

# **The Future of Empirically Established Cosmology**

**On the occasion of Joe Silk's 75<sup>th</sup> Birthday**

**IAP December 2017**

**PJE Peebles**



- (1) We all make non-empirical judgements, for better or worse.
- (2)  $\Lambda$ CDM is empirically well established. It certainly is incomplete.
  - (a) But all physics is incomplete. Consider Maxwell's equations  $\rightarrow$  QED  $\rightarrow$  ??
  - (b) But surely there is a better cosmology for  $z \lesssim 10^{10}$  than I guessed at in 1982 and 1984, with an empirically more interesting dark sector.
- (3) Seeking detection of DM, evolution of  $\Lambda$ , and more interesting dark & gravity physics:
  - (a) No compelling DM detection after decades of searches; no problem for  $\Lambda$ CDM.
  - (b) Might completion of MOND or emergent gravity replace  $\Lambda$ CDM? A very long shot.
- (4) Challenges to  $\Lambda$ CDM may point to a better theory, or only misreadings of the evidence. My choices of challenges that seem less likely to be misinterpretations:
  - (a) Scaling laws & stellar halo luminosities challenge the expected growth by merging.
  - (b) Stellar bulges of galaxy are much fainter than models. Can feedback, as by the enigmatic central massive black holes, resolve this long-standing problem?
  - (c) Galaxies edging into the Local Void look similar to those in the Local Plane.
- (5) Dreams of a final cosmology:
  - (a) The empirical case for inflation is promising, but not persuasive.
  - (b) Hazards of the Anthropic Principle: e.g.  $\Lambda$ , a superabundance of homes for us.
  - (c) The nightmare: a final cosmology that is logically complete, fits all observations, but rotten at the core, which we'd never know if the core could not be probed.
- (6) Dreams of empirical surprises to come:
  - (a) Maybe it's successive incomplete approximations all the way down.
  - (b) But final or incomplete, our universe is immense, surely full of empirical surprises.

Landau and Lifshitz,  
the 1951 translation  
of the 1948 Russian  
*Theory of Field*

THE  
CLASSICAL THEORY  
OF FIELDS

---

by

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Translated from the Russian

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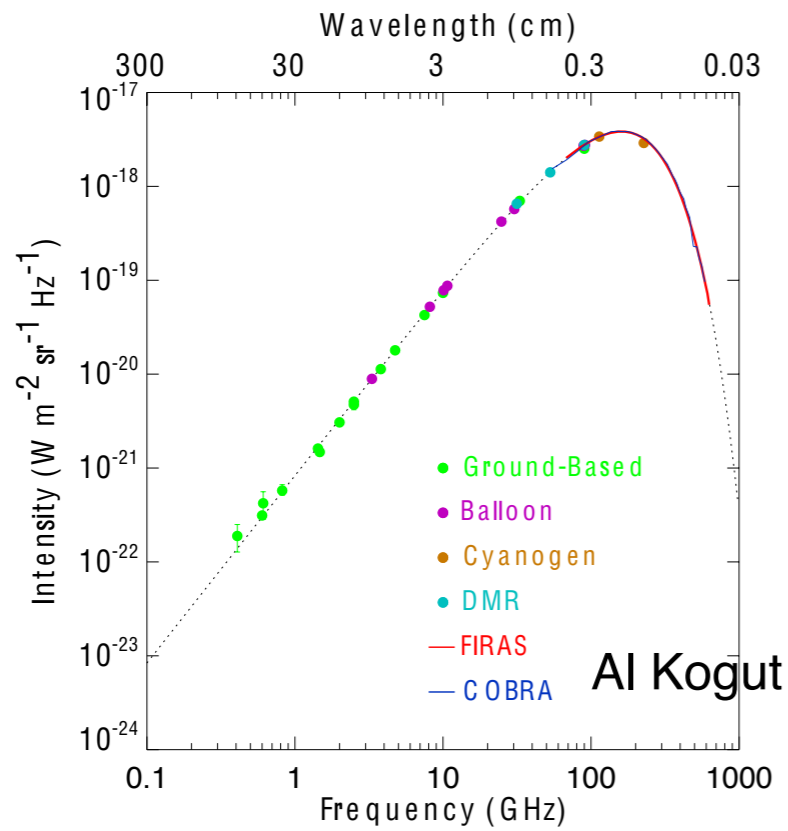
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\* Nowhere in our equations do we consider the so-called cosmological constant, since at the present time it has finally become clear that there is no basis whatsoever for such a change in the equations of attraction.

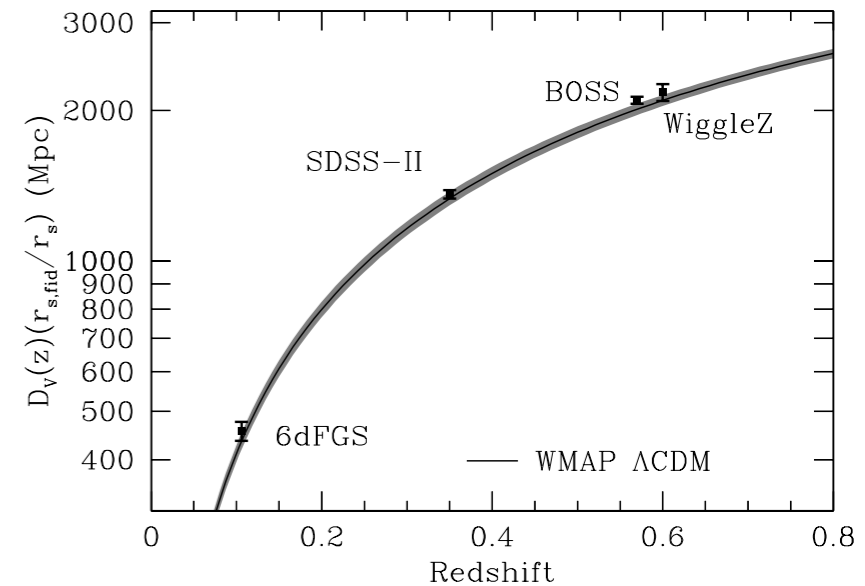
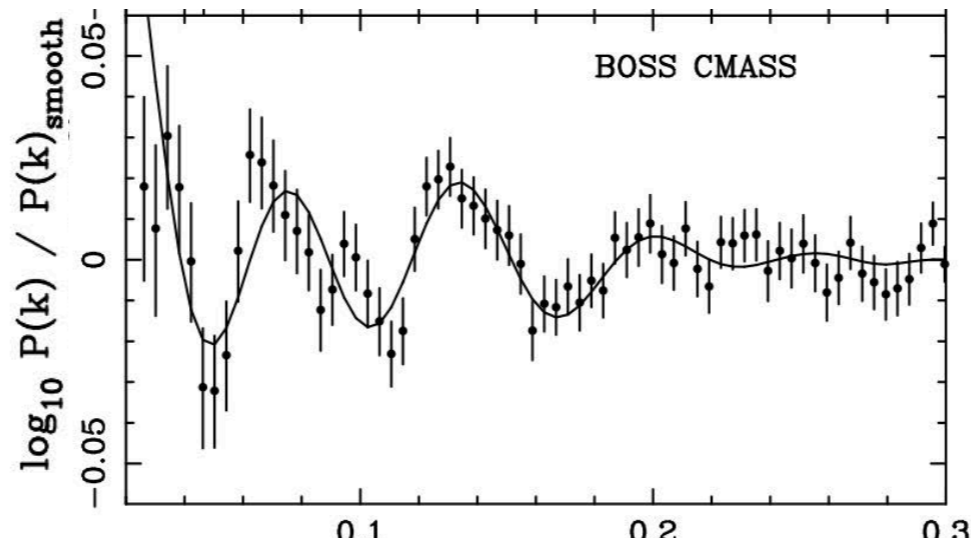
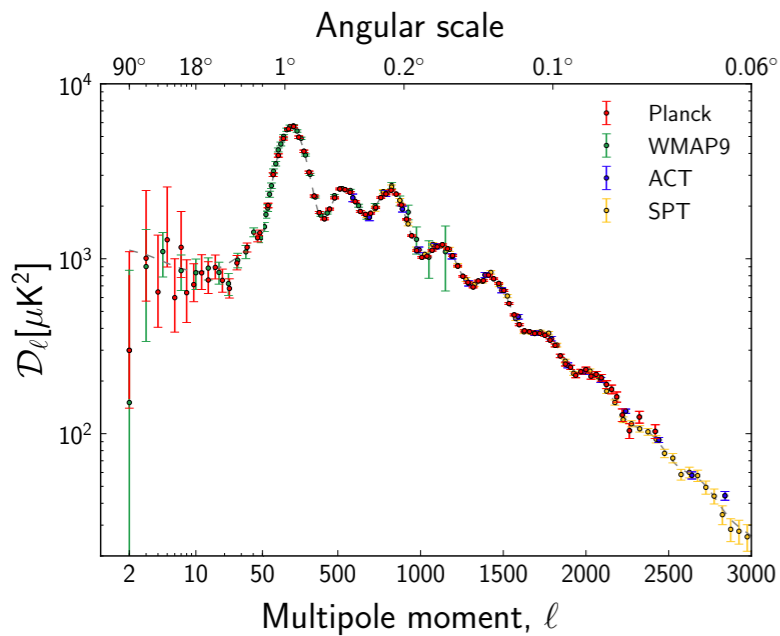


### Selected Measurements of CMB Spectrum



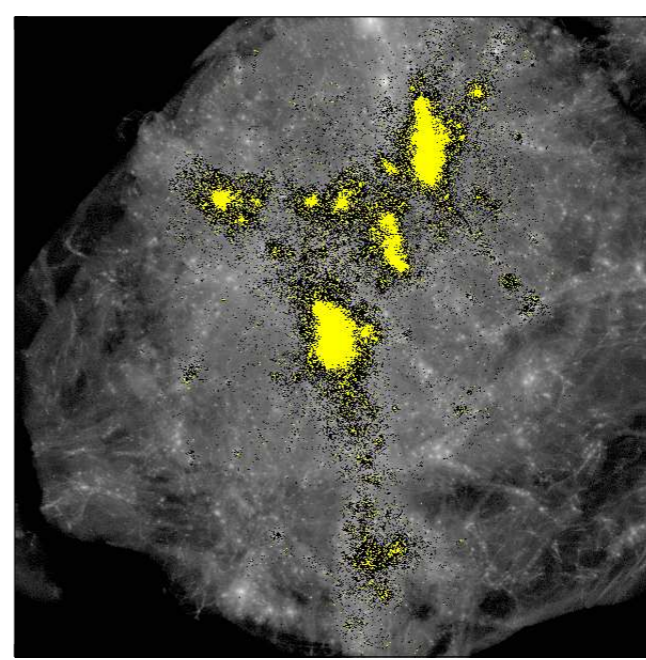
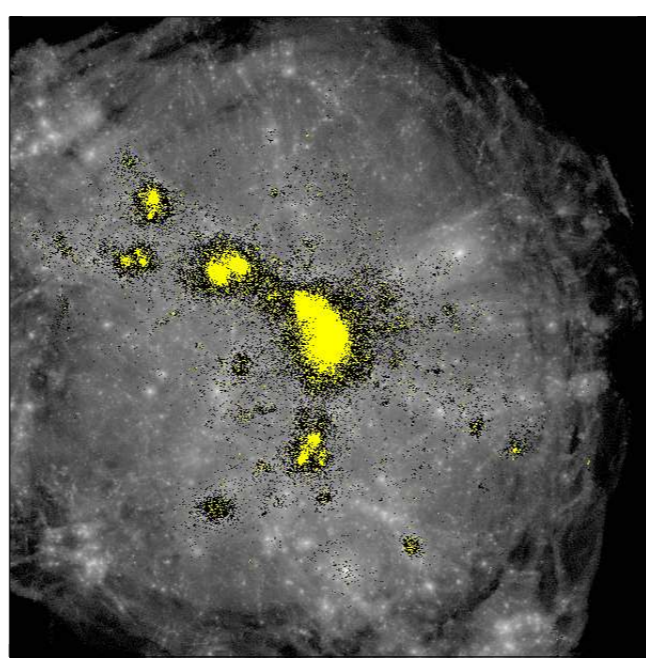
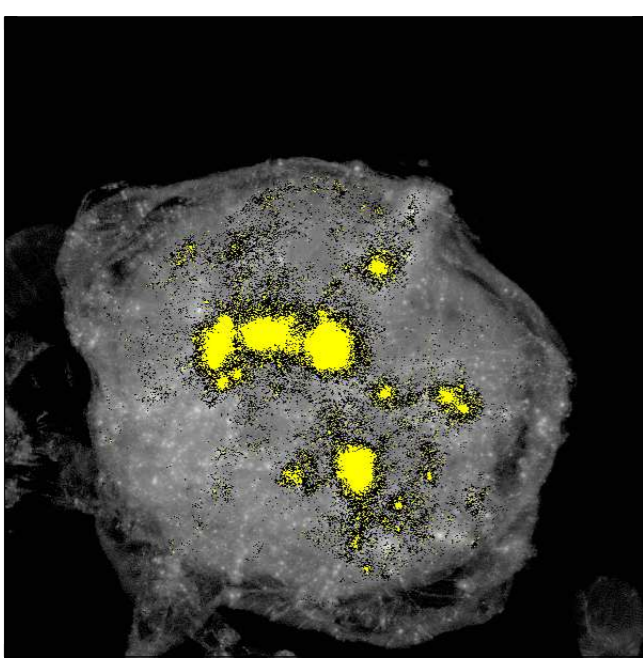
$\Lambda$ CDM is is convincingly established as a good approximation to “reality” by passing far more empirical tests than guided its formulation.

$\Lambda$ CDM is incomplete, as is all the rest of our physics.





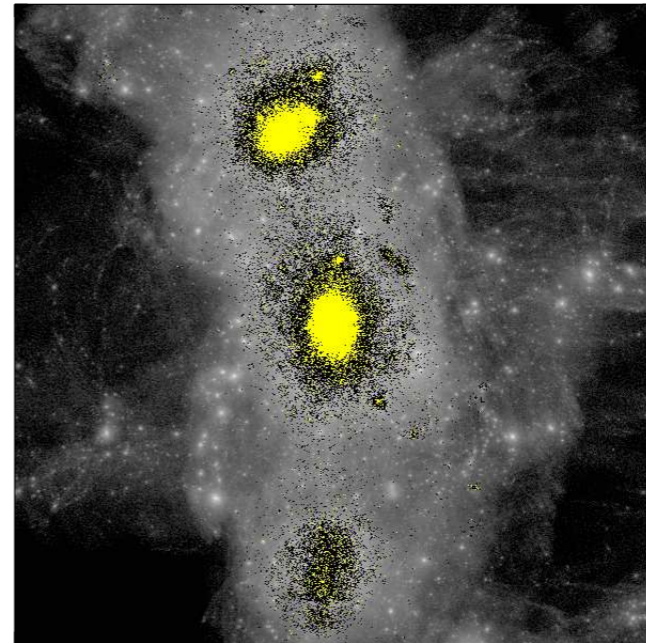
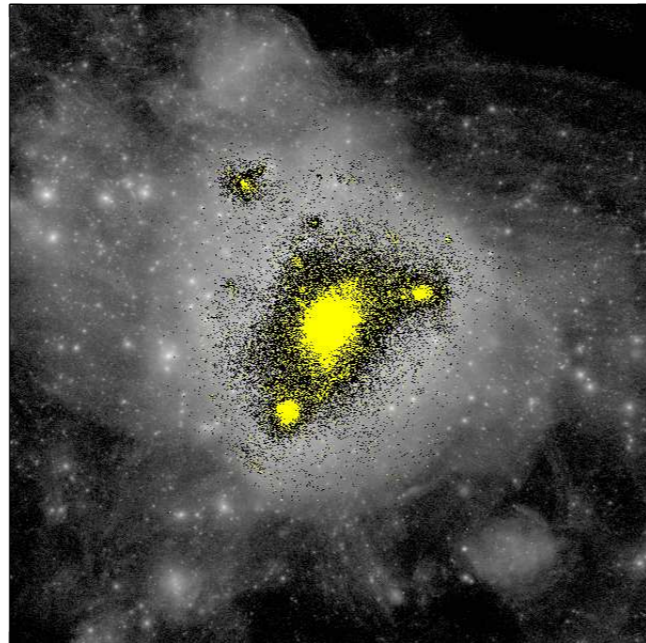
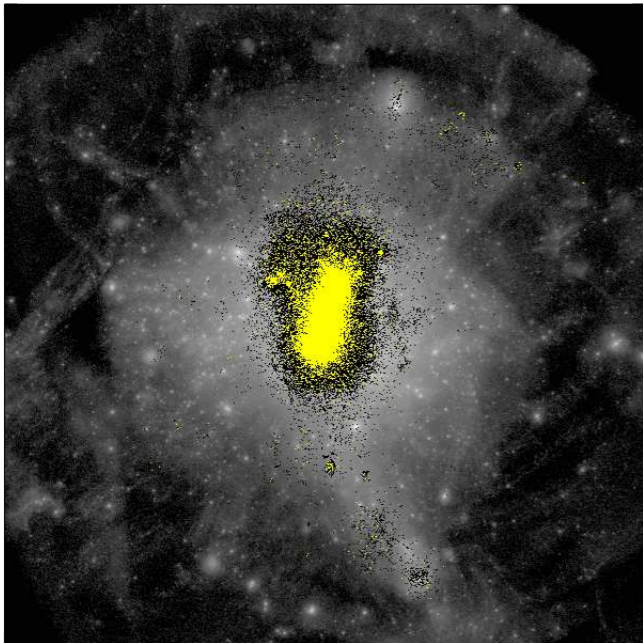
$z=3.1$



AQUARIUS pure DM halos of  $L \sim L^*$  galaxies in  $\Lambda$ CDM (Springel et al. 2008). Lengths are physical.

Images by Jie Wang, Durham, in collaboration with Adi Nusser, Technion.

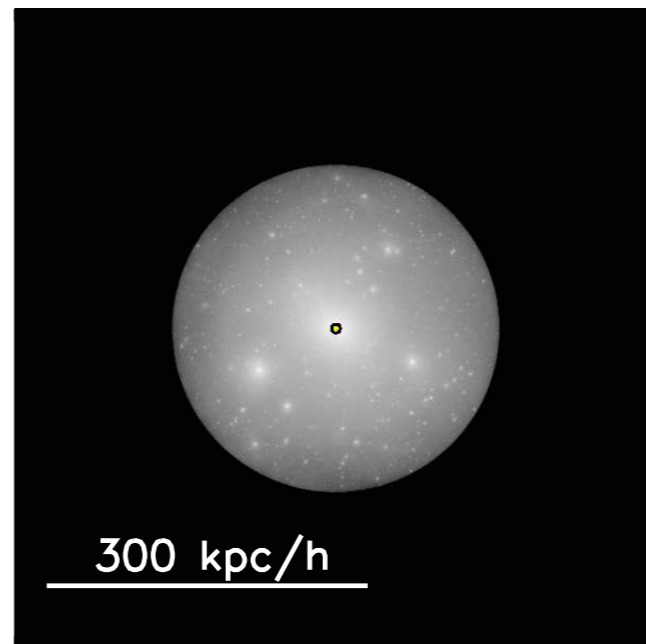
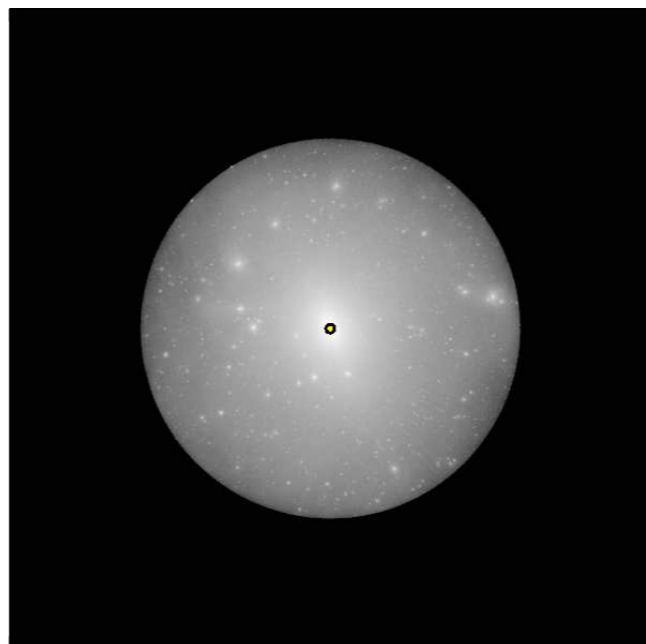
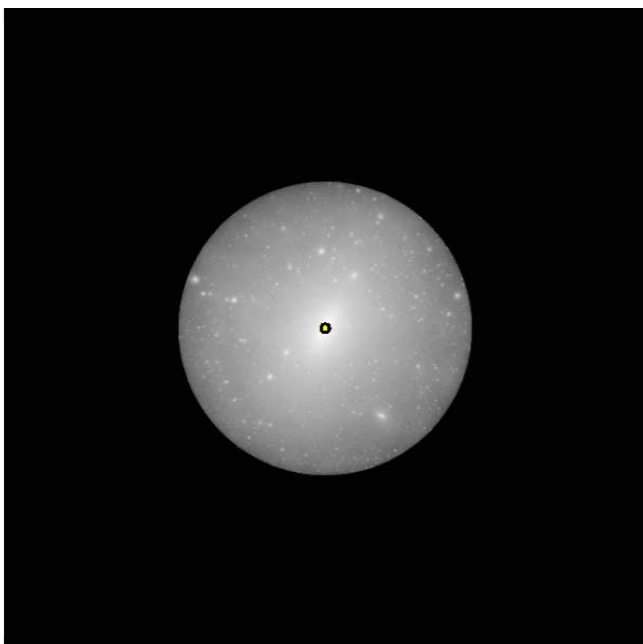
$z=1.0$



The grey scale shows particles that are at  $r_{200} > r > 7$  kpc at  $z = 0$ .

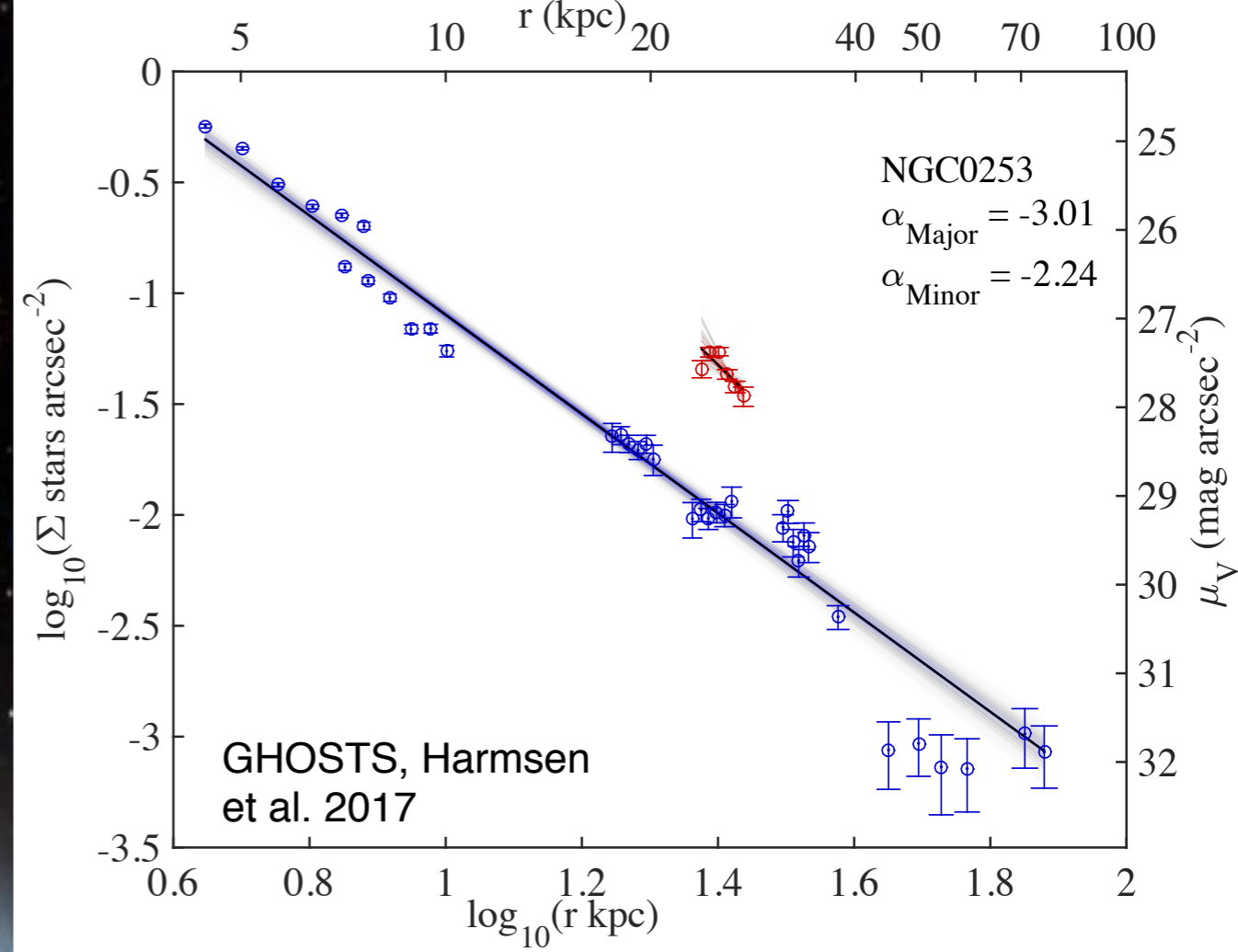
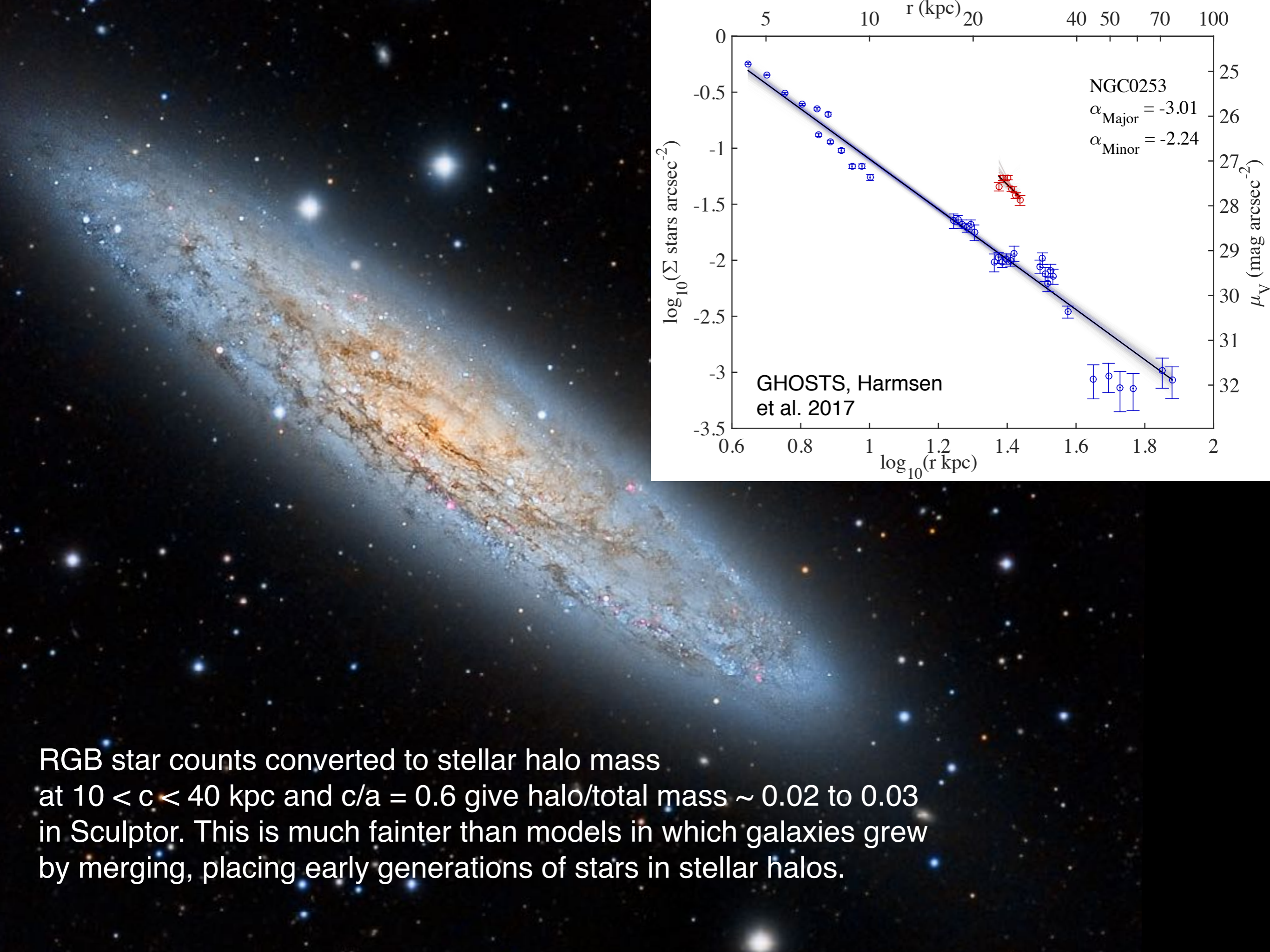
Overplotted in black are particles at  $3 < r < 7$  kpc at  $z = 0$ .

$z=0.0$

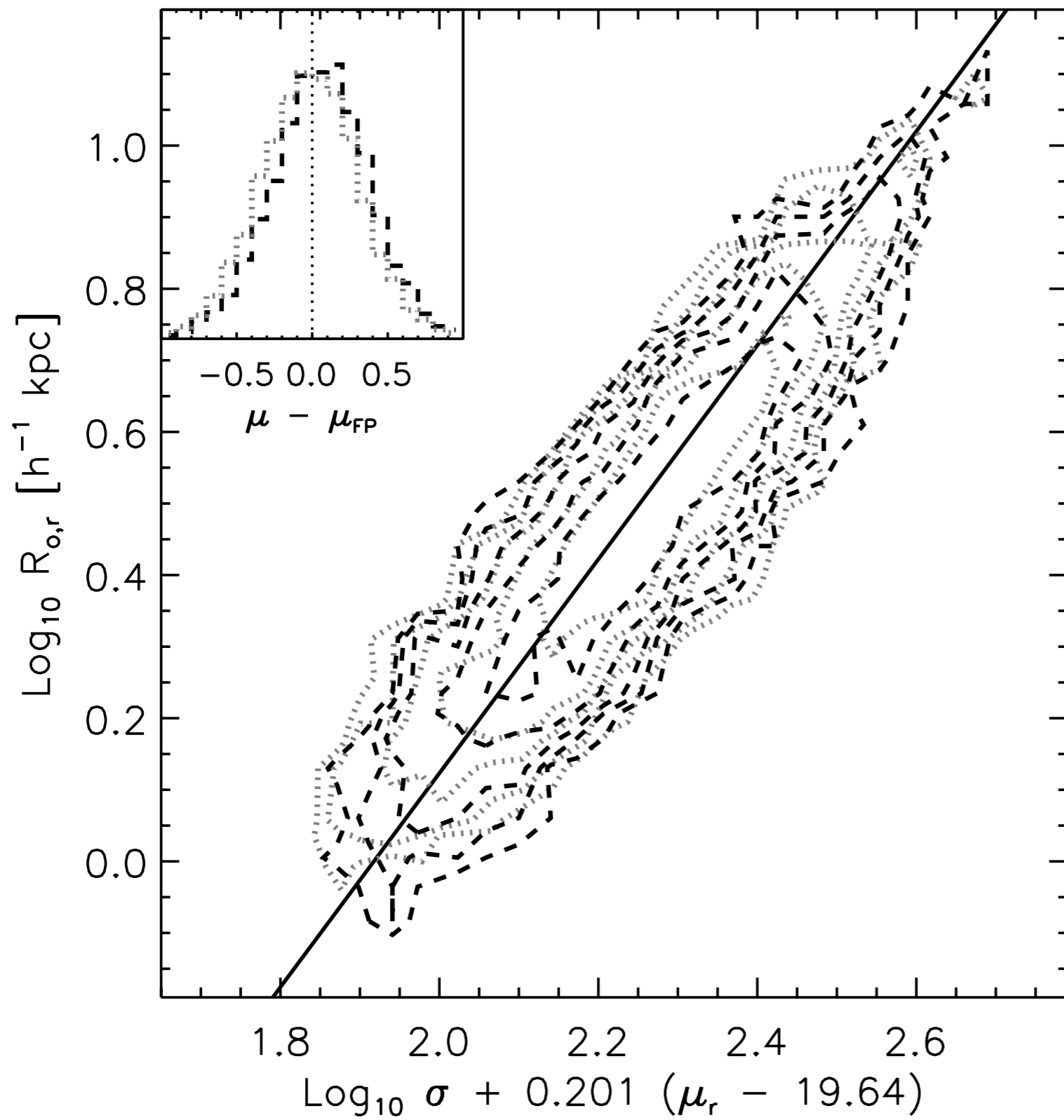


Overplotted in yellow are particles at  $r < 3$  kpc at  $z = 0$ .





RGB star counts converted to stellar halo mass  
at  $10 < c < 40$  kpc and  $c/a = 0.6$  give halo/total mass  $\sim 0.02$  to  $0.03$   
in Sculptor. This is much fainter than models in which galaxies grew  
by merging, placing early generations of stars in stellar halos.



Mariangela Bernardi 2006  
early-type galaxies

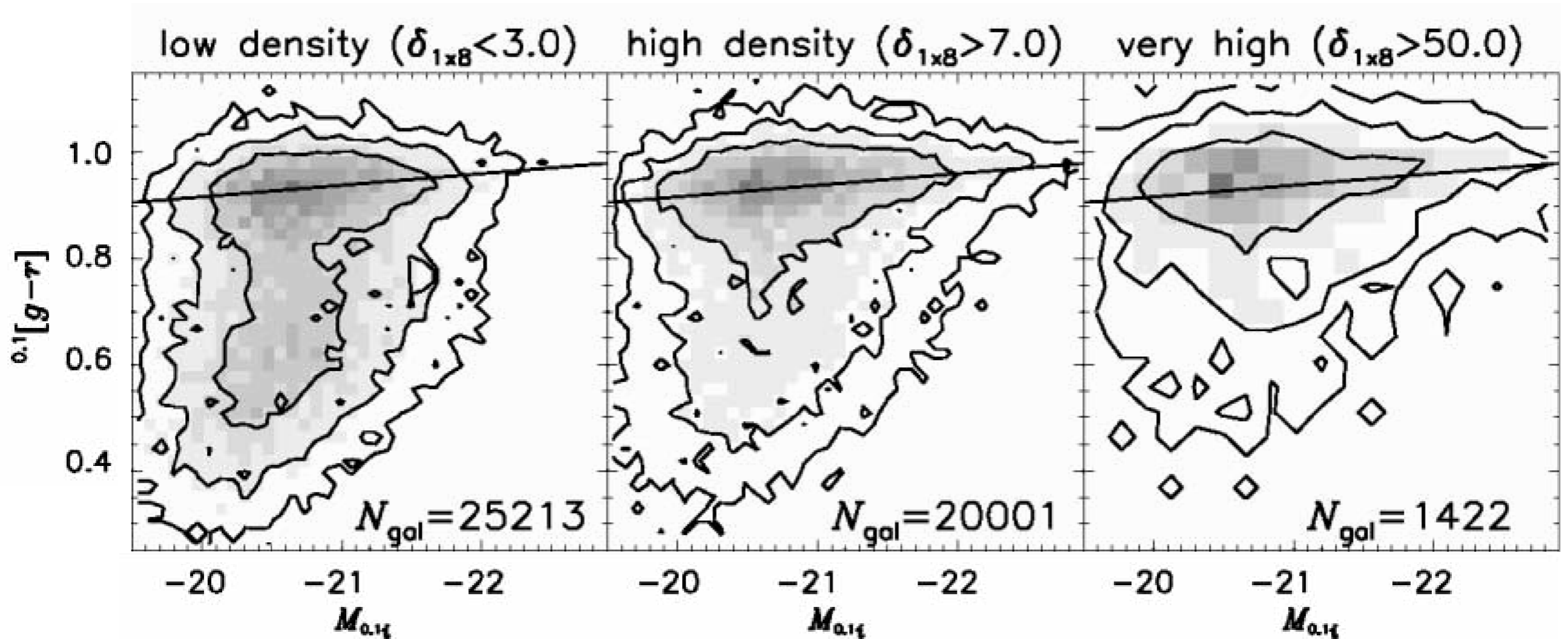


# THE DEPENDENCE ON ENVIRONMENT OF THE COLOR-MAGNITUDE RELATION OF GALAXIES

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 J. BRINKMANN,<sup>7</sup> AND AVERY MEIKSIN<sup>8</sup>

*Received 2003 July 11; accepted 2003 December 2; published 2004 January 16*

*(bowdlerized)*



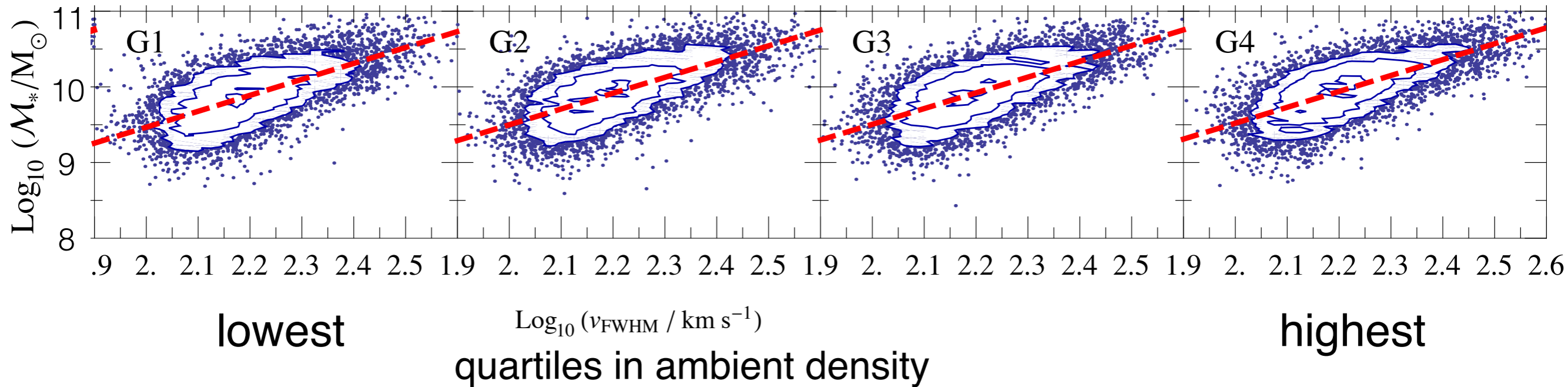
The local number density contrast is the average within a cylinder of radius  $1h^{-1}$  Mpc and half-length  $8h^{-1}$  Mpc in redshift space.

The SDSS magnitudes and colors are measured at  $\sim 80\%$  of the nominal Petrosian magnitude, that is, well outside the half-light radius.

# The Tully–Fisher relation for 25 000 Sloan Digital Sky Survey galaxies as a function of environment

P. Mocz,<sup>1,2★</sup> A. Green,<sup>1★</sup> M. Malacari<sup>1,3★</sup> and K. Glazebrook<sup>1★</sup>

Late-type SDSS galaxies selected by color.  
See the familiar insensitivity to ambient conditions.



$\Lambda$ CDM predicts galaxies grew by merging, yet scaling says galaxies evolved pretty much as island universes.\*

\* I mean evolution, not whatever caused the morphology-density relation.

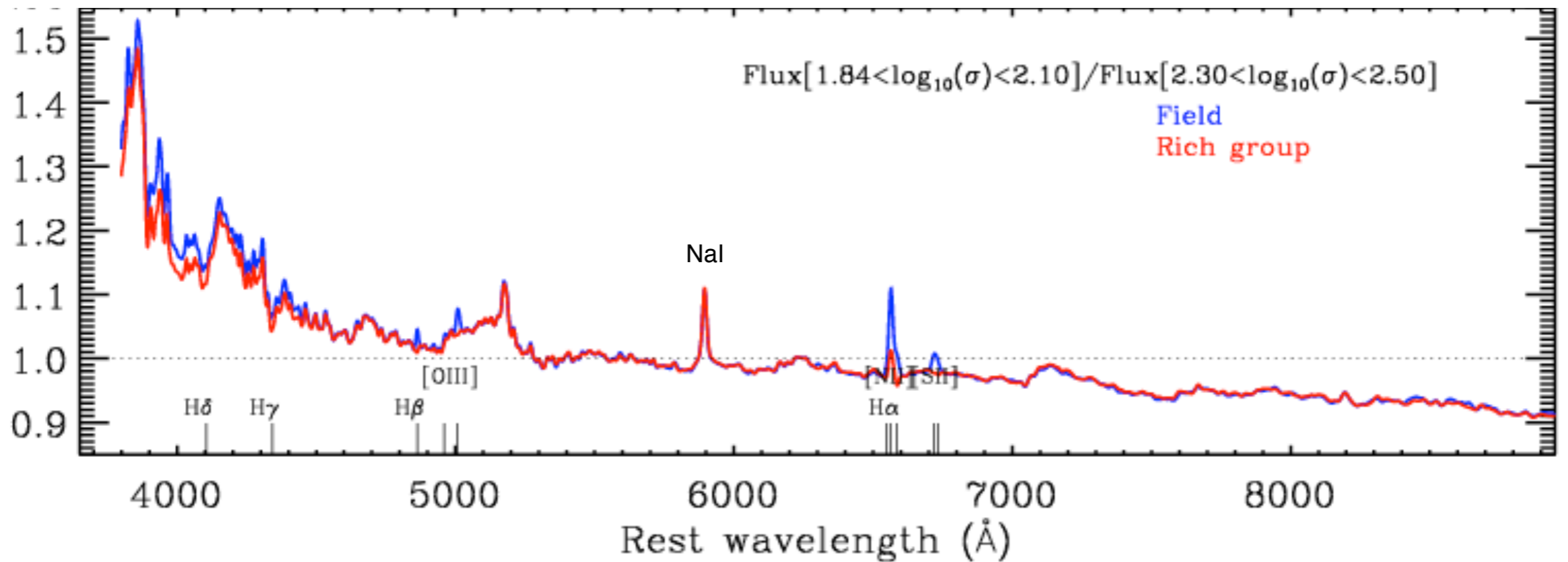


Figure courtesy of private communication from Guangtun Zhu, based on analyses of SDSS data in

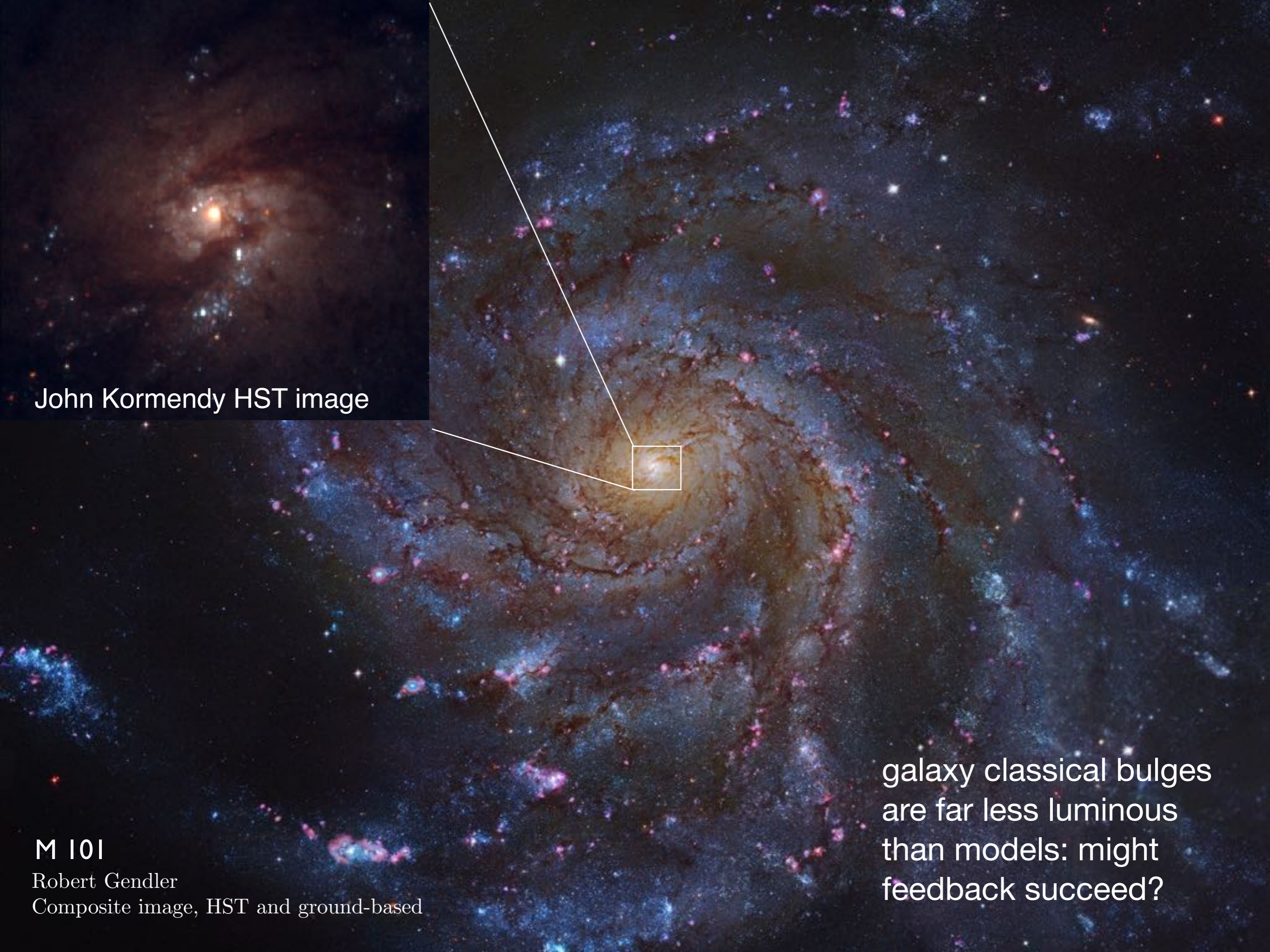
STELLAR POPULATIONS OF ELLIPTICAL GALAXIES IN THE LOCAL UNIVERSE ApJ 2010

GUANGTUN ZHU<sup>1</sup>, MICHAEL R. BLANTON<sup>1</sup>, AND JOHN MOUSTAKAS<sup>2</sup>

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John Kormendy HST image

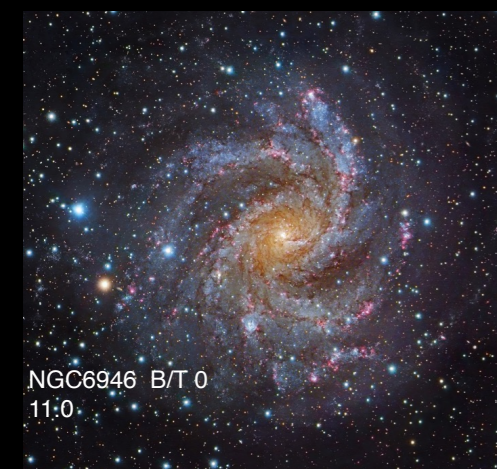
**M 101**

Robert Gendler

Composite image, HST and ground-based

galaxy classical bulges  
are far less luminous  
than models: might  
feedback succeed?

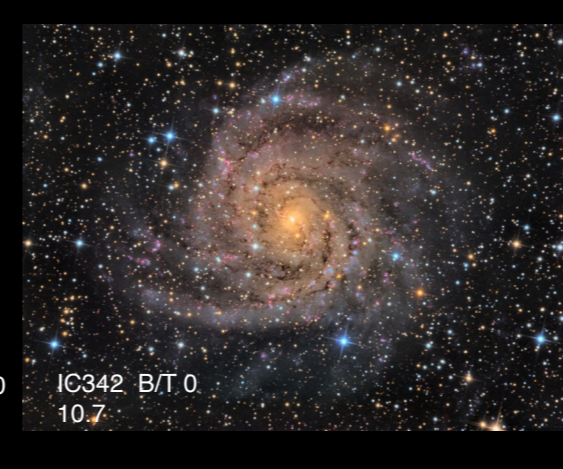




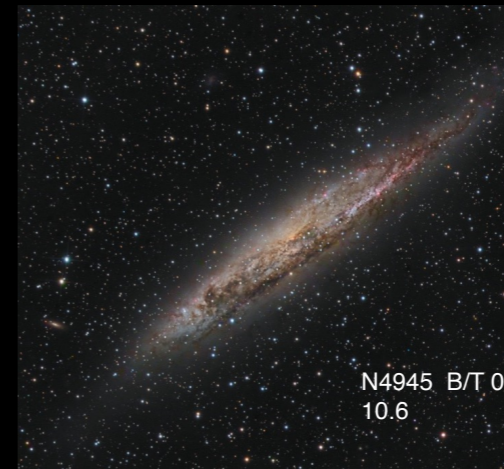
NGC 6946 B/T 0  
11.0



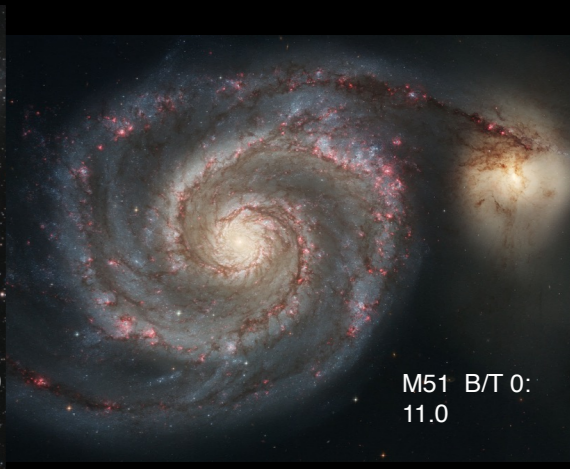
M 101 B/T 0  
10.8



IC 342 B/T 0  
10.7



N 4945 B/T 0  
10.6



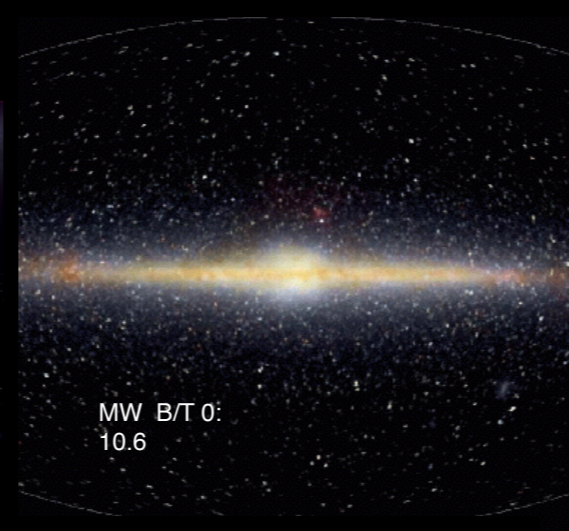
M 51 B/T 0  
11.0



M 83 B/T 0  
10.9



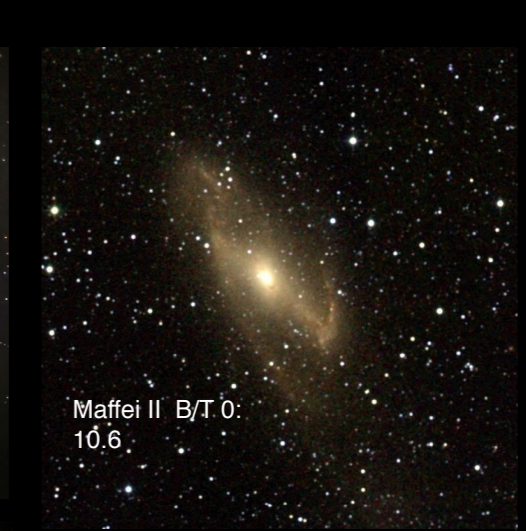
N 253 B/T 0  
10.9



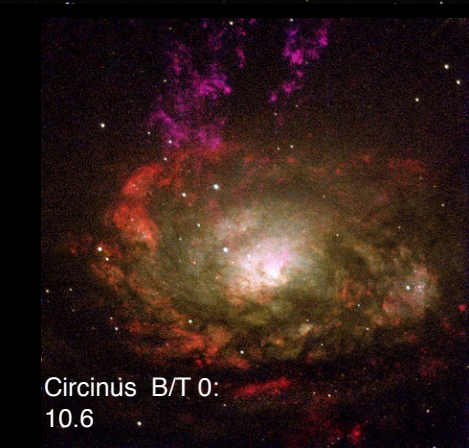
MW B/T 0  
10.6



M 94 B/T 0  
10.6



Maffei II B/T 0  
10.6



Circinus B/T 0  
10.6



N 2683 B/T 0.05  
10.6



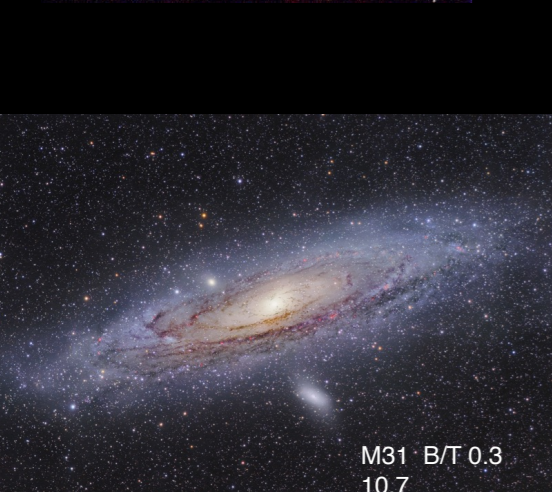
M 64 B/T 0.1  
10.5



N 2787 B/T 0.1  
10.5



M 106 B/T 0.1  
10.9



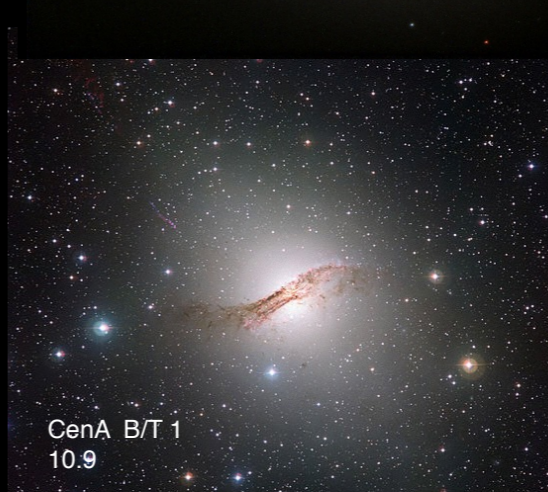
M 31 B/T 0.3  
10.7



M 81 B/T = 0.3  
10.9



Maffei I B/T 1  
10.7



Cen A B/T 1  
10.9

The 19 galaxies with  
Kormendy et al. B/T,  
Tully  $D < 10$  Mpc,  
 $L_K > 10^{10.5}$ .





N4559 B/T 0



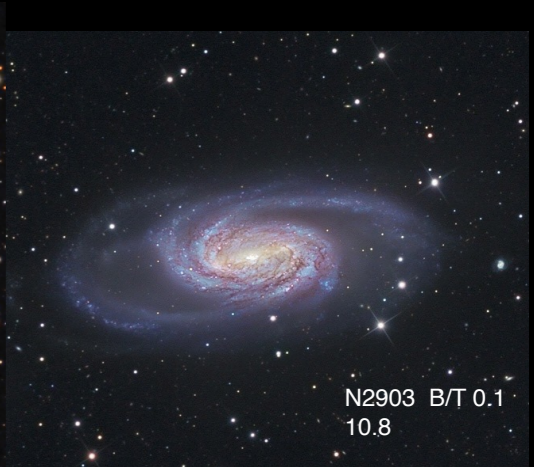
N463  
10.4



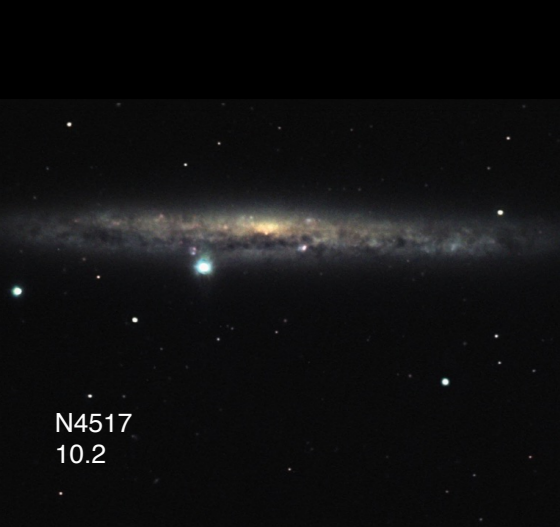
M82 B/T 0  
10.6



N925 B/T 0.1  
10.1



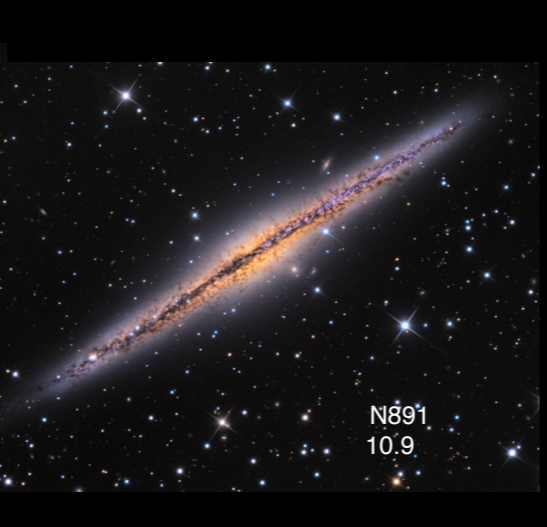
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10.8



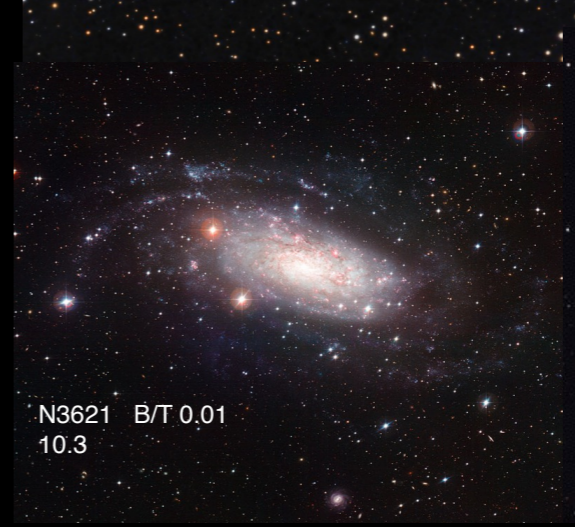
N4517  
10.2



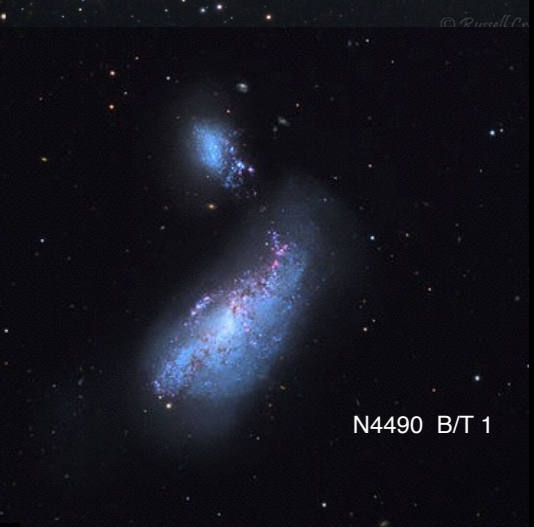
N6744 B/T 0.15  
1.0



N891  
10.9



N3621 B/T 0.01  
10.3



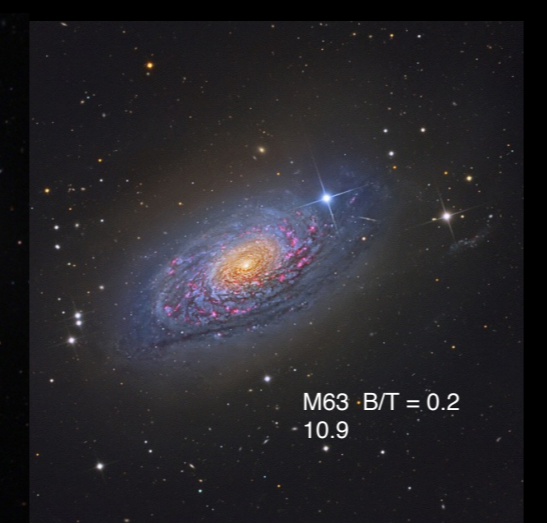
N4490 B/T 1



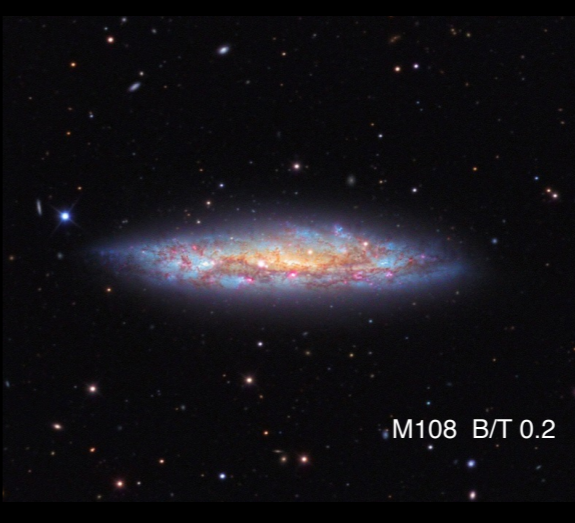
N3344 B/T 0.1  
10.3



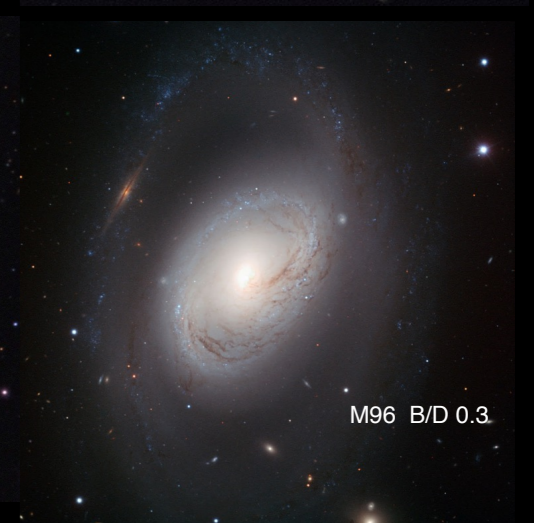
M66 B/T 0.1



M63 B/T = 0.2  
10.9



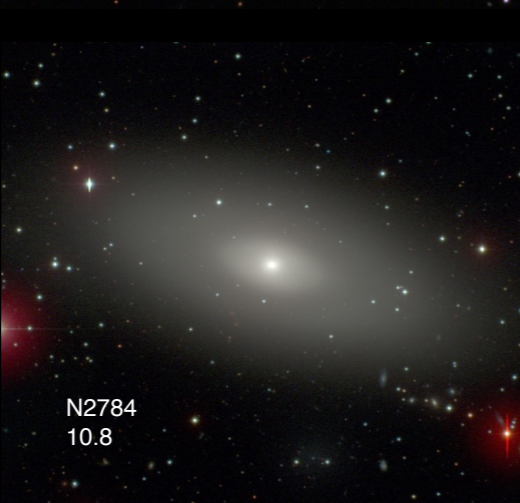
M108 B/T 0.2



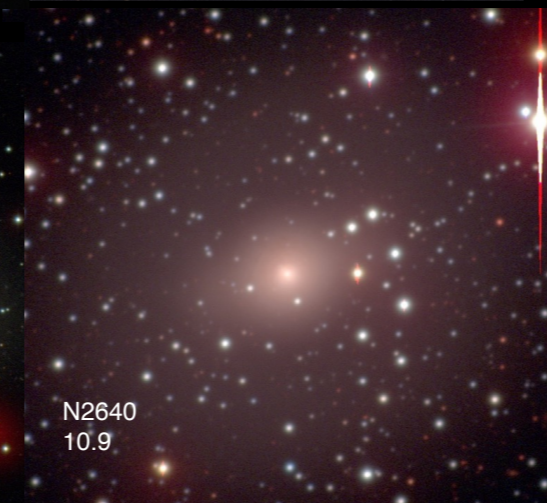
M96 B/D 0.3



M104 B/T 0.5  
11.3



N2784  
10.8



N2640  
10.9



M105 B/T 1  
11.3

19 more galaxies at  
 $D < 10$  Mpc,  
 $L_K > 10^{10}$ ,  
some with Fisher and  
Drory B/T



