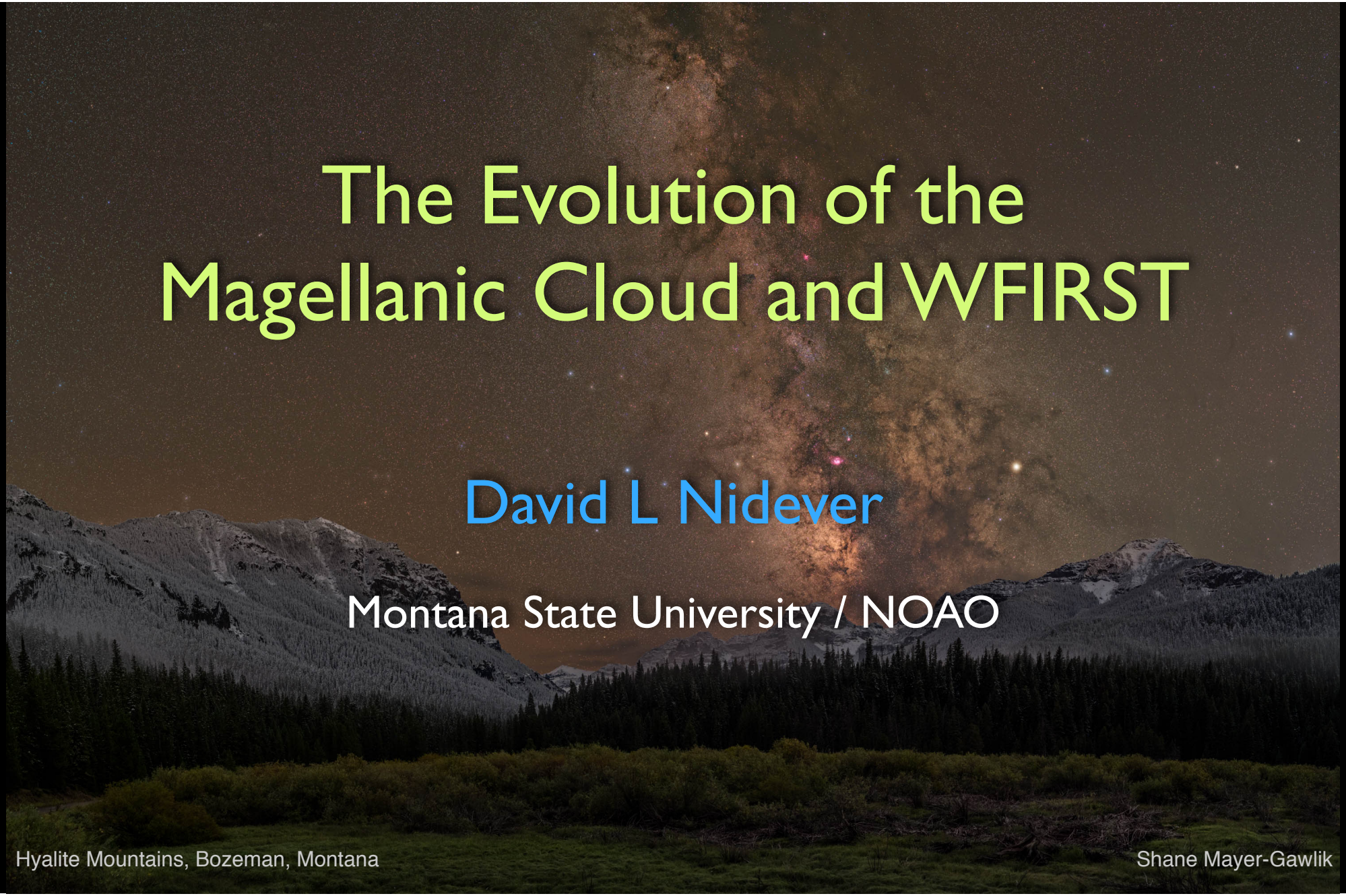


The Evolution of the Magellanic Cloud and WFIRST

David L Nidever

Montana State University / NOAO

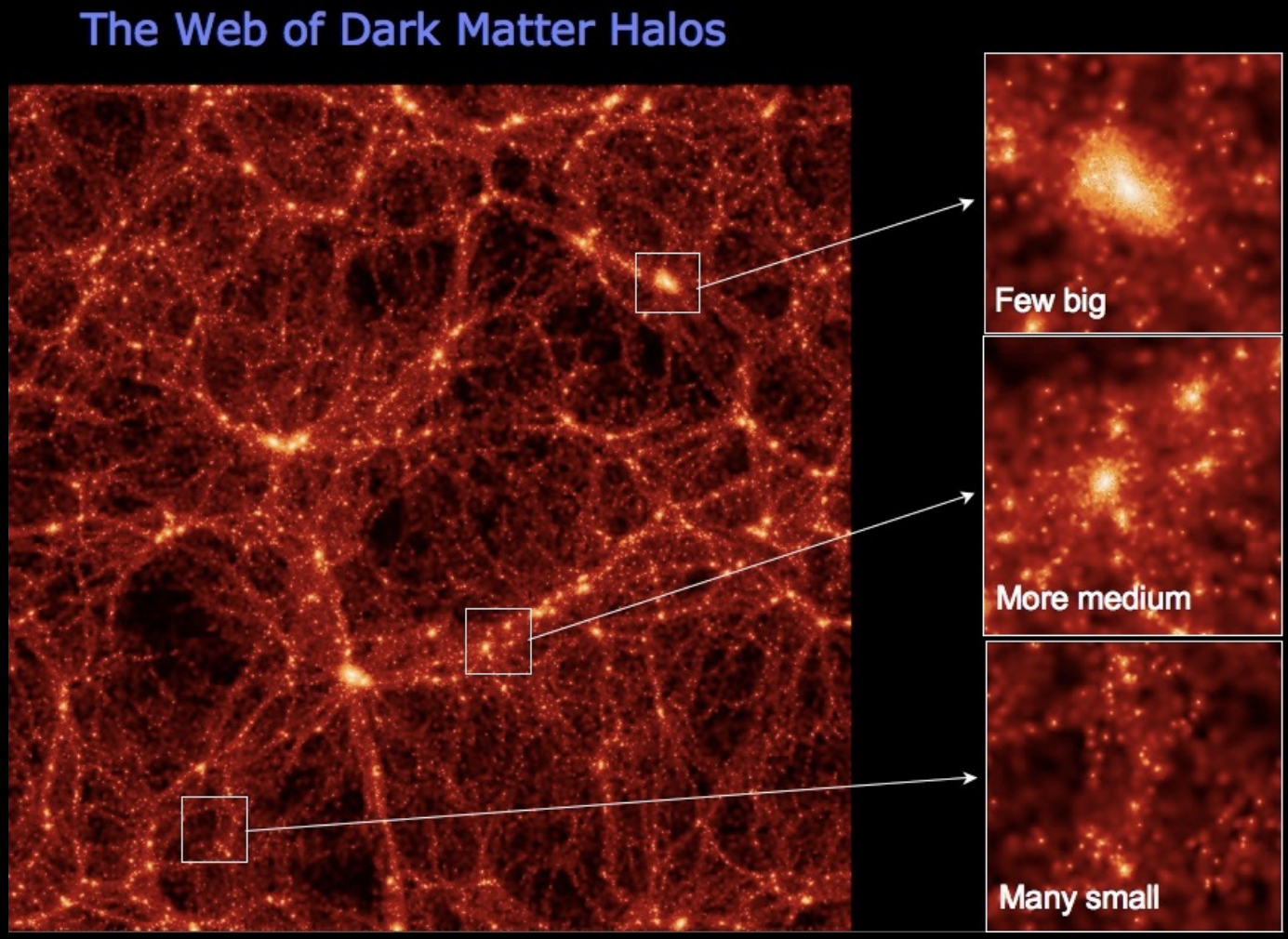
Hyalite Mountains, Bozeman, Montana

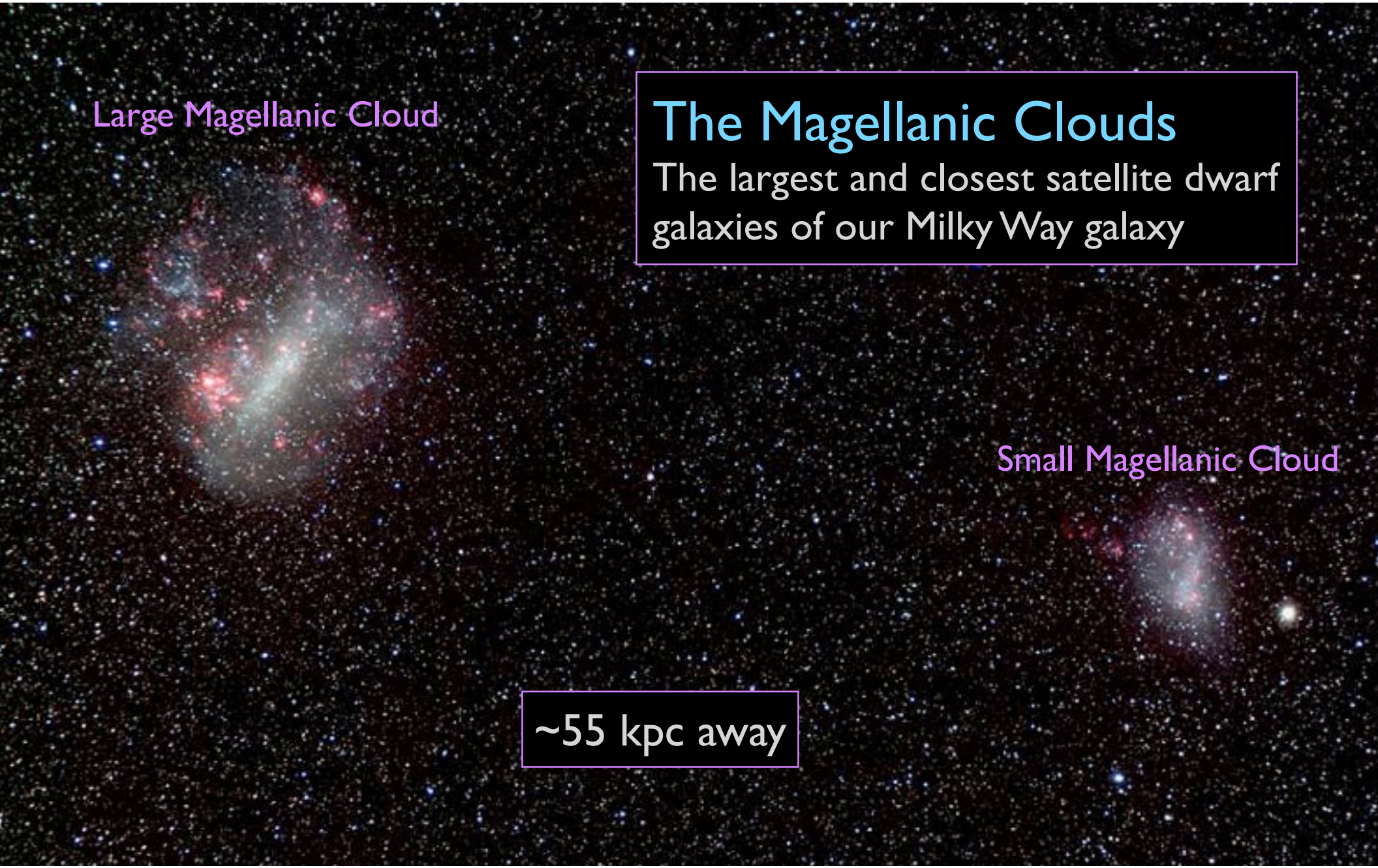
Shane Mayer-Gawlik

How do Galaxies form?

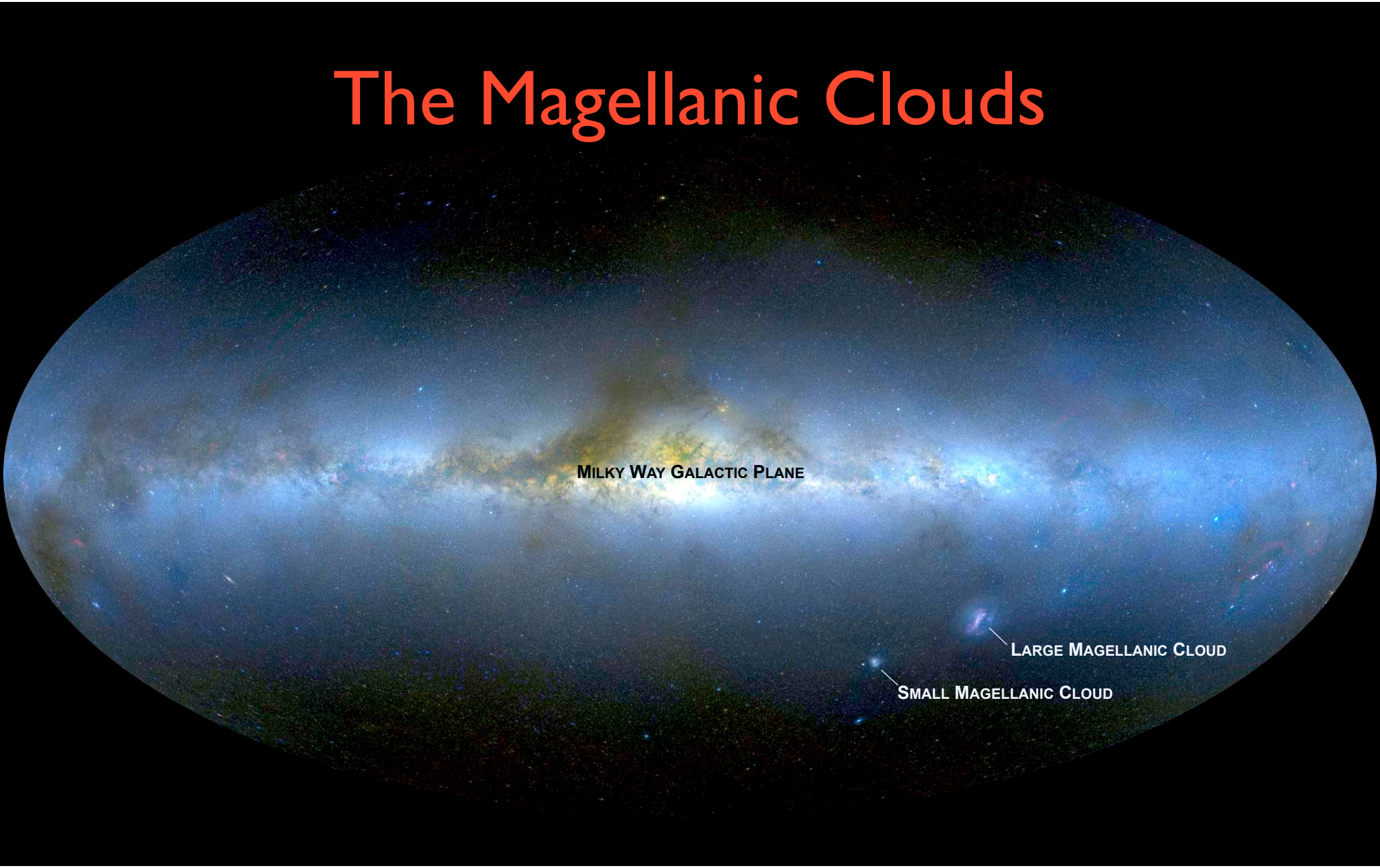
?

Most galaxies in the Universe are dwarfs

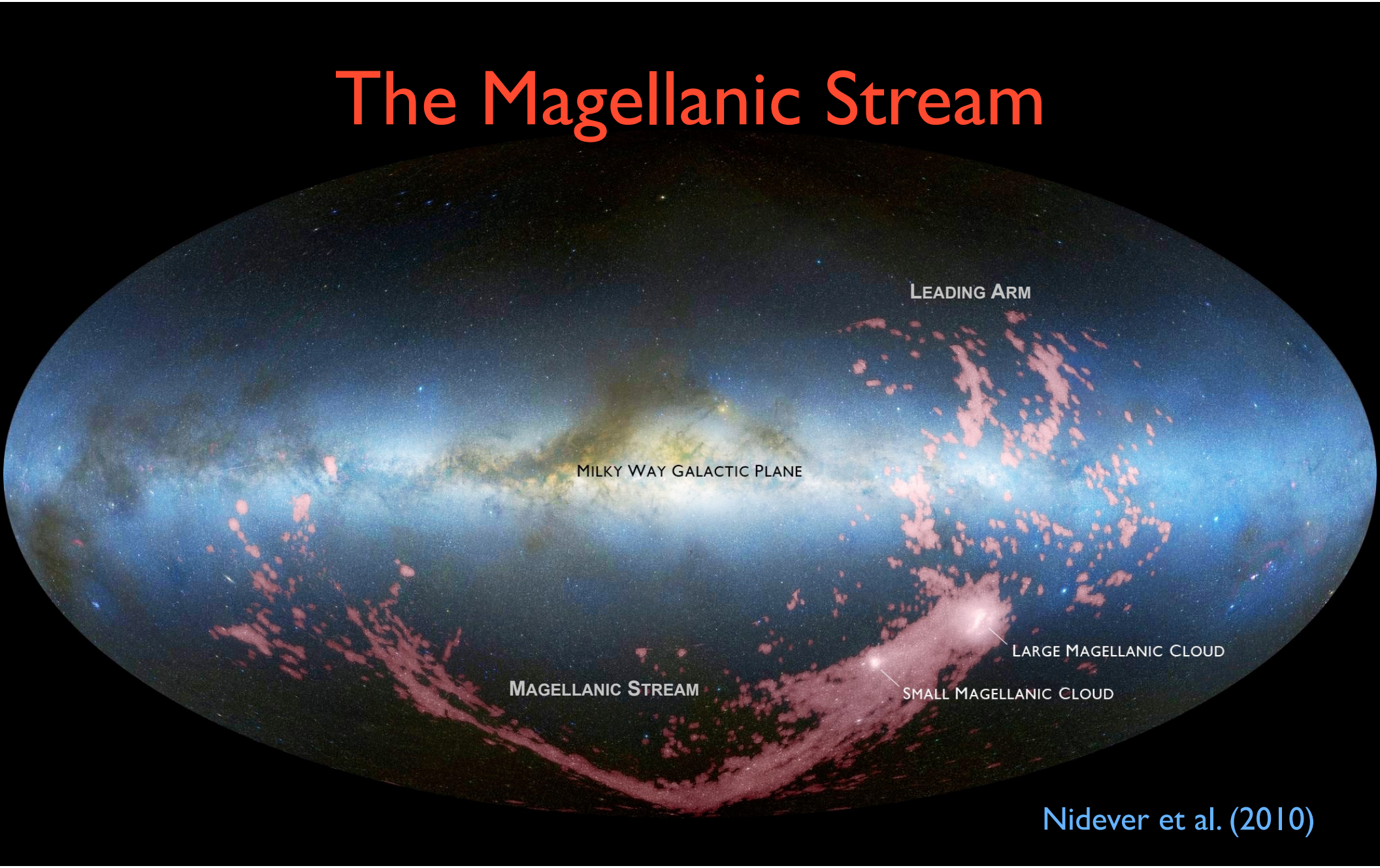



Large Magellanic Cloud
The Magellanic Clouds
The largest and closest satellite dwarf galaxies of our Milky Way galaxy
Small Magellanic Cloud
~55 kpc away

The Magellanic Clouds

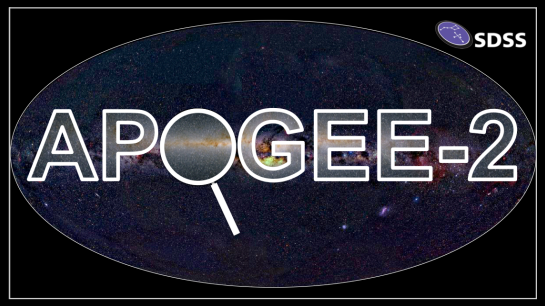


The Magellanic Stream



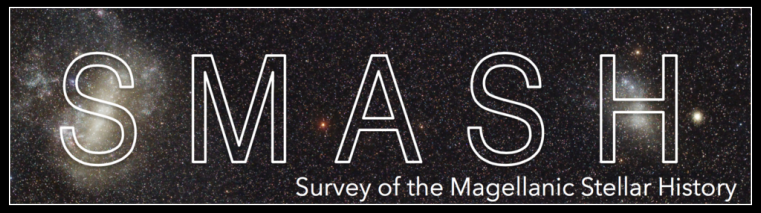
Nidever et al. (2010)

Dual Magellanic Surveys



Magellanic Clouds Survey

- High-res spectroscopic survey
- Chemical abundances
- Radial velocities



- Deep photometric survey of Magellanic Clouds
- Map stellar structure
- Detailed SFH maps

Dual Magellanic Surveys

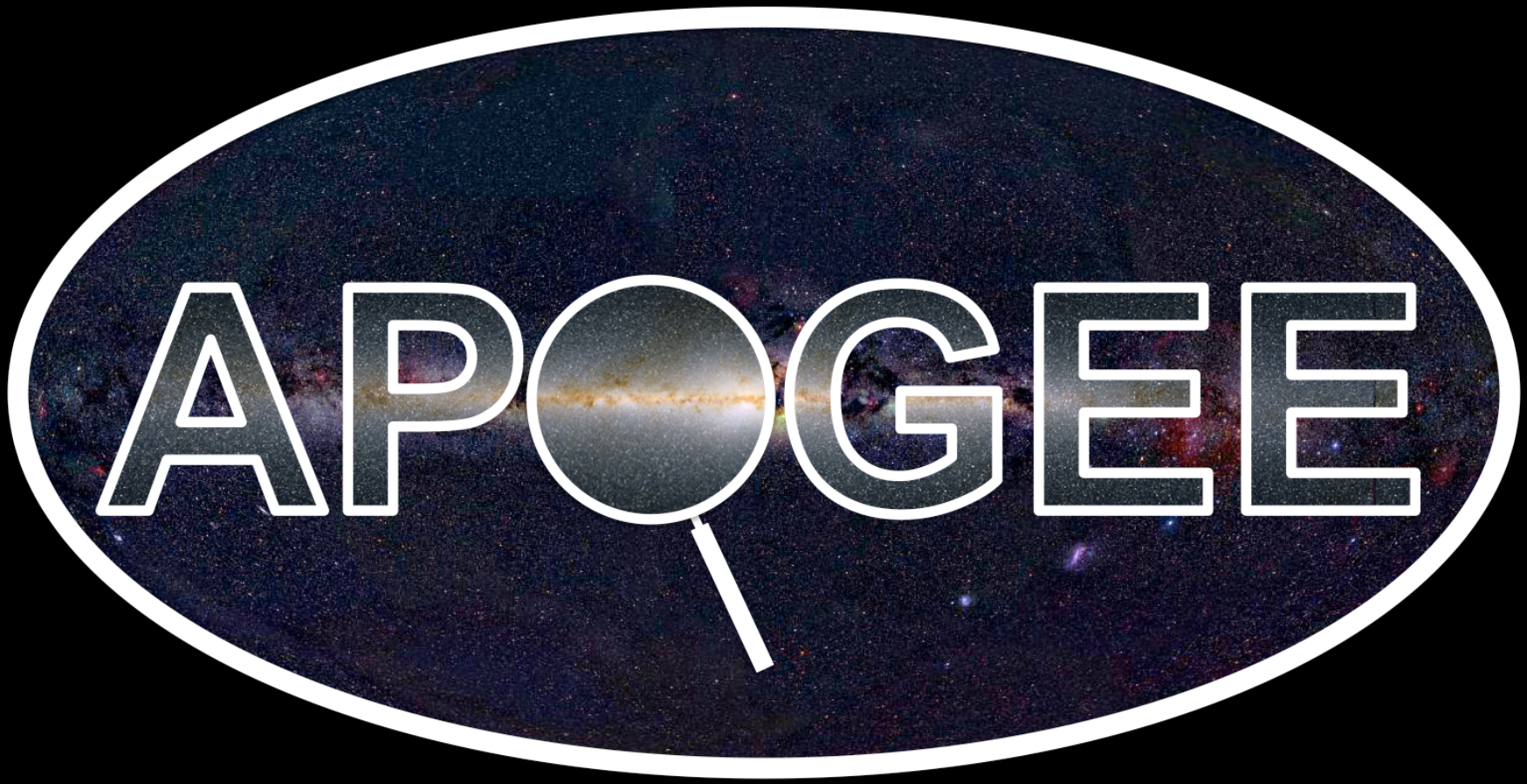
Combination allows tighter constraints on evolution

- Can't uniquely solve SFH with chemistry ***alone***

➡ Accurate SFH from deep photometry

➡ Chemistry constrains other parameters

(e.g., IMF, outflows/inflows, SN Ia/II contributions)


APOGEE

All sky image in the Near Infrared

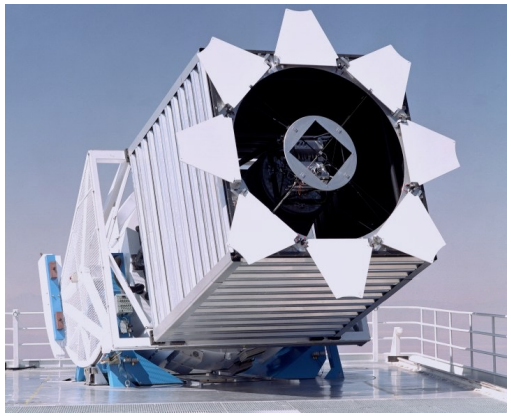
APOGEE

Apache Point Observatory Galactic Evolution Experiment

Explore chemistry and kinematics over *entire* MW with high-resolution, near-infrared spectra of 400,000 stars

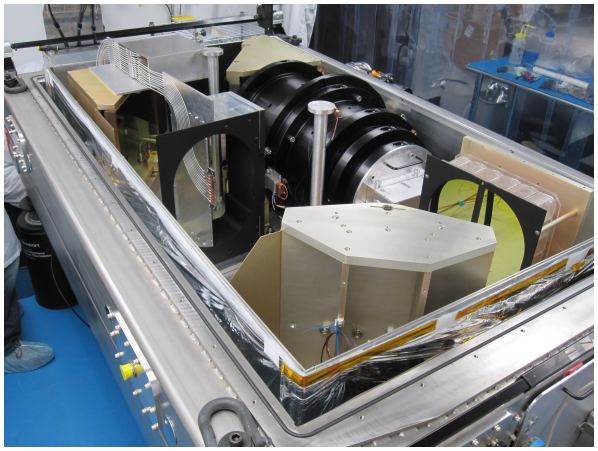
APOGEE

2.5m telescope



Plug plate
with 300 holes

Spectrograph



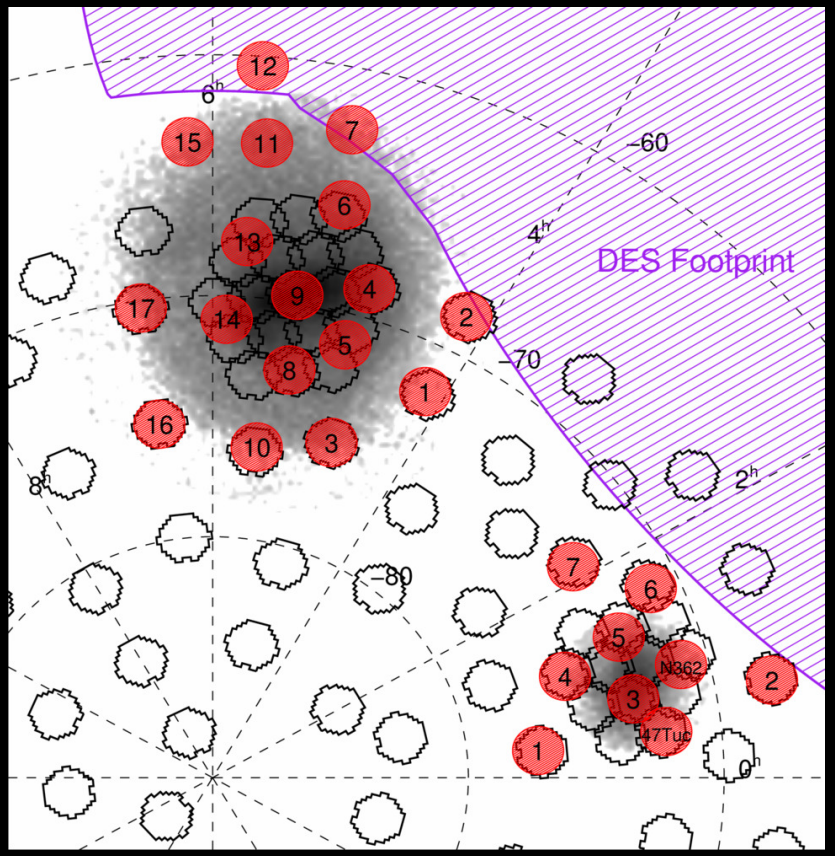
- FOV 7 deg^2
- 300 fibers
- R=22,000
- Dual-hemisphere
- 1.5-1.7 microns
- ~400,000 MW star
- Abundances for ~24 elements

A New SDSS Eye:
The APOGEE Southern Spectrograph

Irénée du Pont Telescope

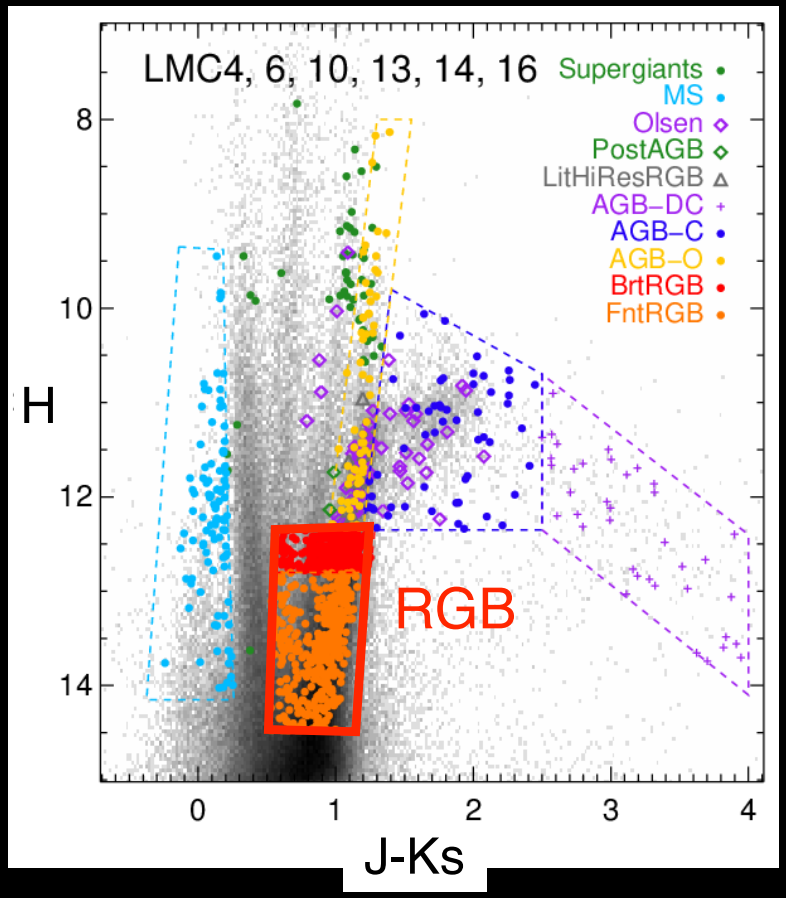
APOGEE South

Chemistry of the Magellanic Clouds



- APOGEE-2S Magellanic Clouds survey
- ~5,000 stars in 26 fields
- Two seasons of observations completed
- Combined SMASH + APOGEE data to constrain chemical evolution
- Detailed spatial and chemical exploration of these massive dwarfs

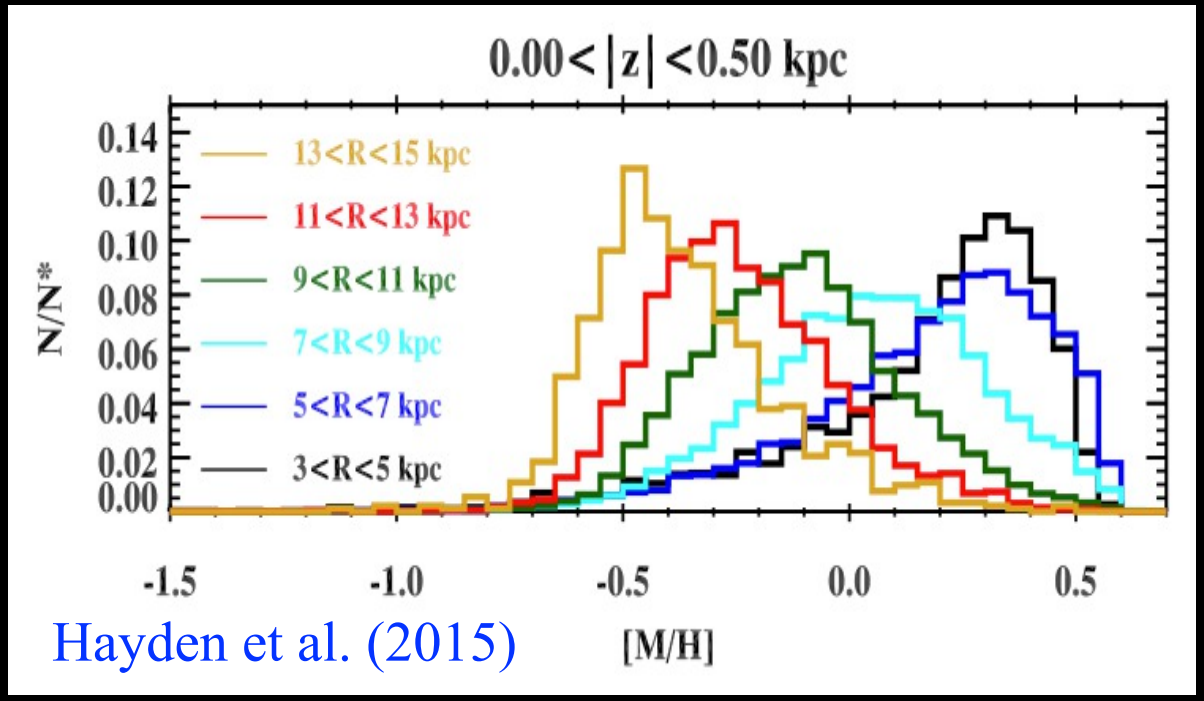
Target Selection



- 10 target classes including
  - supergiants
  - PostAGB
  - AGB
  - RGB
- Most fields have ~200 RGB stars, 50 minimum

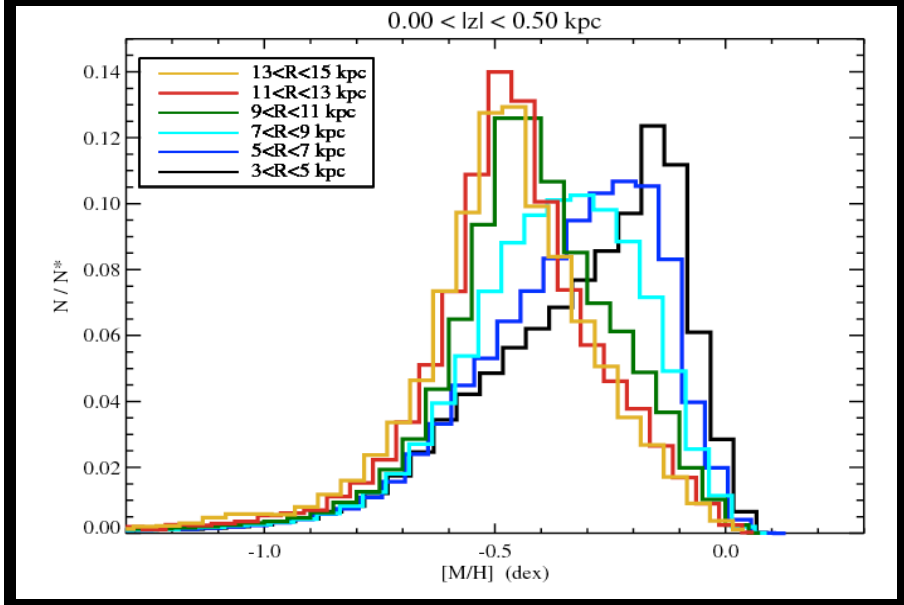
Radial Migration

APOGEE Observations



Hayden et al. (2015)

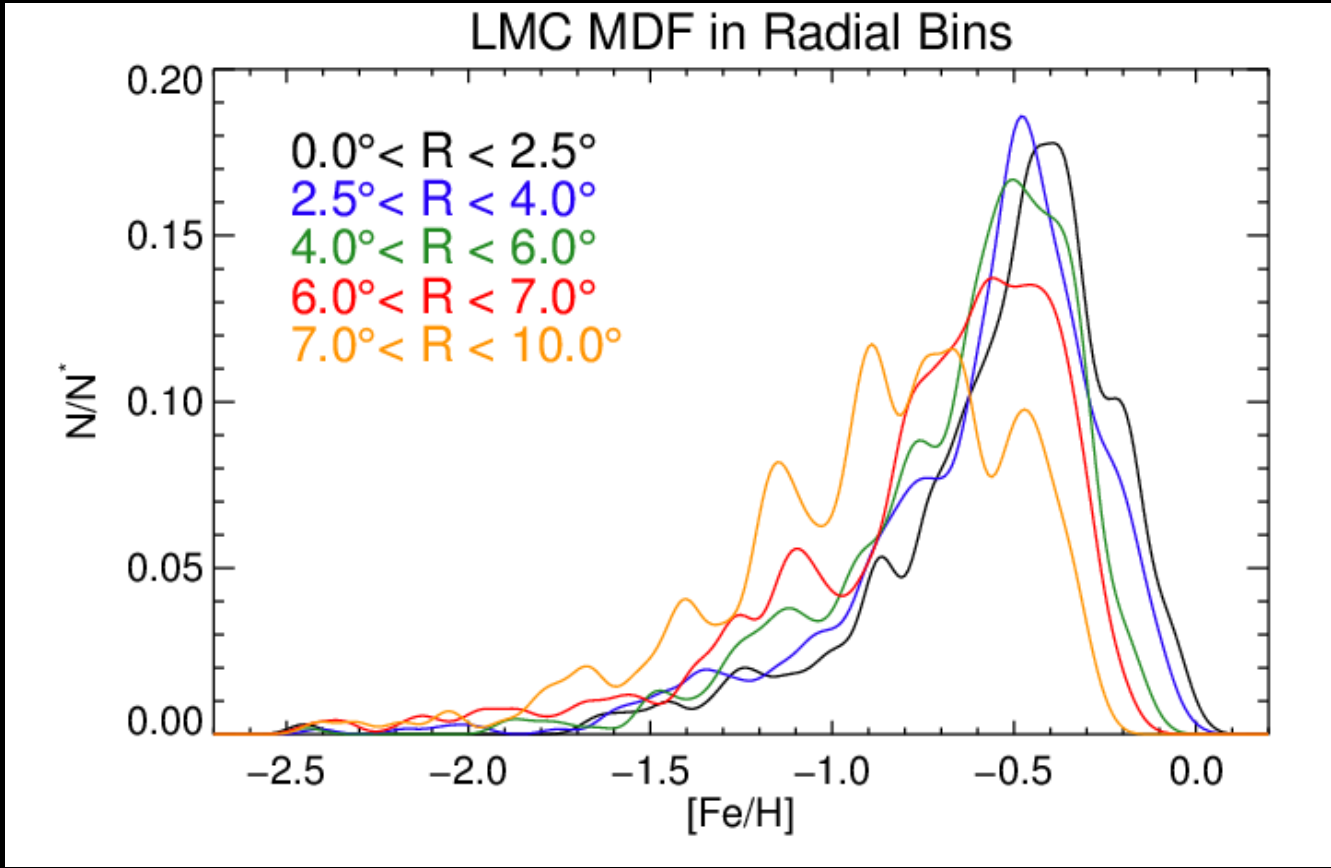
Simulation



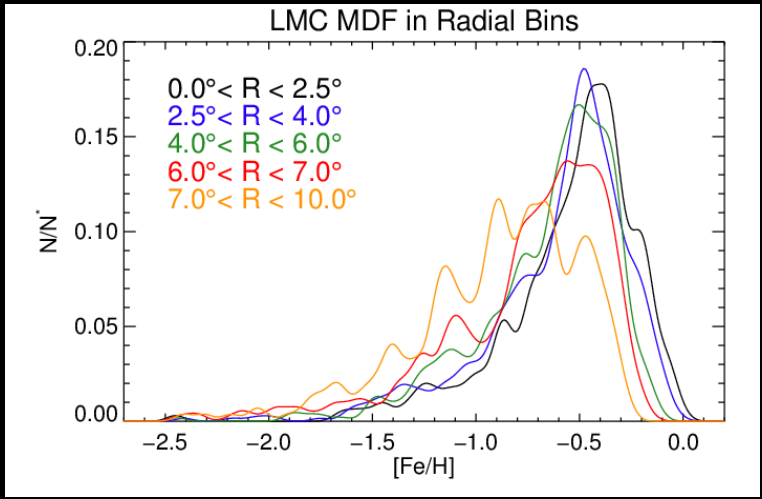
- Radial migration in simulation qualitatively reproduces the observed change in MDF skewness in MW midplane

Loebman, Debattista, Nidever et al. (2016)

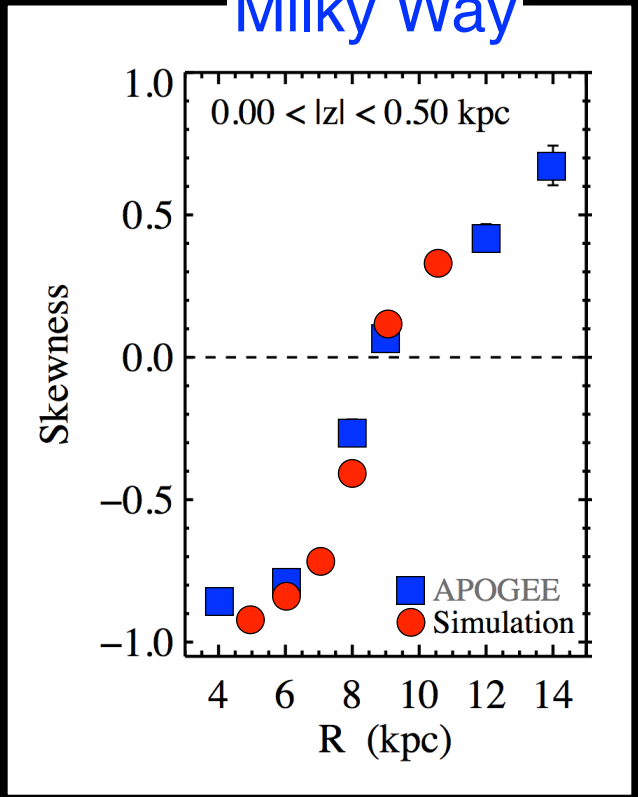
Radial Migration



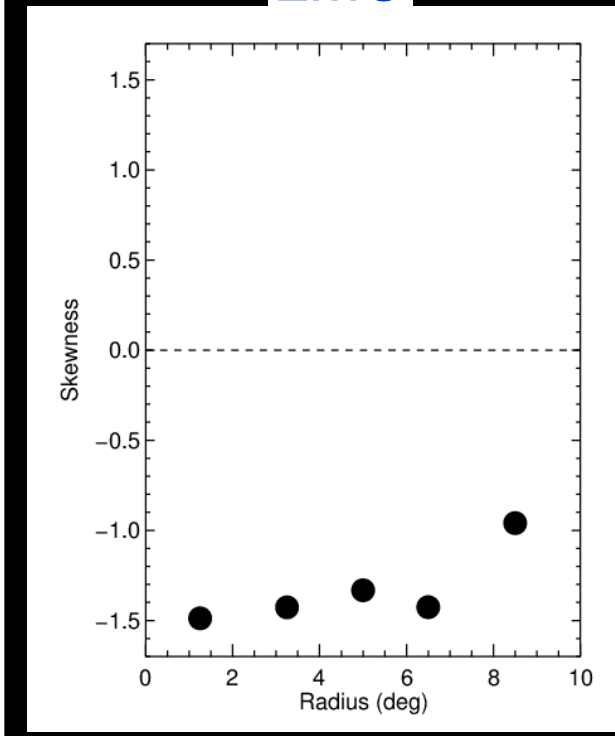
Radial Migration



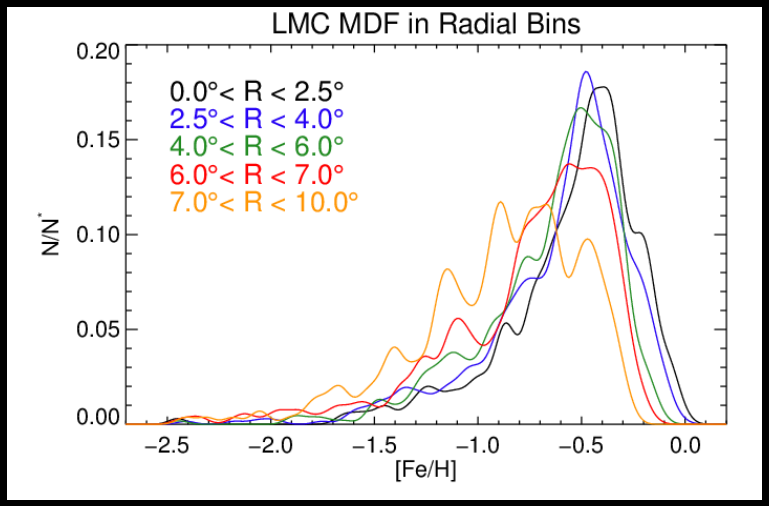
Milky Way

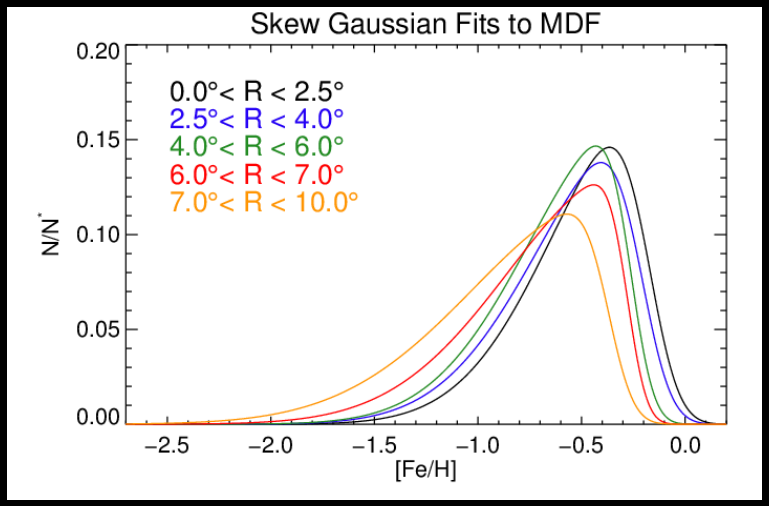


LMC

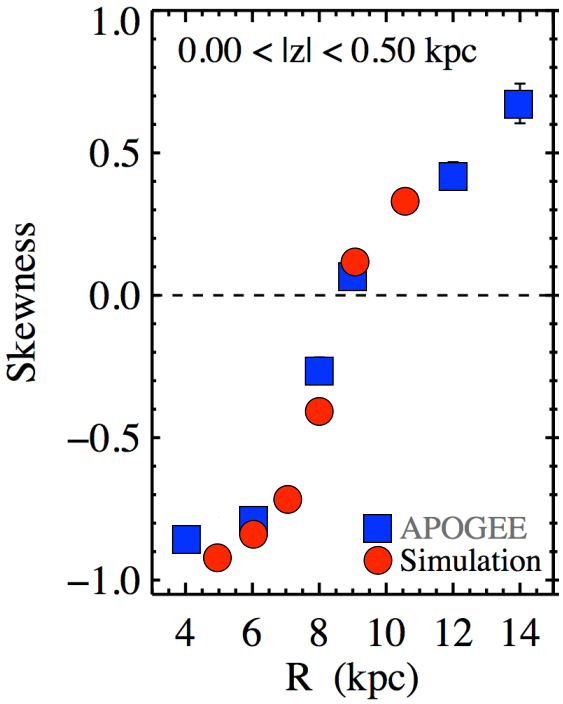


Radial Migration

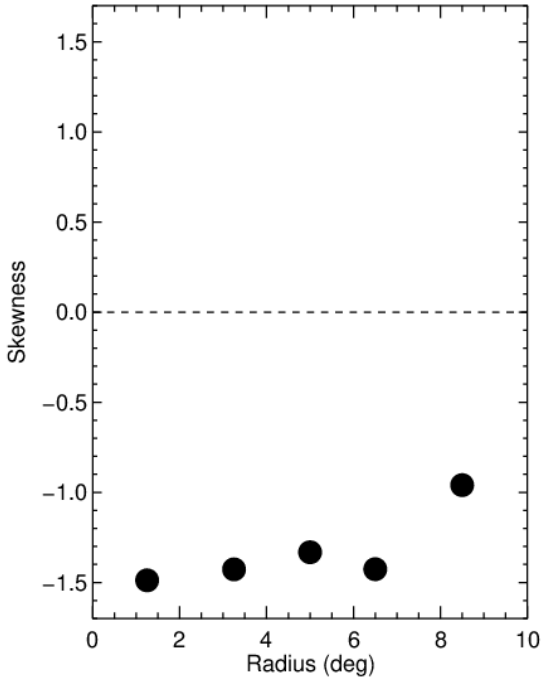




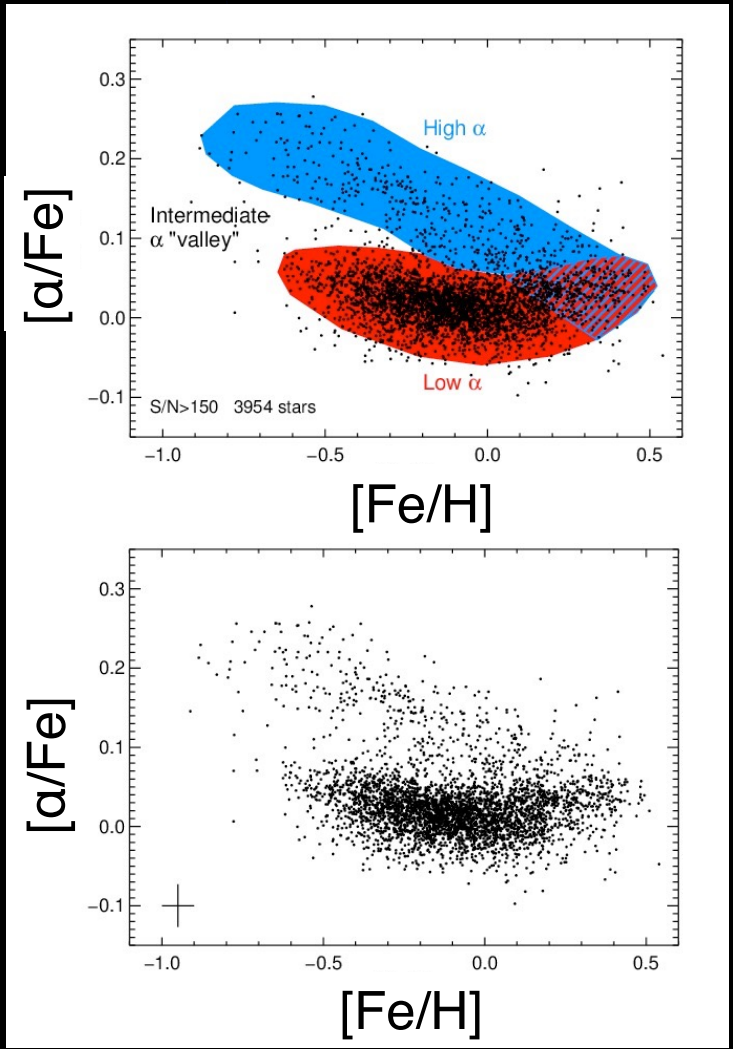
Milky Way



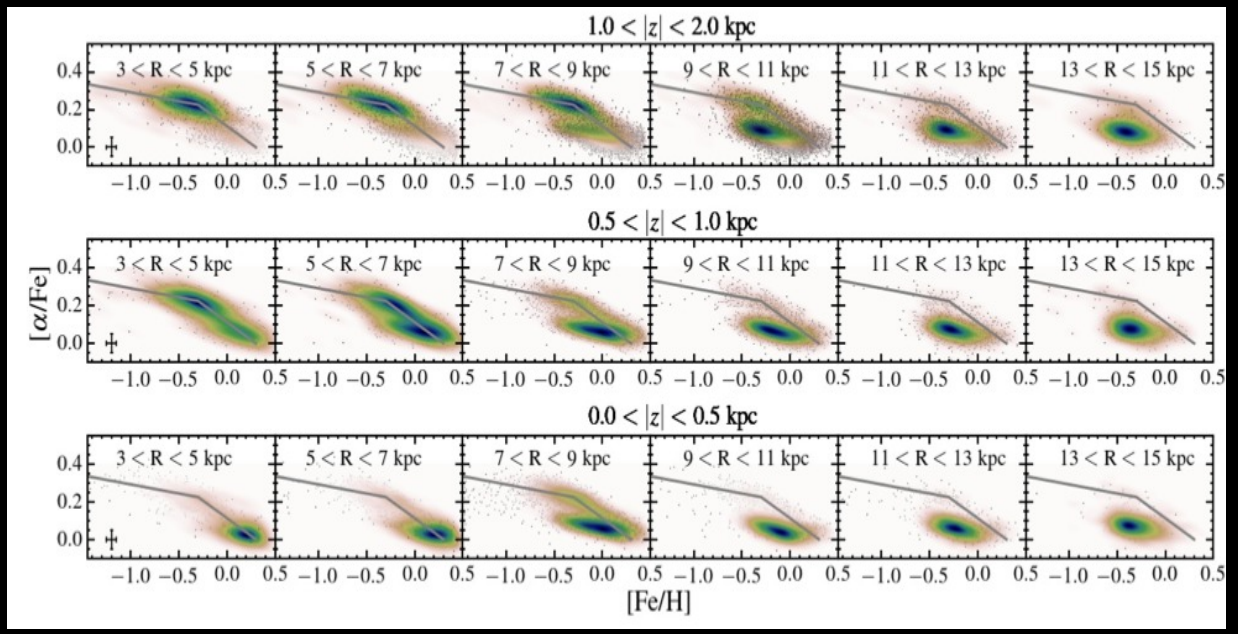
LMC



The α-bimodality

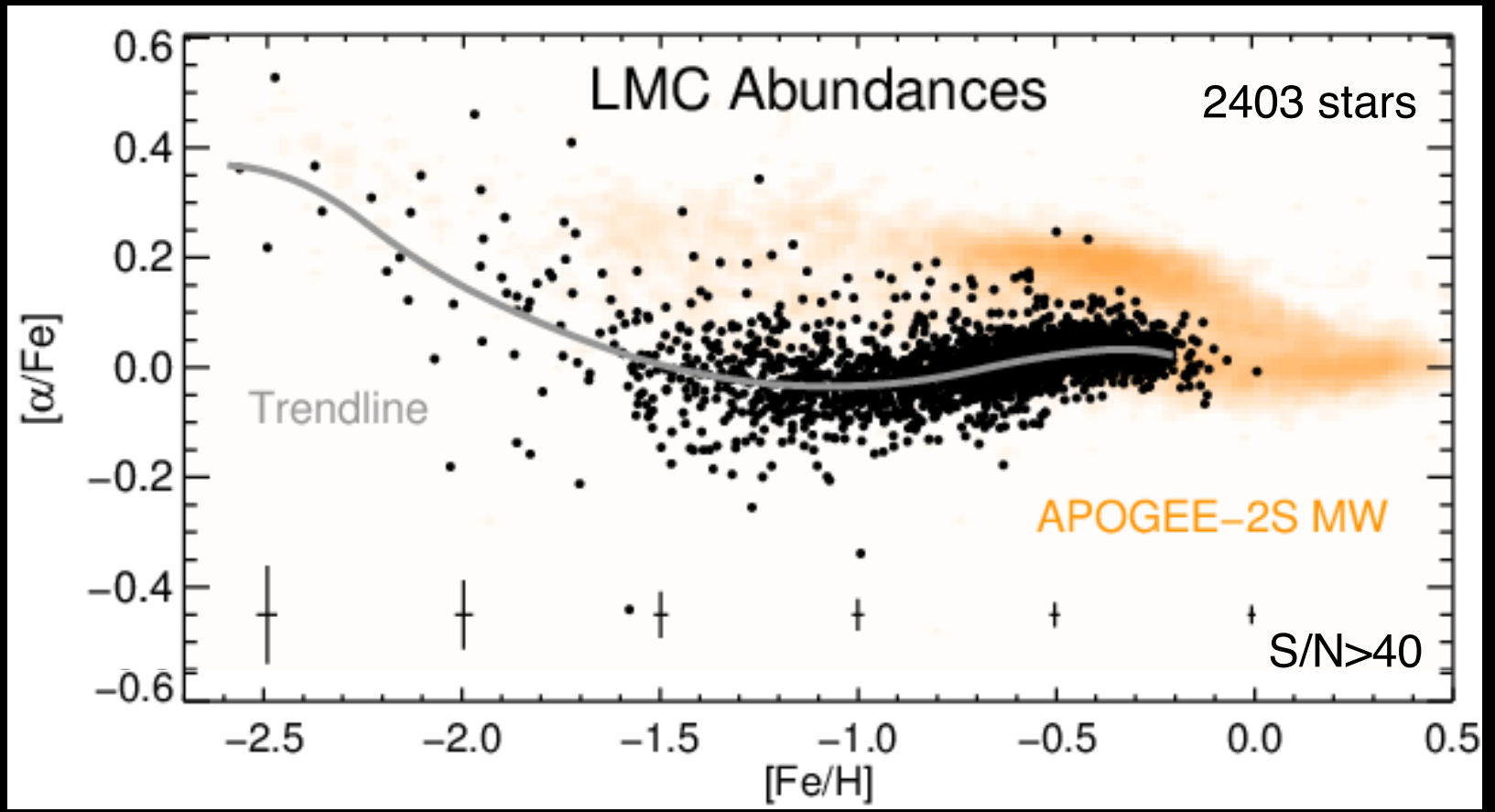


Nidever et al. (2014)



Hayden, Bovy, Holtzman, Nidever et al. (2015)

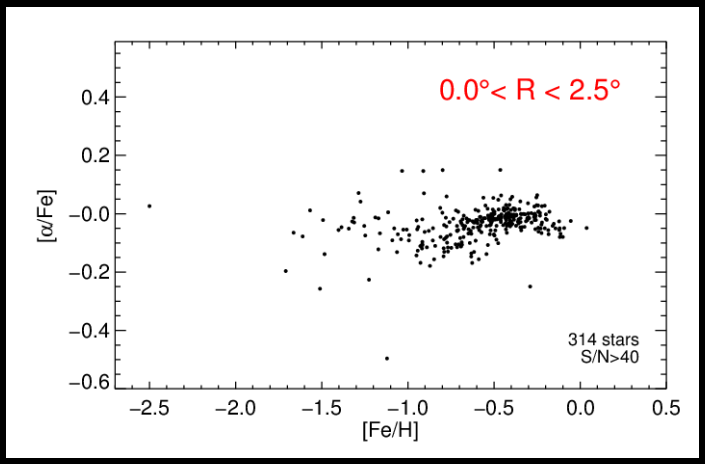
LMC α Abundances

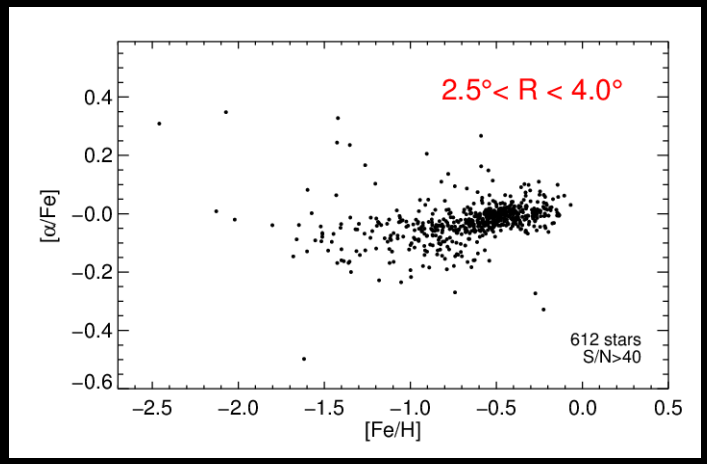


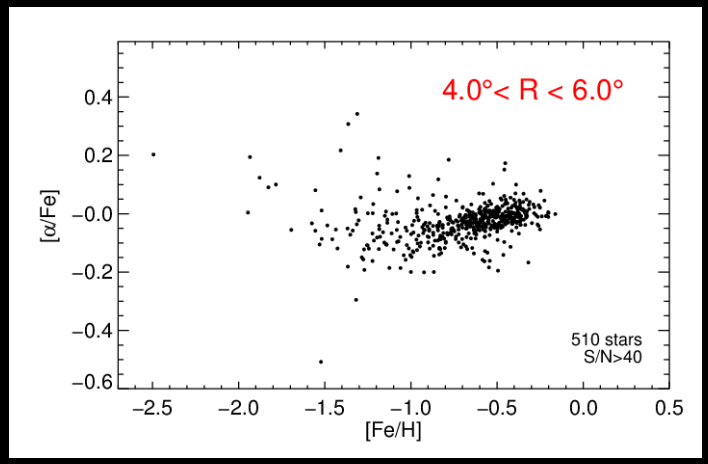
Nidever et al. (2019b)

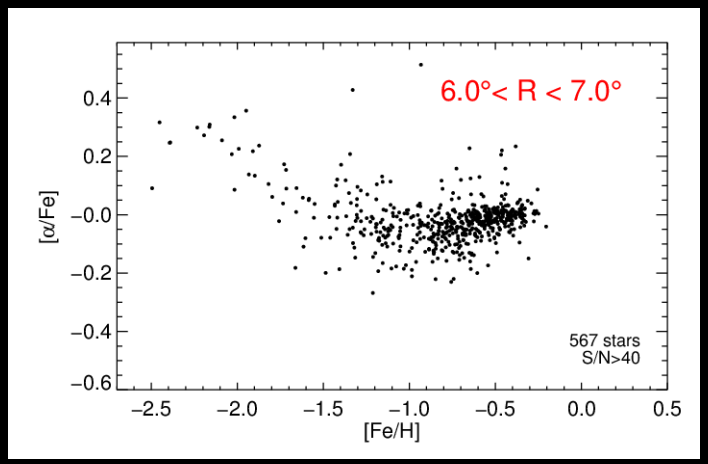
Chemical Cartography

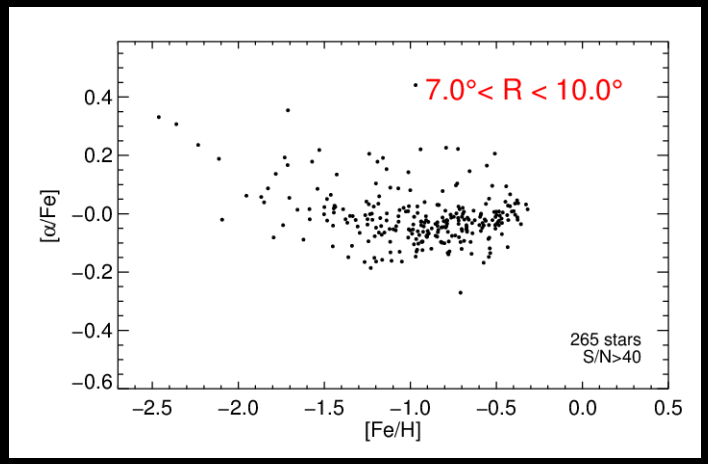
LMC



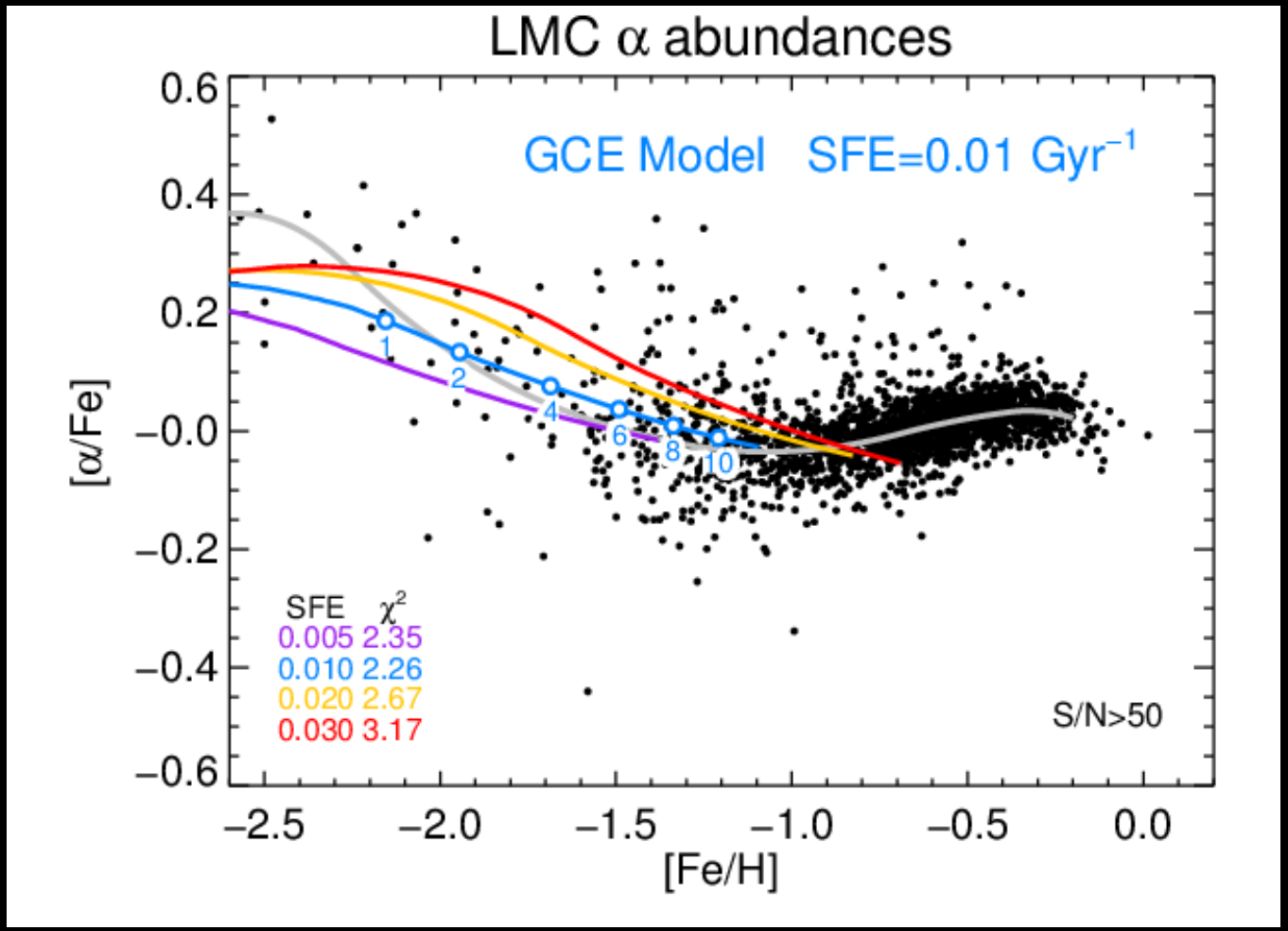








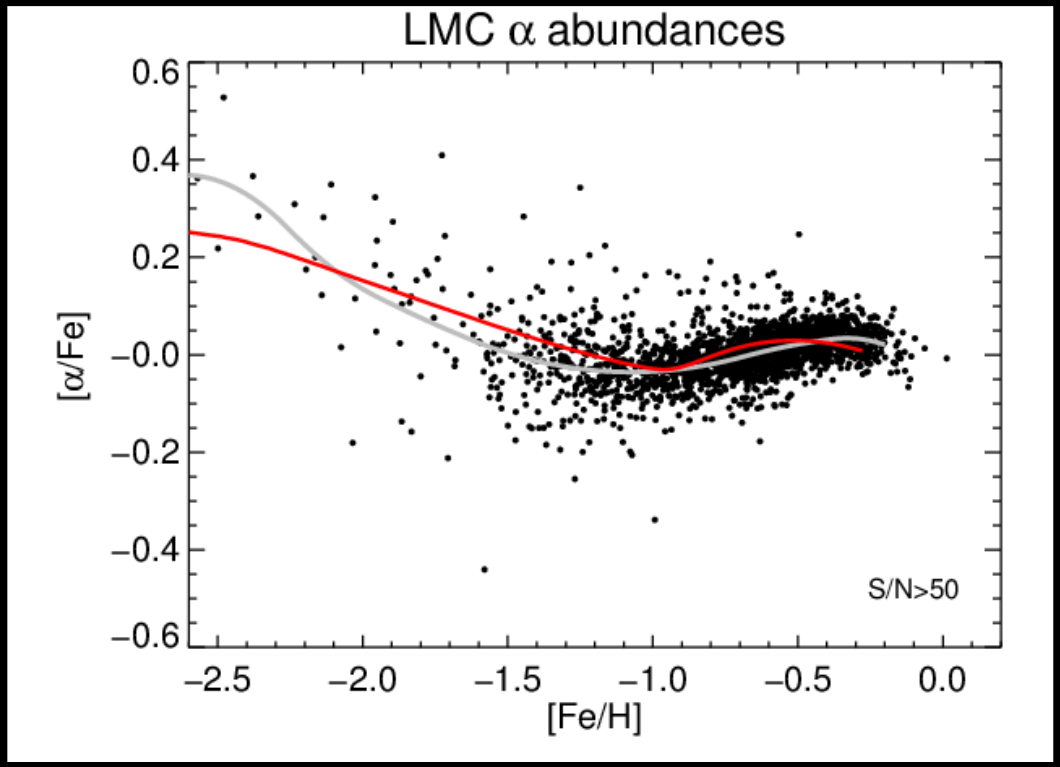
LMC α Abundances

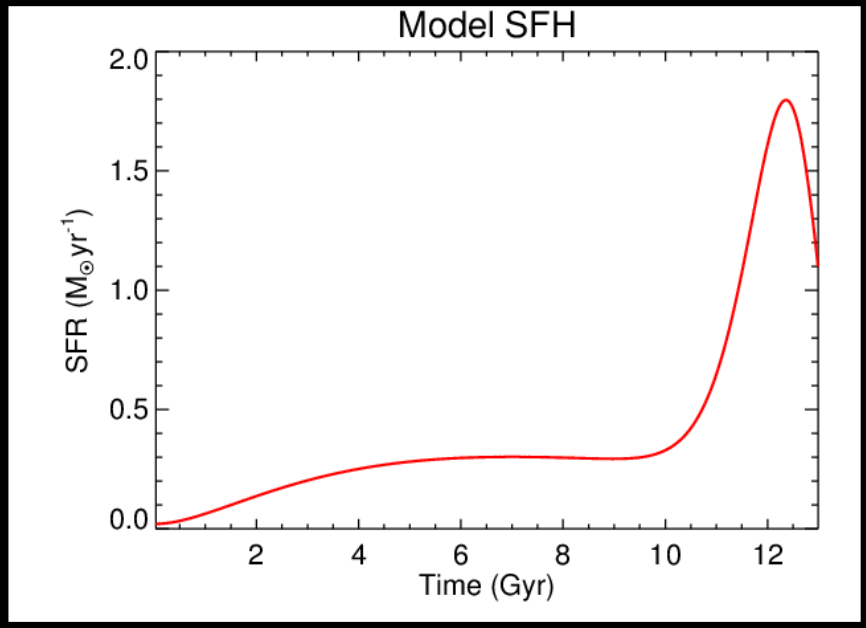


- Very low SFE
- 50x lower than MW high-α sequence
- Gas consumption timescale of 100 Gyr

Nidever et al. (2019b)

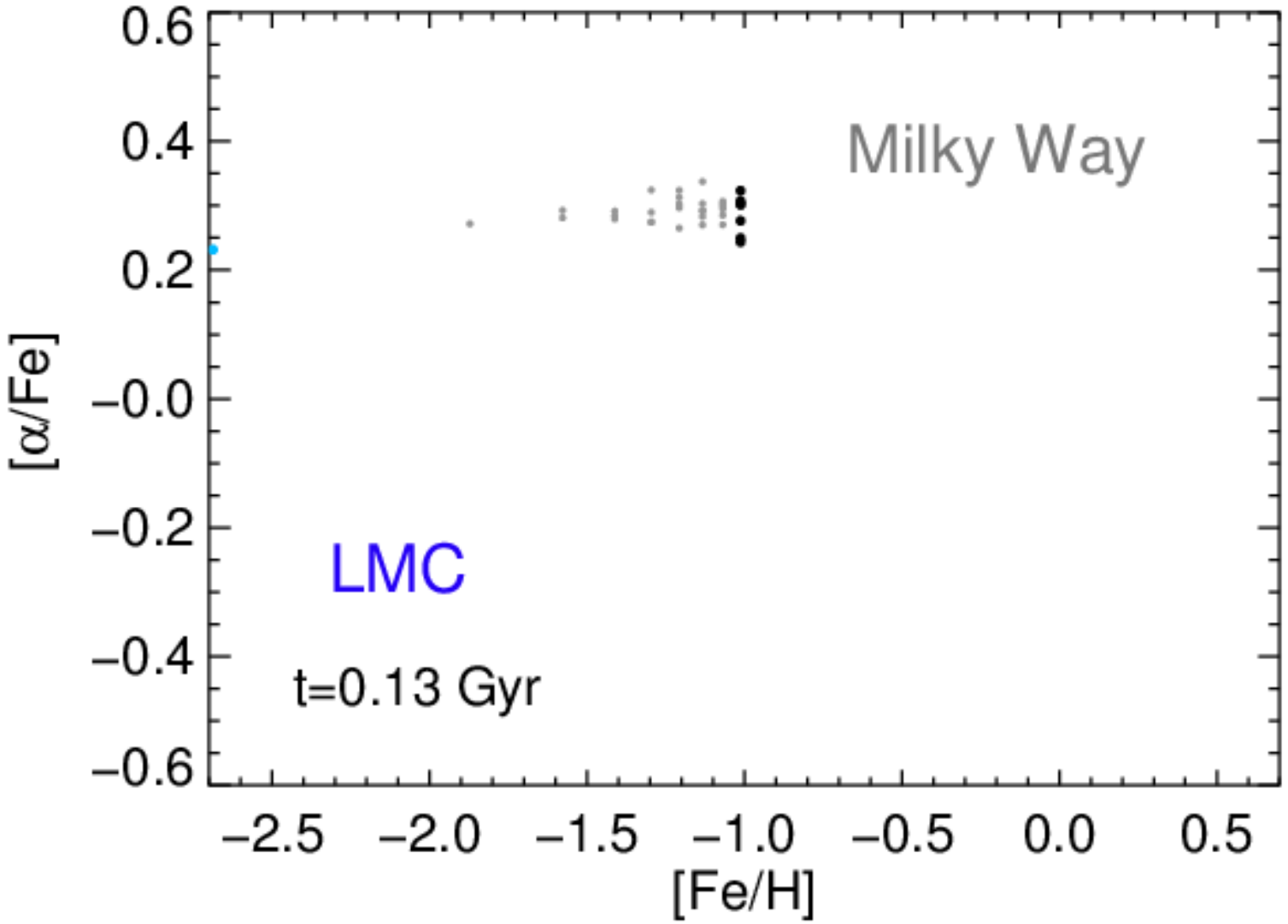
Recent Starburst



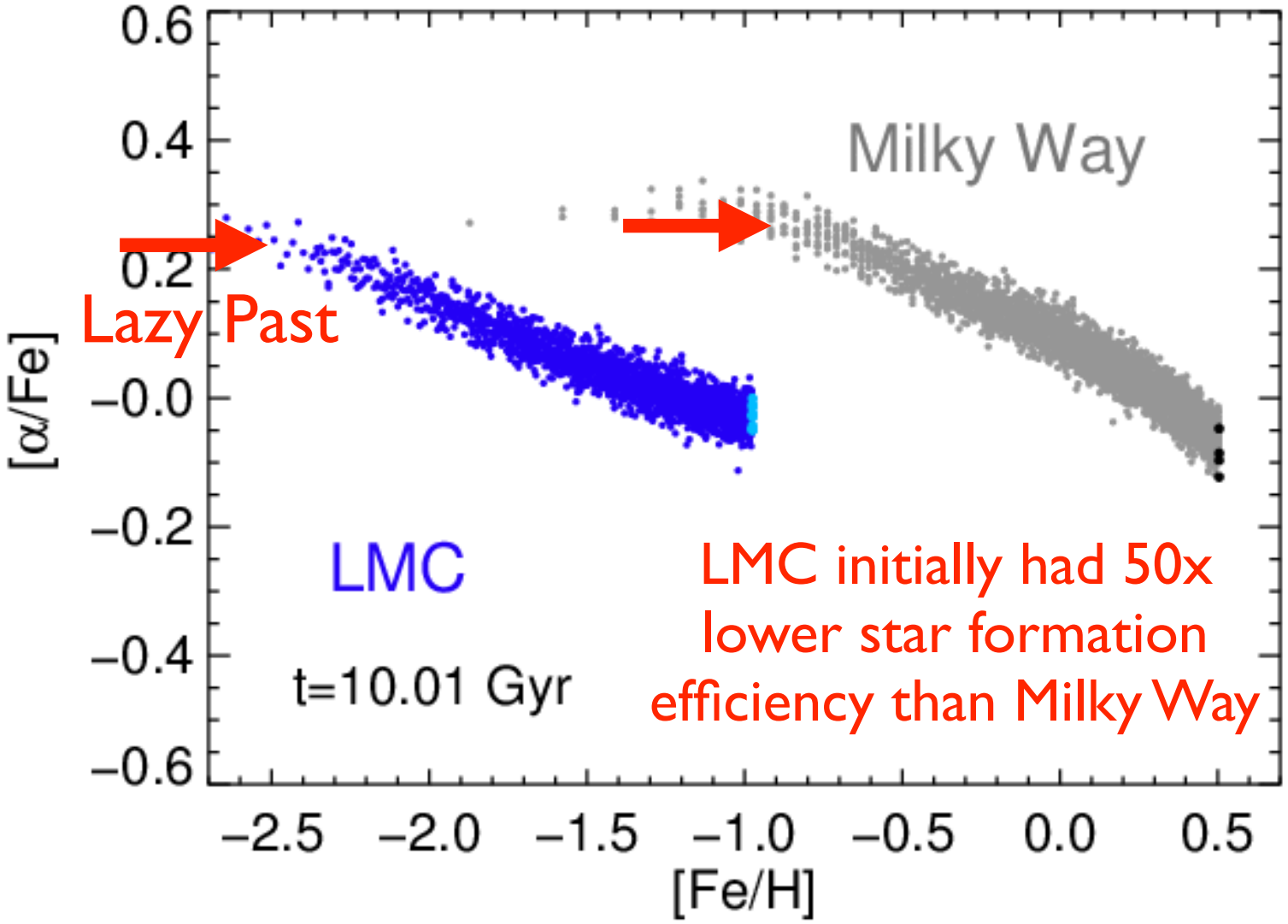


Nidever et al. (2019b)

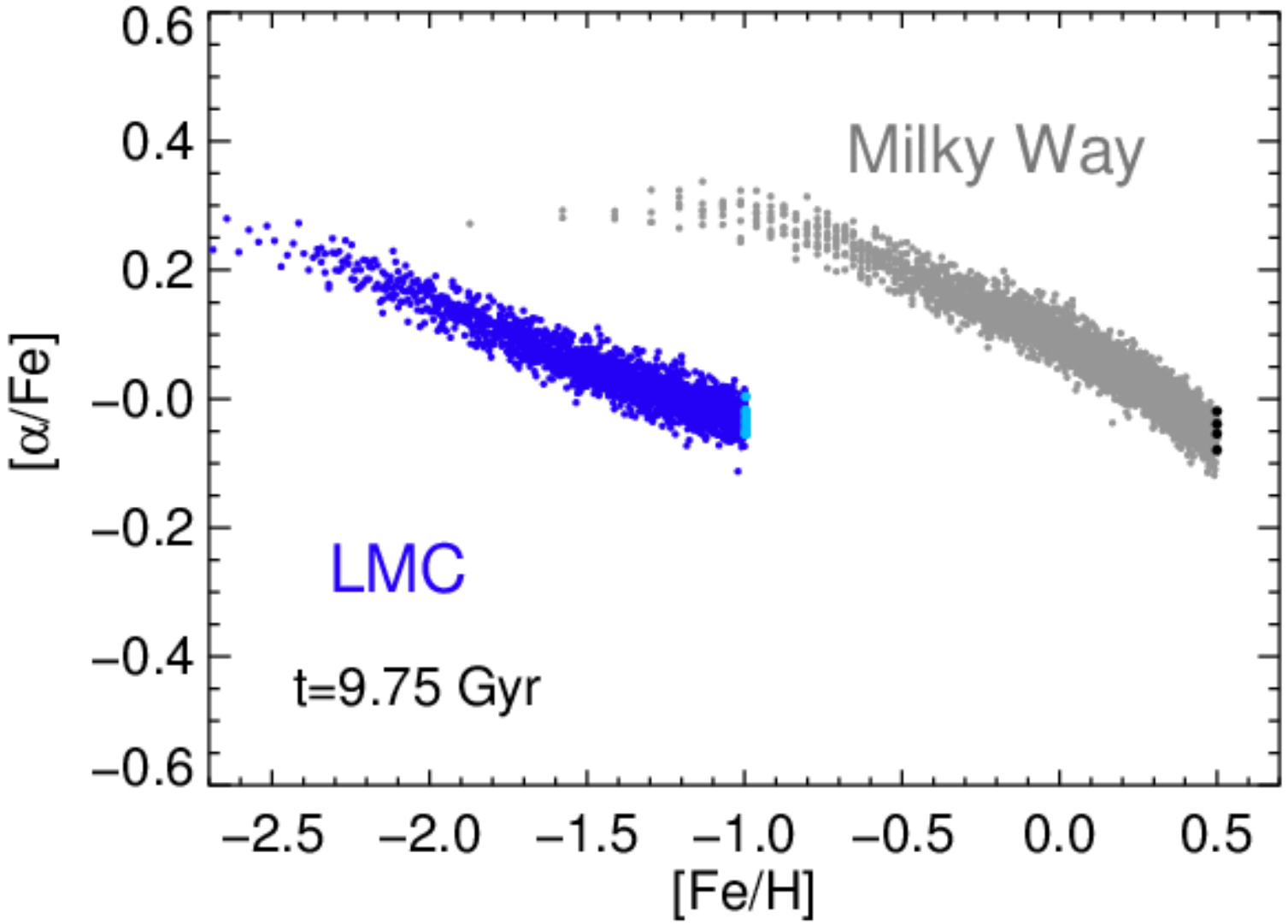
Galactic Chemical Evolution Models



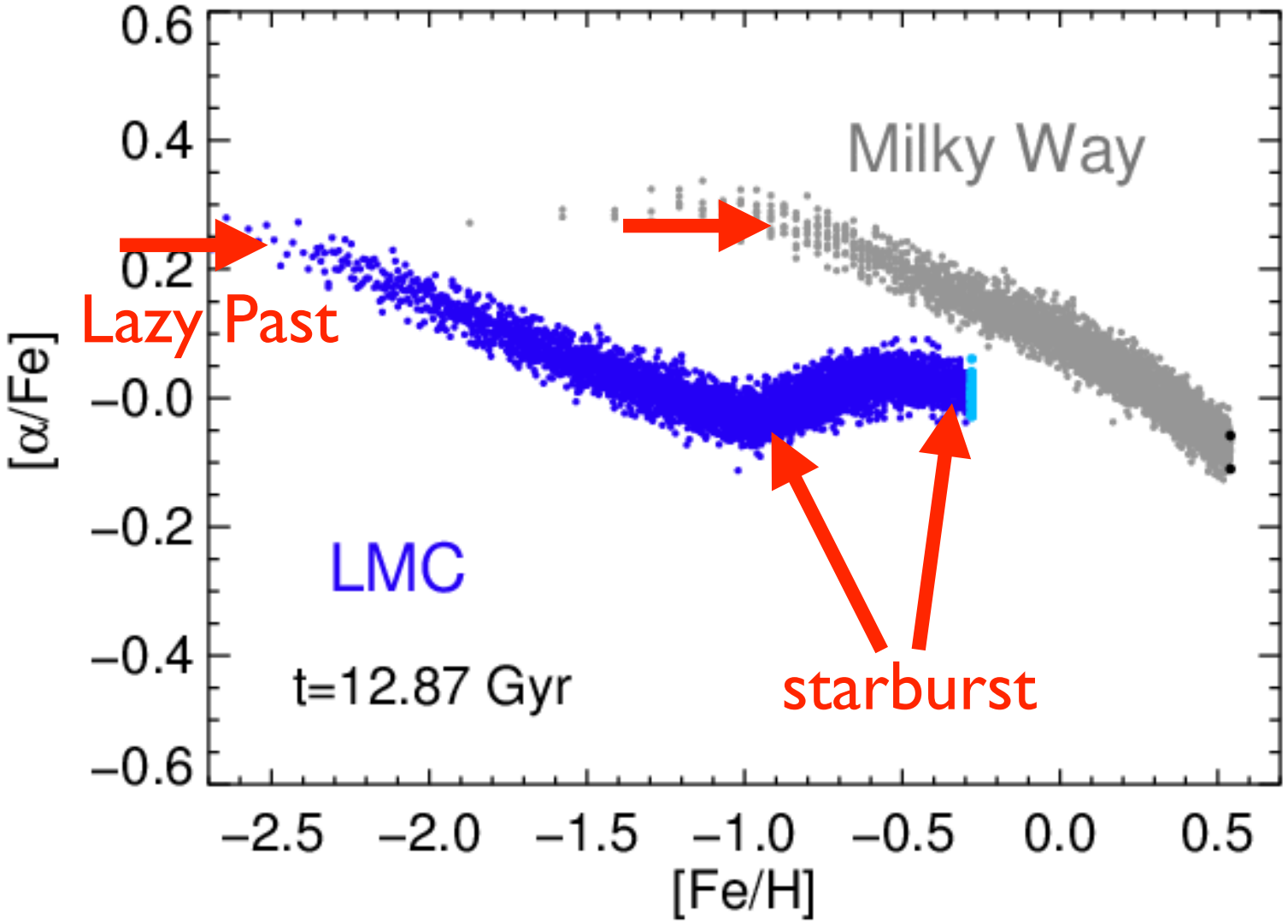
Galactic Chemical Evolution Models



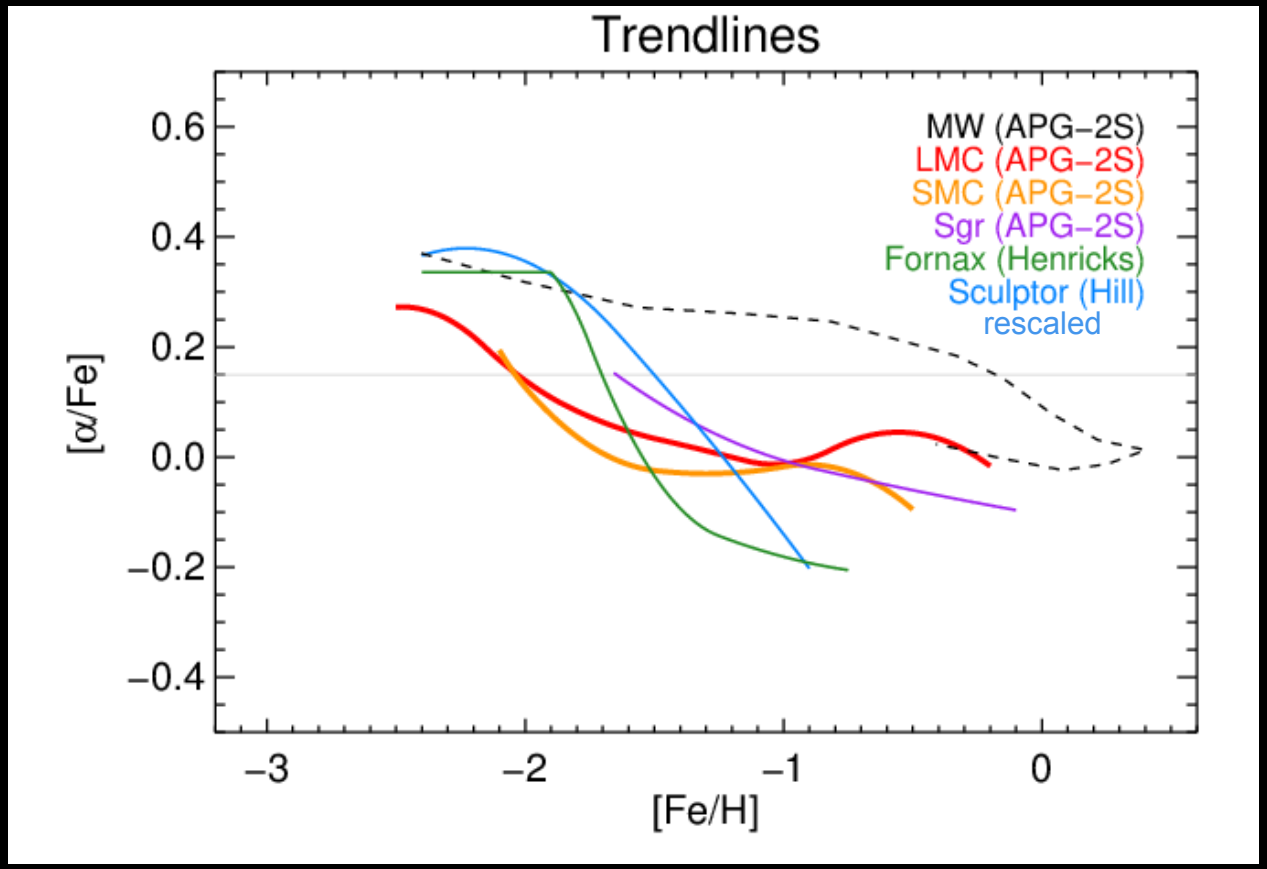
Galactic Chemical Evolution Models



Galactic Chemical Evolution Models



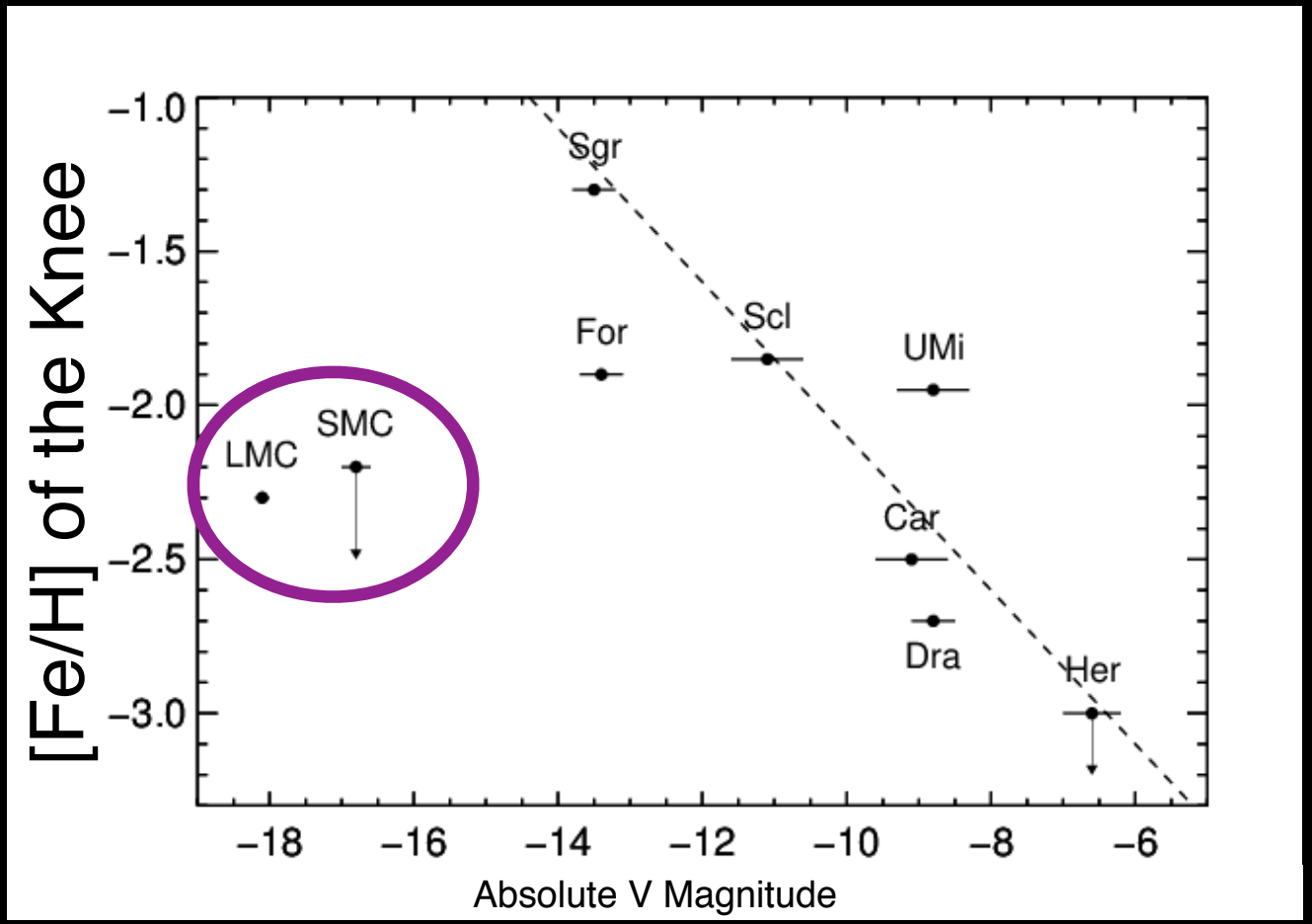
The α-Knee



Stellar Mass ($M_\odot$)	
MW	6×10^{10}
LMC	2×10^{9}
SMC	5×10^{8}
Sgr	2×10^{6} (4×10^{8})
Fornax	2×10^{7}
Sculptor	2×10^{6}

Nidever et al. (2019b)

The α-Knee



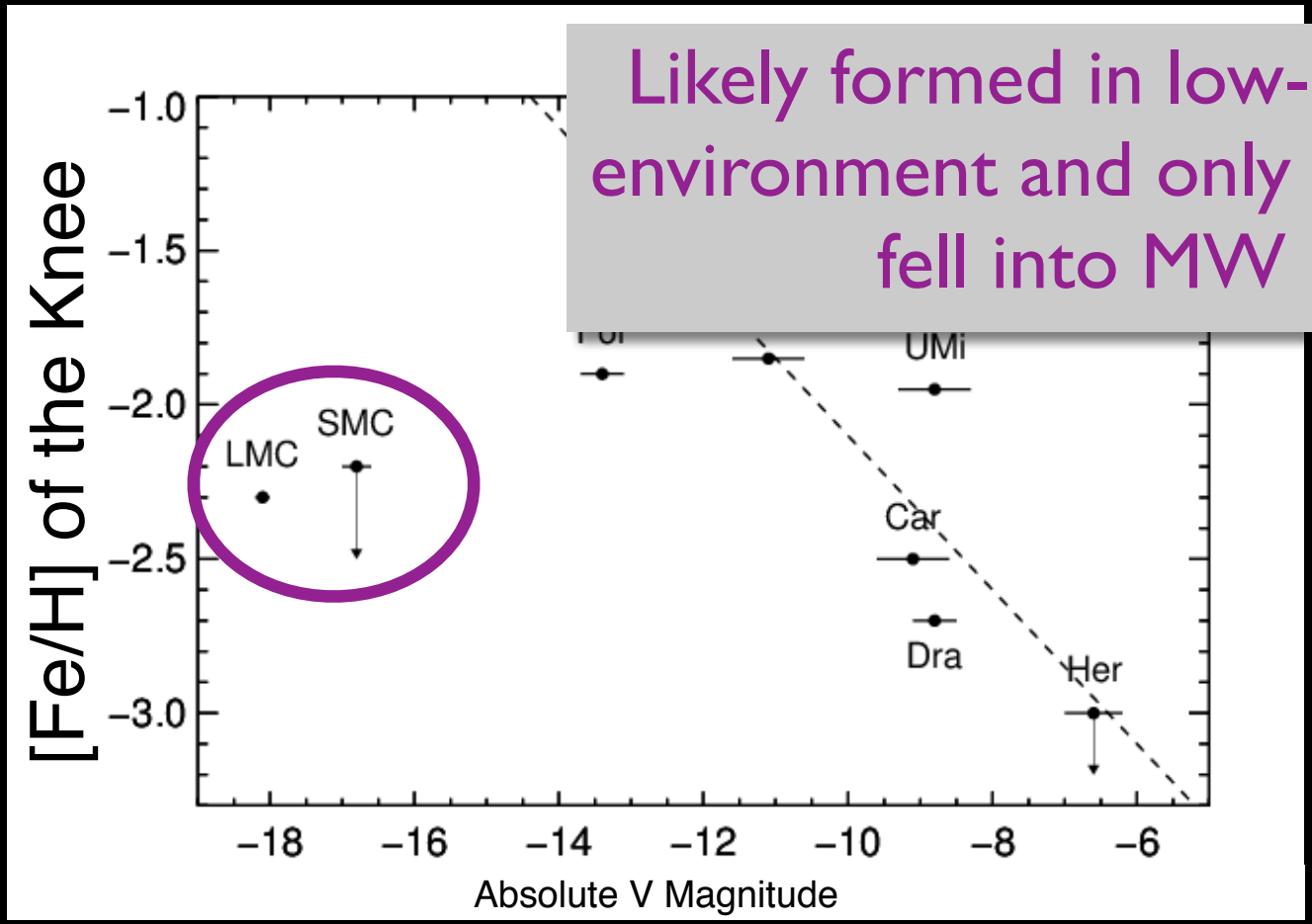
Higher Star Formation Rate

More Massive

Nidever et al. (2019b)

The α-Knee

Likely formed in low-density environment and only recently fell into MW



Higher Star Formation Rate

More Massive

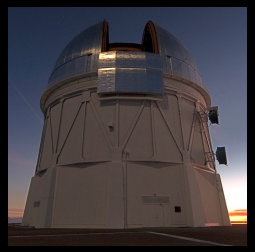
AAS 233, Seattle 2019 SDSS Press Release/Conference Nidever et al. (2019b)

SMASH

Survey of the Magellanic Stellar History

- PI: Nidever
- Large and deep imaging survey of the Magellanic Clouds
- 50 nights on Blanco-4m telescope + DECam
- 40 member international team
- NSF funded project

Blanco 4m



The 520 megapixel
Dark Energy Camera (DECam)

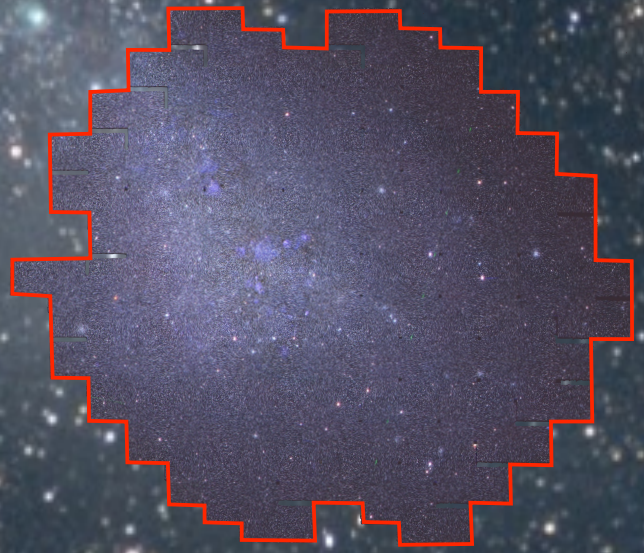
Nidever et al. (2017)

The Small Magellanic Cloud

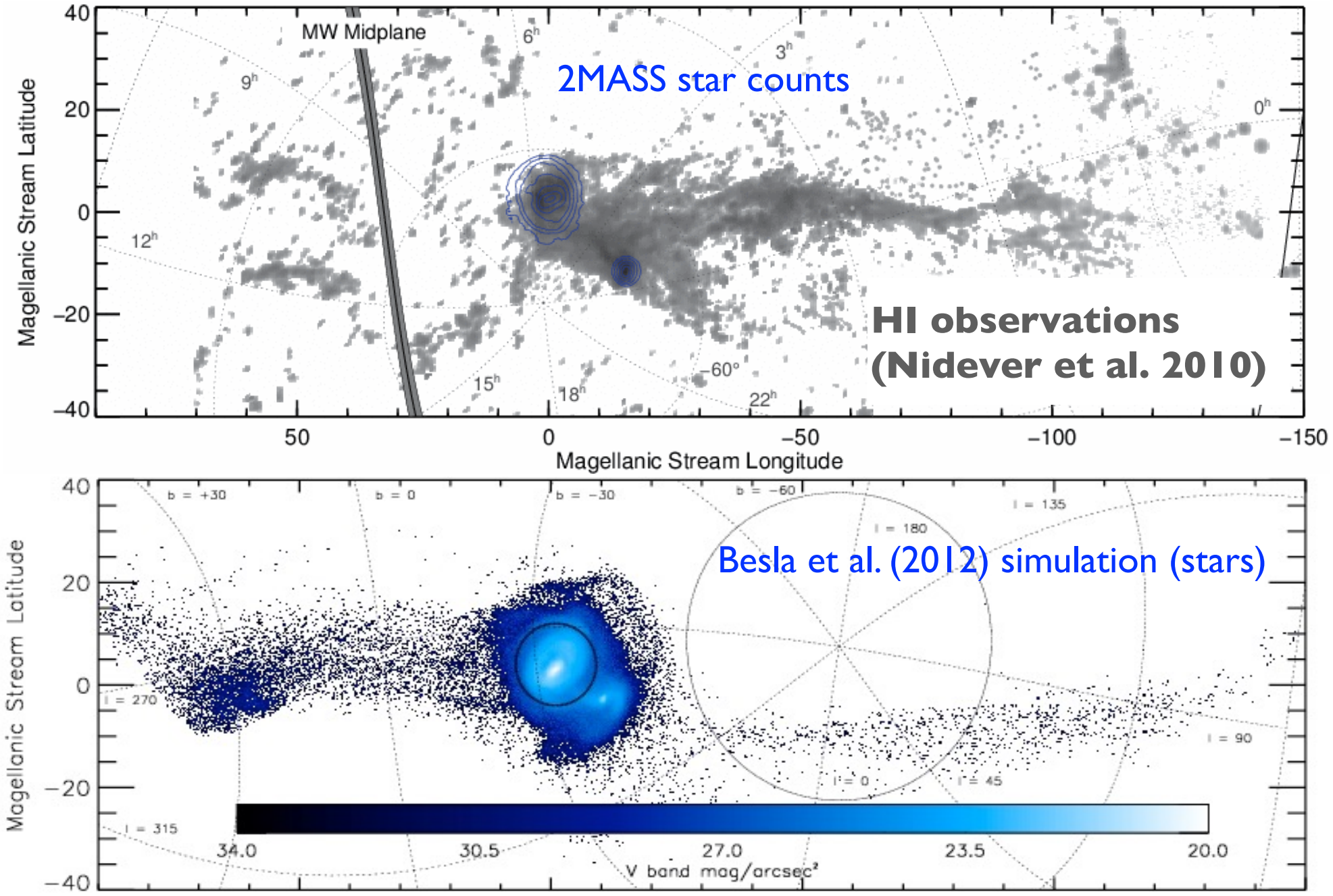
Moon shown for scale

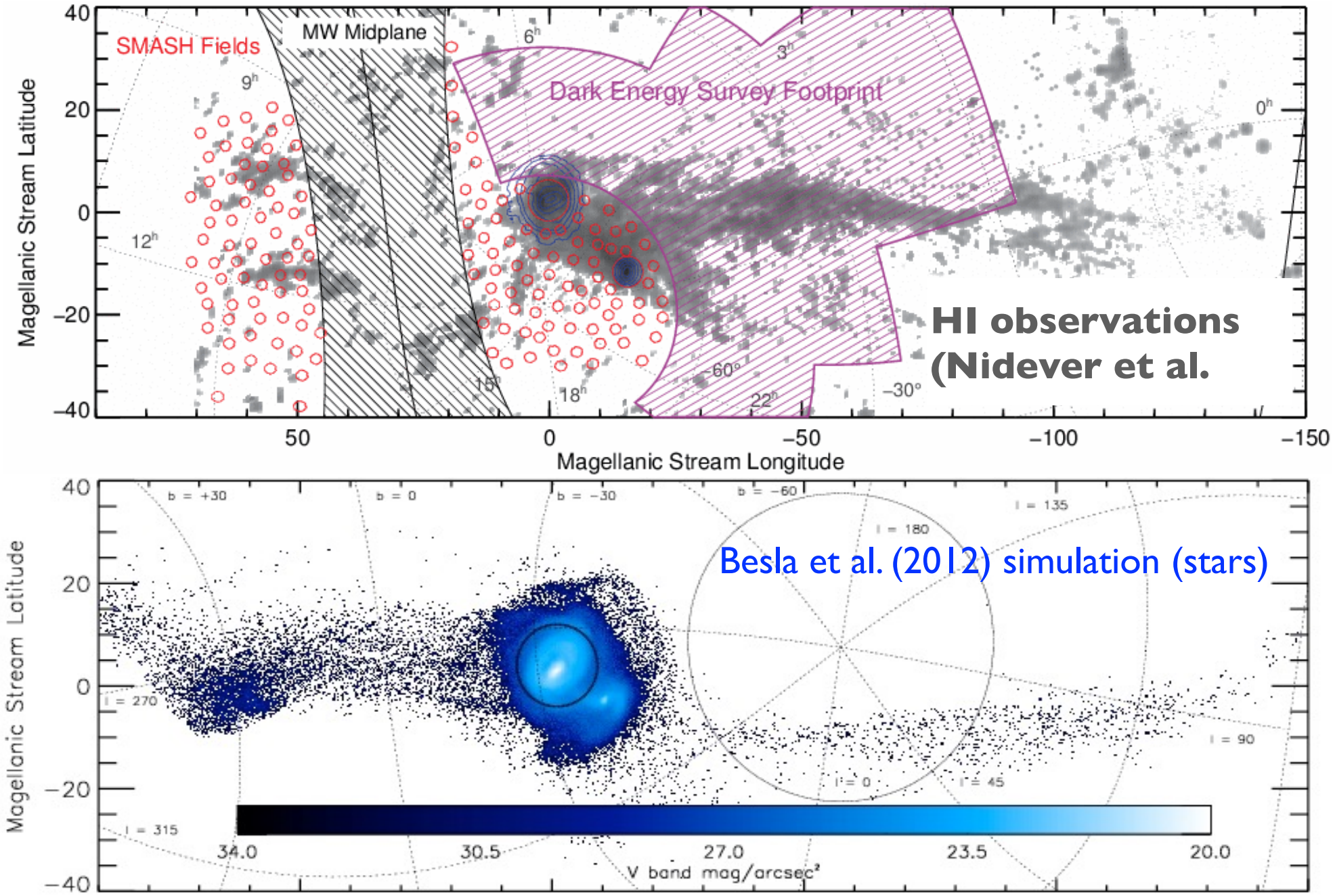
The Small Magellanic Cloud

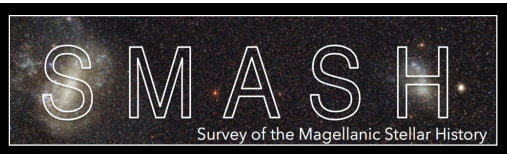
Moon shown for scale



One DECam image


MW Midplane
2MASS star counts
HI observations
(Nidever et al. 2010)
Magellanic Stream Latitude
Magellanic Stream Longitude
Besla et al. (2012) simulation (stars)
V band mag/arcsec²
34.0
30.5
27.0
23.5
20.0

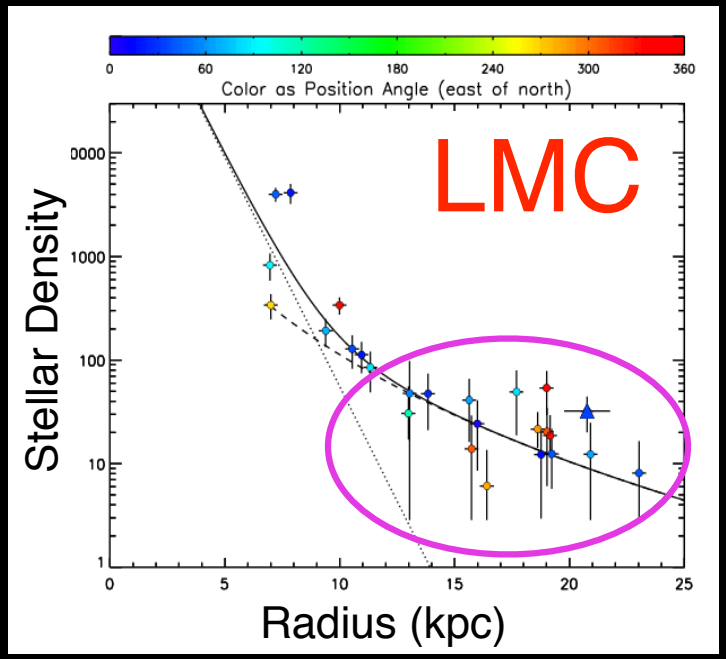

SMASH Fields
MW Midplane
Dark Energy Survey Footprint
HI observations (Nidever et al.
Magellanic Stream Latitude
Magellanic Stream Longitude
Besla et al. (2012) simulation (stars)
V band mag/arcsec²



SMASH Catalog

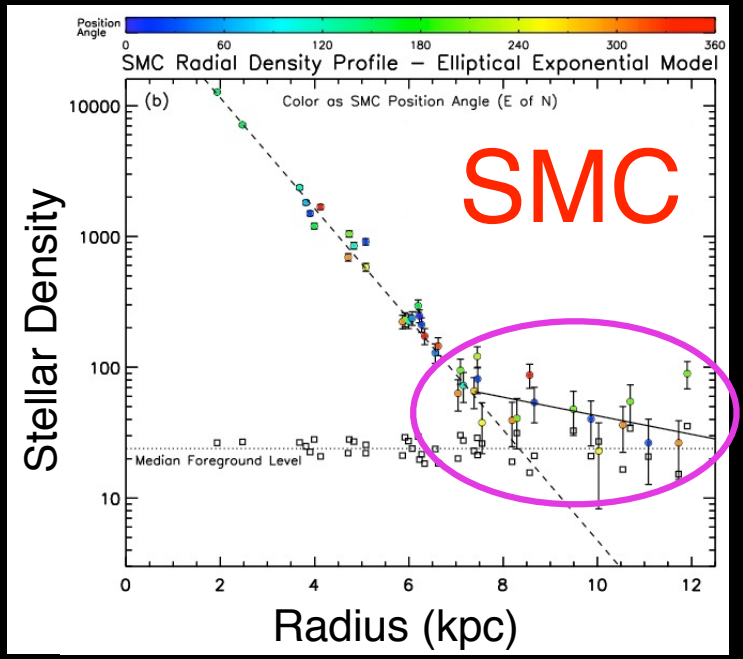
- Overview paper (Nidever et al. 2017)
- 420 million objects, 4 billion source measurements
  (more objects than all of Sloan Digital Sky Survey!)
- 5σ point source depths: 23.9, 24.8, 24.5, 24.2, 23.5 mag (*ugriz*)
  ~6.5x deeper than SDSS and ~4x deeper than Pan-STARRS
- First data release (Jan 2017)
  - » 61 fields
  - » 100 million objects
  - » via NOAO Data Lab https://datalab.noao.edu
- Final data release (Sep 2019)
  - » 197 fields
  - » 420 million objects

MAPS Discovery of LMC and SMC Stellar Halos



- Uncovered very extended population to 20 kpc
- *Large LMC stellar halo*

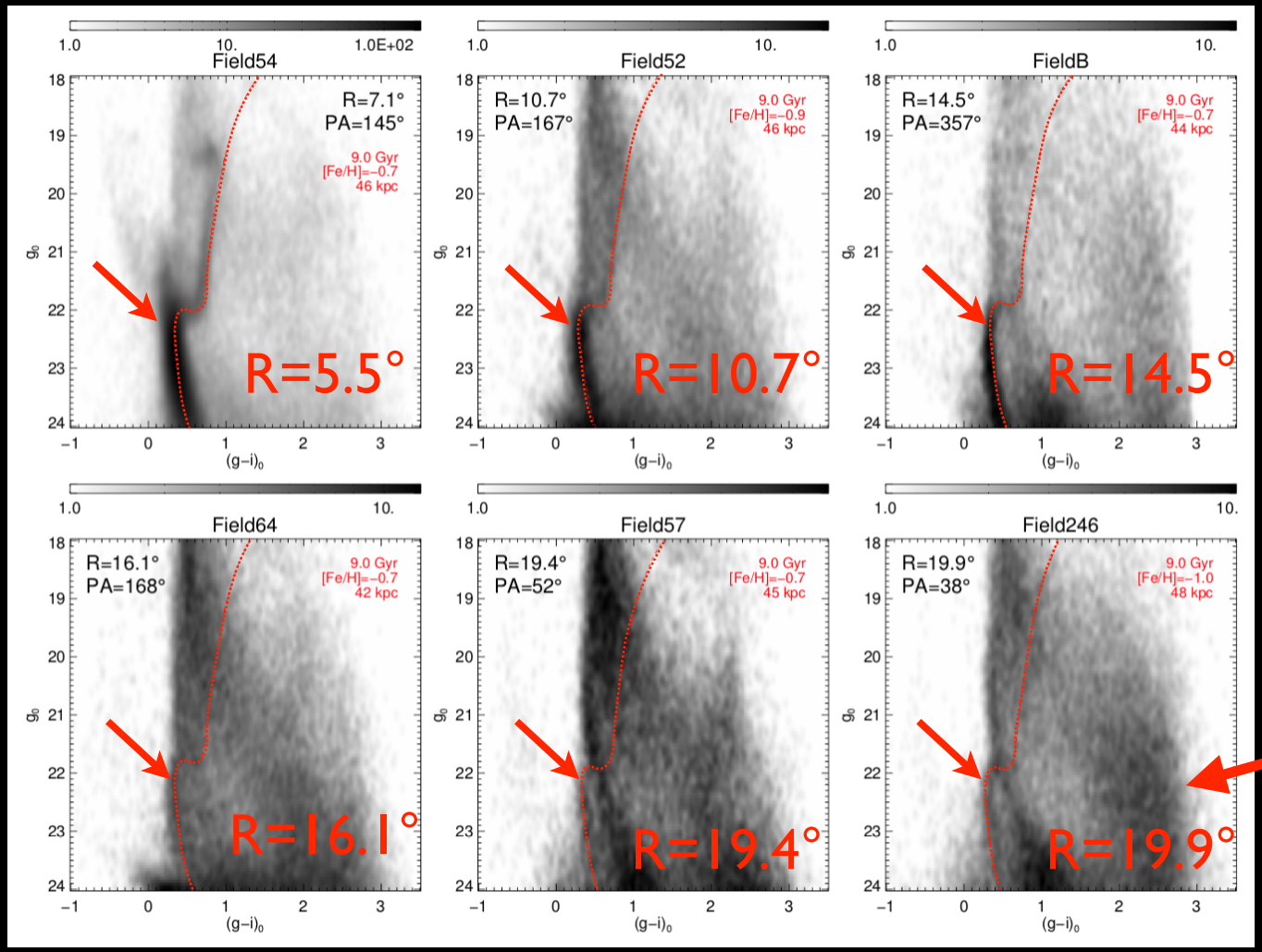
Majewski, Nidever et al. (2009)



- Uncovered very extended population to 12 kpc
- *Large SMC stellar halo*

Nidever et al. (2011)

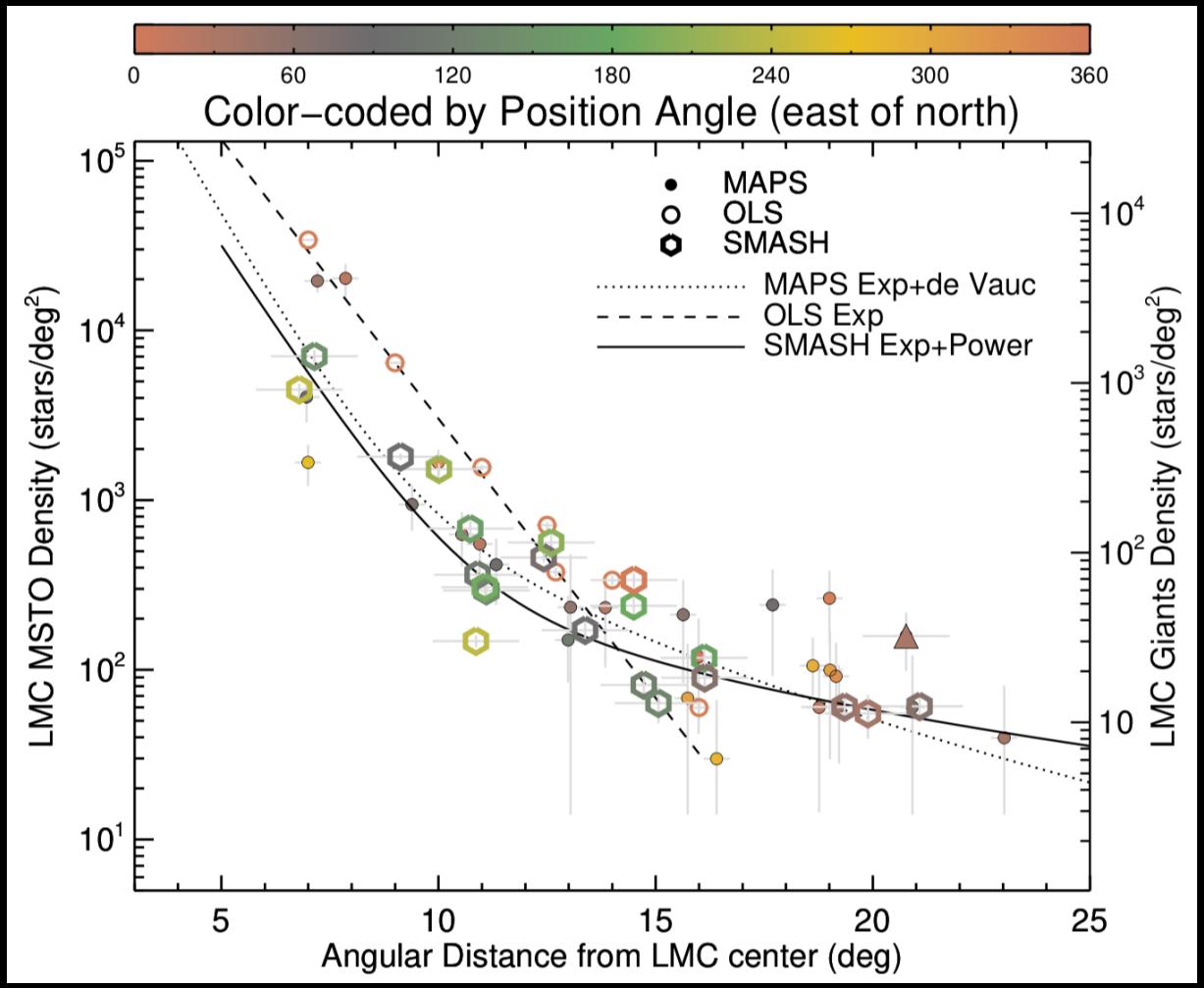
SMASH CMDs



34 mag/arsec^2!

Nidever et al. (2019a)

SMASH Density Profile

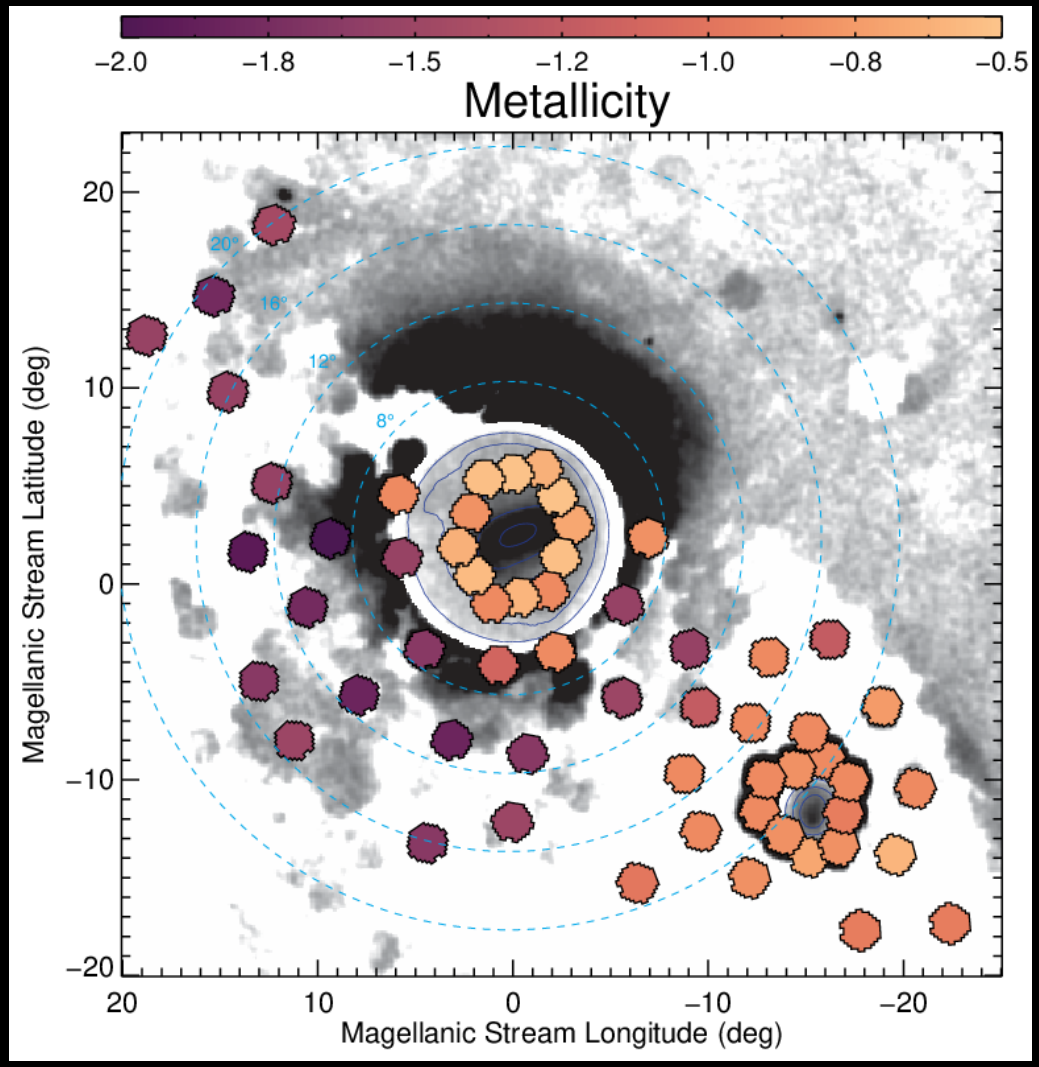


- SMASH confirms the MAPS results on the extended LMC periphery
- Extends to ~21°
- *LMC surrounded by large "envelope" of stars of old, metal-poor stars*

Nidever et al. (2019a)

SMASH
Survey of the Magellanic Stellar History

Photometric Metallicity Map

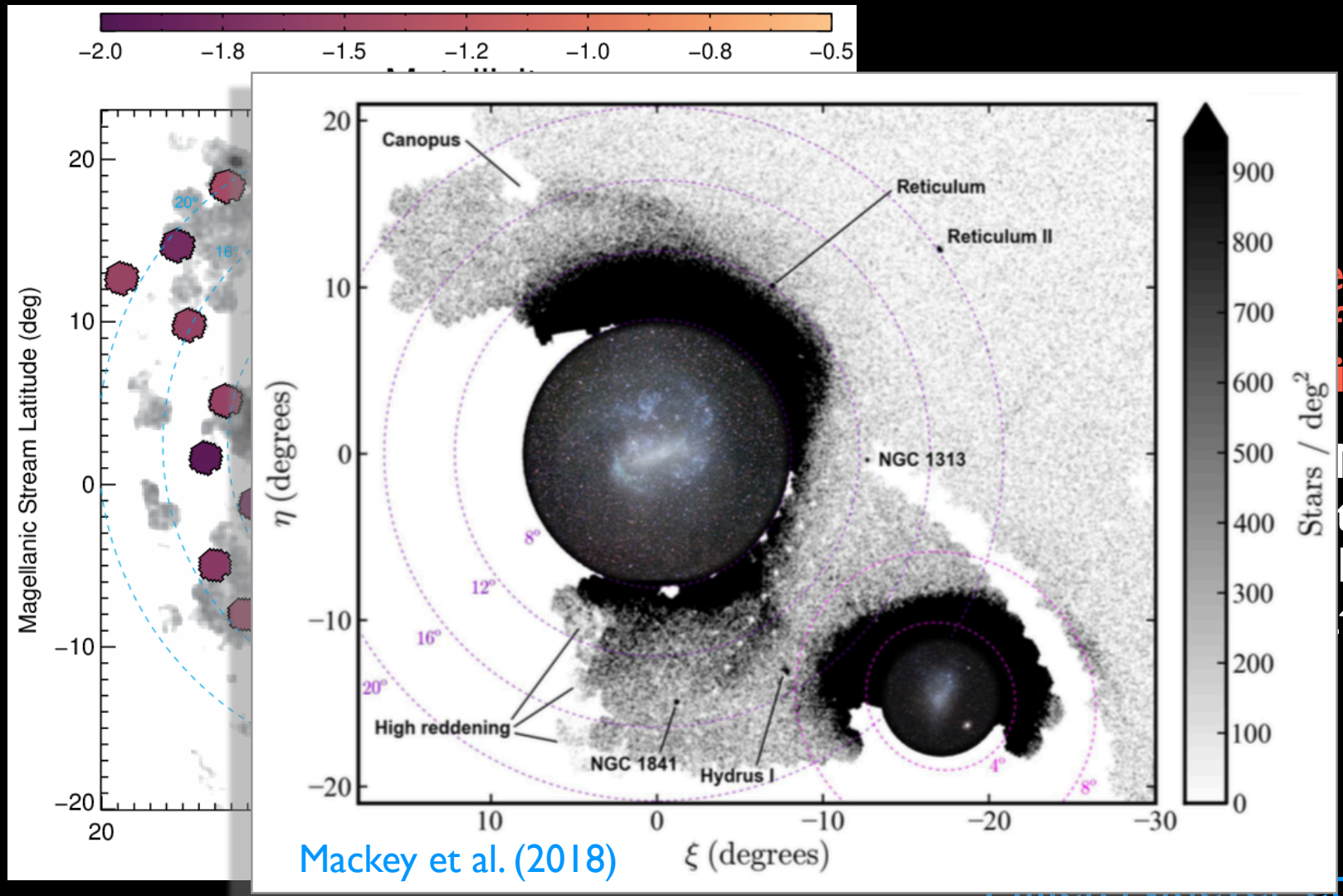


- Shallow LMC metallicity gradient slightly favors **outer disk origin**
- Homogeneous SMC metallicity indicates **recently tidally disturbed material**

Miller, Nidever et al., in prep.

SMASH
Survey of the Magellanic Stellar History

Photometric Metallicity Map



Mackey et al. (2018)

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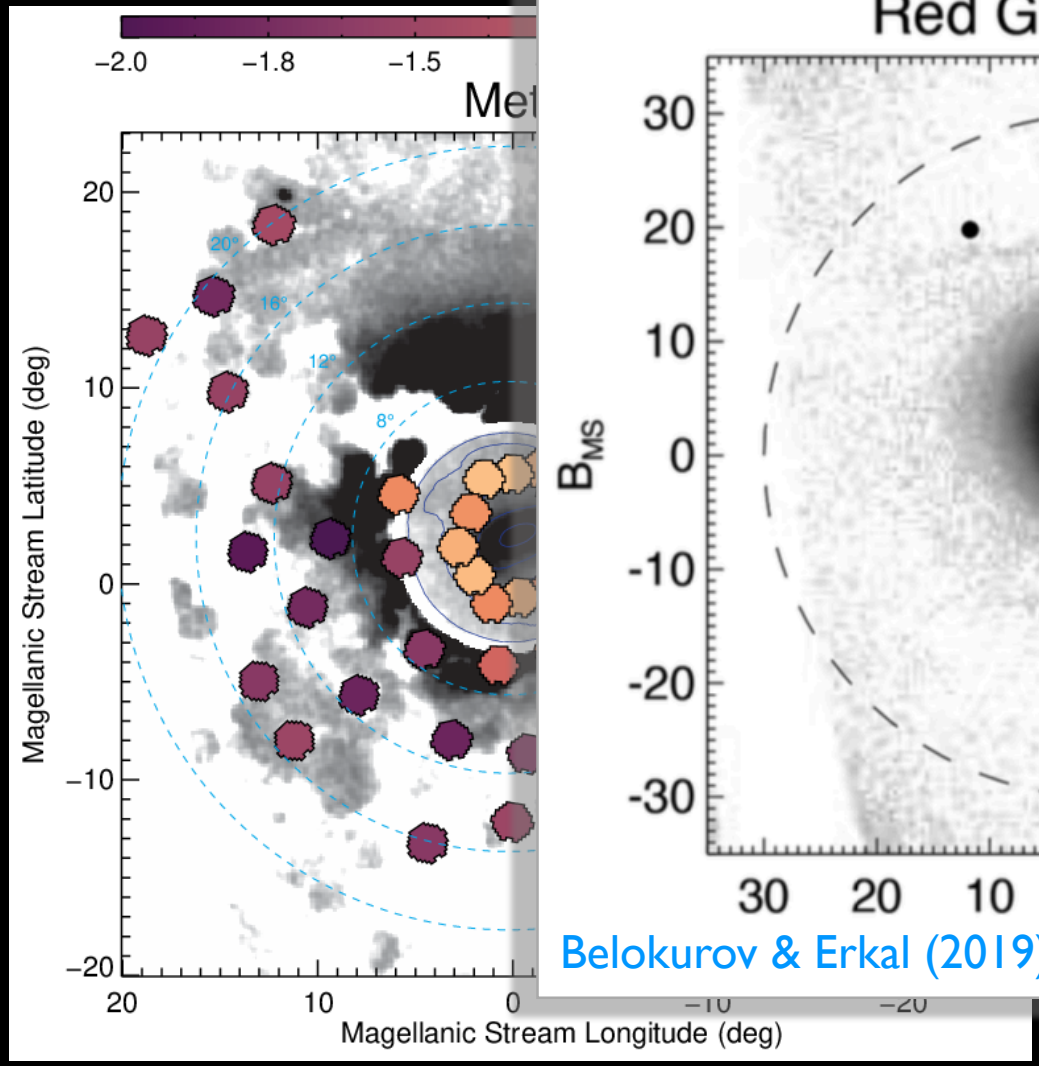
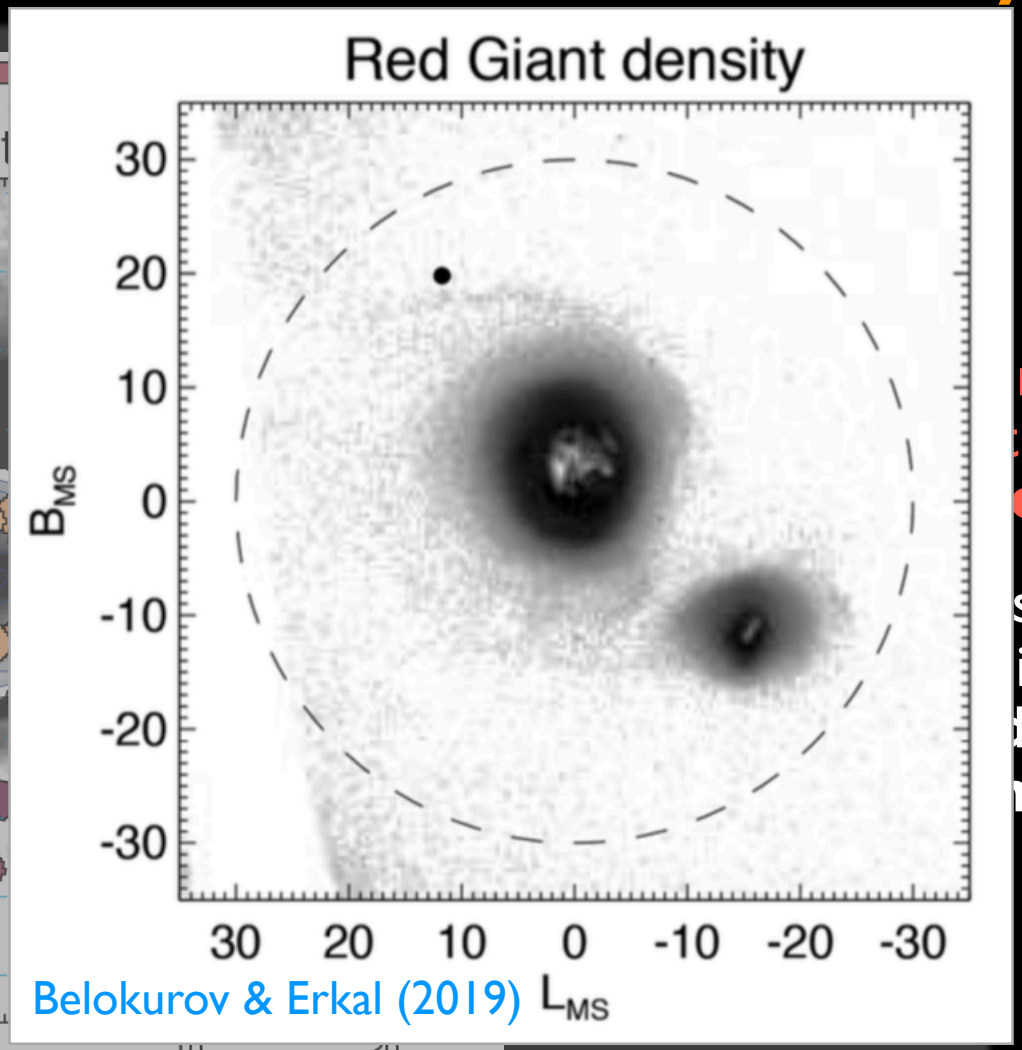
SMASH
Survey of the Magellanic Stellar History

Photometric Metallicity Map





Belokurov & Erkal (2019)

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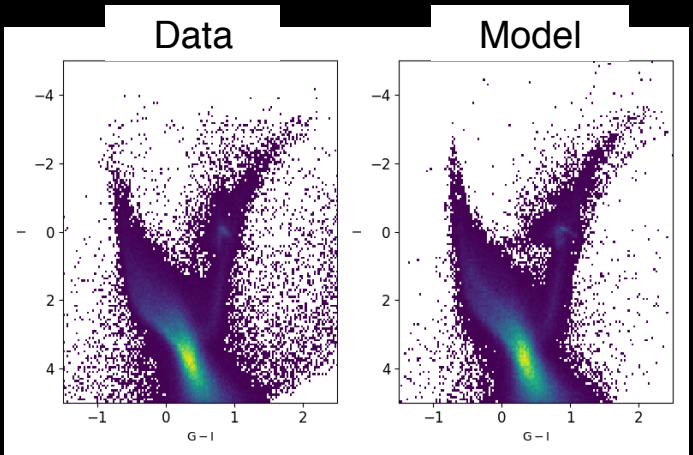
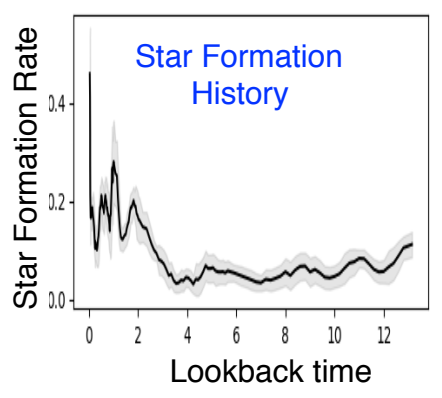
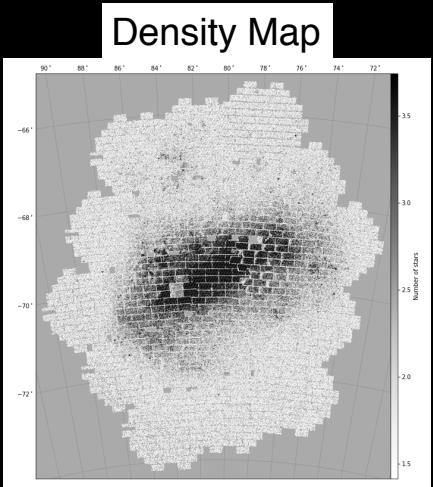
Miller, Nidever et al., in prep.

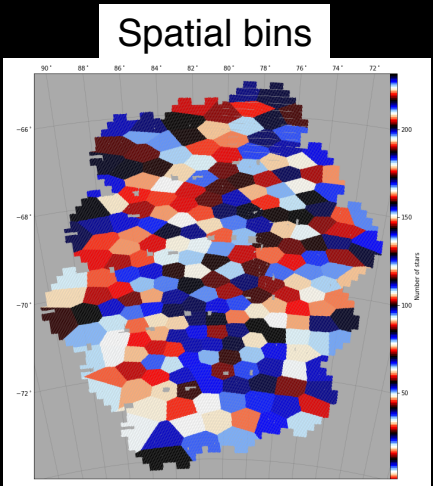
SMASH
Survey of the Magellanic Stellar History

Star Formation Histories



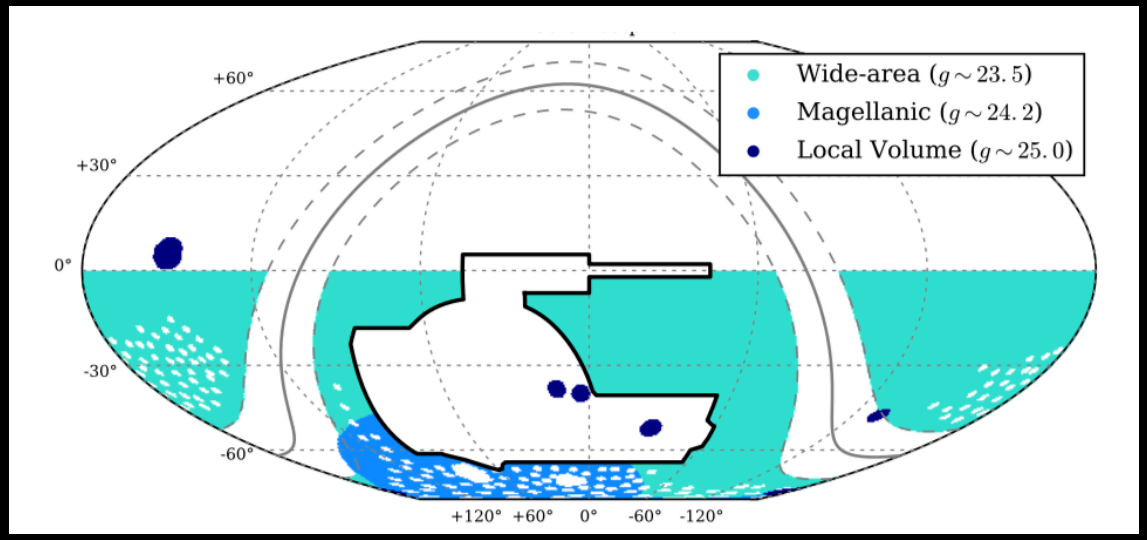






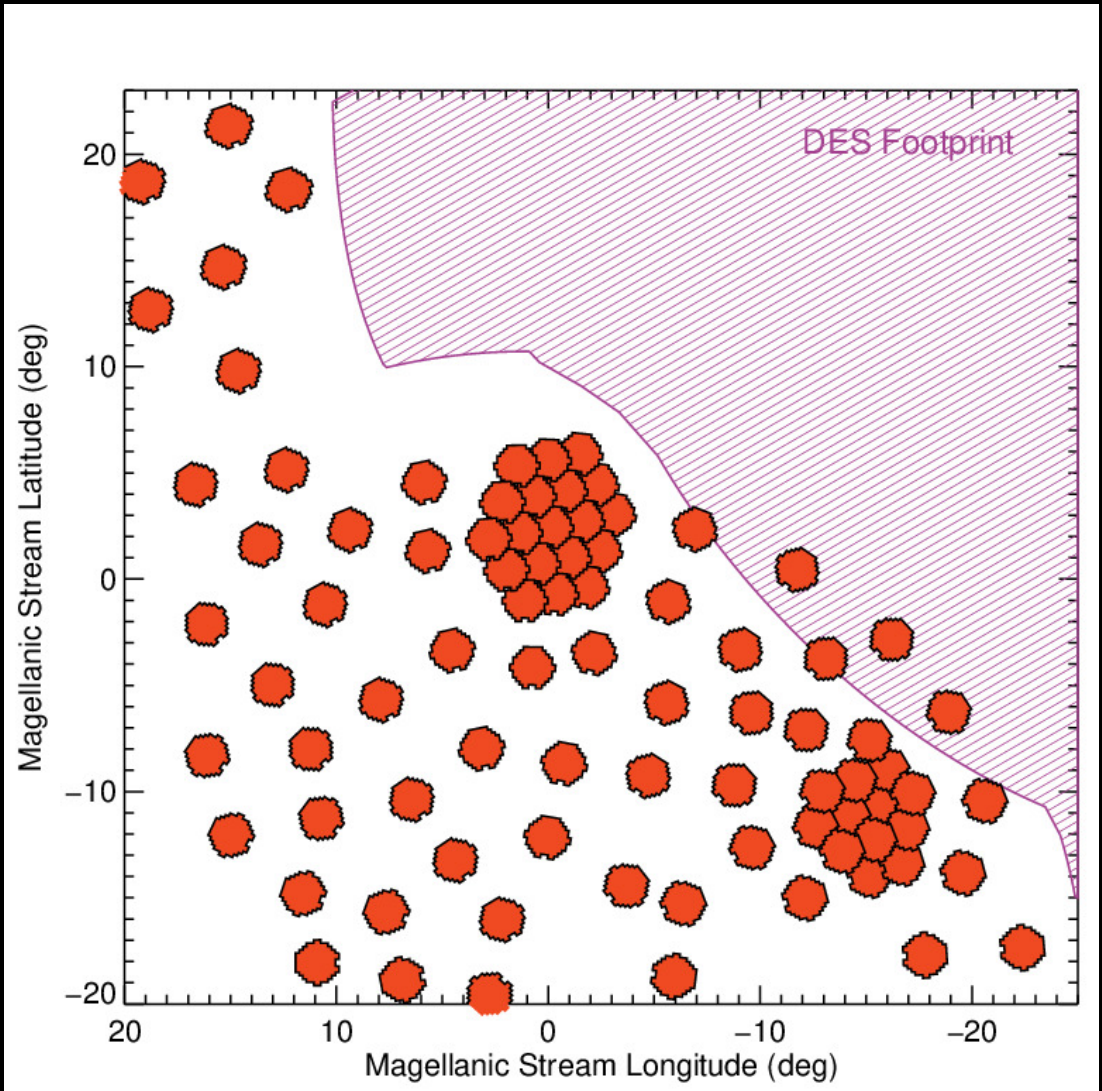
- Much current effort on LMC/SMC SFH
- Artificial star tests of all inner fields nearly done
- Will have star formation ***movie*** of inner LMC and SMC

DECam Local Volume Exploration (DELVE) Survey

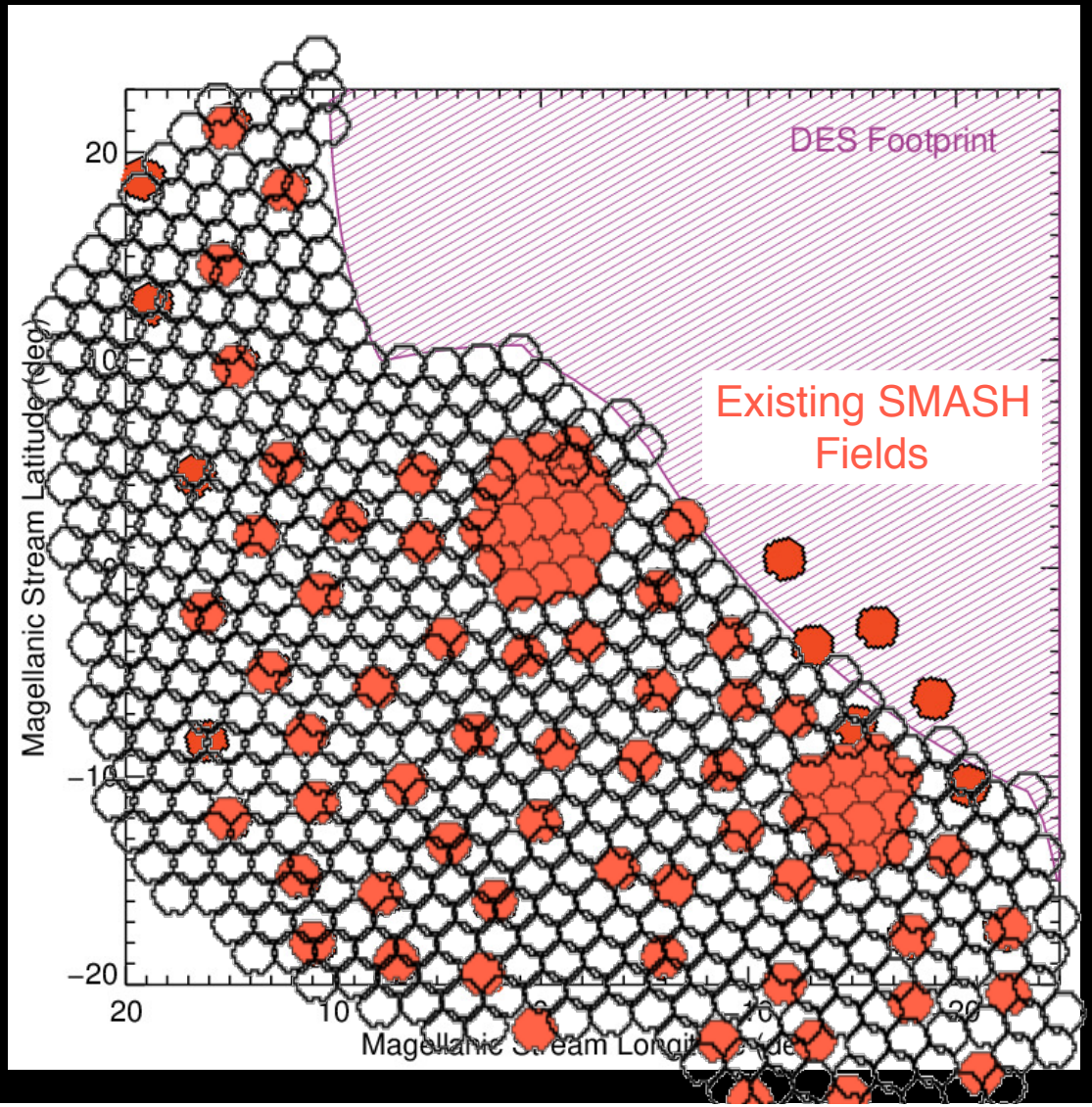


- Large DECam survey of dwarf galaxy in the southern hemisphere
- 128 nights of DECam observing, 100 member team
- Three components:
  - WIDE: Shallow, wide-area survey of MW dwarfs **(Choi co-chair)**
  - Magellanic: Fully-filled, deep survey of MCs **(Nidever)**
  - DEEP: Deep survey of 6 LV dwarf galaxies

DELVE Magellanic Clouds

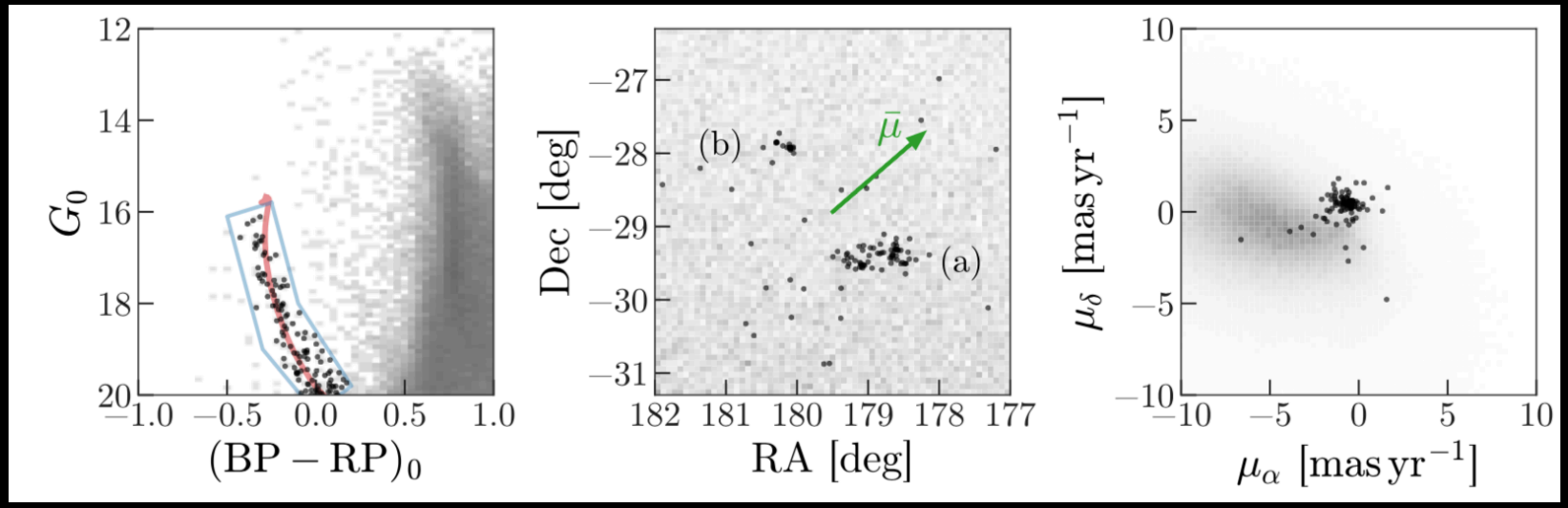


DELVE Magellanic Clouds



- Complete deep coverage!
- Map out Magellanic stellar structure to high fidelity
- Unravel stellar halos, accretion history, interaction

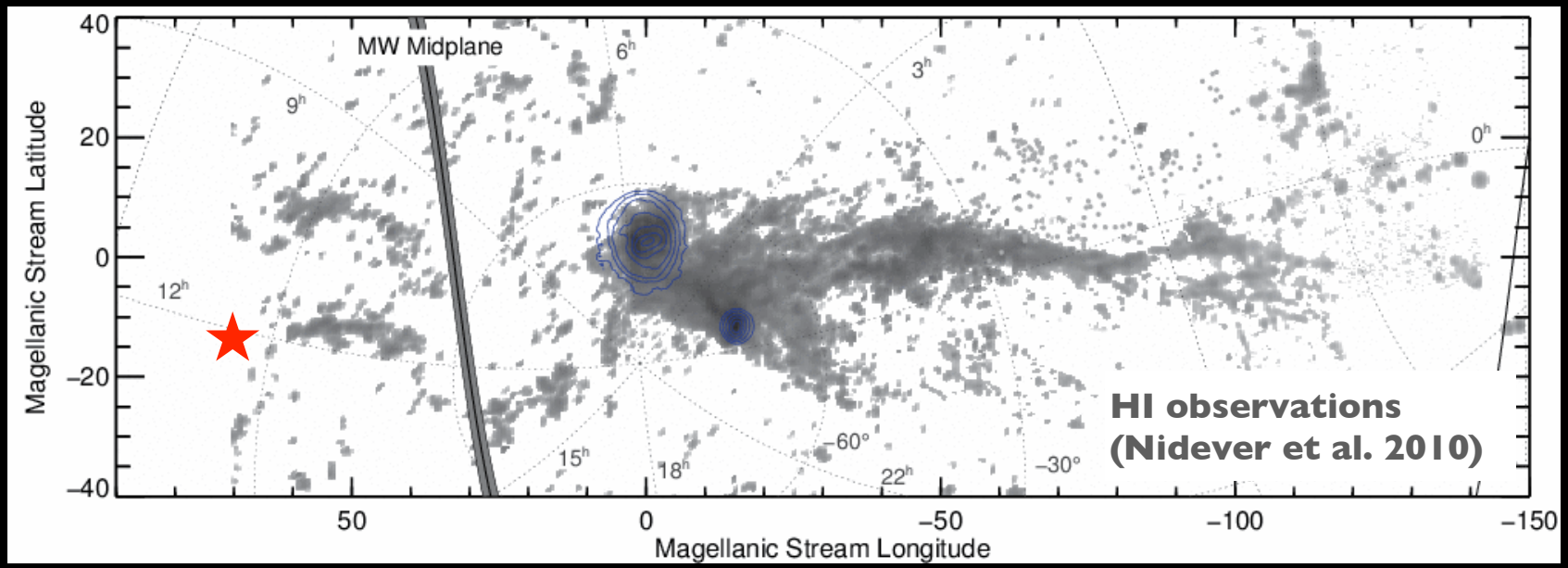
Price-Whelan 1: Young LAF Cluster?



- Young cluster discovered in Gaia DR2 near the Leading Arm
- Consistent in CMD, spatial, proper motion space

Price-Whelan, Nidever, Choi et al. (2019).

Price-Whelan 1: Young LAF Cluster?



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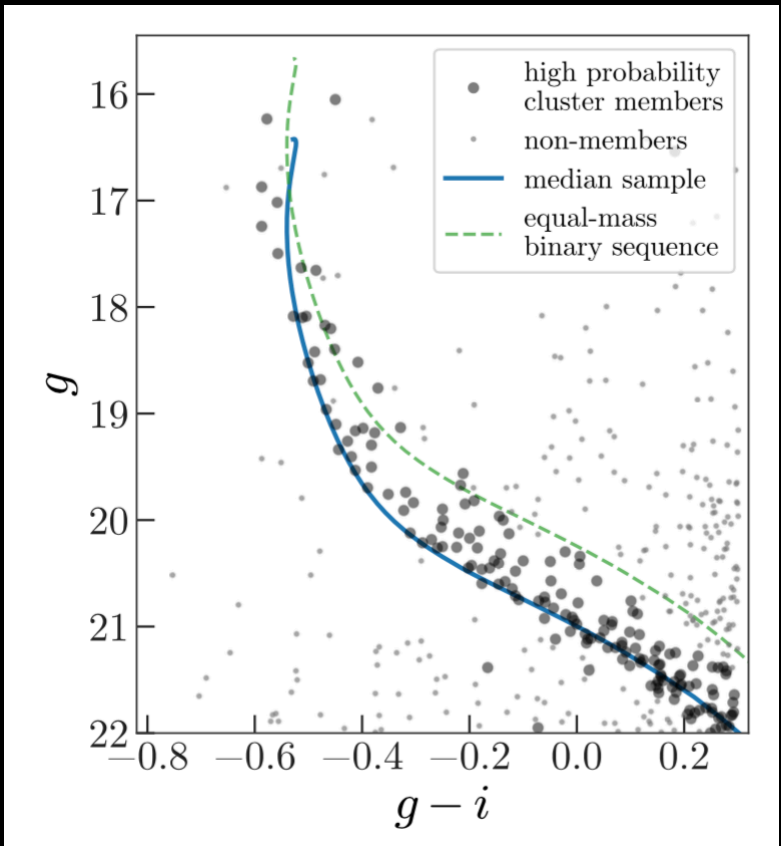
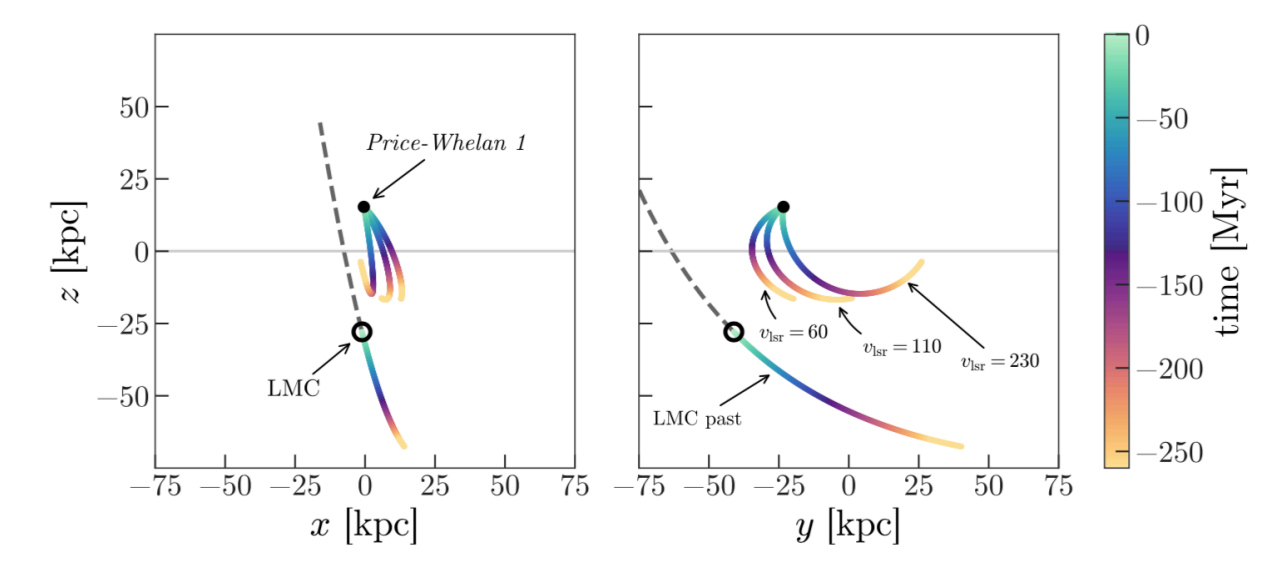


Isochrone fitting

- *Age:* 130 Myr
- *Mass:* 1200 $M_\odot$
- *Metallicity:* [Fe/H]= -1.1
- *Distance:* 28.9+/-0.1 kpc

Price-Whelan, Nidever, Choi et al. (2019).

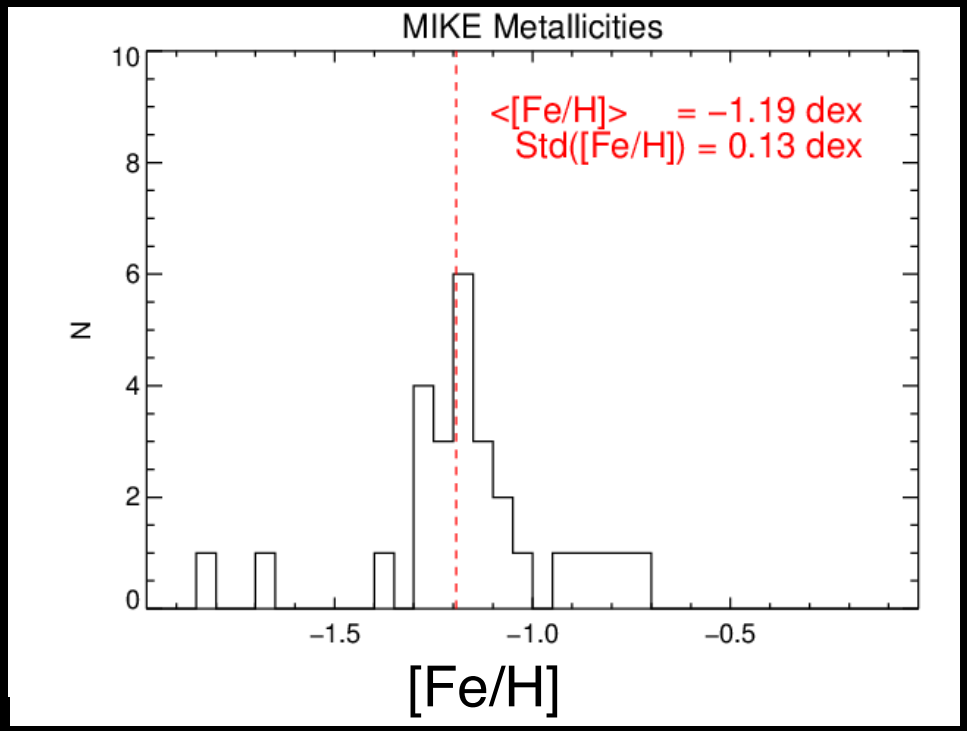
Price-Whelan 1: Young LAF Cluster?



- Orbits roughly consistent with Magellanic origin
- **Orbits indicate it passed through the MW disk ~130 Myr ago, likely triggered the star formation event**

Price-Whelan, Nidever, Choi et al. (2019).

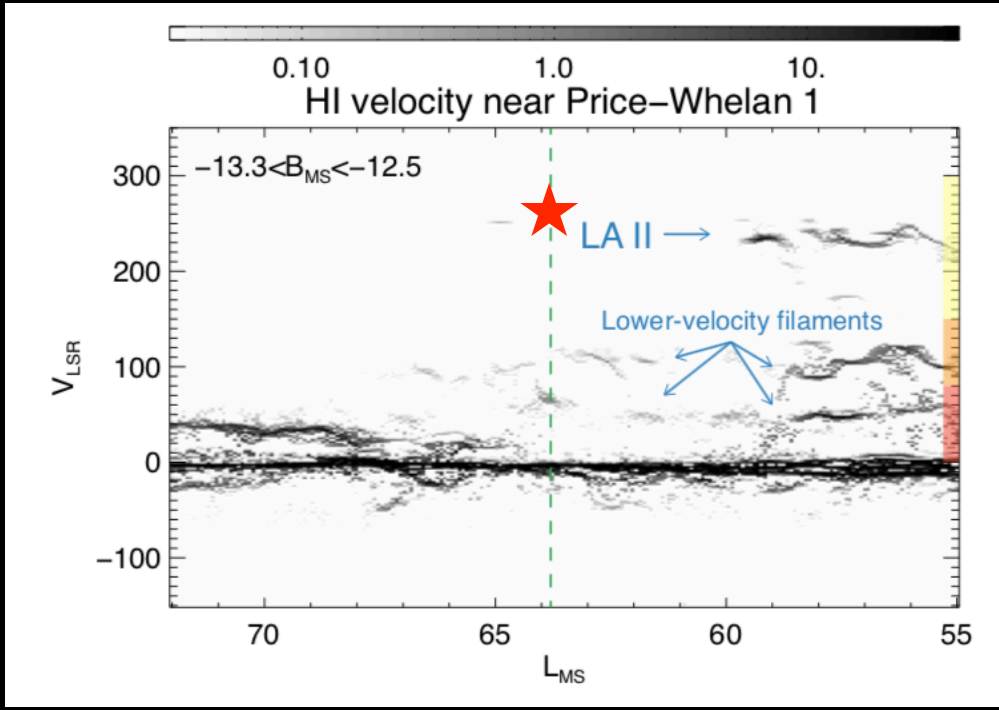
Price-Whelan 1: Spectroscopy



- Follow-up Magellan+MIKE spectroscopy
- S/N~10-15 spectra of 28 stars
- **[Fe/H] = -1.19**
- Confirms isochrone fitting value of -1.1!
- Consistent with LAF and MS metallicity

Nidever et al., (2019c), in prep.

Price-Whelan 1: Spectroscopy



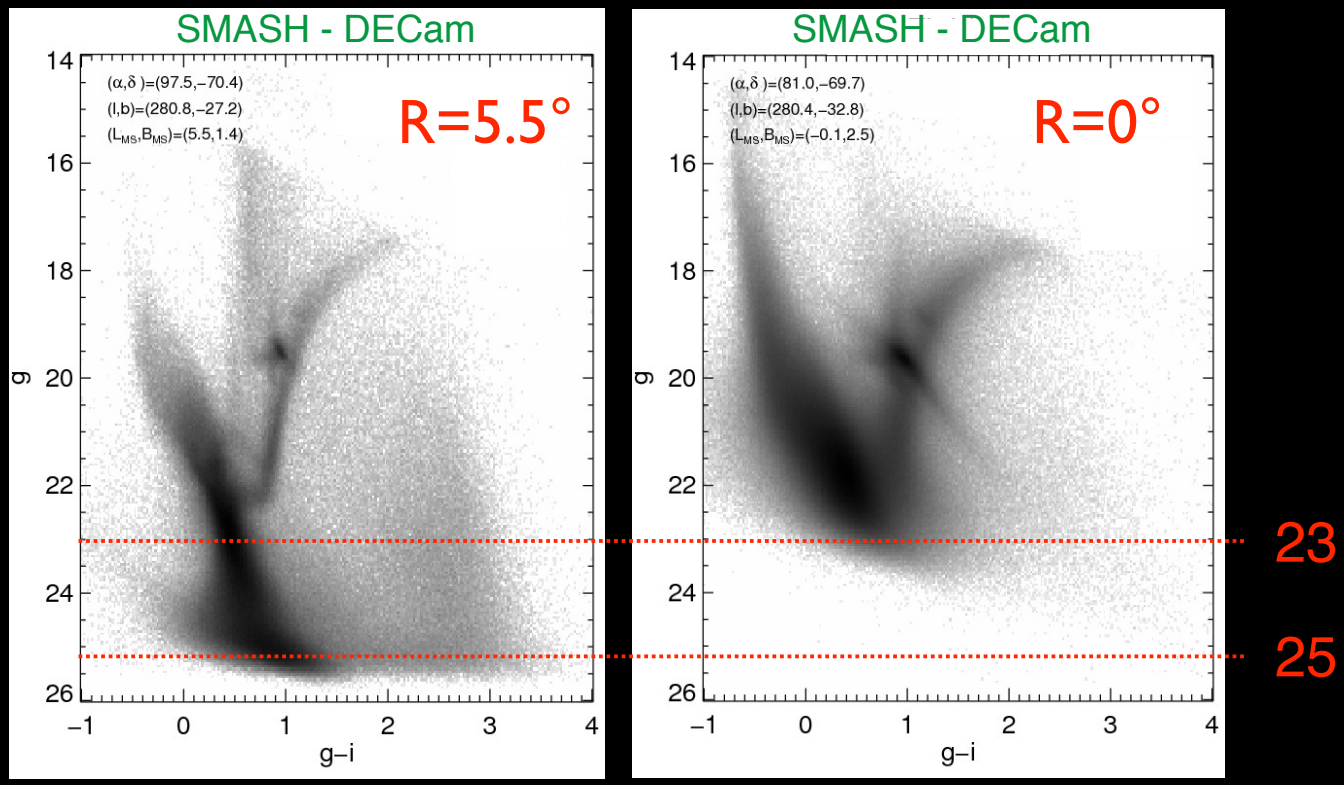
- **V_{LSR} = 272 km/s**
- About ~40 km/s faster than LA II gas, consistent with ram pressure slowing gas down
- Confirms association with LA II
- Will use RV and spatial offset to constrain MW hot halo density

Nidever et al., (2019c), in prep.

What big outstanding questions can WFIRST answer?

WFIRST
Wide Field Infrared Survey Telescope

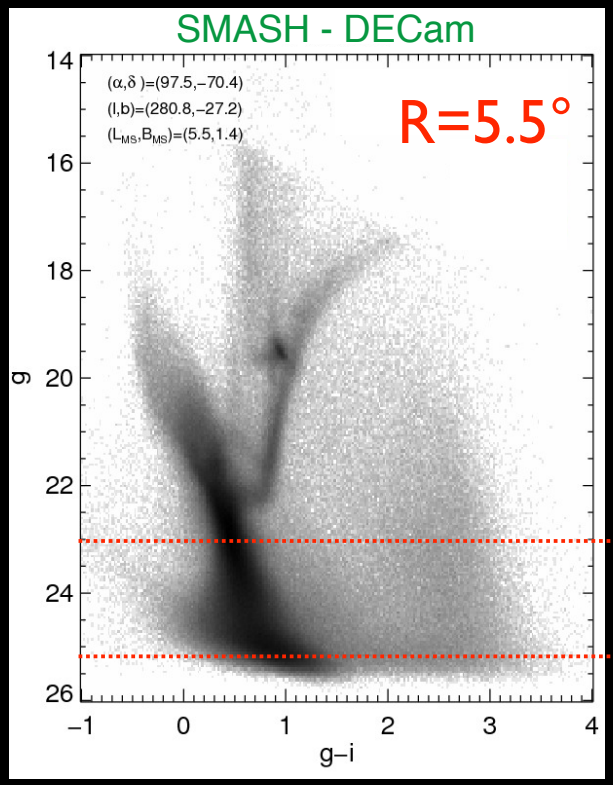
Central LMC

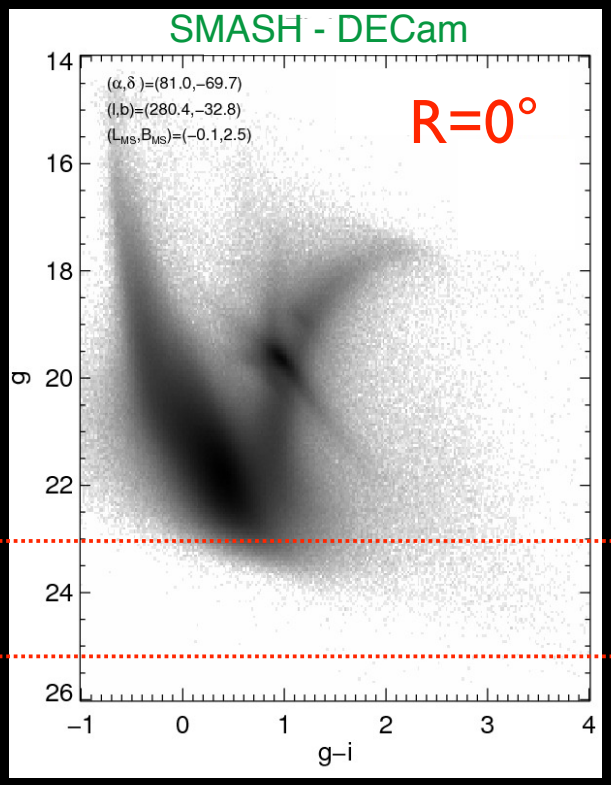


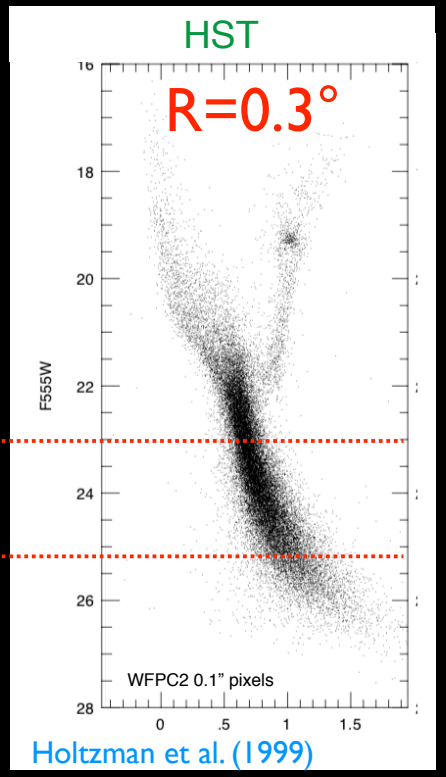
- Central LMC is very crowded, challenging from ground

WFIRST
Wide Field Infrared Survey Telescope

Central LMC







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- Central LMC is very crowded, challenging from ground
- Obtain deep CMDs of central R<2° from WFIRST

WFIRST
Wide Field Infrared Survey Telescope

Central LMC

Star formation History

- Central LMC is oldest part of the galaxy
- Need deep CMDs to study the SFH of the old component

WFIRST
Wide Field Infrared Survey Telescope

Central LMC

Star formation History

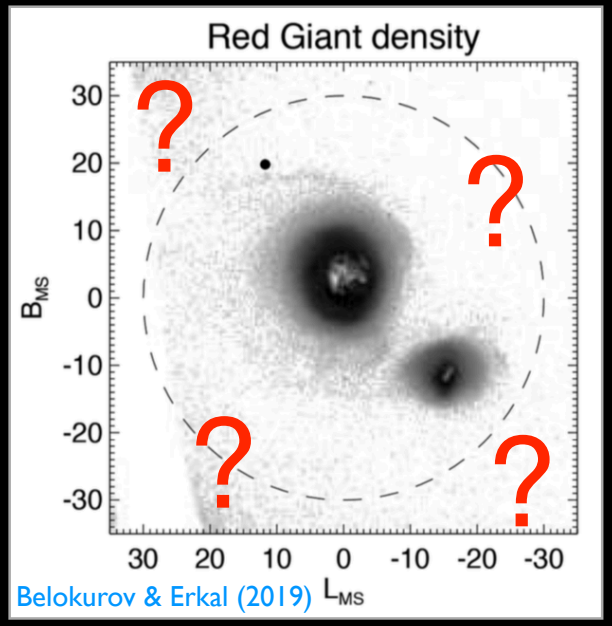
- Central LMC is oldest part of the galaxy
- Need deep CMDs to study the SFH of the old component

Supermassive Black Hole

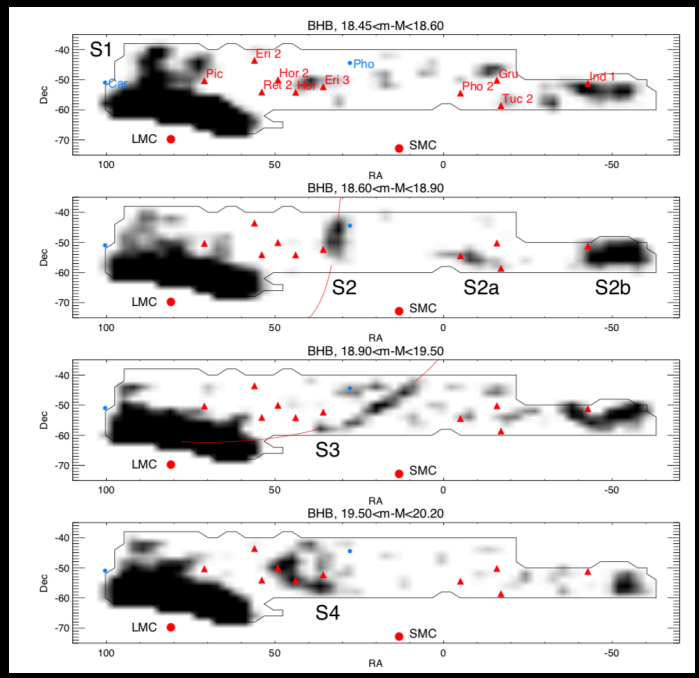
- Reines et al. (2013) found ~150 SMBH in LMC/SMC mass galaxies
- None found in LMC/SMC so far
- Sphere of influence small (~40") and center of LMC not well constrained
- Need proper motions of many stars over large area to find SMBH dynamically

WFIRST
Wide Field Infrared Survey Telescope

Far Periphery



Belokurov & Erkal (2019)

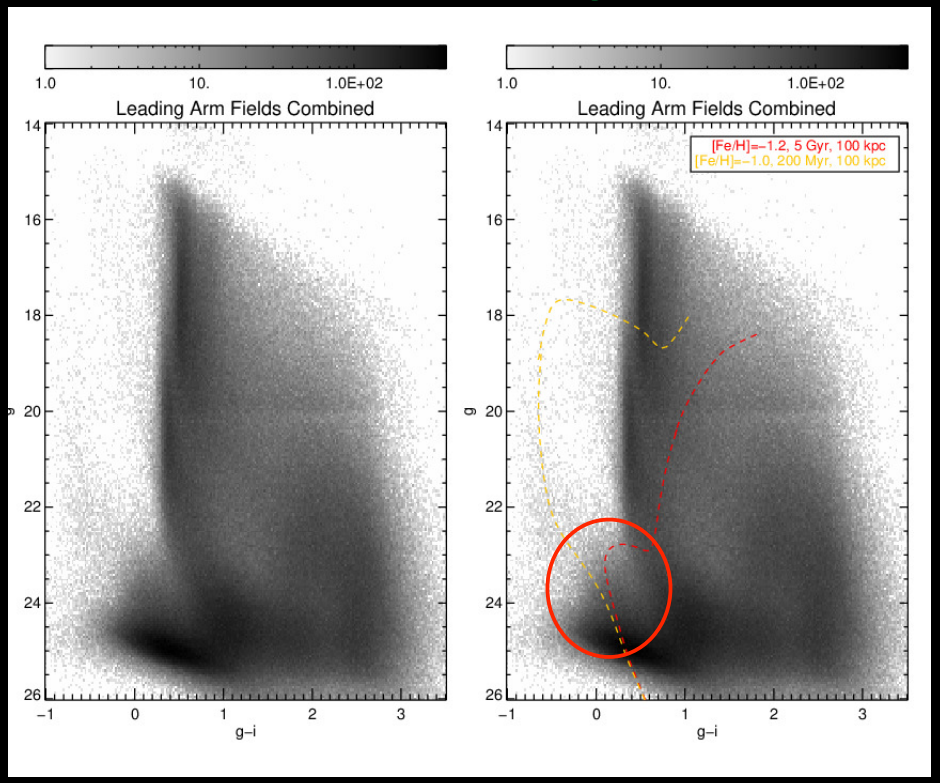


Belokurov & Koposov (2016)

- Are there Magellanic stellar populations at even larger radii?
- There are indications of some diffuse BHB streams R=30-50 deg
- WFIRST will be able to detect these extremely diffuse populations with deep CMDs

Stars in the Magellanic Stream

18 SMASH Leading Arm Fields



star/galaxy separation algorithm applied

- **Are there stripped stars in the Magellanic Stream and Leading Arm?**
- SMASH leading arm fields show a feature that could be MSTO stars at 100 kpc
- *Lots of unresolved blue galaxies at these magnitudes*
- Hard to stars from galaxies in this regime even with deep, multi-band data
- Need large-area, deep, high spatial-resolution data to resolve this issue.
- Need WFIRST mapping

Conclusions

APOGEE

- No sign of radial migration in MDF skewness or alpha-bimodality in LMC or SMC
- MCs were "lazy" early on with low-SFE likely due to low density environment. Consistent with first infall. (Nidever et al. 2019b)

SMASH

- Mapped relatively metal-poor stellar envelope around LMC to 18 kpc (Nidever et al. 2019a)
- Photometric metallicities suggest LMC periphery population may have come from outer disk and SMC highly tidally disturbed (Miller, Nidever et al. 2019, in prep.)

Leading Arm Cluster

- Young cluster discovered in Leading Arm (Price-Whelan et al. 2019)
- Spectroscopy confirm LAF origin and metal-poor (Nidever et al., 2019c, in prep.)

WFIRST

- SFH of old populations and search for SMBH in central LMC
- Search for stars in far LMC periphery and Magellanic Stream / Leading Arm


Thank You
APOGEE
SMASH
Survey of the Magellanic Stellar History