

Testing Modified Gravity with the DiskMass Survey

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Spiral (disk) galaxies.
Often gas rich => star formation.

The Spitzer Infrared Nearby Galaxies Survey

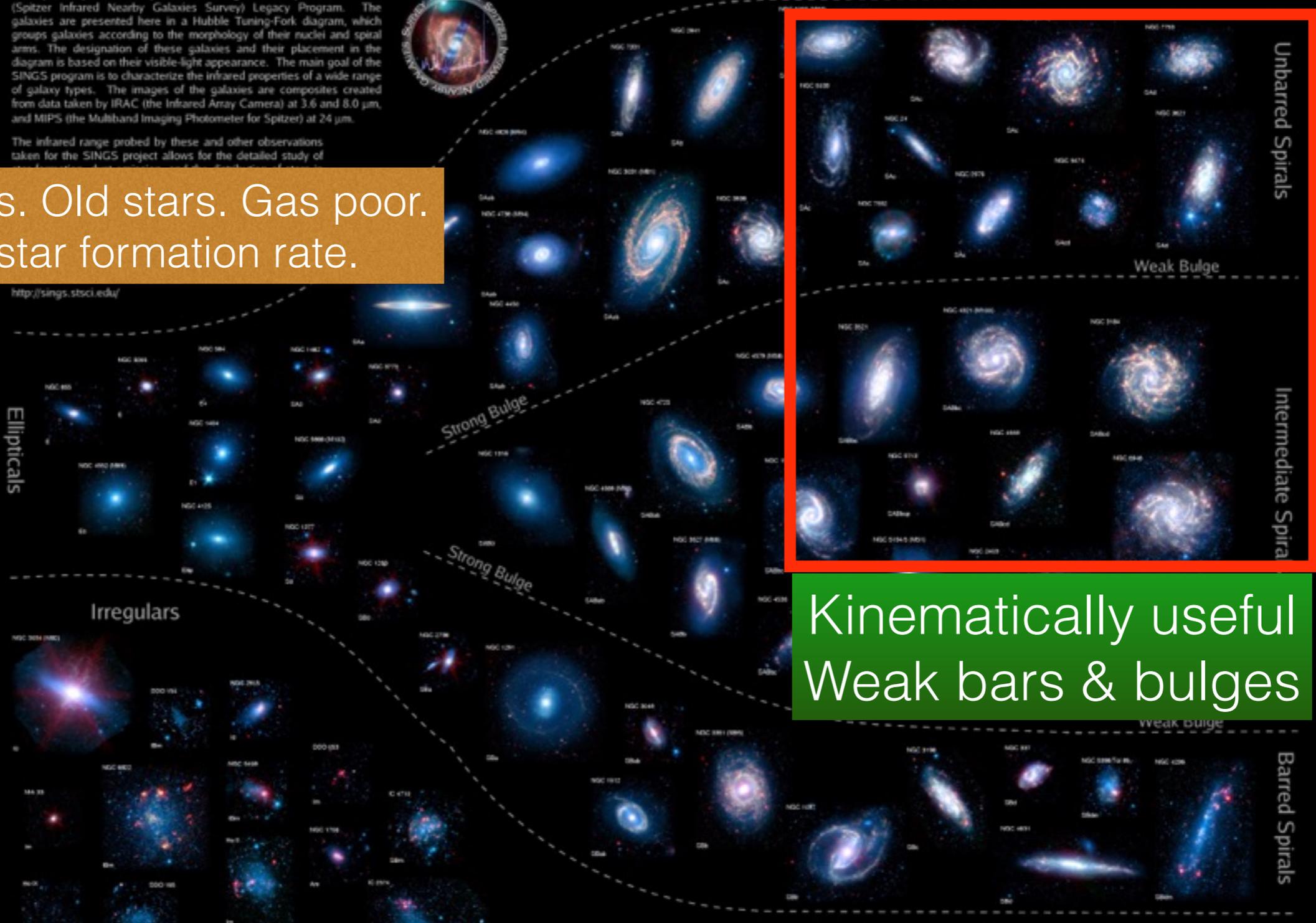
The Spitzer Space Telescope observed 75 galaxies as part of its SINGS (Spitzer Infrared Nearby Galaxies Survey) Legacy Program. The galaxies are presented here in a Hubble Tuning-Fork diagram, which groups galaxies according to the morphology of their nuclei and spiral arms. The designation of these galaxies and their placement in the diagram is based on their visible-light appearance. The main goal of the SINGS program is to characterize the infrared properties of a wide range of galaxy types. The images of the galaxies are composites created from data taken by IRAC (the Infrared Array Camera) at 3.6 and 8.0 μm , and MIPS (the Multiband Imaging Photometer for Spitzer) at 24 μm .

The infrared range probed by these and other observations taken for the SINGS project allows for the detailed study of



Ellipticals. Old stars. Gas poor.
Low star formation rate.

<http://sings.stsci.edu/>



Kinematically useful
Weak bars & bulges

Bar strength

Bulge strength



Poster and composite images created from SINGS observations by Karl D. Gordon (PI), Robert Kennicutt, Jr. (Principal Investigator), Daniela Calzetti (Deputy Principle Investigator), Charles Beckwith, John van Dokkum, John M. Lotz, Tom Jarrett, Lisa Kew, Eric Murphy, Smith, Michele

The inclination is important

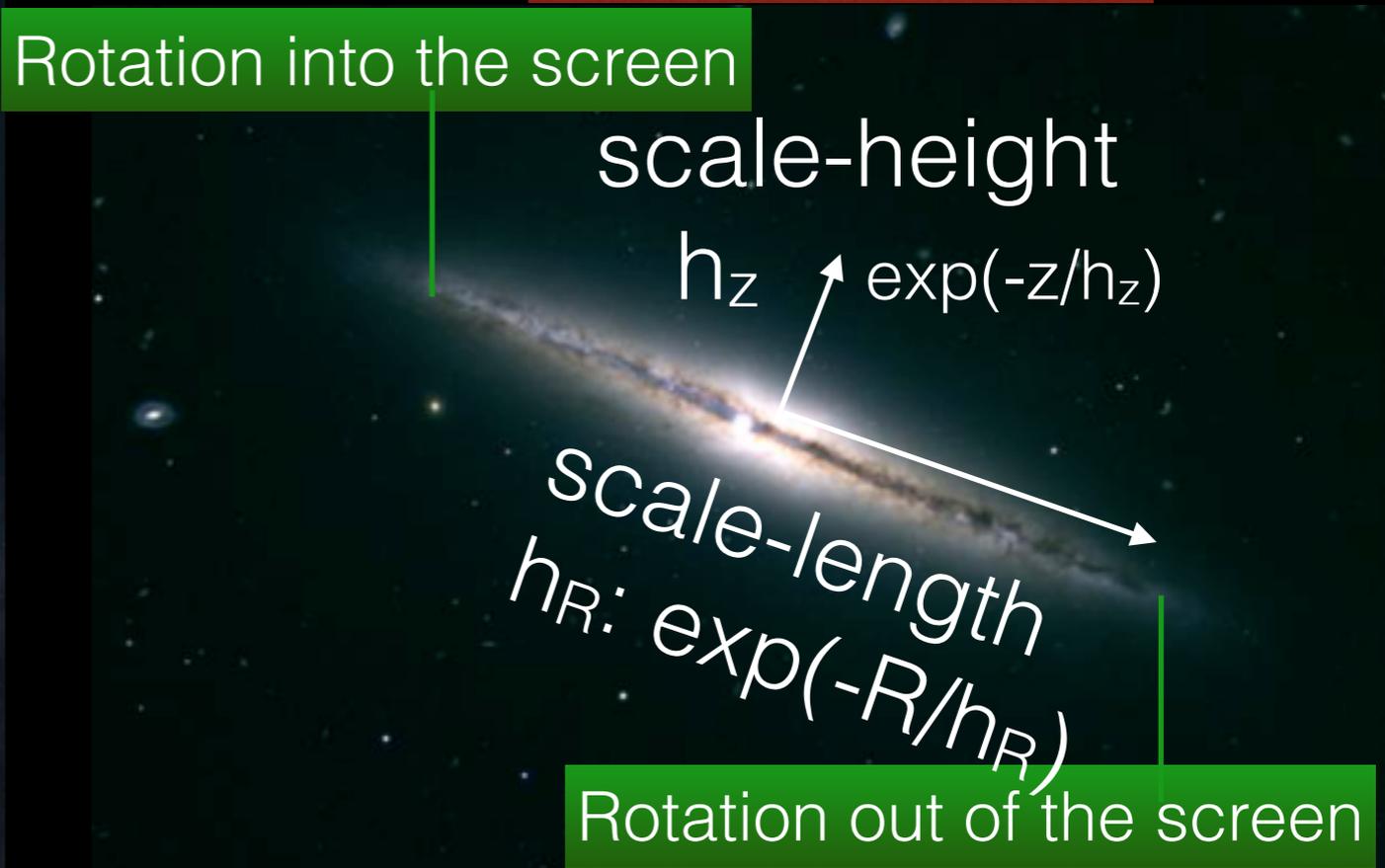
Face-on : $i=0$ deg



Clockwise rotation

Edge-on : $i=90$ deg

Rotation into the screen



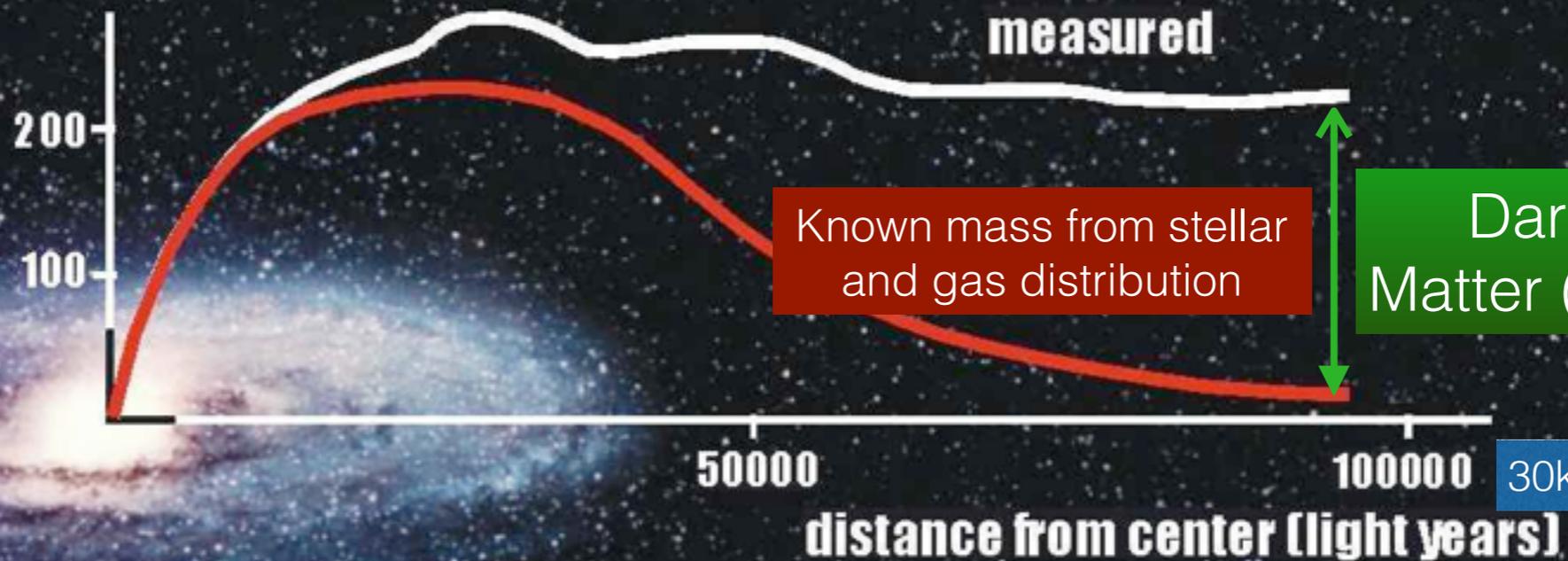
Rotation out of the screen

We want to measure rotation speed of galaxy as function of radius, $V(R) \Rightarrow M(R)$

if it helps: $V(R) \rightarrow M(R)$

Take a nearly edge on galaxy and measure its rotation using neutral hydrogen emission (radio - 21cm)

rotational velocity
[km/s]



Known mass from stellar and gas distribution

Dark Matter (DM)

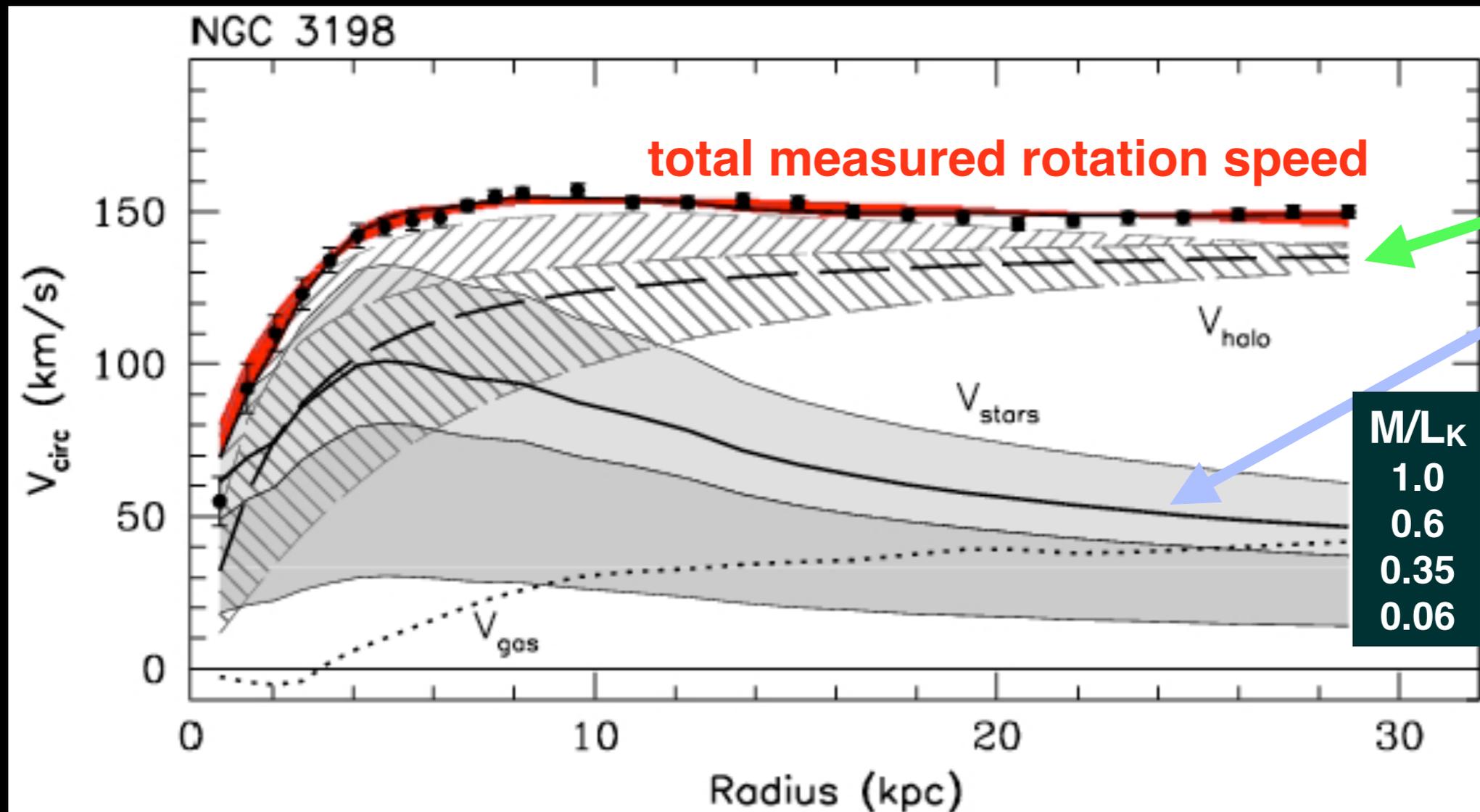
30kpc

1 light year ~ 0.3 parsec

M31/Andromeda, $i \sim 77$ deg

$$M_{\star} = L_{\star} \times \text{M/L}_K \rightarrow \text{Mass-to-light ratio K-band - NIR}$$

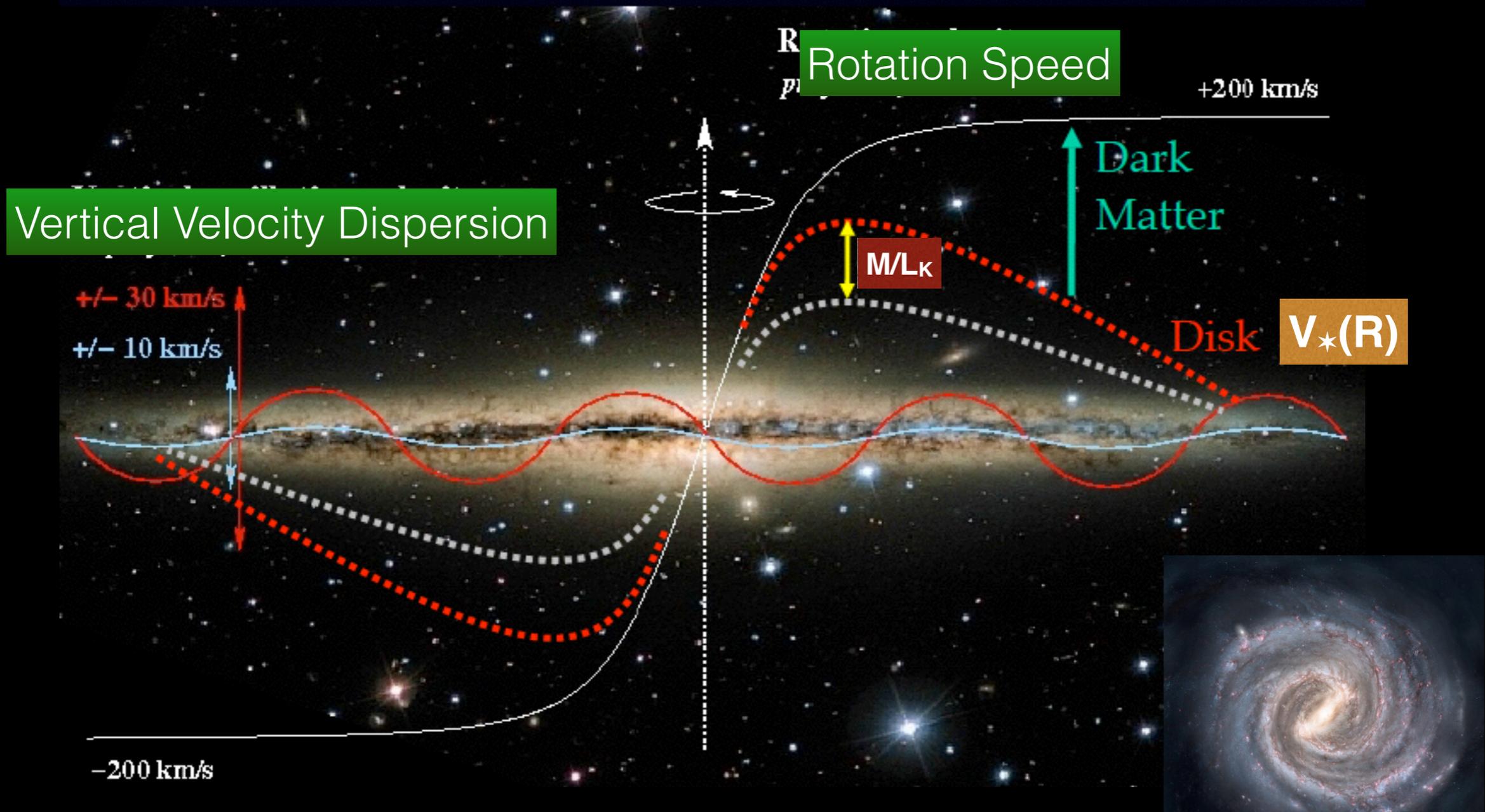
Influence of M/L_K on DM halo



Possible contribution from **DM** and **stars**

DM halo abundance depends on mass of stars (M/L_K).
Numerical stellar evolution models favour $M/L_K \sim 0.6$.
Can we measure M/L_K directly?

What if we had a 2nd (independent) measure of the dynamics?



Stellar Vertical VelDisp gives
 $\sigma_z^2 \propto \Sigma_{\text{total}} \times h_z \propto M/L_K \times h_z$
 Need galaxies with $i \sim 15\text{-}40$ deg to
 simultaneously measure $V(R)$ and σ_z

The DiskMass Survey

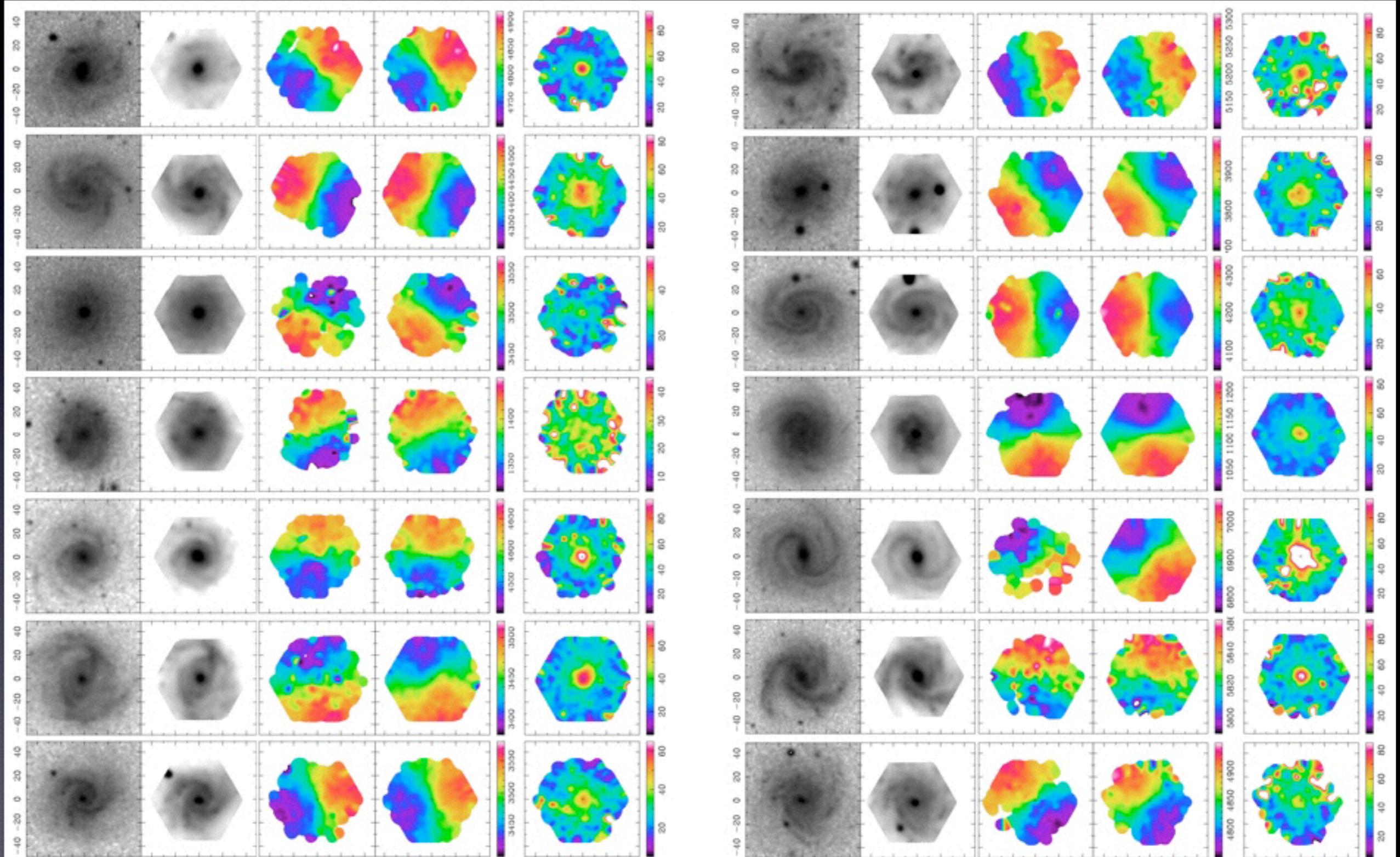
Bershady et al. 2010

Surface brightness

Rotation speed

stellar velocity dispersion

DSS red continuum [OIII] stars σ_{LOS} DSS red continuum [OIII] stars σ_{LOS}

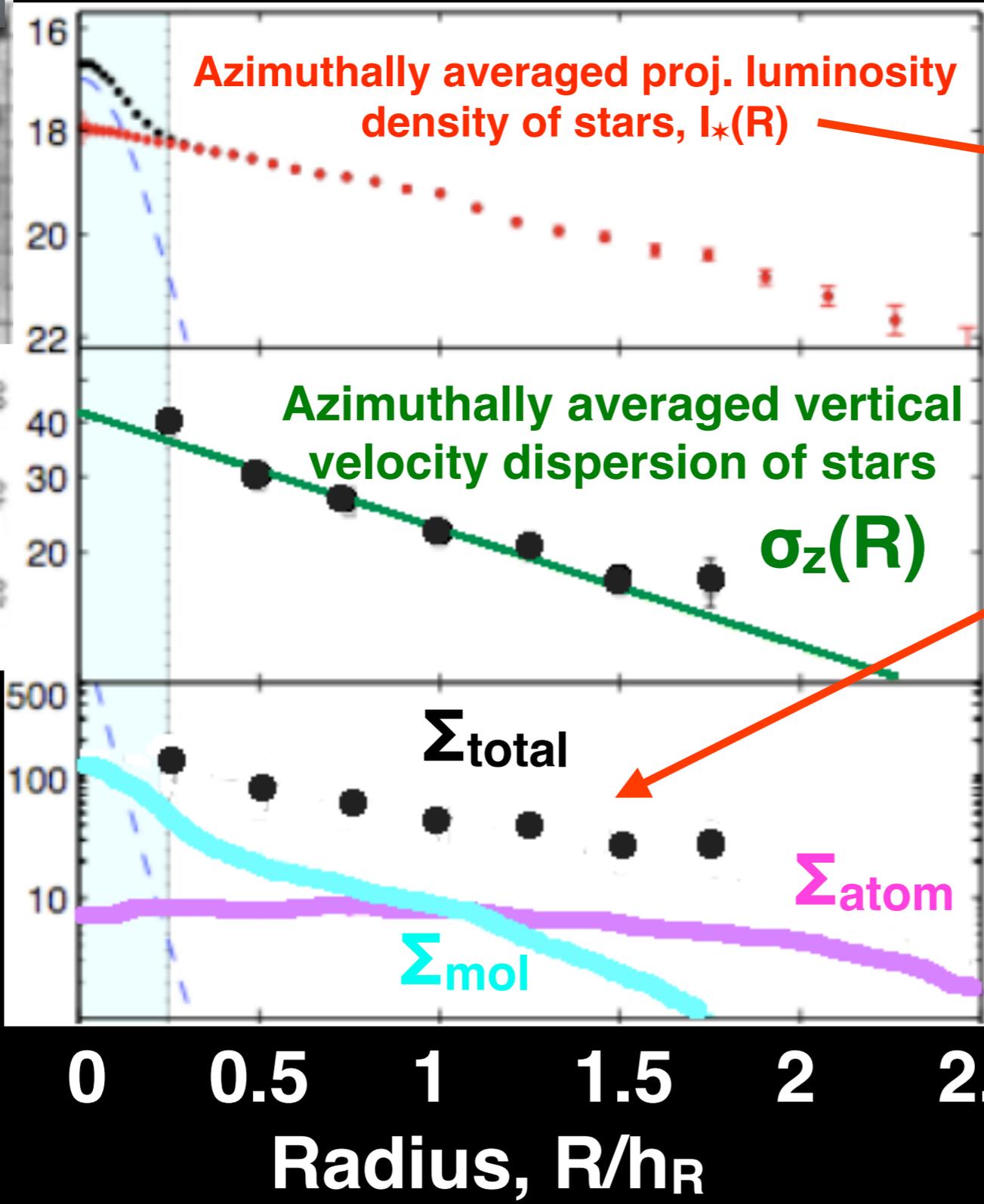
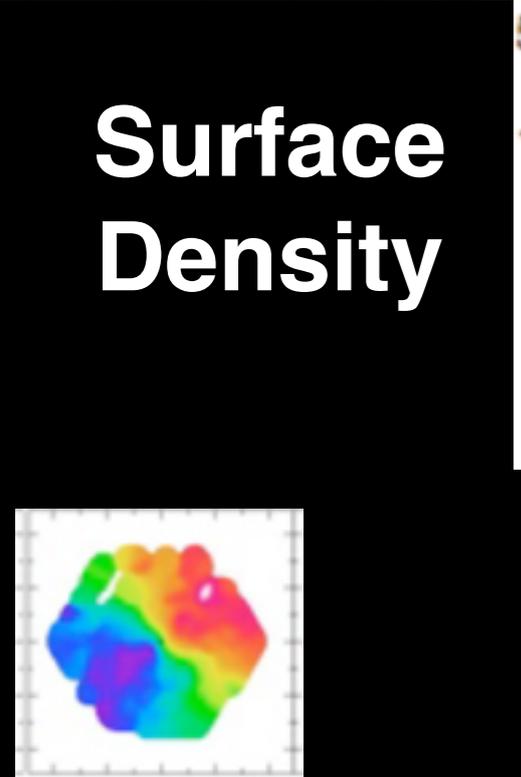
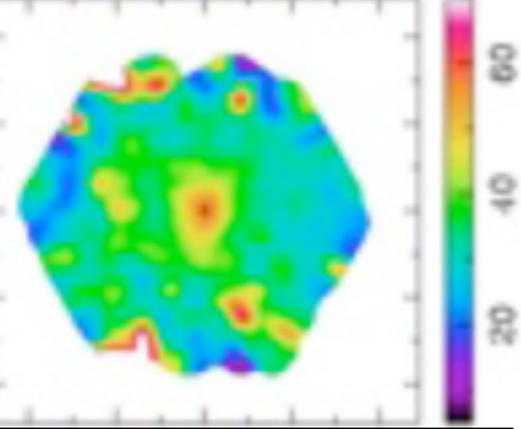
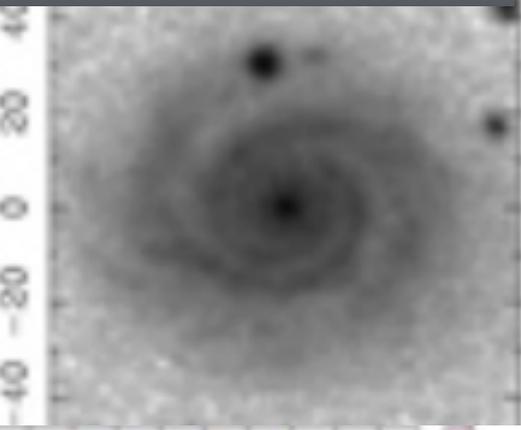


Surface Brightness
 =Proj. Luminosity Density
 =Luminosity/Area

Martinsson et al. 2013ab

k is a parameter fixed by the vertical stellar distribution.
 G is Newton's constant.
 h_z is the exponential scale-height of the galaxy disk.
 Σ_* is the stellar disk surface density.
 Σ_{total} is the total disk surface density.
 Σ_{atom} is the atomic gas (HI, He) surface density.
 Σ_{mol} is the molecular gas (H2) surface density.

$M_* = L_* \times M/L_K$
 $\Sigma_* = I_* \times M/L_K$



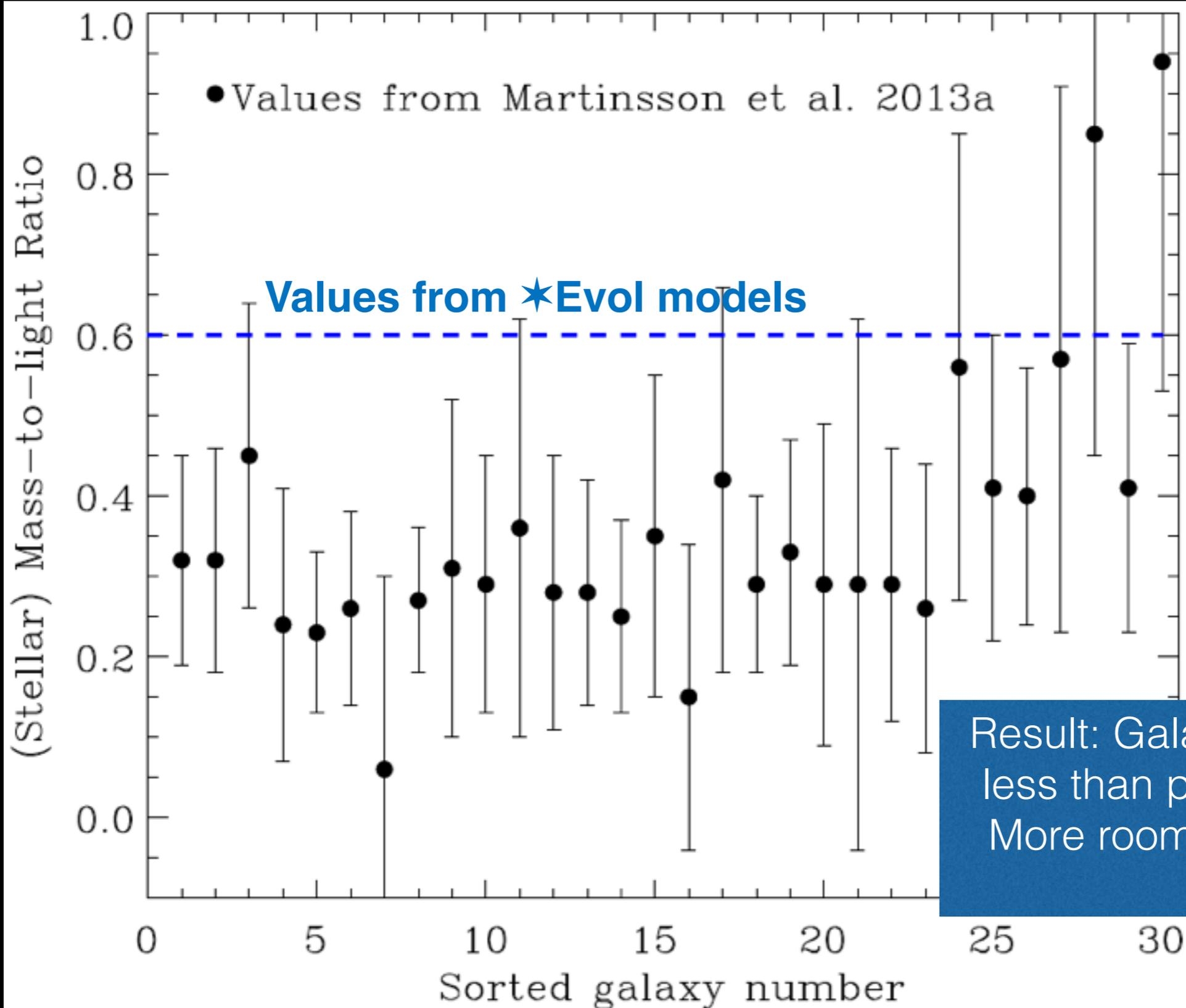
Σ_*
 M/L_K

$\Sigma_{\text{total}} \approx \sigma_z^2 / \pi G k h_z$

Combining all this info gives
 $\Sigma_* = \Sigma_{\text{total}} - \Sigma_{\text{atom}} - \Sigma_{\text{mol}} (-\Sigma_{\text{DM}})$

Surface Density

Galaxy disks have been dieting



Result: Galaxy disks weigh 2x less than previously thought. More room for DM in central parts.

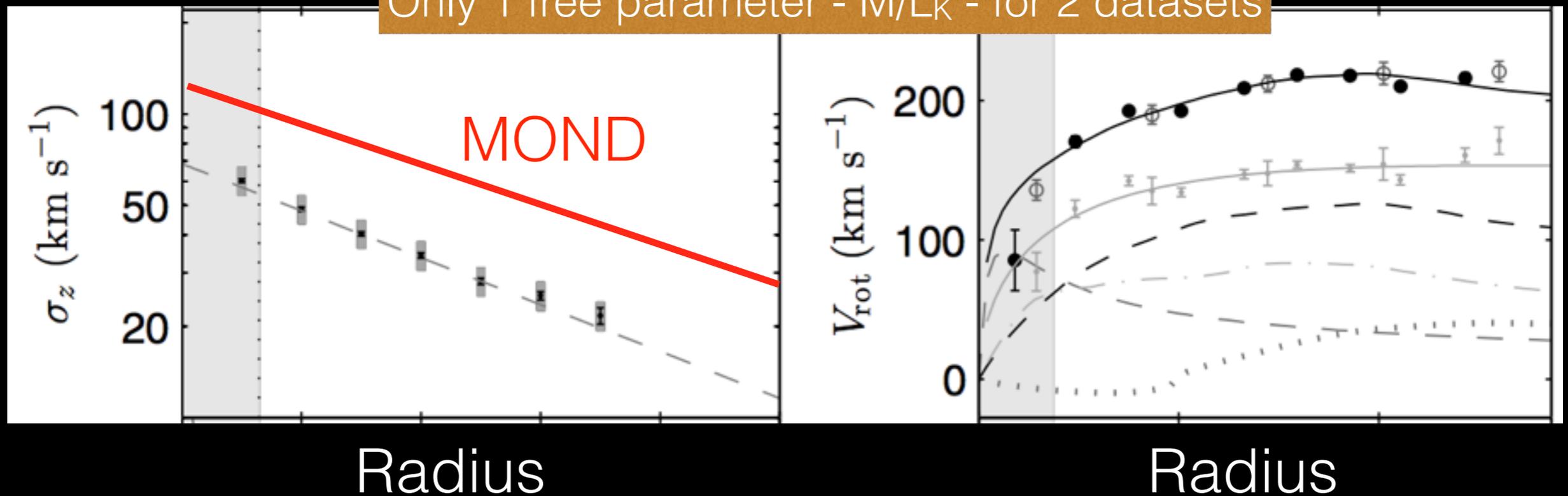
Modified Newtonian Dynamics (MOND)

$a_N \gg a_0 \rightarrow$ Newtonian dynamics: $1/r^2$ (Milgrom 1983)

$a_N \ll a_0 \rightarrow$ Modified force law : $a \sim \sqrt{a_N a_0} \sim 1/r$

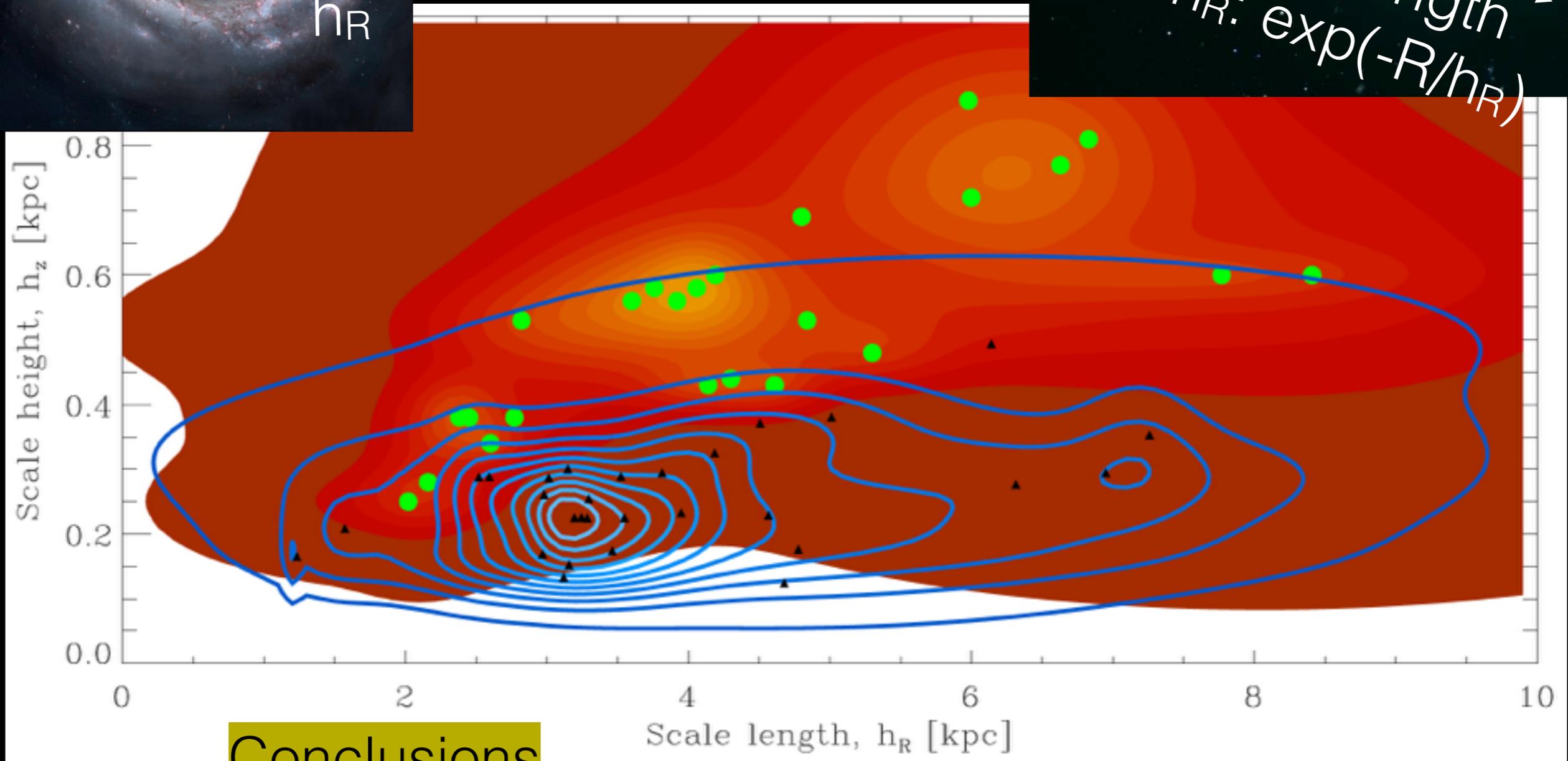
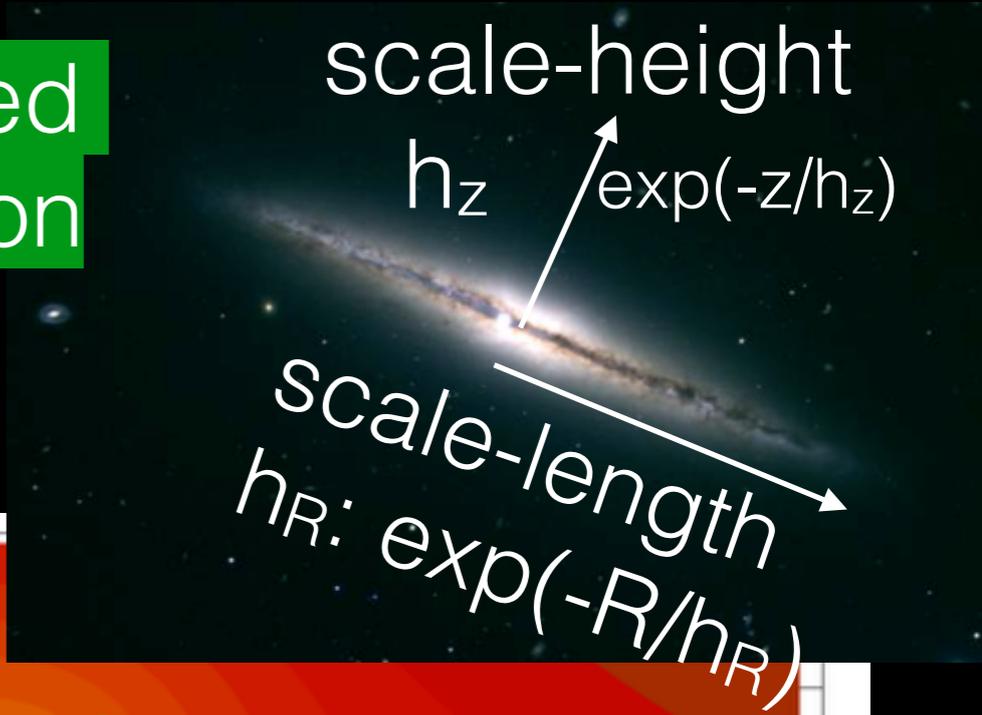
Angus, Diaferio, et al., 2015, MNRAS

Only 1 free parameter - M/L_K - for 2 datasets





Compare with observed scale-height distribution



Conclusions

Galaxy disks are significantly lighter than previously thought. Modified gravity theories are at odds with the DiskMass Survey data.



Using scaling relations to find

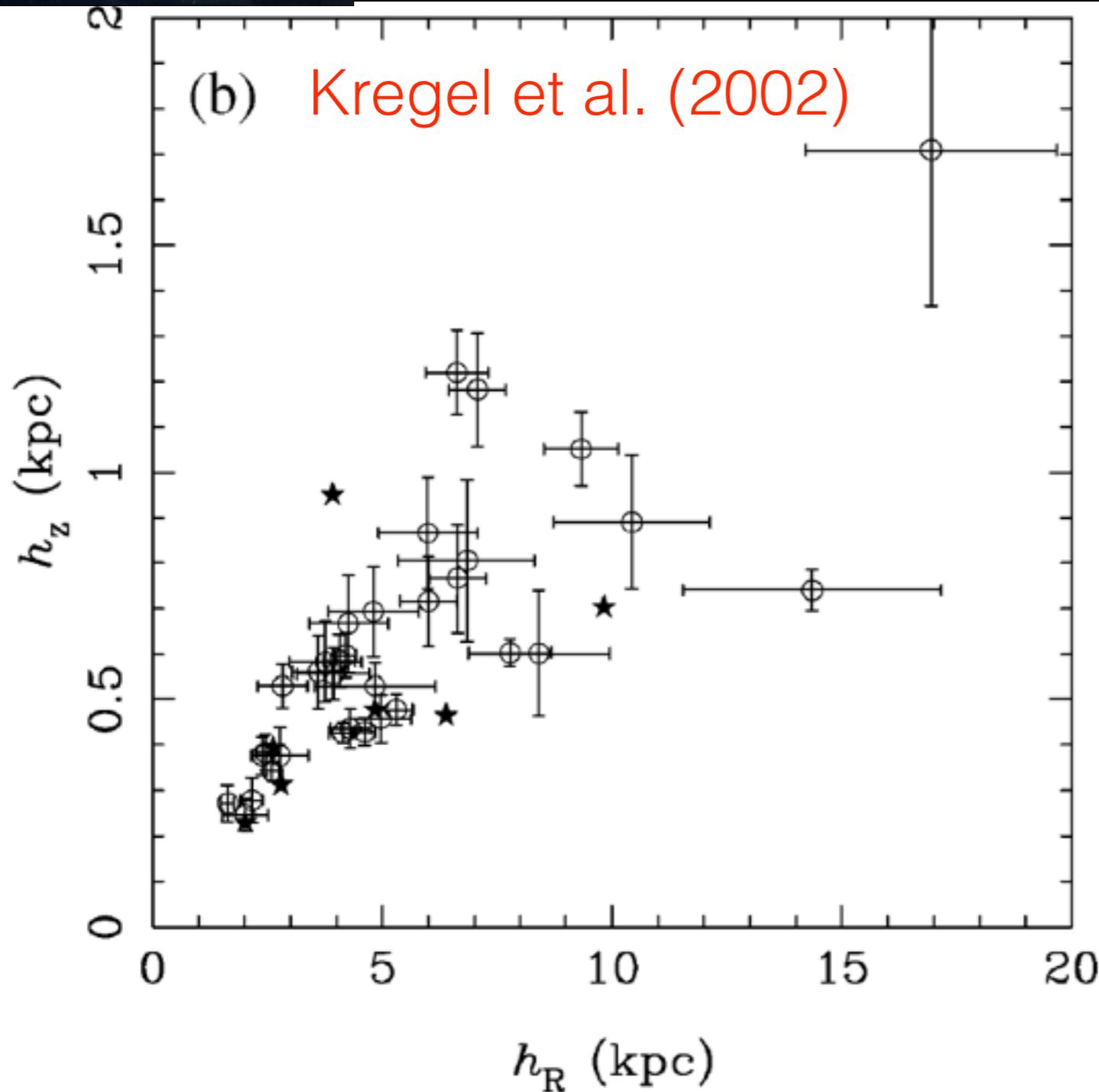
scale-height, h_z

and

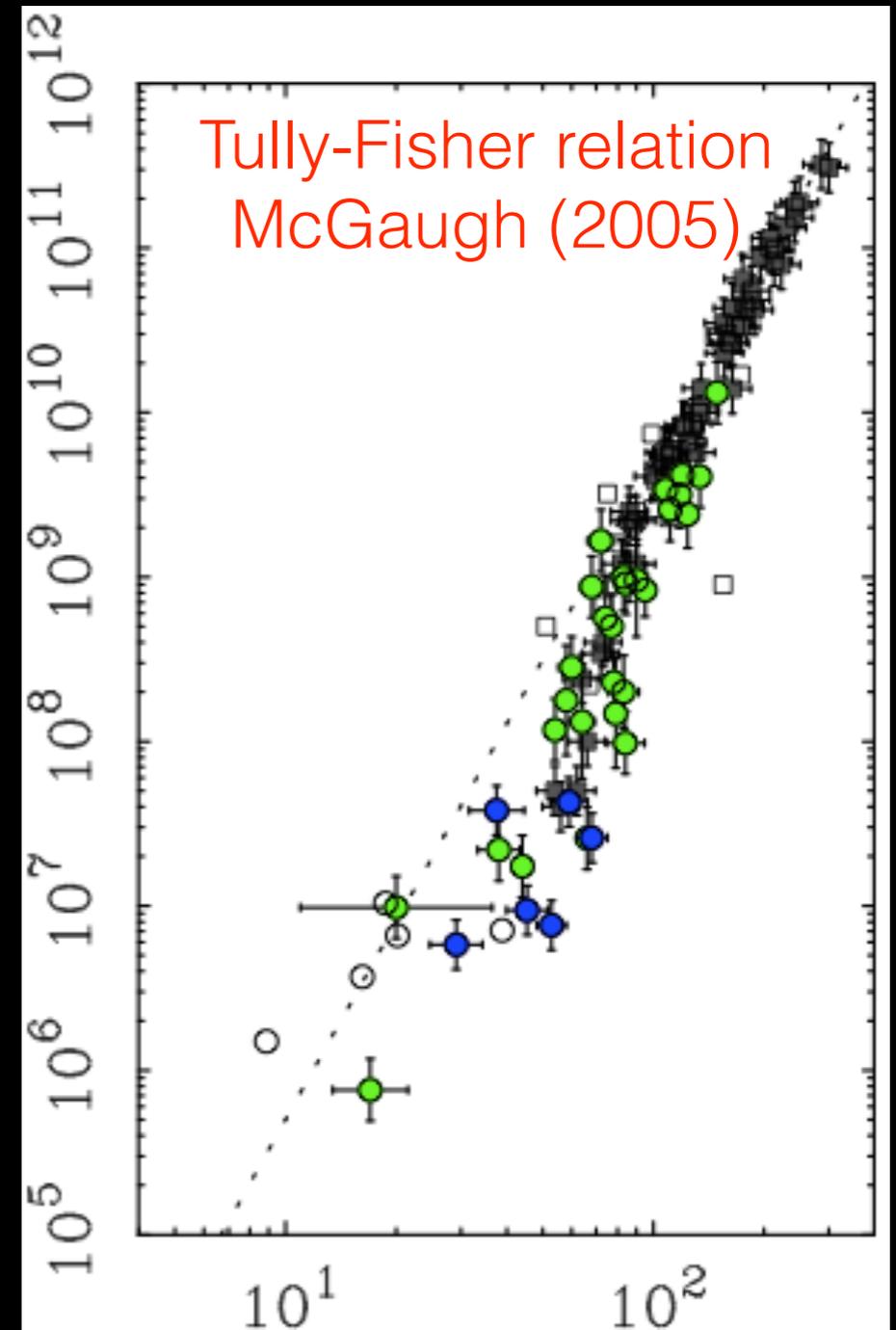
inclination, i



(b) Kregel et al. (2002)



Galaxy Luminosity, L_{sun}



Rotation velocity, km/s

After accounting for DM

Angus, Gentile & Famaey 2015

