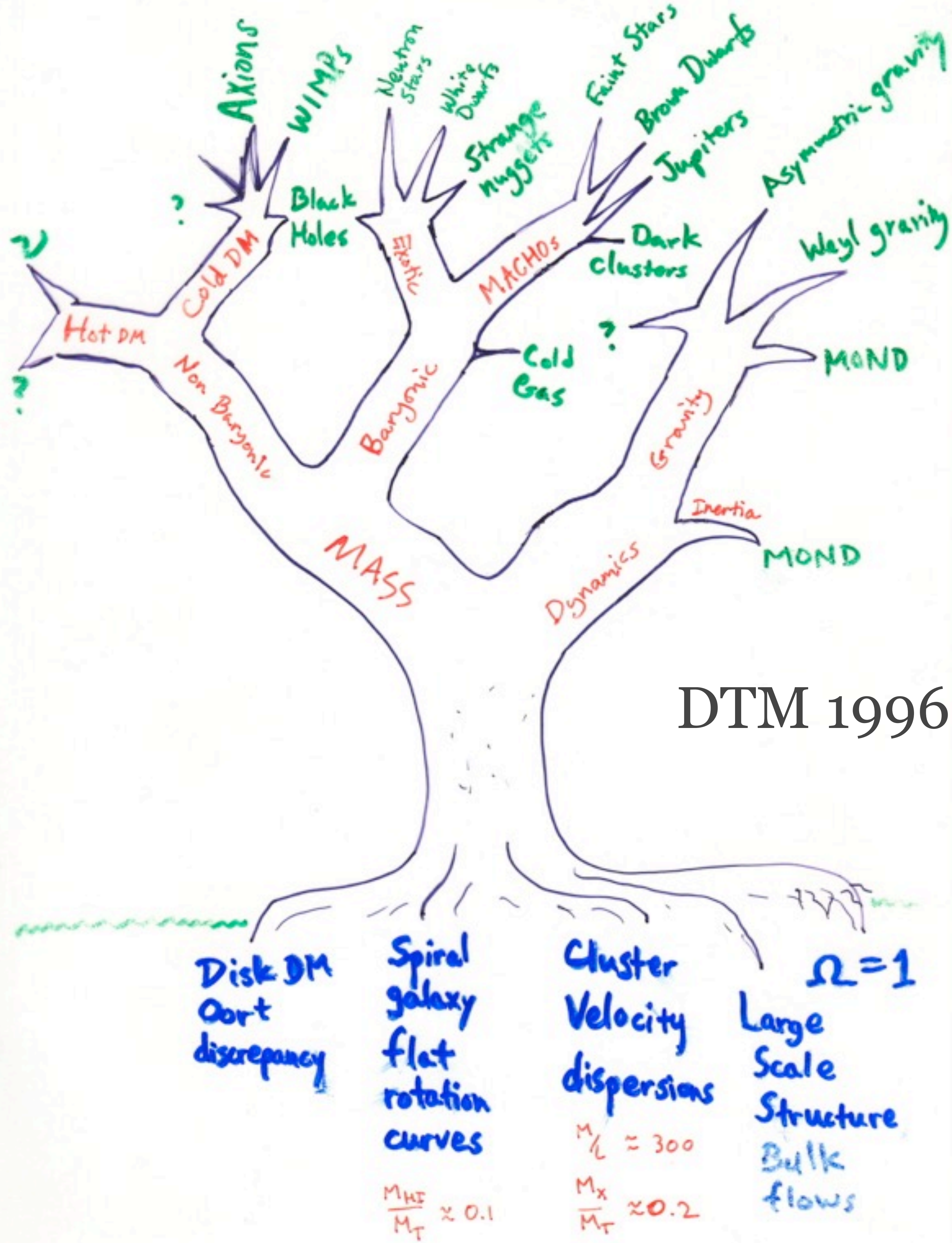
Dark Matter & MOND: Up the Proverbial Creek

Stacy McGaugh

Case Western Reserve University EST. 1826

with collaborators
Federico Lelli (CWRU)
Marcel Pawlowski (CWRU)
Jim Schombert (U. Oregon)

and support from
NSF
NASA
The John Templeton Foundation



DTM 1996

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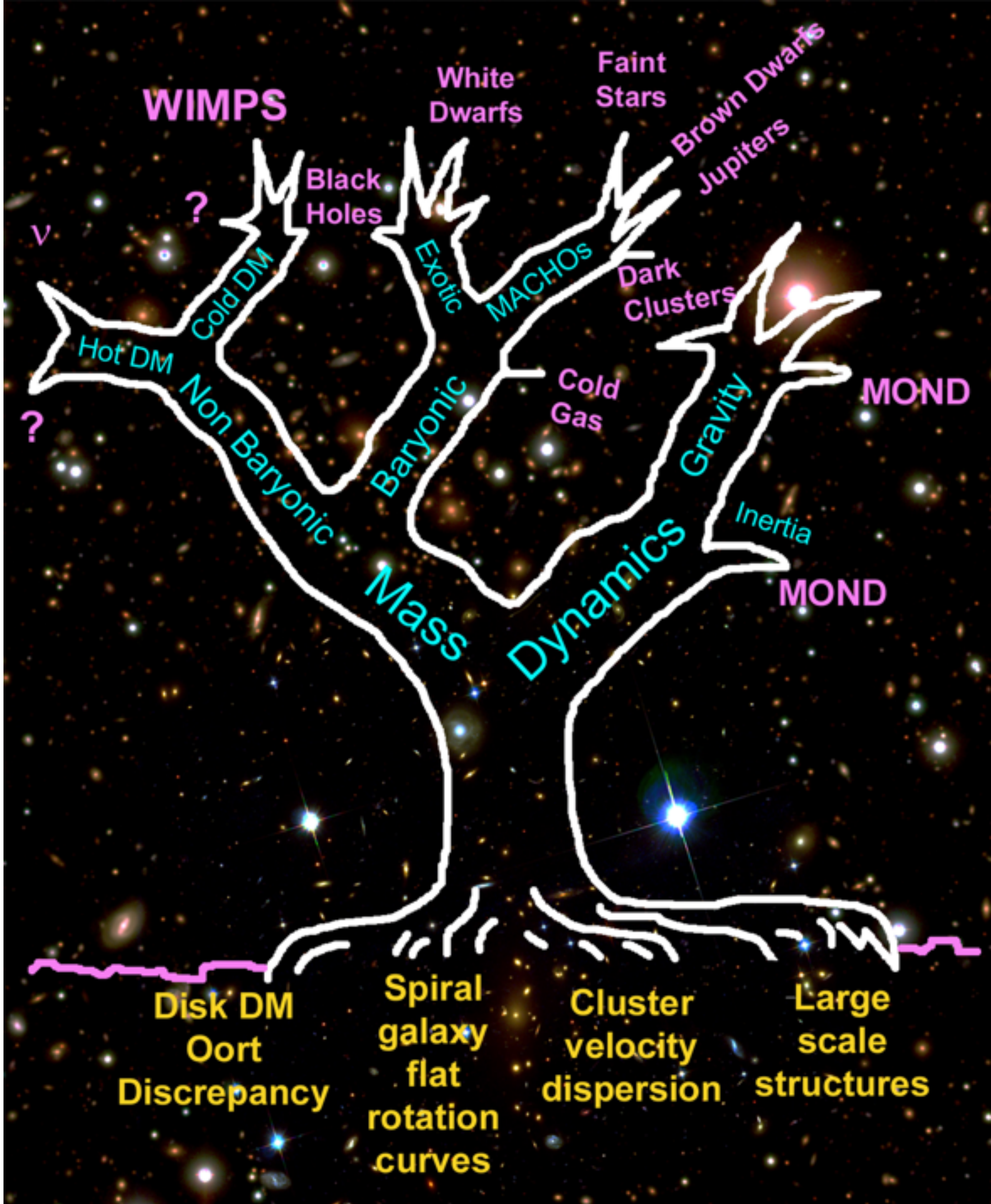


Physics Teacher cover March 2013

A Field of Two Attitudes

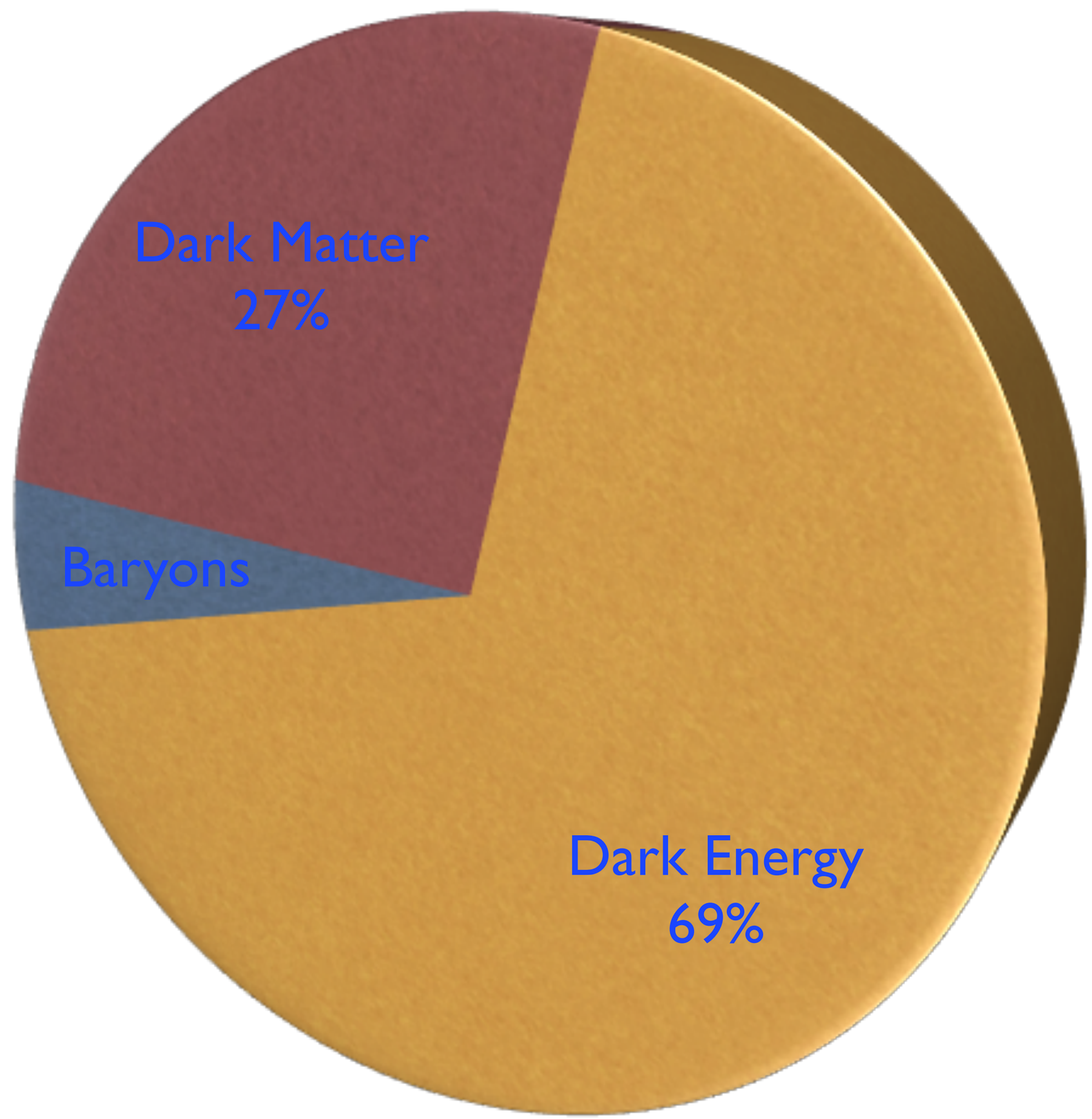
ΛCDM is obviously correct. Or not.

ΛCDM is the current cosmological paradigm.

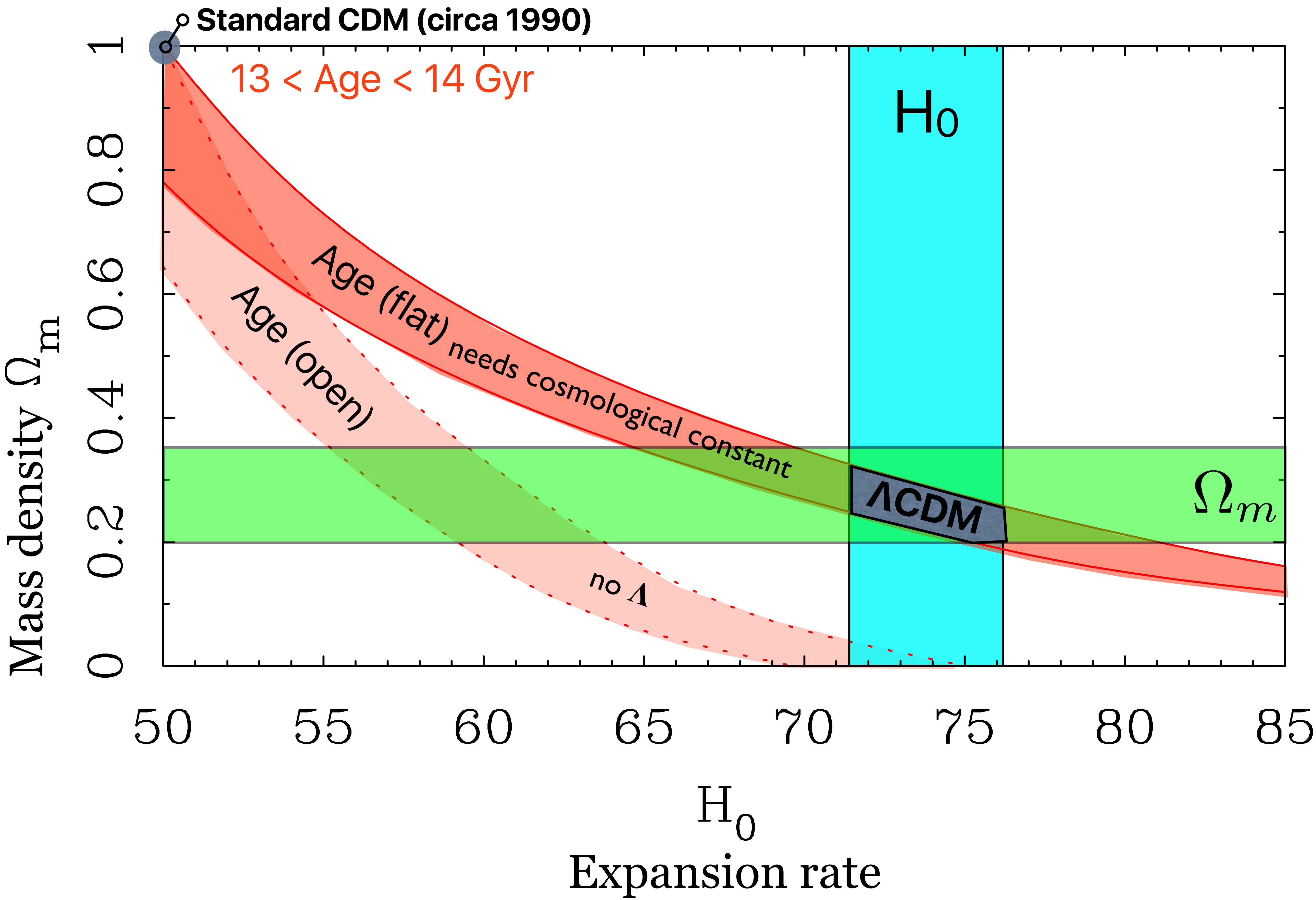
The product of decades of large scale measurements

Modern cosmology nicely explains

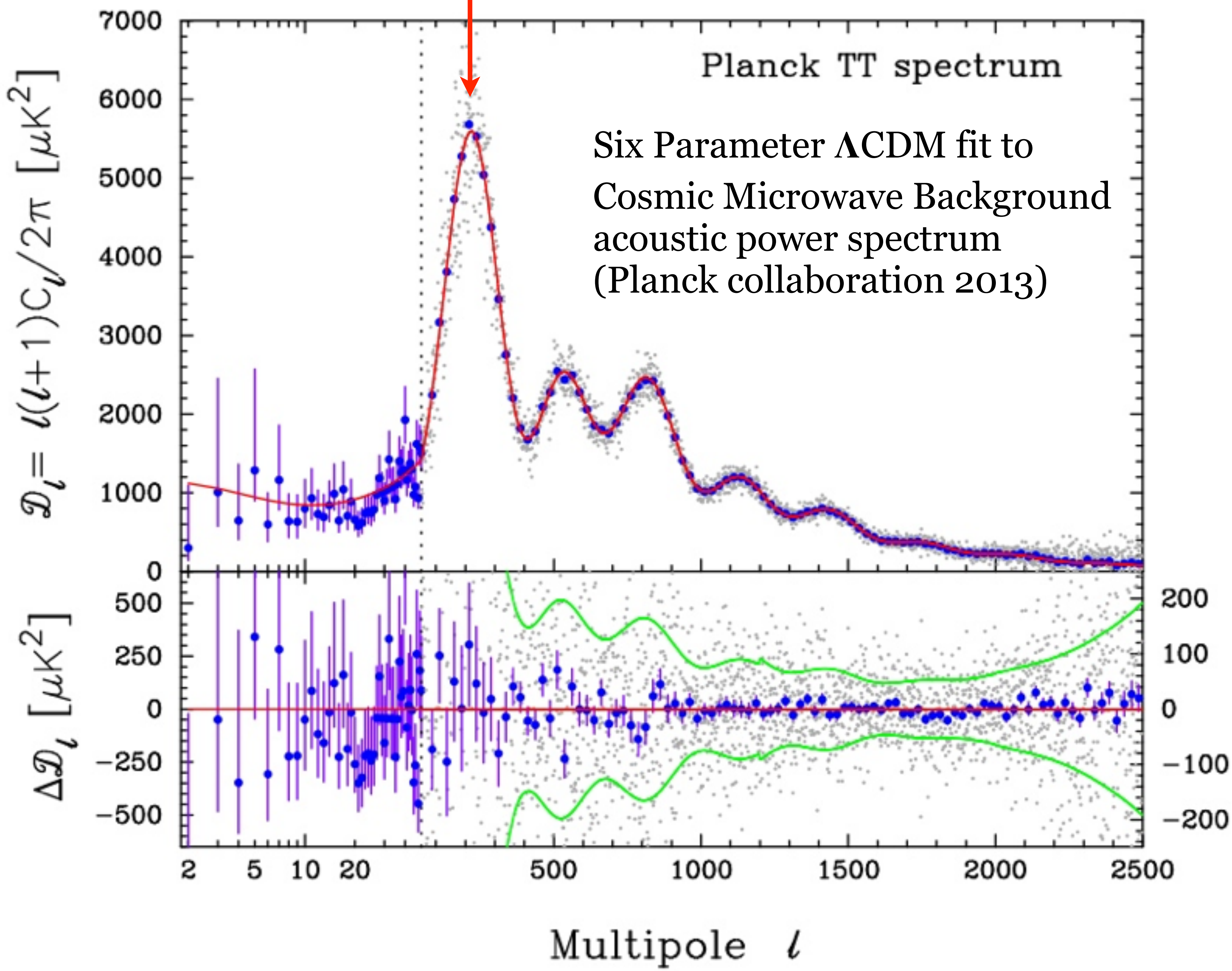
- Expanding Universe
  - redshift-distance relation
  - geometry of space-time
- Finite Age (~ 14 Billion years)
- Early hot phase (Big Bang)
  - Nucleosynthesis of the light elements (H, He, Li)
  - Cosmic Microwave Background



Cosmology predating SN, CMB (circa 1995)



First peak position indicates flat geometry.
Again need $\mathbf{\Lambda}$ if $\Omega_m < 1$ as observed.



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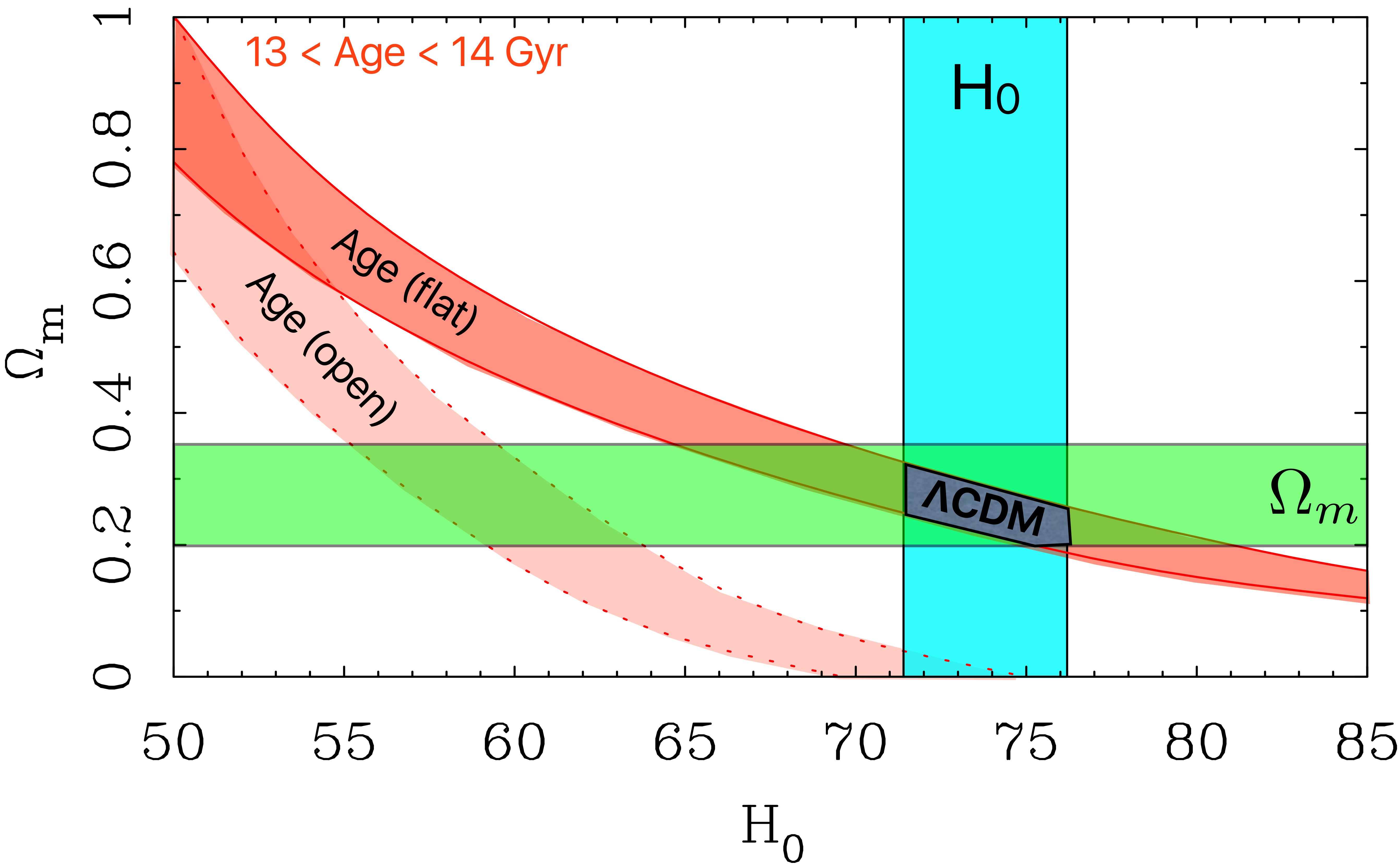
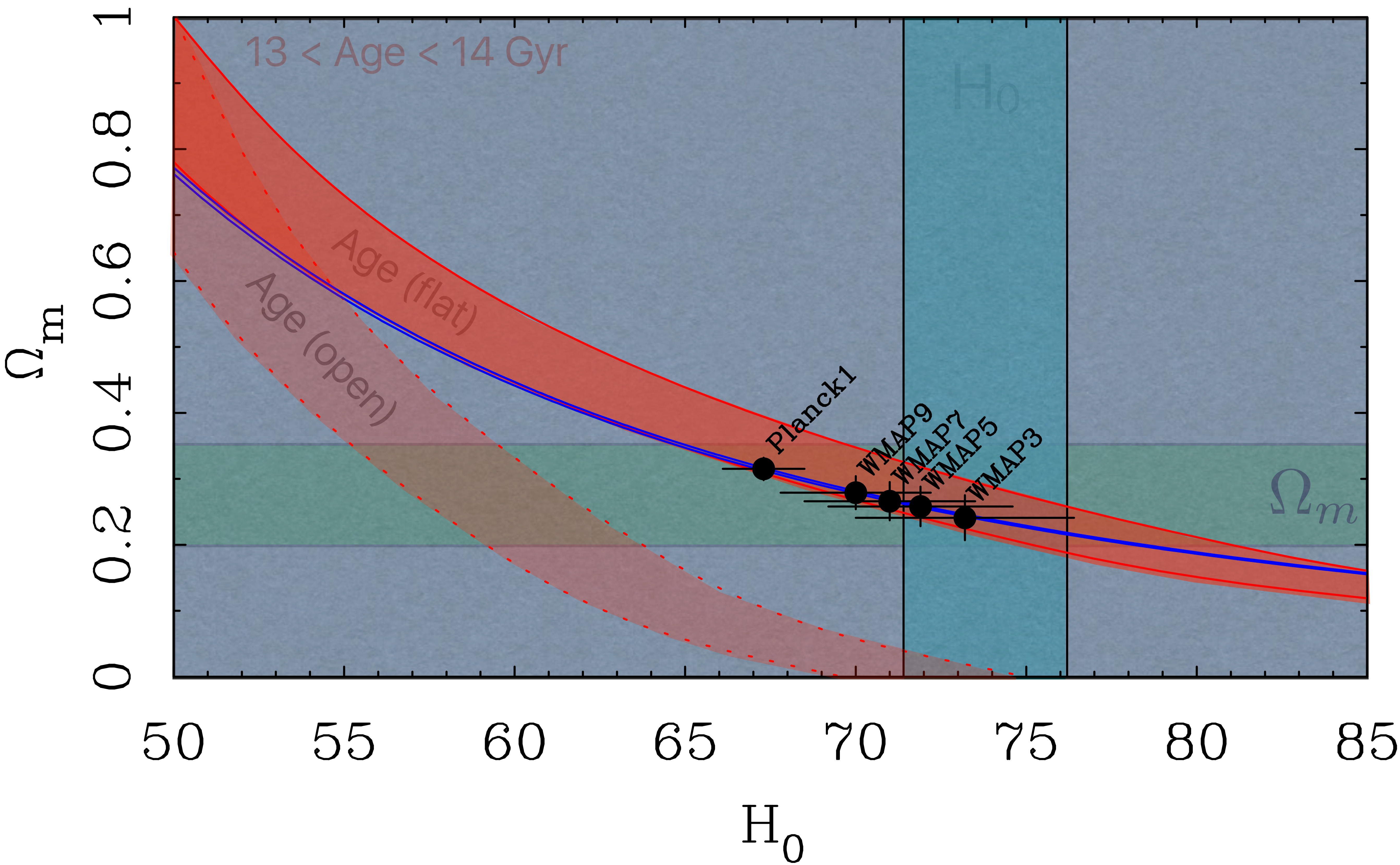


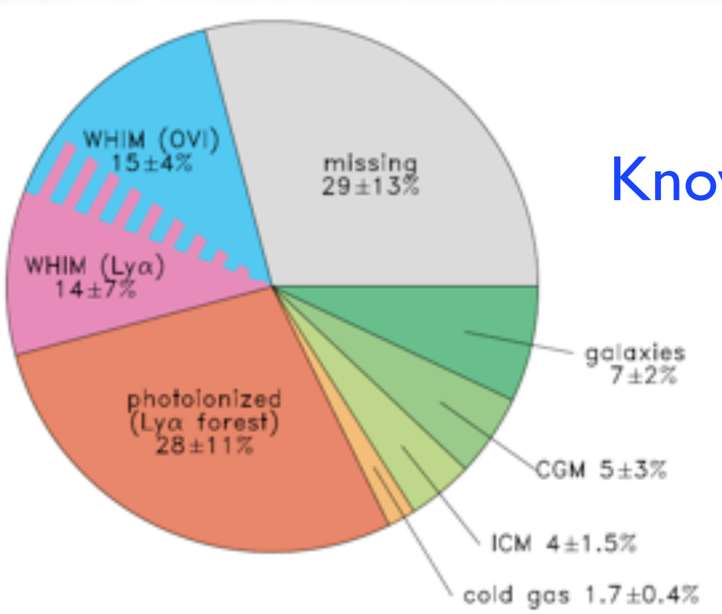
2013 Planck constraint: $\Omega_m h^3 = 0.0959 \pm 0.0006$

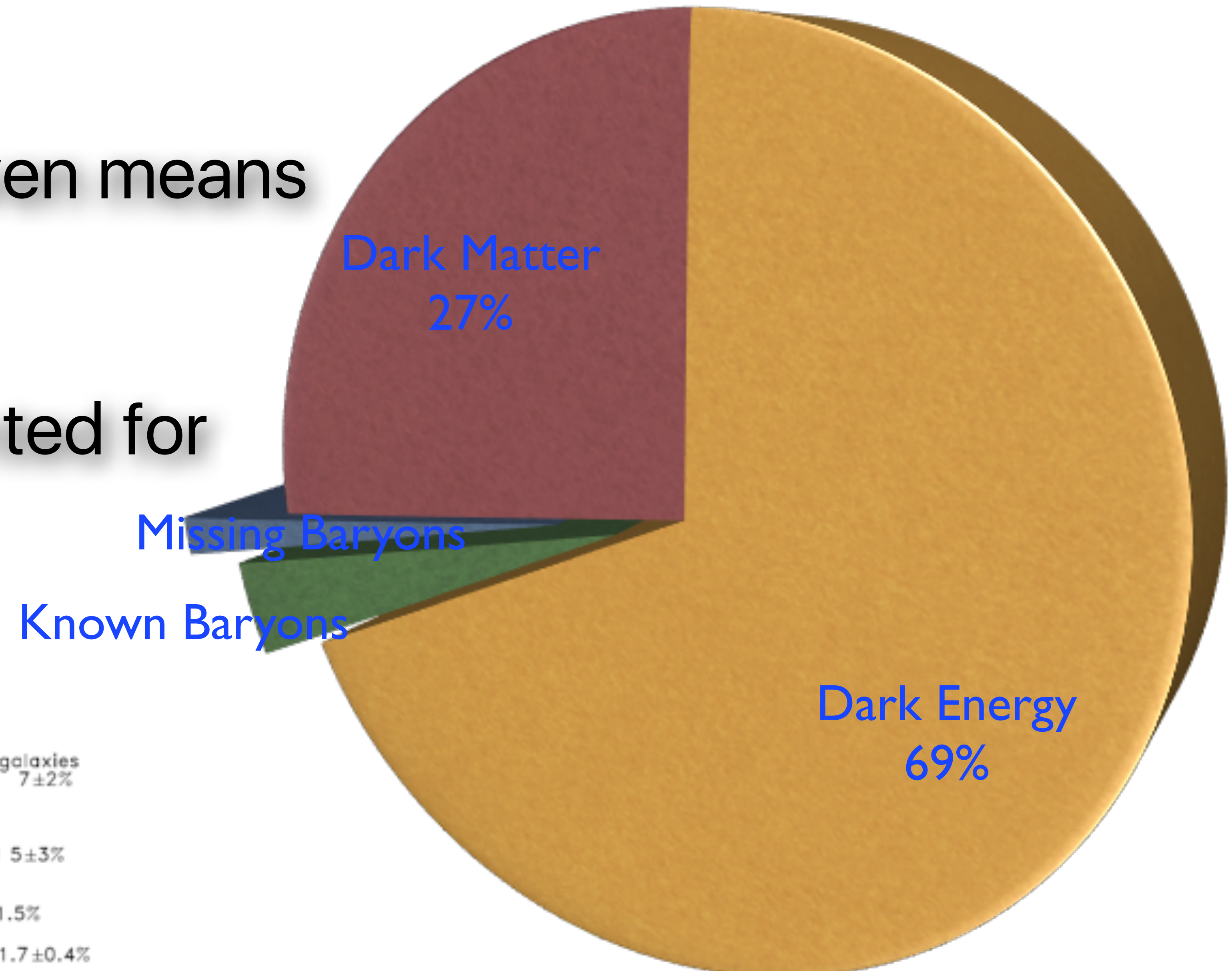


Everything outside the narrow blue band is excluded

Modern cosmology only works with

- non-baryonic cold dark matter
  - whatever it is
- dark energy
  - whatever that even means
- dark baryons
  - 29% not accounted for

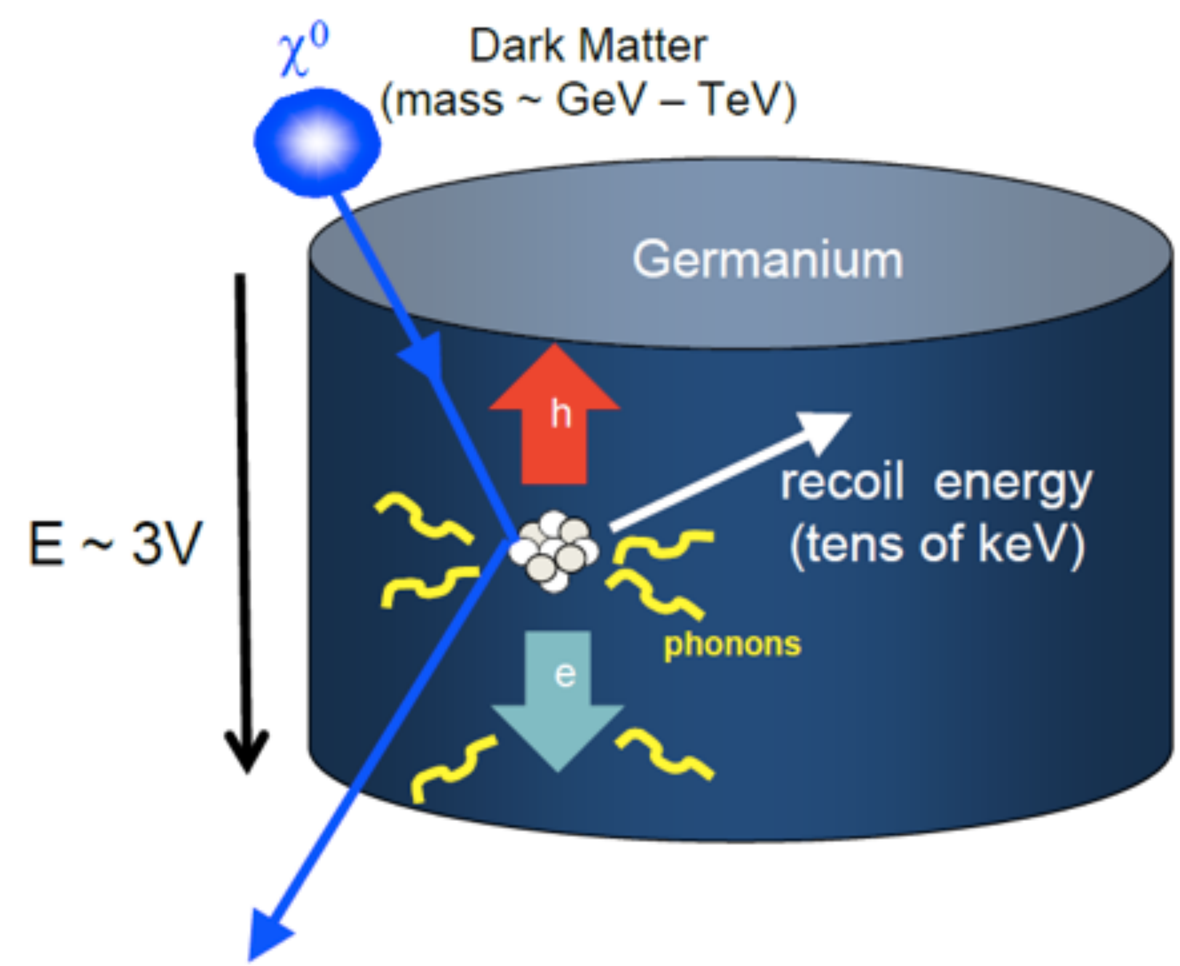




We have direct knowledge of only a few % of the total mass-energy density of the universe

The most favored dark matter candidate is the **WIMP** - ***W**eakly **I**nteracting **M**assive **P**article* - thought to reside in the supersymmetric sector
(which itself remains hypothetical)

<u>WIMP detection</u>

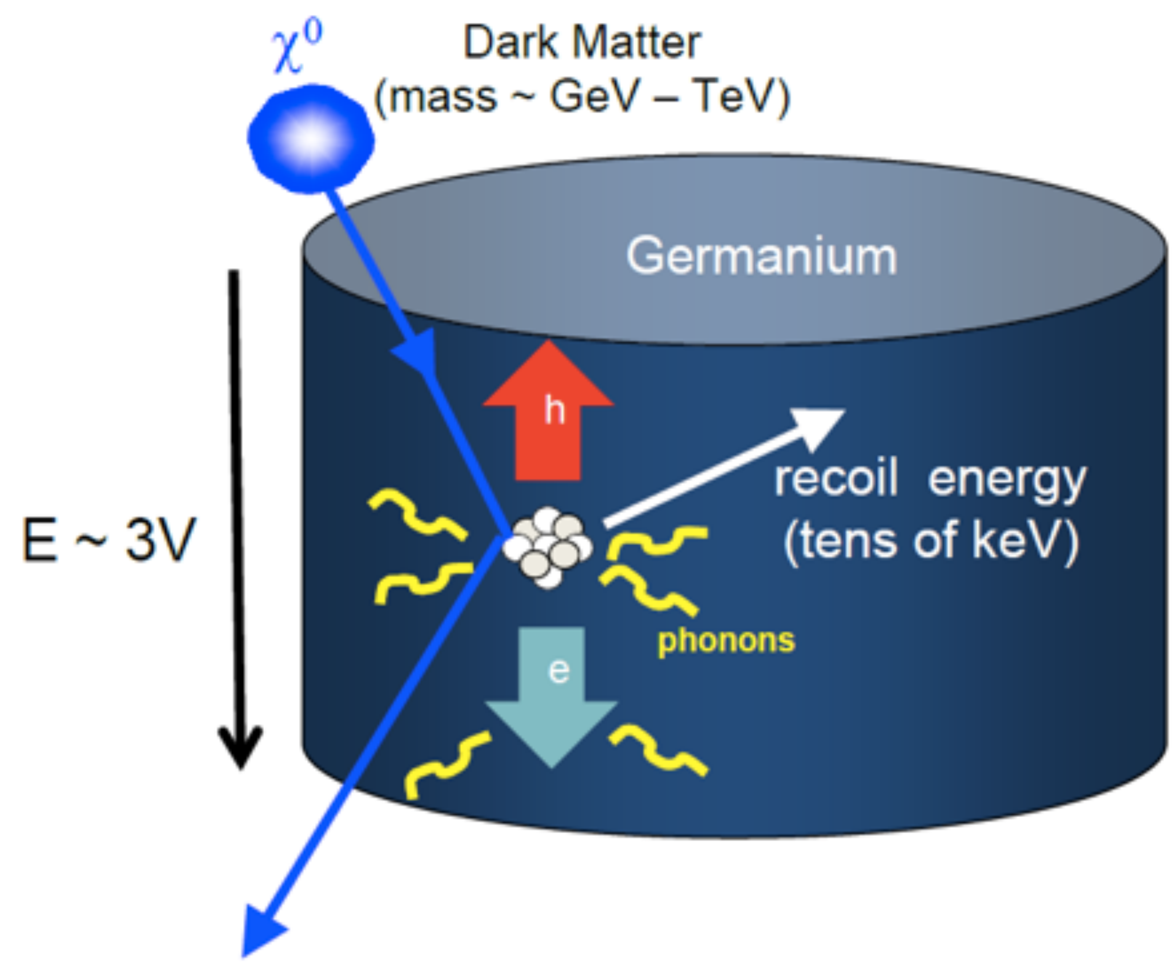


Experimental results to date (early 2016): nada

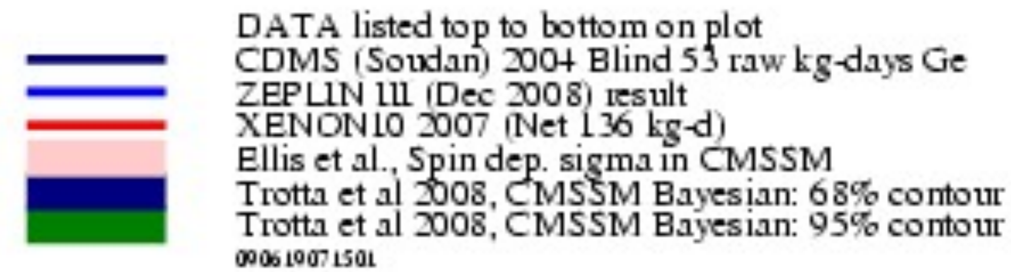
Direct detection: Many, *many* experiments
CDMS, LUX, XENON, DAMA, etc., etc.

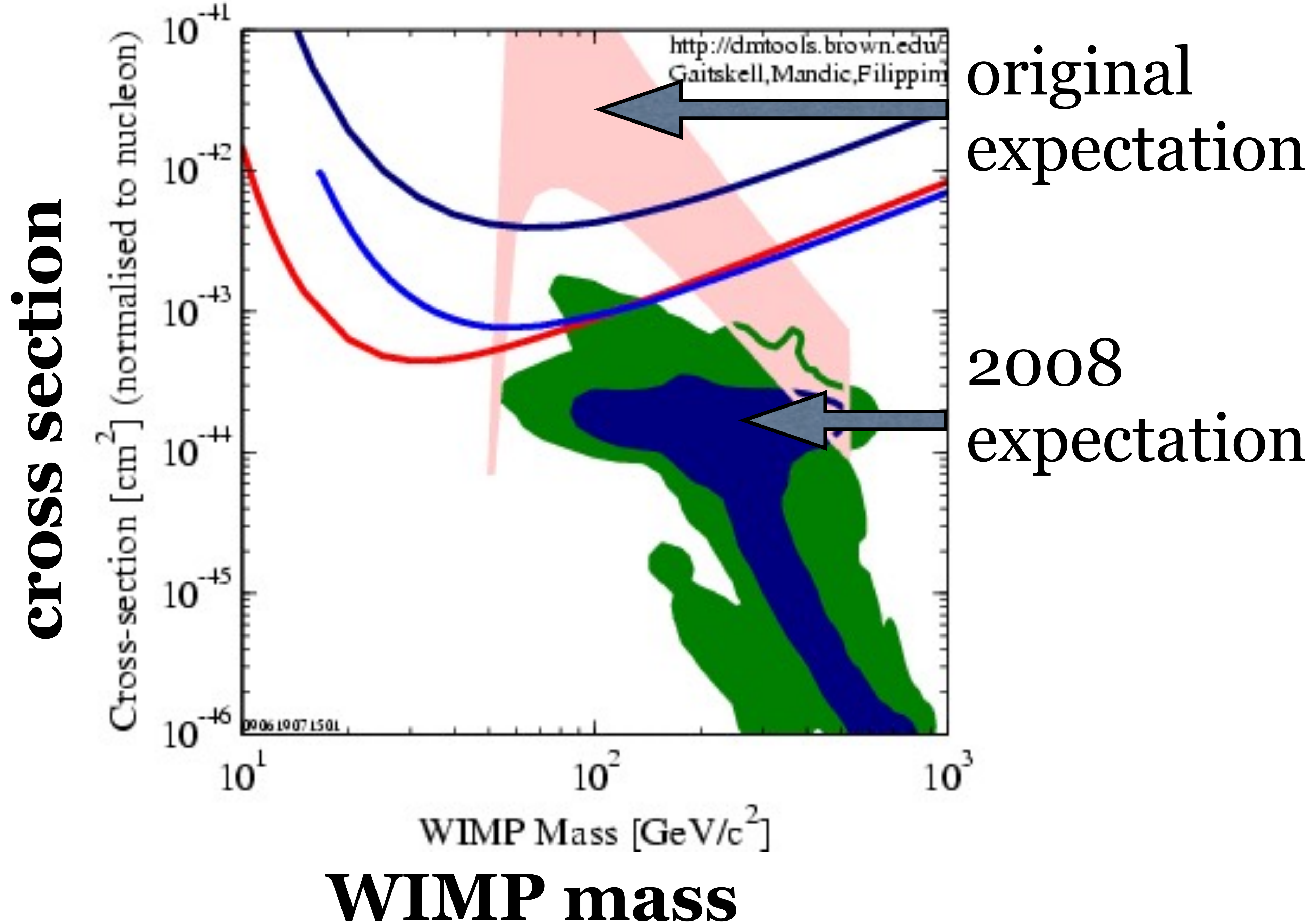
Basic idea: WIMP passing through detector interacts via weak force; scatters off nucleus. Detect deposited energy of recoil. (analogous to neutrino detection).

WIMP detection



Searches for
Cold Dark Matter
usually expressed as exclusion
reguiobs in the
WIMP mass-cross section diagram

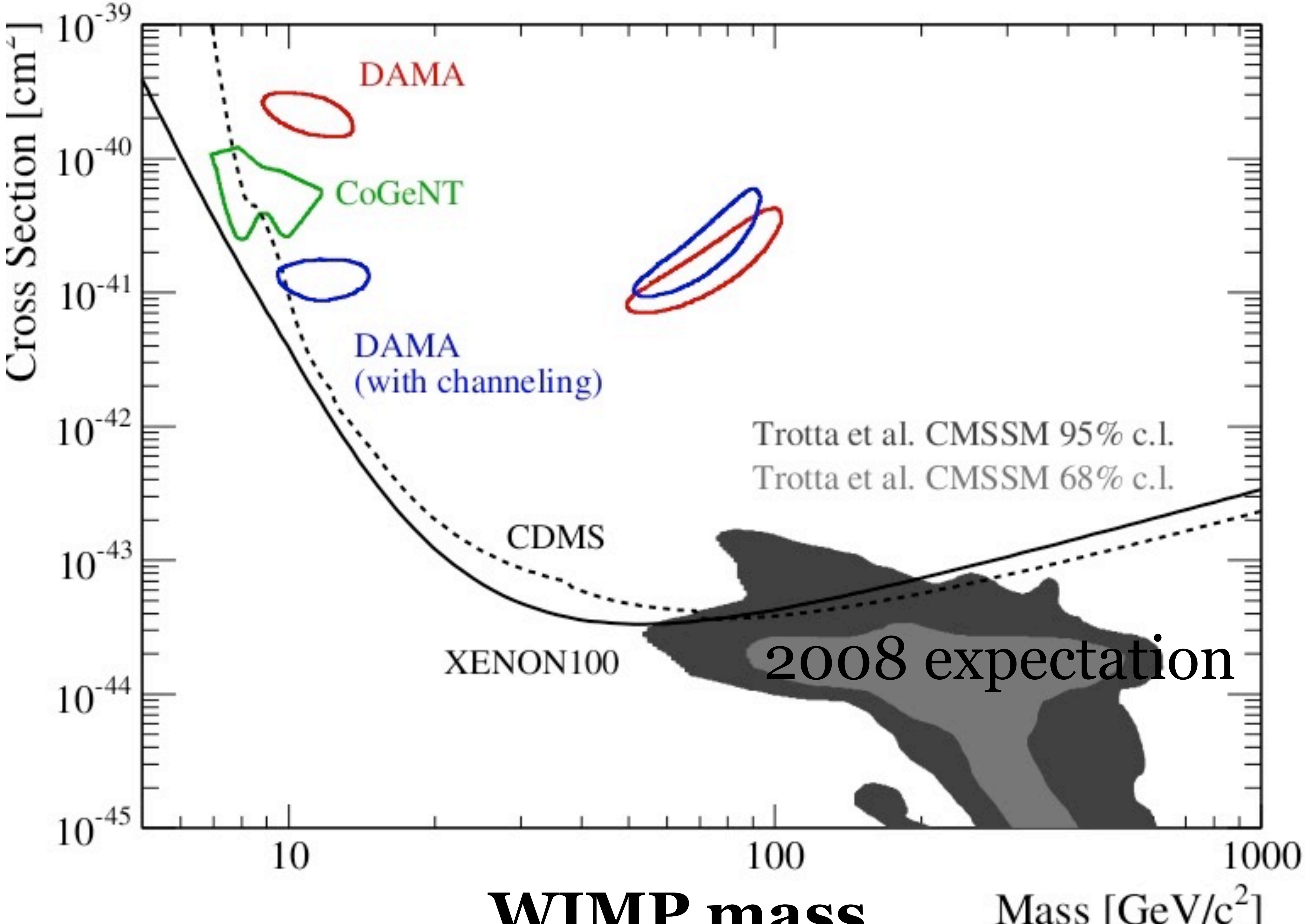




2010 exclusion

WIMP detection

cross section

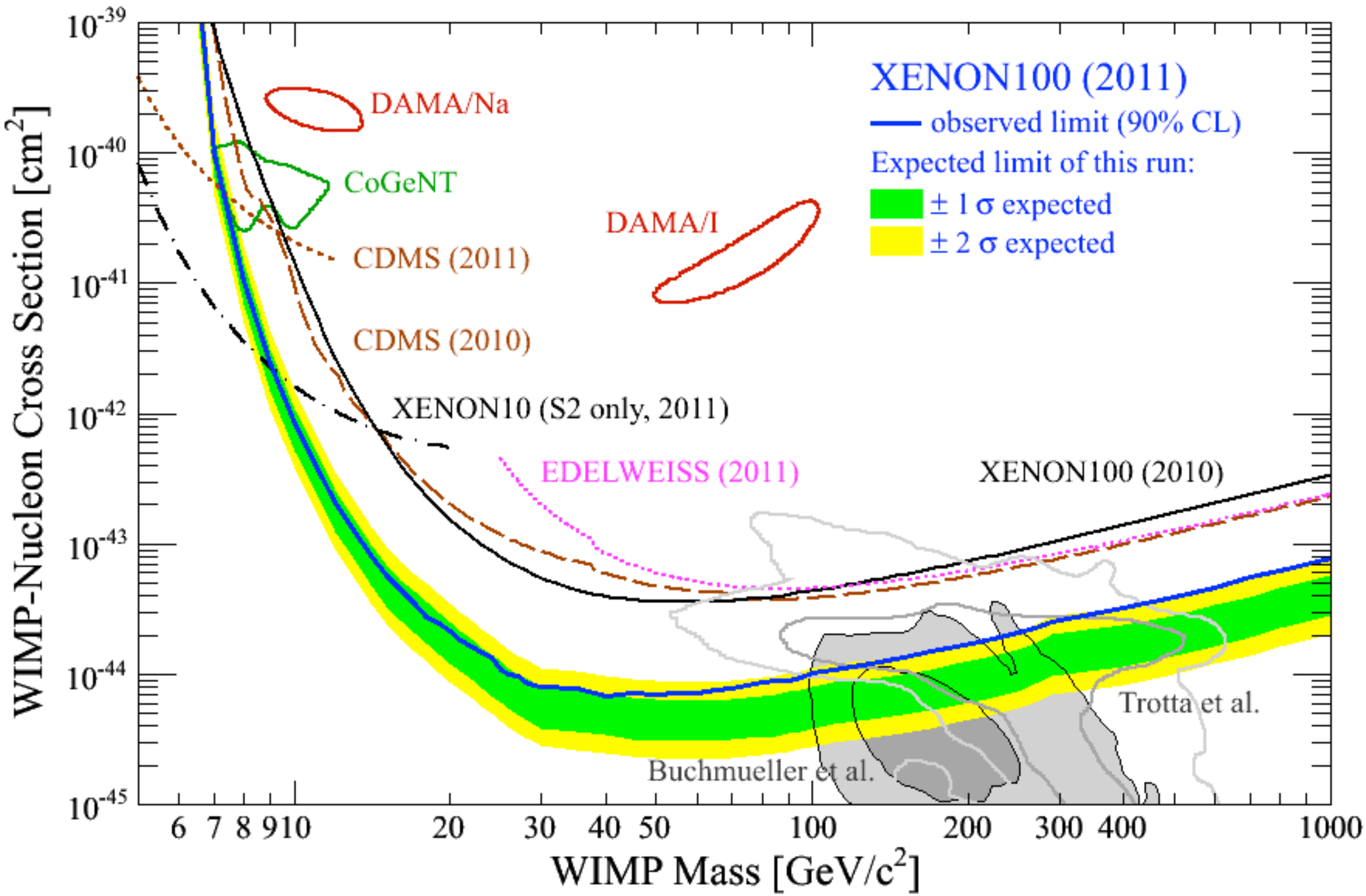


WIMP mass

2011 exclusion

<u>WIMP detection</u>

cross section

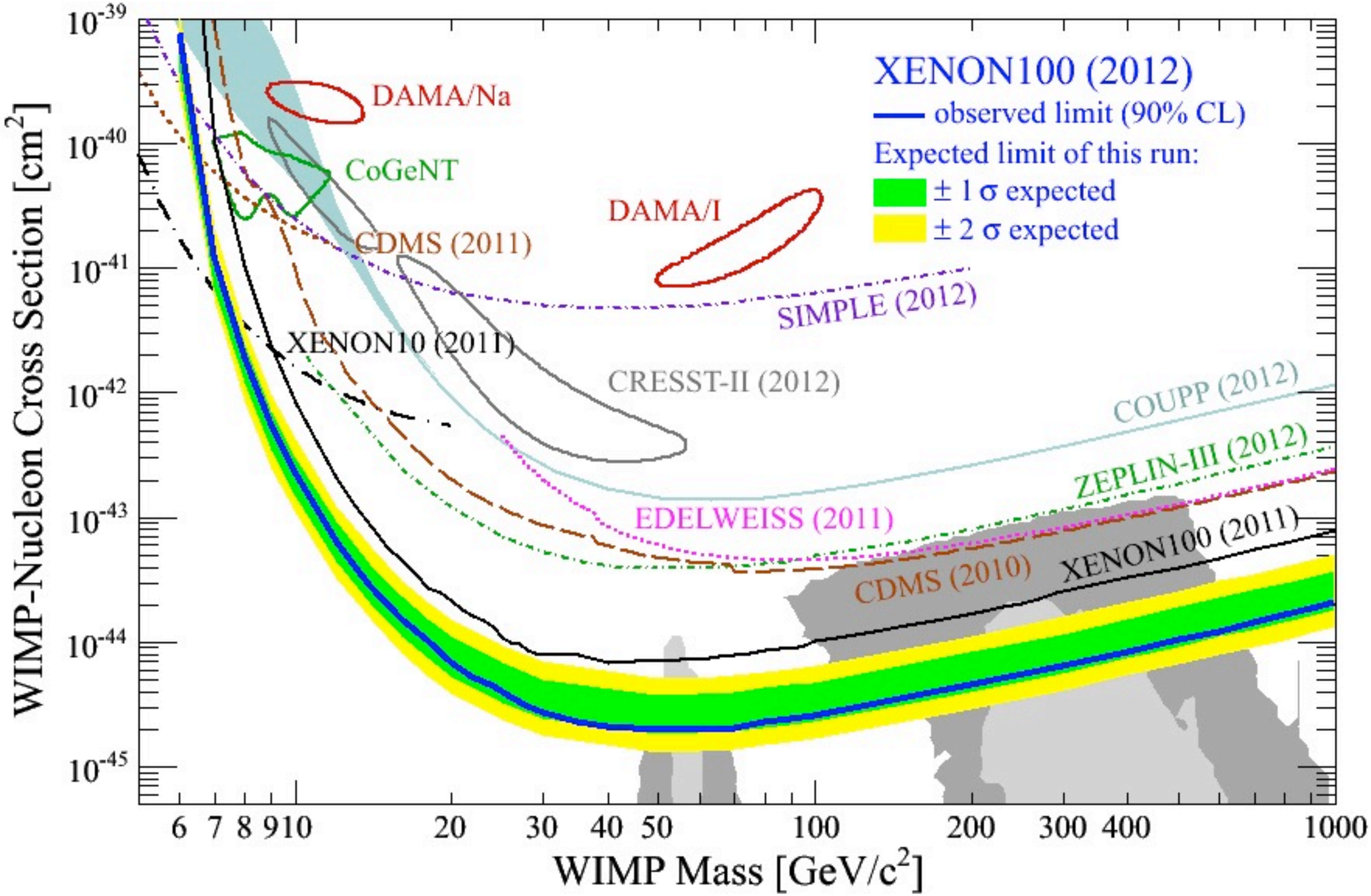


2008 expectation morphs downwards

WIMP mass

2012 exclusion

WIMP detection

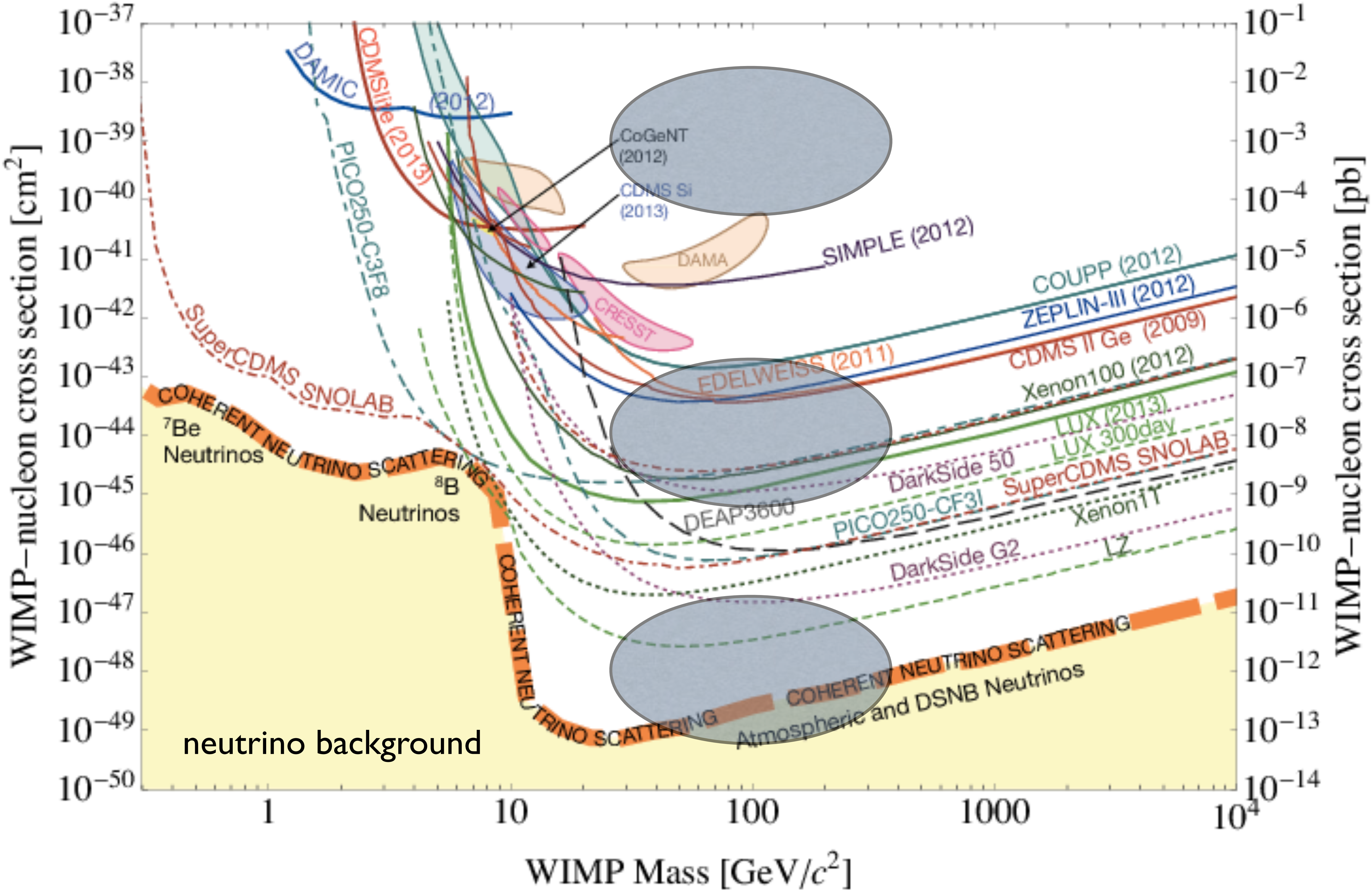


cross section

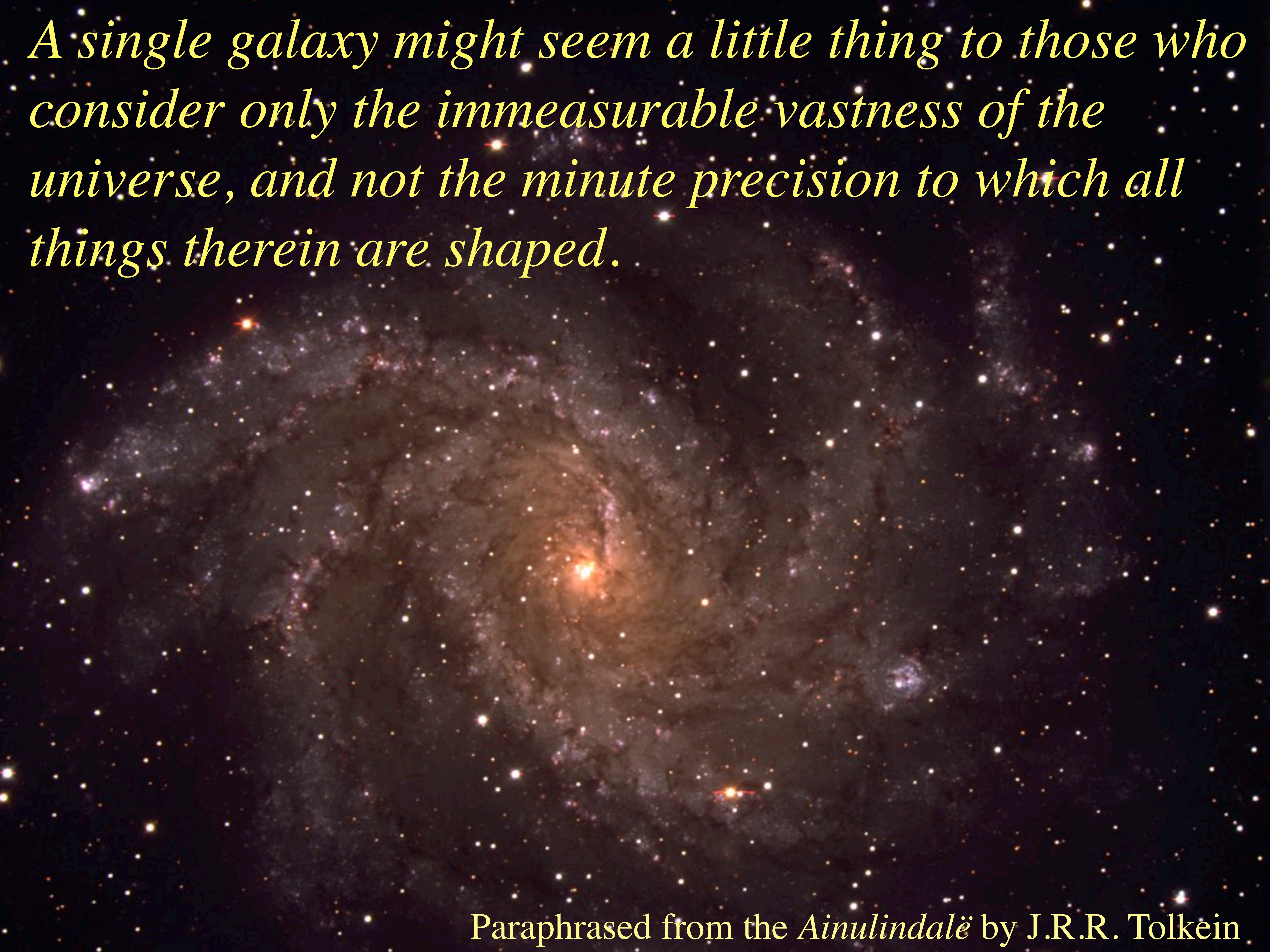
WIMP mass

cross section: 10^{-39} 'natural'. Then 10^{-44}. Next: 10^{-48}

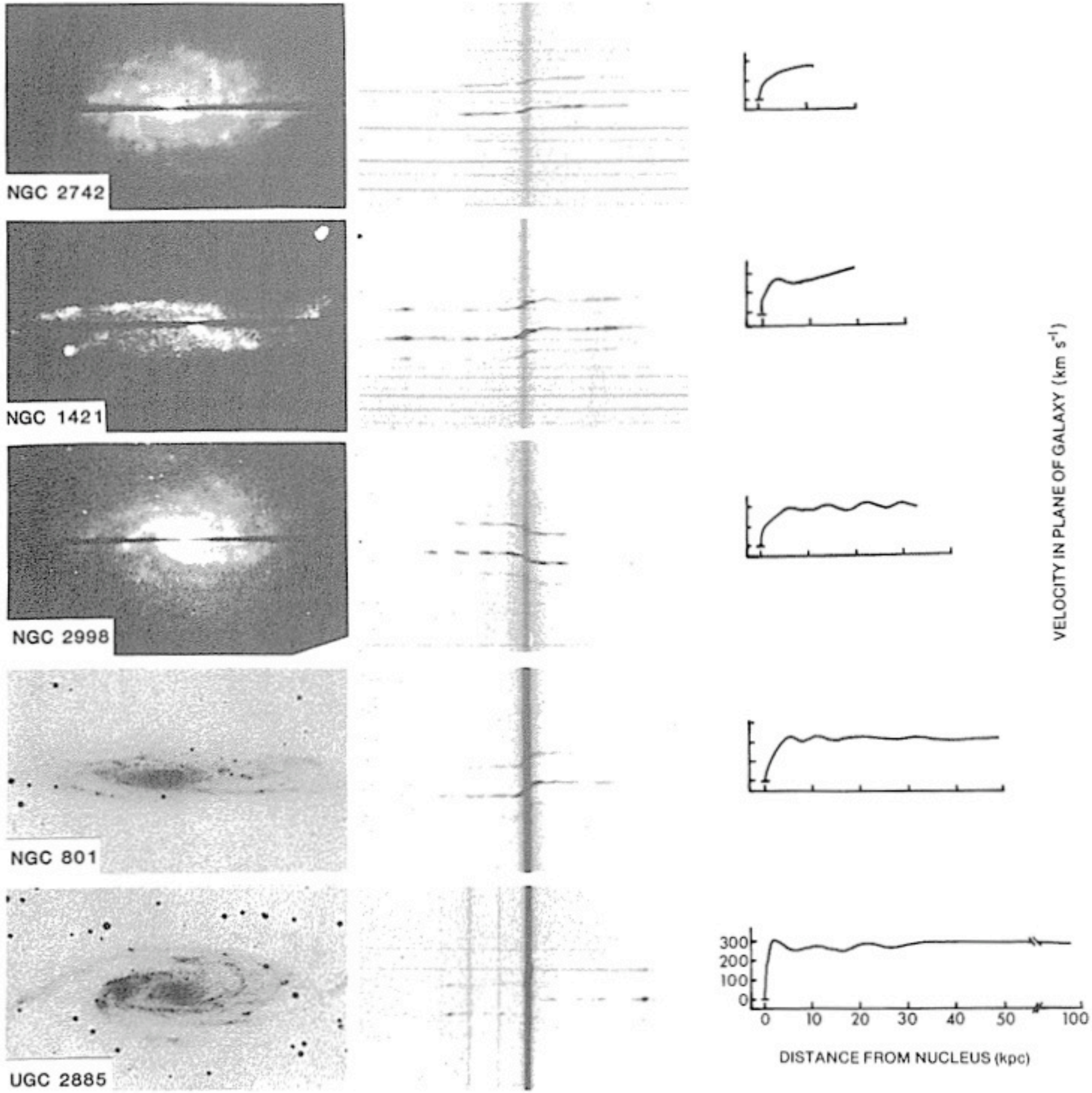
cross section



WIMP mass (~100 GeV natural)


A single galaxy might seem a little thing to those who consider only the immeasurable vastness of the universe, and not the minute precision to which all things therein are shaped.
Paraphrased from the *Ainulindalë* by J.R.R. Tolkein

Rubin, Thonnard, & Ford 1978, ApJ, **225**, L107



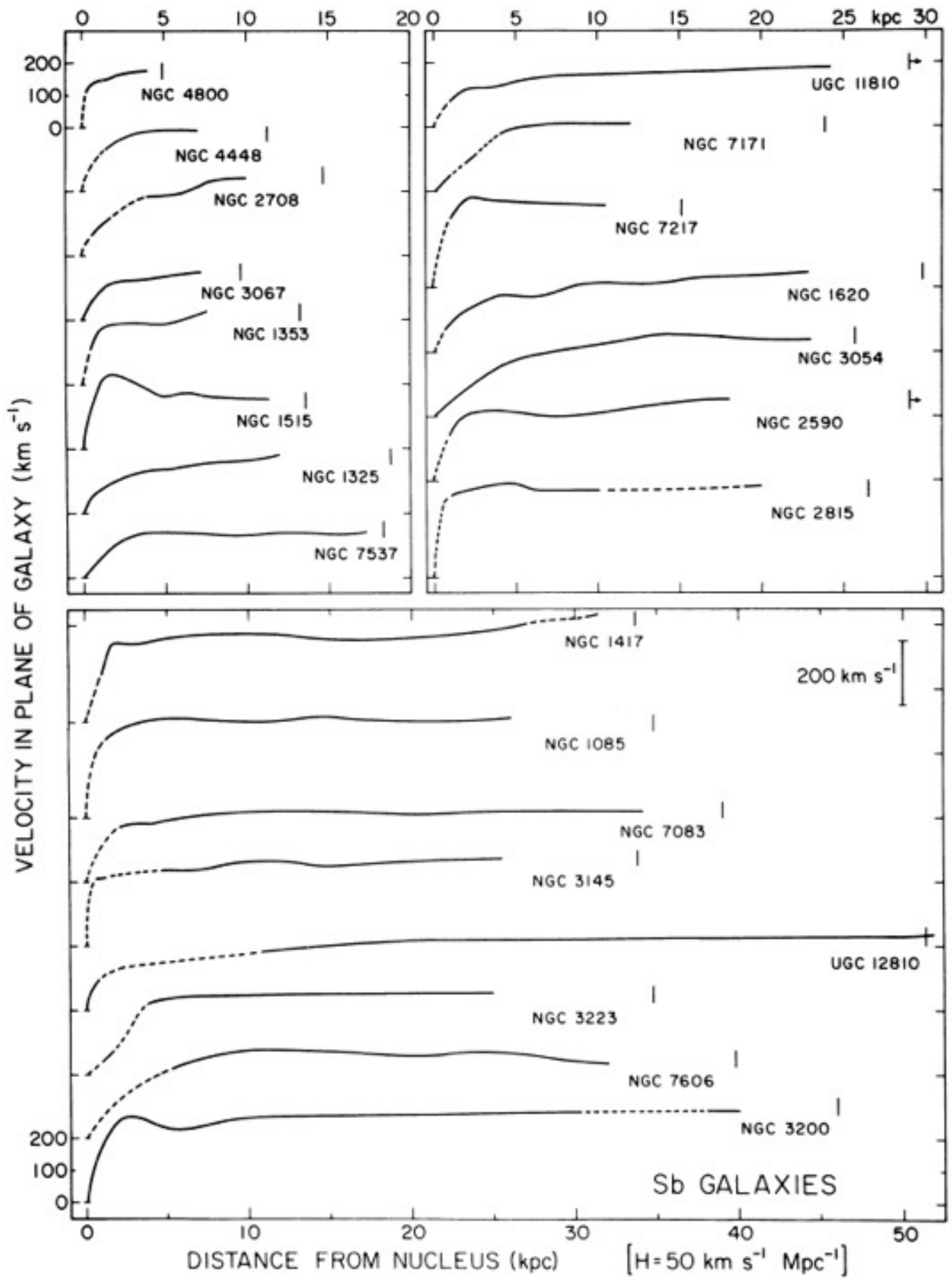


FIG. 3.—Mean velocities in the plane of the galaxy, as a function of linear radius for 23 Sb galaxies, arranged approximately according to increasing luminosity. Adopted curve is rotation curve formed from the mean of velocities on both sides of the major axis. Vertical bar marks the location of R_{25}, the isophote of 25 mag arcsec^{-2}, corrected for effects of internal extinction and inclination. Regions with no measured velocities are indicated by dashed lines.

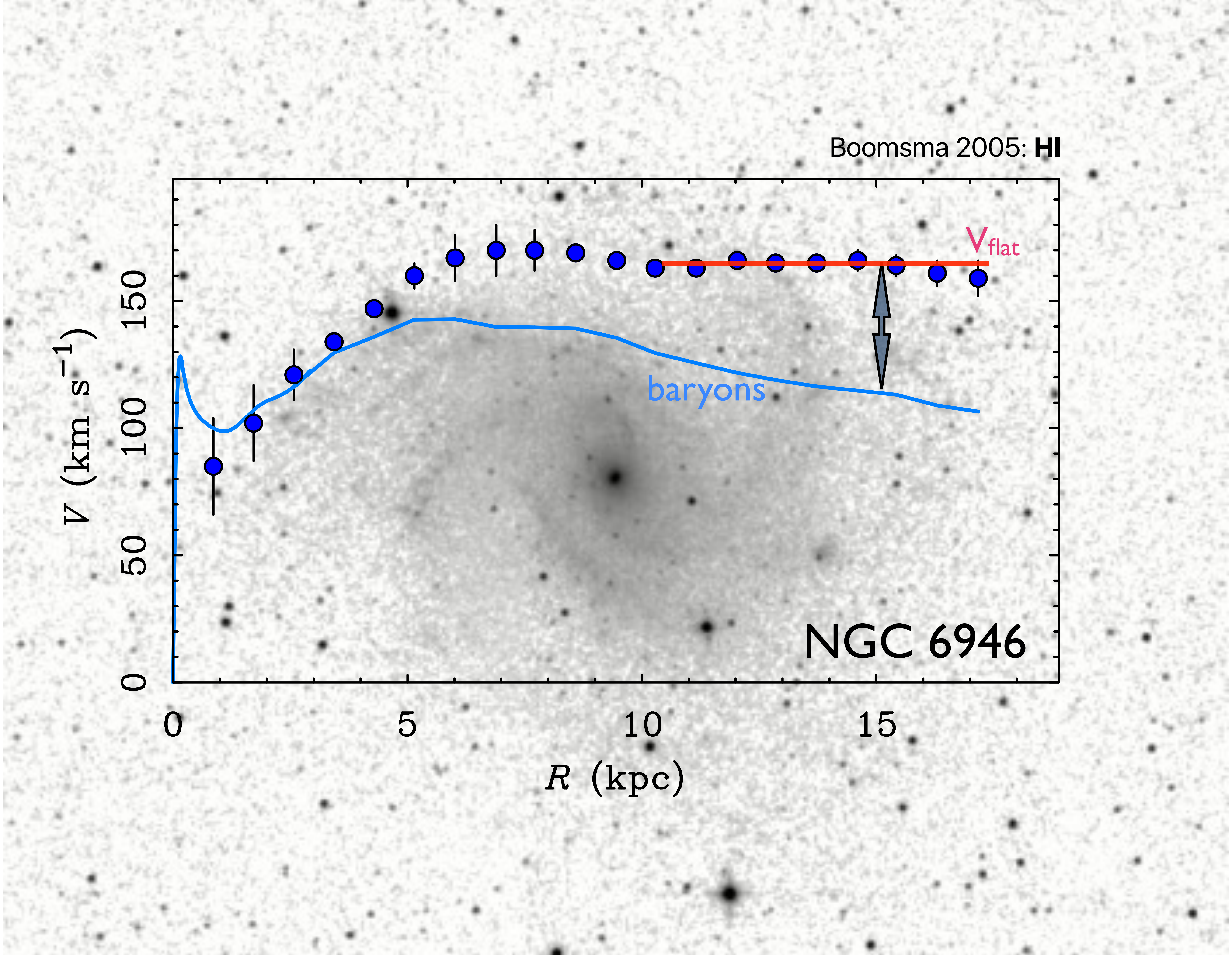
Rubin, Thonnard, & Ford 1978, ApJ, **225**, L107

Rotation curves become flat at large radii

$$V \propto \text{const}$$

$$M \propto R$$

$$\rho \propto R^{-2}$$



Boomsma 2005: **HI**
V_flat
baryons
NGC 6946
V (km s−1)
R (kpc)
0
50
100
150
0
5
10
15

SPARC
Spitzer Photometry & Accurate Rotation Curves

Federico Lelli | Stacy McGaugh | James Schombert

SPARC is a sample of
- 175 disk galaxies with resolved observations of both stars and gas
- Spitzer [3.6] photometry tracing the stellar mass
- 21 cm maps of the atomic (HI) gas
- high-quality HI/Hα rotation curves tracing the gravitational potential

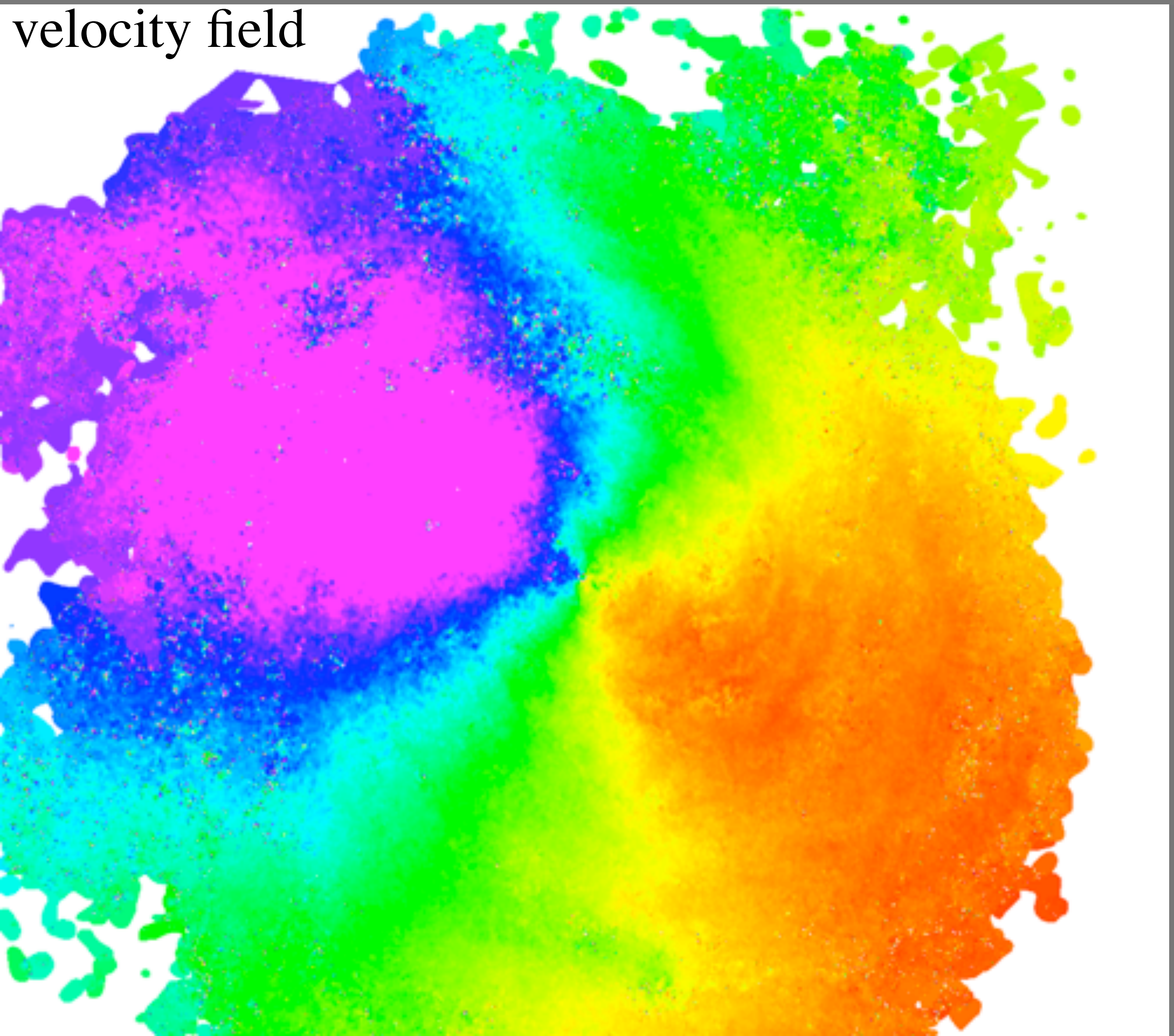
SPARC spans a wide range in
- morphological types (S0 to Irr - basically everything that rotates)
- stellar masses (5 dex) $10^7 < M_* < 10^{12}$ M$_\odot$
- surface brightnesses (4 dex) $5 < \Sigma_0 < 10^4$ M$_\odot$ pc^{-2}
- all gas fractions $0.01 < f_g < 0.99$

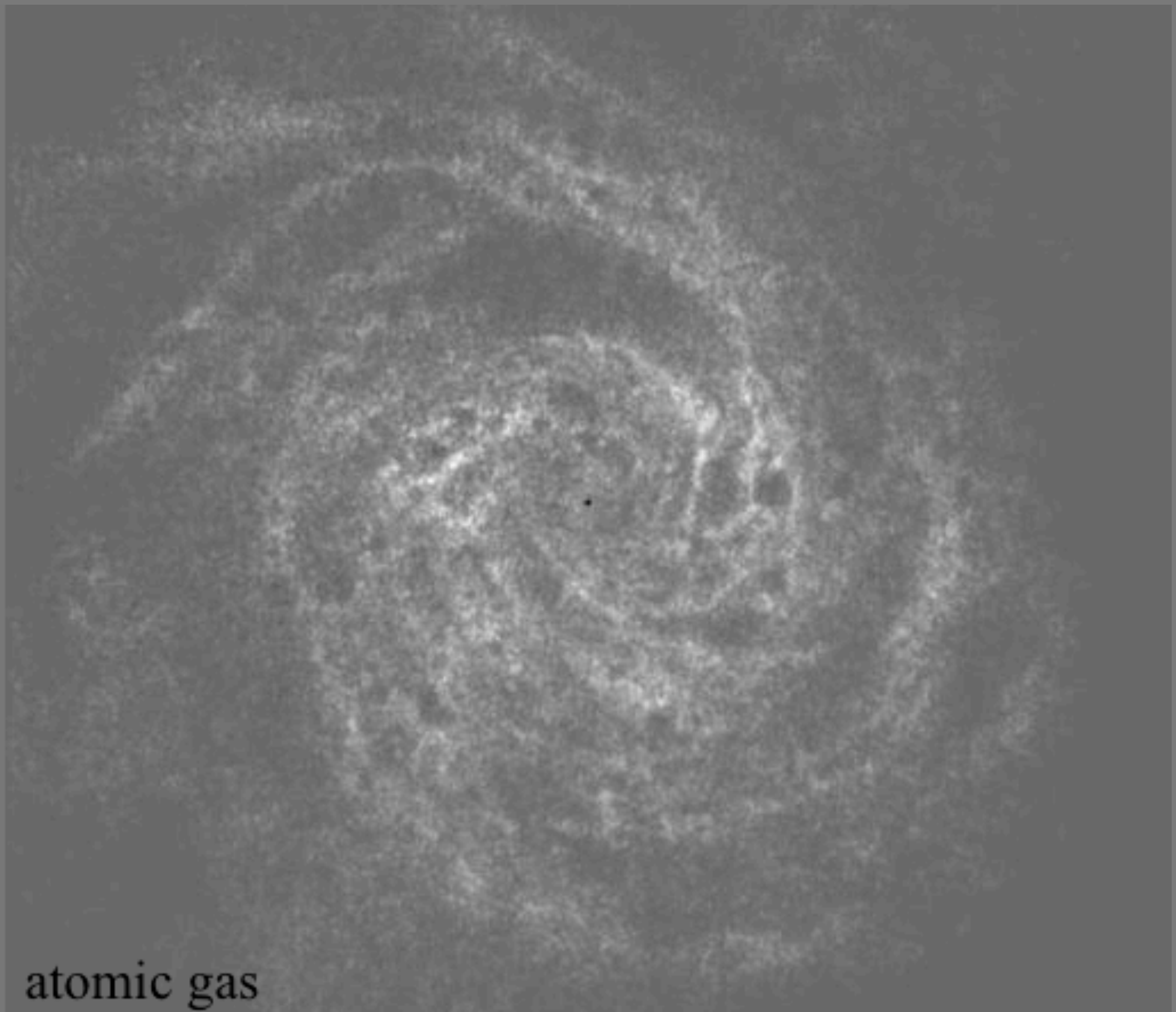
NGC 6946

For each galaxy,
have at least
- near-IR [3.6] image (stars)
- HI map (atomic gas)
- HI velocity field

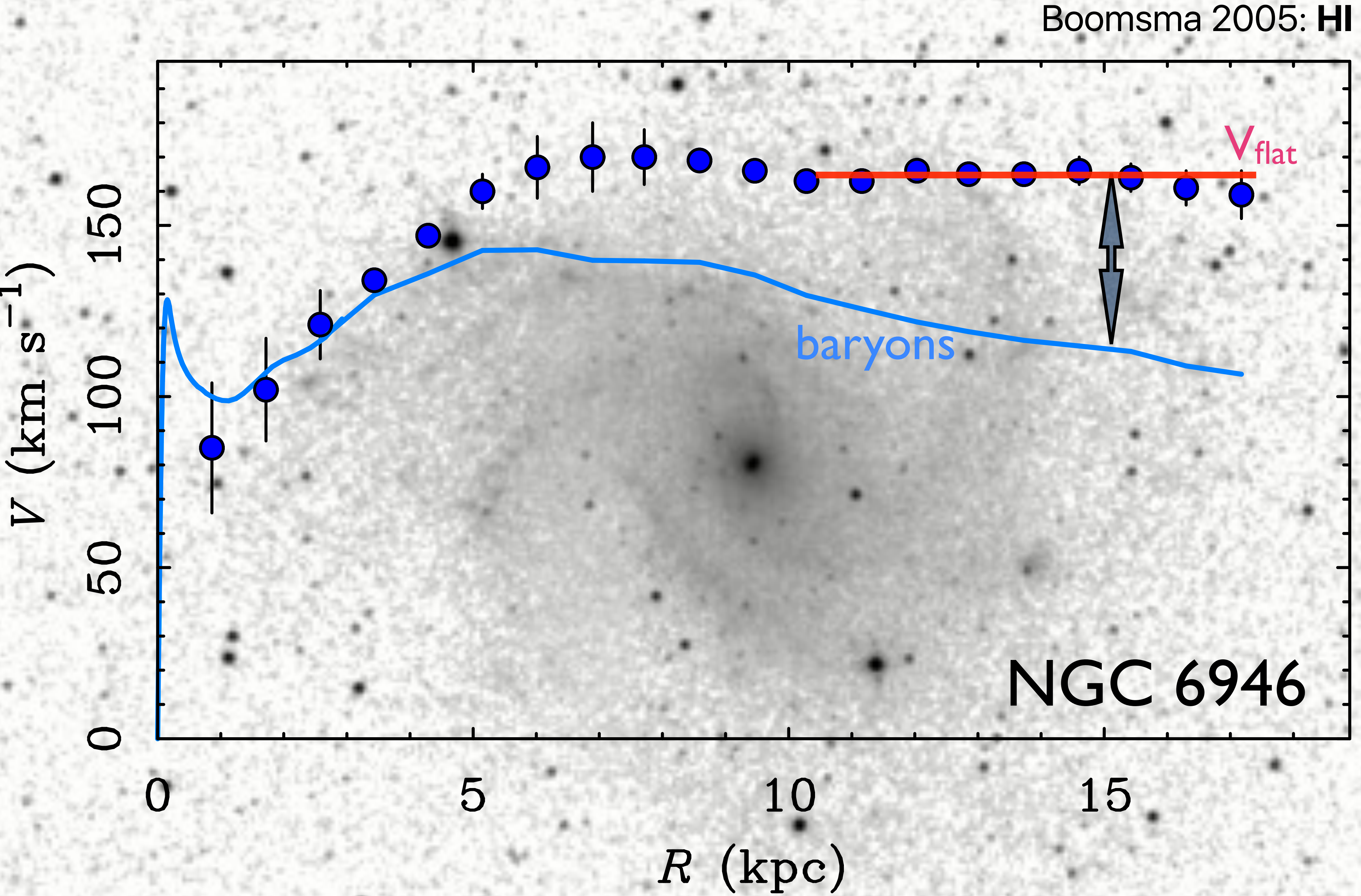
optical

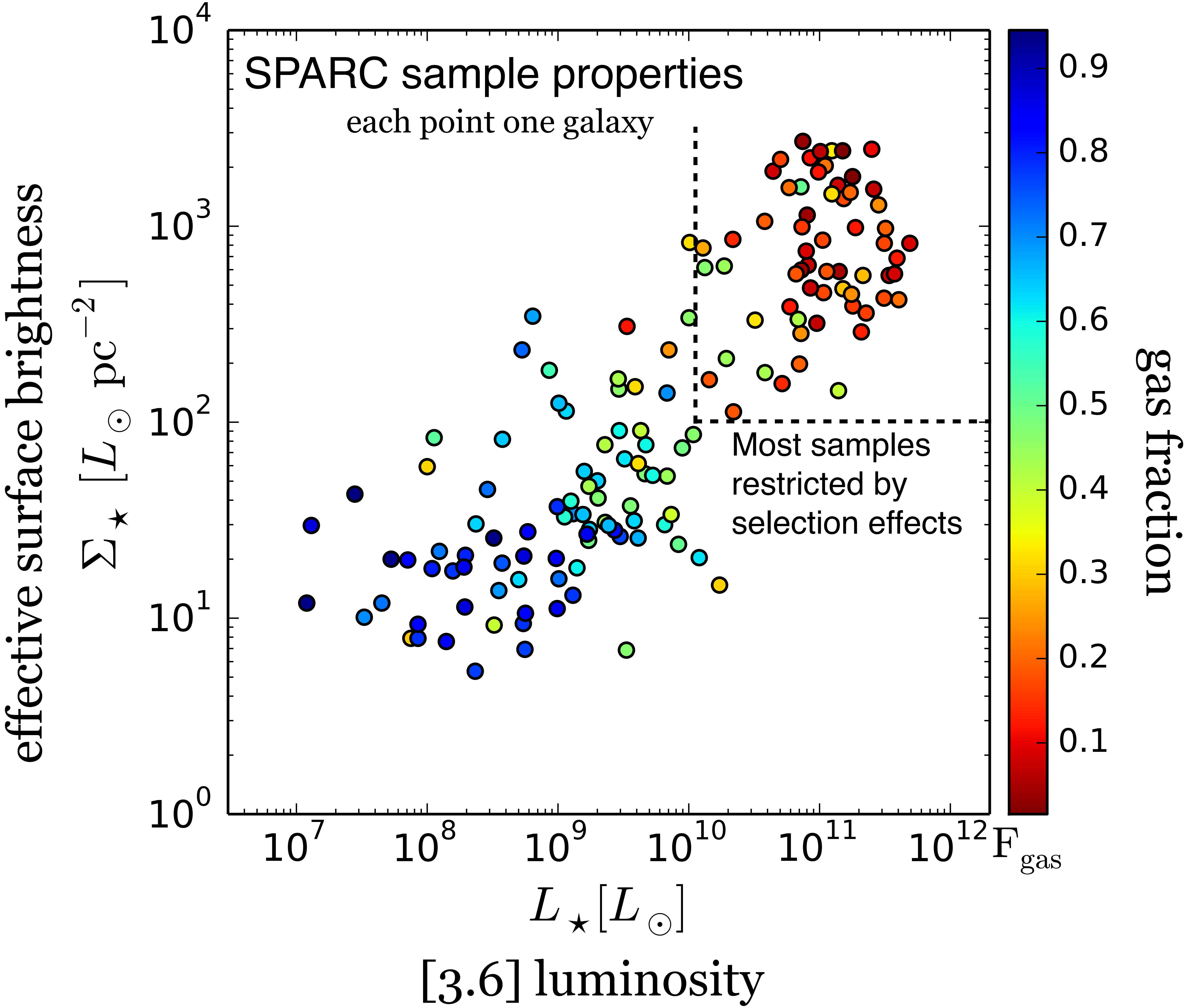
near infrared





Excess rotation indicates new physics: dark matter or modified gravity





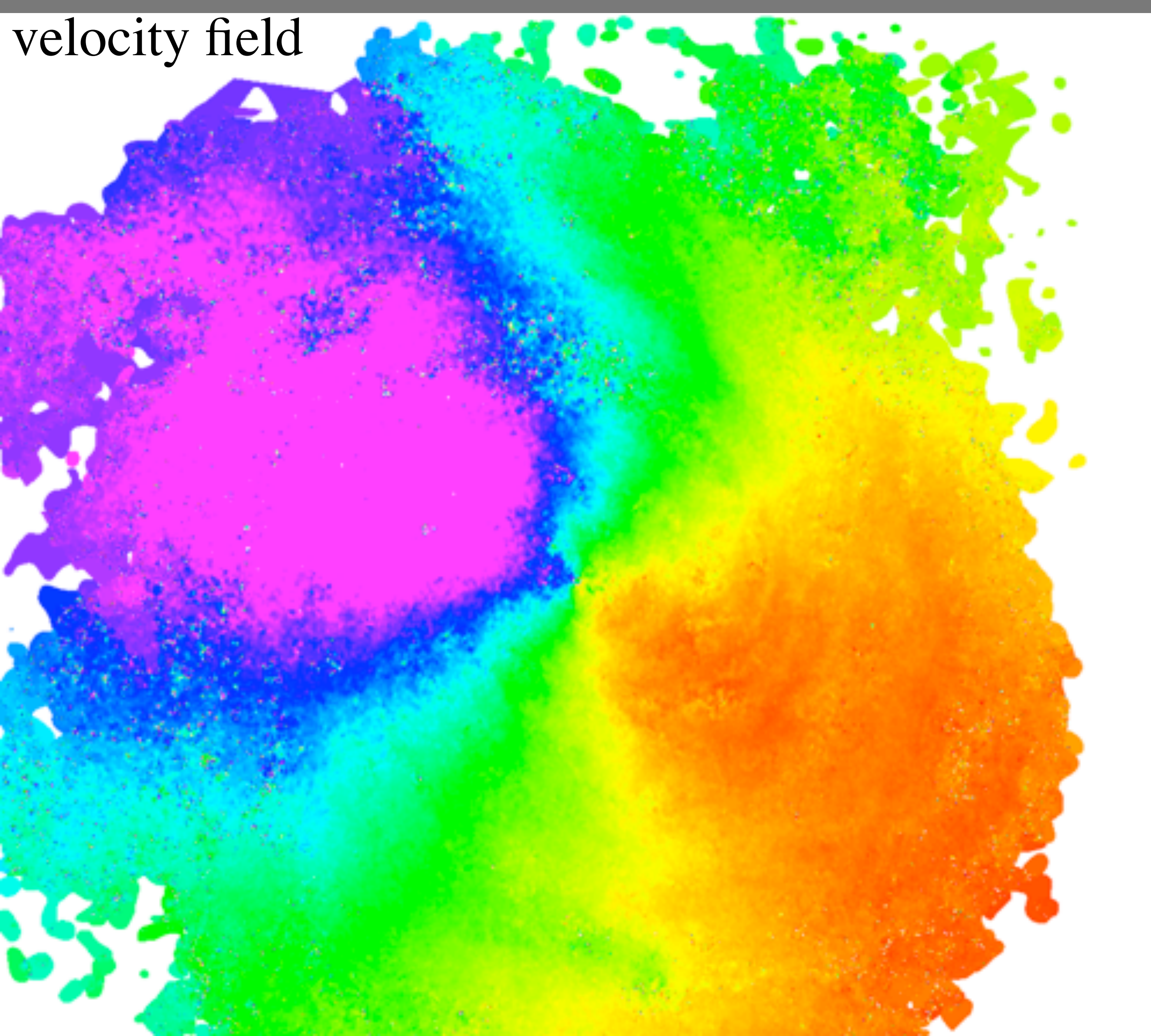
SPARC sample properties
each point one galaxy
Most samples
restricted by
selection effects
effective surface brightness
$\Sigma_\star\ [L_\odot\ \mathrm{pc}^{-2}]$
10^0
10^1
10^2
10^3
10^4
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
$L_\star[L_\odot]$
[3.6] luminosity
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
F_{gas}
gas fraction

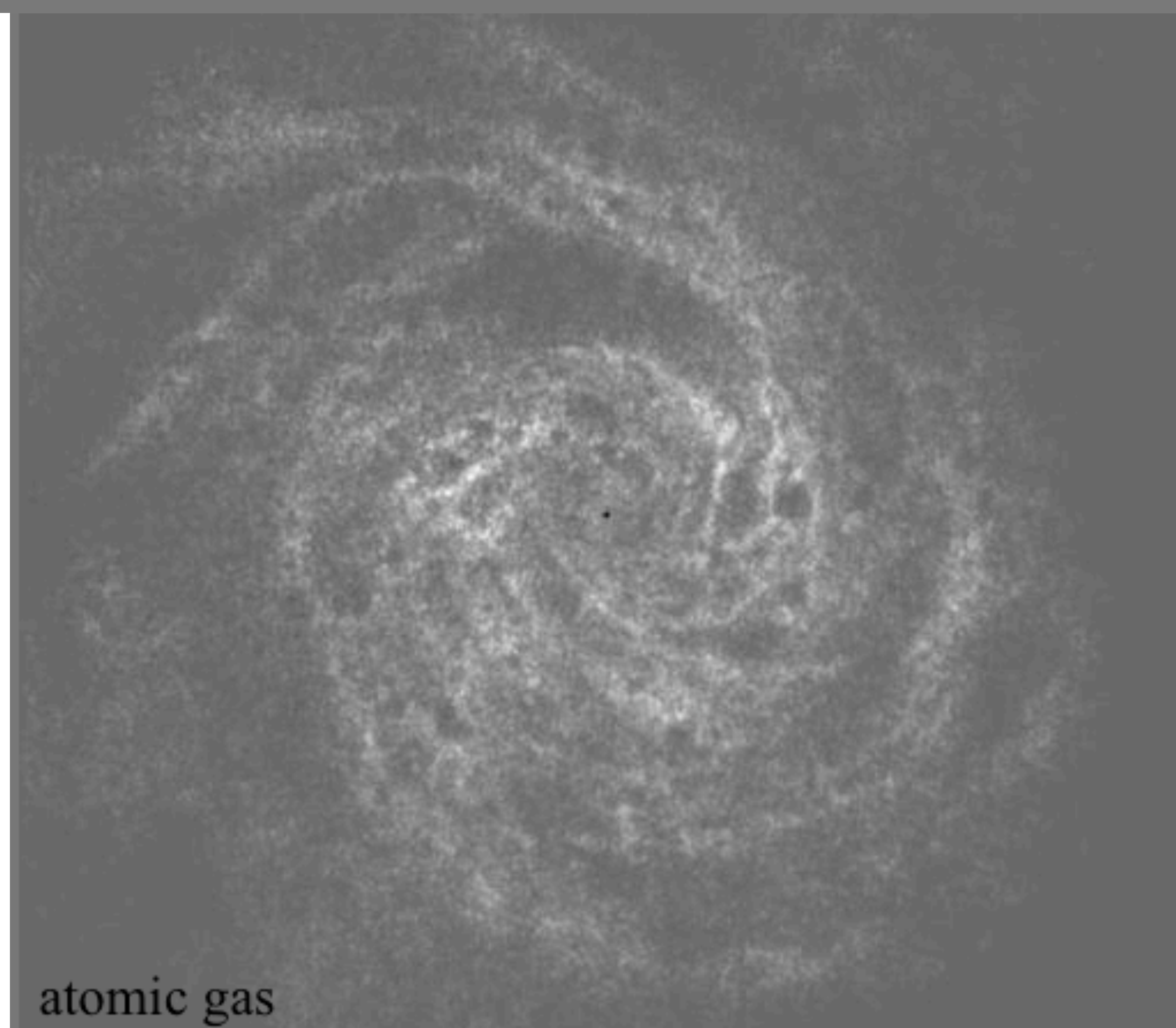
NGC 6946

For each galaxy,
construct mass models
- [3.6] image -> stellar mass
- HI map -> gas mass
velocity field -> rotation curve

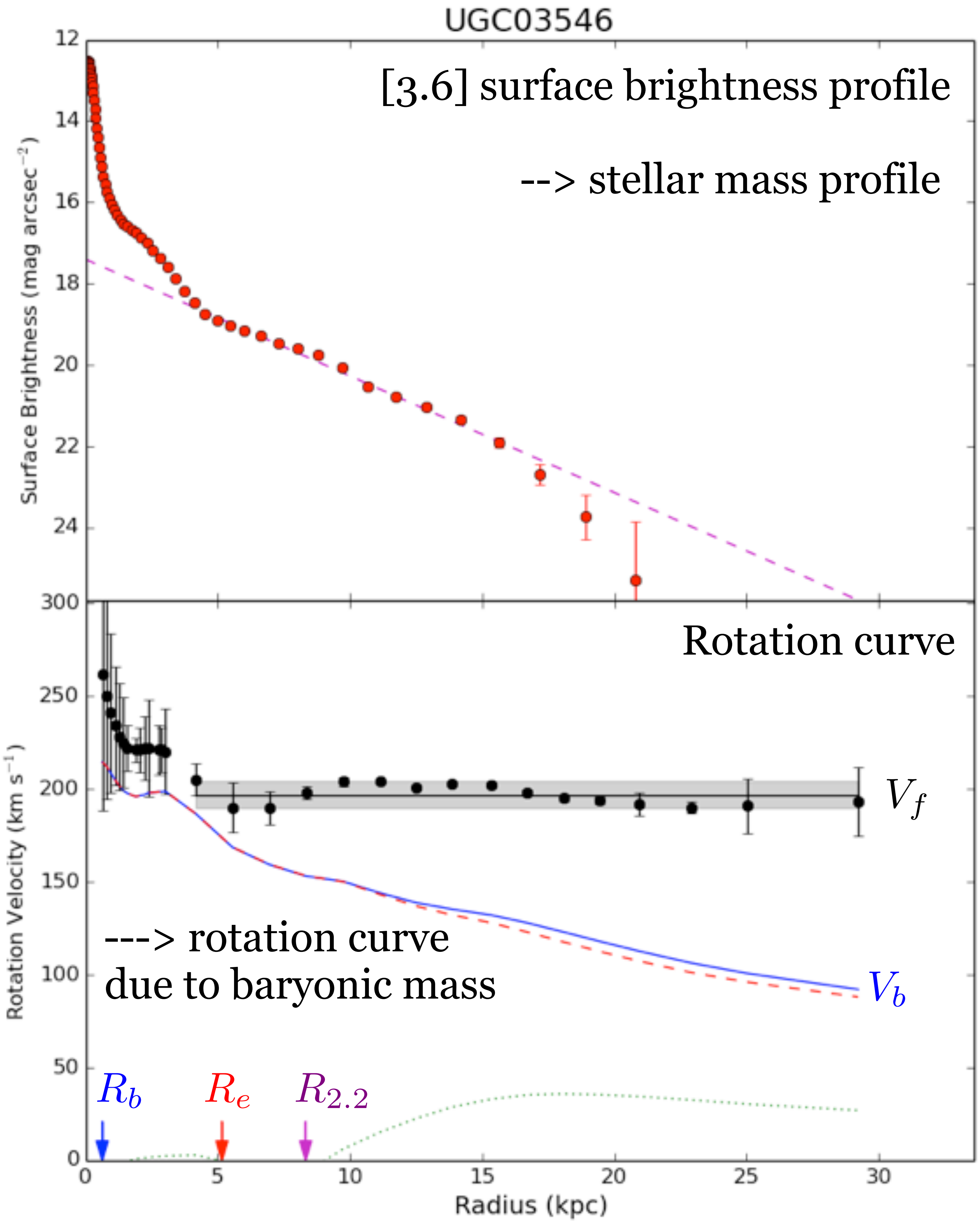
optical

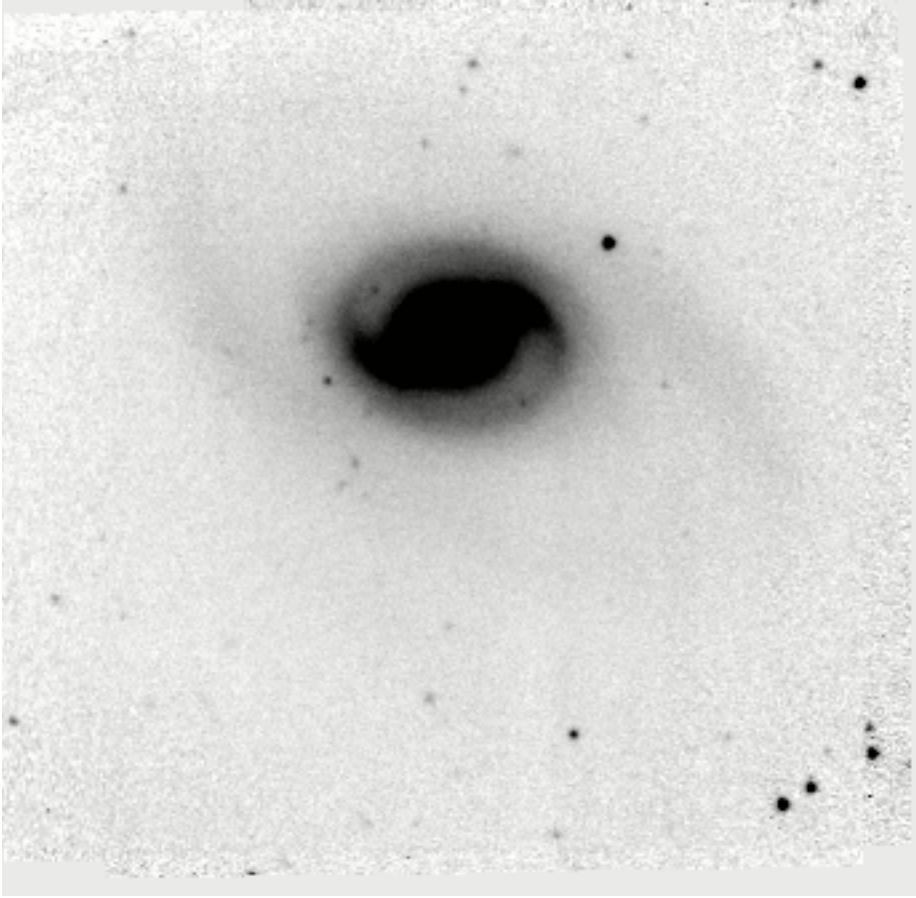
near infrared





Fast rotator

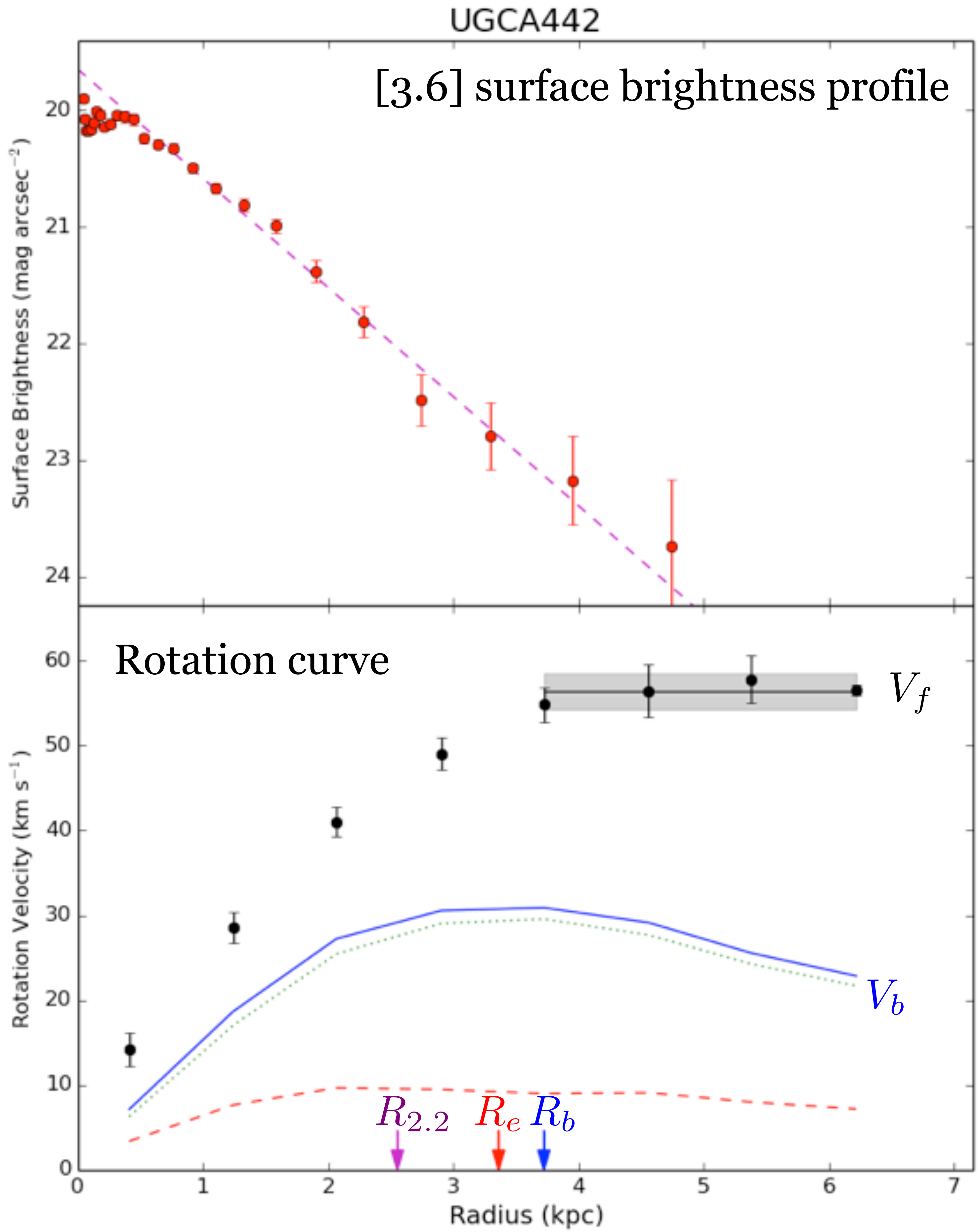


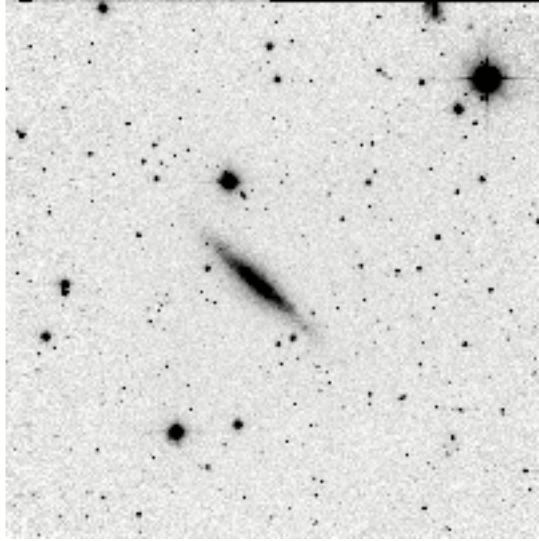


Observed mass scales with rotation velocity: Tully-Fisher Relation

Fast rotators are high mass

Slow rotator

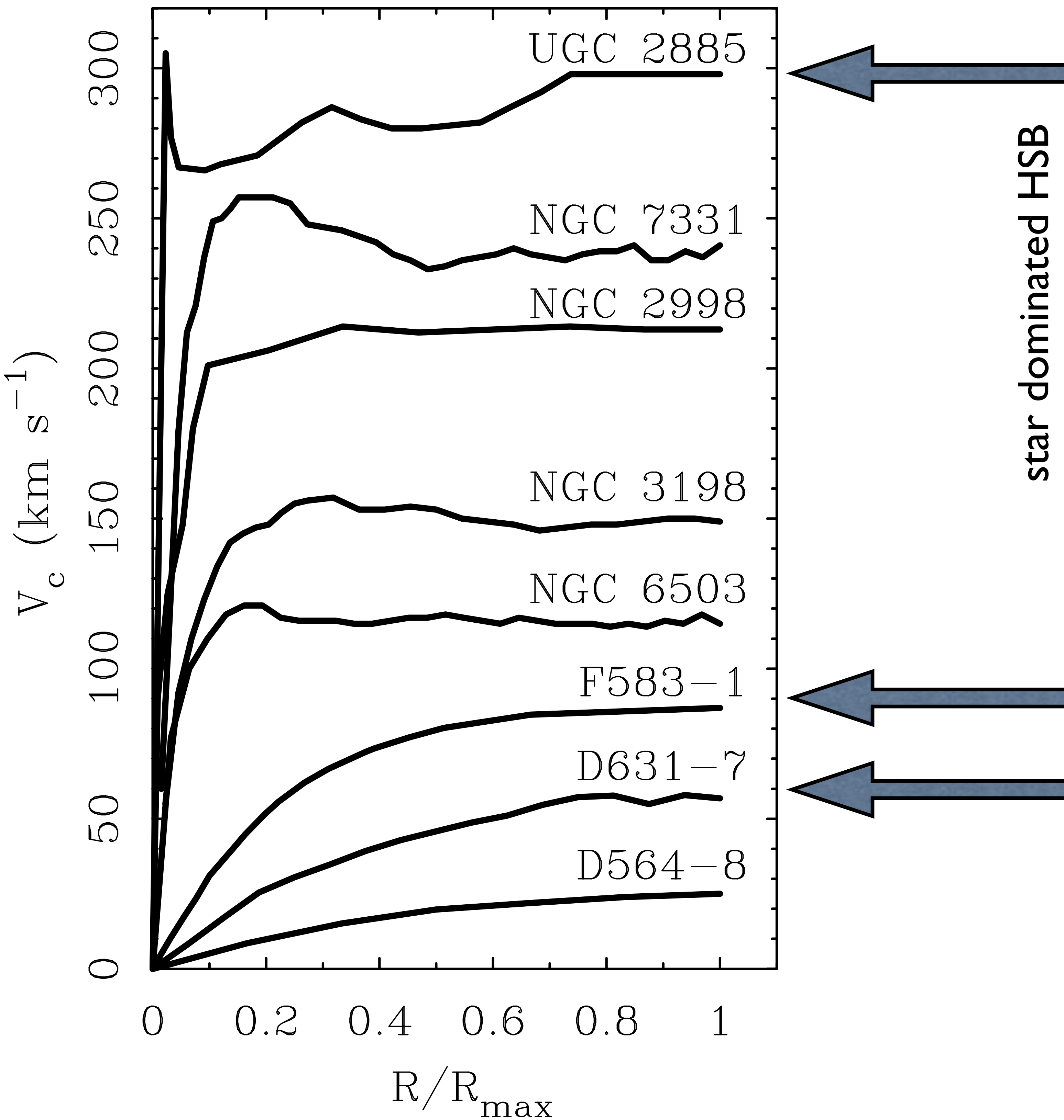




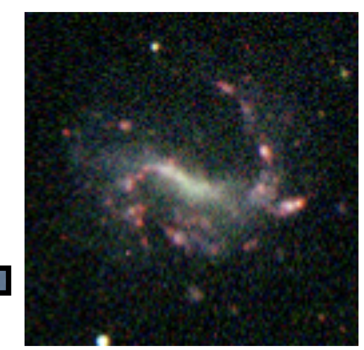
Observed mass scales with rotation velocity: Tully-Fisher Relation

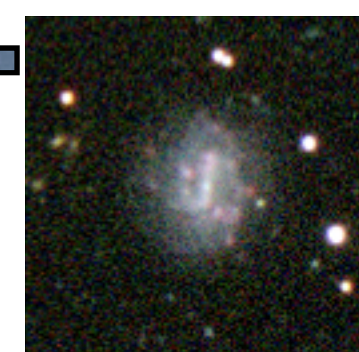
Slow rotators are low mass

Flat rotation speed correlates with mass

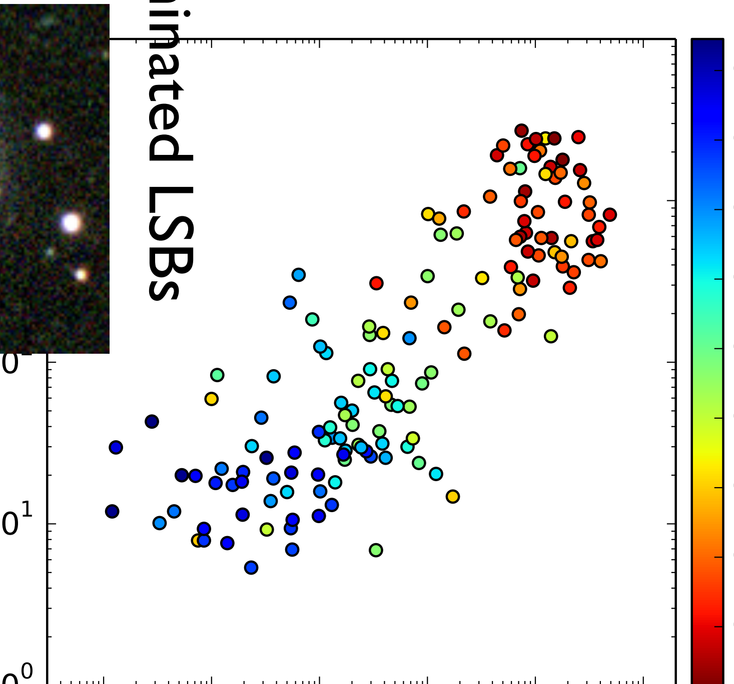


star dominated HSB



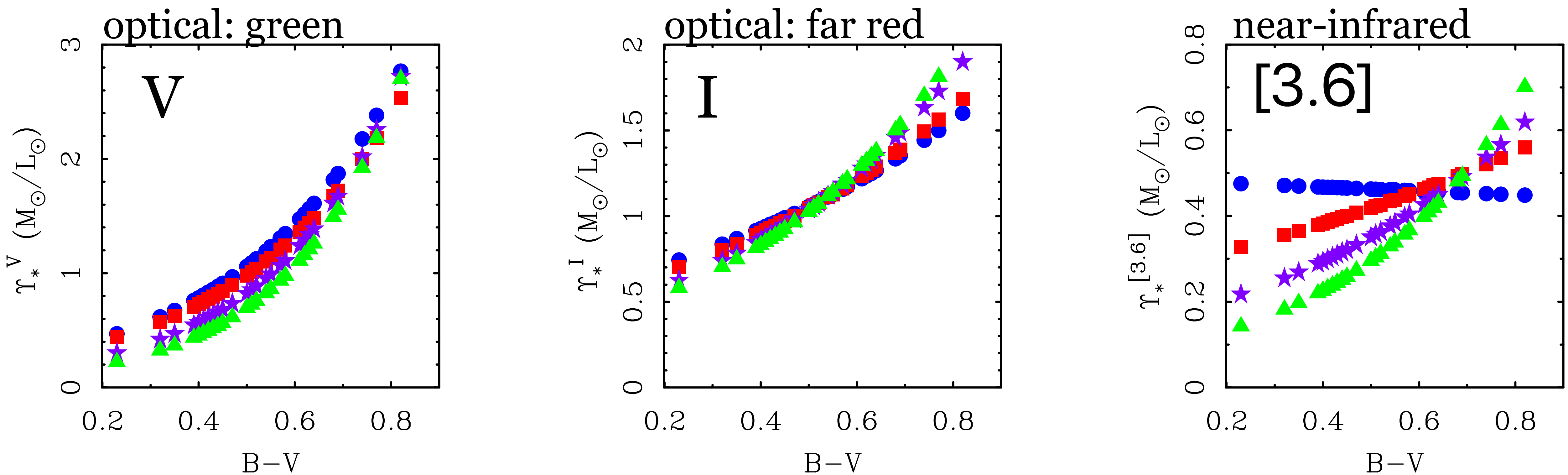


gas dominated LSBs



Stellar Mass

McGaugh & Schombert 2014, AJ, 148, 77



Stellar population synthesis models modified for self-consistency
Band dependent mass-to-light ratios correlate with color

Table 7
Revised CMLR

Model	a_V	b_V	α_I	β_I	$\alpha_{[3.6]}$	$\beta_{[3.6]}$	$\Upsilon^V_{0.6}$	$\Upsilon^I_{0.6}$	$\Upsilon^K_{0.6}$	$\Upsilon^{[3.6]}_{0.6}$
Bell et al. (2003) ●	−0.628	1.305	−0.275	0.612	−0.322	−0.007	1.43	1.24	0.61	0.47
Portinari et al. (2004) ■	−0.654	1.290	−0.321	0.701	−0.594	0.467	1.32	1.26	0.63	0.49
Zibetti et al. (2009) ▲	−1.075	1.837	−0.477	1.004	−1.147	1.289	1.07	1.33	0.54	0.42
Into & Portinari (2013) ★	−0.900	1.627	−0.421	0.898	−0.861	0.849	1.19	1.31	0.58	0.45

Note. — Stellar mass-to-light ratios in the V, I, and K-bands given by the formula $\log \Upsilon^j_* = \alpha_j + \beta_j(B-V)$. For each model, the V-band is identical to that in Table 2, but the I and [3.6] bands have been revised to attain self-consistency with the V-band, and further corrected for $V-I$ as a second color term: the Δ of Table 6 have been incorporated to produce these revised CMLR. The resulting lines are fits to the data in Fig. 8, providing our best estimate of the CMLR. For reference, the mass-to-light ratio at $B-V = 0.6$ is also given. For the K_s-band, we assume $\Upsilon^K_* = 1.29\Upsilon^{[3.6]}_*$.

Schombert & McGaugh 2014, PASA, 31, e036

Situation at [3.6] improved by proper treatment of metallicity distribution

Net result:
to a good approximation, M*/L constant in the near-IR

For disk component

$$\Upsilon_*^{[3.6]} = 0.5\ M_\odot/L_\odot$$

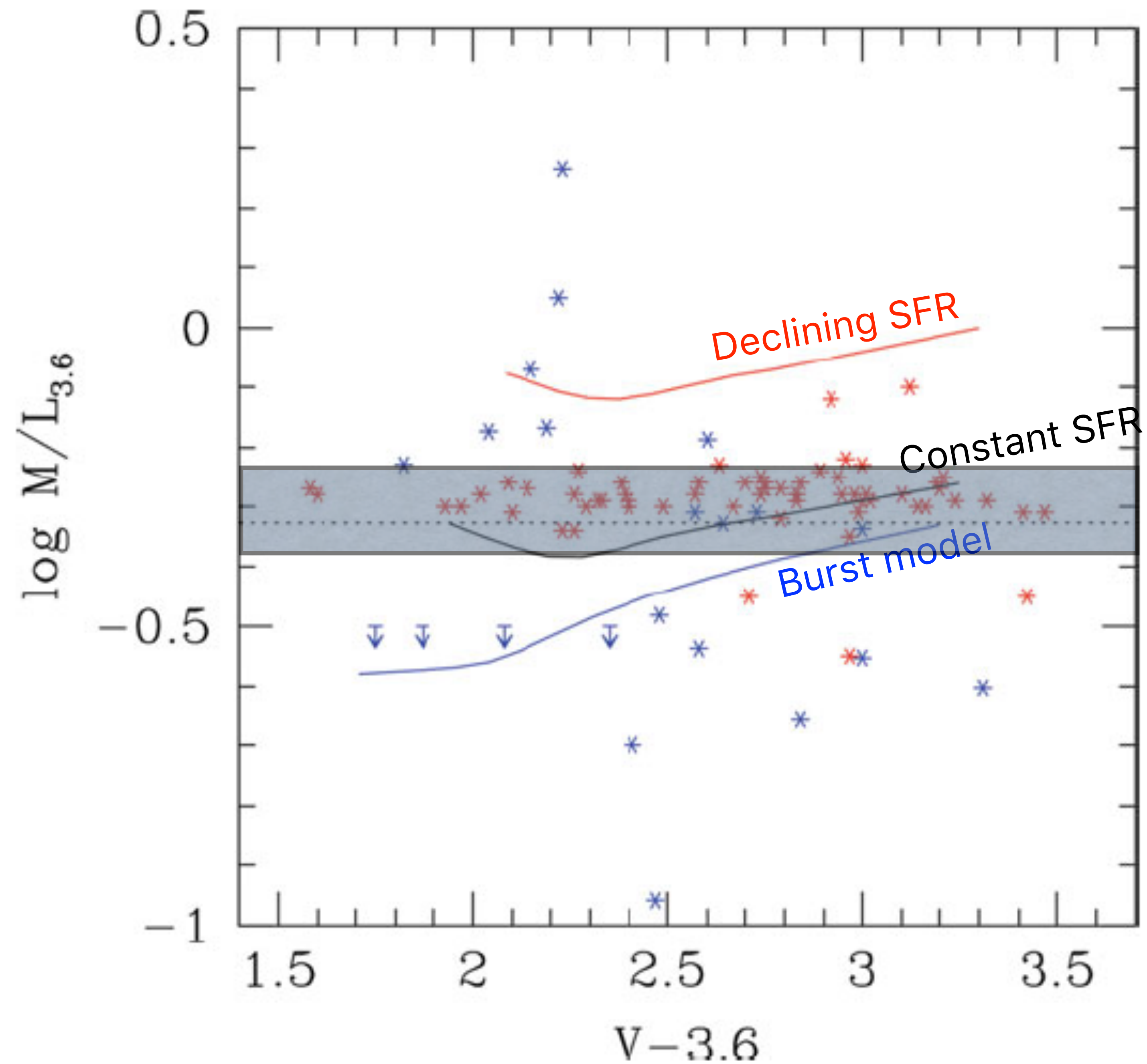
to +/- 20%

For bulge component

$$\Upsilon_*^{[3.6]} = 0.7\ M_\odot/L_\odot$$

only 31 galaxies have bulges

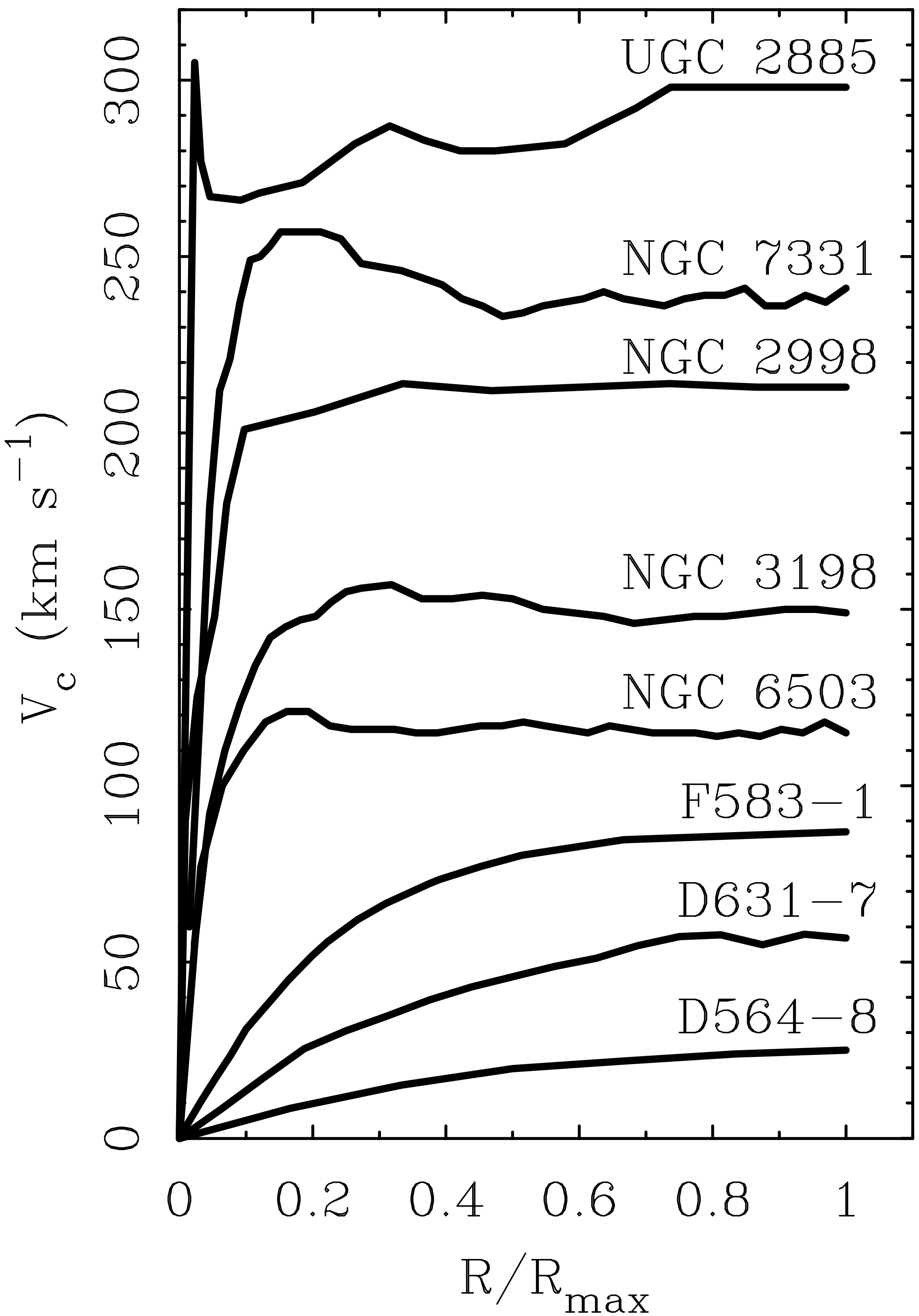
The metallicity distribution matters as well as the age distribution



Models with realistic metallicity distributions predict flatter CMLR in near-IR

There should always be some scatter in the CMLR

Flat rotation speed correlates with mass



Measures of mass

Stellar mass

$$\Upsilon_*^i = \alpha_i + \beta_i(B - V)$$

$$M_* = \Upsilon_*^i L_i$$

e.g., $\Upsilon_*^{[3.6]} = 0.5\ \mathrm{M}_\odot/\mathrm{L}_\odot$

Gas mass

Direct from 21 cm flux
corrected for helium abundance

Baryonic mass

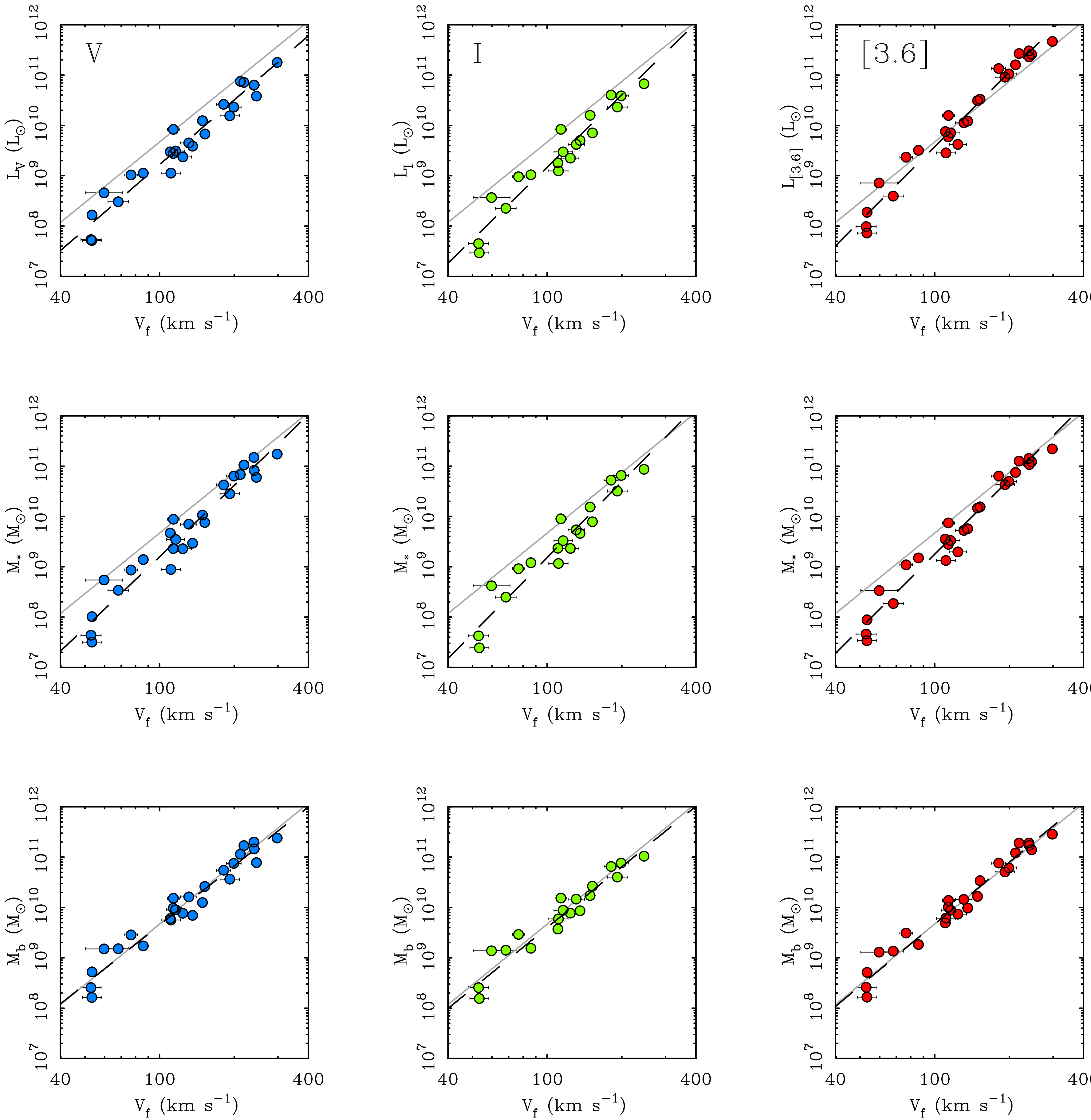
$$M_b = M_* + M_g$$

Tully-Fisher

L
Luminosity

M*
Stellar mass

$M_b = M_* + M_g$
Baryonic mass



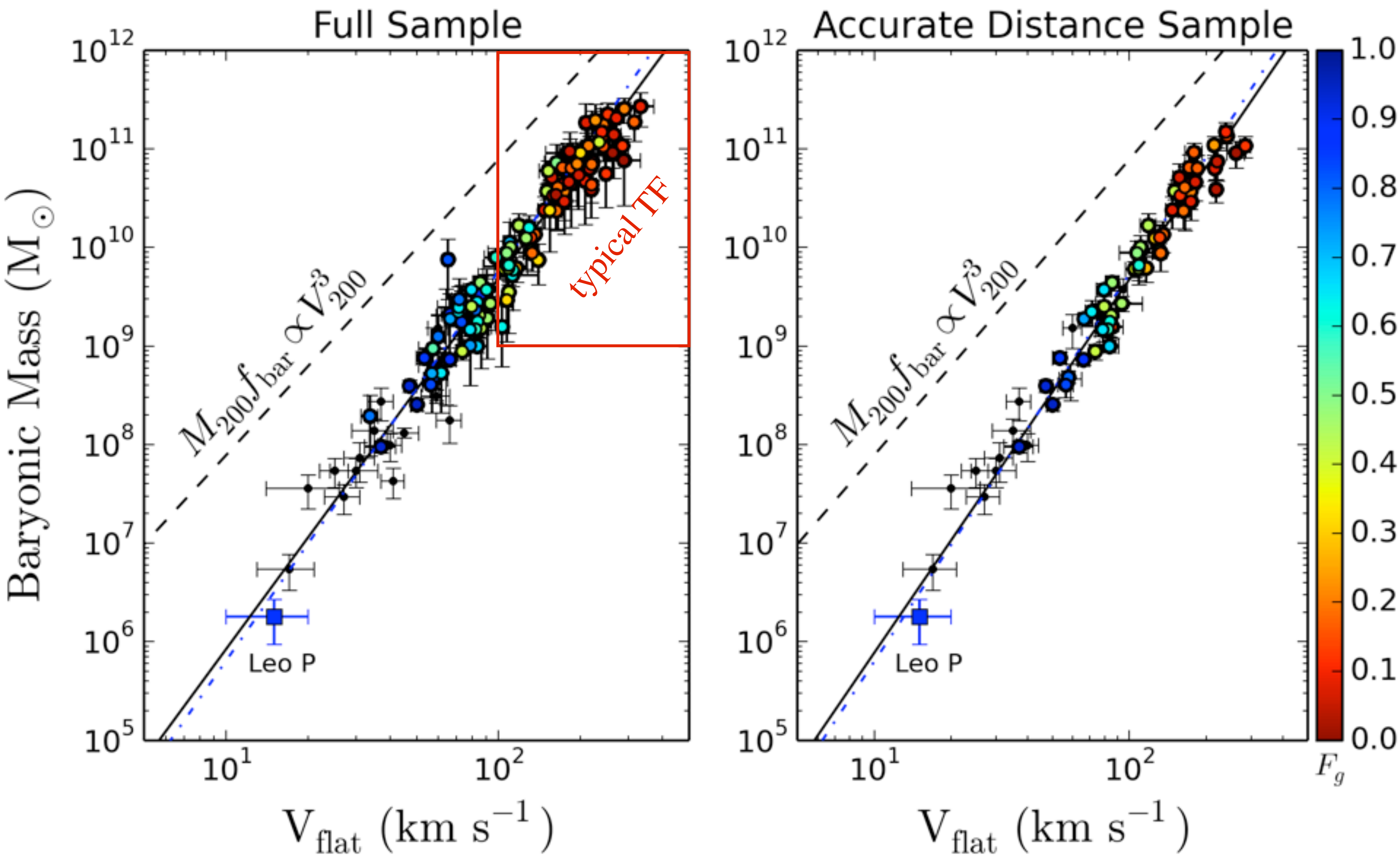
Stellar mass-to-light ratio color-dependent in optical bands

Stellar mass-to-light ratio effectively constant at [3.6]

$\Upsilon_* = 0.5\ M_\odot/L_\odot$

flat rotation speed

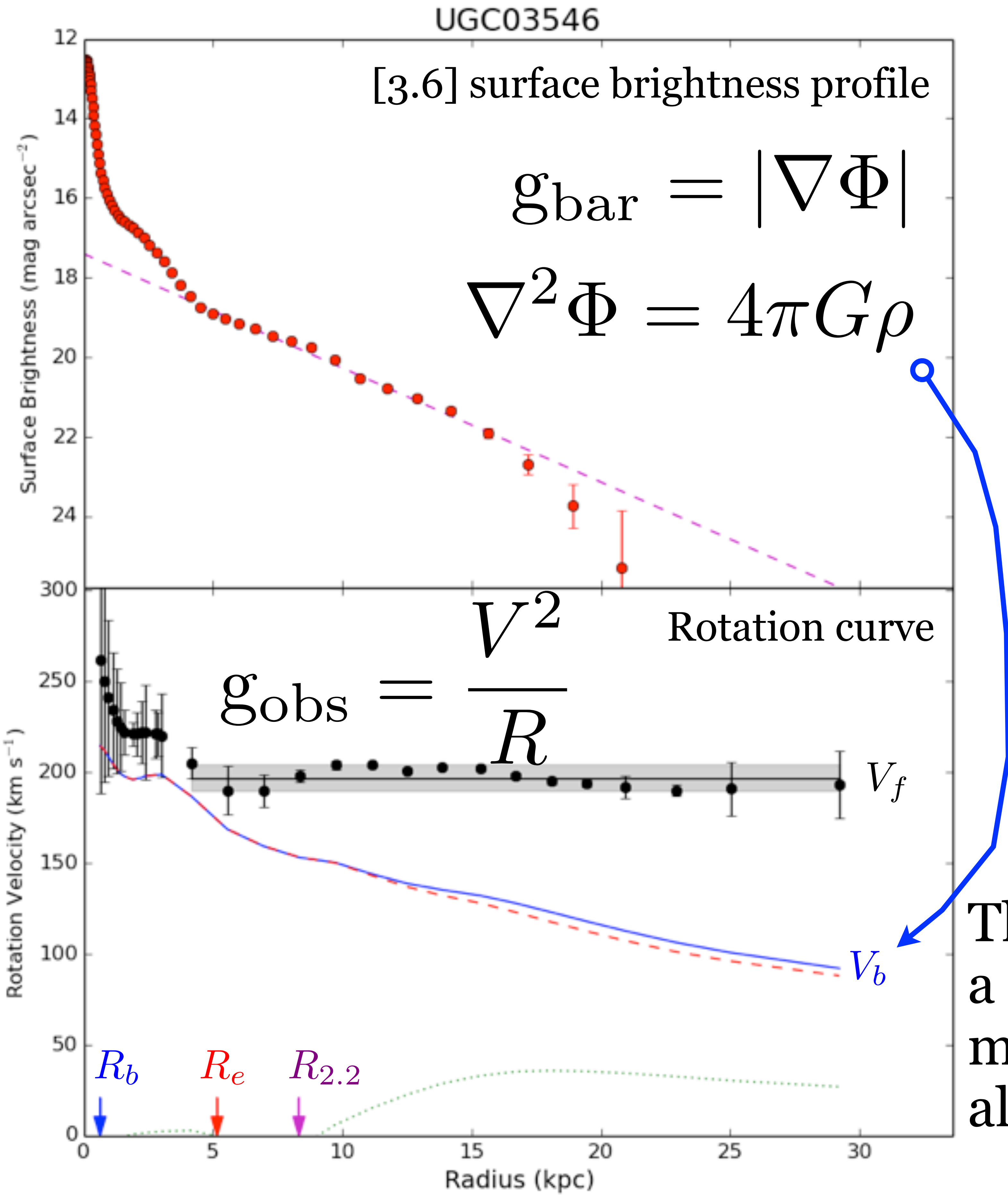
Baryonic Tully-Fisher relation: $M_b = 47\ V^4$

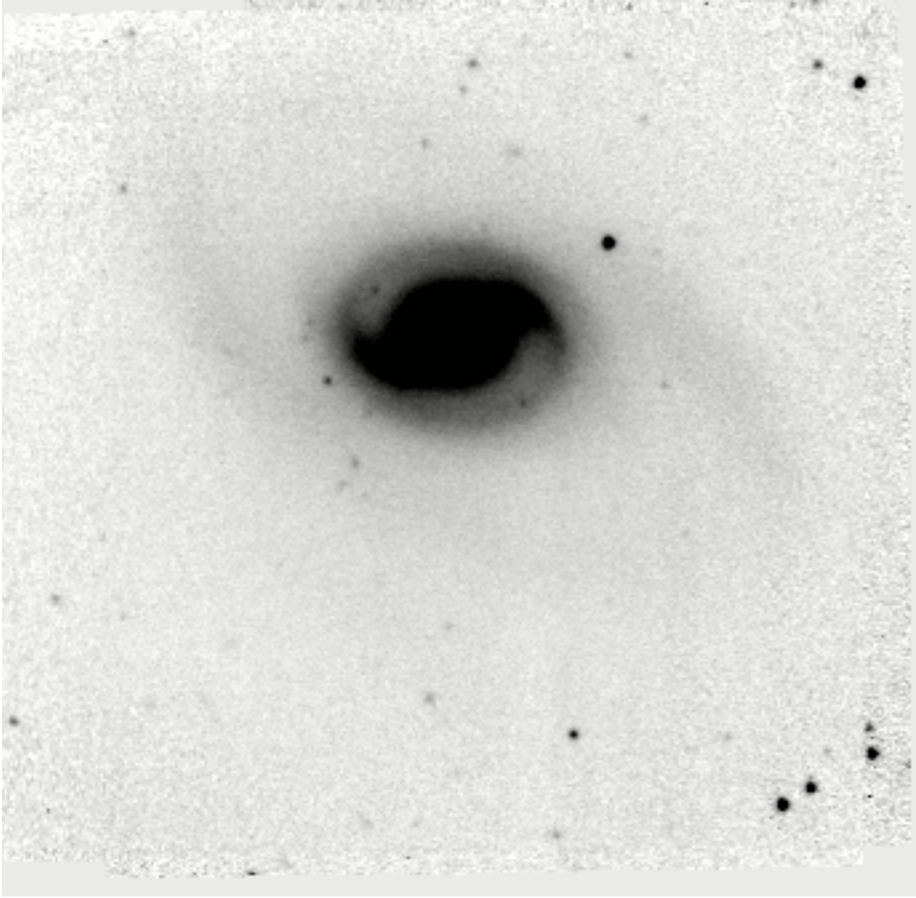


negligible intrinsic scatter

$\sigma_{M,intrinsic} < 0.15$

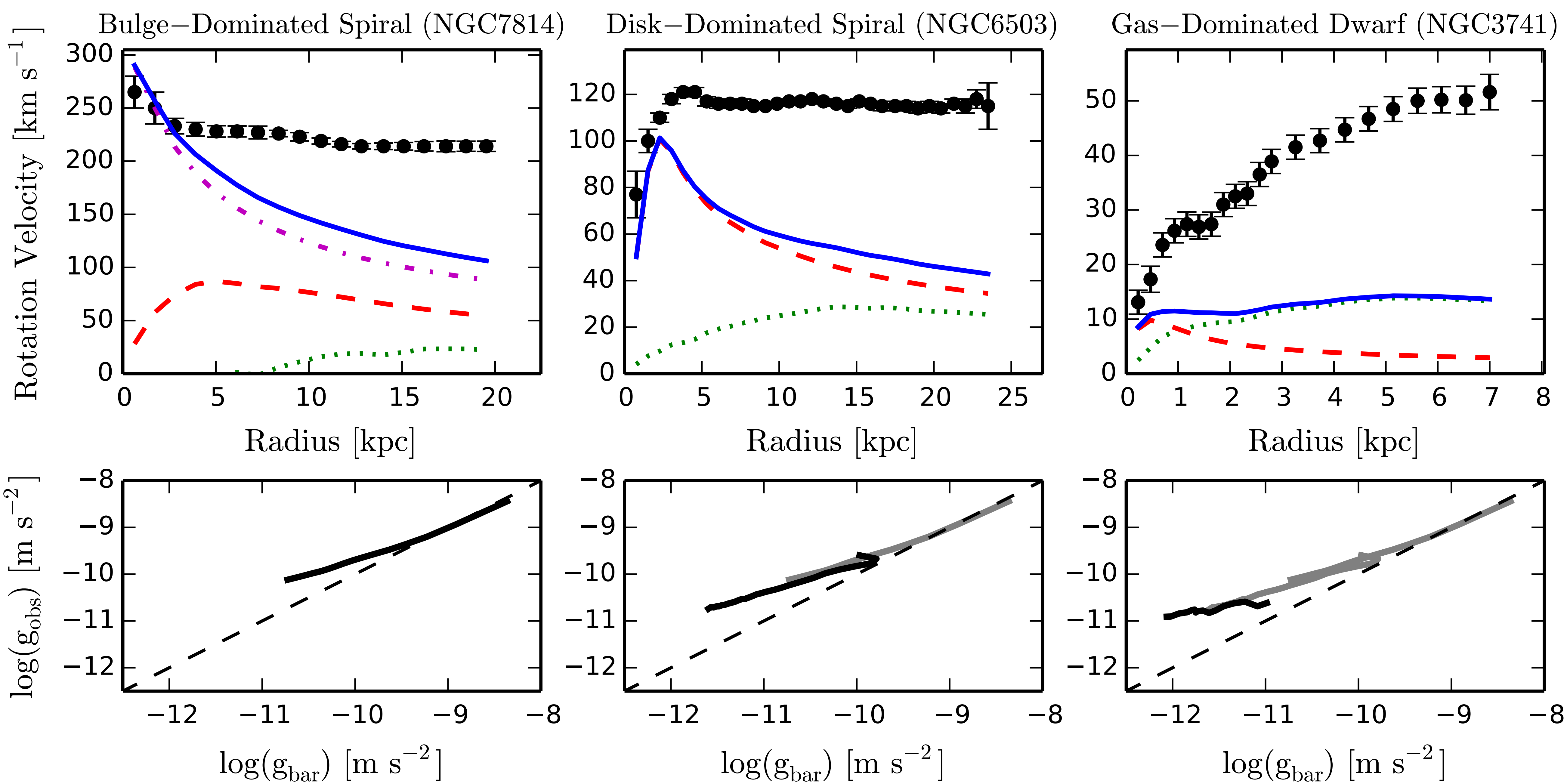
Fast rotator





The Tully-Fisher Relation is a global coupling between mass and light. There is also a local relation.

Use the same [3.6] mass-to-light ratio for all galaxies

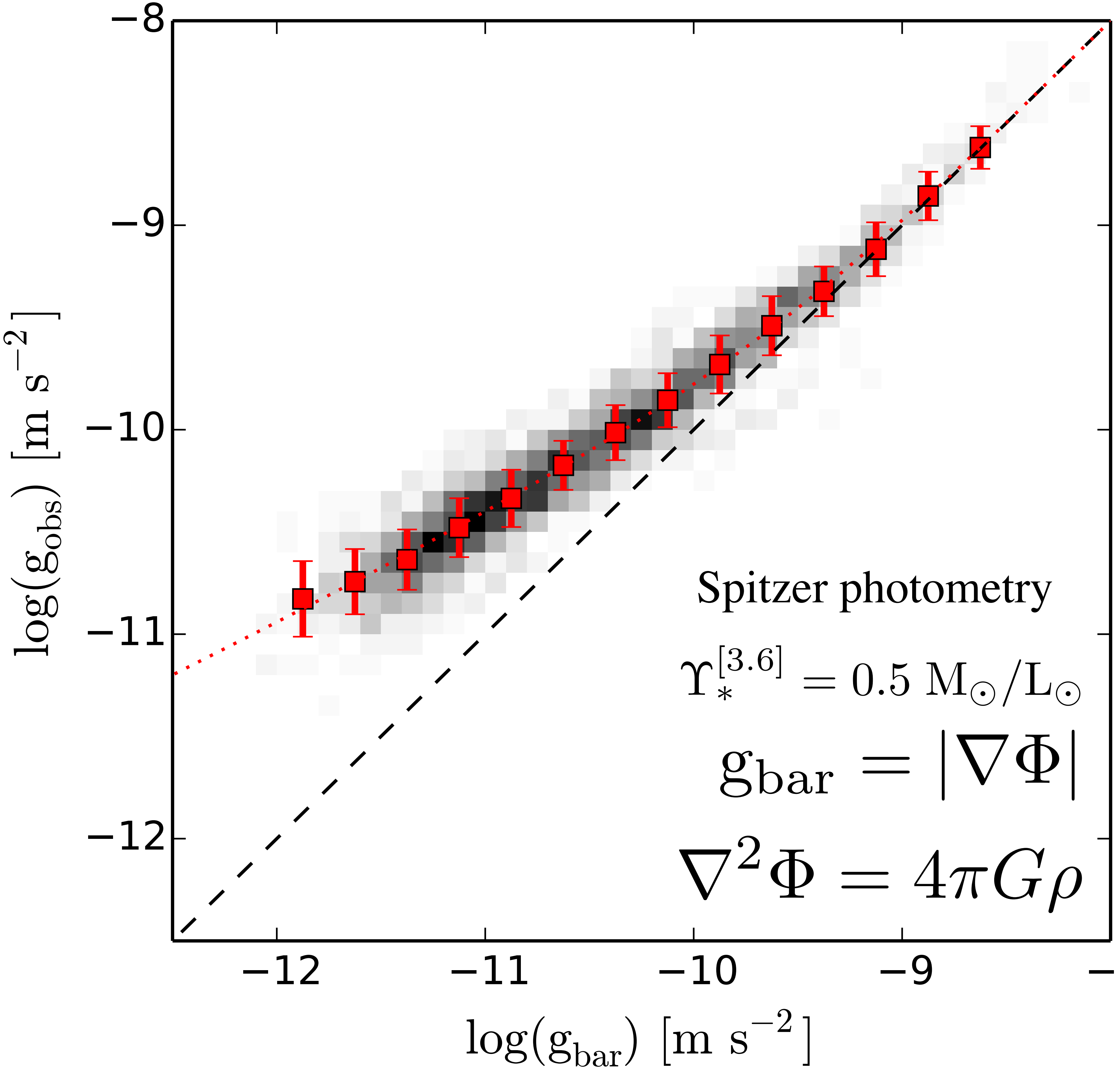


$$g_{obs} = \frac{V^2}{R} \quad \text{correlates with} \quad g_{bar} = \left| \frac{\partial \Phi_{bar}}{\partial R} \right|$$

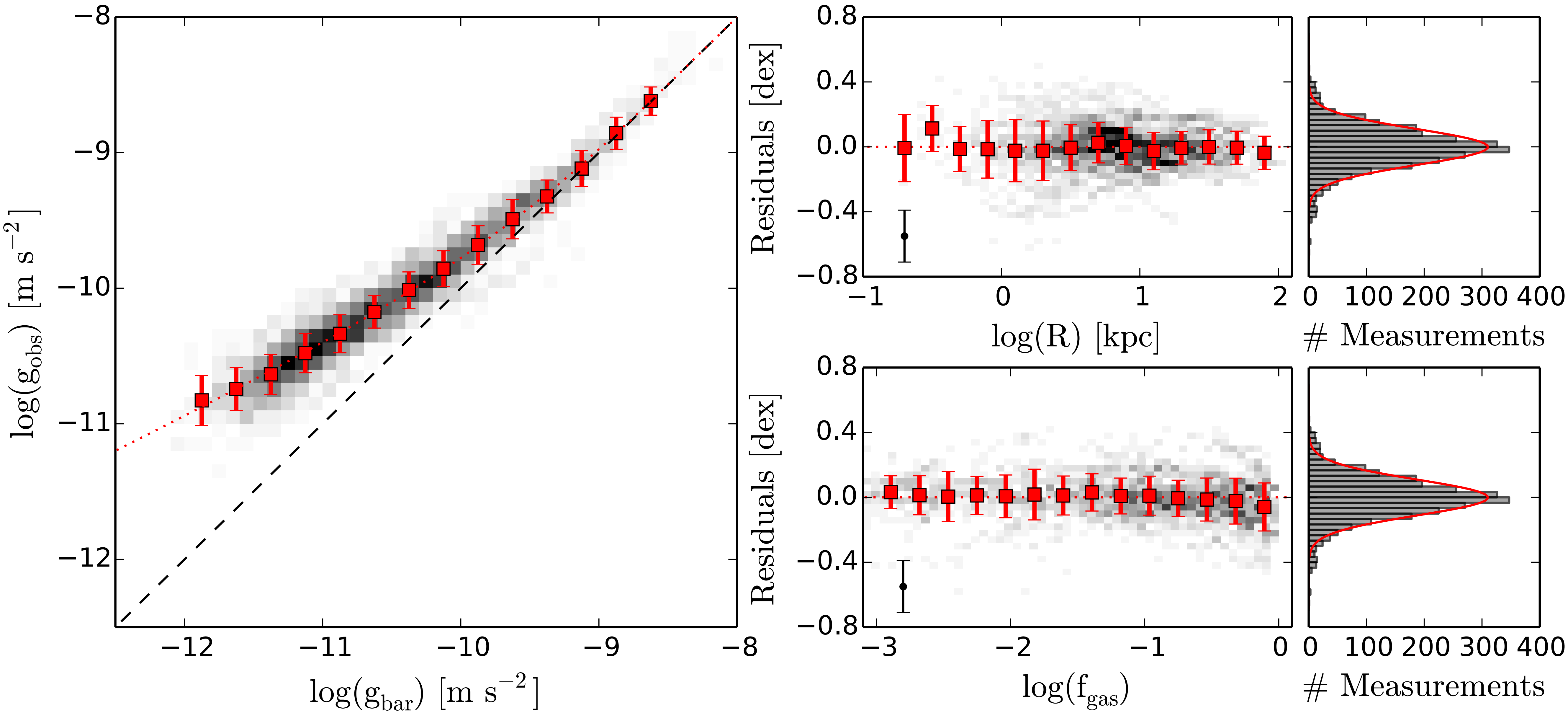
Mass couples to light

Rotation curves
~ 2700 points in
153 galaxies
(disturbed gals &
i < 30° excluded)

$$g_{\rm obs} = \frac{V^2}{R}$$



Mass couples to light



$$g_{\rm obs} = \frac{g_{\rm bar}}{1 - e^{-\sqrt{\frac{g_{\rm bar}}{g_\dagger}}}}$$

$$g_\dagger = 1.2 \times 10^{-10}\ \mathrm{m\,s^{-2}}$$

± 0.02 (random) $\pm\, 0.24$ (systematic)

3 Laws of Galactic Rotation

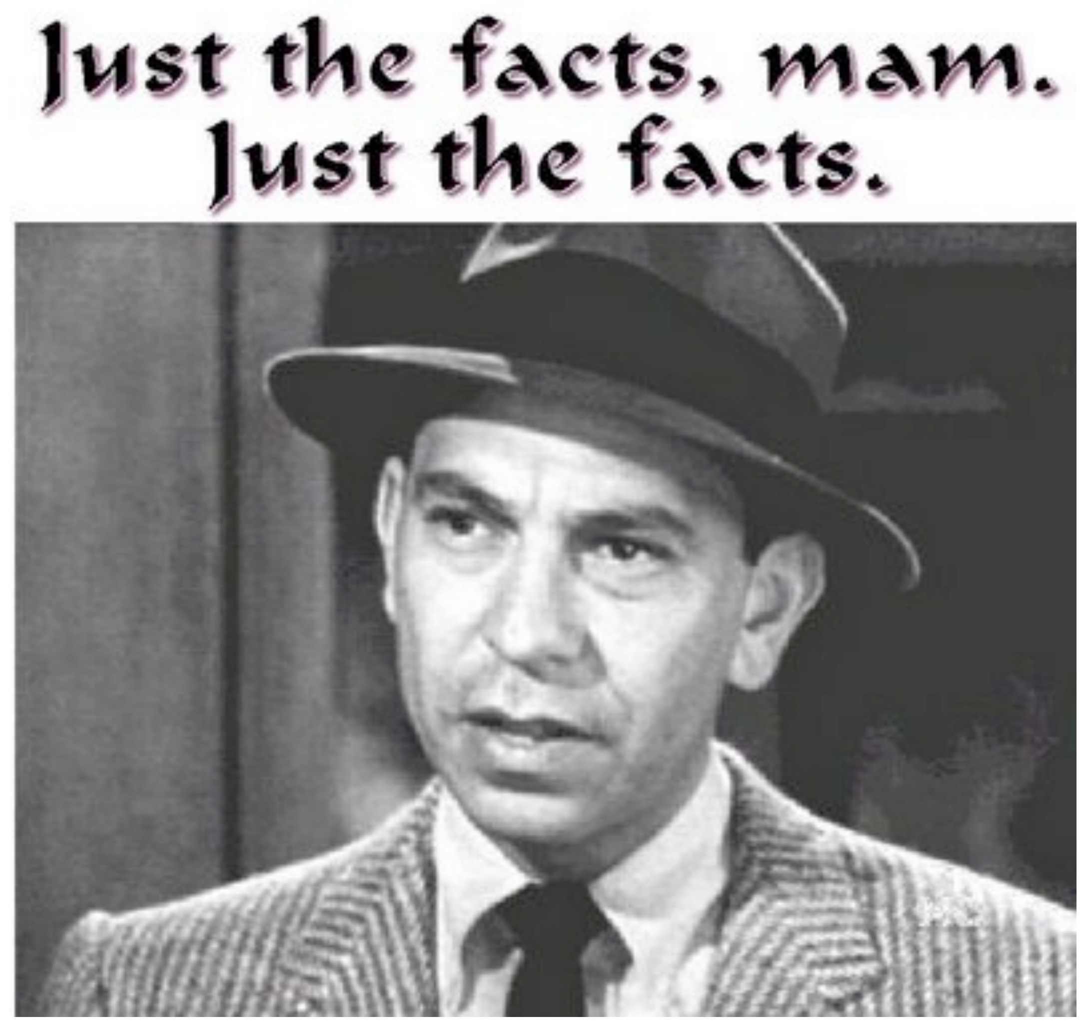
1. Rotation curves tend towards asymptotic flatness $V_f \rightarrow \text{constant}$

2. Baryonic mass scales as the fourth power of rotation velocity (Baryonic Tully-Fisher Relation) $M_b \propto V_f^4$

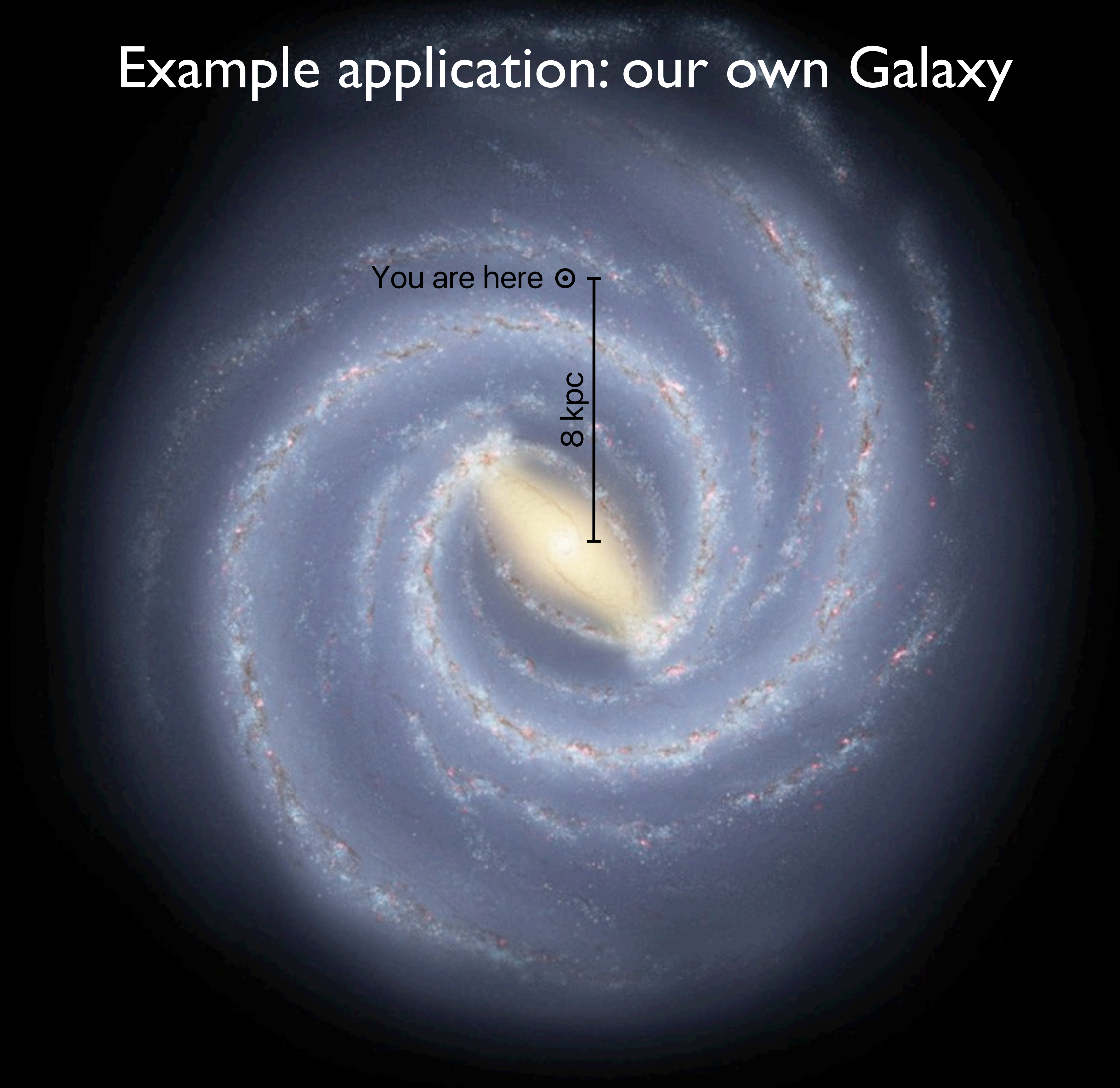
3. Gravitational force couples to baryon distribution

$$g_{\text{bar}} = \left| \frac{\partial \Phi_{\text{bar}}}{\partial R} \right|$$

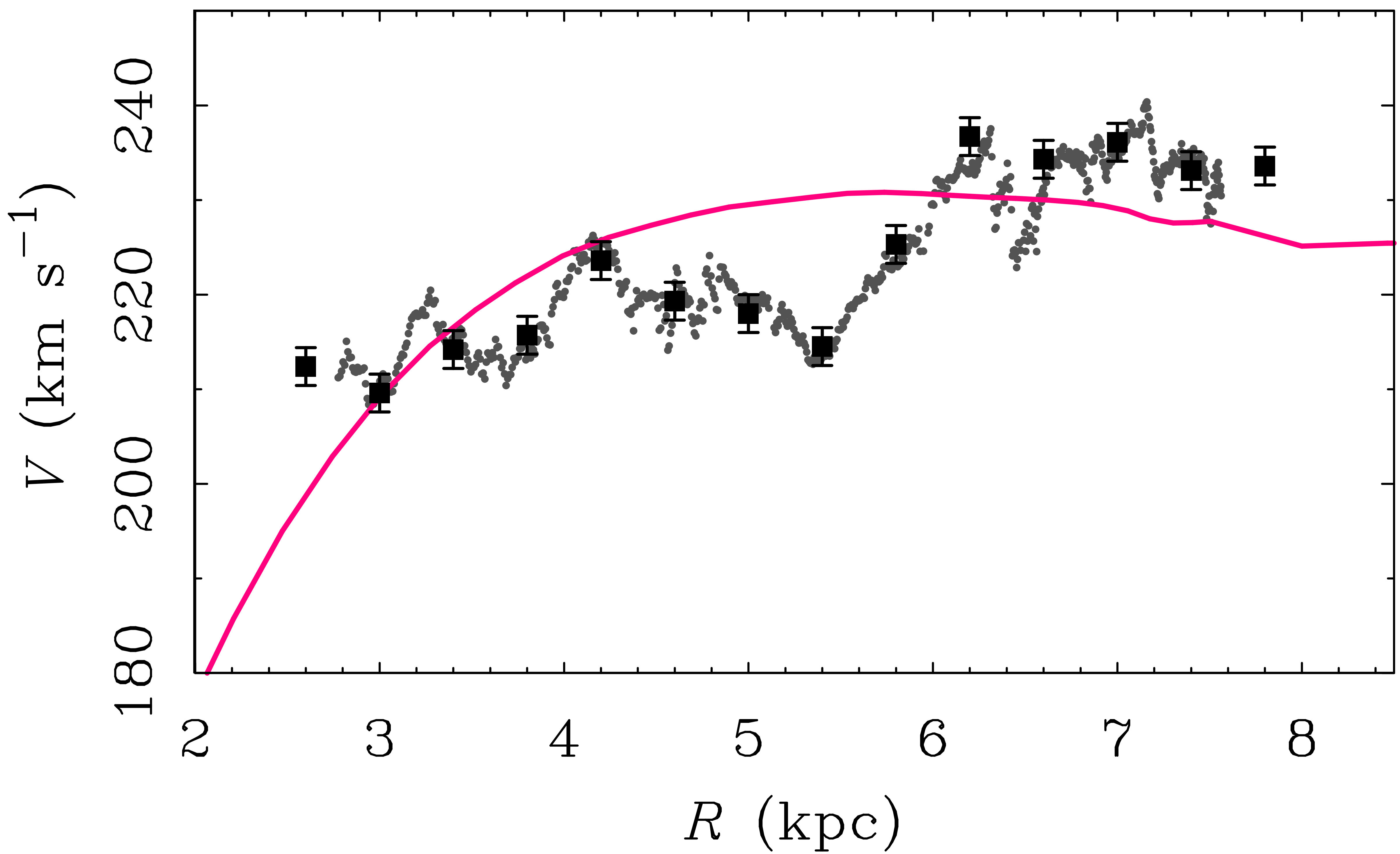
predictive of *total* gravitational potential



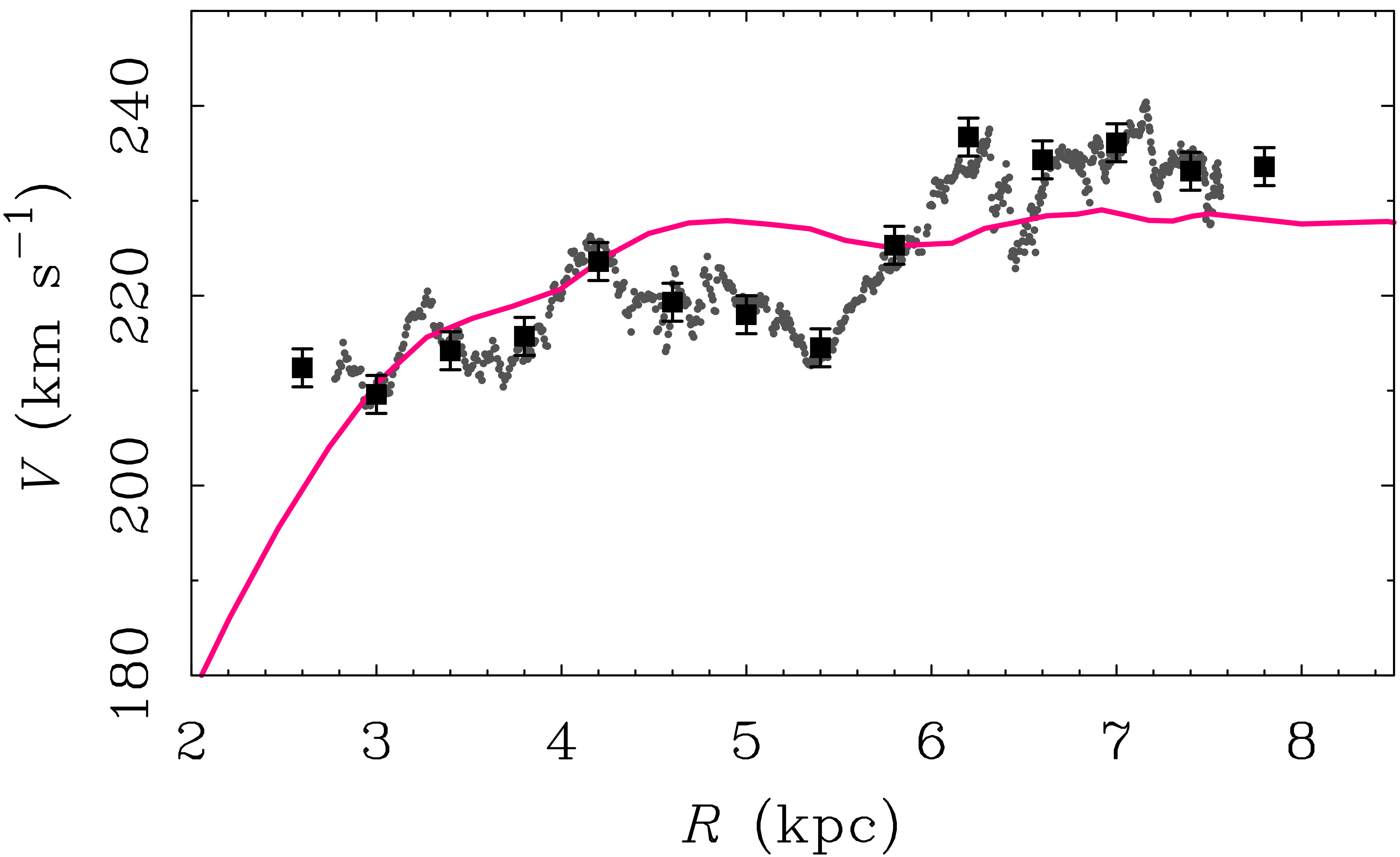
Example application: our own Galaxy



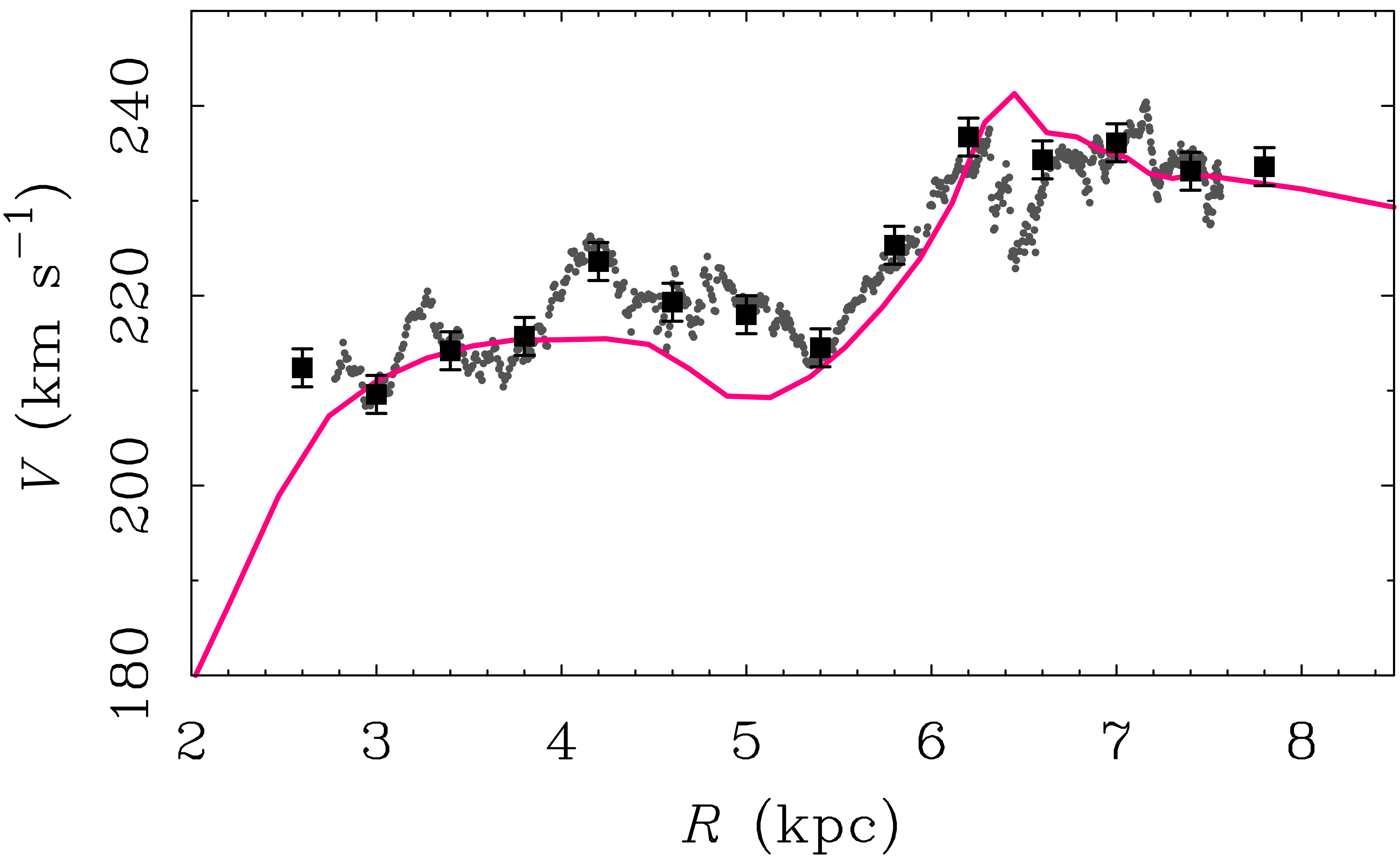
Fitting the details of the terminal velocity curve:
infer the stellar mass distribution from V(R)



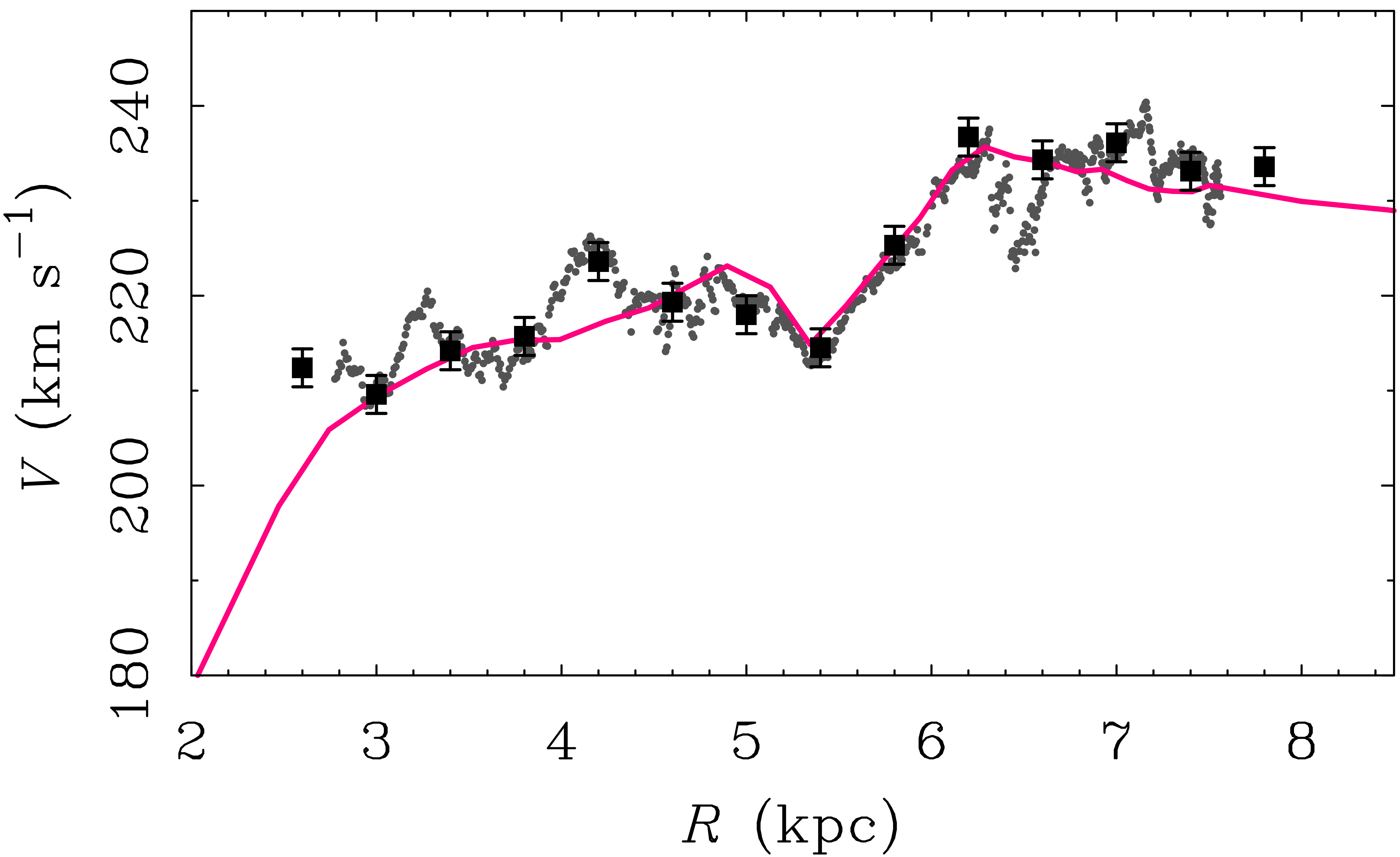
Fitting the details of the terminal velocity curve



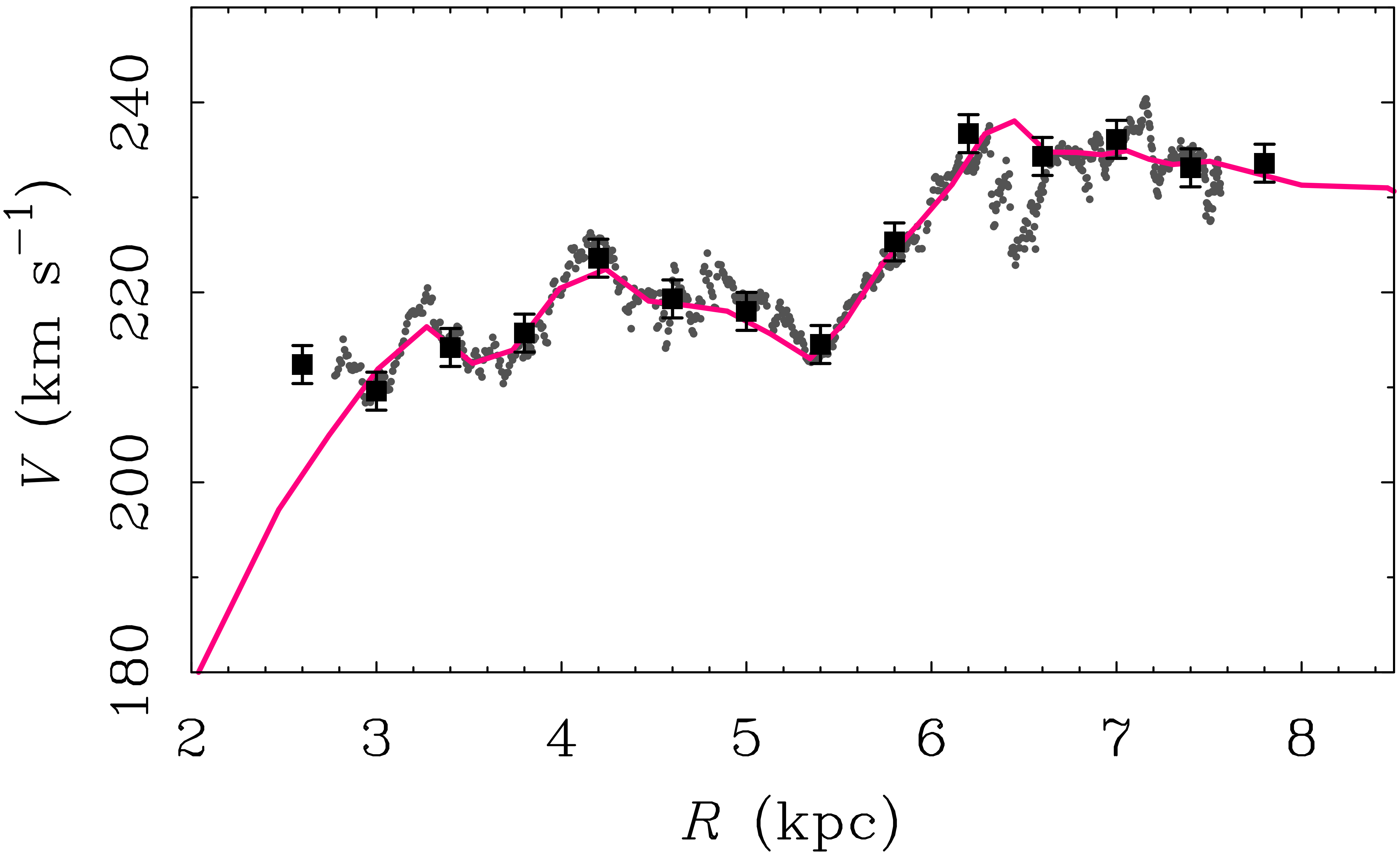
Fitting the details of the terminal velocity curve



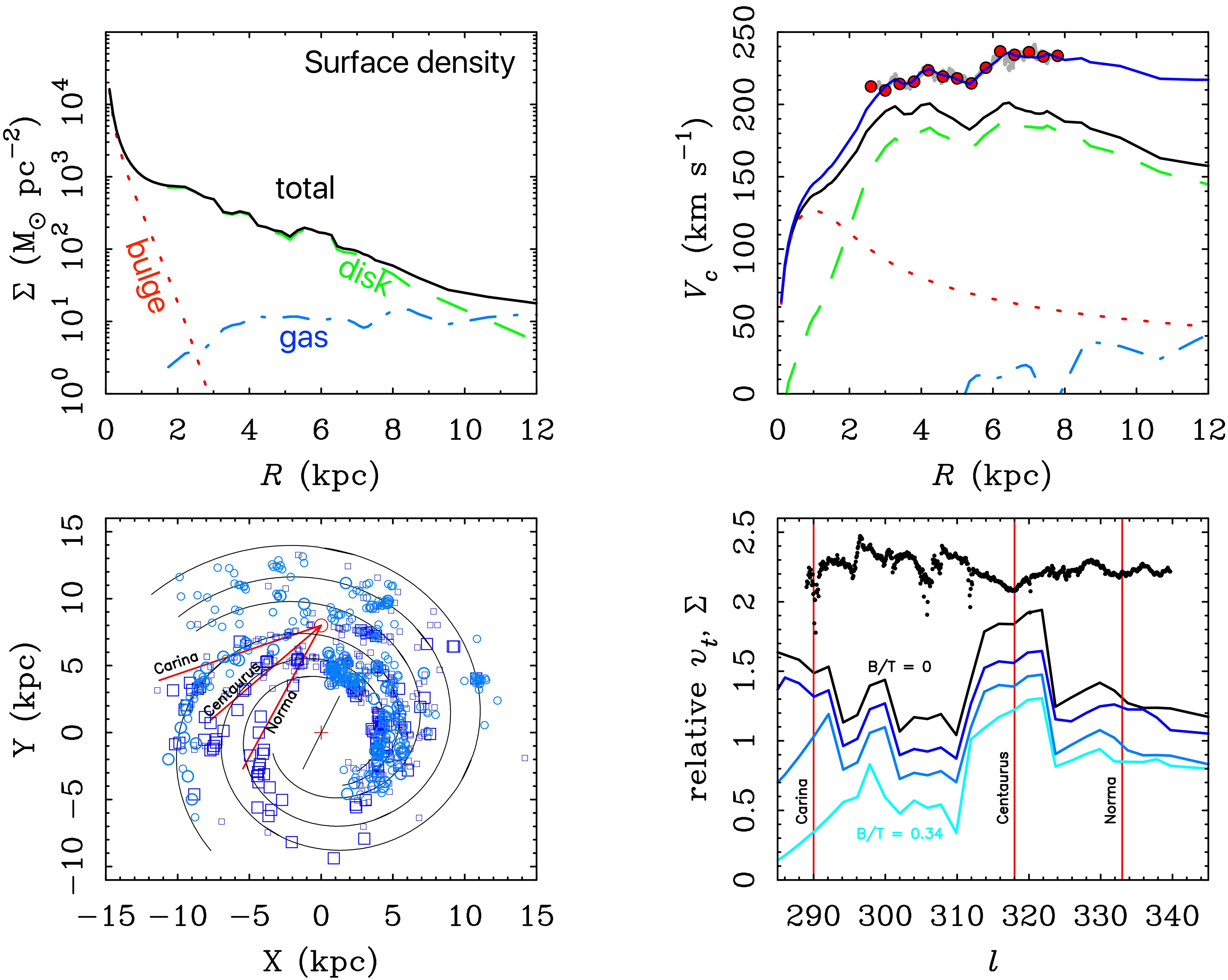
Fitting the details of the terminal velocity curve

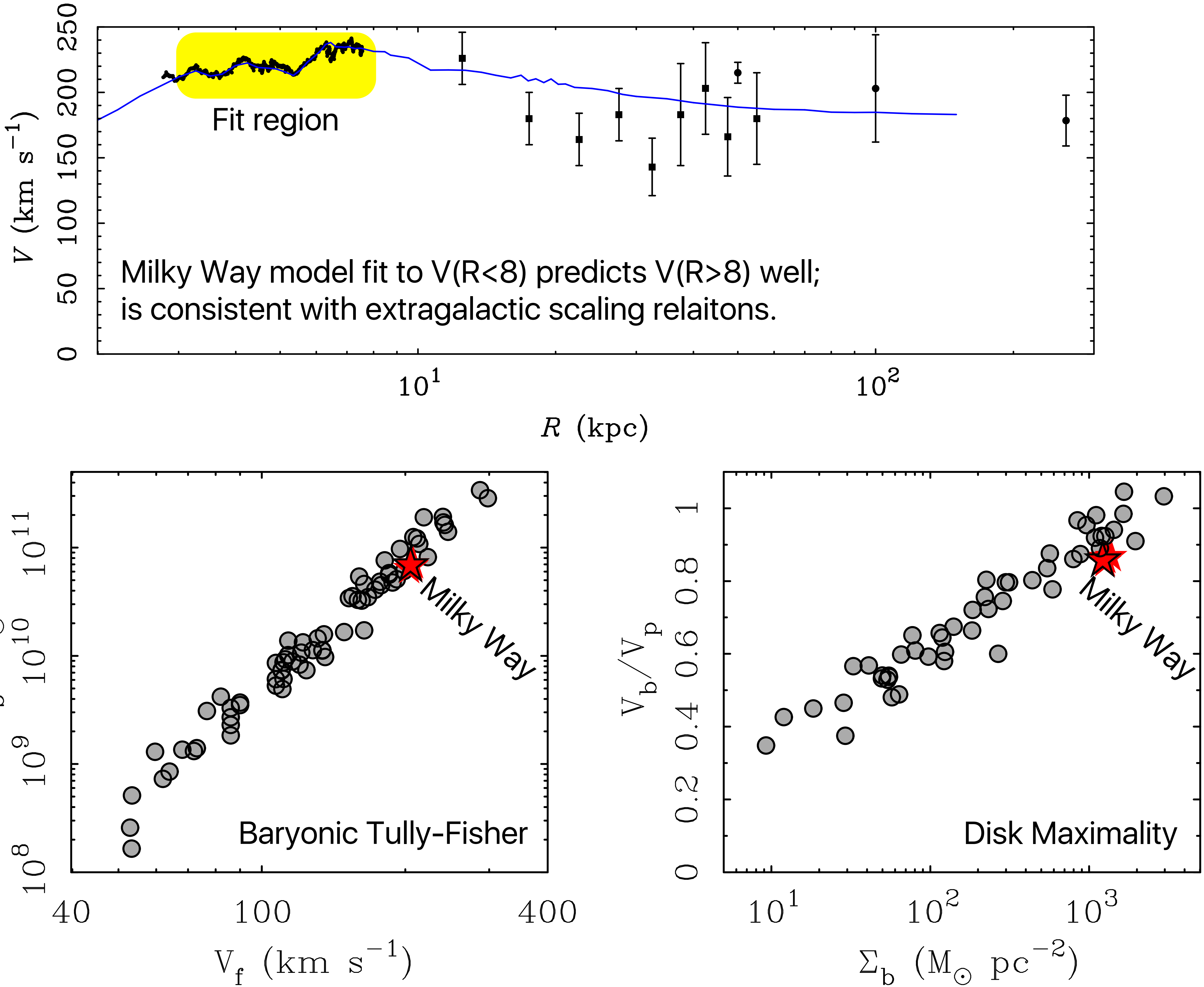


Fitting the details of the terminal velocity curve



Fitting the details of the terminal velocity curve uncovers details of Milky Way structure: the inferred density enhancement corresponds to the Centaurus spiral arm.





Fit region
Milky Way model fit to V(R<8) predicts V(R>8) well;
is consistent with extragalactic scaling relaitons.
V (km s^-1)
R (kpc)
Baryonic Tully-Fisher
Milky Way
M_b (M_⊙)
V_f (km s^-1)
Disk Maximality
Milky Way
V_b/V_p
Σ_b (M_⊙ pc^-2)

3 Laws of Galactic Rotation

1. Rotation curves tend towards asymptotic flatness $V_f \rightarrow \text{constant}$
2. Baryonic mass scales as the fourth power of rotation velocity $M_b \propto V_f^4$ (Baryonic Tully-Fisher Relation)
3. Gravitational force couples to baryon distribution

$$g_{\rm bar} = \left|\frac{\partial \Phi_{\rm bar}}{\partial R}\right| \rightarrow g_{\rm obs} = \left|\frac{\partial \Phi_{\rm tot}}{\partial R}\right|$$

These are empirical results that must be explained by a successful theory.

Requires considerable fine-tuning to interpret in terms of dark matter.

Follows more naturally from a universal force law.

THIS ISN'T THE THEORY YOU'RE LOOKING FOR...
Yes, it is.
MOND

MOND

Modify gravity at an acceleration scale

$$a_0 \approx 10^{-10}\ \mathrm{m\,s^{-2}} \sim cH_0 \sim c\Lambda^{1/2}$$

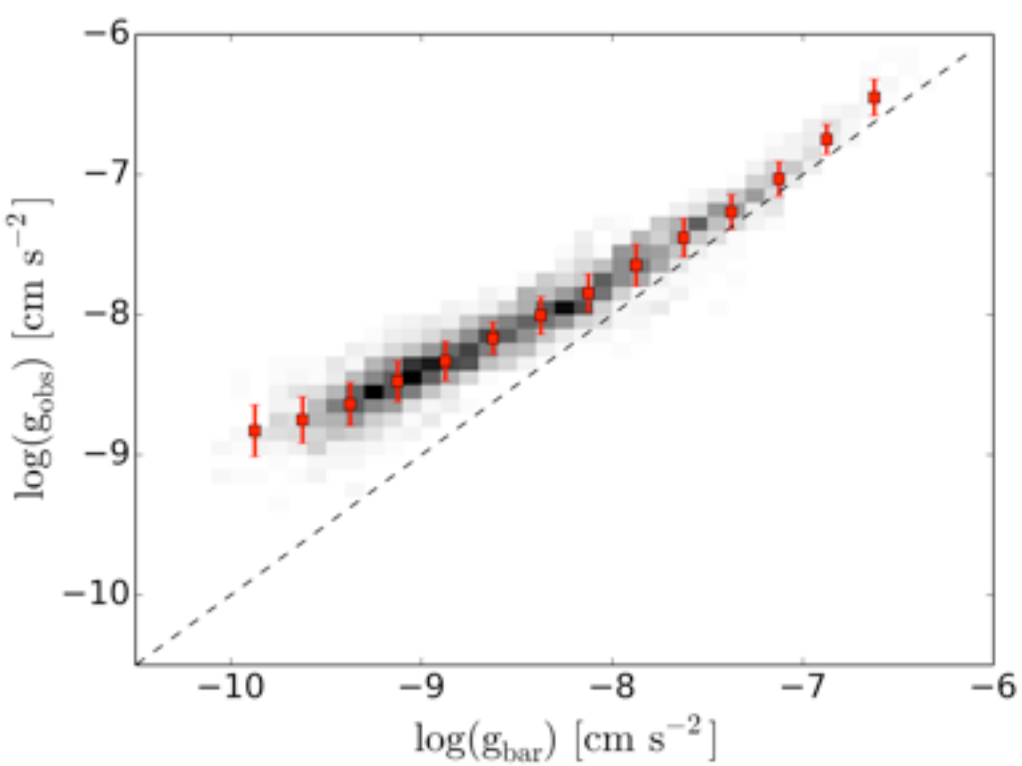
$$a \gg a_0 \qquad a \rightarrow g_N$$

$$a \ll a_0 \qquad a \rightarrow \sqrt{g_N a_o}$$

Hypothesized by Milgrom (1983)

MOND predictions

The 3 Laws are a natural consequence of MOND, which already has a long string of successful predictions



- The Tully-Fisher Relation
  - ✔ Slope = 4
  - ✔ Normalization = $1/(a_0 G)$
  - ✔ Fundamentally a relation between Disk Mass and V_{flat}
  - ✔ No Dependence on Surface Brightness

✔ Dependence of conventional M/L on radius and surface brightness

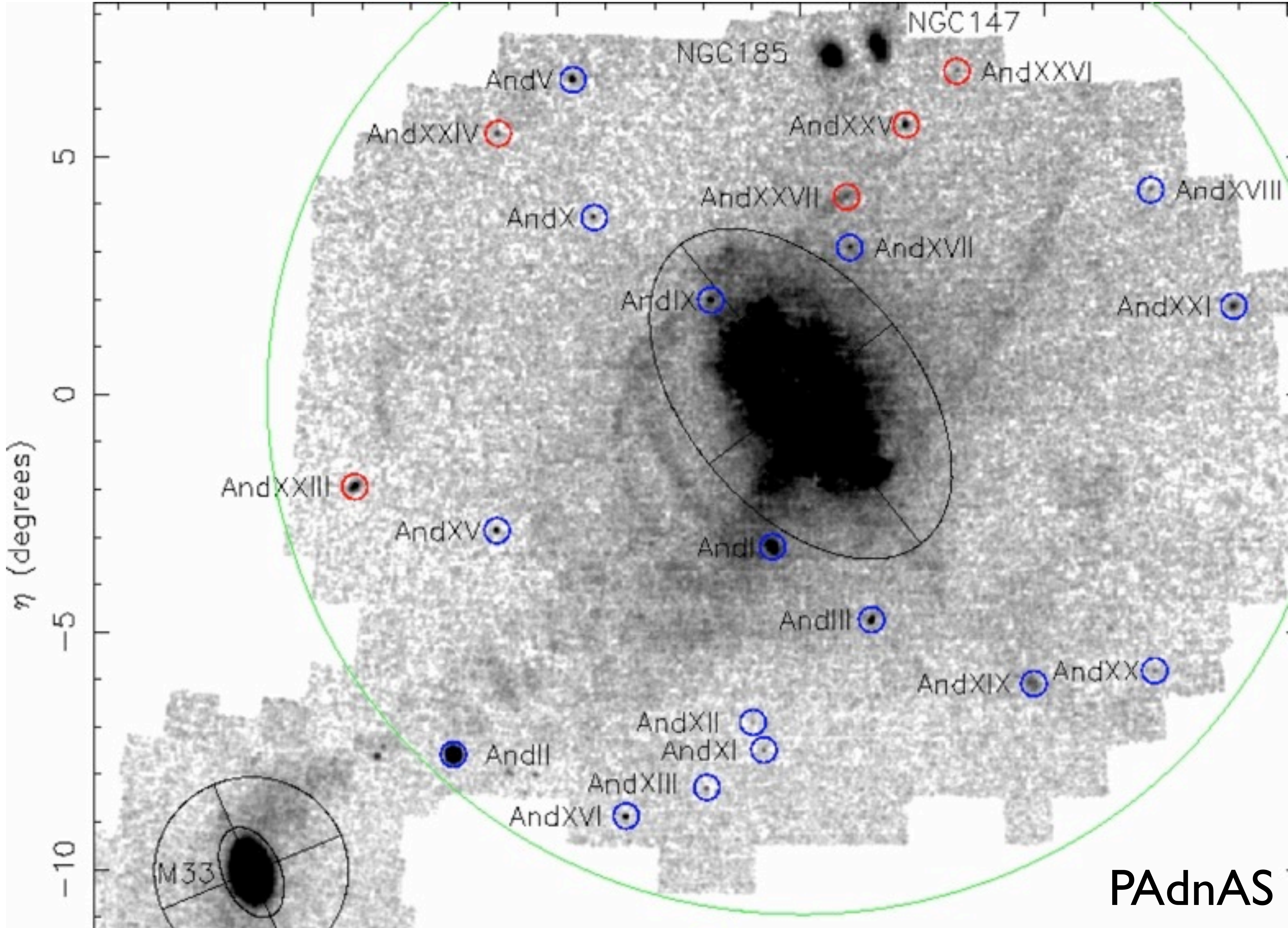
✔ Rotation Curve Shapes

✔ Surface Density ~ Surface Brightness

✔ Detailed Rotation Curve Fits

✔ Stellar Population Mass-to-Light Ratios

A new test: the dwarf satellites of Andromeda (McGaugh & Milgrom 2013a,b)



Newtonian regime

$$g_{in} > a_0 \qquad M = \frac{RV^2}{G}$$

e.g., surface of the Earth

ISO

MOND regime

$$g_{in} < a_0 \qquad M = \frac{V^4}{a_0 G}$$

e.g., remote dwarf Leo I

External Field dominant Newtonian regime

$$g_{in} < a_0 < g_{ex} \qquad M = \frac{RV^2}{G}$$

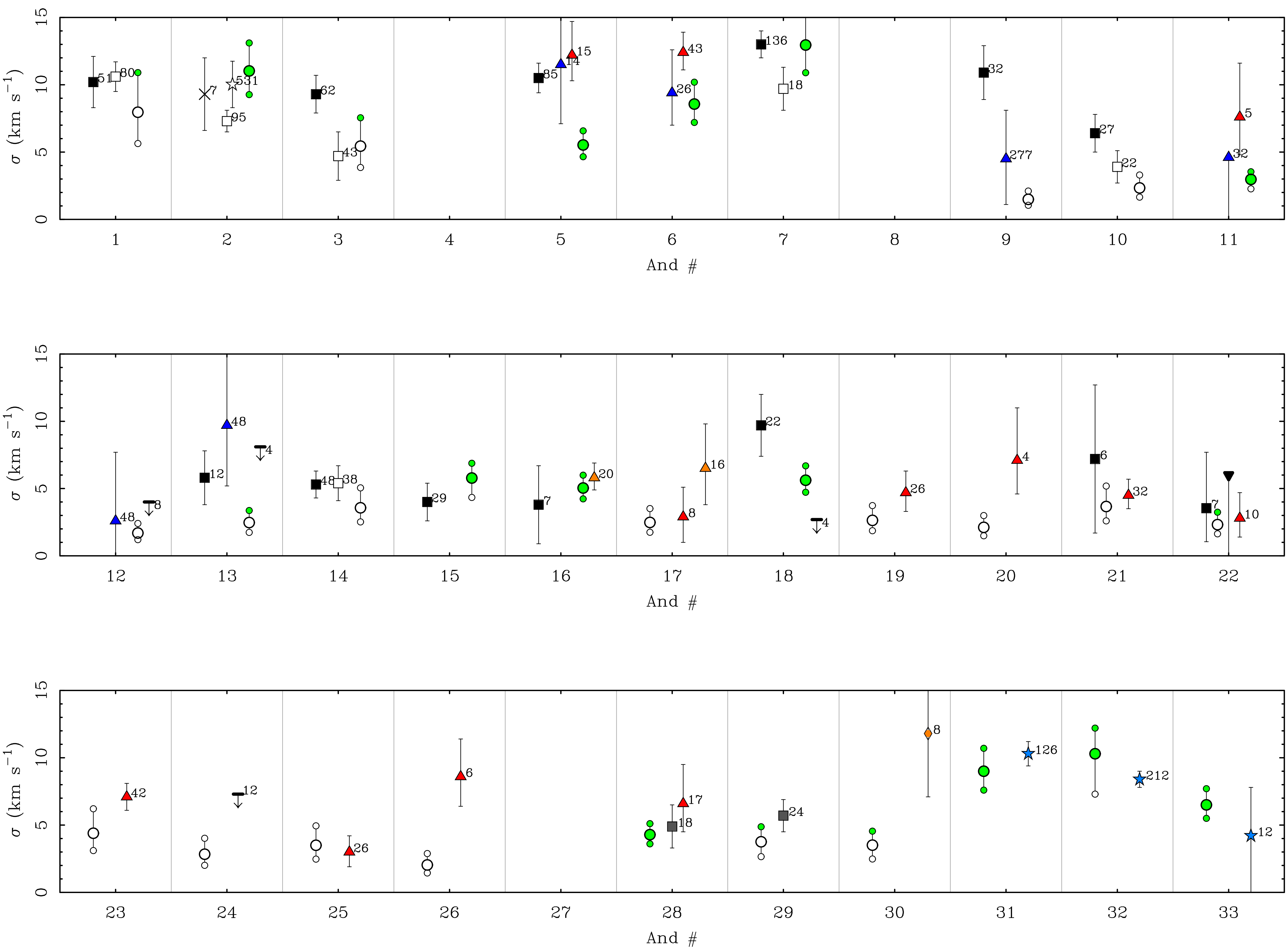
e.g., Eotvos-type experiment on the surface of the Earth

EFE

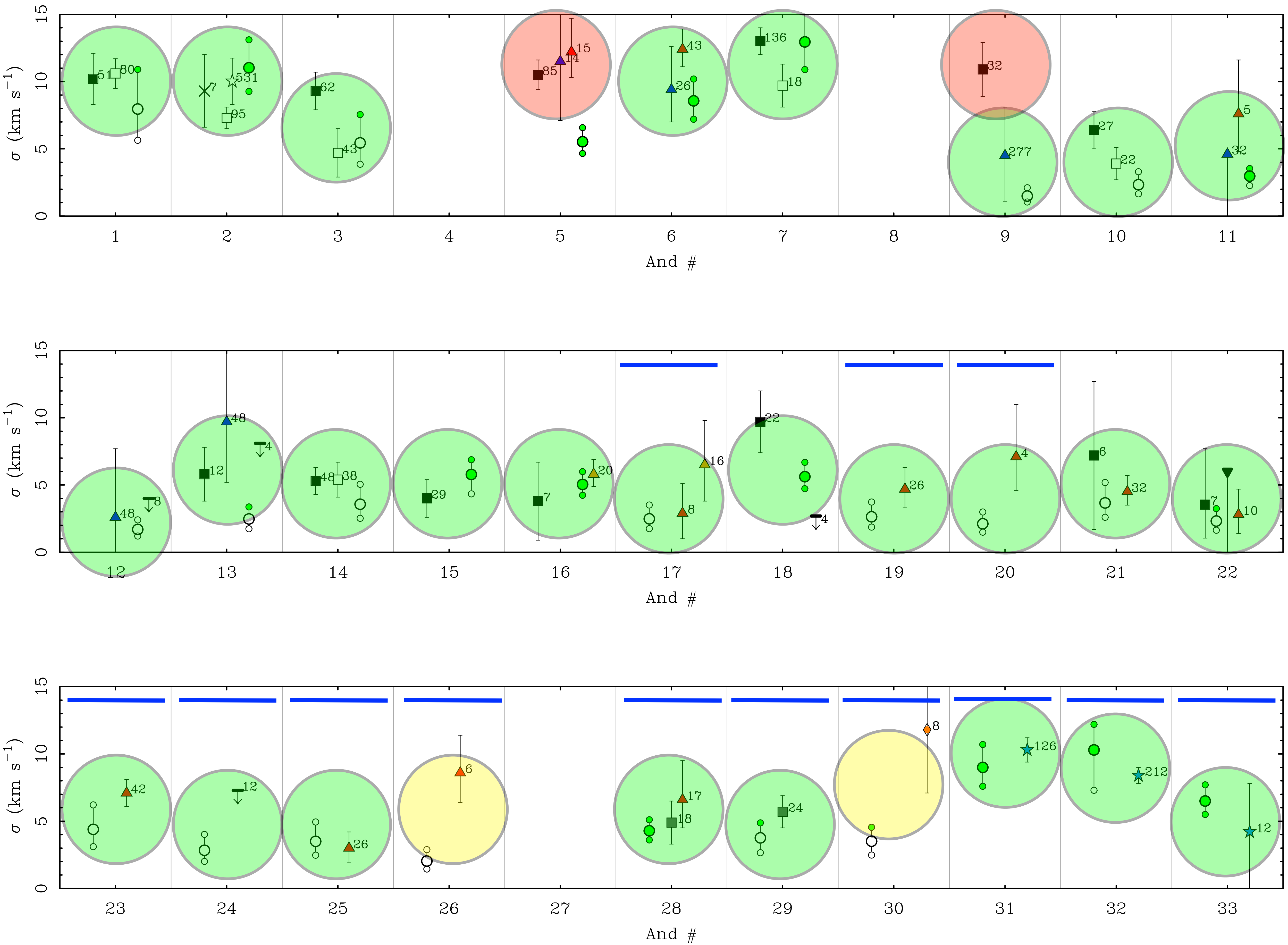
External Field dominant quasi-Newtonian regime

$$g_{in} < g_{ex} < a_0 \qquad M = \frac{g_{ex}}{a_0}\frac{RV^2}{G}$$

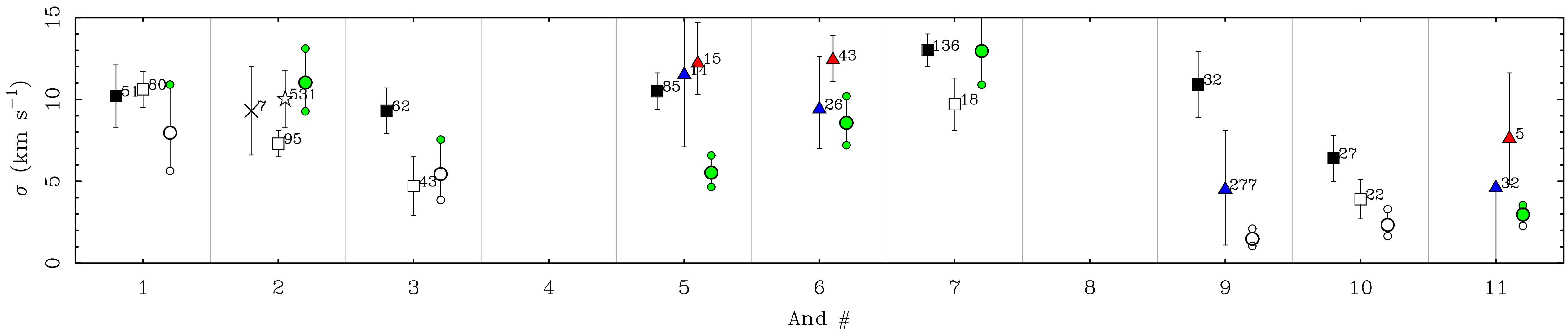
e.g., nearby dwarf Segue 1



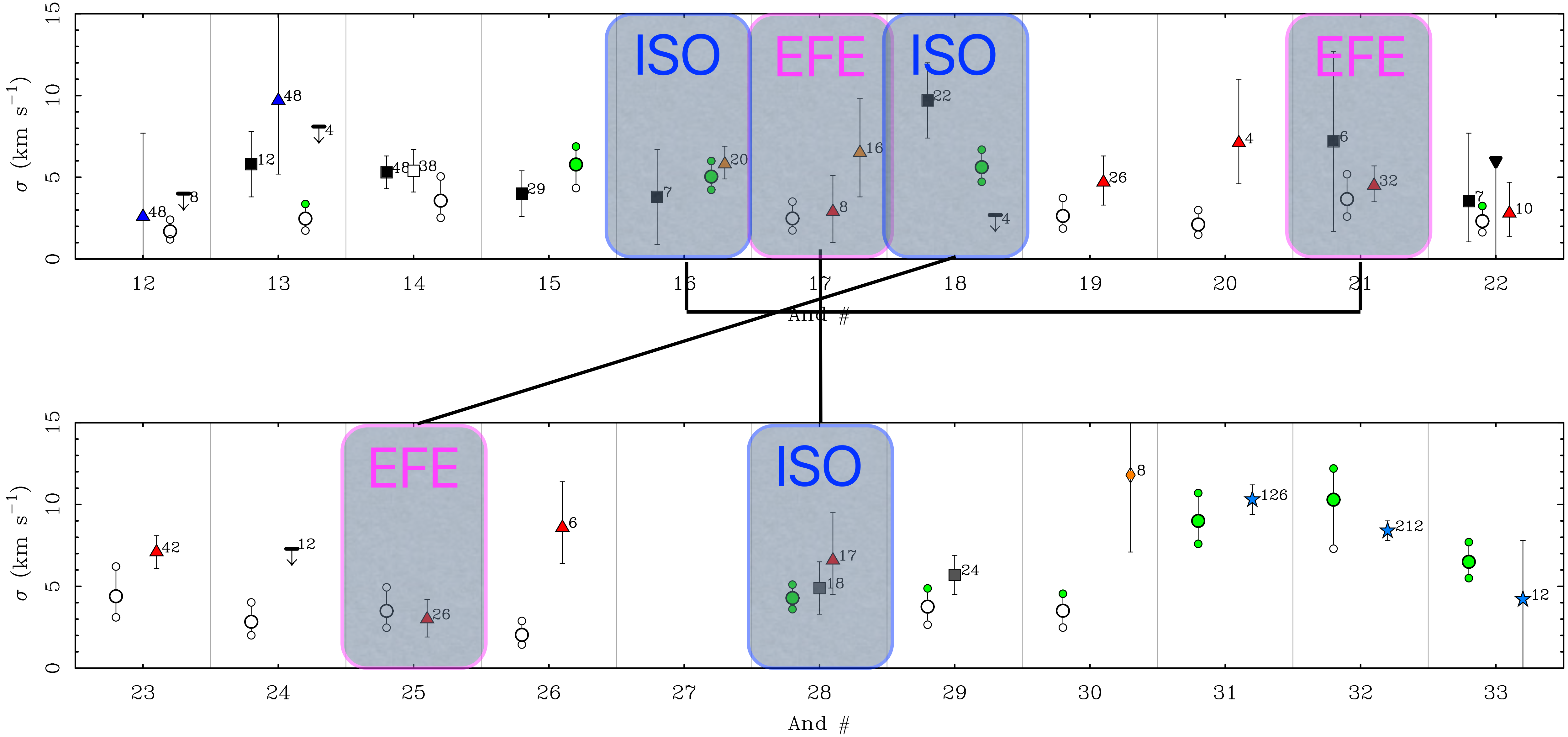
Velocity dispersions of M31 dwarfs correctly predicted (a priori in many cases) by MOND.



Velocity dispersions of M31 dwarfs correctly predicted (a priori in many cases) by MOND.

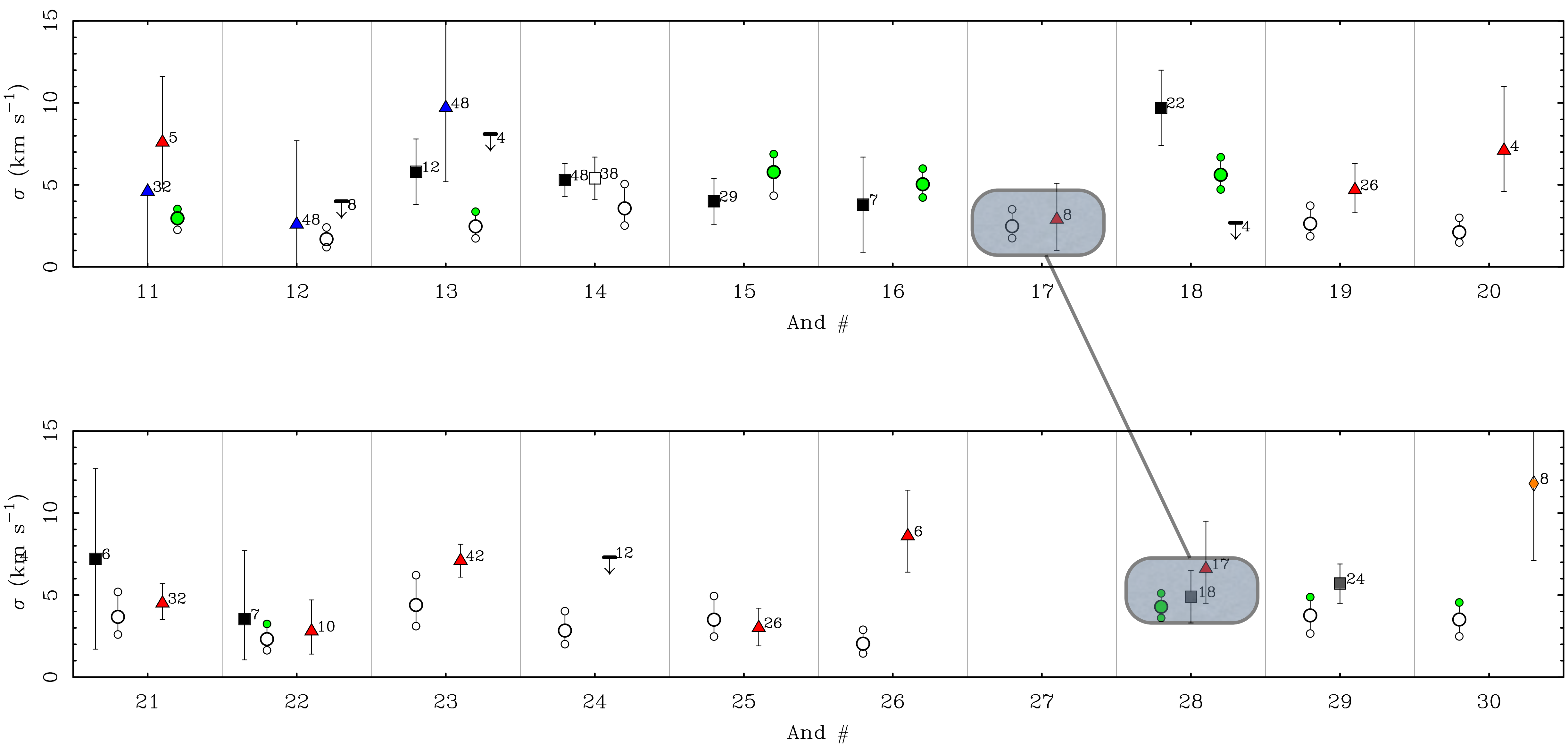


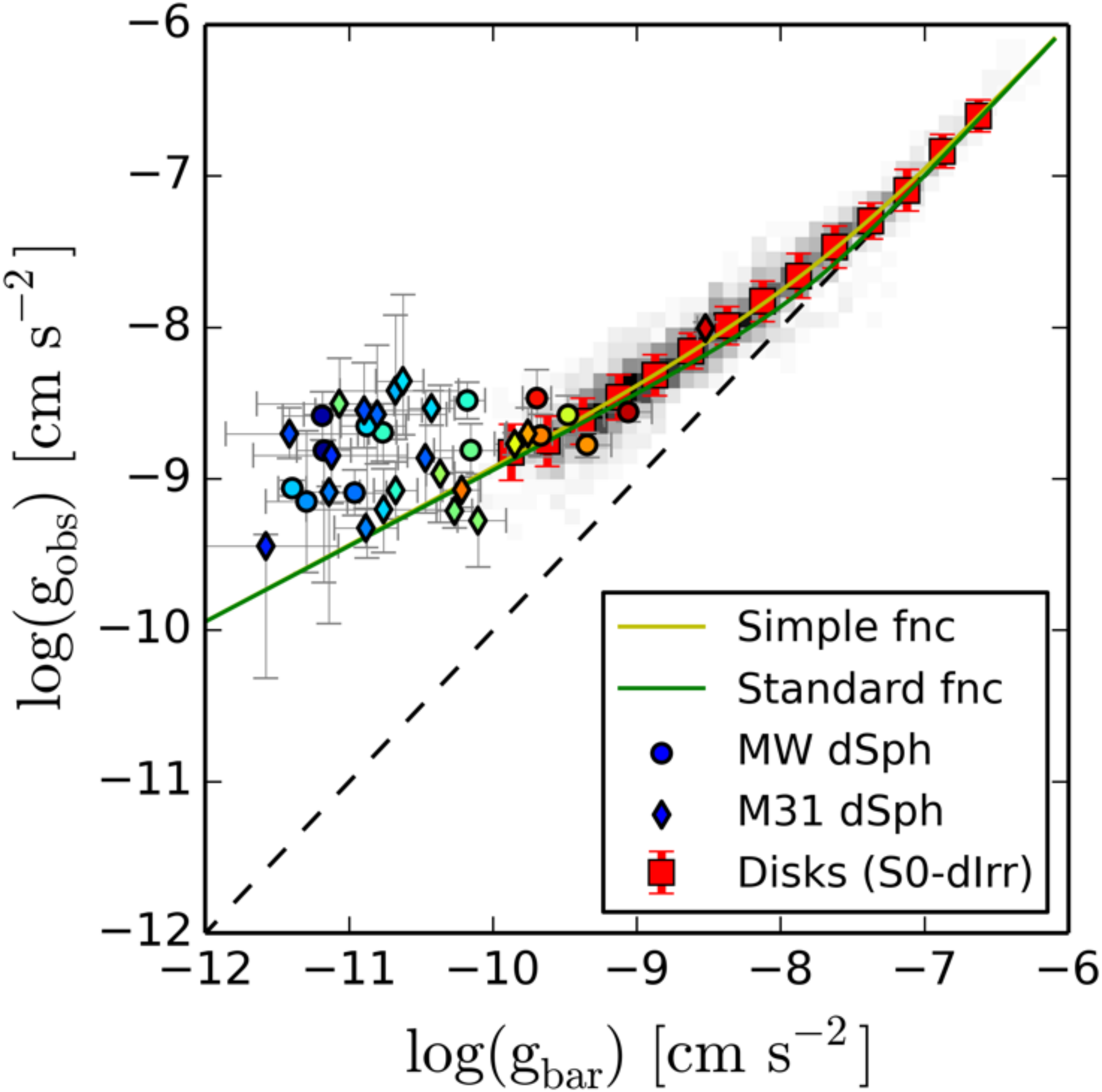
Pairs of photometrically identical dwarfs should have different velocity dispersion depending on whether they are isolated are dominated by the external field effect.



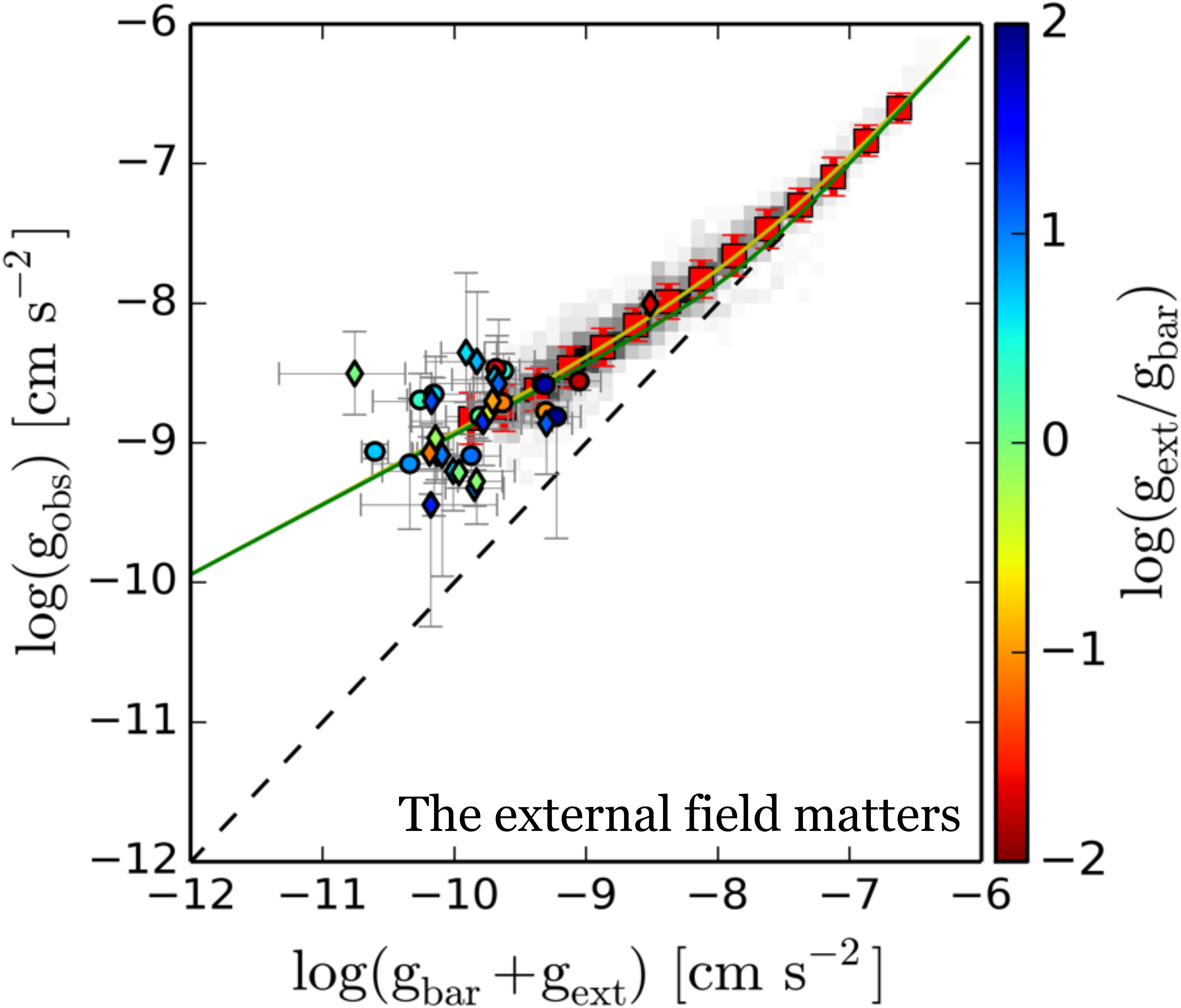
There is no EFE in dark matter - this is a unique signature of MOND.

Name	Luminosity	R_e	σ_{obs}	σ_{pred}	
And XVII	2.60E+05	381	2.9	2.5	EFE
And XXVIII	2.10E+05	284	4.9	4.3	isolated





−6
−7
−8
−9
−10
−11
−12
log(g_obs) [cm s^−2]
−12
−11
−10
−9
−8
−7
−6
log(g_bar) [cm s^−2]
Simple fnc
Standard fnc
MW dSph
M31 dSph
Disks (S0-dIrr)



The external field matters
log(g_obs) [cm s^-2]
log(g_bar + g_ext) [cm s^-2]
log(g_ext/g_bar)
−6
−7
−8
−9
−10
−11
−12
2
1
0
−1
−2

Other MOND tests

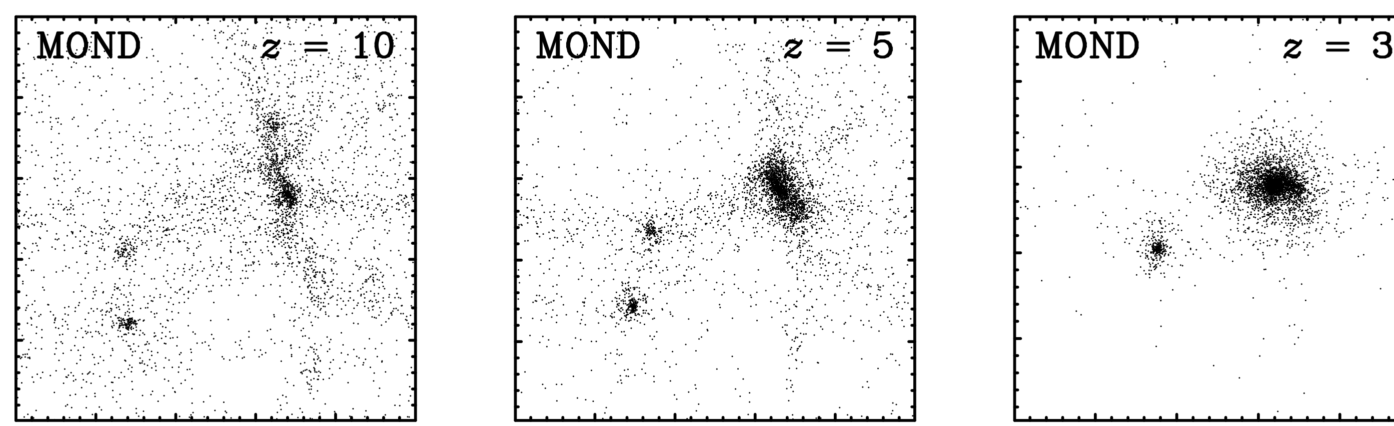
- Disk Stability
  - ✔ Freeman limit in surface brightness distribution ☆
  - ✔ thin disks
  - ✔ velocity dispersions
  - ✔ LSB disks not over-stabilized ☆
- ✔ Dwarf Spheroidals ☆★
- ✔ Giant Ellipticals
- X Clusters of Galaxies ✸

Predicts high speed collisions ☆★

- ? Structure Formation

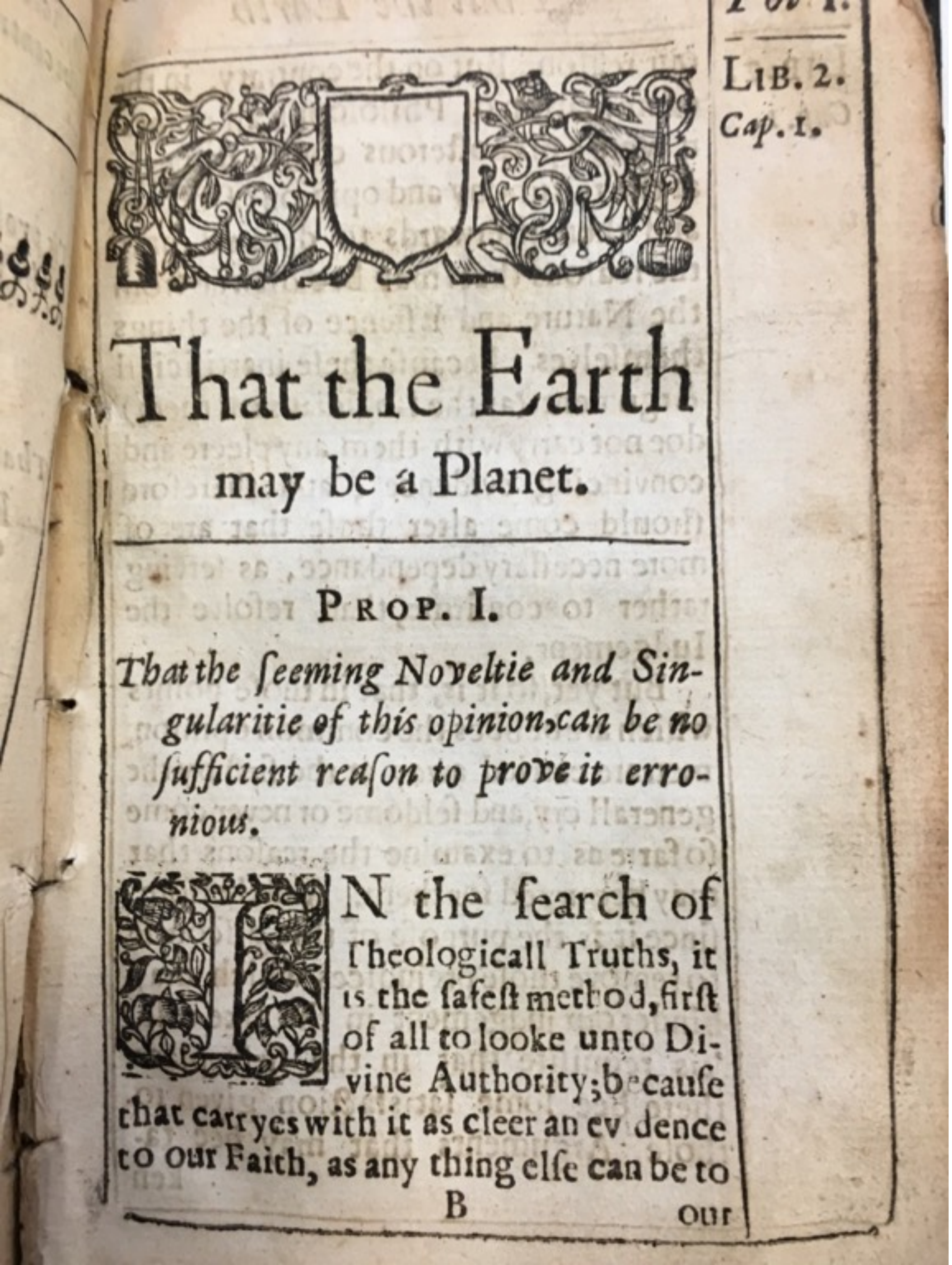
I predict lots of structure at high redshift ?

- Microwave background
  - ✔ 1st:2nd peak amplitude; BBN ★
  - ✔ early reionization ★
  - ✔ enhanced ISW/gravitational lensing
  - X 3rd peak ✸



X No Metric

X Don't know expansion history



That the Earth
may be a Planet.

PROP. I.

That the ſeeming Noveltie and Singularitie of this opinion, can be no ſufficient reaſon to prove it erronious.

IN the ſearch of Theologicall Truths, it is the ſafeſt method, firſt of all to looke unto Divine Authority; becauſe that carryes with it as cleer an evidence to our Faith, as any thing elſe can be to

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That the Earth
may be a Planet

the seeming novelty and singularity of this opinion can be no sufficient reason to prove it erroneous