3 Bulge Survey Programs: A Progress Report

Blanco DECam Bulge Survey (R. M. Rich, C. I. Johnson PIs)

Bulge Asymmetry and Dynamics Experiment (Y. Phylstrom, PI)

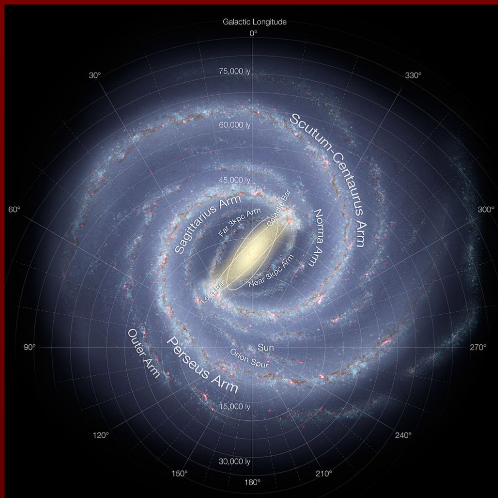
Chemistry of Bulge Globular Clusters
C. I. Johnson, PI

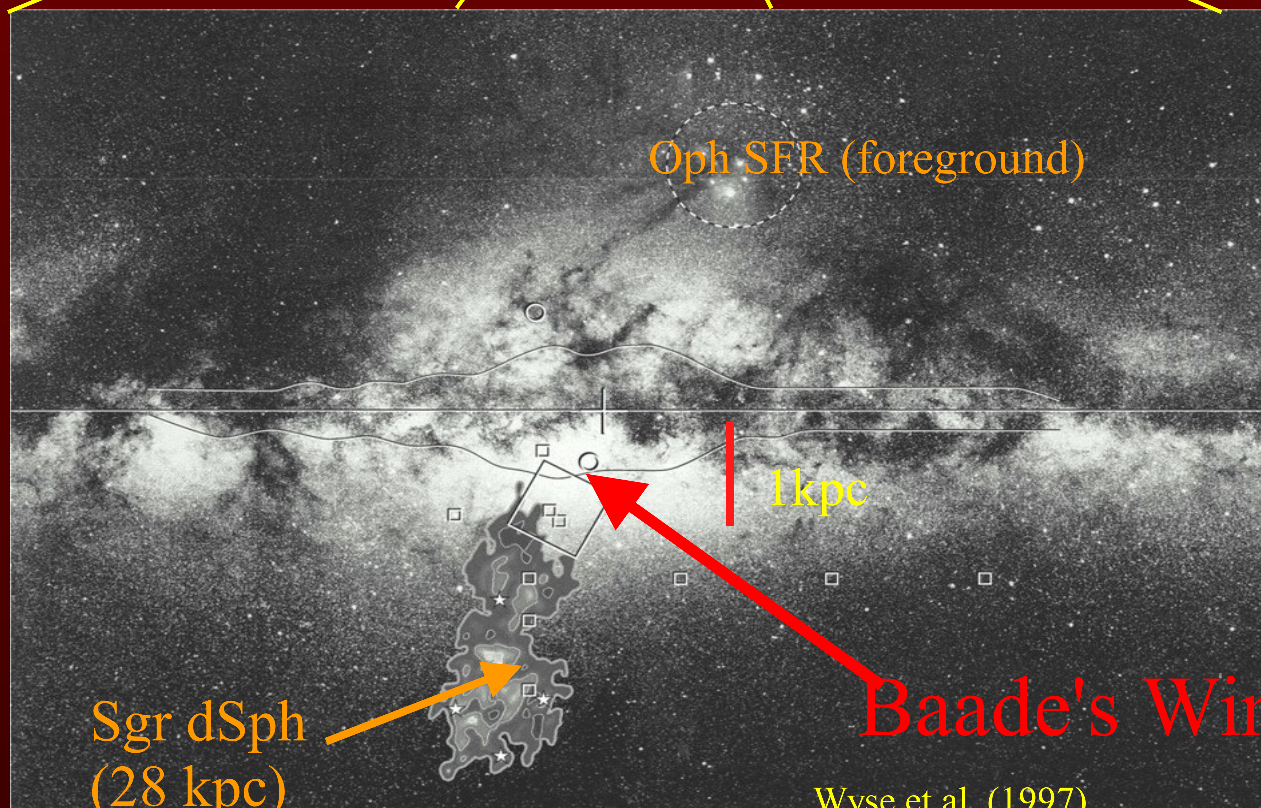
The Blanco Dark Energy Camera Bulge Survey

R. Michael Rich (UCLA) PI Collaborative NSF grant

Will Clarkson (U. Michigan, Dearborn) co-PI
Caty Pilachowski (Indiana University), Scott Michael & Mike Young
(Pervasive Technology Institute, IU) co-PI
Christian Johnson, Clay Fellow CfA collaborator
Rod Ibata, Strasbourg Obs; Kathy Vivas (NOAO/CTIO)
Z. Ivezic (U. Washington), A. Kunder (AIP)

Bulge in Context





Sun is 8 kpc from the Milky Way Center. Nearest similar large galaxy is 100 times farther

Fabian Neyer

Our new picture of the Galactic Central Bulge

The Bulge has a “bar structure” and is internally complex, including an X-shaped component

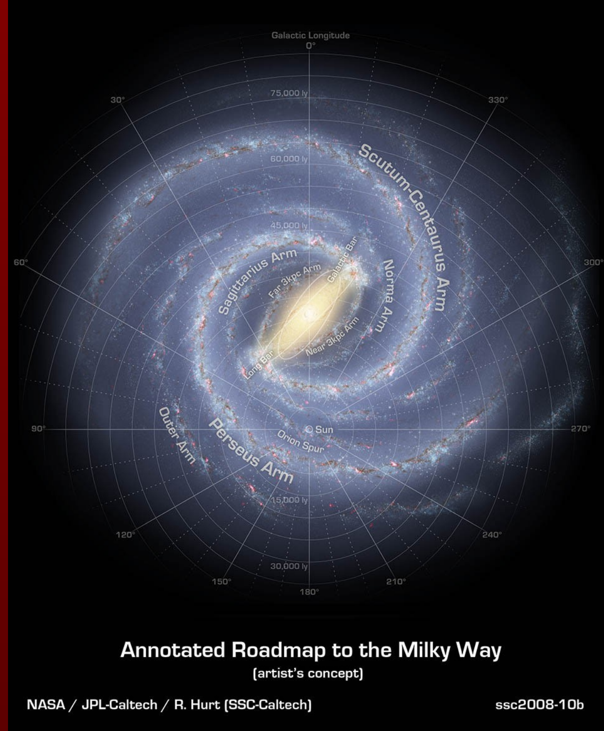
Evidence from ages and composition support the idea that the bulge is older than 10 billion years (10 Gyr)

But the bar appears to have formed from a disk, and that process should be slow.

Some features remained unexplained. How did the bulge survive infall of dark matter?

“bars”

non-barred “classical”




M104 (Hubble)

"classical"

Our bulge is X-shaped/boxy

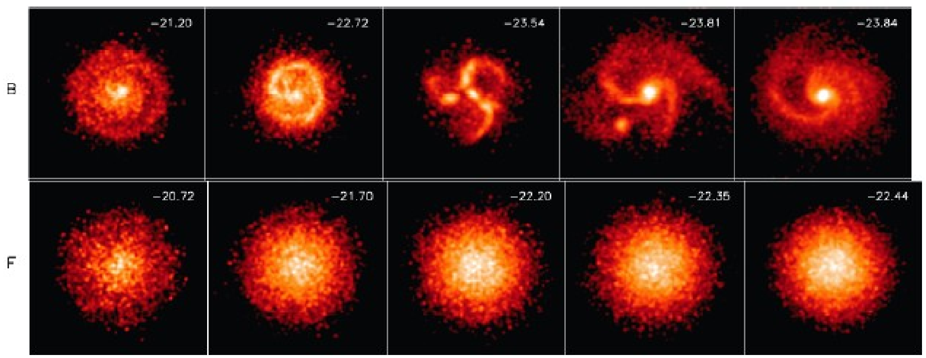
NGC 4710 (Hubble)

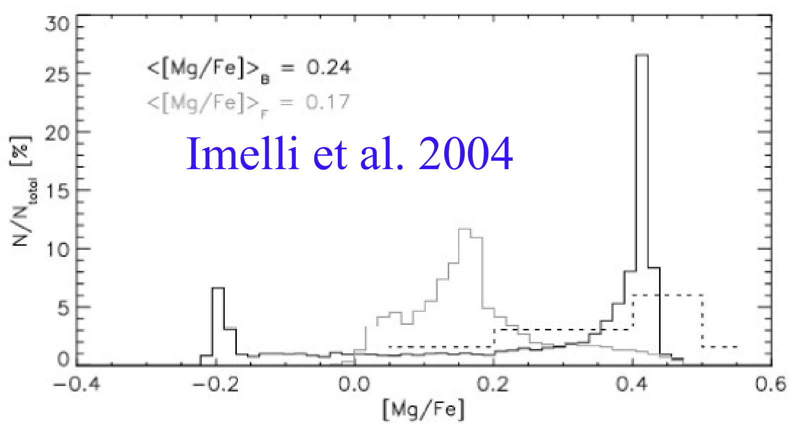

NGC 4565

"boxy/ X-shaped"

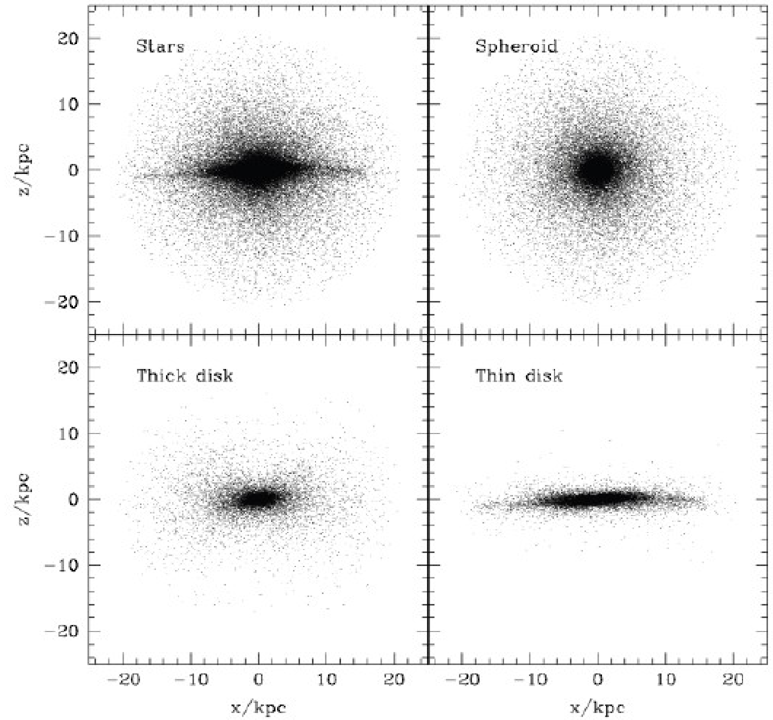
Formation of the bulge? Classical merger? Or clumps?

Multiple star forming clumps might produce kinematic subgroups with distinct chemical or dynamical fingerprints.





Abadi 2003



Imelli et al. 2004; Elmegreen et al. (2008) See also Inoue et al. 2013, Elmegreen et al.

Or N-body bar?

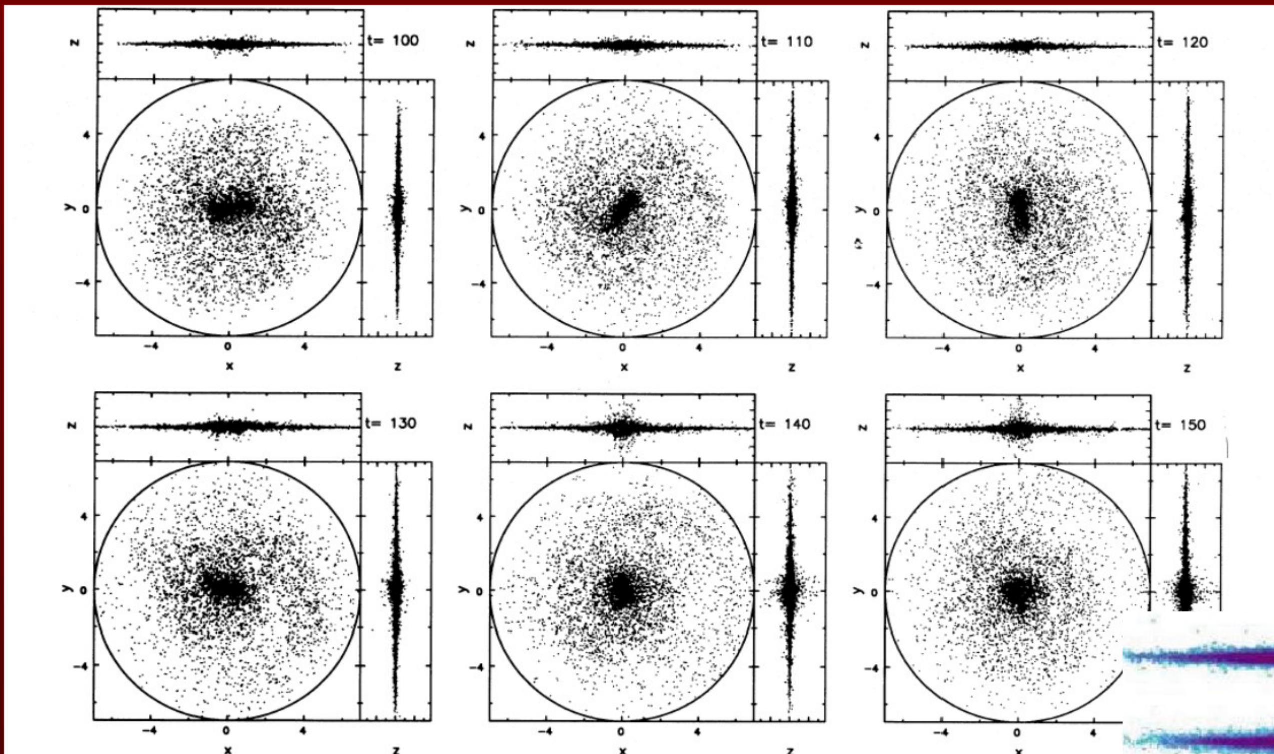
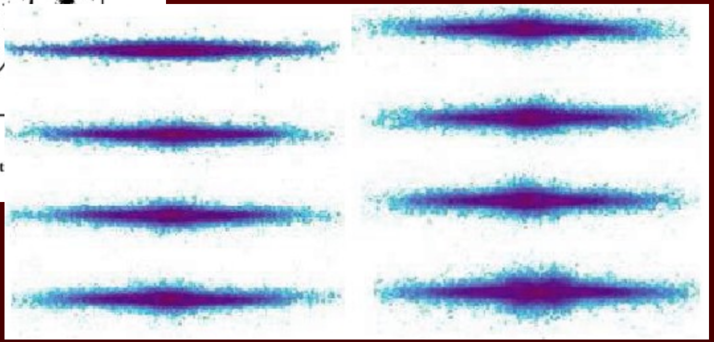


FIG. 6.—The evolution of a three-dimensional model in which a 5% central mass is grown from time 100 to time 140. The whole calculation volume is shown, but only one part
bar dissolves abruptly between times 130 and 140, forming a spheroidal bulgelike feature at the center.

Combes 09- bar resurrection via gas inflow



Vertical thickening of the bar into a bulge would leave no abundance gradient in the z-direction.

The Bulge is hard to study

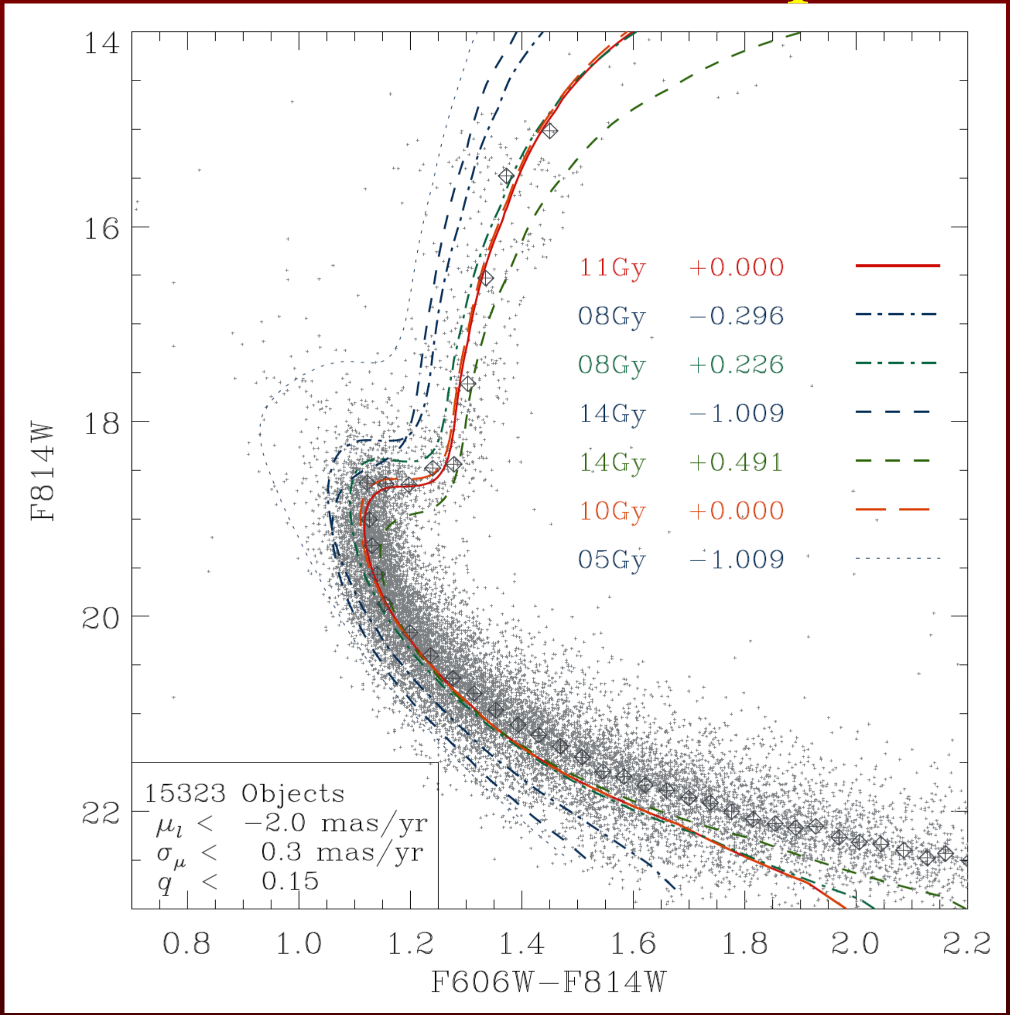
Relatively far – 8.3 kpc

Signficant foreground “dust” extinction (stars are faint)

Starfields are very crowded

We look through the Galaxy and see disk Stars in the foreground

Age constraint from PM separation



~99% of bulge older than 5Gyr; pure 10+ Gyr likely (Clarkson+ 08, 09

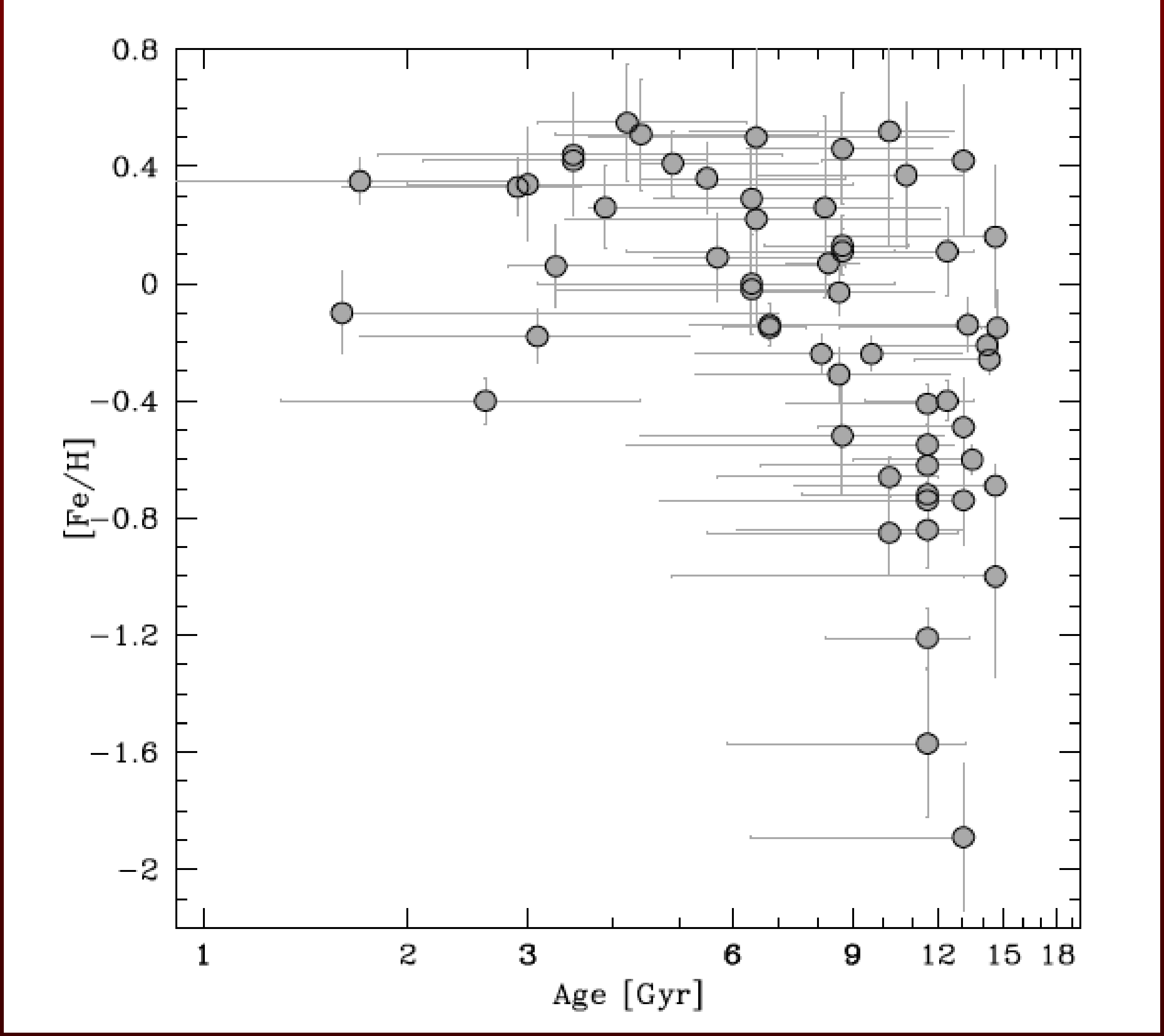
Age still controversial

Bulge dwarfs brightened by microlensing

[Fe/H] , log g Teff

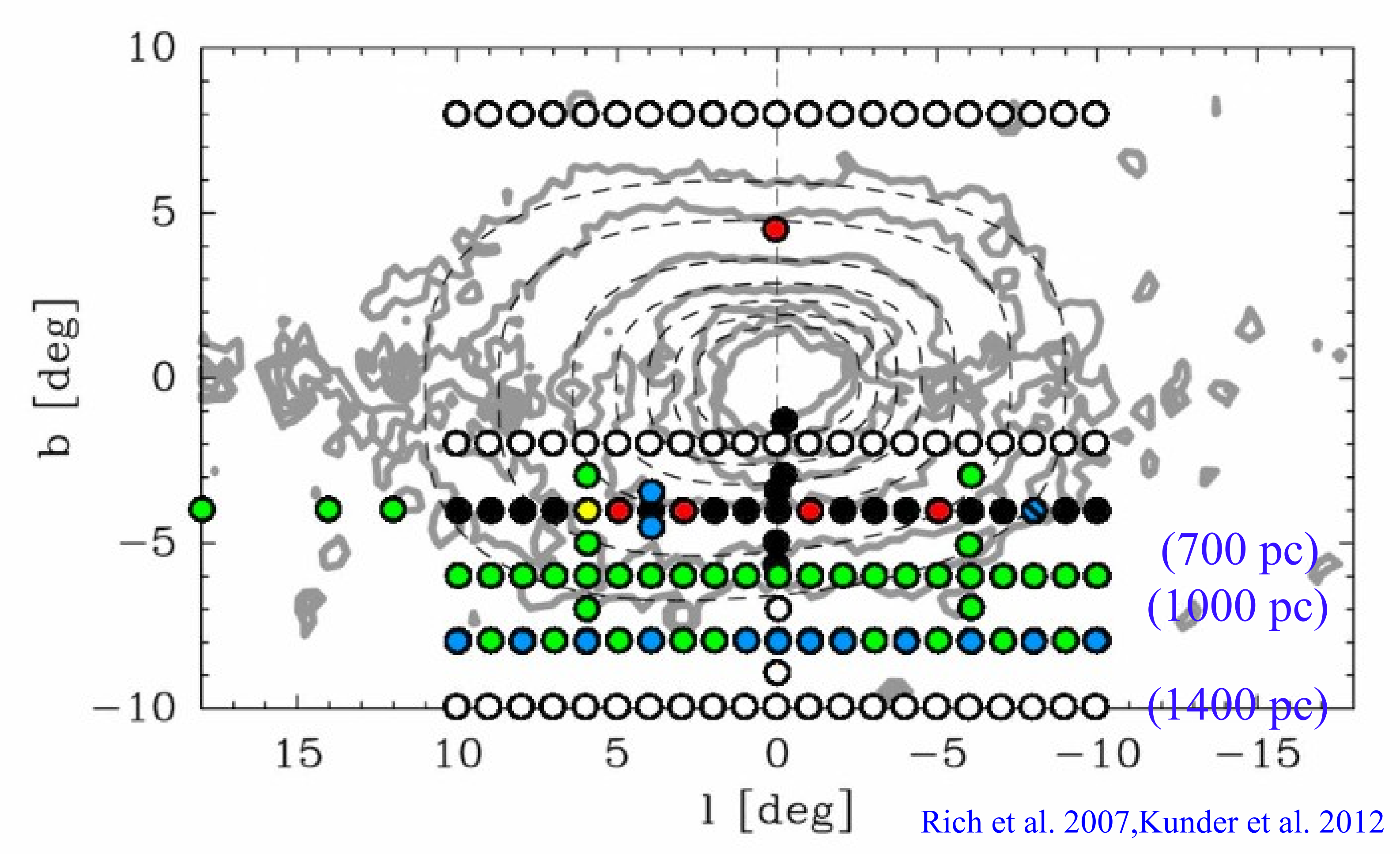
Age from the HR diagram

25% “young??”



Bensby et al. 2013

BRAVA survey (Rich+07, Kunder+12)

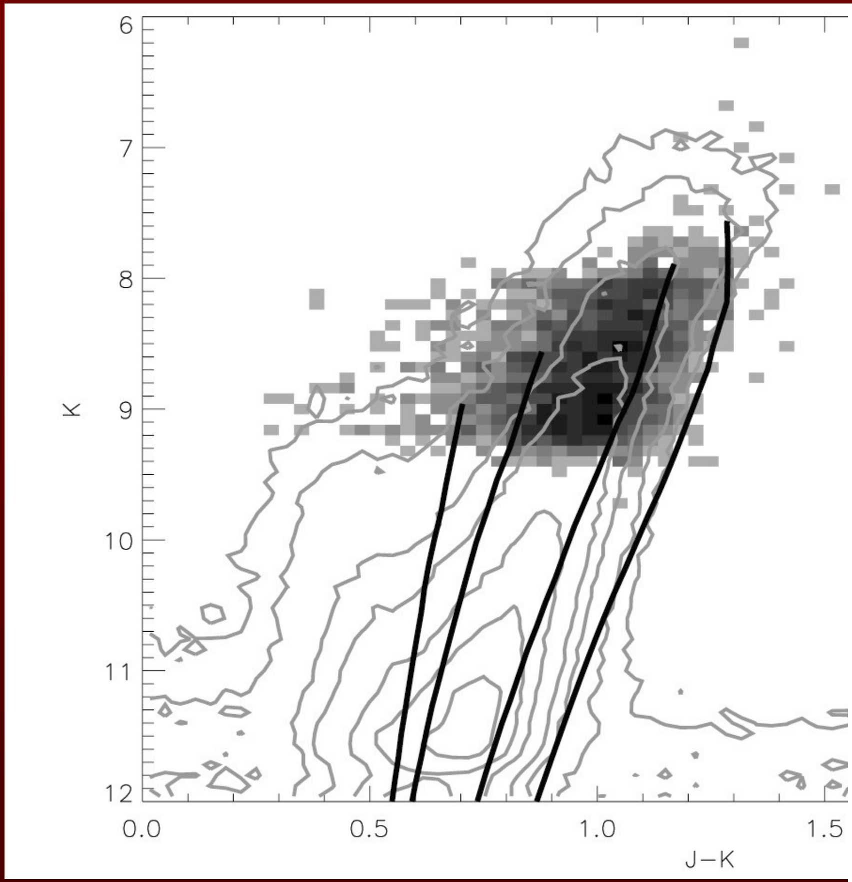


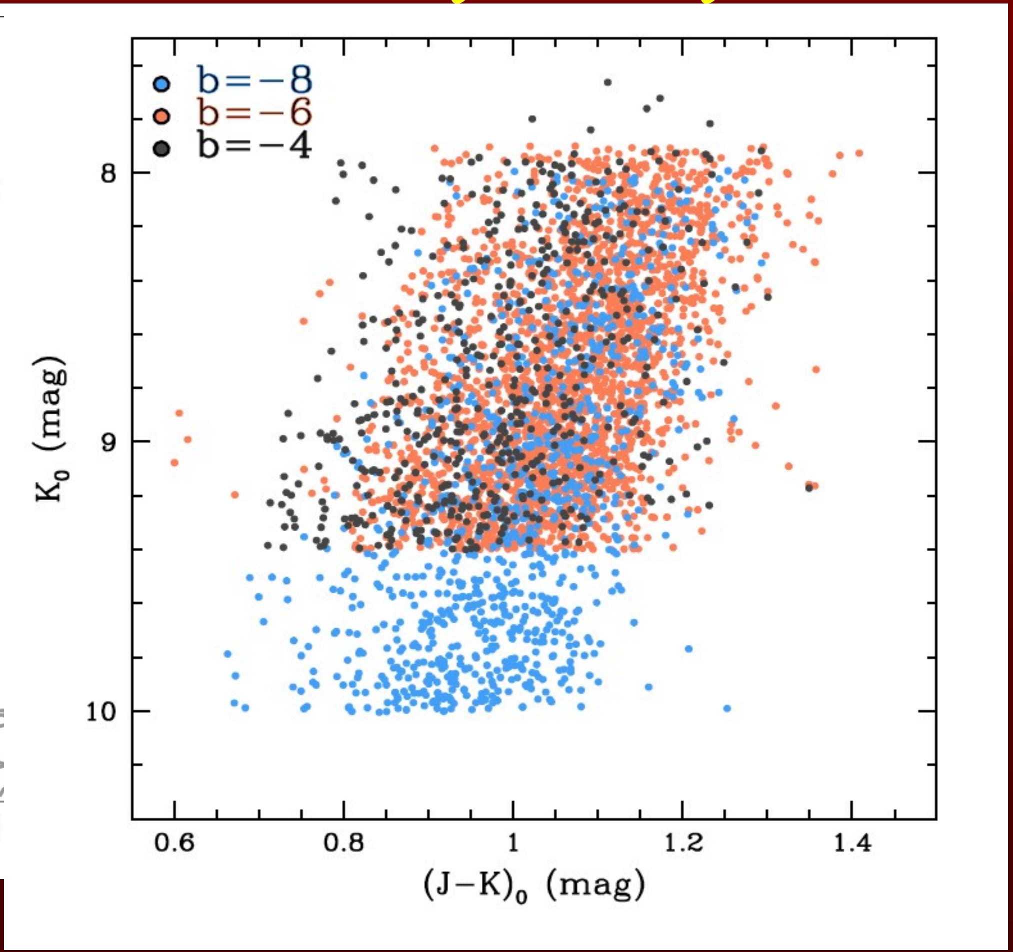
Survey Fields 2005: blue 2006: red 2007: green

Goal: Grid of fields at 1 deg intervals, covering 10x10 deg box, pushing as close to plane as possible

Select the brightest red giants

From 2 micron-All-sky survey

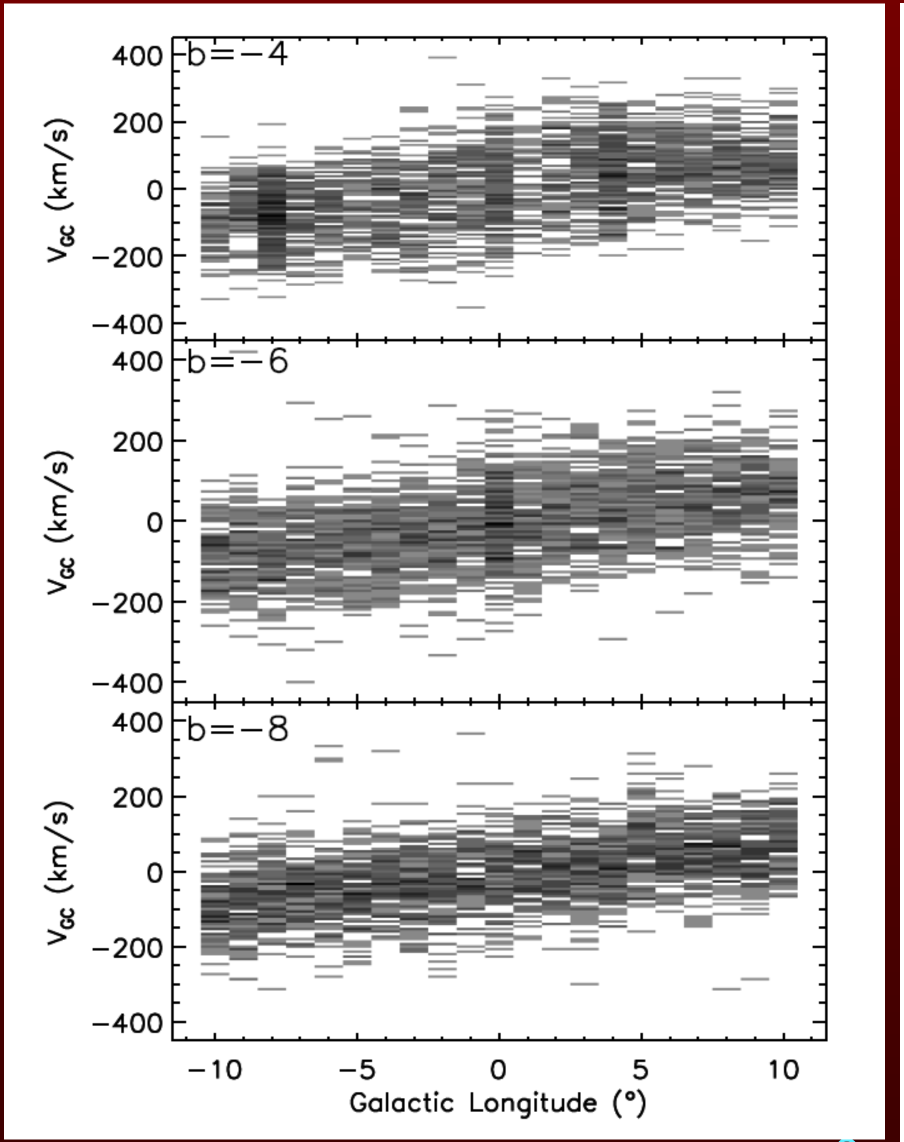


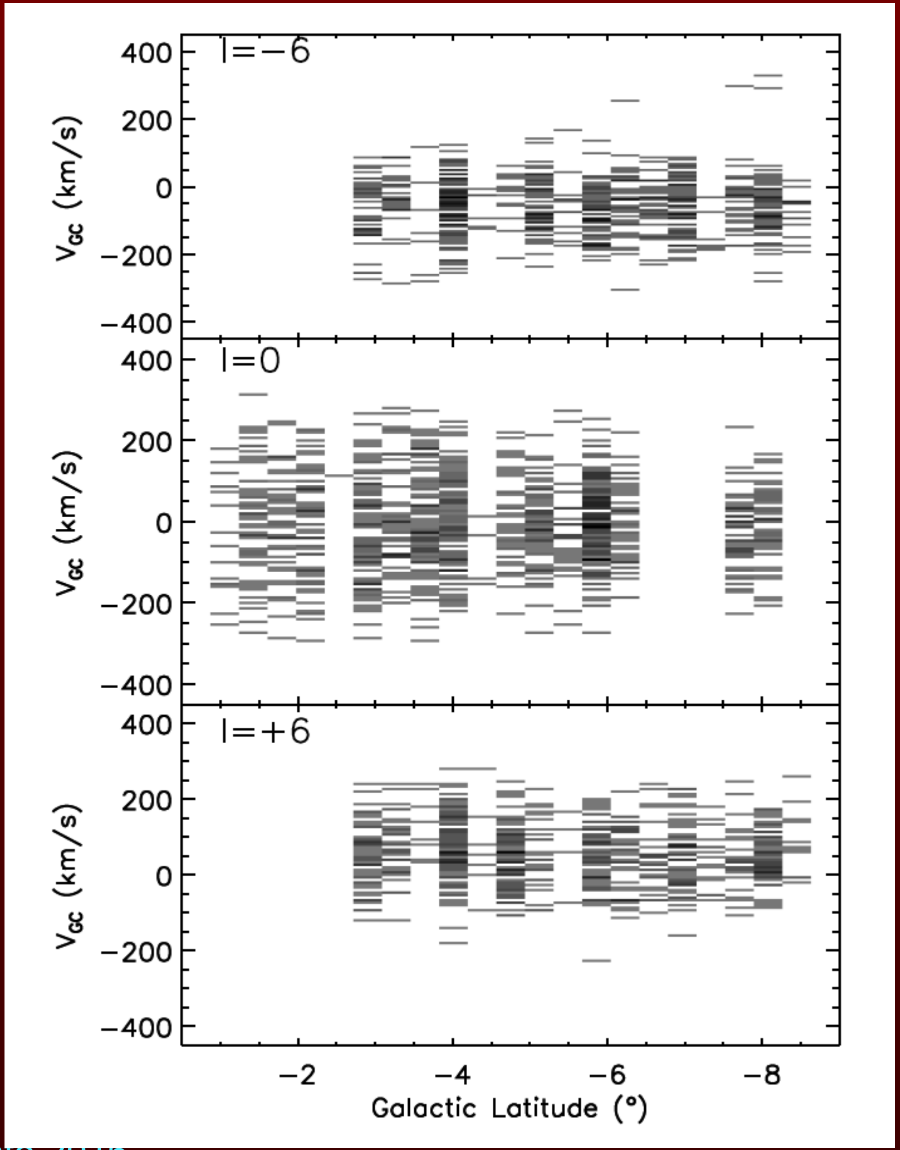


Howard et al. 2008 b=-4 dereddened

Kunder et al. 2011, new sample

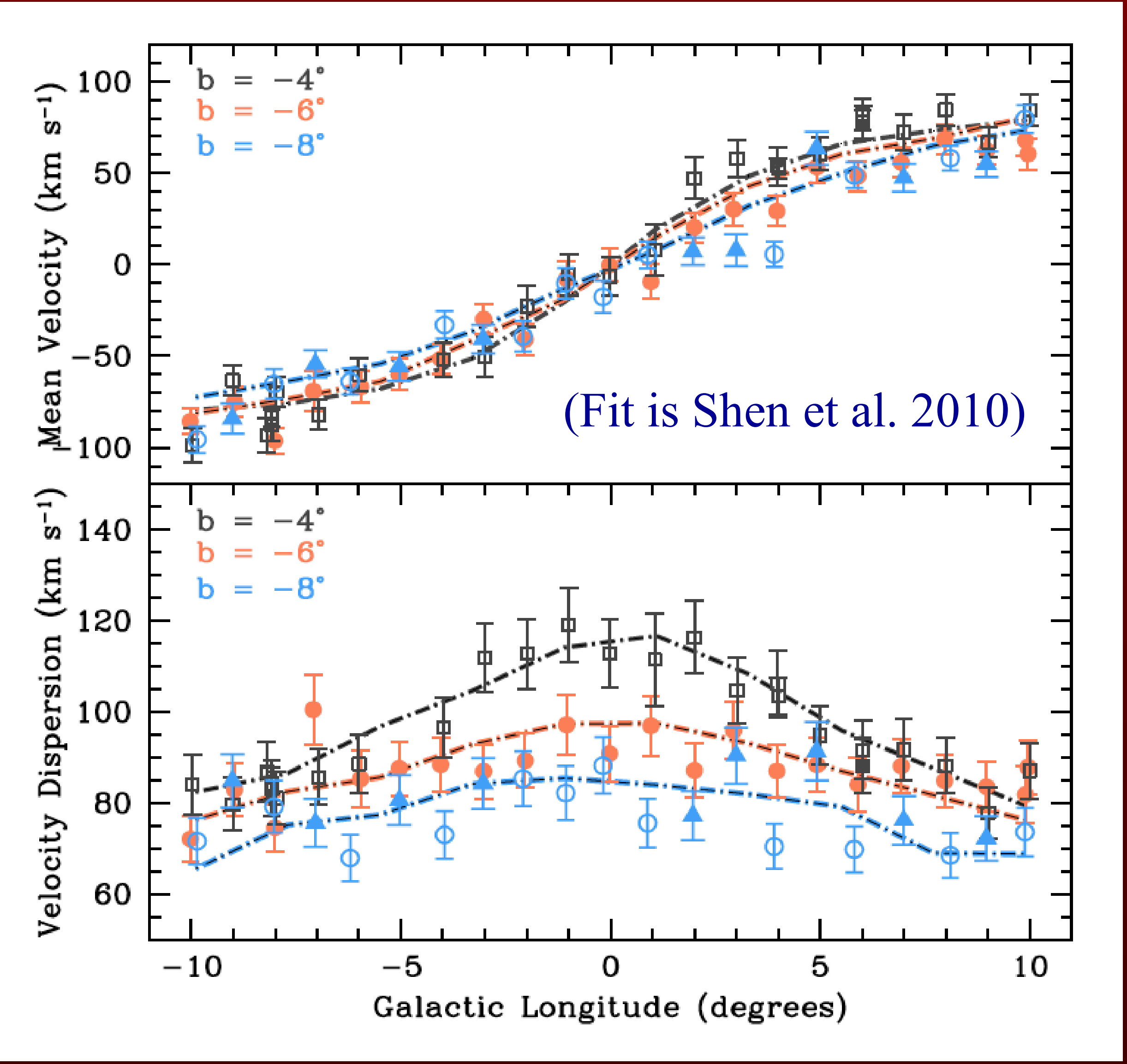
The rotation speed is independent of Galactic latitude
No hot component at 1kpc for "classical bulge"





Sesto 2016

“Cylindrical” rotation consistent with the velocity field of a rotating “bar”.



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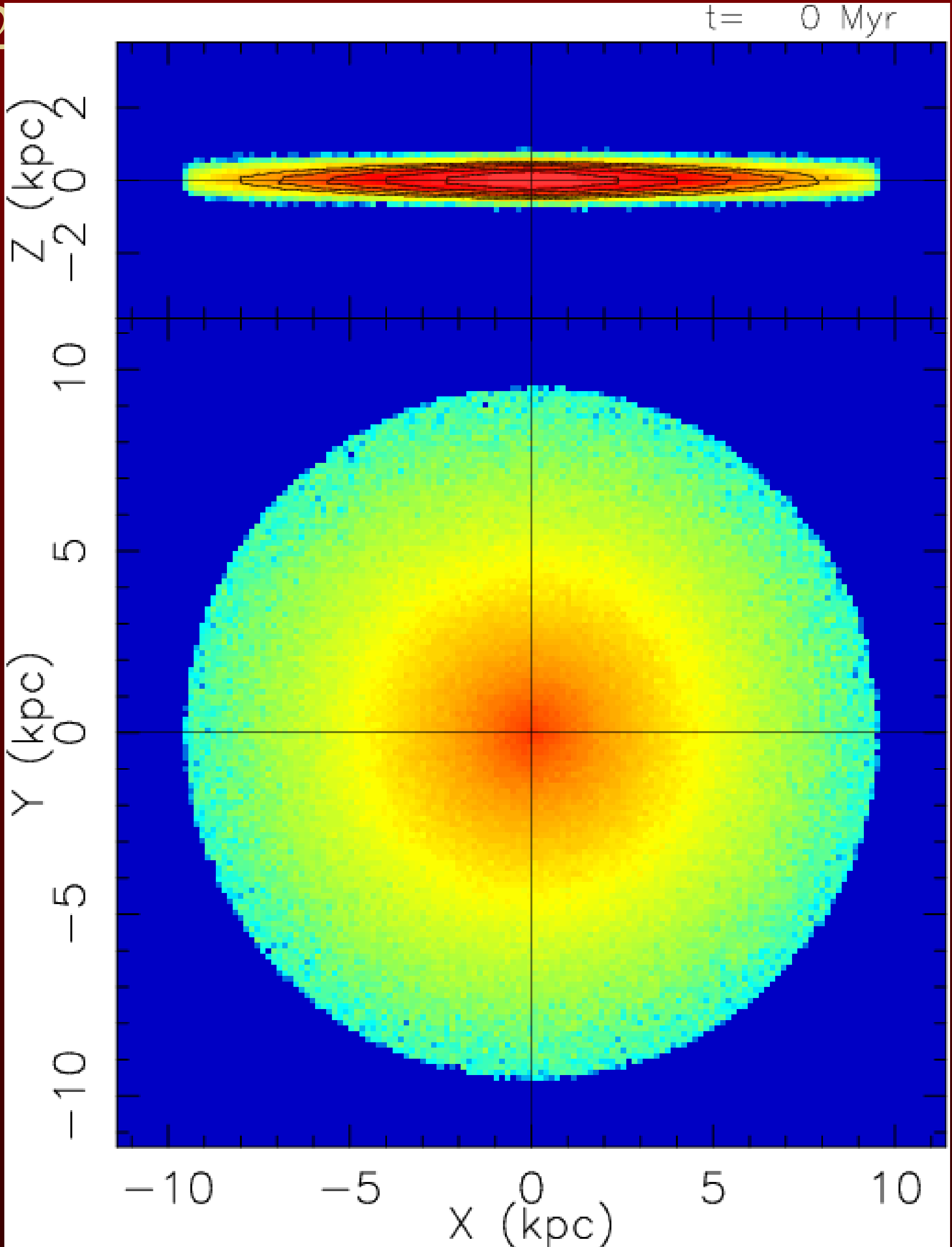
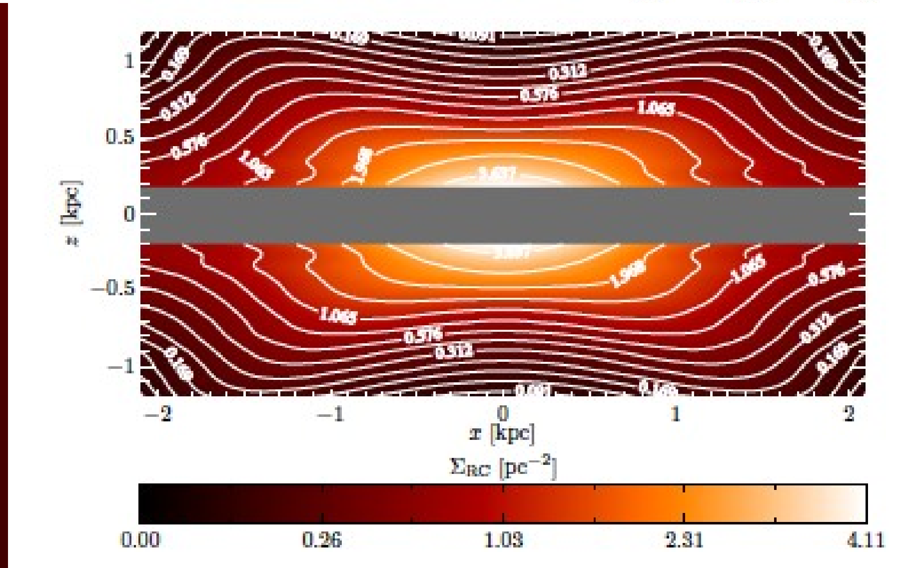
Modeling the Milky Way Bulge

Shen, Rich et al. 2



- A simple model of the Galactic bulge matches the BRAVA data extremely well in almost all aspects:
  - *b* = -4° major axis
  - *b* = -8° degree major axis
  - *l* = 0° degree minor axis
  - Surface density
  - **Shen, J., RMR, Kormendy** et al 2010, ApJL

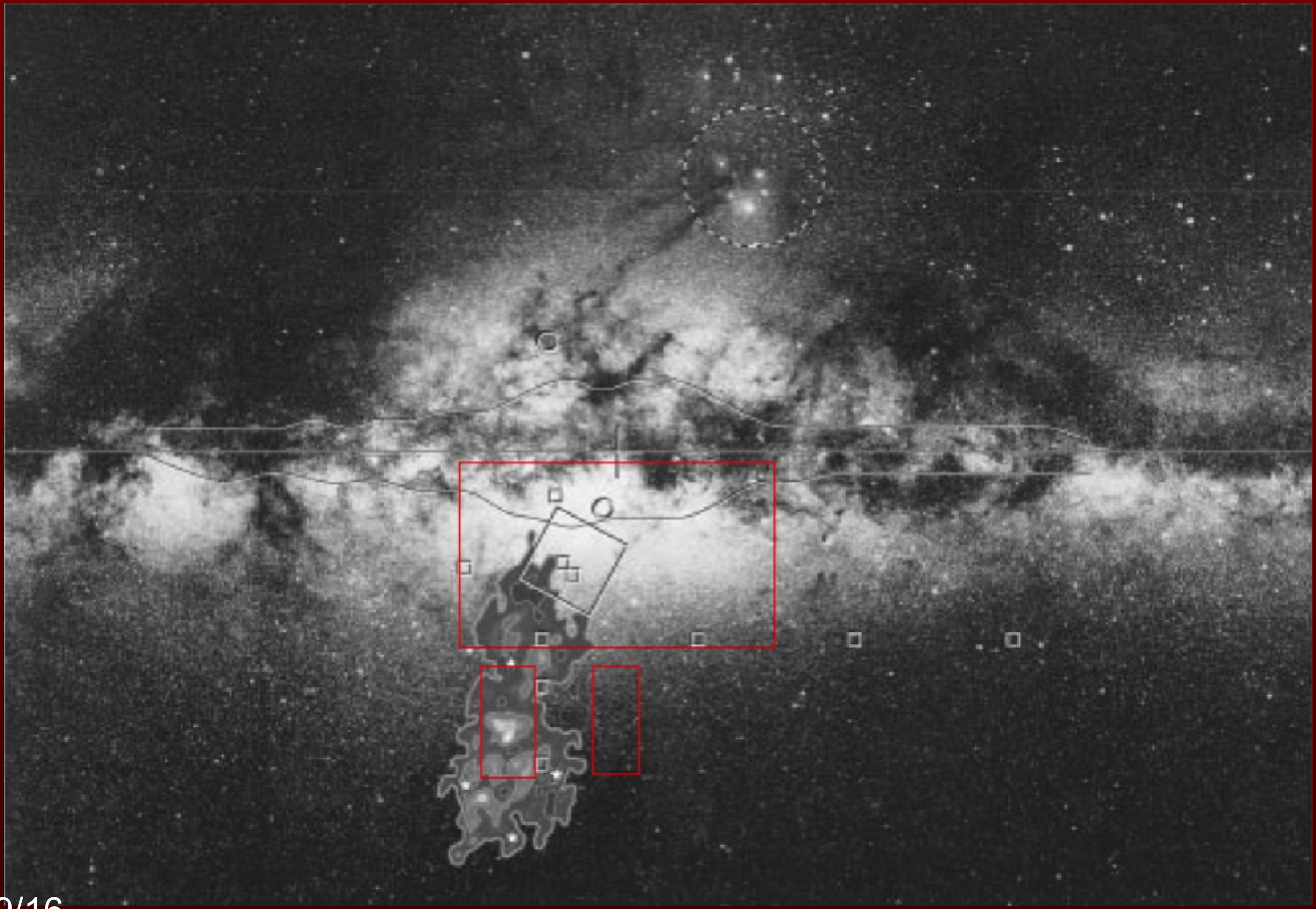
The infrared VVV survey dataset is modeled to reveal an X-shaped bar/bulge in the Milky Way, explaining earlier observations.



27.3° alignment
X is 400pc off plane
10:6.3:2.6 axis ratio

Wegg & Gerhard 2013

Blanco DEcam Bulge Survey



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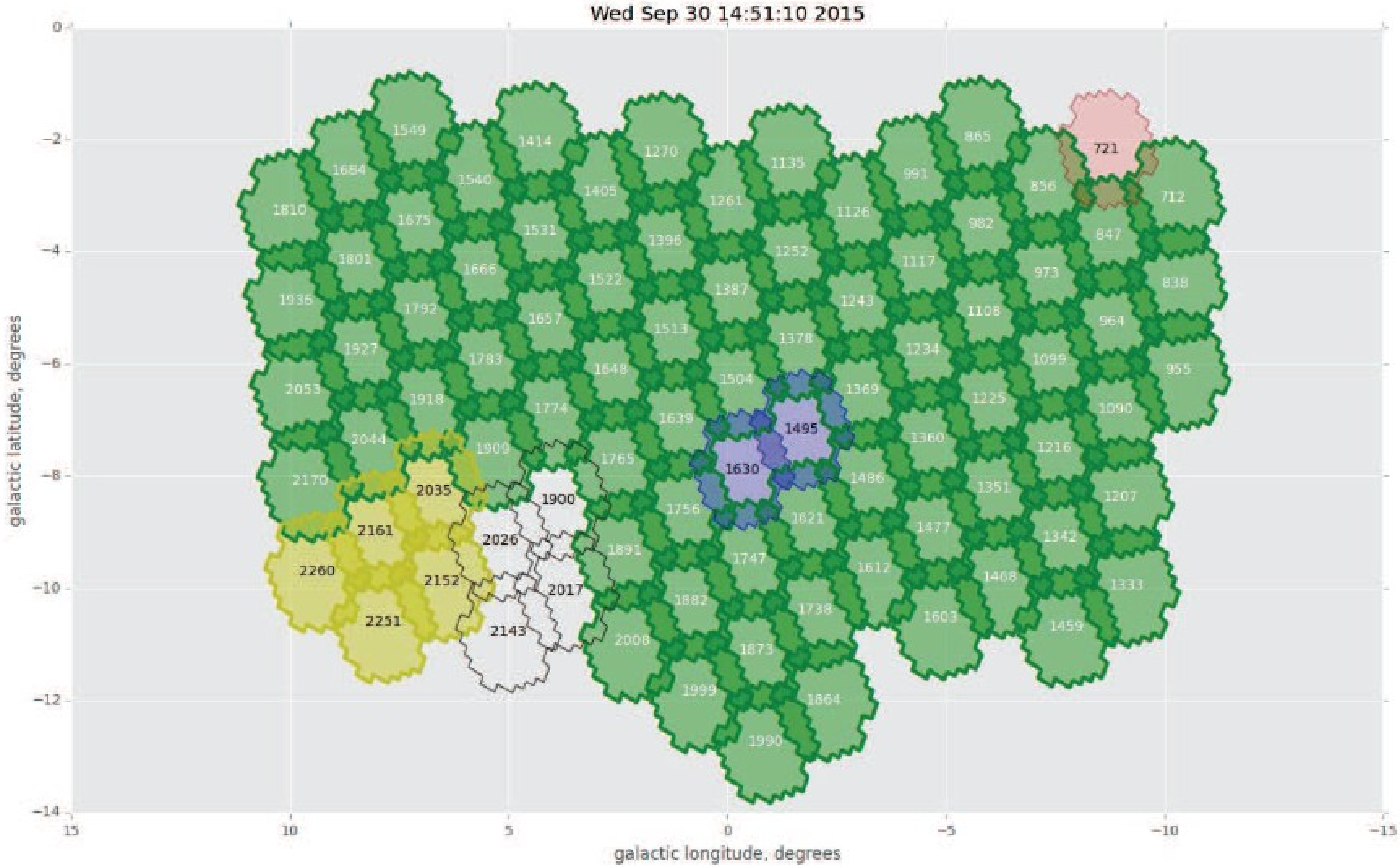
2015 progress on BDBS

Dark Energy Camera at CTIO Blanco 4m telescope.   3 sq. deg. field of view, 62 CCDs ugrizY SDSS colors imaging at 0.2"/pixel


Wed Sep 30 14:51:10 2015
galactic latitude, degrees
galactic longitude, degrees
0
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−6
−8
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712
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1531
1396
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1801
1666
1522
1387
1243
1108
973
838
1936
1792
1657
1513
1378
1234
1099
964
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1090
955
2053
1918
1774
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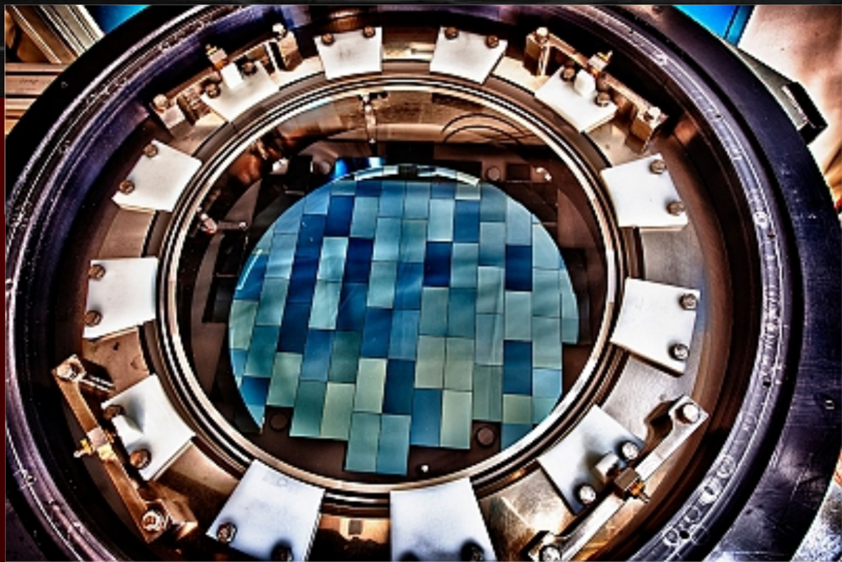
1630
1486
1351
1207
2170
2035
1900
1756
1621
1477
1342
2161
2026
1891
1747
1612
1468
1333
2260
2152
2017
1882
1738
1603
1459
2251
2143
2008
1873
1999
1864
1990

DECam – the Dark Energy Camera

- CTIO 4m + DECam
  - ~36% the collecting area of LSST
  - 3 sq deg field of view
    - ~31% the field of view of LSST
  - Seeing-limited
  - 520 MPix
    - ~16% the pixel-count of LSST



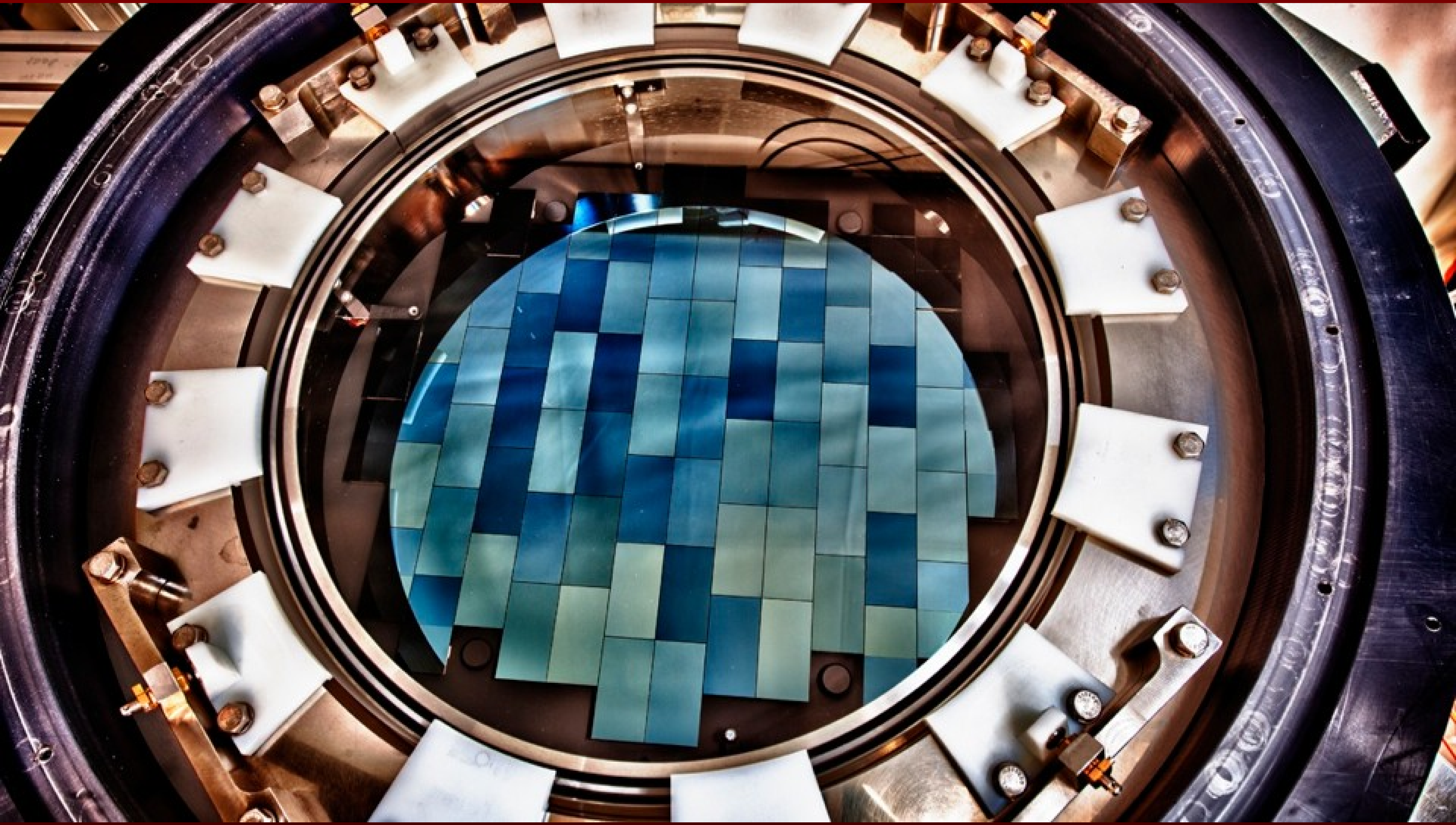


Image: W. Clarkson

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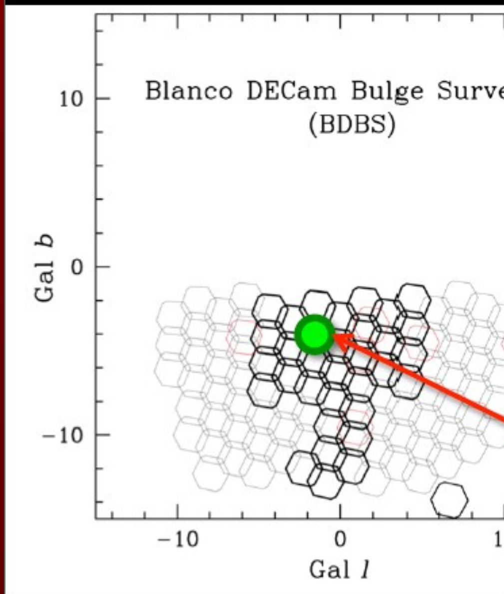
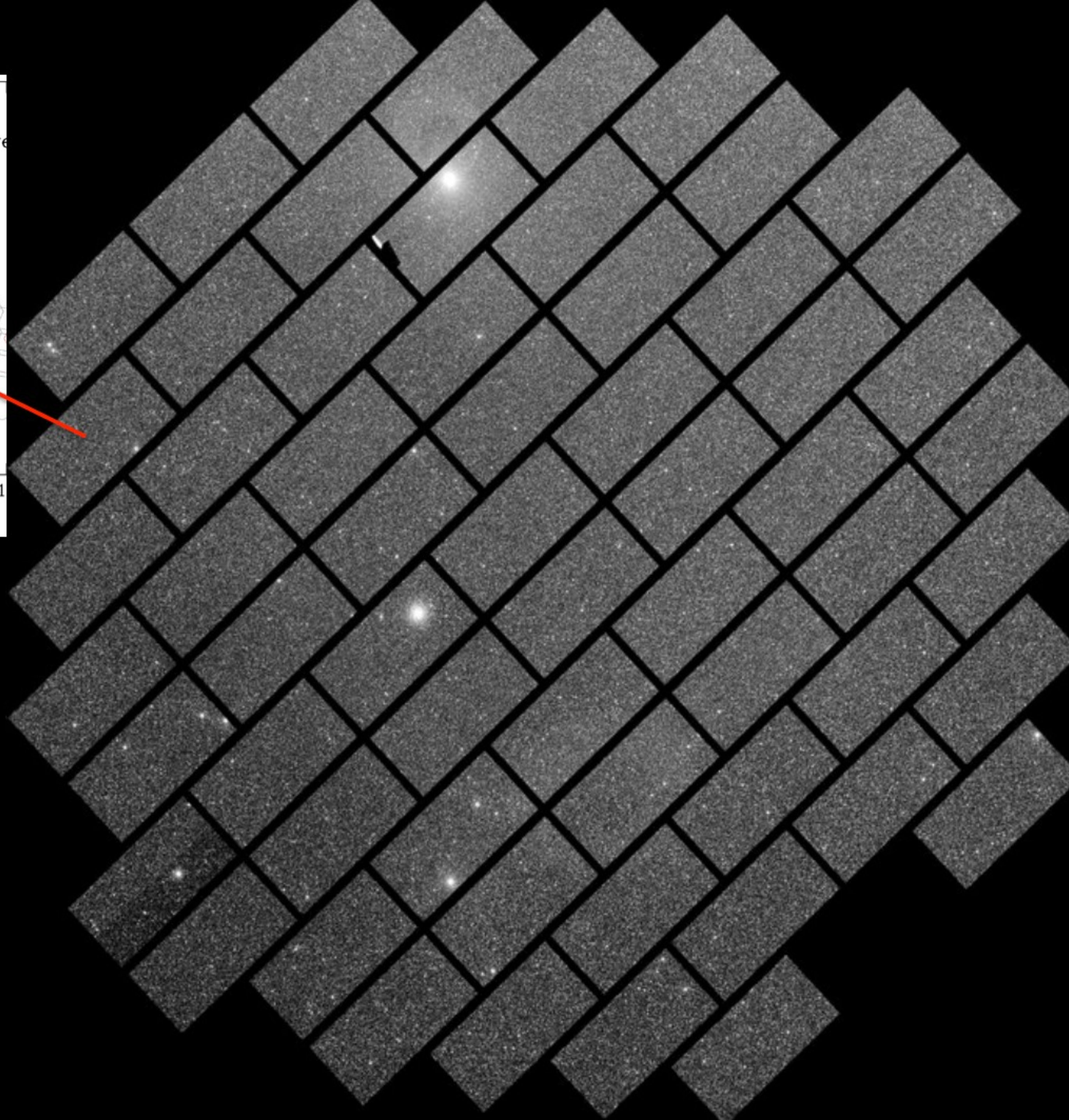
Image: W. Clarkson





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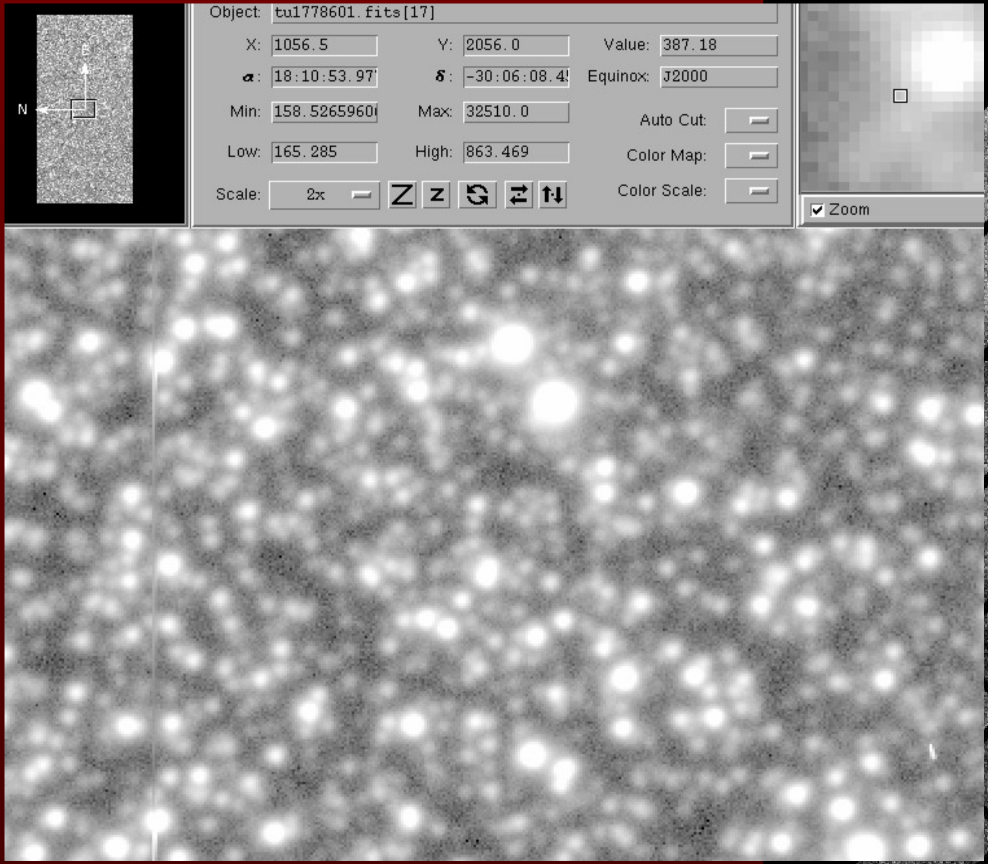
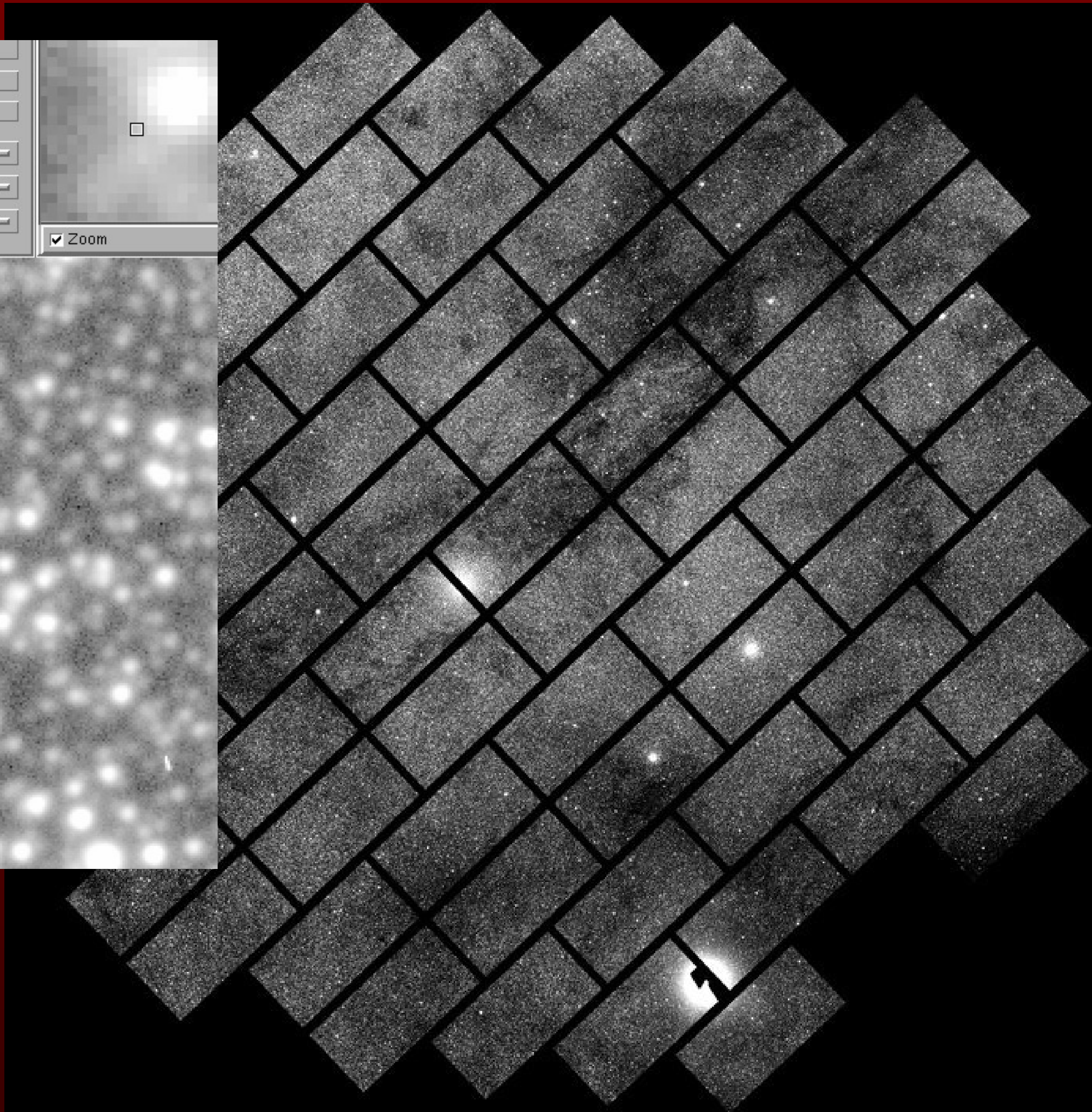
BDBS operates in quite a crowded regime:





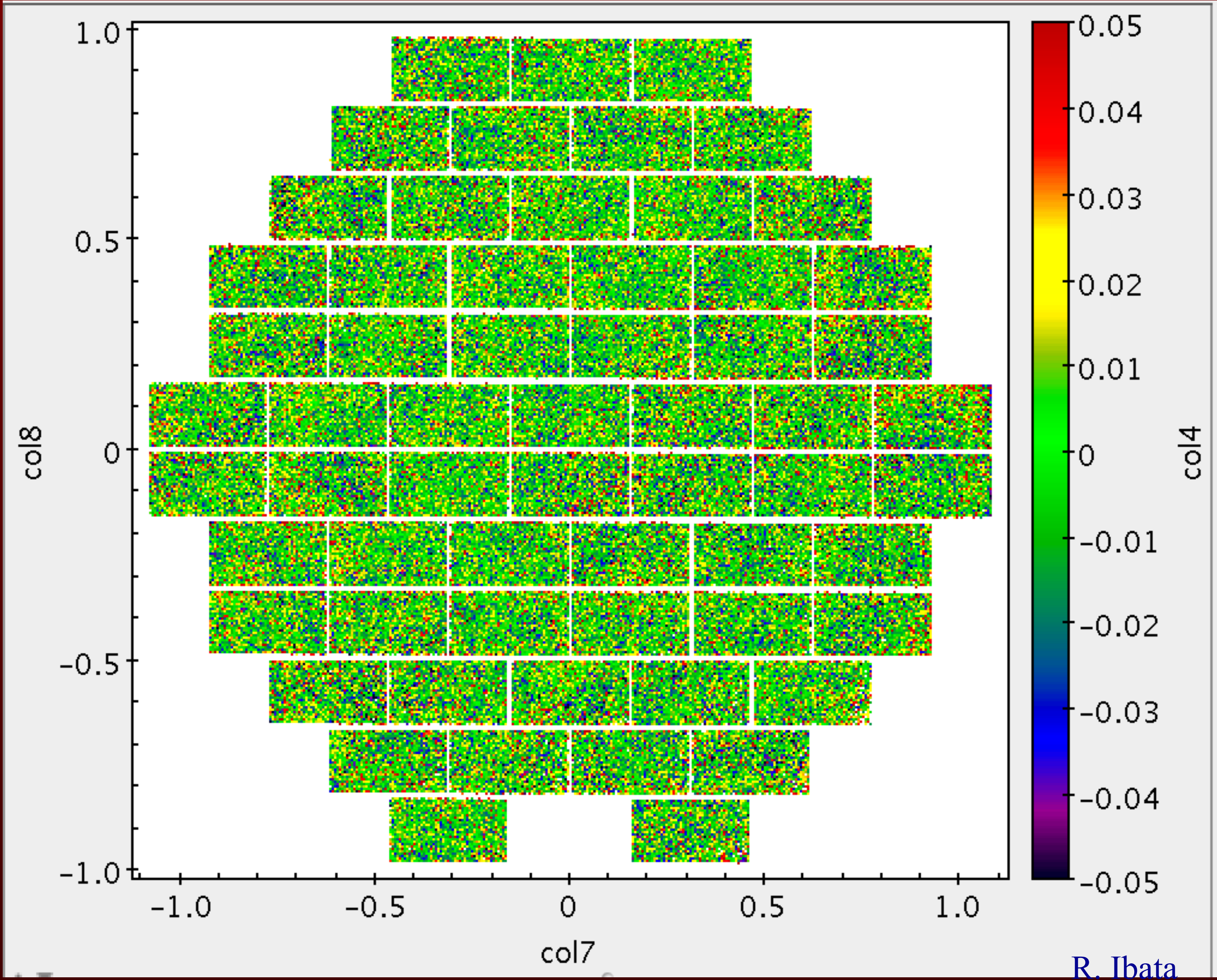
The Blanco DECam Bulge Survey (BDBS)

- Processing the full dataset:
- 2013A: 126,514 chip-images
  - ~5 TB uncompressed
- Full area: DOPHOT
  - Developing initial catalog
- Other approaches tested on select fields.

Images processed on the Quarry-II infrastructure at Indiana University.

With hundreds of cores, takes about 1 week for the entire dataset.

Three approaches to photometry underway (CASU, DoPhot, Daophot). Present catalog has 10^9 stars



Preliminary photometric calibration using Panstarrs1 (R. Ibata, N. Martin)

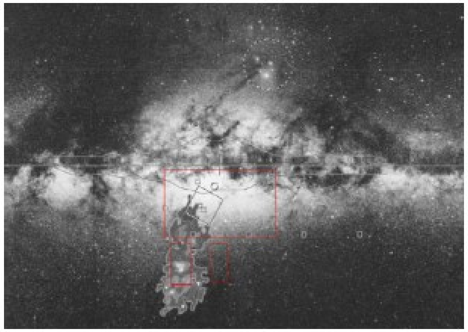
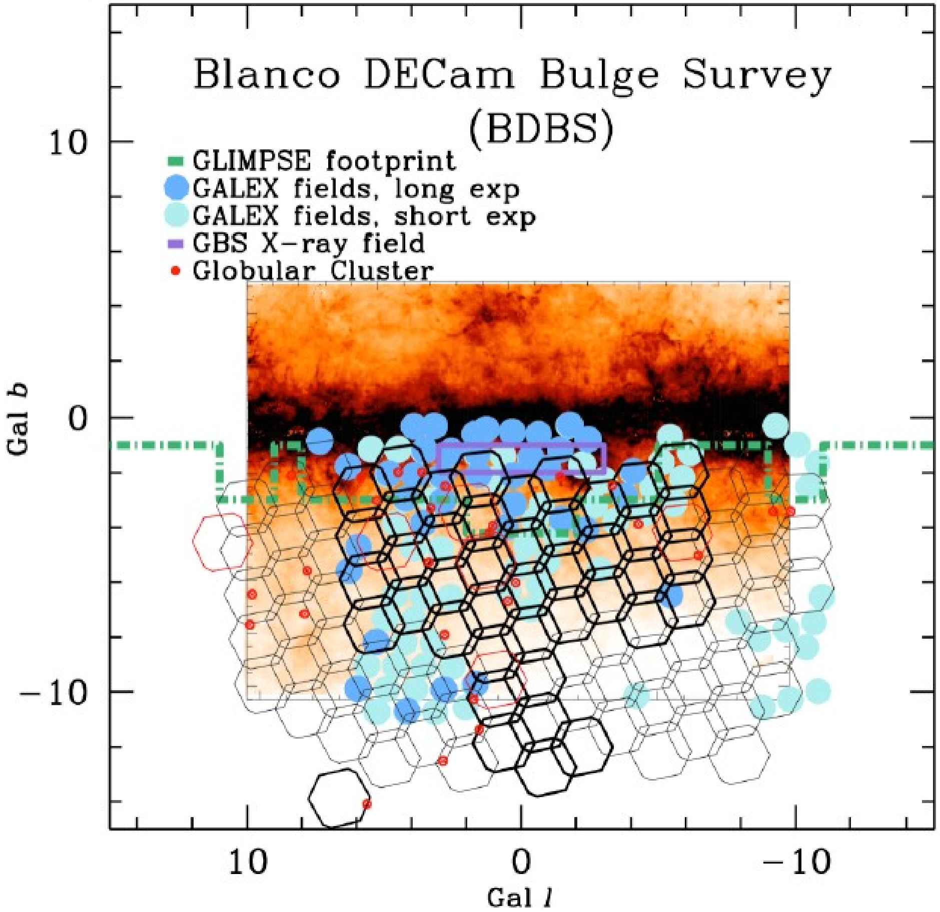
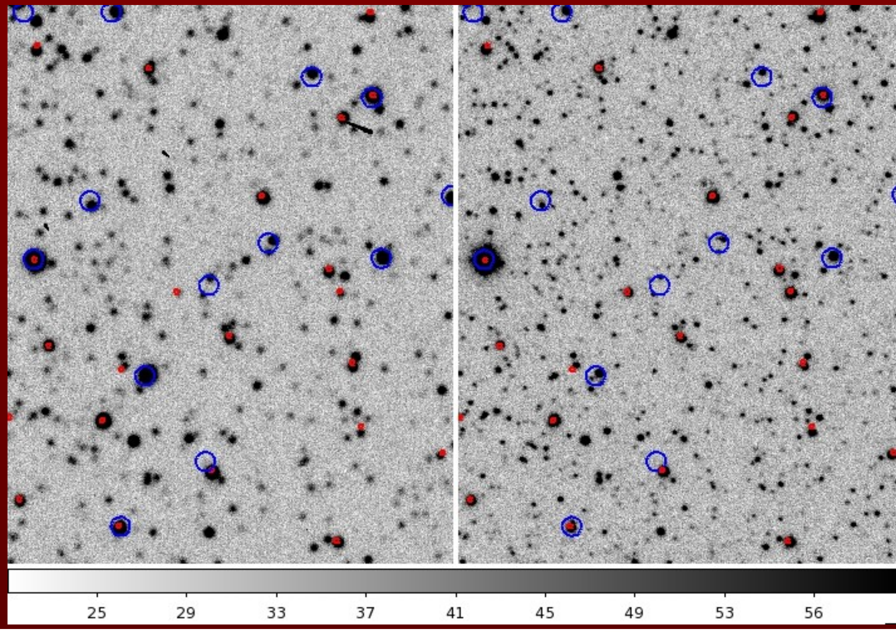
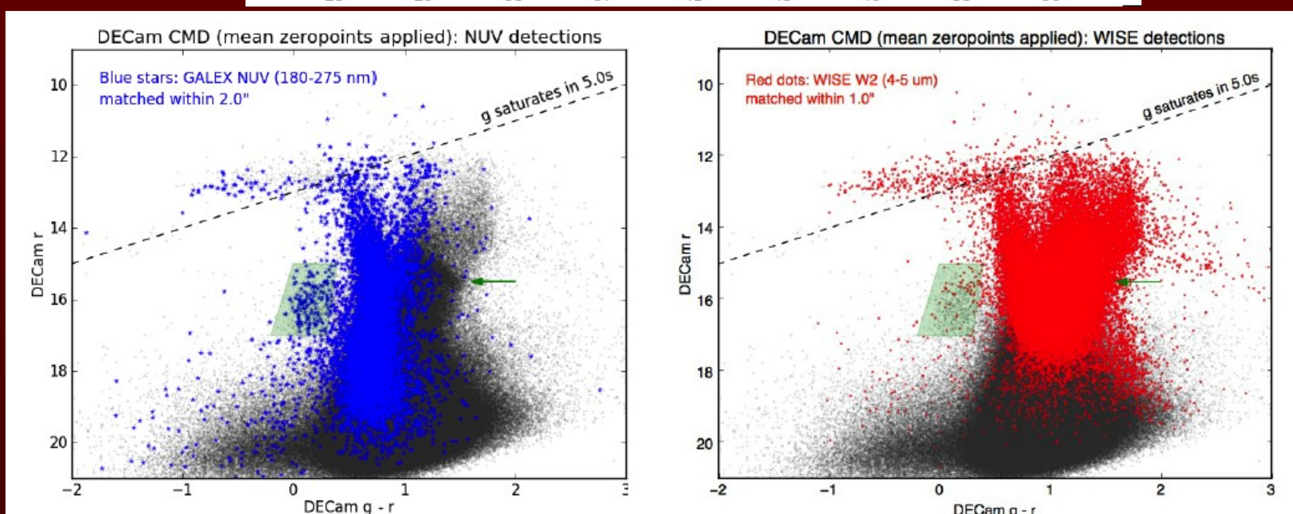


Figure 1-(Left) Visible light image of the Milky way with the bulge and Sgr dwar galaxy (illustrated as a blobby structure below the bulge) superimposed (Wyse, Gilmore, & Franx 1997). The red square regions cover the approximate location of the Blanco DECam bulge survey illustrated below.



Match Galex, WISE



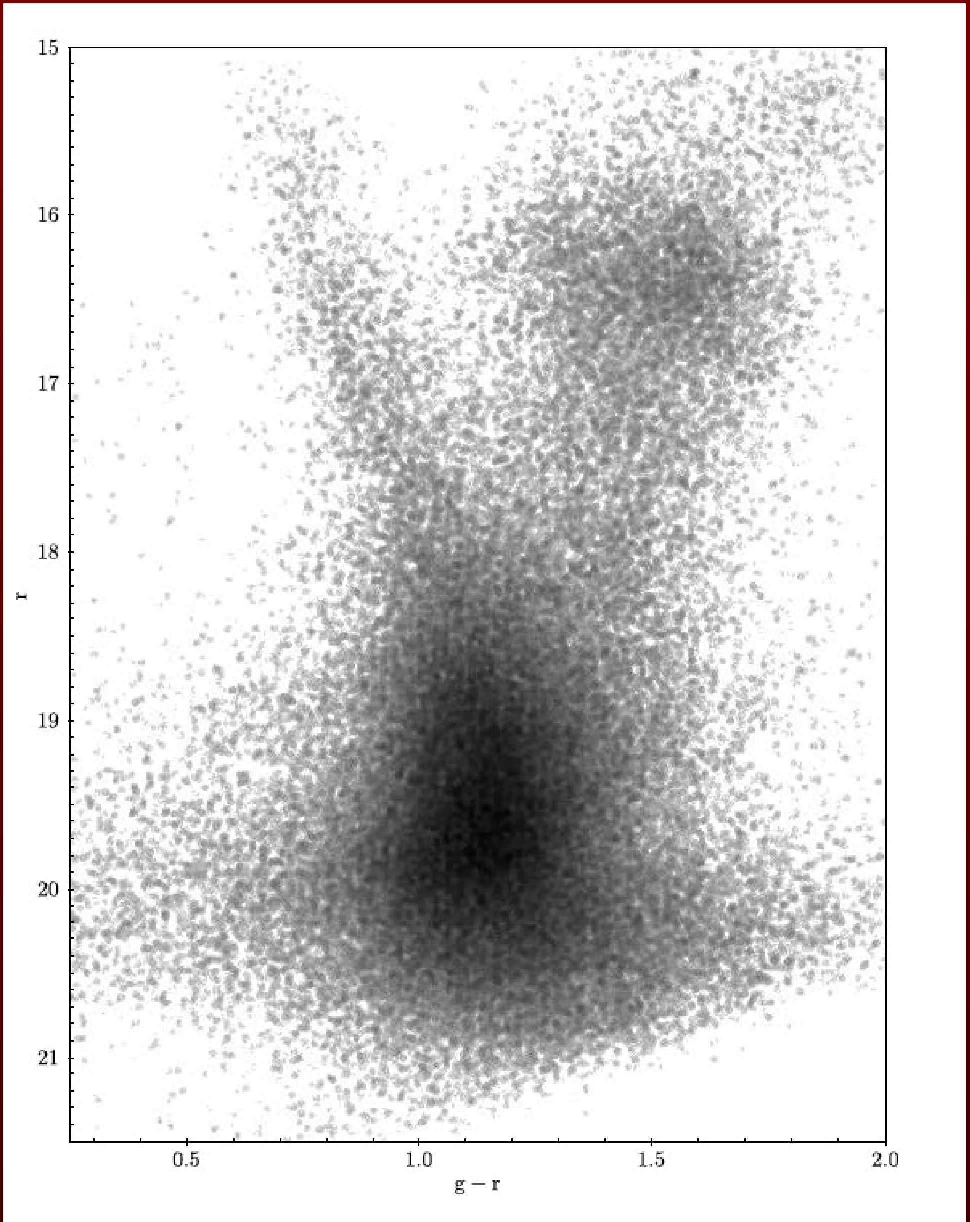


Reductions by C. Johnson and Will Clarkson

Science Goals

- Produce a community catalog and image server to be served by PTI (IU)
- Separate the bulge from the foreground disk, background halo by statistical subtraction and proper motions
- Map bulge structures (bar, X) as a function of age, metallicity; photometric metallicities for abundance gradient
- Produce a map of the Sagittarius dwarf spheroidal galaxy core
- Search for streams and substructure in the bulge
- Search for ultra-metal poor stars in the bulge region
- Use proper motions to explore the kinematics of the bar and X structure and to search for a “classical” bulge component

Preliminary CMD near Baade's Window



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Sesto 2016

Bulge Asymmetries and Dynamic Evolution

The BAaDE Project

As presented by Ylva Philstrom (University of New Mexico) at 2016 AAS meeting

Ylva Pihlström (UNM)
Loránt Sjouwerman (NRAO)
Mark Claussen (NRAO)
Isaiah Santistevan (UNM)
Michael Rich (UCLA)
Mark Morris (UCLA)
Cameron Trapp (UNM)
Michael Stroh (UNM)

The BAaDE project

Aim: To significantly improve models of the dynamics and structure of the Galactic bulge and the inner Galaxy, using SiO masers (red giants)

- Using radio detected point-masses probing regions with extinction too high for optical surveys ($-6 < b° < 6$).

- Surveying up to ~34,000 stars for SiO maser emission using both VLA and ALMA.
  - Direct line-of-sight velocity distributions obtained

- Using the extreme resolution of the VLBA for detailed orbit characteristics in a subsample of the sources.

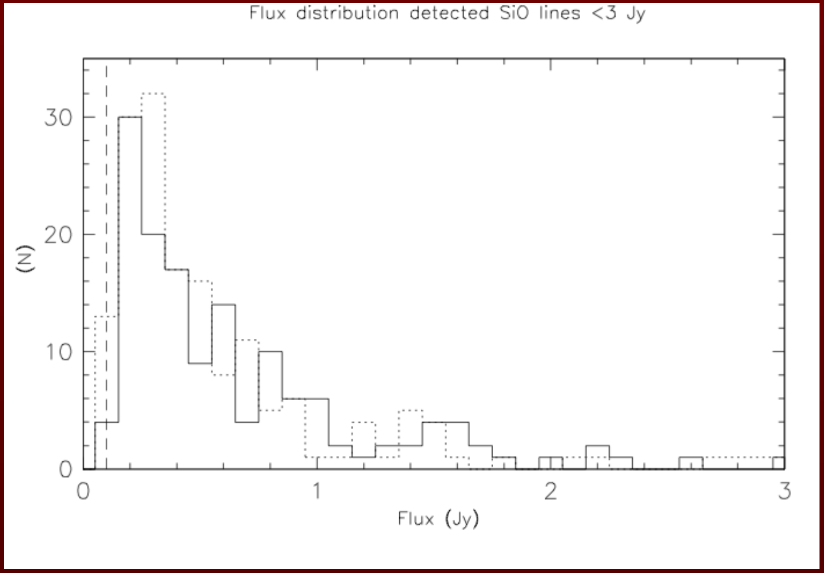
- OH/IR stars are more luminous, but they are far more rare. Presently there is no known characteristic of SiO masers indicative of age or mass.

Main research goals

1. Galactic dynamics and detailed Galactic structure
   - LOS velocities + location => global dynamical model
   - Velocity rotation curves & velocity dispersions (for dynamical models)
   - Instabilities and asymmetries
   - High-velocity stars, are they an entire population influenced by the bar?

2. Statistics of SiO masers in the Galaxy
   - Detection statistics as functions of MSX color, Galactic location and velocity
   - Comparison with 2MASS, GLIMPSE, WISE, AKARI, etc.
   - Correlation between different maser transitions in the shell

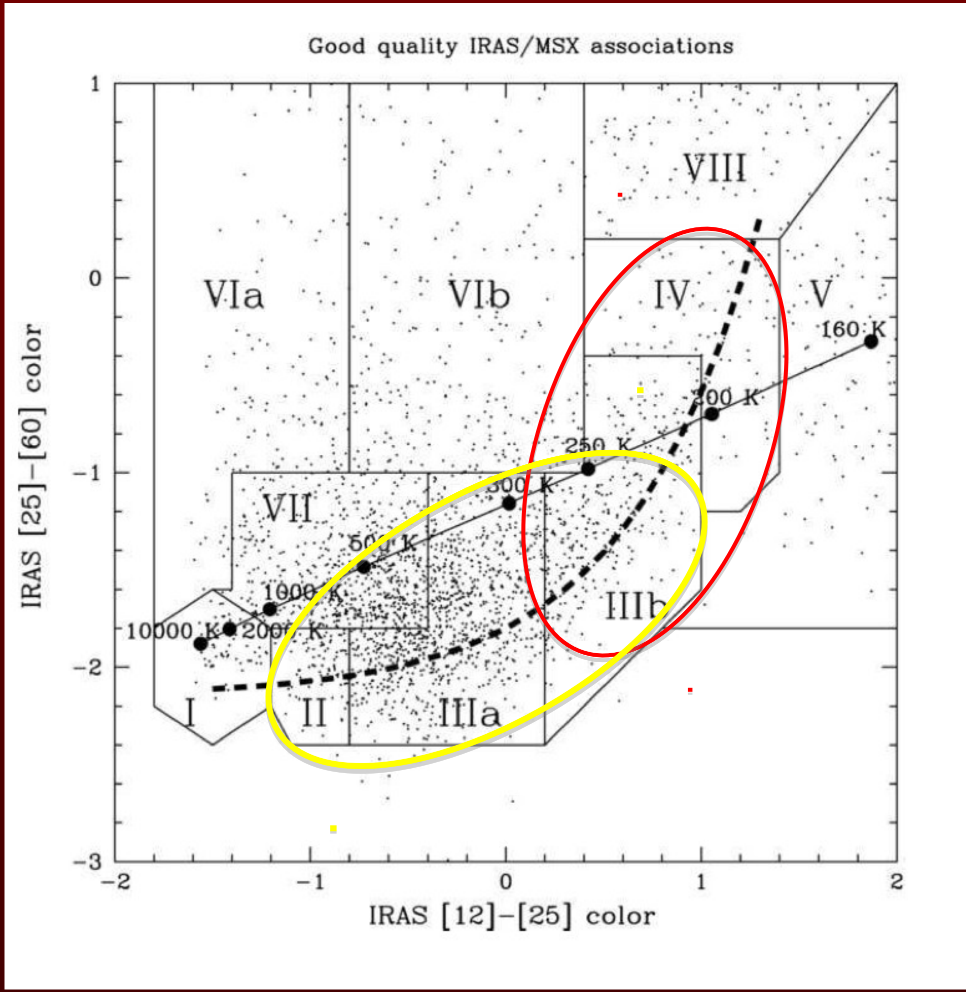
3. VLBI proper motions of Galactic orbits and structure of individual stars
   - Proper motions and perhaps orbit family, and parallax distances when possible
   - Orbits will significantly improve modeling of the Galactic dynamics



4. SiO maser characteristics and stellar and circumstellar properties
   - SiO maser stellar properties to be studied, like magnitude, color, variability, distance position, age, metallicity if possible, SEDs
   - Correlation with maser intensity

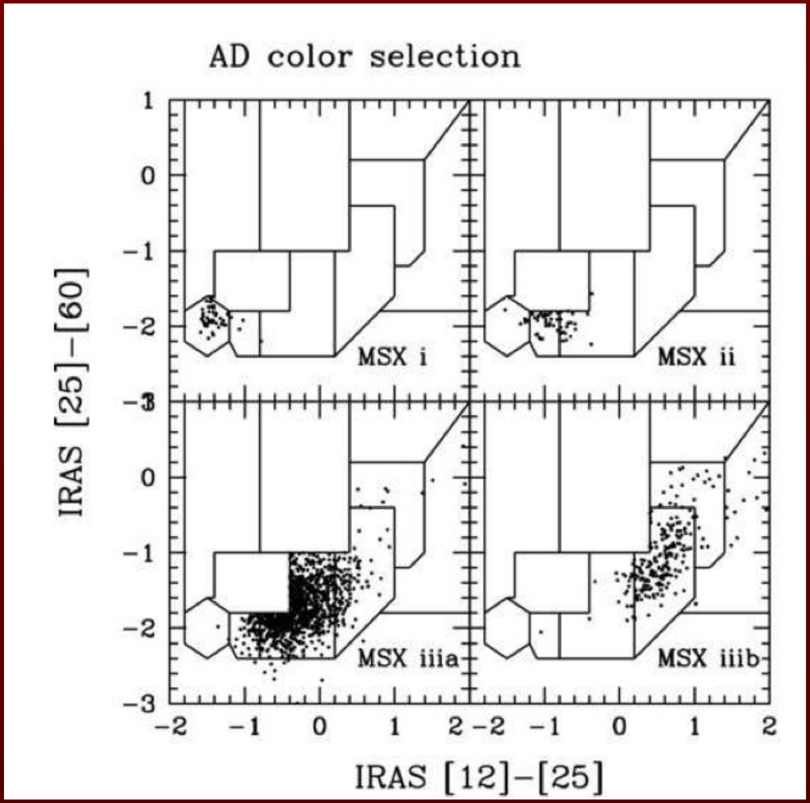
OH and SiO maser stars

- Masers in OH/IR stars have previously been used for kinematical studies of the Milky Way (e.g., Habing et al. 2006)
  - Only 3000 OH maser stars in MW
- IRAS colors predictive of finding sources with circumstellar material.



Van der Veen & Habing 1988
Habing 1996

Target selection from MSX



MSX PSC 2.3 (0<*l*°<360, -6<*b*°<6)

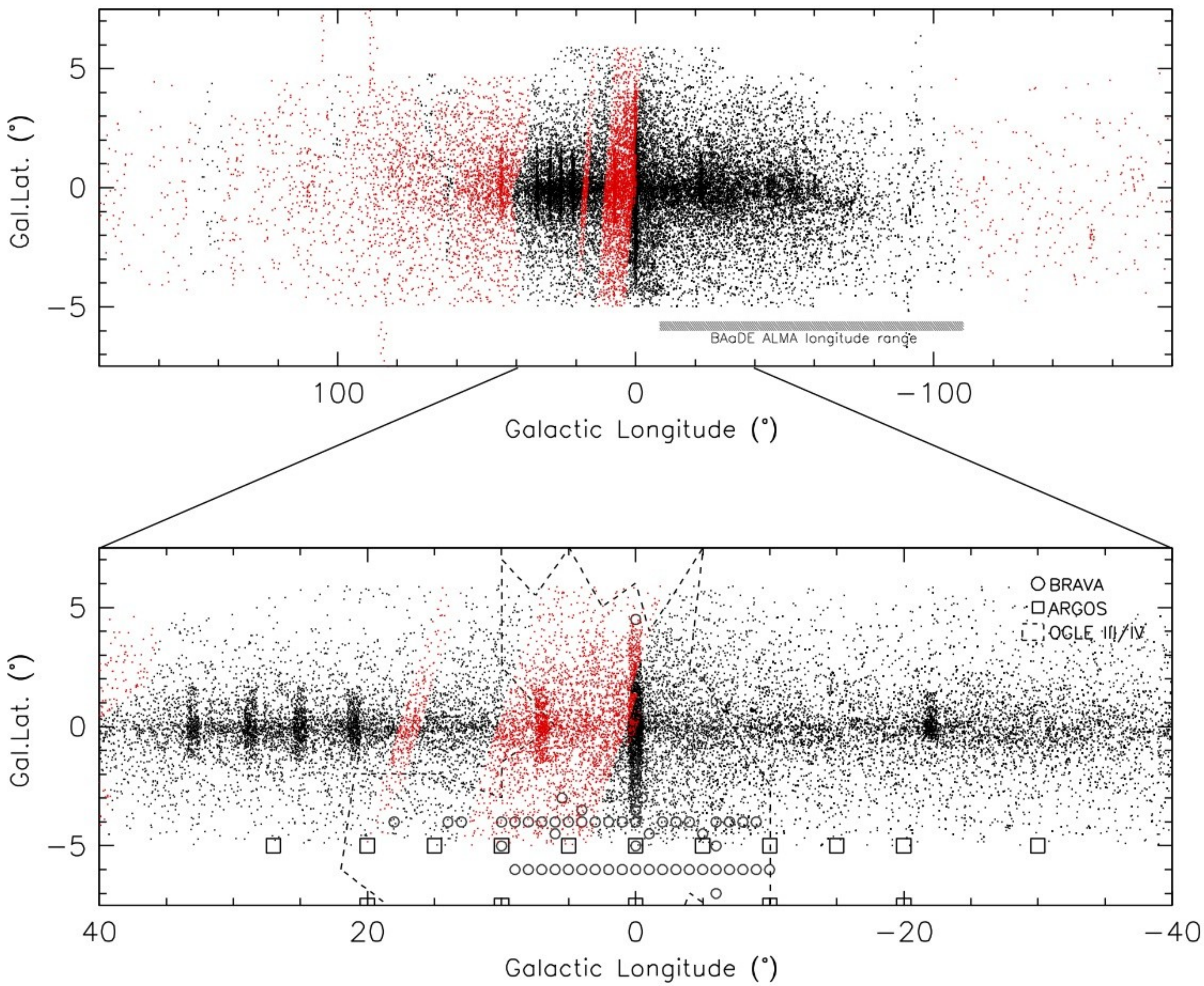
⇒ ~19,000 out of 440 000 sources for MSX color regions ii, iiia and iiib

⇒ Another ~14,000 with ALMA

- Stellar sources within certain MSX color regions can be expressed similar to IRAS color regions

Sjouwerman et al. 2009, Messineo et al. 2002.

- In these regions the detection rate of SiO masers is between 50-90%.



Gal.Lat. (°)
5
0
−5
100
0
−100
Galactic Longitude (°)
BAaDE ALMA longitude range
BRAVA
ARGOS
OGLE III/IV
40
20
−20
−40

Summary status

VLA

•Observed about 155 of ~500h in total (7,000 stars), detection rate ≥60 %

•Another 80h allocated this fall/winter (3,500 stars)

•Line of sight velocities derived for a subset of these (1,850 stars)

ALMA

•Cycle 2 4h (200 stars), detection rate ≥65%

•Cycle 3 26h (1200 stars) approved (out of ~300h in total)

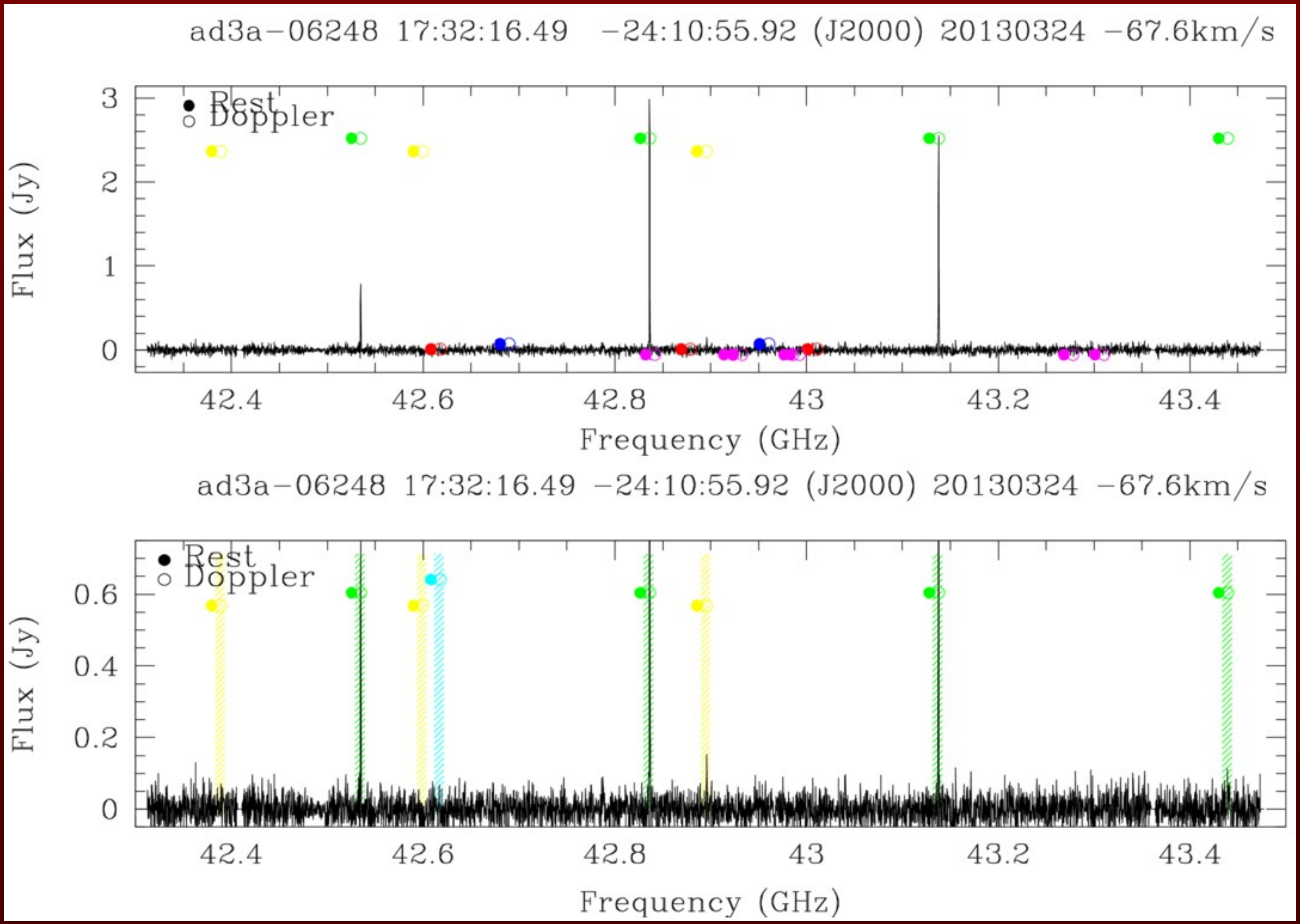
VLBA

•50h ongoing pilot program (4 stars)

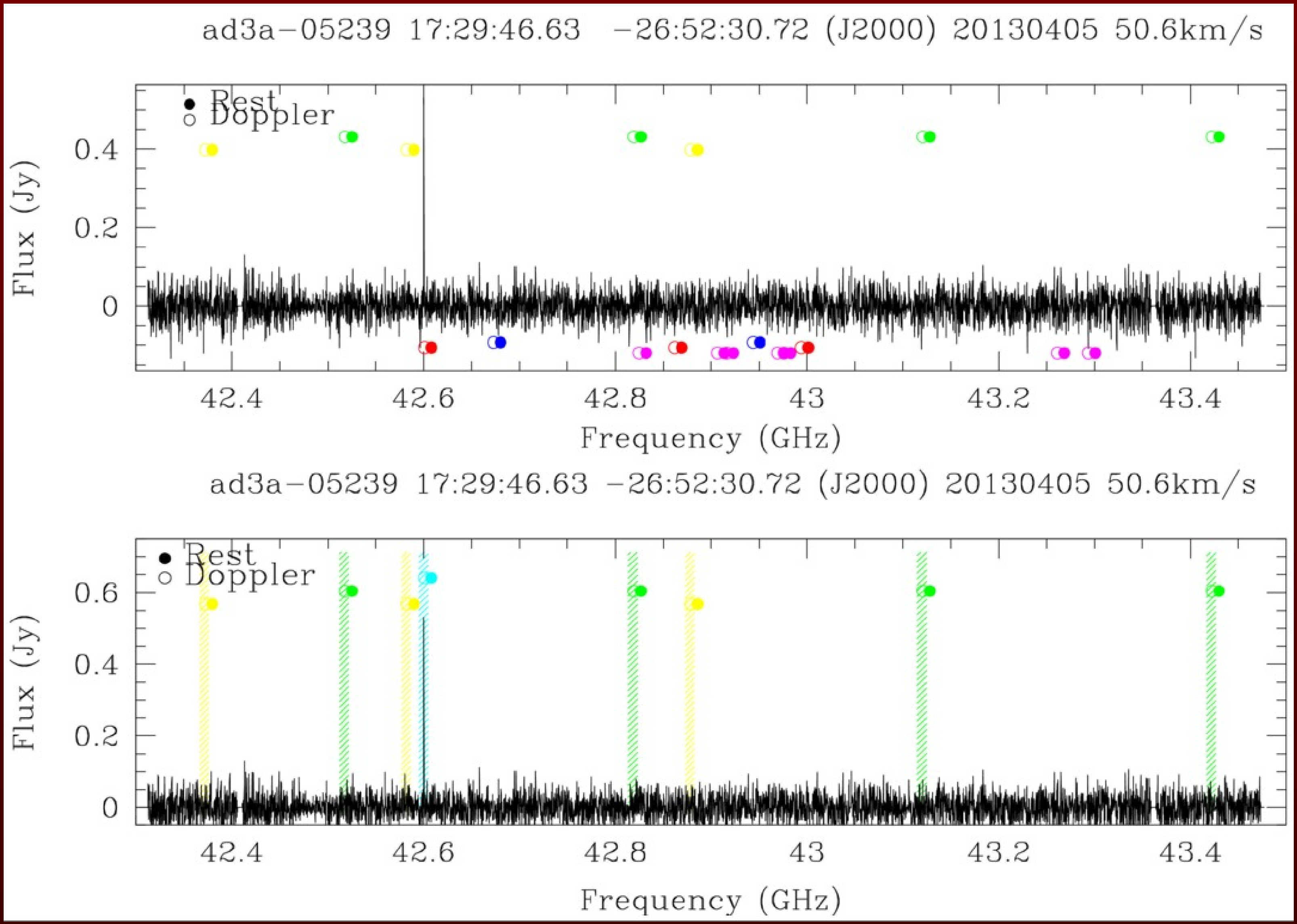
•Another 50h approved starting spring 2016

•Calibrator search programs approved/observed (6h VLA, 9h VLBA, 12h EVN)

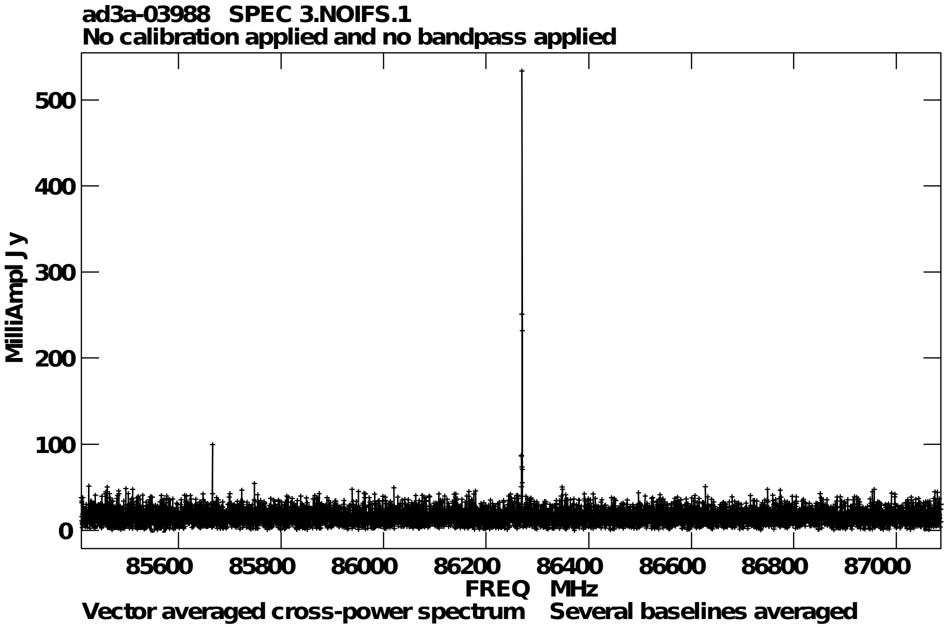
Example VLA spectra: (v=1,2,3 and isotope ^{29}SiO v=0)

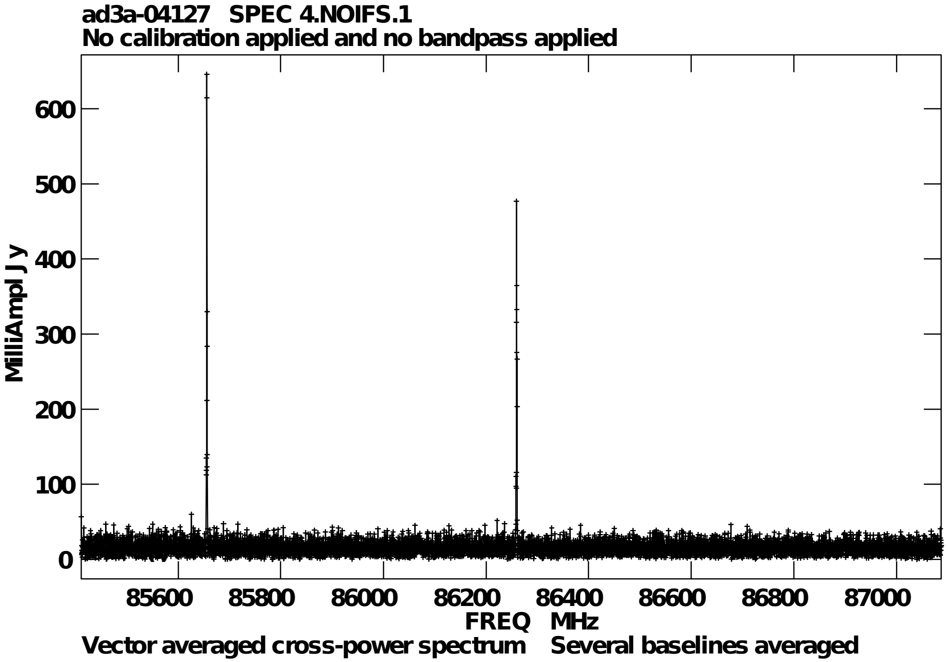


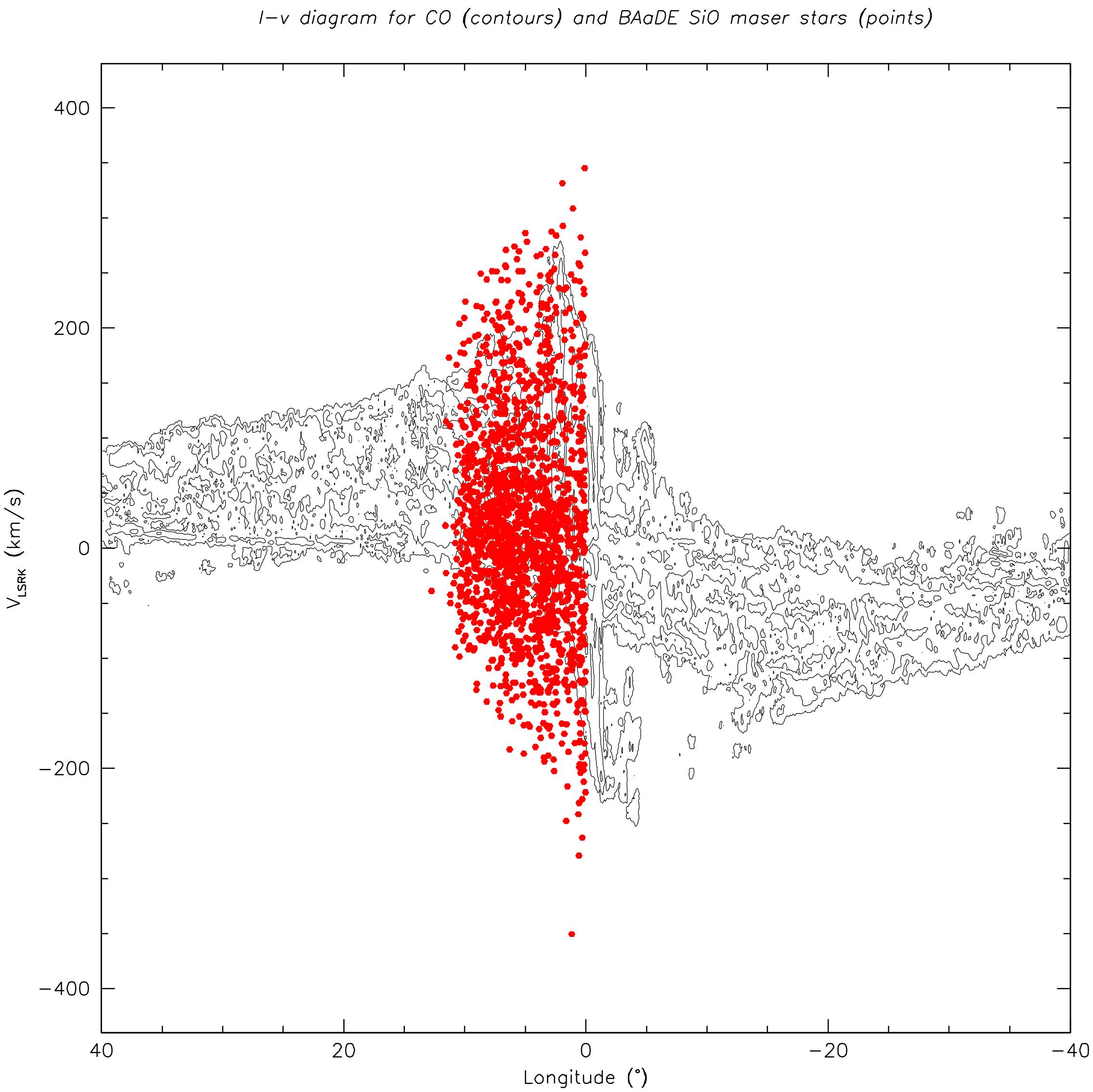
Example VLA spectra: carbon



Example ALMA spectra: Dual (v=1, v=2)

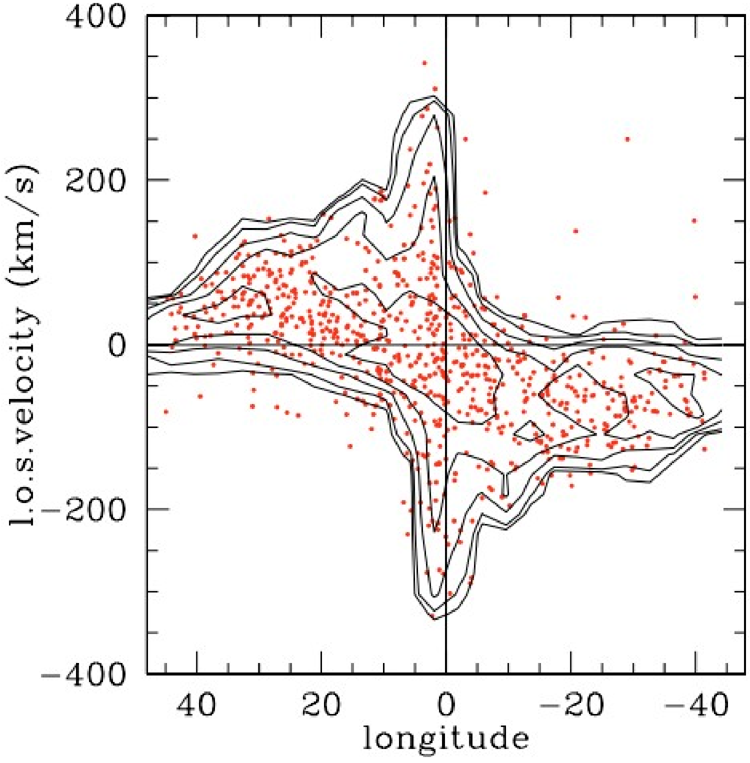


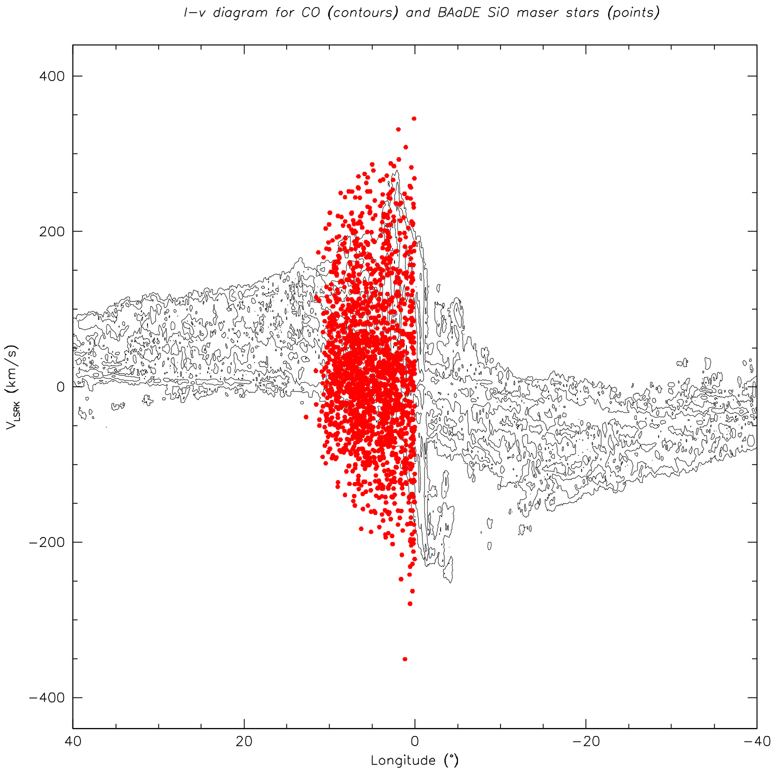




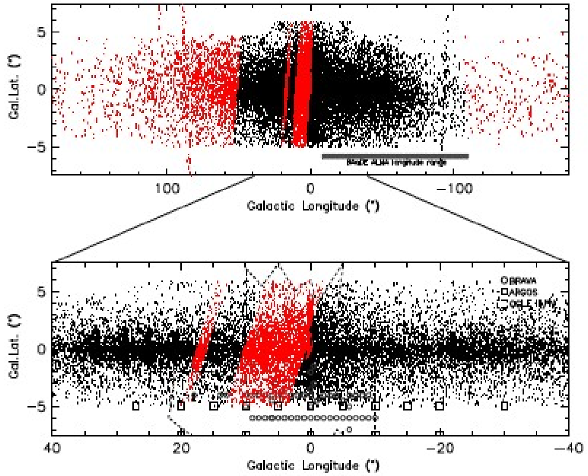
Dame et al. (2001)

- CO distribution along *b*=0°, and the BAaDE first set of detections.
- Different populations.
- Non circular motions.





Habing et al. (2006)



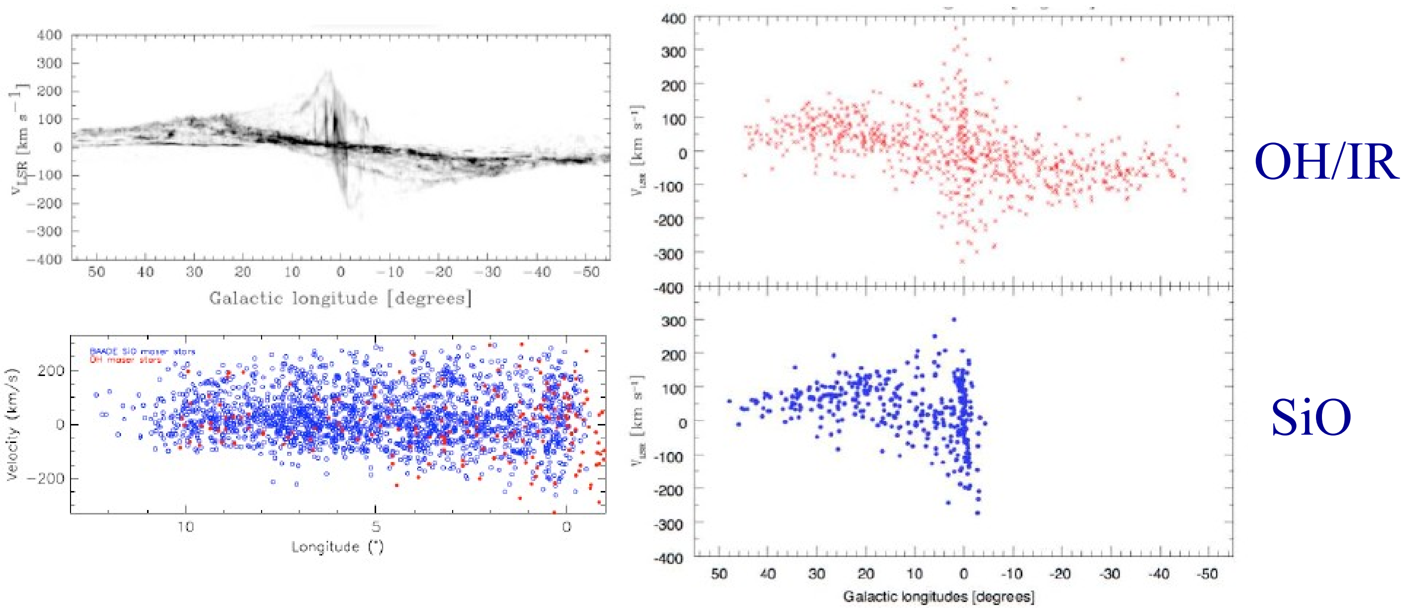
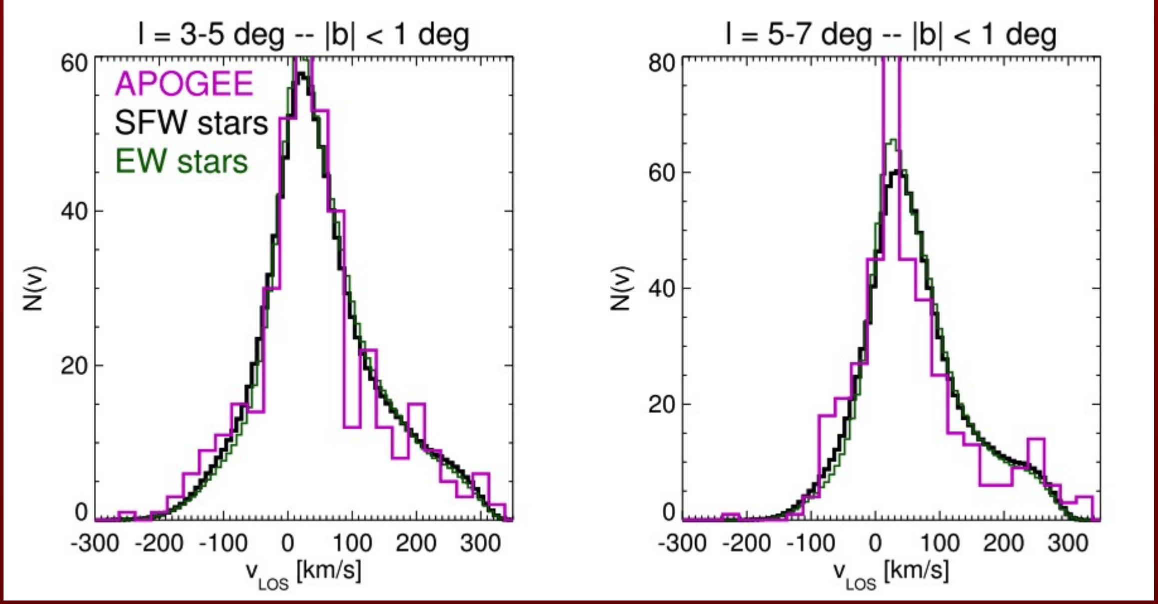


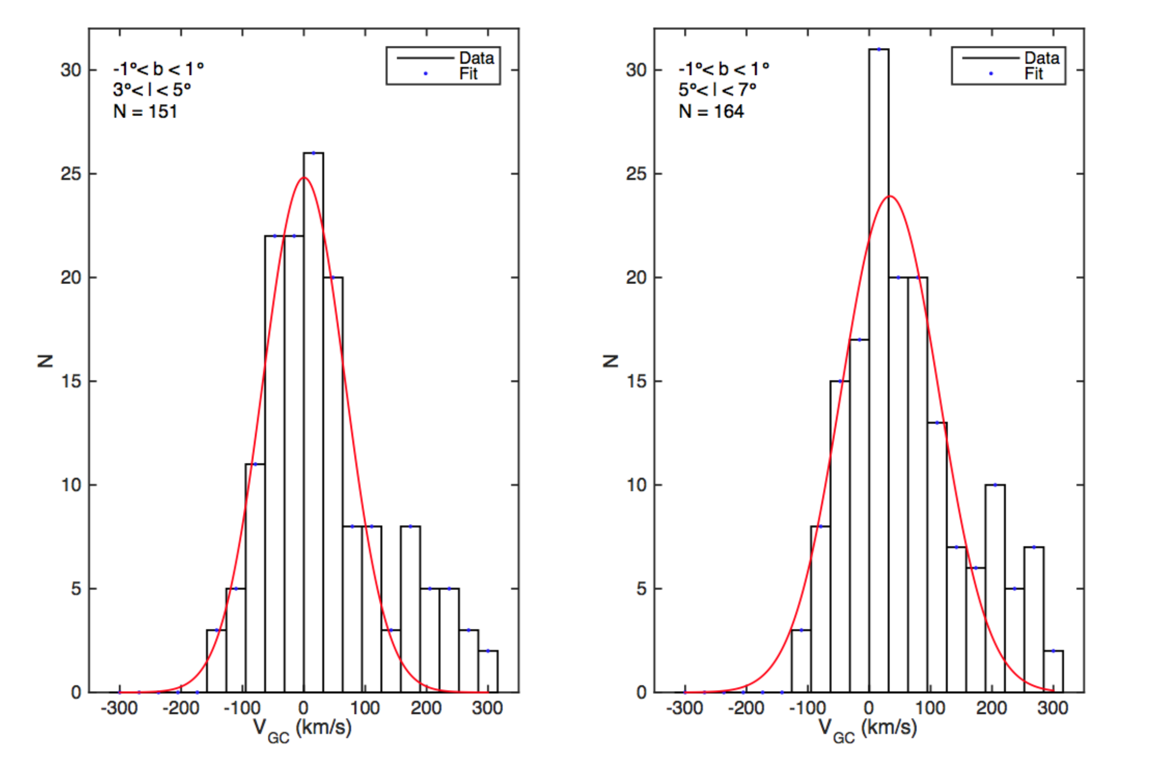
Fig 1a- (Top) Survey of Galactic SiO masers; candidates are in black, with detections in red (current to Sep 2015; Sjouwermann et al. 2016 in prep). **Fig 1b**- (Bottom) Top left: *l*−*v* (longitude-velocity) diagram of CO gas from Dame et al. (2001). Right hand side: 766 OH/IR stars (red, top) from Sevenster et al. (1997a; 1997b; 2001) and 360 SiO maser stars (blue, bottom) from Messineo et al. (2002; 2004). The distribution of OH/IR and SiO maser stars hints toward kinematic structures (e.g., the steep vertical signature near l = 0) but are not yet sampling the stellar



Aumer & Schönrich (2015)

- Modeling investigating the "200 km/s feature", testing with APOGEE data.

- Dynamically cool and young stars captured by the bar?



- Will be tested by observations to negative longitudes and orbital determinations with the VLBA

Summary

- At the point where we are collecting the basic data (VLA, ALMA)
  - SiO masers/velocities
  - IR data
- Preparing for follow-up VLBA studies
  - Calibrator searches
  - Determining suitable samples/key sources
- First data release/paper early Spring 2016
- Webpage: http://www.phys.unm.edu/~ylva/baade/

Internal Chemistry of Bulge Globular clusters

C. Johnson (CfA)

R. M. Rich, C. Pilachowski, N.Caldwell, M. Mateo

Uses multifiber high resolution spectrograph at Magellan/CTIO (M2FS) by M. Mateo (Michigan)

Survey searches for internal chemical complexity in previously unstudied bulge/massive globular clusters

M19= NGC 6273

The Astronomical Journal, 150:63 (21pp), 2015 August
doi:10.1088/0004-6256/150/2/63

A SPECTROSCOPIC ANALYSIS OF THE GALACTIC GLOBULAR CLUSTER NGC 6273 (M19)*

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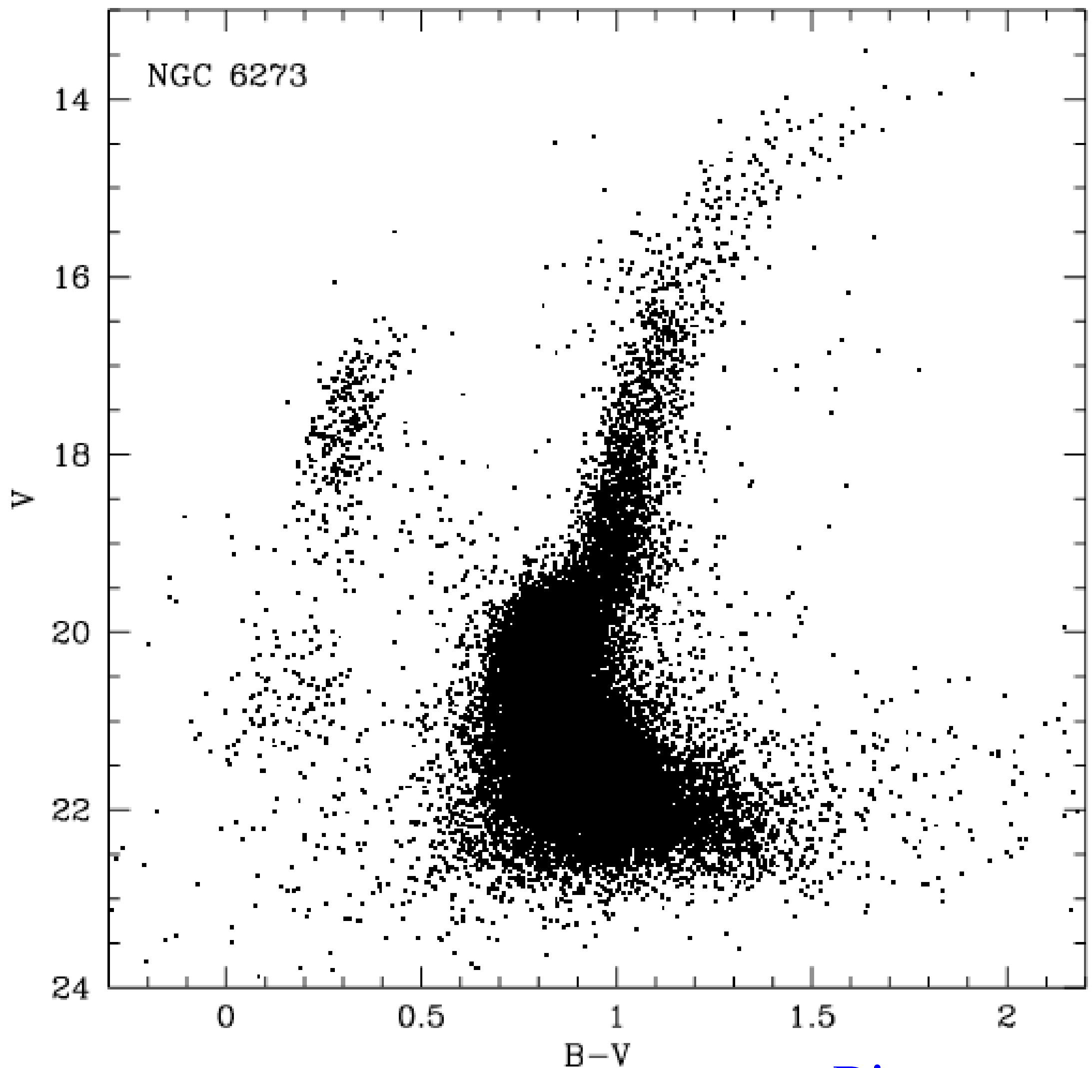

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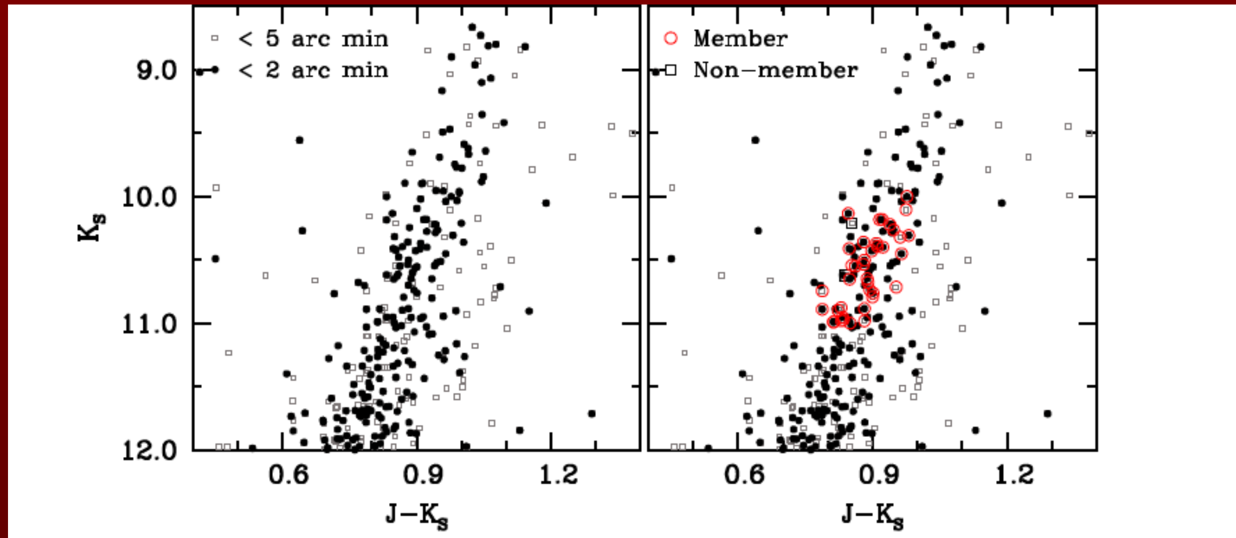
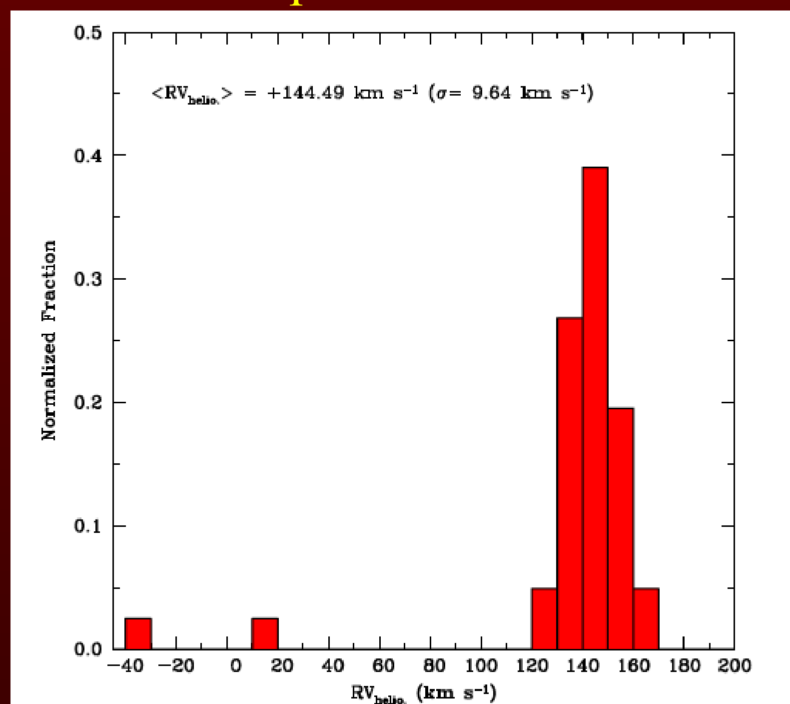
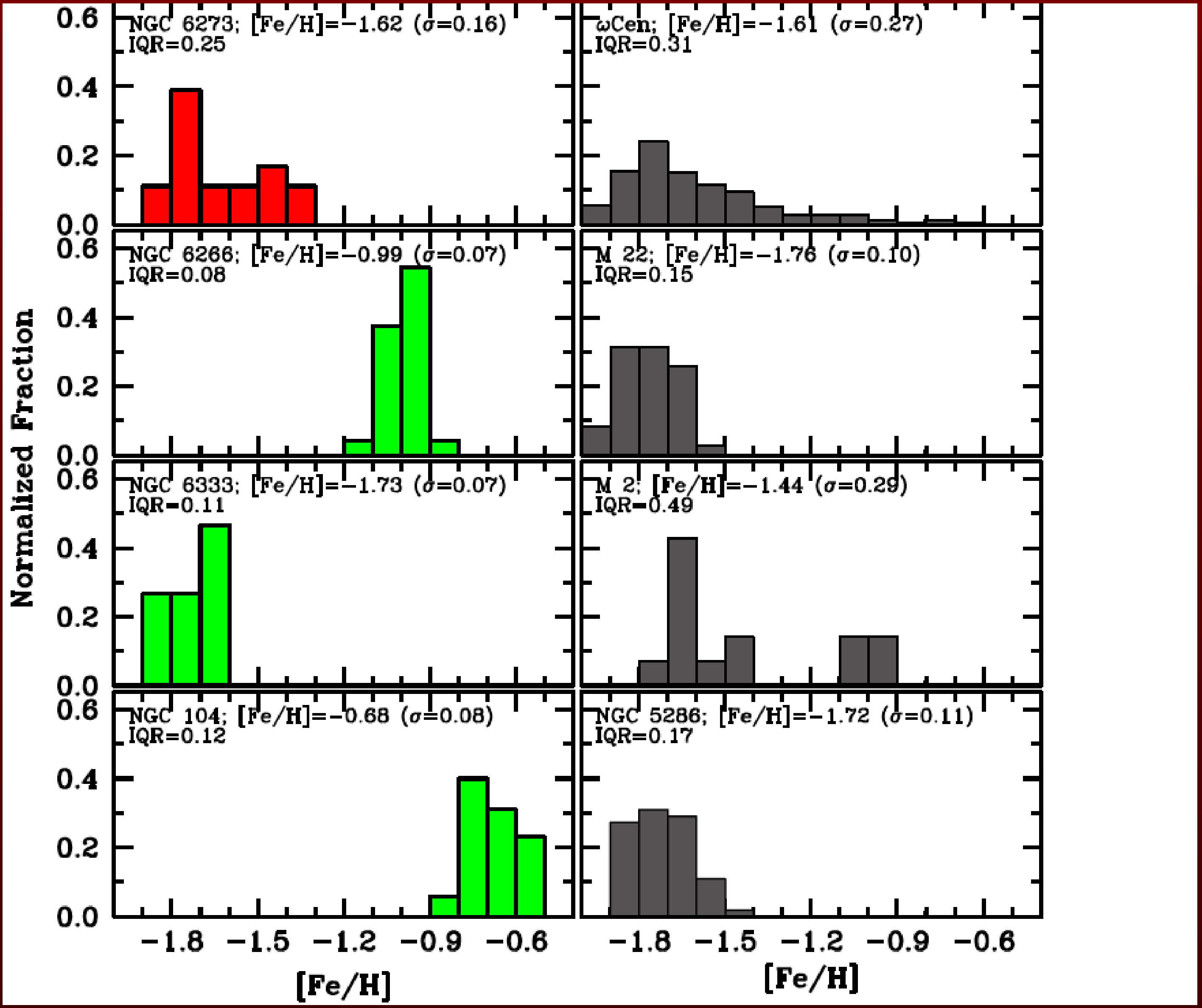
FIG. 1.—Color-magnitude diagram for ~28,000 stars in the central region of NGC 6273. All the stars identified in the Planetary Camera and in the three Wide Field Cameras are shown.



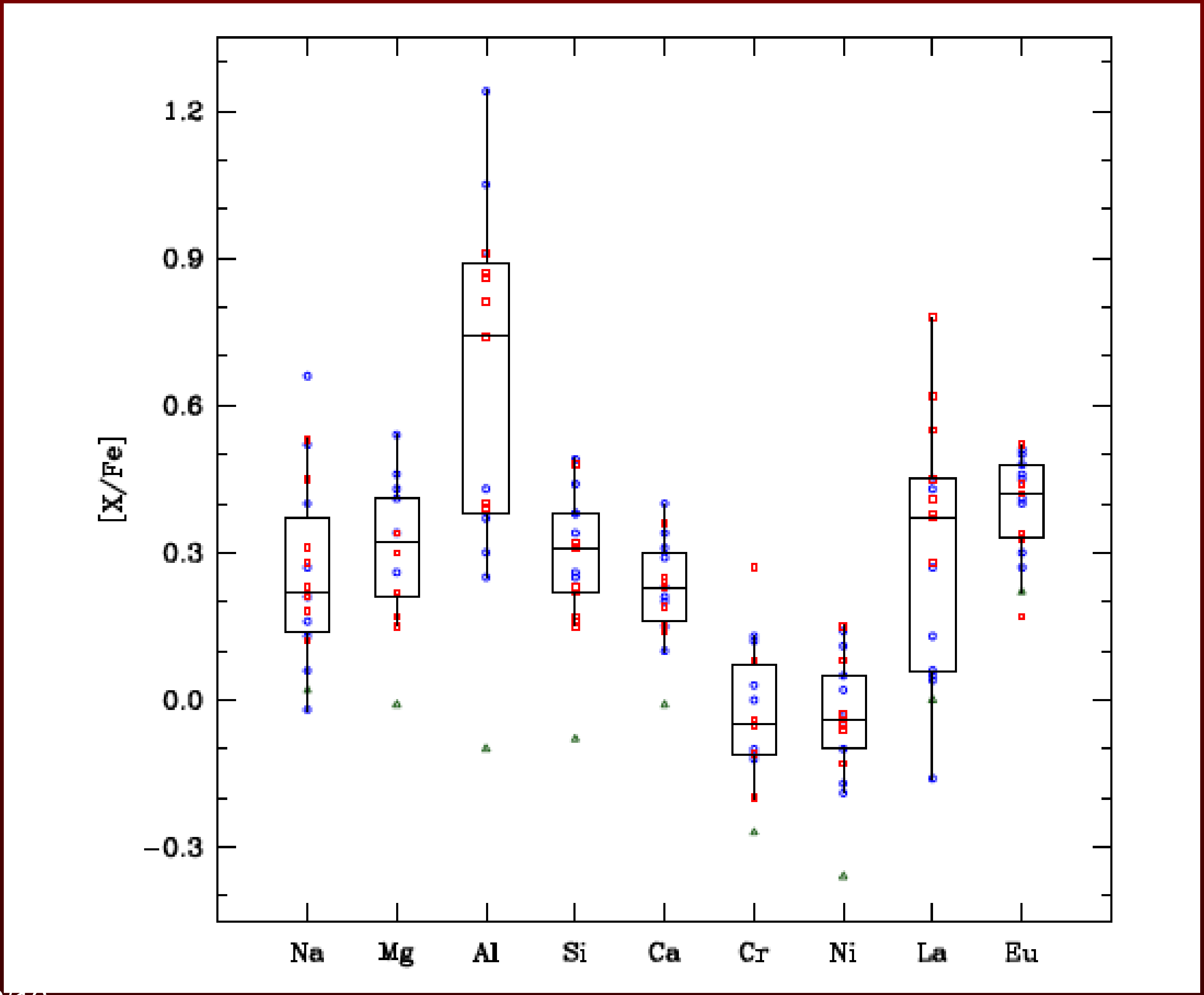
Sample selection

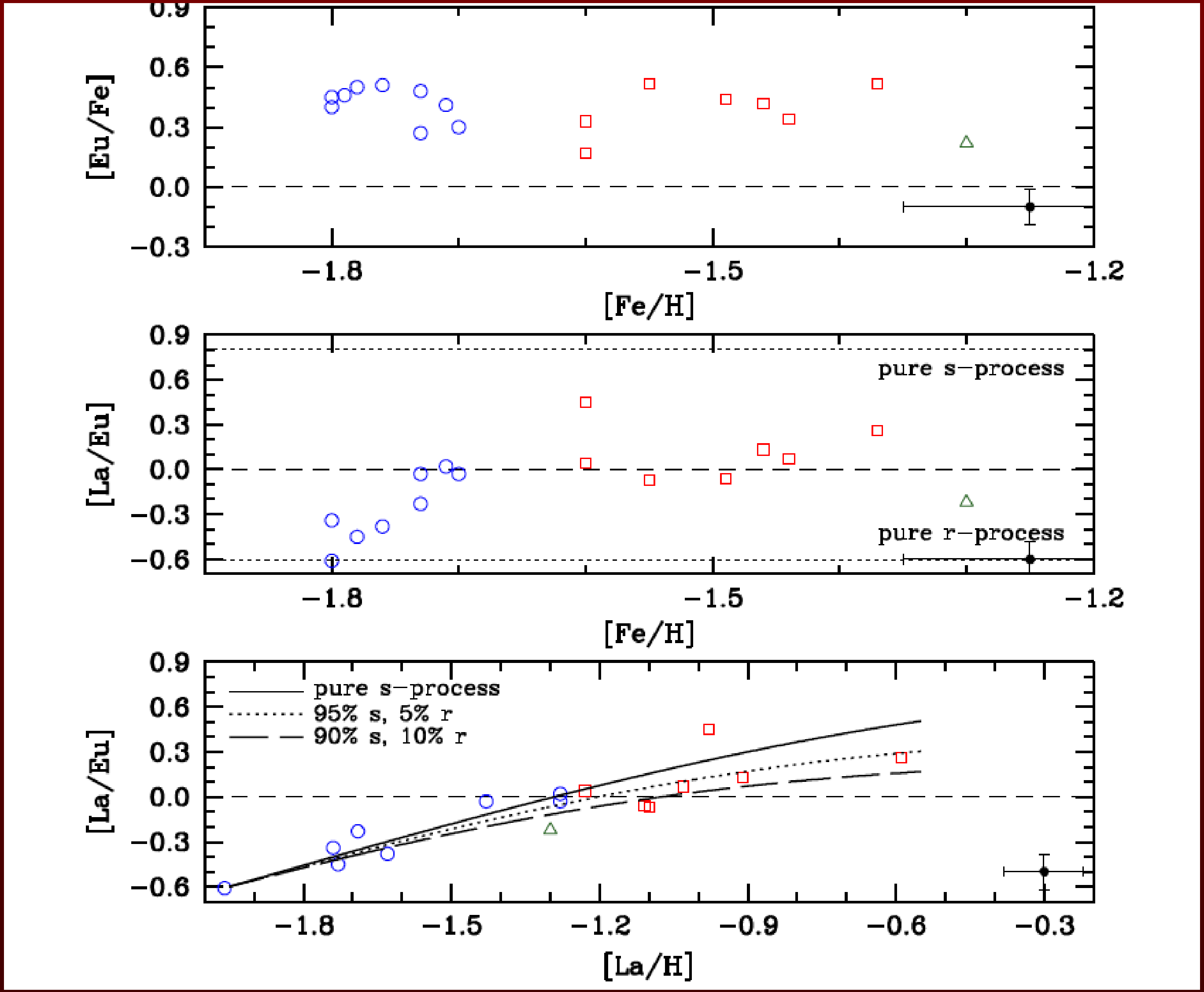


NGC 6273 has one of the largest [Fe/H] spreads



[X/Fe] dispersions by element





[Eu/Fe]
[Fe/H]
[La/Eu]
pure s−process
pure r−process
[Fe/H]
[La/Eu]
pure s−process
95% s, 5% r
90% s, 10% r
[La/H]

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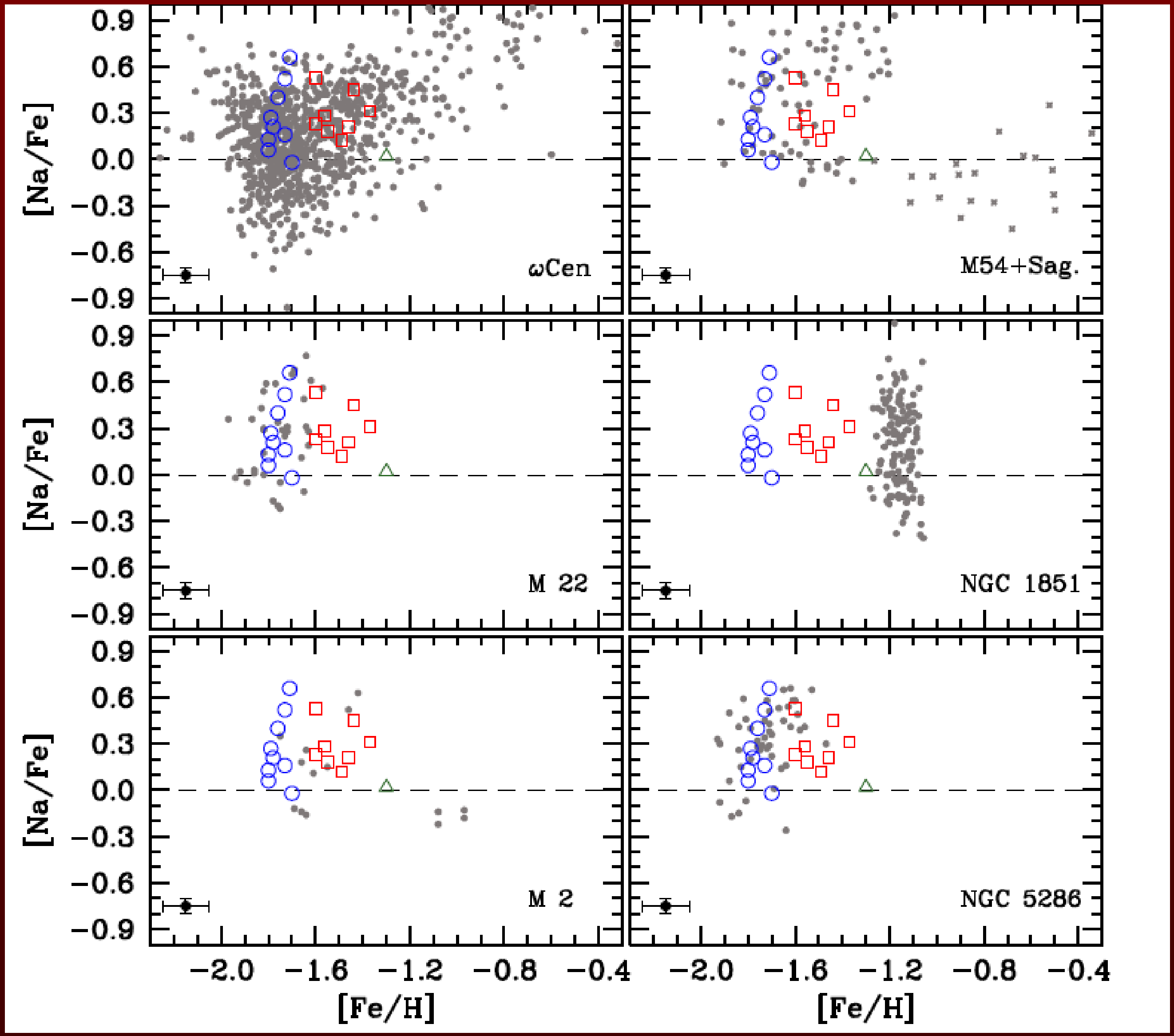

01/29/16

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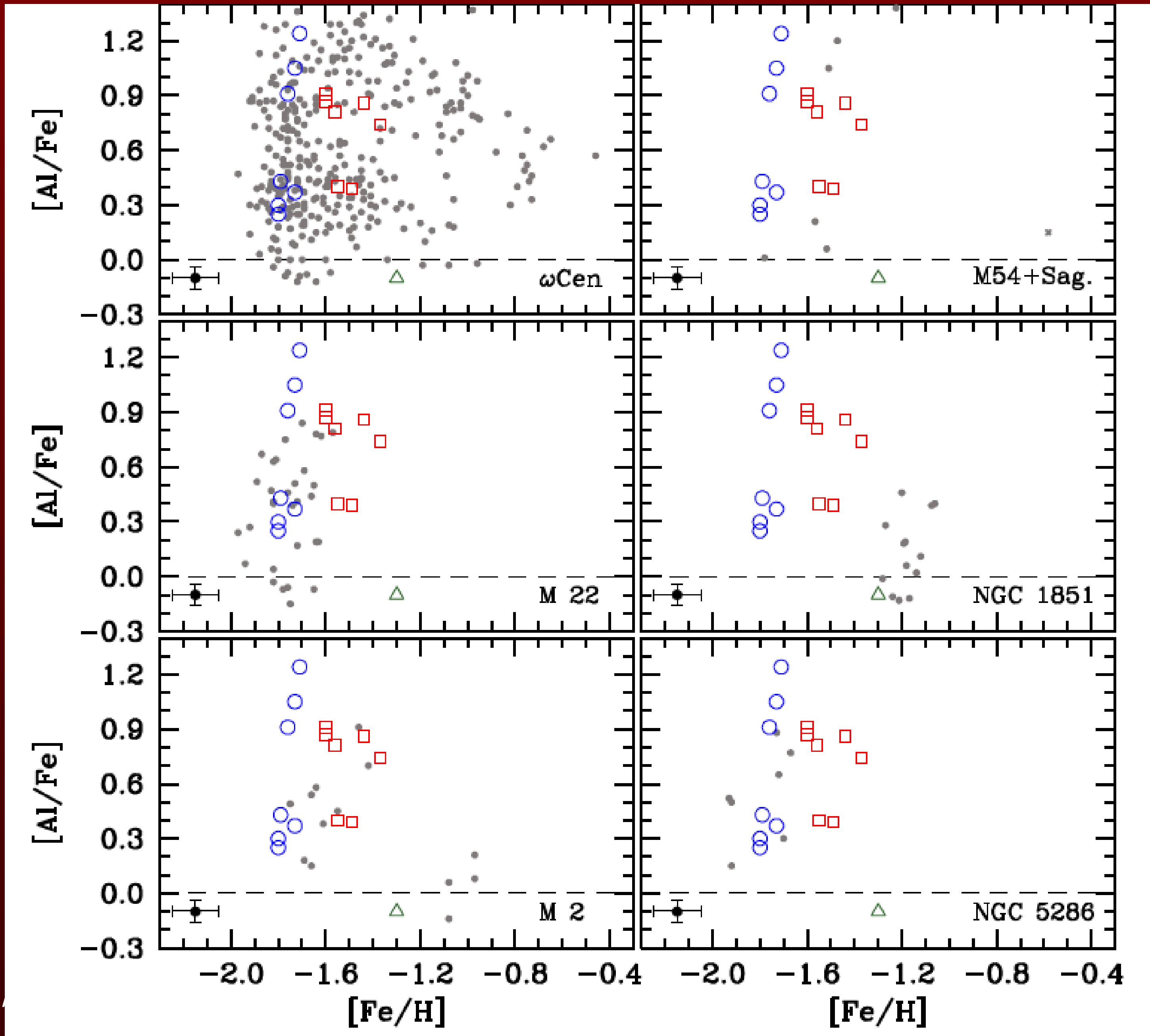
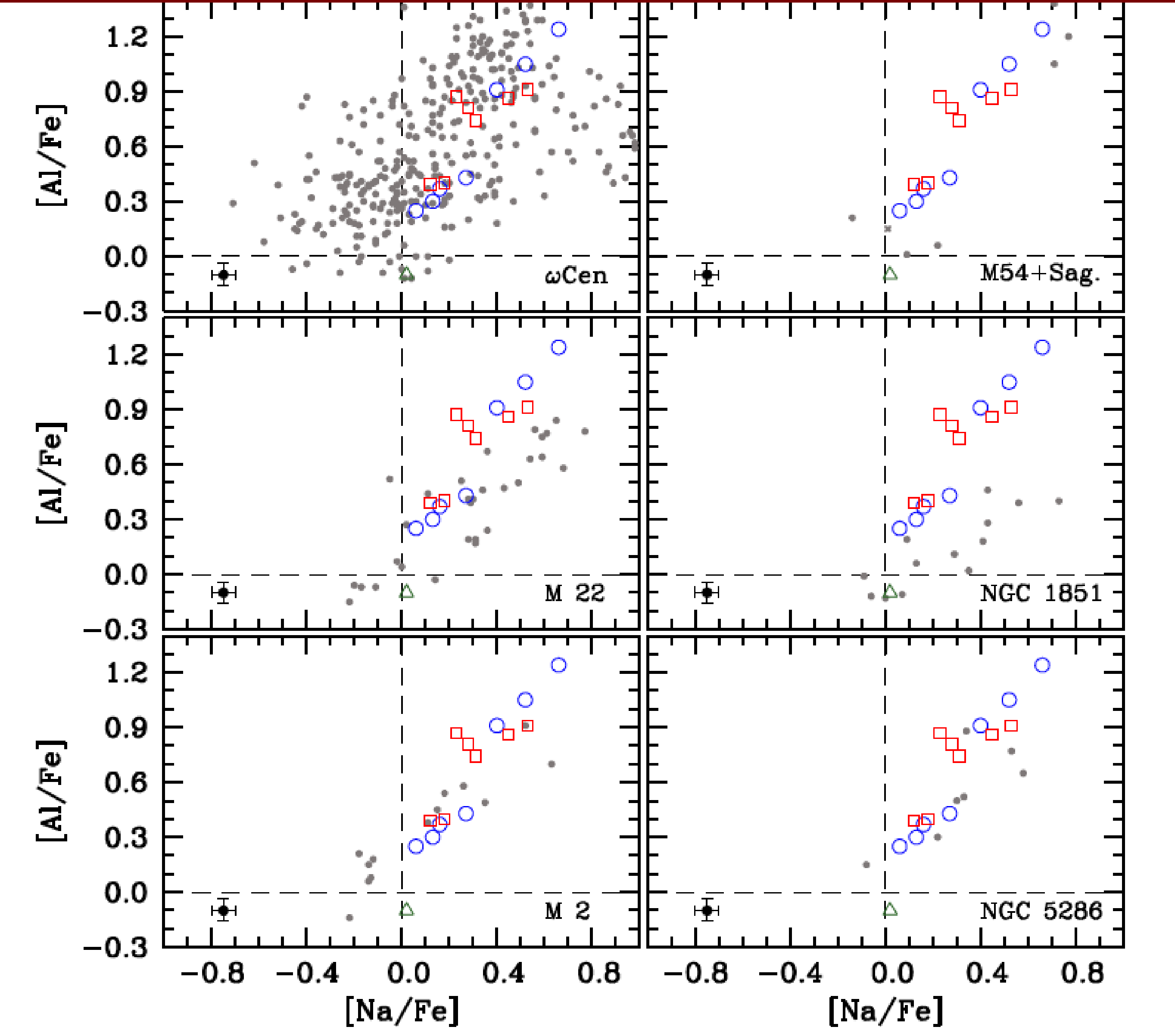

[Al/Fe]
[Al/Fe]
[Al/Fe]
ωCen
M54+Sag.
M 22
NGC 1851
M 2
NGC 5286
[Fe/H]
[Fe/H]



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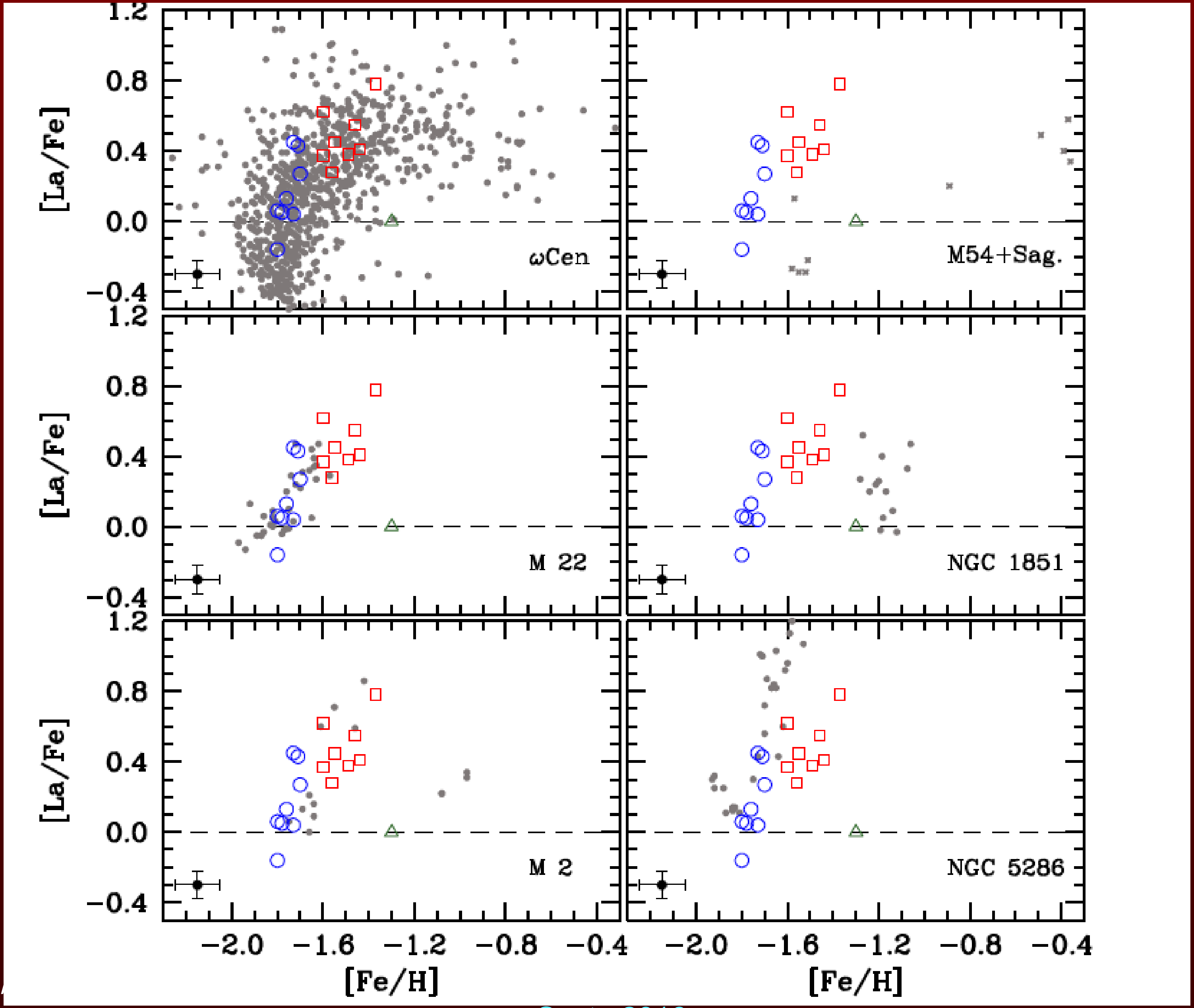
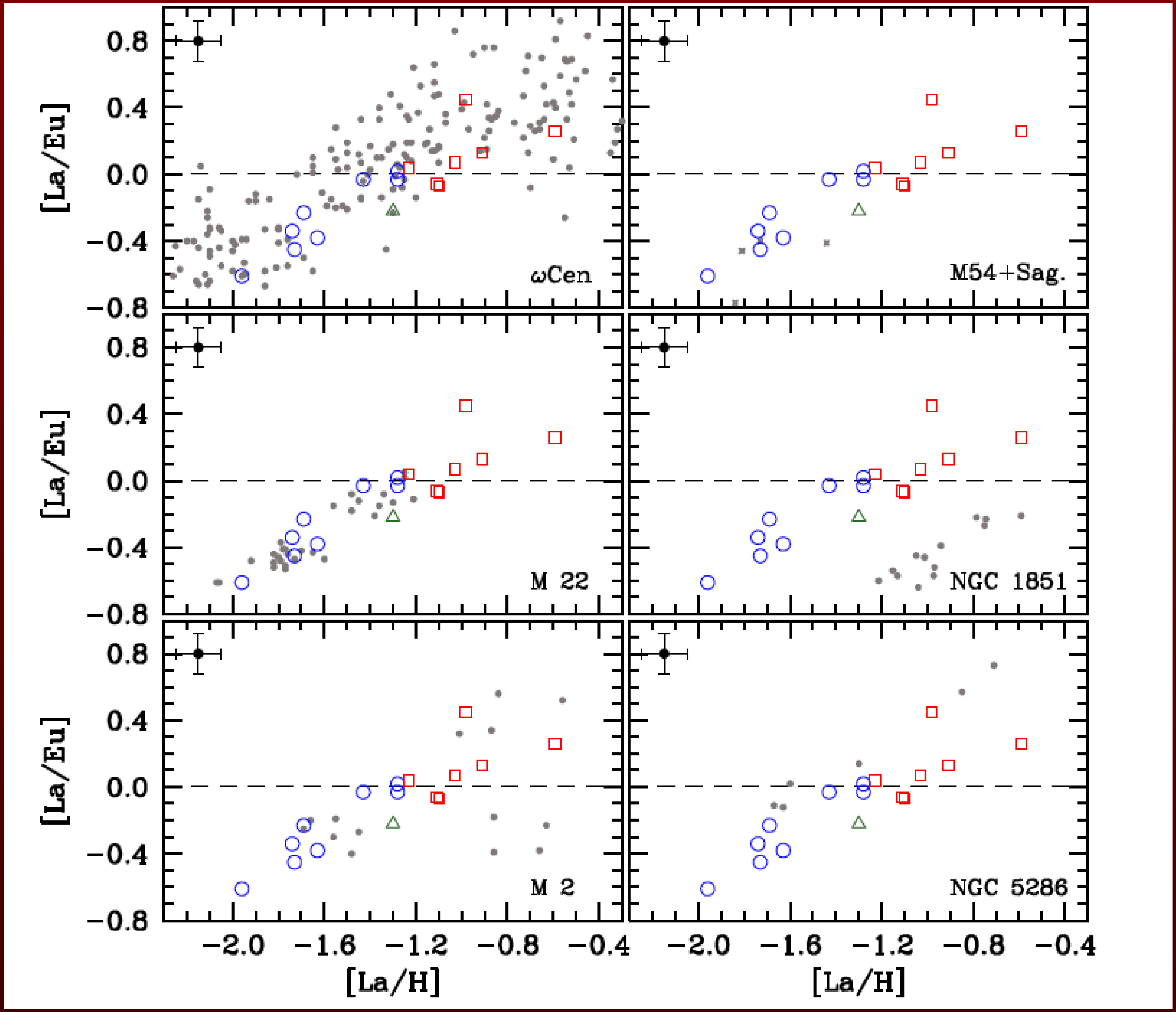

[La/Fe]
[Fe/H]
ωCen
M54+Sag.
M 22
NGC 1851
M 2
NGC 5286
1.2
0.8
0.4
0.0
−0.4
−2.0
−1.6
−1.2
−0.8
−0.4



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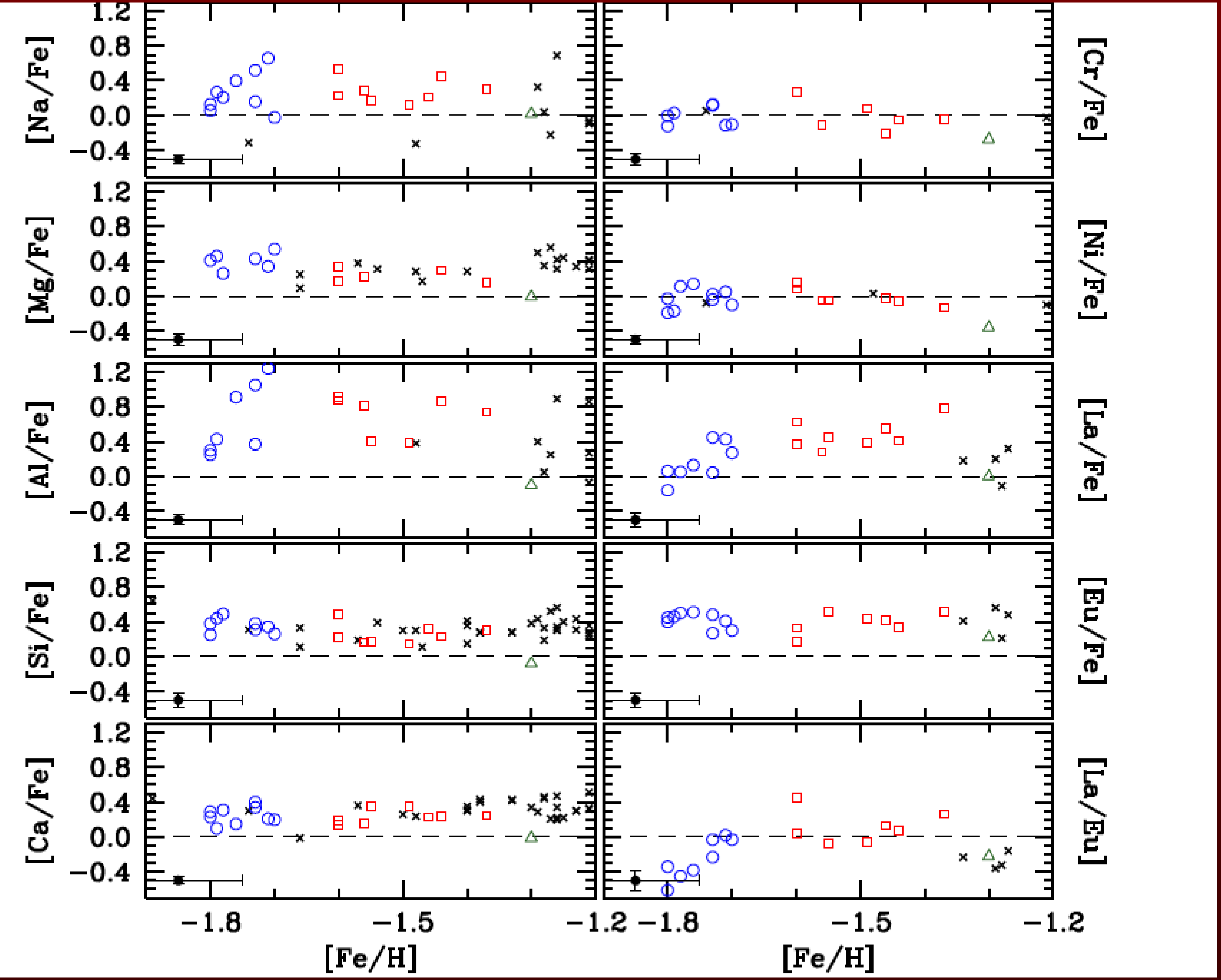
NGC 6273 vs metal poor bulge field



Both Fe-poor & Fe-rich populations show Na-Al correlation

[La/Fe] increasing with [Fe/H] as if pure s-process

Only cluster to exhibit composition and trends similar to those seen in ω Cen

HST followup studies underway to study multiple populations