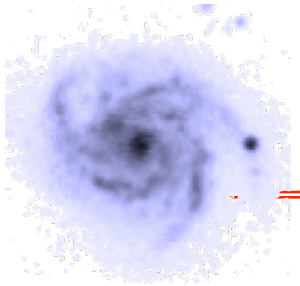
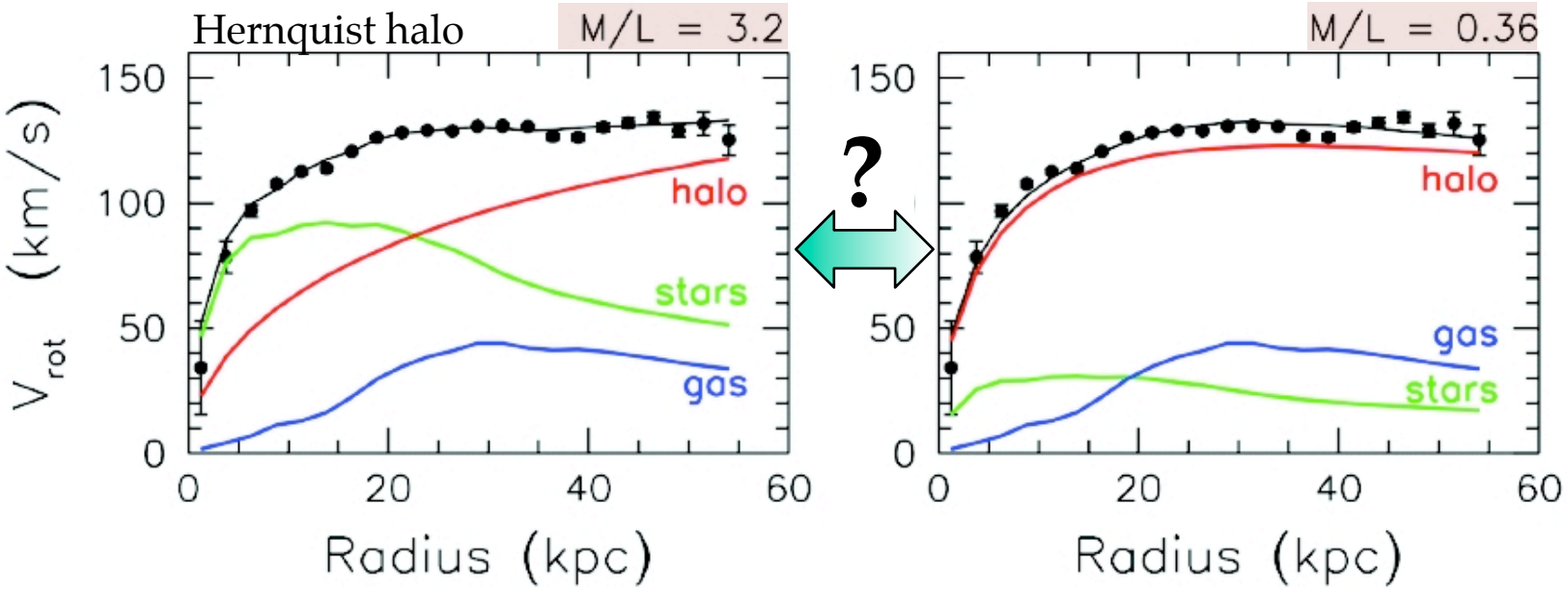


Galaxy Disks Are Sub-maximal

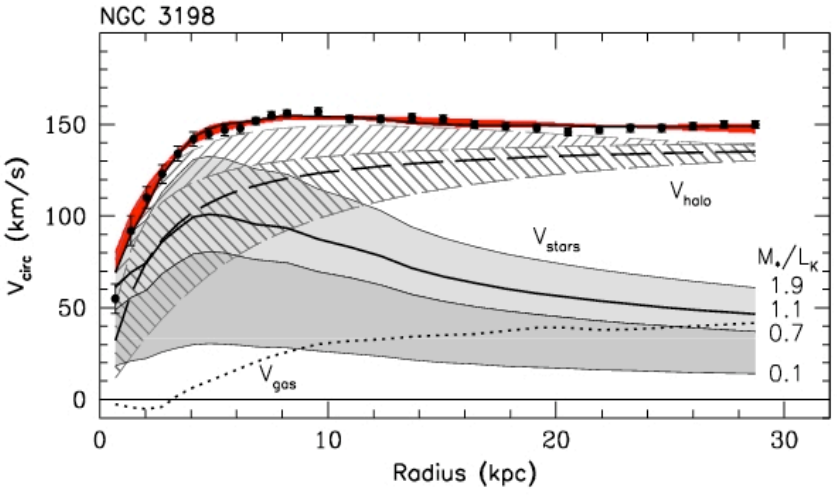
M. Bershady (Wisconsin), M. Verheijen, K. Westfall, T. Martinsson (Kapteyn),
D. Andersen (HIA), R. Swaters (NOAO)

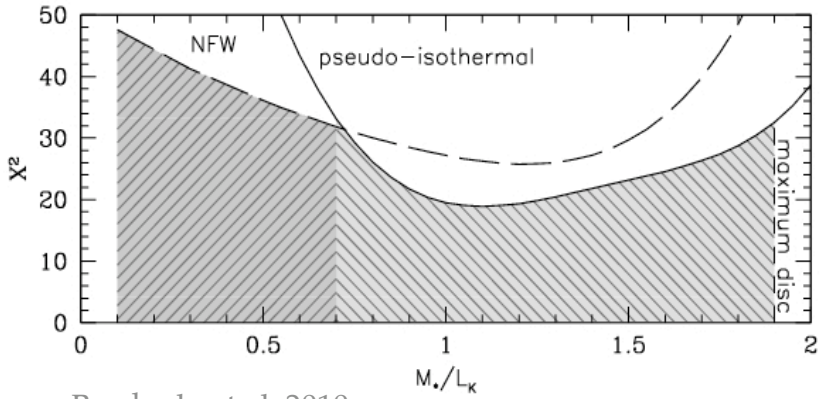


The Disk-Halo Degeneracy

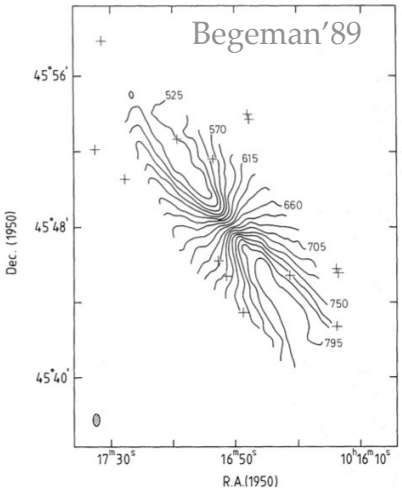
- Rotation curve decompositions constrain:
  - ➔Maximum disk – *yes*
  - ➔Minimum disk – ***NO***

Fundamental impasse



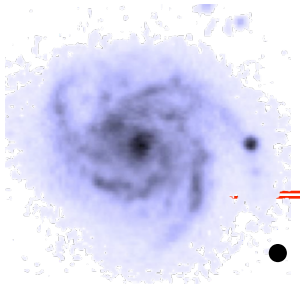


Bershady et al. 2010



Degenerate solutions…

➢ A surfeit of dark matter or dim stars?



Breaking the Degeneracy

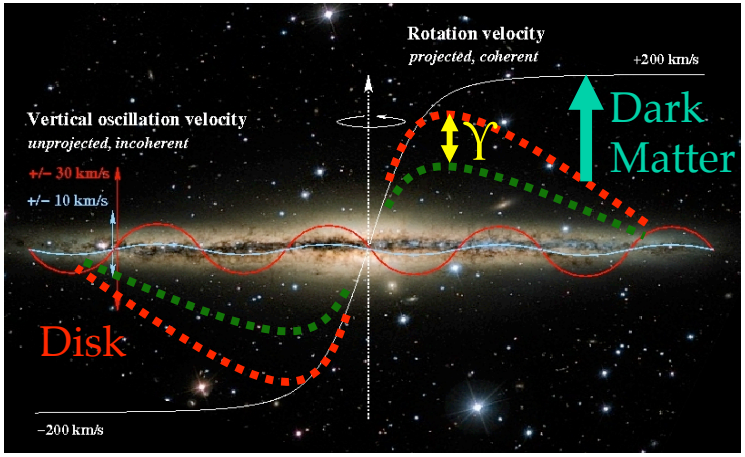
- Disks in equilibrium
- Rotation provides *total* mass within a given radius.
- Vertical oscillations of disk stars provides *disk* mass within given height:

vertical distribution* — thickness — vertical oscillations

Disk mass surface density

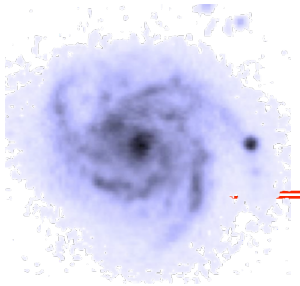
$$\Sigma = 100 \left(\frac{k}{3/2}\right)^{-1} \left(\frac{h_z}{444\ \mathrm{pc}}\right)^{-1} \left(\frac{\sigma_z}{30\ \mathrm{km/s}}\right)^{2} \mathrm{M_{sol}\ pc^{-2}}$$

Use *statistical* measure of *disk thickness* from edge-on galaxies…



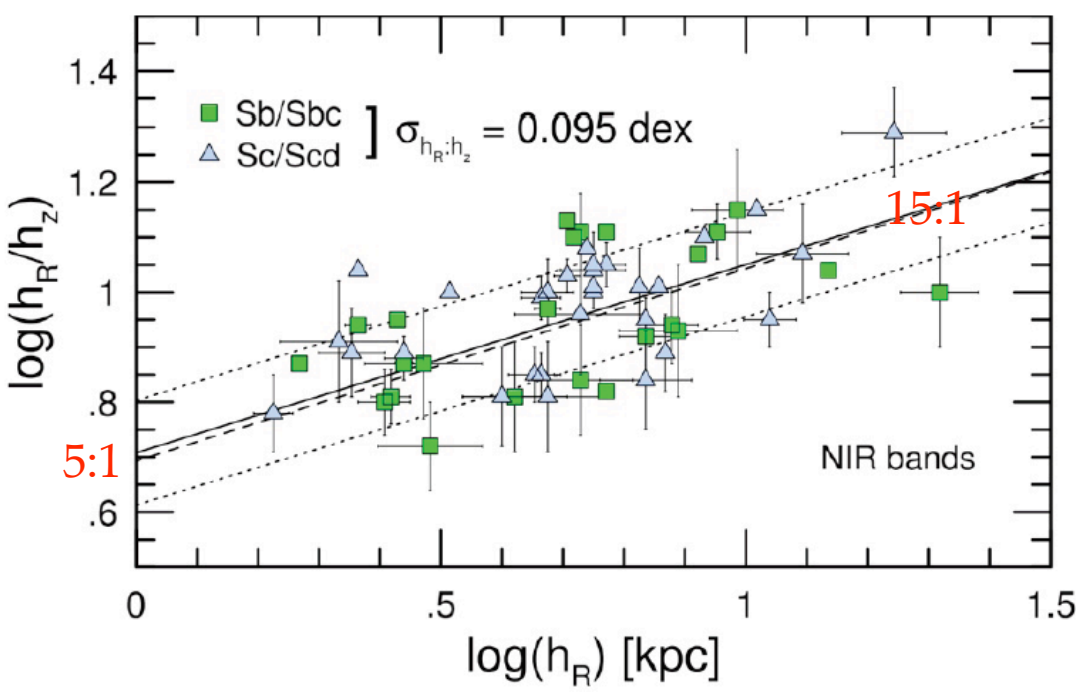
…apply relation to face-on galaxies where *vertical oscillations* can be measured.

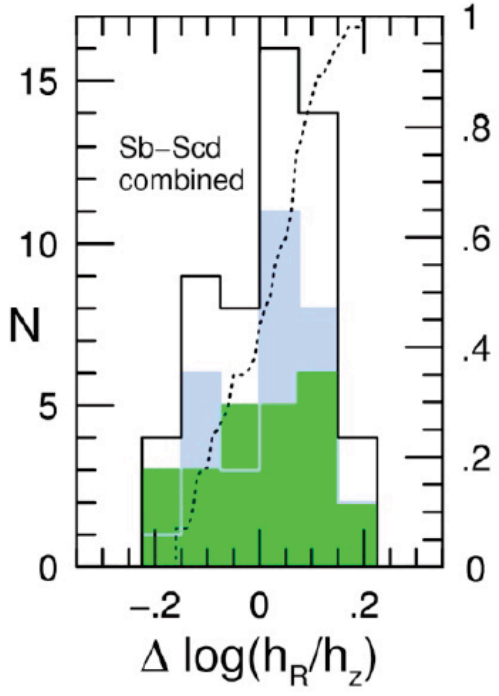
* 1.5<k<2 for exp (*observed*), sech (*intermediate*), sech^2 (*isothermal*)



Scale-height systematics < 25%

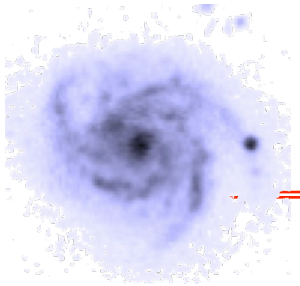
From edge-on surveys…tuned to the **DiskMass** *sample*





Schwarzkopf & Dettmar 2000
Kregel et al. 2002, 2004
Xilouris et al. 1997, 199

$$\log (h_R/h_z) = 0.367 \log (h_R/\mathrm{kpc}) + 0.708 \pm 0.095$$

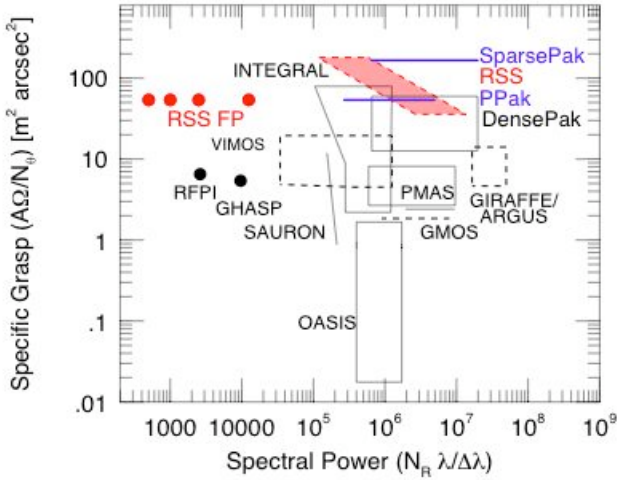


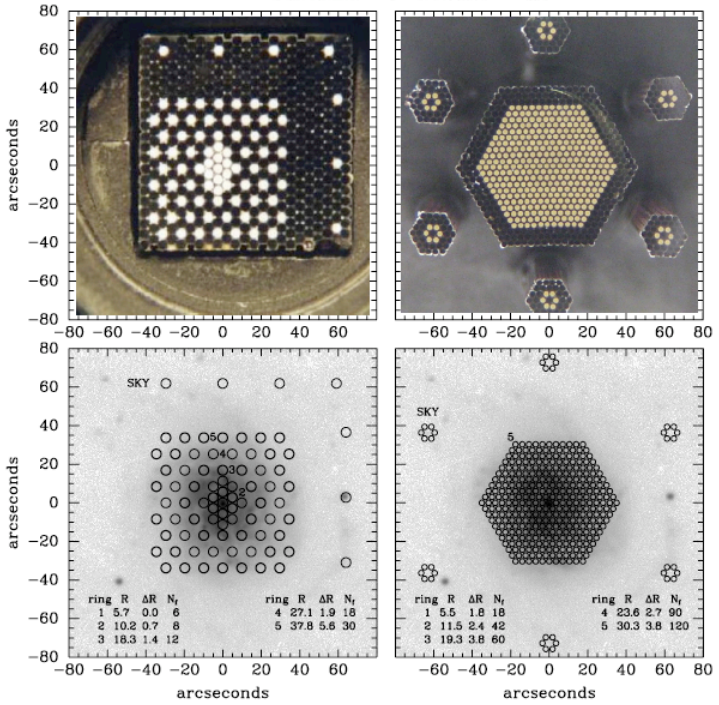
DiskMass Survey

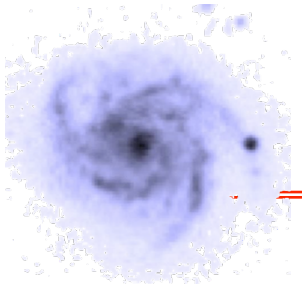
- Design survey protocol
  - *normal, nearly face-on spiral galaxies*
- Build 2 high-grasp (AΩ) IFUs on 3.5m telescopes achieving λ/Δλ ~12000
- Pilot survey
- Phase A: Hα kinematics , 145 galaxies
  - Kinematic inclinations
  - Tully-Fisher

  bright-time observations!
- Phase B: stellar kinematics, 40 galaxies
  - Σ_{disk} , M/L and ρ_{DM}

  wide range in color, L, μ

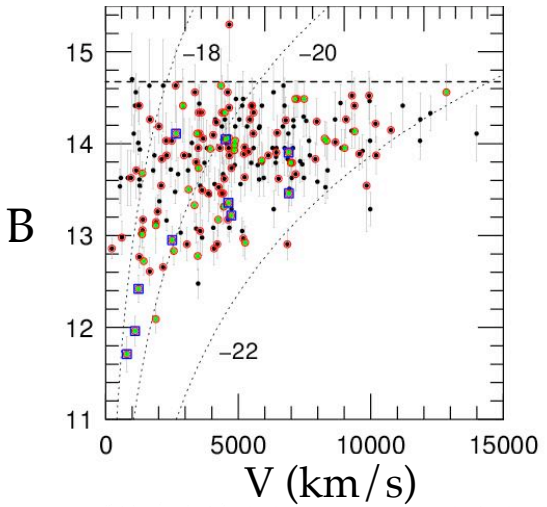


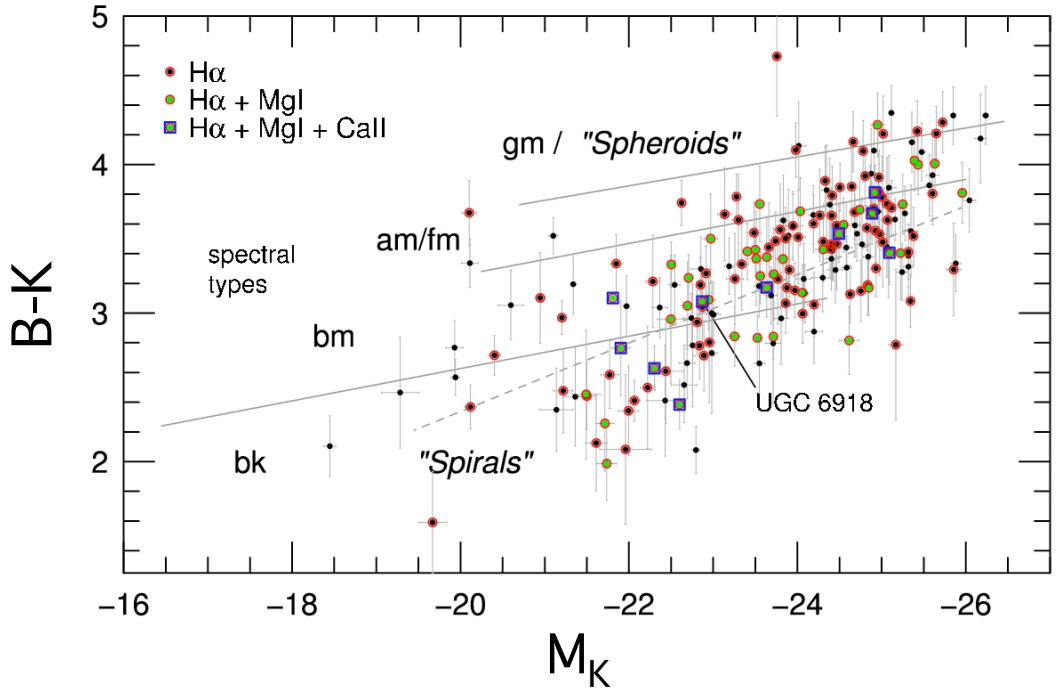


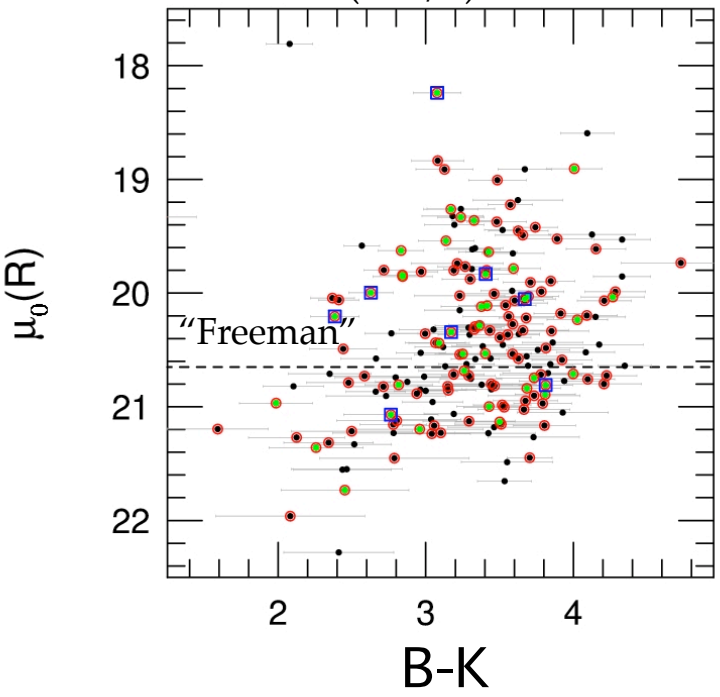


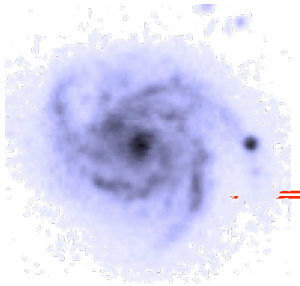
Sample: Normal Face-on Spirals from UGC

Sample spans
- x60 in L_K,
- x6 in L_B/L_K,,
- x10 in surface-brightness



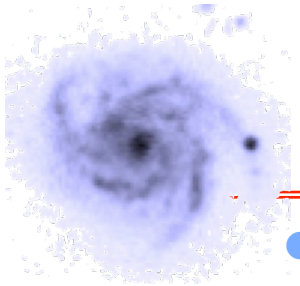






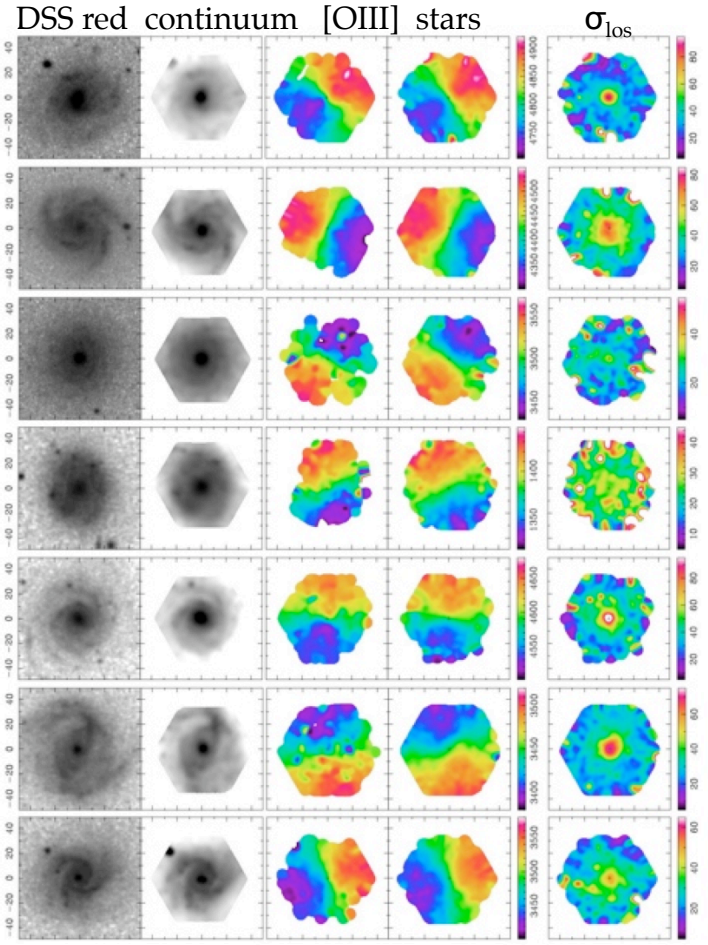
Sample morphology

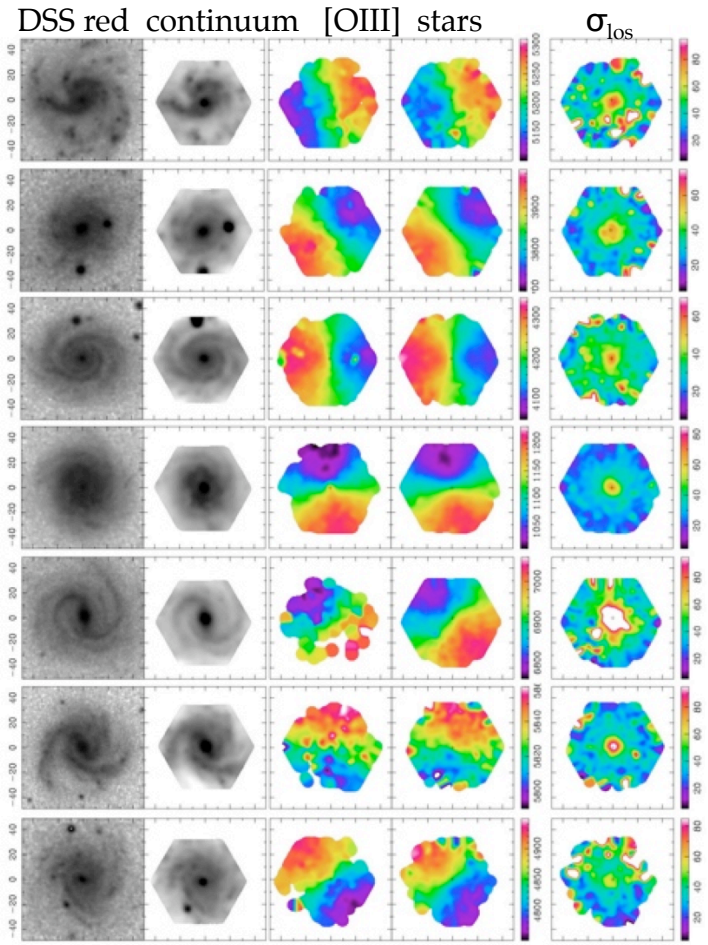
2 x 2 arcmin: SDSS



DiskMass Survey: Phase B

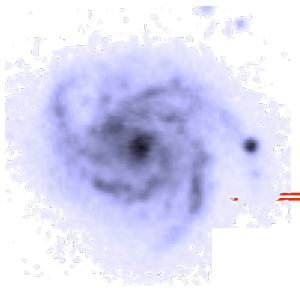
- Continuum and stellar kinematic maps
- 40^{+} stellar σ_z measurements *.....115 nights (3.5m)*
- Spitzer 4.5, 8, **24** and 70 μm images *.....26 hours*
- HI mapping *.....400 hours (VLA, WSRT, GMRT)*



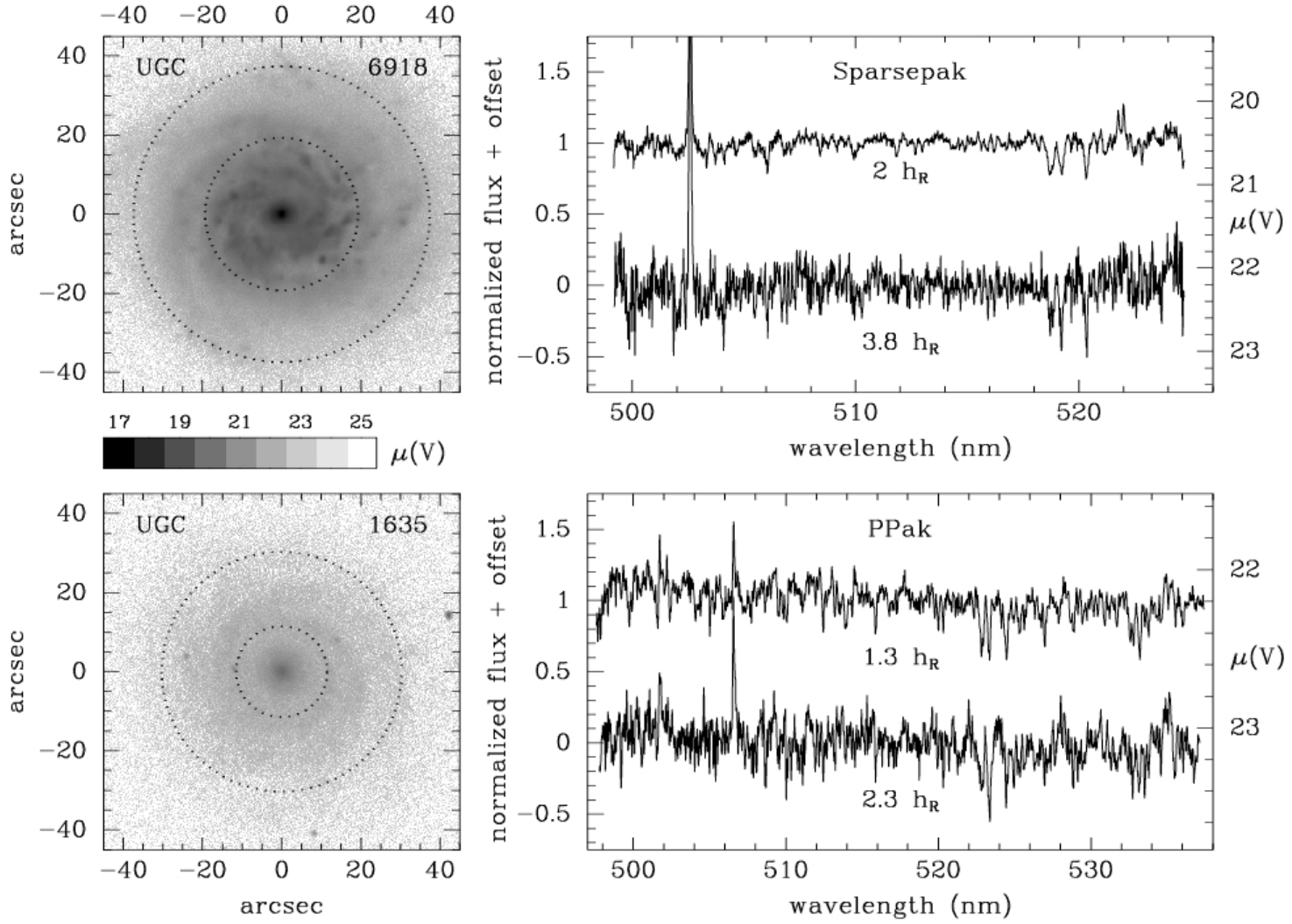


30% of sample

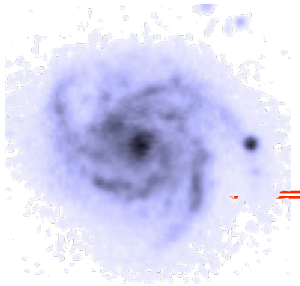
Martinsson et al. 2011



Coadded spectra in radial bins

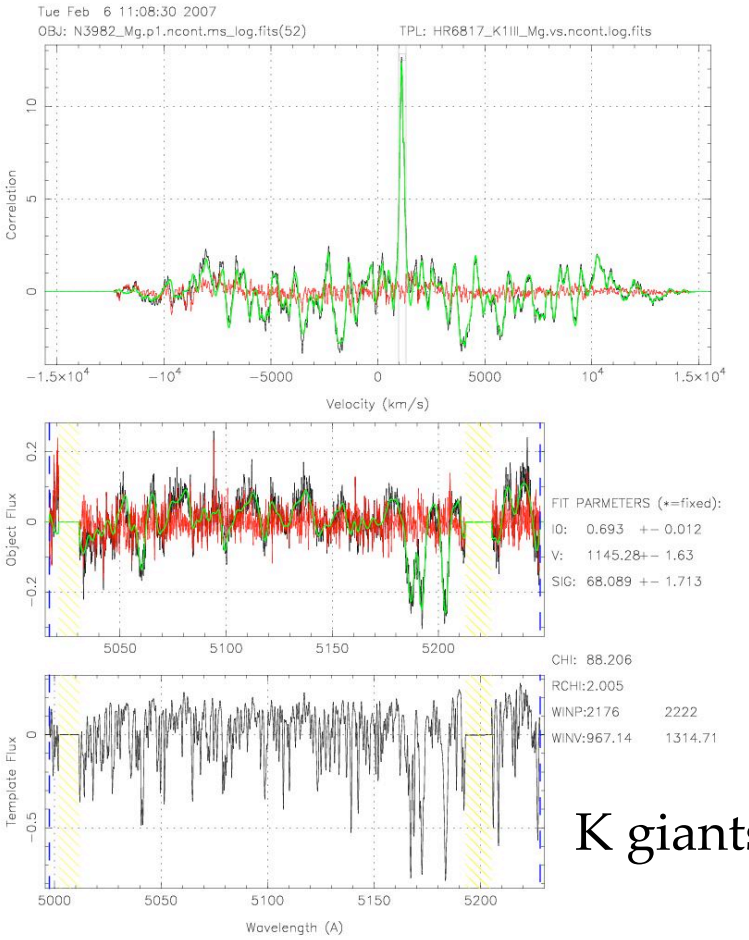


Wide range in surface-brightness



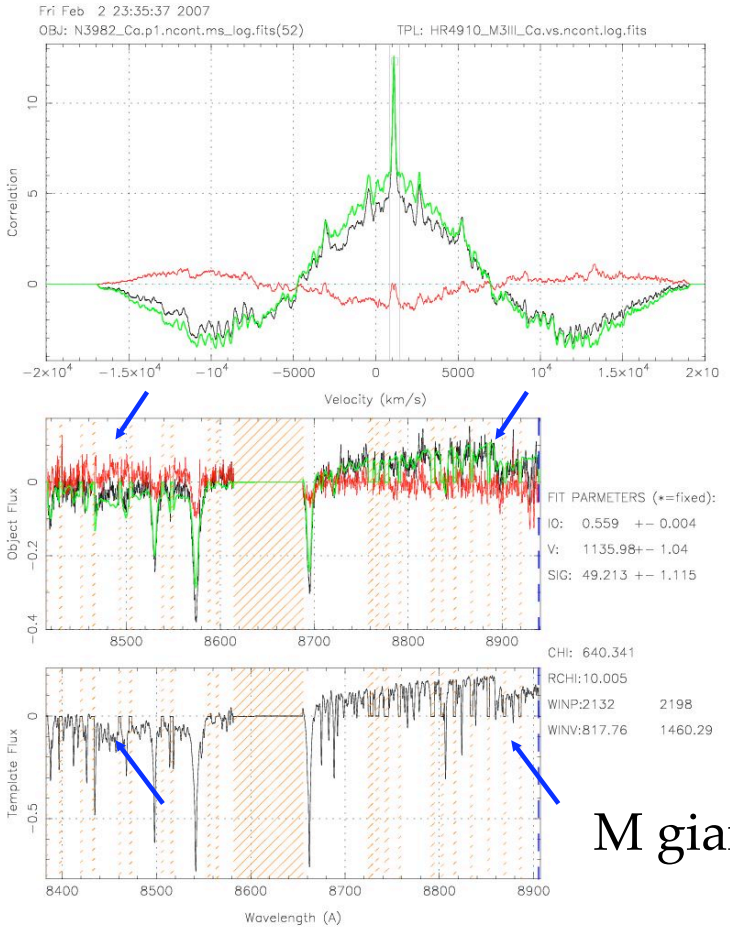
Determining the Broadening: σ_{LOS}

MgI region, 513nm



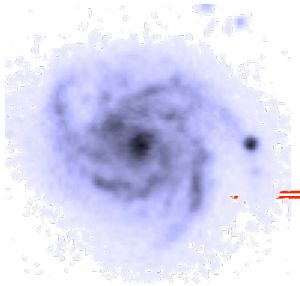
K giants

CaII region, 867 nm



M giants

Two spectral regions probe two stellar components of old disk population

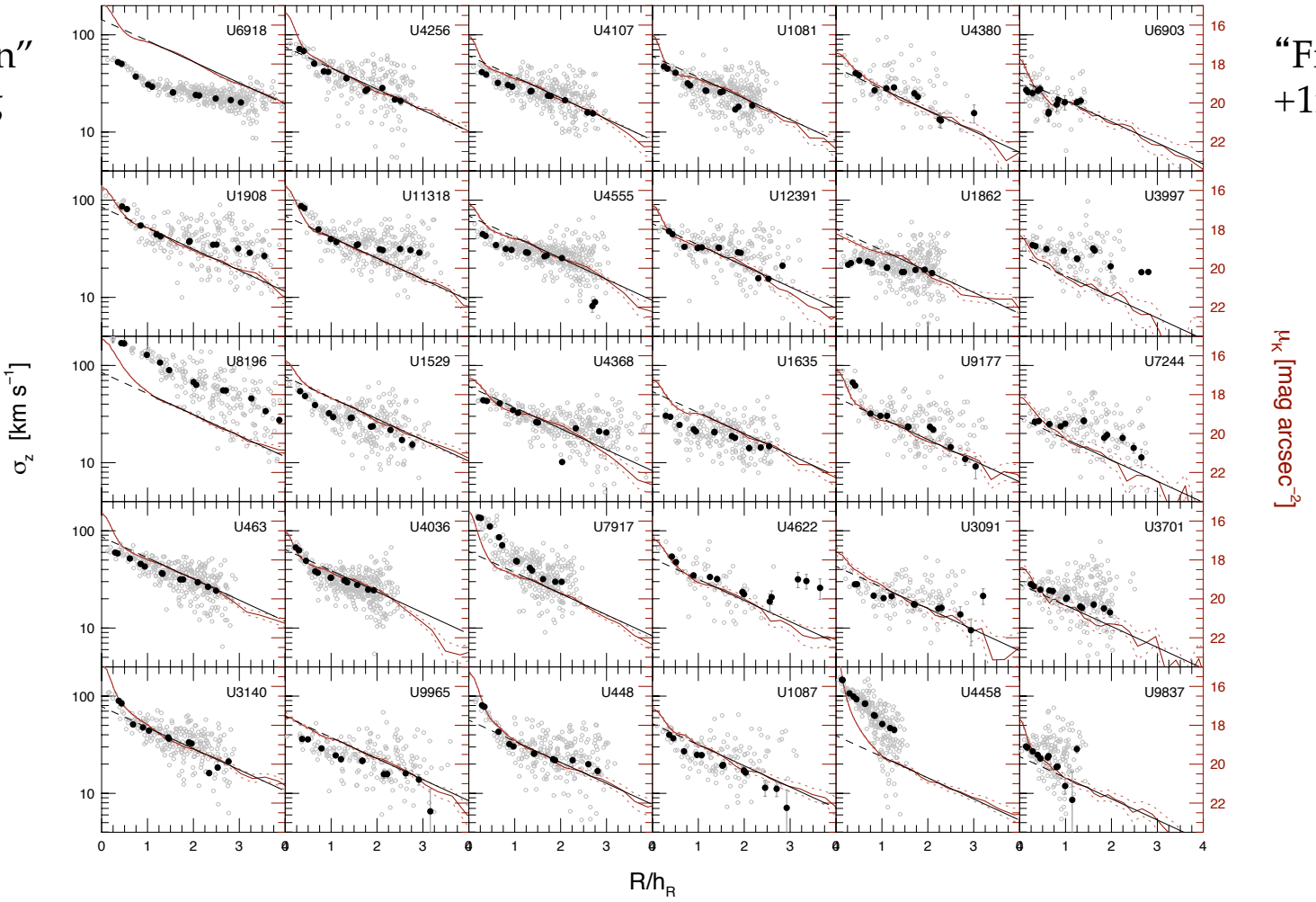


Light Traces Mass…

…*but with some significant variations*

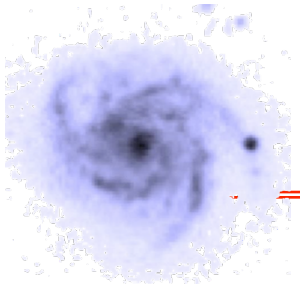
High ⟶ surface-brightness ⟶ Low

"Freeman" -1.5 mag



"Freeman" +1mag

UCSC-080811



A simple argument for submaximal disks:

- Recall:

$$\Sigma = \sigma_z^2 / \frac{3\pi G}{2} h_z$$

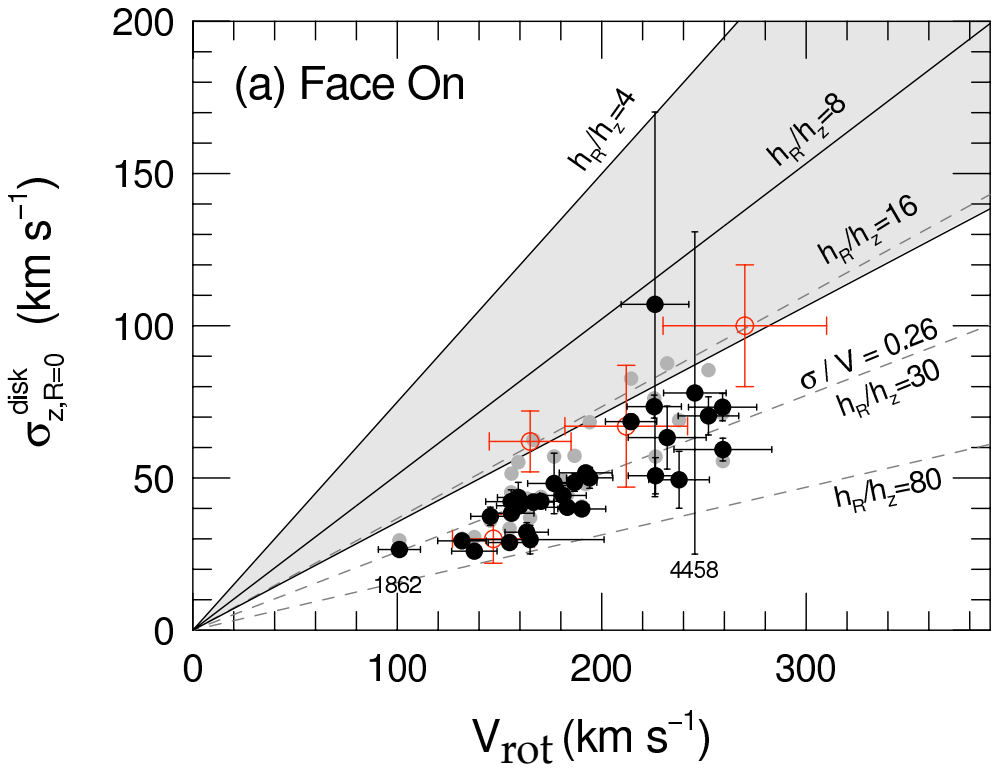
- If disks are self-gravitating (Freeman 1970)

$$V_{\max}^{\text{disk}} = 0.88\sqrt{\pi G \Sigma_0 h_R}$$

- From which it follows

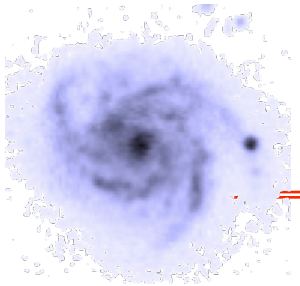
$$\sigma_{z,R=0}^{\text{disk}} = 0.43 \left(\frac{h_R / h_z}{8} \right)^{1/2} V_{\max}^{\text{disk}}$$

DiskMass sample + Bottema '93 face-ons

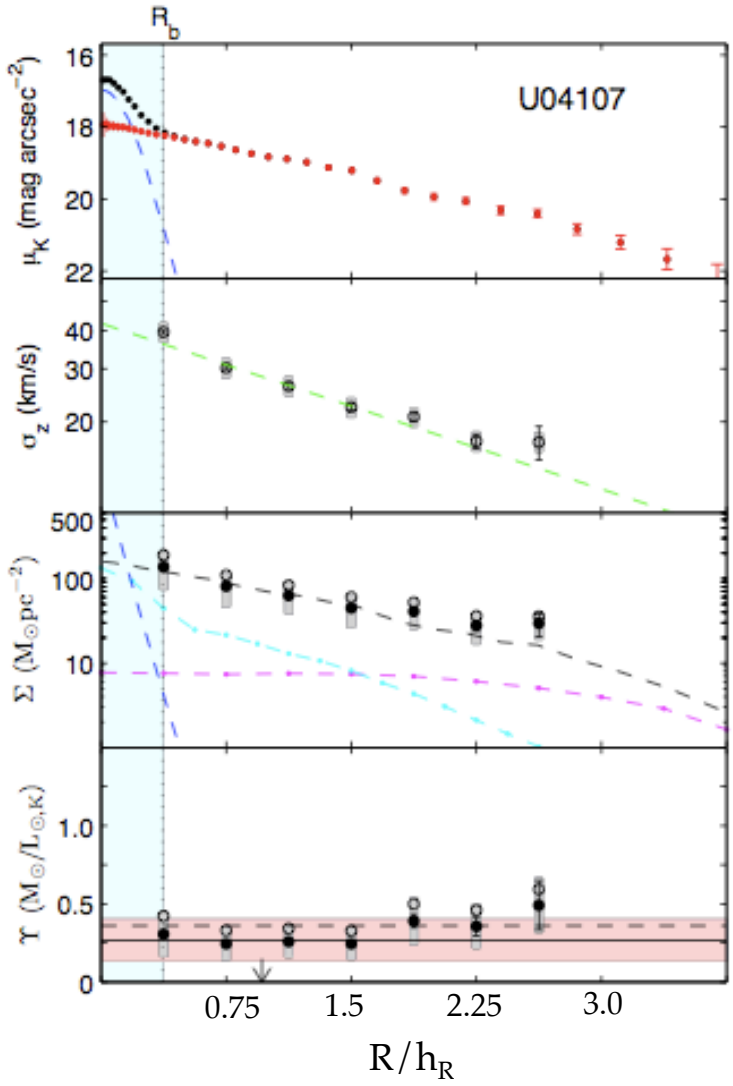


But disks aren't this thin!
➔ **substantially submaximal**

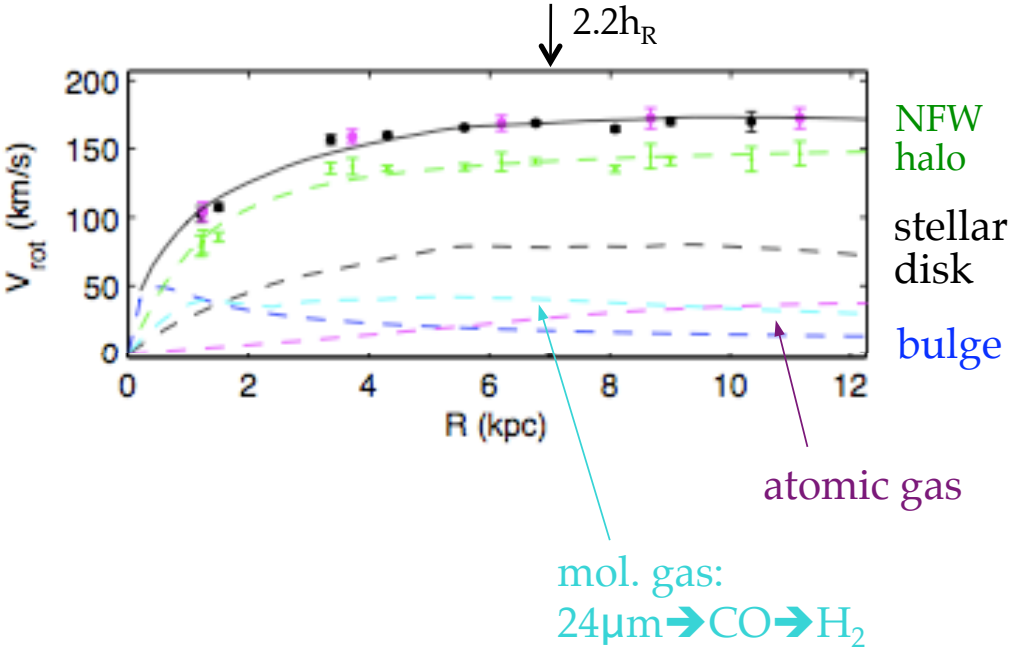
Bershady et al. 2011



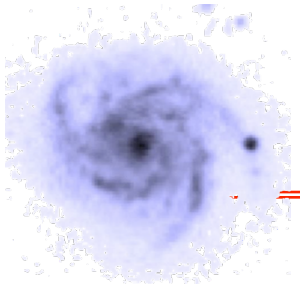
Rotation Curve Decompositions



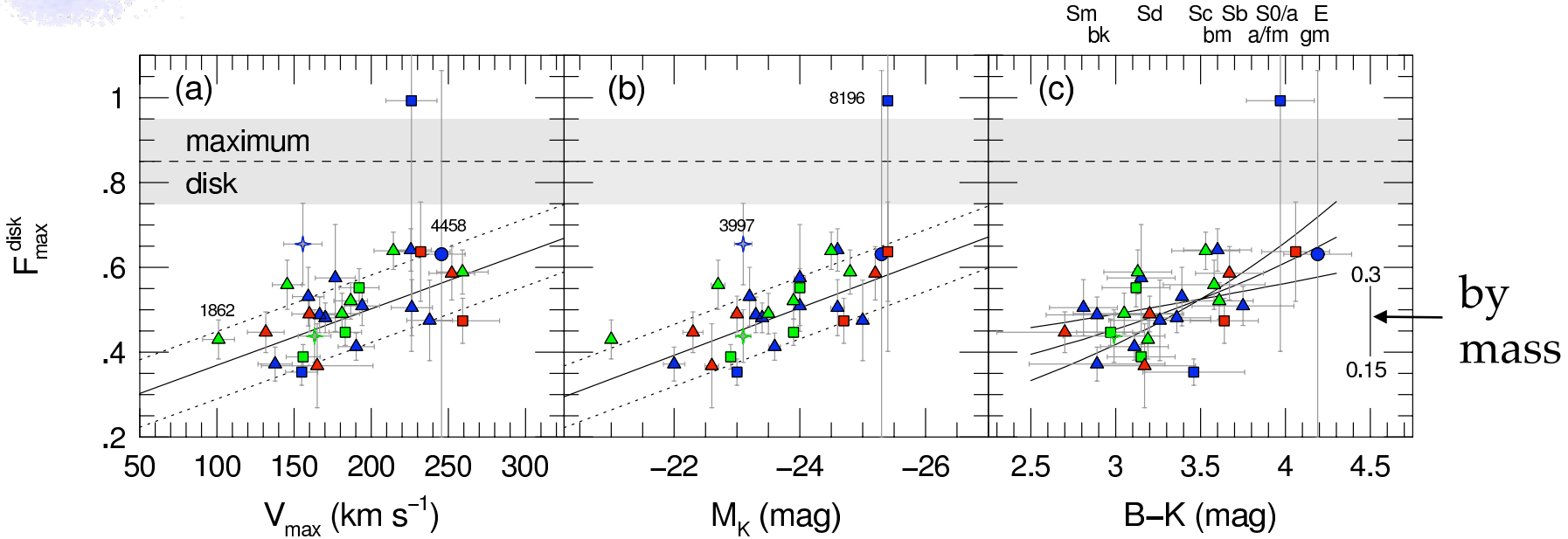
$$F_{\max}^{\text{disk}} \equiv V_{\max}^{\text{disk}} / V_{\text{rot}} = 0.48 \pm 0.04$$



Martinsson Ph.D. thesis 2011



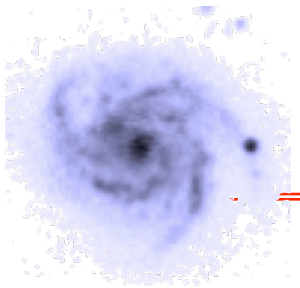
Why *all* disks are submaximal



- "Maximum" disks have

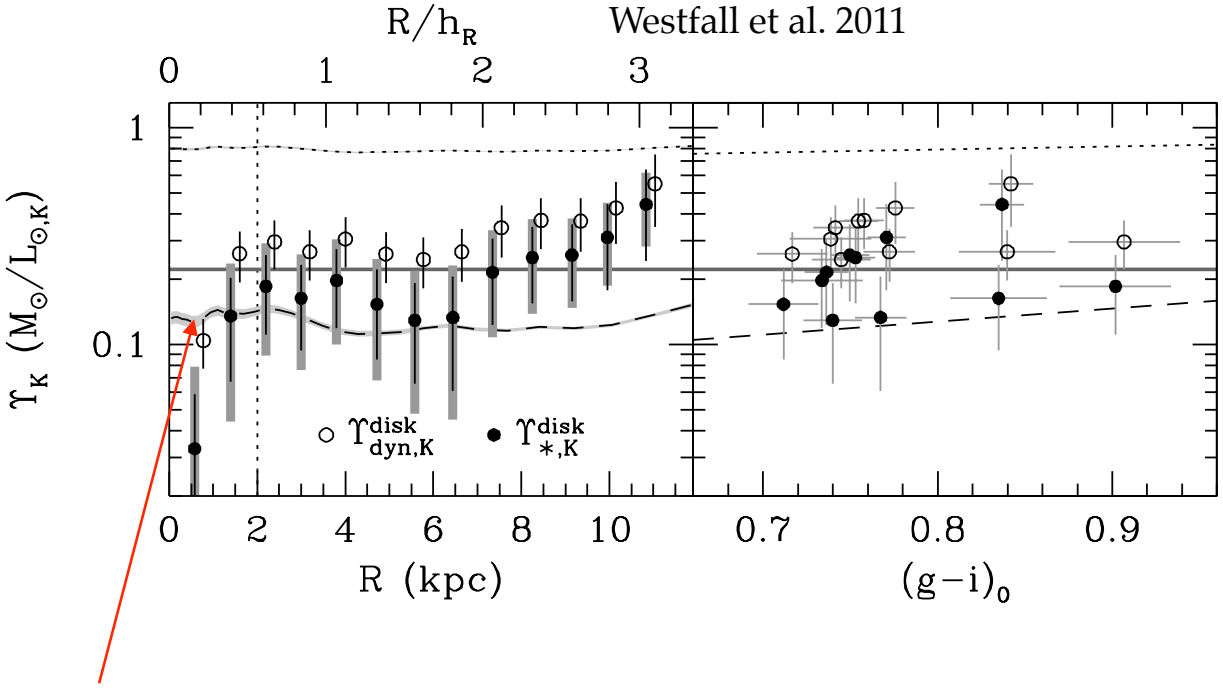
$$F_{\max}^{\text{disk}} \equiv V_{\max}^{\text{disk}} / V_{\text{rot}} = 0.85 \pm 0.1$$

- Disks contribute *relatively* more mass to systems with larger *V*, *L*, redder color…
- …but not enough to be maximal.



M/L: older SPS models 3x too high

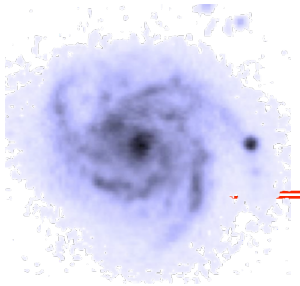
- Survey *means*:
  - $\Upsilon_{*,K} = 0.25 \pm 0.1\ ran \pm 0.1\ sys$
  - $\Upsilon_{*,B} = 0.9 \pm 0.4\ ran \pm 0.1\ sys$
- UGC 463 range:



Bell et al.'03
Portinari et al.'04
Bell & de Jong'01

Zibetti et al.'09
better match

Importance of TP-AGB stars, e.g.:
Maraston'05, Conroy'08



Summary

- **2D Galaxy kinematics:** **dynamical mass decompositions**
- Galaxy disks are ***sub-maximal*:** $\left\langle V_{\rm max}^{\rm disk} / V_{\rm rot} \right\rangle = 0.5 \pm 0.2$

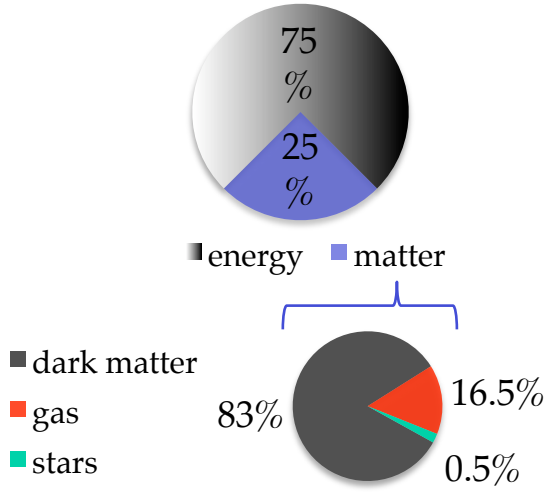
  15-30% by mass at $2.2h_R$ (Max disk: 0.85 ± 0.1)

  ★ *increases with galaxy scale*

  - M/L model zero-points: **~ −0.5 dex adjustment** $(0.15 < \Upsilon_{*,K} < 0.45)$

    e.g., Komatsu et al. '09 (WMAP)

    - Challenges for population-synthesis models
      - IMF, TP-AGB ?
    - Do we understand how Υ_* evolves?
    - No room for disk dark-matter



- **Baryon matter fraction f_b already small (17%)**
- ***Fraction in stars today: ~ 0.5%***