The Faint End of the HI Mass Function

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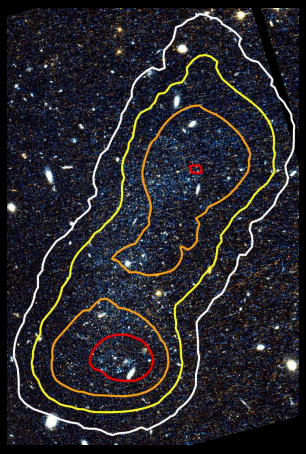
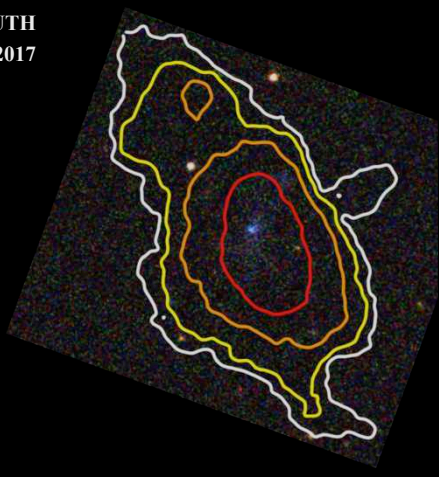
Meudon - LUTH
October 12, 2017





MACALESTER COLLEGE

ALFALFA

Outline

- Context and cosmological importance of low-mass galaxies
- New observational tools and techniques: ALFALFA
- A fully populated HI mass function
  - Sources with optical counterparts
    - SHIELD
    - The ALFALFA Dwarf Census
    - XMDs: Leo P and Leoncino
  - Sources without optical counterparts
    - UCHVCs
    - "Almost Dark" Galaxies
- Synthesis: the local HI universe from ALFALFA

Cosmological Importance of Low-mass Galaxies

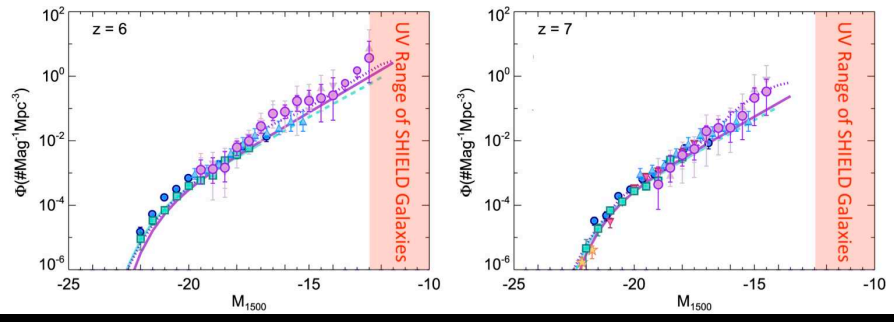
- The most most numerous type of extragalactic system at all epochs
- Likely played a role in cosmic reionization
- Local systems allow unique astrophysical and cosmological perspectives that are unavailable in more distant or more massive systems

The λCDM paradigm predicts more low-mass dark matter halos in the local universe than are observed

"The missing satellites problem"

λCDM simulations predict a population of subhalos within Galactic halos that have higher central densities than those measured in M.W. satellites; also extends into the field

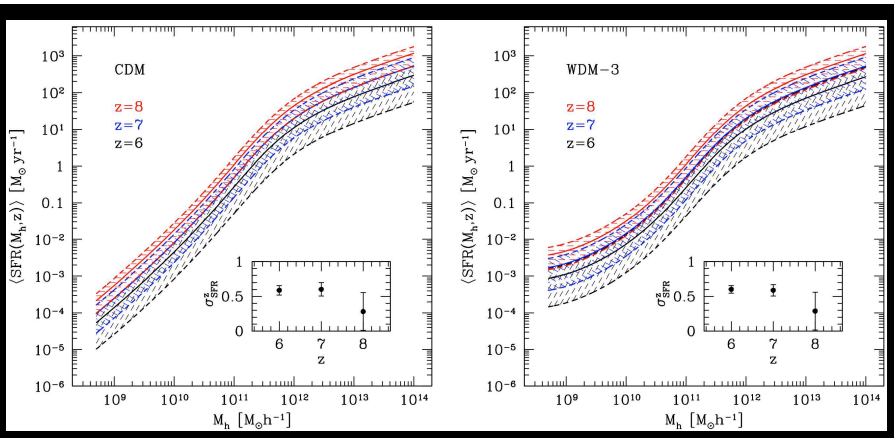
"The too big to fail problem"



Livermore *et al.* (2017)

The high-*z* UV luminosity function remains beyond the reach of HST and JWST

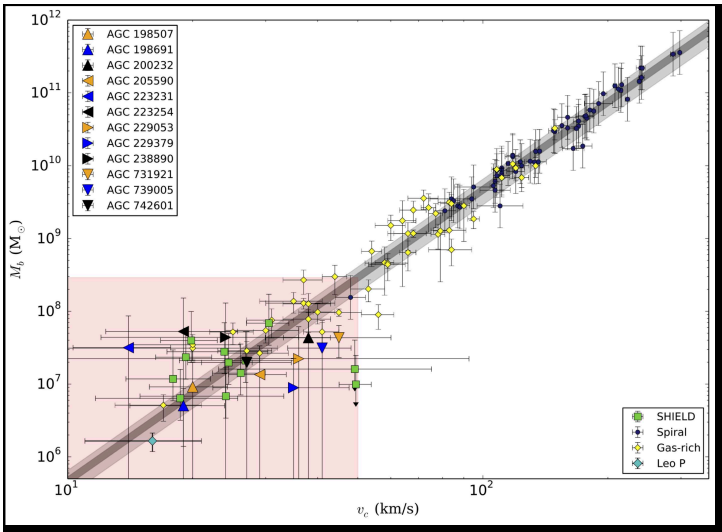
Unique comparison samples vs. high-*z* galaxies



Corasaniti *et al.* (2017)

The high-*z* UV luminosity function remains beyond the reach of HST and JWST

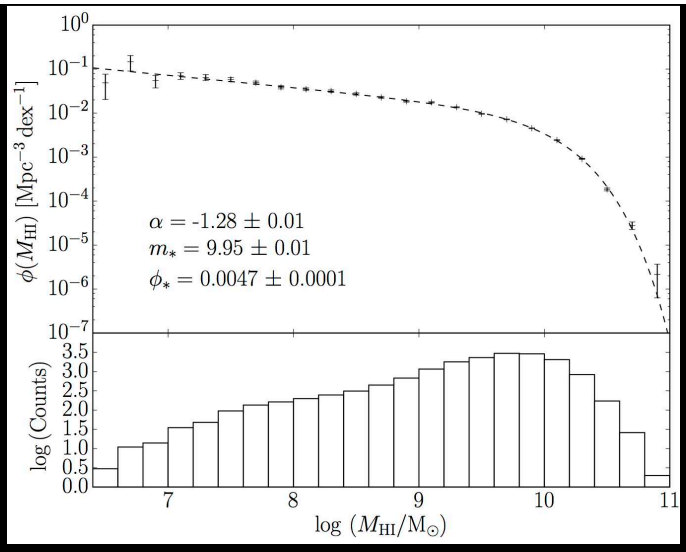
Differentiate between DM carriers



Gordon *et al.* in prep.

The low-velocity end of the baryonic Tully Fisher relation is being populated for the first time

Unique constraints on fundamental scaling relations

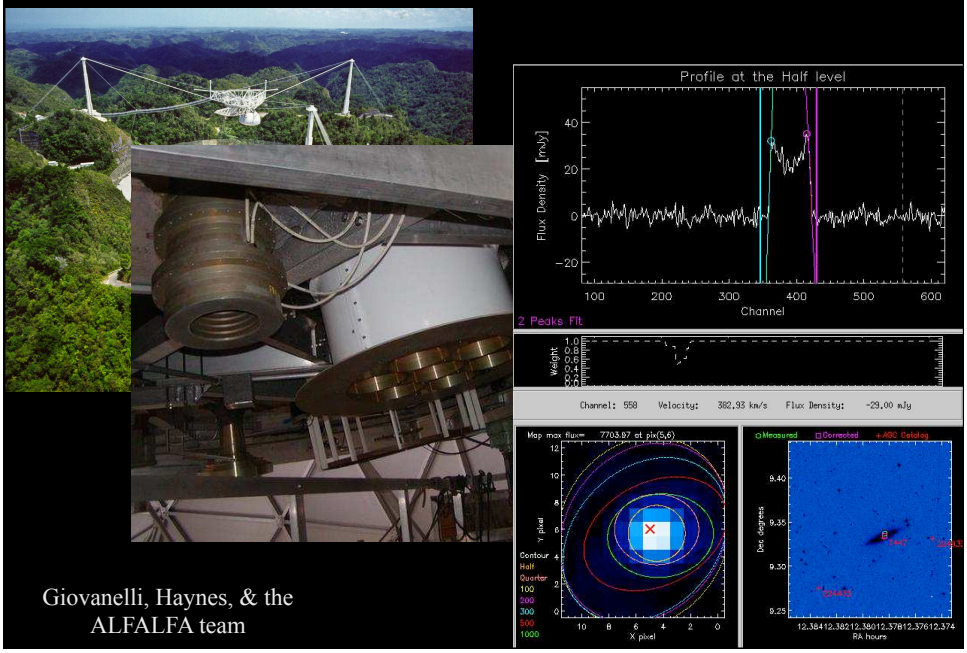


Jones *et al.* in prep.

The faint end of the HI mass function has been robustly populated for the first time

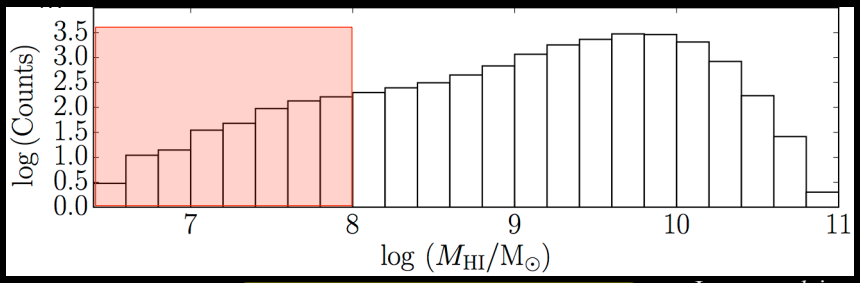
Opportunities for leaps forward in our understanding

Terra Incognita: ALFALFA



Giovanelli, Haynes, & the ALFALFA team

Terra Incognita: ALFALFA



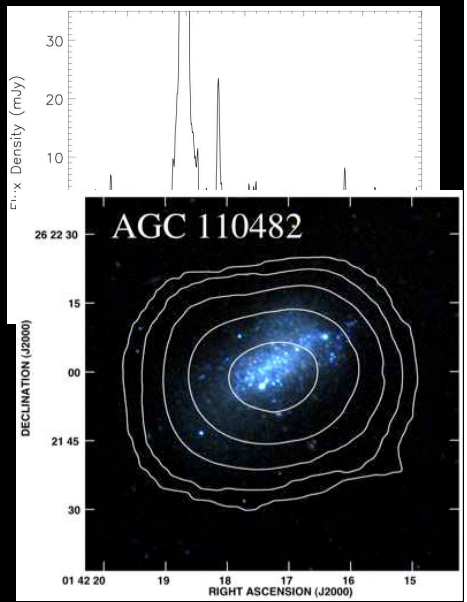
Jones *et al.* in prep.

ALFALFA now has cataloged >400 previously unknown galaxies with $M_{HI} < 10^8\ M_\odot$ and 82 with $M_{HI} < 10^7\ M_\odot$

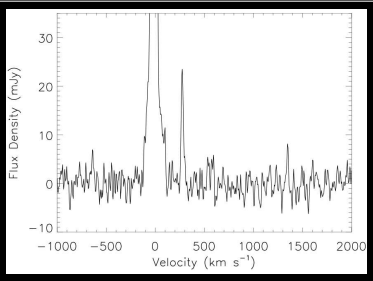
Volumetrically complete sample within 10 Mpc

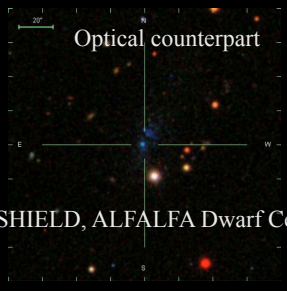
Harvesting ALFALFA

Detailed follow-up



Harvesting ALFALFA





Optical counterpart

SHIELD, ALFALFA Dwarf Census

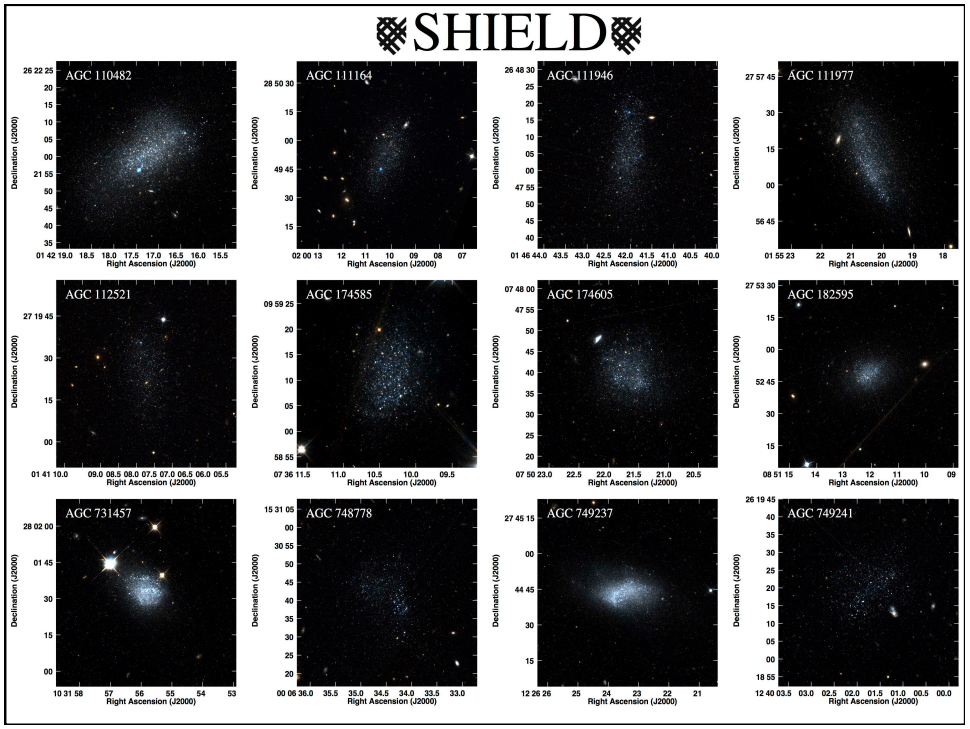
No optical counterpart

UCHVC, "Almost Dark"

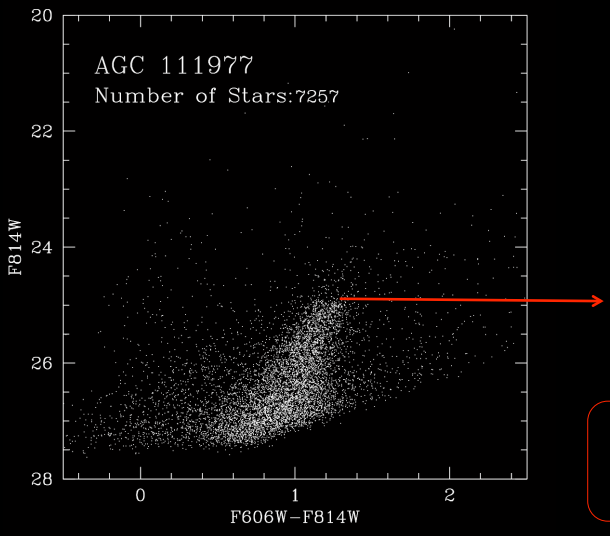
www.macalester.edu/~jcannon/SHIELD

SHIELD: Program Goals

- *What fraction of the mass in low-mass dwarfs is baryonic?*
- *Is the character of the SF process different in low-mass galaxies?*
- *What properties change between mini-halos, very low-mass dwarfs, and more massive systems?*



SHIELD: HST Imaging



AGC 111977

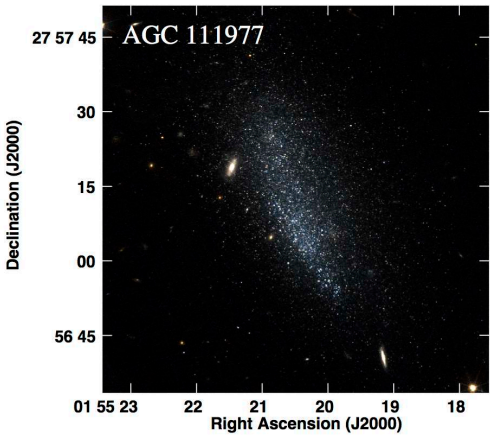
TRGB = distance

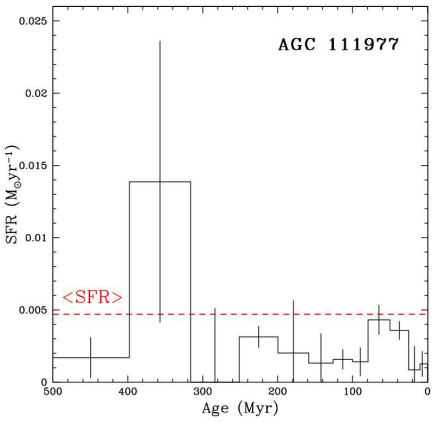
D = 5.5±0.5 Mpc

$M_{HI} = 6.1 \times 10^6\ M_\odot$

McQuinn, Cannon *et al.* (2014)

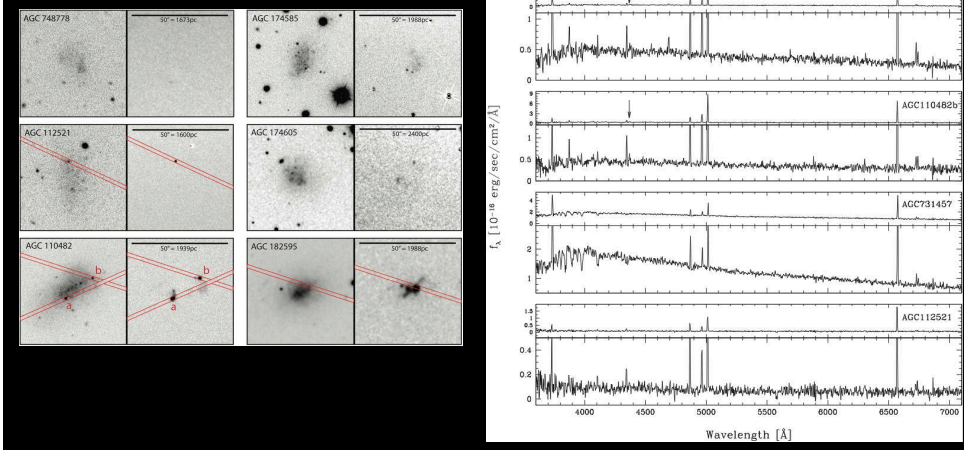
SHIELD: HST Imaging



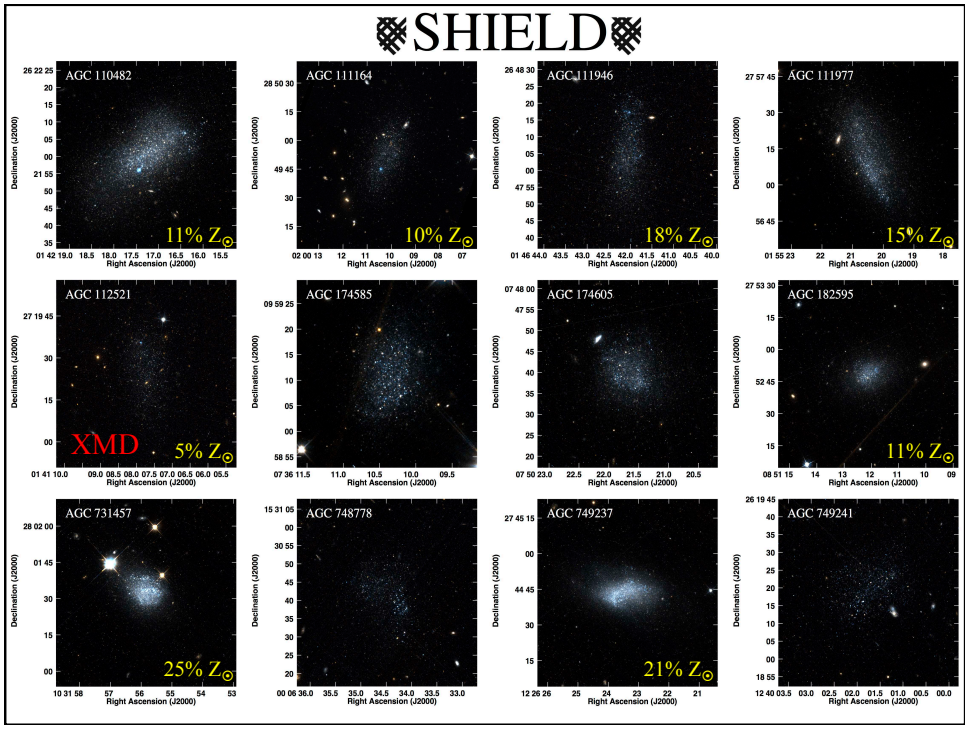


McQuinn, Cannon *et al.* (2015)

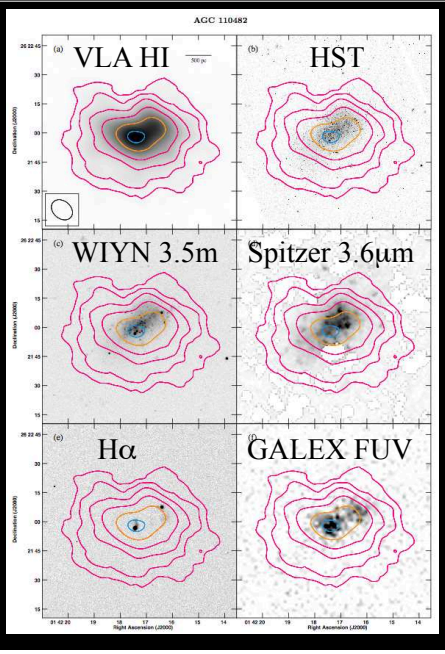
SHIELD: KPNO Imaging and Spectroscopy

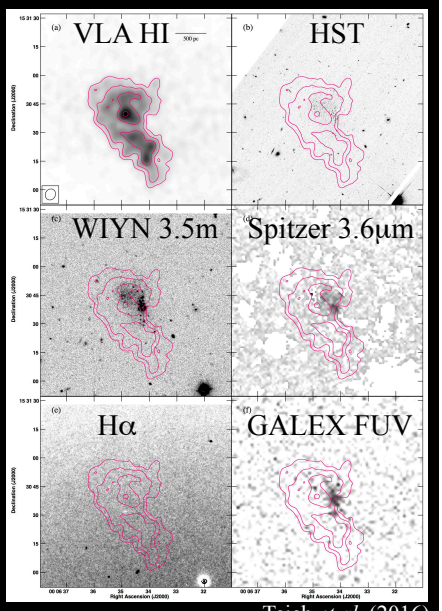


Haurberg *et al.* (2015)



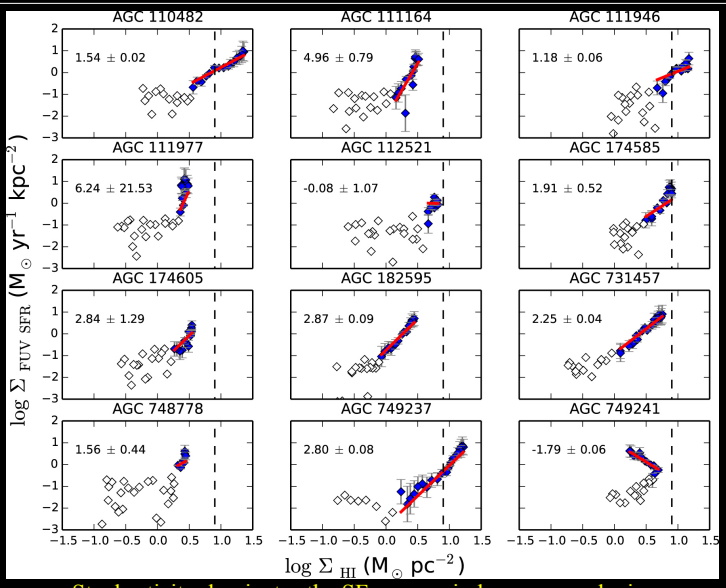
SHIELD: Star Formation Properties





Teich *et al.* (2016)

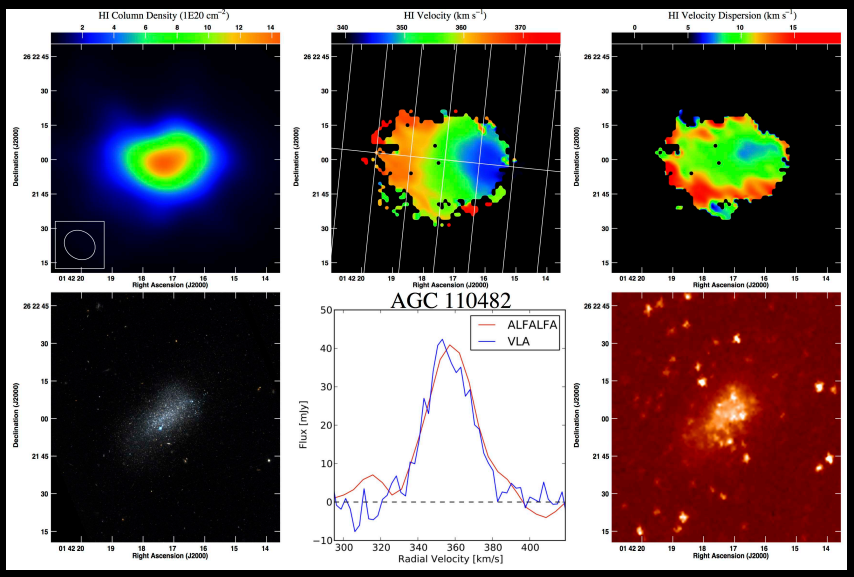
SHIELD: Star Formation Properties



Stochasticity dominates the SF process in low-mass galaxies

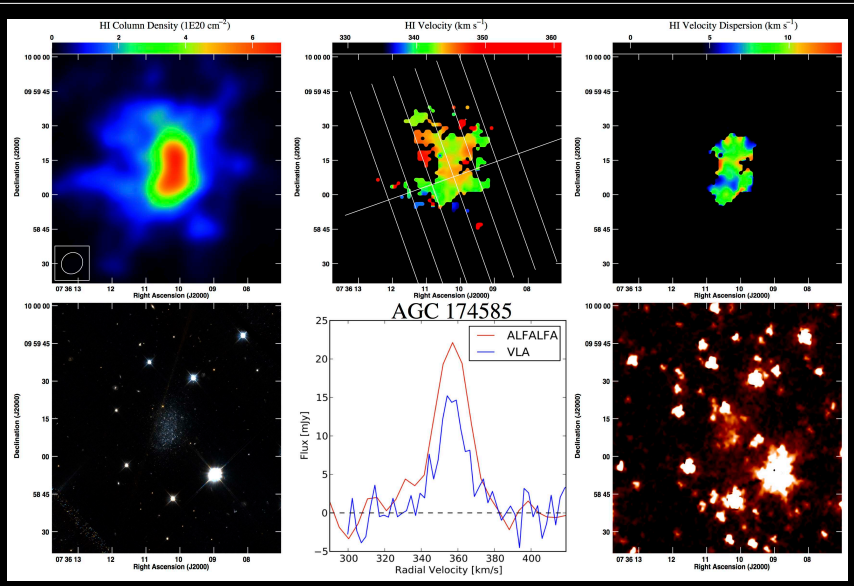
Teich *et al.* (2016)

SHIELD: Dynamics



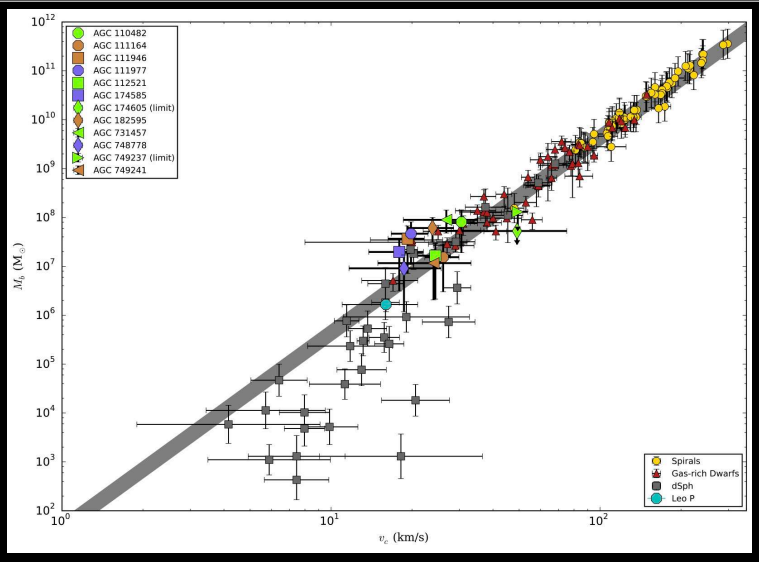
McNichols *et al.* (2016)

SHIELD: Dynamics



McNichols *et al.* (2016)

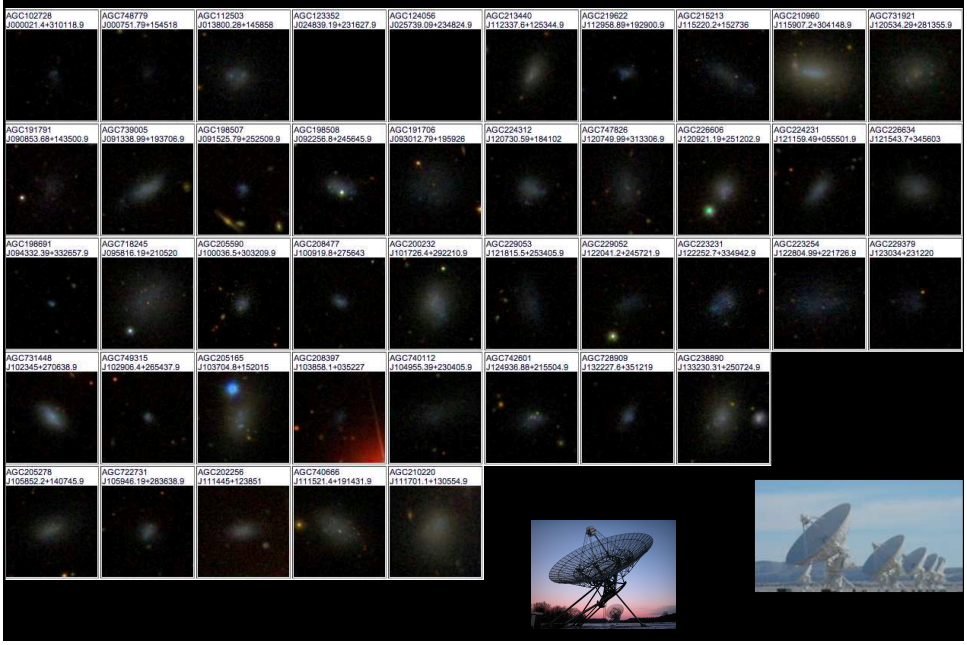
SHIELD: Dynamics



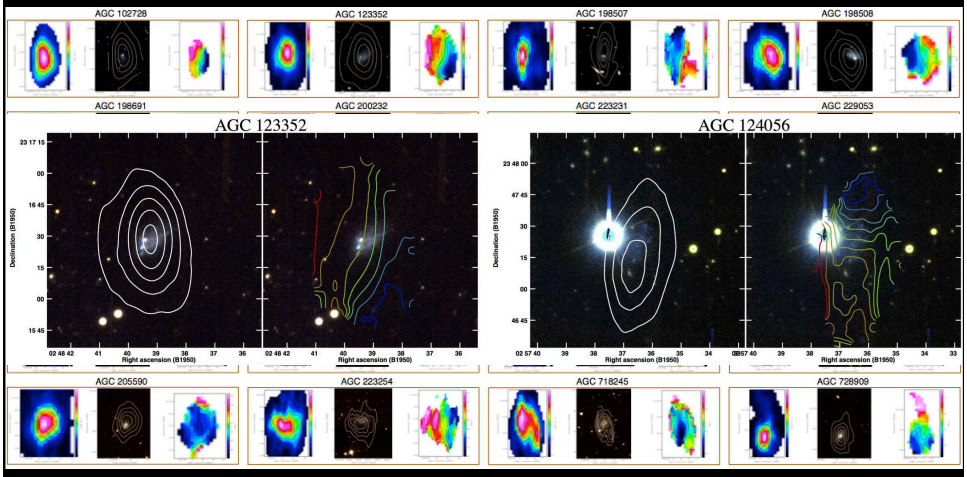
Transition from rotational to pressure support

McNichols *et al.* (2016)

The ALFALFA Dwarf Census

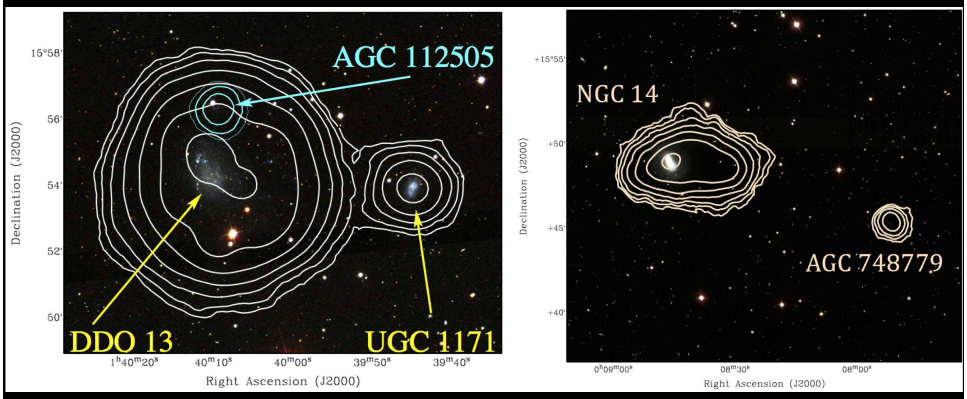


The ALFALFA Dwarf Census



HST G.O. 13750; Gordon *et al.* (in prep.)

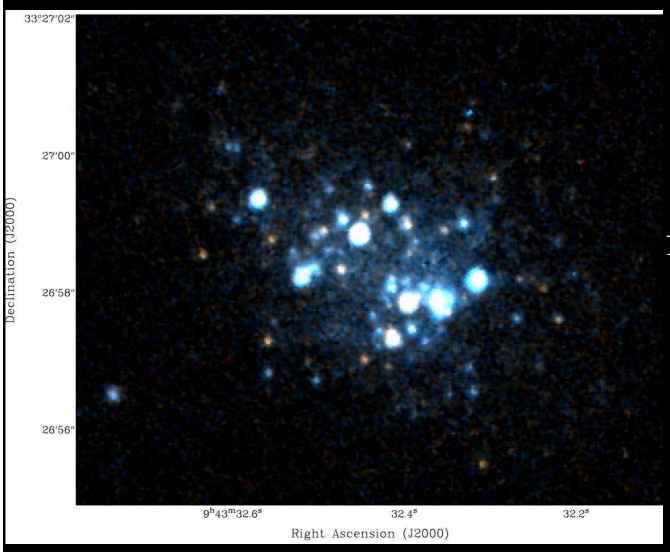
The ALFALFA Dwarf Census



Unique constraints on the interaction fraction in the low mass regime

Ruvolo *et al.* (in prep.)

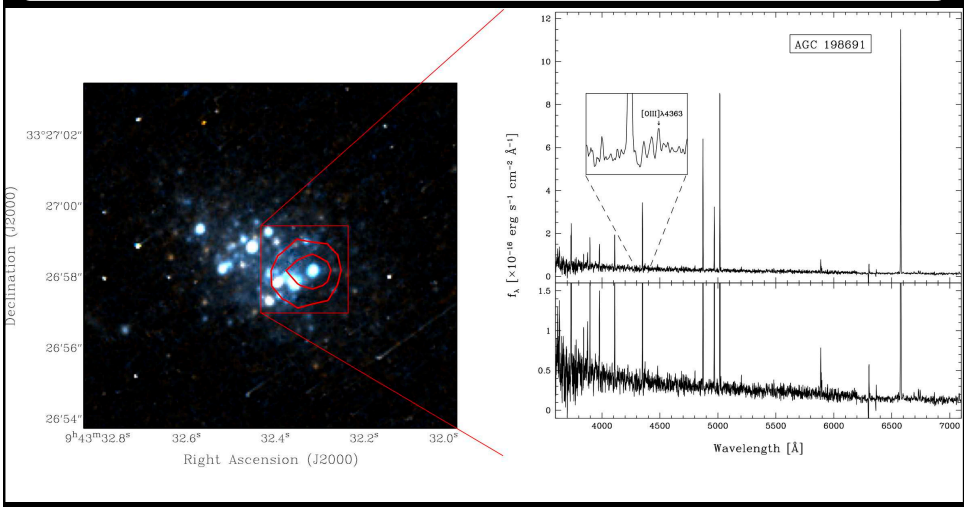
The ALFALFA Dwarf Census: The Leoncino Dwarf



An extremely compact star-forming galaxy

HST G.O. 13750

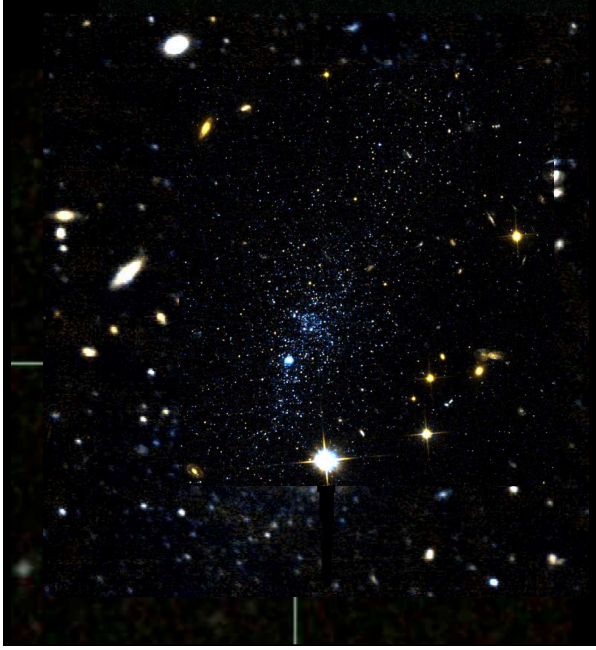
The ALFALFA Dwarf Census: The Leoncino Dwarf



The most metal-poor galaxy known (2% $Z_{\odot}$)

Hirschauer *et al.* (2016)

The ALFALFA Dwarf Census: Leo P



WIYN 2.1m
LBT 8.2m
HST

S/N = 25 from ALALFA

W_{20} = 24 km s^{-1}

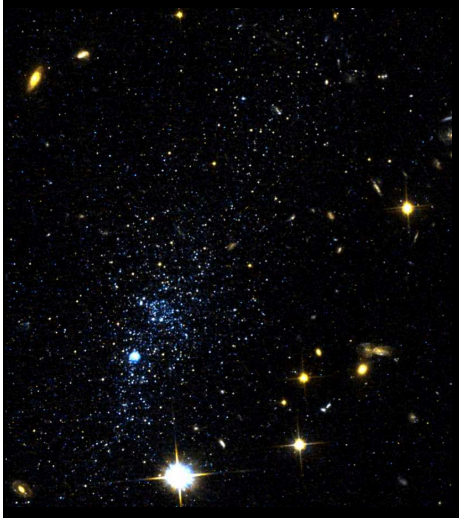
S_{HI} = 1.3 Jy km s^{-1}

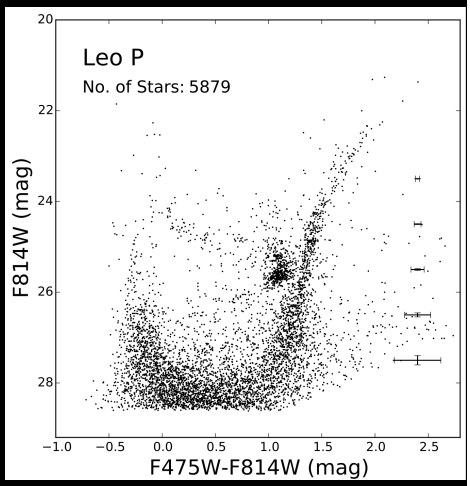
V = 264 km s^{-1}

Classified as a compact group of galaxies by McConnachie *et al.* (2009)

Not identified by SDSS as a resolved galaxy

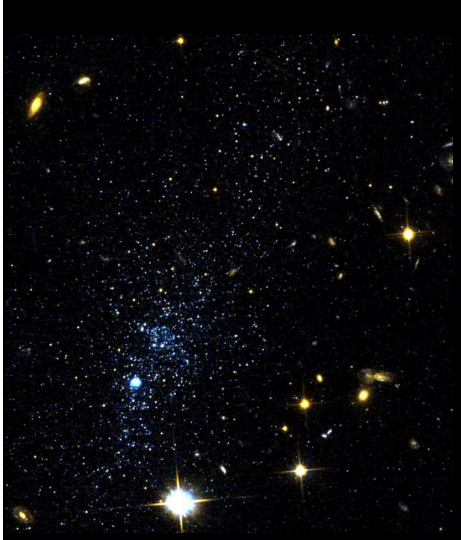
The ALFALFA Dwarf Census: Leo P

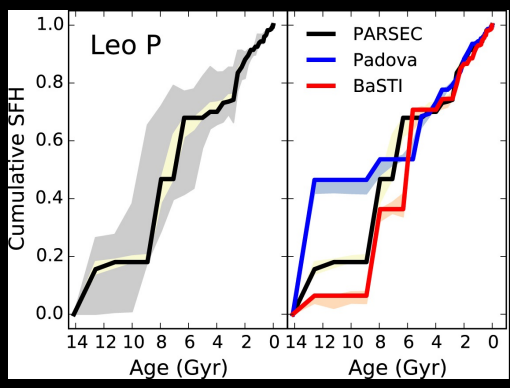




McQuinn *et al.* (2015a)

The ALFALFA Dwarf Census: Leo P

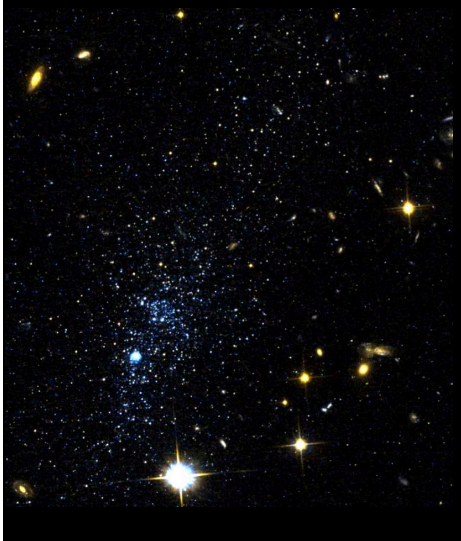


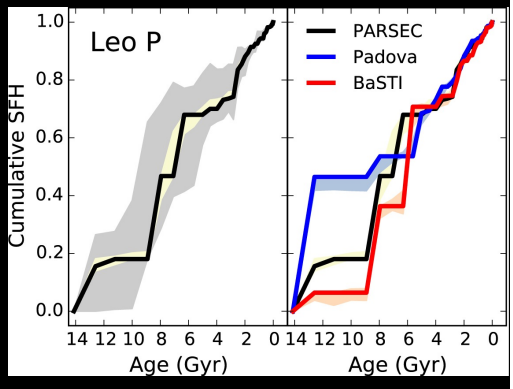


Star formation at all epochs: not a young galaxy

McQuinn *et al.* (2015a,b)

The ALFALFA Dwarf Census: Leo P

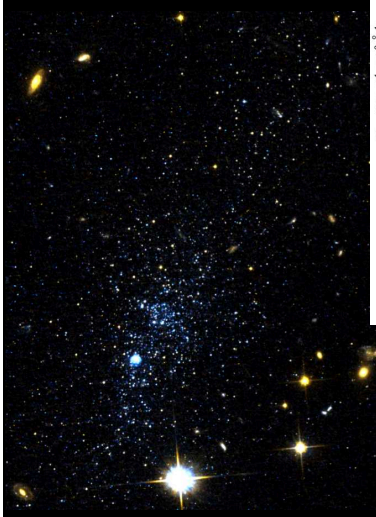


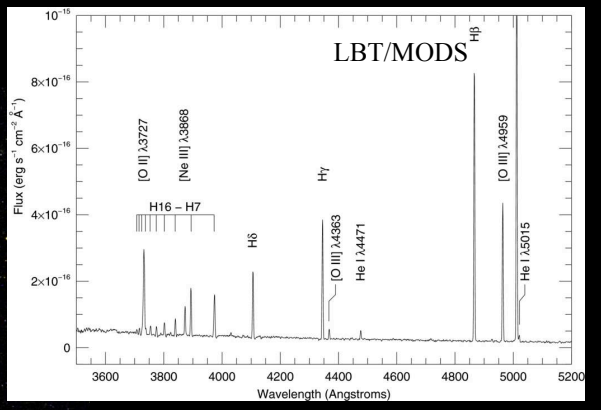


Metal retention fraction = 5% c.f. massive galaxies, 20-25%

McQuinn *et al.* (2015a,b)

The ALFALFA Dwarf Census: Leo P



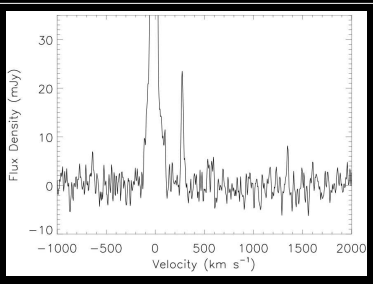


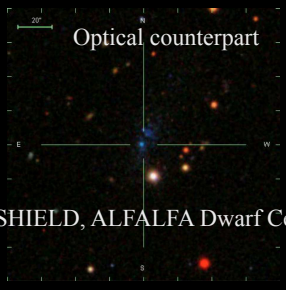
Oxygen abundance = 3% $Z_\odot$
c.f. I Zw 18, 3% $Z_\odot$

Primordial He abundance = $0.2509^{+0.0184}_{-0.0123}$
c.f. WMAP = 0.2483±0.0002

Skillman *et al.* (2013)

Harvesting ALFALFA

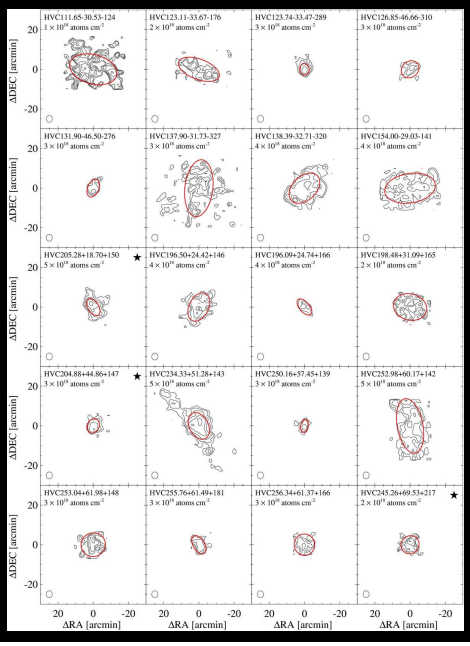




SHIELD, ALFALFA Dwarf Census

UCHVC, "Almost Dark"

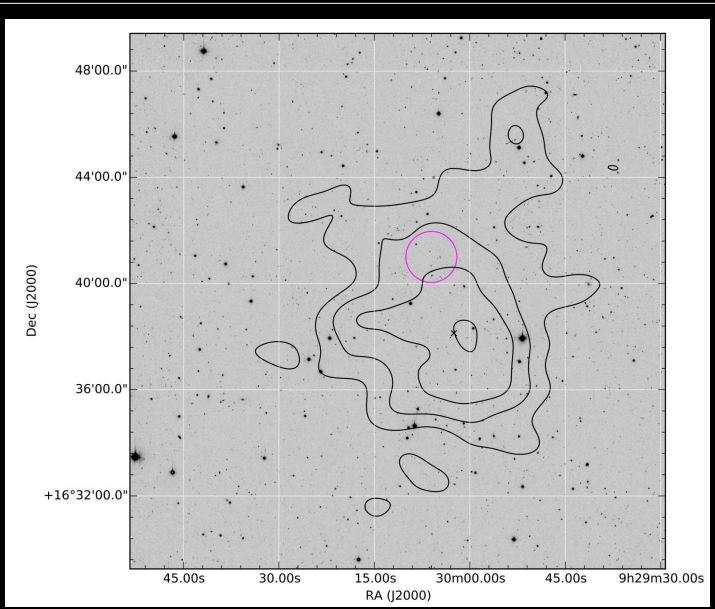
UCHVC



HI clouds with structural parameters that match those of gas-bearing "mini-halos" if located within ~1 Mpc

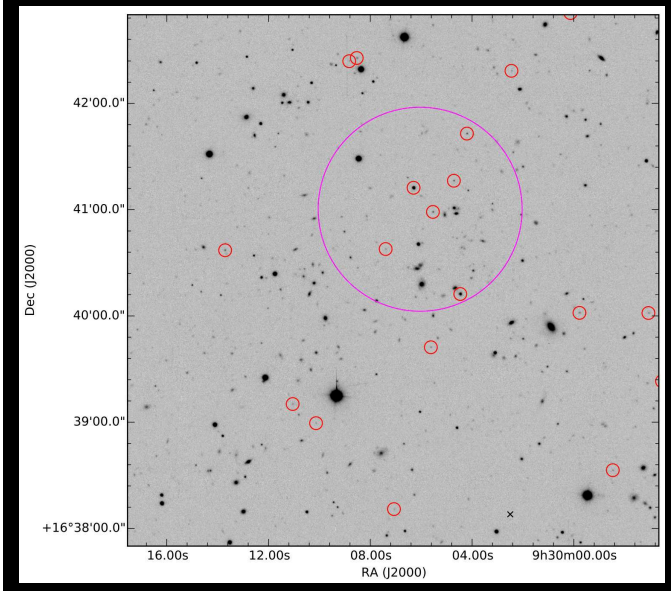
Adams *et al.* (2013)

UCHVC: AGC198606



Adams *et al.* (2015a), Janesh *et al.* (2015)

UCHVC: AGC198606



V=51 km s^{-1}

$M_{HI}=3.5x10^6\ D(Mpc)^2\ M_\odot$

Optical counterpart:
a few *dozen* stars

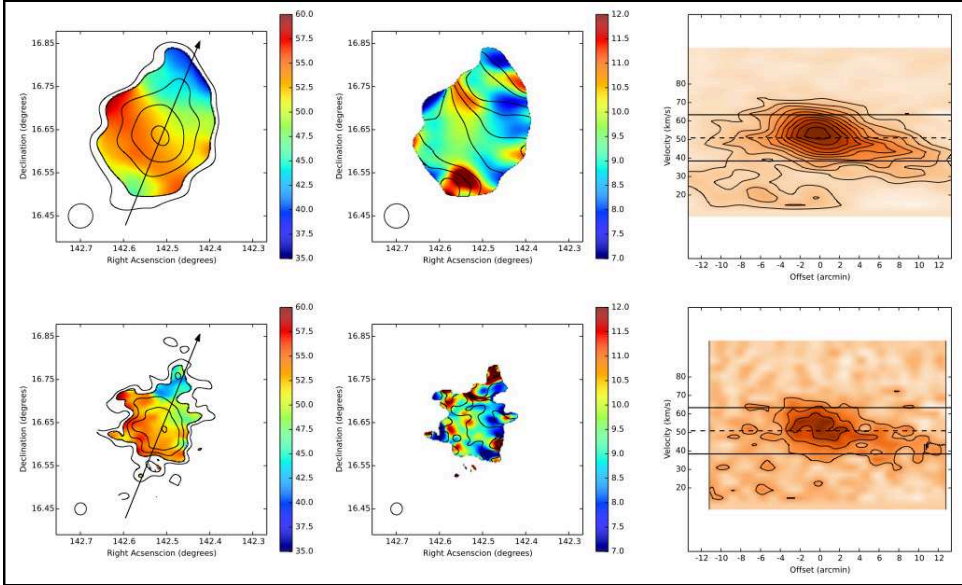
D = 383 ± 10 kpc

$M_I = -4.67 \pm 0.09$

$45 < M_{HI} / M_* < 110$

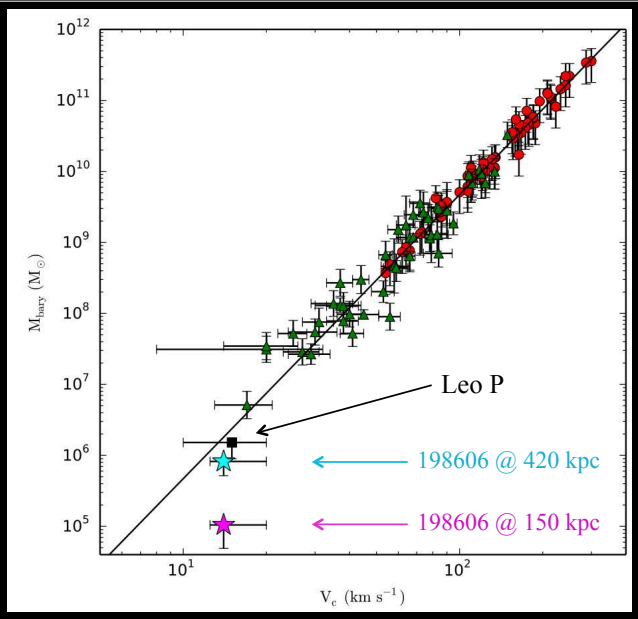
Adams *et al.* (2015a), Janesh *et al.* (2015)

UCHVC: AGC198606



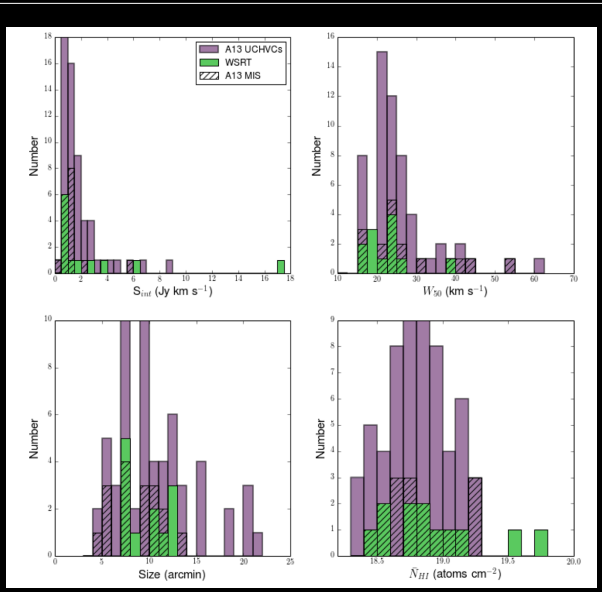
Adams *et al.* (2015a)

UCHVC: AGC198606



Adams *et al.* (2015a)

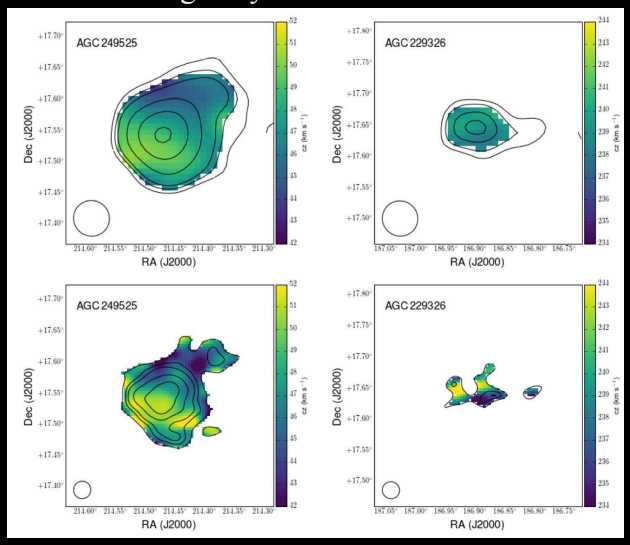
UCHVC



Adams *et al.* (2016)

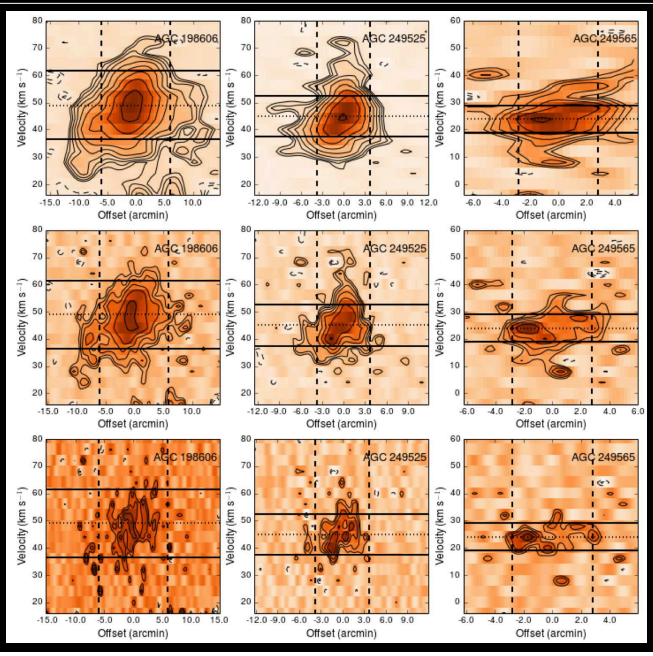
UCHVC

Candidate galaxy MW halo cloud



Adams *et al.* (2016)

UCHVC

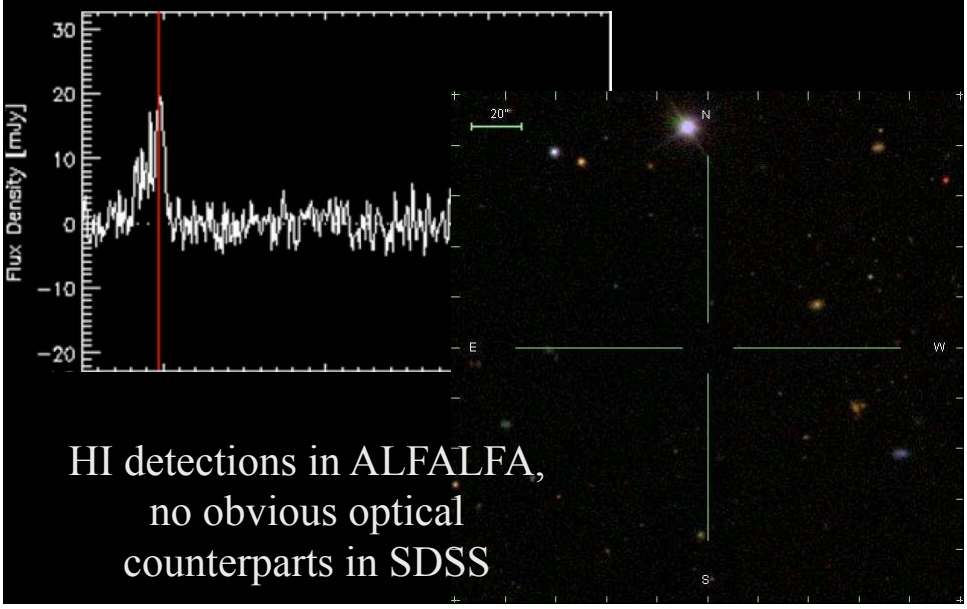


Candidate local galaxies, *discovered in HI alone*

Optical counterparts of seven systems detected to date (Janesh *et al.* in prep.)

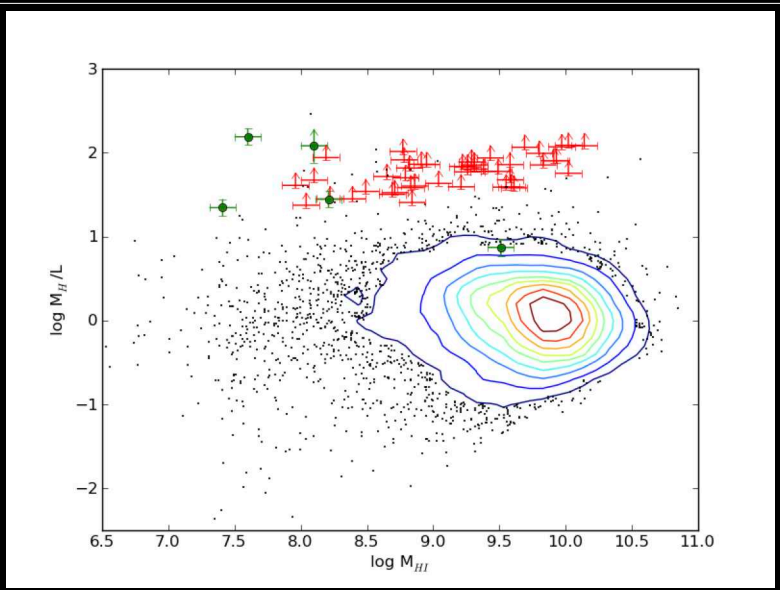
Adams *et al.* (2016)

"Almost Dark" Galaxies



HI detections in ALFALFA, no obvious optical counterparts in SDSS

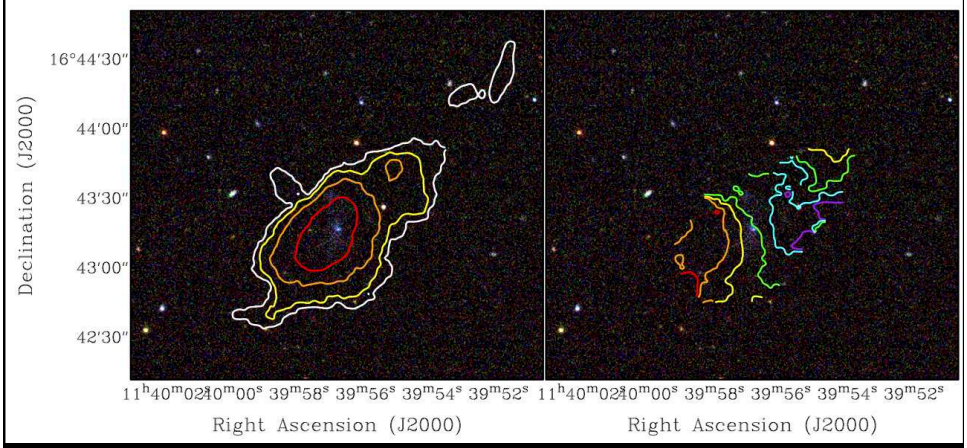
"Almost Dark" Galaxies



Cannon *et al.* (2015)

"Almost Dark" Galaxies

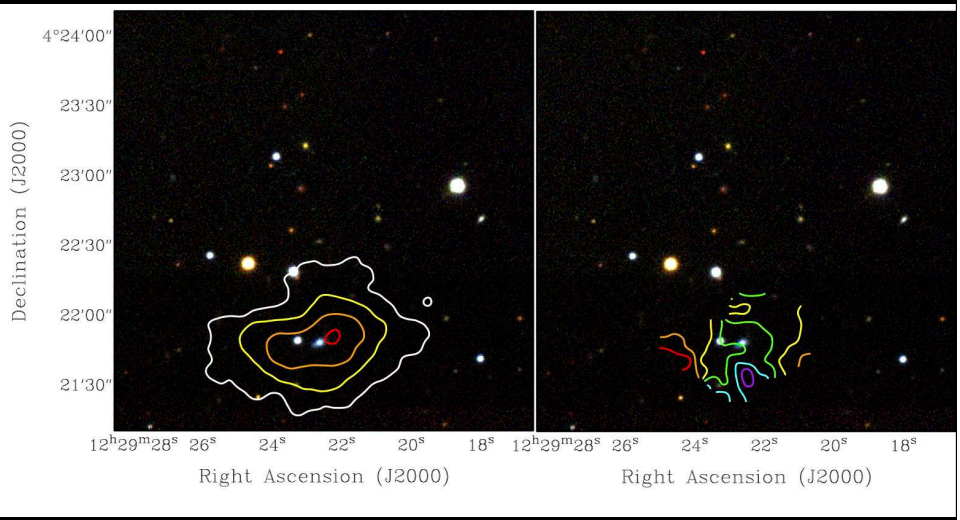
AGC 219533: very low surface brightness optical counterpart



Singer *et al.* (2017)

"Almost Dark" Galaxies

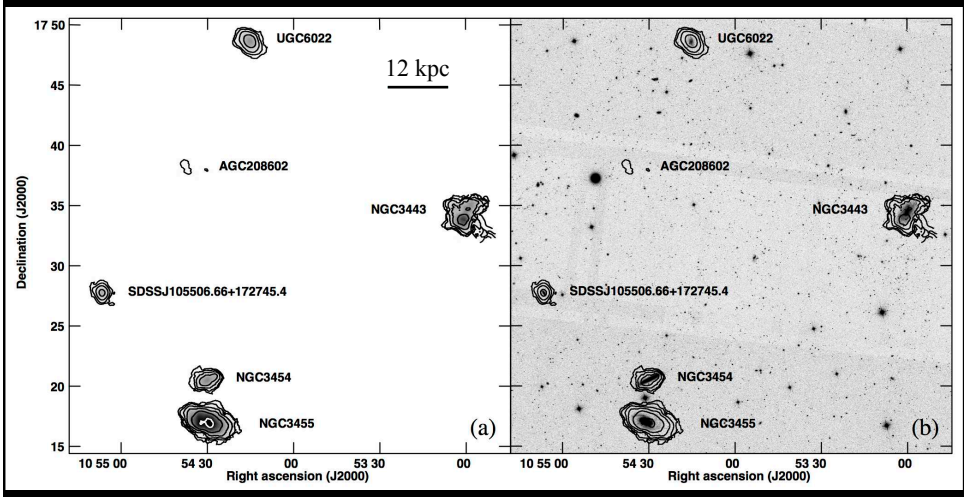
AGC 227982: offset optical counterpart from ALFALFA HI centroid



Singer *et al.* (2017)

"Almost Dark" Galaxies

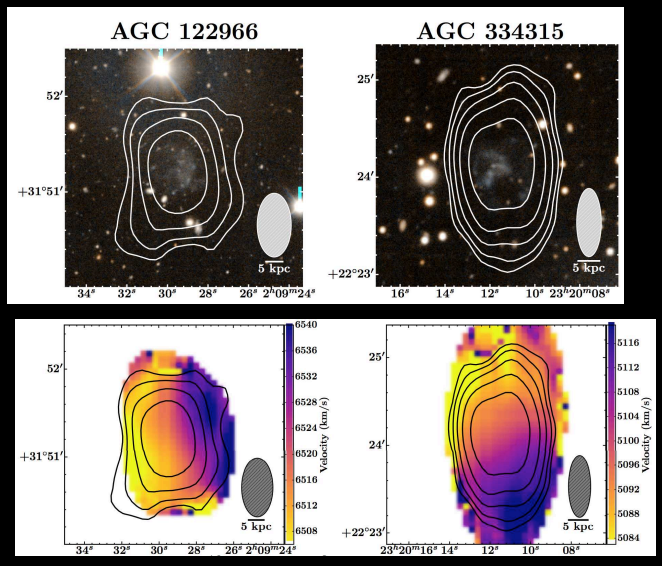
AGC 208602: tidal material



No bona fide "dark galaxies" have yet been identified

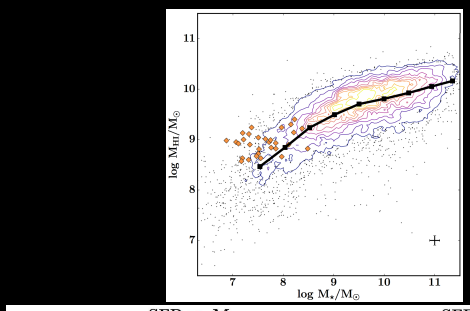
Cannon *et al.* (2015)

"Almost Darks": Ultra-Faint Dwarf Analogs?

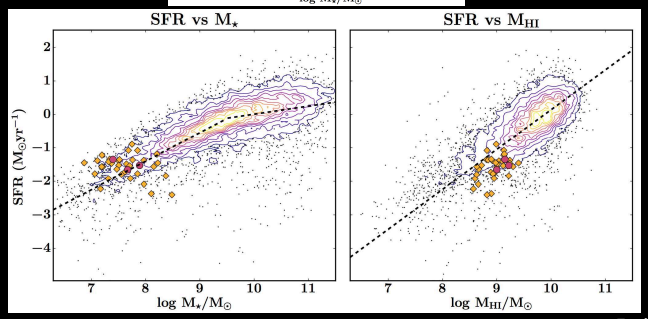


Leisman *et al.* (2017)

"Almost Darks": Ultra-Faint Dwarf Analogs?

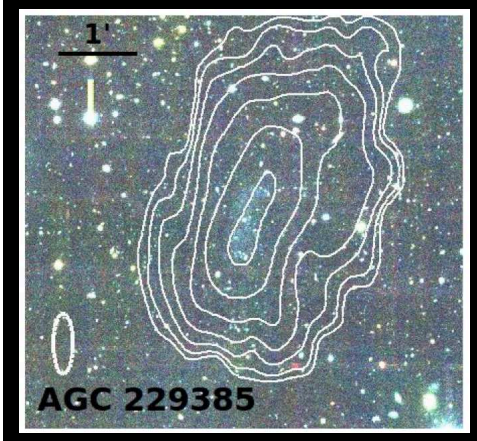


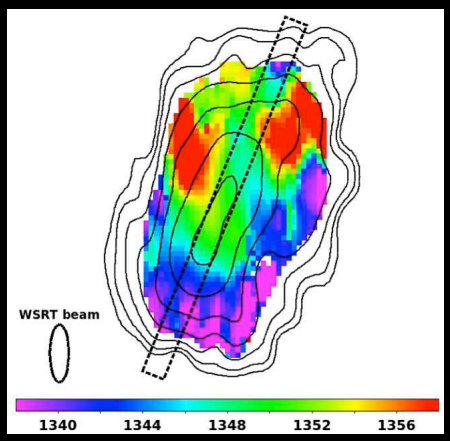
Suppressed star formation



Leisman *et al.* (2017)

"Almost Darks": Coma P



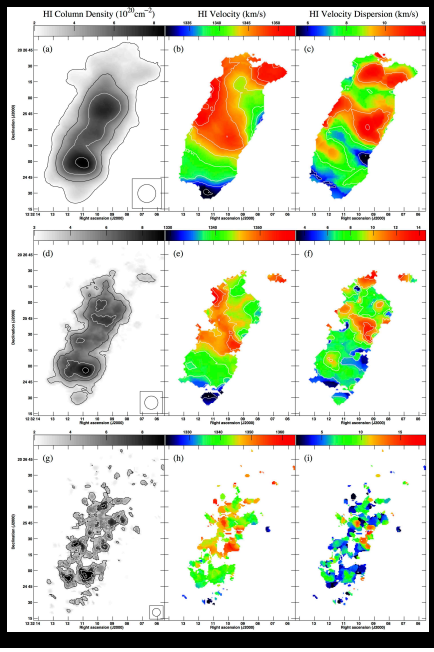


M_{HI} / L > 30

Highest HI mass-to-light ratio ever measured using resolved stars

Janowiecki *et al.* (2015)

"Almost Darks": Coma P

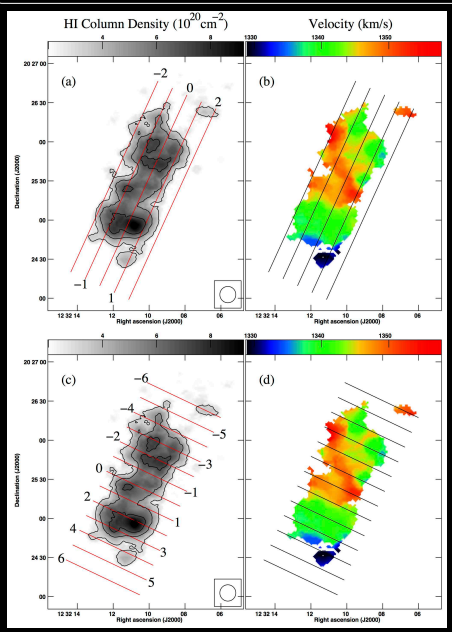


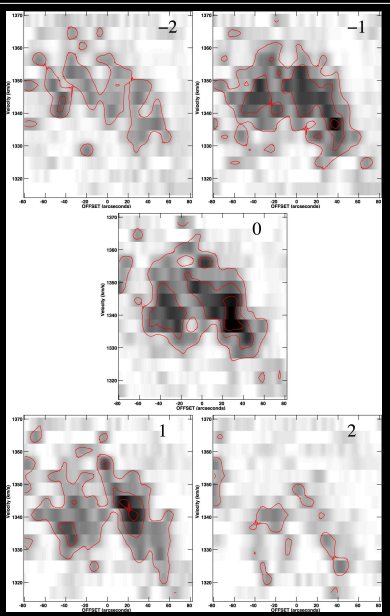
$M_{HI} = (3.5\pm0.4)\times10^7\ M_\odot$

HI kinematics favor infall or outflow

Ball *et al.* (in prep.)

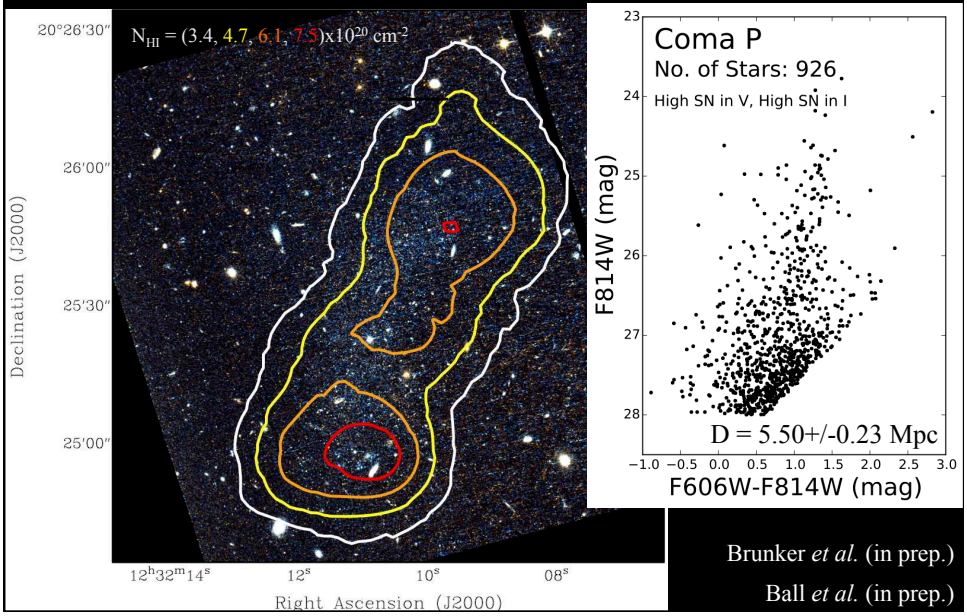
"Almost Darks": Coma P





Ball *et al.* (in prep.)

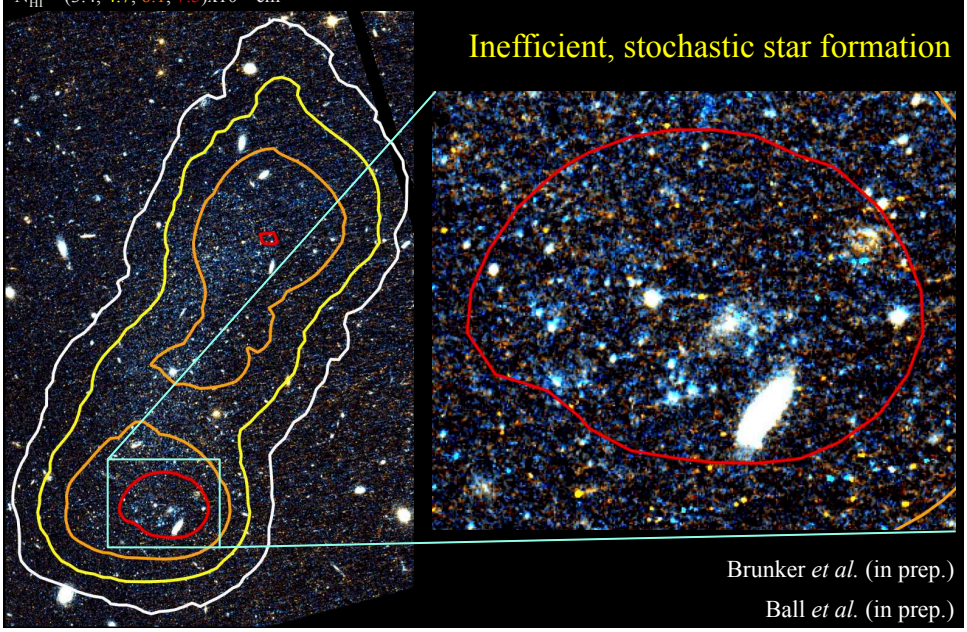
"Almost Darks": Coma P



Brunker *et al.* (in prep.)

Ball *et al.* (in prep.)

"Almost Darks": Coma P



Brunker *et al.* (in prep.)

Ball *et al.* (in prep.)

Conclusions

- SHIELD
  - Despite low mass surface densities, all systems have star formation during the last ~200 Myr
  - Star formation is dominated by stochasticity in the ISM
  - Galaxies in this mass range probe the transition from solid-body rotators to pressure-supported systems
- The ALFALFA Dwarf Census
  - ALFALFA has discovered two of the six most metal-deficient galaxies known, *by their HI signatures alone*
  - Volumetrically complete sample allows statistically robust analysis of physical properties in an unexplored region of parameter space
- UCHVCs and "Almost Darks"
  - No "dark" galaxies have yet been discovered
  - Extreme systems challenge well-established galaxy scaling relations

There is a very bright future for very dim galaxies