Fresh Views of Nearby Enigmatic Dwarf Galaxies

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Nearby Dwarf galaxies, 2009 Sep 14-18, SAO of RAS,
Nizhnij Arkhyz, Karachaevo-Cherkesia, Russia

A brief history of my dwarf work

- **Started with Paul Hodge in late 80's**
- Hiking in 2009?

A brief history of my dwarf work

- **Started with young pops in dwarfs**
- e.g., HII regions in IC10 (Hodge & Lee 1990)

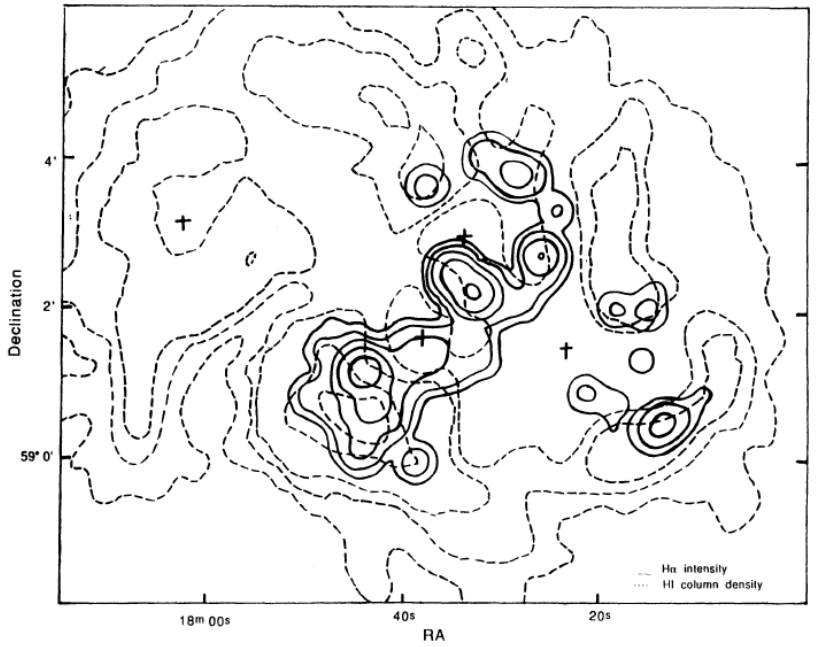
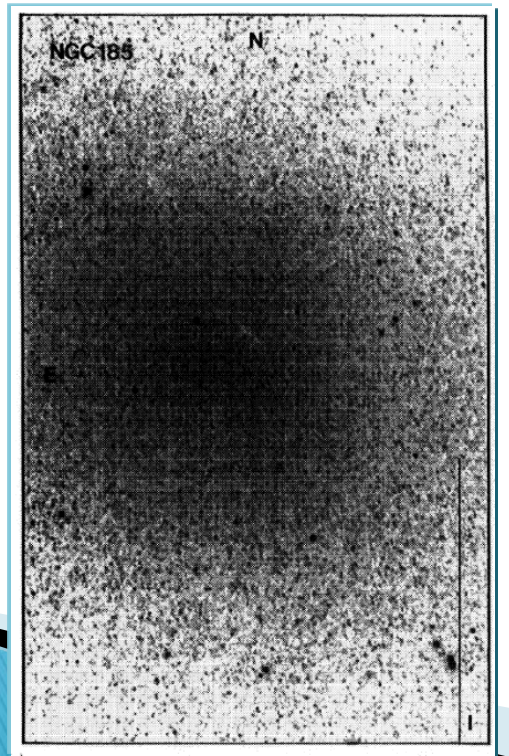
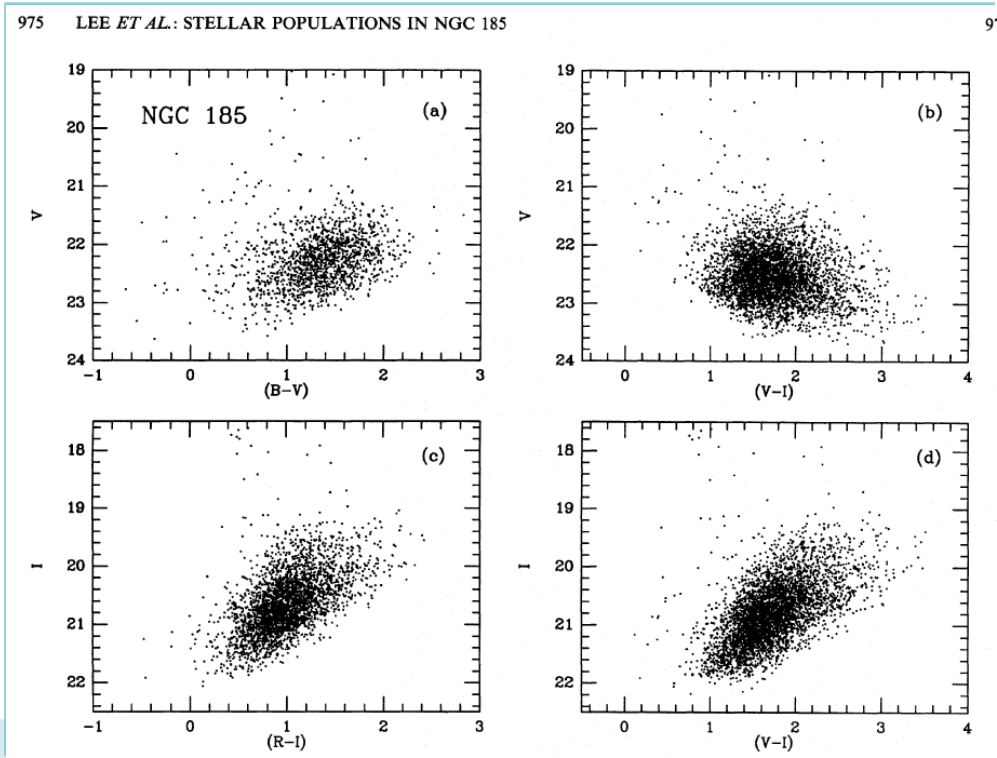


FIG. 11b–Contours of hydrogen in the main body of the galaxy. The Hα contours have been smoothed as in Figure 10. Crosses indicate the hydrogen "holes" discussed by Shostak and Skillman (1989).

A brief history of my dwarf work

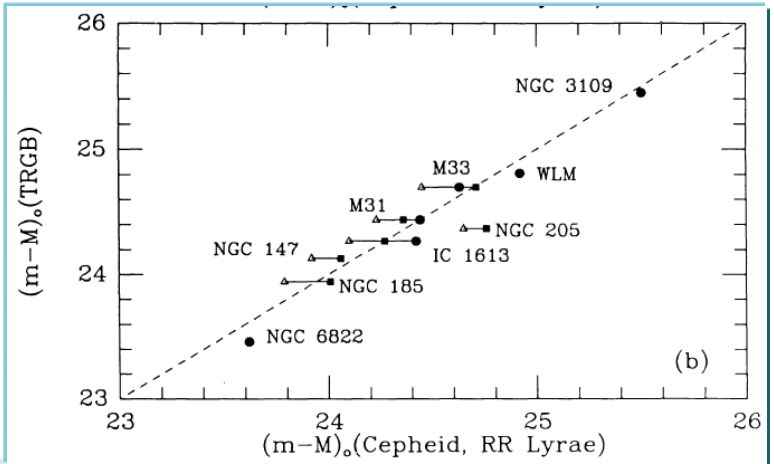
- **Then working on old pops as well in dwarfs**
- NGC 185, NGC 205 (Lee, Freedman & Madore (1993a), Lee(1996))
- **How to estimate a distance to NGC 185?**





A brief history of my dwarf galaxies

- **Struggling with NGC 185 led me to establish TRGB as a primary distance indicator.**
  - Lee (1993), Lee, Freedman & Madore (1993b):
- **I-band TRGB**
  - **A powerful primary distance indicator!**
  - **Much more efficient than Cepheids and RR Lyraes**
  - **Ideal for dwarfs (and halo of giants) in Local Universe!**



A brief history of my dwarf work

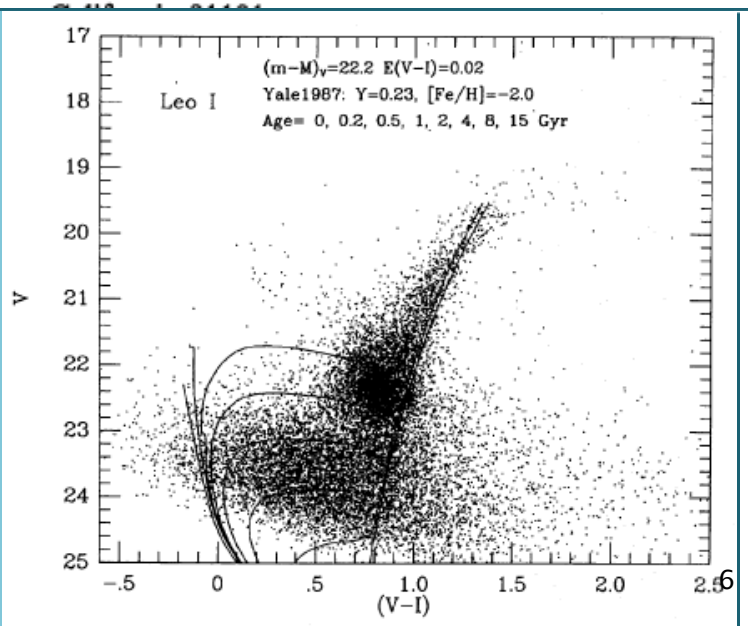
- Big questions in 1993:
- What is the age of galaxies? Do all galaxies have old pops? Are there young galaxies?

ASTRONOMICAL JOURNAL VOLUME 106, NUMBER 4 OCTOBER 1993

LEO I: THE YOUNGEST MILKY WAY DWARF SPHEROIDAL GALAXY?

MYUNG GYOON LEE, WENDY FREEDMAN, MARIO MATEO,[1] AND IAN THOMPSON

- We were looking at the tip of a big iceberg then!



A Golden Era for Dwarf Galaxies after HST

- **A great contribution by Russian and SAO astronomers** (Karachentsev, Karachentseva, Pustilnik, Tikhonov, Sharina, Makarov, and many)
- Sep 2009: "Nearby Dwarf Galaxies" at SAO
  - **Covering from our neighbors to distant dwarfs, even dark matter and dark energy.**

Current issues on dwarf galaxies

- How to explain diverse episodic star formation in dSphs?

- Which of stars, globular clusters, and dwarf galaxies formed first in the universe?
- What are the first galaxies like? Where are they?

- The most distant galaxies observed today are starburst galaxies. How are they compared with starburst galaxies at z=0? How and why do starbursts happen?

Today

- Presenting fresh(?) views of some enigmatic dwarf galaxies in the nearby universe

- showing challenges rather than answers

Enigmatic dwarf galaxies?

- dIrrs: NGC 6822, IC10, WLM, Phoenix (NOAO LGS –Massey et al),
- dEs: NGC 147, NGC 185, NGC 205, M32 (2MASS–JHK)

- **Which nearby dwarf galaxies are enigmatic?**
- **Basically every dwarf.**
- **However, focusing on the nearest starburst galaxies today!**

Enigmatic dwarf galaxies?

- IC10
  - Hubble (1936) "one of the most curious objects in the universe"
  - A starburst galaxy, popular in Russia
    (several talks in this conference)
- M82:
  - A mysterious exploding starburst galaxy?
- NGC 6822
  - The nearest polar ring galaxy

IC 10 famous for

- A nearest starburst galaxy, BCD
  - Many WR stars , High SFR
- A variable X-ray source (Prestwich et al 2007)
  - a massive binary of WR+CMO.
  - The most massive stellar blackhole, 24-34 Mo
- An HI disk much larger than optical body
  - Counter-rotating (Wilcots & Bryan 1998)

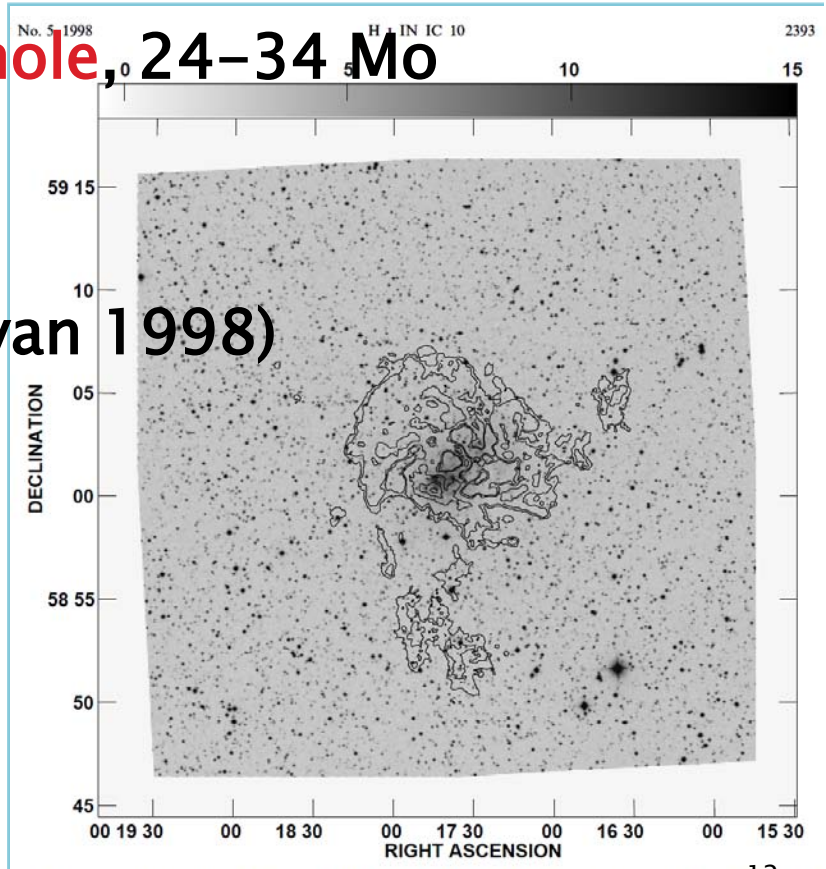


FIG. 18.—Low-resolution H I contours superimposed on a Digital Sky Survey image of IC 10. The first contour corresponds to a column density of 5×10^{19} cm^{-2}. The figure shows that the optical extent of IC 10 is well contained within the H I disk. There appears to be no stellar component to the complex and extended gas around IC 10.

However,

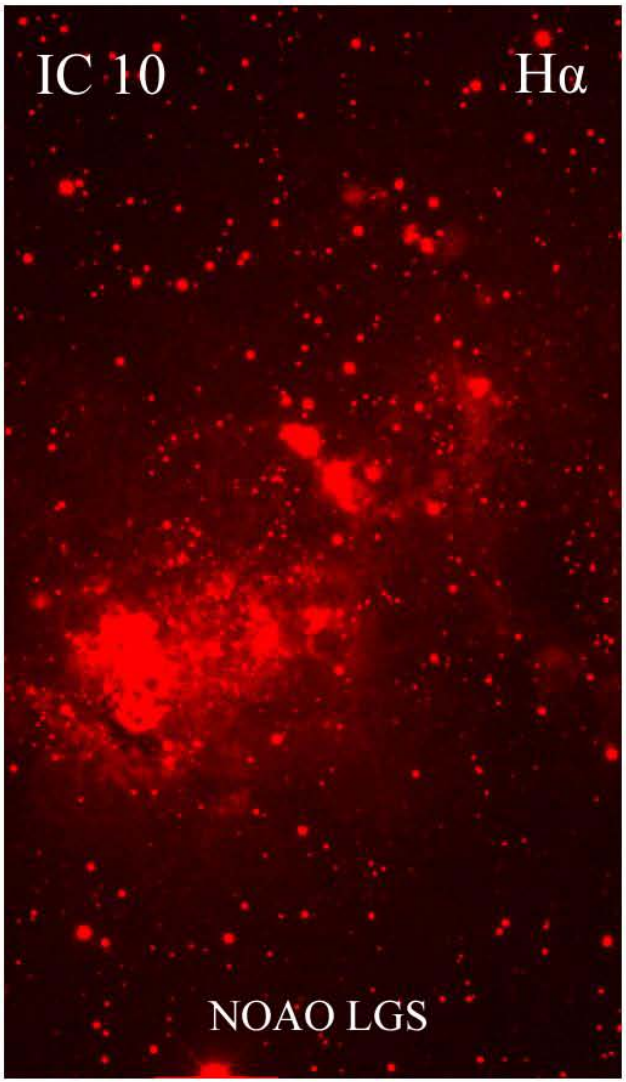
- Located close to the Milky Way (b~-3deg)
- High extinction
- Uncertainty in distance and reddening
  - $(m-M)_0$=23.5 – 24.6 (1995-2008)
  - E(B-V)=0.5 – 1.2
- The first enigma for IC10: How far is it?

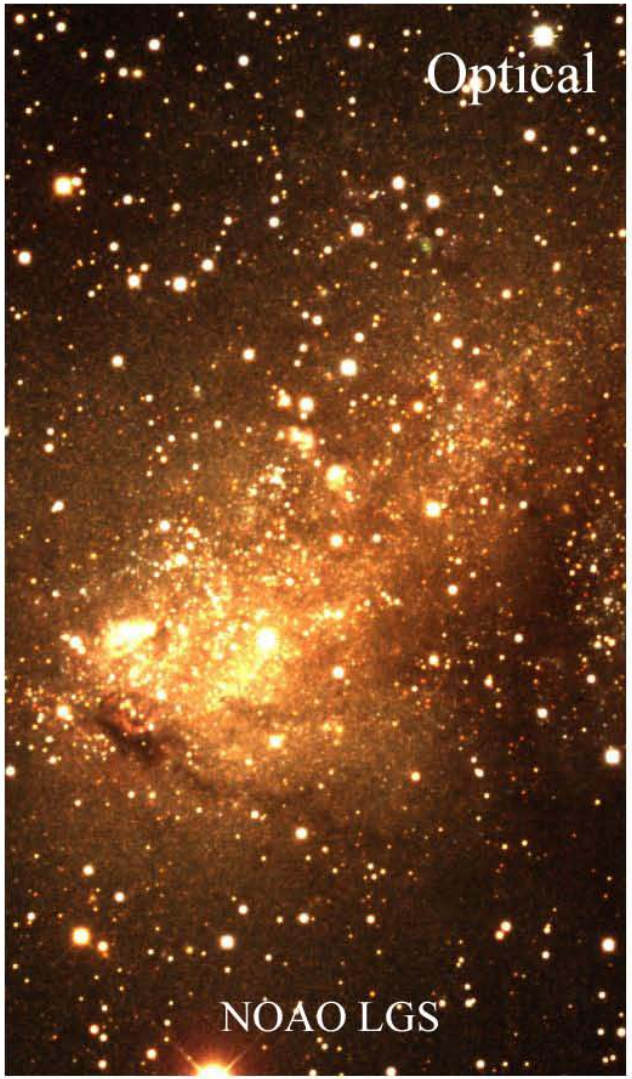
A fresh view: Deep NIR Imaging of IC 10

- **JHKs photometry with SUBARU/MOIRCS**
- Kim, M., Lee, M.G. et al. (2009) ApJ Sep 20

- **Additional data**
  - UBVRI Photometry from the NOAO Local Group Survey (Massey et al 2007)
  - **VI photometry from HST/WFPC2 & ACS (Lim & Lee 2009, in prep)**

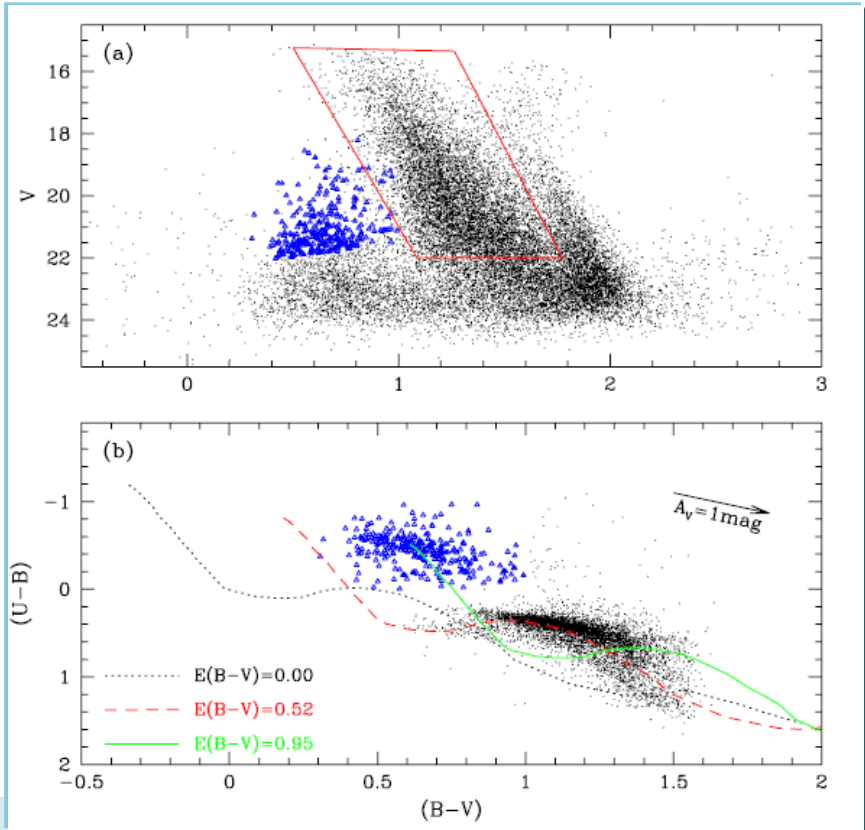
Deep NIR Imaging of IC10





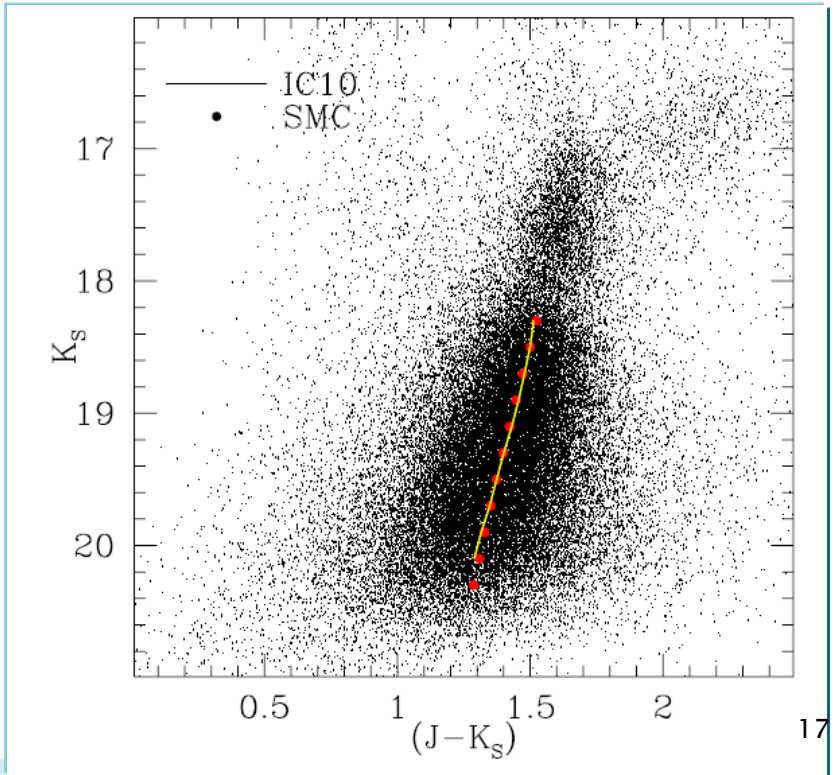
Reddening for IC10

- Massey et al (2007) NOAO LGS-UBVRI
- Foreground red stars: E(B-V)(fg)=0.52
- Blue MS stars in IC10: E(B-V)(total)=0.95±0.06



Reddening for IC10

- CMD for outer regions of IC 10 in comparison with SMC
- RGB(IC10)-RGB(SMC): E(B-V)=1.03±0.03
- Final value: E(B-V)= 0.98±0.06
  - differential reddening.
  - higher in the inner region



NIR-TRGB Distance to IC10

- [Fe/H](J-K) calibration: Kim et al (2009)
- TRGB(JHK) calibration: Valenti et al (2004)
- Reddening: E(B-V)=0.98,

  A_K=0.4E(B-V)=0.39, A_V=3.3E(B-V)=3.23

- Metallicity: [Fe/H](RGB)=-1.1 ±0.3
- Distance: $(m-M)_0$=24.27 ±0.03(ran)±0.18(sys)
- d=715 ±10 ±60 kpc
- (similar to the M31 distance)
- a member of M31 group!

IC10

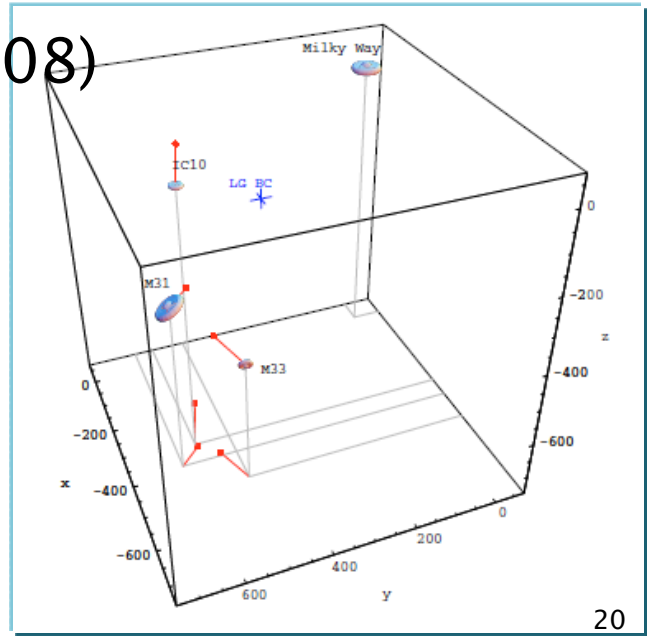
Table 5
A Summary of Distance Estimates for IC 10

Method (1)	$(m-M)_0$ (2)	$E(B-V)$ (3)	Filter (4)	Refere (5)
WR/Blue plume	24.90	0.75–0.80	sp/BV	1
Cepheid	24.59 ± 0.30	0.94	gri	2
Cepheid	24.57 ± 0.21		*JHK*	3
Cepheid	24.10 ± 0.20	1.16 ± 0.08	*VI*	4
TRGB	23.51 ± 0.19	1.16 ± 0.08	*VI*	4
Red supergiants	23.86 ± 0.12	1.05 ± 0.10	*JHK*	5
TRGB	24.95 ± 0.20	0.77	F555W, F814W	6
Carbon star	24.35 ± 0.11	Variable	R, I, CN, TiO	7
TRGB	24.48 ± 0.08	0.95	F814W, K′	8
TRGB	24.51 ± 0.08	0.78 ± 0.06	F555W, F814W	9
TRGB	$24.27 \pm 0.03 \pm 0.18$	0.98 ± 0.06	JHK_S	10

Notes. Column 1: methods for determining the distance to IC 10. Column 2: distance modu
Column 3: adopted reddening of IC 10. Column 4: filters. Column 5: references (1) Massey
Armandroff 1995, (2) Saha et al. 1996, (3) Wilson et al. 1996, (4) Sakai et al. 1999, (5) Boriss
et al. 2000, (6) Hunter 2001, (7) Demers et al. 2004, (8) Vacca et al. 2007, (9) Sanna et al. 20
and (10) this study.

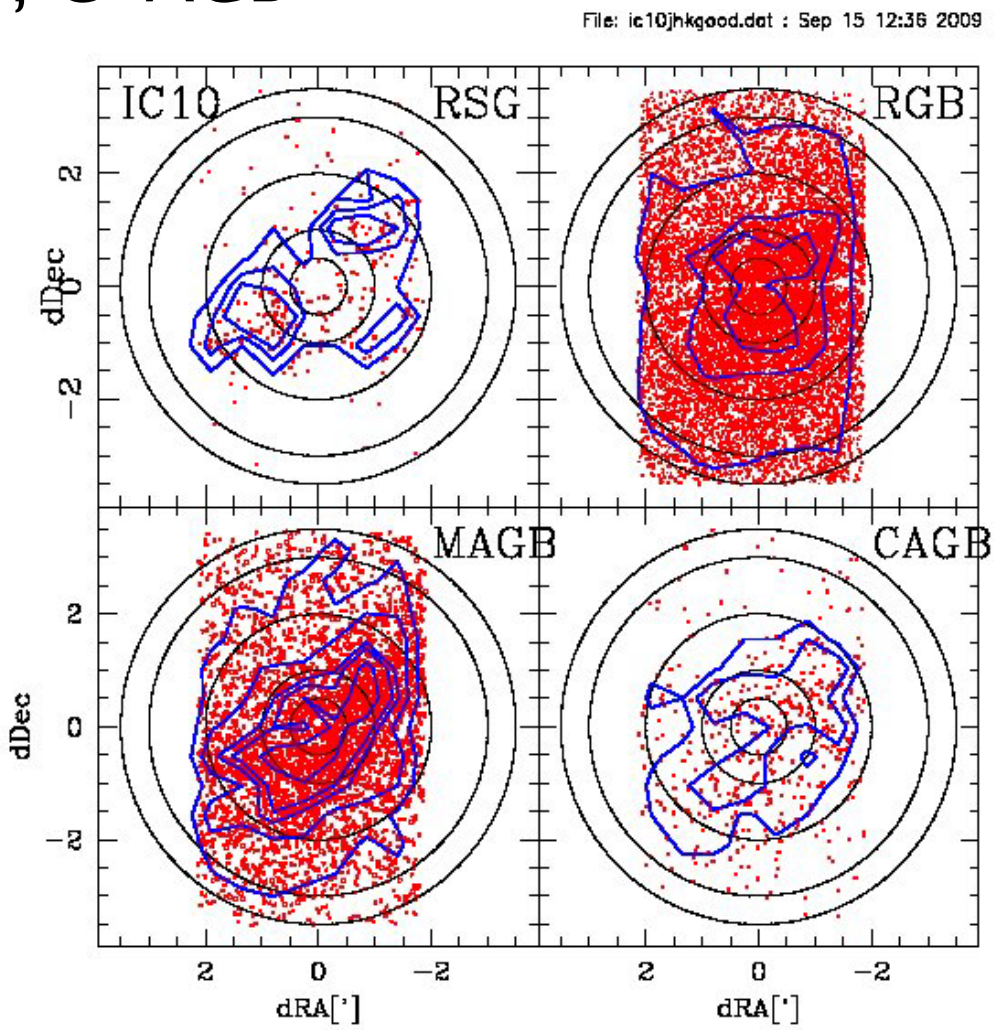
Dynamics of IC10 in LG

- **d(IC10)=715 kpc, and r(M31-IC10)=280 kpc,** showing that it is a member of M31 group!
- IC10 is Interacting with M31! -> Starburst!
- With H_2O maser proper motion (Brunthaler et al 2007) we estimate the mass, M(M31) > 8×10^{11} Mo.
- Consistent with the value from GC kinematics: 20×10^{11} Mo (R<100kpc) (Lee et al 2008)



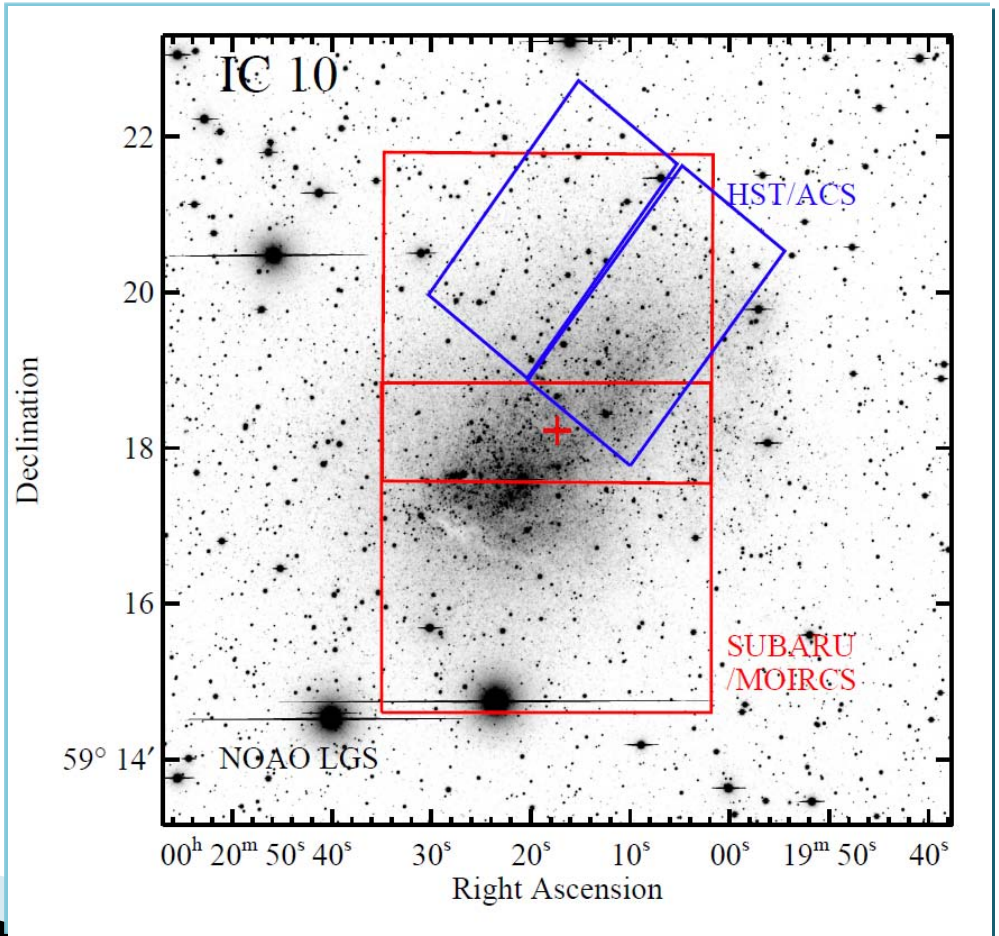
Spatial variation of pops in IC 10

- RSG, RGB, M-AGB, C-AGB



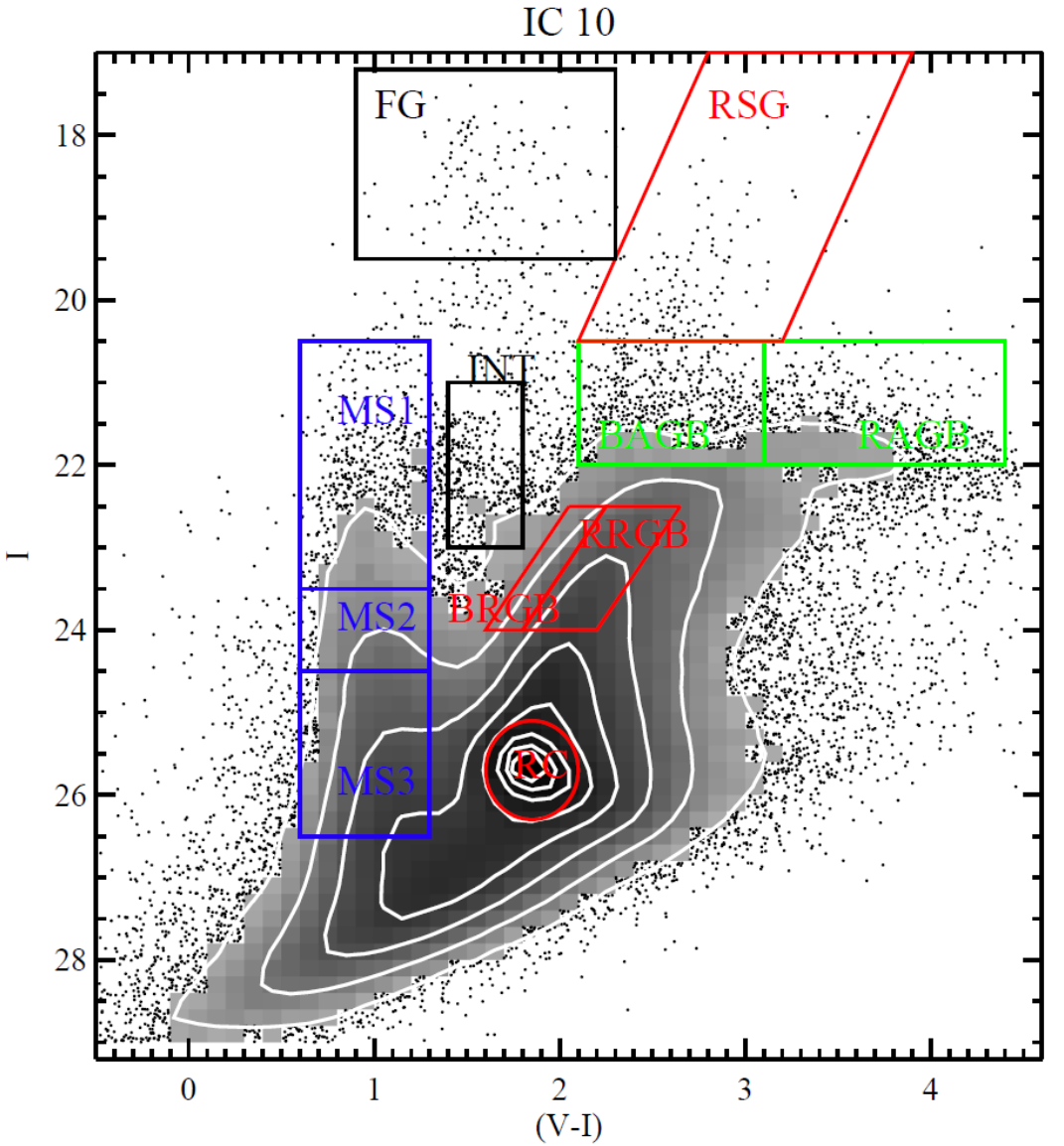
HST/ACS photometry of IC10

- HST Archive HST/ACS F555W,F814W
- To study stellar pops in a halo



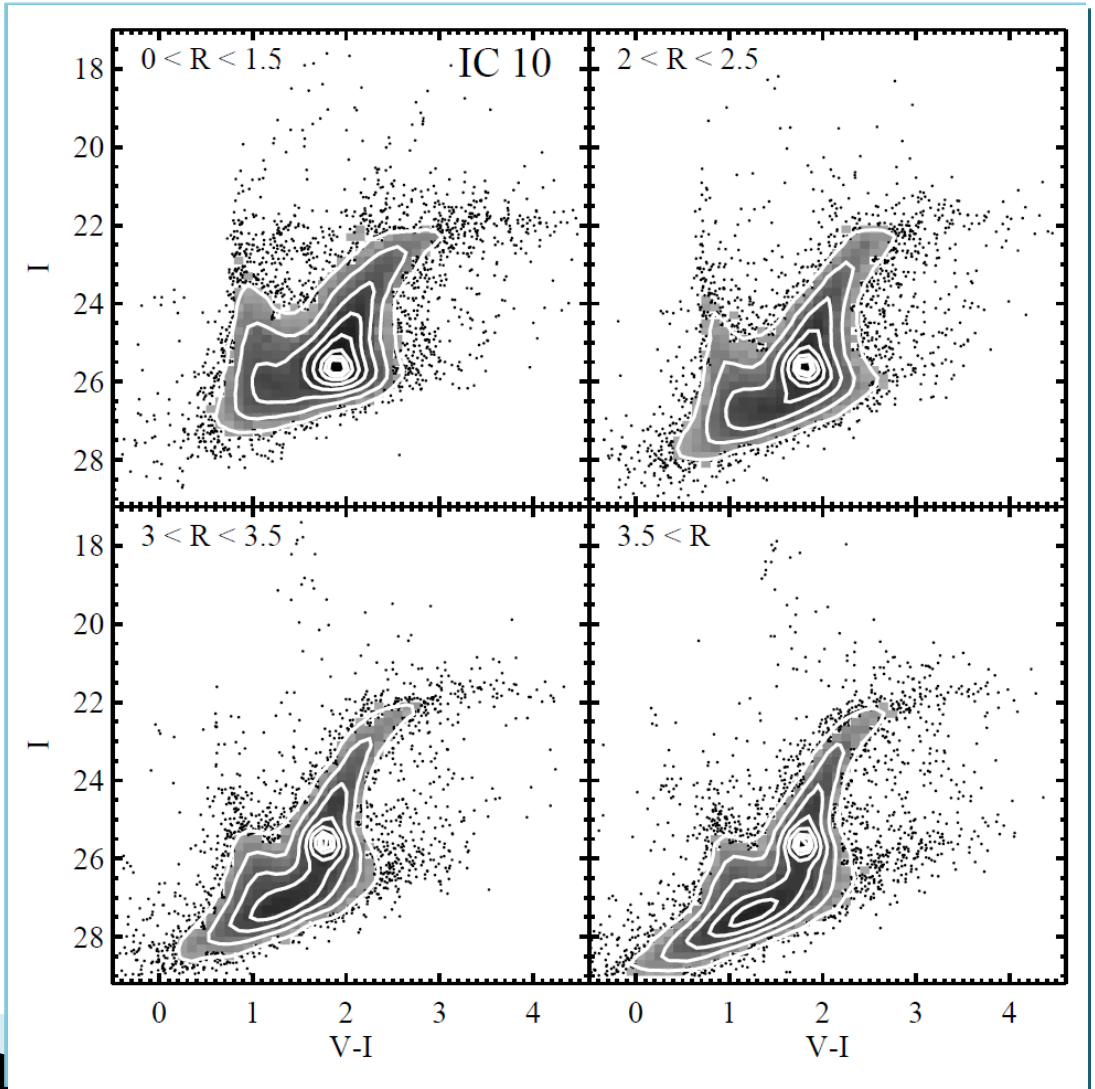
HST/ACS CMD of IC10

- Various pops



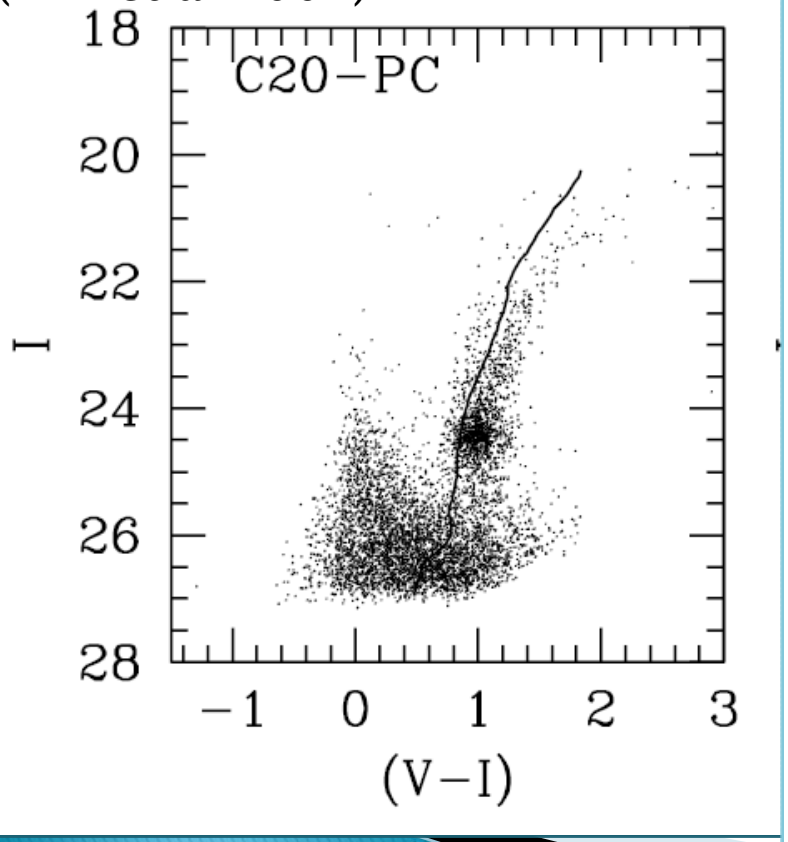
HST/ACS CMD of IC10

- Varying on galactocentric distance

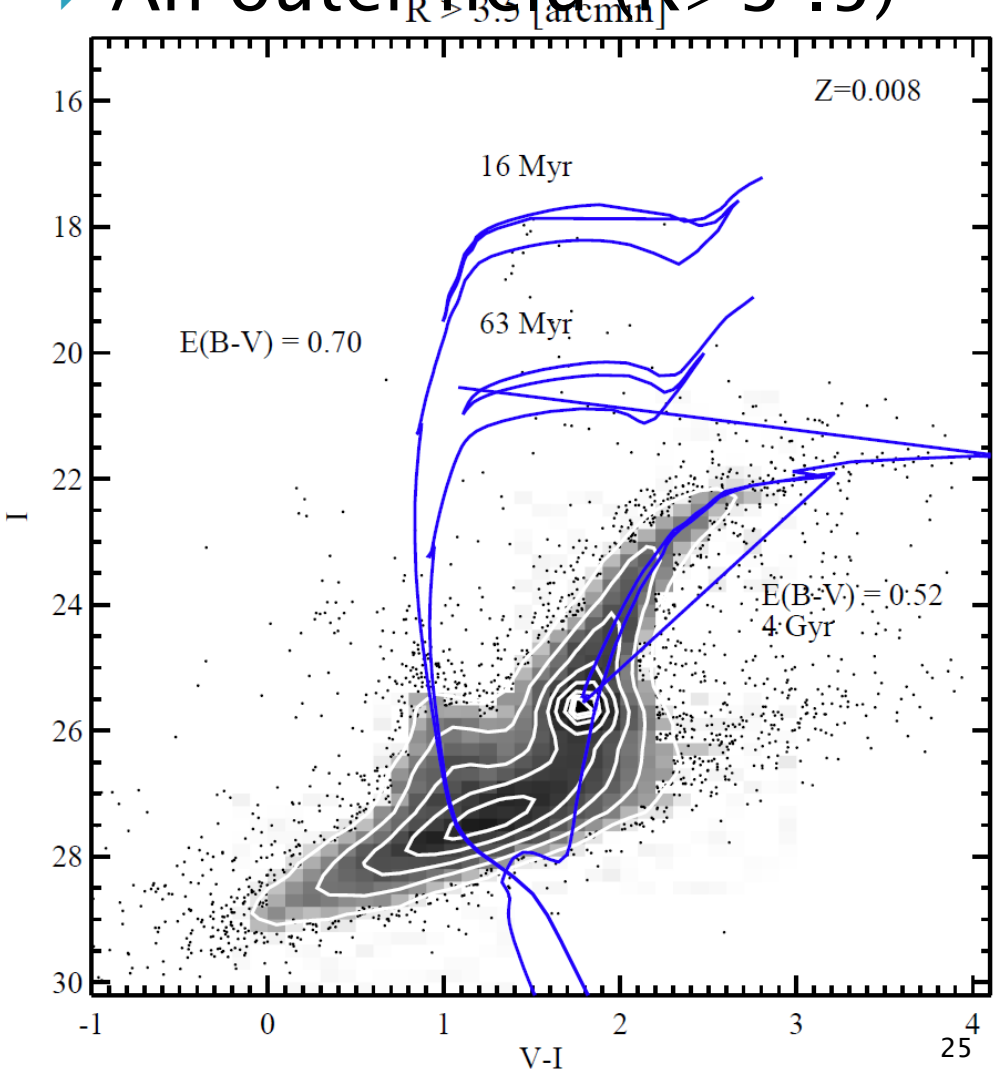


HST/ACS CMD of IC10

- M33 field (R~17')
- E(V-I)=0.06
- (Kim et al 2002)

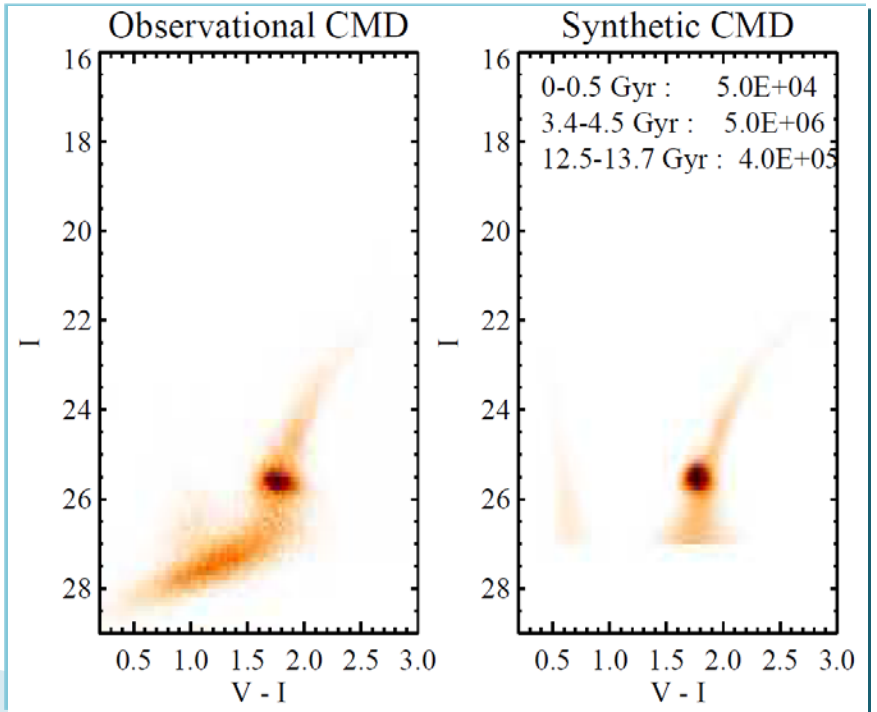


- An outer field (R>3'.5)



A dominant pop of IC10?

- challenging to derive SFHs
- A test for an outer field (R>3'.5):
- Dominant 4 Gyr, weak 13Gyr, some 0.3Gyr
- Similar to a halo field in M33



M82

- Huge outflow and complex central structure!
- An isolated Exploding galaxy!!!!

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EVIDENCE FOR AN EXPLOSION IN THE CENTER OF THE GALAXY M82

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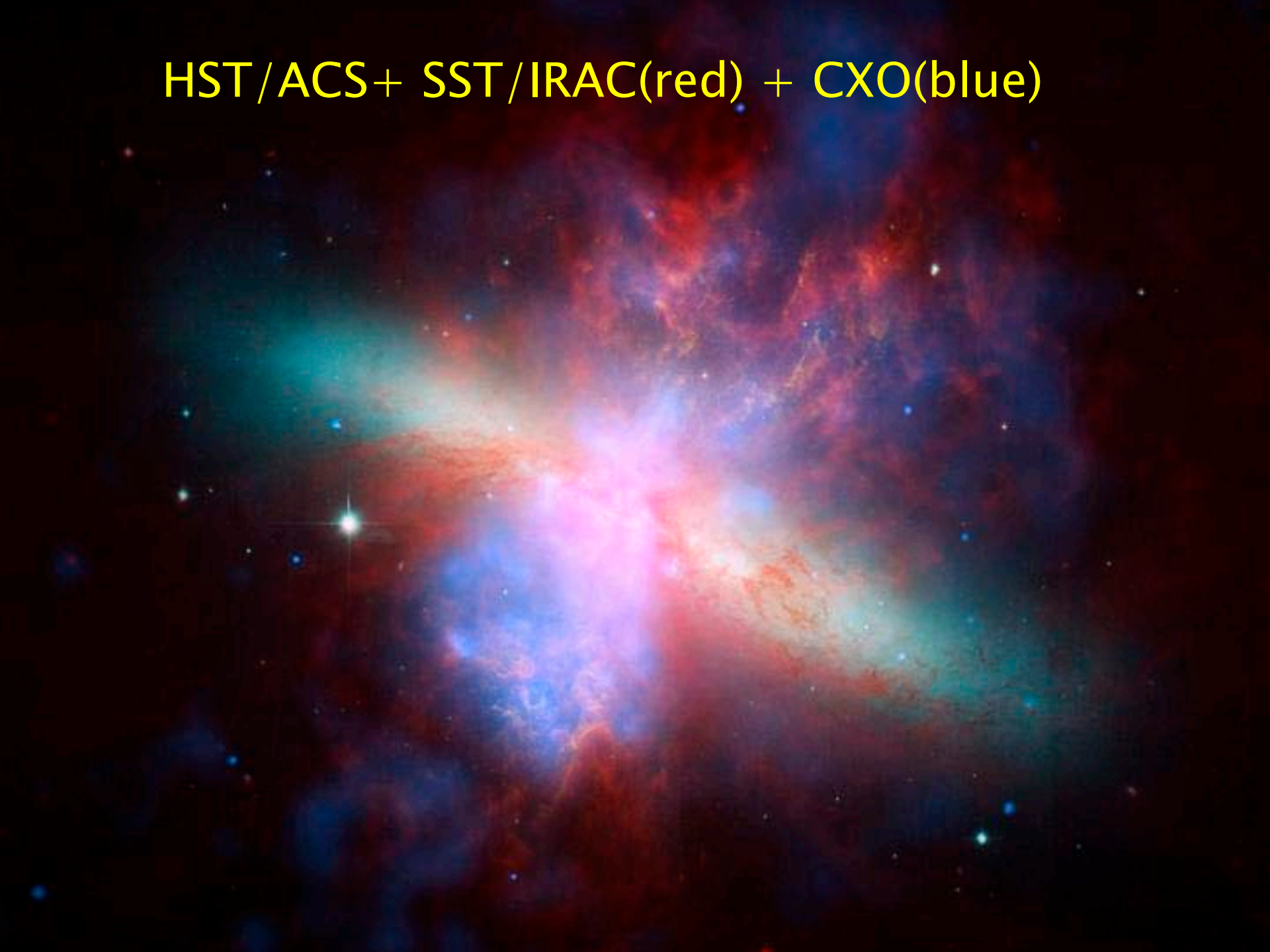
Received November 17, 1962; revised January 14, 1963

ABSTRACT

Mysterious M82

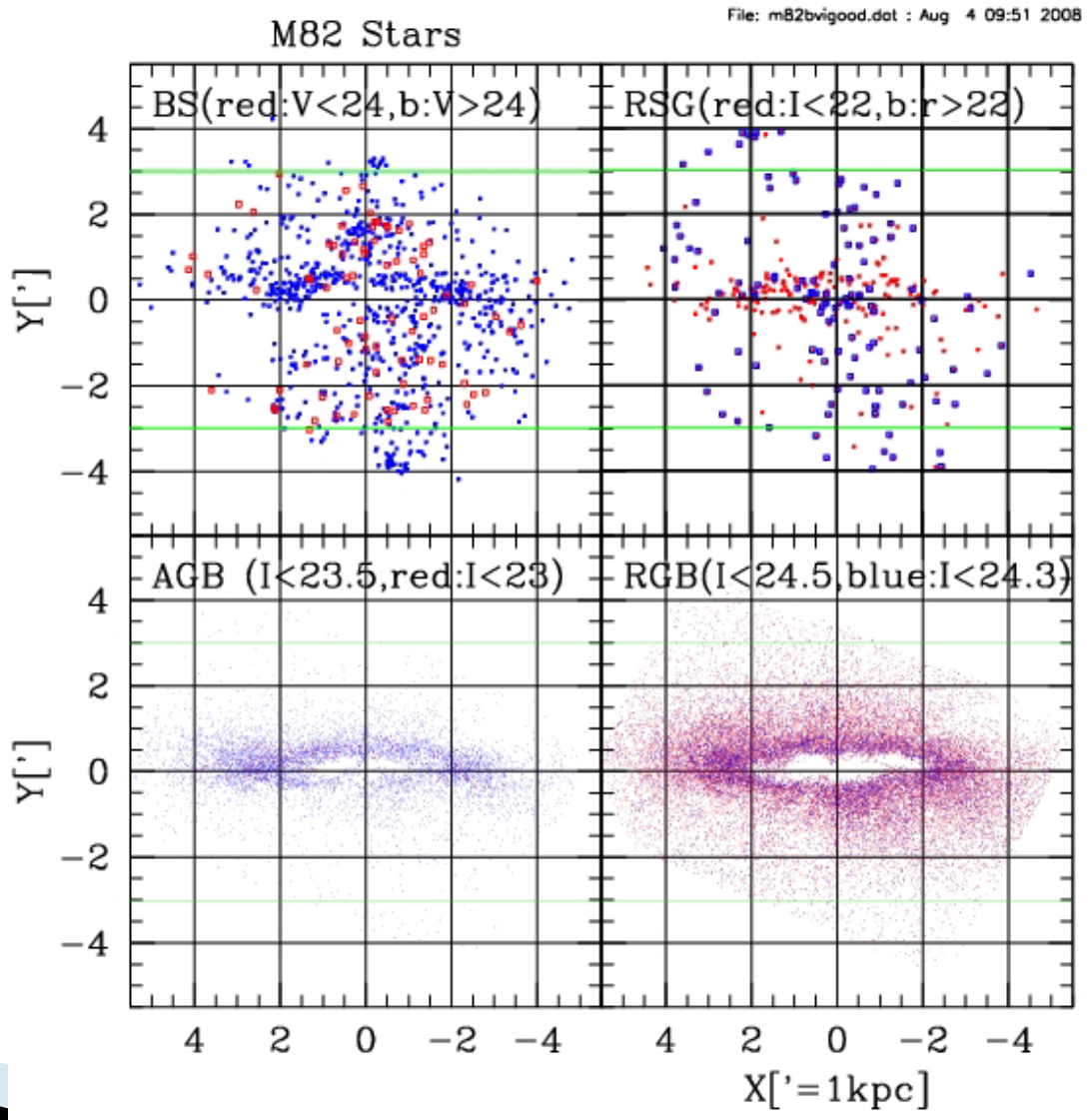
- A small dwarf Irr in the M81 group
- Second nearby starburst
- Very luminous in IR (template for IRG)
- Ha emission outflow from the disk
- several bright knots in optical images
- X-ray emission perpendicular to the disk
- MIR emission perpendicular to the disk


HST/ACS+ SST/IRAC(red) + CXO(blue)

M82 stars from HST/ACS

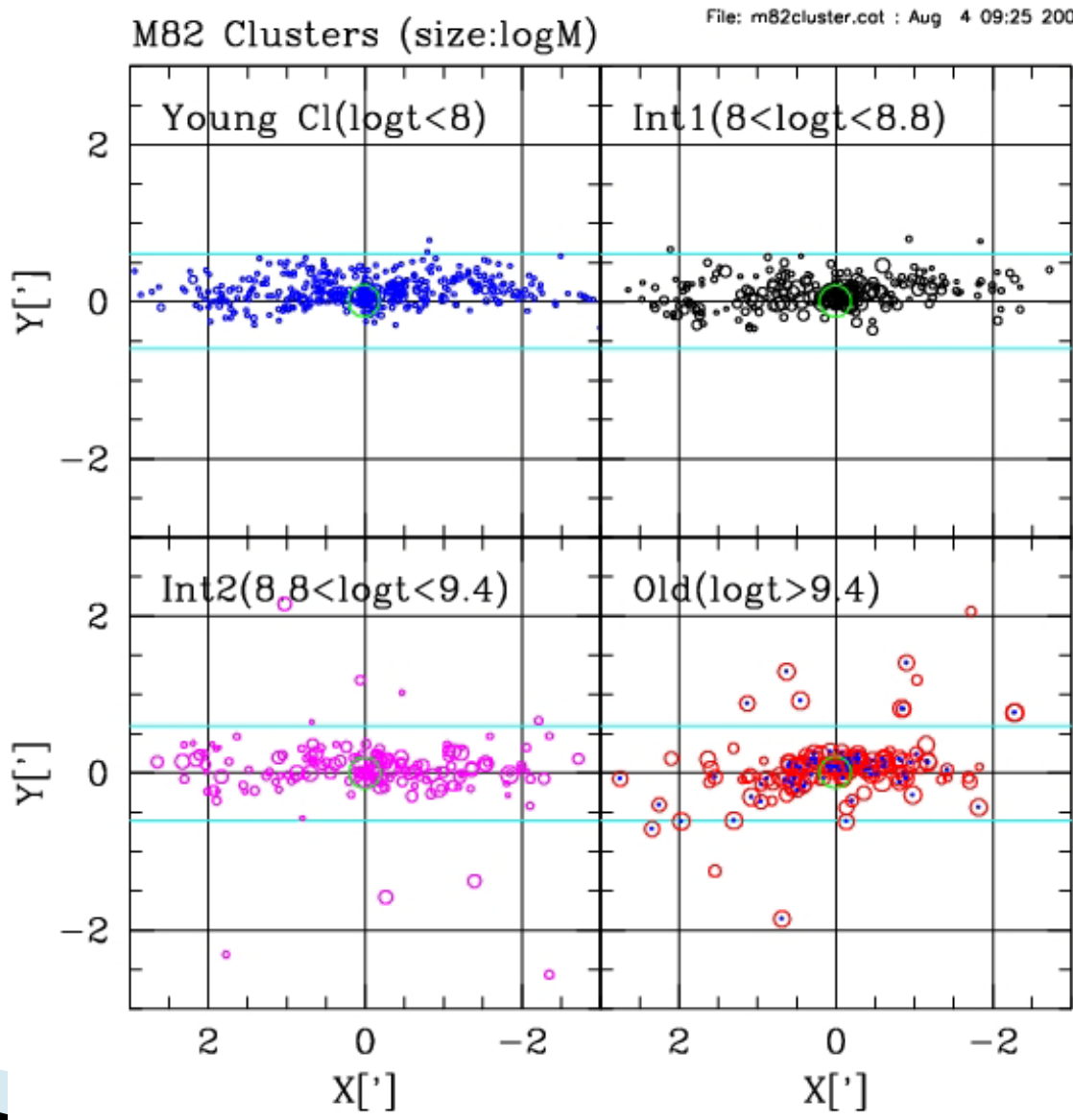
- BSG
  (disk+outflow)
- RSG
  (bar+outflow)
- AGB
  (thick disk)
- Old RGB

(thick disk+halo)



M82 Clusters

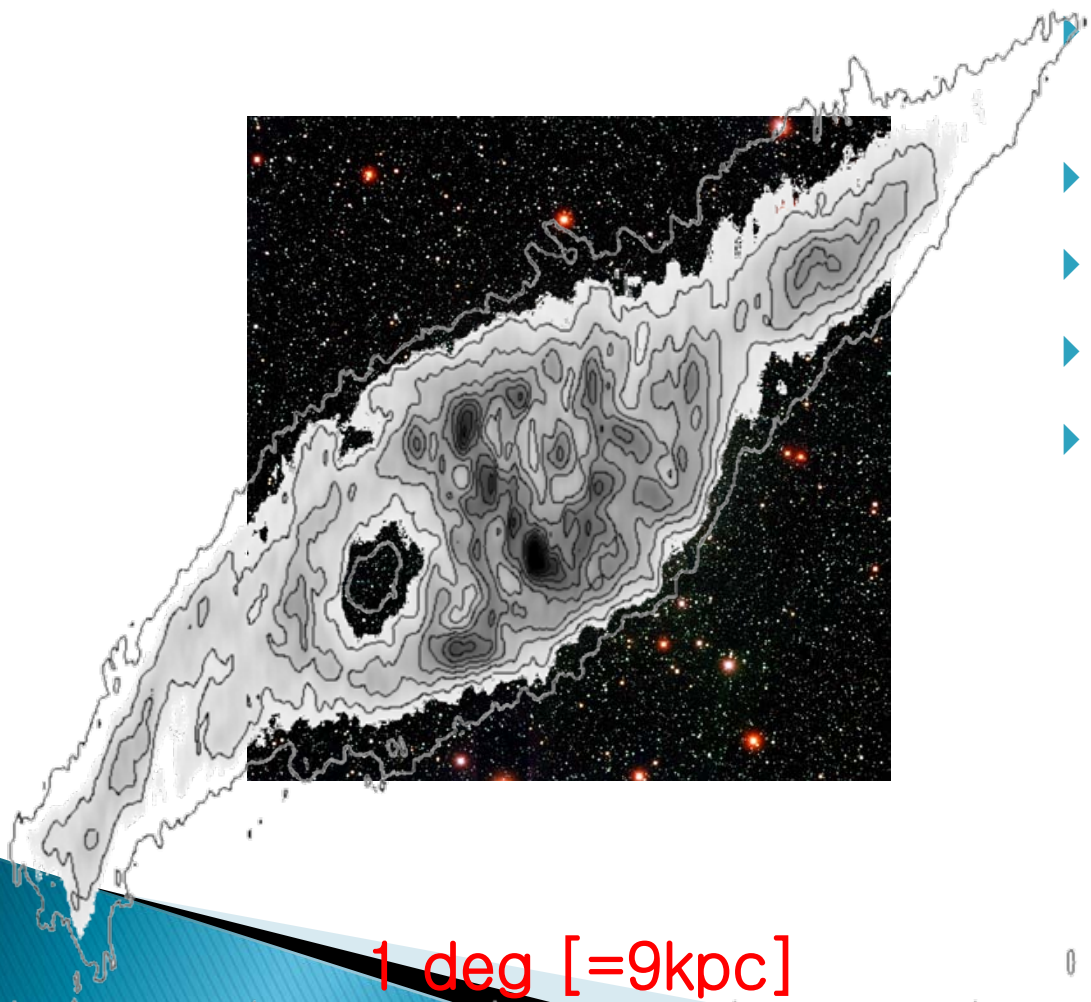
- Young clusters are in the disk.
- Old clusters in the halo-GCs!!!
- Old clusters in the inner disk???
  (old, reddened, or a new kind?)



NGC 6822

- The first dwarf studied in detail: Hubble (1926)

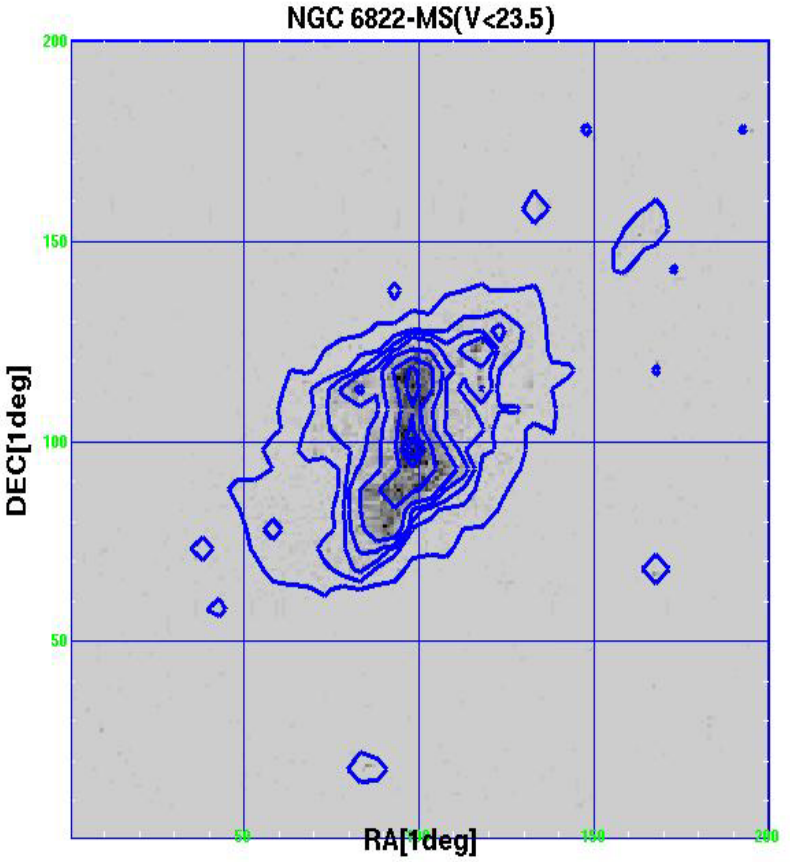
HI gas in NGC 6822

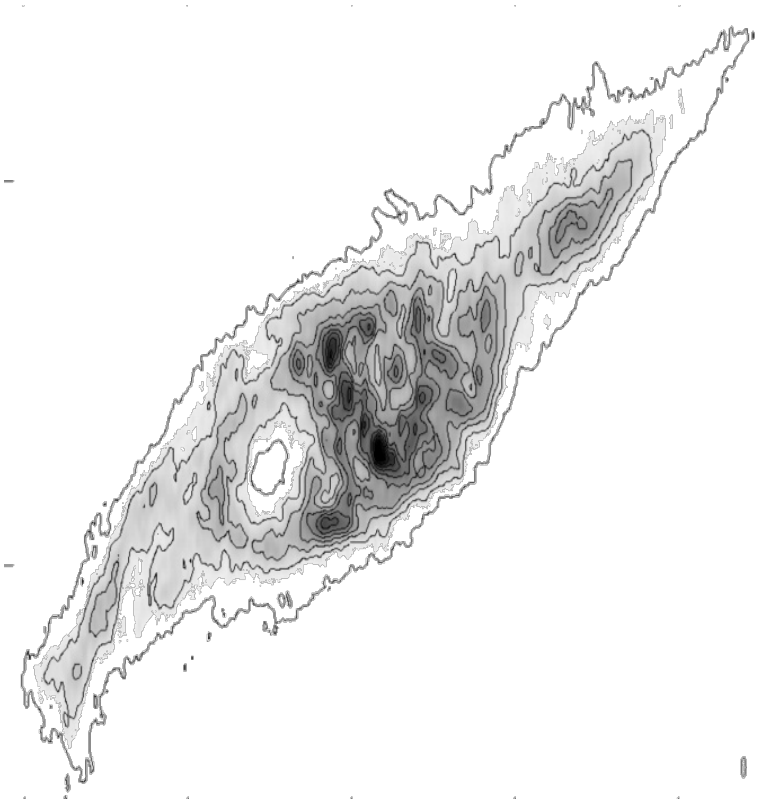


- HI map (Roberts 1972, de Blok & Walter 2000)
  - A huge rotating disk
  - A supergiant HI hole
  - SE tidal arm
  - NW cloud

Spatial Distribution:MS

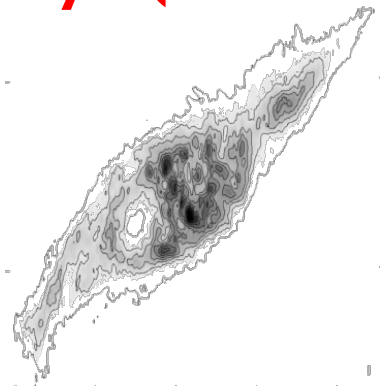
- **Vertical optical bar-bright stars**
- **Consistent with HI map (deBlock & Walter 2000)**

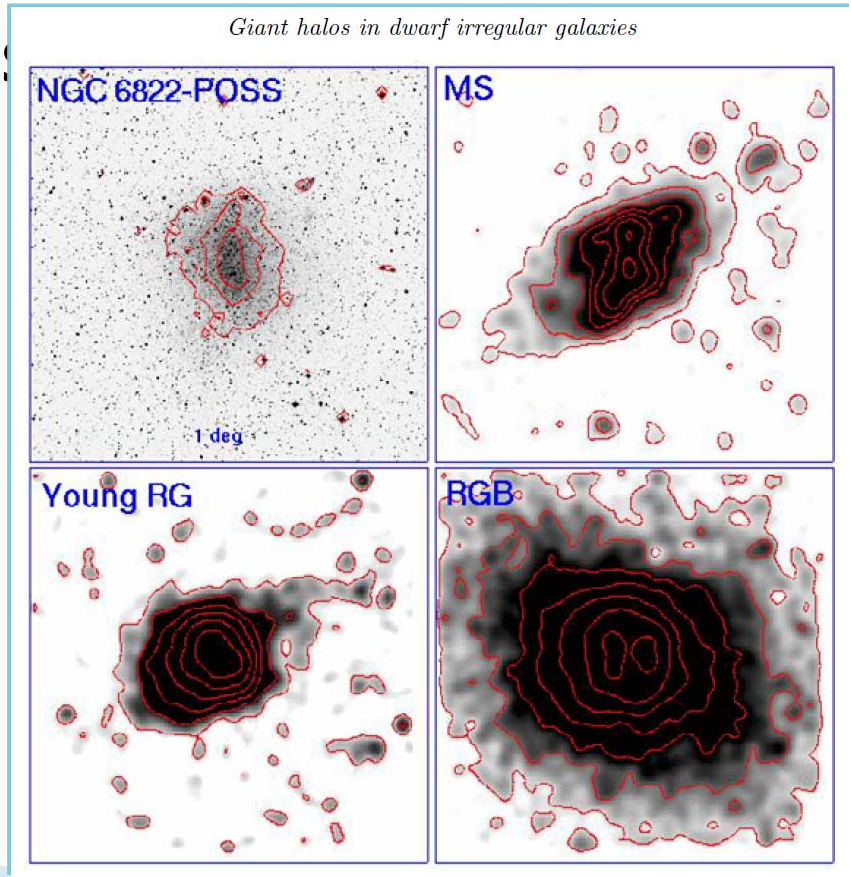




NGC 6822: star

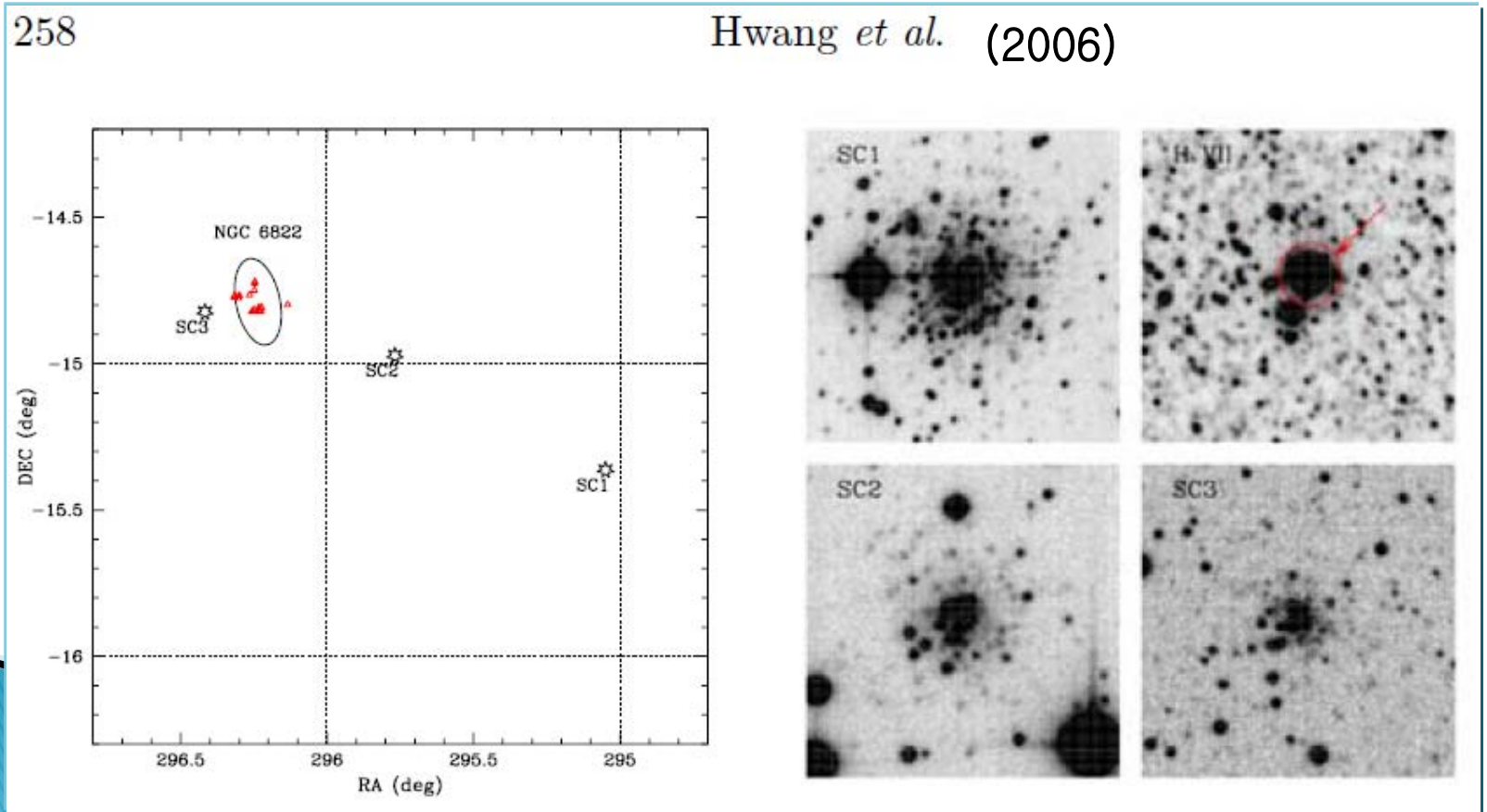
- Dramatically different spatial distribution of MS, young RG and RGB (Lee 2006)
- It is an isolated galaxy!
- A merger origin?
- A polar ring galaxy ?(Demer





NGC 6822: Star Clusters

- Three extended star clusters in the remote halo
- Are they satellite dwarfs?
- Multiple populations in these?



Summary

- A common key for enigmatic dwarfs:
  interaction (with host galaxies or other dwarfs)!
- **Standing questions:**
  - **How can a dSph have multiple SF?**
  - **Where are the stars formed first in the U? in D or GC?**
  - **What are mechanisms for starburst in galaxies?**
- **Need fresh ideas (possibly from SAO)!**

A lesson in this conference

- Galaxy groups are defined by dwarfs in the Local Universe (Brent and Igor in this conference)
- The Local Universe is fractal!
- The Local Group of galaxies
  - MWG+ dwarfs
  - M31+dwarfs

A solution for dwarf enigma?

- The Local Group at SAO
  - IK (Interacting K)+dwarfs
  - BT (Bold T)+dwarfs MD(Matter dark) & Dark energy

- That's how we are here. Interaction is the key to solving the enigma of dwarfs!