

What is the MUSCEL behind Low Surface Brightness Galaxies?

- Properties of Low Surface Brightness Galaxies (LSBs)
- Cosmological Significance
- The MUSCEL Program: Star Formation Histories

What are LSB galaxies?

Properties of LSBs

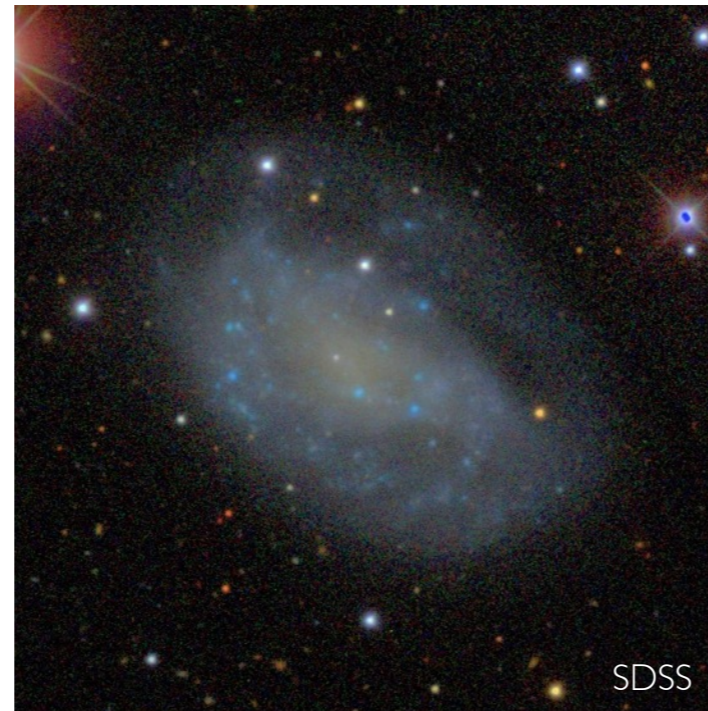
General Structure

dSphs:



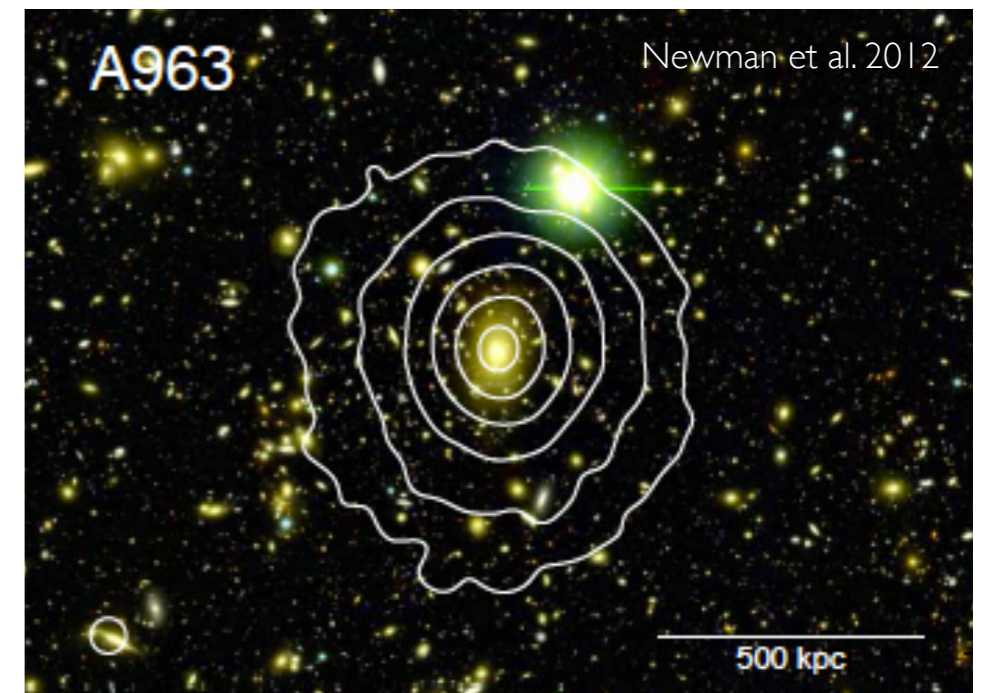
velocity dispersion
 $\sim 10^7 M_{\odot}$

LSBs:



rotation
 $\sim 10^{10} M_{\odot}$

Galaxy Clusters:



gravitational lensing
 $\sim 10^{15} M_{\odot}$

Properties of LSBs

General Structure



Lacking bright, striking features like bars and bulges

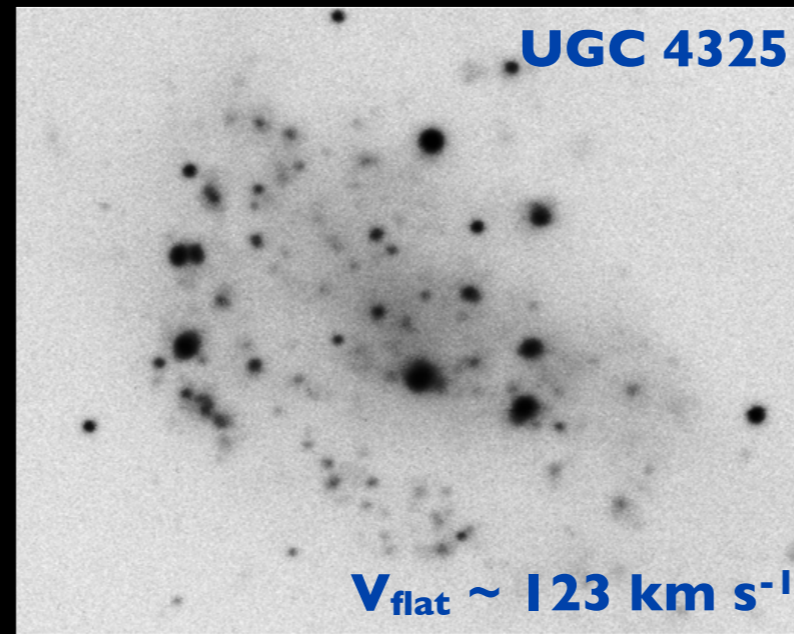
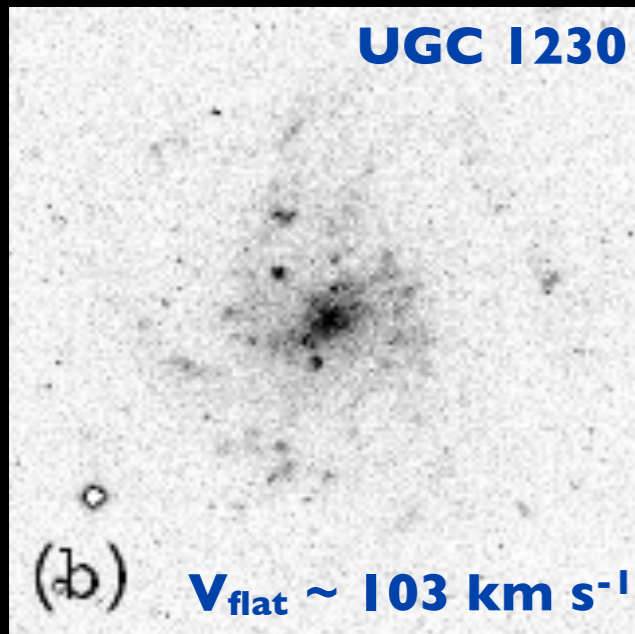


Properties of LSBs

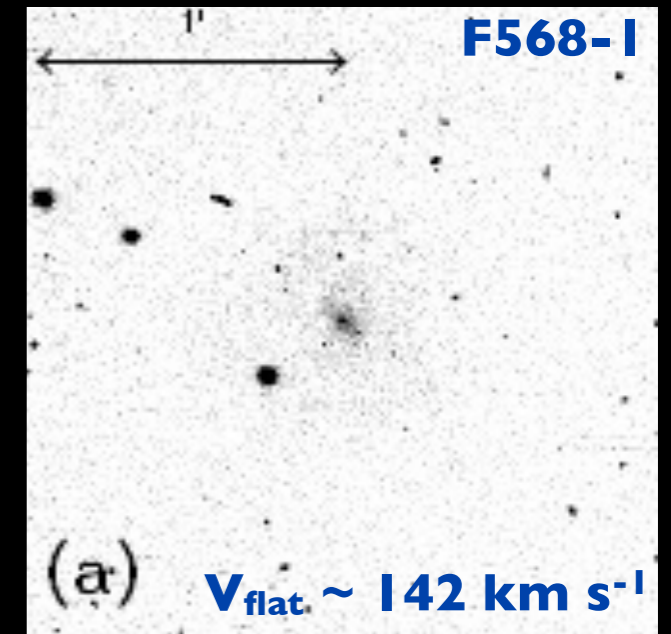
General Structure

Blue, dark matter-dominated, late-type disks

$$\mu_0 \gtrsim 23 \text{ B mag arcsec}^{-2}$$



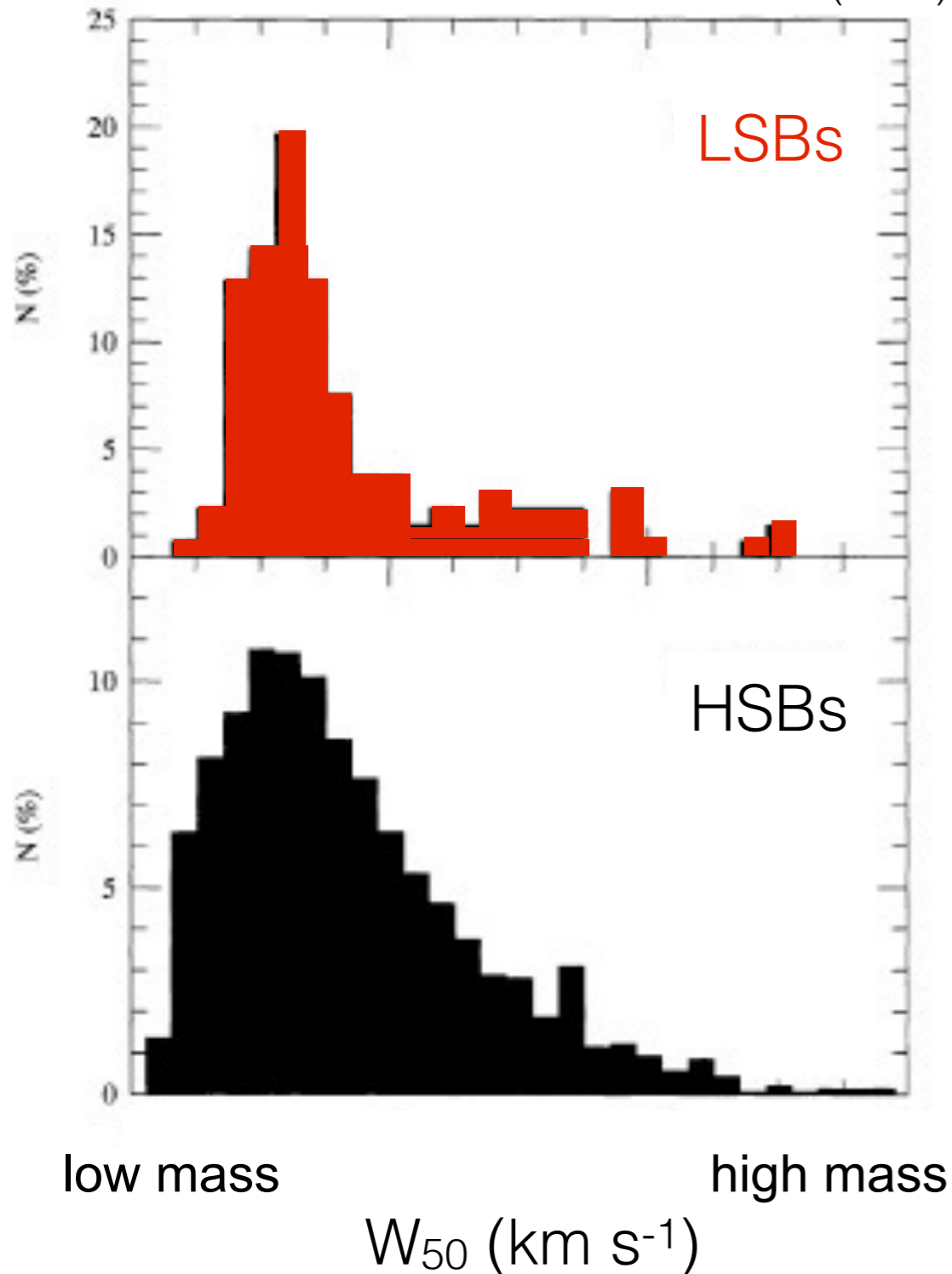
(Kuzio de Naray 2007; Kim 2007)



Properties of LSBs

Mass

Bothun et al. (1997)



LSBs span a range of masses

LSBs are *not* all low mass dwarf galaxies

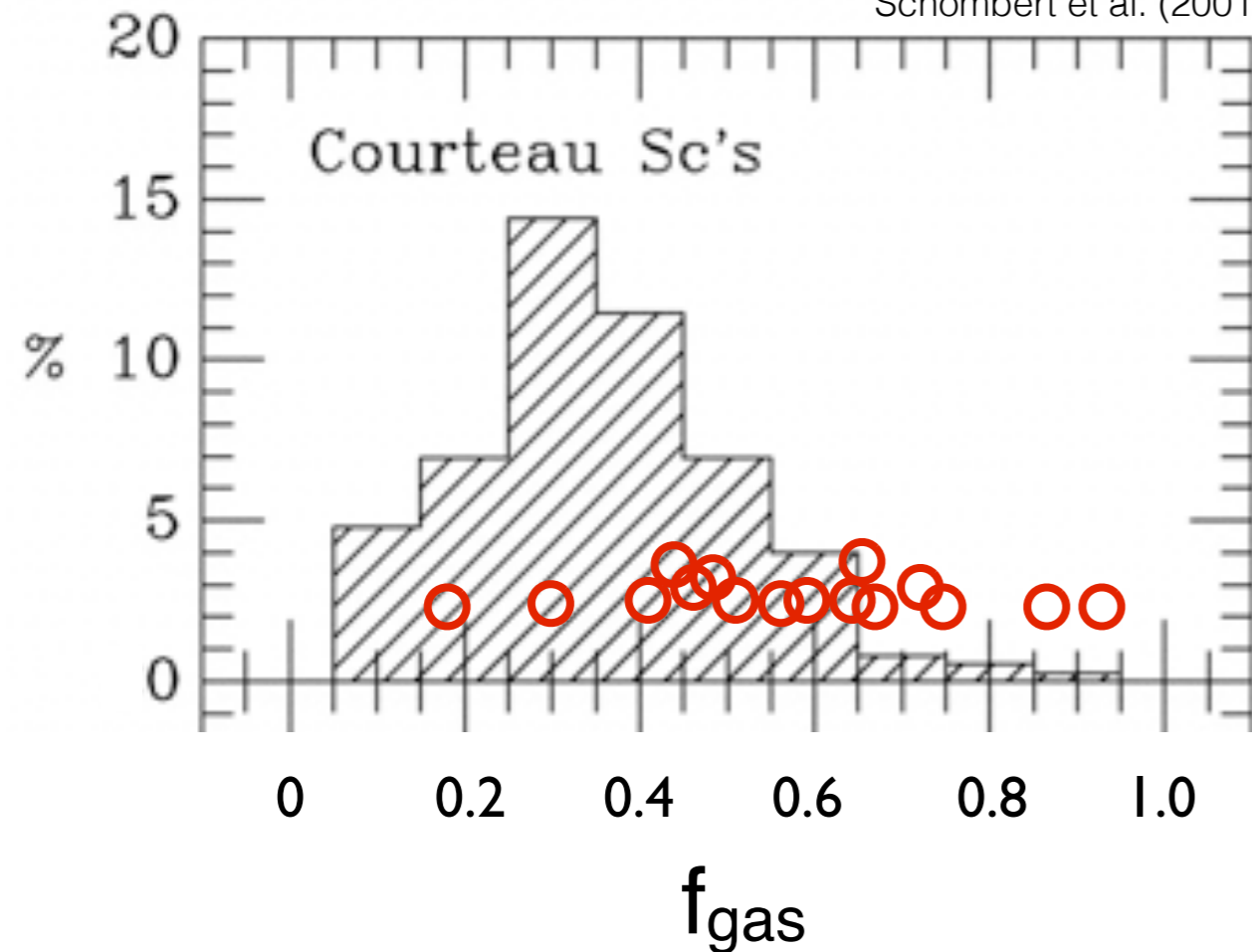
Properties of LSBs

Gas

Large gas fraction



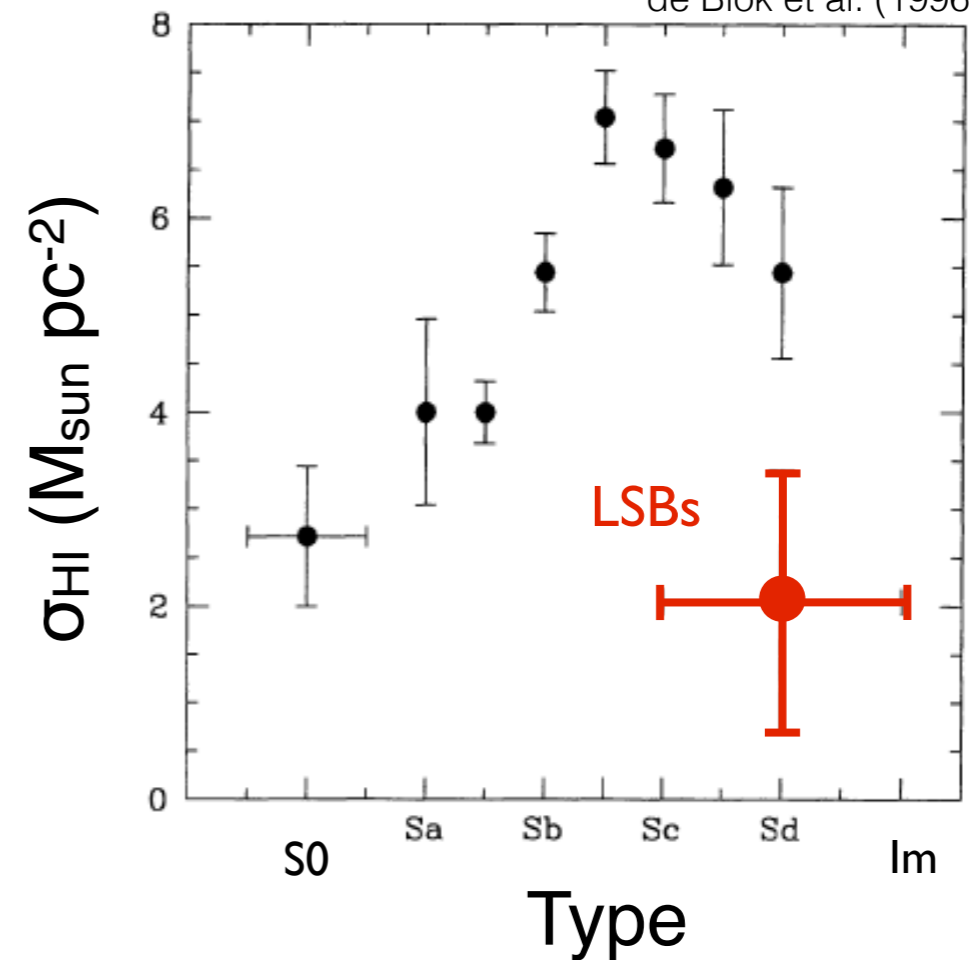
Schombert et al. (2001)



Low gas surface density



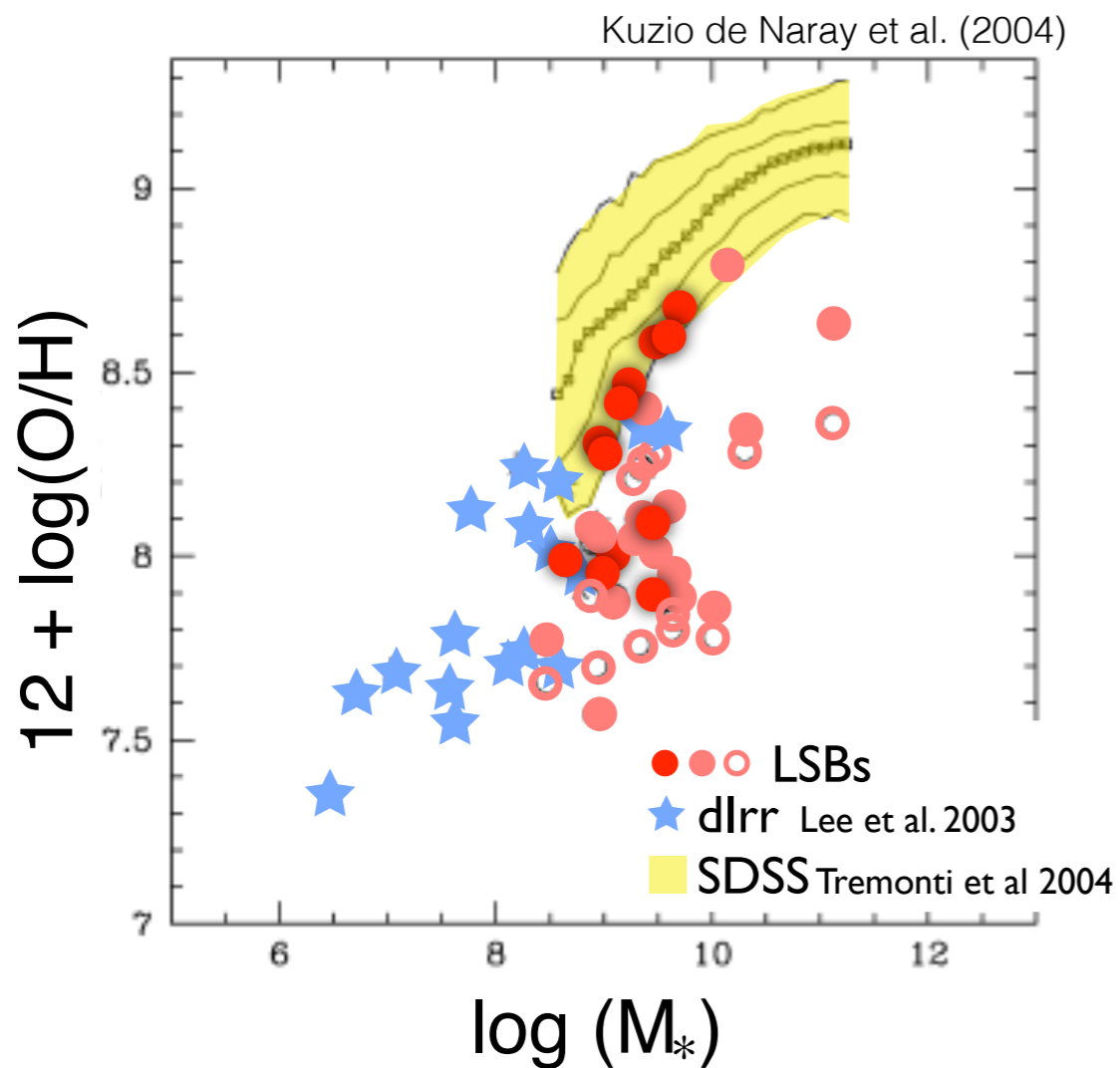
de Blok et al. (1996)



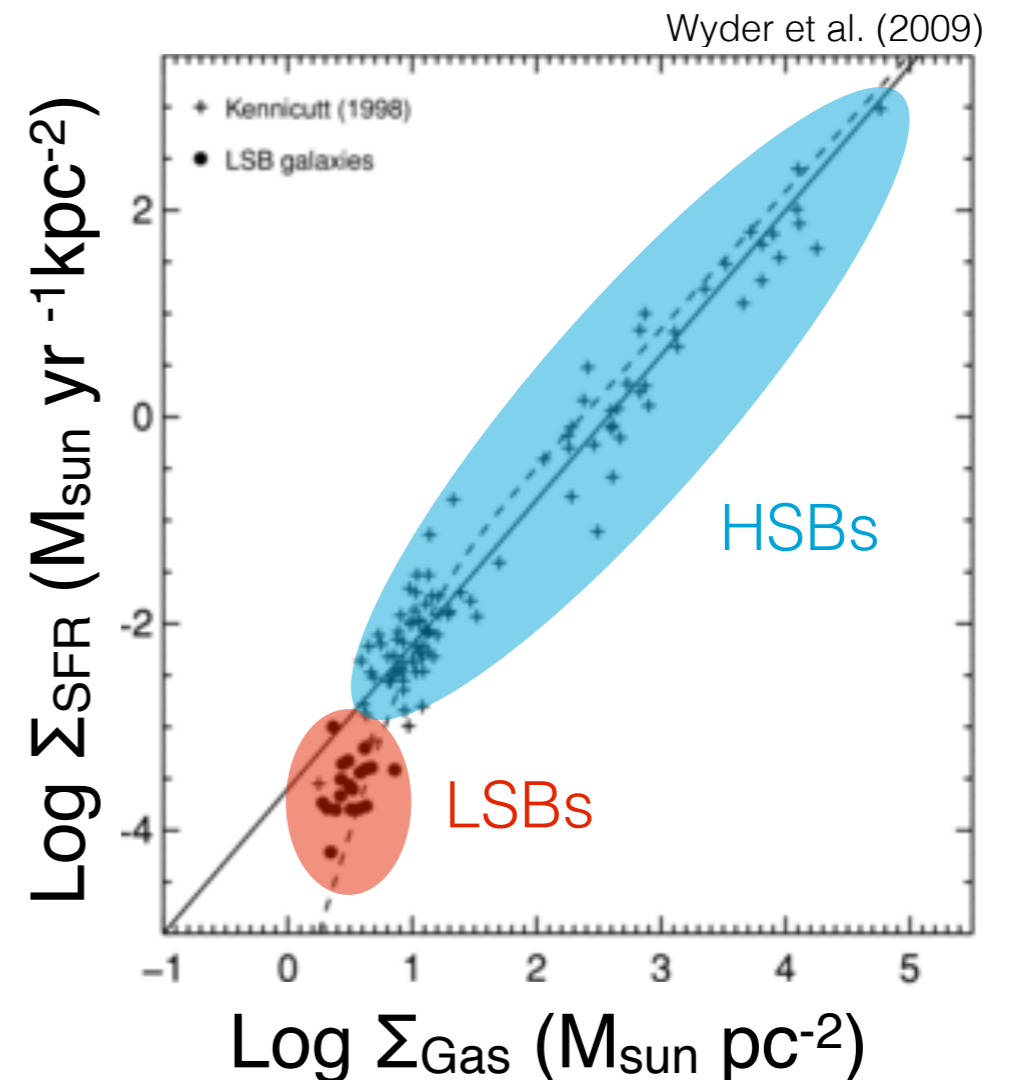
Properties of LSBs

Stars

Low metallicity



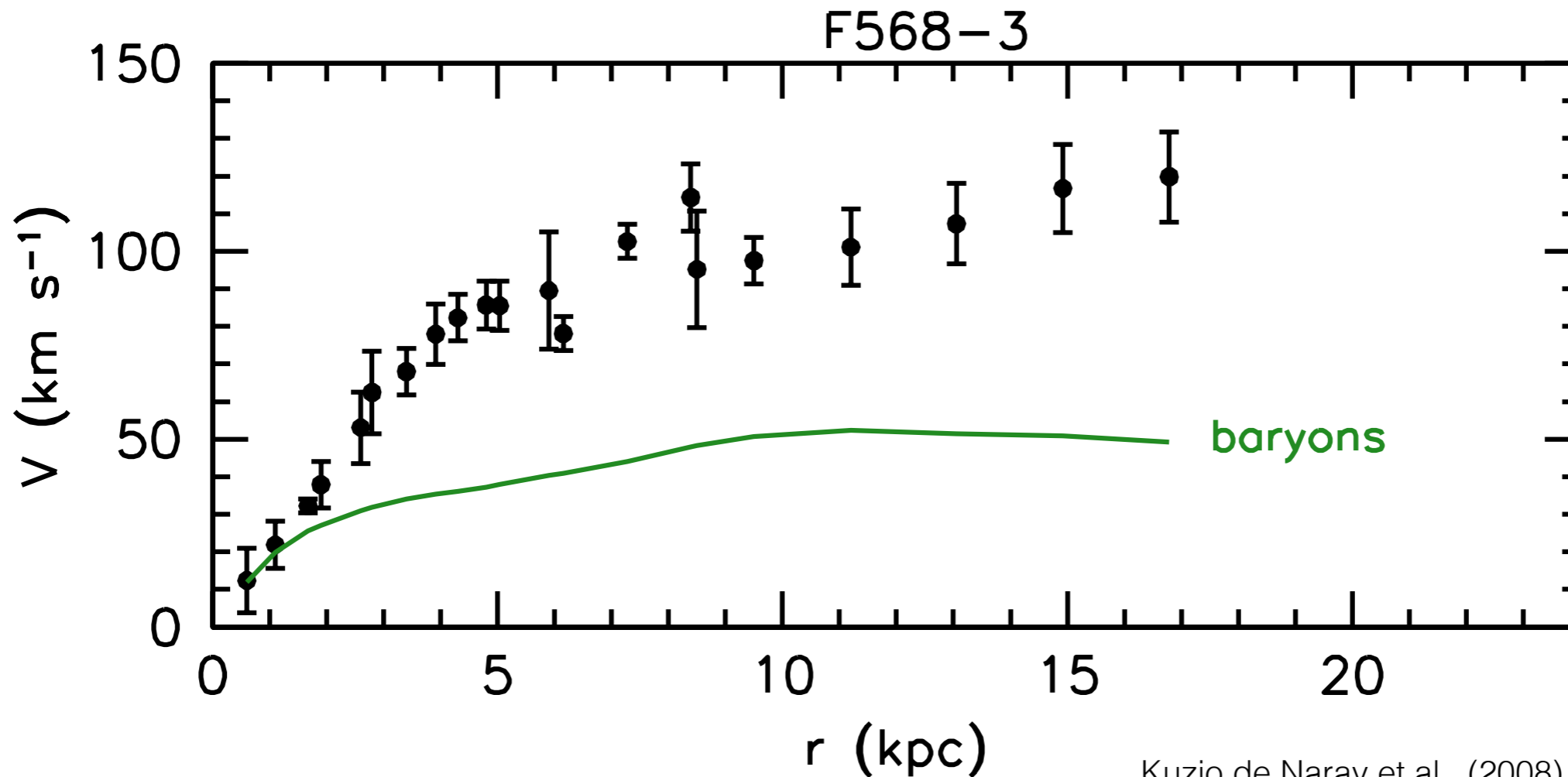
Low past & present SFR



Properties of LSBs

Dark Matter

LSBs require lots of dark matter at all radii to explain their observed rotation



Kuzio de Naray et al. (2008)

Cosmological Significance

Probes of Dark Matter

Dark Matter Halos

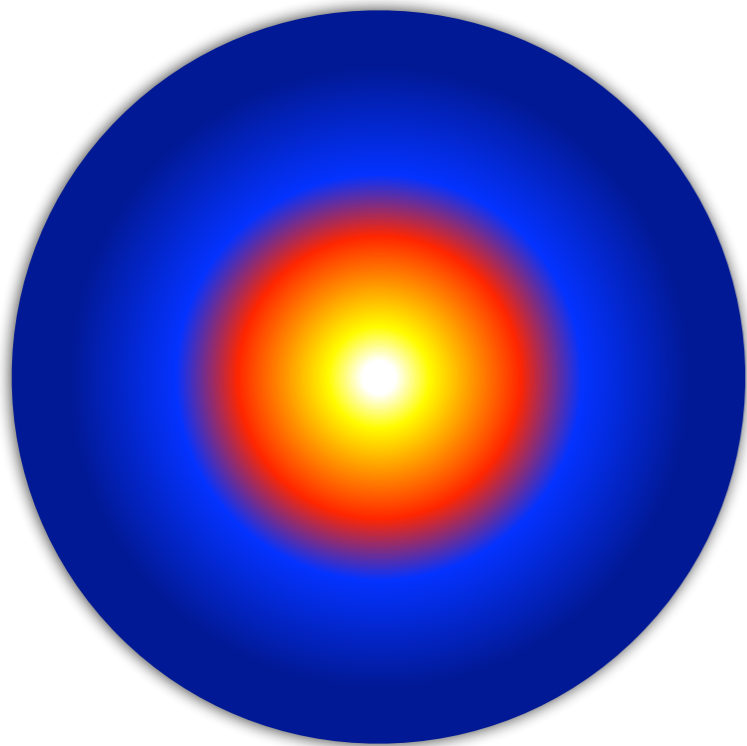
LSBs are Great for Testing Dark Matter Theories

- Can (almost) make the approximation of no baryons
- Slowly and inefficiently form stars
- Appear relatively “unevolved, untouched, pristine”

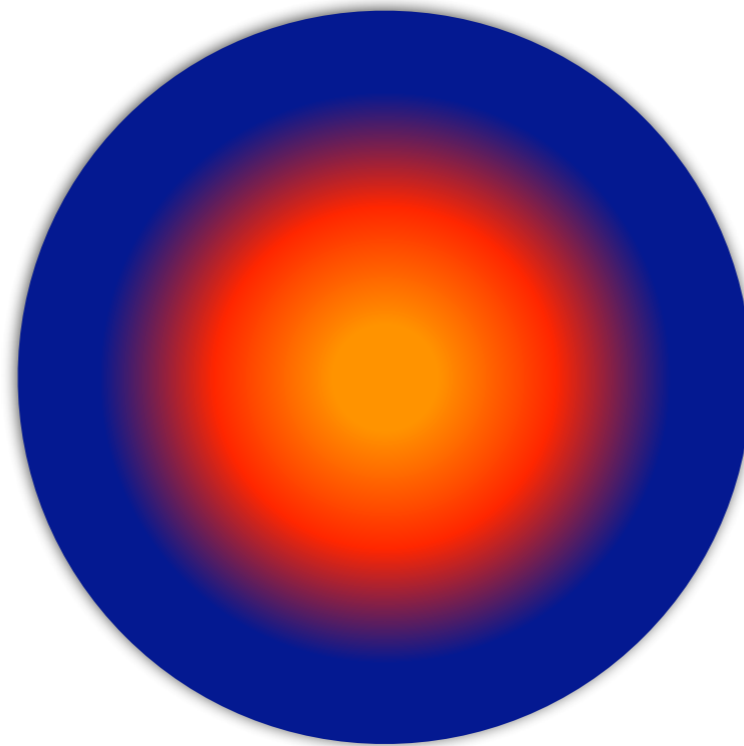
Probes of Dark Matter

Dark Matter Halos

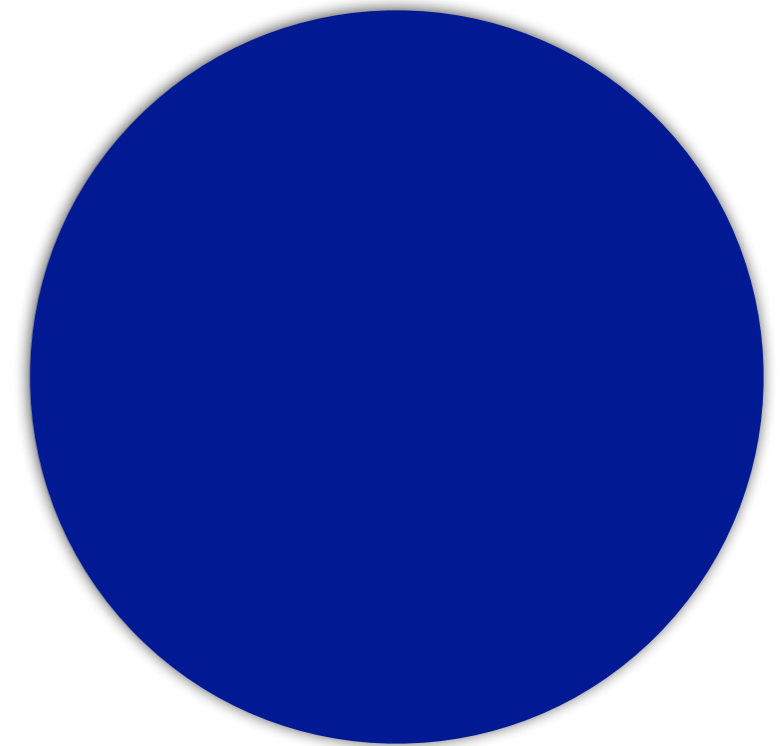
What is the density structure of the halo?



central density spike
(cuspy)



increases to a constant value
(cored)

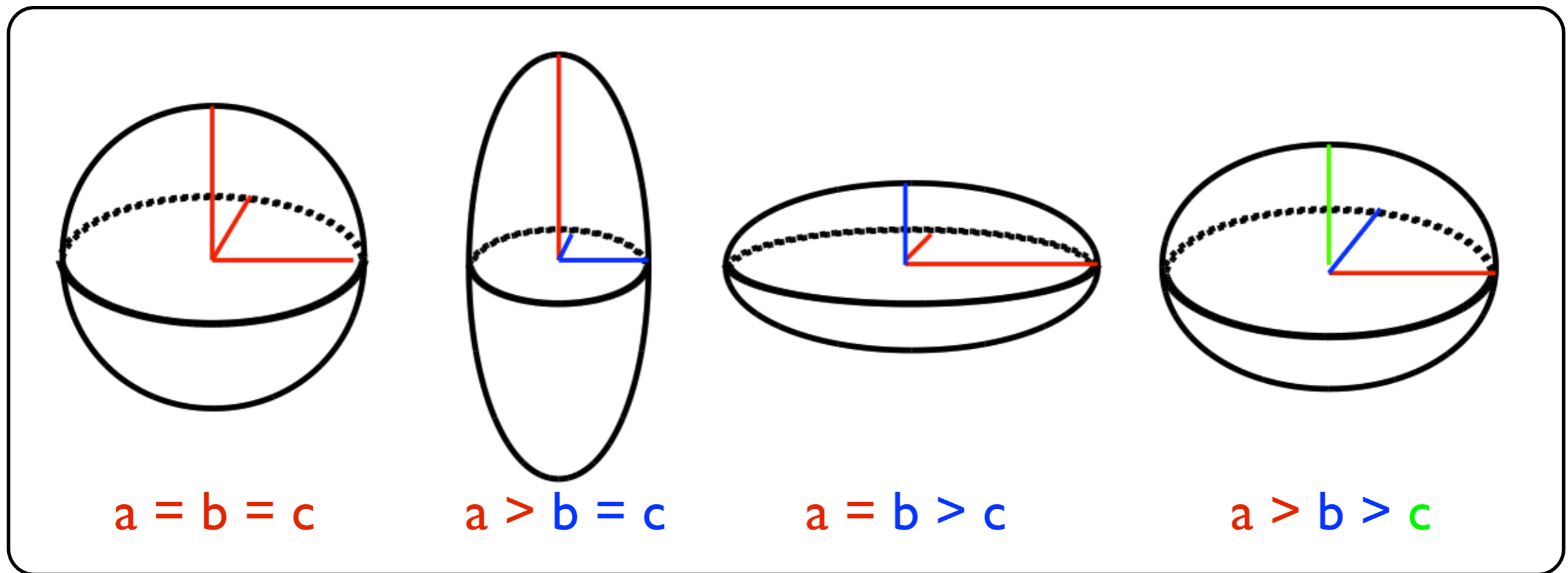


constant everywhere

Probes of Dark Matter

Dark Matter Halos

What is the shape of the halo?



Spherical

Prolate

Oblate

Triaxial

three equal

one long axis
football

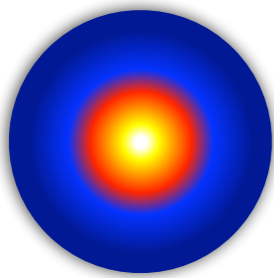
one short axis
frisbee

three different

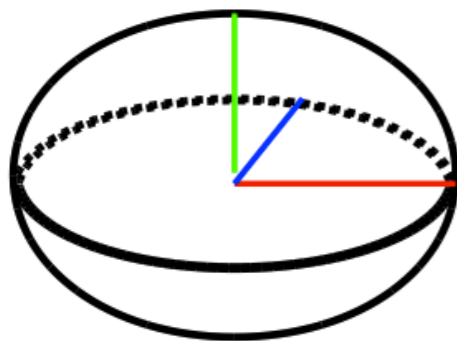
Probes of Dark Matter

Cold Dark Matter

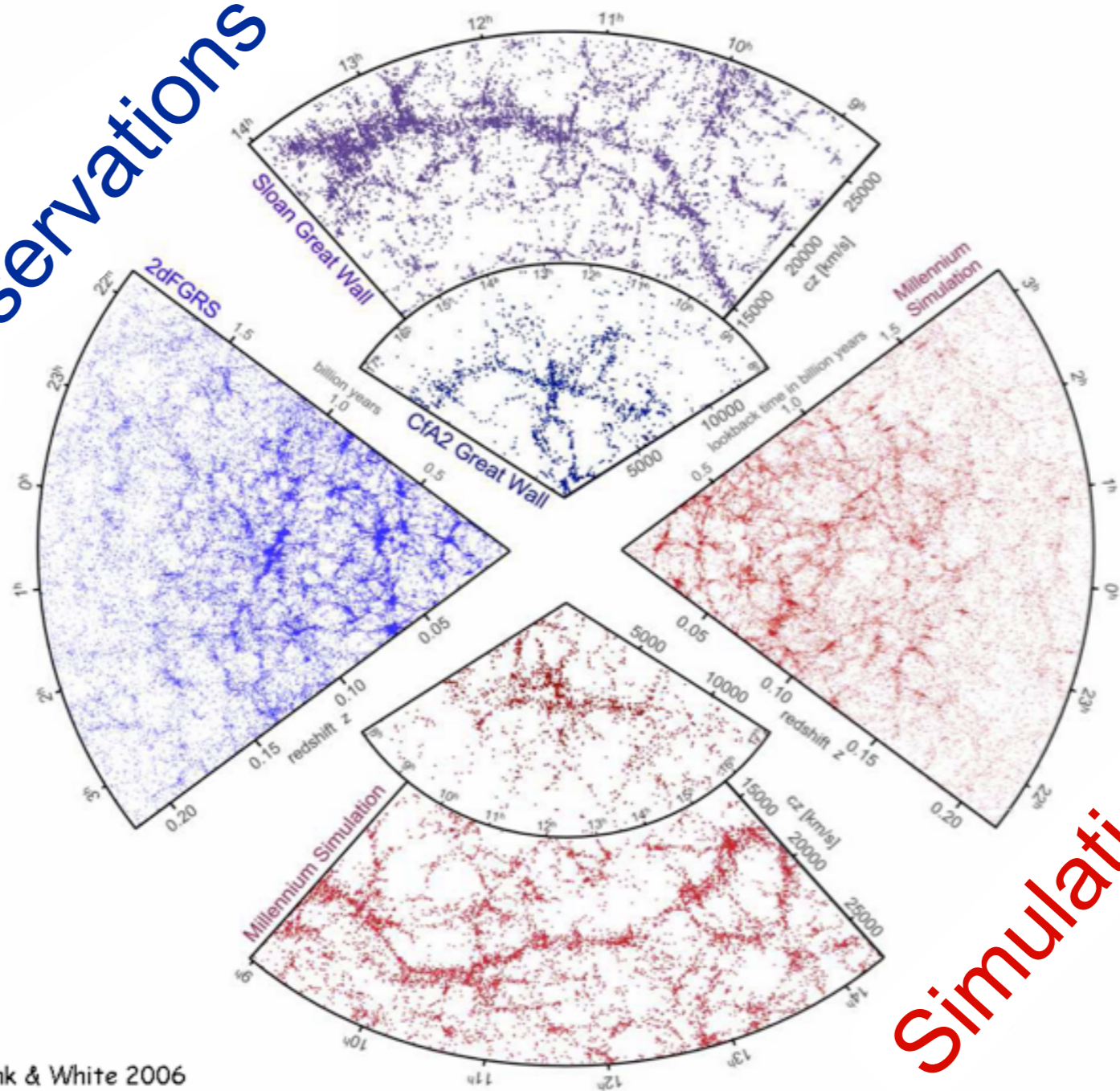
Cuspy



Triaxial



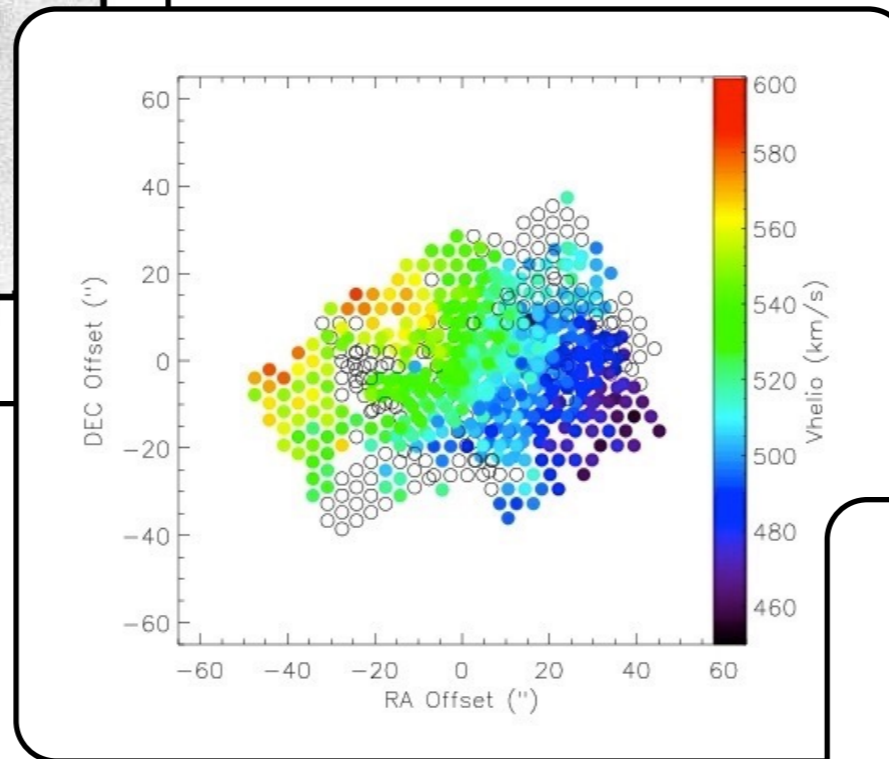
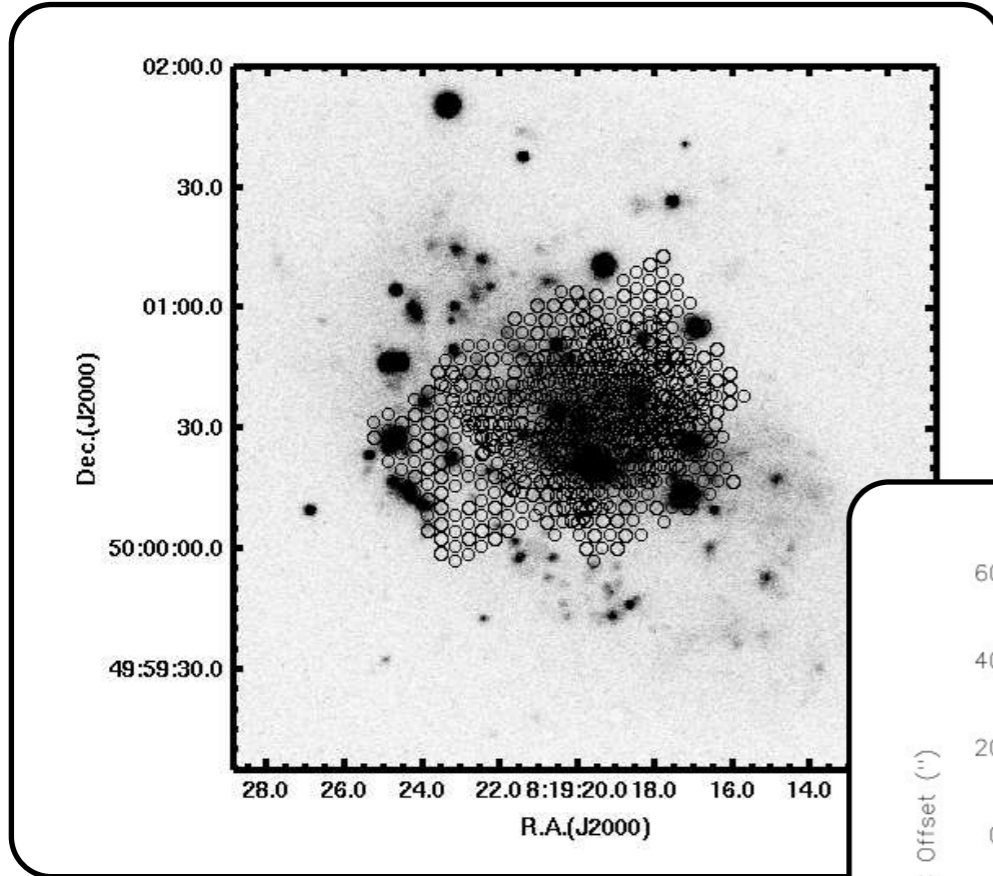
Observations



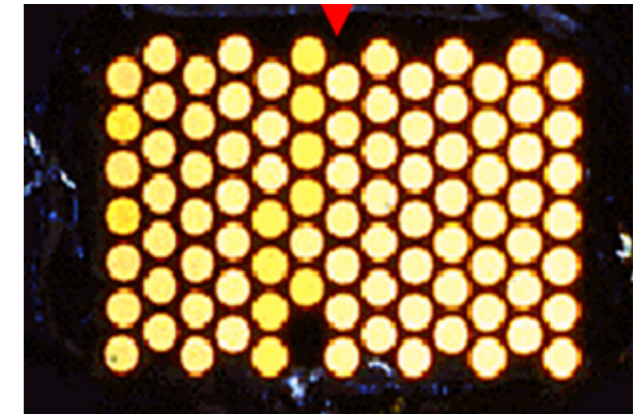
Simulations

Springel, Frenk & White 2006

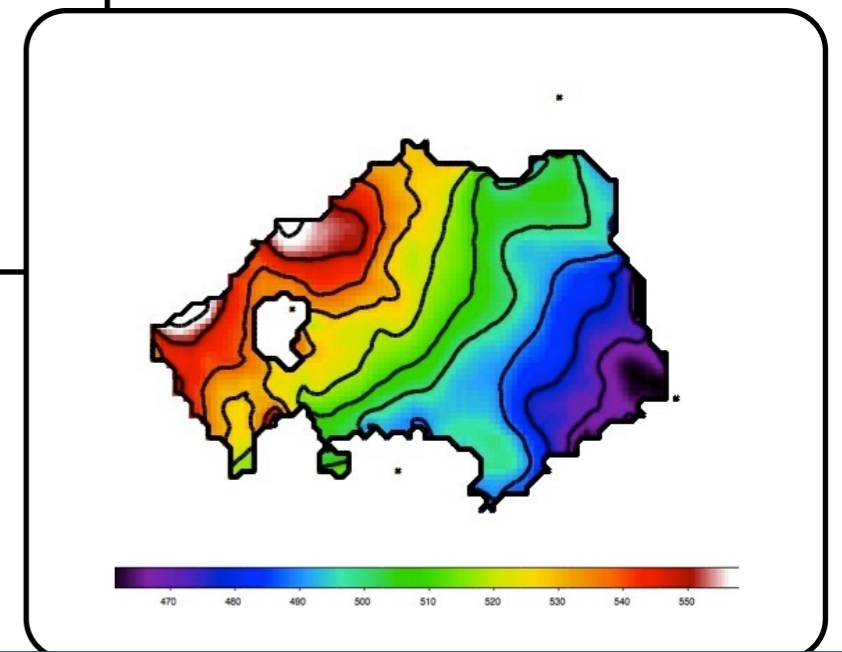
Probes of Dark Matter *Observations*



DensePak IFU



Sawyer 1997

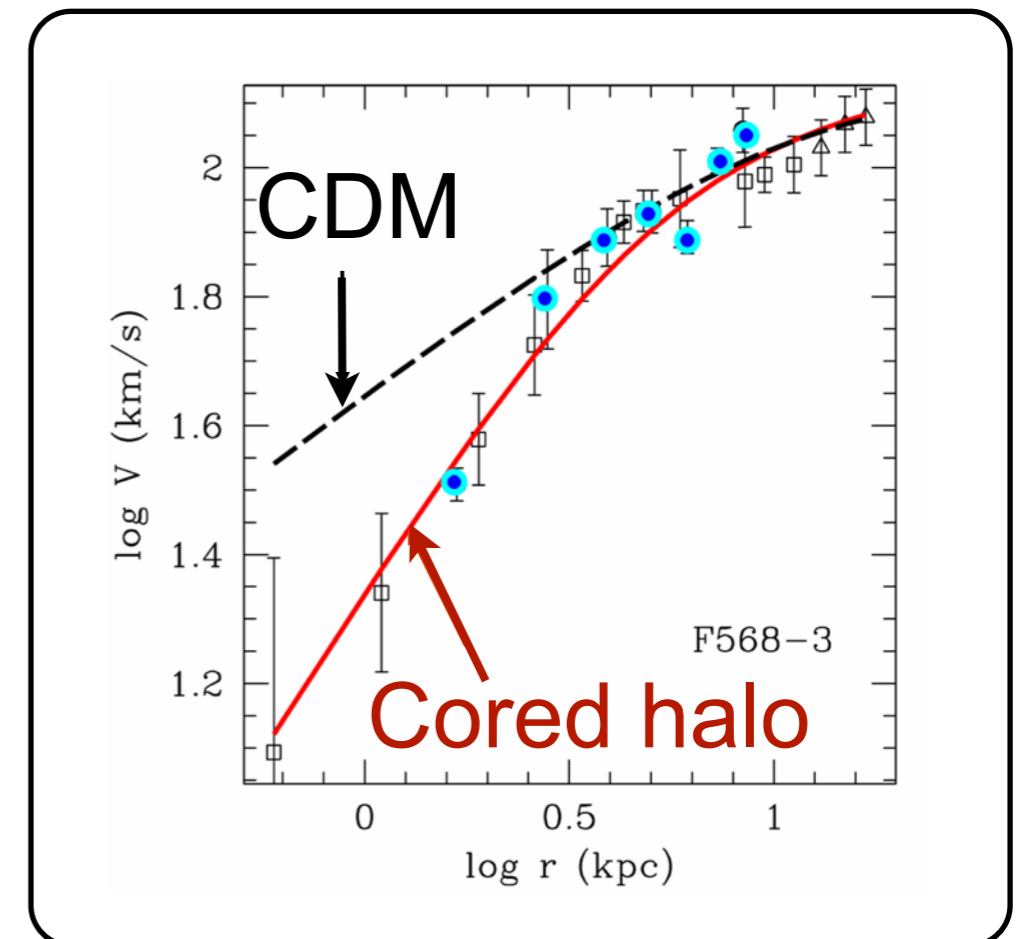
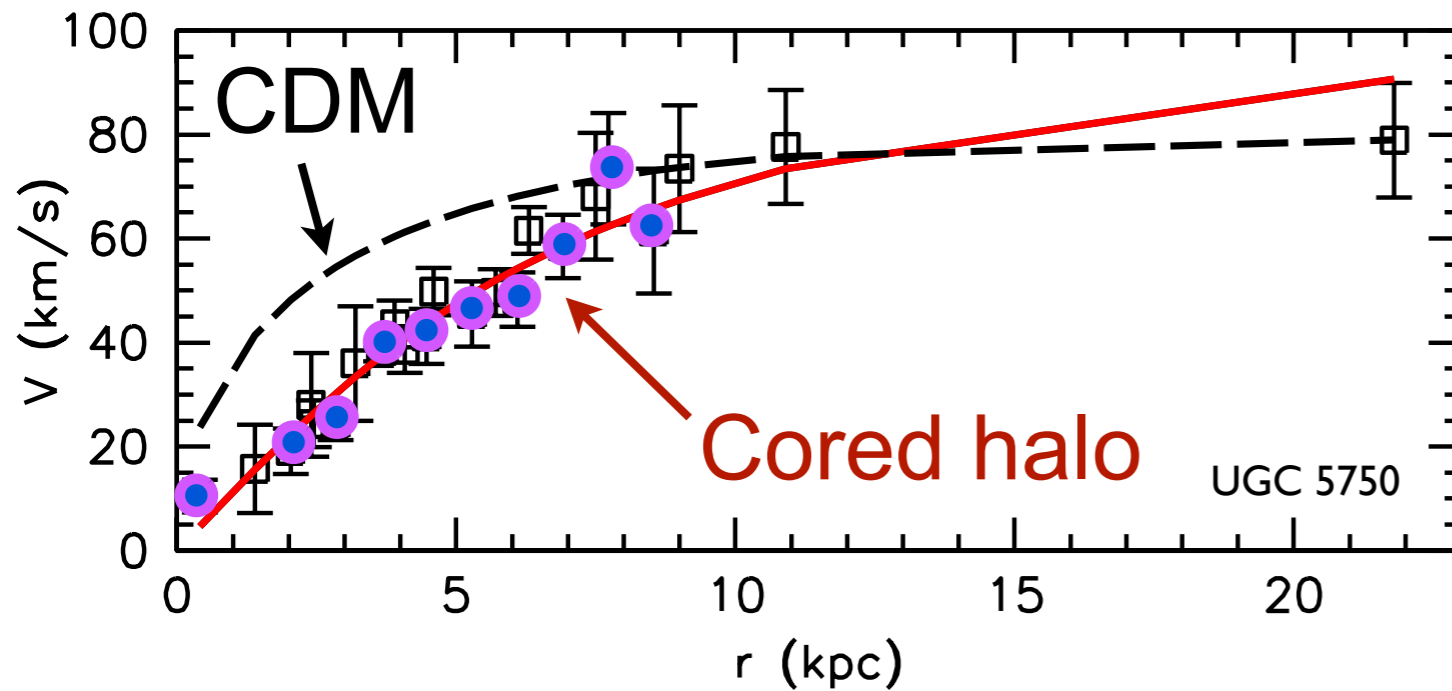


Map of velocities in 2 dimensions
High spatial resolution

Probes of Dark Matter

LSB Galaxy Rotation Curves

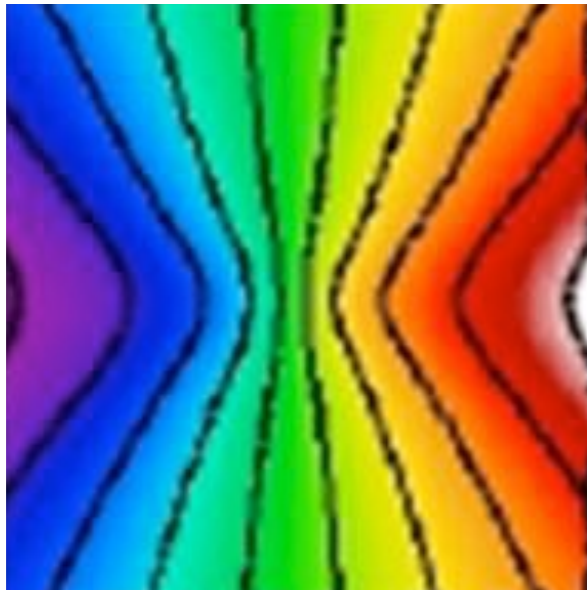
Most are better-described by cored halos



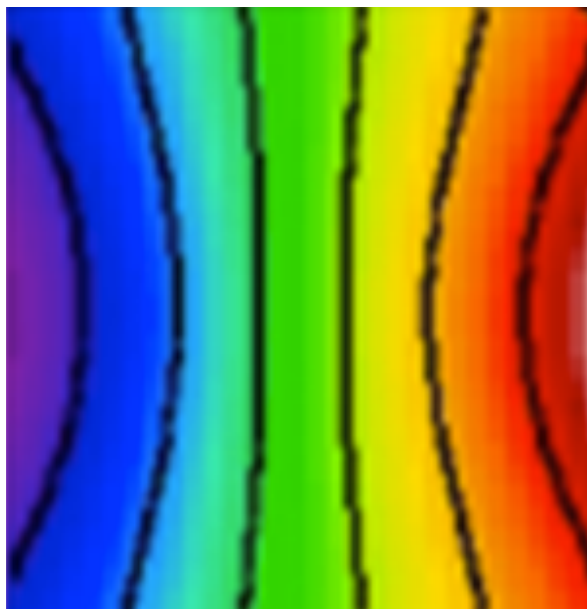
Kuzio de Naray et al. (2006,2008)

Probes of Dark Matter

Velocity Fields of IDEAL Halos



CUSPY: 
Isovelocity contours are PINCHED

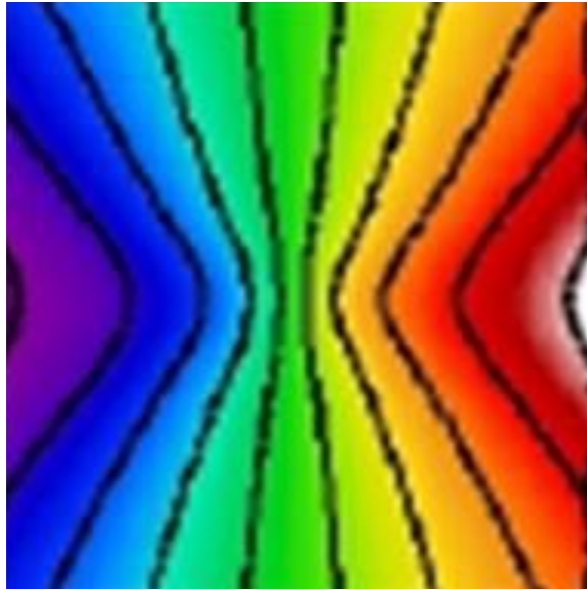


CORED: 
Isovelocity contours are PARALLEL

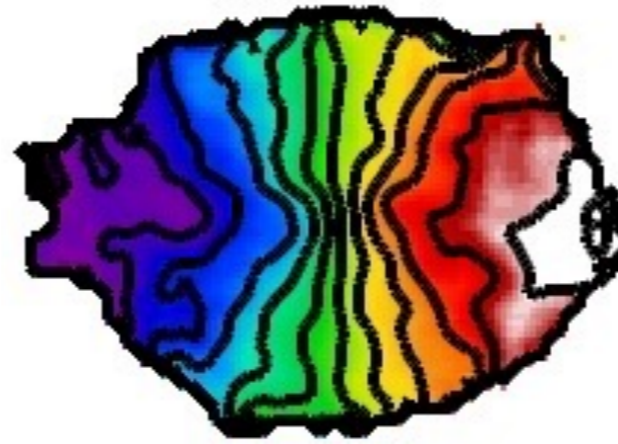
Probes of Dark Matter

Mock Velocity Fields

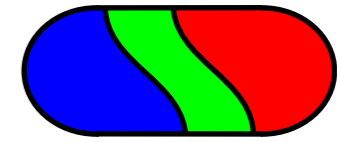
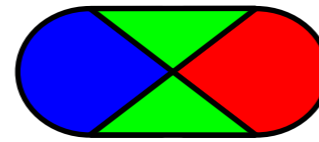
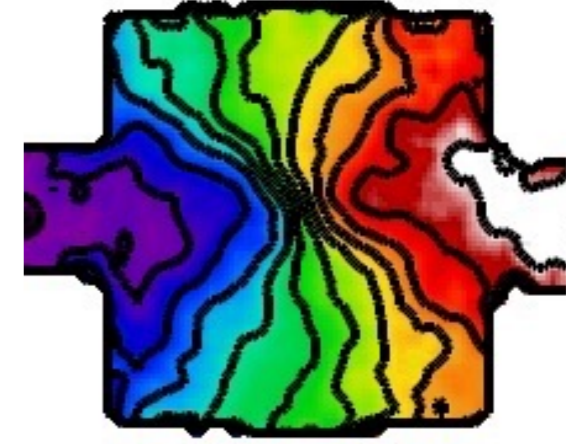
Cuspy



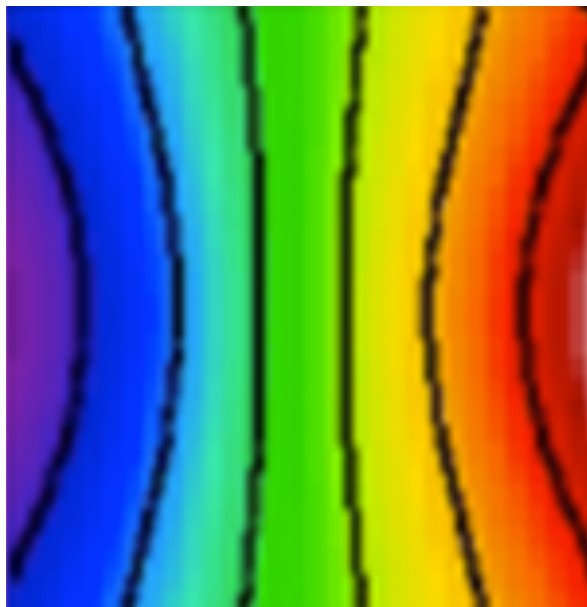
spherical



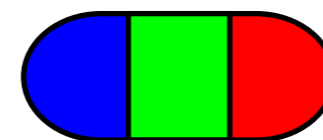
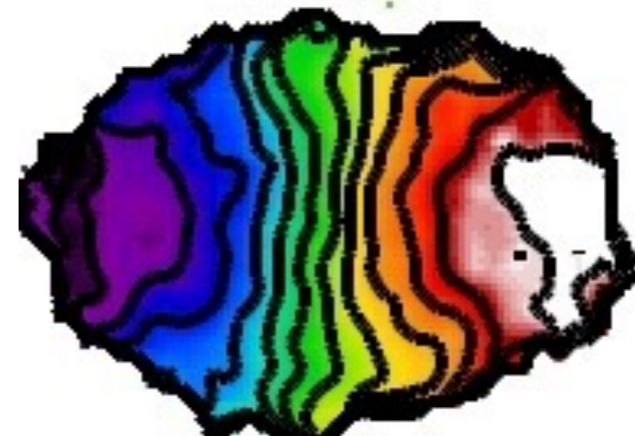
triaxial



Cored



spherical

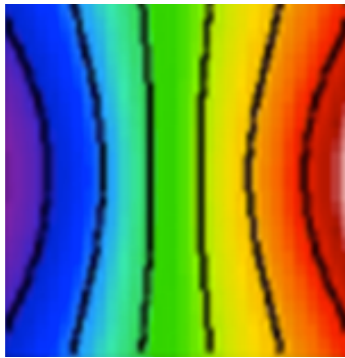


Kuzio de Naray & Kaufmann (2011)

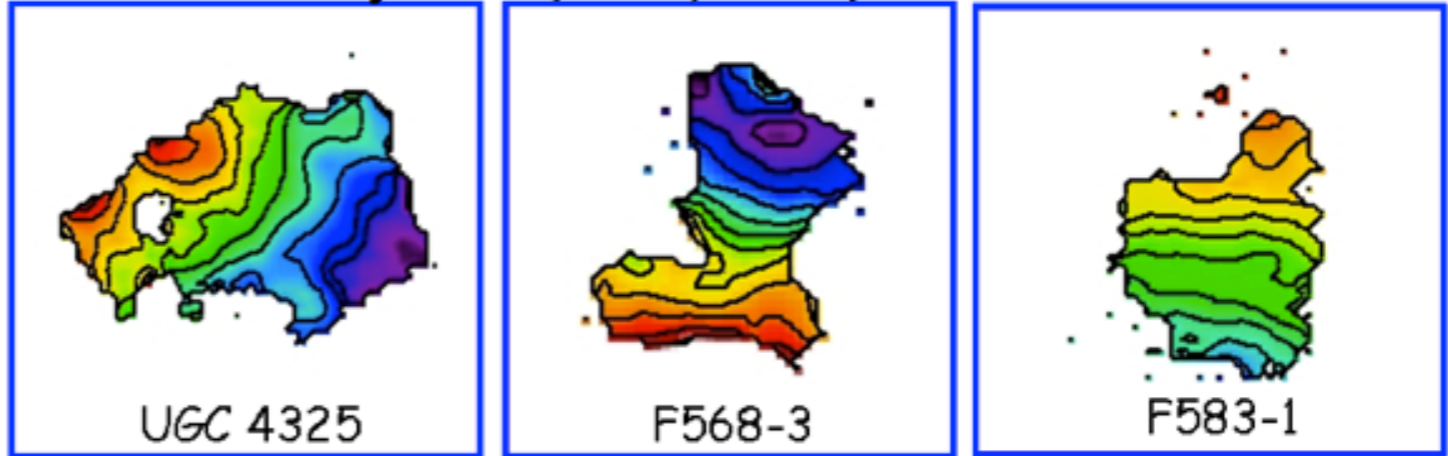
Probes of Dark Matter

Velocity Fields of REAL LSB Galaxies

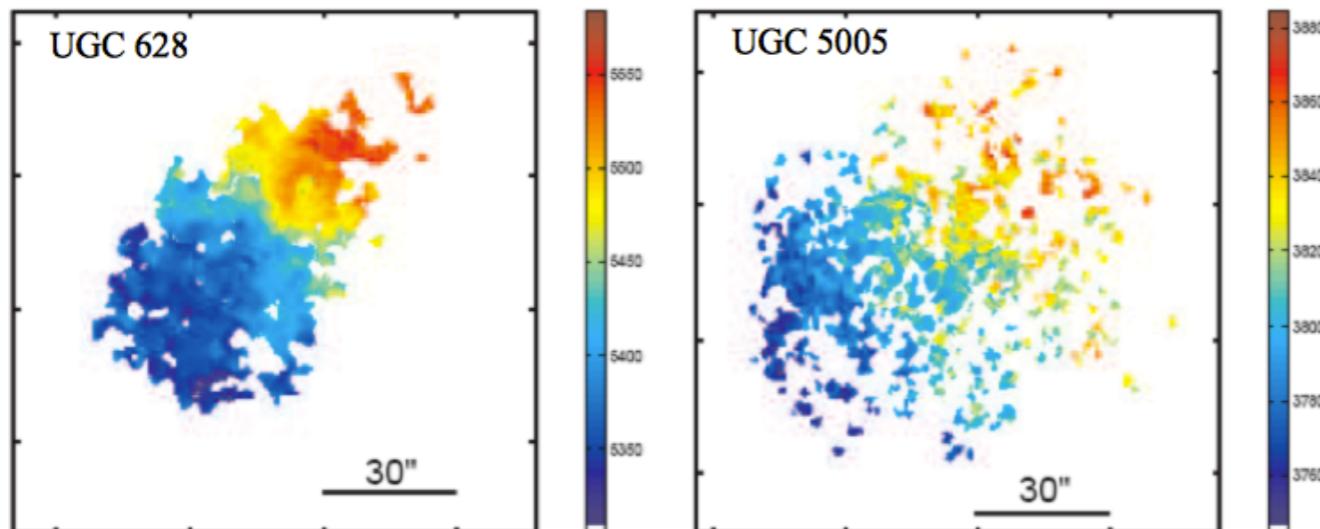
Real data look cored



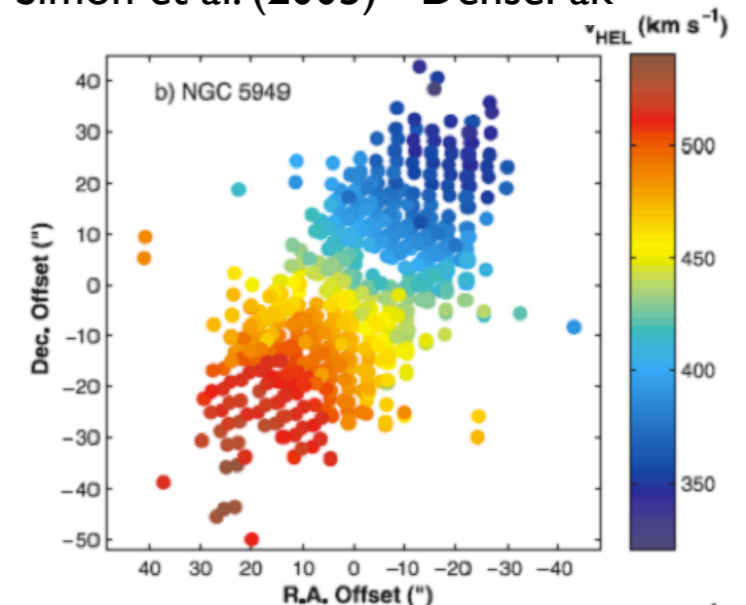
Kuzio de Naray et al. (2006, 2008) – DensePak



Chemin et al. (2004) - FaNTOmM



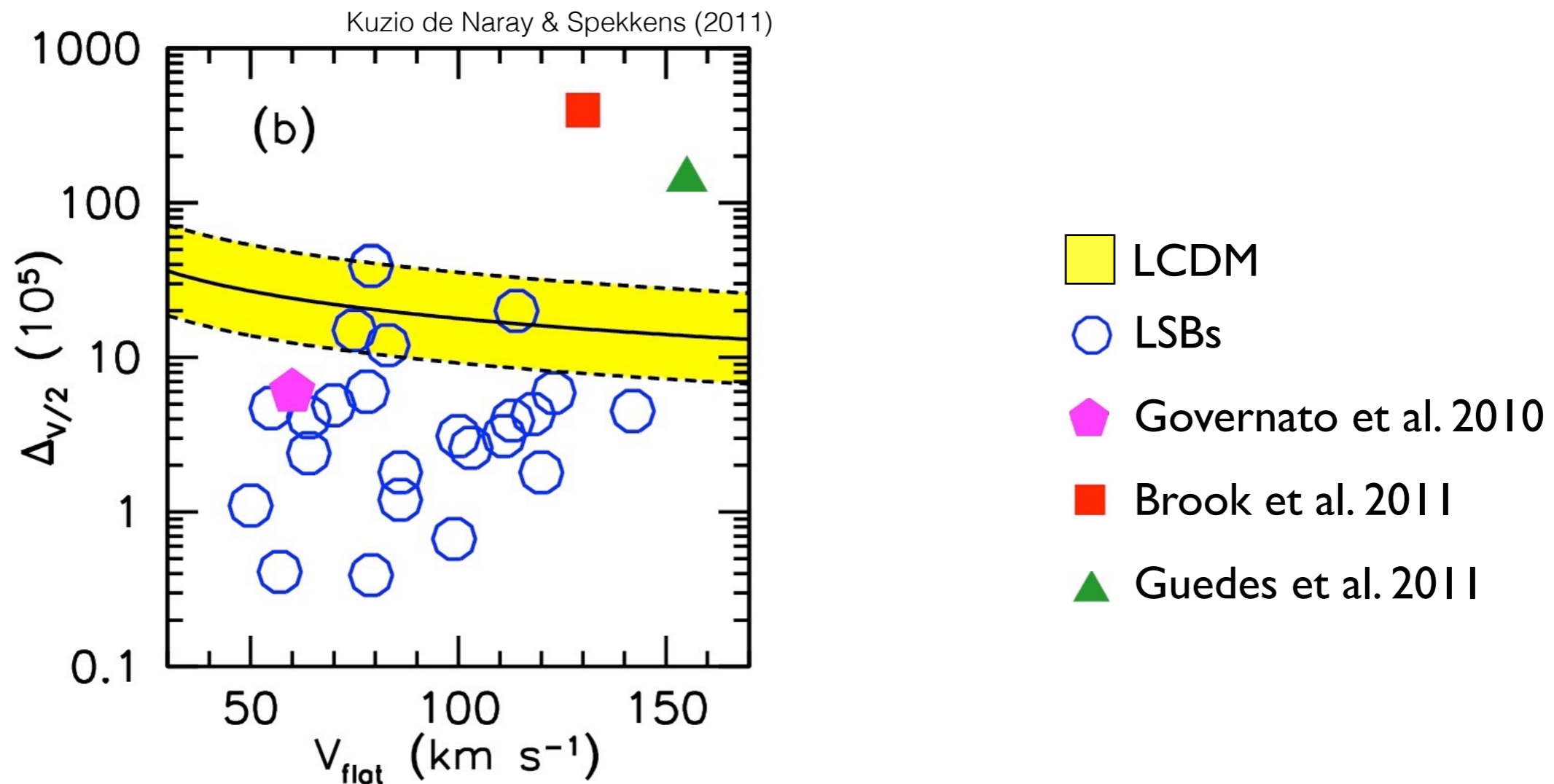
Simon et al. (2005) - DensePak



Probes of Dark Matter

Halo Density

LSB halos are underdense compared to LCDM



Probes of Dark Matter

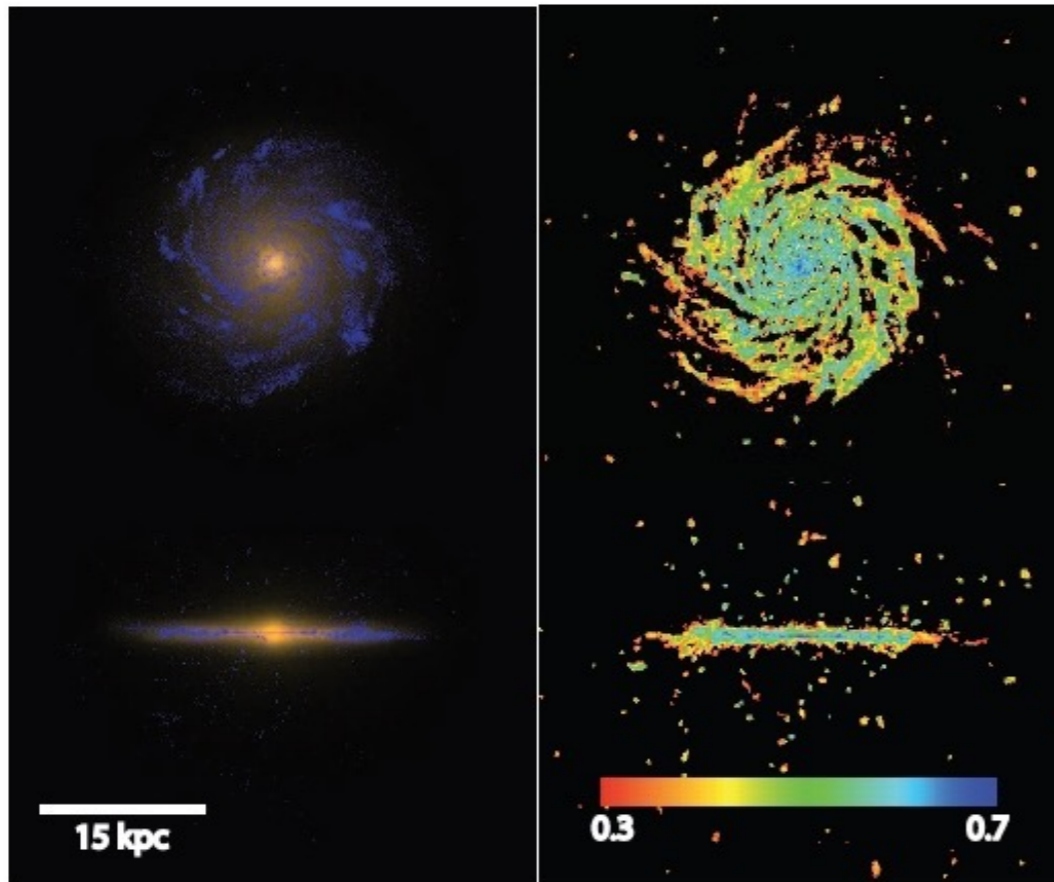
Puzzles

Why do LSB galaxies look so odd?

Probes of Dark Matter

Puzzles

Could star formation have altered the dark matter halos?



Guedes et al. 2011

Star formation physics helps simulate realistic “bulgeless” disks

Probes of Dark Matter

Puzzles

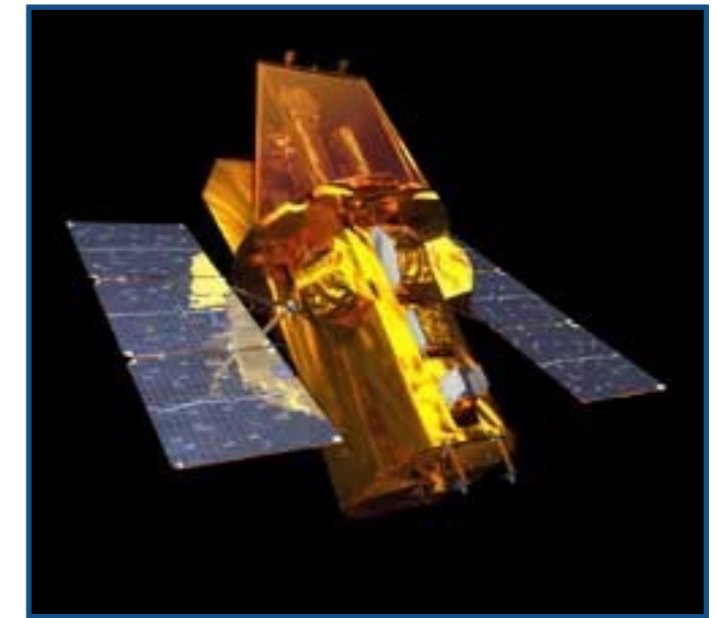
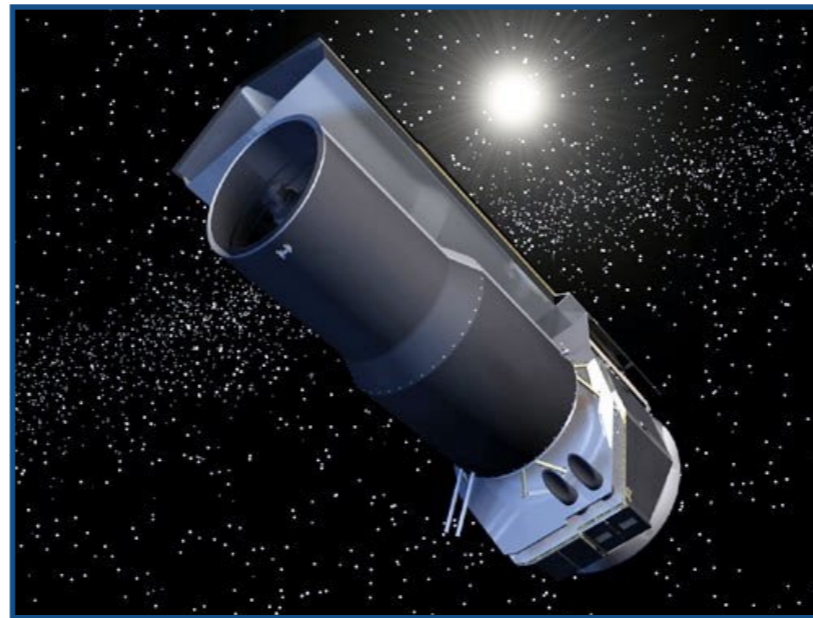
What is the star formation history of LSBs?

- Nearly constant, but extremely low, over galaxy lifetime
(e.g. Schombert & McGaugh 2014)
- Recent, but not ongoing, galaxy-wide burst
(e.g. Zackrisson et al. 2005)
- Sporadic and in spatially-isolated bursts
(e.g. Auld et al. 2006, Boissier et al. 2008)

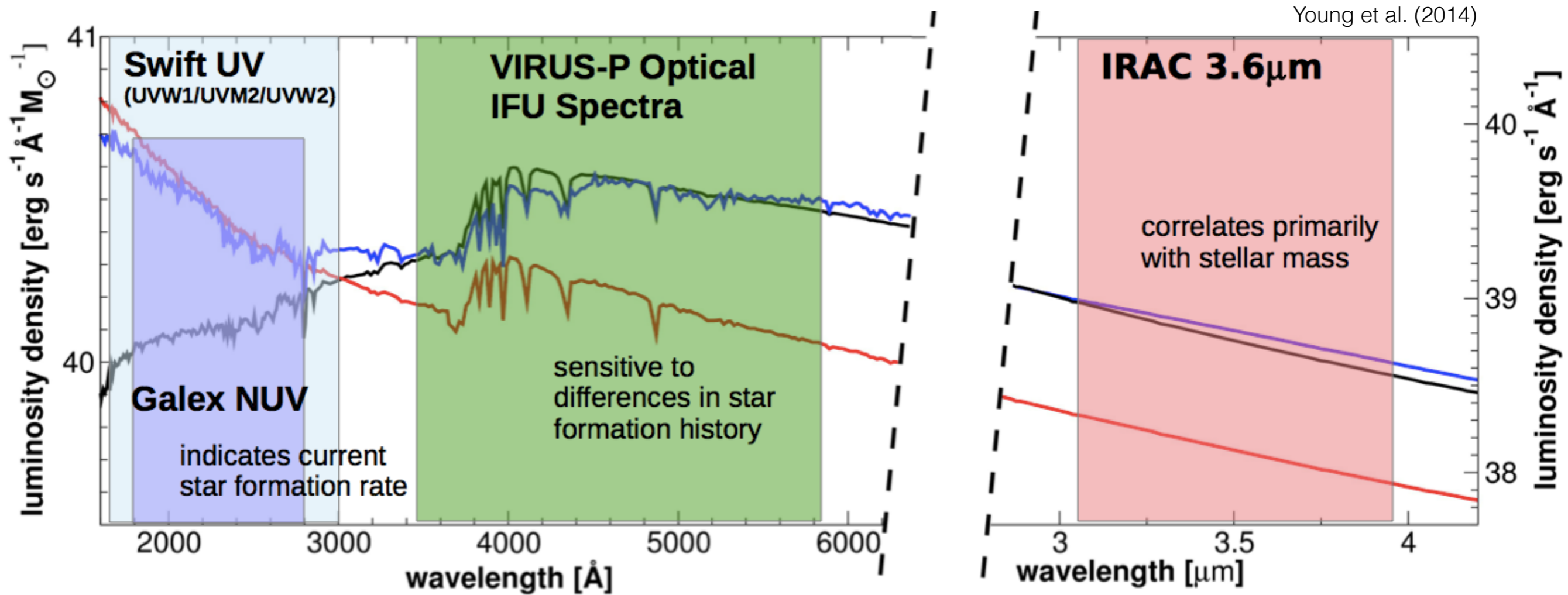
The MUSCEL Program

*M*ultiwavelength observations of the *S*tructure, *C*hemistry, and *E*volution of *LSB* galaxies

Goal is to fully constrain
the spatially-resolved
star formation histories
of a sample of
LSB galaxies



How does an LSB form its stars?

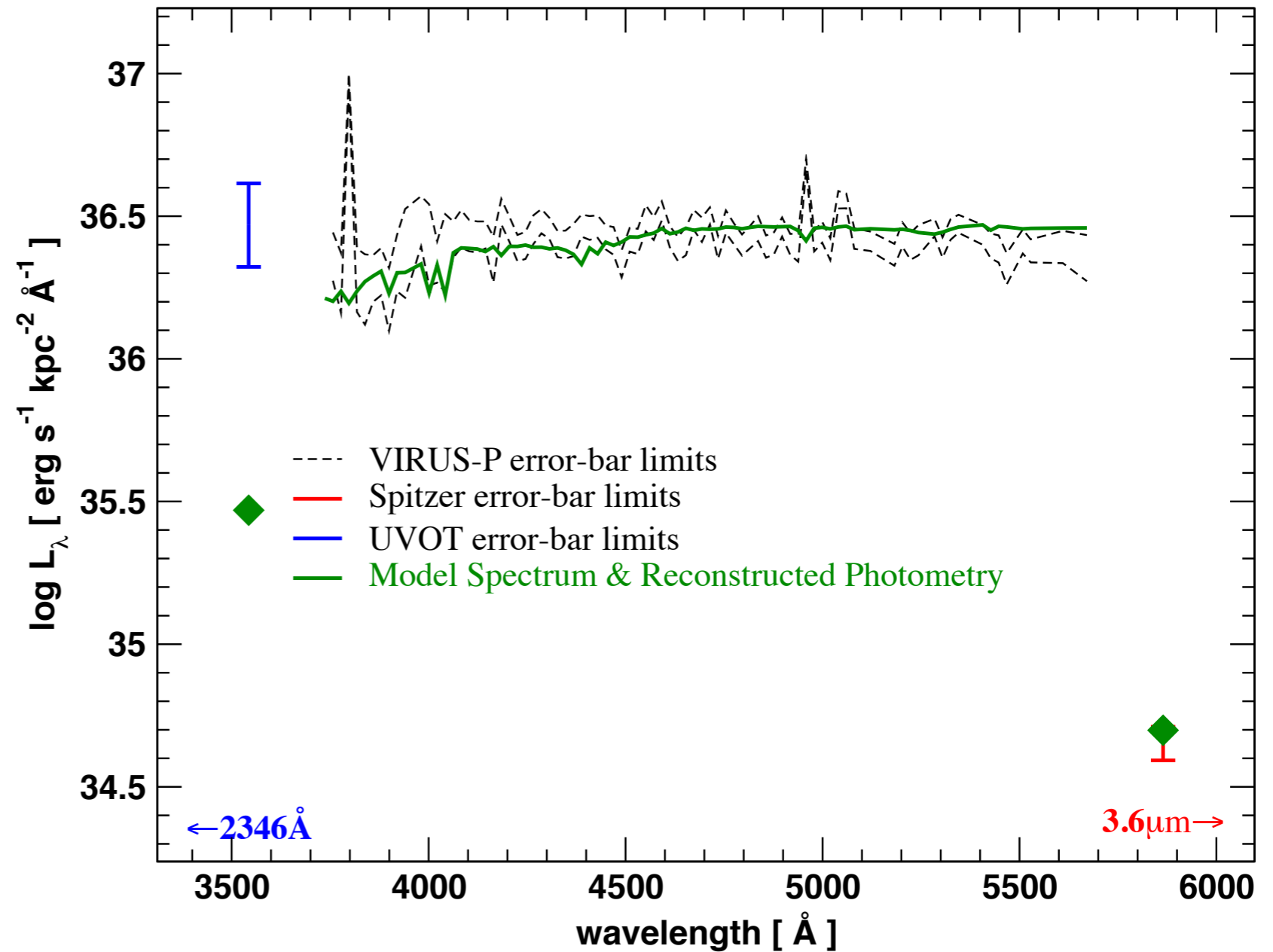
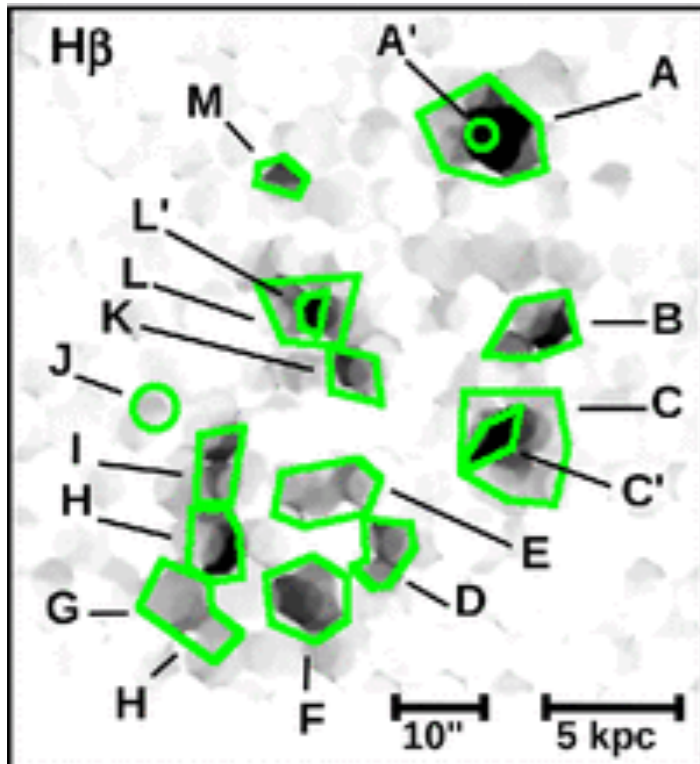
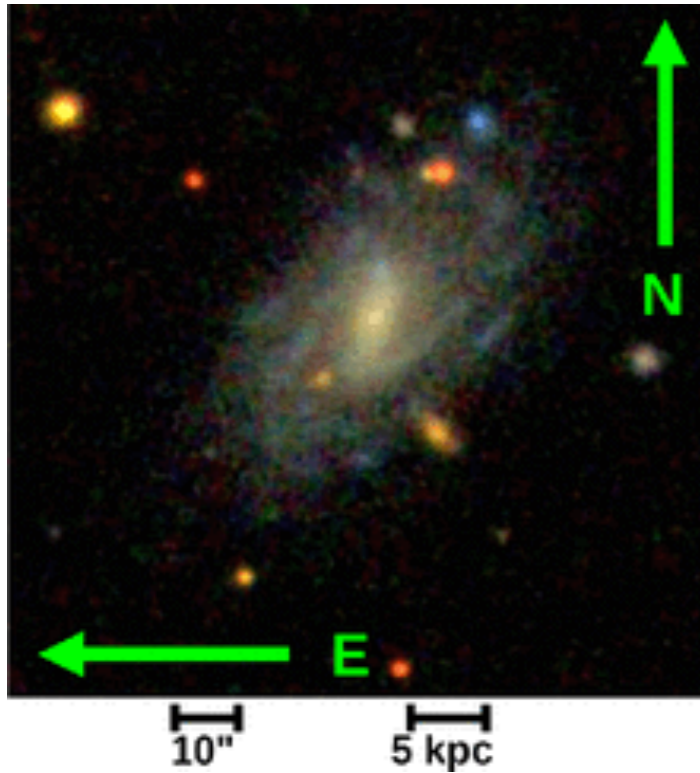


- $6.5 \times 10^{10} M_{\odot}$ forming stars at an exponentially decaying rate, currently $0.5 M_{\odot} \text{ yr}^{-1}$
- $1.0 \times 10^{10} M_{\odot}$ forming stars at an constant rate of $0.5 M_{\odot} \text{ yr}^{-1}$ for the past 3 Gyr
- $6.5 \times 10^{11} M_{\odot}$ 3 Gyr after an instantaneous burst

MUSCEL

How does an LSB form its stars?

UGC 628

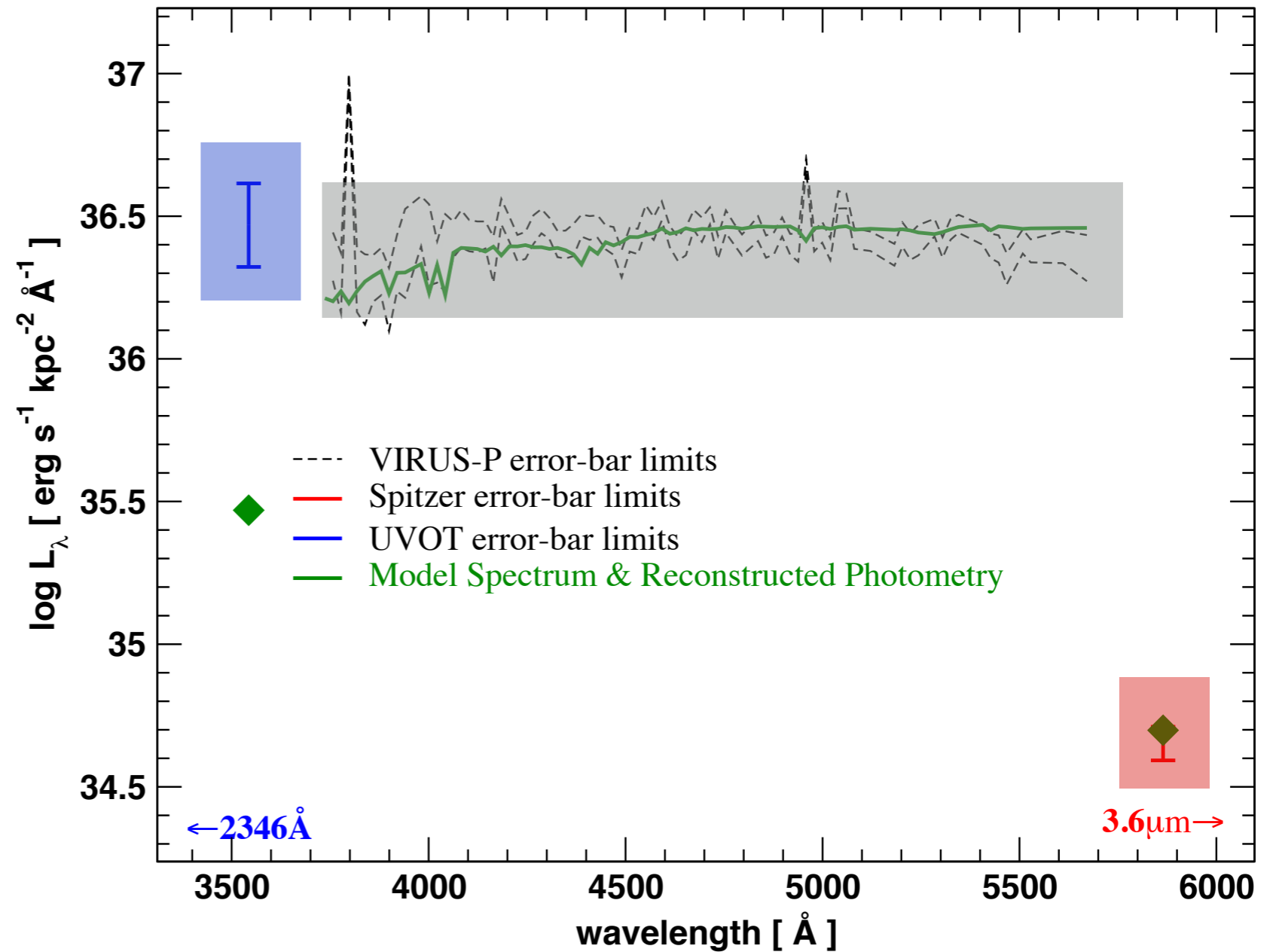
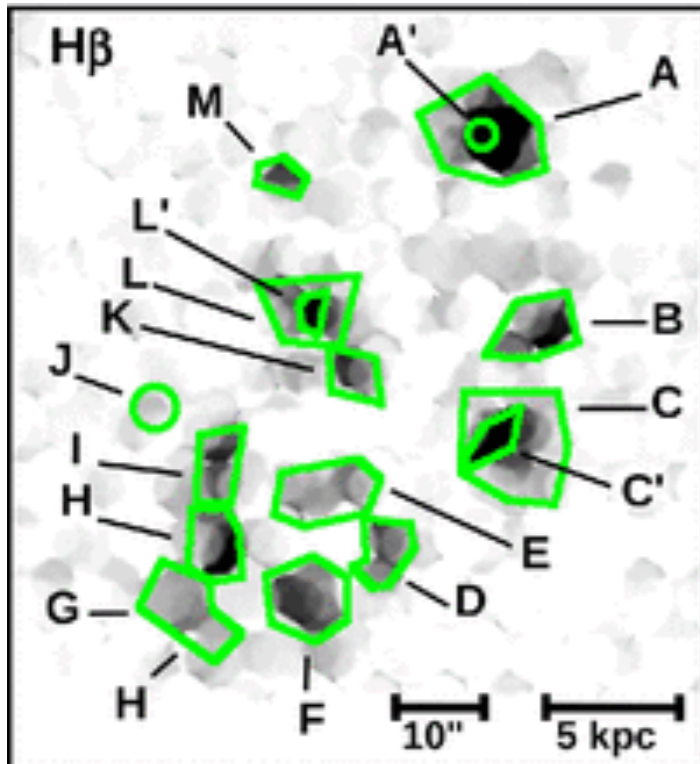
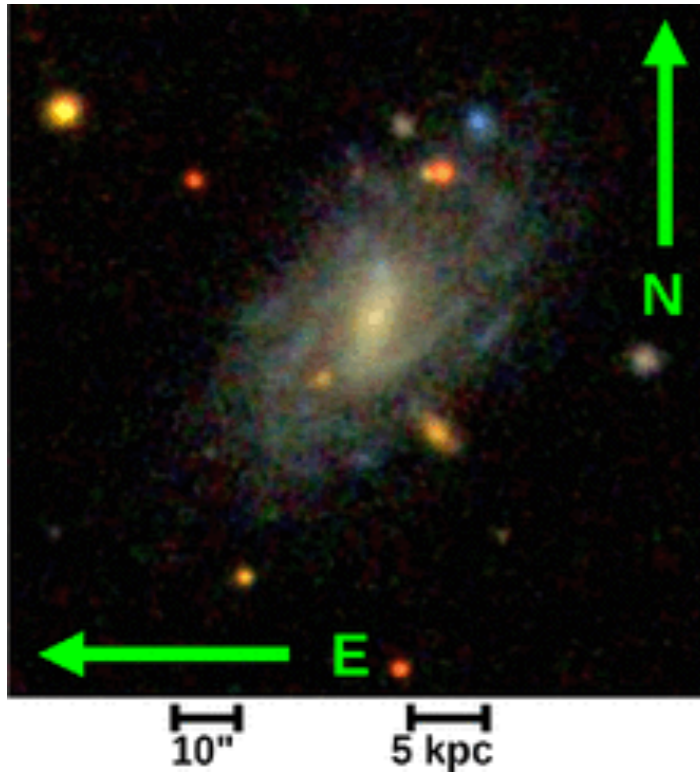


Young, Kuzio de Naray, & Wang (2015)

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How does an LSB form its stars?

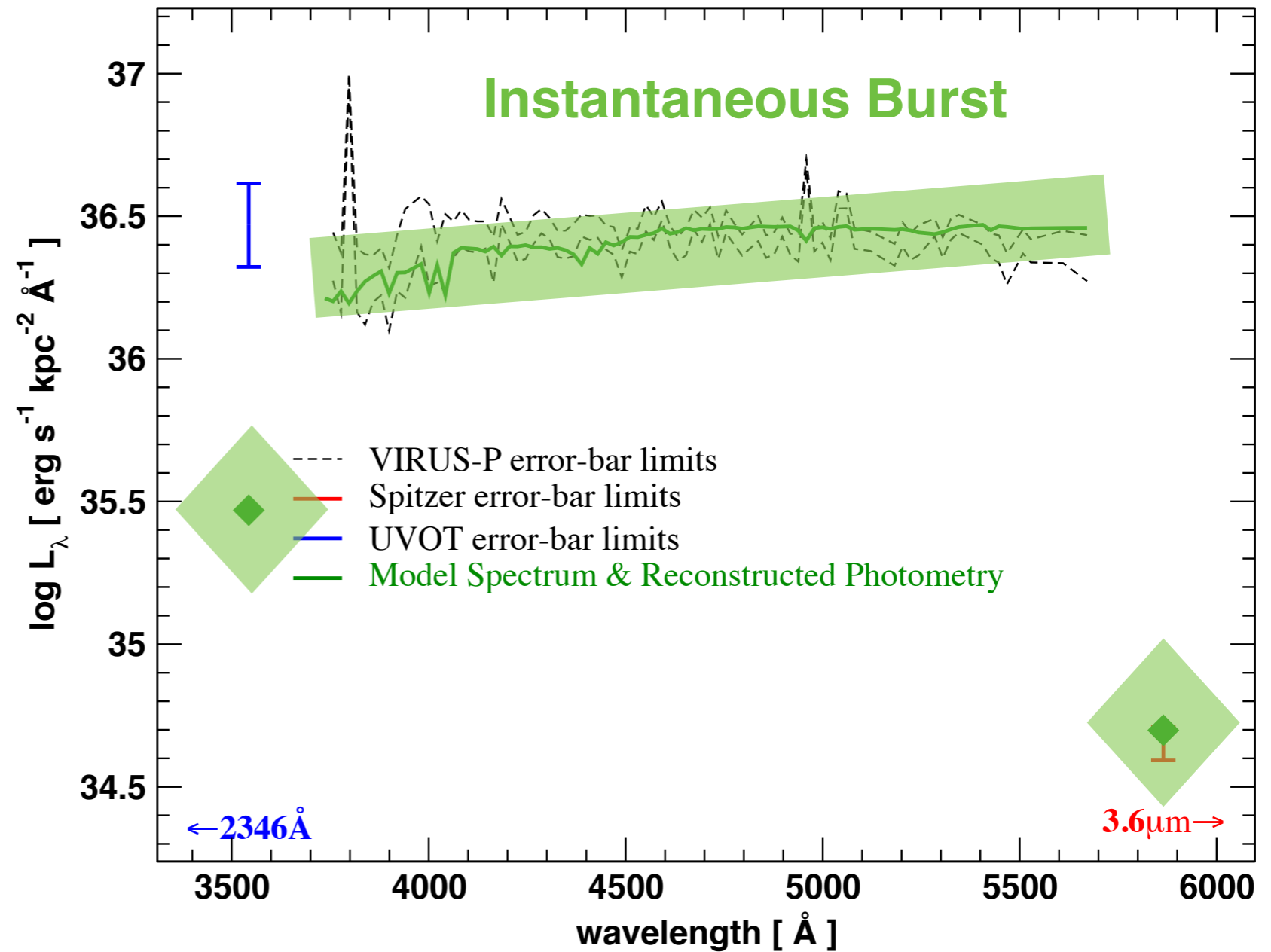
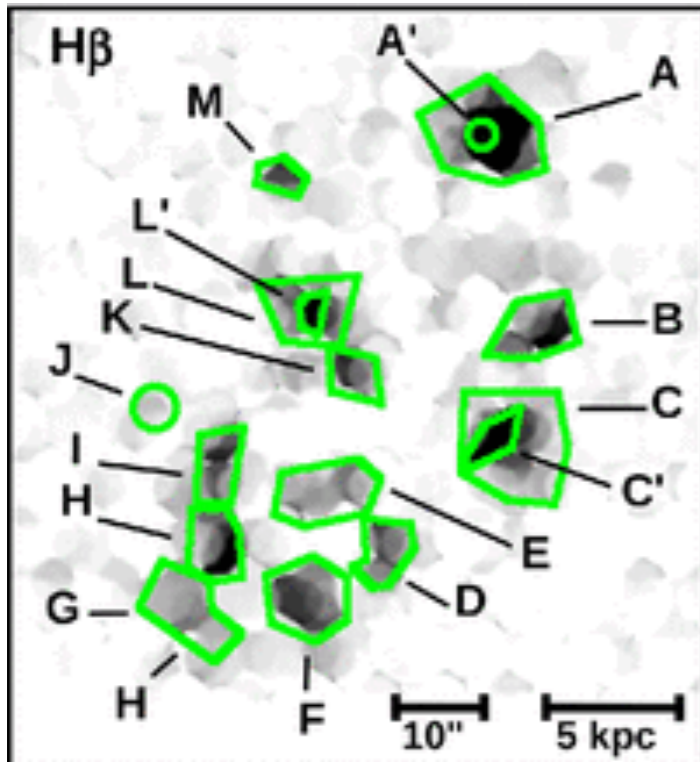
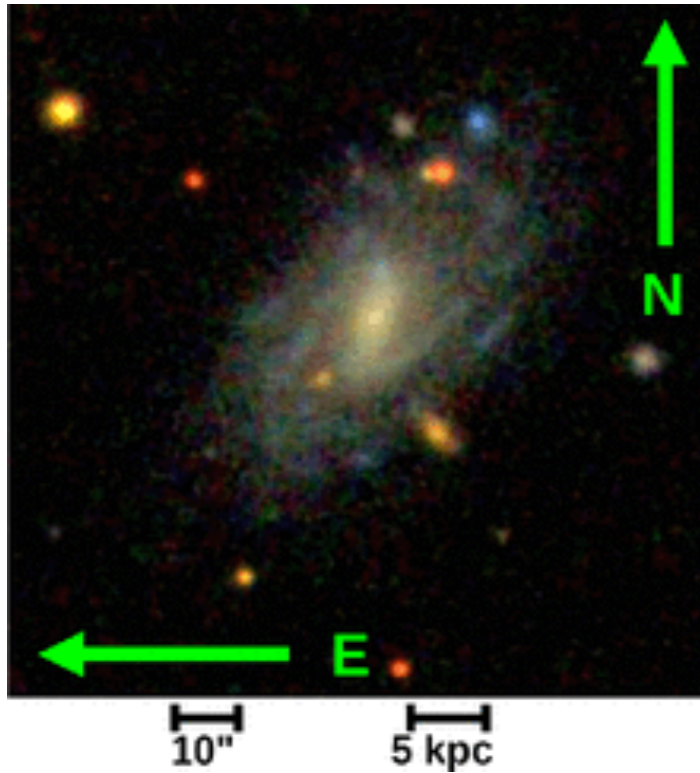
UGC 628



Young, Kuzio de Naray, & Wang (2015)

How does an LSB form its stars?

UGC 628

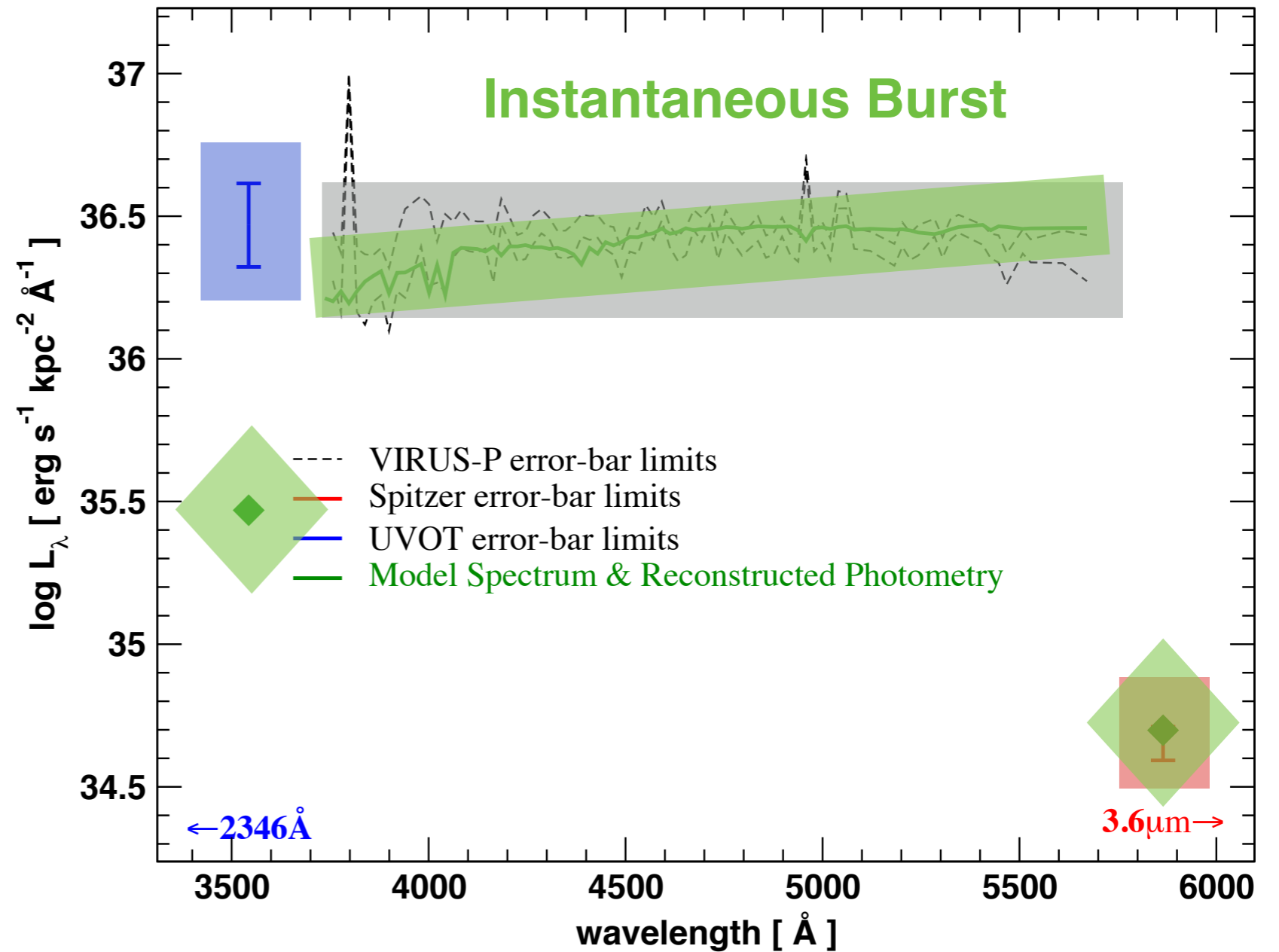
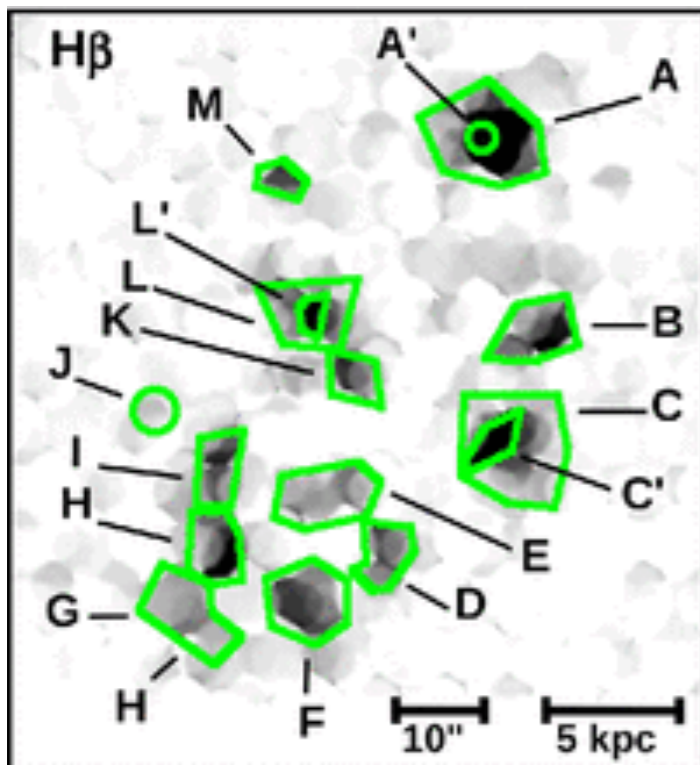
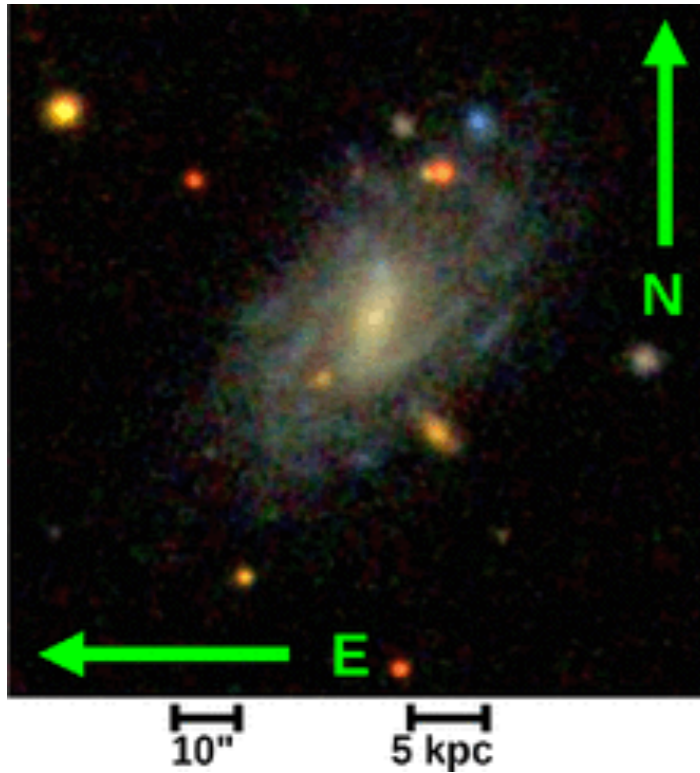


Young, Kuzio de Naray, & Wang (2015)

MUSCEL

How does an LSB form its stars?

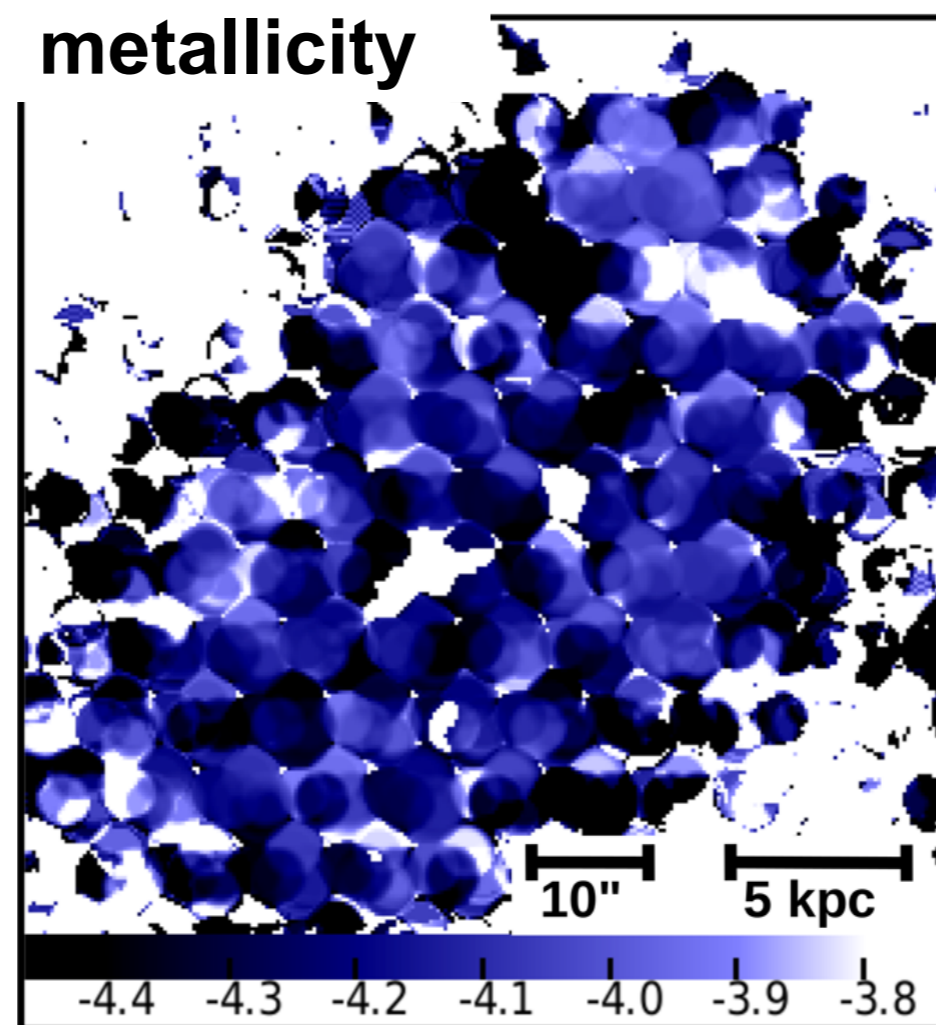
UGC 628



Young, Kuzio de Naray, & Wang (2015)

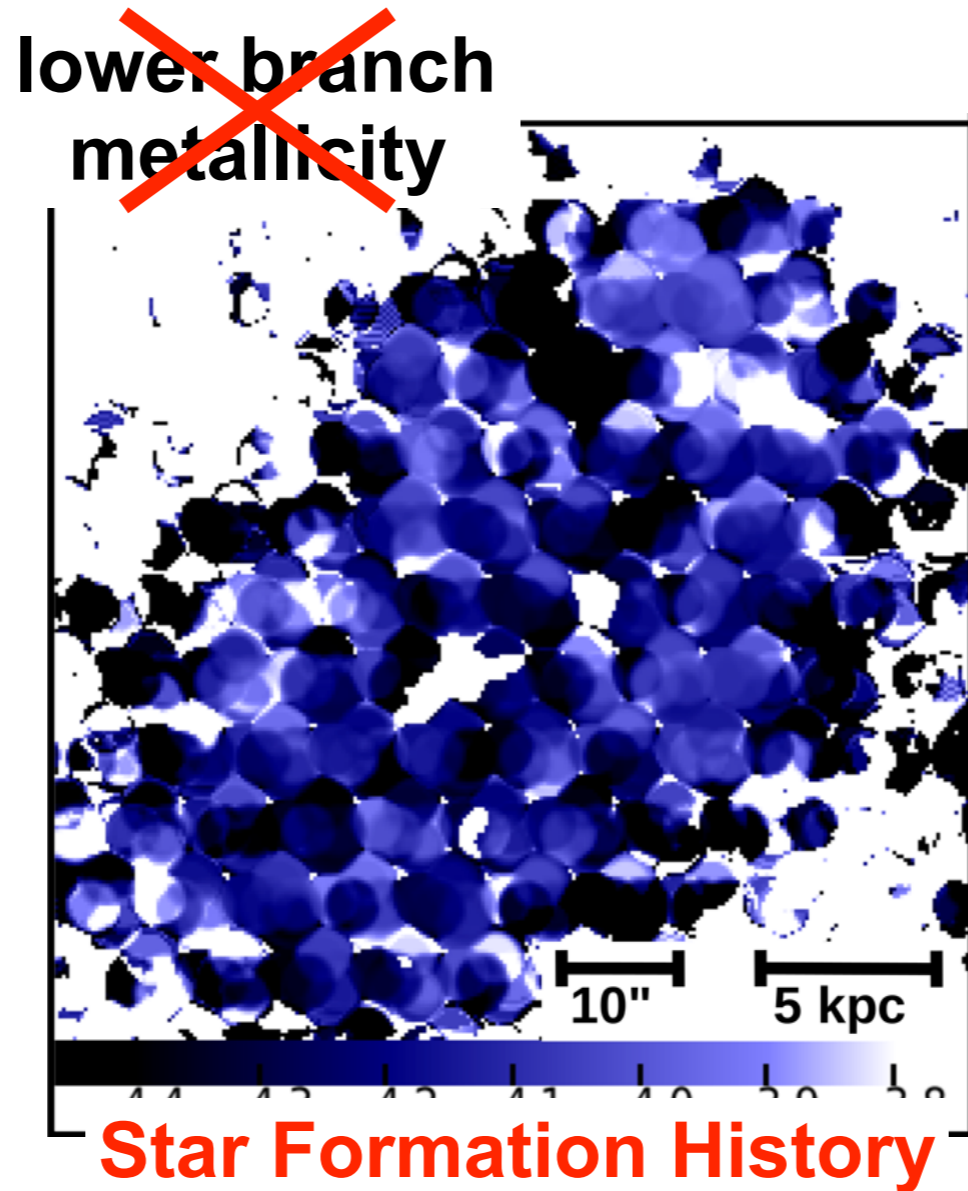
Map of the star formation history

**lower branch
metallicity**



Young, Kuzio de Naray, & Wang (2015)

Map of the star formation history



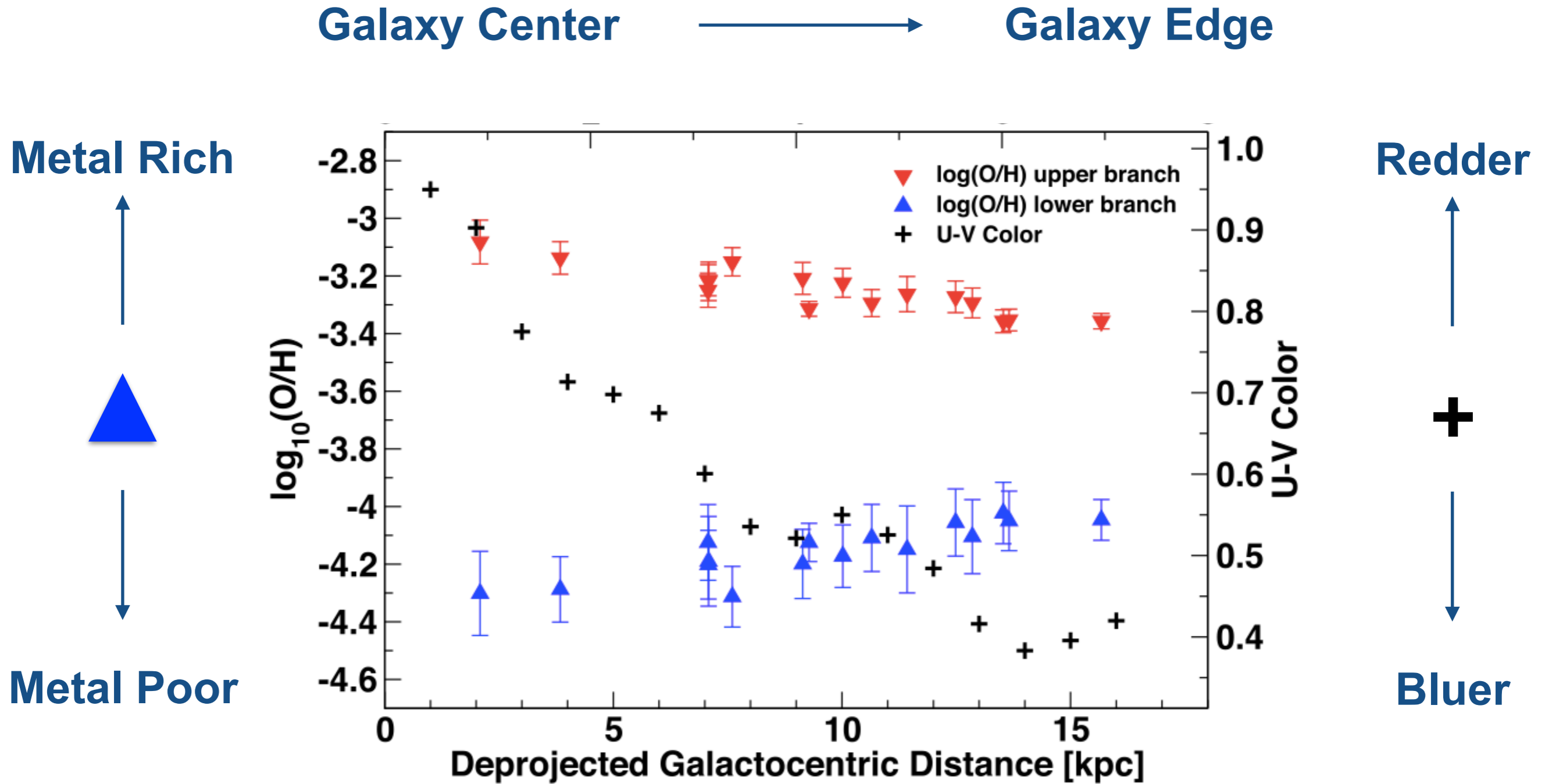
Constant SF

Burst & Quench Cycle

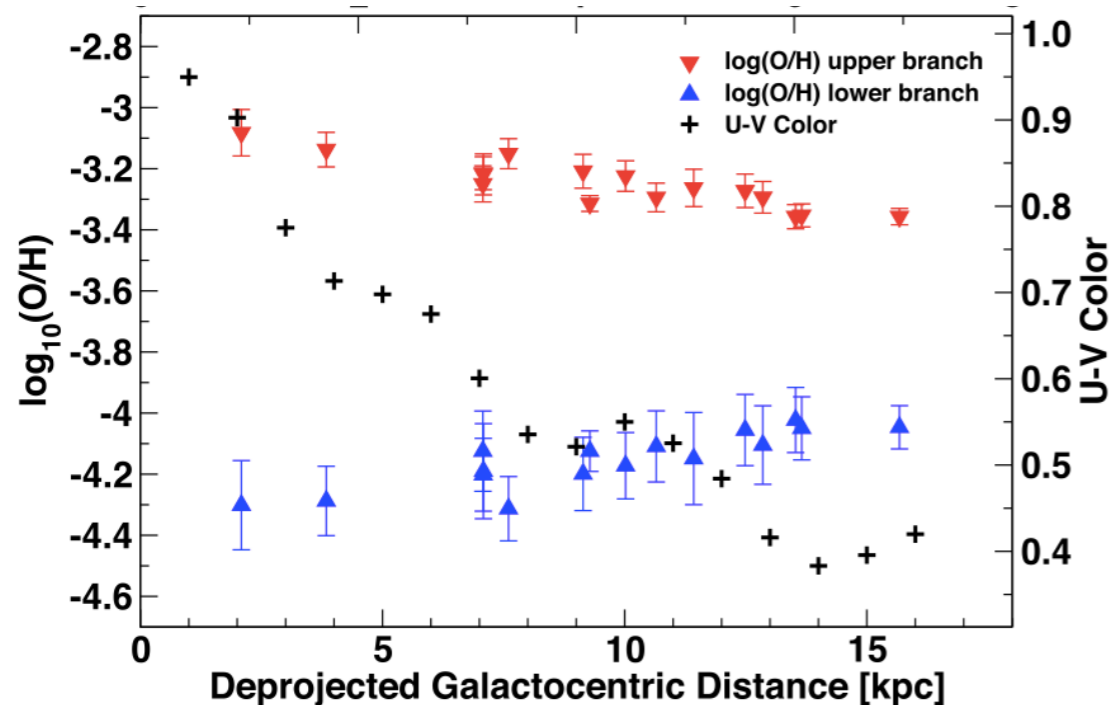
Exponential Decline

Single Burst

Where does an LSB form its stars?



Where does an LSB form its stars?



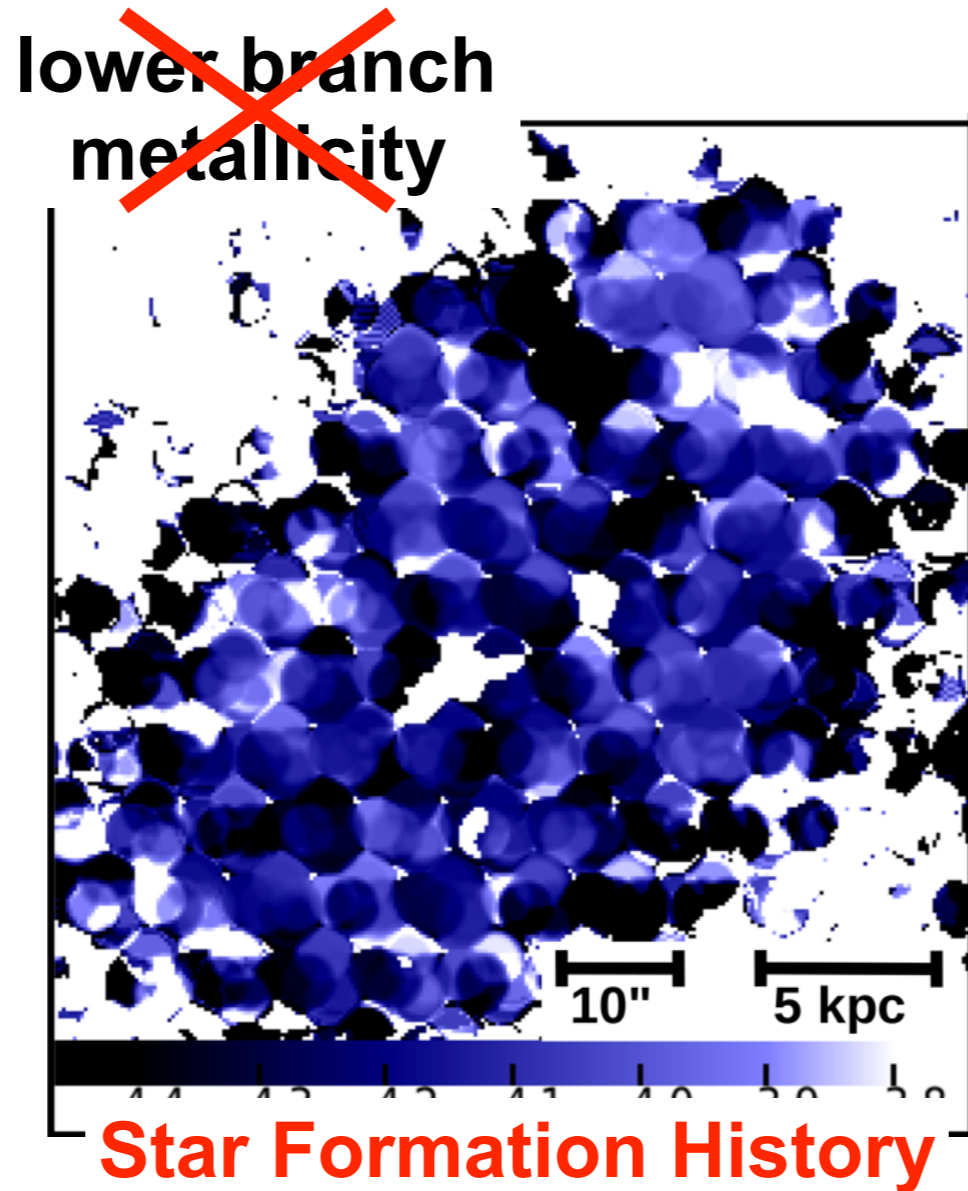
Young, Kuzio de Naray, & Wang (2015)

Localized bursts of star formation
 ↓
 flat abundance gradient or,
 in the case of very young galaxies,
 random radial fluctuations in abundance
 Vorobyov et al. (2009)

The observed gradient is also in stark contrast to the negative metallicity gradients typically found in HSB galaxies that signal inside-out star formation.

BUT, the color gradient *is* consistent with inside-out formation....

Map of the star formation history



Constant SF

Burst & Quench Cycle

Exponential Decline

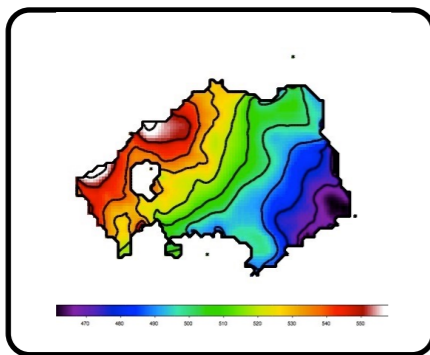
Single Burst

- Properties of Low Surface Brightness Galaxies (LSBs)



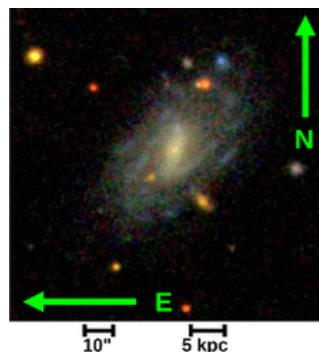
Blue, gas rich, metal-poor, dark matter-dominated

- Cosmological Significance



Cored halos despite global properties that suggest minimal interference by baryons

- The MUSCEL Program: Star Formation Histories



How and Where do LSBs form their stars?