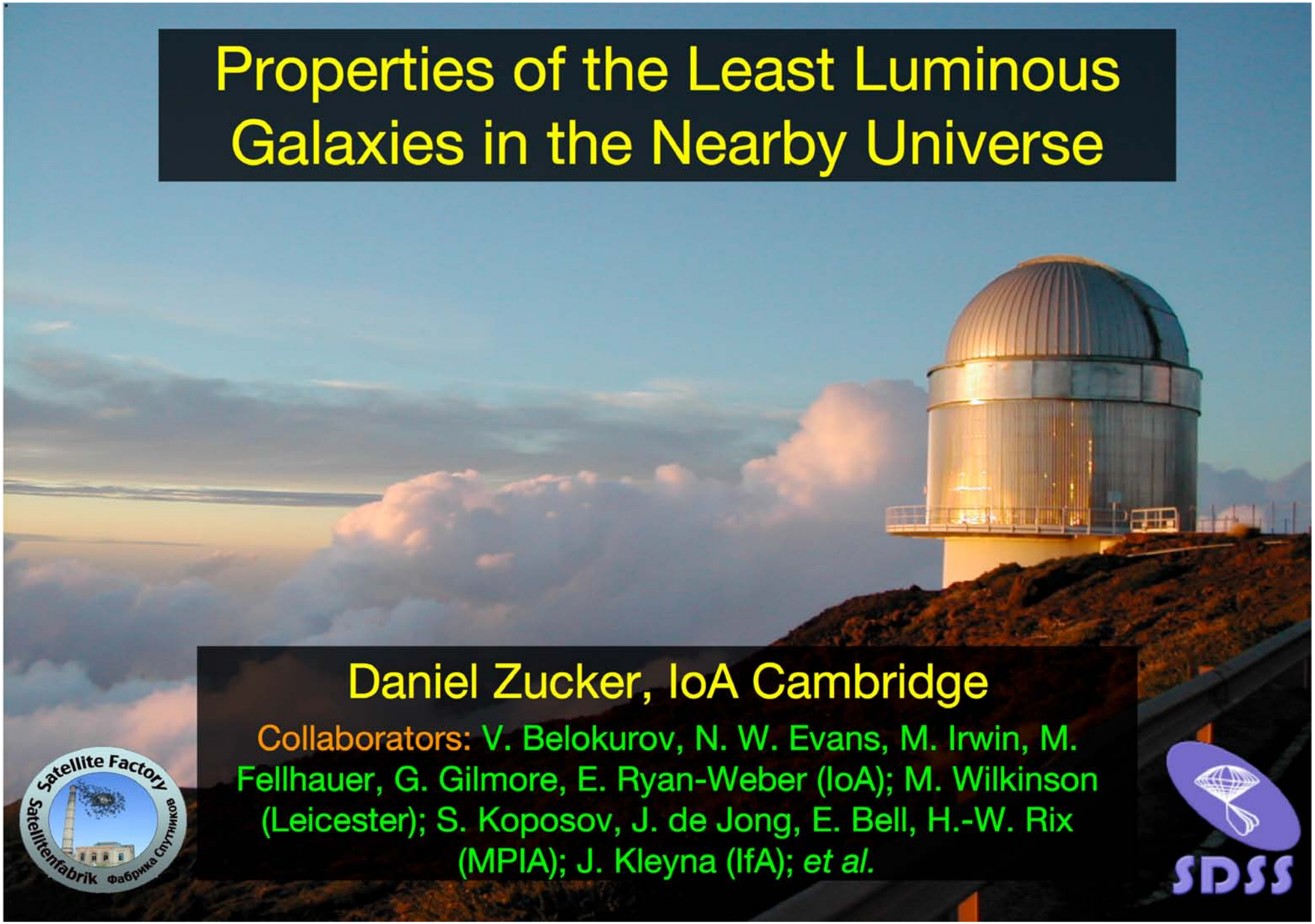
Properties of the Least Luminous Galaxies in the Nearby Universe

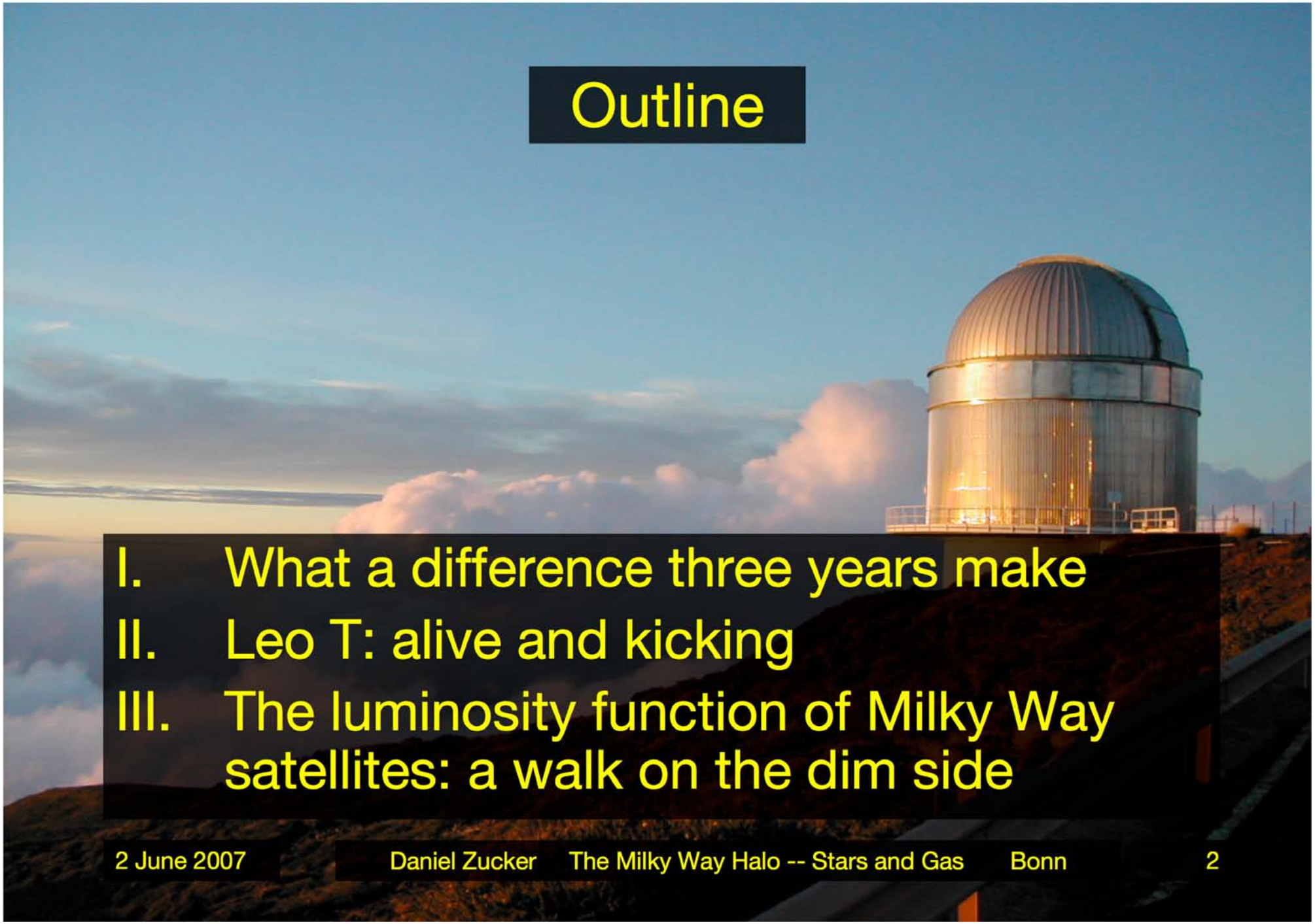


Daniel Zucker, IoA Cambridge

Collaborators: V. Belokurov, N. W. Evans, M. Irwin, M. Fellhauer, G. Gilmore, E. Ryan-Weber (IoA); M. Wilkinson (Leicester); S. Koposov, J. de Jong, E. Bell, H.-W. Rix (MPIA); J. Kleyna (IfA); *et al.*

Satellite Factory
Satellitenfabrik Фабрика Спутников

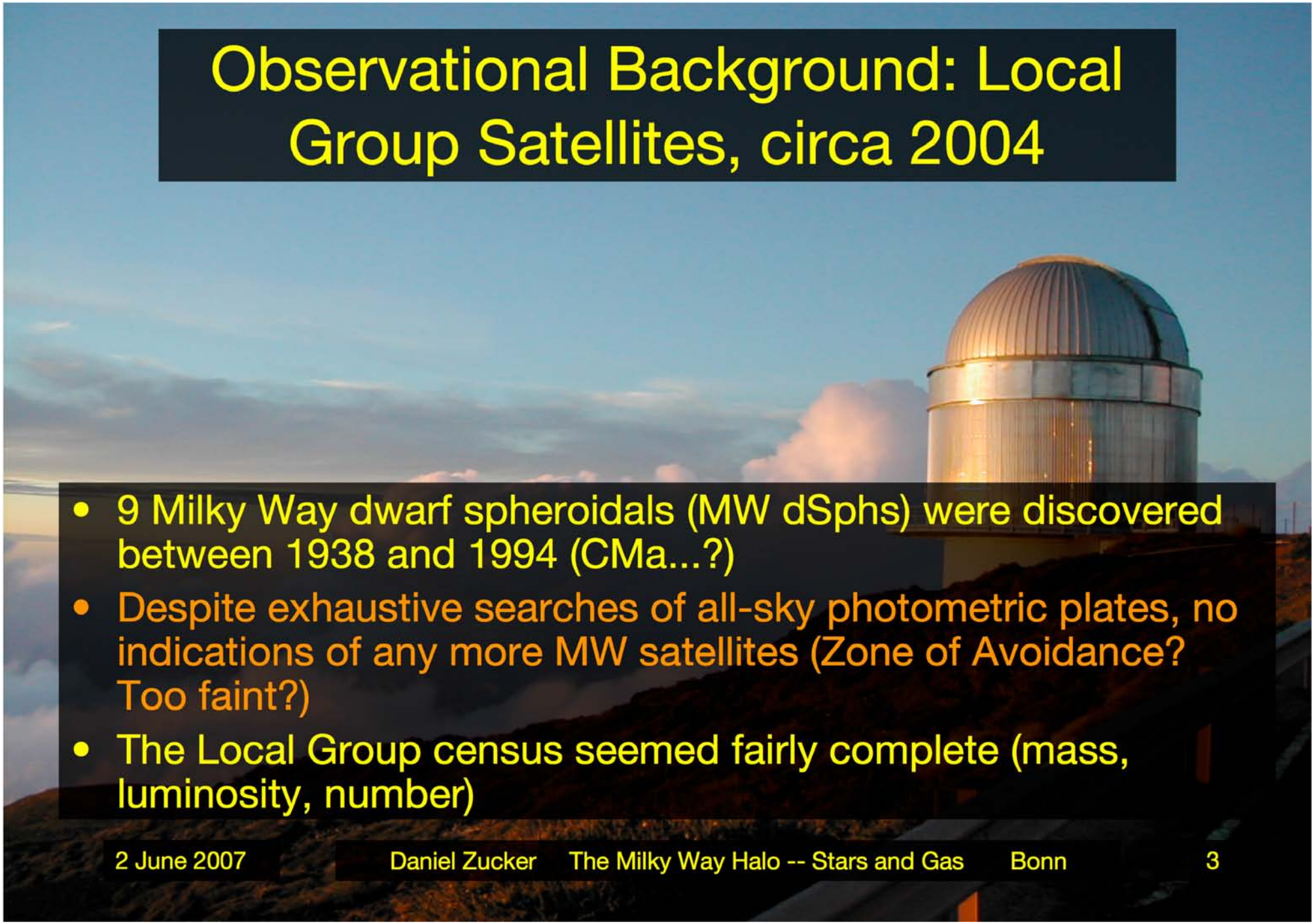
SDSS



Outline

I. What a difference three years make
II. Leo T: alive and kicking
III. The luminosity function of Milky Way satellites: a walk on the dim side

Observational Background: Local Group Satellites, circa 2004

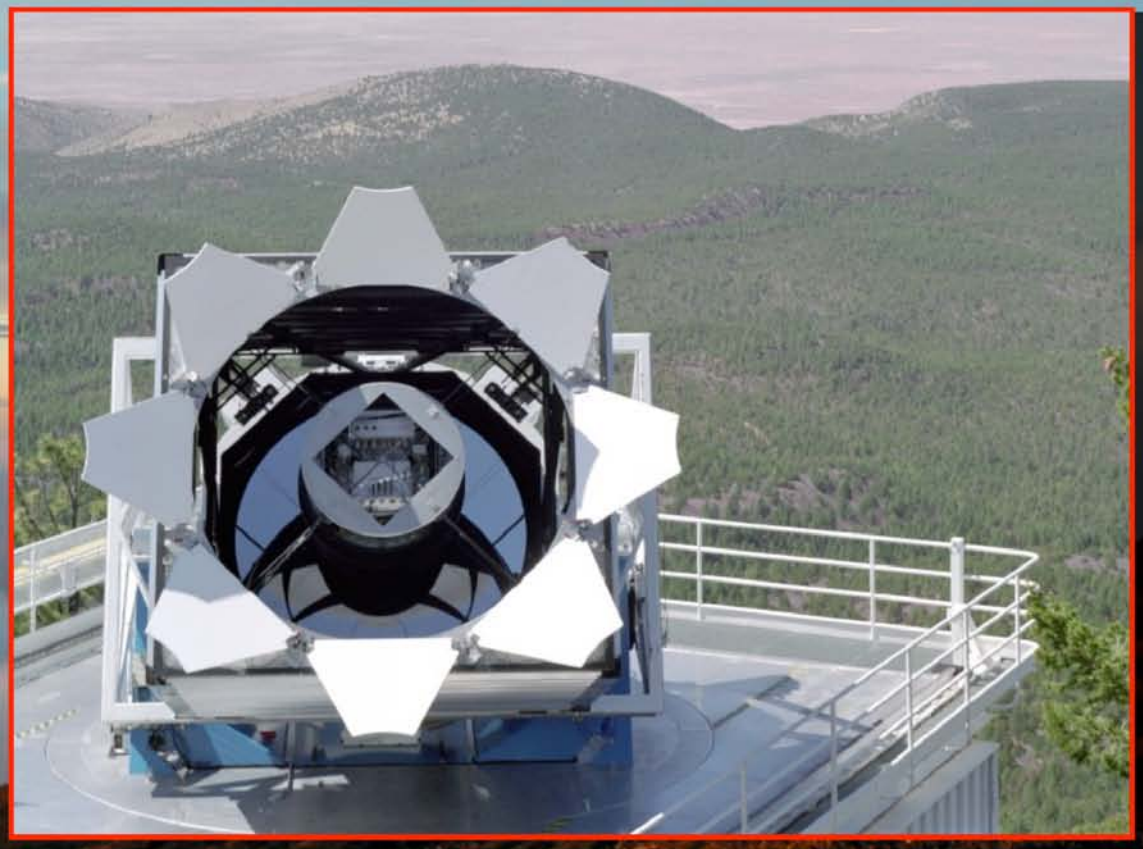


- 9 Milky Way dwarf spheroidals (MW dSphs) were discovered between 1938 and 1994 (CMa...?)
- Despite exhaustive searches of all-sky photometric plates, no indications of any more MW satellites (Zone of Avoidance? Too faint?)
- The Local Group census seemed fairly complete (mass, luminosity, number)

Theoretical Background, 2004

- CDM models predict too many low-mass dark subhalos, by at least 1-2 orders of magnitude compared to observed dwarfs -- the "missing satellite" problem (e.g., Klypin et al. 1999, Moore et al. 1999, Benson et al. 2002b)
- Some proposed solutions: inhibited star formation (e.g., photoionization), observed satellites actually much more massive, observed satellites *originally* more massive but tidally stripped (e.g., Somerville 2002, Benson et al. 2002a, Stoehr et al. 2002, Kravtsov et al. 2004)

The Sloan Digital Sky Survey

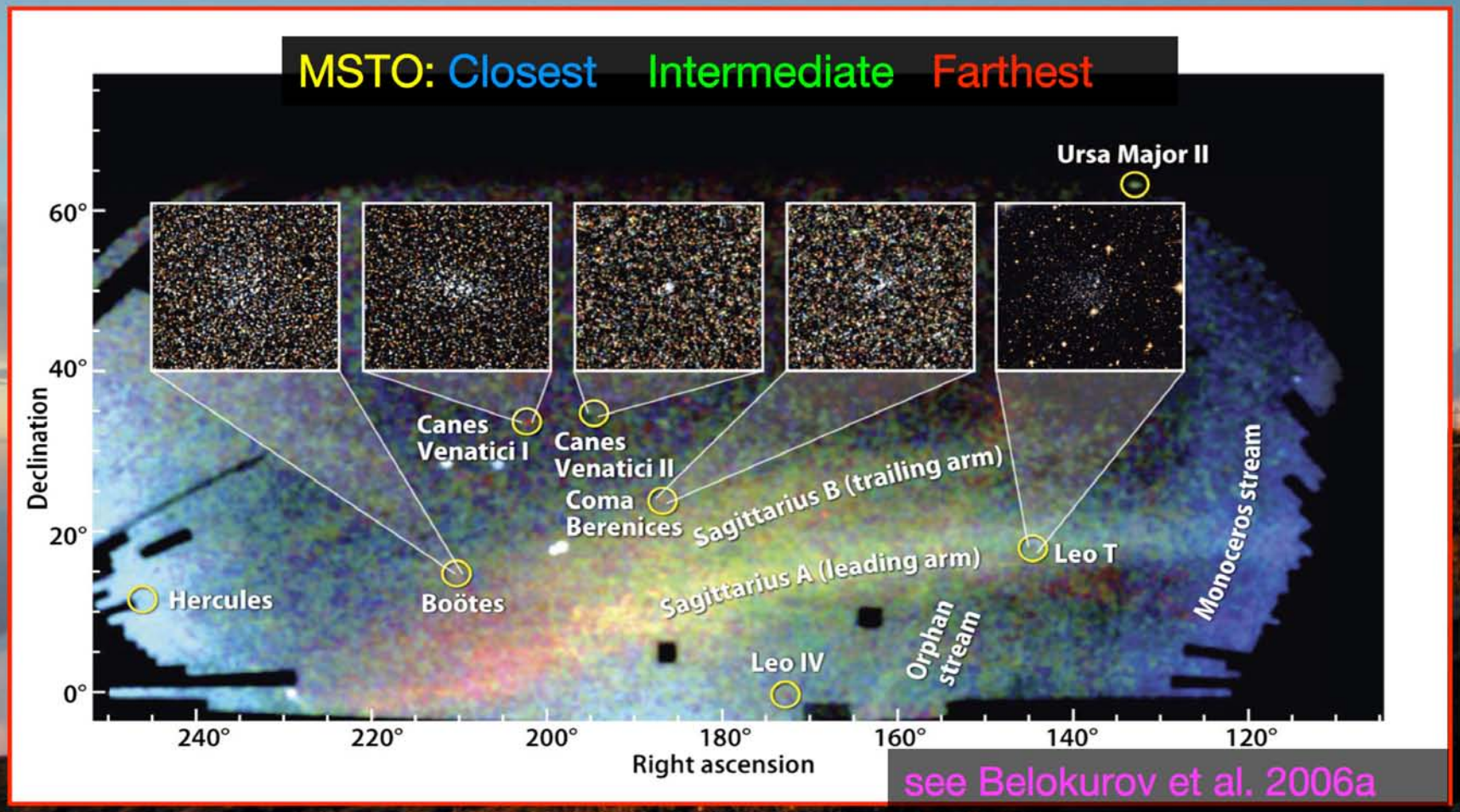


- SDSS - I: Imaging (*ugriz*) and spectroscopic survey, covering ~1/4 of the sky
- SDSS - II: includes SEGUE (Sloan Extension for Galactic Understanding and Exploration)

SDSS and the Growing Local Group

- 2004: Andromeda IX (Zucker et al.); at time, lowest luminosity, lowest surface brightness galaxy known (M_V ~ -8.3, μ_V~ 26.8 mag arcsec^{-2})
- 2005: Ursa Major (Willman et al. [b]); MW satellite, lower luminosity (M_V ~ -6.5?)
- 2005: Andromeda X (Zucker et al.);
- Odds and ends or the tip of an iceberg?

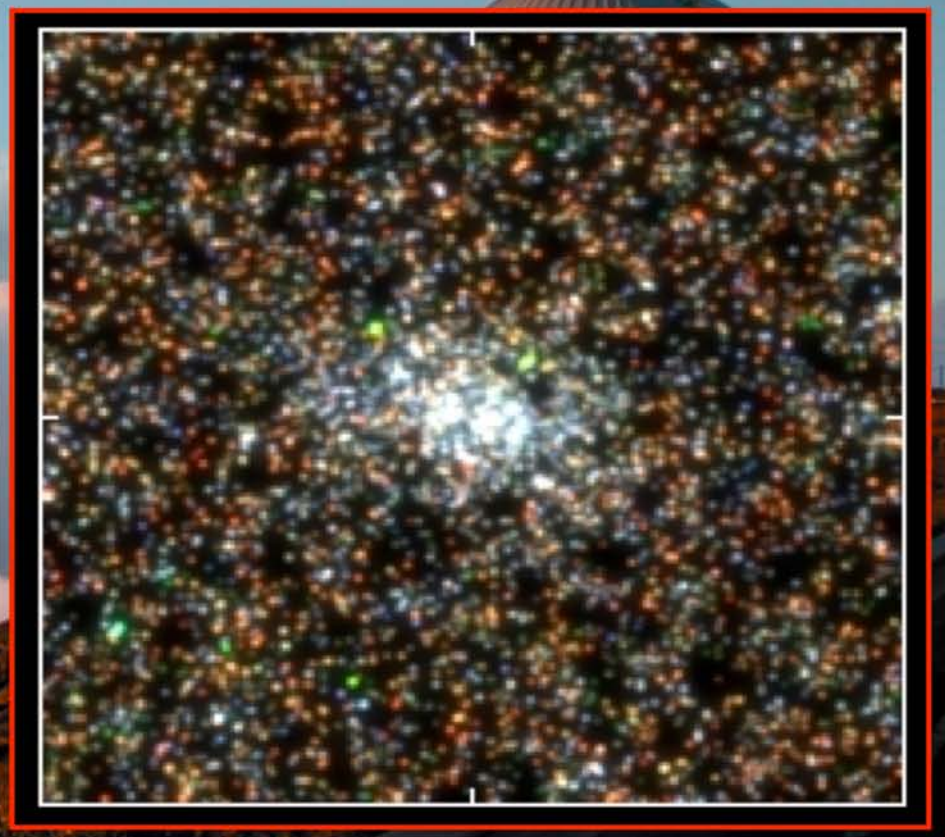
The North Galactic Cap as Seen by SDSS: A Field of Streams...and Dots



see Belokurov et al. 2006a

The New Dwarfs...Similar, but Fainter?

- CVn I: most "normal" (Zucker et al. 2006a), but two kinematic components, σ~14 km s^{-1} and σ < 2 km s^{-1} (Ibata et al. 2006)
- Boo (Belokurov et al. 2006b): strange morphology, σ~7 km s^{-1} (Muñoz et al. 2006)
- UMa II: lumpy, elongated, associated with Orphan Stream? (Zucker et al. 2007; + Complex A? Fellhauer et al. 2007)



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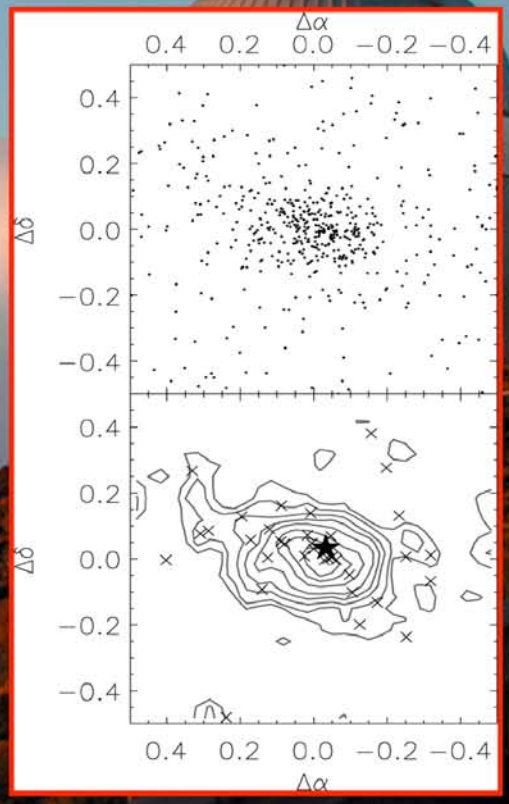

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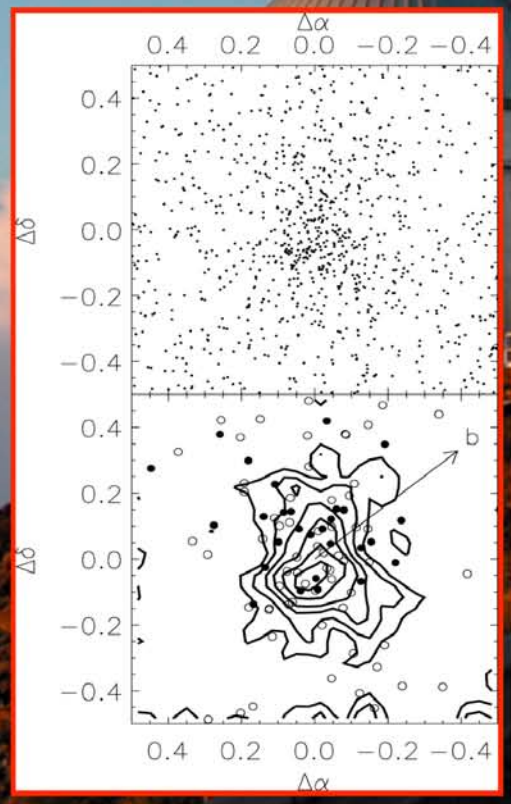

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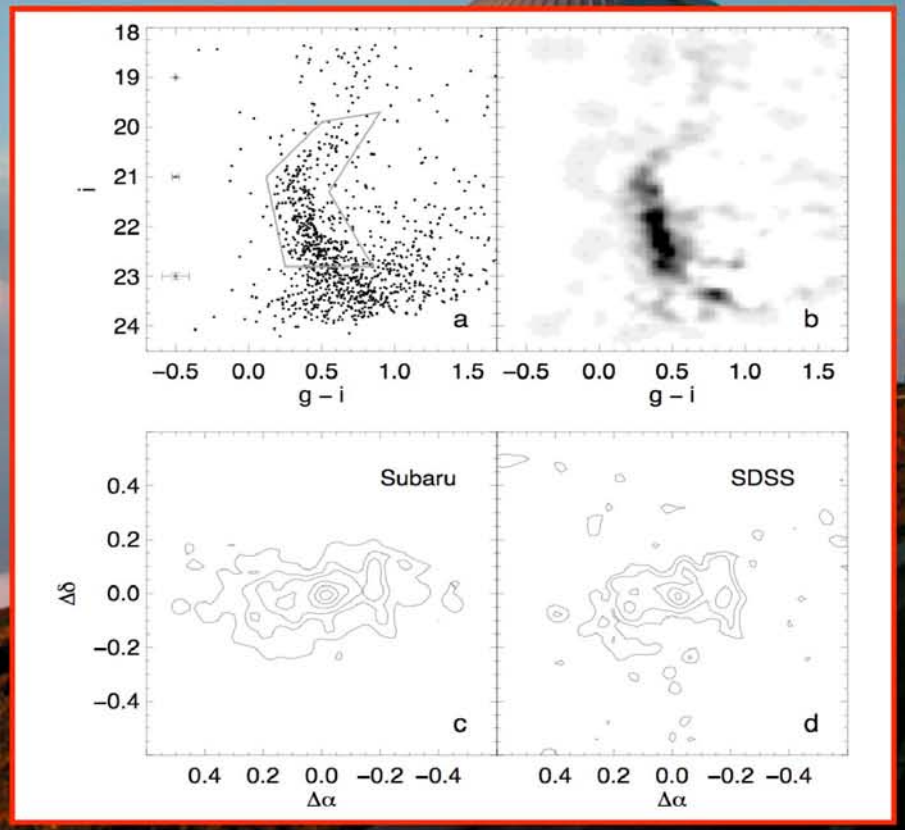

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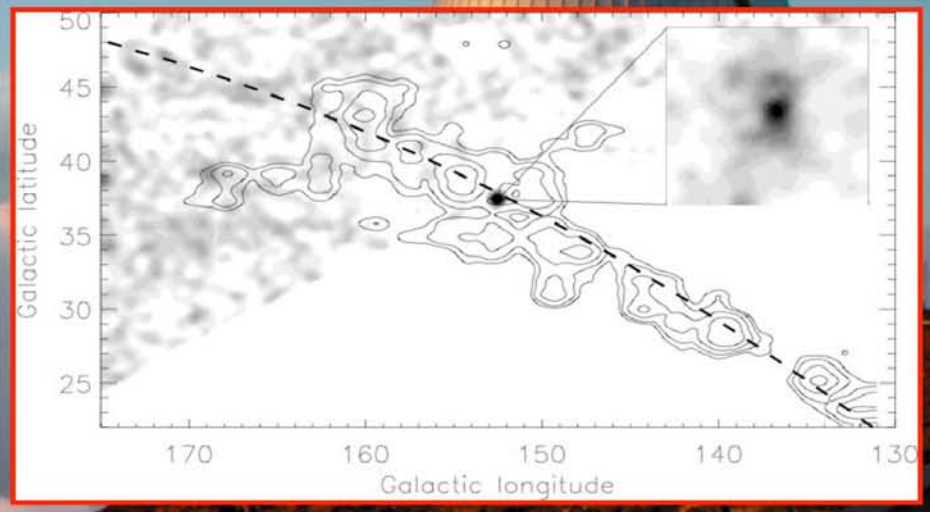
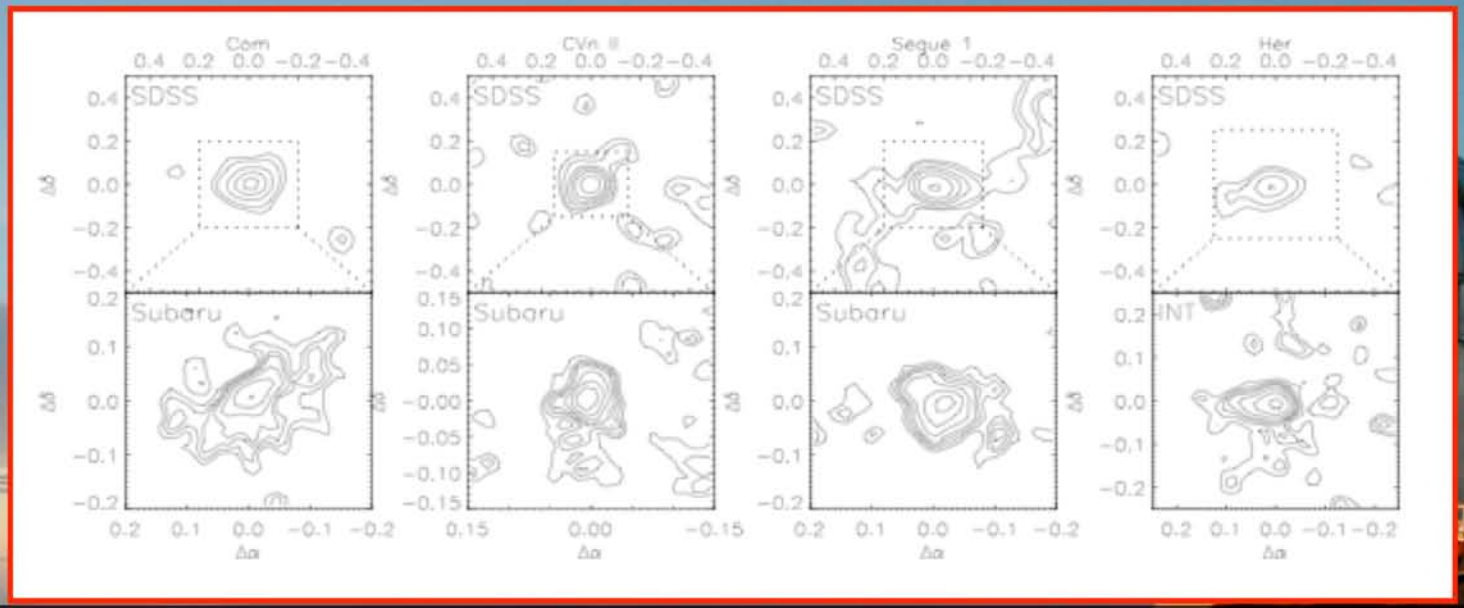


They Just Keep Coming...



- Four more MW satellites (Coma, CVn II, Her, Leo IV: Belokurov et al. 2007), two globulars (?) (Willman 1, Segue 1: Willman et al. 2005a, Belokurov et al. 2007), a possible free-floating dwarf (**Leo T**: Irwin et al. 2007), and most recently Boo II (Walsh et al. 2007)
- Meanwhile, over at M31: And XI, XII, XIII (Martin et al. 2006); And XIV (Majewski et al. 2007); And XV, XVI (Ibata et al. 2007)

Why Now?

- Advent of large-area digital surveys and wide-field imagers (2MASS, SDSS, et al.)
- Structure and substructure only detectable via stars
- NB: SDSS FoS data only cover 20% of sky ⇒likely dozens more dwarfs!

Bullock & Johnston 2005

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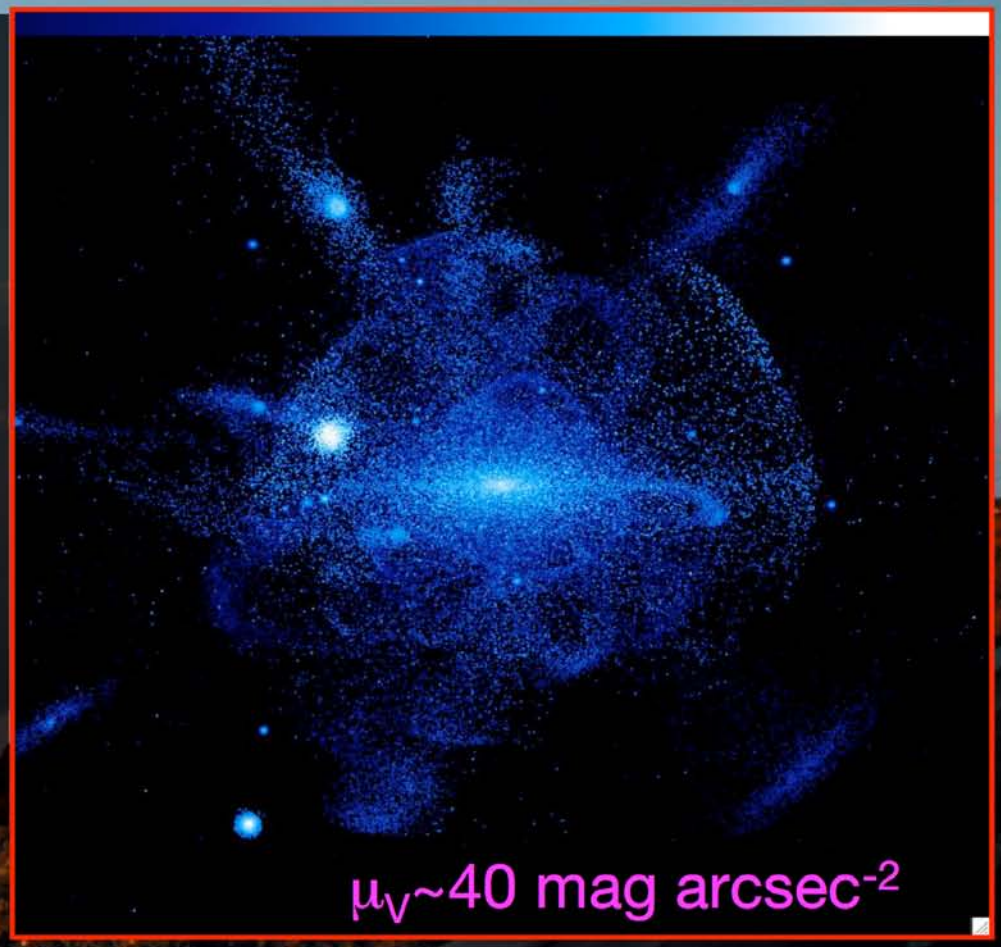
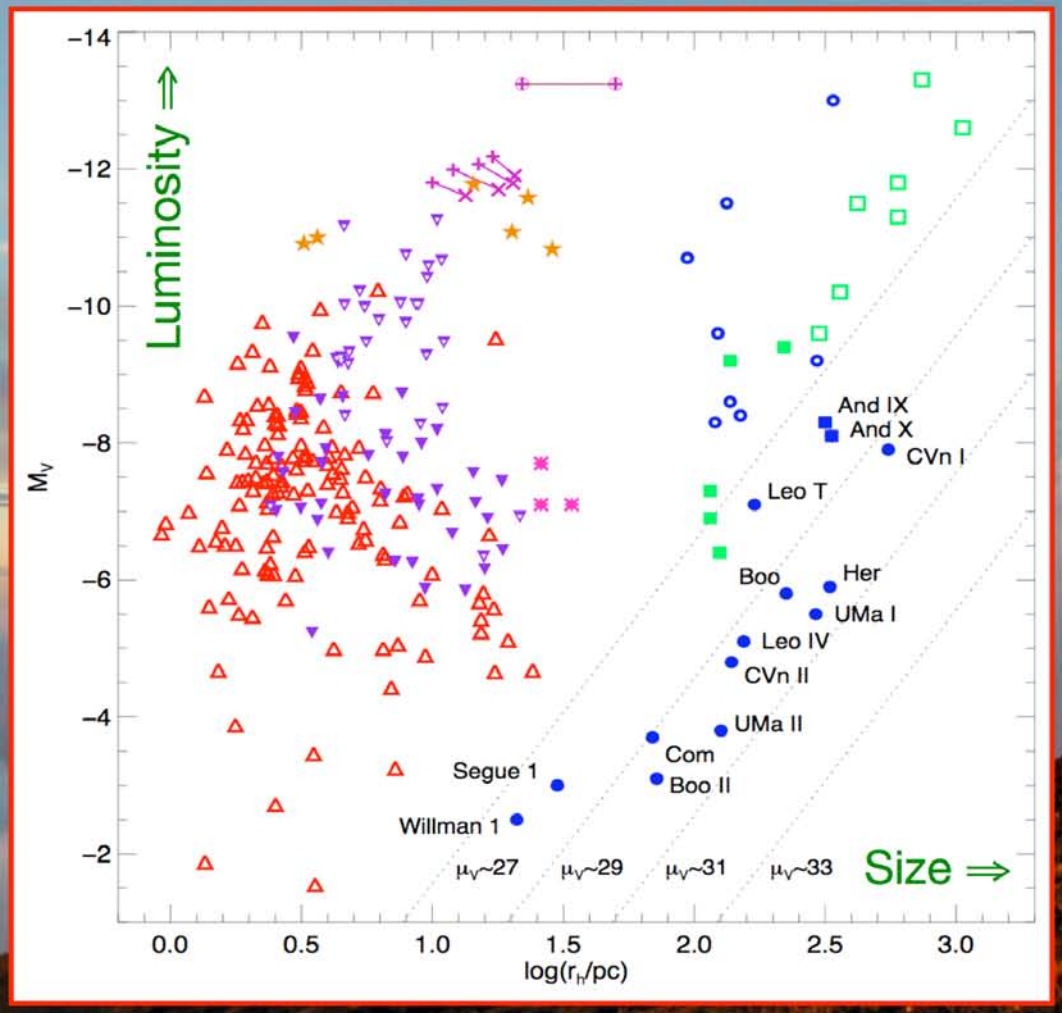


Bullock & Johnston 2005

Some Properties of the New Milky Way Dwarfs

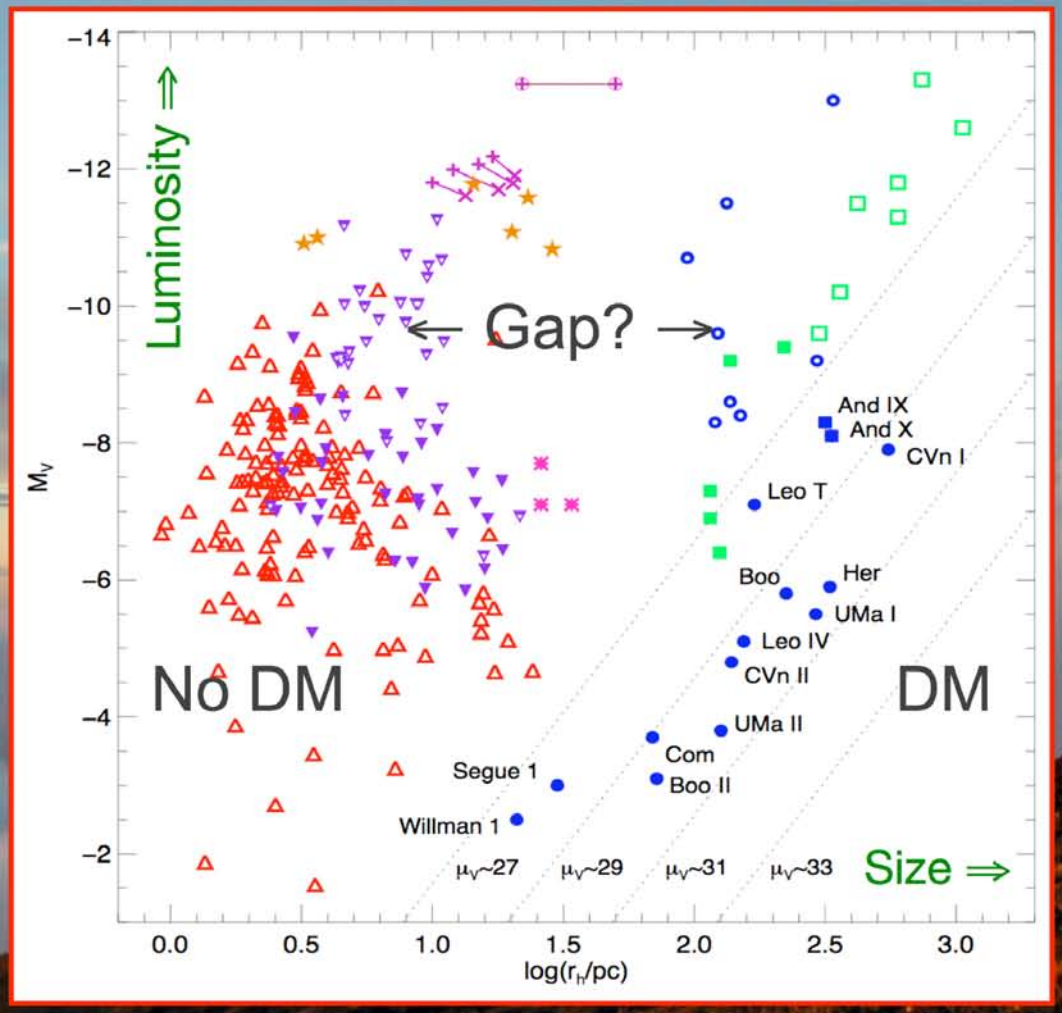
	UMa I	CVn I	Boo	UMa II	Com	CVn II	Her	Leo IV
M_V	-5.5*	-7.9	-5.8	-3.8	-3.7	-4.8	-6.0	-5.1
r_h (pc)	290	550	225	125	70	135	310	150
$D_{\odot kpc}$	100	220	60	30	45	150	140	160
$L_{\odot tot}$	$1x10^4$	$1x10^5$	$2x10^4$	$3x10^3$	$2x10^3$	$7x10^3$	$2x10^4$	$1x10^4$

M_V vs. r_h for the New Dwarfs



- Few objects with r_h between ~40 pc and ~100 pc ⇒ characteristic size scale for objects with dark matter?
- What does this indicate about the properties of DM, galaxy formation, or both?

M_V vs. r_h for the New Dwarfs



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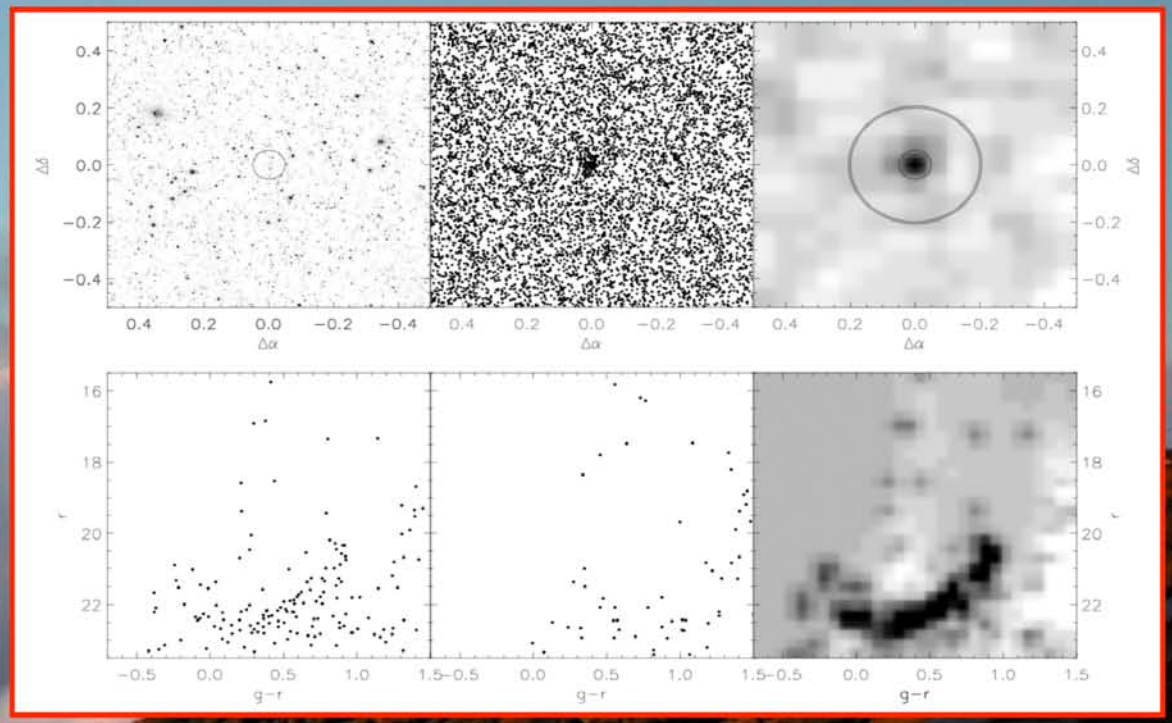
Leo T: A Different Kind of Dwarf

- $M_V \sim -7.1$, $\mu_V \sim 26.9$ mag arcsec^{-2}
- $(m - M)_0 \sim 23.1$, ~420 kpc, $r_h \sim$ 170 pc
- Recent (< 1 Gyr) star formation -- blue loop/MS stars



SDSS data

Irwin et al. 2007

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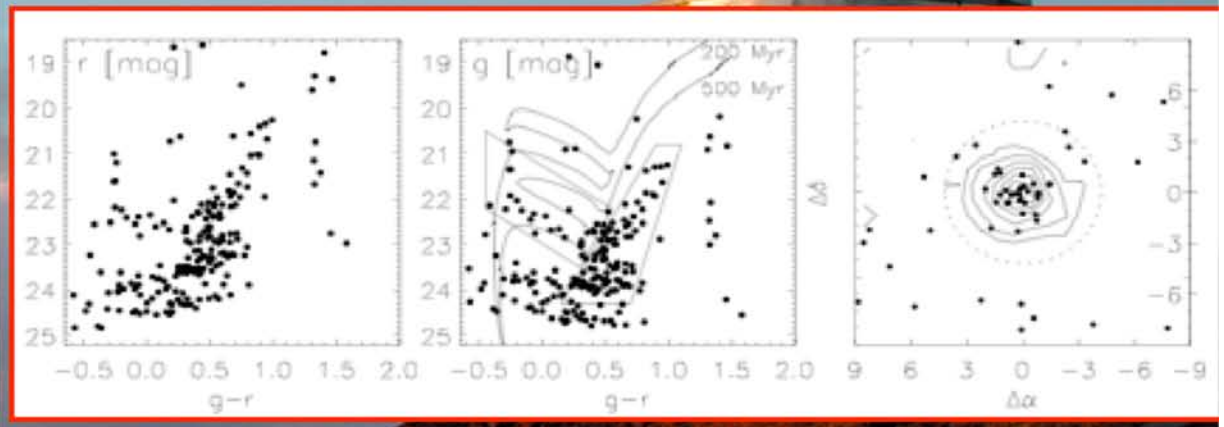

INT Data

Irwin et al. 2007

The Smallest Star-Forming Galaxy

- Leo T not dead yet: stars formed within past few x 10^8 yr
- HIPASS: Coincident H I, $RV_\odot$ ~ 35 km/s
- @ 420 kpc, ~ 2 × 10^5 $M_\odot$ in H I ($M_{H\,I}/M_\star$ ~ 1, cf. dIrrs)

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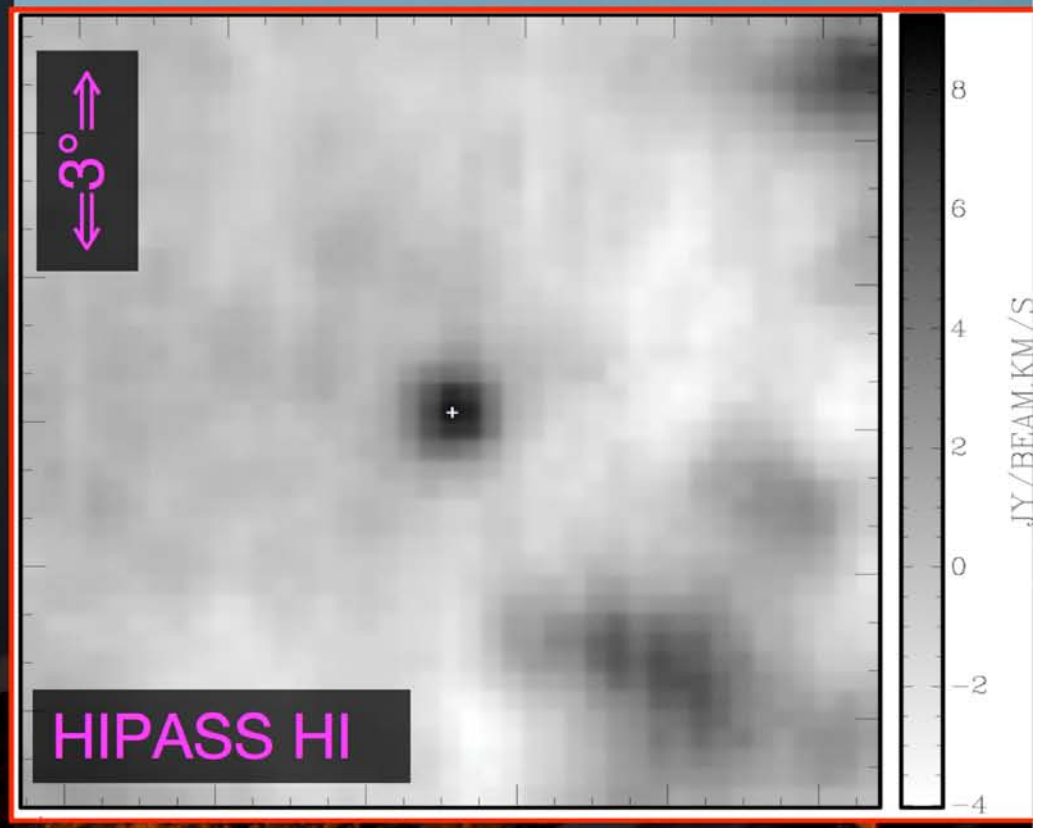
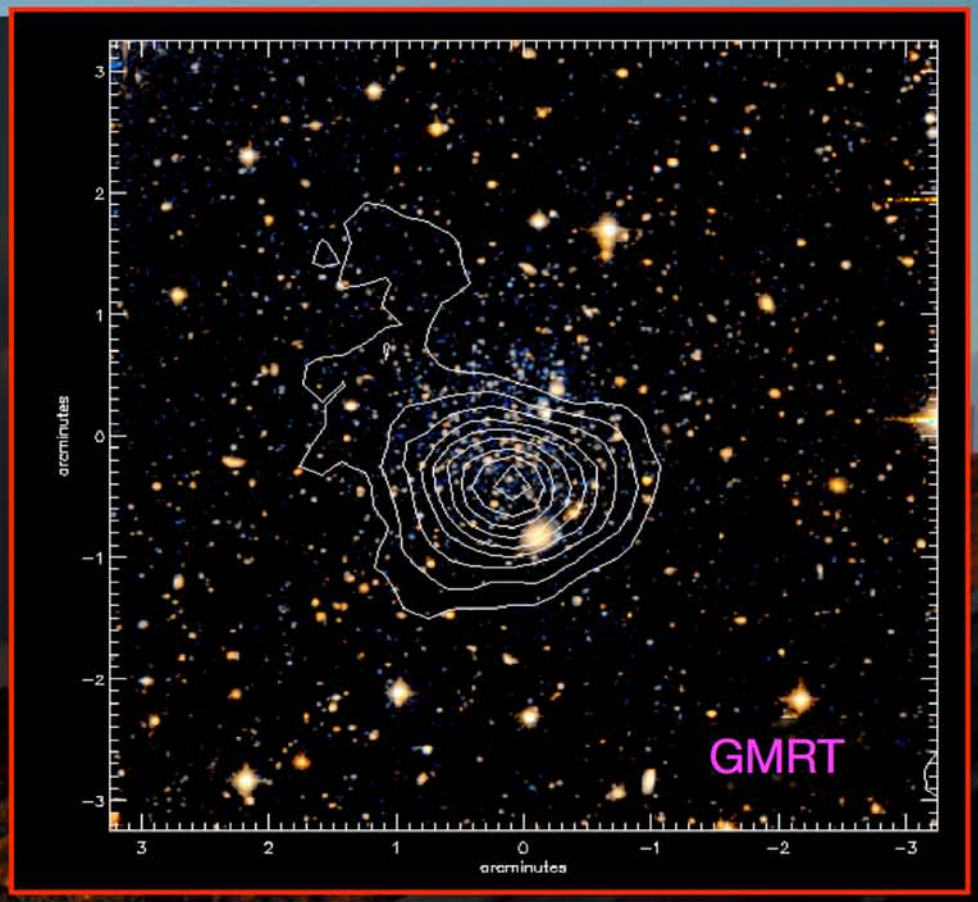


More on Leo T

- GMRT: cool (σ~3 km s^{-1}) central H I core, ~1.2x10^5 M$_\odot$, v$_\odot$~38 km s^{-1} ($\approx$ stars; Geha, priv. com.; cf. M$_*$~1.2x10^5 M$_\odot$)
- WSRT: global σ~7 km s^{-1}, central σ~2 km s^{-1}, total H I ~2.8x10^5 M$_\odot$
- (Virialized) M$_{dyn}$~ 7x10^6 M$_\odot$



Ryan-Weber, in prep.

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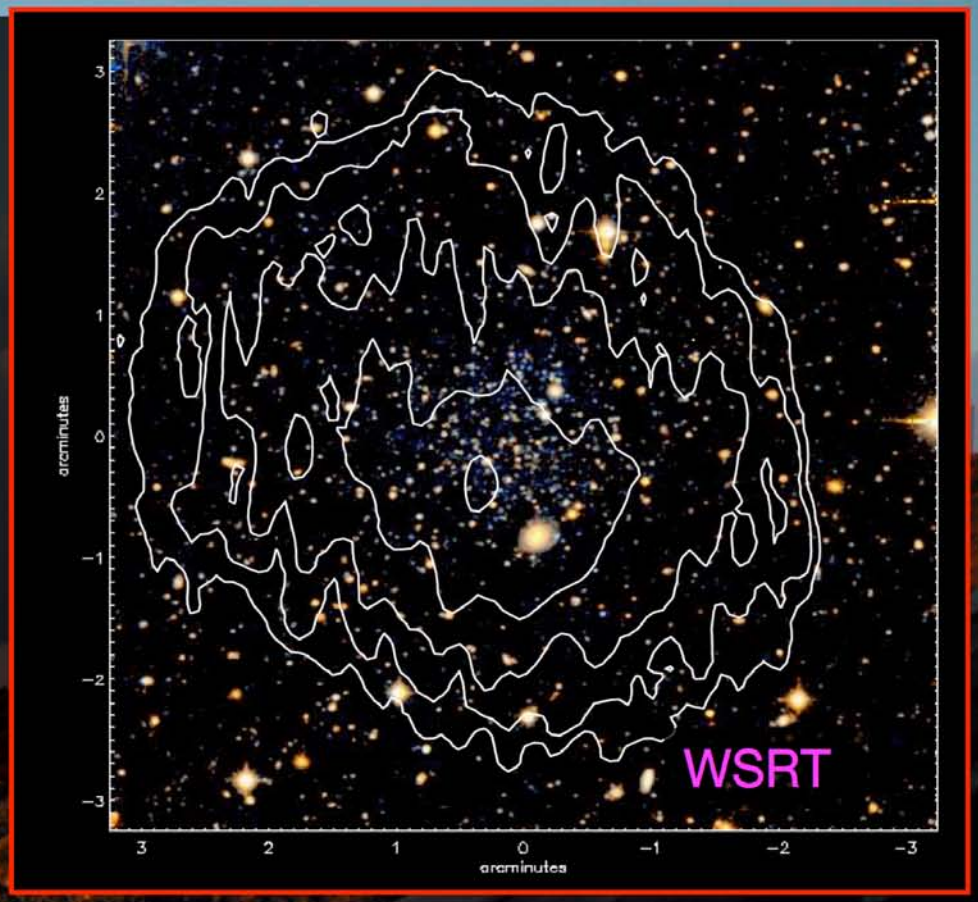
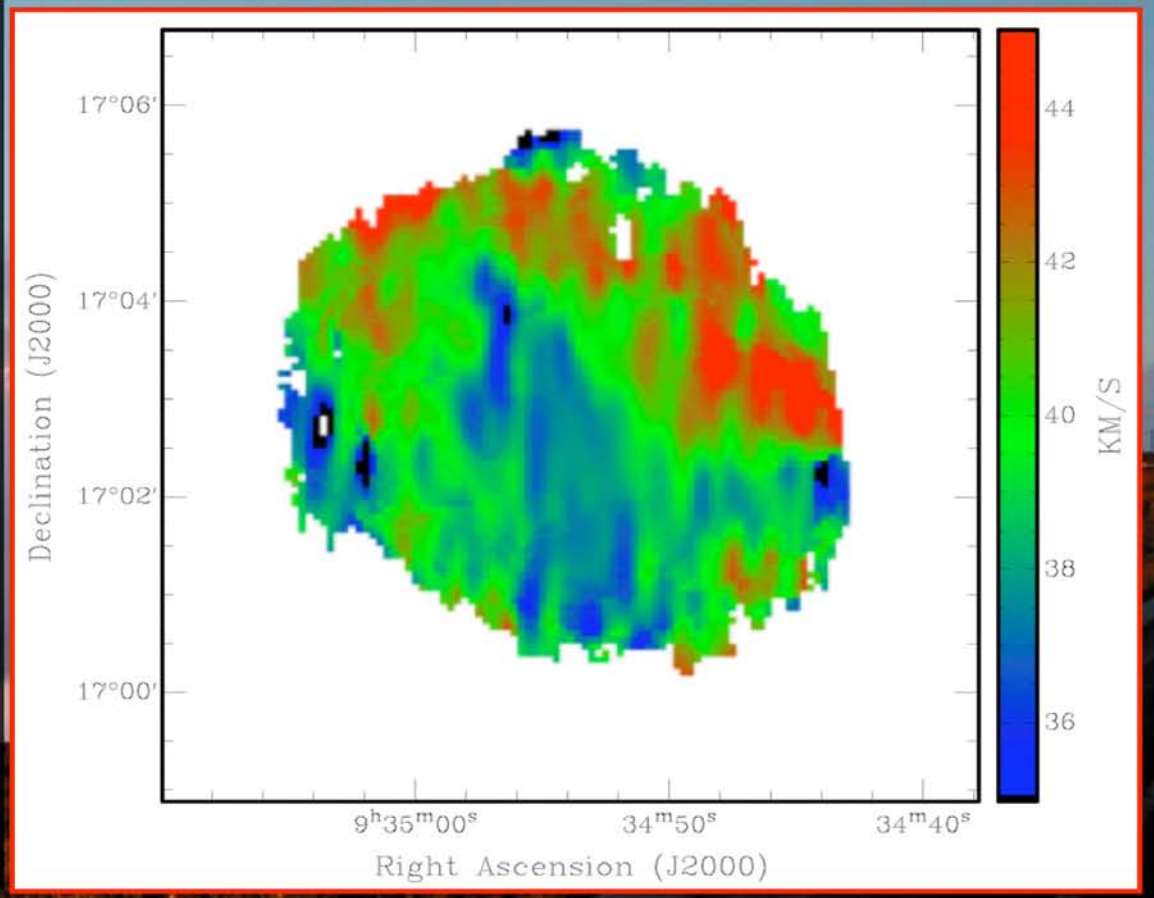


Ryan-Weber, in prep.

Significance of Leo T

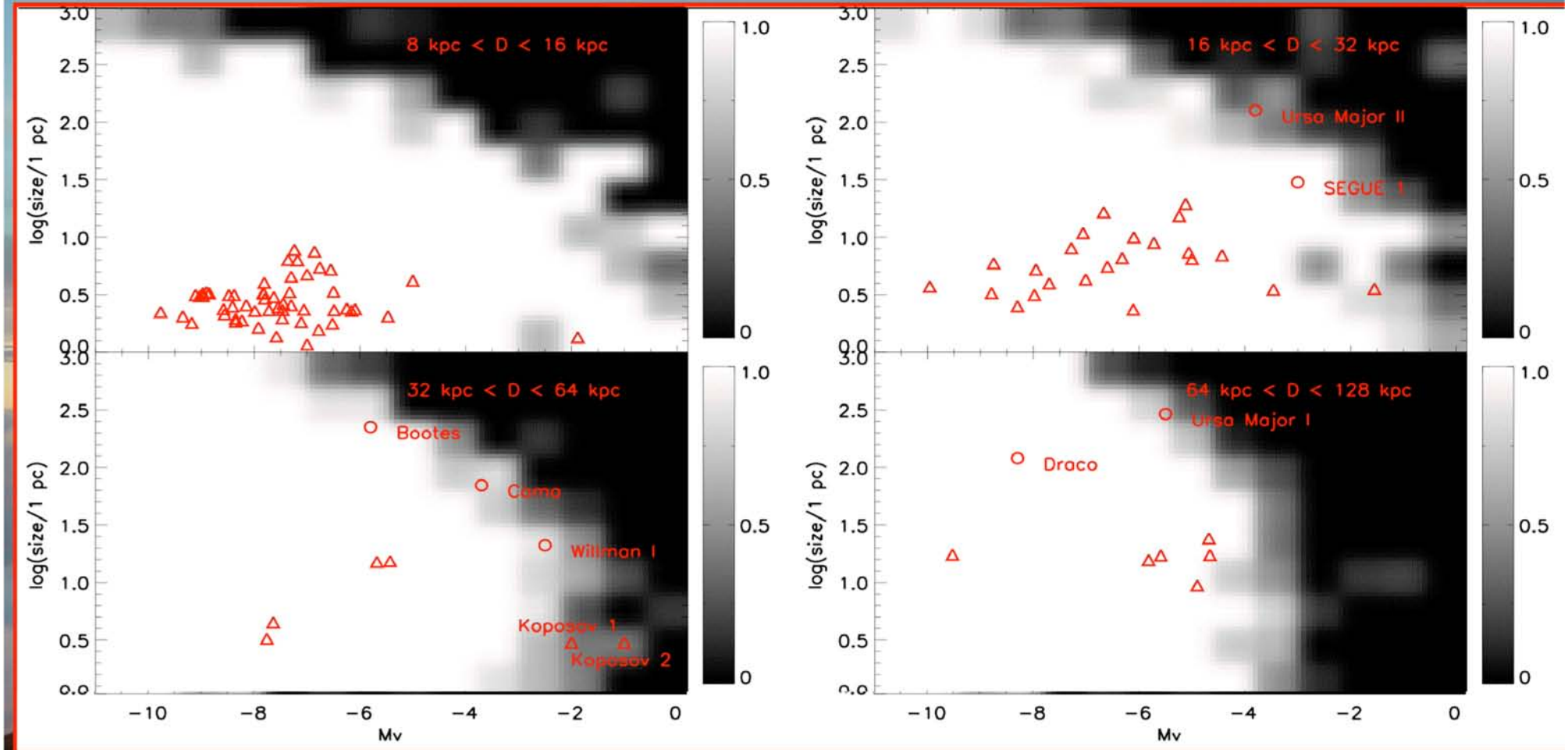
- Leo T: ~few 10^5 $M_\odot$ stars, ~few 10^5 $M_\odot$ H I, 10^6-10^7 $M_\odot$ m_{tot} (?), recent star formation
- Gas retained/ accreted? (Distance?) Free-floaters predicted...
- Difficult to detect - are there (many) more?



(A Step) Toward the Big Picture: The Luminosity Function of Milky Way Satellites from SDSS

- Automated detection pipeline for stellar overdensities in SDSS DR5 photometric data (Koposov et al., 2007)
- Convolve stellar density maps with a kernel which is the difference of two Gaussians (small inner - large outer)
- Tested pipeline with 8000 artificial Plummer law galaxies generated from the CMD of M92 (Clem 2006) and added to the DR5 database

Detection Efficiencies



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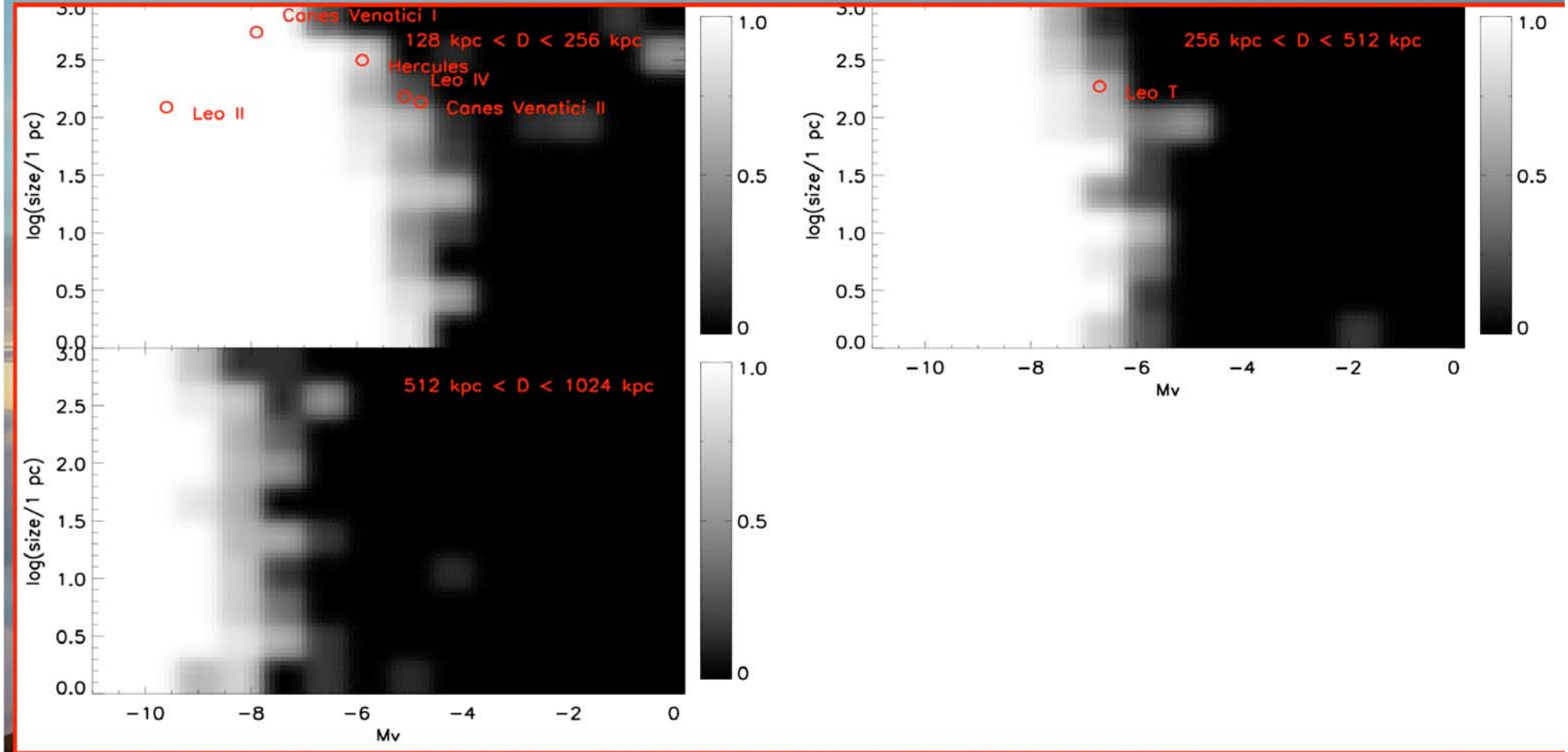
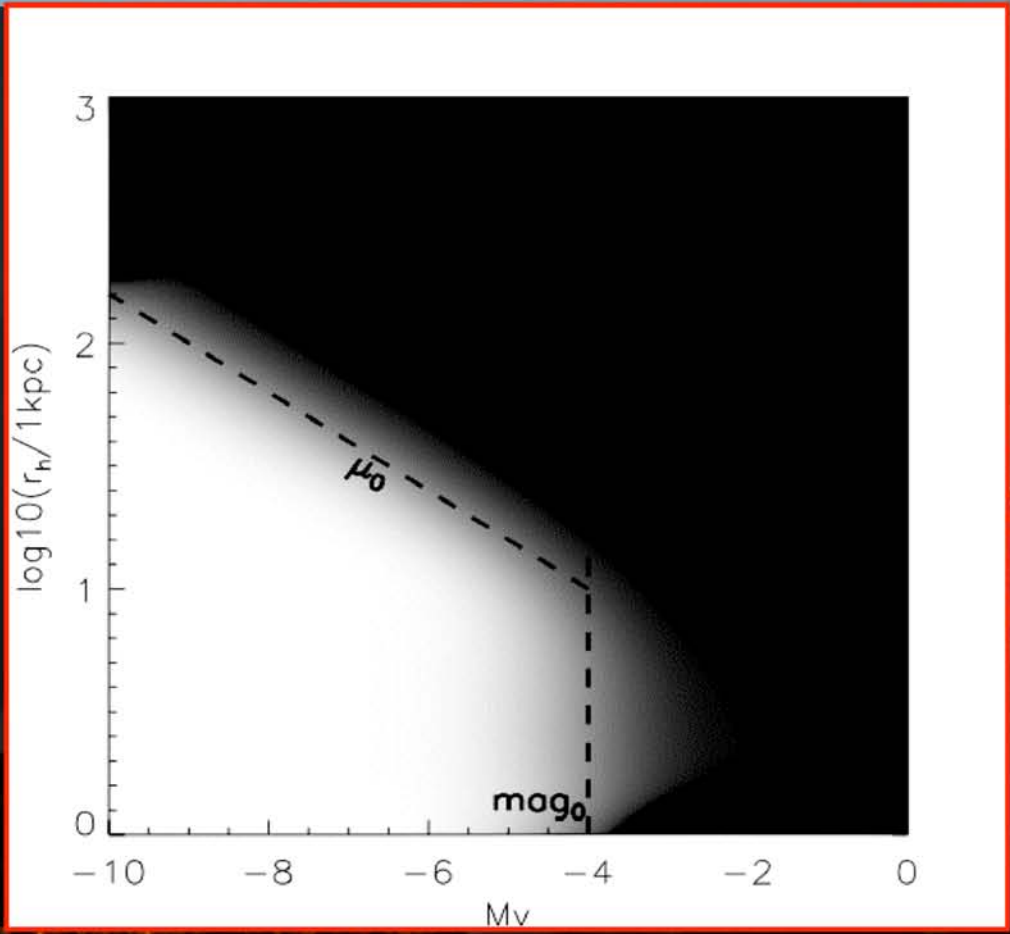
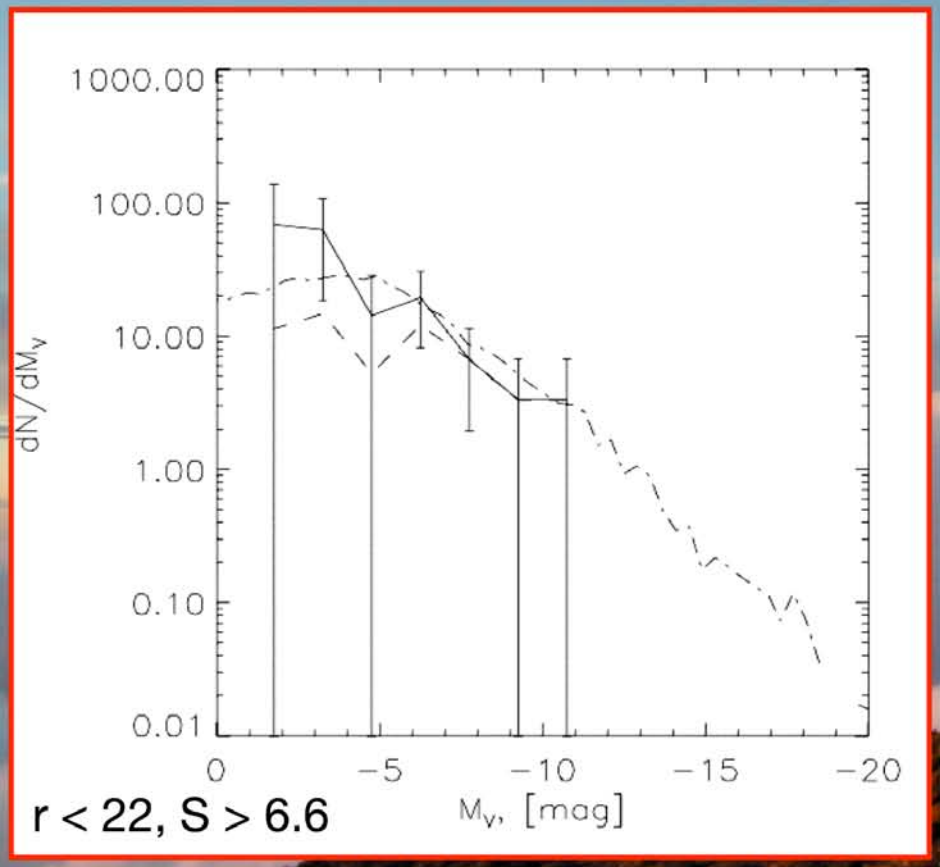


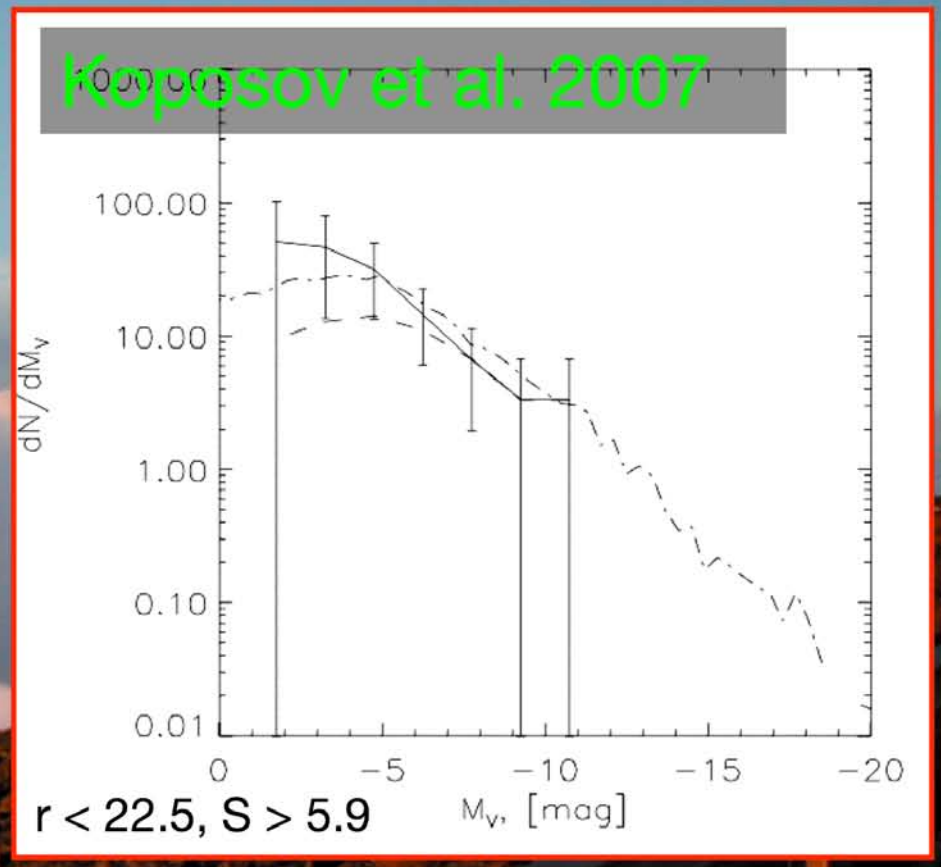
Efficiencies and Application to SDSS Data

- Efficiency function $\varepsilon(M_V,\mu_V)$ with M_V and μ_V limits
- Explored effects of different color cuts and kernel sizes
- Searched SDSS-identified galaxy catalog to eliminate galaxy clusters, set thresholds to minimize false detections



The Luminosity Function of Milky Way Satellites





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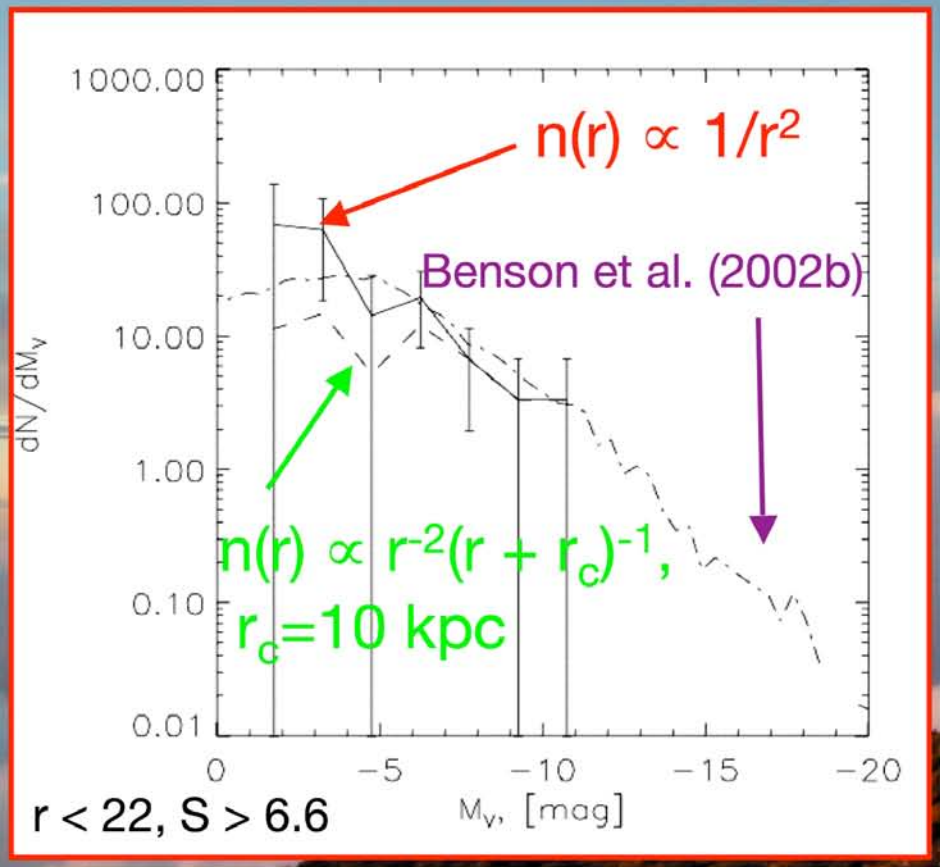

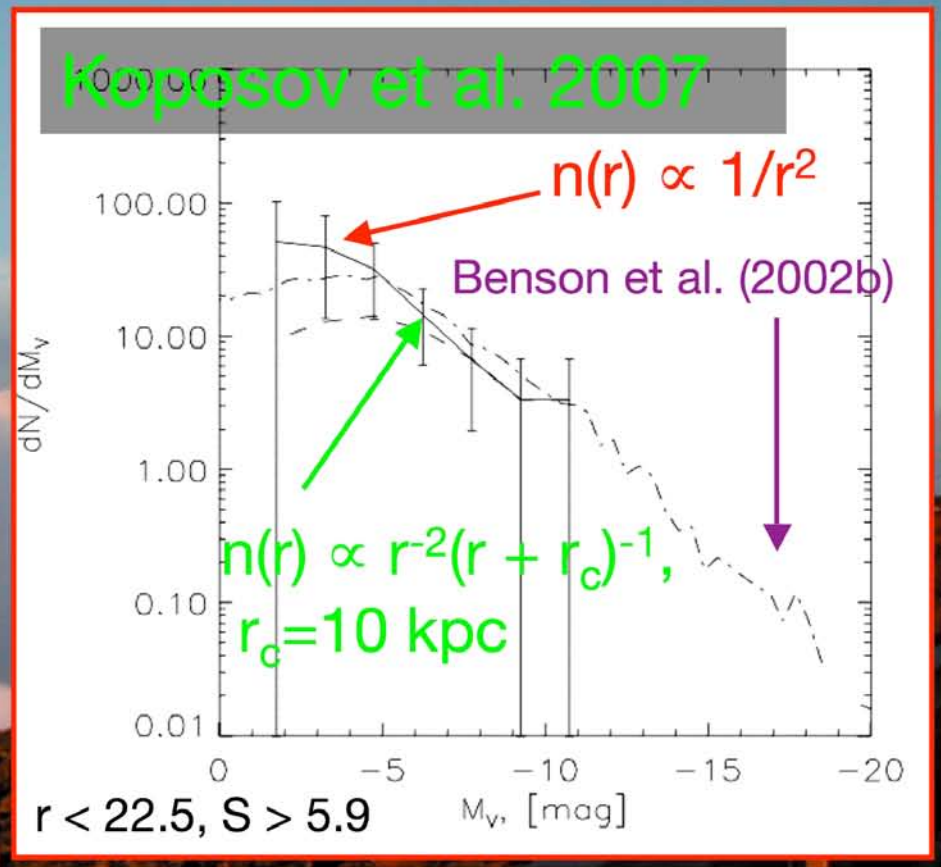

However, Benson et al. for 26 mag arcsec^{-2} (vs. ~31!)

Conclusions (and Questions)

- The Local Group (at least around the MW and M31) is significantly more crowded than three years ago -- are there dozens more ultra-low luminosity dwarfs in the Local Group?
- Is the gap in r_h indicative of a fundamental distinction between star clusters and galaxies? (What does it say about DM behavior/galaxy formation on the smallest scales?)
- Is Leo T the tip of a free-floating iceberg? How did Leo T retain/accrete gas to form stars recently?
- Using SDSS data, we can calculate the luminosity function of Milky Way satellites; shape and normalization ~agree with some predictions (but *not* surface brightness)

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