DARK MATTER

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SPRING 2026
TR 11:30AM–12:45PM
SEARS 552

http://astroweb.case.edu/ssm/ASTR333/

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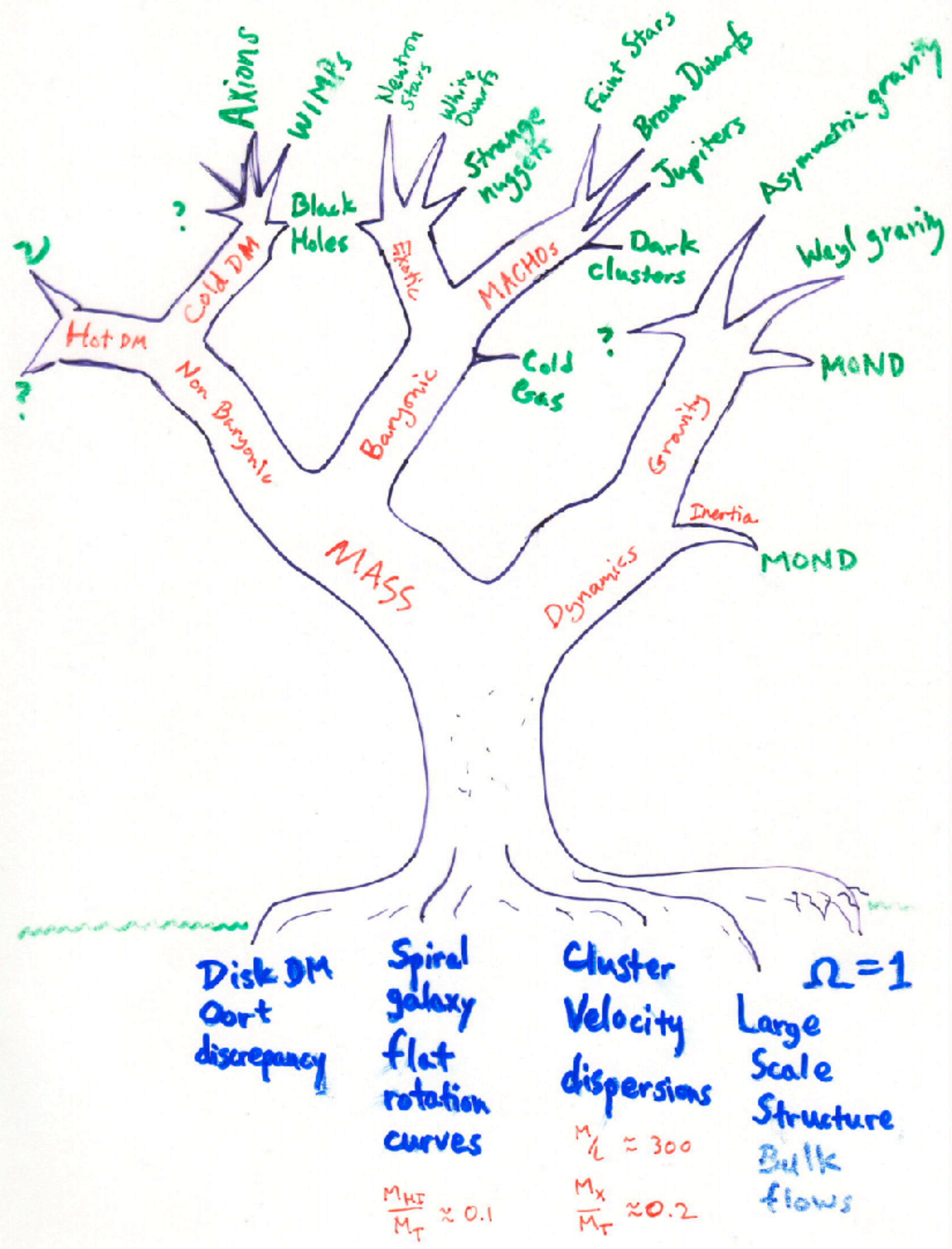
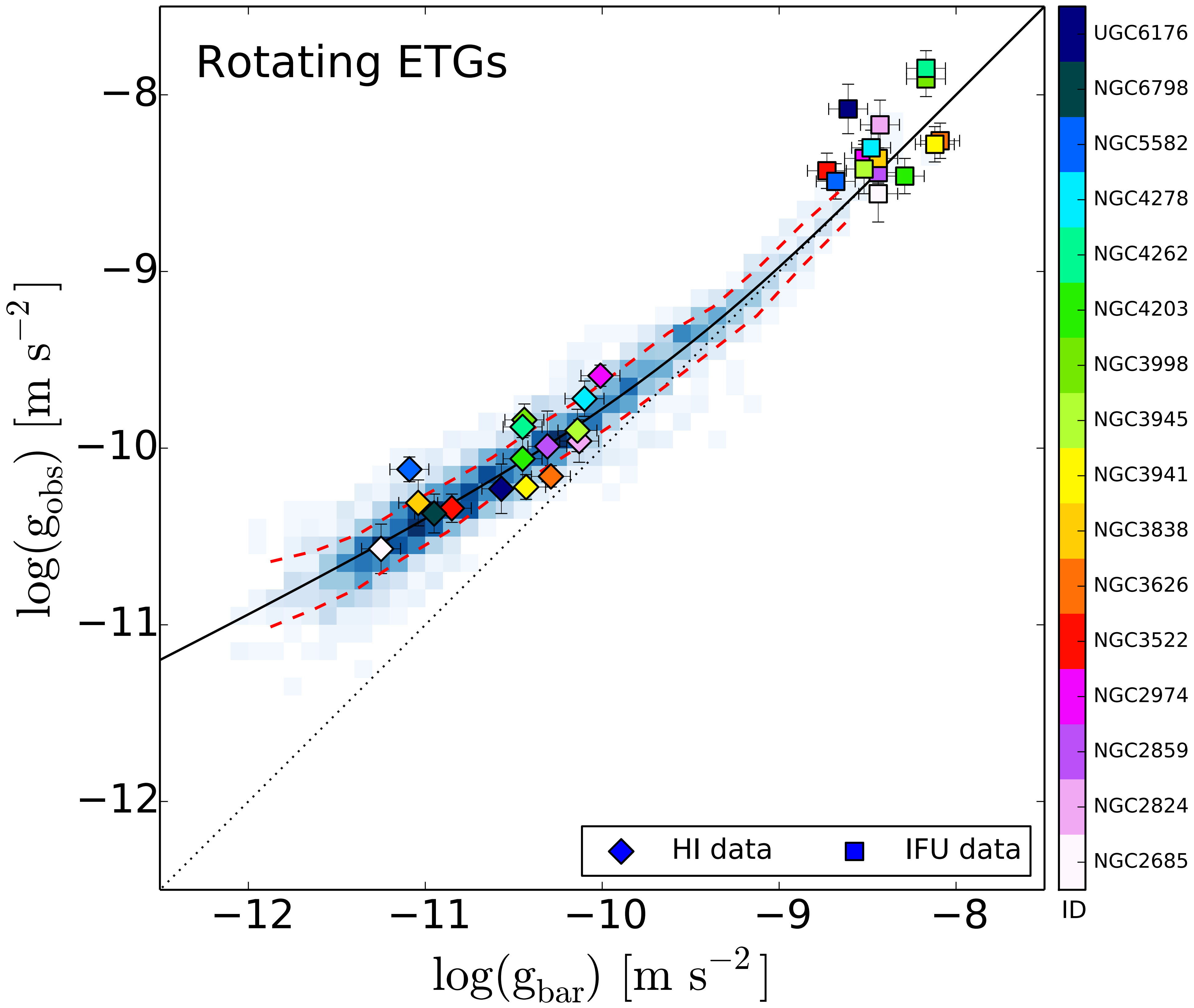


CASE WESTERN RESERVE UNIVERSITY EST. 1826

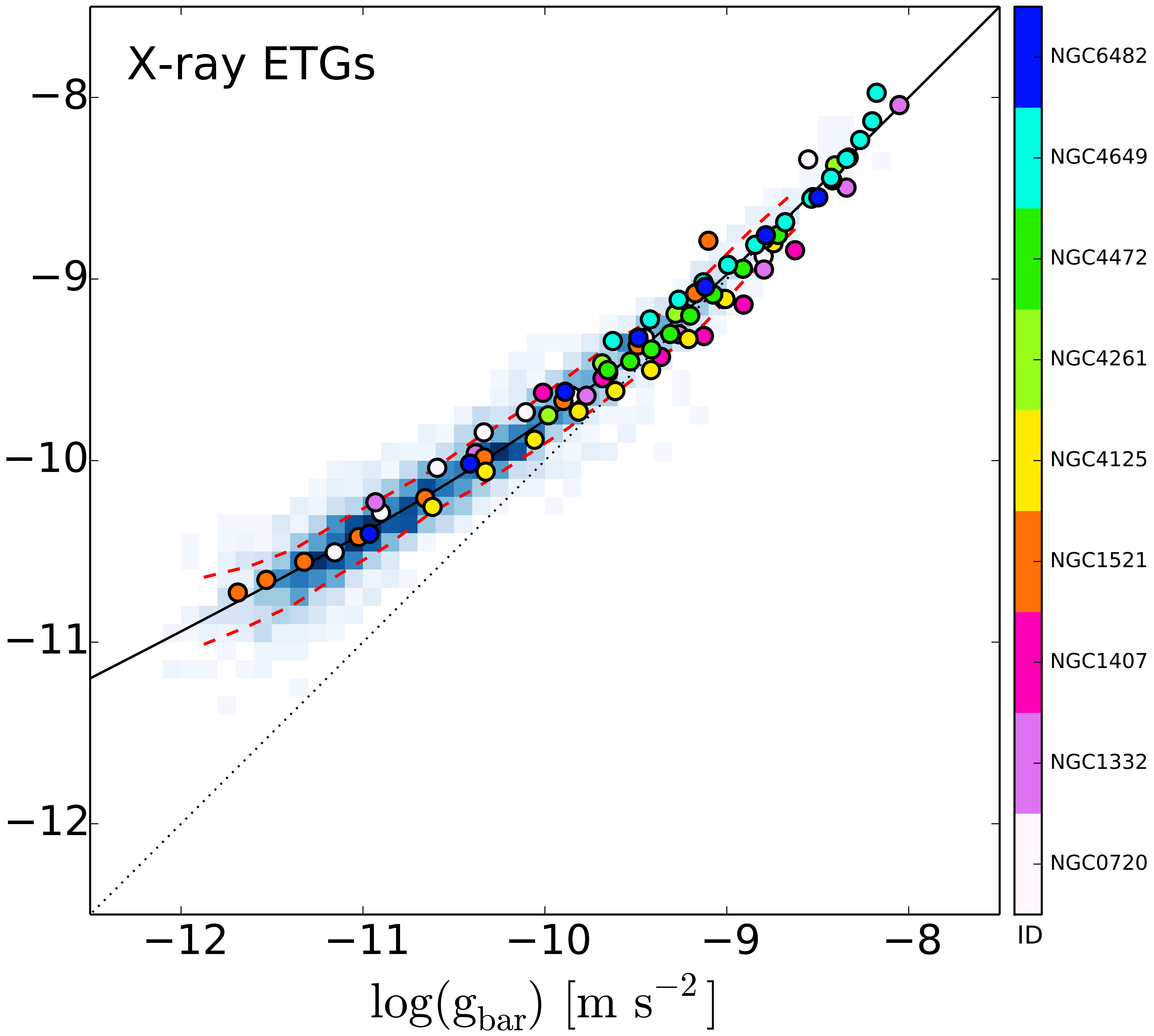
Radial Acceleration Relation in Elliptical galaxies

ATLAS^{3D} data (fast rotators)

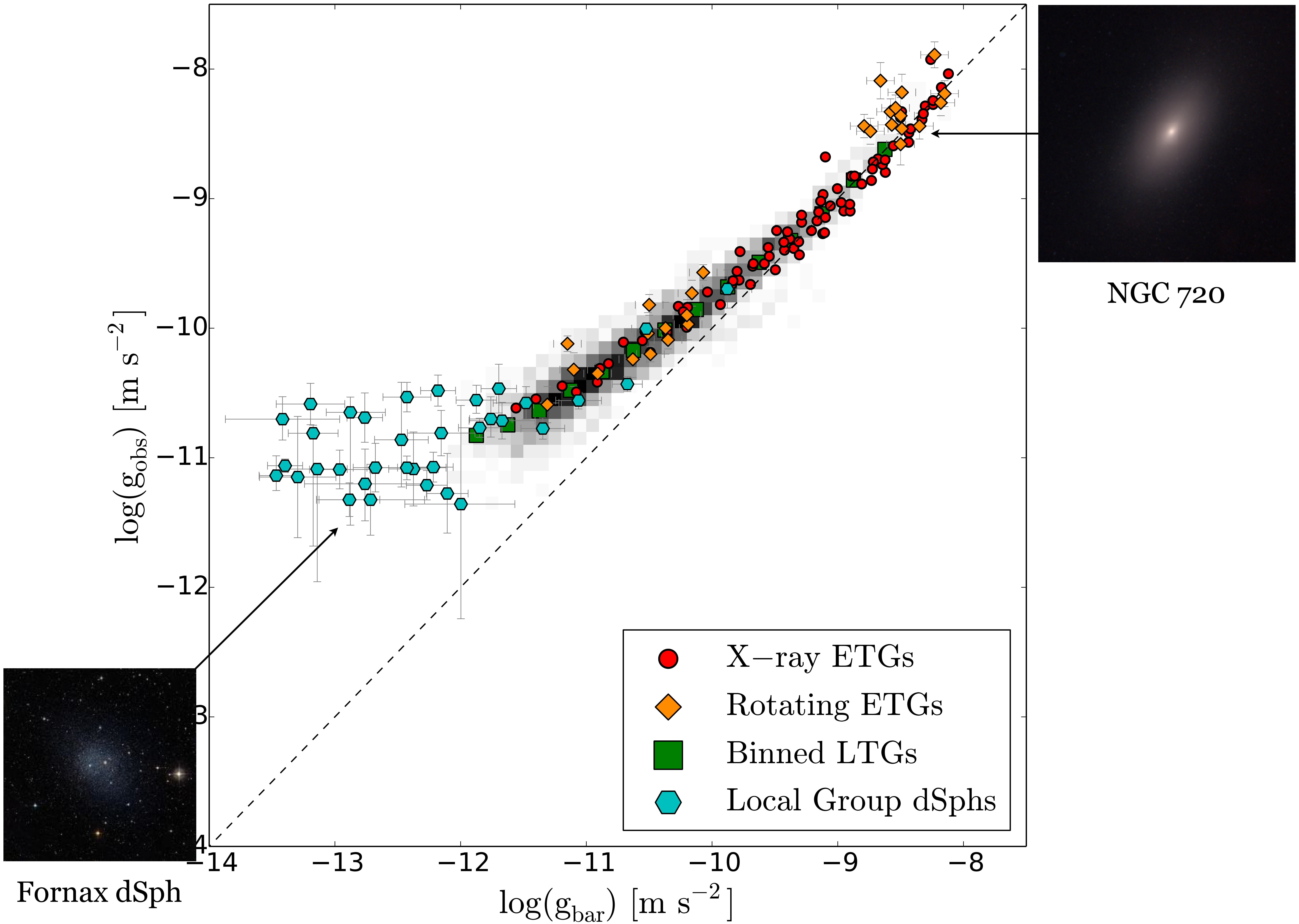


Inner, high acceleration
data from optical IFU
Outer, low acceleration
points from HI 21 cm

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 Halos

Many models; none entirely appropriate

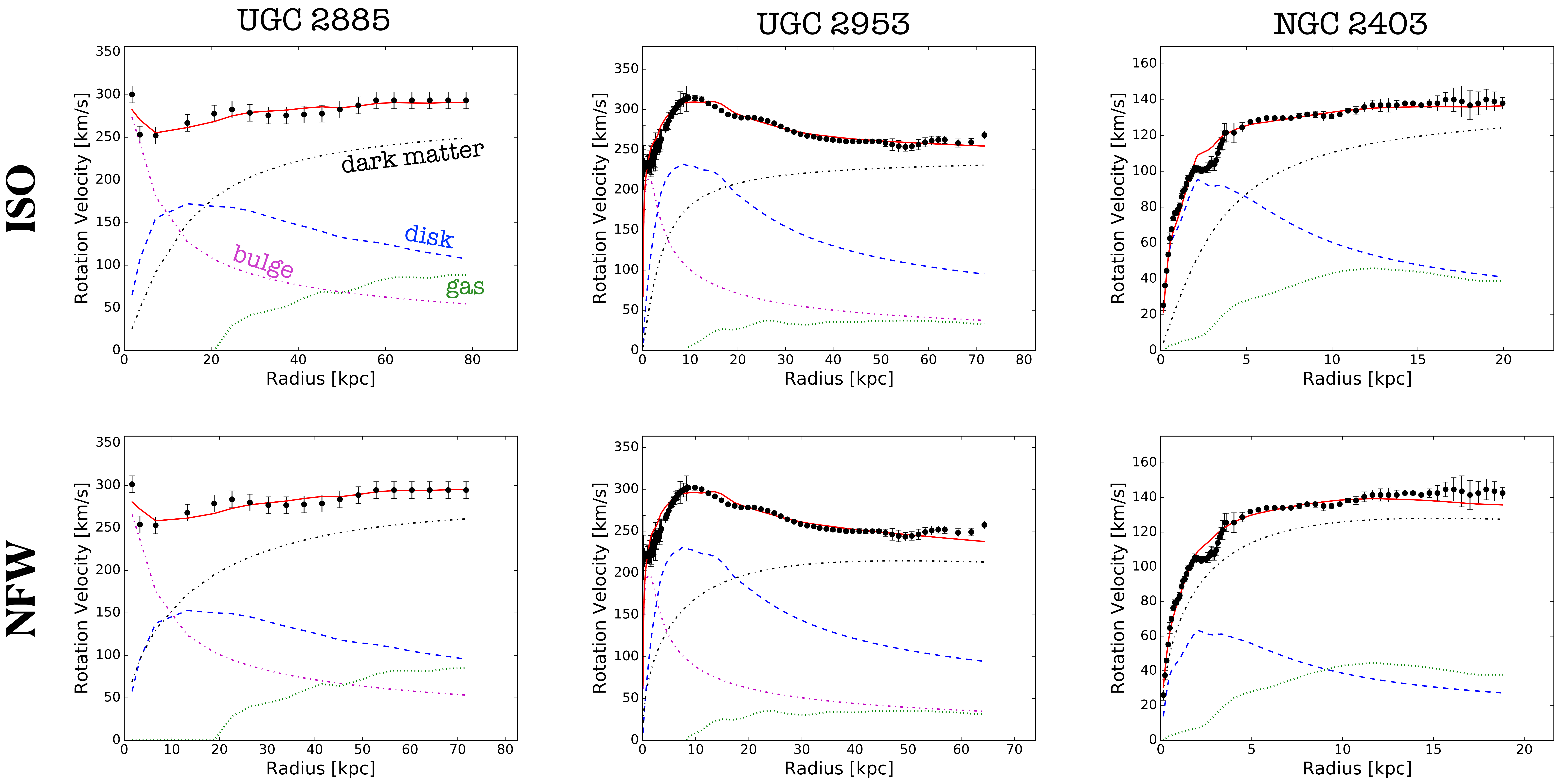
- Pseudo-isothermal
- NFW
- Burkert
- Einasto
- DC14
- coreNFW
- etc. - see Li et al. (2020, ApJS, 247, 31 ; arXiv:2001.10538)

$$V_{\mathrm{iso}}(R) = V_\infty \sqrt{1 - \frac{R_C}{R} \arctan\left(\frac{R}{R_C}\right)} \qquad V_\infty = \sqrt{4\pi G \rho_0 R_C^2}$$

$$V_{\mathrm{NFW}}(R) = V_{200} \sqrt{\frac{\ln(1+cx) - cx/(1+cx)}{x[\ln(1+c) - c/(1+c)]}} \qquad x = \frac{R}{R_{200}} \qquad c = \frac{R_{200}}{R_s}$$

sometimes refer to halos by their “virial” temperature $kT_{vir} \propto \sigma^2$ $\quad \sigma = \frac{1}{\sqrt{3}} V_{200}$

Rotation curve fits: two halo models fit to three galaxies



Cumulative distribution of χ_ν^2 for dark matter halo fits with different Bayesian priors

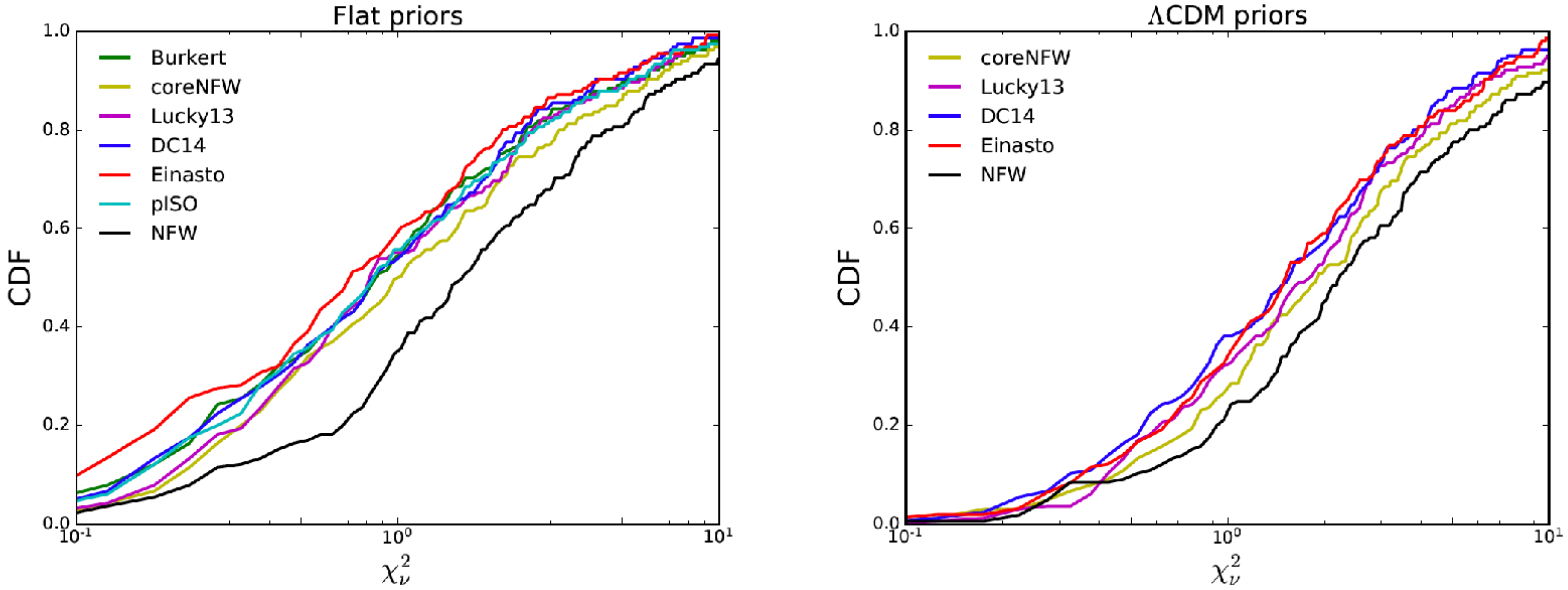


Figure 1. Cumulative distributions of the reduced χ_ν^2 for seven halo profiles with flat (left) and ΛCDM priors (right).

Li et al. (2020)

ΛCDM priors

halo mass-concentration relation

$$c - M_{200}$$

$$V_{\rm NFW}(R) = V_{200}\sqrt{\frac{\ln(1+cx) - cx/(1+cx)}{x[\ln(1+c) - c/(1+c)]}}$$

$$x = \frac{R}{R_{200}} \qquad c = \frac{R_{200}}{R_s}$$

stellar mass-halo mass relation

$$M_* - M_{200}$$

$$M_{200} = B\,V_{200}^3$$

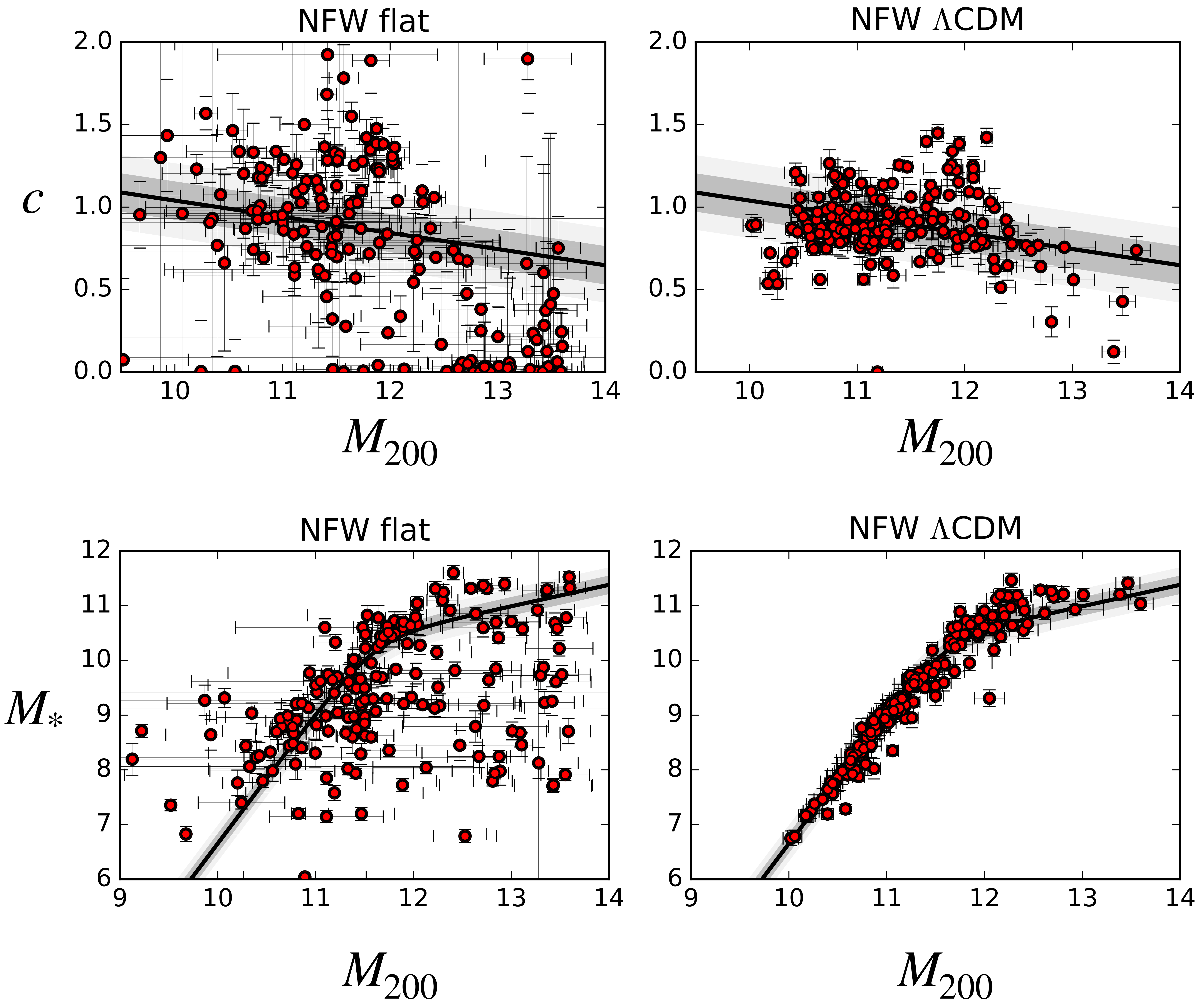
$B = 3.3 \times 10^5\ \mathrm{M_\odot\,km^{-3}\,s^3}$

for $H_0 = 73\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$

- Li et al. (2020, ApJS, 247, 31)

flat priors

LCDM priors



ΛCDM priors

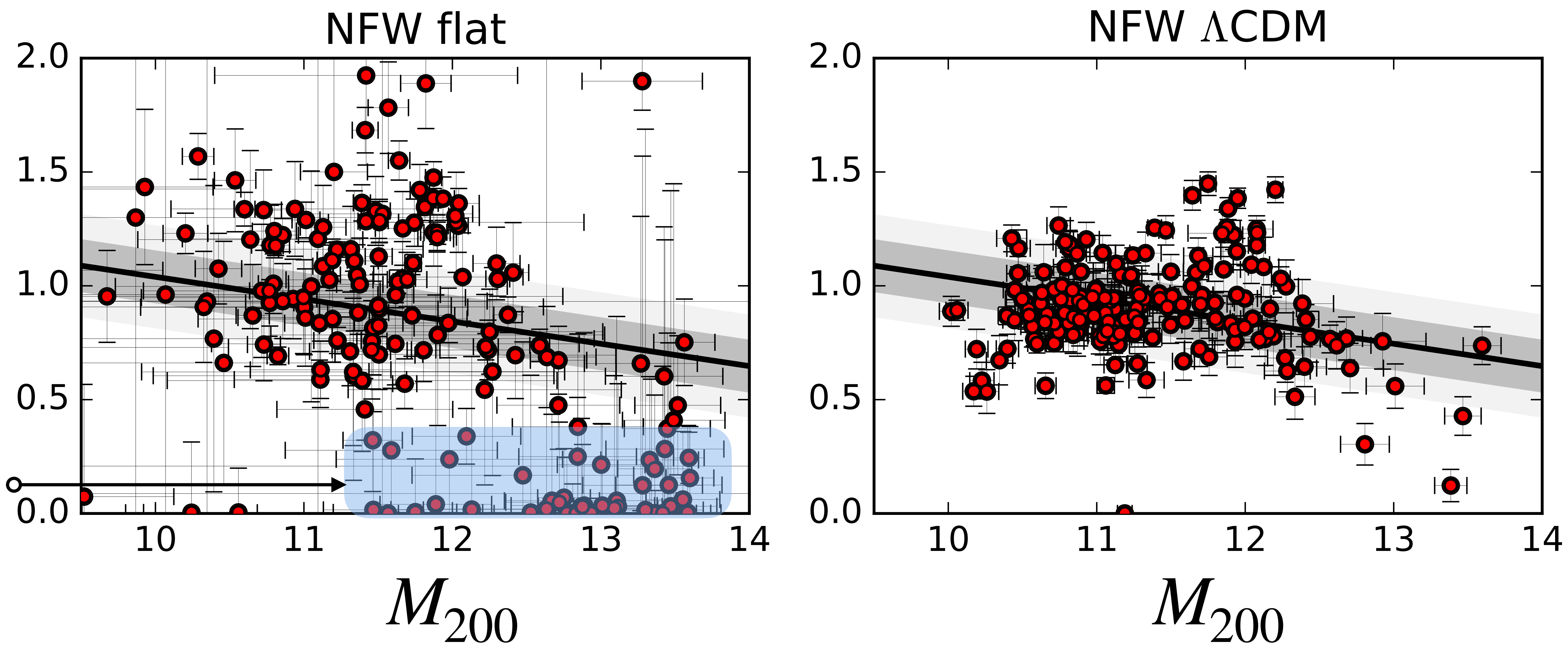
flat priors

LCDM priors

halo mass-concentration relation

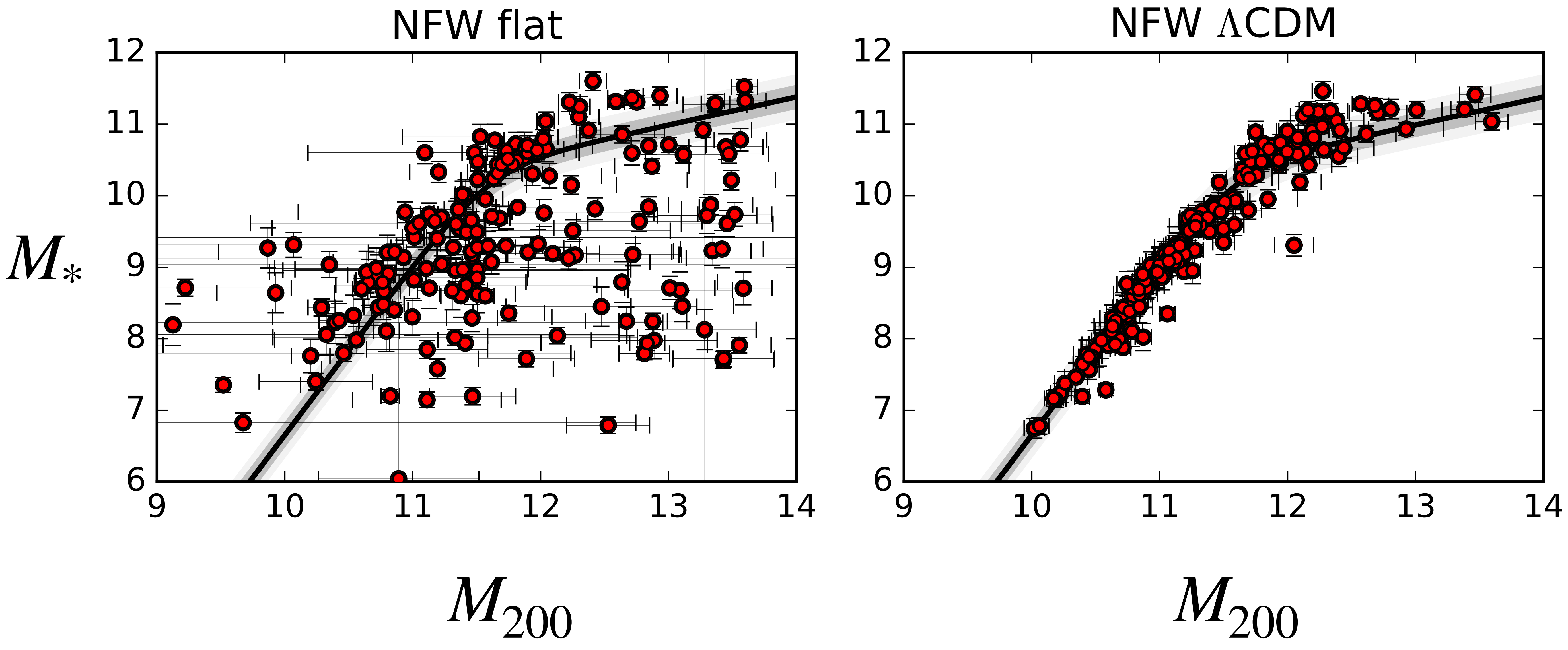
$c - M_{200}$

cusp-core problem



stellar mass-halo mass relation

$M_* - M_{200}$



- Li et al. (2020, ApJS, 247, 31)

Radial Acceleration Relation

The observed acceleration correlates
with that predicted by the baryons

The data are well fit by

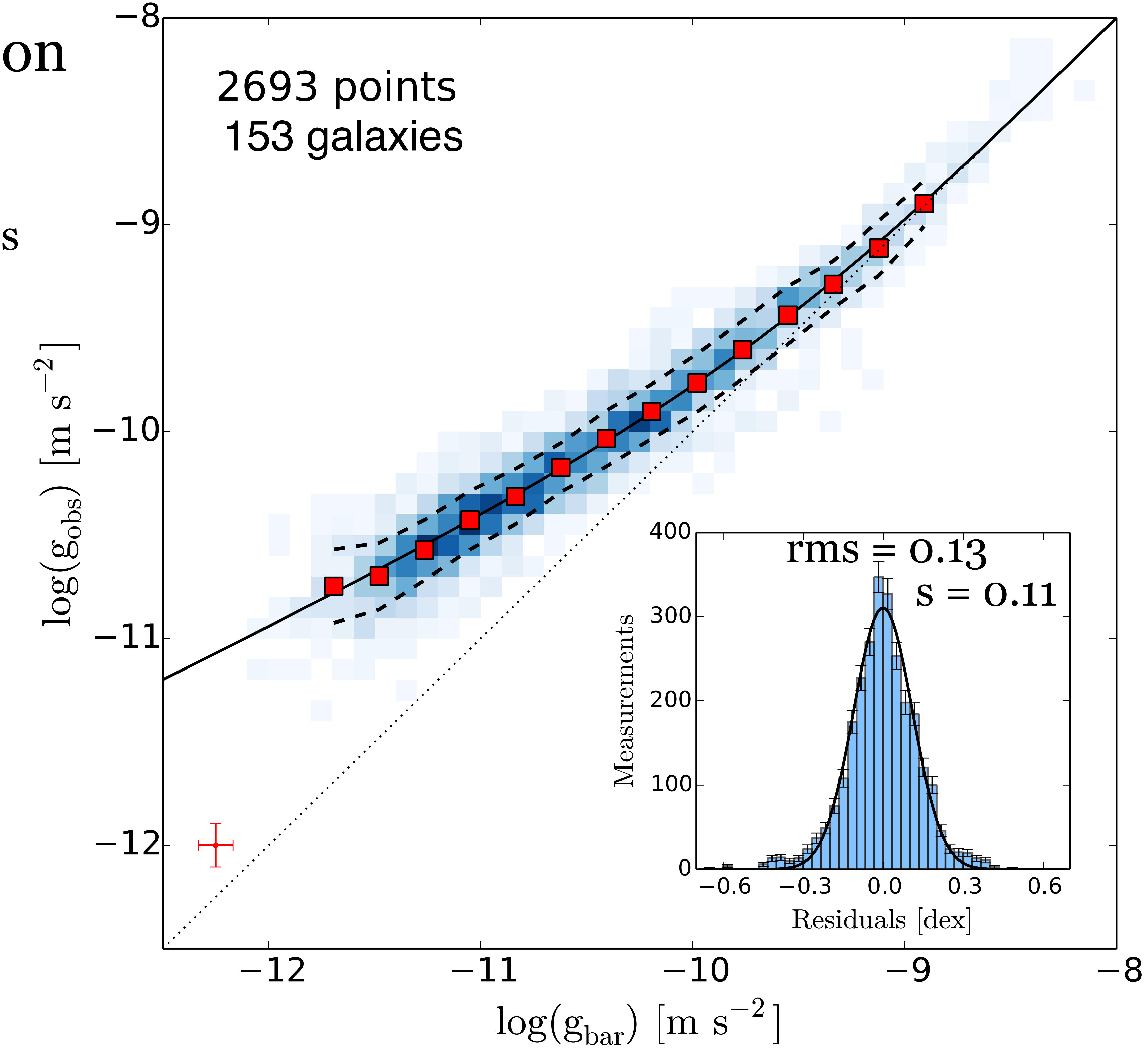
$$g_{\rm obs} = \frac{g_{\rm bar}}{1 - e^{-\sqrt{g_{\rm bar}/g_\dagger}}}$$

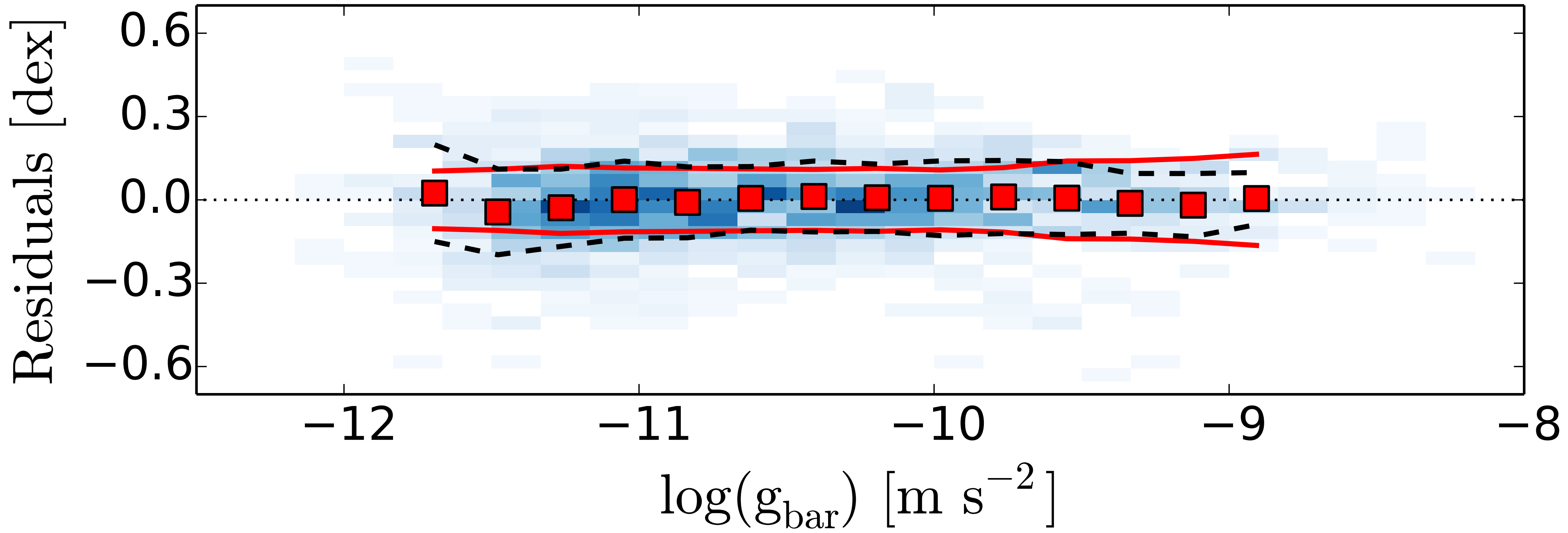
$$g_\dagger = 1.20 \times 10^{-10}\ \mathrm{m\,s^{-2}}$$

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

Lelli et al. (2017)
McGaugh et al. (2016)

That means the dark matter
acceleration is predicted by the baryons





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

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

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

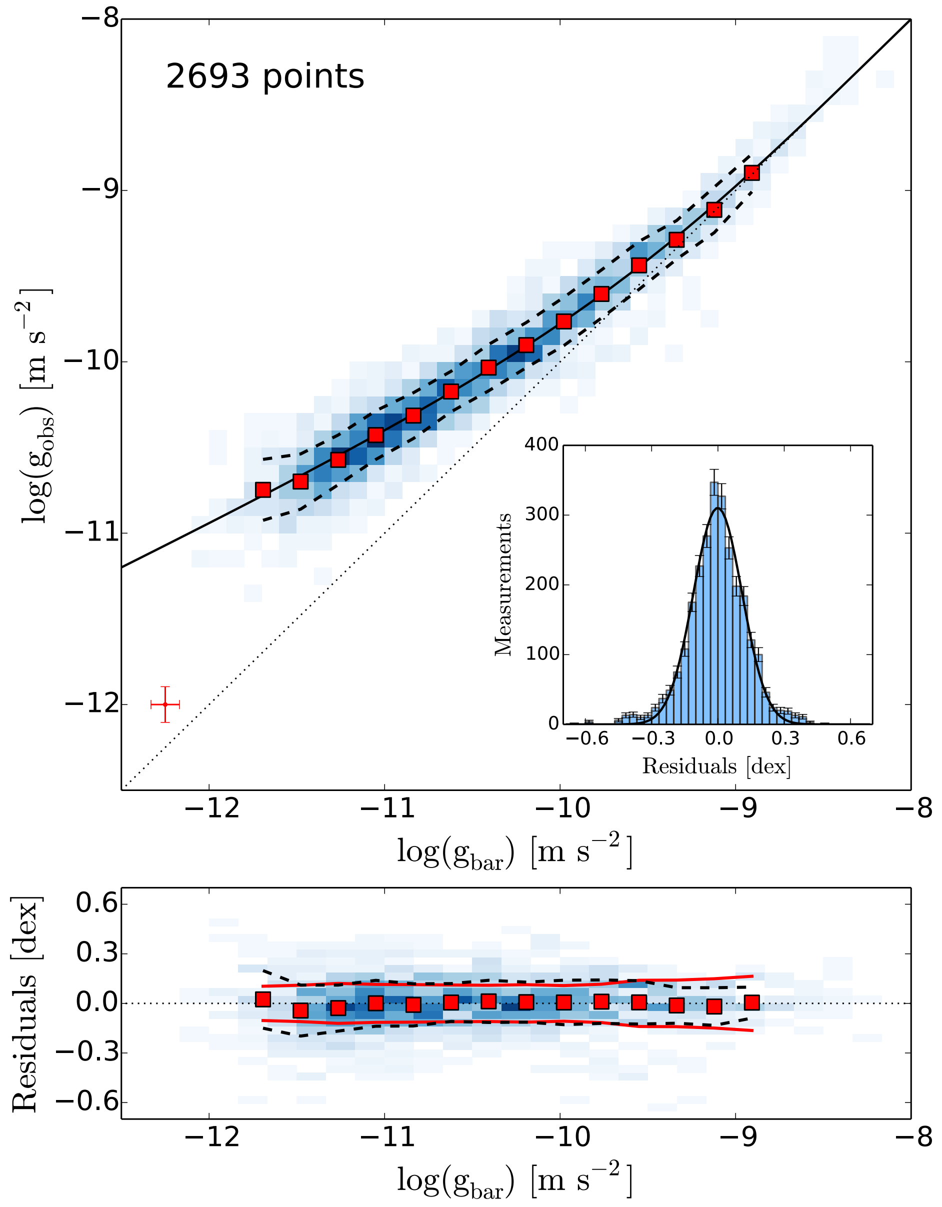
dark matter $$g_{\rm DM} = g_{\rm obs} - g_{\rm bar}$$

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

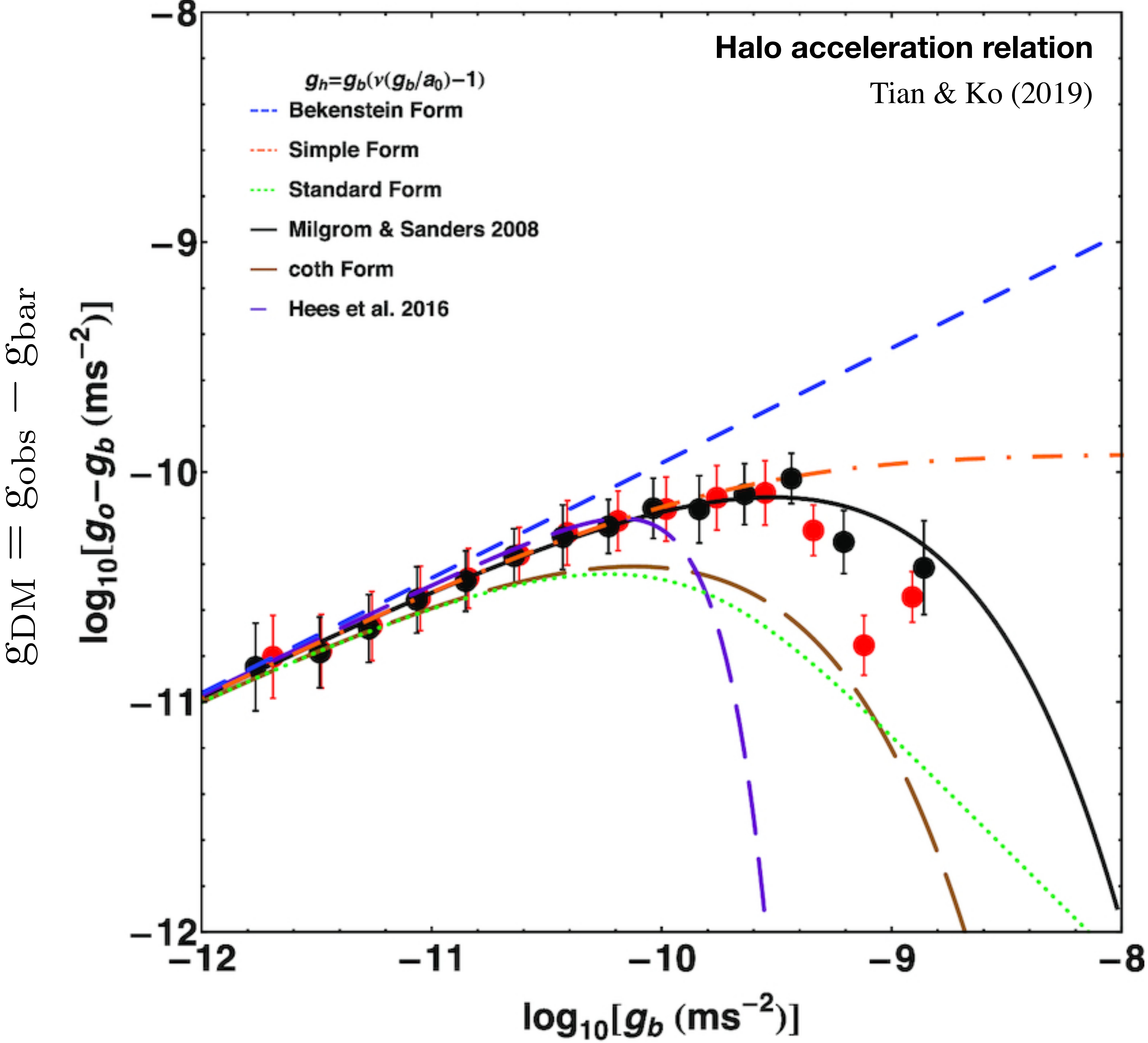
$$\pm 0.02\ ({\rm random}) \pm 0.24\ ({\rm systematic})$$

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

The dark matter distribution is specified by the baryon distribution



That's weird



There is a maximum acceleration that can be provided by

Dark Matter halos

$$g_{DM} \lesssim g_{\dagger}$$

Brada & Milgrom (1999)

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:

$$\mathrm{g}_{\mathrm{obs}} = \mathcal{F}(\mathrm{g}_{\mathrm{bar}})$$

$$\mathrm{g}_{\mathrm{DM}} = \mathcal{F}(\mathrm{g}_{\mathrm{bar}}) - \mathrm{g}_{\mathrm{bar}}$$

Galaxy Formation

A many faceted problem
(sort of like Cthulhu being a multi-tentacled nightmare cult god)

Competition between gas accretion (to form disks) and lumpy fragments (forms spheroids, substructure)

Monolithic galaxy formation

collapse of one big gas cloud

(e.g., Eggen, Lynden-Bell, & Sandage 1962)

Hierarchical galaxy formation

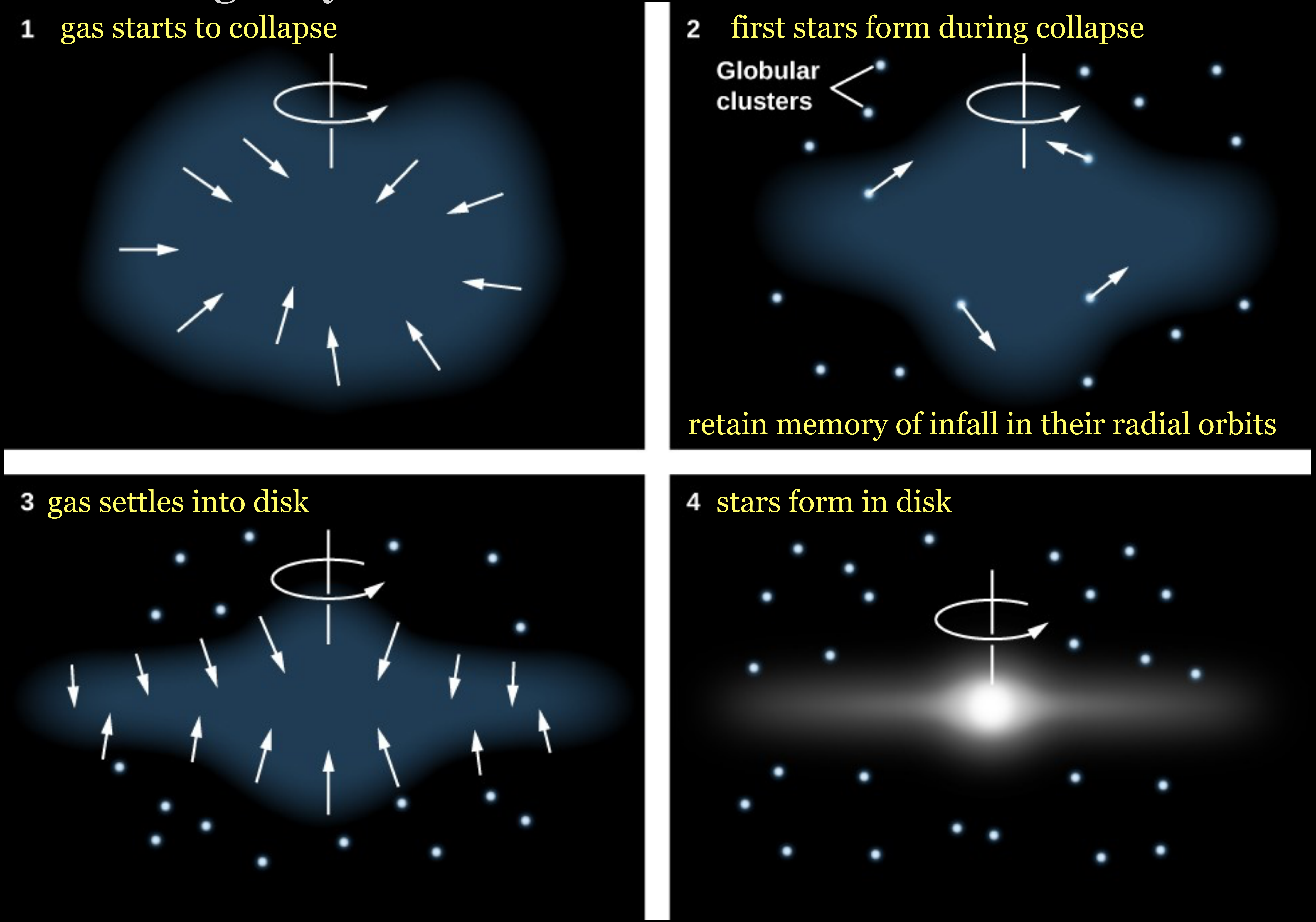
"bottom up" formation from sequence of mergers

(big galaxies are built up with small galaxies - modern picture with CDM)

Searle-Zinn (1978) fragments:

"…halo [globular] clusters originated within transient protogalactic fragments that gradually lost gas while undergoing chemical evolution and continued to fall into the Galaxy after the collapse of its central regions had been completed."

Monolithic galaxy formation



gas starts to collapse

first stars form during collapse

retain memory of infall in their radial orbits

gas settles into disk

stars form in disk

plane of disk specified by initial angular momentum

Good at forming spiral galaxies

Hierarchical galaxy formation
(bottom up -
not monolithic)

Small objects conglomerate to make big ones

Gas dissipates and cools to form thin disks.

Stars cannot cool: if hot coming in, stay hot.

merger tree