Observational constraints on disk galaxy formation from Tully-Fisher relation and weak gravitational lensing

Reina Reyes
(Chicago/KICP)

with Jim Gunn (Princeton) and
Rachel Mandelbaum (Princeton/CMU)

IPMU
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Outline

- **Motivation**
- **Observational methods**
  - Sample selection
  - Weak lensing
  - Disk kinematics
- **Observational constraints**
  - Tully-Fisher relation
  - Dynamical-to-stellar(baryonic) mass ratios
  - Halo-to-stellar mass ratios
  - Virial-to-optical velocity ratios
- **Implications** for disk galaxy formation

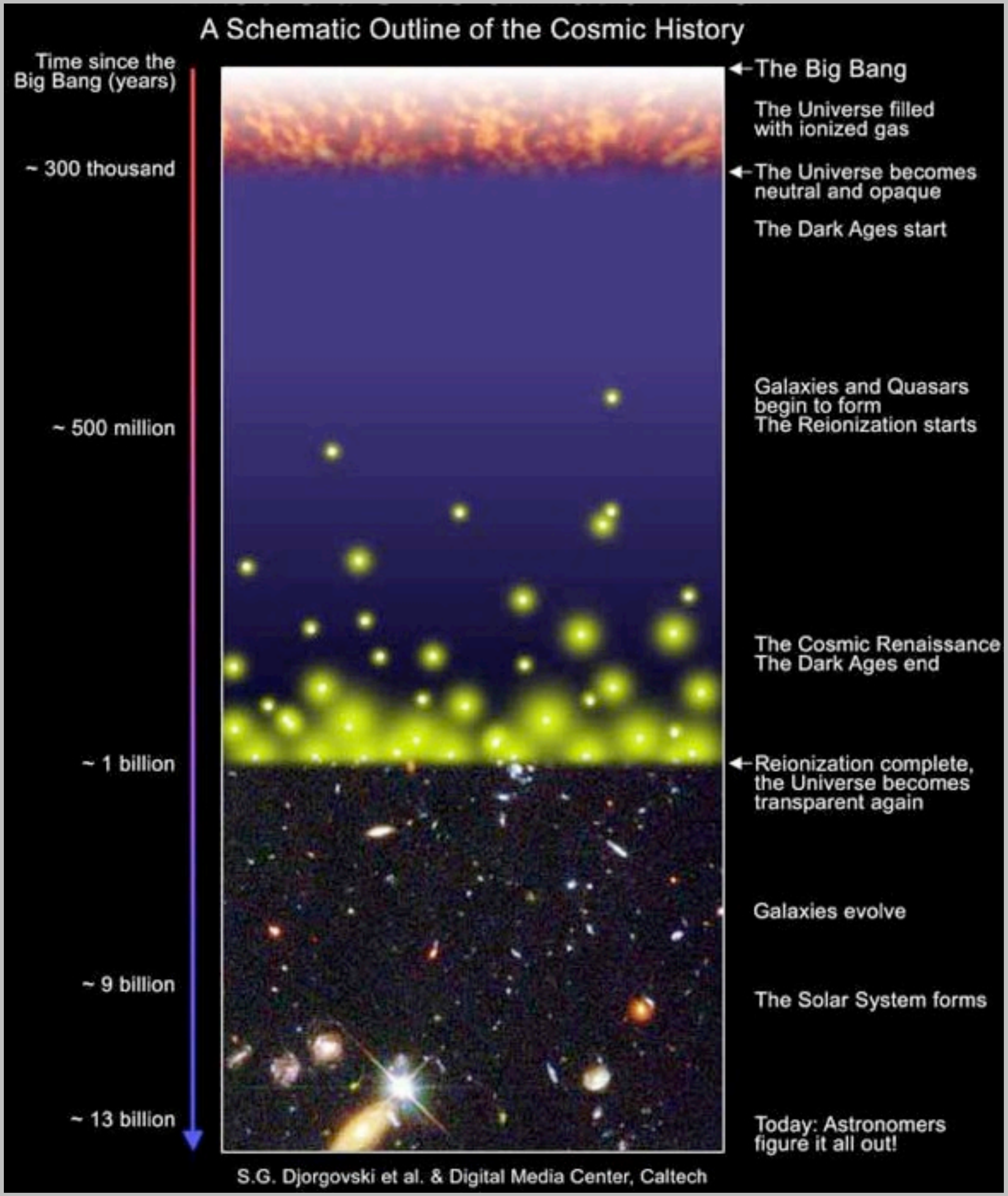
Galaxy formation: The big picture

- Structure grew hierarchically in a LCDM Universe.

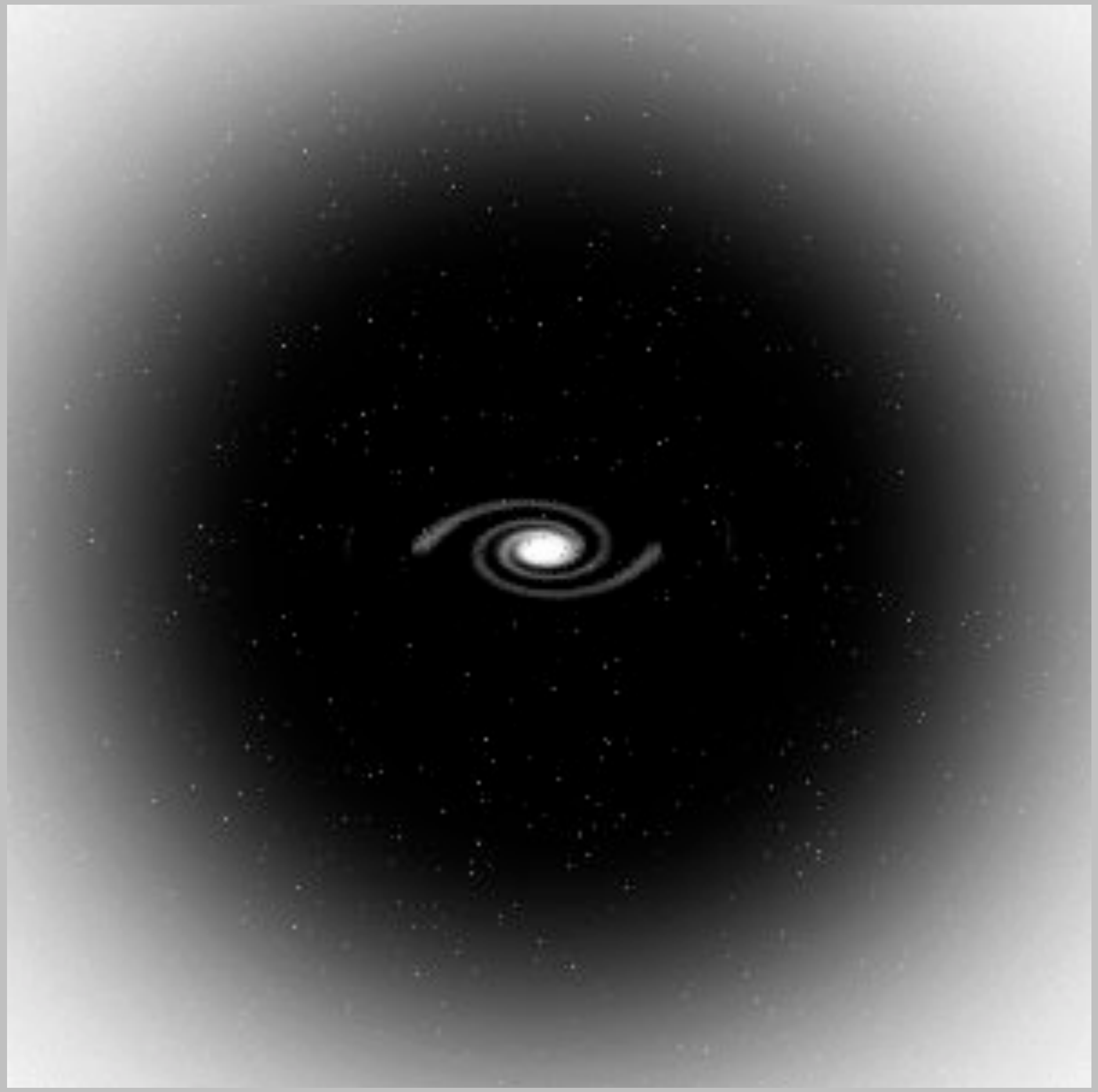
- The **goal** of galaxy formation studies is:

- to explain the observed properties of galaxies

- understand the underlying physical processes



Disk galaxy formation:
The basic picture



Dark matter and gas acquire angular momentum via tidal torques in the early universe.

Gas cools and condenses to form galaxies in the centers of cold DM haloes.

Angular momentum halts the collapse to form rotationally-supported disks.

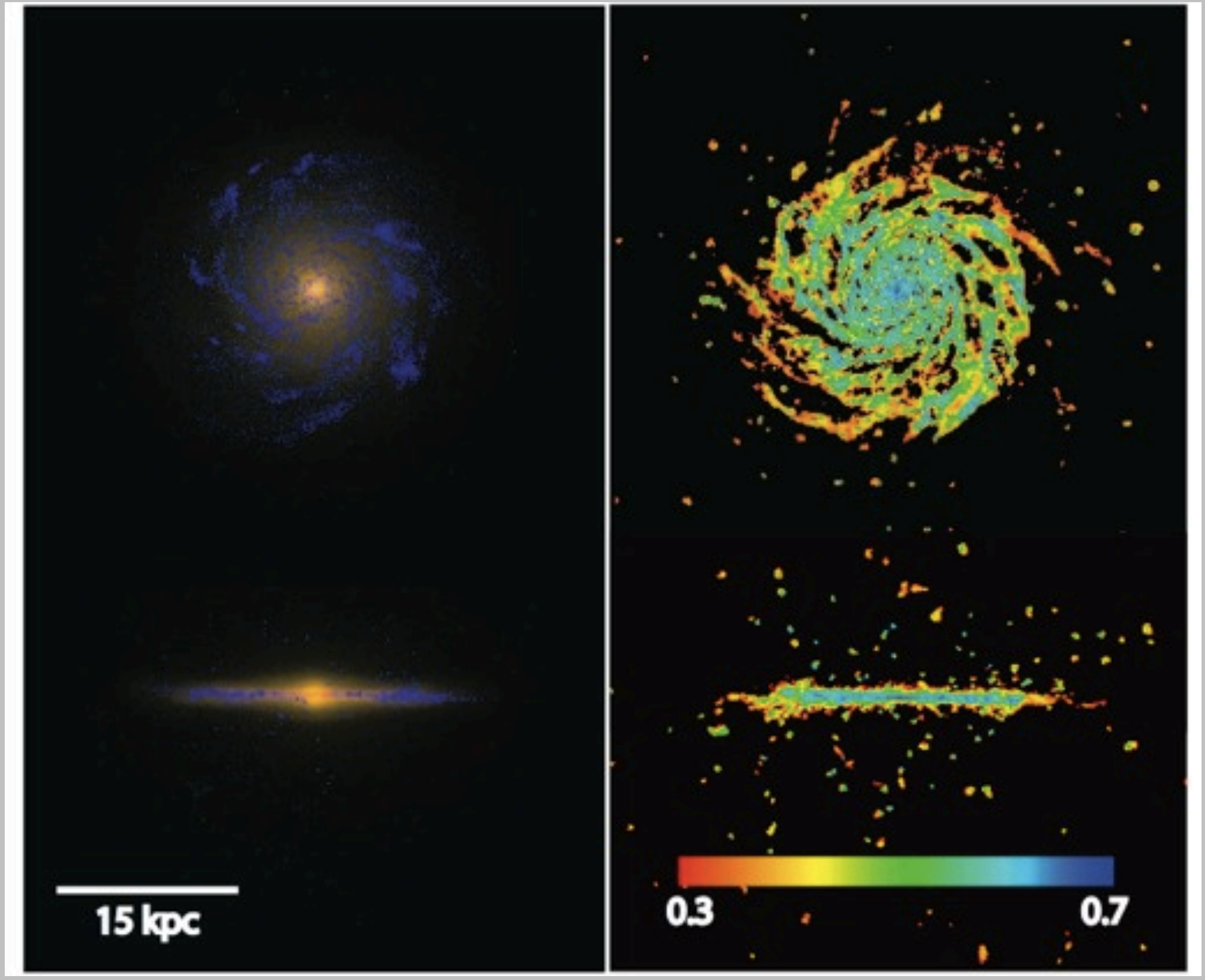
White & Rees 1978
Fall & Efstathiou 1980
Dalcanton, Spergel & Summers 1997
Mo, Mao & White 1998

Disk galaxy formation: approaches

2 main theoretical approaches to galaxy formation:

- Hydrodynamic simulations
(e.g. Governato et al. 2010, Guedes et al. 2011, Brook et al. 2011, Agertz et al. 2011)

- Semi-analytical modeling
(e.g., Benson & Bower 2010)



“Eris” simulation (Guedes et al. 2011)

Disk galaxy formation: approaches

2 main theoretical approaches to galaxy formation:

- Hydrodynamic simulations
- Semi-analytical modeling

In both cases:

- Several physical processes remain **poorly understood** (e.g., cooling, SF, feedback, angular momentum transfer, halo contraction).
- Observations are needed to **test** theoretical models.

Disk galaxy formation: approaches

2 main theoretical approaches to galaxy formation:

- Hydrodynamic simulations
- Semi-analytical modeling

A *third* approach:

- Semi-empirical modeling

  (e.g. Dalcanton, Spergel & Summers 1997, Mo, Mao & White 1998, Dutton et al. 2011, Reyes et al. in prep)

Disk galaxy formation: Semi-empirical modeling

- Use set of observational relations as inputs to the model
- Use *another* set of observations to constrain free parameters

Disk galaxy formation: Semi-empirical modeling

- Example: Mass modeling in Dutton et al. (2011)

Mass Model

DM halo
(M_{200}, c_{200},
halo contraction model)
+
stellar disk
(M_*, R_d, D/T, stellar IMF)
+
cold gas disk
(M_{gas}, R_{gas})

Independent constraint

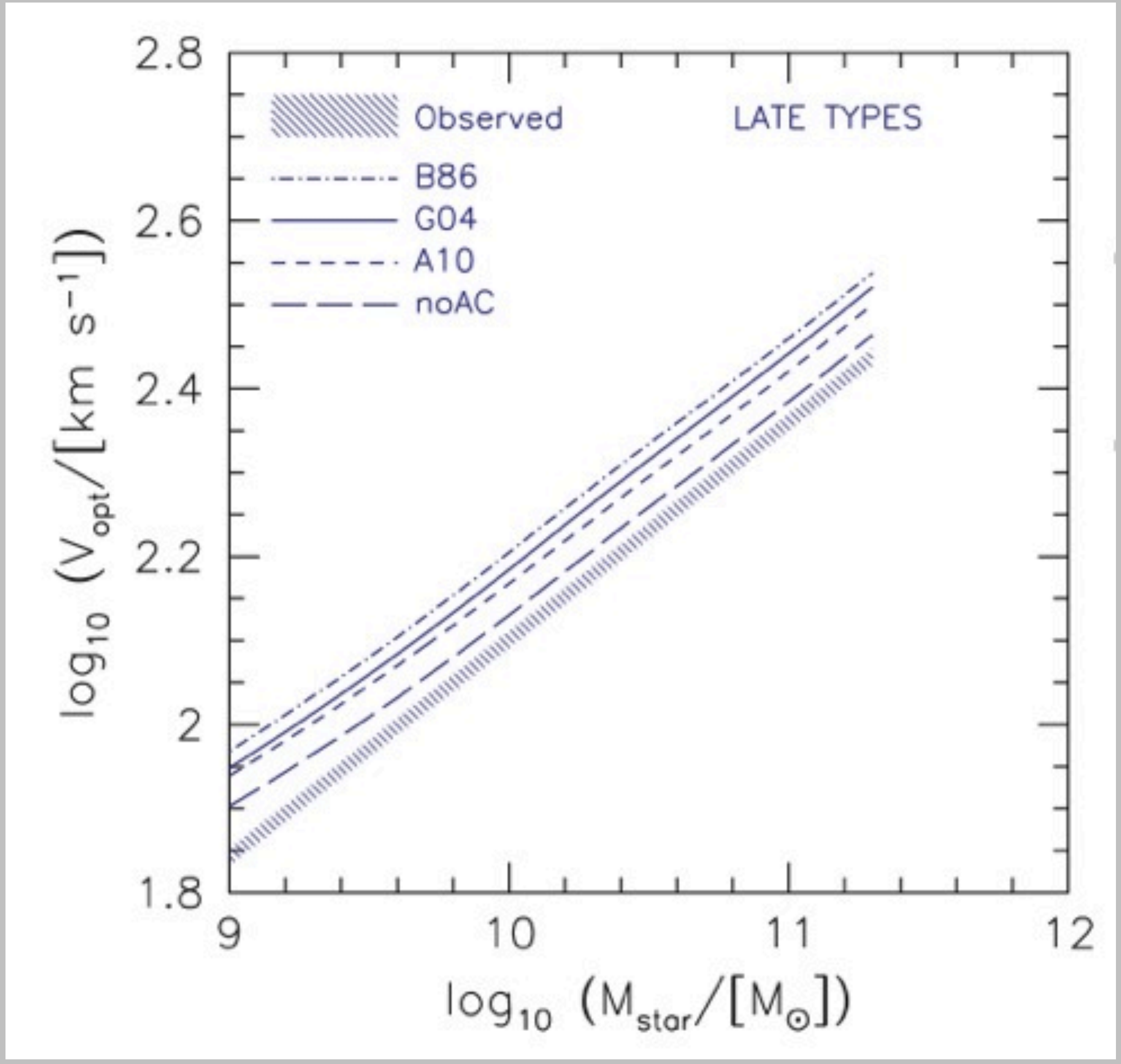
Tully-Fisher relation
(V_{opt} vs. M_*)

Unknowns

- halo contraction model
- stellar IMF

Disk galaxy formation: Semi-empirical modeling

- Example: Mass modeling in Dutton et al. (2011)



Independent constraint

Tully-Fisher relation
(V_{opt} vs. M_*)

Unknowns

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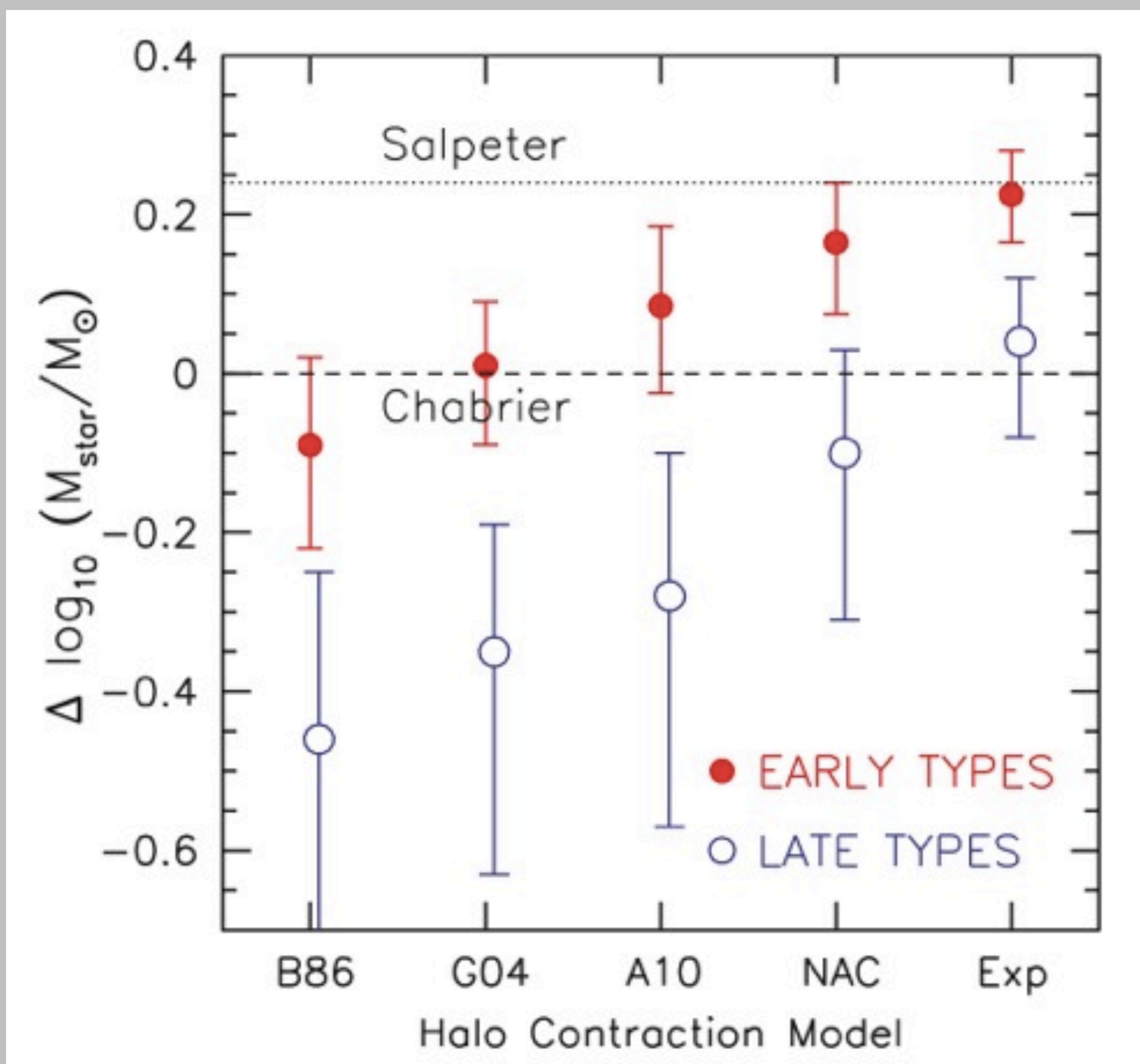
Disk galaxy formation: Semi-empirical modeling

- Example: Mass modeling in Dutton et al. (2011)



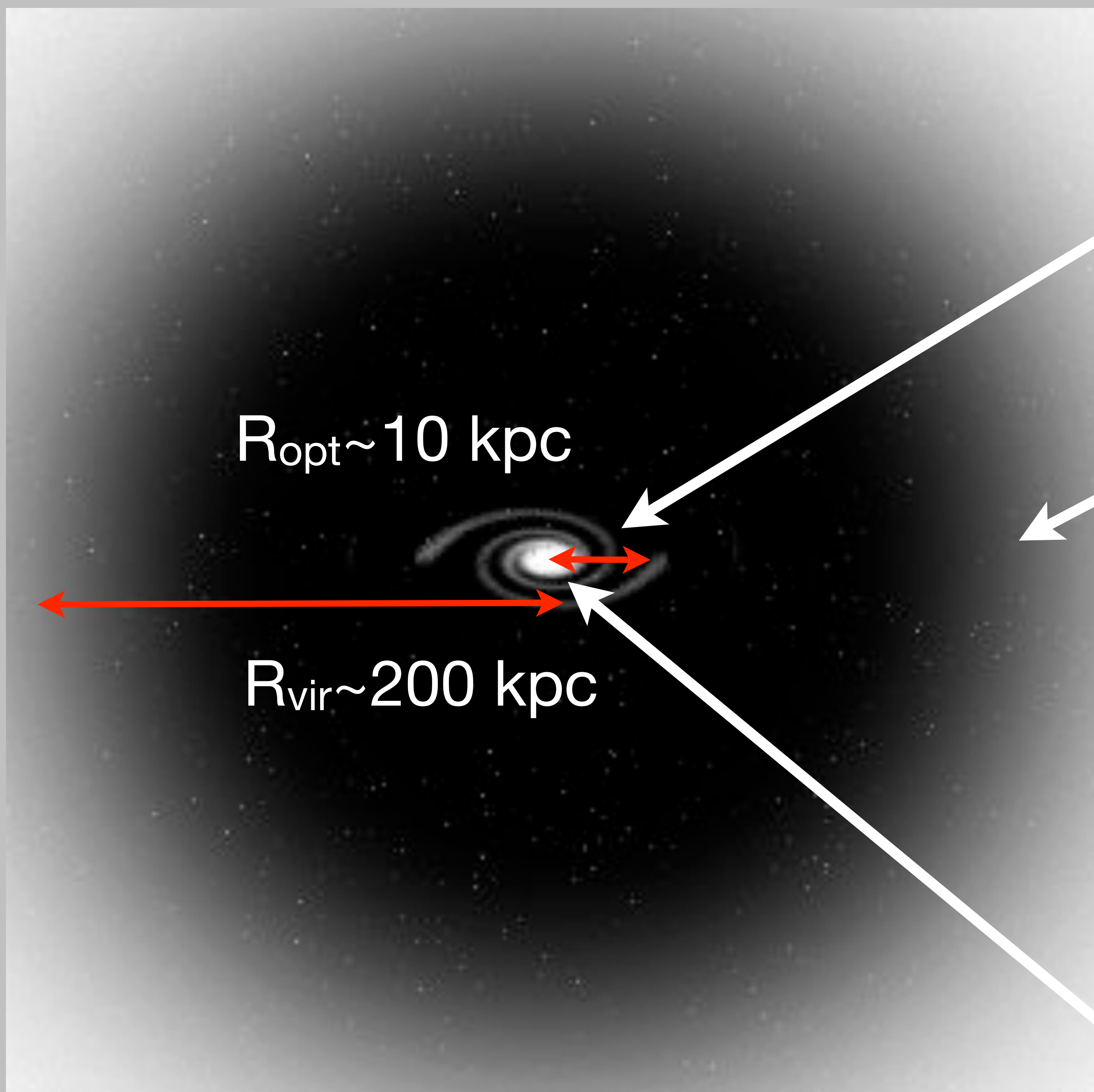
Independent constraint

Tully-Fisher relation
(V_{opt} vs. M_*)

Unknowns

- halo contraction model
- stellar IMF

Disk galaxy formation: observational constraints



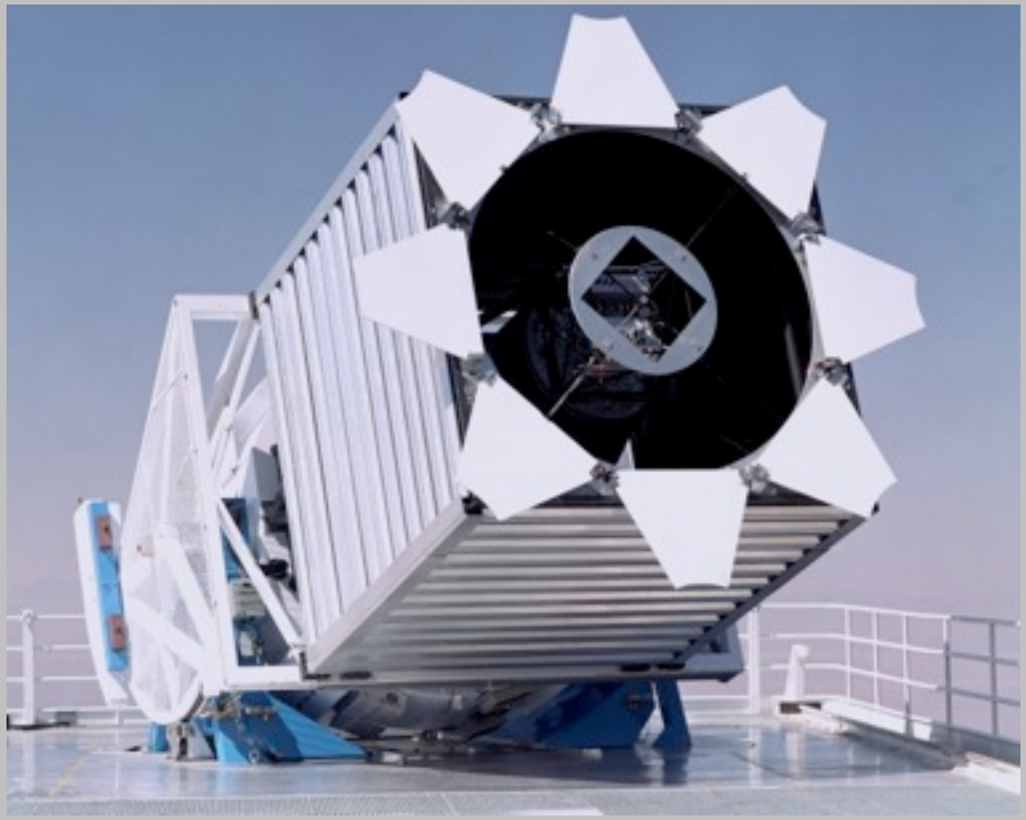
kinematics -> V_{opt} (TFR)

weak lensing
-> DM halo masses

Combined measurement covers large dynamic range in length scales -> constrains the total mass profile (Seljak 2002)

photometry -> M_{star}

Sample selection



SDSS -> parent sample
(~10^5 galaxies)

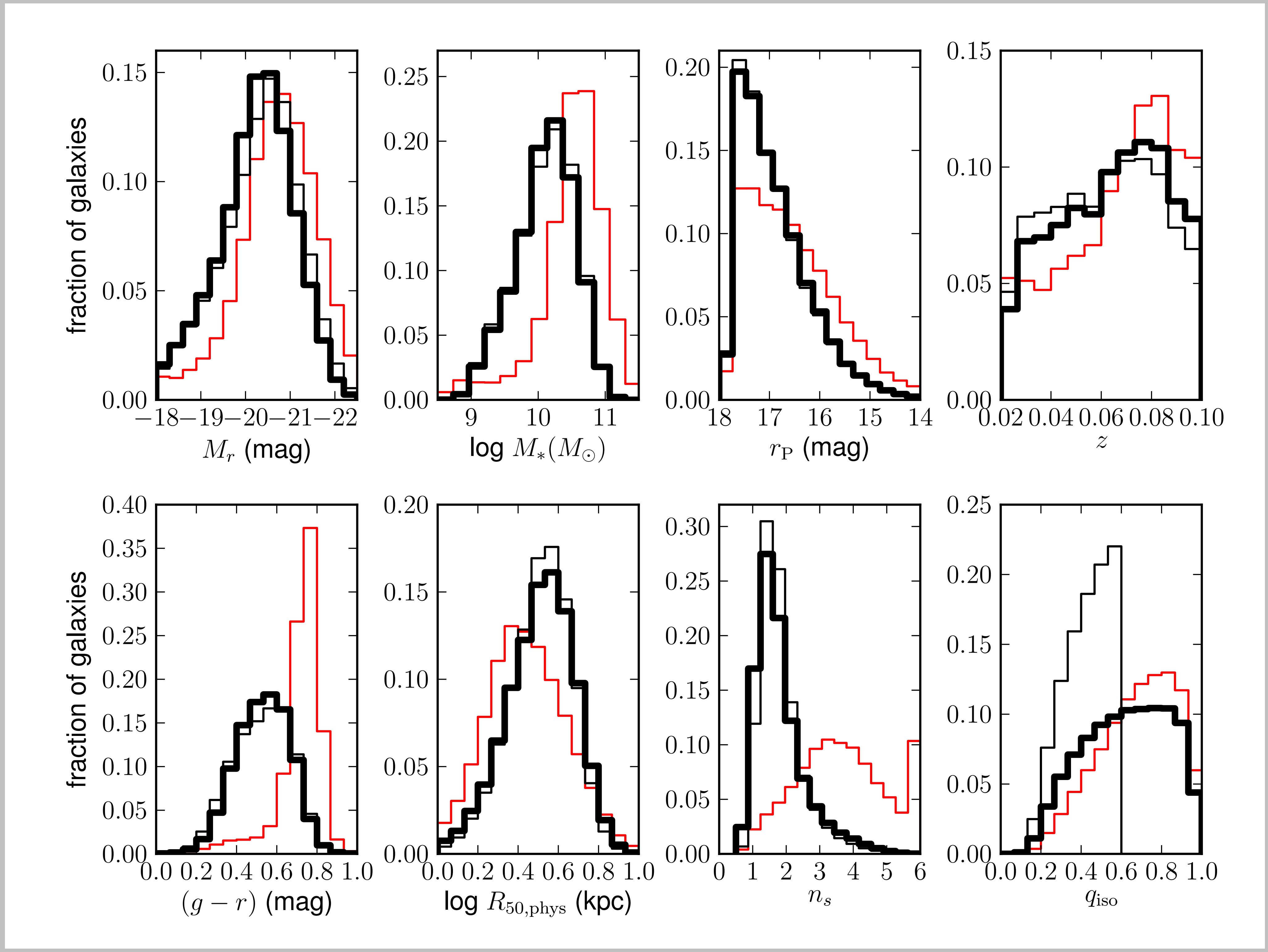
Goal: Define a large sample of disk galaxies adequate for weak lensing analysis.

APO 3.5m -> TFR sample
(~10^2 galaxies)

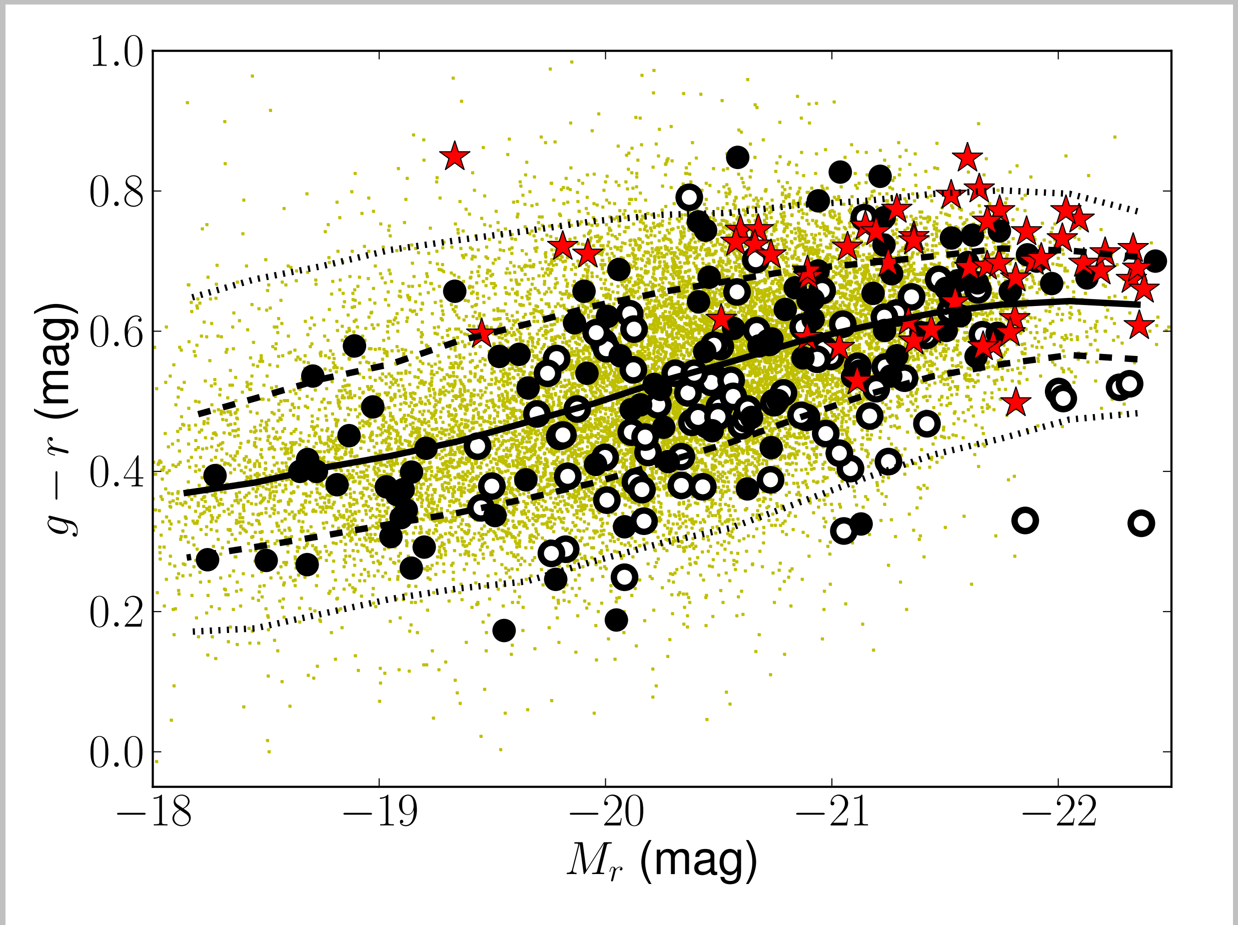
Goal: Define a TFR sample that is a fair subsample of the parent sample.

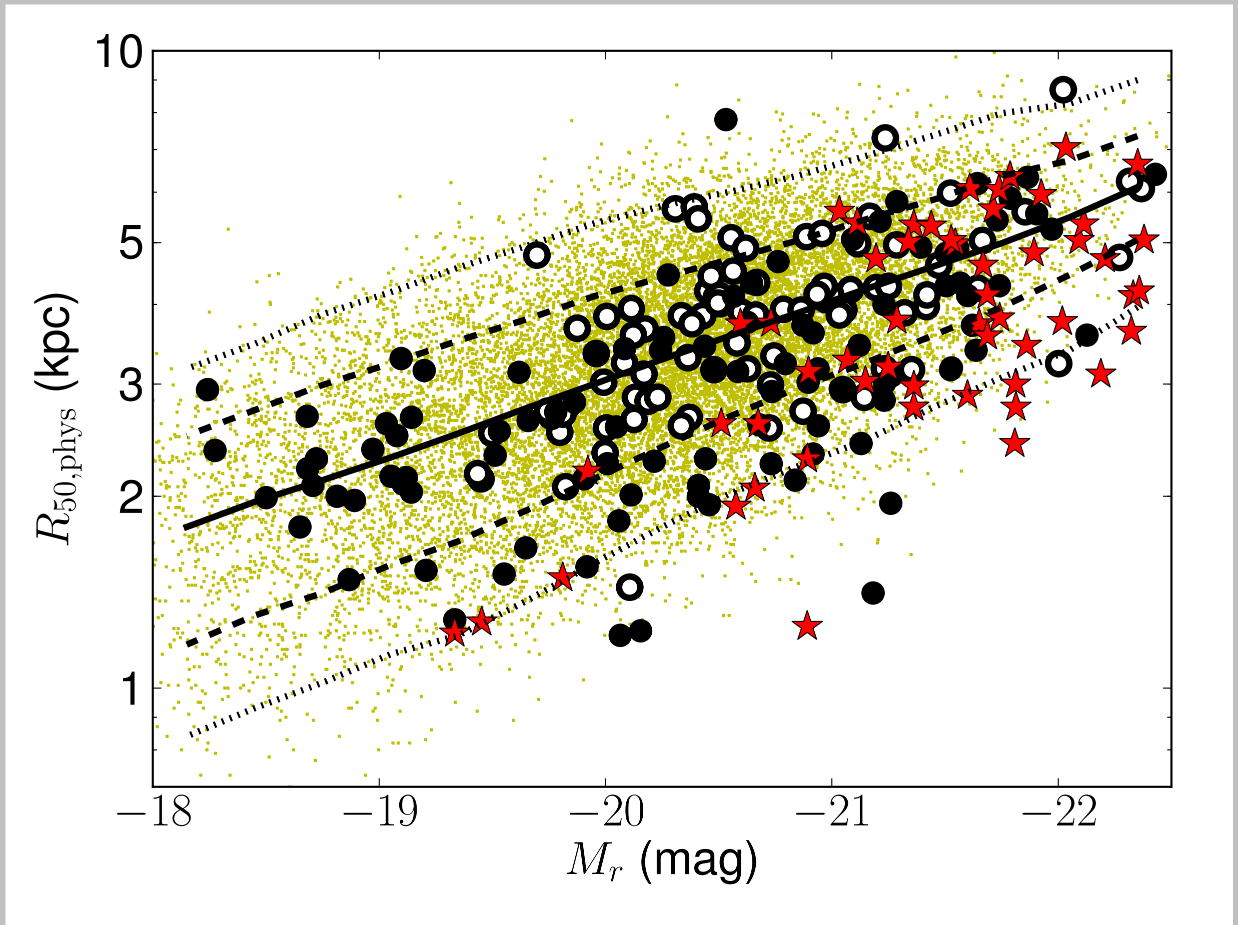
Sample selection

~**176,000** galaxies selected from the SDSS DR7 VAGC



Sample selection

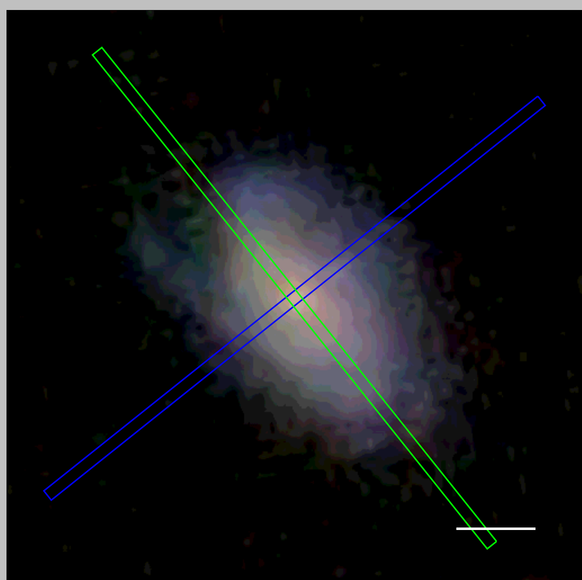


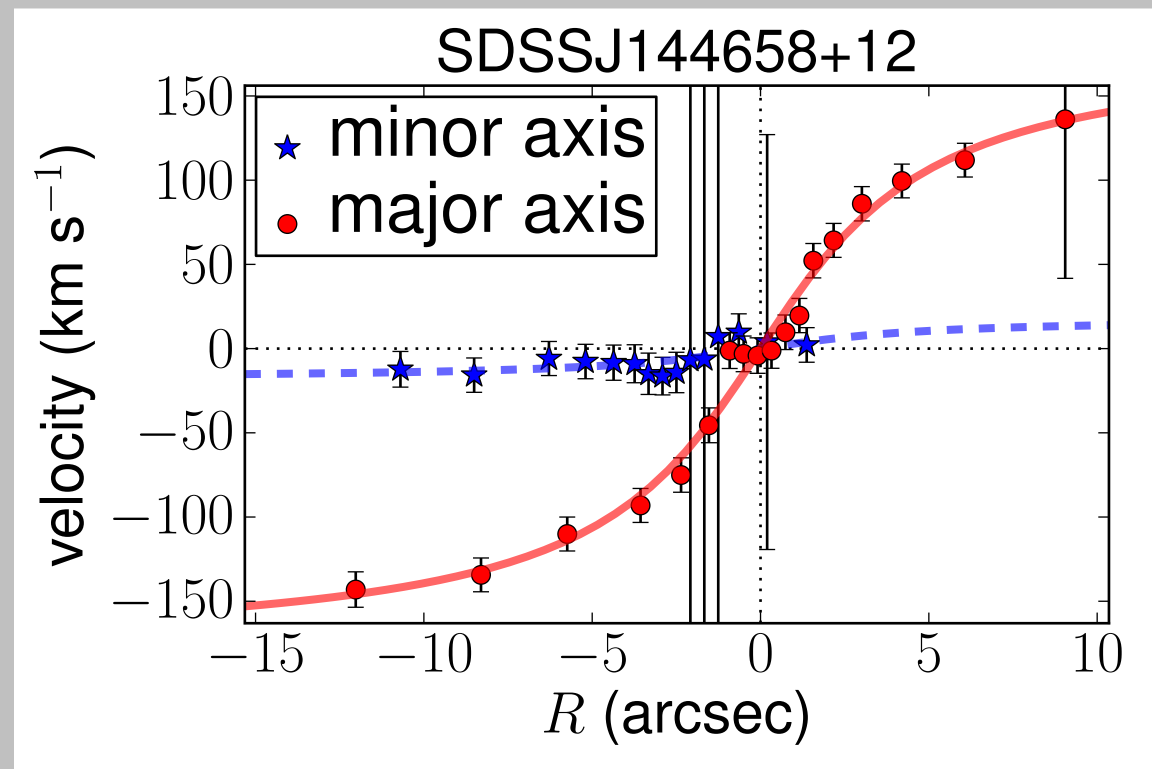


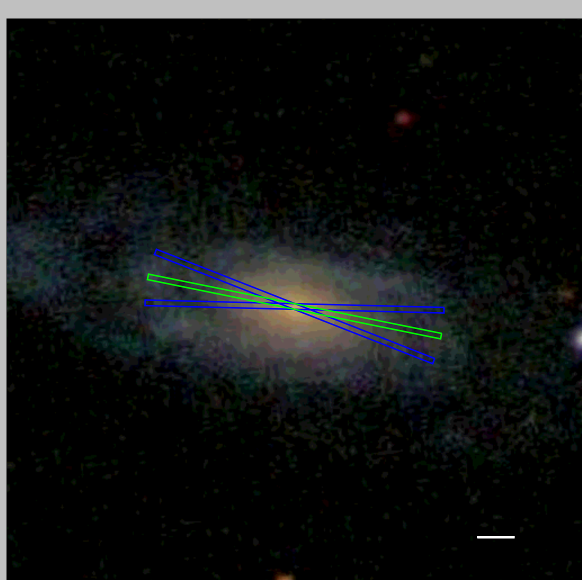
- **189 galaxies** in the TFR sample
  - 99 galaxies from Pizagno et al. (2007)
  - 90 galaxies with new observations

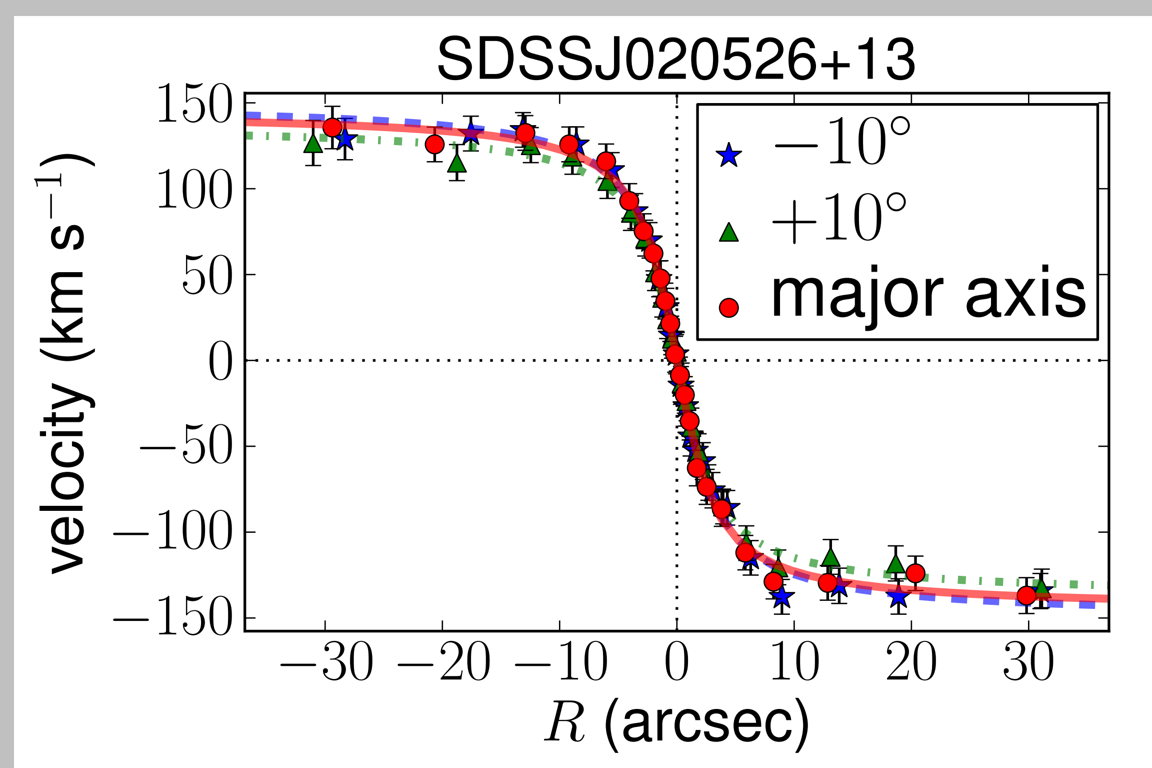
- By construction, a **fair subsample** of the parent disk sample, covering the parameter space in luminosity, g-r color and disk size

Rotation curves







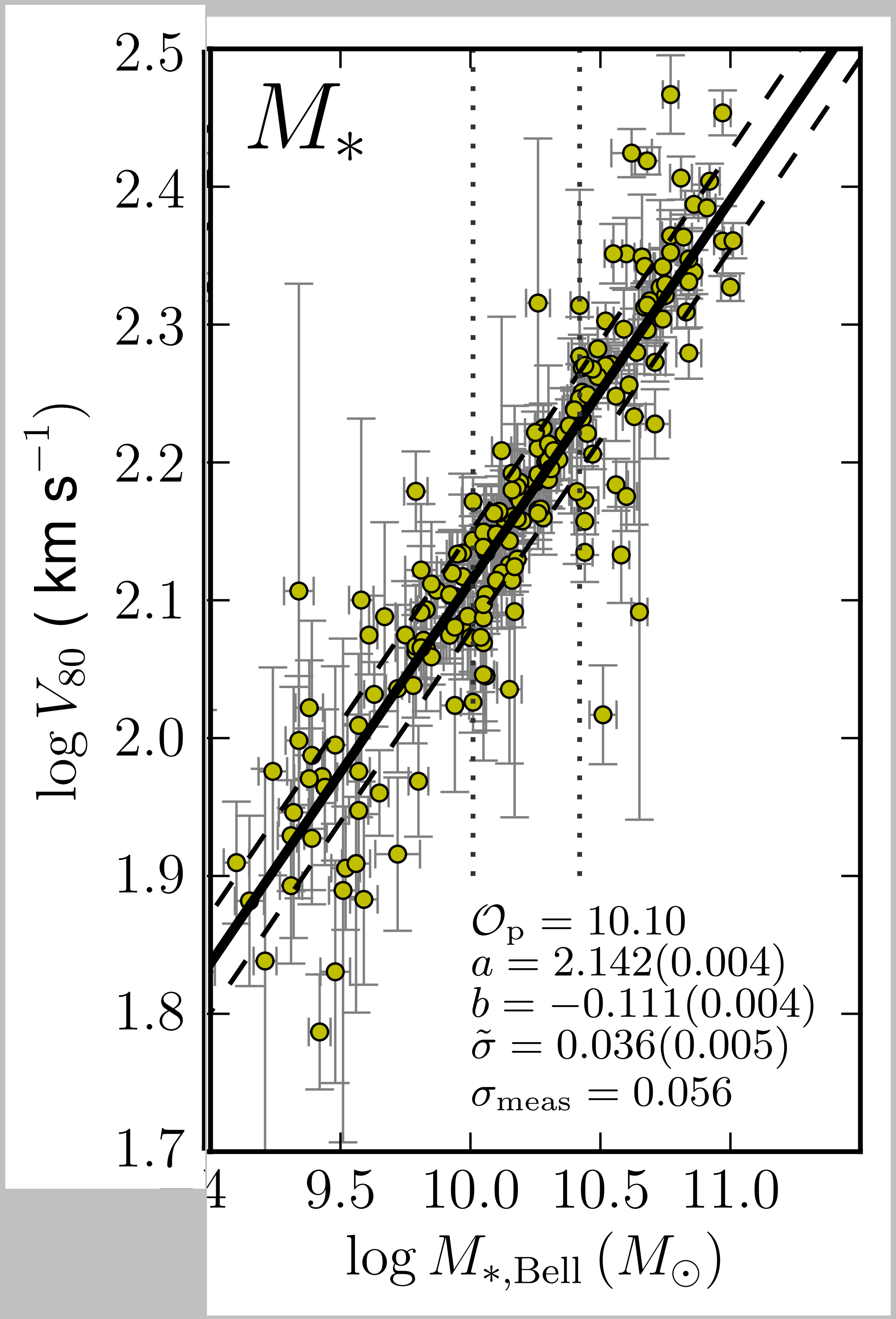


90 galaxies observed for long-slit spectroscopy with DIS at the 3.5m telescope at APO over 25 half-nights.

Arctangent model fits the observed rotation curves adequately for ~99% of the sample.

Define rotation velocity $\mathbf{V_{80}}$.

Tully-Fisher relation



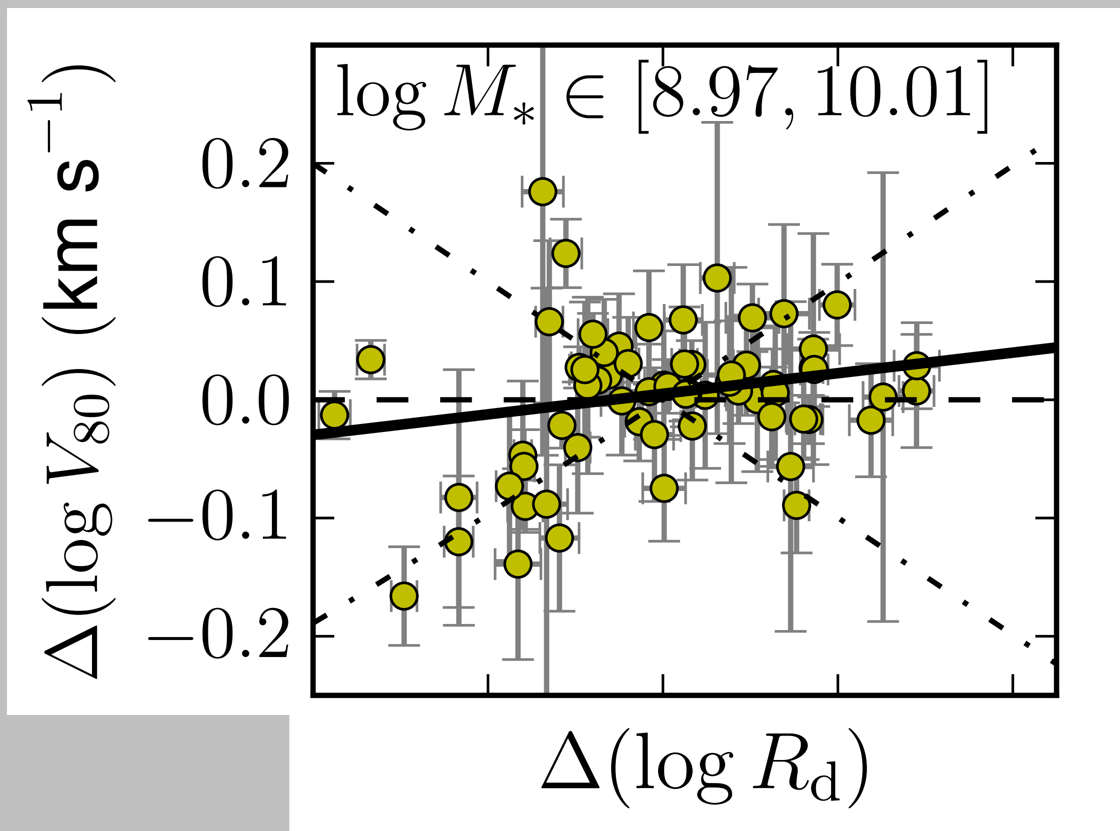
Goal: Find a minimal scatter estimate of rotation velocity.

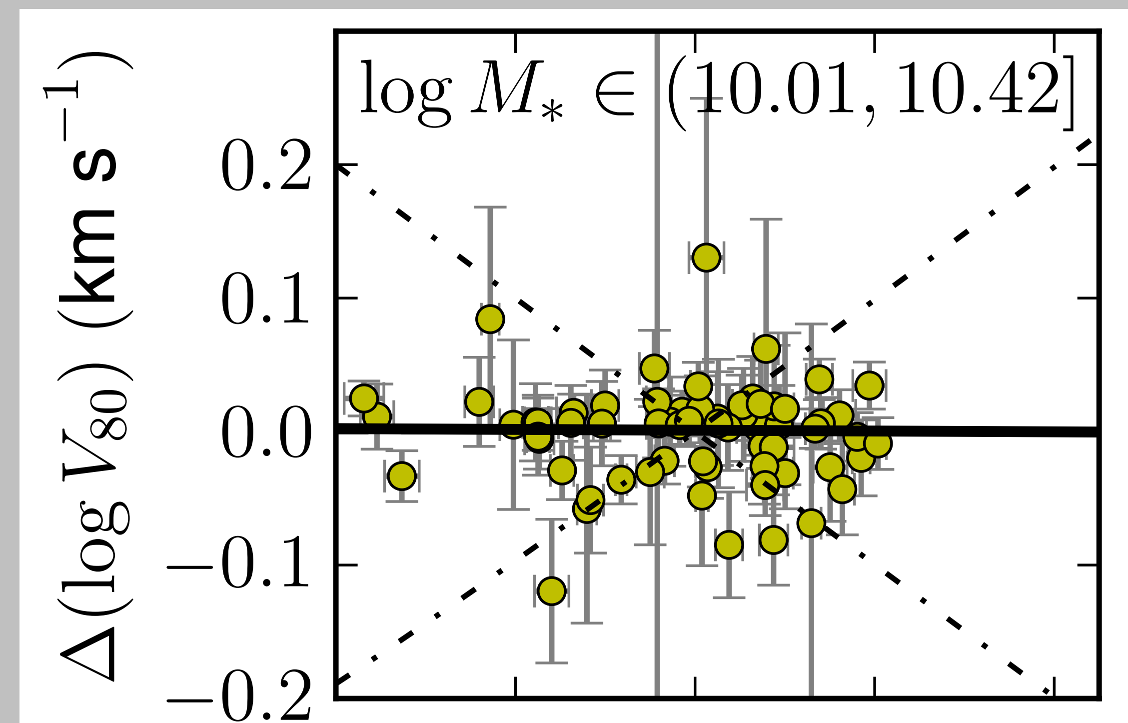
Stellar mass M_{star} (based on Bell et al. 2003 M_{star}/L) is optimal photometric estimator of rotation velocity $\mathbf{V_{80}}$:

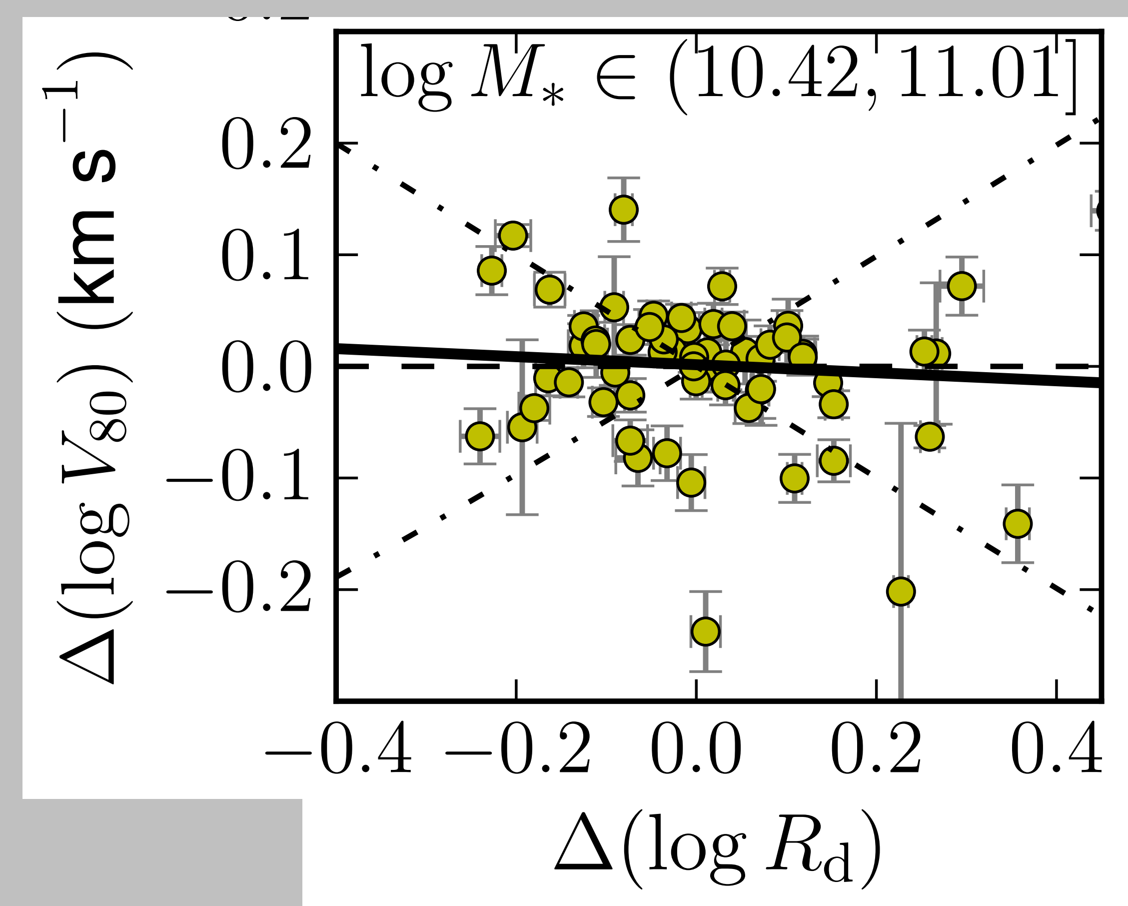
log $\mathbf{V_{80}}(\mathbf{M_*})$ = (2.142 ± 0.004)
+ (0.278 ± 0.010) (log $\mathbf{M_*}/M_{sun}$ - 10.10)

with an intrinsic scatter in log V_{80} of **0.036 ± 0.005 dex** and a total scatter of **0.056 dex**.

TF residual correlations





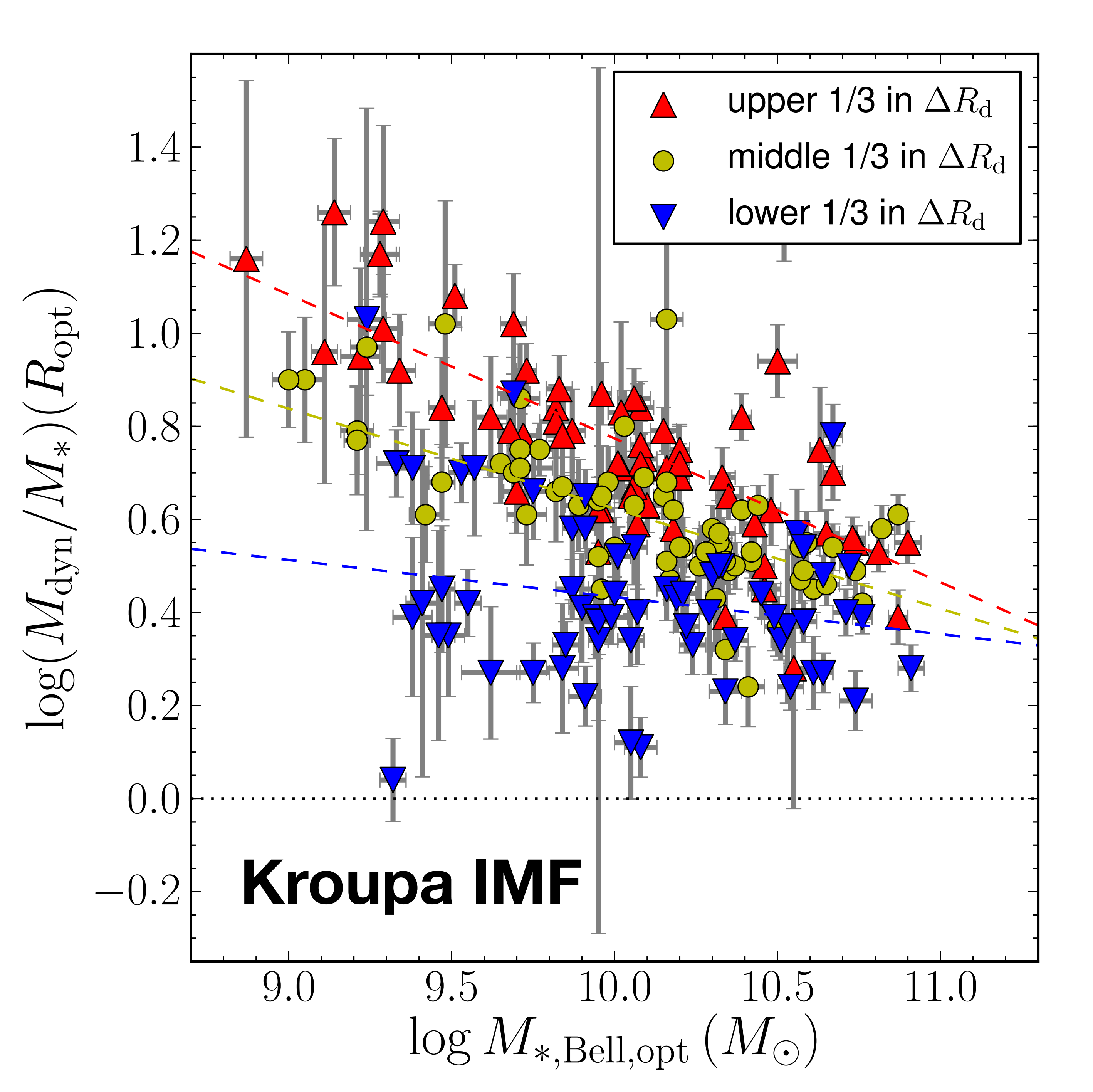


Pure disk: slope=**-0.5**
Pure NFW halo: slope=**+0.5**.

For the 3 stellar mass bins,
slopes are consistent with zero.

-> Neither disk nor halo dominate

Dynamical-to-stellar mass ratios

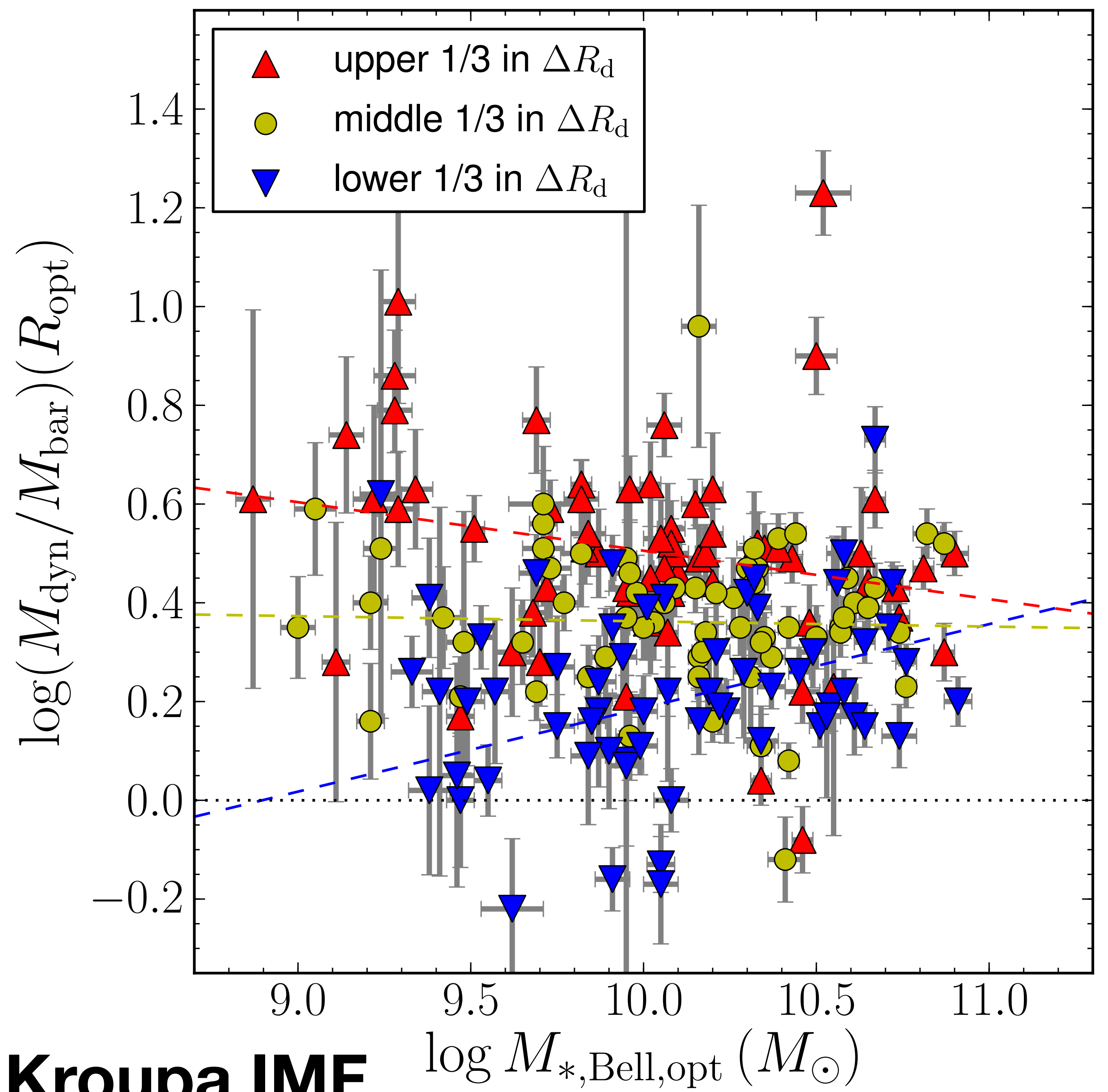


M_{dyn}/M_{star} within the optical radius decreases from ~10 to 3 as stellar mass increases from M_{star}~10^9 to 10^{11} M_{sun}.

Larger disks have **higher M_{dyn}/M_{star}.** at a given stellar mass.

The smallest disks have **low M_{dyn}/M_{star}** at all stellar masses.

Dynamical-to-baryon mass ratios



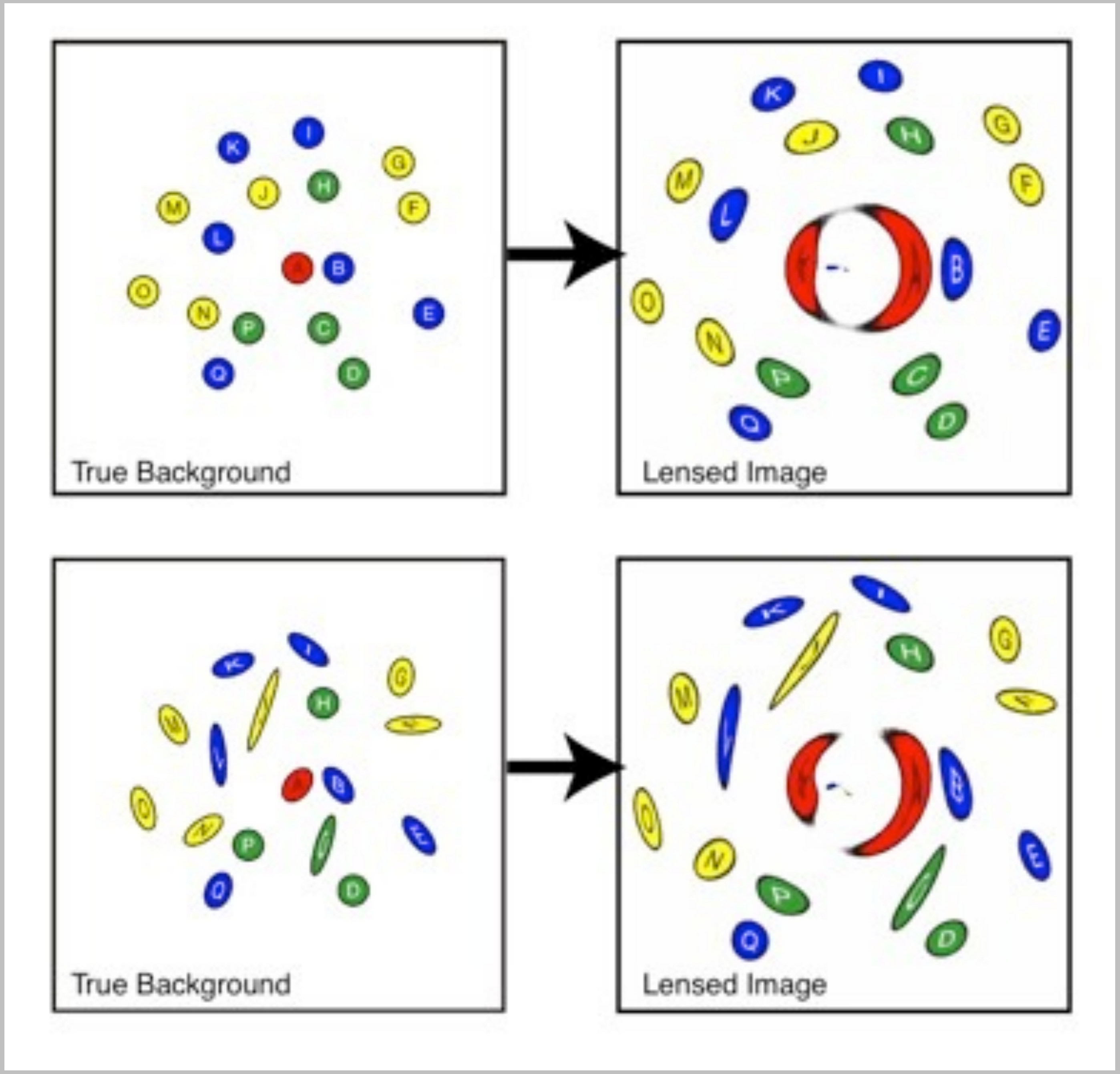
Kroupa IMF

M_{dyn}/M_{bar} within the optical radius is roughly constant with stellar mass at ~ 2.6.

Larger disks have **higher M_{dyn}/M_{bar}.** at a given stellar mass.

-> At larger R_{opt}, one “sees” more of the halo.
-> R_{halo} scales with R_{opt}?

Weak (galaxy-galaxy) lensing

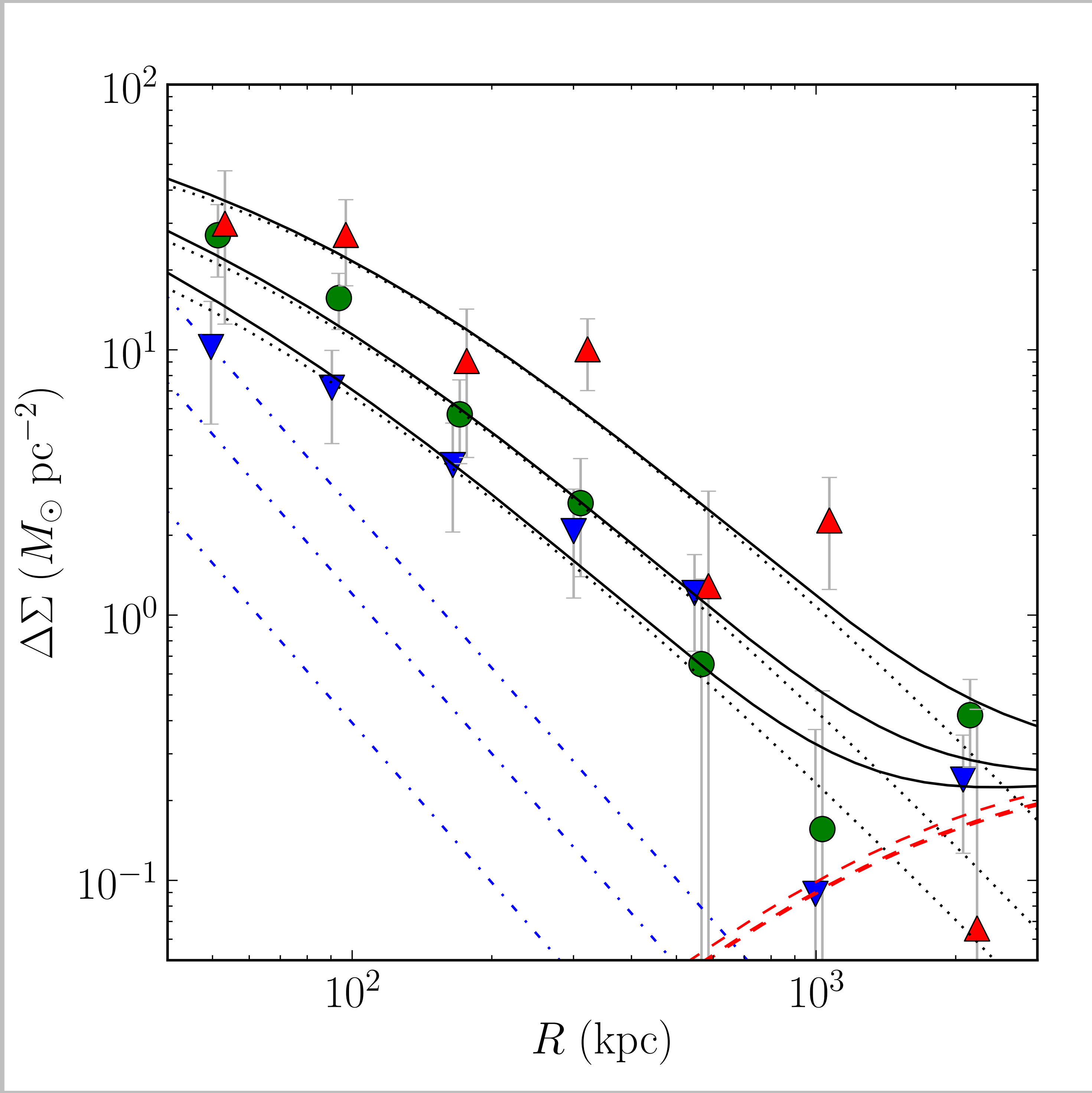


Galaxy images are weakly distorted due to the bending of light by intervening matter.

Powerful direct probe of total mass (dark + luminous).

Stacked measurements yield adequate S/N to obtain DM halo masses.

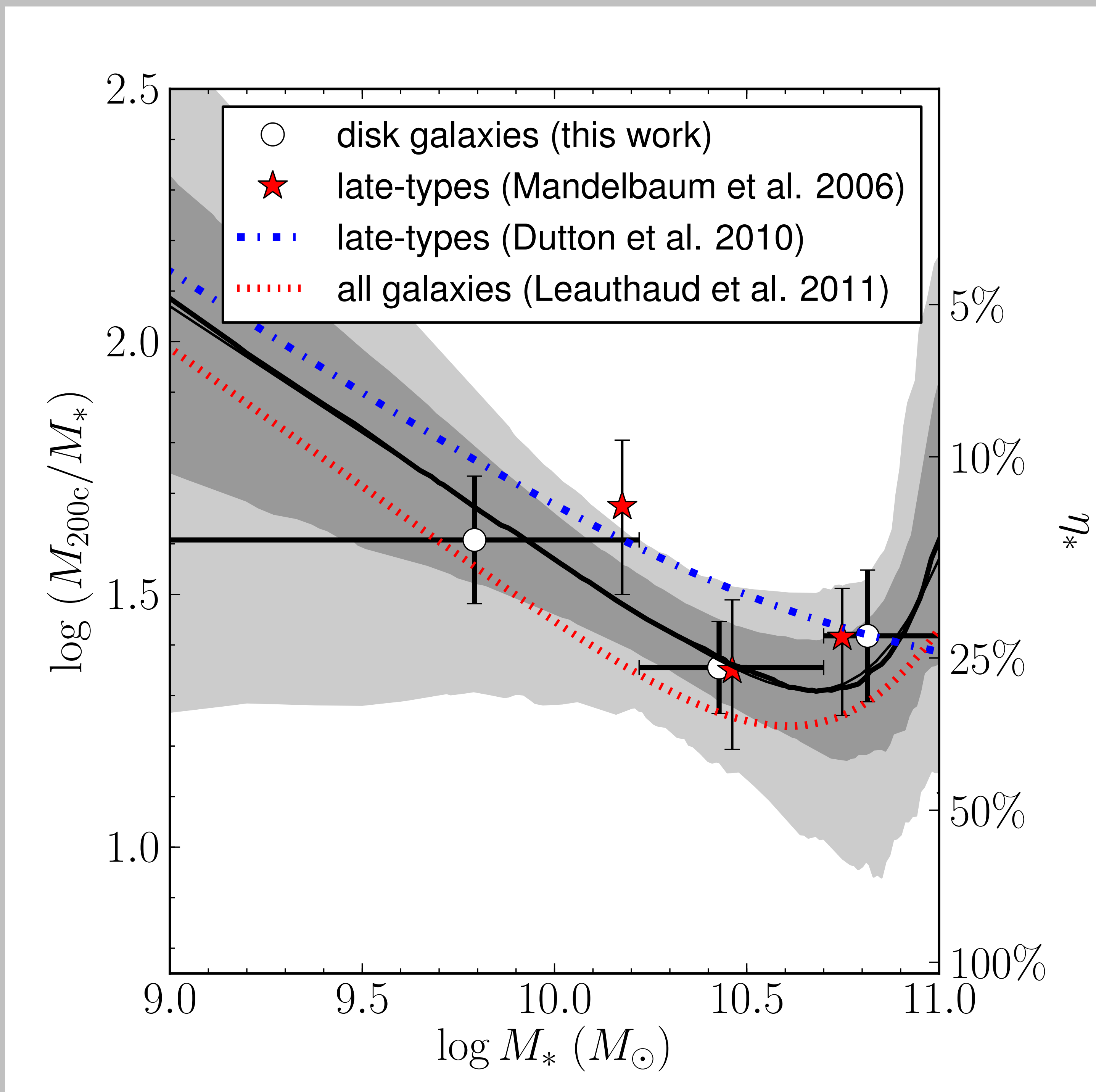
Galaxy-galaxy lensing profile



Bins in stellar mass have
N ~ 78, 47, 8x10^3 galaxies
and
<log M$_*$>~9.79, 10.43, 10.81
(in units of M$_{sun}$).

Fits to NFW profiles give
halo virial masses
<log M$_{200c}$>
~11.40, 11.79, 12.23
± 0.13, 0.09, 0.13
(in units of M$_{sun}$).

Halo-to-stellar mass ratios



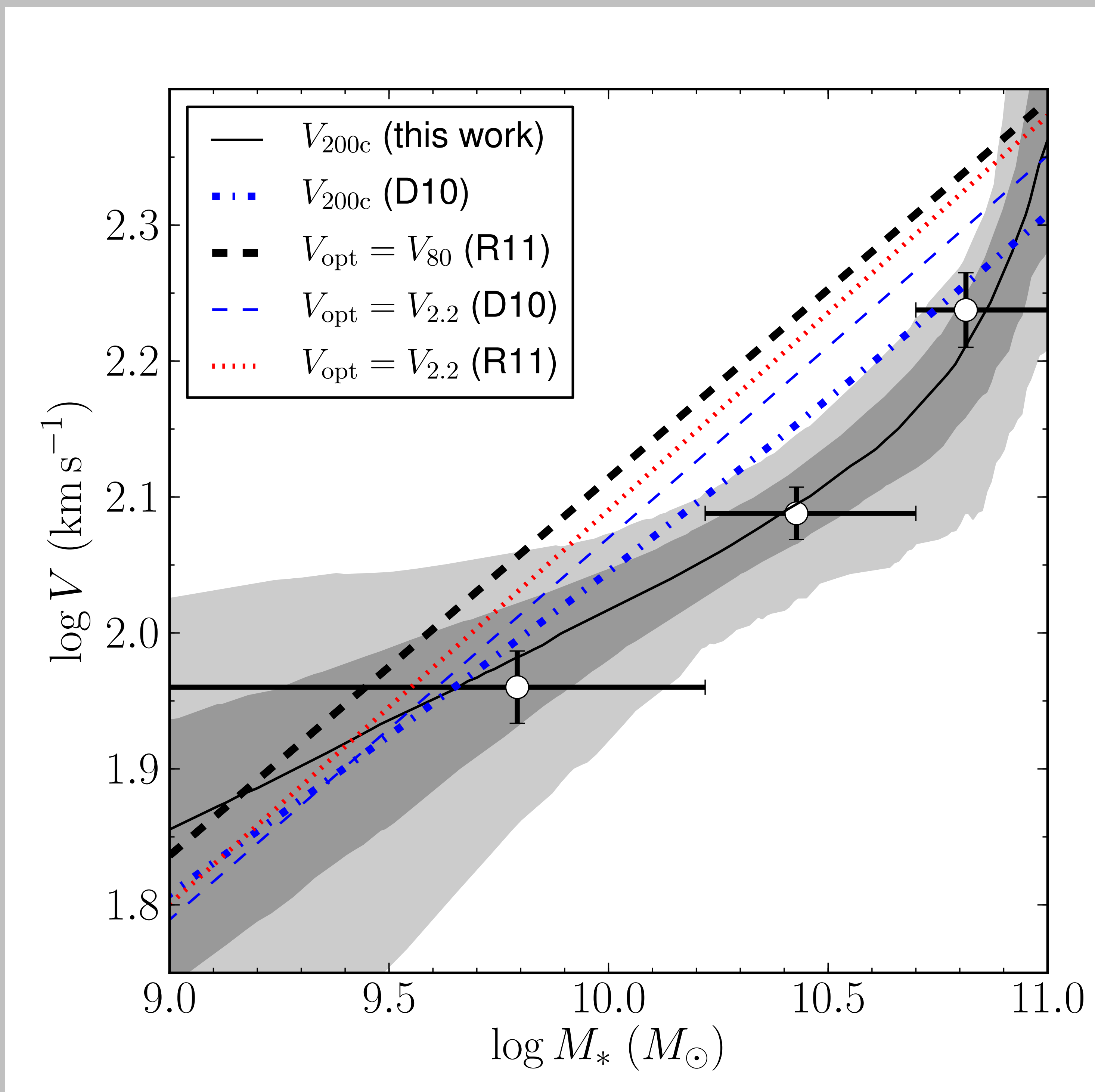
M_{200c}/M_{star} decreases from ~10^2 to a minimum of ~20 at M_{star} ~ 3 x 10^{10} M_{sun}.

For our 3 stellar mass bins:
M_{200c}/M_{star} = 41, 23, 26
± 5, 2, 3 (1σ)

stellar conversion efficiency
<η★>= (M_{star}/M_{200c})/(Ω_b/Ω_m)=15, 26, 23 ± 5, 6, 8% (1σ)

baryon retention fraction
<η$_b$>= (M_{bar}/M_{200c})/(Ω_b/Ω_m) = 30, 37, 29%
(using gas-to-stellar mass ratios of 0.99, 0.41, 0.24)

Virial vs. optical velocities



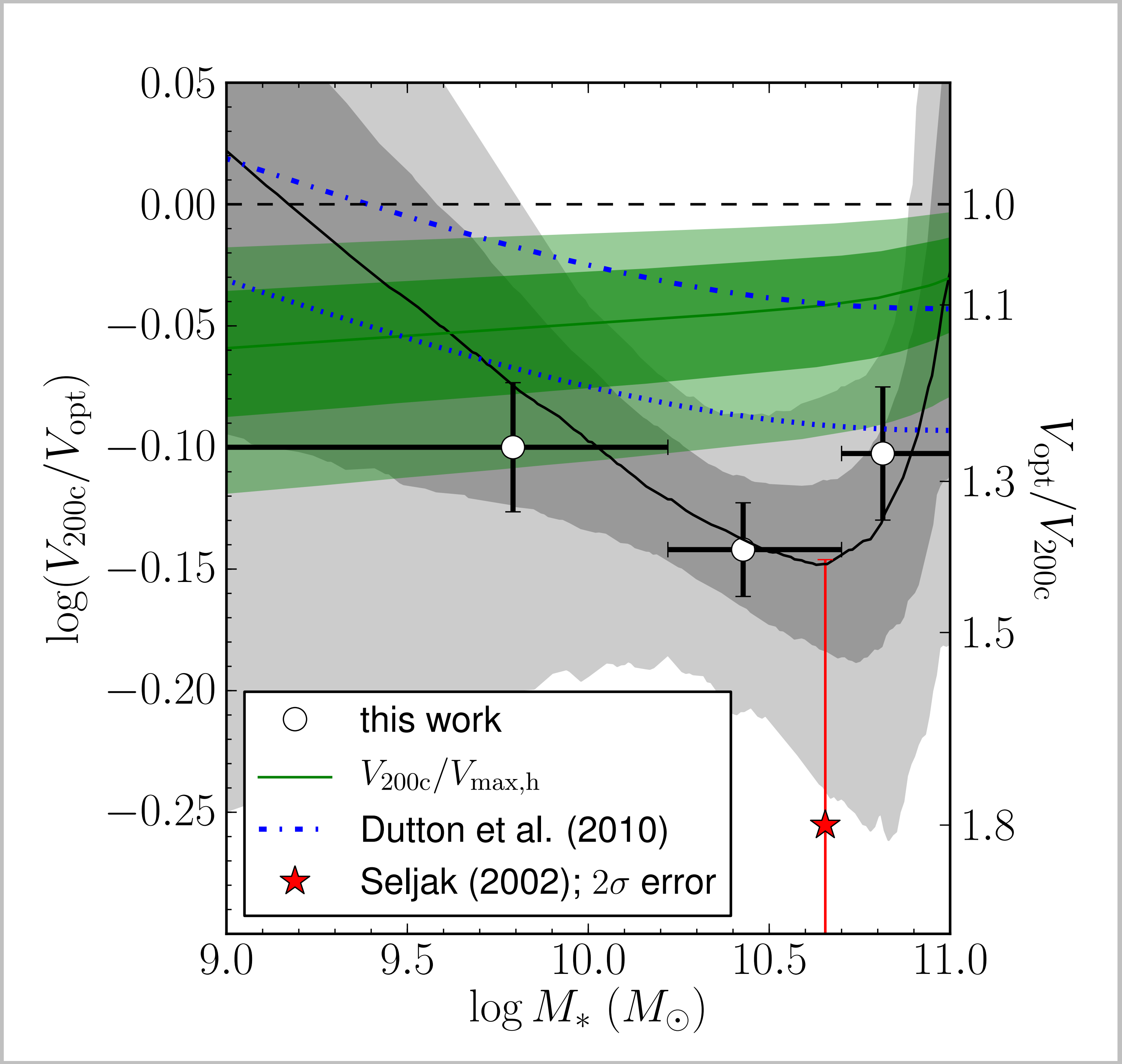
- **V_{200c}** from weak lensing:

$V_{200c} = (GM_{200c}/R_{200c})^2$

- **V_{opt}** from Tully-Fisher relation:

log $\mathbf{V_{80}}(\mathbf{M_*})$ = 2.142
+ 0.278 x (log $\mathbf{M_*}$ - 10.10)

Virial-to-optical velocity ratios

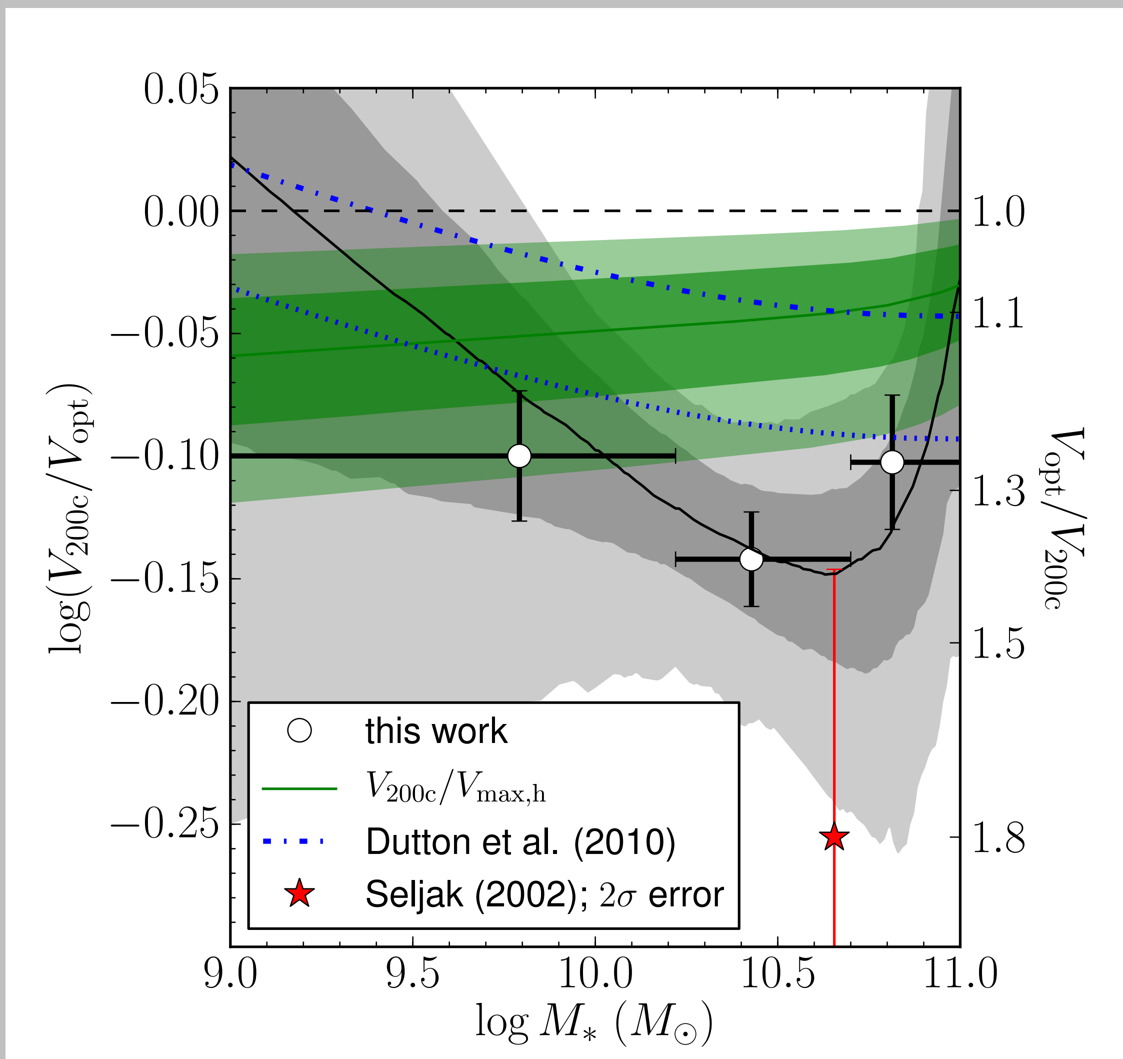


V_{200c}/V_{opt} is insensitive to uncertainties in the stellar mass estimates.

For our 3 stellar mass bins log M_* = 9.79, 10.43, 10.81:

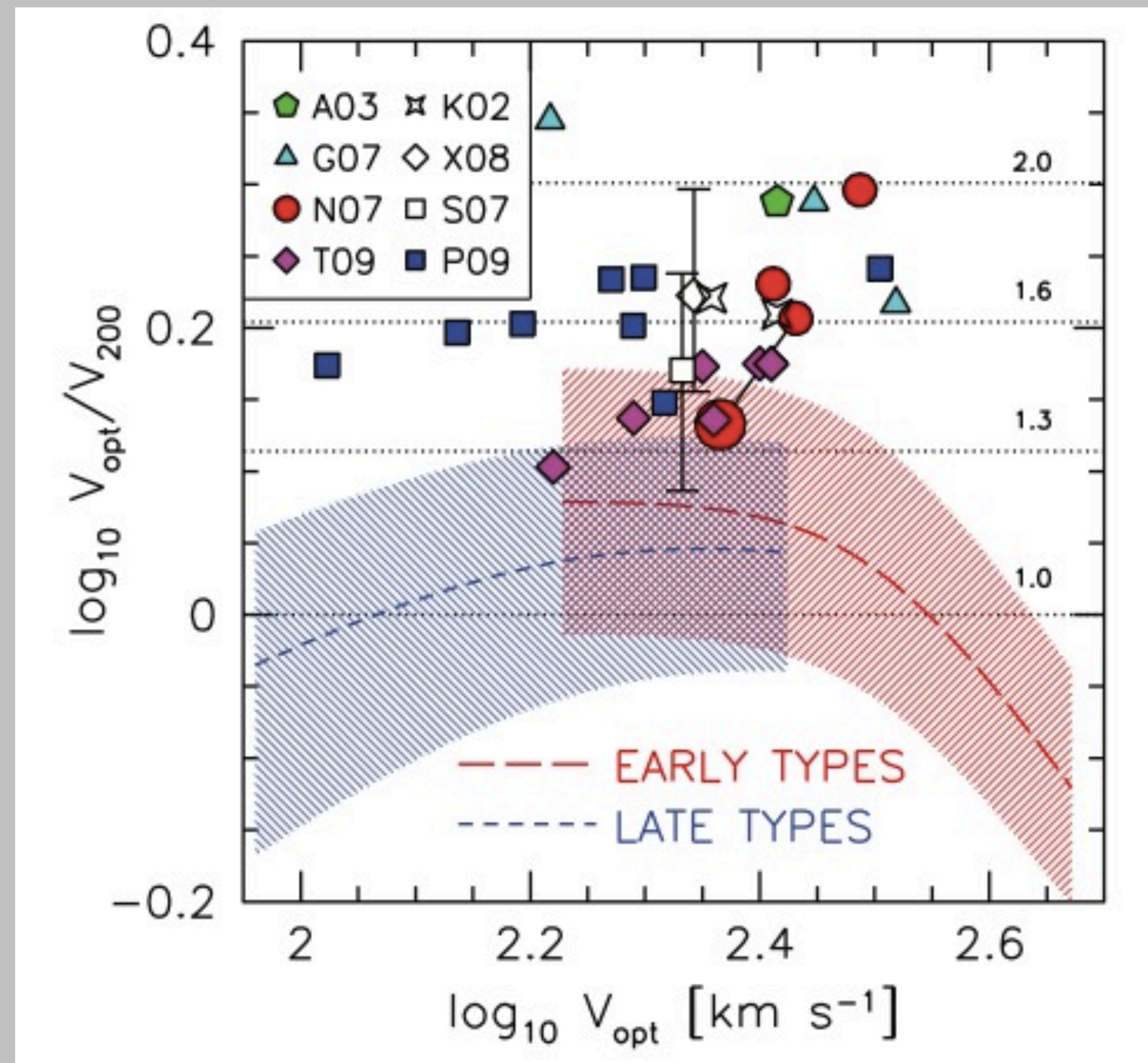
V_{opt}/V_{200c} = 1.27, 1.39, 1.27
± 0.08, 0.06, 0.08 (1σ)

Virial-to-optical velocity ratios

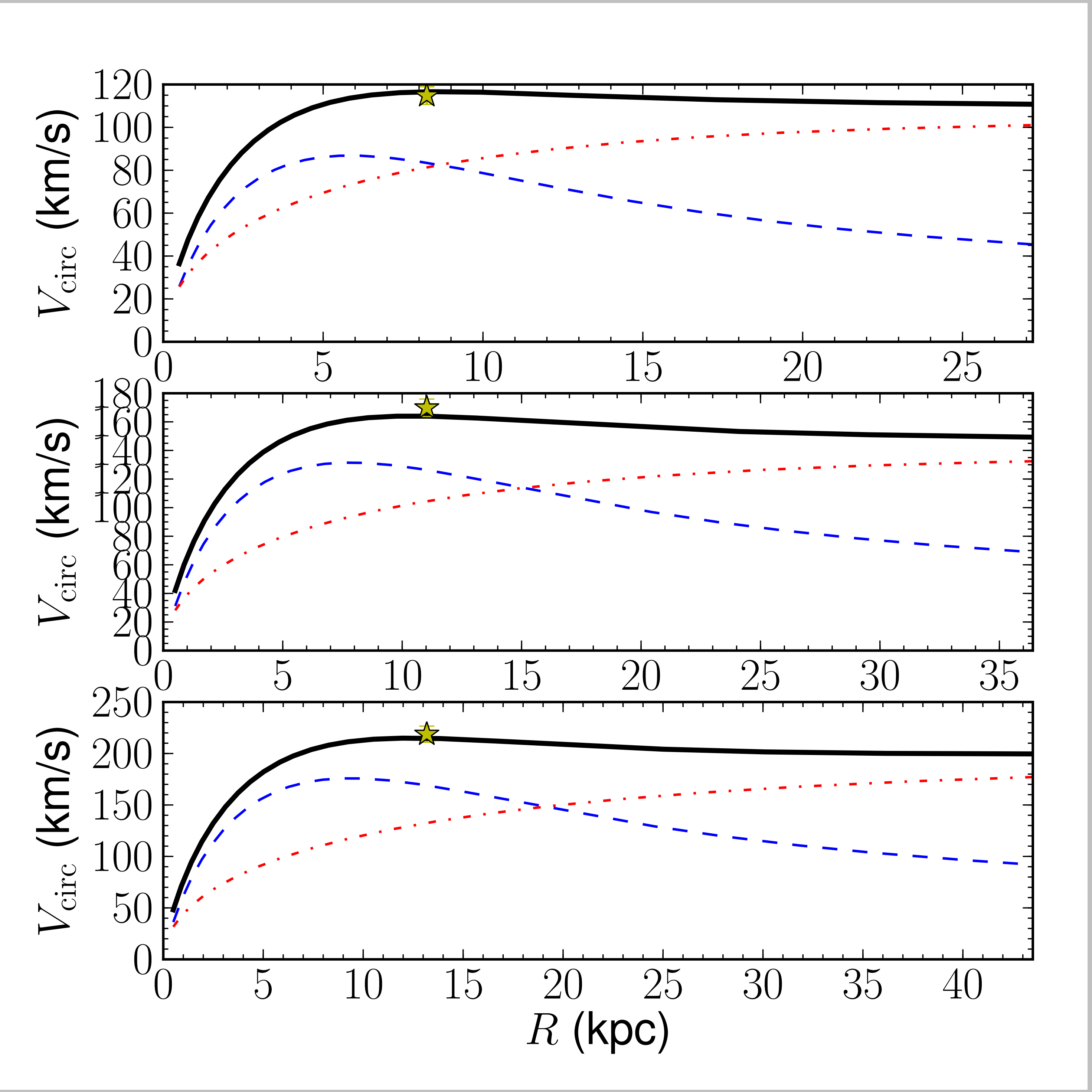


Reyes et al. 2012

Dutton et al. 2010



Current work: Galaxy mass modeling



****PRELIMINARY****

Exponential baryon disk + unmodified NFW DM halo for log M_* = 9.79, 10.43, 10.81:

- No halo contraction is consistent with TF

- need to do a proper accounting of scatter in both model and observations

Current work: Semi-empirical modeling

Halo population

- **M_{200c}, $c_{200c}(M_{200c})$, $P(\lambda_{halo})$**

Model

Disk galaxy population

- **M_{*}, R_{d}, M_{gas} , R_{gas}**

Constraints

- Tully-Fisher relation
- Tully-Fisher residuals
- Dynamical-to-stellar(baryonic) mass ratios
- Disk size-stellar mass relation

Unknowns

- halo contraction model
- stellar IMF
- **$\lambda_{halo}/\lambda_{disk}$**
  (selective accretion of baryons, angular momentum exchange, feedback)

Summary

- **Observational constraints** on disk galaxy formation serve as essential tests of and guides to theoretical modeling (hydrodynamic sims, SAMs).

- Combining **kinematics** and **weak lensing** traces the mass distribution from 1-200 kpc and provides strong constraints on galaxy formation.

- **Semi-empirical modeling** of disk galaxy formation can constrain uncertain ingredients, such as halo contraction and the stellar IMF.