# Dark matter in galaxies

## some observational insights

*"A modern take on classical methods"*

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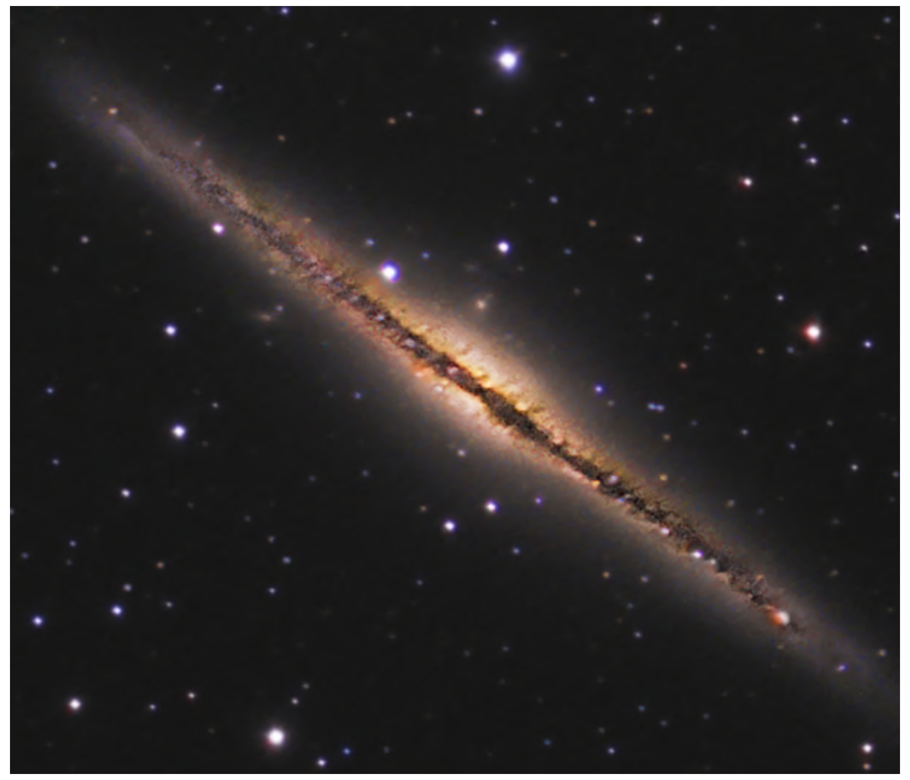
**A. Marasco** (INAF-Arcetri), **E. di Teodoro** (Johns Hopkins), **K. Oman** (Durham)*







# The galaxy—halo connection


- How much dark matter is there in galaxies? How is it distributed?

- Can we constrain the properties of DM halos from dynamical observations?

- Can we test LCDM and/or alternative gravity theories, e.g. MOND?

- MOND (Milgrom 1983): $g \rightarrow \sqrt{\mathrm{a}_0 g_N}$ for $g \ll \mathrm{a}_0$

# Observations of galaxy rotation curves

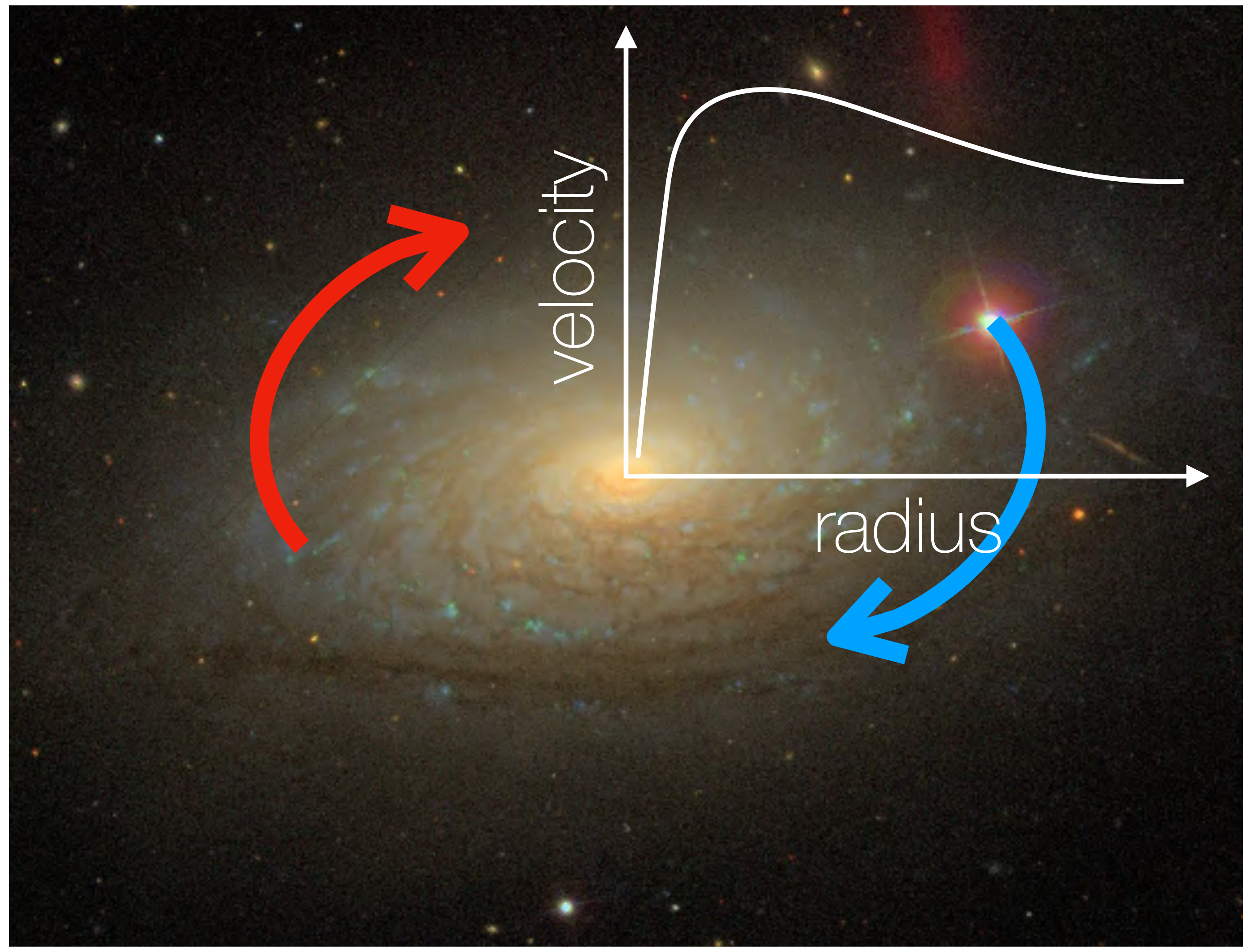
- Main observable: kinematics of stars/gas in galaxies

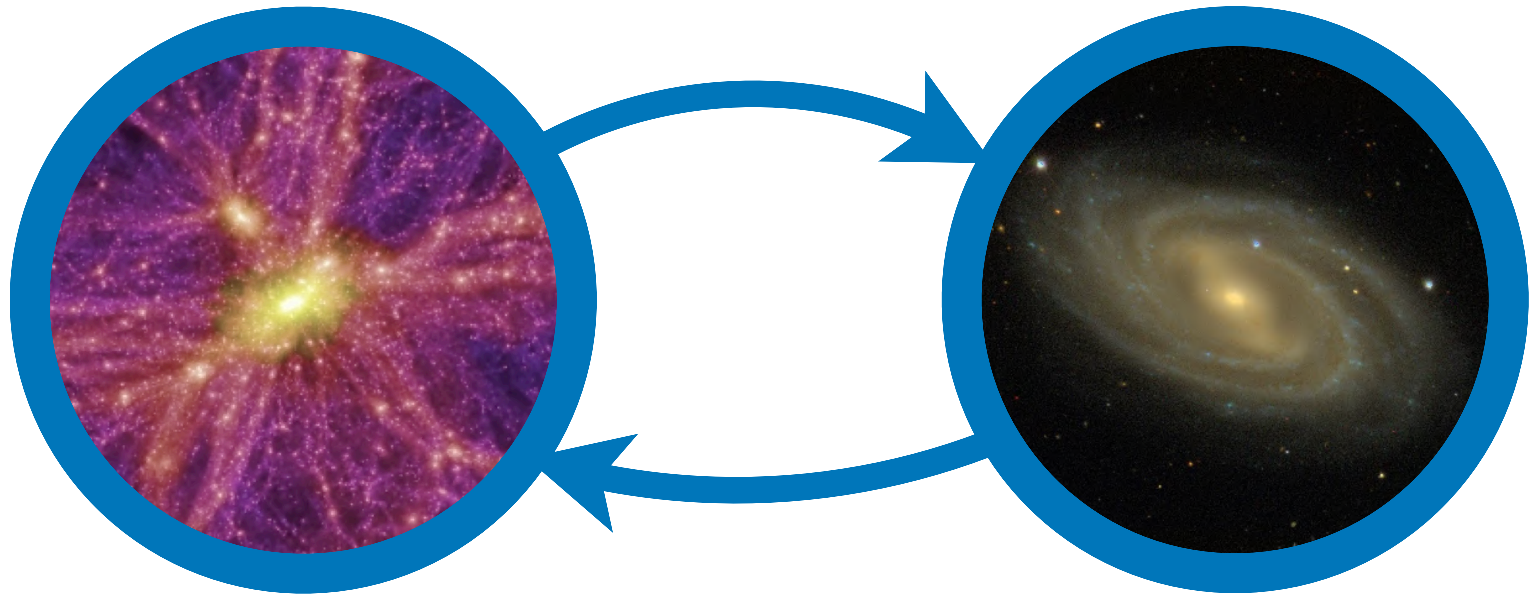
- For disc galaxies we obtain **rotation curves** from observations

- What do we measure from rotation curve observations?

    - the relation between baryonic mass—dark matter mass

      *both directly and indirectly (via the Tully-Fisher)*



Problematic observations for LCDM / successes for MOND?

- the Tully-Fisher relation
- the mass—light correspondence (a.k.a. RAR, Renzo's Rule)

# Radio interferometric observations

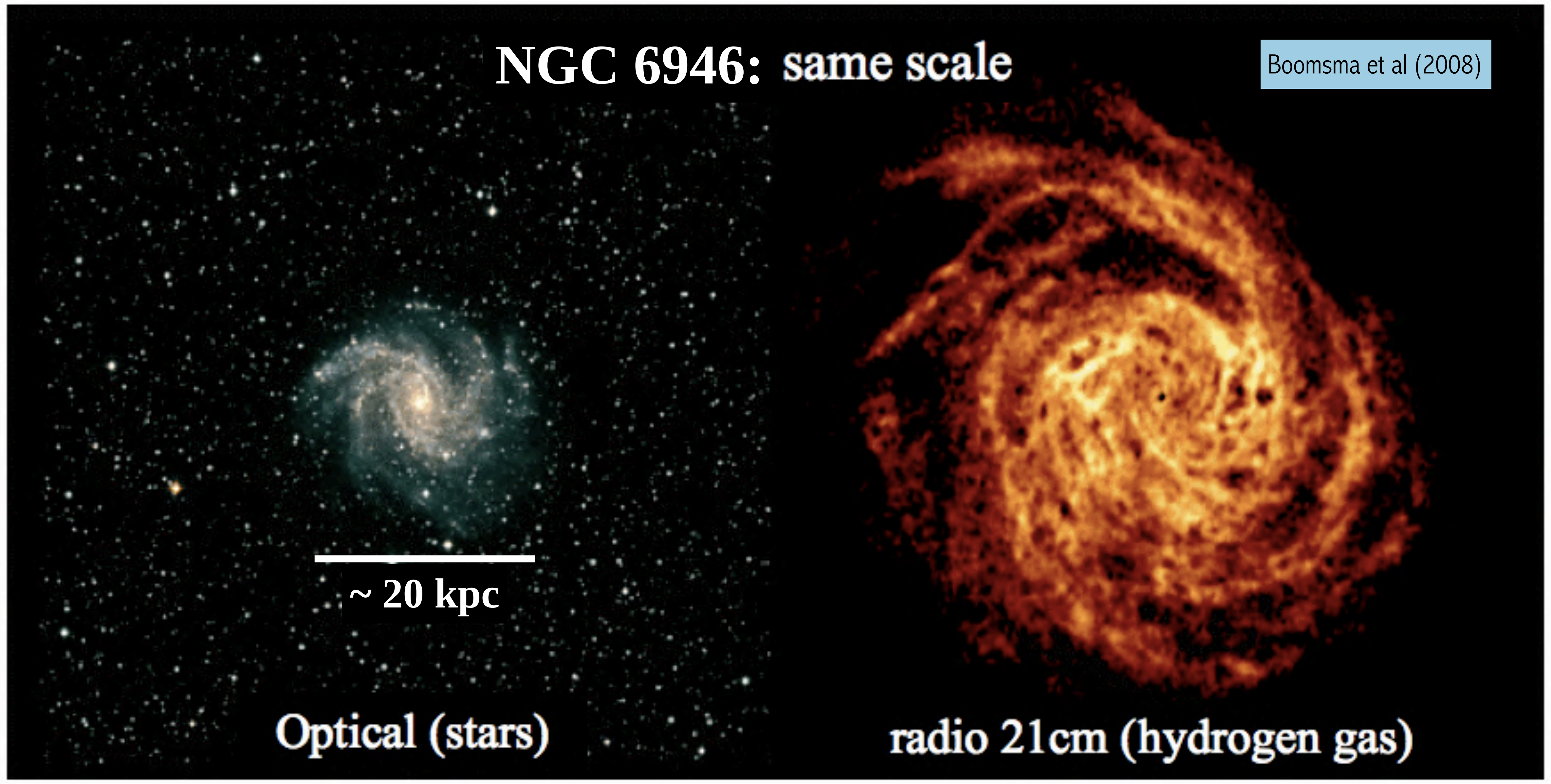
- Rotation curves from radio interferometric observations


- HI 21cm line: cold gas kinematics ⟶ $\nabla\phi$

- Probing $\nabla\phi$ in the outskirts of galaxies

- Focus on nearby galaxies with superb data

  *high spatial resolution, wide radial coverage*

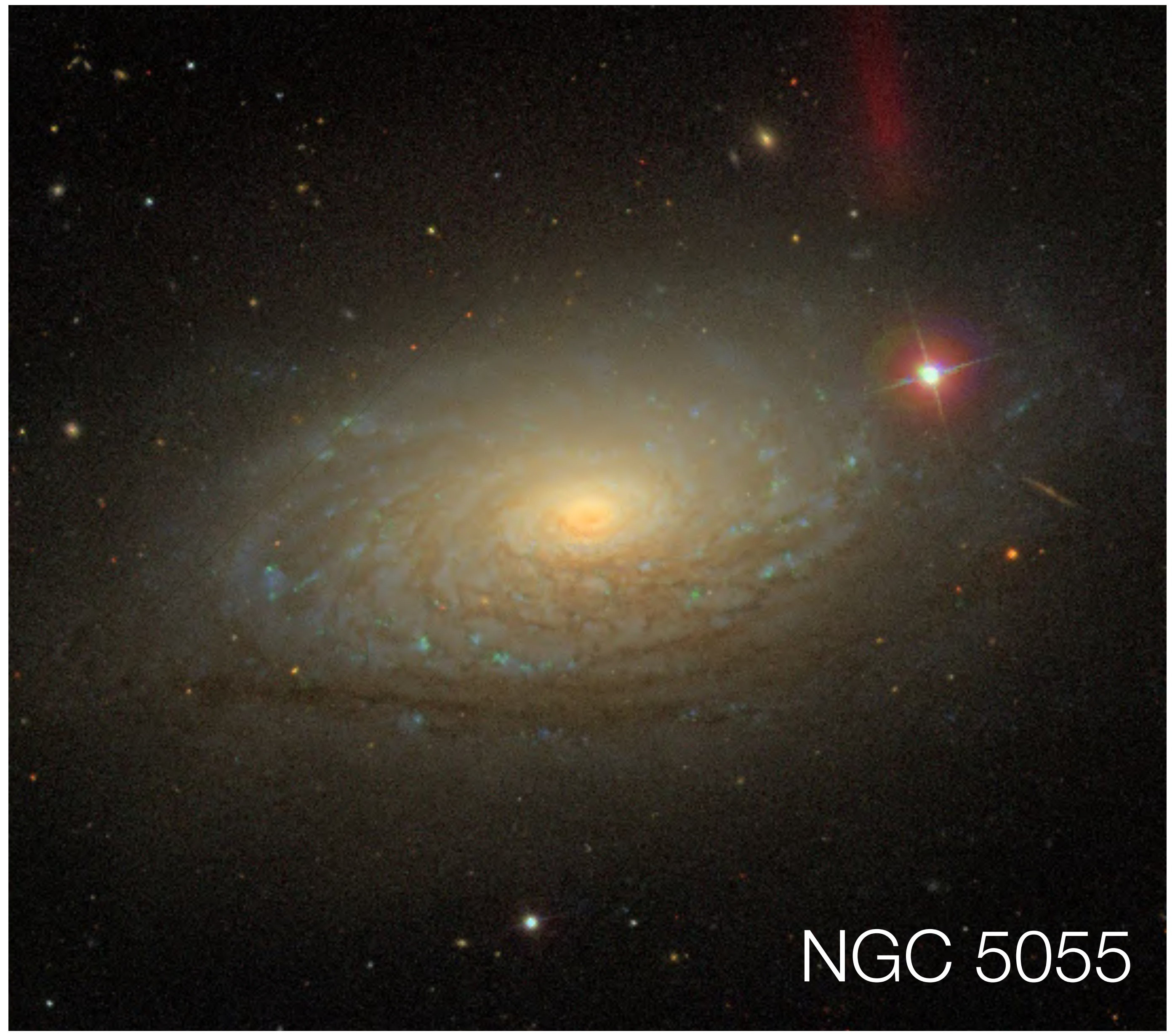



- The field is moving towards high-z, but typically with poor resolution and radial coverage

  *however our inference on DM deteriorates rapidly without extended data*

# Halo masses from rotation curves

$$V_{\rm obs}^2 \simeq V_{\rm circ}^2 = \Upsilon_\star V_\star^2 + V_{\rm gas}^2 + V_{\rm DM}^2$$

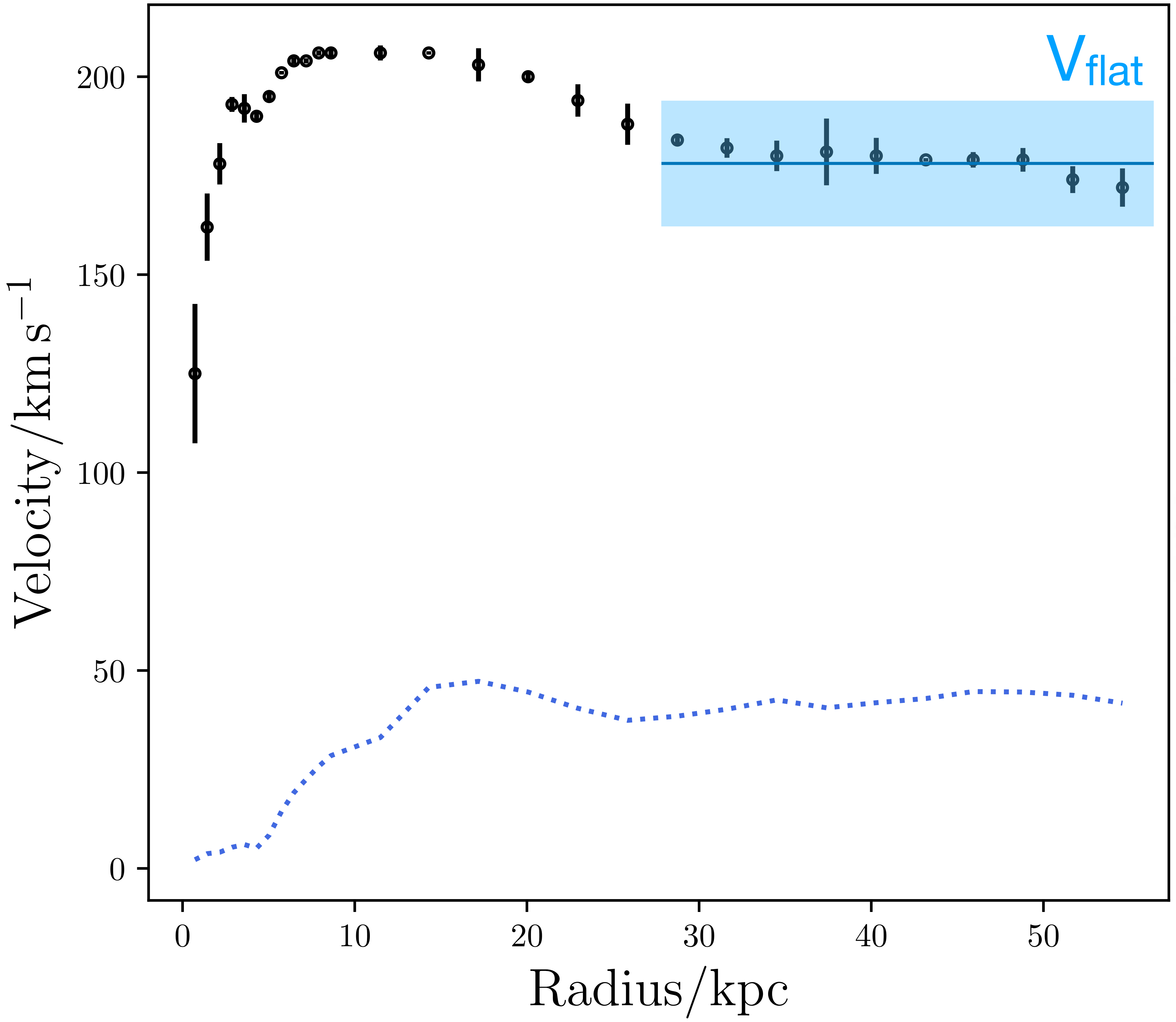


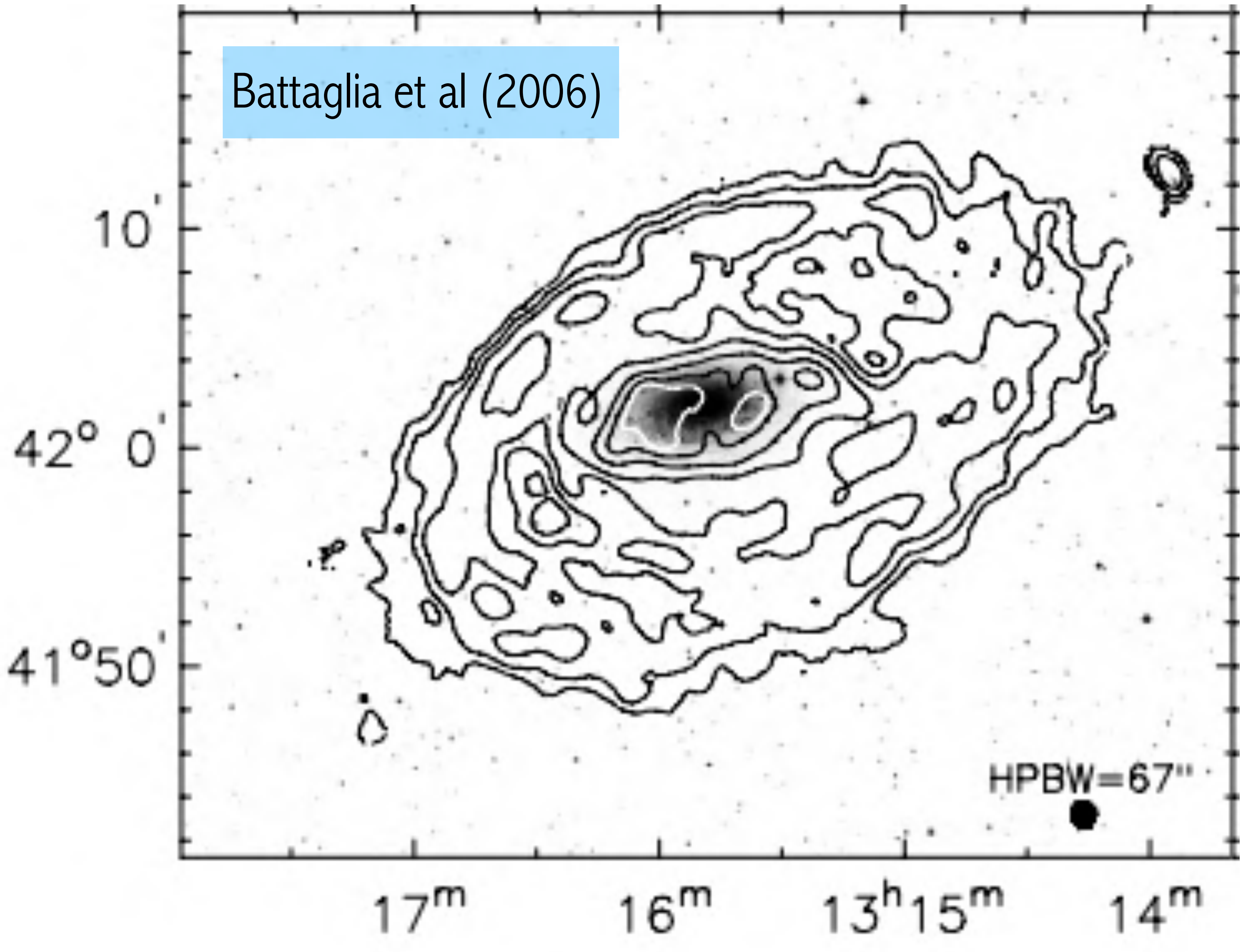
# Halo masses from rotation curves

$$V_{\rm obs}^2 \simeq V_{\rm circ}^2 = \Upsilon_\star V_\star^2 + V_{\rm gas}^2 + V_{\rm DM}^2$$

HI rotation curve

HI flux




Gas surface density → Invert Poisson's equation → Get Vgas

Casertano (1983)

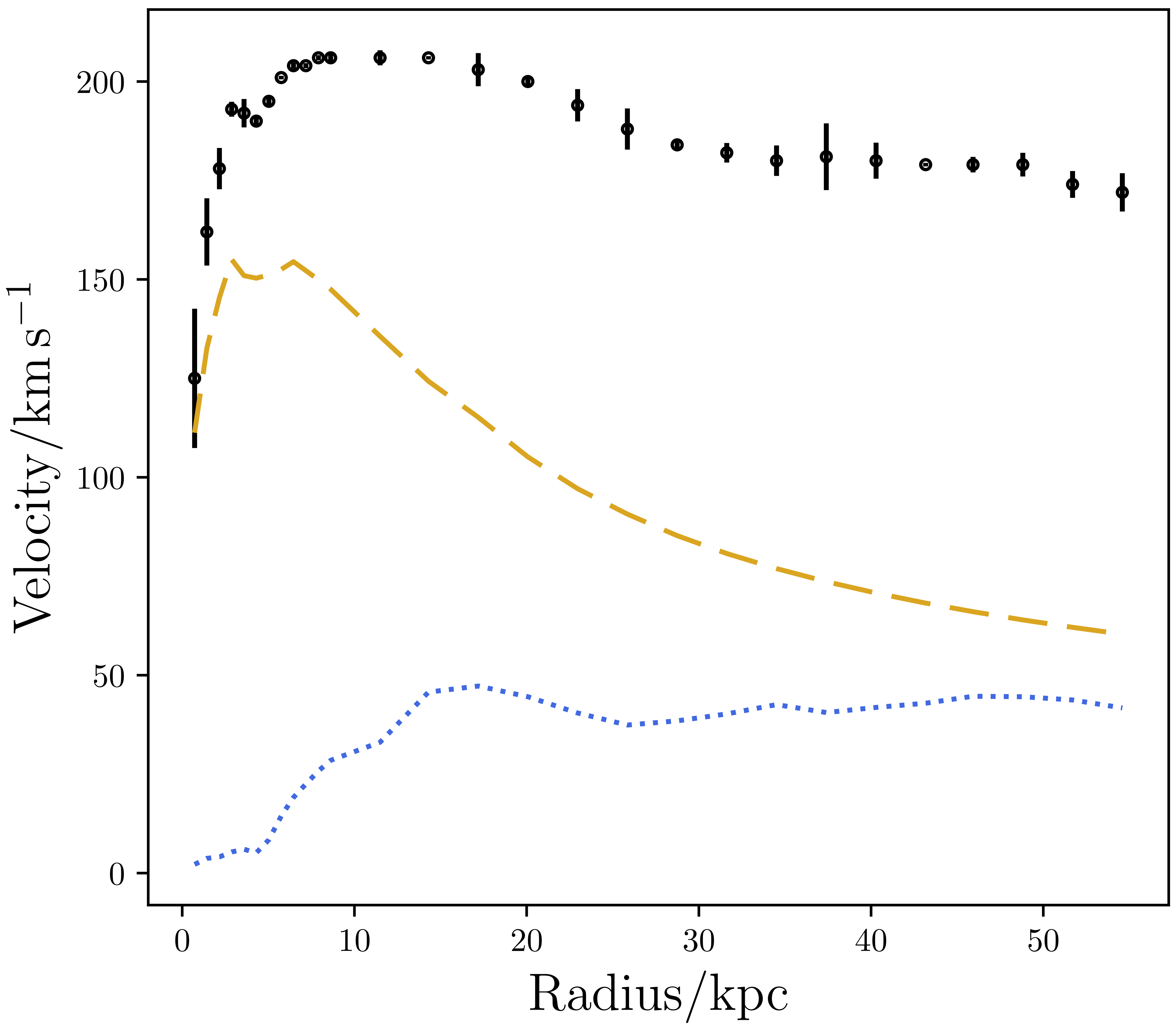
# Halo masses from rotation curves

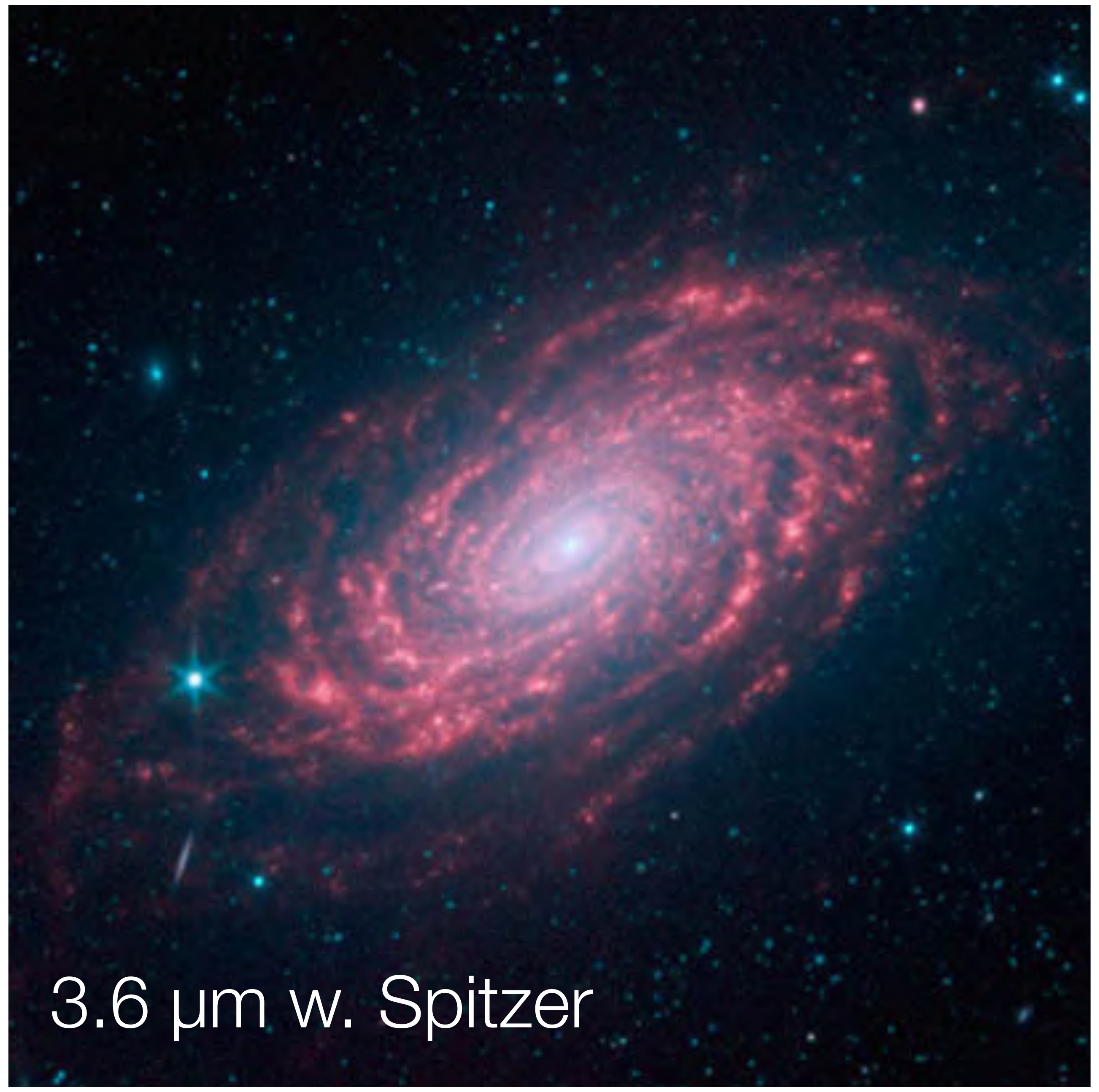
$$V_{\rm obs}^2 \simeq V_{\rm circ}^2 = \Upsilon_\star V_\star^2 + V_{\rm gas}^2 + V_{\rm DM}^2$$

HI rotation curve

3.6 μm

HI flux



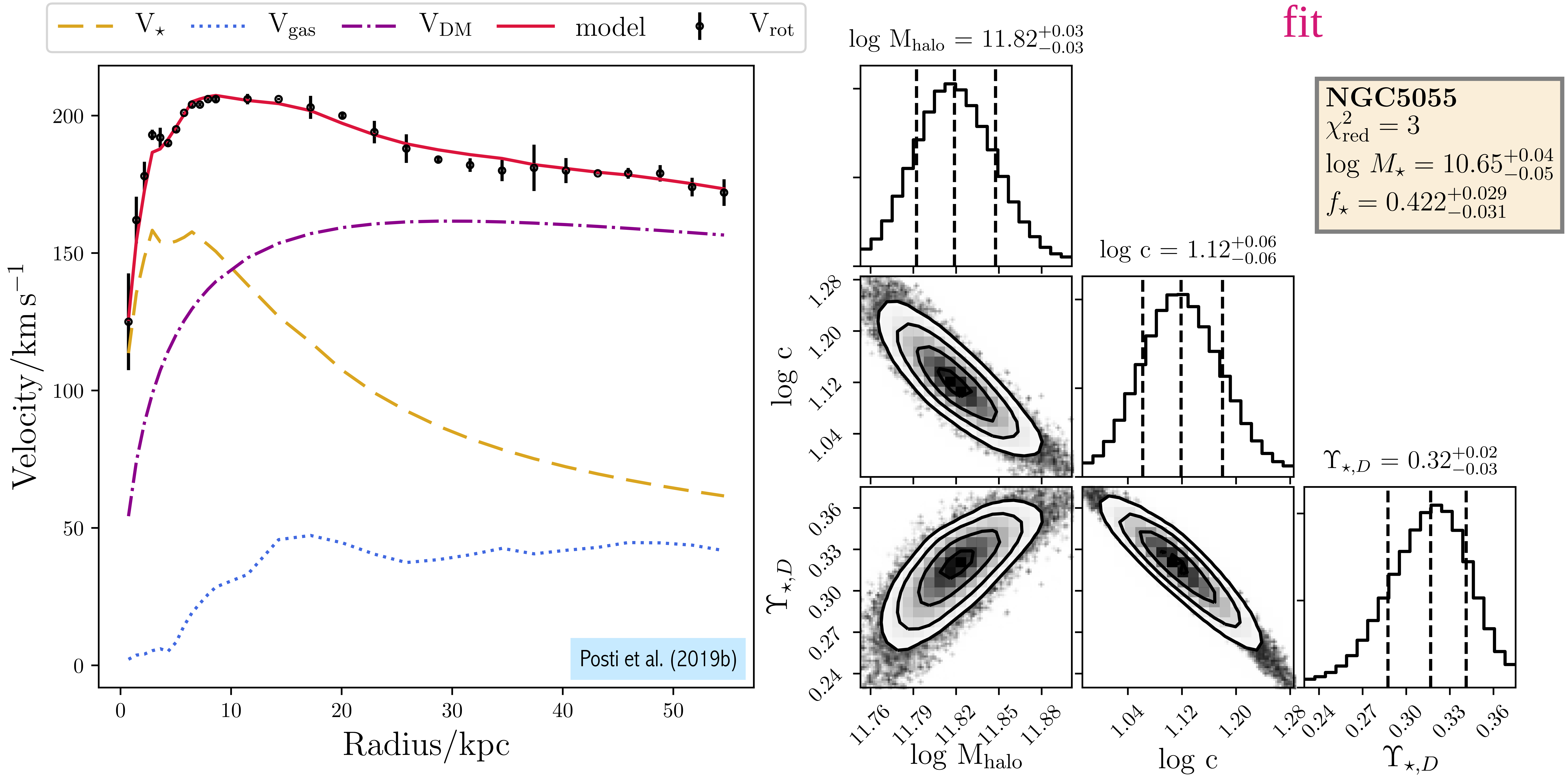

IR surface brightness → Invert Poisson's equation → Get Vstar

Casertano (1983)

# Halo masses from rotation curves

$$V_{\rm obs}^2 \simeq V_{\rm circ}^2 = \Upsilon_\star V_\star^2 + V_{\rm gas}^2 + V_{\rm DM}^2$$

fit



# Halo masses from rotation curves

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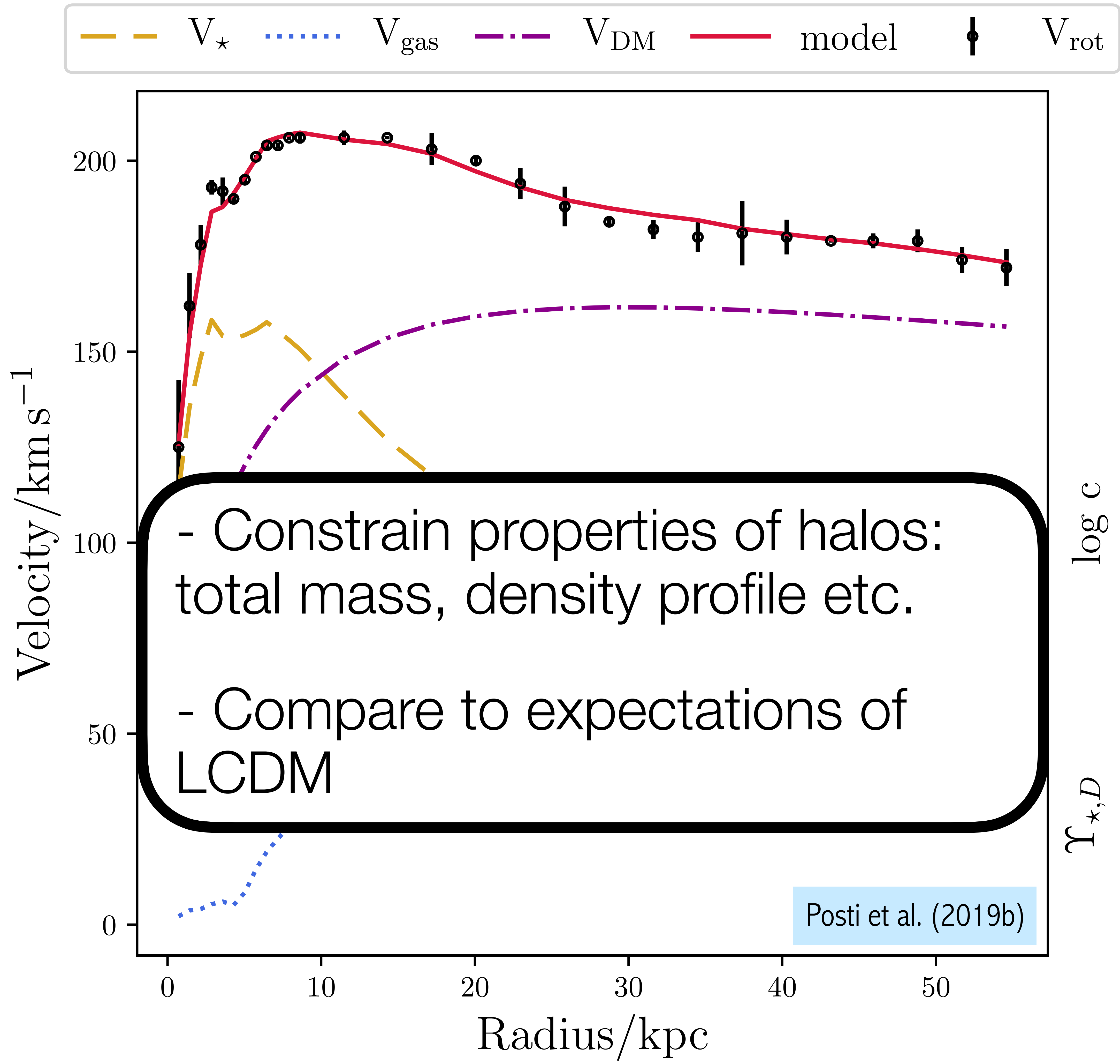
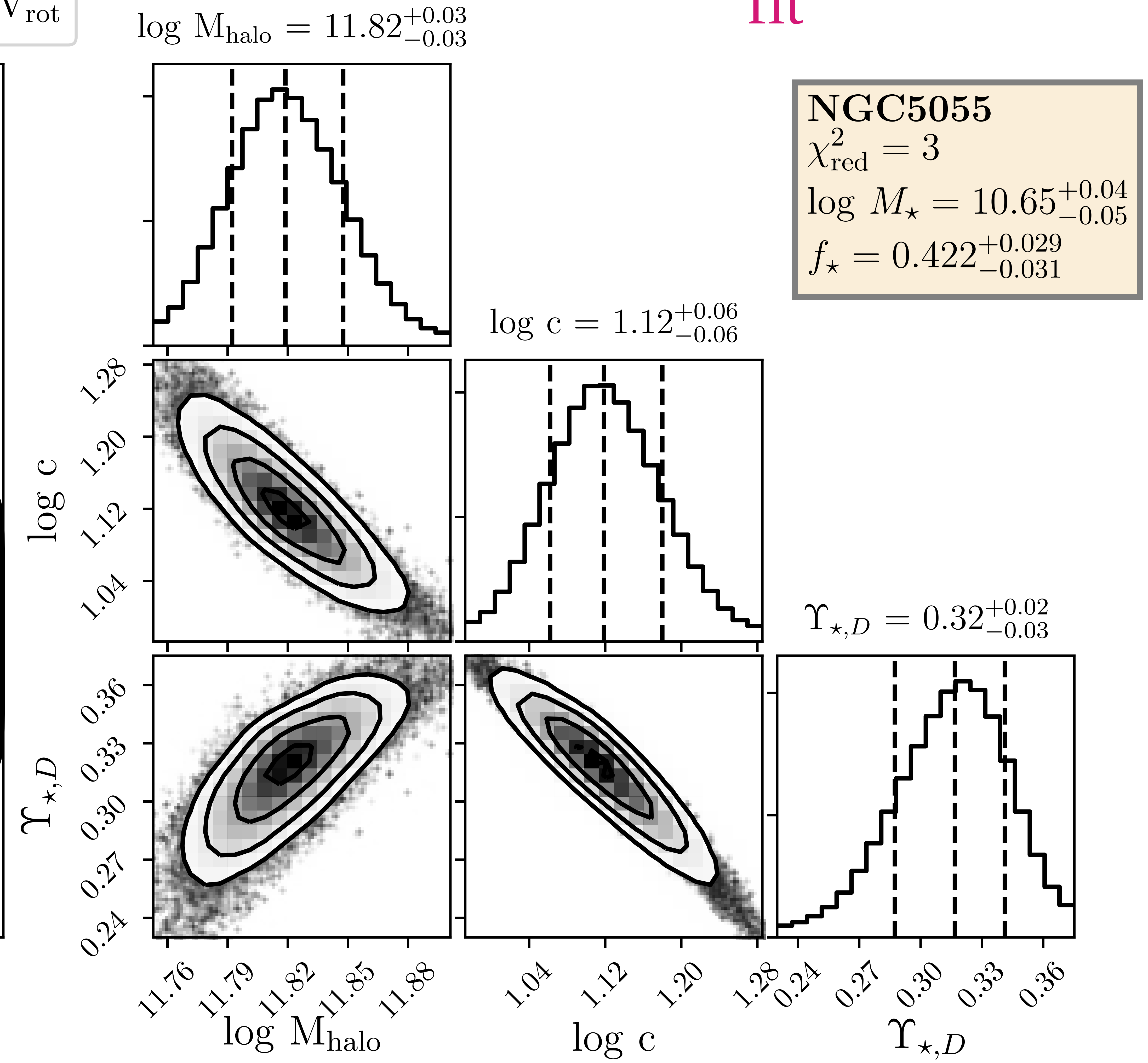
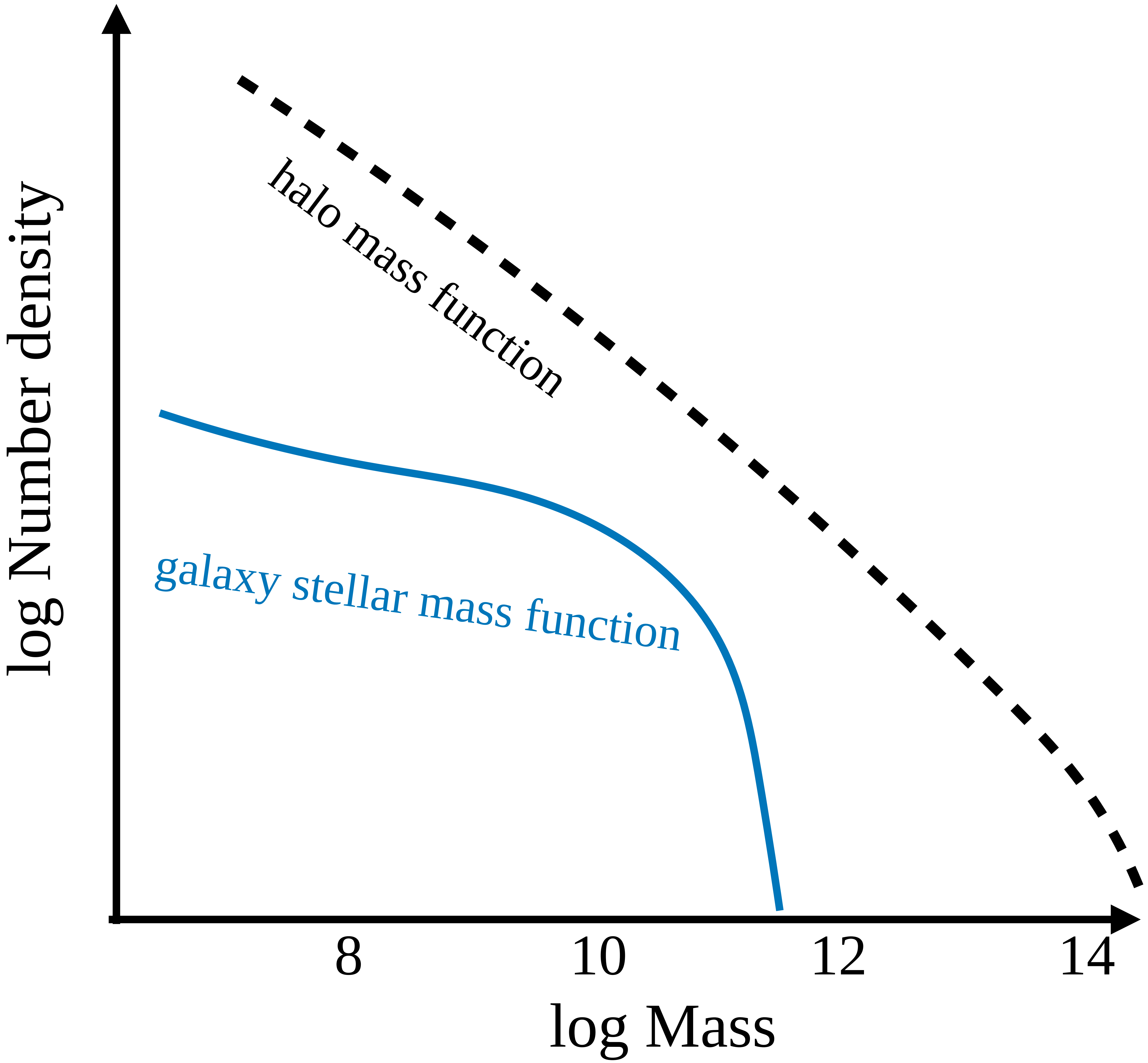



- Constrain properties of halos: total mass, density profile etc.

- Compare to expectations of LCDM



# The stellar-to-halo mass relation



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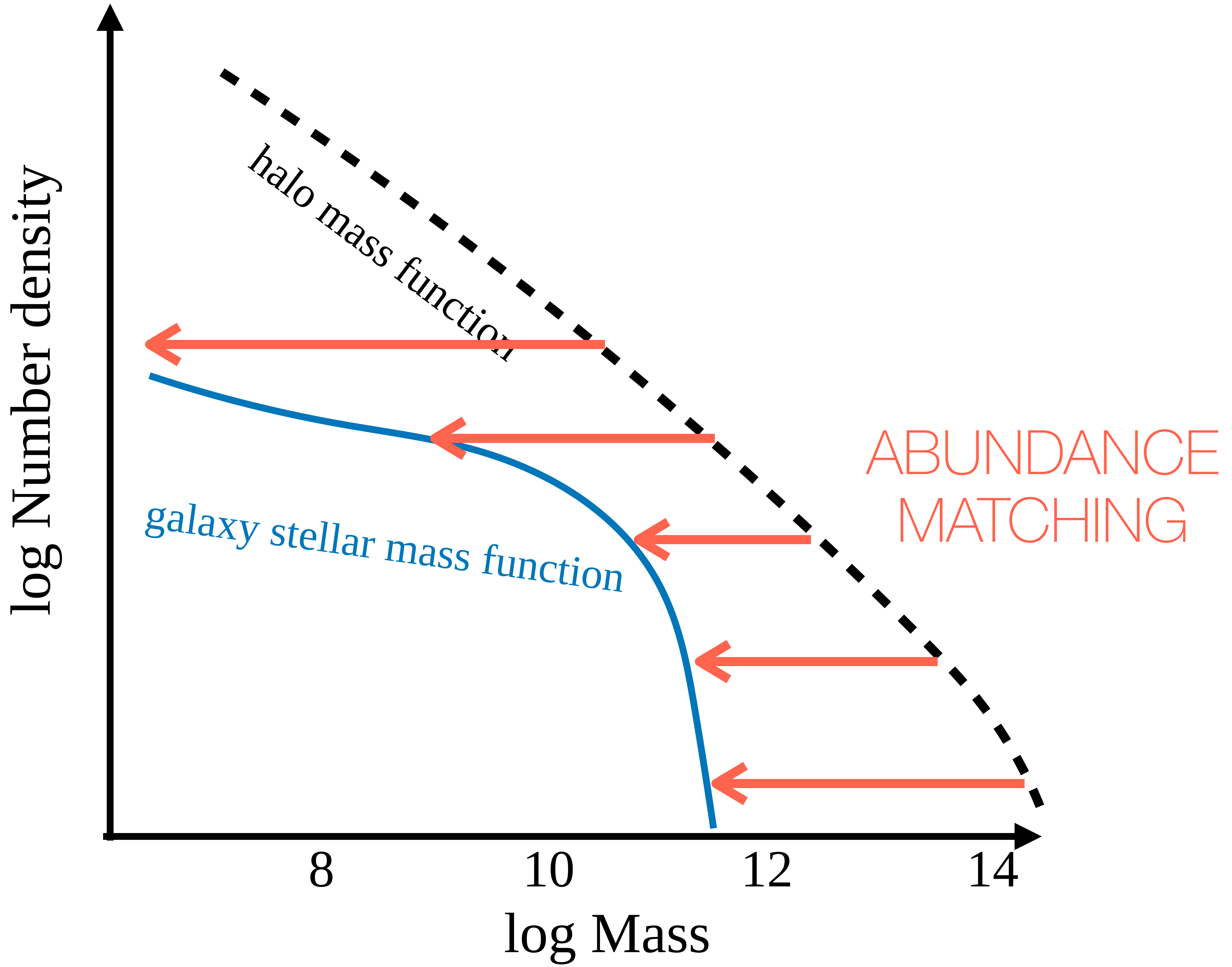

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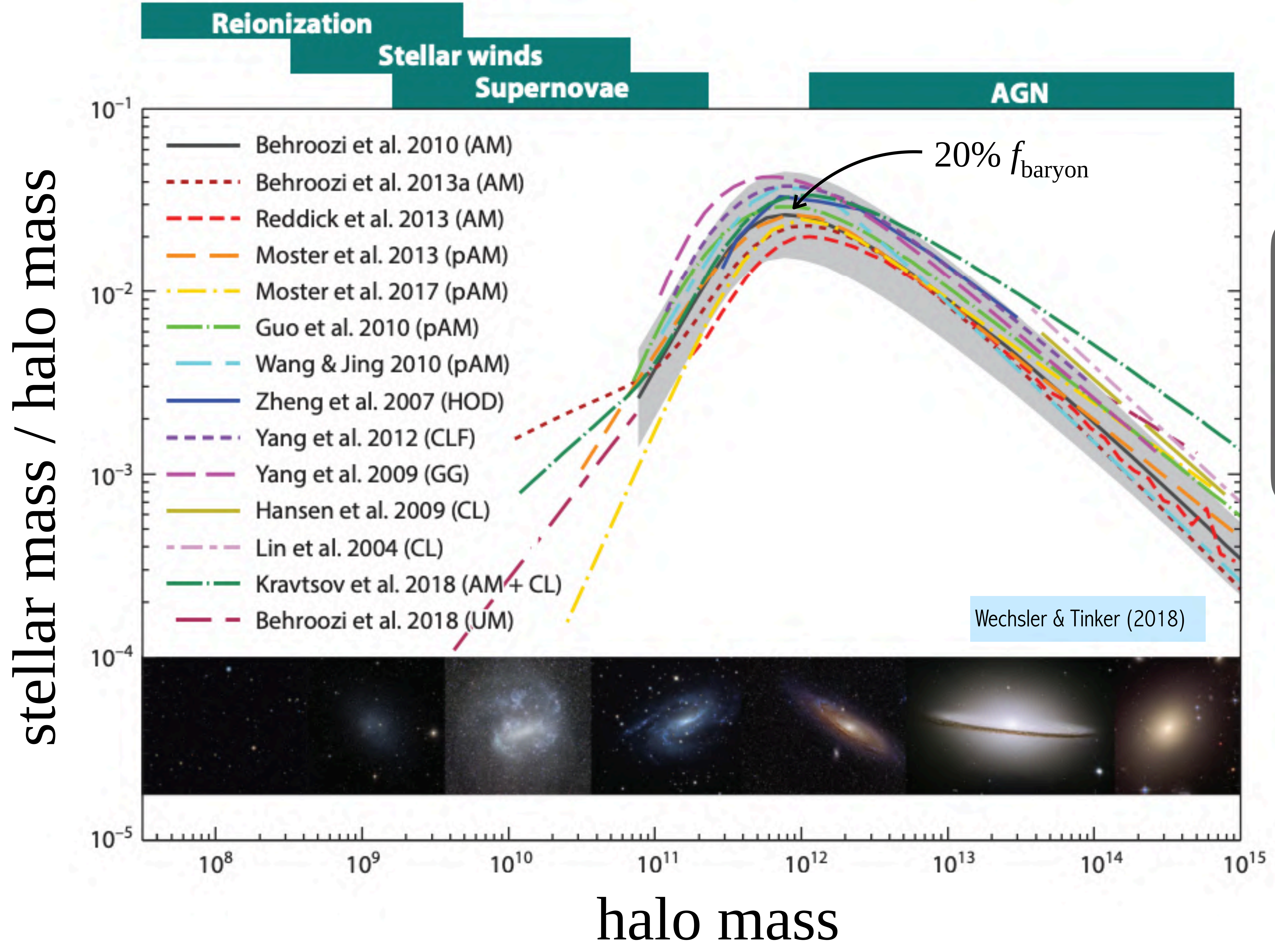
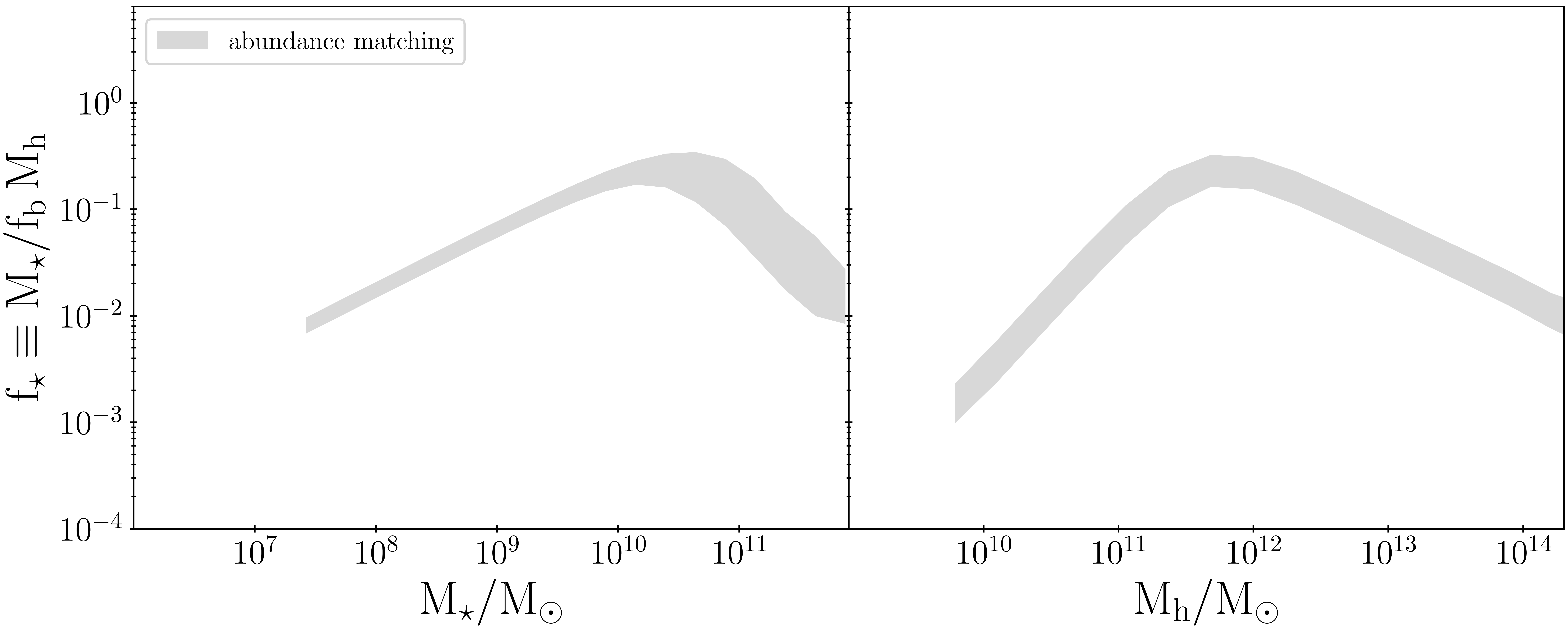



A clear prediction from standard LCDM:

Relation between *baryonic mass* & *dynamical mass* is **highly non-linear**

# Stellar-to-halo mass relation as a function of morphology



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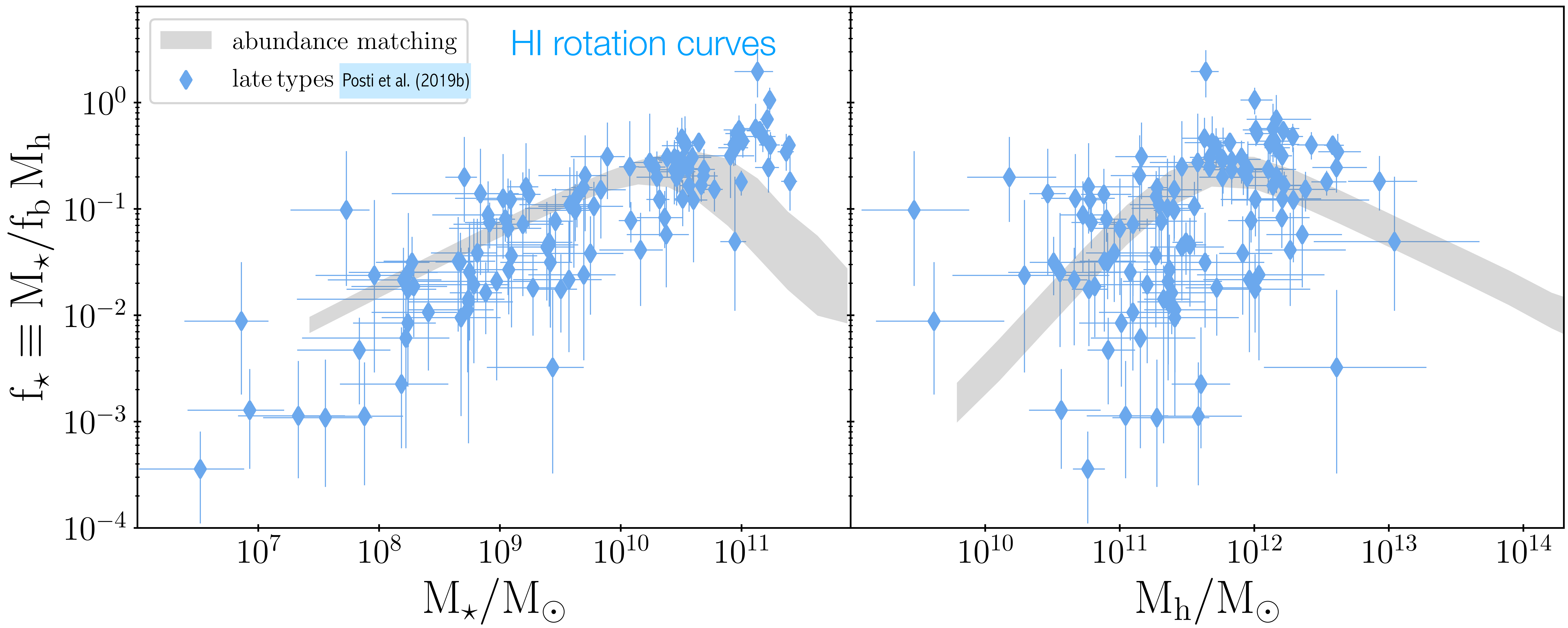

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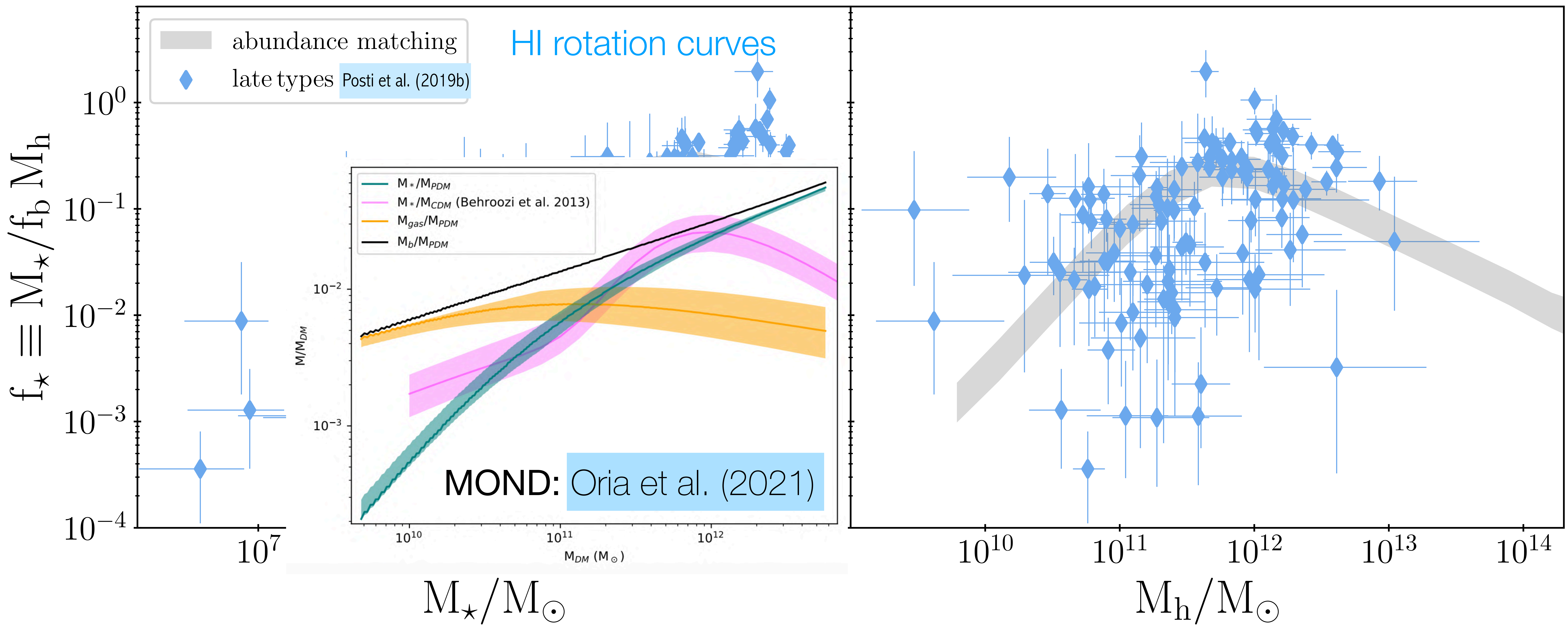

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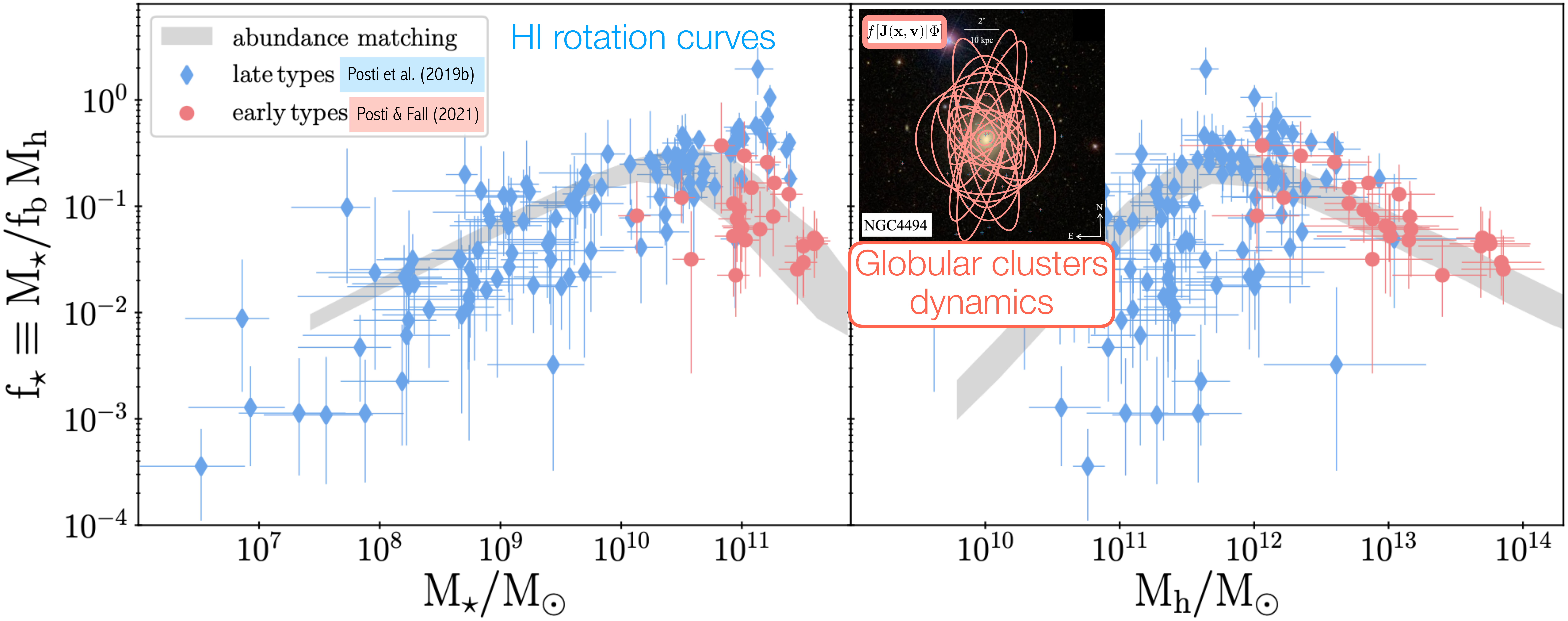

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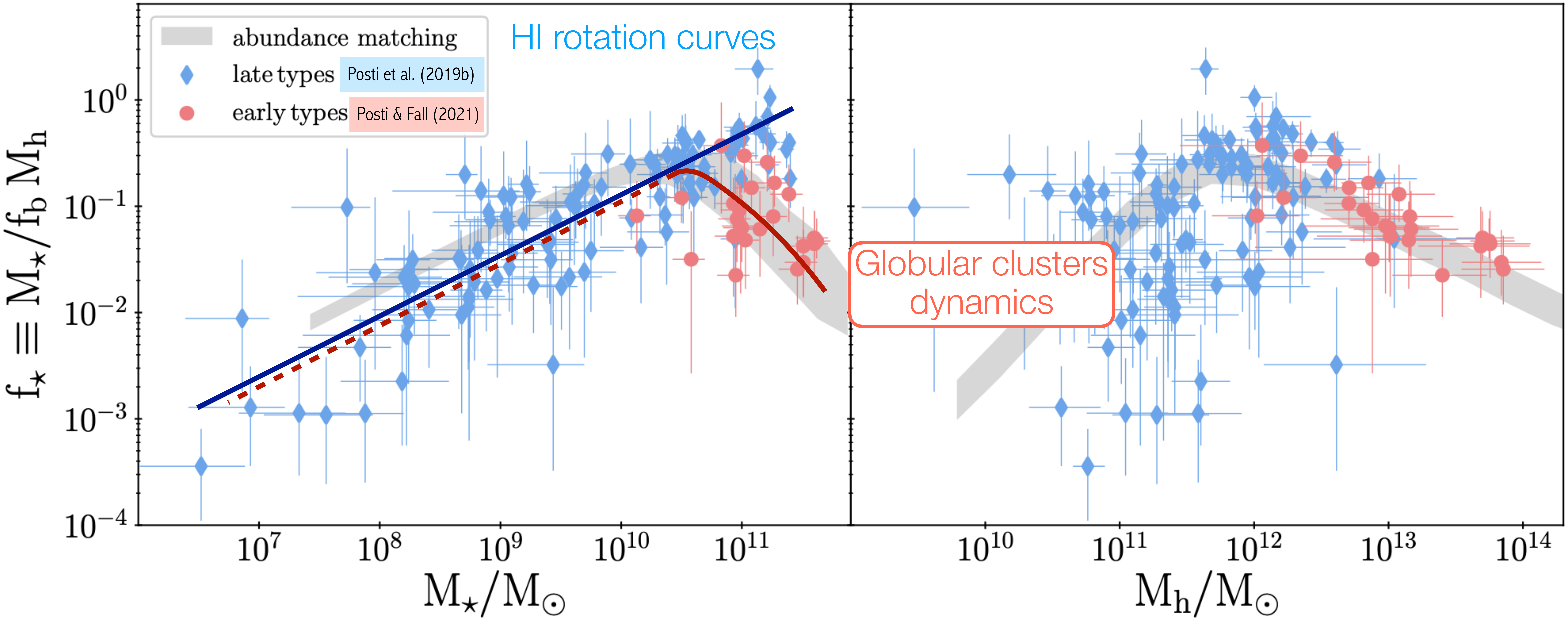
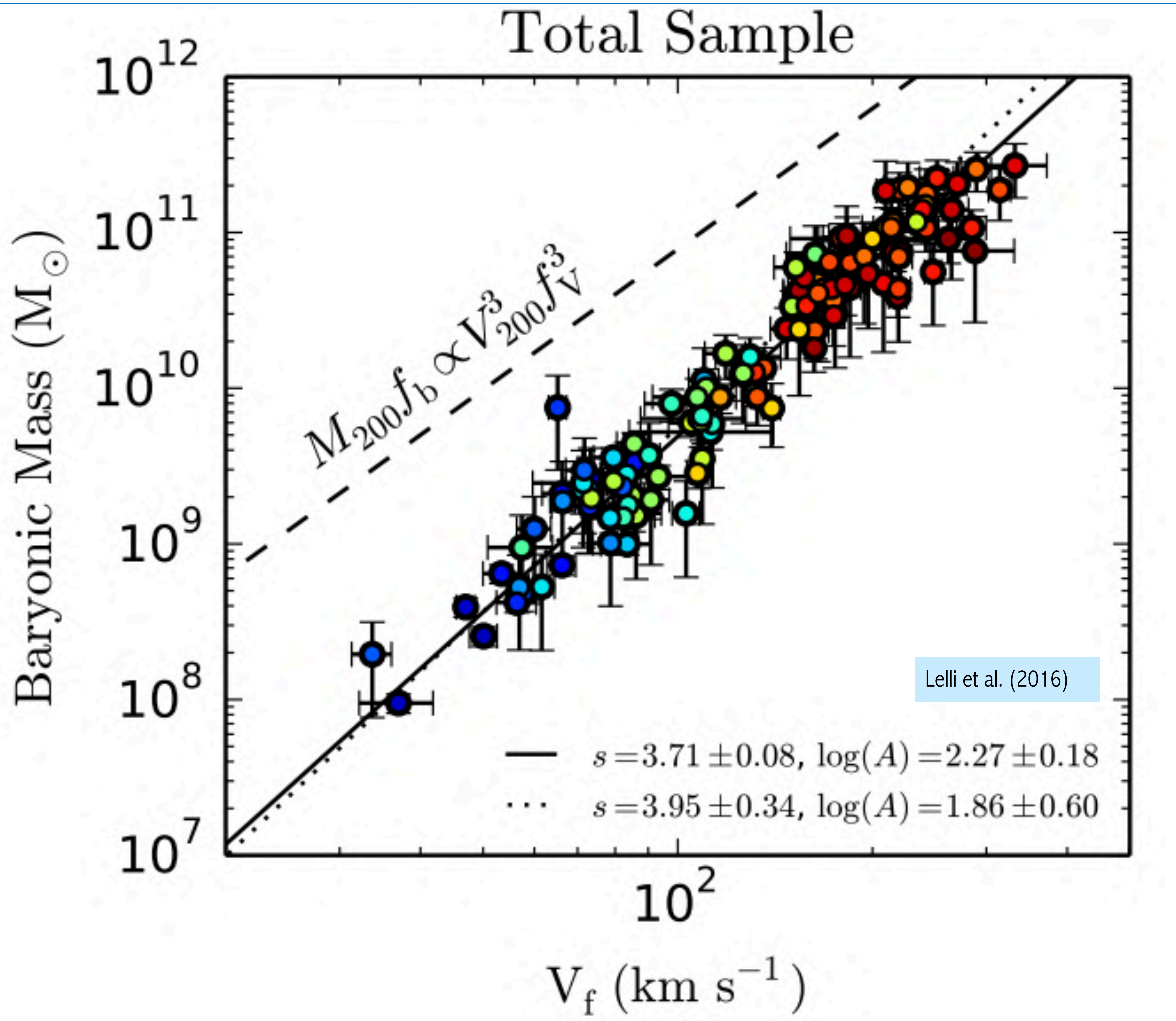


# The Tully-Fisher relation



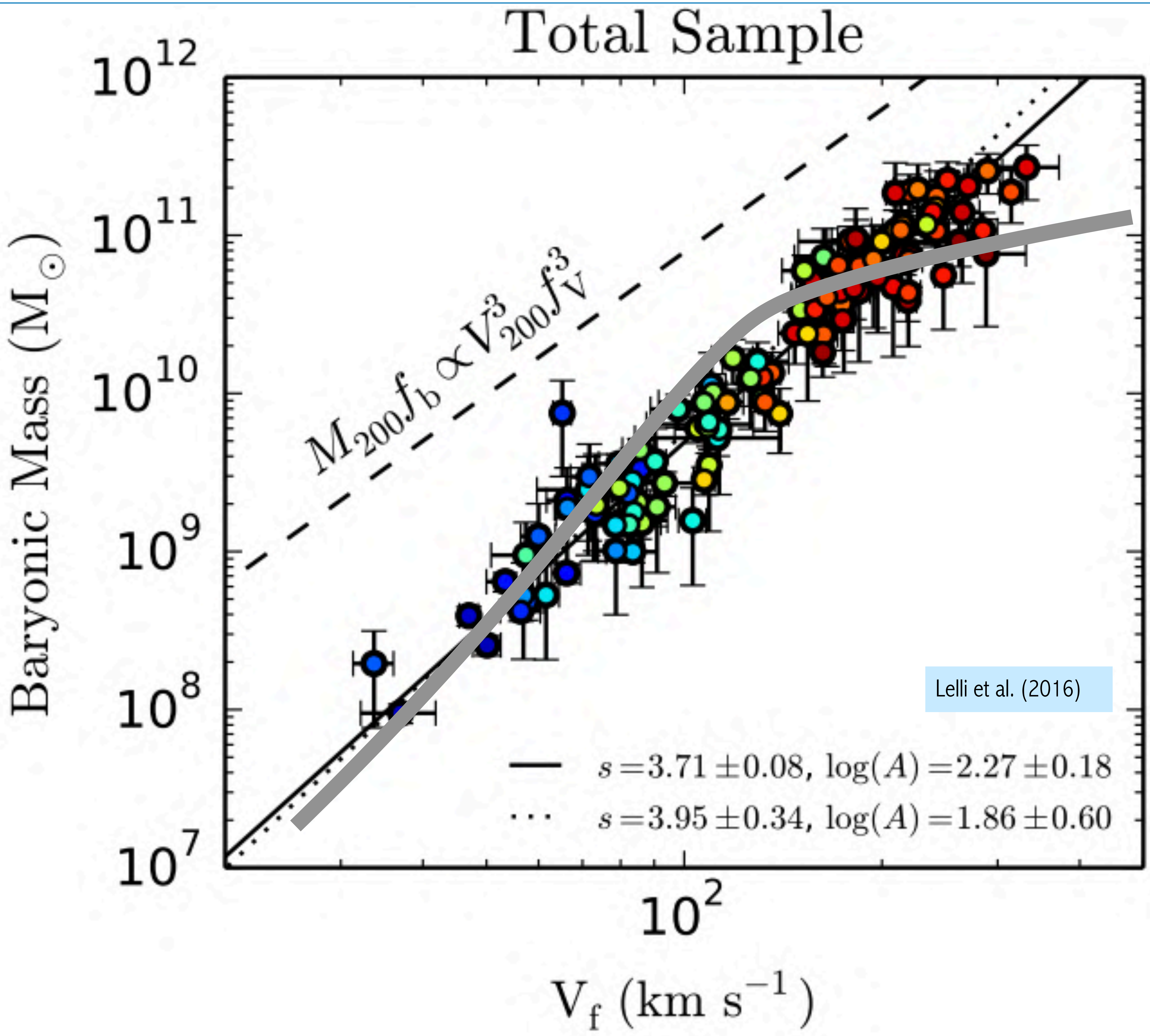

- Tight, simple power law relation between mass & velocity

$M \sim V_{flat}^4$

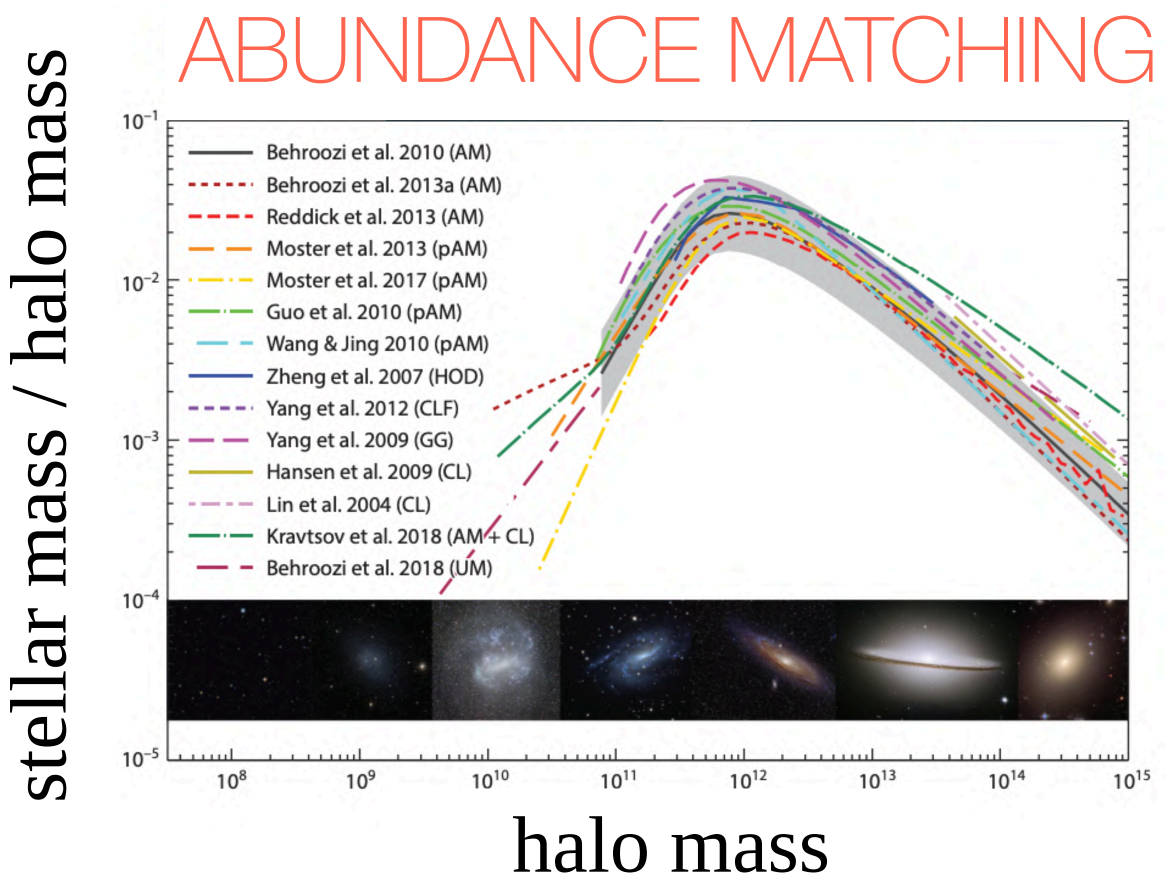
- MOND reproduces this easily, and predicts **no scatter**

- in LCDM, this is a consequence of the stellar-to-halo mass relation

# The Tully-Fisher relation: a problem for LCDM / a success for MOND?

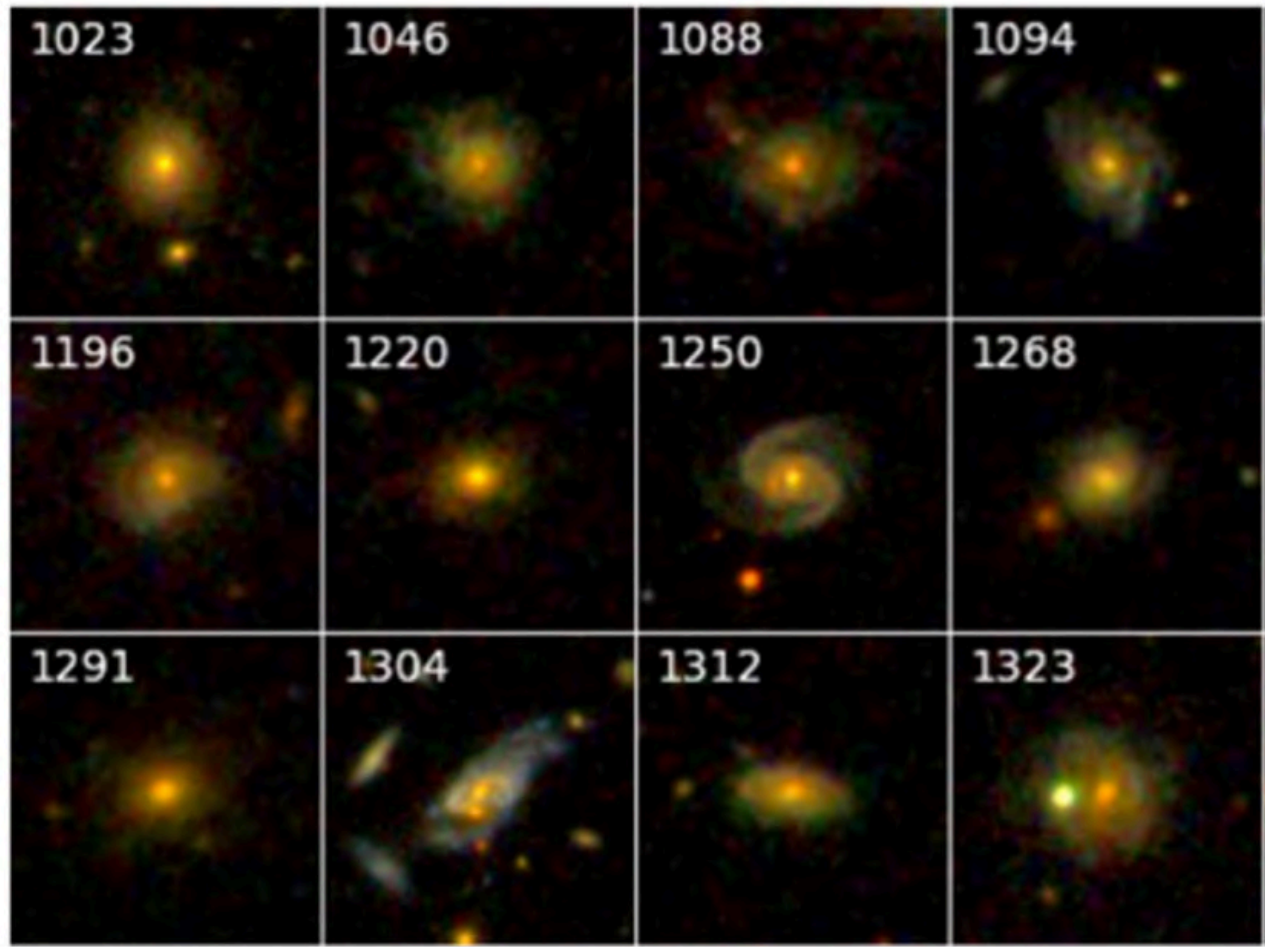


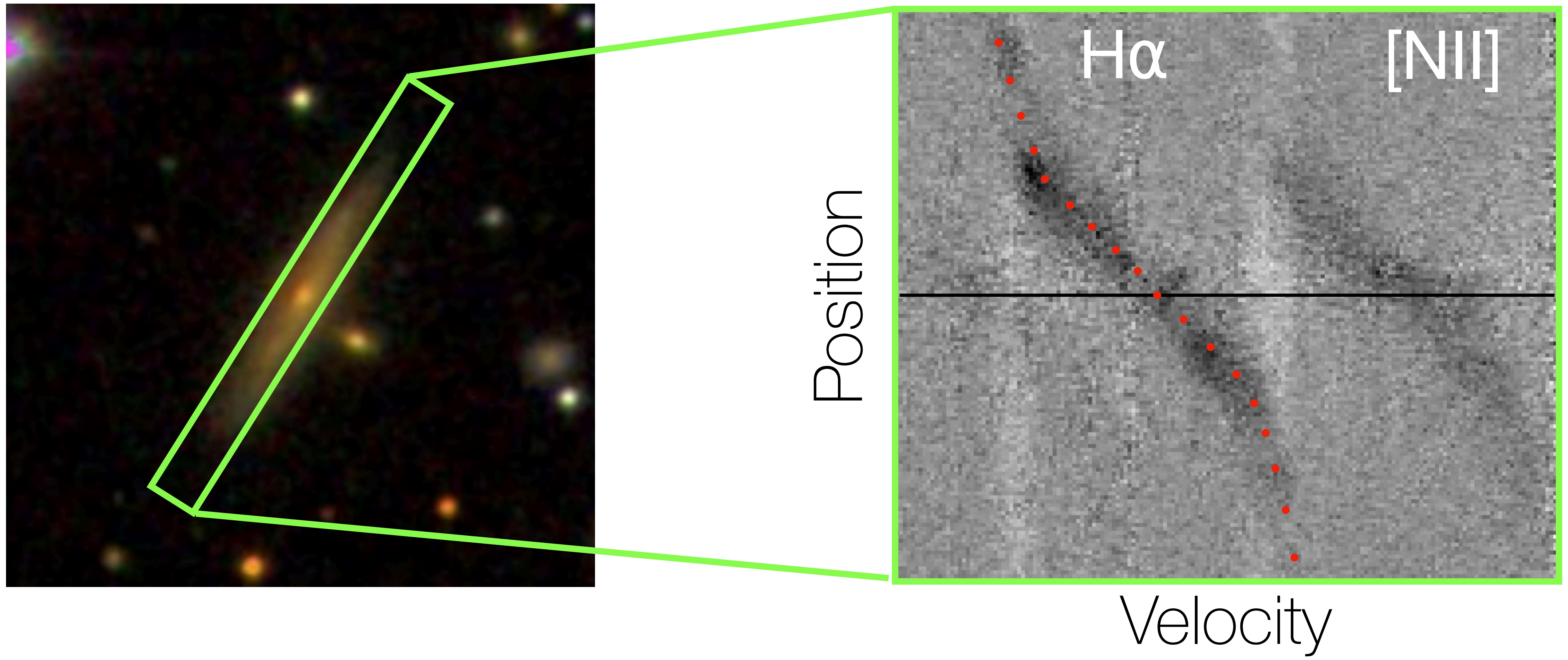

Is this a problem for LCDM?




- in LCDM, this is a consequence of the stellar-to-halo mass relation

# The high-mass end of the Tully-Fisher




- Super Spirals: the most massive disc galaxies in SDSS @ z<0.3 (Ogle et al. 2019)

- Hα slit spectra of 43 super spirals (di Teodoro et al. 2021)

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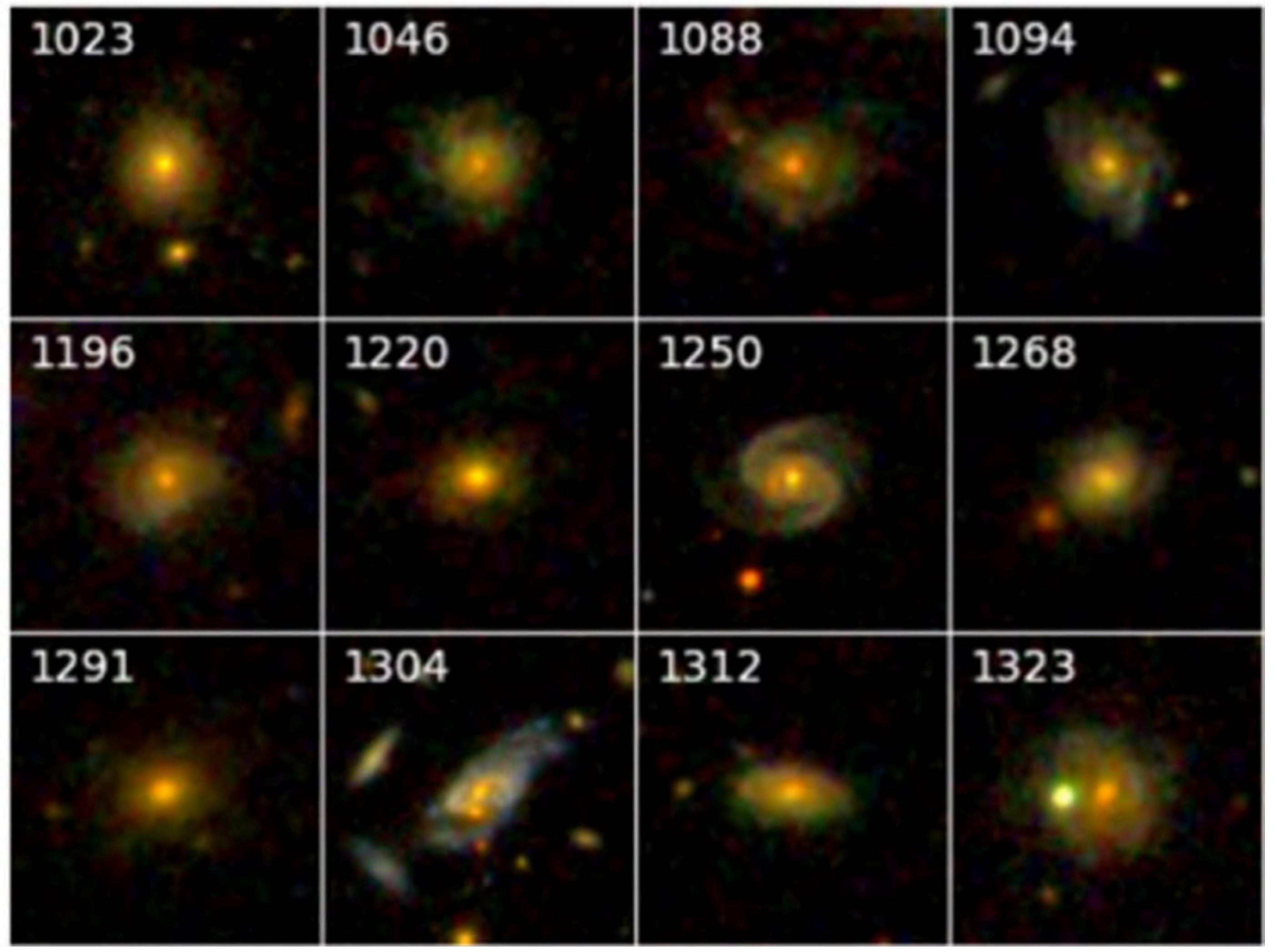


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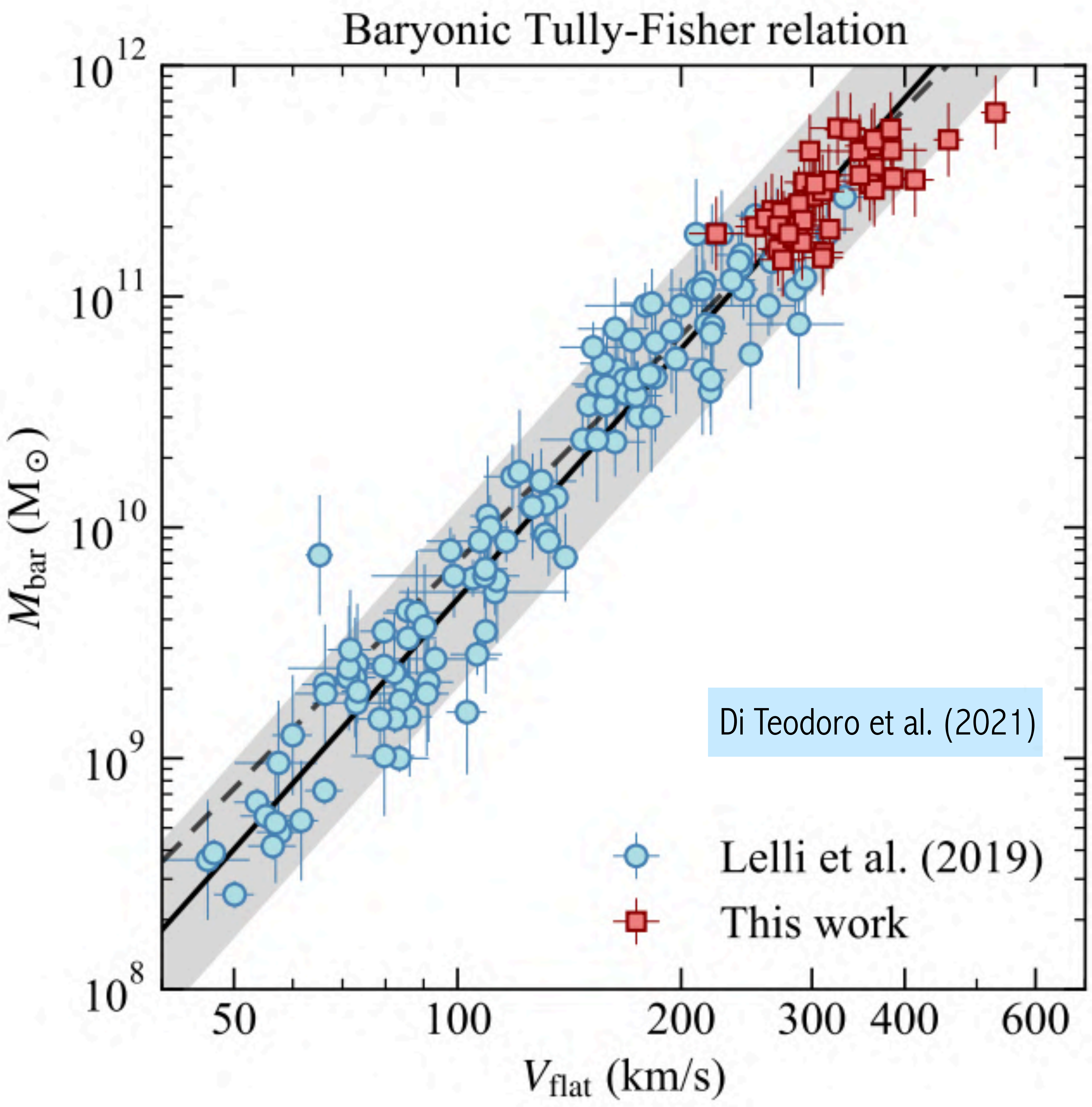
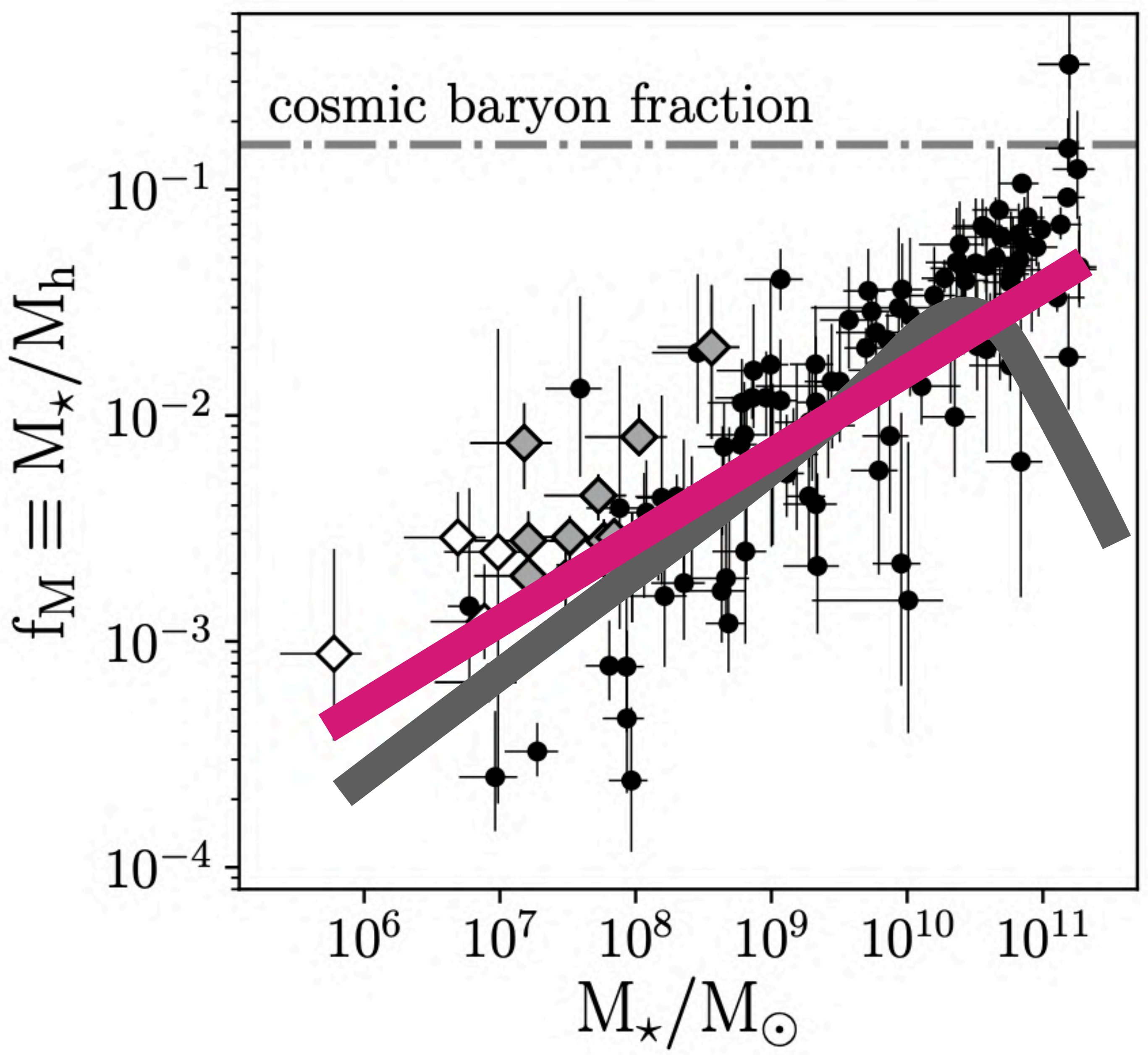


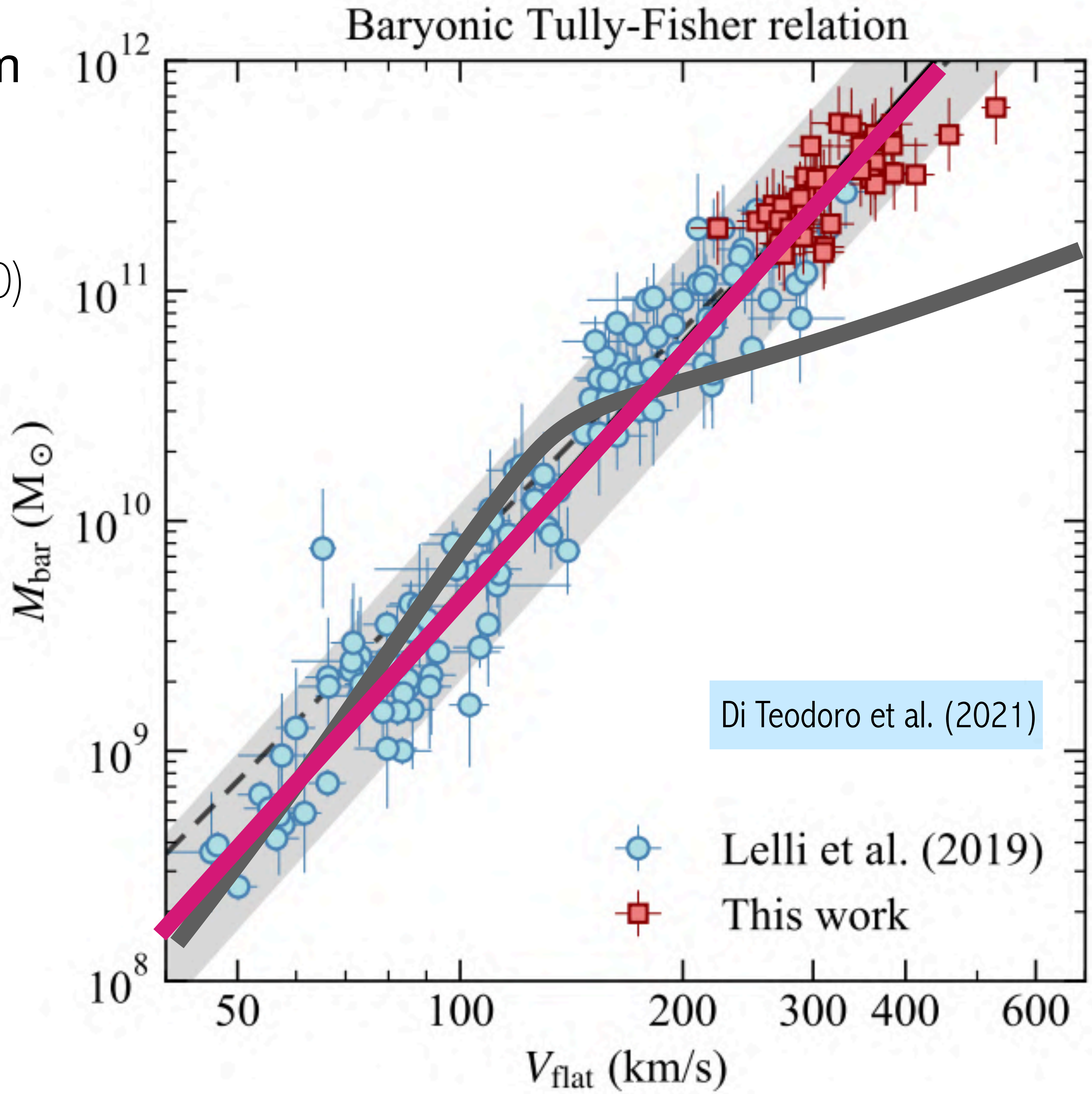
# The high-mass end of the Tully-Fisher

Is the shape of the Tully-Fisher a problem for LCDM?

- Not really, as long as the stellar-to-halo mass relation of discs is **linear** (Posti+19,20)

-the scatter however is problematic!

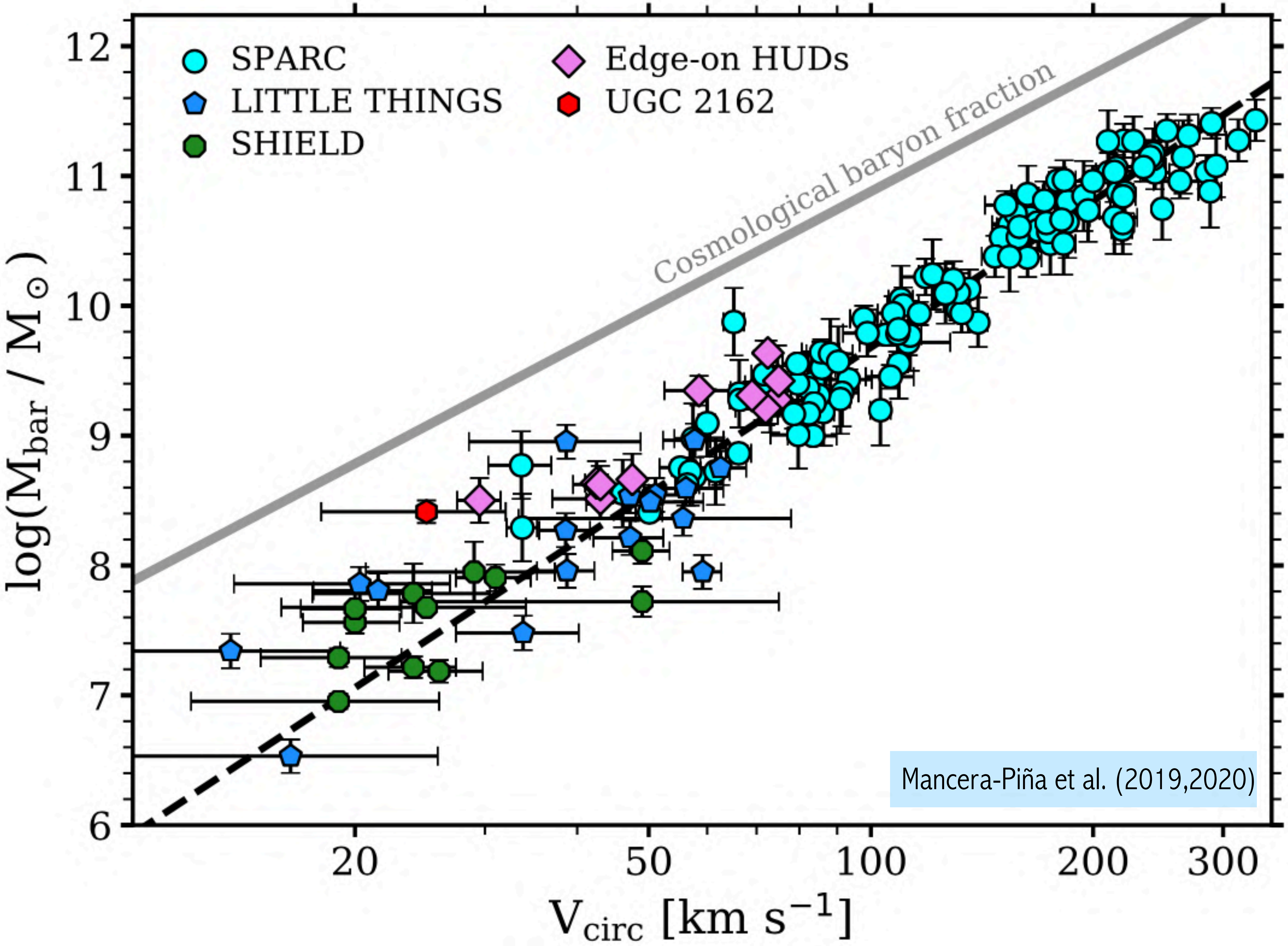


# The low-mass end of the Tully-Fisher

- Dwarf galaxies with high-quality data follow the TF

- maybe larger scatter - are there any outliers?



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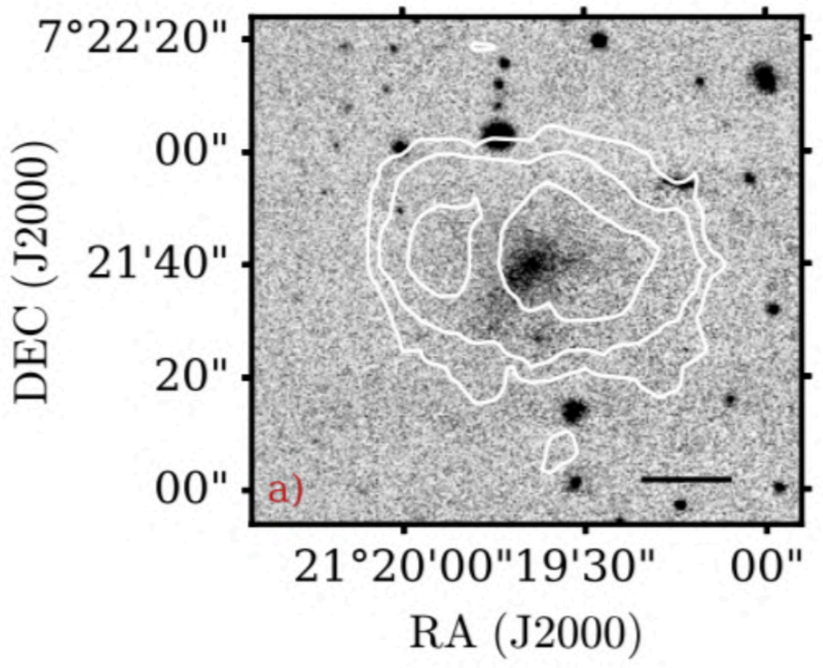
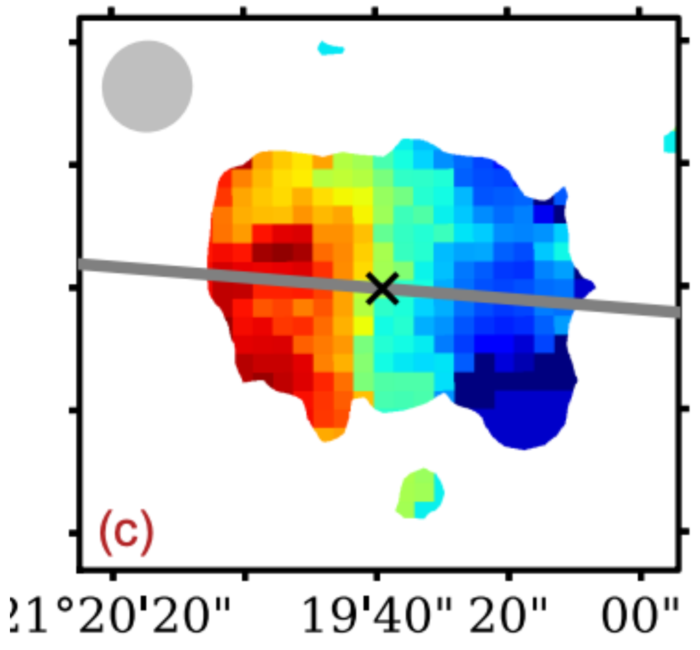
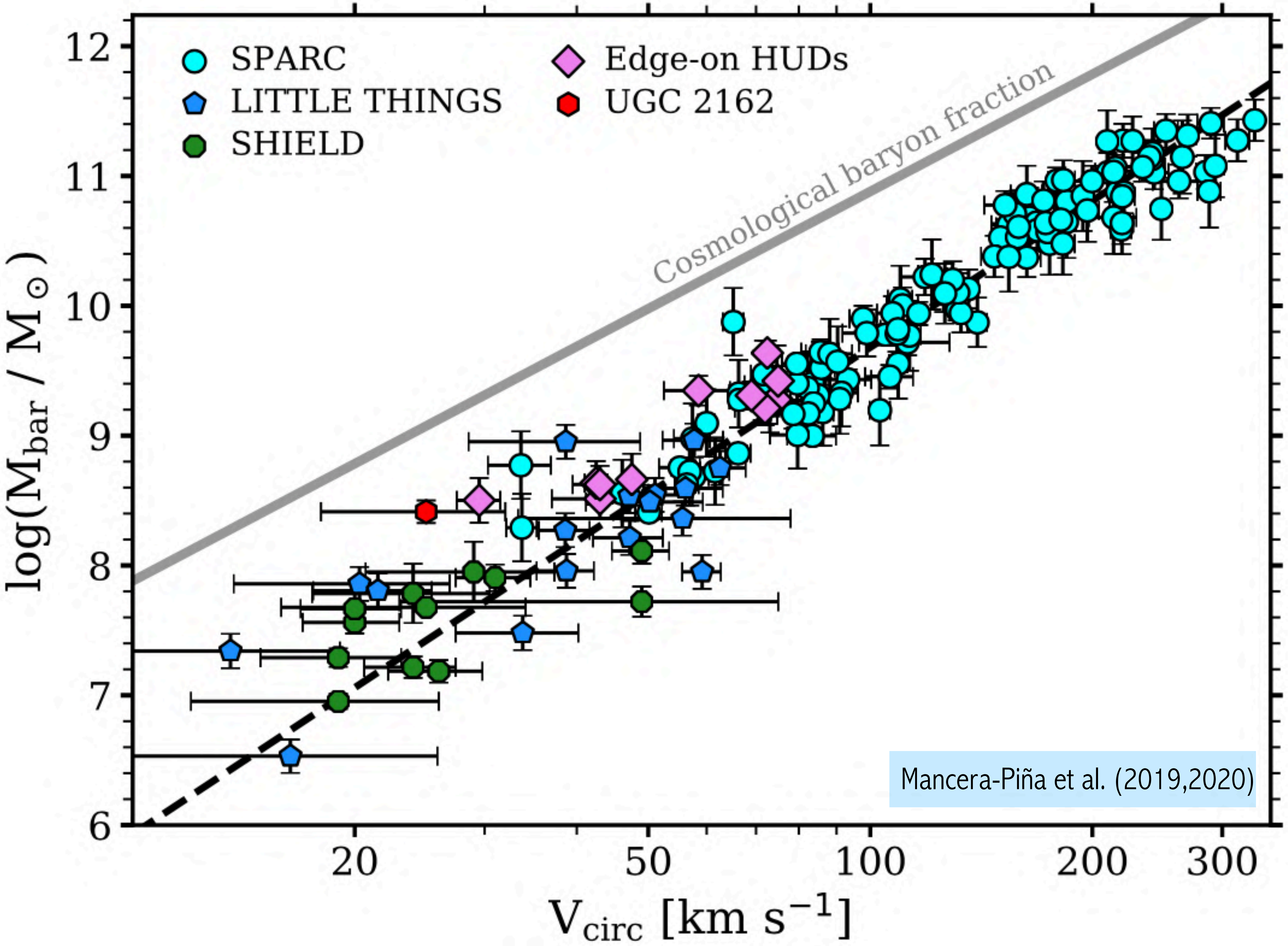
- a population of HI-rich, extremely low surface brightness dwarfs



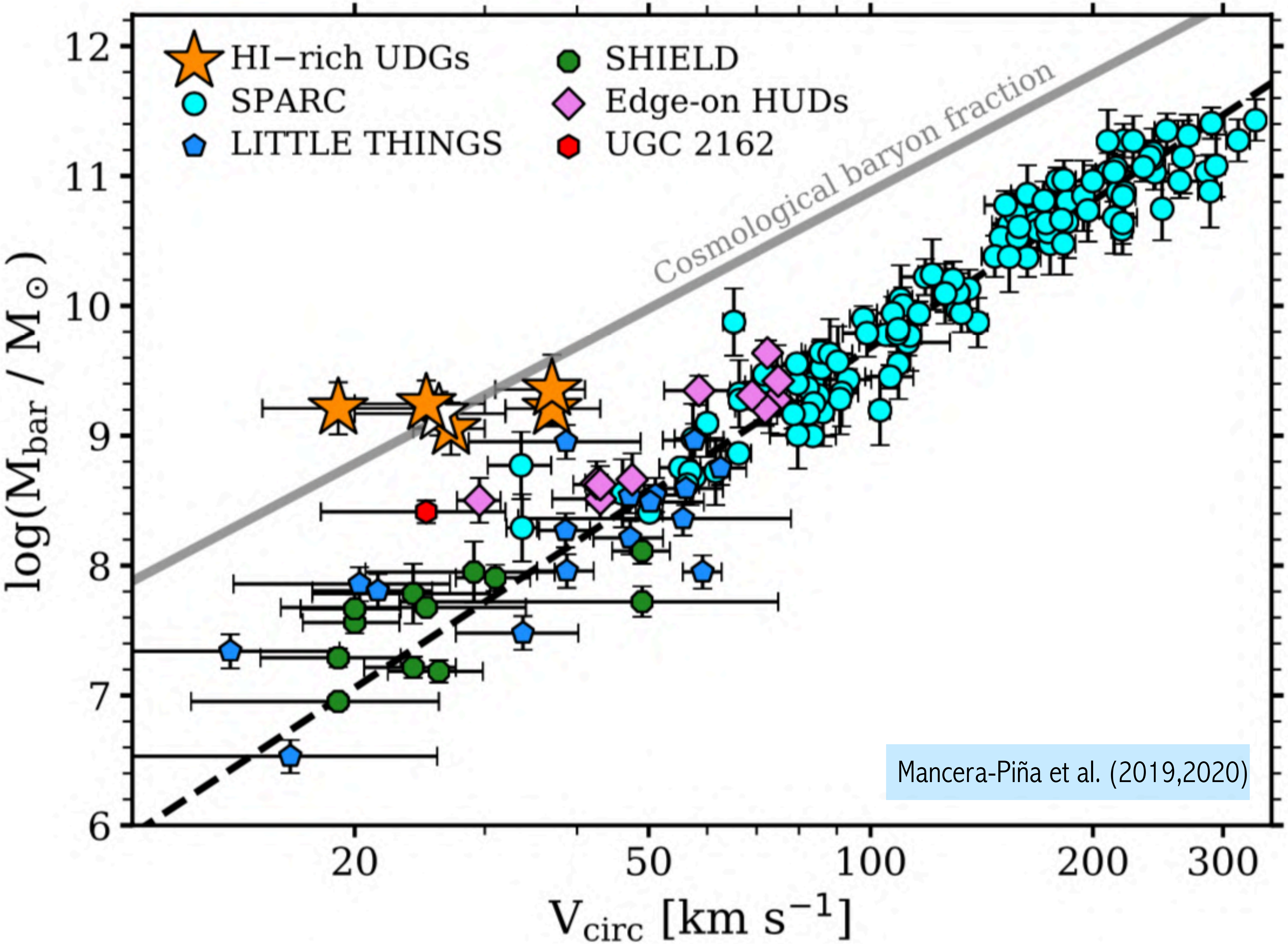

Mancera-Piña et al. (2020)




Mancera-Piña et al. (2019,2020)

# The low-mass end of the Tully-Fisher

- HI-rich ultra-diffuse galaxies (UDGs) are all off the TF



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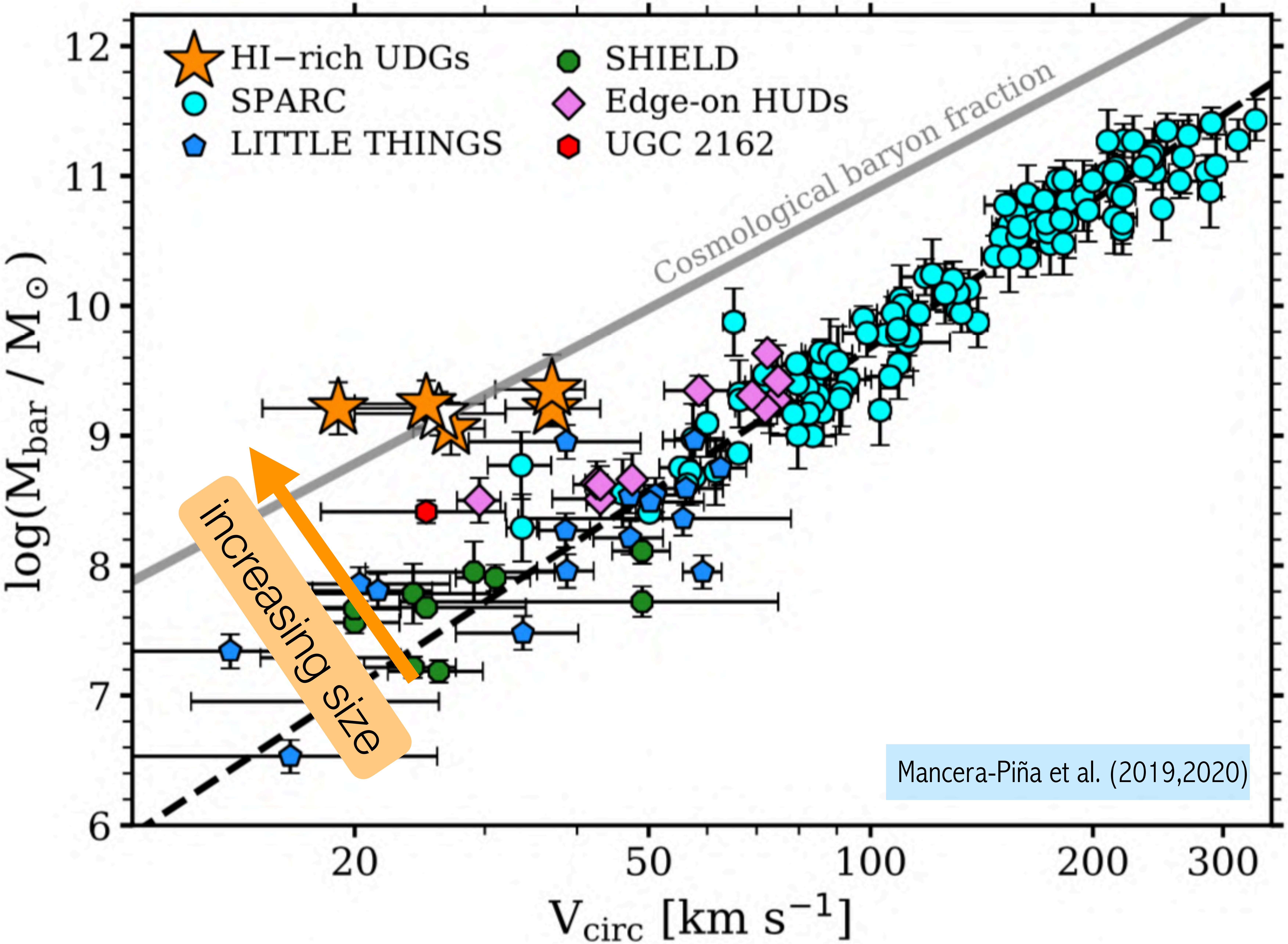
- HI-rich ultra-diffuse galaxies (UDGs) are all off the TF

- larger galaxies (lower SB) are more distant from the TF



# The low-mass end of the Tully-Fisher

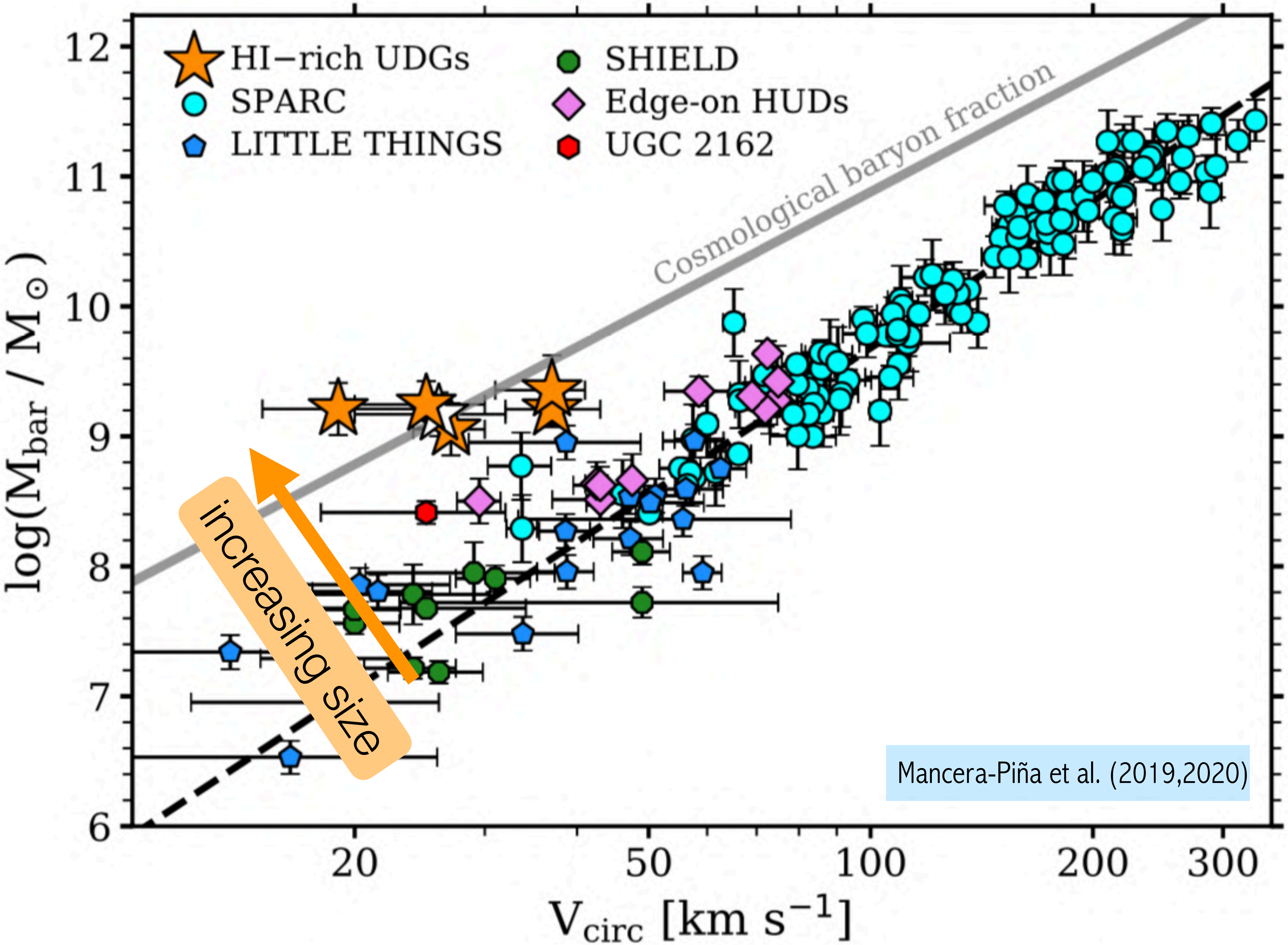
- HI-rich ultra-diffuse galaxies (UDGs) are all off the TF

- larger galaxies (lower SB) are more distant from the TF

- Mbar ~ Mgas is solid, so they have too low Vc for their mass

- in LCDM they have no DM

- in MOND they should not exist at all!

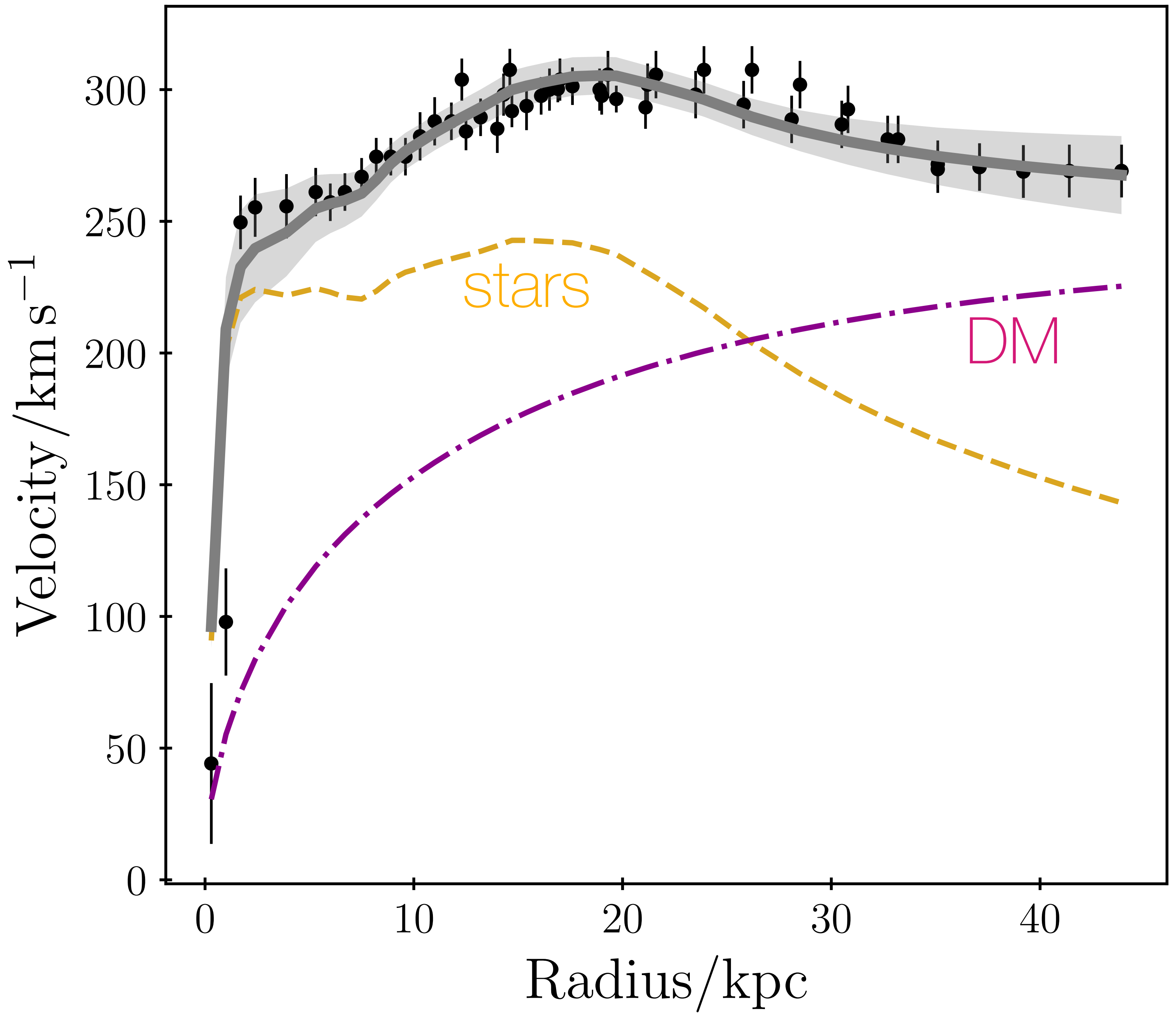


# Halo response in high-mass galaxies

- NFW is the appropriate halo to fit rotation curves in LCDM

- But NFW is valid in a dark matter-only Universe

- How does the DM halo respond to the formation of a galaxy?

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- NFW is the appropriate halo to fit rotation curves in LCDM

- But NFW is valid in a dark matter-only Universe

- How does the DM halo respond to the formation of a galaxy?

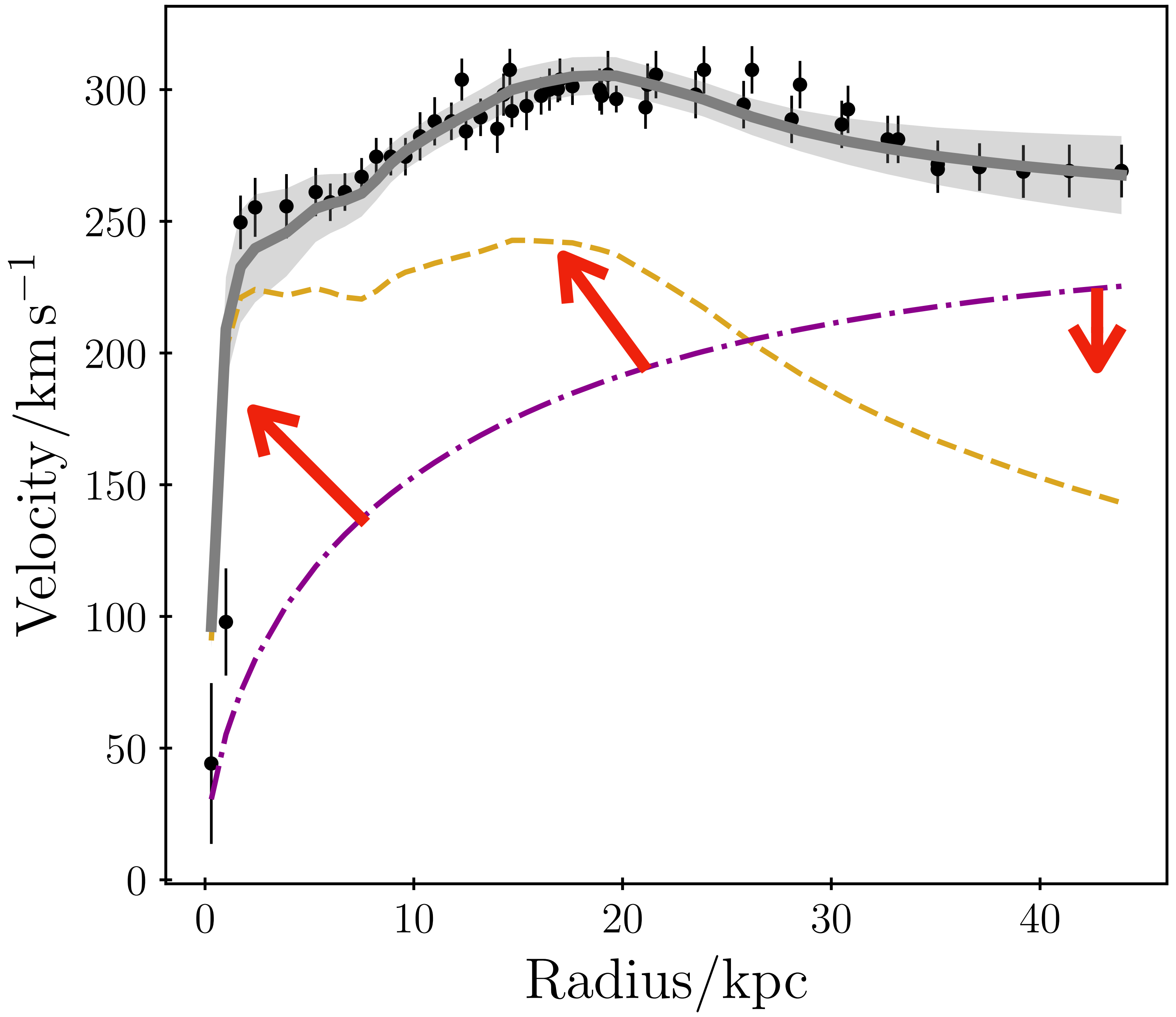
- Blumenthal et al. (1986) adiabatic contraction model:

    - spherical symmetry
    - all DM particles are on circular orbits

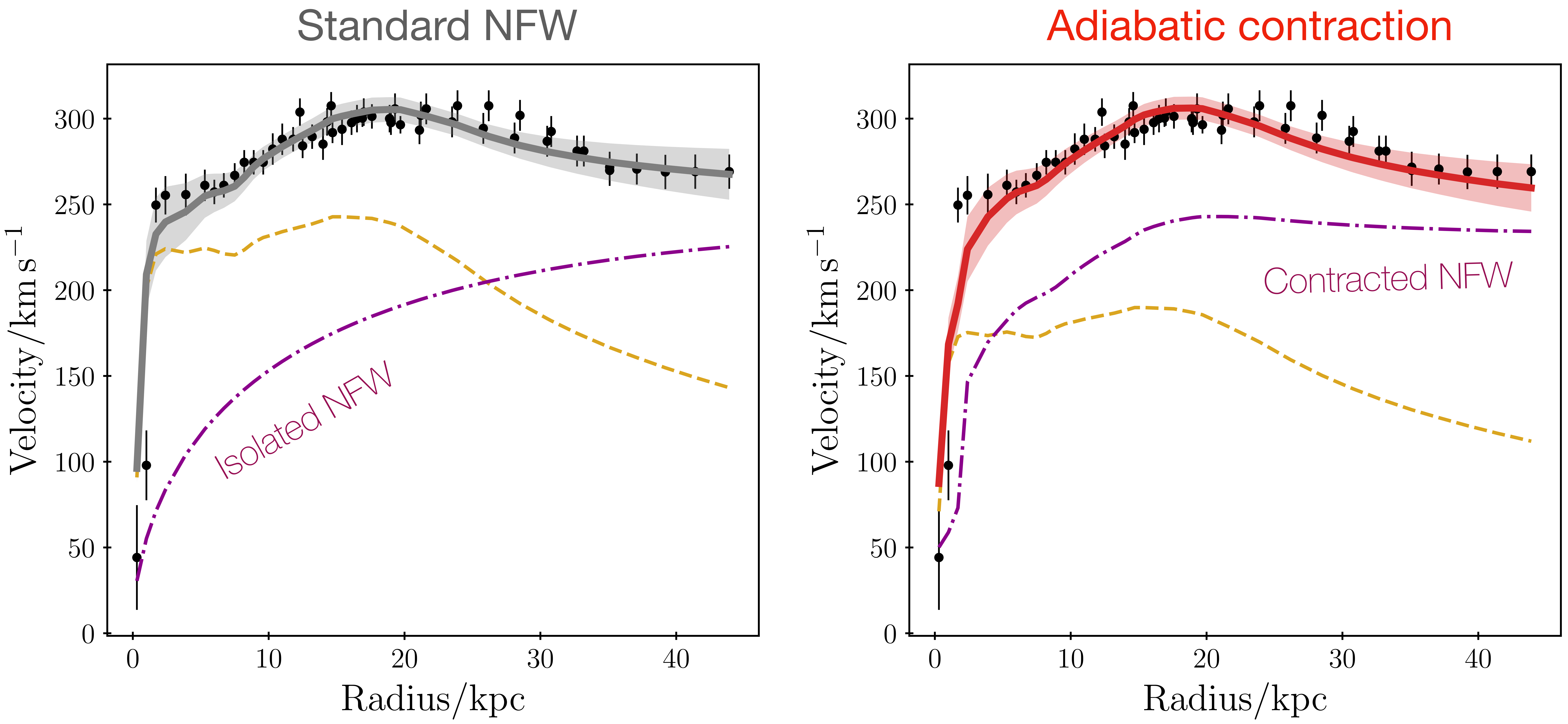
→ $r\,M(r)$ is an adiabatic invariant

- The halo contracts responding to the steady accumulation of gas and stars at the centre

- How does the DM mass distribution changes in realistic cases?

# Adiabatic contraction in high-mass galaxies



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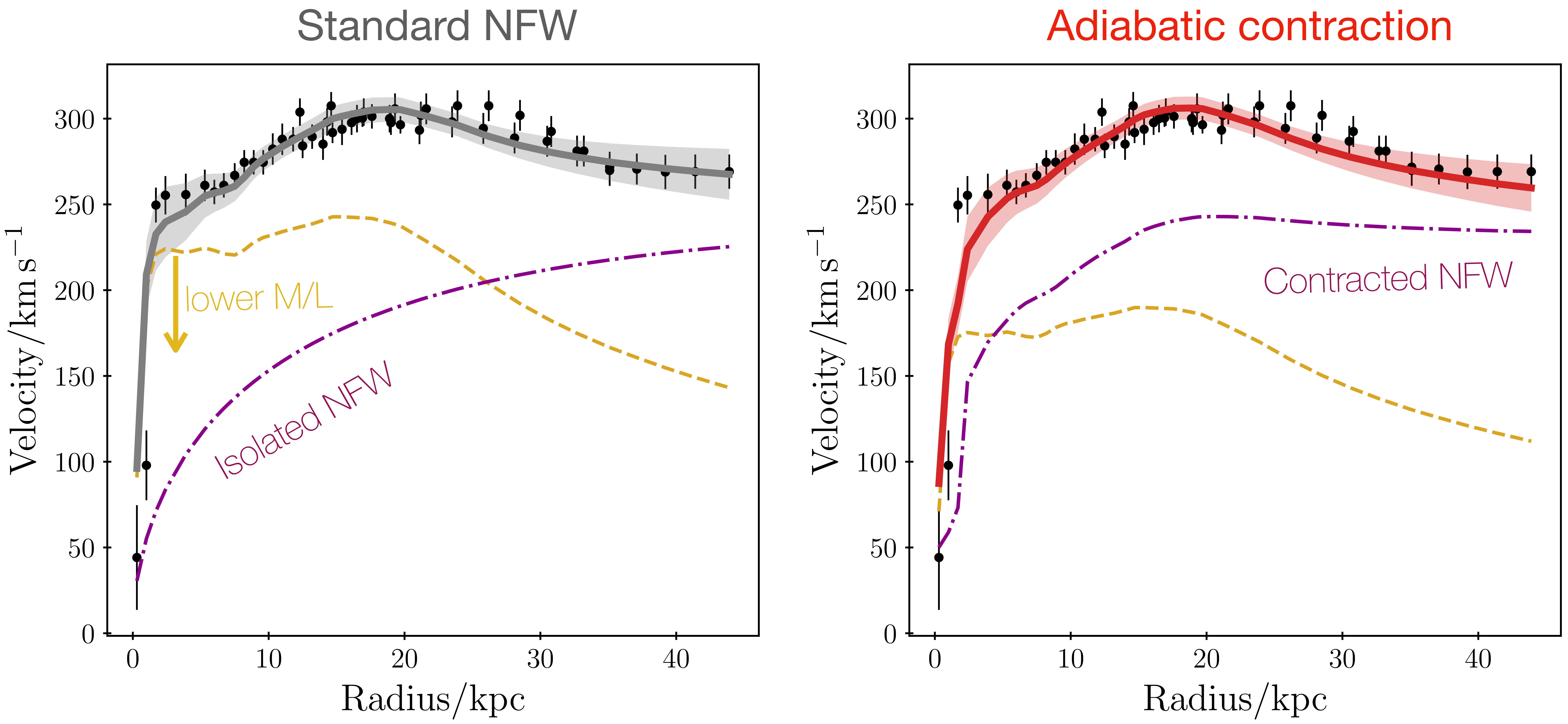

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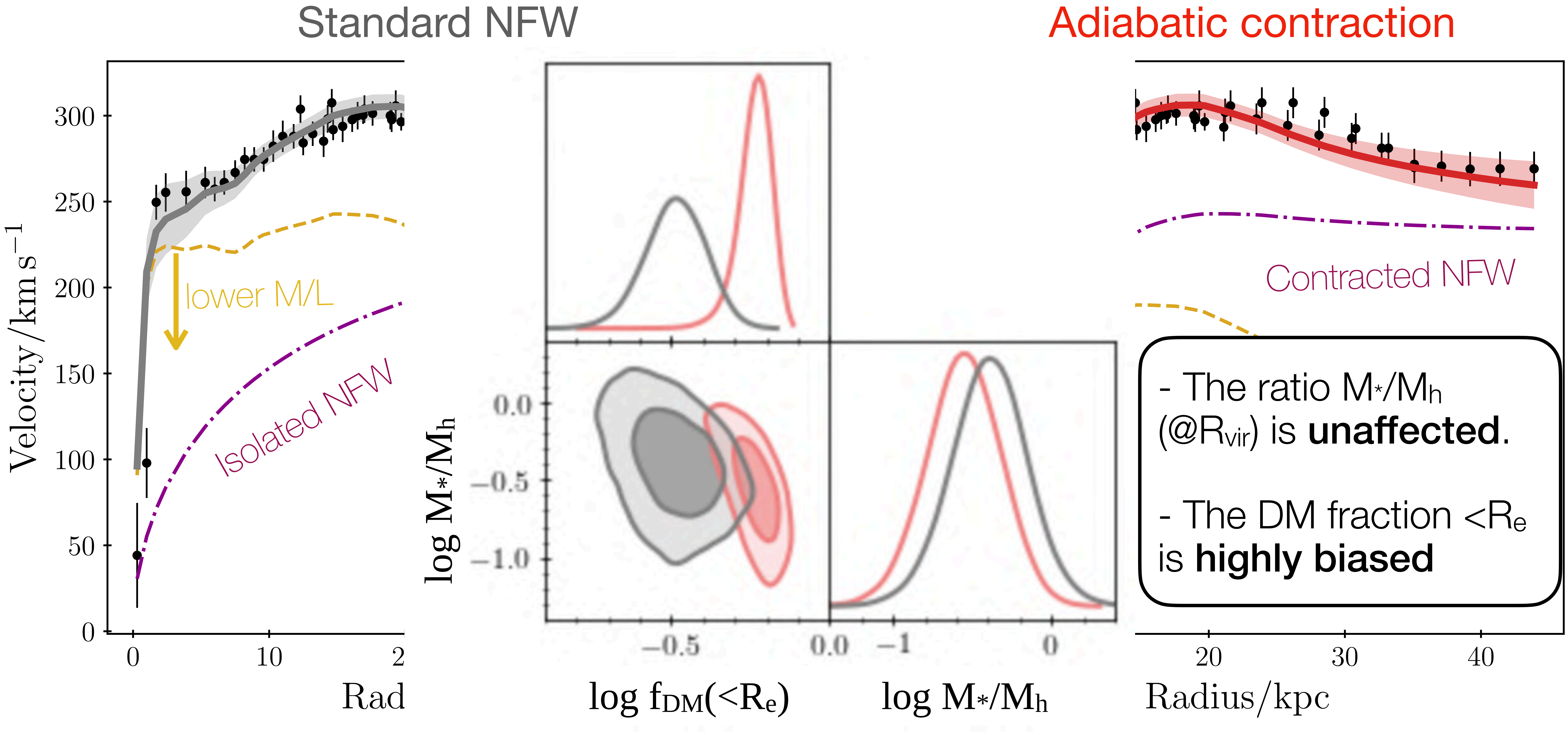
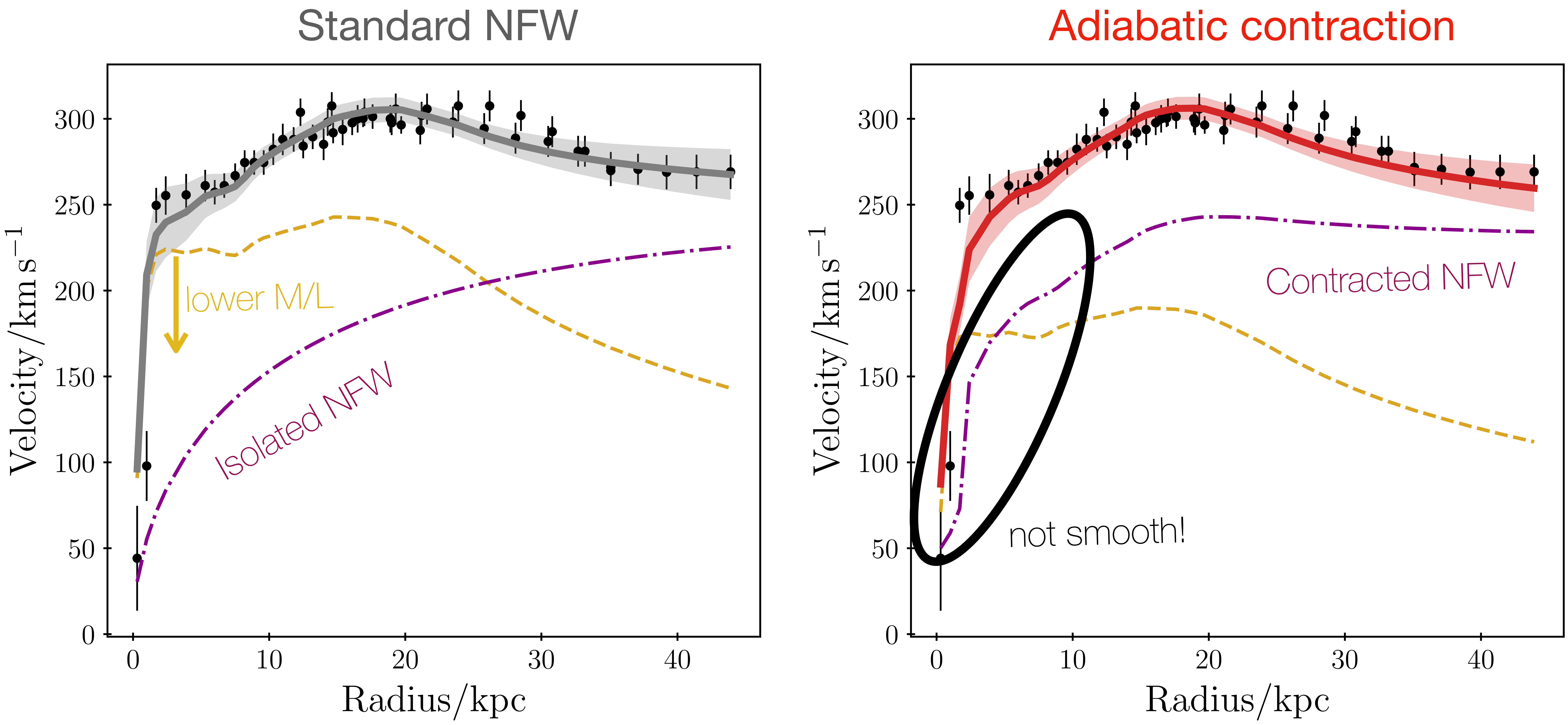



- The ratio $M_*/M_h$ (@$R_{vir}$) is **unaffected**.

- The DM fraction $<R_e$ is **highly biased**

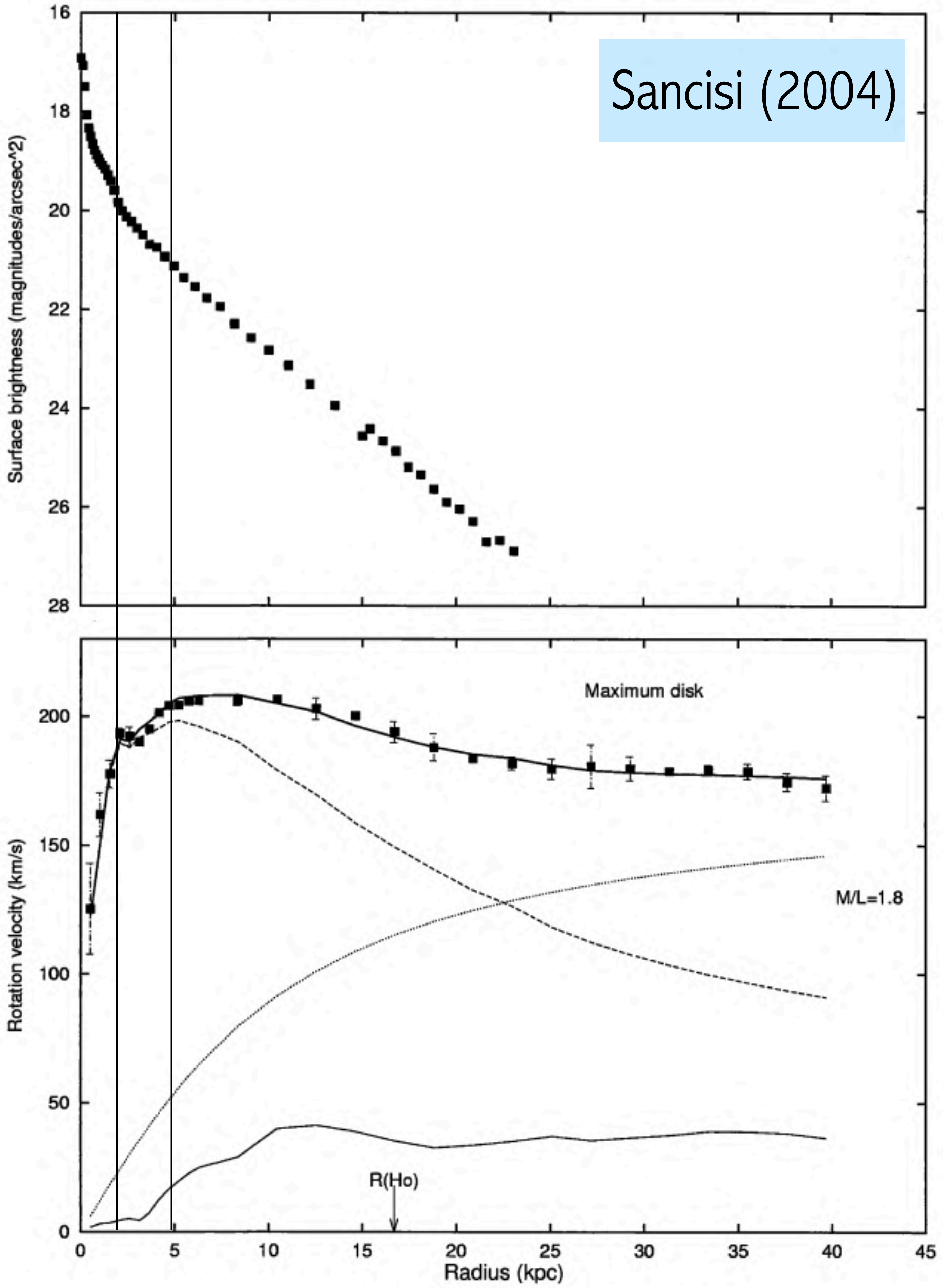
# Adiabatic contraction in high-mass galaxies



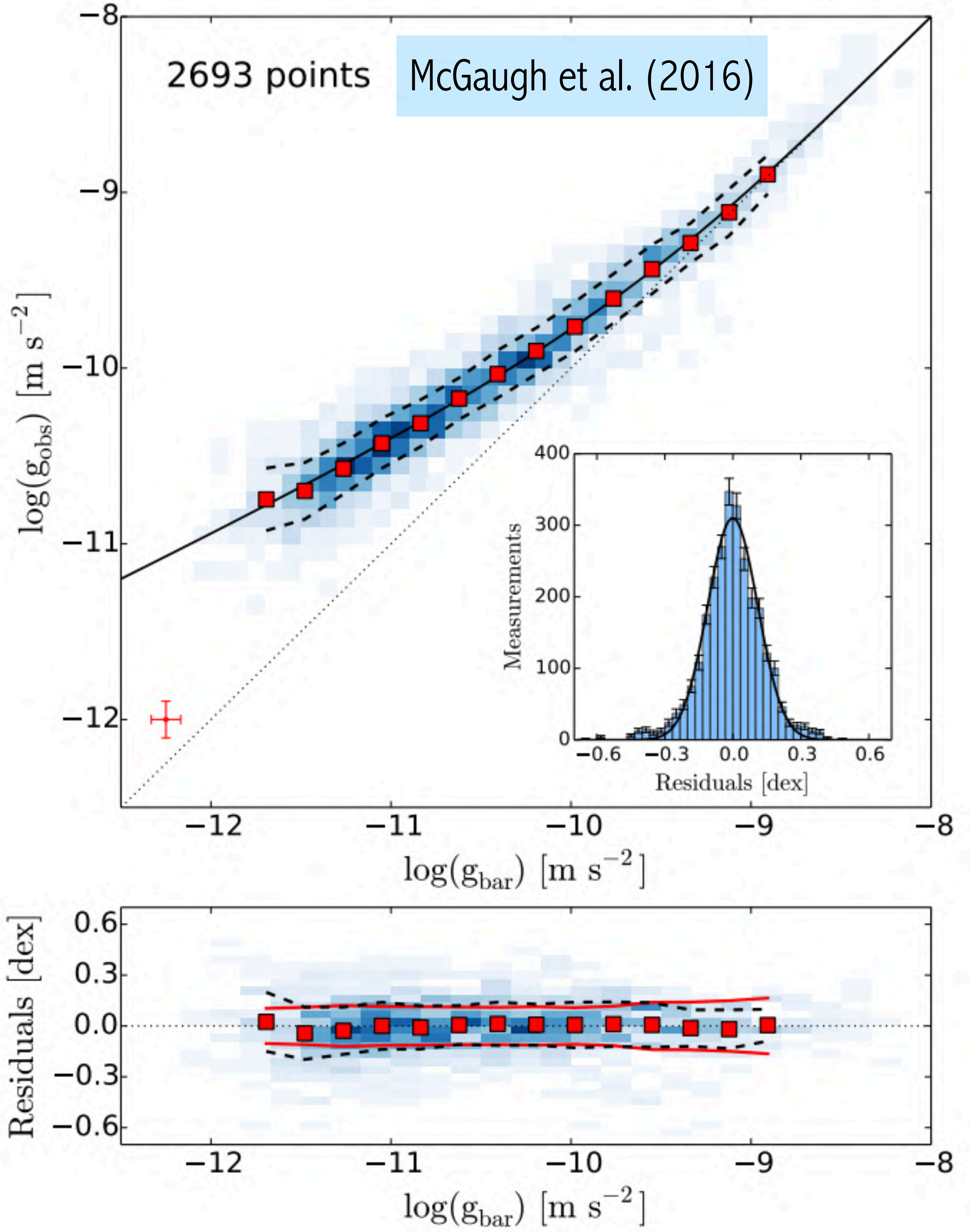
# Renzo’s rule

- Renzo’s rule (Sancisi 2004):

*“For every feature in the luminosity profile there is a corresponding feature in the rotation curve and viceversa”*



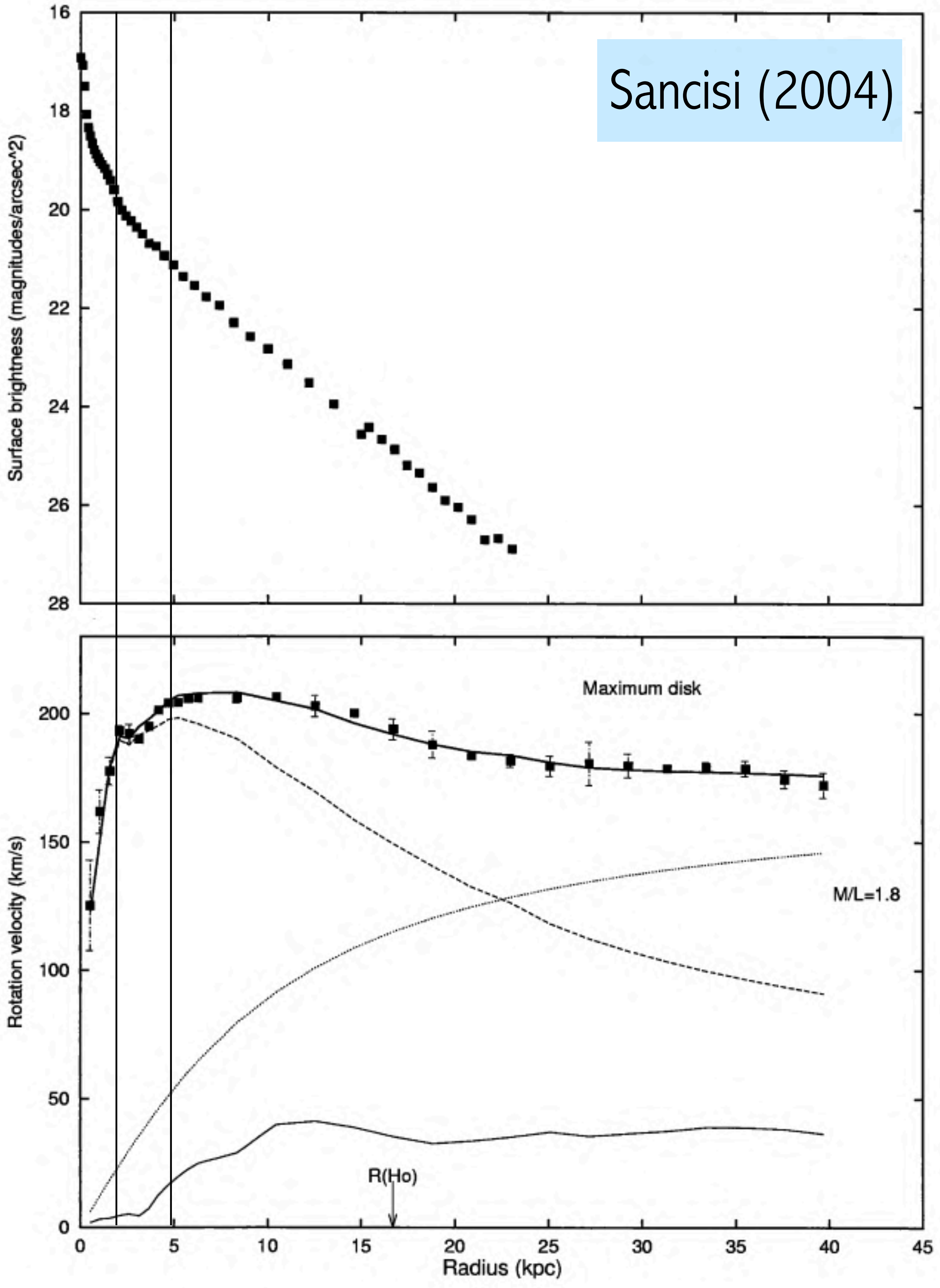

Radial Acceleration Relation (RAR)

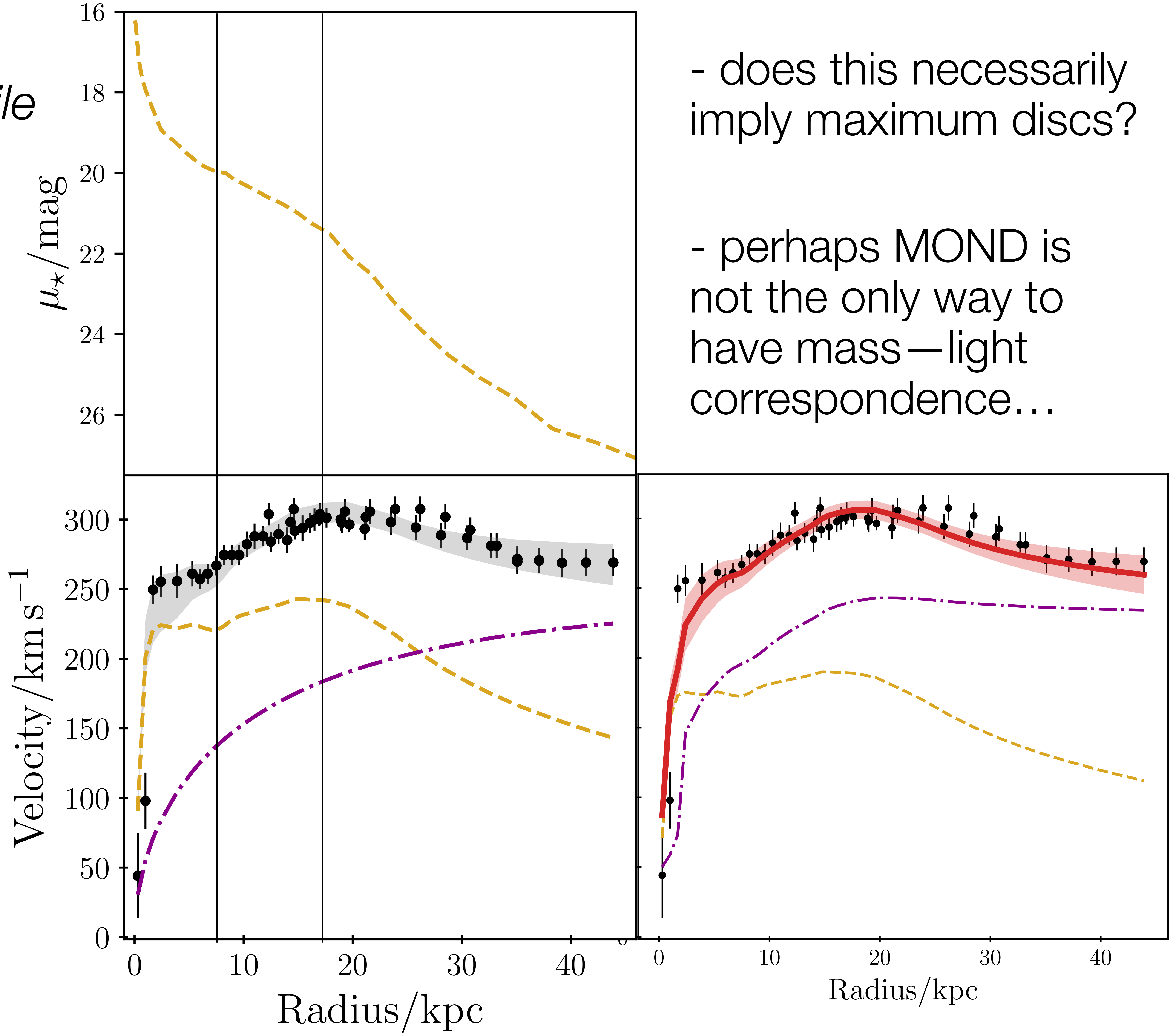


# Renzo's rule in HSB galaxies

- Renzo's rule (Sancisi 2004):

*"For every feature in the luminosity profile there is a corresponding feature in the rotation curve and viceversa"*




- does this necessarily imply maximum discs?

- perhaps MOND is not the only way to have mass—light correspondence…

# Renzo’s rule in LSB galaxies

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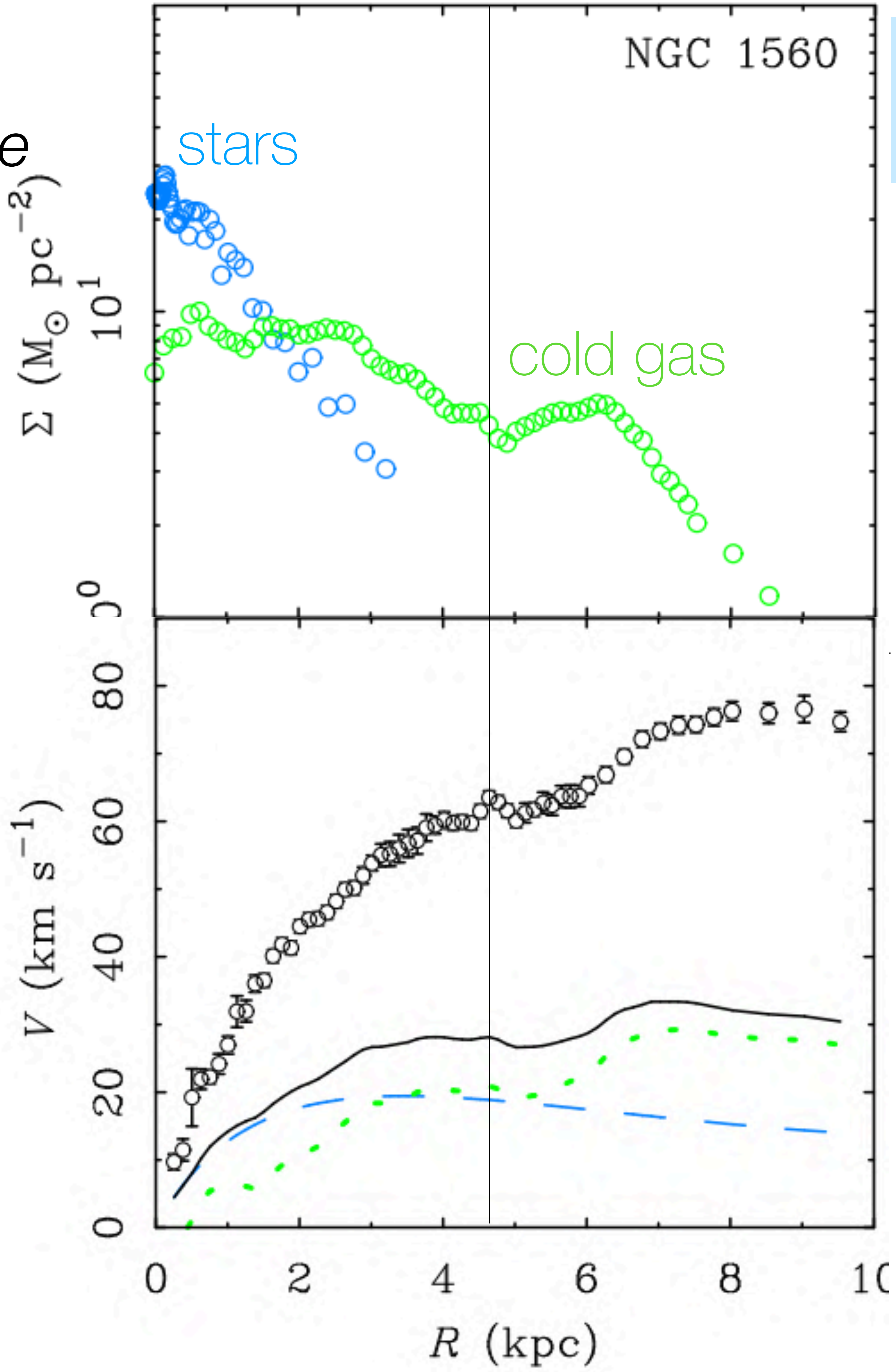
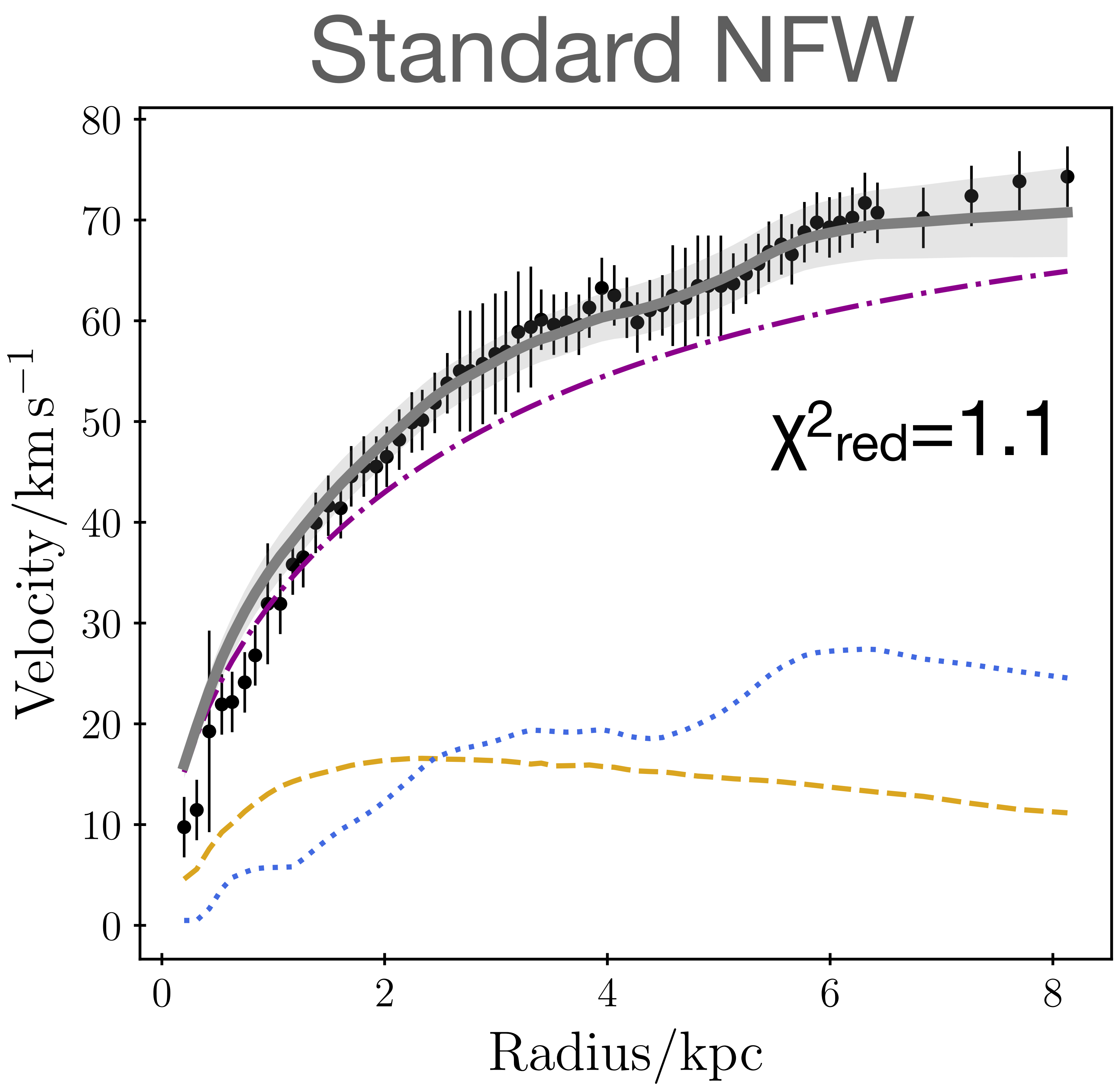
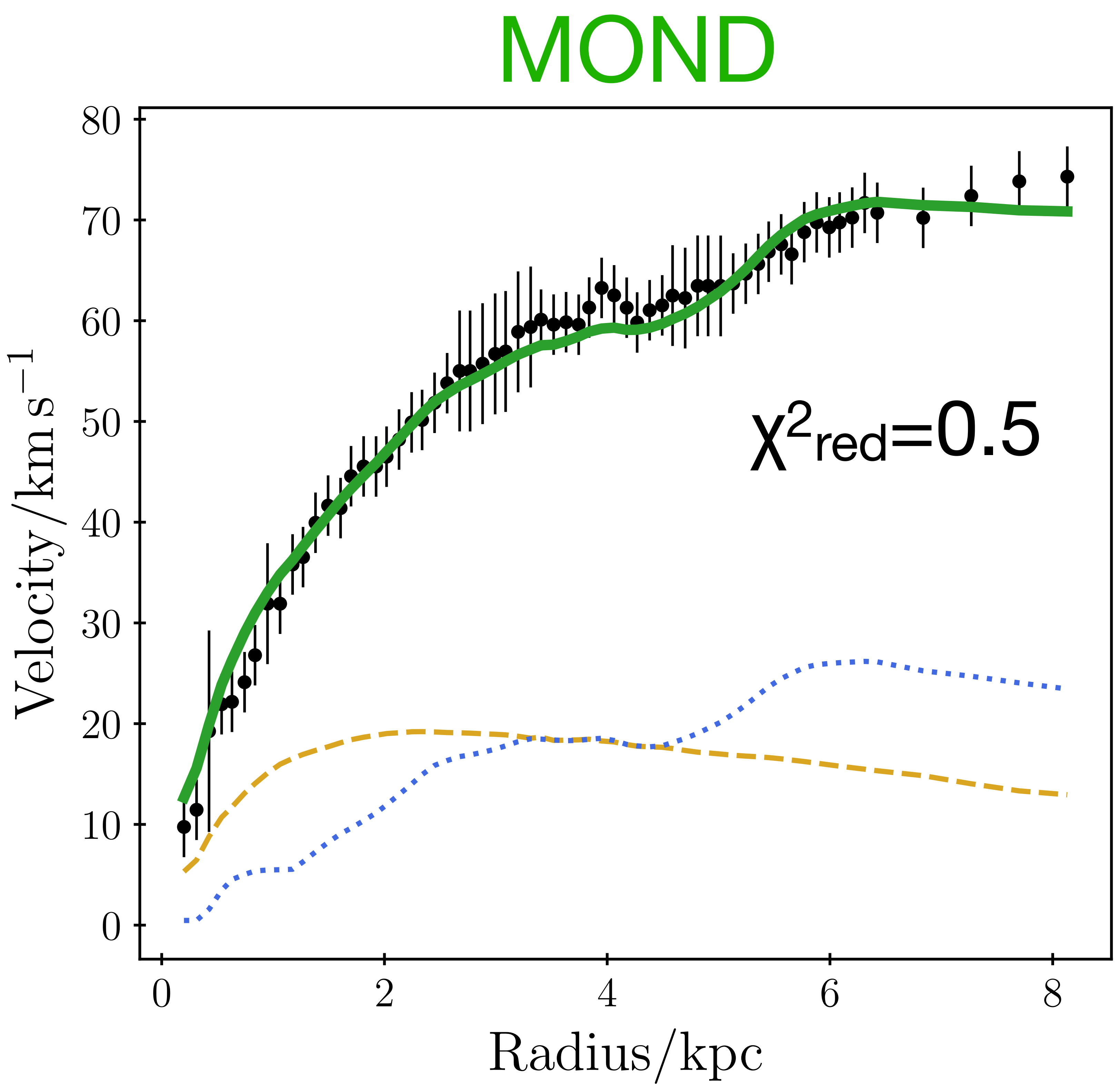



Gentile et al. (2010)

Famaey & McGaugh (2012)

# Renzo’s rule in LSB galaxies



# Renzo's rule in LSB galaxies

# Renzo's rule in LSB galaxies


- Perhaps halo contraction can account for Renzo's rule in LCDM

# A better adiabatic contraction model

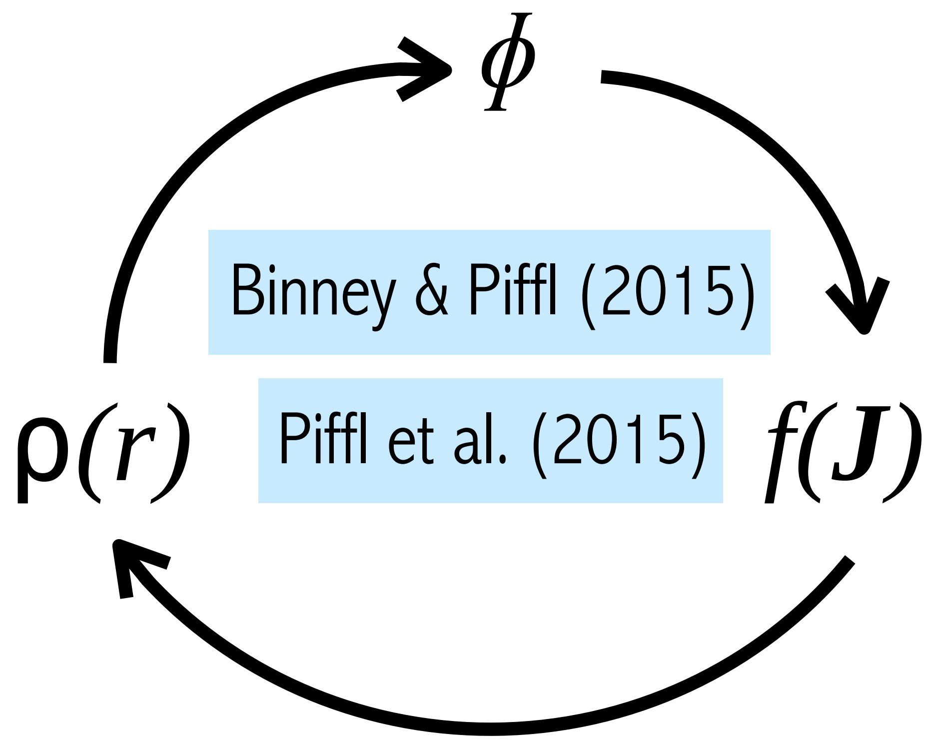
- How can we overcome Blumenthal's assumptions?

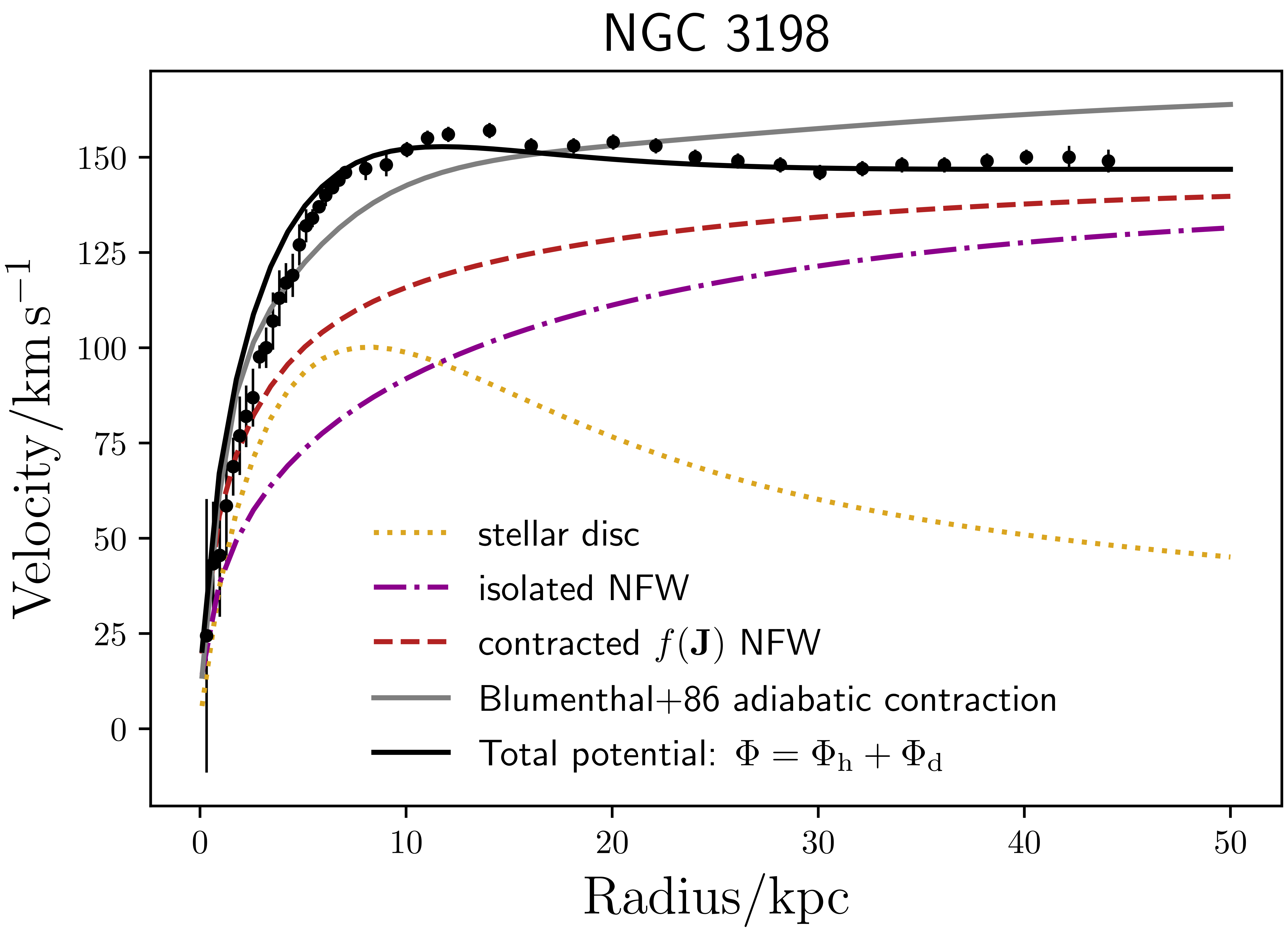
  *spherical symmetry, circular orbits*

- DM halos with distribution functions ***f(J)***, depending on action integrals

- Actions ***J***, hence the DF ***f(J)***, are by construction adiabatic invariants

- Set-up an ***f(J)*** NFW, add baryons as external potential, let ***f(J)*** relax to a flattened contracted halo



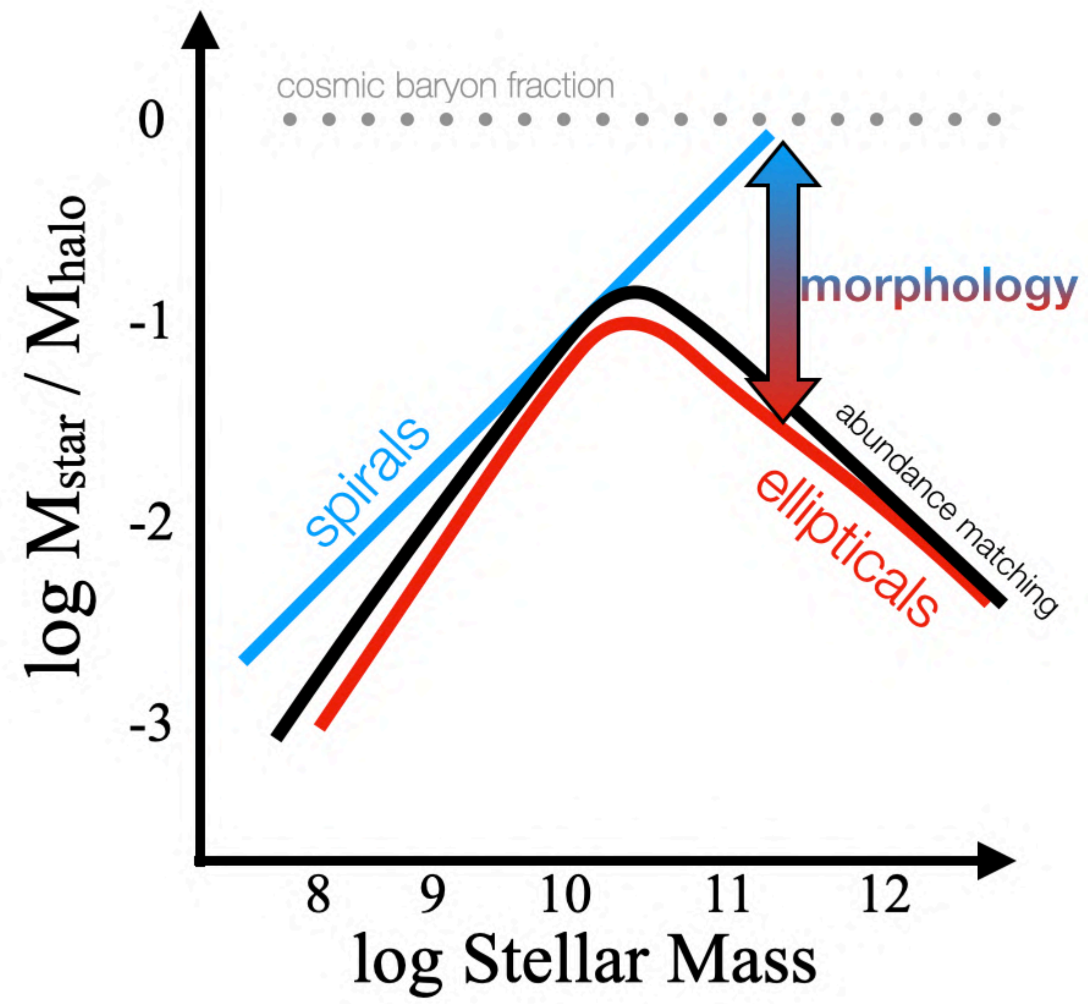



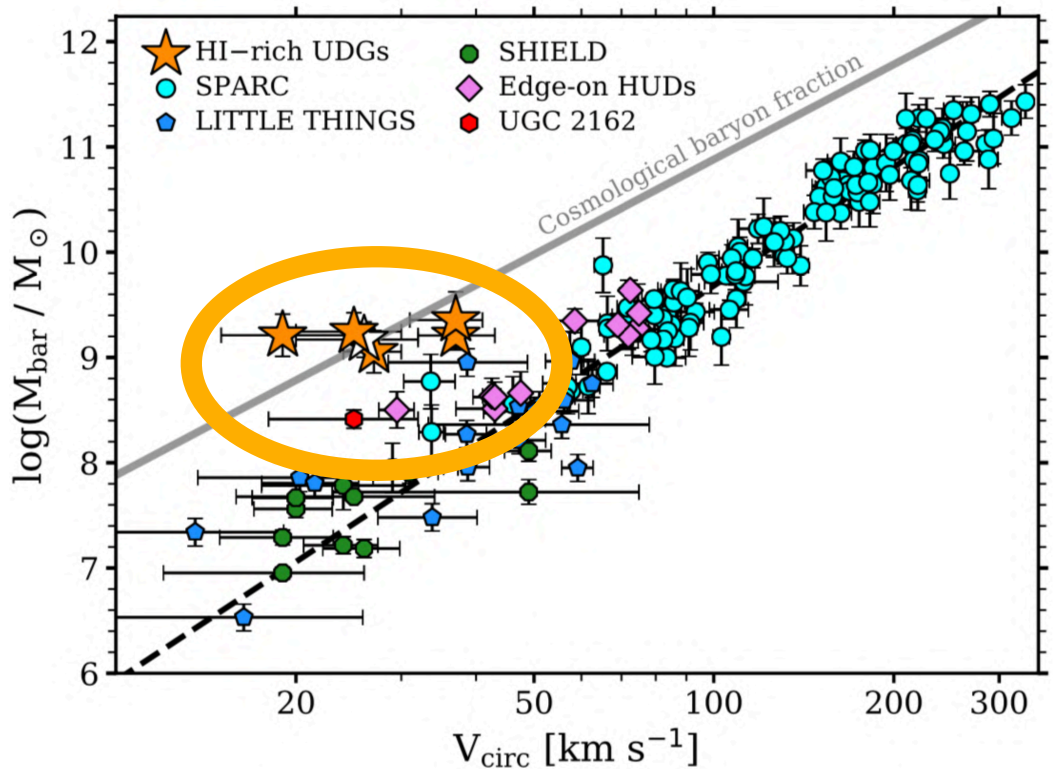
# Take home messages

- Galaxy rotation curves probe the stellar-to-halo mass relation

- Massive disc galaxies follow a separate branch from ellipticals

- Consistent with the latest Tully-Fisher estimates at high masses

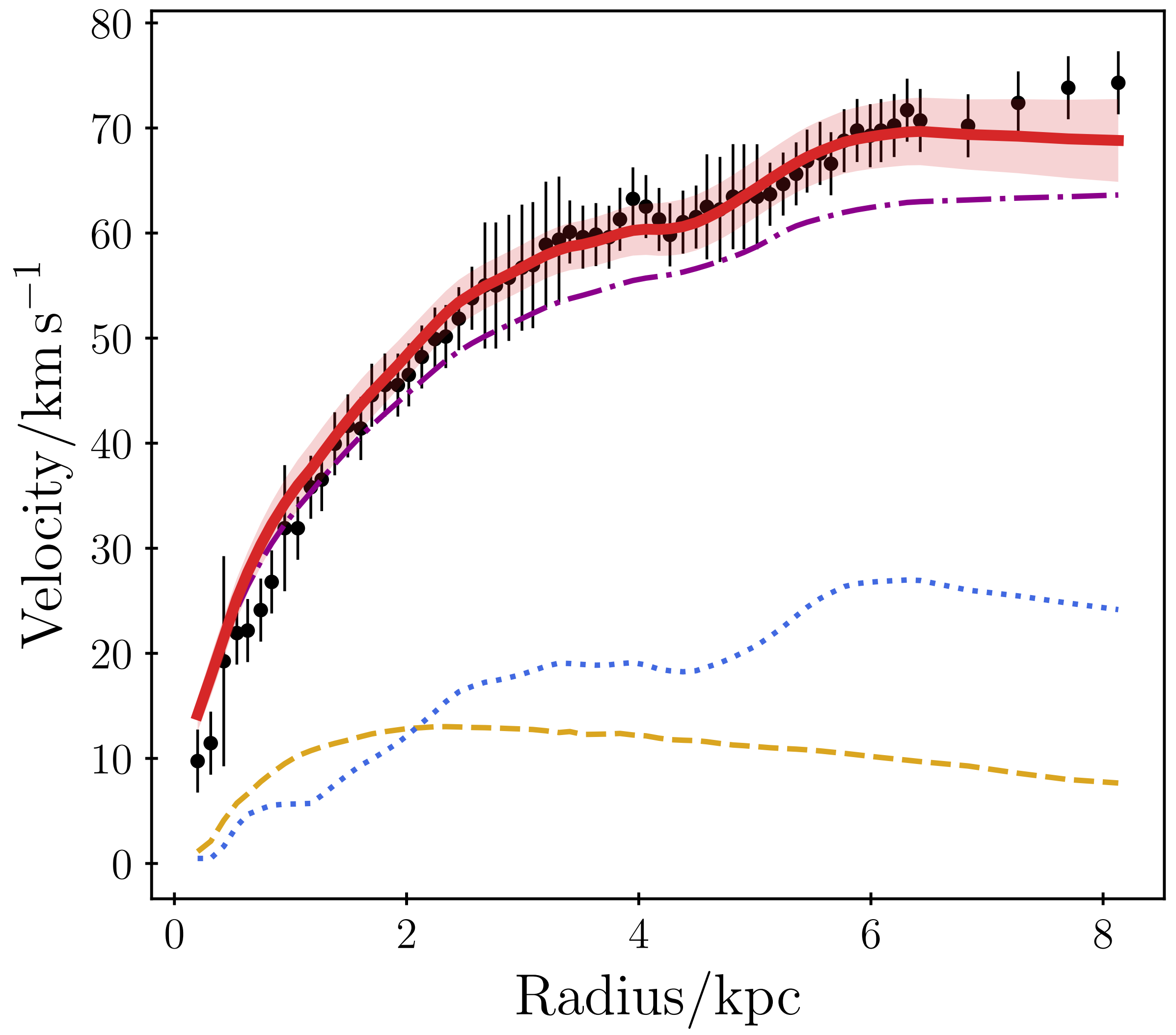



- Outliers of the Tully-Fisher at low masses are challenging both for LCDM and even more so for MOND

- Halo contraction can severely alter the shape of DM halos

- Might provide a long-sought explanation for Renzo's rule in LCDM



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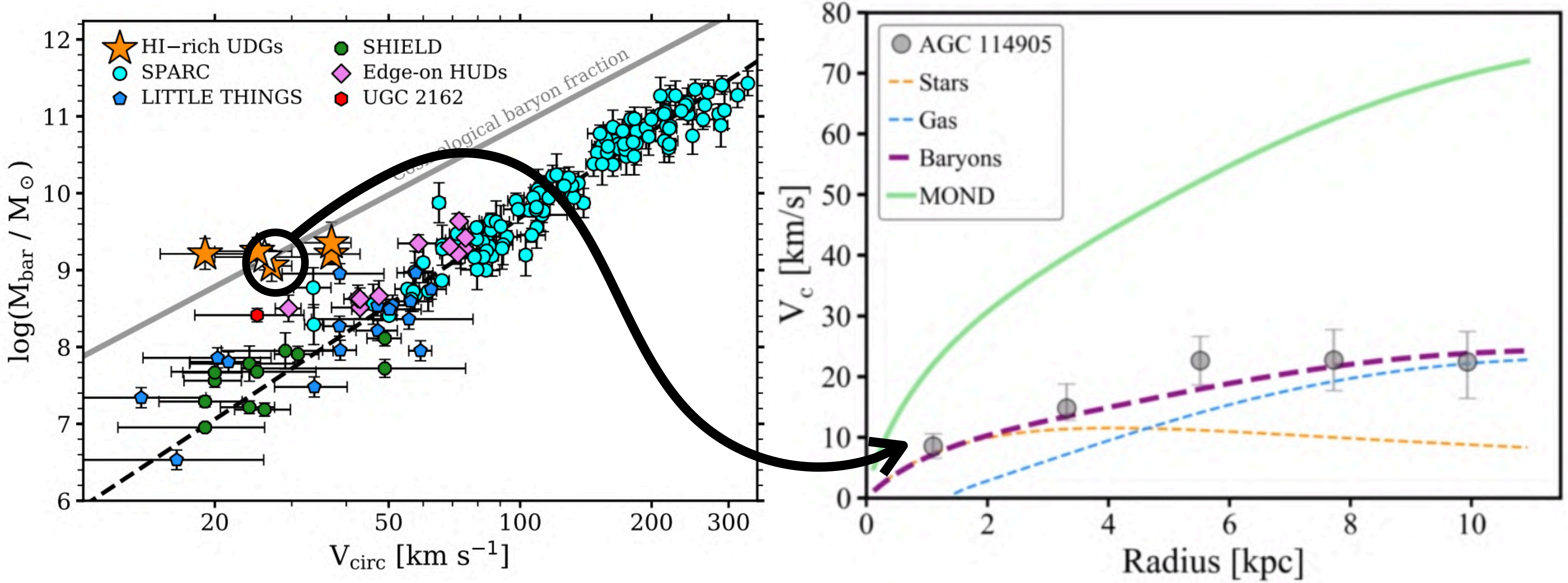


Credit: P. Mancera-Piña