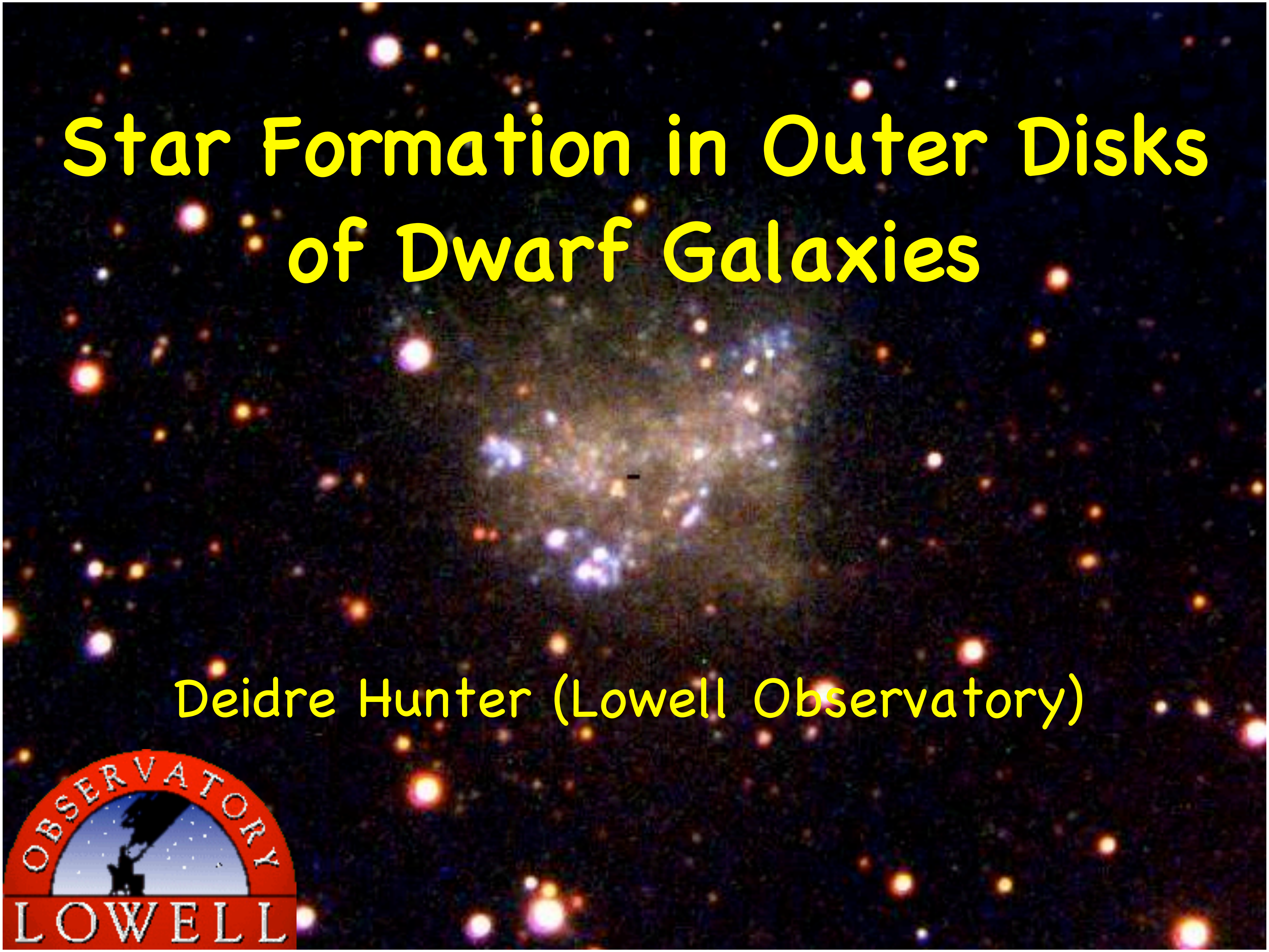
Star Formation in Outer Disks of Dwarf Galaxies

Deidre Hunter (Lowell Observatory)



Motivation

- Star formation processes in outer stellar disks of dwarfs
- The role of the gas in determining the nature of stellar disks

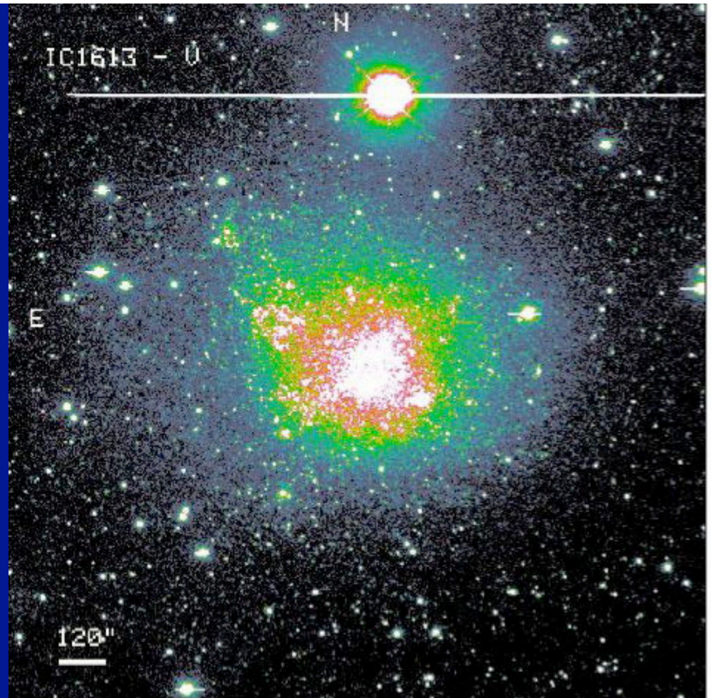
Data and Collaborators

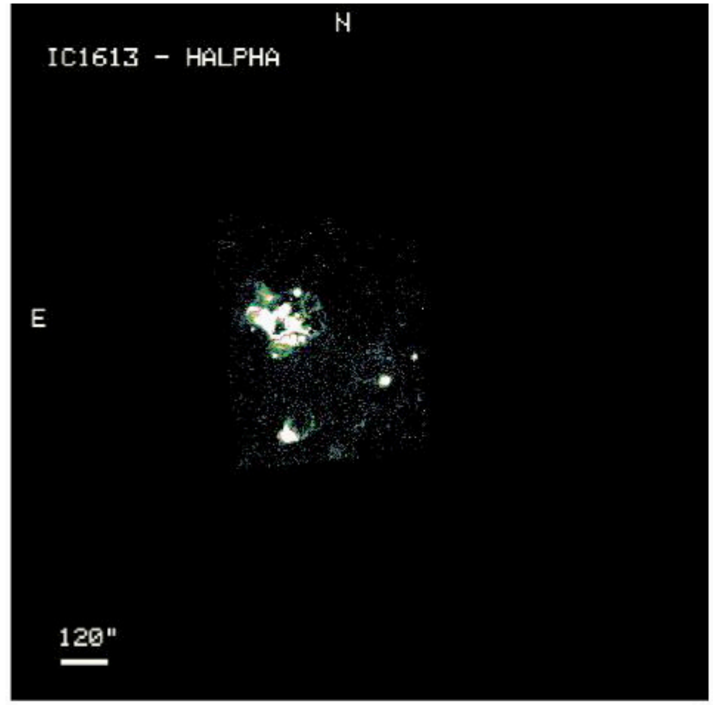
- Ultra-deep optical (*B,V*) and *GALEX* imaging (5 dIm)
- *GALEX* imaging (29 dIm, 8 BCDs, 7 Sm)
- HI profiles (15 dIm, 2 BCDs, 2 Sm)
- Larger survey: *UBVJHK*,Hα imaging

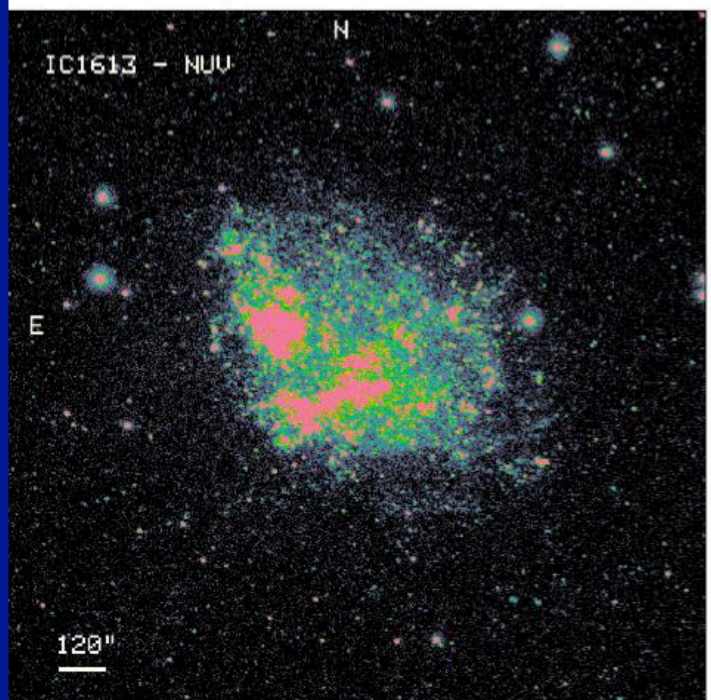
Collaborators:

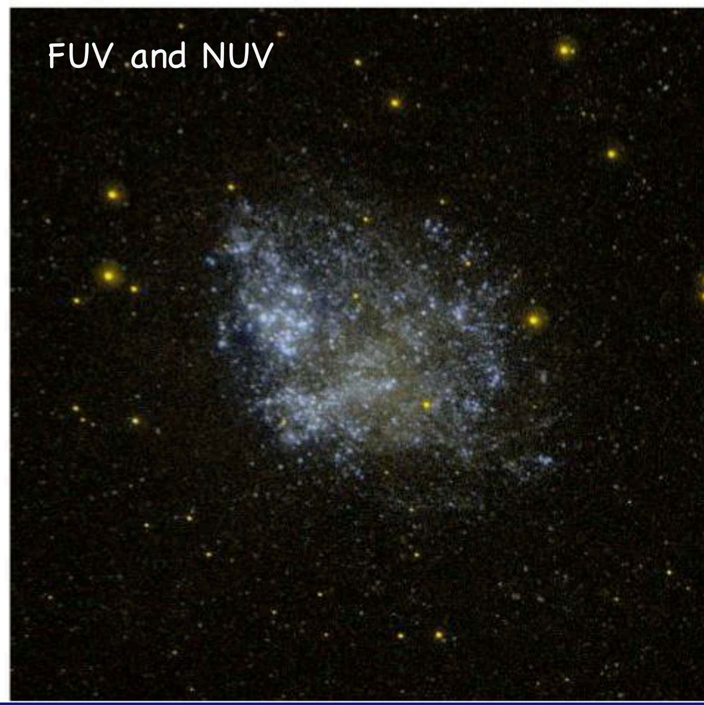
- Bruce Elmegreen (IBM T. J. Watson Research Center)
- Ed Anderson (Northern Arizona Univ)
- Phil Massey (Lowell Observatory)
- Tyler Nordgren (Redlands Univ)
- Bonnie Ludka (undergraduate, James Madison Univ)
- Nick Melena (undergraduate, Univ Arizona)
- Malanka Riabokin (undergraduate, Univ Wisconsin)
- Nicholas Wilsey (undergraduate, Truman State Univ)
- Lea Zernow (undergraduate, Harvey Mudd)

An example of the data: IC1613



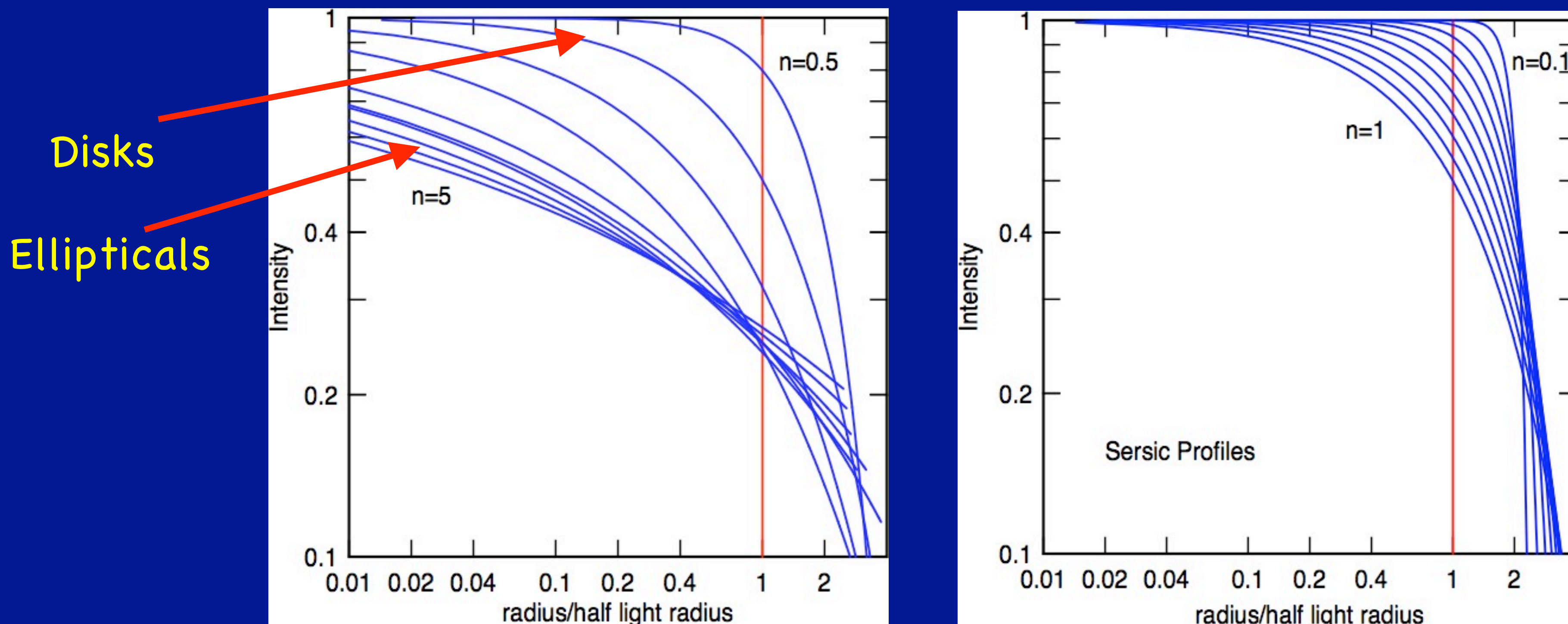






We fit the fall-off of the gas surface density with a Sersic function:

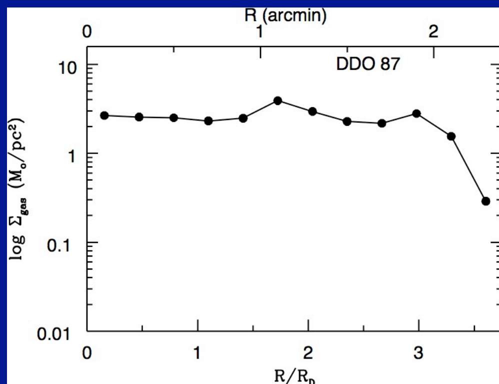
$$\log \Sigma_{gas}(R) = (\log \Sigma_{gas})_0 - 0.434\ (R/R_0)^{1/n}$$



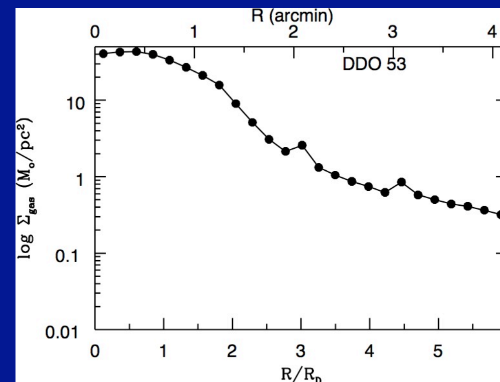
➔ HI profiles of dwarfs are fit well with n≤1.

➔ There's a wide variety of gas fall-offs with radius.

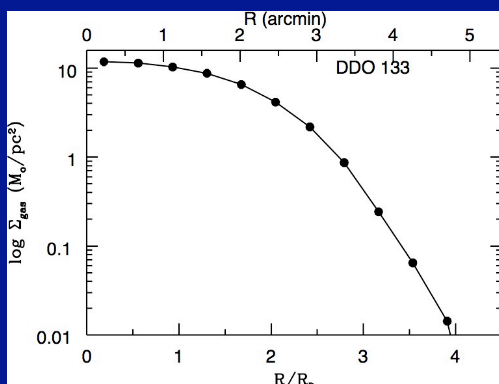
Flat



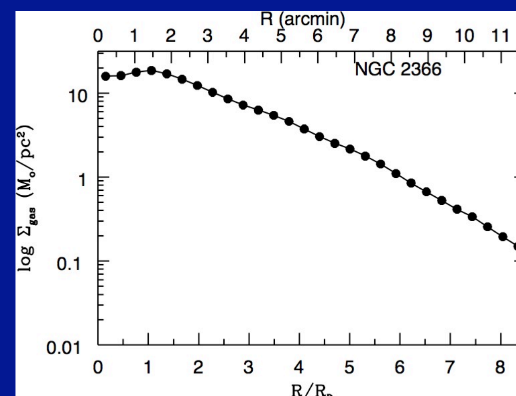
Two parts



n=0.29



n=0.67



But, does the variety of gas profiles translate into observable differences in the optical galaxy?

Parameterized the rotation curve:

$V_R = V_c / (1 + x^{\gamma})^{1/\gamma}$

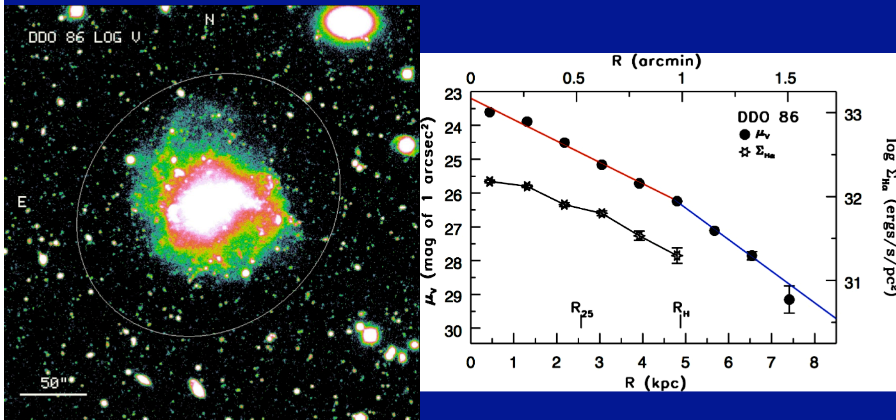
- V_C - asymptotic velocity
- $x = R_t / R$
- R_t - turnover radius
- γ - Sharpness of turnover

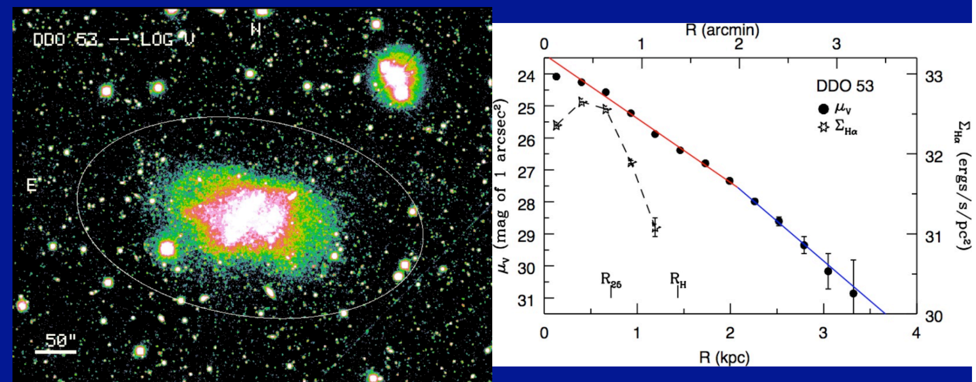
(Courteau 1997)

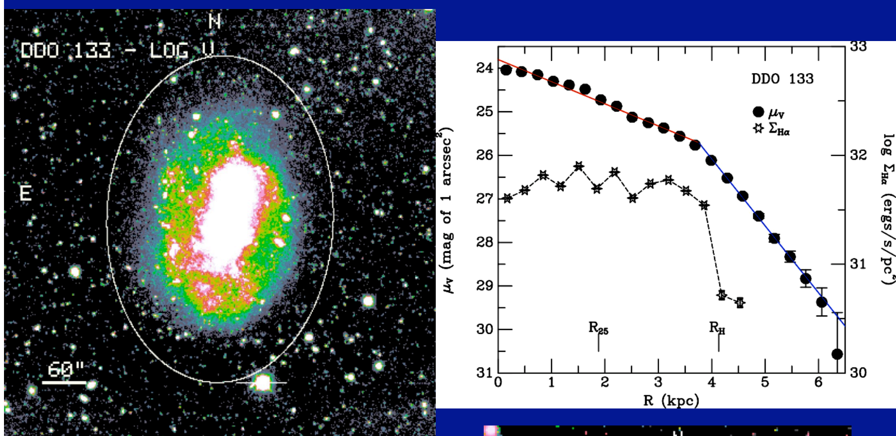
For Andreas Burkert

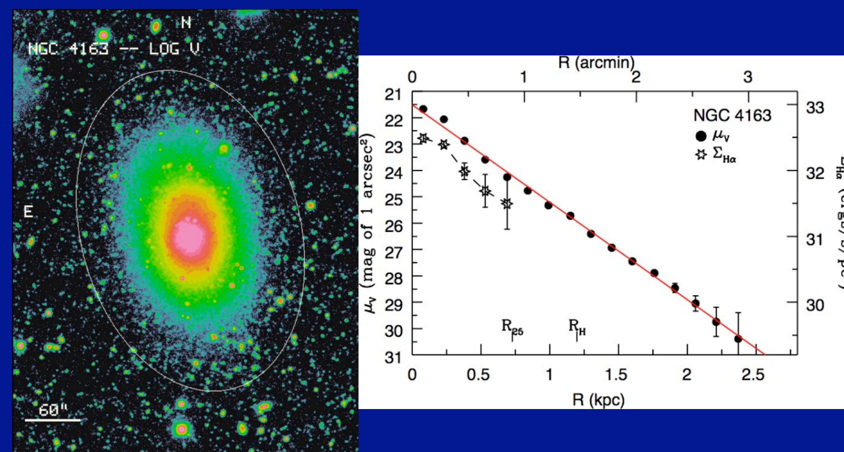
Disk extents

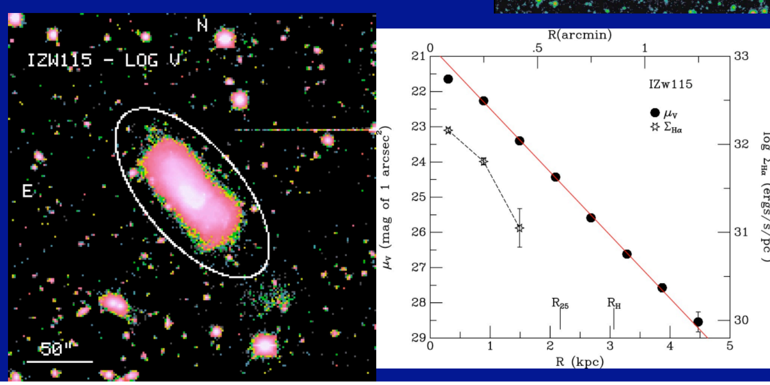
Deep optical imaging…to μ_V~30 mag/arcsec^2







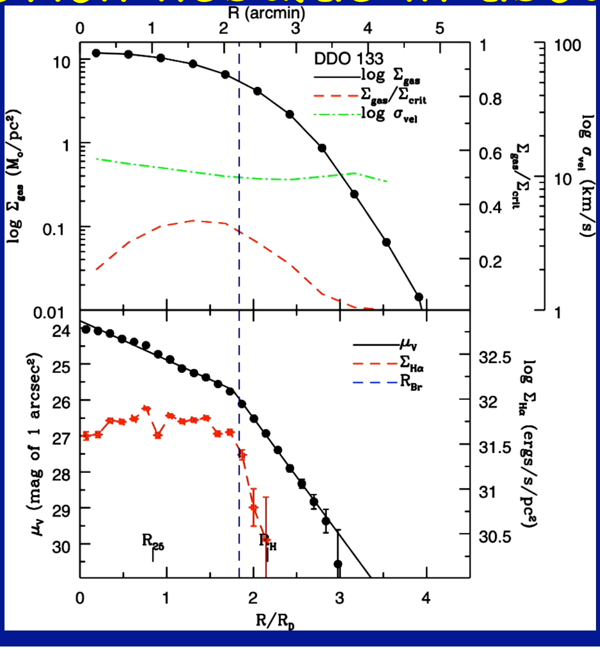




→ Outer galaxy continues as far as we measure it.

To μ_V of 29-30 mag/arcsec^2.

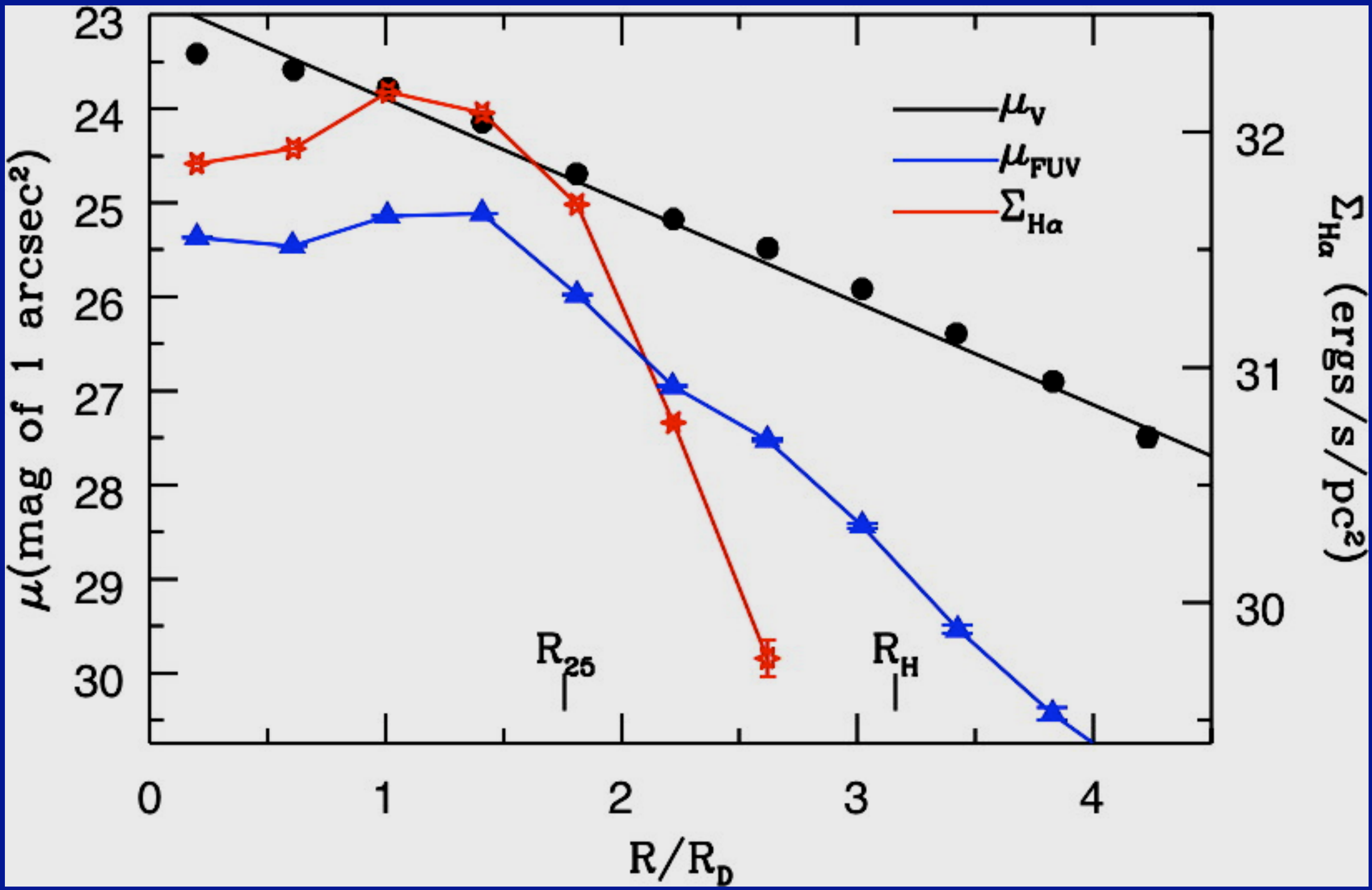
What does this mean? In DDO 133, that's ×160 down from the center. A 1 kpc-wide annulus at 29.5 mag/arcsec^2 corresponds to a star formation rate of 0.0004 $M_\odot$/yr, for constant star formation, or roughly 7 Orion nebulae in about 10 Myrs.



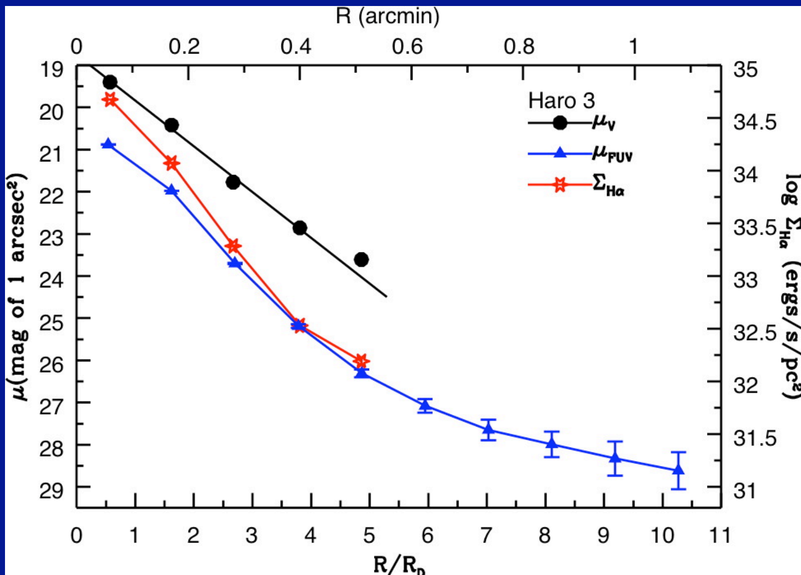
The Toomre model predicts a precipitous end to star formation where $\Sigma_{gas} = \Sigma_{crit}$. These data go into the realm of highly sub-critical gas---1/20 Σ_{crit}.

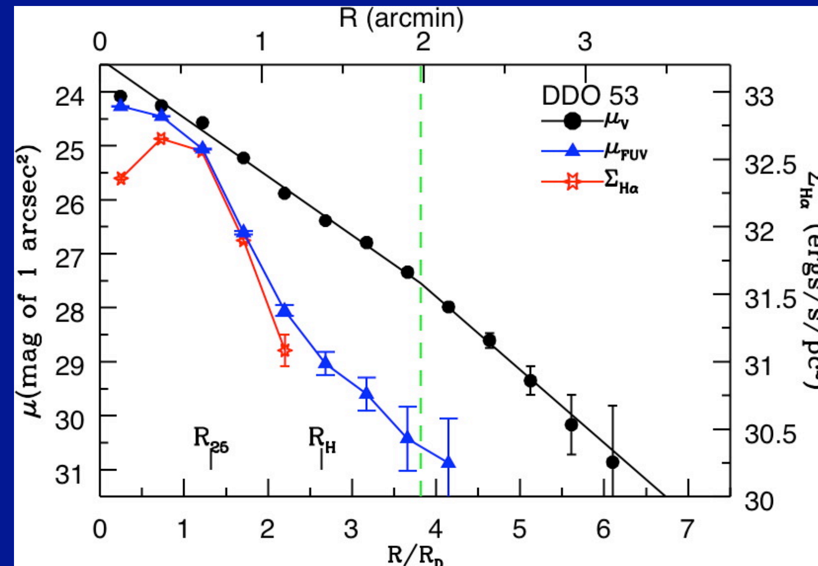
An example of the data: IC1613

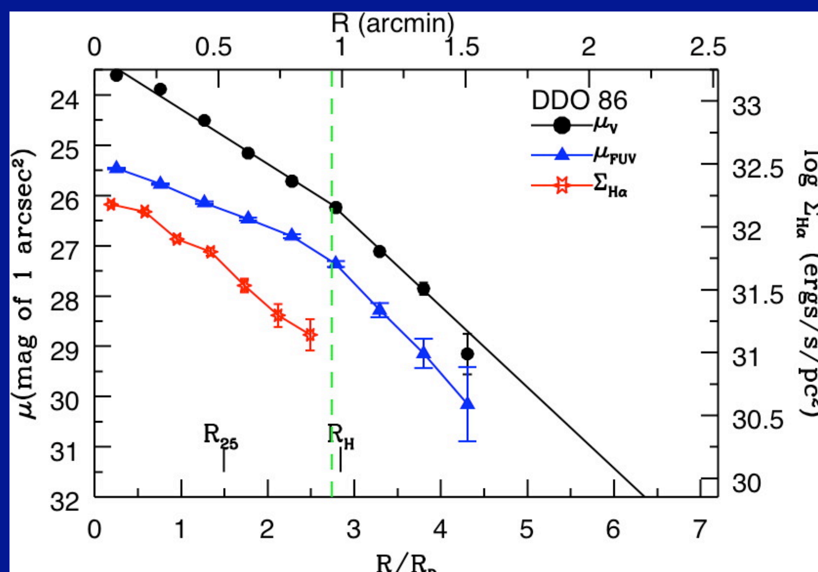
FUV continues beyond Hα in most dwarfs



With no end in sight…even to $0.1\ M_\odot/pc^2$

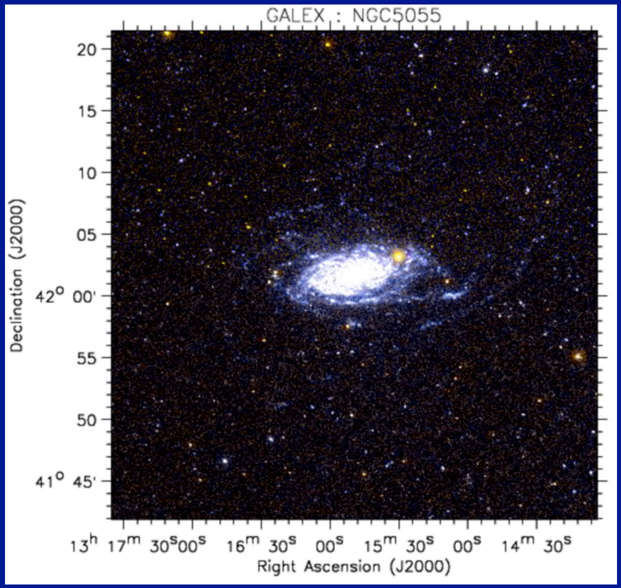




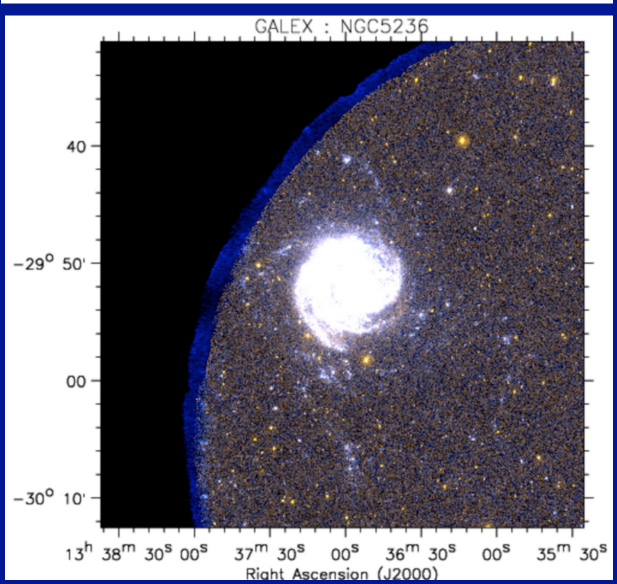


Not just dwarfs

- Deep Ha imaging reveals HII regions in spiral outer disks. (Ferguson et al. 1998; Werk 2008 and this meeting)
- *GALEX* UV imaging: extended UV disks with clumps. (Thilker et al. 2007a and this meeting)
  - *HST* CMDs: Clumps are low mass, evolved OB associations. (Thilker et al. 2007b)

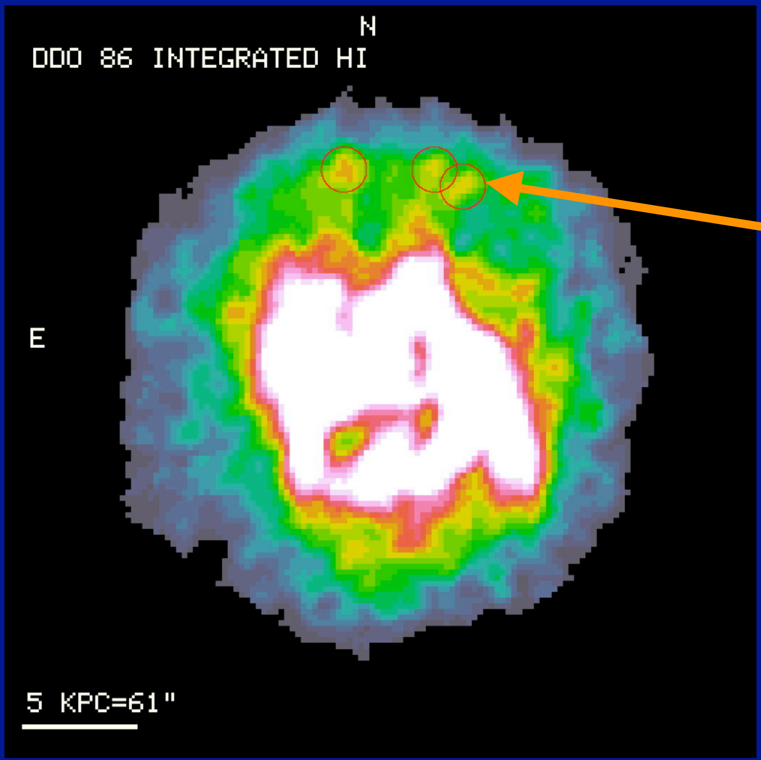


M63



M83

How can star formation take place in outer disks?

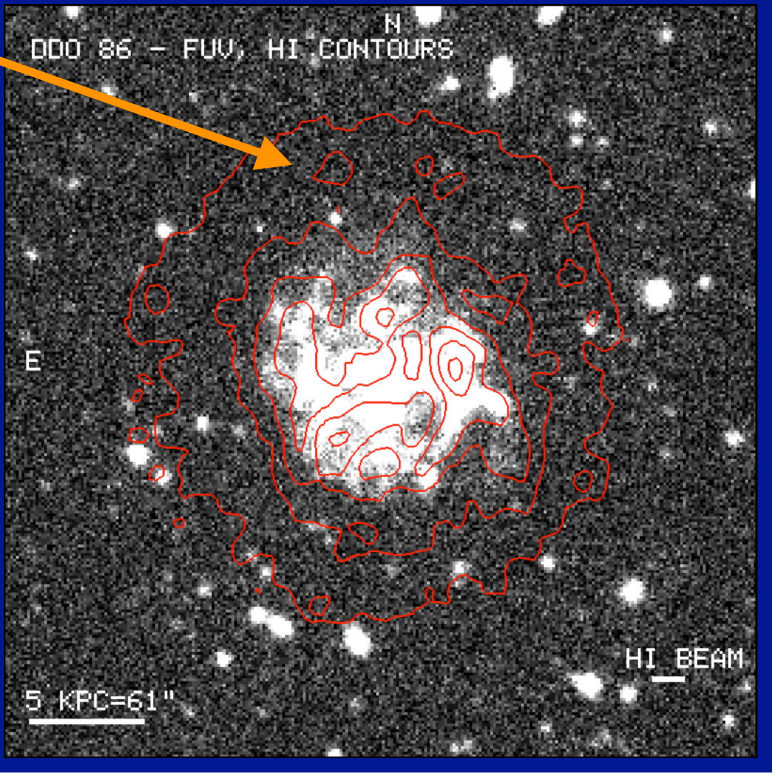


Hunter et al., in prep; Beam 17″×14″

DDO 86: Average in outer parts: 3× 10^{20}/cm^2, std dev of 1×10^{20}/cm^2.

Peaks in outer parts, R=8-9 kpc = 5R_D: 5×10^{20}/cm^2.

But…

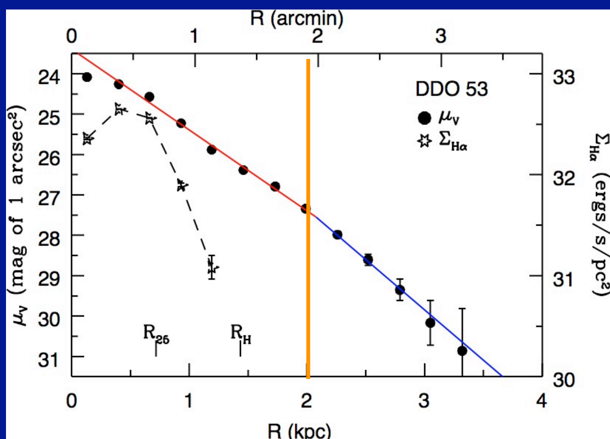


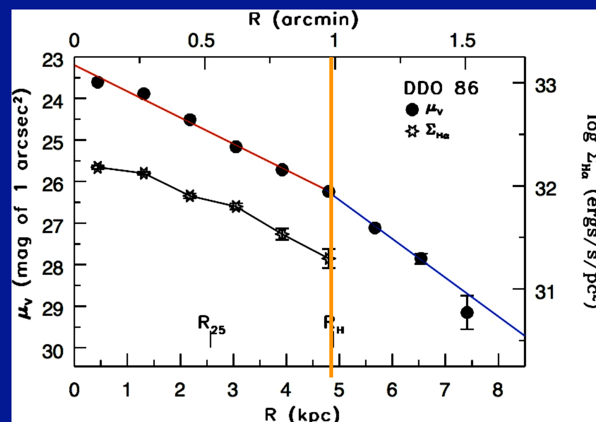
Disk Extents

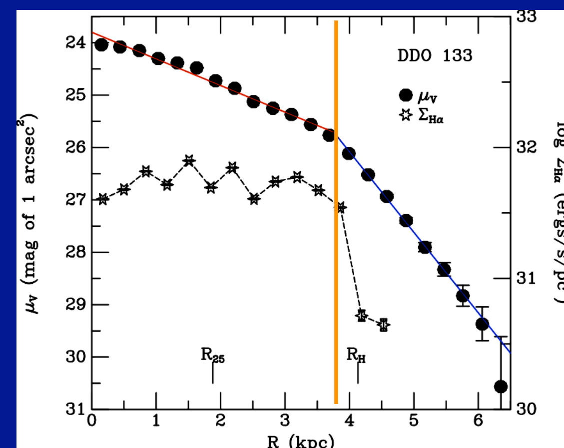
➔ Dwarf disks can be traced to very low stellar surface densities, with no obvious end in sight.

Double exponential profiles

➔ Sometimes there is a change in slope in the outer exponential disk.



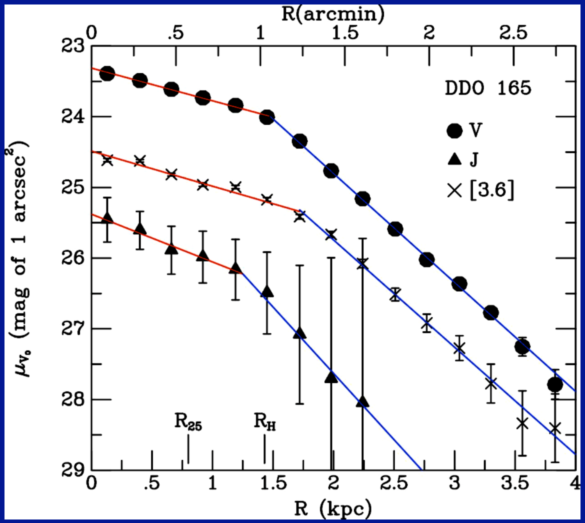




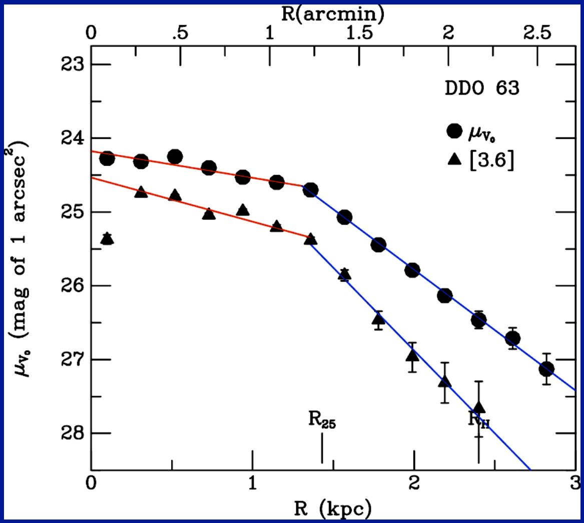
Shallow survey: 24% of 94 dIm have a steeper outer exponential disk.

The break is there in other passbands.

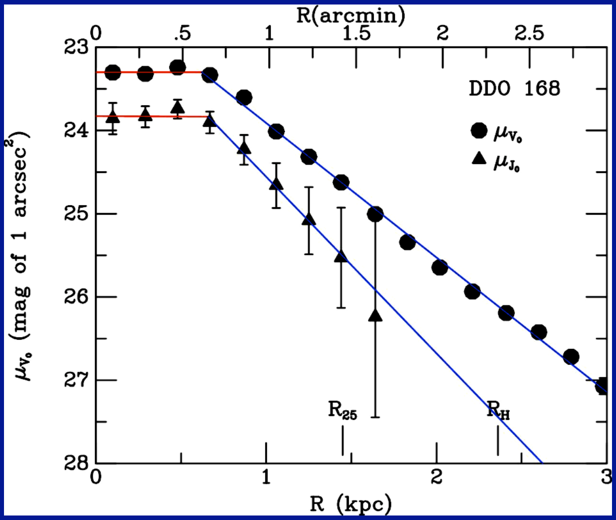
V, J, and 3.6 μm

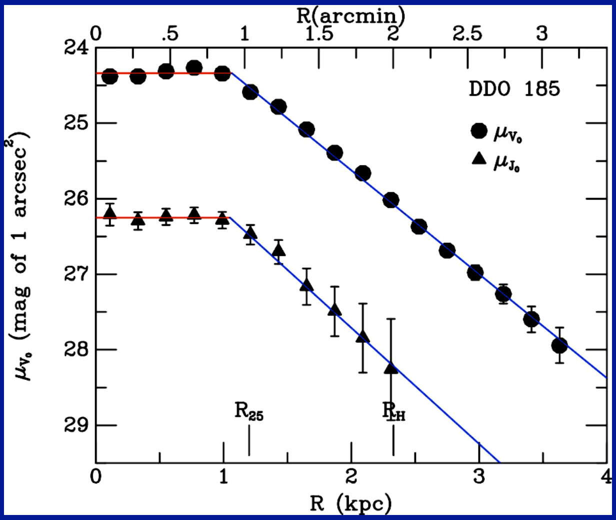


V and 3.6 μm



V and J

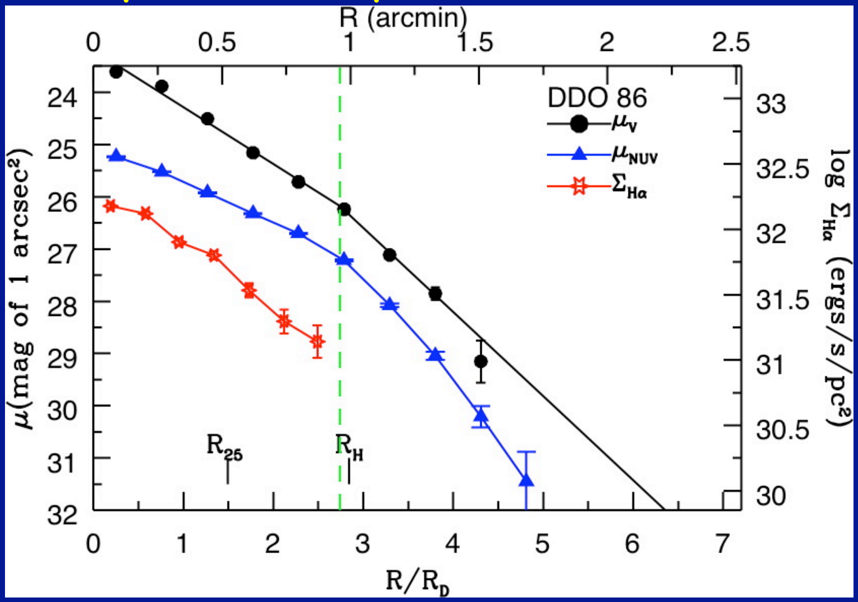




Hunter, Elmegreen, & Martin (2006)

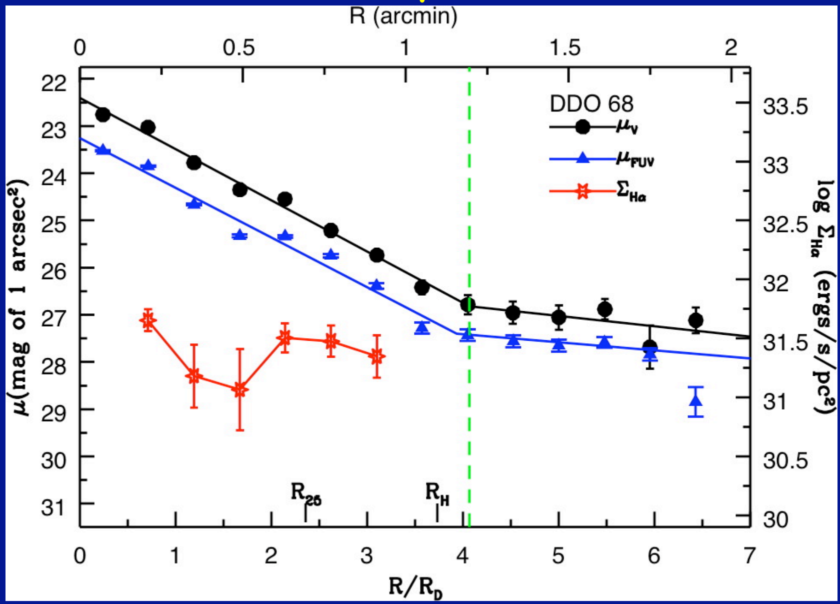
Double exponential *NUV* profiles

Steeper outer profile:



9/30 dIm, 4/7 Sm

Shallower outer profile:



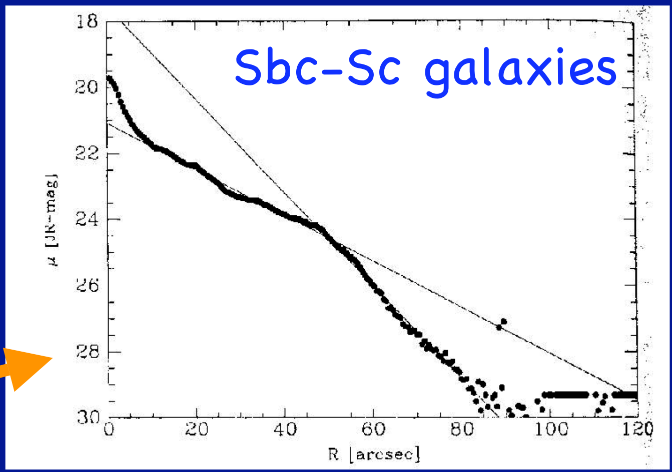
1/30 dIm, 5/8 BCDs

➔ A μ_V break almost always means a μ_{NUV} break

Steeper outer profiles in spirals

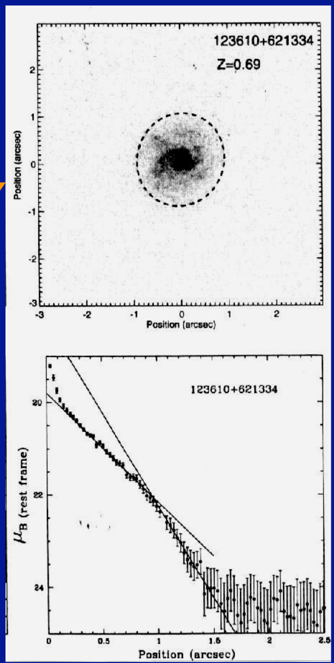
- Outer parts of spirals
  - Van der Kruit & Shostak 1982
  - Shostak & van der Kruit 1984
  - Bell et al. 2000
  - De Grijs et al. 2001
  - Kregel et al. 2002
  - Pohlen et al. 2002
  - MacArthur et al. 2003
  - Kregel & van der Kruit 2004
- Low luminosity spiral
  - Simon et al. 2003
- High redshift disks (0.6 < z < 1.0)
  - Pérez 2004 (6/16 galaxies)

μ_{JR}



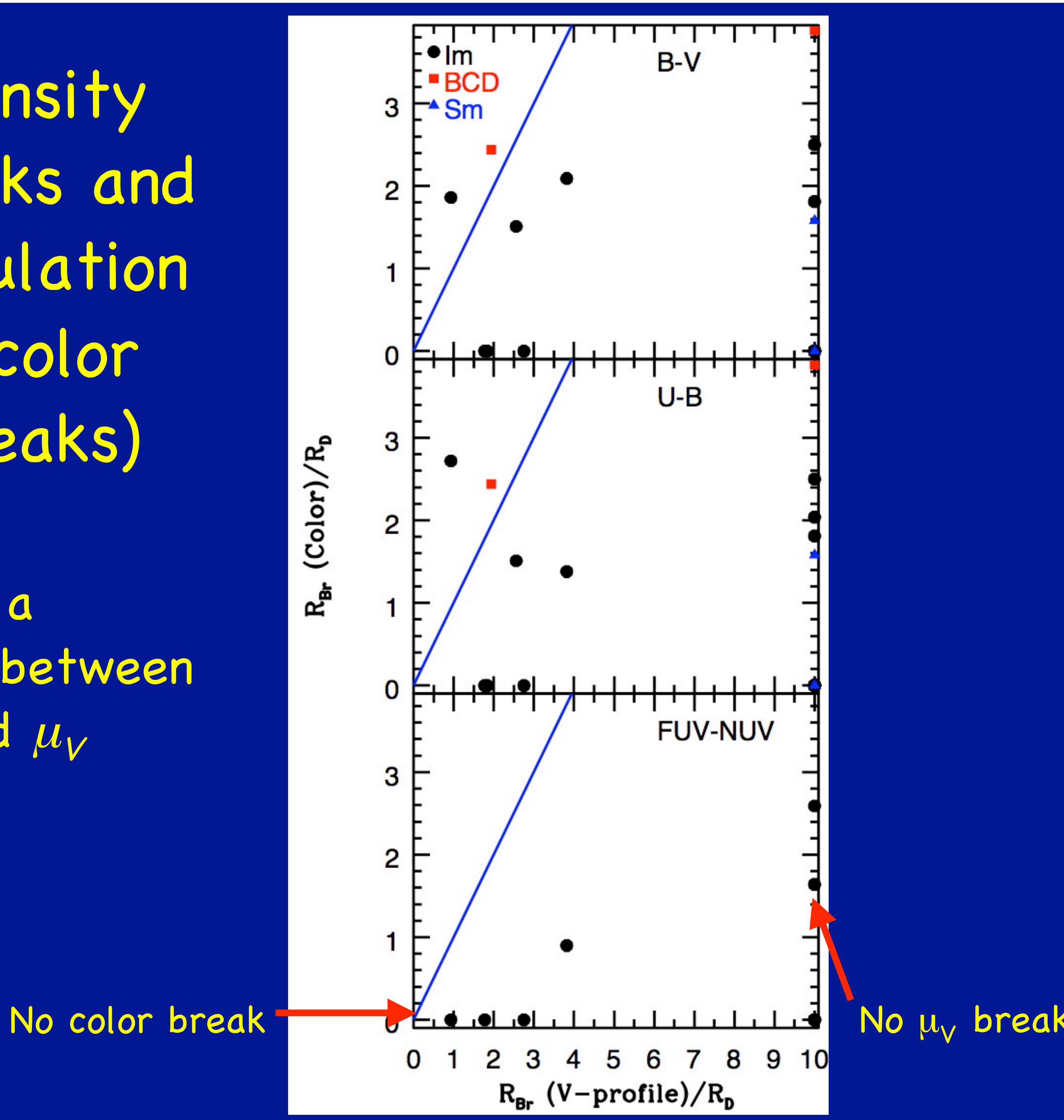
R (arcsec)

Sa-Sc galaxies

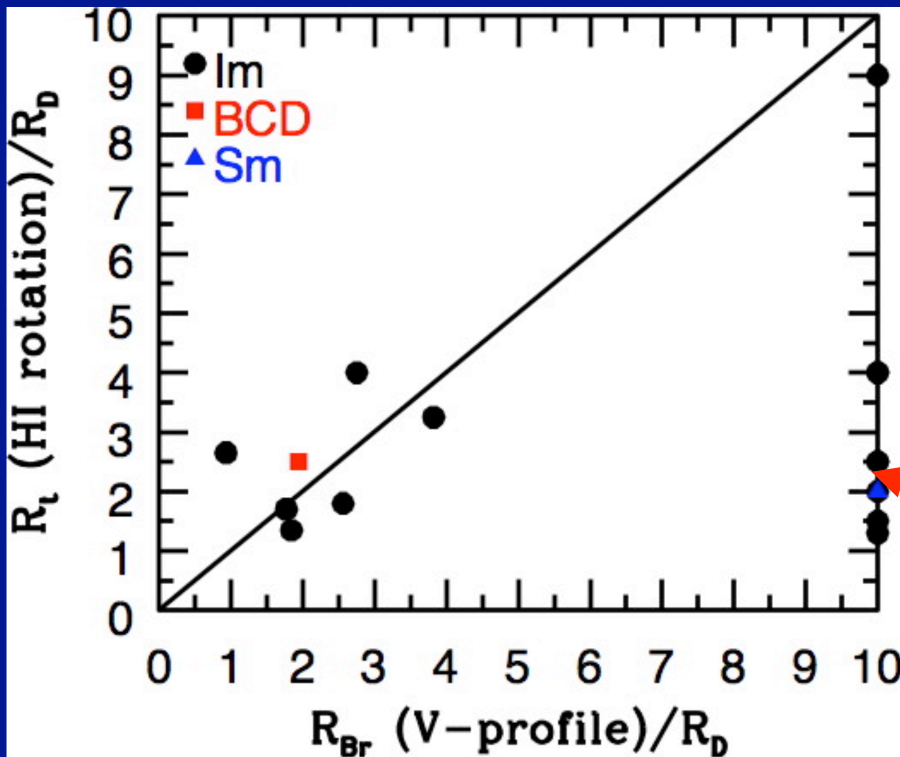


Stellar density profile breaks and stellar population changes (color profile breaks)

➔ Not much of a correspondence between color breaks and μ_V breaks



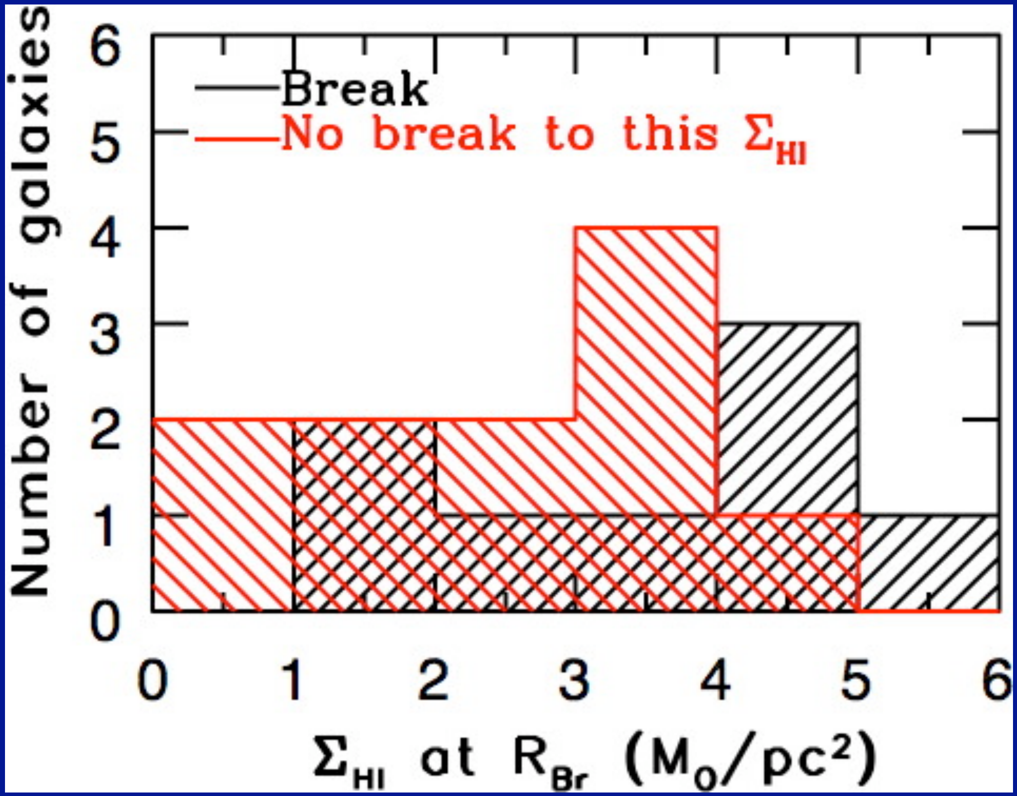
Stellar density profile breaks: Rotation curve



No break in stellar density as far as we measure it

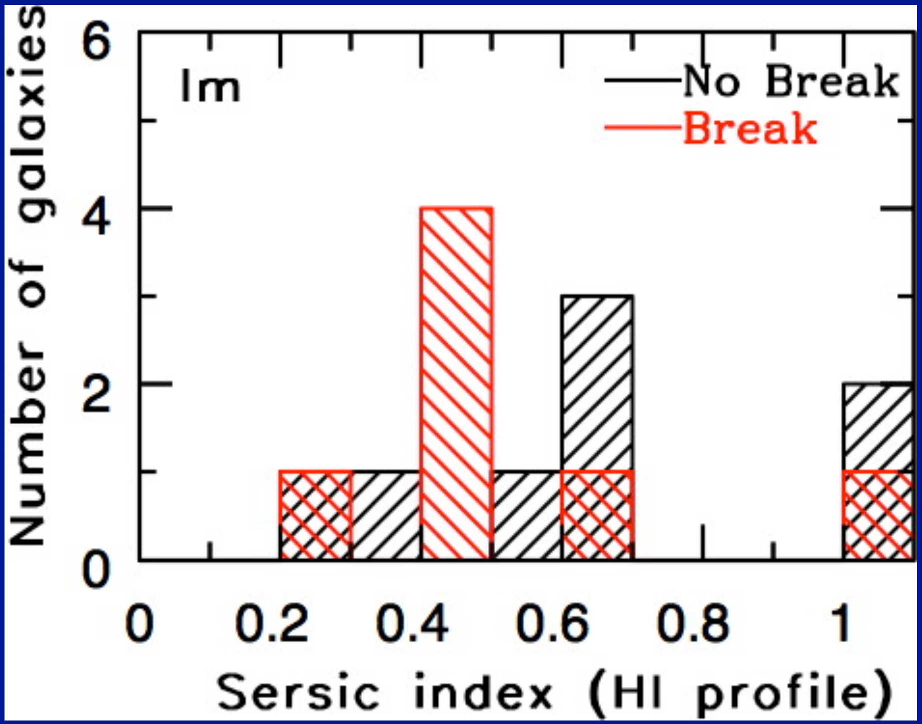
➔ Breaks occur at roughly the rotation curve turnover radius, but not a necessary condition.

Stellar density profile breaks: Gas density

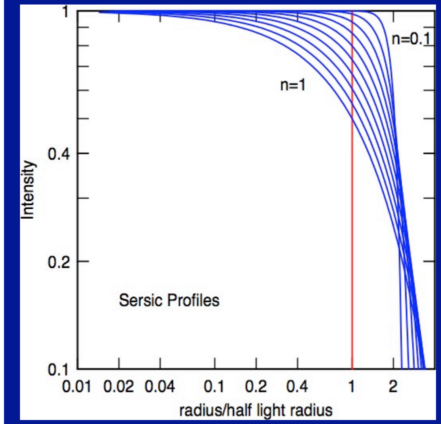


➔ Breaks occur at modest Σ_{HI}, but not all galaxies have breaks at those Σ_{HI}.

Stellar density profile breaks: Sersic HI profiles



n



➔ Galaxies with optical profile breaks have HI profiles with lower, on average, Sersic n.

Double Exponential Profiles

➔ Stellar surface brightness profile breaks correlate somewhat with the kinematics and shape of the HI profiles.

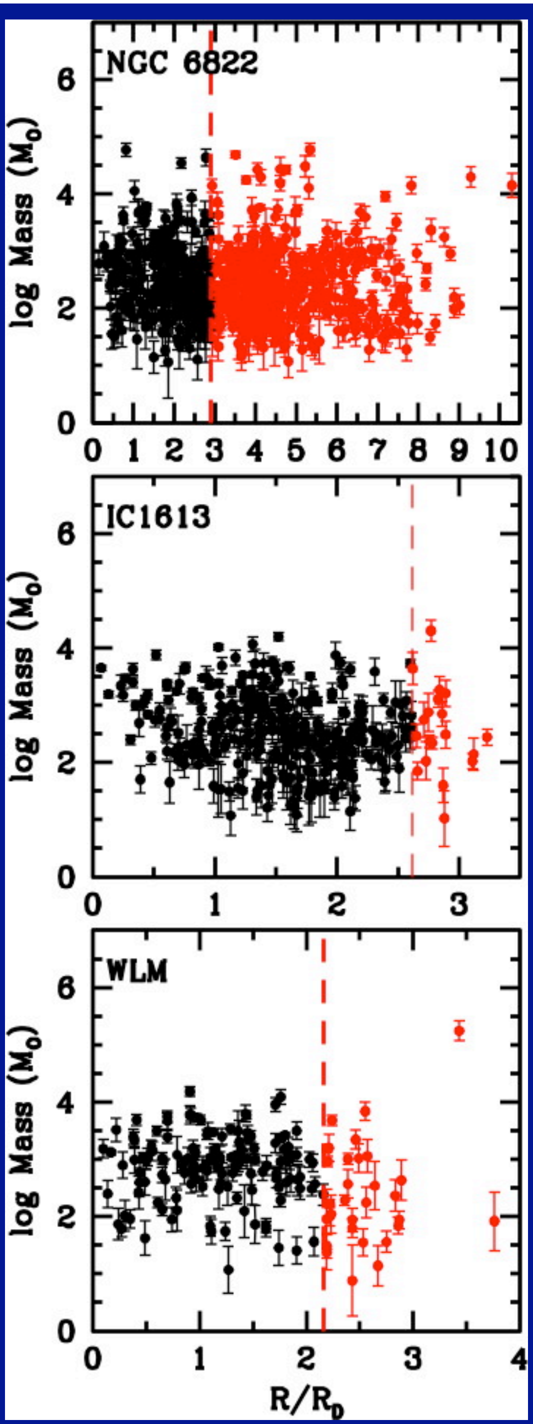
Young regions in the outer disk

Do young regions in the outer disk differ from those in the inner disk?

➔ Not usually. Young regions in the outer disk cover the same range in masses and ages as those in the inner disk.

Red: Beyond Hα emission

From sample of 11 dIm.

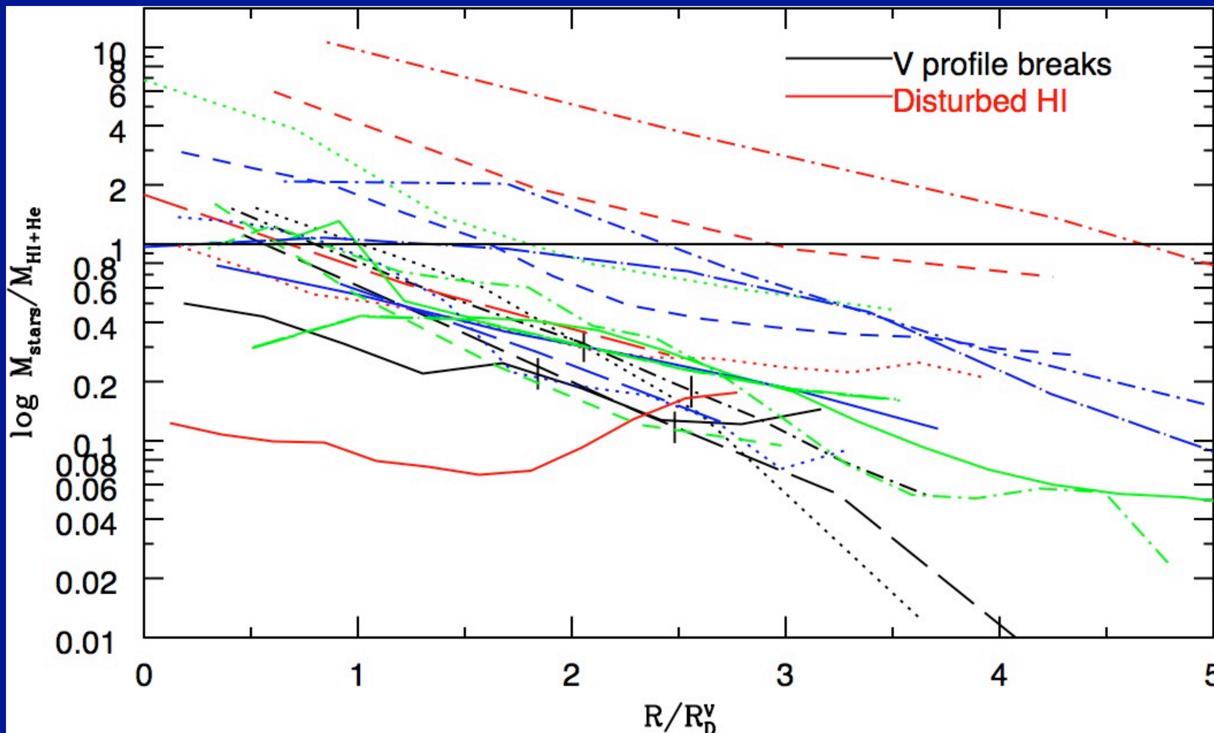


Young regions in the outer disk

➔ The star formation products are the same in the outer disk as in the inner disk.

Star Formation Rate profiles

M_{stars}/M_{gas}



$M_{stars} > M_{gas}$

$M_{stars} = M_{gas}$

$M_{stars} < M_{gas}$

➔ In most, the galaxy is gas-dominated and becomes increasingly gas-rich with radius.

➔ Implies a steadily decreasing large-scale cloud formation efficiency. (See Leroy et al. 2008; Frank Bigiel's talk on Monday)

Surface Photometry → Star formation rates

Salpeter IMF, 0.1–100 $M_\odot$

$$SFR_{FUV}(M_\odot/yr) = 1.08\times10^{-28}\ L_{FUV}(ergs/s/Hz)$$

Kennicutt (1998), Salim et al. (2007)

$$SFR_{H\alpha}(M_\odot/yr) = 6.9\times10^{-42}/1.15\ L_{H\alpha}(ergs/s)$$

Kennicutt (1998), Leitherer et al. (1999)

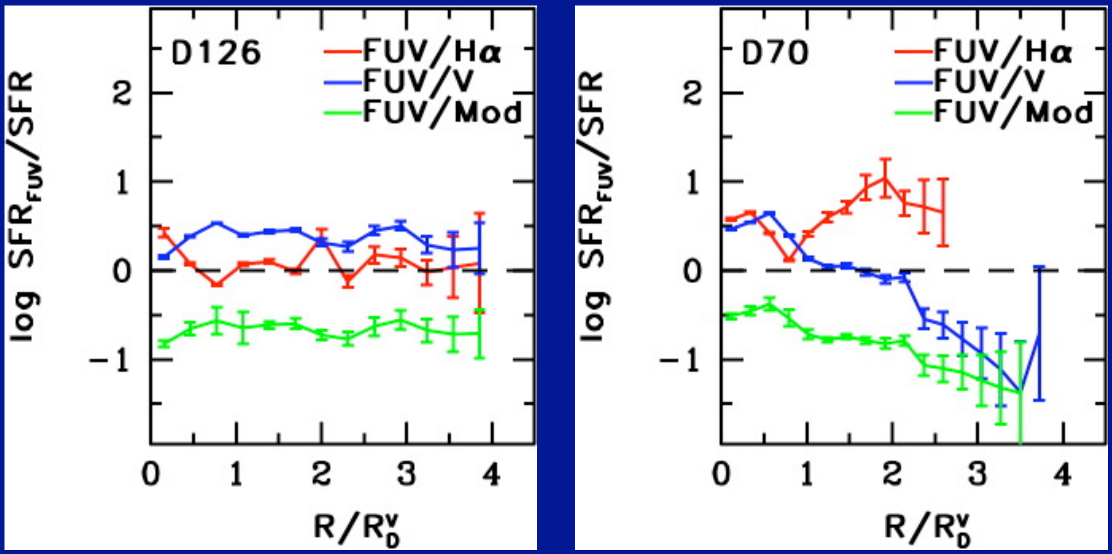
$$SFR_V(M_\odot/yr) = -0.4M_V + \log(M/L_V) - 8.143$$

M/L_V from B-V, age 12 Gyr, Bell & de Jong (2001)

$SFR_{Mod}(M_\odot/yr)$ - stellar population fits to colors

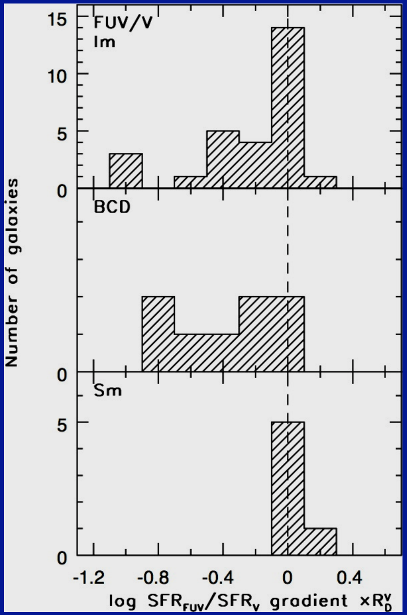
Bruzual & Charlot (2003)

SFR profiles



FUV dominates ↑

FUV/ V



➔ In most dIm and Sm the UV, Hα, *V*-band, and model SFRs track each other. But in some Im and BCD the *FUV* SFR decreases with radius relative to the *V*-band SFR.

FUV dominates in outer disk ➔

Modeling colors and surface brightnesses in the outer disk

Best fit with a SSP model instead of a constant SFR model. With age of order 1 Gyr.

➔ Star formation in the outer disk isn't continuous. Gaspy on Gyr time scales.

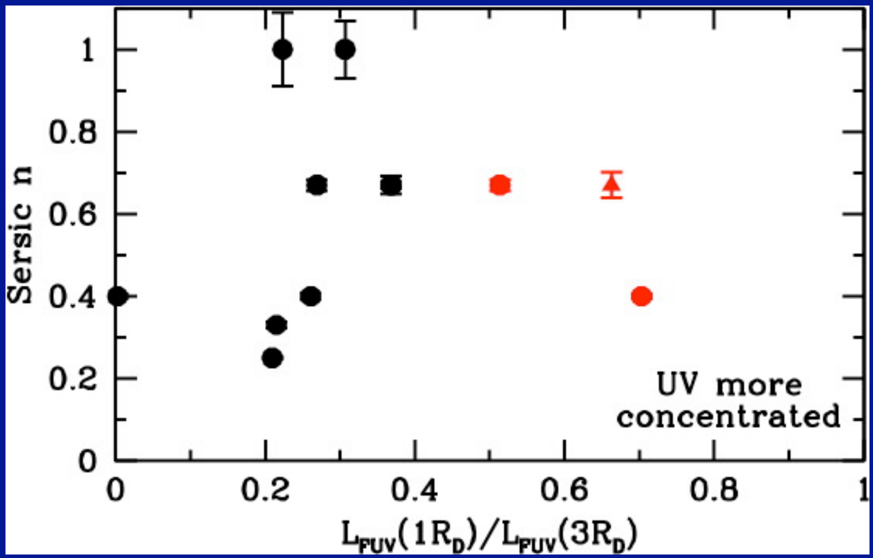
Star Formation Rate Profiles

- ➔ SFRs in the outer disk appear to be gaspy on Gyr timescales.

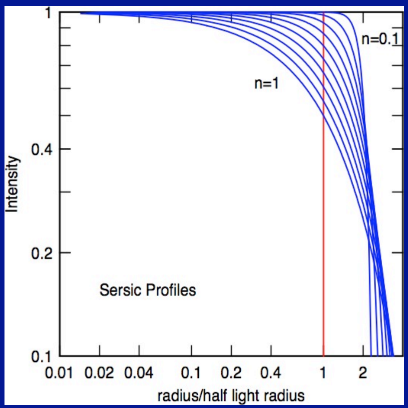
Integrated Star Formation Rates

The HI profile and central concentration of star formation

Sersic n



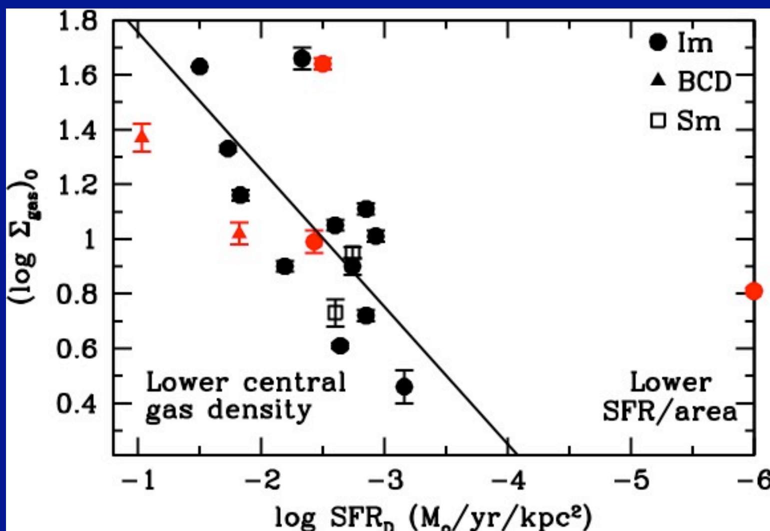
Degree of central concentration of recent star formation.



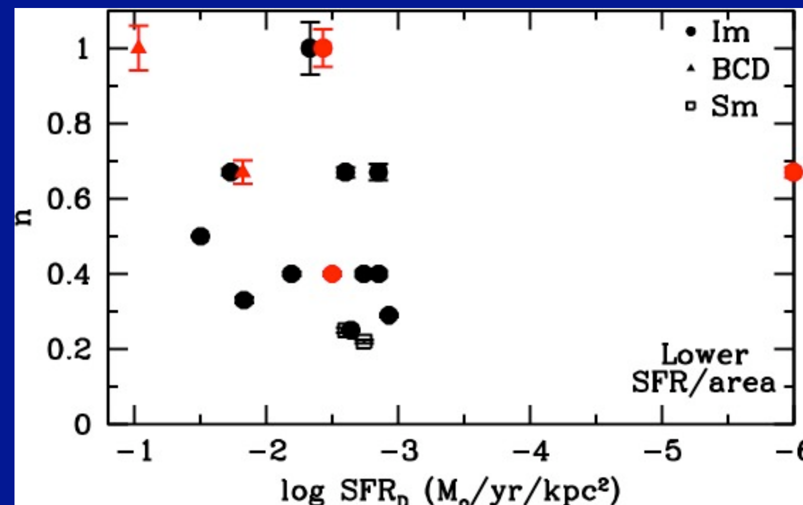
➔ Concentration of star formation to the galaxy center is not related to how the gas falls off with radius.

The HI profiles and integrated star formation rates

Central gas density



Sersic n



$SFR/\pi R_D^2$ measured from $H\alpha$

➔ The higher the central gas density, the higher the integrated star formation rate.

Integrated Star Formation Rates

➔ Integrated SFRs depend only on the central gas density. Why?

Summary

- Stars form in extreme outer disks---regions of very low average gas densities.
- No edges yet, but sometimes complex surface brightness profiles.
- Large-scale star formation efficiency (ability to turn gas into star-forming clouds) decreases steadily into the outer disk.
- No obvious change in young region properties with radius.
- The role of the gas in determining the stellar disk properties is subtle.

➔ A very nice challenge for star formation models

The LITTLE THINGS Survey: HI maps of 42 dIm

Co-Is: Brinks, Elmegreen, Rupen, Simpson, Walter, Westpfahl, Young