Examining Galaxy Formation and Evolution with the Milky Way and Its Massive Satellites

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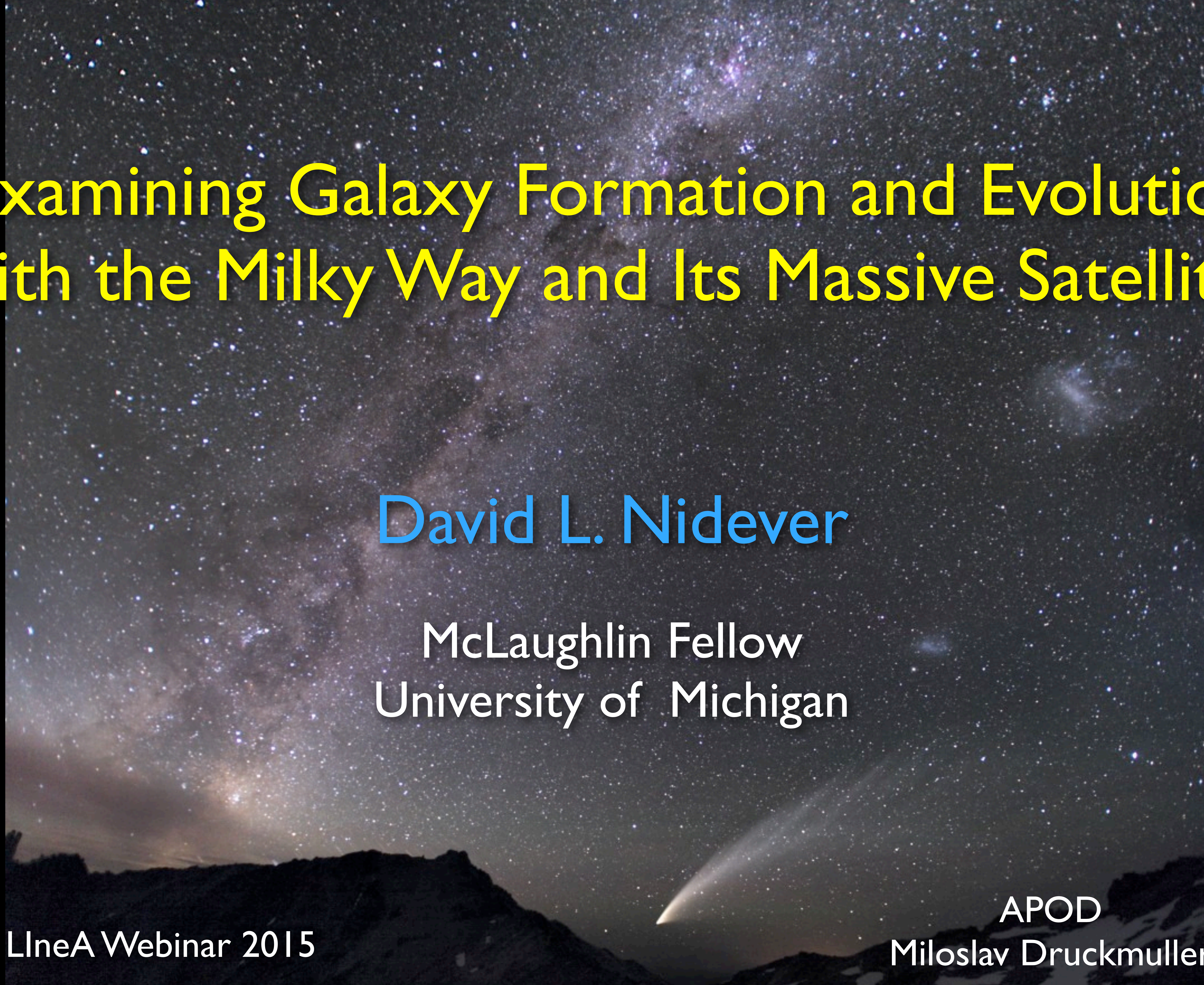
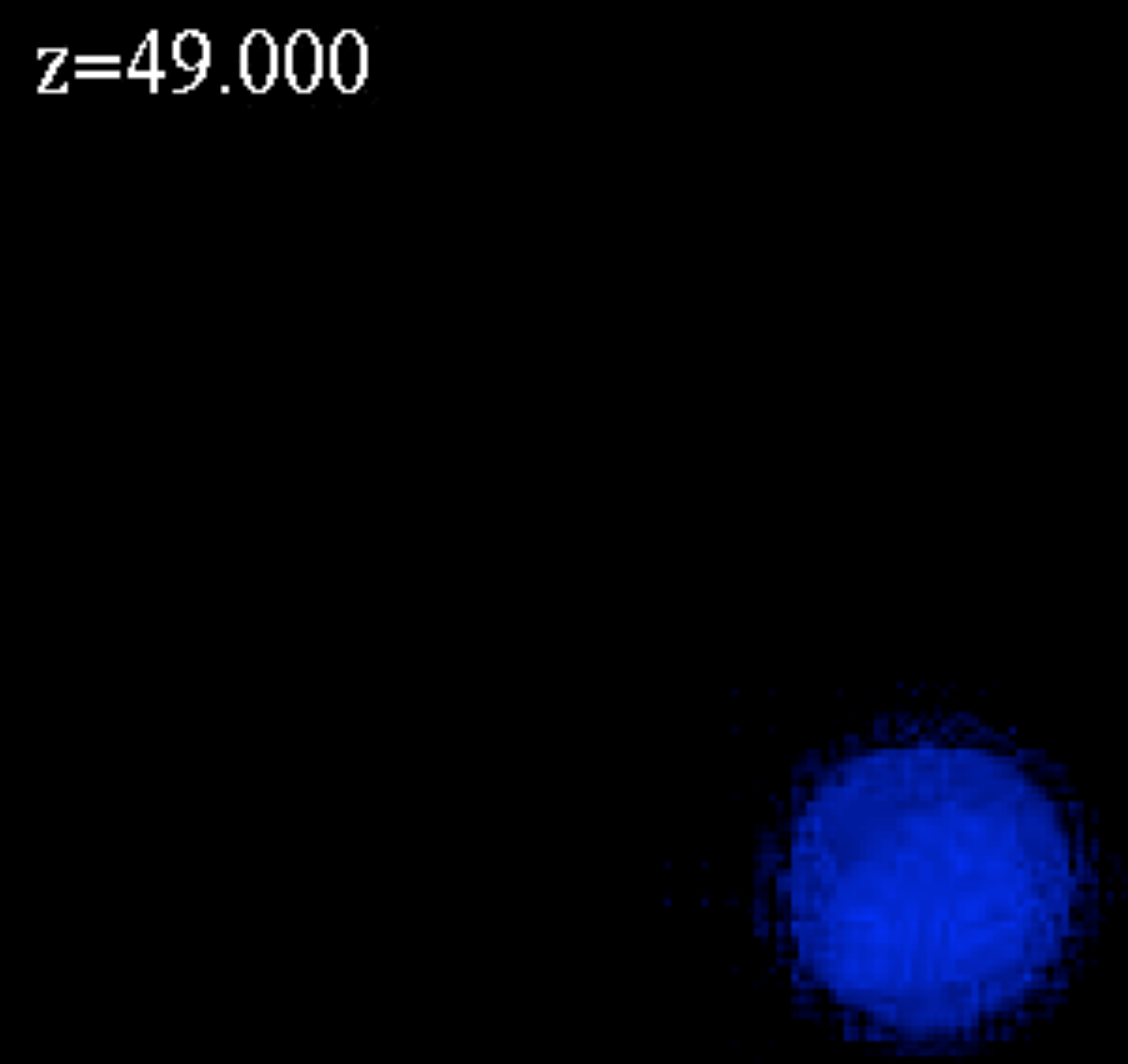


LIneA Webinar 2015

APOD
Miloslav Druckmuller

Introduction: Galaxy Formation



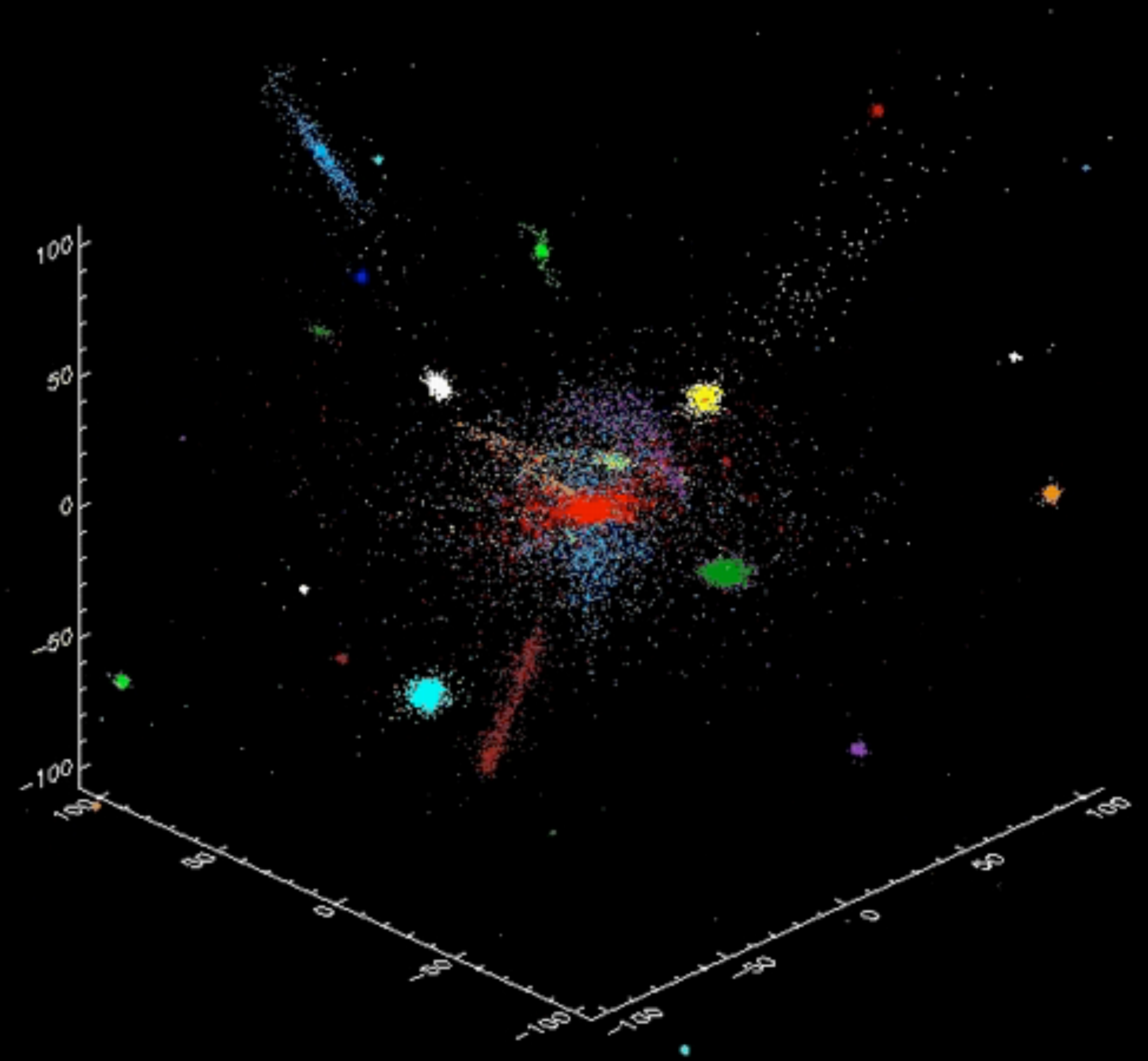
ΛCDM Simulation
By Ben Moore
University of Zurich

Including Baryons

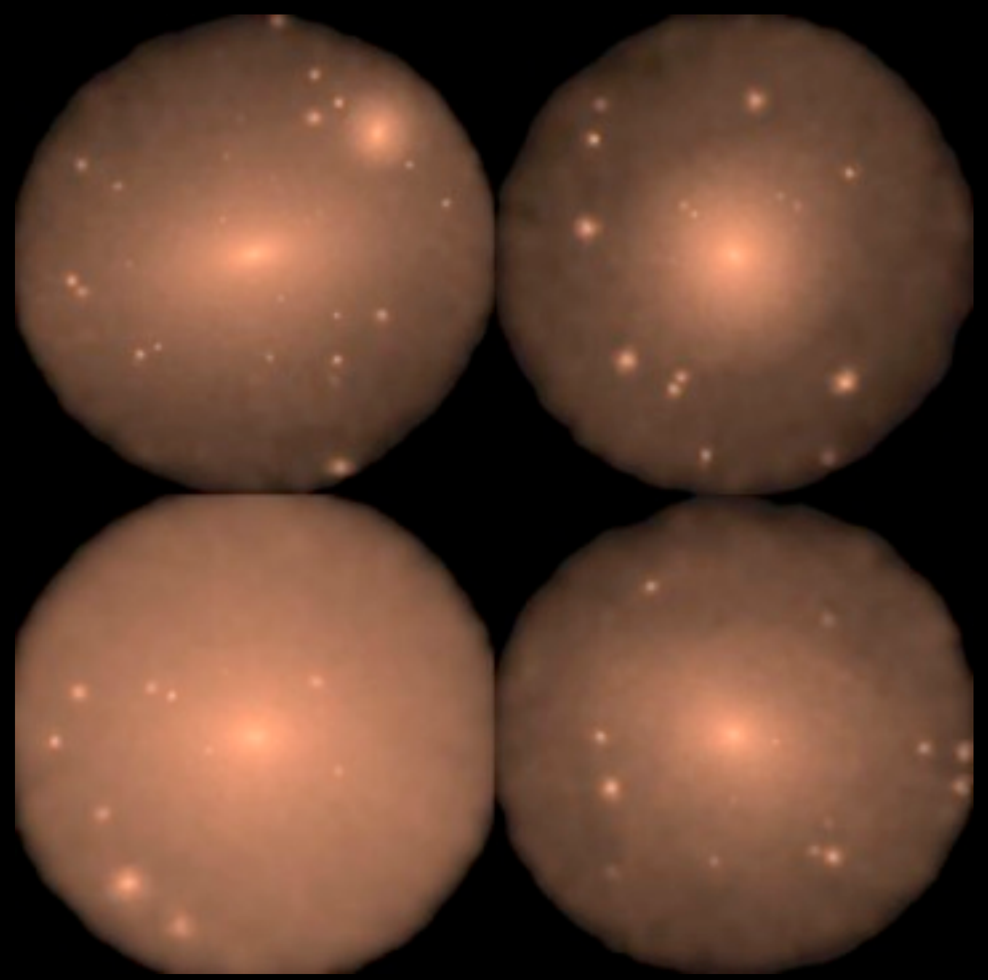
gas
young stars
old stars
DM not shown

Courtesy of S. Loebman
Using Alyson Brooks/Charlotte Christensen simulation (Christenson et al. 2012)

Predictions



Animation by James Bullock (UC-Irvine) & Kathryn Johnston (Wesleyan)



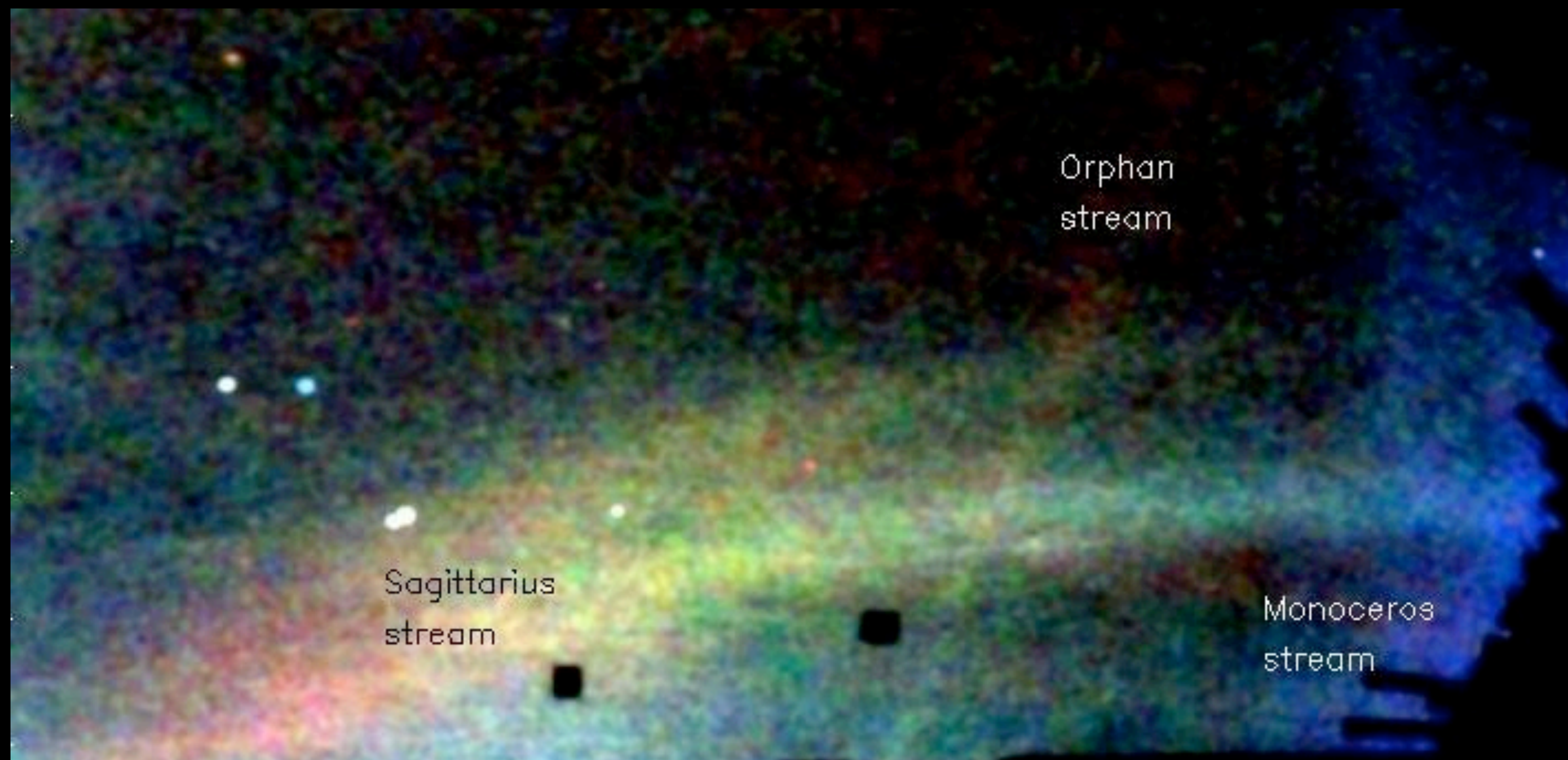
MW subhalos with subhalos in Via Lactea simulation Diemand et al. (2007)

- Disks form inside-out
- Galaxies have stellar halos
- Stellar streams in the galactic halo
  - kinematically cold
  - chemically distinct
- Substructure should occur on all scales
- Gaseous infall helps fuel star formation

Observations

The hierarchical model has been validated by the discovery of multiple streams in the MW halo and other galaxies

Field of Streams

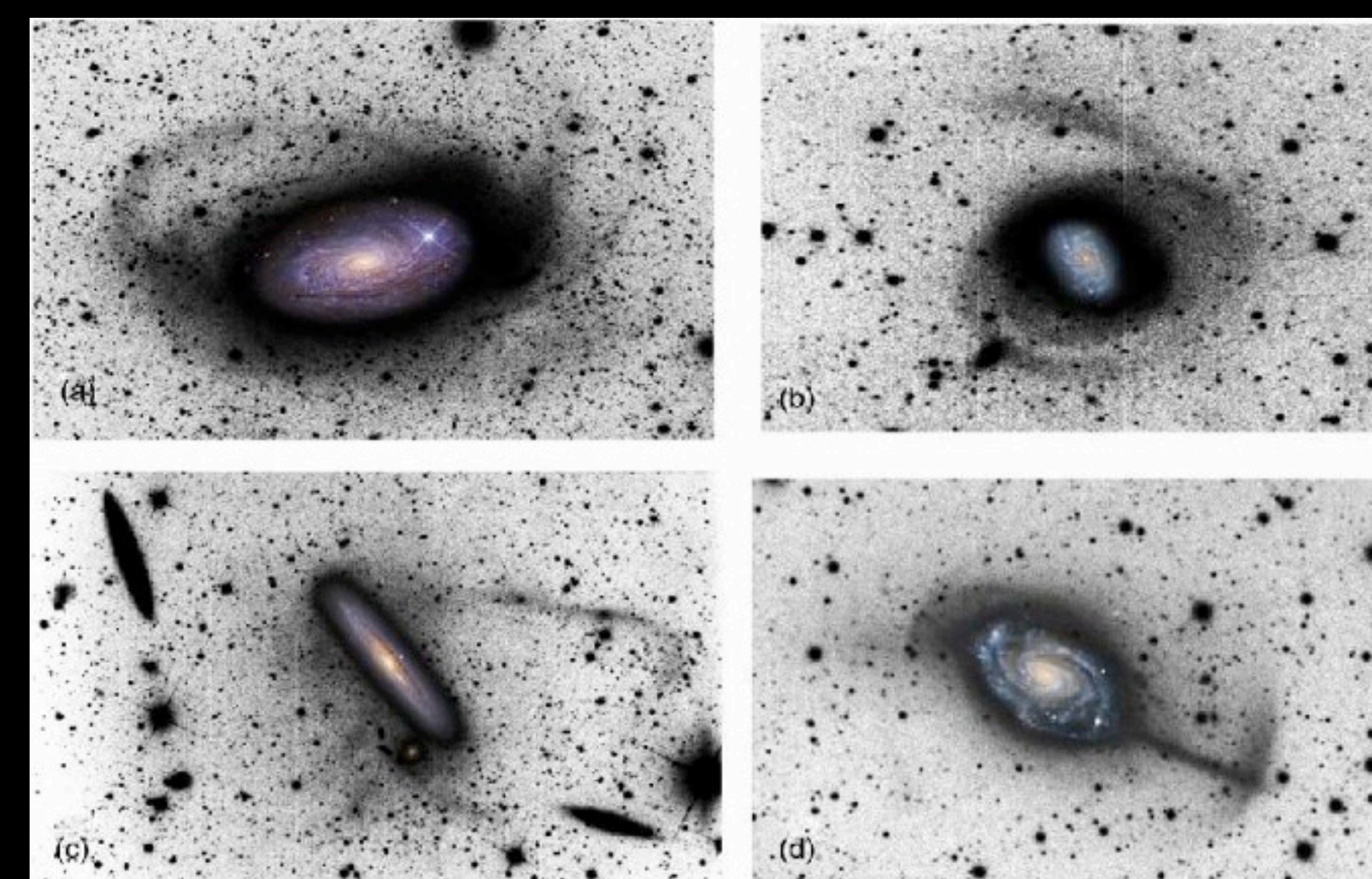


by V. Belokurov

Magellanic Stream

Nidever et al. (2010)

Streams Around External Galaxies



Martinez-Delgado et al. (2010)

The Importance of the Local Group/Universe

Hubble Ultra-Deep field

Important Galactic Evolution Regimes to Explore

1. The Milky Way disk and bulge
   - Study chemodynamical evolution and investigate earliest accretion events
   - Difficult to study because of extinction
   - Explore with NIR spectra, kinematics and chemistry

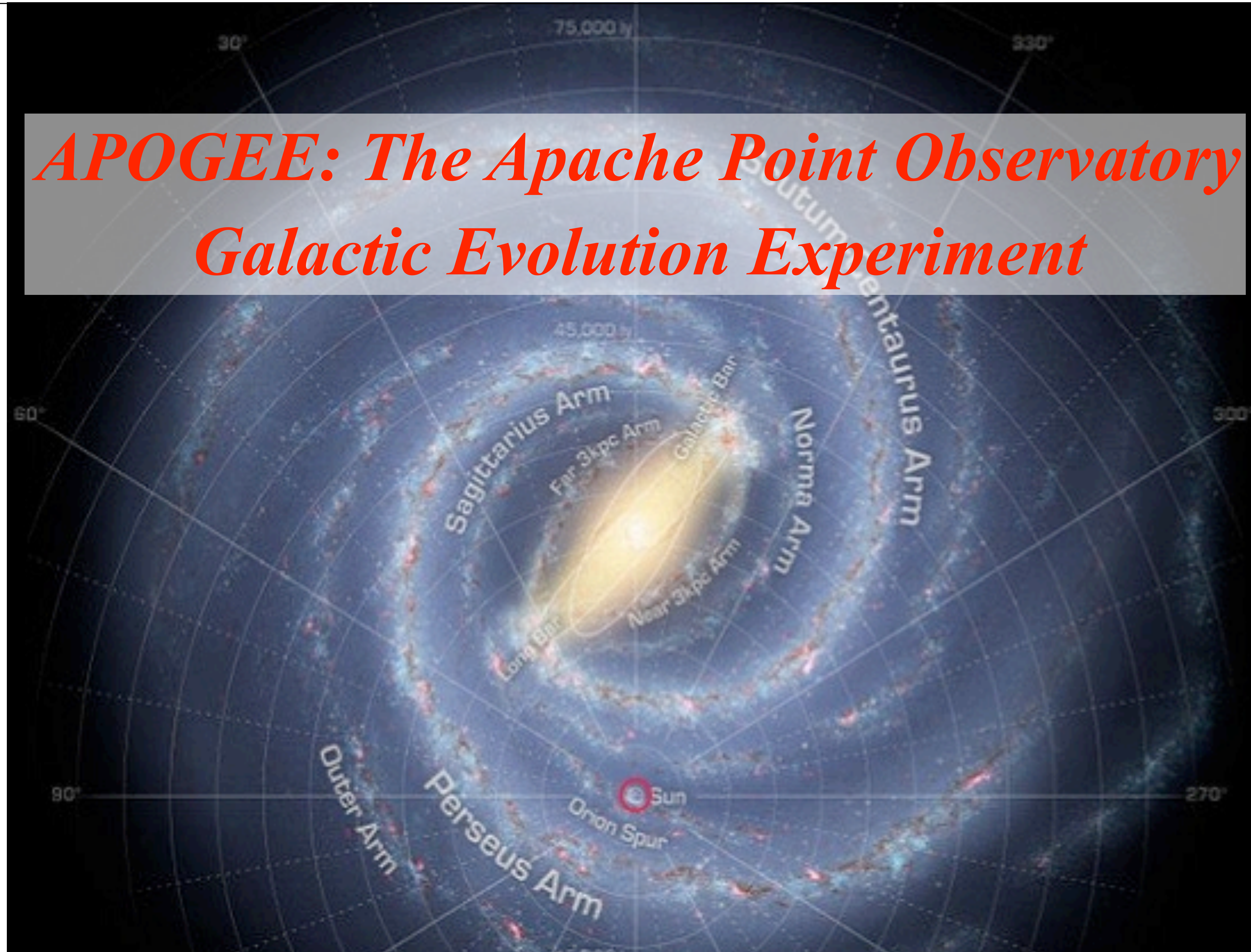
Important Galactic Evolution Regimes to Explore

1. The Milky Way disk and bulge
   - Study chemodynamical evolution and investigate earliest accretion events
   - Difficult to study because of extinction
   - Explore with NIR spectra, kinematics and chemistry
2. Stellar halos and streams in Dwarf Galaxies
   - Should see substructure on all scales
   - The Magellanic Clouds, good local laboratory to study dwarf galaxies

Outline

1. APOGEE
2. Magellanic Steller Periphery

APOGEE: The Apache Point Observatory Galactic Evolution Experiment



Evolution of the Milky Way

- Use MW as prototype to understand galaxy formation and evolution, can study in great detail
- Study the chemistry and kinematics throughout the disk
- Outstanding questions:
  - How did our Galaxy form?
  - What is the MW's star formation history?
  - Chemical and dynamical evolution?
- Most past samples very local
- APOGEE allows us to probe most of the galaxy, see through dust
- Constrain chemical/dynamical evolution models

Galactic Archaeology

Heyday for Galactic chemistry and archaeology studies

Current (R>20,000)

Name	Years	Nstars	λ	Depth	Telescope	N/S
APOGEE	2011-14 2014-19	10^5 $\sim 4 \times 10^5$	NIR	H<12.5	APO APO/LCO	N N/S
Gaia-ESO	2011-16	10^5	optical	V<19	VLT	S
GALAH	2014-17?	10^6	optical	V<14	AAT	S

Future (R>20,000)

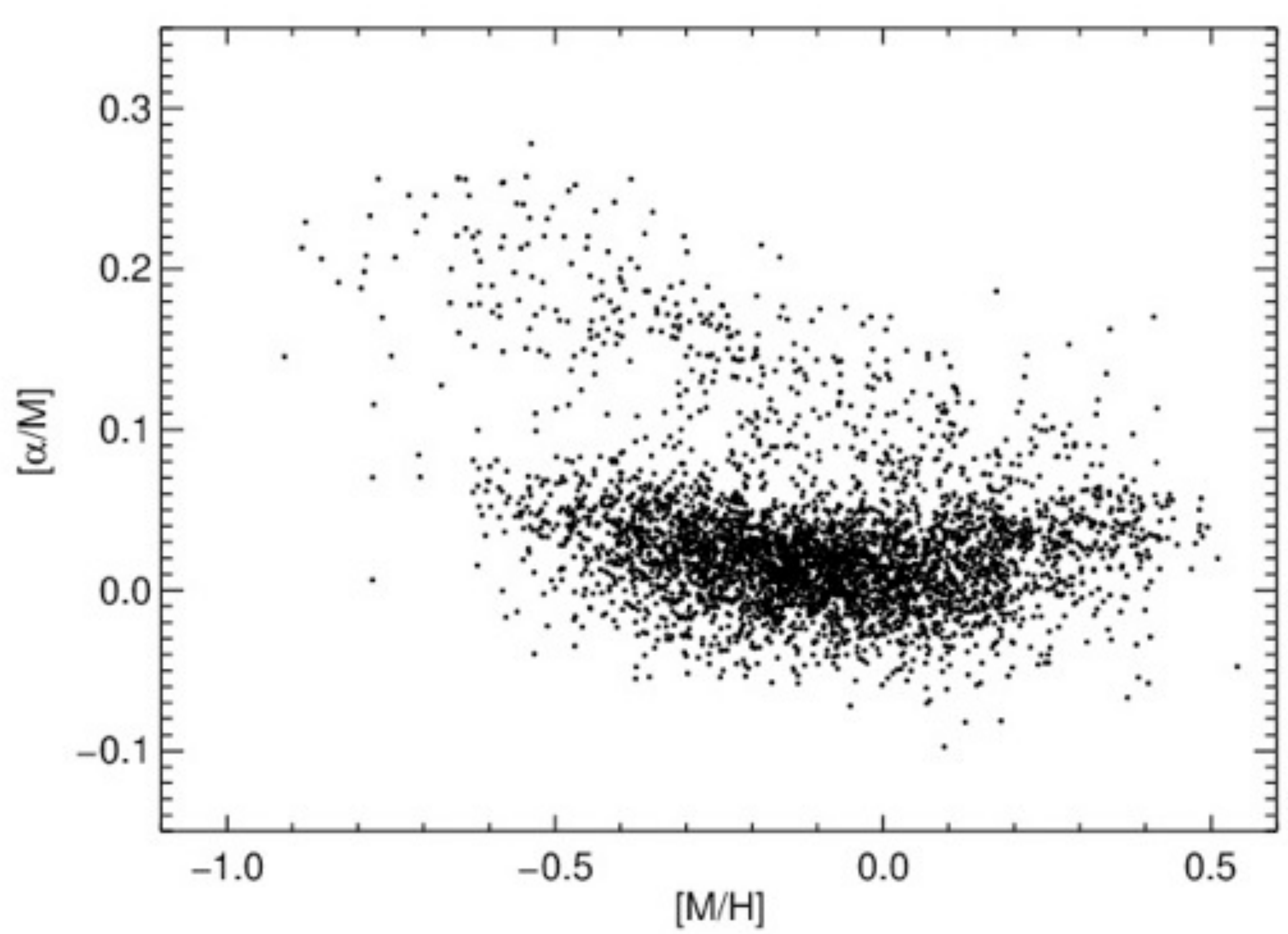
WEAVE	2018	5×10^4	optical	V<18	VHT	N
MOONS	2019	$\sim 2 \times 10^6$	NIR	H<15.5	VLT	S
4MOST	2019	2×10^6	optical	V<16	VISTA	S
MSE	2021	$\sim 2 \times 10^6$	optical	V<19	CFHT	S

APOGEE Overview

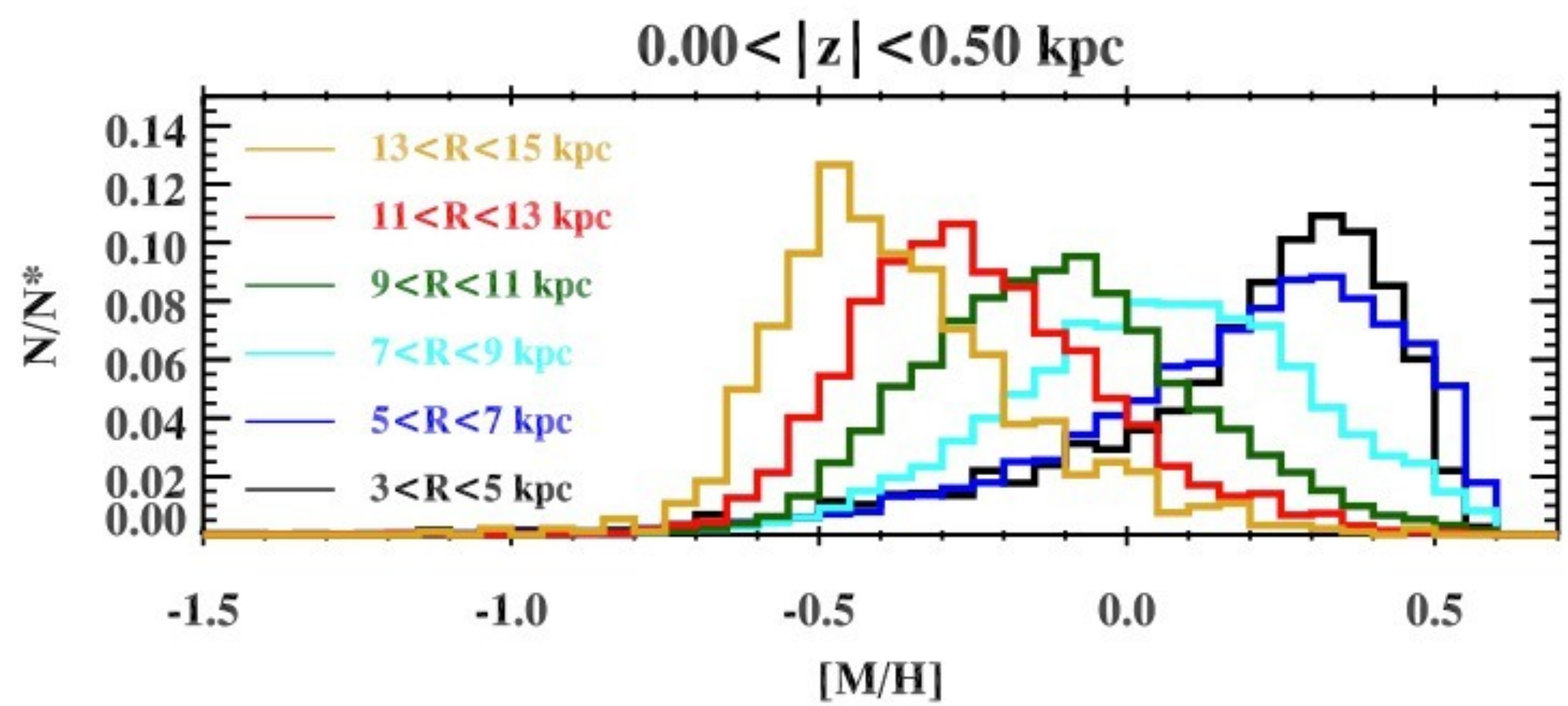
- Part of Sloan Digital Sky Survey (SDSS)-III
- 300 fiber, $R \geq 22{,}500$, cryogenic spectrograph
- H-band: 1.51-1.68μ ($A_H / A_V \sim 1/6$)
- S/N = 100/pixel @ H=12.2 for 3-hr total integration
- RV uncertainty ~0.1 km/s
- 0.1 dex precision abundances for ~15 chemical elements

  (including Fe, C, N, O, α-elements, odd-Z elements, iron peak elements, possibly even neutron capture)
- 100,000+ 2MASS-selected giant stars across all Galactic populations.
- APOGEE-1 is finished! First year of APOGEE-2 almost done.

Tracing Chemical Evolution Over the Extent of the Milky Way's Disk with APOGEE Red Giant Stars



Nidever et al. (2014)

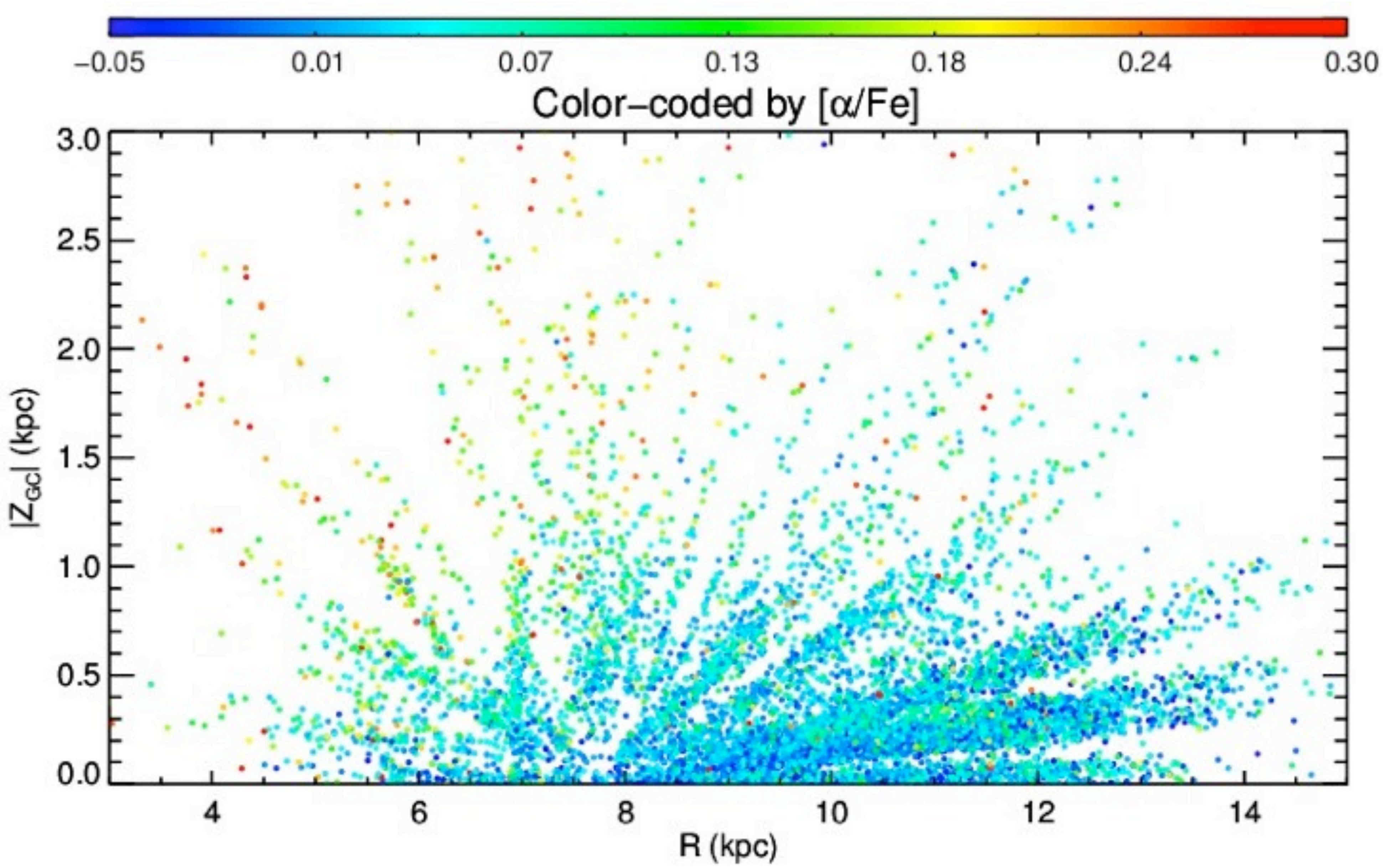


Hayden et al. (2015)

Brief Disk Background

- Classically two disk components:
  - Thick disk: older, high [α/Fe] , larger h_z, high σ_z
  - Thin disk: younger, low [α/Fe] small h_z, low σ_z
- But they might not be so "distinct" (e.g. Bovy et al. 2012b)
- Origin of disk variation unclear
  - Major merger puffing older stars up
  - Disk formed "hot" and settled/cooled over time

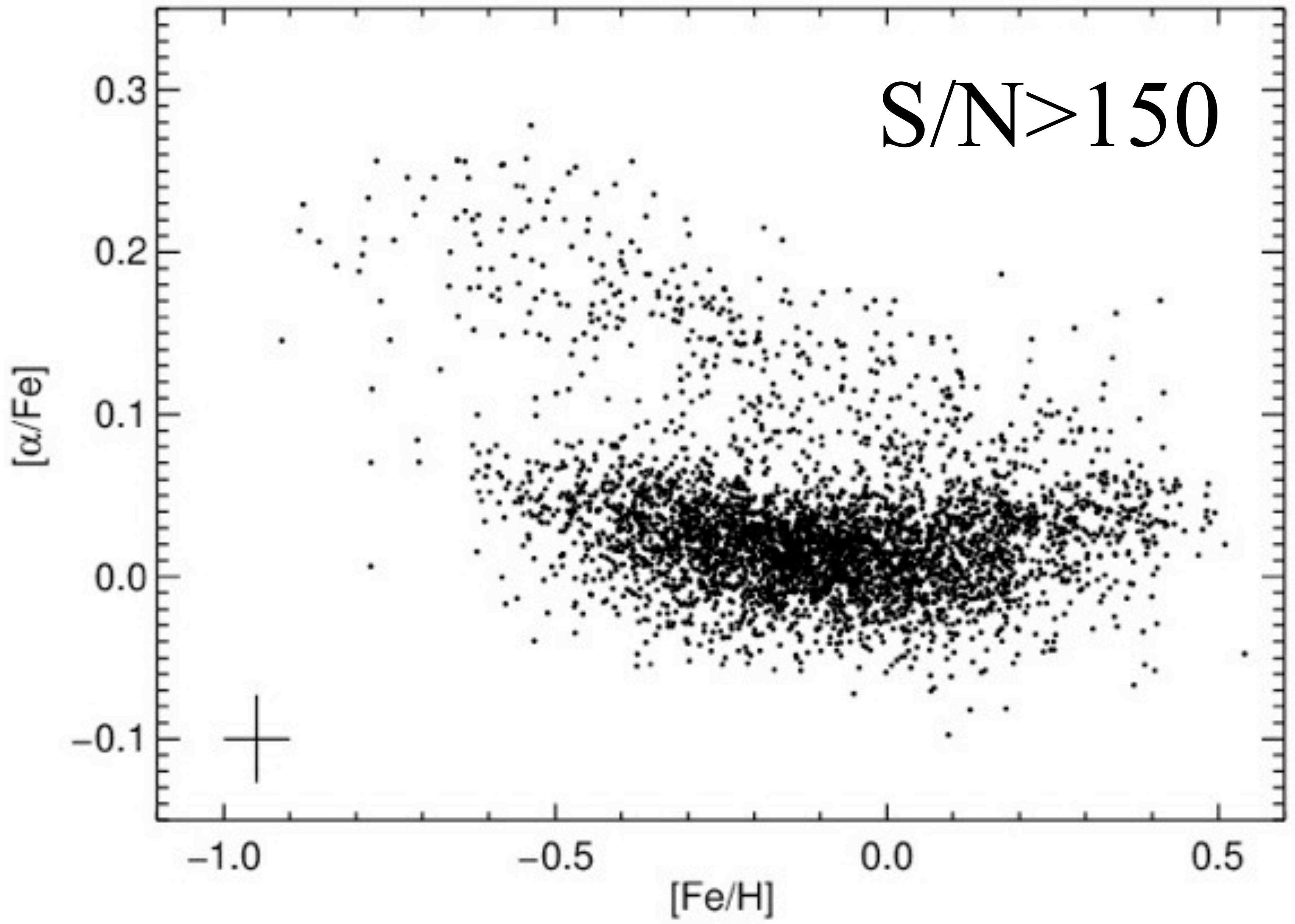
APOGEE Red Clump Stars

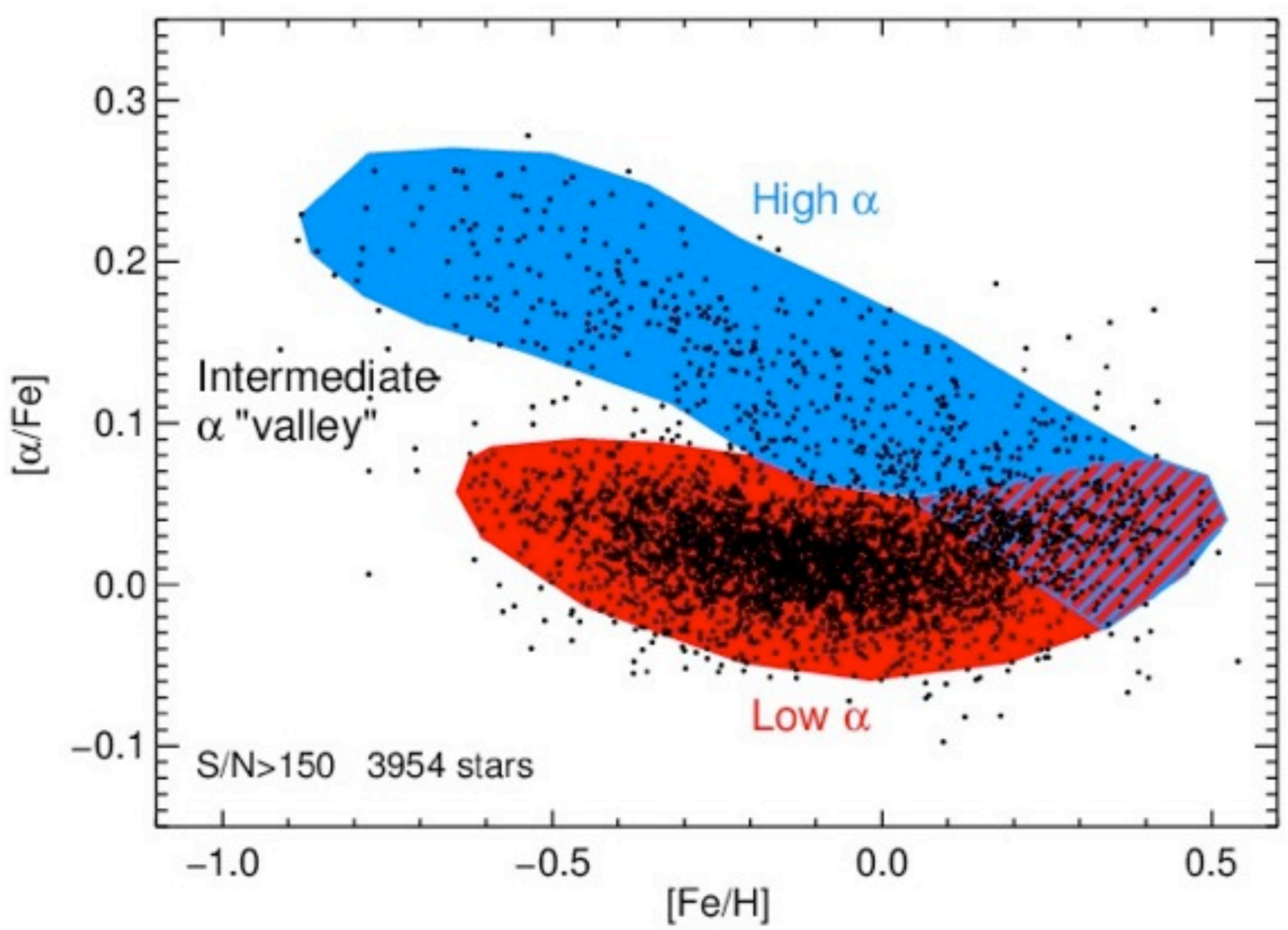


- Use α-element abundances of the red clump catalog (Bovy, Nidever et al. 2014)
- ~10,000 RC stars (~20,000 in DR12)
- Standard candles, accurate distances (~5%)
- Most stars within ~4 kpc of the sun

Use APOGEE to explore chemical abundances through the MW disk

Abundance Features



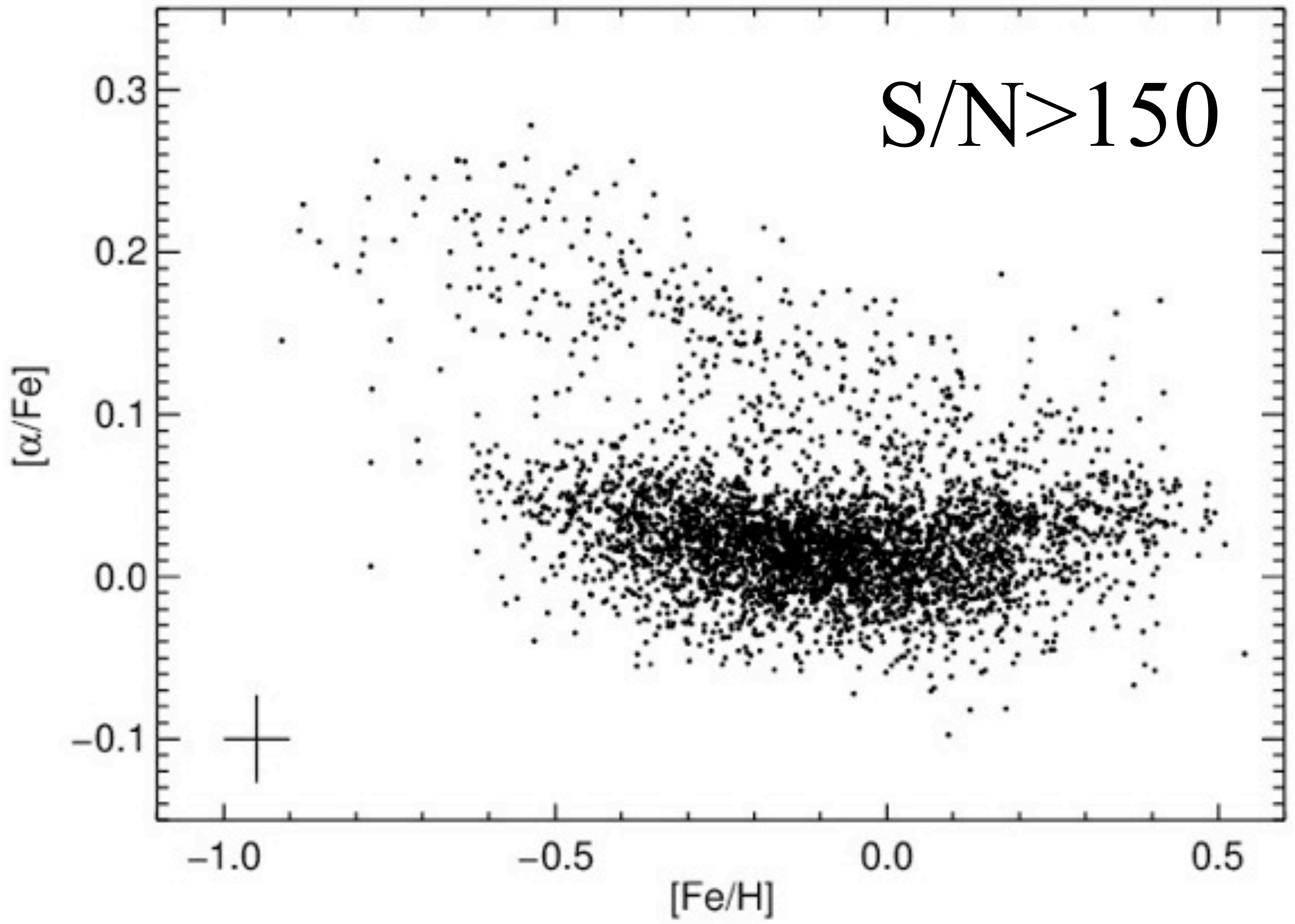


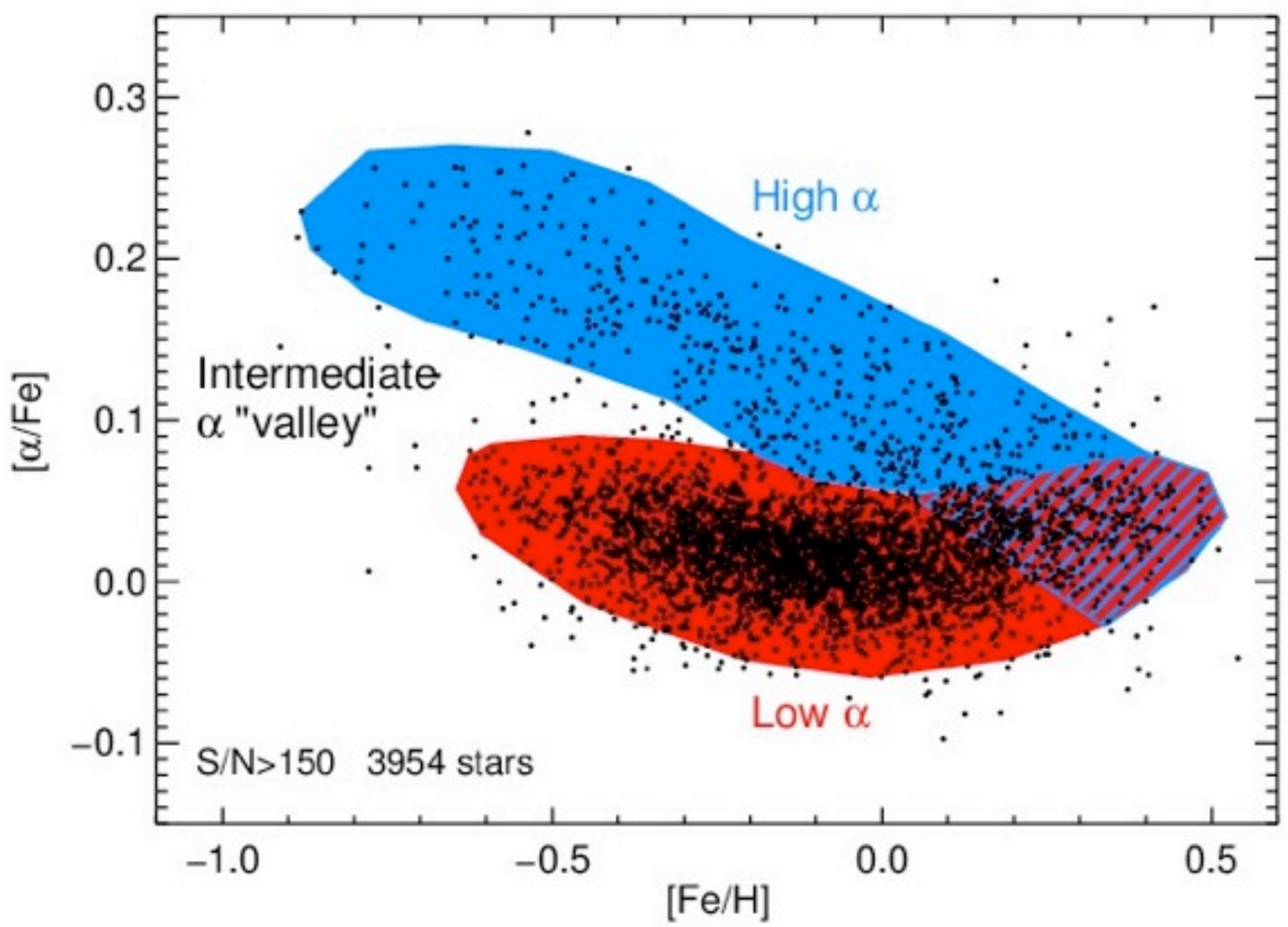
Qualitative Features

1. α-bimodality at intermediate metallicity
2. Merging of two α groups at [Fe/H]~+0.2
3. Valley between groups not empty

Nidever et al. (2014)

Abundance Features





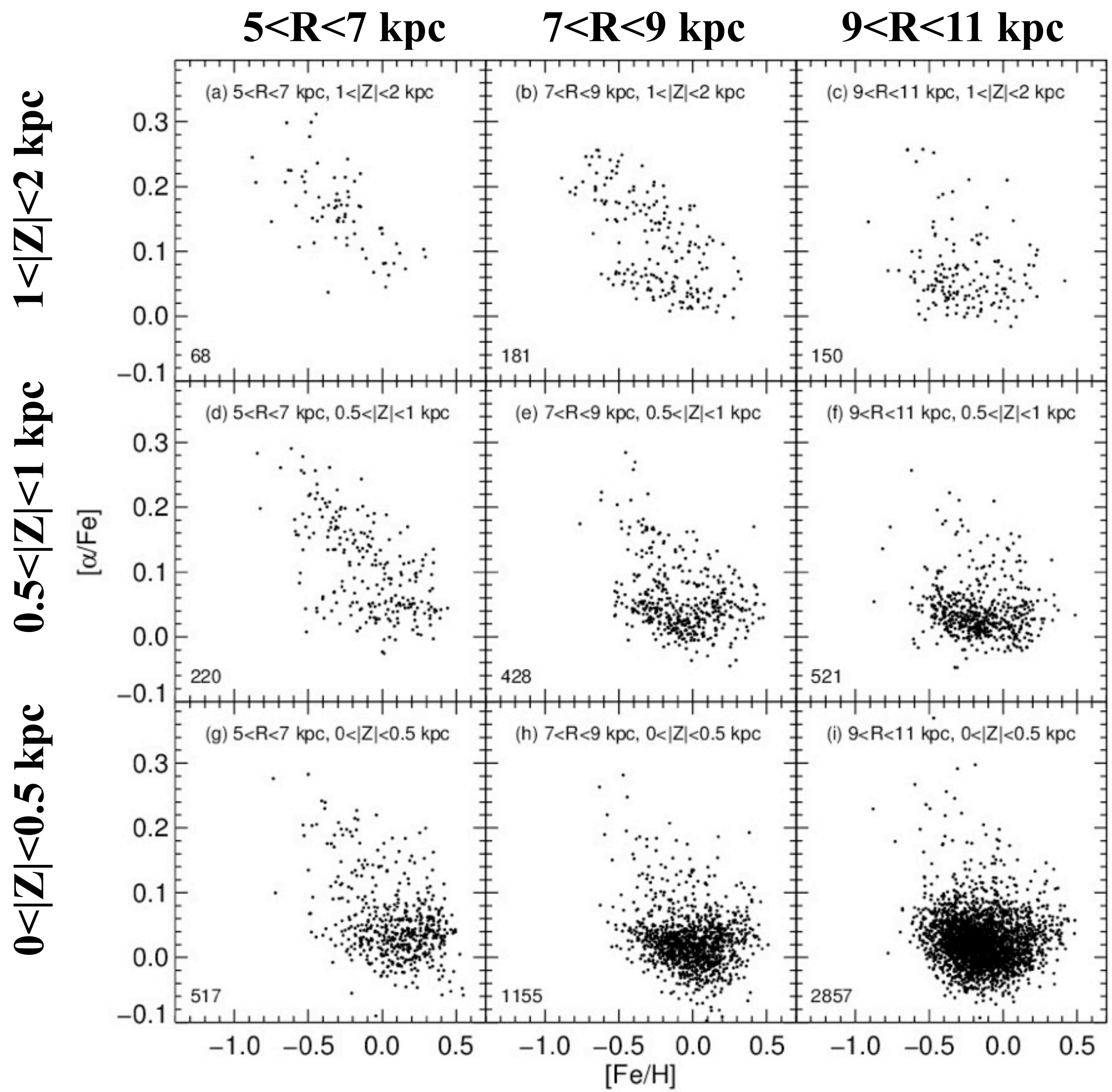
Qualitative Features

1. α-bimodality at intermediate metallicity
2. Merging of two α groups at [Fe/H]~+0.2
3. Valley between groups not empty

- Selection effects have little impact on overall abundance *patterns*

Nidever et al. (2014)

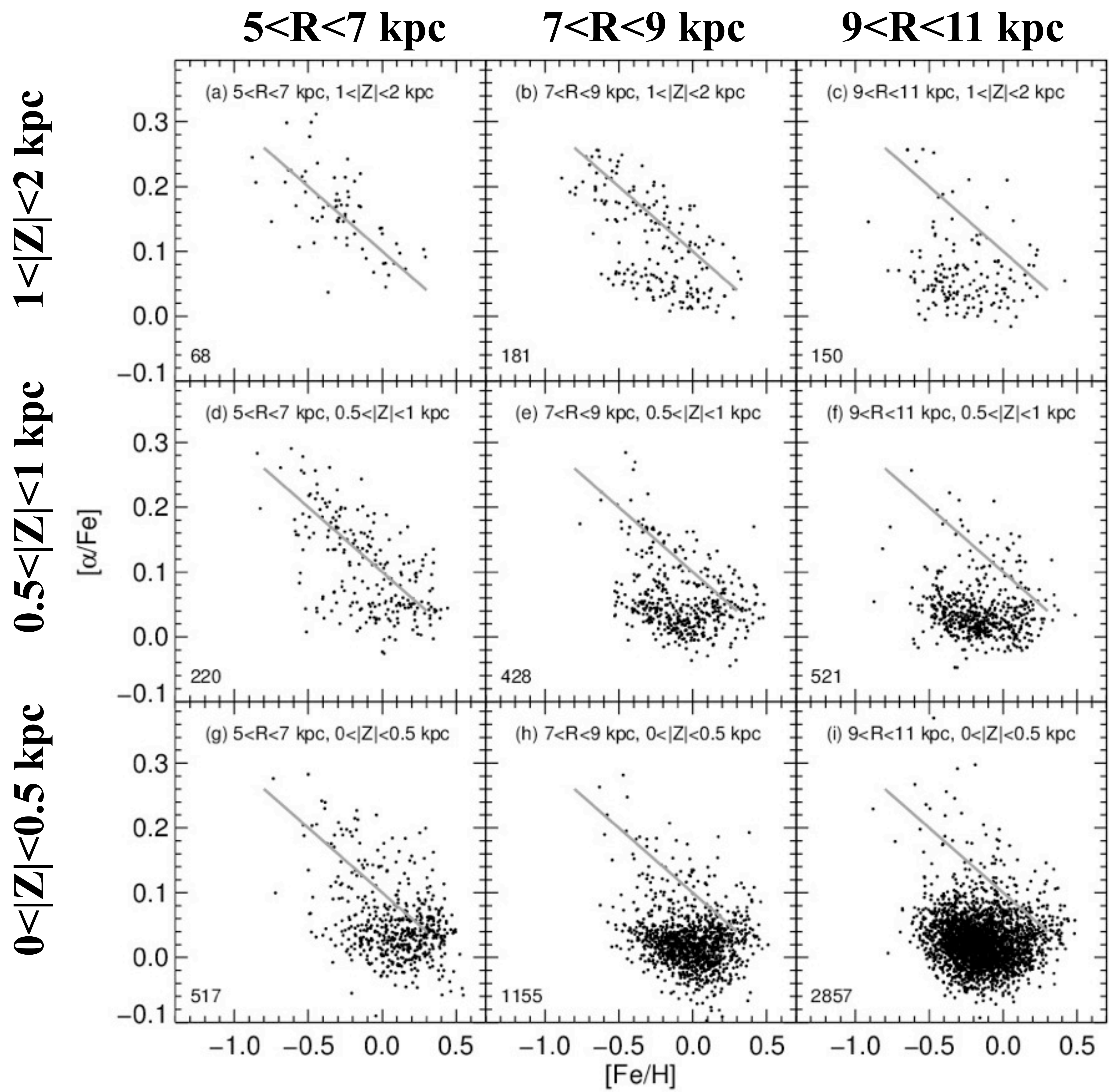
Chemical Cartography



- Chemical cartography
- Look at abundance patterns across the MW disk

Nidever et al. (2014)

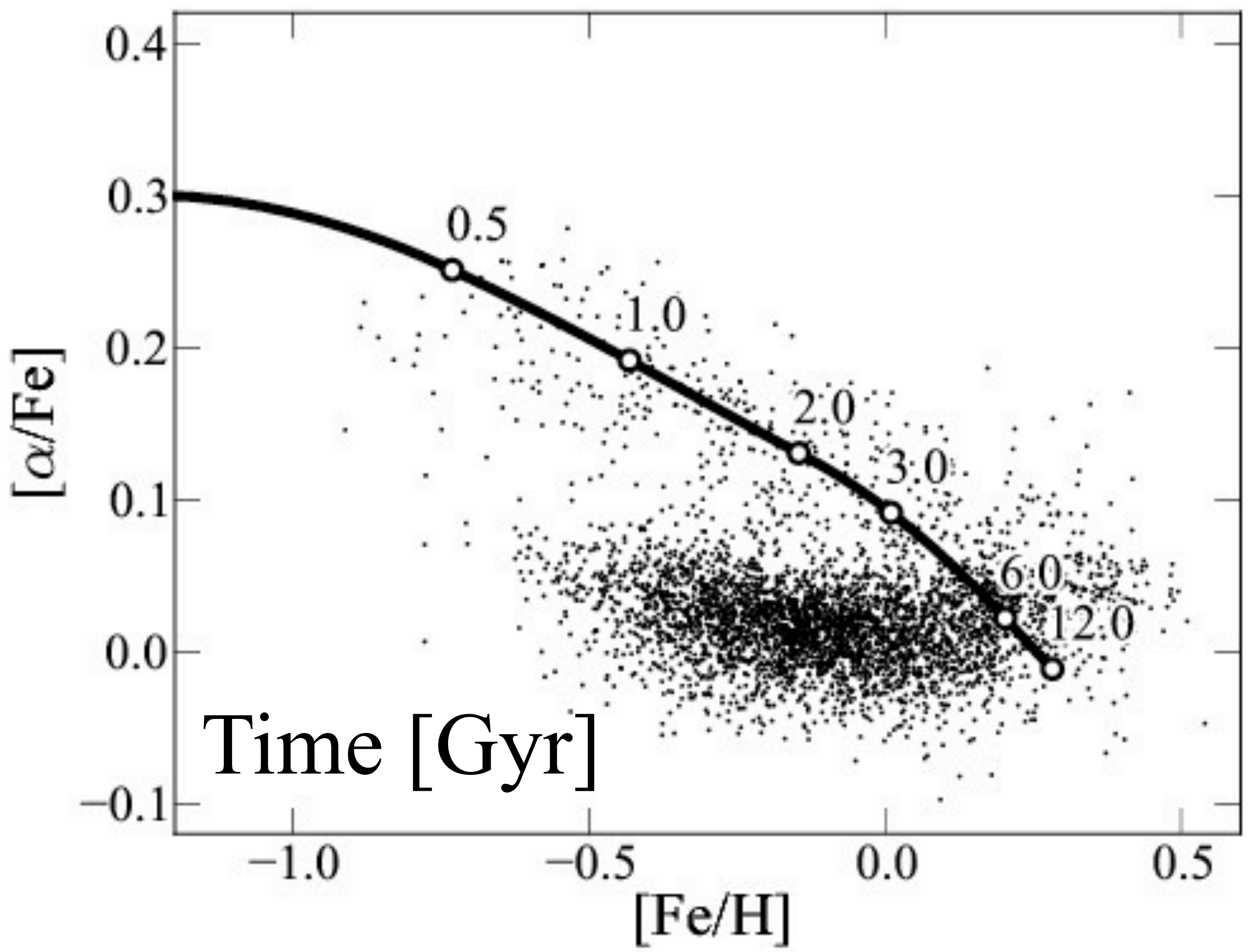
Chemical Cartography

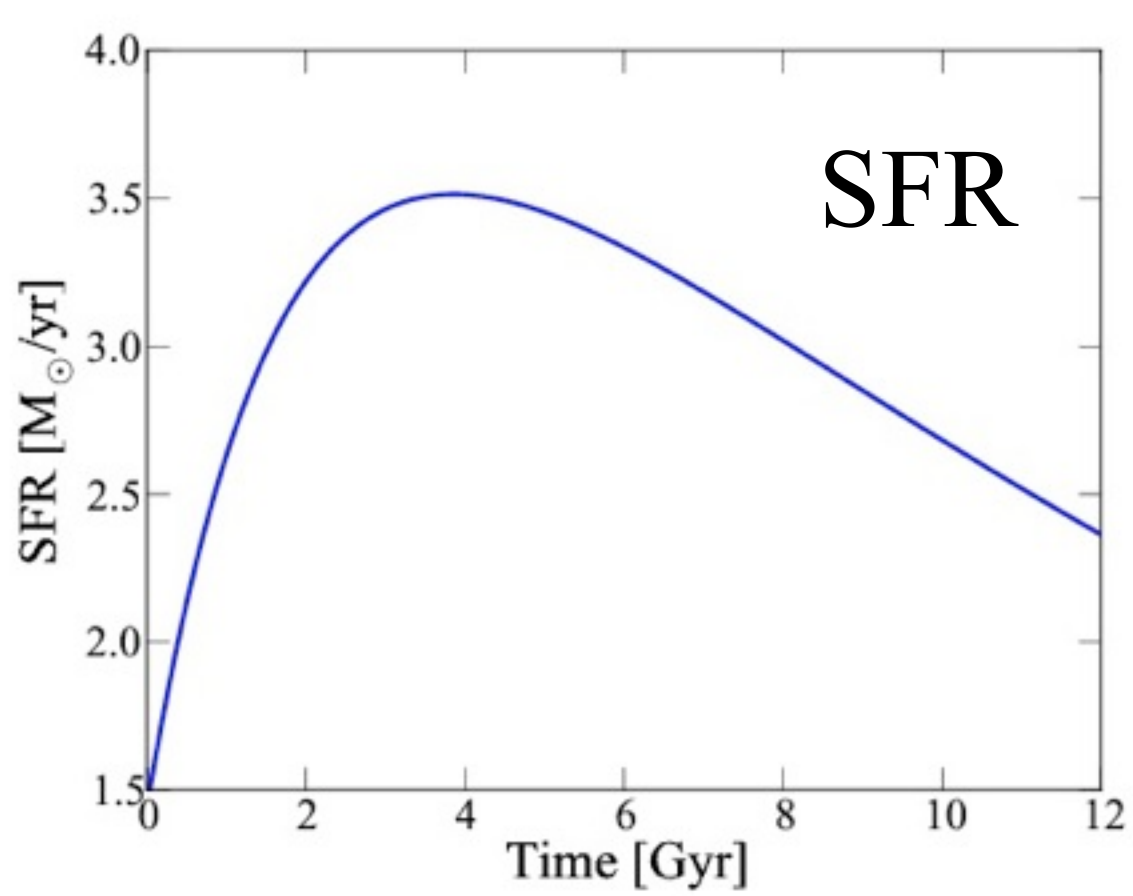


- Chemical cartography
- Look at abundance patterns across the MW disk
- Shape of the high-α stars similar in all panels
- Only varies ~10% spatially across the Galaxy

Nidever et al. (2014)

Chemical Evolution Models



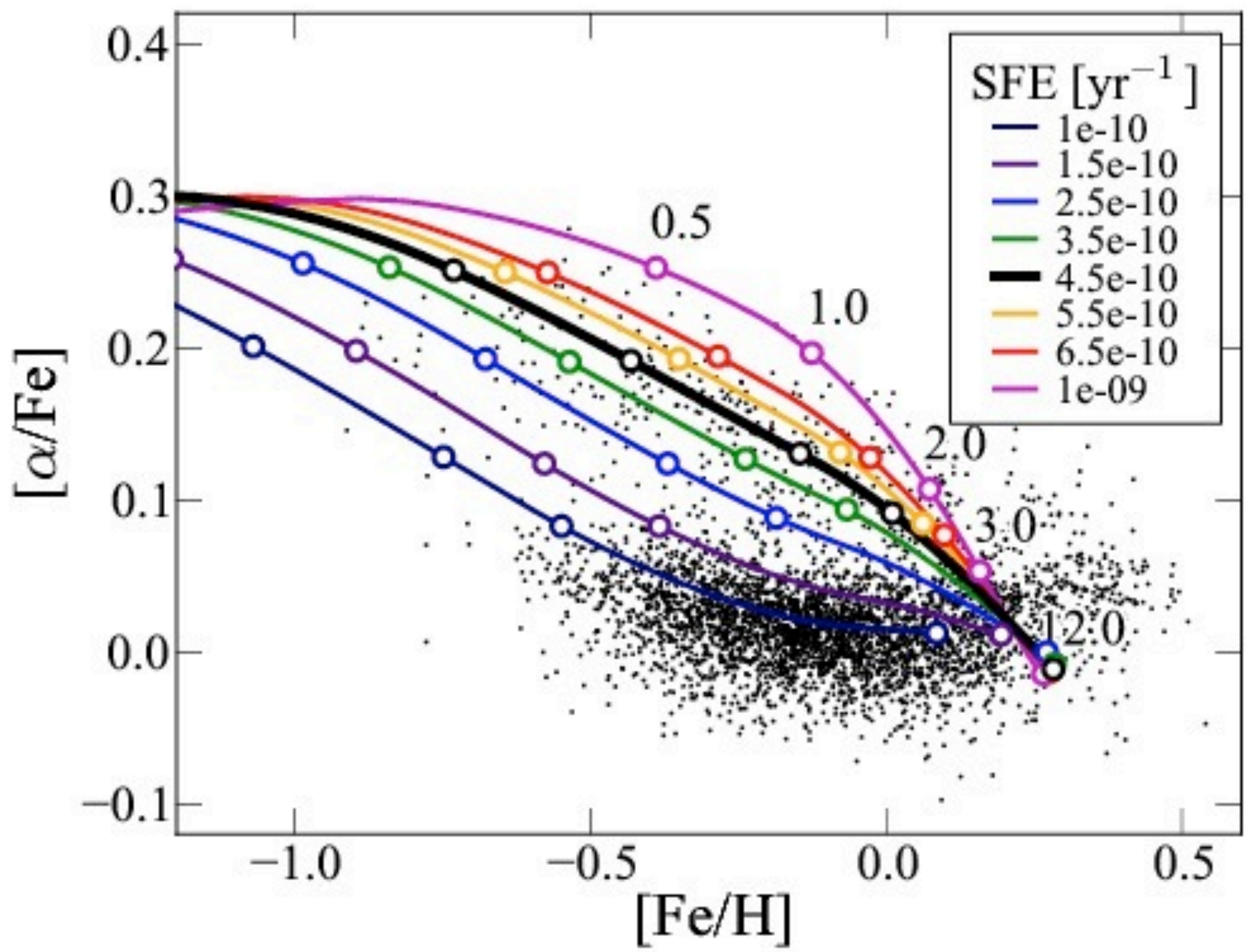


- Simple, one-zone chemical evolution model (Andrews et al. 2015, in prep.)
- SFR = SFE x M_{gas}
- Outflow = η x SFR
- Inflow exponential with e-folding time of 14 Gyr

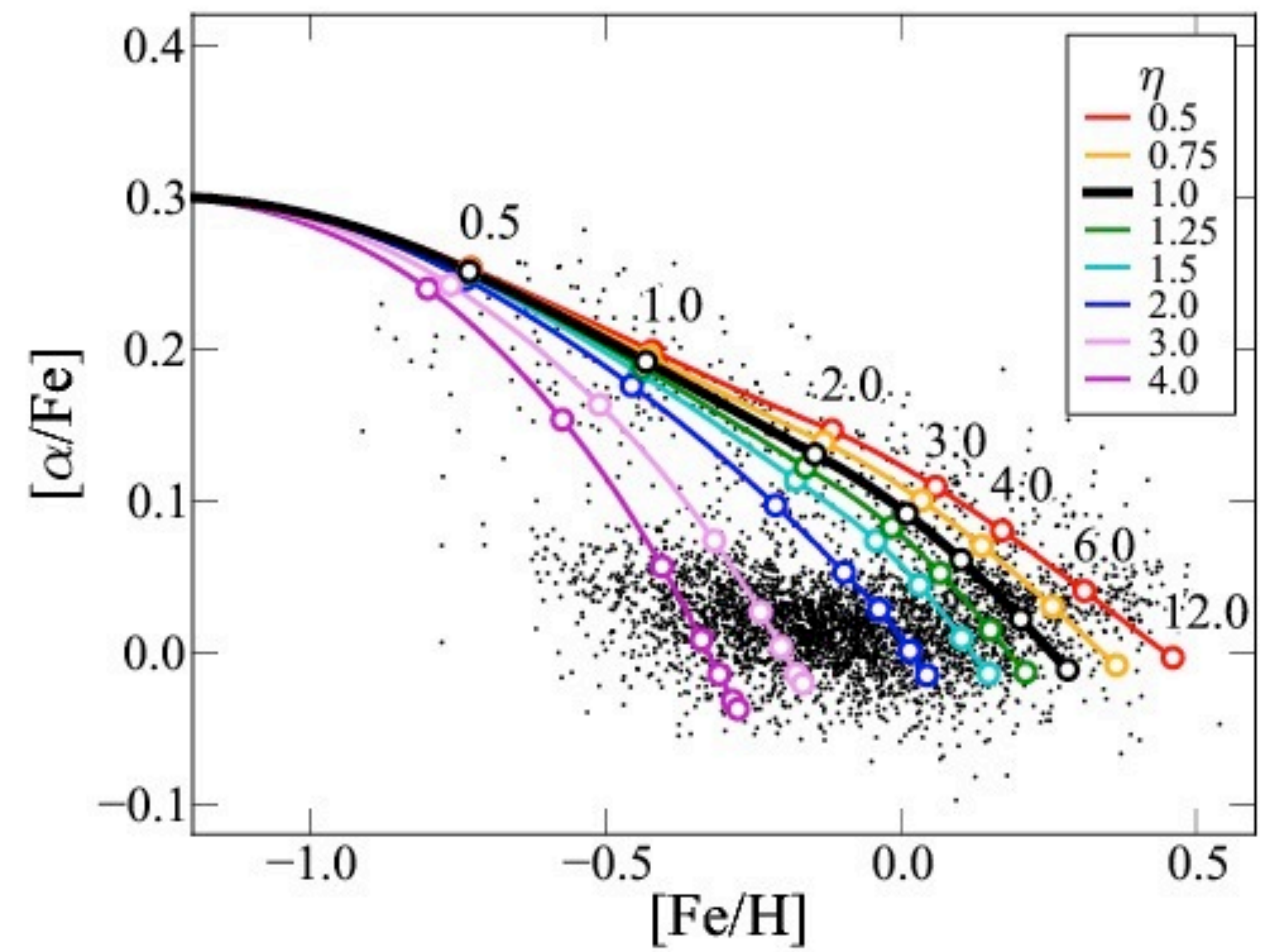
Nidever et al. (2014)

Chemical Evolution Models

Star Formation Efficiency



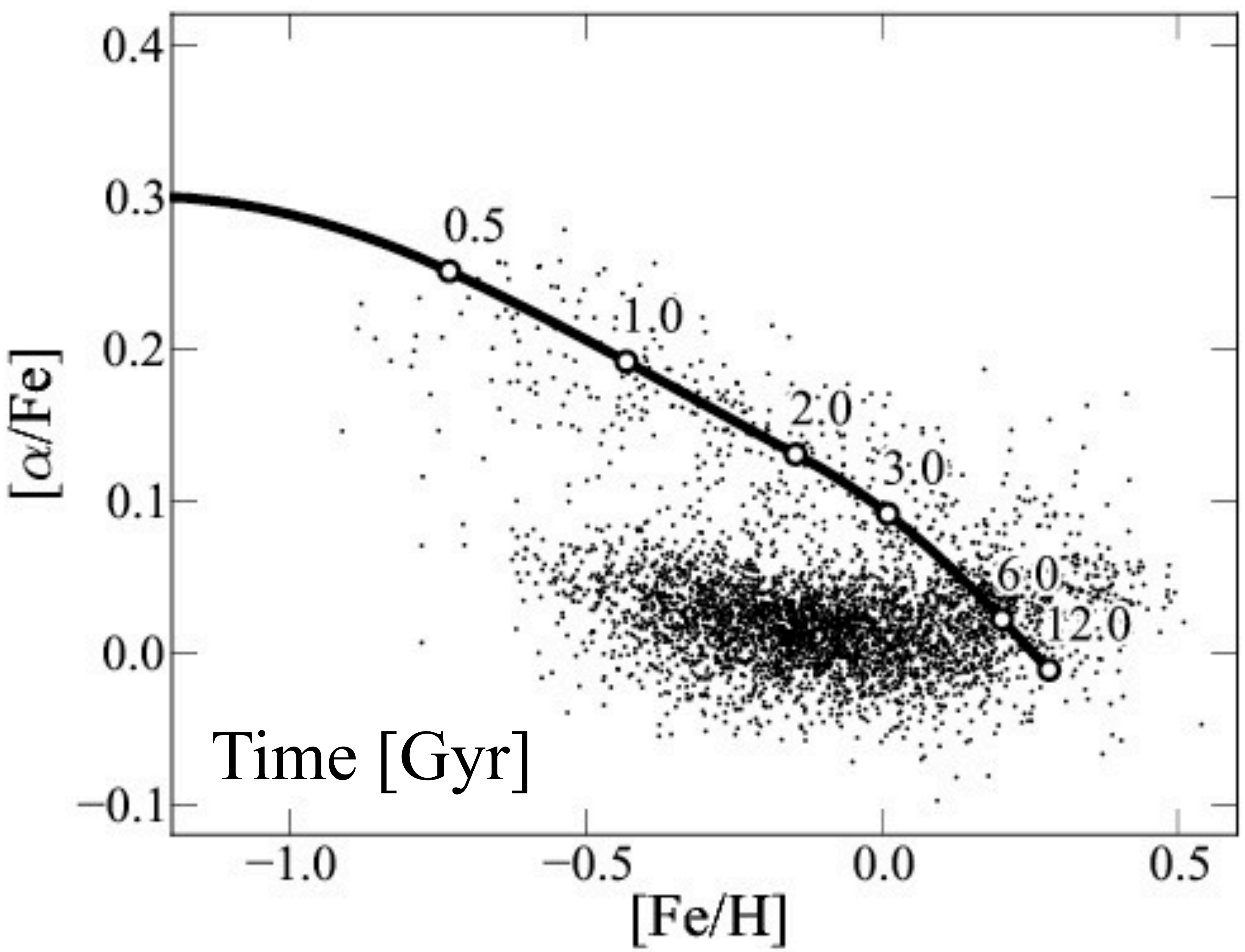
Outflow Rate



- SFE mainly affects "knee" metallicity
- Outflow rate mainly affects final metallicity
- Data can constrain outflow rate and SFE

Nidever et al. (2014)

High-α Sequence

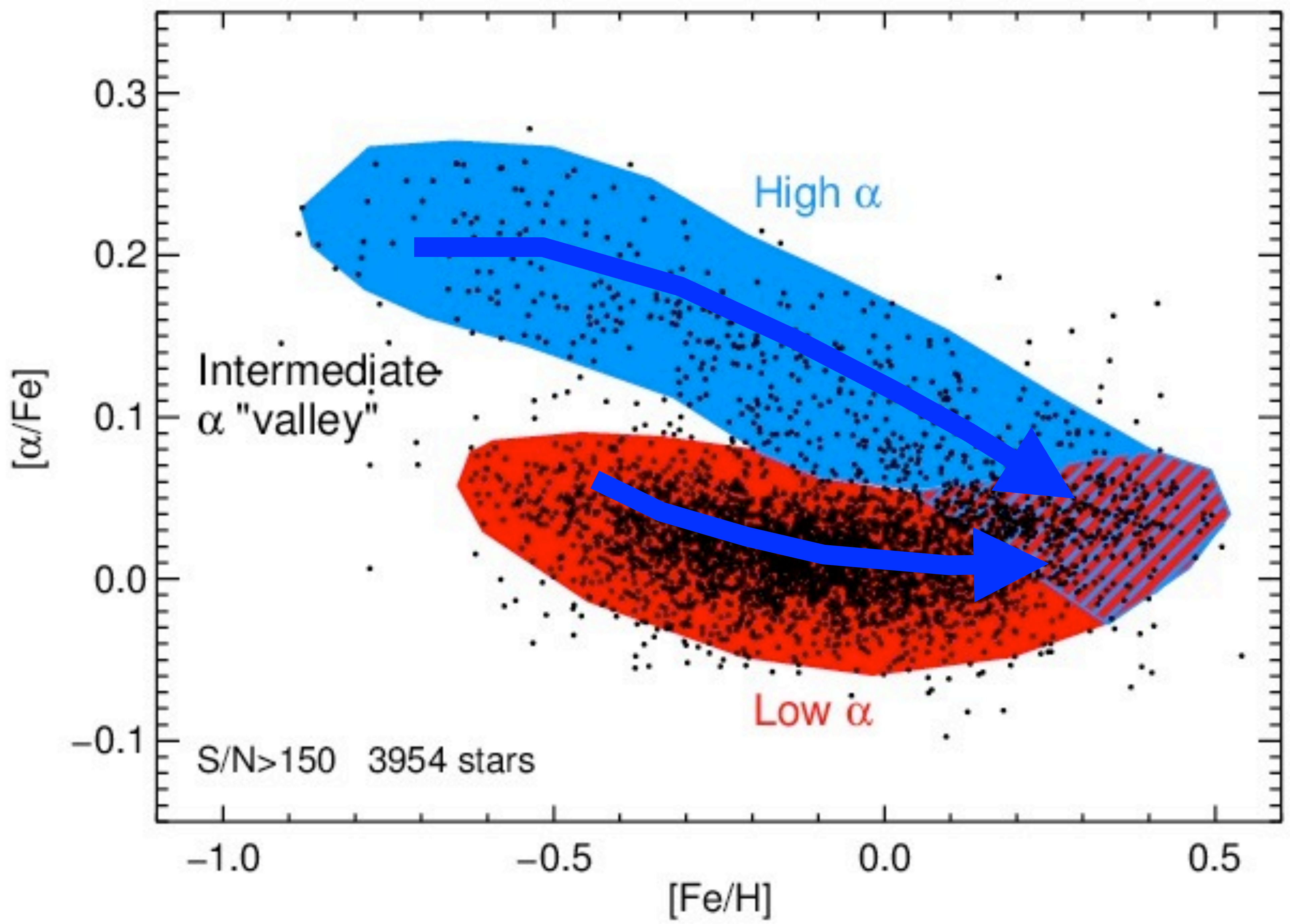


- Fit to the high-α sequence
- **SFE=4.5x10^{-10} yr^{-1}, η=1.0**
- Gas consumption timescale **~2 Gyr** (SFE^{-1})
- Only ~10% spatial variation of SFE
- Uniform, high-SFE in the early MW
- Contradicts simple expectation of higher SFE in inner Galaxy where densities are higher
- *Uniform SFE suggests star formation in well-mixed, turbulent ISM*

Nidever et al. (2014)

SFE Transition

Two Sequences



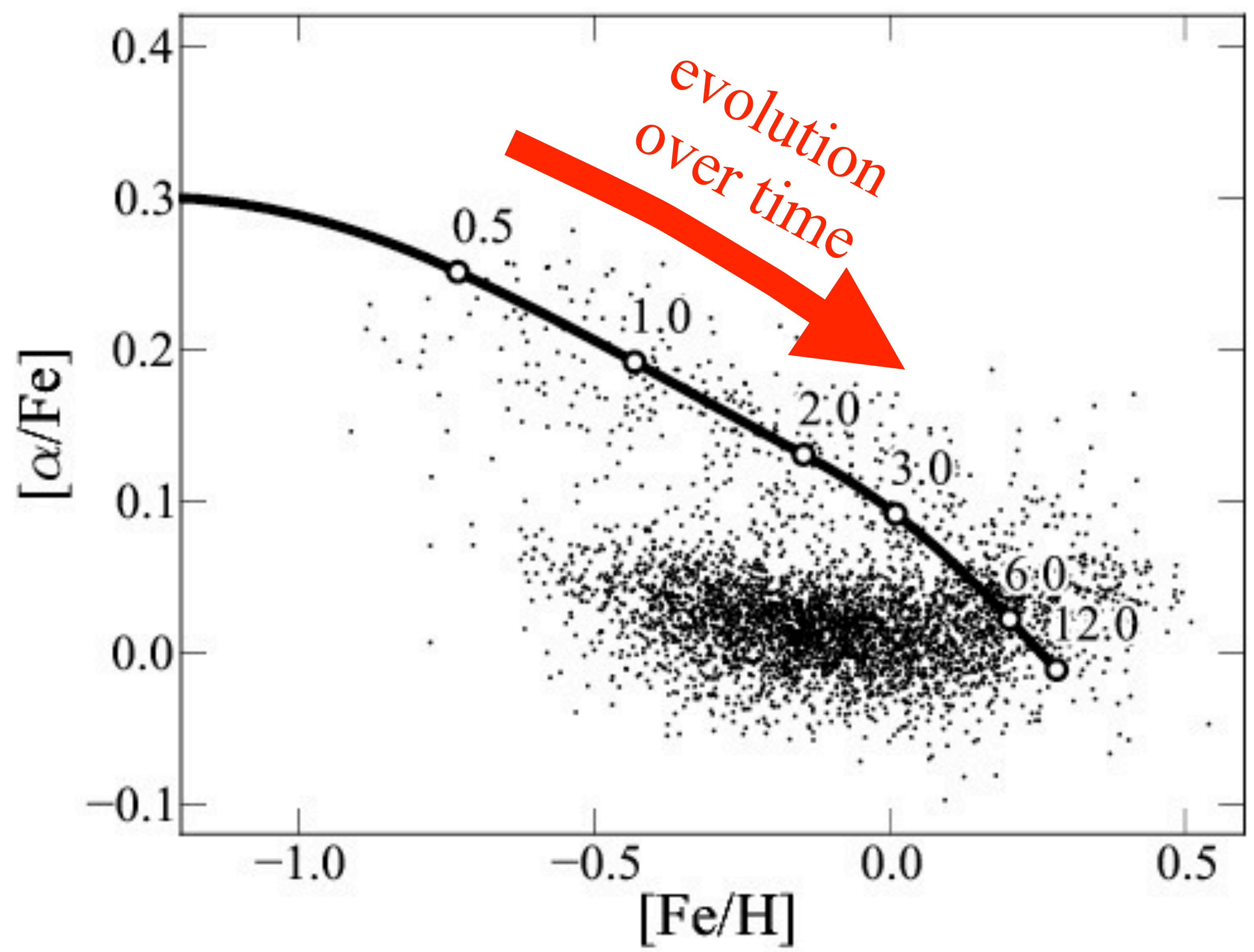
- Two α-sequences are two separate *evolutionary sequences* with different SFE:
  1. High-α → High-SFE
  2. Low-α → Low-SFE

Nidever et al. (2014)

SFE Transition

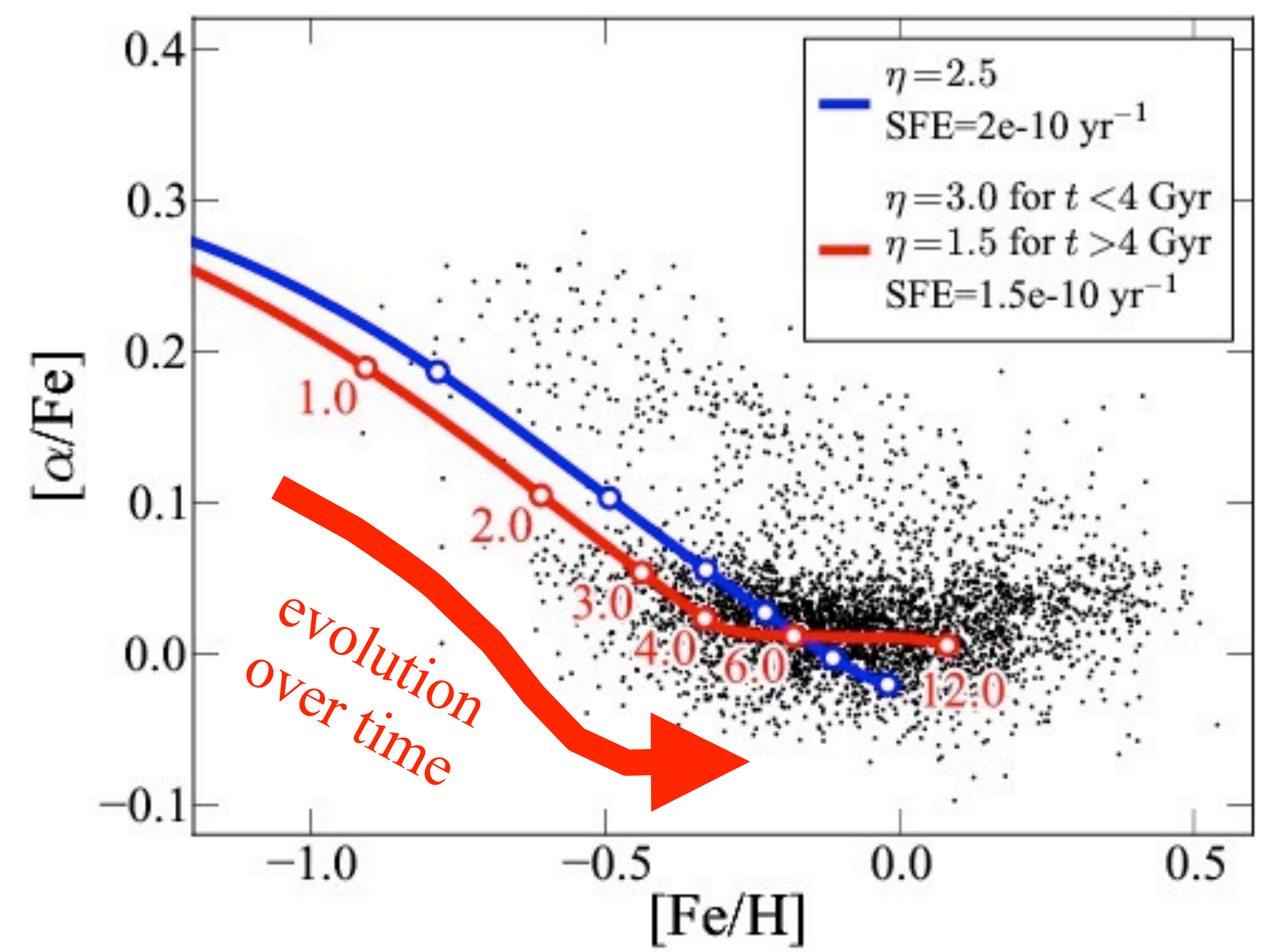
Two Evolutionary Sequences

High-α



High-SFE, 4.5×10^{-10}

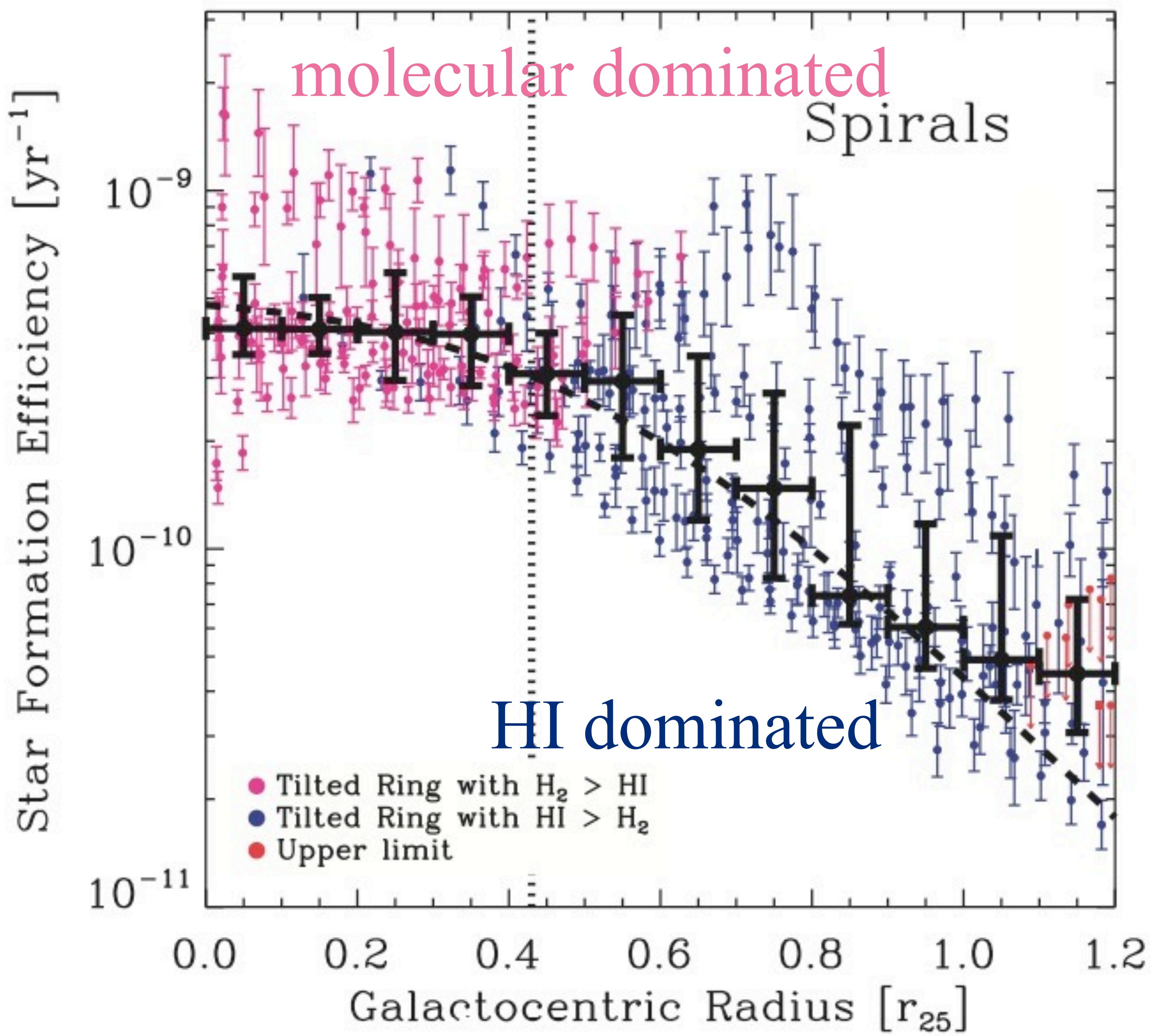
Low-α



Low-SFE, $\sim 1.5 \times 10^{-10}$

Nidever et al. (2014)

SFE Transition



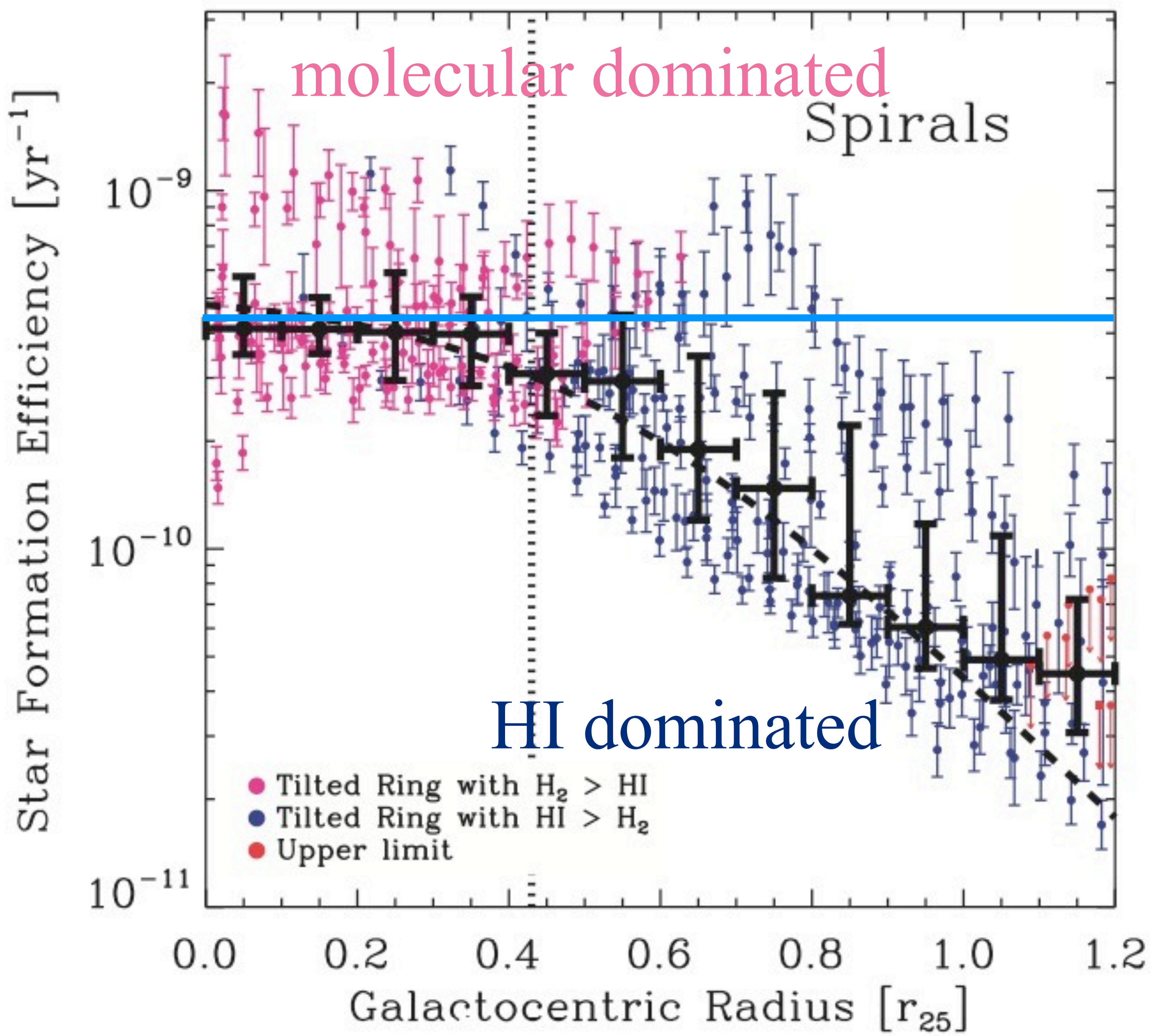
Leroy et al. (2008)

- 12 nearby star-forming spirals
- each point represents a 800pc x 800pc region of the galaxy

Nidever et al. (2014)

SFE Transition

- High-α sequence SFE very close to the nearly-constant SFE in molecular-dominated regions of nearly galaxies (inner regions)



4.5×10^{-10} APOGEE-RC high-α sequence

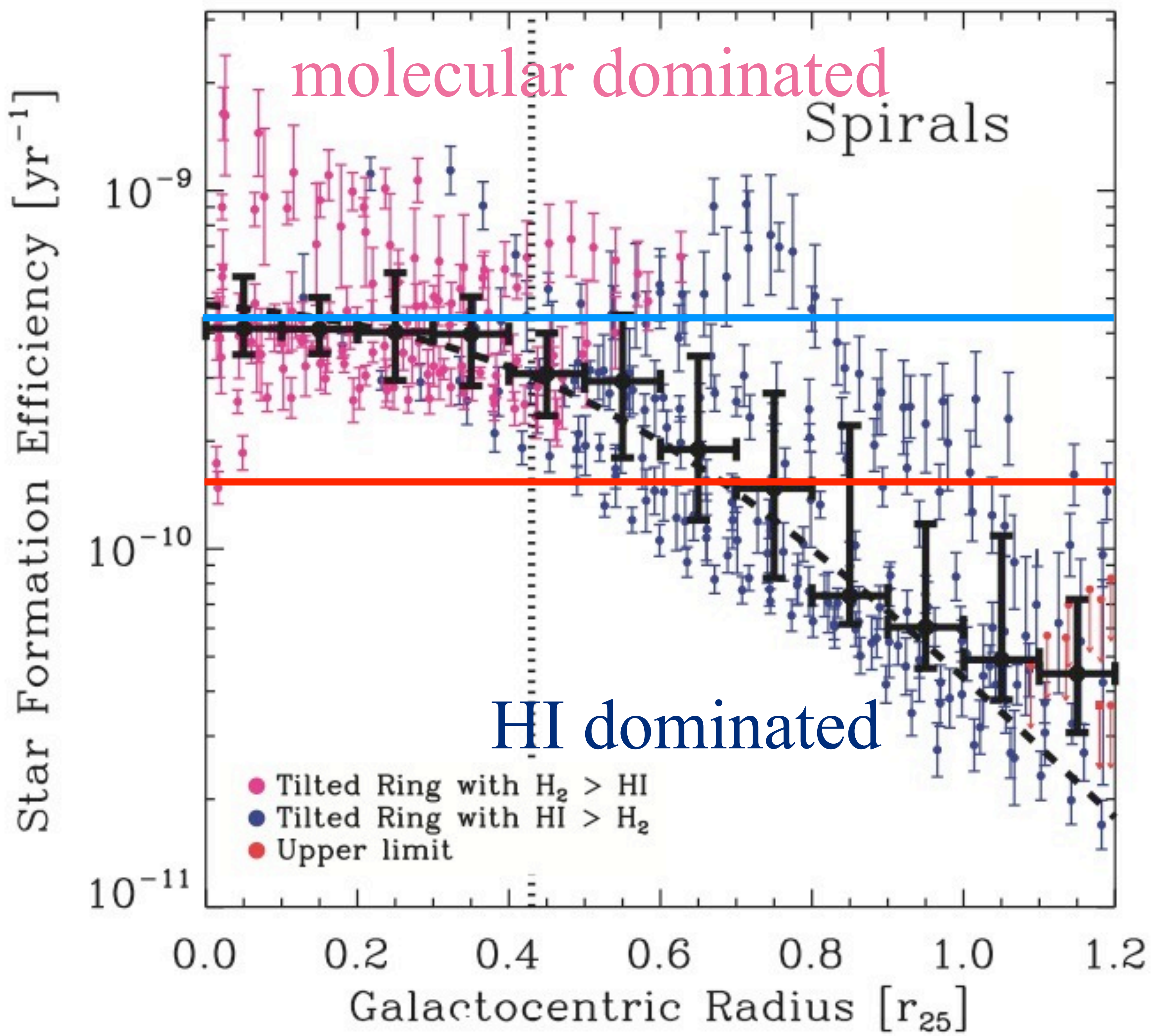
- 12 nearby star-forming spirals
- each point represents a 800pc x 800pc region of the galaxy

Leroy et al. (2008)

Nidever et al. (2014)

SFE Transition

- Low-α sequence SFE in middle of HI-dominated region, varies with radius, outer regions



Leroy et al. (2008)

4.5×10^{-10} APOGEE-RC high-α sequence

1.5×10^{-10} APOGEE-RC low-α sequence

- 12 nearby star-forming spirals
- each point represents a 800pc x 800pc region of the galaxy

Nidever et al. (2014)

SFE Transition

Two sequences

1. High-α sequence
   - High-SFE
   - Inner Galaxy
   - *Molecular-dominated*

2. Low-α sequence
   - Low-SFE
   - Outer Galaxy
   - *HI-dominated*

Leroy et al. (2008)

Nidever et al. (2014)

SFE Transition

Two sequences

1. High-α sequence
   - High-SFE
   - Inner Galaxy
   - *Molecular-dominated*
   - *Older, ~8-12 Gyr*

2. Low-α sequence
   - Low-SFE
   - Outer Galaxy
   - *HI-dominated*
   - *Younger, ~1-8 Gyr*

Leroy et al. (2008)

Haywood et al. (2013)

Nidever et al. (2014)

SFE Transition

Two sequences

1. High-α sequence
   - High-SFE
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2. Low-α sequence
   - Low-SFE
   - Outer Galaxy
   - *HI-dominated*
   - *Younger, ~1-8 Gyr*

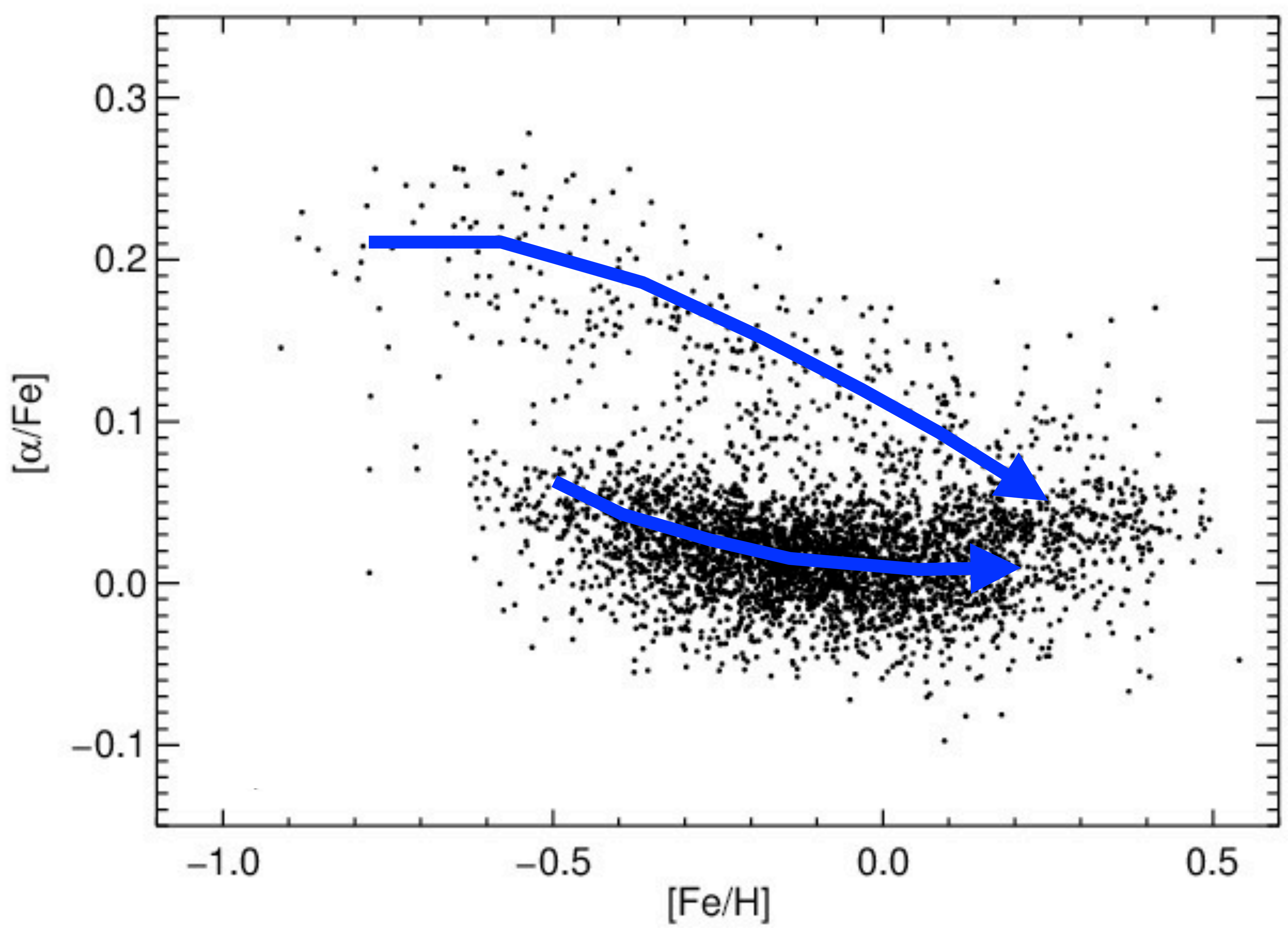
Leroy et al. (2008)
Haywood et al. (2013)

➡**SFE transition**, ~8 Gyr ago (but position dependent?)
molecular-dominated → HI-dominated SF

Nidever et al. (2014)

SFE Transition

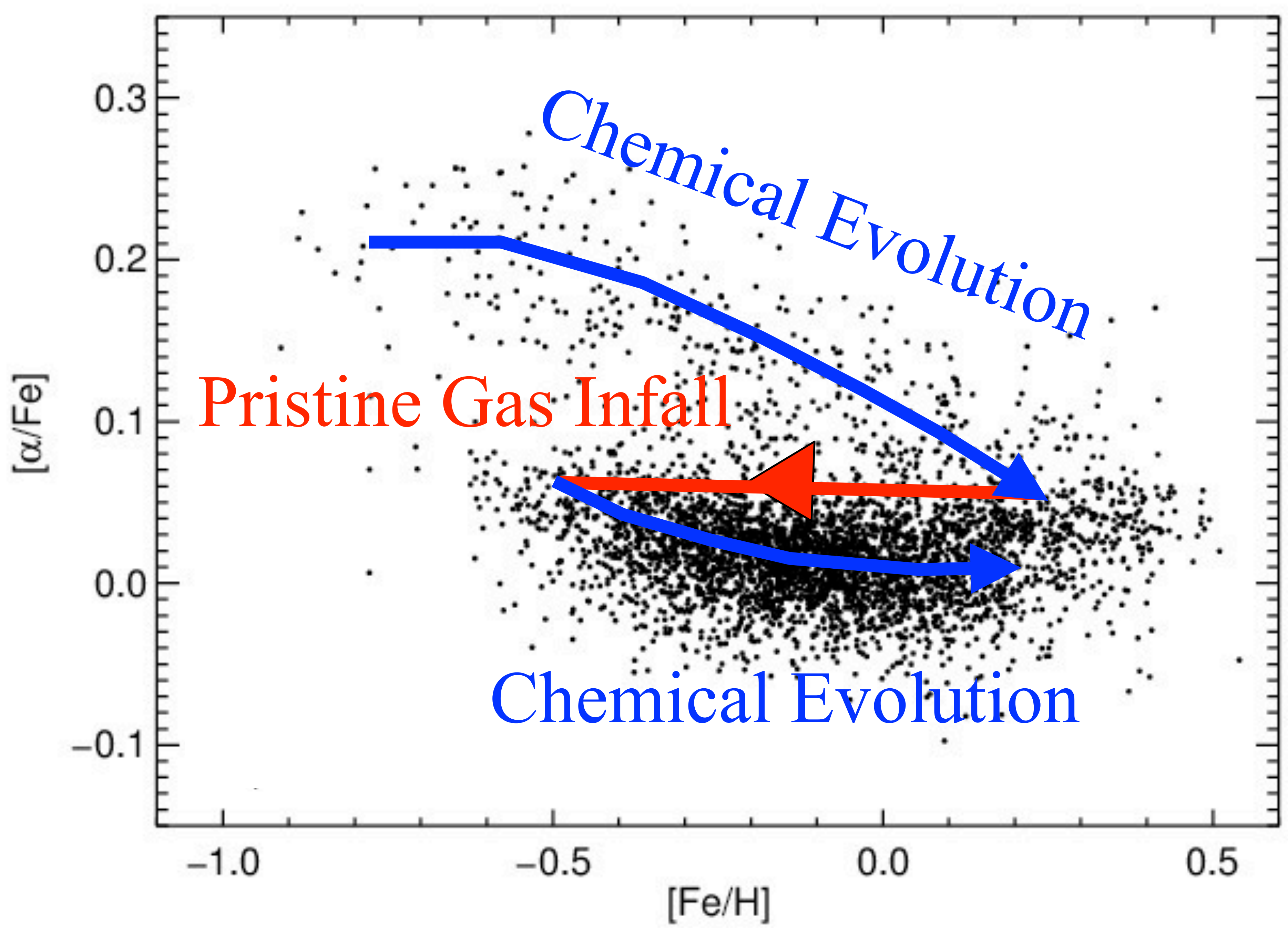
- To also match the chemistry, need gas infall at SFE transition



Nidever et al. (2014)

SFE Transition

- To also match the chemistry, need gas infall at SFE transition
- Infall of pristine gas, lower [Fe/H], [α/Fe] constant
- Low SFE and SNIa from older “High-α” population keep α low

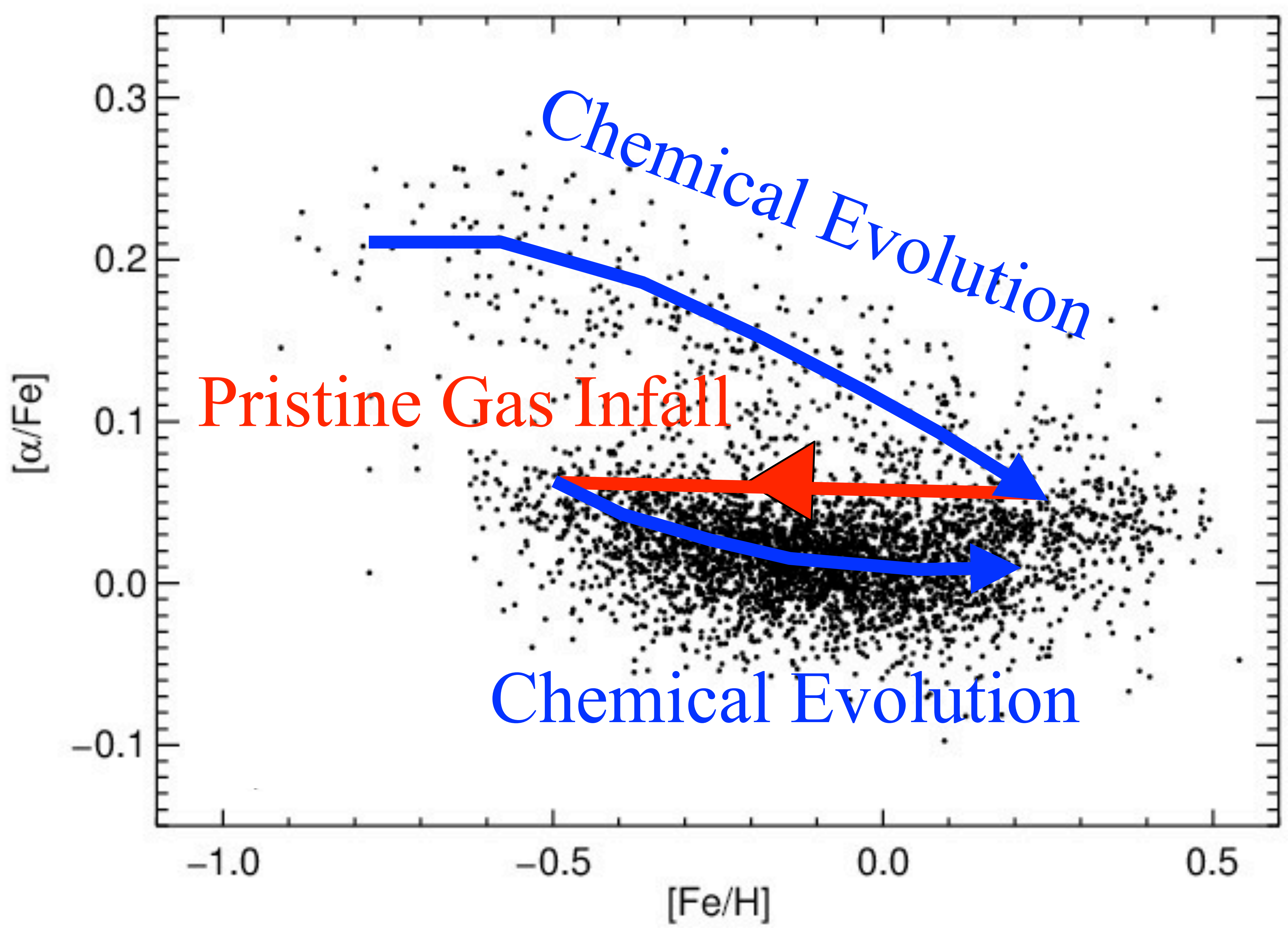


- Infall of pristine gas ~8 Gyr ago

Nidever et al. (2014)

SFE Transition

- Infall of pristine gas combined with gas depletion from early rapid SF could have triggered the transition
  (also suggested by Chiappini et al. 2009, two-infall model)

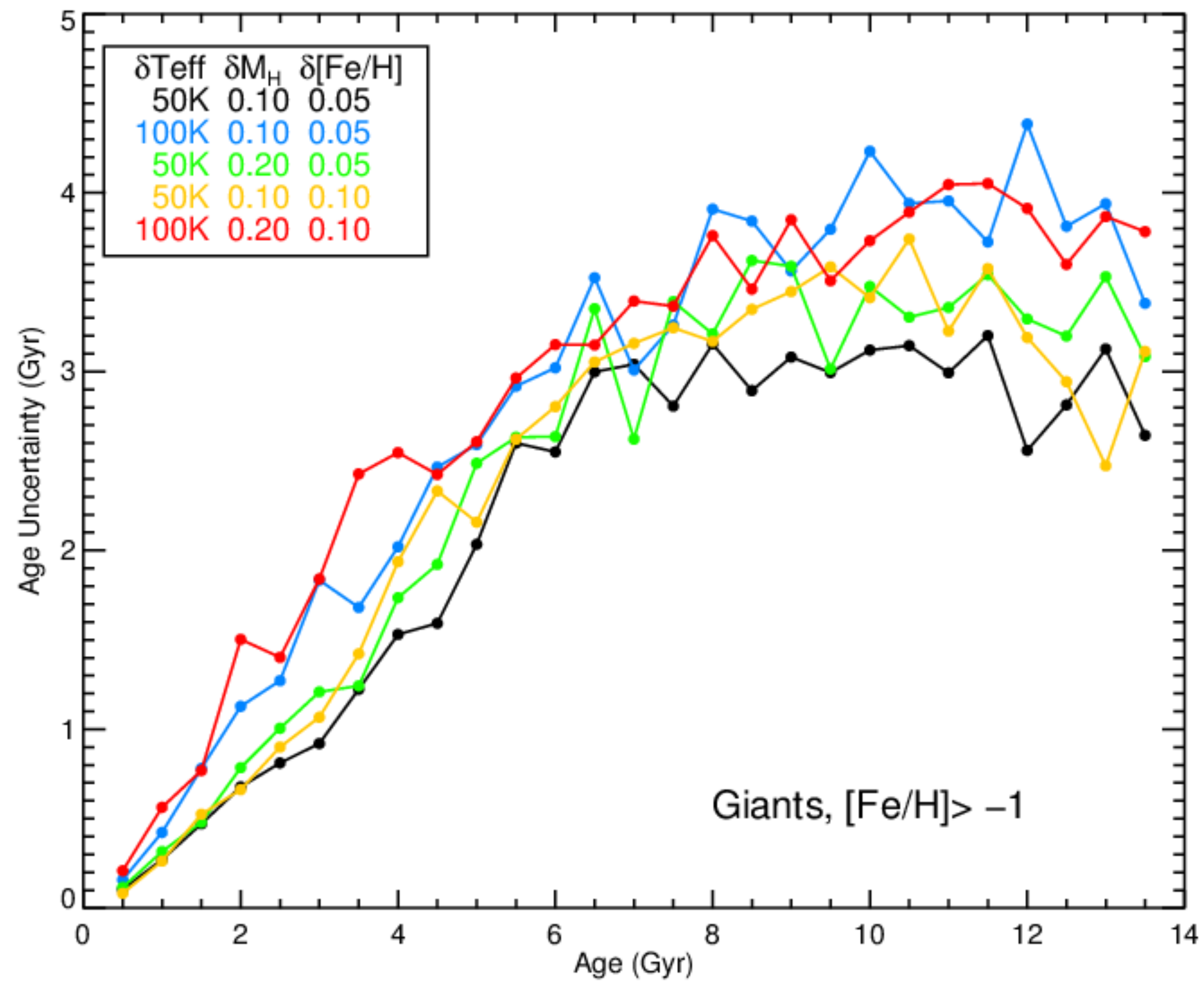


- Infall of pristine gas ~8 Gyr ago

Nidever et al. (2014)

Ages with Gaia

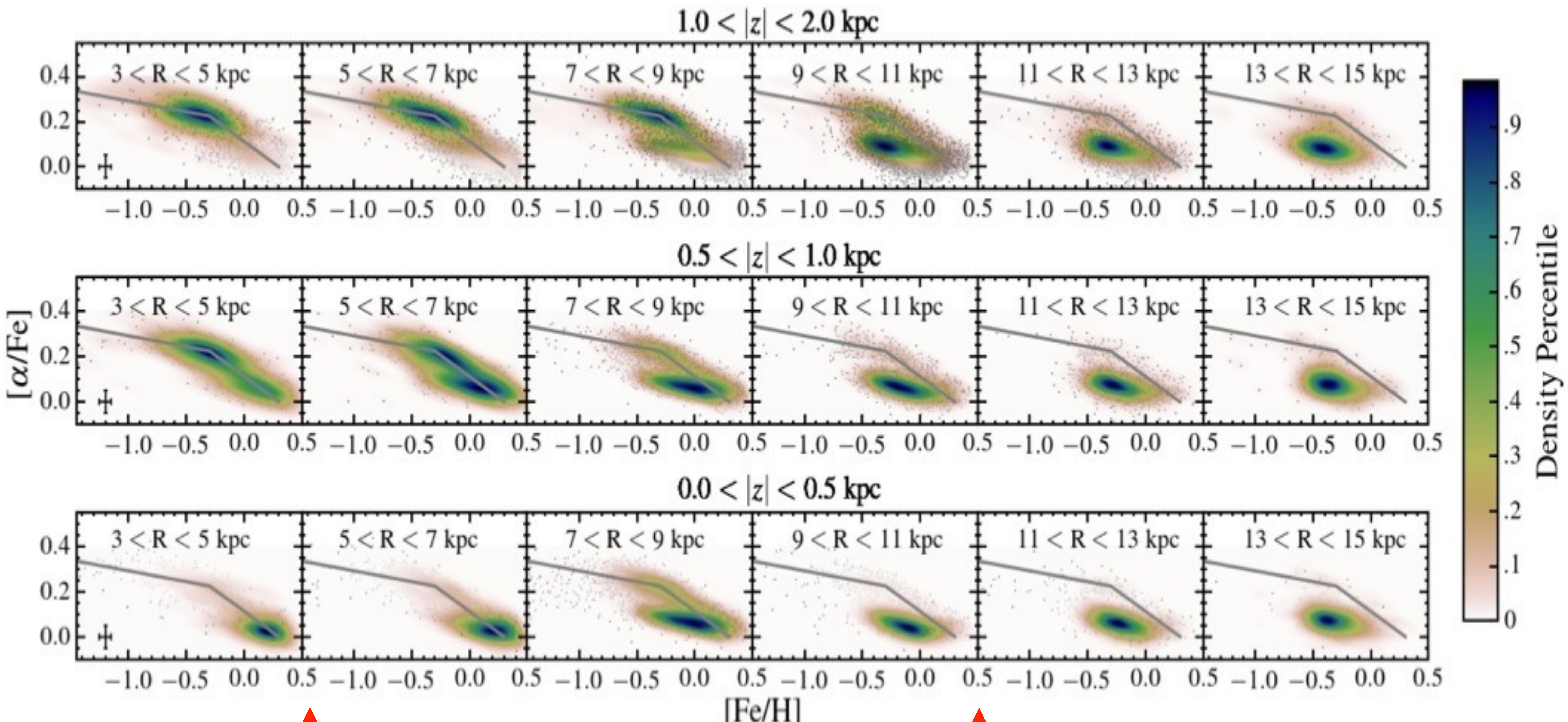
APOGEE RGB Age Uncertainties



Ages from Teff, logg, [Fe/H], distance, photometry and isochrones

RGB Chemical Pattern

- Extending the reach with ~70,000 RGB stars, 3<R<15 kpc



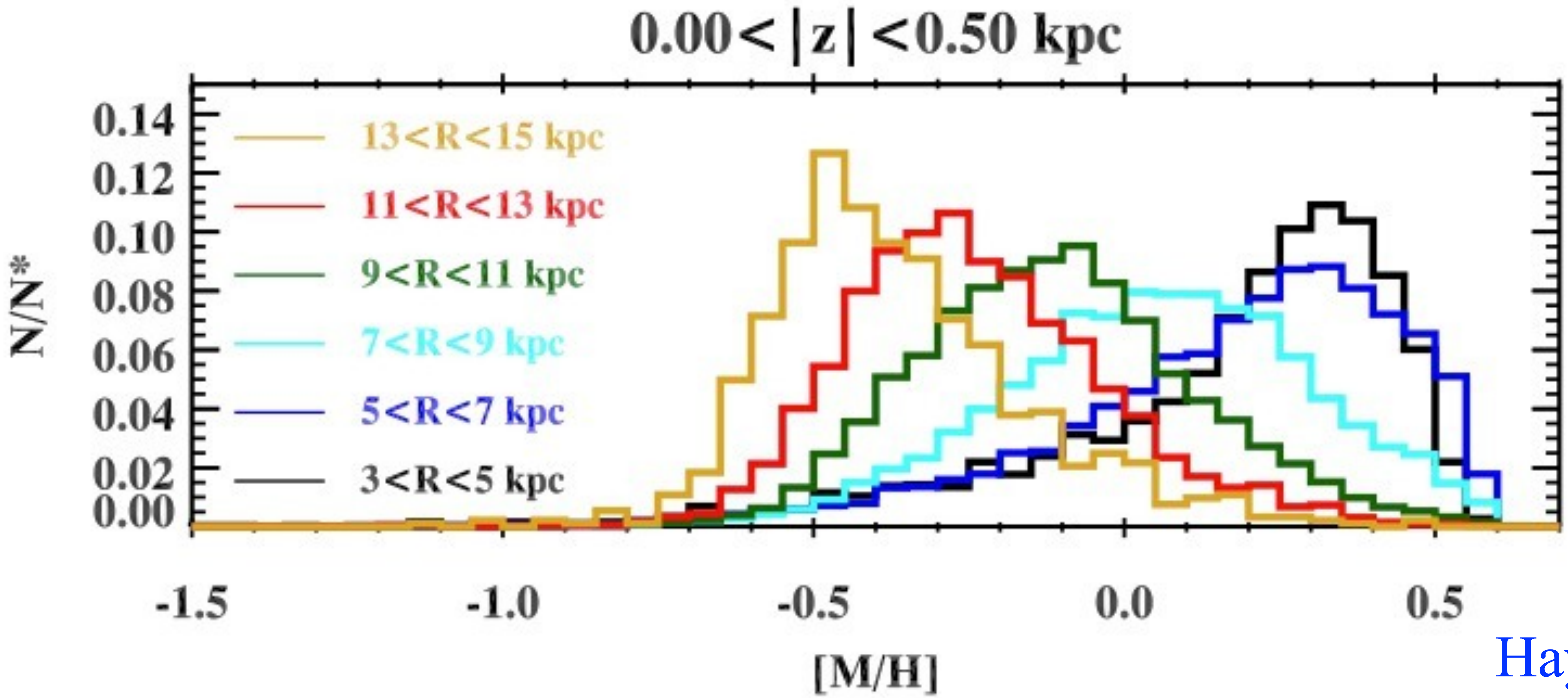
RC range

Hayden et al. (2015)

Metallicity Distribution Functions

MDF shape change with radius

- Skew-negative in inner galaxy
- Roughly Gaussian at solar circle
- Skew-positive in outer galaxy

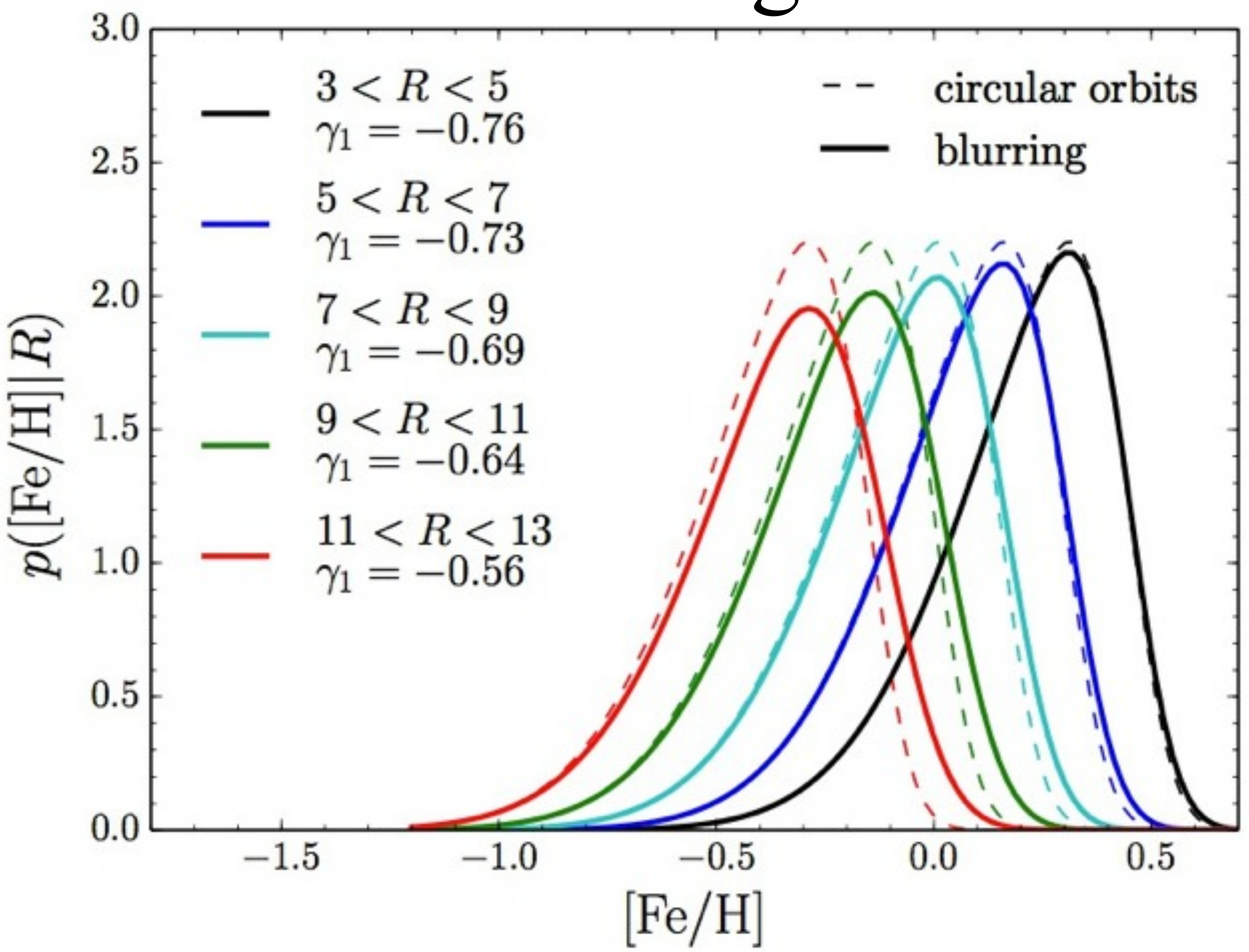


Hayden et al. (2015)

Metallicity Distribution Functions

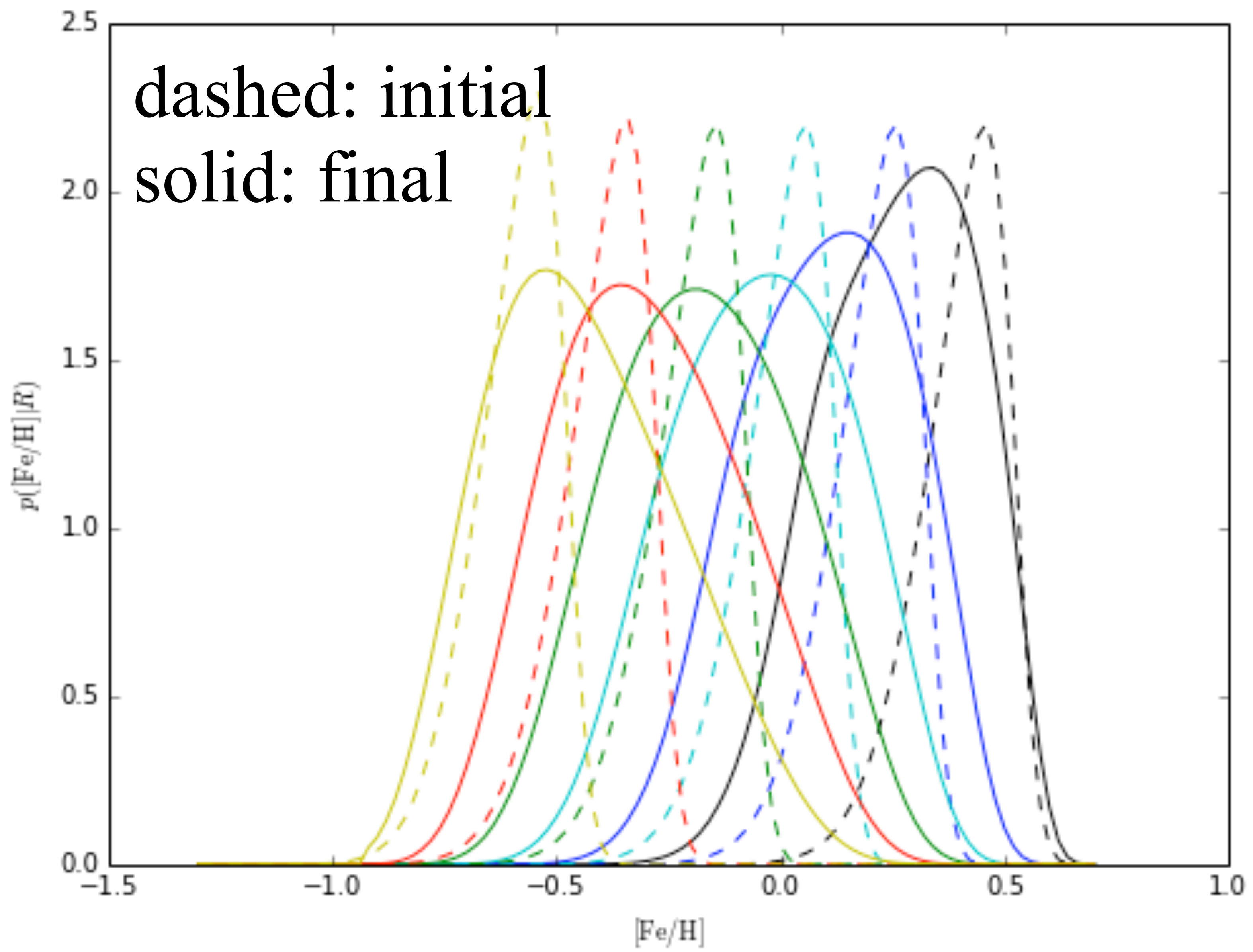
- Blurring (asymmetric drift) does *not* work
- Churning (radial migration) *reproduces* the observed behavior

Blurring



blurring with 30 km/s velocity dispersion

Churning



analysis by J. Bovy

Hayden et al. (2015)

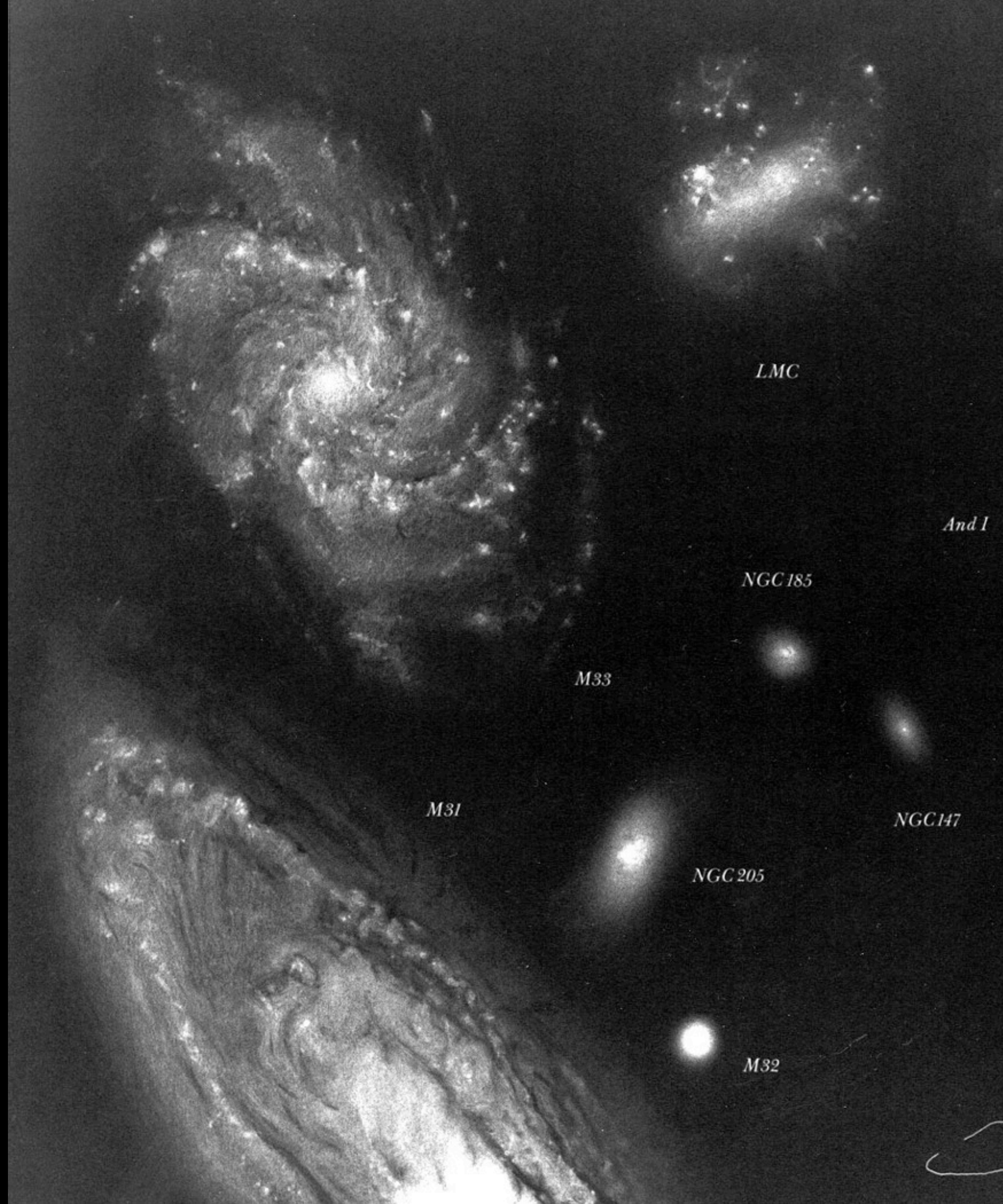
APOGEE Conclusions

- α bimodality at intermediate metallicity, throughout MW
- Little spatial variation of high-α sequence chemical pattern (~10%)
- Suggests early MW stellar evolution was in well-mixed, turbulent, molecular-dominated environment
- Can explain low/high-α sequences SFE-transition from high to low SFE ~8 Gyr ago
- MDFs skewness change with radius, inner-negative, outer-positive
- Evidence for radial migration

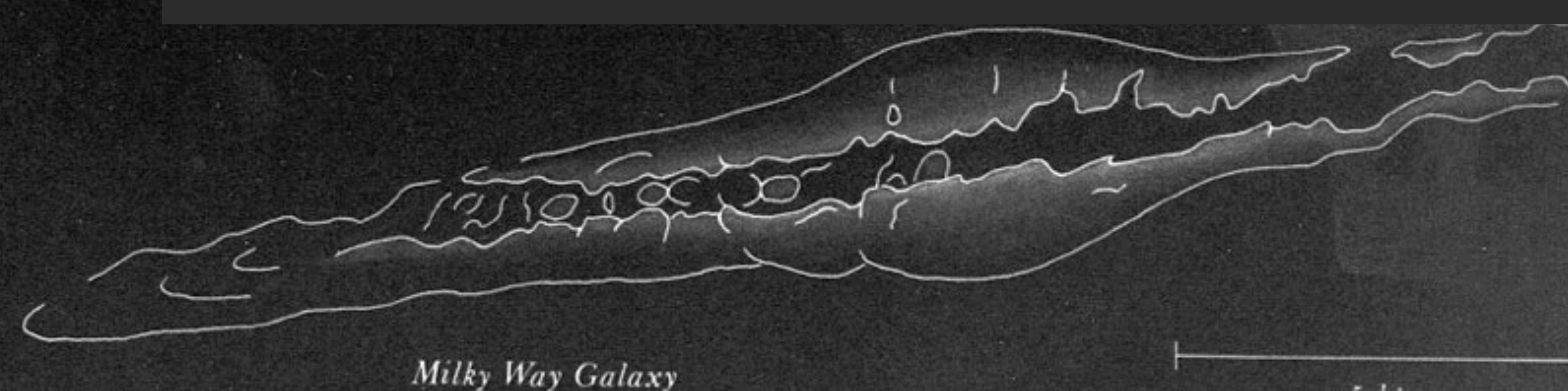
Nidever et al. (2014) Hayden et al. (2015)

The Magellanic Stellar Periphery

Local Group Stellar Halos

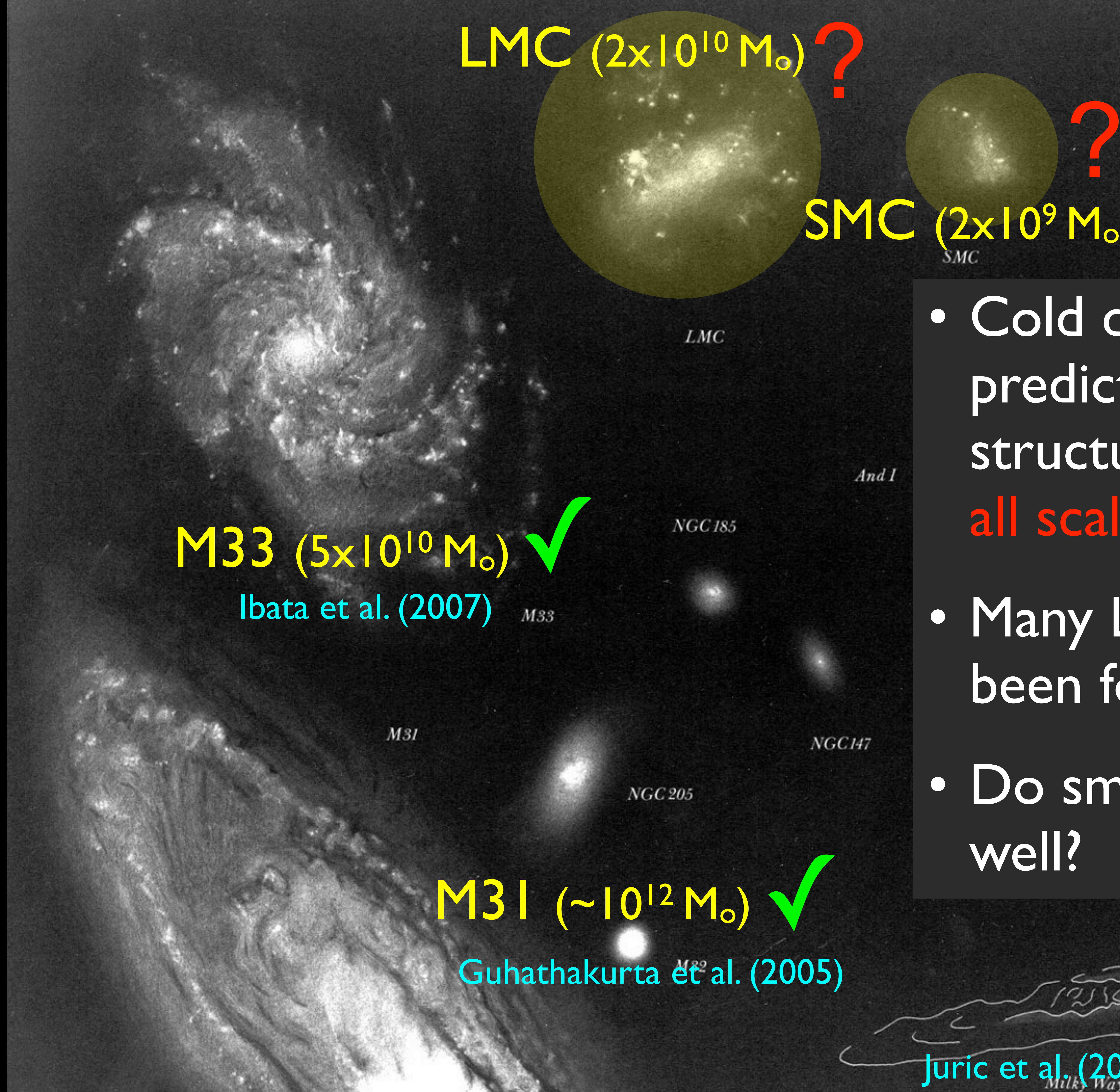


- Cold dark matter simulations predict that hierarchical structure formation occurs on all scales
- Many Local Group spirals have been found to host stellar halos

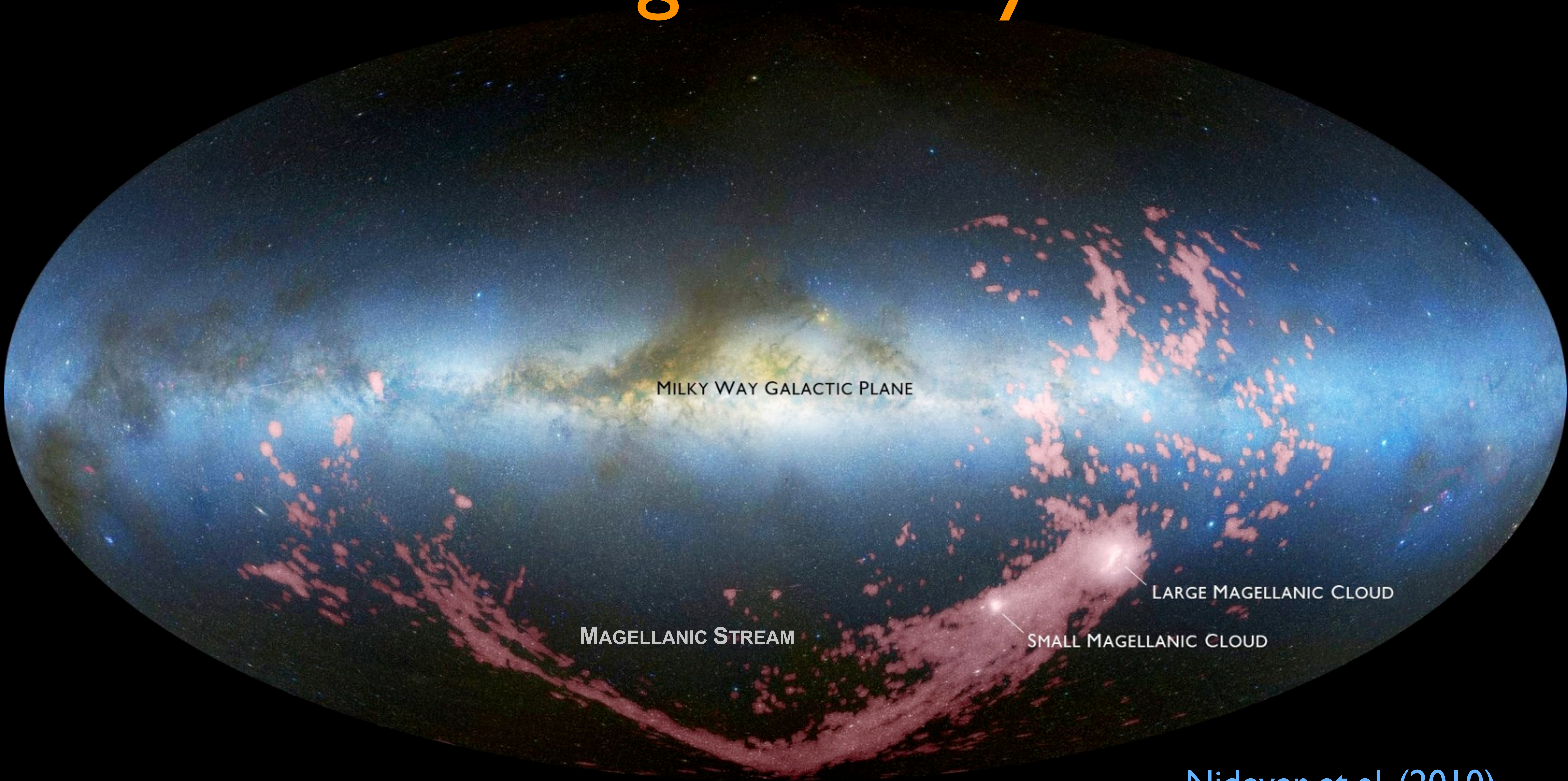


Local Group Stellar Halos

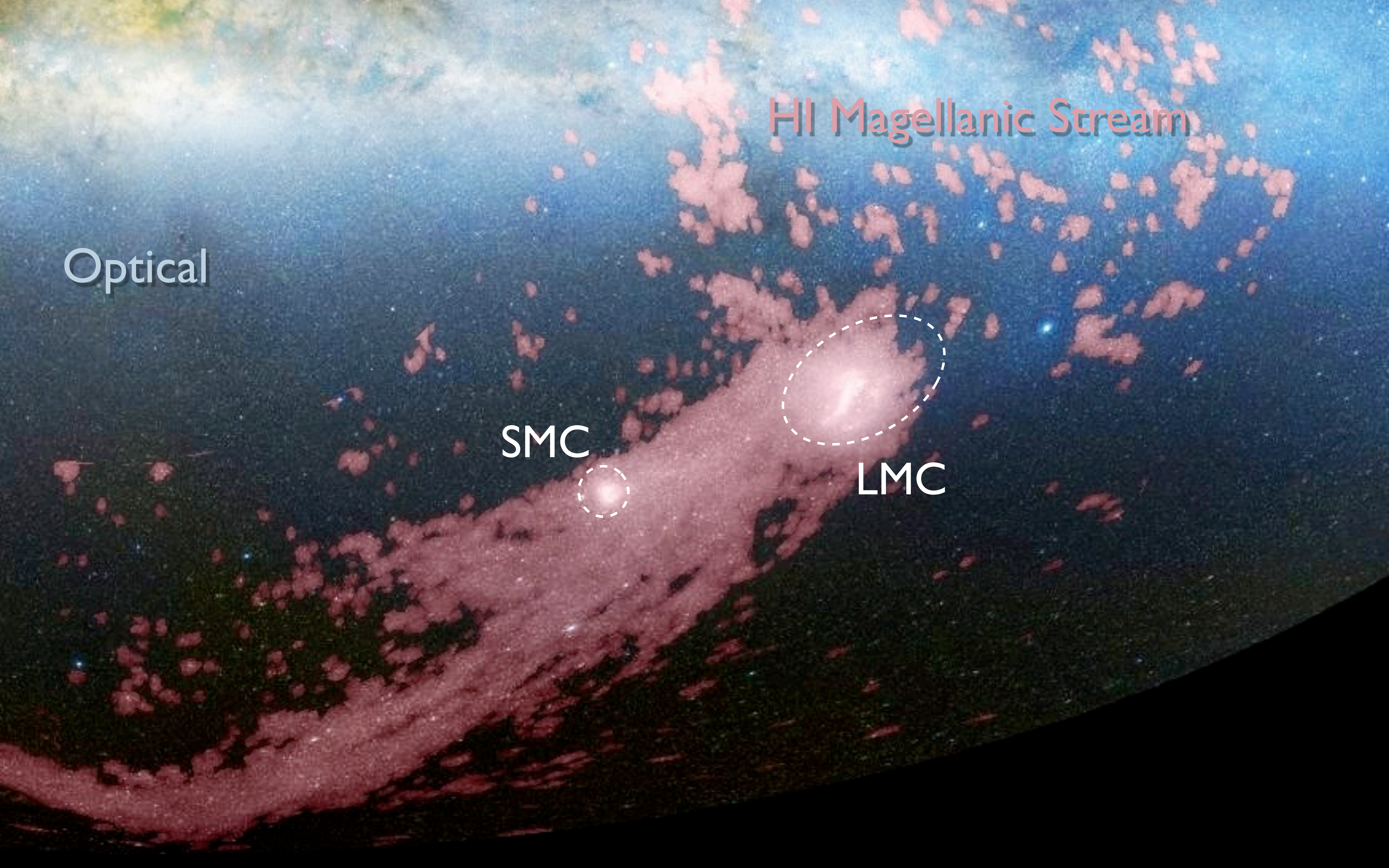
- Cold dark matter simulations predict that hierarchical structure formation occurs on all scales
- Many Local Group spirals have been found to host stellar halos
- Do small dwarfs have halos as well?



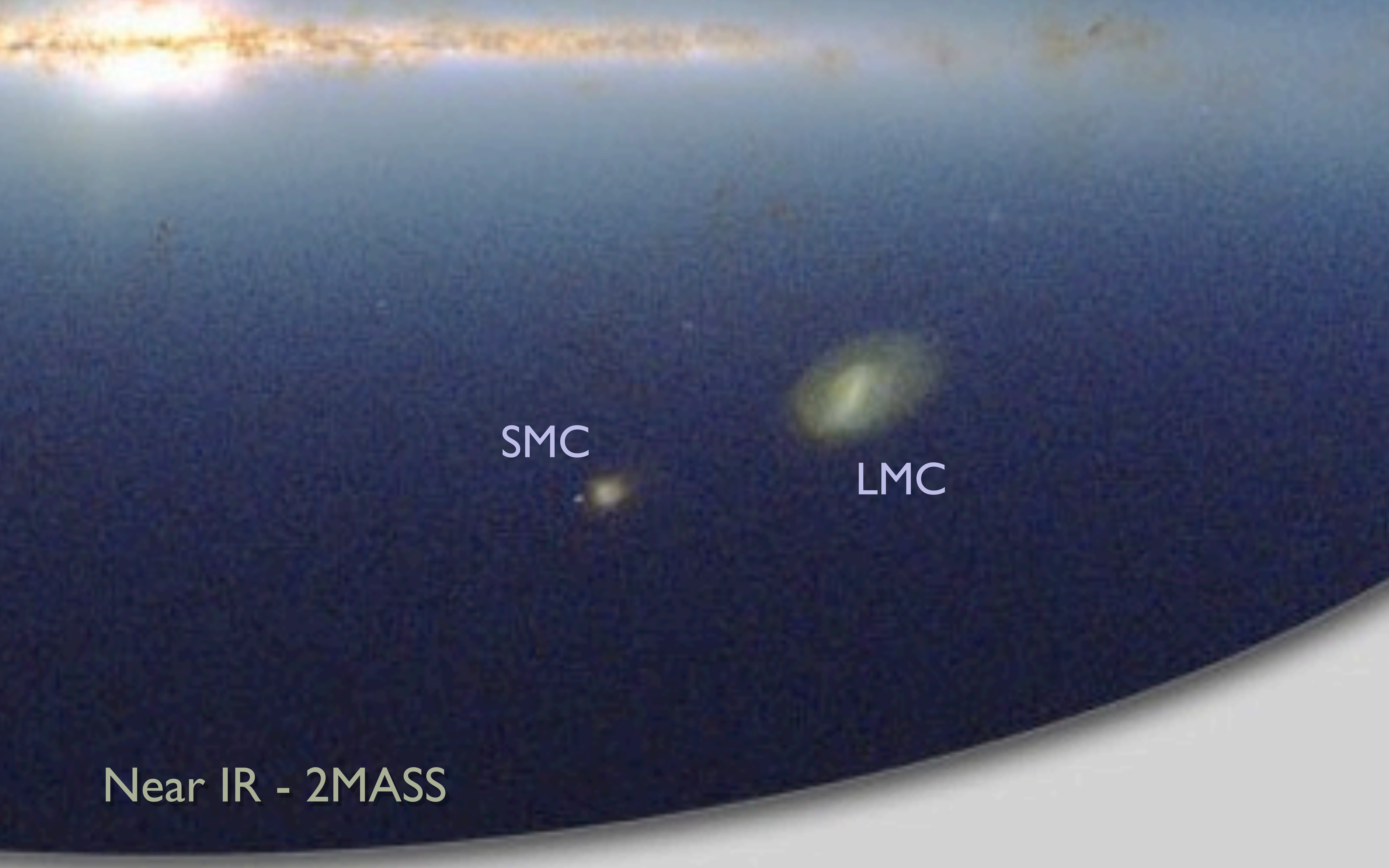
The Magellanic System

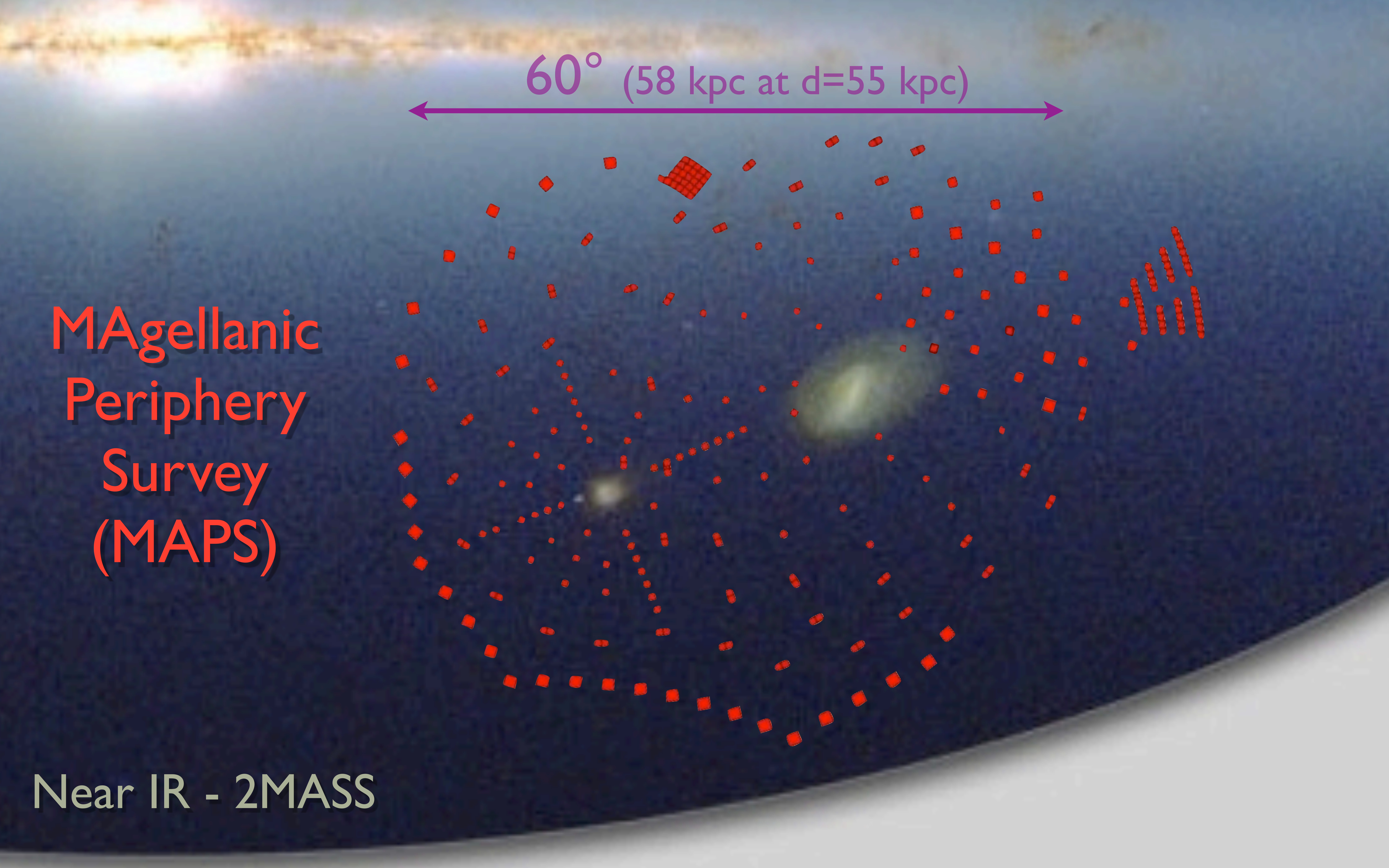


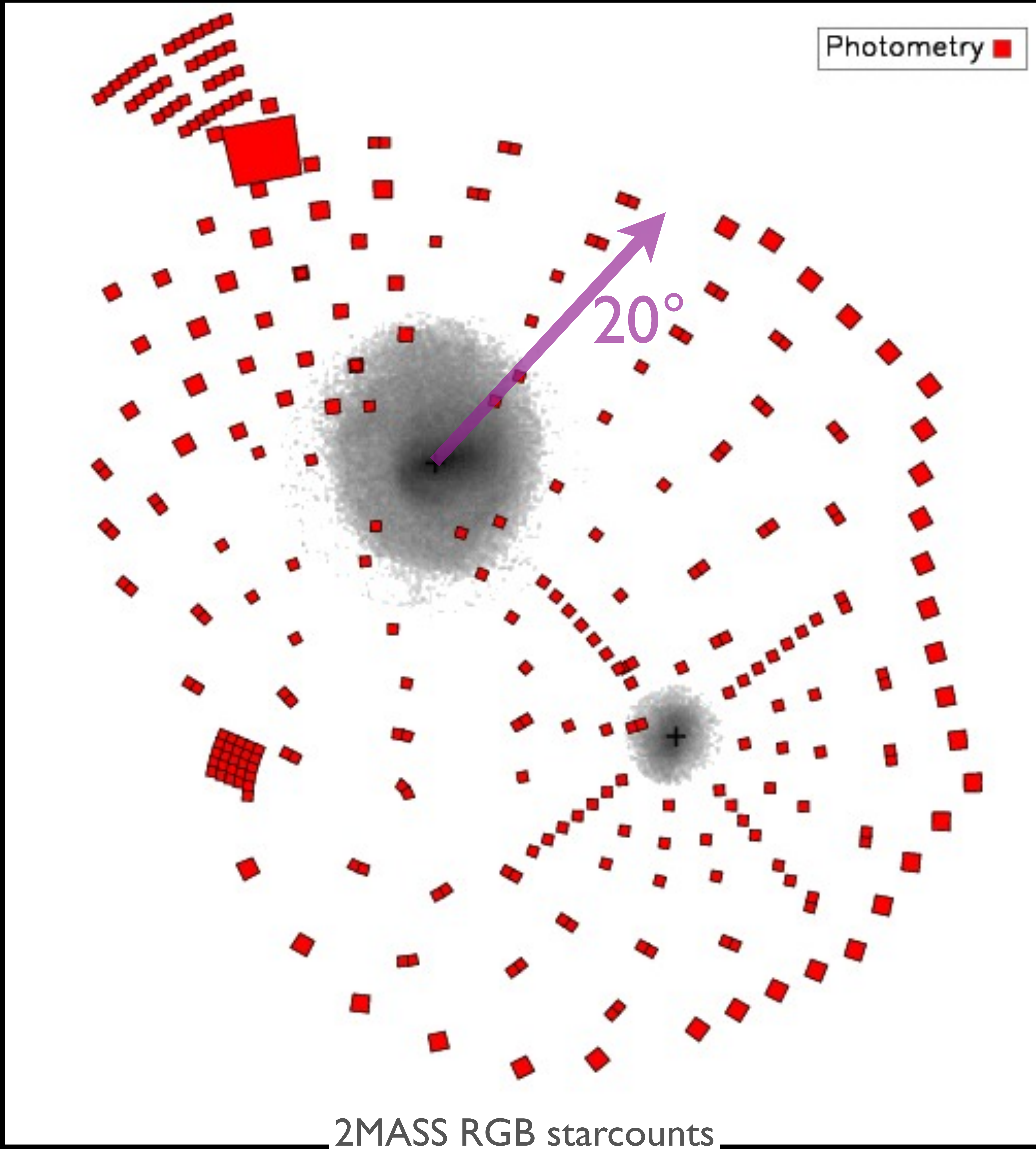
Nidever et al. (2010)



HI Magellanic Stream
Optical
SMC
LMC


SMC
LMC
Near IR - 2MASS


60° (58 kpc at d=55 kpc)
MAgellanic Periphery Survey (MAPS)
Near IR - 2MASS

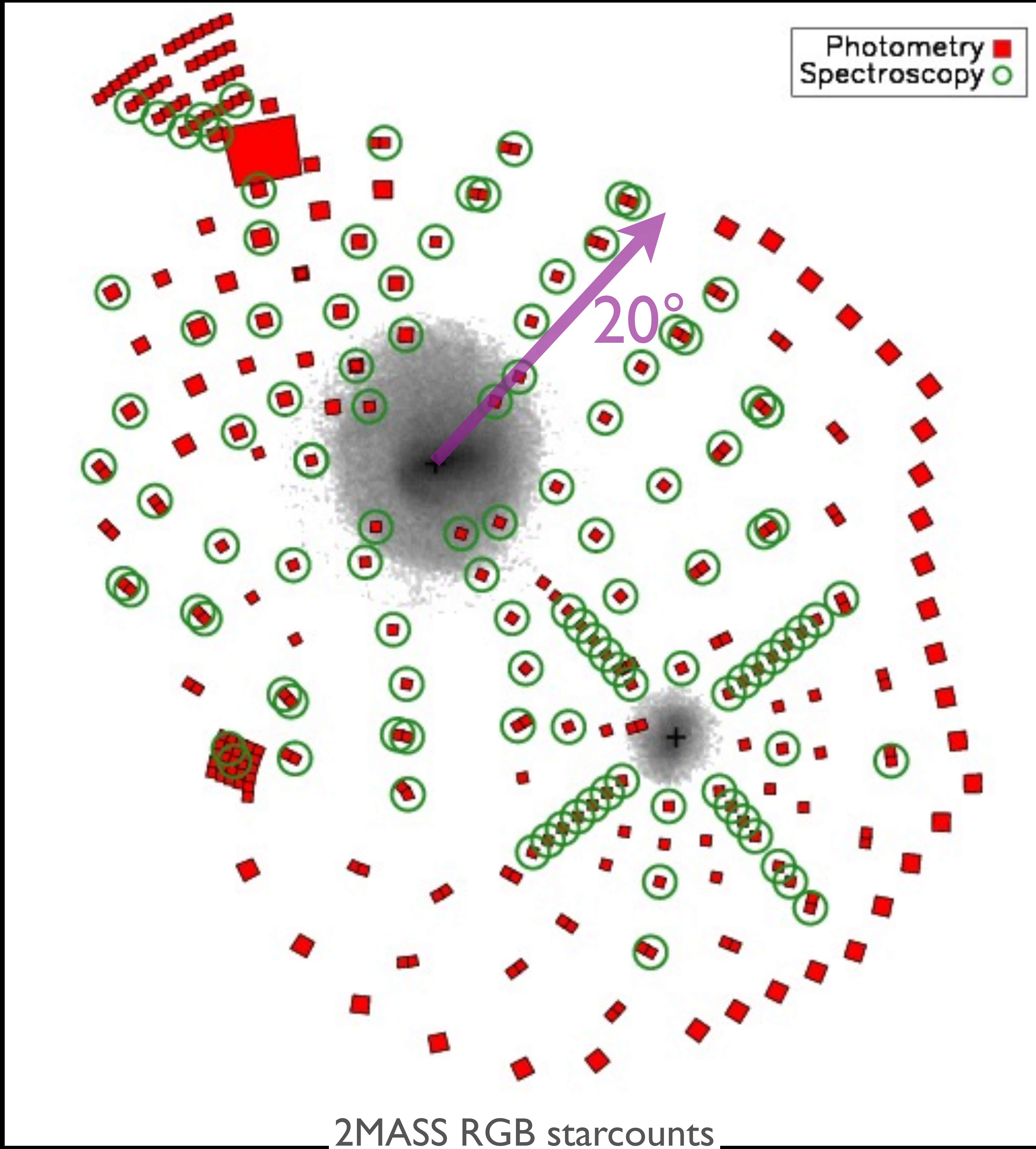


MAPS

MAgellanic Periphery Survey

Photometry

- Washington M,T_2+DDO51 filters
- Depth: V=22-24
- Coverage: ~100 deg^2
- Area sampled: ~2000 deg^2



MAPS

MAgellanic Periphery Survey

Photometry

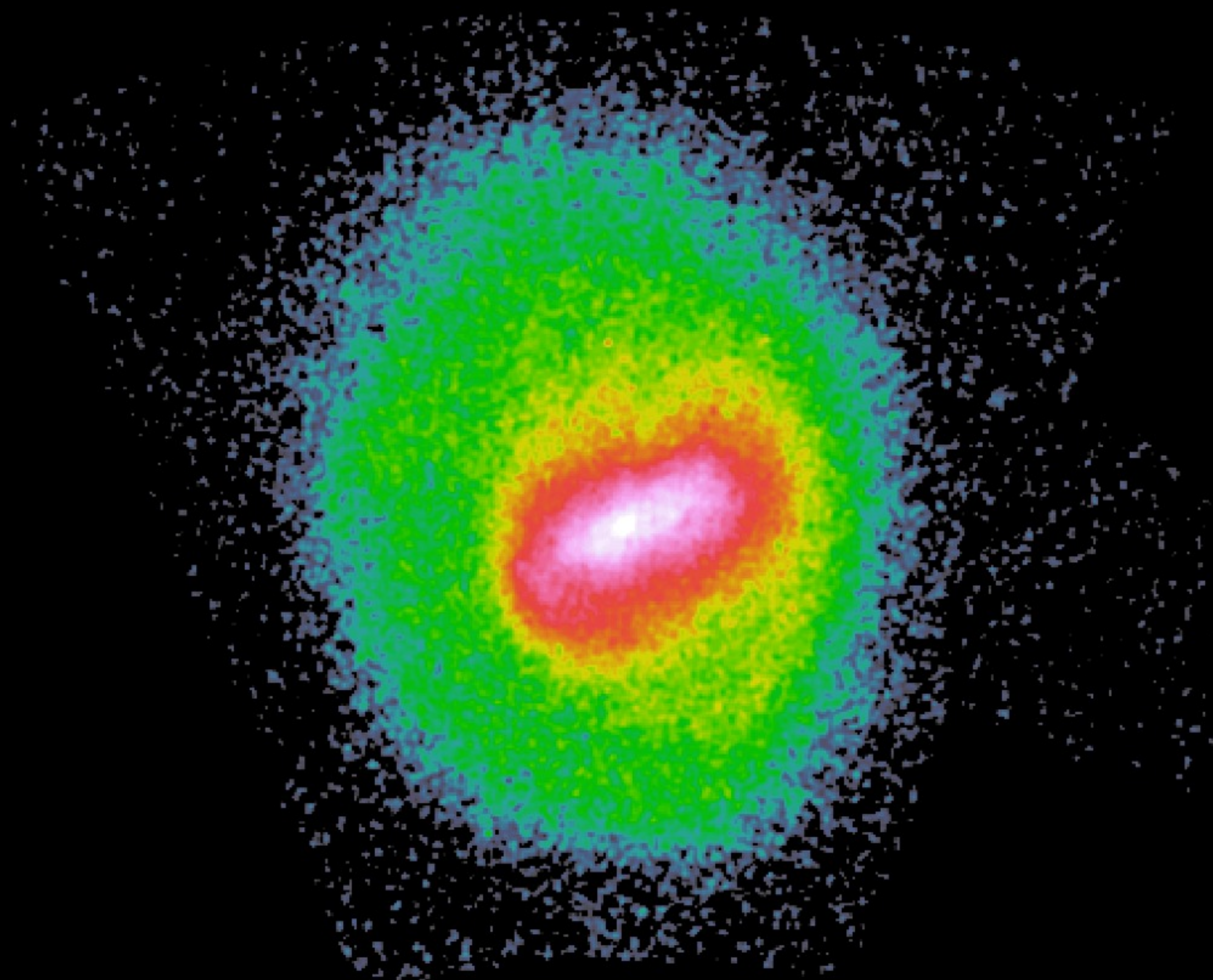
- Washington M,T_2+DDO51 filters
- Depth: V=22-24
- Coverage: ~100 deg^2
- Area sampled: ~2000 deg^2

Spectroscopy

- R~3,000
- ~11,000 spectra
- 2/3 of data reduced so far

Roughly 40 nights of data on 4-6m telescopes

LMC Stellar Periphery

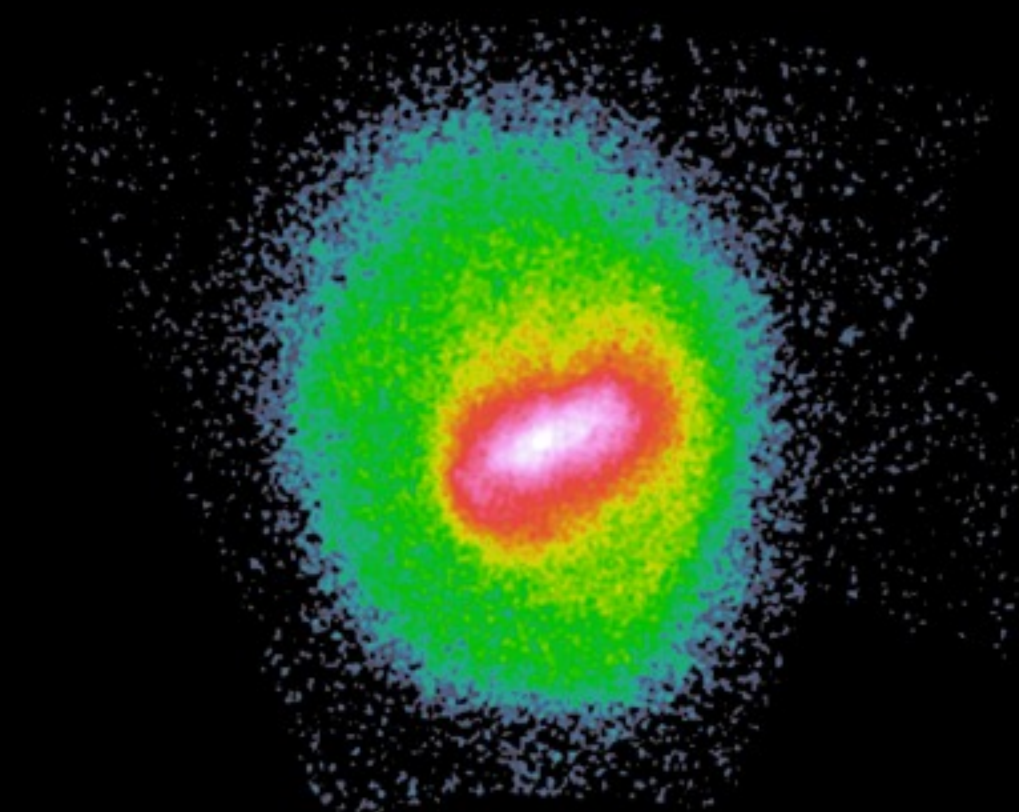


van der Marel (2001)

Background: LMC Disk and Halo

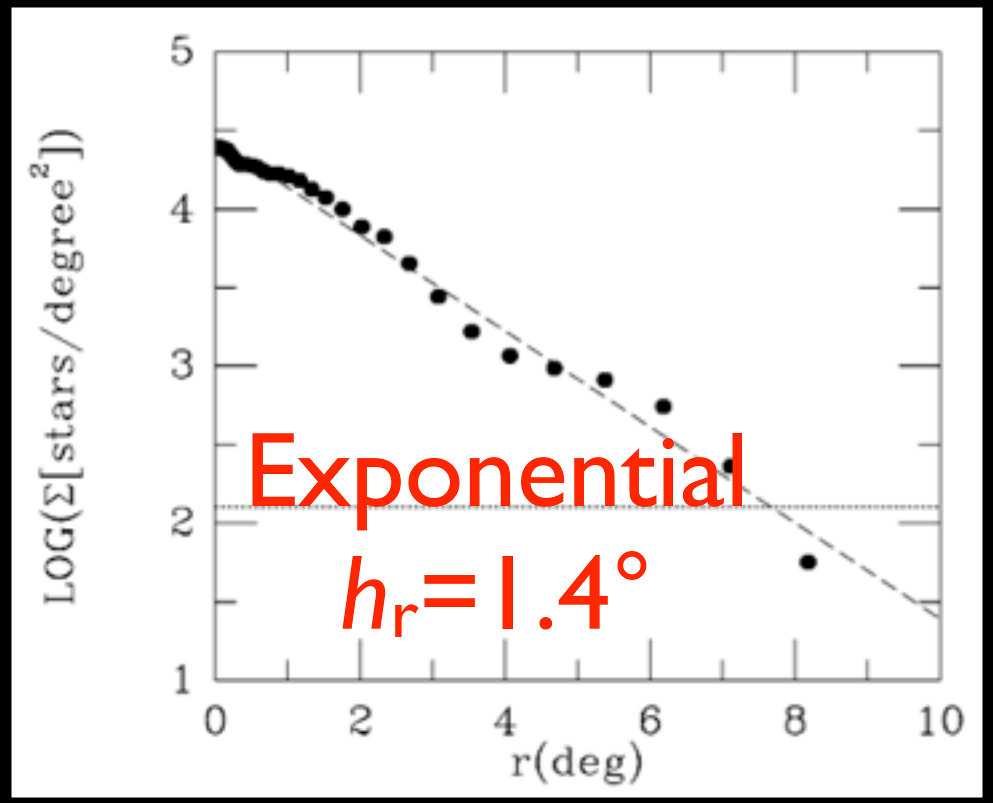
- **Exponential Disk** extends to *R*=10° with scale length h_r=1.4-1.7° (van der Marel 2001; Harris 2007, Meschin 2008)
- **Old, metal-poor halo** from RR Lyrae stars (Macho and OGLE identified) (Minniti et al. 2003; Borissova et al. 2004, 2006; Alves 2004)
  - σ_v=53 km/s
  - [Fe/H]= -1.53 +/- 0.02
  - But, density profile is Exponential to R=15°, h_r=1.68° → *Same as disk!*

LMC Disk (RGB stars)



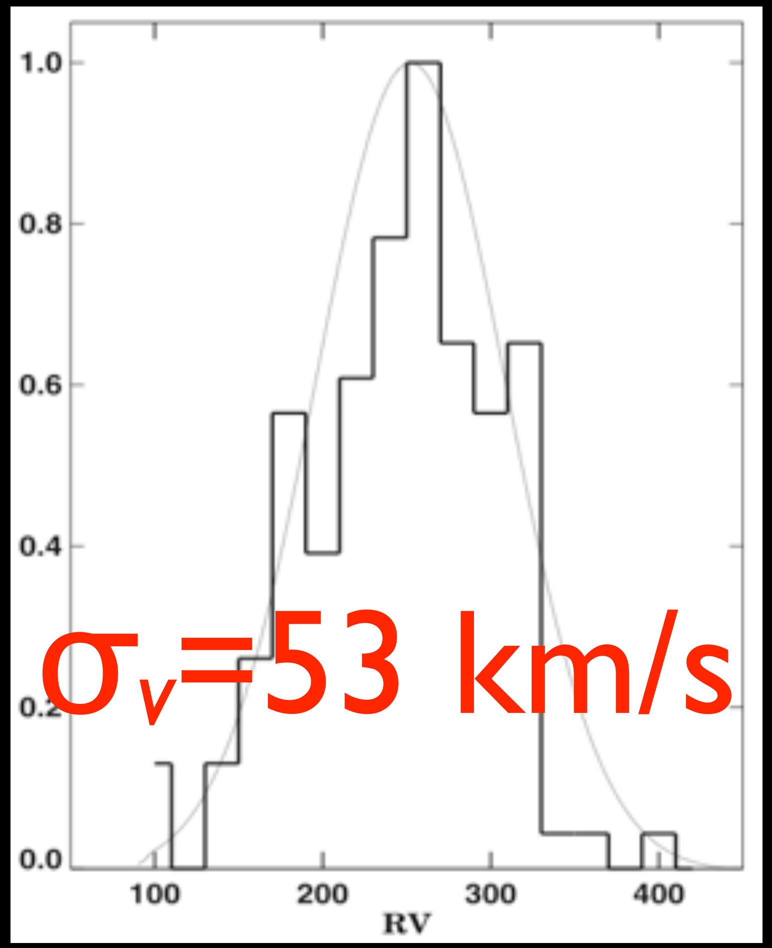
van der Marel (2001)

Disk Density Profile



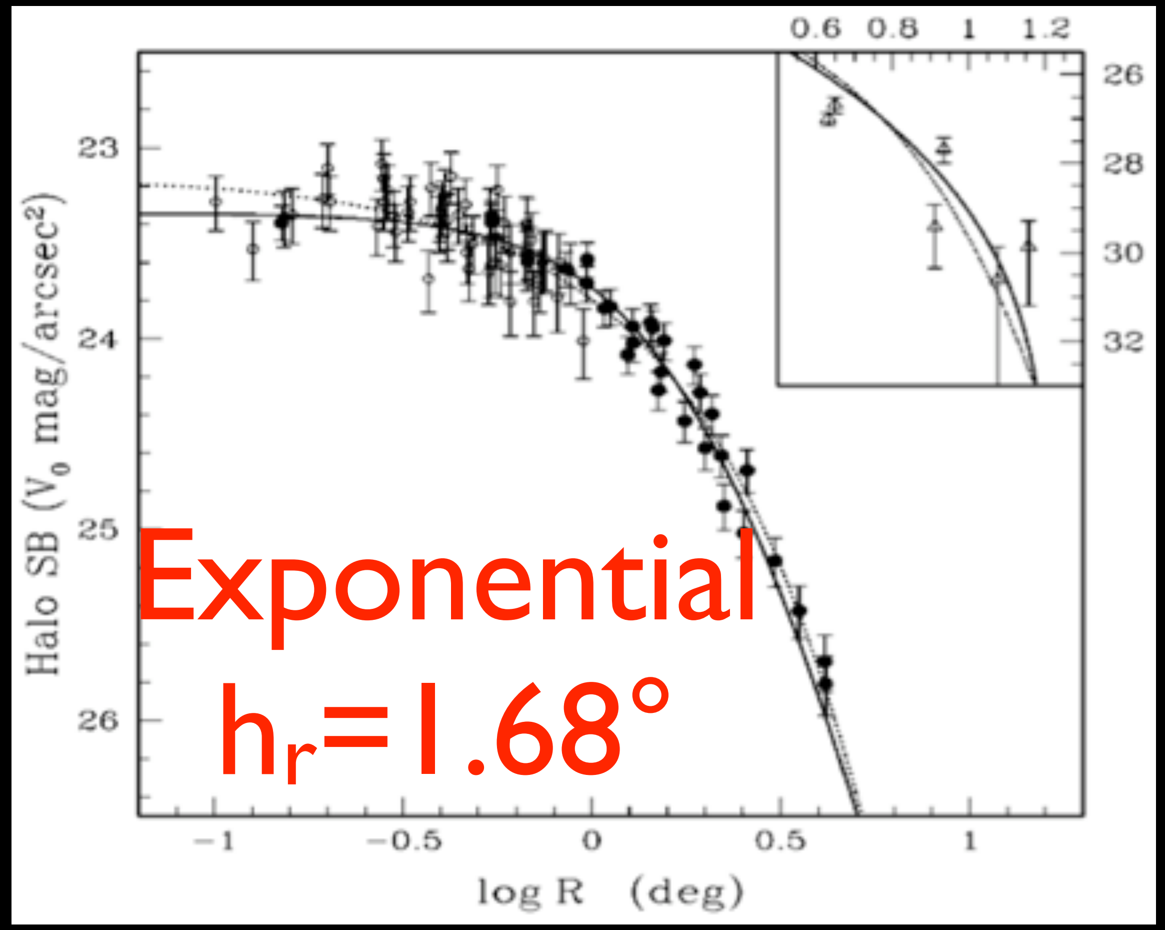
van der Marel (2001)

RR Lyrae RVs



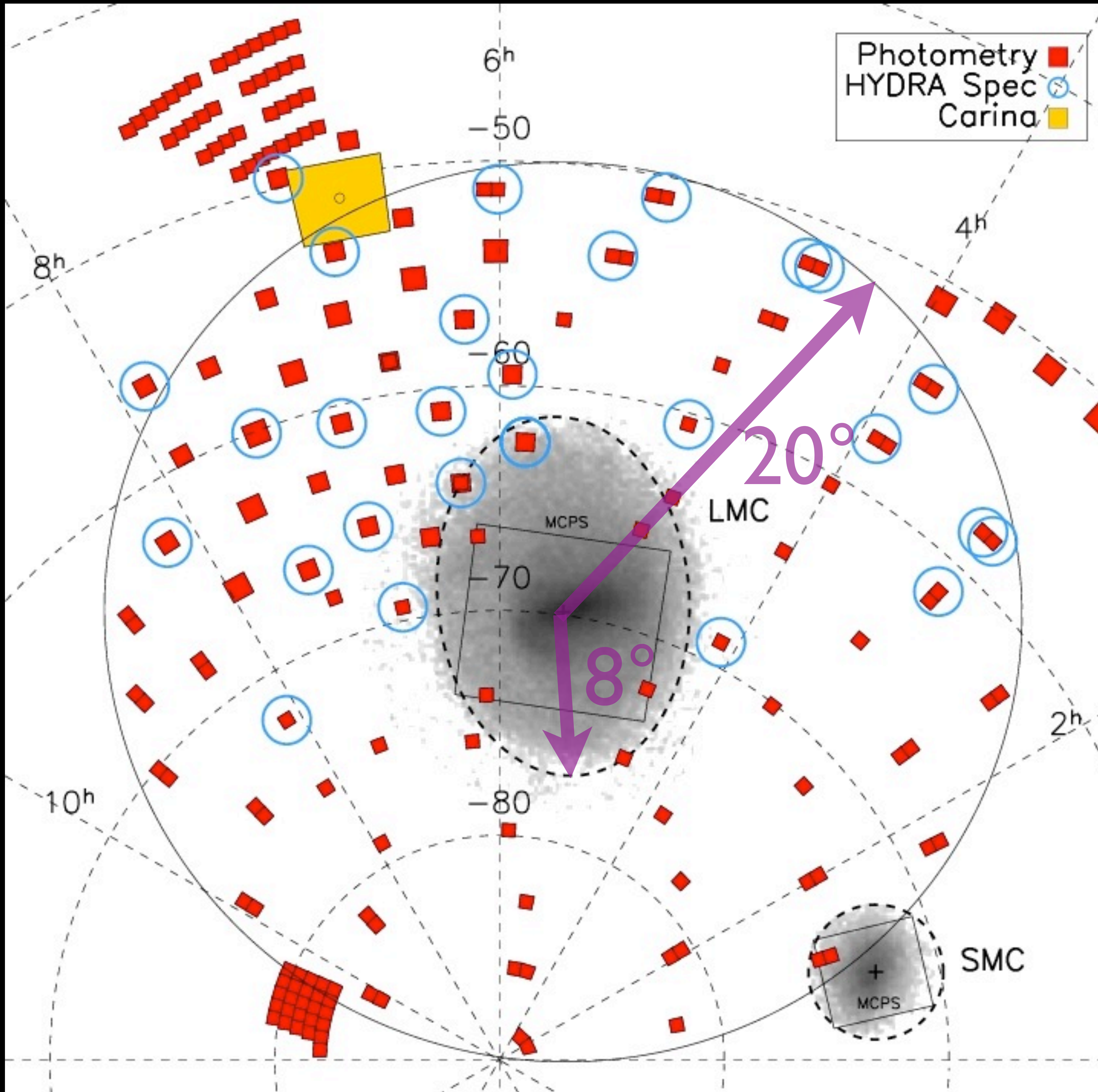
Borissova et al. (2006)

RR Lyrae Density Profile



Alves (2004)

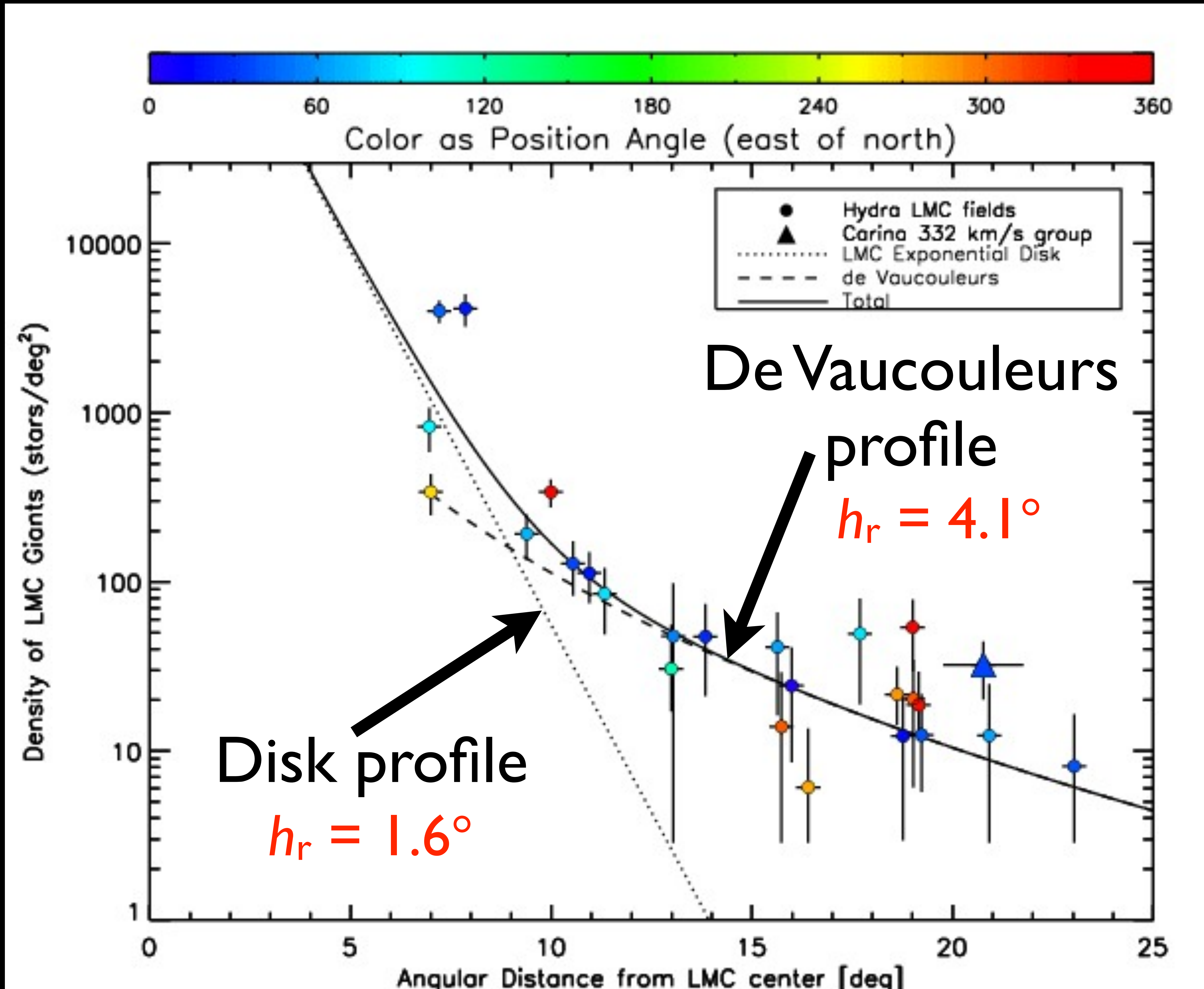
MAPS Follow-up Survey



SPECTROSCOPY

- CTIO 4m + HYDRA
- R~3000
- 4600-7000A
- 27 fields (reduced so far)
- Radial range=7-23°
  Azimuthal coverage=180°
- Exp. time ~ 3.5 hours to reach V~19.3 (LMC red clump)
- ~3000 stars total
  ~900 LMC stars

LMC Density Profile

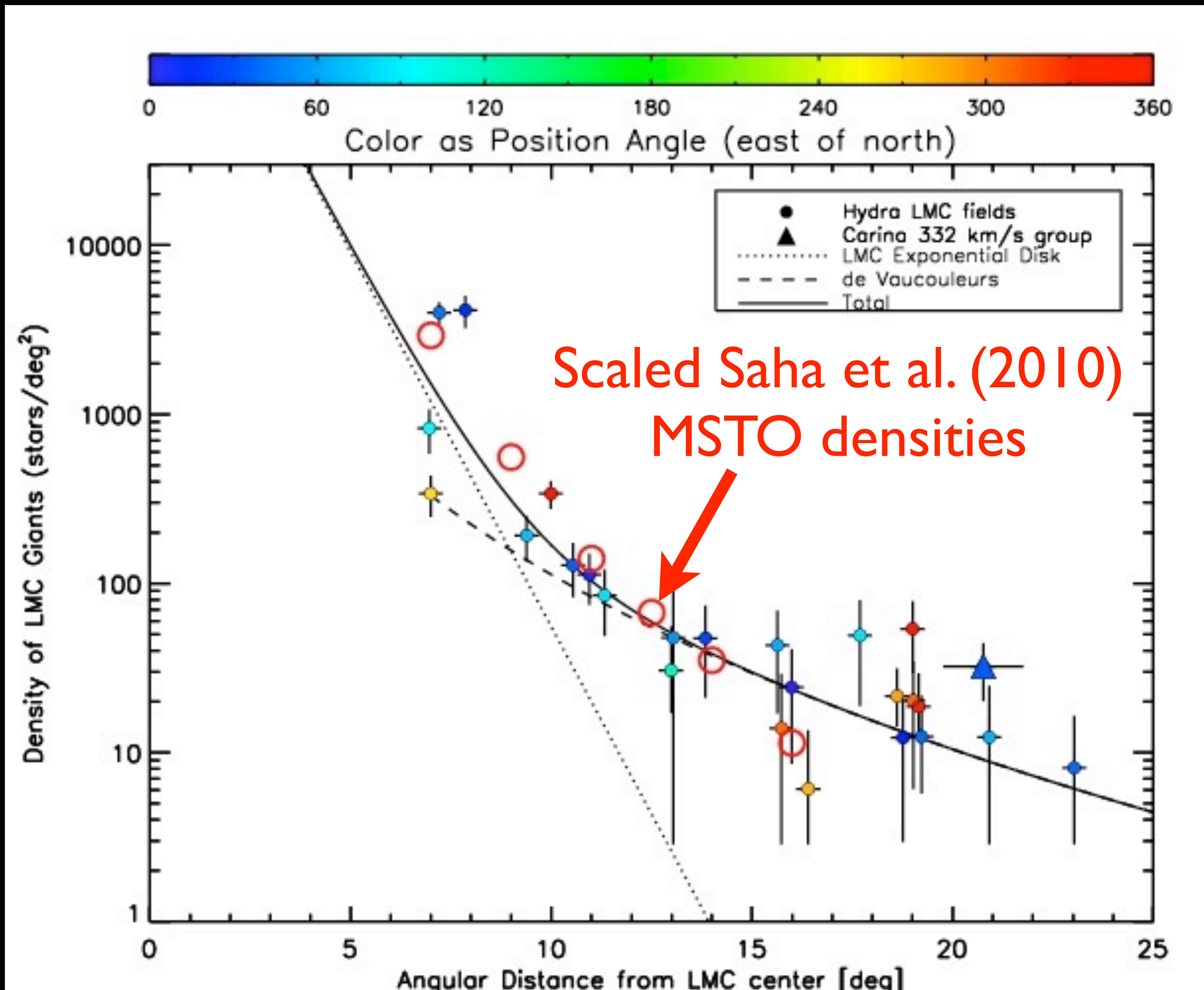


* Stars selected to be LMC by velocity, CMD and 2CD used to account for spectroscopic
- selection function
- RV member fraction

- Outer density profile well-fitted by
  - de Vaucouleurs profile (core radius = 2.4°)
  - exponential of h_r = 4.1°

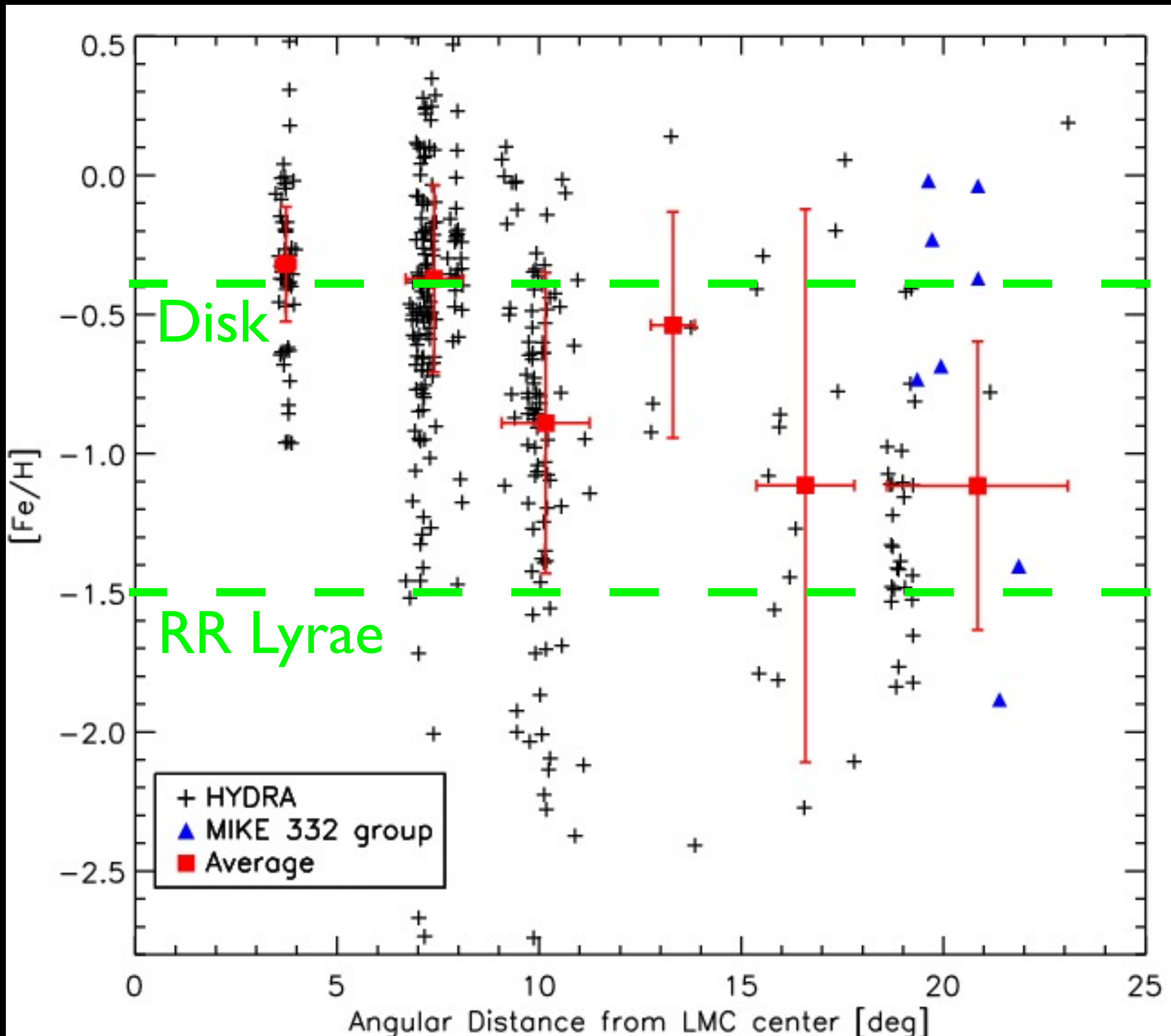
New, very extended LMC population

Comparison of Saha et al. Density Profile



- Saha et al. detect LMC MSTO stars to R=16°
- No detection at R=17, 19°
- Single position angle
- Scatter at large R suggests *substructure*
- Maybe Saha et al were "unlucky" in their field placement

Spectroscopic Metallicity Profile



- [Fe/H] from Lick indices
- Metallicity gradient out to *R*~20° (and maybe beyond?)
- But *large* [Fe/H] spread everywhere

New, very extended *metal poor,* LMC halo population

(though not as metal-poor in the mean as Milky Way or M31)

Majewski, Nidever, et al. (2009) Nidever et al. (2014), in prep.

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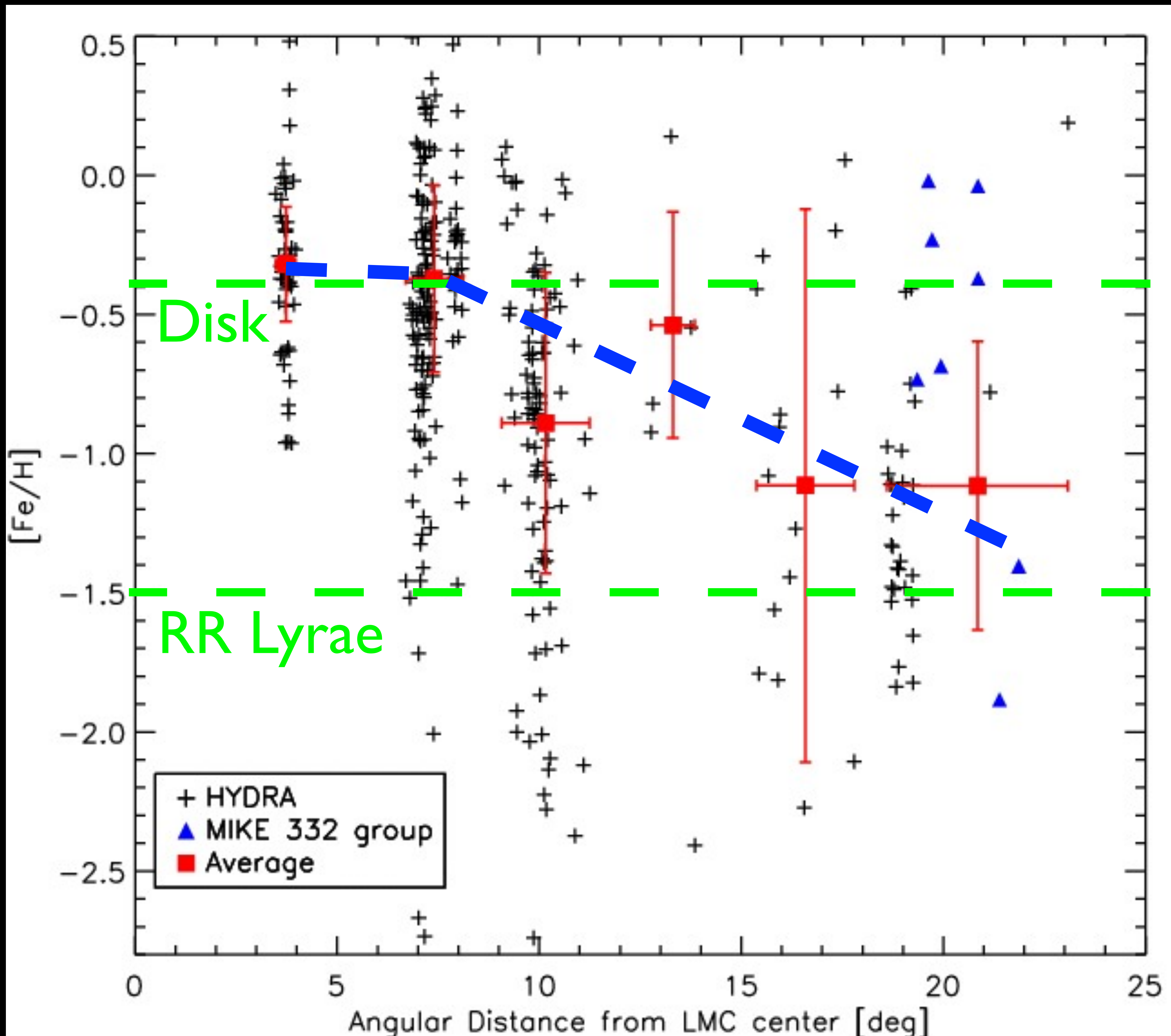

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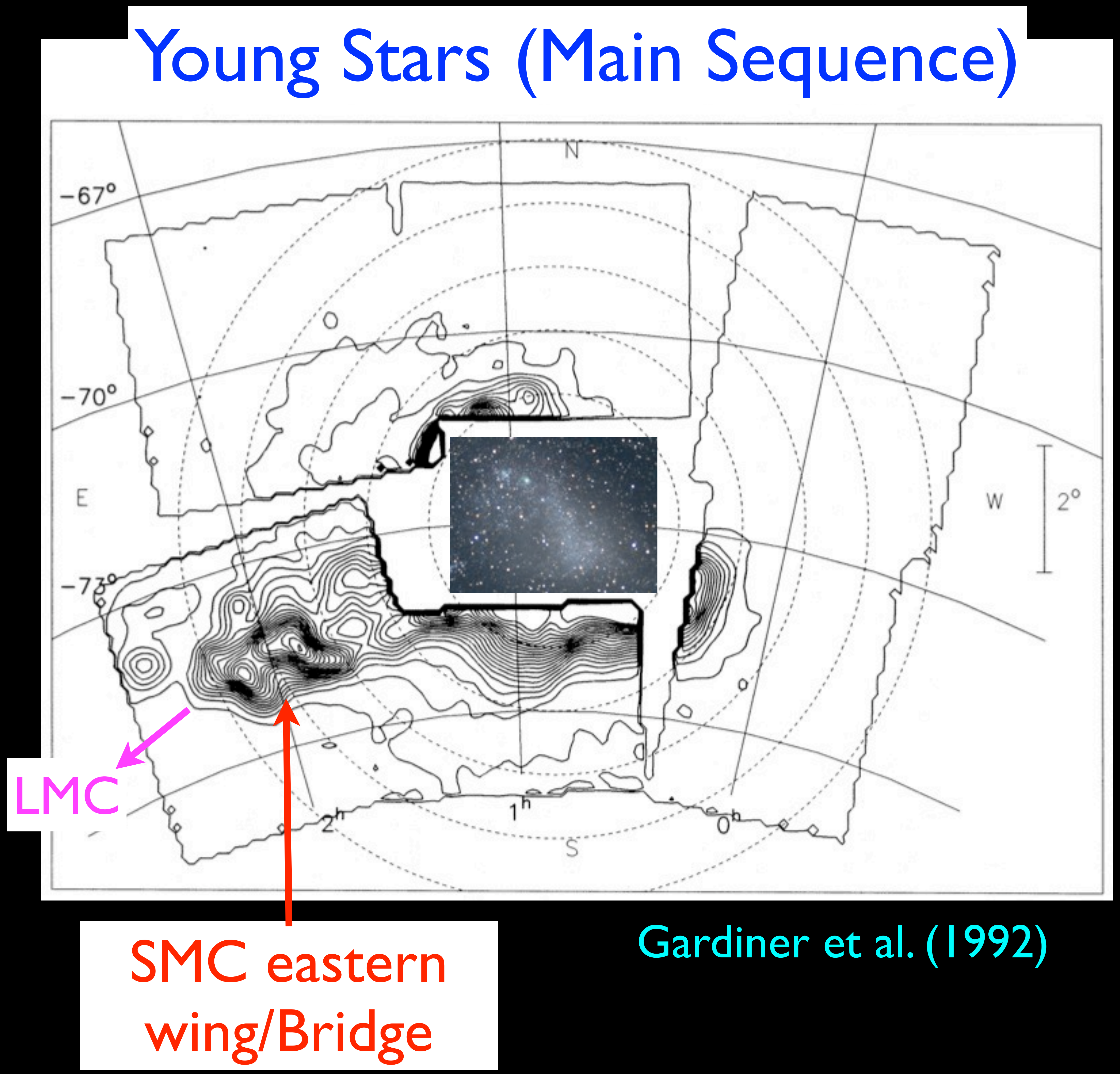
SMC Stellar Periphery

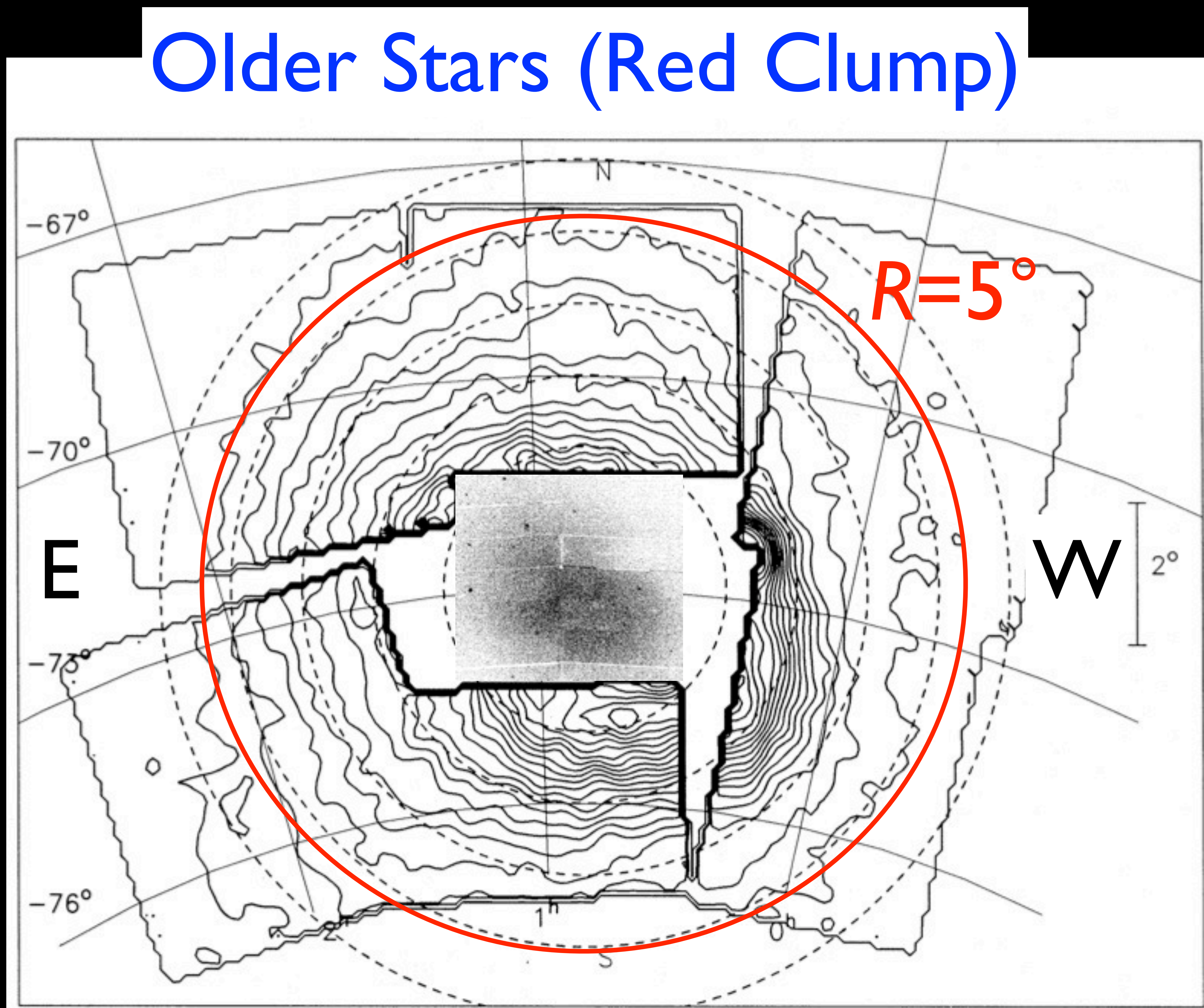
Background: SMC Structure



Gardiner et al. (1992)

- Hatzidimitriou, Hawkins, and Gardiner
- Used photographic plate photometry to study the SMC periphery
- Distribution of young stars very irregular and elongated to towards the LMC
- Also seen in HI
- SMC eastern wing/Bridge

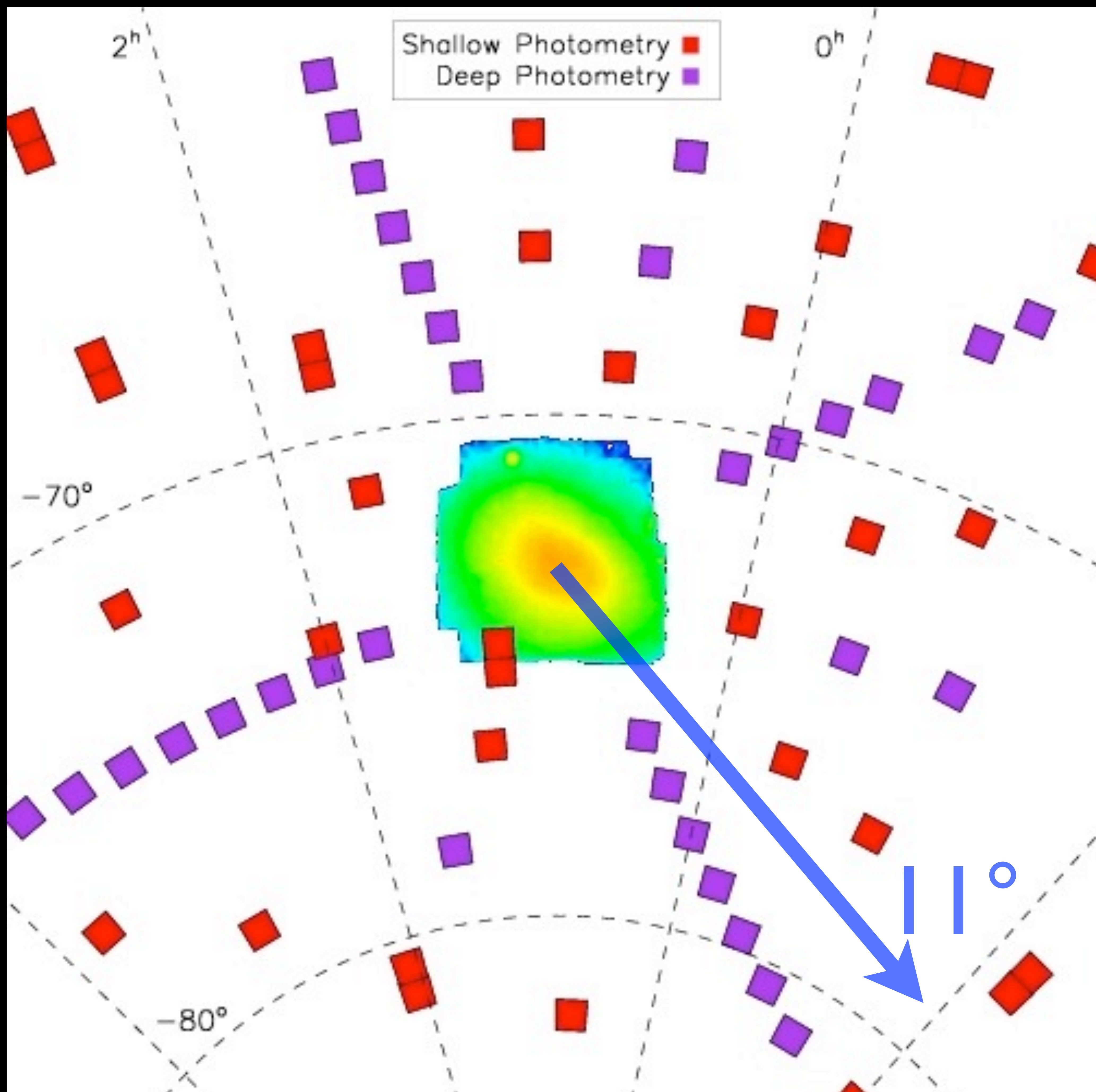
Background: SMC Structure



Gardiner et al. (1992)

- Distribution of older/red stars is much more regular, symmetric
- Find red clump stars out to *R*~4-5°
- Steeper dropoff on the western side

Our SMC fields



OGLE III+MCPS SMC RGB Starcounts

Photometric Data

- CTIO-4m+MOSAIC photometry
- Washington M,T_2+DDO51 filters
- Depth: V=22-24
- Fields out to *R*~11°
- Coverage: ~22 deg^2
- Area sampled: ~400 deg^2

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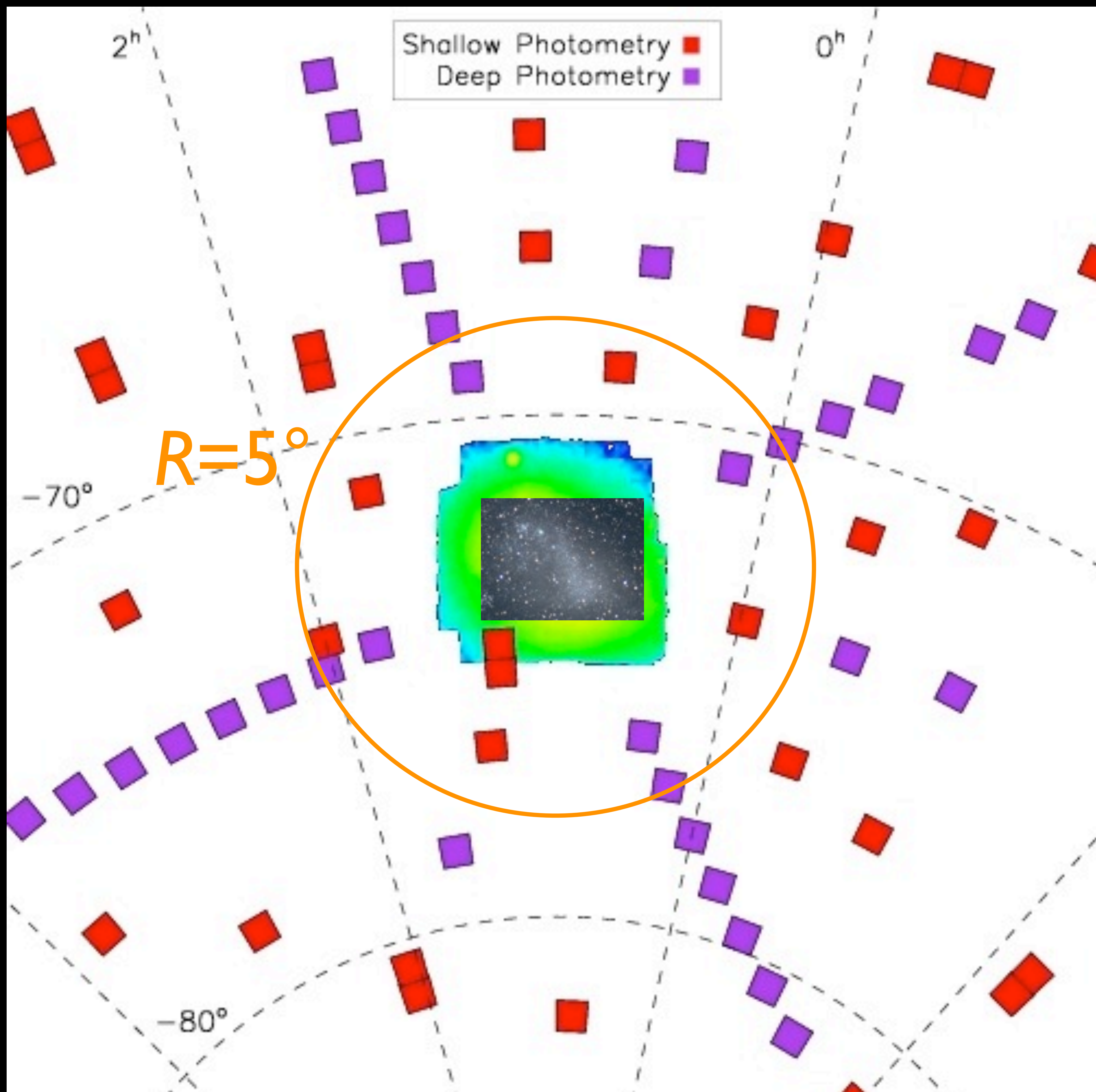

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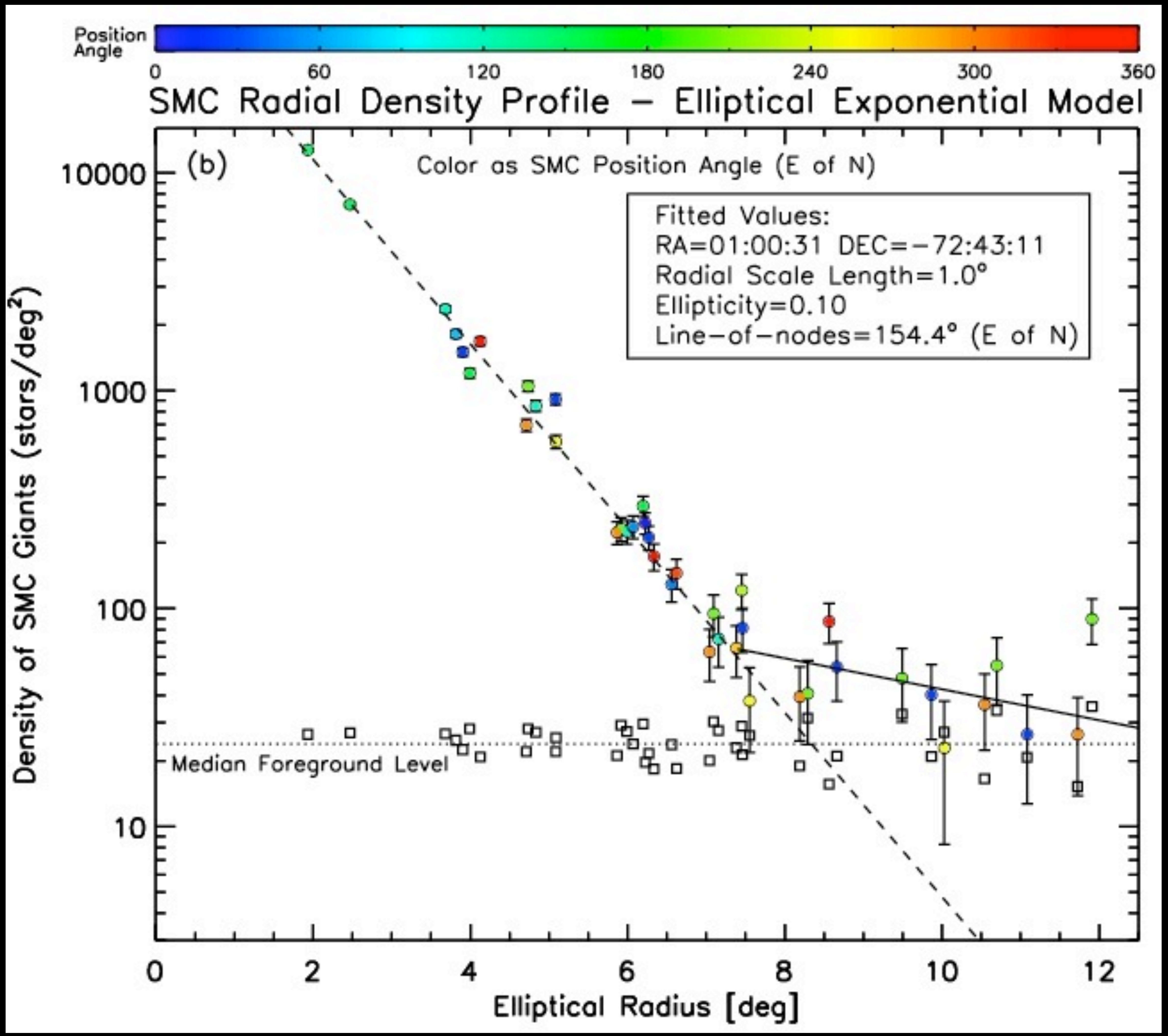
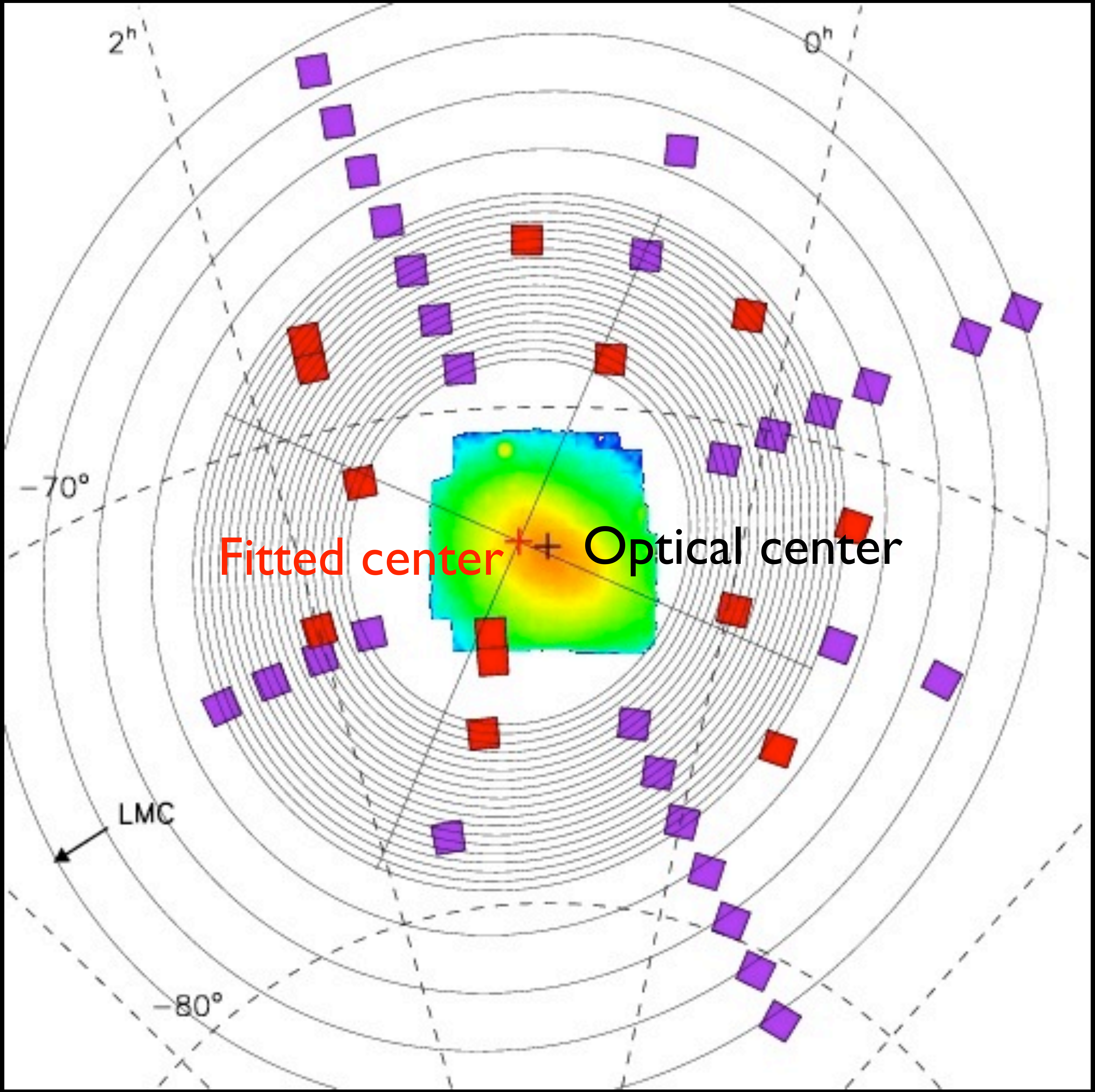
SMC Radial Density Profile

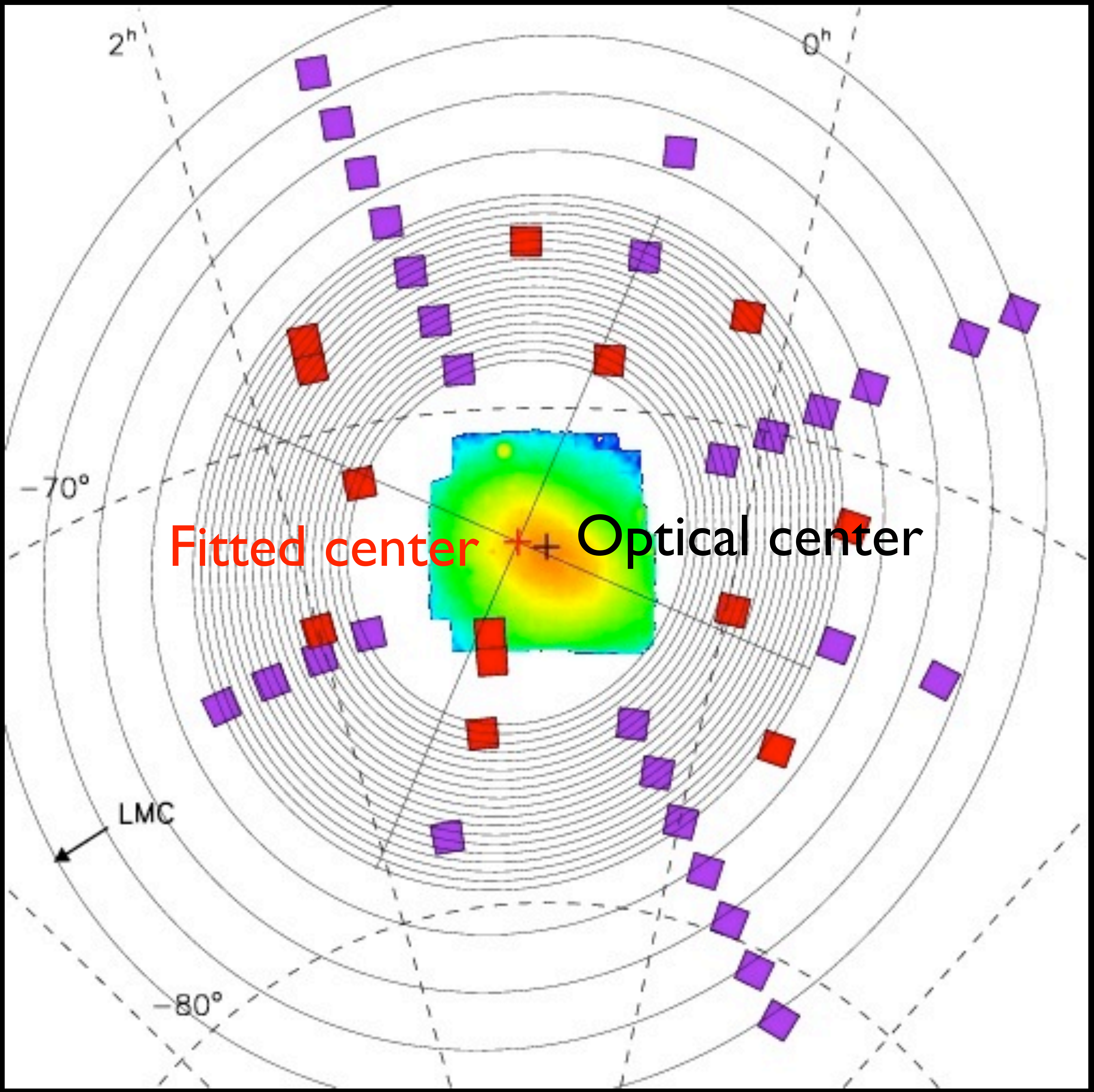


- shifted by 0.59° (0.6 kpc) to the east
- Elliptical exponential fit
- Slightly elliptical
- Fitted to R<8°
  - e = 0.10
  - radial scale length = 1.0°
- Break population for R>7.5°

Model of Outer SMC Distribution

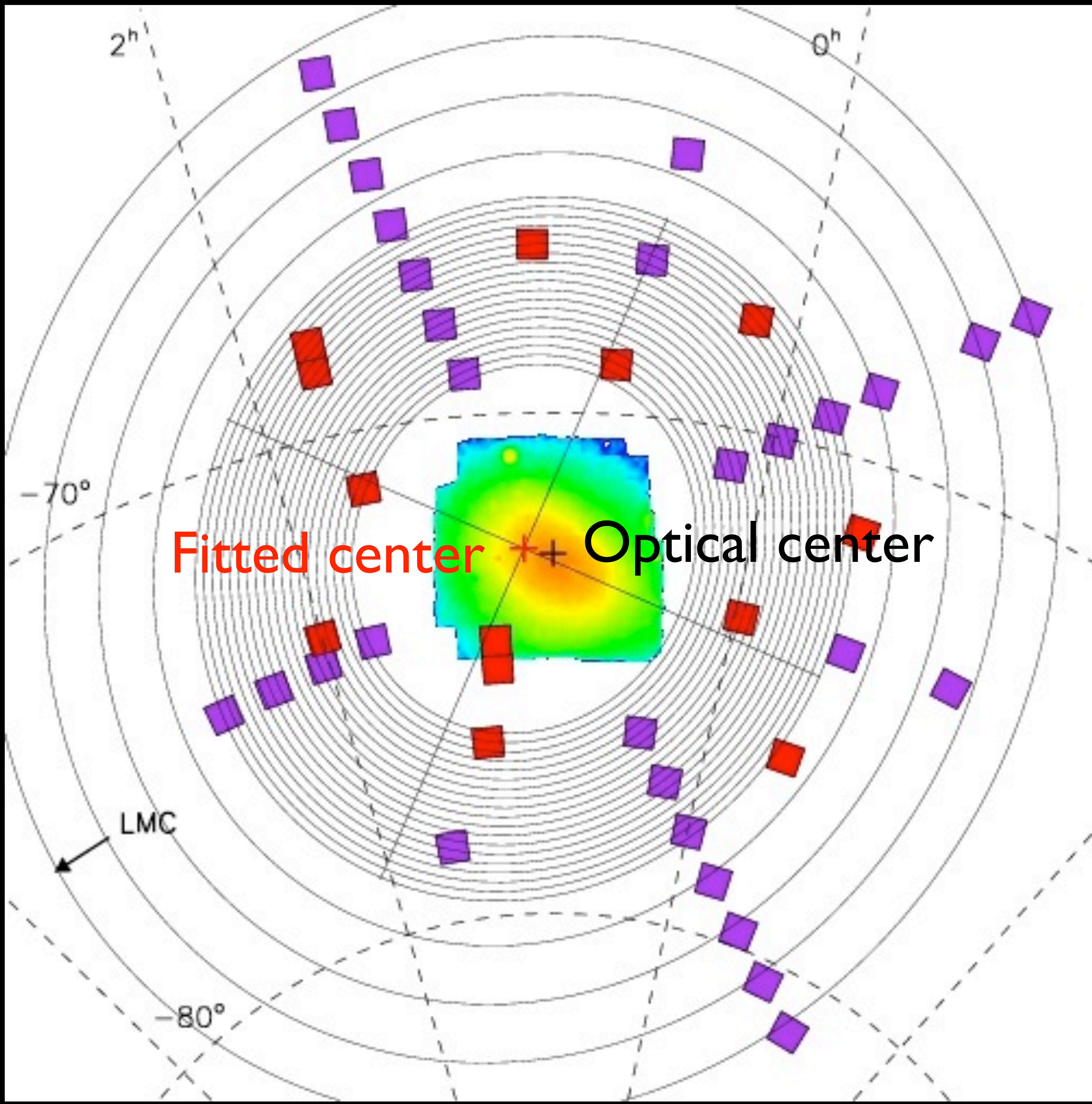


Results



- Detected SMC out to ~11 kpc

Results



- Detected SMC out to ~11 kpc
- Center offset by 0.6 kpc from optical center. Perspective effect.

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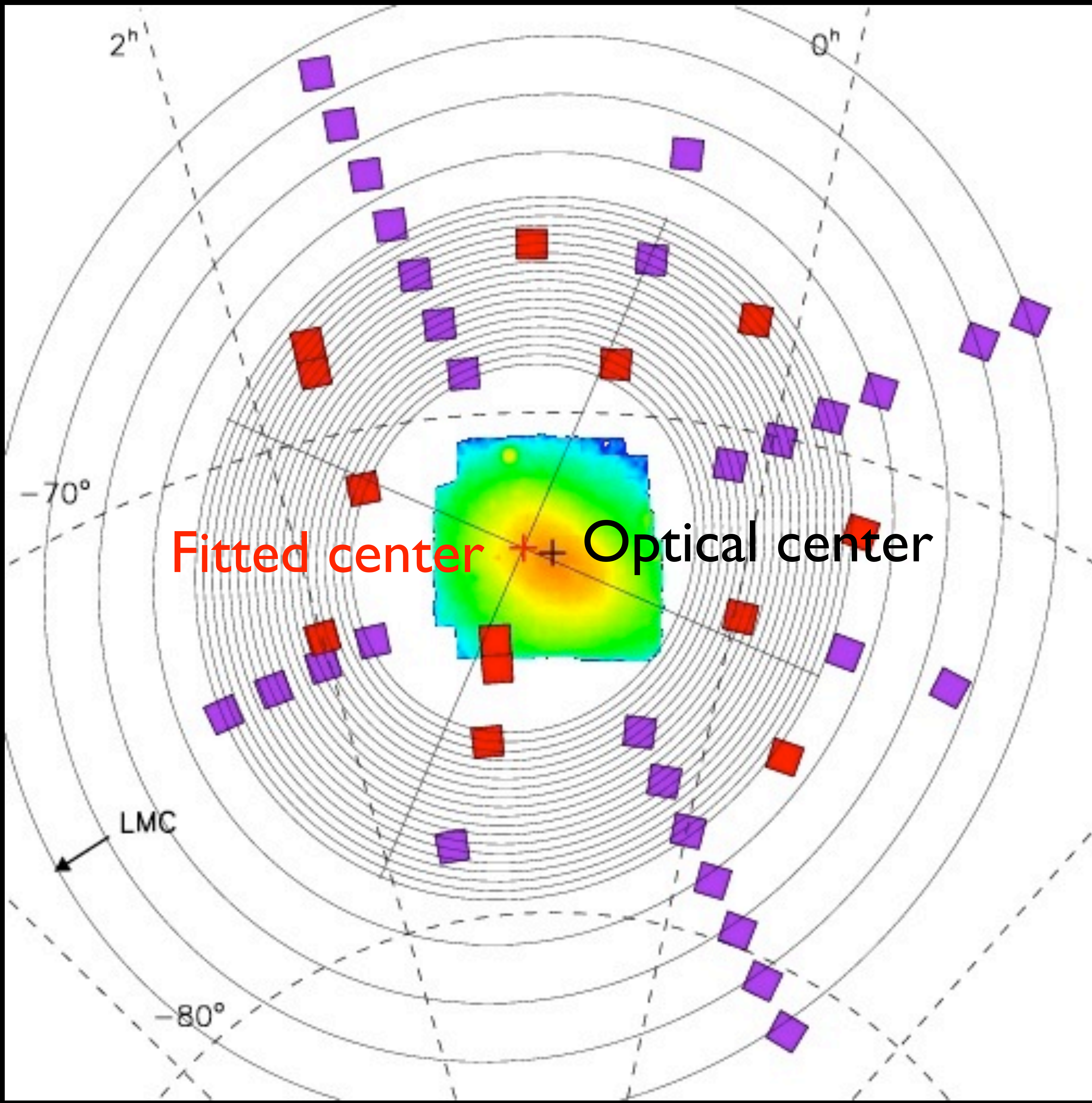

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- Inner/Outer distributions very different:
  - Eccentricities very different $e_{inner}=0.3$ $e_{outer}=0.1$
  - Major axes misaligned by ~105°

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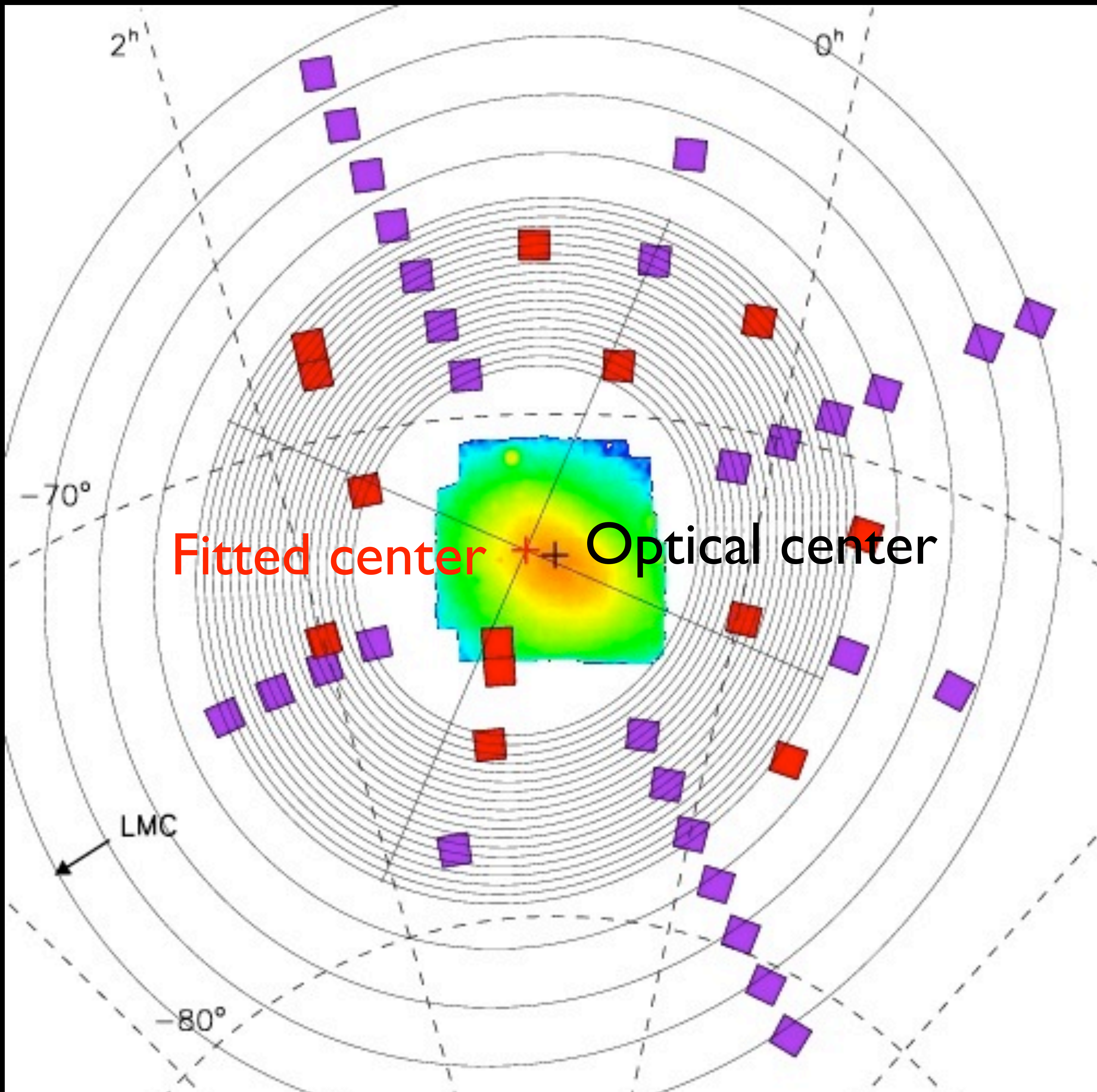

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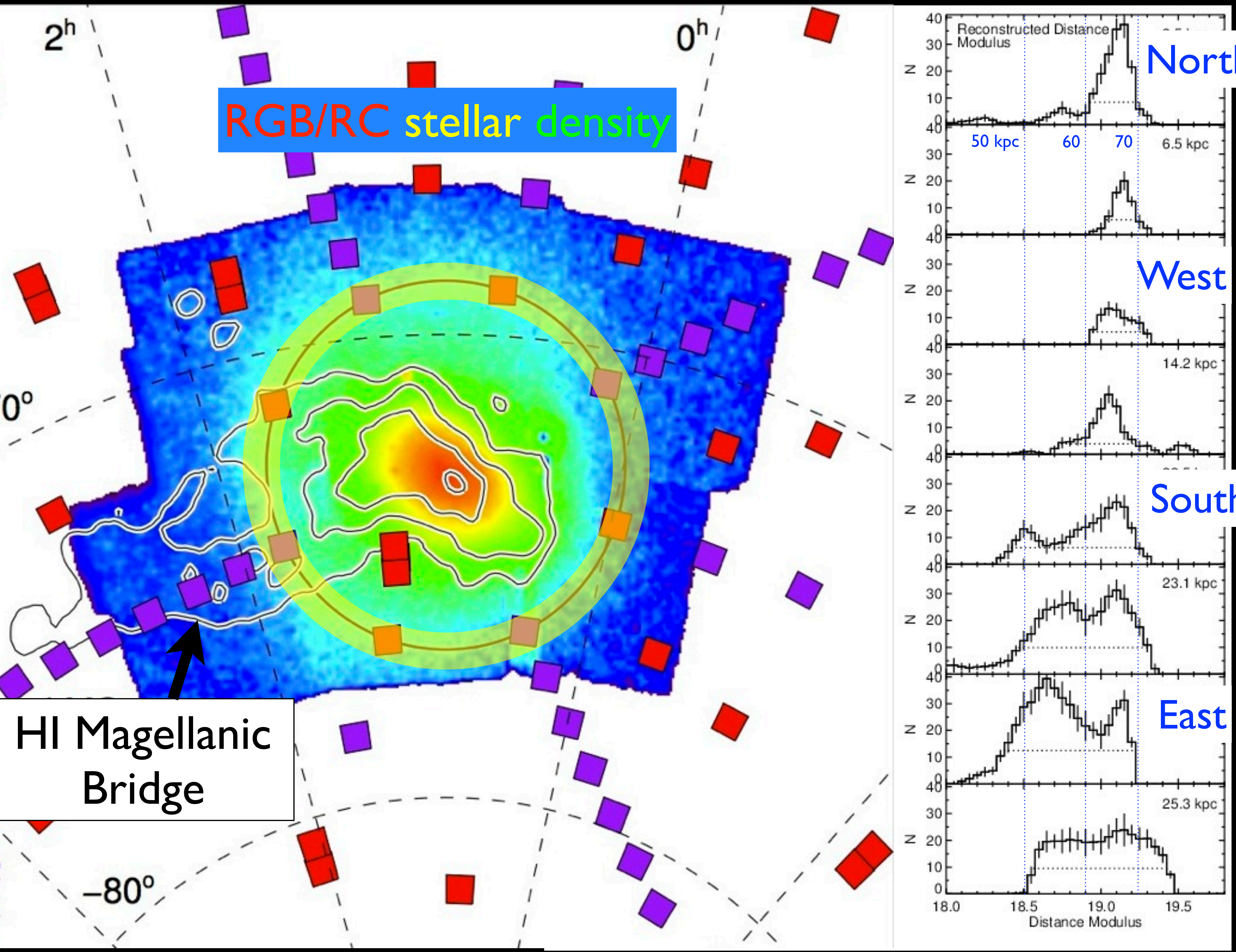
- Break population

Nidever et al. (2011)

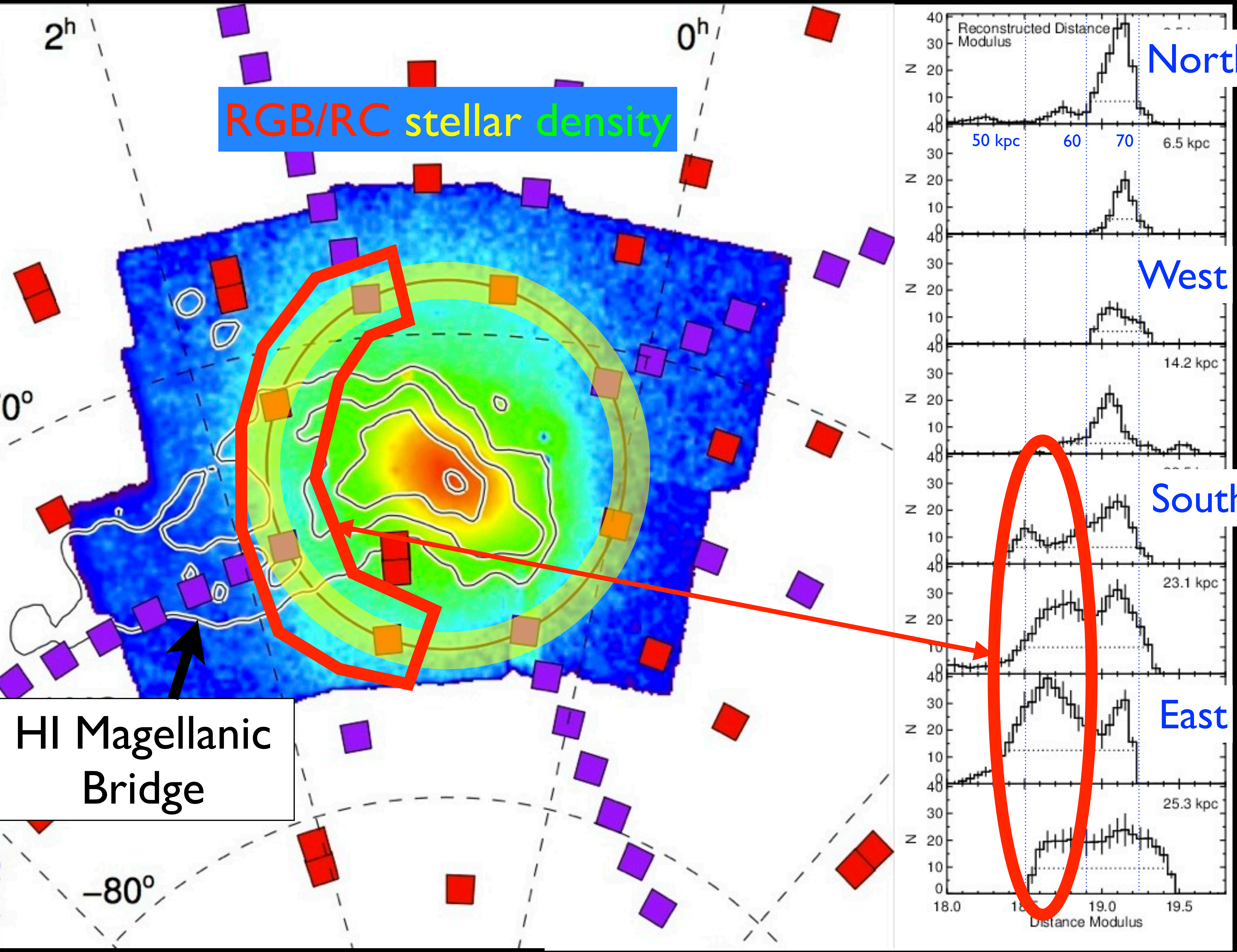
SMC Line of Sight Depth



Nidever et al. (2013a)

- SMC has large los depth
- Derive distances using red clump stars in 8 fields at R=4°
- Bimodality in distance function on eastern side
- New structure at ~55 kpc, near-side of SMC
- Likely stellar counterpart of Magellanic Bridge

Stellar Componont of the Bridge



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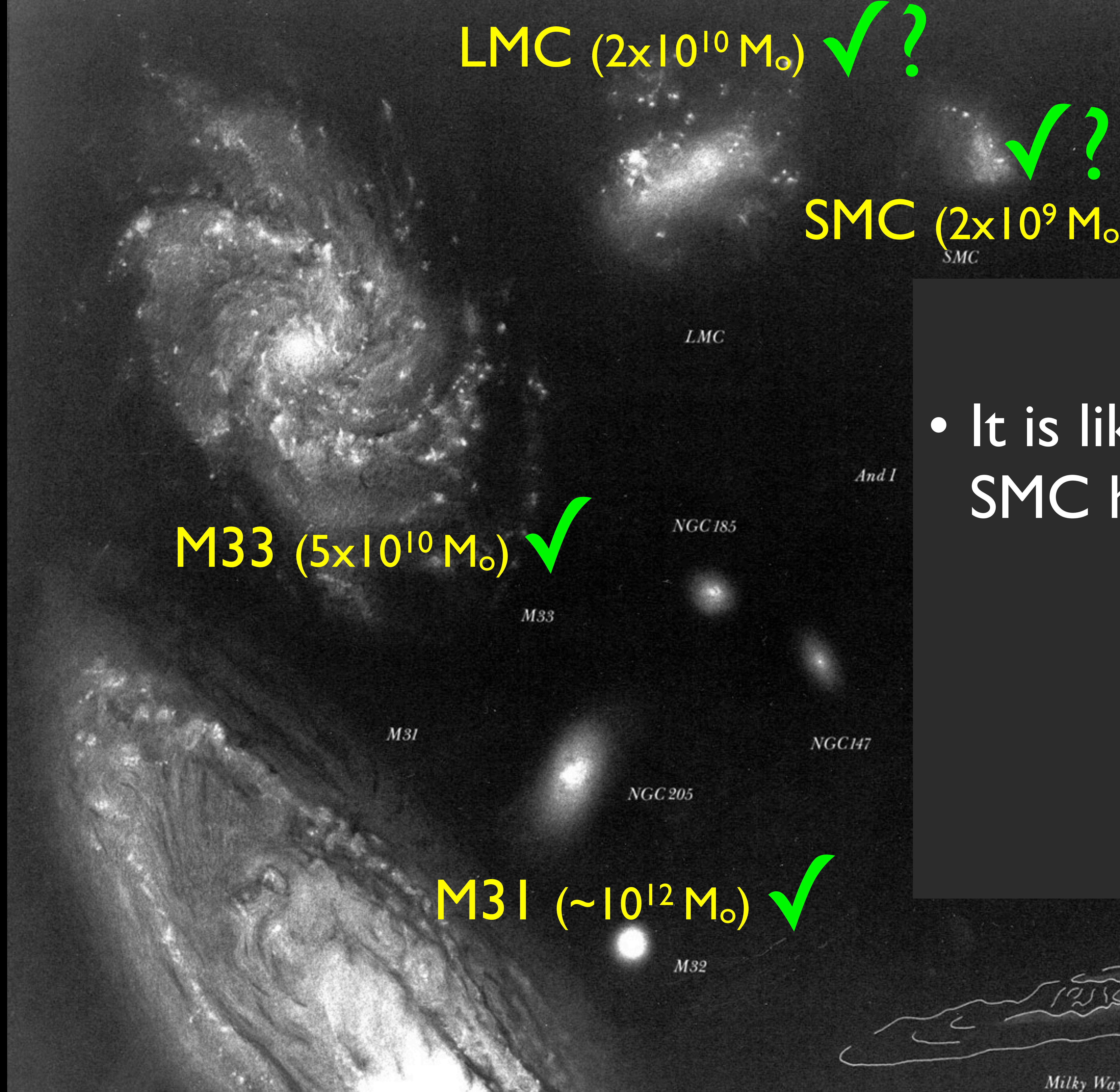
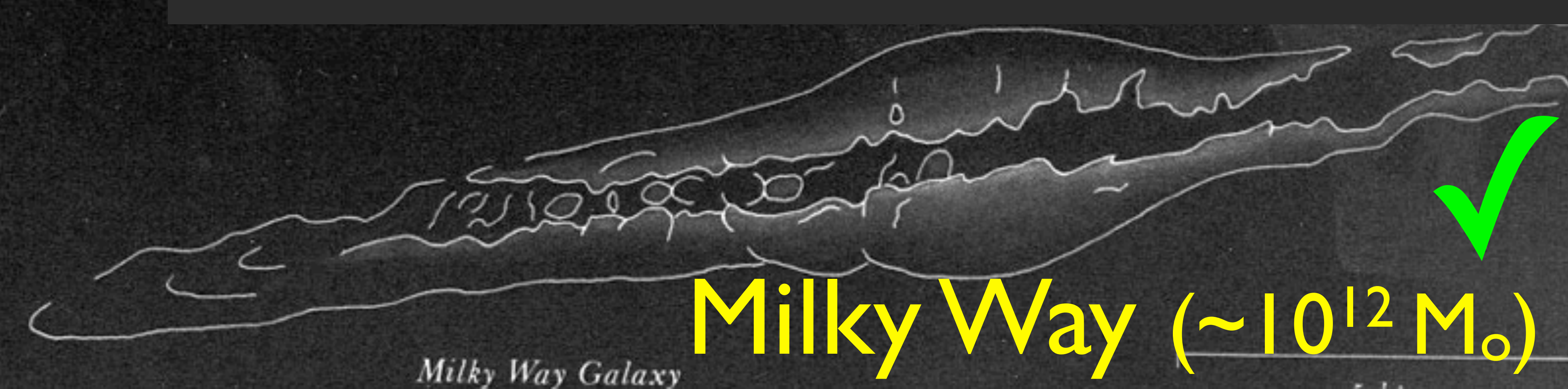
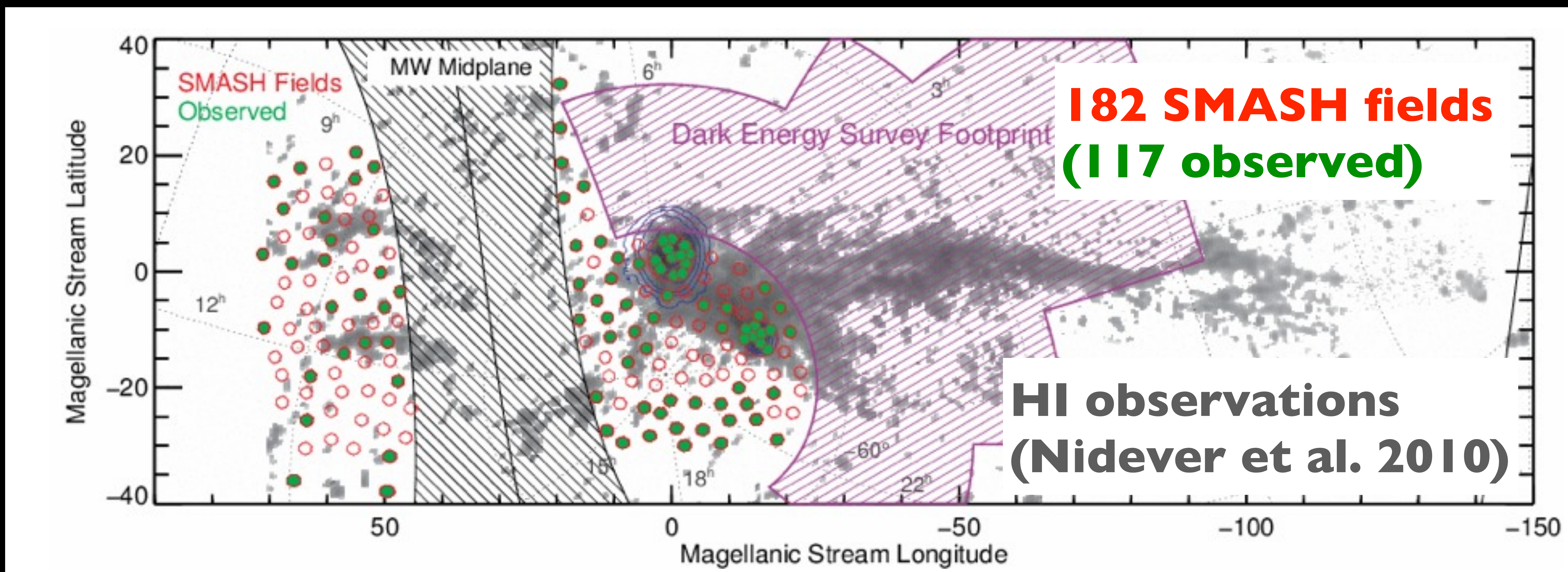
Local Group Stellar Halos

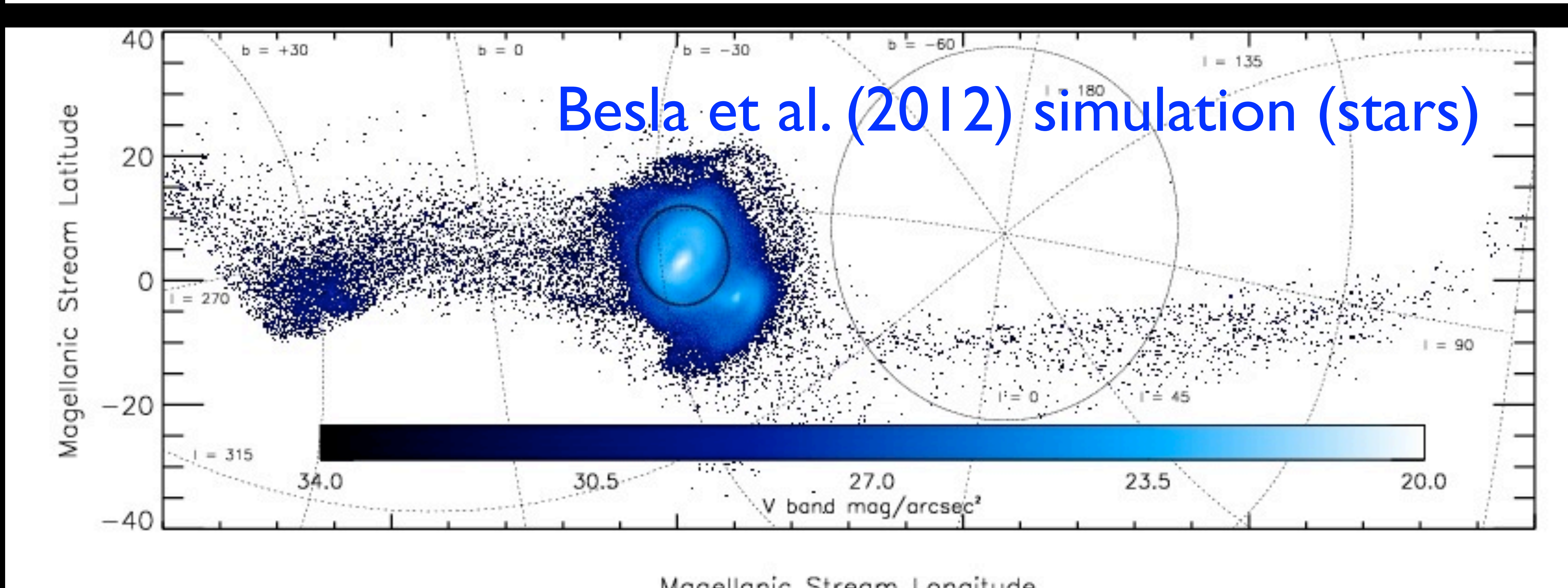


- It is likely that the LMC and SMC have stellar halos



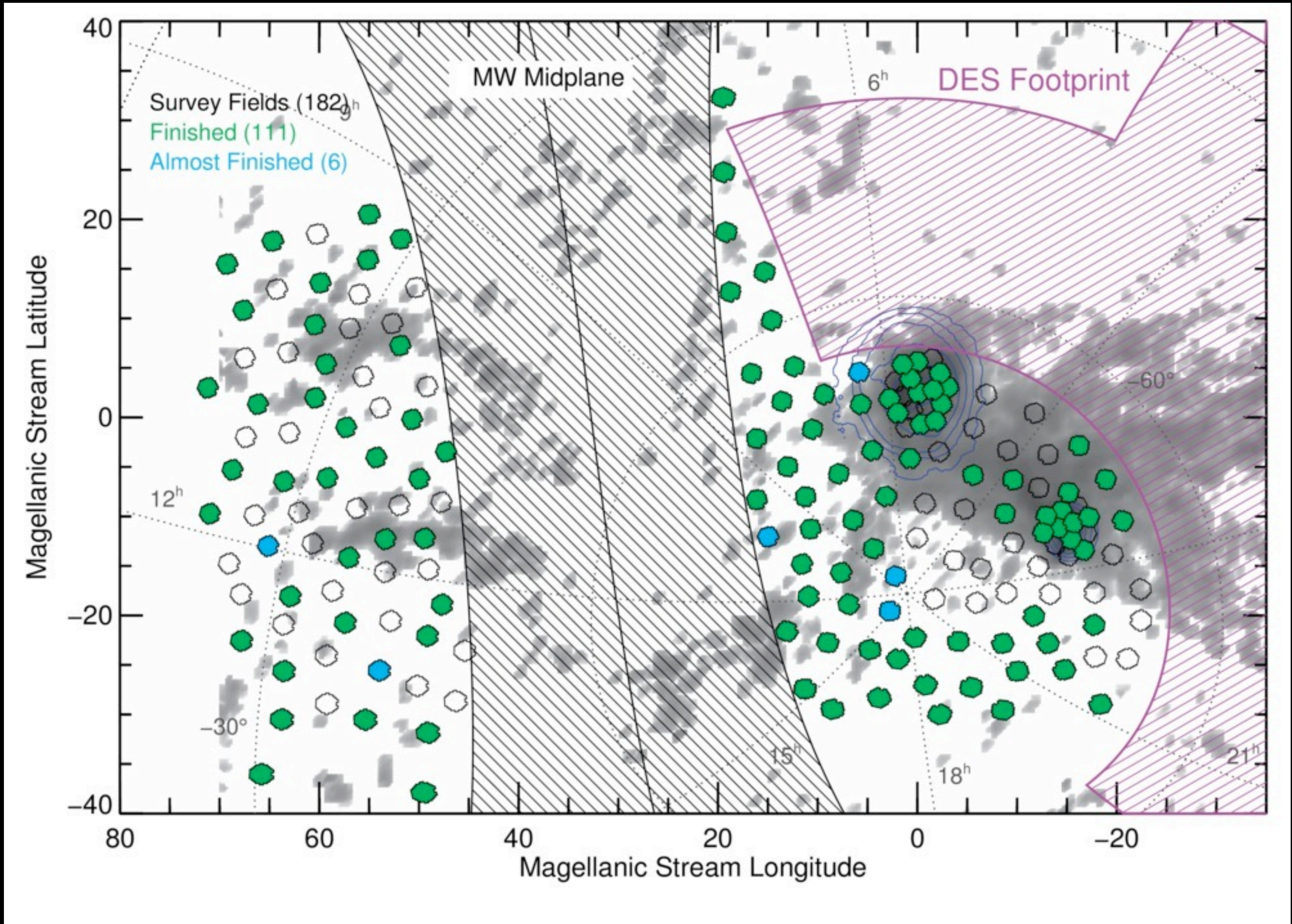
SMASH
Survey of the MAgellanic Stellar History





- PI: Nidever
- Large MC DECam survey
- Map 2500 deg^2 (at ~20% filling factor) to **~35.5 mag/arcsec^2**
- Depth of **gri~24 mag** and **uz~23 mag** to detect oMSTO stars
- 40 nights on DECam, 28 nights on 0.9m (calibration)
- After 1.5 years, 117 of 182 fields observed

SMASH



MW Midplane
DES Footprint
Survey Fields (182)
Finished (111)
Almost Finished (6)
Magellanic Stream Latitude
Magellanic Stream Longitude
6h
9h
12h
15h
18h
21h
−30°
−60°
40
20
0
−20
−40
80
60
40
20
0
−20

Collaboration Members

- PI: David Nidever (UMich)
- Knut Olsen (NOAO)
- Robert Gruendl (Illinois/NCSA)
- Carme Gallart (IAC)
- Matteo Monelli (IAC)
- Gurtina Besla (UAz)
- Ricardo Munoz (U.Santiago)
- Abi Saha (NOAO)
- Alistair Walker (CTIO)
- Robert Blum (NOAO)
- Catherine Kaleida (ASU/CTIO)
- Eric Bell (UMich)
- Kathy Vivas (CTIO)
- Ed Olszewski (UAz)
- Roeland van der Marel (STSci)
- Steve Majewski (UVa)
- Blair Conn (Gemini)
- Dennis Zaritsky (UAz)
- Shoko Jin (Groningen)
- Nicolas Martin (Strasbourg)
- Noelia Noel (ETH/U. of Surrey)
- Hwihyun Kim (ASU)
- Maria-Rosa Cioni (Hertfordshire)
- Antonela Monachesi (MPIA)
- Cliff Johnson (UW)
- Guy Stringfellow (Colorado)
- David Martinez-Delgado (ARI)
- You-Hua Chu (Illinois/KITP Taiwan)
- Thomas de Boer (IoA, Cambridge)
- Andrea Kunder (AIP)

SMASH - Goals

1. Search for the stellar component of the Magellanic Stream and Leading Arm

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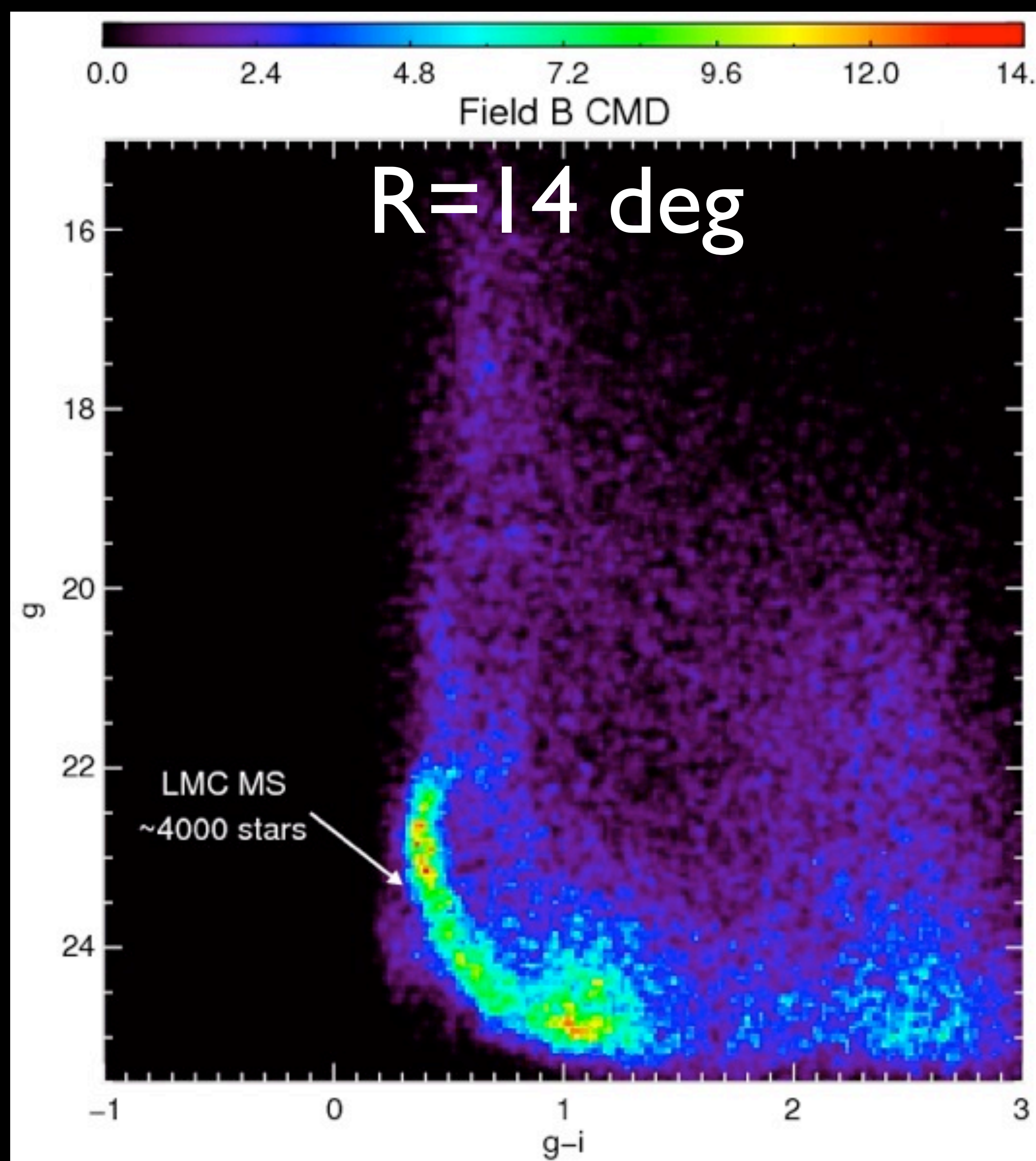
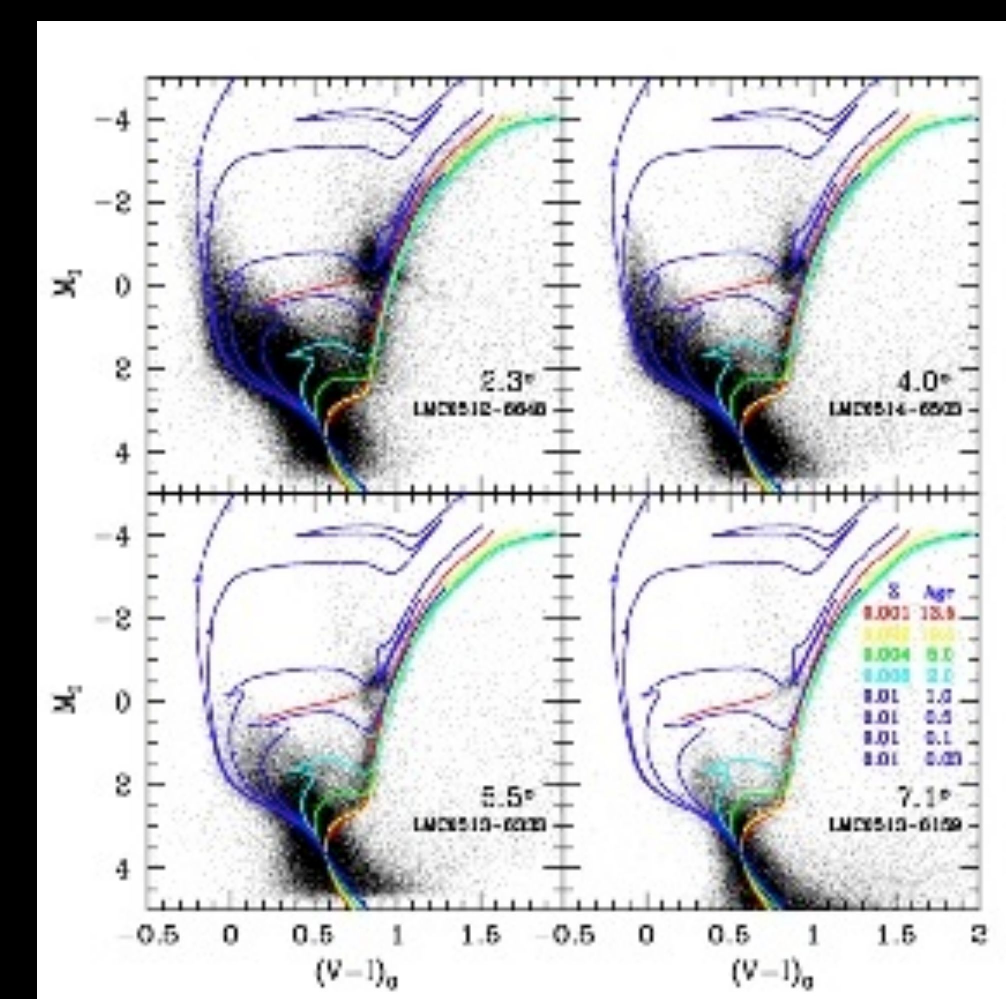
4. Derive spatially resolved, precise star formation histories covering all ages of the MCs and to large radii
5. Enable many community-led projects, including studies involving the LMC/SMC main bodies and Galactic structure

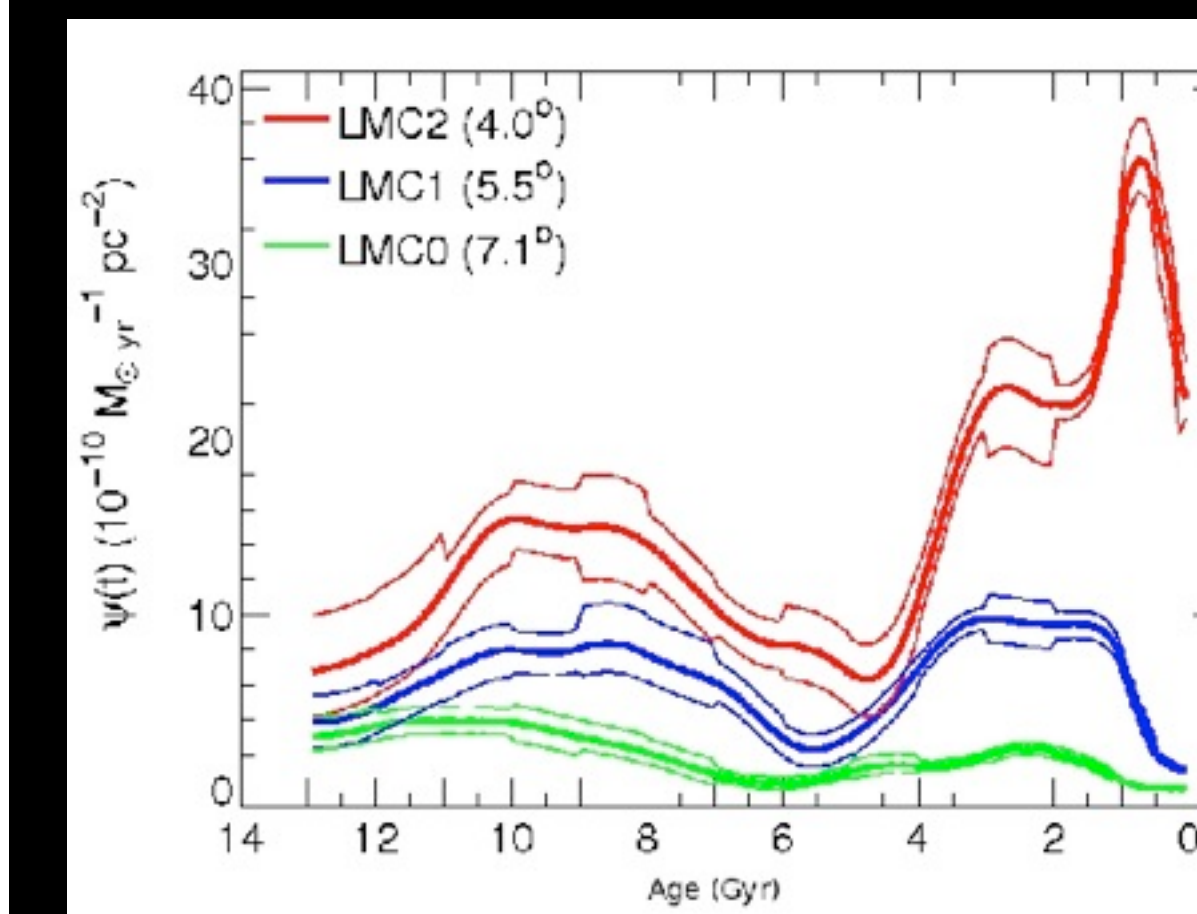
SMASH

Stellar Structure



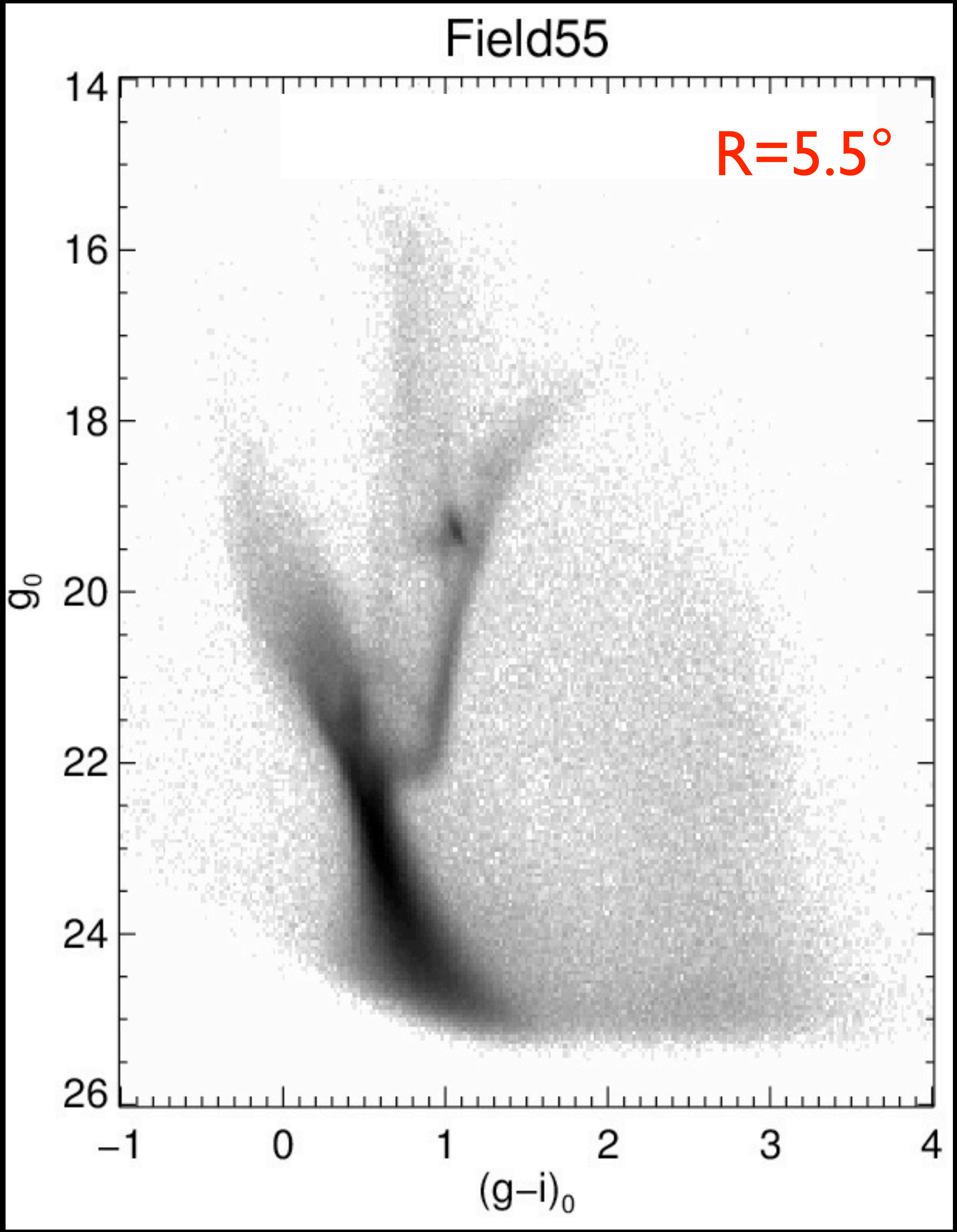
Spatially Resolved Star Formation Histories





Gallart et al. (2008)

Use old main-sequence stars to trace structure in the periphery to ~35.5 mag/arcsec^2



Preliminary SMASH Results

LMC

- DAOPHOT ALLFRAME reduction

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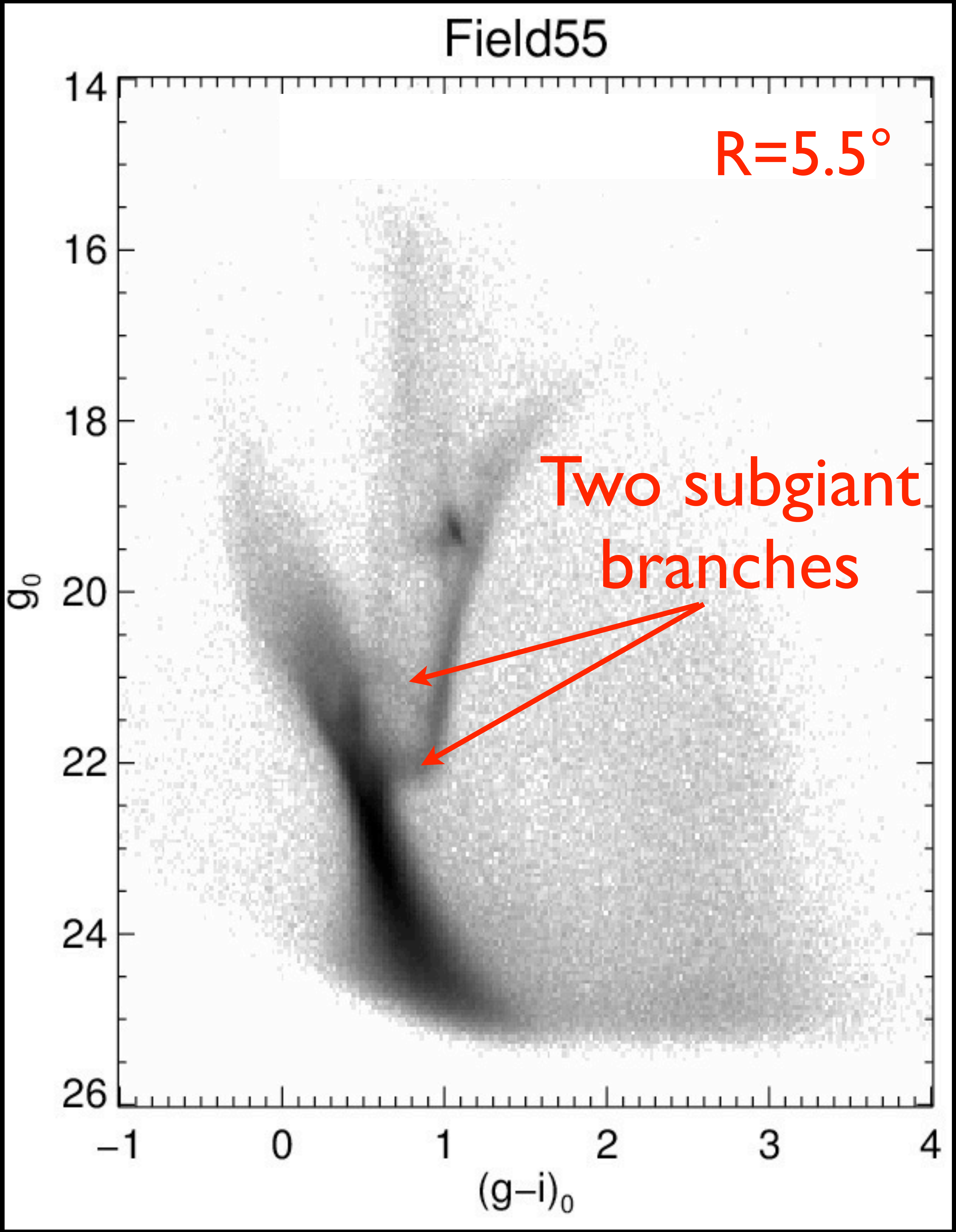
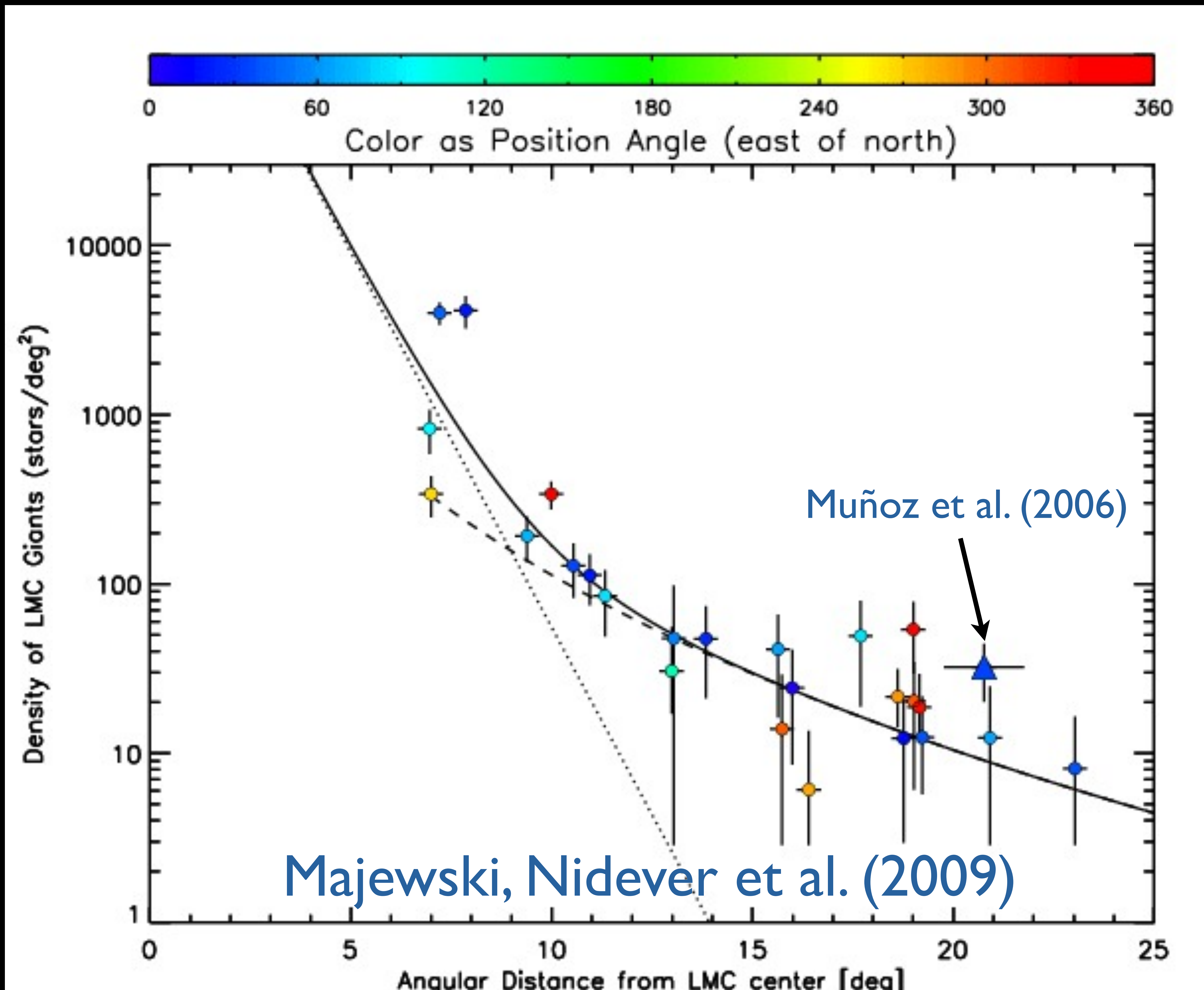


- DAOPHOT ALLFRAME reduction
- Double-peaked star formation

LMC Density Profile



- Studies of spectroscopically-confirmed giant stars find evidence for very extended LMC to R~20°
  - Muñoz et al. (2006)
  - Majewski, Nidever et al. (2009)

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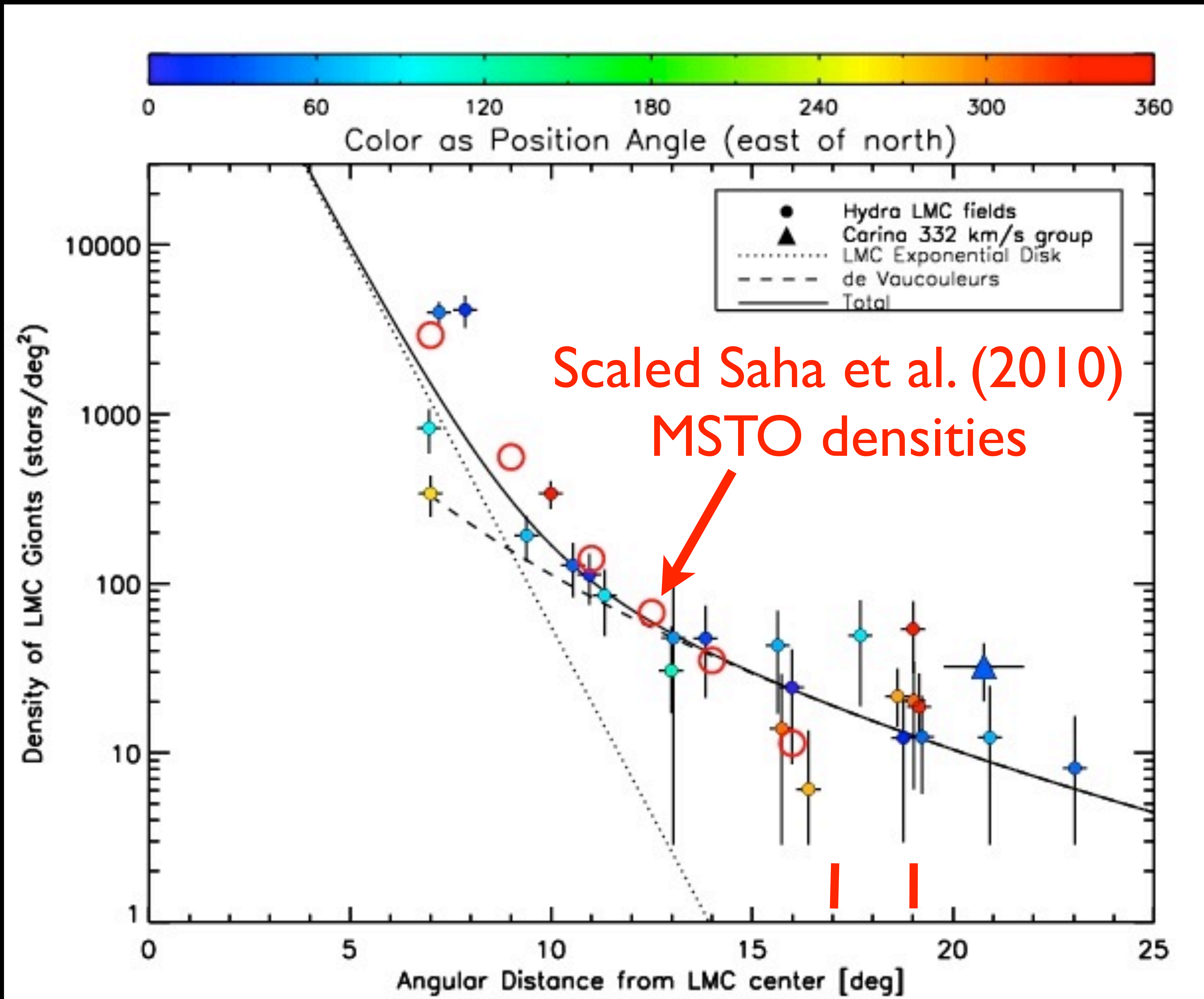

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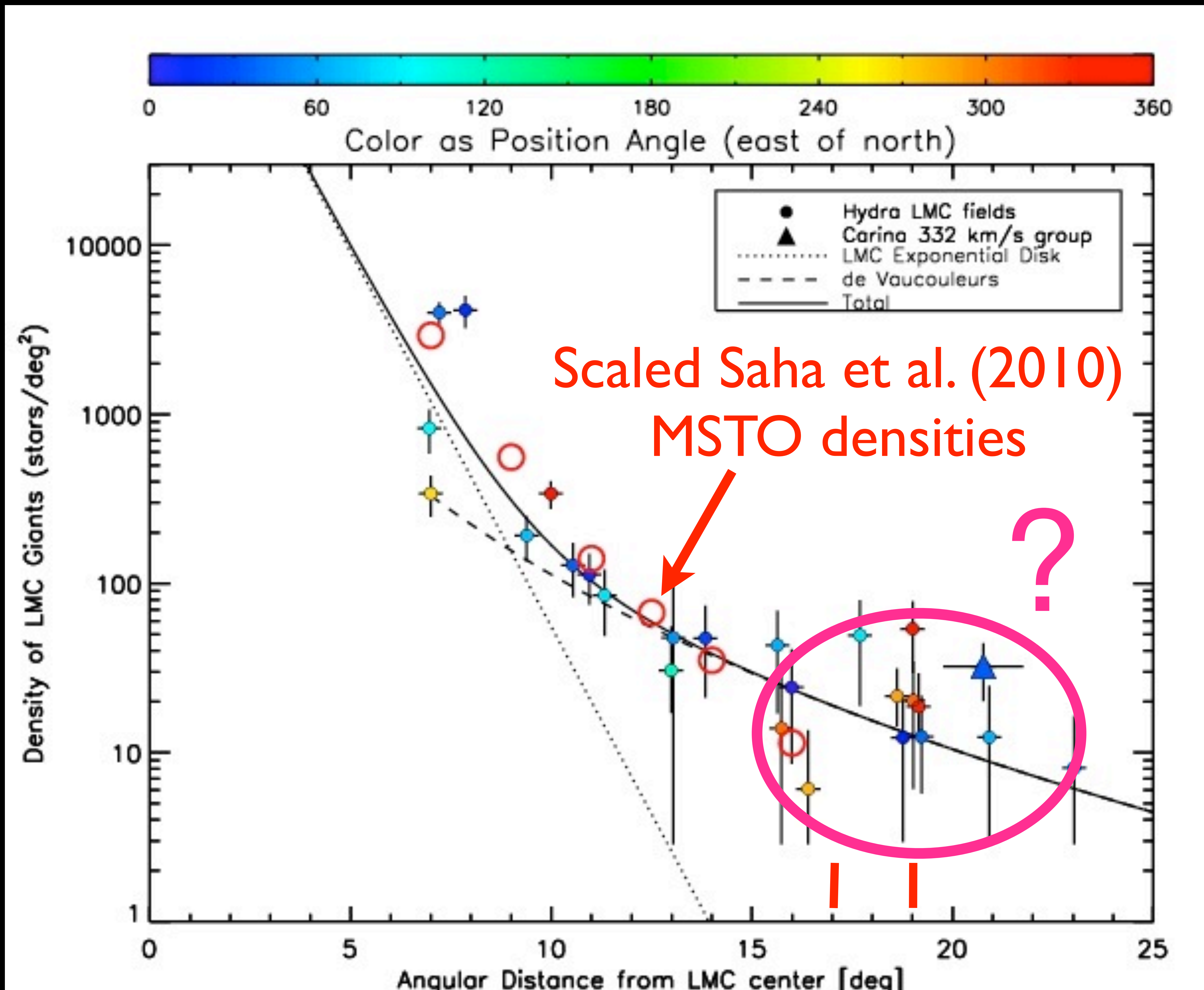

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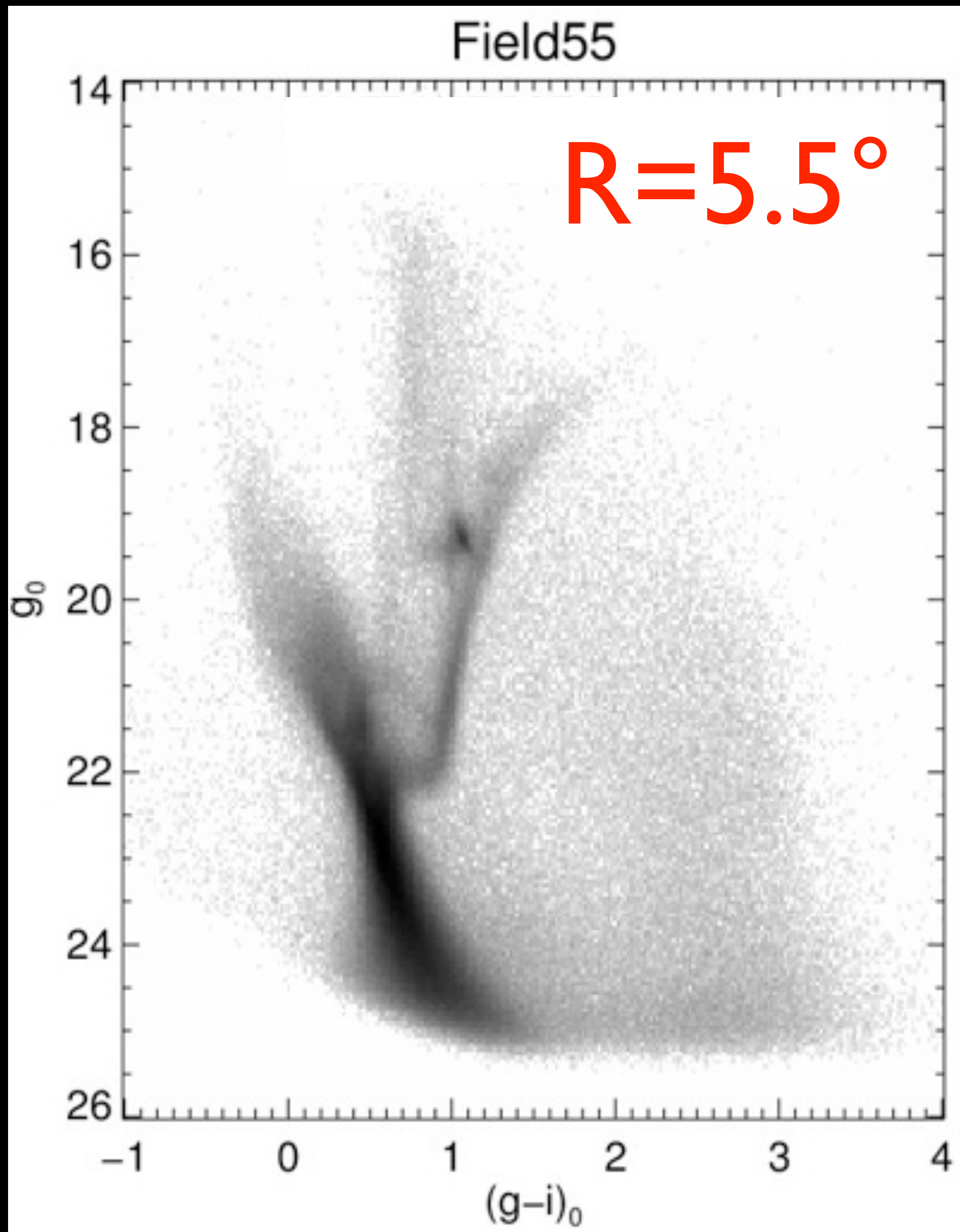
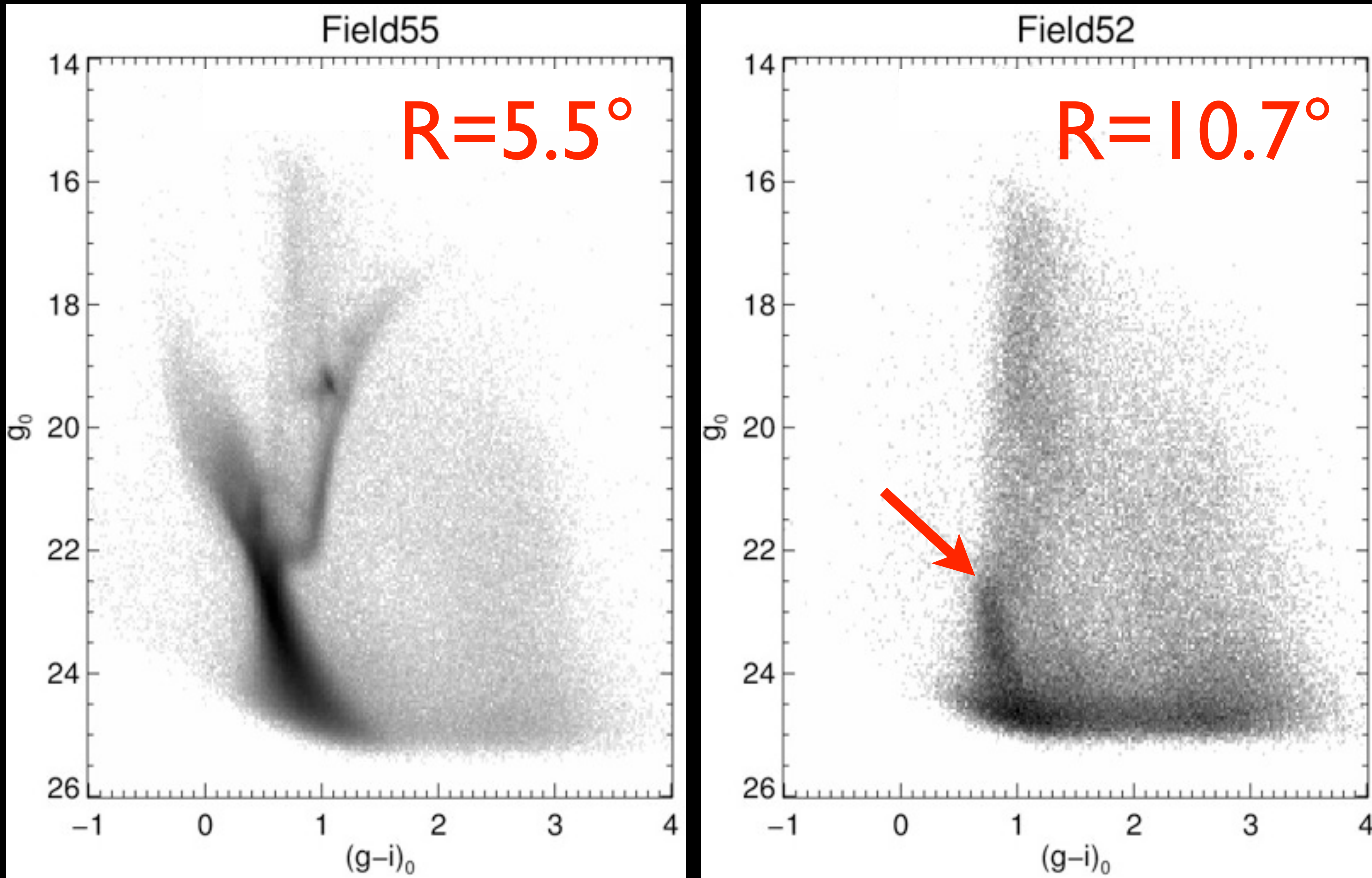


LMC Periphery

Trace LMC stars out to large distances



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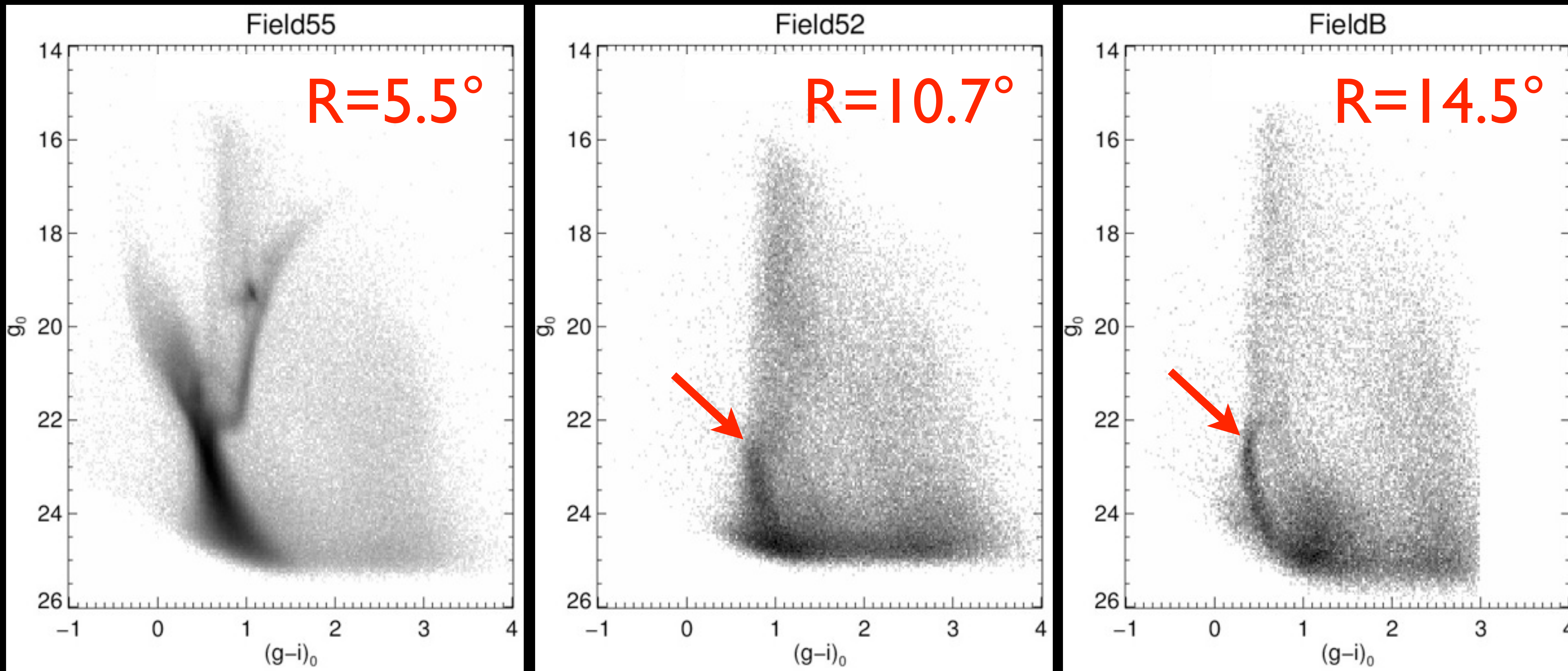

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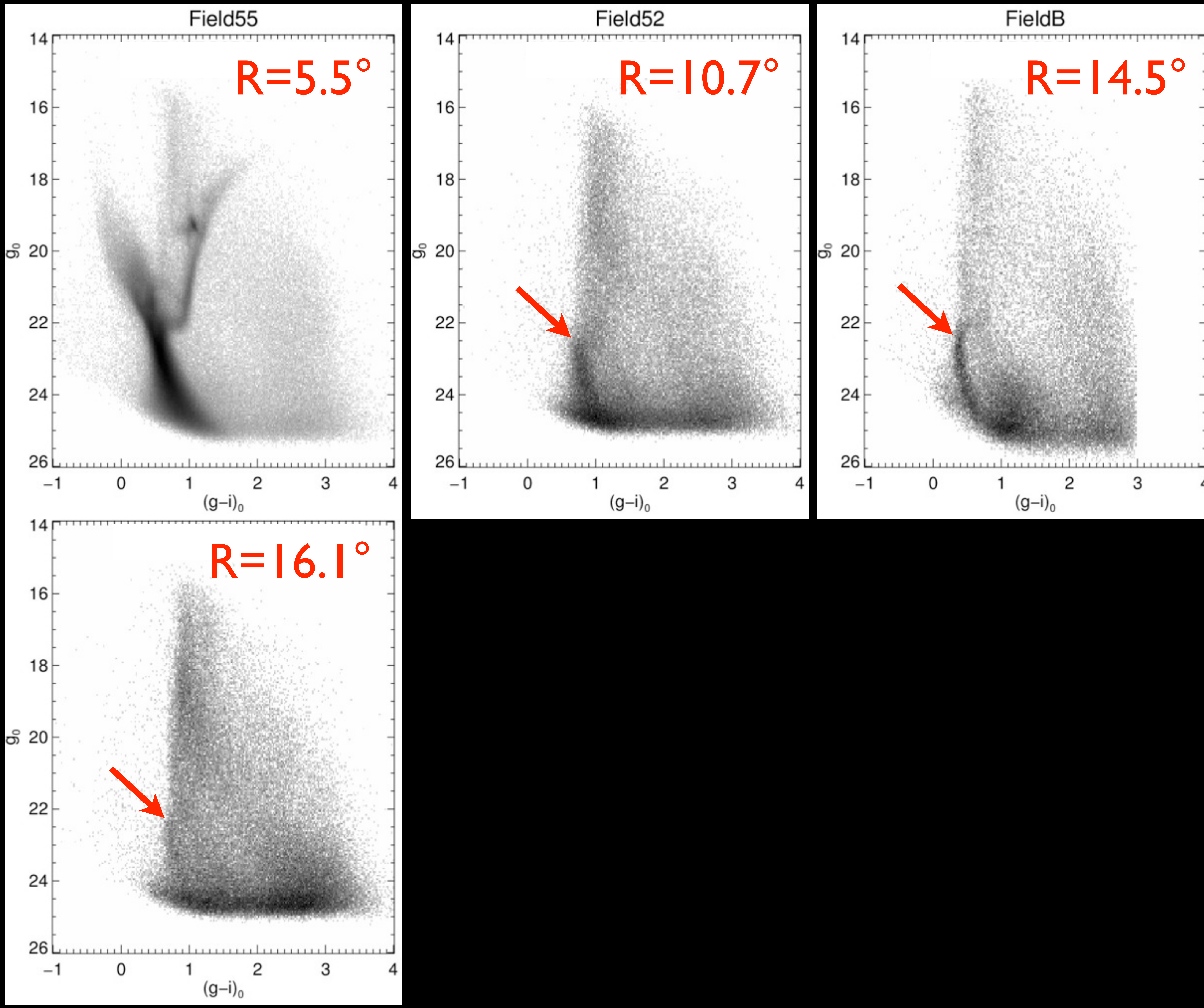

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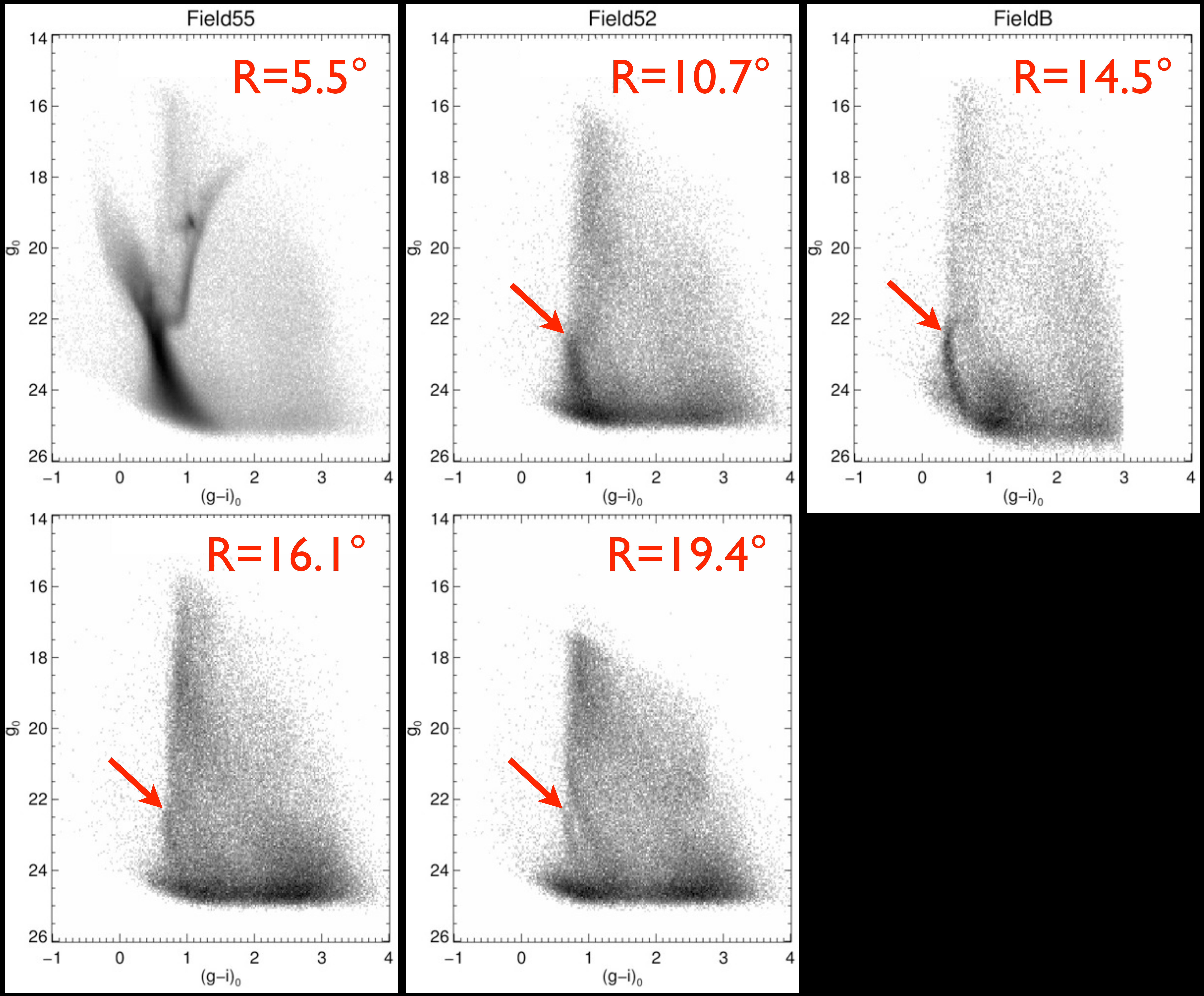

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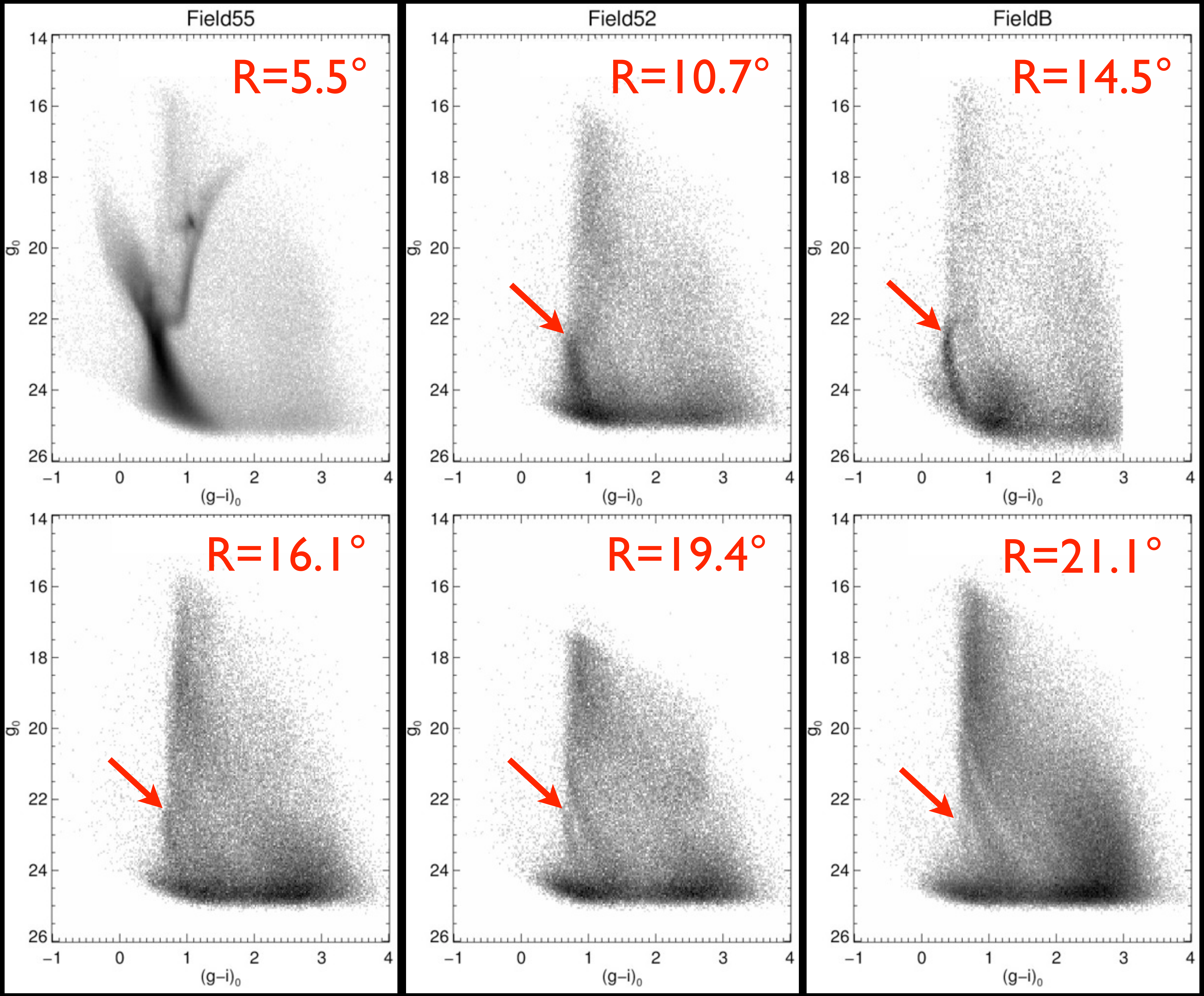
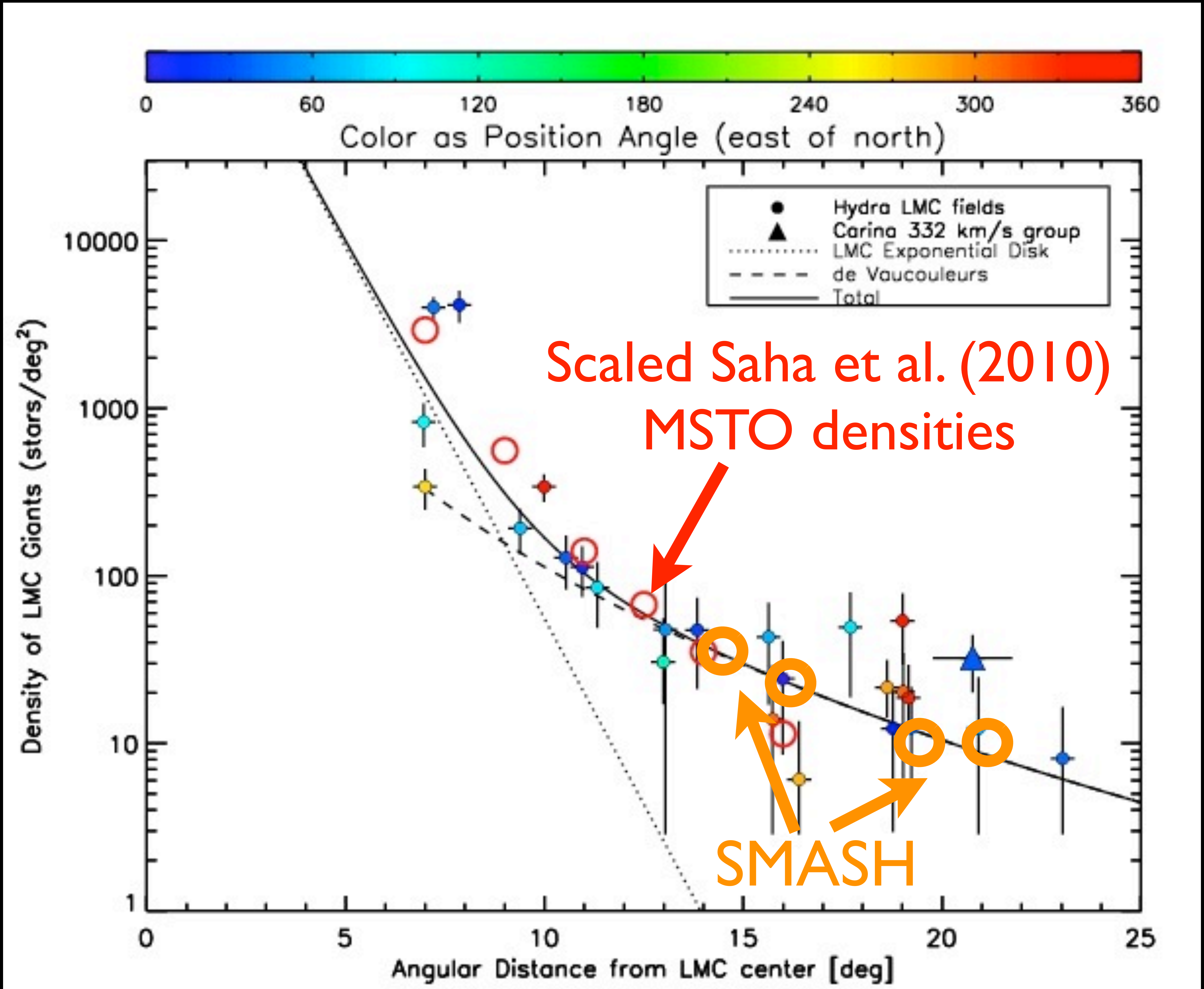


LMC Periphery

Detect LMC stars in fields extending out to **21.1°=18.4 kpc**

SMASH LMC Density Profile

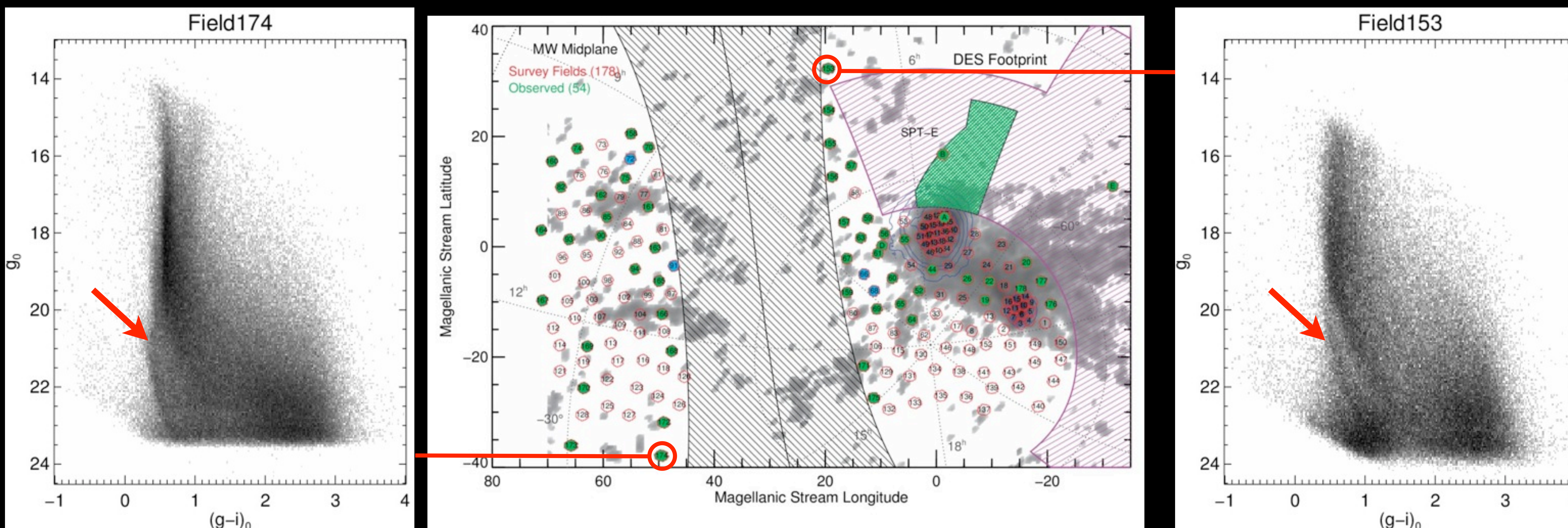


- SMASH LMC densities:
  - R=14.5°, 32.0 mag/arcsec^2
  - R=16.1°, 32.5 mag/arcsec^2
  - R=19.4°, 33.30 mag/arcsec^2
  - R=21.1°, 33.35 mag/arcsec^2
- Very extended LMC
- McMonigal et al. (2014) also detected LMC stars in front of Carina


18.4 kpc
Large Magellanic Cloud
Milky Way
Small Magellanic Cloud

Milky Way Halo Substructure

- Structure at ~20-30kpc in many fields along the MW midplane
- Likely an extension to the Monoceros stream and/or the Virgo Overdensity



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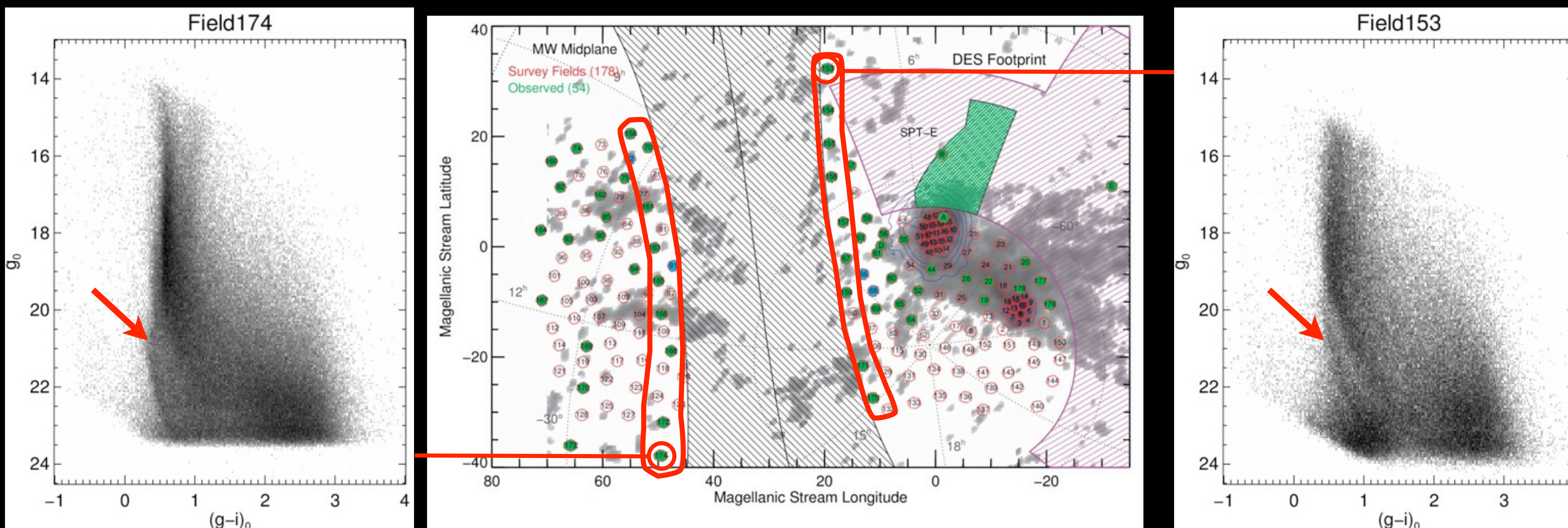
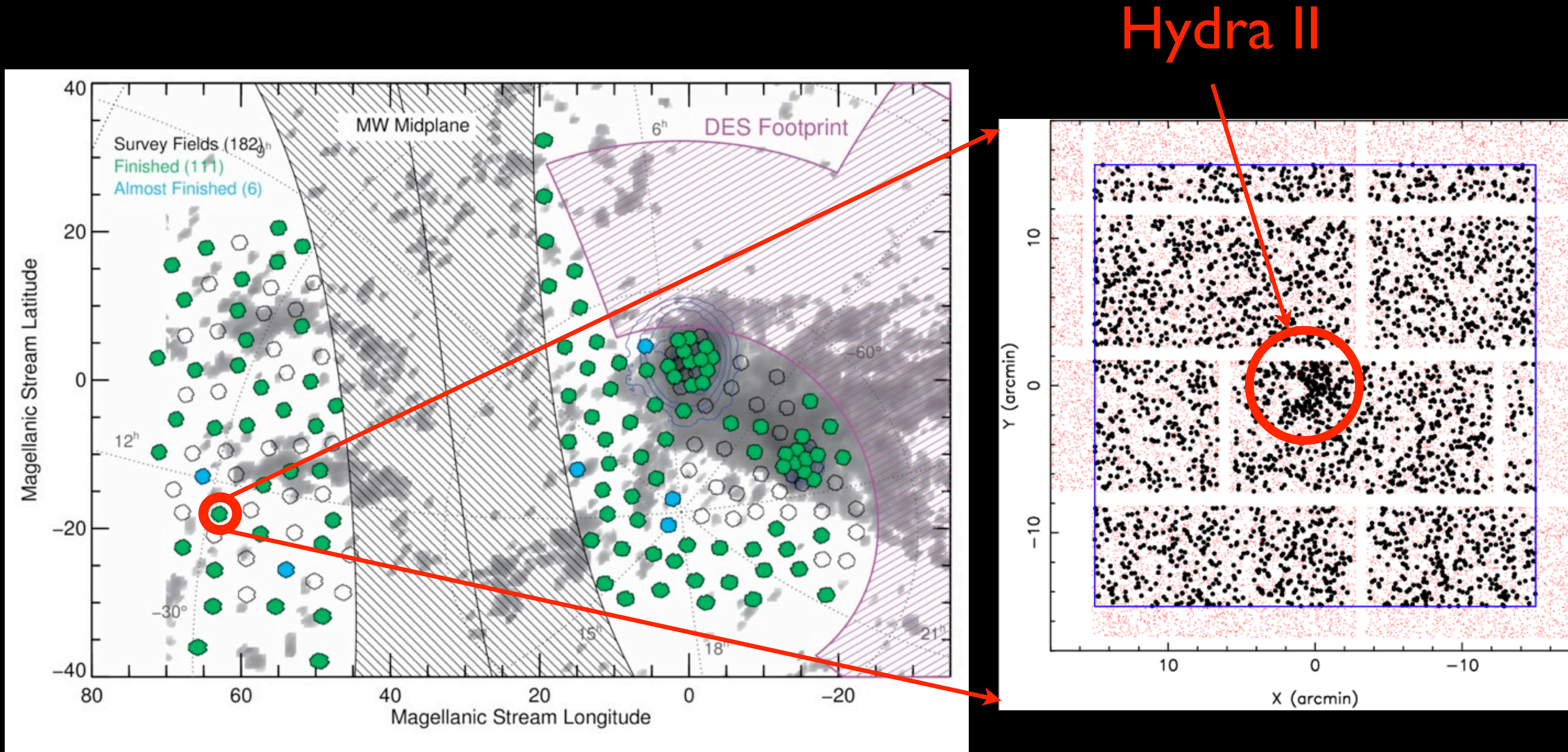


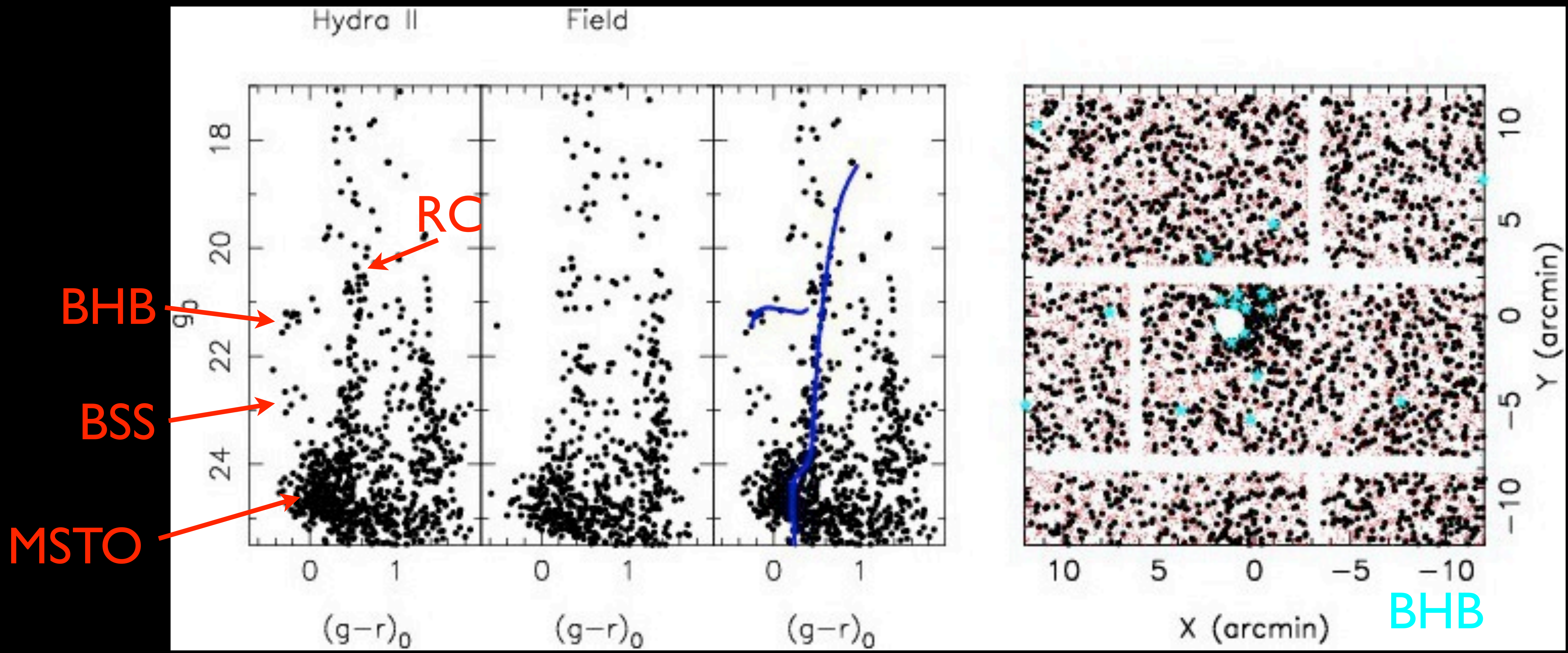
Hydra II



Martin, Nidever & SMASH (2015)

Hydra II

- CMD shows blue horizontal branch, faint red clump, red giant branch, MSTO, and some blue stragglers
- Well-fit by isochrone, [Fe/H]=-2.2, 13 Gyr, 134 kpc



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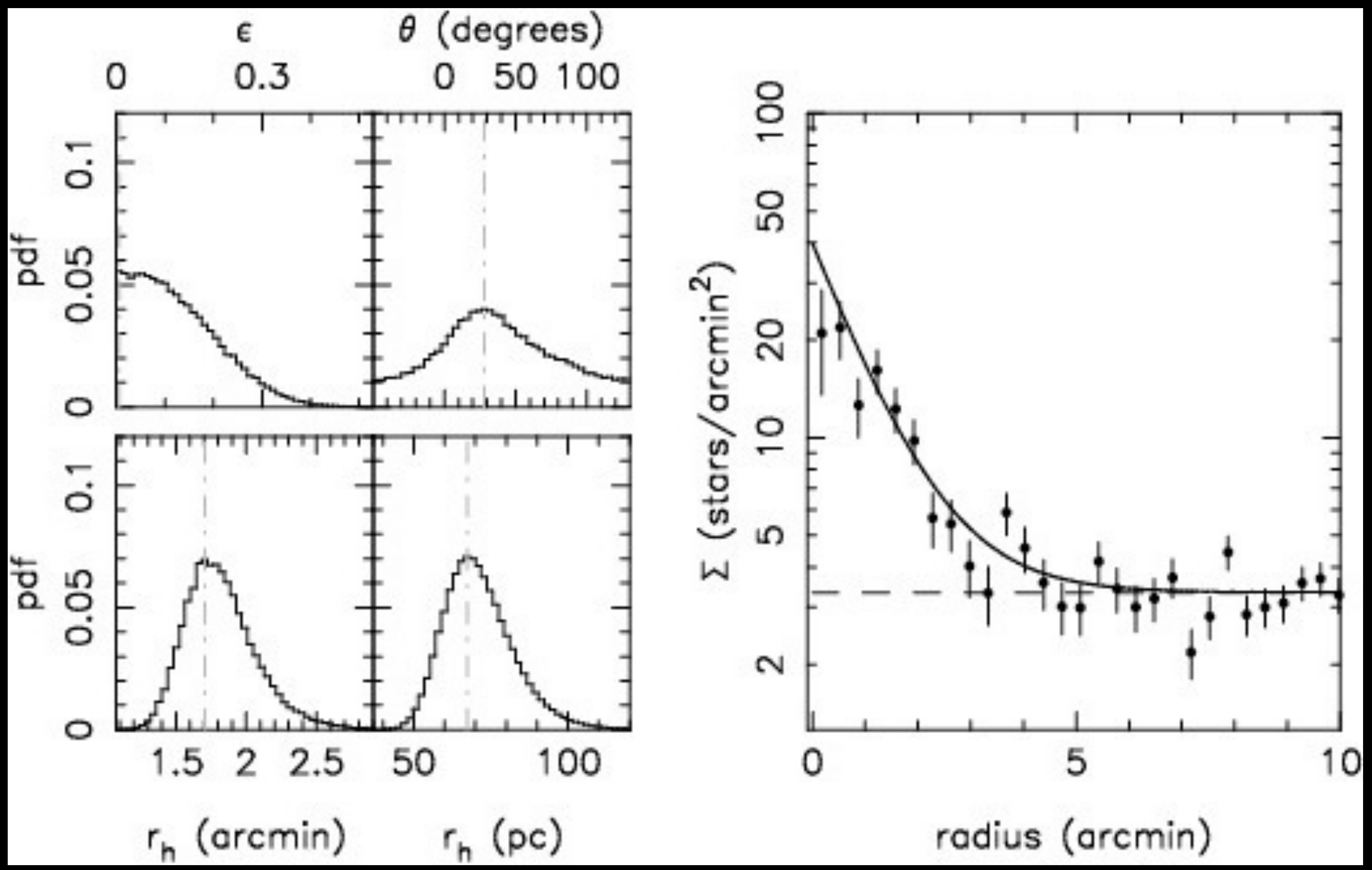
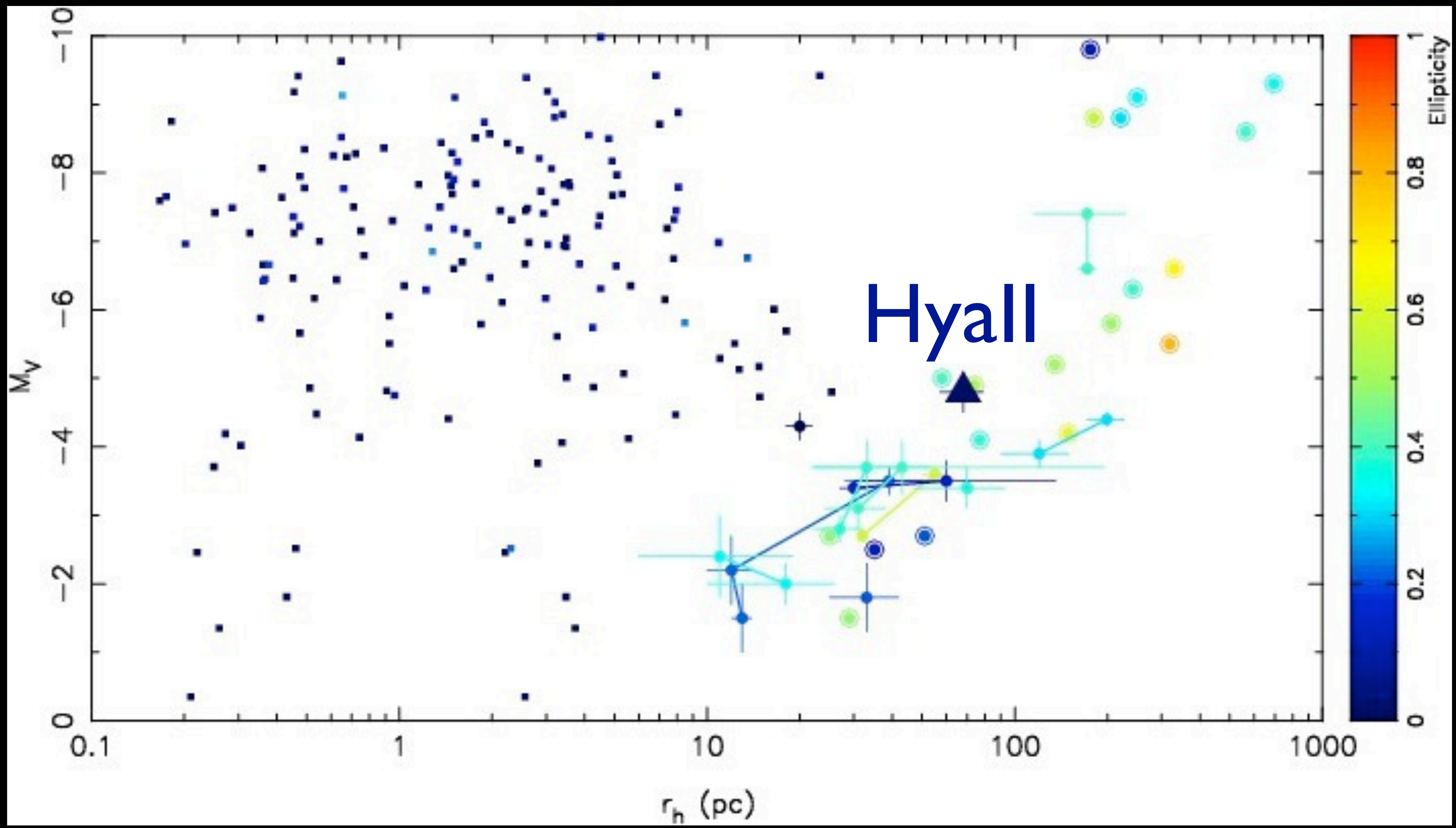
- Well-fit by isochrone, [Fe/H]=-2.2, 13 Gyr, 134 kpc
- Round, ellipticity = $0.01^{+0.19}_{-0.01}$
- Compact, rh = $1.7'^{+0.3}_{-0.2}$ = 68+/-11 pc



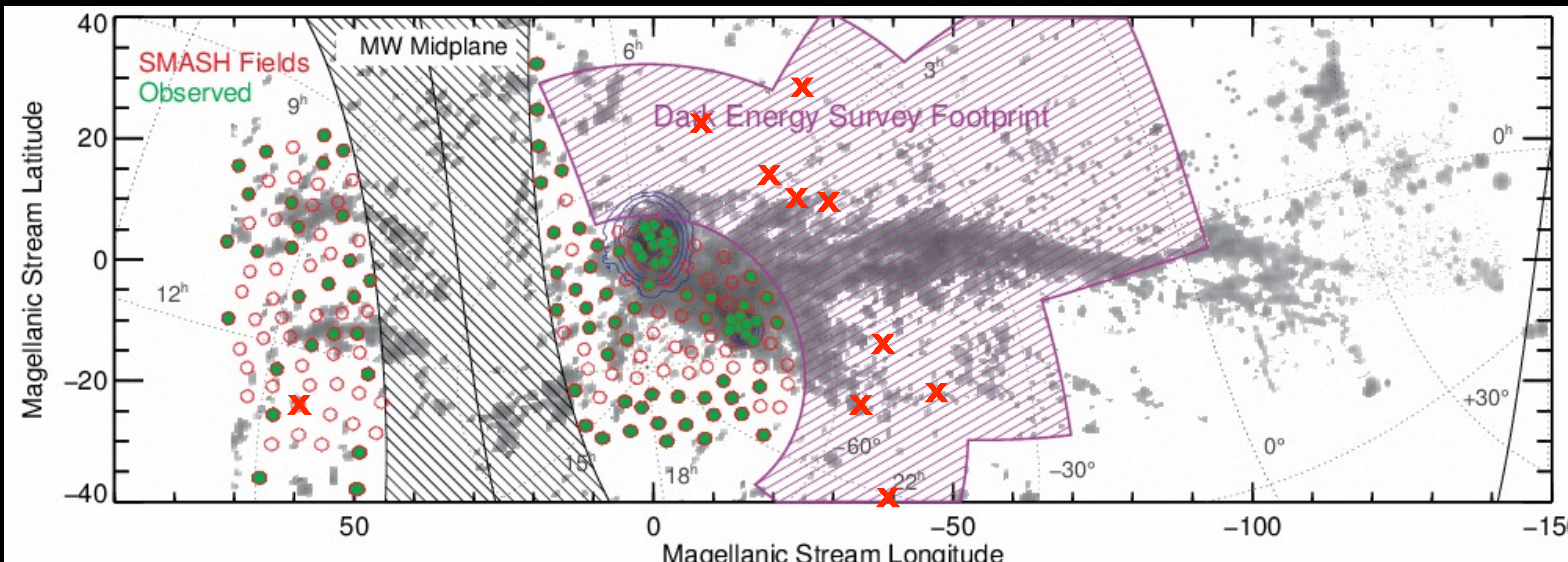
Hydra II

- Lands squarely in the region of dwarf Spheroidal galaxies in the size-luminosity diagram, similar to Coma Ber
- But need velocity dispersion from follow-up spectroscopy to confirm it is a galaxy



Hydra II - Magellanic Connection?

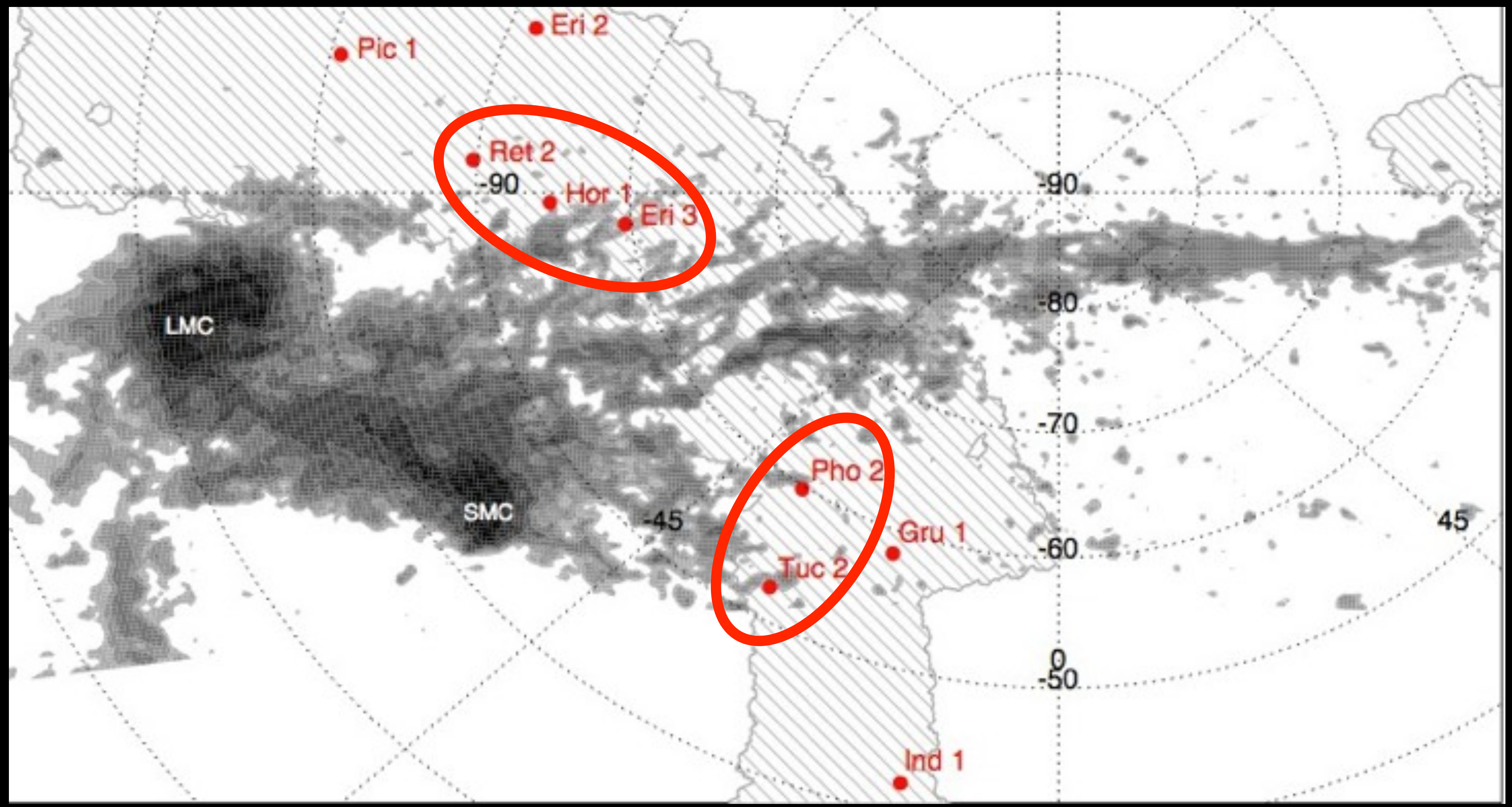
- Could some of these dwarfs be satellites of the MCs?



DES dwarfs: Bechtol & DES (2015), Koposov et al. (2015)

Hydra II - Magellanic Connection?

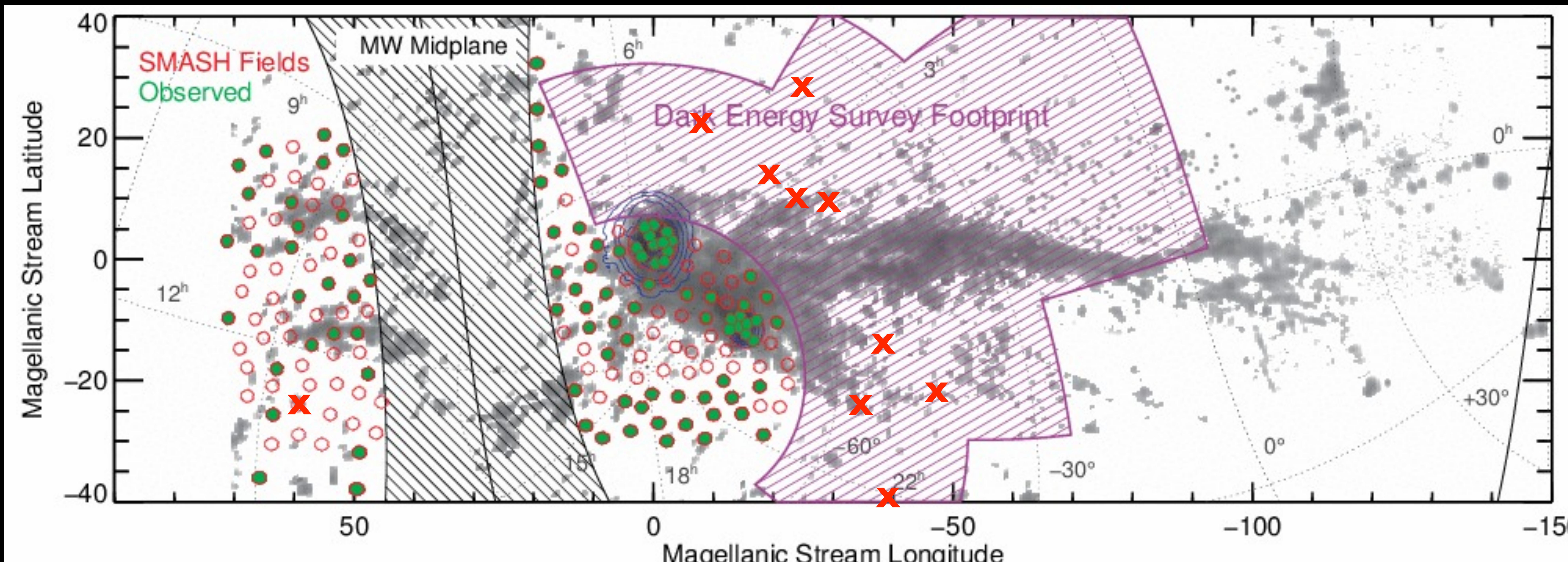
- ~4-5 of the DES dwarfs are "close" to the MCs on the sky and in distance
- Outside LMC tidal radius but within the LMC virial radius
- Could have recently become unbound as the MCs interacted with each other and the MW
- Even bound satellites could have large spatial and velocity dispersion



Koposov et al. (2015)

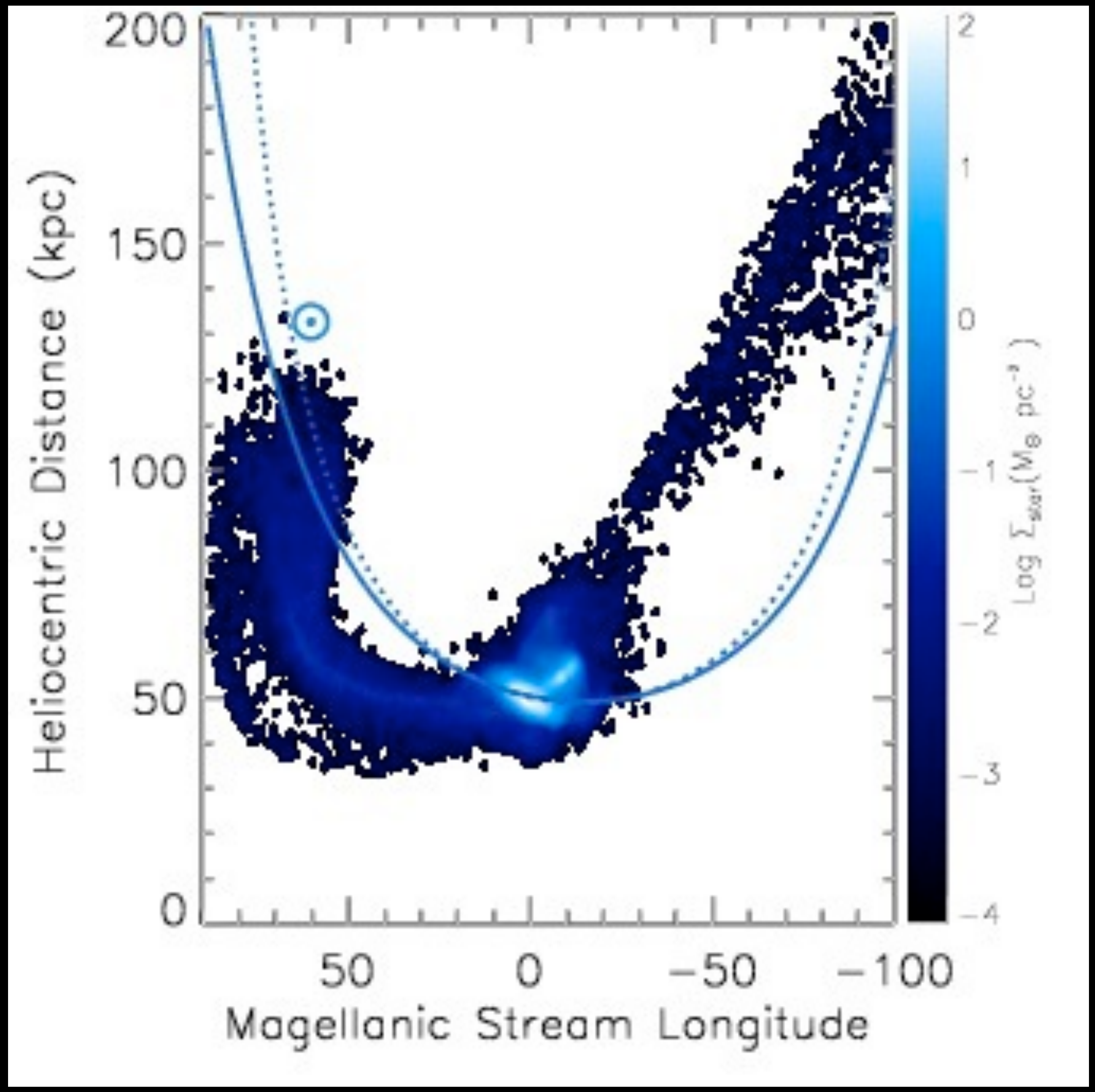
Hydra II - Magellanic Connection?

- How about Hydra II?



Hydra II - Magellanic Connection?

- How about Hydra II?
- Close to the leading arm of the Magellanic Stream
- Could it be a stripped dwarf galaxy in the stream?
- Stripped stars in Besla model go up to d~130 kpc
- Need RV to test this hypothesis, proper motions even better but harder



Conclusions

- Examining galaxy formation and evolution with MW and MCs
- Early MW disk stellar evolution of MW in similar star formation history and were formed in a well-mixed and molecular-dominated ISM with a short gas consumption timescale
- Discovery of very extended stellar peripheries around the Magellanic Clouds consistent with hierarchical model
- Discovery of Hydra II, dwarf galaxy potentially connected to the Leading Arm of the Magellanic Stream

The End