MOND

“The future is already here –
it's just not evenly distributed.”

–William Gibson

Mar 9	Laws of Galactic Rotation	Dynamical Regularities in Rotating Galaxies	McGaugh	
Mar 14	Spring Break			
Mar 16	Spring Break			
Mar 21	Fitting and Predicting	Hypothesis testing with gas rich galaxies	talk among yourselves	Prof. McGaugh at IAU 379
Mar 23	Data Interpretation	Declining Rotation Curves at High Redshift?	talk among yourselves	Prof. McGaugh at IAU 379

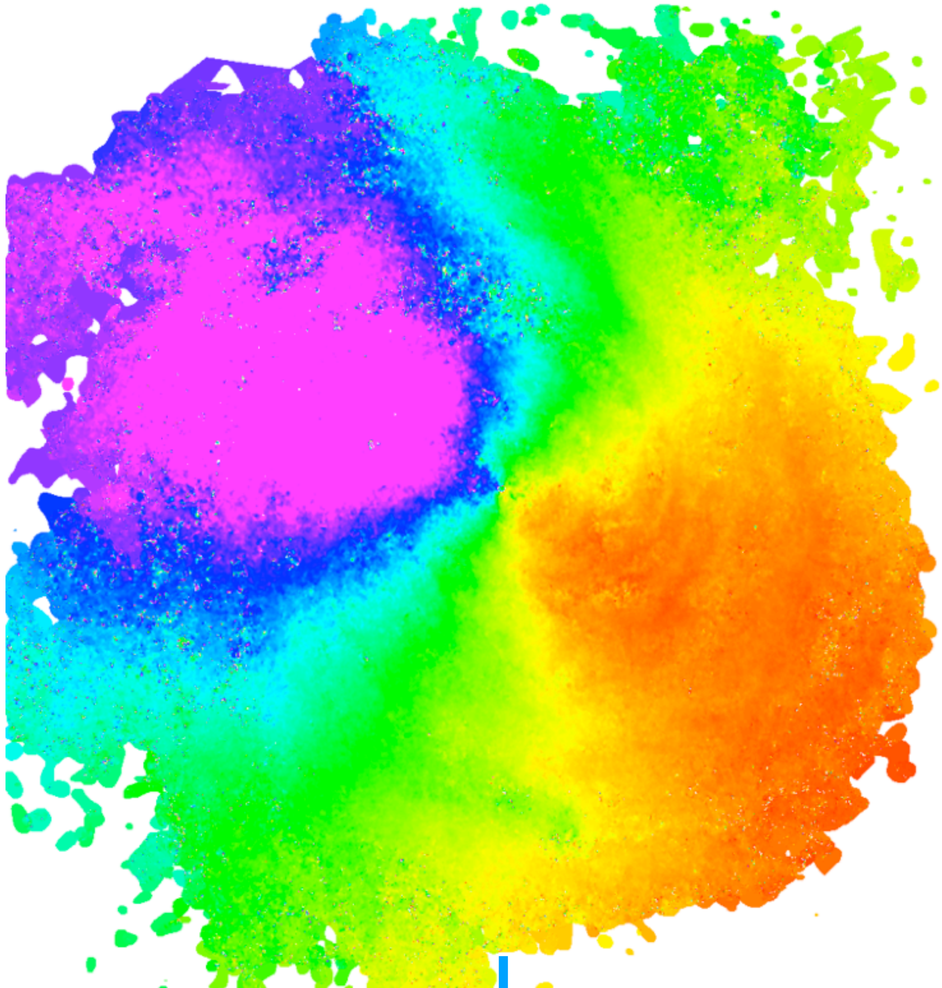
the future that now has passed

“The past is a frozen image we can
never fully perceive.”

–some stuff I just made up to fill this space

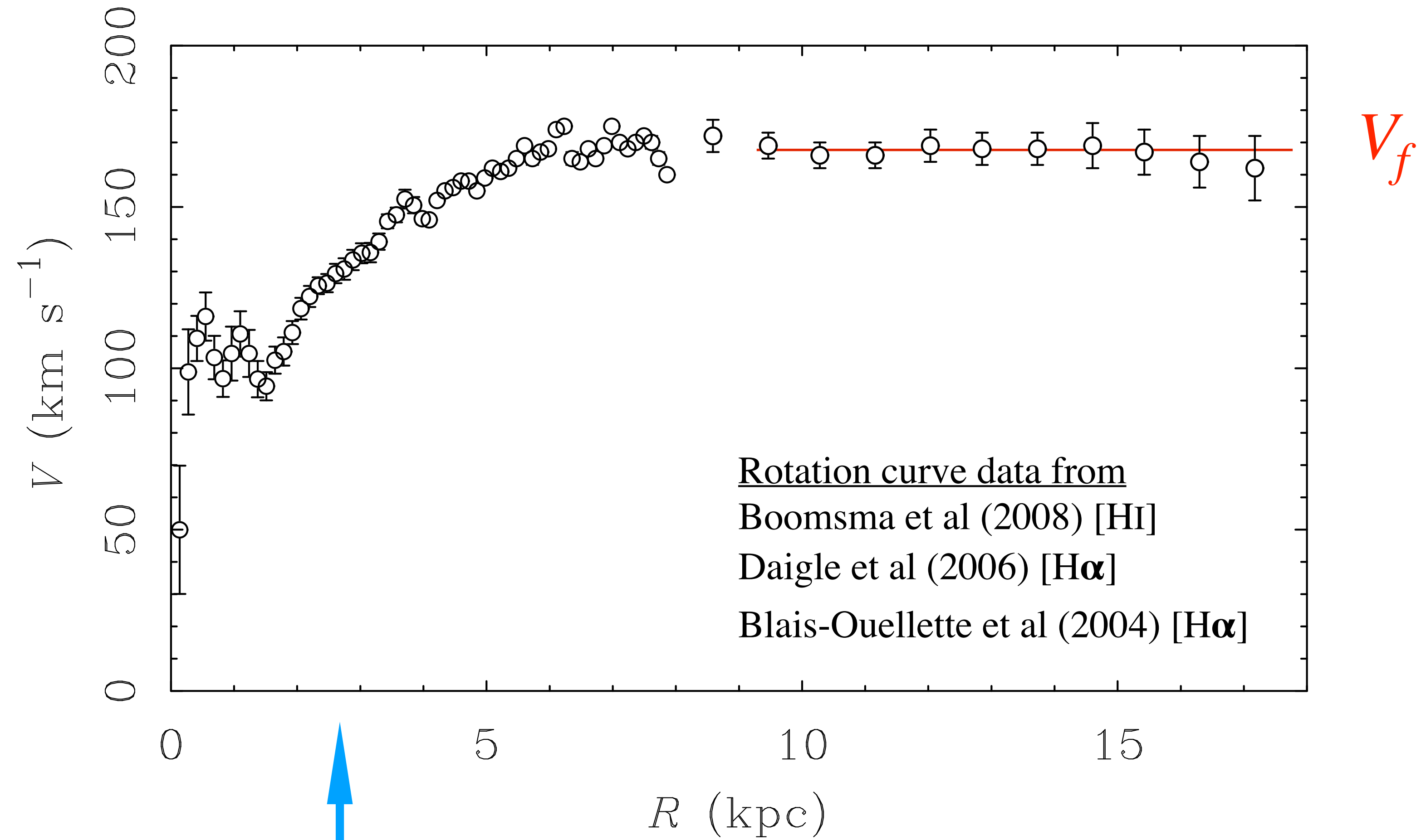
21cm interferometric observations give atomic gas distributions and velocity fields

NGC 6946

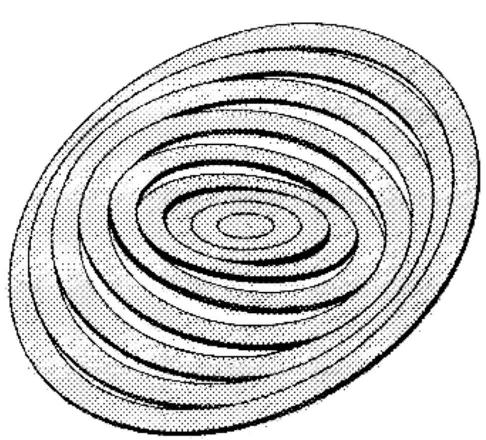


THINGS (Walter et al. 2008; de Blok et al. 2008)

Rotation curve



tilted ring model



to which we make tilted ring fits

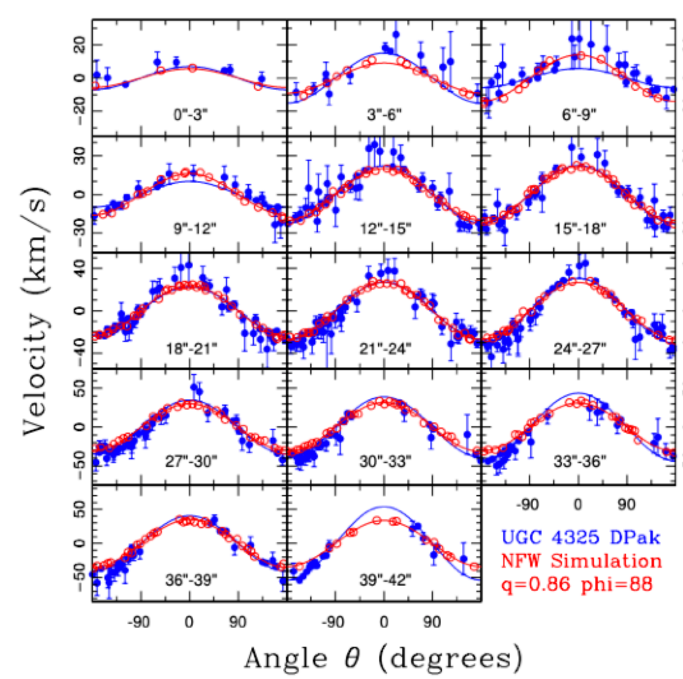
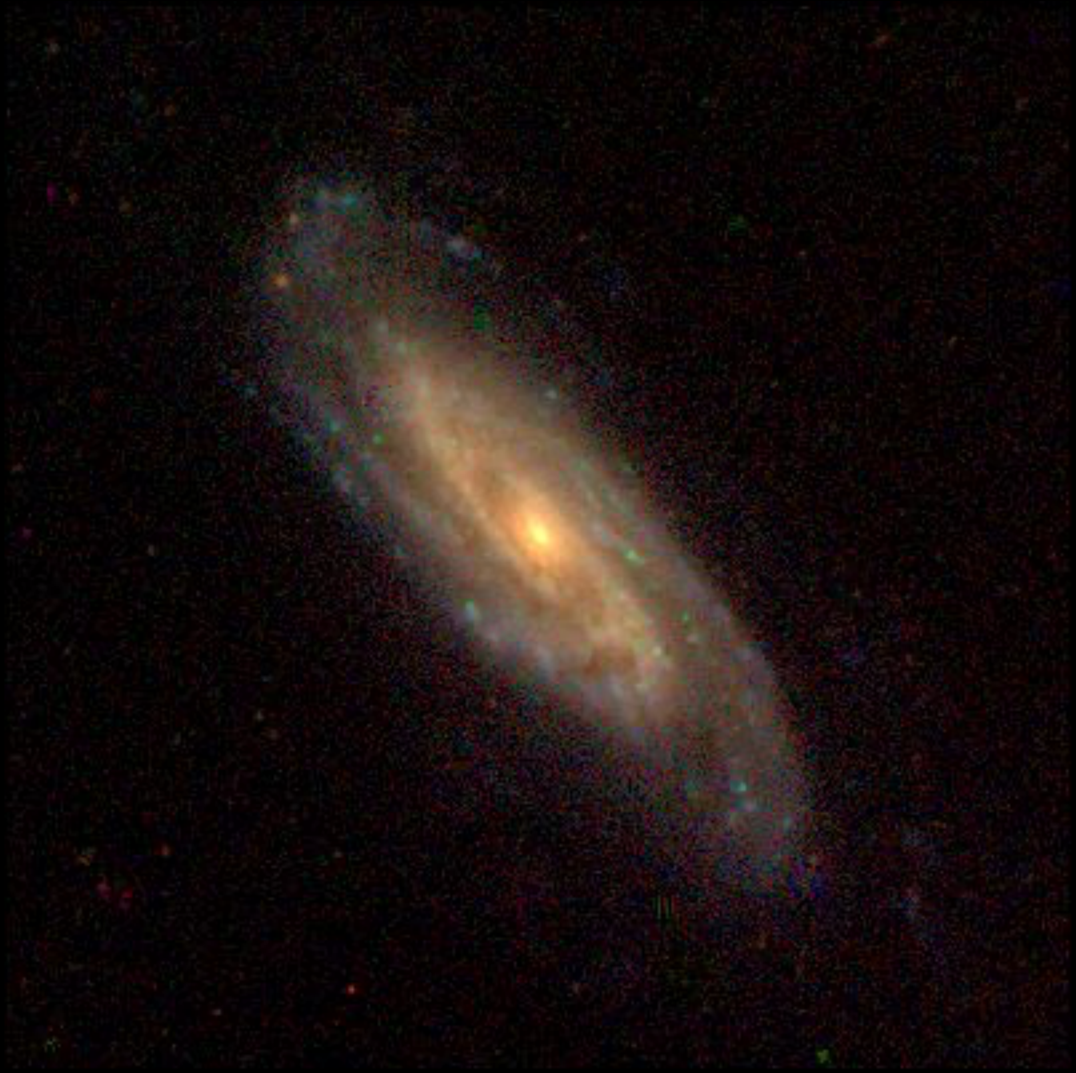


Figure 5.6: – The (0.86, 88°) simulation results (red) over-plotted with the observed UGC 4325 data (blue). The simulation and data match well between ~ 12″ - 30″.

The sinusoidal variation of velocity in each ring measures the position angle, inclination, and rotation curve $V_c(R)$.

$$V \sin i = V_{sys} + V_c \cos\theta + V_r \sin\theta$$

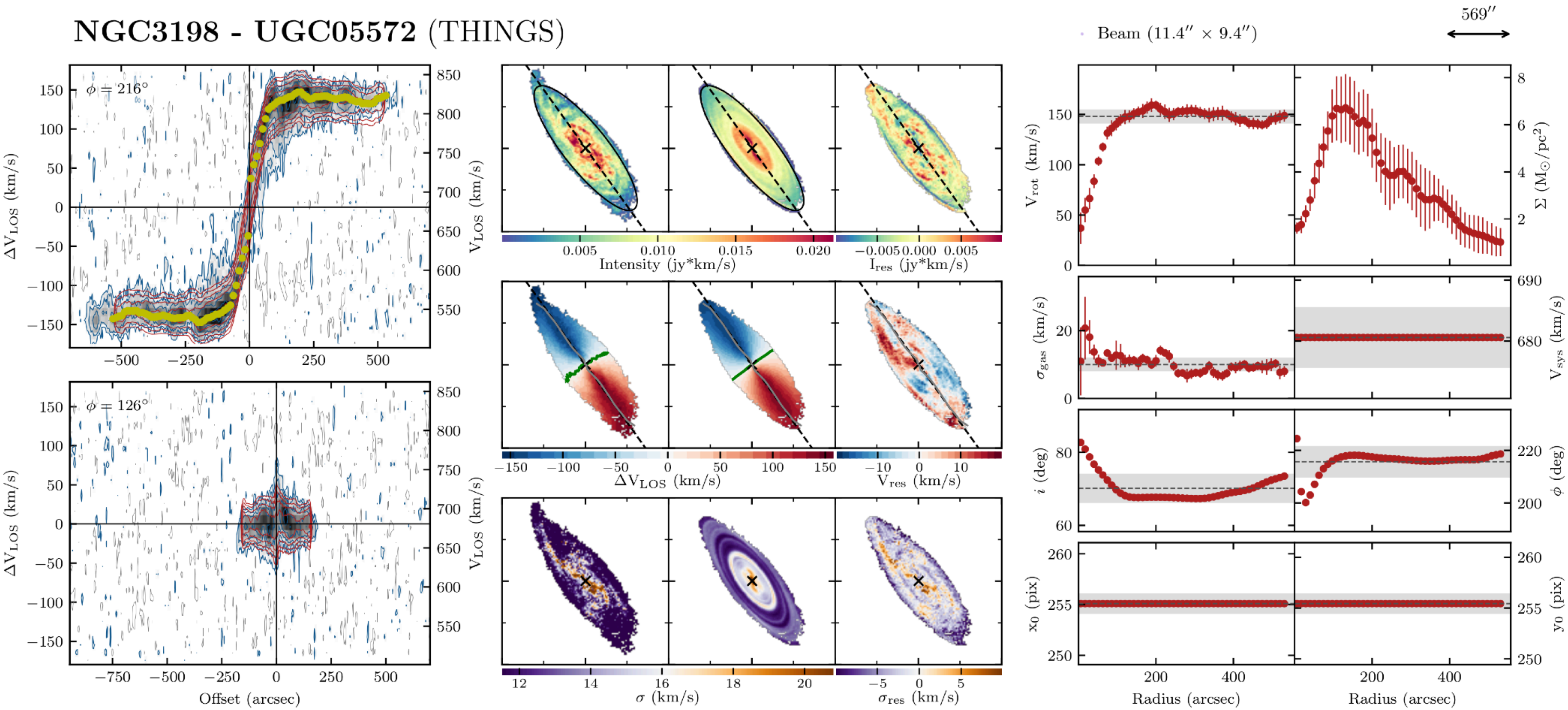
NGC 3198



Stars
Optical (SDSS)

Atomic gas
HI (THINGS)

3D modeling

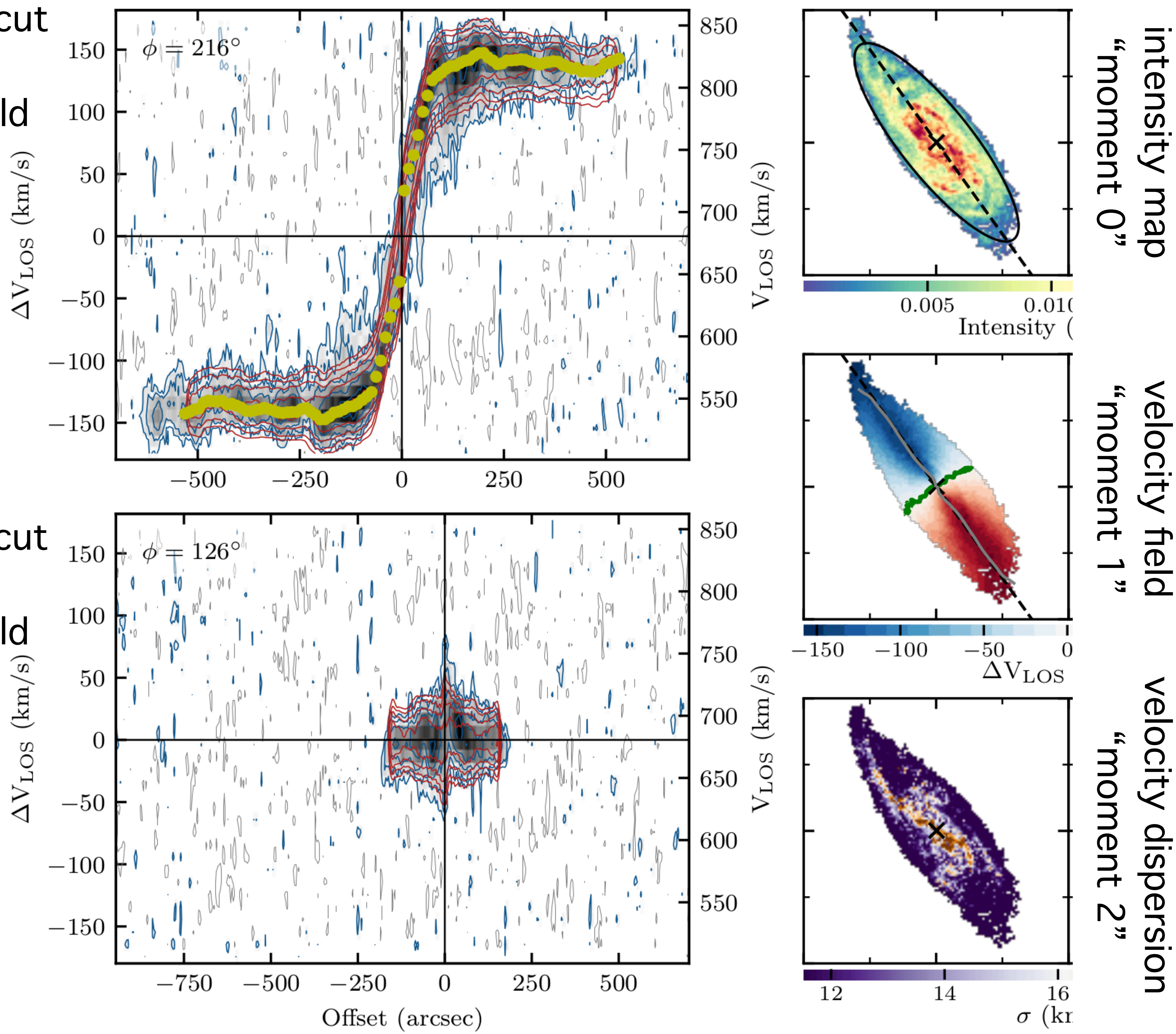


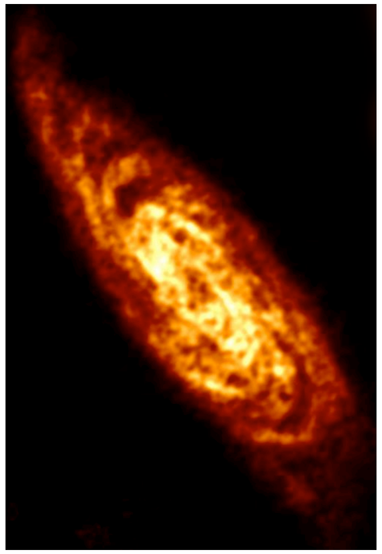
Example analysis for one galaxy. Left: position–velocity diagrams along the major (top) and minor (bottom) axis. Center: 2D Hi map (top), velocity field (middle), and velocity dispersion (bottom). The left panels show the data, the center panels the fitted model, and the right panels the residuals. Right: derived radial quantities: the rotation curve (top left, with Vf noted in grey), the Hi surface density (top right), followed by the velocity dispersion, system redshift, inclination, position angle, and x and y centroids.

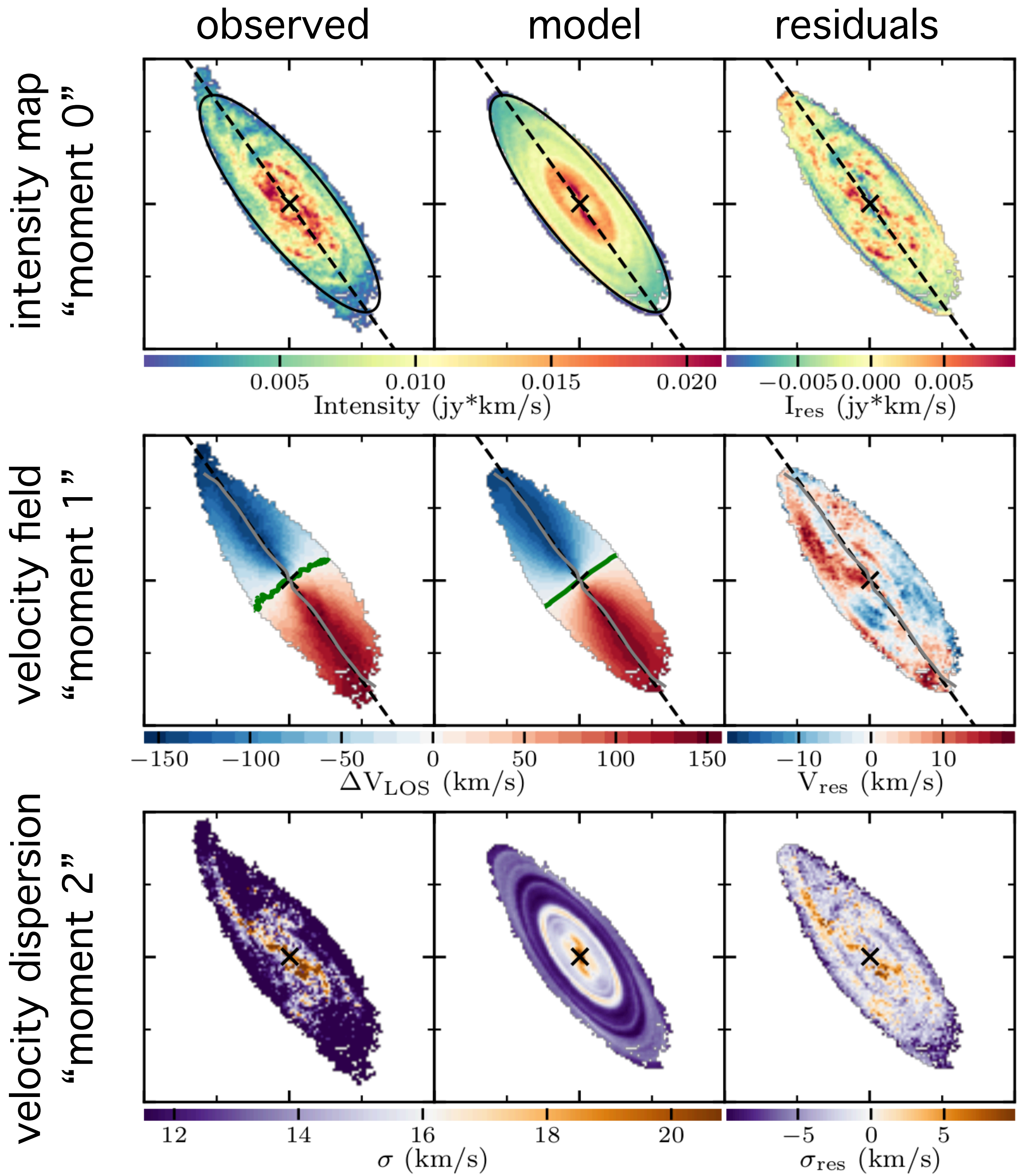
NGC3198 - UGC05572 (THINGS)

Major axis cut through velocity field

Minor axis cut through velocity field







The model is axisymmetric.

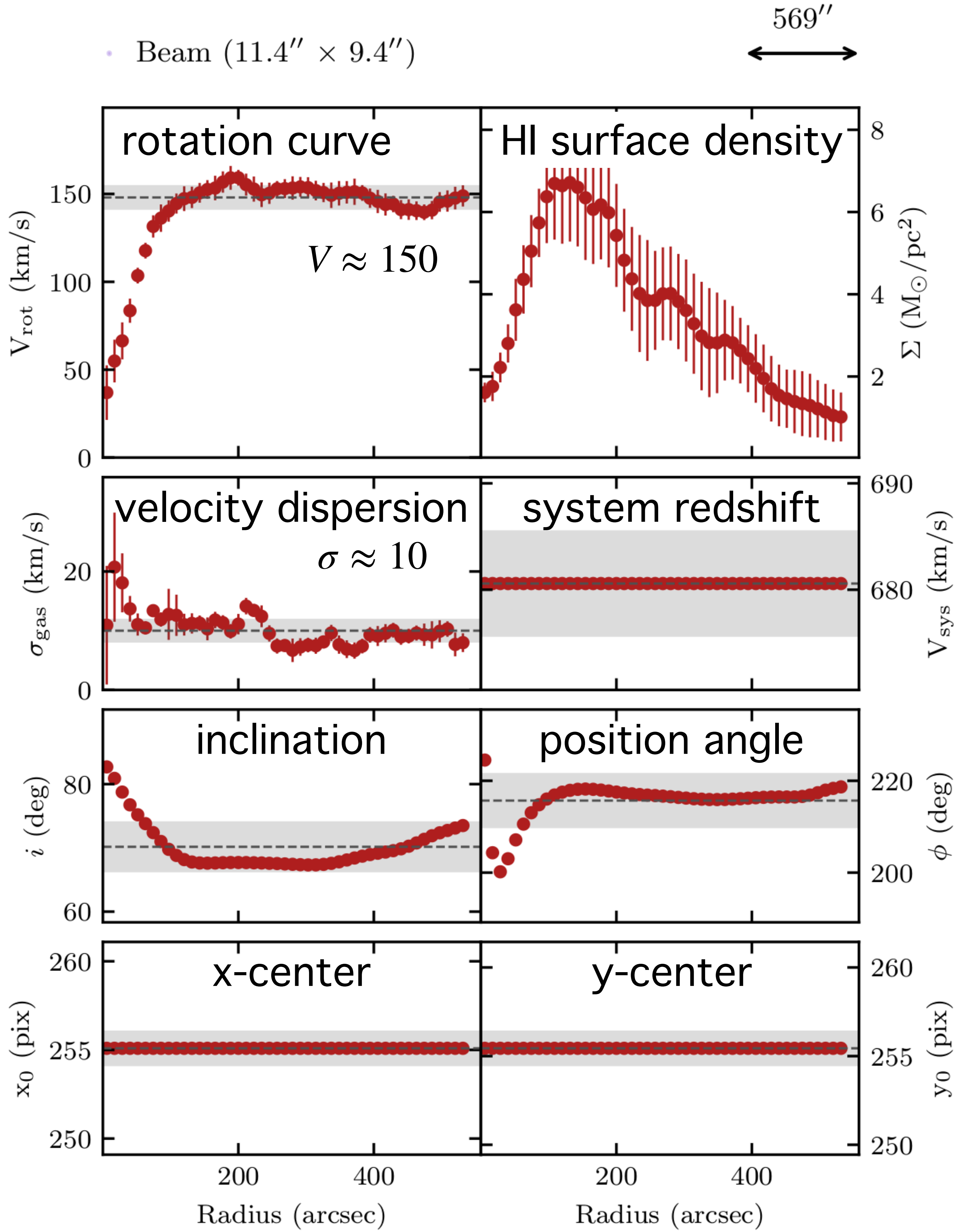
Spiral arms visible in the residual.

Most spirals have large V/σ. In this case,

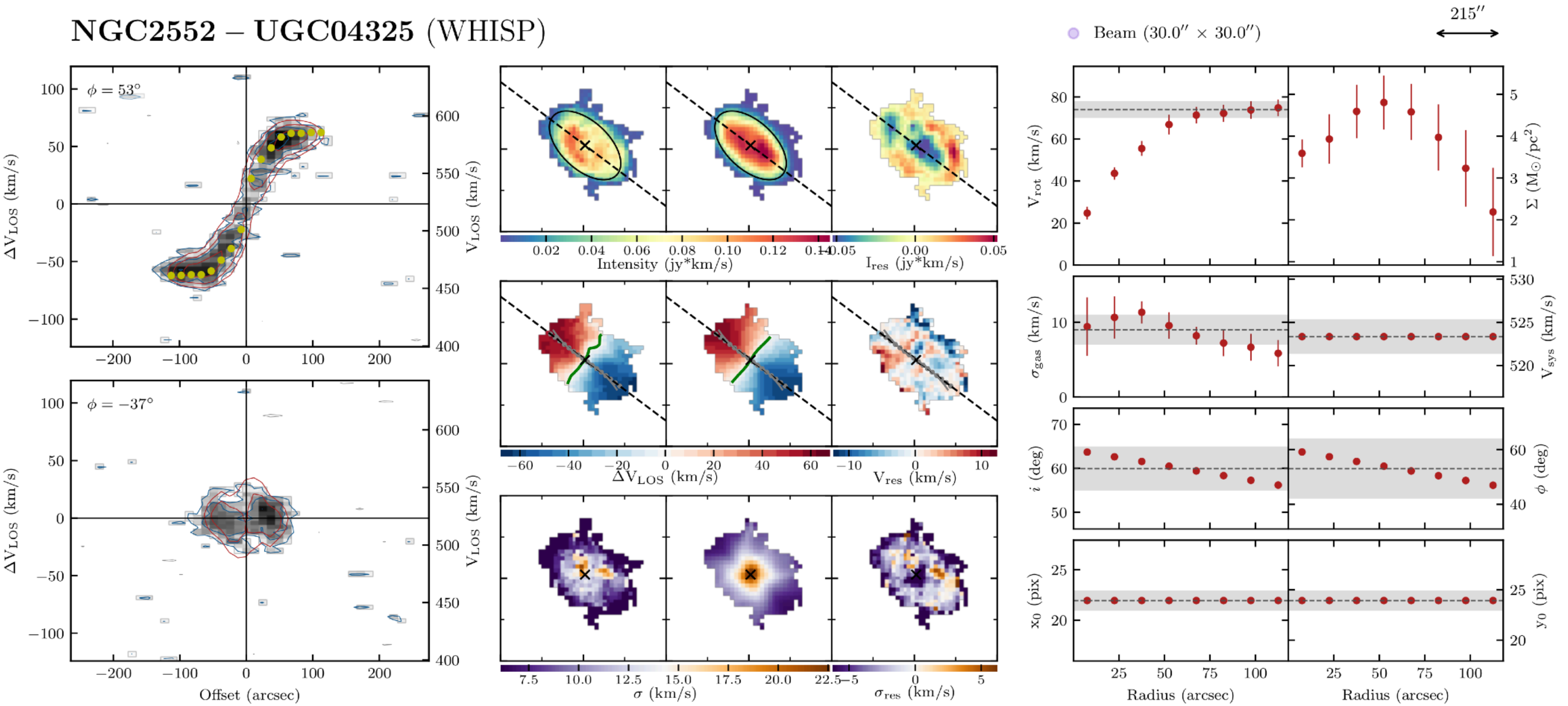
$$\frac{V}{\sigma} \approx 15$$

so almost all kinetic energy is in rotation. This is a "cold" disk.

Don't need to worry (too much) about the velocity dispersion or flows along the spiral arms (both of order 10 km/s)



Gotta do this for every galaxy, each of which has its own individual mass distribution



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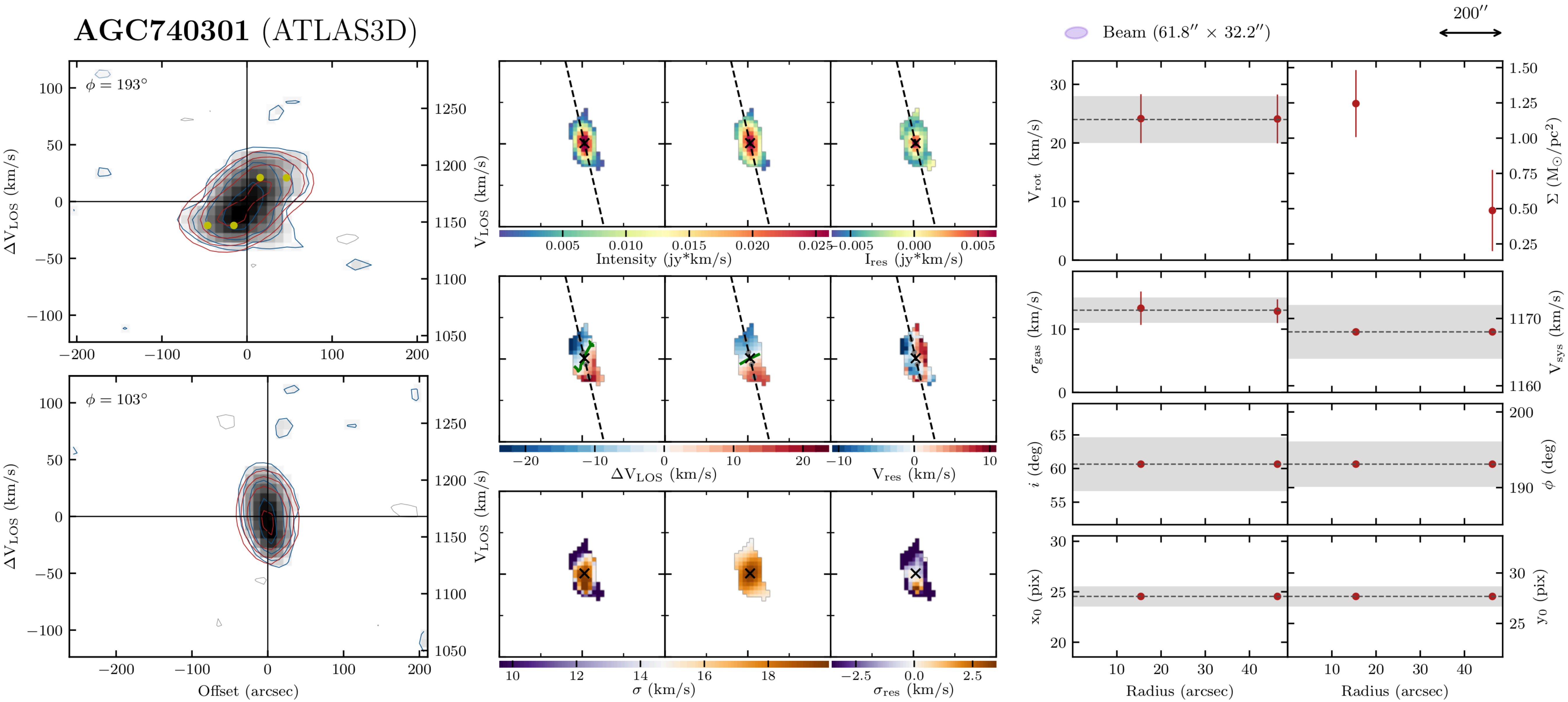
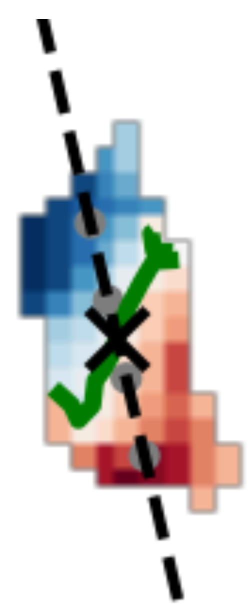
Sometimes the data leave something to be desired



Example analysis for one galaxy. Left: position–velocity diagrams along the major (top) and minor (bottom) axis. Center: 2D Hi map (top), velocity field (middle), and velocity dispersion (bottom). The left panels show the data, the center panels the fitted model, and the right panels the residuals. Right: derived radial quantities: the rotation curve (top left, with Vf noted in grey), the Hi surface density (top right), followed by the velocity dispersion, system redshift, inclination, position angle, and x and y centroids.



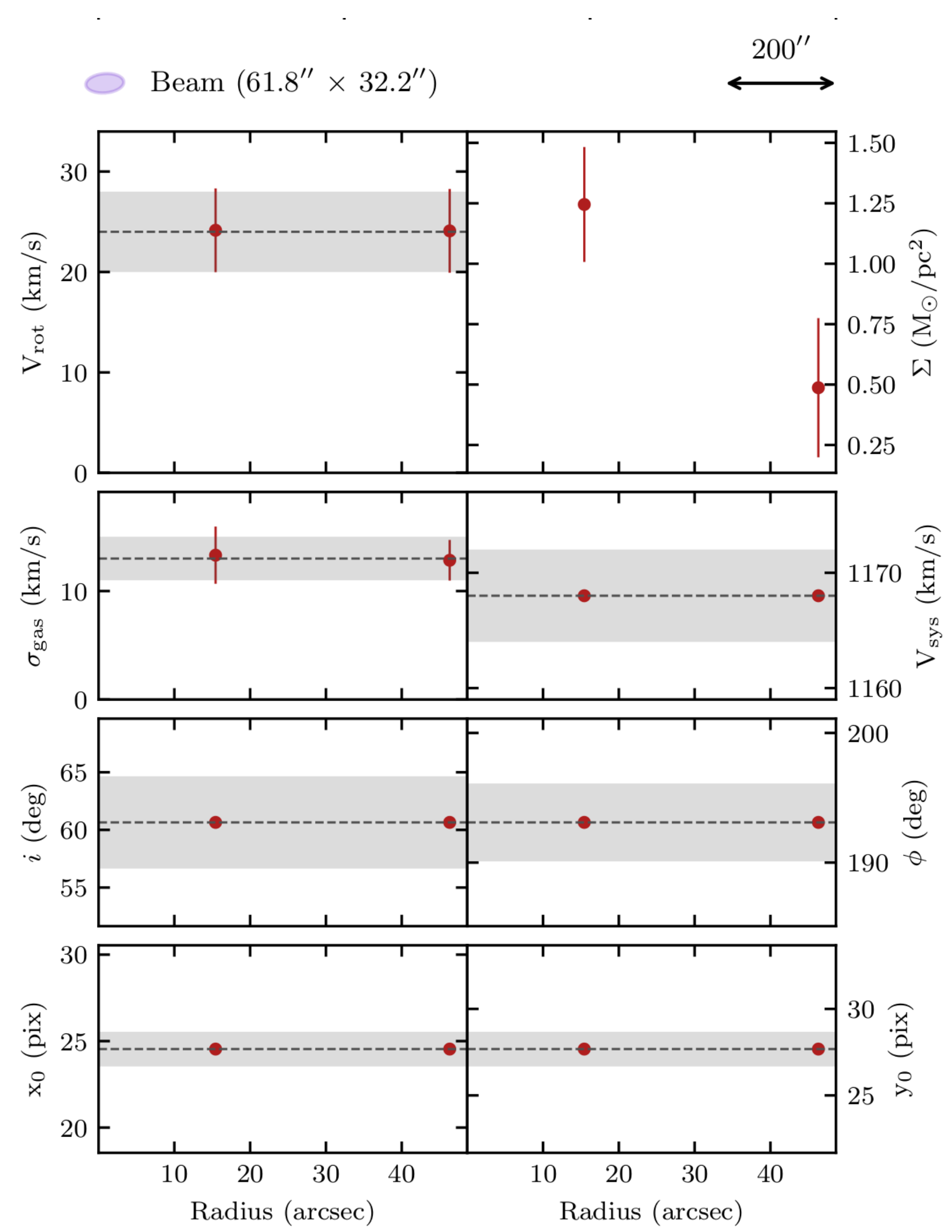
Note that in this case, the kinematic minor axis is not orthogonal to the major axis.

Sometimes the data leave something to be desired

In this case, the velocity dispersion is comparable to the rotation speed, $\sigma = 12$ km/s and $V_{rot} = 23$ km/s. Need to account for total kinetic energy to assess the gravitational potential.

(Noncircular motion sometimes referred to as "asymmetric drift")

The Jeans equation is one approach to account for noncircular motion:



$$V_c^2(R) = \langle V_\phi \rangle^2 - \langle V_R \rangle^2 \left(1 + \frac{\partial \ln \nu}{\partial \ln R} + \frac{\partial \ln \langle V_R \rangle^2}{\partial \ln R} \right)$$

Slope of the radial velocity dispersion profile

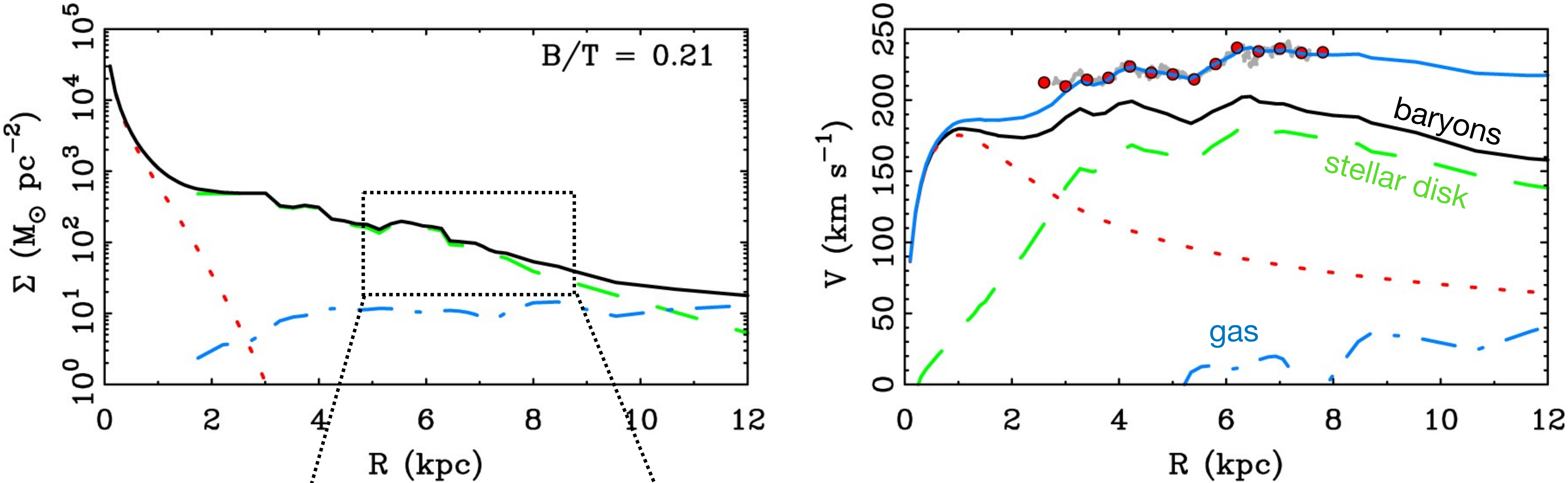
Slope of the density profile of tracer particles

Measured velocity dispersion in radial direction (large when noncircular motions are important)

Measured speed in rotation direction

Velocity of a test particle on a circular orbit (a representation of the potential)

Example: model Milky Way



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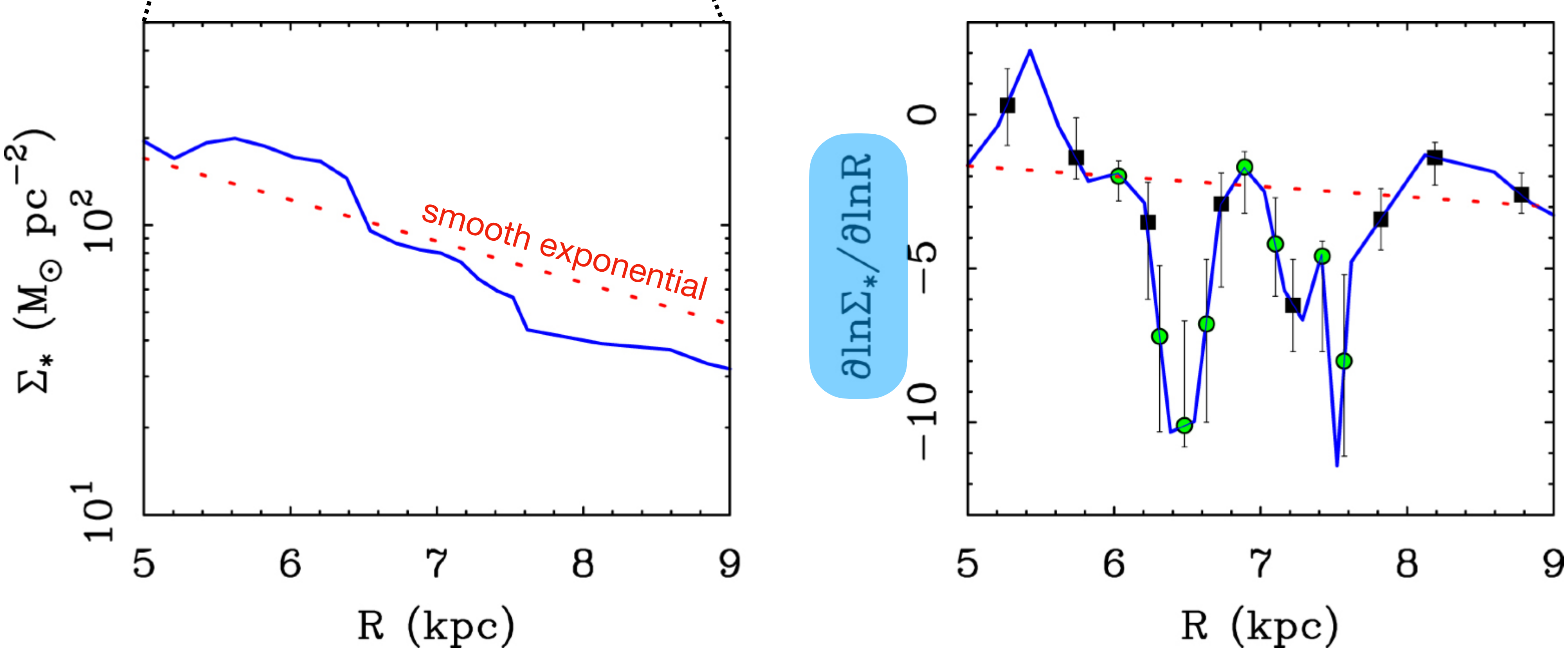


Now have all that we need to describe the mass distribution, the corresponding gravitational potential, and the resulting equilibrium kinematics

- Mass distribution
  - stellar disk
  - central bulge
  - atomic gas
  - molecular gas
  - etc.

- Gravitational Potential
  - Each component distinct
  - Add linearly in Newton
- Kinematics
  - rotation
  - pressure (velocity dispersion)

Empirical Laws of Galactic Rotation

- Flat rotation curves (Rubin-Bosma Law)

  Rotation curves tend asymptotically towards a constant rotation velocity that persists to indefinitely large radii: $V(R \to \infty) \to V_f$

- Tully-Fisher relation (Luminous, Stellar Mass, and Baryonic TF relations)

  The baryonic mass of galaxies scales as the fourth power of the flat rotation velocity: $M_b = AV_f^4$

- Central density relation (lower surface brightness galaxies exhibit larger mass discrepancies)

  The central dynamical surface densities of galaxies is related to their central surface brightnesses: $\Sigma_{dyn}(R \to 0) = f[\Sigma_*(R \to 0)]$

- Renzo's rule (Sancisi's Law)

  "For any feature in the luminosity profile there is a corresponding feature in the rotation curve and vice versa." (Sancisi 2004).

- Radial acceleration relation

  The observed centripetal acceleration is related to that predicted by the observed distribution of baryons: $\mathrm{g_{obs}} = \mathcal{F}(\mathrm{g_{bar}})$

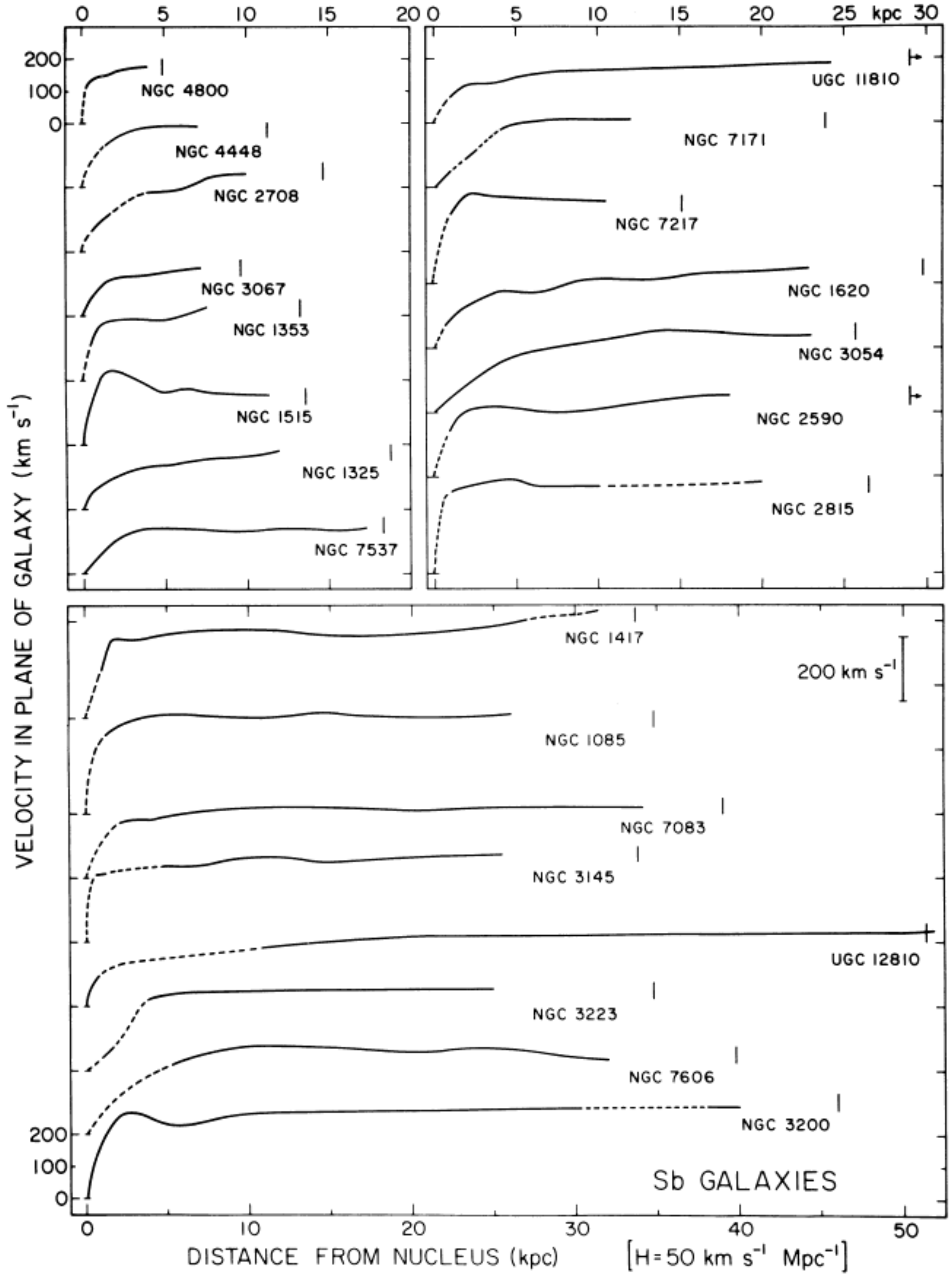


FIG. 3.—Mean velocities in the plane of the galaxy, as a function of linear radius for 23 Sb galaxies, arranged approximately according to increasing luminosity. Adopted curve is rotation curve formed from the mean of velocities on both sides of the major axis. Vertical bar marks the location of R_{25}, the isophote of 25 mag arcsec^{-2}, corrected for effects of internal extinction and inclination. Regions with no measured velocities are indicated by dashed lines.

Rotation curves tend to become flat at large radii

$$V \propto \text{const}$$

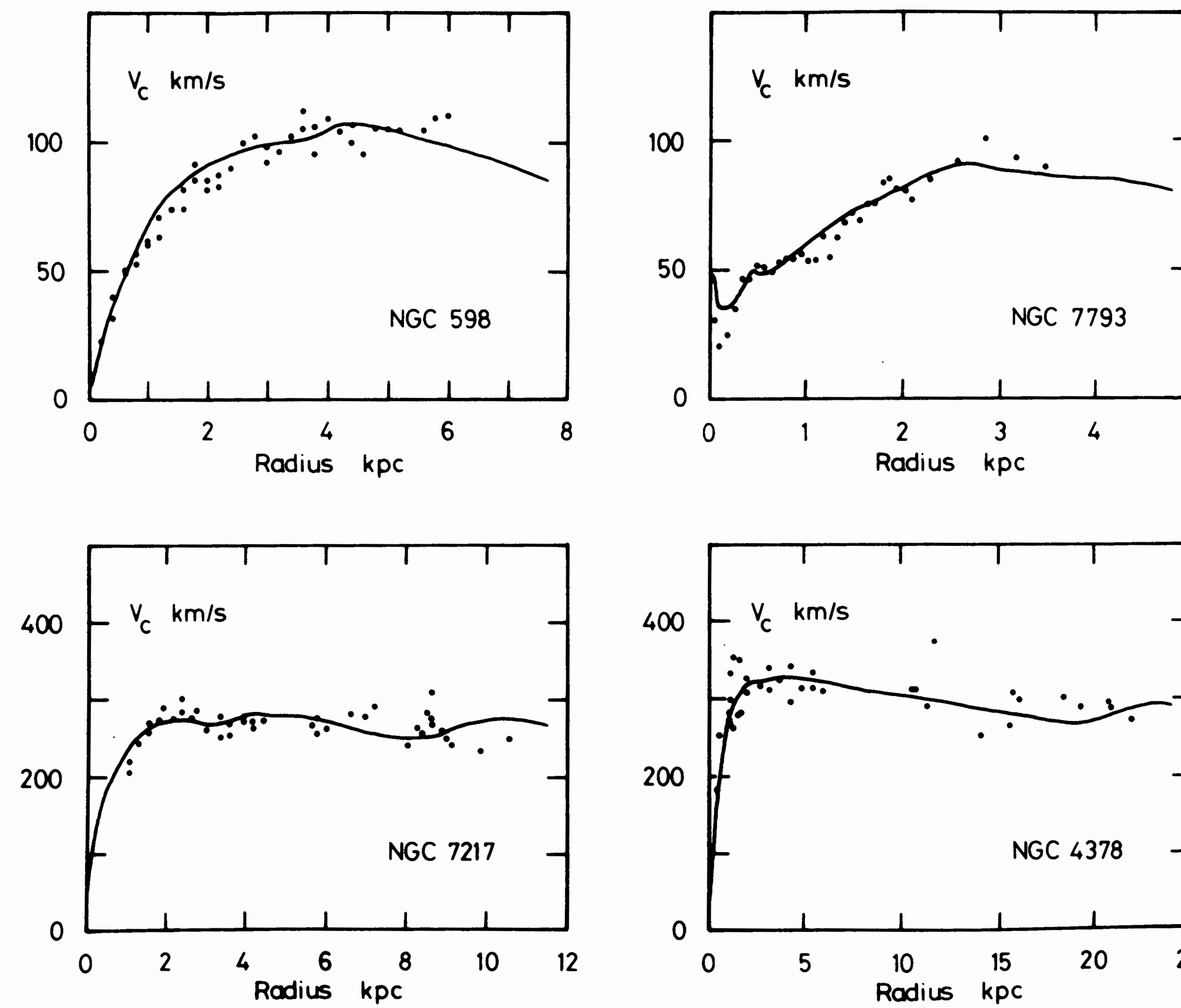
$$M \propto R$$

$$\rho \propto R^{-2}$$

Optical data from
Rubin, Thonnard, & Ford 1978, *ApJ*, **225**, L107

Kalnajs
IAU 100
(1982)

KALNAJS : The customary approach of deducing mass distribution from rotation curves involves an implicit or explicit extrapolation of the velocity data, and the often reported rise of M/L usually begins where the observed information runs out. I would like to show you a slide depicting four rotation curves computed from photometric data which has been converted into mass distributions by assuming that M/L is constant within a galaxy. The photometry extends to faint enough limits to completely determine the rotation curves. For NGC 4378 it was necessary to decompose the light into a bulge and a disk. For the others the decomposition gave essentially the same curves as would have been obtained from pure disks.
The rotation curves agree well with the observed velocity points, and thus demonstrate that the flat rotation curves of NGC 7217 and NGC 4378 need not lead one to conclude that there is dark matter in the outer parts of these galaxies.



Rotation curves computed from photometry assuming a constant M/L within each galaxy. The dots are the measured velocities. The values of M/L used are 5.0, 2.9, 4.2 and 6.5.

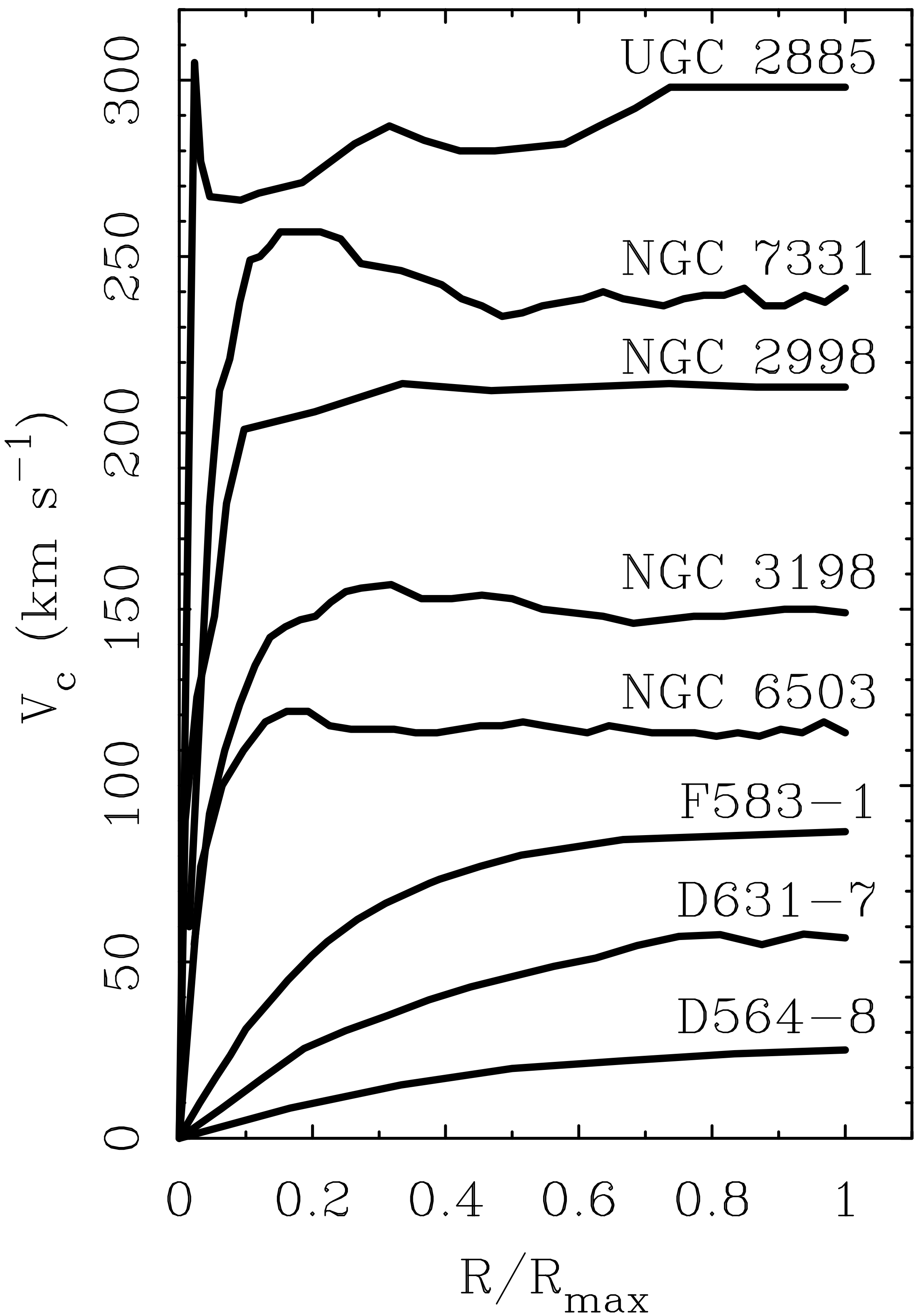
IAU 100 (1982)

.... :
.... : ?
.... : !!!!!
somebody : HA, HA, HA.
.... : ***, ???, !!!
(The audience becomes restive and the massive halo enthusiasts slowly regain their composure).

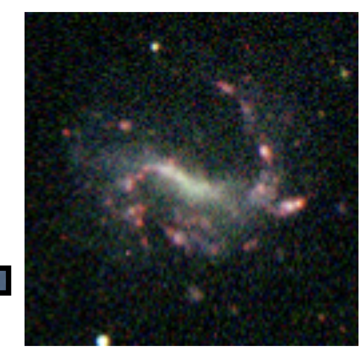
HAUD : This is very interesting, but note the limited extent of the rotation curves of these four galaxies. Three of them extend to radii less than 12 kpc and the fourth one reaches 25 kpc. Usually the M/L starts to increase rapidly only outside roughly 30 kpc, and only giant galaxies have coronas.

RUBIN (to Kalnajs) : It is true that the analysis of the rotation curves presents the mass interior to any R, but not the distribution of the mass. Thus, while the mass could be in a disk, there are other reasons, stability especially, that suggest a halo. The velocities you show for NGC 4378 and 7217 come from our data, and both rotation curves are fairly exceptional in that the velocities fall slightly with increasing R. I suspect you would have more difficulty in fitting with constant M/L a flat or slightly rising rotation curve which extends to very large radii. In any case, it seems to me, you must be saying that the surface brightness of these galaxies falls slower than exponentially with increasing R.

Tully-Fisher: Rotation curve amplitude correlates with observed mass:



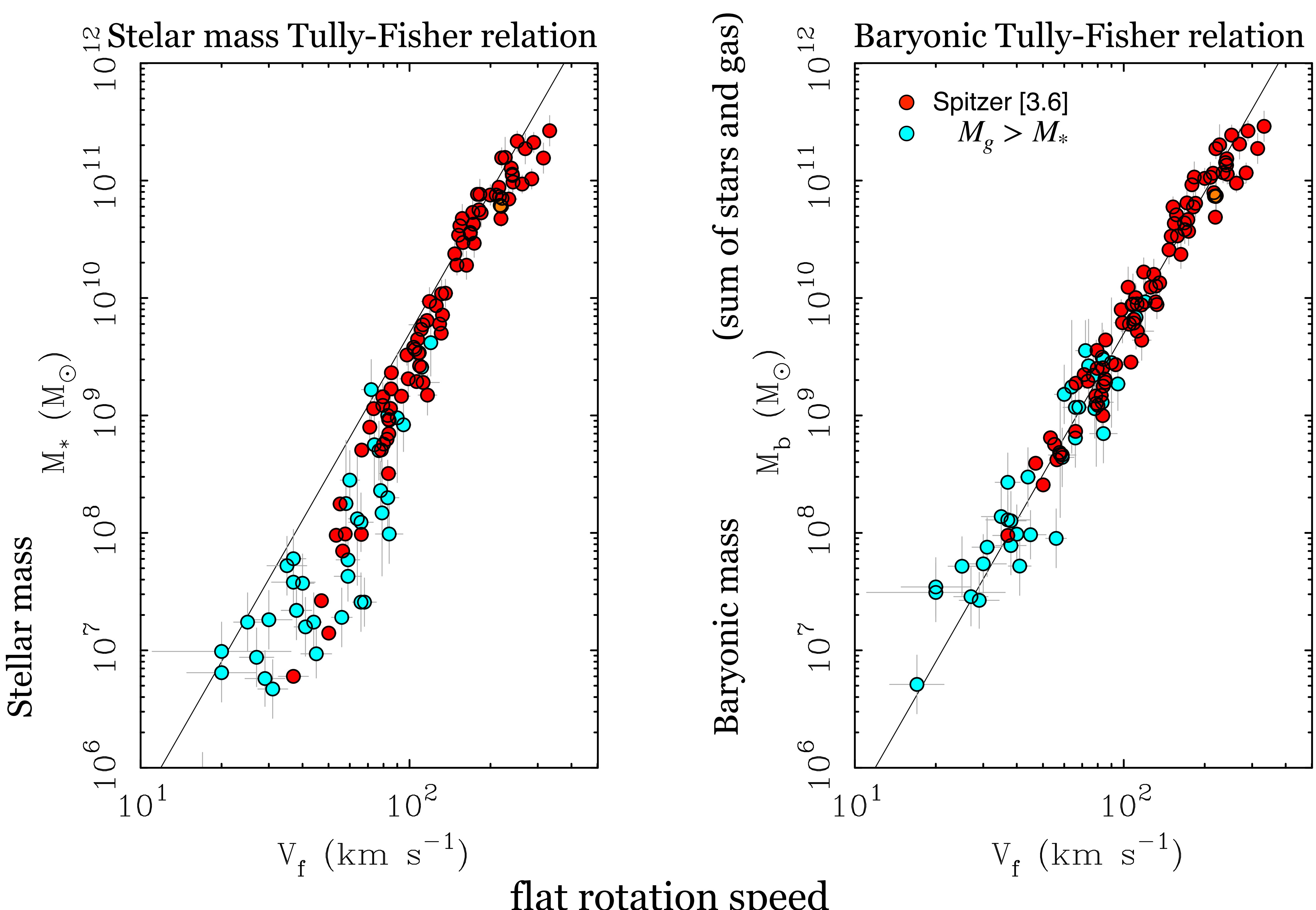
star dominated HSB



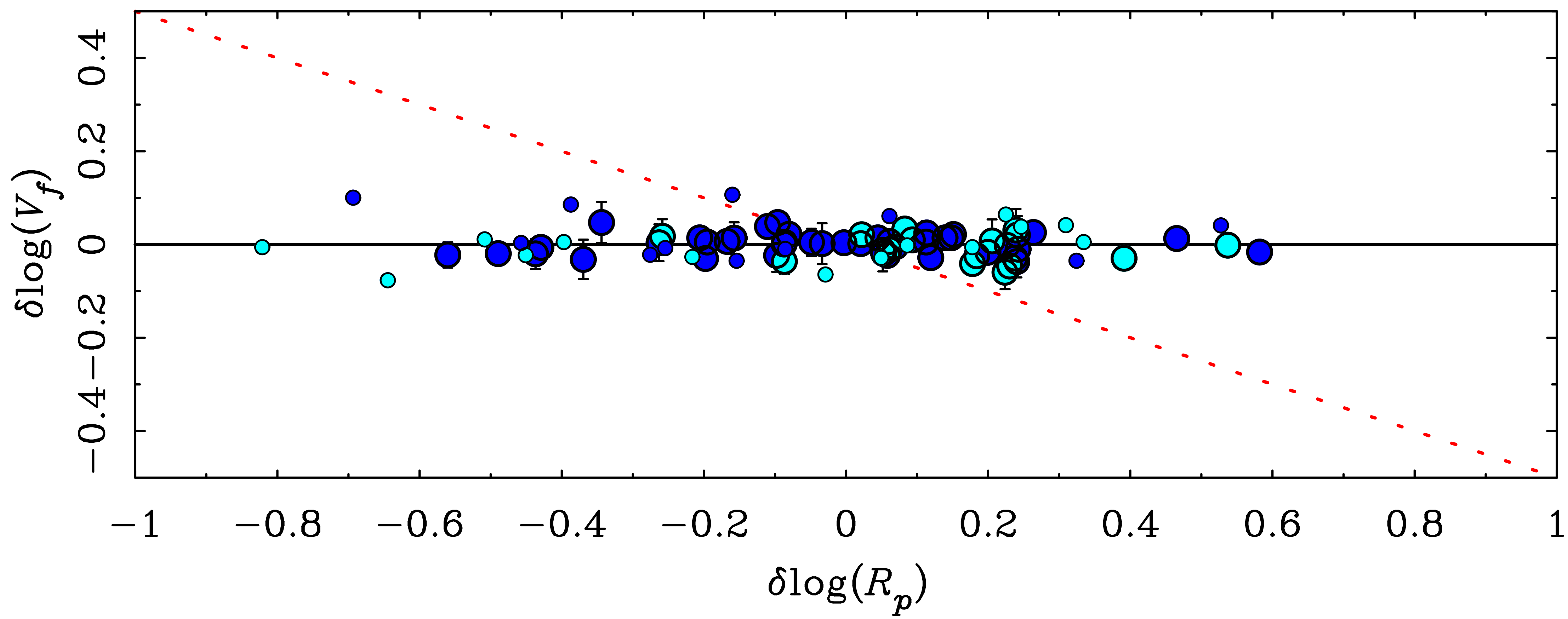
gas dominated LSBs

Flat rotation curves continue to occur in quite small systems (e.g., Leo P with V_f ~ 15 km/s)

Tully-Fisher relations: amplitude of flat rotation speed correlates with mass

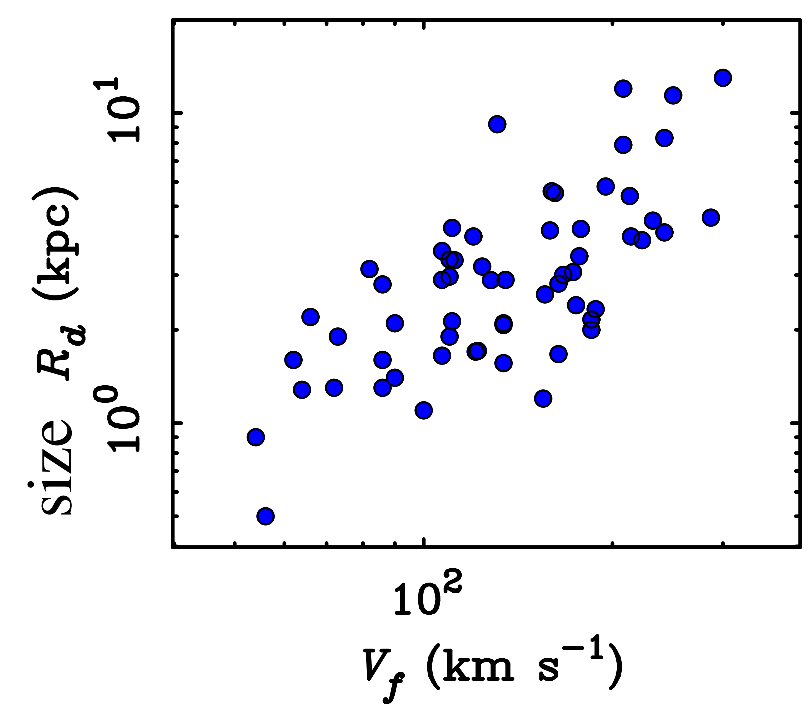


No residuals from BTFR with size or surface density for disks

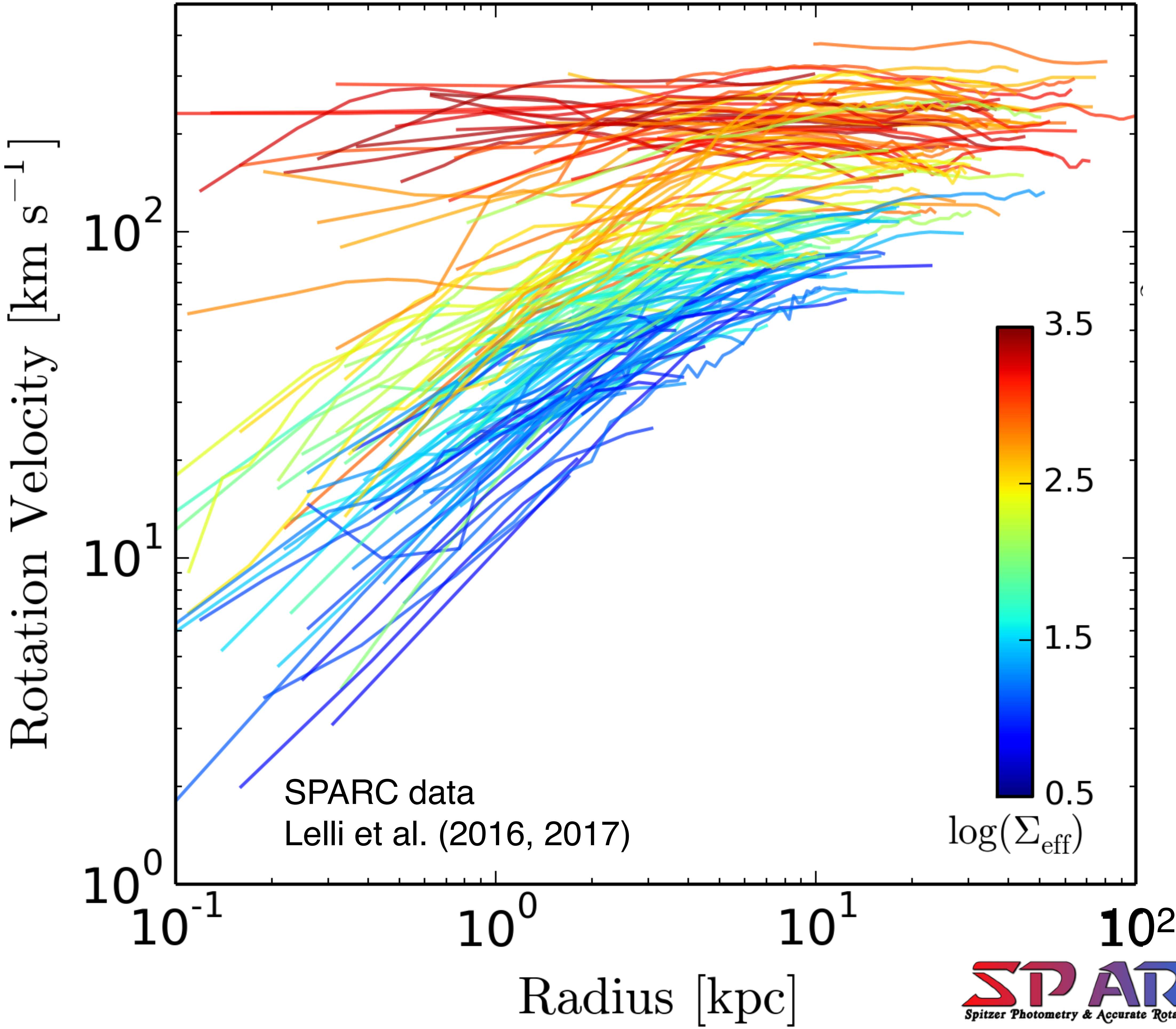


$$V^2 = \frac{GM}{R} \rightarrow \frac{\delta\log(V)}{\delta\log(R)} = -\frac{1}{2}$$ expected slope (dotted line)

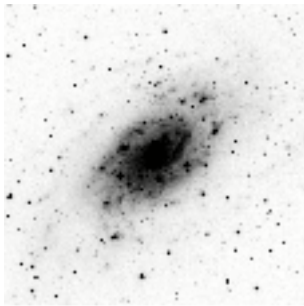
Note: large range in size at a given mass or velocity

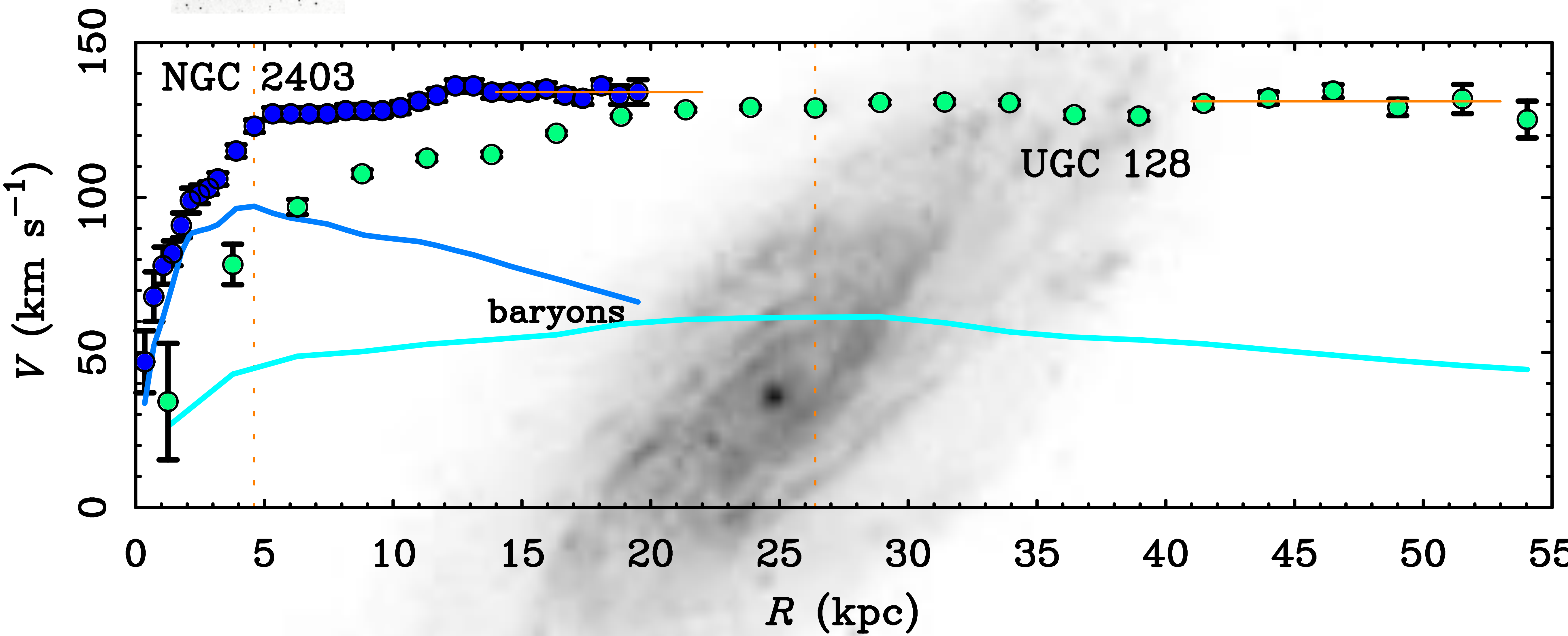


Rotation curve shape correlates with baryonic surface density



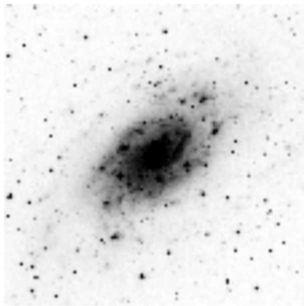
TF pair



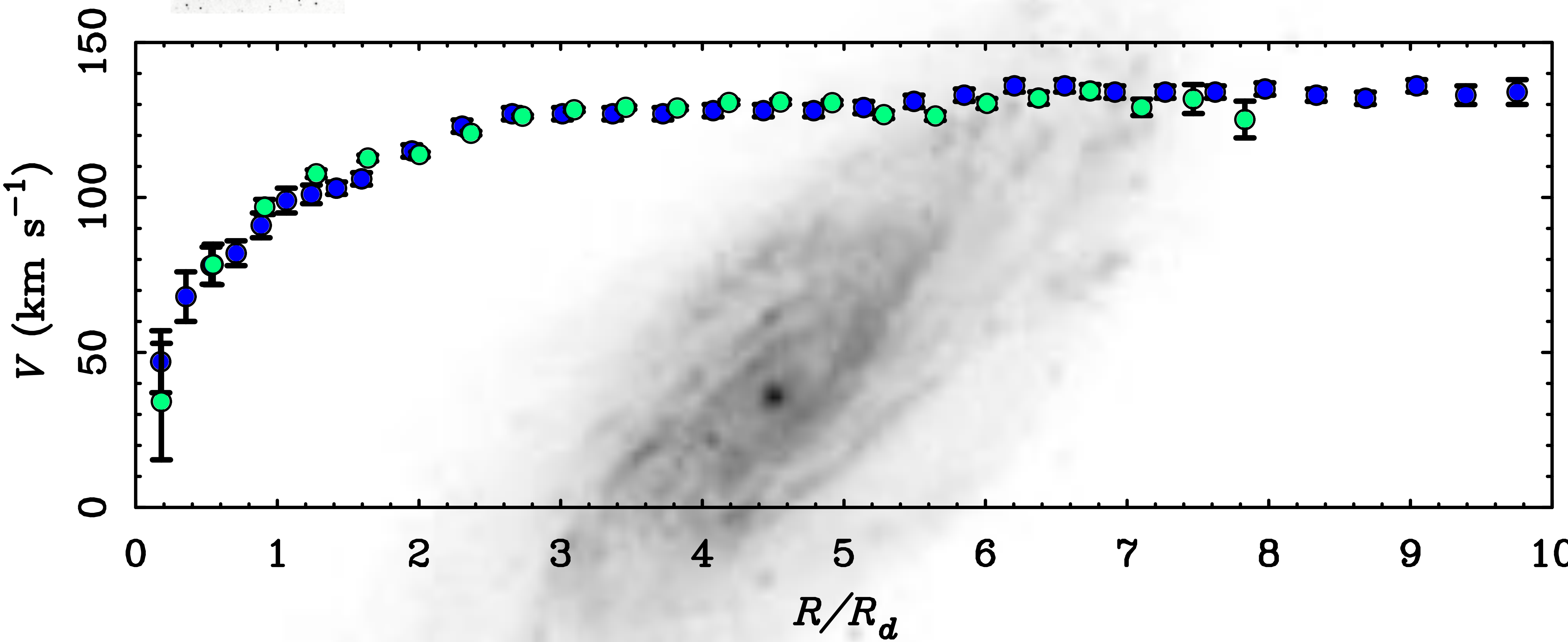


Radius in physical units (kpc)

Persic & Salucci 1996
de Blok & McGaugh 1996
Tully & Verheijen (1998)
Nordermeer & Verheijen (2007) [URC nor quite right formulation]
Swaters et al. (2009)



The dynamics knows about the distribution of baryons, not just their total mass



Radius normalized by size of disk.

Persic & Salucci 1996
de Blok & McGaugh 1996
Tully & Verheijen (1998)
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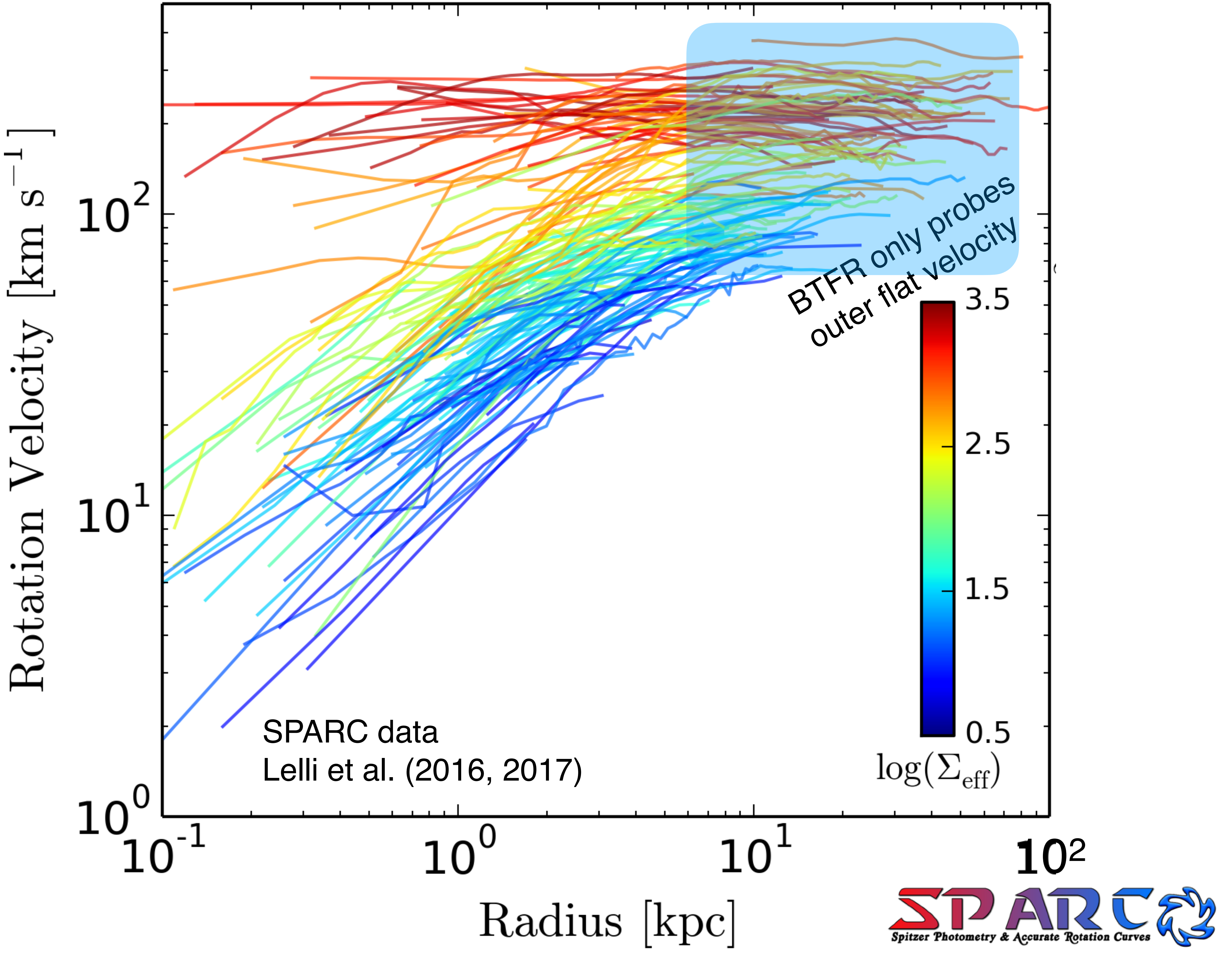
Swaters et al. (2009)

Rotation curve shape correlates with baryonic surface density



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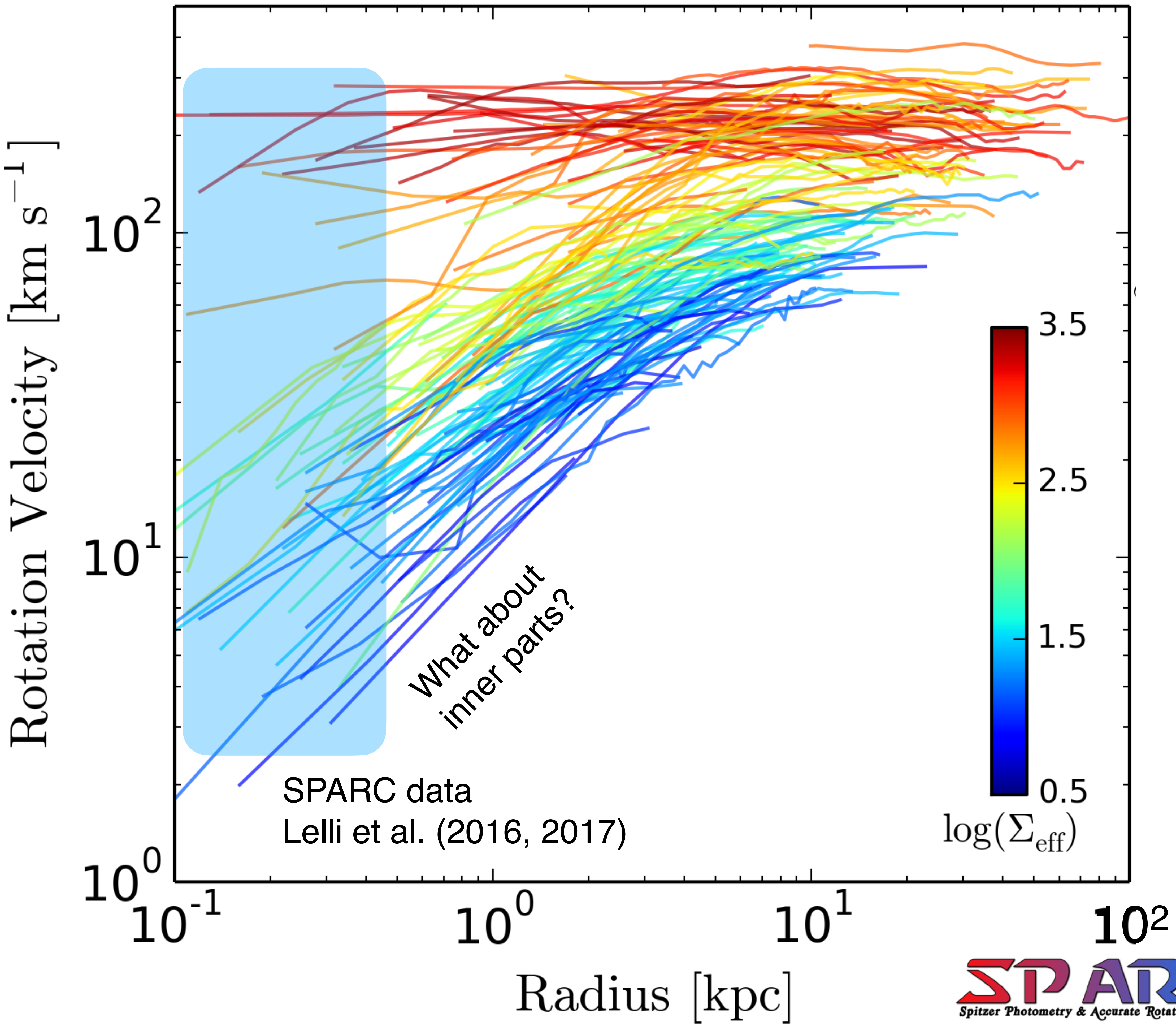
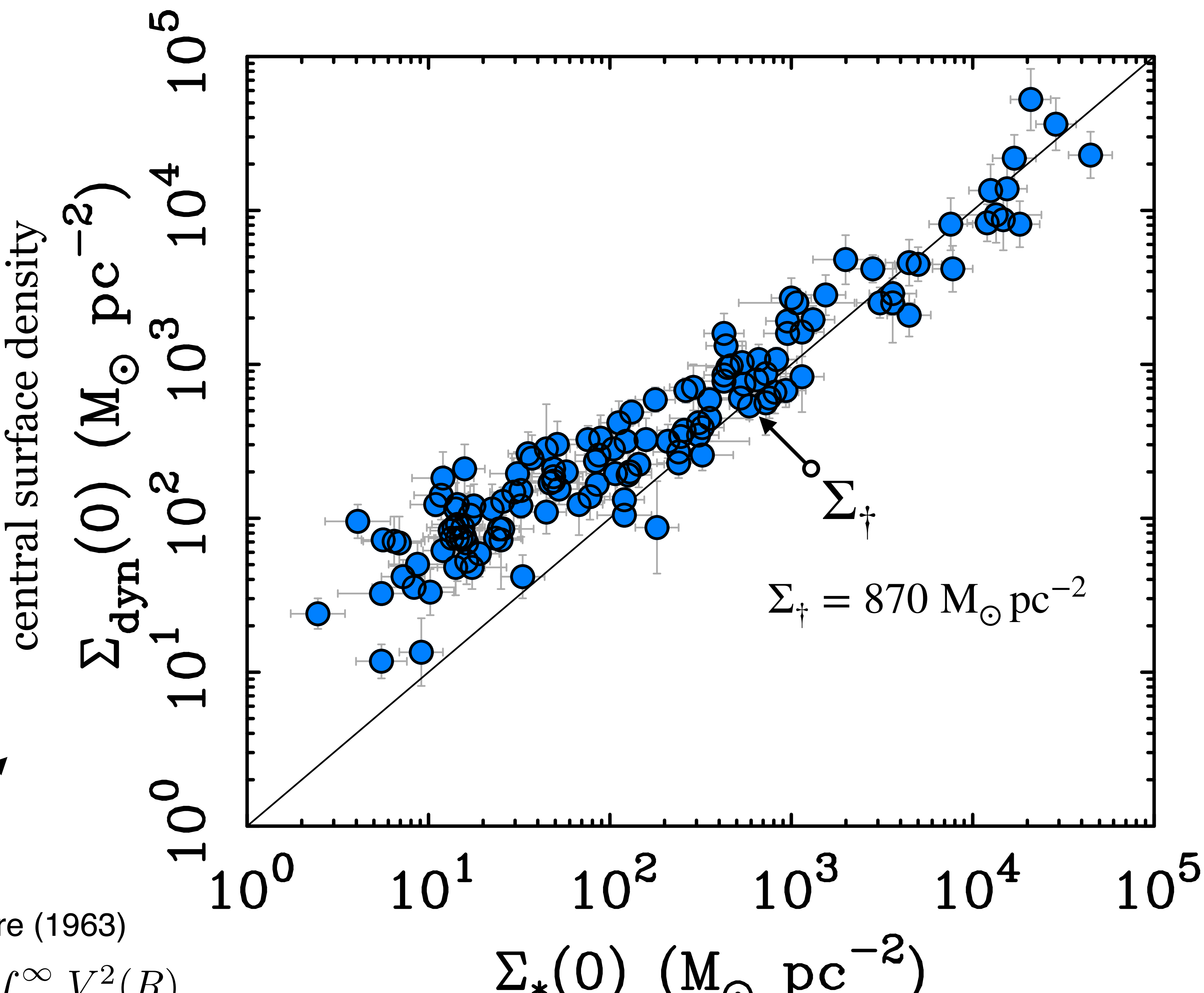


Central Density Relation

Lelli et al. (2016)

The *dynamical* central mass surface density correlates with the central surface brightness of stars in galaxies.

Mass surface density indicated by kinematics

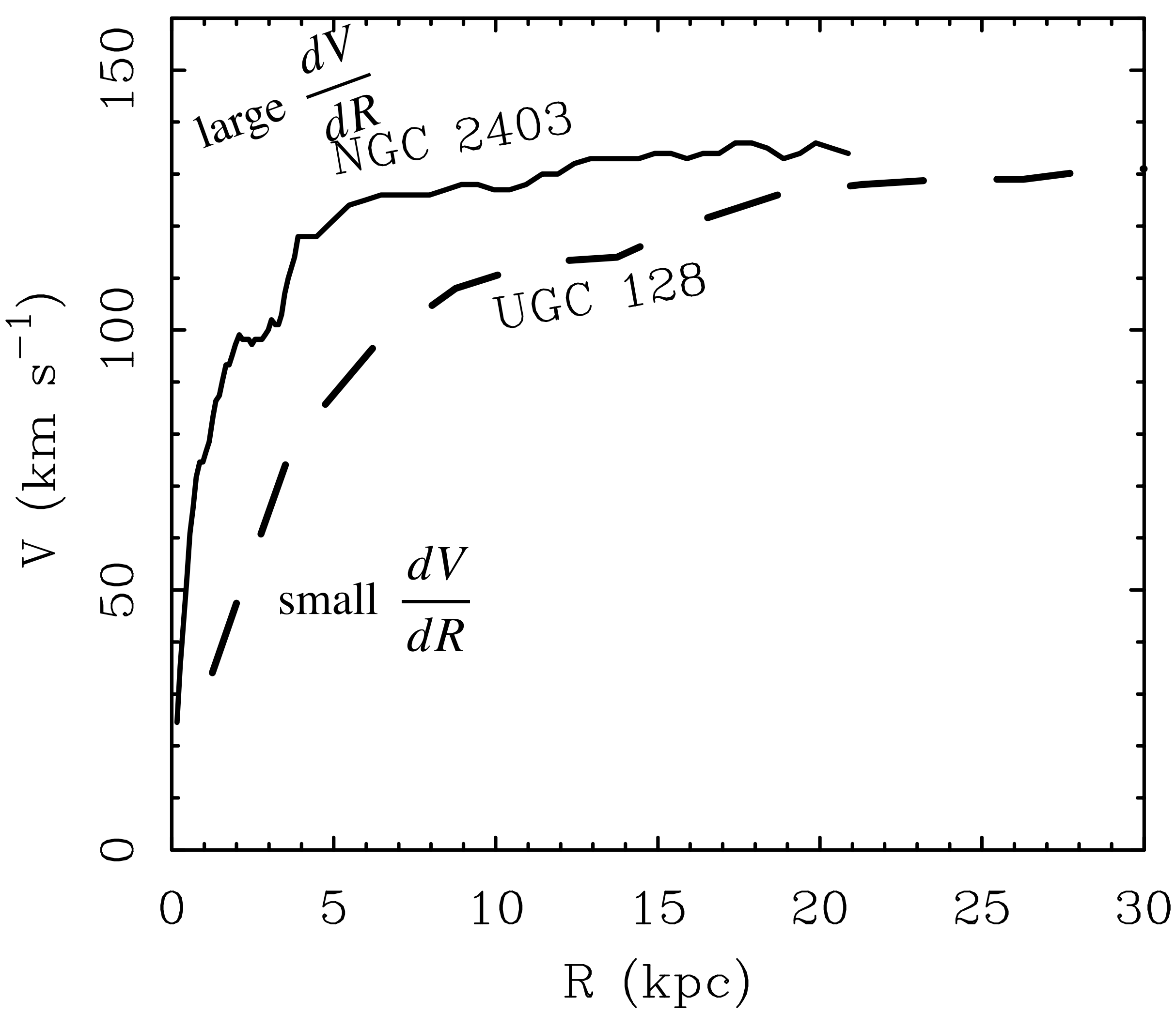


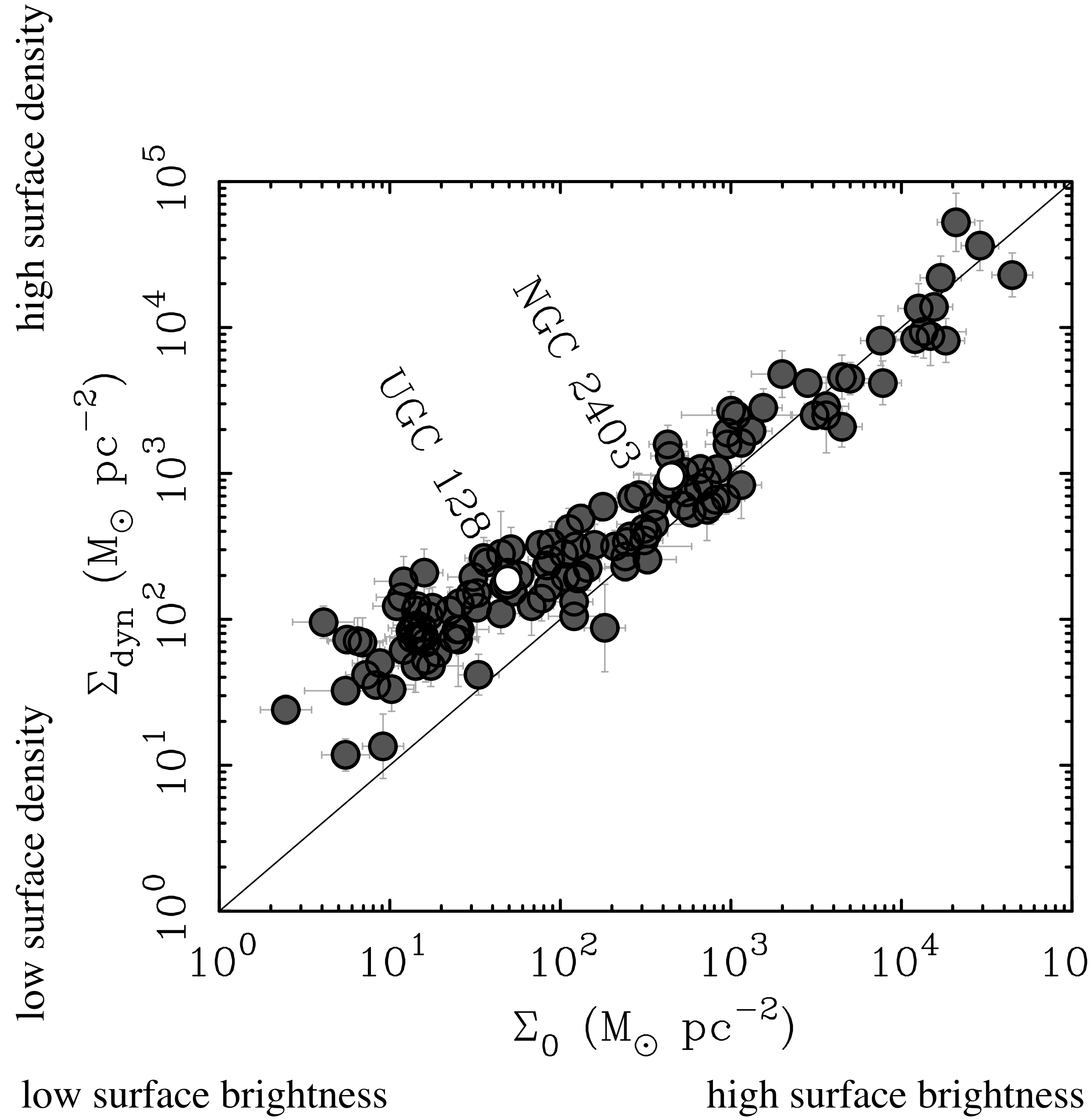
central surface brightness

Toomre (1963)

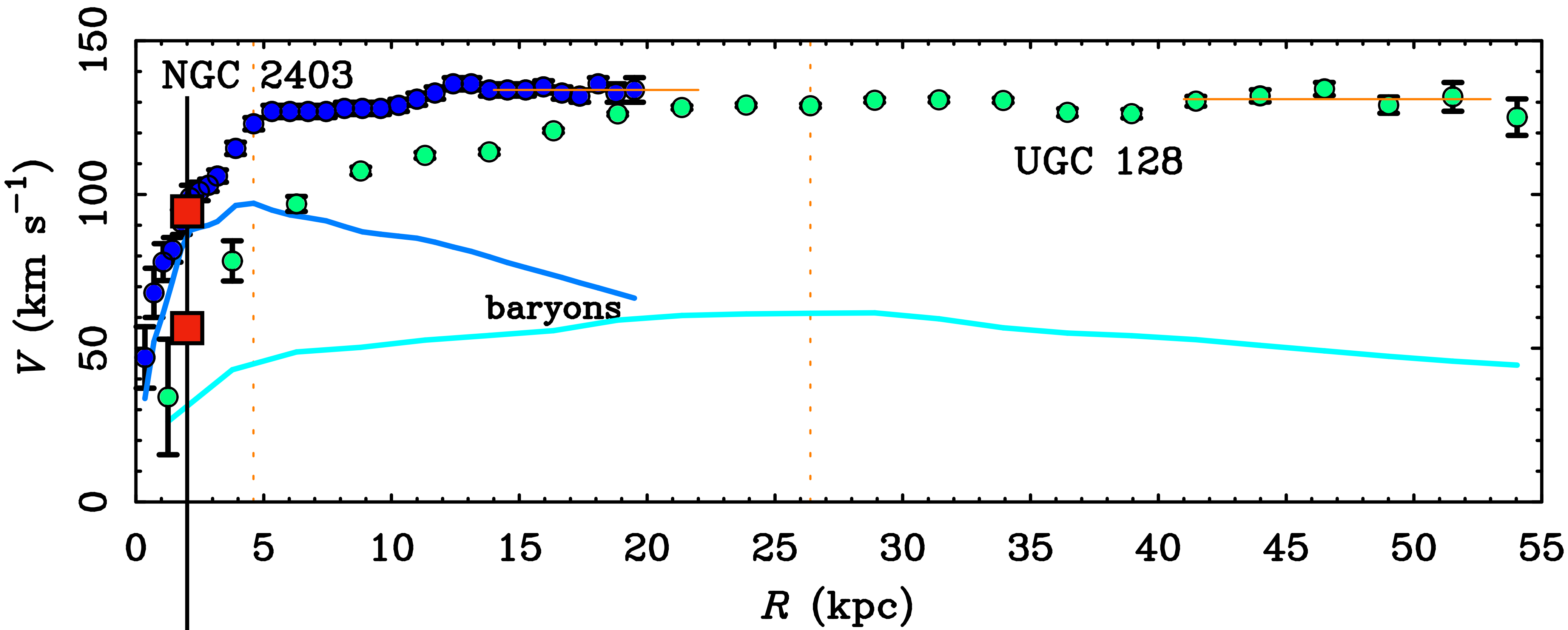
$$\Sigma_{dyn}(0) = \frac{1}{2\pi G}\int_0^\infty \frac{V^2(R)}{r^2}dR$$

Central Density Relation



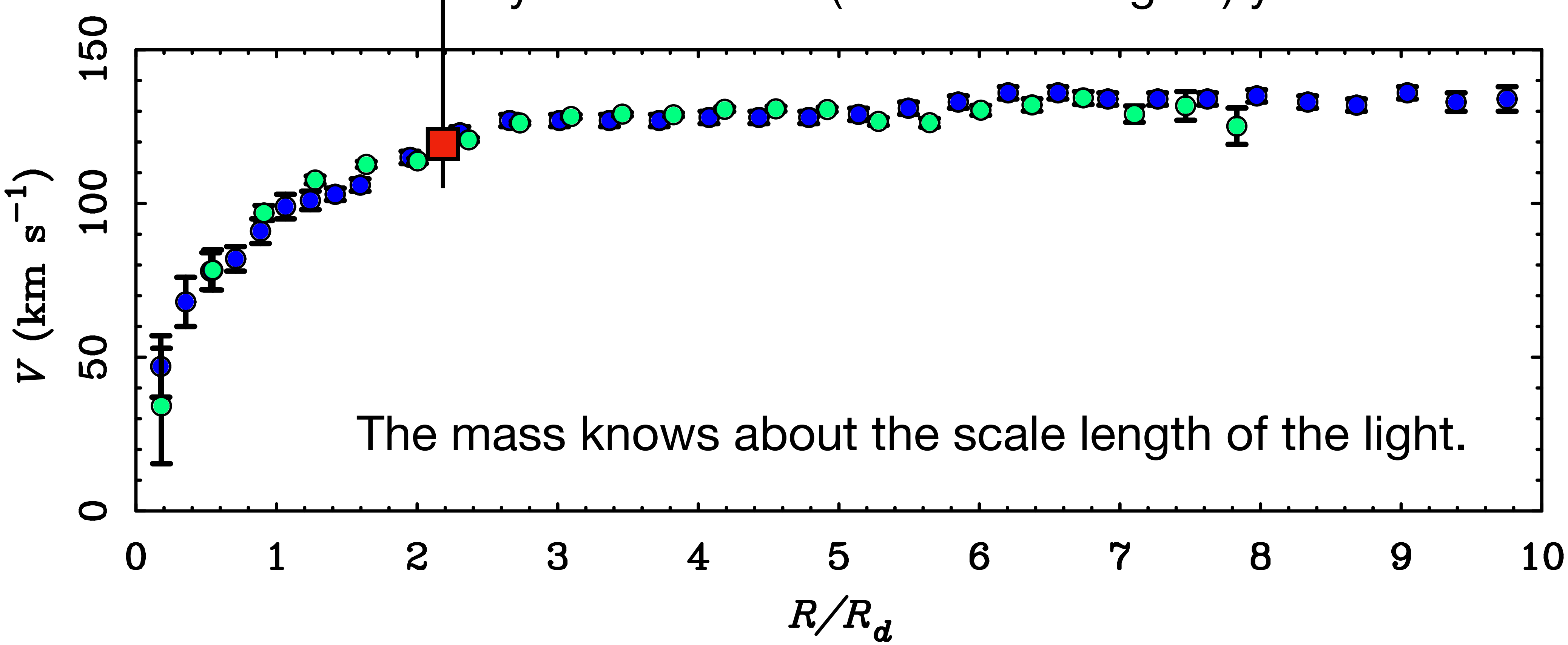


What you get depends on how you look at it: what you assume & what you choose to measure:

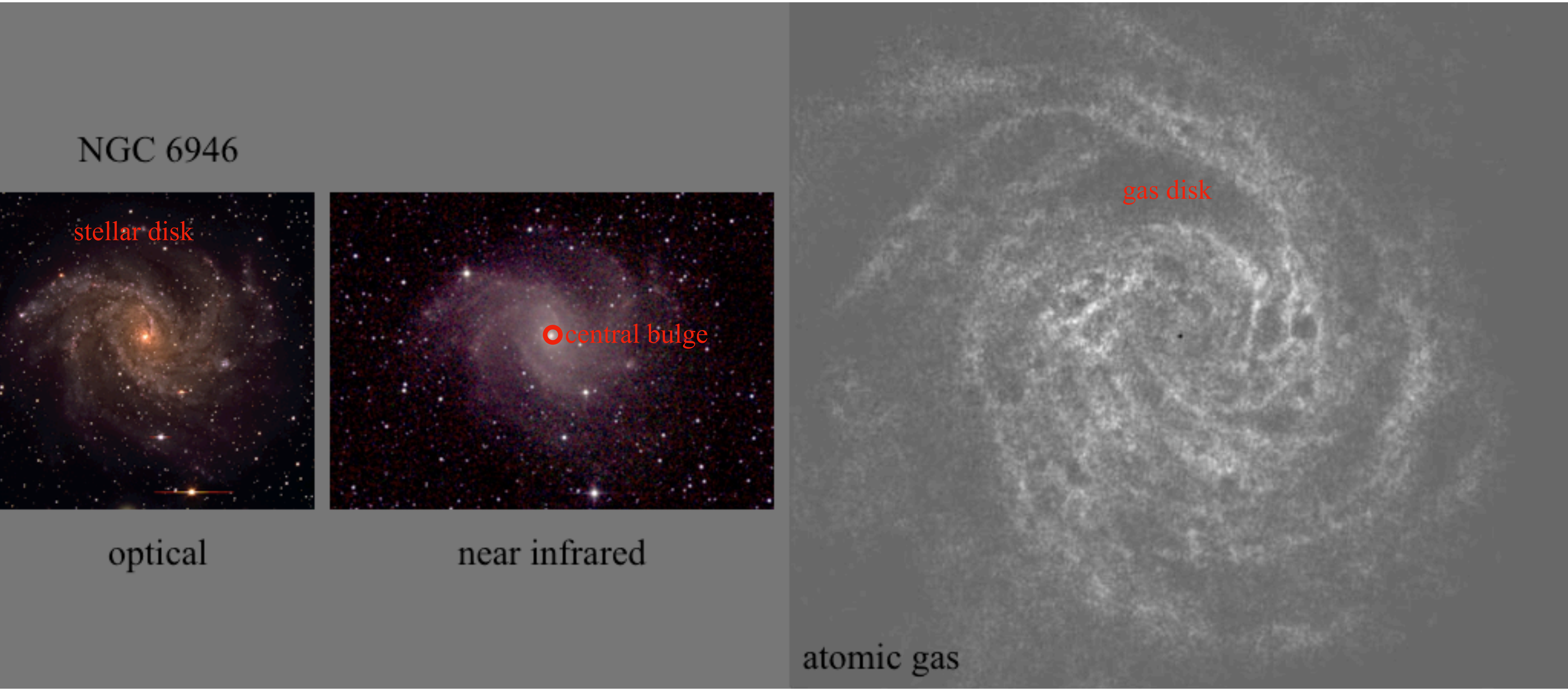


If you measure V(R in kpc) you infer **diversity**.

If you measure V(R in scale lengths) you infer **uniformity**.



- Renzo's Rule: (2004 IAU; 1995 private communication) *"When you see a feature in the light, you see a corresponding feature in the rotation curve."*

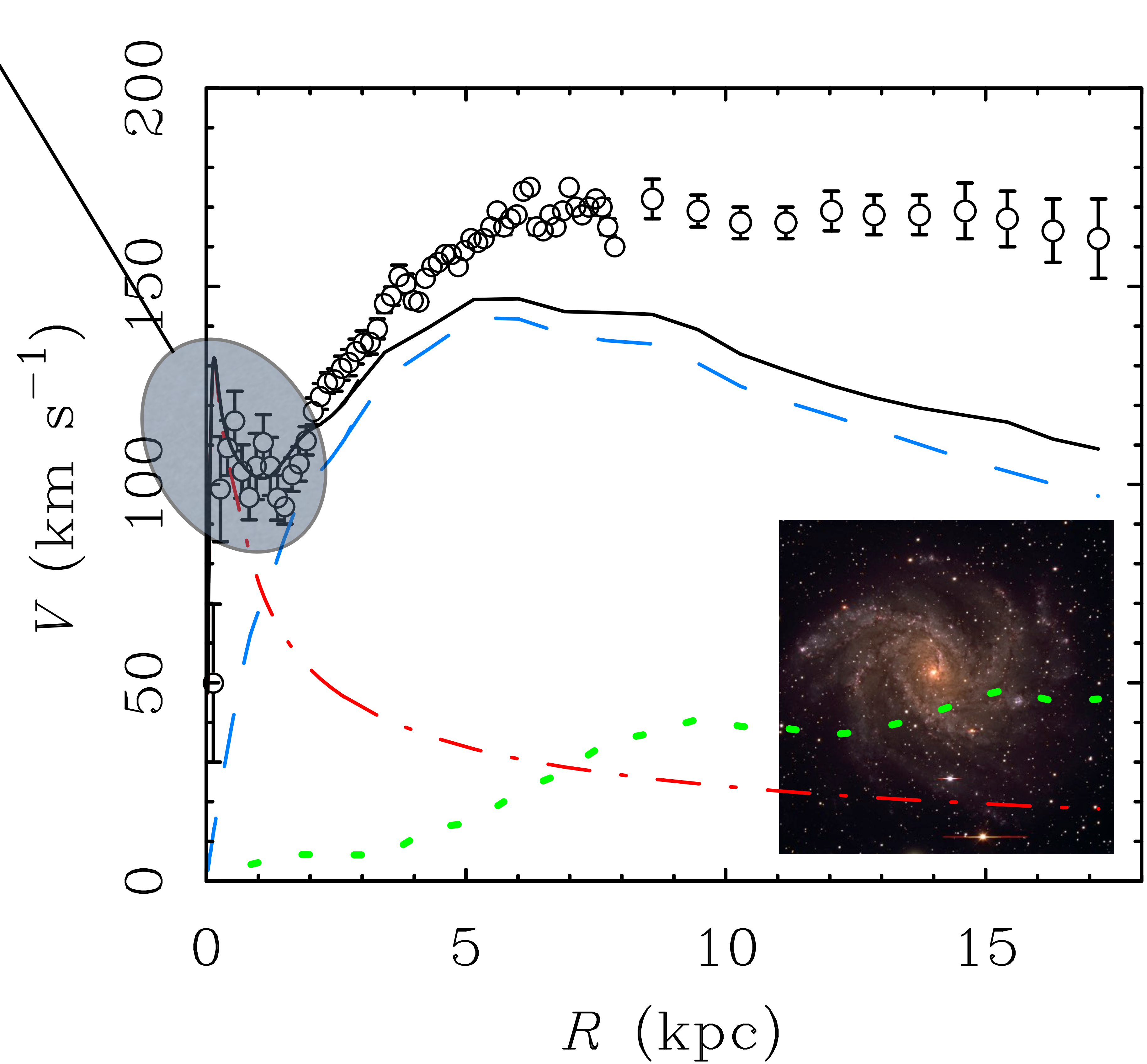


The central bulge component of NGC 6946 is only ~5% of the total light, but it has a perceptible effect on the kinematics.

Note the up-down-up morphology - this requires a maximal bulge; can't explain that with a dark matter halo.

V^2 = GM/R

M is small
but so is **R**



Renzo's Rule:

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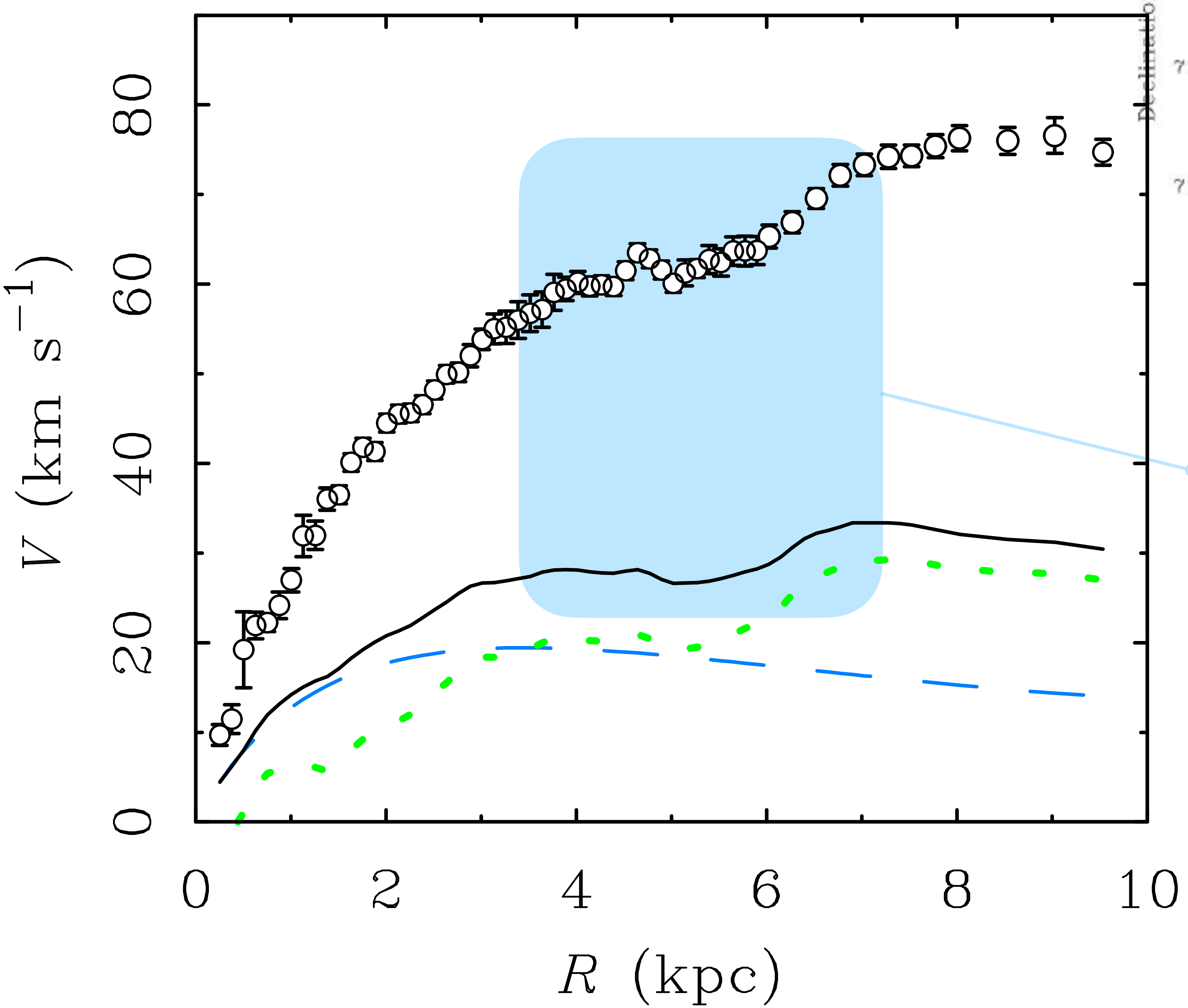
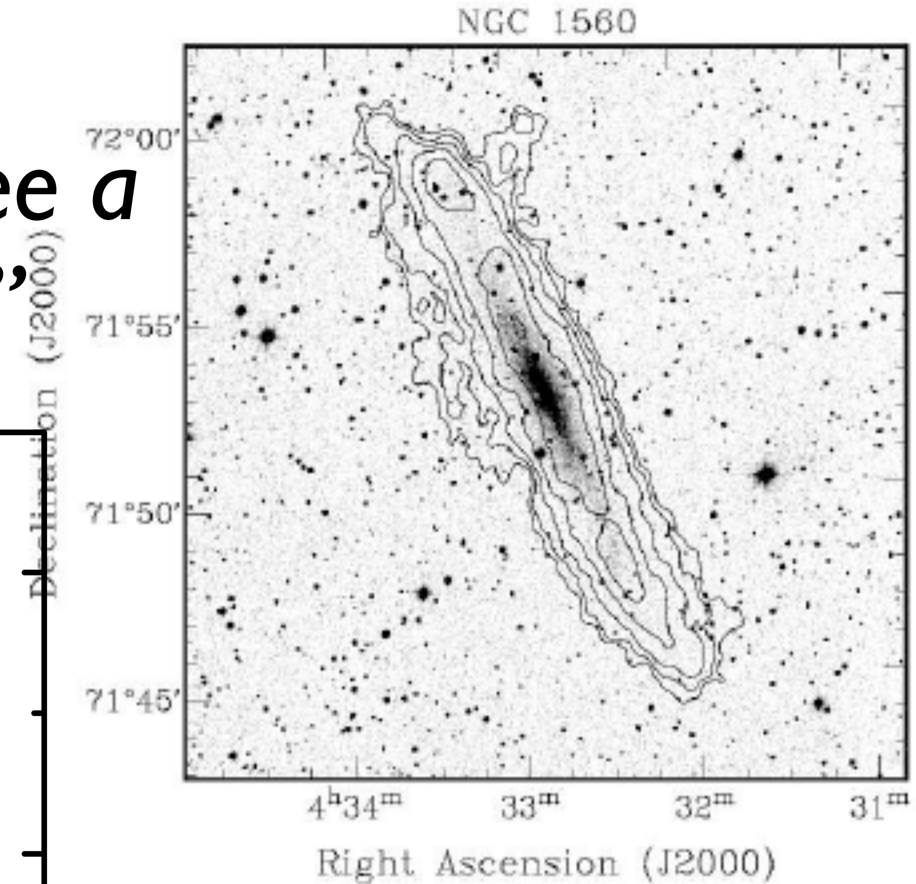
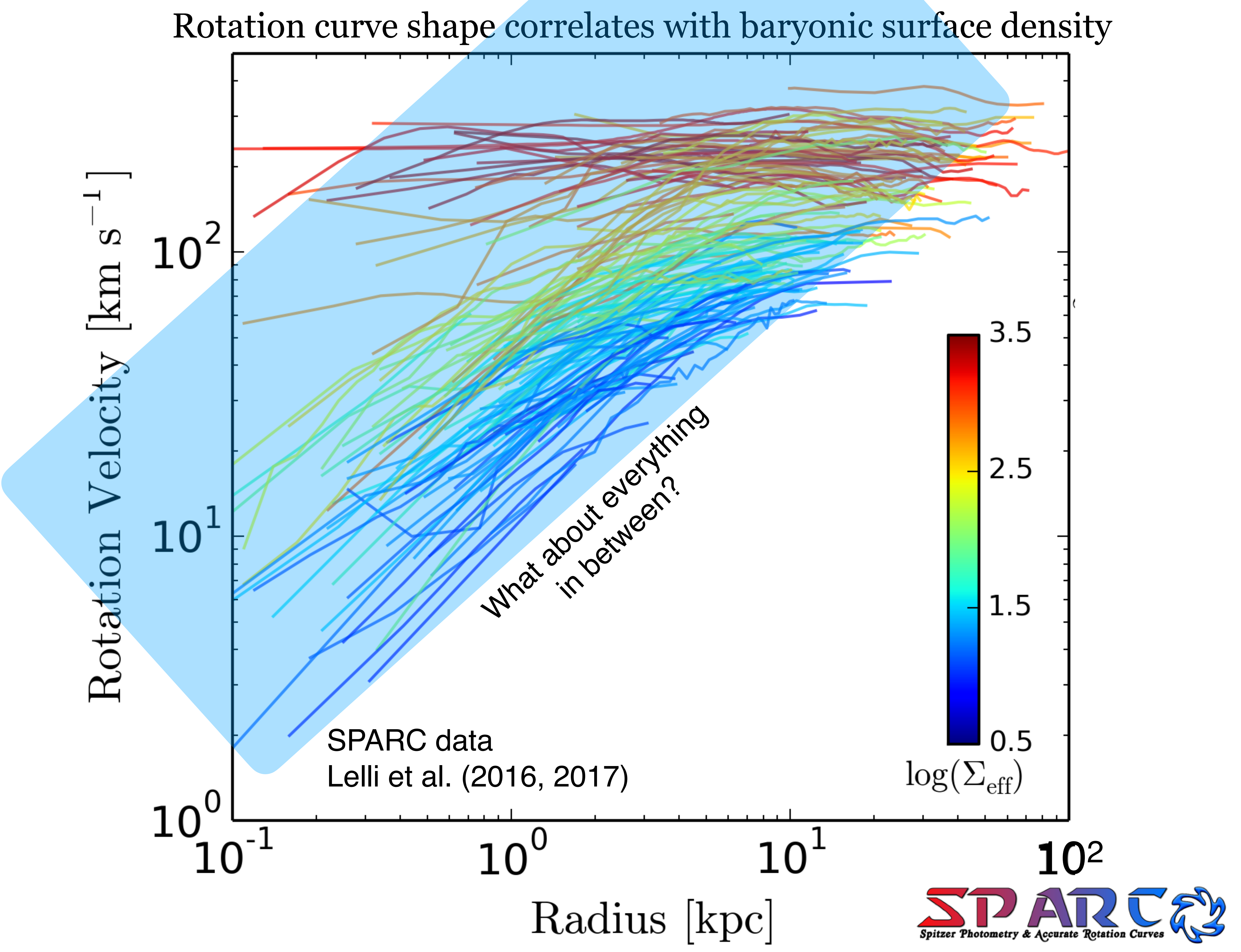




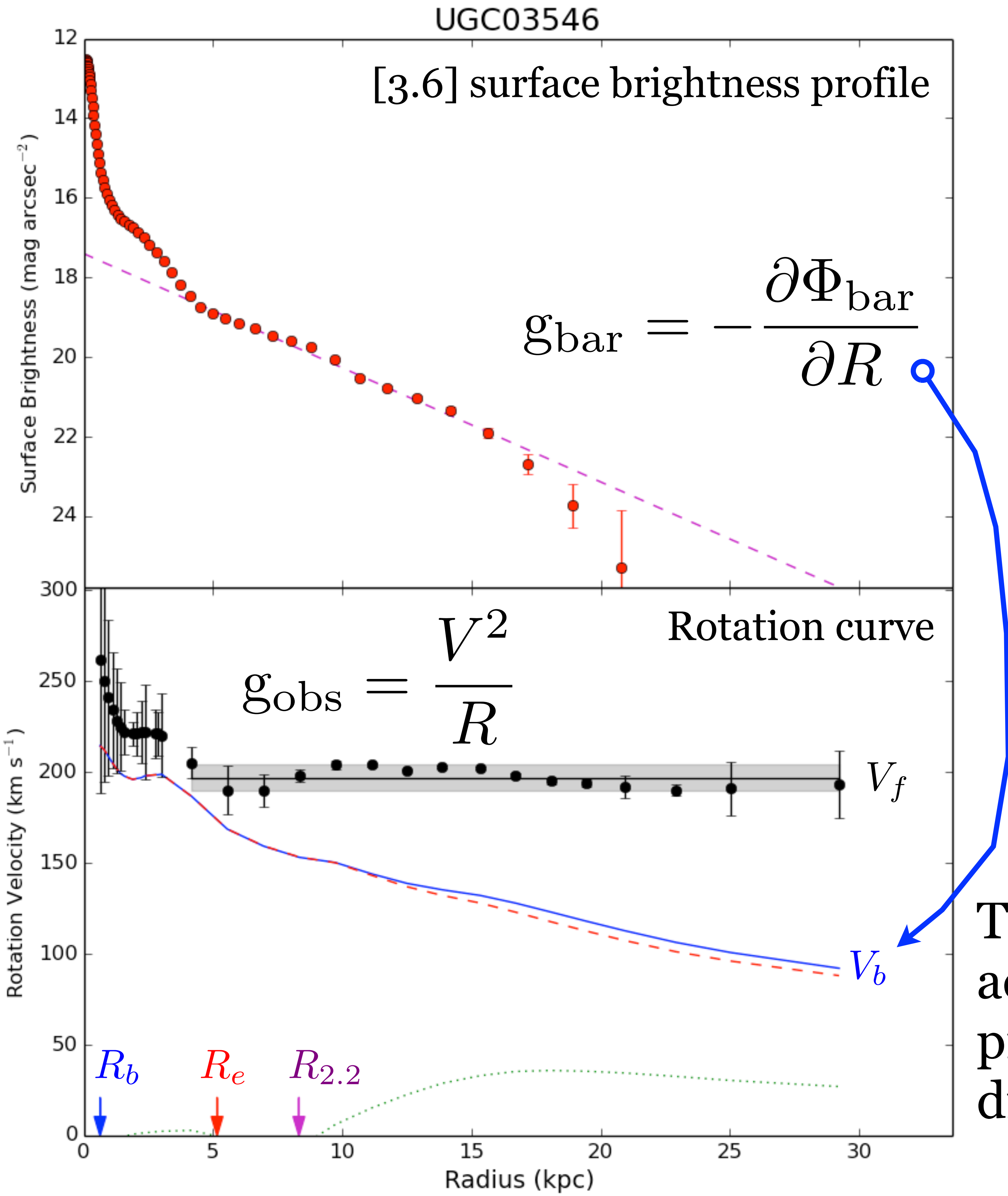
Gentile et al. (2010)

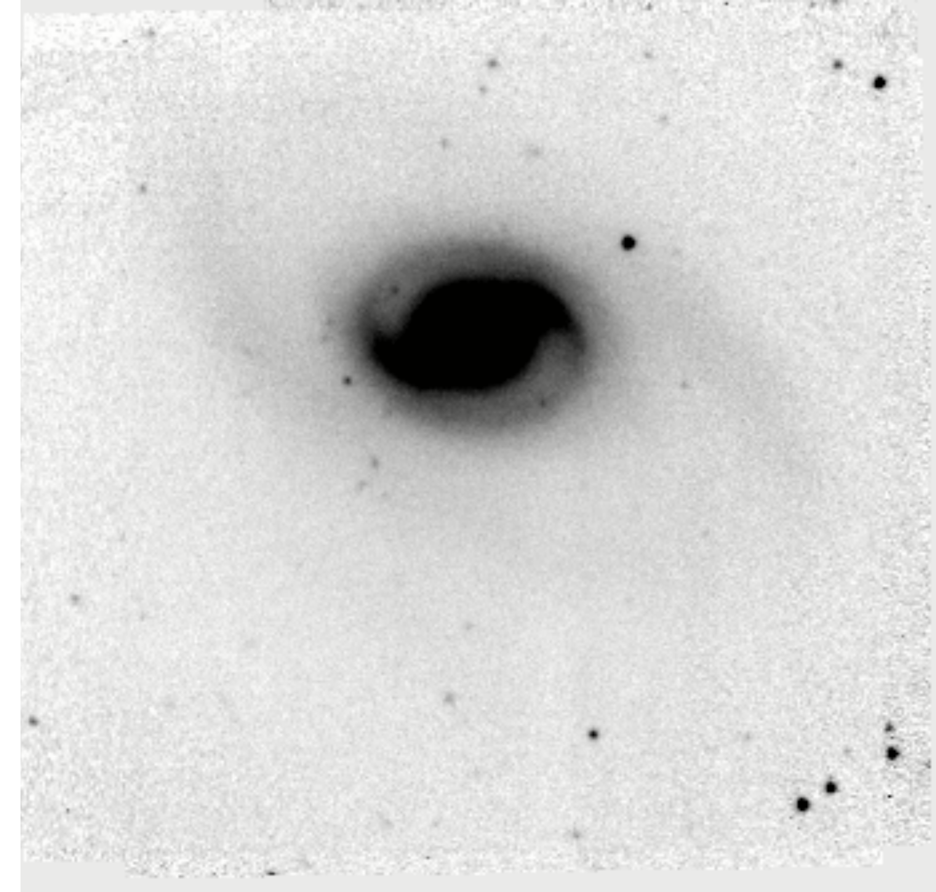
In NGC 1560, a marked feature in the gas is reflected in the kinematics, even though it accounts for little of the dynamical mass.

Rotation curve shape correlates with baryonic surface density

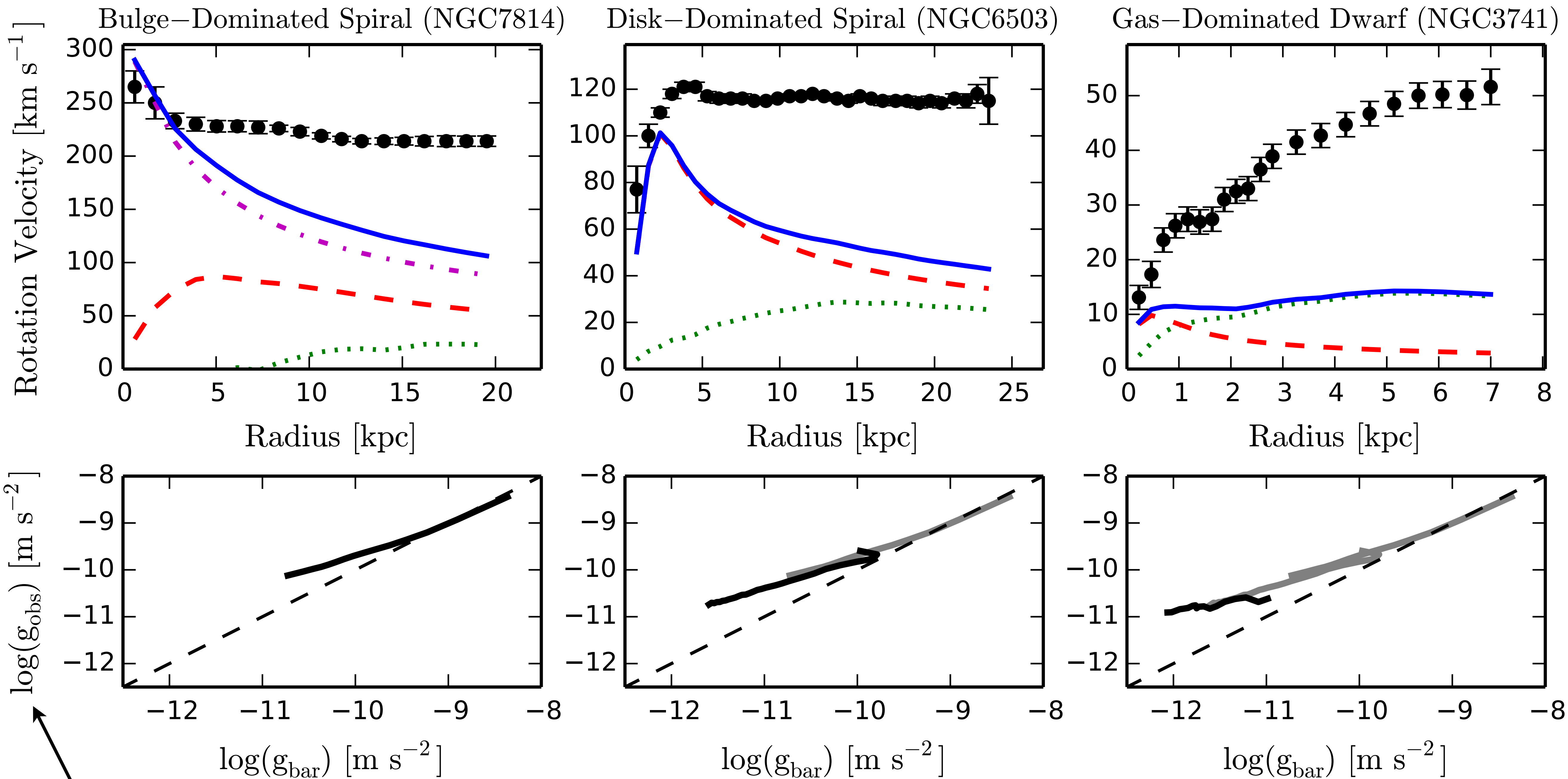


What about everything in between?





The observed centripetal acceleration is linked to that predicted by the observed distribution of baryons.



$$g_{\mathrm{obs}} = \frac{V^2}{R}$$

independent quantities

$$g_{\mathrm{bar}} = -\frac{\partial \Phi_{\mathrm{bar}}}{\partial R}$$

determined from rotation curve

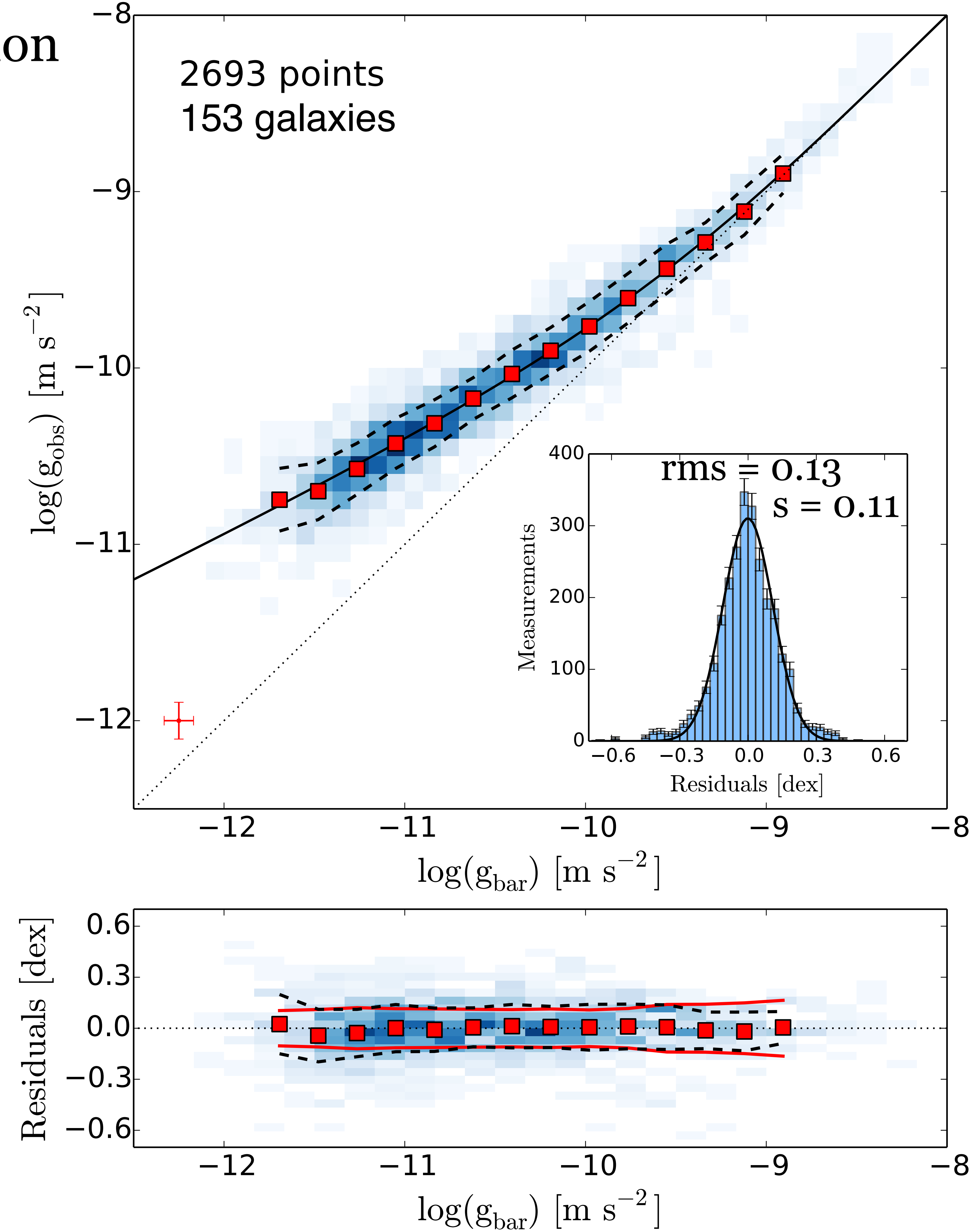
determined from baryon distribution

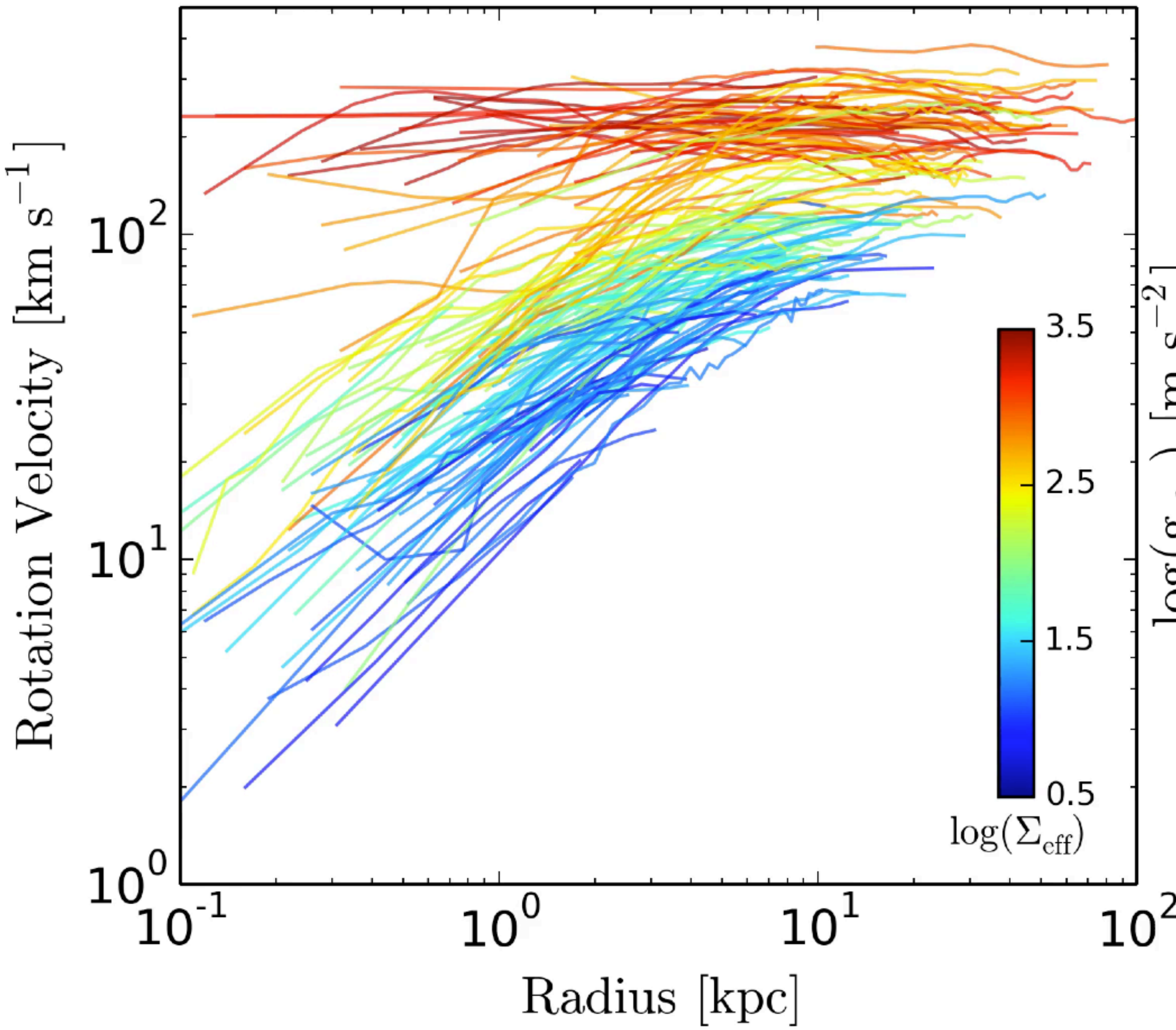
Radial Acceleration Relation

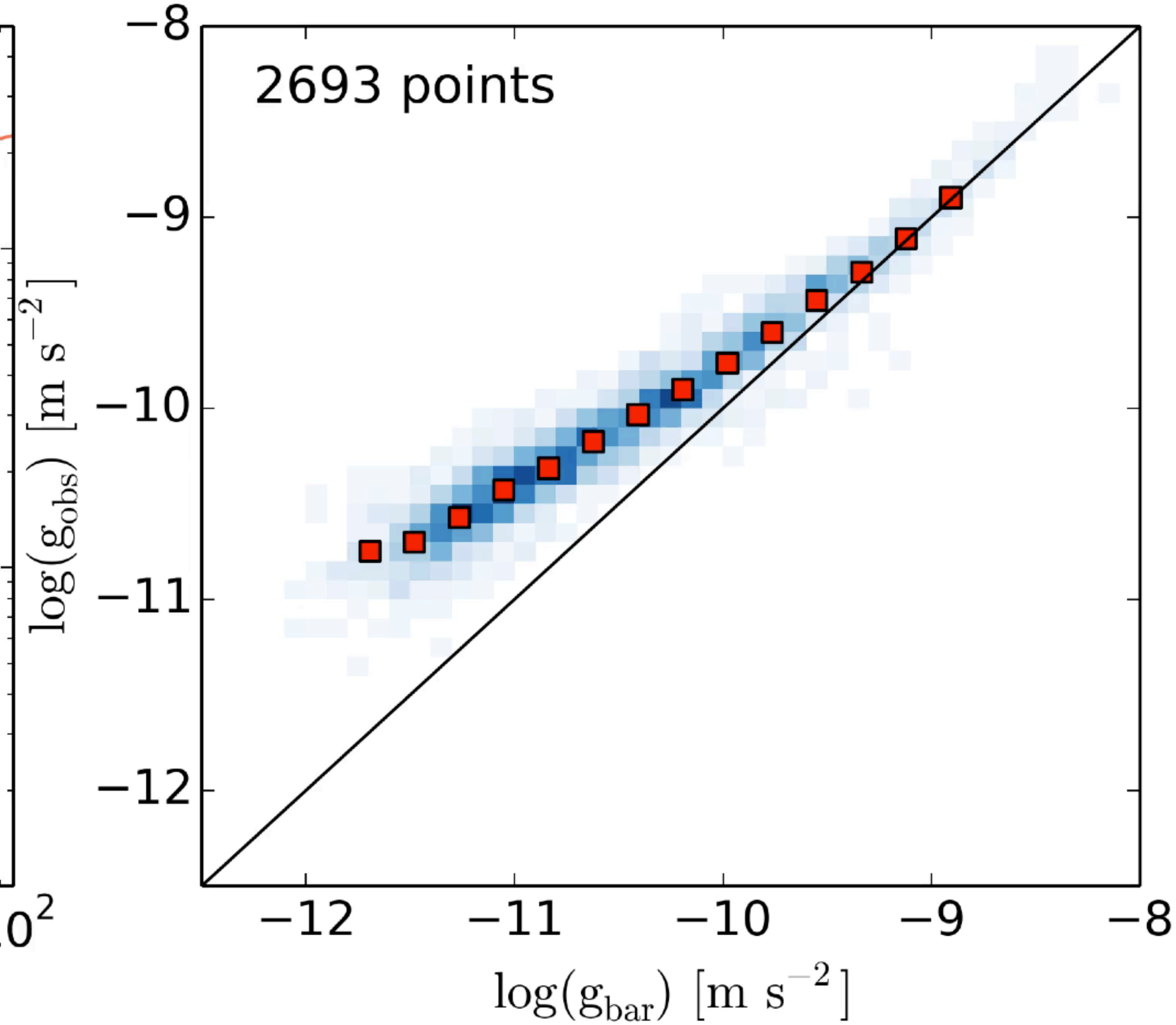
(RAR)

Constructed from 153 galaxies with 21cm rotation curves and near-IR surface photometry from the *Spitzer* space telescope.

Apparently the mass-to-light ratio in the near-IR is close to constant: individual galaxies do not stand out in this relation.







http://astroweb.case.edu/SPARC/RARmovie.mp4

Empirical Laws of Galactic Rotation

- Flat rotation curves (Rubin-Bosma Law)

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- Tully-Fisher relation (Luminous, Stellar Mass, and Baryonic TF relations)

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  "For any feature in the luminosity profile there is a corresponding feature in the rotation curve and vice versa." (Sancisi 2004).

- Radial acceleration relation

  The observed centripetal acceleration is related to that predicted by the observed distribution of baryons: $\mathrm{g}_{\mathrm{obs}} = \mathcal{F}(\mathrm{g}_{\mathrm{bar}})$