Dwarf Galaxies on the Shoulders of Giants

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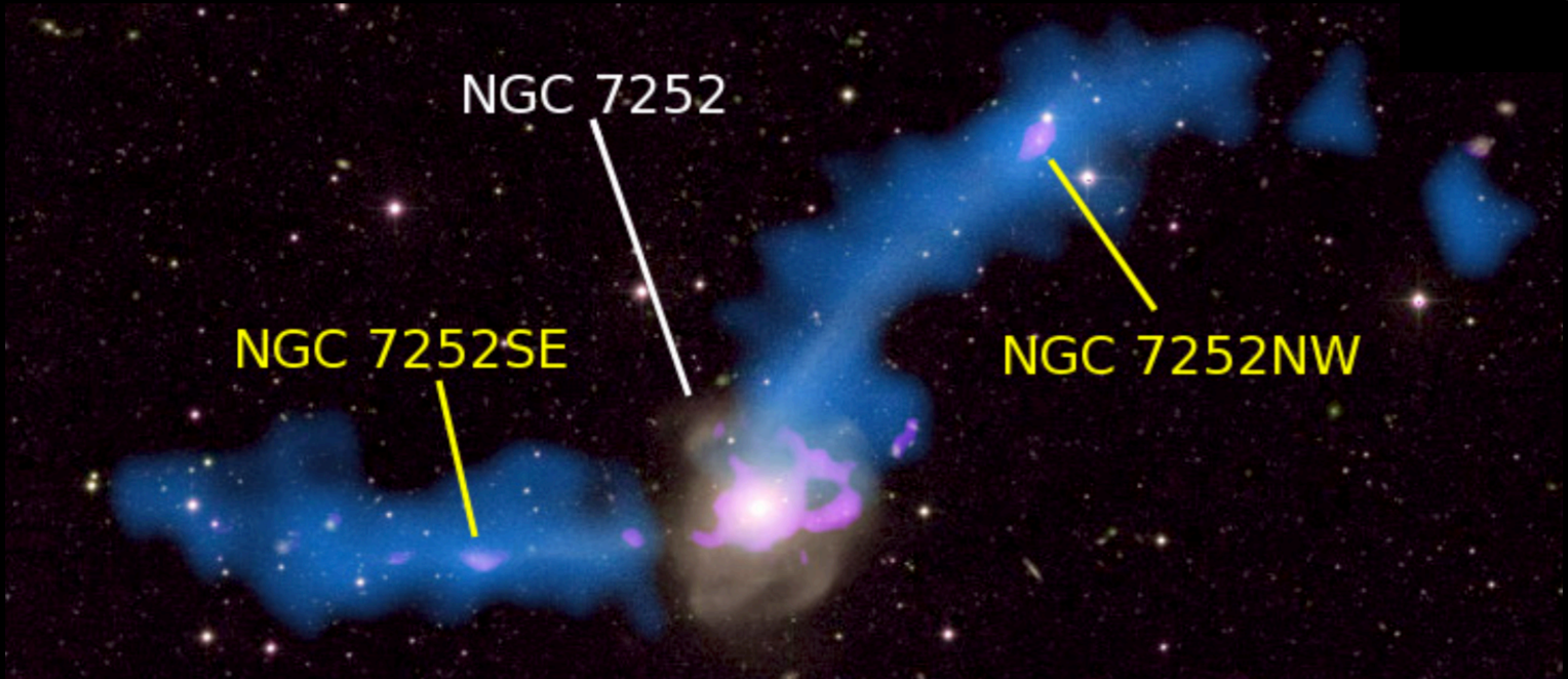
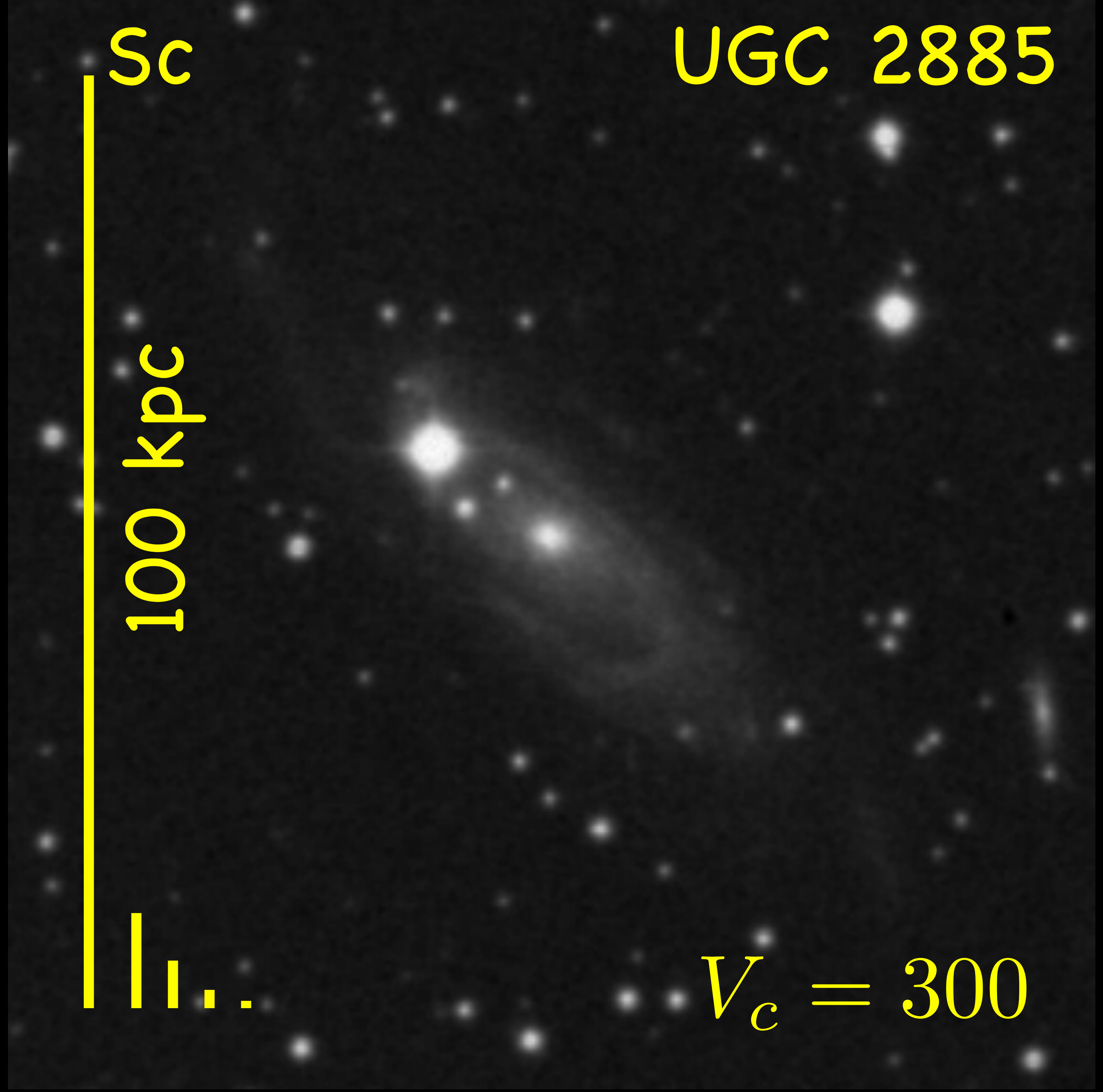
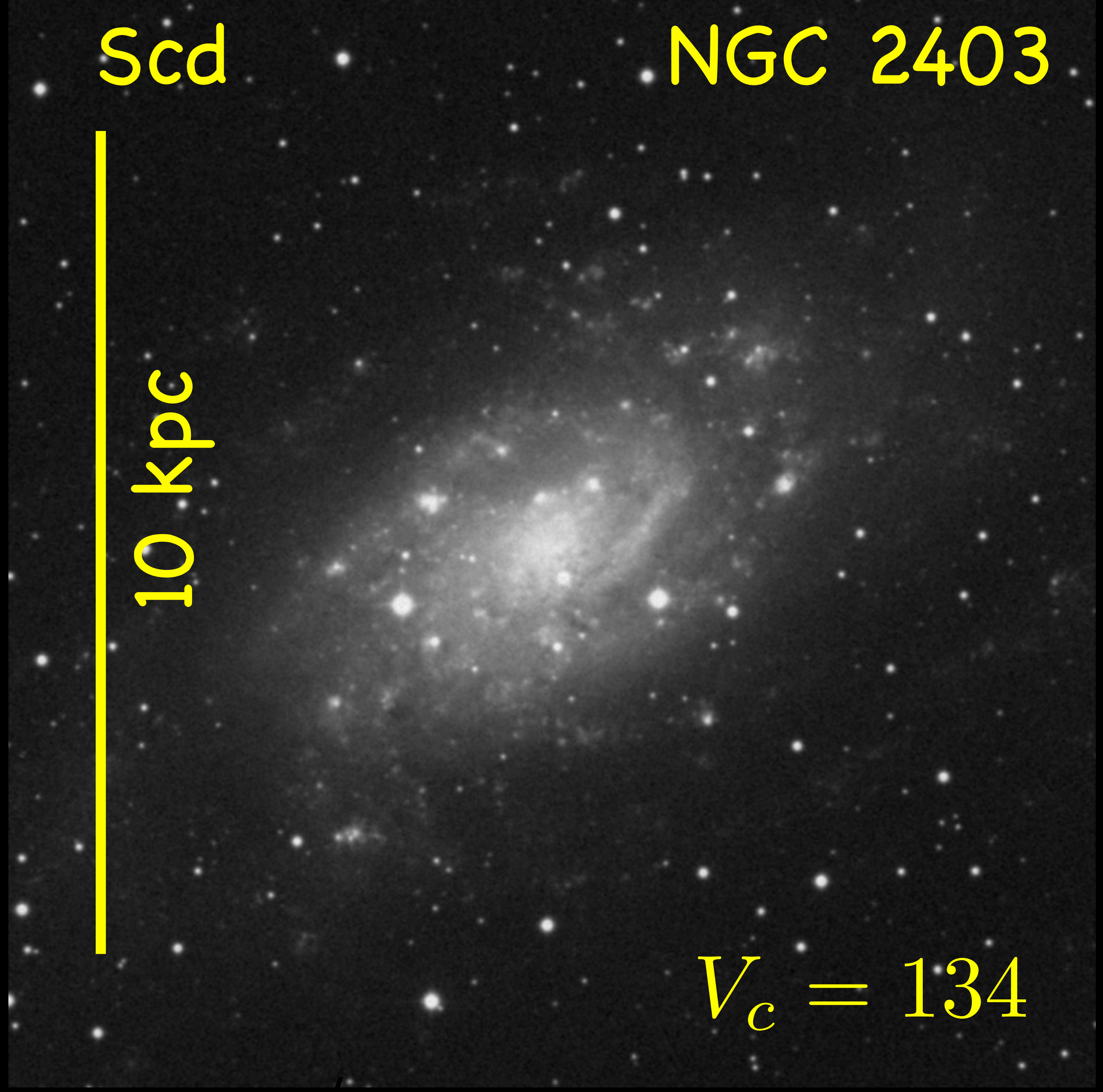
Case Western Reserve University

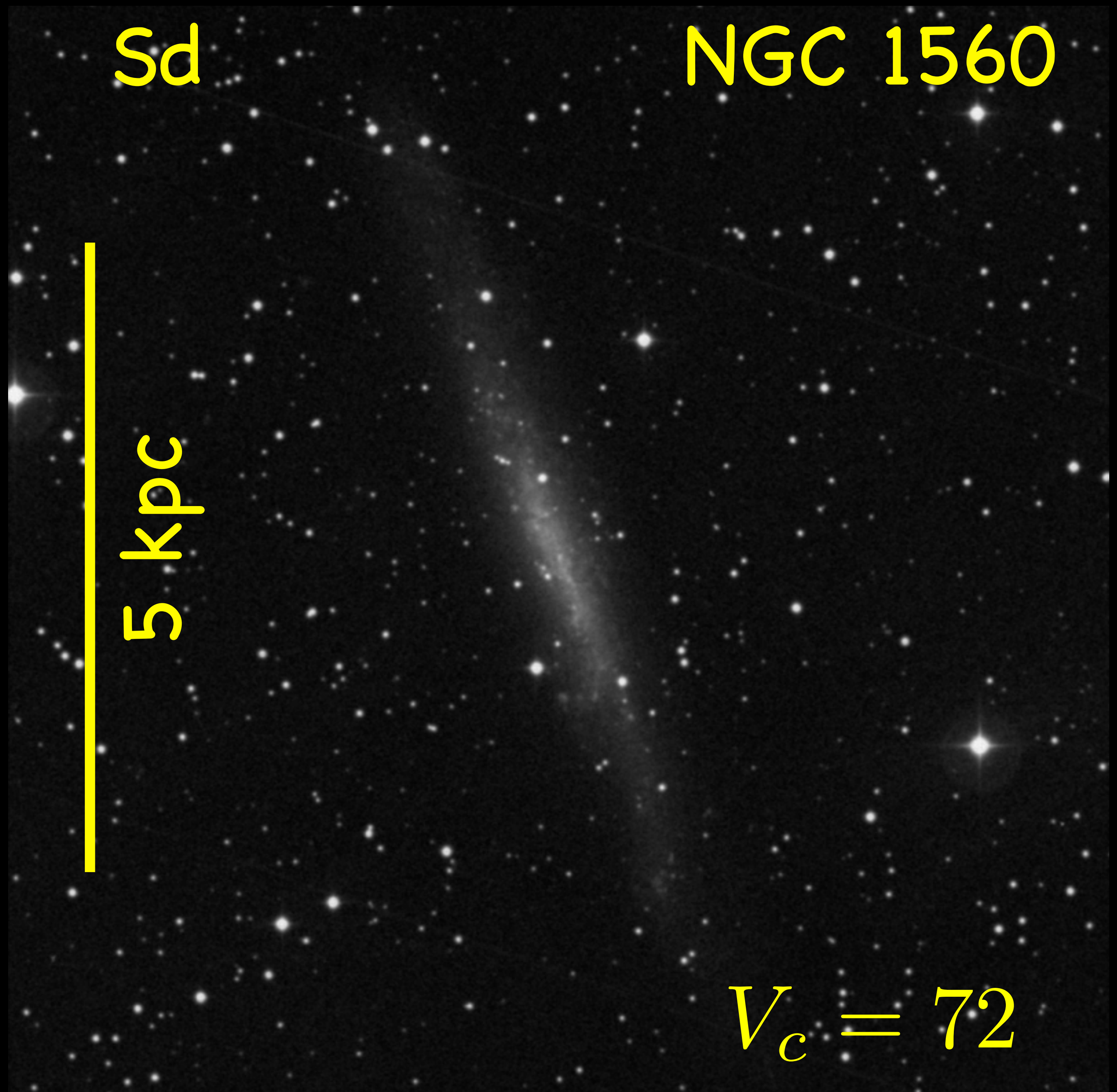
with support from
The John Templeton Foundation

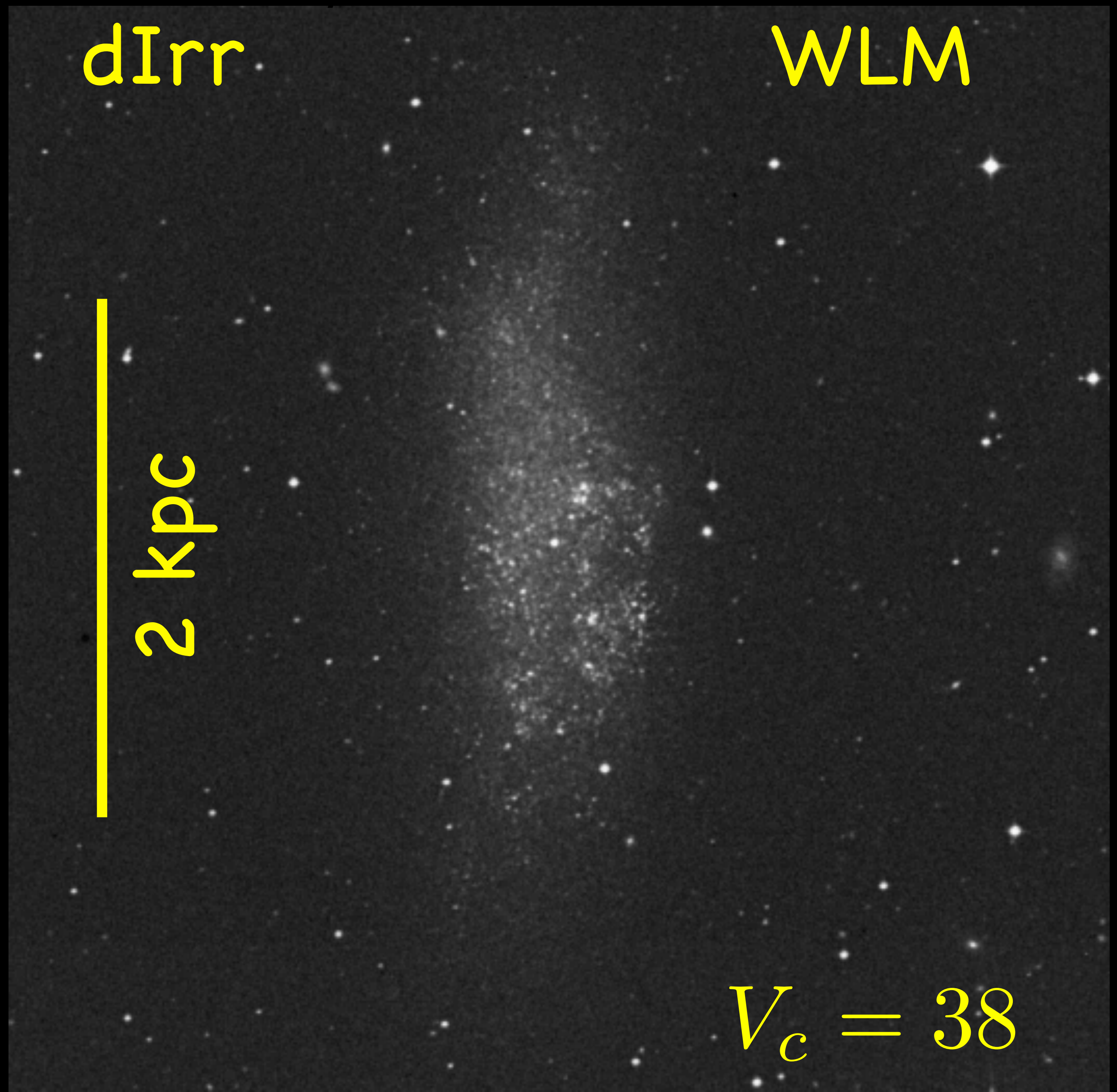


ROTATIONALLY SUPPORTED



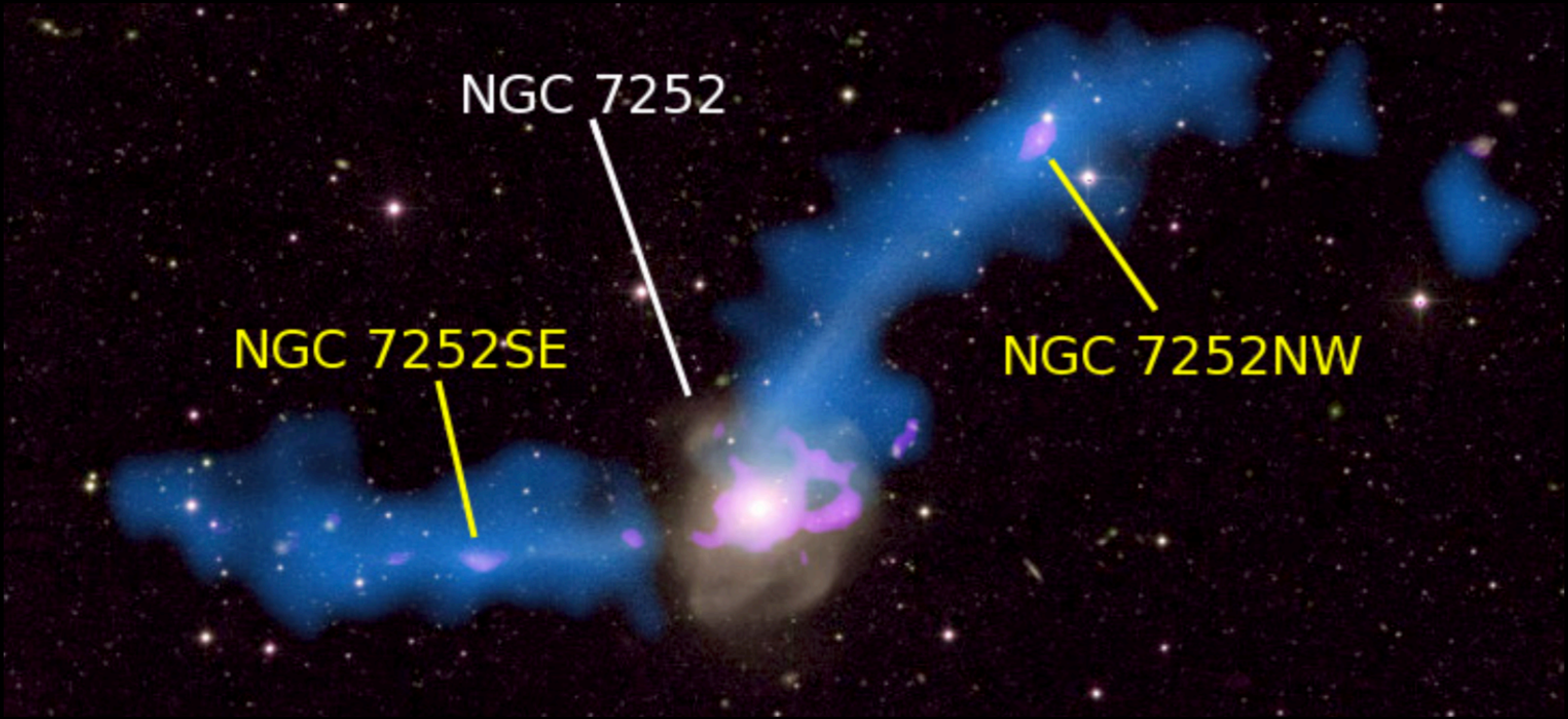




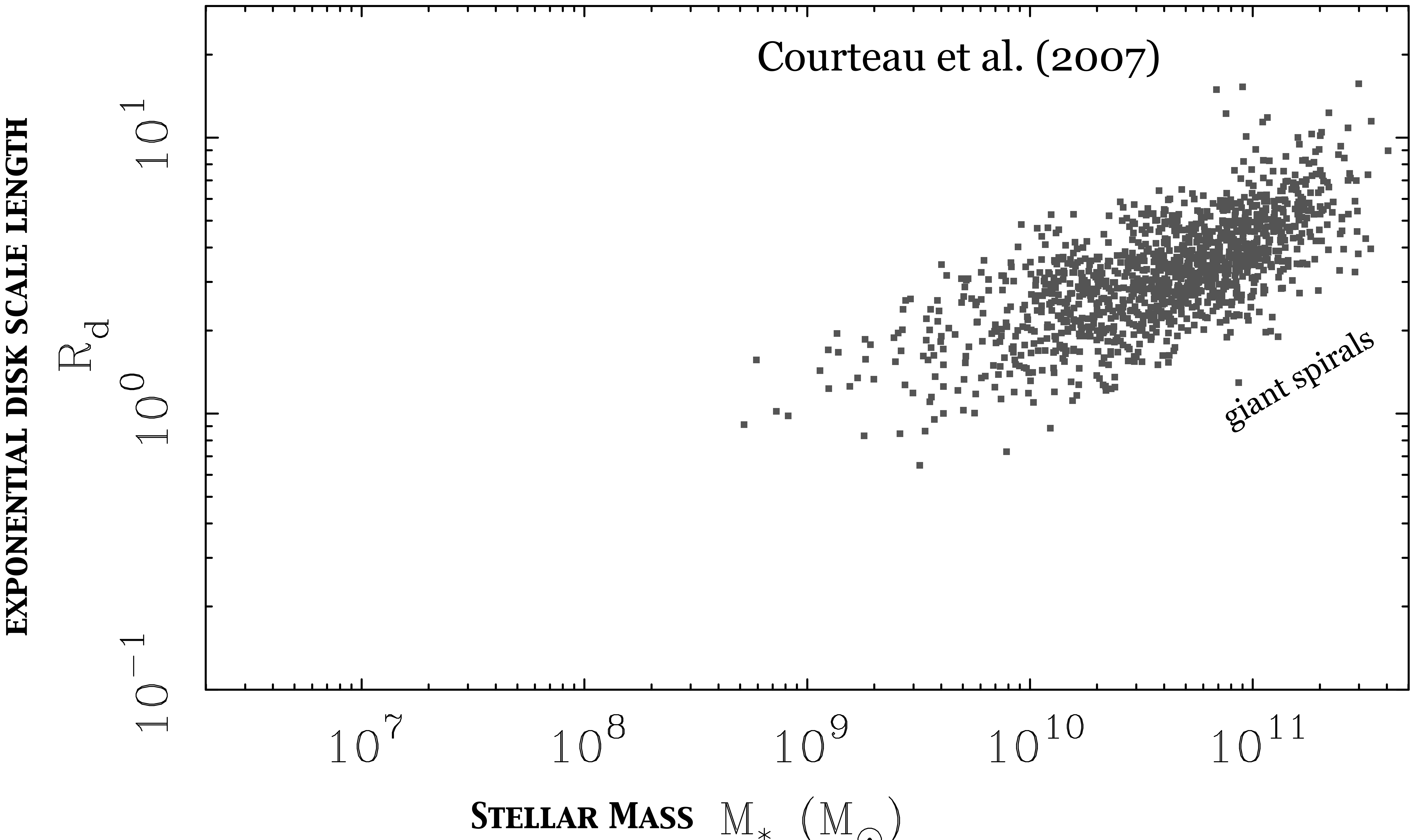


PRESSURE SUPPORTED

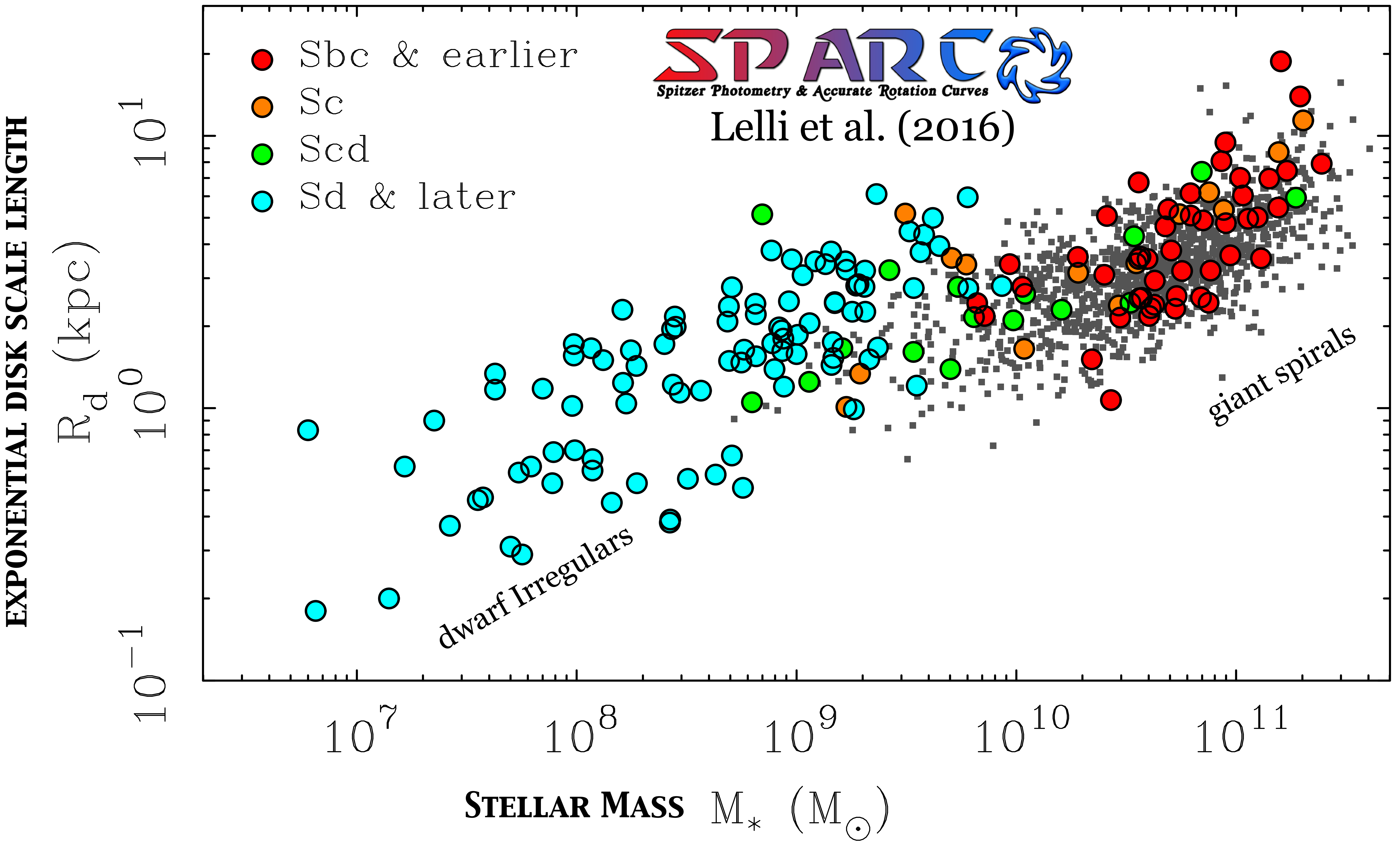
Tidal Dwarf Galaxies



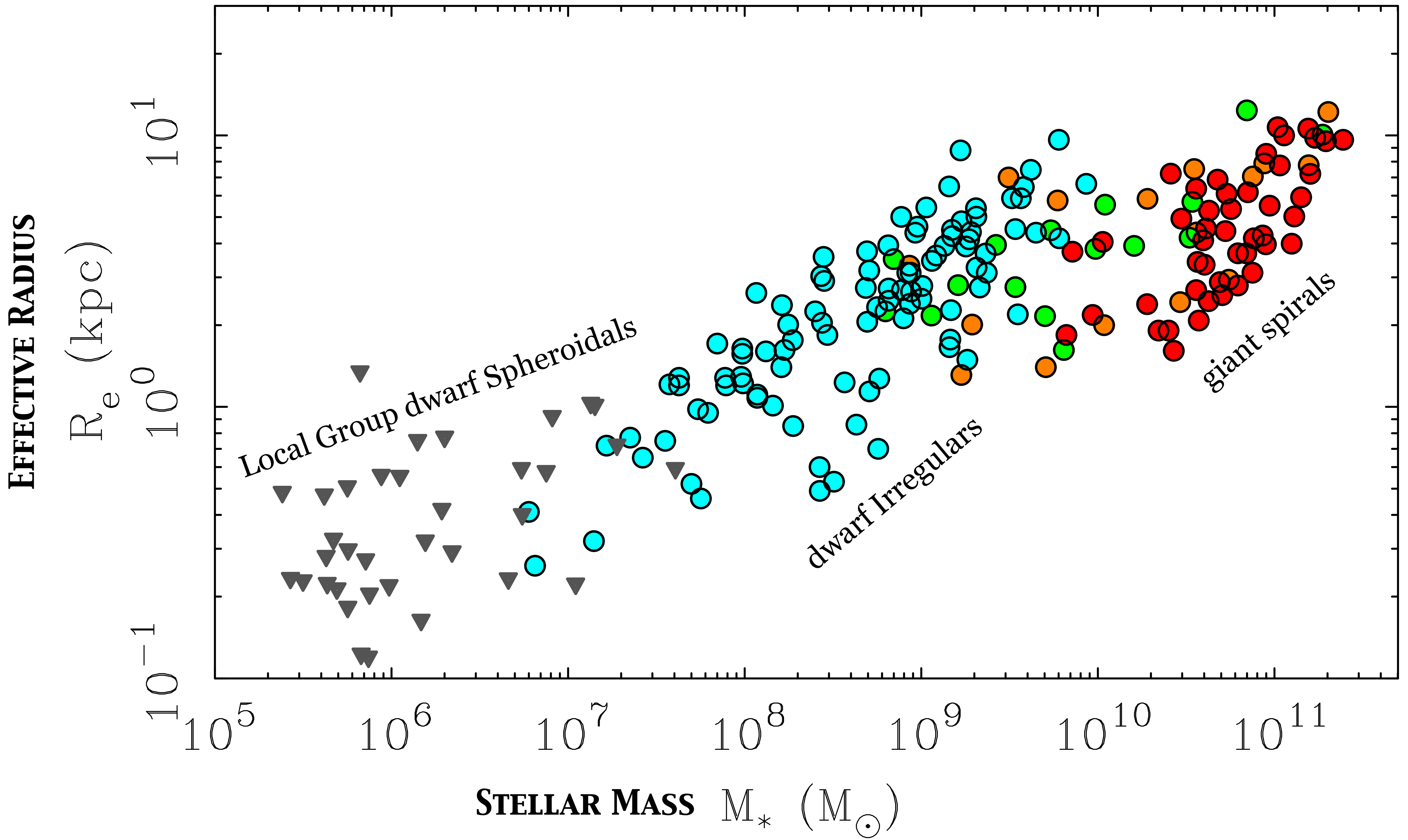
Lelli et al. (2015)

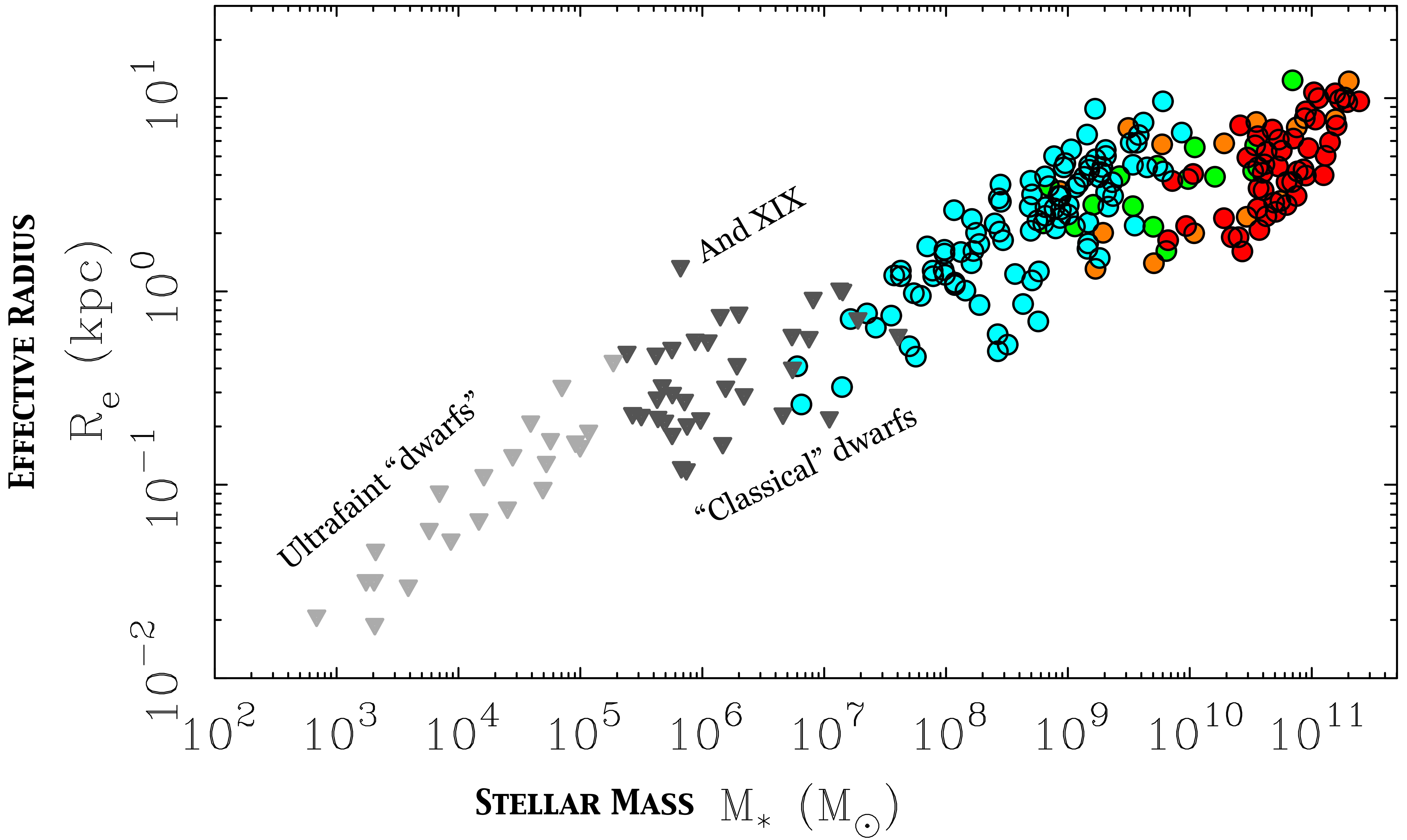


Courteau et al. (2007)
giant spirals
EXPONENTIAL DISK SCALE LENGTH
R_d
10^1
10^0
10^{-1}
10^7
10^8
10^9
10^{10}
10^{11}
STELLAR MASS M_* $(M_\odot)$



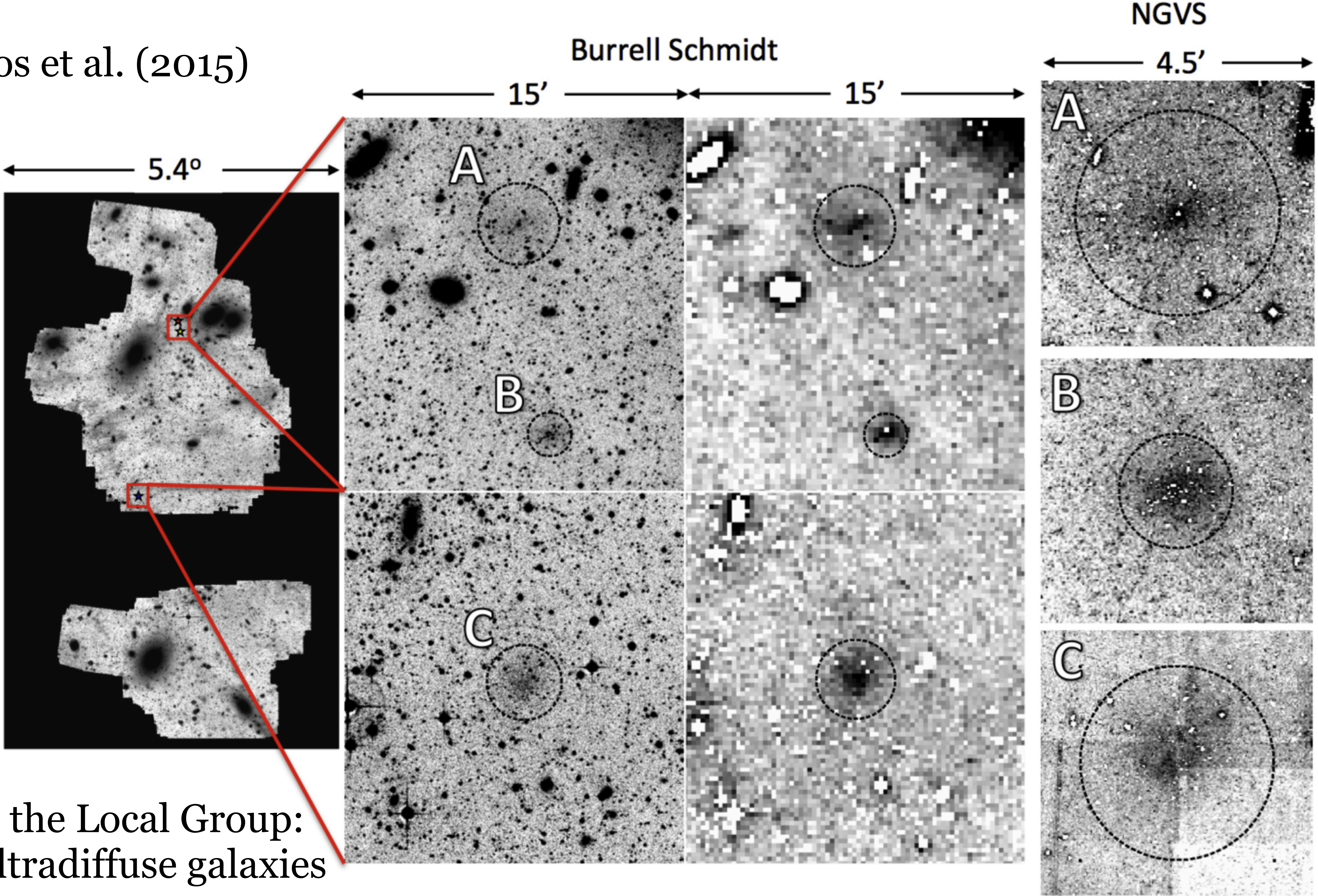
Sbc & earlier
Sc
Scd
Sd & later
SPARC
Spitzer Photometry & Accurate Rotation Curves
Lelli et al. (2016)
dwarf Irregulars
giant spirals
EXPONENTIAL DISK SCALE LENGTH
R_d (kpc)
10^{1}
10^{0}
10^{-1}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
STELLAR MASS M_* ($M_\odot$)


Effective Radius R_e (kpc)
10^{-1}
10^0
10^1
Stellar Mass M_* ($M_\odot$)
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
Local Group dwarf Spheroidals
dwarf Irregulars
giant spirals



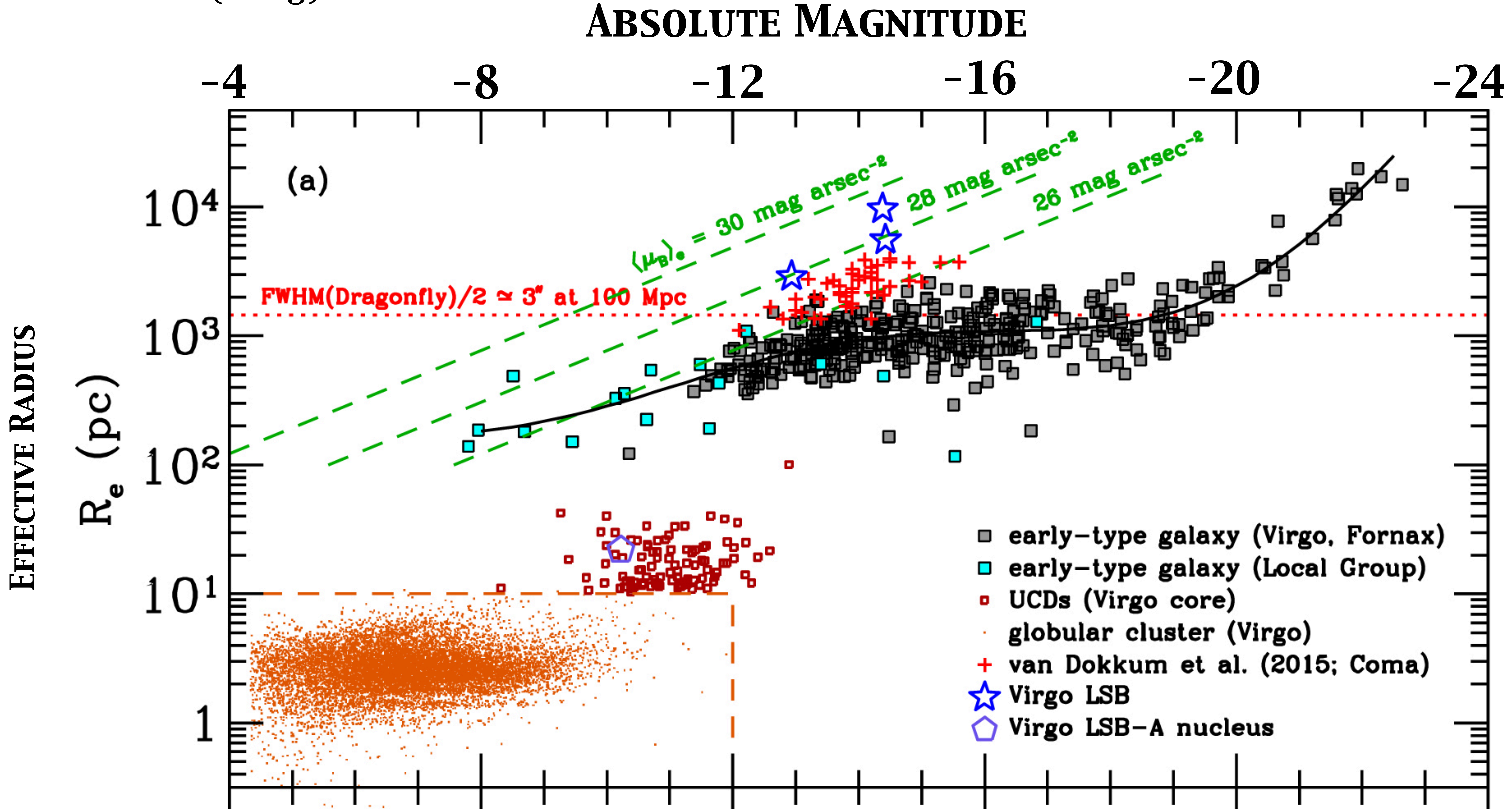
Effective Radius R_e (kpc)
10^1
10^0
10^{-1}
10^{-2}
And XIX
Ultrafaint "dwarfs"
"Classical" dwarfs
10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11}
Stellar Mass M_* ($M_\odot$)

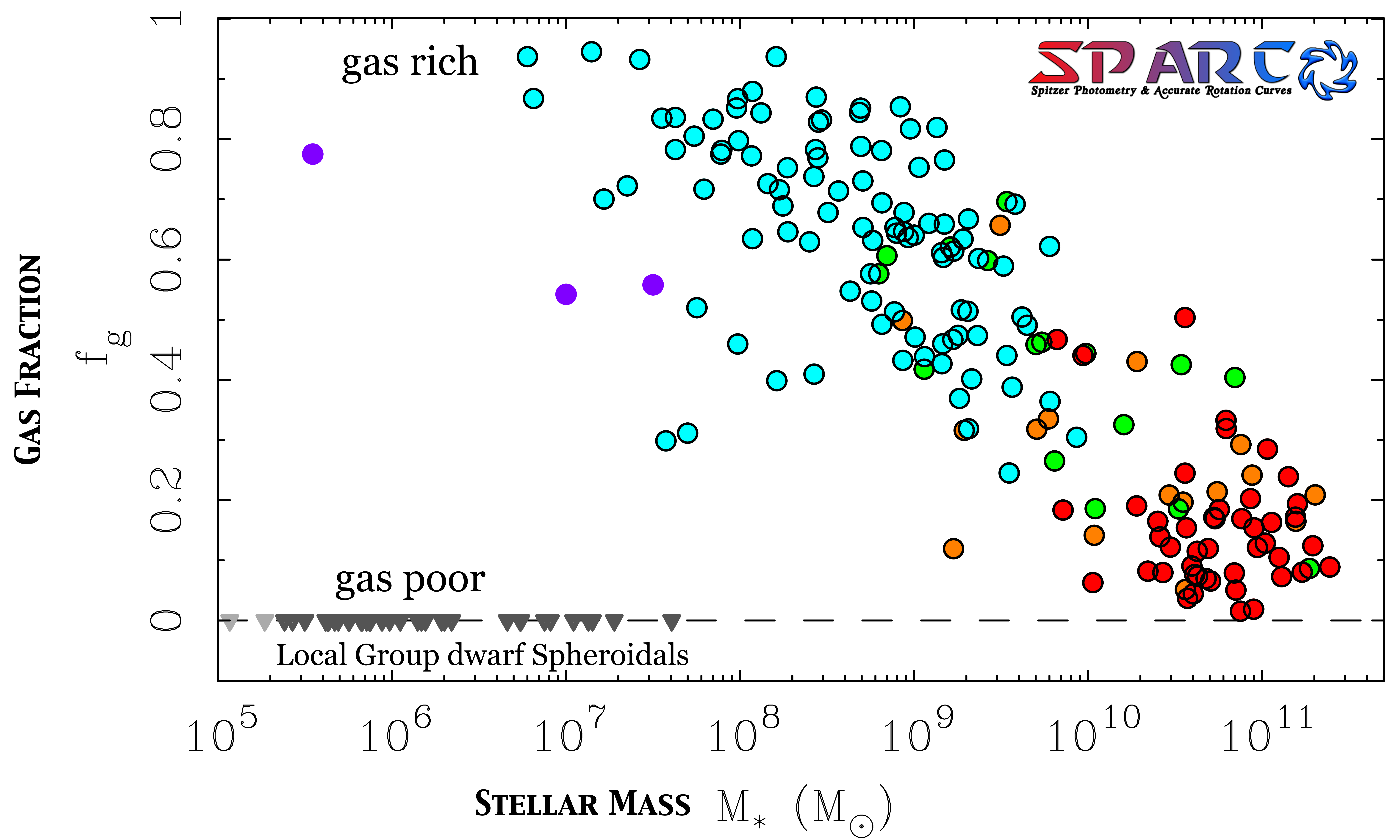
Mihos et al. (2015)



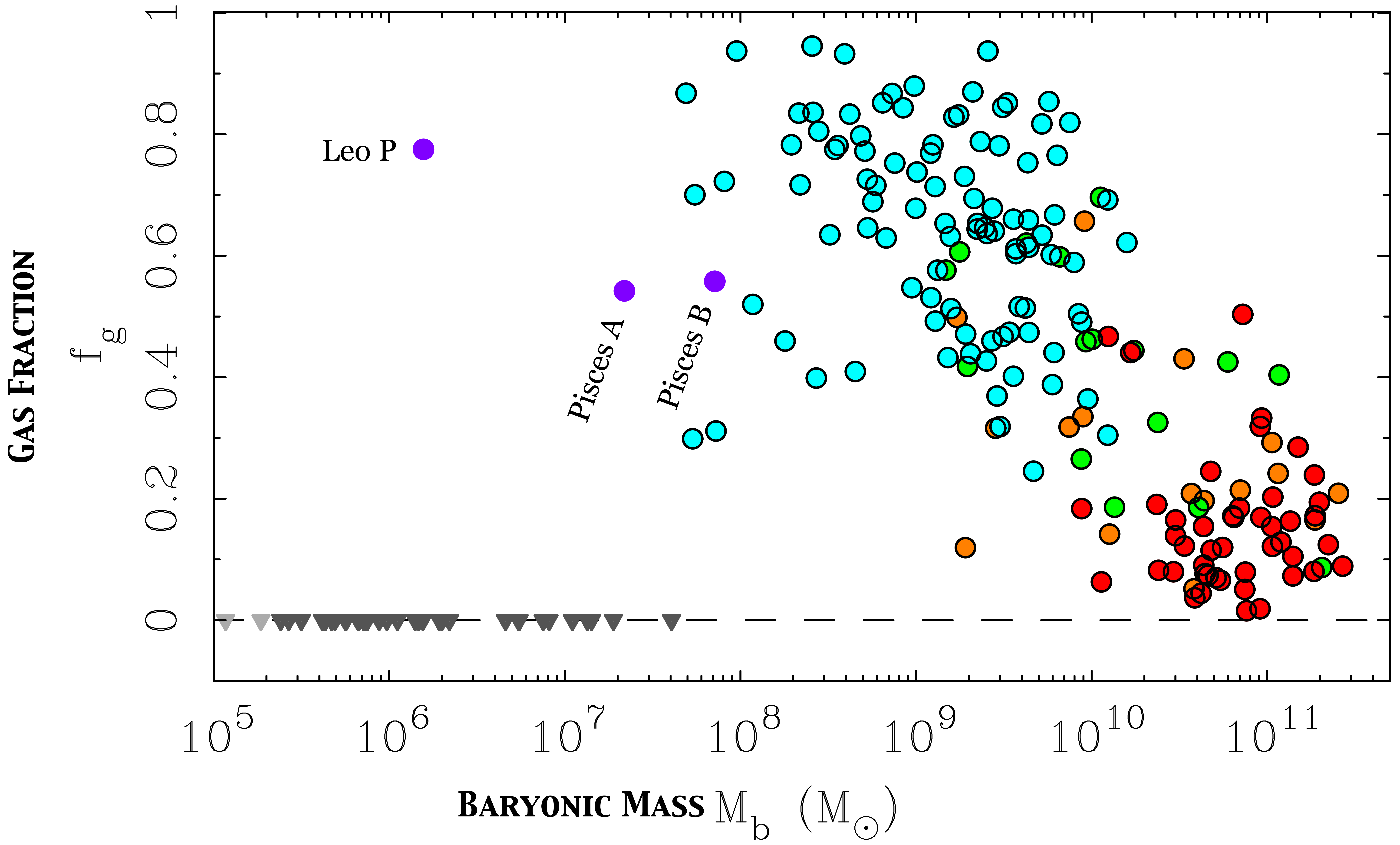
Beyond the Local Group:
Virgo ultradiffuse galaxies

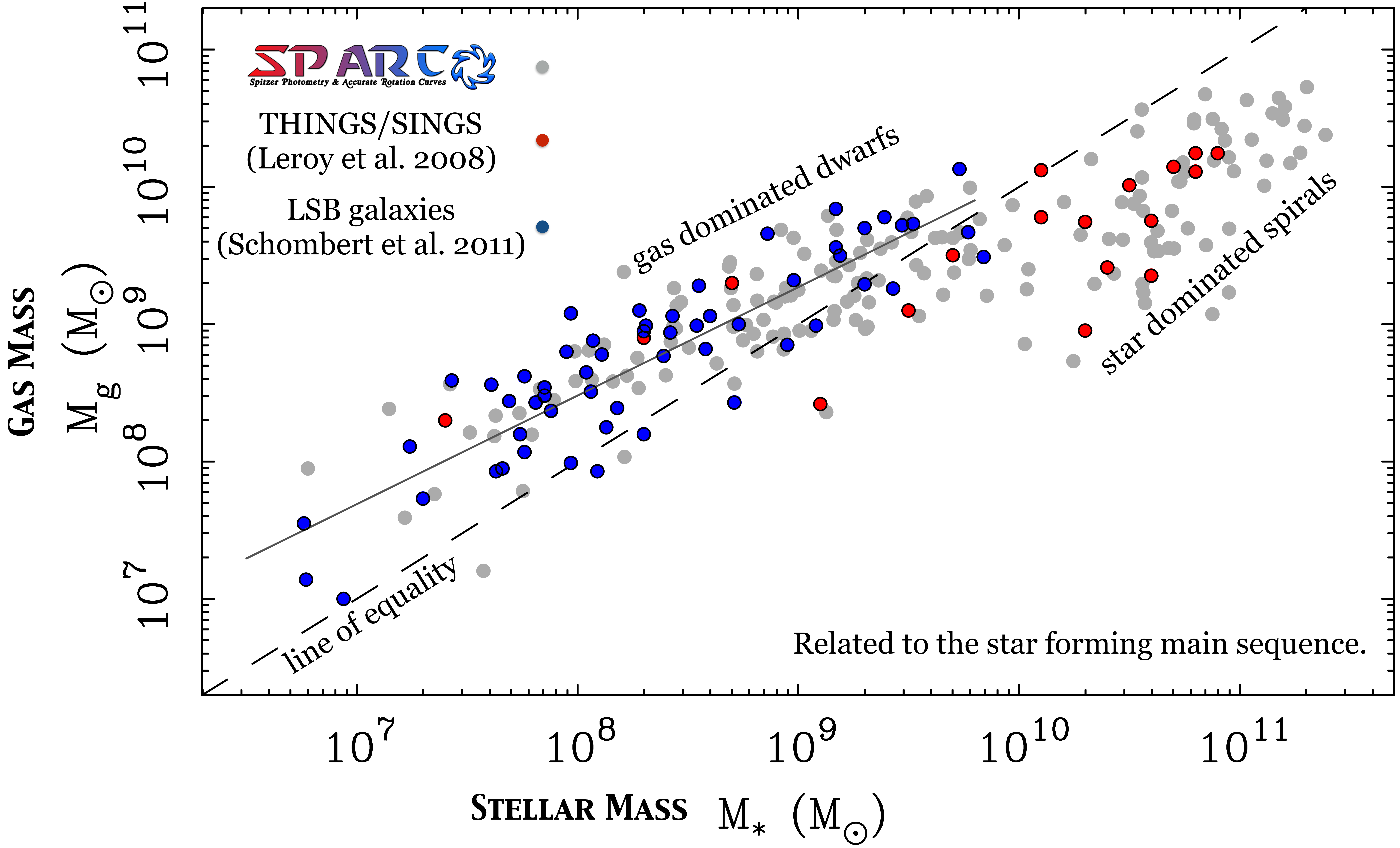
Mihos et al. (2015)





gas rich
gas poor
Local Group dwarf Spheroidals
SPARC
Spitzer Photometry & Accurate Rotation Curves
Gas Fraction f_g
Stellar Mass M_* ($M_\odot$)
0
0.2
0.4
0.6
0.8
1
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}

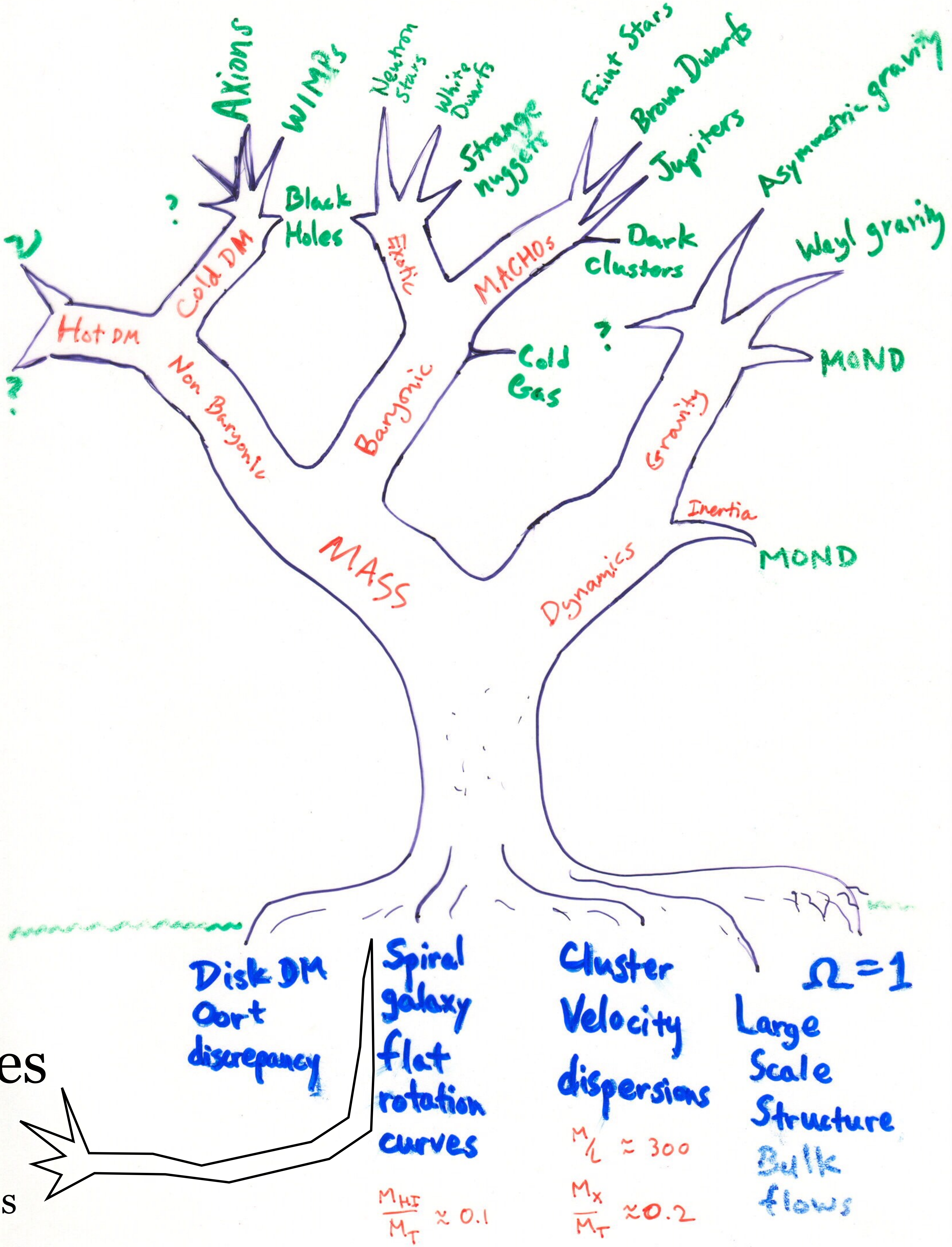

Gas Fraction
f_g
Baryonic Mass M_b ($M_\odot$)
Leo P
Pisces A
Pisces B
0
0.2
0.4
0.6
0.8
1
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}


SPARC
Spitzer Photometry & Accurate Rotation Curves
THINGS/SINGS
(Leroy et al. 2008)
LSB galaxies
(Schombert et al. 2011)
gas dominated dwarfs
star dominated spirals
line of equality
Related to the star forming main sequence.
Gas Mass M_g $(M_\odot)$
Stellar Mass M_* $(M_\odot)$
10^7
10^8
10^9
10^{10}
10^{11}

Star Forming Main Sequence
Star Formation Rate
SFR ($M_\odot$ yr^{-1})
Stellar Mass M_* ($M_\odot$)
THINGS/SINGS
(Leroy et al. 2008)
LSB galaxies
(Schombert et al. 2011)
unity slope
fading giants
$\dot{M}_* \propto M_*$ for most star forming galaxies.
Only the most massive “turn off” the main sequence.
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}

Dwarf galaxies evince the largest *mass discrepancies* observed.

with the exception of
Tidal dwarf galaxies

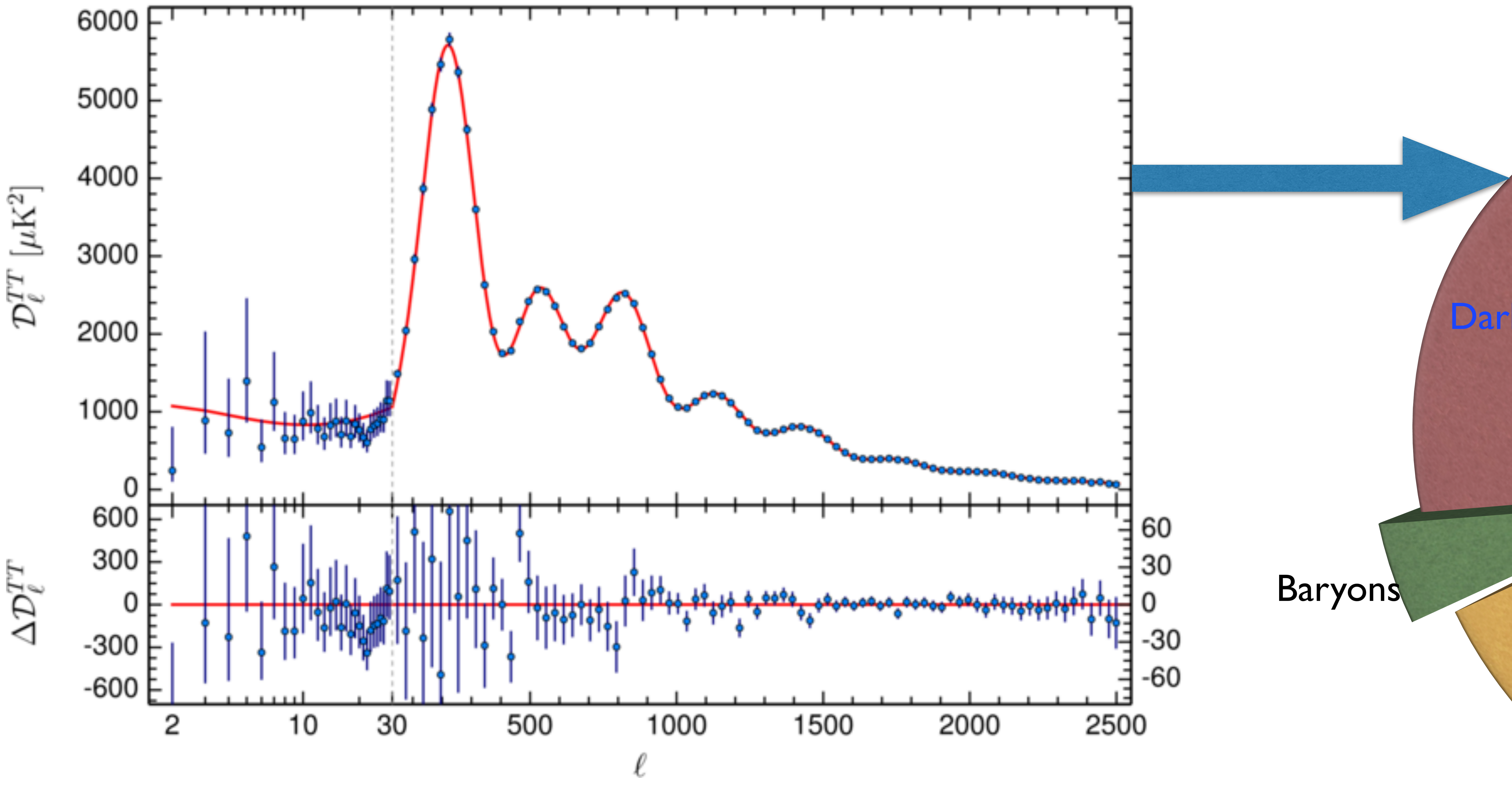


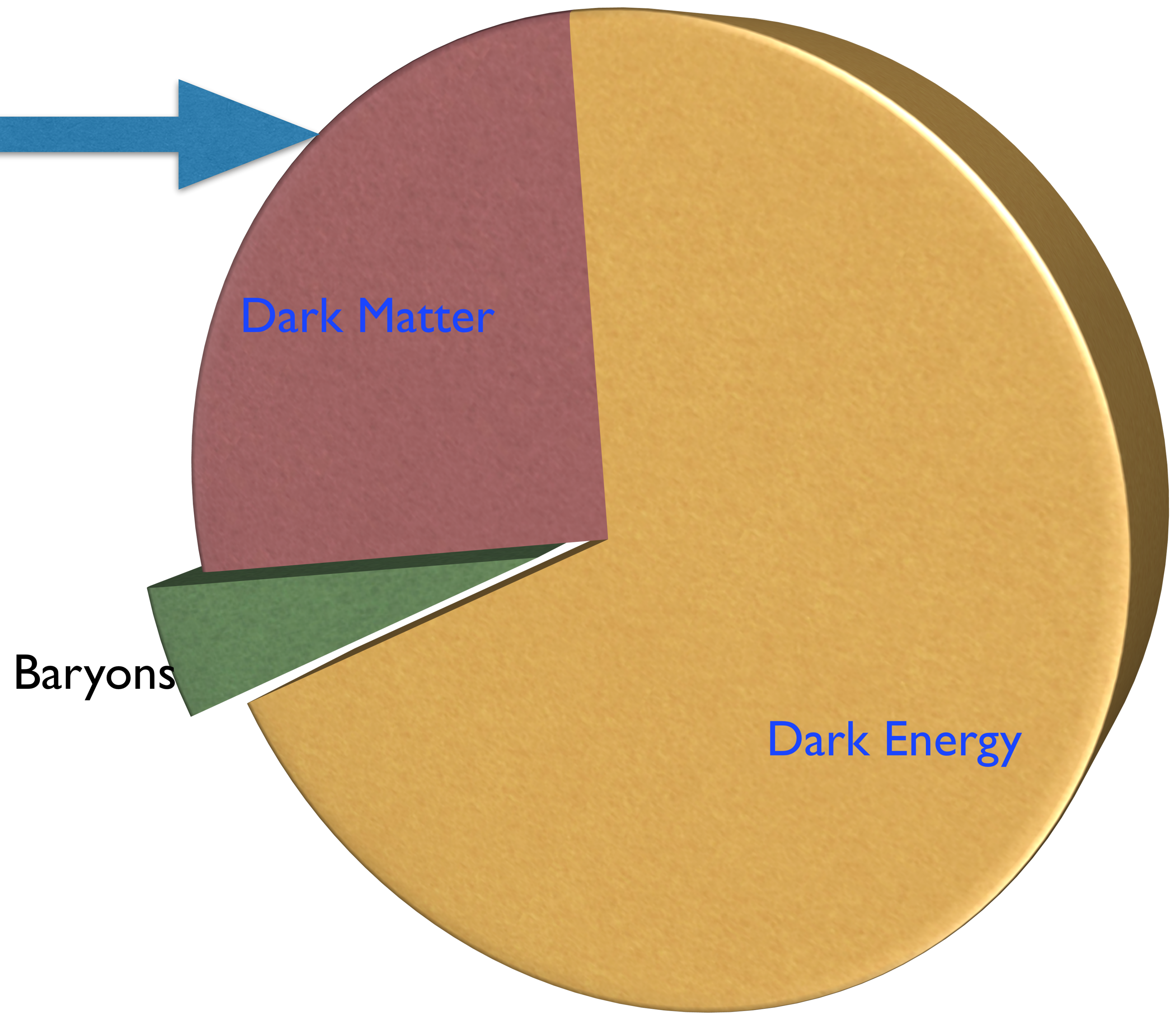
Dwarf galaxies
dwarf Irregulars
dwarf Spheroidals
Tidal dwarf galaxies

There is ample evidence for *mass discrepancies* -
dark matter?
new dynamics?
something novel?

Common attitude: CMB so well fit ΛCDM *must* be true

corollary: all apparent problems will be solved,
never pose genuine challenges (much less falsification)



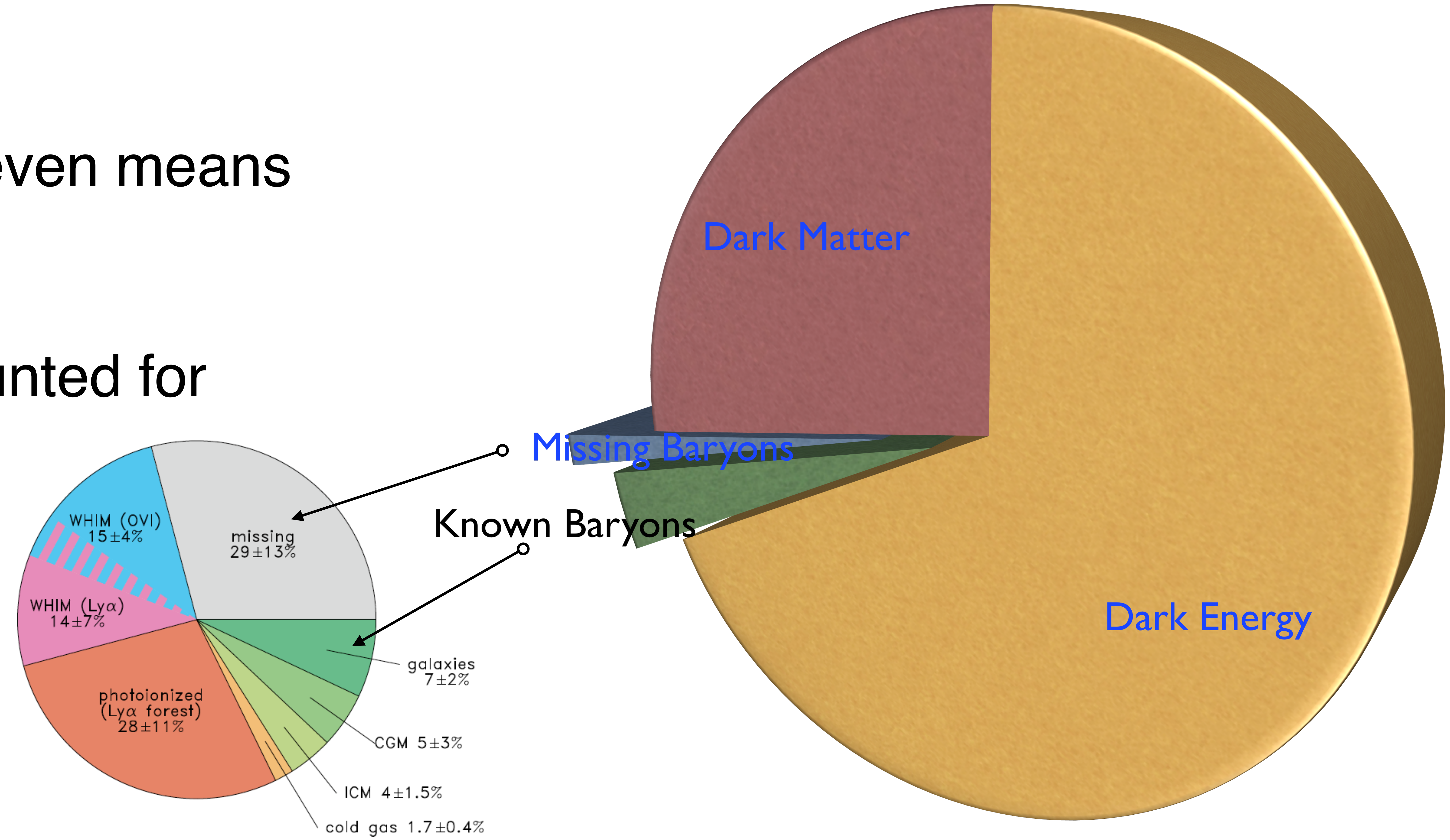


Cosmology works if and only if there exists

- non-baryonic cold dark matter
  - whatever it is (e.g., WIMPs)

- dark energy
  - whatever that even means

- dark baryons
  - 29% not accounted for

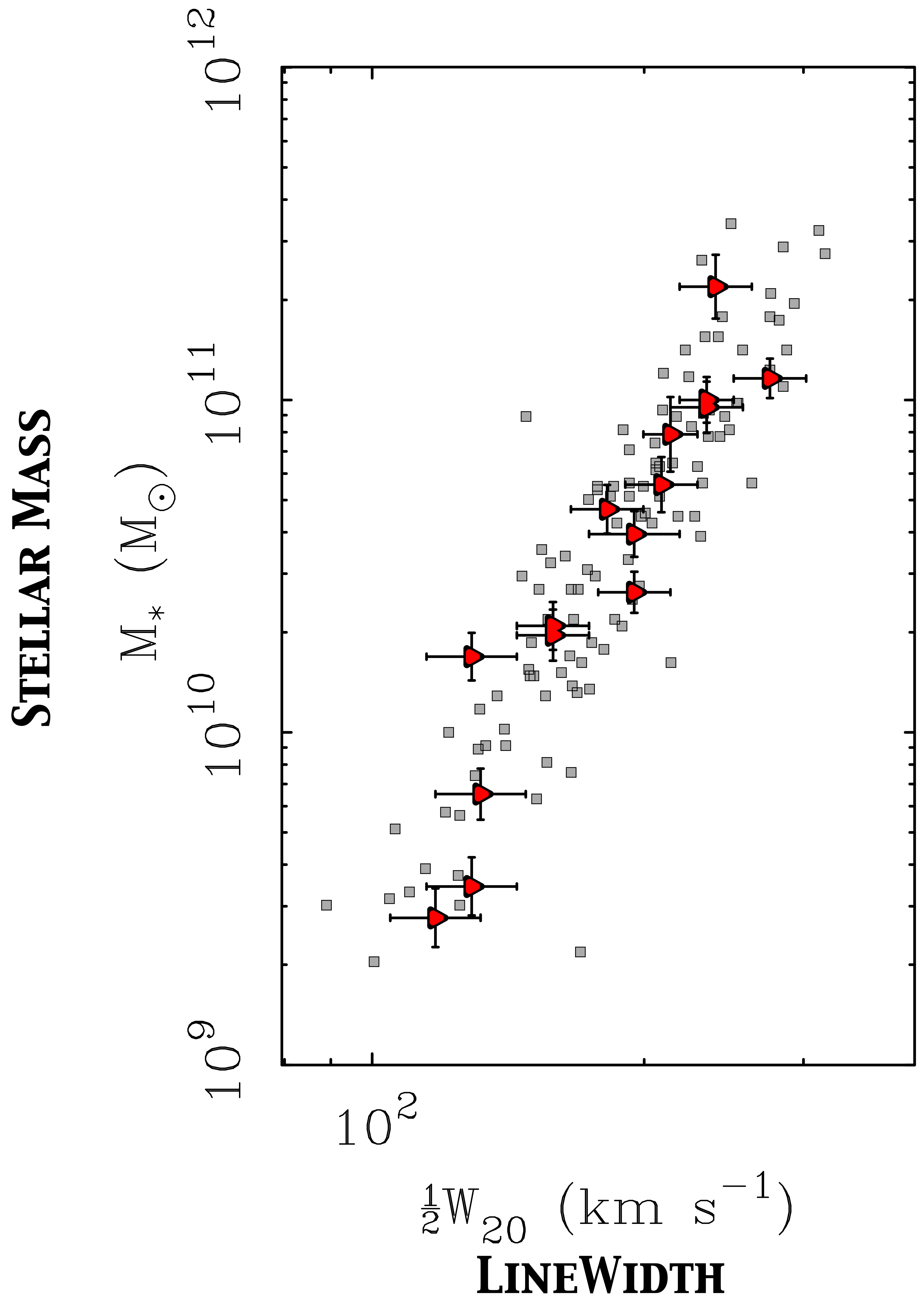


We have direct knowledge of < 4% of the mass-energy density of the universe

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.

- J.R.R. Tolkein
  (paraphrased)

e.g., **Scaling Relations**

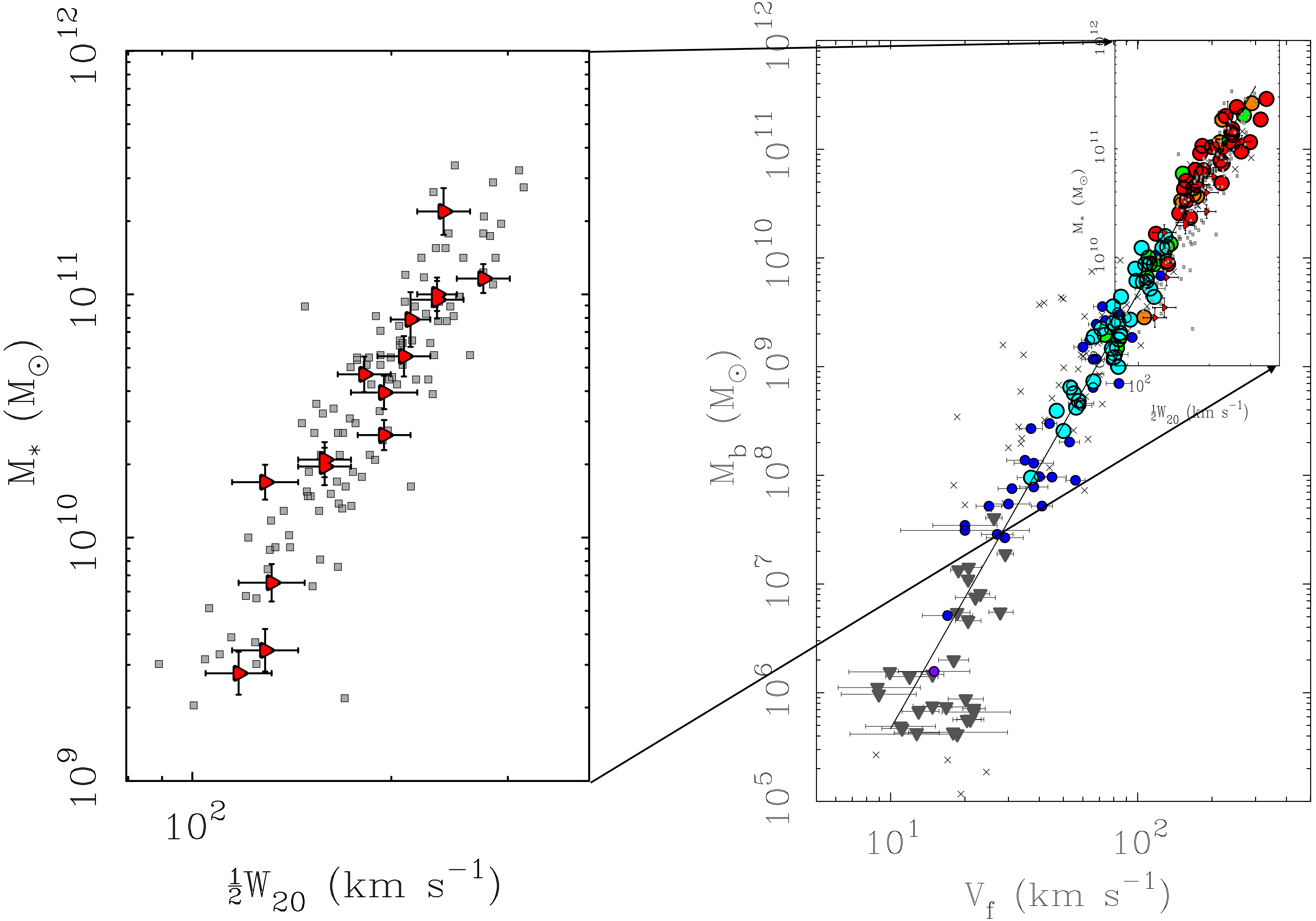


Tully-Fisher Relation

also

Renzo's Rule
Central Density Relation
Radial Acceleration Relation

- Bothun et al. (1985)
- Sakai et al. (2001)



M_* $(M_\odot)$
$\frac{1}{2}W_{20}$ (km s^{-1})
M_b $(M_\odot)$
V_f (km s^{-1})

Baryonic Tully-Fisher Relation

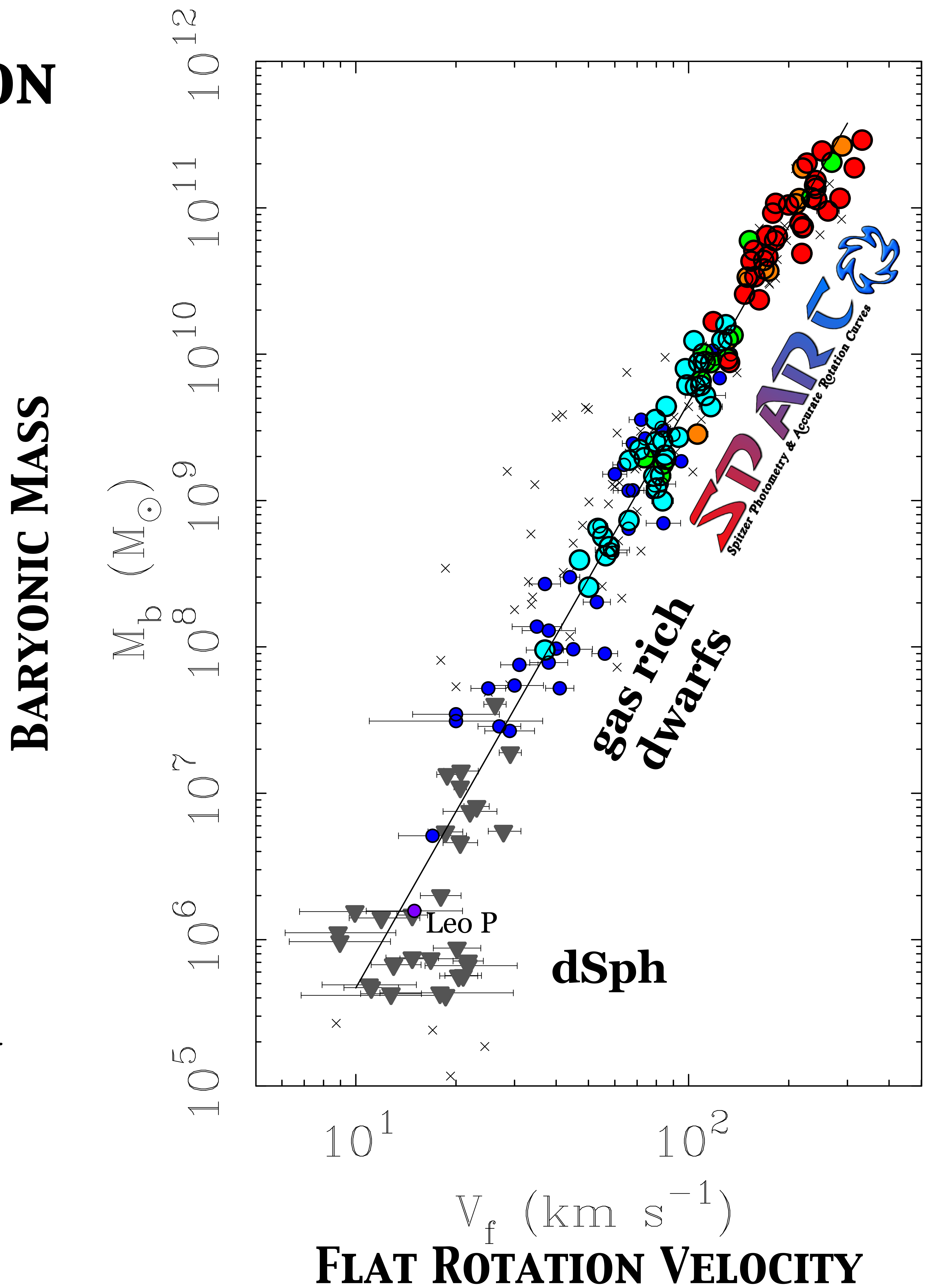
$$M_b = 47V_f^4$$

fit to

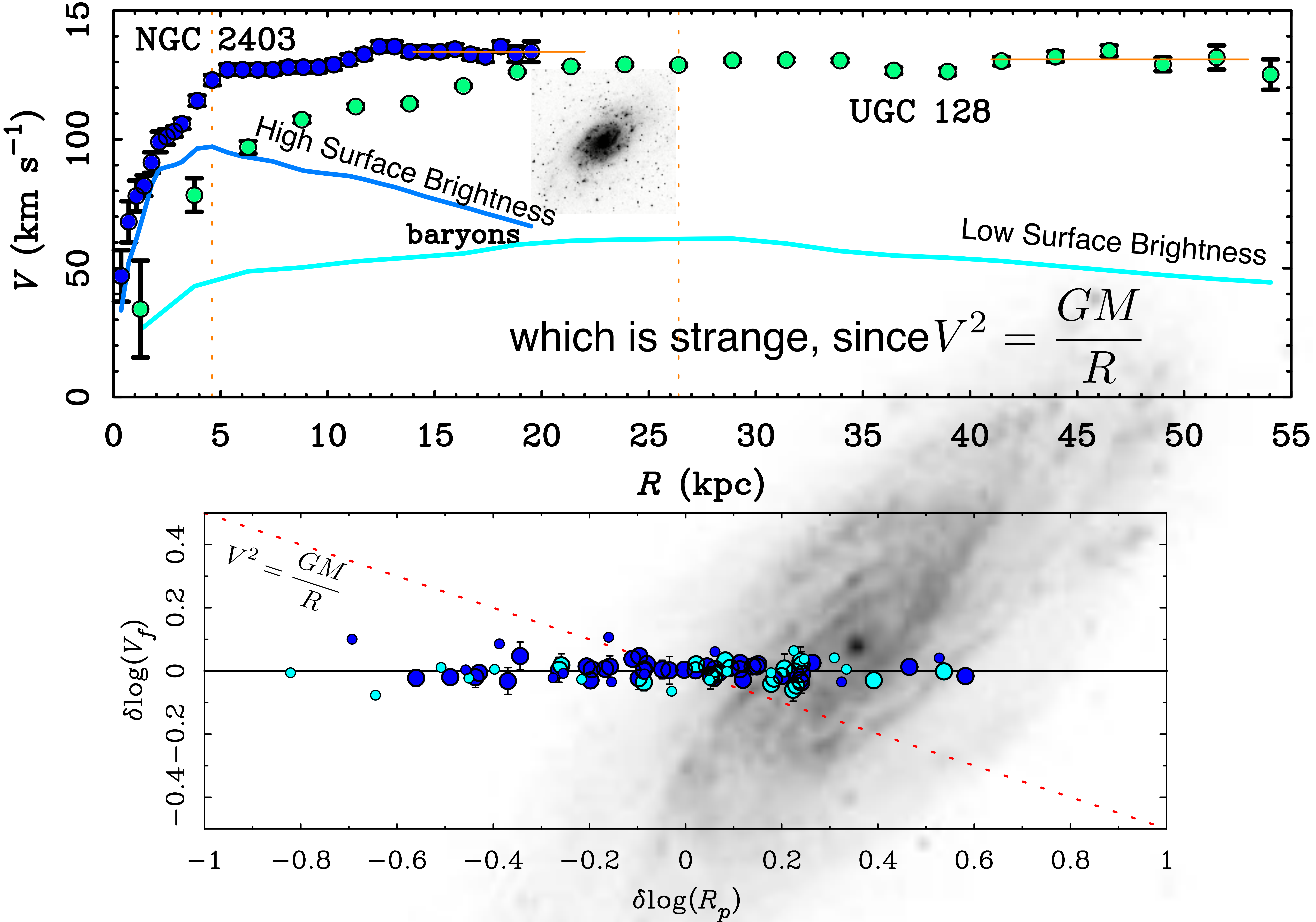
- gas rich dwarfs only (McGaugh 2012)

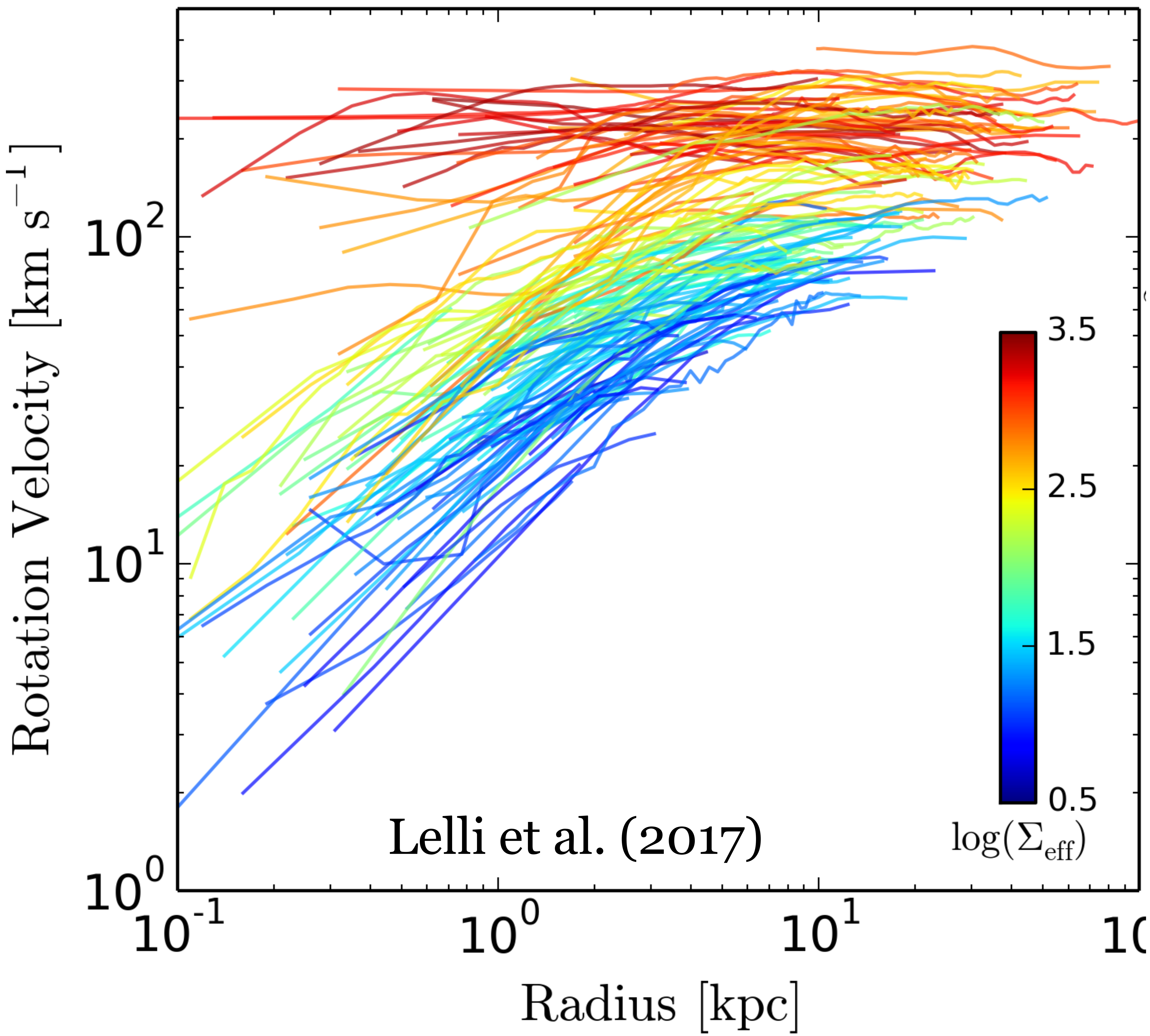
extrapolates well to both higher and lower masses

dSph plotted assuming $V_f = 2.24\sigma$ (McGaugh & Wolf 2010)

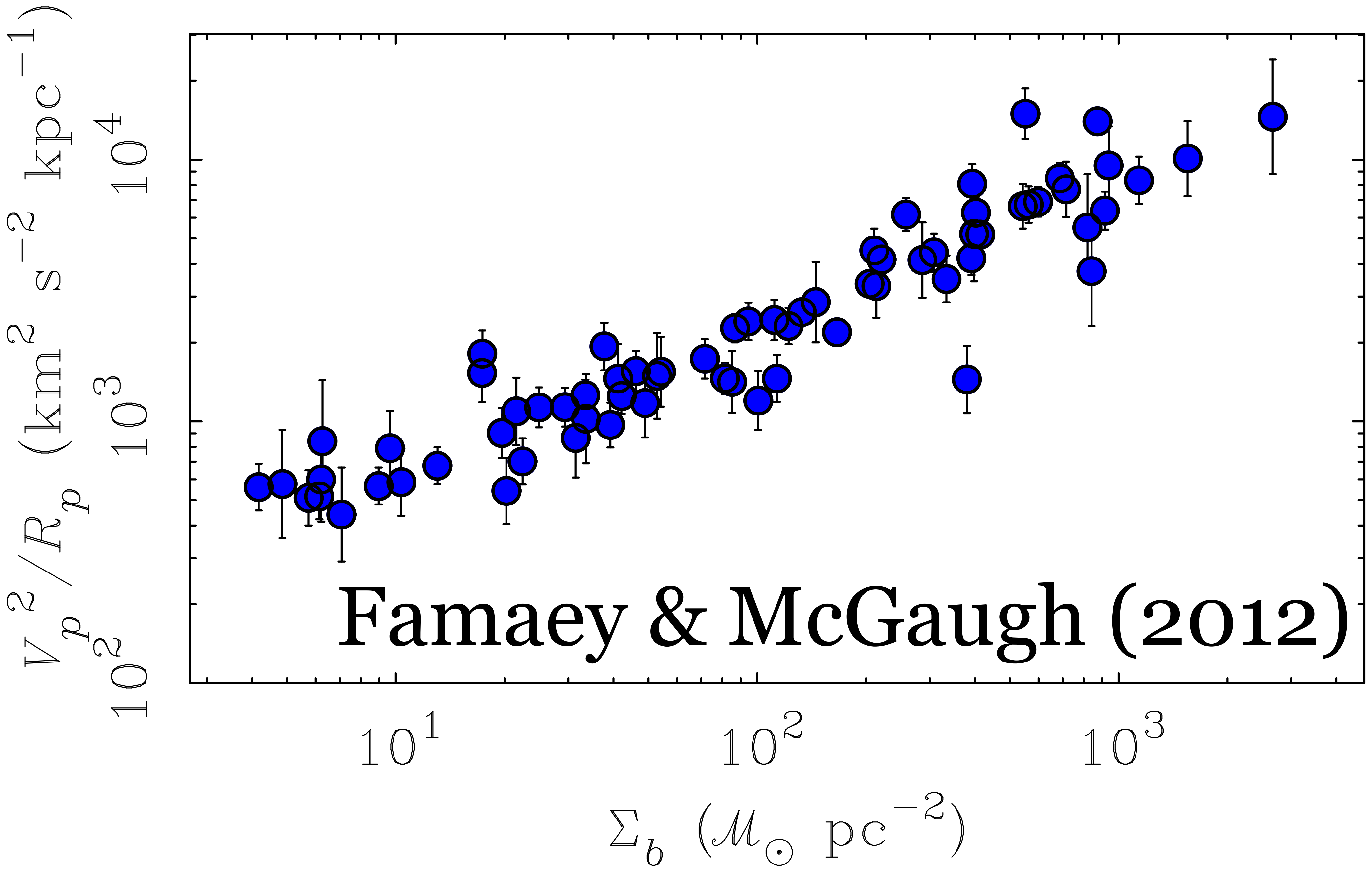


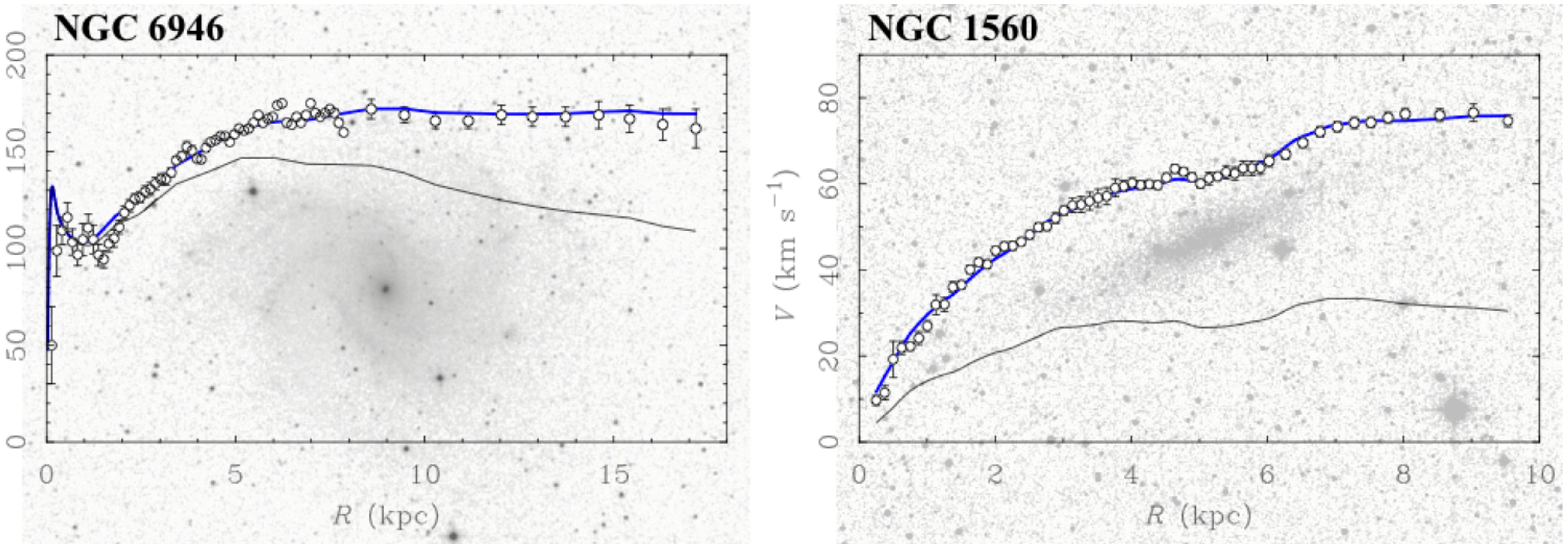
No residuals from TF with size or surface density





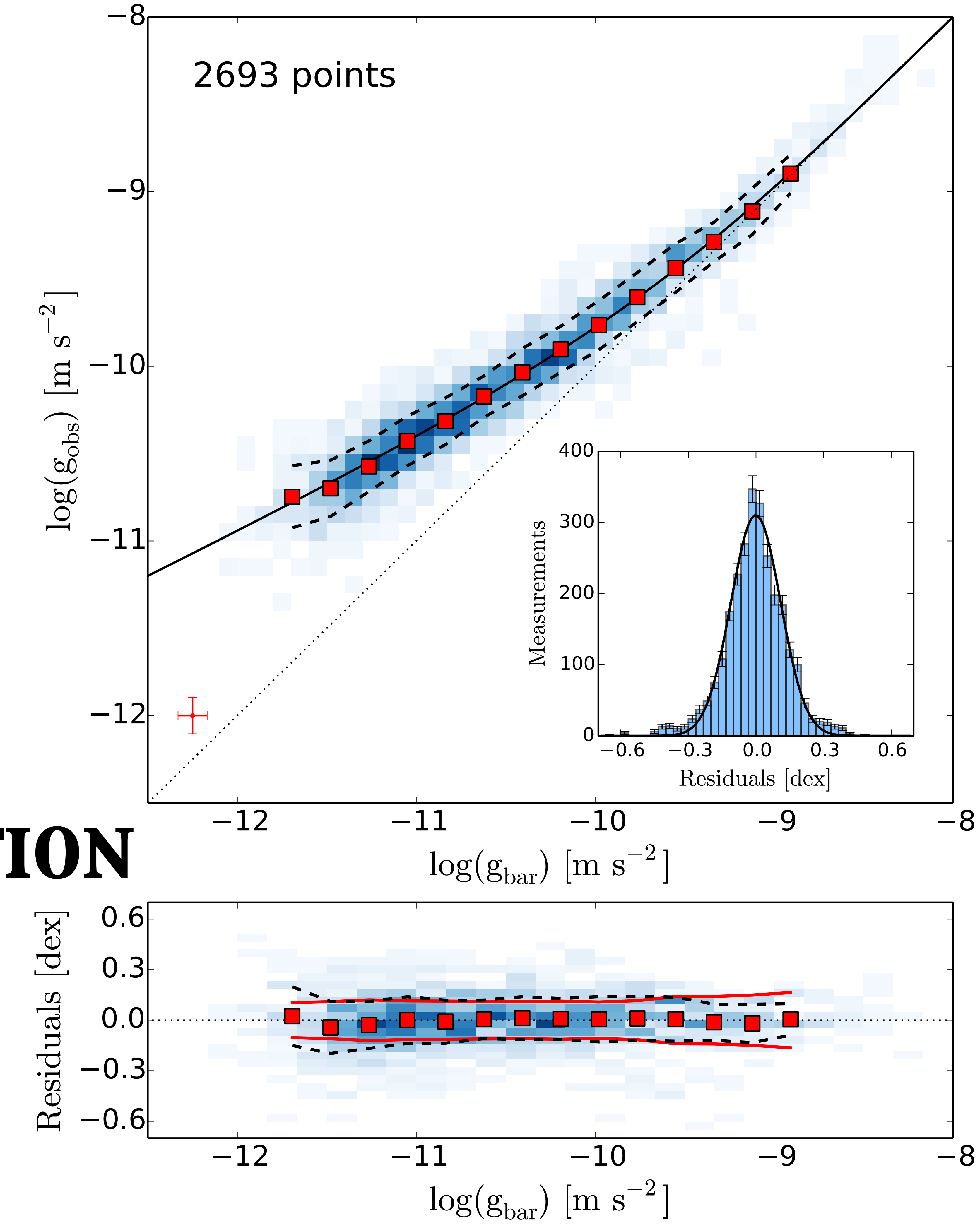
Dynamical acceleration well correlated with baryonic surface density



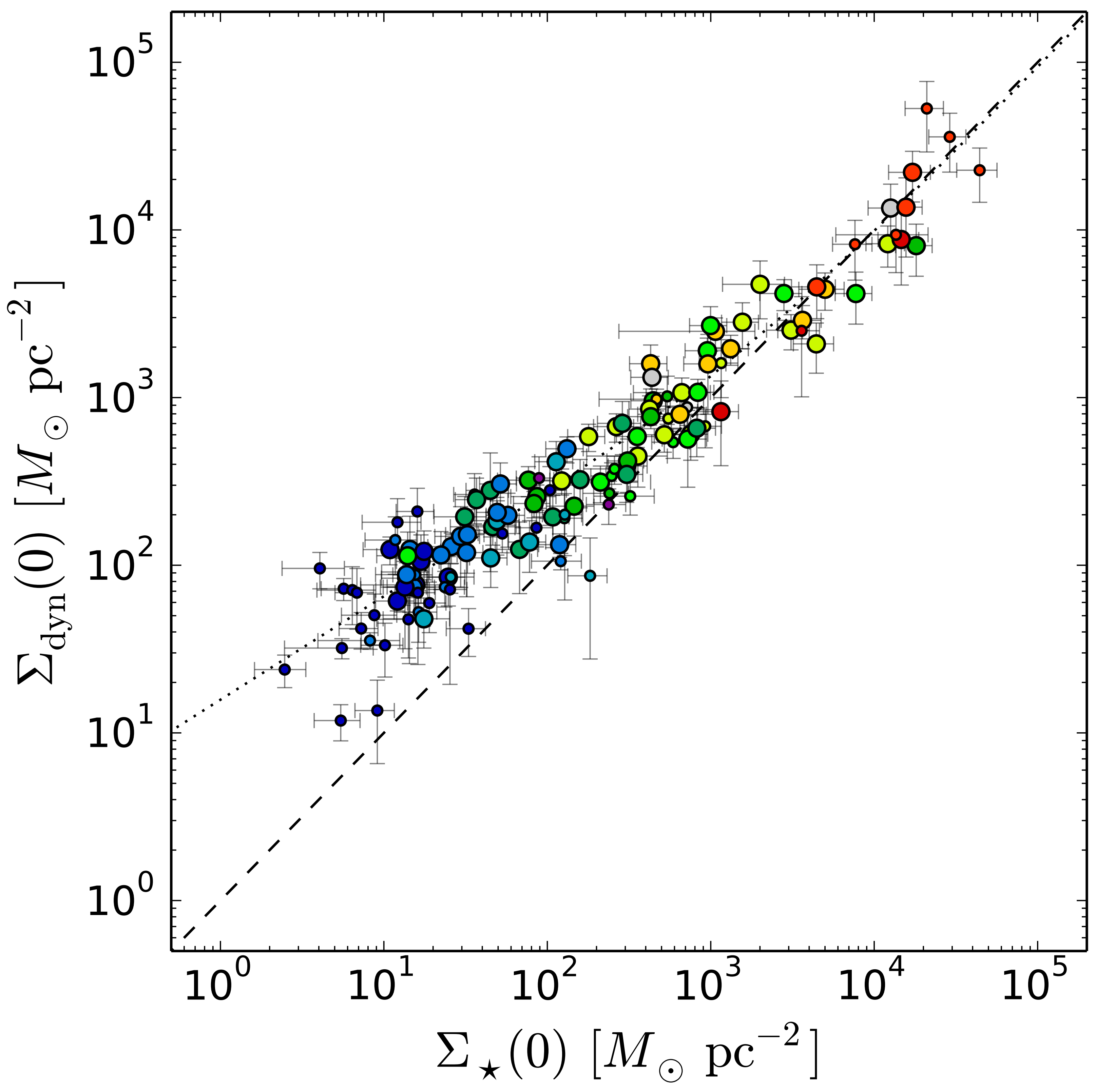


Renzo's Rule

"When you see a feature in the light, you see a corresponding feature in the rotation curve."



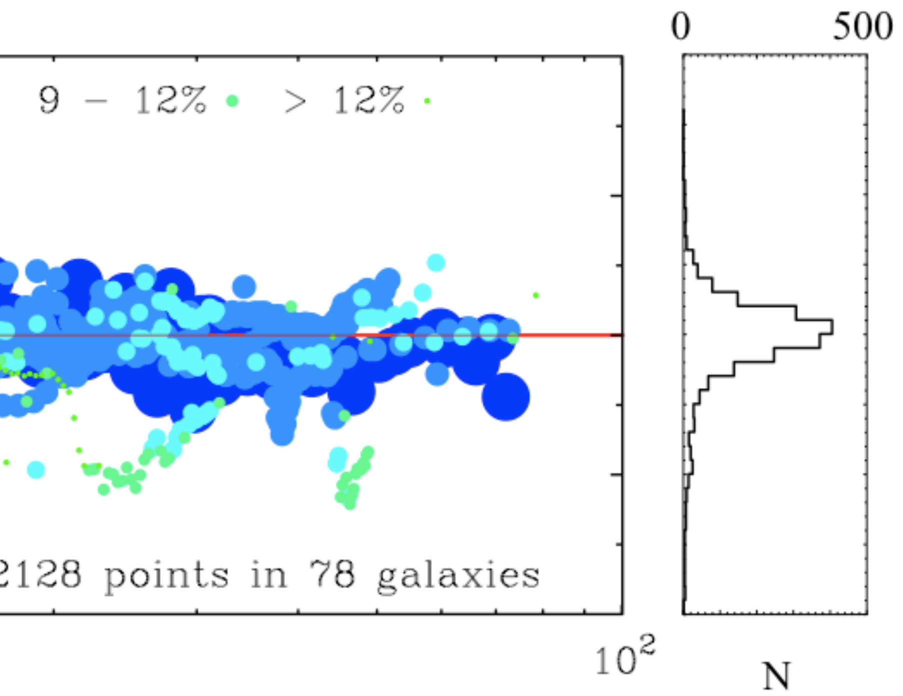
Radial Acceleration Relation



Central Density Relation

All these things and more were predicted by MOND. **WHY?**

MOND predictions



- The Tully-Fisher Relation
  - ✔ Slope = 4 ★
  - ✔ Normalization = $1/(a_0G)$ ★
  - ✔ 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

✓Radial Acceleration Relation

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

★ New Andromeda dwarfs and Crater 2 velocity dispersions predicted correctly in advance

MOND

Modify gravity at an acceleration scale

Hypothesized by Milgrom (1983)

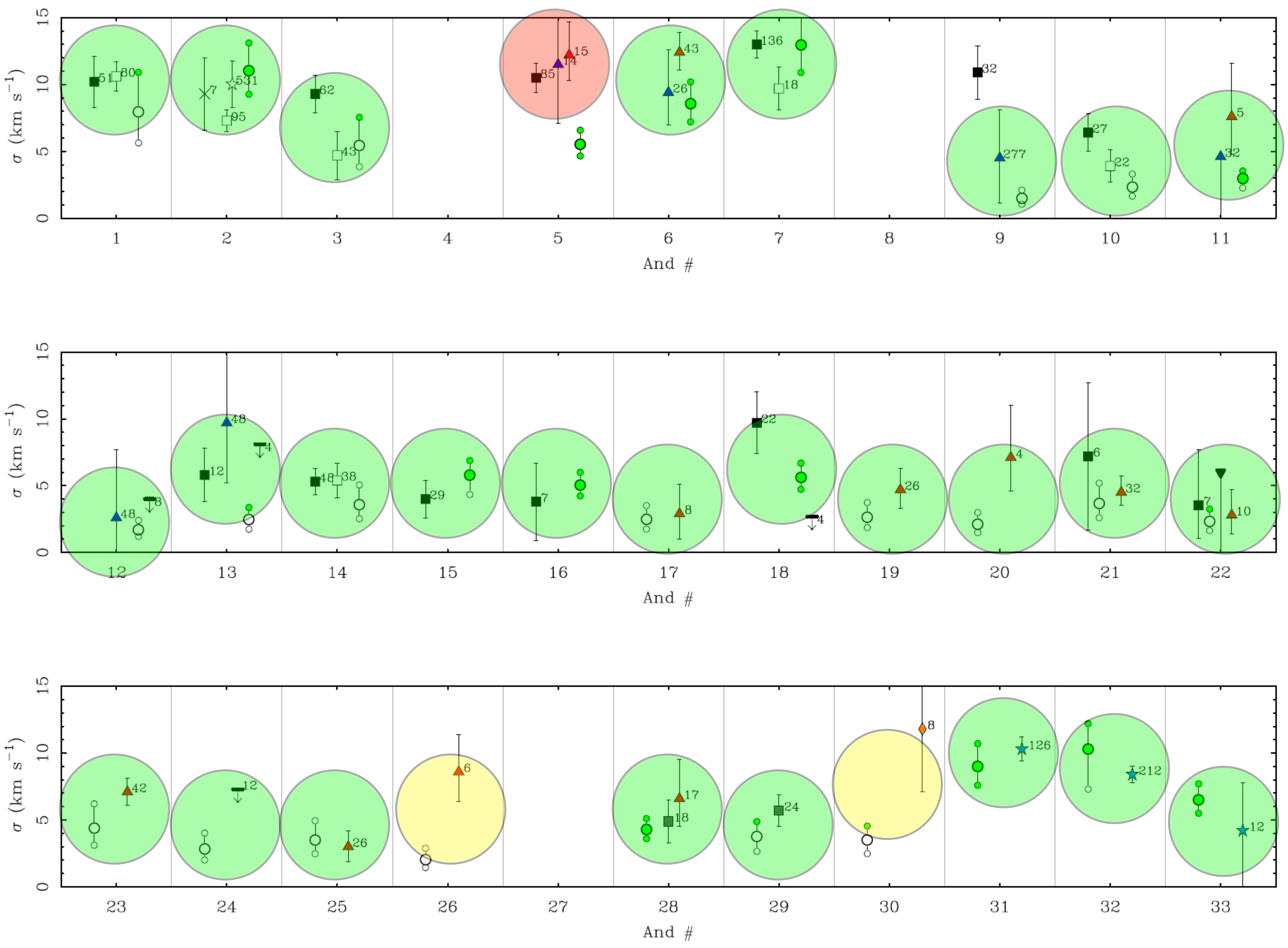
$a \gg a_0 \qquad a \rightarrow g_N$

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

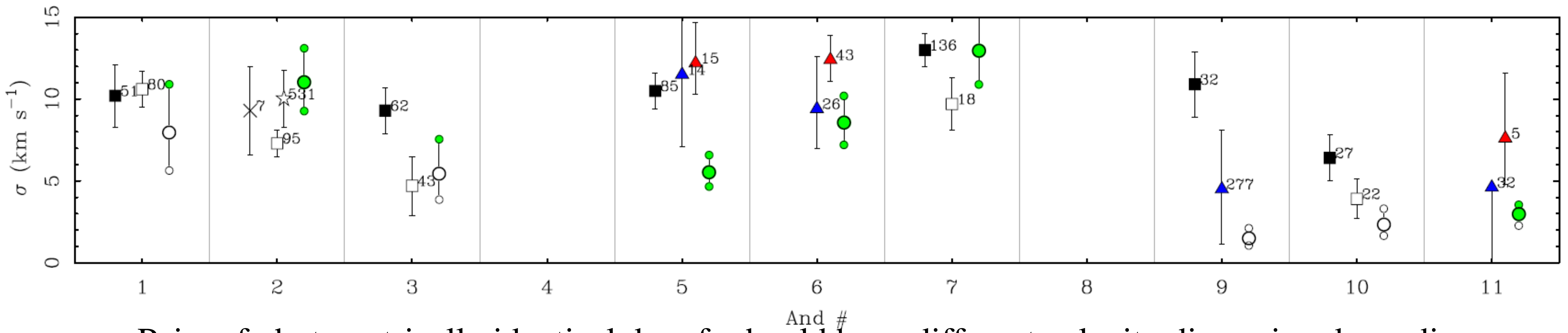
$a_0 = 1.2 \times 10^{-10}\,\mathrm{m\,s^{-2}}$

Unique & unsettling feature of MOND: the external field matters (violates Strong Equivalence)

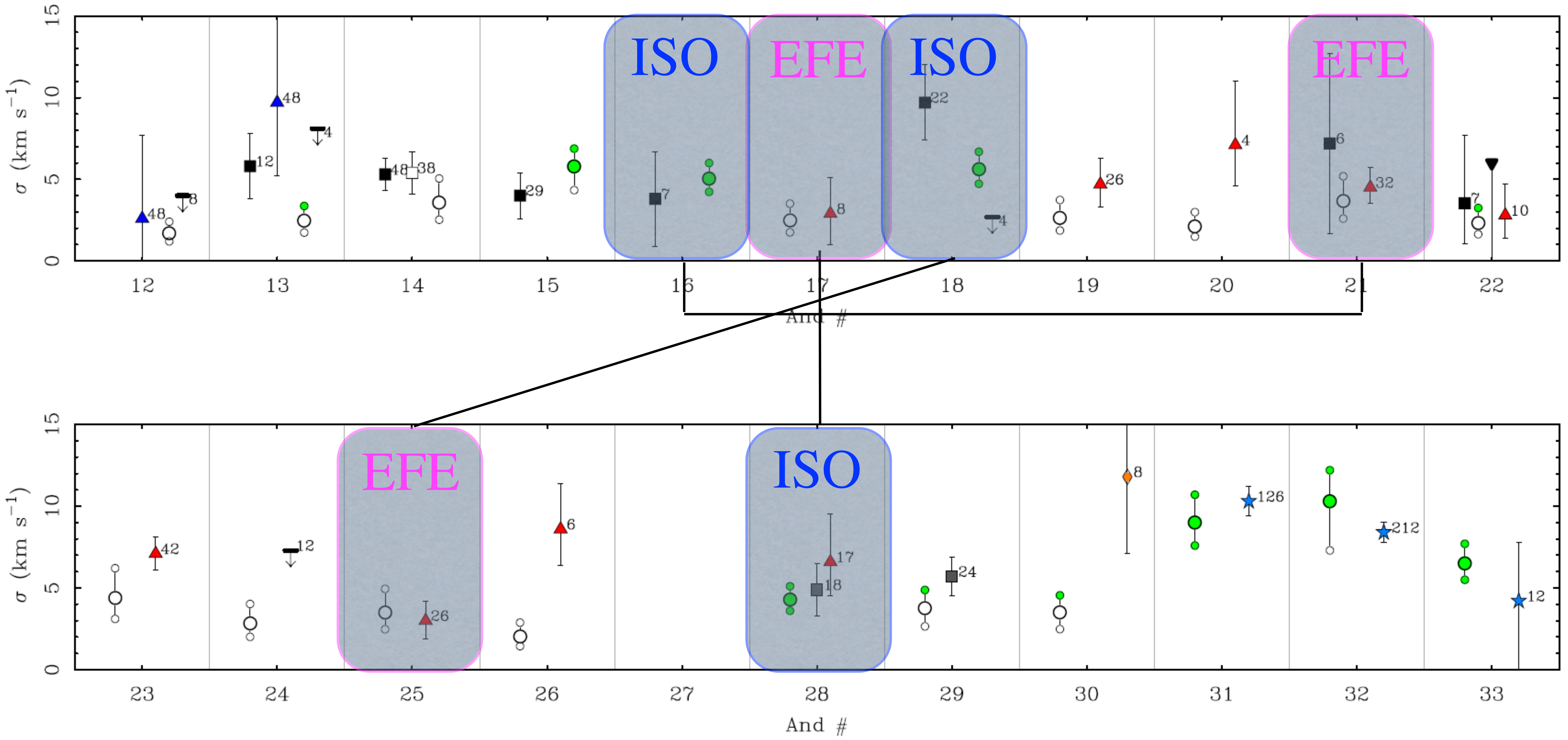
Isolated MOND regime ISO	EFE External Field Effect
$g_{ex} < g_{in} < a_0$	$g_{in} < g_{ex} < a_0$
Internal gravity of dwarf dominates	External gravity of host dominates
$\sigma_{iso} = \left(\frac{4}{81} a_0 G M_*\right)^{1/4}$	$\sigma_{efe} = \left(\frac{a_0 G M_*}{3 g_{ex} r_{1/2}}\right)^{1/2}$
Prediction depends only on ***stellar mass***	Prediction also depends on the ***size*** of dwarf and ***mass*** of and ***distance*** from host galaxy



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.

MOND

Crater 2

The recently discovered, ultra-diffuse Crater 2 provides another test.

$$L_V = 1.6 \times 10^5\ L_\odot$$
$$r_h = 1066\ \text{pc}$$

LCDM anticipates 10 - 17 km/s
(abundance matching; size-v. disp. rel'n)

MOND predicts 2.1 +0.9/-0.6 km/s
(in EFE regime arXiv:1610.06189)

Subsequently observed: 2.7 ± 0.3 km/s
(Caldwell et al. arXiv:1612.06398)

Consistent with a priori MOND prediction ★

Very hard to understand in the context of ΛCDM - incredibly low velocity at a very large radius.

Why does MOND get any prediction right?

Boylan-Kolchin et al. (2012) MNRAS, 422, 1203
"Too Big To Fail"