vera Rubin and colleagues measured the orbital velocities of hot HII regions as a function of radius in spiral galaxies (Andromeda etc). Though most of the luminous mass was concentrated in a central bulge, the velocities did not fall off with distance in the predicted Keplerian way, suggesting a larger halo of non-luminous "dark" matter.



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

Discovering Dark Matter with Orbits



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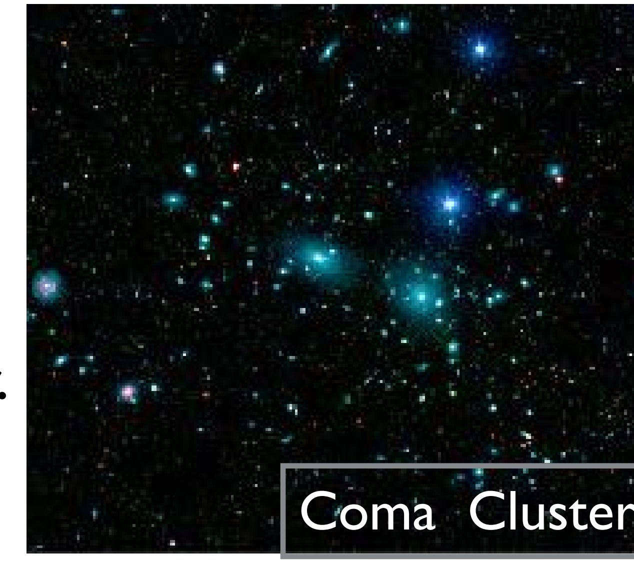

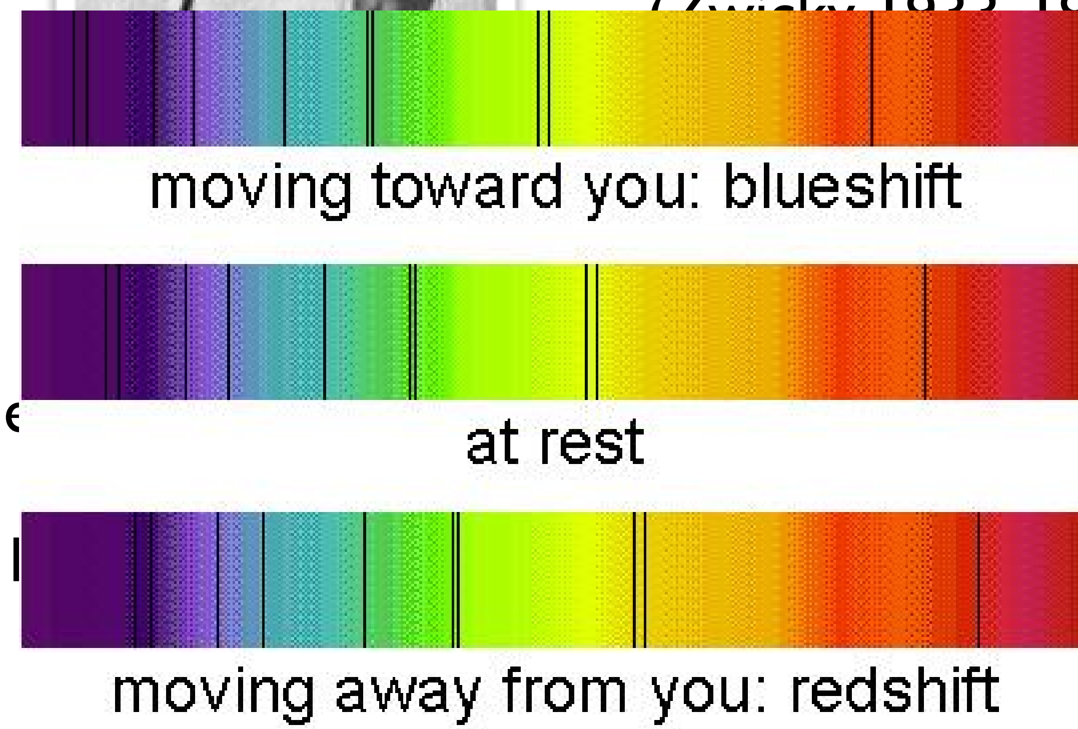

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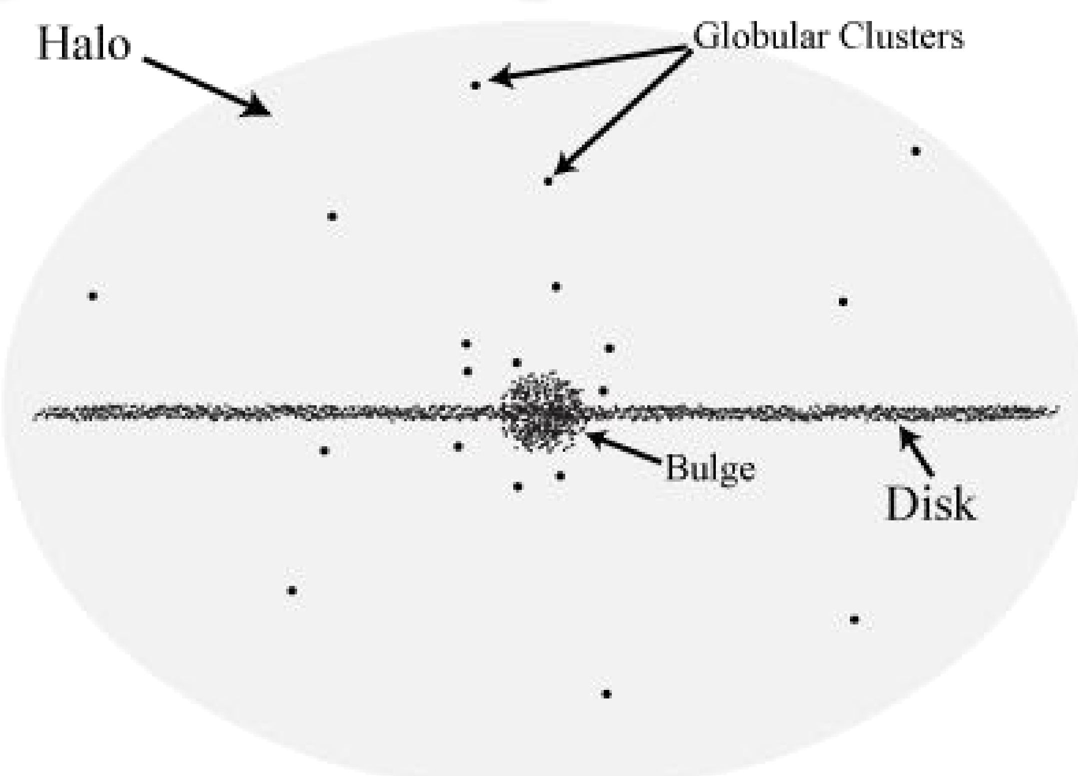

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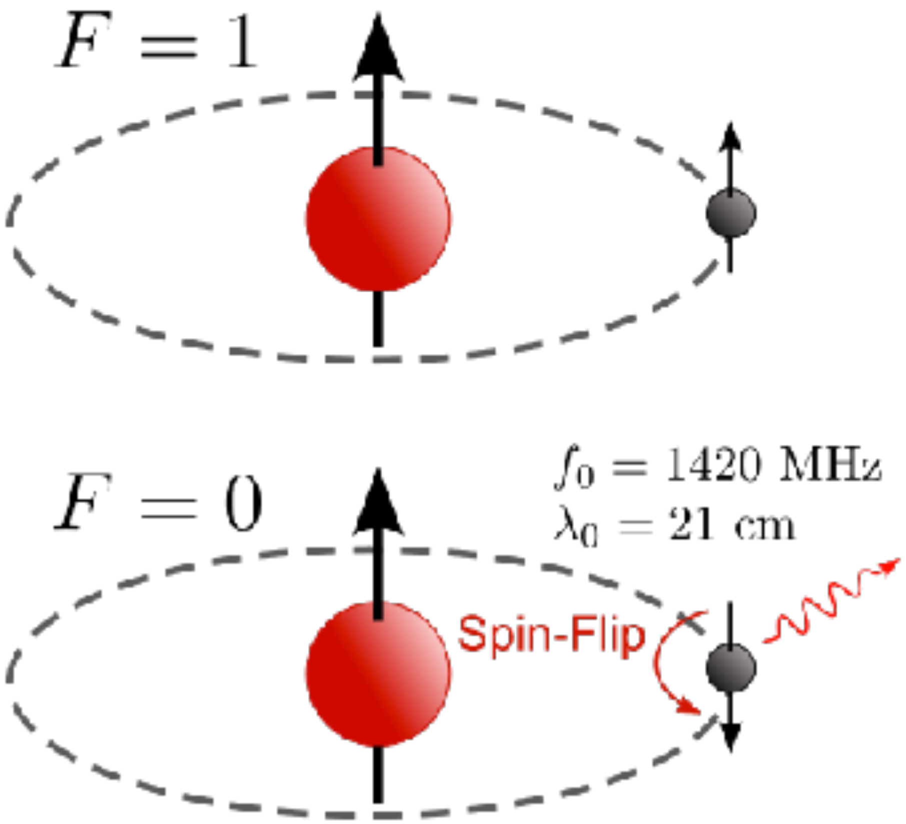
Radio-wave Measurements of Rotation Curves

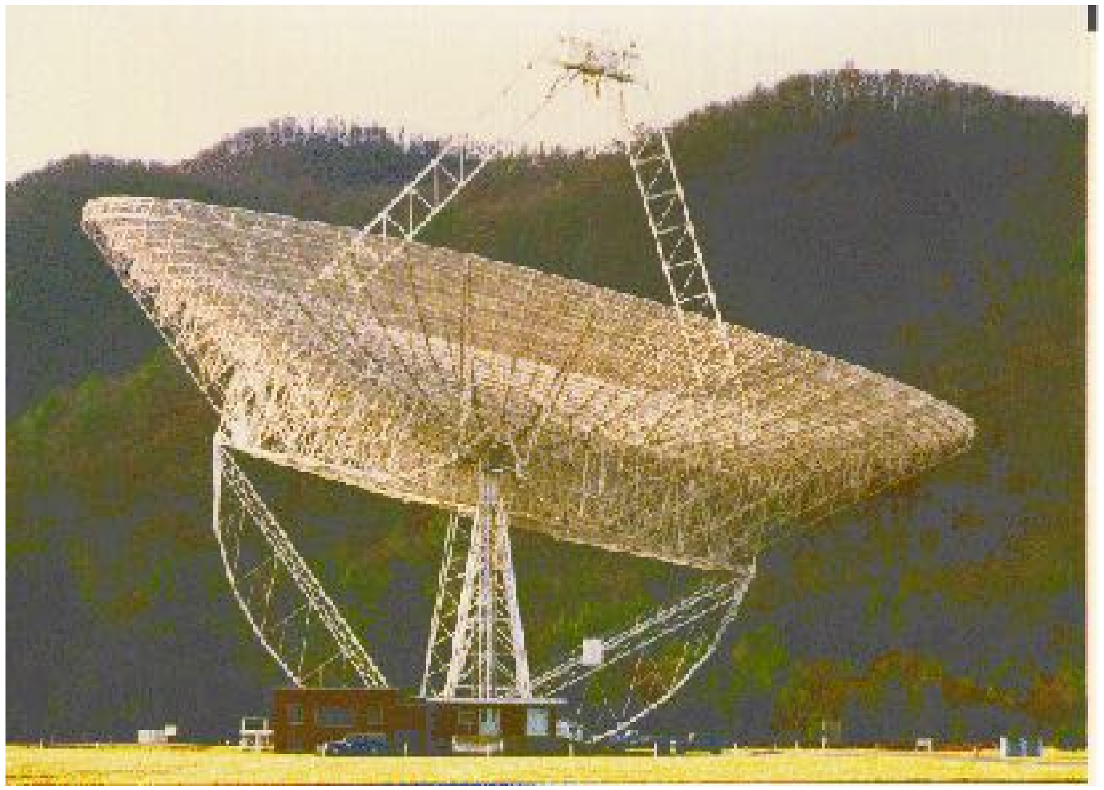


Spin-flip transition in neutral hydrogen produces 21-cm wavelength radiation.*

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.

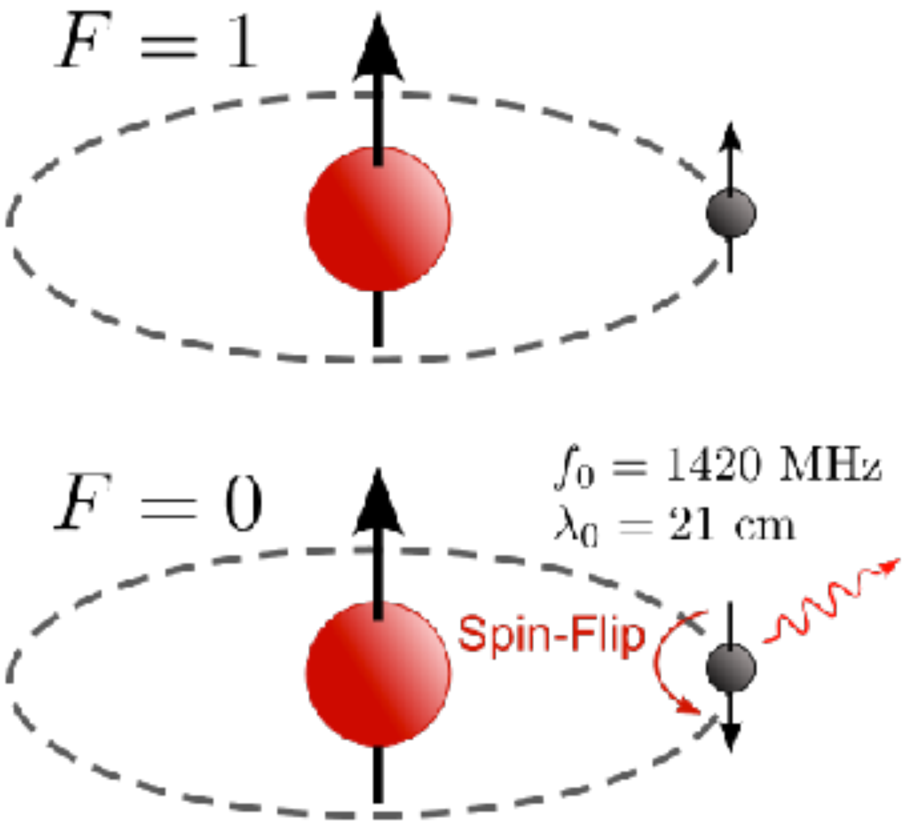
* ("Forbidden" transition with 10 Myr lifetime, but there are many atoms in low density environments in space.)



"Old" Greenbank 300 ft Telescope; West Virginia

Westerbork Synthesis Radio Telescope; Netherlands

Radio-wave Measurements of Rotation Curves



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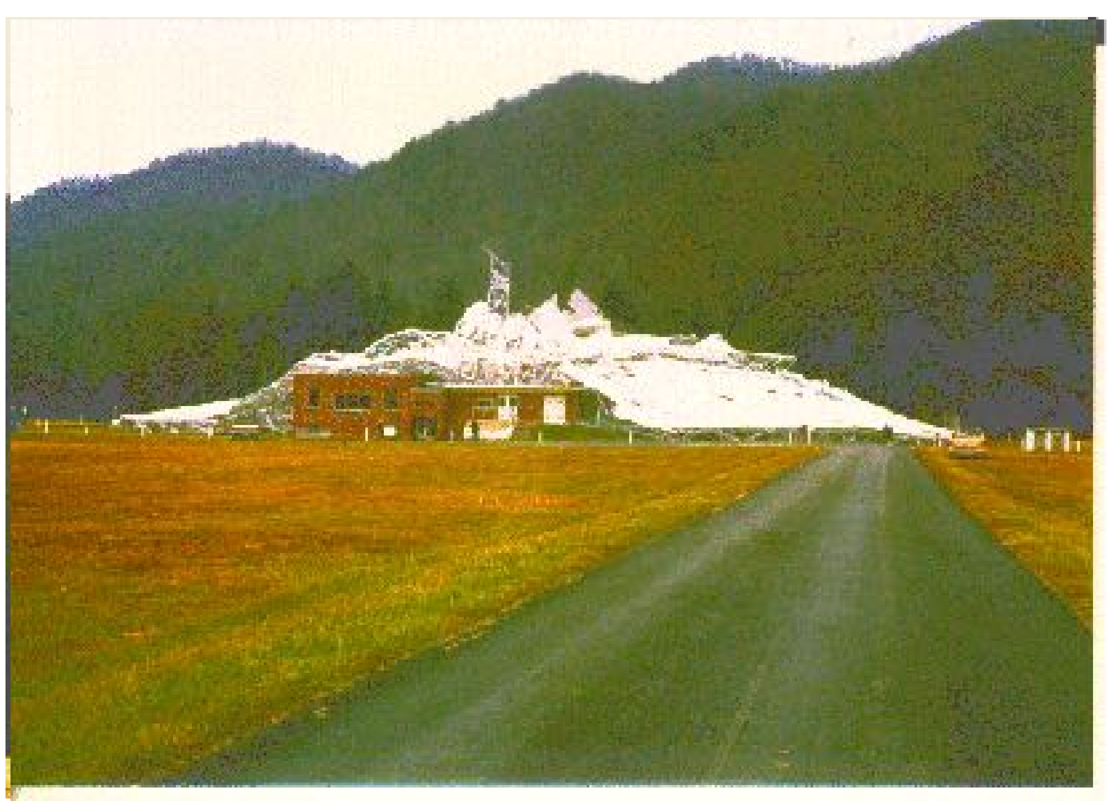
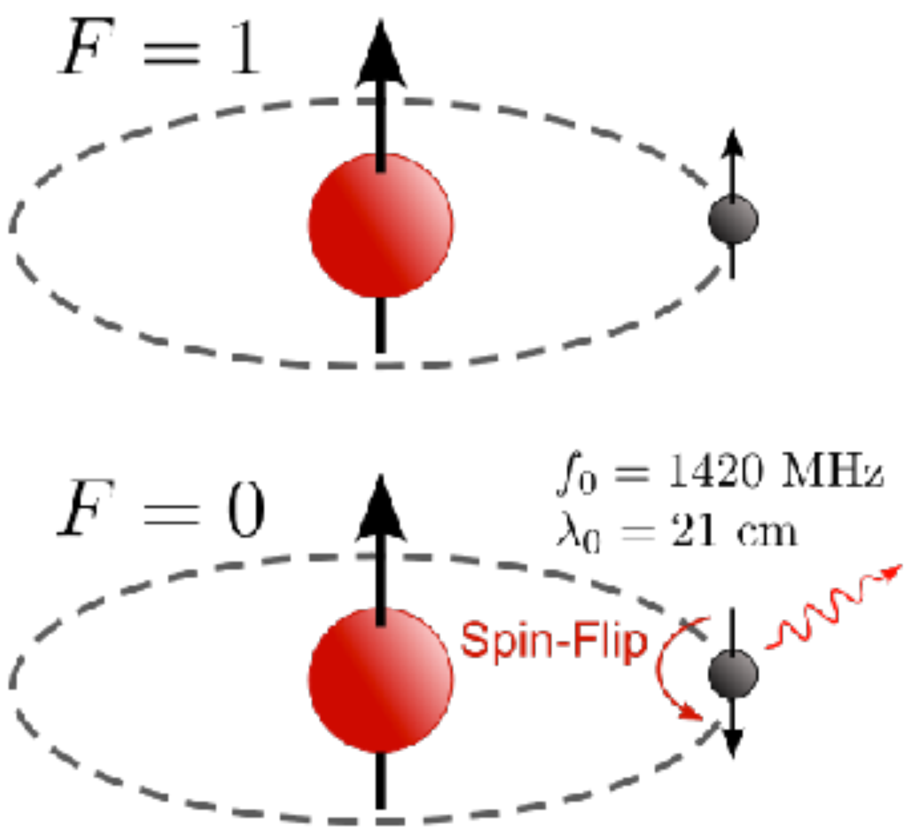


1988 Collapse

Westerbork Synthesis Radio Telescope; Netherlands

Radio-wave Measurements of Rotation Curves



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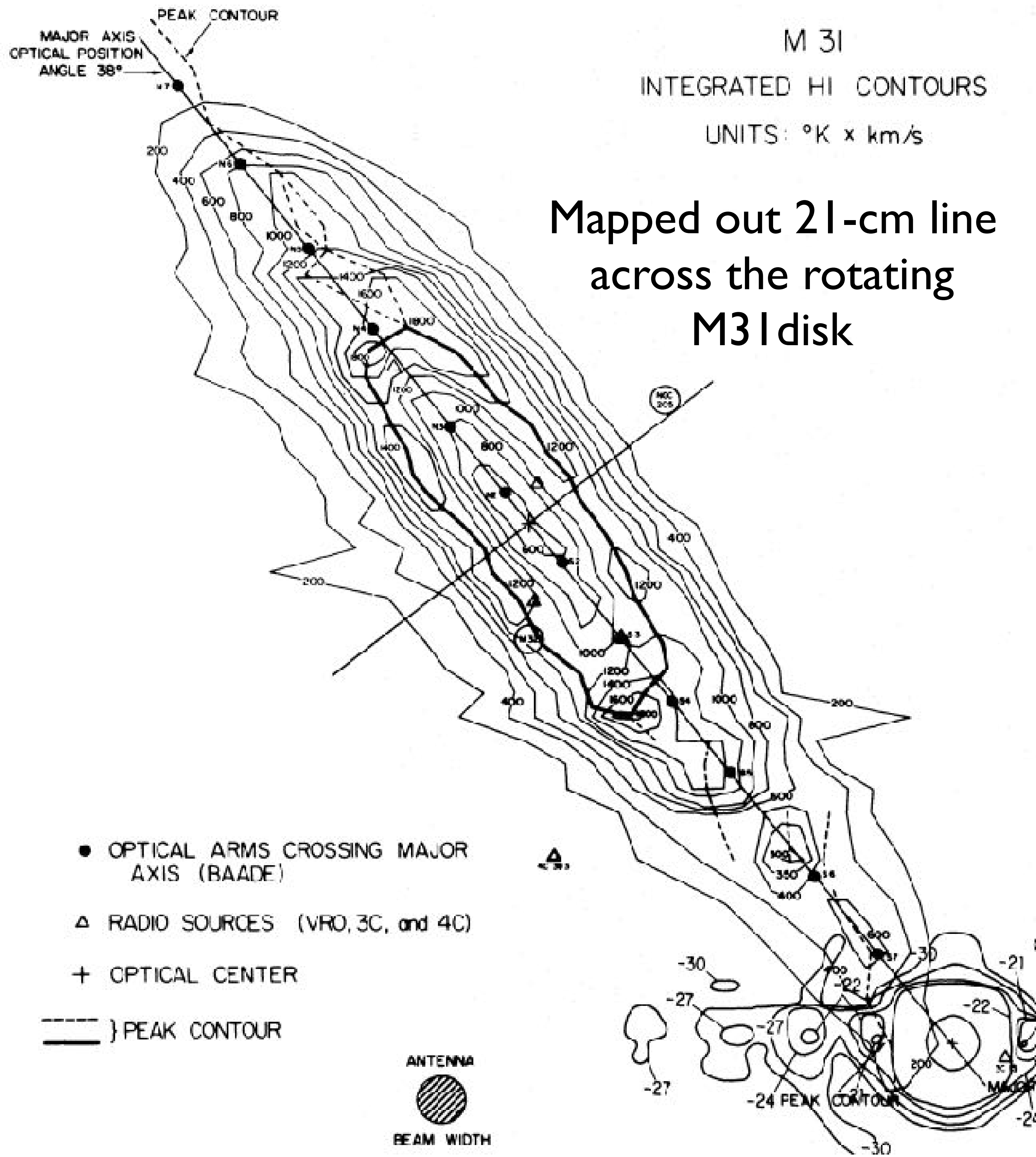


Mapped out 21-cm line across the rotating M31disk

21-cm Study of Andromeda

(Roberts & Whitehurst 1975)

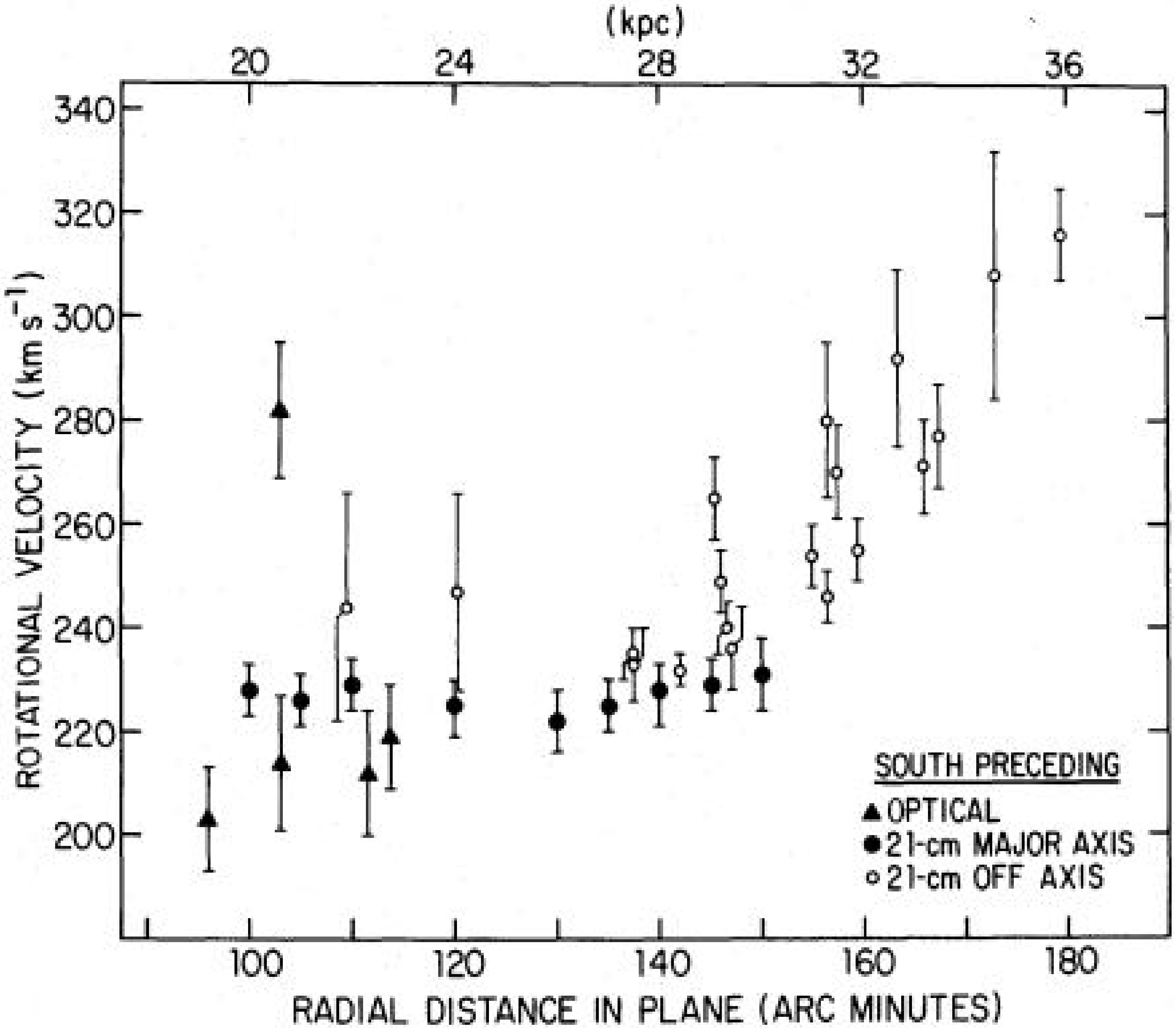
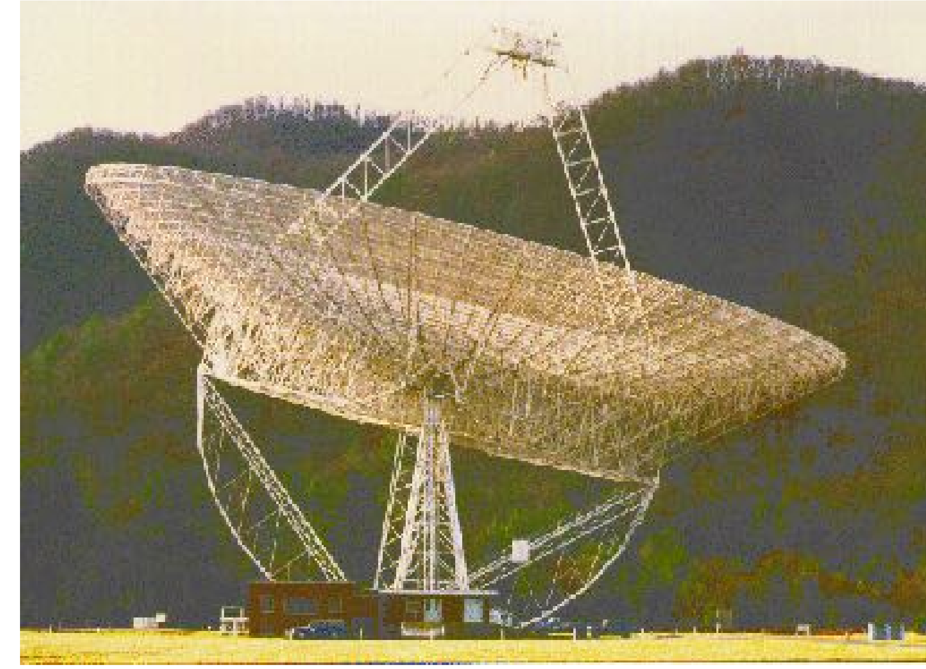


FIG. 10.—Rotational velocities derived from optical observations (Rubin and Ford 1970), 21-cm major axis positions, and 21-cm off-axis positions. The increase in rotational velocity at large radii as well as the differences between axis and off-axis velocities at similar radii are artificial and are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

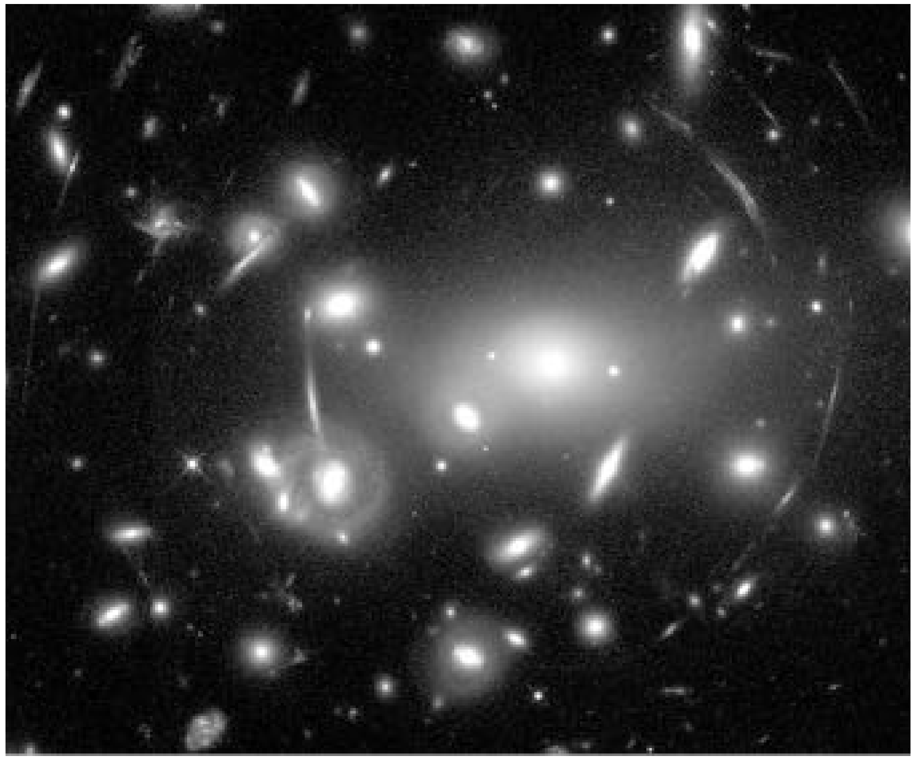


21-cm Study of Andromeda

(Roberts & Whitehurst 1975)

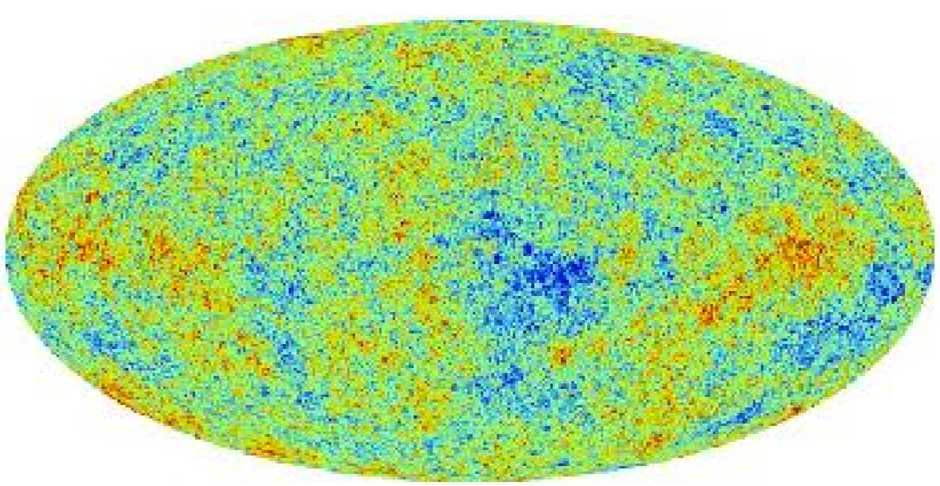
Also Rogstad & Shostak 1972, Roberts & Rots 1973, etc

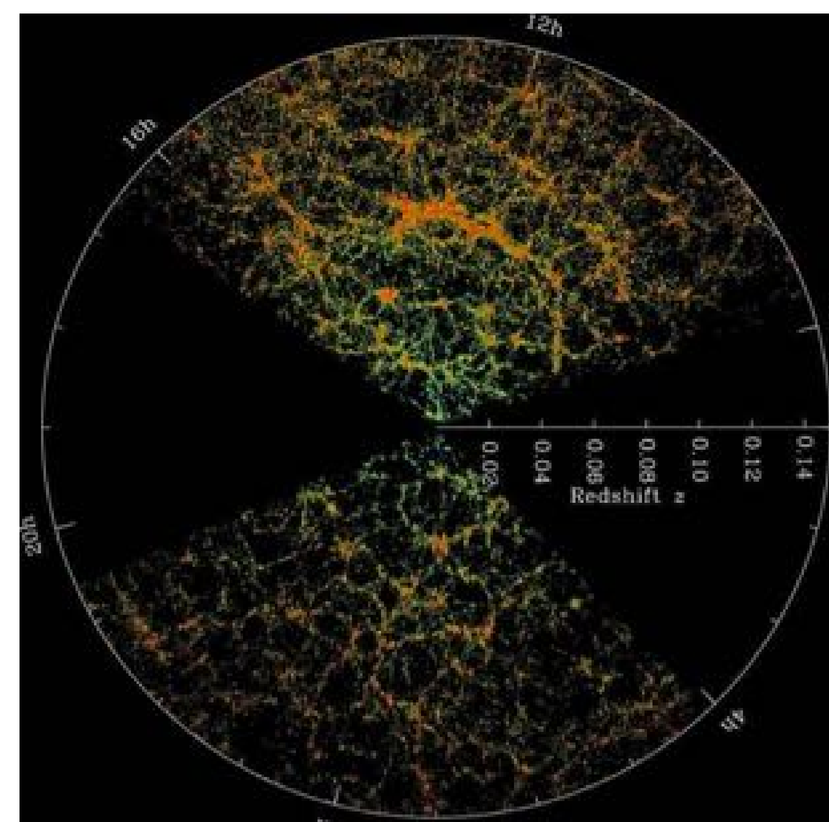
Other Evidence for Dark Matter



Gravitational lensing of background galaxies indicates there must be much more mass than is present in the observable luminous 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.





Units for Astronomy

Distance: "parsec" (pc); 1 kpc = 3.1×10^{19} m

Mass: "Solar Mass" $M_\odot = 2.0 \times 10^{30}$ kg

Velocity: km/s

Newton's Constant G: 4.3×10^{-6} kpc $M_\odot^{-1}$ (km/s)^2

$\boxed{\text{Theory}}$

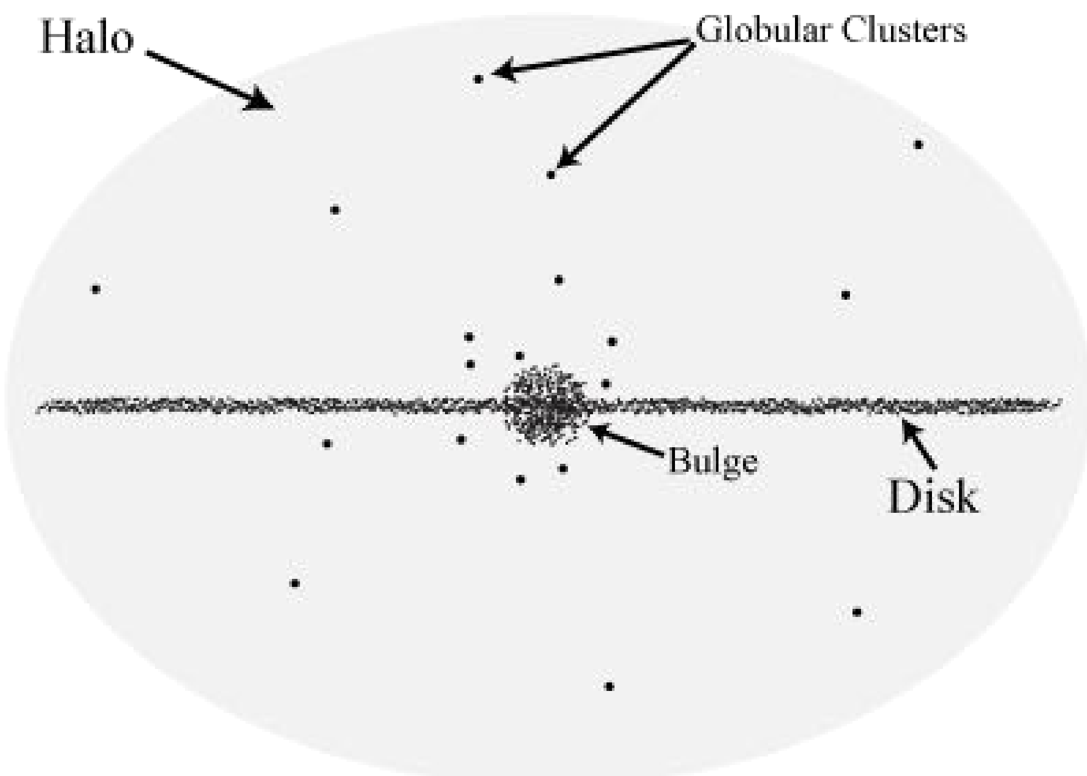
Orbits and Galactic Models

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

v : Orbital velocity at radius r

M : Mass within radius r

$$v(r) = \frac{[GM(r)]^{1/2}}{r^{1/2}}$$



Two models for M(r):

"Luminous Matter Only"
vs
"Luminous & Dark Matter"

Orbits and Galactic Models

$$v(r) = \frac{[GM(r)]^{1/2}}{r^{1/2}}$$

"Luminous Matter Only"
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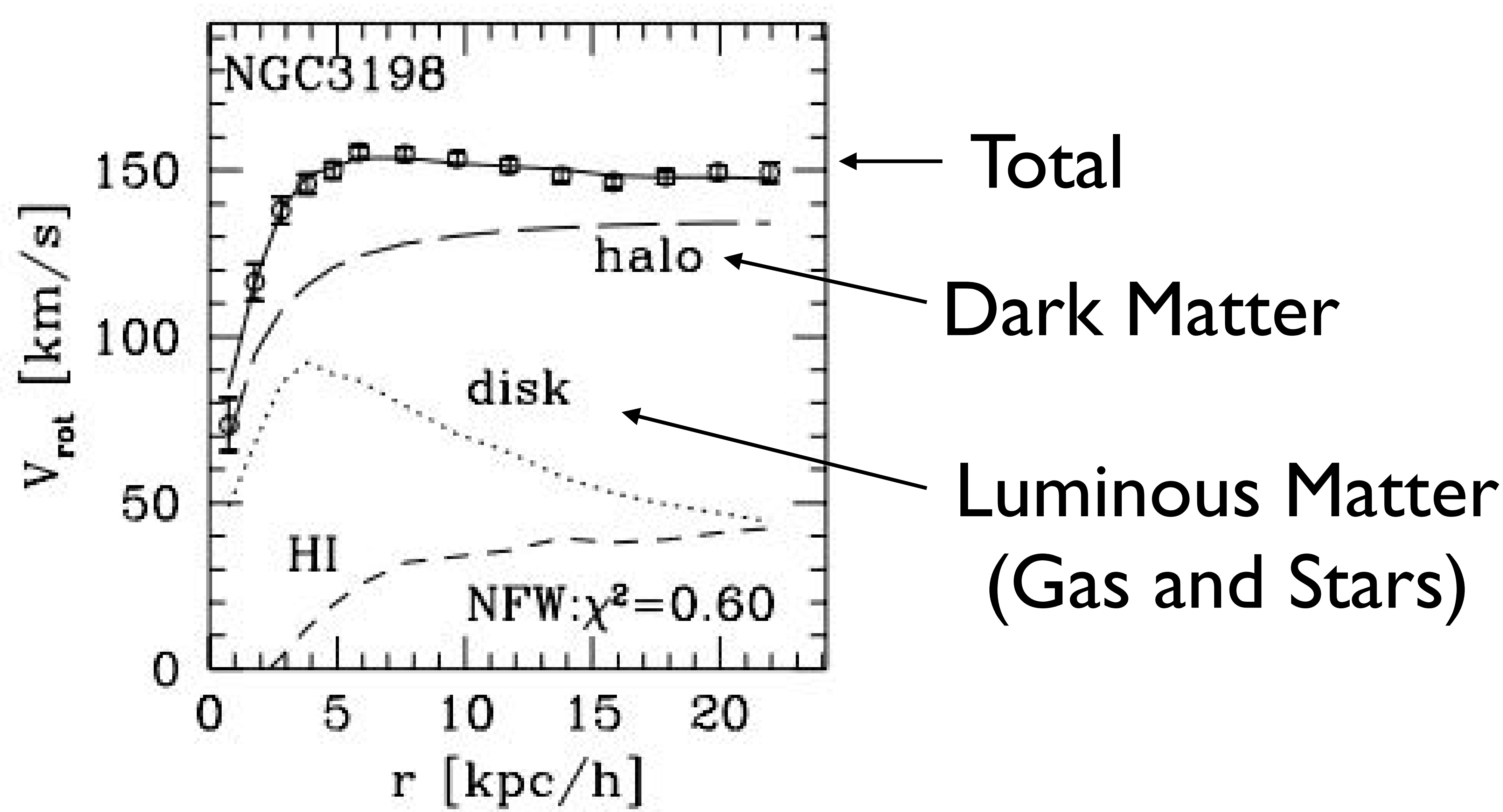
Navarro 1998



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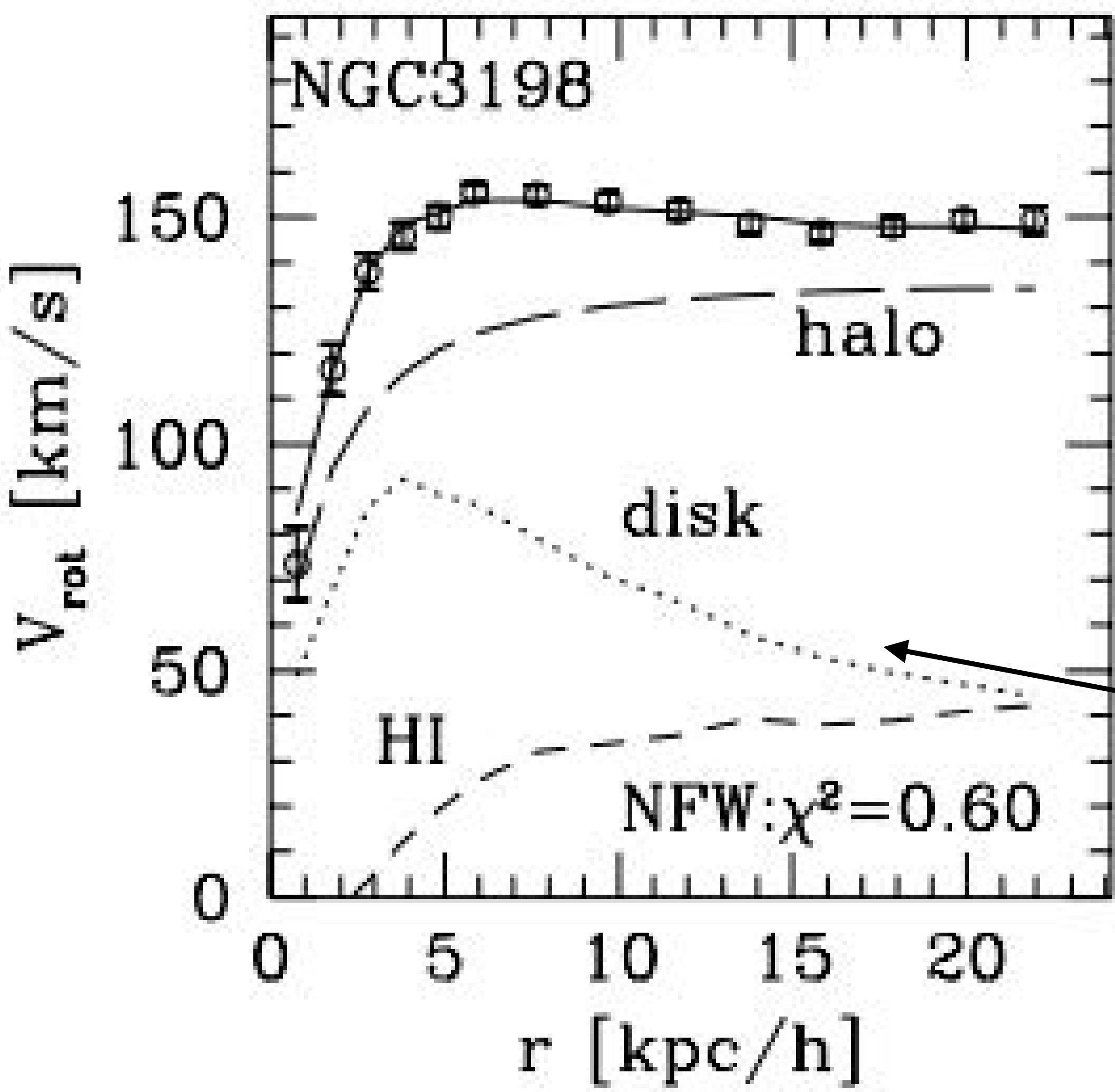


Luminous Matter Only

Centrally Concentrated:
Most mass within r = 4 kpc

(Piffl et al 2014)

$M(\ r > 4\ \text{kpc}\ ) \sim M_L$

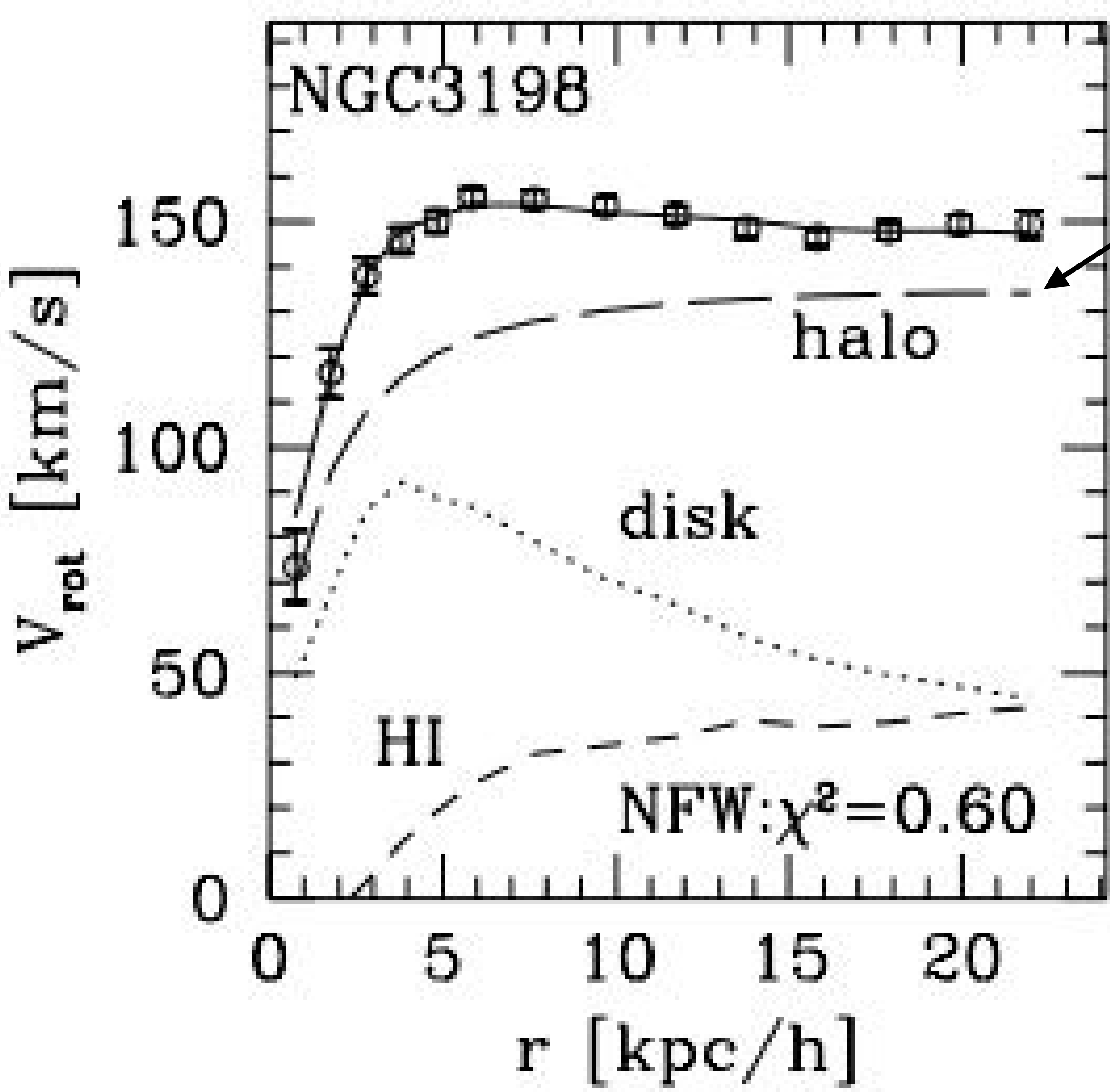
(A Constant)

$v \propto r^{-1/2}$

$$v(r) = \frac{[GM(r)]^{1/2}}{r^{1/2}} = \frac{[GM_L]^{1/2}}{r^{1/2}}$$

Orbits and Galactic Models

Navarro 1998



Luminous & Dark Matter

Additional Extended DM Halo creates "flat rotation curve"

$$M(\ r > 4 \text{ kpc}\ ) \sim M_D(r) + M_L$$

$$v(r) = \frac{[G(M_D(r) + M_L)]^{1/2}}{r^{1/2}}$$

$M_D(r)$ — So what is this?

Navarro, Frenk and White (NFW) DM Profile

Paper: N, F, W 1996 Derived from "N-body" Simulations

$$\rho_D(r) = \frac{4\rho_s}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$$

r_s : Scale radius

ρ_s : Density at r_s

$$M_D(r) = 4\pi\int_0^r \rho_D(r')\, r'^2 dr'$$

$$= 16\pi\rho_s r_s^3 \int_0^{x=r/r_s} \frac{x'^2\, dx'}{x'\,(1+x')^2}$$

$$= 16\pi\rho_s r_s^3 \left(\ln(1+x) - \frac{x}{x+1}\right)$$

$M_s = M_{DM}(r_s)$
A new model parameter

$r_s \sim 10$ kpc
for Milky Way

Solve: what is $M_D(r)$ in terms of Ms and $x=r/r_s$?

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$$= 16\pi\rho_s r_s^3 \left(\ln(1+x) - \frac{x}{x+1}\right)$$

$$= \frac{M_s}{\ln(2) - 1/2} \left(\ln(1+ r/r_s) - \frac{r/r_s}{r/r_s+1}\right)$$

$M_s = M_{DM}(r_s)$

A new model parameter

$r_s \sim 10$ kpc for Milky Way

Luminous Matter Only

$$v(r) = \frac{[GM_L]^{1/2}}{r^{1/2}}$$

One parameter: M_L

Luminous & Dark Matter

$$v(r) = \frac{[G(M_D(r) + M_L)]^{1/2}}{r^{1/2}}$$

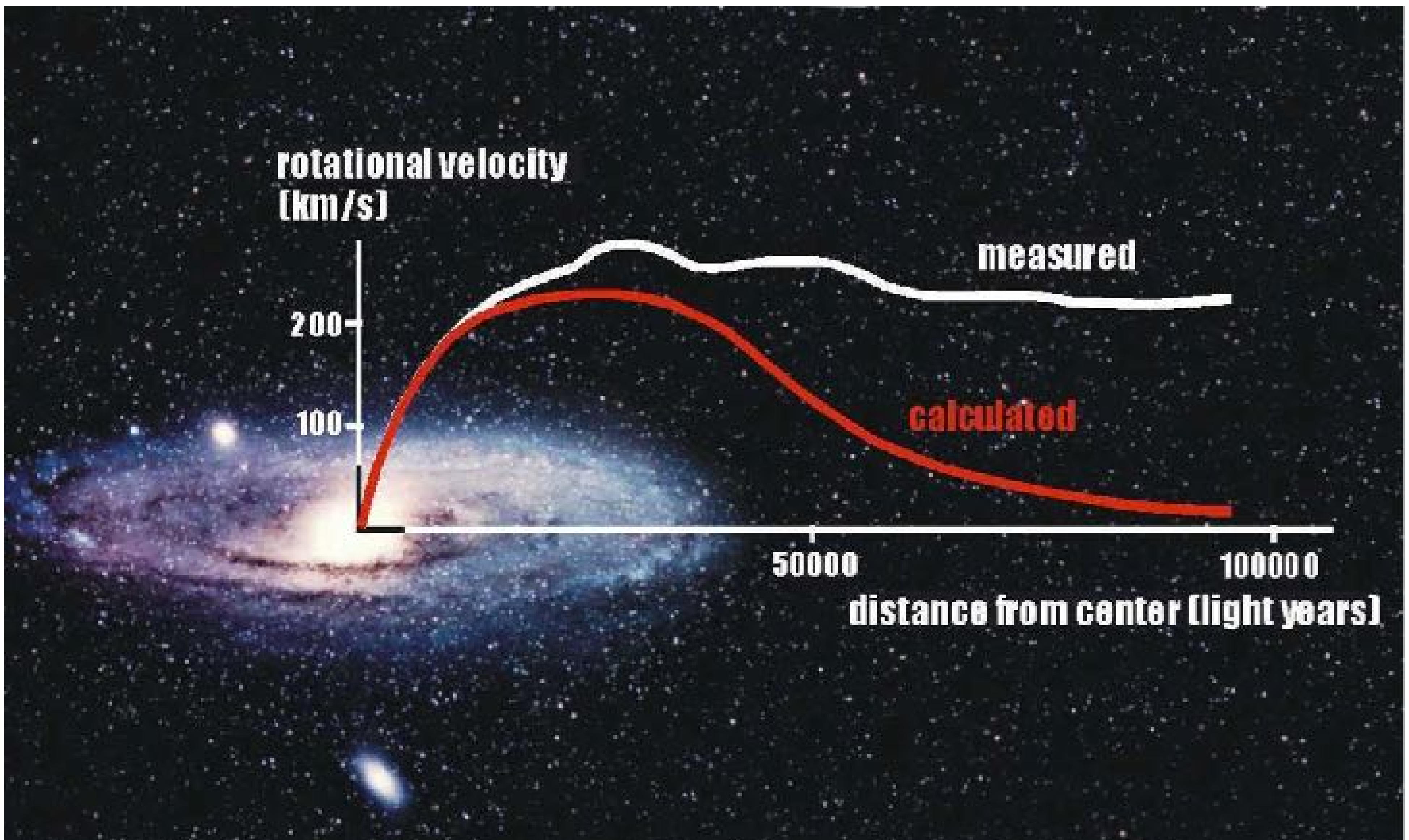
Two parameters: M_L, M_s

So by measuring v(r), the "rotation curve", we can test which model is the best fit and also obtain estimates for the mass of the galaxy.

Quick Calculation:

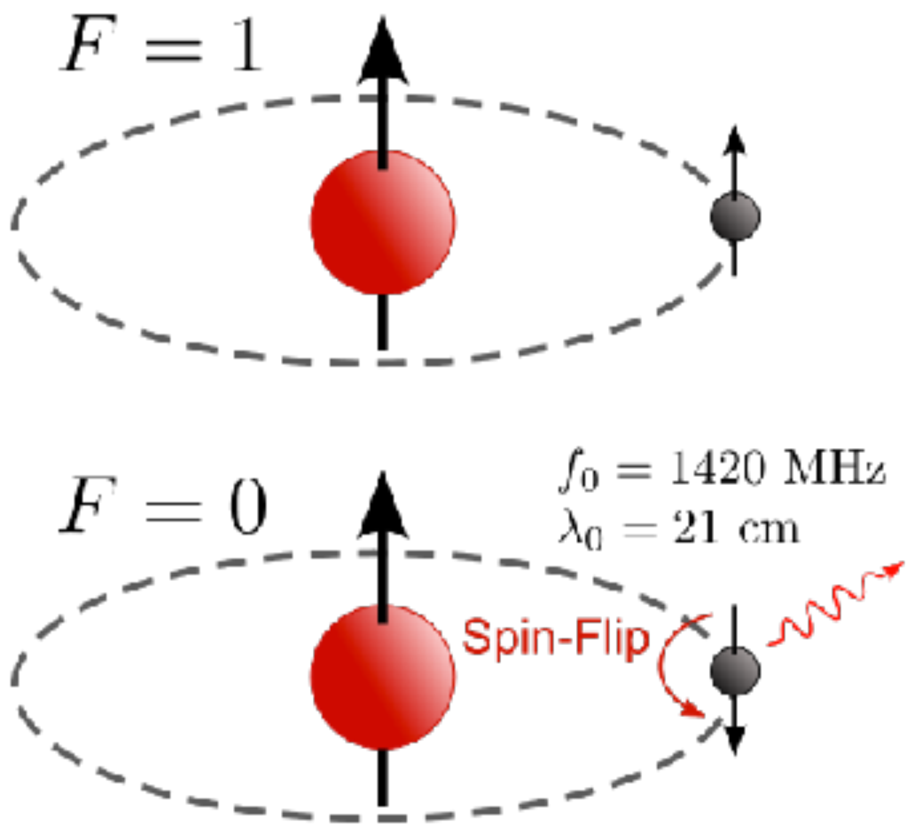
Estimate M(r=10 kpc)

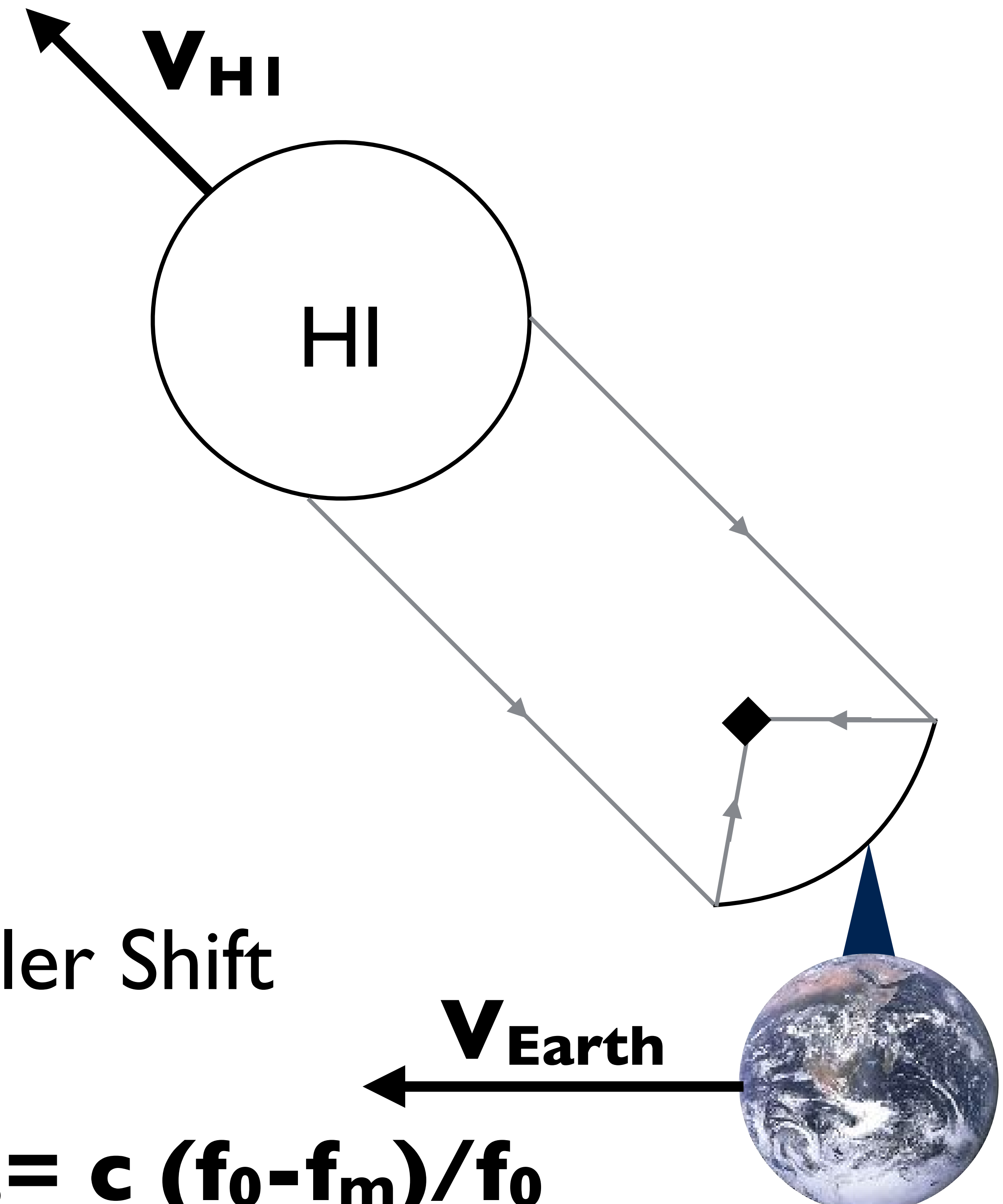
(G = 4.3×10^{-6} kpc $M_\odot^{-1}$ (km/s)^2)



Experiment and Data

Hyperfine Transition in Neutral Hydrogen (HI)





Doppler Shift

$$\mathbf{v_{Doppler} = (v_{HI} - v_{Earth})_{LOS} = c\,(f_0 - f_m)/f_0}$$

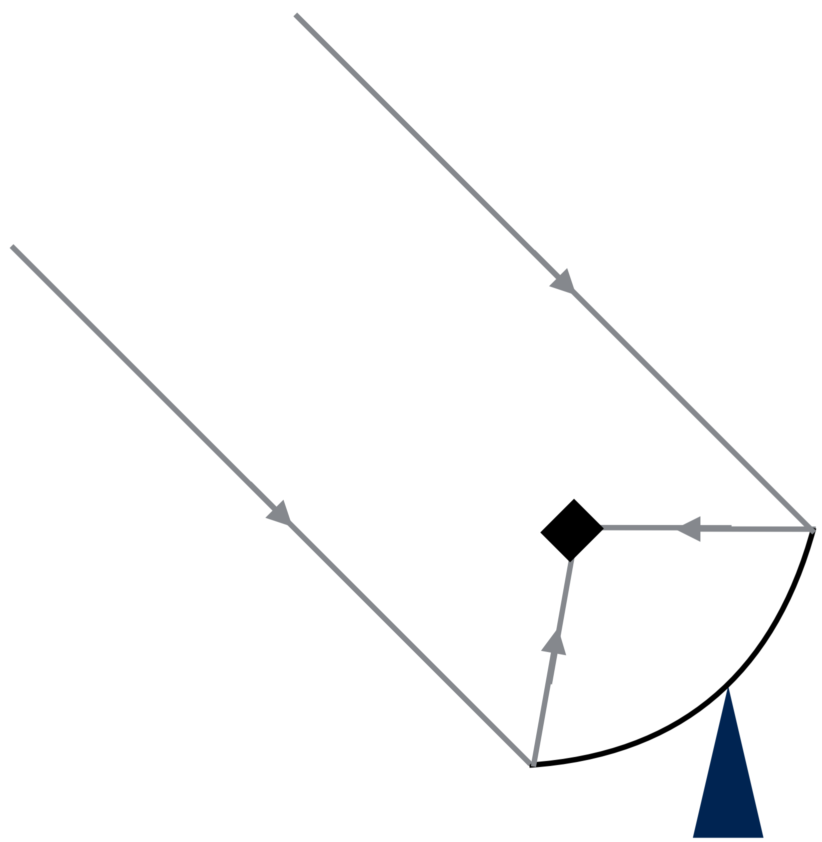
LOS: Line of Sight

Projected Velocities

f_0 = 1420.4 MHz

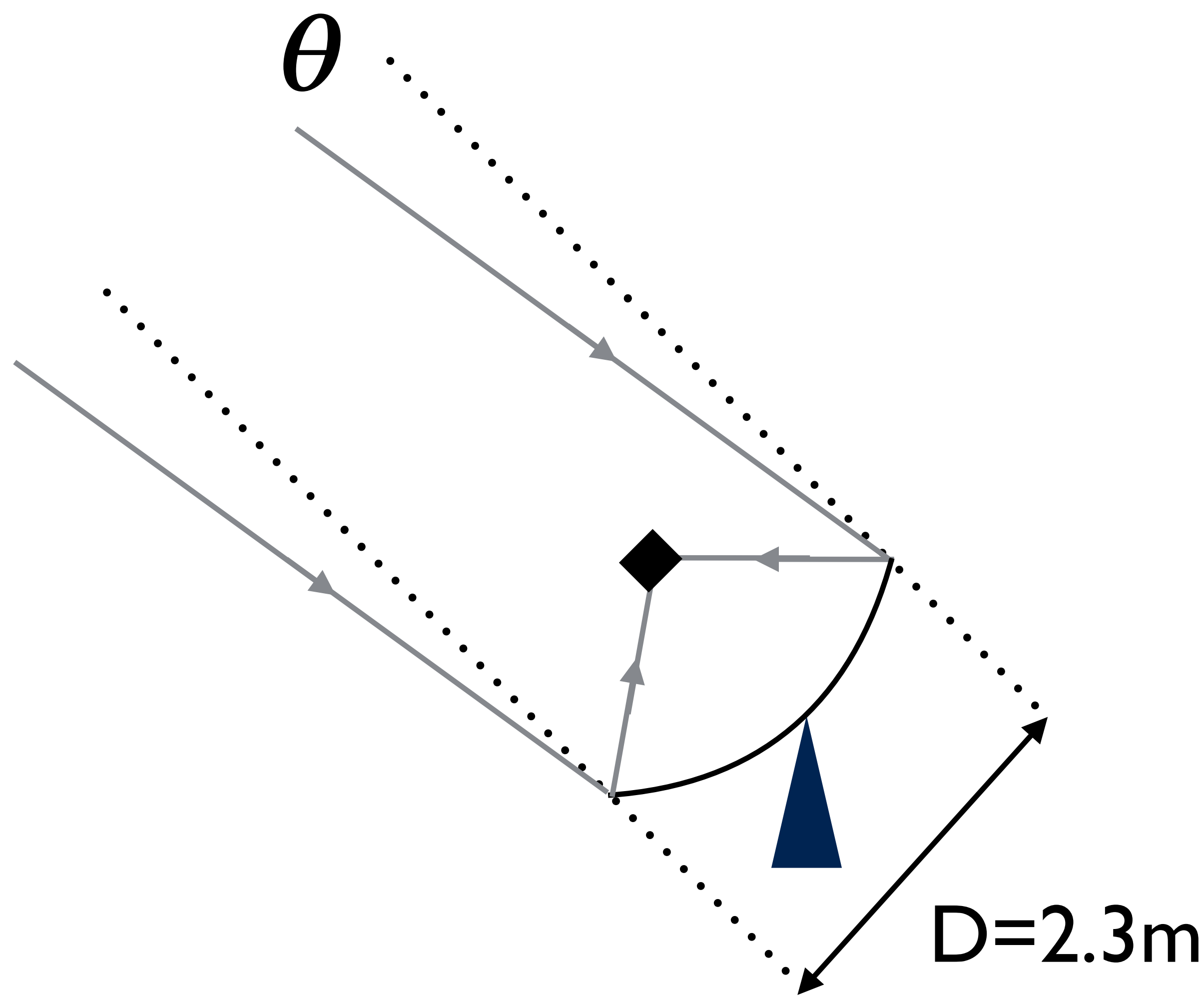
f_m : measured frequency

Radio Telescope Basics



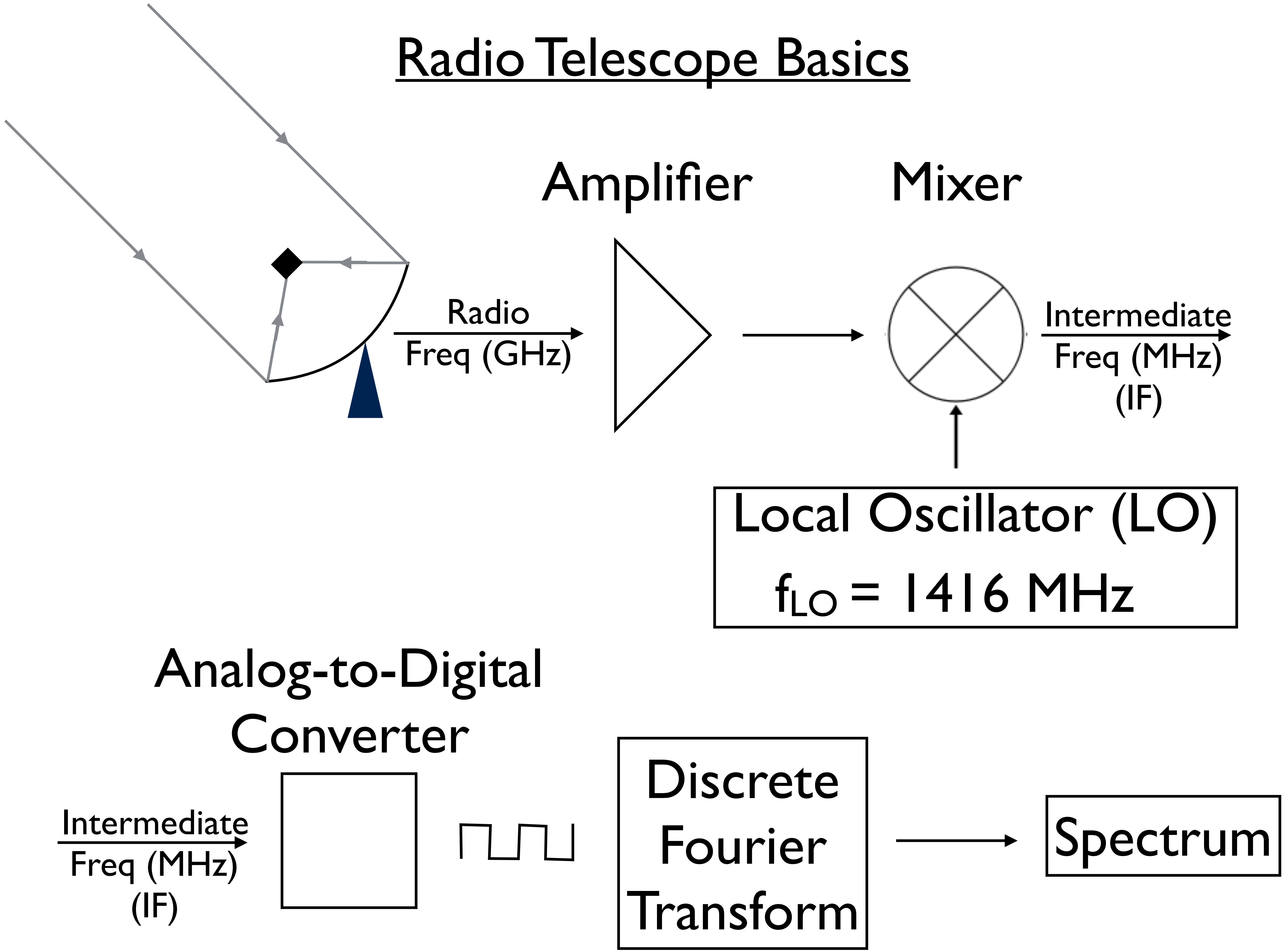
The Small Radio Telescope (SRT)
has a parabolic dish a D=2.3 m diameter
that focuses rays on a “feed” (black square)

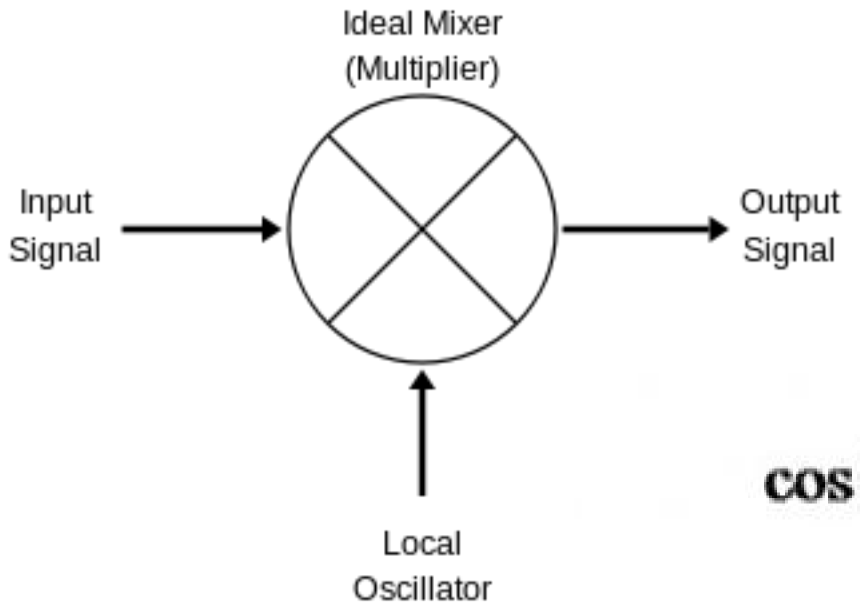
Radio Telescope Basics



Compute angle θ at which rays of 21-cm radiation at edge of dish interfere destructively at the "feed". (Twice this angle is roughly the resolution.)

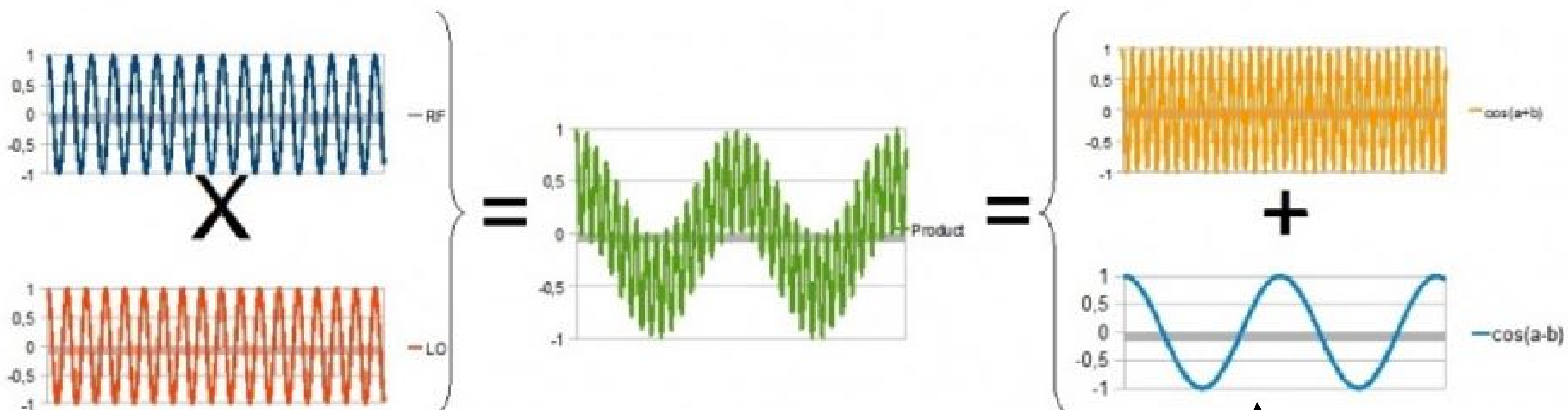
Radio Telescope Basics

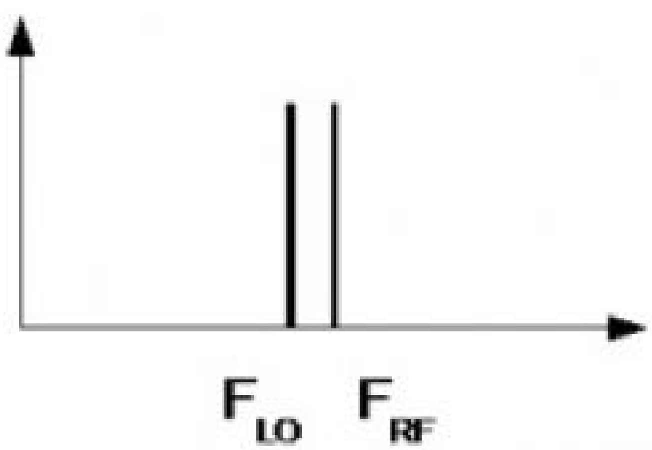




Frequency Mixer

$$\cos(\omega_{RF}.t).\cos(\omega_{LO}.t) = \frac{1}{2}[\cos((\omega_{RF}+\omega_{LO}).t) + \cos((\omega_{RF}-\omega_{LO}).t)]$$





LO: Local Oscillator
(reference frequency)

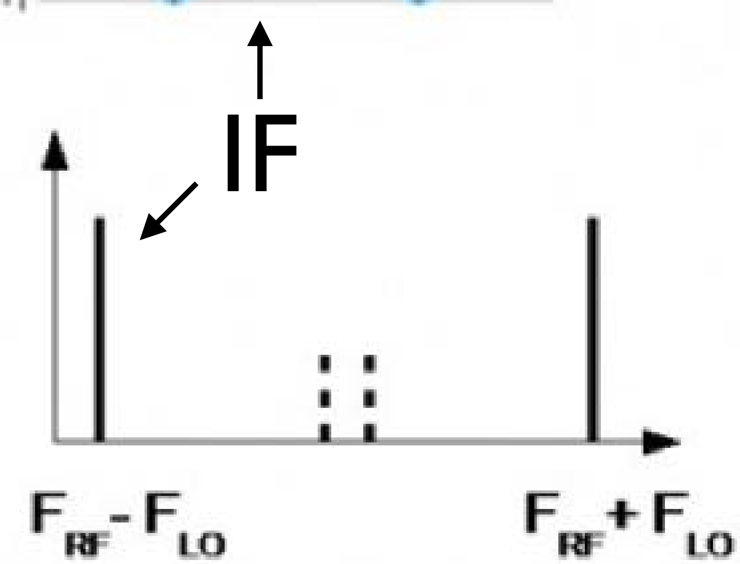
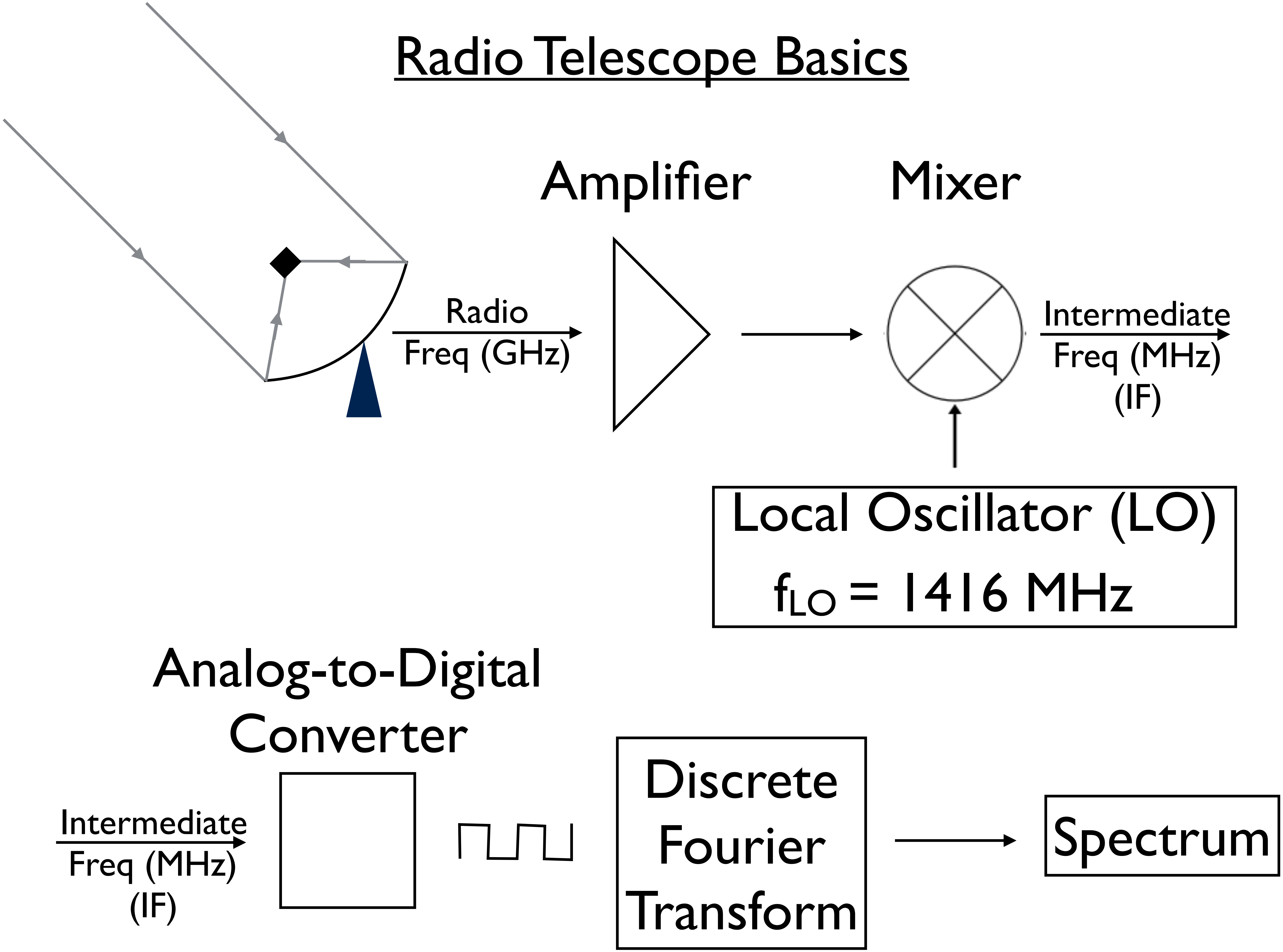


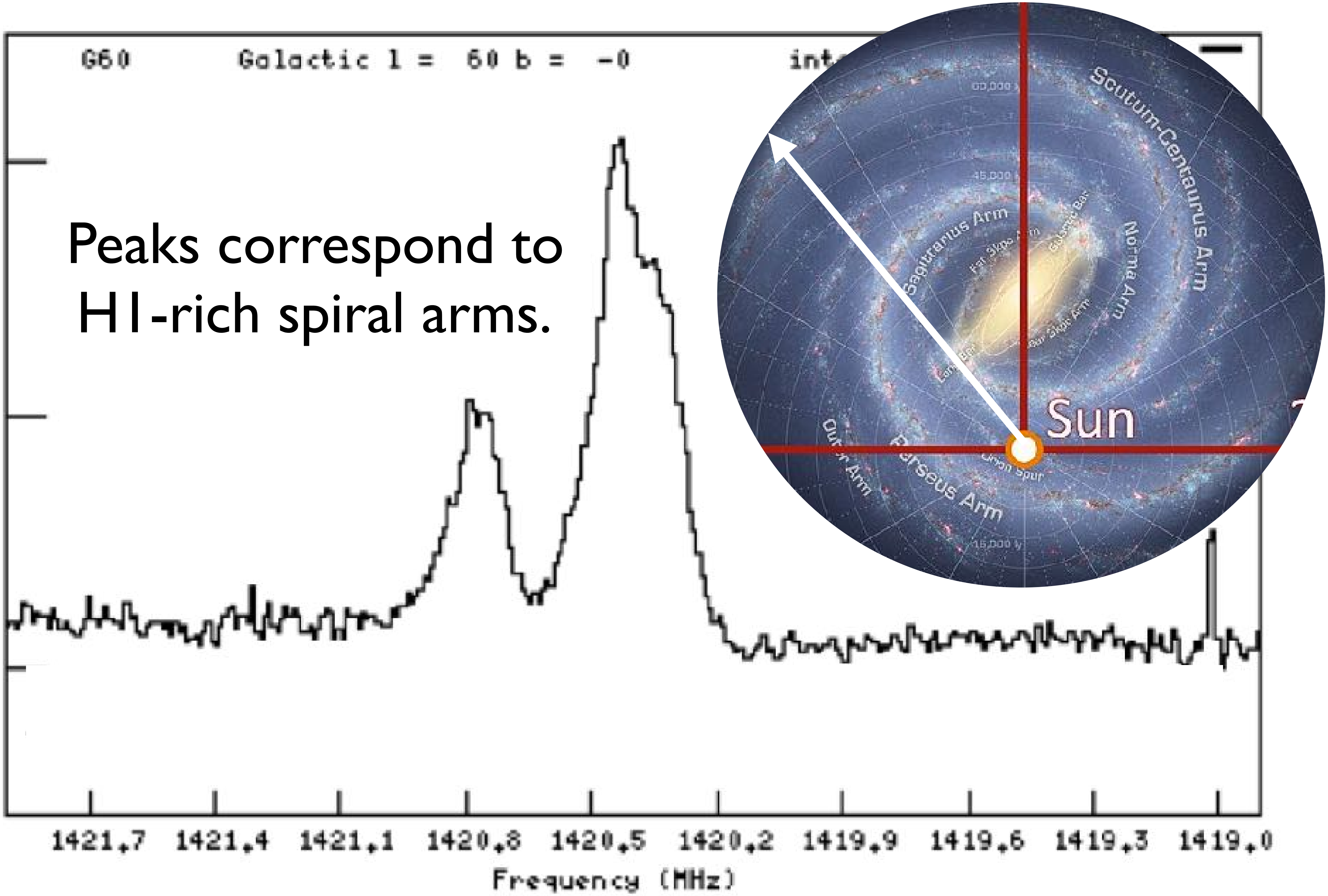
Image from: http://circuitcellar.com/cc-blog/fundamentals-of-iq-signals/

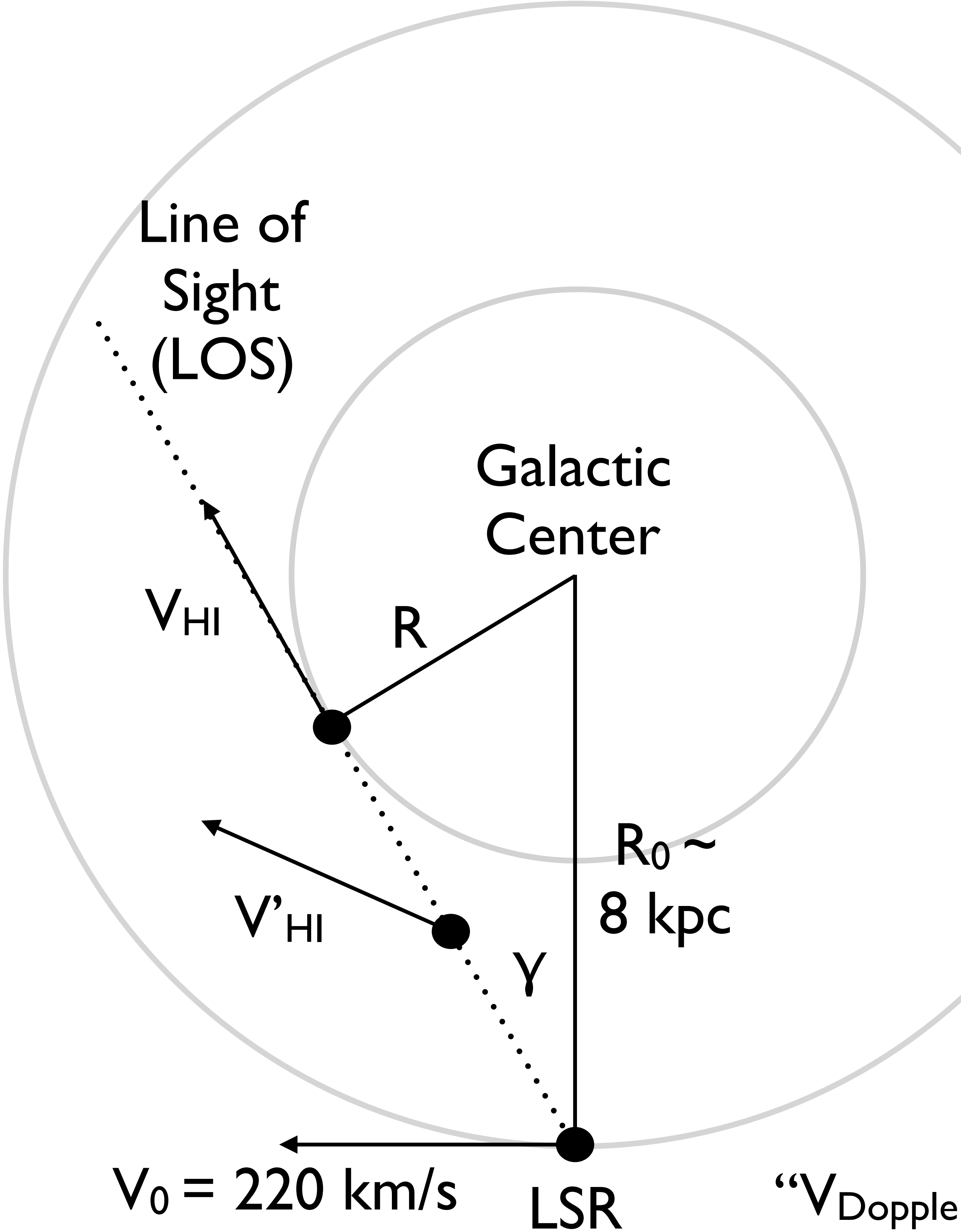
Radio Telescope Basics



Spectrum of HI Emission

Peaks correspond to H1-rich spiral arms.





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 $R=R_0\sin(\gamma)$.

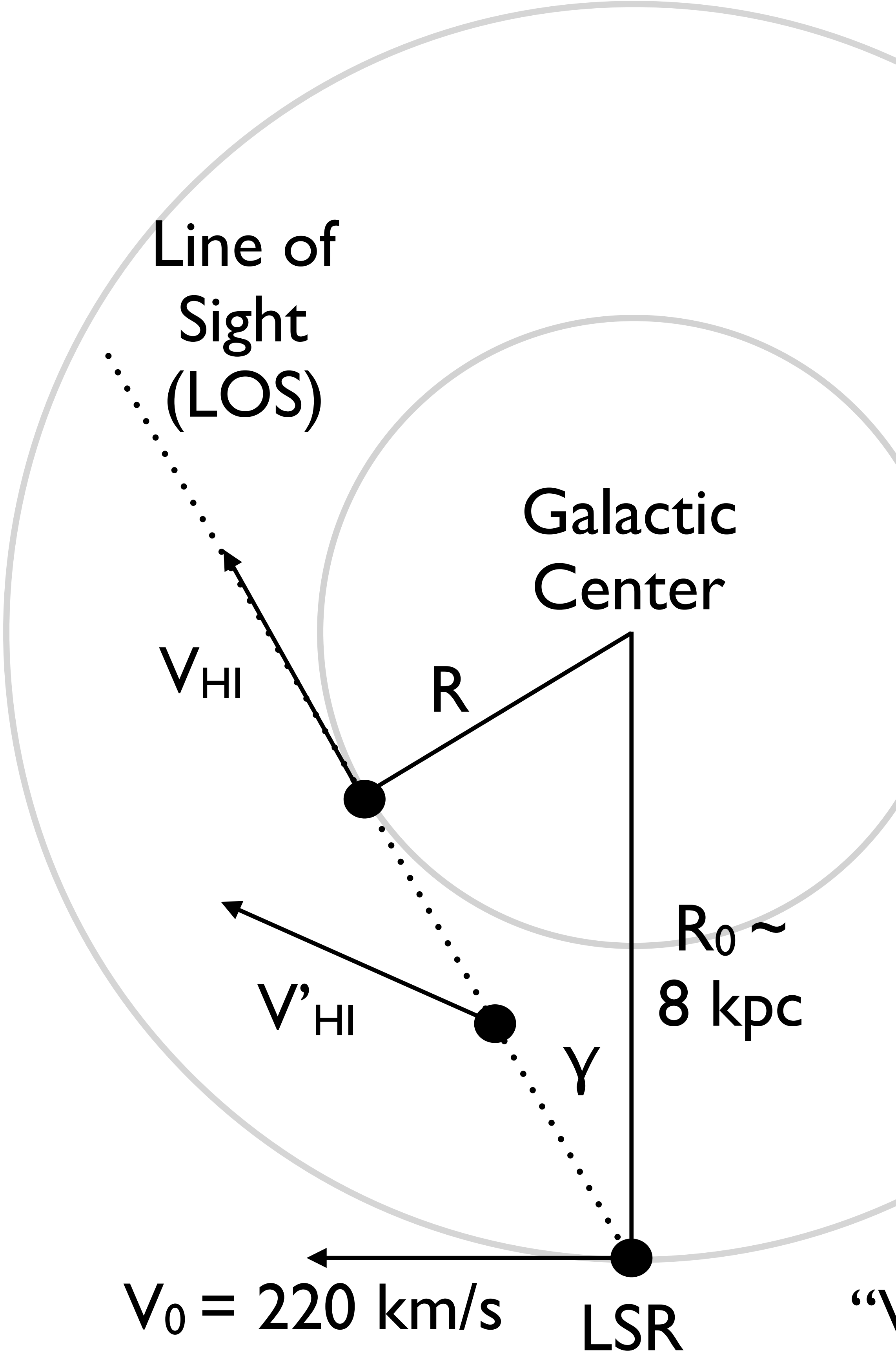
Rotation Curve:

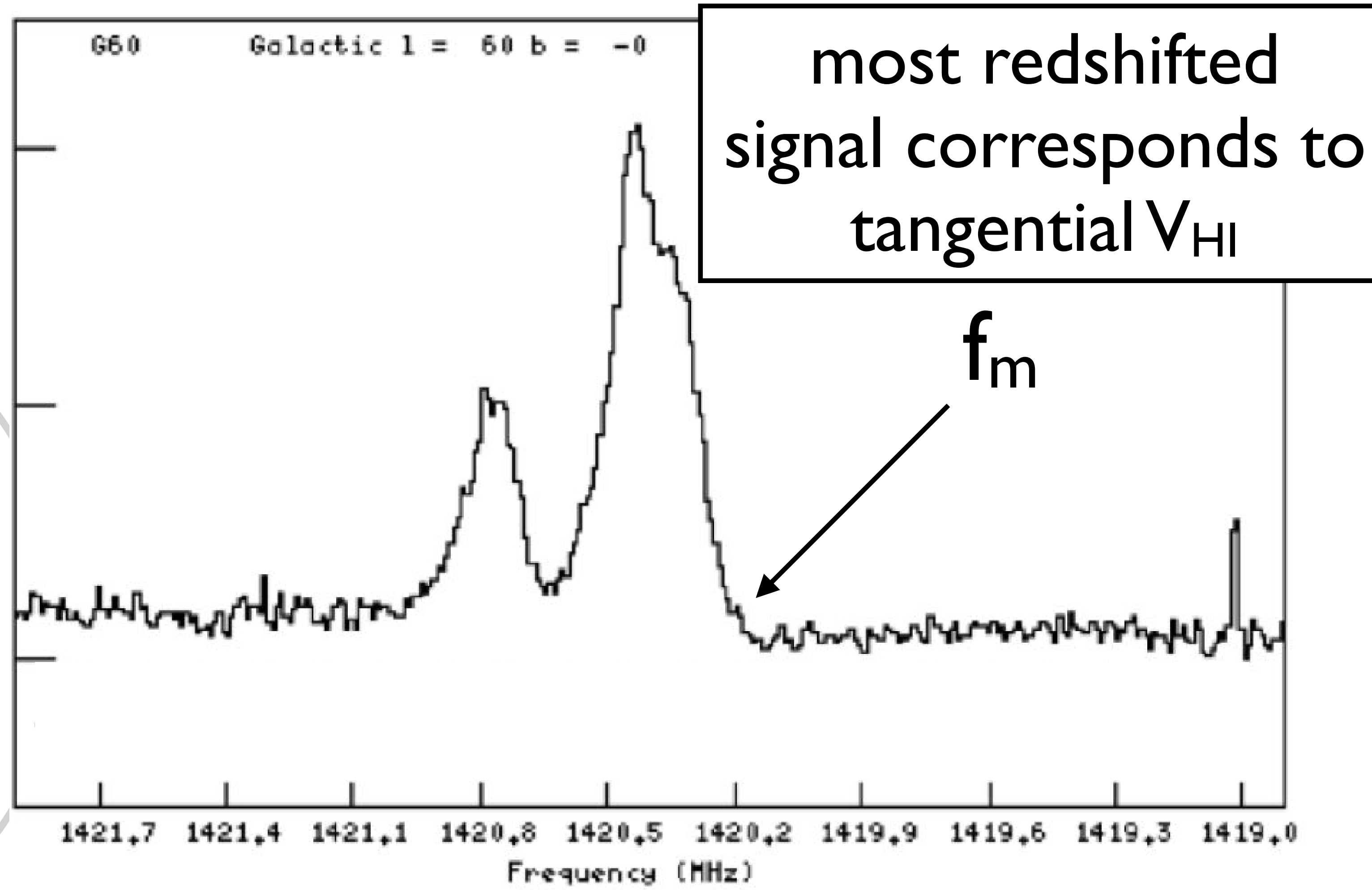
$$V_{HI}(R)=[V_{HI}-V_0\sin(\gamma)]+V_0\sin(\gamma)$$

↑

"$V_{Doppler}$" Measured from **most redshifted** H1 emission

(Almost…One important detail)





Rotation Curve:

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

↑

"$V_{Doppler}$" Measured from **most redshifted** H1 emission

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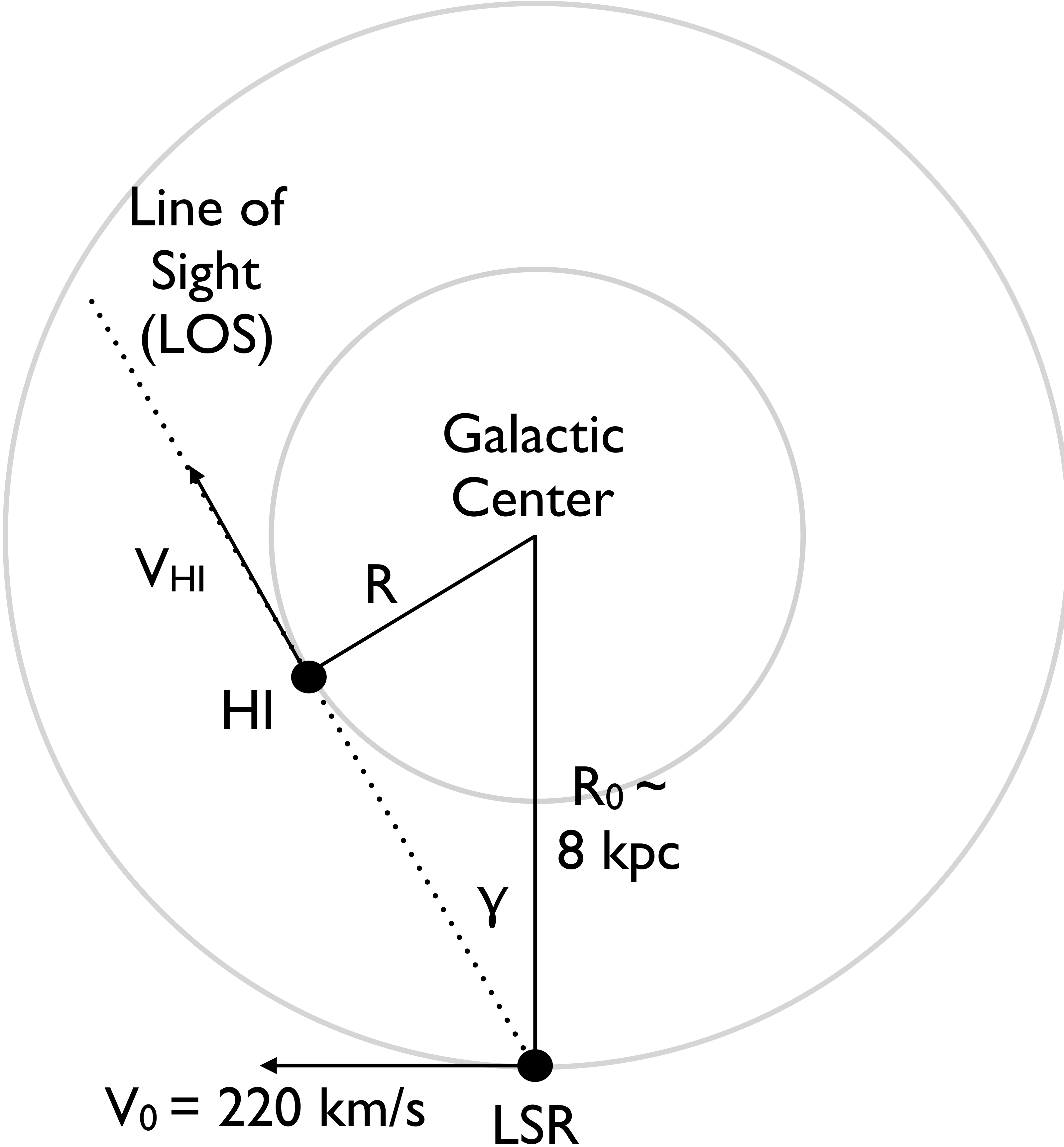


One important detail

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

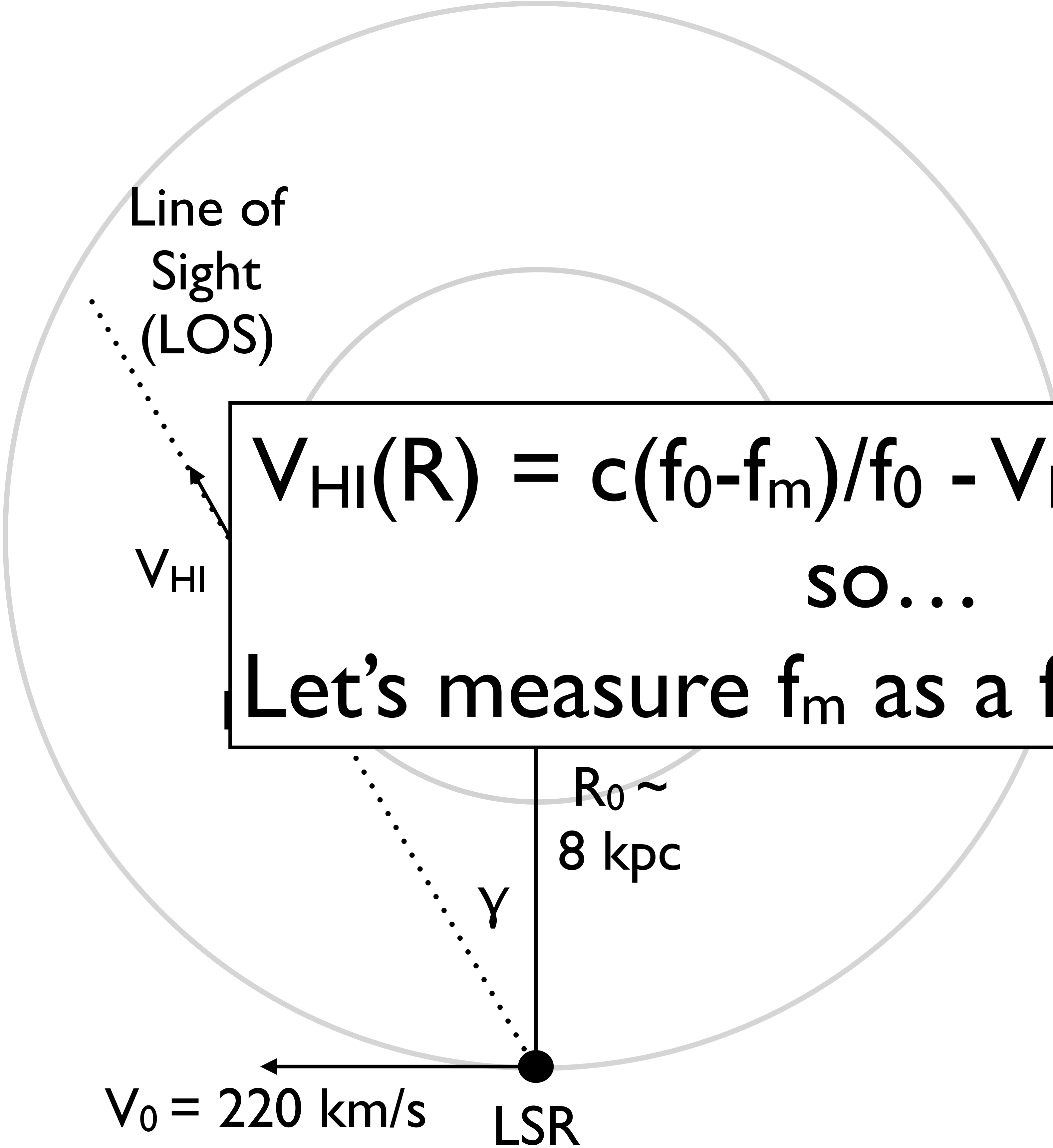
The velocity of the Earth with respect to the LSR must be taken into account.

$V_{HI} - V_0 \sin(\gamma) = V_{Doppler} - V_{LSR}$

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

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

One important detail



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

Earth
LSR
account.

pler-V_{LSR}

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

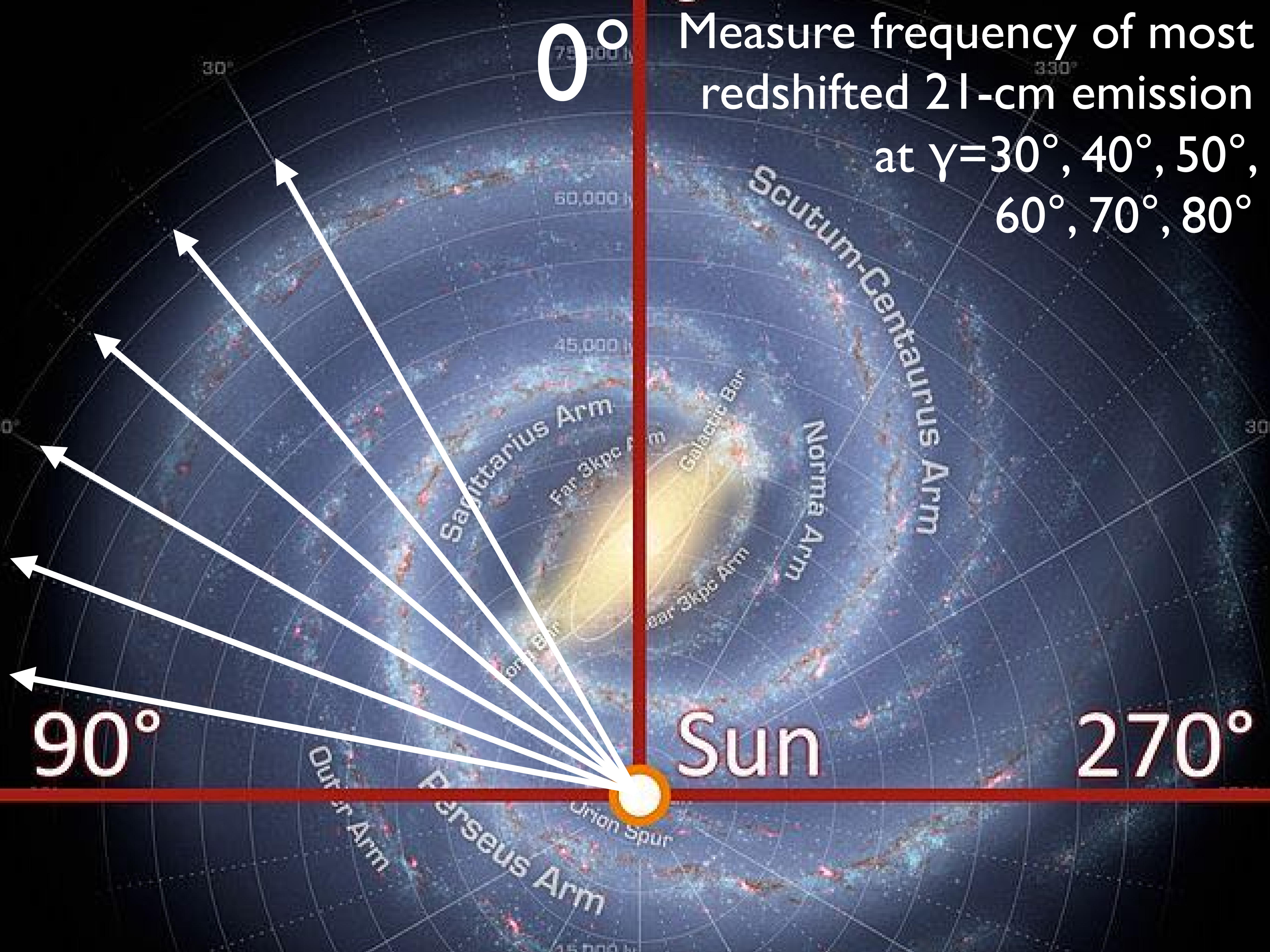
so…

Let's measure f_m as a function of γ!

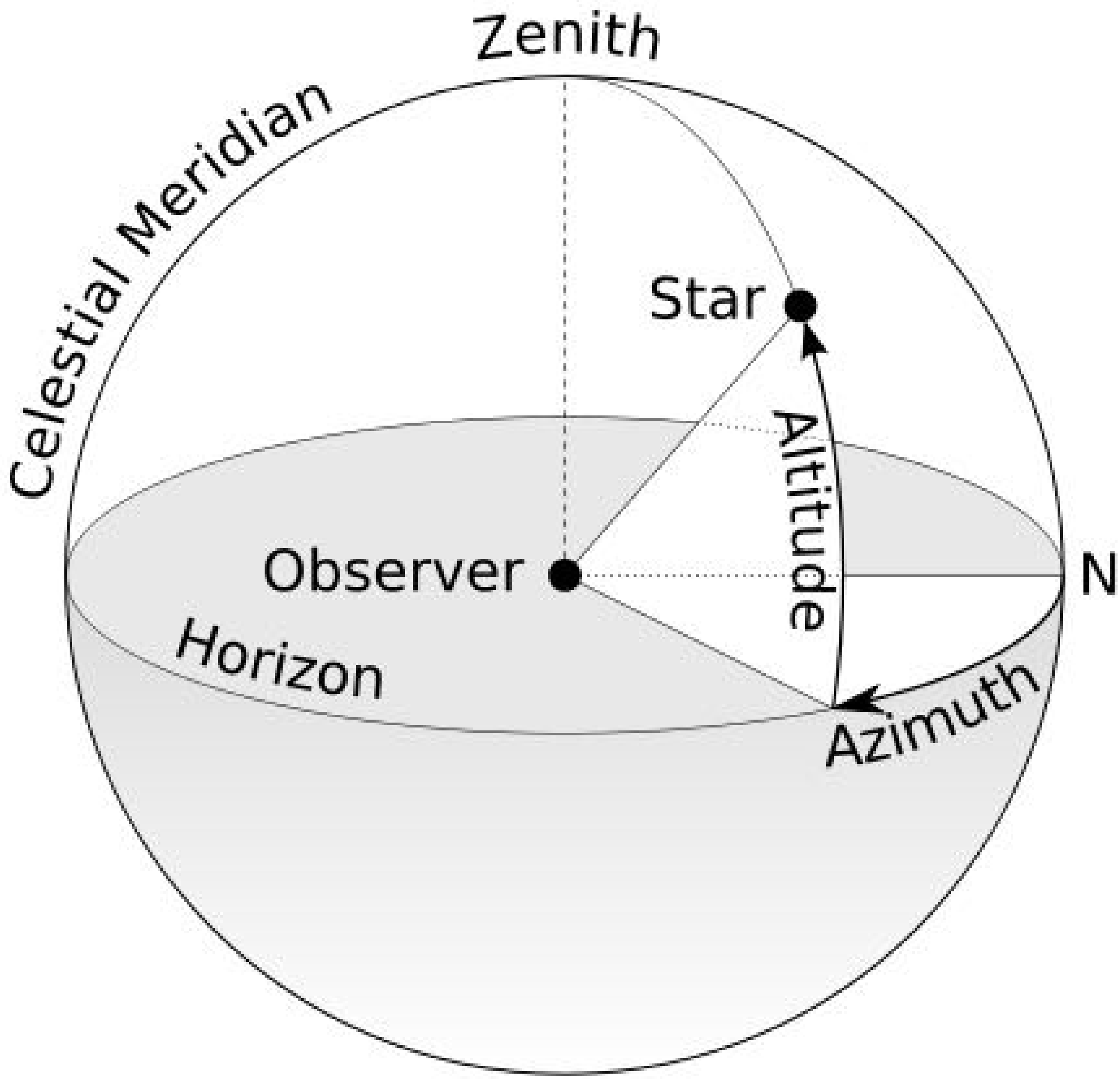
V_{LSR}: Earth's velocity with respect to the LSR along the LOS

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

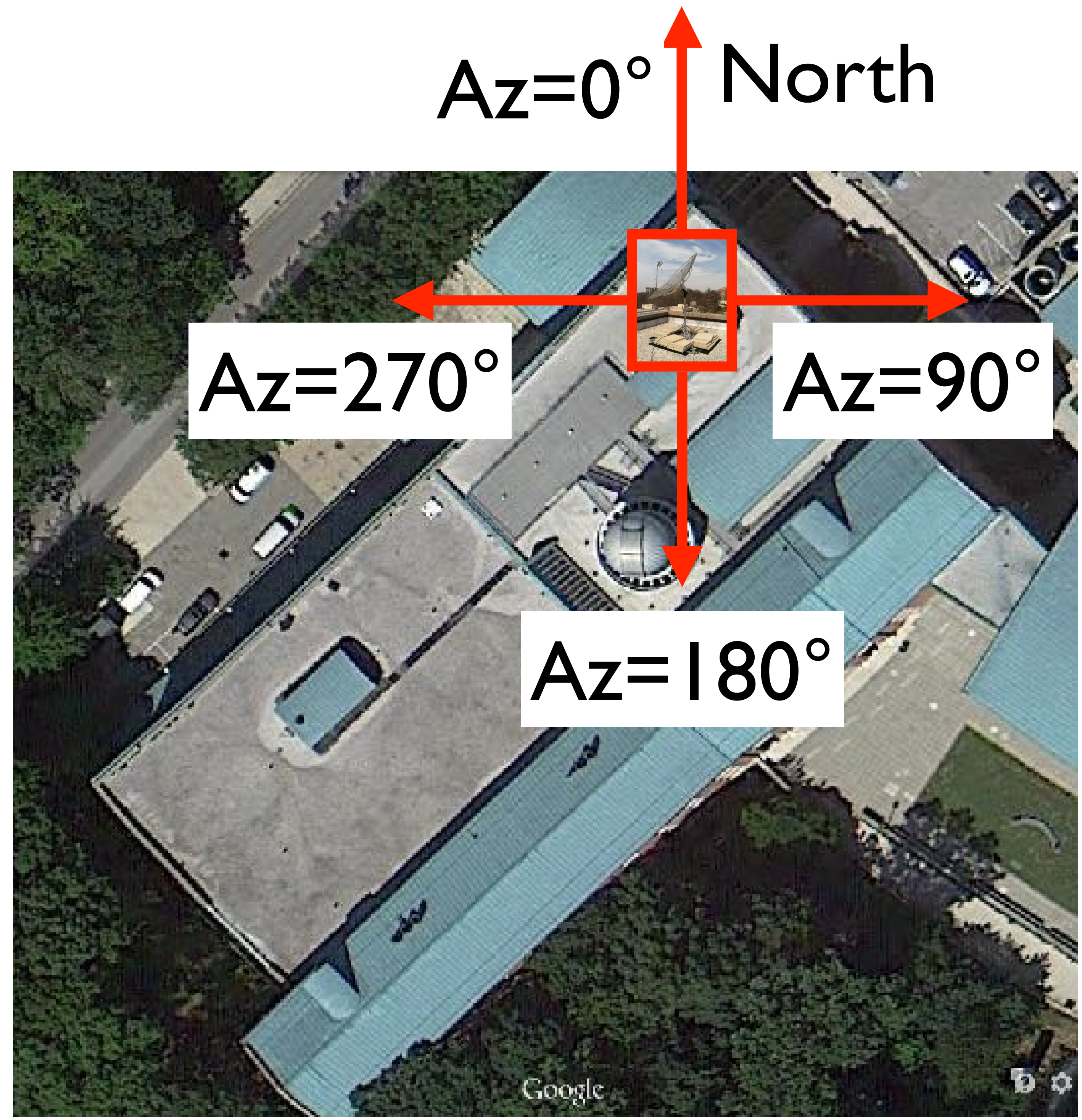
Measure frequency of most redshifted 21-cm emission at γ=30°, 40°, 50°, 60°, 70°, 80°



Horizon Coordinates: Azimuth and Elevation



Altitude is also called Elevation



Galactic targets available (Elevation > 30°) 4am-10am each day.

For Next Week:

Use Telescope Scheduler

1) Make sure to practice with the telescope before actual observations.
2) Obtain a reference spectrum off the plane of the galaxy (10 minute integration). This can be used to model/remove the systematic signal not associated with the galactic emission.
3) Record 10 minutes of data at γ=30°, 40°, 50°, 60°, 70°, 80°
4) Make a composite plot of the average of all spectra. See sample code on wiki.
5) Start writing up Intro, Theory and Experiment/Data for next Monday.
6) Watch Python Tutorial 3 (also on wiki) for next Monday.