

# **ASTR-3301: Extragalactic Astronomy**

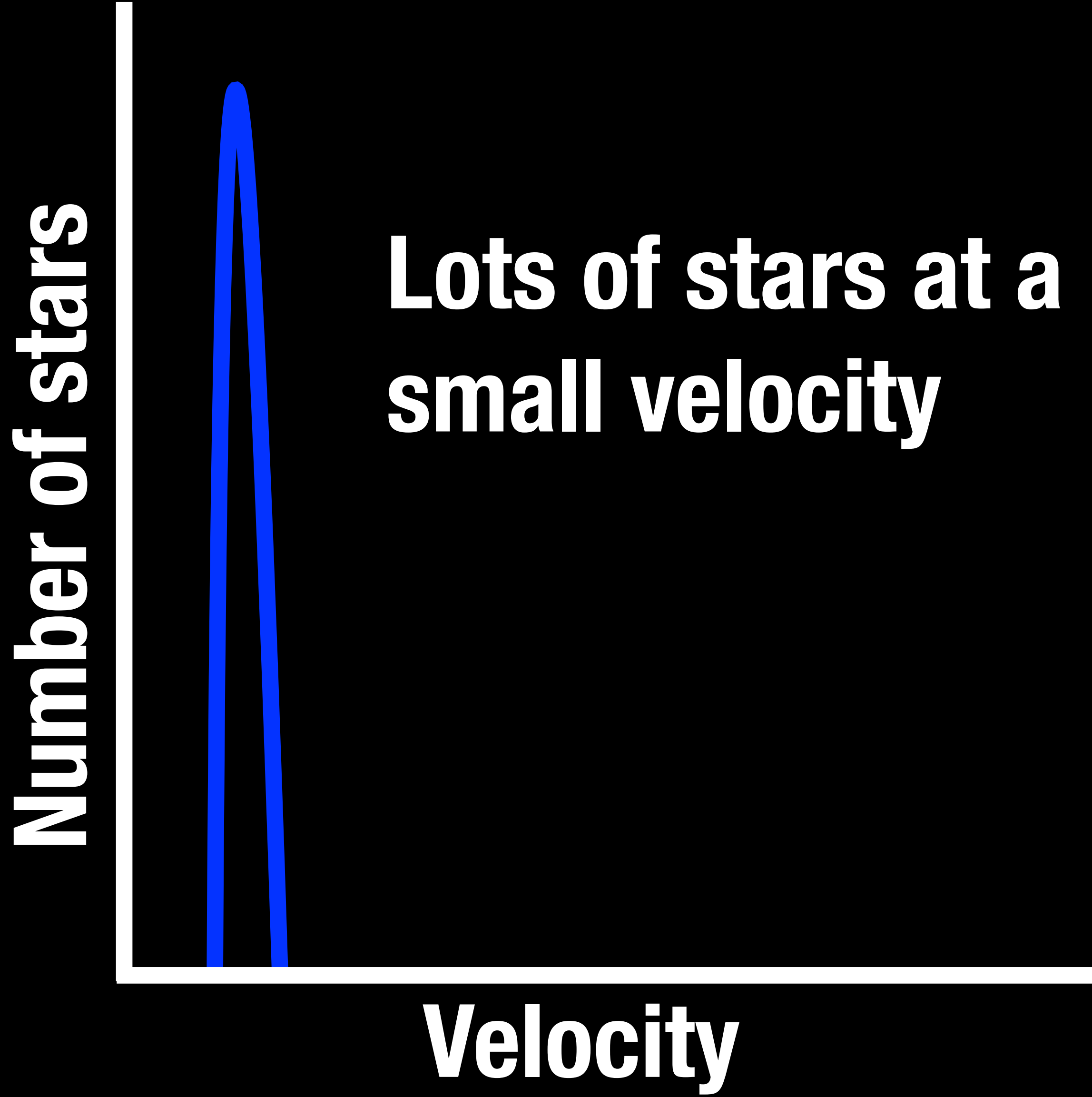
A deep-field image of galaxies, showing a variety of shapes and colors (orange, yellow, blue, white) against a dark background. A faint grid of blue lines is overlaid on the image, suggesting a coordinate system or a survey field.

## **Lecture #12: Galaxy Kinematics**

# Results for Ellipticals: Kinematic Correlations



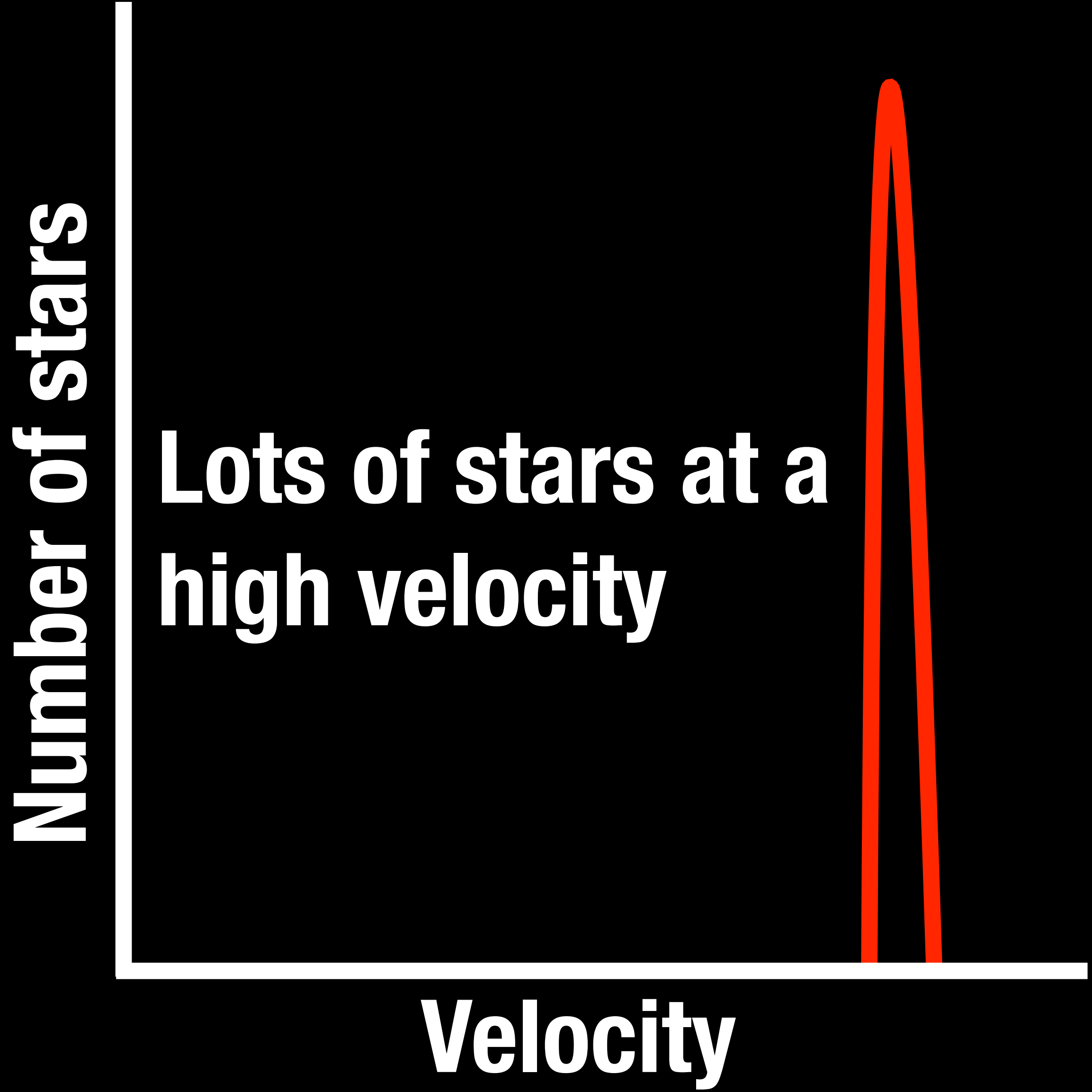
**If all stars were blueshifted  
(all moving towards us)**



# Results for Ellipticals: Kinematic Correlations



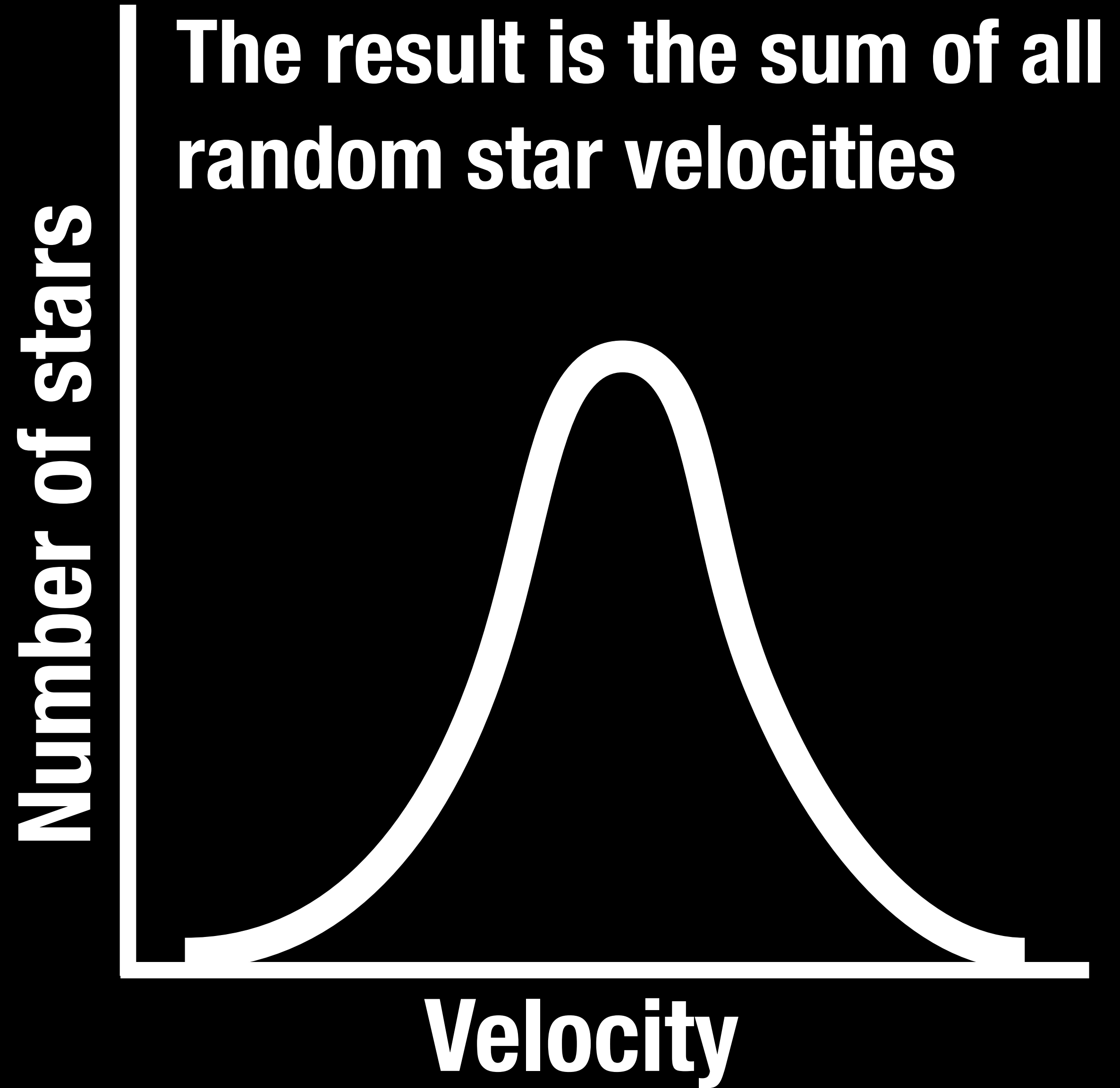
If all stars were redshifted  
(all moving away from us)



# Results for Ellipticals: Kinematic Correlations

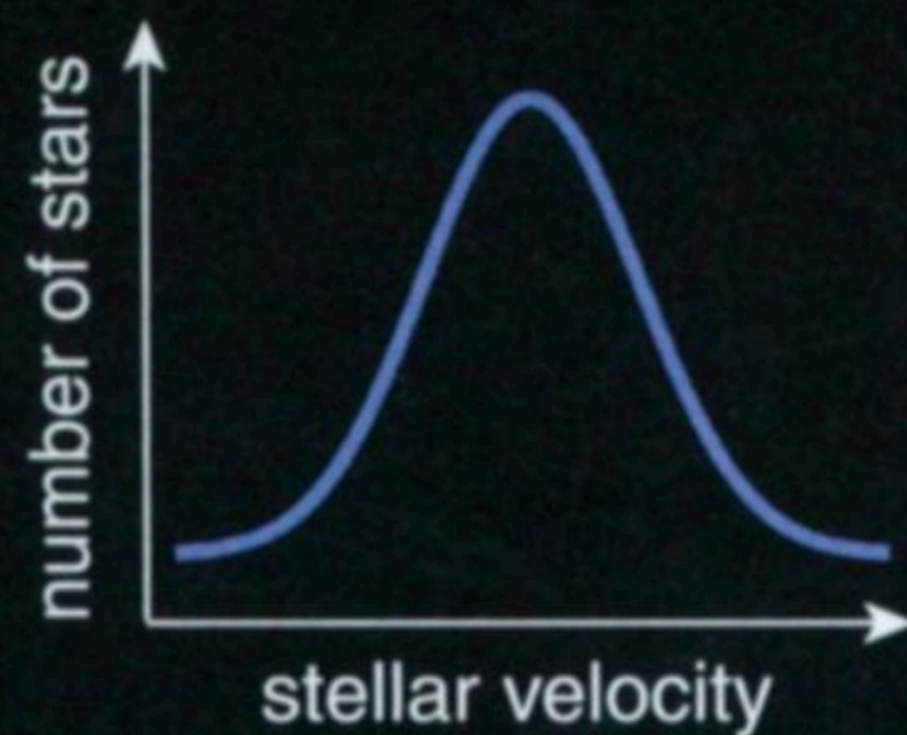
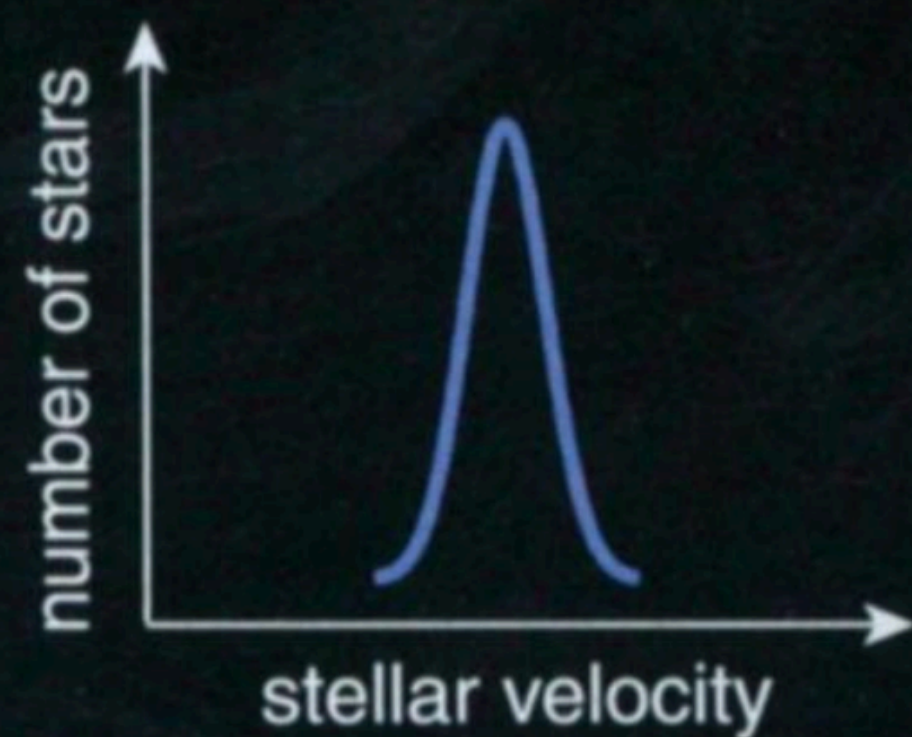
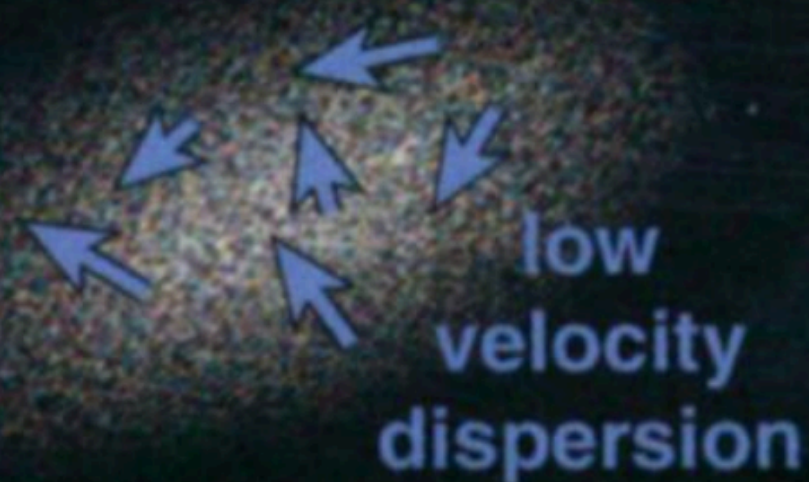


But stars are moving on ellipses in billions of orientations



# Results for Ellipticals: Kinematic Correlations

velocity dispersions in elliptical galaxies

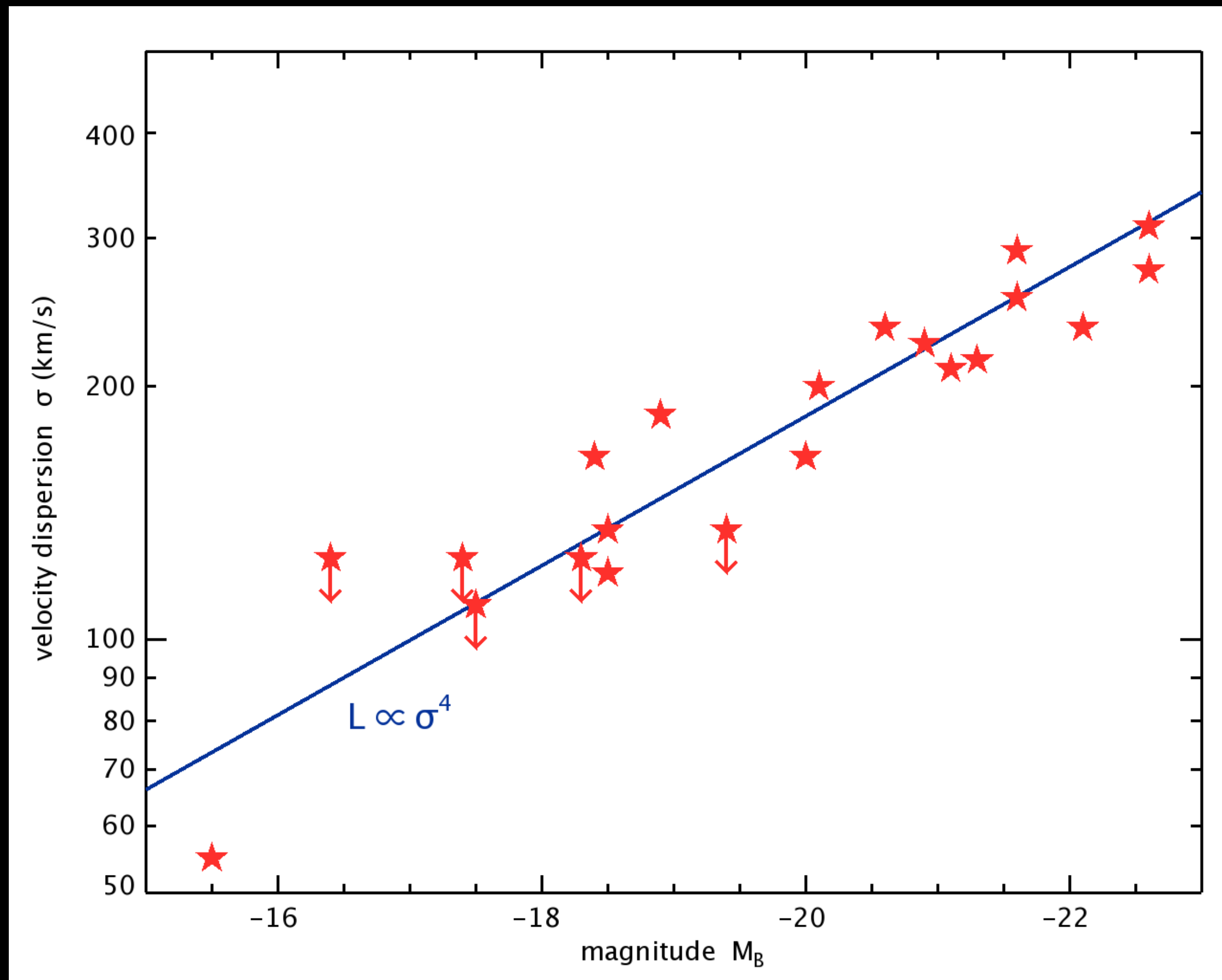


**Low velocity dispersion:  
skinny distribution**

**High velocity dispersion: fat  
distribution**

# The Faber-Jackson Relation

By measuring  $\sigma$  in elliptical galaxies with known distances, Faber and Jackson discovered the correlation between  $\sigma$  and  $M$  for Es

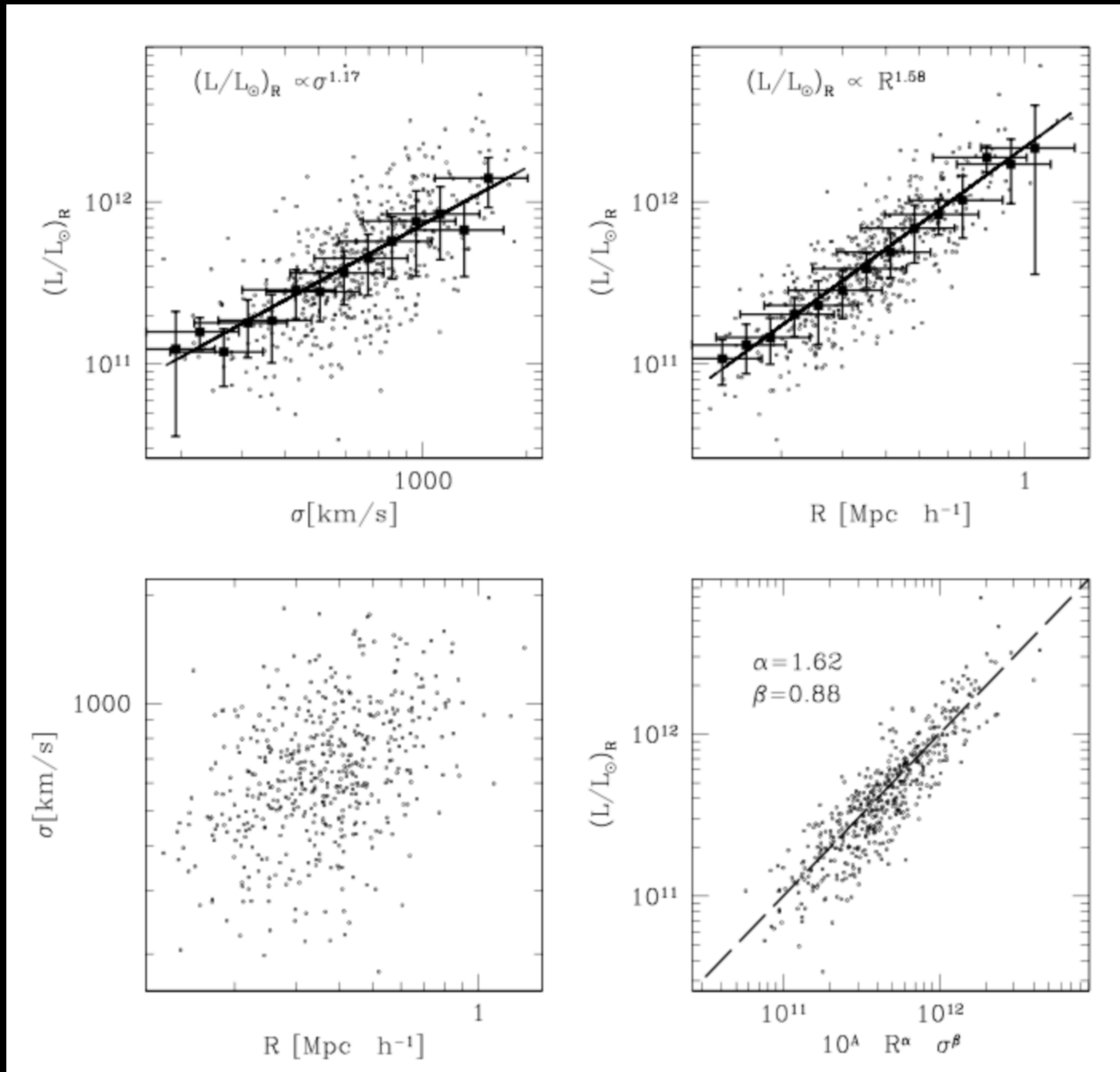


Faber-Jackson relation:  $L \sim \sigma^4$  ( $\sigma$ : central velocity disp.)

$$\frac{L_V}{2 \times 10^{10} L_{\odot}} = \left( \frac{\sigma}{200 \text{ km s}^{-1}} \right)^4$$

(Faber & Jackson 1976, ApJ, 204, 668)

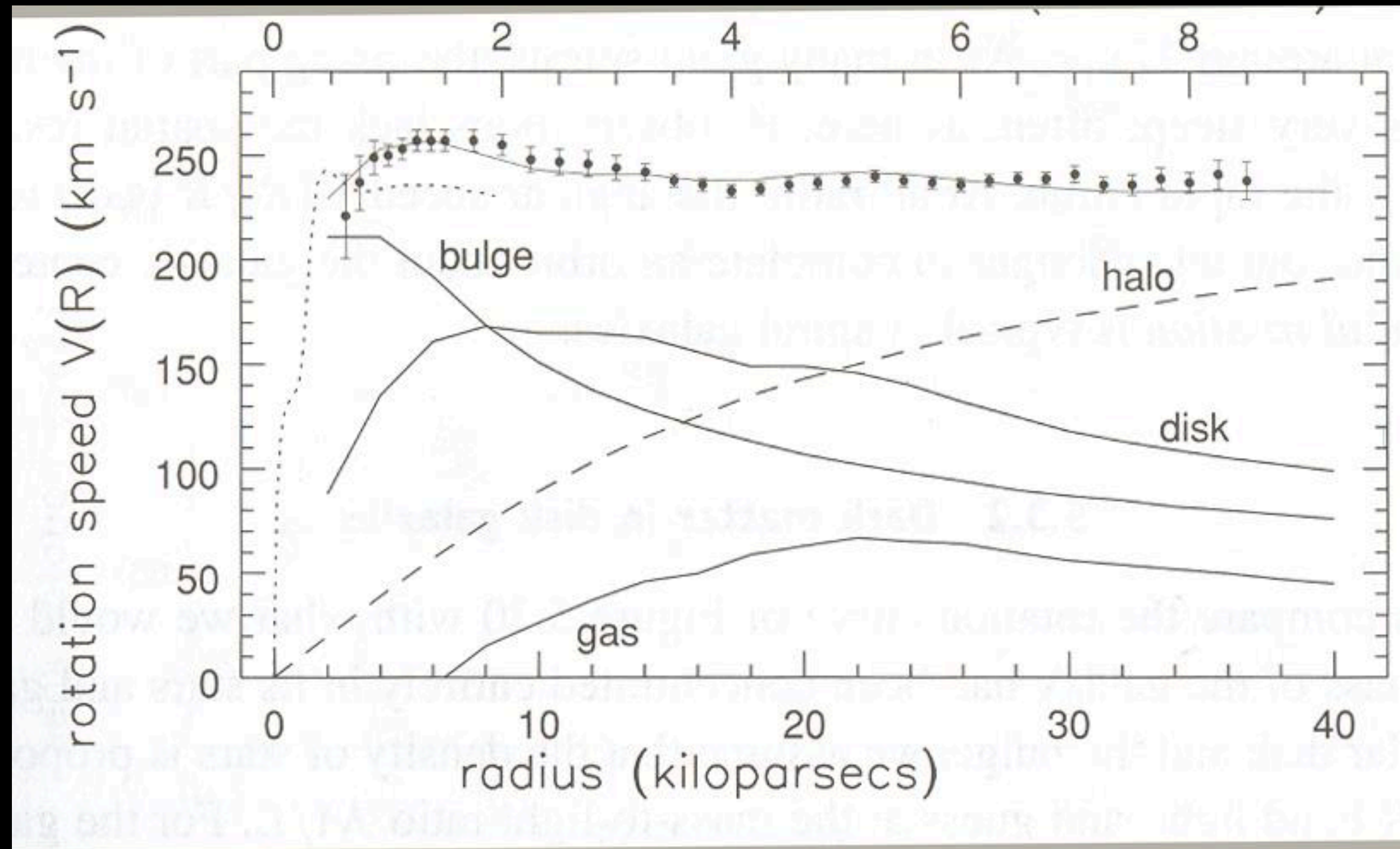
# The Fundamental Plane Relation



(Diaz & Muriel, MNRAS, 364, 1299)

- Reexaminations over the years yielded an abundance of scatter about the FJ relation (top left panel)
- Tighter correlation found for  $L$  vs galaxy radius ( $R$ ) and  $\sigma \rightarrow$  renamed “Fundamental Plane” (3 variables instead of 2)

# Spiral Galaxy Rotation Curves



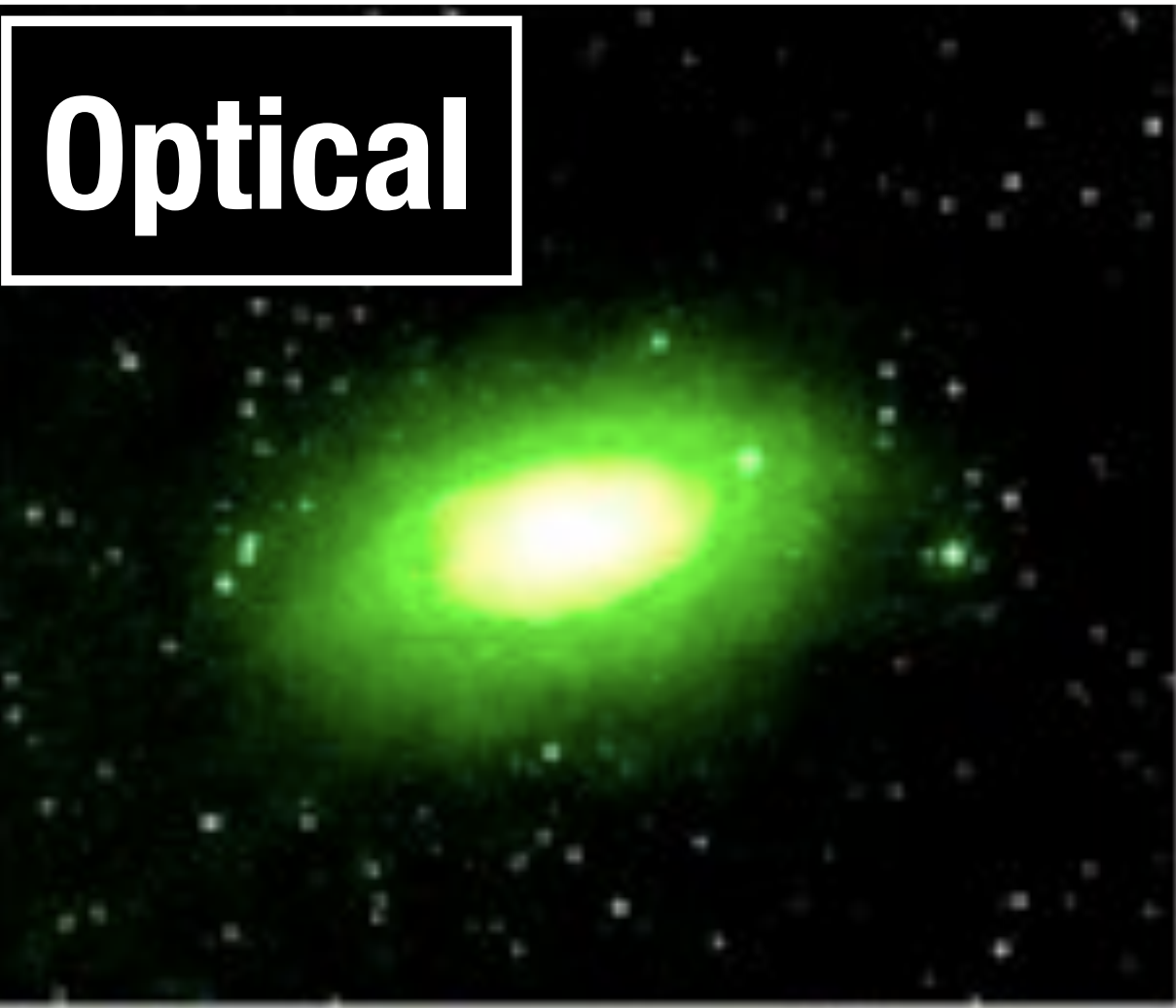
(Sparke & Gallagher, p 197)

- Dotted line: CO observations (traces colder molecular gas)
- Points and solid line: H I 21-cm measurements
- Bulge, disk, and gas: deduced from surface-brightness profiles
- Inferred dark halo mass: 2 to 4 times visible mass (in general)

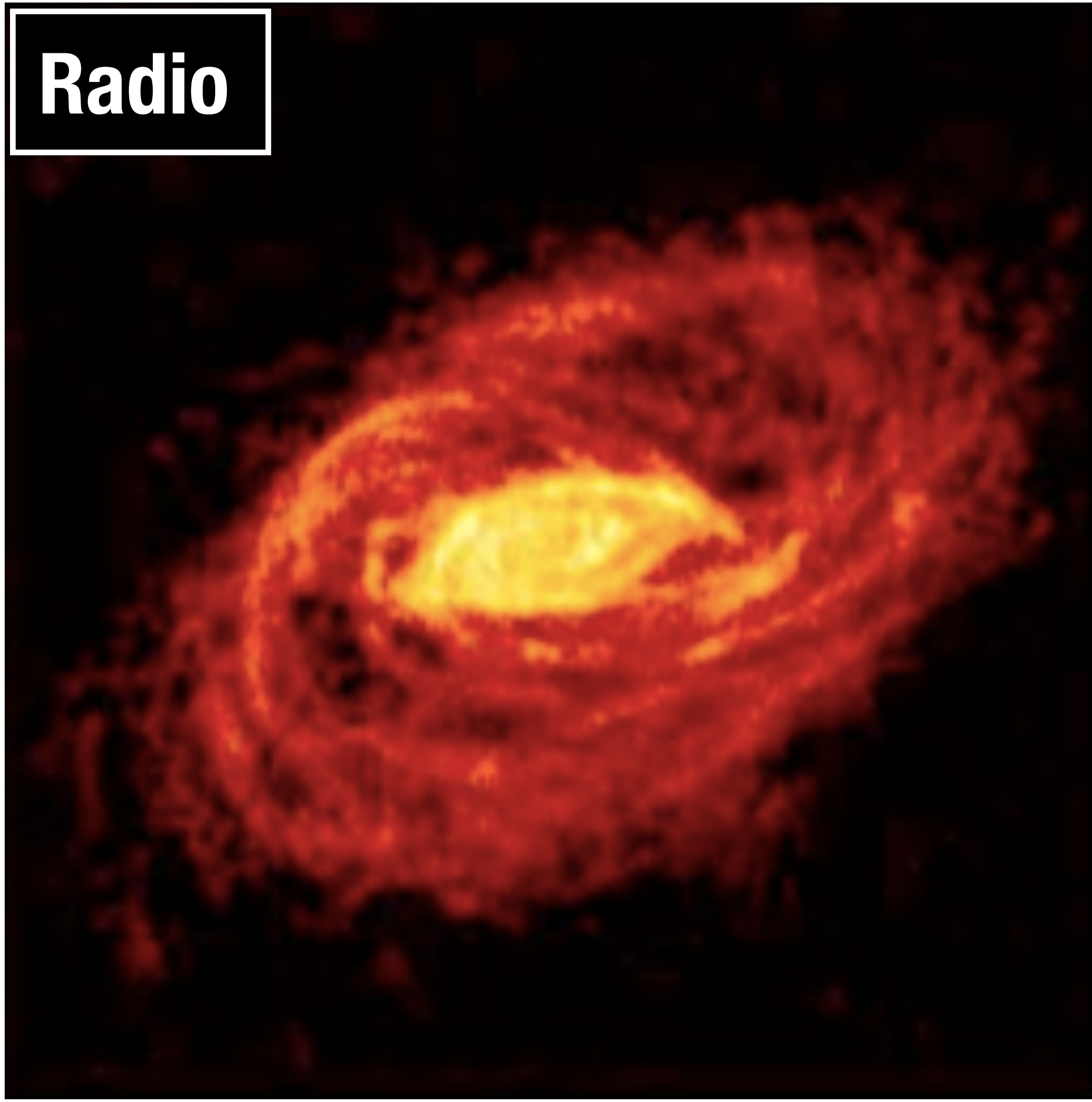


# HI 21cm Emission Line

**Optical**



**Radio**

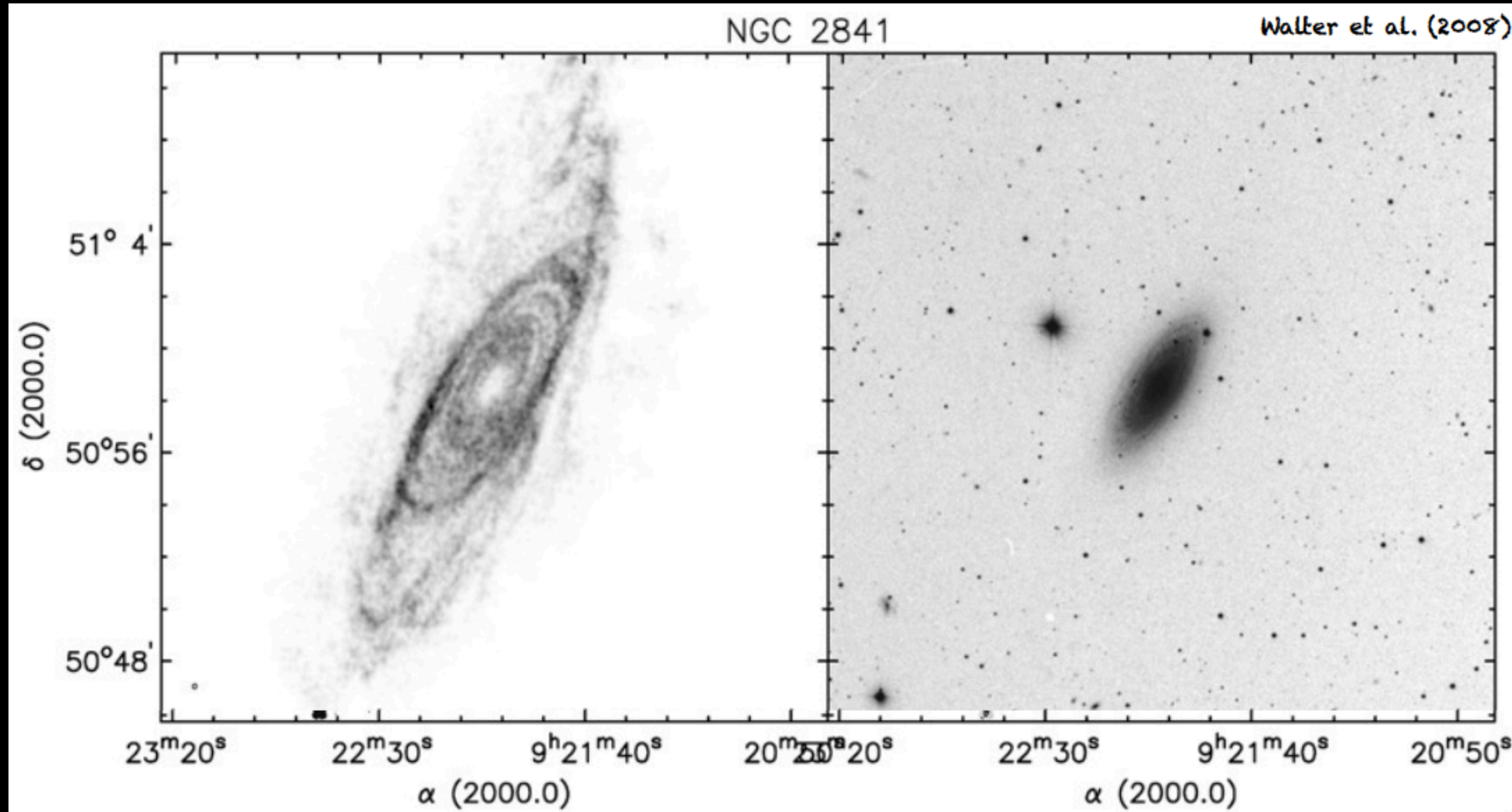


**Ultraviolet**



**Because HI is so prevalent in gas-dominated galaxies (spirals, mostly), the extent of the 21cm radiation extends much further past the stellar radius (cold gas more abundant than stars)**

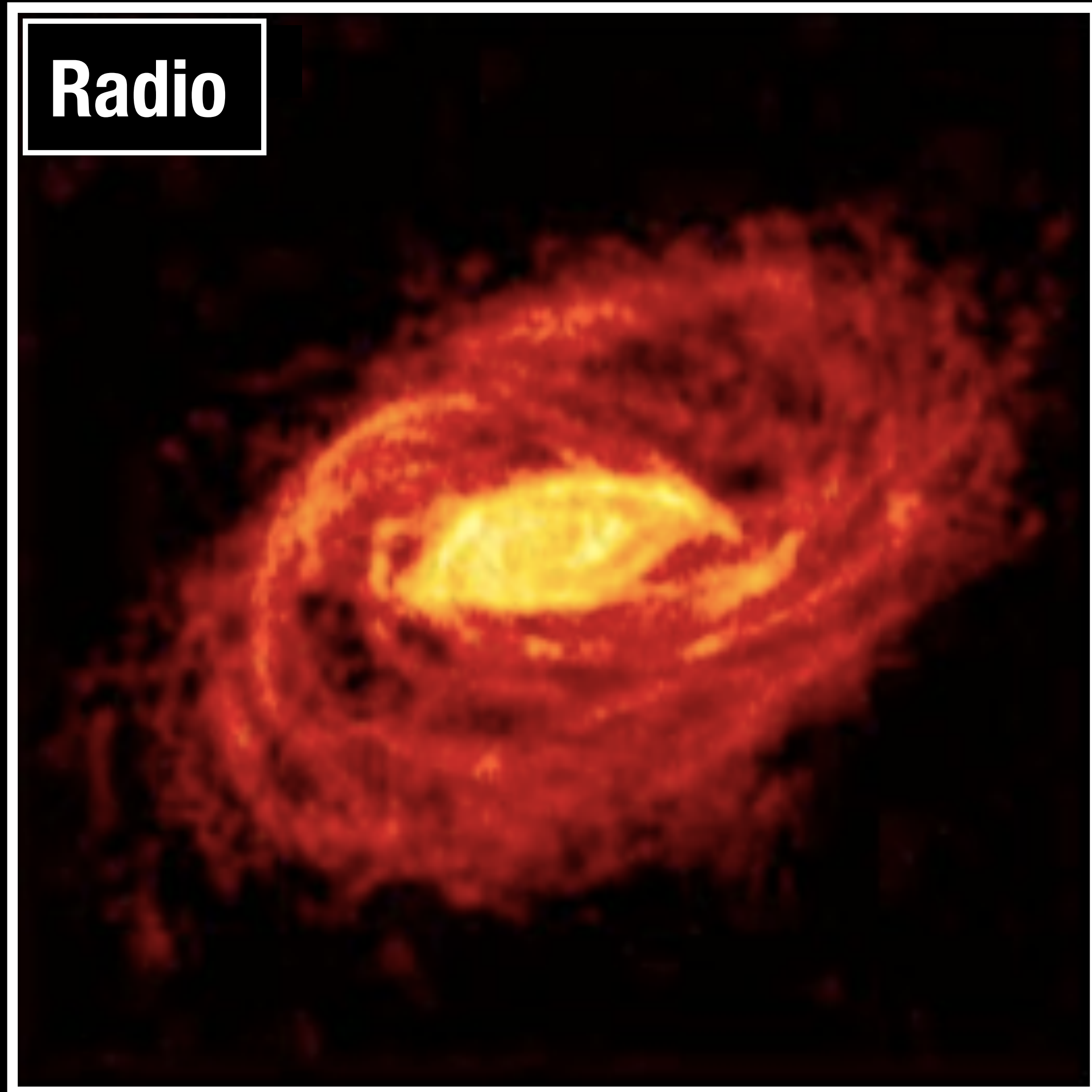
# HI 21cm Emission Line



**Optical image (right) and HI 21cm emission map (left) of NGC 2841**

# HI 21cm Emission Line

Radio



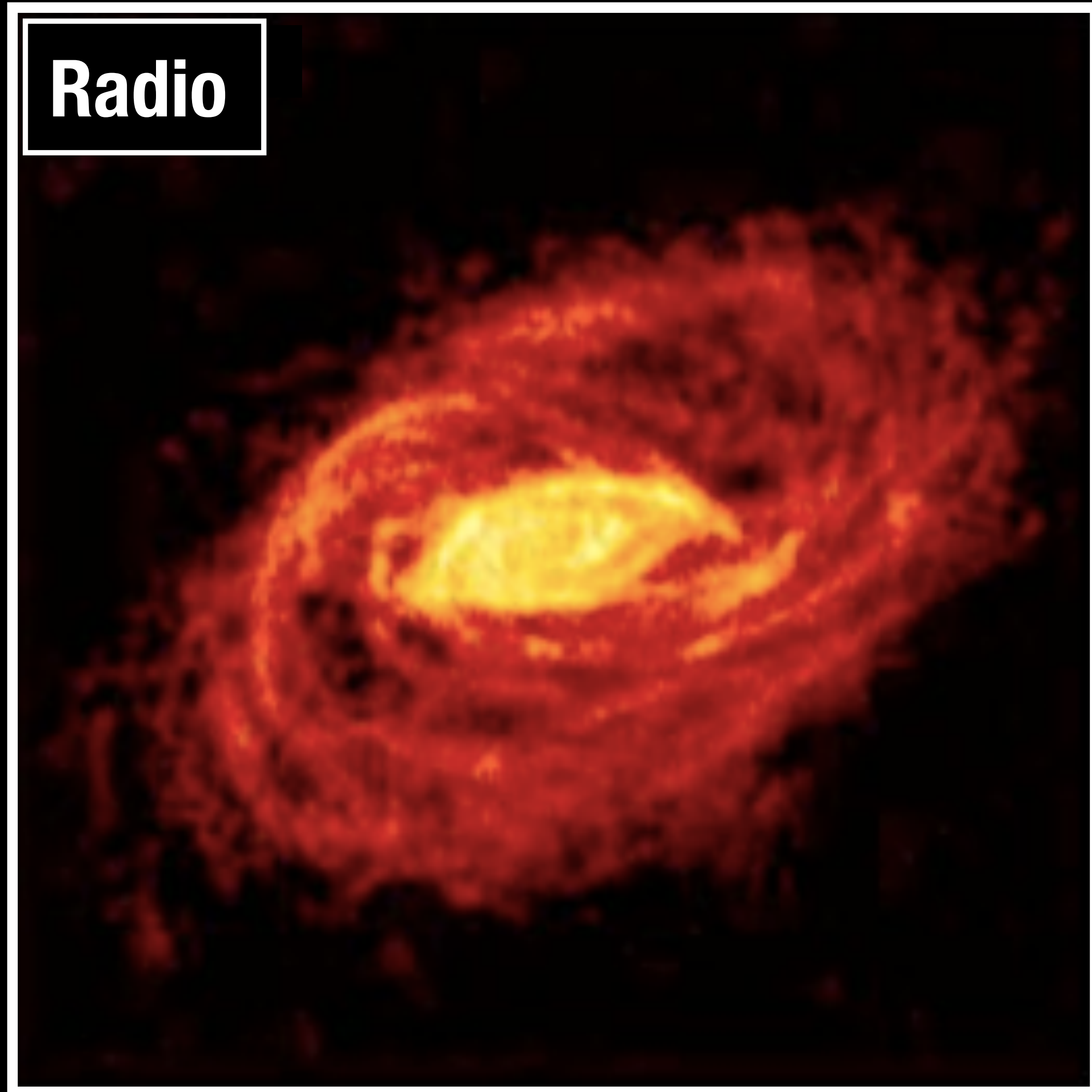
HI 21cm Flux

Radial Velocity (km/s)

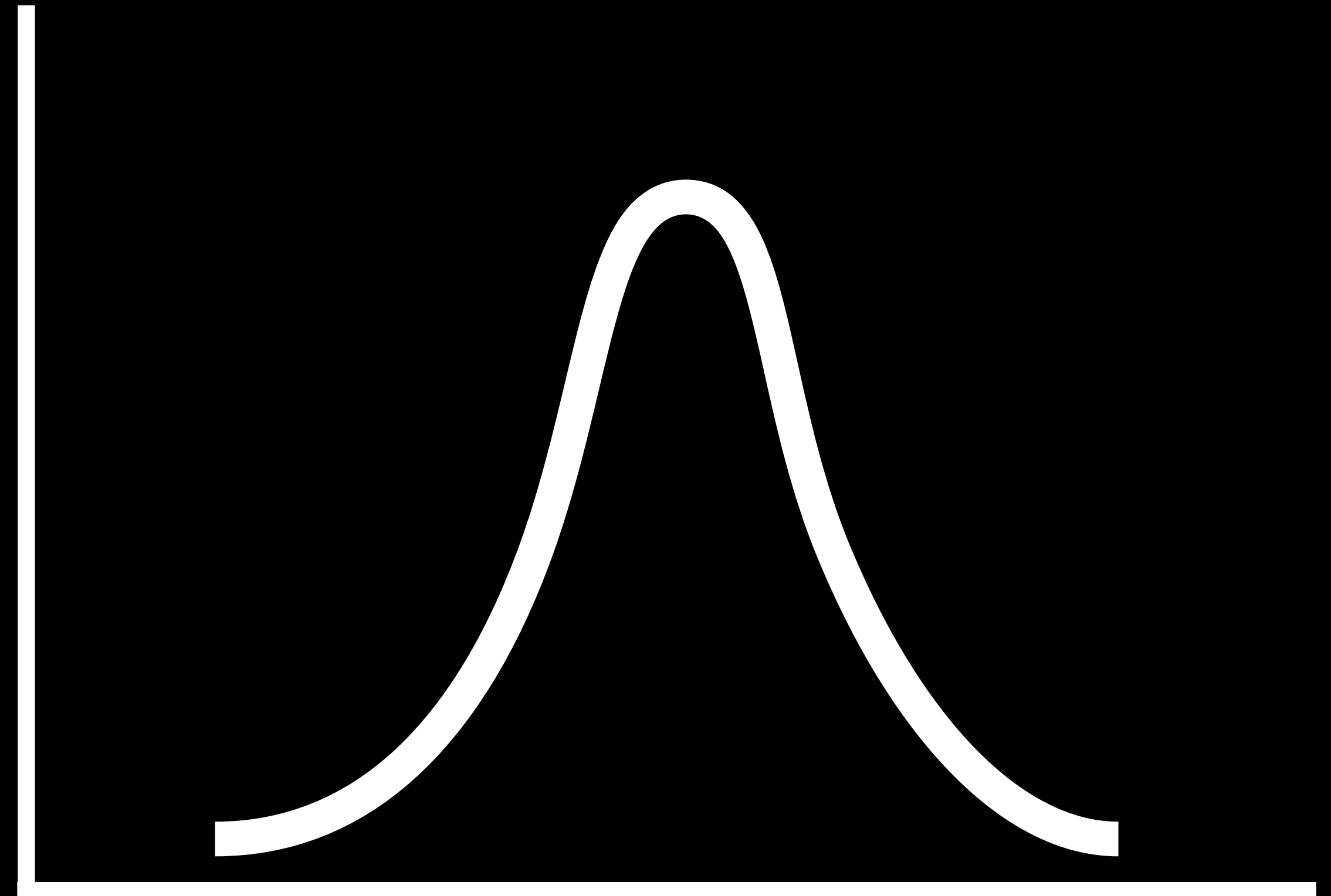
Integrate 21cm emission over the whole galaxy and plot as a function of radial velocity (or  $\lambda$ )

# HI 21cm Emission Line

Radio



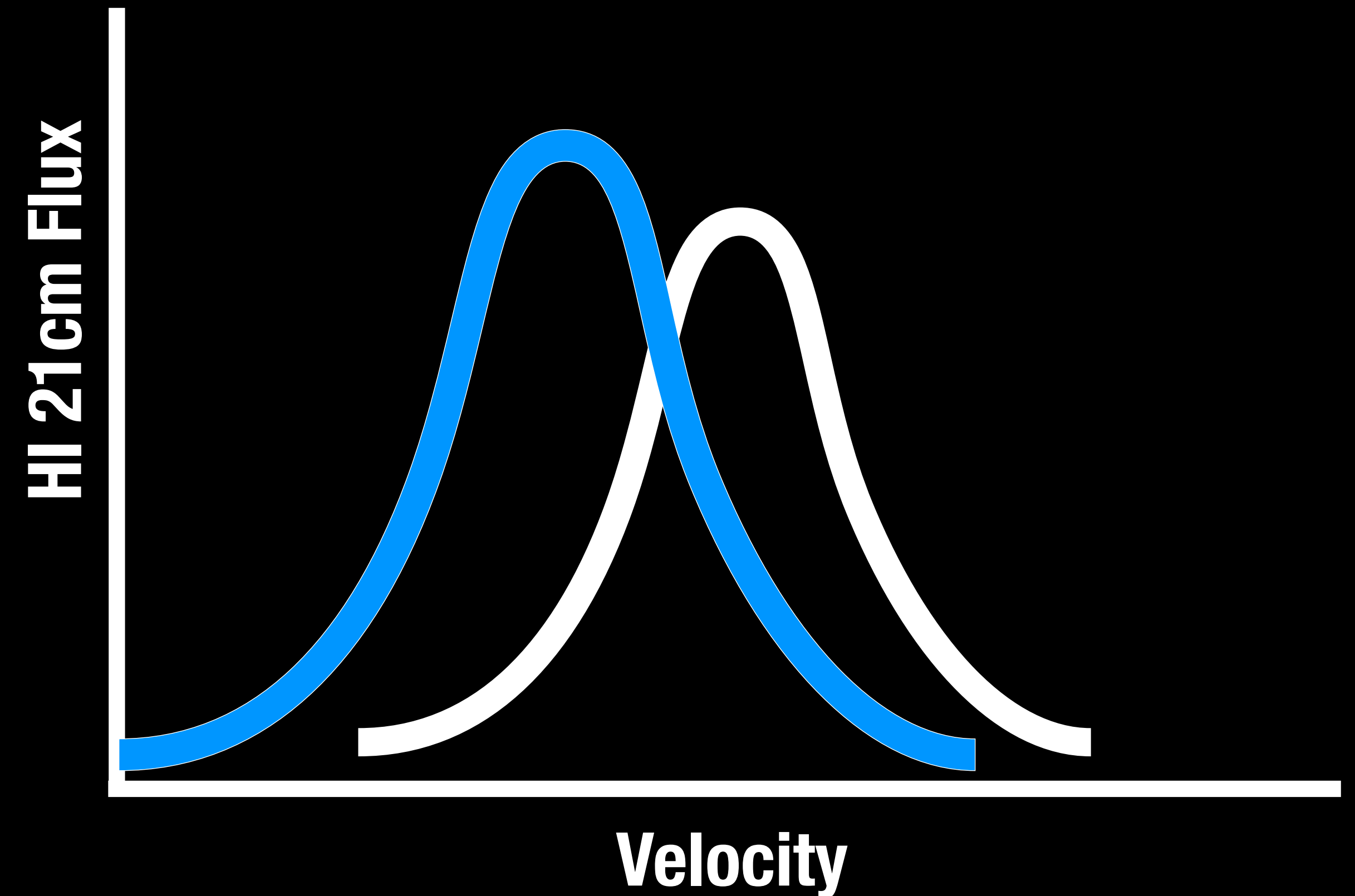
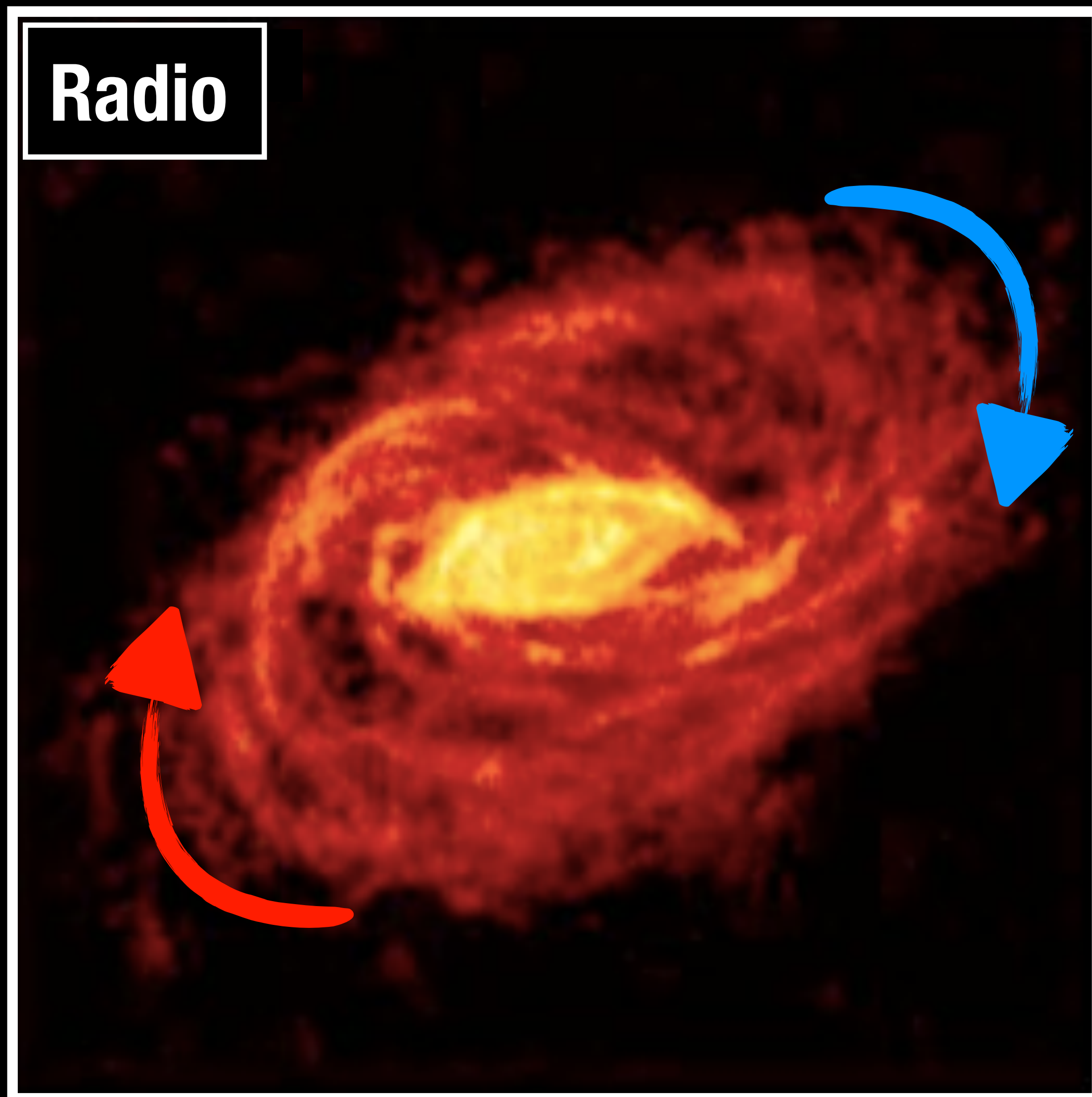
HI 21cm Flux



Radial Velocity (km/s)

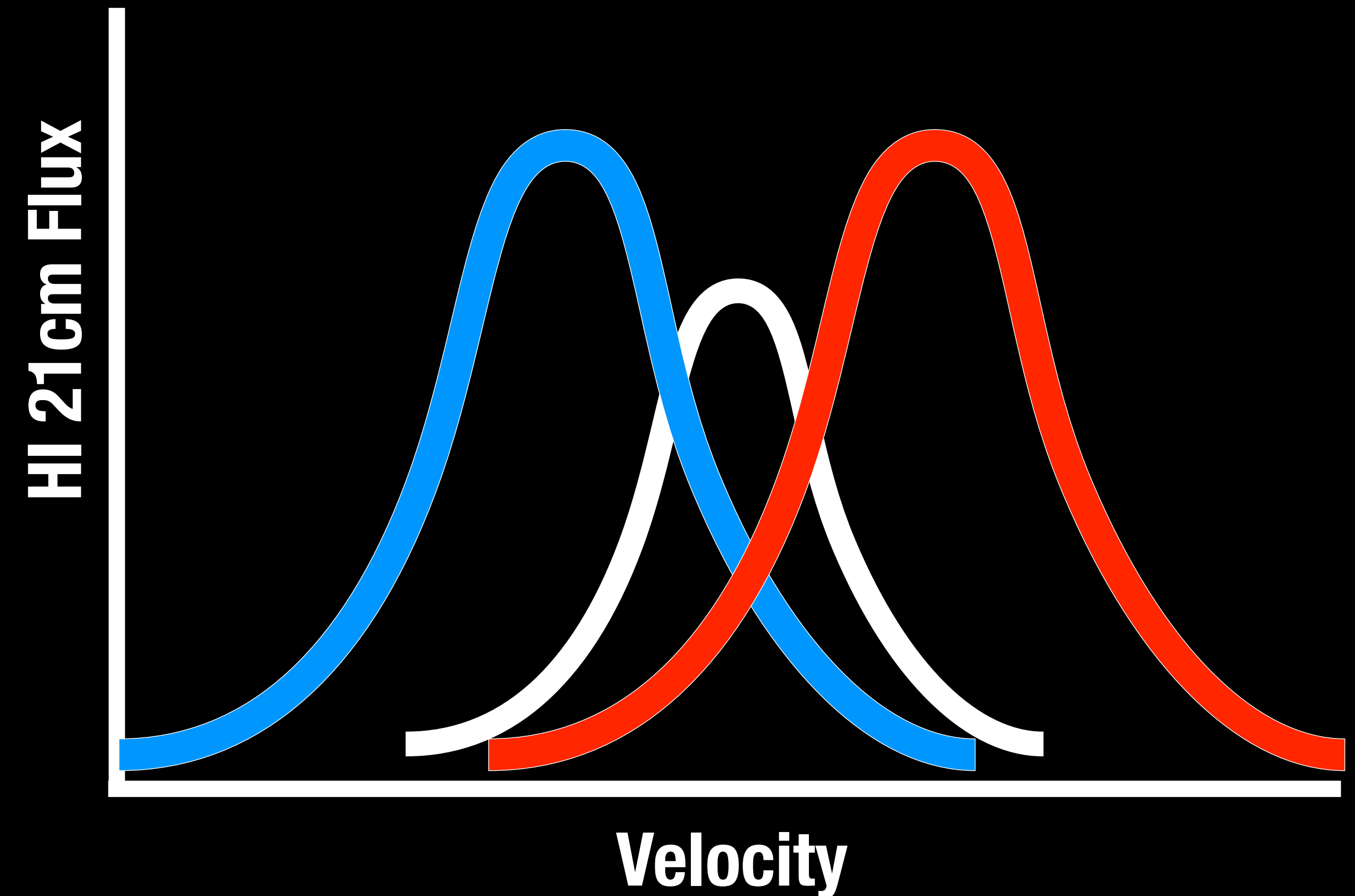
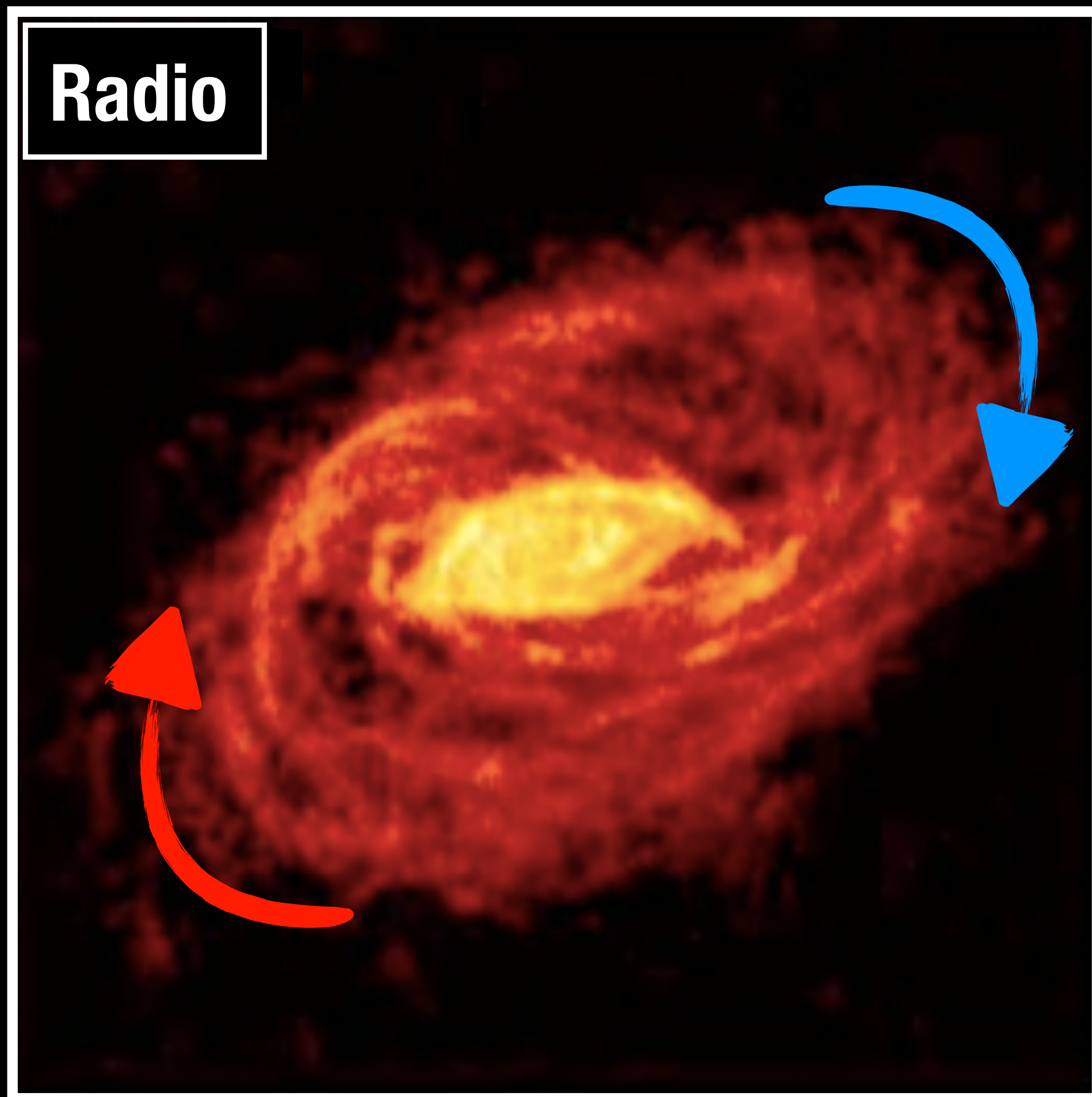
**A uniform, non-rotating distribution of gas would yield a Gaussian distribution of flux**

# HI 21cm Emission Line



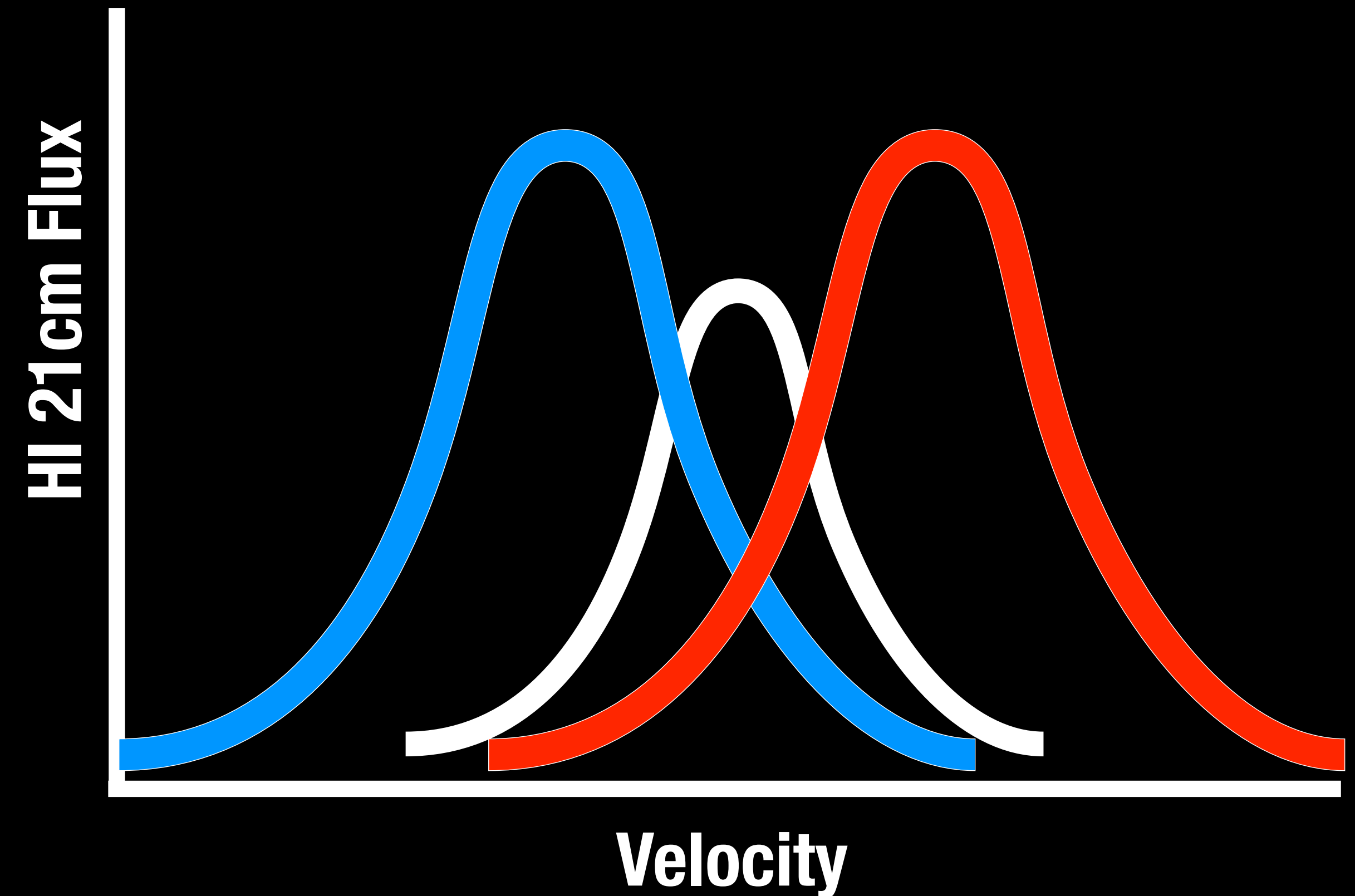
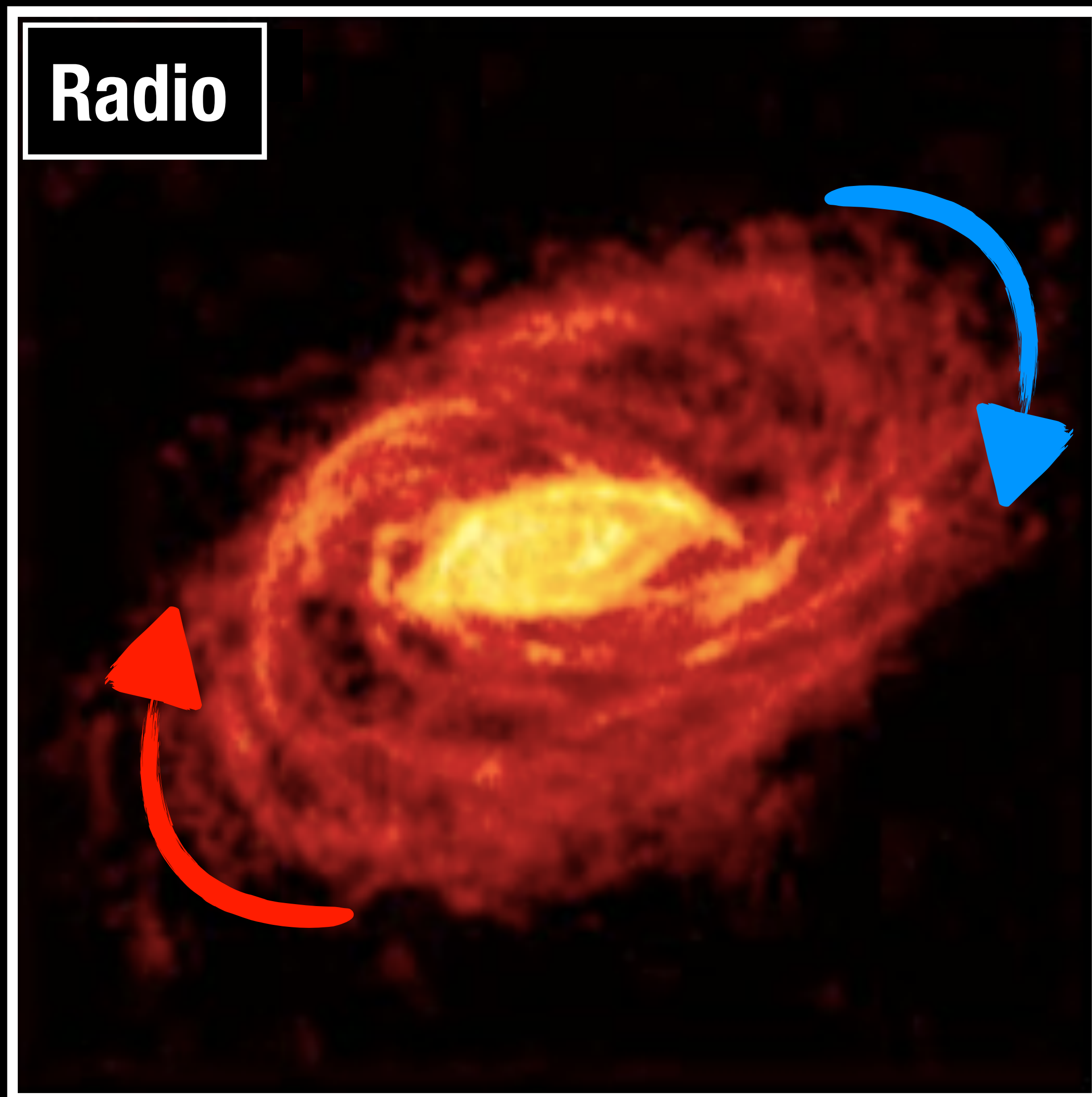
**However: every galaxy rotates, so one side is blueshifted (some fraction of flux is shifted to slower velocities)**

# HI 21cm Emission Line



**And one side is redshifted (some fraction of flux is shifted to faster velocities)**

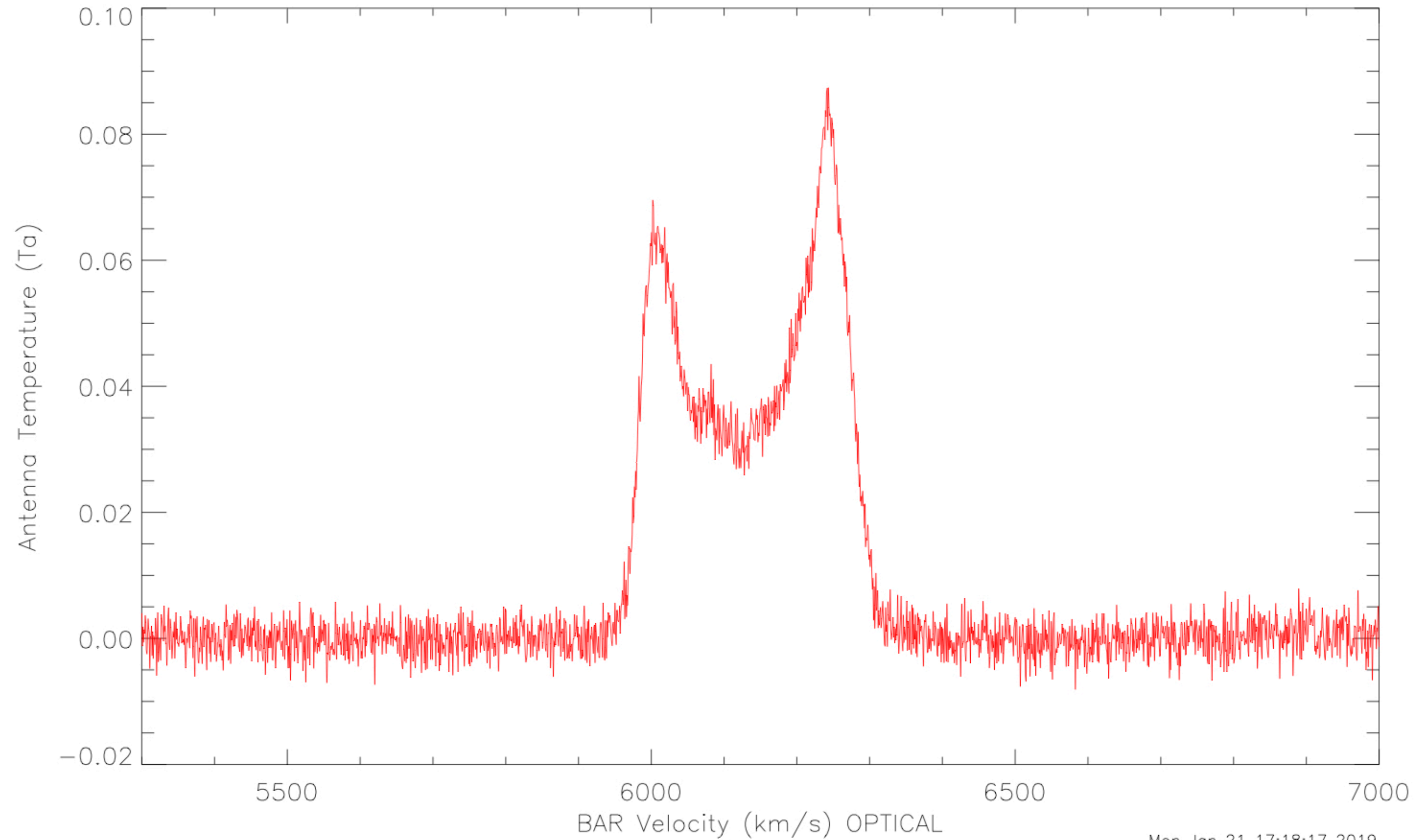
# HI 21cm Emission Line



**The faster the rotation, the broader the width of the emission line becomes**

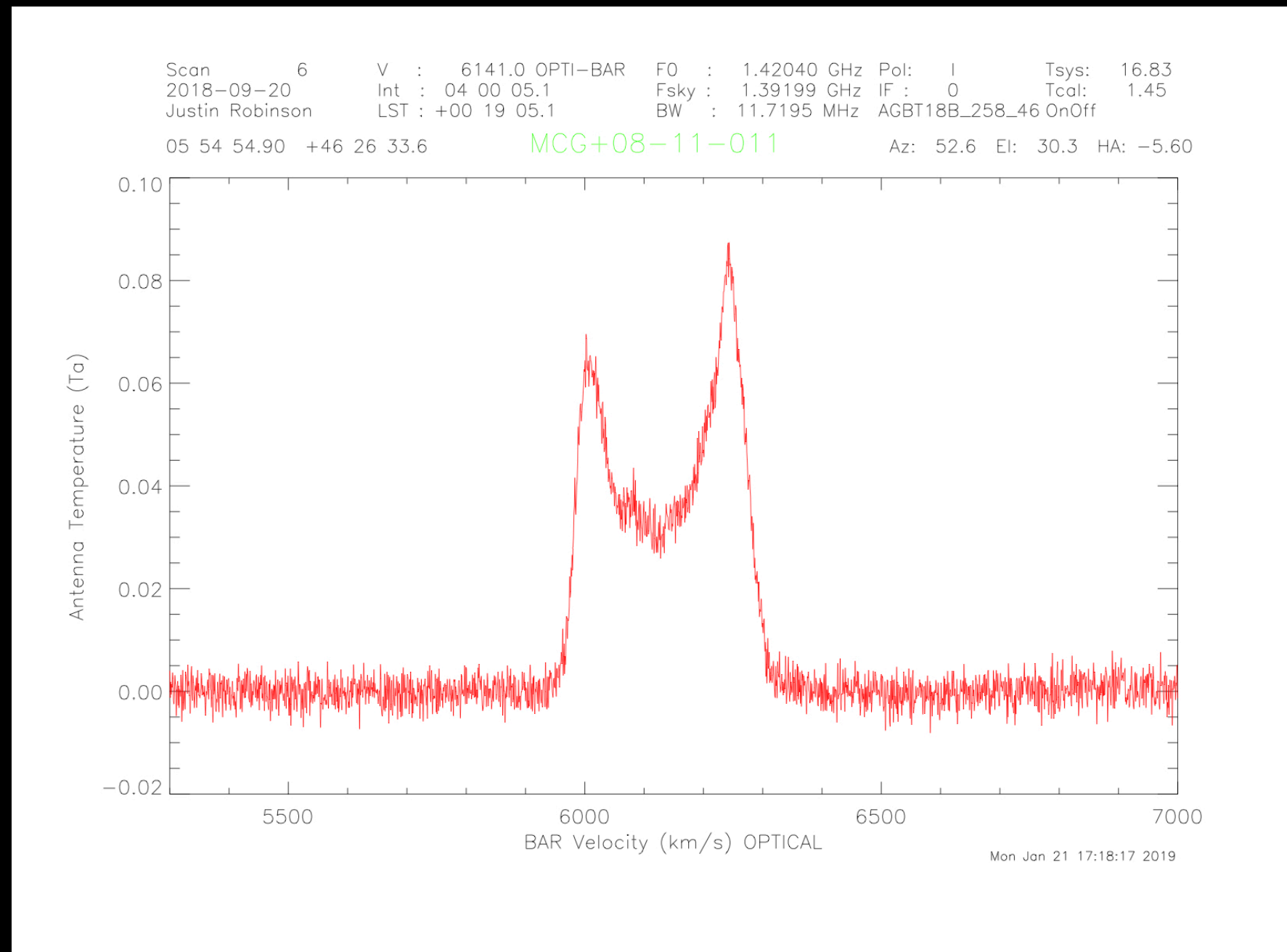
# HI 21cm Emission Line

Scan 6 V : 6141.0 OPTI-BAR F0 : 1.42040 GHz Pol: I Tsys: 16.83  
2018-09-20 Int : 04 00 05.1 Fsky : 1.39199 GHz IF : 0 Tcal: 1.45  
Justin Robinson LST : +00 19 05.1 BW : 11.7195 MHz AGBT18B\_258\_46 OnOff  
05 54 54.90 +46 26 33.6 MCG+08-11-011 Az: 52.6 El: 30.3 HA: -5.60





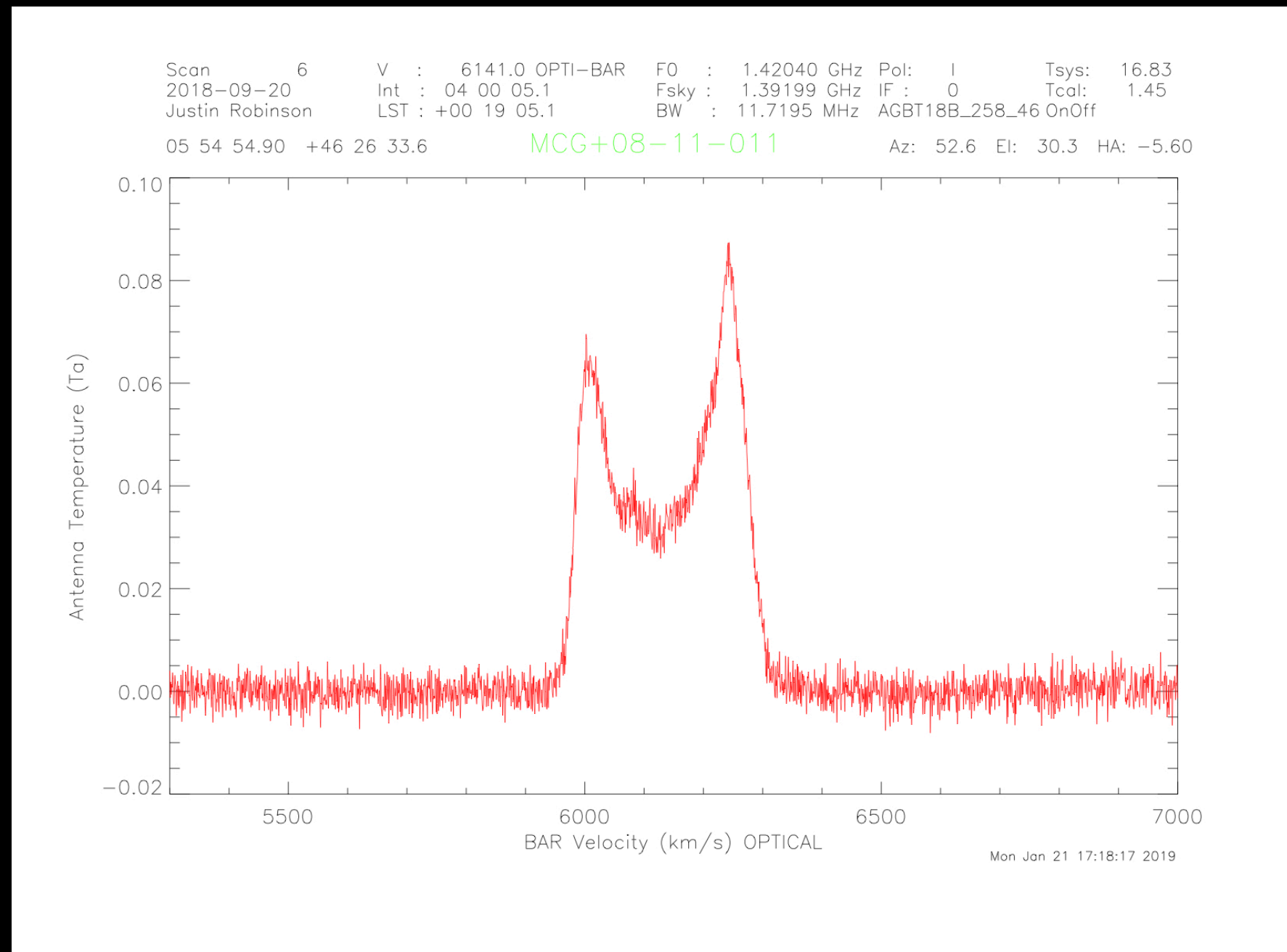
# HI 21cm Emission Line



**One of the most important uses of the 21cm line is redshift measurement**

**Theoretically, any emission line from another galaxy can be used to measure redshift. Why would the 21cm line provide a more accurate measurement?**

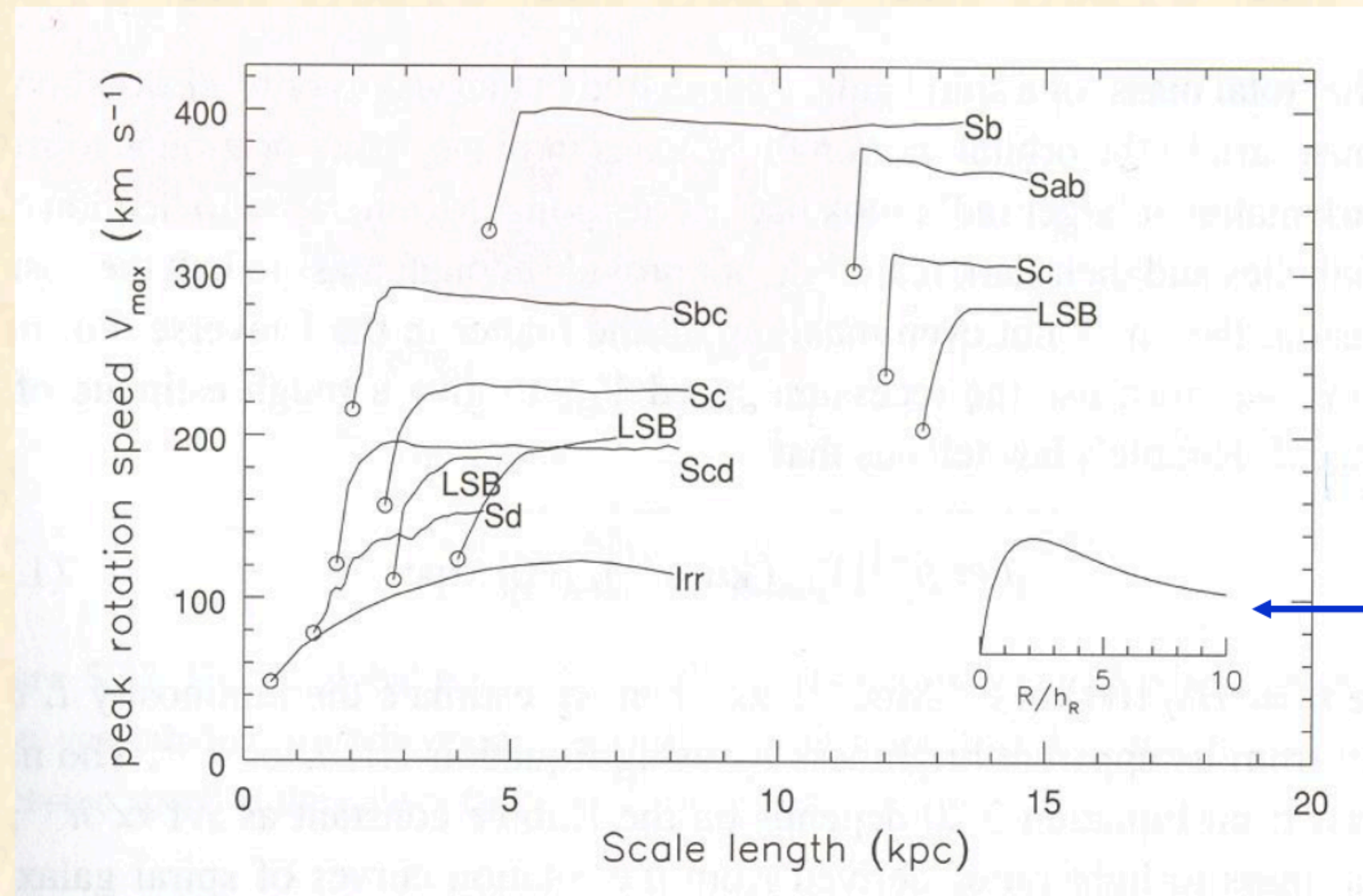
# HI 21cm Emission Line



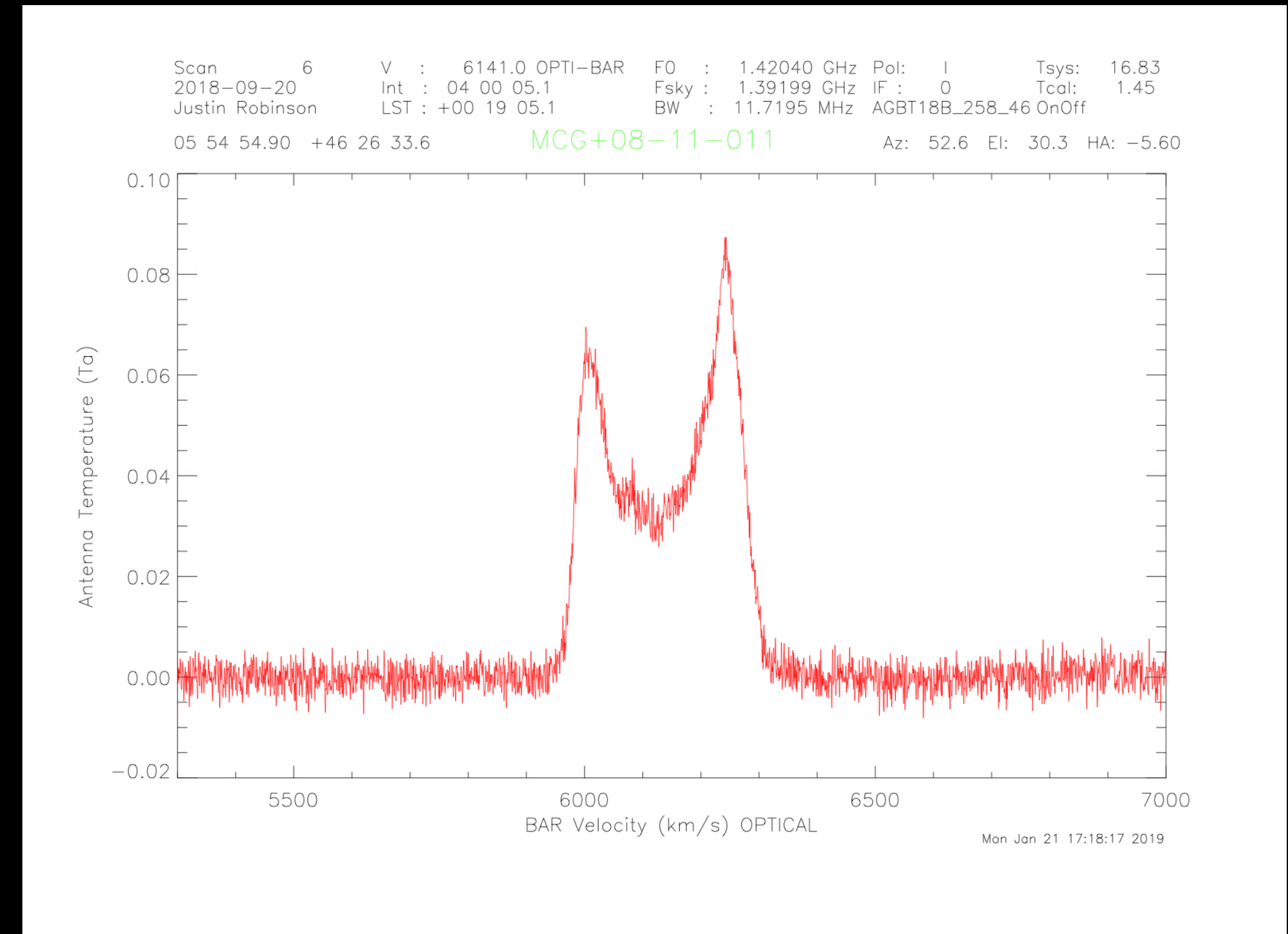
-> HI is cold, thus only moved by galaxy rotation. Other lines (like the H Balmer series, [O III]) are in significantly warmer environments

Warm environments (like star-forming regions) can induce internal motions of gas, which directly effects redshift (something is making the gas move other than the motion of the galaxy)

# Spiral Galaxy Rotation Curves

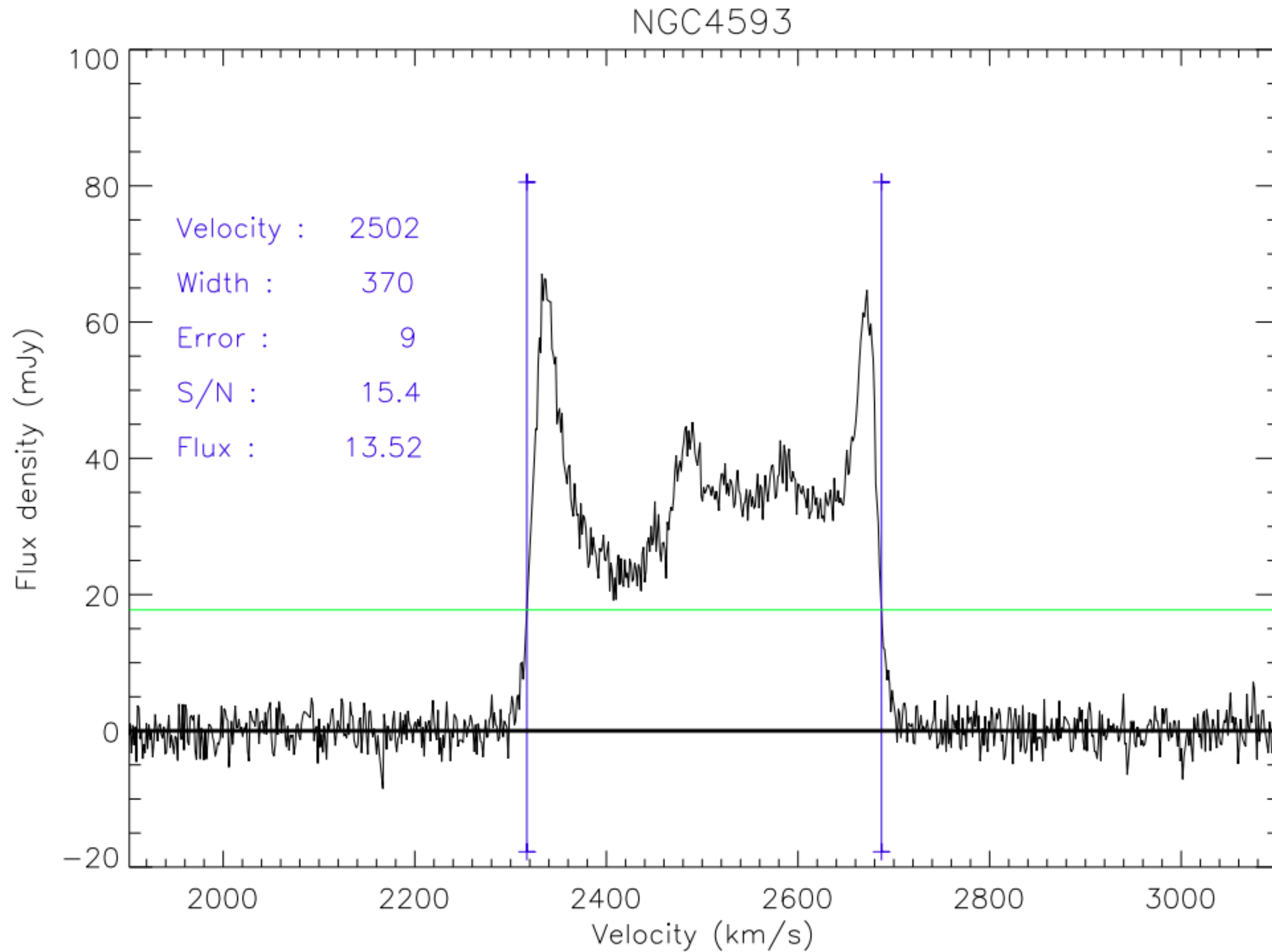


(Sparke & Gallagher, p. 218)



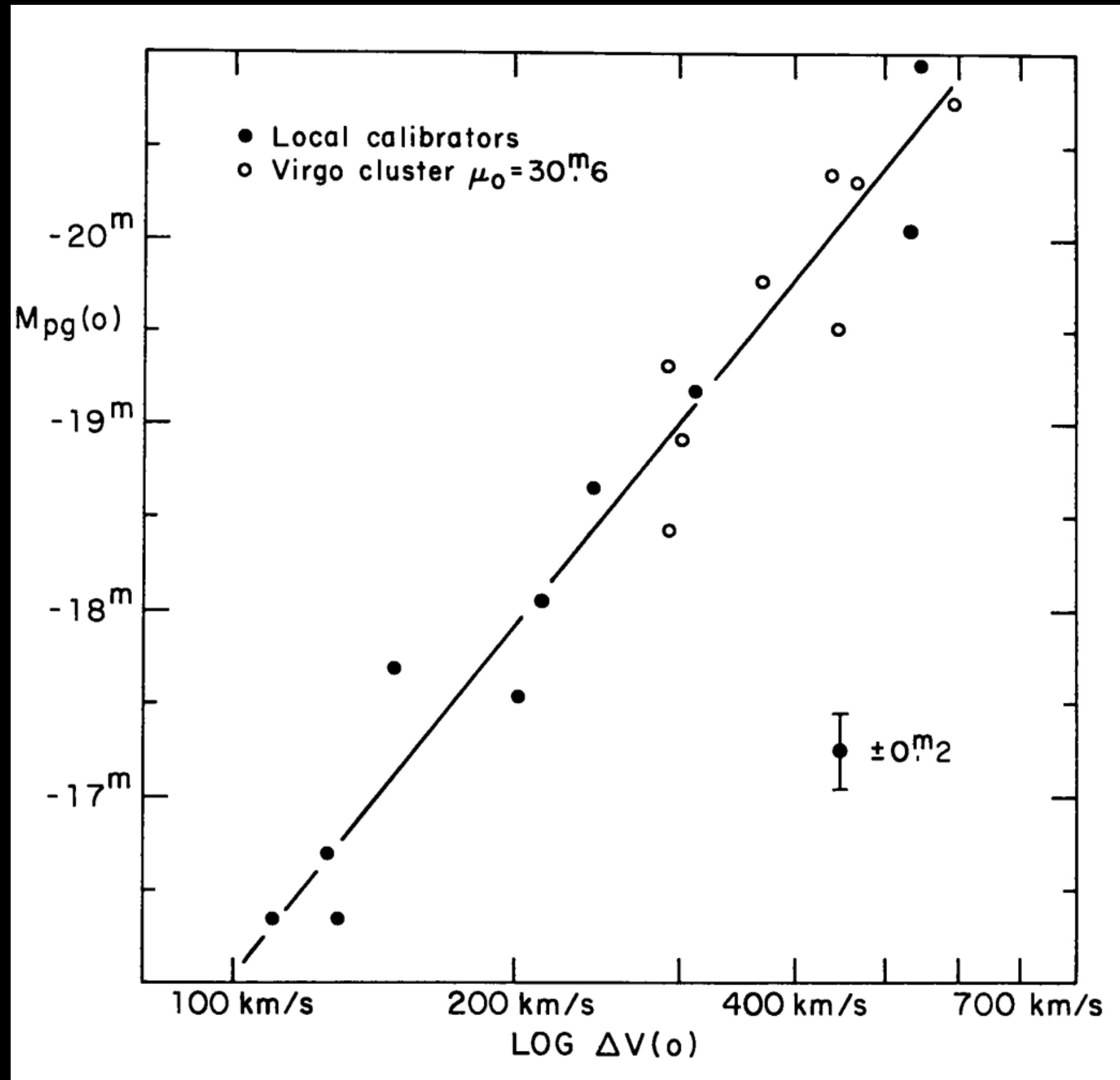
- Larger disk galaxies rotate faster
- Early types tend to rise more steeply
- Flat rotation curves: evidence for dark halos in disk galaxies
- Rotation curves not possible for more distant spirals, have to use unresolved HI 21cm emission line to trace rotational velocity (from width of emission line and inclination)

# Spiral Galaxy Rotation Curves



- **Green horizontal line between blue vertical lines:  $W$**
- **$V_{\max} = 1/2 W/\sin(i)$**

# The Tully-Fisher Relation



**By measuring rotation of spiral galaxies with known distances (from Cepheids), Tully & Fisher discovered that rotation rate (here  $\Delta V$ ) and  $M$  were related**

**(Tully & Fisher 1977, A&A, 54, 661)**

# The Tully-Fisher Relation

Astron. Astrophys. 54, 661—673 (1977)

## ASTRONOMY AND ASTROPHYSICS

### A New Method of Determining Distances to Galaxies

R. Brent Tully<sup>1\*</sup> and J. Richard Fisher<sup>2</sup>

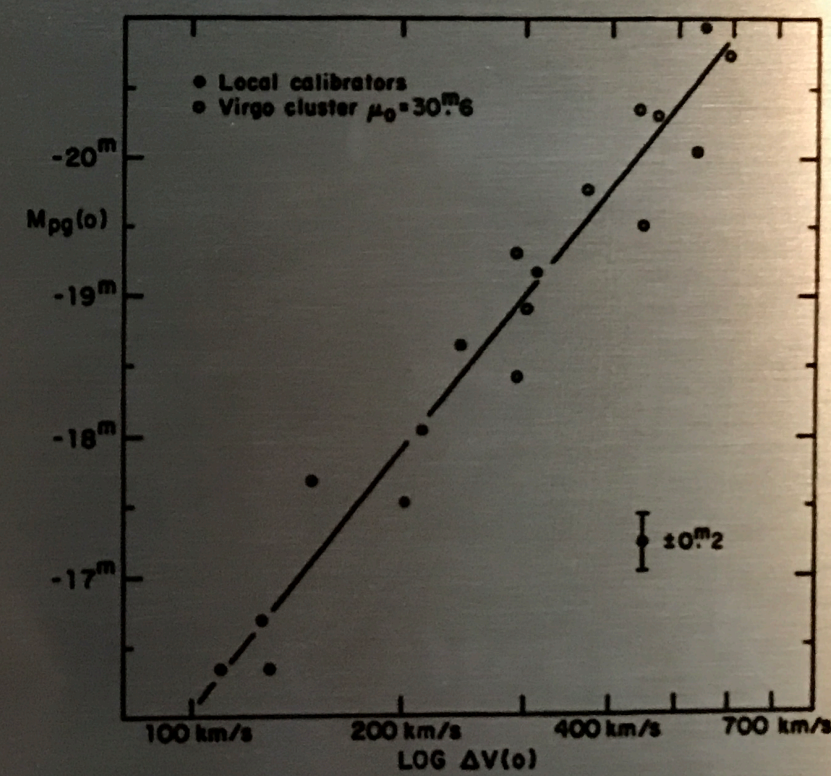
<sup>1</sup> Observatoire de Marseille, France

<sup>2</sup> National Radio Astronomy Observatory\*\*, P.O. Box 2, Green Bank, W. Va. 24944, USA

Received July 15, 1975, revised April 26, 1976

**Summary.** A good correlation between a distance-independent observable, global galaxian H I profile widths, and absolute magnitudes or diameters of galaxies offers a new extragalactic distance tool, as well as potentially being fundamental to an understanding of galactic structure. The relationships are calibrated with members of the Local Group, the M81 group, and the M101 group and have been used to derive distances to the Virgo cluster ( $\mu_0 = 30^m.6 \pm 0^m.2$ ) and the Ursa Major cluster ( $\mu_0 = 30^m.5 \pm 0^m.35$ ). A preliminary estimate of the Hubble constant is  $H_0 = 80$  km/s/Mpc.

**Key words:** galaxies — distances — neutral hydrogen



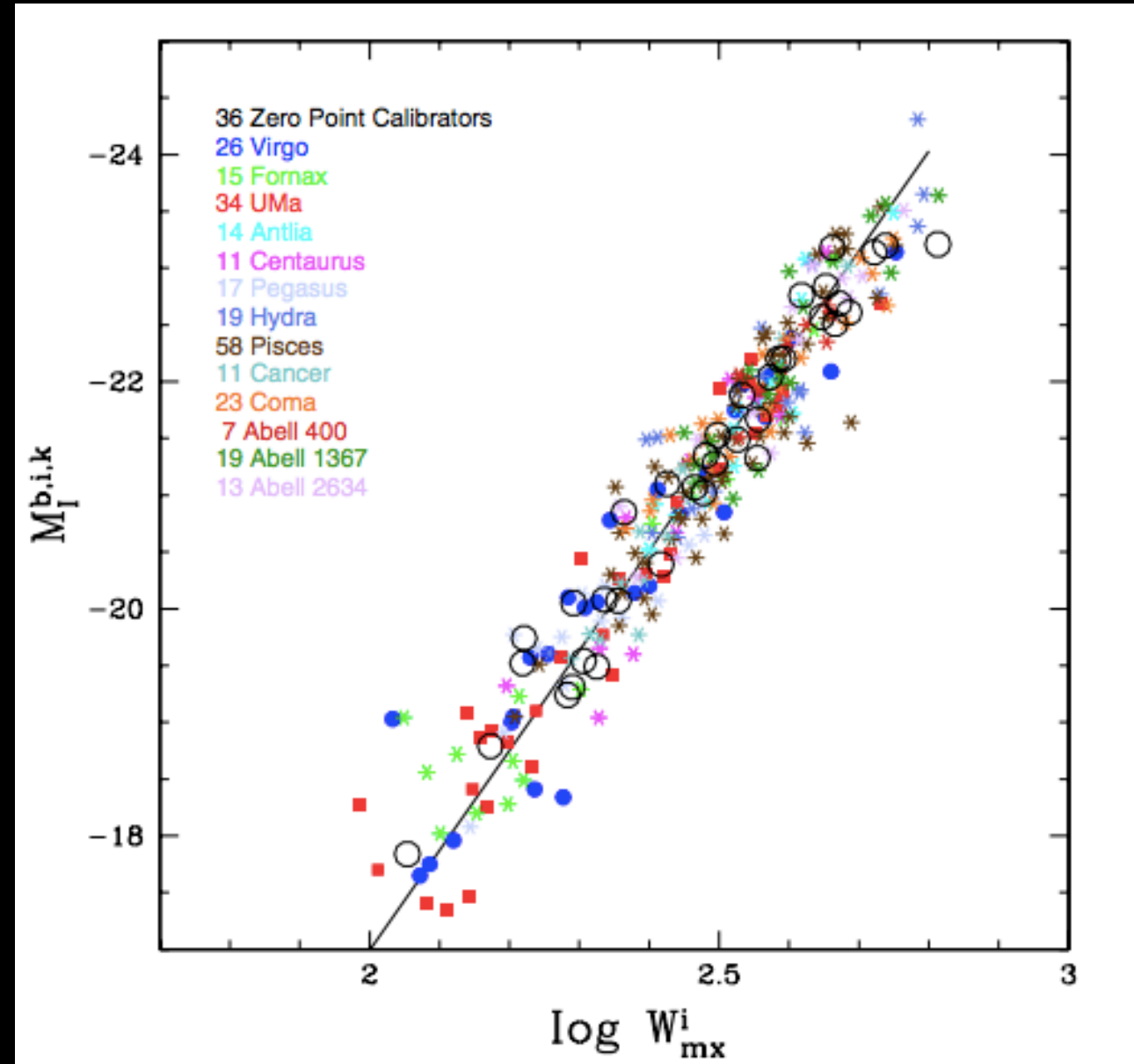
Brent Tully



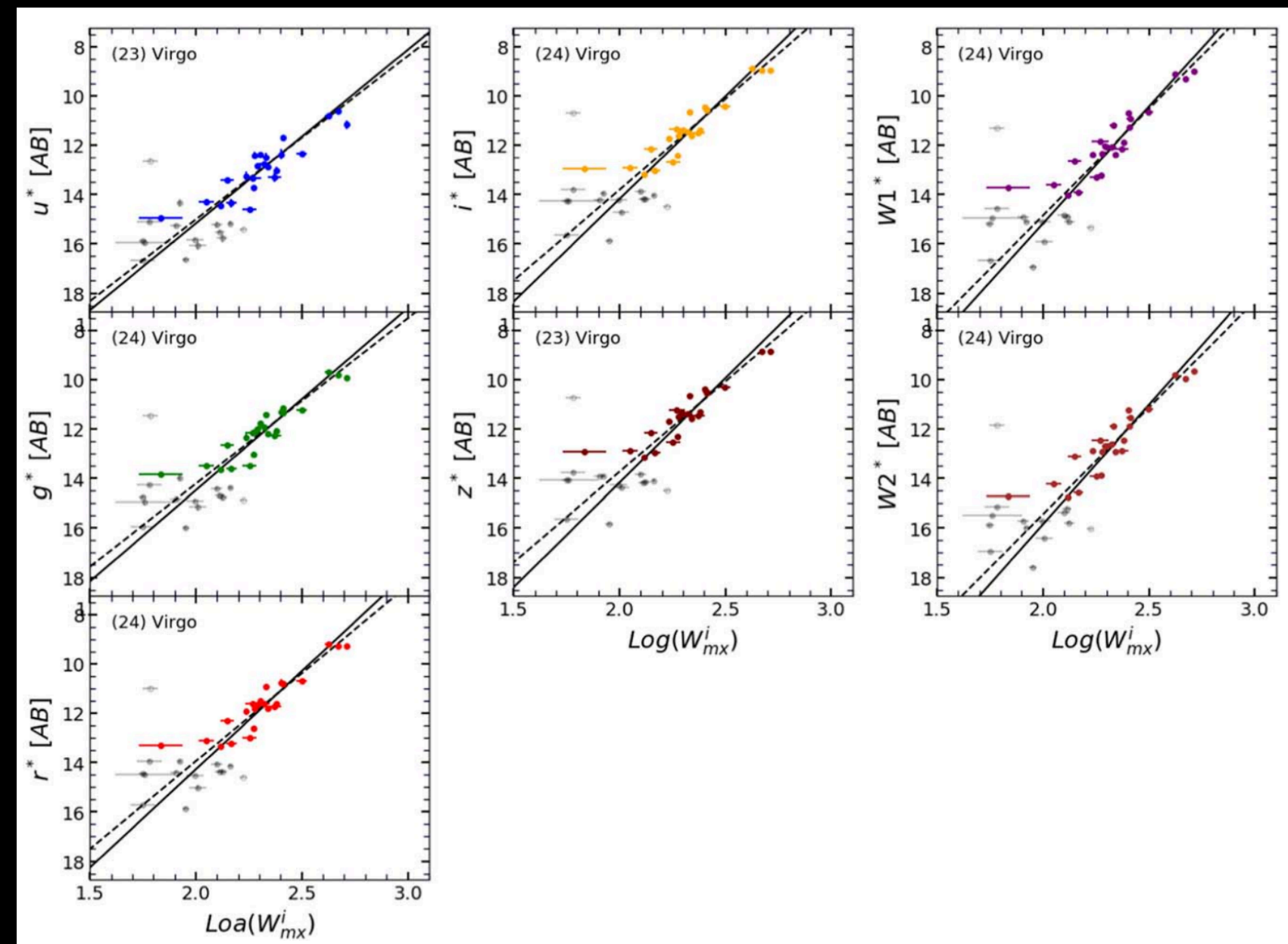
# The Tully-Fisher Relation

(Tully & Courtois  
2012, ApJ, 749, 78)

(Kourkchi et al.  
2020, ApJ, 896, 3)

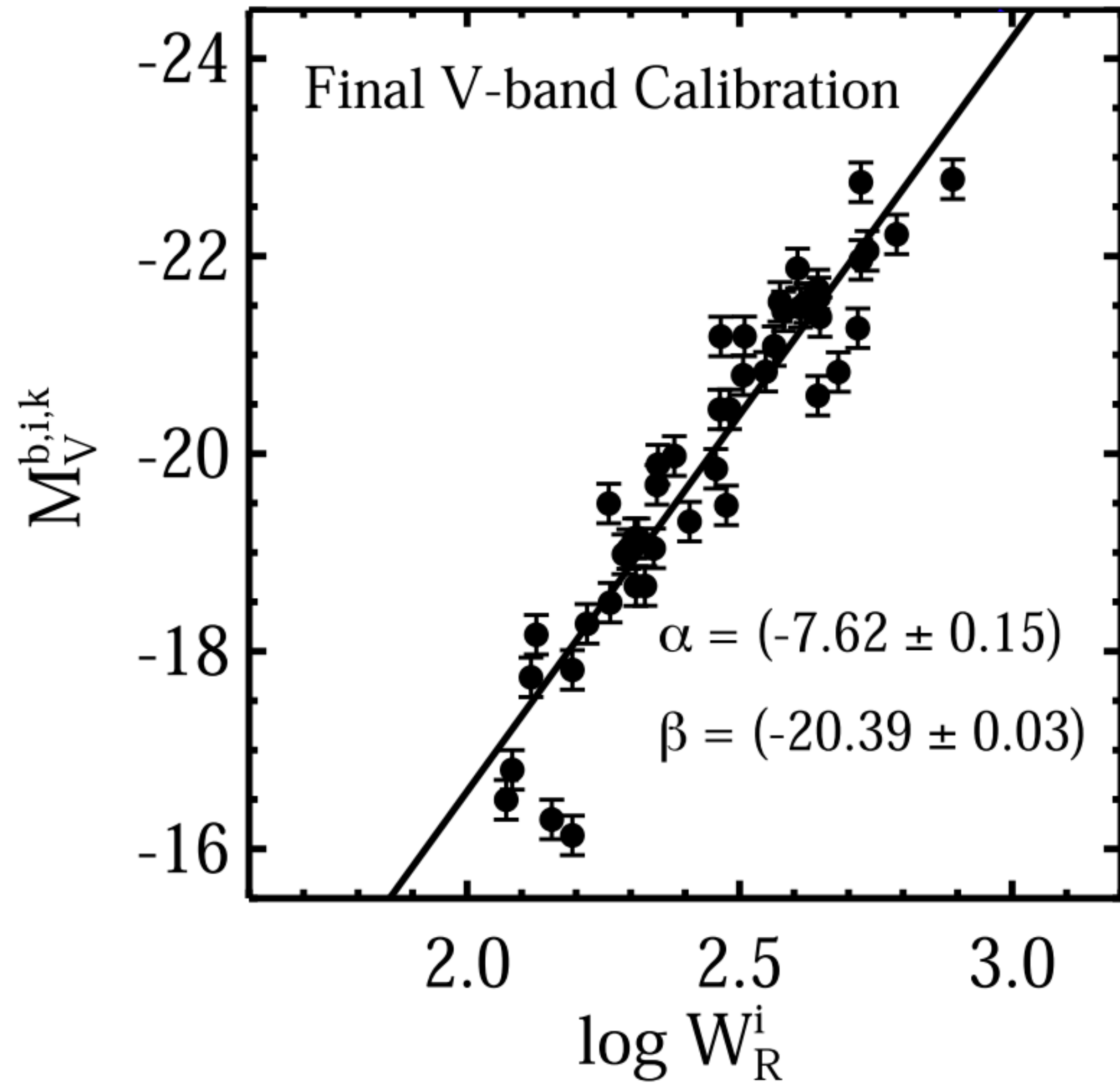


The Tully-Fisher Relation has been calibrated for most filters, including B, R, I (top image), and lots of infrared filters (bottom image)



For a while, the V filter (middle of the optical) calibration was missing...

# The Tully-Fisher Relation

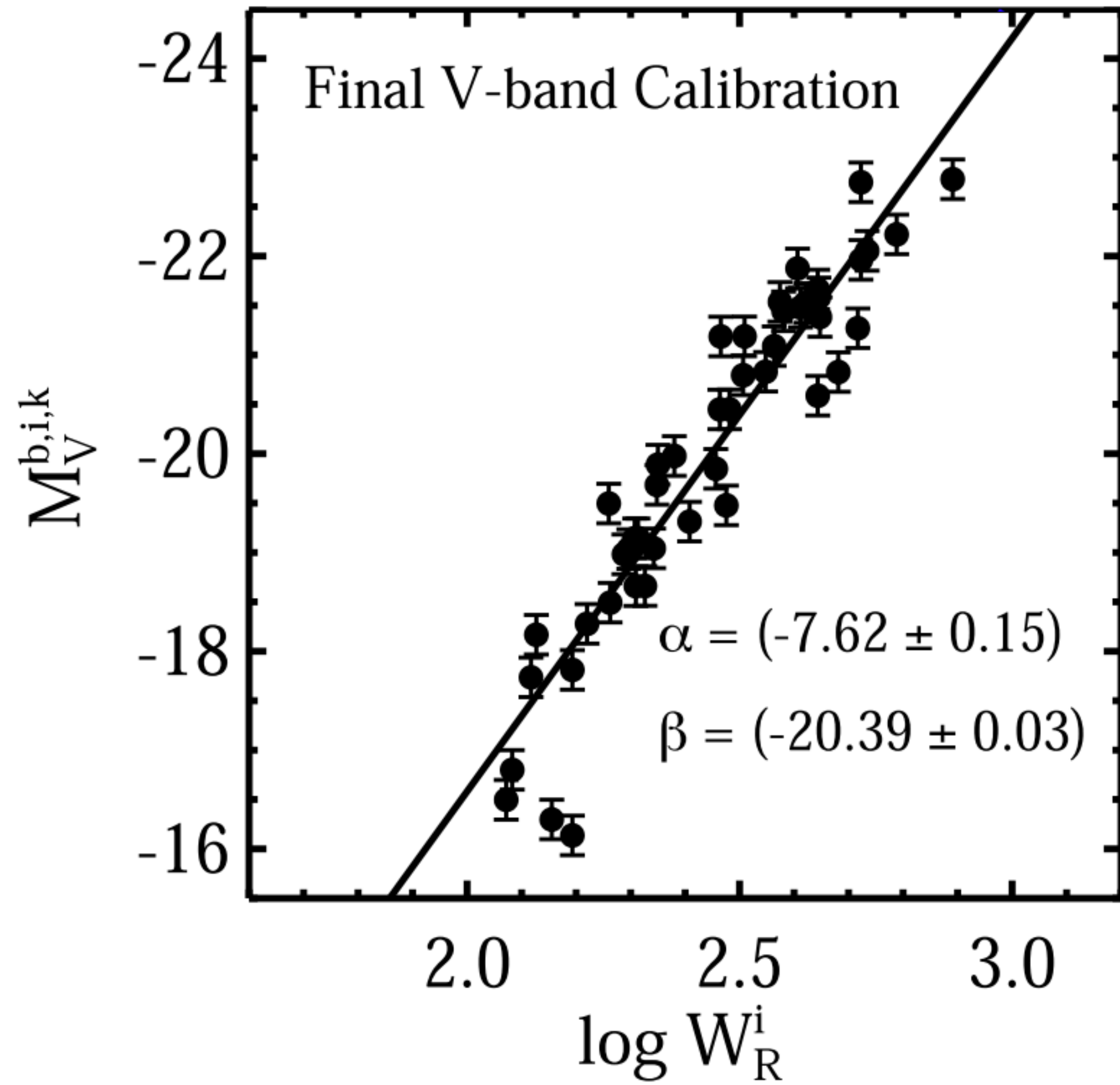


**So I calibrated the relationship for the V filter :)**

**(Robinson et al. 2021, ApJ, 912, 160)**



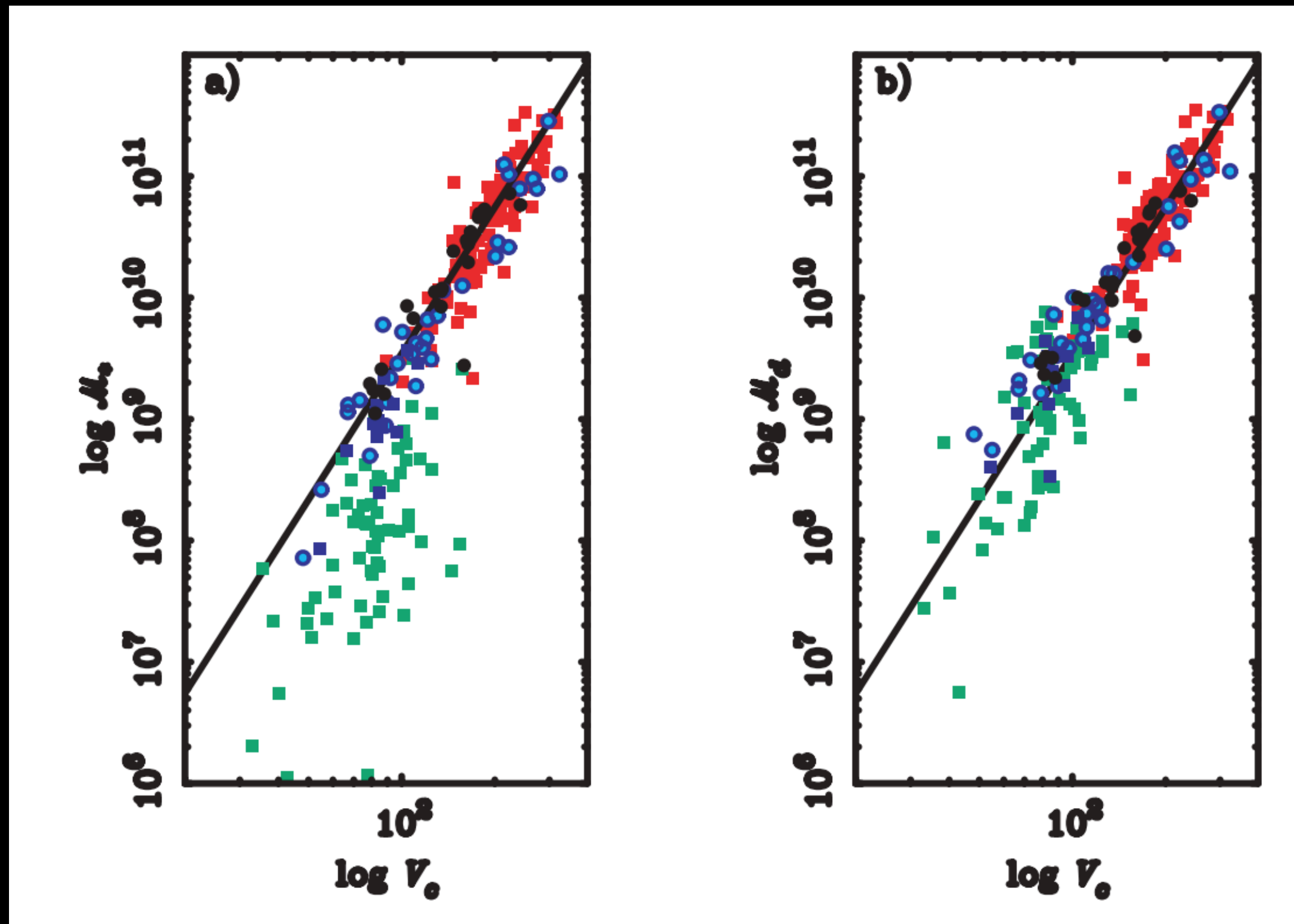
# The Tully-Fisher Relation



(Robinson et al. 2021, ApJ, 912, 160)

- The TF relation effectively uses stellar light (absolute magnitude) as a mass tracer (more massive galaxies rotate faster)
- Earlier observations used the brightest galaxies -> much higher stellar mass than gas mass

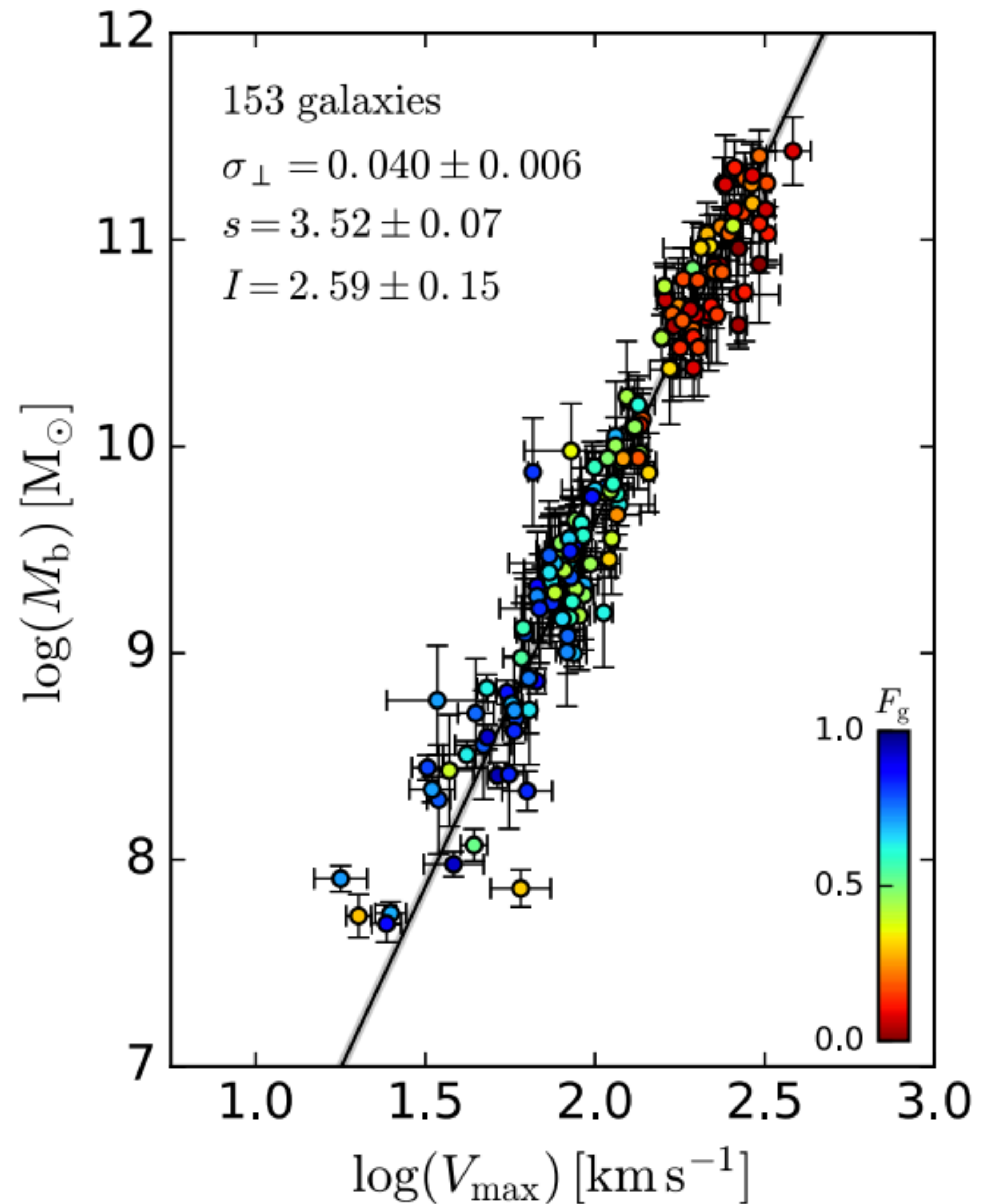
# The Baryonic Tully-Fisher Relation



Left: stellar mass ; Right: baryonic mass  
(McGaugh et al. 2000, ApJ, 533, L99)

- For systems of lower stellar mass, gas mass begins to dominate (later-type spirals)
- More fundamental form of TF: the Baryonic Tully-Fisher (BTF) Relation
- Gas + Stars (baryonic matter) as a function of maximum rotational velocity

# The Baryonic Tully-Fisher Relation



- Considered the “true” form of the TF relation, one of the most tightly-correlated relations in astrophysics

(Lelli et al. 2019, MNRAS, 484, 3267)