The close link between baryons and dark matter in disc galaxies

Federico Lelli

Astronomy Department, Case Western Reserve University,

Cleveland, Ohio, USA

Main Collaborators:

Stacy McGaugh (Case Western Reserve)
James Schombert (University of Oregon)
Marcel Pawlowski (Case Western Reserve)
Marc Verheijen (University of Groningen)
Filippo Fraternali (University of Bologna)
Renzo Sancisi (Observatory of Bologna)

Outline:

- The Baryonic Tully-Fisher relation:

  Linking total amount of baryons and DM

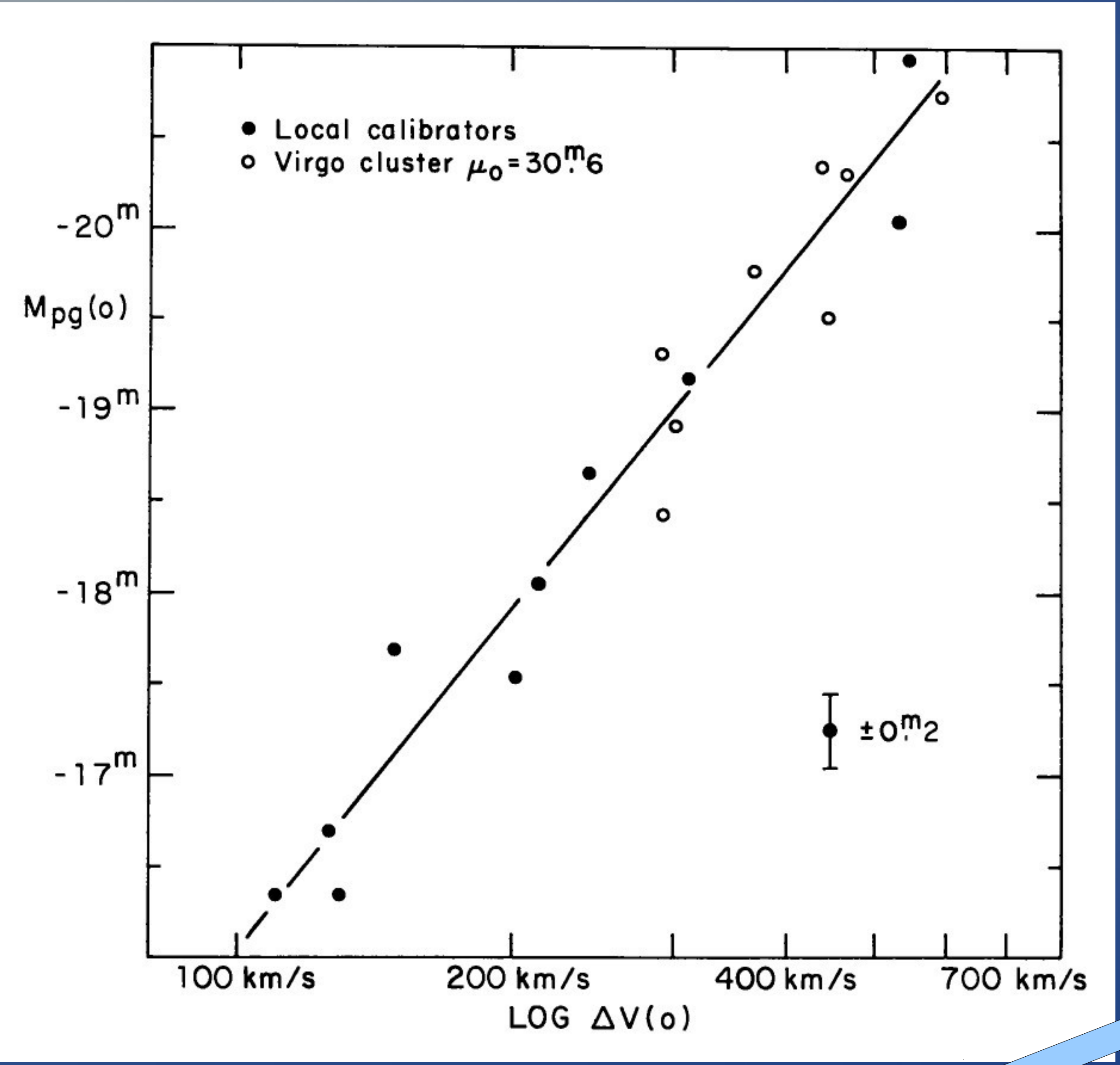
- Local "counterparts" of the BTFR:

  Linking distribution of baryons and DM

I. The baryonic TF relation:

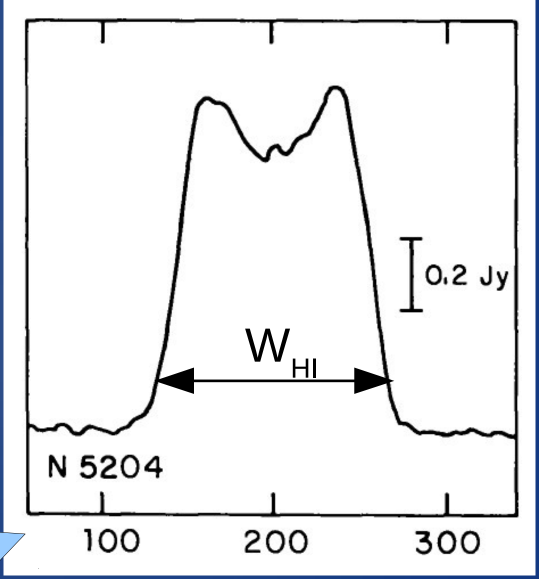
Observations & ΛCDM models

The "original" TF Relation



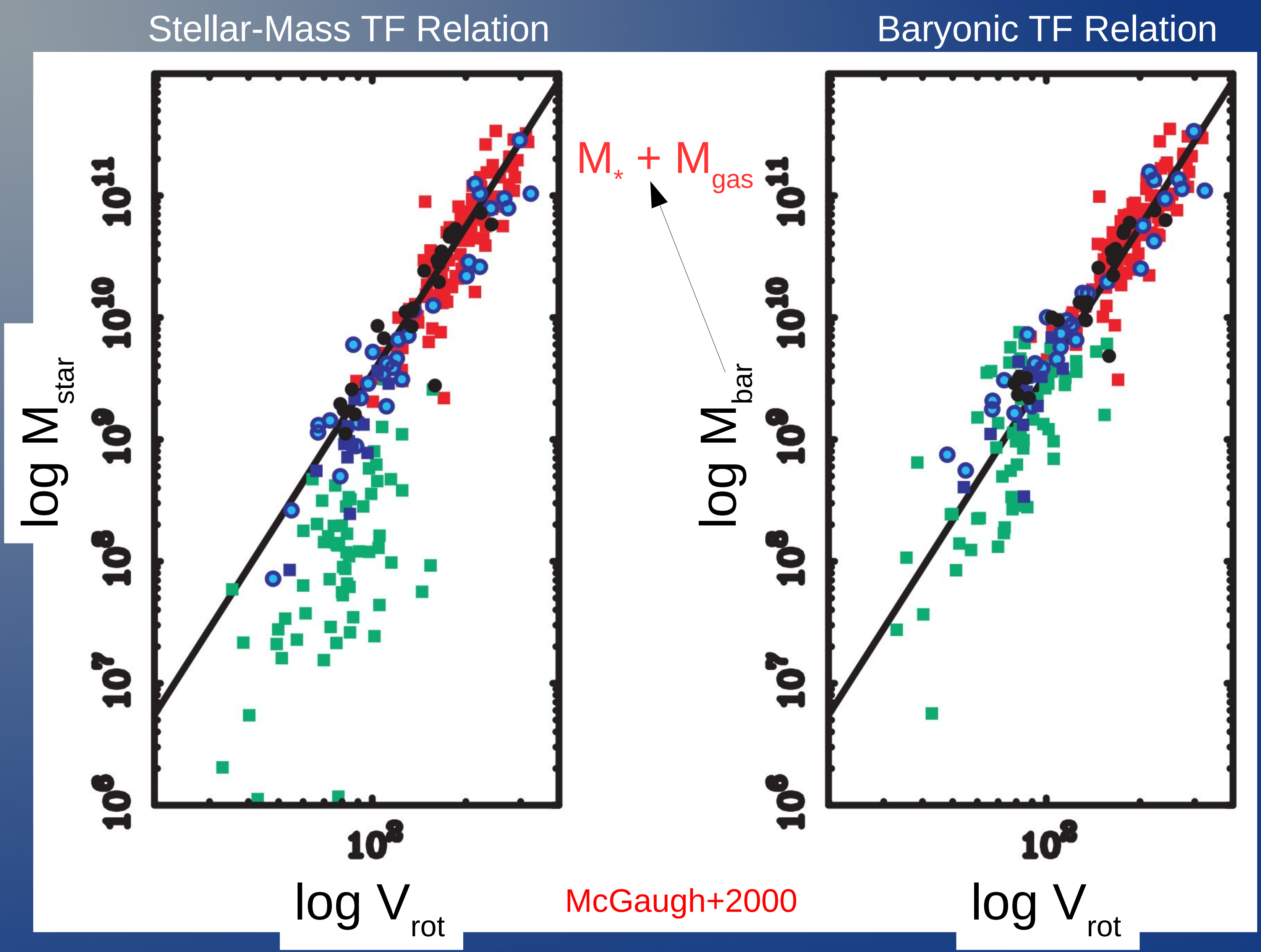
HI Line-Width (~Rotation Velocity)

Tully & Fisher (1977):
18 spiral galaxies with global HI spectra from single-dish telescopes



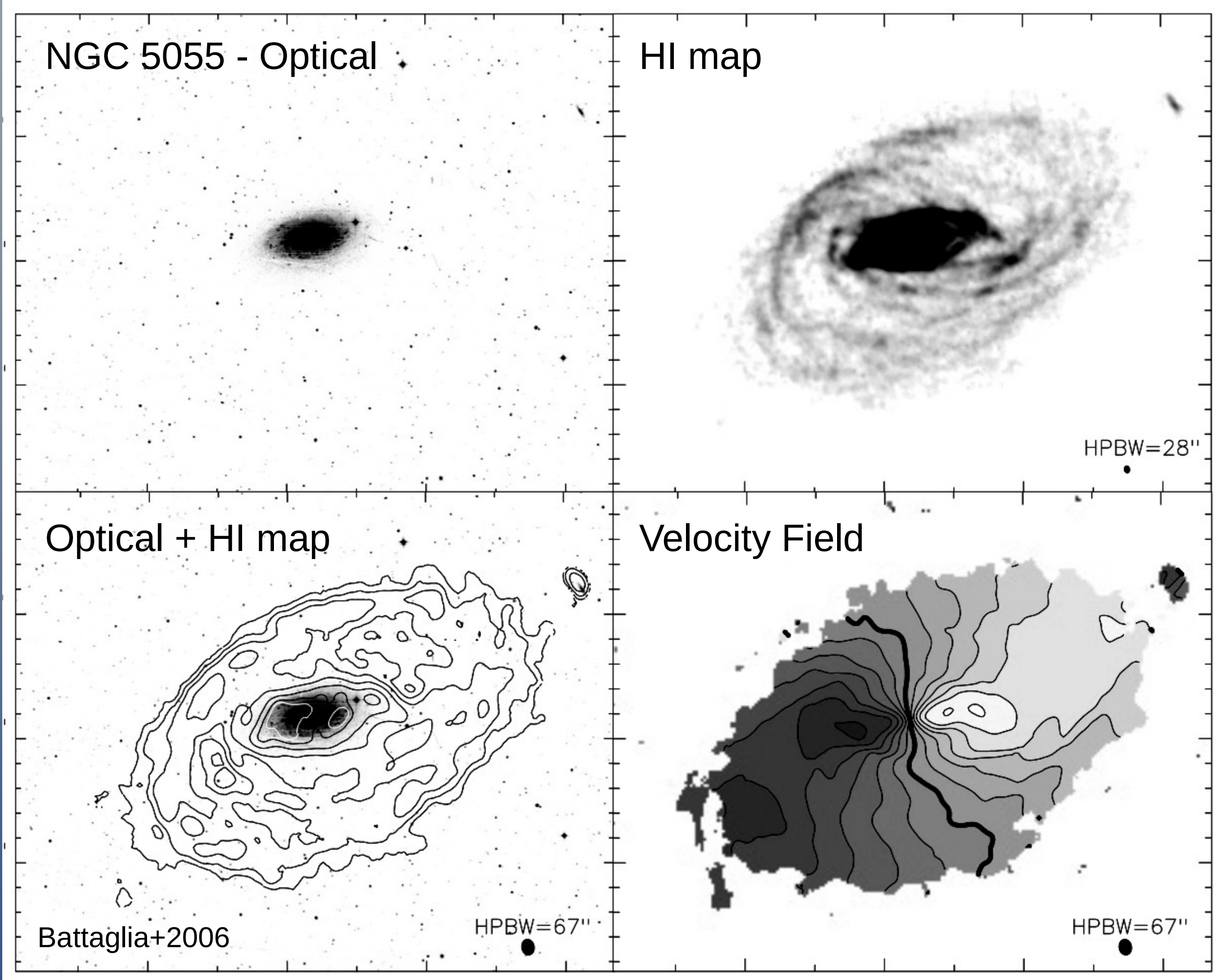
Heliocentric Velocity (km/s)

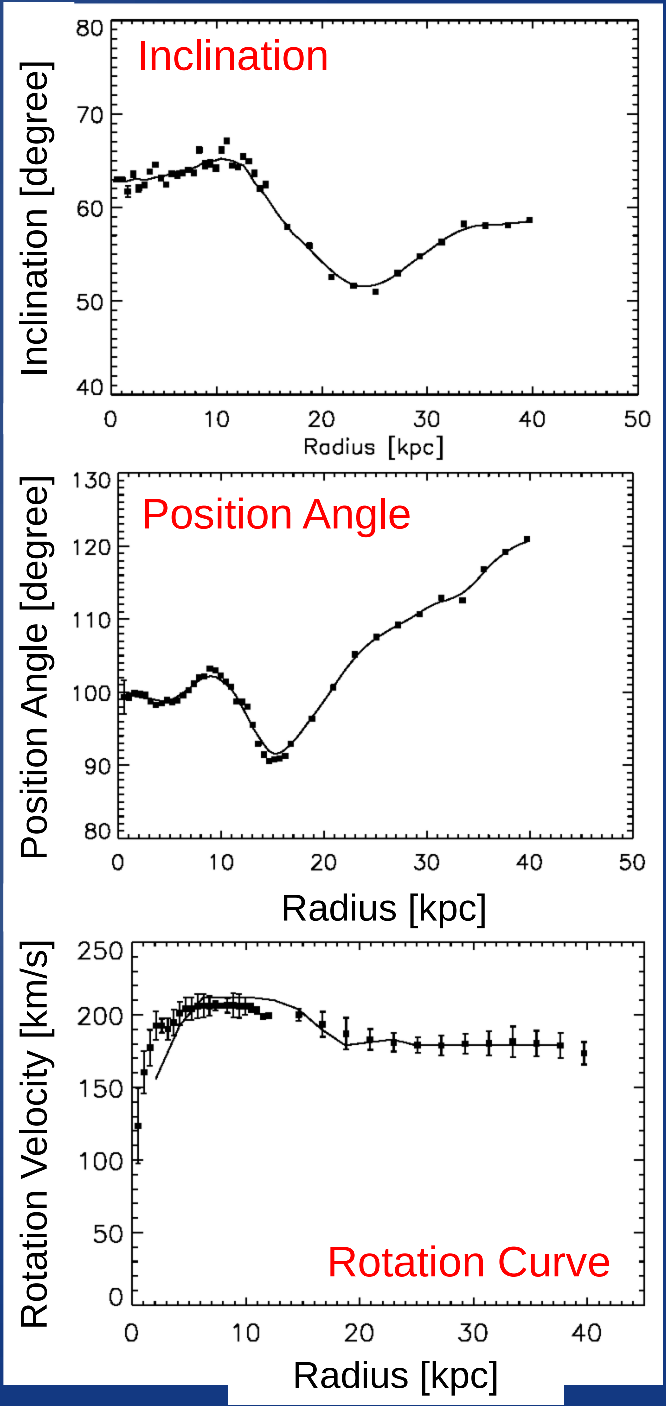
The total baryonic mass is the key!



Some BTFR studies: Freeman 1999; Walker 1999; McGaugh+2000; Verhejen 2001; Bell & de Jong 2001; McGaugh 2005; Geha+2006; Noordermeer & Verheihen+2007; Begum+2008; Avila-Reese+2008; Stark+2009; Trachternach+2010; Gurovich+2010; Hall+2012; McGaugh 2012; Catinella+2012; Zaritsky+2014

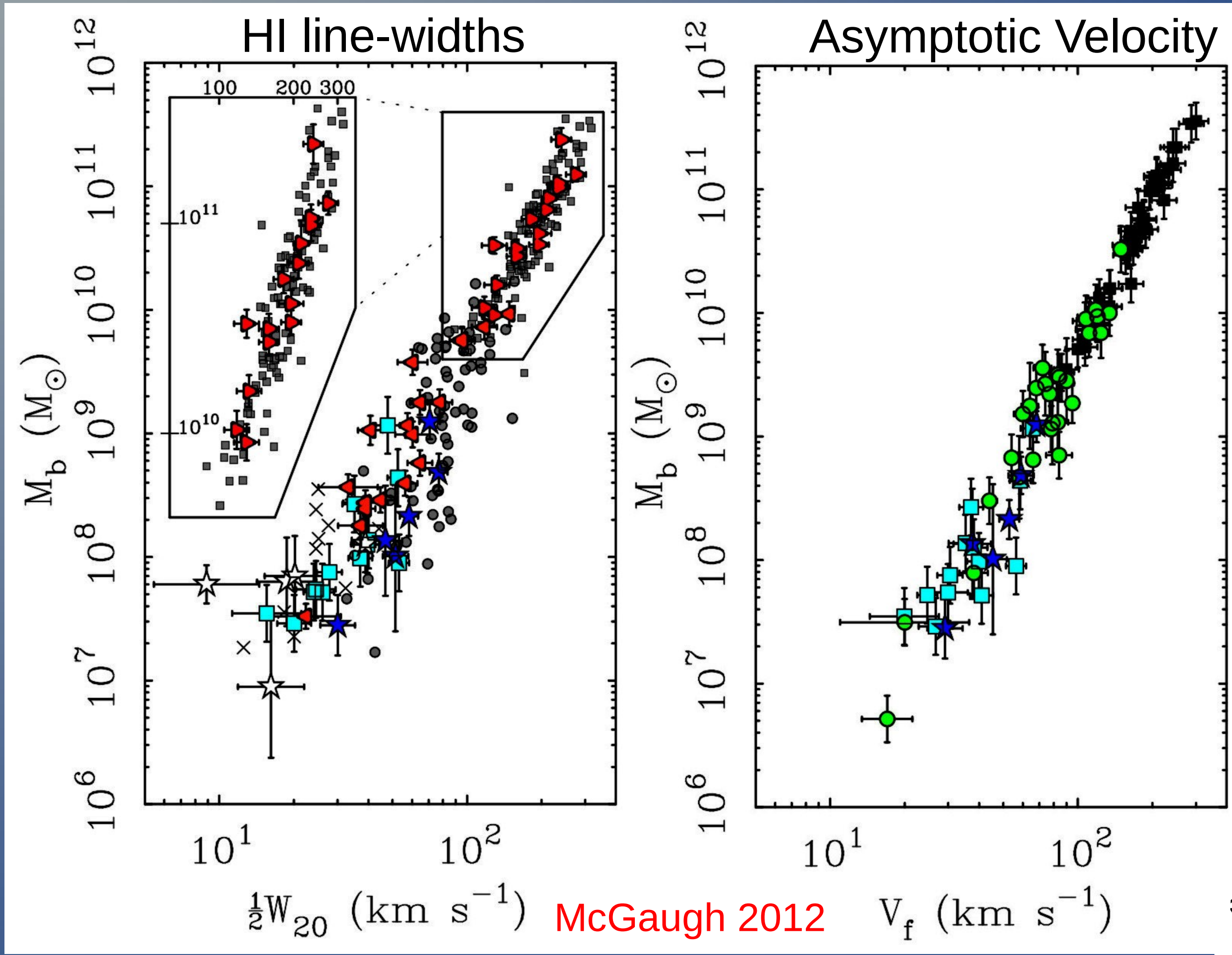
Interferometric HI observations

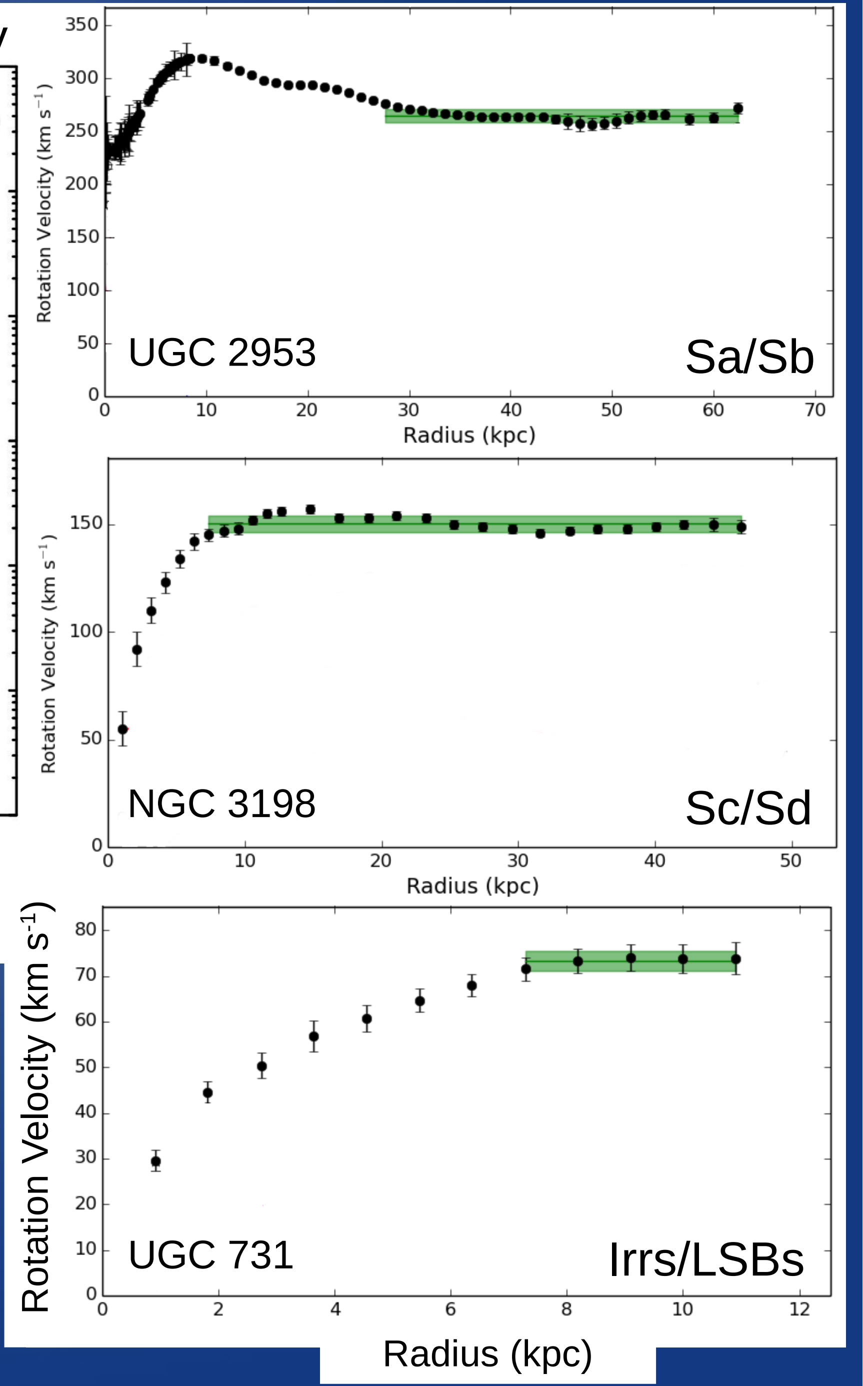




Detailed kinematic analysis considering possible warps, asymmetries, interactions.

A scaling relation between M_{bar} – V_{flat}





The scatter is minimized using V_{flat}
(Verheijen 2001; Noordermeer & Verheijen 2007)

This requires interferometric HI data
and detailed modelling (time costly!).

Open Questions:

- What is the origin of the BTFR?
- What is the slope of the BTFR?
- Is there any intrinsic scatter?

Building a "large" galaxy sample

- HI rotation curves for ~120 objects (Sa to Irrs):
  - Results of ~30 years of interferometric HI observations (WSRT, VLA, ATCA, and GMRT).
  - Mostly PhD thesis from the University of Groningen (Begeman 1987; Broeils 1992; Verheijen 1997; de Blok 1997; Swaters 1999; Noordermeer 2005; Lelli 2013 – *Thanks to:* Sancisi, van Albada, van der Hulst)

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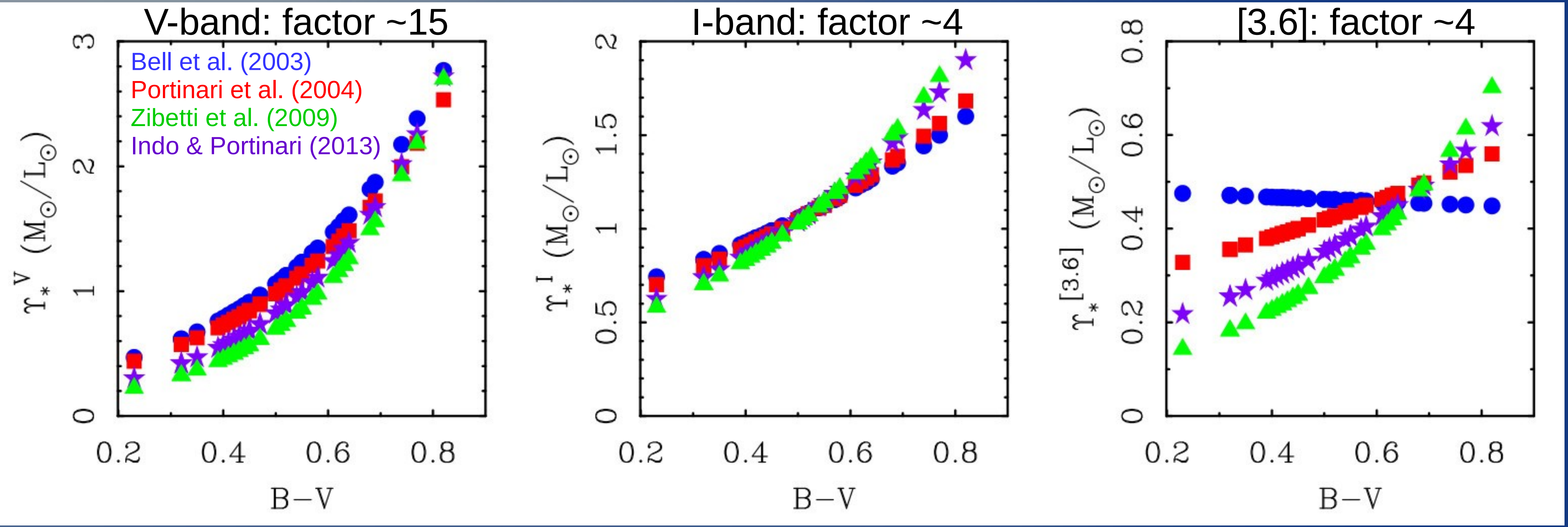
- Uniform NIR surface photometry (best tracer of M_*)

  - K-band from 2MASS or [3.6] from Spitzer

  - Data analysis using ARCHANGEL (Schombert 2011)

Stellar masses from NIR photometry

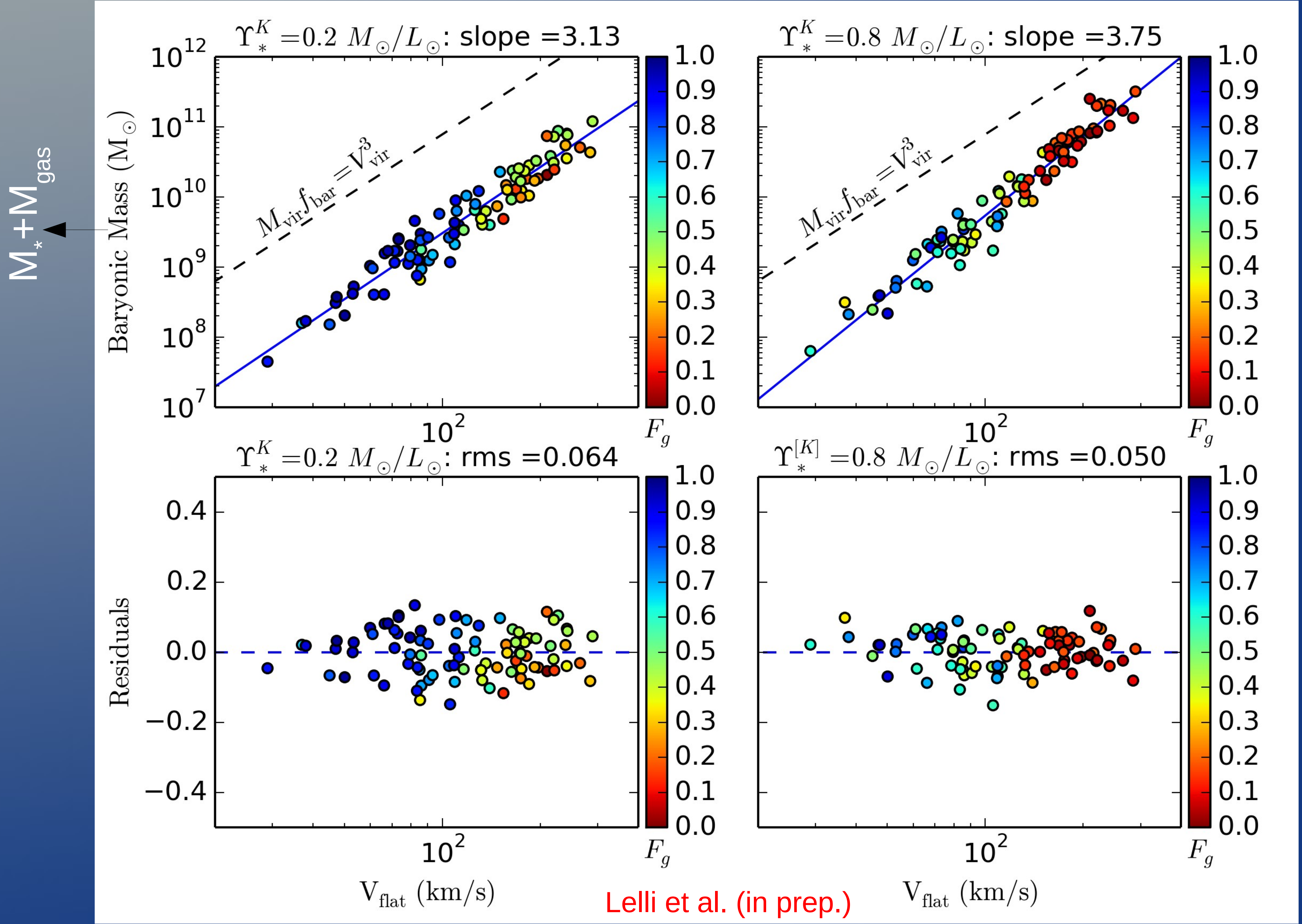
$M_{bar} = M_{gas} + \Upsilon_*^i L_i$ Υ_* = stellar mass to-light ratio



Corrected Υ_*-color relations from self-consistent SPS models (McGaugh & Schombert 2014)

- Small variation of Υ_* in the NIR
- Details depend on SPS model and assumed IMF

The BTFR for different M_*/L



Lelli et al. (in prep.)

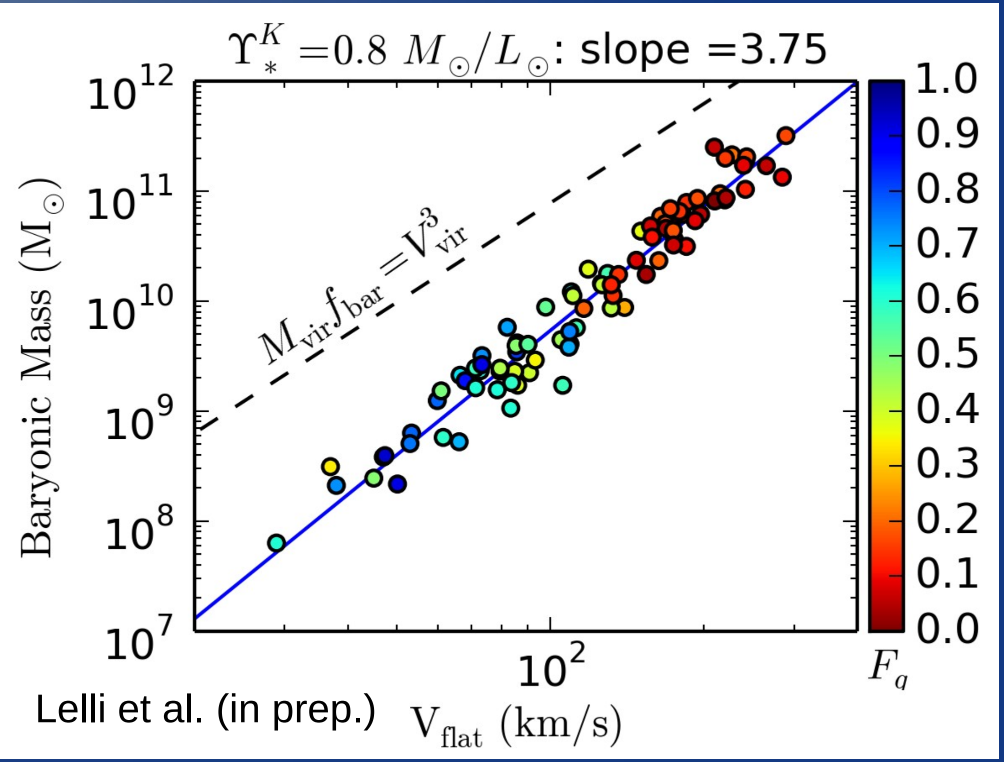
The BTFR in a ΛCDM context

Following Mo, Mao, & White (1998):

Halo Mass: $M_{vir} = (4/3)\pi R^3_{vir} \Delta \rho_{crit}$ $\rho_{crit} = 3H_0^2/8\pi G$

Halo Velocity: $V^2_{vir} = GM_{vir}/R_{vir}$

TF-like relation: $M_{vir} = A V_{vir}^3$ $A = \sqrt{(½\Delta)}/(GH_0)$



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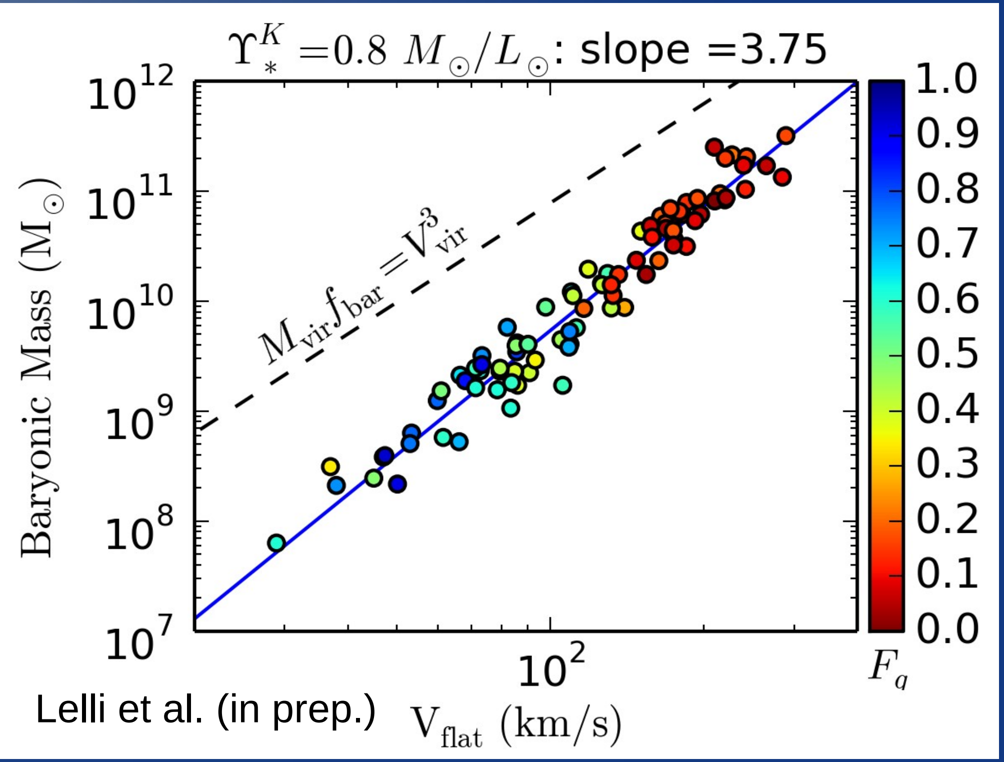
To baryons: $M_{bar} = f_{bar}\, f_{disc}\, M_{vir}$

$f_{bar} = 0.17$ (CMB & clusters)

f_{disc} = baryons in galaxy discs



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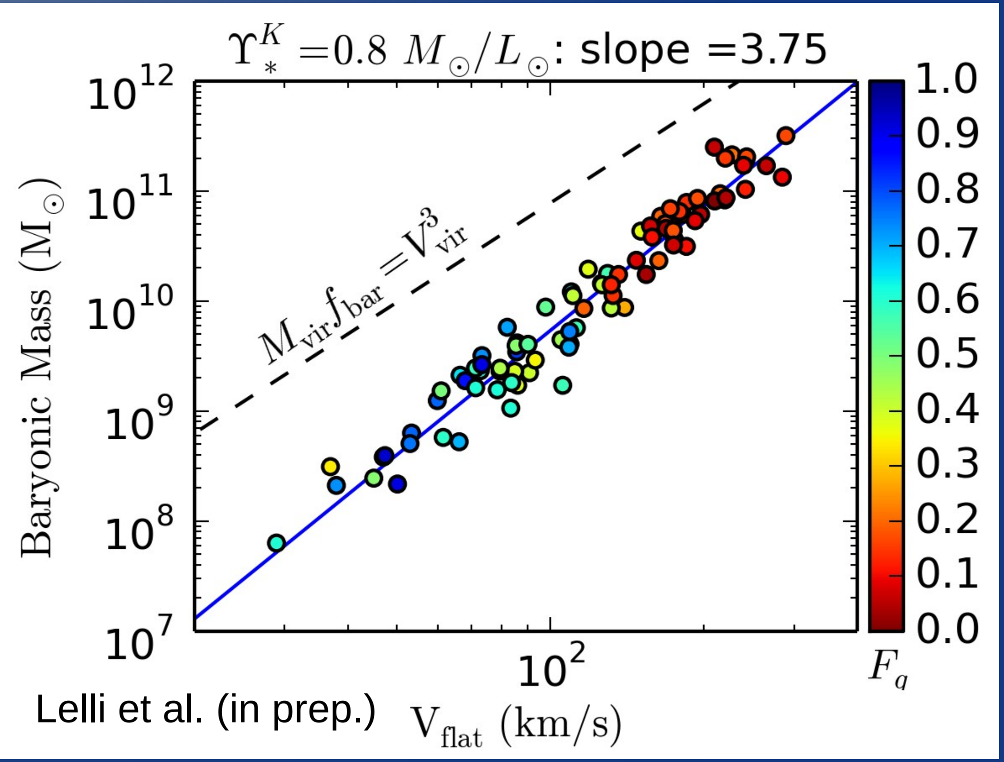
To velocities: $V_{flat} = f_V\, V_{vir}$

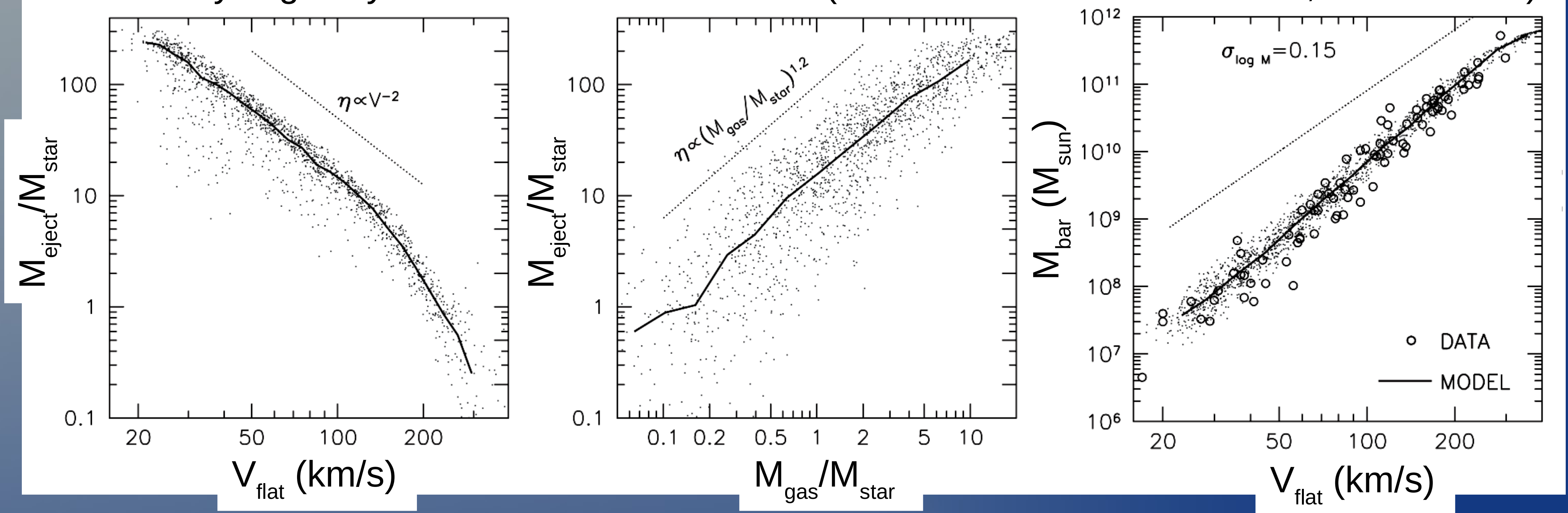
f_V = halo response to baryons

>>> $M_{bar} = (A\, f_{bar})\, (f_{disc}/f_V^{\,3})\, V_{flat}^{\,3}$



The BTFR with gas outflows?

Semi-analytic galaxy formation model in ΛCDM (Dutton & van den Bosh 2009; Dutton 2012)



Basic Idea: Feedback eject more baryons from low-mass galaxies

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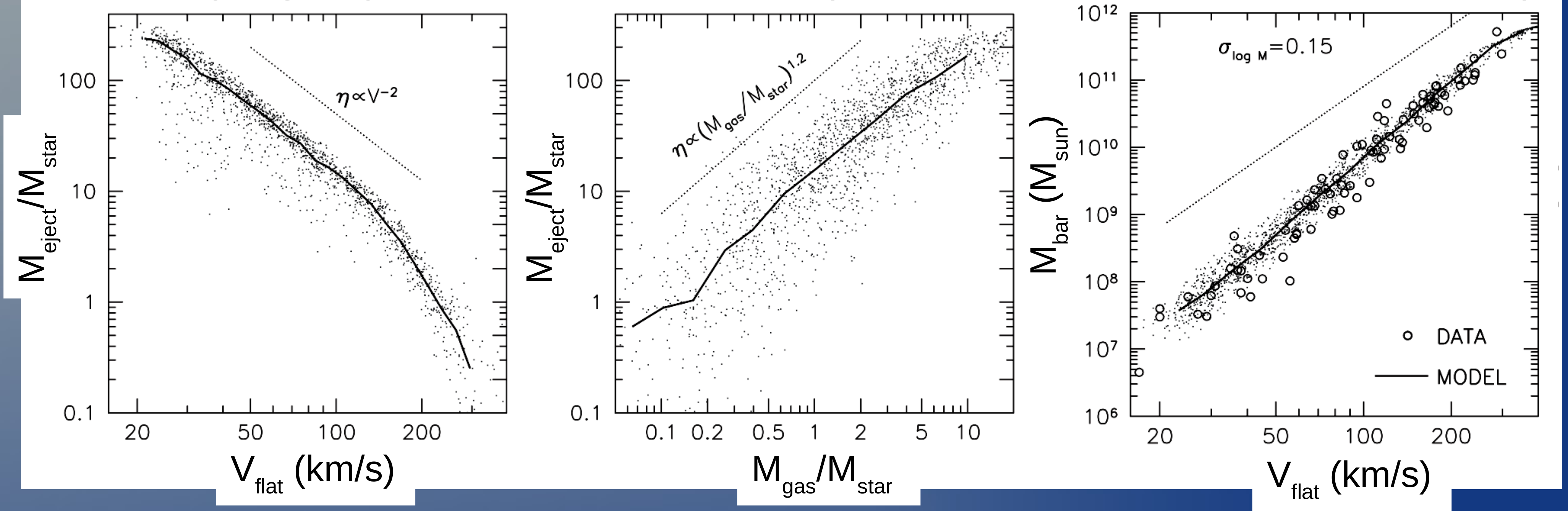


Basic Idea: Feedback eject more baryons from low-mass galaxies

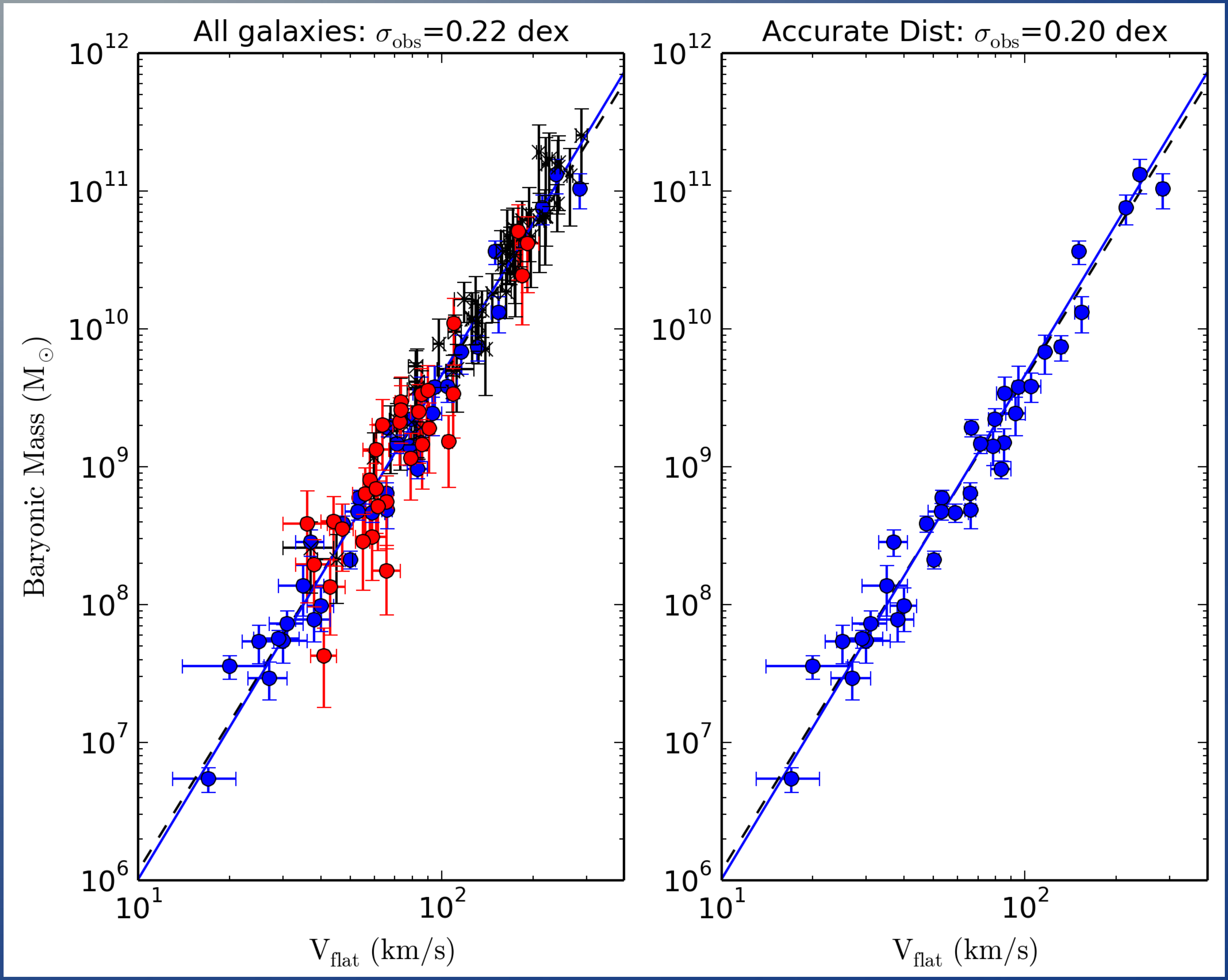
Conceptual Problems:

- <u>Minimum</u> intrinsic scatter = 0.15 dex

  (mostly driven by mass-concentration relation of DM halos)

- Does stellar feedback really works in this way?

Intrinsic Scatter on the BTFR



$\sigma_{obs} \sim 0.2$ dex
$\sigma_{int} \sim 0.1$ dex

σ_{int} is formally below ΛCDM lower limit!

$M_{bar} \propto Dist^2$

70% sample: Dist from V_{sys} & flow models

30% sample: Good Dist from Ceph or TRGB

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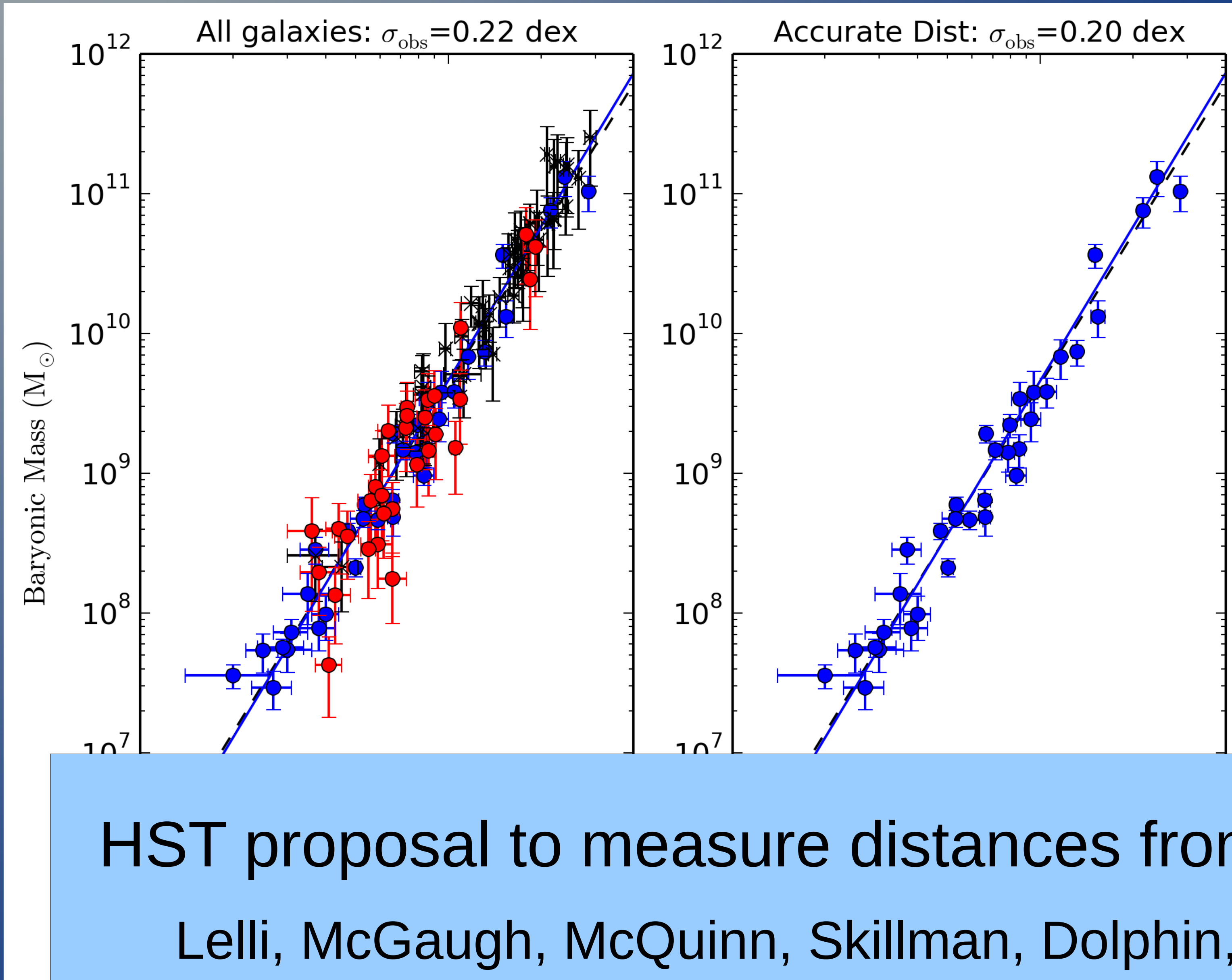

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70% sample:
Dist from V_{sys}
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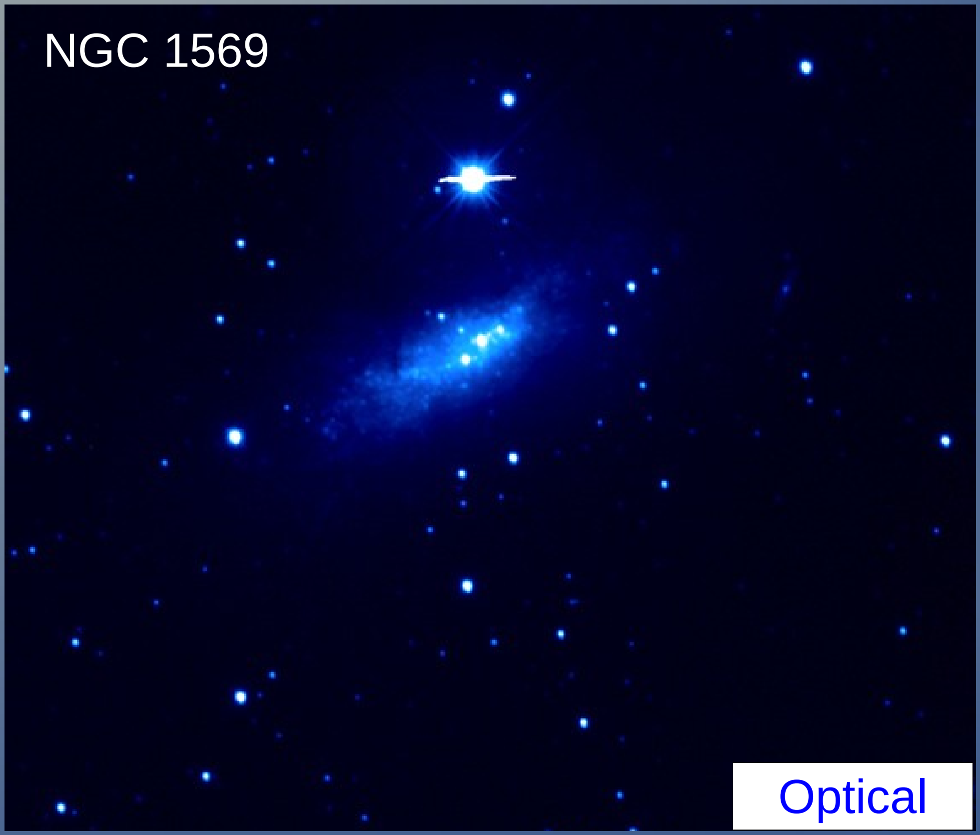
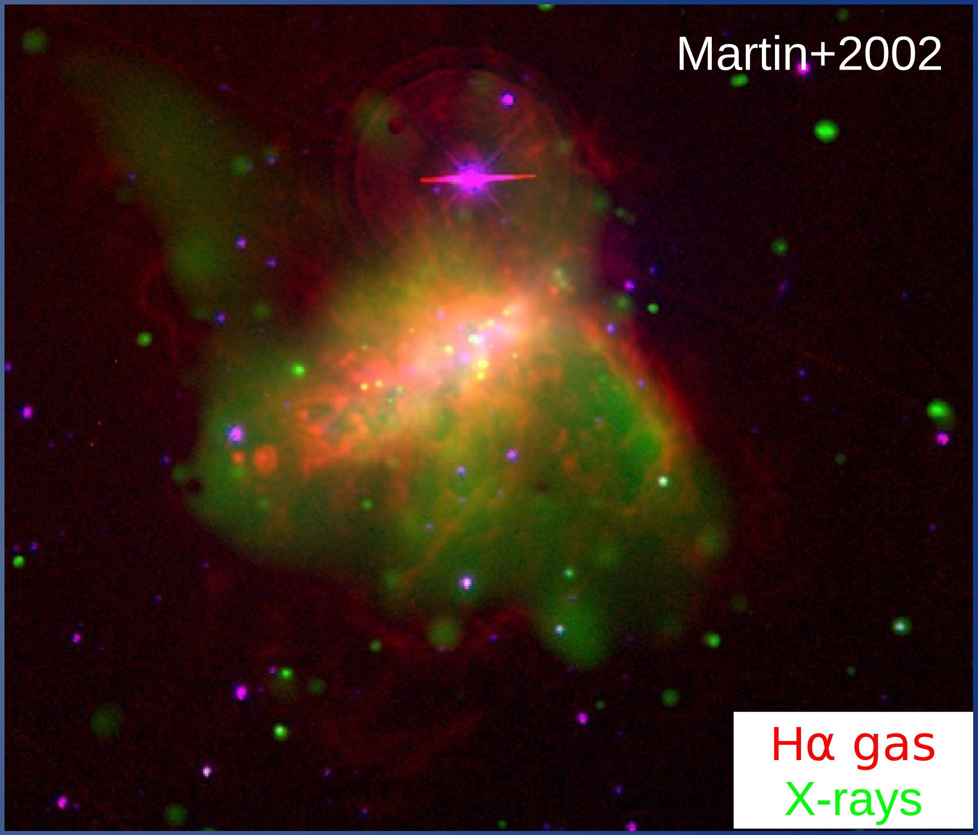
HST proposal to measure distances from the TRGB.

Lelli, McGaugh, McQuinn, Skillman, Dolphin, Schombert

Stellar Feedback in Starburst Dwarfs



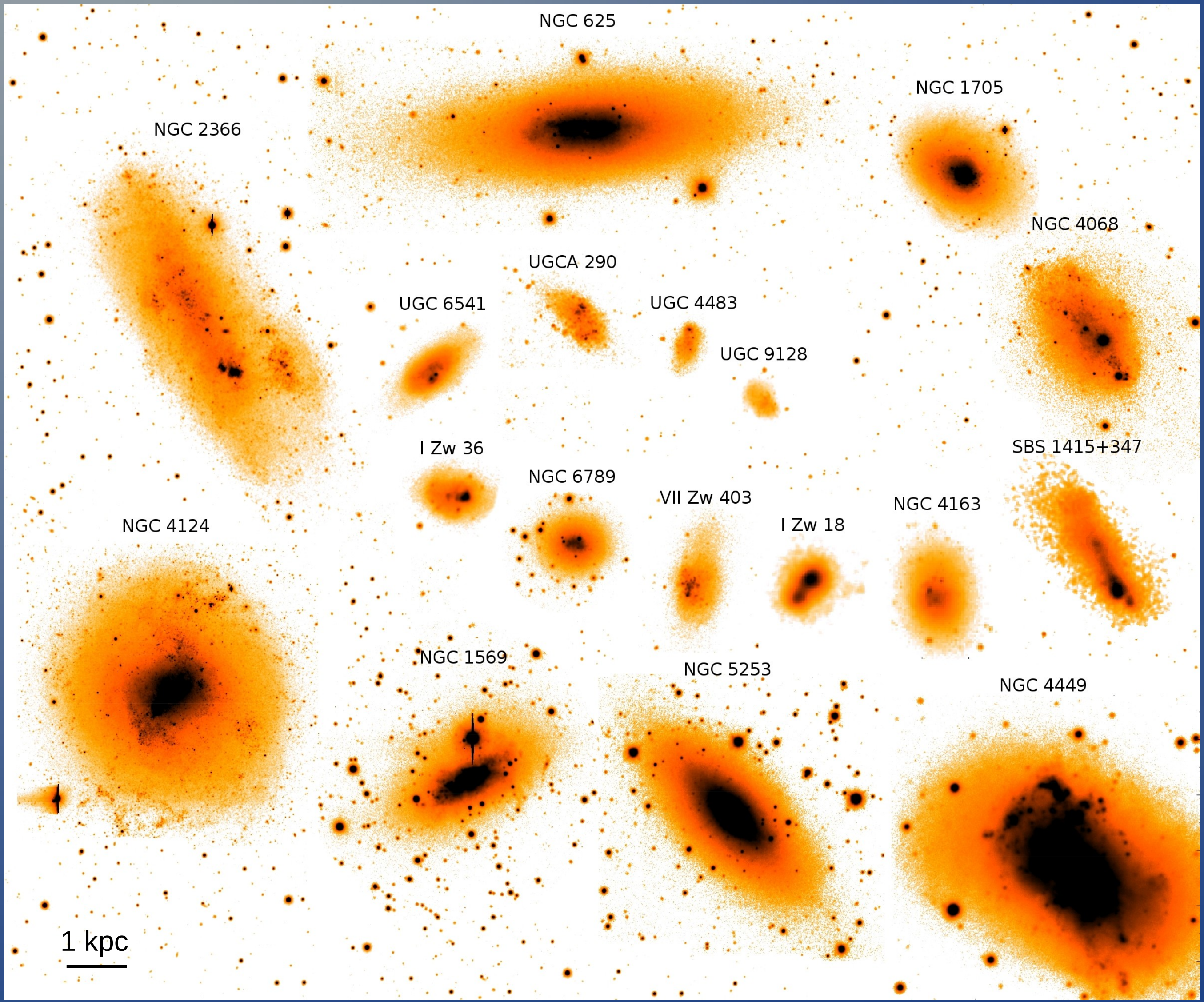


- Velocity of the ionized gas does *not* exceed V_{esc}

  (e.g. Martin 1996, 1998; Schwartz & Martin 2004; van Eymeren+2009, 2010)

- Mass of the hot gas ~1% M_{HI} (e.g. Ott+2005)

Sample of 18 Starburst Dwarf Galaxies



Resolved into single stars by HST obs:

- Distance (<5 Mpc)
- Star Formation History
- $b = SFR(t_{peak}) / \overline{SFR} \geq 3$

$M_* \sim 10^7 - 10^9 M_\odot$ $R_{opt} \sim 0.5 - 5$ kpc

Lelli+2012a, 2012b, 2014a, 2014b, 2014c

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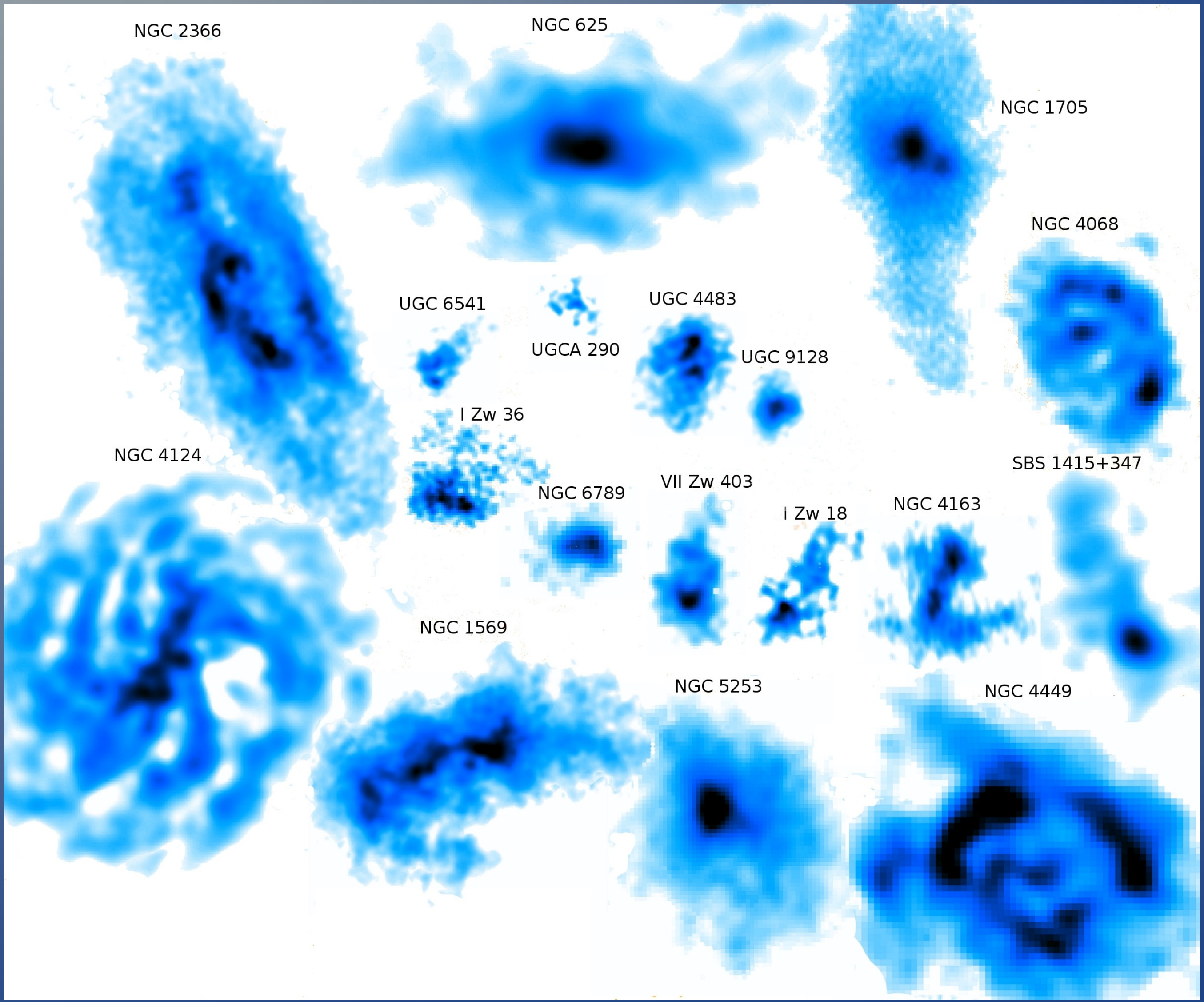

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HI observations (VLA, WSRT, ATCA):

- HI distribution
- HI kinematics

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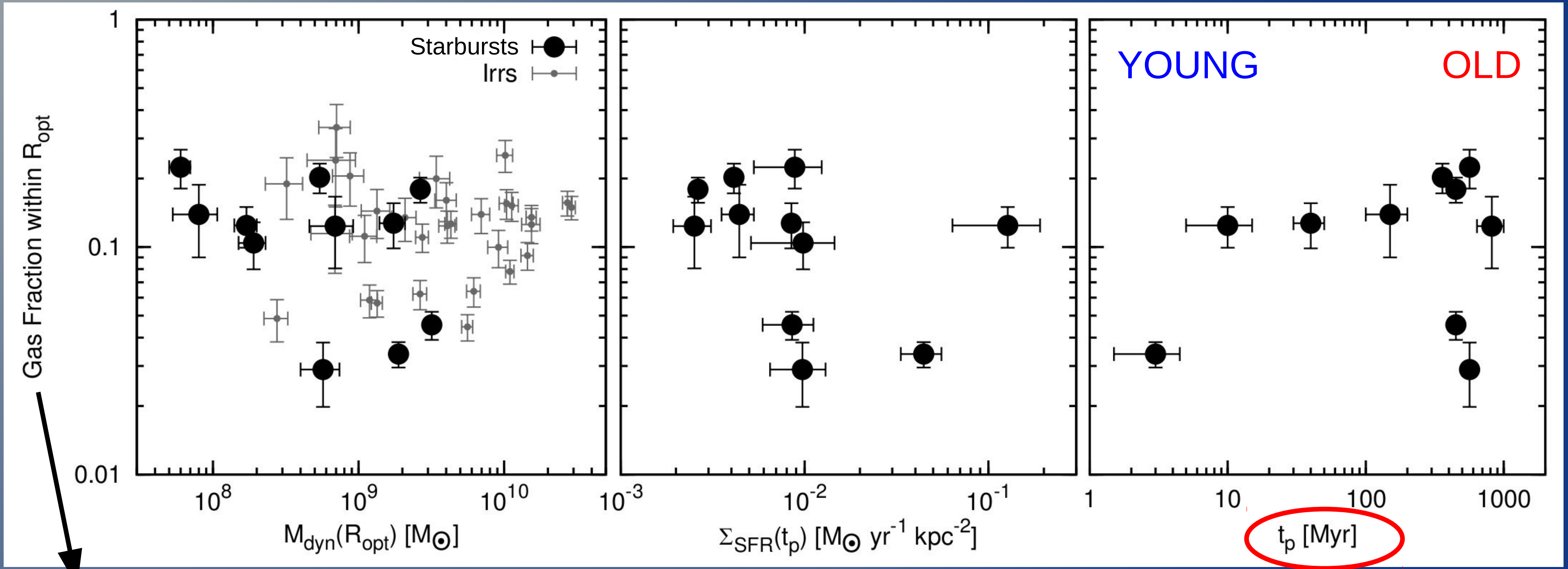
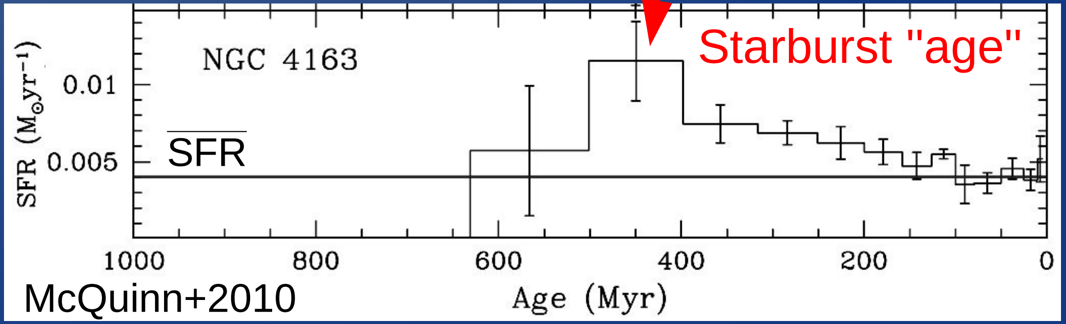
Gas Fractions: Starburst Dwarfs vs Irrs



$f_{gas} = M_{HI}/M_{dyn}$ within R_{opt} (Irrs from Swaters+2009)

Similar f_{gas} as typical Irrs

Star-Formation History



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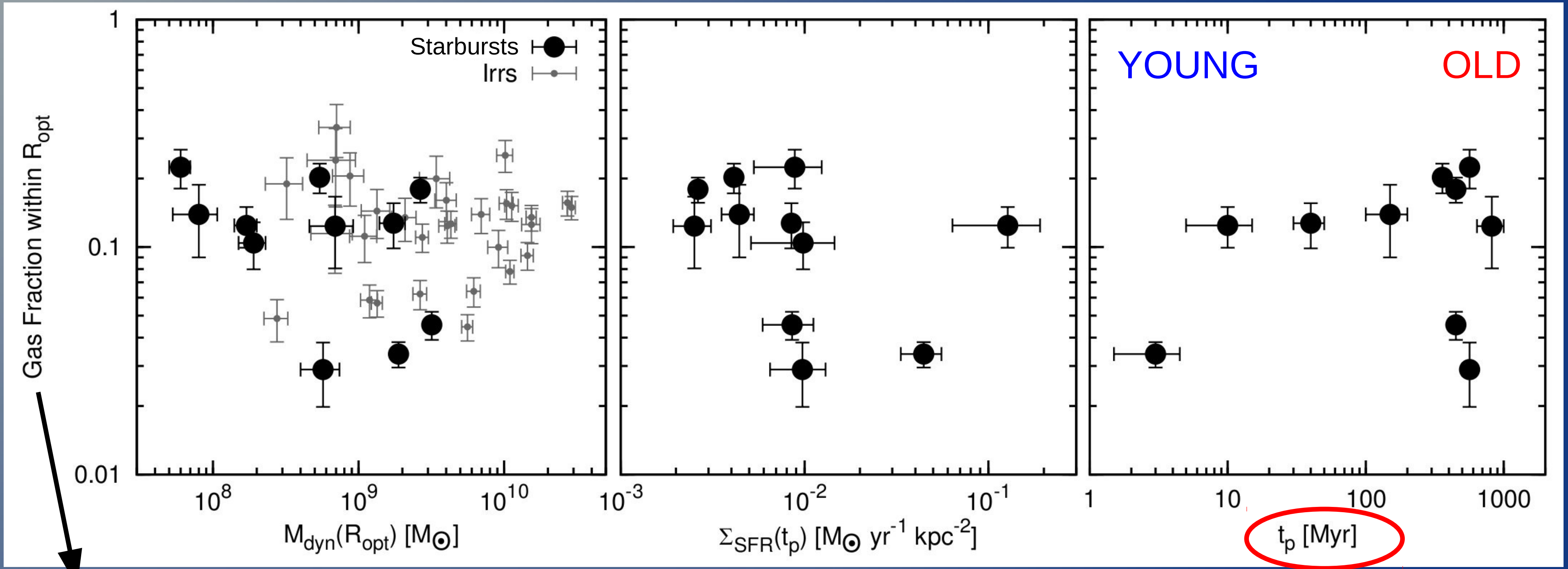

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Similar f_{gas} as typical Irrs

No evidence for *massive* gas outflows!

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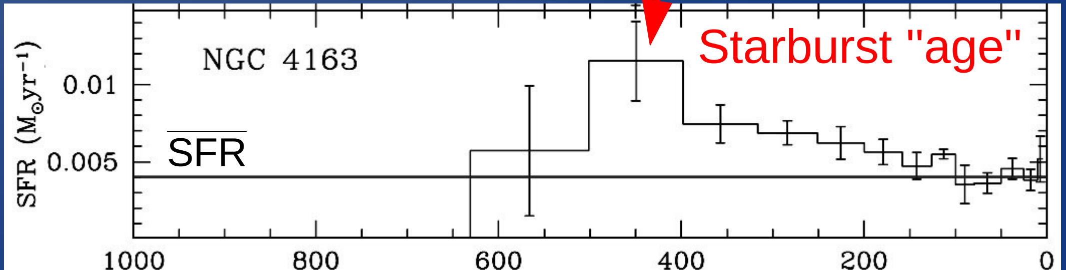

McQuinn+2010

Summary on BTFR

- Scaling Law extending for ~5 dex in M_{bar}
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  - Crucial problem for ΛCDM (independent on baryon physics)

- Origin unclear. Massive gas outflows?

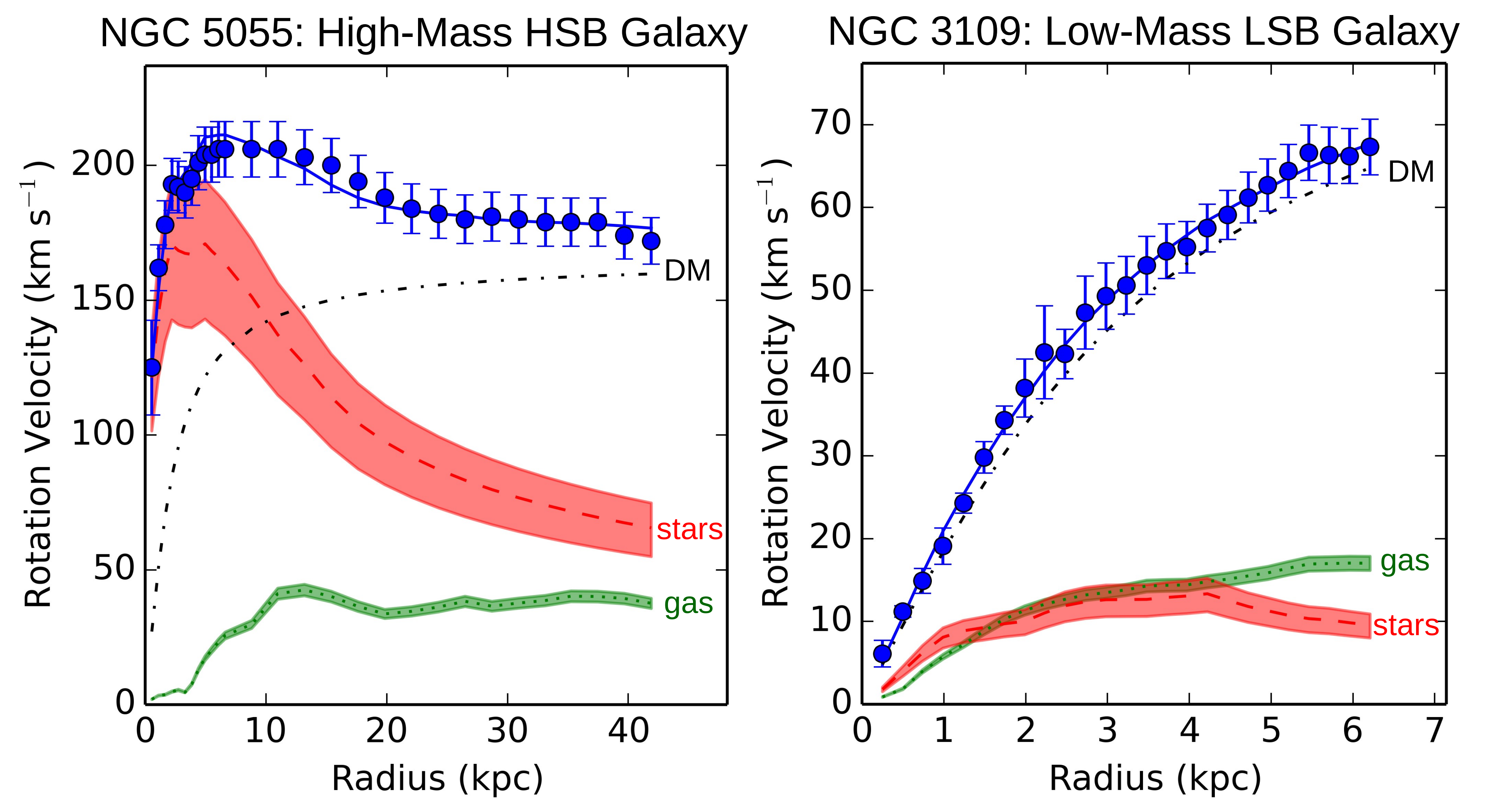
  - Stellar feedback does NOT work in this way at z=0.

II. Local counterparts of BTFR:

Linking distribution of baryons & DM

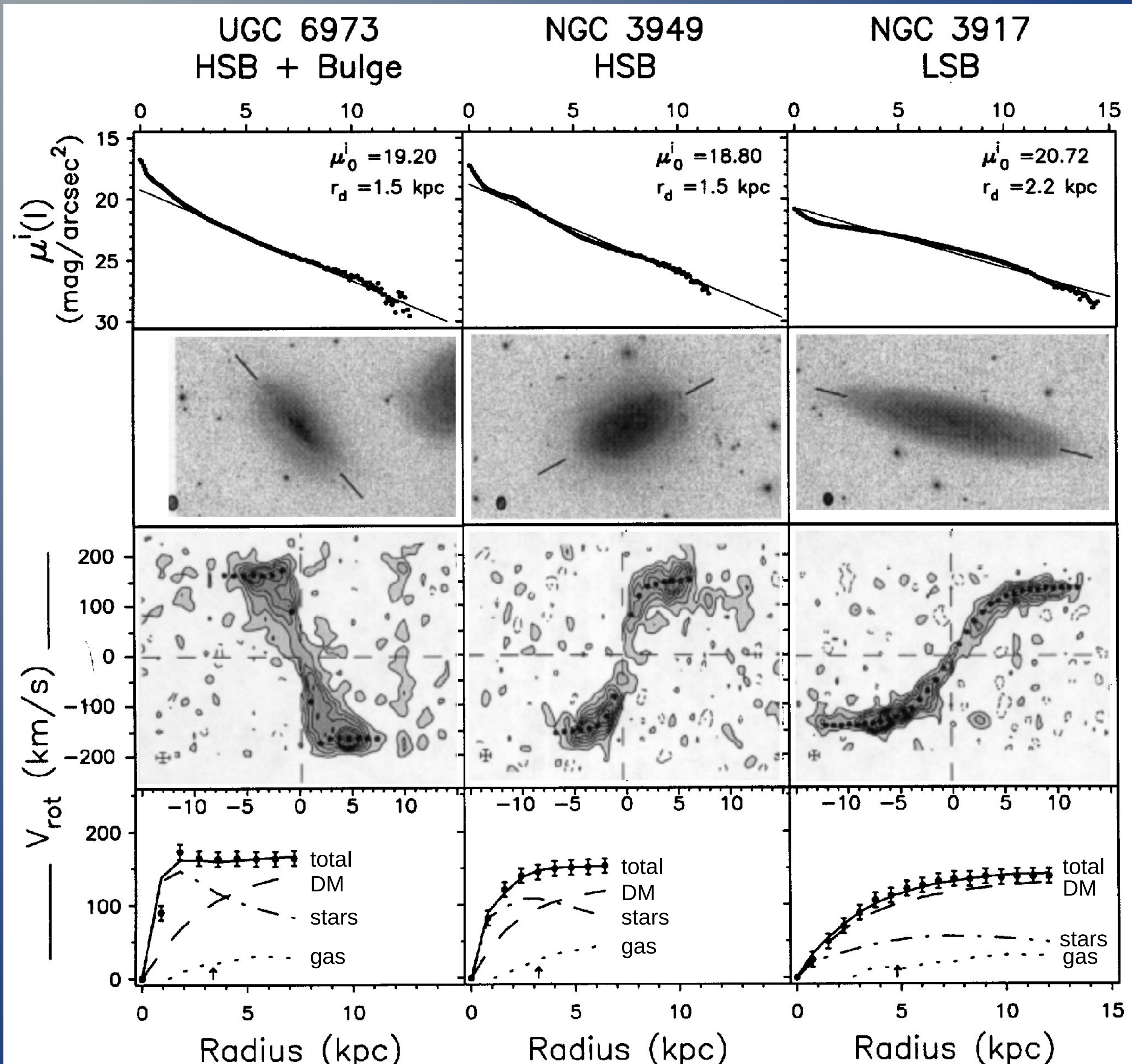
Mass Models for Disc Galaxies

$$V^2_{obs} = M_*/L_K \times V^2_{stars} + V^2_{gas} + V^2_{DM}(\rho_0, r_s)$$



Lelli et al. (in prep)

A galaxy triplet on the BTFR

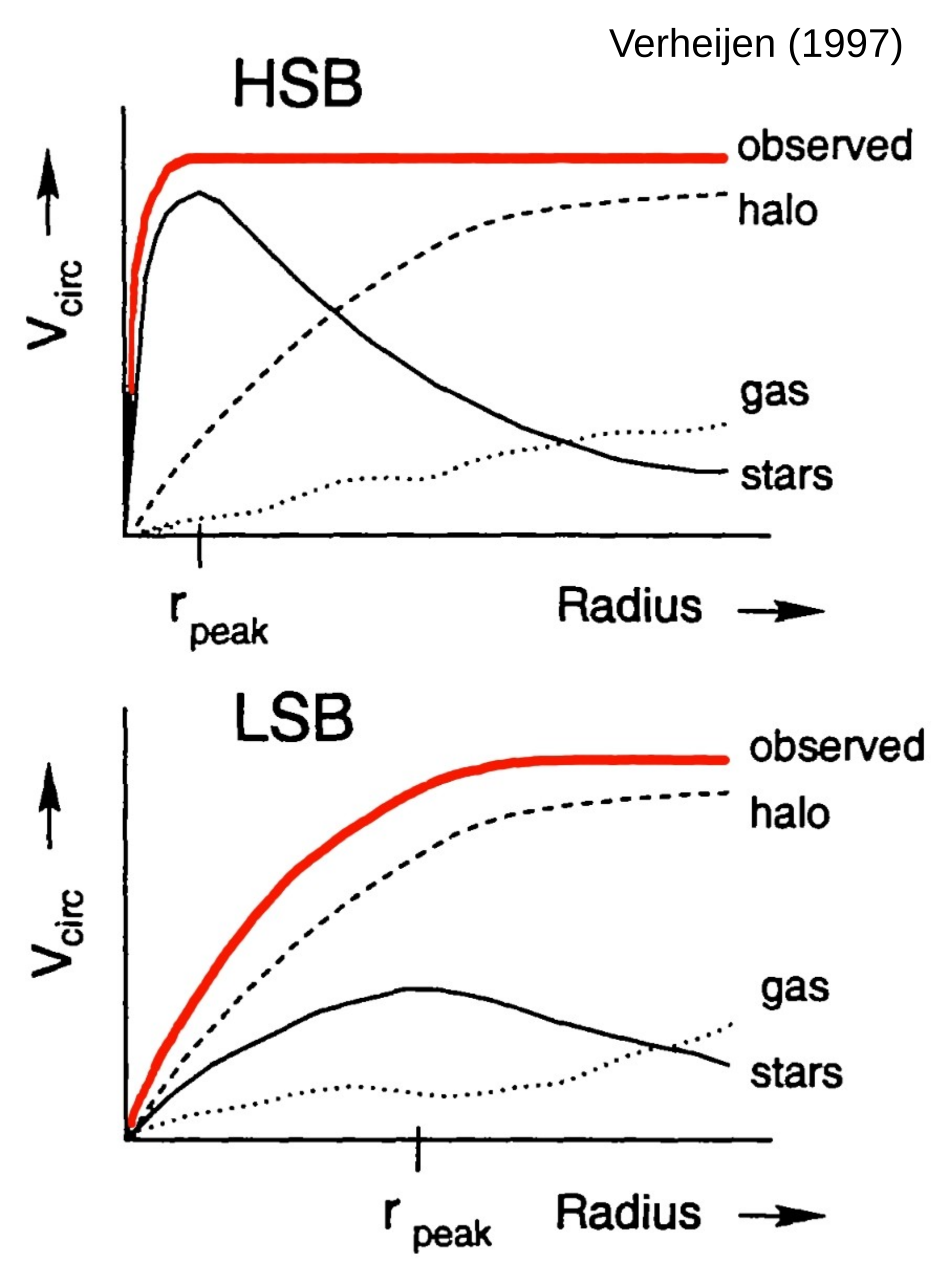


Same M_{bar} & V_{flat} but different SB

Different Rotation Curves & Mass Models

Tully & Verheijen (1997)

The HSB – LSB dichotomy



HSB galaxies:

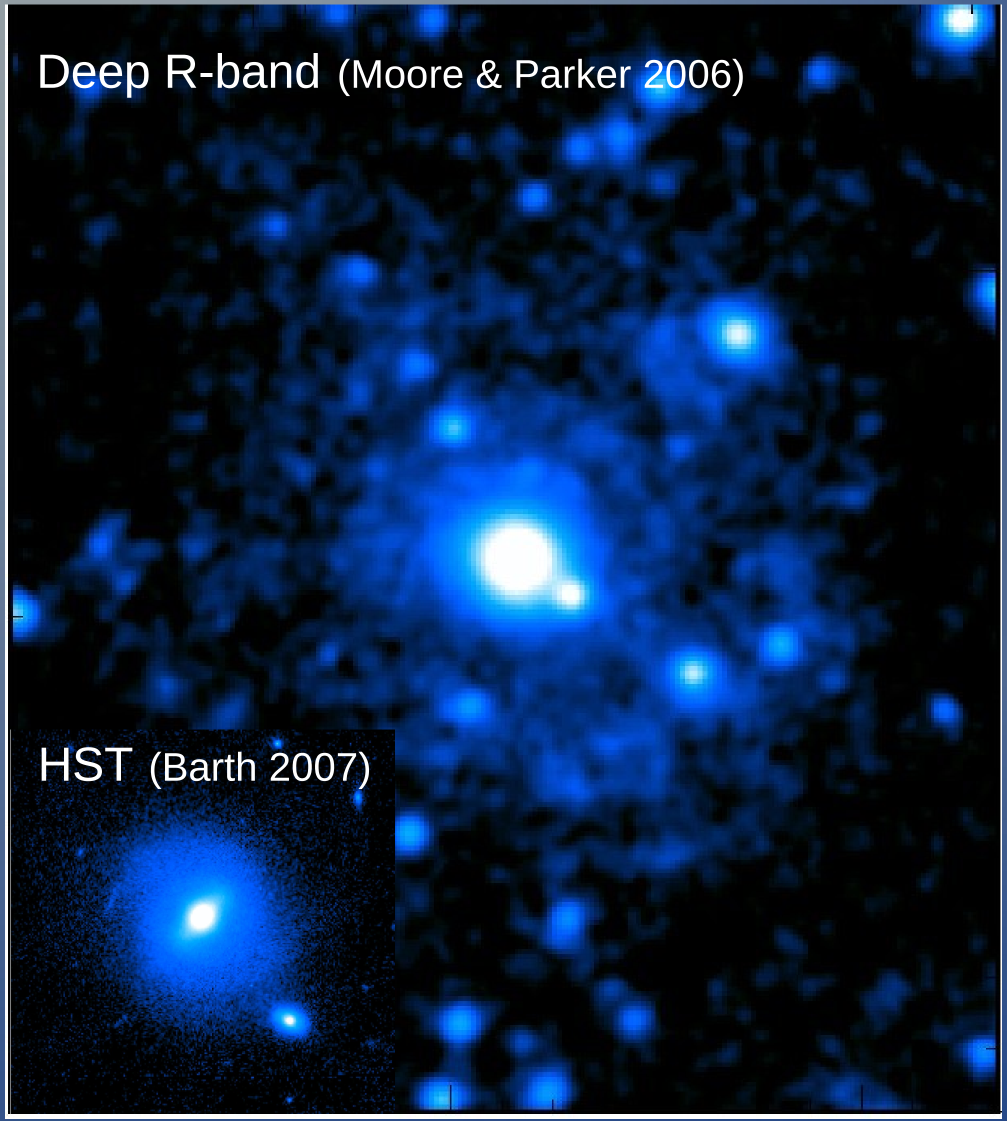
- Steeply rising rotation curves
- Maximum disk hypothesis

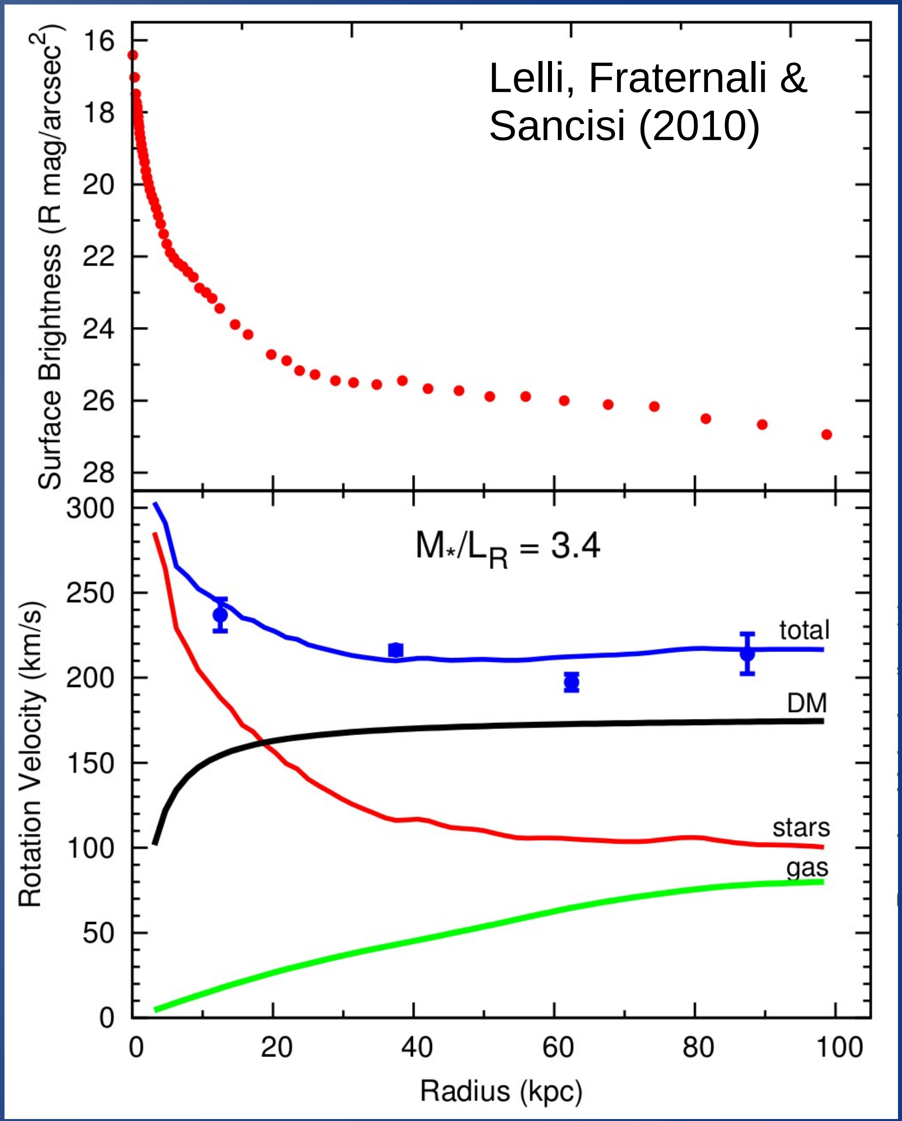
→ Baryons dominate inner galaxy regions

LSB galaxies:

- Slowly rising rotation curves
- DM dominates everywhere

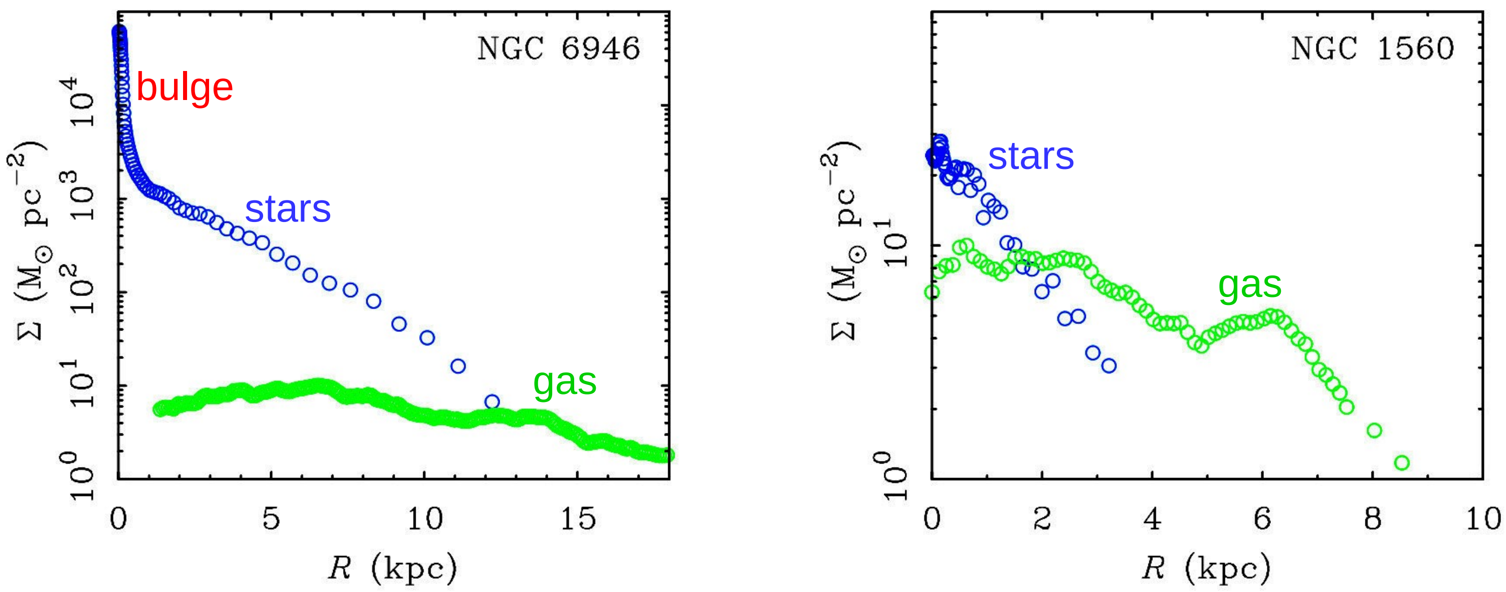
Malin 1: double HSB-LSB structure



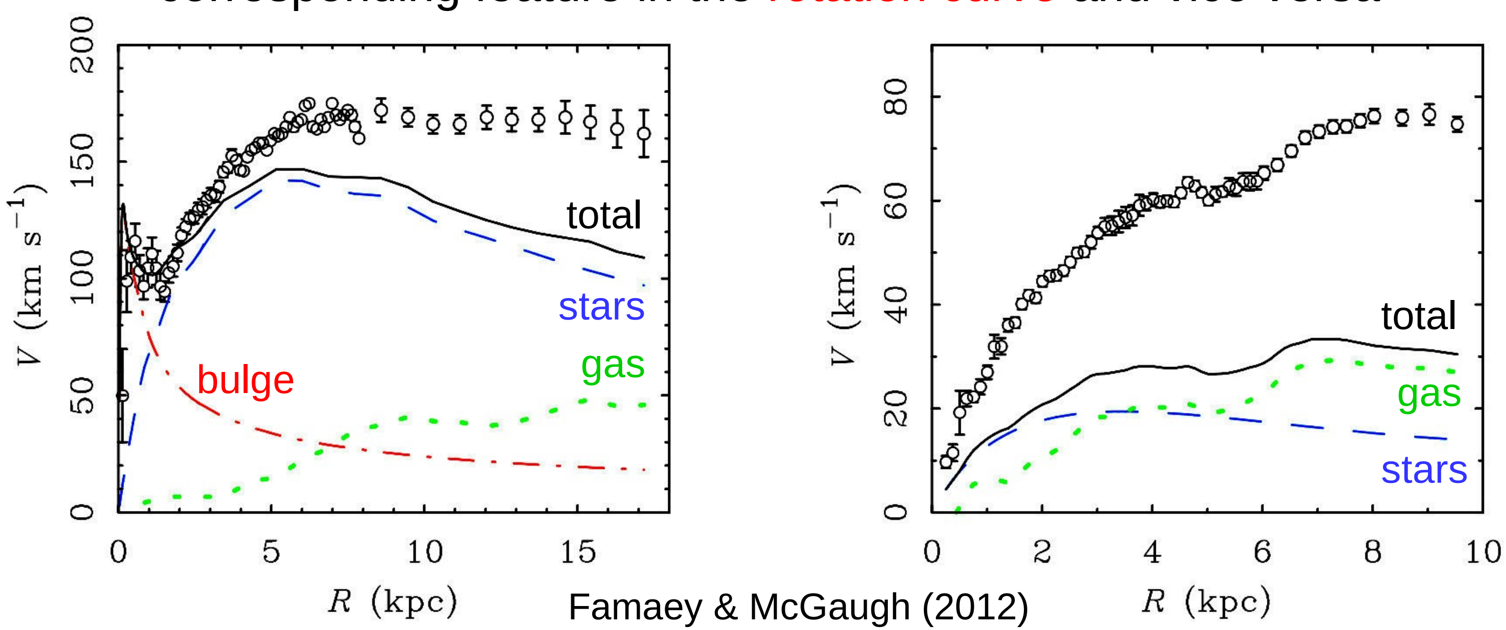


Renzo’s Rule: "For any feature in the luminosity profile there is a corresponding feature in the rotation curve and vice versa" (Sancisi 2004)

The Rule applies to both stars & *gas*



"For any feature in the luminosity profile of a galaxy there is a corresponding feature in the rotation curve and vice versa"



Famaey & McGaugh (2012)

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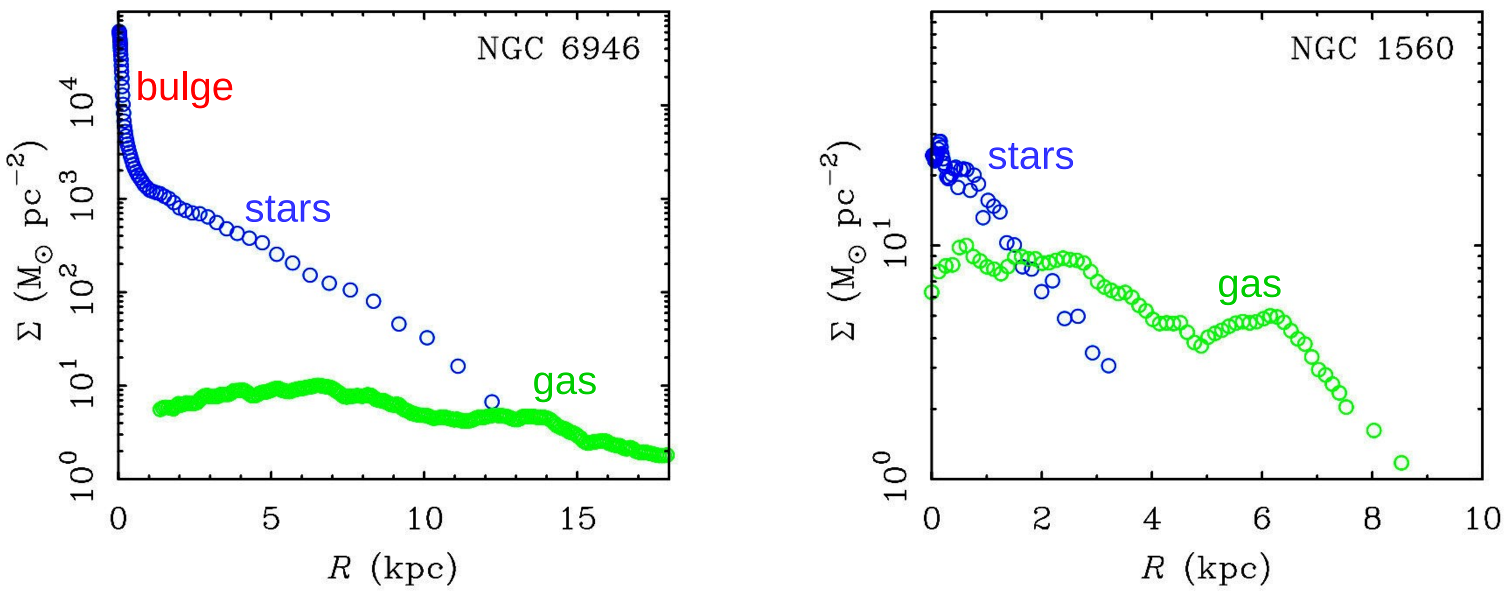
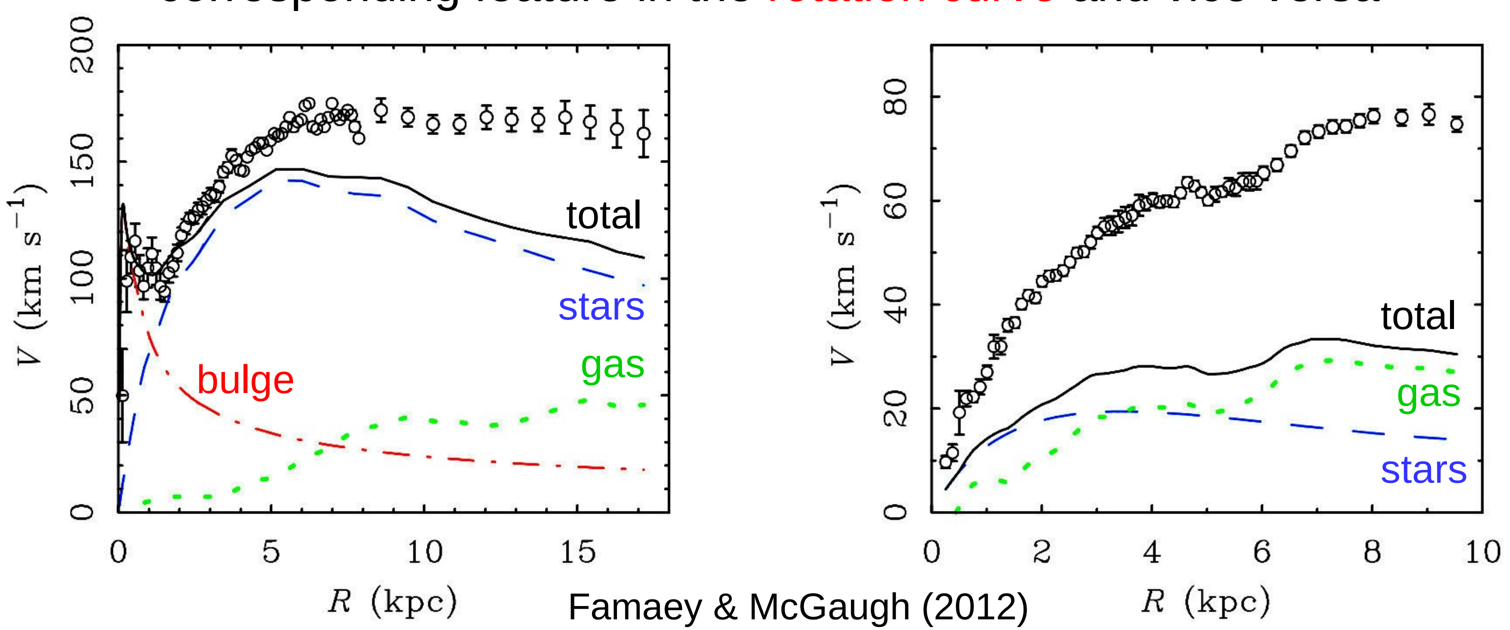
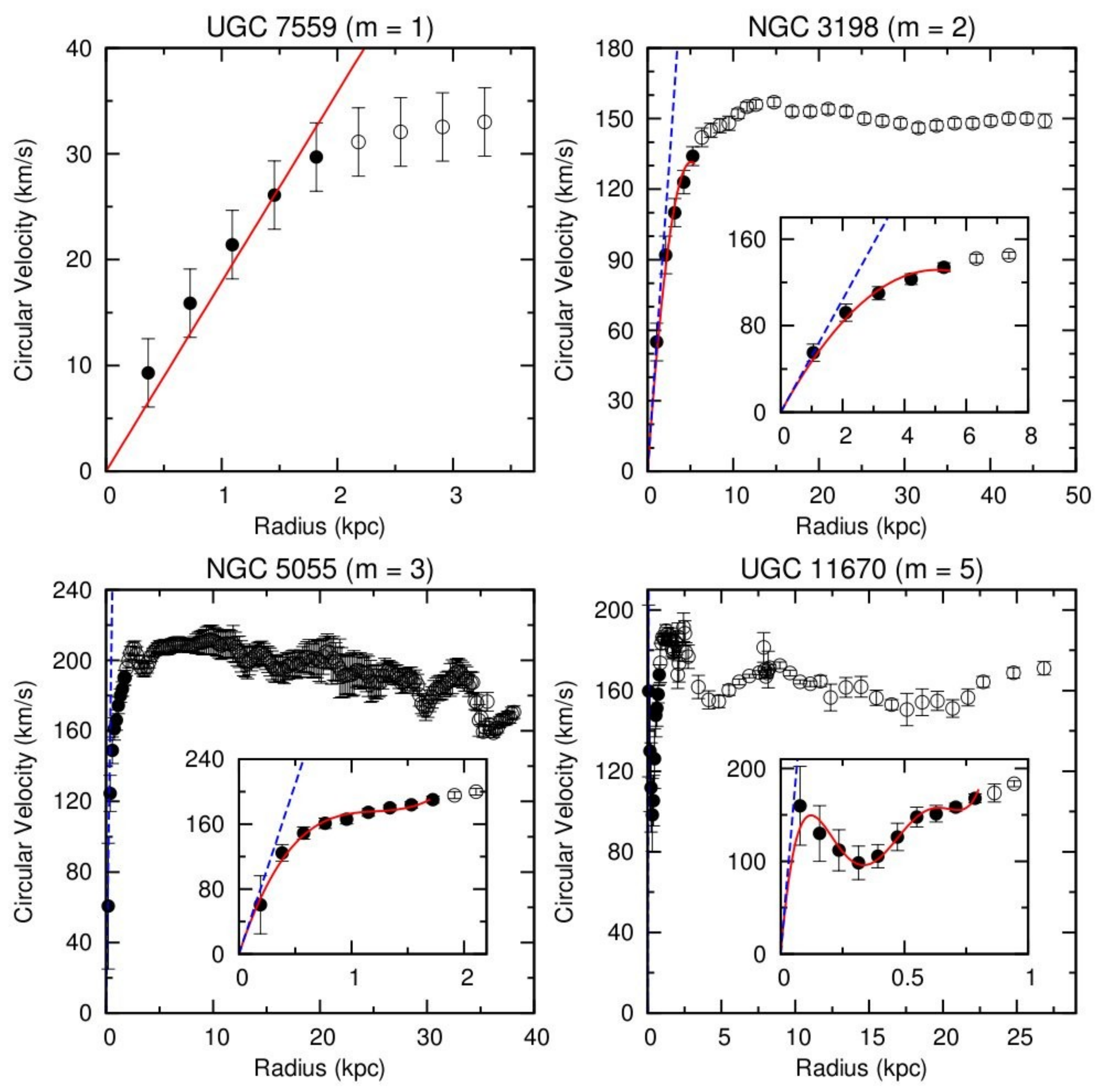


"For any feature in the baryonic mass profile of a galaxy there is a corresponding feature in the rotation curve and vice versa"



Famaey & McGaugh (2012)

Inner Circular-Velocity Gradient



$$V(R) = \sum_{n=1}^{m} a_n \times R^n$$

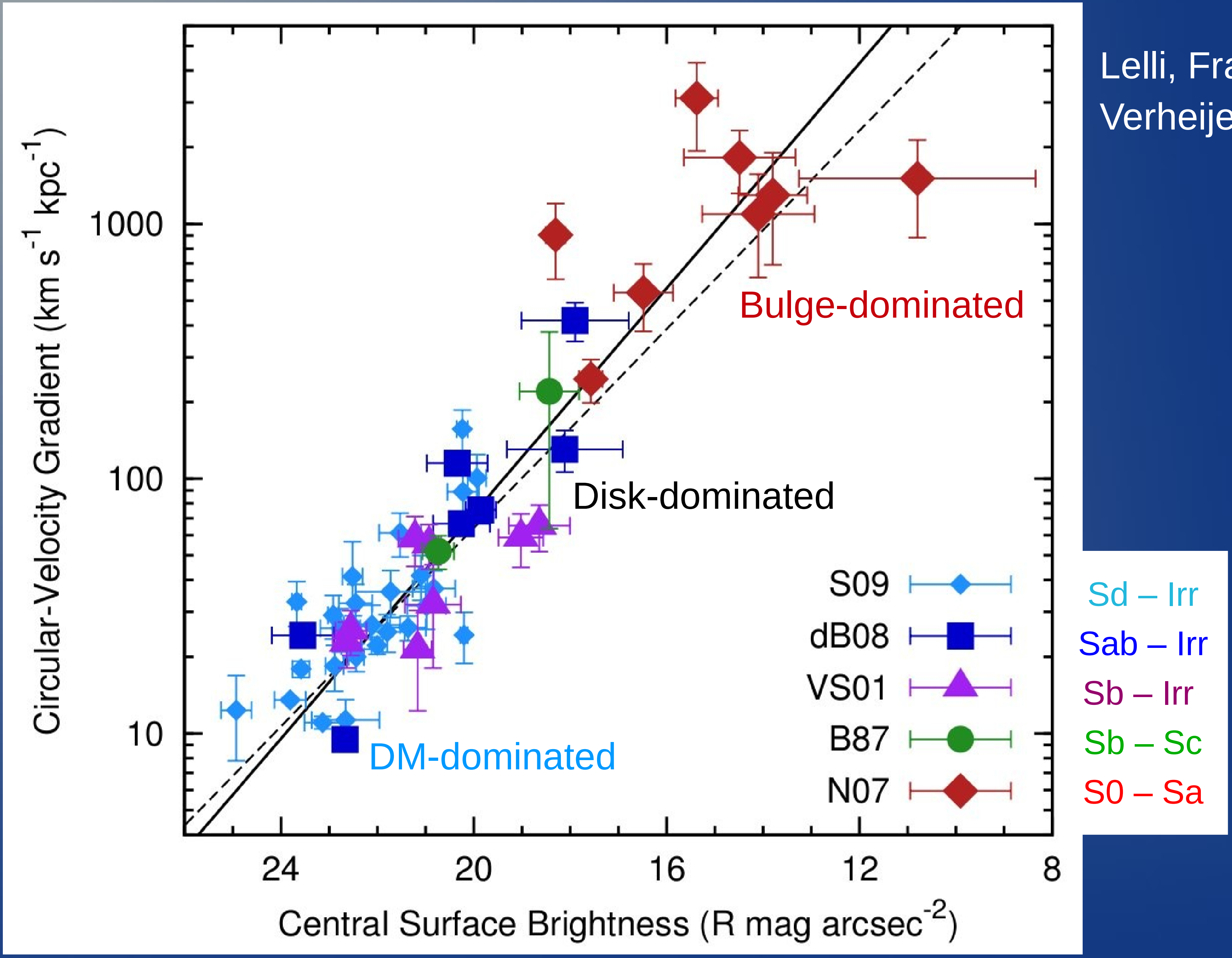
$$a_1 = \lim_{R \to 0} dV/dR.$$

Lelli, Fraternali & Verheijen (2013)

5 Galaxy Samples:

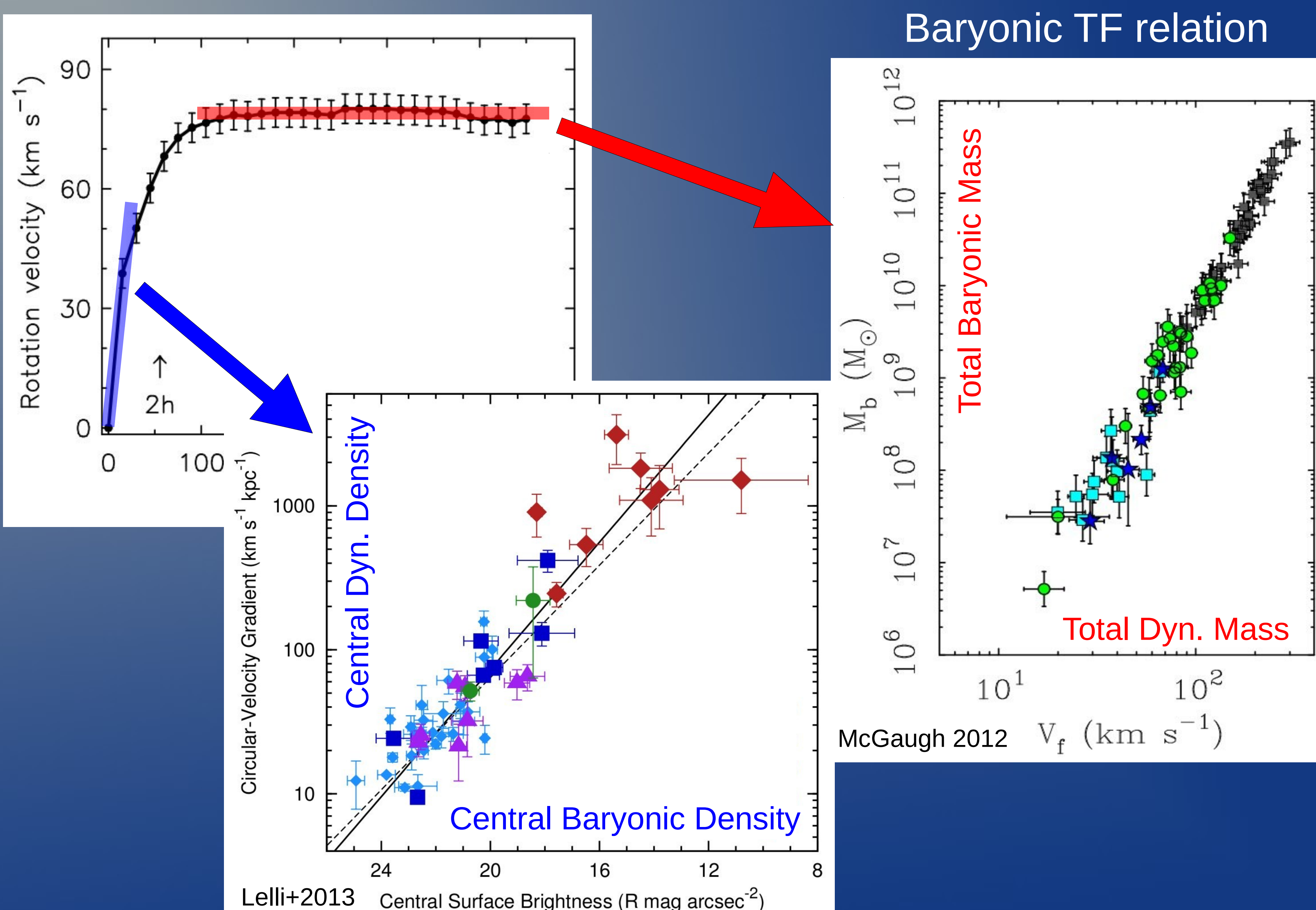
- Noordermeer 06: S0 – Sa
- de Blok+2008: Sab – Irr
- Begeman 1987: Sb – Sc
- Verheijen 1997: Sb – Irr
- Swaters 1999: Sd – Irr

Inner Velocity Gradient *vs* Central SB



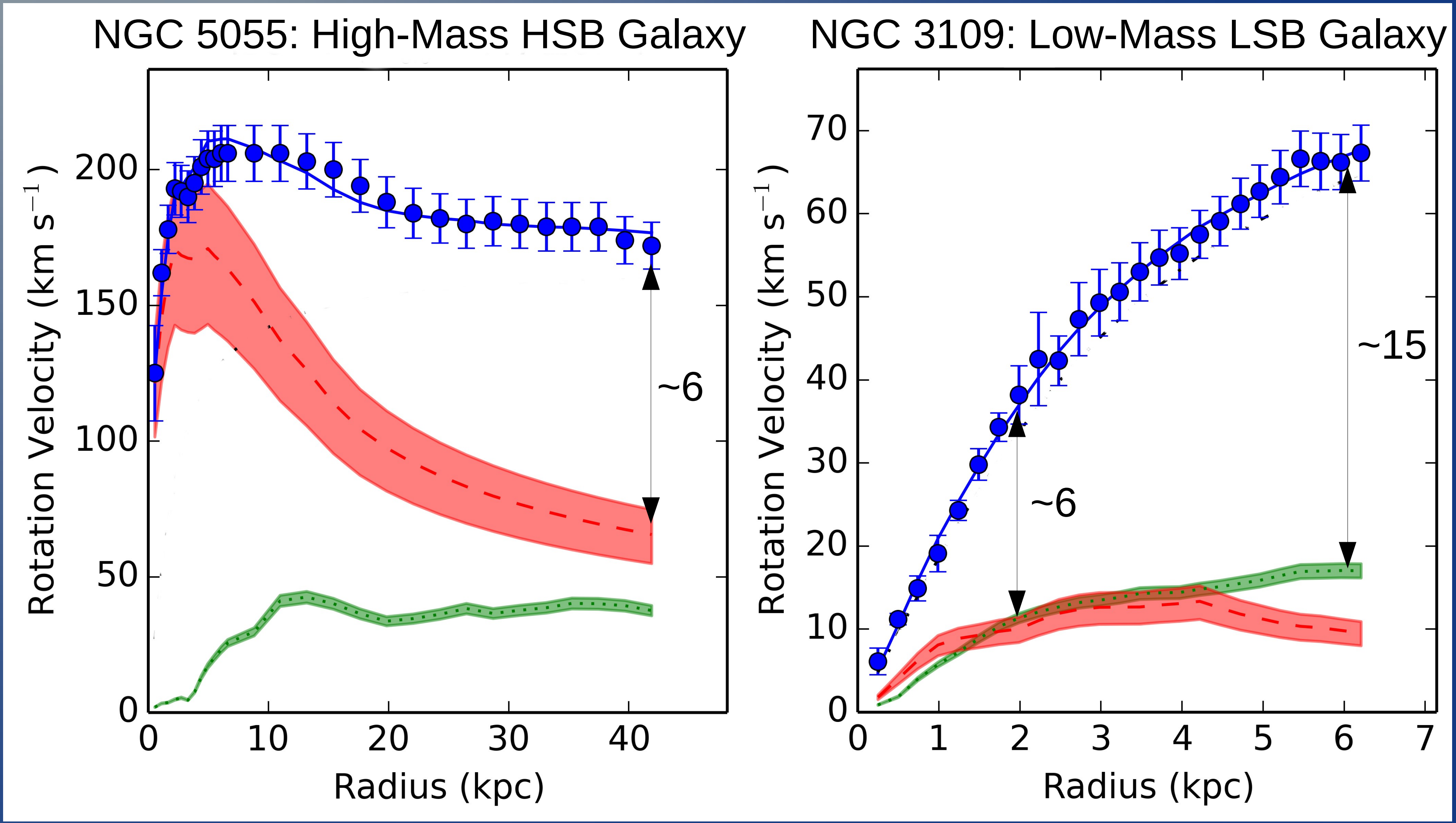
Lelli, Fraternali & Verheijen (2013)

Scaling Relations for Rotating Galaxies



The link exists also at a local level...

Mass Discrepancy = $V^2_{obs} / V^2_{bar} \sim M_{tot}(R) / M_{bar}(R)$



Lelli et al. (in prep)

Mass Discrepancy – Acceleration Relation

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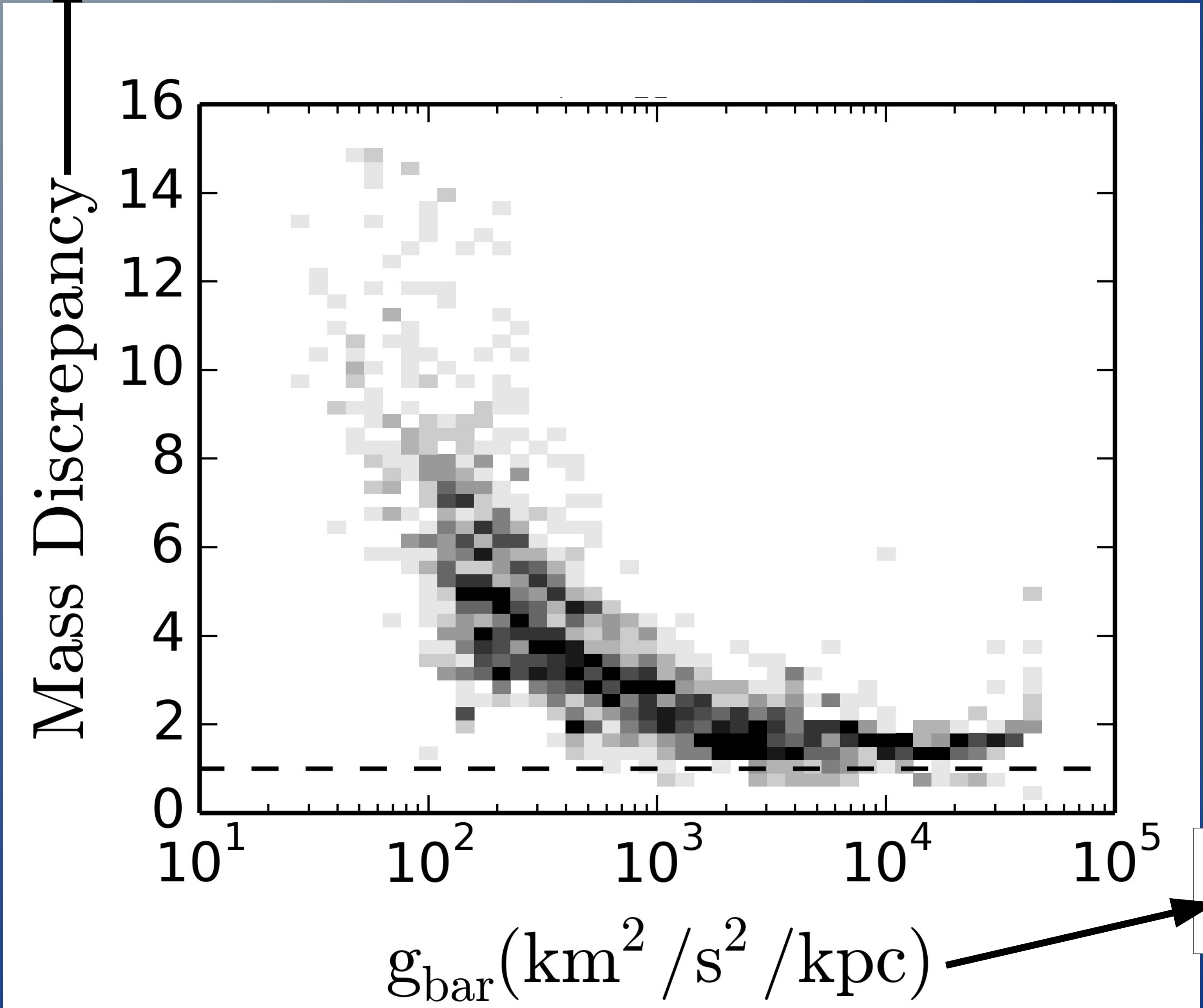

~2000 individual measurements at different radii

Lelli et al. (in prep.)
+ McGaugh (2004)

$V^2_{bar}/R = -\nabla\Phi_{bar}$

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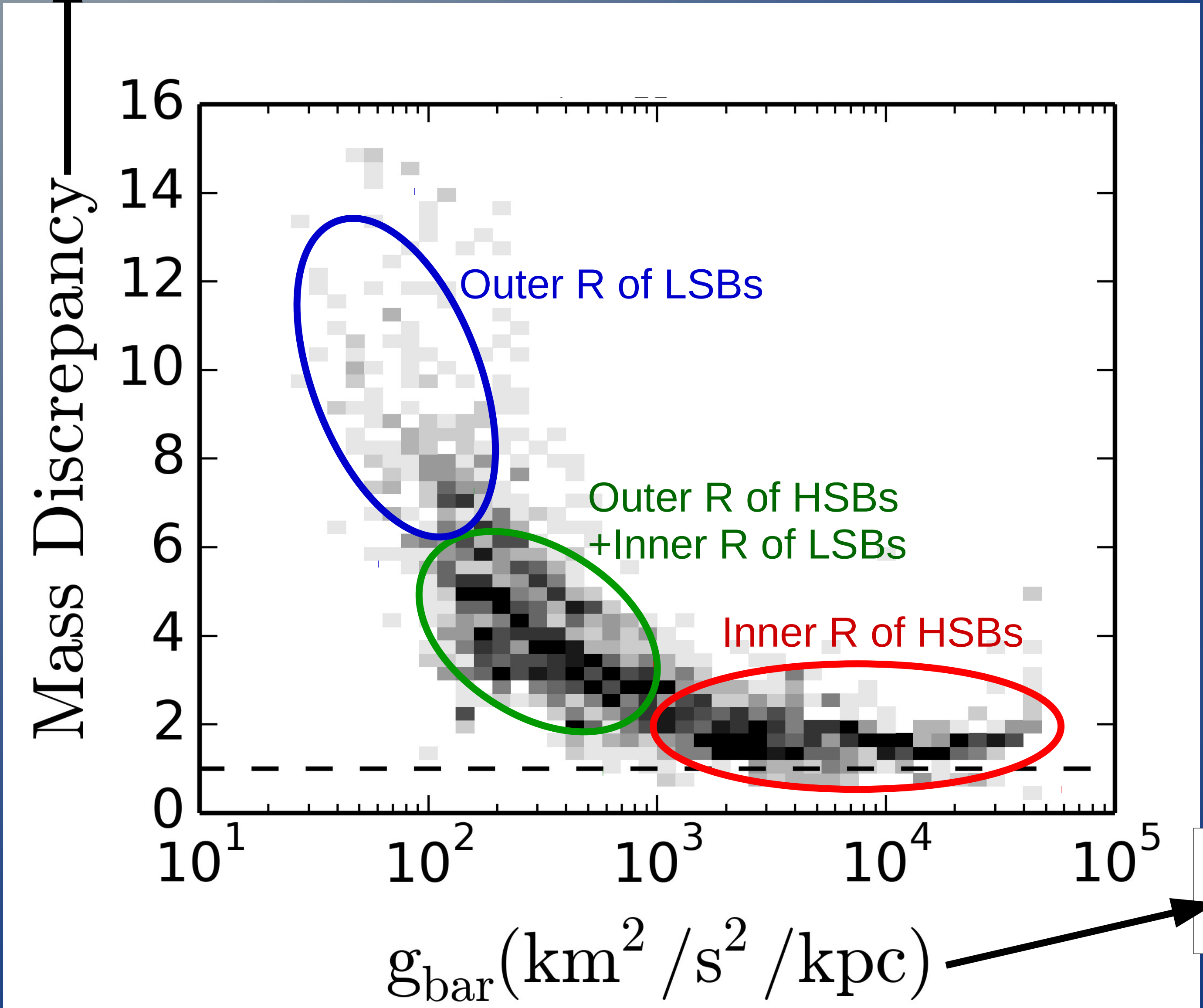

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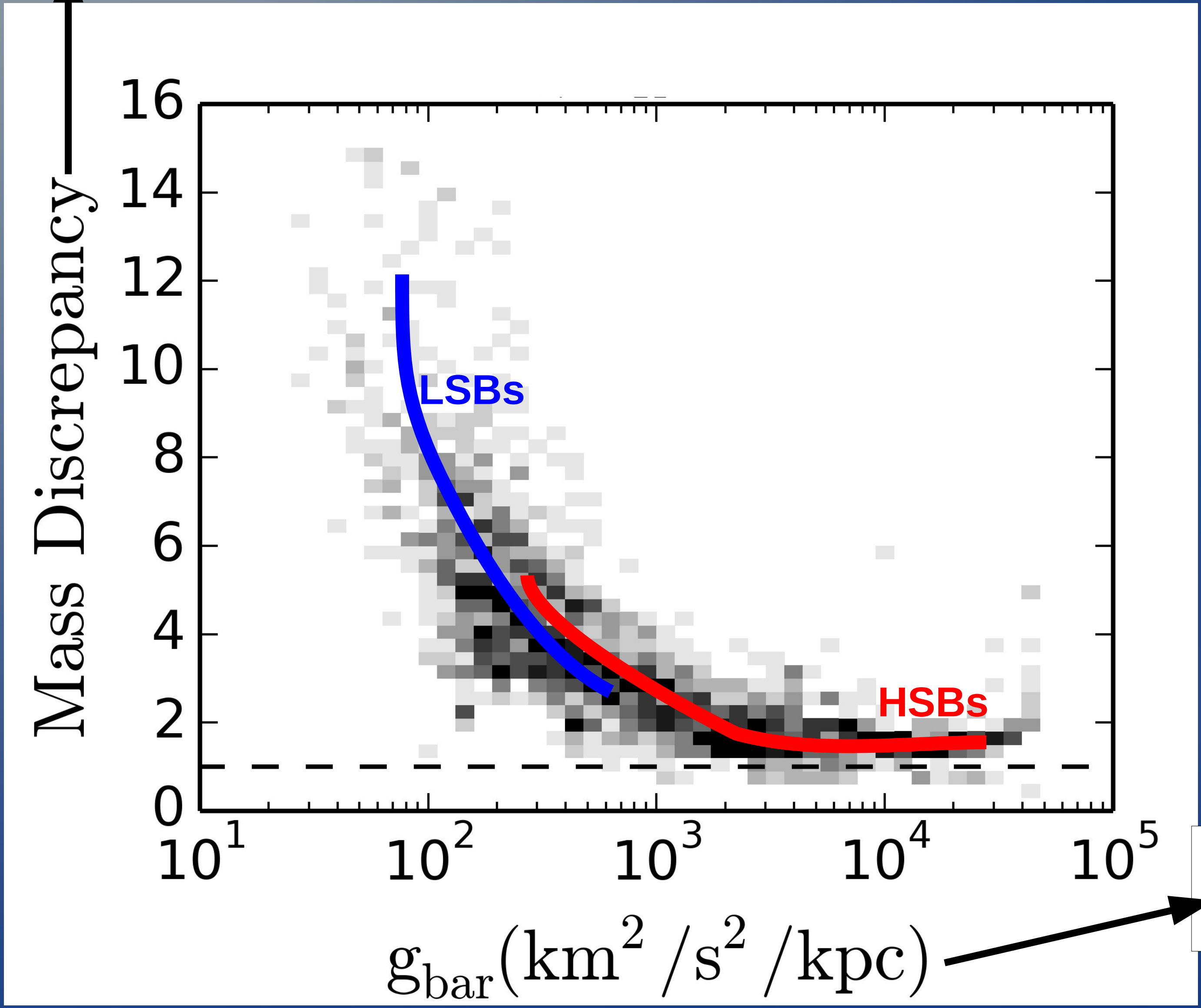

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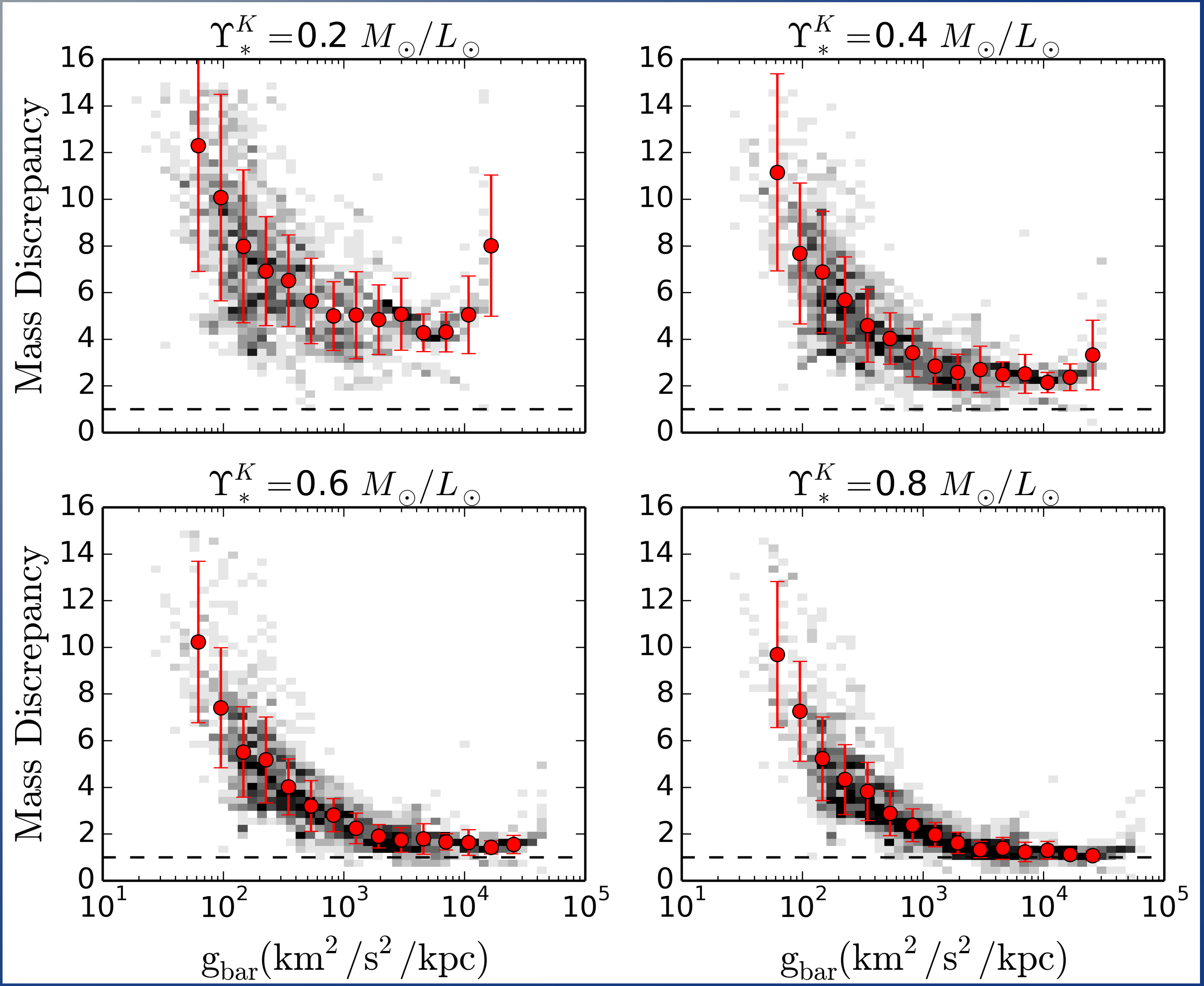
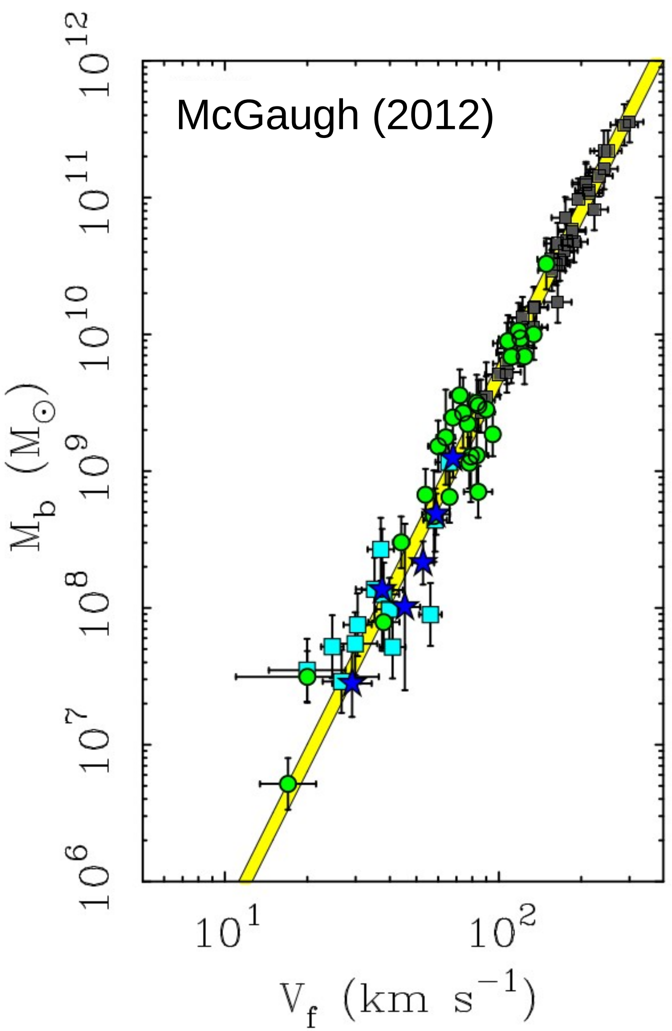
MD-Acc Relation using different M_*/L



Empirical laws explained by MOND

Baryonic Tully-Fisher Relation



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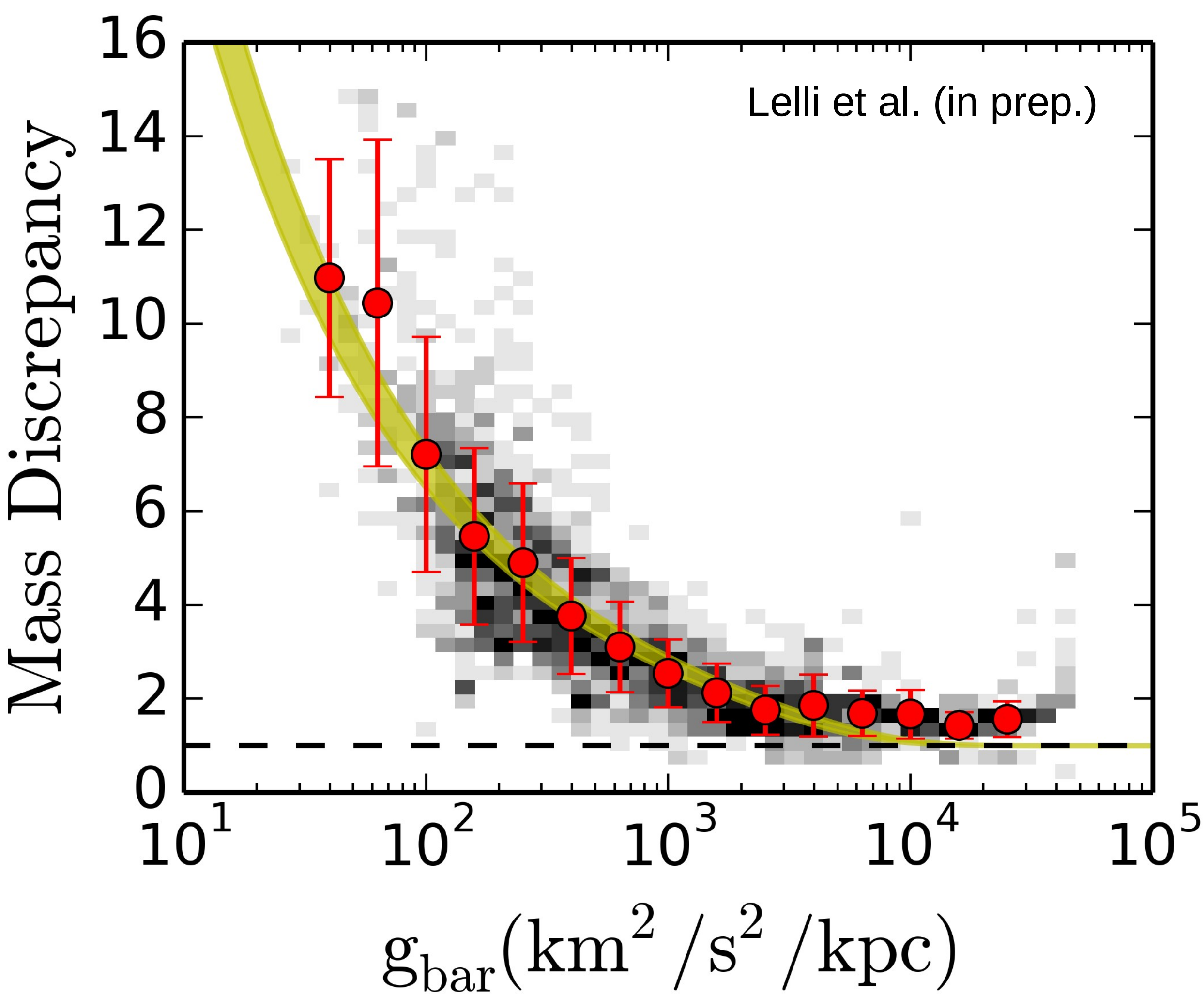


Yellow bands: predictions by Moti Milgrom (1983) using scale-invariant dynamics (MOND)

Conclusions

Baryons and DM are tightly coupled in galaxies:

- Global relation: M_{bar} – V_{flat} (BTFR)

  Total baryonic mass – Total dynamical mass

- Central relation: central SB – dV/dR(0)

  Central baryonic density – Central dynamical density

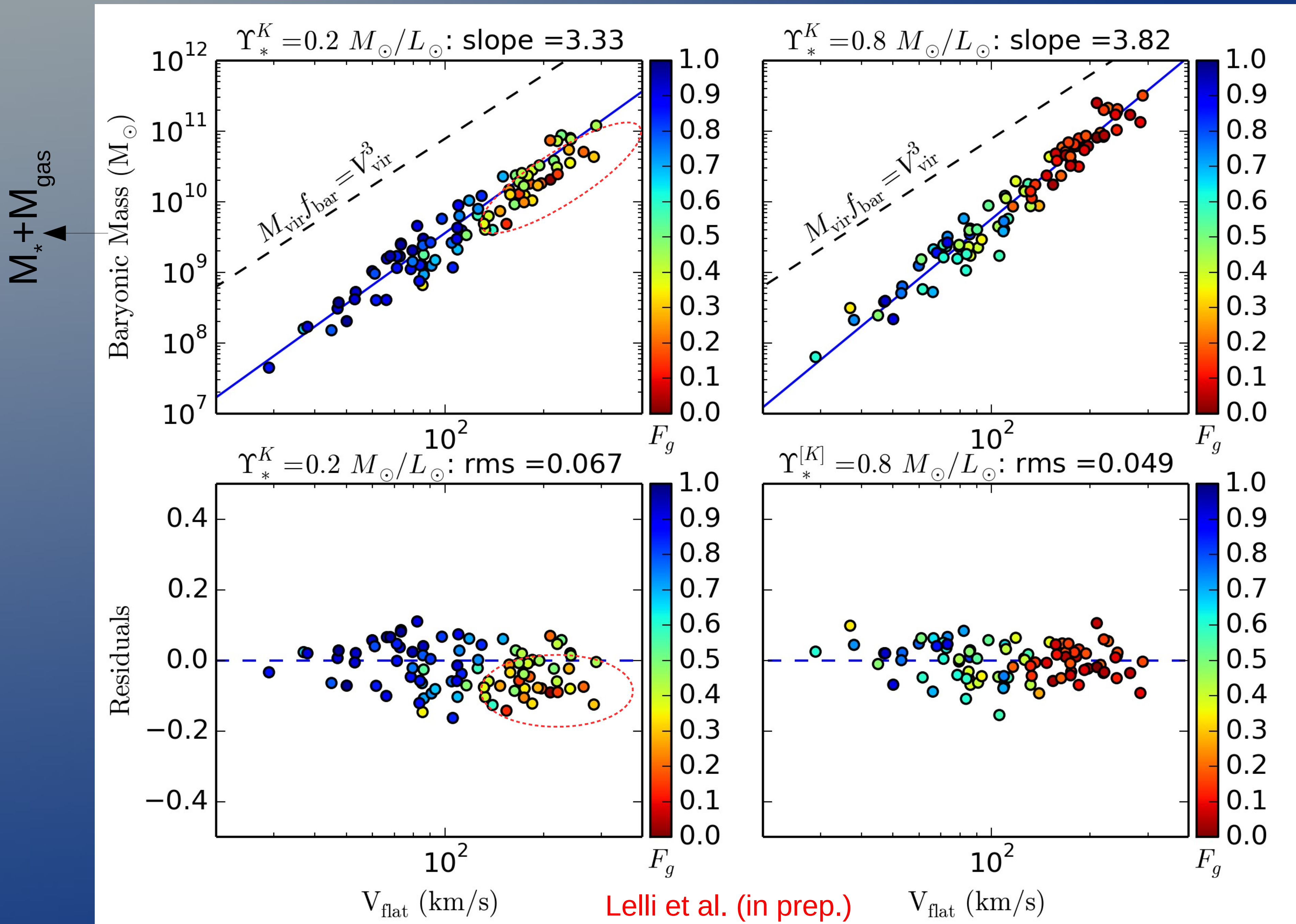
- Local relation: Mass Discrepancy – Acceleration

  Local DM excess – Baryonic gravitational force

Fine-tuning challenge for ΛCDM models!

More Slides

Fits weighting by $F_{gas} = M_{gas}/M_{bar}$



dV/dR(0)-SB relation: toy model

Expected relation:

$$\log[d_R V(0)] = -0.2\,\mu_0 + 0.5\log\left(\alpha G \frac{M_*/L}{z_0\, f_{\rm bar,0}}\right).$$

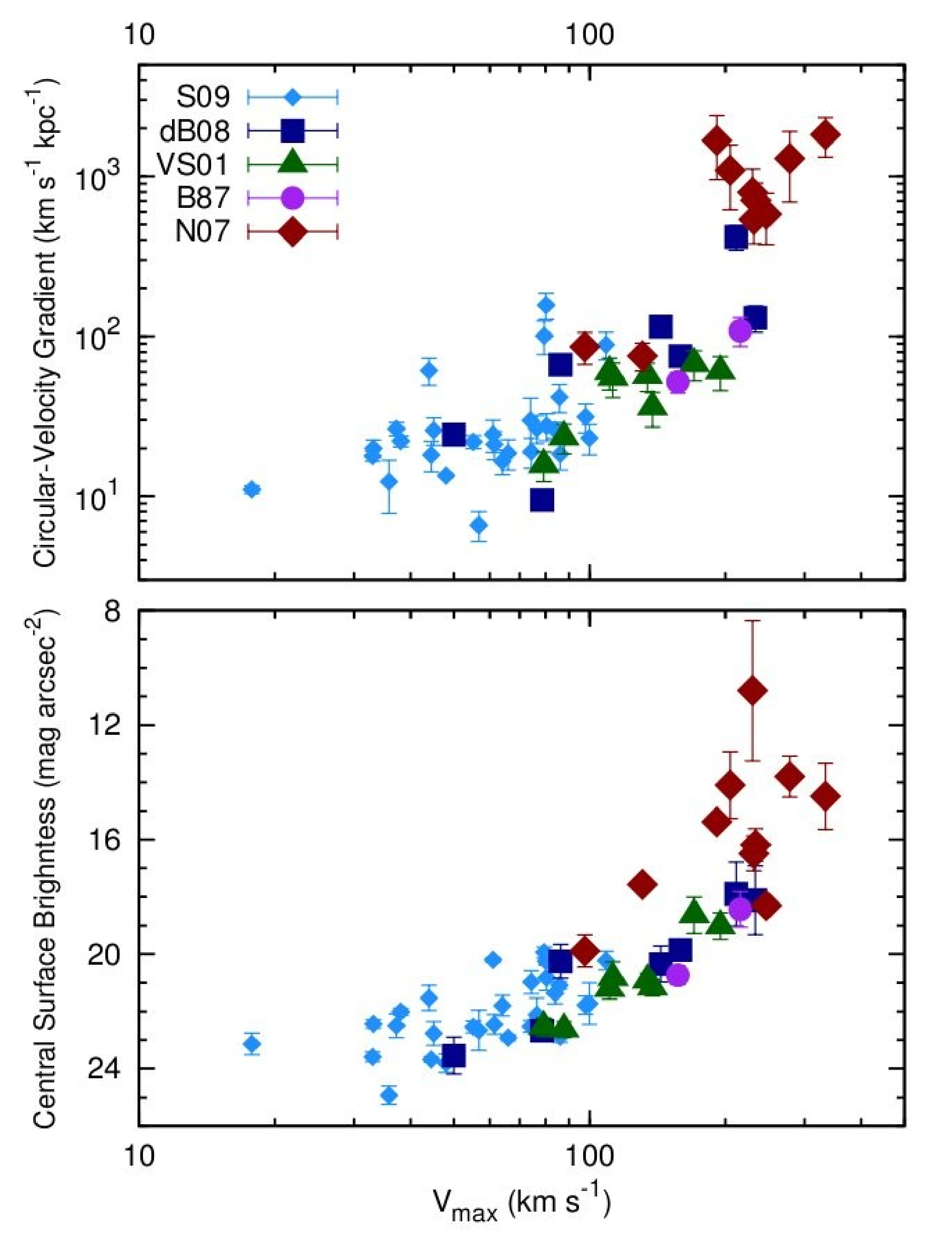
Observed relation:

$$\log[d_R V(0)] = (-0.205 \pm 0.023)\,\mu_0 + (5.91 \pm 0.52).$$

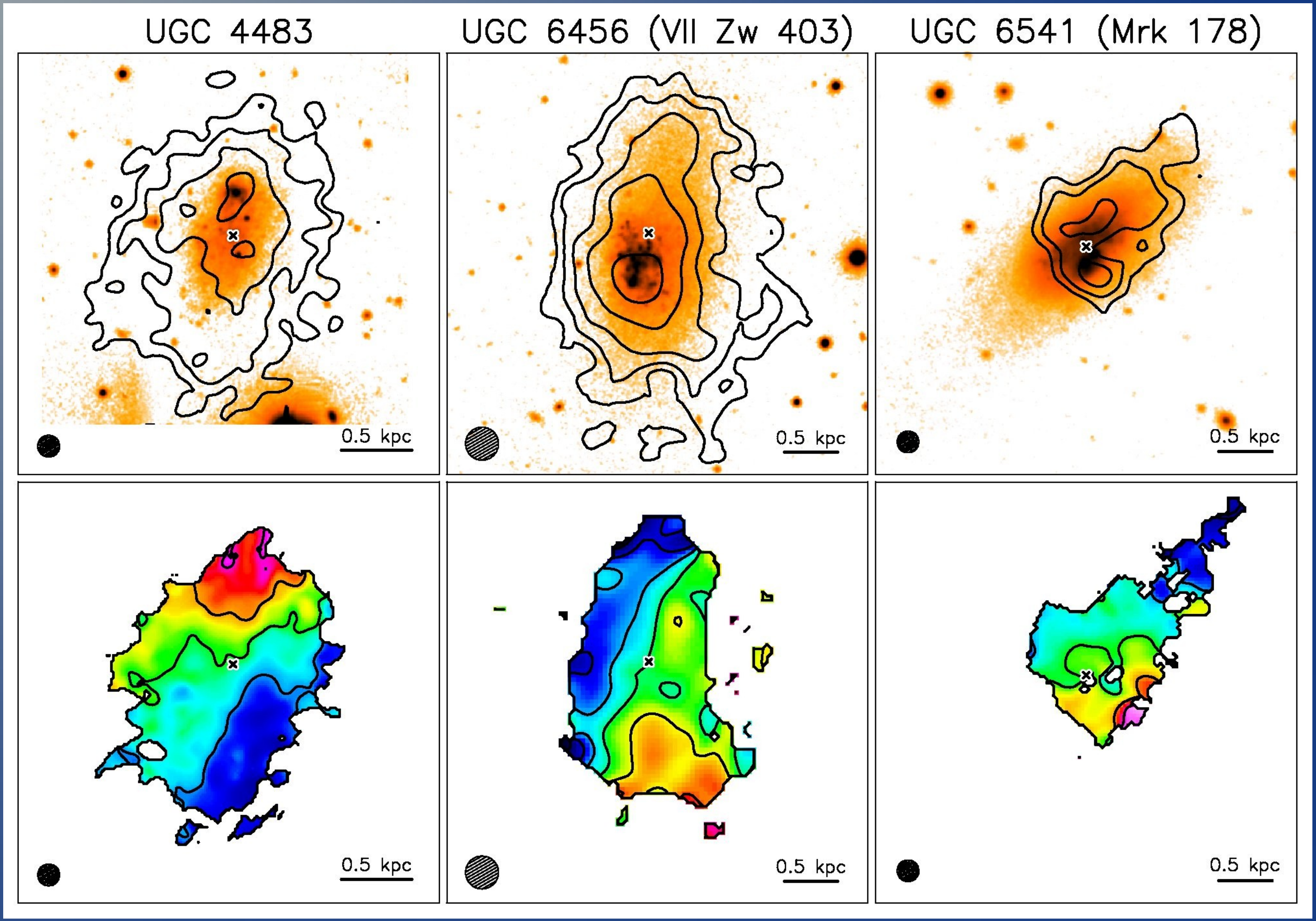
If slope = -0.2, puzzling fine-tuning between:

- geometrical parameters (α, z_0)
- stellar populations (M_*/L)
- dark matter content ($f_{\rm bar,\,0}$)

Inner Velocity Gradient *vs* V_{max}



Starburst Dwarfs have "regular" discs

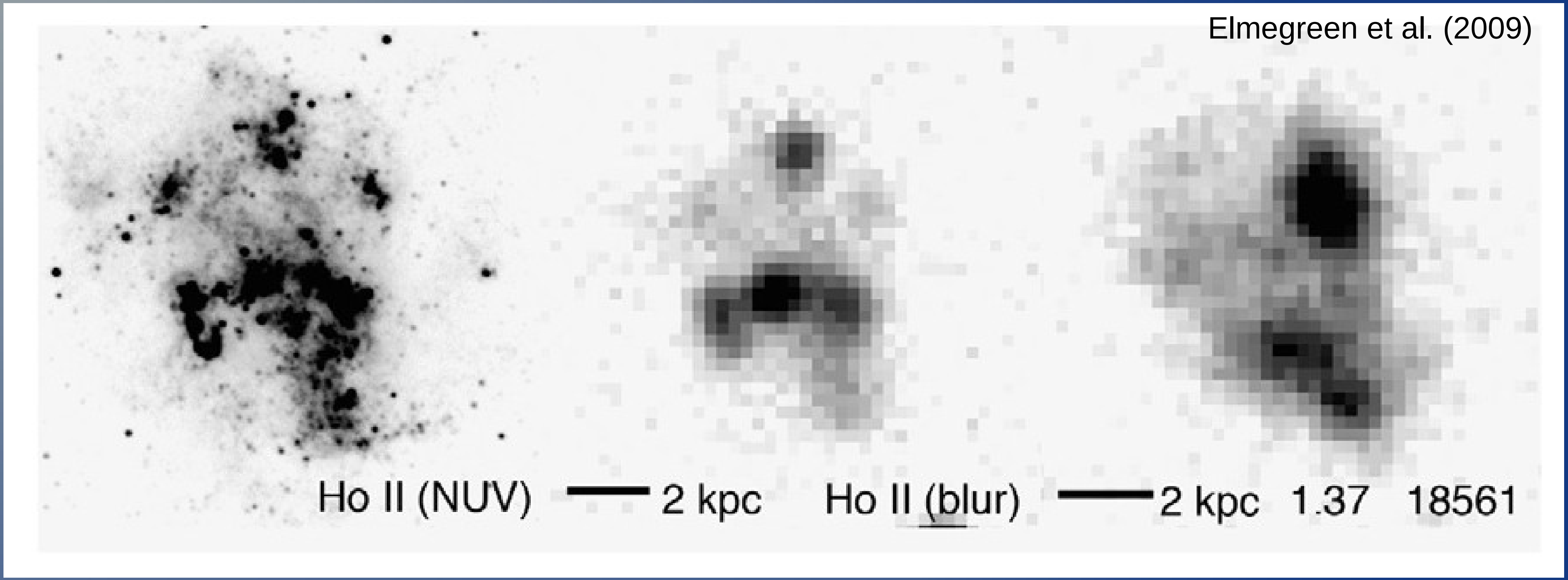


~50%
rotating HI disk

~40%
kin. disturbed HI disk

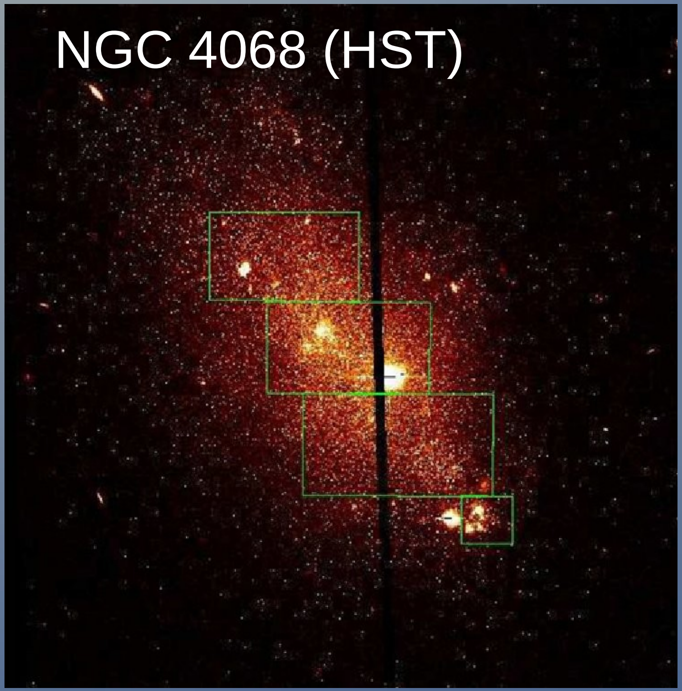
~10%
unsettled HI distr.

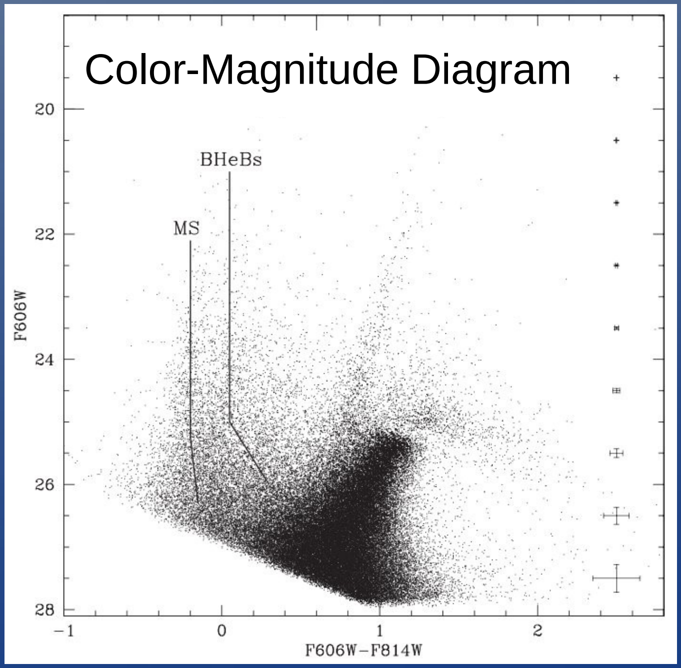
Starburst dwarfs ~ high-z galaxies?

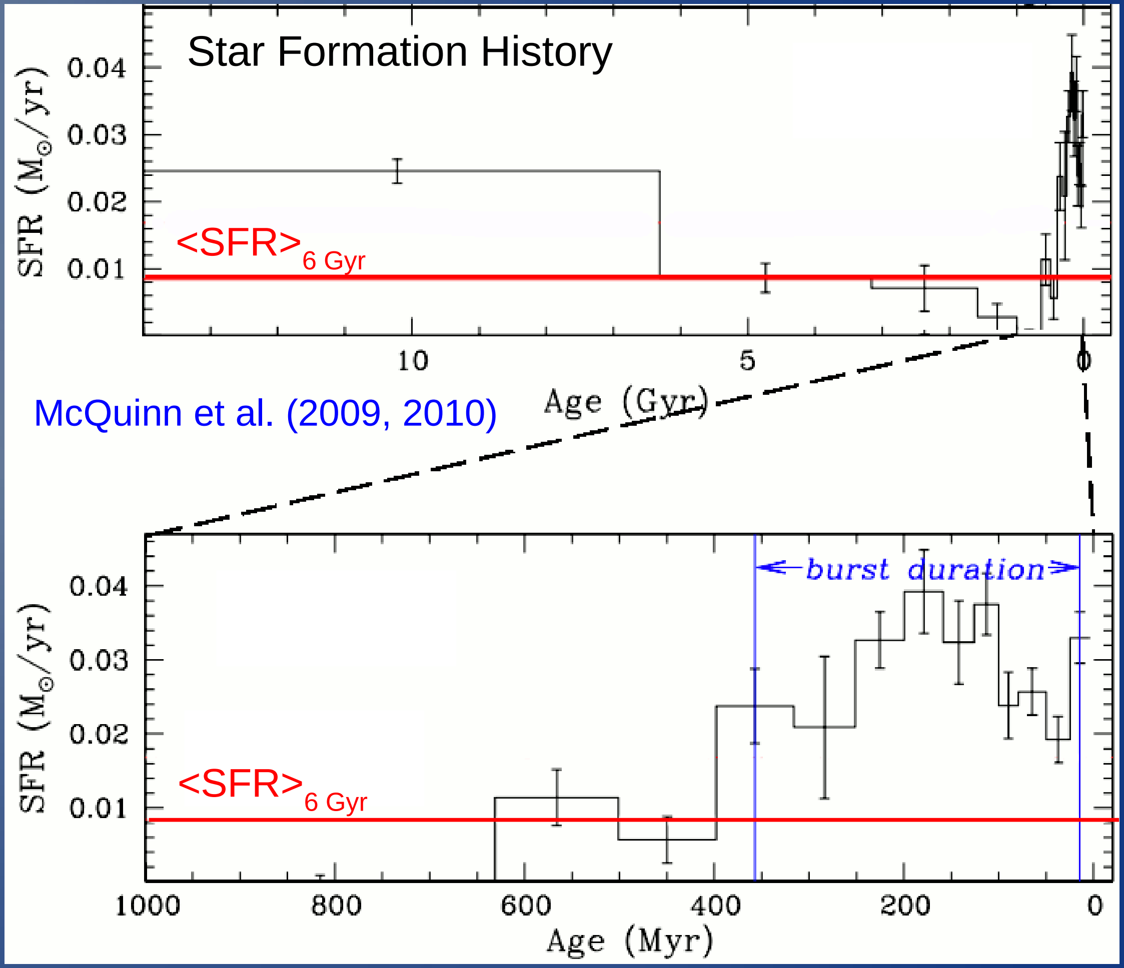


- clumpy morphologies
- high gas fractions ($M_{gas}/M_{*} > 1$)
- low metallicities ($0.3 < Z/Z_{\odot} < 0.03$)
- turbulent gaseous disks ($V_{rot}/\sigma_{V} < 5\text{-}6$)

Starburst properties from CMD fits



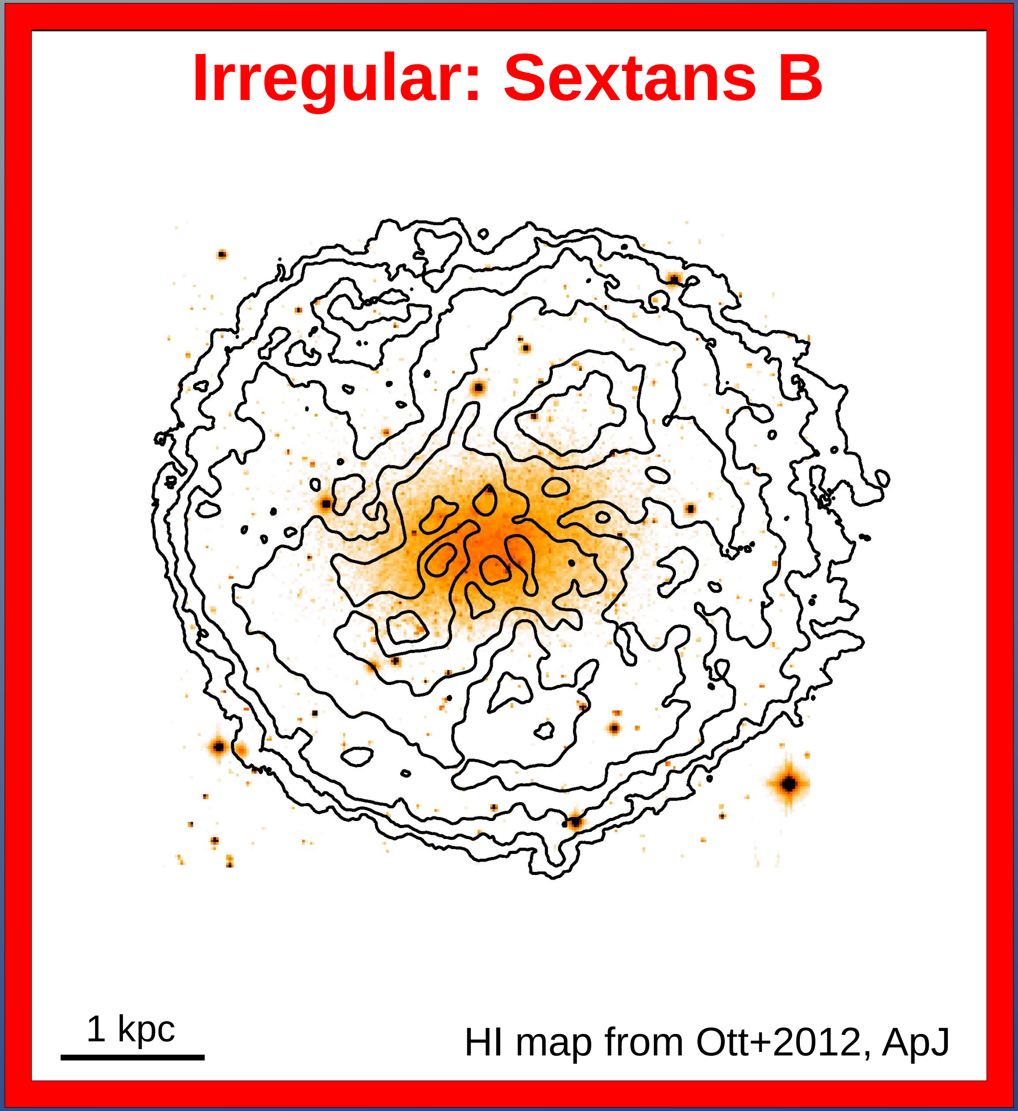


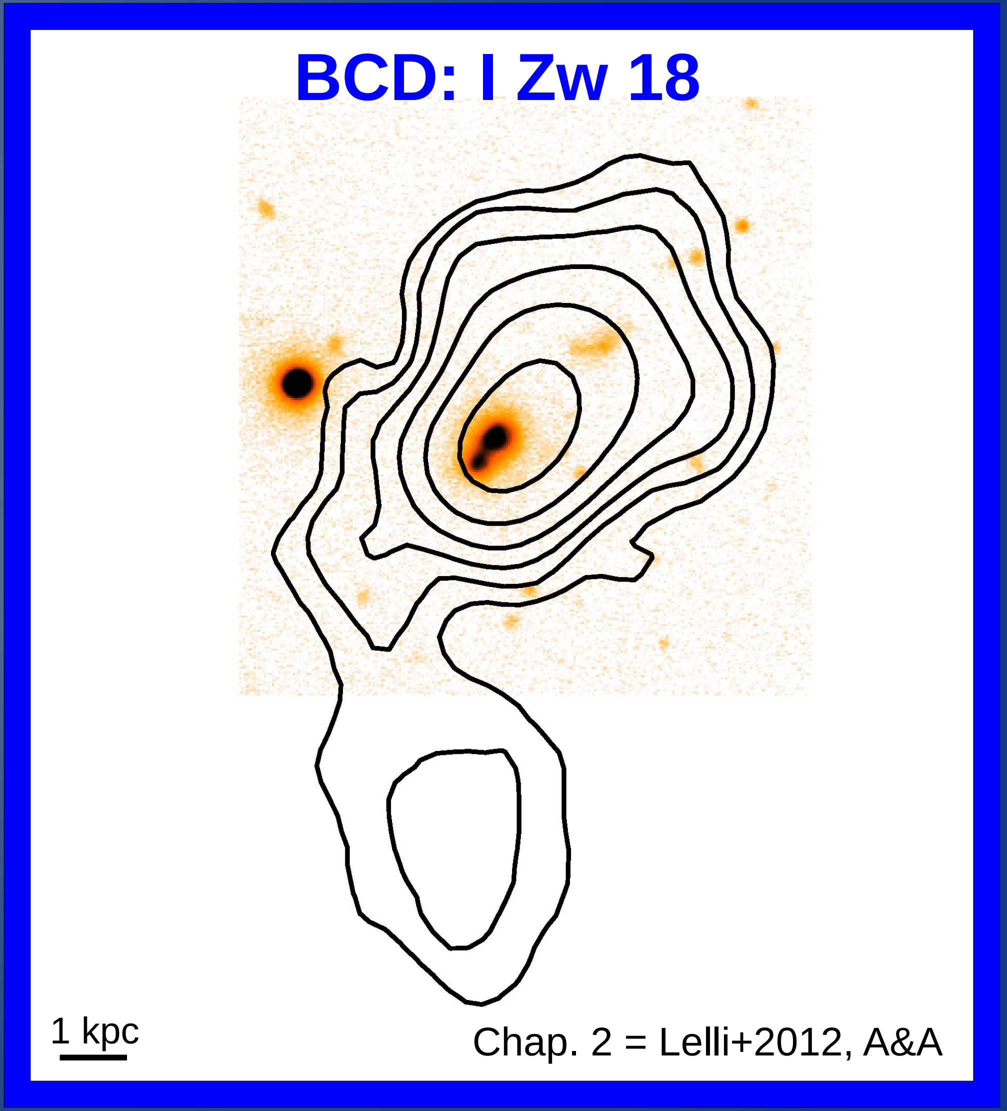


The SFH provides:

- birthrate = $SFR(t_{peak}) / \overline{SFR} \geq 3$
- starburst durations (~100 Myr)
- energies from SN & stellar winds

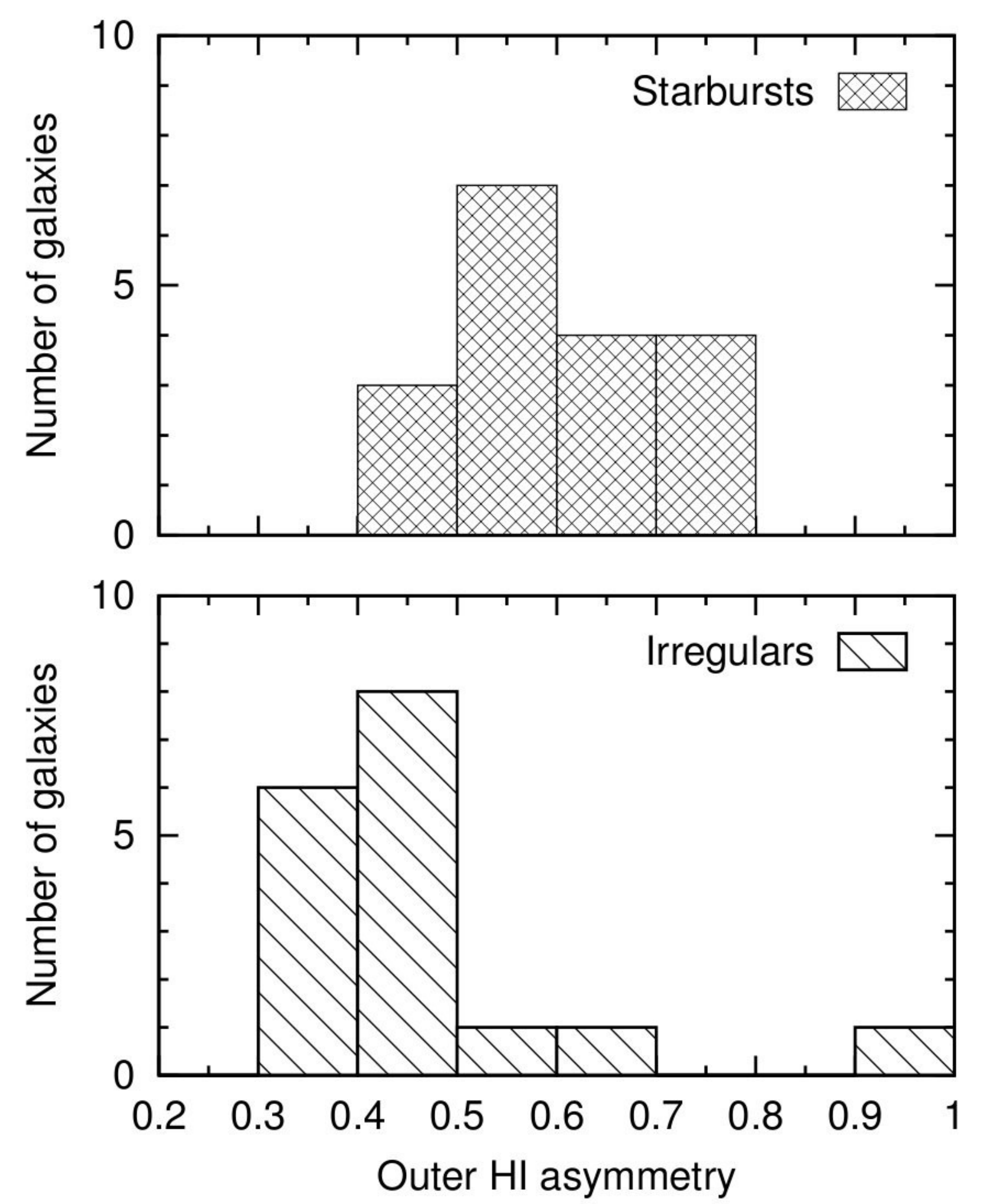
Large-scale HI distribution





Lowest HI contour = 5 x 10^{19} cm^{-2}

HI Asymmetry: Starbursts *vs* Irrs



BCDs have more asymmetric large-scale HI distributions than Irrs

External mechanisms triggered the starburst:

- Interactions/mergers?
- Cold gas accretion?

Irregulars from the VLA-ANGST survey (Ott et al. 2012)