# ULTRA-FAINT GALAXIES

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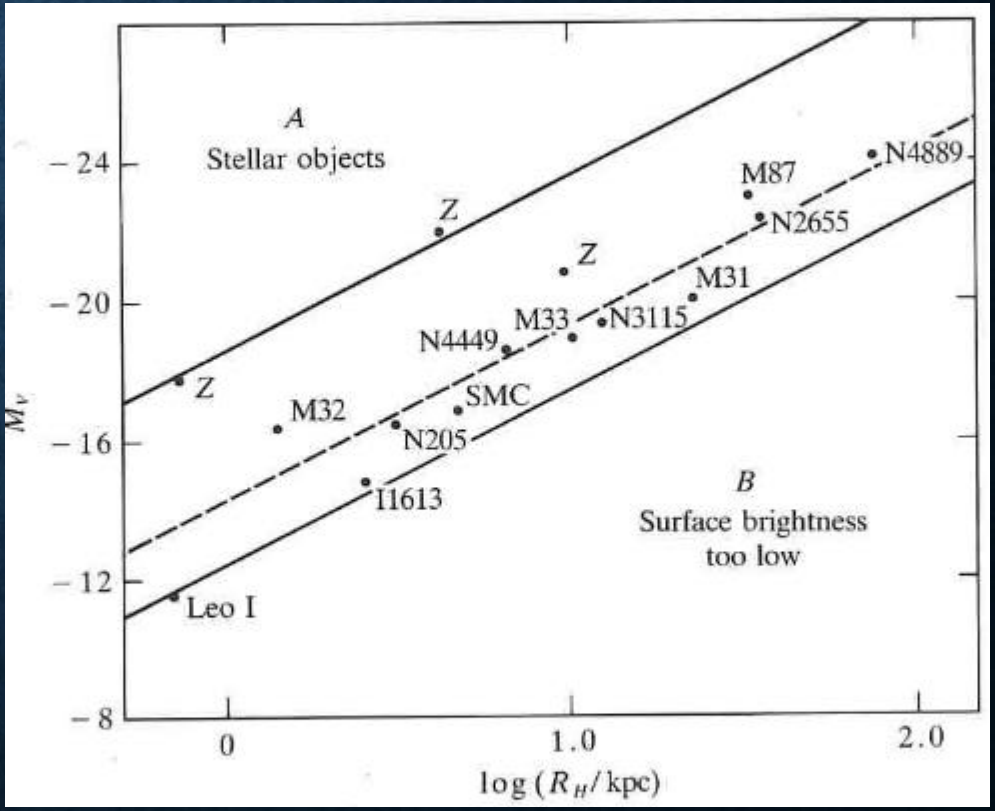
# OUTLINE

- Potential importance of low surface-brightness galaxies
- Ultra Diffuse Galaxies are baryon rich
- Why is this?

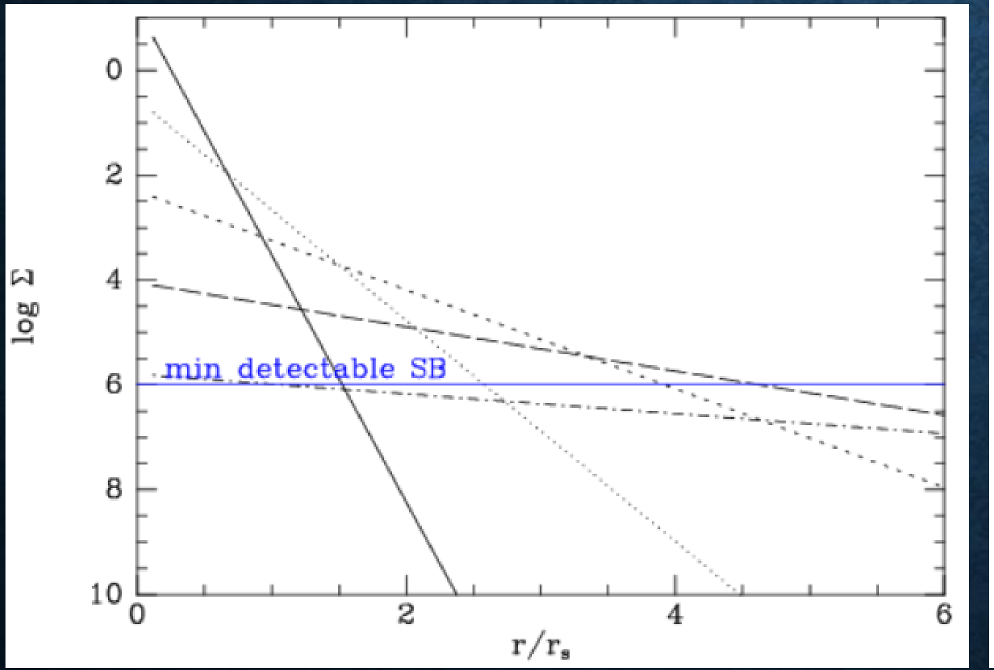
# IS THERE MORE THAN MEETS THE EYE?

- Zwicky's principle
  - If it can exist it will exist
- Arp
  - We see all we can see

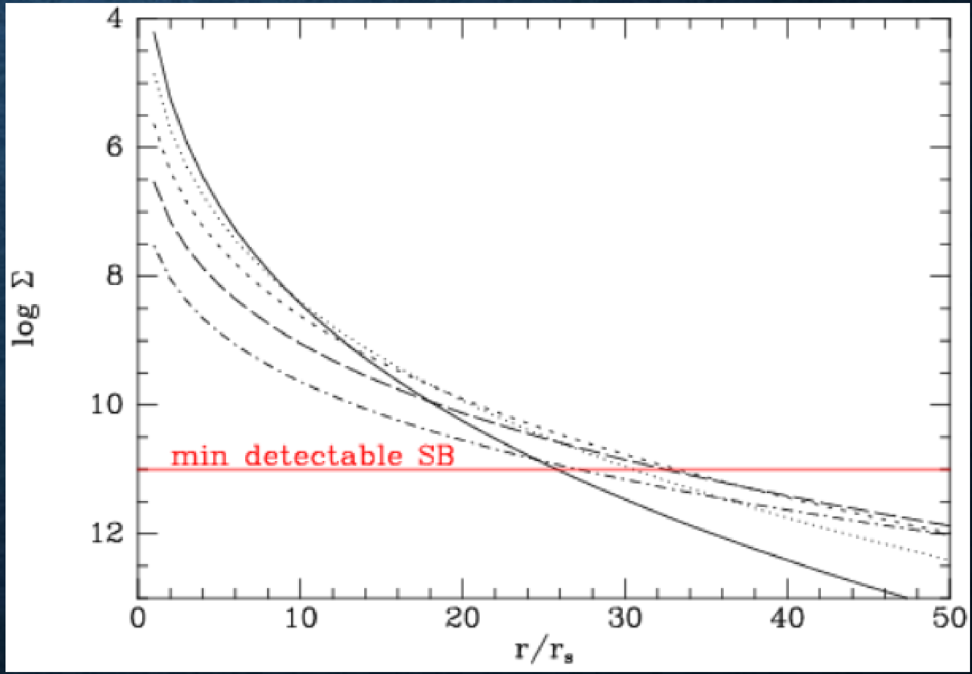


# DISNEY'S (1976) ARGUMENT

- Sersic law $$\log_{10}\left[\frac{\Sigma(r)}{\Sigma(0)}\right] = -\left(\frac{r}{r_s}\right)^{1/\beta}$$




β=1



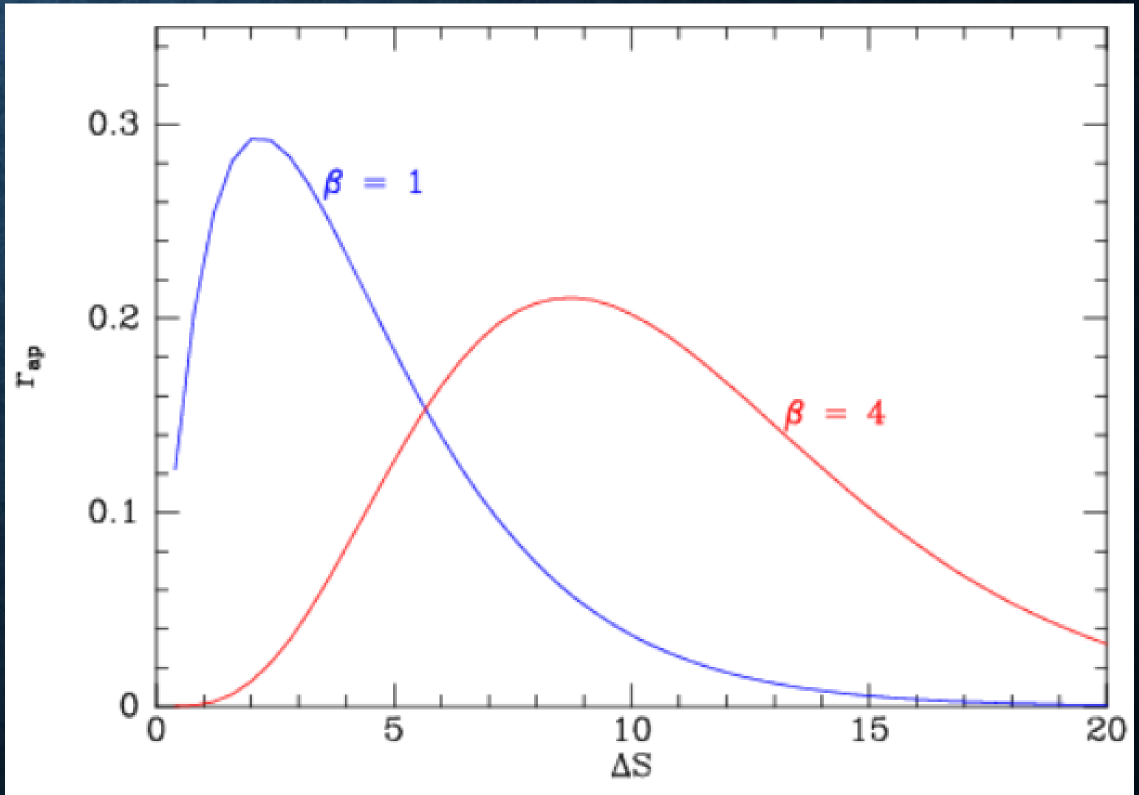

β=4

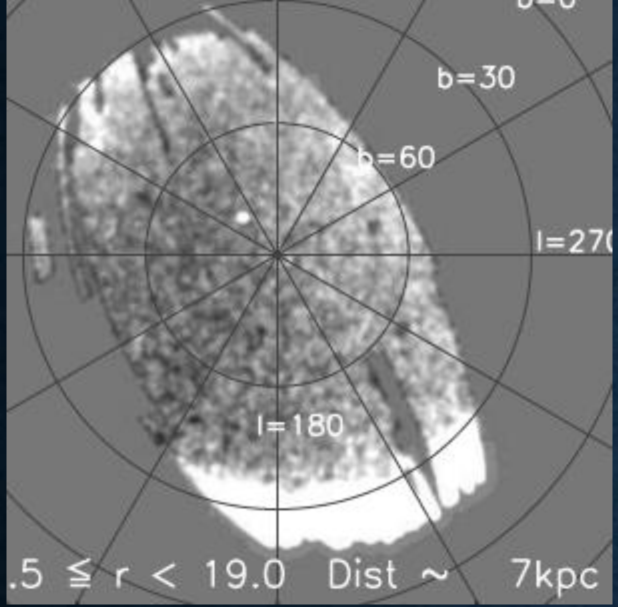
# DISNEY'S (1976) ARGUMENT

- Fix L and $\Sigma_{ap}$ and ask how $r_{ap}$ varies with $\Sigma(0)$
  - Define $\Delta S = 2.5 \log(\Sigma_0/\Sigma_{ap})$

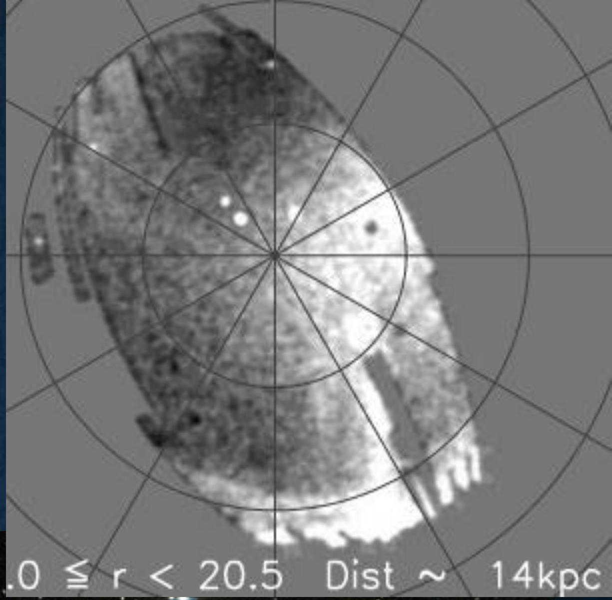
$$r_{ap} = [L_i/\Sigma(r_{ap})]^{1/2}[\pi(2\beta)!]^{-1/2}(0.4 \ln 10)^{\beta}\, 10^{-0.2\Delta S}\, (\Delta S)^{\beta}$$

- For spirals rap peaks at ΔS=2.2 mag
- For ellipticals peak at 8.71 mag
- Values reproduce well difference in central SBs of Es and Ss
- Given typical central SB of Ss, get credible $\Sigma_{ap}$
- Suggests classical galaxies are precisely those that are (a) bright enough to be see, and (b) can be identified as non-stellar

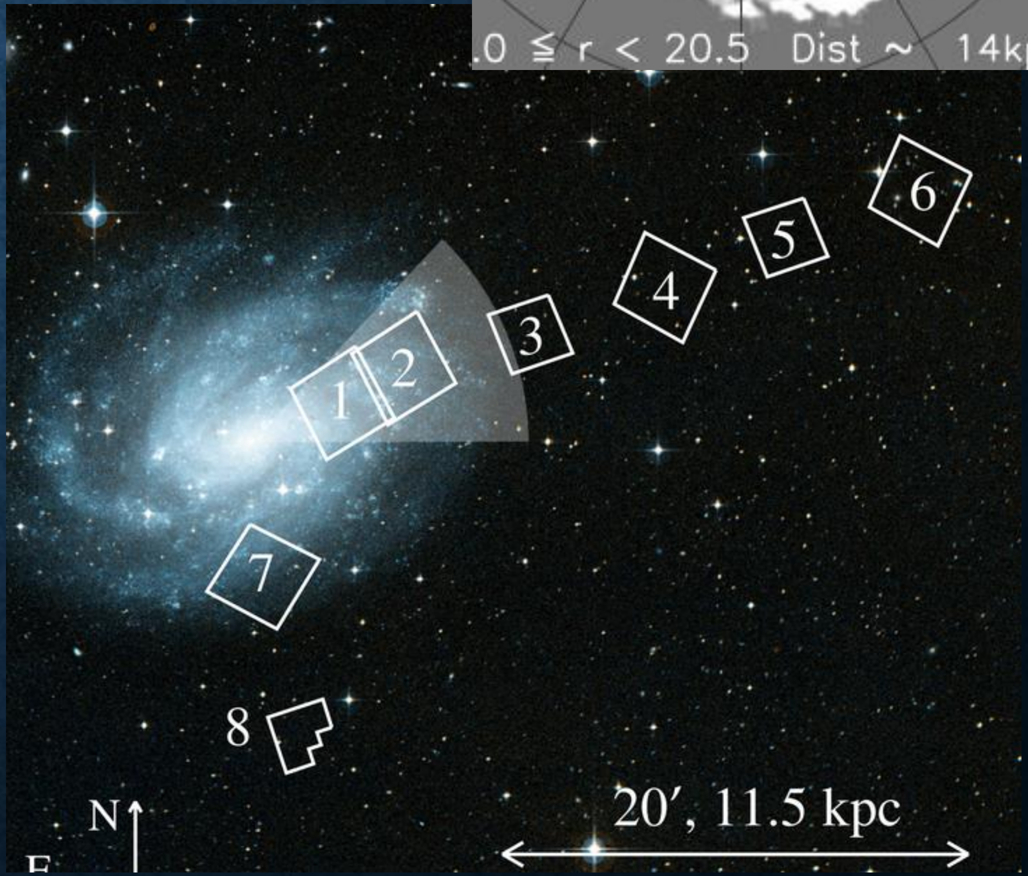





# WHAT HAPPENED THEN?




- At higher SB photometry improved dramatically due to CCDs from ~1980
  - But format to small to improve determination of sky SB
- At low SB dramatic advances through star counts
  - HST e.g. NGC 300 Vlajic+ (2009)
  - SDSS Bell+ (2008)
  - (Gaia?)



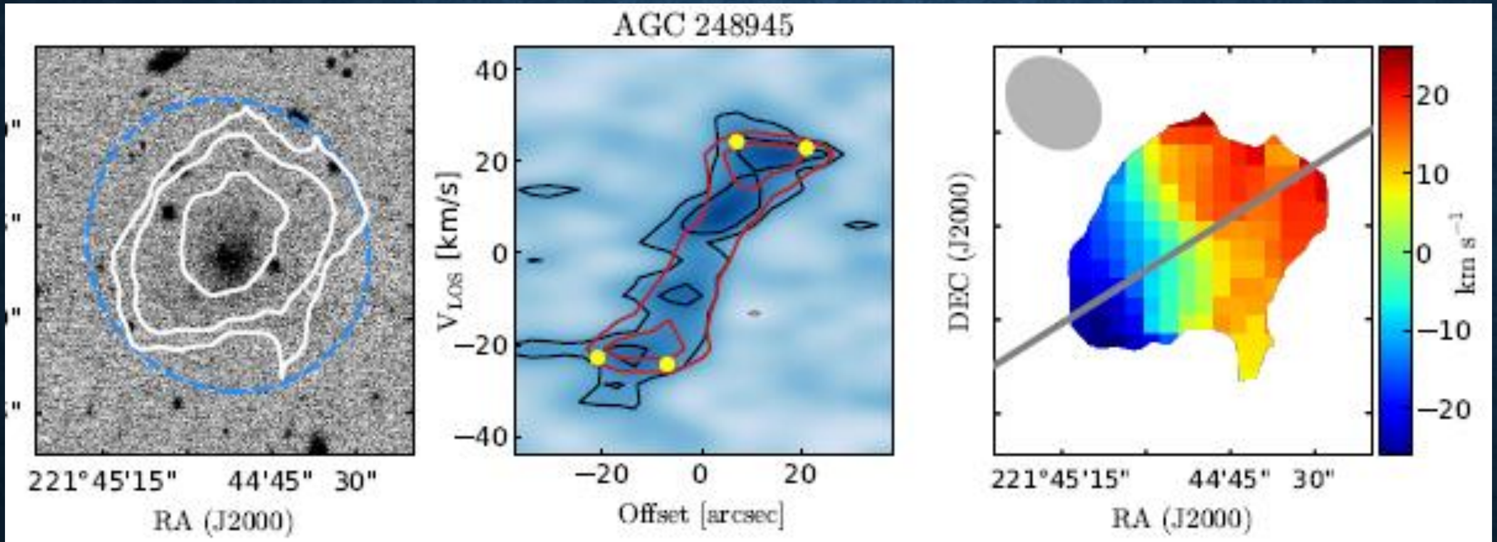
# UFGS

- Galaxies with v low surface brightness first found in clusters (Sandage & Binggeli 1984, Impey+ 1988, van Dokkum+ 2015)
- More recently they've turned up in the field
  - Easier to investigate because (a) nearer, (b) often gas-rich
- Leisman+ (2017) studied 115 UDGs in ALFALFA HI survey
- $V_c$ first estimated from W(single dish) but recently interferometric mapping at VLA & Westerbork establishes that $V=V_c \sin(i)$ & gets grip on i

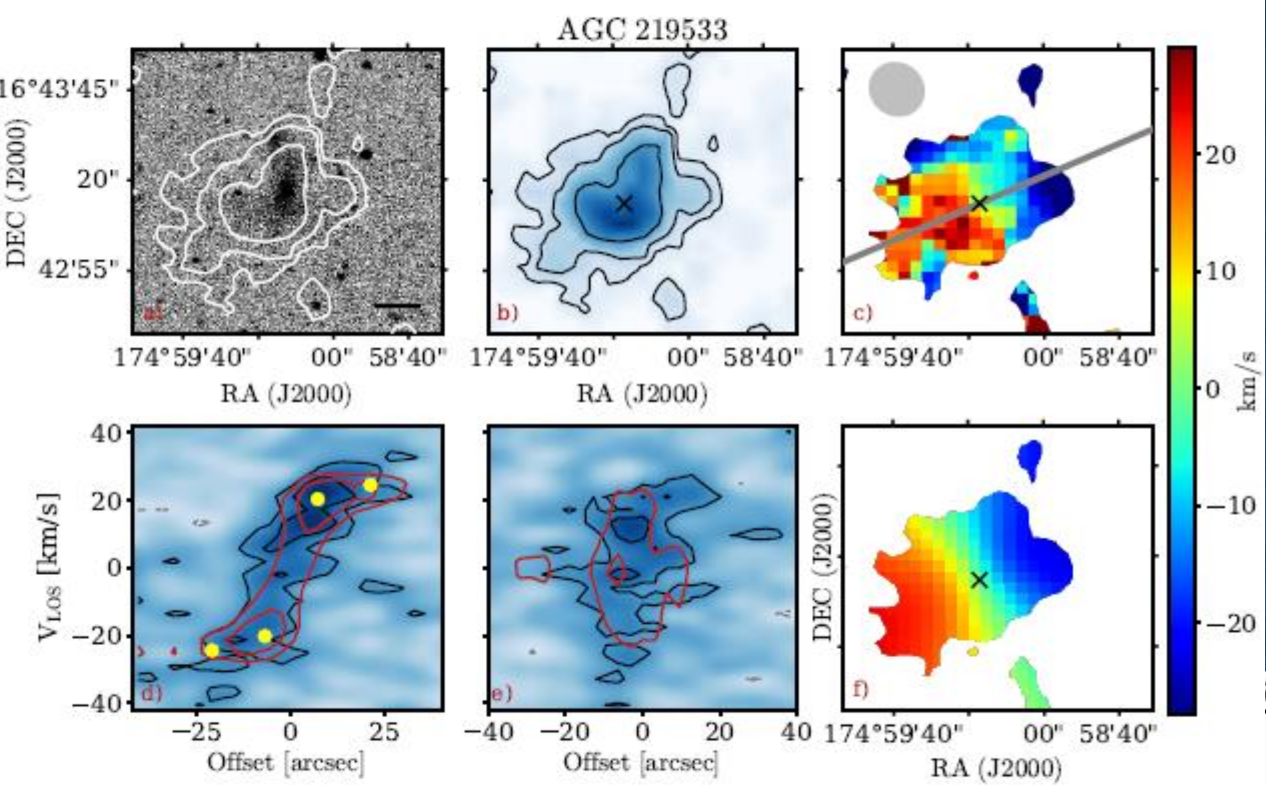
# MANCERA-PINA+ 2019, 2020

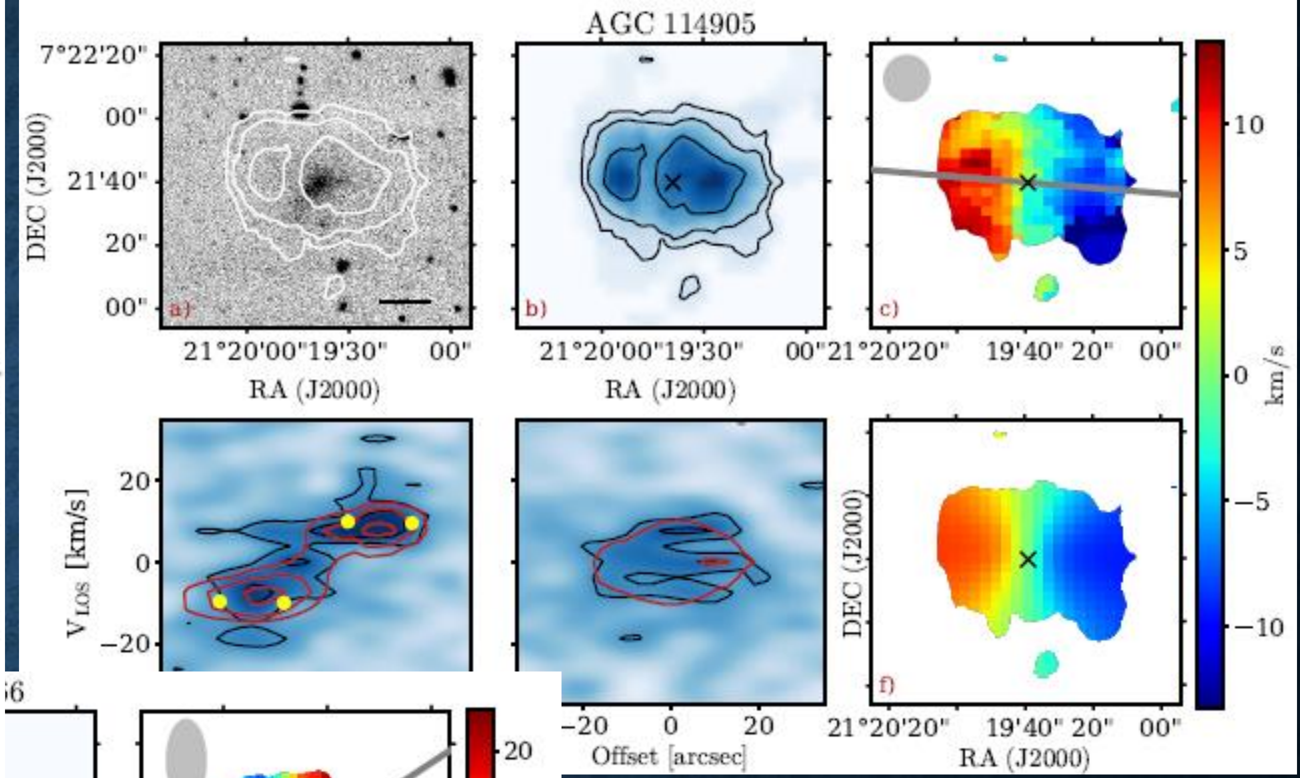
- 6 isolated UDGs from Leisman+ (2017) with $M_{HI}$~$10^9$ $M_{sun}$, $R_e$>2 kpc
- $M_{bar} = 1.33M_{HI} + M_*$ with $M_*$ from g,r photometry at WYN telescope
- $<M_{HI}/M_*> = 15$ so strongly gas dominated => $M_{bar}$ is secure
- Tilted-ring model fitted to HI data cube by $^{3D}$Barolo (Di Teodoro & Fraternali 2015)

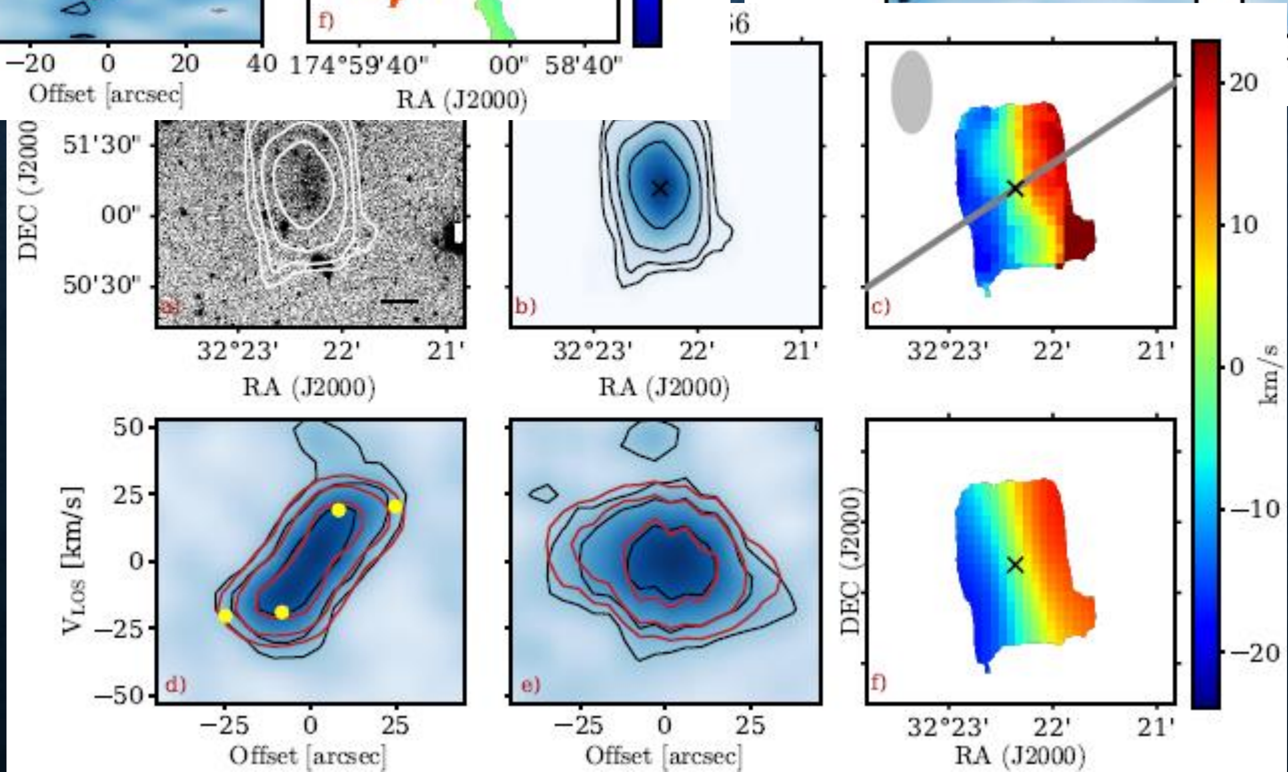
| Name AGC | Distance (Mpc) | Inclination (deg) | $\log(M_{bar}/M_\odot)$ | $M_{gas}/M_\star$ | $V_{circ}$ (km $s^{-1}$) | $\mu(g,0)$ (mag $arcsec^{-2}$) | $g-r$ (mag) |
|---|---|---|---|---|---|---|---|
| 114905 | 76 | 33 | $9.21 \pm 0.20$ | $7.1^{+4.9}_{-2.3}$ | $19^{+6}_{-4}$ | $23.62 \pm 0.13$ | $0.30 \pm 0.12$ |
| 122966 | 90 | 34 | $9.21 \pm 0.14$ | $29.1^{+11.9}_{-7.0}$ | $37^{+6}_{-5}$ | $25.38 \pm 0.23$ | $-0.10 \pm 0.22$ |
| 219533 | 96 | 42 | $9.36 \pm 0.27$ | $19.7^{+12.2}_{-8.8}$ | $37^{+5}_{-6}$ | $24.07 \pm 0.33$ | $0.12 \pm 0.12$ |
| 248945 | 84 | 66 | $9.05 \pm 0.20$ | $2.4^{+1.6}_{-0.8}$ | $27^{+3}_{-3}$ | $23.32 \pm 0.35$ | $0.32 \pm 0.11$ |
| 334315 | 73 | 52 | $9.32 \pm 0.14$ | $23.7^{+9.8}_{-5.9}$ | $26^{+4}_{-3}$ | $24.52 \pm 0.13$ | $-0.08 \pm 0.18$ |
| 749290 | 97 | 39 | $9.17 \pm 0.17$ | $6.1^{+2.9}_{-1.7}$ | $26^{+6}_{-6}$ | $24.66 \pm 0.30$ | $0.17 \pm 0.12$ |




- Key uncertainty: *i* (blue contour to be on BTF reln)
- Yellow points in pv diagram show recovered Vc (beam smearing)
- Velocity dispersion low (<~4 km/s)

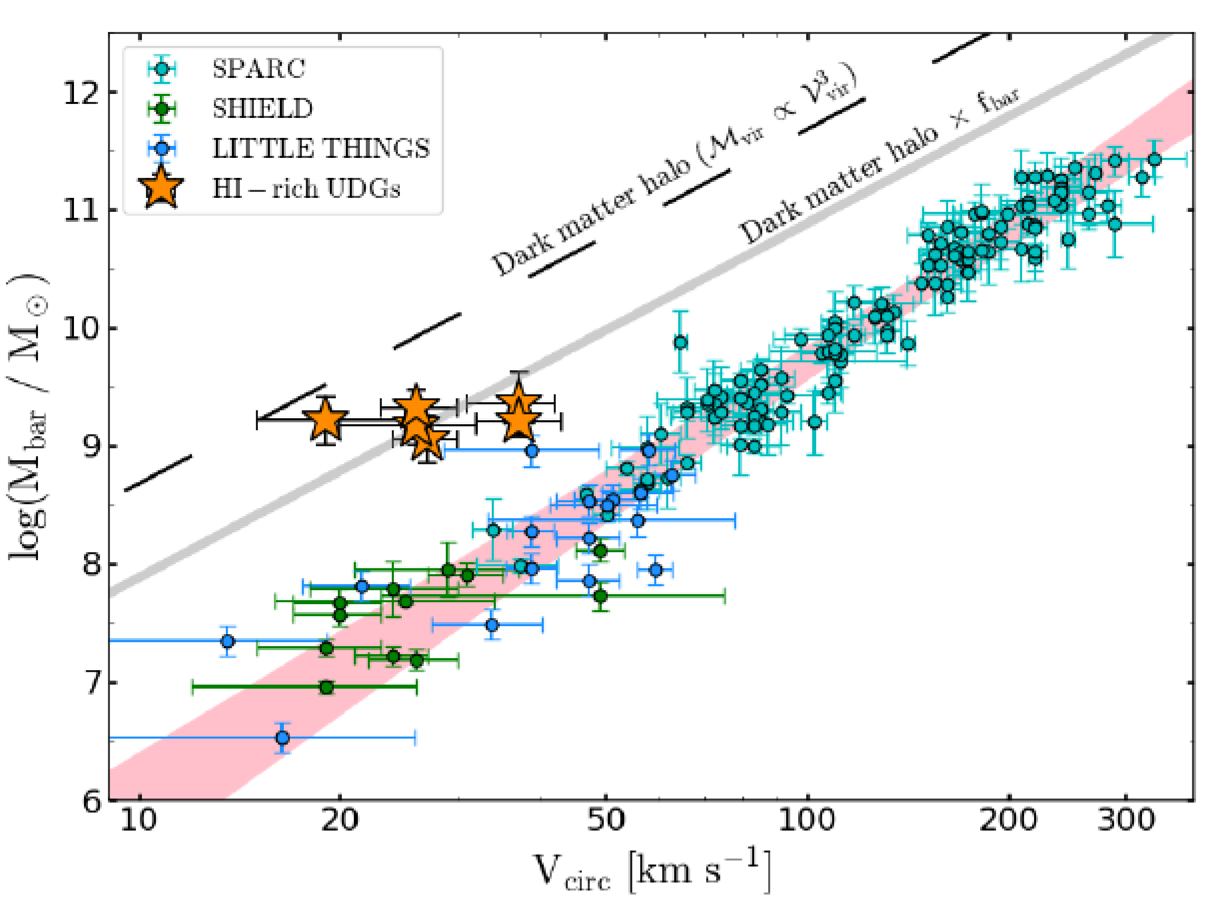

AGC 219533
16°43'45"
20"
42'55"
DEC (J2000)
174°59'40"
00"
58'40"
RA (J2000)
a)
b)
c)
d)
e)
f)
km/s
V_LOS [km/s]
Offset [arcsec]


AGC 114905
7°22'20"
00"
21'40"
20"
DEC (J2000)
21°20'00"
19'30"
00"
21°20'20"
19'40"
20"
RA (J2000)
a)
b)
c)
f)
km/s
V_LOS [km/s]
Offset [arcsec]


51'30"
00"
50'30"
DEC (J2000)
32°23'
22'
21'
RA (J2000)
a)
b)
c)
d)
e)
f)
km/s
V_LOS [km/s]
Offset [arcsec]

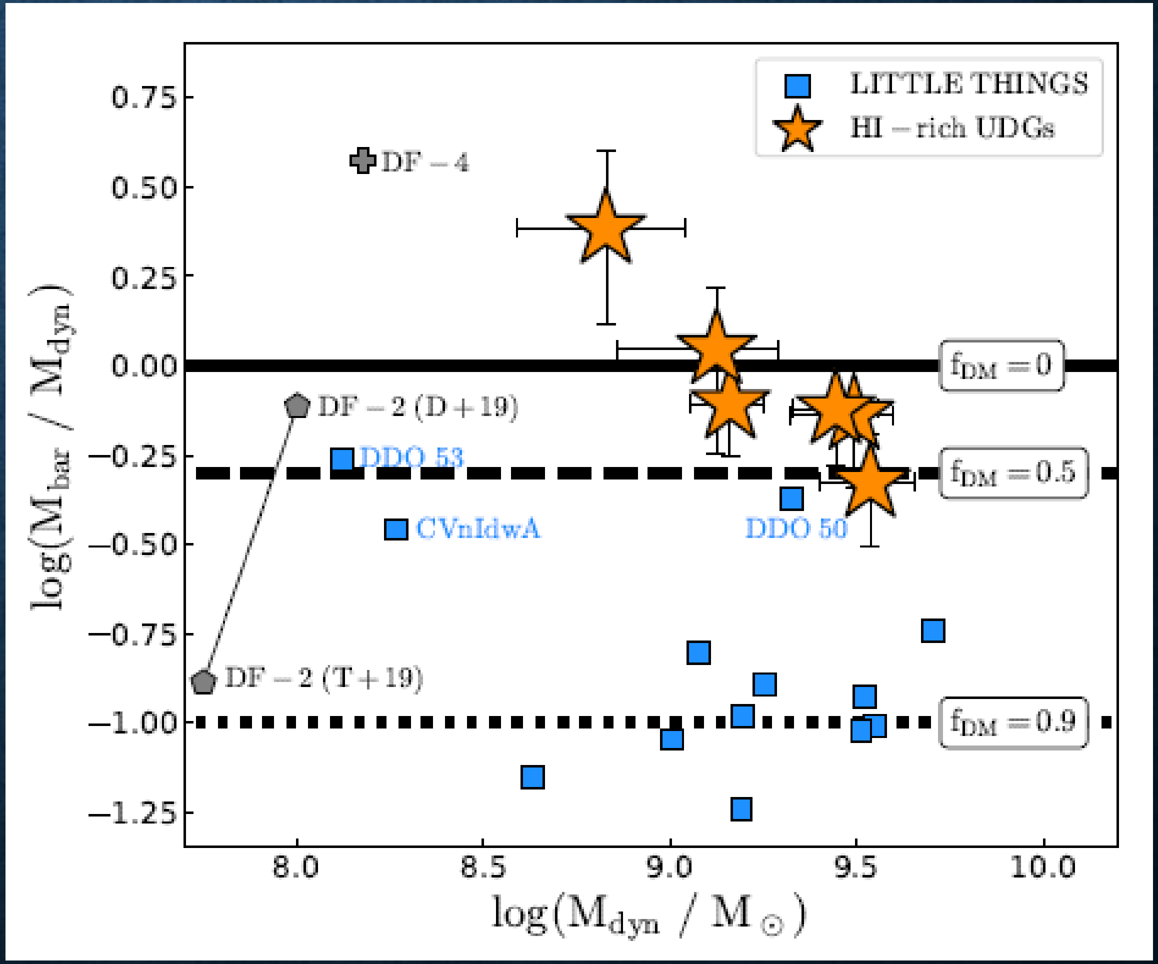
# OFF THE BTF RELATION

- Consistent (?) with no missing baryons



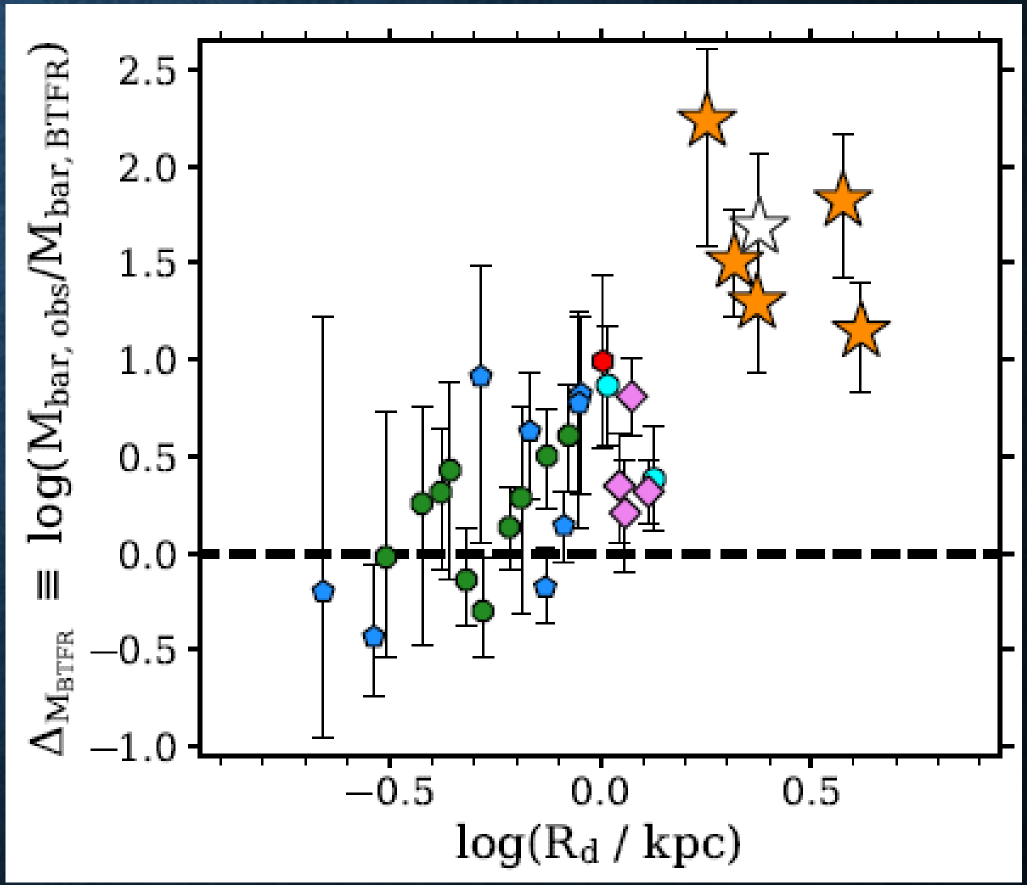
# EVIDENCE FOR DM?

- Consistent (?) with no DM



# ARE UDGS AT END OF A WIDER TREND?

- But a correlation is inevitable
  - $M_{dyn} \sim V_c^2 R_d$



# WHAT TO CONCLUDE FROM UFGS?

- Major challenge for MOND!
- Most discussions within Fall-Efstathiou (1980)
  - Each dark halo has quota of baryons, which collapse more
- But this picture led to
  - too much star formation
  - discs too small
- Fix was powerful feedback
  - Feedback blows baryons right out of halos up to $M_{DM}>10^{12}M_{sun}$

# NAÏVE INTERPRETATION OF HIGH MB

- Are UFGs systems in which feedback failed (Mancera-Pina 2020)?
  - No!
  - Basic principles can't be suspended in individual cases (miracles!)
  - No feedback -> compact not diffuse galaxies
- More promising explanation:
  - Capture of gas expelled by other halos
- Not all expelled gas is hot
  - Galactic fountain - Reynolds layer
  - H$\alpha$ filaments in eg Perseus cluster
- Natural for expelled gas to have high angular momentum wrt centre of another halo
  - Hence large Rd

# CONCLUSIONS

- We are liable to under-estimate the importance of objects with low surface brightness
- UDGs have unexpectedly high baryon fractions (may even lack DM)
- Hard o see how they can be reconciled with MOND
- Their low SB reflects large $R_d$, because large $L_z$
- This could be a natural consequence of the powerful feedback now known to be essential