Dark Matter

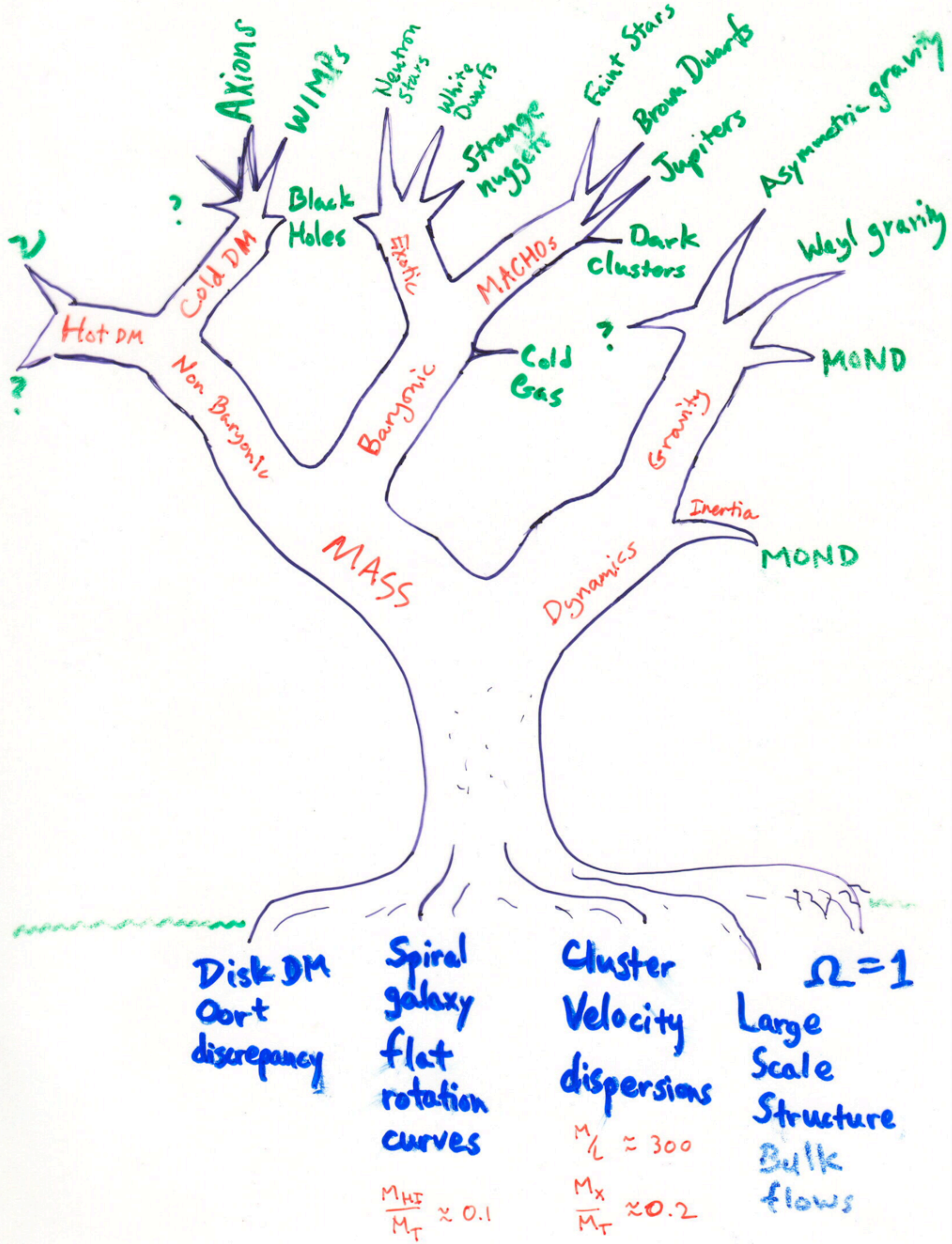
ASTR 333/433

TODAY

Central Density Relation
Renzo's Rule
Radial Acceleration Relation

Acceleration Scale

HW2 posted



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: $\Sigma_{dyn}(R \to 0) = f[\Sigma_*(R \to 0)]$

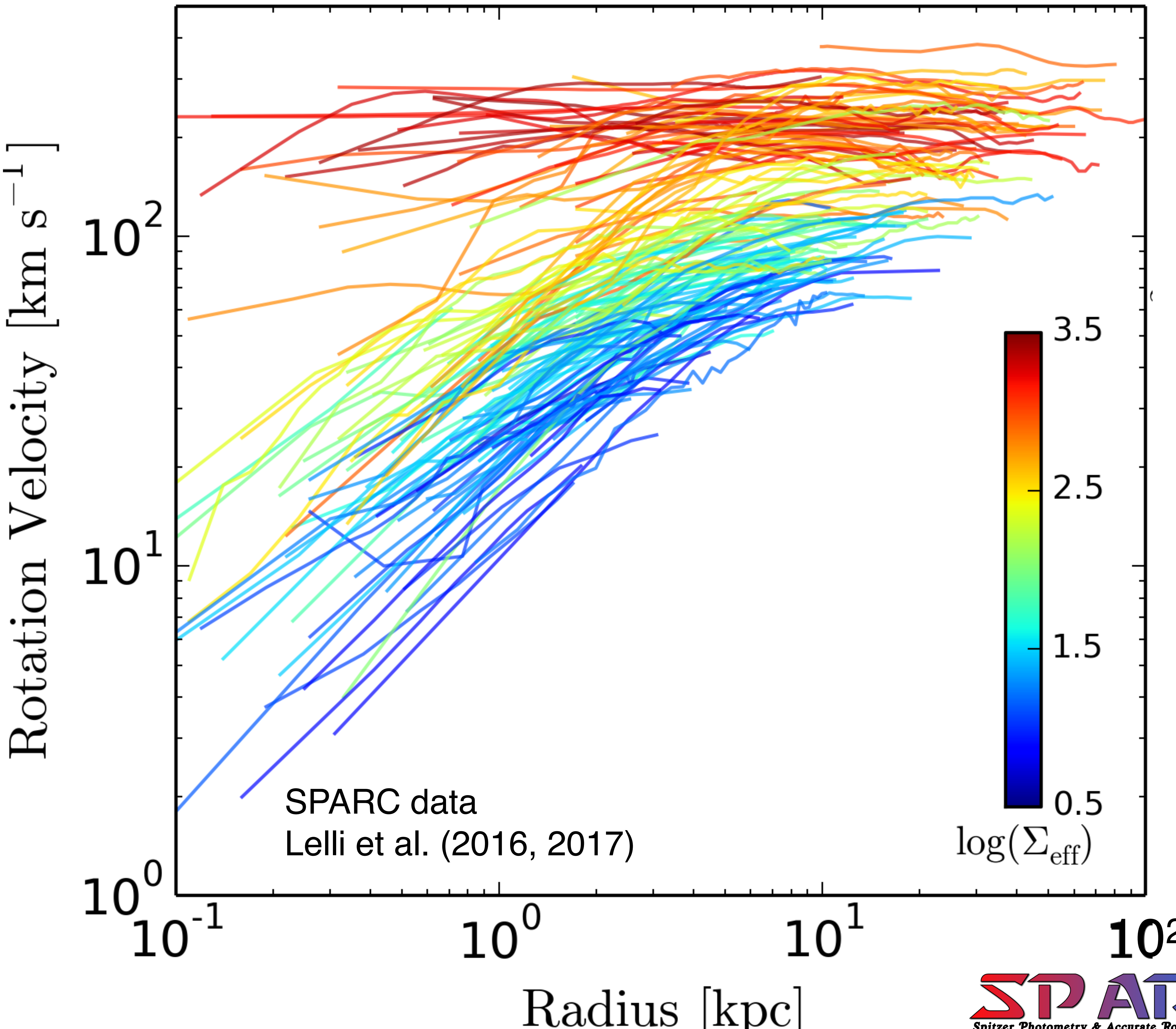
- Renzo's rule (Sancisi's Law)

  "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: $\mathrm{g_{obs}} = \mathcal{F}(\mathrm{g_{bar}})$

Rotation curve shape correlates with baryonic surface density



SPARC
Spitzer Photometry & Accurate Rotation Curves

Central Density Relation

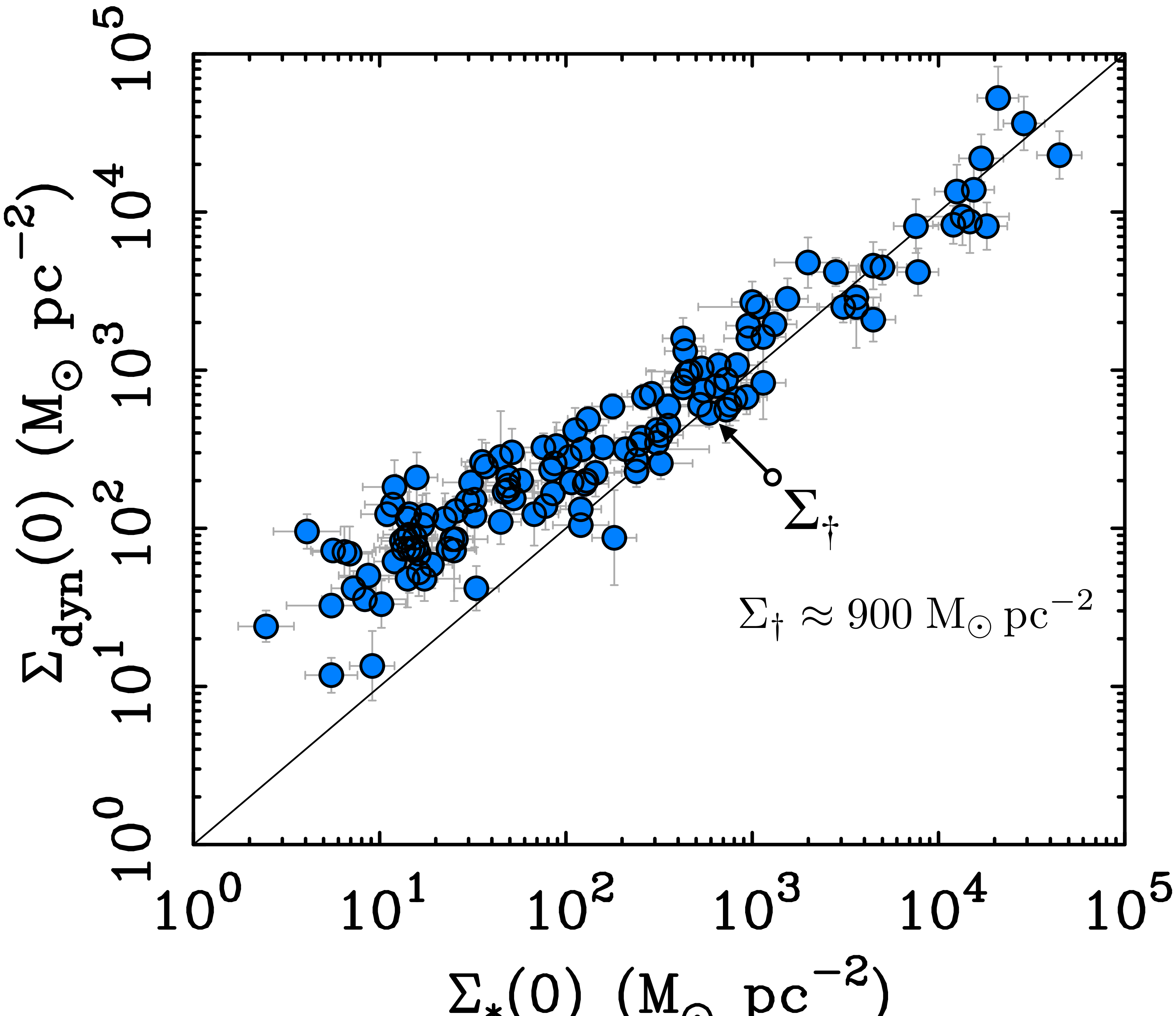
Lelli et al. (2016)

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

central dynamical surface density

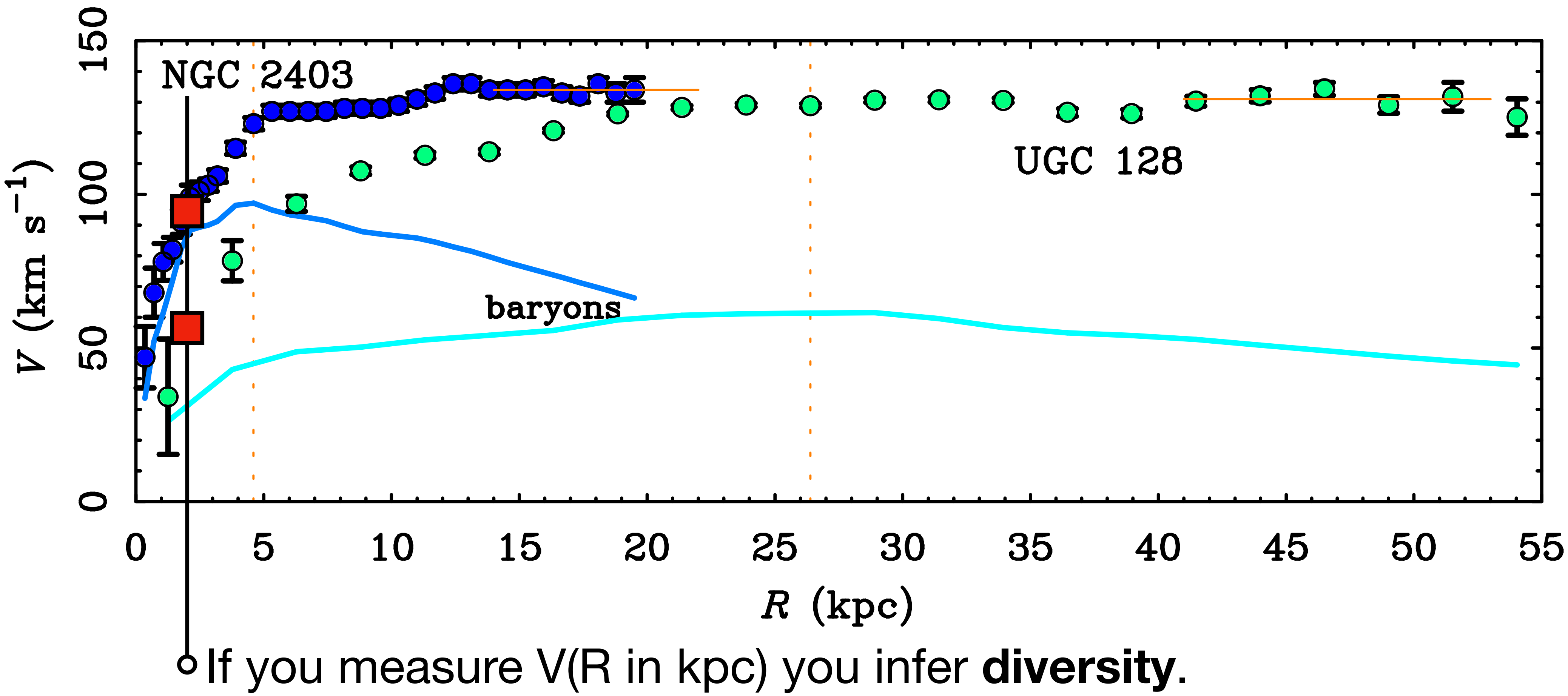
Toomre (1963)

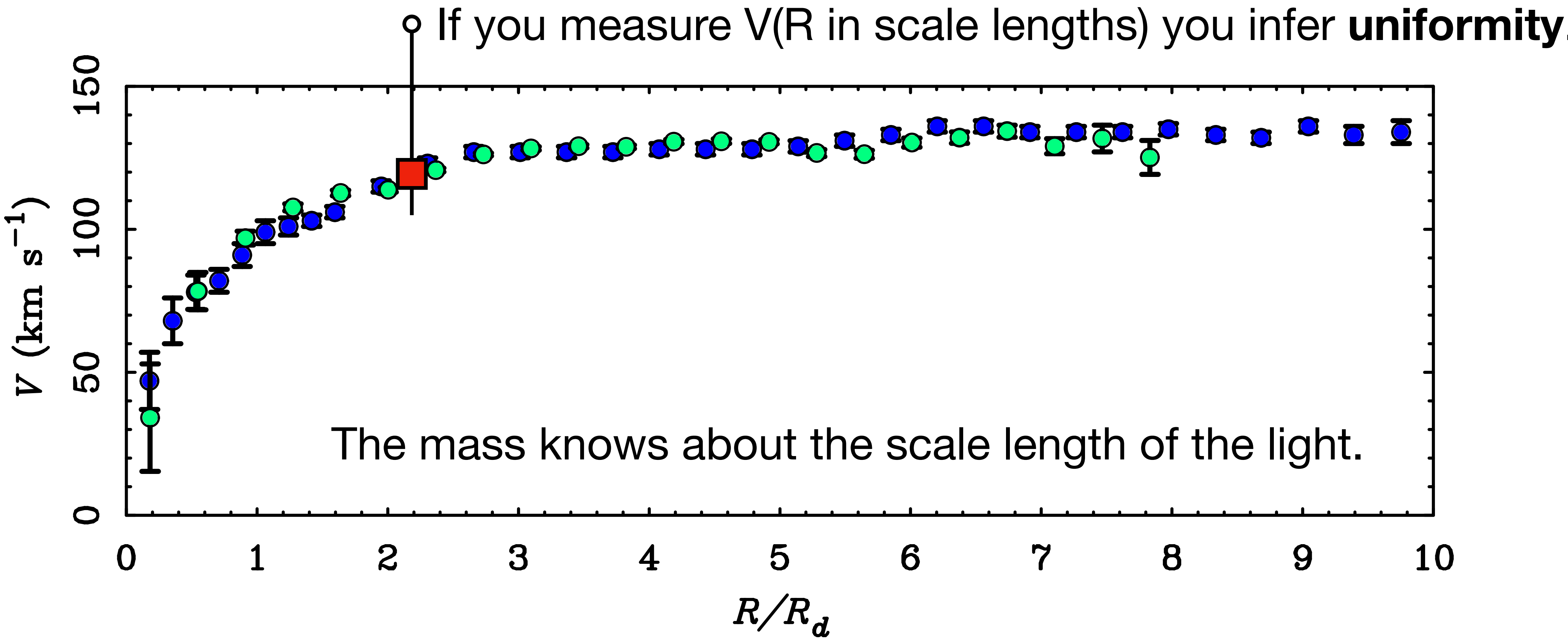
$$\Sigma_{dyn}(0) = \frac{1}{2\pi G}\int_0^\infty \frac{V^2(R)}{r^2}dR$$



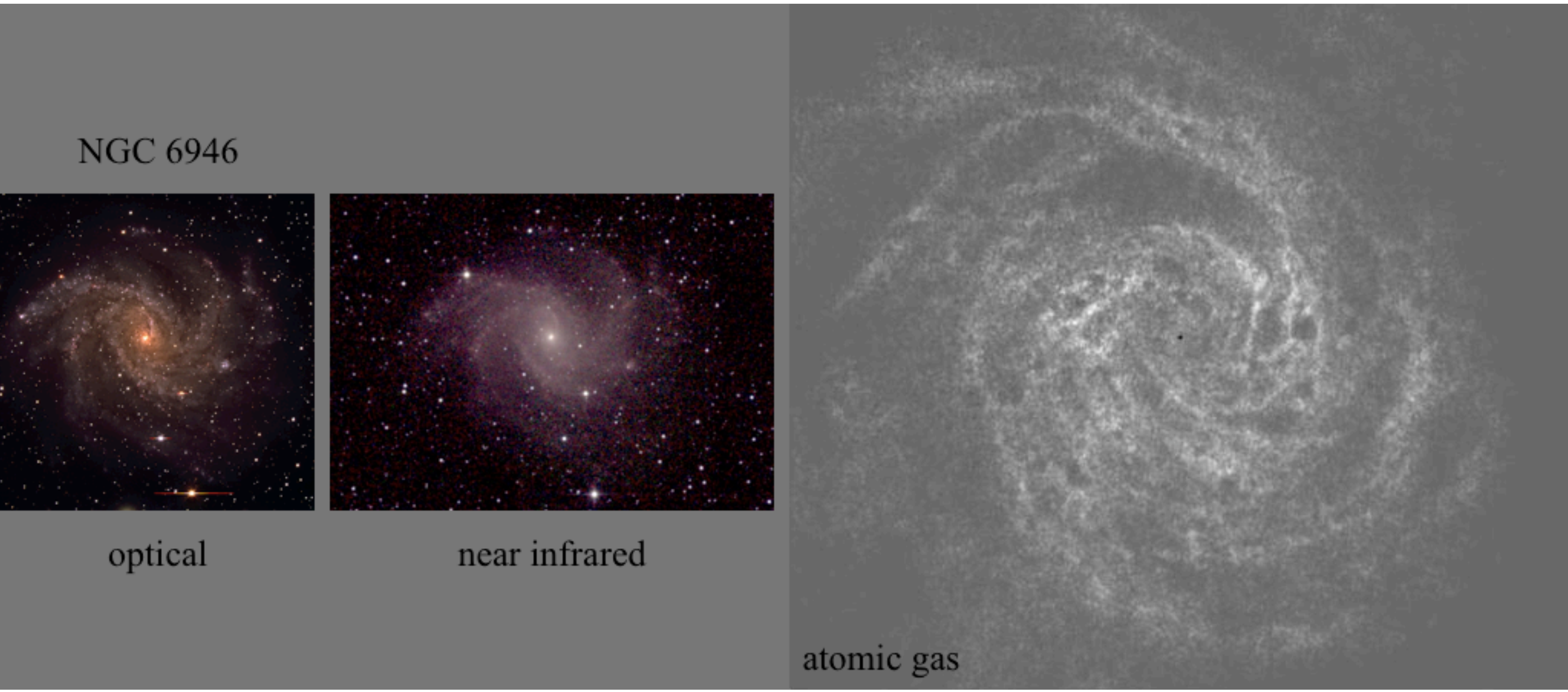
central surface brightness

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





- 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."

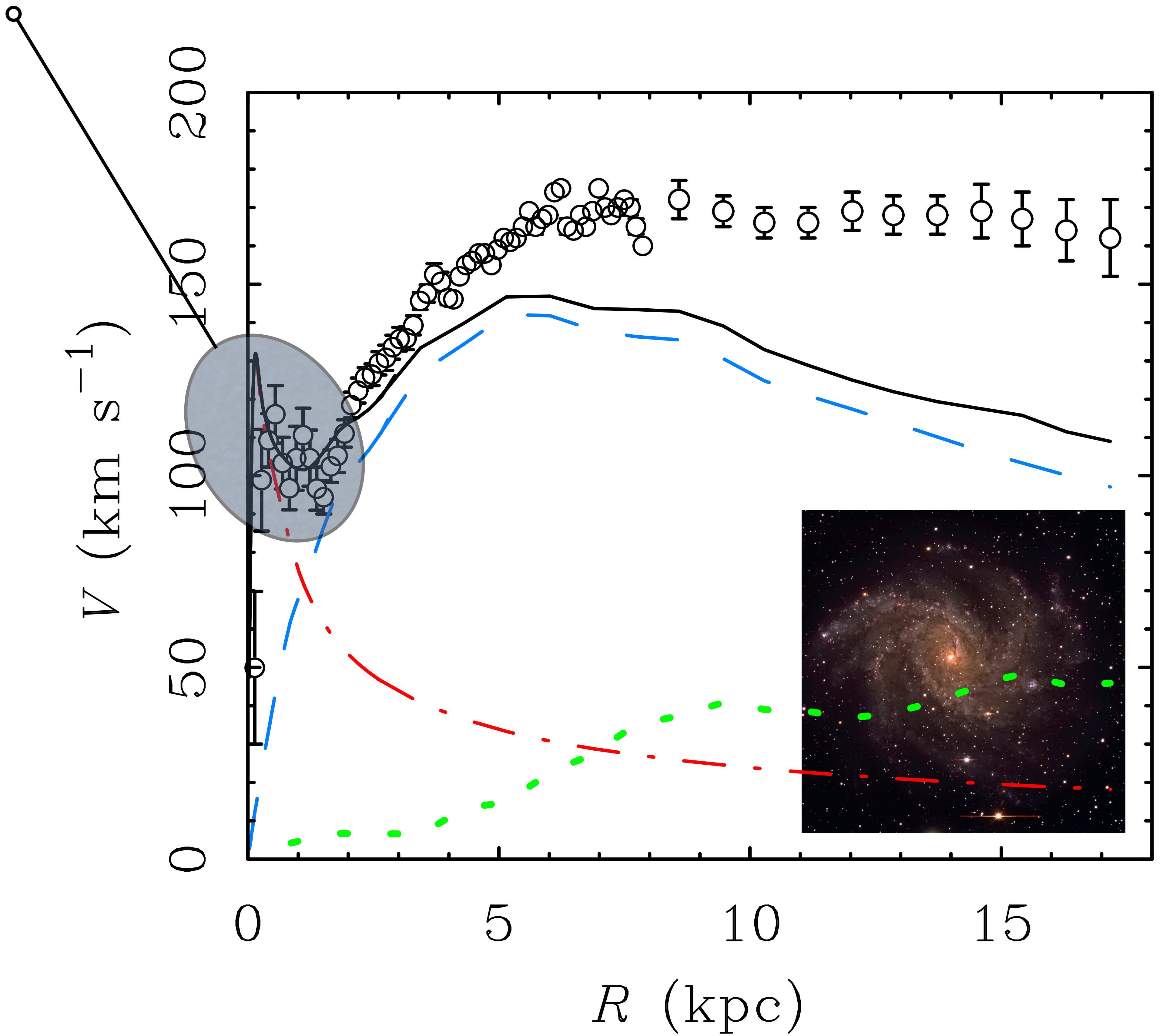


The central bulge component of NGC 6946 is only 6% of the total light, but it has a perceptible effect on the kinematics.

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

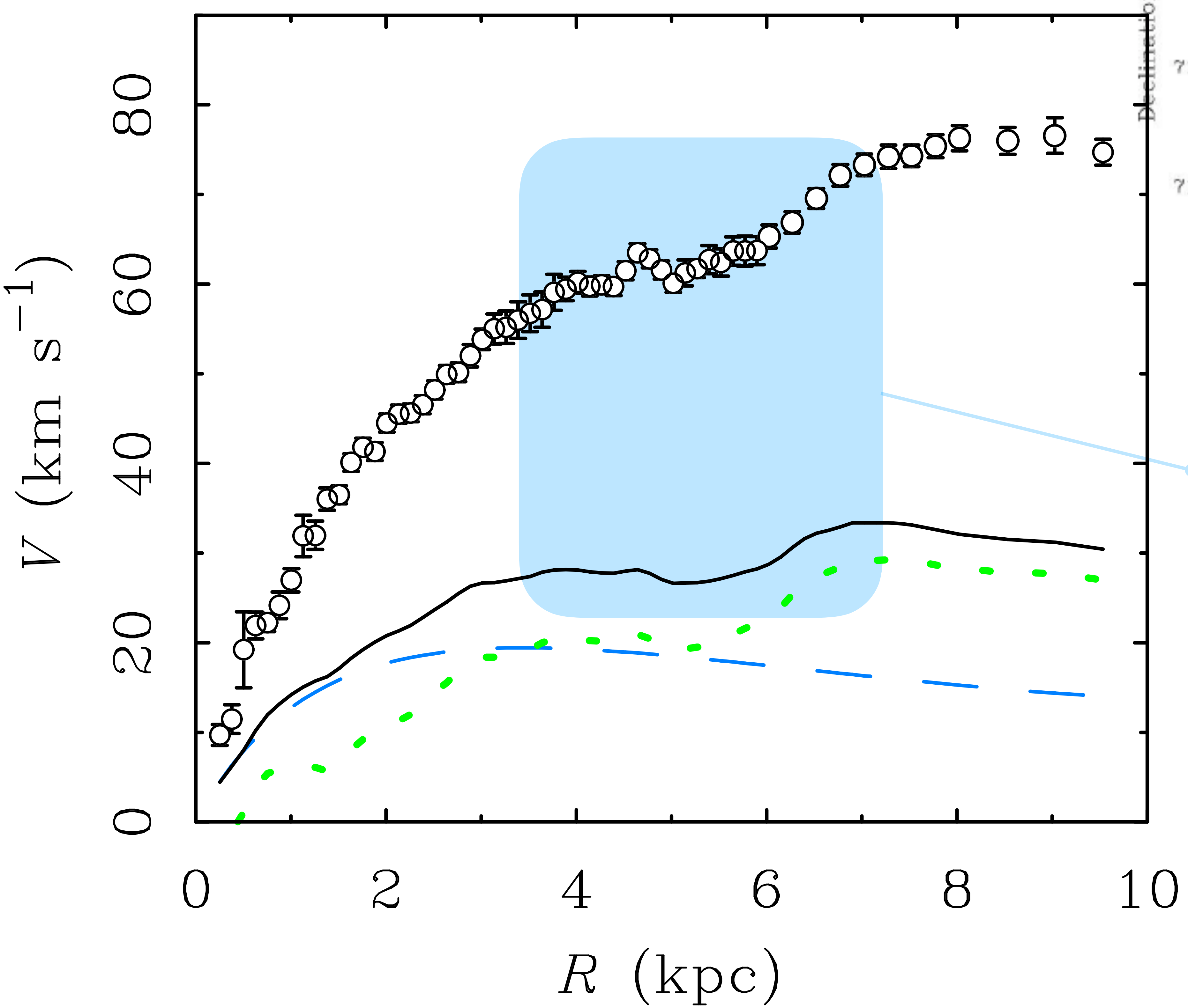
V^2 = GM/R

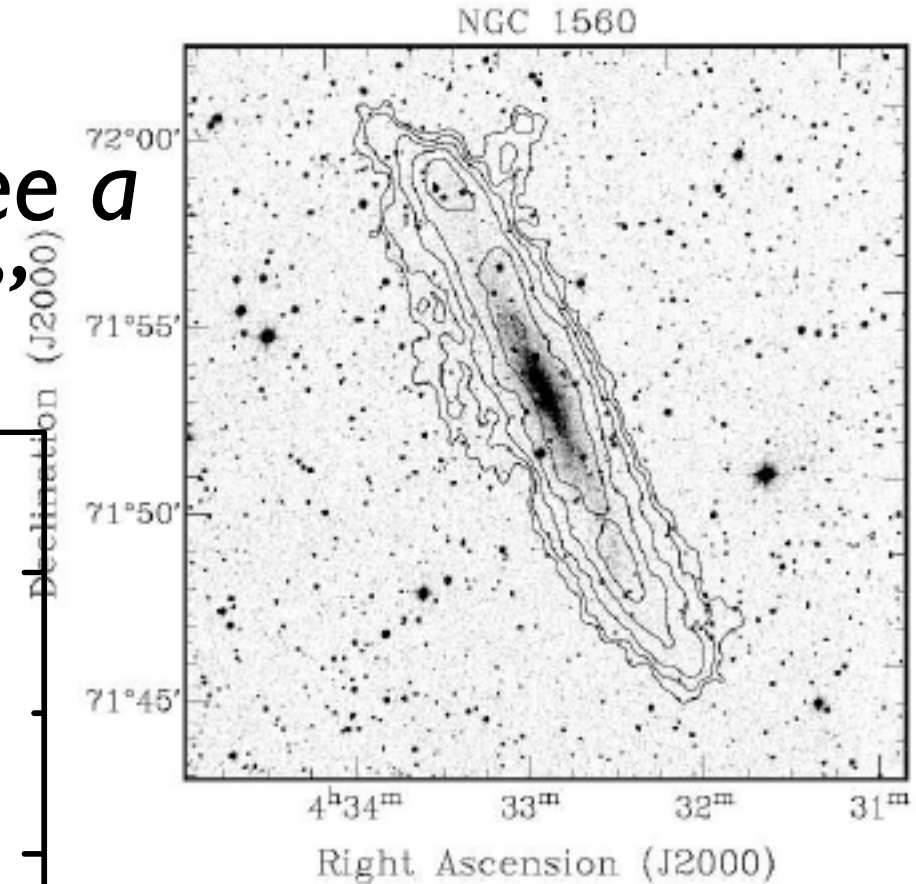
M is small
but so is **R**



Renzo's Rule:

"When you see a feature in the light, you see a corresponding feature in the rotation curve."





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.

Baryonic models

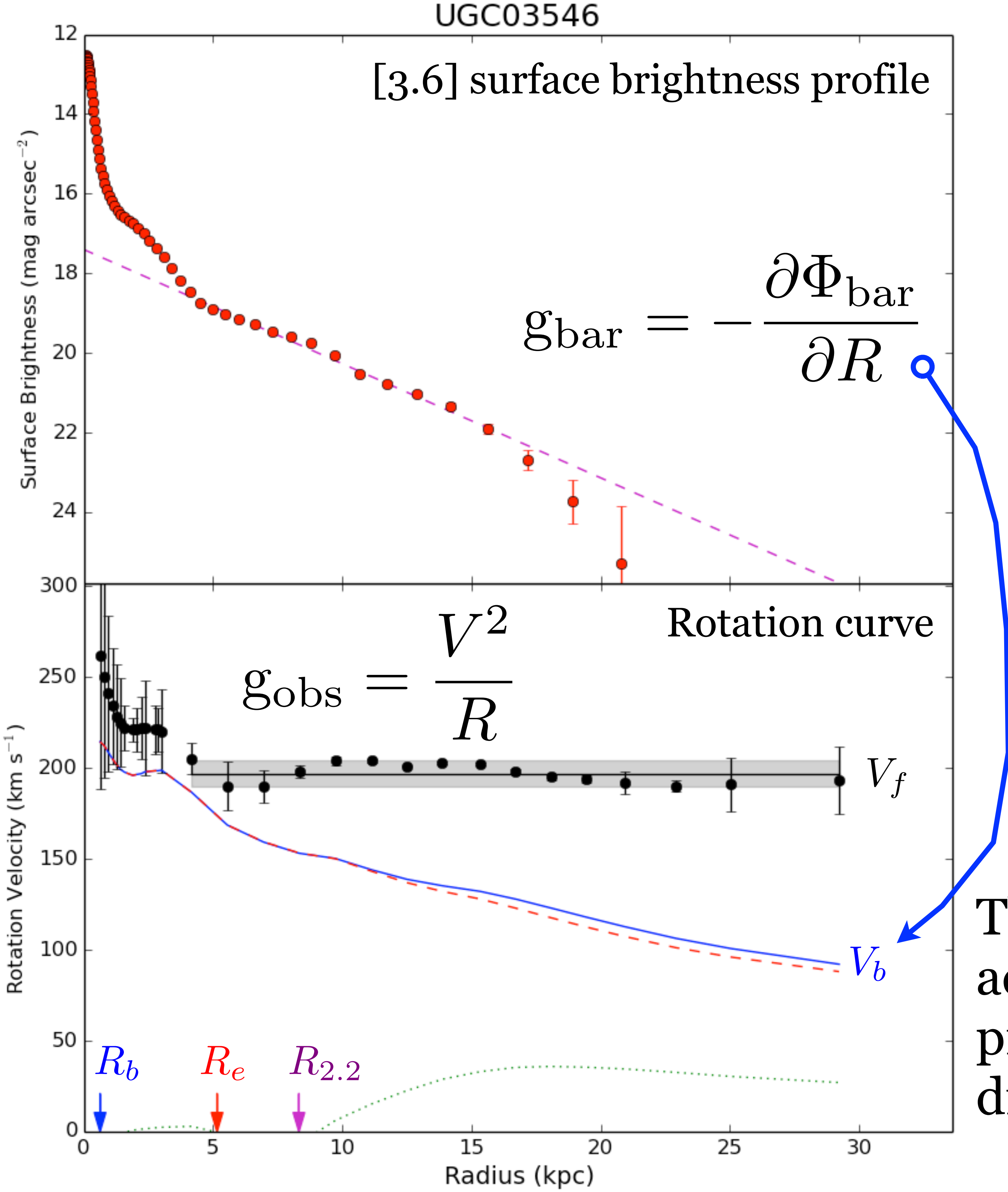
$$V_b^2(r) = V_{bulge}^2(r) + \underbrace{V_{disk}^2(r)}_{\text{depends on } M_*/L} + V_{gas}^2(r)$$

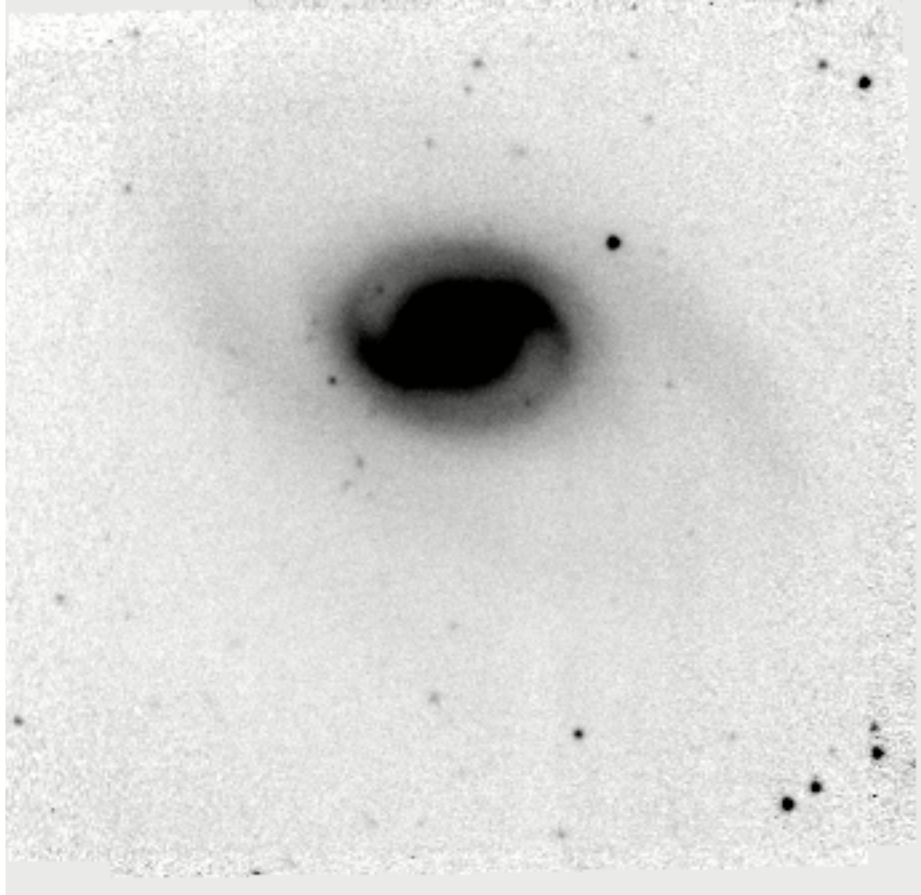
- Bulge
  - not always spherical; sometimes more bar-like
- Stellar Disk
  - exponential a crude approximation
  - in practice, solve numerically for the observed surface brightness profile with DISKFIT or ROTMOD (in GIPSY)

$$g_{\rm bar} = \frac{V_b^2}{R}$$

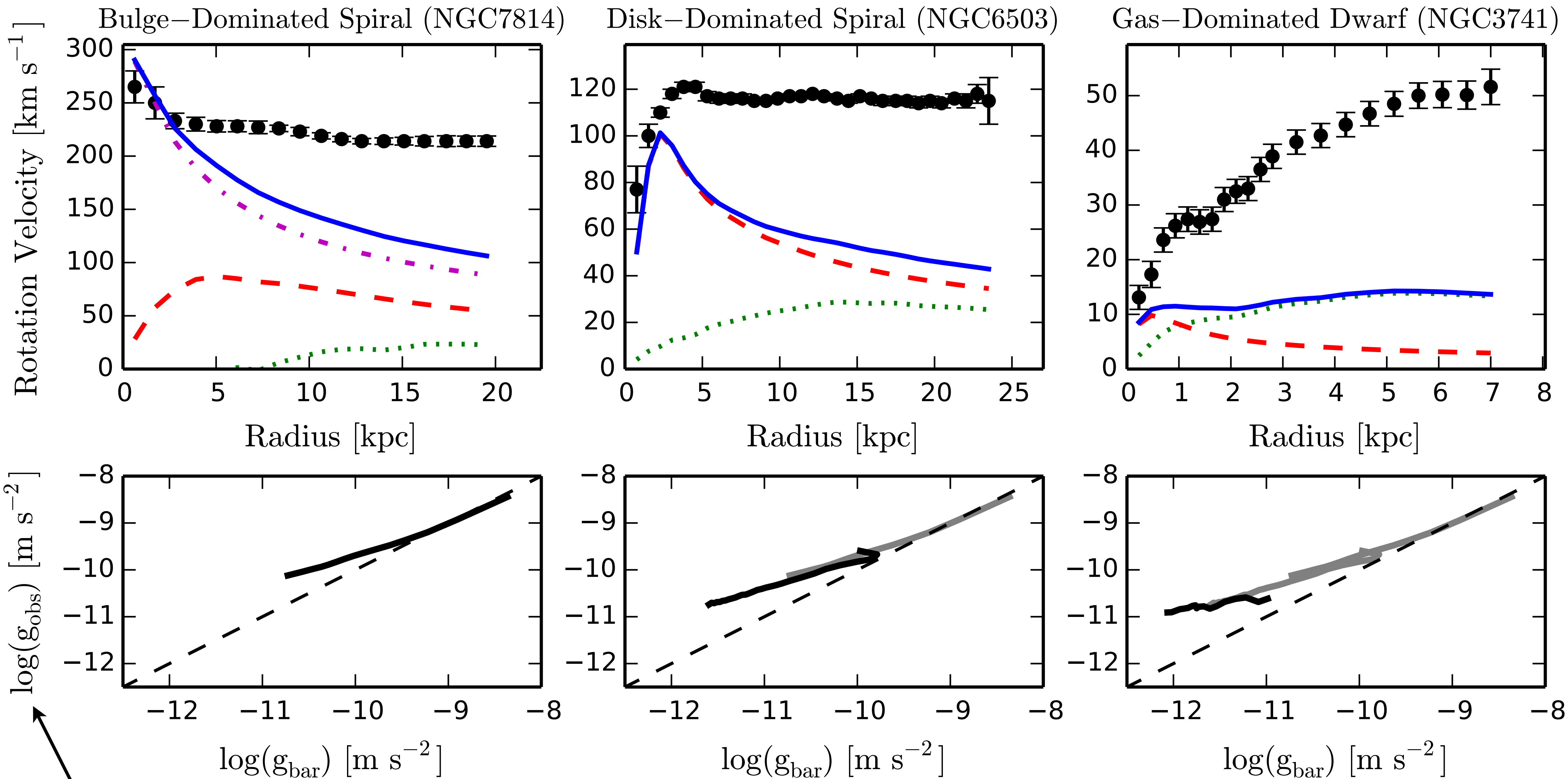
- Gas disk
  - usually just HI; CO tracks stars

What about everything in between?





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



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

independent quantities

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

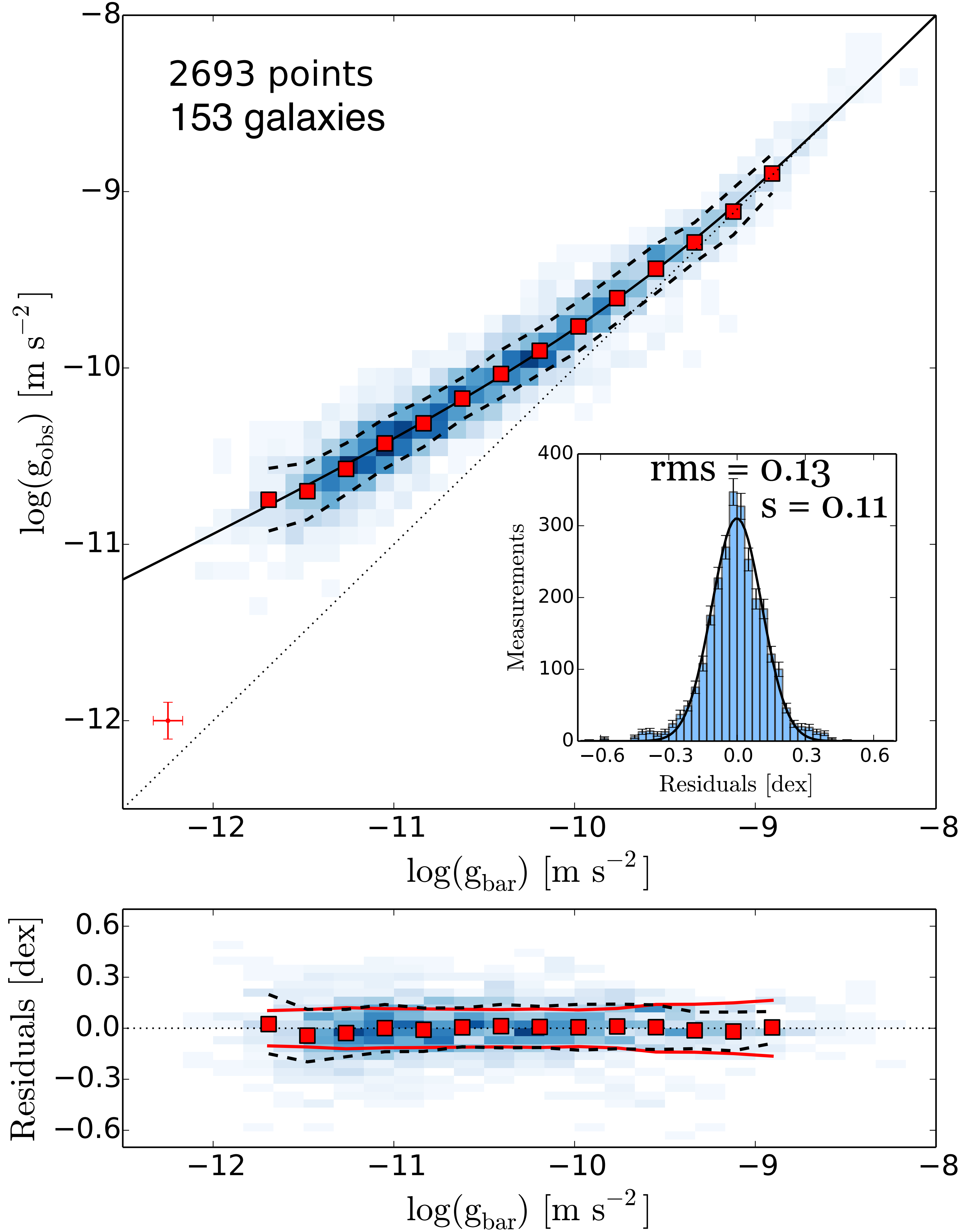
determined from rotation curve

determined from baryon distribution

Radial Acceleration Relation

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

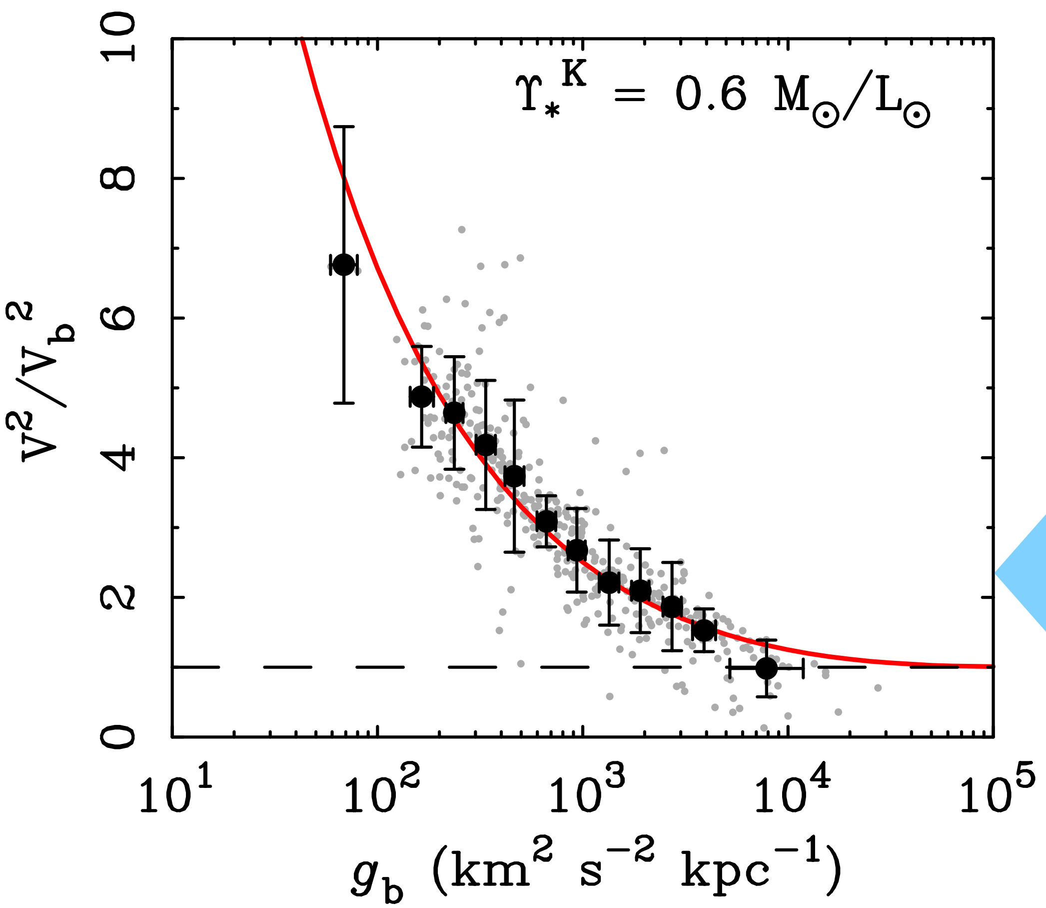
Apparently the mass-to-light ratio in the near-IR is close to constant: individual galaxies do not stand out in this relation.



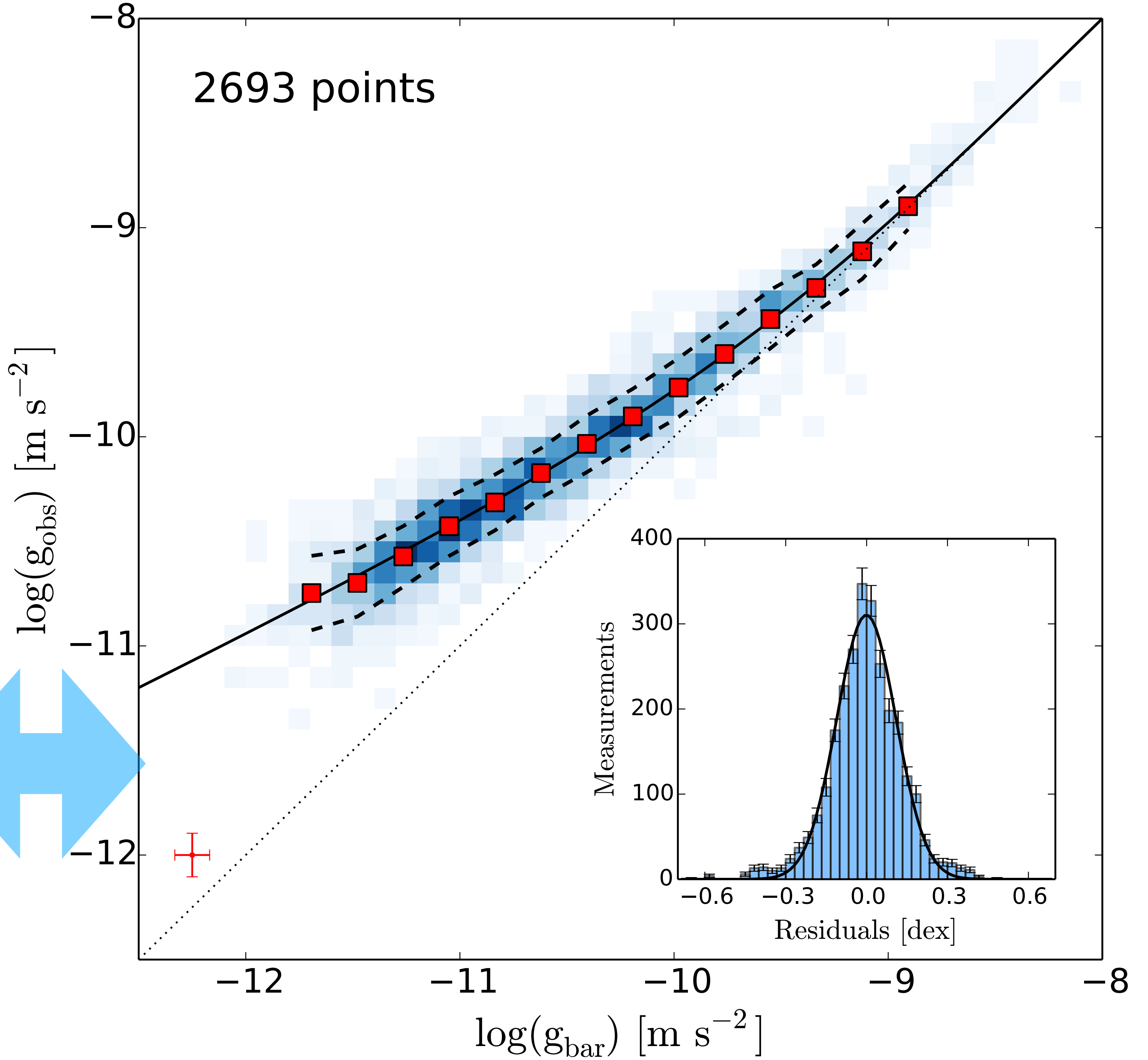
The Radial Acceleration Relation is equivalent to the Mass Discrepancy-acceleration relation, just with independent x & y axes.

$$\mathcal{D} = \frac{\mathrm{g_{obs}}}{\mathrm{g_{bar}}} = \frac{V^2}{V_b^2}$$

MDAR



RAR



Radial Acceleration Relation

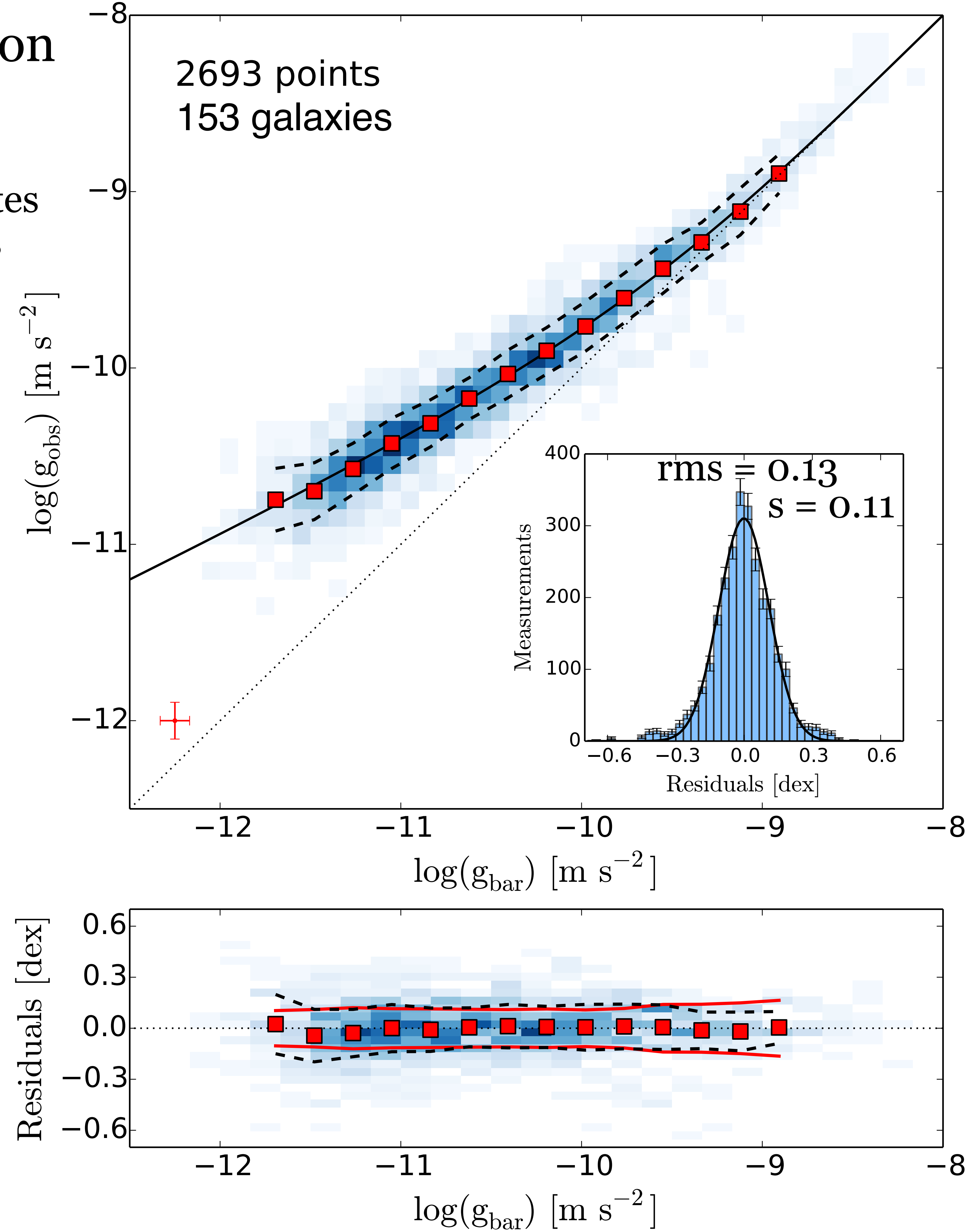
The observed acceleration correlates with that predicted by the baryons

The data are well fit by

$$g_{\rm obs} = \frac{g_{\rm bar}}{1 - e^{-\sqrt{g_{\rm bar}/g_\dagger}}}$$

$$g_\dagger = 1.20 \times 10^{-10}\ \mathrm{m\,s^{-2}}$$

± 0.02 (random) $\pm$ 0.24 (systematic)



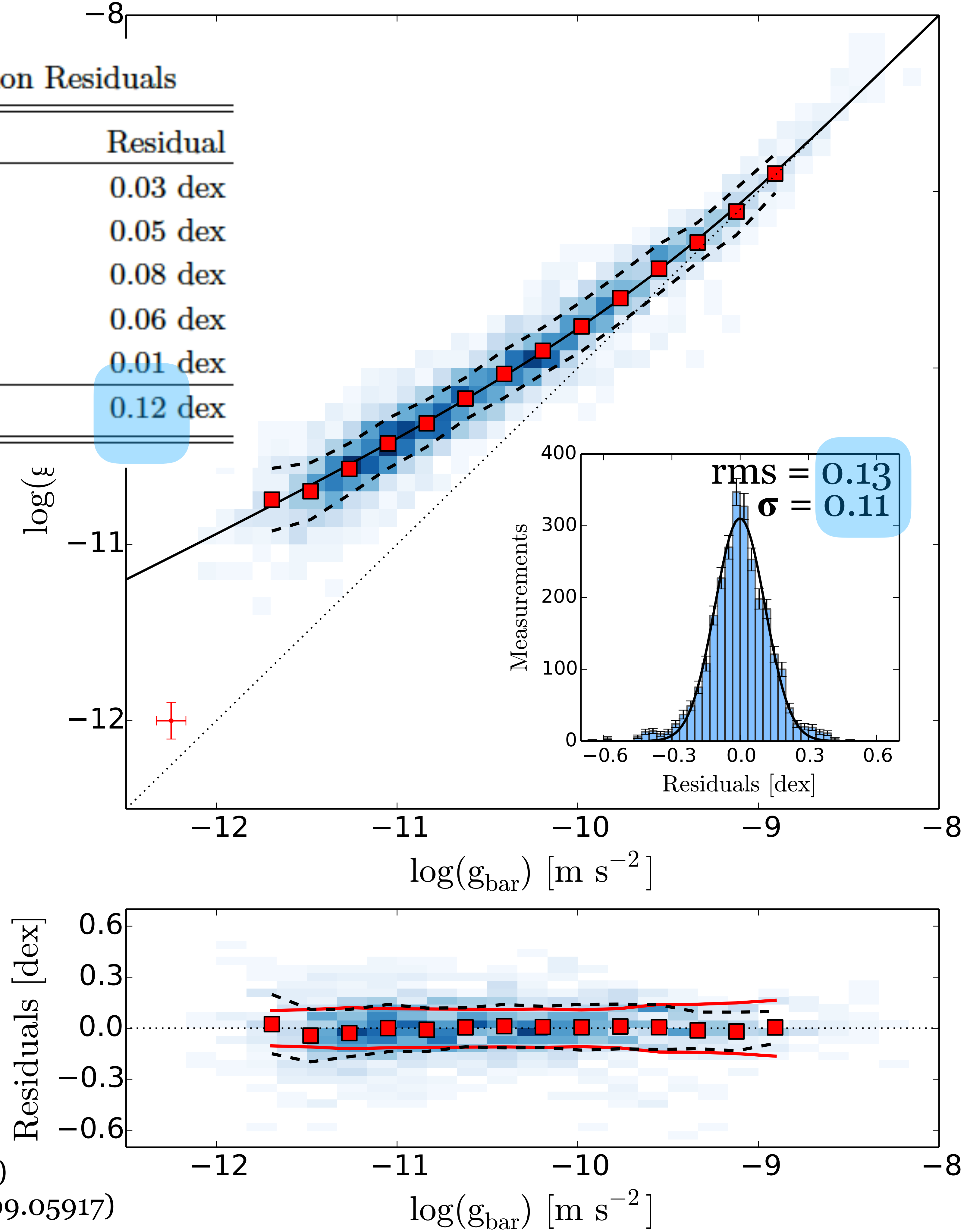
observed rms scatter

scatter expected from observational errors

The data are consistent with zero intrinsic scatter

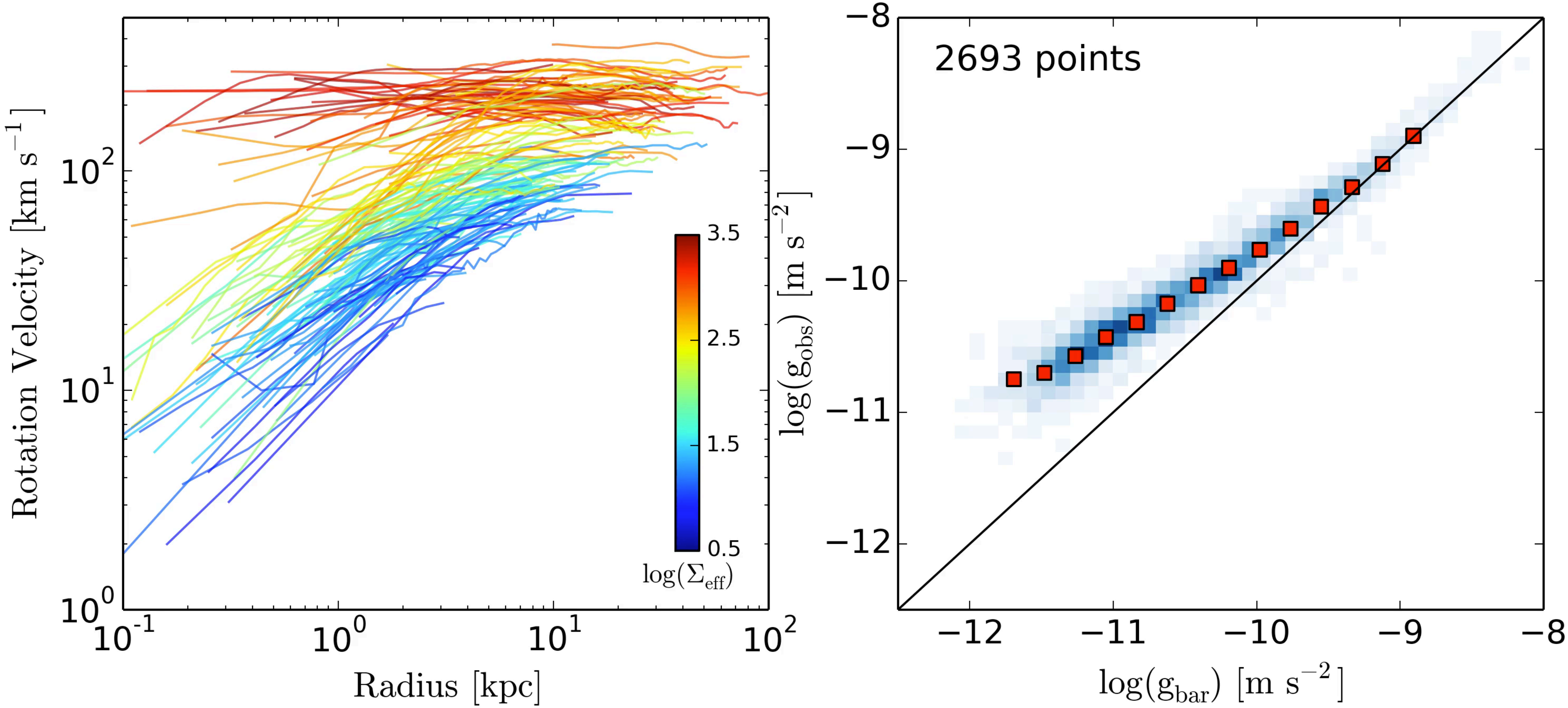
TABLE I. Scatter Budget for Acceleration Residuals

Source	Residual
Rotation velocity errors	0.03 dex
Disk inclination errors	0.05 dex
Galaxy distance errors	0.08 dex
Variation in mass-to-light ratios	0.06 dex
HI flux calibration errors	0.01 dex
Total	0.12 dex



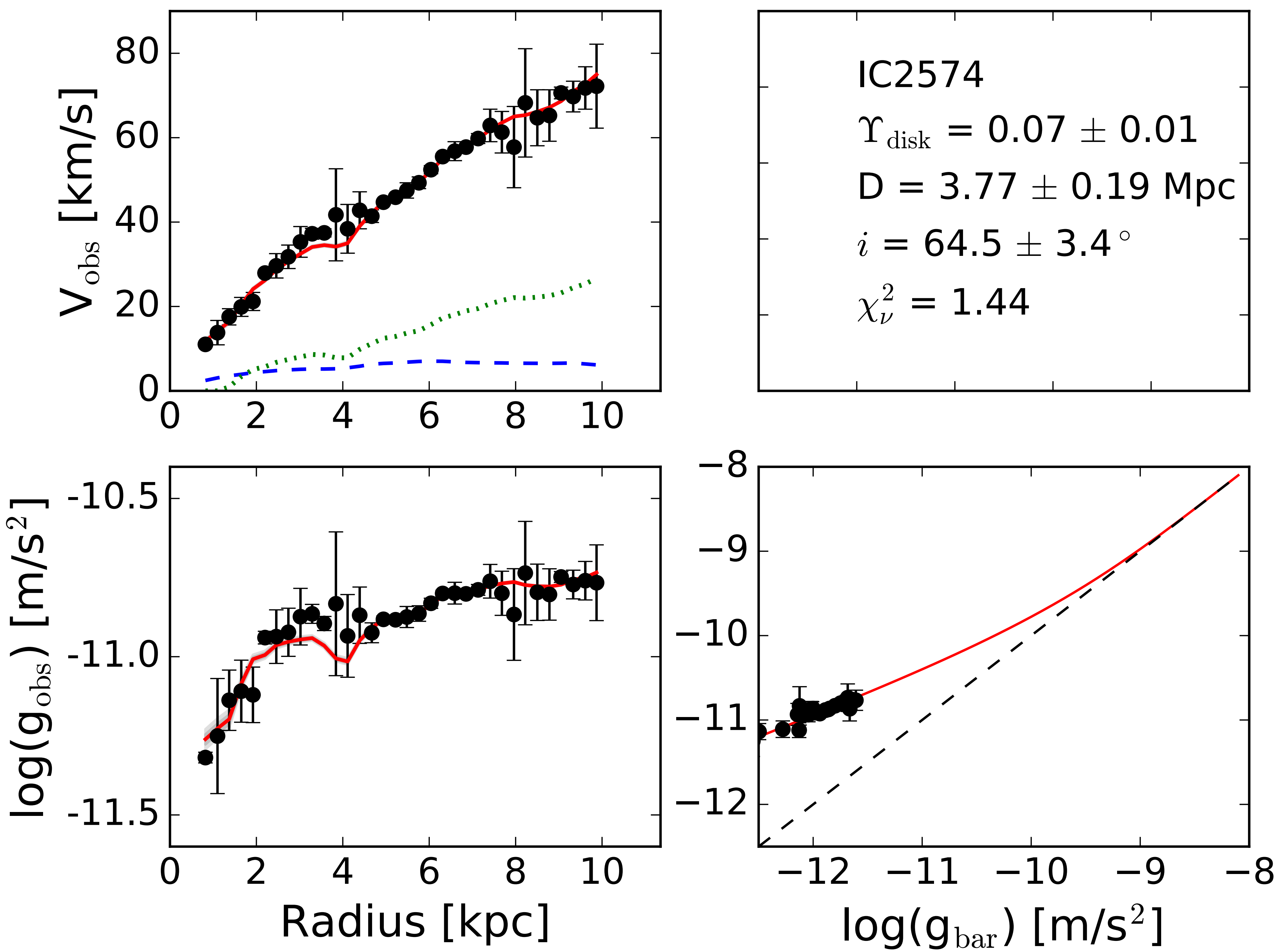
The observed scatter is consistent with that expected from known uncertainties: the radial acceleration relation is consistent has negligible intrinsic scatter.

Lelli et al. 2017, ApJ, 836, 152 (arXiv:1610.08981)
McGaugh et al. 2016, PRL, 117, 201101 (arXiv:1609.05917)

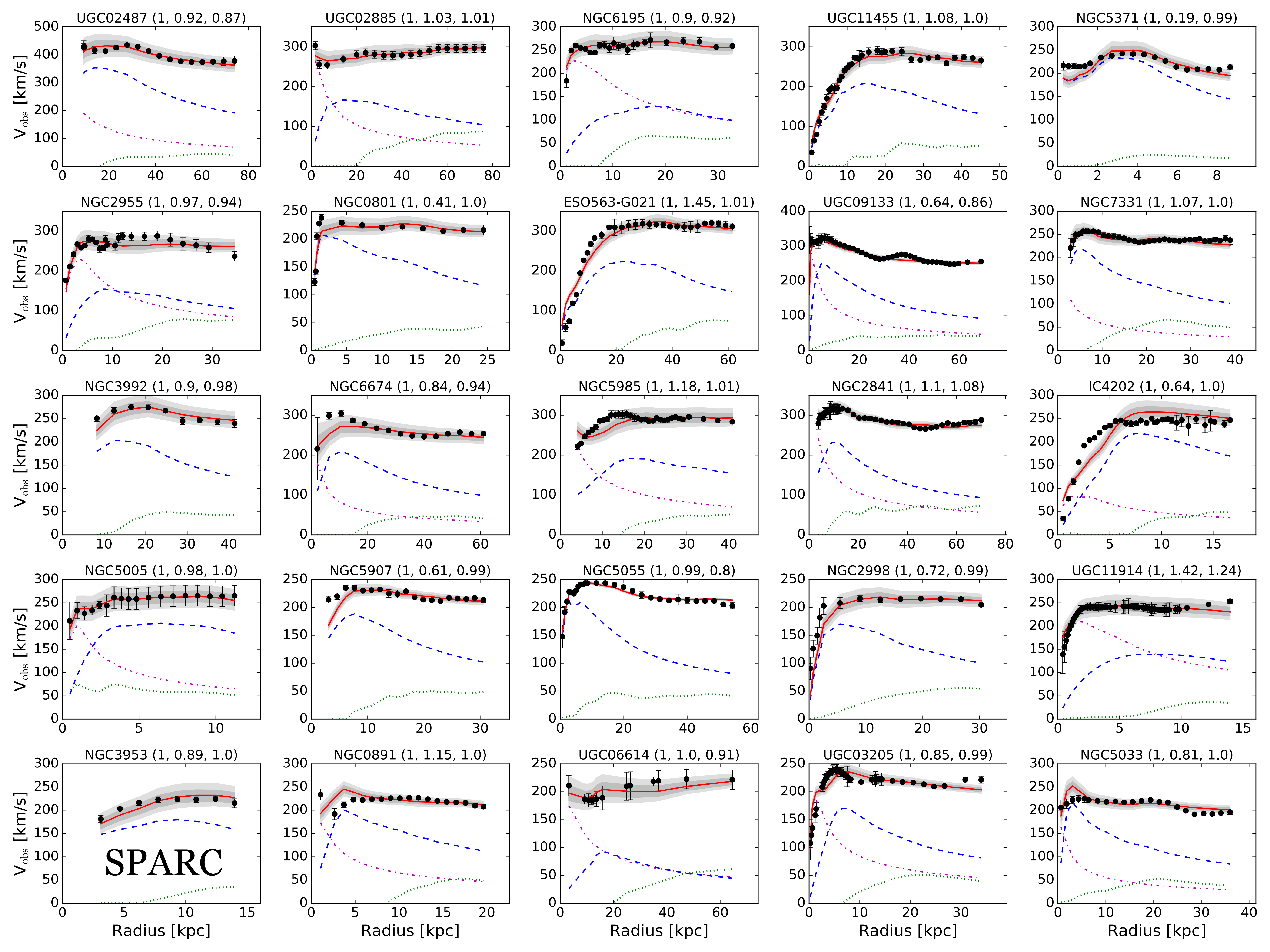


http://astroweb.case.edu/SPARC/RARmovie.mp4

That just assumed constant M*/L. We can fit to the mean RAR, marginalizing over distance and inclination as nuisance parameters (Li et al. 2018)



Li et al. 2018, A&A, 615, A3 (arXiv:1803.00022)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NGC5371 (1, 0.19, 0.99)
NGC2955 (1, 0.97, 0.94)
NGC0801 (1, 0.41, 1.0)
ESO563-G021 (1, 1.45, 1.01)
UGC09133 (1, 0.64, 0.86)
NGC7331 (1, 1.07, 1.0)
NGC3992 (1, 0.9, 0.98)
NGC6674 (1, 0.84, 0.94)
NGC5985 (1, 1.18, 1.01)
NGC2841 (1, 1.1, 1.08)
IC4202 (1, 0.64, 1.0)
NGC5005 (1, 0.98, 1.0)
NGC5907 (1, 0.61, 0.99)
NGC5055 (1, 0.99, 0.8)
NGC2998 (1, 0.72, 0.99)
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NGC3953 (1, 0.89, 1.0)
NGC0891 (1, 1.15, 1.0)
UGC06614 (1, 1.0, 0.91)
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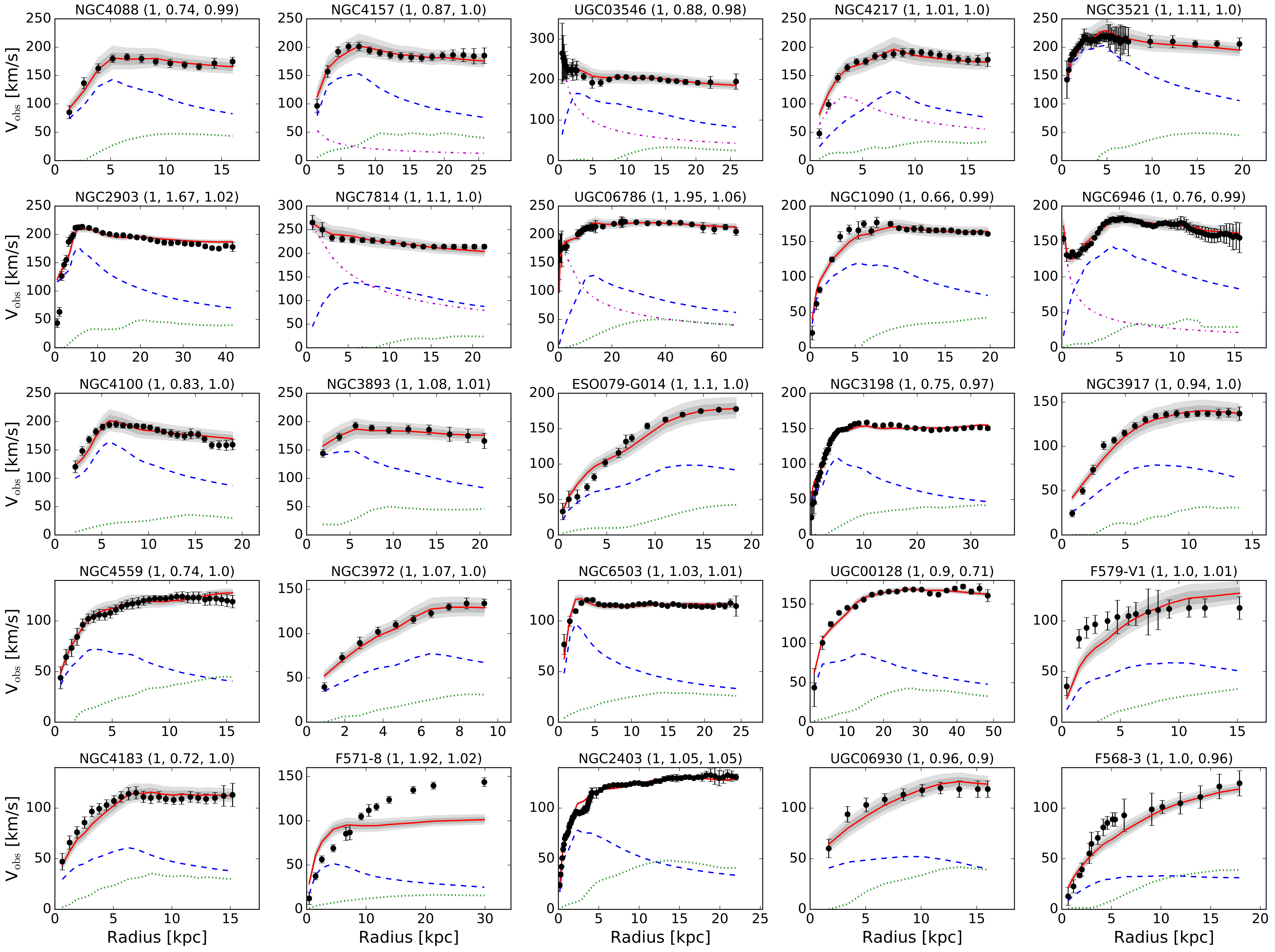
V_{obs} [km/s]
Radius [kpc]
SPARC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NGC3521 (1, 1.11, 1.0)
NGC2903 (1, 1.67, 1.02)
NGC7814 (1, 1.1, 1.0)
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NGC1090 (1, 0.66, 0.99)
NGC6946 (1, 0.76, 0.99)
NGC4100 (1, 0.83, 1.0)
NGC3893 (1, 1.08, 1.01)
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NGC3198 (1, 0.75, 0.97)
NGC3917 (1, 0.94, 1.0)
NGC4559 (1, 0.74, 1.0)
NGC3972 (1, 1.07, 1.0)
NGC6503 (1, 1.03, 1.01)
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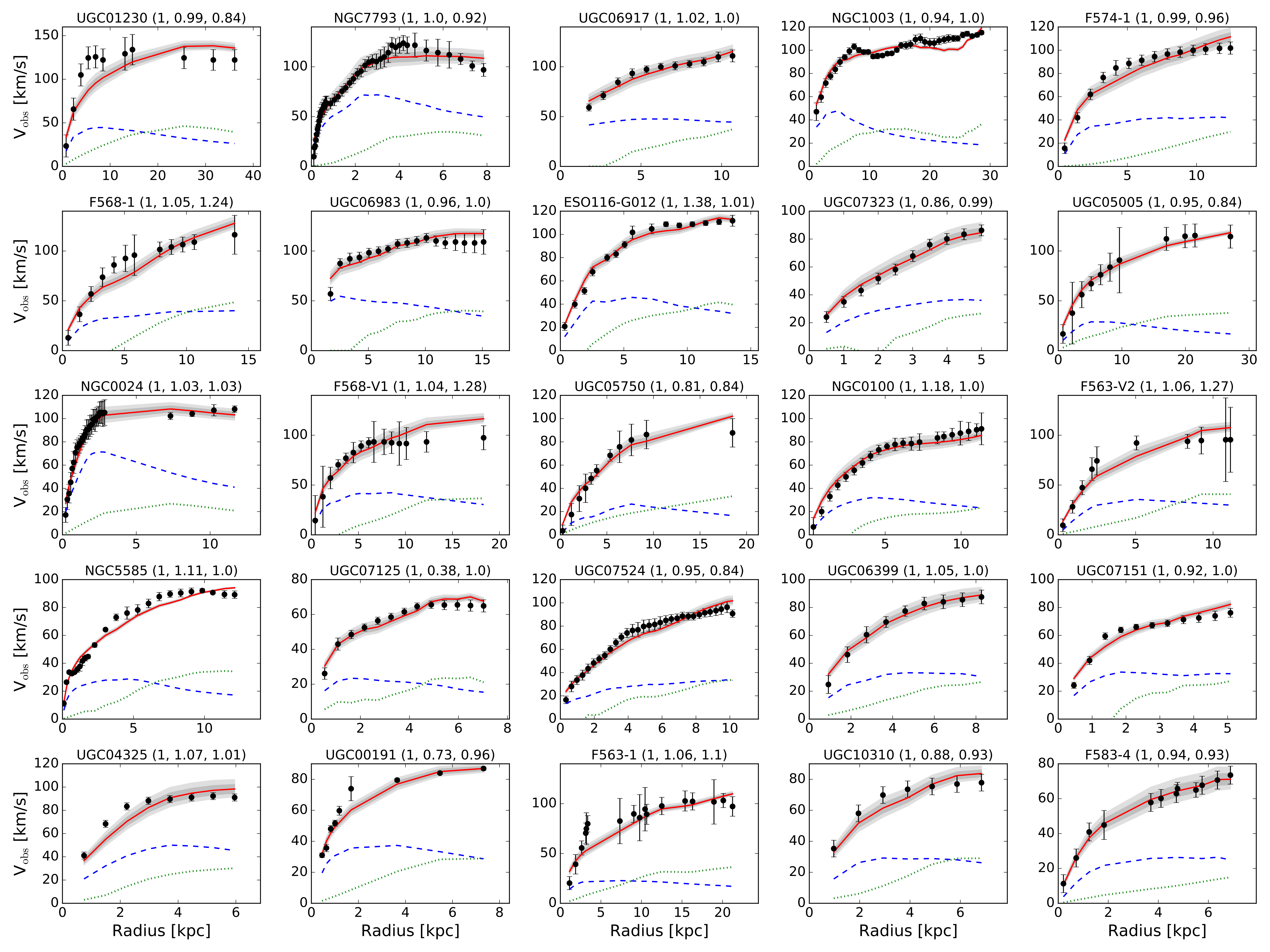
V_{obs} [km/s]
Radius [kpc]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NGC0024 (1, 1.03, 1.03)
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NGC0100 (1, 1.18, 1.0)
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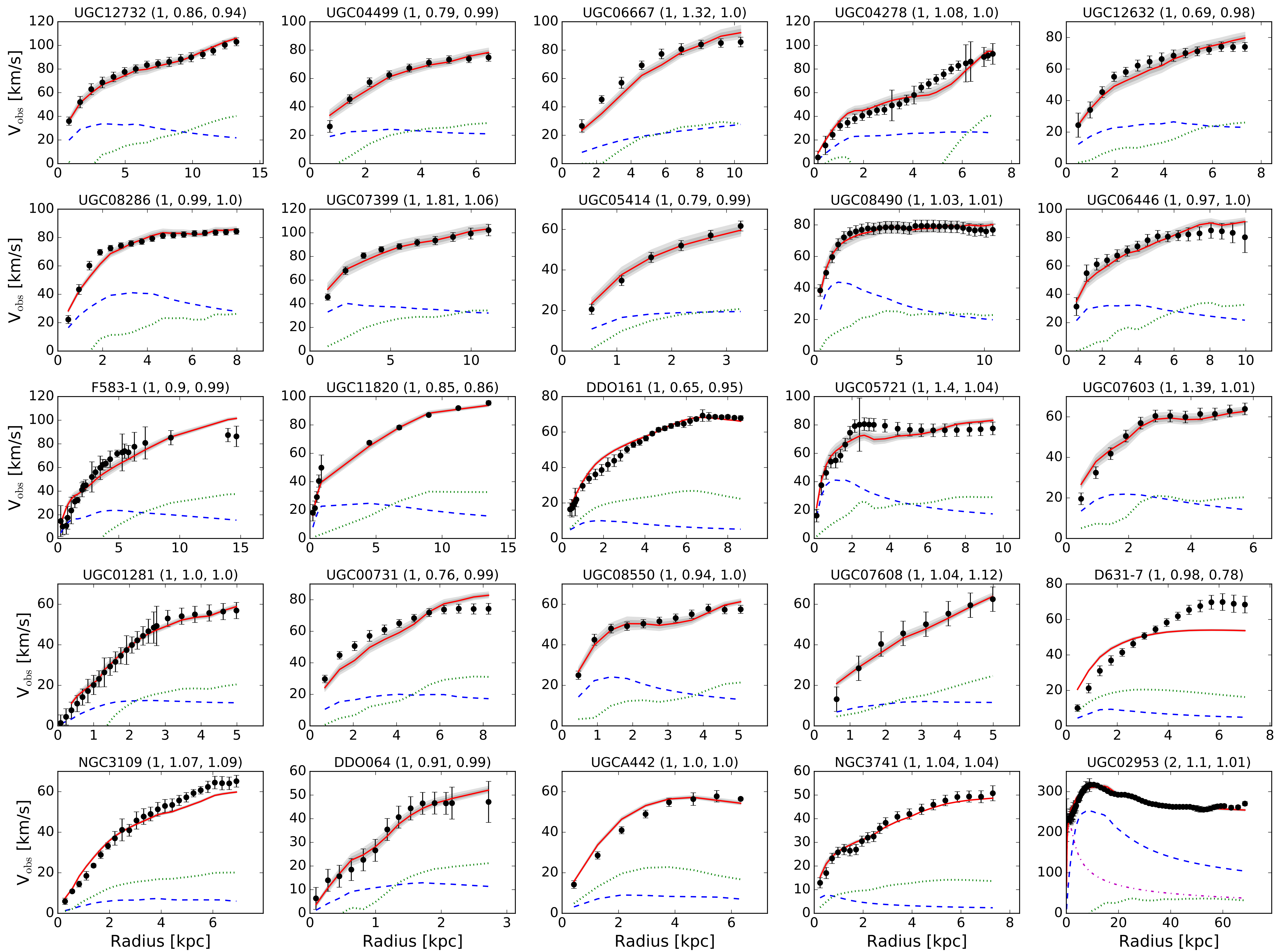
V_{obs} [km/s]
Radius [kpc]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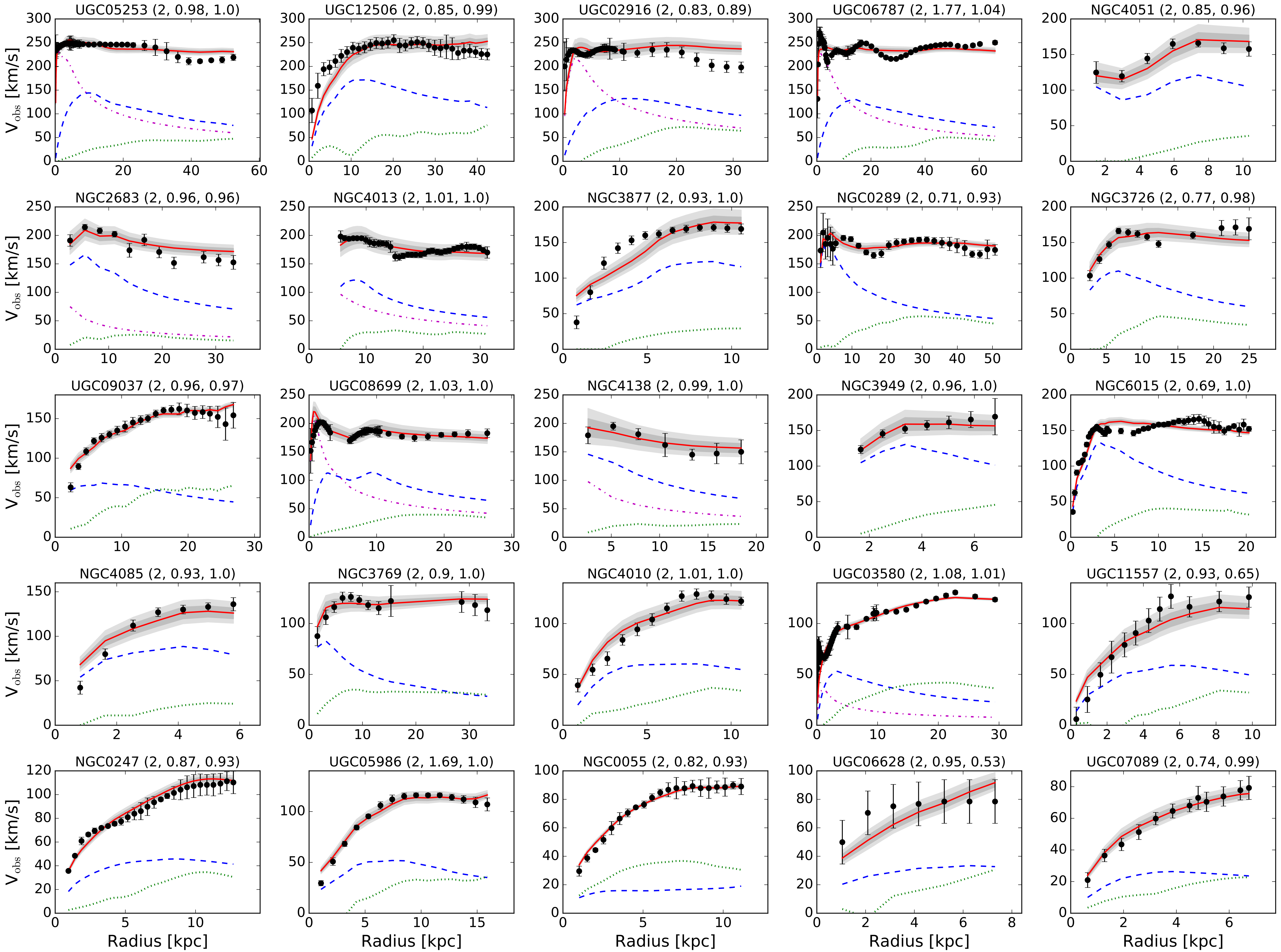
V_obs [km/s]
Radius [kpc]



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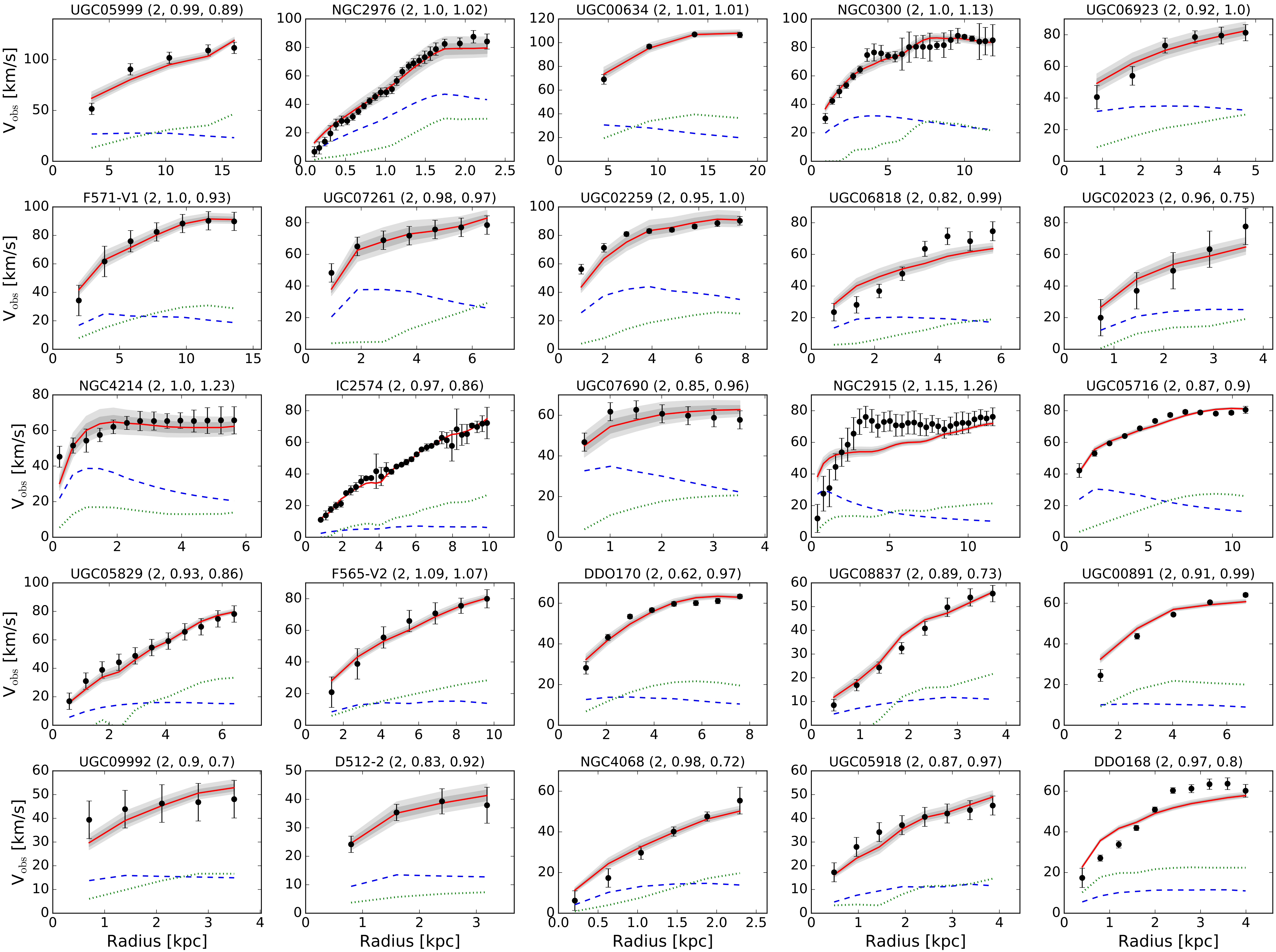
V_obs [km/s]
Radius [kpc]



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NGC4214 (2, 1.0, 1.23)
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UGC05918 (2, 0.87, 0.97)
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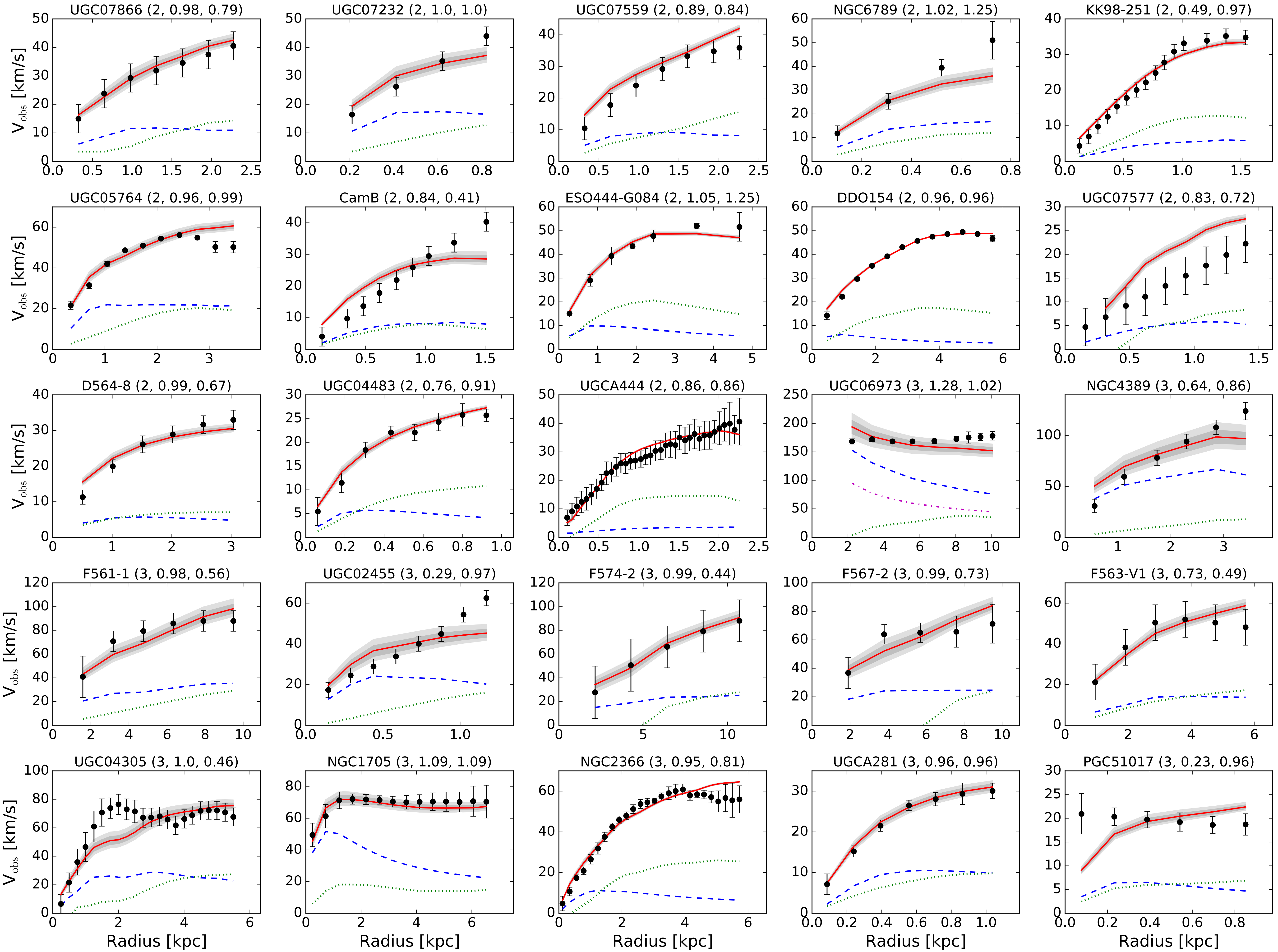
V_obs [km/s]
Radius [kpc]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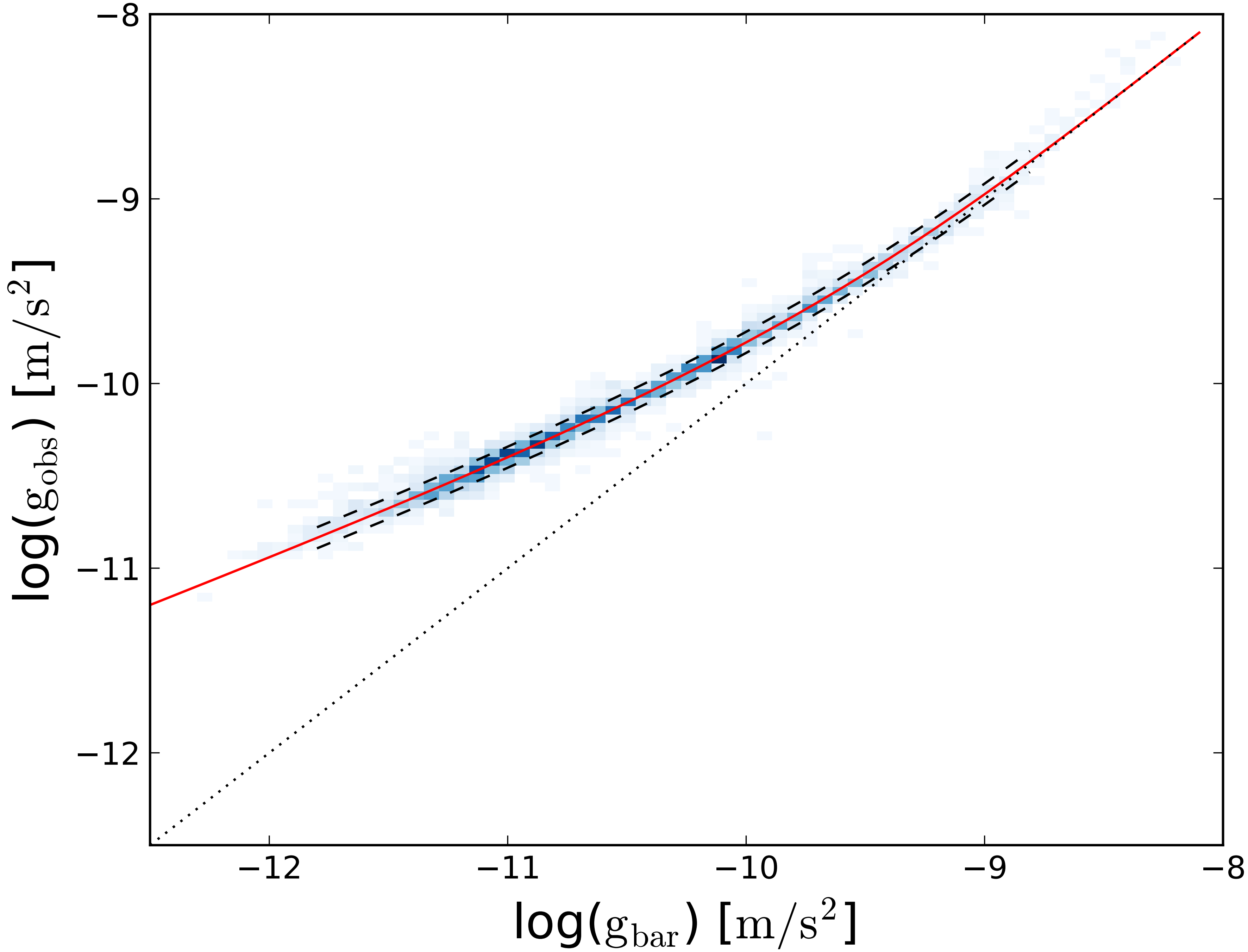
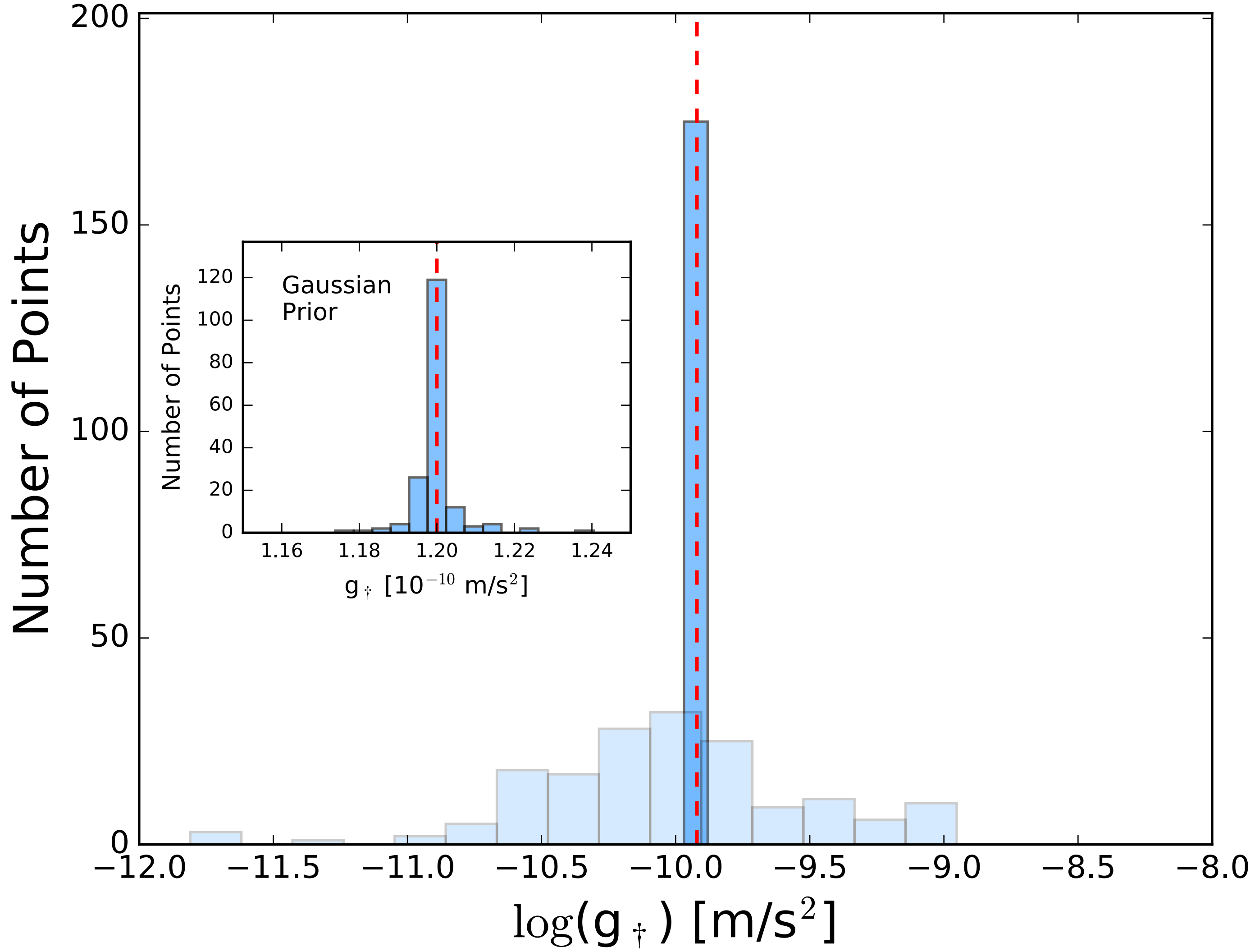
UGCA281 (3, 0.96, 0.96)
PGC51017 (3, 0.23, 0.96)
V_{obs} [km/s]
Radius [kpc]

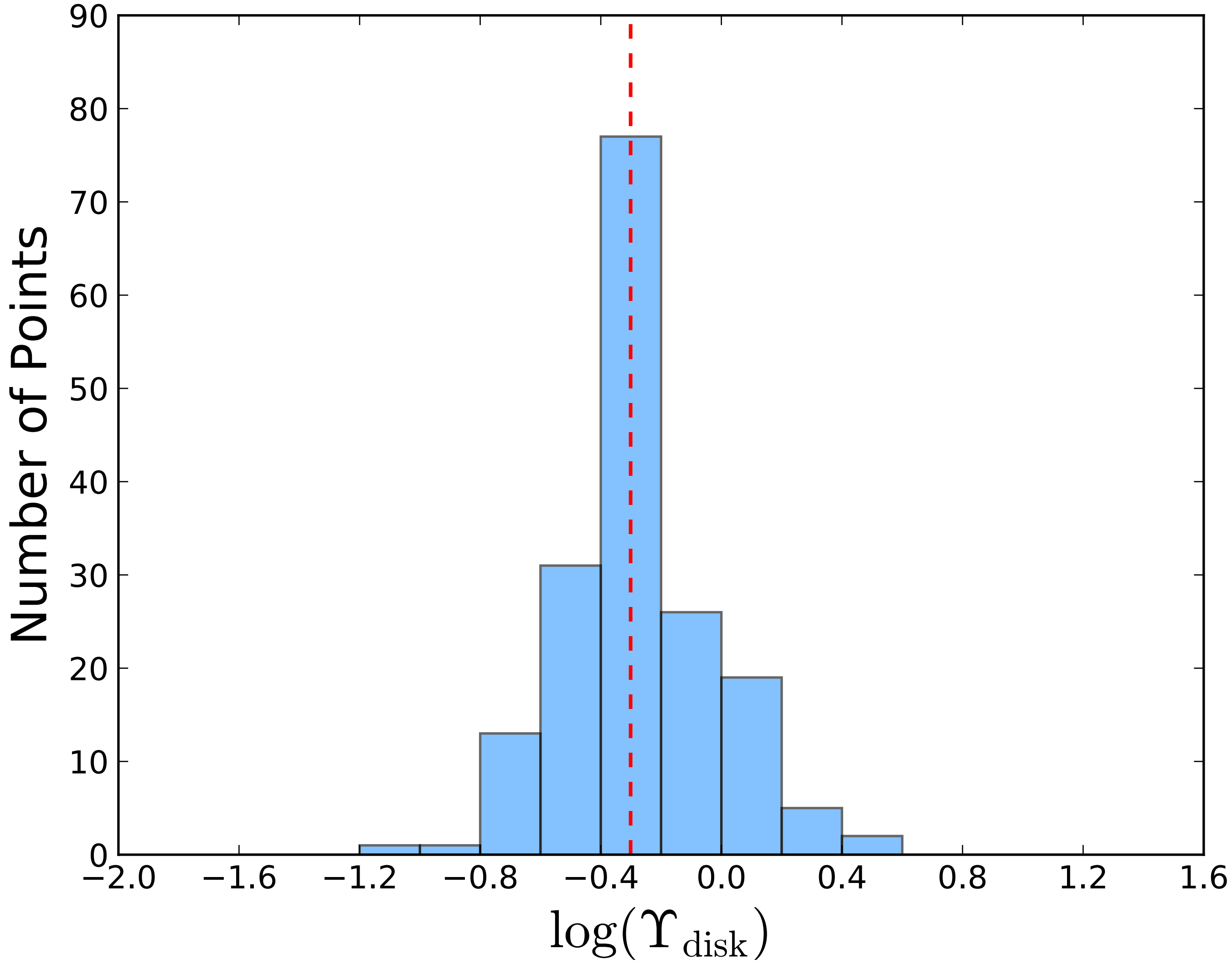
Residuals from SPARC data
(Li et al. 2018)



No need to vary g+, which covaries with M*/L
The data constrain one or the other; not both
(Li et al. 2018)



The distribution of fitted M*/L is reasonable



There are striking regularities in galaxy dynamics

- Flat Rotation Curves
- Baryonic Tully-Fisher Relation
- Central Density Relation
- Renzo’s Rule
- Radial Acceleration Relation

All the systematic properties involve a critical acceleration scale.

- Baryonic Tully-Fisher Relation

$$g_\dagger^{\mathrm{BTFR}} = 1.24 \pm 0.14 \times 10^{-10}\ \mathrm{m\,s^{-2}}$$

(McGaugh 2011)

- Central Density Relation

$$g_\dagger^{\mathrm{CDR}} = G\Sigma_\dagger = 1.27 \pm 0.05 \times 10^{-10}\ \mathrm{m\,s^{-2}}$$

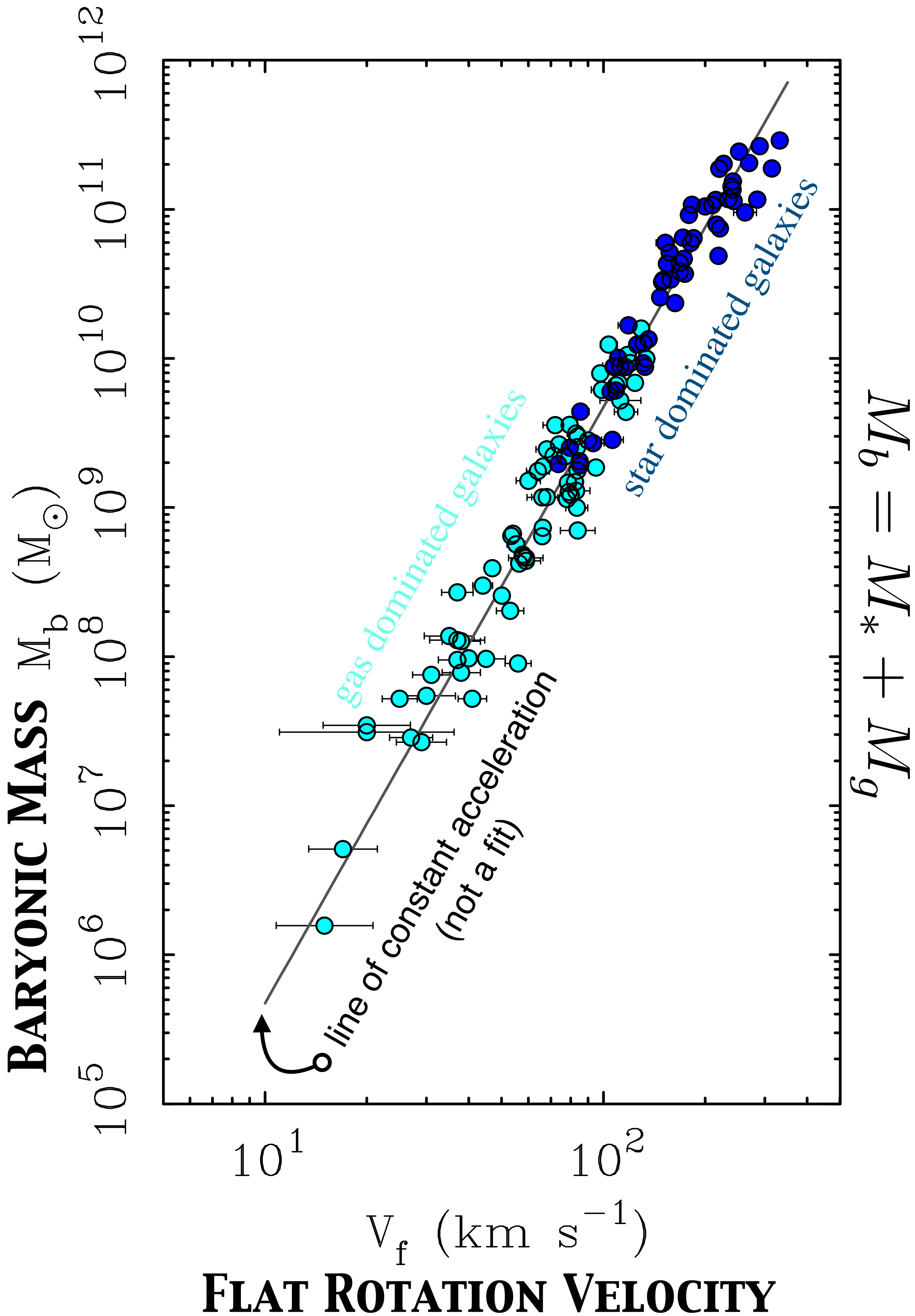
(Lelli et al. 2016)

- Radial Acceleration Relation

$$g_\dagger^{\mathrm{RAR}} = 1.20 \pm 0.02 \times 10^{-10}\ \mathrm{m\,s^{-2}}$$

(McGaugh et al. 2016)

Baryonic Tully-Fisher Relation

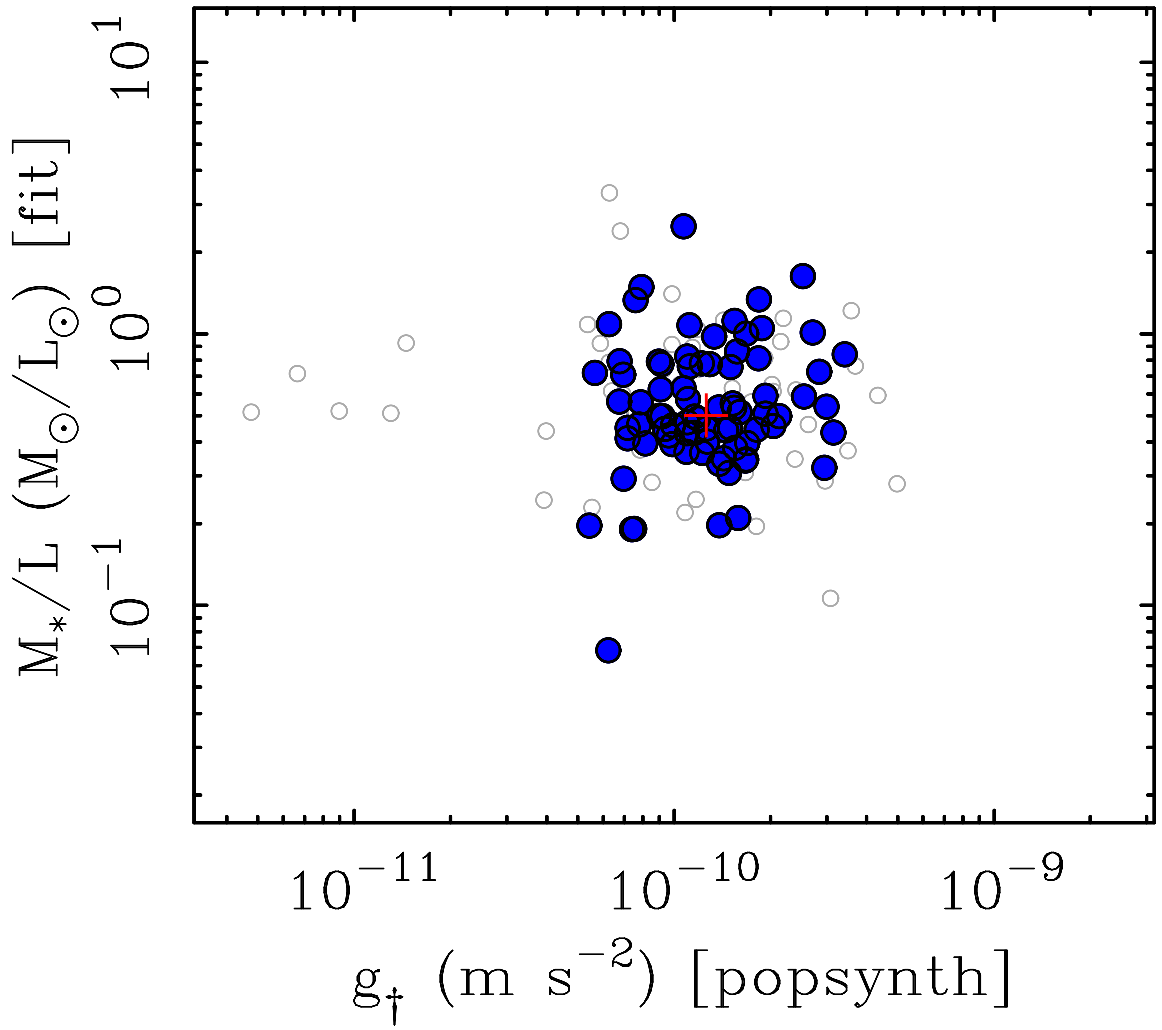


Can construct a characteristic acceleration for each galaxy

$$g_\dagger = \frac{\chi V_f^4}{G M_b}$$

Galaxies closely follow a single, universal acceleration.

χ is a factor of order unity that accounts for the geometry of disk galaxies, which are not spherical cows. We adopt $\chi = 0.8$ (McGaugh 2005).



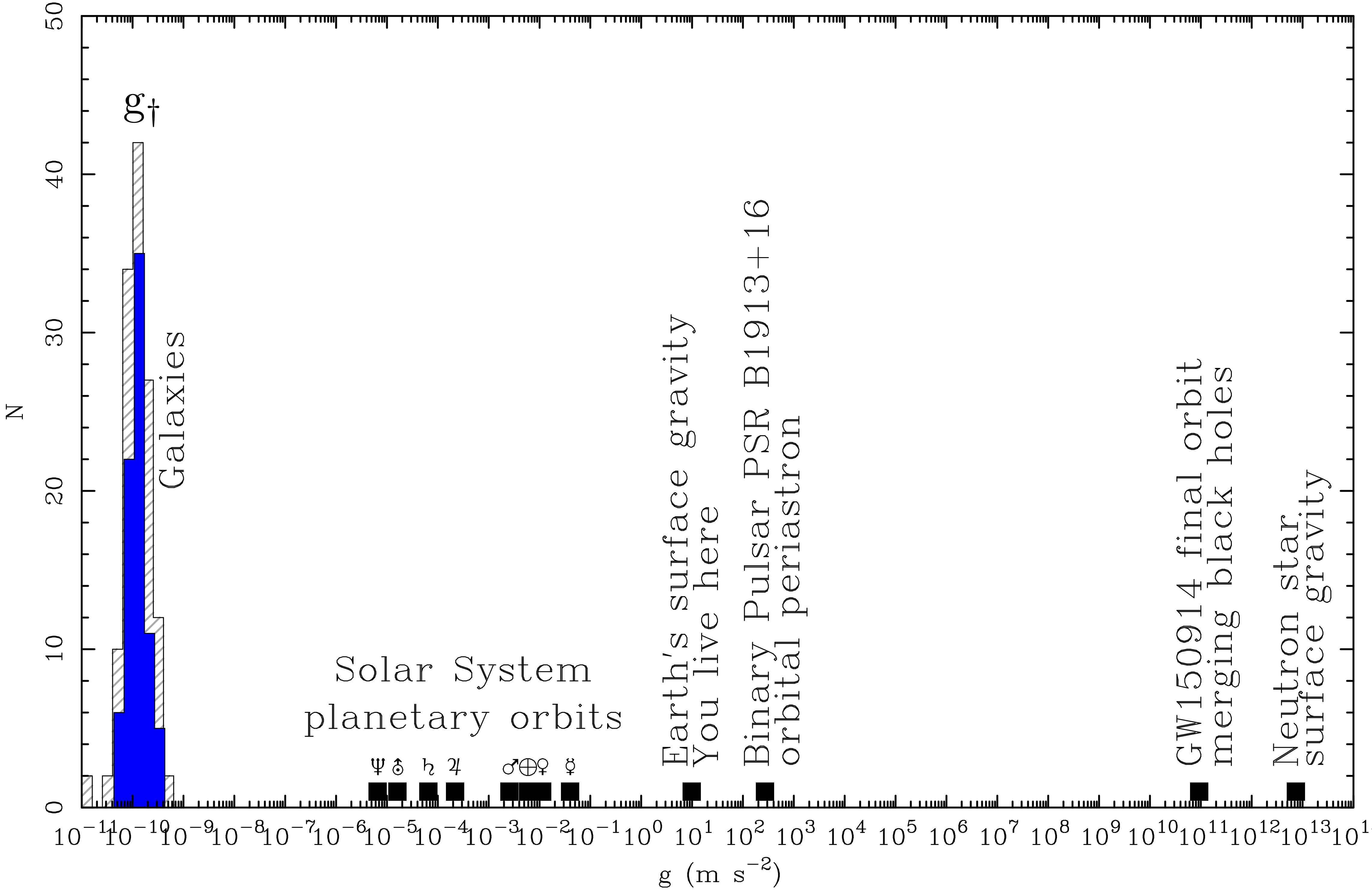
M*/L inferred with fixed acceleration scale

acceleration scale inferred with fixed M*/L

Filled points: distances uncertainties < 20%
Open points: distances uncertainties > 20%

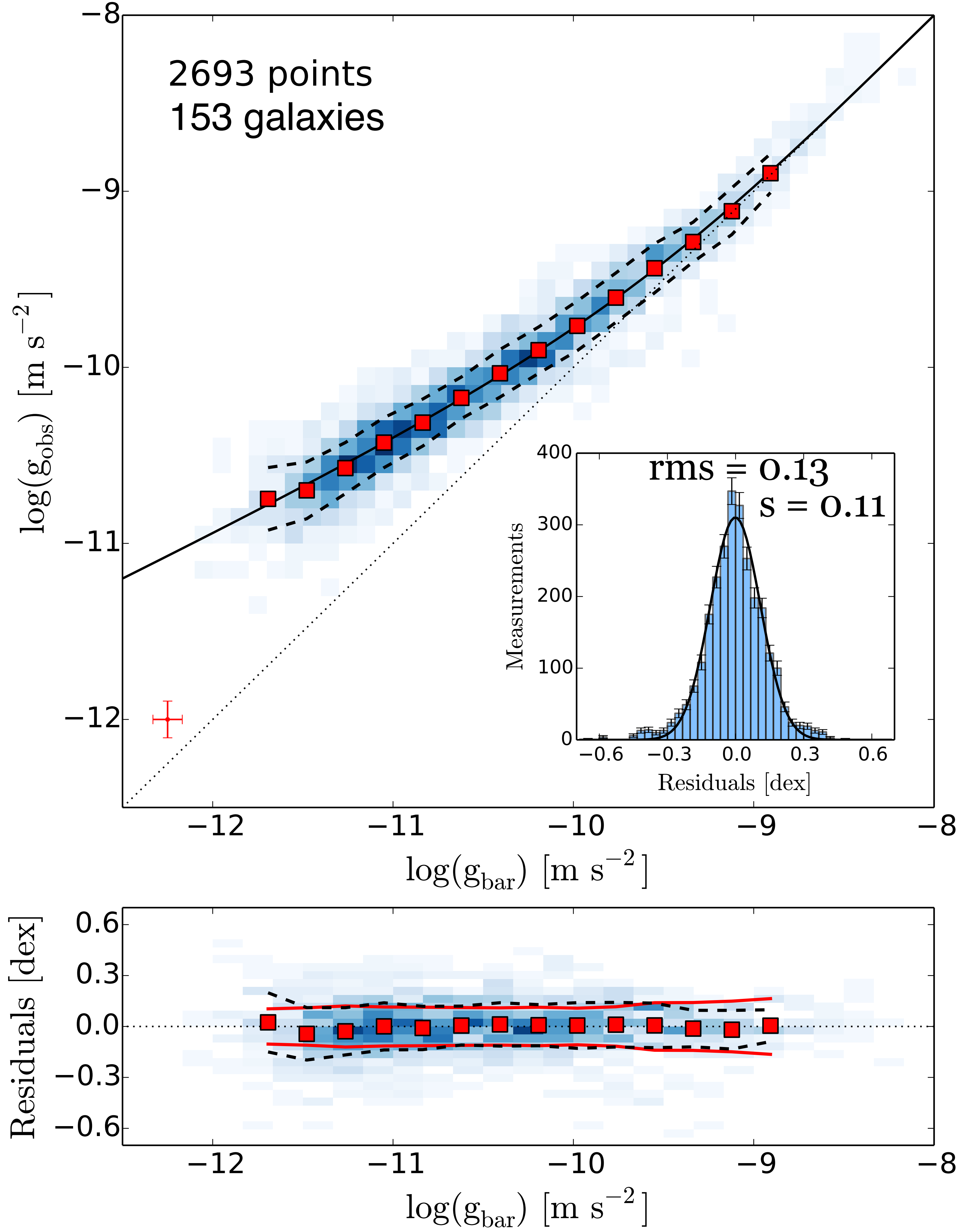
Over 25 decades in acceleration, galaxies only exist around 1 Å/s/s

$g_\dagger$ is a special value

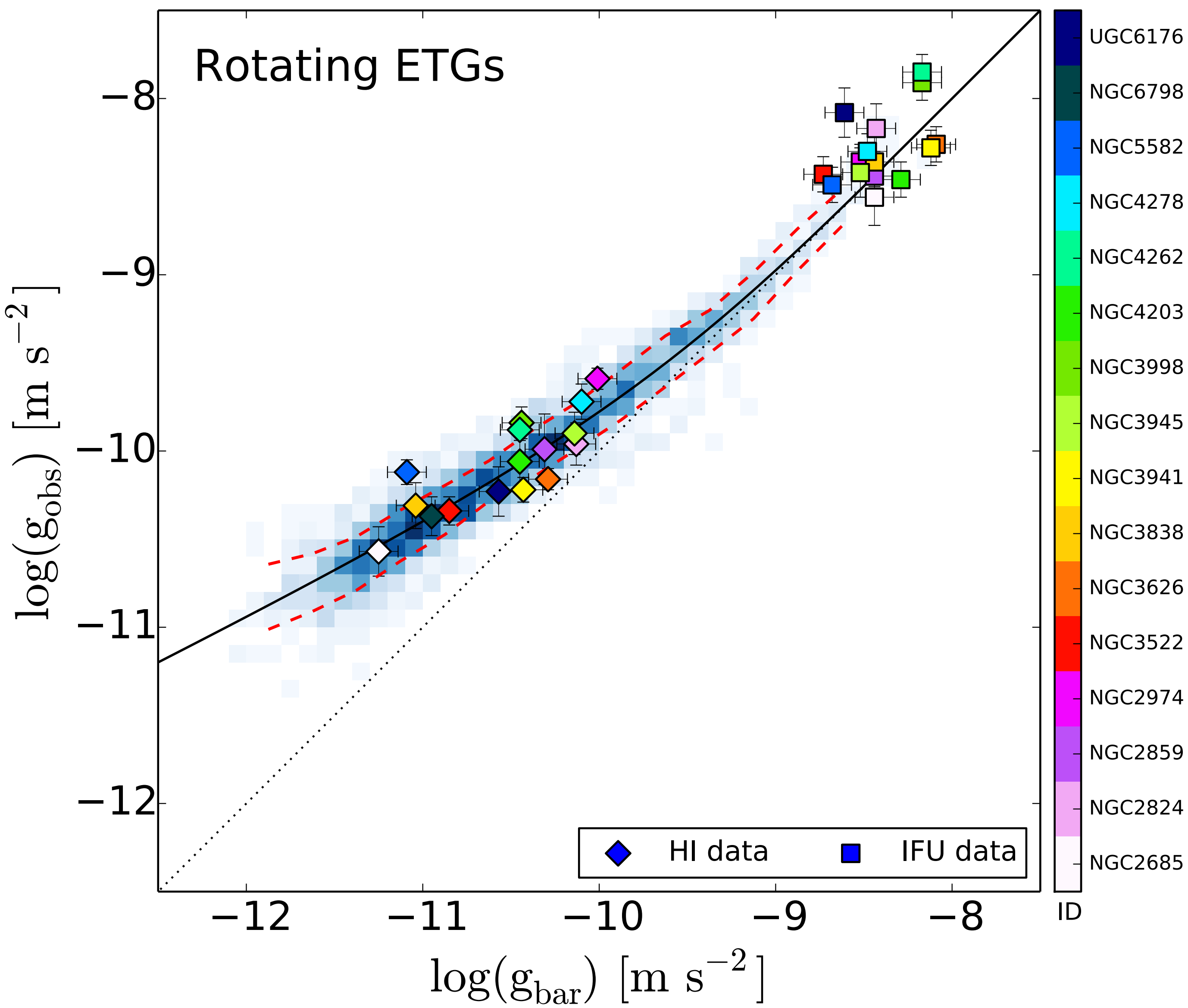


Radial Acceleration Relation

So far, just talking about rotating galaxies. What about pressure supported Ellipticals?

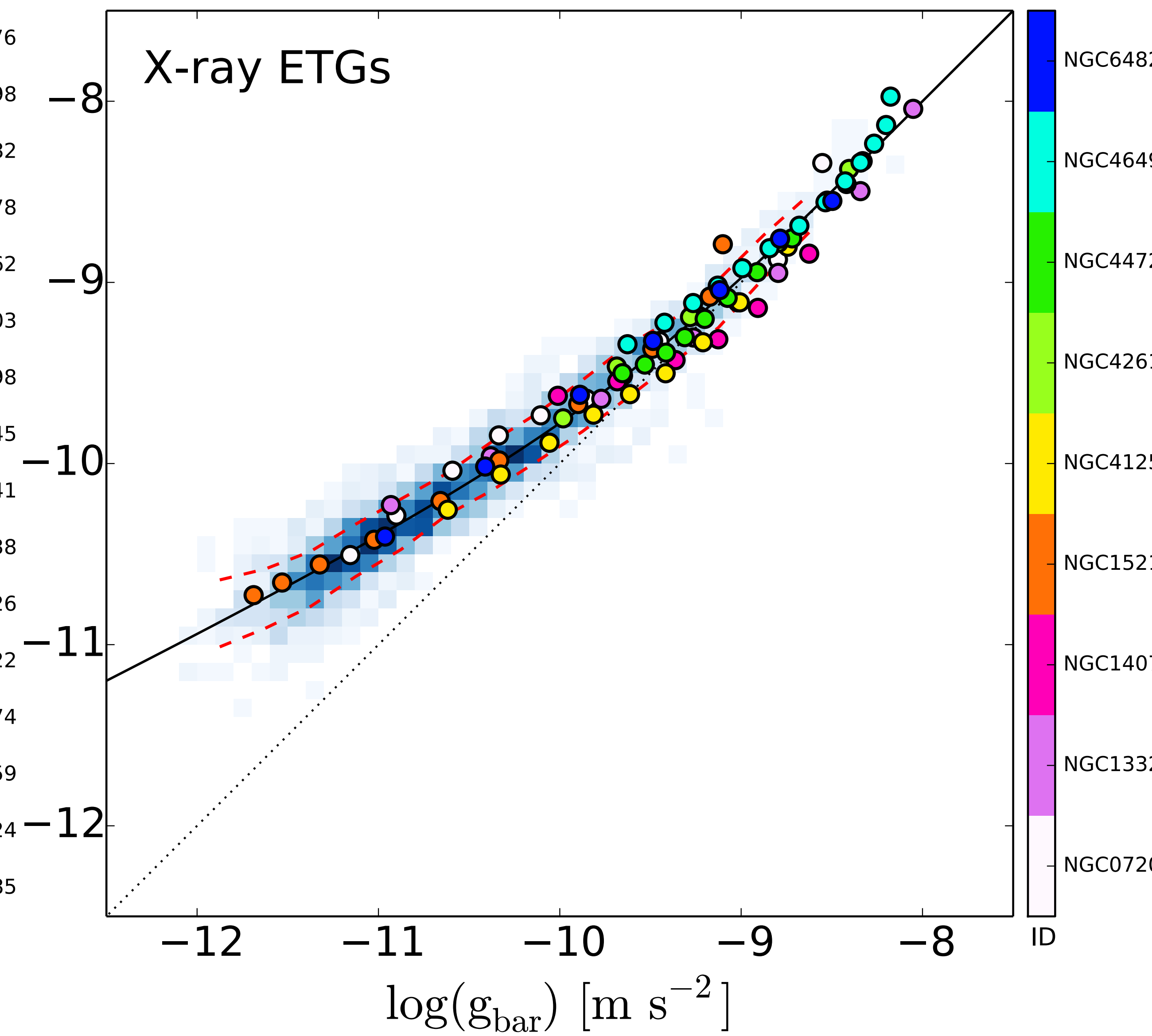


ATLAS^{3D} data (fast rotators)

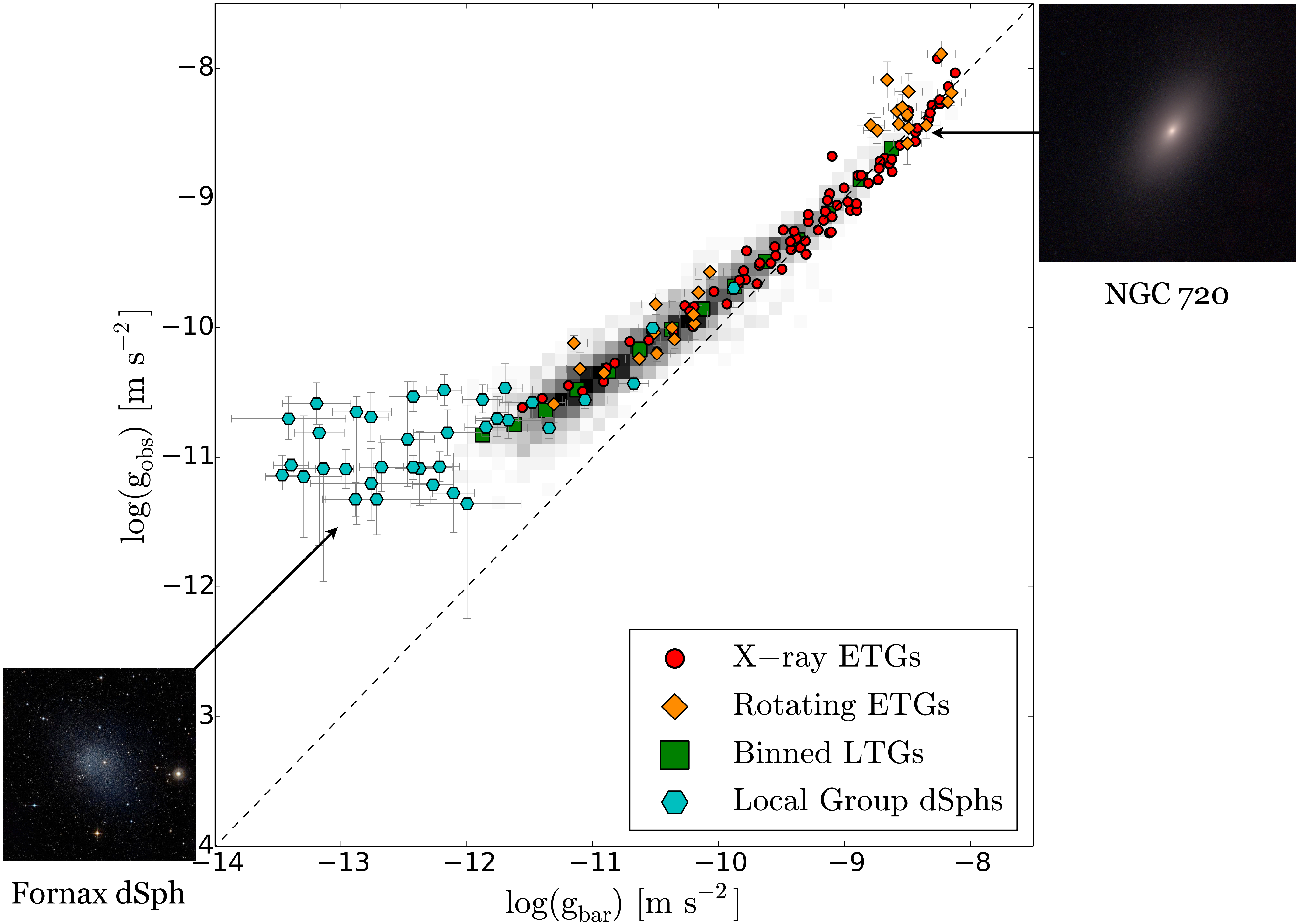


Inner, high acceleration data from optical IFU
Outer, low acceleration points from HI 21 cm

X-ray Ellipticals (slow rotators)



Mass profiles from hydrostatic equilibrium of X-ray gas.



−8
−9
−10
−11
−12
3
4
−14
−13
−12
−11
−10
−9
−8
log(g_obs) [m s^−2]
log(g_bar) [m s^−2]
X−ray ETGs
Rotating ETGs
Binned LTGs
Local Group dSphs
NGC 720
Fornax dSph

Dark Matter

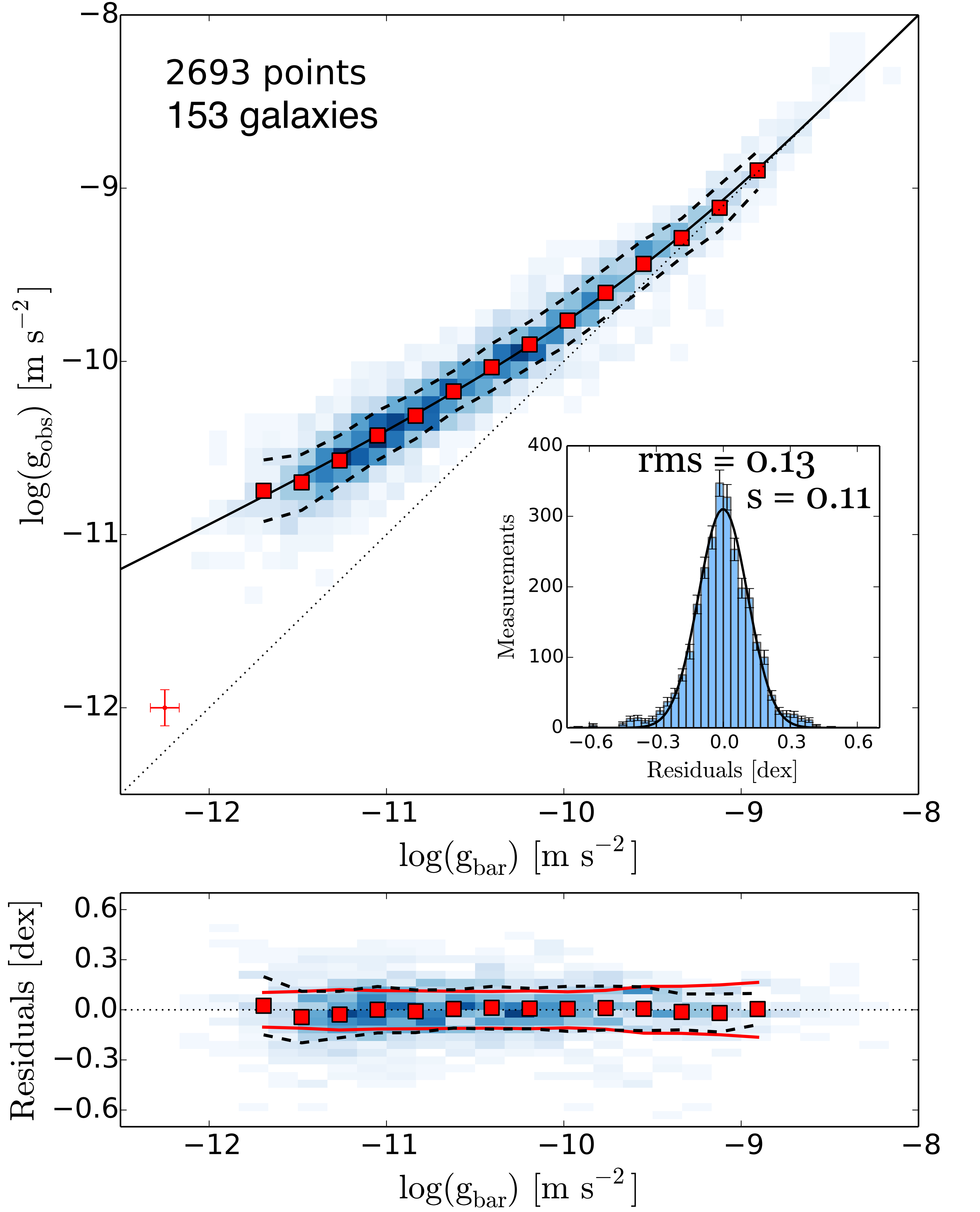
Radial Acceleration Relation

One consequence:
the dark matter distribution is strongly coupled to the baryons

$$g_{\rm obs} = \frac{g_{\rm bar}}{1 - e^{-\sqrt{g_{\rm bar}/g_{\dagger}}}}$$

$$g_{\rm DM} = g_{\rm obs} - g_{\rm bar}$$

You can work out the dark matter distribution just by looking at the baryons



Dark Matter - one consequence

The Radial Acceleration Relation can be used to infer the dark matter distribution just by looking at a galaxy.

total $$g_{obs} = \mathcal{F}(g_{bar})$$

$$\mathcal{F} = \frac{g_{bar}}{1 - e^{-\sqrt{g_{bar}/g_{\dagger}}}}$$

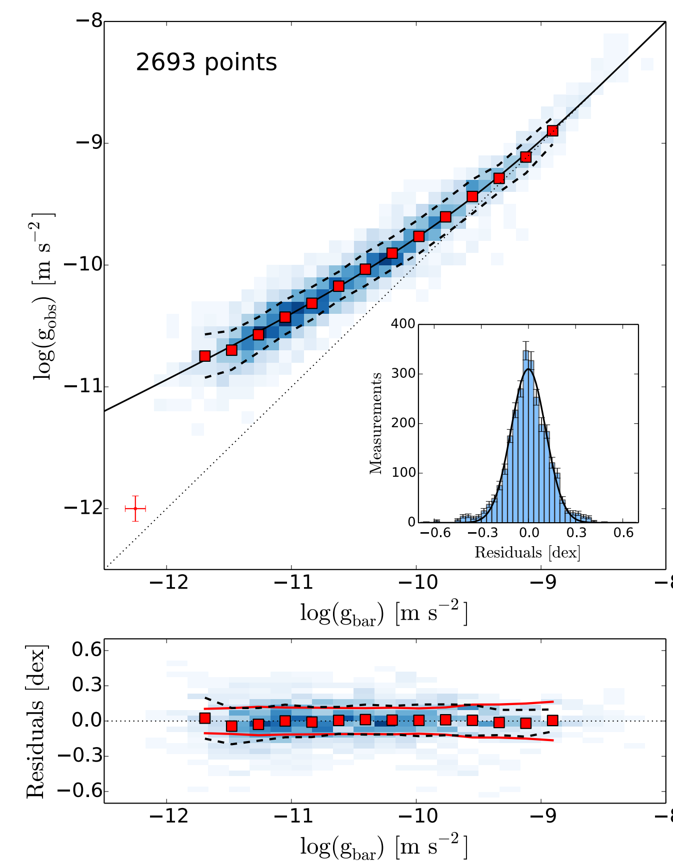
dark matter $$g_{DM} = g_{obs} - g_{bar}$$

$$g_{\dagger} = 1.20 \times 10^{-10}\ \mathrm{m\,s^{-2}}$$

$$\pm 0.02\ (\text{random}) \pm 0.24\ (\text{systematic})$$

$$g_{DM} = \mathcal{F}(g_{bar}) - g_{bar}$$

The dark matter distribution is specified by the baryon distribution



That's weird