



Globular cluster contributions to the assembly of the Galactic halo

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In collaboration with

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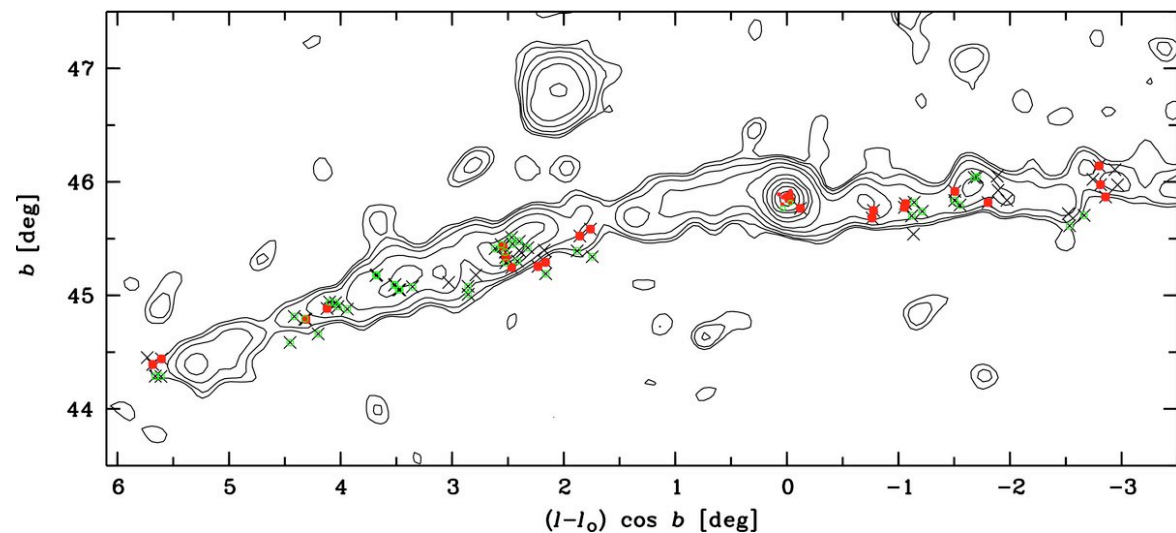
David Lai (UCSC)

Big-picture goal

- Understand the role of in situ star formation in Galactic halo construction
- "All stars form in clusters"
 - Globular clusters were a site of very strong star formation ~ 12 Gyr ago
- Clusters lose stars in several ways
 - Early: residual gas loss
 - Baumgardt et al. 2008
 - Persistent: tidal effects, 2-body interactions,...

Globular cluster dissolution in progress

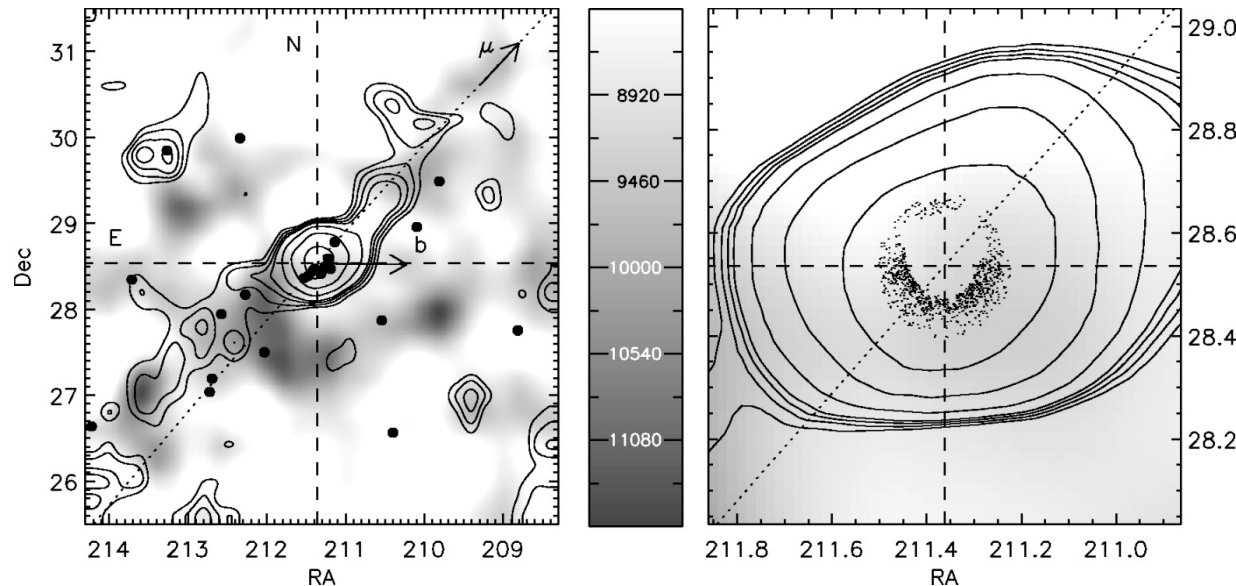
- Palomar 5
 - Known to have low density, significant mass segregation
 - Known to have CN variations
 - Smith 1985
- Large tidal tails found in SDSS star counts, matched-filter photometry
 - Odenkirchen et al 2001, Rockosi et al 2002



Odenkirchen et al. 2003

Globular cluster dissolution in progress

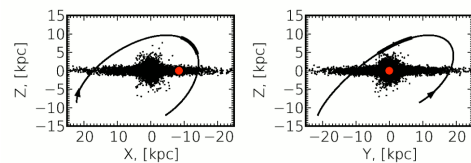
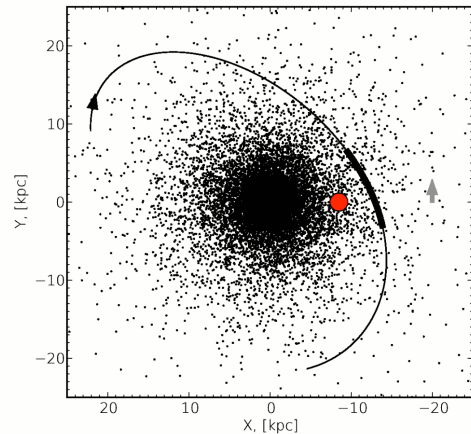
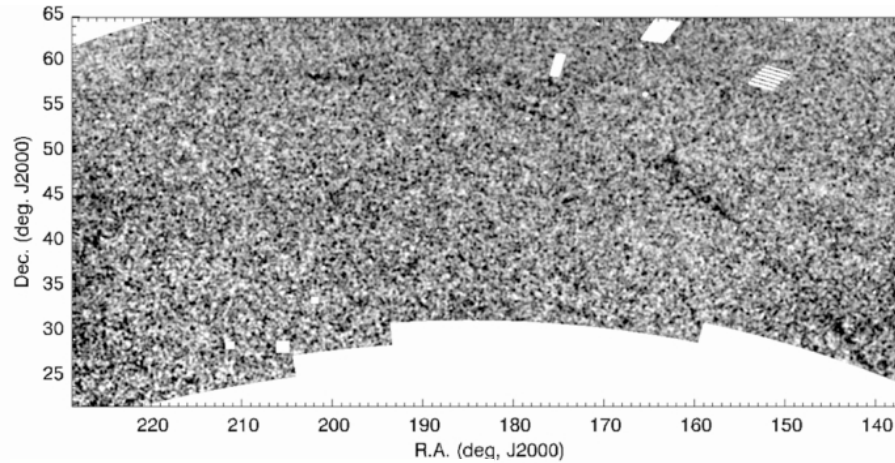
- NGC 5466
 - Low mass, relatively small r_{gc}
 - Tidal tails found through matched-filter photometry



Belokurov et al. 2006

Globular cluster dissolution in progress

Grillmair & Dionatos 2006



Koposov et al. 2010

GD-1

- Stream of stars found first through SDSS star counts
- Fairly uniform metallicity, small width: disrupted globular cluster?

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The Globular Cluster-Galaxy Connection

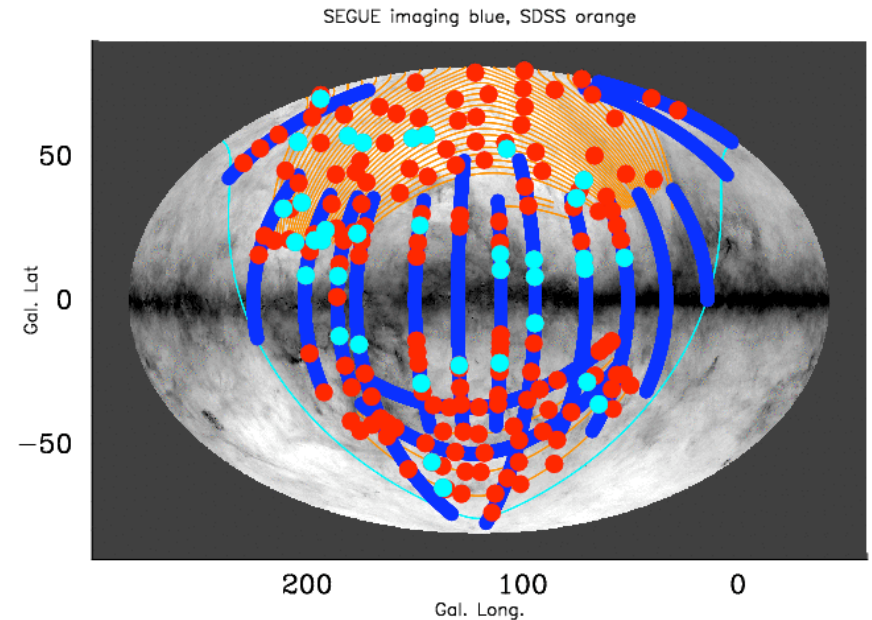


More specifically

- Identify stars in the halo that originally formed in globular clusters, using their light-element abundances

CN-strong stars in the SEGUE survey

- SEGUE-I:
Spectroscopic extension of the SDSS, targeted at specific stellar populations
 - Low-metallicity stars
 - BHB stars
 - G, K dwarfs
 - K giants
- 640-fiber spectrograph, 7 deg² field of view, R~2000, broad wavelength coverage
- 240,000 stars

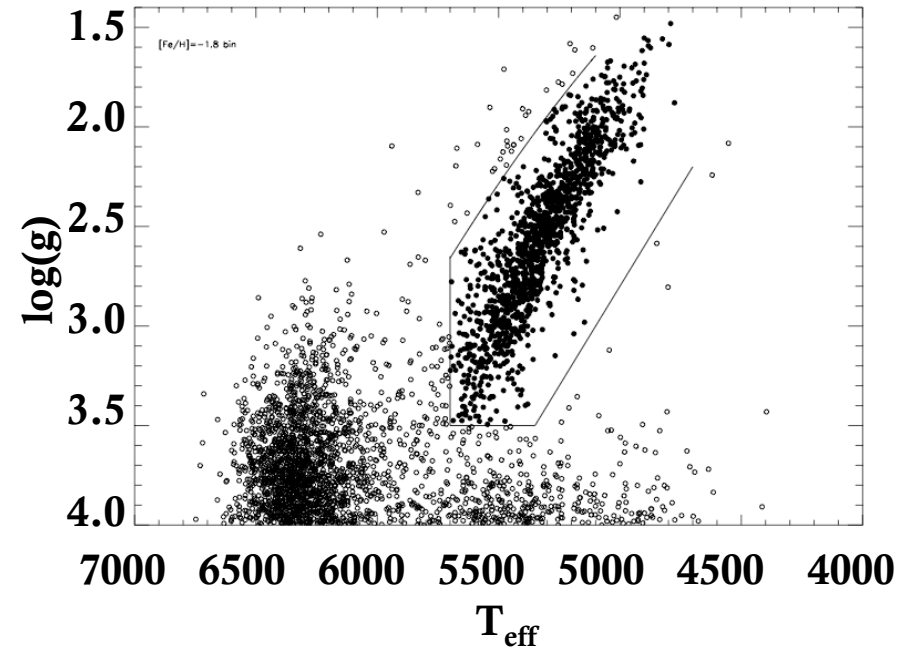


CN-strong stars in the SEGUE survey

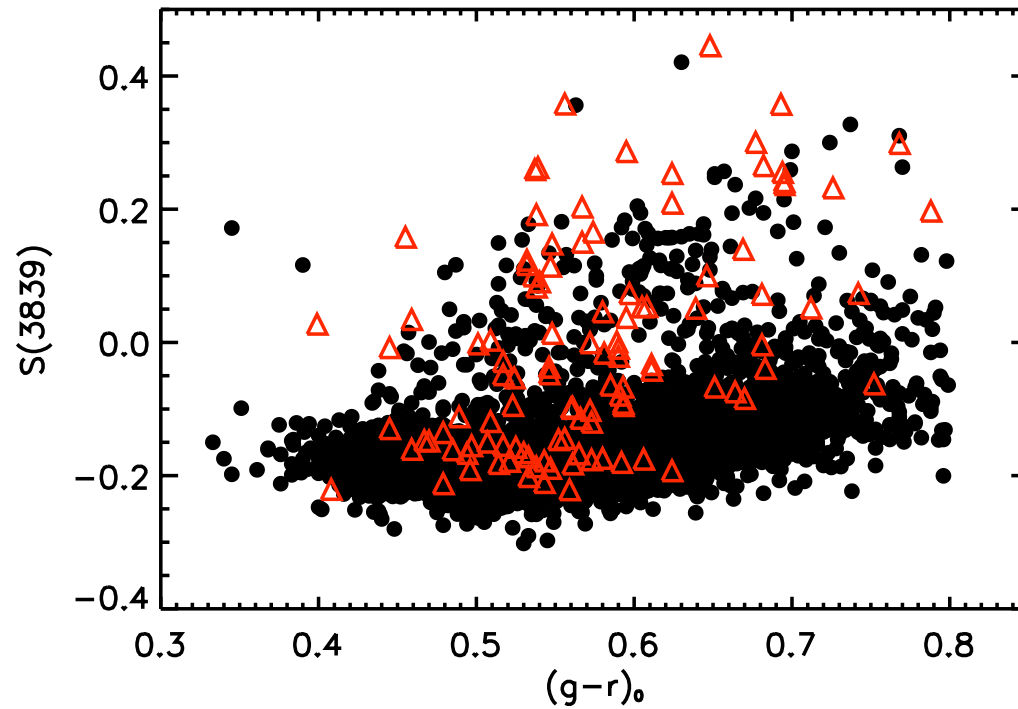
- Data accessible via online SQL query
 - Flux-calibrated spectra, photometry, stellar parameters and abundances from the SSPP (Lee et al. 2008)
- Selected a piece of parameter space:
 - $[\text{Fe}/\text{H}] < -1.0$
 - $\text{S}/\text{N} (4000\text{-}4100\text{\AA}) > 15$
 - $\log(g) < 4.0$
 - $(g-r)_0 > 0.2$
 - 22784 stars

CN-strong stars in the SEGUE survey

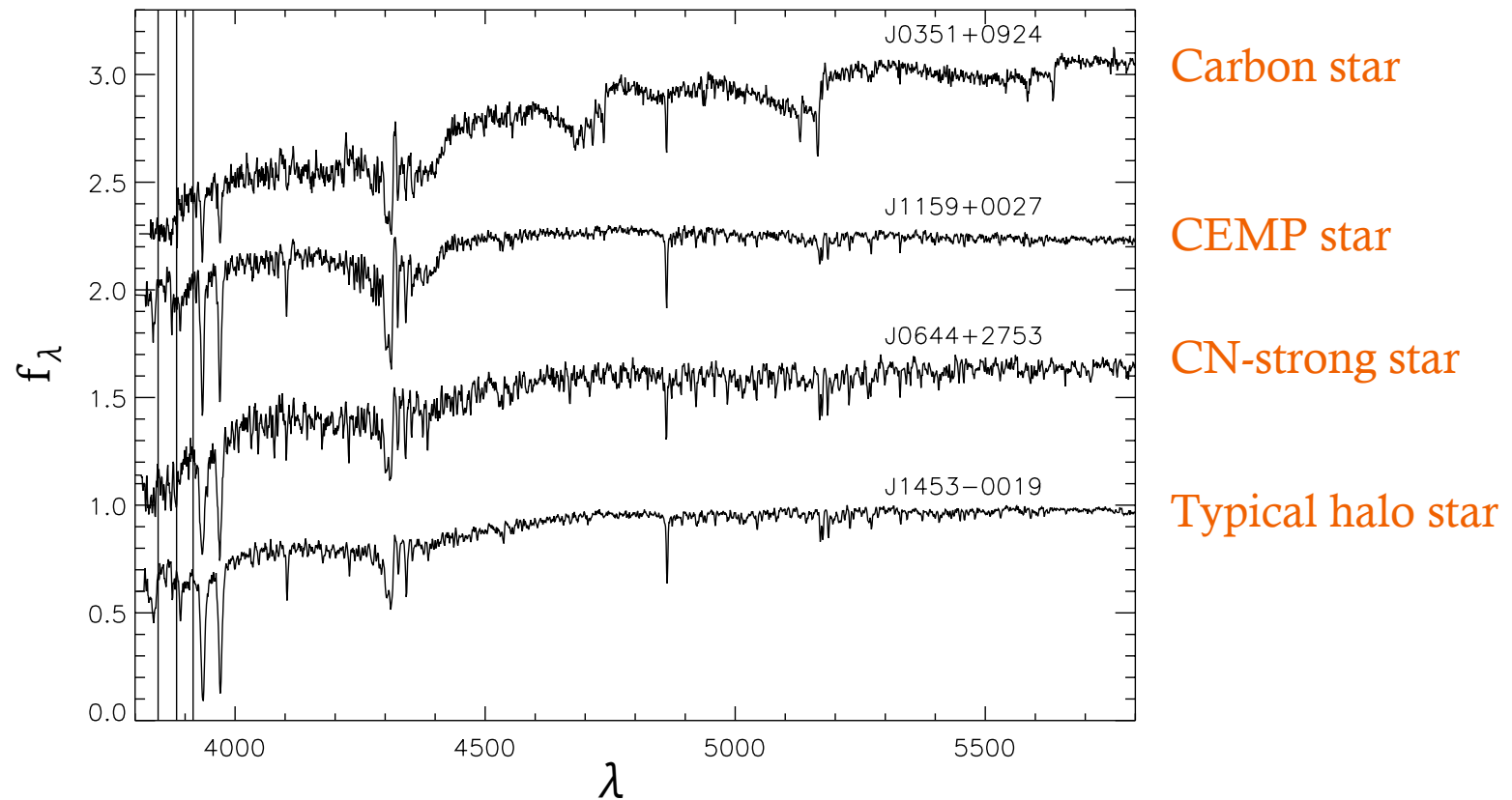
- Trim down to 5066 RGB stars
 - Divide into 0.2-dex-wide bins in $[\text{Fe}/\text{H}]$, draw fiducials, remove stars $> 3\sigma$ away
 - Lower $\log(g)$ limit
 - Remove carbon stars
- Cut further to 1958 stars
 - $-1.8 < [\text{Fe}/\text{H}] < -1.0$



CN-strong stars in the SEGUE survey

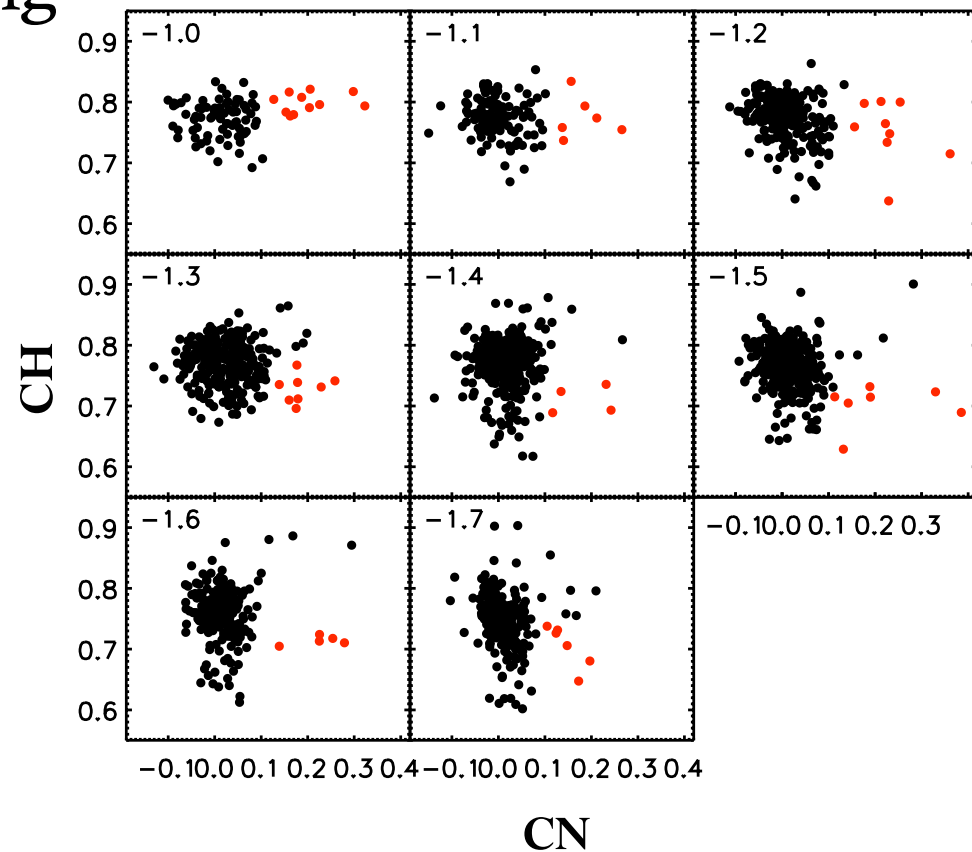


CN-strong stars in the SEGUE survey



CN-strong stars in the SEGUE survey

- Select stars with relatively strong CN, weak CH
 - 49 of 1958 (2.5%)
- Implication: GCs matter for halo formation



Martell & Grebel 2010

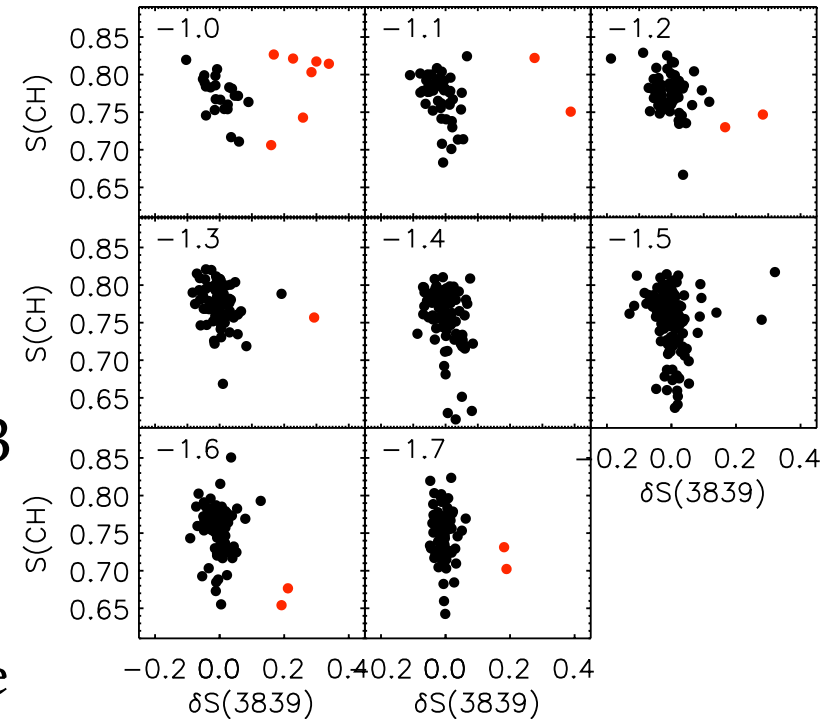


Same search, new data: SEGUE-2

- Same spectrograph, new goals
 - Fewer, more distant stars
 - More focus on the halo
 - 120,000 new spectra

Same search, new data: SEGUE-2

- Selected 2019 SEGUE-2 stars:
 - $-1.8 < [\text{Fe}/\text{H}] < -1.0$
 - mean $S/N > 20$
 - $\log(g) < 3.0$
 - $(g-r)_0 > 0.2$
- Trim down to 561 RGB stars
 - Divide into 0.2-dex-wide bins in $[\text{Fe}/\text{H}]$, draw fiducial sequence, remove stars $> 3\sigma$ away
 - Blue $S/N > 15$
 - Remove carbon stars
 - $M_V < +1.5$



- Similar result: 16 stars (3%) are CN-strong

Martell et al. 2011

Implications for halo formation

- Present-day globular clusters are 50/50 CN-strong and CN-weak
 - So for every CN-strong halo star, there must be one CN-weak star in the halo that came from the same cluster of origin
- 5% of the stellar halo (in mass) is equivalent to 100 present-day globular clusters (at $5 \times 10^5 M_{\odot}$ each)
 - Not unreasonable: Mackey & van den Bergh estimate that the present-day GC population is 2/3 of its initial number (whereas we find 3/5)

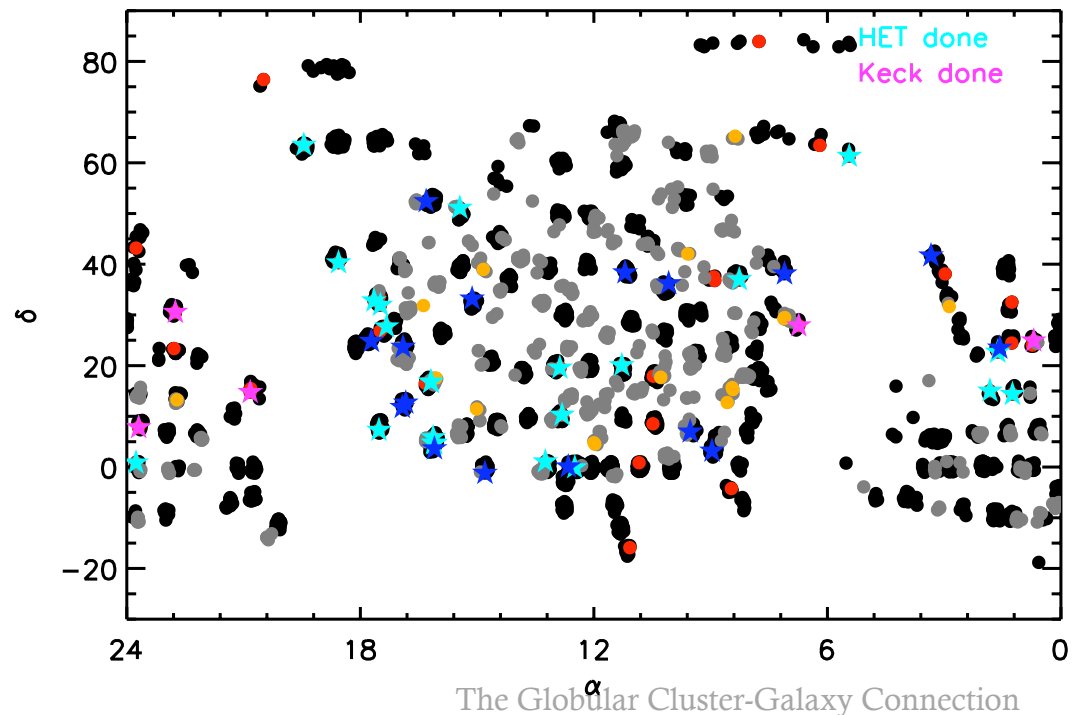


Implications for halo formation

- The 2.5% of CN-strong halo stars can be extrapolated to 17%+ of halo stars that originally formed in globular clusters
 - All of the stars from completely dissolved clusters
 - 90% of the first-generation stars from surviving clusters
 - Mainly CN-normal stars

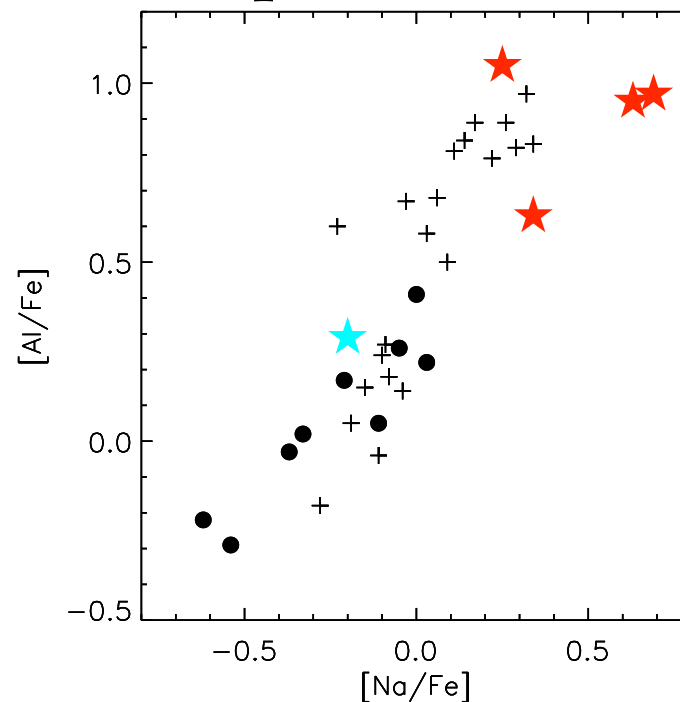
High-resolution followup

- Measuring O, Na, Mg, Al abundances to confirm that CN-strong field giants carry the full globular cluster abundance pattern



High-resolution followup

- Measuring O, Na, Mg, Al abundances to confirm that CN-strong field giants carry the full globular cluster abundance pattern
- Preliminary: 24 CN-strong stars plus 16 CN-normal "control" stars already observed at HET, plus 5 at Keck
- 5 analyzed, behave as we expect



More CN-strong field stars



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The Globular Cluster-Galaxy Connection

Anticipated Spatial Distribution Model

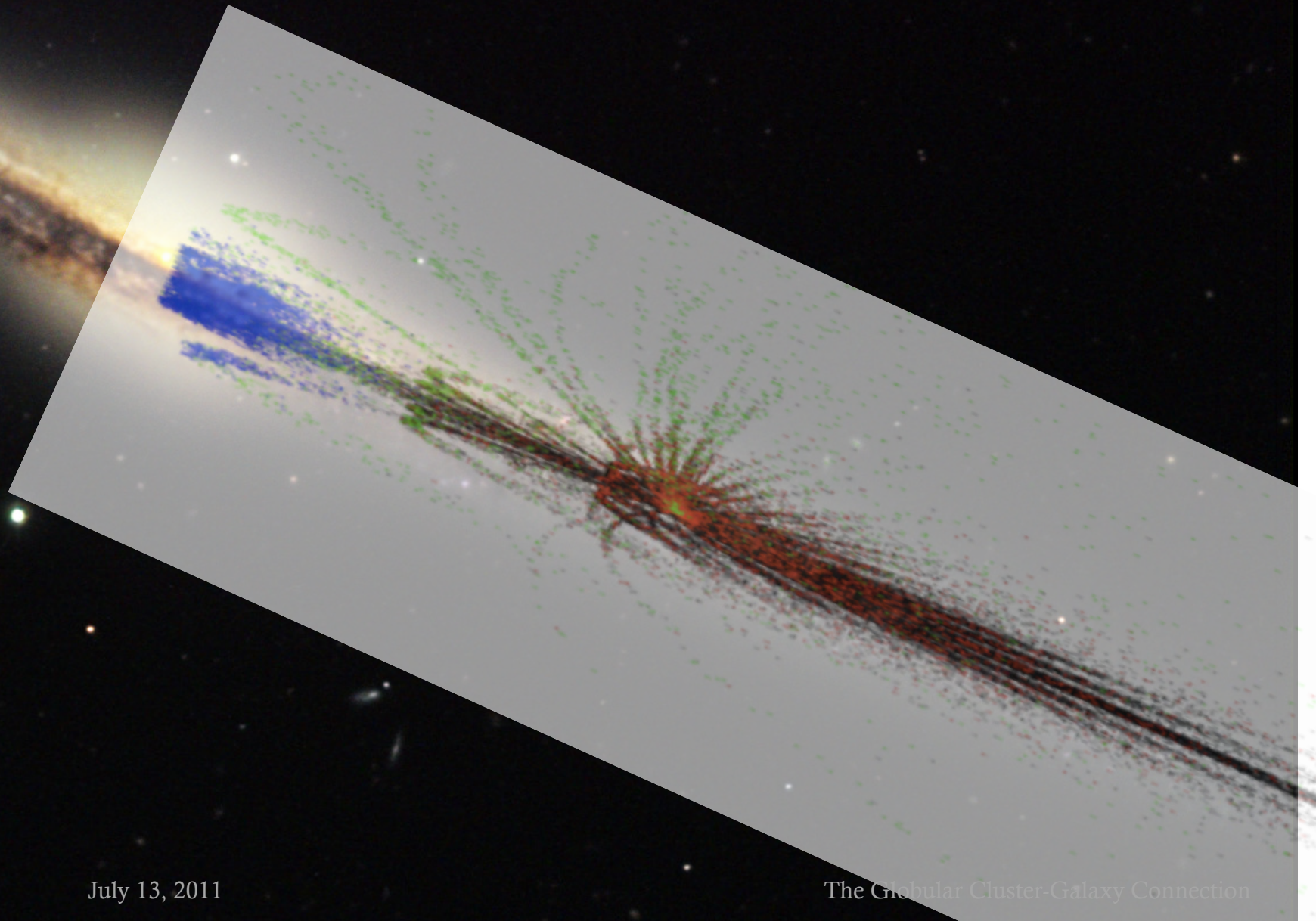
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Anticipated Spatial Distribution Model



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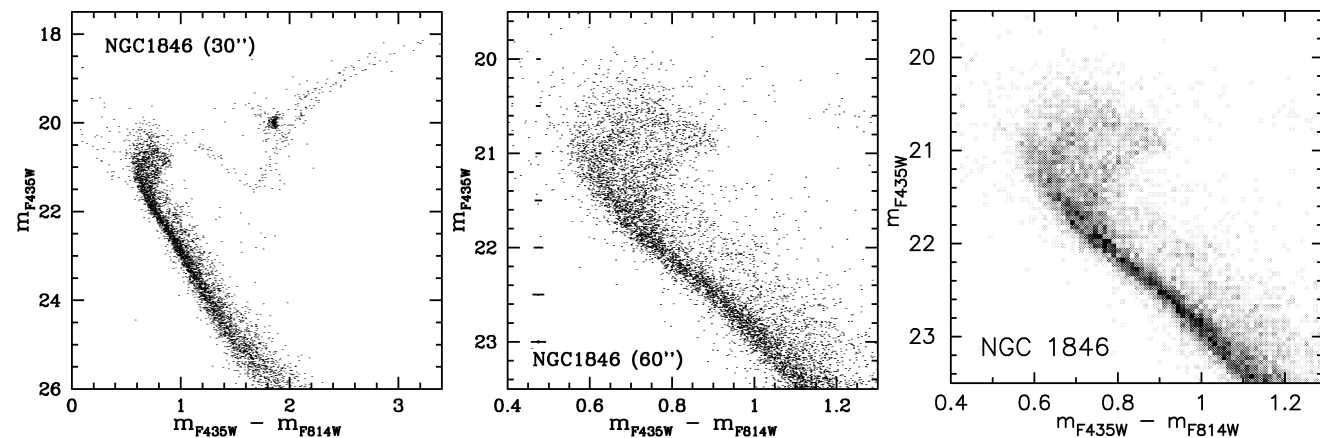
The Globular Cluster-Galaxy Connection

Next step: LMC/Sgr clusters

- Intermediate-age populous clusters
 - From high-resolution spectroscopic studies in LMC clusters: O-Na anticorrelation only in old globulars, not in intermediate-age clusters (Mucciarelli et al. 2008; 2009)
 - Caution: small sample size
 - Photometry at turn-off is broad/bimodal for several clusters: multiple populations?
 - Sgr clusters have unusual iron-peak abundances, few light-element abundance studies in literature

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Mackey et al. 2008

Next step: LMC clusters + Ter 7

- Take low-resolution (VLT/FORS2) spectra of 20-30 RGB stars per cluster
- Look for CN-CH anticorrelation
- Look at effects of large-scale environment on cluster self-enrichment

