Atomic Hydrogen in the Universe

B: Redshift 0

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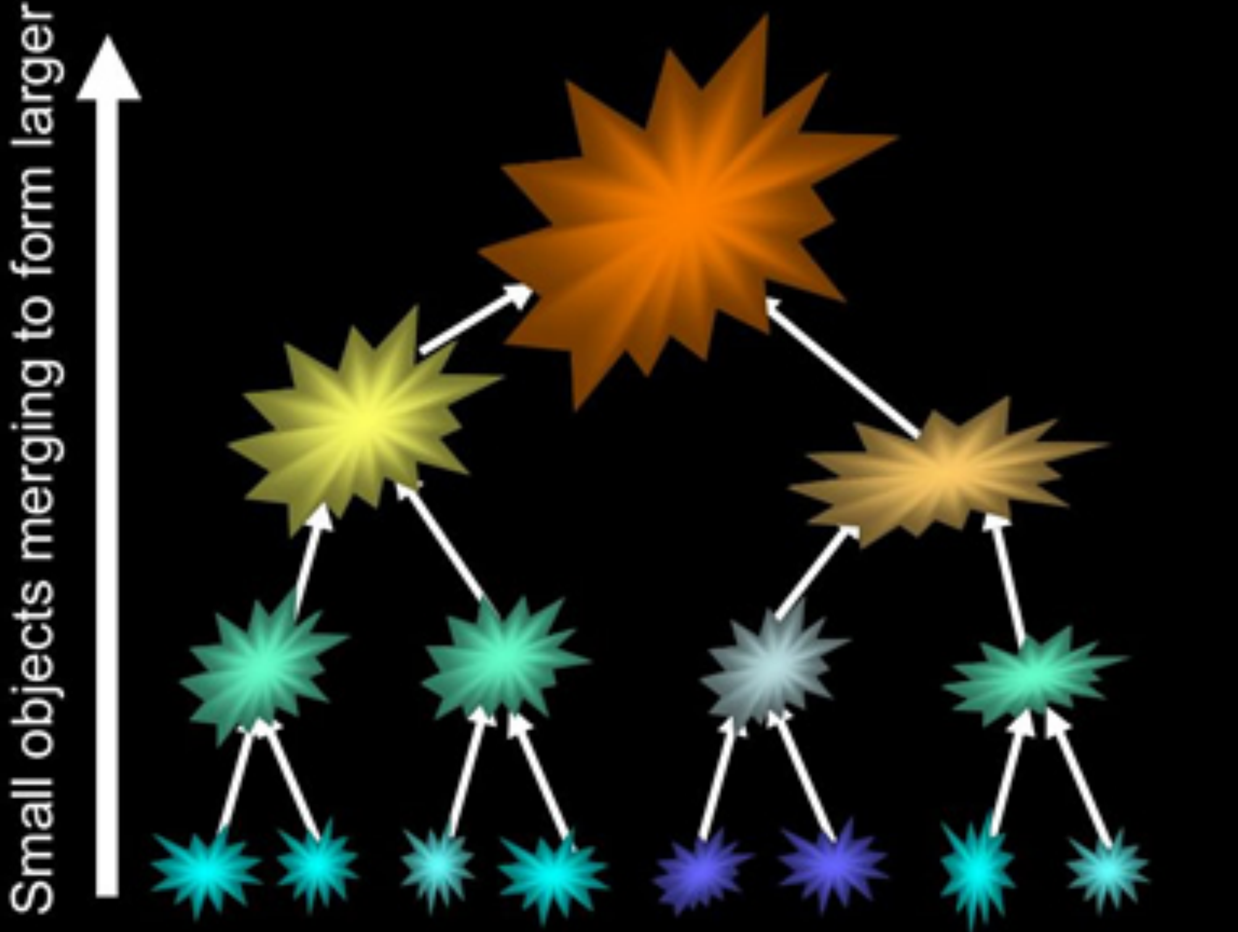
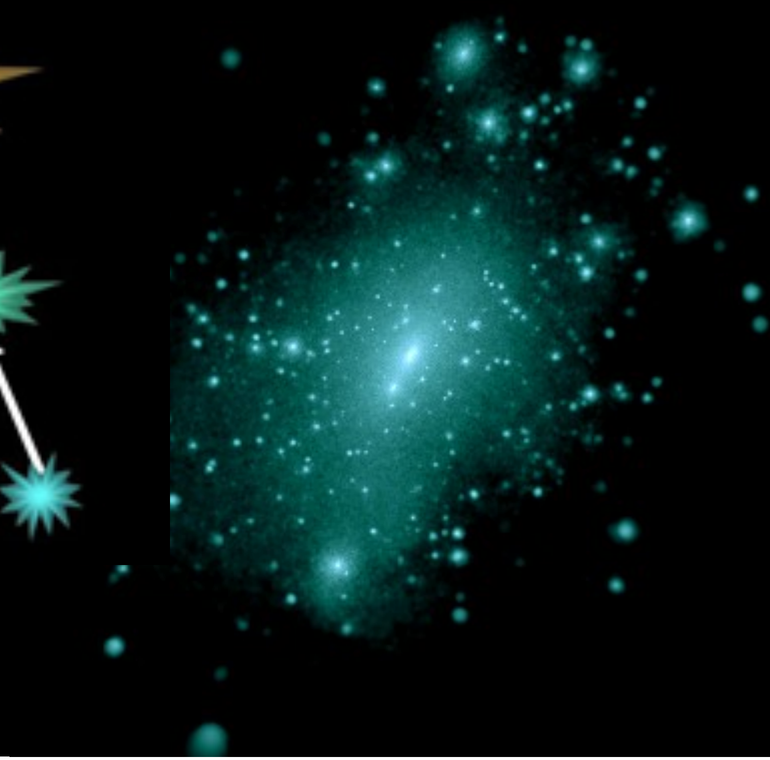
Near field cosmology from Dwarf Galaxies





Specific Questions

- Dark Matter
  - What is the ratio of dark to baryonic matter in dwarfs?
  - How is the dark matter distributed in dwarfs?
- Star formation
  - When does gas collapse to form stars?
- DLAs
  - How do the properties of dwarfs compare to that of DLAs?

The Faint Irregular Galaxy GMRT Survey: *FIGGS*

- GMRT observations of the neutral hydrogen (HI) in a well defined sample of nearby dwarf galaxies.
  - Selected from KK catalog

- 65 galaxies identified using the selection criteria

  $M_B > -14.5$, HI Flux > 1 Jykm/s,

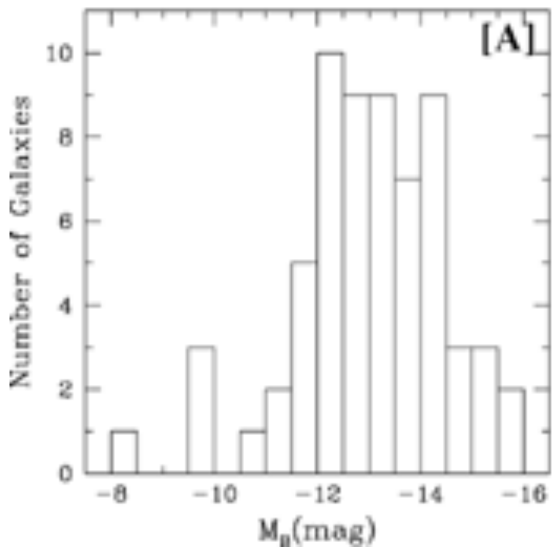
  $D_{opt} > 1'$, $\delta > -40^o$

- Accurate distances are known for a large fraction of the sample

  complimentary multi-wavelength data (HST, Ground based optical broad band, Hα, GALEX UV…)

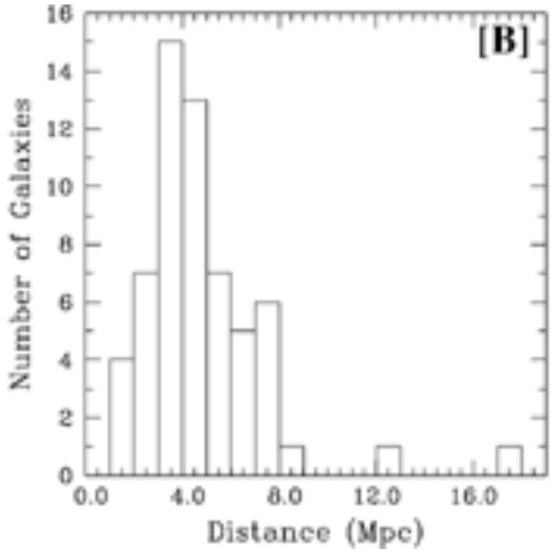
By far the largest interferometric HI study of dwarf galaxies

Properties of the FIGGS sample

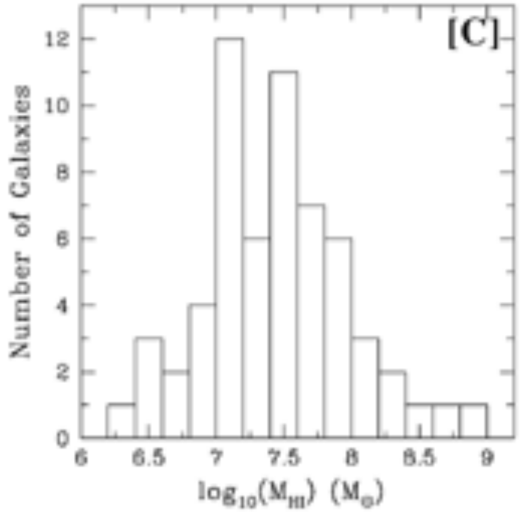


$\langle M_B \rangle \sim -13$

$\langle D \rangle \sim 4$Mpc



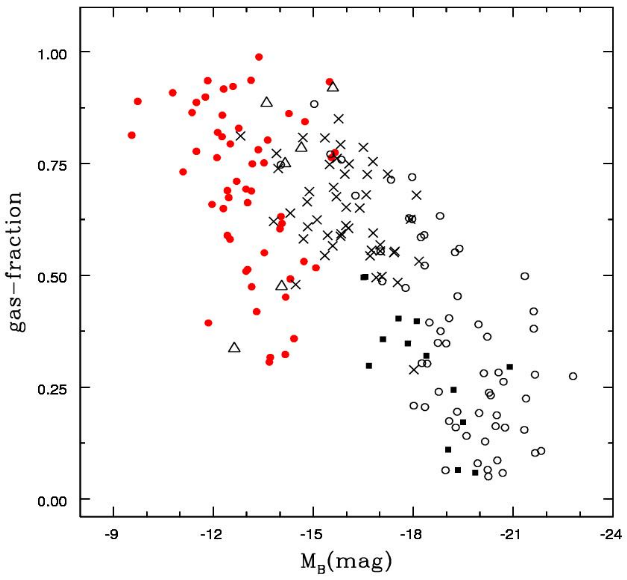
$\langle M_{HI} \rangle \sim 3 \times 10^7\ M_{sun}$



Begum et al. MNRAS,386,1667 (2008)

FIGGS vs. other large interferometric HI surveys

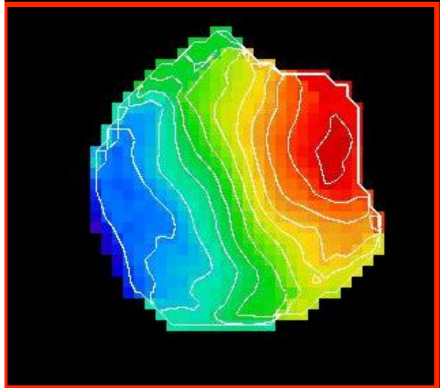
Begum et al. arXiv:0711.1807 (2008)

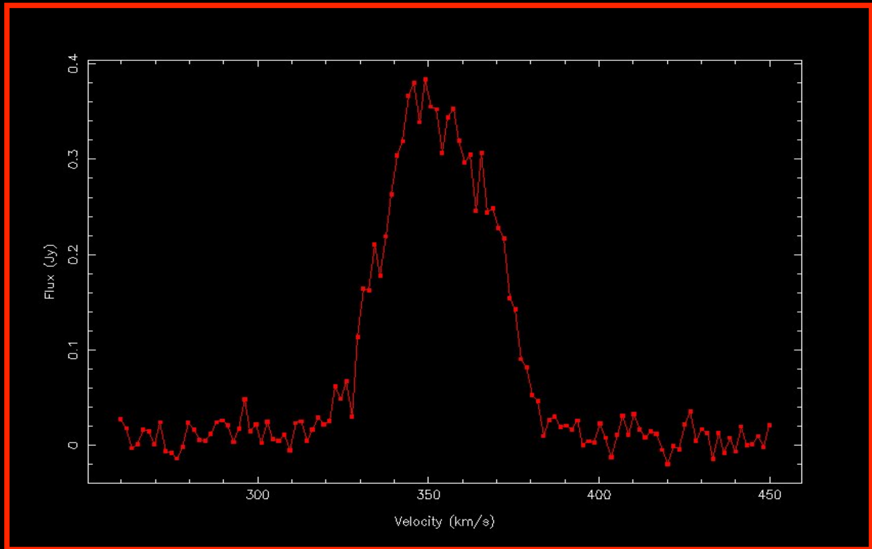


Average gas fraction of FIGGS galaxies < f_{gas} >~ 0.7

➔ *FIGGS probes the regime of faint, very low mass, gas rich galaxies extending the baseline for a comparative study of galaxy properties*

FIGGS Data Products





HI Spectrum

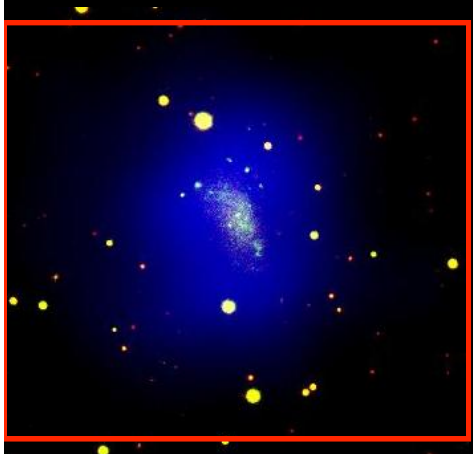
Velocity Field

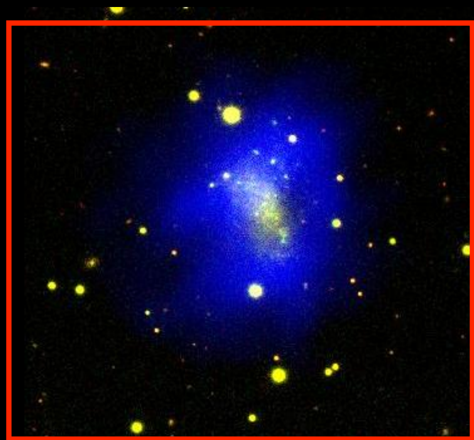
HI (28")

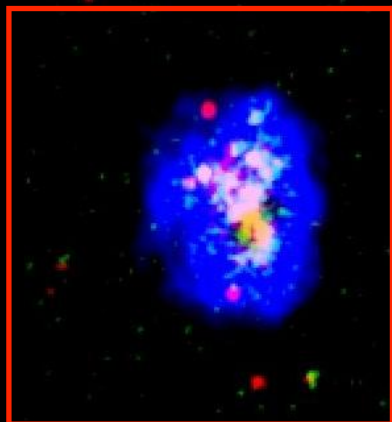
+

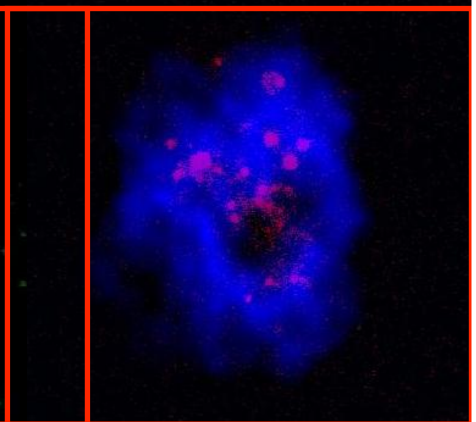
GALEX UV

CCD V + B



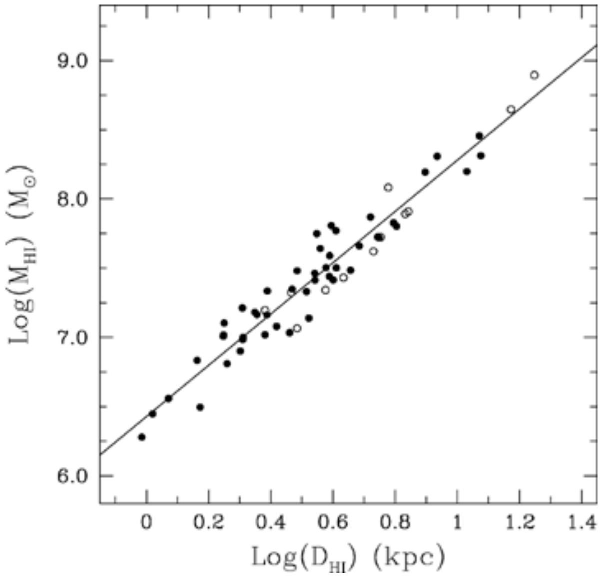


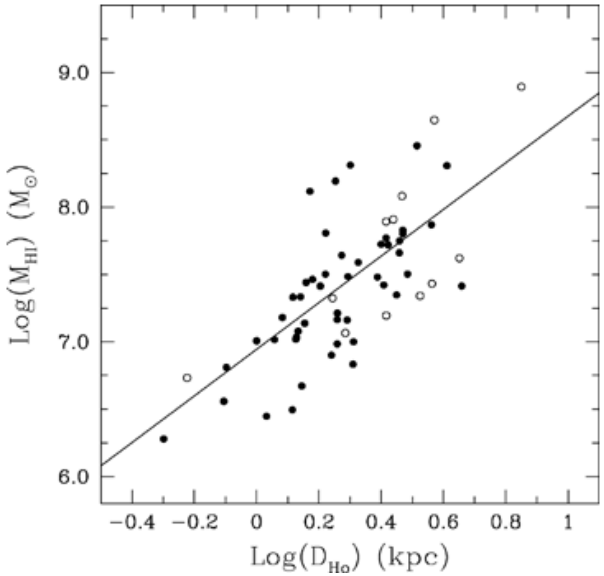




Scaling relations for gas disks

Begum et al. MNRAS,386,1667 (2008)



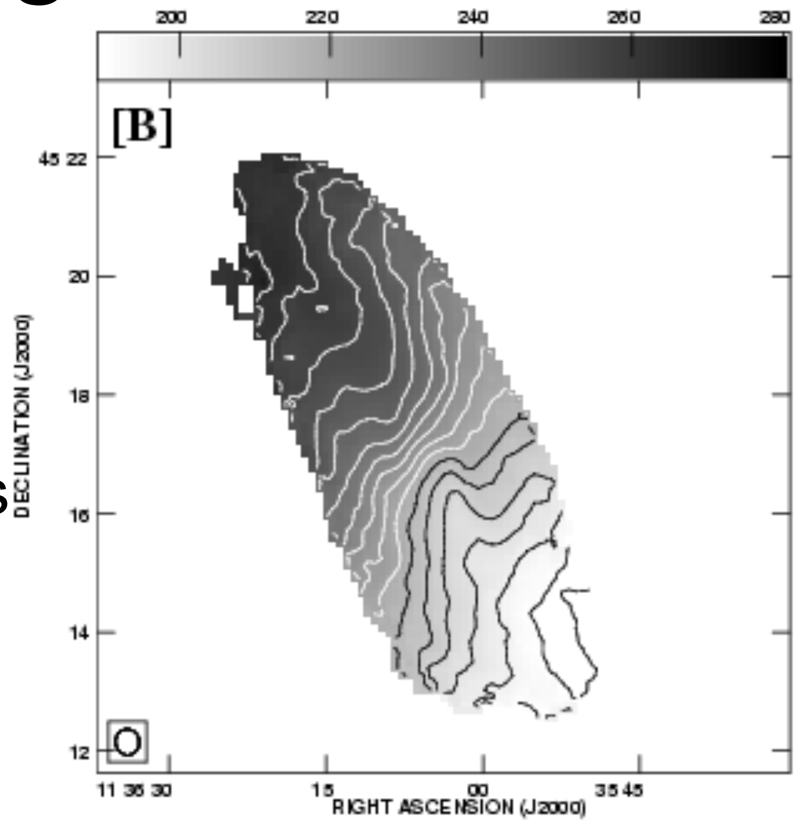


- HI mass correlates tightly with D_{HI} (1 Msun/pc^2)
- Relationship matches within error bars with that found for large spirals (Broeils & Rhee 1997)
  - Over 3 orders of magnitude of HI mass, disks of galaxies can be described as being drawn from a family with fixed average Σ_{HI}
- Correlation of HI mass with optical diameter weaker than for spirals
  - Coupling between gas and star formation in dwarfs not as tight as in spirals?

Dark Matter in Dwarf Galaxies

HI kinematics and rotation curves

- For gas in a rotating disk, the rotation speed and the inclination can be determined from the HI velocity field
- The total mass of the stars and gas can be obtained assuming
  - *A mass to light ratio for the stars*
  - *The HI is optically thin*
- In general the total mass exceeds the mass in stars & gas (“baryon mass”) by a factor of a few



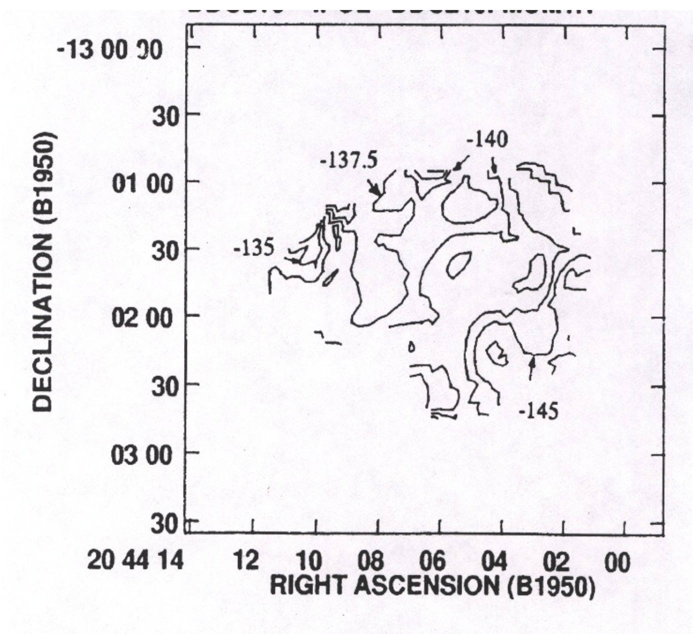
Begum et al. A&A 433, L1,

But do dwarf galaxies have rotating HI disks?

DDO 210 (M_B -10.6 mag)

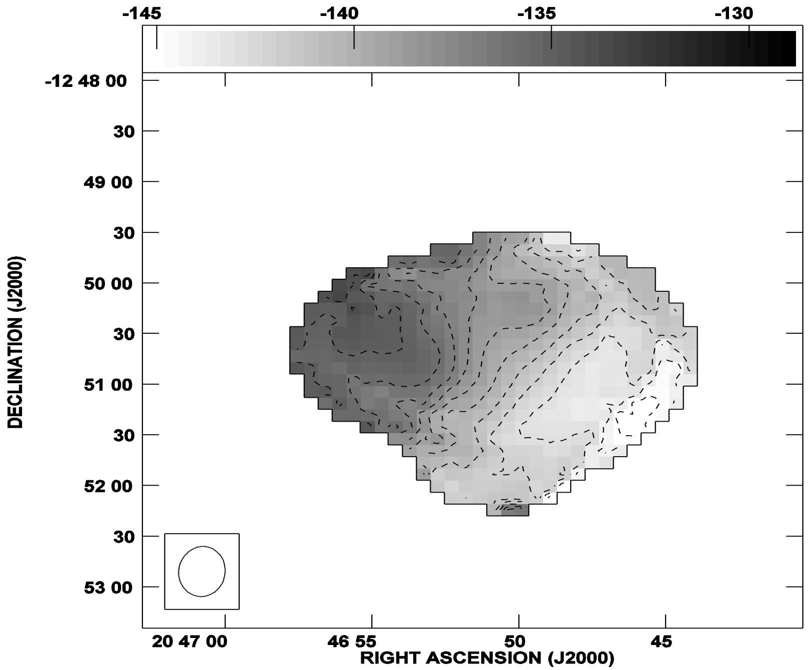
Is there an ordered component to the gas motions in the faintest dwarf galaxies?

$\Delta V \sim 6.5$ km/s (VLA Darray)



Lo et al. 1993 AJ, 106, 507

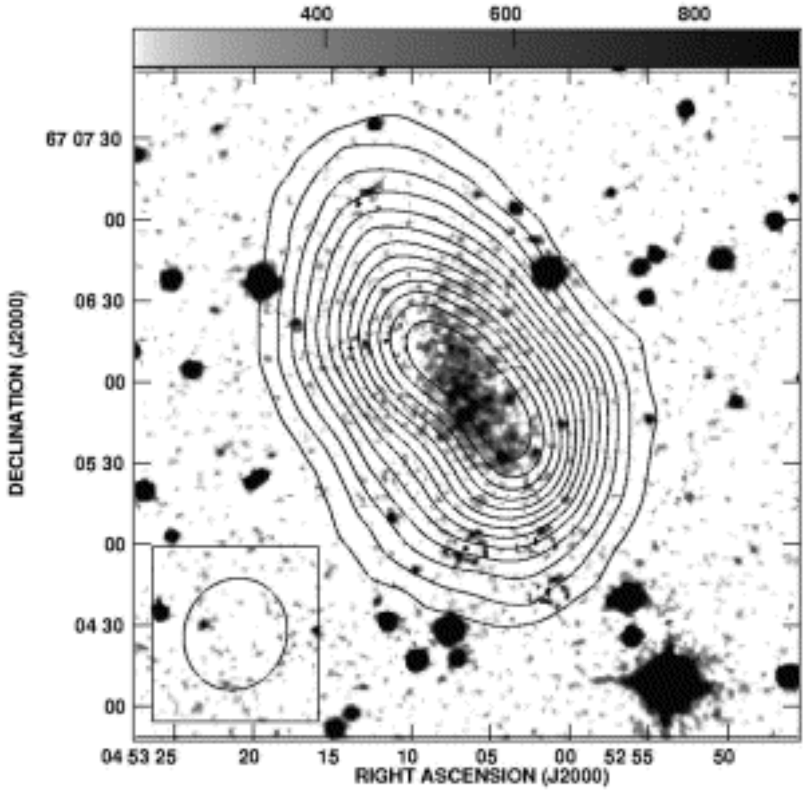
$\Delta V \sim 1.6$ km/s (GMRT)

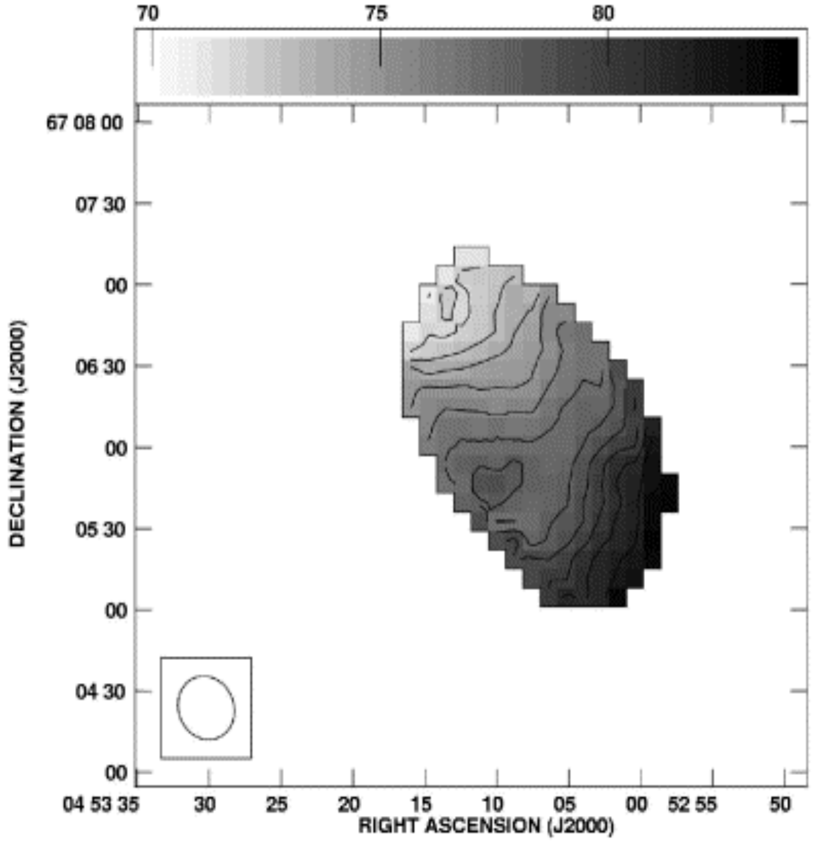


Begum & Chengalur 2004 A&A, 413, 525

HI in Cam B (M_B ~ -12.0)

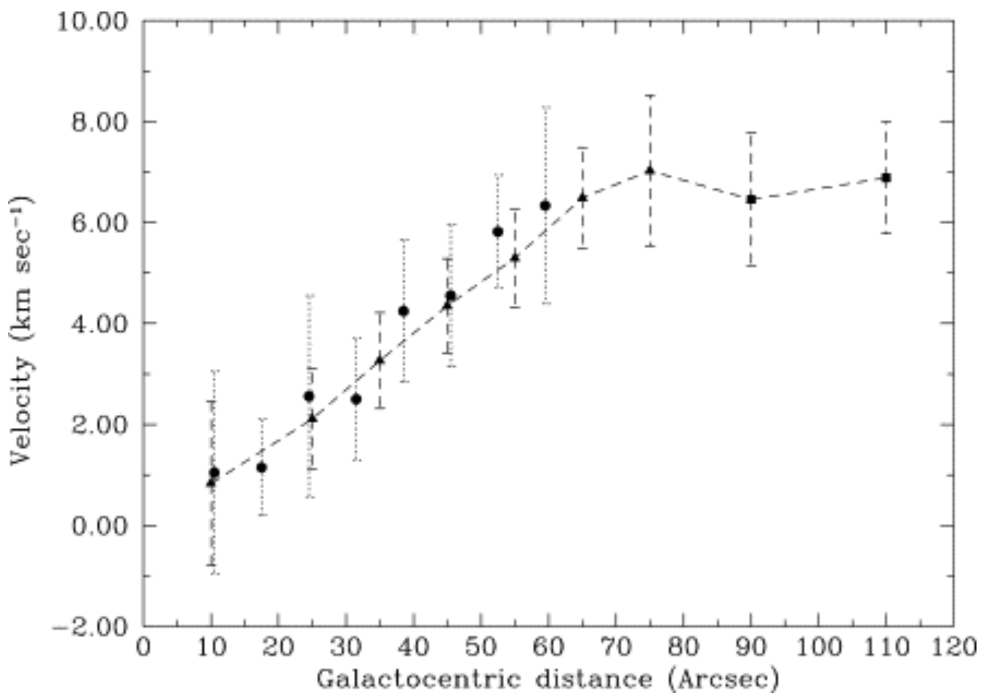
Begum, Chengalur & Hopp New Ast, 2003, 8, 267





Cam B : Rotation Curve

Begum et al. New Ast, 2003, 8, 267



- Peak rotation velocity comparable to velocity dispersion
- Important to correct for pressure support before determining the dynamical mass

Dark matter density profiles

•Traditionally used (phenomenological) dark halo models have constant density cores

$$\rho(r)=\rho_0/[1+(r/r_c)^2]$$

•Numerical simulations of hierarchical models predict cusped density core ("NFW") dark matter halos

$$\rho_{NFW}(r)=\rho_i / [(r/r_s)(1+r/r_s)^2]$$

(Navarro et al. 1997 ApJ 490 493)

•Dwarf galaxies are well suited to distinguish between these models
- •Larger galaxies have substantial mass in stars in the central regions, uncertain M/L ratio of the stars leads to ambiguities

Mass model for CamB

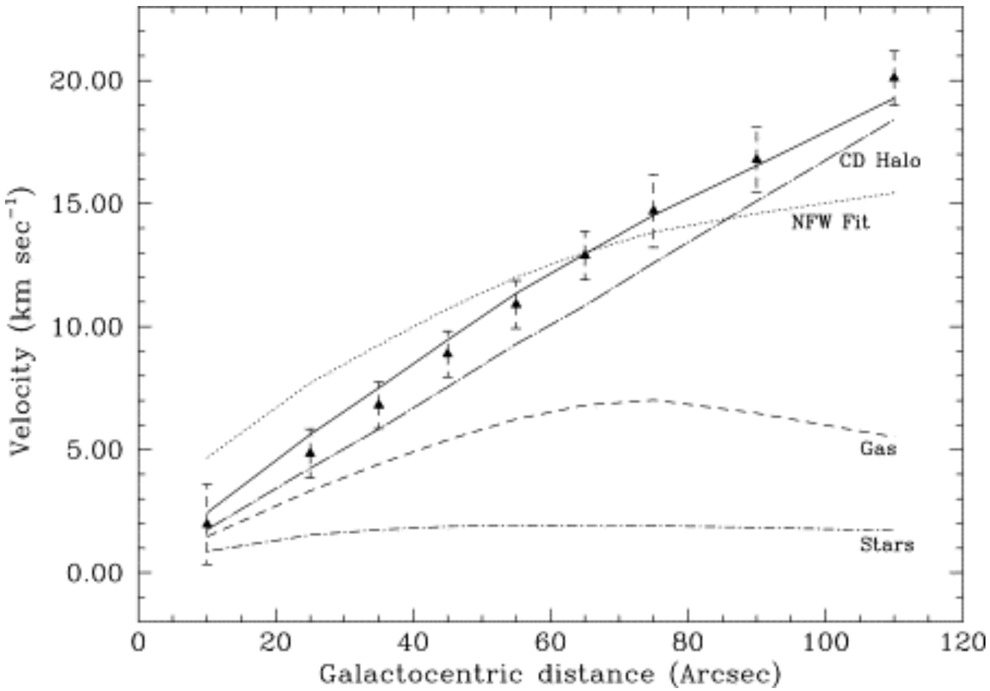
Constant density core provides a good fit, but "NFW" type halo does not

» NWF halos in general do not provide a good fit to our sample galaxies.

Feedback from star formation could lead to decrease in baryonic (and dark matter) density in the central regions

Governato et al. (2010)

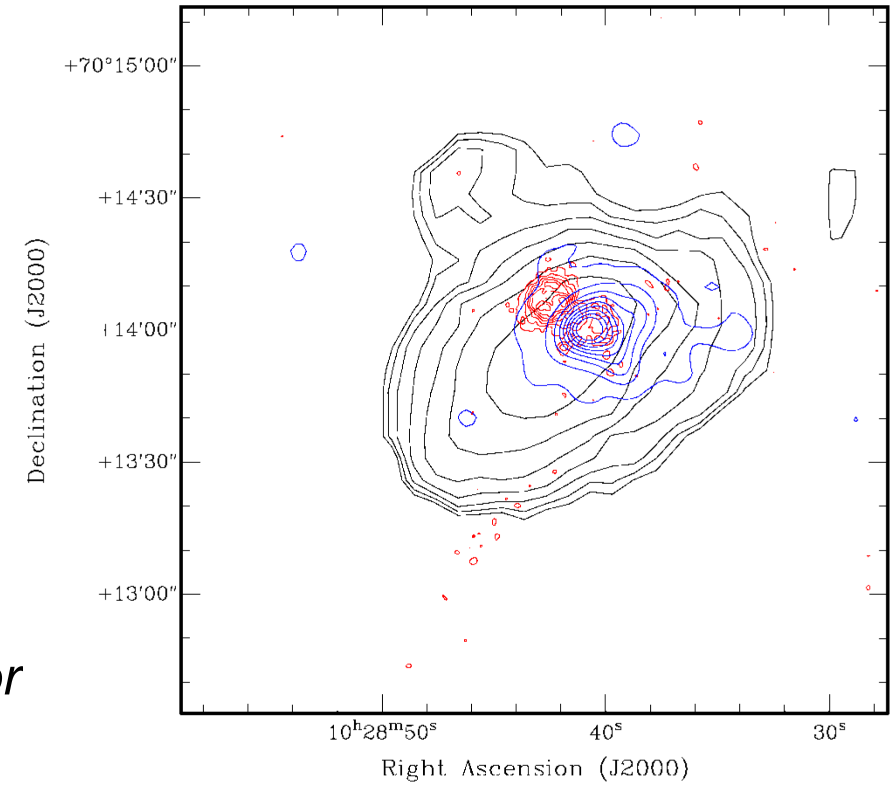
Begum et al. New Ast, 2003, 8, 267



Feedback in the smallest BCDs

- D1028+66 is one of the smallest BCDs known
  - $M_{HI} \sim 10^6 M_{sun}$
- Undergoing an intense burst of starformation
  - *Excellent candidate to look for feedback into the ISM*
- Clear evidence for outflow of HI associated with star formation
  - *One of the most direct evidence for such feedback seen in atomic HI*

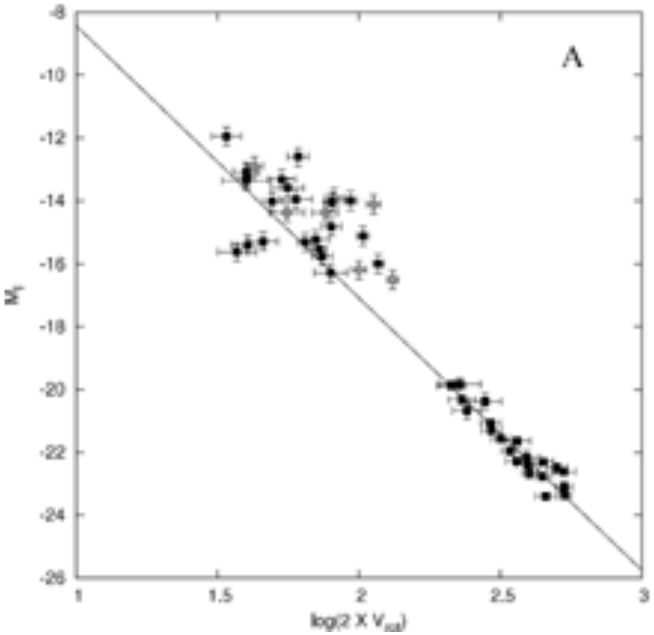
Roychowdhury et al., 2011: MNRAS, 414, L55



TF relations

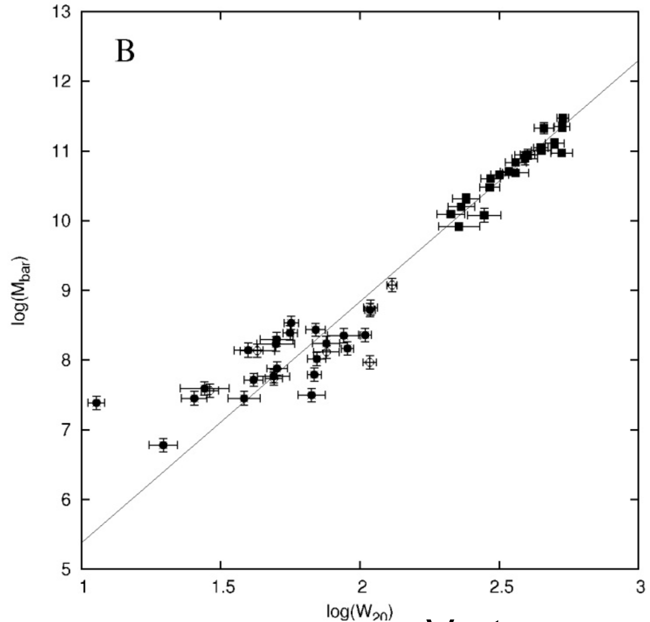
Begum et al., MNRAS,386,138*, (2008)*

I band Magnitude



Vrot

Baryonic Mass



Vrot

*Compare FIGGS sample with HST large spiral Sample (both samples have **accurate distances**)*

FIGGS galaxies are slightly under luminous for their velocity width, but have about the right amount of baryons

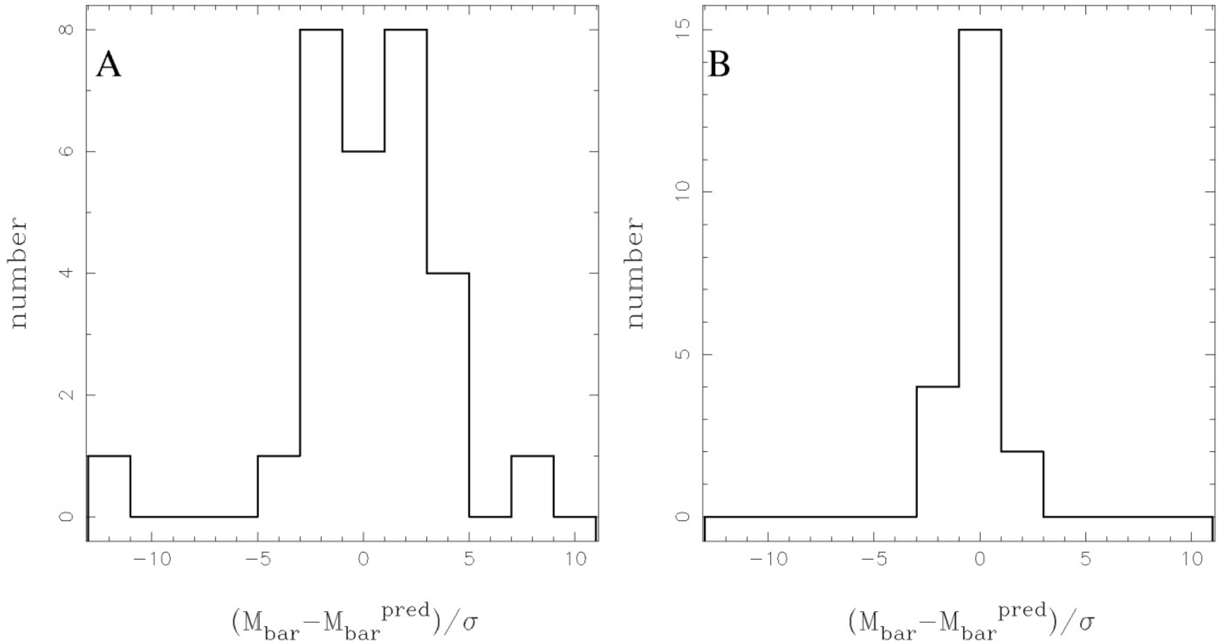
Dwarf galaxies have been less efficient at converting gas into stars

Scatter about the TF

Begum et al., MNRAS,386,138*, (2008)*

FIGGS

HST

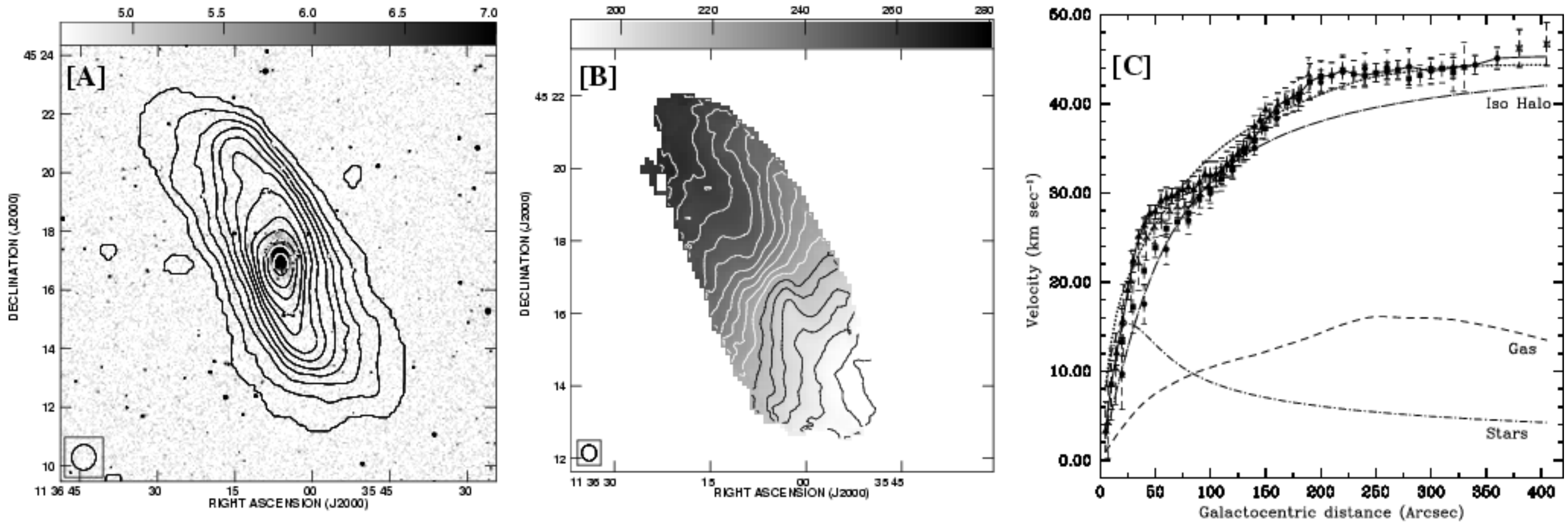


The scatter about the BTF/TF is much larger for the FIGGS sample as compared to the spiral sample

*Star formation efficiency is **lower** and shows **more scatter** in dwarf galaxies as compared to large spirals*

Dark matter in NGC 3741

Begum et al. A&A 433, L1, (2005)

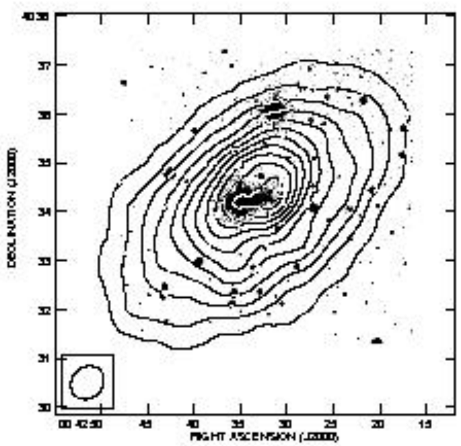


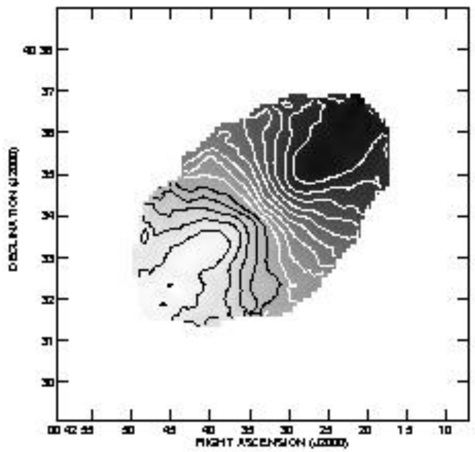
Rotation curve measured to ~ 38 optical disk scalelengths

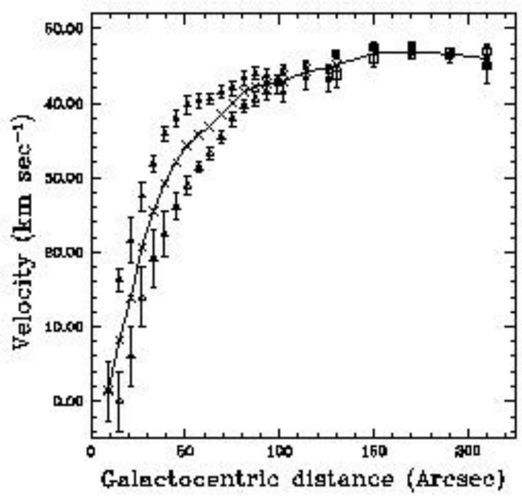
M_{dyn}/L_B ~ 107 – one of the "darkest" galaxies known.

HI in AND IV

Chengalur et al. arXiv:0711.2153 (2008)







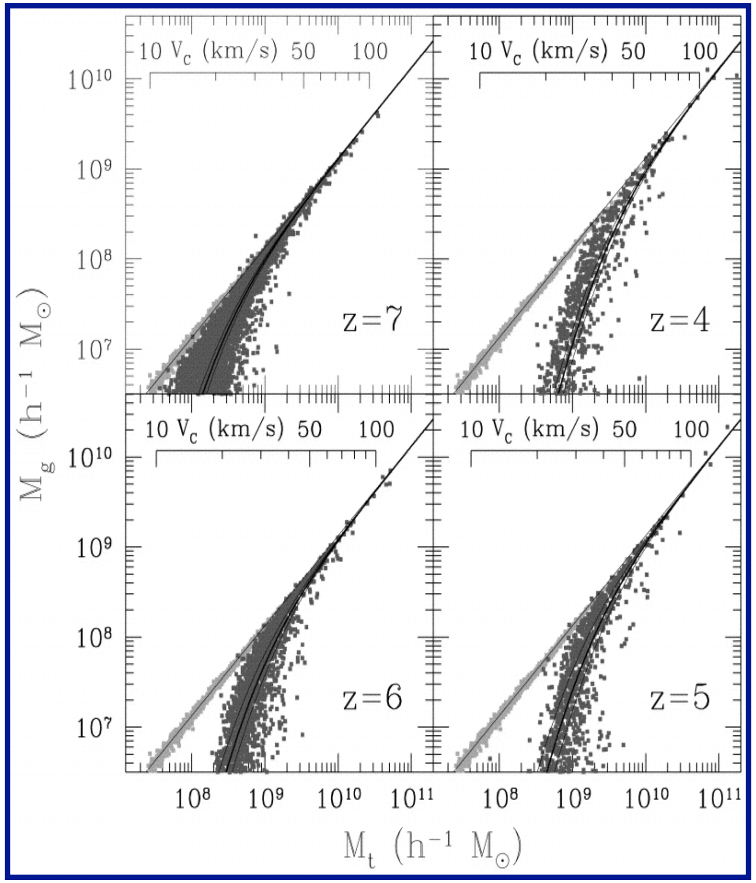
HI disk extends out to more than 6 Holmberg radii

Mass/Luminosity ~ 237 !

Do “dark” galaxies also have anomalously low baryon fractions?

Baryon fraction in dwarf galaxies

- Small halos are less efficient at capturing baryons
  - hot baryons escape during the epoch of reionization
  - Feed back from star formation drives baryons out of shallow dwarf galaxy potential wells
- Baryon fraction expected to vary inversely with galaxy mass



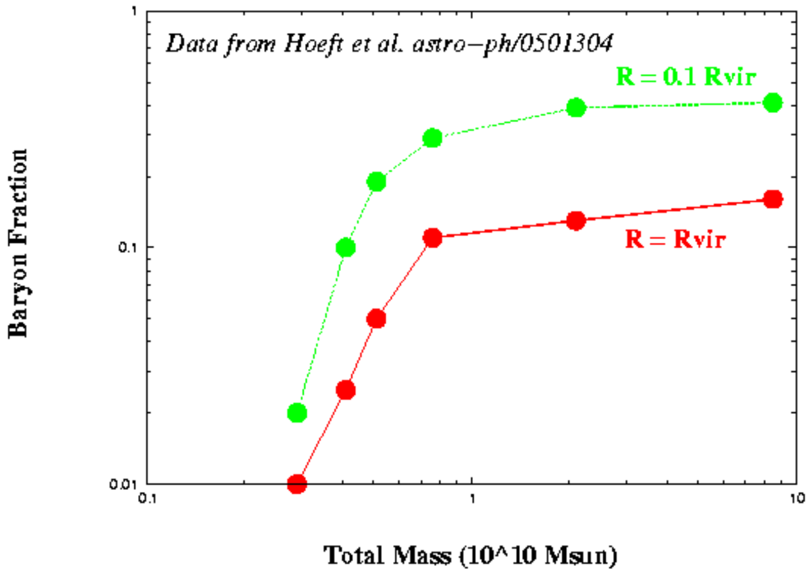
Gnedin ApJ 542, 535, (2000)

Baryon fraction: Theory vs Observation

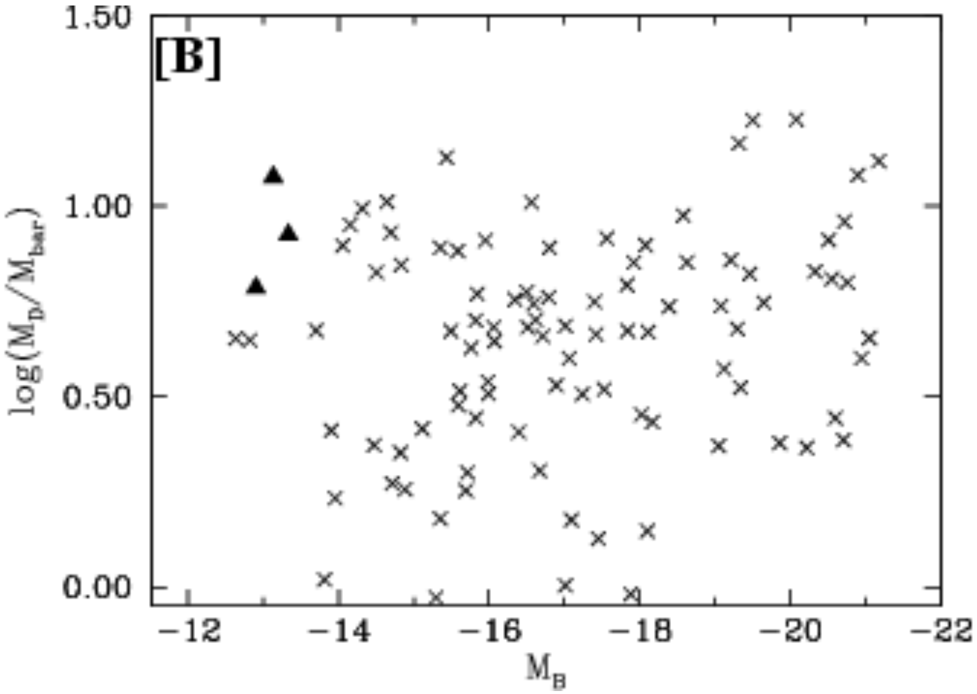
- Since baryons cool and collect at the center of the halo, the baryon fraction increases with decreasing radius

- Simulations give baryon fraction as measured at the virial radius
  - Observations determine the baryon fraction up to the last measured point of the rotation curve

- Simulations *suggest* that the baryon fraction within the last measured point of the rotation curve should vary inversely with halo mass



Baryon fraction in gas rich galaxies



Large scatter in baryon fraction for all galaxies

Dwarf galaxies don't have systematically smaller baryon fractions

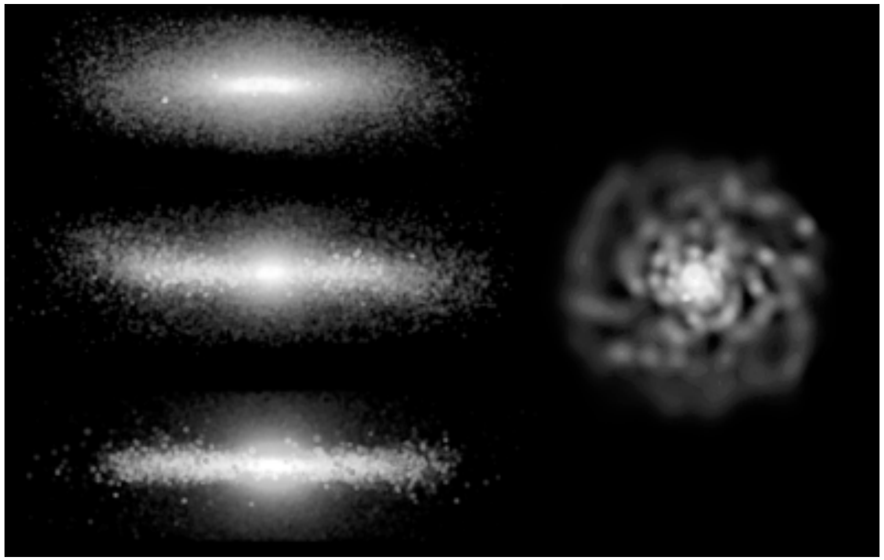
NGC 3741 got its fair share of baryons – it just couldn't convert them to stars!

Star formation in extremely faint dwarfs

Star formation recipes and galaxy formation simulations

- Numerical simulations accurately follow the gravity driven merger of the dark matter halos
- Physics of the baryonic material is complex and poorly understood
  - heating/cooling, collapse to form stars, feed back from star formation
- Most simulations of galaxy formation use “recipes” for following the star formation process
  - Recipes are generally derived from observations of nearby galaxies.

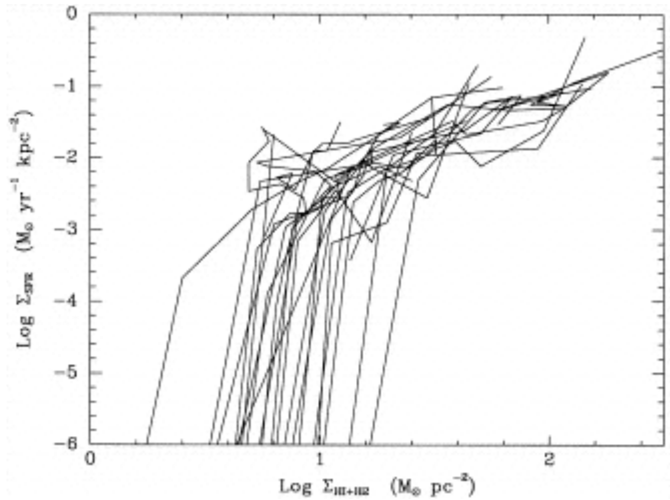
Numerical simulations of galaxy formation in LCDM cosmology are able to produce realistic disk galaxies. While the gravity driven infall and merger are accurately computed, star formation and feedback are incorporated largely via “recipes” (e.g. Fabio et al. MNRAS 2007, 374,1479)



Star formation recipes for spirals and starburst galaxies

(Kennicutt ApJ 498, 541, 1998)

- Star formation occurs only above a fixed threshold gas column density
  - Star formation rates determined from Hα observations
  - Related to instabilities in thin disks?
    (Safronov AnAp 23, 979, 1960;Toomre ApJ 139, 1217, 1964)



Above this threshold column density, the star formation rate has a power law dependence on the gas column density

$$\Sigma_{SFR} = (2.5 \pm 0.7)10^{-4}(\Sigma_{gas}/1M_{sun}pc^{-2})^{1.4\pm0.15}M_{sun}yr^{-1}kpc^{-2}$$

(Kennicutt ApJ 498, 541, 1998)

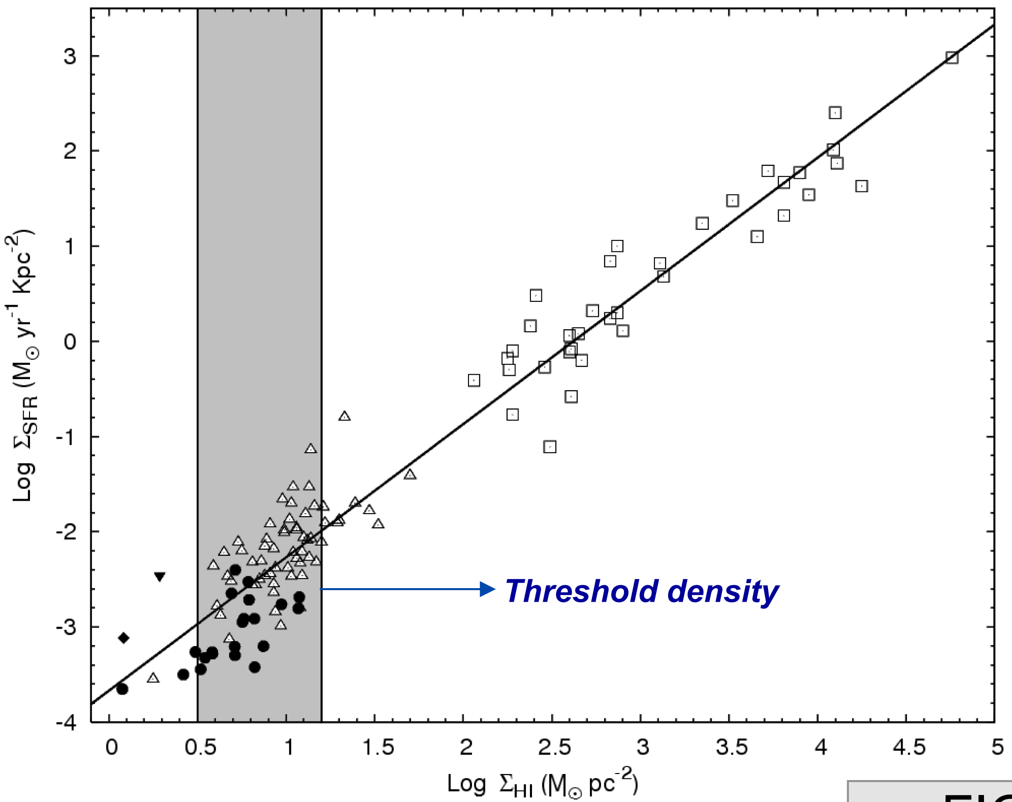
Unclear if recipes derived from large spirals apply to dwarf ("primordial") galaxies

Roychwodhury et al. 2009: MNRAS, 397, 1435

Star formation in FIGGS Dwarfs: The GALEX view

- Subsample of 23 galaxies with GALEX FUV data
    - HI images at a resolution of ~ 400pc were made for all of these galaxies.
- SFR derived from the GALEX FUV images using standard formulae from Kennicutt (1998)
- Pixel by pixel comparison of the HI column density and GALEX SFR done
    - – Linear resolution of both GALEX and HI images were made identical, i.e. 400 pc

GLOBAL STAR FORMATION



Hollow symbols – data for spiral and ultraluminous starbursts from Kennicutt(1989,1998)

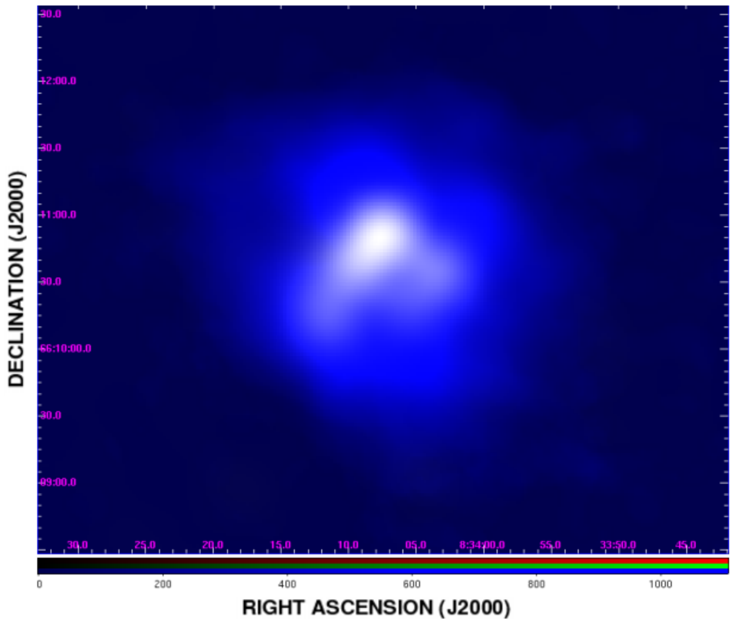
Filled symbols – FIGGS sample

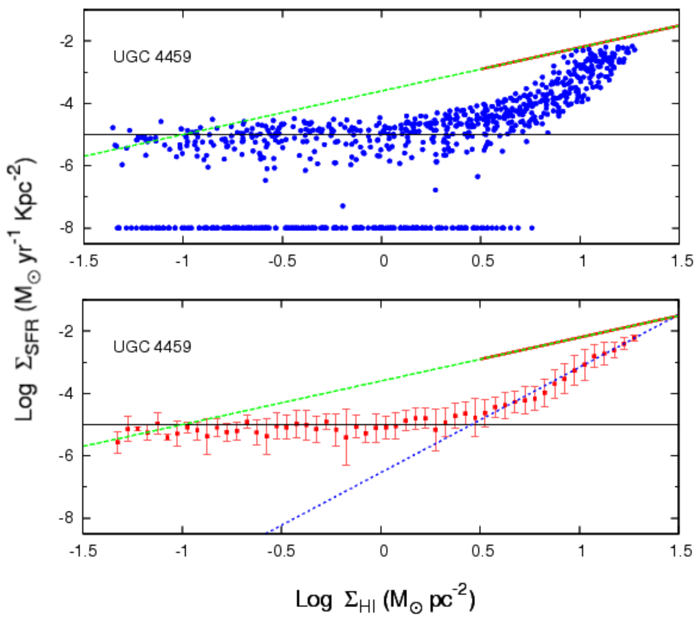
Roychwodhury et al. 2009: MNRAS, 397, 1435

FIGGS galaxies lie near or below the “threshold density” and have star formation somewhat lower than predicted by the Global Schmidt Law

Roychwodhury et al. 2009: MNRAS, 397, 1435

Pixel by Pixel Correlation

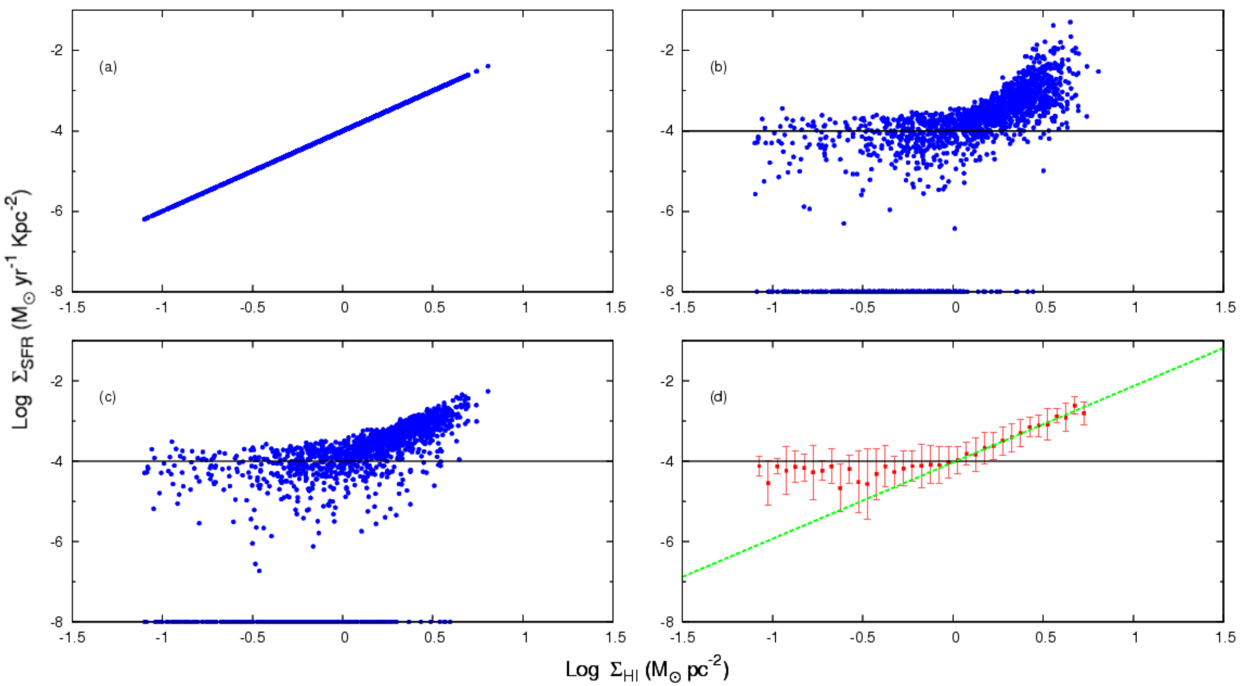




- Several galaxies show "Schmidt Law" type behaviour but the slope is
  - *Generally much steeper than 1.4*
  - *Power law continues below the canonical threshold until one reaches the sensitivity limit of the GALEX data.*
  - *Similar to results found in outskirts of disk galaxies (e.g. Boissier et al. 2007, Bigiel et al. 2008)*

Roychwodhury et al. 2009: MNRAS, 397, 1435

Simulated Pixel by Pixel Correlation for a power law + noise (but no threshold)



Observations are consistent with no threshold, and a stochastic star formation law.

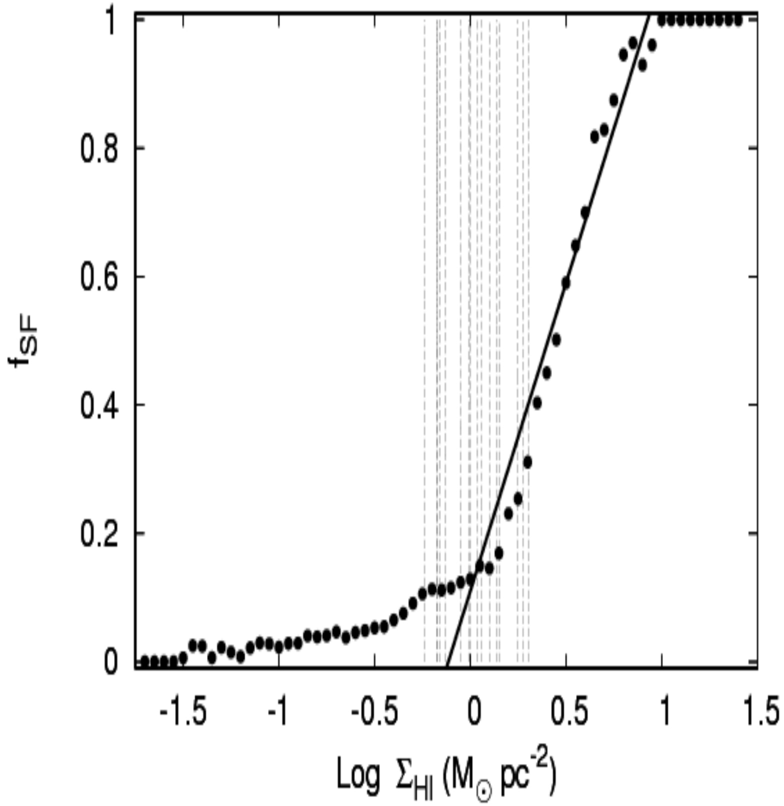
- First panel shows the underlying power law $\Sigma_{SFR}=A\Sigma_{gas}^{\alpha}$
- Second panel shows the pixel-by pixel correlation after addition of noise and allowing α to vary
  - Horizontal line shows the noise level
- Third panel is for fixed α but power law coefficient A varying
- Simulation with varying A, and *no threshold*, matches the observations well

Stochastic star formation

Roychowdhury et al., 2011: MNRAS, 414, L55

All gas above a column density of 10 $M_{\odot}$ pc^{-2} has associated star formation

below 10 $M_{\odot}$ pc^{-2} the fraction of gas with associated star formation decreases linearly



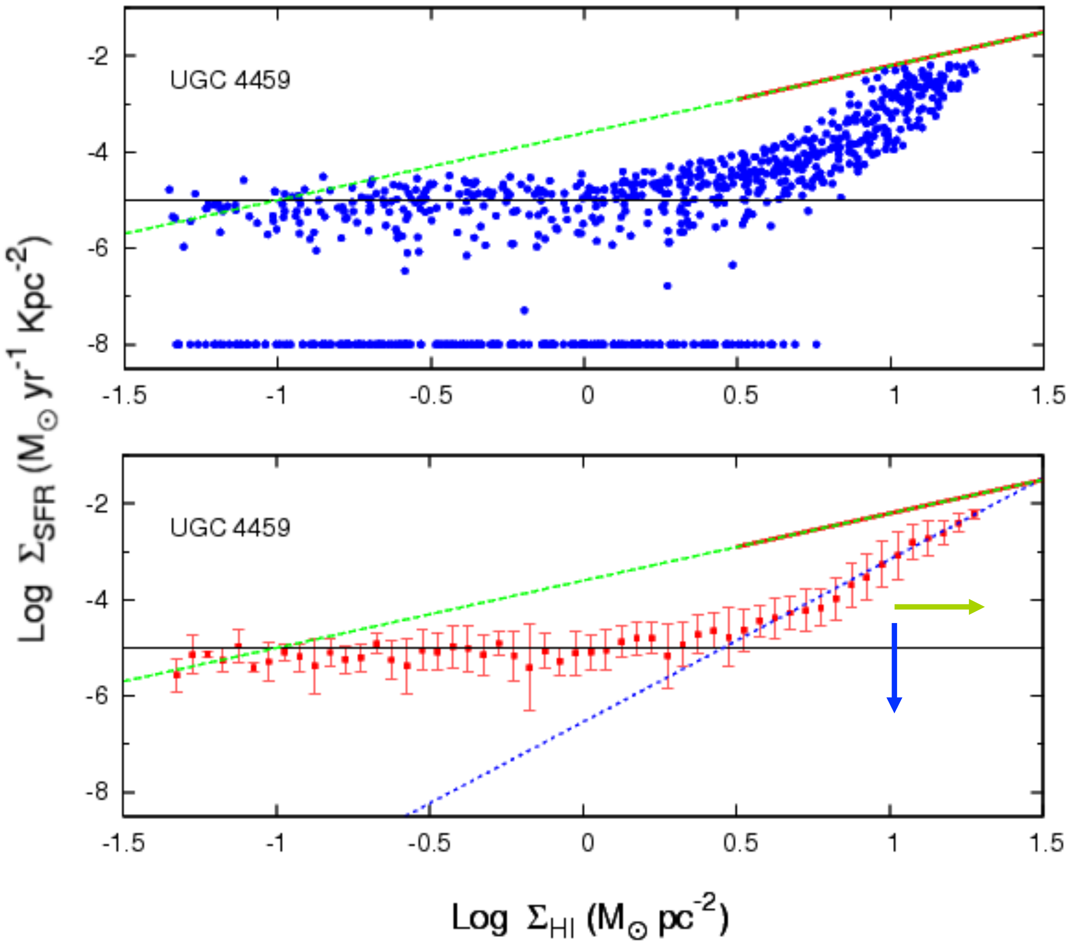
Roychwodhury et al. 2009: MNRAS, 397, 1435

FIGGS SFR Law: Caveats

- SFR recipes are generally derived using total (i.e. atomic + molecular gas densities)
- Here we are using only the atomic gas density
  - CO is notoriously difficult to detect in small dwarfs
- SFR derived from the UV flux assuming standard Salpeter IMF and solar metalicity
  - Dwarf galaxies have low metalicities → SFR derived from UV flux is probably an overestimate

Caveat's Revisited

Roychwodhury et al. 2009: MNRAS, 397, 1435



Correcting the SFR calibration for low metalicity will increase the deviation from the "Kennicutt-Schmidt" SFR law

Correcting Σ_{gas} for possible molecular gas content will have the same effect

To bring agreement with the "Kennicutt-Schmidt" law one will need truncation of the IMF at the upper end.

Formation of massive stars

- FUV emission
  - “low” mass ($M > 3\ M_{sun}$) stars, i.e. star formation over last ~ 10^8 yr

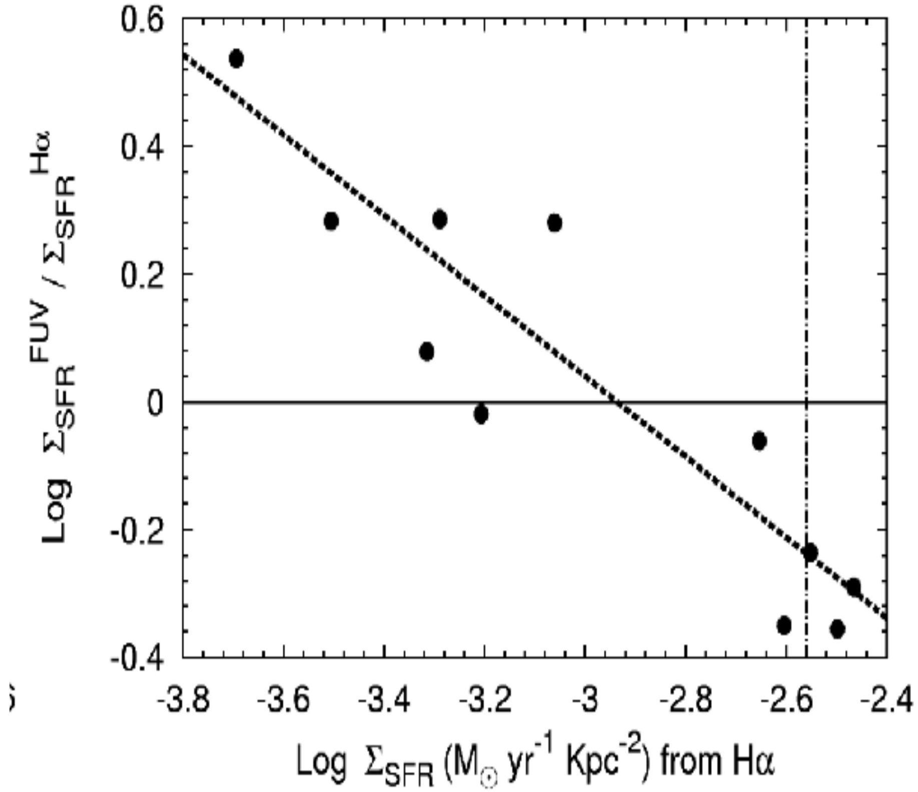
- $H\alpha$ emission
  - massive ($M > 17\ M_{sun}$) , i.e. star formation over the last ~ 10^6 yr.

- Comparison of FUV and $H\alpha$ emission would allow one to constrain the IMF

- Calibrations are fixed so that for a constant SFH and a Salpeter IMF $\Sigma_{SFR}(FUV) = \Sigma_{SFR}(H\alpha)$

Formation of massive stars

- However for our dwarfs Σ_{SFR}(FUV)/ Σ_{SFR}(Hα) varies systematically with Σ_{SFR}(Hα)
    - Similar results found by others, e.g. Hunter et al (2010)



Roychowdhury et al., 2011: MNRAS, 414, L55

Roychowdhury et al., 2011: MNRAS, 414, L55

Formation of massive stars

- On small scales we find that $\Sigma_{SFR}(H\alpha)/\Sigma_{SFR}(FUV)$ increases with Σ_{HI},
- galaxies with globally low $\Sigma_{SFR}(H\alpha)/\Sigma_{SFR}(FUV)$ lack high column density gas
- Supports models in which high mass stars form preferentially in regions with high gas density (e.g. Krumholz et al. 2010).

Dwarf galaxies and DLAs

What are the DLA host galaxies?

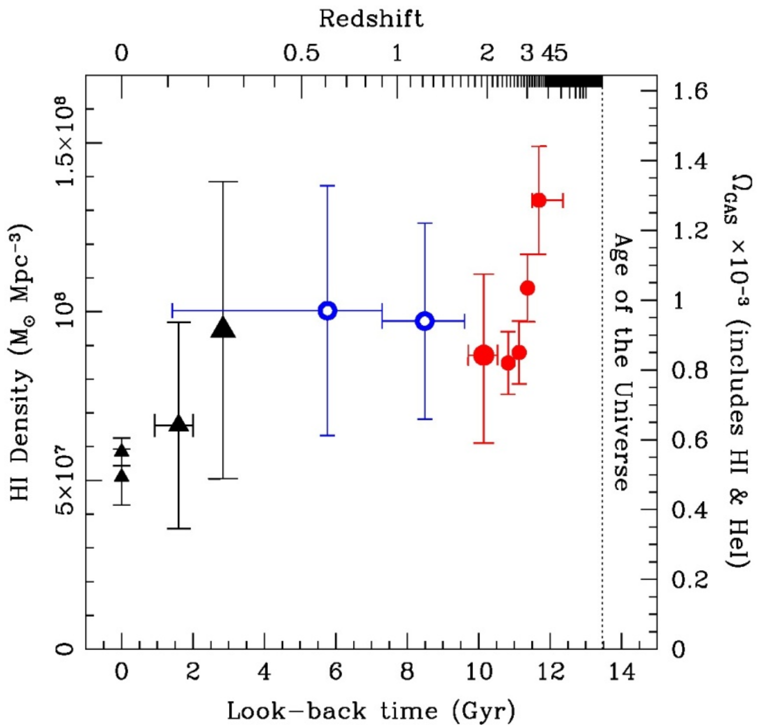
- What kind of systems give rise to DLAs?

    •*Large spiral disks (e.g. Prochaska & Wolfe 1997,1998)*

    •*Small "dwarf like" systems (e.g. Haehnelt et al. 1998)*

- The morhphological mix of galaxies evolves

    • *very few disk galaxies at high redshift (e.g. Conselice et al. 2005)*



•Gas density also evolves

$$\Omega_{HI}(z=0) \sim \tfrac{1}{2}\Omega_{HI}(z=2)$$

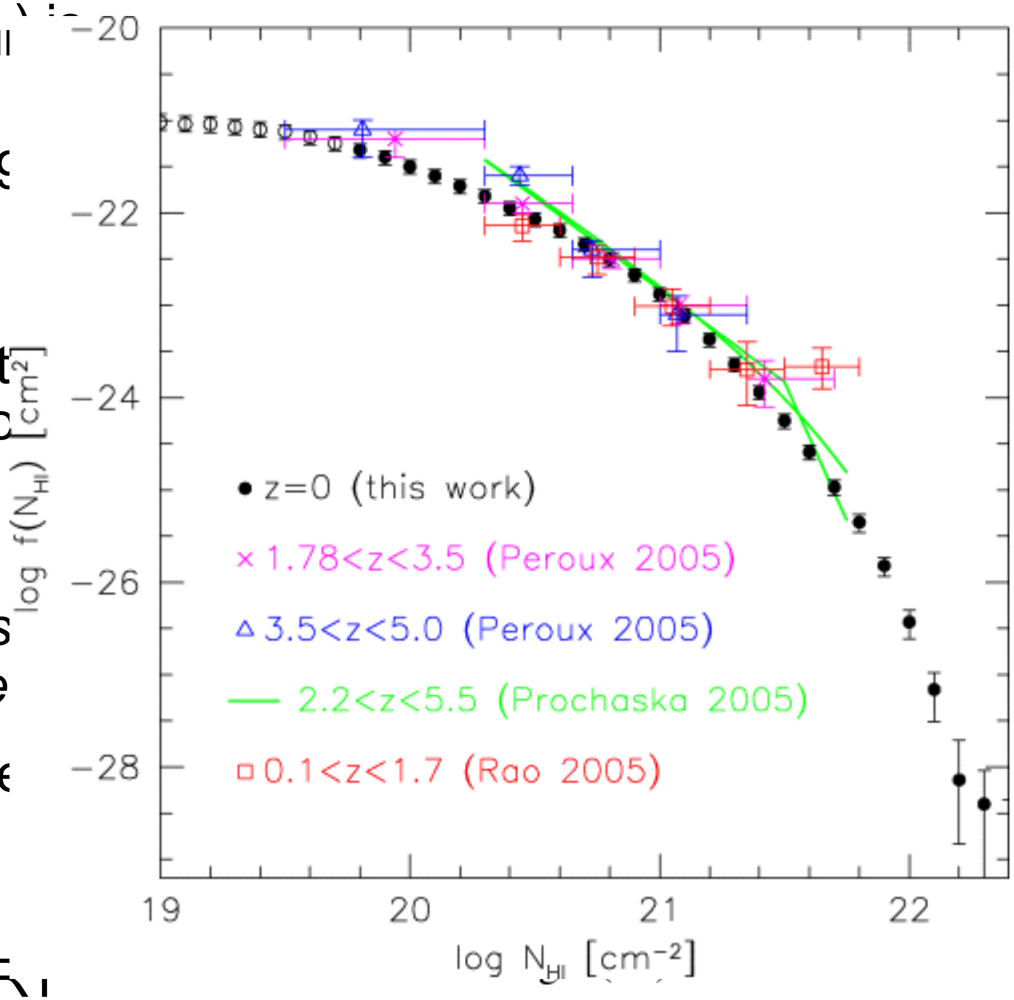
One would expect that the detailed properties of DLAs would not match that of gas rich local galaxies

Gas column density distribution

Zwaan et al., 2005: MNRAS 364, 1467

- The column density distribution $f(N_{HI})$ is well measured in DLAs
    - e.g. Prochaska et al. (2005, 2009 Notredame et al. (2009)

- Surprisingly, this is well matched by the observed column density distribution of the z ~ 0 galaxy population (Zwaan et al. 2005)
    - *Sample consists of a more or less representative mix of morphologies*
    - Cross section at z ~ 0 is dominated by large spirals
    - Column density computed using modest resolution (30" – 15") WSRT images



Results from the FIGGS sample

- The FIGGS sample provides robust observations of the gas column density distribution in dwarfs

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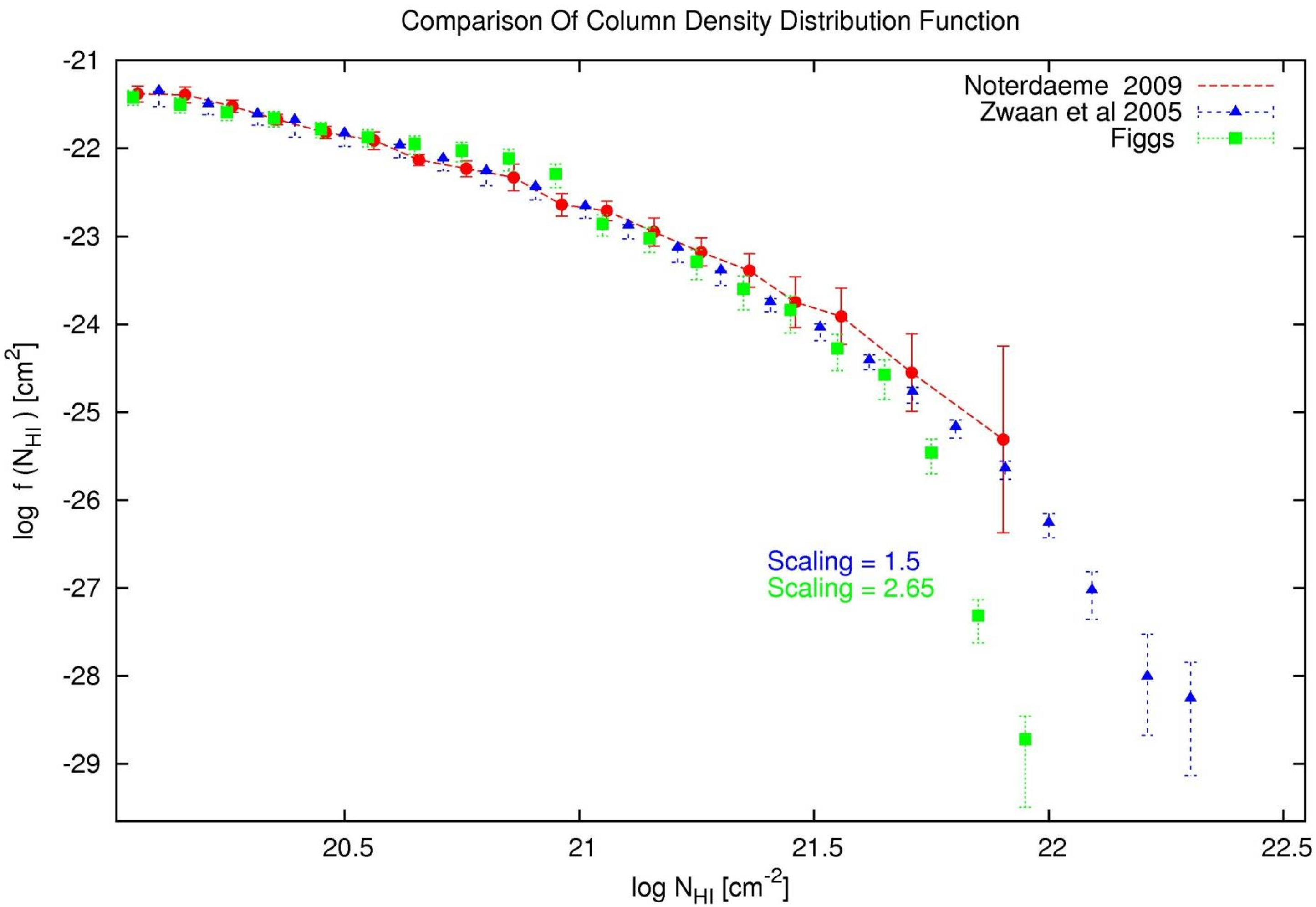


Thank you

Reference

- Begum et al., 2008: Faint Irregular Galaxies GMRT Survey – overview, observations and first results, MNRAS, 386, 1667.
- Begum et al., 2005: A dwarf galaxy with a giant HI disk, A&A, 433, L1
- Lo, K. Y., 1993: THE HI STRUCTURE OF NINE INTERINSICALLY FAINT DWARF GALAXIES, AJ, 106, 507L
- Begum, A. & Chengalur, J. N., 2004: Kinematics of the faintest gas-rich galaxy in the Local Group:DDO210, A&A, 413, 525
- Begum, A., Chengalur, J. N., Hopp. U., 2003: The little galaxy that could: Kinematics of Camelopardalis B, New Ast, 8, 267.
- Begum et al., 2008: Baryonic Tully-Fisher relation for extremely low mass Galaxies, MNRAS, 386, 138.

- Begum et al., 2005: A dwarf galaxy with a giant HI disk, A&A, 433, L1

- Gnedin, N. Y., 2000: Effect of Reionization on Structure Formation in the Universe, ApJ, 542, 535.
- Hoeft et al., 2006: Dwarf galaxies in voids:Suppressing star formation with photo-heating, astro-ph/0501304
- Kennicutt, R. C., Jr., 1998: The Global Schmidt Law in Star-forming Galaxies, ApJ, 498, 541.
- , arXiv:0711.2153.

Reference

- Zwaan et al., 2005: Rconciling the local galaxy population with damped Lyman α coss-sections and metal avandances, MNRAS 364, 1467.
- Roychowdhury et al, 2011: Small Bites: star formation recipes in extreme dwarfs, MNRAS 414, L55.
- Roychowdhury et al., 2009: Star formation in extremely faint dwarf galaxies, MNRAS, 397, 1435.
- Begum et al., 2008: FIGGS: Faint Irregular Galaxies GMRT Survey, arXiv:0711.1807.
- Chengalur et al., 2008: Gas rich galaxies from the FIGGS survey, arXiv:0711.2153.