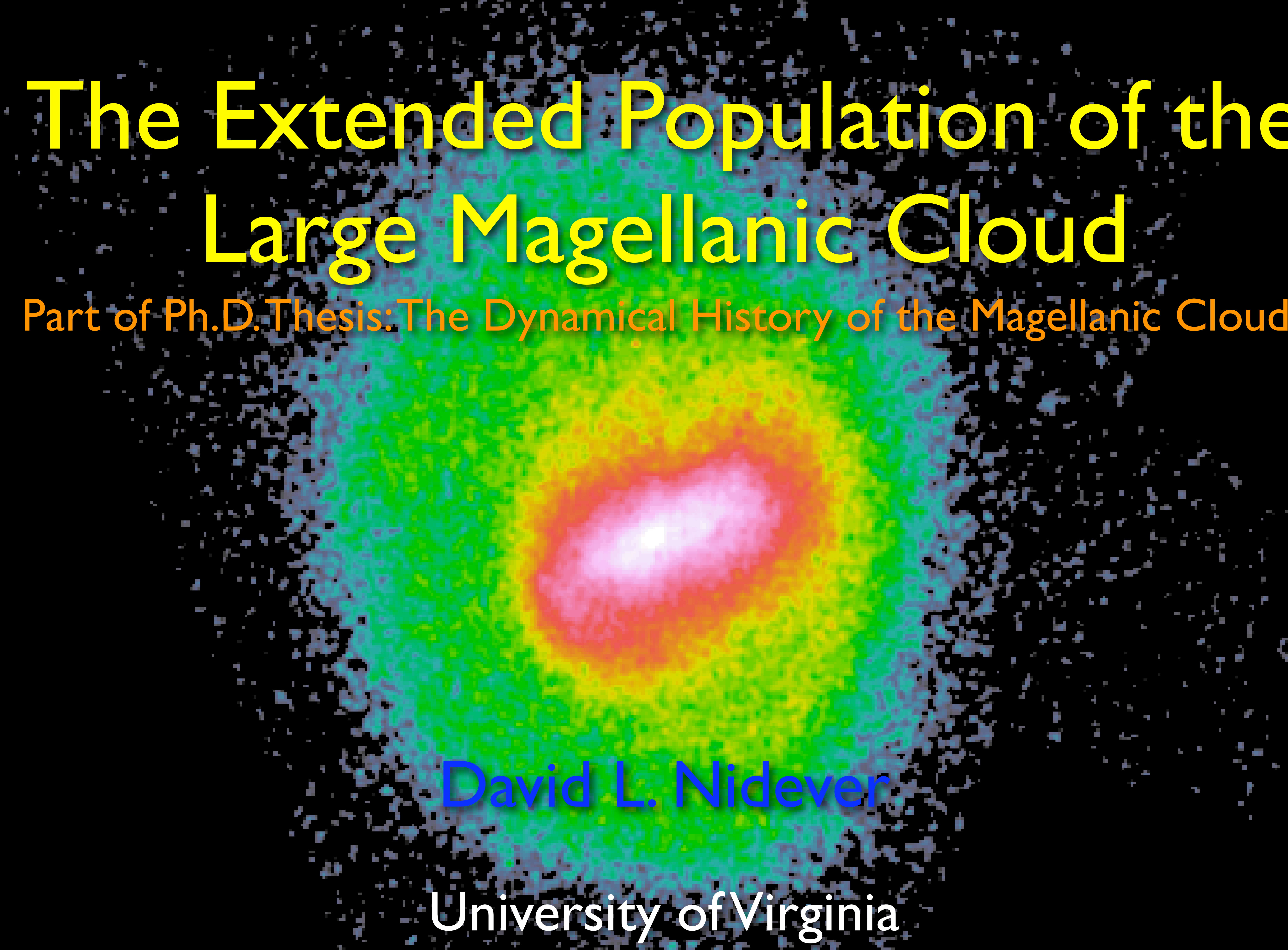
The Extended Population of the Large Magellanic Cloud

Part of Ph.D. Thesis: The Dynamical History of the Magellanic Clouds



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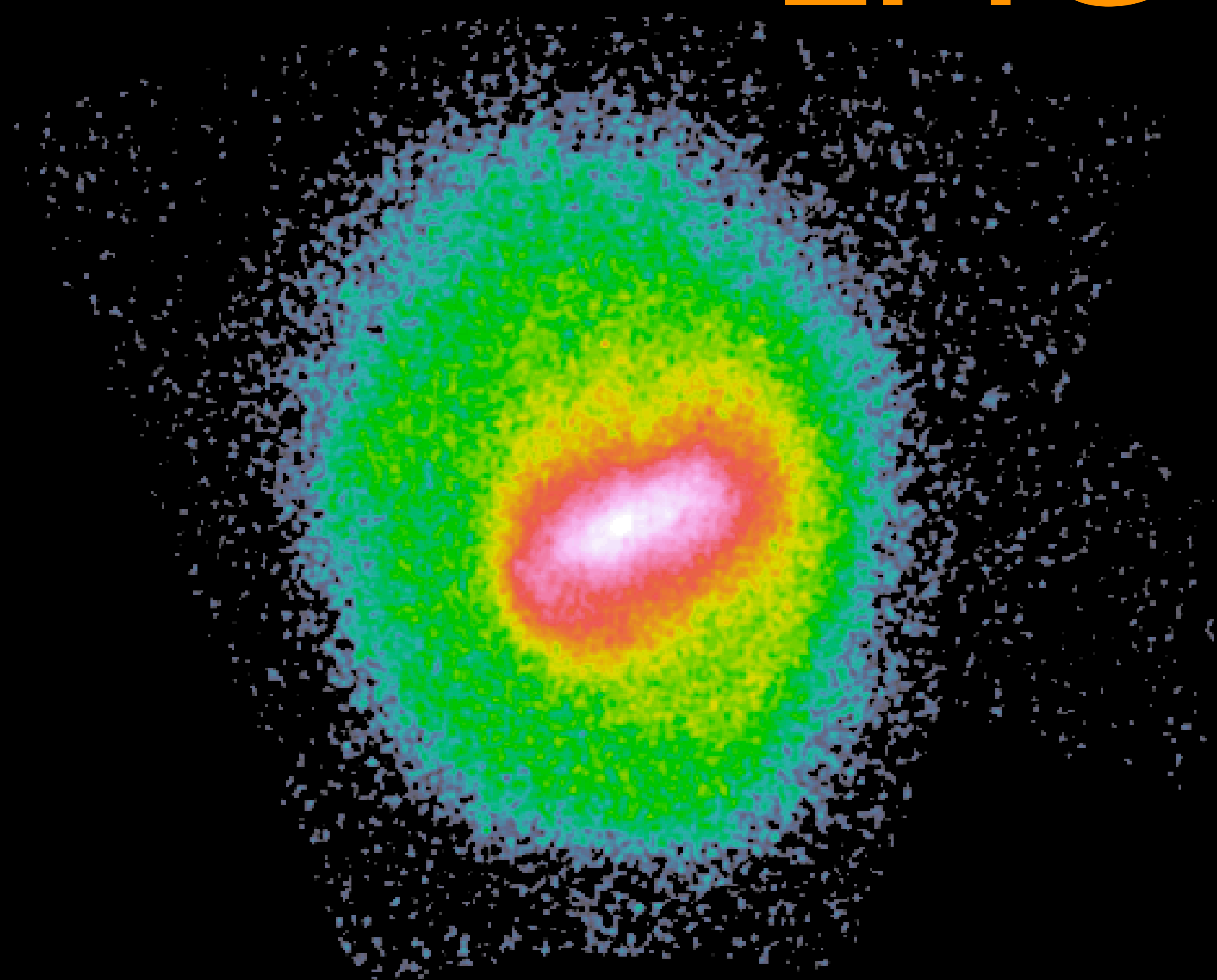
University of Virginia

Collaborators: Steven R. Majewski, Ricardo R. Munoz, Richard J. Patterson, William E. Kunkel (LCO), Jeff Carlin

LMC Disk Density Profile

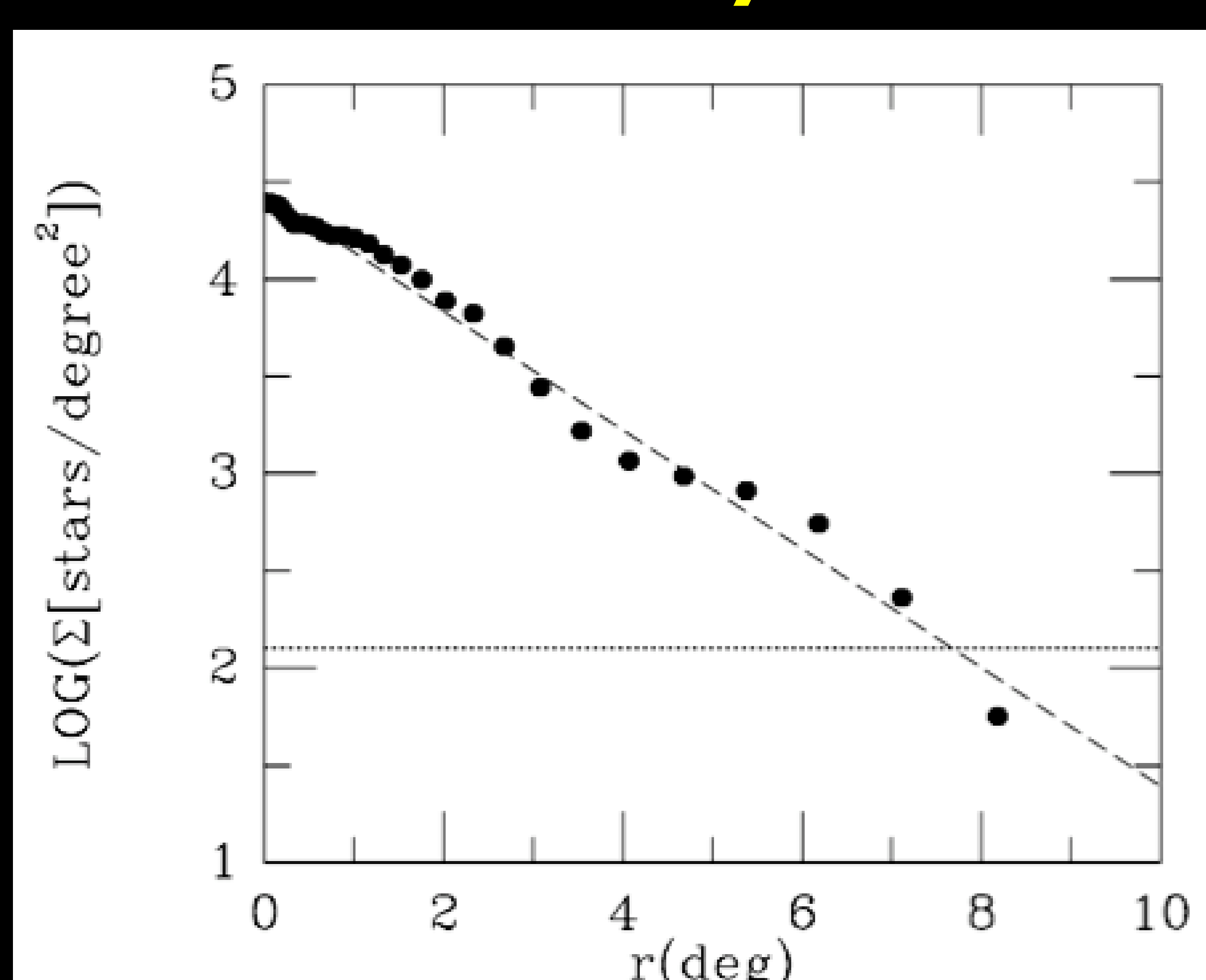


- 2MASS+DENIS LMC red giant branch stars
- Exponential density profile to *R*=8°

  scale length h_r= 1.5-1.7° (van der Marel 2001)
- Elliptical, elongated toward Galactic center

- Harris 2007, exponential disk to *R*~9°
- Meschin et al. find metal-poor main sequence stars to *R*=10°

LMC Density Profile

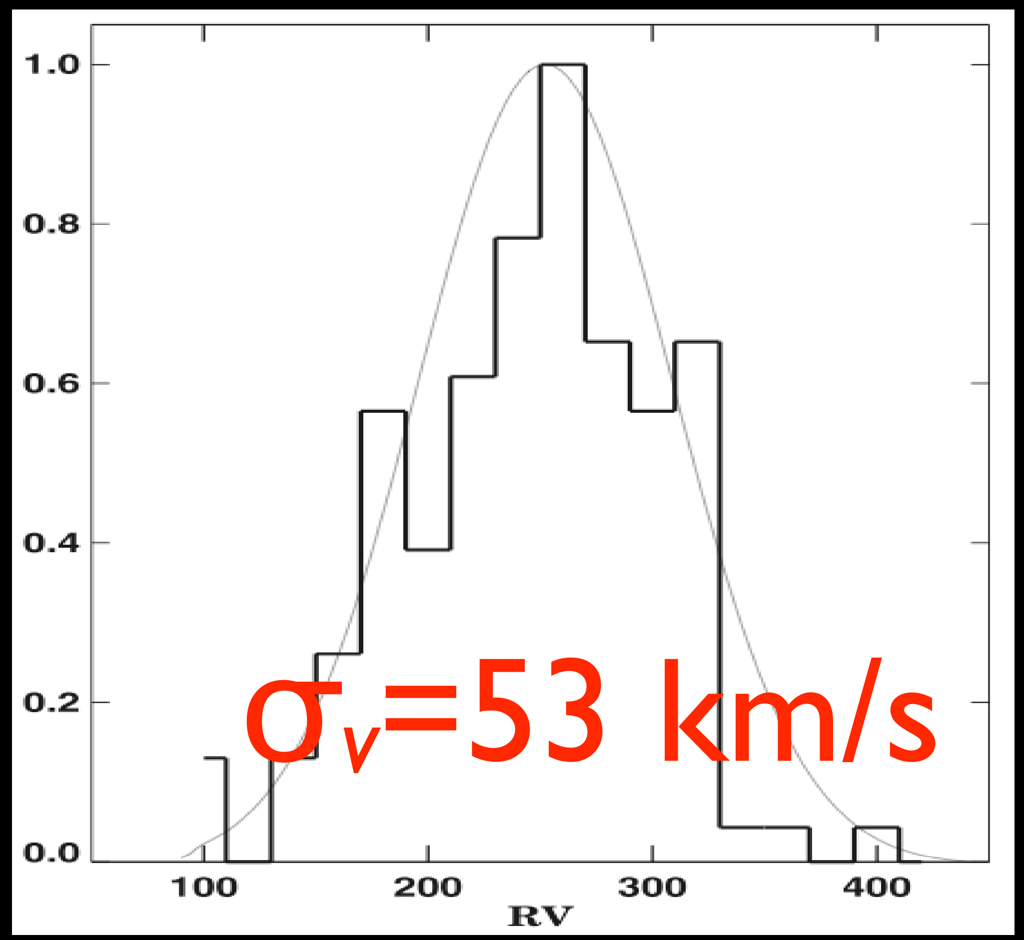


van der Marel 2001, AJ, 122, 1827

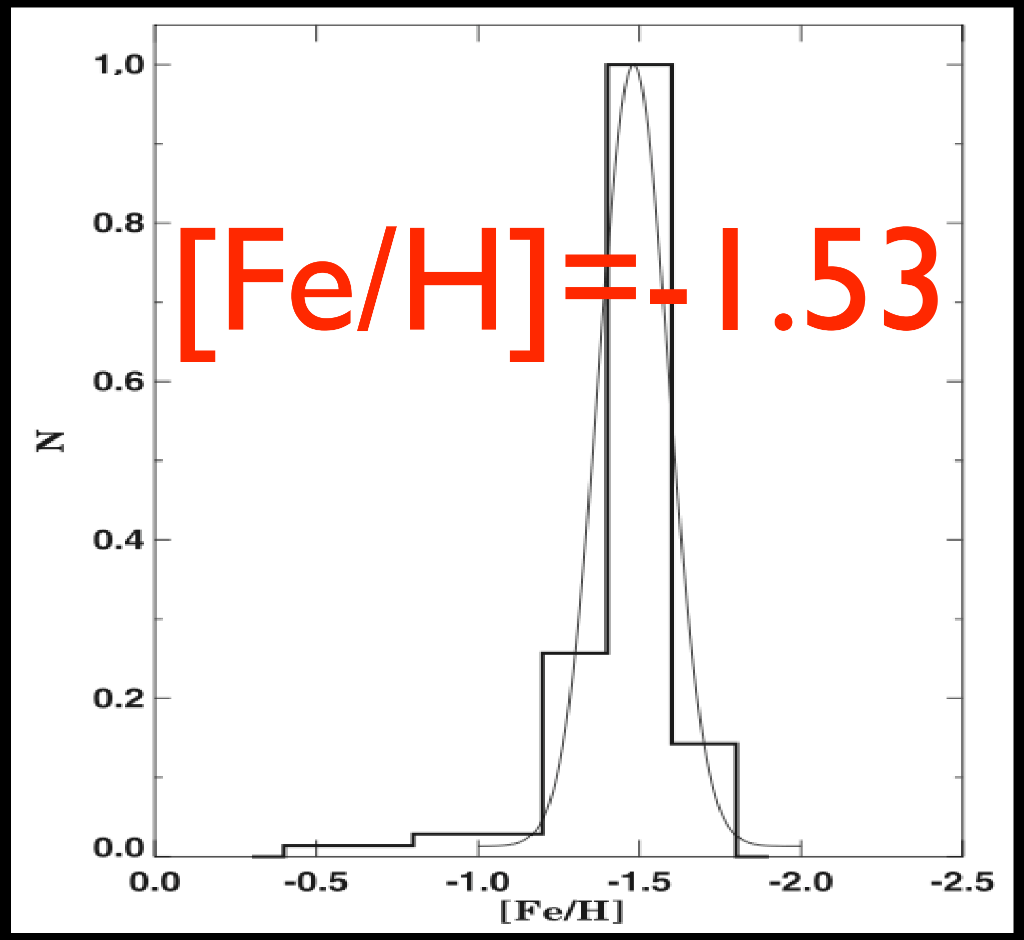
Old, metal-poor halo from RR Lyrae

- MACHO and OGLE identified LMC variables (Minniti et al. 2003; Borissova et al. 2004, 2006; Alves 2004)
    - σ_v=53 km/s
    - [Fe/H]= -1.53 +/- 0.02
    - But, density profile is King or Exponential to R=15°, h_r=1.68° Same as disk!
- Dynamically hot, metal-poor, RGB component (Cole et al. 2005)

RR Lyrae RVs

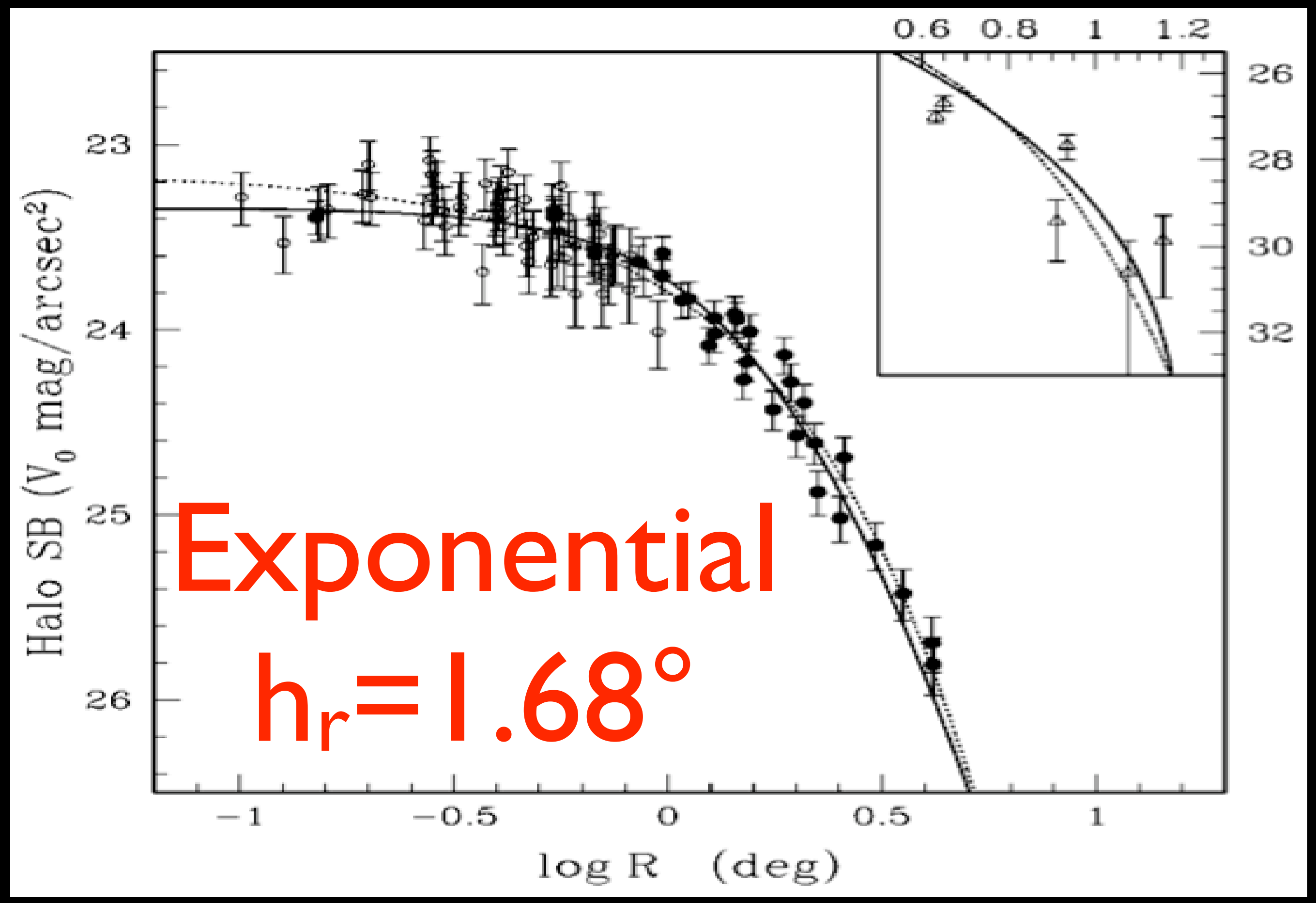


RR Lyrae [Fe/H]



Borissova et al. 2006, A&A, 460, 459

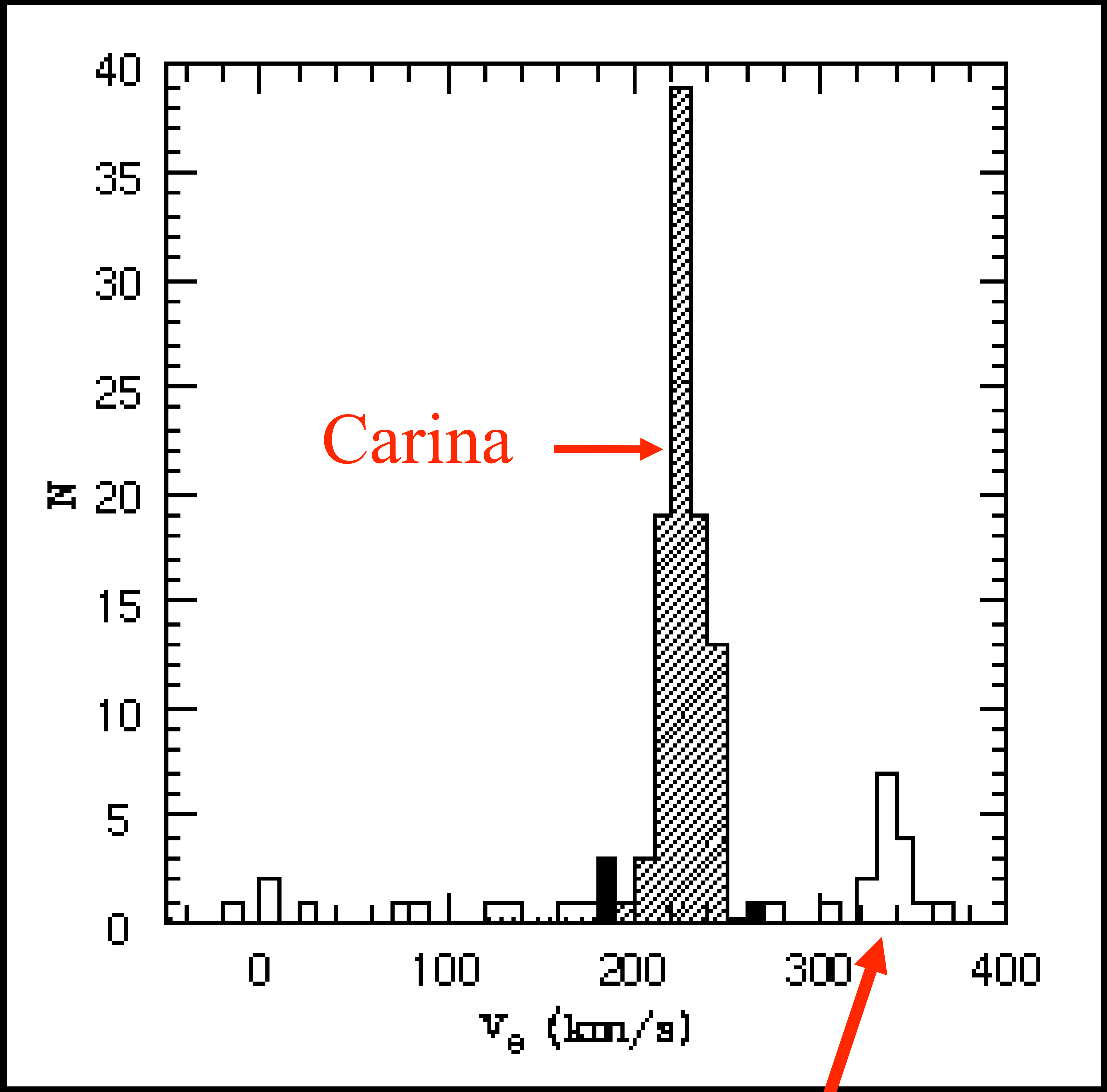
Density Profile



Alves 2004, ApJ, 601, L151

Detection of Well-Separated LMC Stars

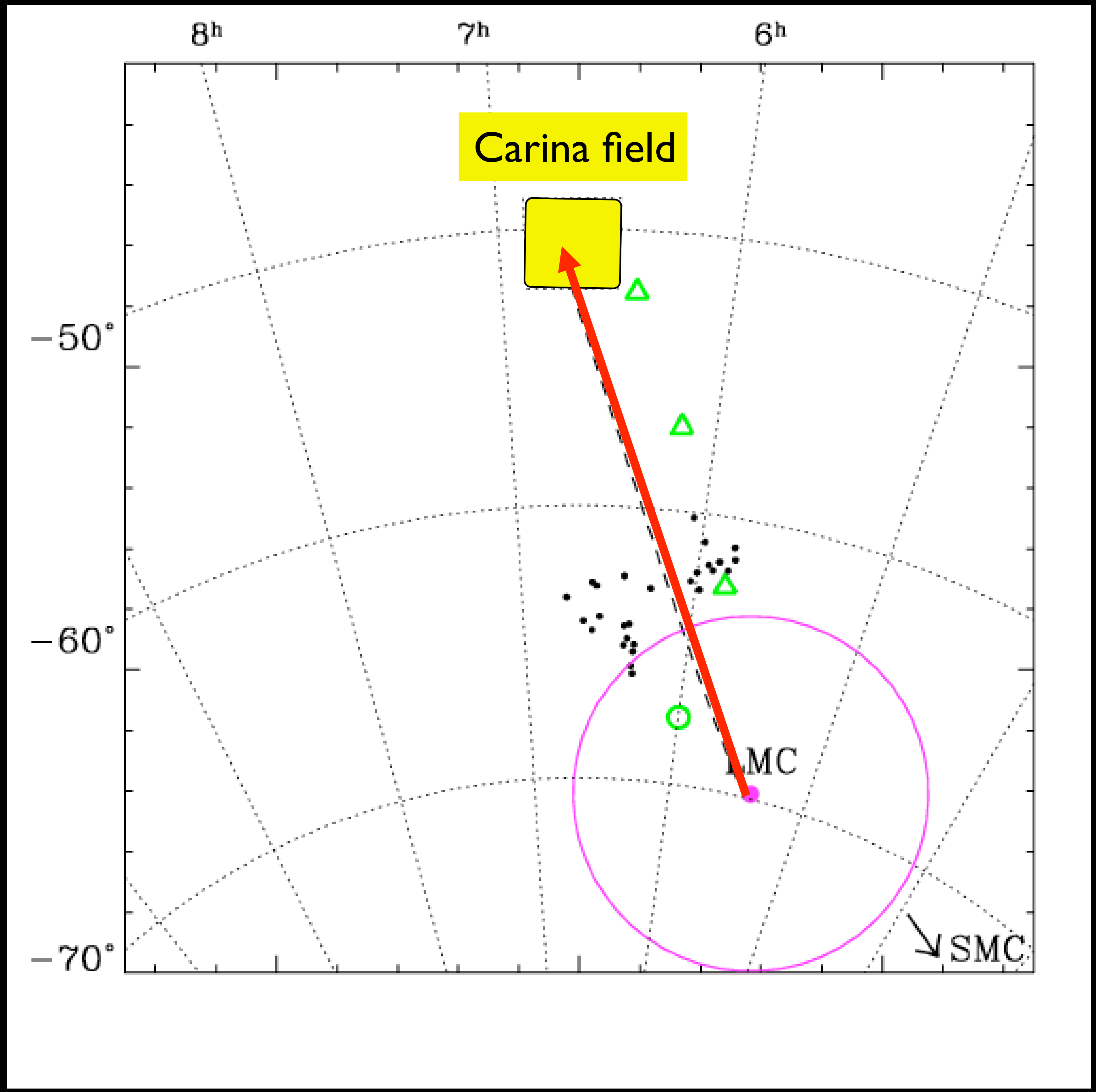
12 deg^2 Carina dSph Study -- Munoz et al. (2006)



Magellan+MIKE echelle spectroscopy

Discovered moving group of foreround LMC stars:
σ_v = 10 km/s, correct distance, metallicity

Carina Spectroscopic Survey and "Linking Fields"



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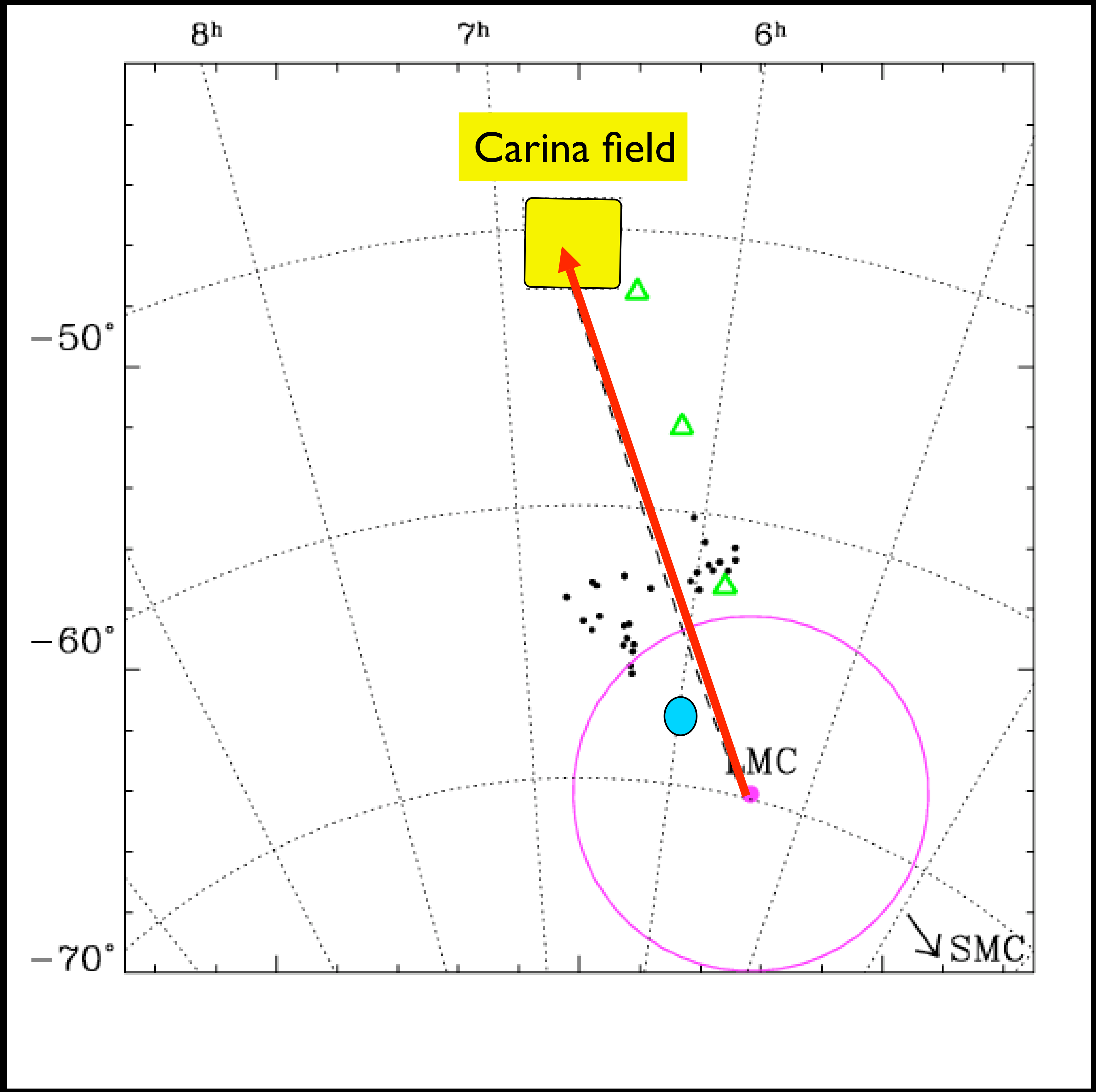

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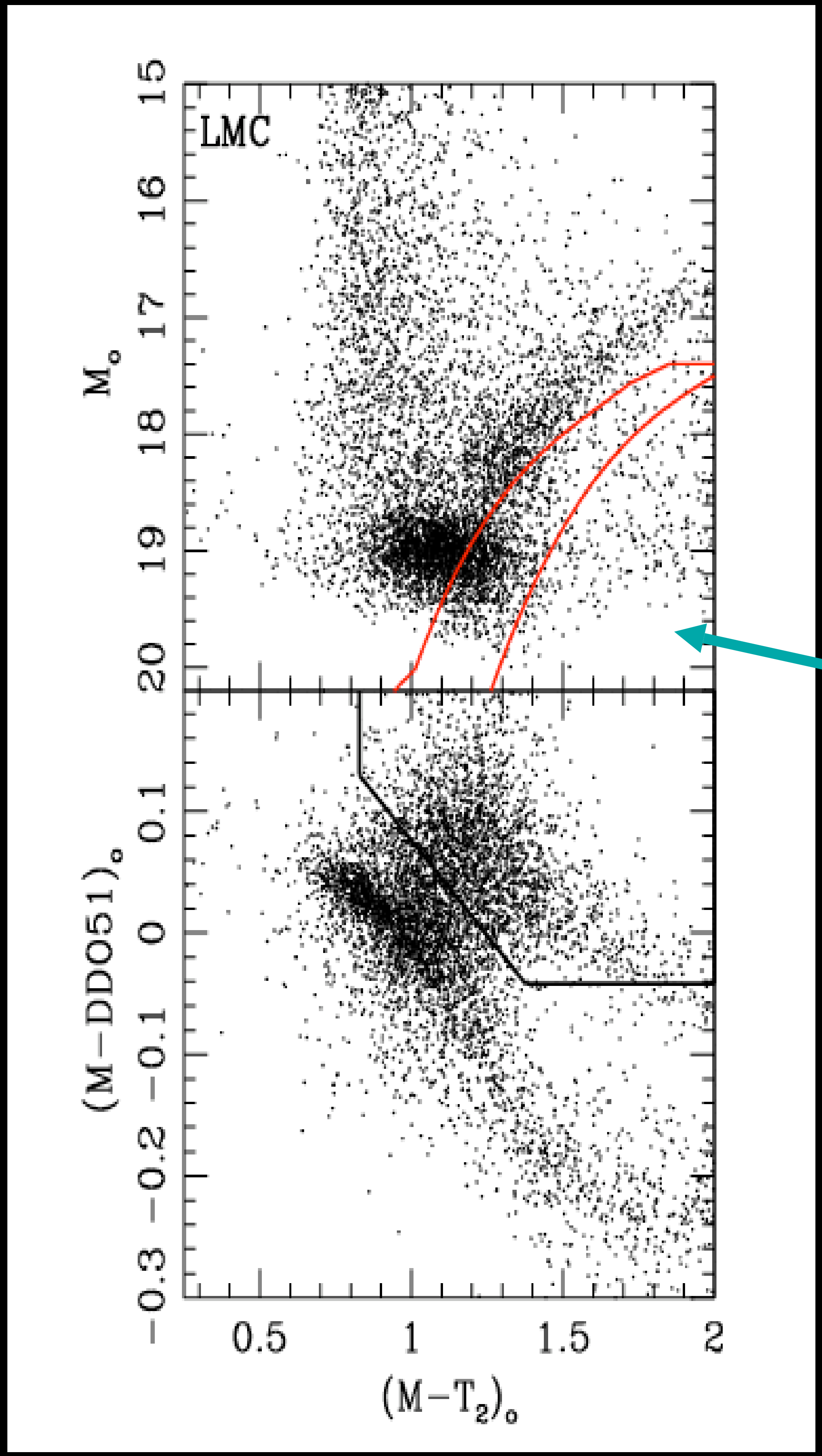

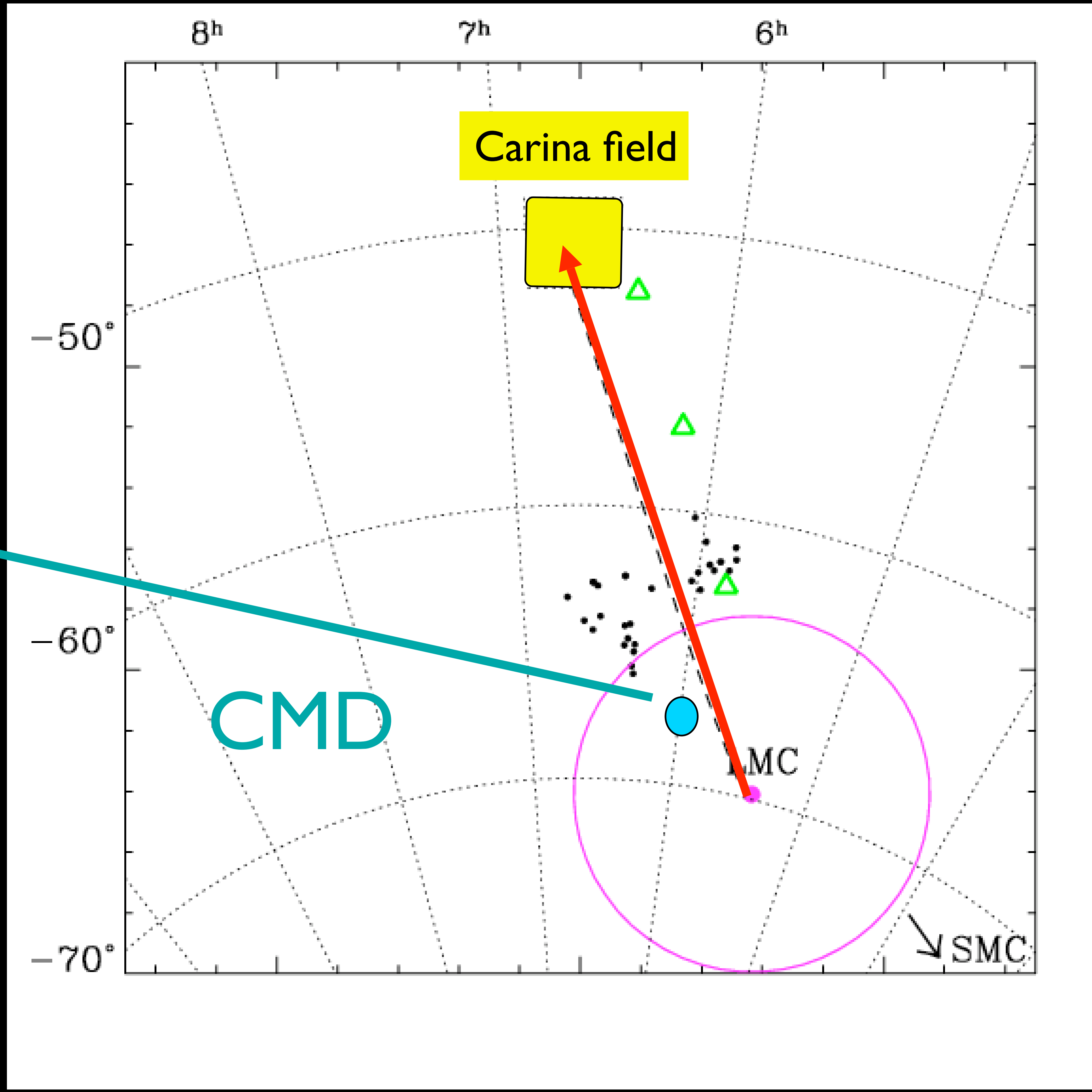

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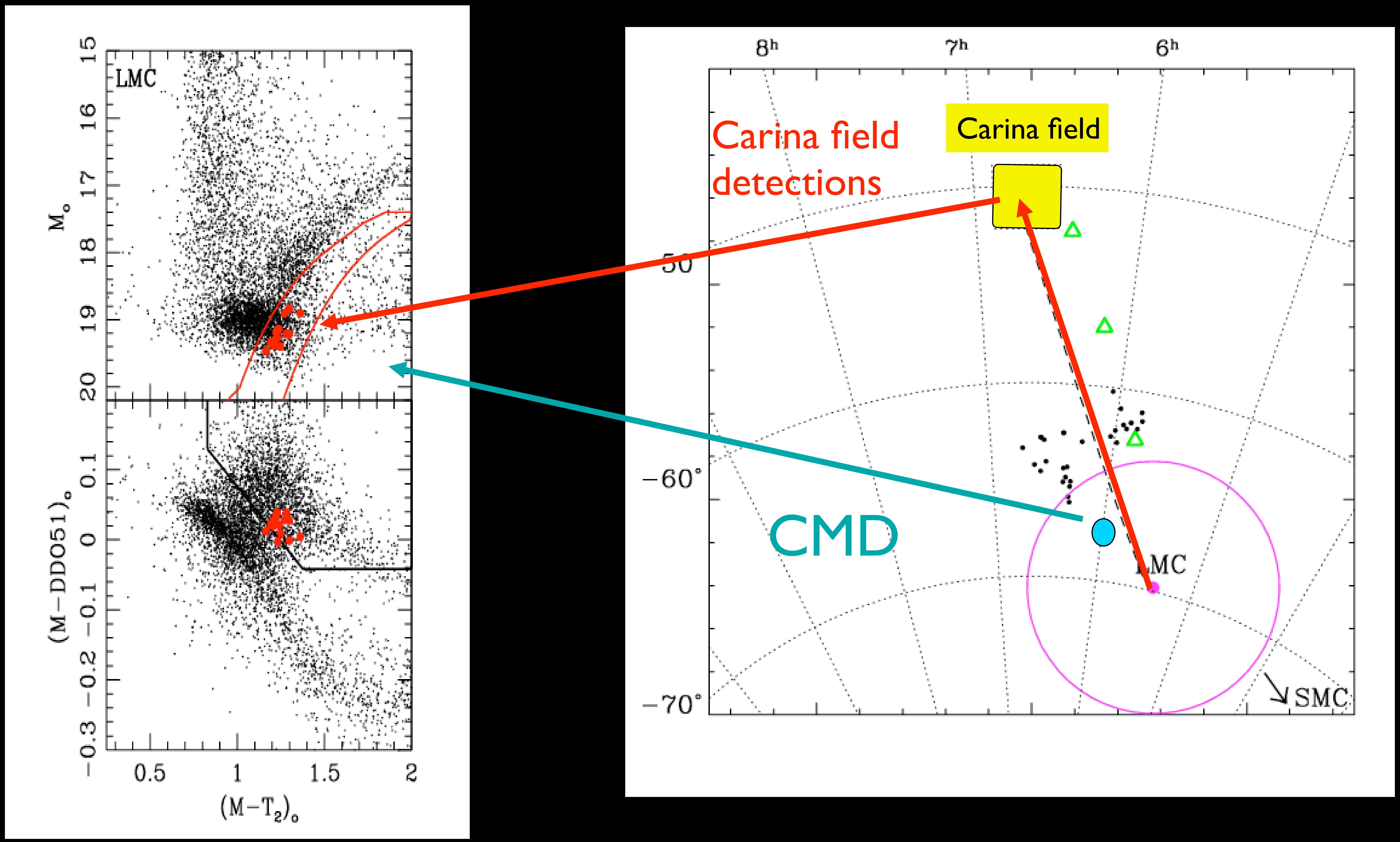

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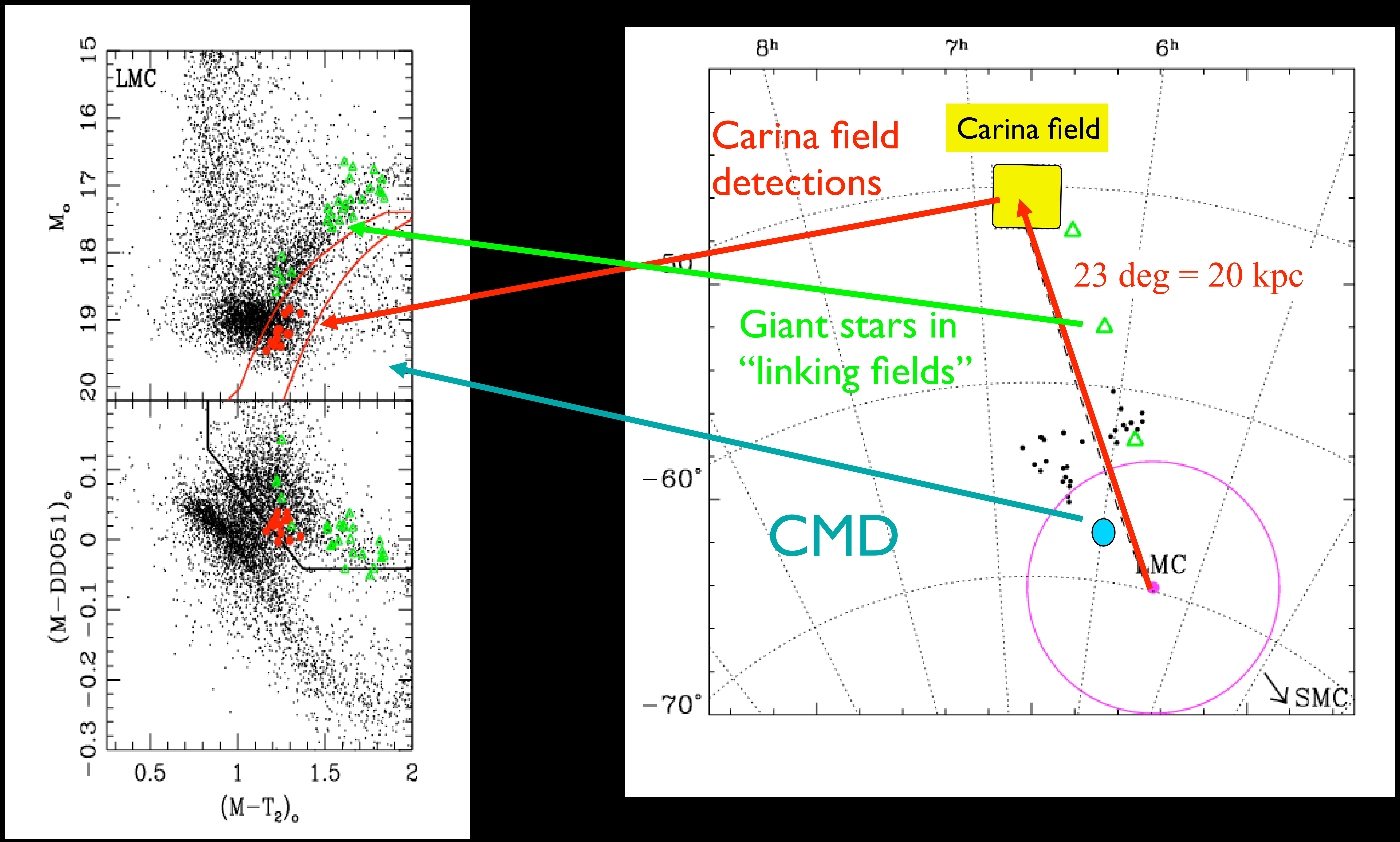
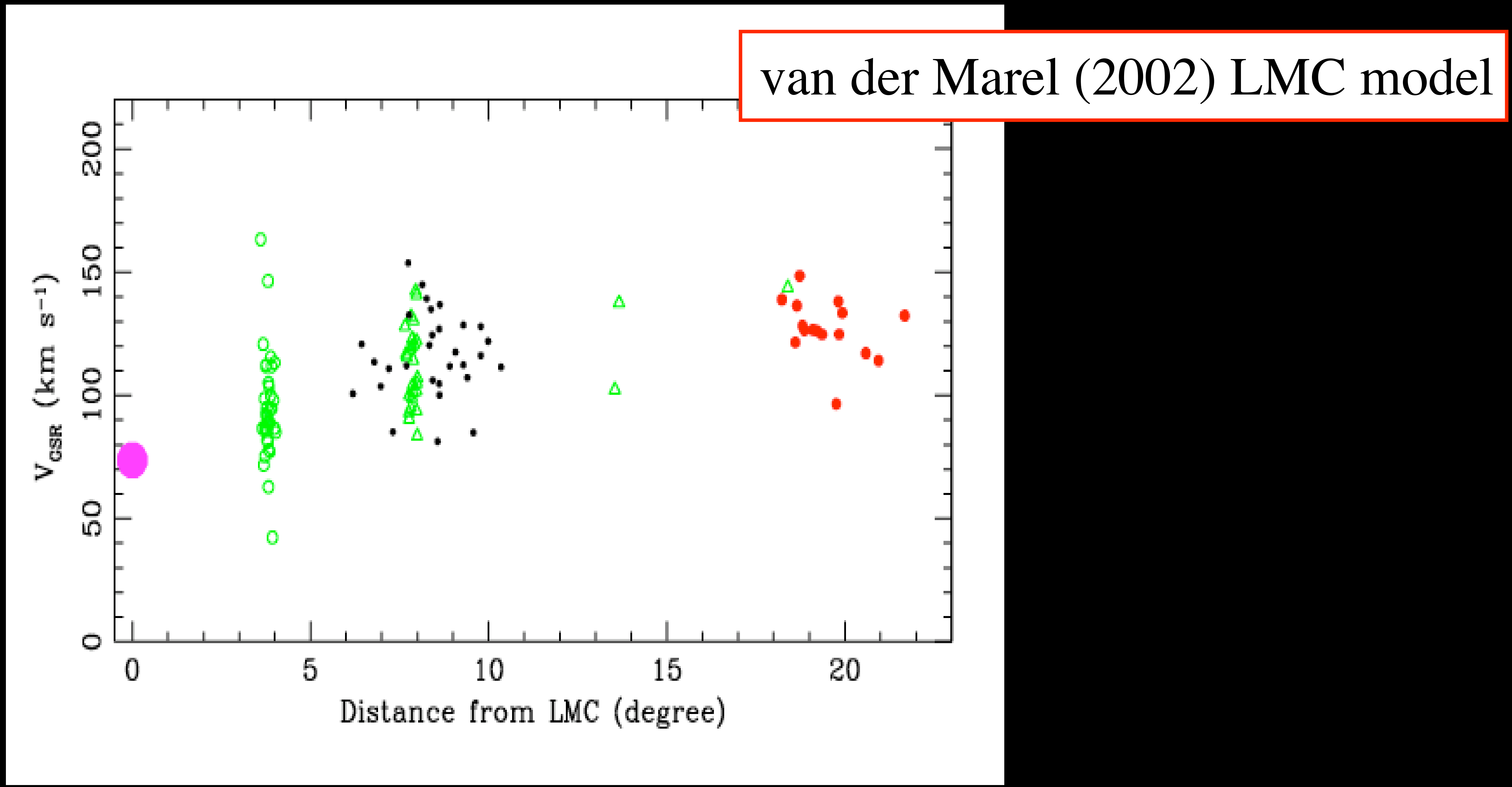
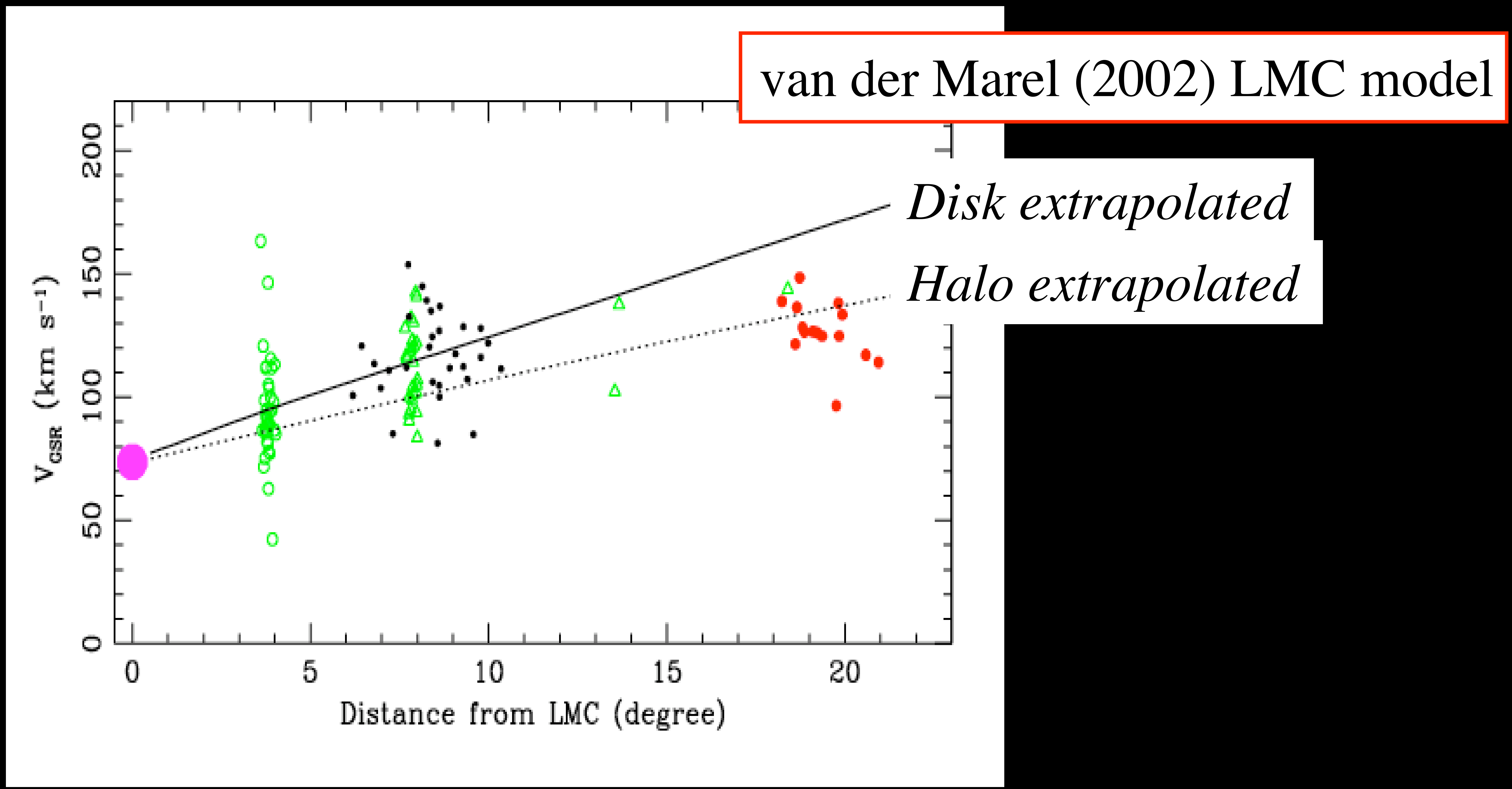


Velocity Trend of LMC stars + Carina 330 group



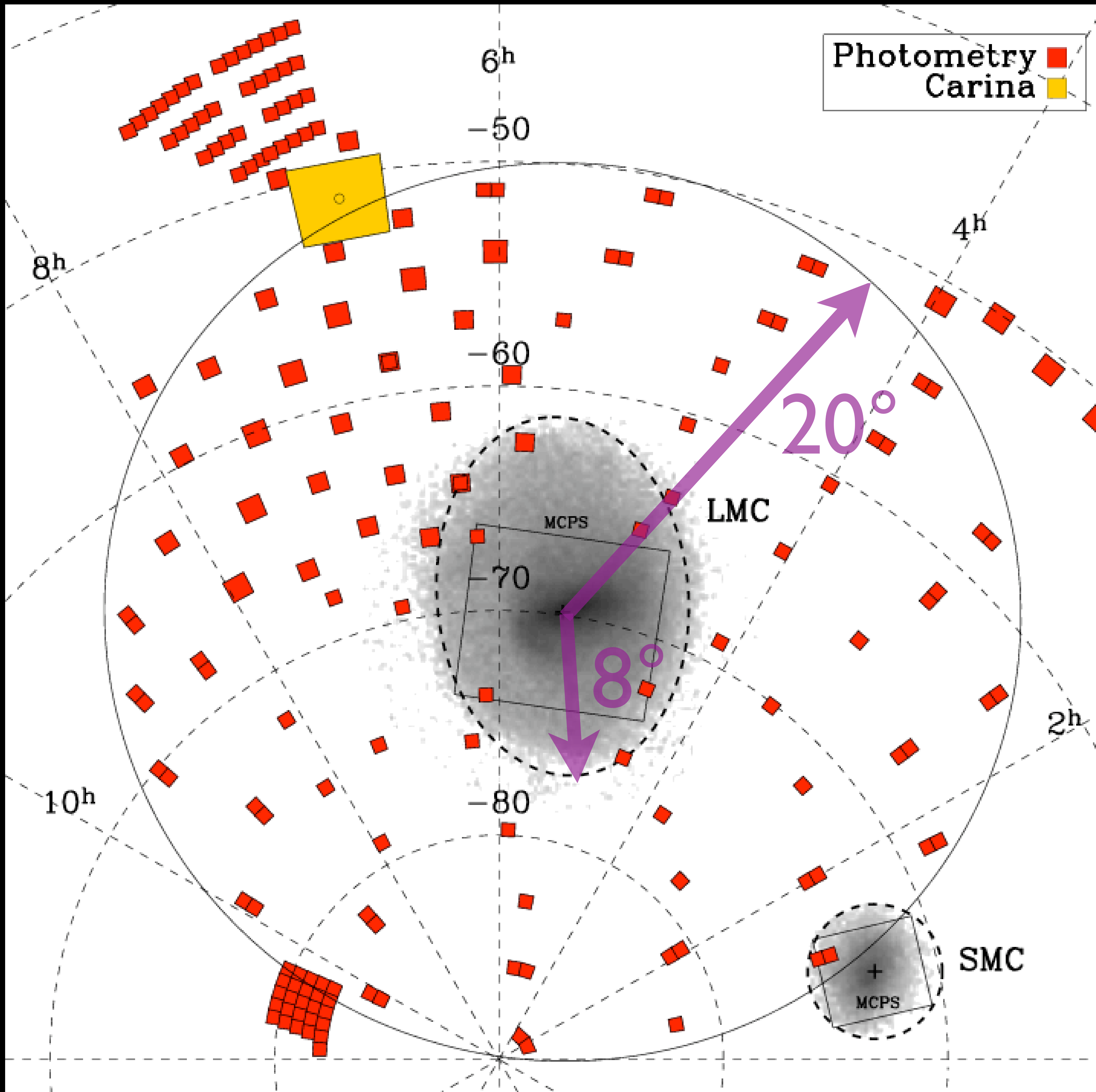
Munoz et al. (2006)

Velocity Trend of LMC stars + Carina 330 group



Munoz et al. (2006)

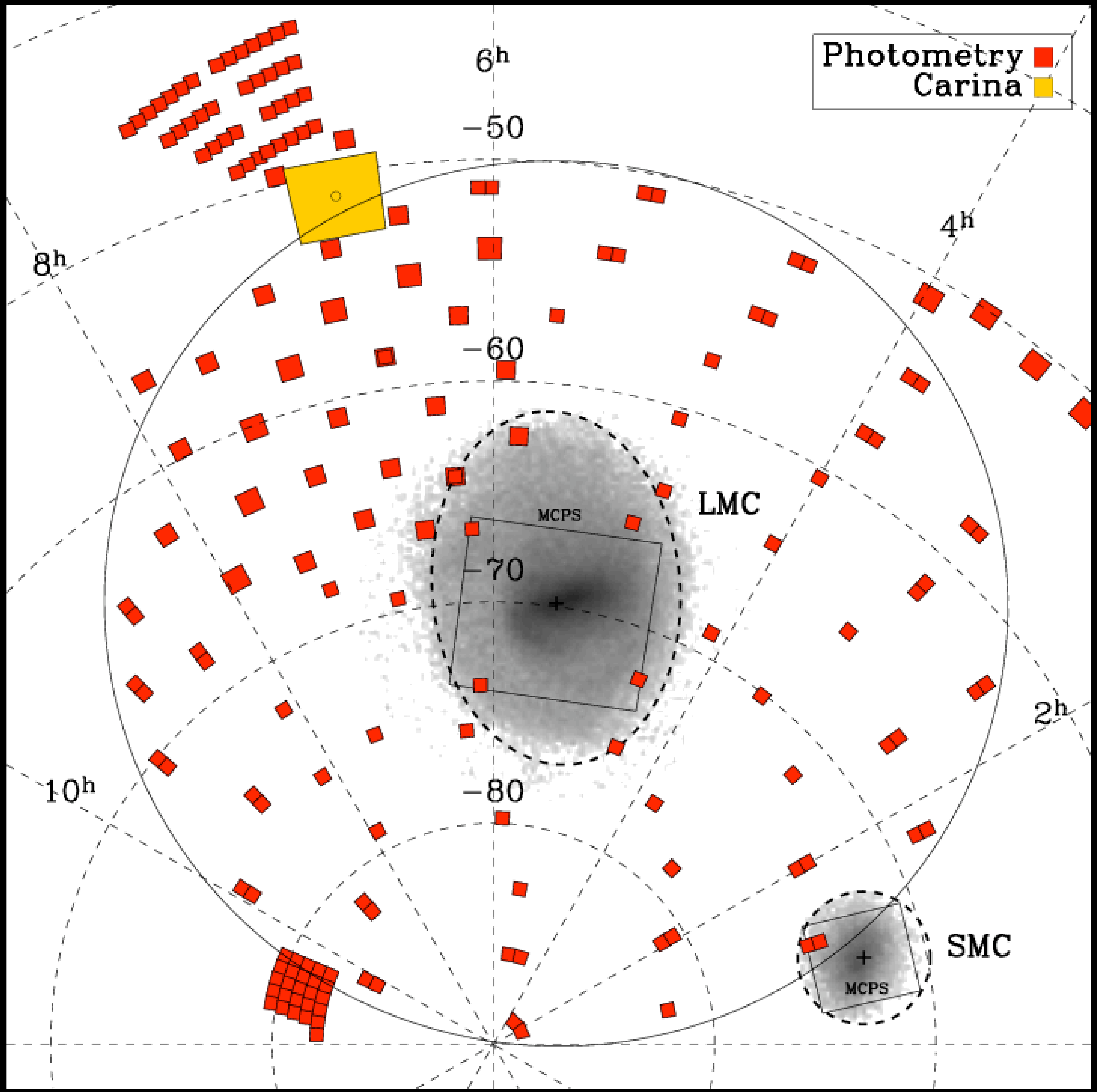
Our Follow-up Survey



PHOTOMETRY

- Washington+DDO51 to *V*~22.5
- CTIO 4m + MOSAIC
- ~170 Fields
- ~60 deg^2

Color-Magnitude Diagrams



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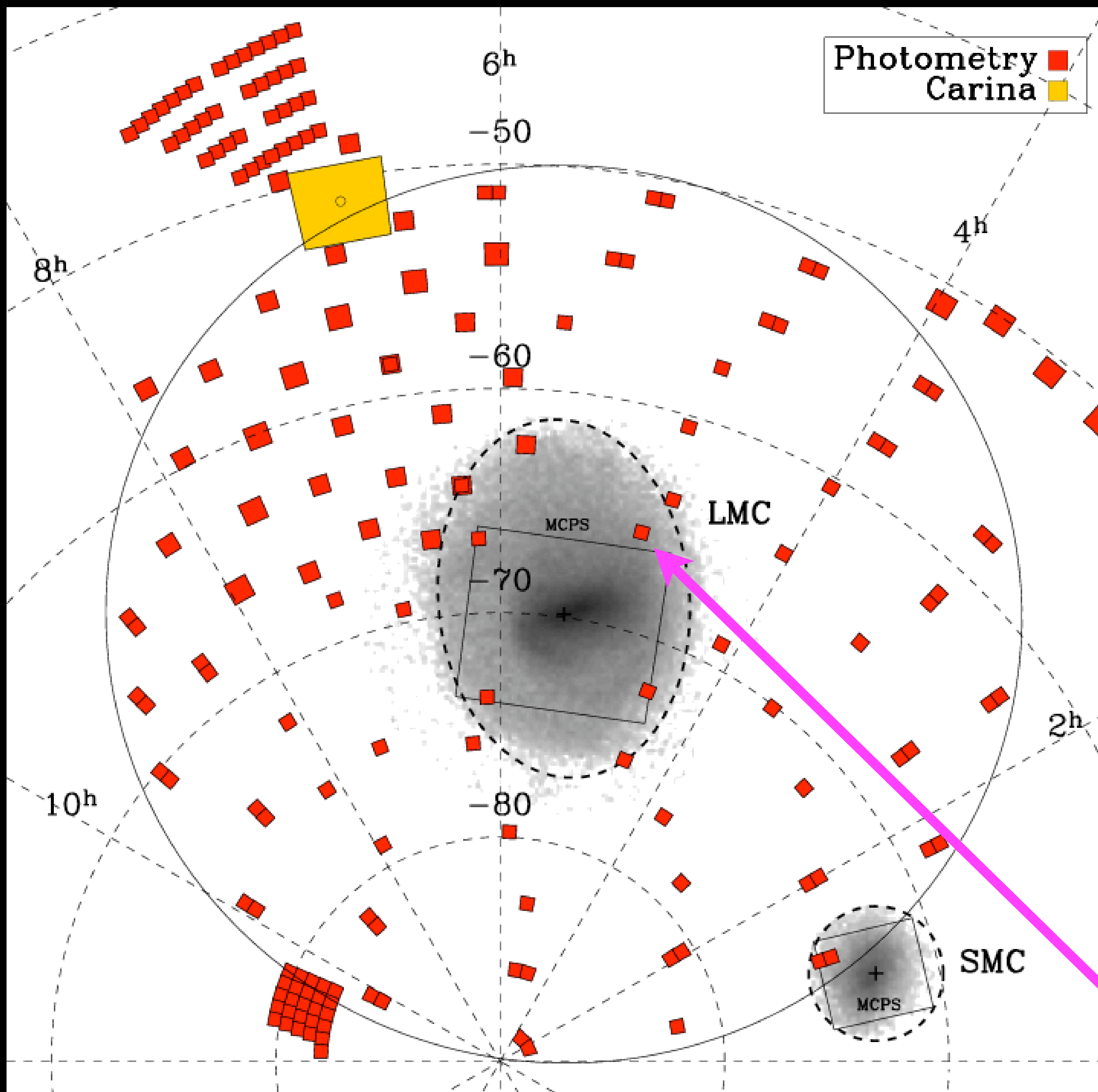

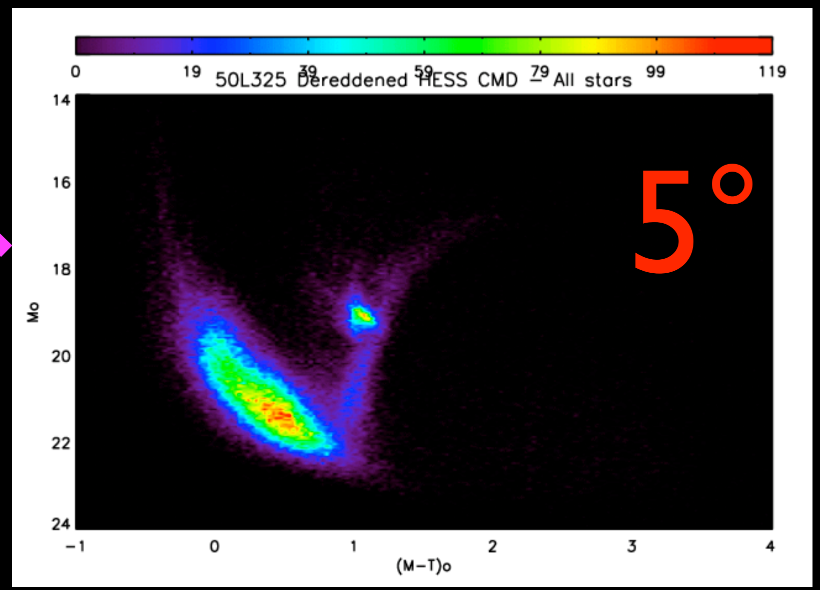

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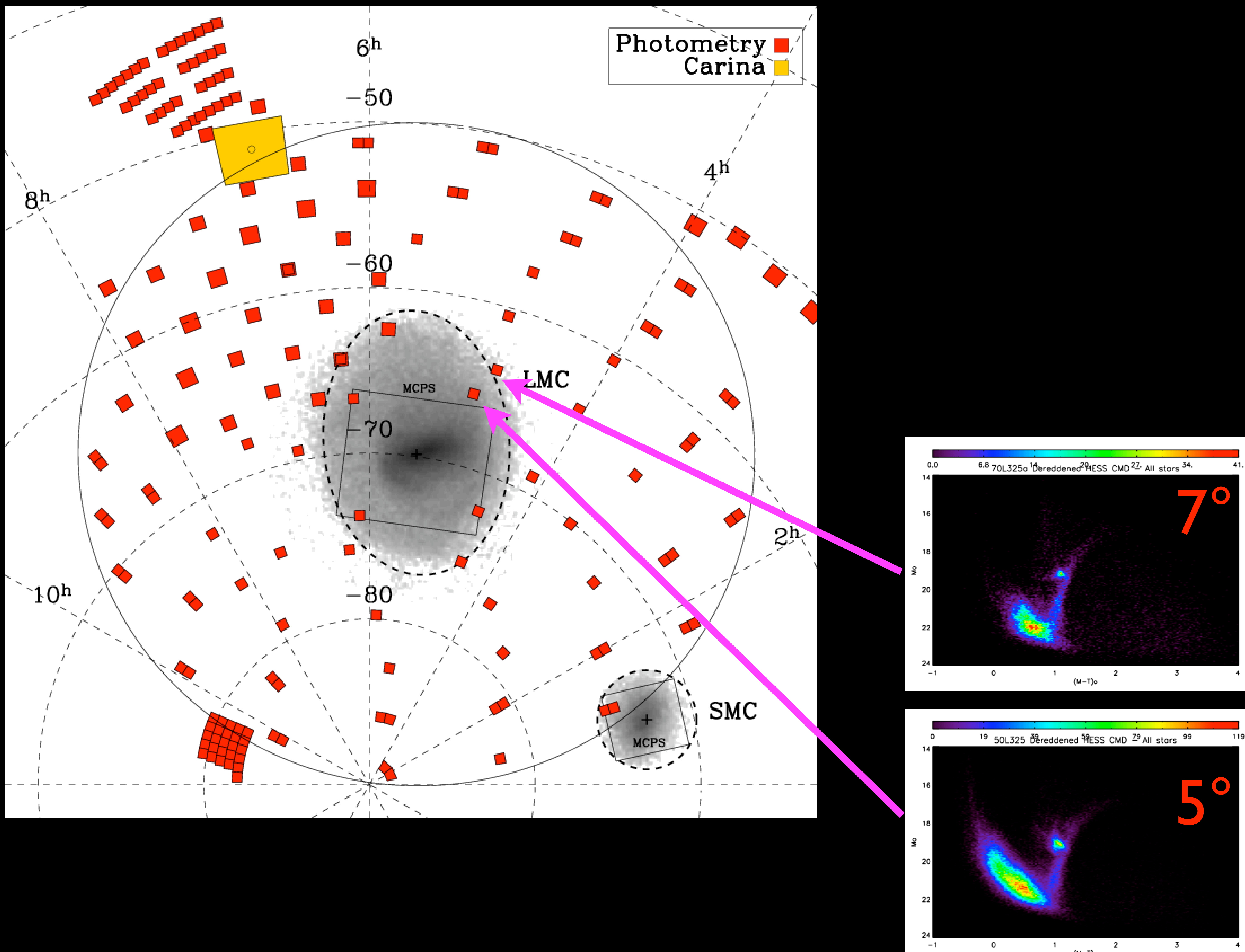

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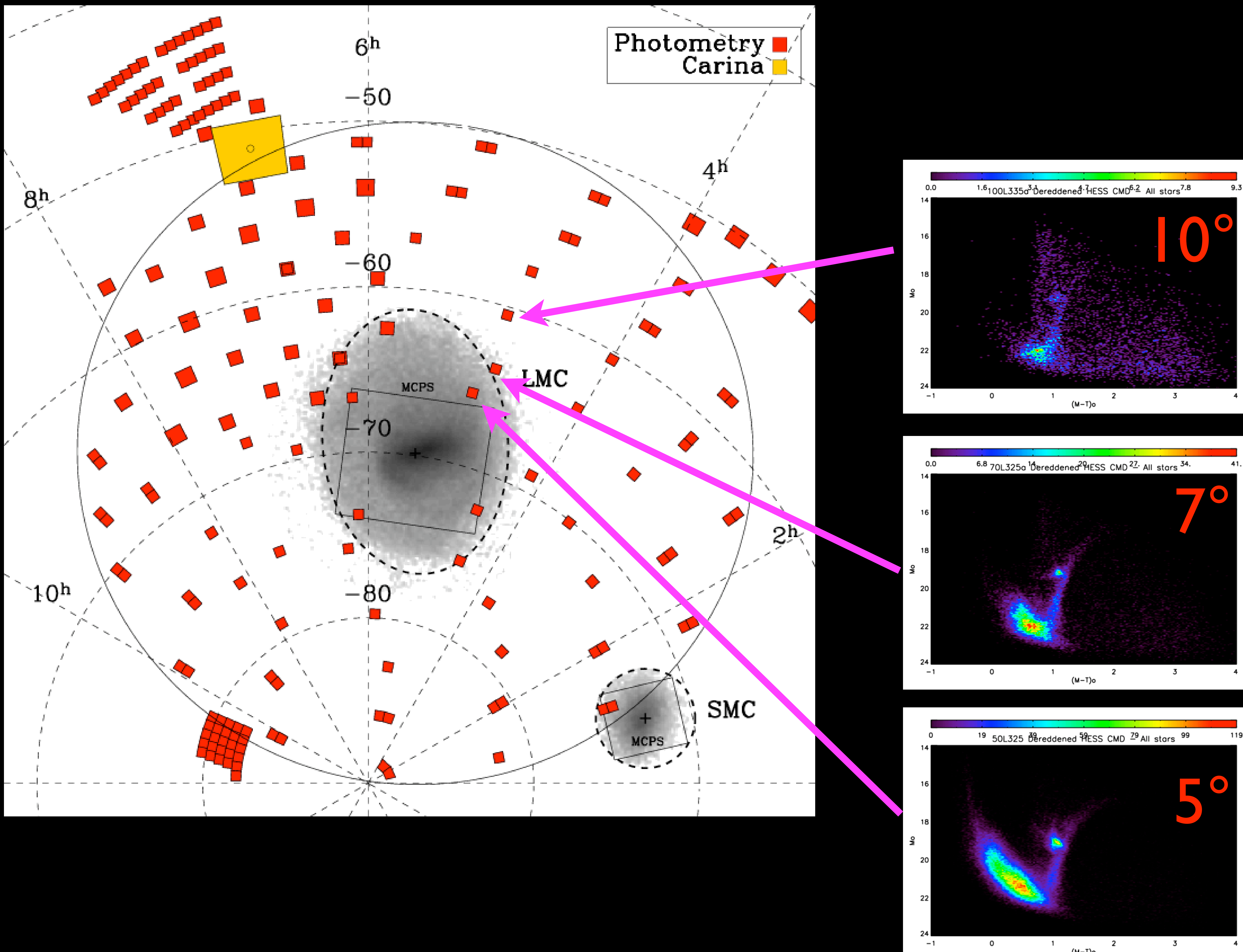

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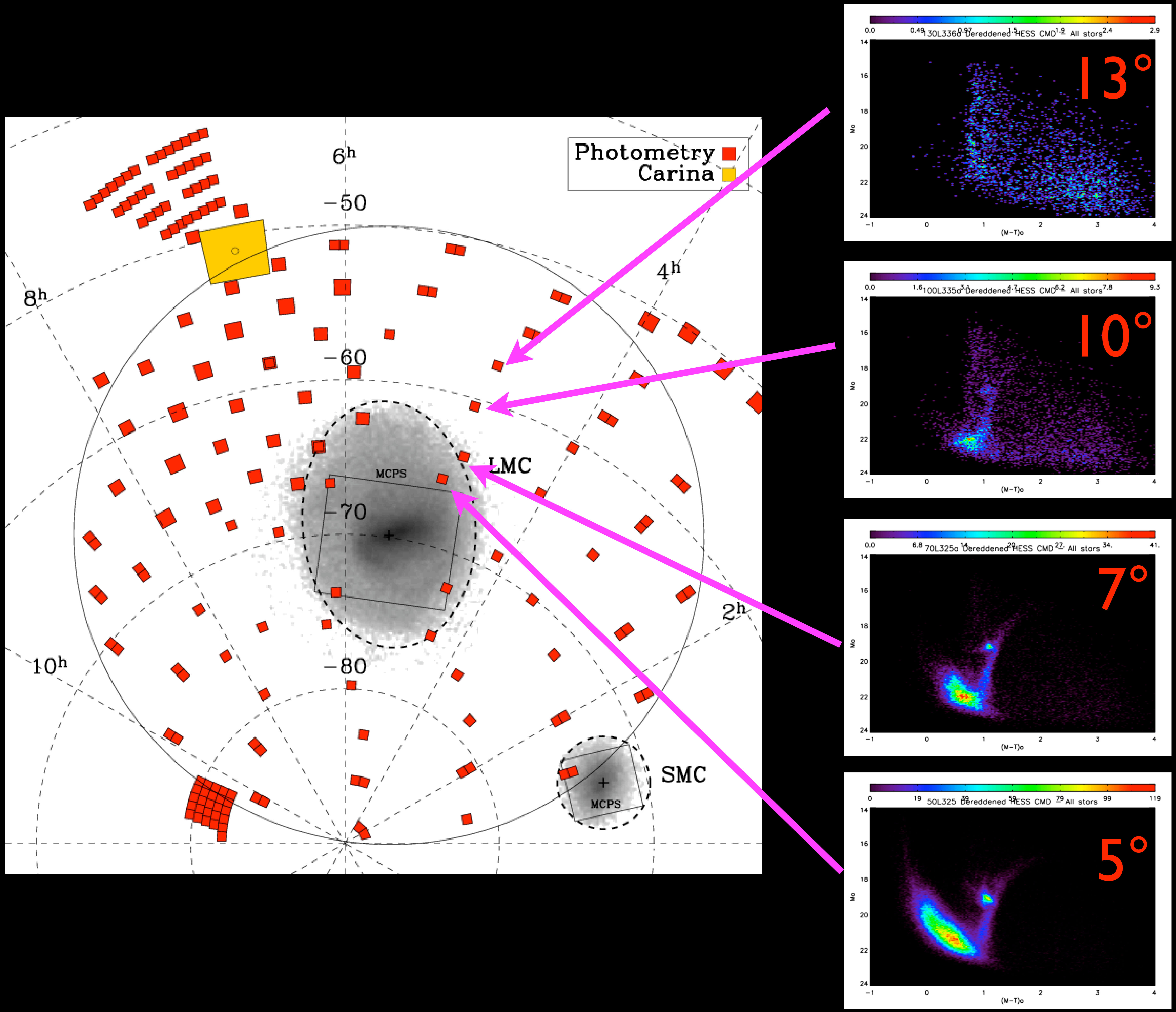

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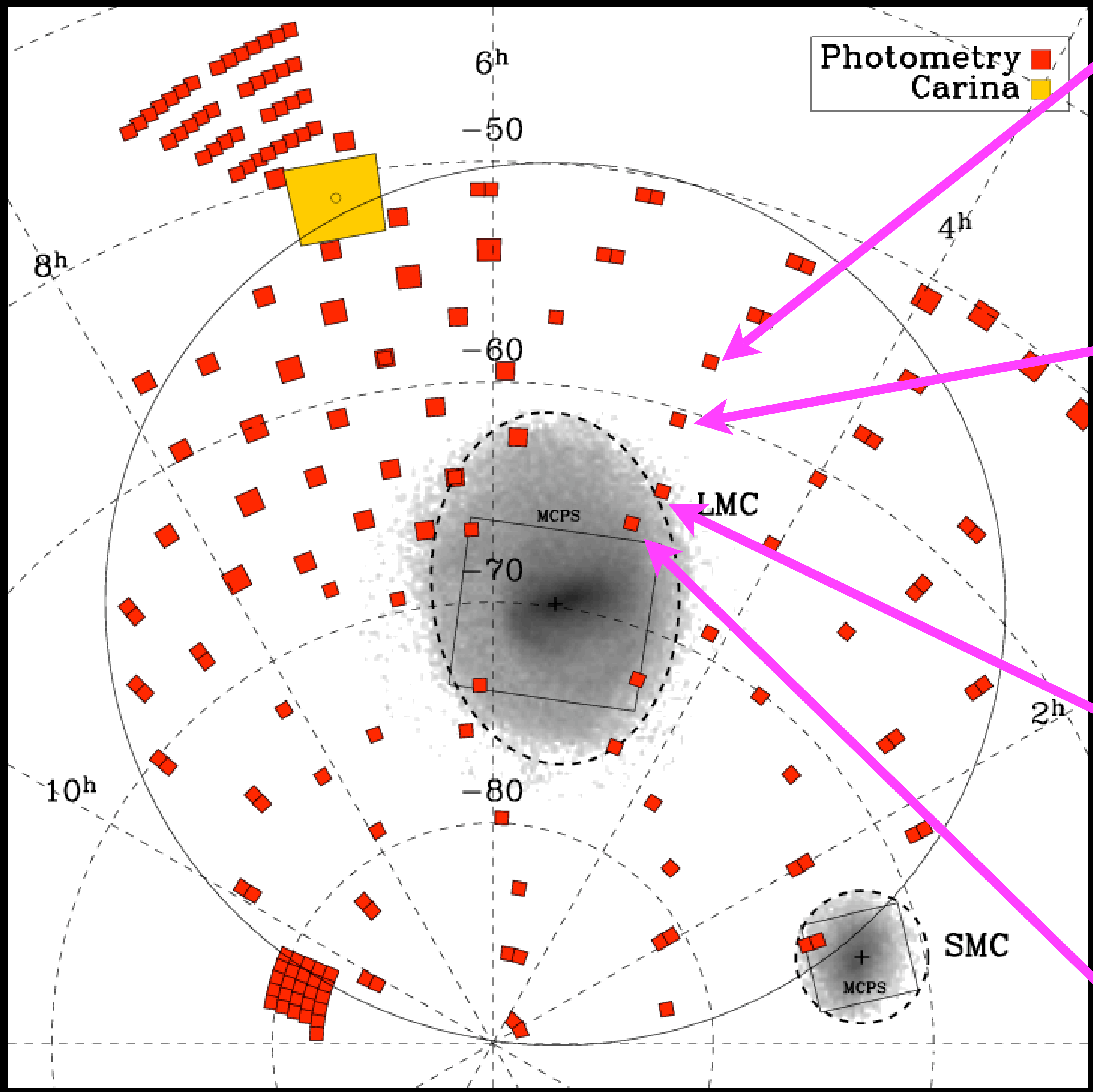
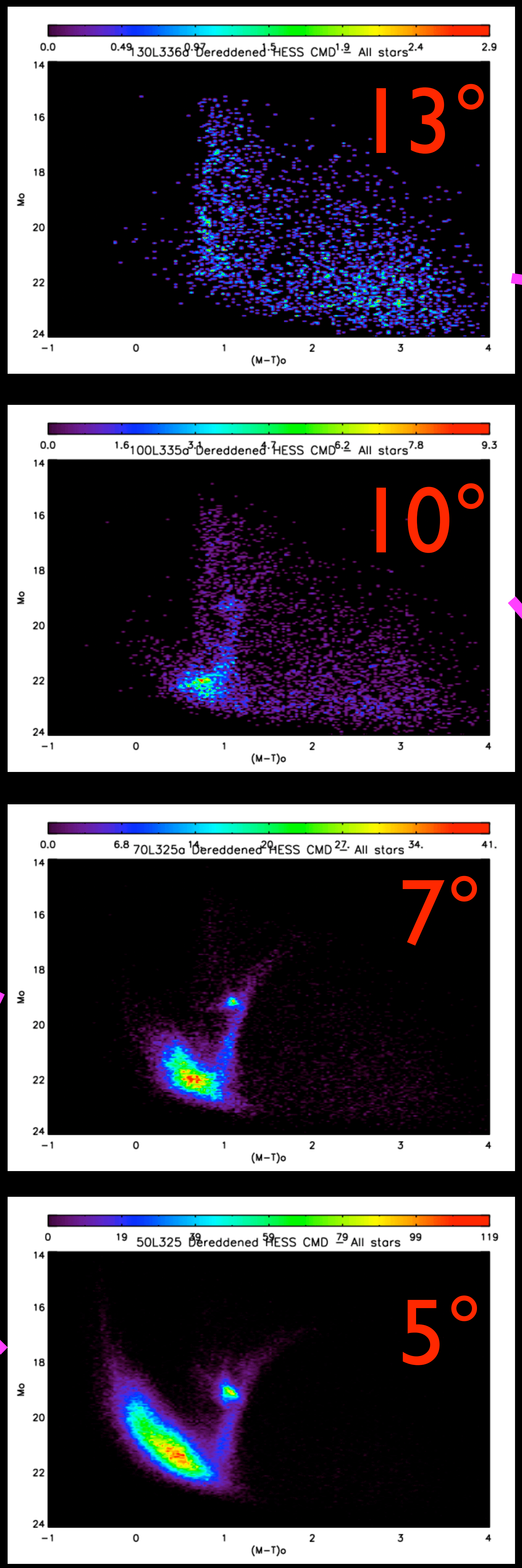
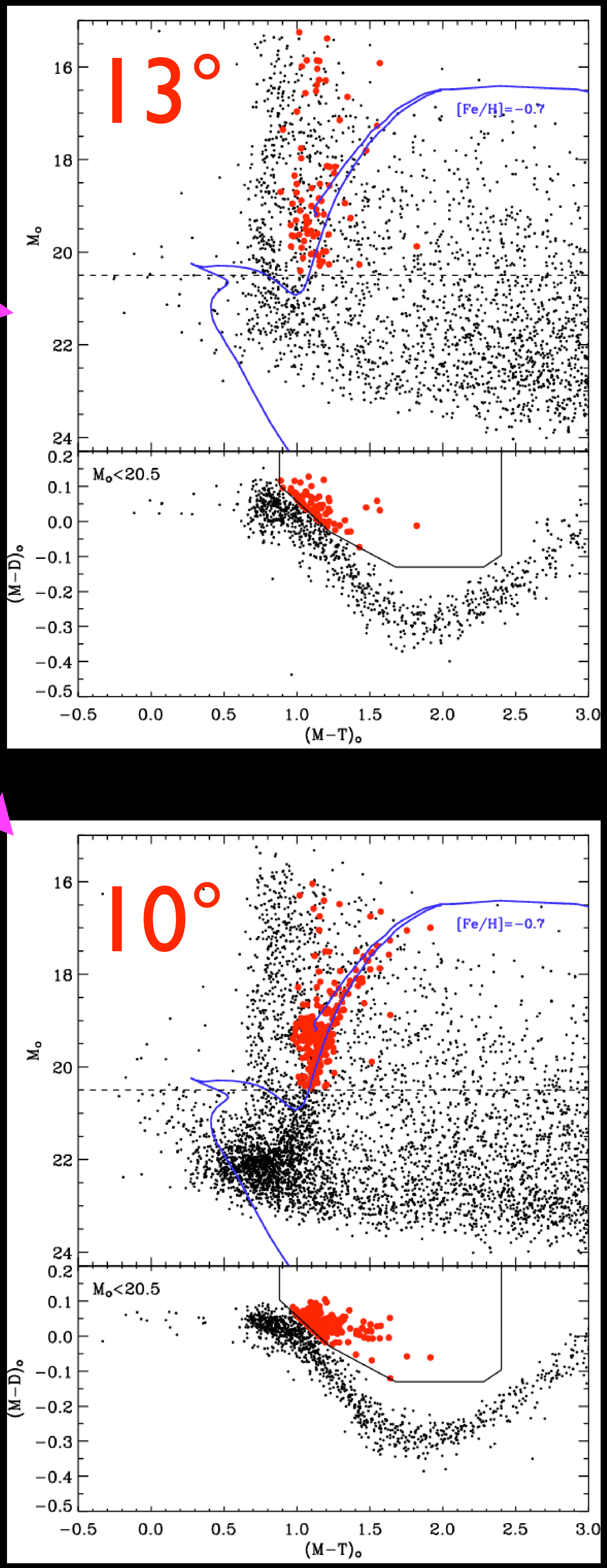




Giant Cut



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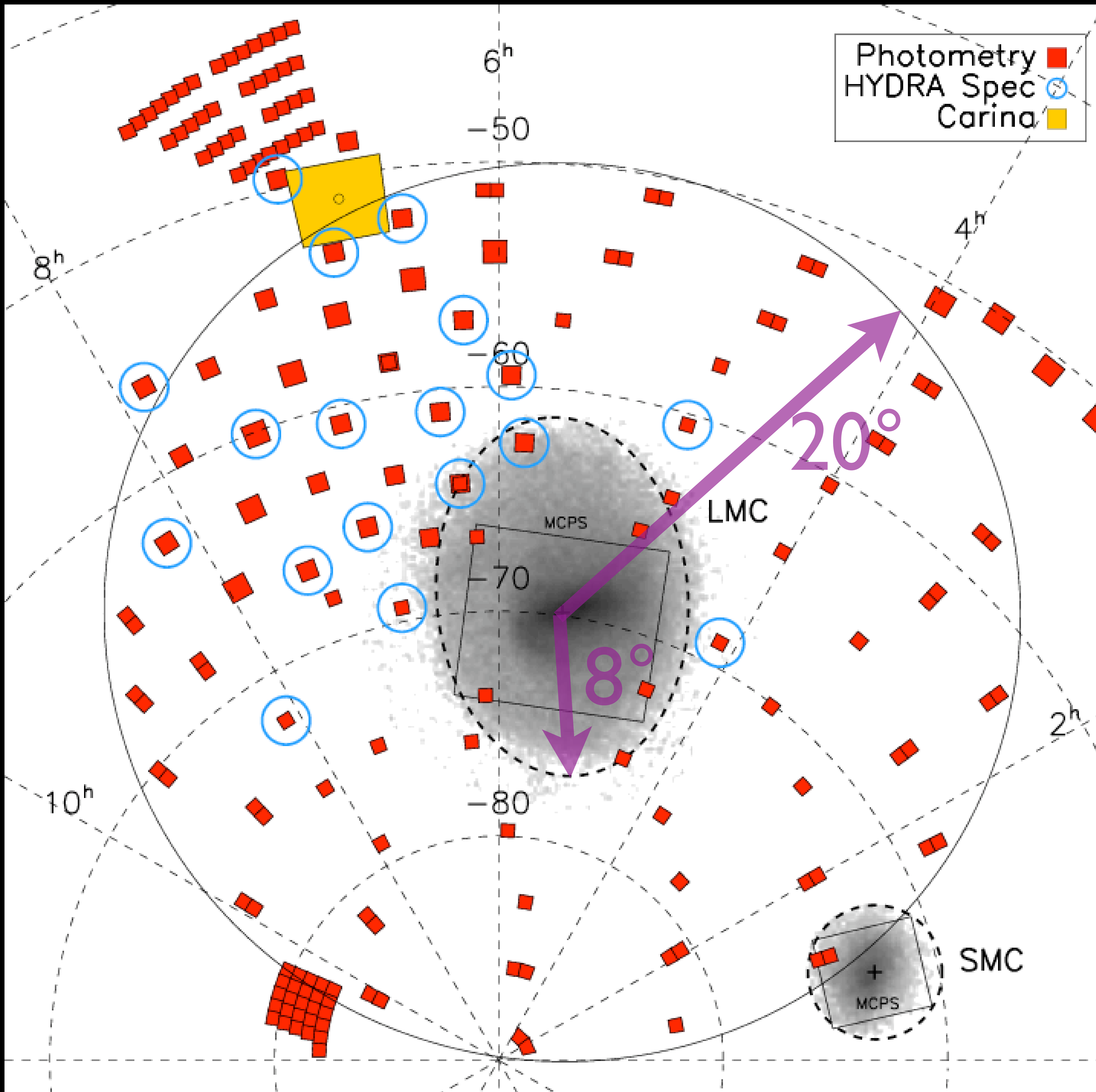
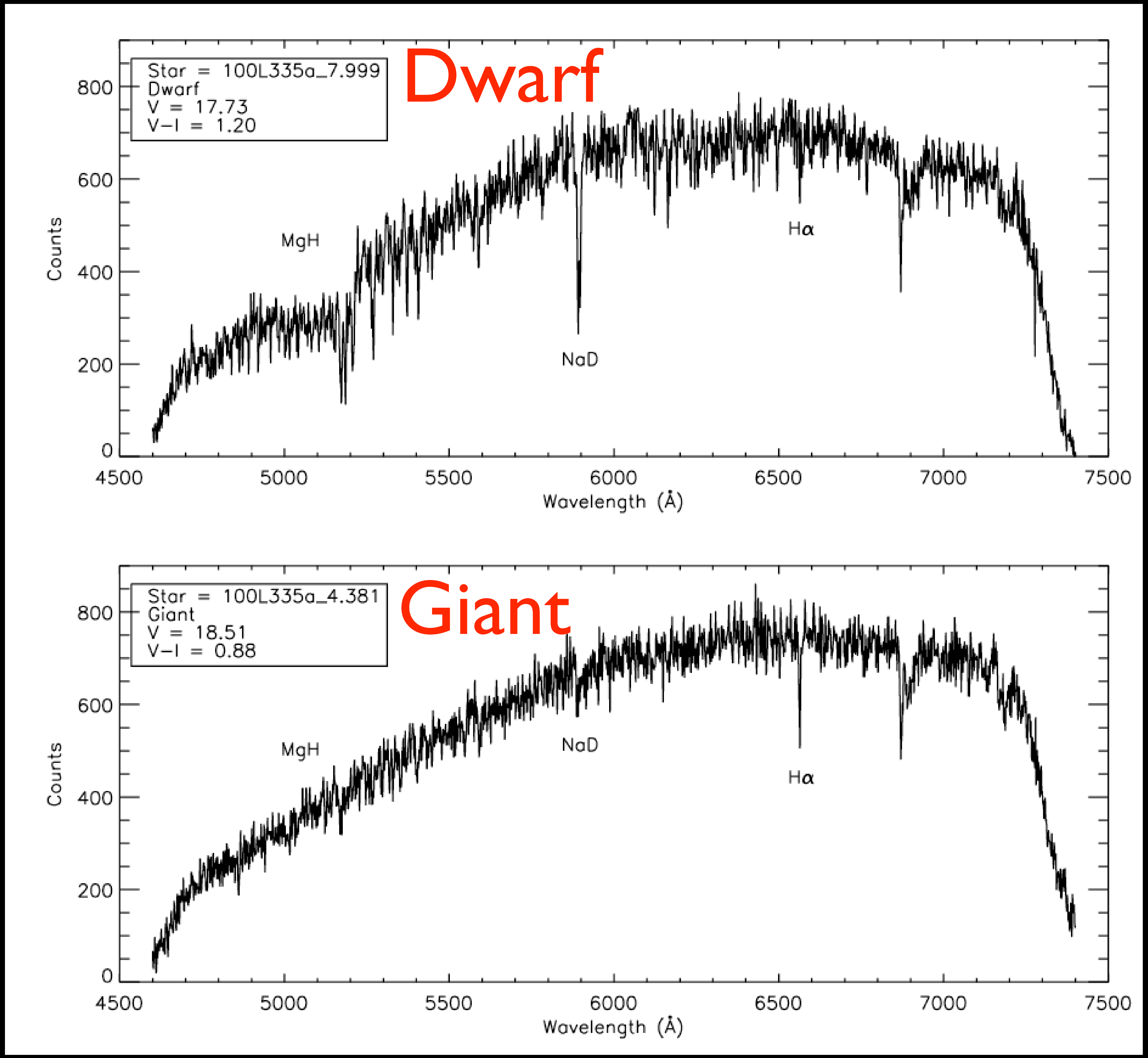


SPECTROSCOPY

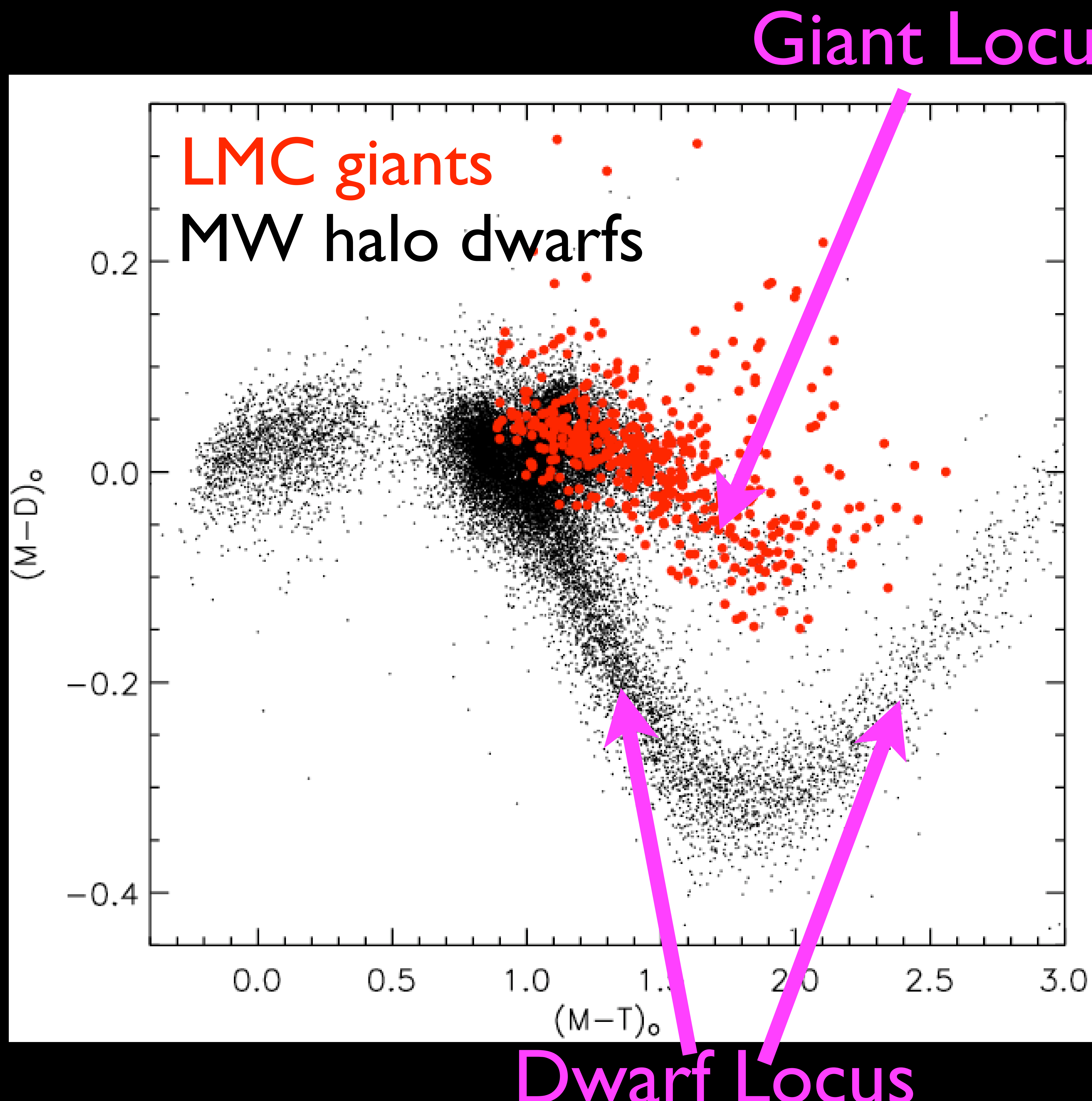
- CTIO 4m + HYDRA
- 18 fields
- Radial range=7-23°
  Azimuthal coverage=110°
- Exp. time ~ 3.5 hours to reach V~19.3 (LMC red clump)
- ~2000 stars total
  ~600 LMC stars

Spectroscopic Observations



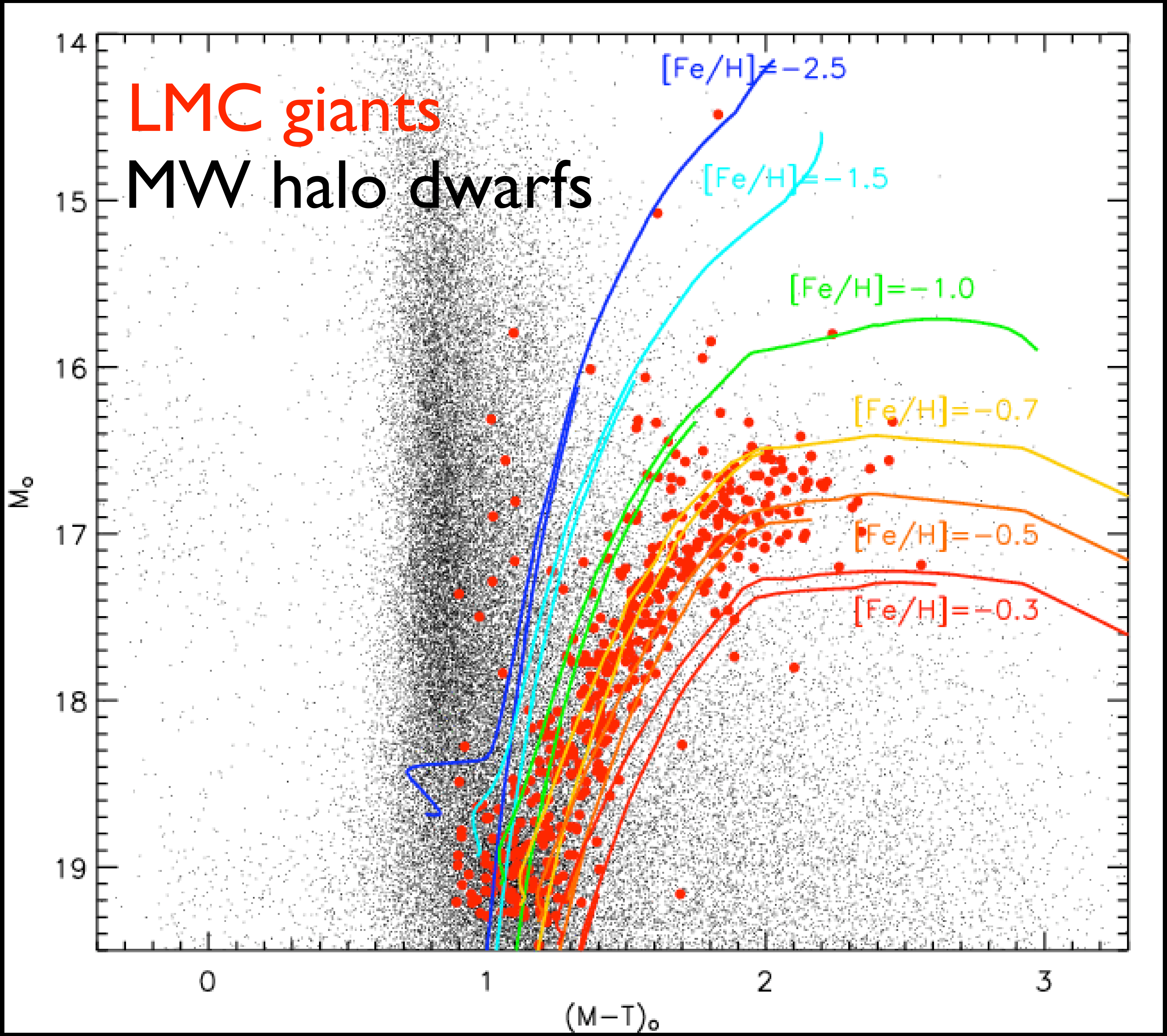
- CTIO 4m + HYDRA
- 40' FOV
- ~100 science fibers
- Resolution~1500
- Spectral Range=4600-7000Å

Color-Color Diagram



- Velocity selected LMC stars are consistent with being giants in the Washington color-color diagram which is gravity sensitive

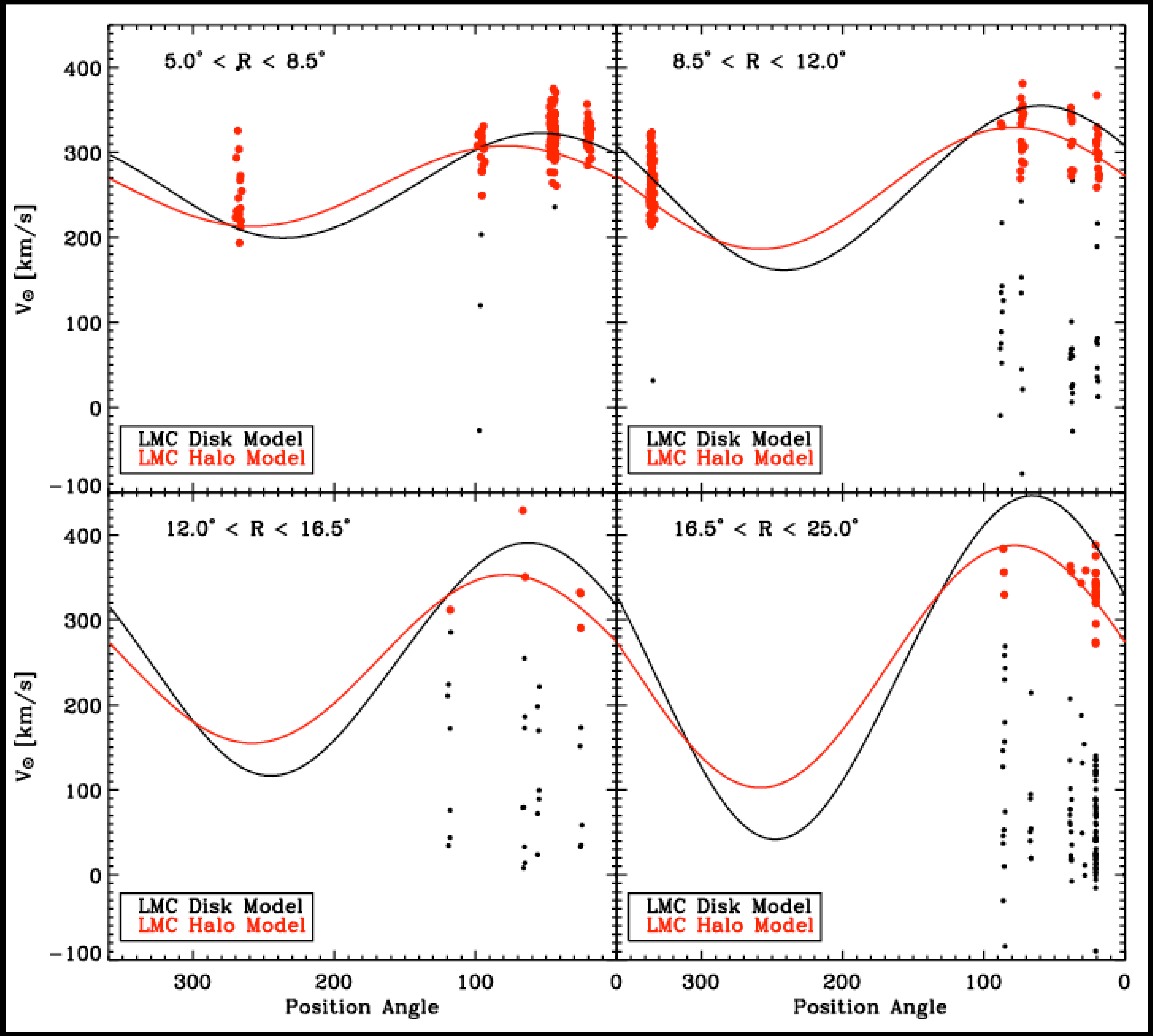
Color Magnitude Diagram



- Consistent with LMC RGB
- close to [Fe/H]= -0.60 isochrone

Velocity Distribution with Position Angle

Stars within the -0.3 to -2.5 dex isochrones



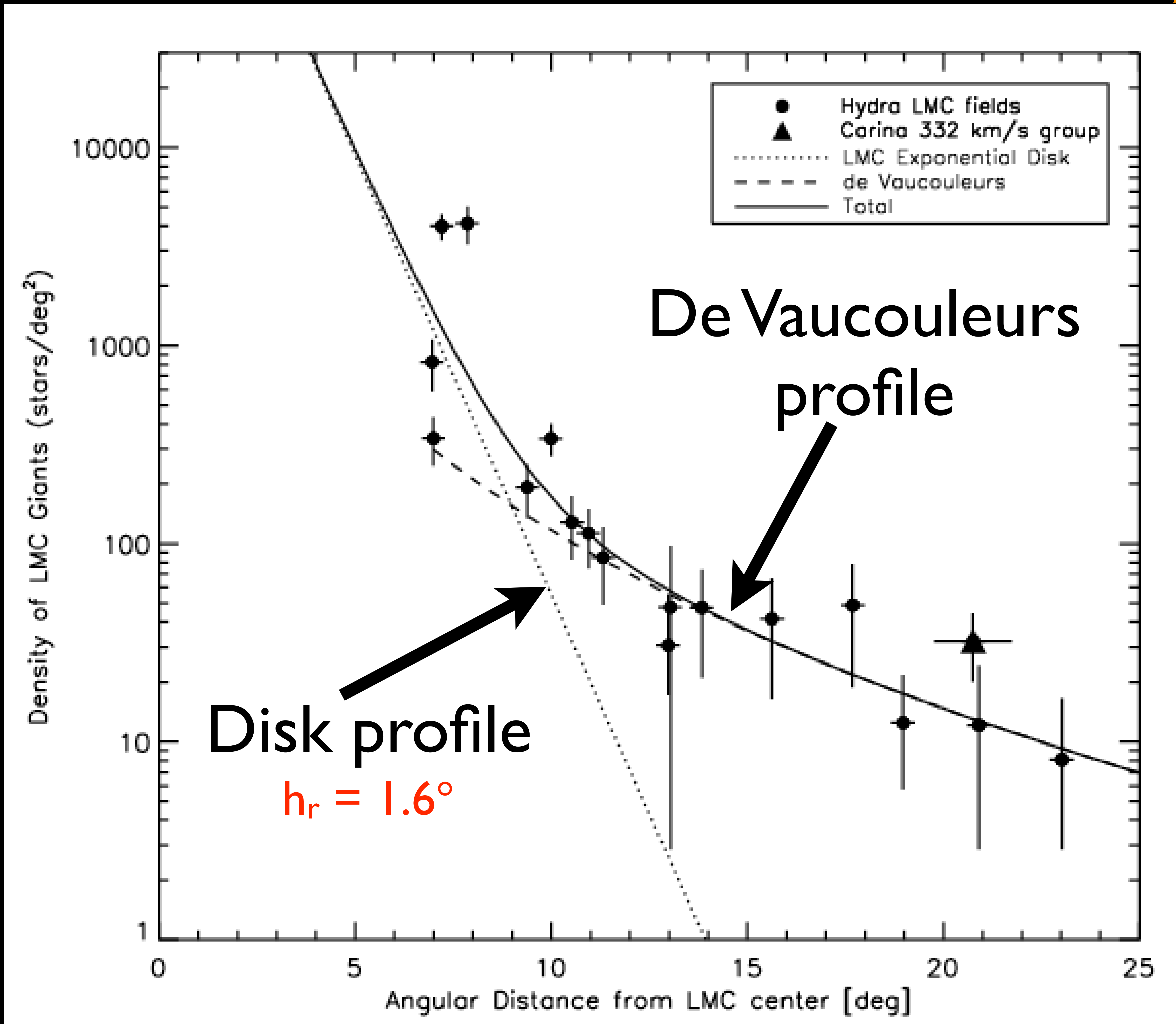
- LMC disk velocity model (van der Marel 2001)
- accounts for projection of space velocity, rotation, etc., onto radial velocity

- Halo velocity model:
  - spherically symmetric
  - no rotation
  - *di*/*dt* = 0

- Suspected LMC stars do follow LMC velocity trend

- LMC halo velocity model fits outer candidates better

Spectroscopically-Corrected* Photometric Density Profile

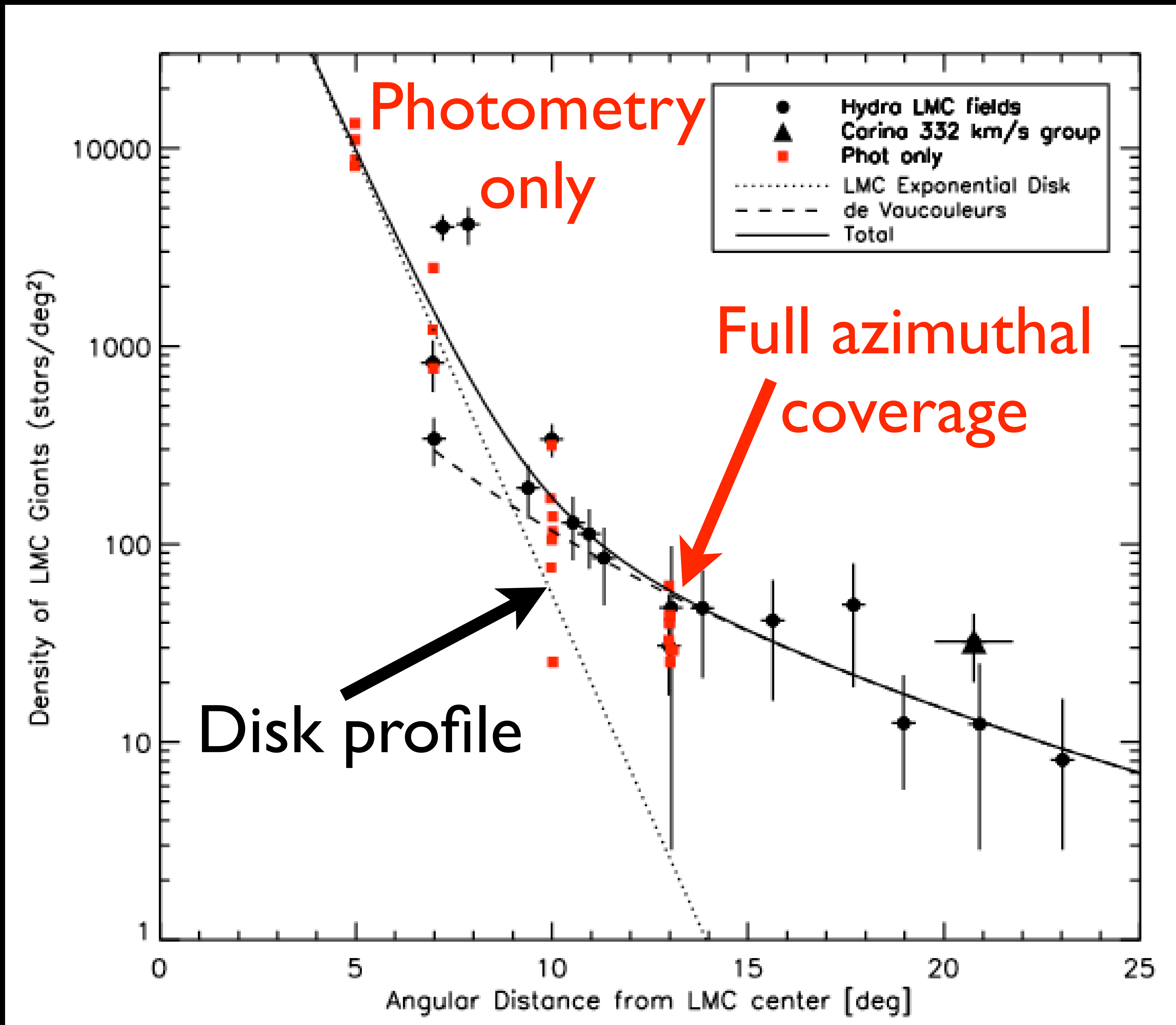


* Stars selected to be LMC by velocity, CMD and 2CD used to account for spectroscopic

- selection function
- RV member fraction

- Outer density profile well-fitted by
  - de Vaucouleurs profile (core radius = 2.4°)
  - exponential of $h_r = 4.9°$

Is the Profile Azimuthally Symmetric?

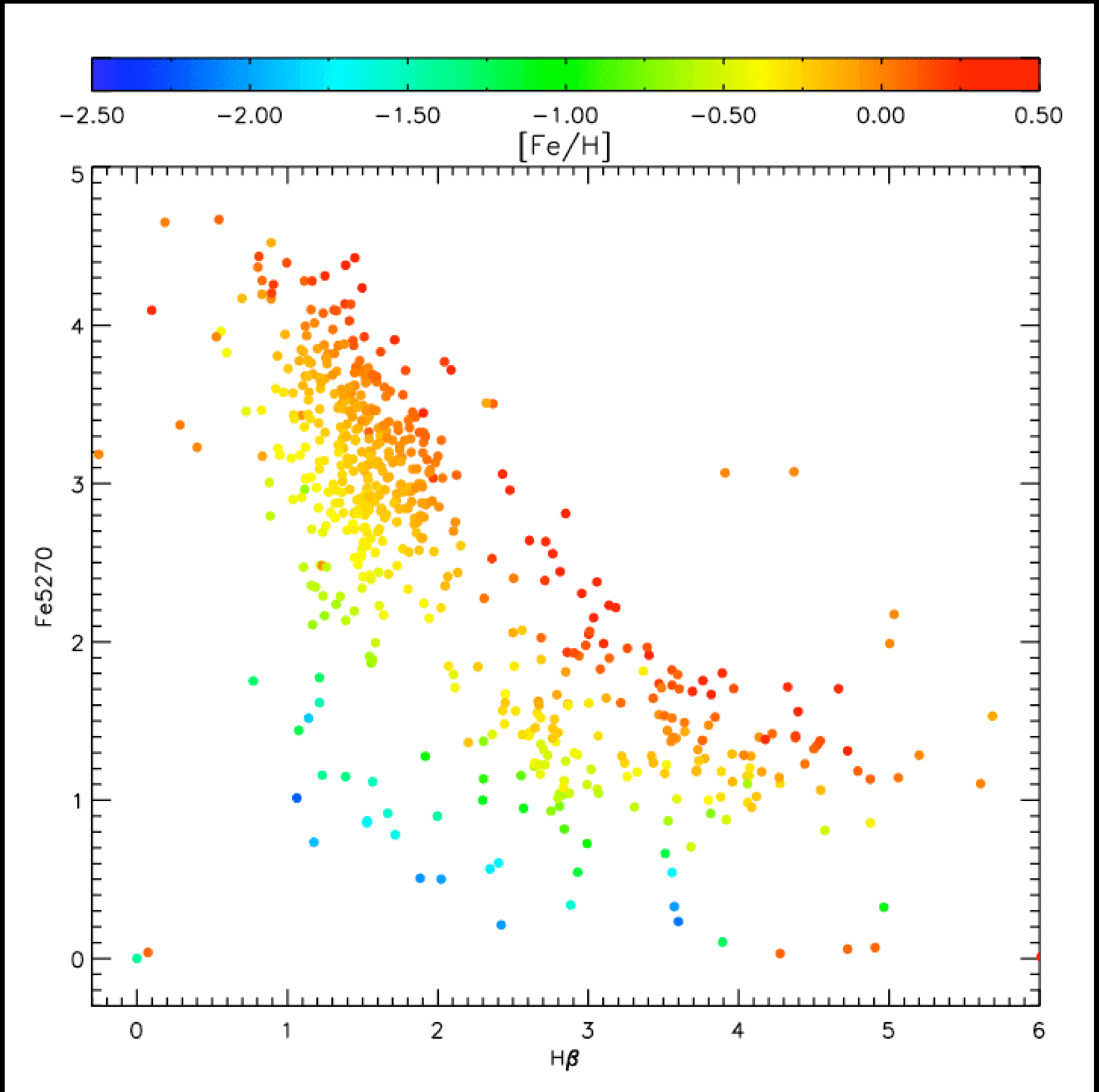


- Check with photometric LMC candidates (background subtracted)
  - At R=13° excess seen at all PA!
  - Suggests stars may be a true halo

  ... not some kind of tidal debris ...

[Fe/H] from Lick Indices

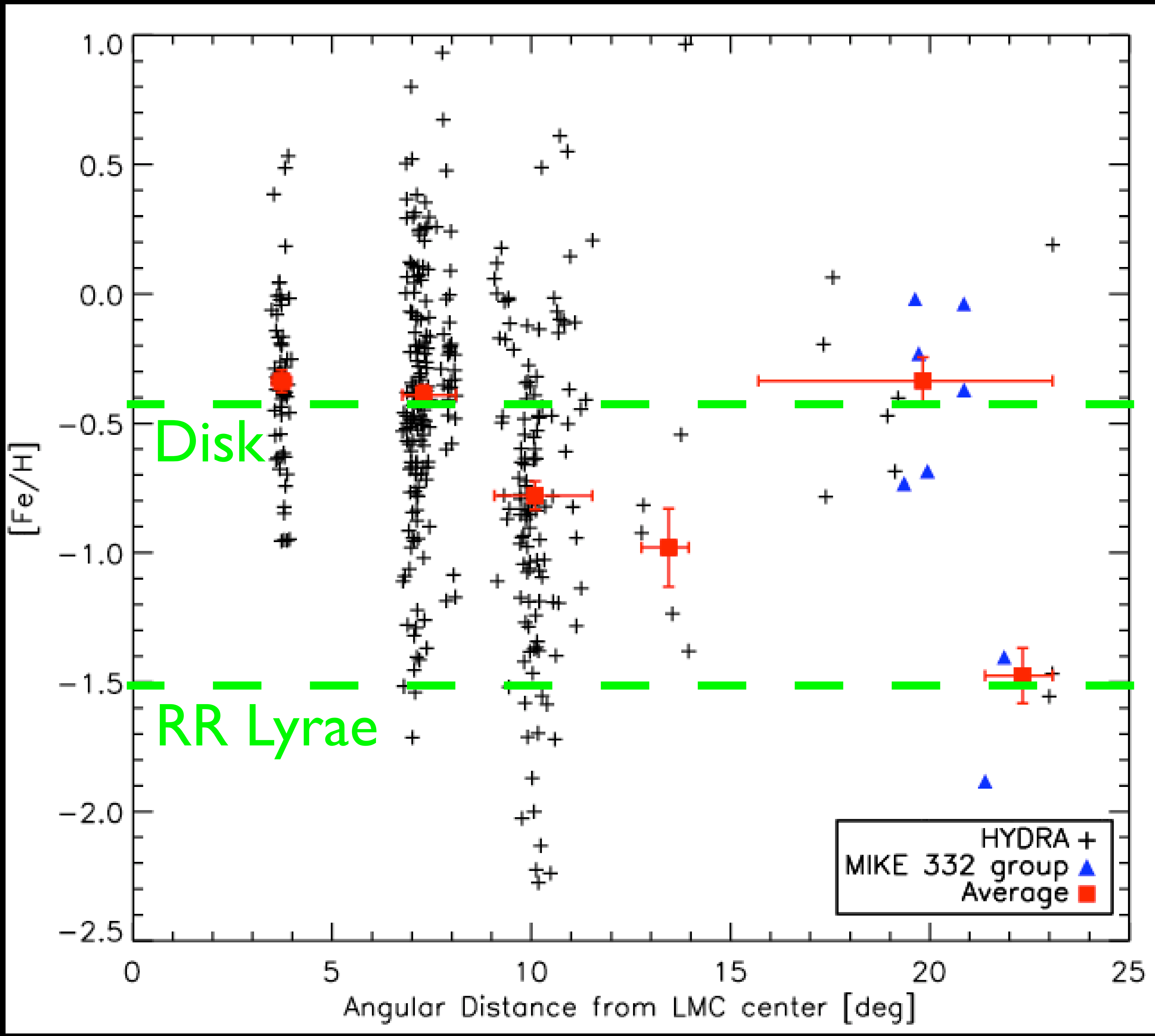
[Fe/H] of Lick Standard Stars



Lick standard stars from Schiavon 2007

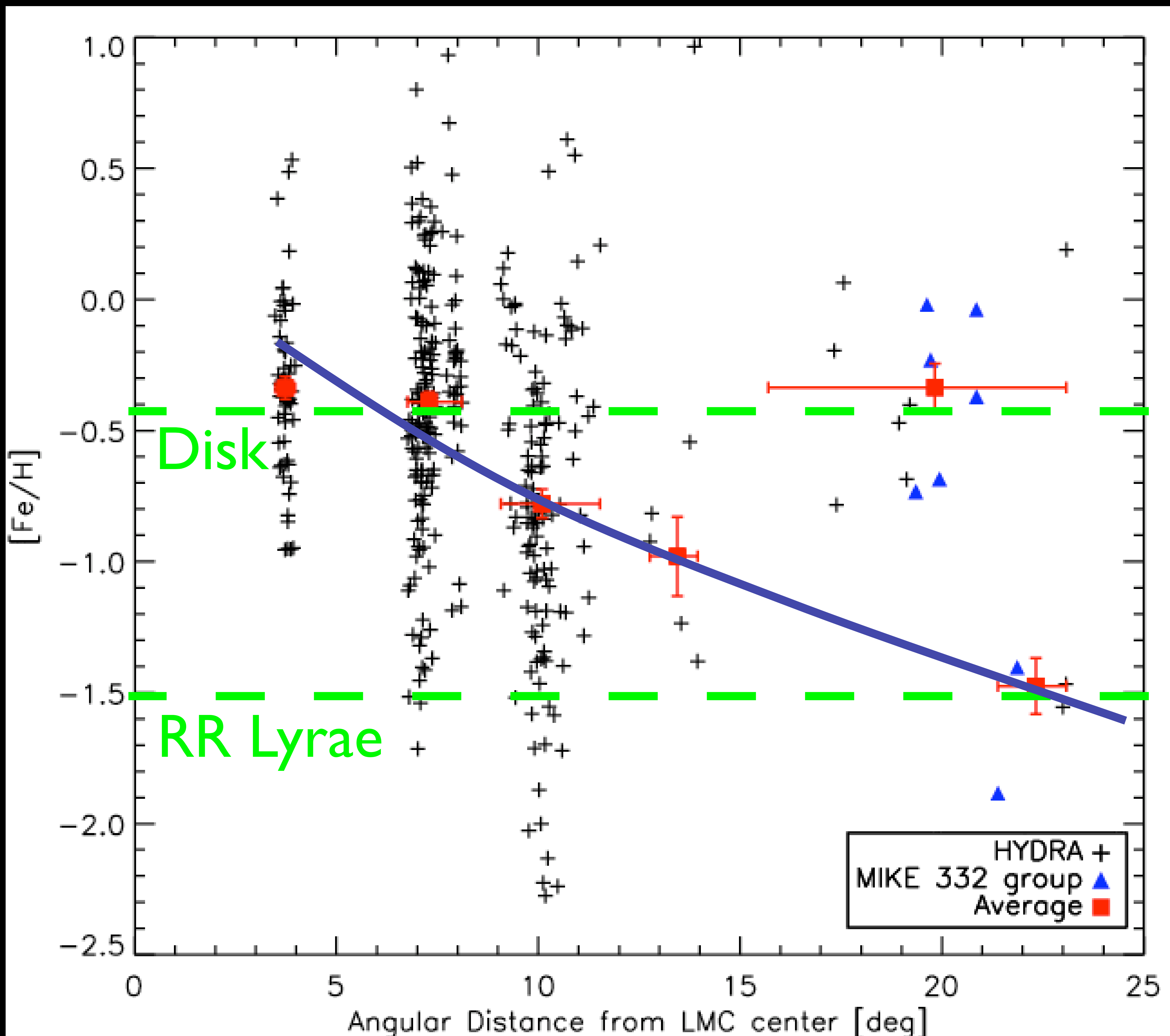
- Stars nicely sort by [Fe/H] in Fe index vs. temperature
- Use a weighted average of 7 Fe indices
- Uncertainties:
  - $\sigma_{[Fe/H]} \sim 0.2$ dex (metal-rich)
  - $\sigma_{[Fe/H]} \sim 0.5$ dex (metal-poor)
- Insensitive to logg

Spectroscopic Metallicity Profile



- [Fe/H] from Lick indices
- Metallicity gradient out to *R*=15° (and maybe beyond?)
- "Halo" bimodal?
  - Some metal-poor stars
  - But dominant [Fe/H]~-0.4 population
    - ~LMC disk metallicity
    - ~SMC metallicity
- Bekki 2005 predicted metal-rich stars in LMC halo (~2%)

Spectroscopic Metallicity Profile



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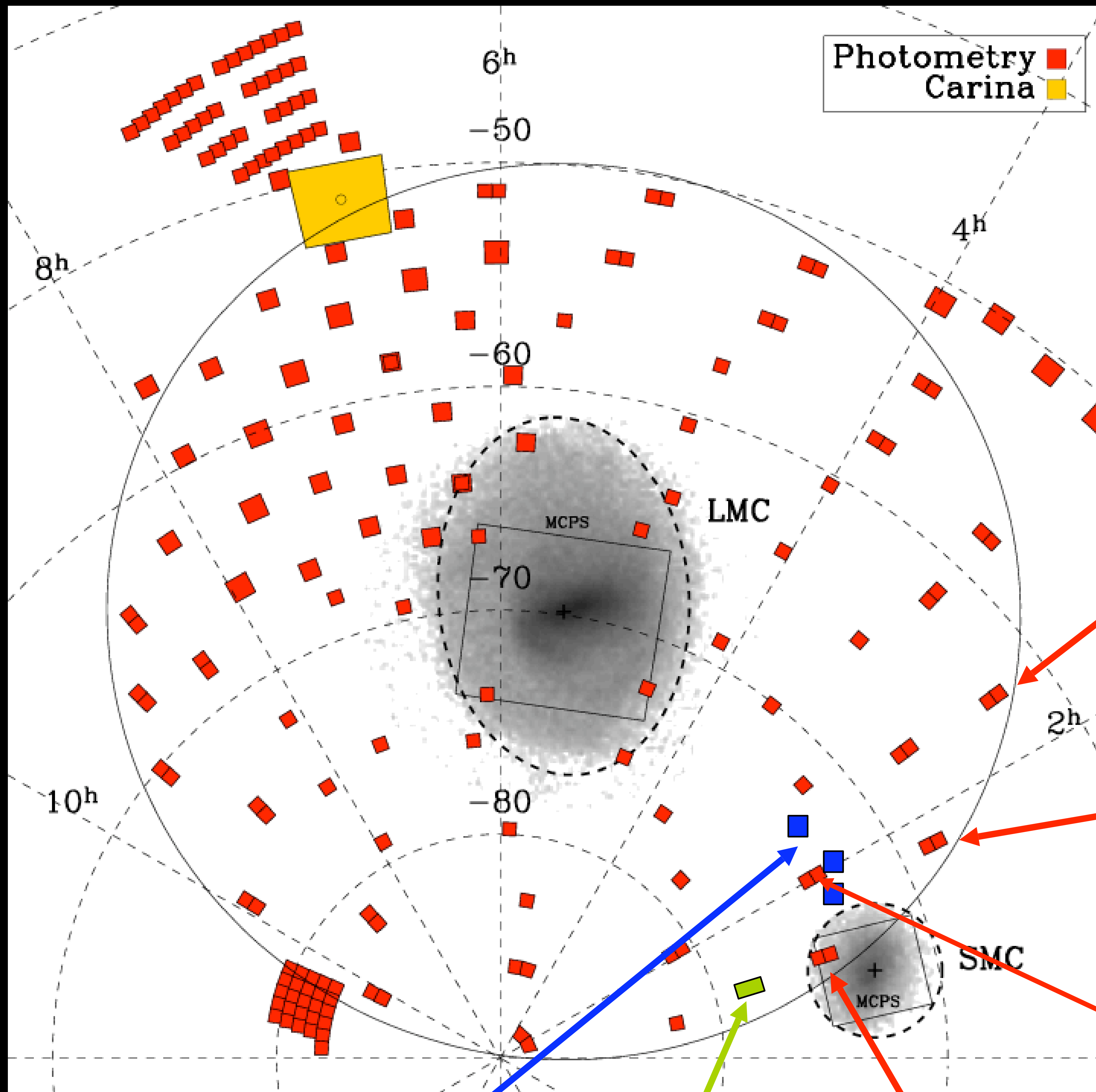
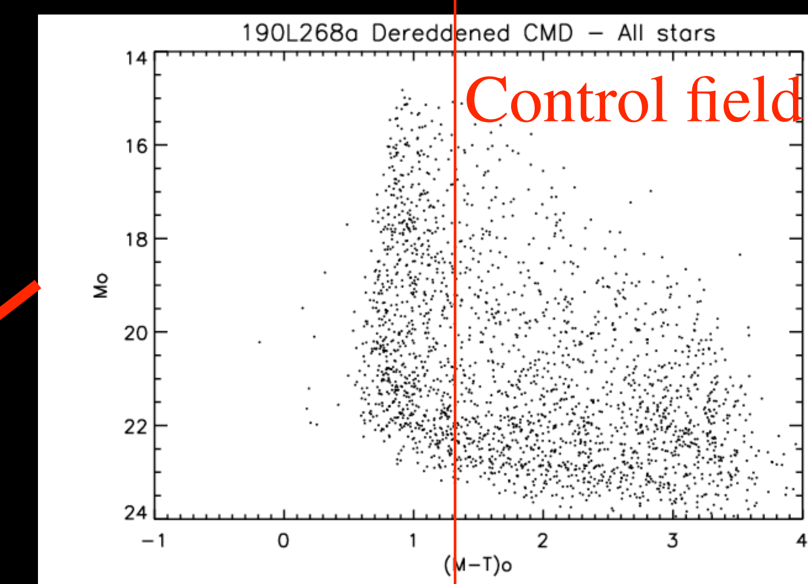
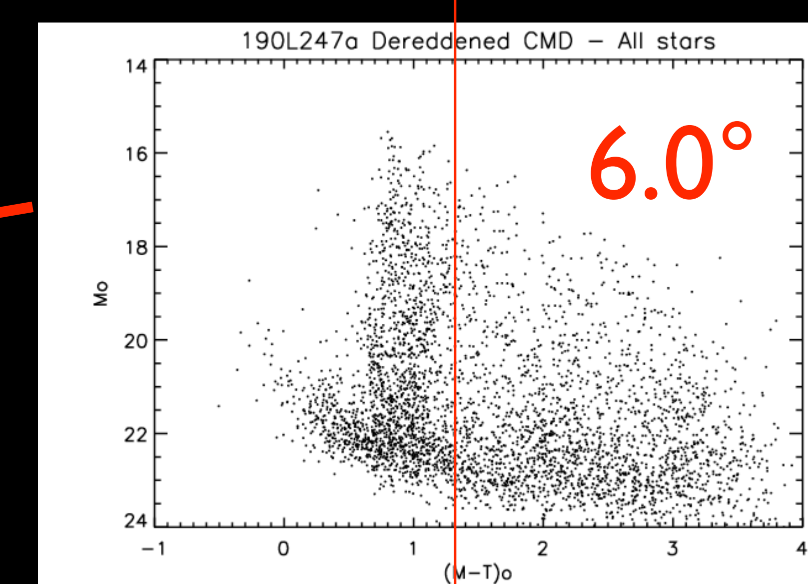
Extended SMC Population?

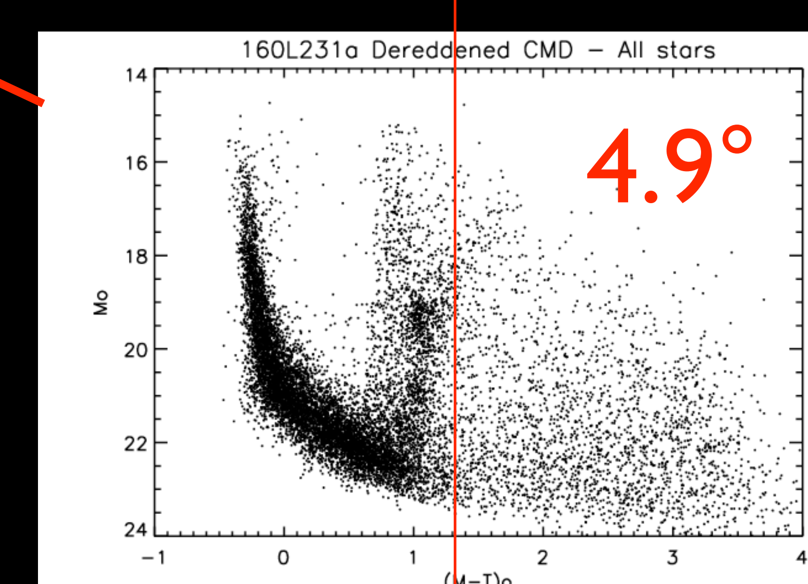


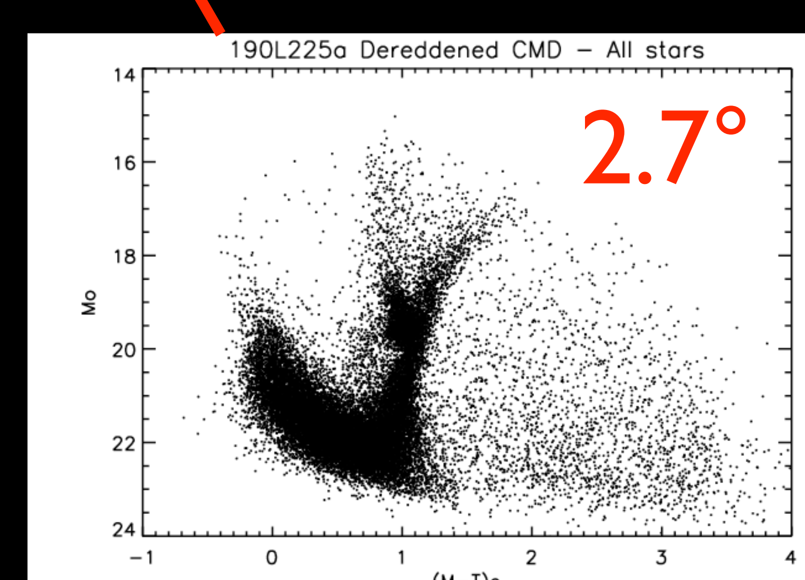
Harris (2007)
young, metal-poor
SMC/Bridge stars

Noel & Gallart (2007)
intermediate, old SMC stars









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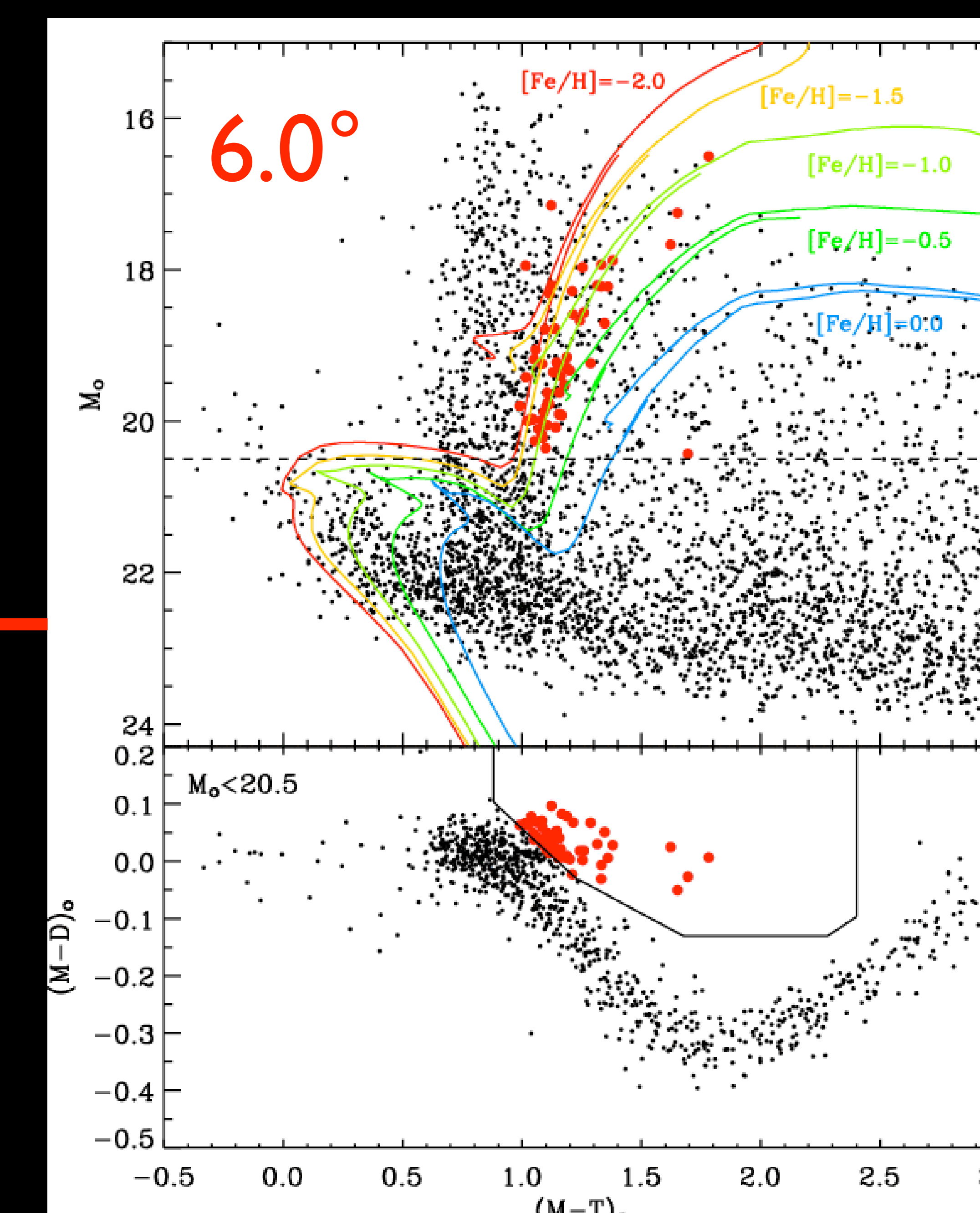


[Fe/H]= -1.0, 2 Gyr

Compare to RR Lyrae halo

RR Lyrae

- Follows disk density profile to R=15°
- Exponential, h_r = 1.68°
- Metal-poor, [Fe/H]= -1.5
- Old, Age>10 Gyr
- Why does it follow the LMC disk density profile?

K giant halo

- Shallow, de Vaucouleur density profile to R=23°
- Exponential, h_r=4.9°
- Bimodal, [Fe/H]= -0.4, and [Fe/H]= -1.5
- Age?? Need to fit MSTO
- Why so metal-rich?

Dual Halos?

Origin of the Outer Metal-rich Population

1. Outside-In: Like MW halo, tidal debris, sub-halo accretion

   PRO: Can account for any metallicity (metal-rich and metal-poor). For example, SMC debris? (Kunkel et al. 1997)

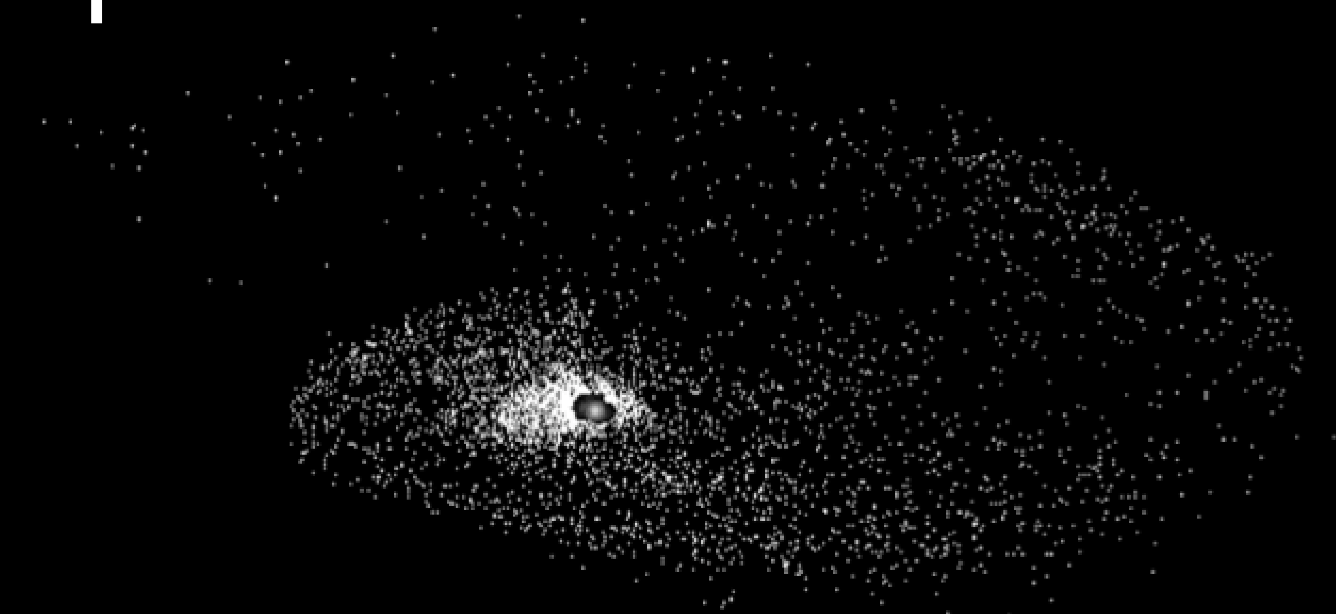
   CON: Fairly virialized, well-mixed
   Suggests MCs bound to each other for multiple encounters

2. Inside-Out: Puffed-up, LMC debris (Weinberg 2000)

   PRO: Accounts for azimuthally symmetric distribution

   CON: Needs to be bound to MW, hyperbolic orbit a problem

- Velocity dispersion profile would clarify
  Tidal debris: dynamically cold
  Puffed-up: dynamically warm
- Detailed chemical abundances could yield clues

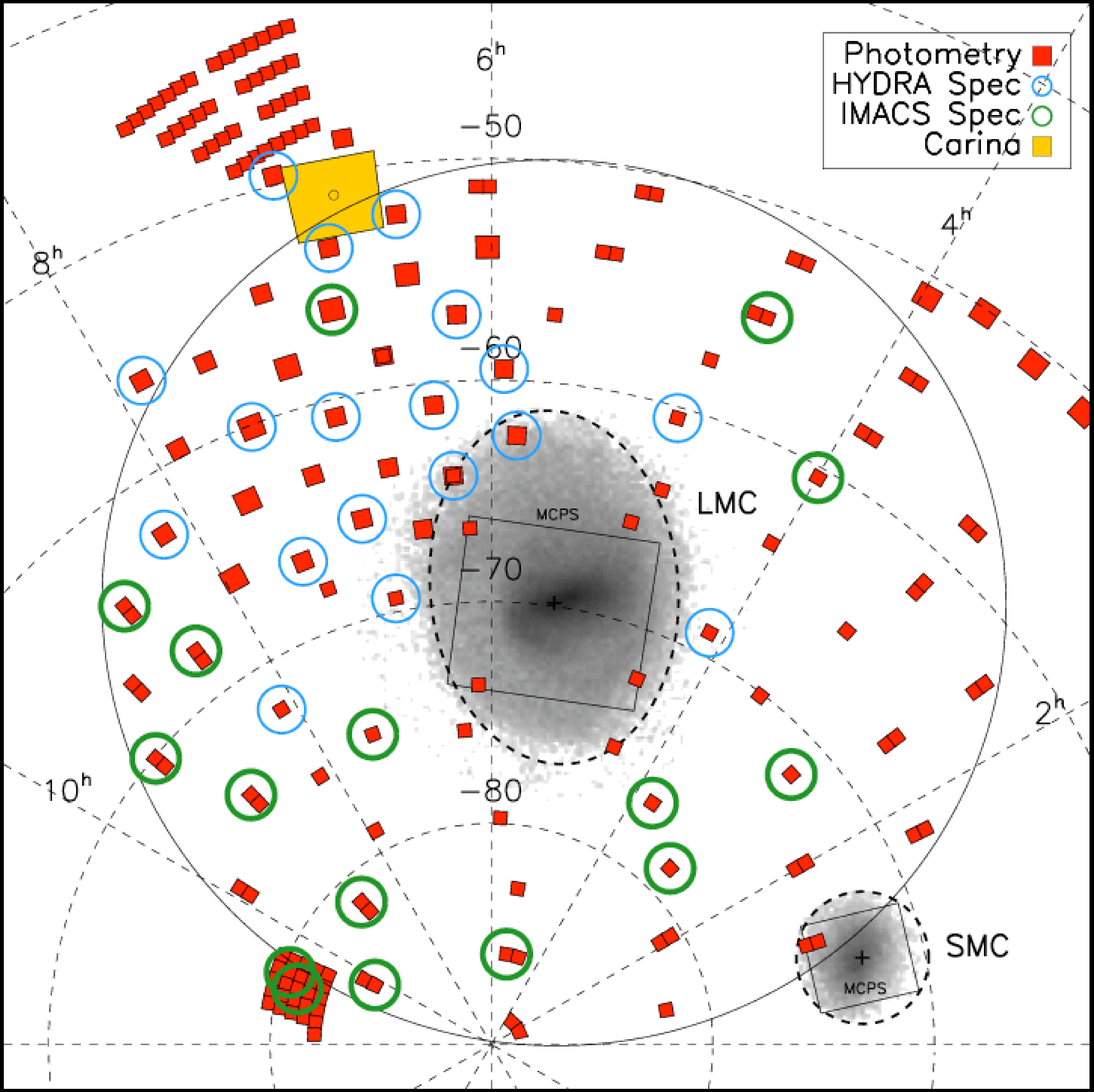


Weinberg (2000)

Summary

- Large area photometric and spectroscopic survey of the LMC periphery
- LMC stars found to R=23°
- If bound, LMC more massive than previously thought
- Bimodal metallicity distribution
- Source of metal-rich stars unclear
- However, SMC stars found to R=6°

Future Work



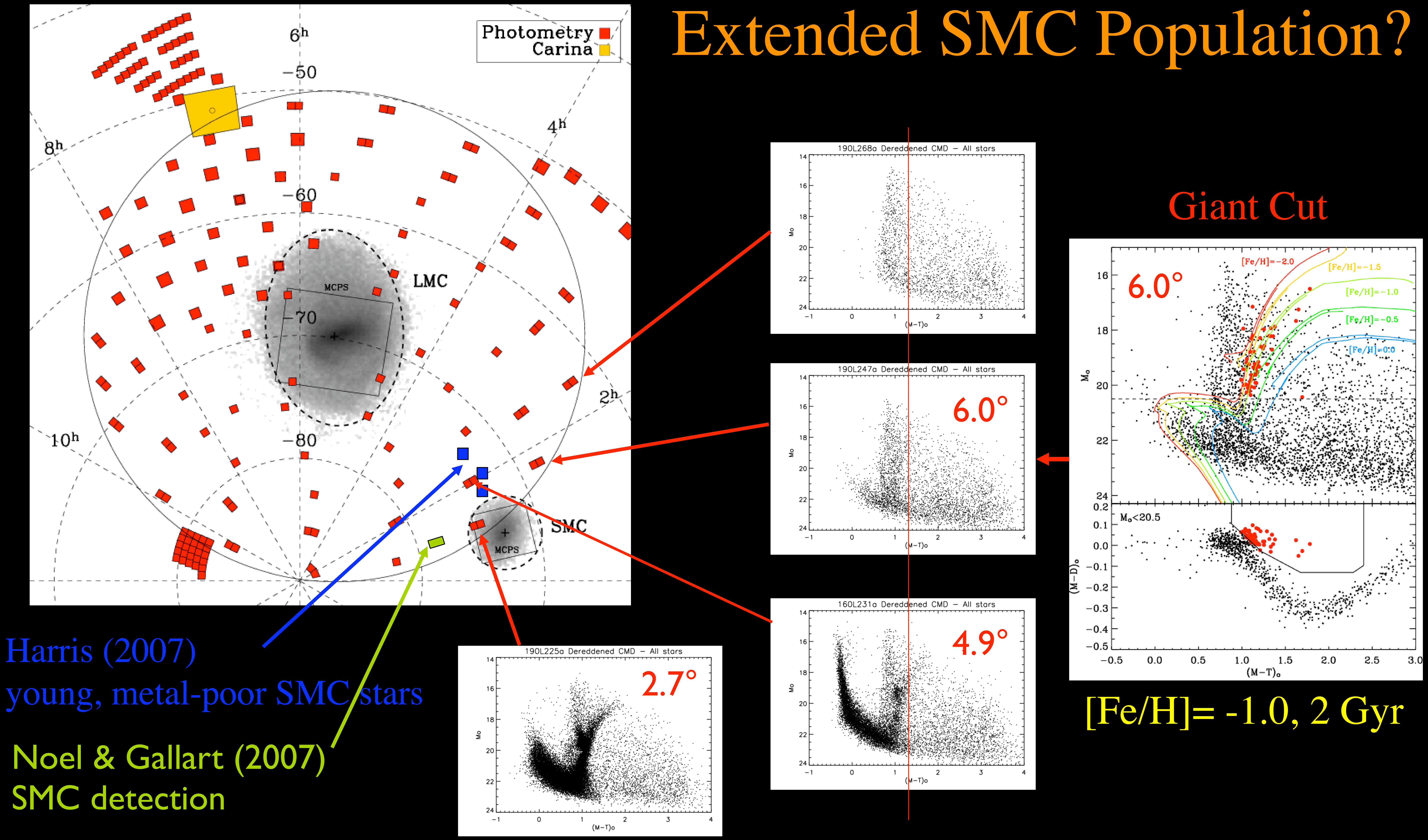
- Fit velocity model
  - constrain proper motion
  - constrain rotation curve
- Velocity dispersion profile
- Already obtained 16 Magellan+IMACS fields. Need to be reduced
- More spectroscopy observing time in December

Nidever et al. 2007, in prep

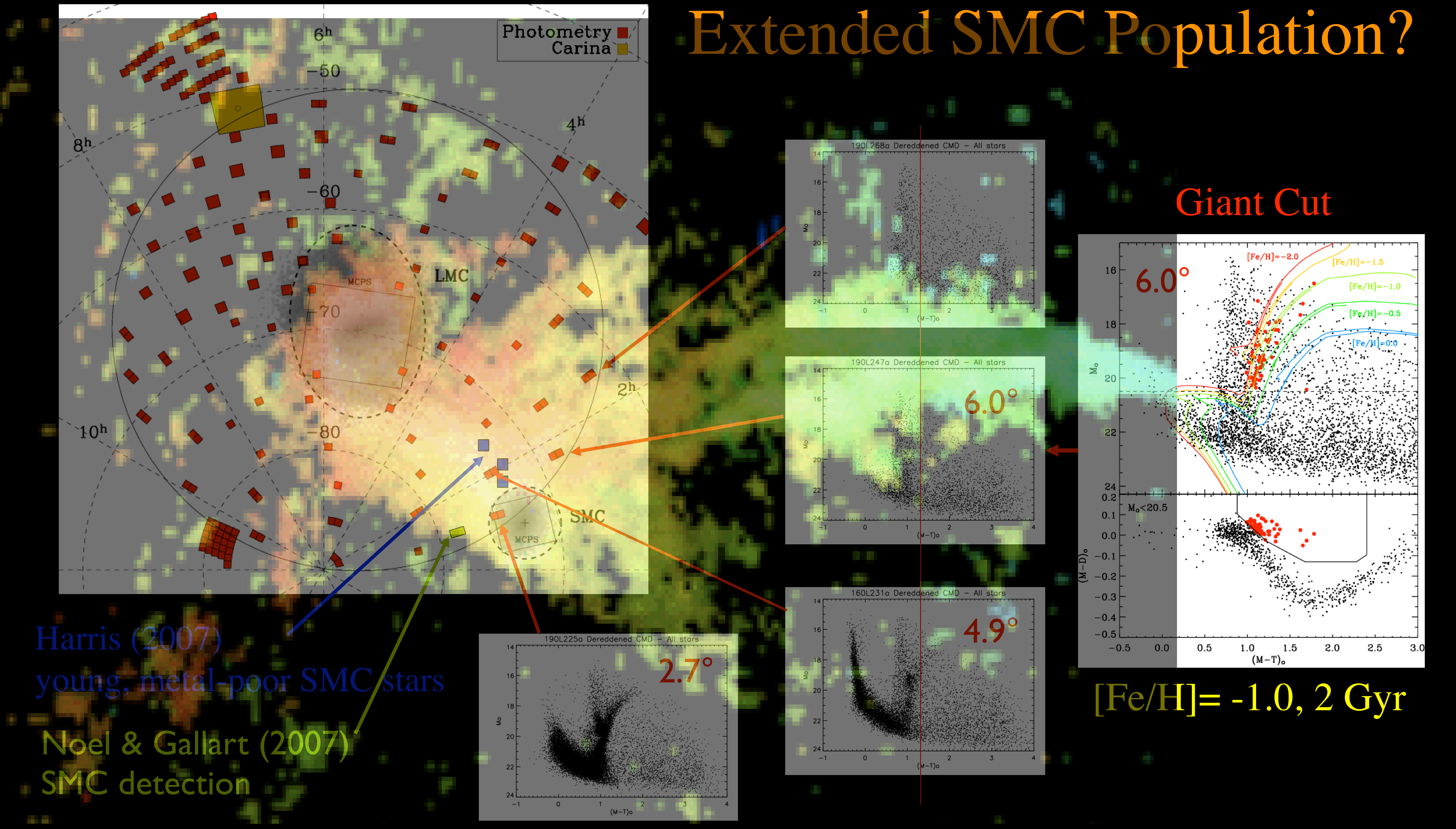
The End

Thank You!

Extended SMC Population?

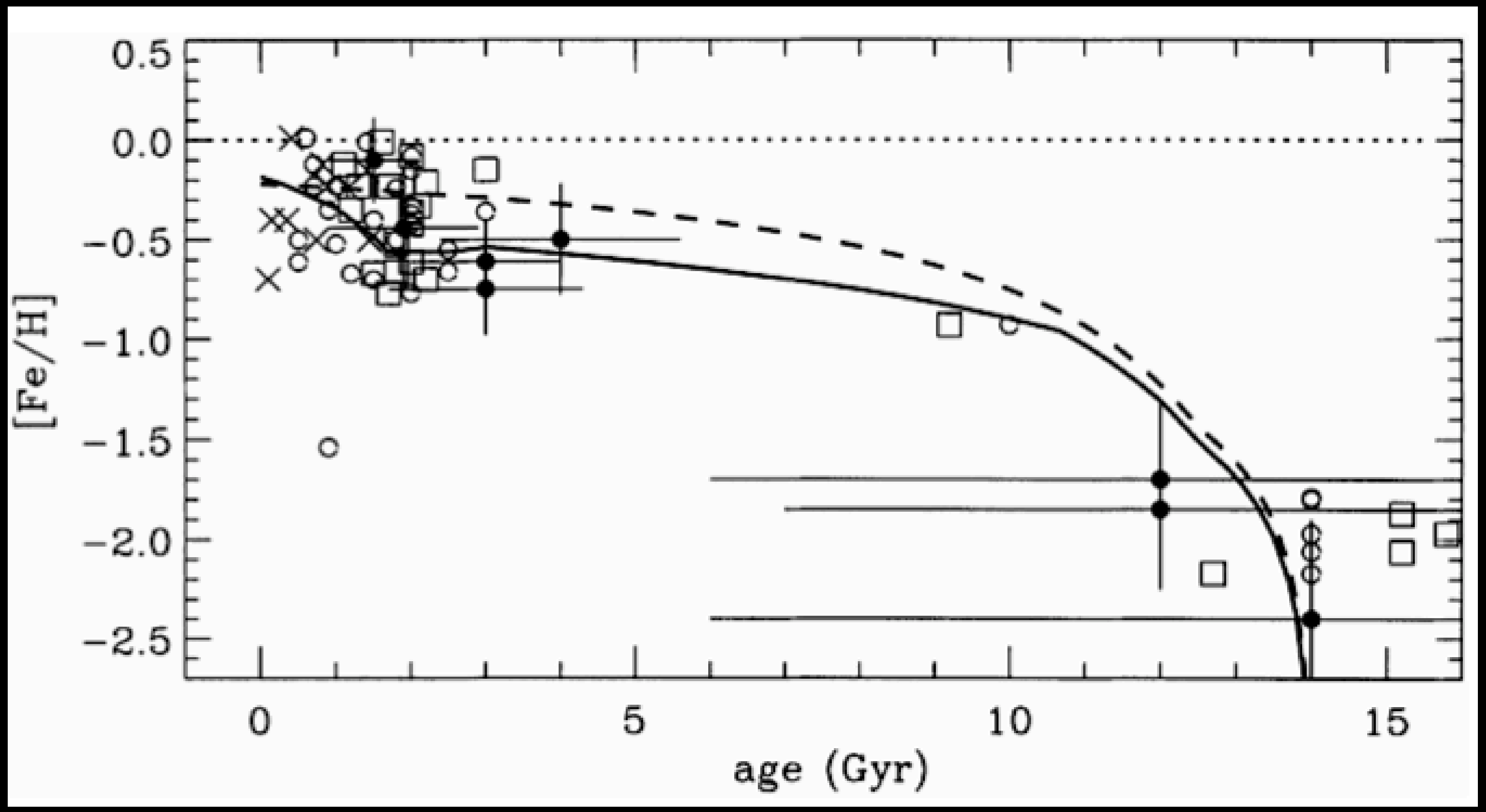


Extended SMC Population?

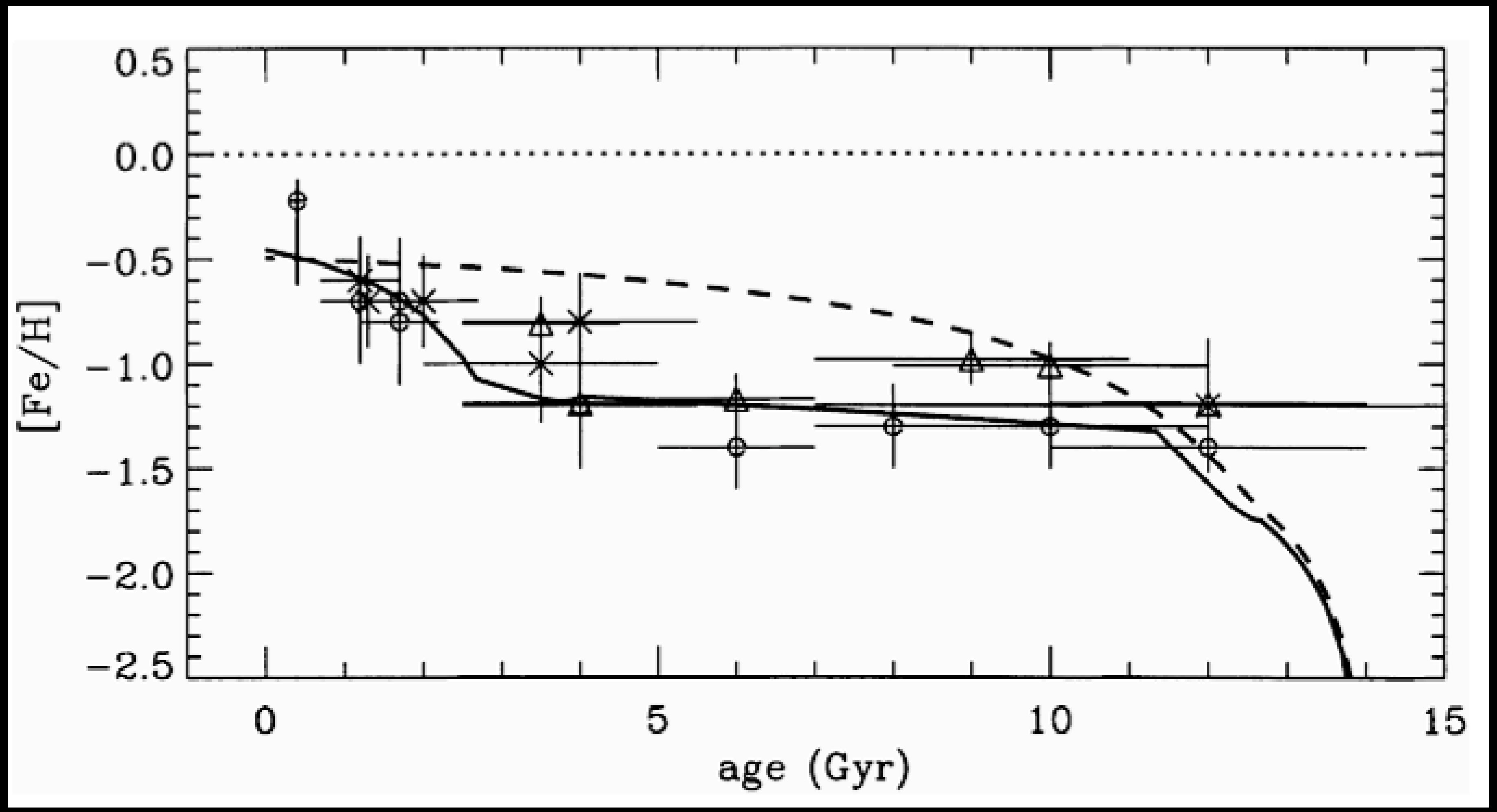


Age Metallicity Relation

LMC AMR



SMC AMR



Pagel & Tautvaišienė 1998

- The LMC halo population with [Fe/H]= -0.5 could be 1-5 Gyr old

Weinberg (2000) puffed-up debris

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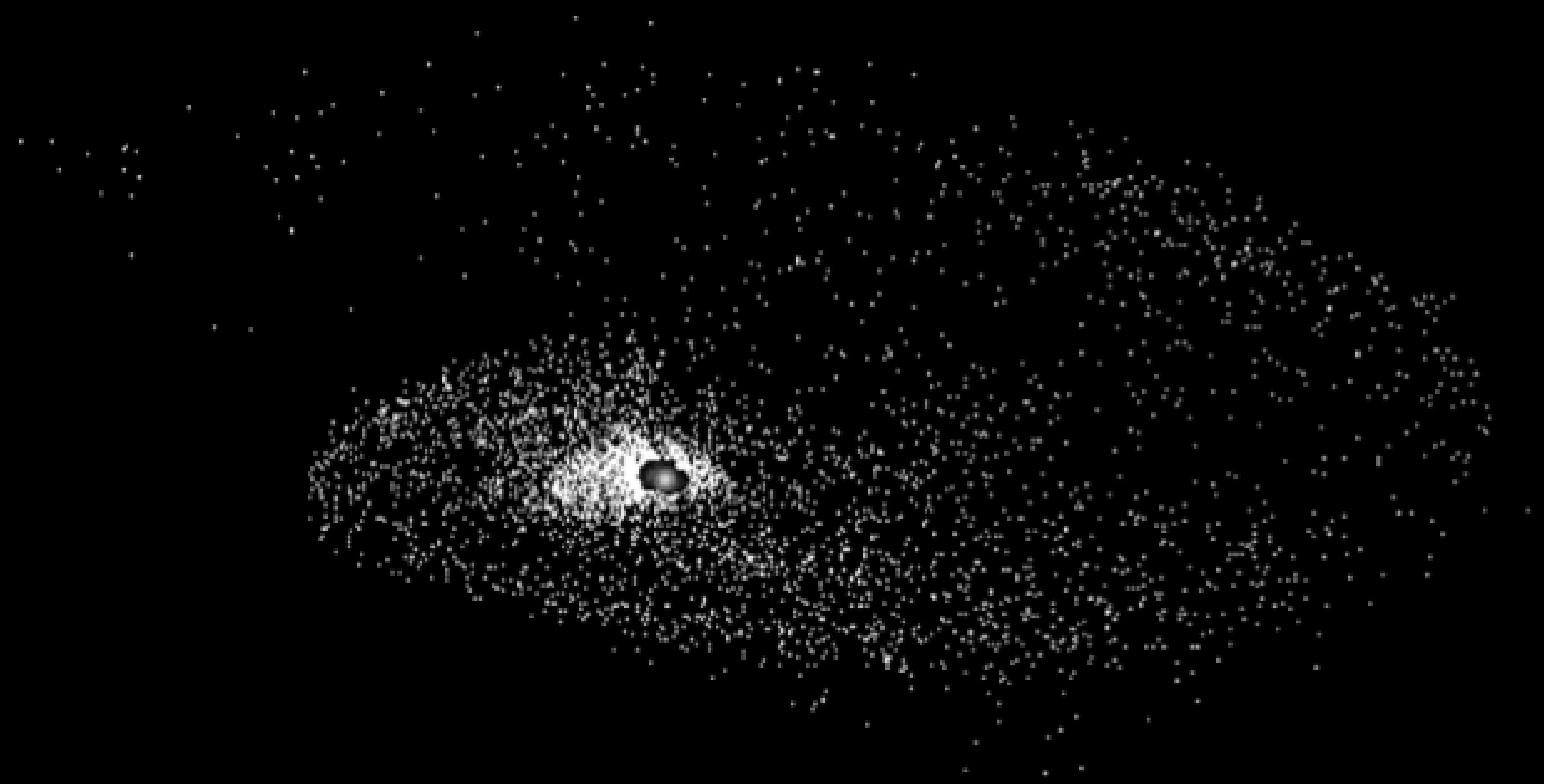
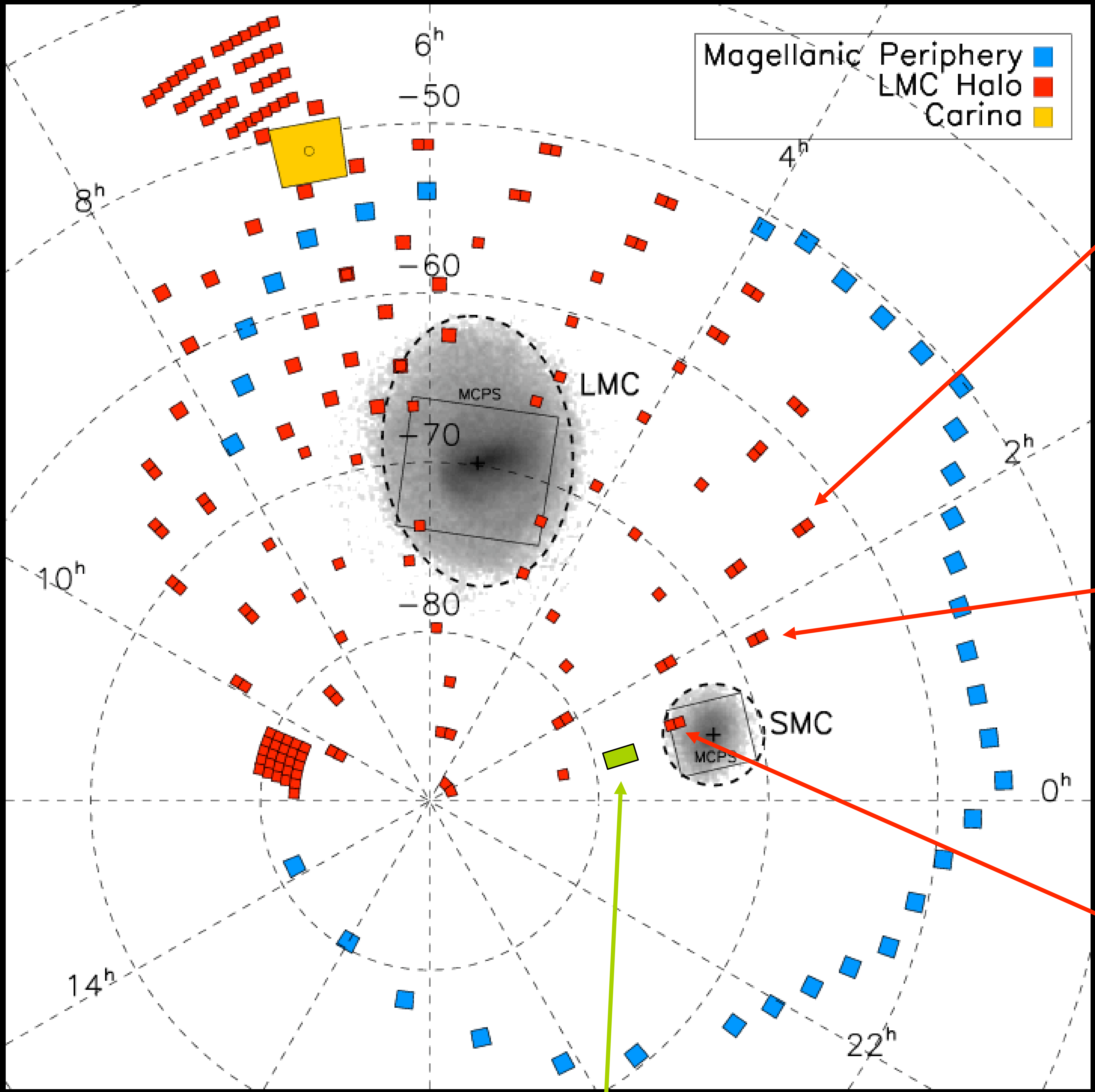
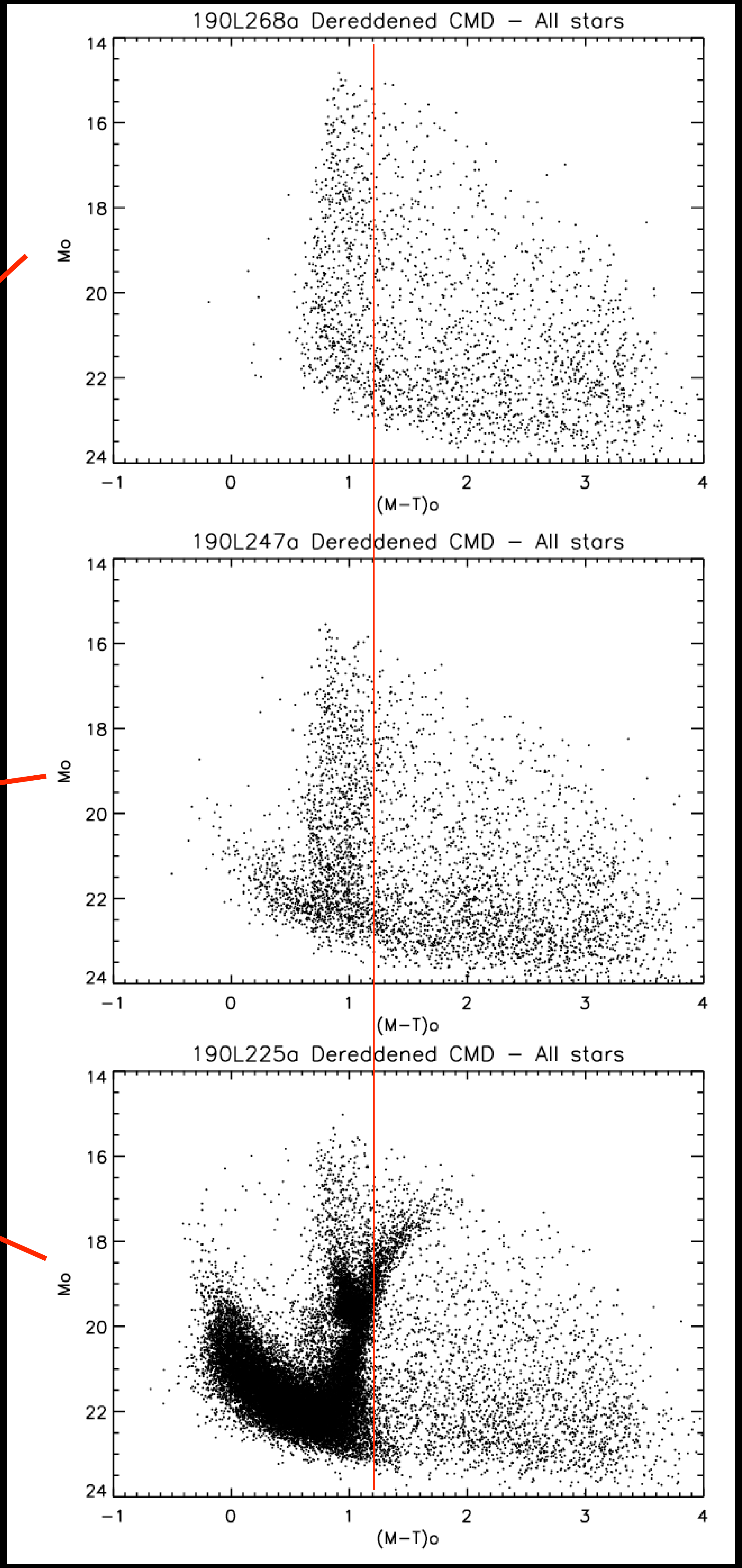


Extended SMC Population?



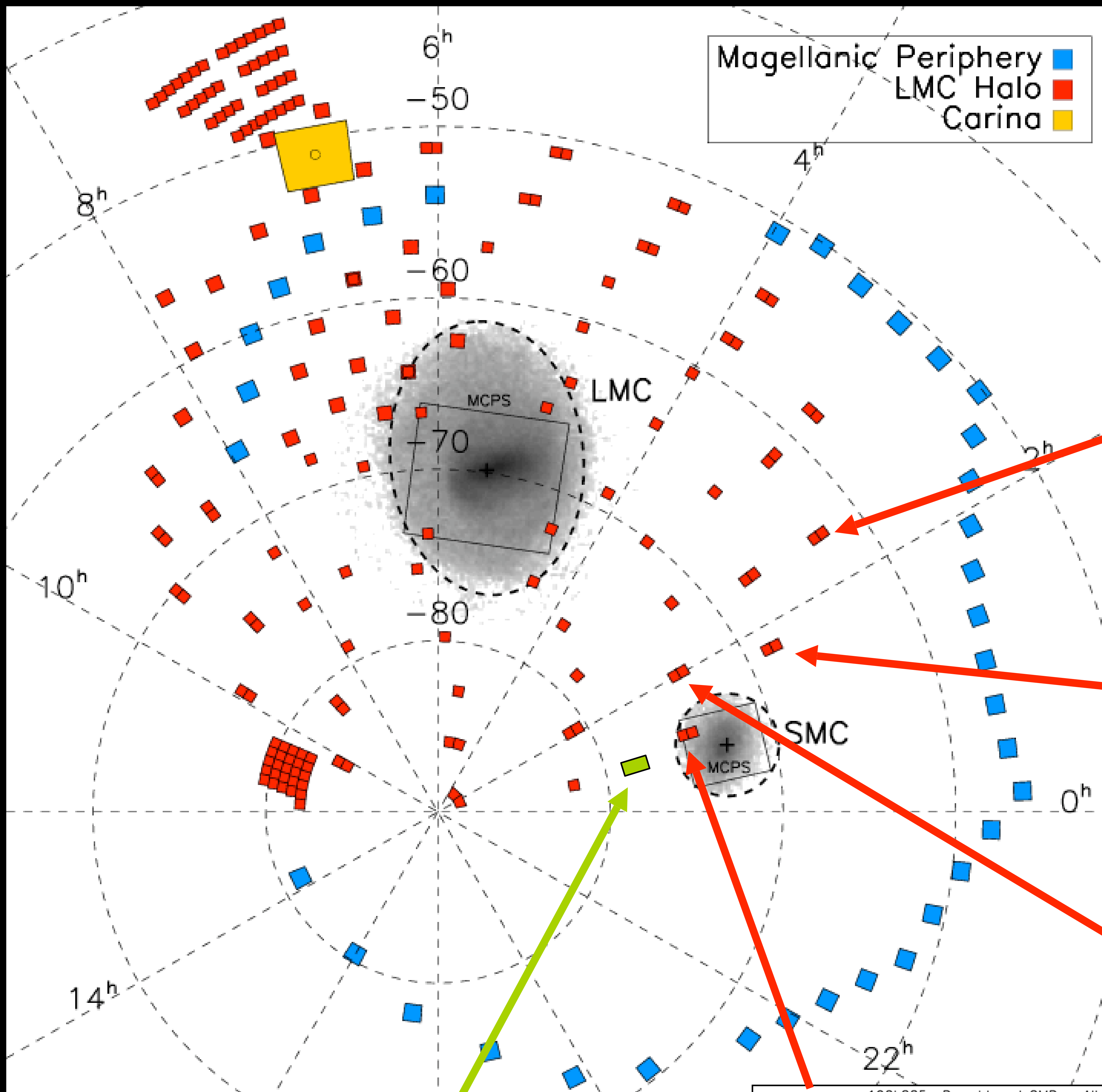


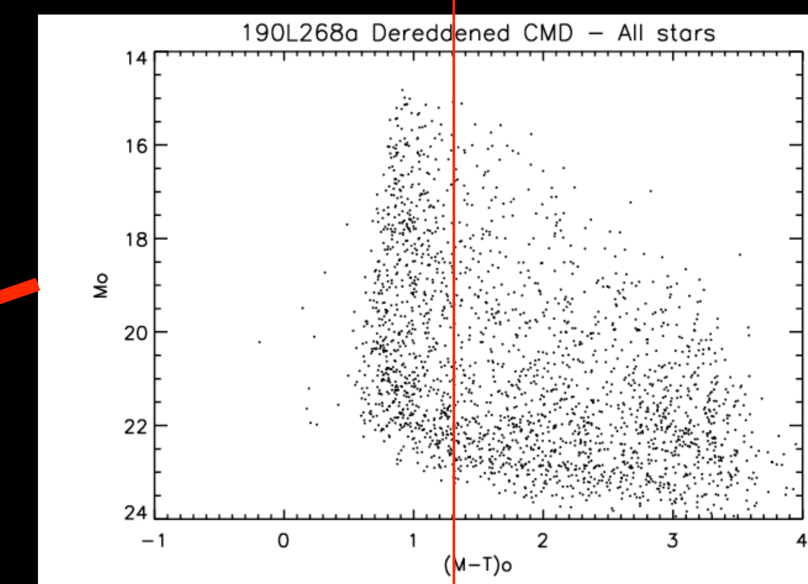
Noel & Gallart (2007) SMC detection

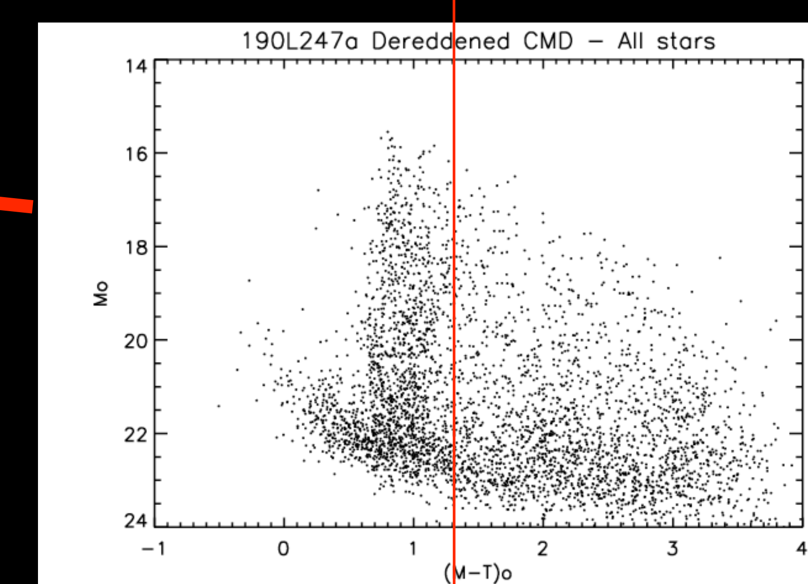
What does it mean?

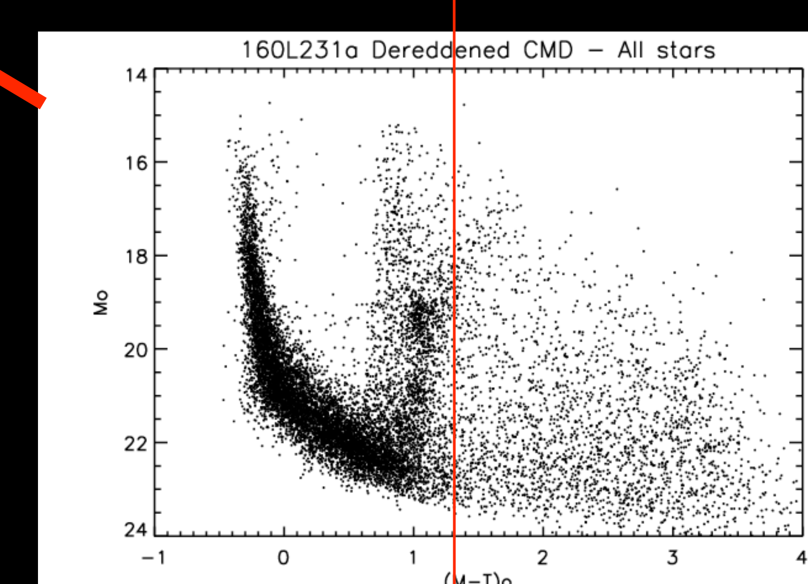
- Old, metal-poor halo and metal-rich halo probably had different formation processes:
  - Outside-In: Like MW halo, tidal debris, SMC debris? (Kunkel et al. 1997)
    - PRO: Correct metallicity
    - CON: Fairly virialized, well-mixed
      Suggests MCs bound to each other for multiple encounters
  - Inside-Out: Puffed-up, LMC debris (Weinberg 2000)
    - PRO: Should be azimuthally symmetric
    - CON: Needs to be bound to MW, hyperbolic orbit a problem
- Velocity dispersion would clarify

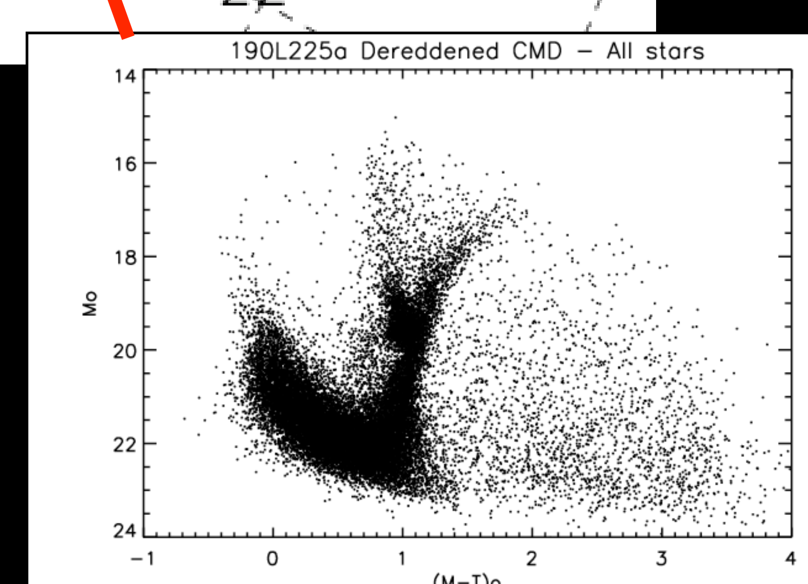
Extended SMC Population?







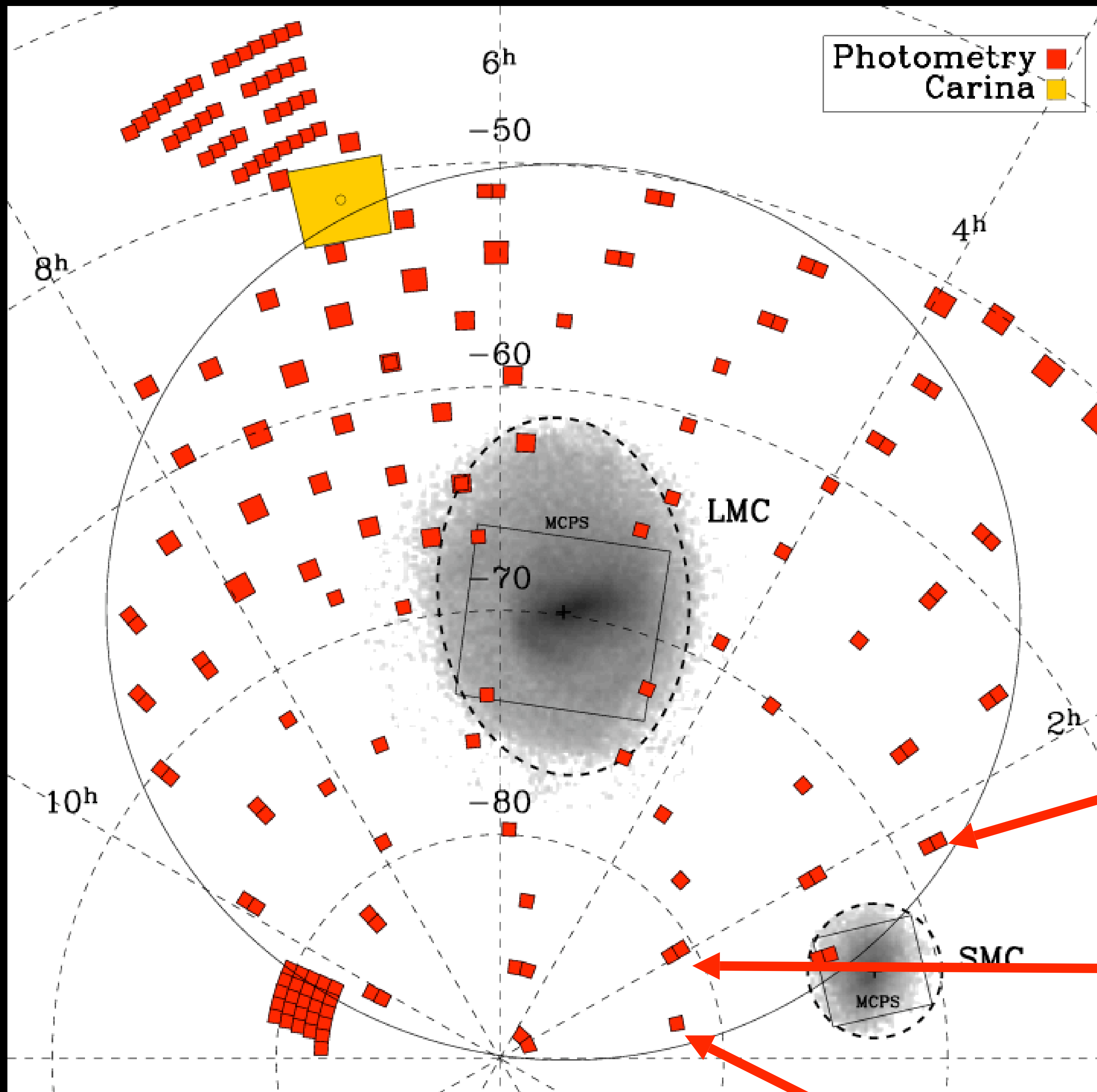




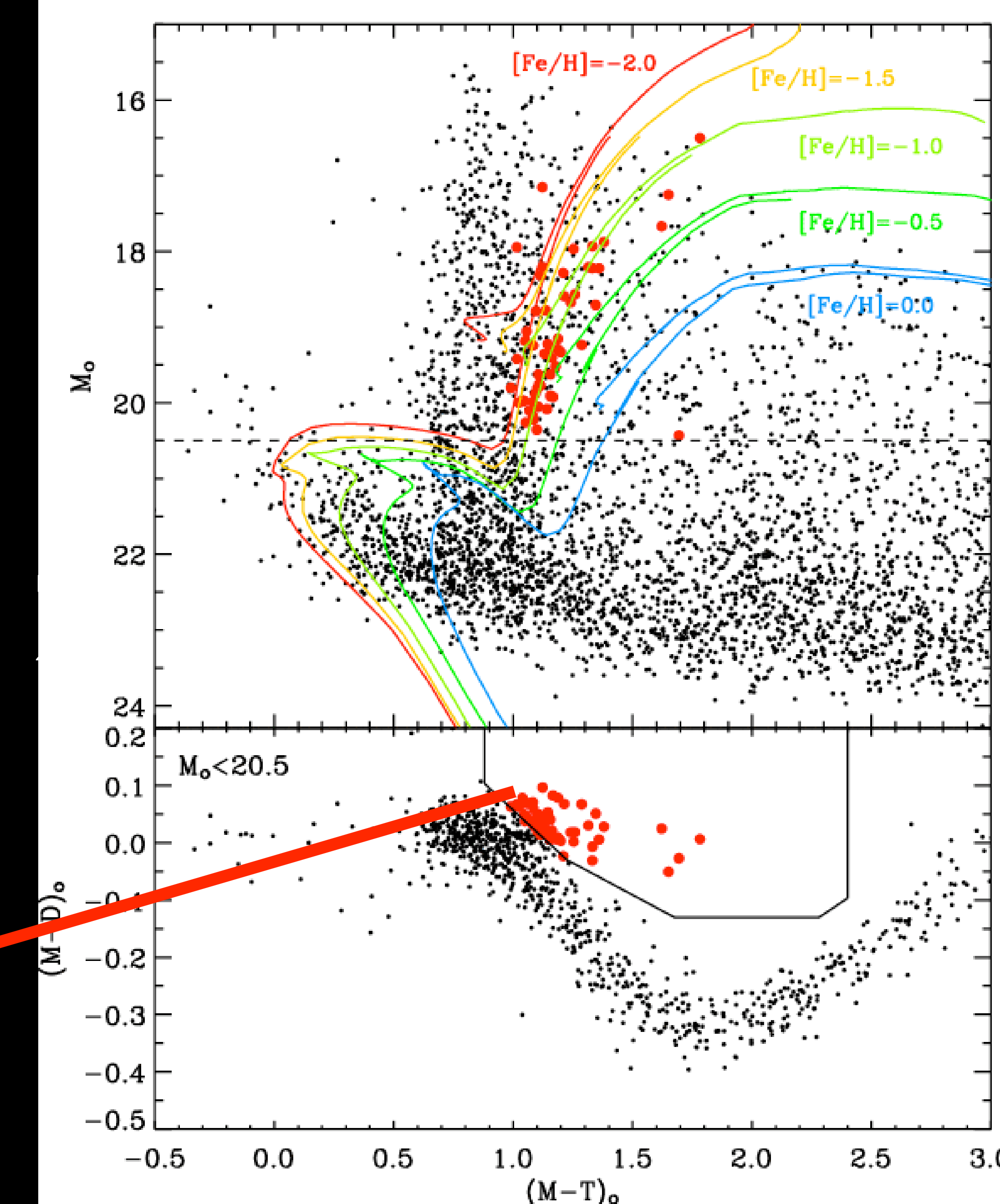
Noel & Gallart (2007)
SMC detection

lo?

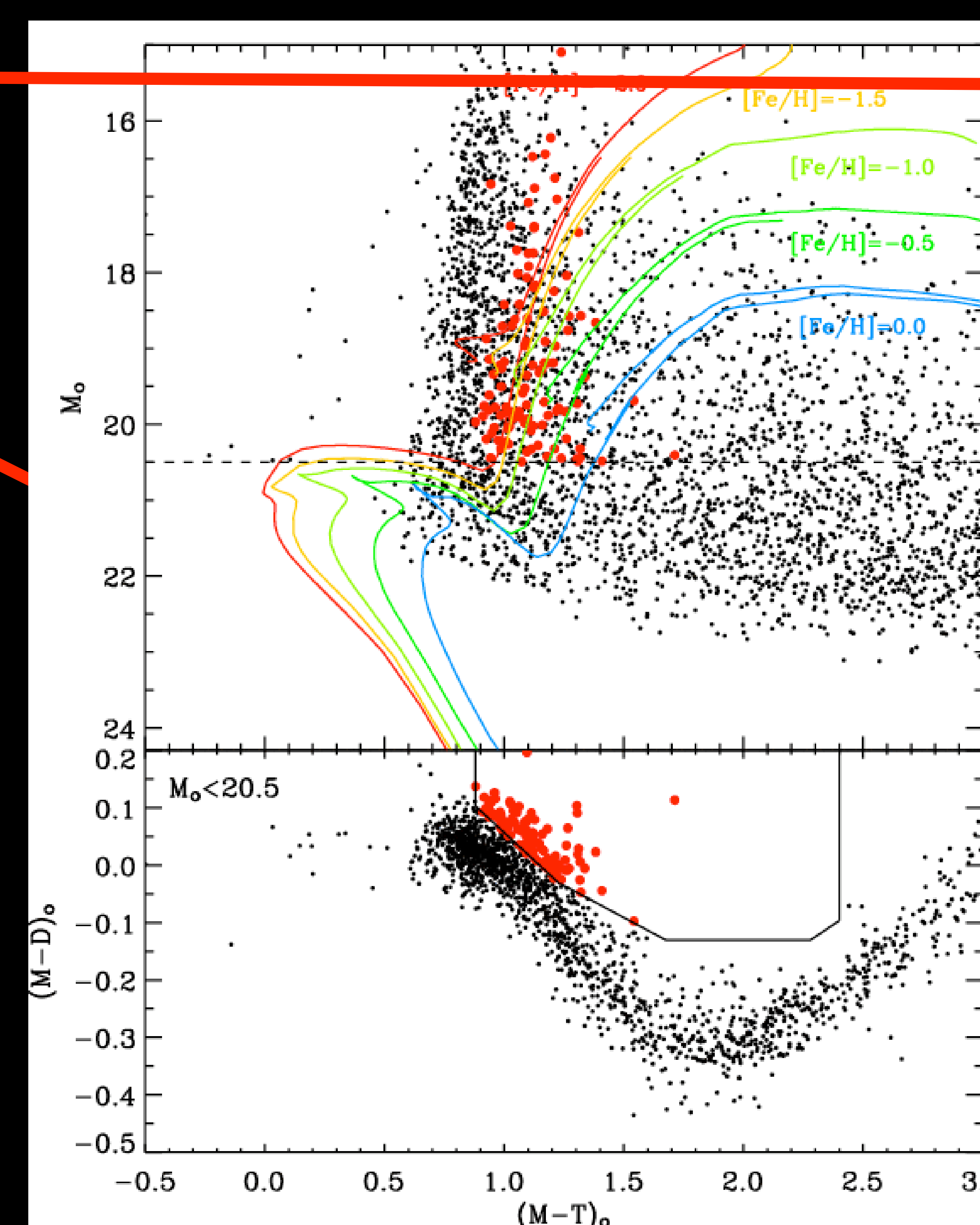
- 0



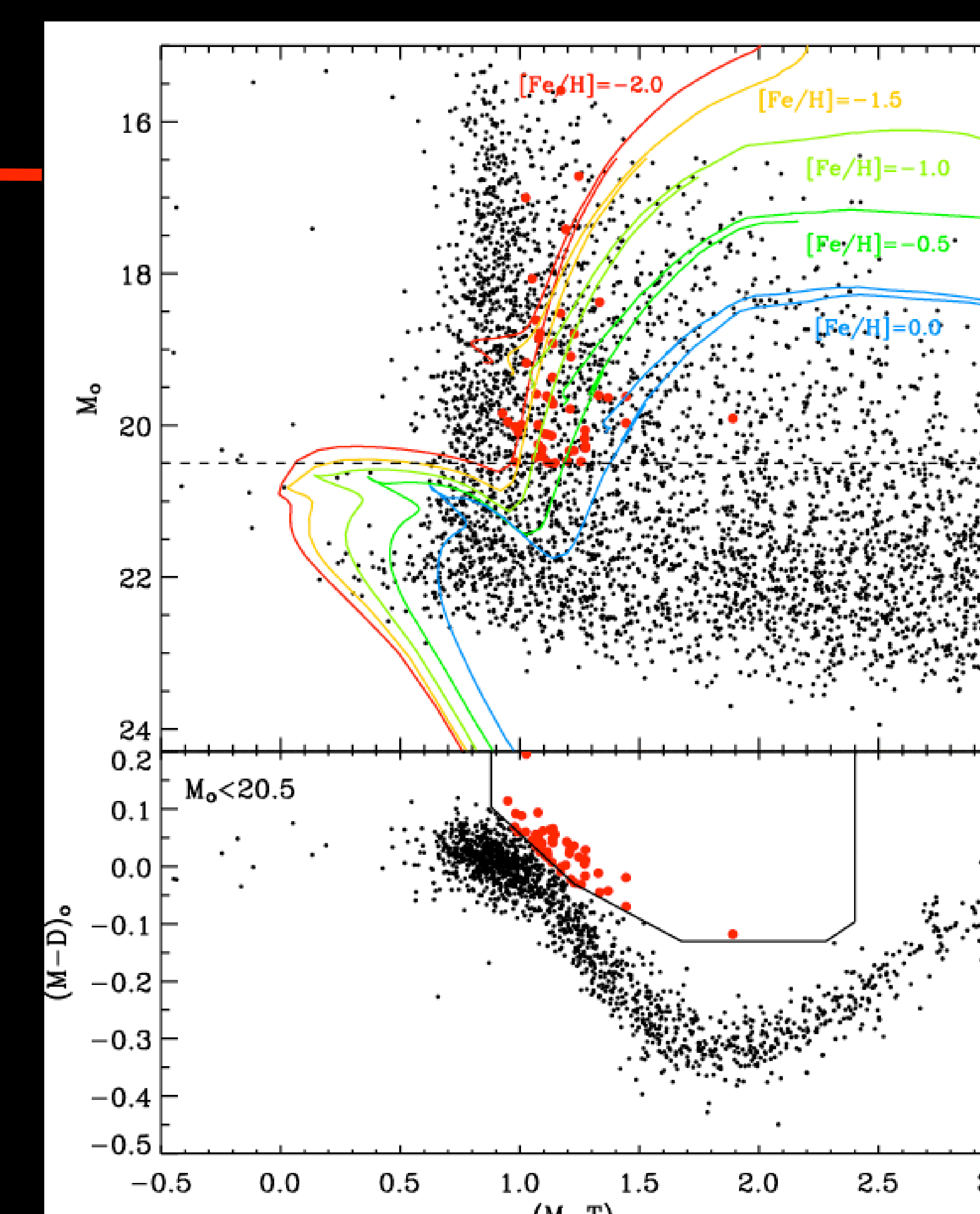
Photometry
Carina
6h
−50
4h
8h
−60
LMC
MCPS
−70
2h
10h
−80
SMC
MCPS



[Fe/H]=−2.0
[Fe/H]=−1.5
[Fe/H]=−1.0
[Fe/H]=−0.5
[Fe/H]=0.0
M₀
M₀<20.5
(M−D)₀
(M−T)₀



[Fe/H]=−1.5
[Fe/H]=−1.0
[Fe/H]=−0.5
[Fe/H]=0.0
M₀
M₀<20.5
(M−D)₀
(M−T)₀



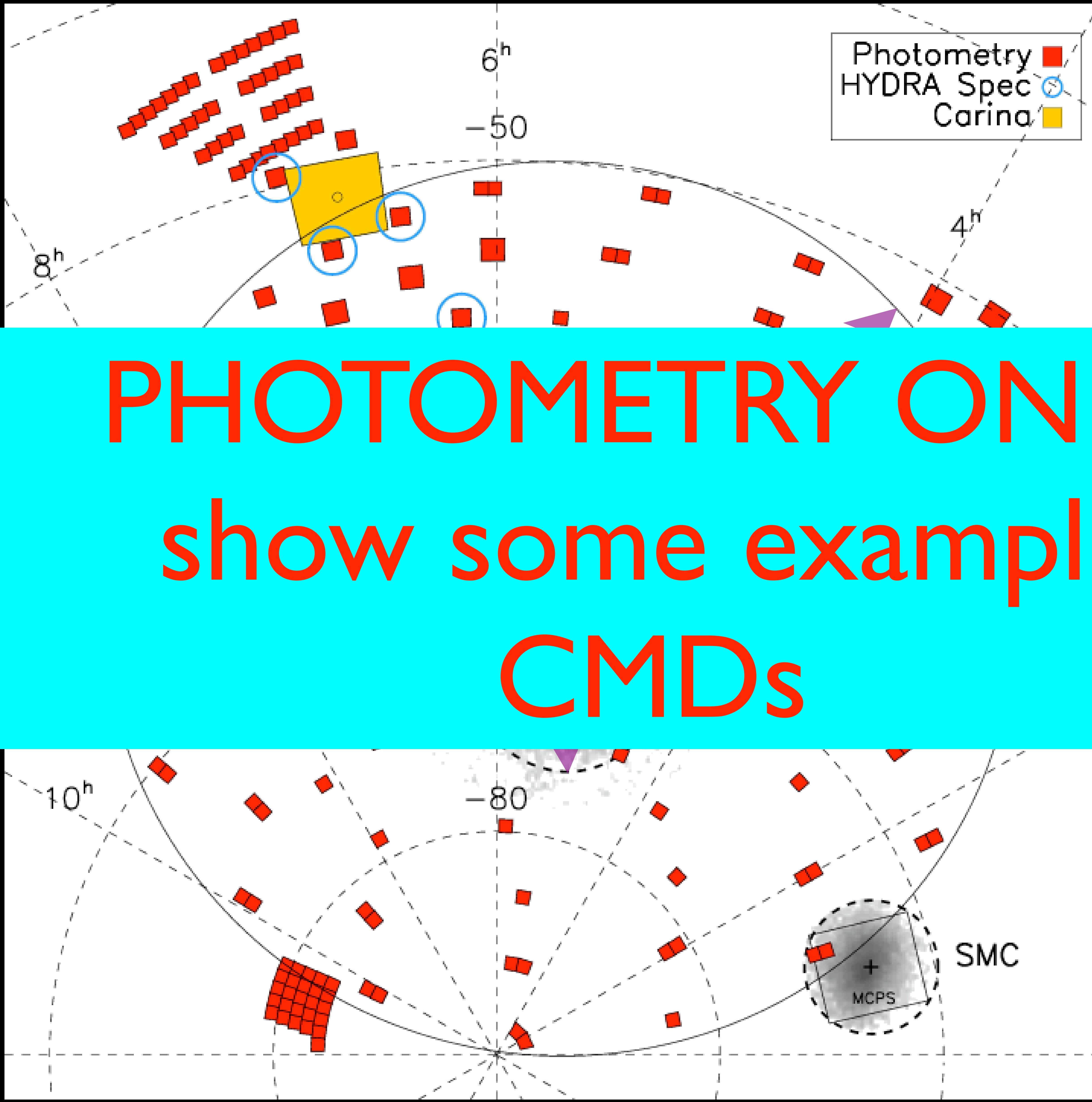
[Fe/H]=−2.0
[Fe/H]=−1.5
[Fe/H]=−1.0
[Fe/H]=−0.5
[Fe/H]=0.0
M₀
M₀<20.5
(M−D)₀
(M−T)₀

- Spectroscopicaly-corrected density profile
- Using only LMC members. Selected in Velocity, CMD and 2CD
- Well-fit by a de Vaucouleurs profile (core radius = 2.4°)
- Exp. scale length h_r=4.9°

van der Marel 2001 - Velocity mo

- Disk velocity model from van der Marel 2001
- Halo velocity model:
  - spherically symmetric
  - no rotation
  - di/dt = 0
- Halo velocity model fits better to the outer fields

Our Follow-up Survey



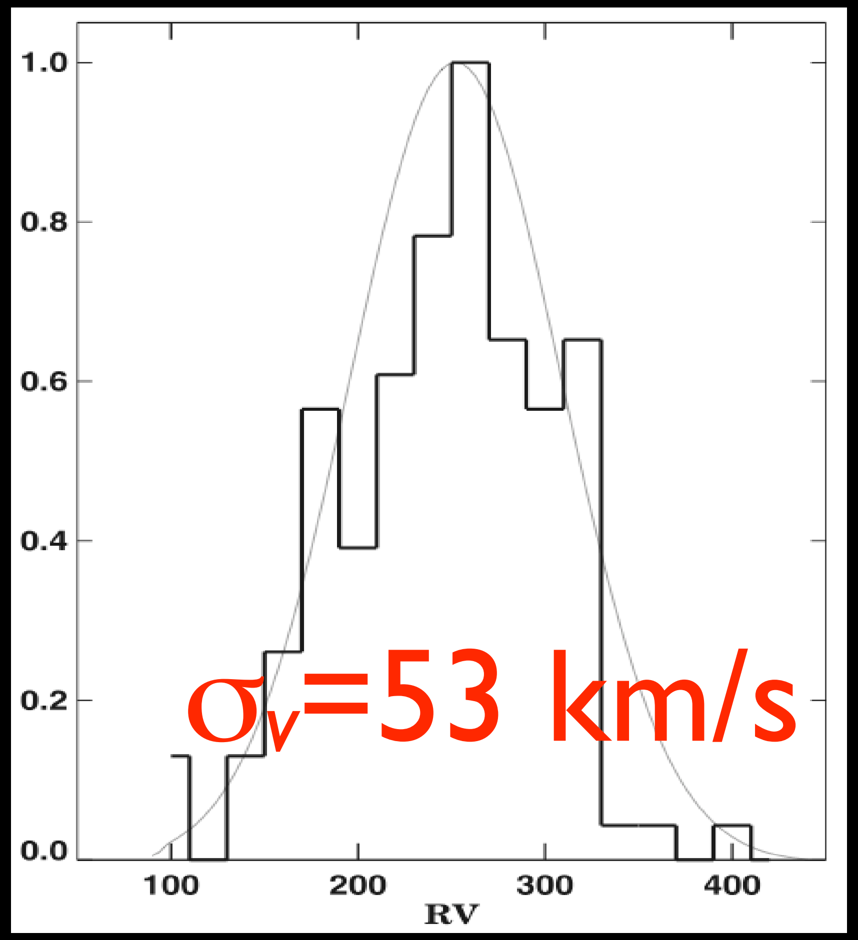
- PHOTOMETRY
- Washington+DDO51 photometry to M~22.5
- IO 4m + MOSAIC
- x36' FOV
- 0 Fields
- 0 deg^2

PHOTOMETRY ONLY
show some example
CMDs

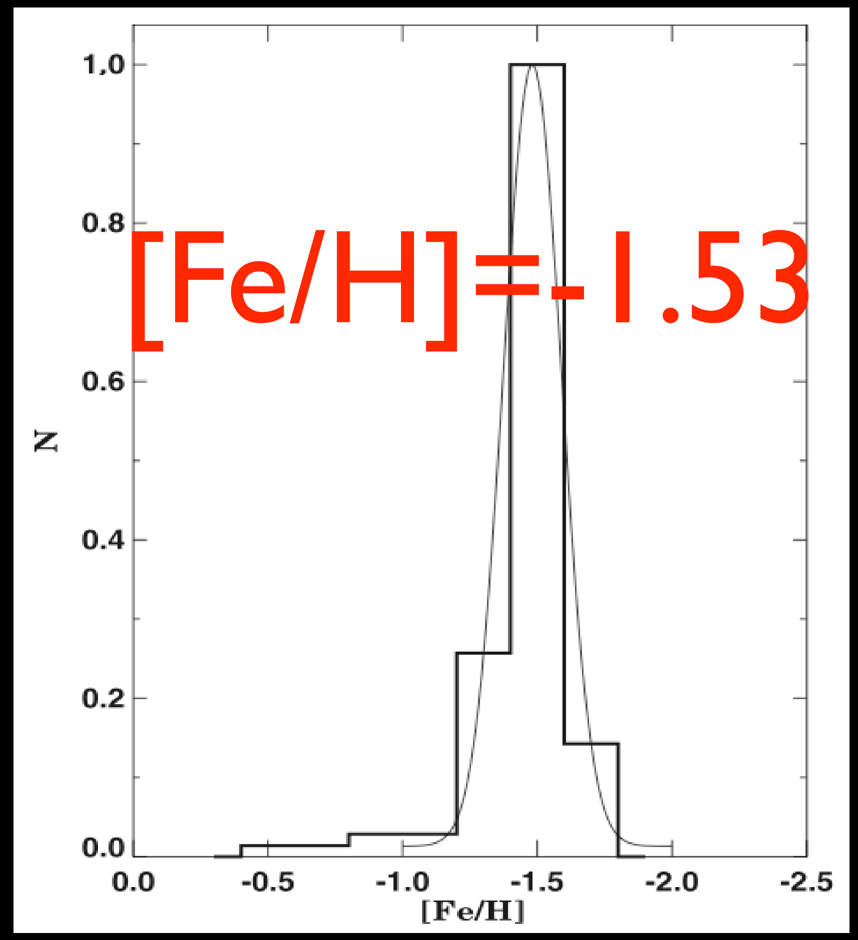
Other discoveries of extended, metal-poor LMC stars

- MACHO and OGLE identified LMC RR Lyrae (Minniti et al. 2003, Borissova et al. 2004, 2006, Alves 2004)
  - σ_v = 53 km/s
  - [Fe/H]= -1.53 +/- 0.02
  - But, density profile is King or exponential to *R*=15°.
- Meschin et al. (*see poster*): metal-poor main sequence to *R*=10°.

RR Lyrae RVs

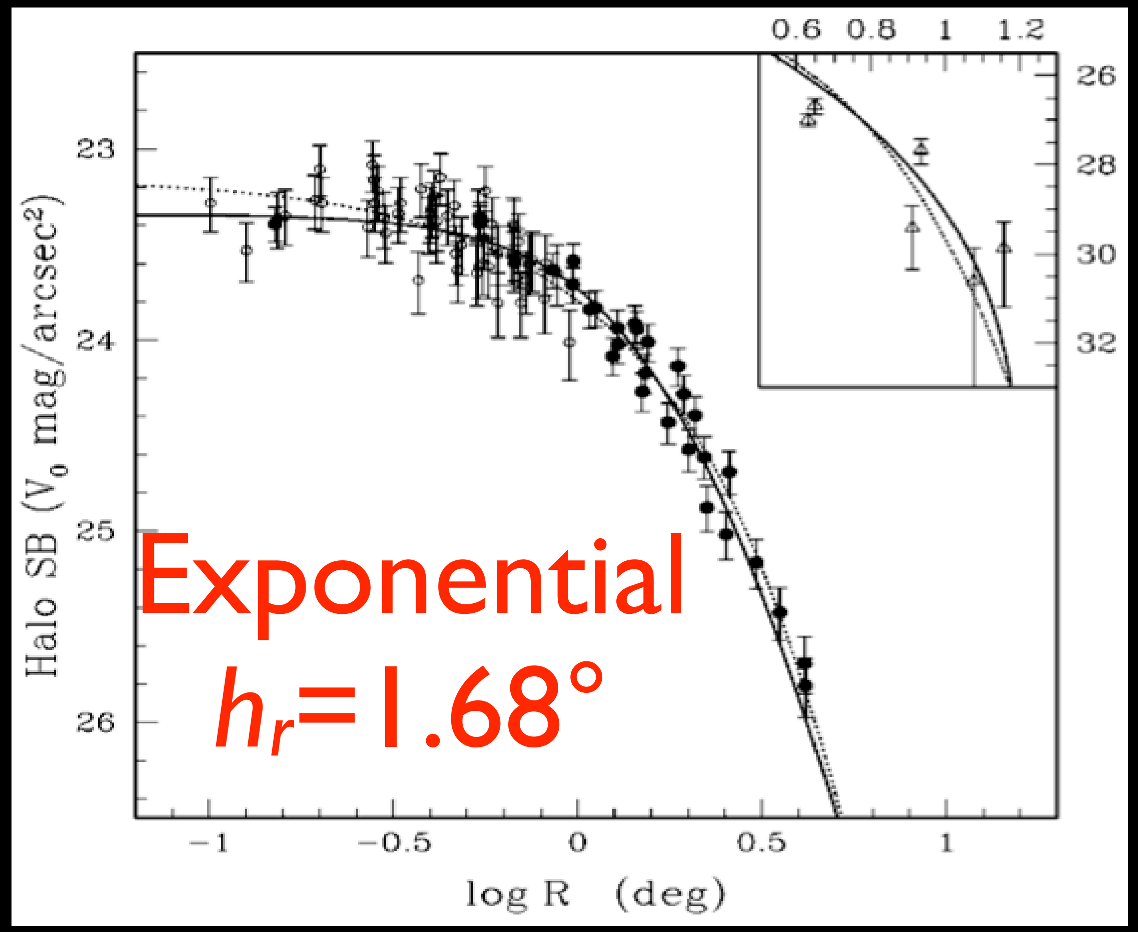


RR Lyrae [Fe/H]



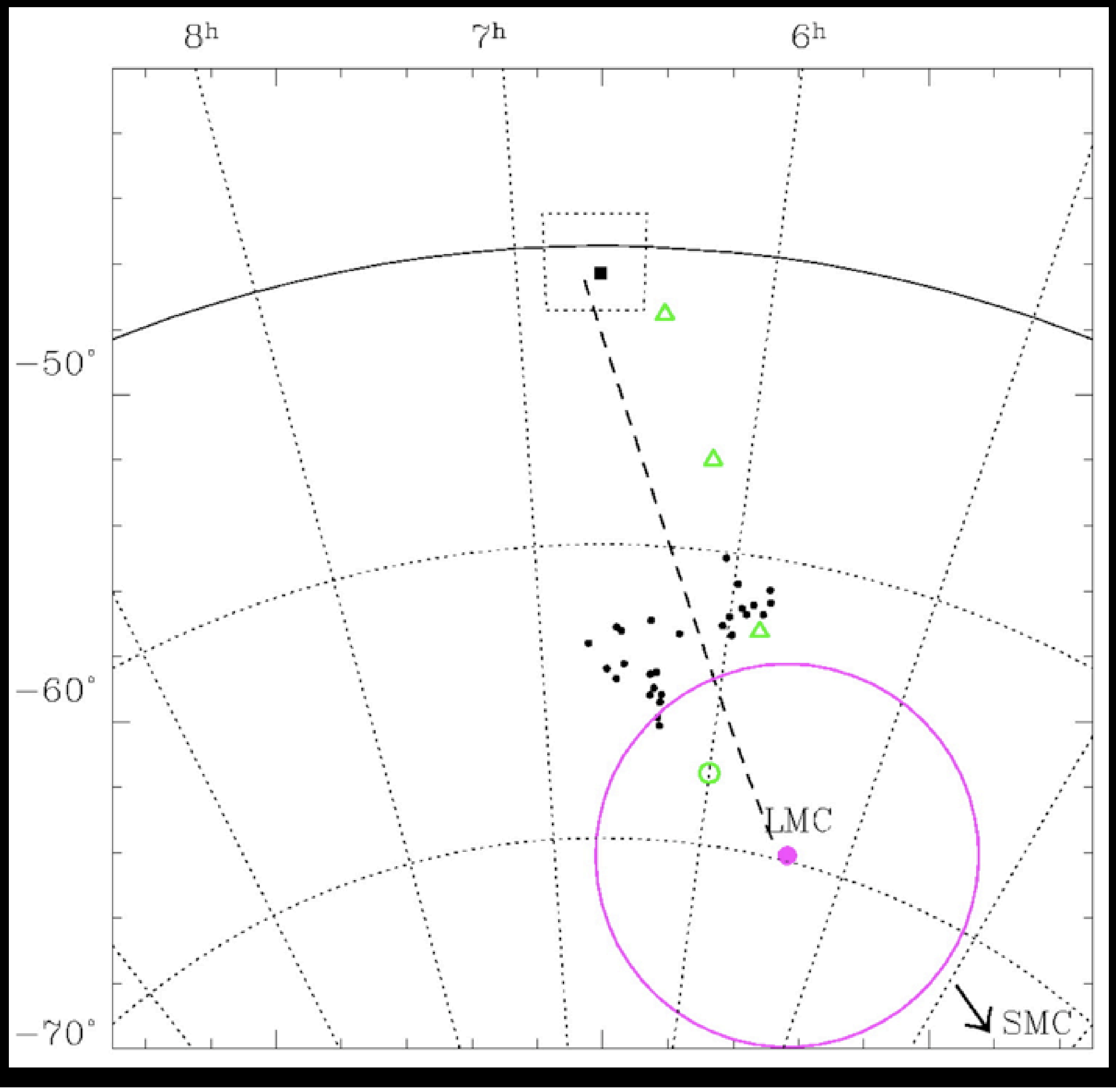
Borissova et al. 2006, A&A, 460, 459

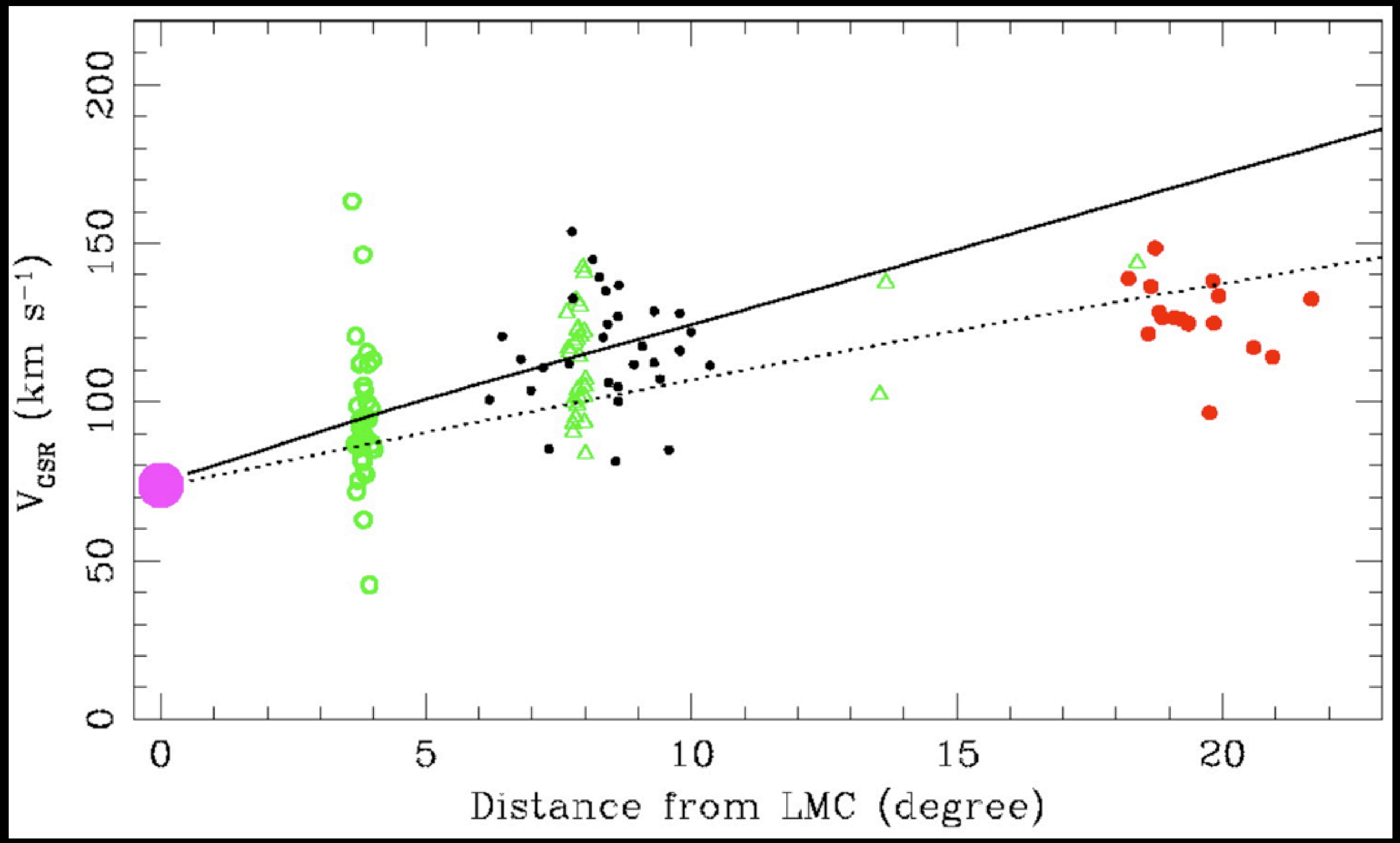
Density Profile



Alves 2004, ApJ, 601, L151

332 km/s moving group



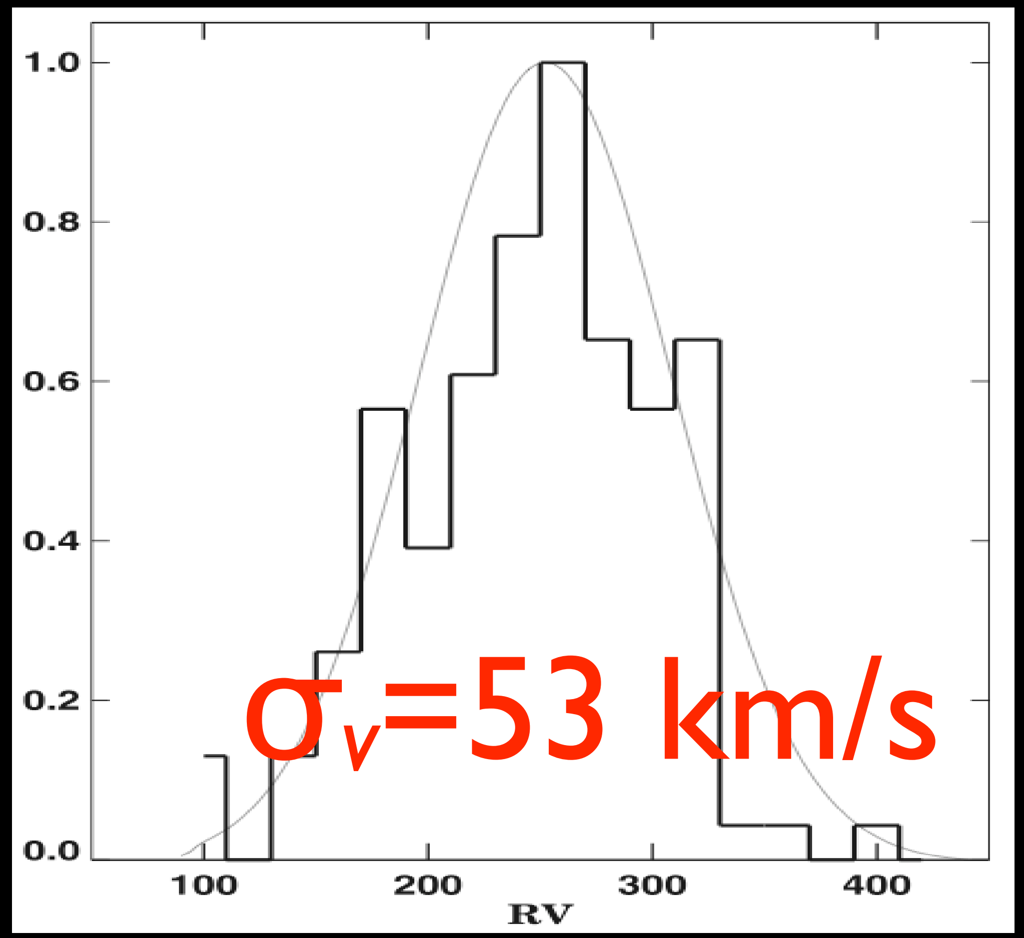


- Falls on the velocity trend of an LMC "halo" population
- Low velocity dispersion of σ_v=9.8 km/s, compared to LMC disk σ_v~20 km/s

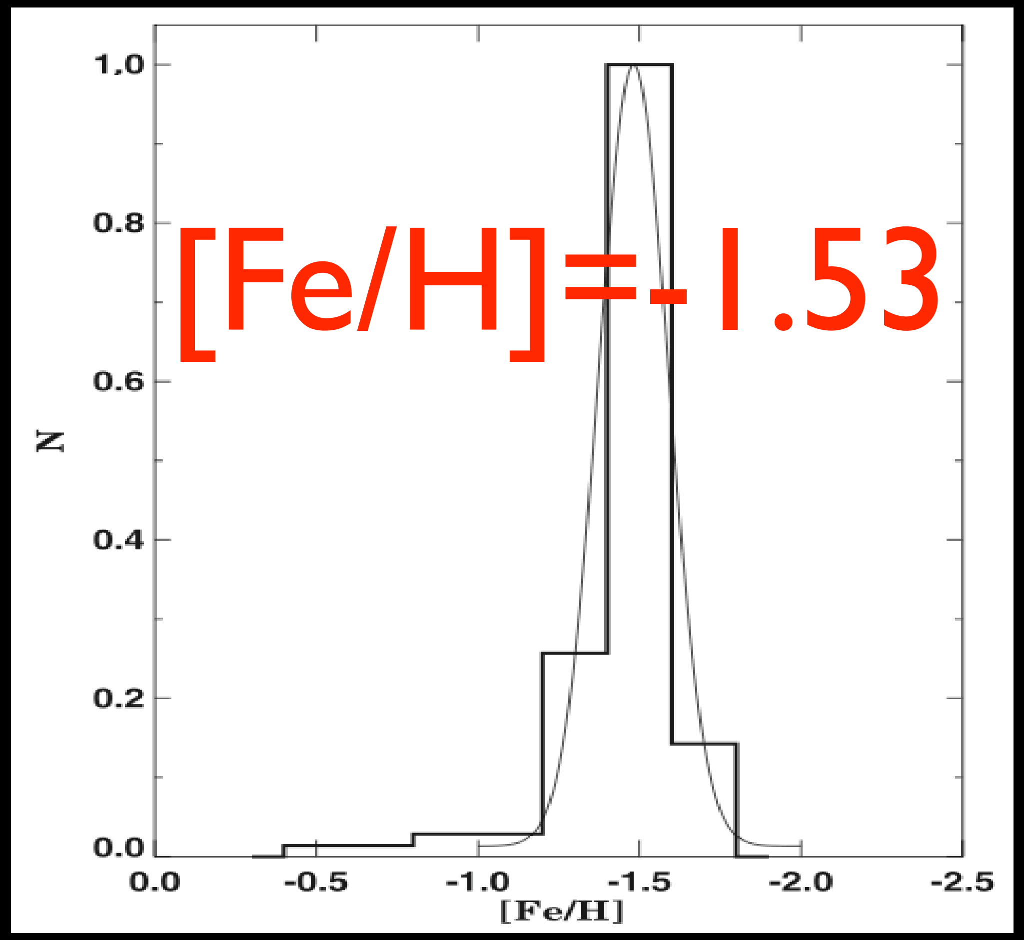
Old, metal-poor halo from RR Lyrae

- MACHO and OGLE identified LMC variables (Minniti et al. 2003; Borissova et al. 2004, 2006; Alves 2004)
- RR Lyrae have a large velocity dispersion σ_v=53 km/s (Minniti et al. 2003, Borissova et al. 2004, 2006)
- Old, metal-poor halo [Fe/H]= -1.53 +/- 0.02 (Borissova et al. 2006)
- Density profile is King or Exponential to R=15°, h_r=1.68° (Alves 2004)
  → Same as disk!
- Dynamically hot, metal-poor, RGB component (Cole et al. 2005)

RR Lyrae RVs

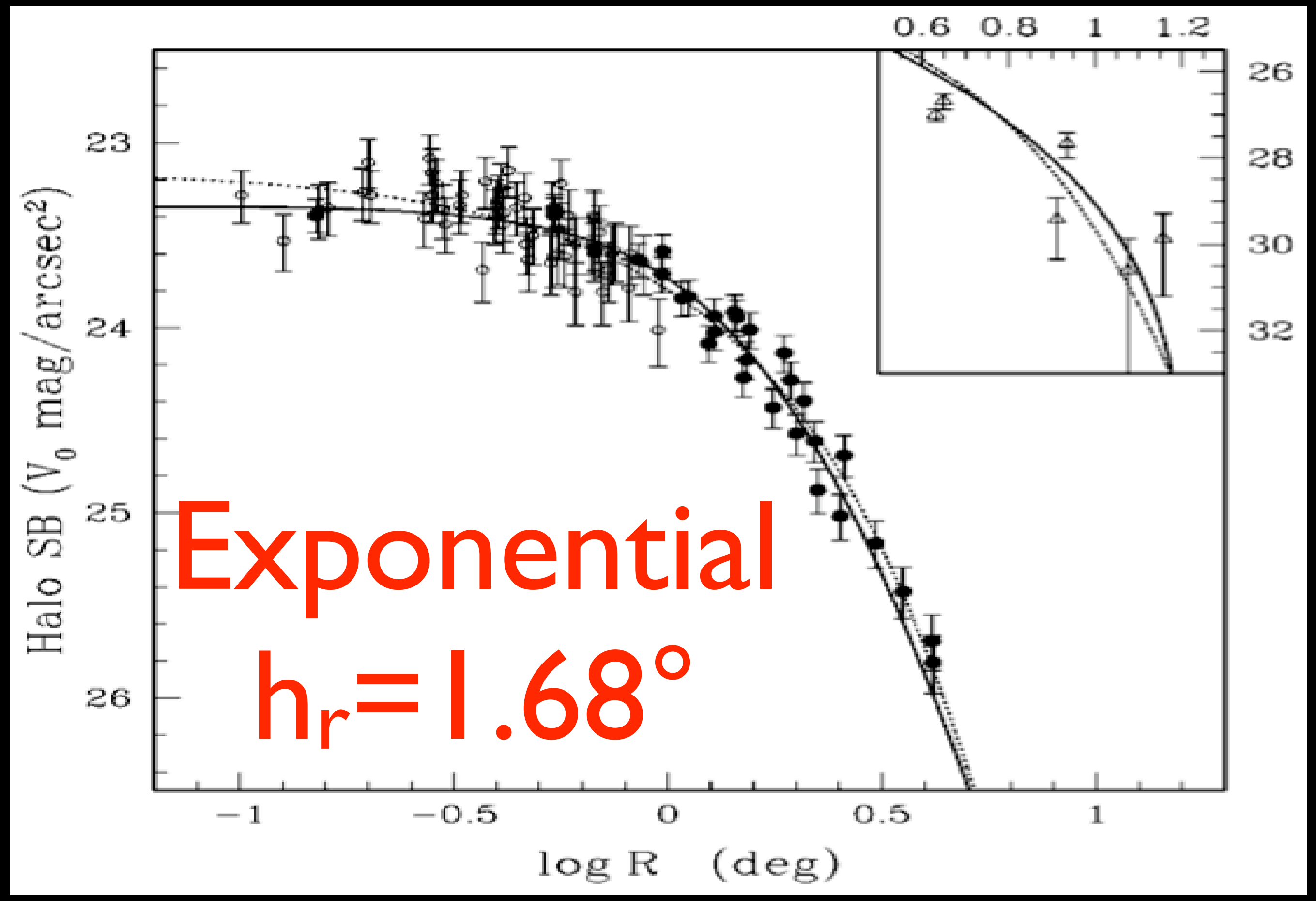


RR Lyrae [Fe/H]



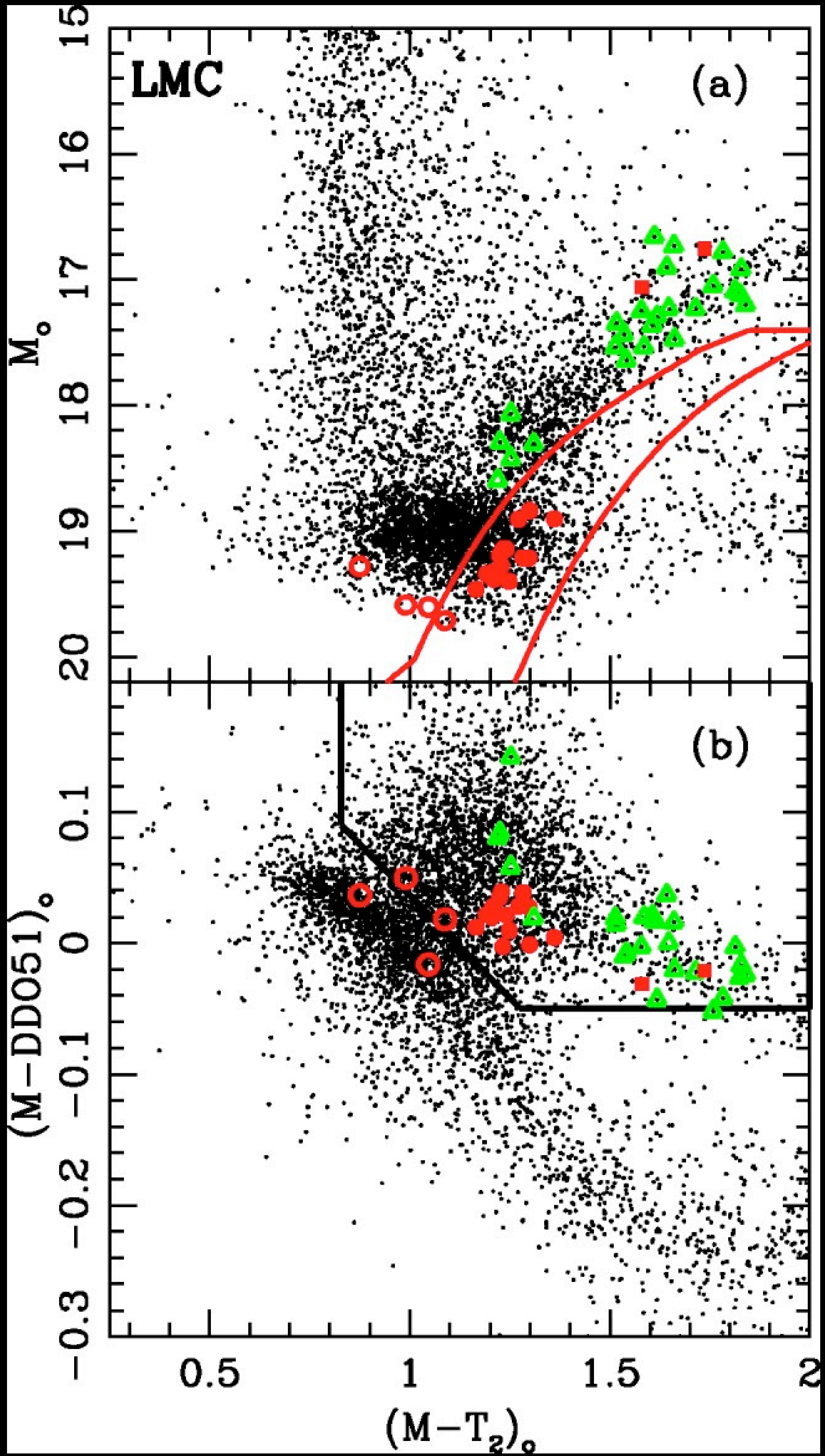
Borissova et al. 2006, A&A, 460, 459

Density Profile



Alves 2004, ApJ, 601, L151

332 km/s moving group

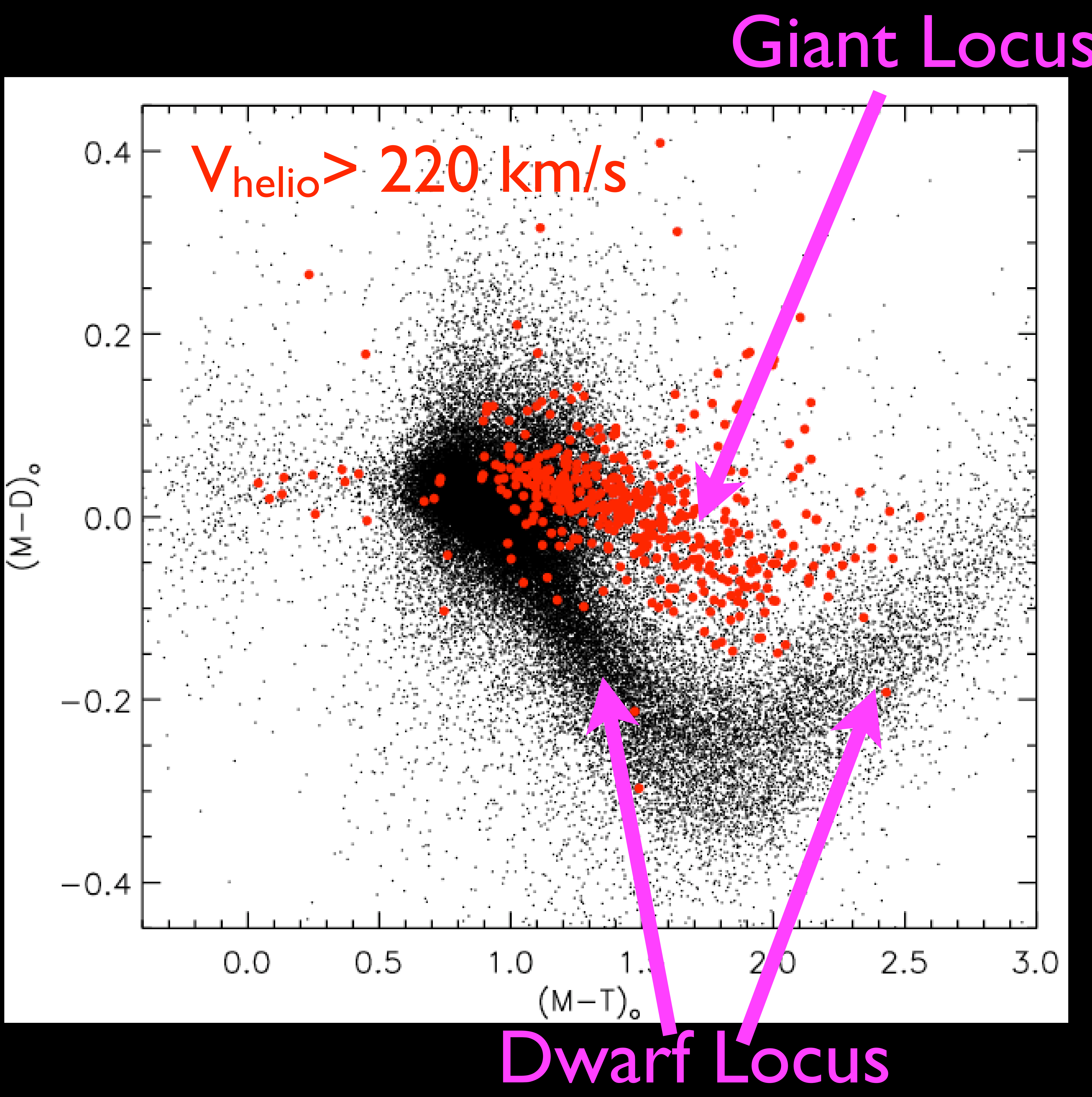


- Muñoz et al. 2006 found a moving group of 15 stars with $<V_{helio}>$=332 km/s in their 10 deg^2 Carina survey
- Consistent with being LMC red clump stars in the CMD and 2CD

→ 20° from LMC center!

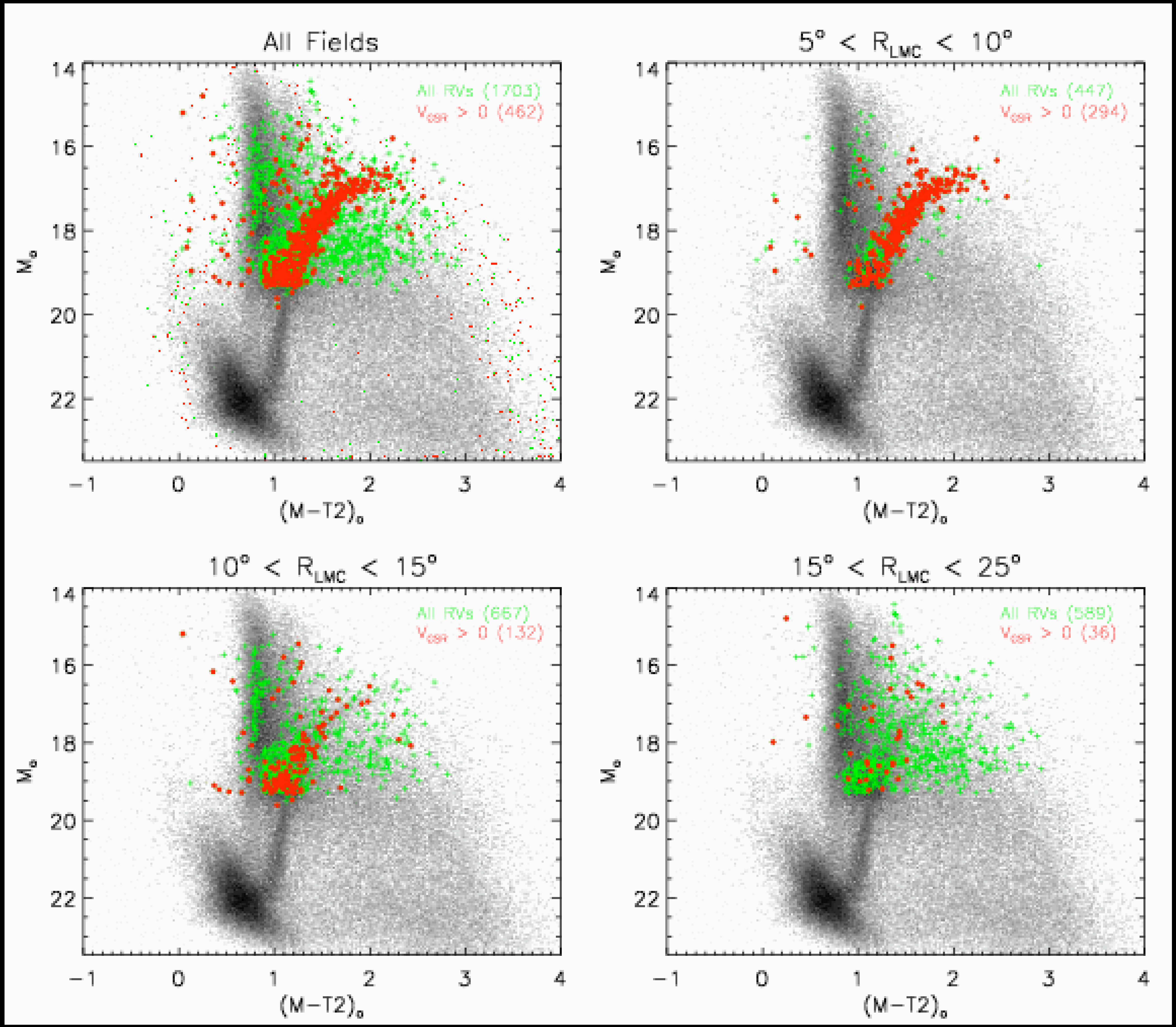
- Falls on the velocity trend of an LMC "halo" population
- Low velocity dispersion of σ_v=9.8 km/s, compared to LMC disk σ_v~20 km/s

Color-Color Diagram



- Velocity selected LMC stars are consistent with being giants in the Washington color-color diagram which is gravity sensitive

Color Magnitude Diagram



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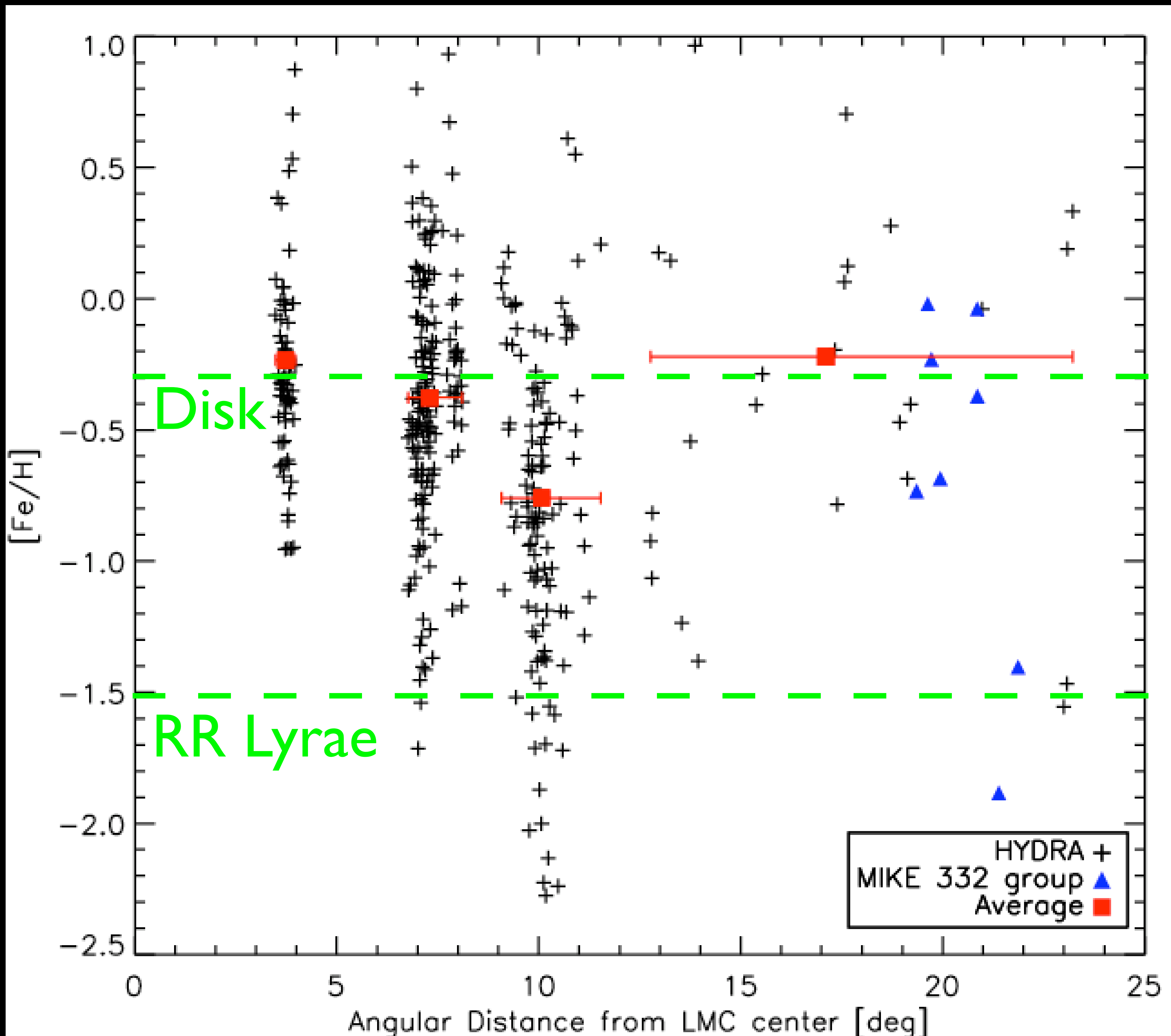
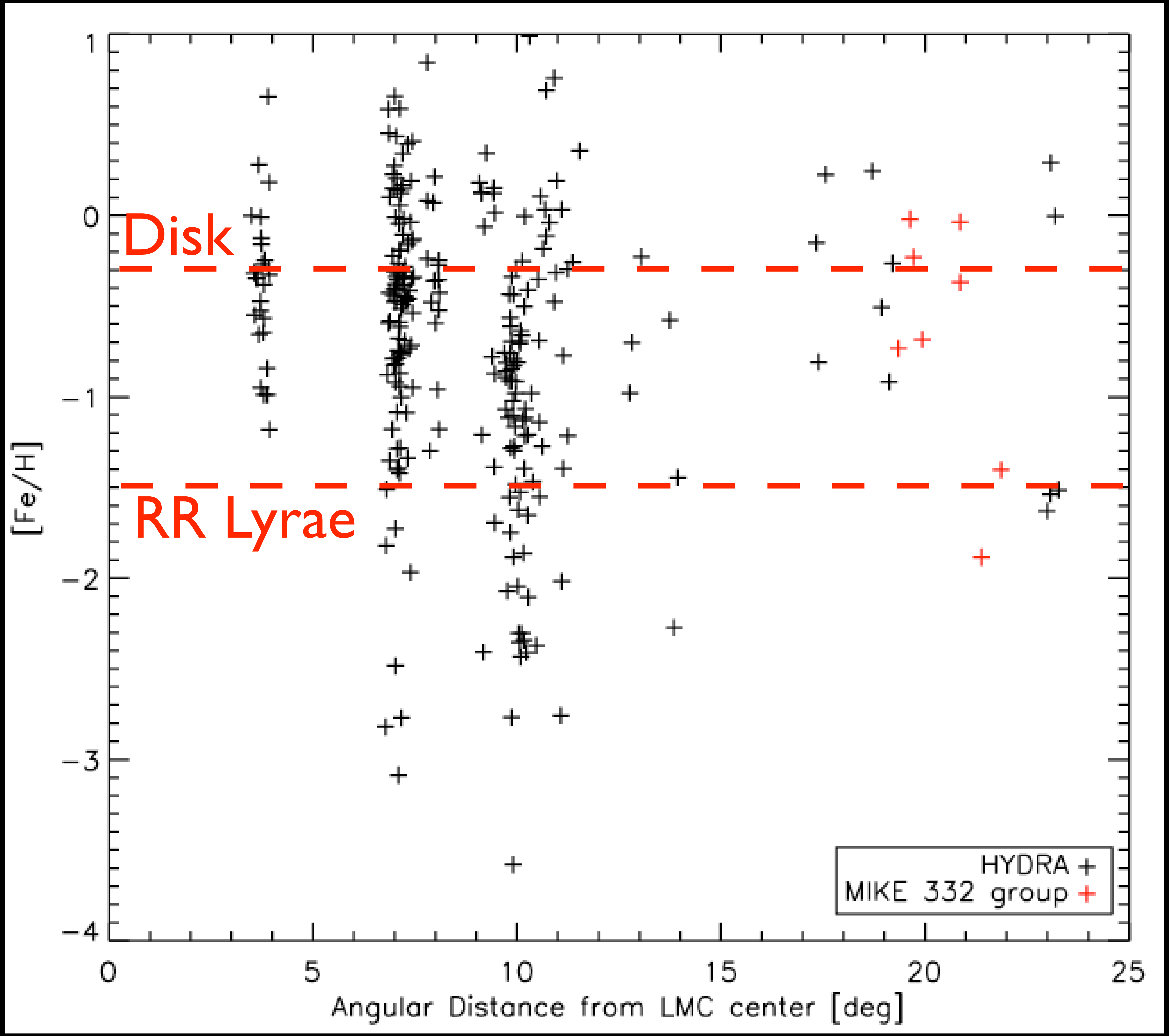
Metallicity



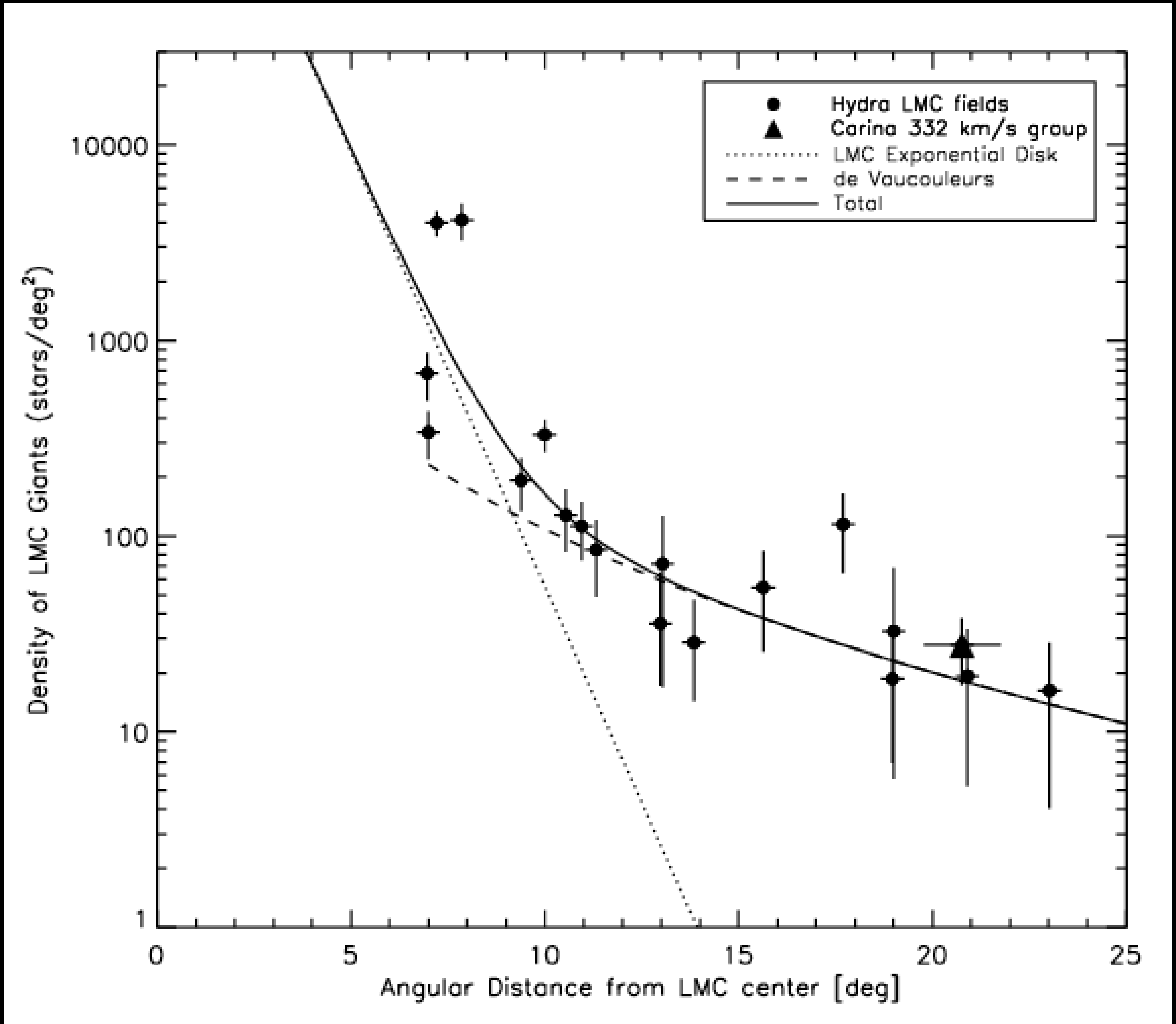
- [Fe/H] from Lick indices
- Relatively metal RICH!
- [Fe/H] = -0.5
- Close to disk metallicity
- Some metal-poor stars

Metallicity



- [Fe/H] from Lick indices
- Relatively metal RICH!
- [Fe/H] = -0.5
- Close to disk metallicity
- Some metal-poor stars

Density Profile

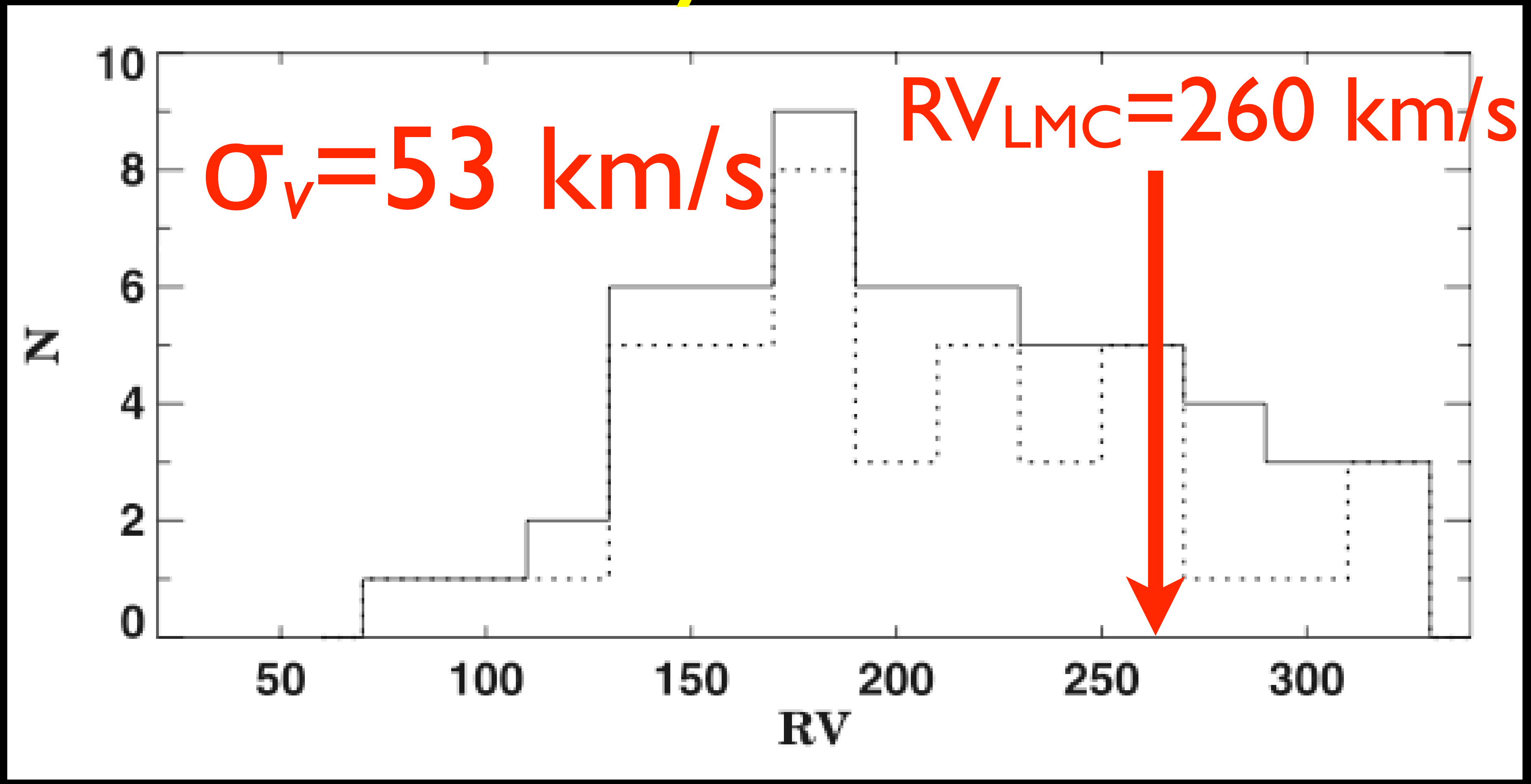


- Spectroscopicaly-corrected density profile
- Using only LMC members. Selected in Velocity, CMD and 2CD
- Well-fit by a de Vaucouleurs profile
- core radius

Old, metal-poor halo from RR Lyrae

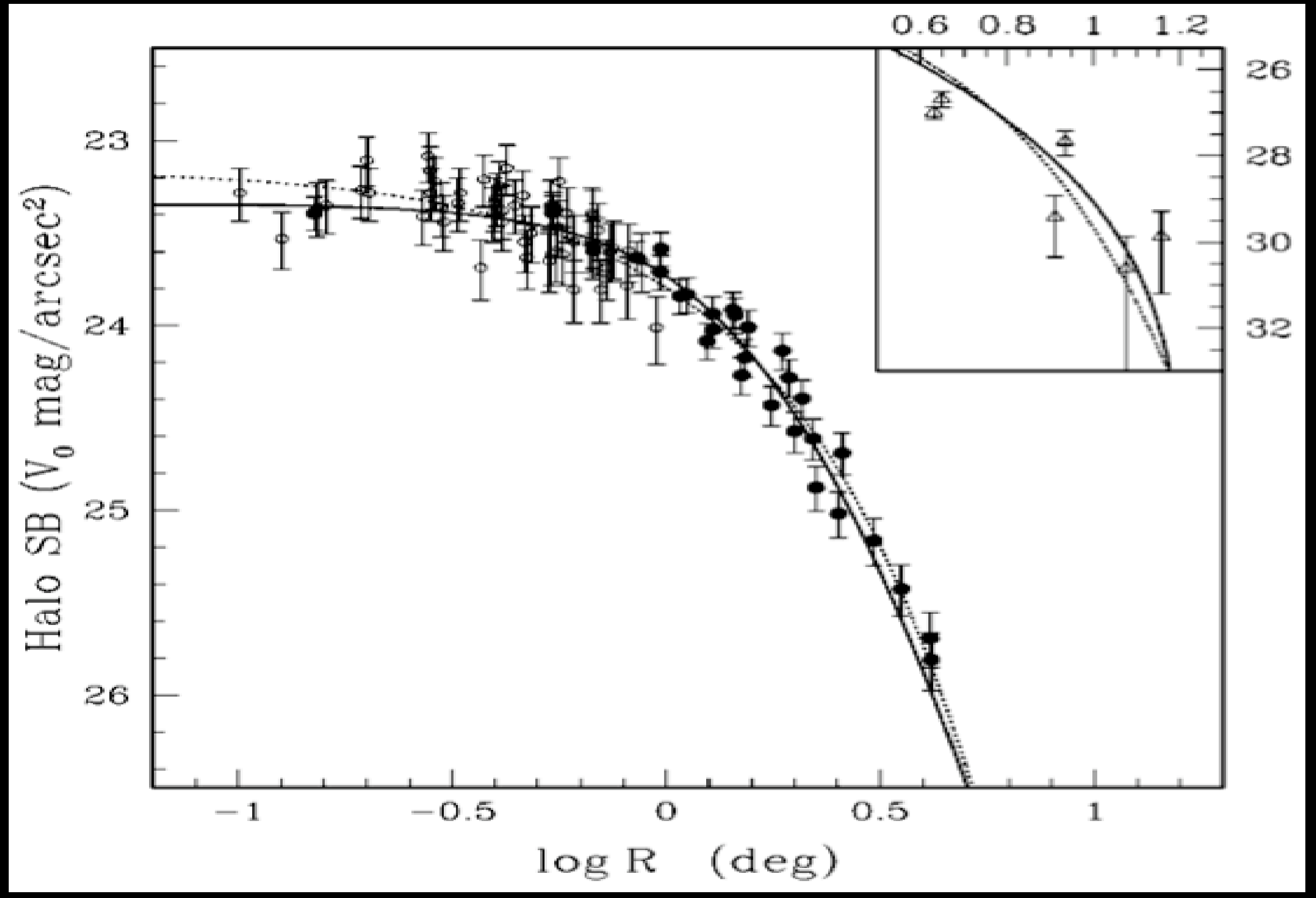
- MACHO and OGLE identified many LMC variables
- RR Lyrae have a large velocity dispersion σ_v=53 km/s (Minniti et al. 2003, Borissova et al. 2004)
- Old, metal-poor halo [Fe/H]= -1.46 +/- 0.09
- Density profile is King or Exponential (Alves 2004)
- scale length = 1.47 kpc
- Same as disk!

RR Lyrae RVs



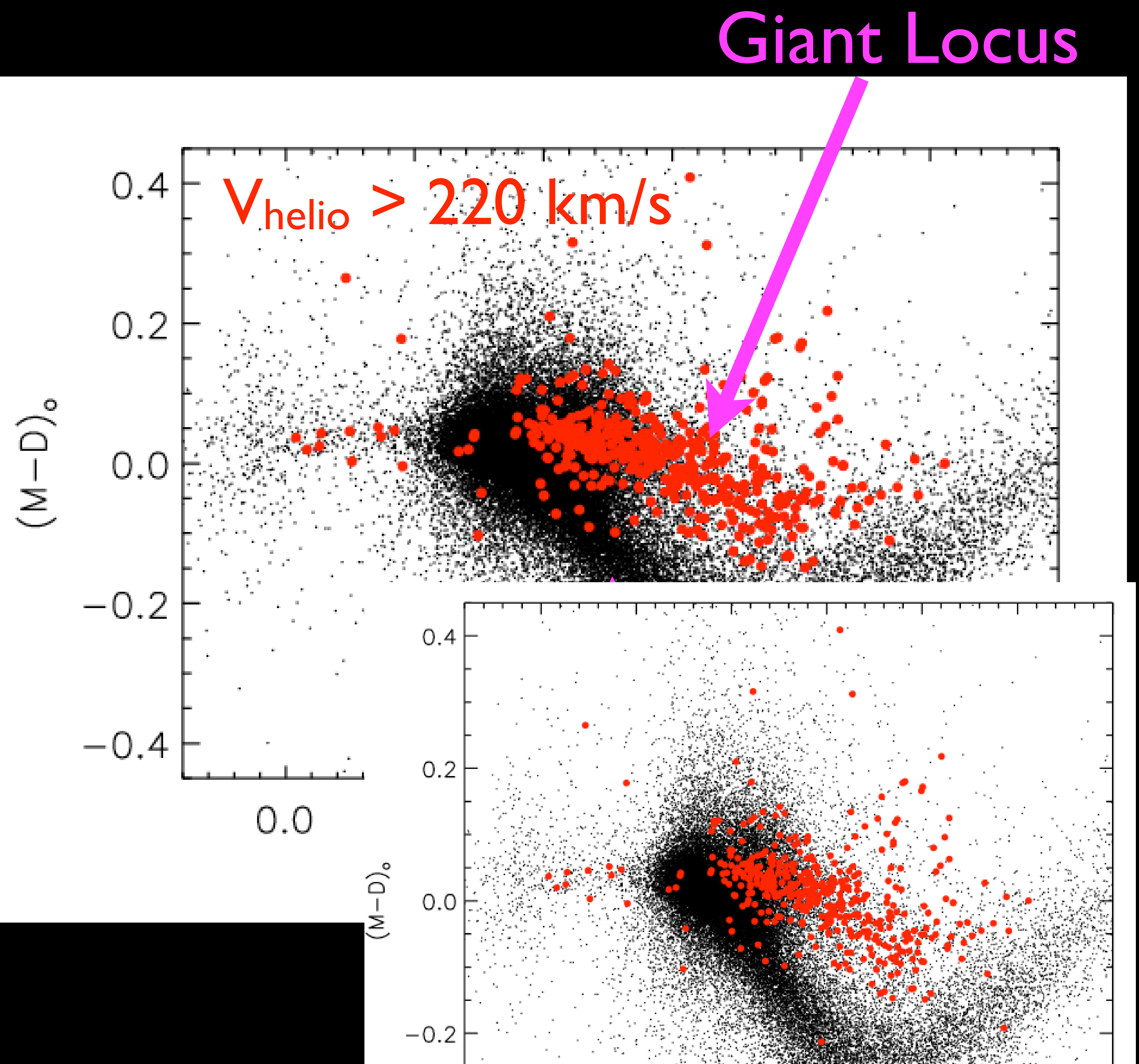
Borissova et al. 2004, A&A, 423, 97

Density Profile

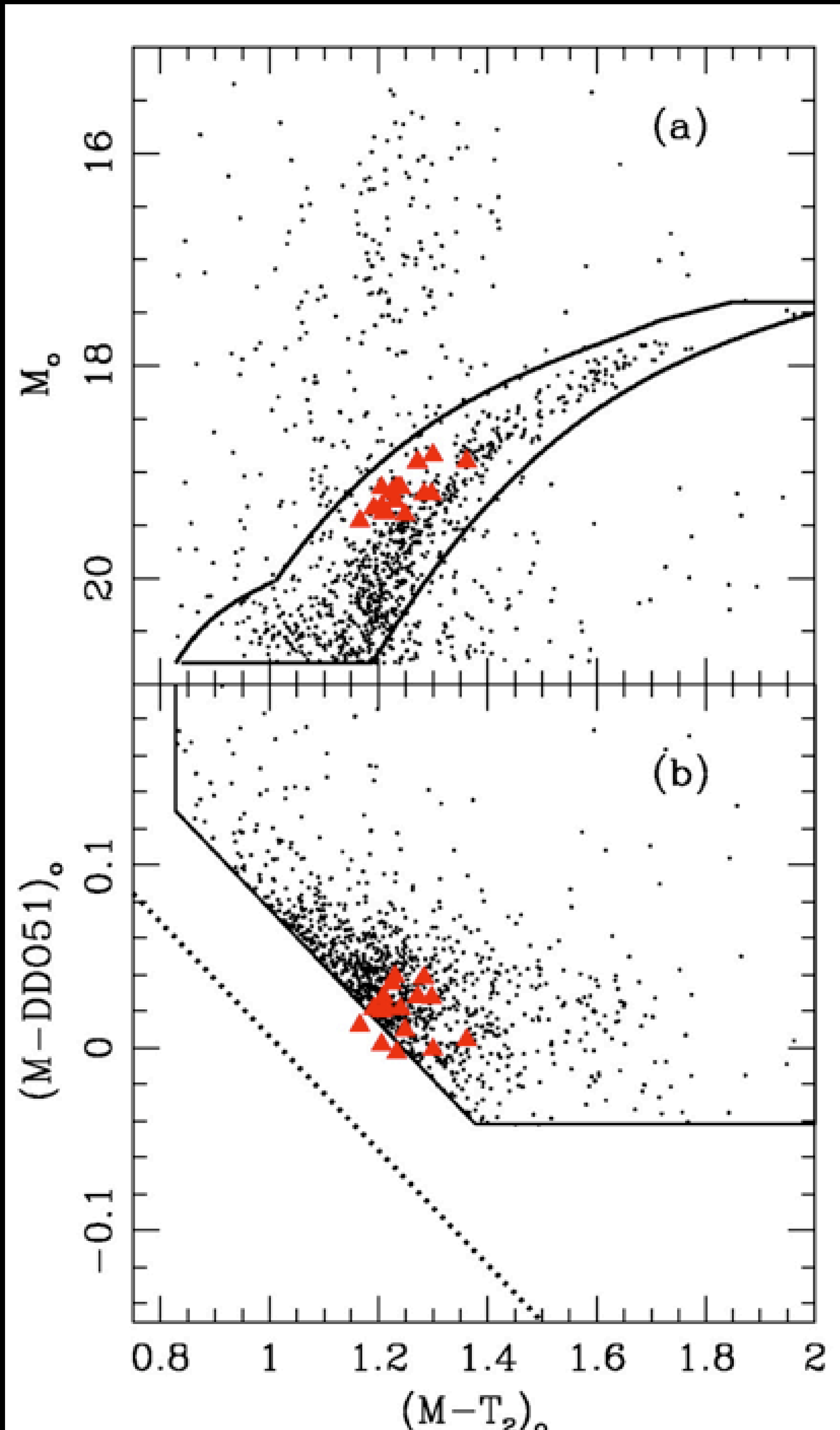


Alves 2004, ApJ, 601, L151

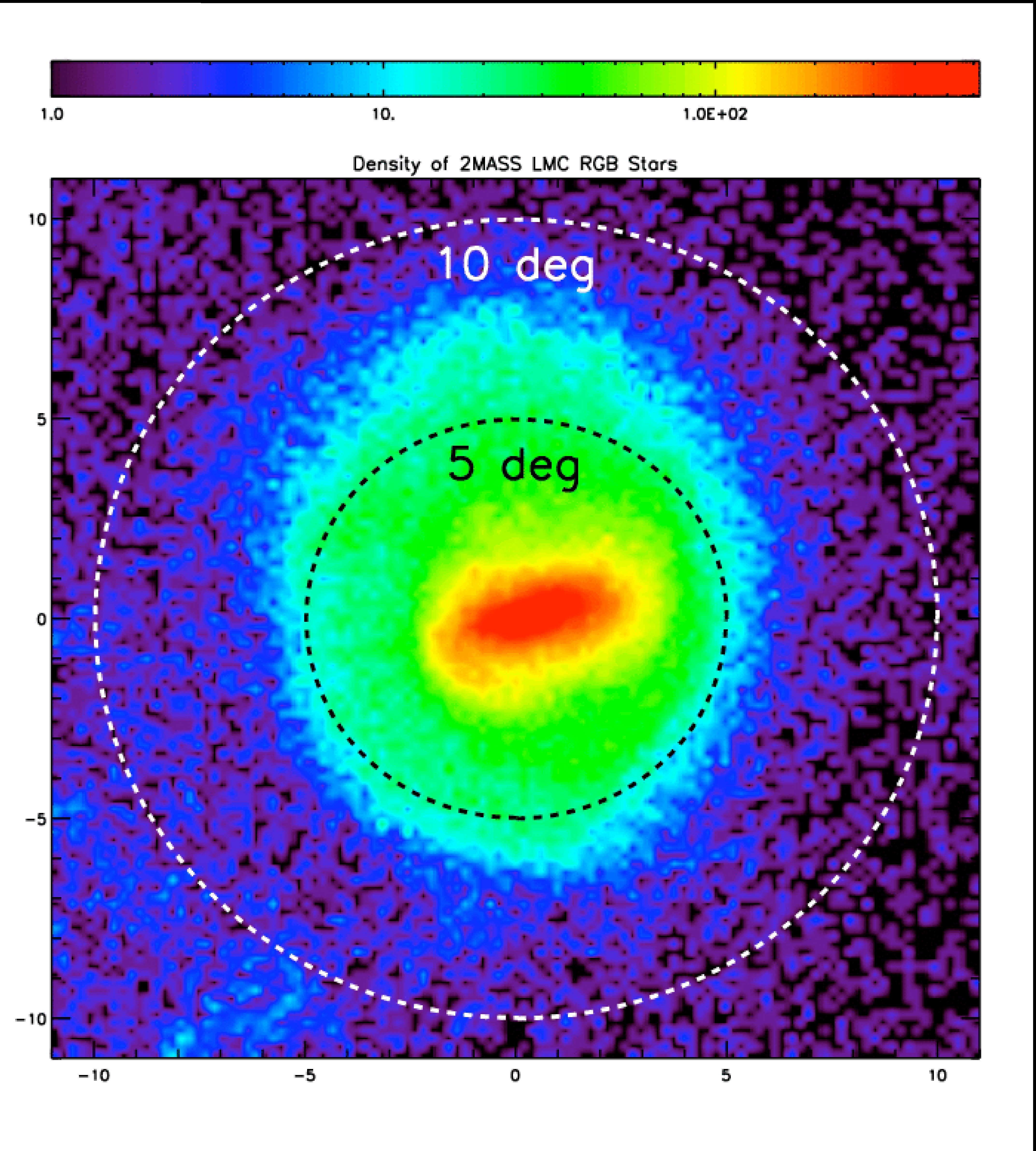
Color-Color Diagram



- Velocity selected LMC stars are consistent with being giants in the Washington color-color diagram which is gravity sensitive


(a)
(b)
M_o
$(M-DDO51)_o$
$(M-T_2)_o$
16
18
20
0.1
0
−0.1
0.8
1
1.2
1.4
1.6
1.8
2

Previous Work



- Magellanic Clouds Photometric Survey (MCPS).
- van der Marel 2001, out to 8 deg
- Alves & Nelson 2000
- Minniti et al. 2003 discover old, metal-poor stellar halo of LMC using RR Lyrae stars.
- Alves 2004 fits a King profile to RR Lyrae stars to R=15 kpc
- Harris 2007, exponential disk to R=11 kpc