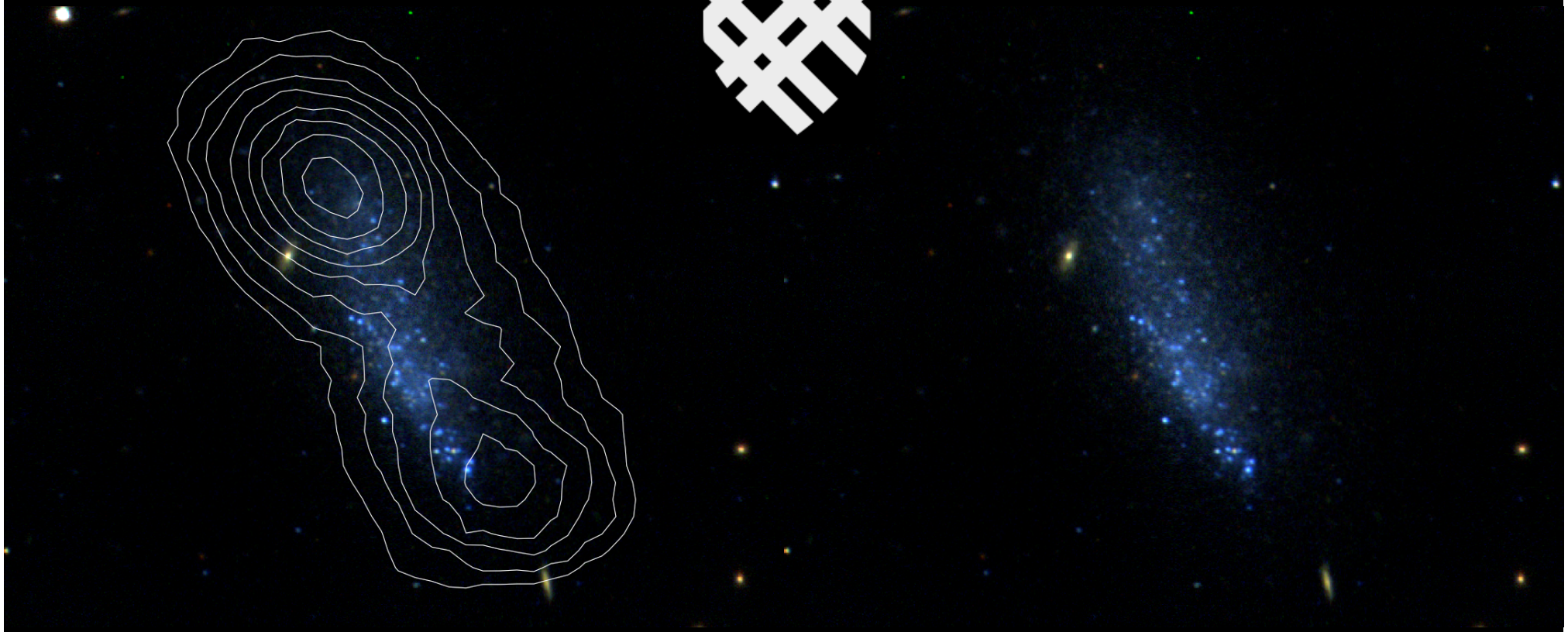
SHIELD: The Survey of HI in Extremely Low-mass Dwarfs



John M. Cannon
Macalester College
Undergraduate ALFALFA Team Workshop
January 16, 2012

SHIELD: Team Members

- PI: John M. Cannon (Macalester College)
- Macalester College (UAT stipend): Clara Thomann

- Cornell: Betsey Adams, Riccardo Giovanelli, Martha Haynes, Shan Huang
- Indiana: Steven Janowiecki, Angela Parker, John J. Salzer
- Minnesota: Kristy McQuinn, Evan D. Skillman
- MPE: Amélie Saintonge
- NRAO: Jürgen Ott
- Western Australia/ICRAR: Ed Elson

- Macalester College (minor): John Allan, Eric Engstrom, Grace Erny, Palmer Fliss, AnnaLeigh Smith

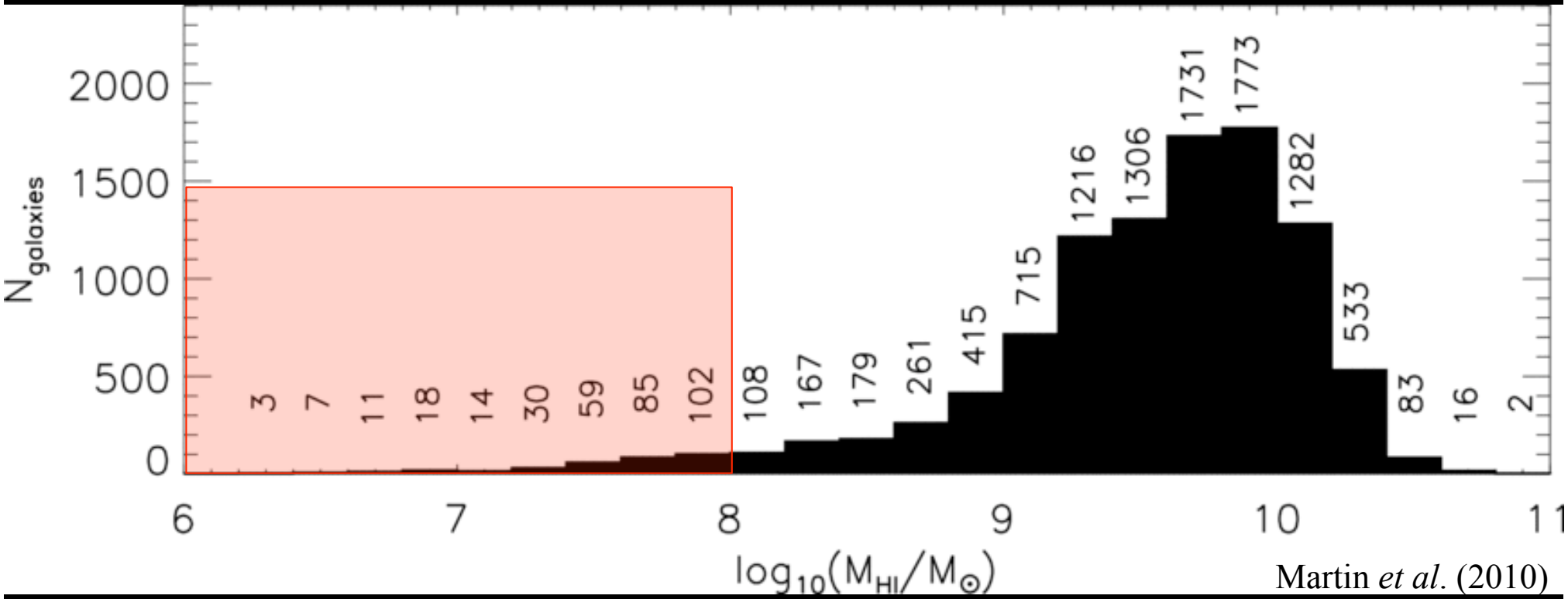
Outline

- Theoretical and observational importance of low-mass galaxies
- Studying *ALFALFA*-discovered low-mass galaxies with the *EVLA*
  - Brief interferometry interlude
  - Concept demonstration
  - SHIELD: overview and program goals
  - SHIELD: preliminary results
  - SHIELD: *HST* imaging
  - SHIELD: *Spitzer* imaging
- Future prospectus

On The Importance of Low-mass Galaxies

- The λCDM paradigm predicts more low-mass dark matter halos in the local universe than are observed
  - "Missing satellite problem"
  - Local low-mass systems are survivors of the structure formation process
- Changes in physical parameters and mechanisms are predicted in low-mass galaxies
  - Decreasing baryon fraction
  - Different relation between mass surface density and star formation rate than in massive galaxies
- Extreme and untested ISM conditions
  - Opportunities for leaps forward in our understanding of galaxy evolution

Terra Incognita: ALFALFA

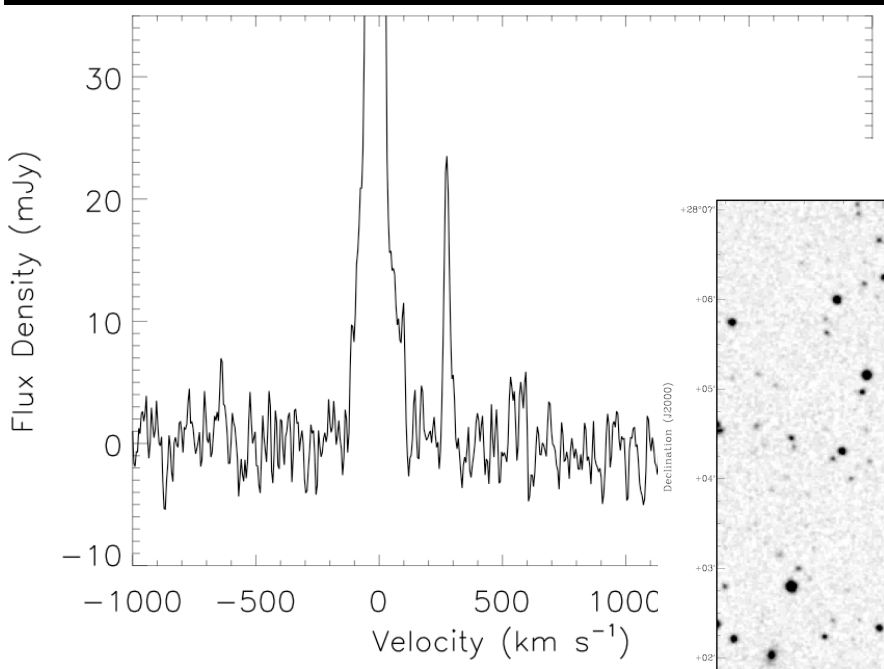


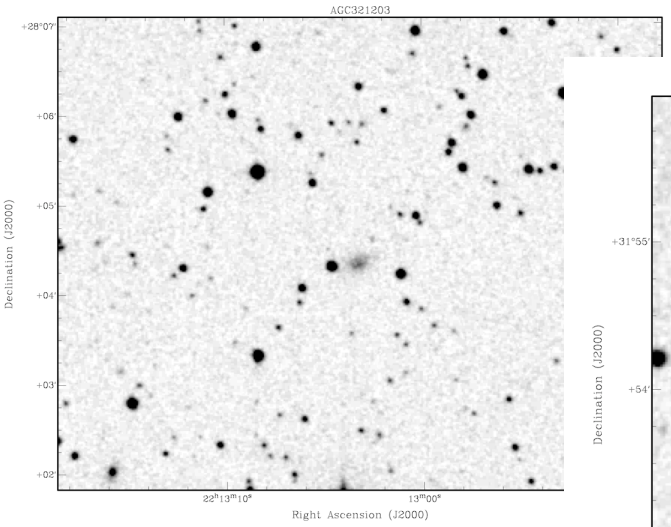
Martin *et al*. (2010)

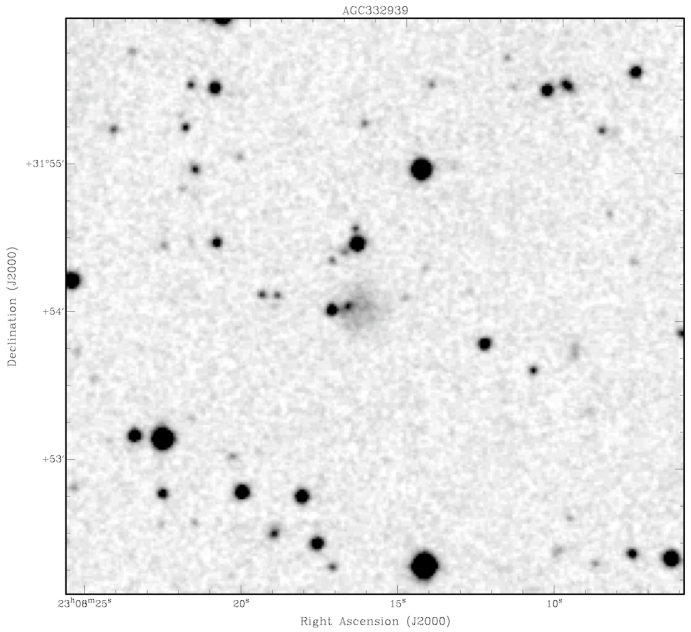
ALFALFA now has cataloged >400 galaxies with $M_{HI} < 10^8\ M_{\odot}$ and a few dozen with $M_{HI} < 10^7\ M_{\odot}$

What is the nature of galaxies with $M_{HI} < 10^7\ M_{\odot}$?

Harvesting ALFALFA: detectable stellar populations





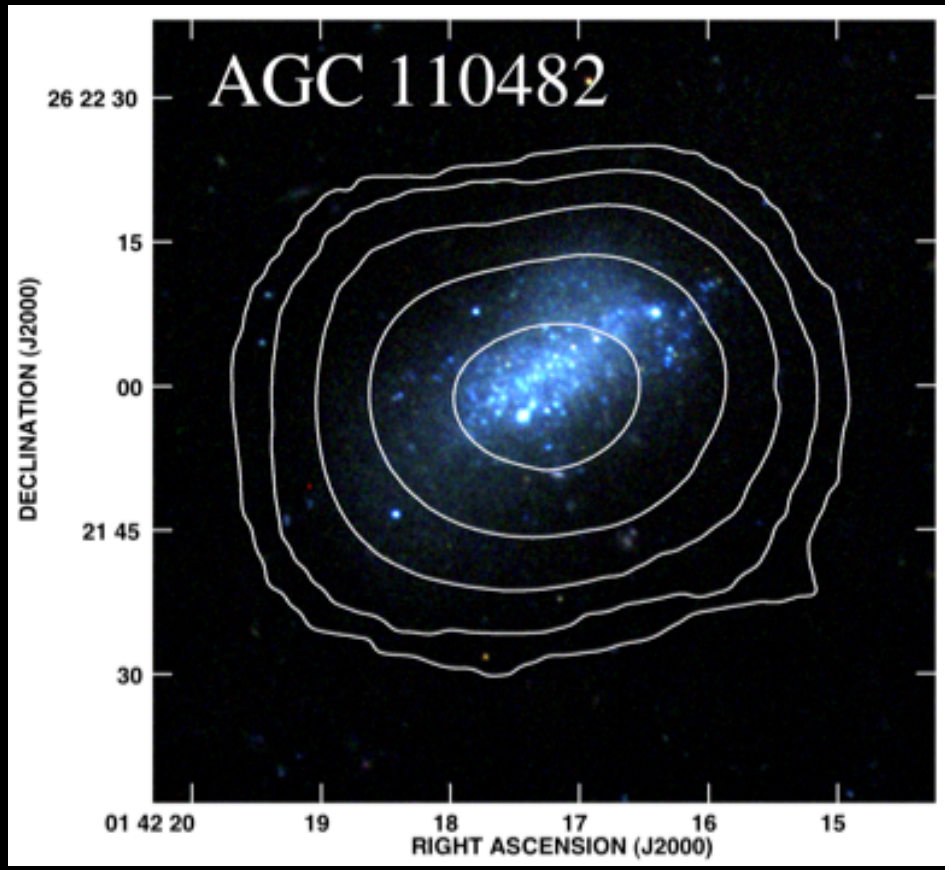


What is the nature of galaxies with HI masses of 10^7 $M_\odot$ and below?

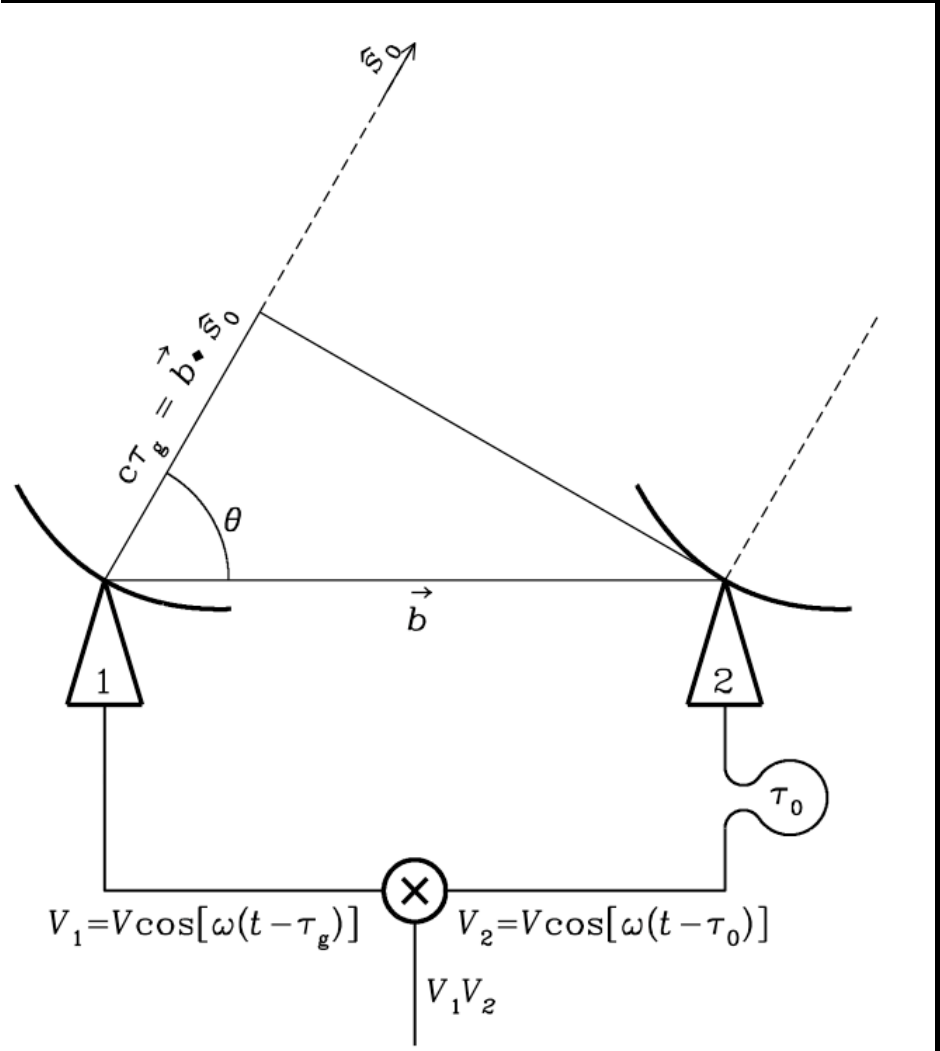
Exploring New Frontiers

ALFALFA = new, low-mass galaxies

EVLA follow-up

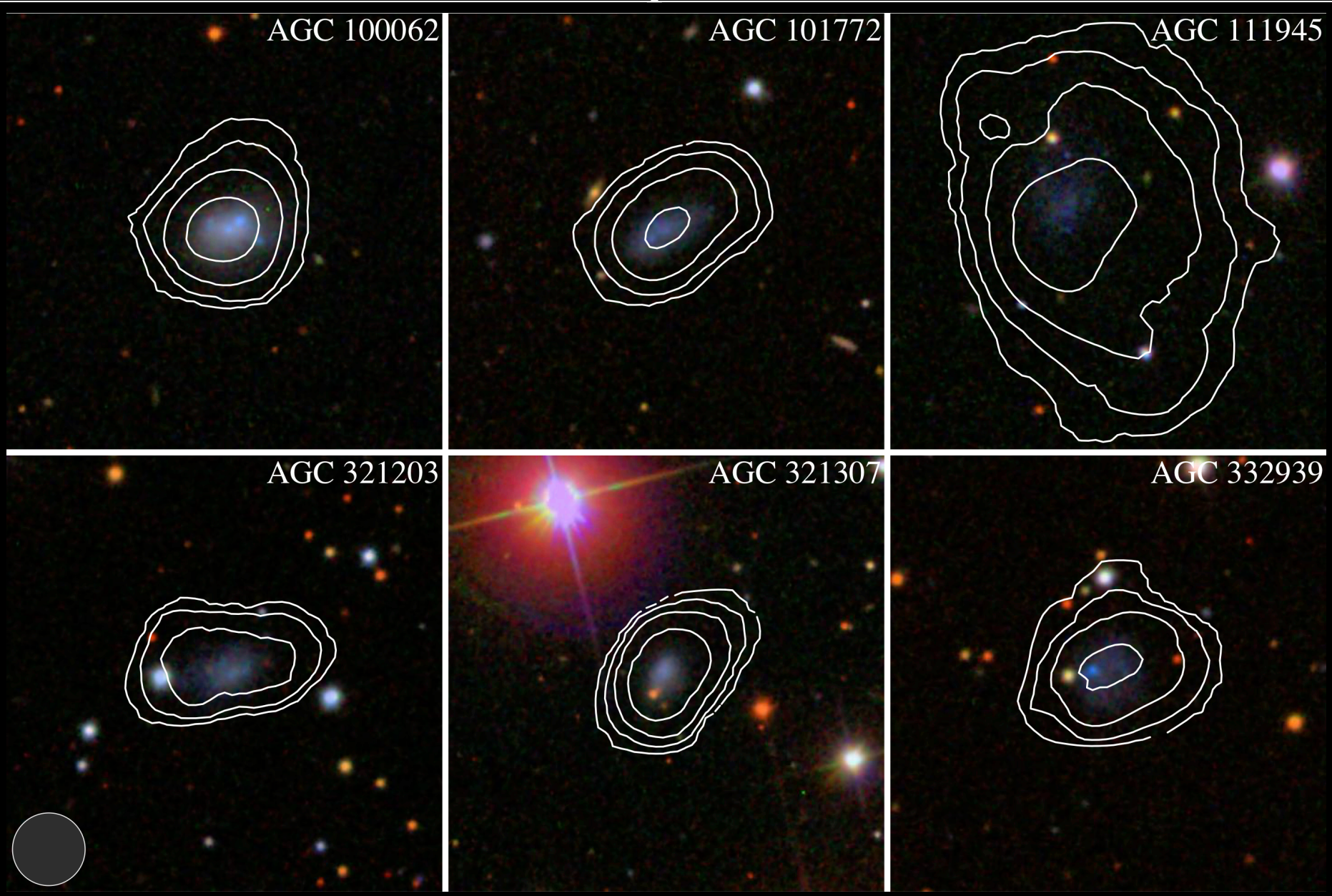


Interferometry (*Very* Briefly)



- Small telescopes (large field of view)
- Separate these by large distances (improves spatial resolution)
- *Correlate* the signals from all antenna pairs (measures intensity at a specific location)
- *Fourier transform* these data into the image plane

SHIELD Concept Demonstration



N_{HI} = (0.5, 1, 2, 4)x10^{20} cm^{-2}

Cannon *et al.* 2011, ApJ Letters (EVLA Special Edition)

SHIELD: Overview and Program Goals

- The Survey of HI in Extremely Low-mass Dwarfs
- 12 systems selected from > 20,000 ALFALFA sources
  - $M_{HI} < 10^7 M_\odot$
  - $W_{50} < 65$ km s^{-1}
  - Model distances < 8 Mpc
- Detectable stellar populations
- 15 hours per source with the *EVLA* (9/4/2 in B/C/D)
- 0.86 km s^{-1} ch^{-1}
- 5σ detection (per channel) of 10^{19} cm^{-2} (2.3×10^{20} cm^{-2}) columns at 40″ (6″) resolution

SHIELD: Sample Overview

TABLE 1
VLA/EVLA Observations of ALFALFA-Selected Low-Mass Dwarf Galaxies

AGC[a] #	α (J2000)	δ (J2000)	Distance (Mpc)	M_r (mag)	(u−r) (mag)	M_B (mag)	(B−V) (mag)	$\%Z_\odot$ [b]	V_{21} (km s^{-1})	W_{21} (km s^{-1})	$\log(M_{HI})$ ($M_\odot$)
				Concept Demonstration Targets							
100062	00:09:52.8	15:43:58	12.7[c]	−15.02	1.02±0.02	N/A	N/A	N/A	869	45	7.82
101772	00:11:08.2	14:14:08	11.7[c]	−13.64	0.98±0.06	N/A	N/A	N/A	802	37	7.54
111945	01:44:42.7	27:17:18	6.3[c]	−11.88[d]	3.35±1.26[d]	N/A	N/A	N/A	420	38	7.28
321203	22:13:03.3	28:04:28	16.4[c]	−14.20	0.98±0.04	N/A	N/A	14%	983	62	7.83
321307	22:14:04.4	25:41:08	18.7[c]	−13.88	1.24±0.07	N/A	N/A	N/A	1152	60	7.96
332939	23:08:16.0	31:53:57	11.4[c]	−13.67	0.69±0.05	N/A	N/A	N/A	692	41	7.74
				The SHIELD Sample							
748778	00:06:34.3	15:30:39	5.4[c]	−10.52	0.81±0.19	−10.02	0.25±0.03	N/A	258	16	6.51
112521	01:41:07.6	27:19:24	7.2[e]	−11.52[d]	2.19±0.42[d]	−10.80	0.45±0.03	6%	274	26	6.92
110482	01:42:17.4	26:22:00	7.2[e]	−13.63	1.25±0.04	−12.86	0.49±0.02	13%	357	30	7.21
111946	01:46:42.2	26:48:05	7.2[e]	−11.49[d]	1.46±0.25[d]	−11.48	0.39±0.03	5%	367	21	6.97
111977	01:55:20.2	27:57:14	5.5[f]	−12.55[d]	2.26±0.16[d]	−12.31	0.47±0.02	N/A	207	26	6.78
111164	02:00:10.1	28:49:52	4.9[f]	−11.50[d]	0.80±0.09[d]	−11.10	0.41±0.02	N/A	163	27	6.57
174585[g]	07:36:10.3	09:59:11	6.1[c]	N/A	N/A	N/A	N/A	N/A	356	21	6.68
174605	07:50:21.7	07:47:40	6.0[c]	−10.46[d]	1.85±0.21[d]	−10.98	0.47±0.05	N/A	351	24	6.75
182595	08:51:12.1	27:52:48	6.1[c]	−12.45	1.27±0.05	−11.75	0.52±0.05	N/A	398	20	6.66
731457	10:31:55.8	28:01:33	5.4[c]	−12.55	1.23±0.03	−12.02	0.39±0.05	N/A	454	36	6.63
749237	12:26:23.4	27:44:44	3.2[c]	−11.58	1.28±0.03	−11.21	0.44±0.05	N/A	372	65	6.64
749241	12:40:01.7	26:19:19	4.3[c]	−9.27	0.83±0.15	−9.57	0.22±0.05	N/A	451	18	6.52

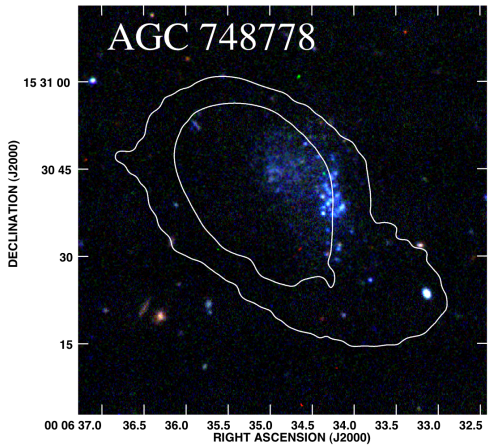
[a] Arecibo General Calalog
[b] Assuming the Solar oxygen abundance From Asplund et al. (2009).
[c] Flow model estimate.
[d] Magnitudes and colors uncertain due to *SDSS* shredding issues.
[e] Probable member of NGC 672 group.
[f] Tip of the red giant branch.
[g] AGC 174585 is outside the SDSS footprint; an absolute calibration of the WIYN 3.5m observations awaits subsequent re-imaging.

- Median (estimated) HI mass = 4.7x10^6 $M_\odot$
- Distances uncertain: critical need for *HST*

SHIELD: Science Drivers

- What properties change between mini-halos, very low-mass dwarfs, and more massive systems?
- What fraction of the mass in these low-mass dwarfs is baryonic?
- Is the character of the SF process different in very low-mass galaxies?
- Use SHIELD results to constrain models of galaxy evolution

SHIELD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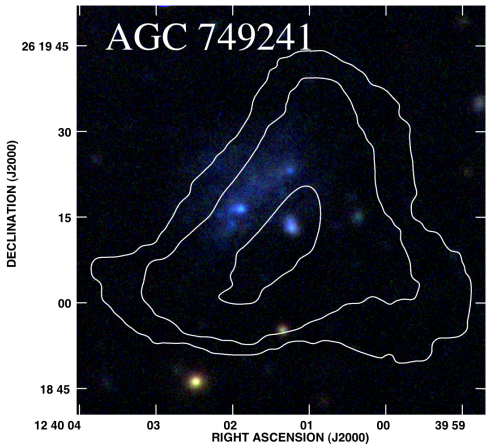
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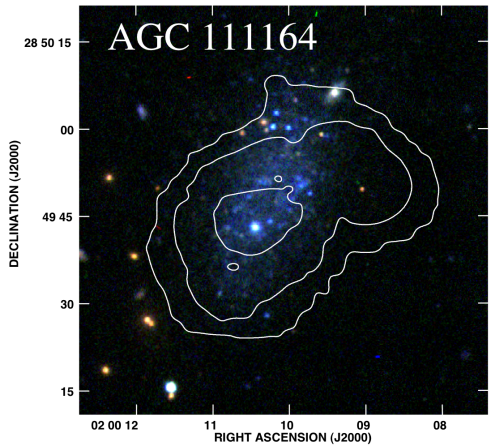
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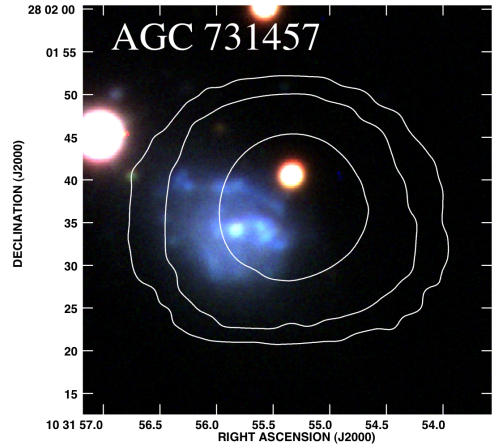
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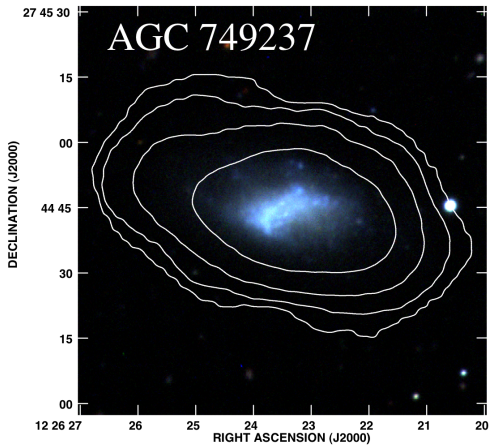
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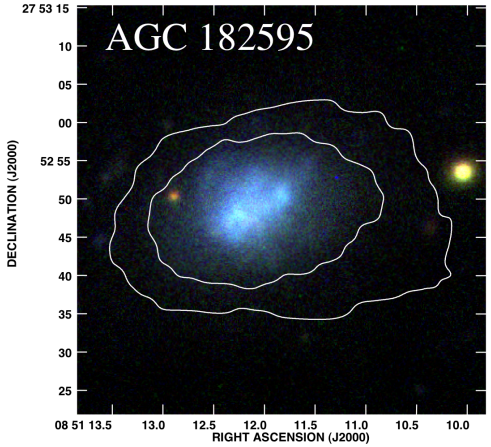
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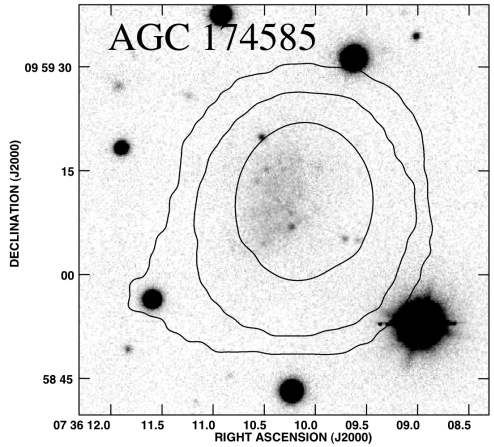
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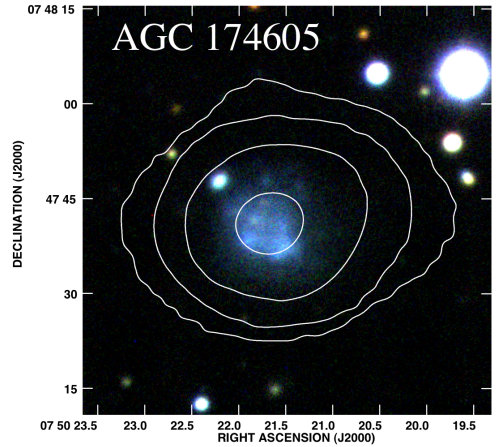
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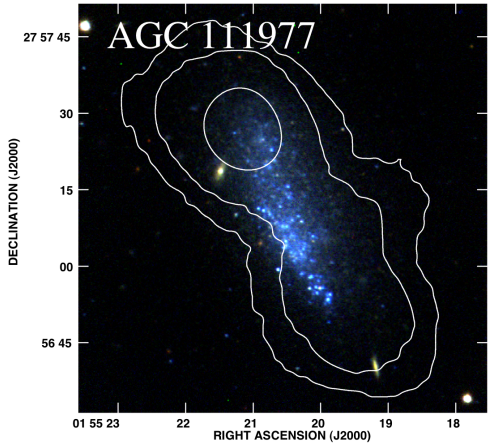
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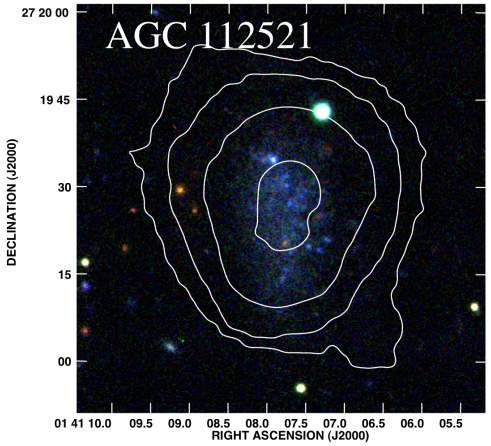
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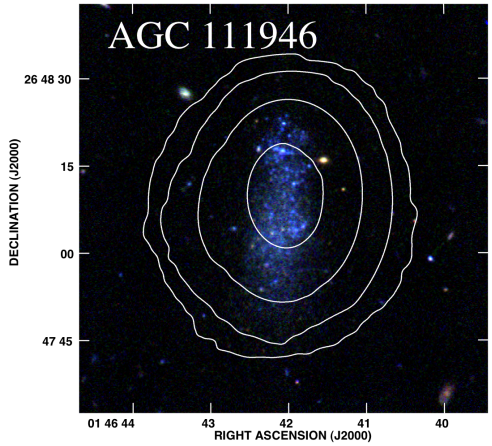
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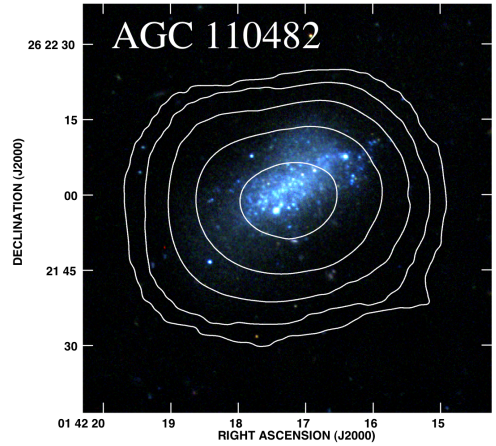
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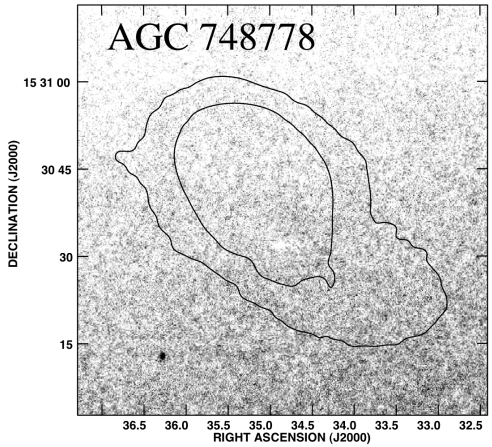
SHIELD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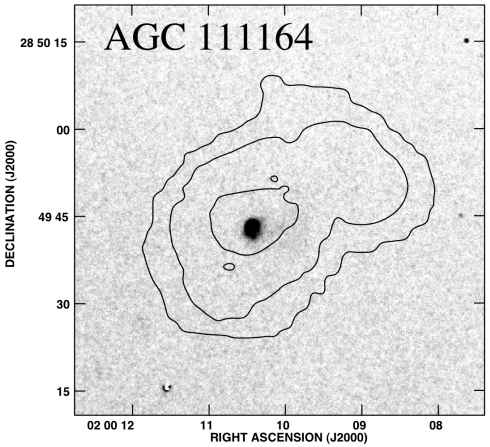
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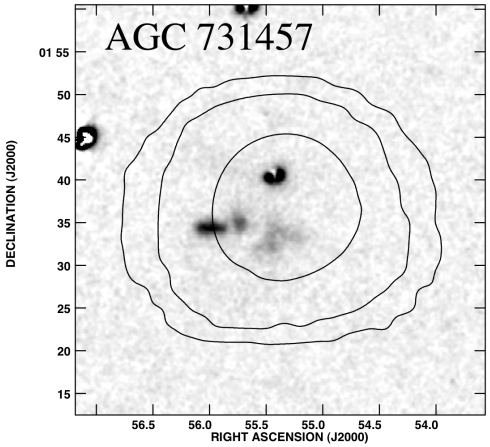
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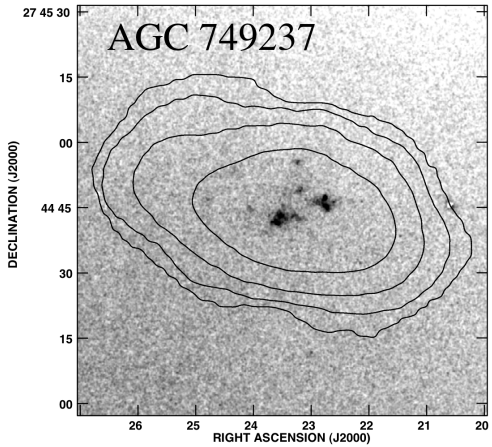
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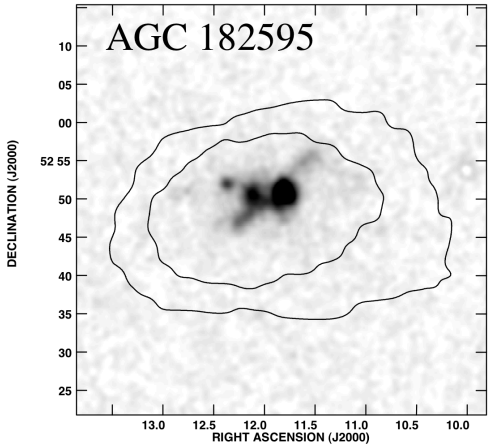
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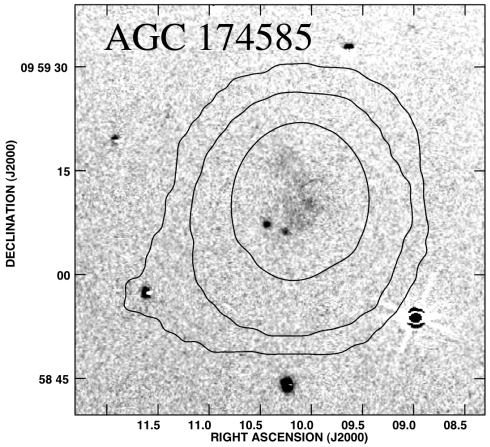
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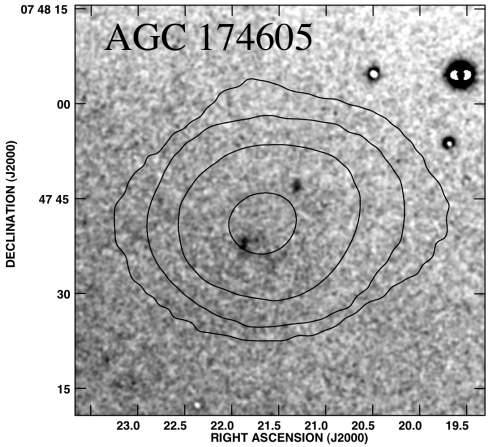
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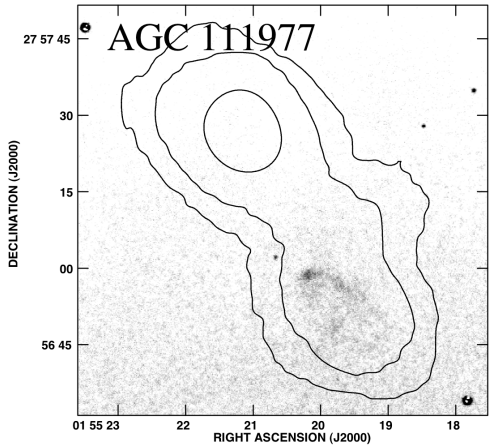
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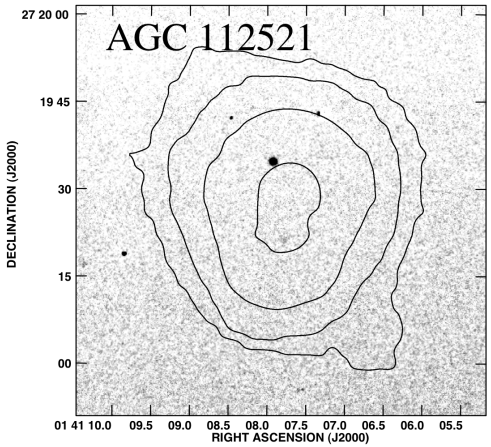
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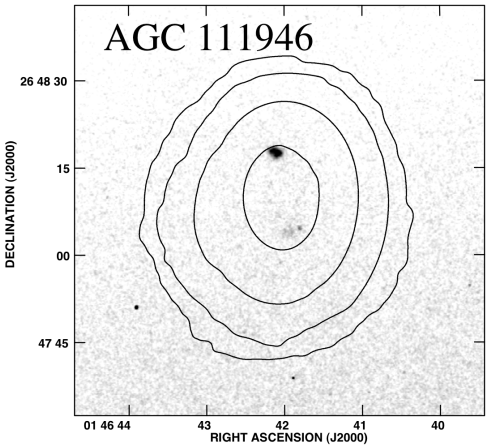
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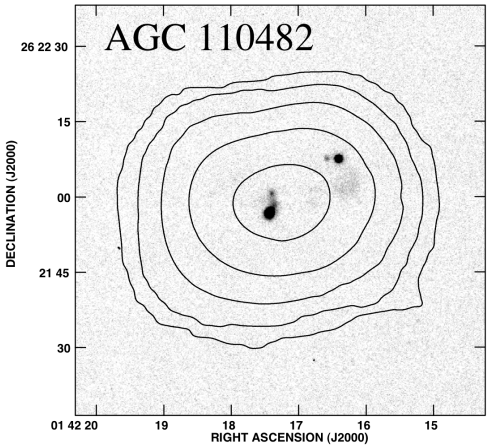
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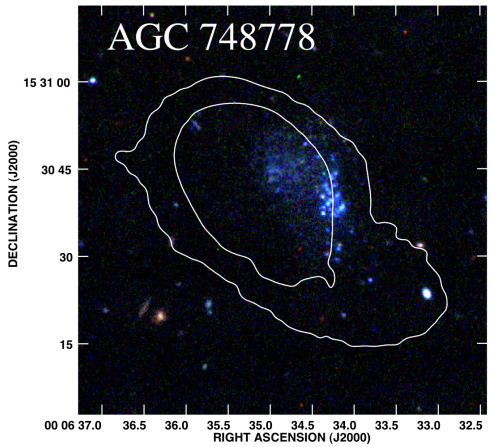
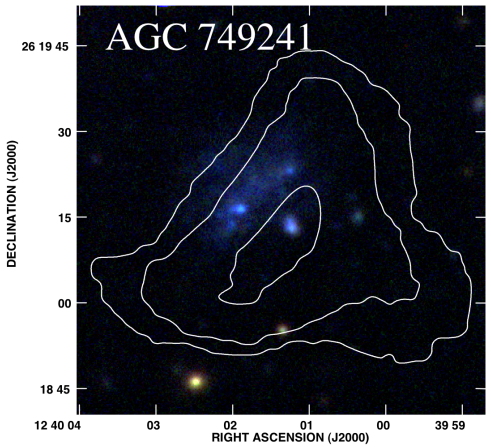
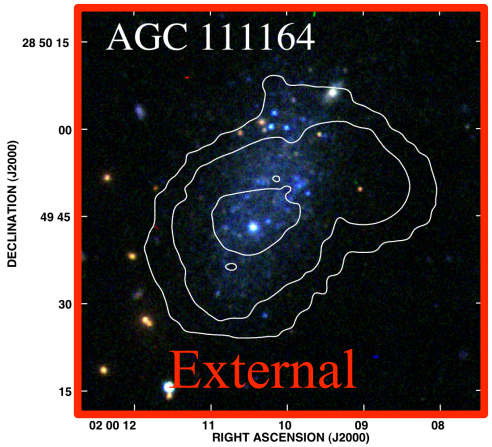
RIGHT ASCENSION (J2000)

SHIELD


AGC 748778
DECLINATION (J2000)
RIGHT ASCENSION (J2000)


AGC 749241
DECLINATION (J2000)
RIGHT ASCENSION (J2000)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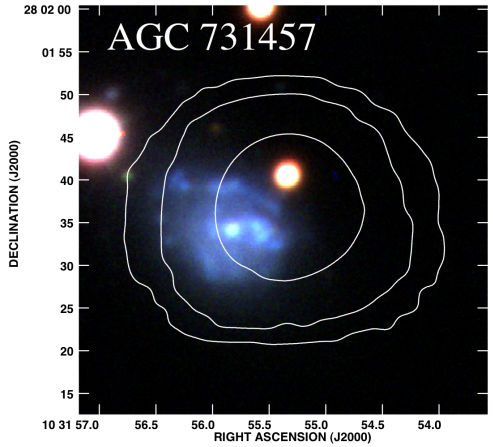
External
DECLINATION (J2000)
RIGHT ASCENSION (J2000)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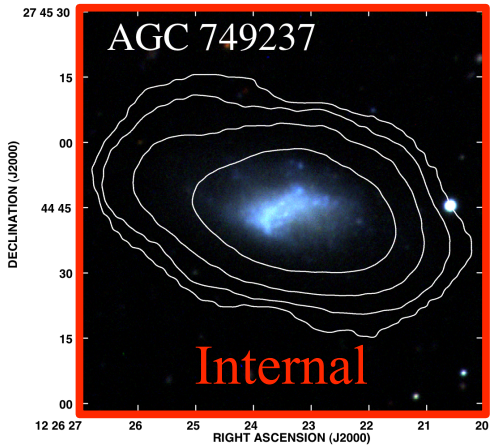
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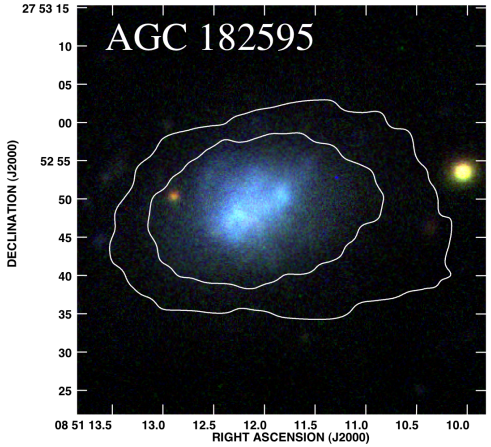
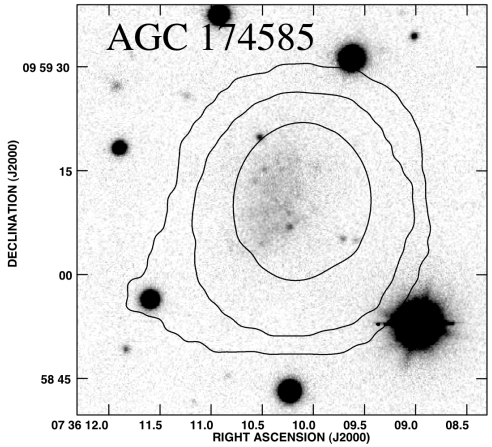
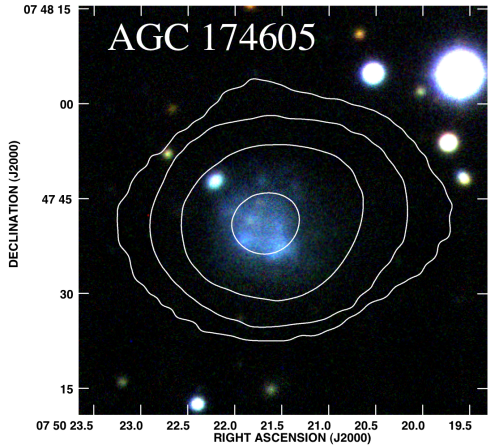
Internal
DECLINATION (J2000)
RIGHT ASCENSION (J2000)


AGC 182595
DECLINATION (J2000)
RIGHT ASCENSION (J2000)


AGC 174585
DECLINATION (J2000)
RIGHT ASCENSION (J2000)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DECLINATION (J2000)
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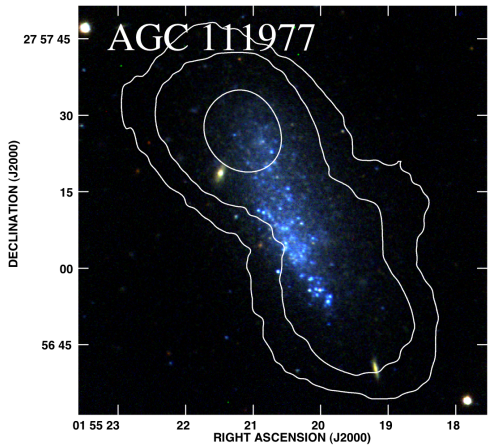
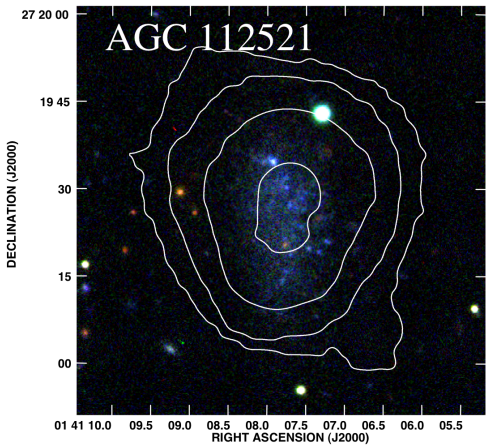

AGC 111977
DECLINATION (J2000)
RIGHT ASCENSION (J2000)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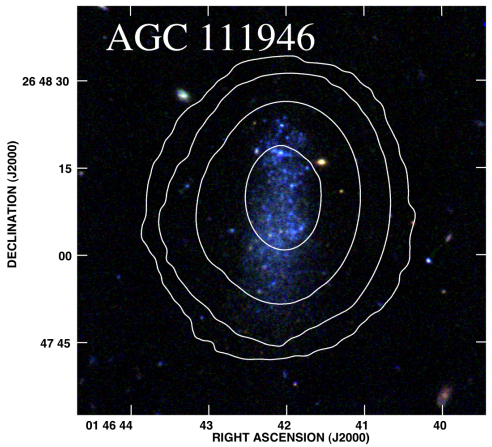
DECLINATION (J2000)
RIGHT ASCENSION (J2000)


AGC 111946
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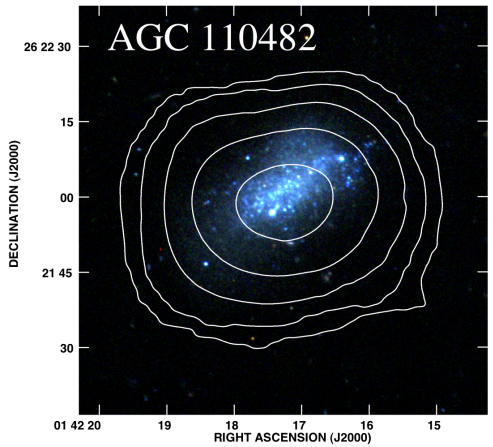
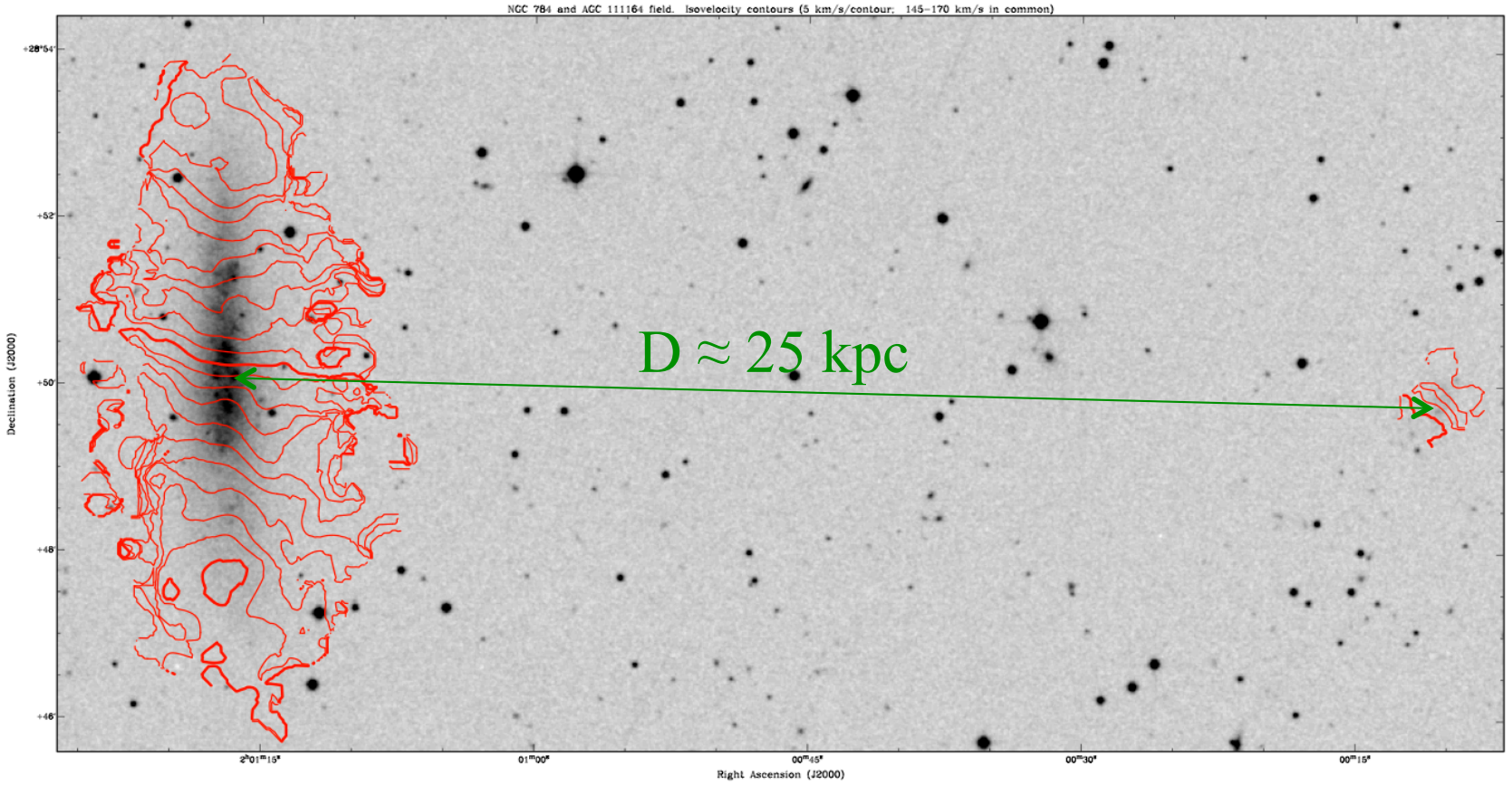
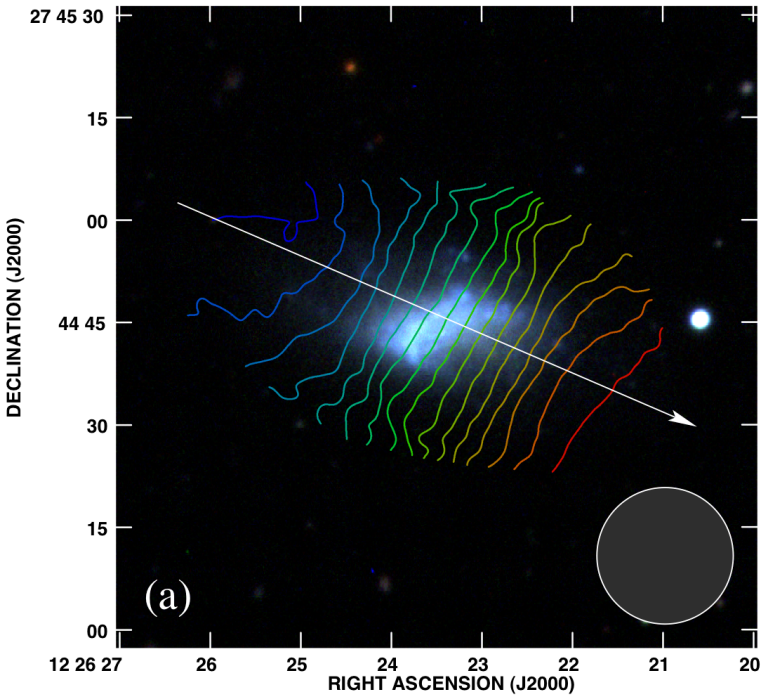

AGC 110482
DECLINATION (J2000)
RIGHT ASCENSION (J2000)

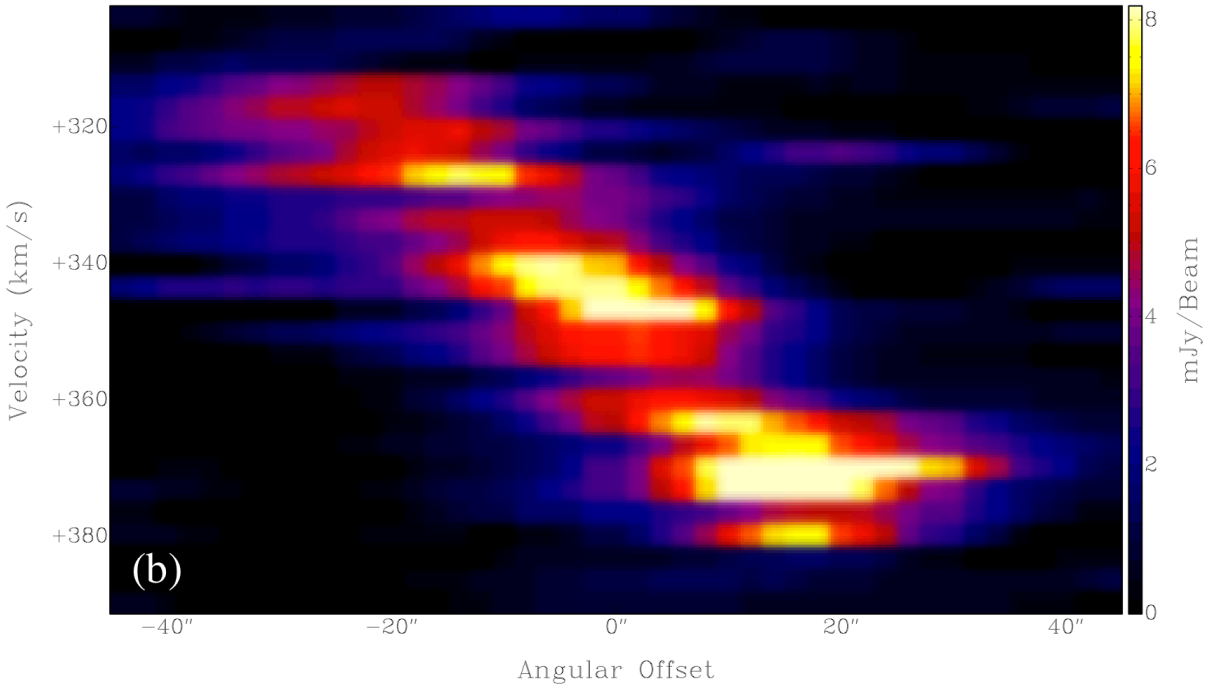
SHIELD: Preliminary Results – AGC 111164



An extremely low-mass, gas-rich satellite, within the virial radius of a relatively massive galaxy (c.f., Sawala et al. 2011)

SHIELD: Preliminary Results – AGC 749237





325-370 km s^{-1}, 3 km s^{-1} intervals

30 km s^{-1} solid-body rotation at R=620 pc

$M_{dyn} \sim 1 \times 10^8 M_\odot$

$M_{dyn}/M_{baryon} \sim 11$

Cannon *et al.* 2011, ApJ Letters (EVLA Special Edition)

SHIELD: Preliminary Results

- HI distributions are remarkably concentrated
- Most systems have coherent rotation
  - Some systems show incoherent motions and disrupted velocity fields
- 11 of 12 galaxies have *WIYN 3.5m* Hα imaging
  - 10 of 11 have active star formation
- Only 1 system with $N_{HI} > 10^{21}$ cm^{-2} at 20″ resolution
  - *The SHIELD galaxies are forming stars in conditions different from those seen in more massive systems*
- Preliminary dynamical analyses reveal high mass-to-light ratios
- The SHIELD galaxies have retained baryons inside halos of total mass $<10^8$ $M_\odot$
  - *Among the lowest-mass gas-bearing halos known*

SHIELD: Preliminary Results

- Are the SHIELD galaxies part of the population that will solve the missing satellite problem?
  - Number density of these systems (with stellar populations) appears too low
  - However, models predict a substantial population of halos of similar mass *without* a stellar population
  - ALFALFA continues to search and find both
- The galaxy population to which the SHIELD members belong remains cosmologically critical
  - Most systems of this dynamical mass have been destroyed
  - How have the systems discovered to date survived?

SHIELD: The Next Steps – HST Imaging

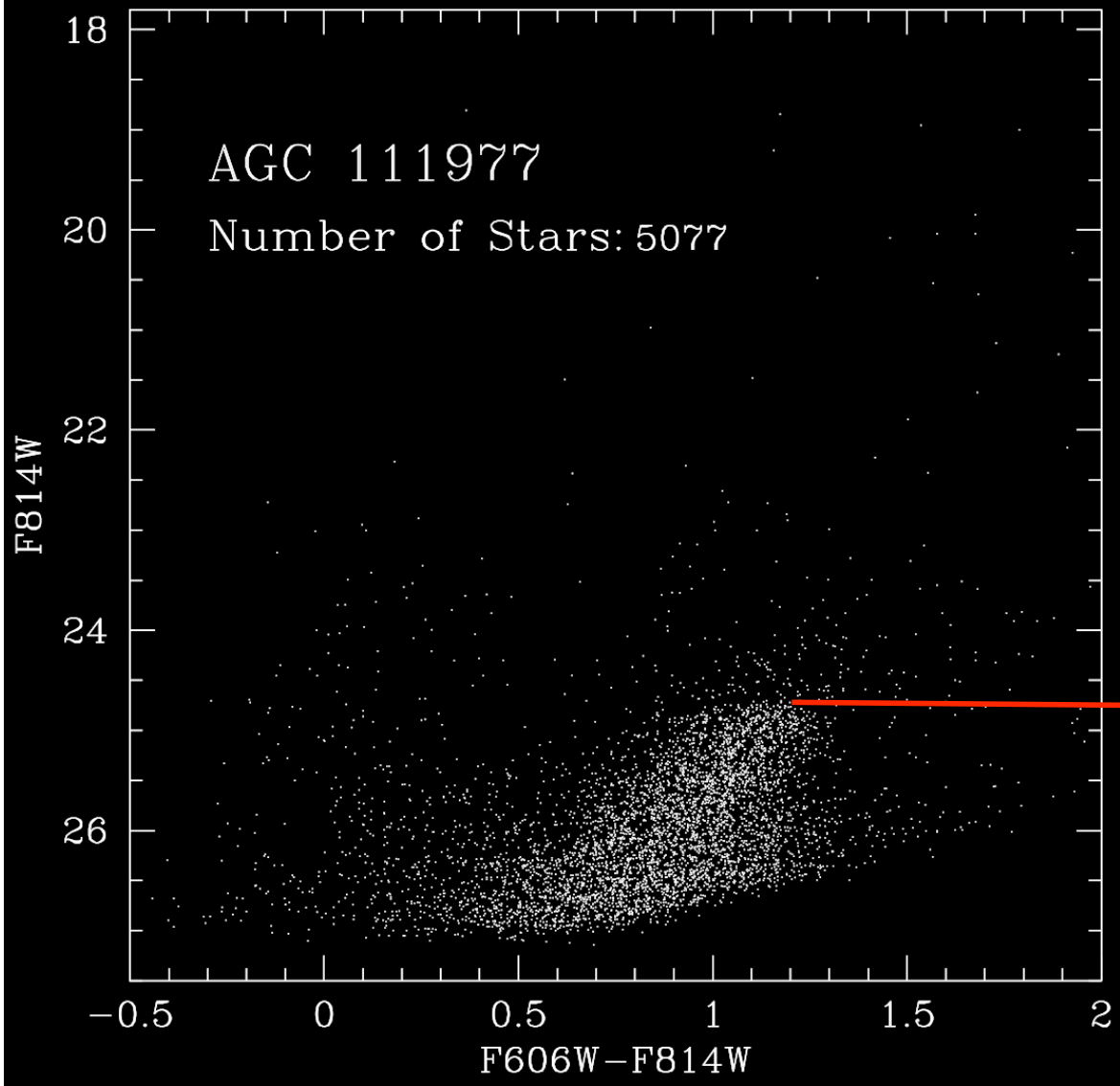
AGC 174585

AGC 111977

AGC 748778

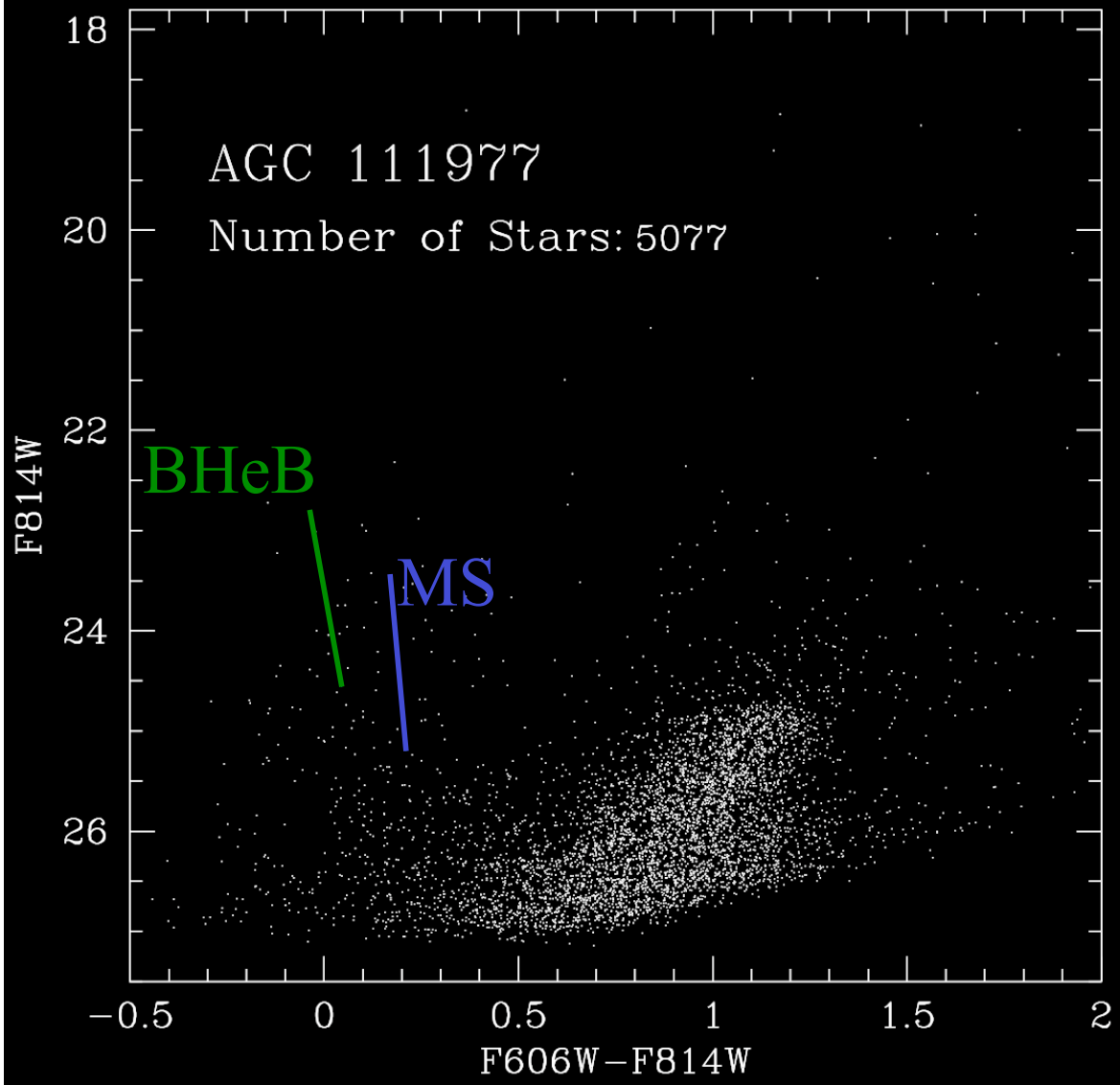
SHIELD: The Next Steps – HST Imaging

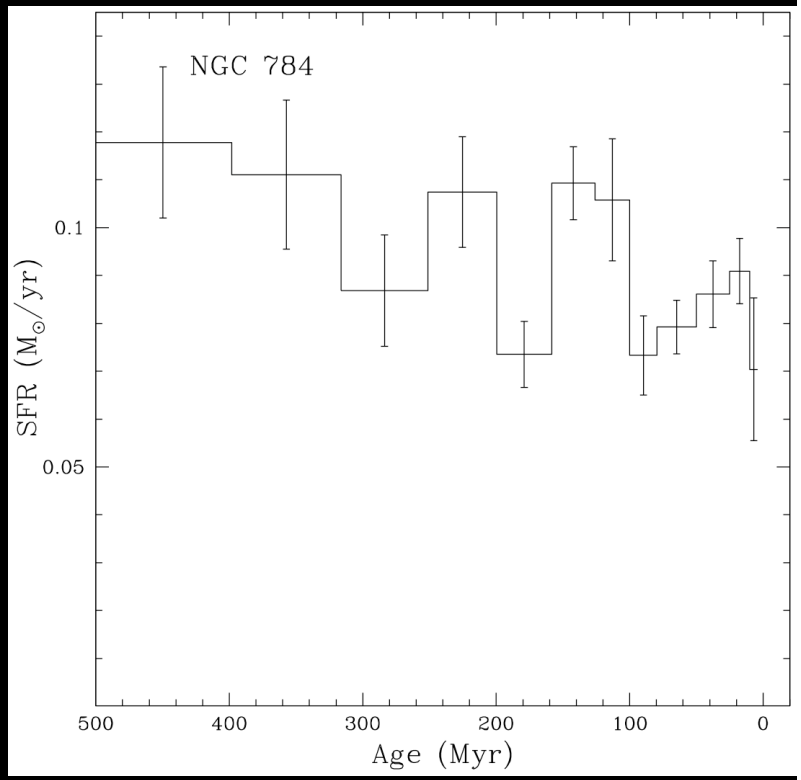
AGC 111977



TRGB = distance

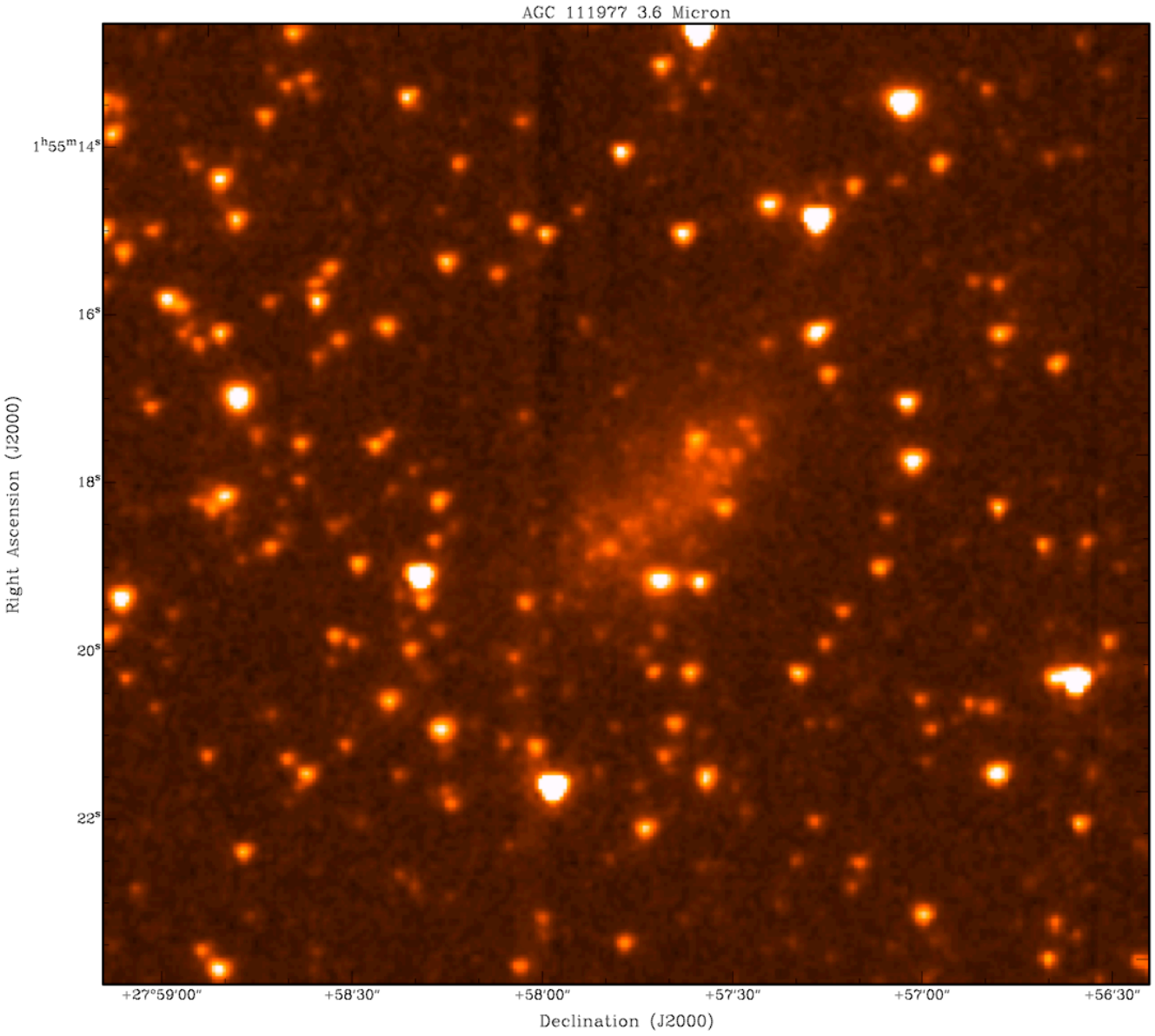
SHIELD: The Next Steps – HST Imaging



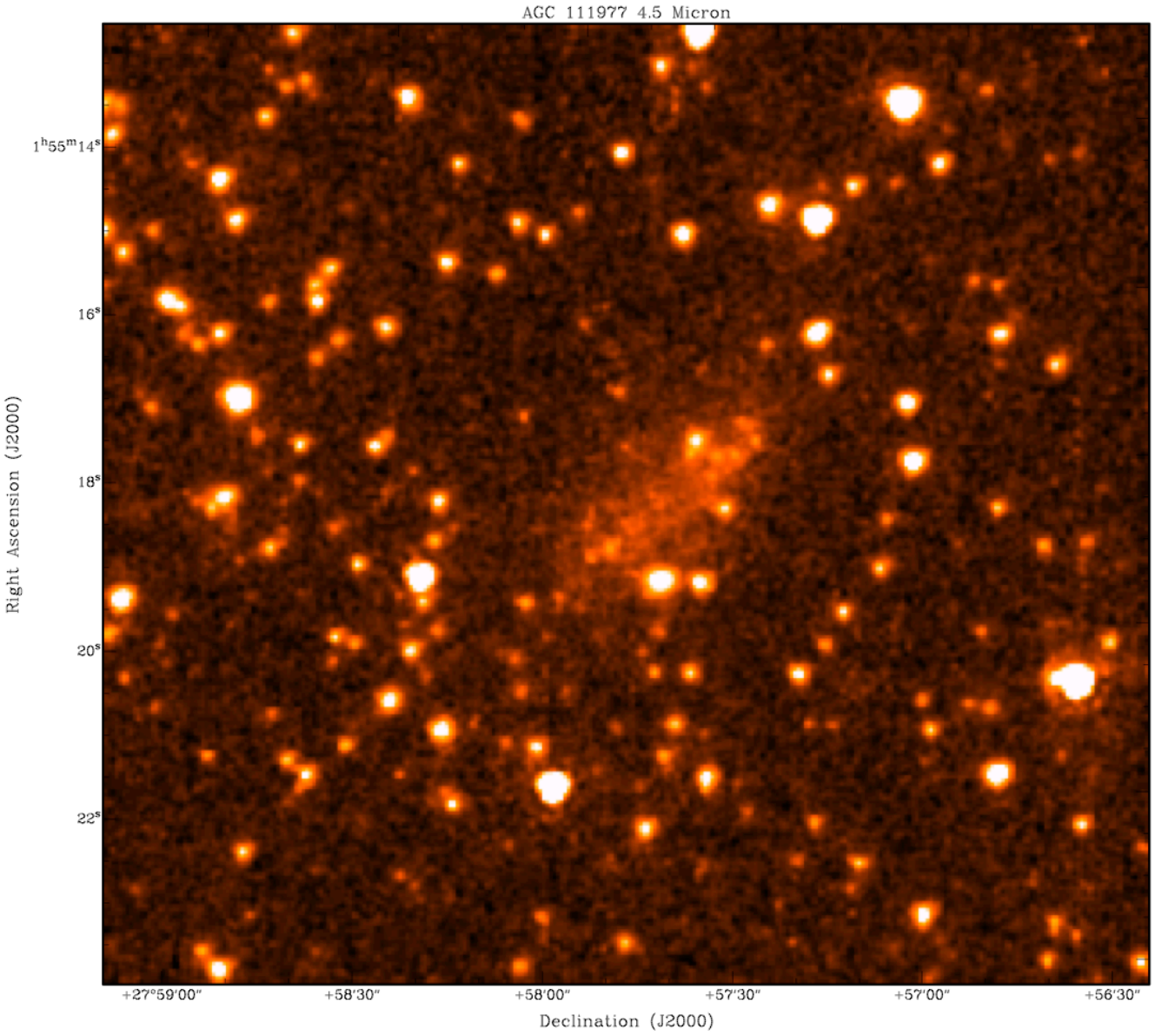


McQuinn *et al.* (2010)

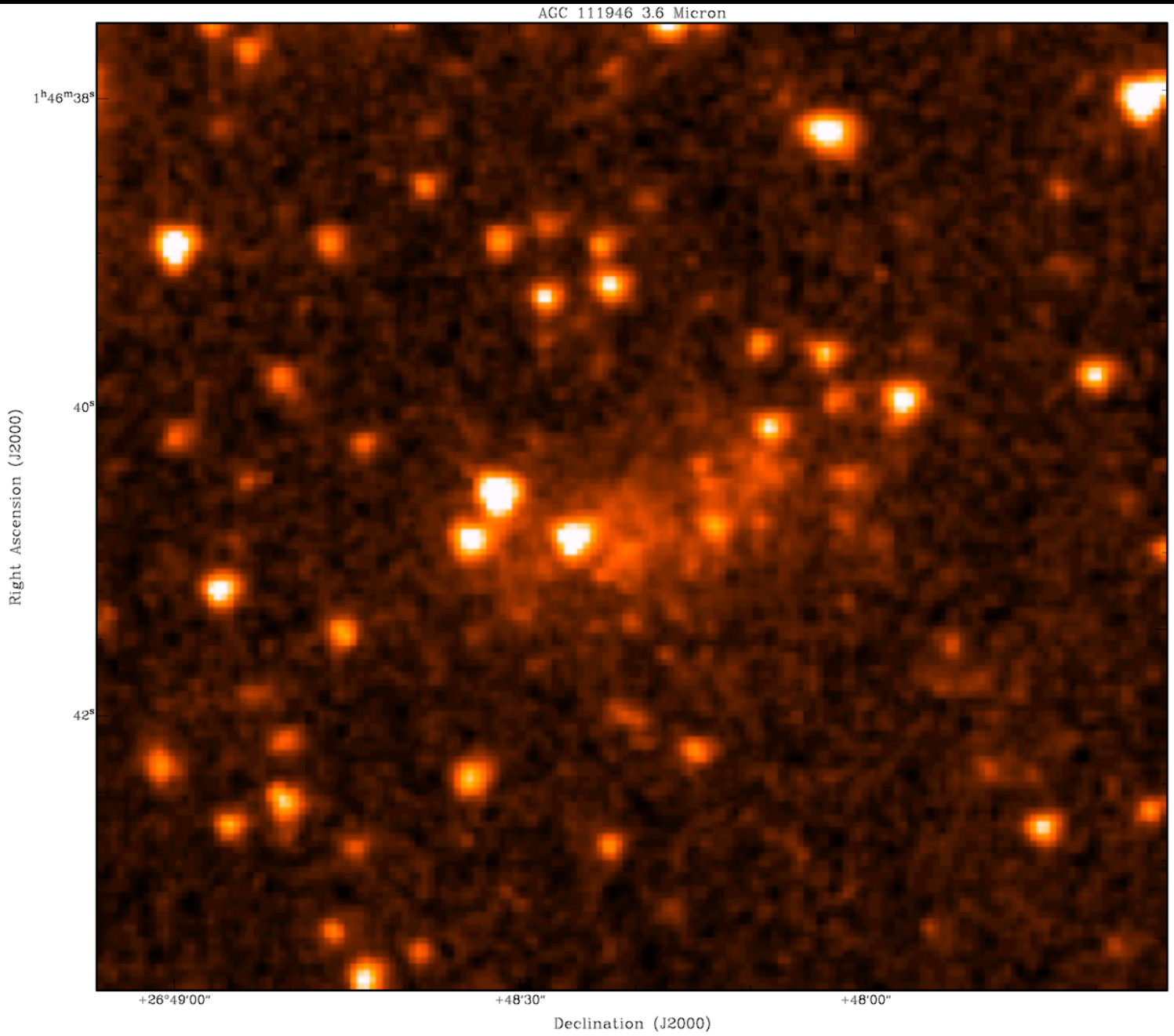
SHIELD: The Next Steps – Spitzer Imaging



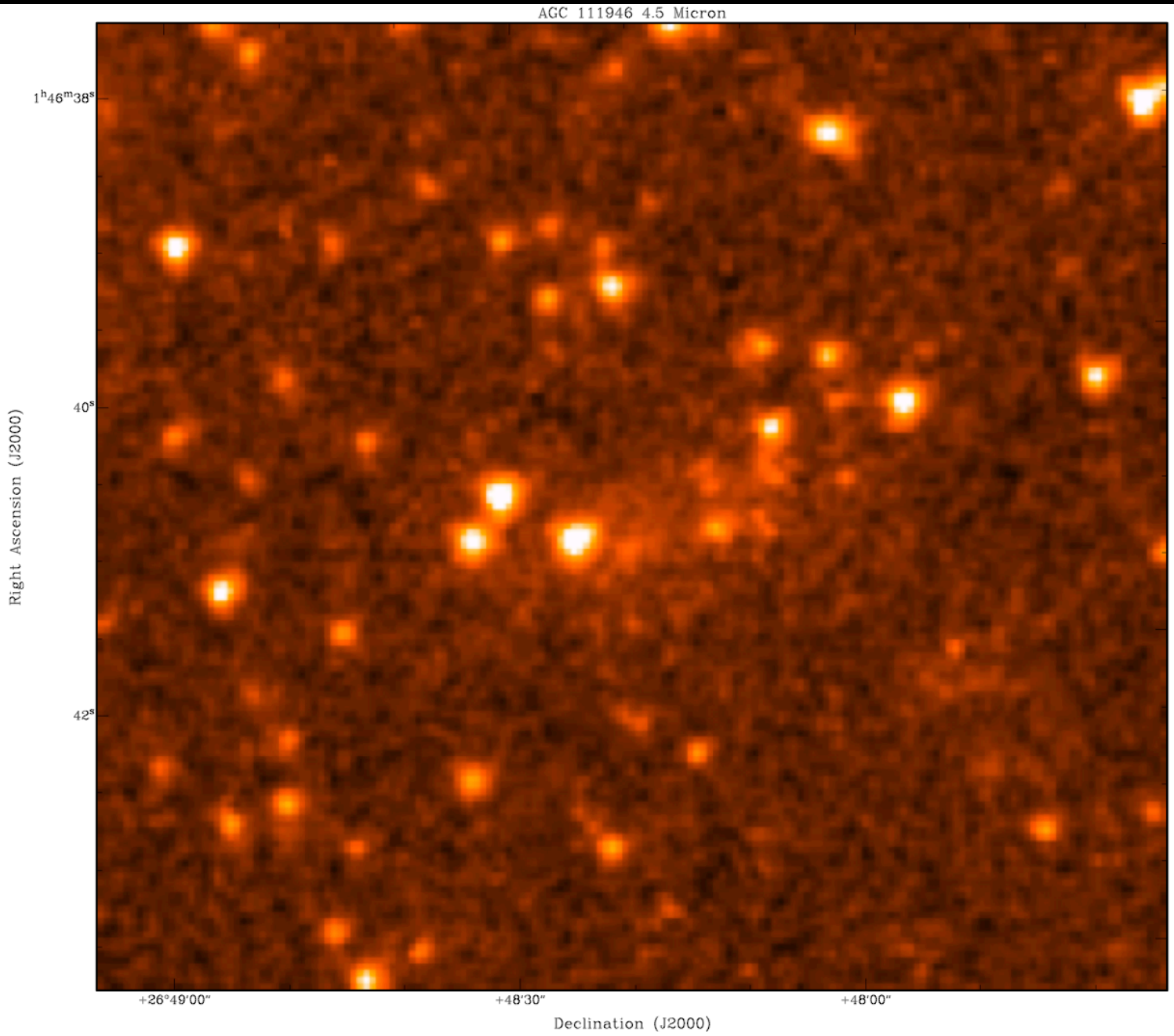
SHIELD: The Next Steps – Spitzer Imaging



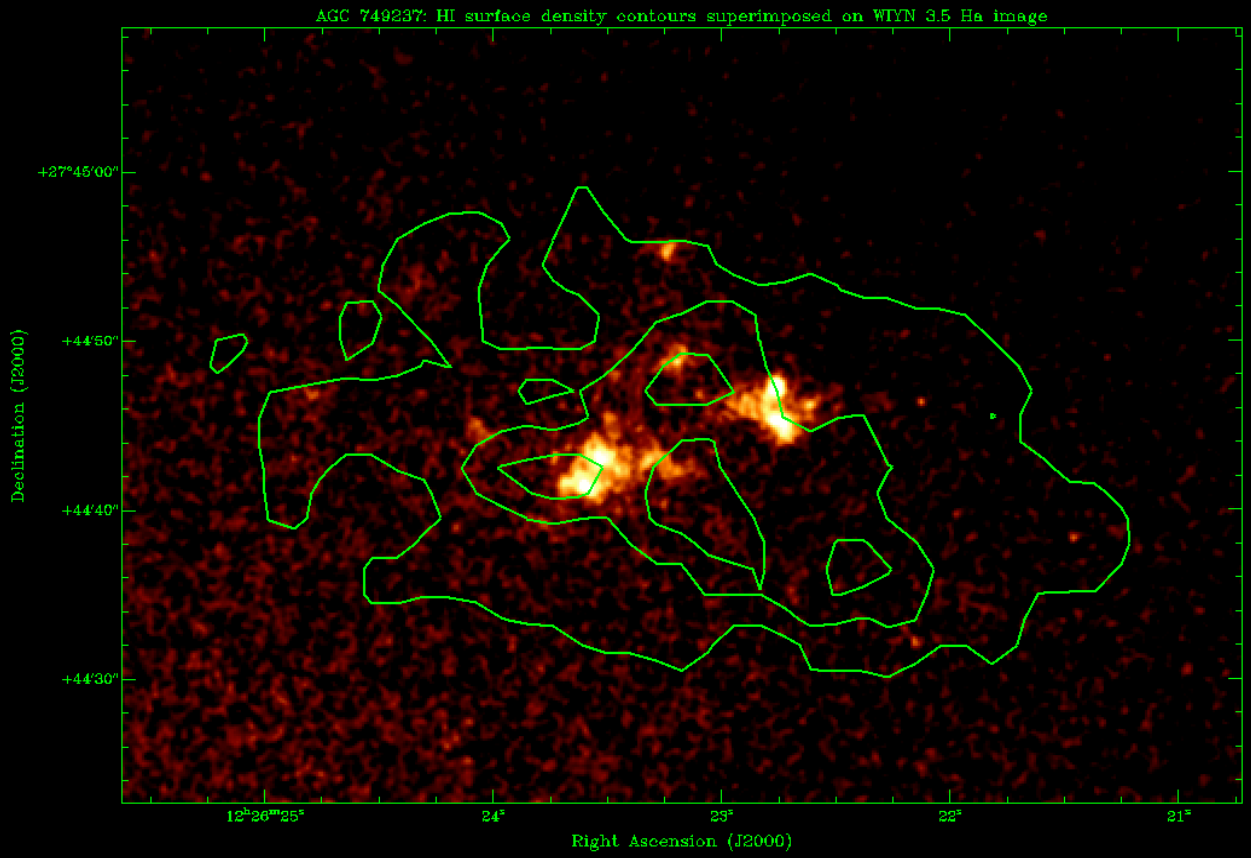
SHIELD: The Next Steps – Spitzer Imaging



SHIELD: The Next Steps – Spitzer Imaging

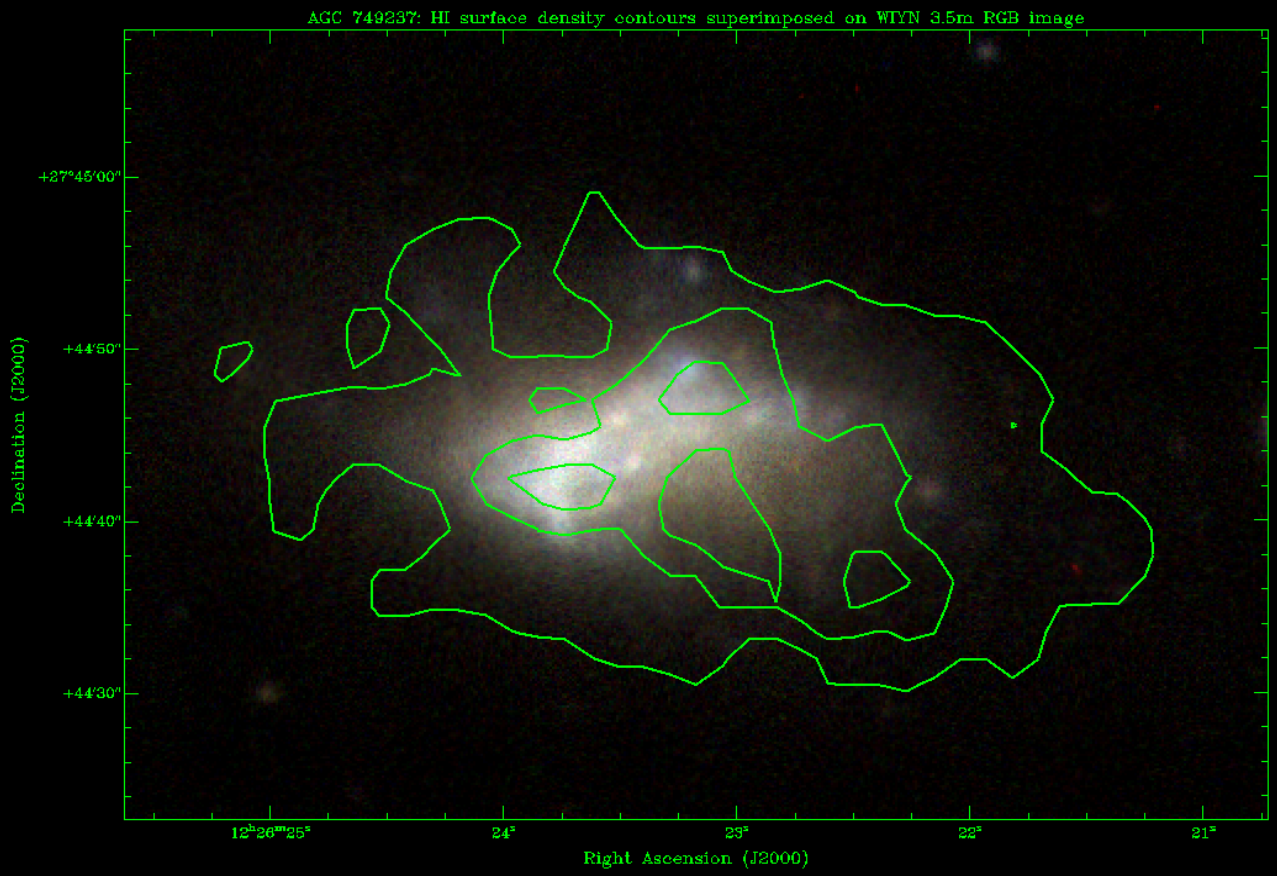


SHIELD: The Next Steps



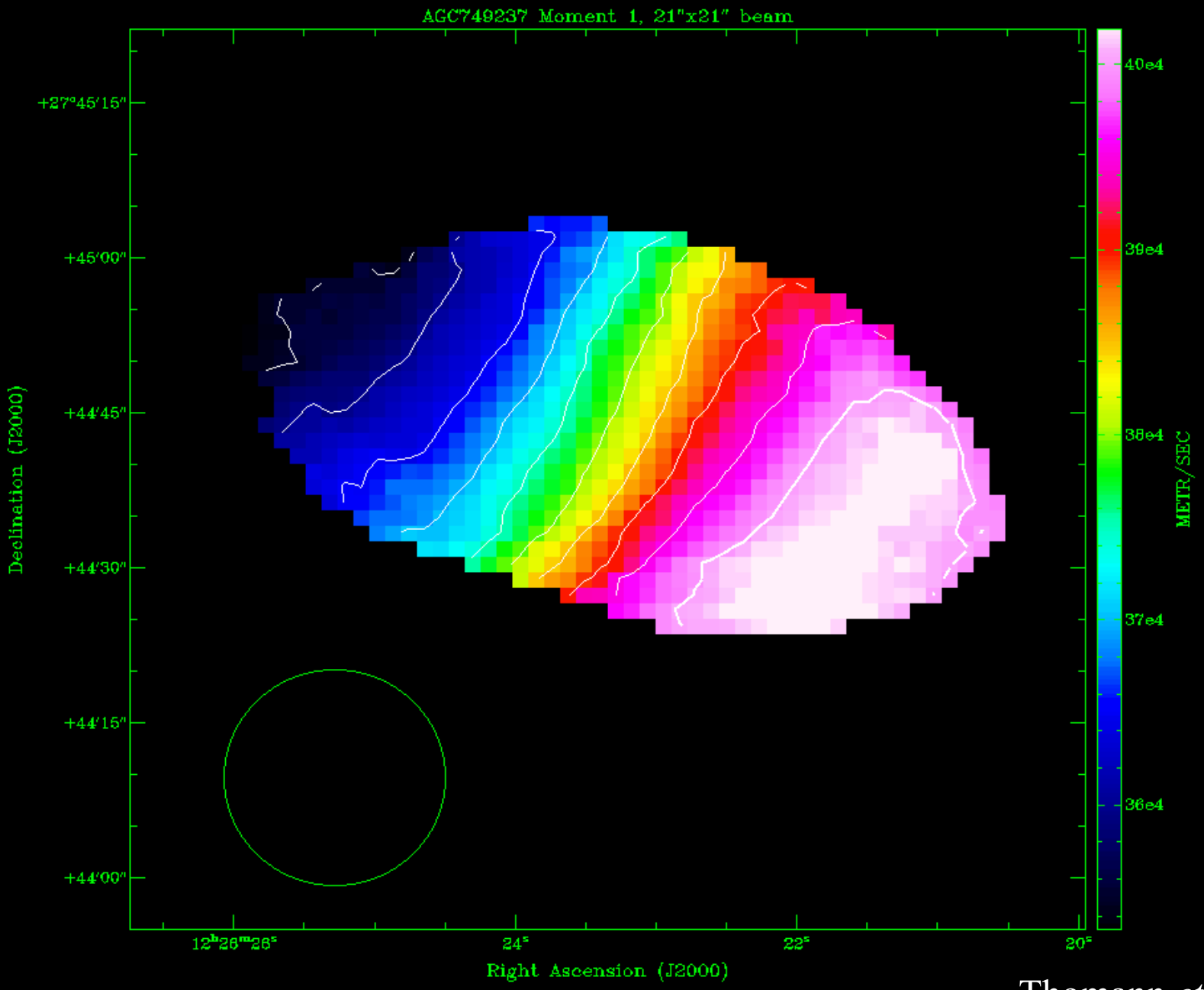
Thomann *et al.* 2012

SHIELD: The Next Steps



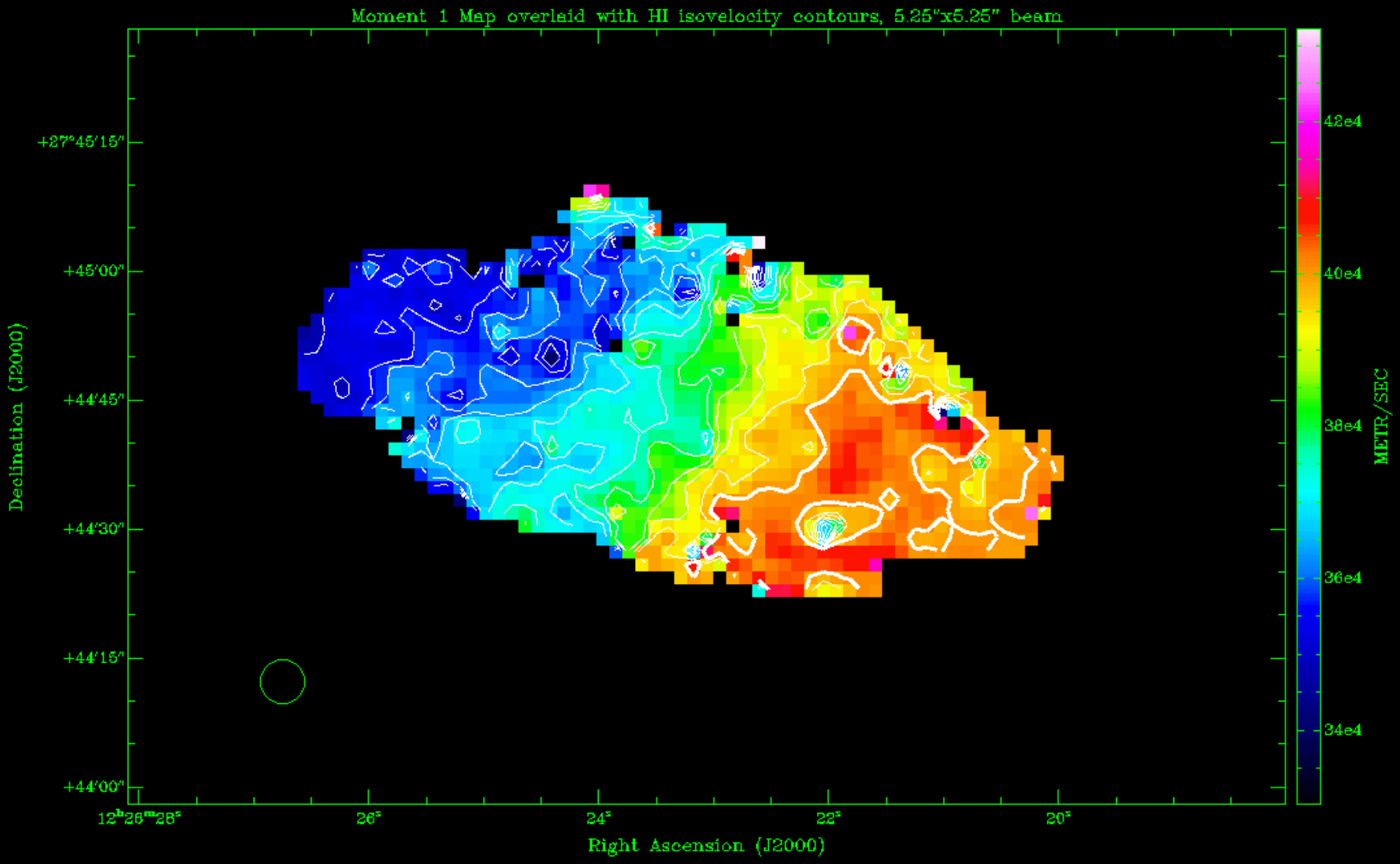
Thomann *et al.* 2012

SHIELD: The Next Steps



Thomann *et al.* 2012

SHIELD: The Next Steps



Thomann *et al.* 2012

SHIELD: Long-Term Prospectus

Large multiwavelength campaign now in progress

Well-studied

$f_b \sim 0.01$ ← → $f_b \sim 0.16$

M_{HI} ($M_\odot$)	10^5	10^6	10^7	10^8	10^9	10^{10}	
M_{dyn} ($M_\odot$)	10^7	10^8	10^8	10^9	10^9	10^{10}	10^{11}