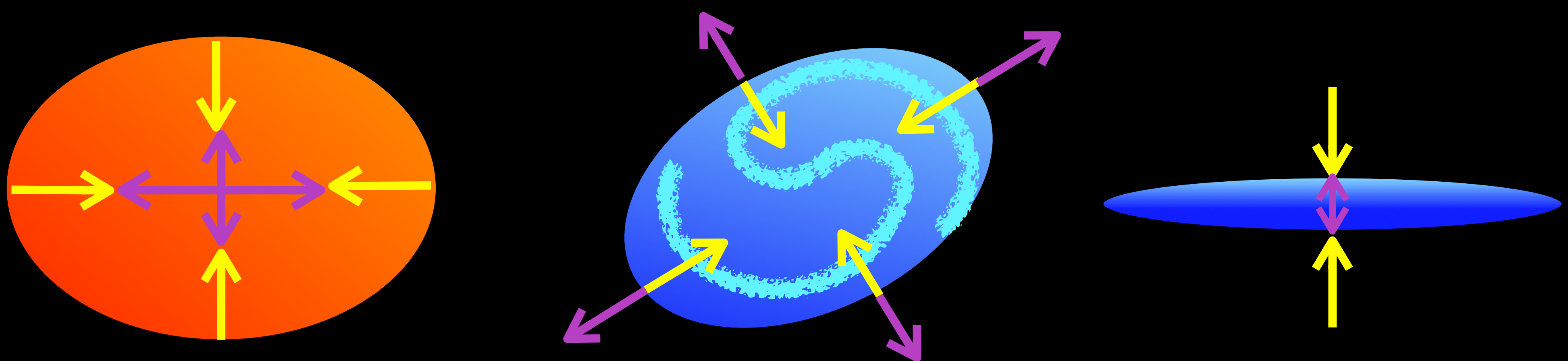
Topics

- What sets the scale of galaxies?
- Characterizing galaxy structure
  - Surface brightness
- Structural parameters
  - Disks
  - Ellipticals
  - Bulges

To first order, many galaxies today can be treated as systems in equilibrium

Gravity: Pulls matter inwards

Motion: Resists the inward pull



Elliptical

Random motion + rotation

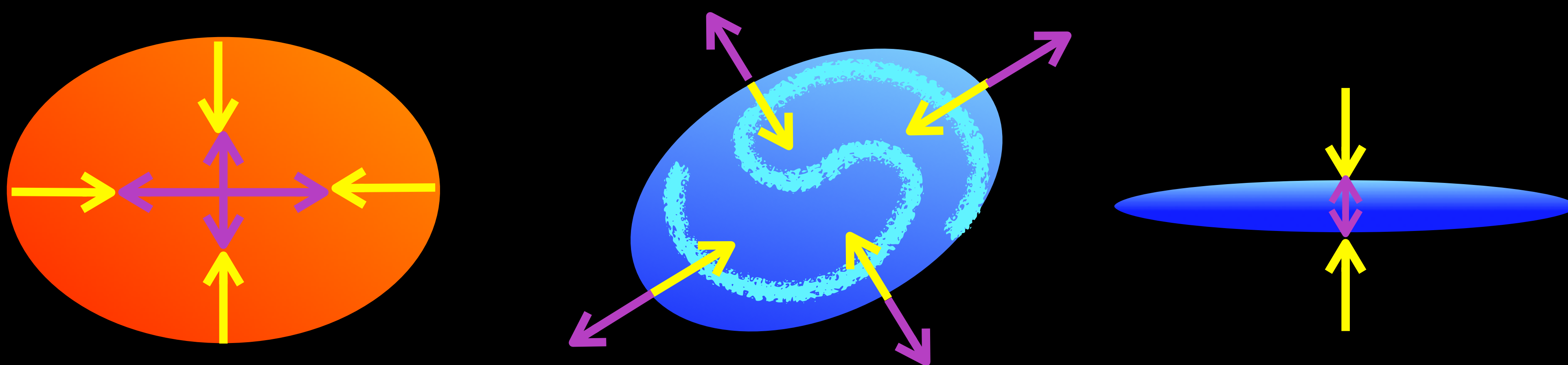
Spiral Disks

Rotation

Random motion

There is information in the equilibrium structures

Characterstic size vs mass?
Characteristic surface density vs mass?



Elliptical Spiral Disks

Size, Surface Density, & Mass

- Size
  - Use "half-light radius" as proxy
  - r_{50} = radius containing half the total light
- Surface density
  - Use surface brightness (stellar light per area) as a proxy for surface mass density
  - "effective surface brightness" μ_{50} defined as average surface brightness within r_{50}
- Mass
  - Use luminosity as a proxy

1. Fainter galaxies are smaller

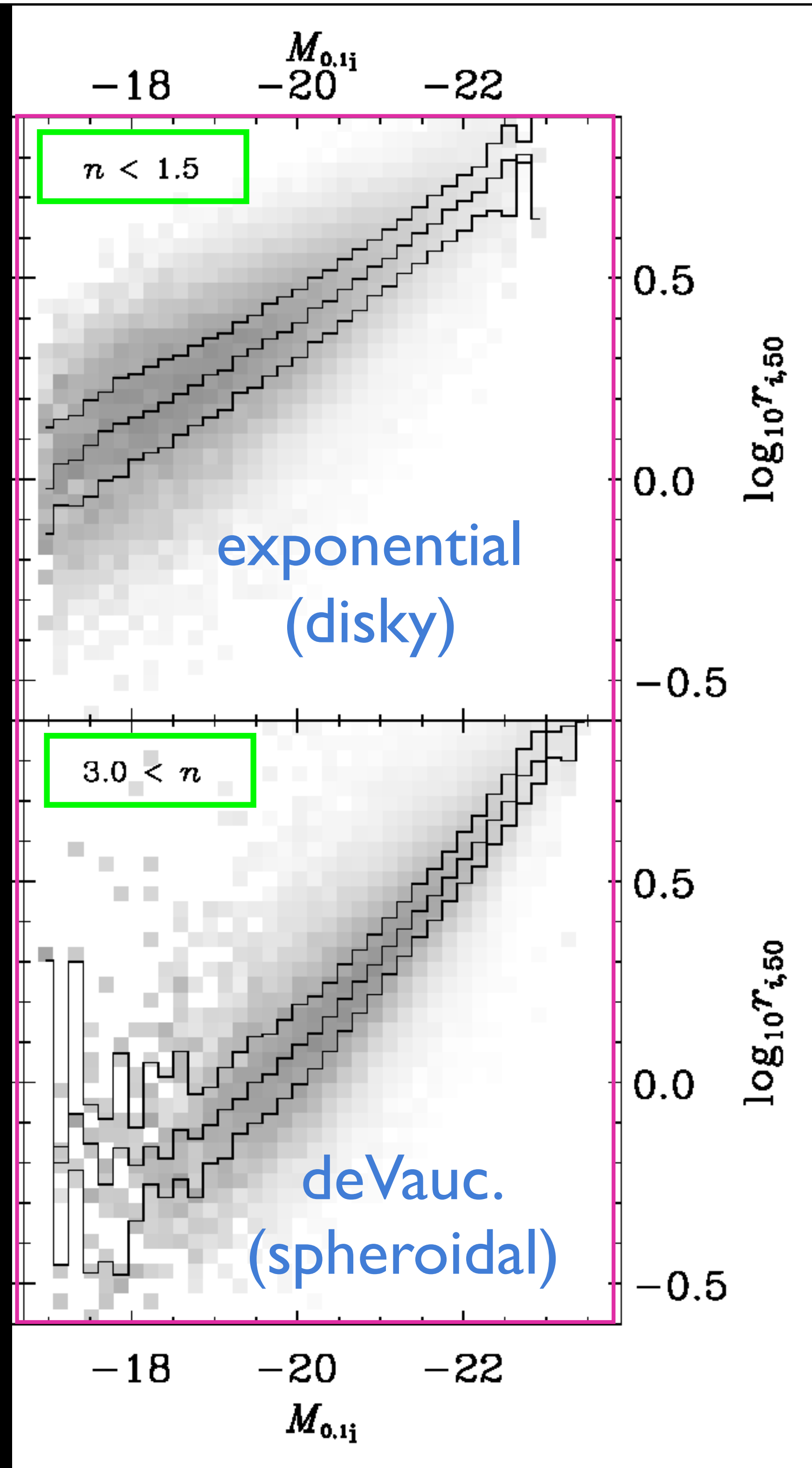
Massive Ellipticals: r_{50} ~ 10 kpc

Massive Spirals: r_{50} ~ 5-8 kpc

Dwarfs: r_{50} ~ 1 kpc

Blanton et al 2003 **(r_{50} in h^{-1} kpc)**

This analysis corrects for relative numbers. At each absolute magnitude, the vertical grayscale indicates the relative distribution of sizes.



2. Fainter Galaxies have lower surface brightnesses

But, the magnitude-surface brightness relation distribution is wide.

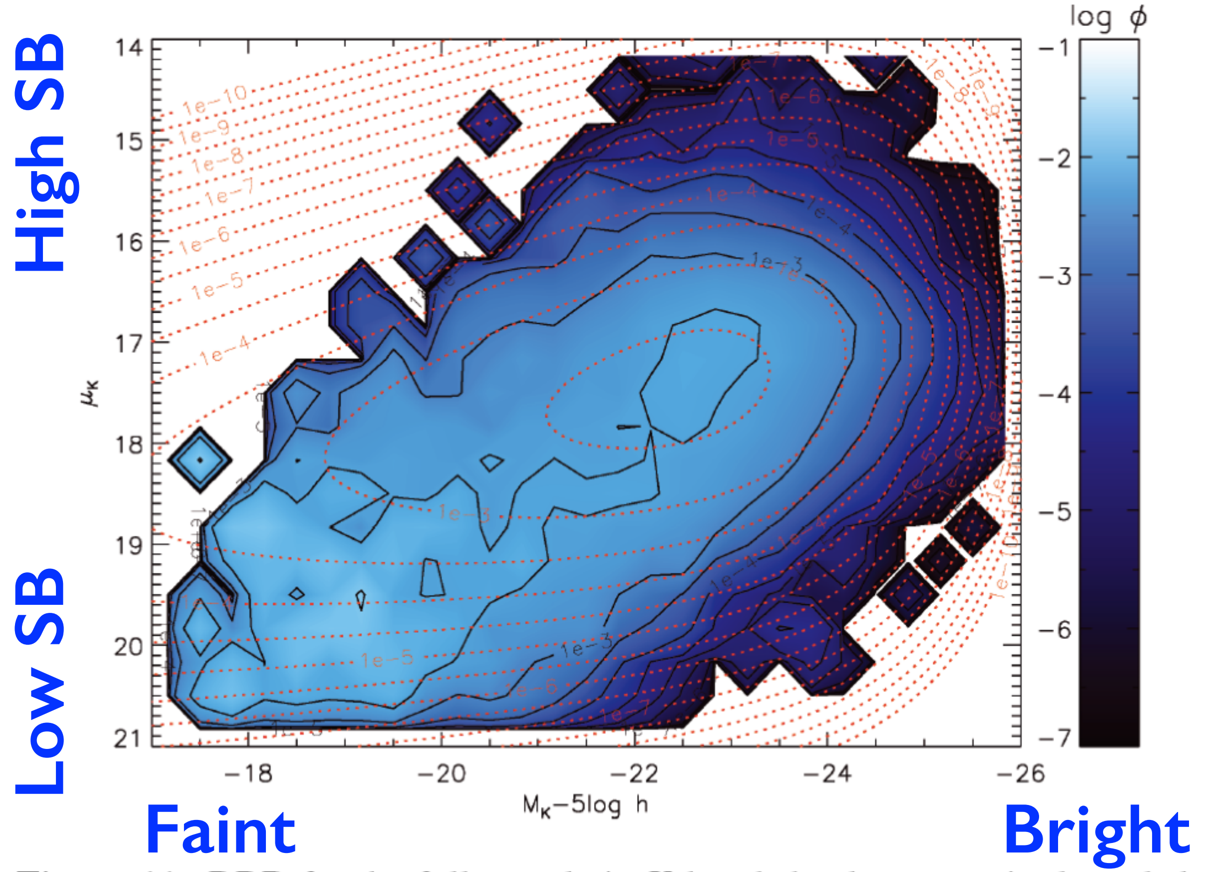


Figure 11. BBD for the full sample in K-band absolute magnitude and absolute effective surface brightness. Shaded regions and solid black contours show the space density, ϕ, as in Fig. 10. The best-fitting Chołoniewski function, estimated using $M_K - 5\log h < -20$ and $\mu_{e,abs} < 19$, is shown by the red dotted contours. Parameters of the fit are $M^* - 5\log h = -22.96$ mag, $\alpha = -0.38$, $\phi^* = 0.0201\, h^3\,\mathrm{Mpc}^{-3}$, $\mu^*_{e,abs} = 17.36$ mag arcsec^{-2}, $\sigma_{\mu_{e,abs}} = 0.672$ mag arcsec^{-2} and $\beta = 0.188$.

Watch selection effects!

("BBD"=bivariate brightness distribution)

Smith et al 2009

This basic behavior drops out of some simple assumptions for gaalxy formation

Not right in detail, but not a bad framework for estimating scalings

Principles of Galaxy Structure

- Initial overdensity
- Statistical properties of surrounding density field

Nature

- Mass
- Angular momentum
- Timing of collapse & subsequent accretion

Galactic structure

- Merging history
- Feedback from star formation & AGN
- Internal dynamics (instabilities, scattering, diffusion)

Nurture

For this exercise…

- Initial overdensity
- Statistical properties of surrounding density field

- Mass
- Angular momentum
- Timing of collapse & subsequent accretion

Nature

Galactic structure

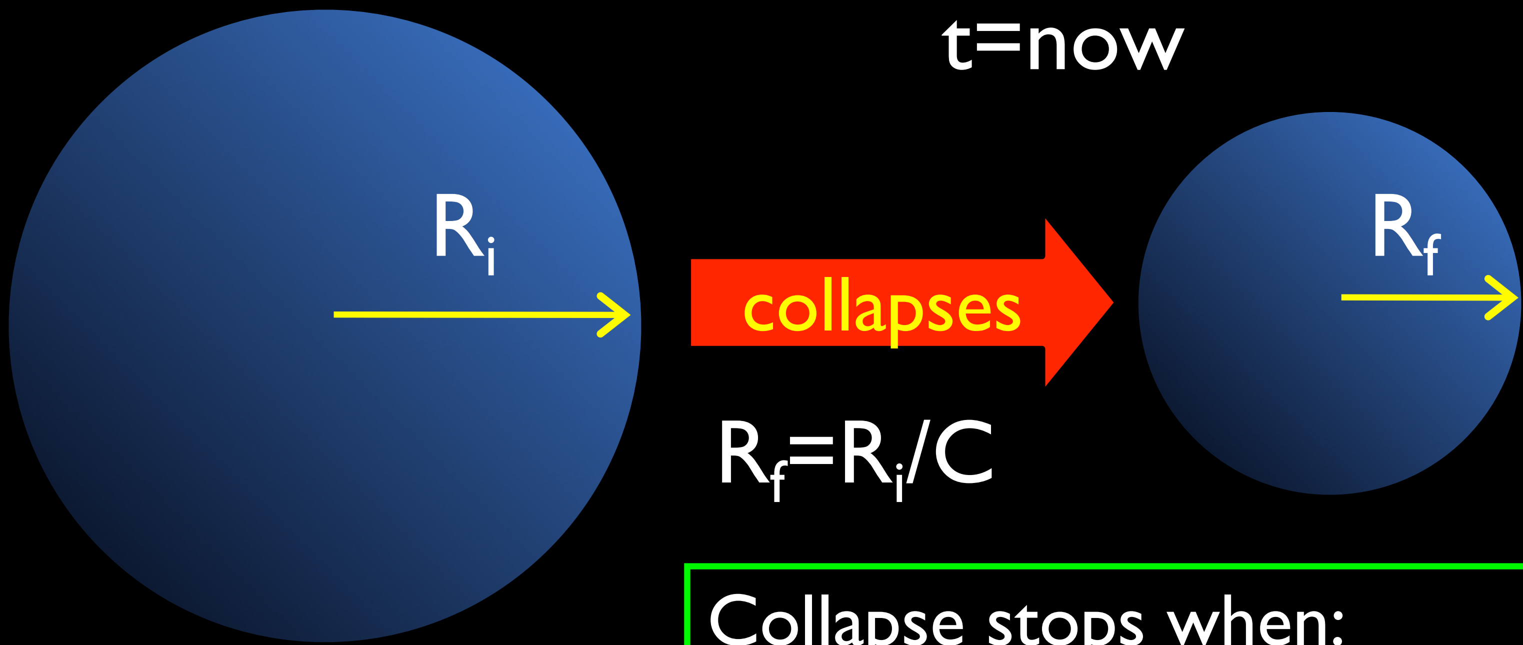
- Merging history
- Feedback from star formation & AGN
- Internal dynamics (instabilities, scattering, diffusion

Nurture

Some simple but useful scalings

$t \approx 0$

$t = now$



$R_f = R_i / C$

Mass $M \sim \rho(t \approx 0) R_i^3$

Density of the early universe, which can be assumed to be fairly uniform

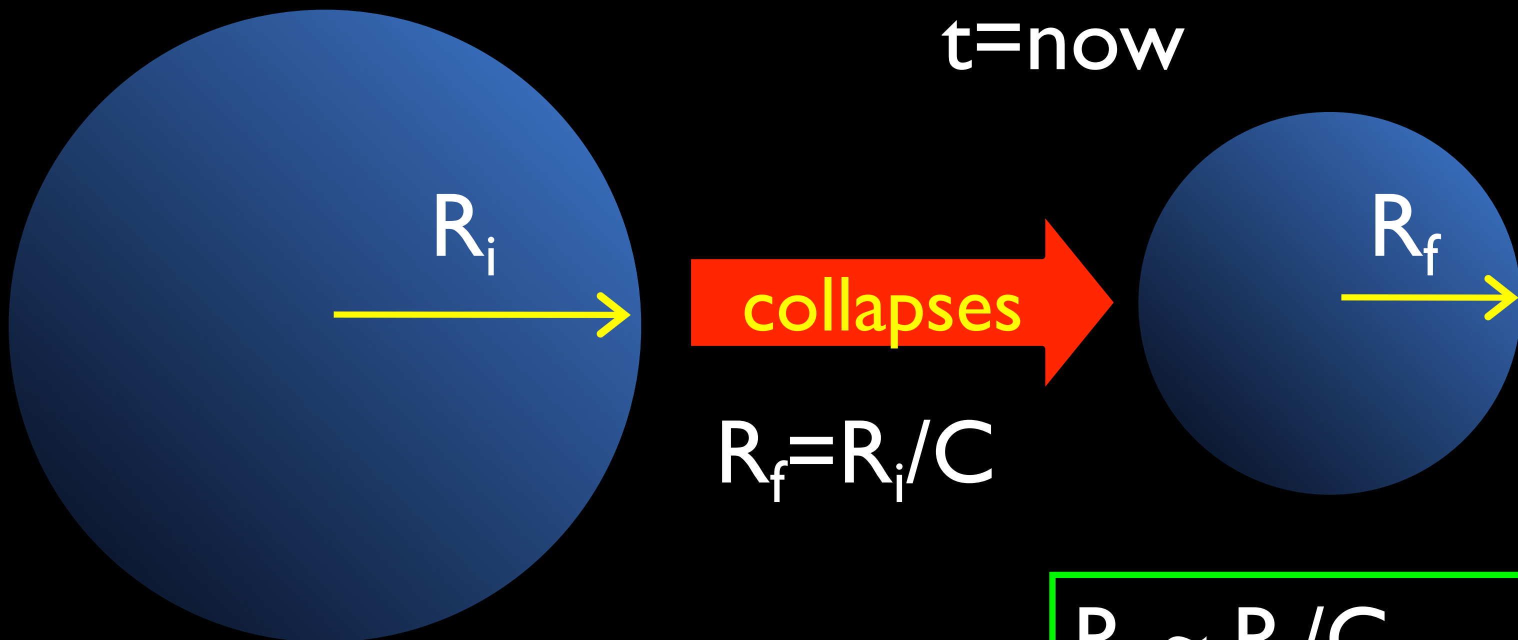
<u>Collapse stops when:</u>

1. Virialization occurs (if dissipationless collapse, like for dark matter or stars)
2. Centripital force (set by angular momentum) balances inwards pull of gravity (if dissipational, like for gas)

Some simple but useful scalings

$t \approx 0$

$t = \text{now}$



$R_f = R_i / C$

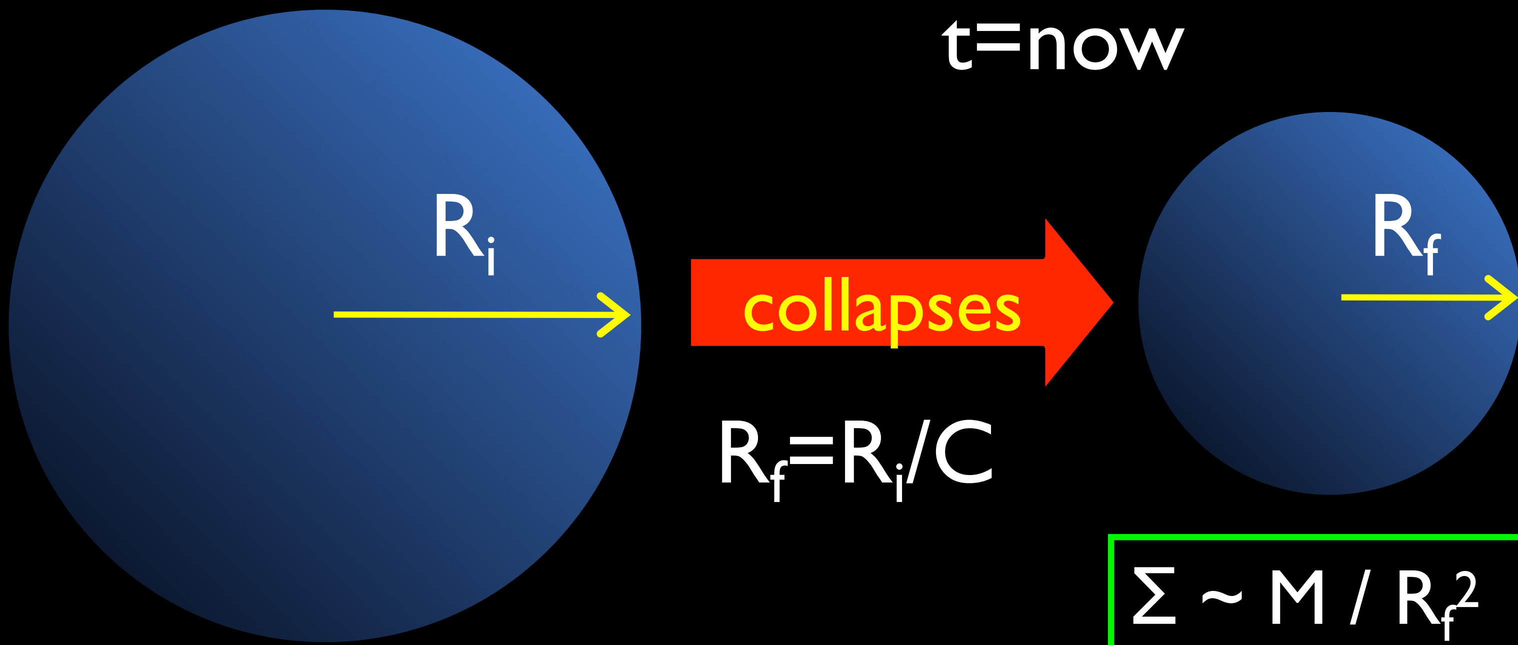
Mass $M \sim \rho(t \approx 0) R_i^3$

$$R_f \sim R_i / C$$
$$\sim (M/\rho)^{1/3} / C$$
$$\sim M^{1/3} \, (C^{-1} \, \rho^{-1/3})$$

So size increases as $M^{1/3}$

Some simple but useful scalings

$t \approx 0$ $t = \mathrm{now}$



$R_f = R_i / C$

Mass $M \sim \rho(t \approx 0) R_i^3$

$$\Sigma \sim M / R_f^2$$
$$\sim C^2 M / R_i^2$$
$$\sim C^2 M / (M/\rho)^{2/3}$$
$$\sim M^{1/3} (C^2 \rho^{2/3})$$

So surface density Σ and size R_f both increase as $M^{1/3}$

Variation with mass?

$$\boxed{R_f \sim M^{1/3}\,(C^{-1}\,\rho^{-1/3})} \qquad \boxed{\Sigma \sim M^{1/3}\,(C^{2}\,\rho^{2/3})}$$

- *At same collapse factor* C, the radius R and surface density Σ increase like $M^{1/3}$
- Within *similar formation pathways*, more massive galaxies will tend to be physically larger and higher surface density

Broad trend does agree with expected scaling

Surface density and size both increase as $M^{1/3}$

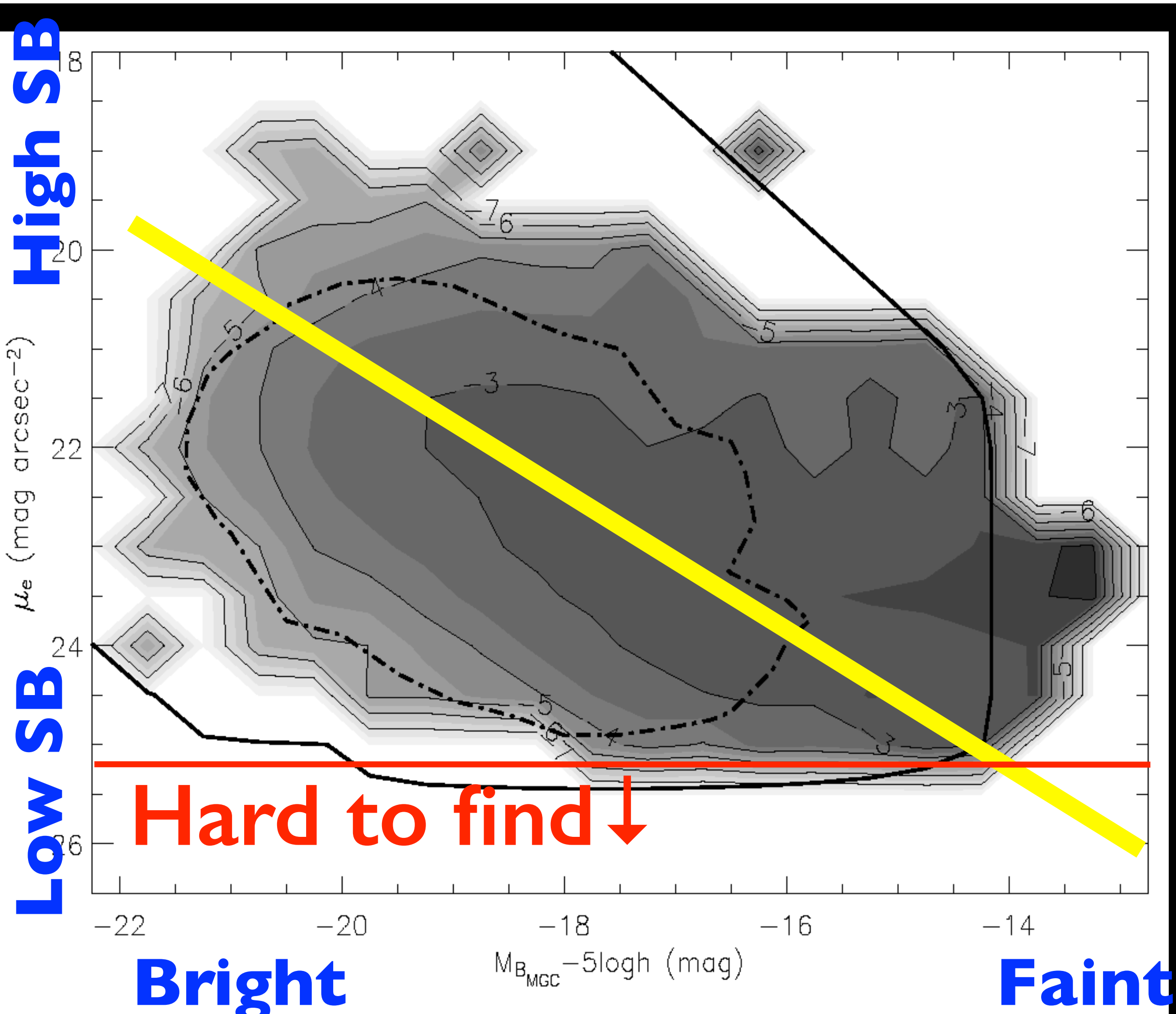


Figure 12. The final space density or bivariate brightness distribution of galaxies shown as both a greyscale image and contours on logarithmic scales in units of h^3 Mpc^{-3} mag^{-1} (mag arcsec^{-2})$^{-1}$. The contour spacing is 1 dex in ϕ with the greyscale at 0.5 dex intervals. The thick solid line denotes the selection boundary defined as the BBD region where at least 100 galaxies could have been detected and is equivalent to an effective volume limit of $1800h^{-3}$Mpc^3. The thick dashed line encompasses the region within which the statistical error is smaller than 25 per cent.

Driver et al 2005

What accounts for spread at fixed mass?

$$\boxed{\Sigma \sim M^{1/3}\,(C^2\,\rho^{2/3})}$$

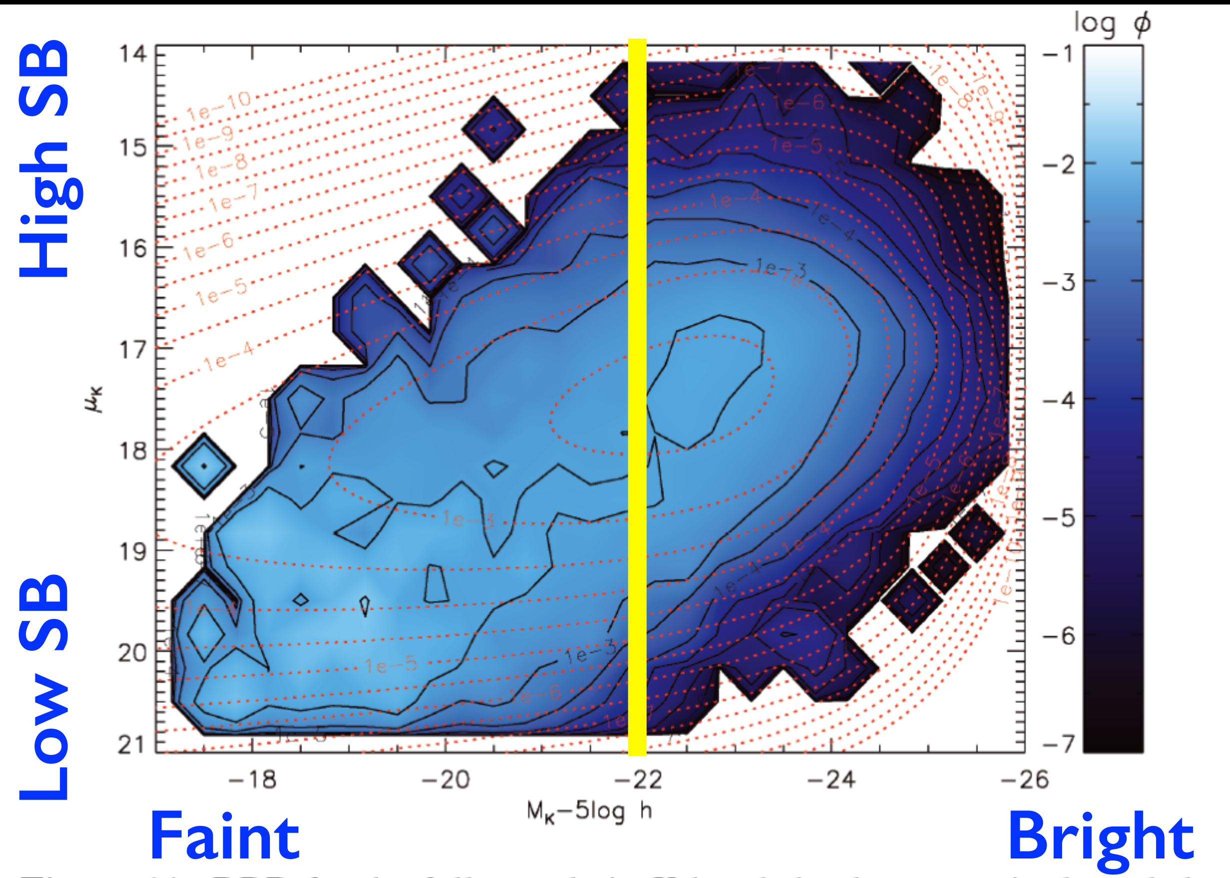


Figure 11. BBD for the full sample in K-band absolute magnitude and absolute effective surface brightness. Shaded regions and solid black contours show the space density, ϕ, as in Fig. 10. The best-fitting Choloniewski function, estimated using $M_K - 5\log h < -20$ and $\mu_{\mathrm{e,abs}} < 19$, is shown by the red dotted contours. Parameters of the fit are $M^* - 5\log h = -22.96$ mag, $\alpha = -0.38$, $\phi^* = 0.0201\,h^3\,\mathrm{Mpc}^{-3}$, $\mu^*_{\mathrm{e,abs}} = 17.36$ mag arcsec^{-2}, $\sigma_{\mu_{\mathrm{e,abs}}} = 0.672$ mag arcsec^{-2} and $\beta = 0.188$.

Smith et al 2009

Variations at *fixed* mass?

$R_f \sim M^{1/3}\ (C^{-1}\ \rho^{-1/3})$

$\Sigma \sim M^{1/3}\ (C^{2}\ \rho^{2/3})$

- *At same mass*, larger collapse factors C lead R to decrease and Σ to increase, with a bigger impact on Σ

- Larger collapse factors can result from:
  - Less initial spin, when the collapse is halted by angular momentum
  - More dissipation, when collapse is halted by dynamical pressure (velocity dispersion)

Effect of initial matter density?

$\boxed{R_f \sim M^{1/3}\ (C^{-1}\ \rho^{-1/3})}$

$\boxed{\Sigma \sim M^{1/3}\ (C^{2}\ \rho^{2/3})}$

- At the same mass and formation pathway (i.e., C) , galaxies that collapsed from higher characteristic initial densities will be more compact and denser
- Can potentially imprint a timing+environmental bias (Larger overdensities collapse faster, starts denser, forms earlier when mean density of universe was higher)

So what detailed equilibrium configurations do galaxies maintain?

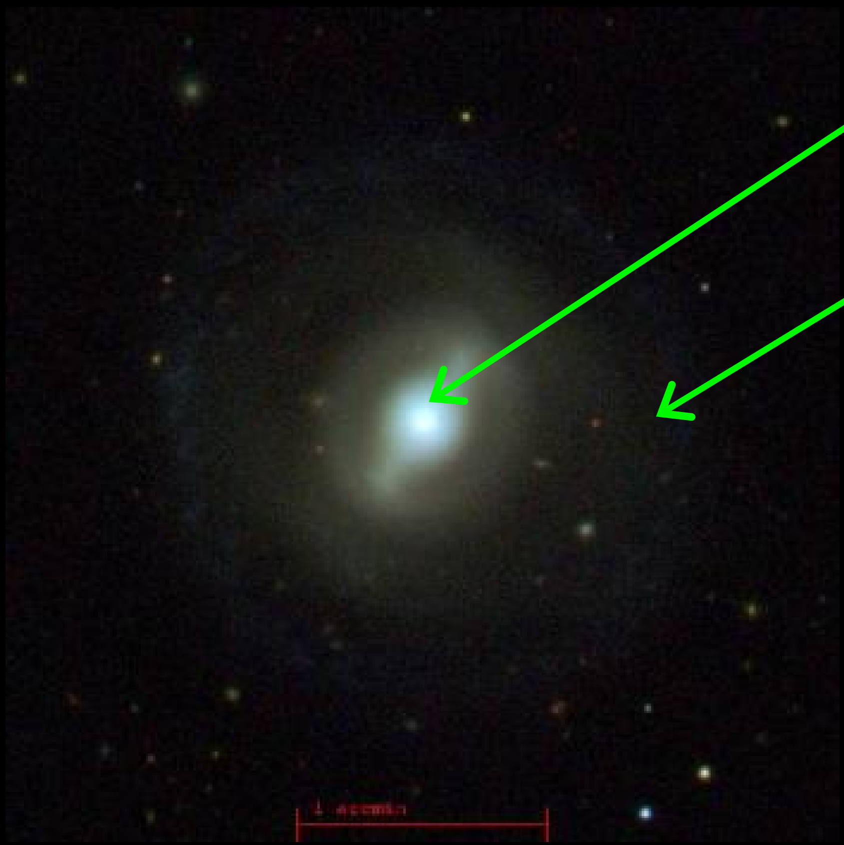
First: How do we quantify internal structure?

Quantifying Galaxy Images:

"Surface Photometry"
Quantify surface brightness as a function of position.

Surface photometry is a good first estimate of the distribution of stellar mass.

Surface Brightness:



High surface brightness

Low surface brightness

Apparent property

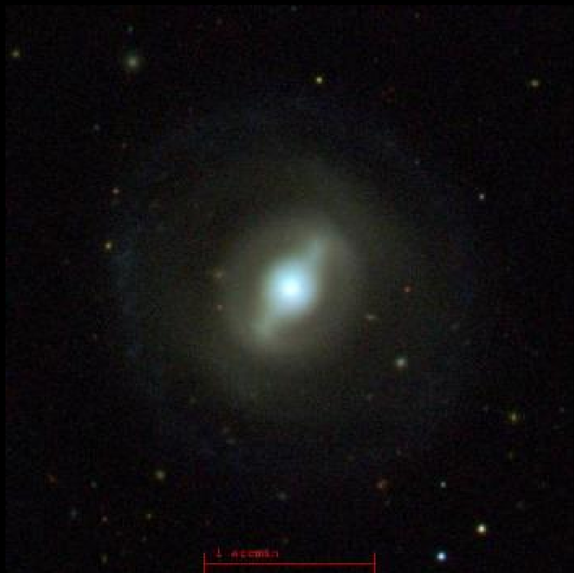
I, Σ = "Intensity" or "Surface Brightness"

= Flux / Angular Area (ergs/s/cm^2/arcsec^2)

= Luminosity / Area (L$_\odot$/pc^2)

Inherent property

Surface Brightness vs Surface Density



Surface density = $\Sigma\Upsilon_\star$

Σ = surface density: $M_\odot/pc^2$

$\Upsilon_\star$ = *stellar** mass-to-light ratio in $M_\odot/L_\odot$

*This is an intrinsic property of the stellar population. It is independent of what the dark matter might be contributing to the mass.

Surface Brightness vs Distance

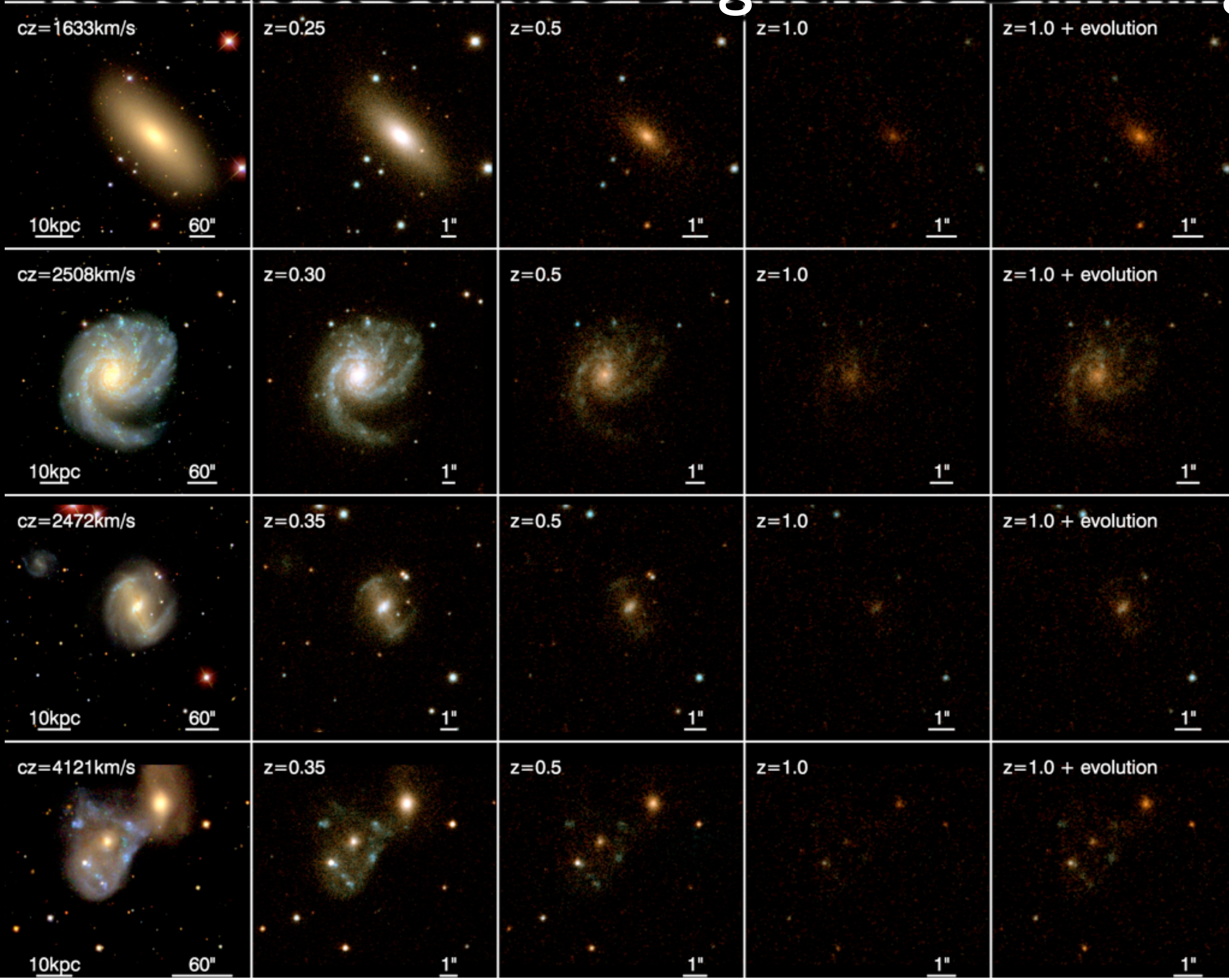
1. Approximately constant with distance nearby:

$$\frac{\text{Flux}}{\text{AngularArea}} = \frac{L/4\pi D_L^2}{\text{Area}/D_A^2} \propto \frac{L}{\text{Area}} = \text{constant}$$

2. Falls off rapidly at high redshift:

$$(D_A/D_L)^2 = (1+z)^{-4}$$

Redshift & Surface Brightness Dimming



Barden et al 2008

Surface Brightness Units

Usually converted to the world's worst astronomical units:

μ = the magnitude of a 1 arcsec^2 patch
= magnitudes / arcsecond^2
= constant - 2.5 $\log_{10} \Sigma$

Typical Surface Brightness Values

μ = the magnitude of a 1 arcsec^2 patch
= magnitudes / arcsecond^2
= constant - 2.5 $\log_{10} \Sigma$

μ_{sky} ~ 22 B-mag/sqr-"

μ_0(spiral disks) ~ 21.7 B-mag/sqr" (“Freeman Value” 1970)

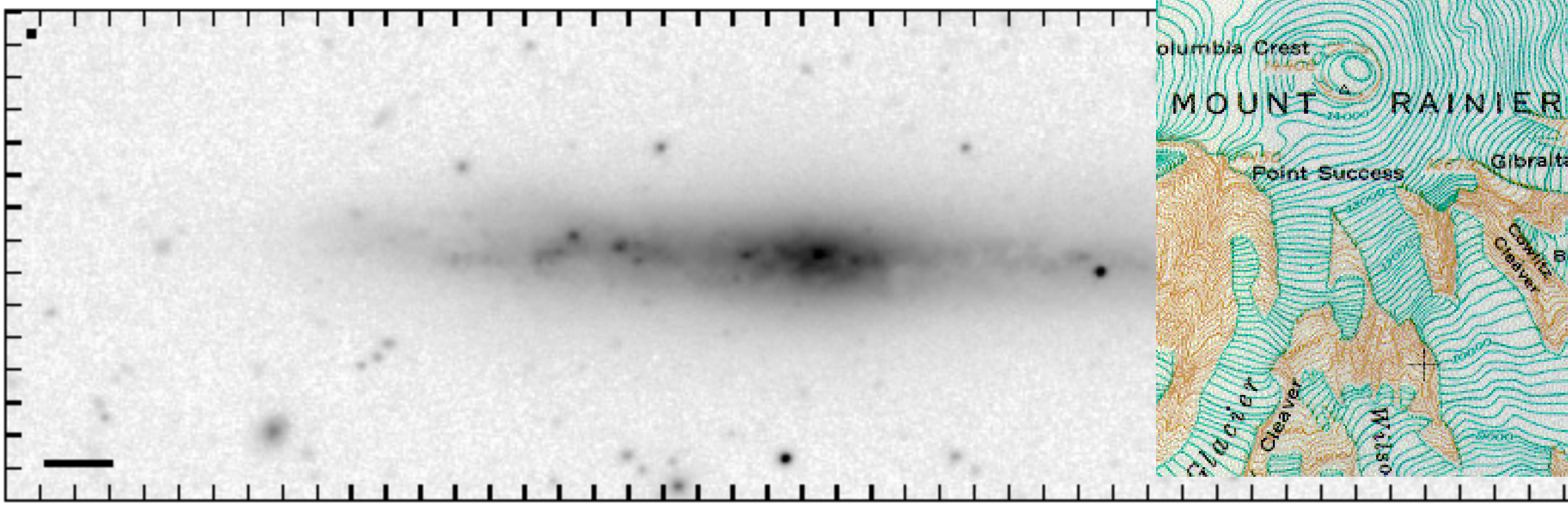
$\mu_{lim,shallow}$ ~ 25 B-mag/sqr"

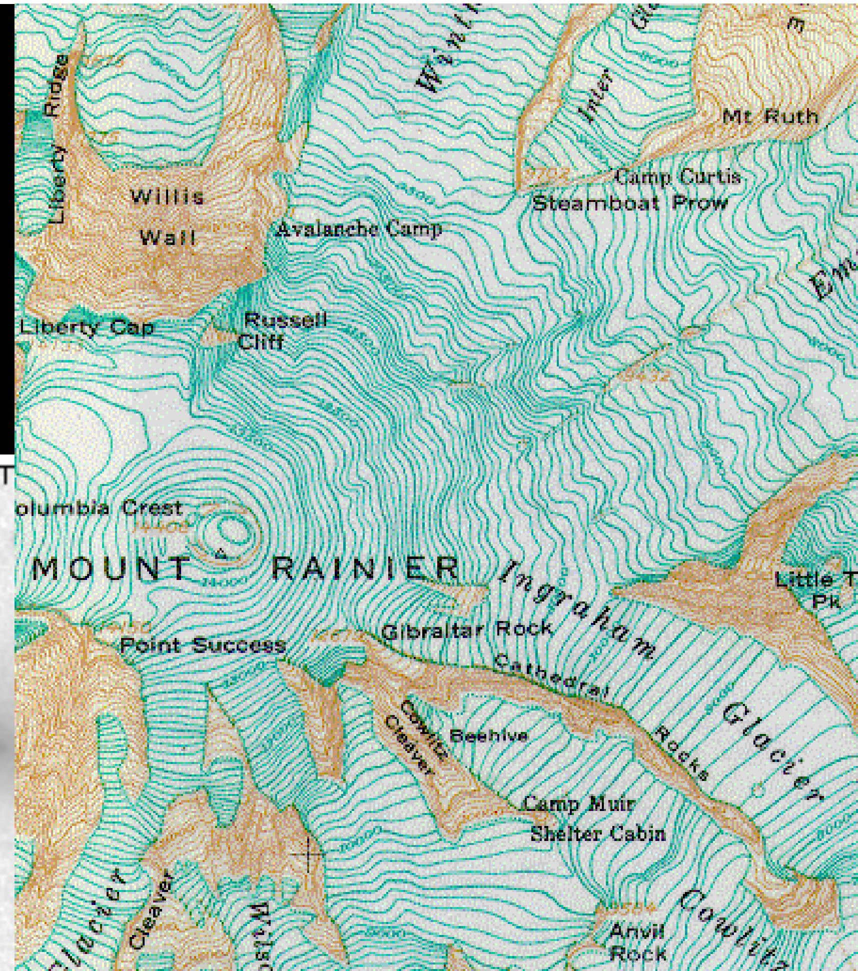
$\mu_{lim,deep}$ ~ 28-29 B-mag/sqr"

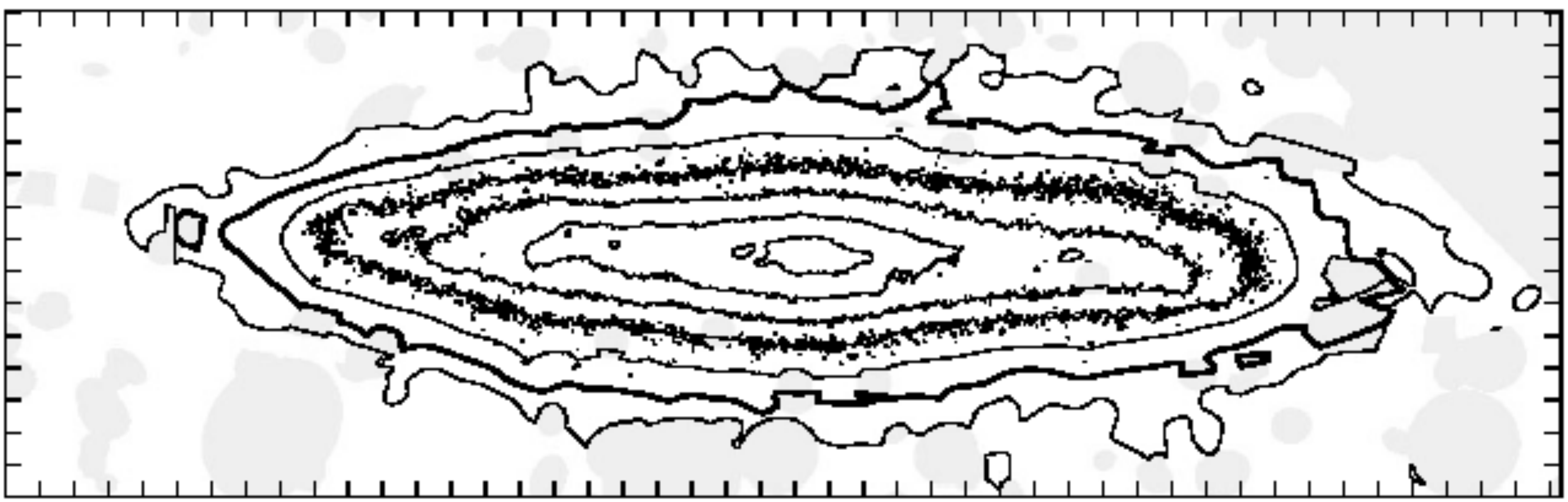
$\mu_{Holmberg}$ ~ 26.5 B-mag/sqr"

Note: Subscript “0” means either “central” or “at the present day”

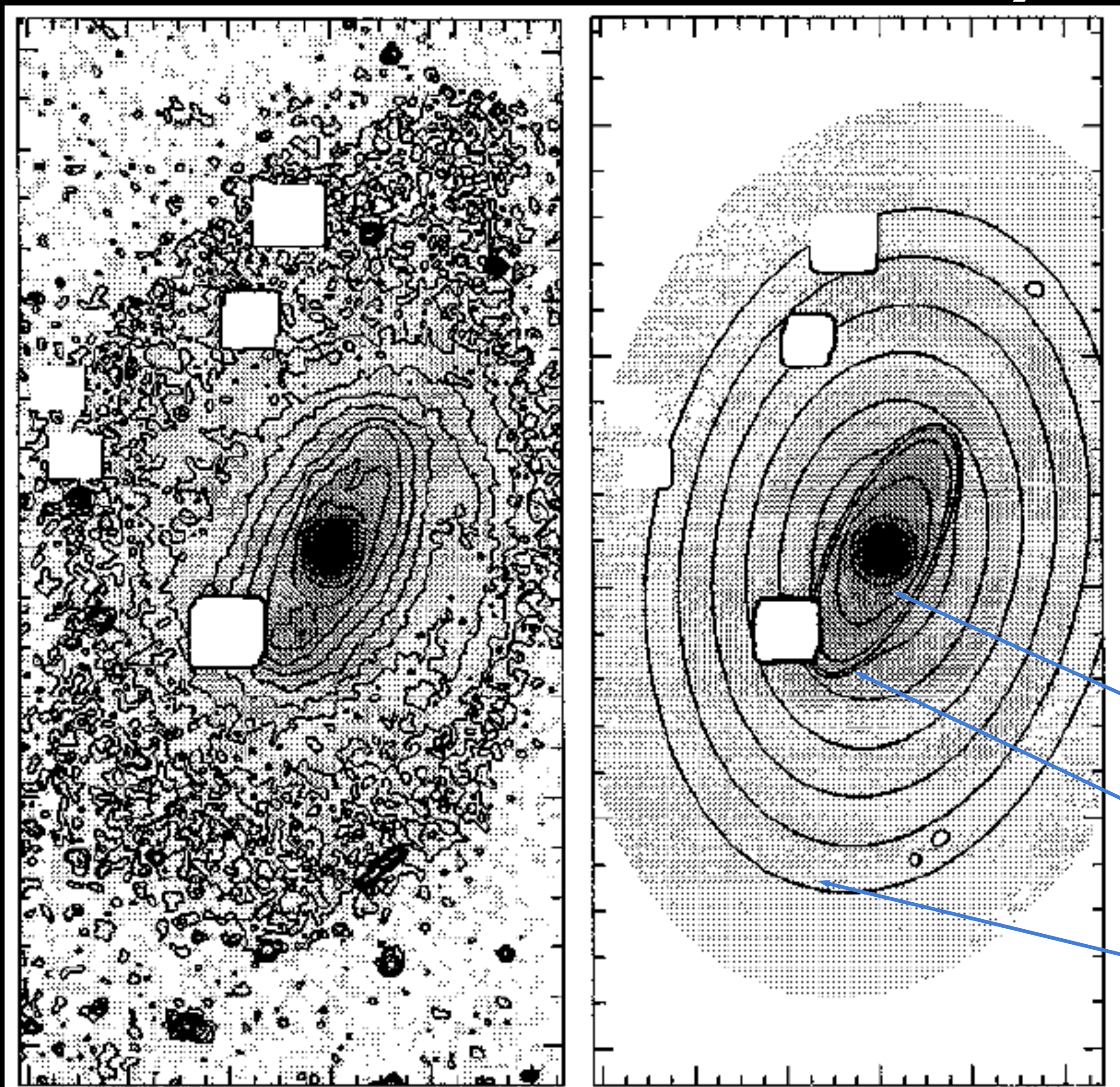
Terminology: "Isophotes" = lines of constant surface brightness





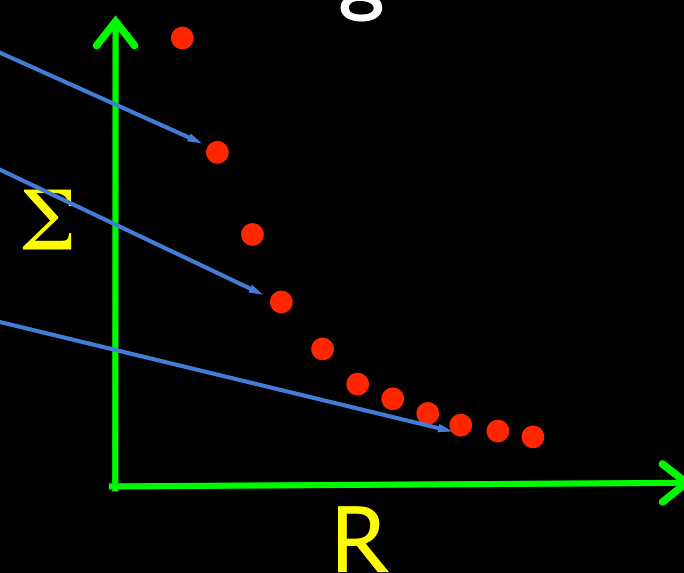


"Surface Photometry" = quantifying Σ



"Surface Brightness Profile"

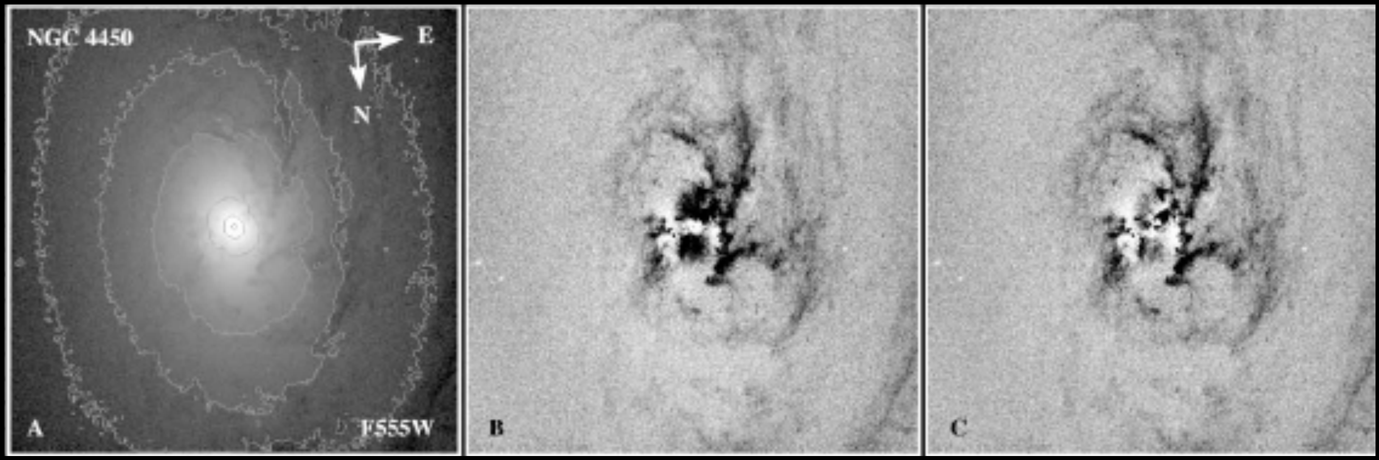
Surface brightness vs. major axis length.



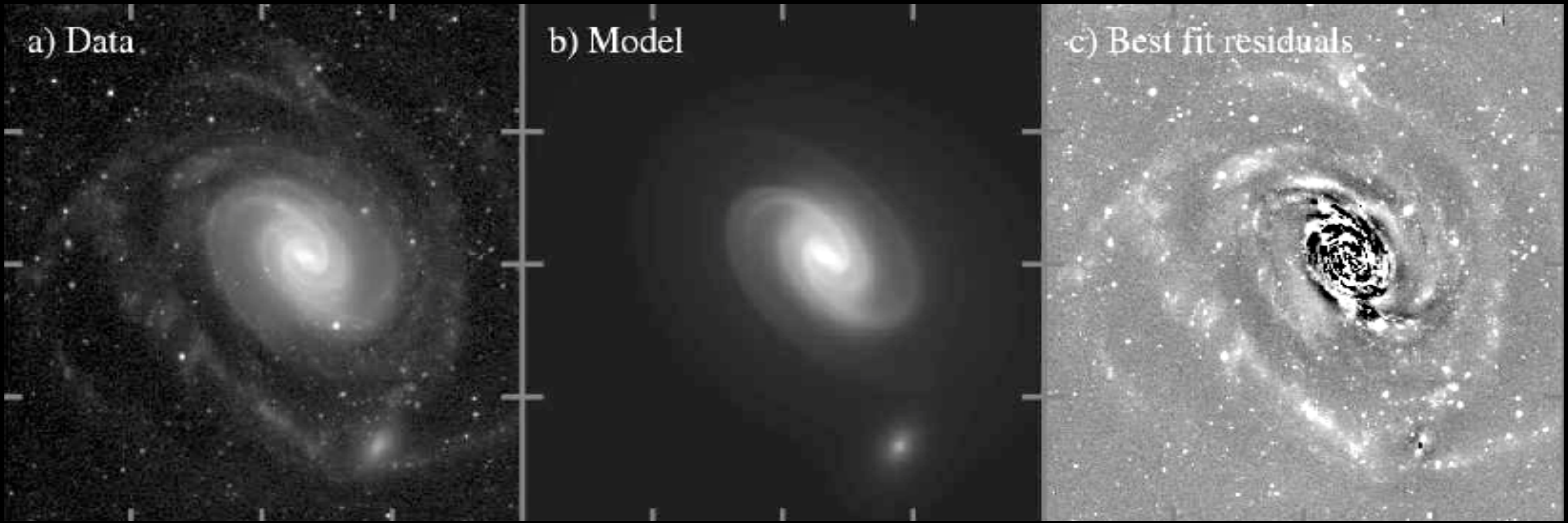
Use elliptical fits or models

Example of model decomposition

Image



Residuals



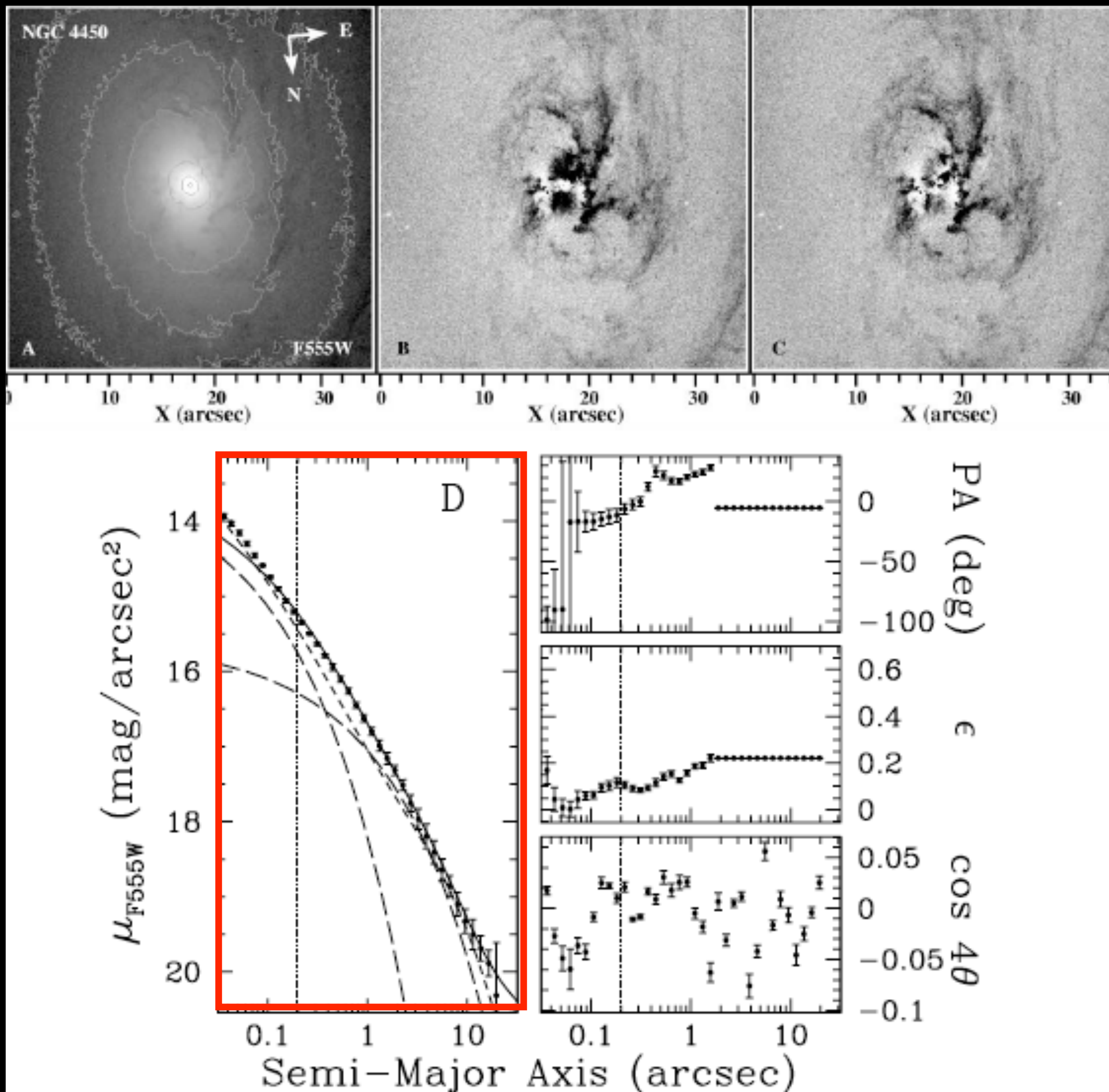
Galfit: Peng et al 2002,2010

Example of model decomposition

Image

Residuals

Surface brightness profile



Peng et al 2002

Surface Brightness vs Luminosity:

$$L(<r) = \int_0^r \Sigma(r) 2\pi r dr$$

Total Luminosity:

$$L_{tot} = L(< r \to \infty) = \boxed{2\pi\Sigma_0 h_r^2}$$

For an exponential disk with scale length h_r, central sb Σ_0

"Half-light radius": $r_{1/2}$ or r_e

$$L(< r_{1/2}) = \int_0^{r_{1/2}} \Sigma(r) 2\pi r dr = \frac{1}{2}\int_0^{\infty} \Sigma(r) 2\pi r dr$$

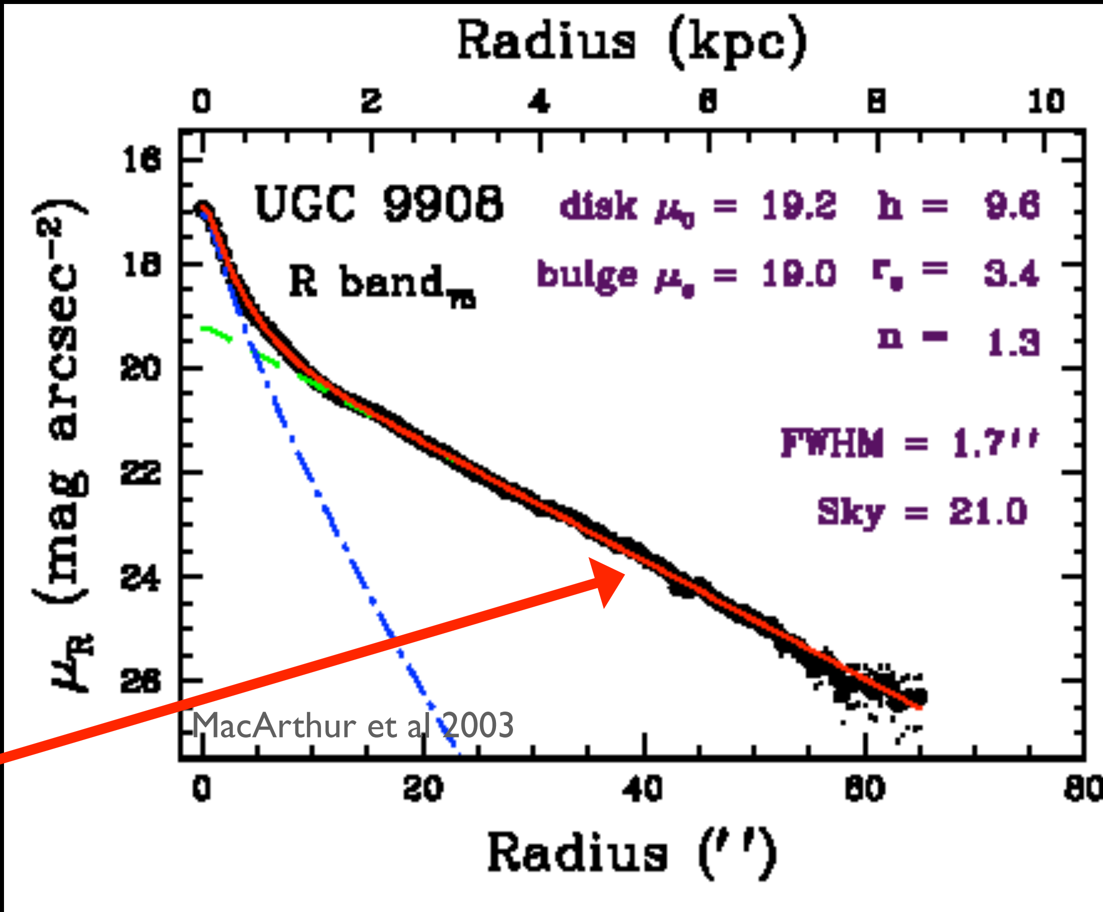
X

Equilibrium configurations of spiral disks, based on surface photometry

1. Radial
2. Vertical

Spirals & Dwarfs are "Exponential Disks"

$$\Sigma_{\rm disk}(r) = \Sigma_0 e^{-r/h}$$



Straight line when plotted logarithmically

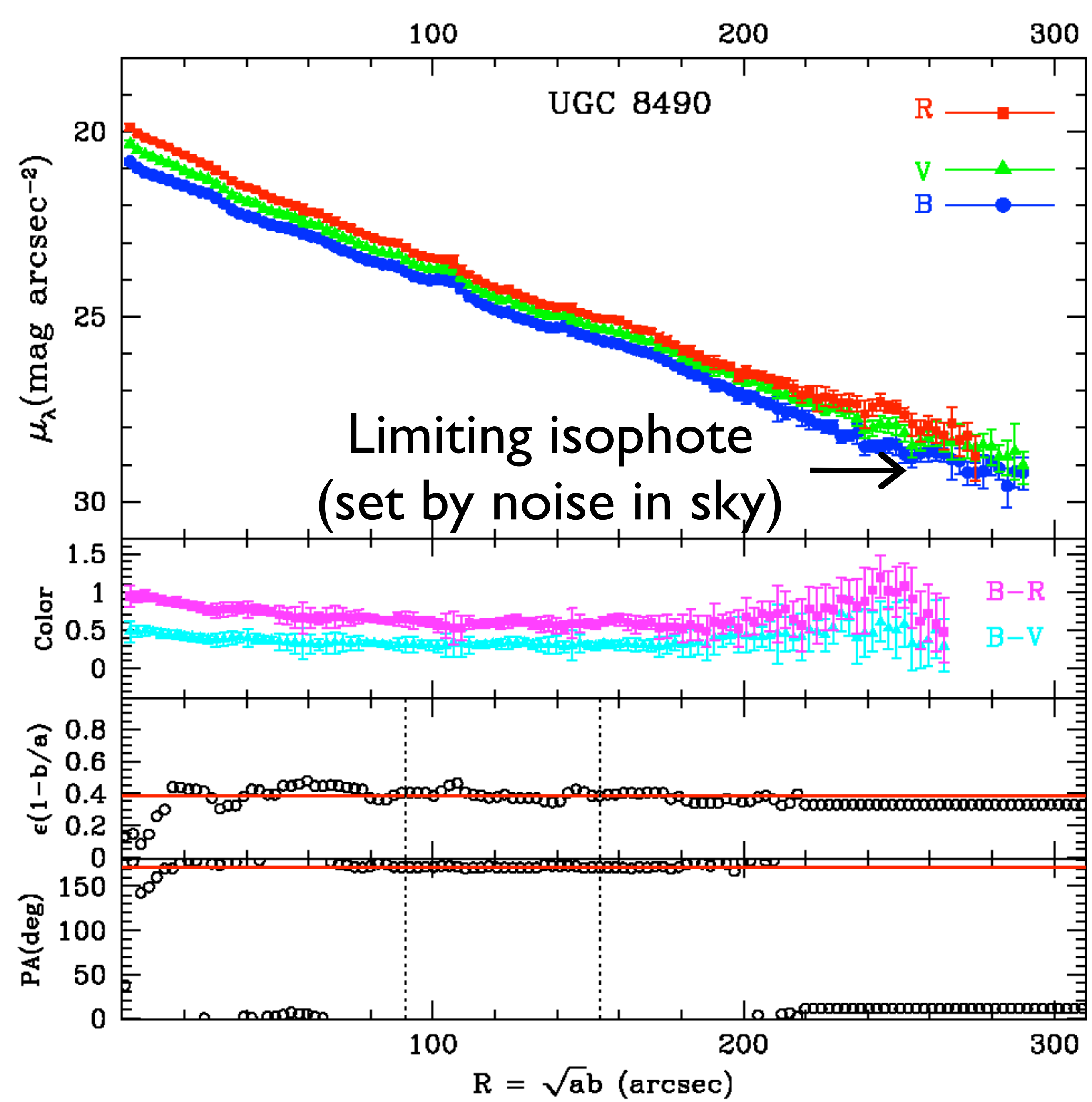
$$\mu_{\rm disk}(r) = \mu_0 + 1.086 r/h$$

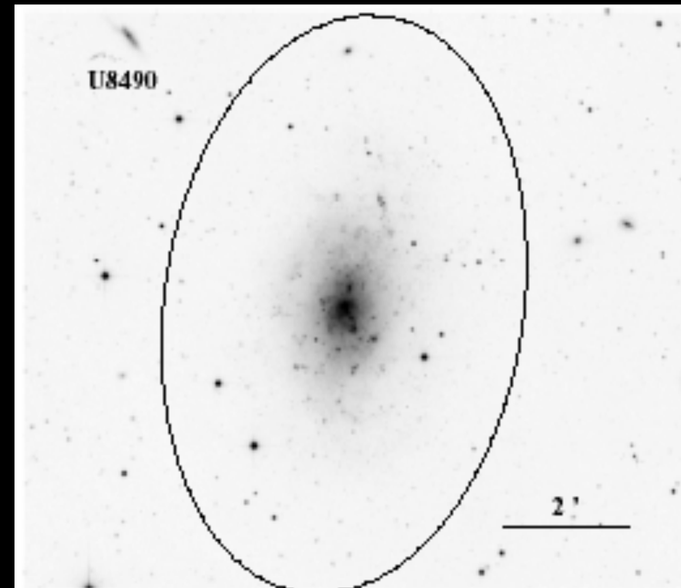
Intercept = Central surface brightness

Slope = 1.086/h

We say: "Exponential Disk with Scale length h_r and central surface brightness Σ_0"

Example of a "pure" exponential disk

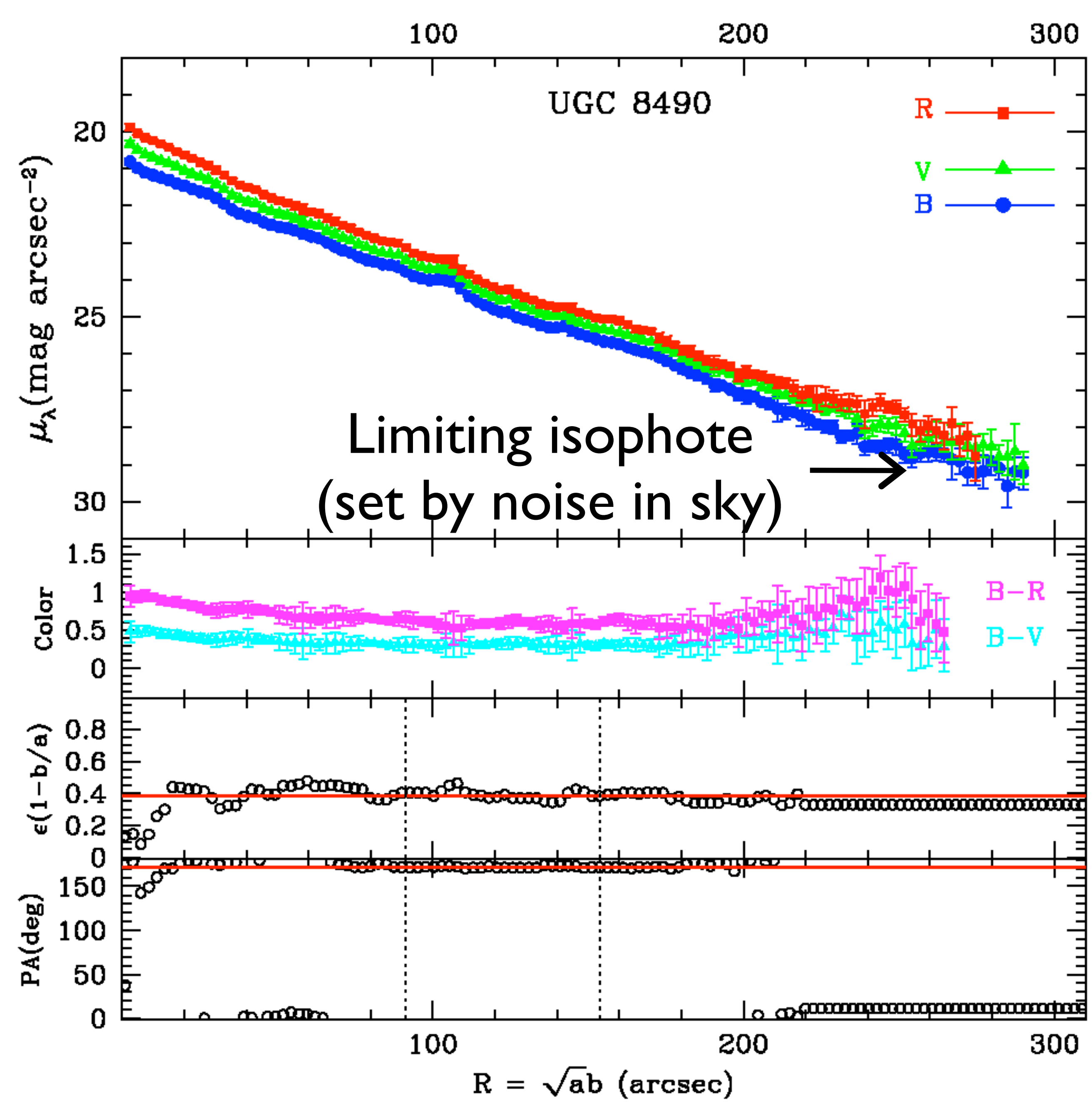


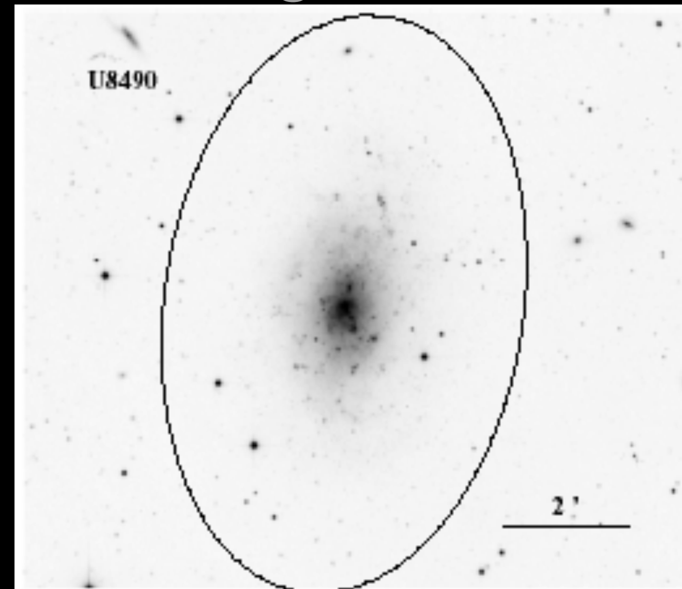


M. Tavarez

Open question: Why???

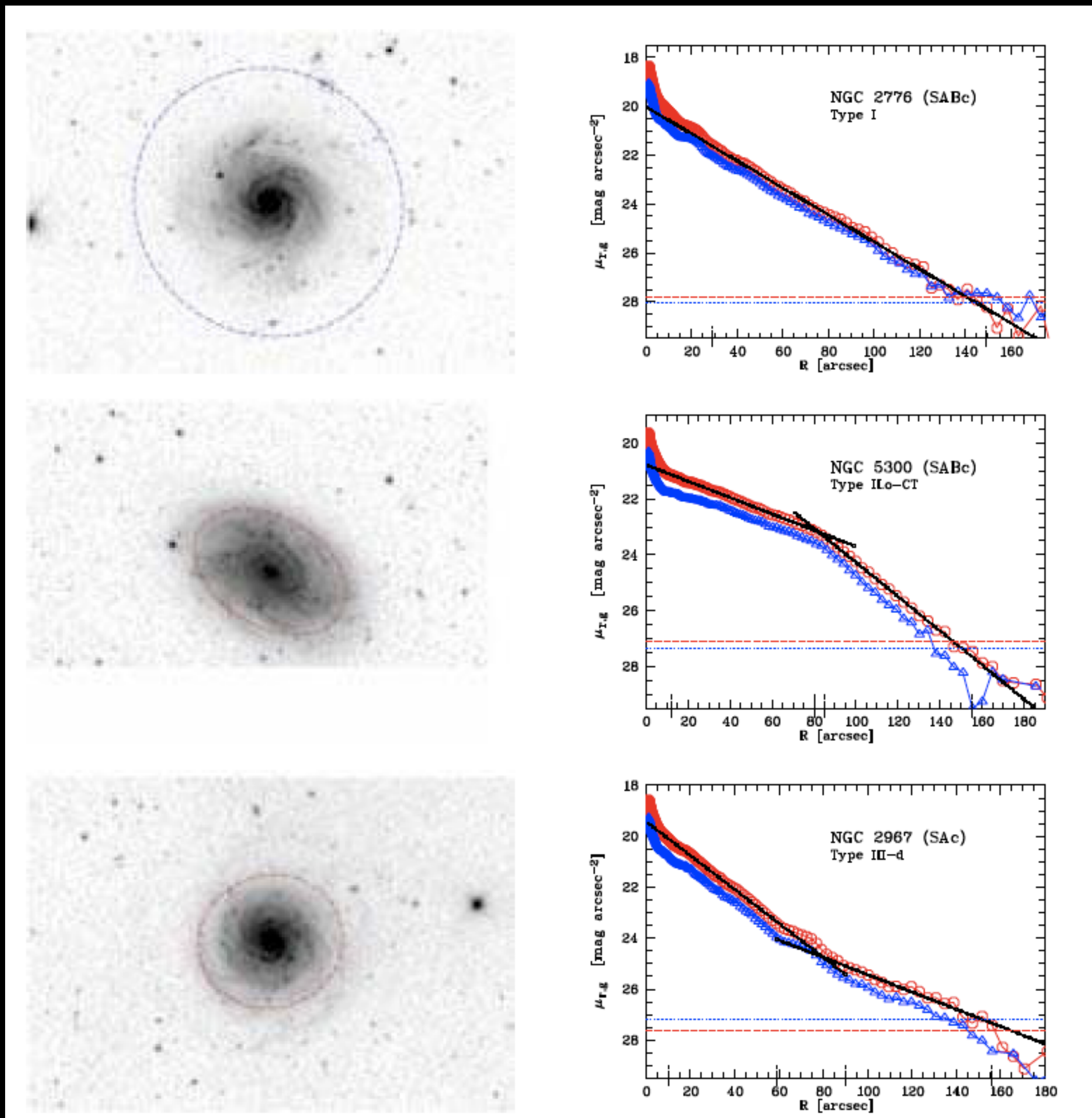
See Struck & Elmegreen 2017, 2018





M. Tavarez

Complex Profiles in Face-On Disks



Unbroken:
10%

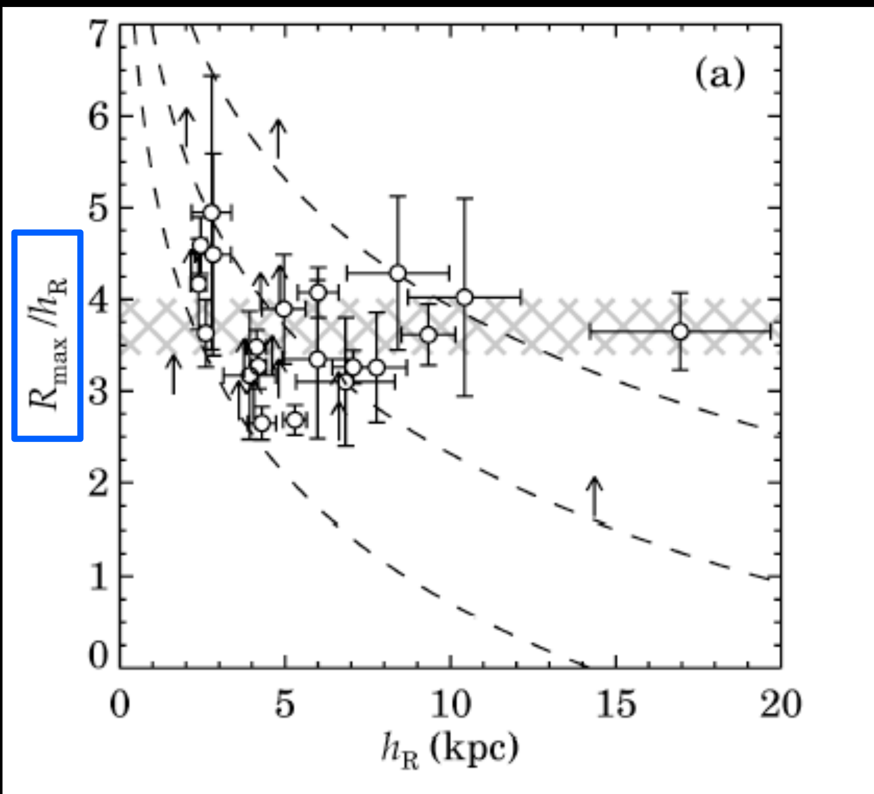
"Truncated":
60%

Upbending:
30%

Pohlen & Trujillo 2006

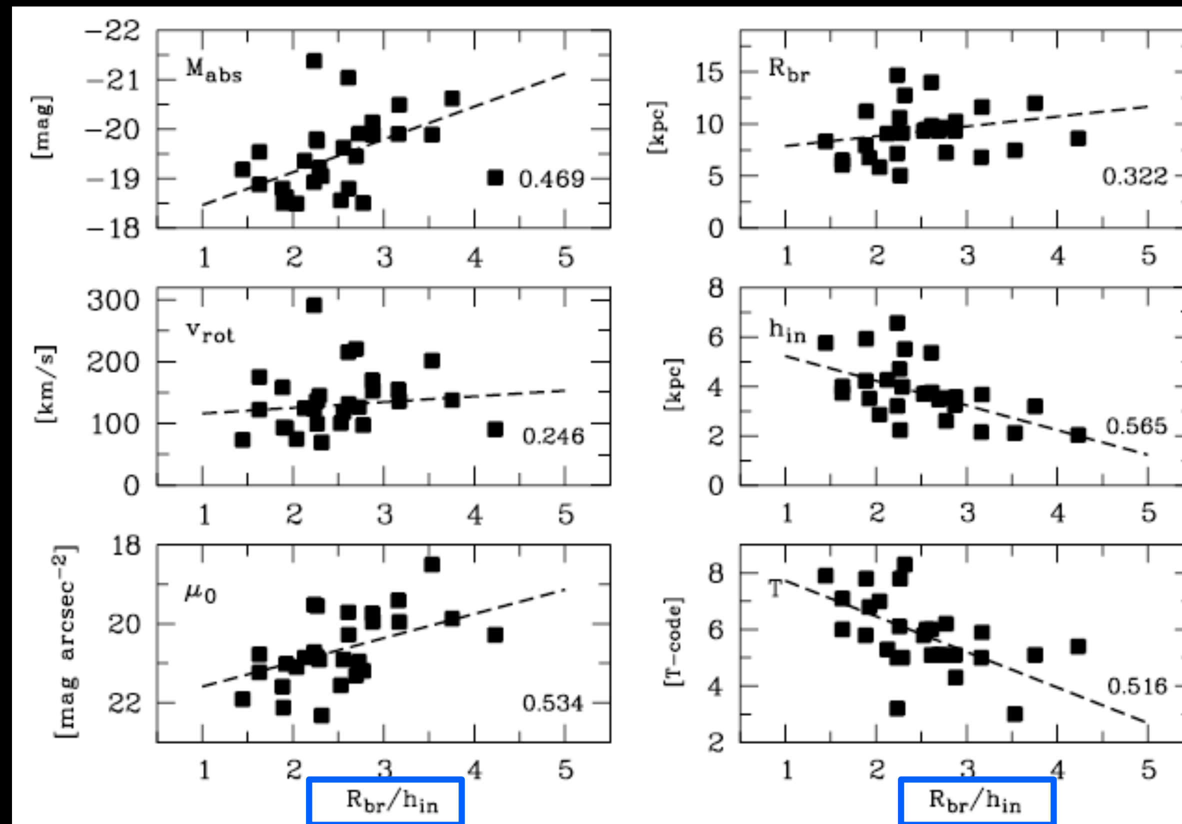
Disk Breaks at ~2-4h_r

Edge-on



Kregel & van der Kruit 2004

Face-on



Pohlen & Trujillo 2006

Open question: Why? Warps?

Star formation threshold + Resonant scattering?

Summary: Radial Structure of Spiral Disks

- Exponential
- “Breaks” at several disk scale lengths, usually downward

What is the equilibrium vertical surface brightness distribution?

Obviously, dust is a problem

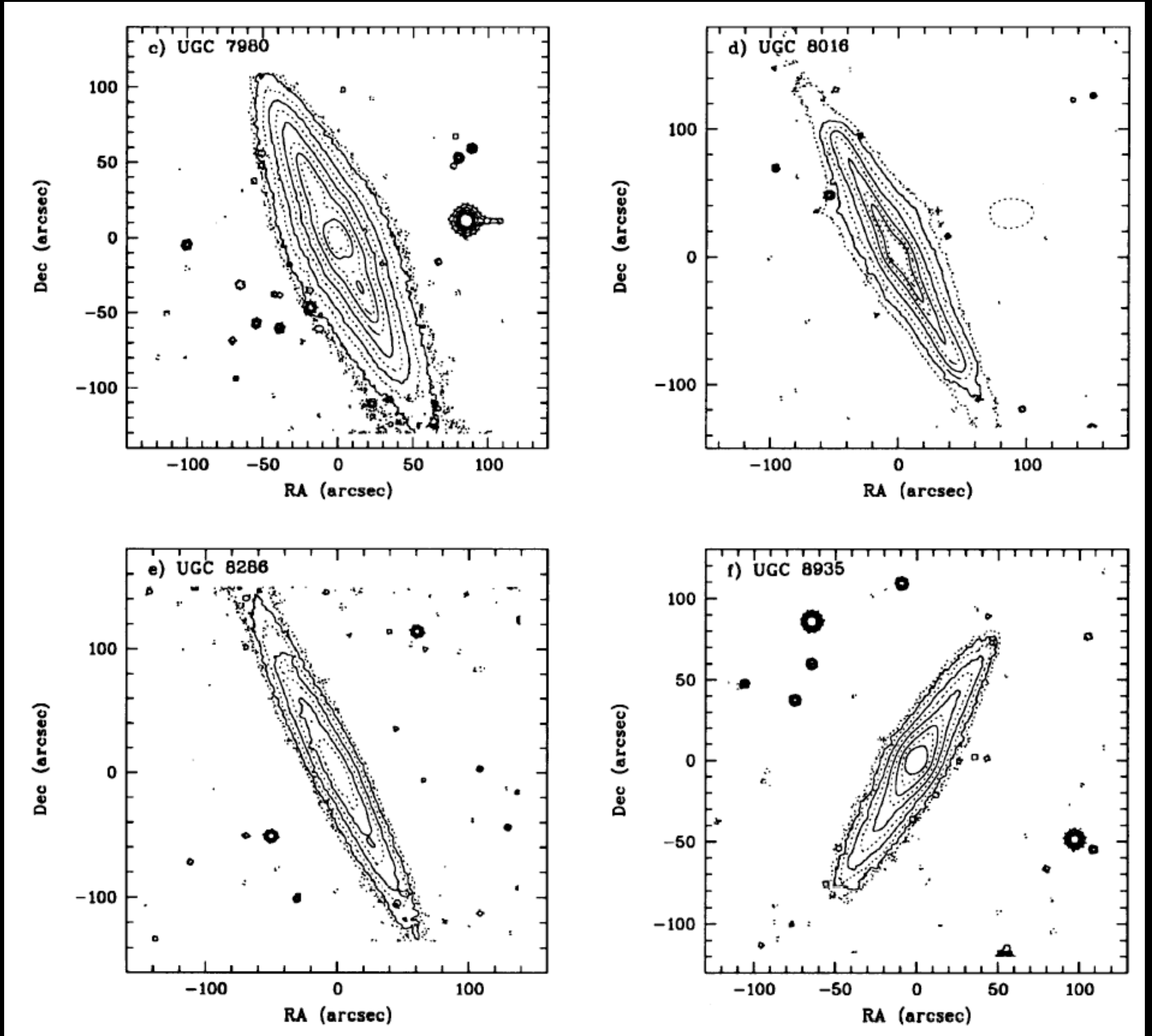
Edge-On Galaxy NGC 4013

- Near-IR ideal
- R- or I-band sometimes used for better FOV and/or sensitivity

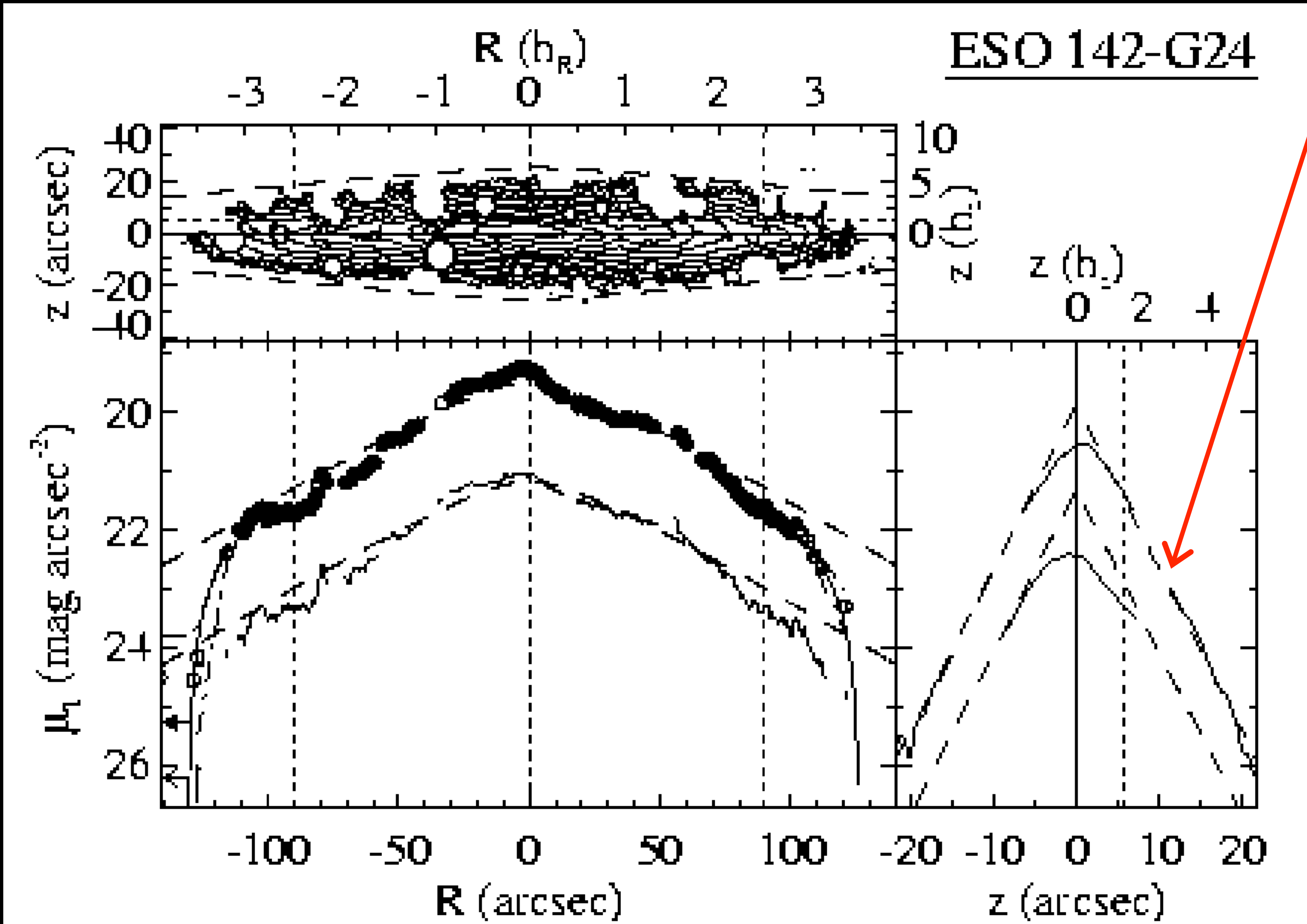
Vertical light distributions of disks:

Edge-on galaxies in the I-band.

Generally rounder at low light levels, probably due to analogs of MW thick disks.



Falls off with *z* as straight line in μ



Kregel et al 2002

A vertical exponential distribution is thus frequently adopted

Approximate luminosity density in space:

$$L(R, z) = L_0 \; e^{-R/h_{\mathrm{R}}} e^{-z/h_{\mathrm{z}}}$$

Will not always capture behavior at the midplane

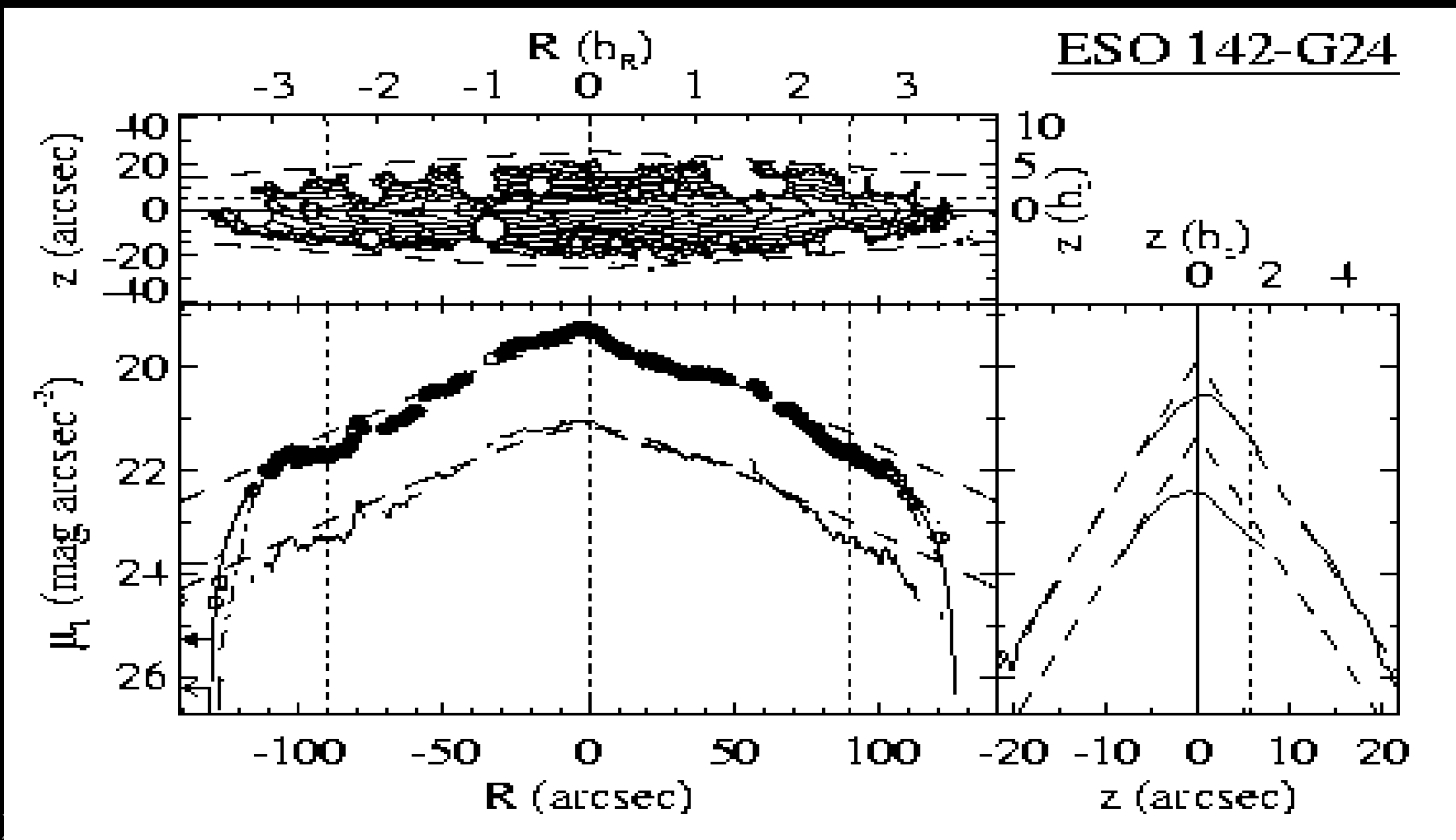
Projected surface brightness, seen edge-on:

$$\boxed{\Sigma_{\rm disc}(R', z) = \Sigma_0 \; (R'/h_{\rm R}) \; K_1(R'/h_{\rm R}) \; e^{-z/h_z}}, \qquad (2)$$

where R' is the projected radius along the major axis, $\Sigma_0 = 2h_{\rm R}L_0$ is the projected *edge-on* central surface brightness and K_1 is the modified Bessel function of the first order.

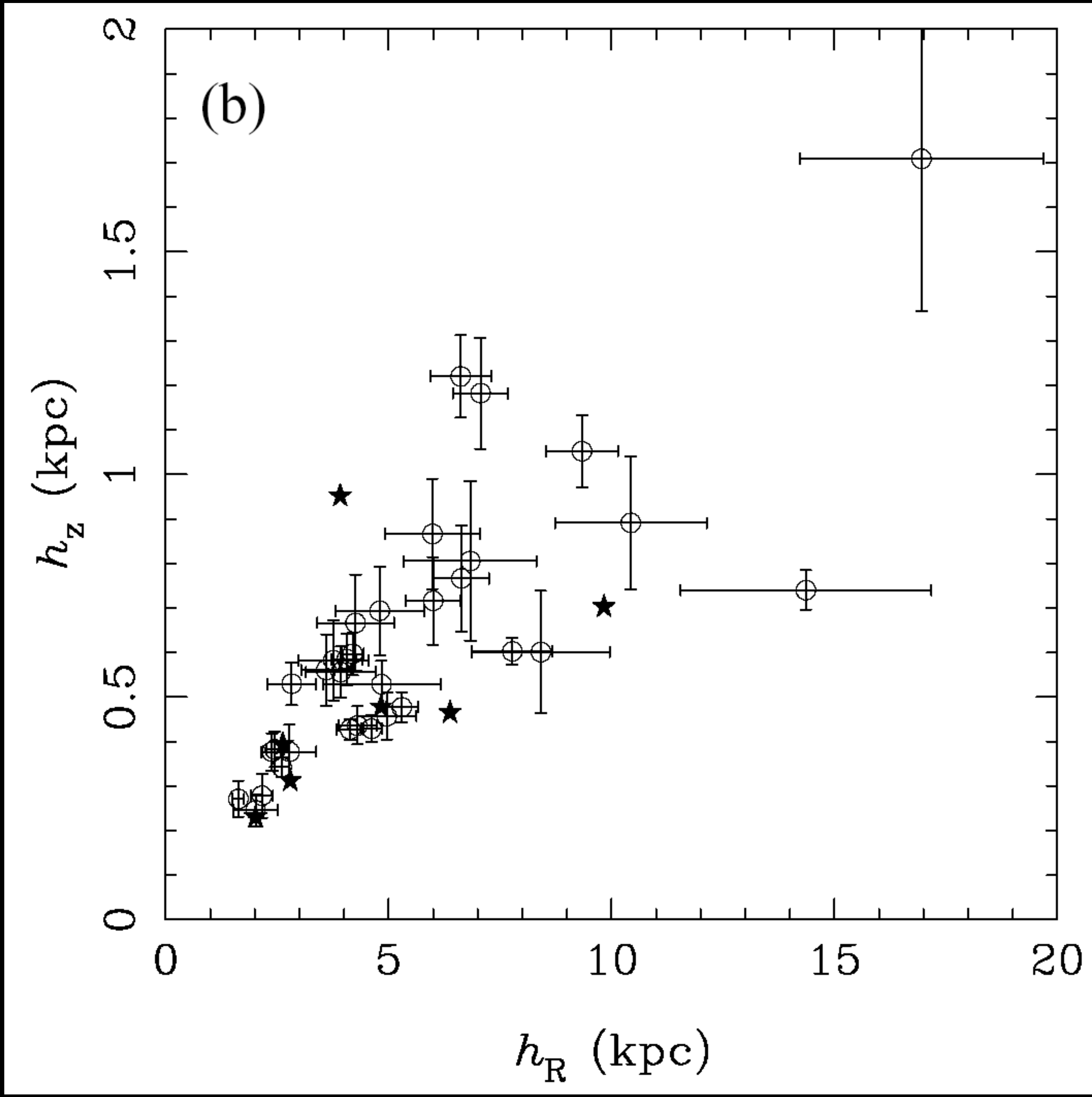
(assumes optically thin disk!)

Van der Kruit & Searle 1981



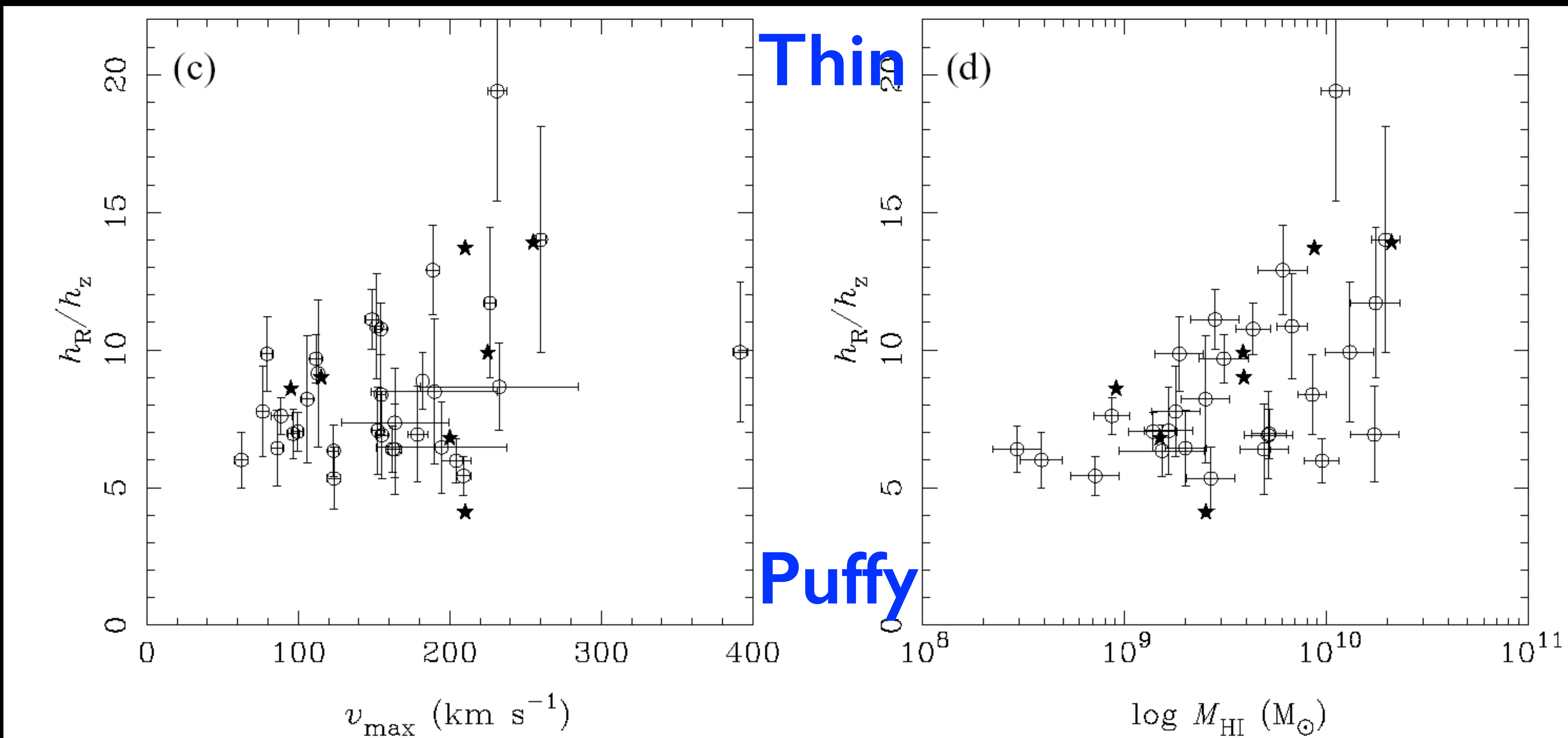
Kregel et al 2002

Scale heights tend to be < 1 kpc



Kregel et al 2002

Lower mass, fainter galaxies tend to be puffier



Rotation Speed

(proxy for total galaxy mass w/ dark matter)

Gas Mass (HI)

Kregel et al 2002

Disk flares for early types, but not late-types

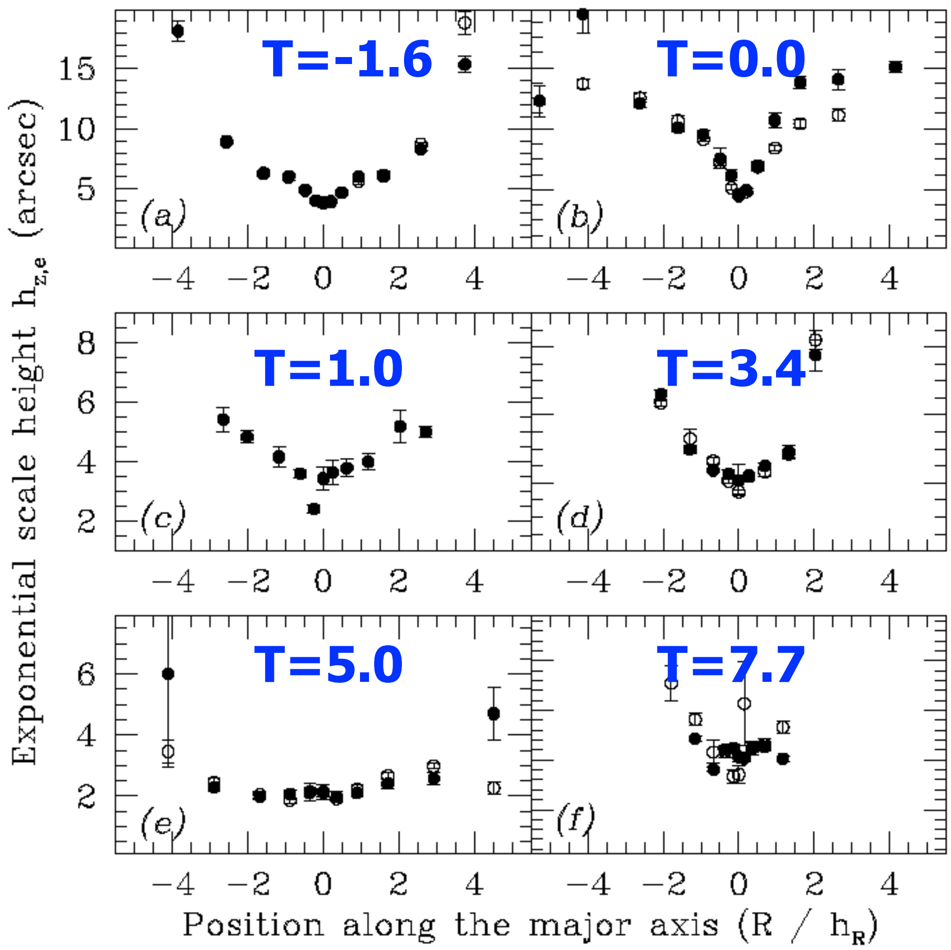
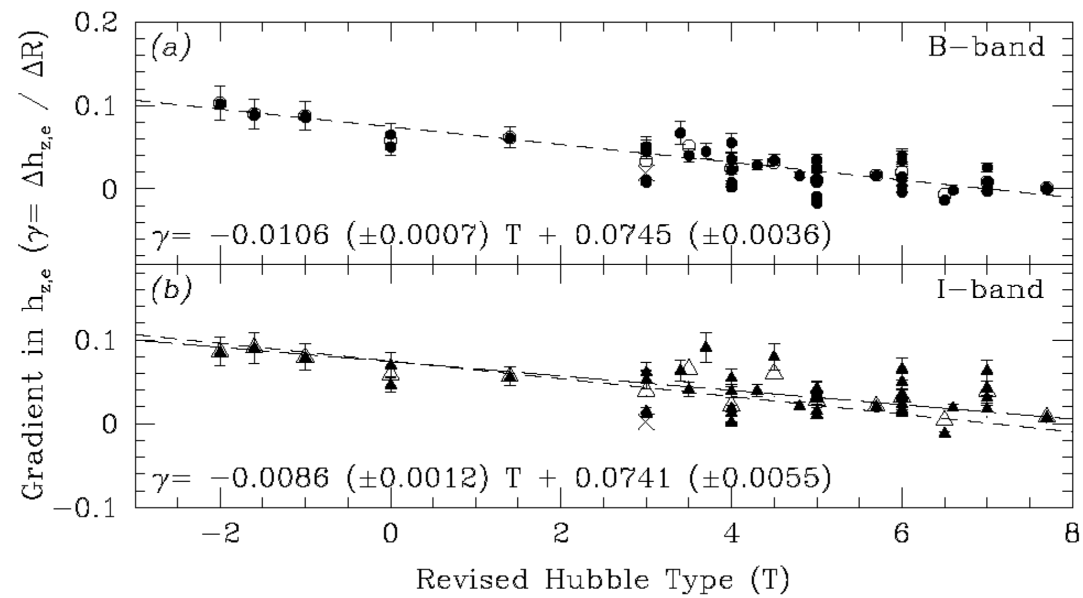
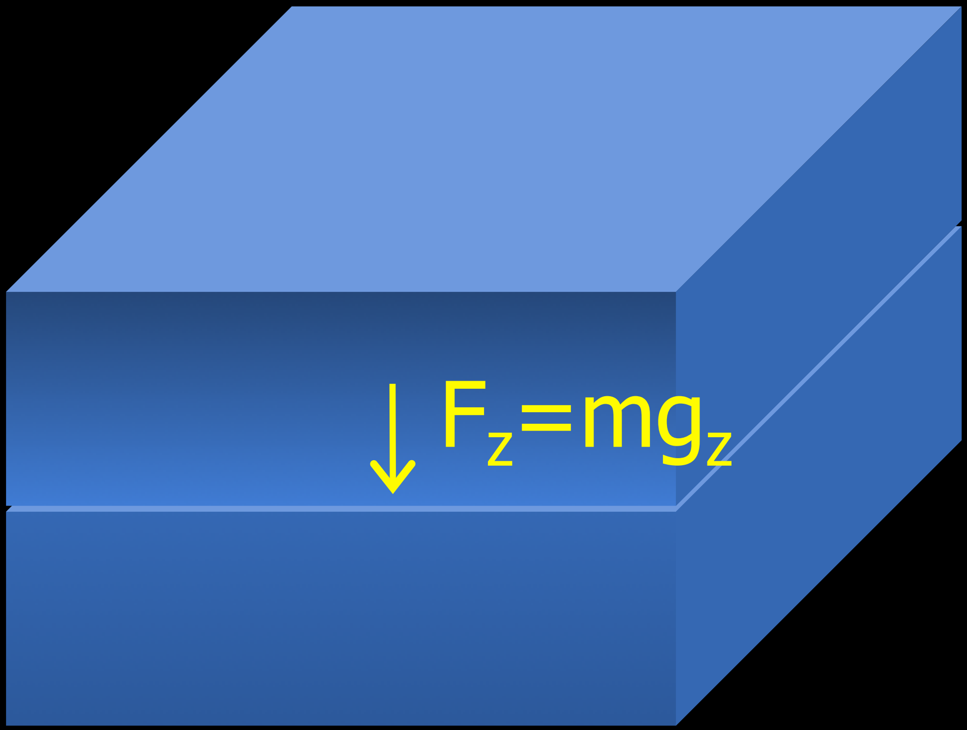


Fig. 1. Examples of the *I*-band scale height behaviour as a function of galactocentric distance for *(a)* ESO 358G-29 (T = −1.6), *(b)* ESO 311G-12 (T = 0.0), *(c)* ESO 315G-20 (T = 1.0), *(d)* ESO 322G-87 (T = 3.4), *(e)* ESO 435G-50 (T = 5.0), and *(f)* ESO 505G-03 (T = 7.7). Open and closed symbols represent data taken on both sides of the galaxy planes.



de Grijs & Peletier 1997

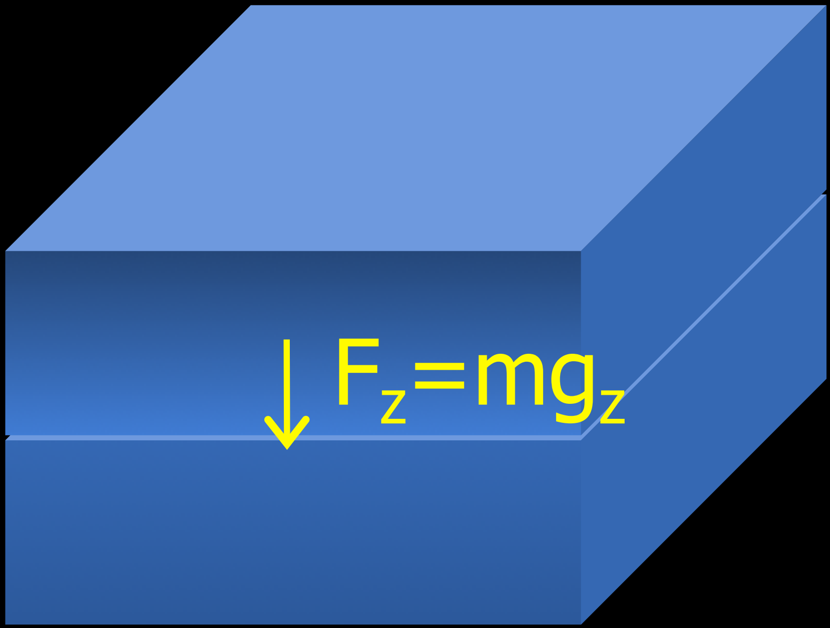
Why you expect the observed vertical structure:



A slab of stars, with total surface density Σ and vertical density profile $\rho(z)$.

Assume that the slab is "self-gravitating"

A particle of mass m at z feels a downward force $F_z = mg_z$, where g_z is the gravitational acceleration.



Via Gauss's Law, with force=0 at the midplane:

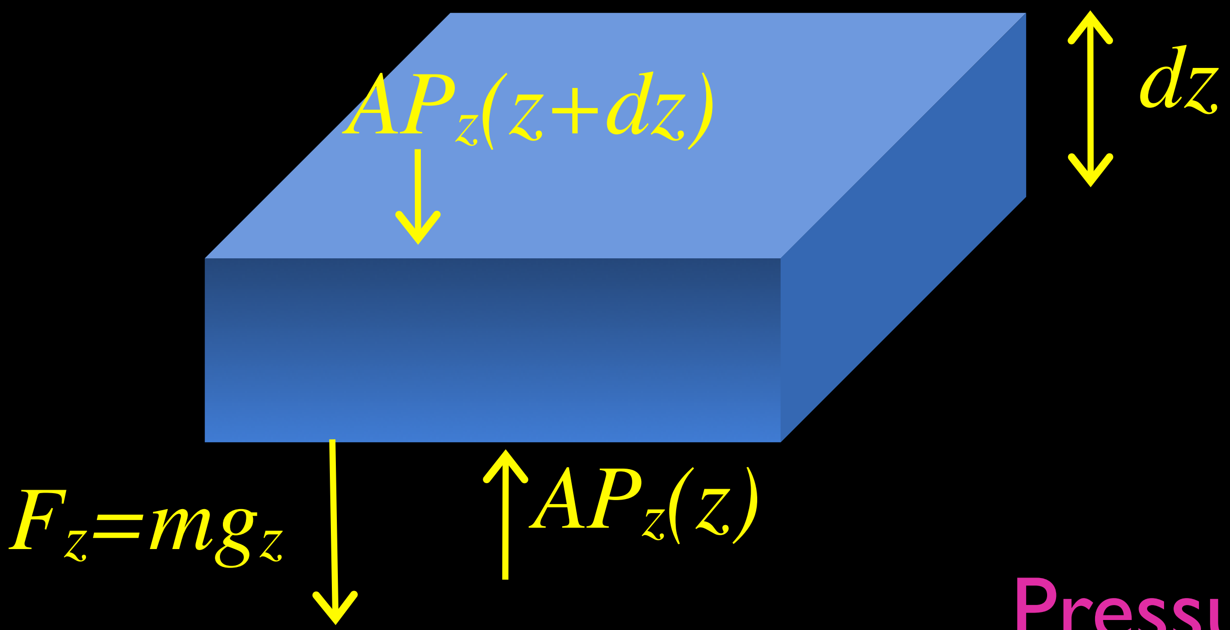
$$g_z = -4\pi G \int_0^z \rho(z')dz'$$

If the disk is in equilibrium, then something must be balancing the the gravitational pull.

Dynamical Pressure: $$\boxed{P_z = \sigma_z^2 \rho}$$

(assuming "isothermal" -- i.e. σ_z constant)

Pressure gradient balances gravity



Consider one layer of the slab, with thickness dz, area A, and mass $\rho A dz$

Pressure = Force / Area

$$[P_z(z+dz) - P_z(z)]A = (\rho A dz) g_z$$

Yielding:

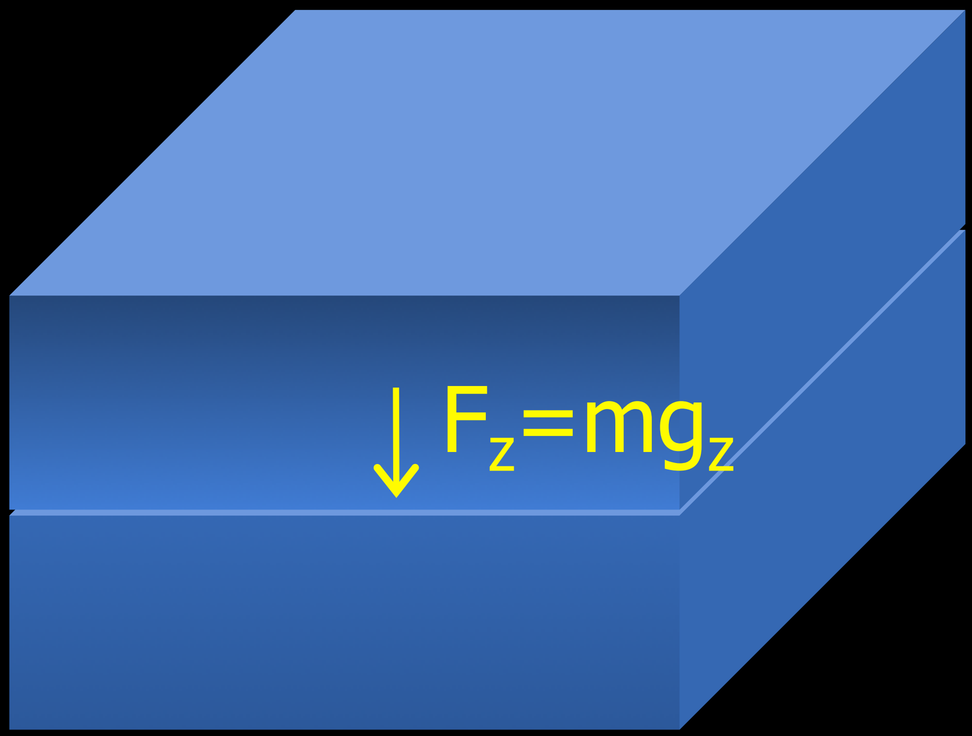
$$\frac{dP_z}{dz} = \rho g_z$$

Similar to stellar structure eqn's

Detour with all the math…

X

Why you expect the observed vertical structure:



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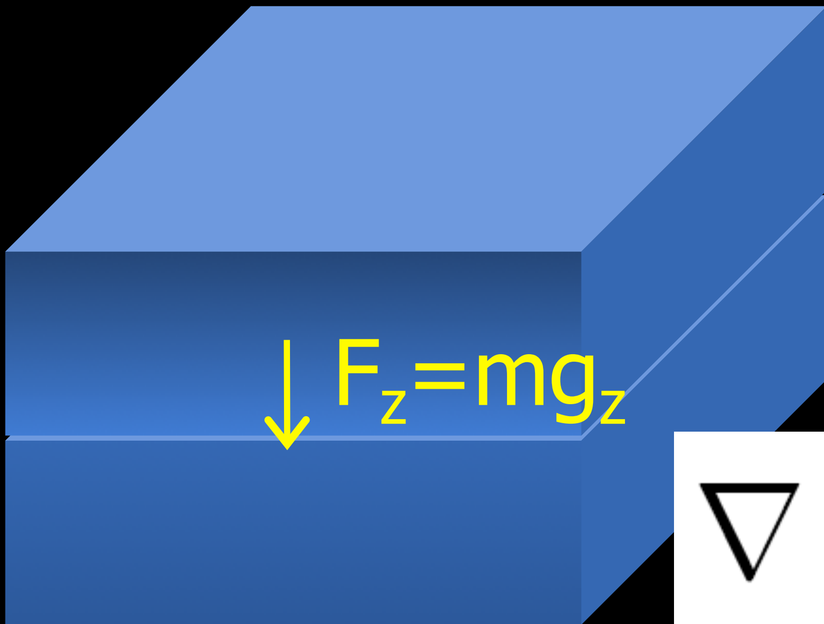
Assume that the slab is "self-gravitating"

A particle of mass m at z feels a downward force $F_z = mg_z$, where g_z is the gravitational acceleration (or force field).

X

Via Gauss's Law:



$$\vec{g} = -\nabla \phi$$

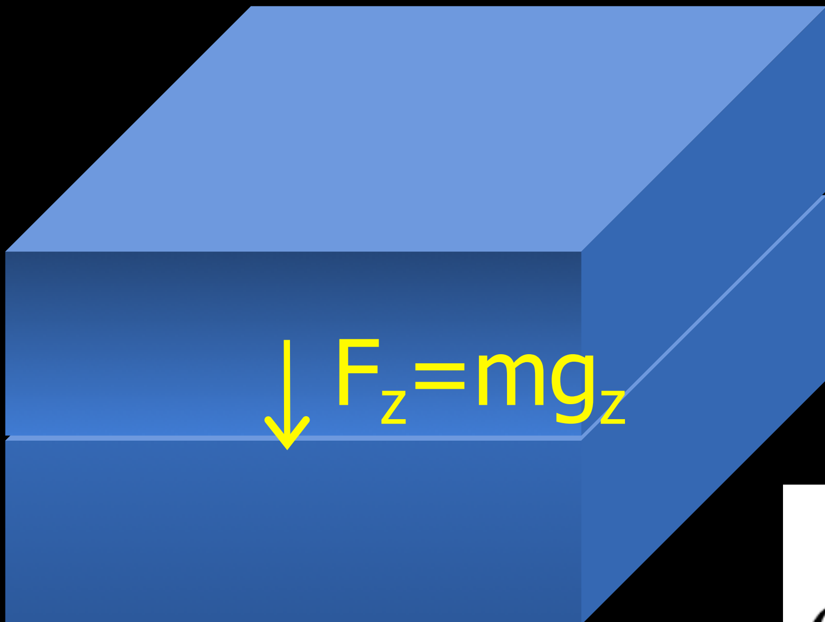
$$\nabla \cdot \vec{g} = \nabla^2 \phi = -4\pi G \rho$$

So ignoring horizontal forces (that in a real disk would be due to $\Sigma(r)$)

$$\nabla \cdot \vec{g} \approx \frac{dg_z}{dz} = -4\pi G \rho$$

This is an equation which can be solved!

Via Gaus…



$$\frac{dg_z}{dz} = -4\pi G\rho$$

Since forces=0 at the midplane:

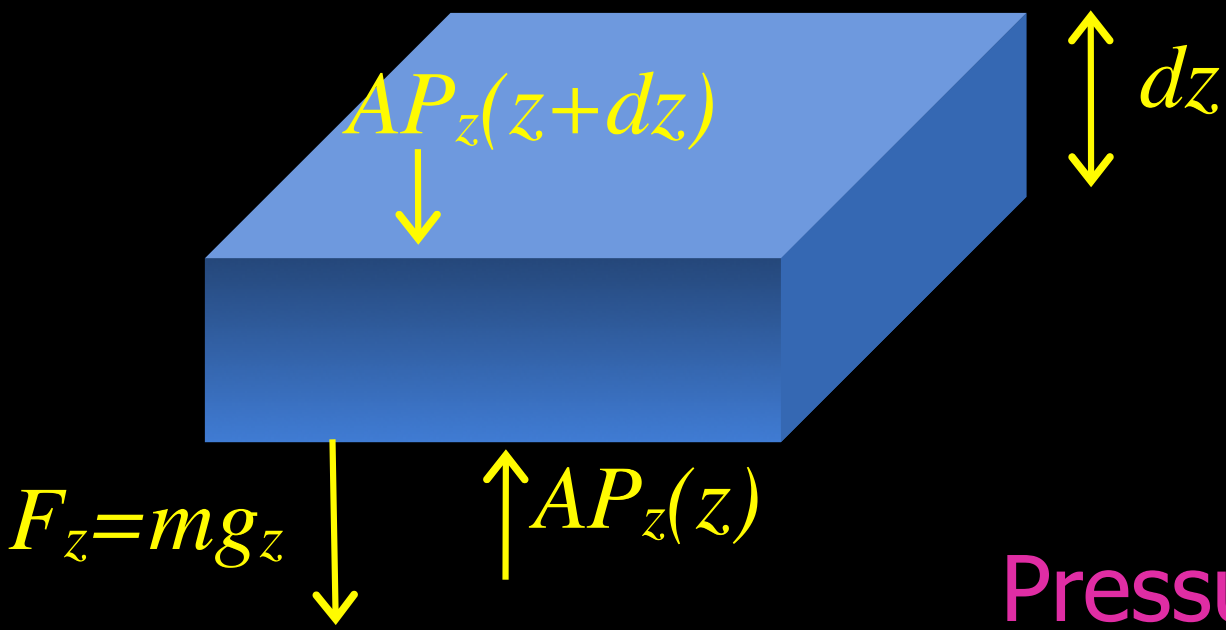
$$g_z = -4\pi G \int_0^z \rho(z')dz'$$

If the disk is in equilibrium, then something must be balancing the the gravitational pull.

Dynamical Pressure: $\boxed{P_z = \sigma_z^2\rho}$

(assuming "isothermal" -- i.e. σ_z constant)

Similar to stellar structure eqn's:



Consider one layer of the slab, with thickness dz, area A, and mass $\rho A dz$

Pressure = Force / Area

$$[P_z(z+dz) - P_z(z)]A = (\rho A dz) g_z$$

Yielding:

$$\frac{dP_z}{dz} = \rho g_z$$

Substituting dynamical pressure:

$$\frac{dP_z}{dz} = \rho g_z \longrightarrow \frac{d(\sigma_z^2 \rho)}{dz} = \rho g_z$$

$$\sigma_z^2 \frac{1}{\rho}\frac{d\rho}{dz} = g_z \quad + \quad g_z = -4\pi G \int_0^z \rho(z')dz'$$

A tasty differential equation:

$$\boxed{\frac{d \ln \rho}{dz} = -\frac{4\pi G}{\sigma_z^2} \int_0^z \rho(z')dz'}$$

X

Substituting dynamical pressure:

$$\frac{dP_z}{dz} = \rho g_z \longrightarrow \frac{d(\sigma_z^2\rho)}{dz} = \rho g_z$$

Rearranging...

$$\sigma_z^2 \frac{1}{\rho}\frac{d\rho}{dz} = g_z$$

Note that this step only worked because the velocity dispersion was constant (I.e. "isothermal"). However, you can model the pressure of more complex distributions as being the sum of the pressure from several populations with different velocity dispersions.

x

This differential equation:

$$\frac{d \ln \rho}{dz} = -\frac{4\pi G}{\sigma_z^2} \int_0^z \rho(z')dz'$$

Has solutions of the form:

$$\rho(z) = \rho_0 \operatorname{sech}^2\left(\frac{z}{2z_0}\right)$$

Where z_0 is some combination of G, σ_z, & ρ_0

x

At large … e plane:

$$\frac{d\ln\rho}{dz} = -\frac{4\pi G}{\sigma_z^2}\int_0^z \rho(z')dz'$$

$$\int_0^{z\to\infty} \rho(z')dz' \to \frac{\Sigma}{2} \longrightarrow \frac{d\ln\rho}{dz} = -\frac{2\pi G\Sigma}{\sigma_z^2}$$

Which has exponential solutions:

$$\boxed{\rho(z) = \rho_0\, e^{-z/z_0}}$$

Where: $$z_0 = \frac{\sigma_z^2}{2\pi G\Sigma}$$

x (z_0 is set by the battle between random motions σ_z and self gravity Σ)

End of mathy detour.

Leads to a differential equation that has solutions of the form

$$\frac{d\ln\rho}{dz} = -\frac{4\pi G}{\sigma_z^2}\int_0^z \rho(z')dz'$$

$$\boxed{\rho(z) = \rho_0 \, \mathrm{sech}^2\left(\frac{z}{2z_0}\right)}$$

Where $z_0 = \dfrac{\sigma_z^2}{2\pi G\Sigma}$ "scale height"

Scale height is balance between gravity (Σ) pulling disk together and velocity dispersion σ keeping disk fluffy (thus "dynamical pressure")

Note: for large z, well above the midplane, density profile is exponential

$$\rho(z) = \rho_0 \, e^{-z/z_0}$$

Fitting formula for vertical surface brightness

Isothermal, self-gravitating sheet (Spitzer 1942)

$$L(z) = L_0 \operatorname{sech}^2(z/z_0)$$

Exponential

$$L(z) = L_0 \exp(-z/h_z)$$

Generalized (van der Kruit 1988)

$[z_0 \approx 2h_z]$

$$L(z) = 2^{-2/n} L_0 \operatorname{sech}^{2/n}(nz/2z_0)$$

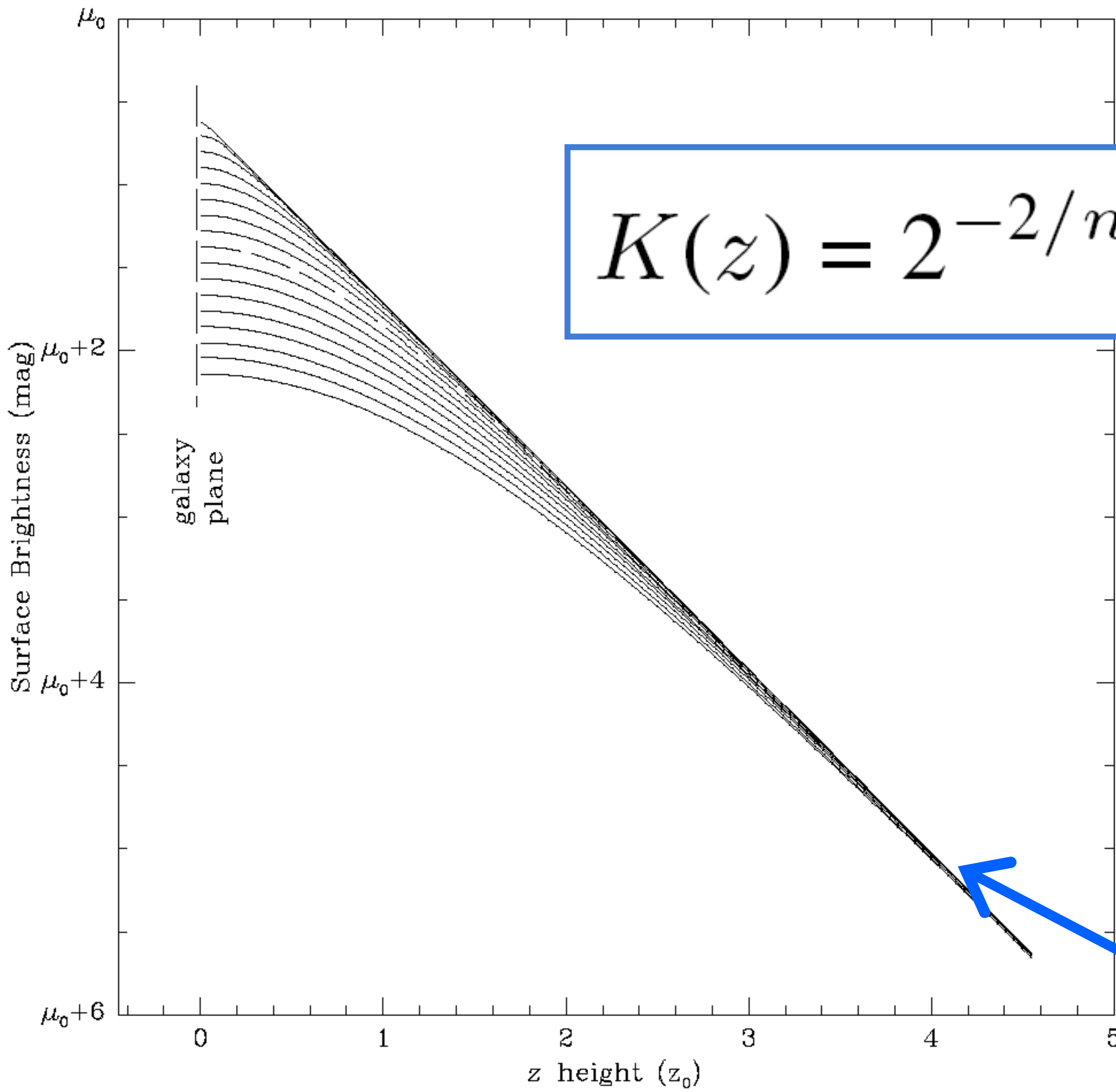


Fig. 4. The family of density (luminosity) laws (6) with the isothermal ($2/n$ = 2.0) and the exponential ($2/n$ = 0.0) distributions as the two extremes. The difference in $2/n$ between two successive model distributions is 0.125; for clarity, the sech(z) model distribution ($2/n$ = 1.0) is shown as the dashed profile (μ_0 is the central surface brightness).

$$K(z) = 2^{-2/n} K_0 \operatorname{sech}^{2/n}(nz/2z_0)$$

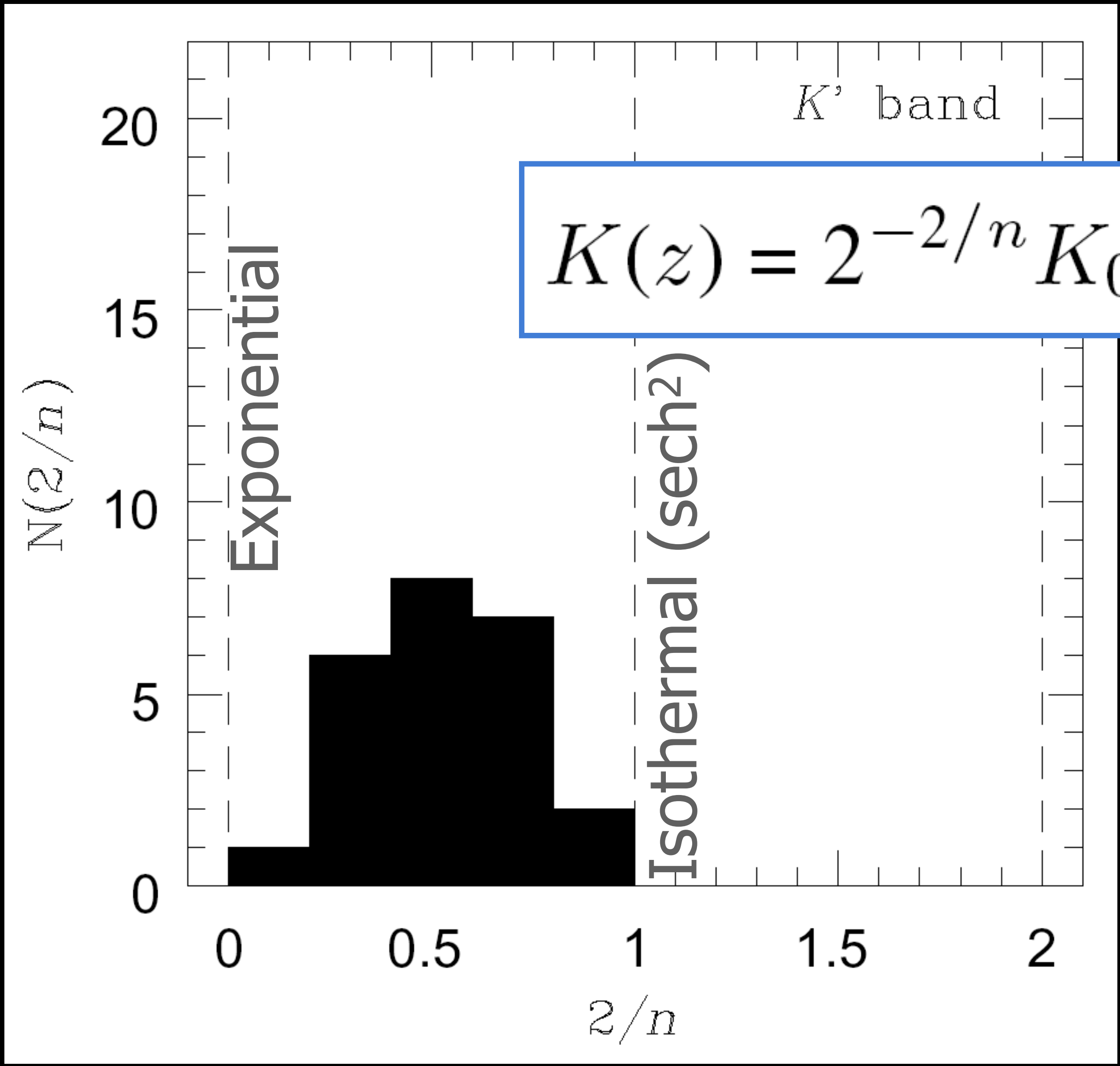
Isothermal if n=1

Exponential if n=∞

They all look the same at large z

de Grijs et al 1997

Real disks are somewhere between an isothermal and an exponential

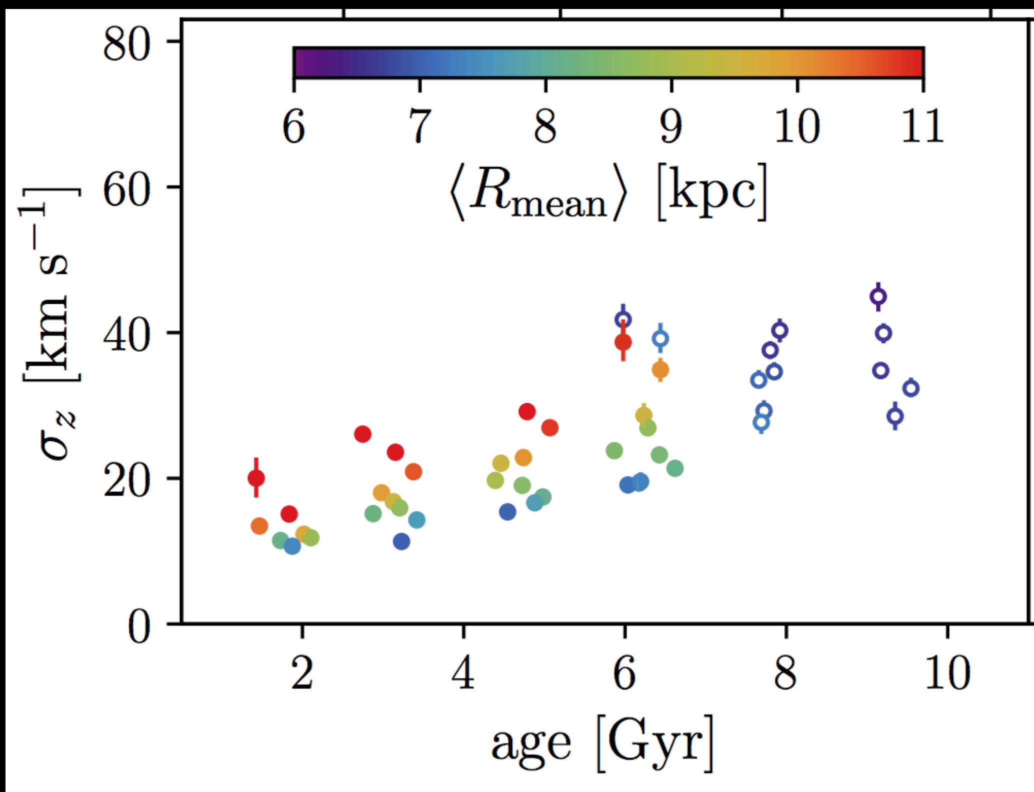


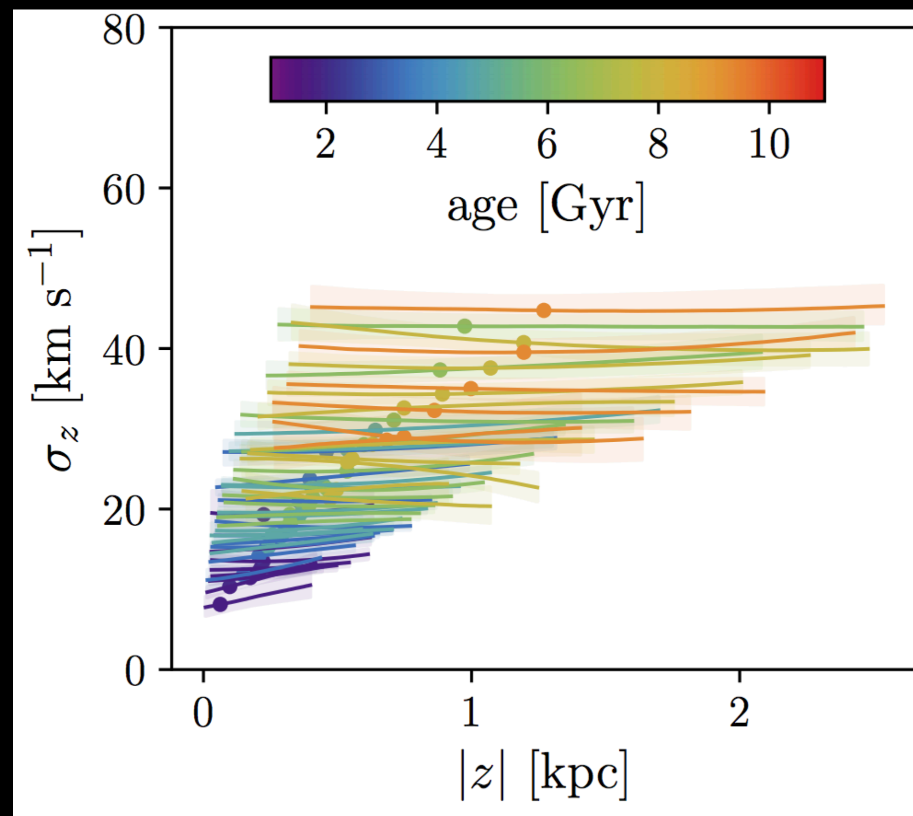
$$K(z) = 2^{-2/n} K_0 \, \mathrm{sech}^{2/n}(nz/2z_0)$$

No single vertical velocity dispersion!

Why not isothermal?

- Scattering off GMCs & spiral arms, and/or accretion “heats” disk stars
- Older stars have had more heating





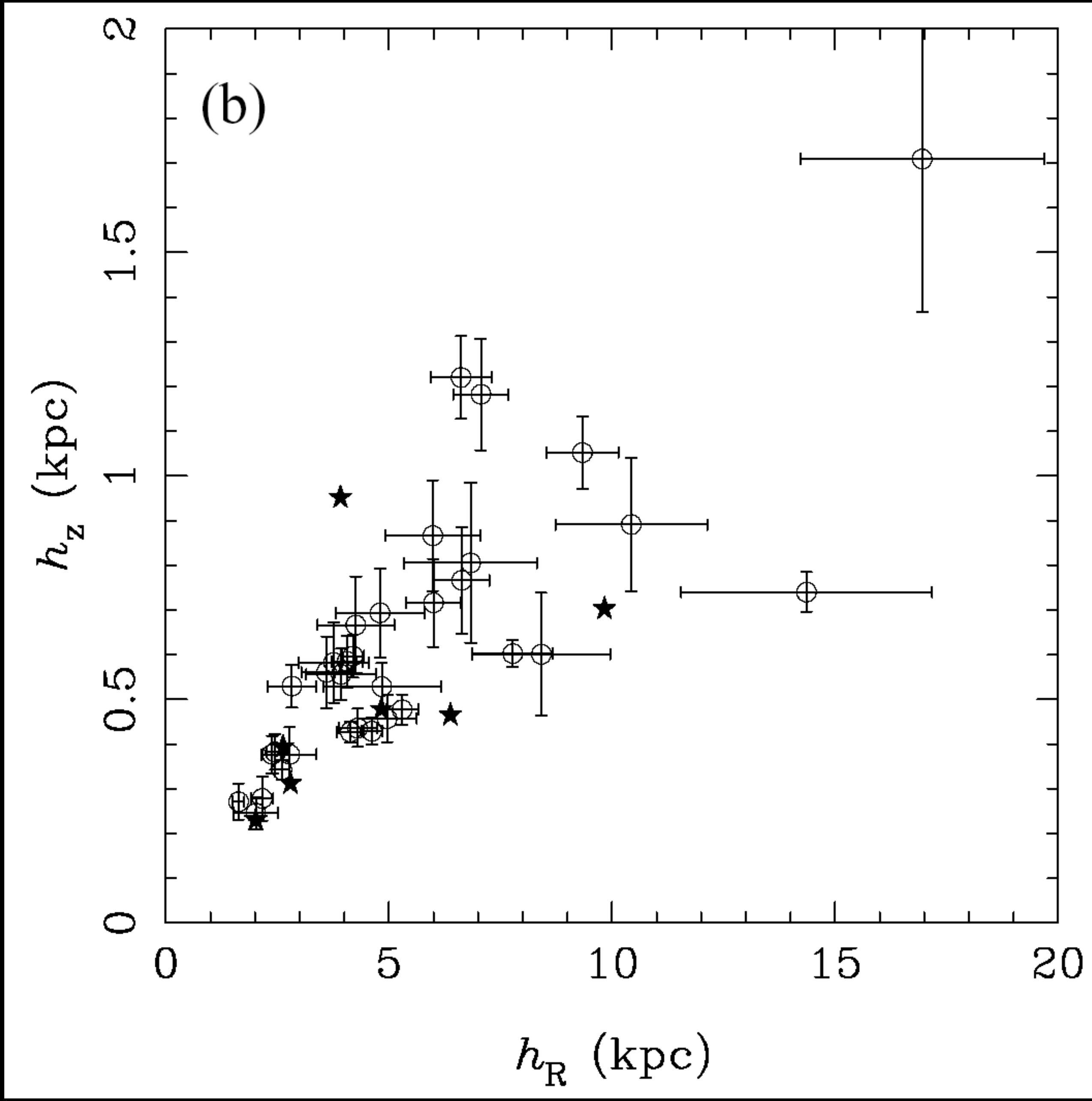
Mackereth et al 2019

Lines for each mono-age, mono-[Fe/H] population. Horizontal with z implies isothermal. But, *total ensemble* is not isothermal.

What might be reasons for scatter in plot?

$$\rho(z) = \rho_0 \, e^{-z/z_0}$$

$$z_0 = \frac{\sigma_z^2}{2\pi G \Sigma}$$



Kregel et al 2002

What might be reasons for flaring?

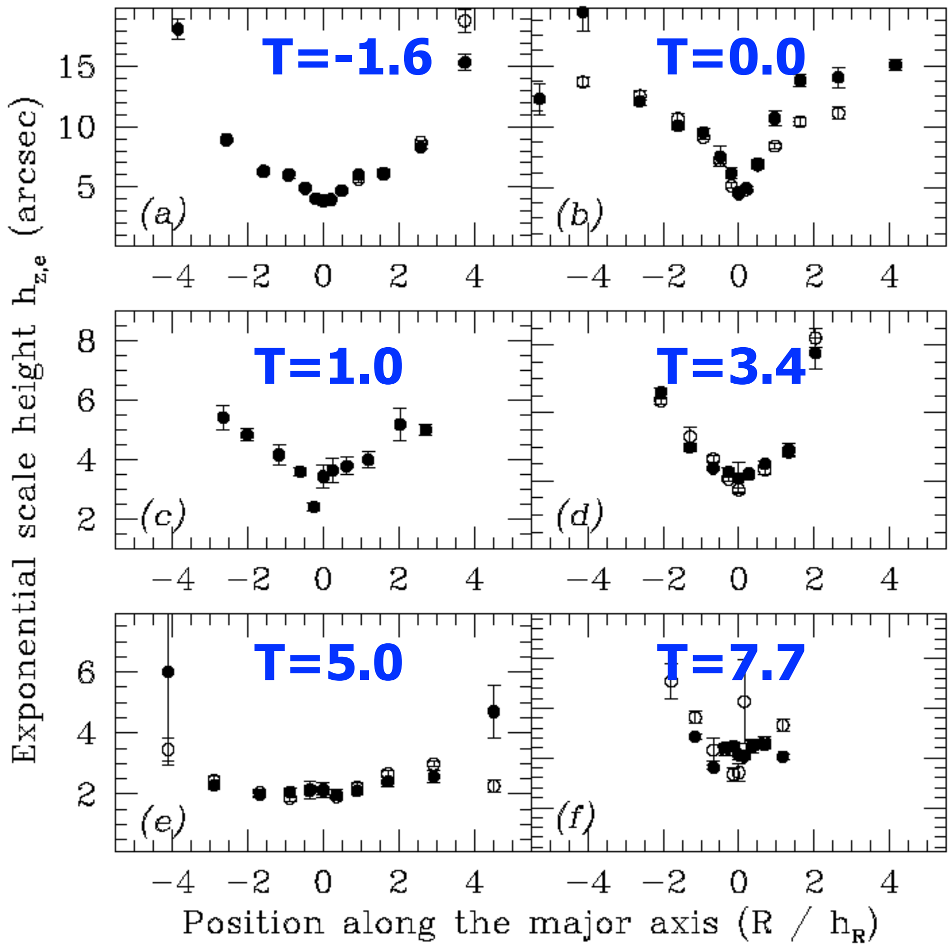
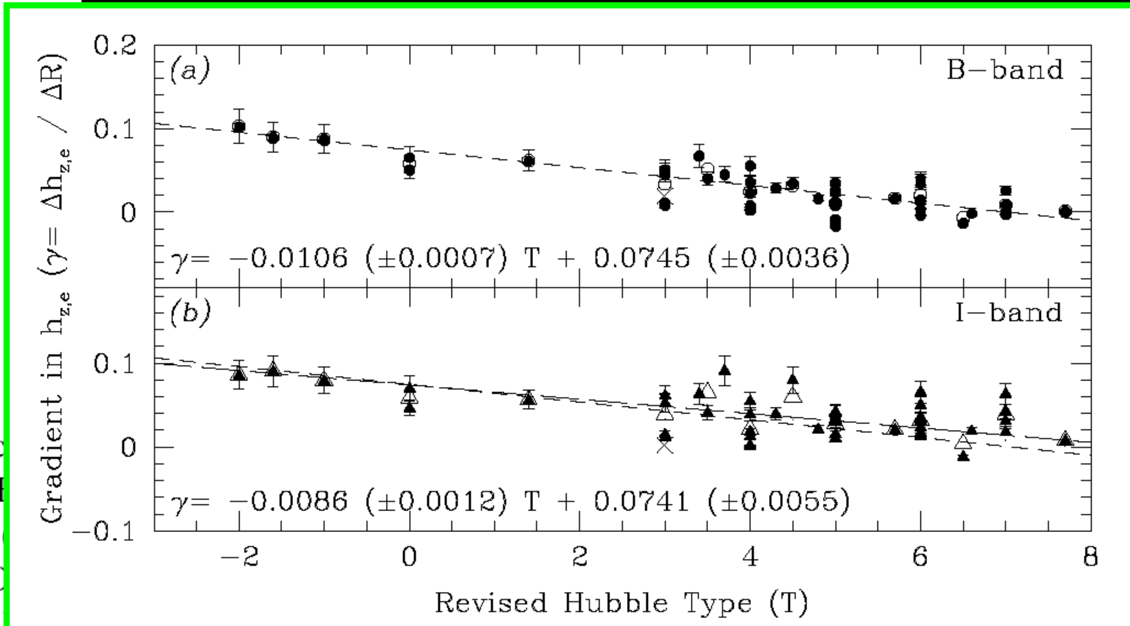


Fig. 1. Examples of the *I*-band scale height behaviour as a func of galactocentric distance for *(a)* ESO 358G-29 (T = −1.6), *(b)* E 311G-12 (T = 0.0), *(c)* ESO 315G-20 (T = 1.0), *(d)* ESO 322G-87 (3.4), *(e)* ESO 435G-50 (T = 5.0), and *(f)* ESO 505G-03 (T = 7.7). O and closed symbols represent data taken on both sides of the ga planes.

$$\rho(z) = \rho_0 \, e^{-z/z_0}$$

$$z_0 = \frac{\sigma_z^2}{2\pi G \Sigma}$$



de Grijs & Peletier 1997

Summary: Vertical Structure of Disks

- Exponential at large scale heights
- Different possible structures at midplane
- Profile set by balance of gravity and dynamical pressure
- Dynamical pressure set by "vertical heating"
- Depends on galaxy mass and/or T-type
- Scale height can vary with radius, but fairly flat when there's no bulge