Abundance Trends in the Milky Way Disk as Observed by the SEGUE Survey:

Constraints on thick disk formation and other galaxy-shaping processes

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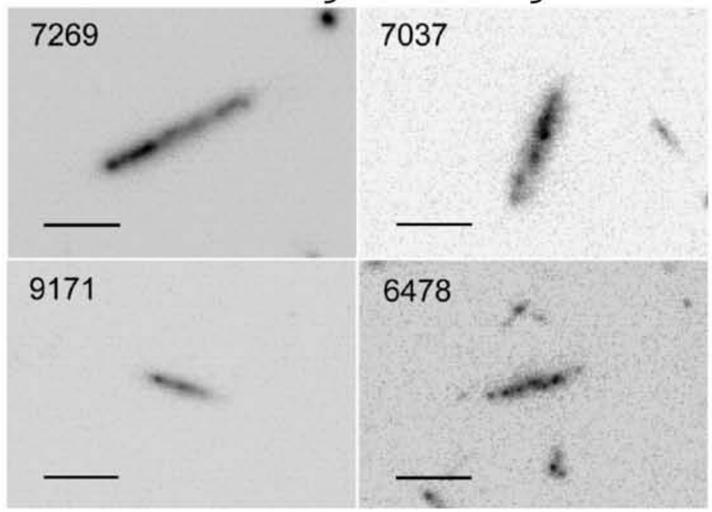
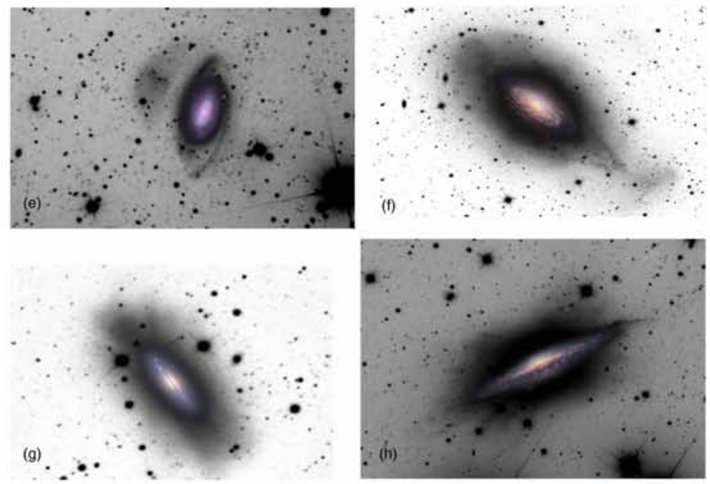
What processes shape the formation and evolution of galactic disks?

- High gas accretion at early times leads to turbulent clumpy disks (Elmegreen & Elmegreen 2005, 2006, Dekel et al. 2009)
- Minor mergers are common (Stewart et al. 2008, Martinez-Delgado et al. 2010)
- Stars can change their orbits through resonant radial migration processes (Sellwood & Binney 2002, Roskar et al. 2008, Schönrich & Binney 2009, Minchev et al. 2011)

Elmegreen & Elmegreen 2006



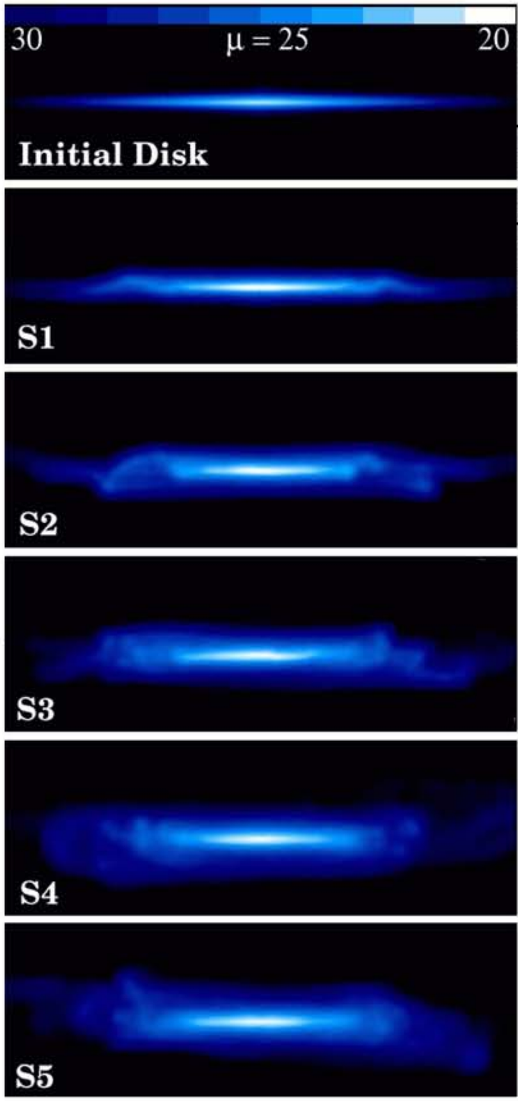


Martinez-Delgado et al. 2010

These mechanisms have been proposed to explain the Milky Way thick disk

- Heating by molecular clouds and other density perturbations cannot explain the observed thickness (Jenkins 1992)
  - Stars formed *in situ* in turbulent gas clumps (Brook et al. 2005, Bournaud et al. 2009)
  - Minor mergers directly deposited stars in a thick disk (Abadi et al. 2003)
  - Minor mergers puffed up an existing thin disk (Kazantzidis et al. 2008, Bird et al. 2011)
  - Radial migration thickened an existing thin disk (Schönrich et al. 2009, Loebman et al. 2011)

- We can use observations of the thick disk to constrain the relative importance of these mechanisms in shaping the Milky Way disk

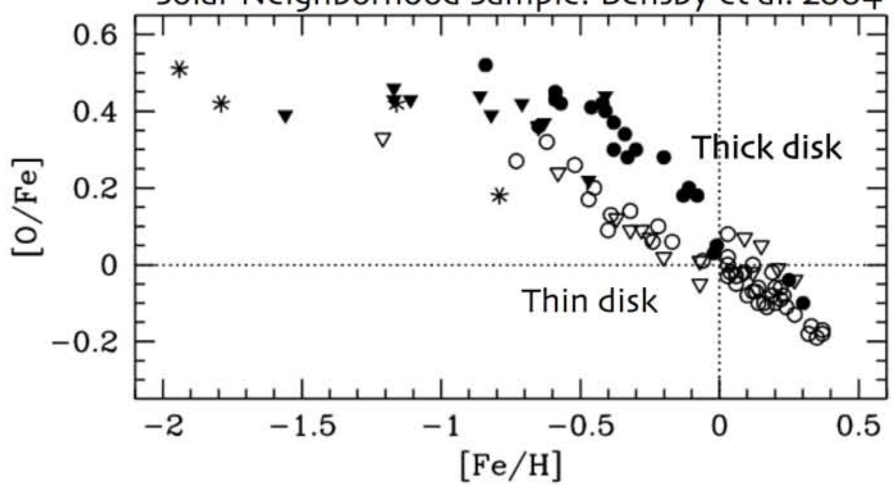


Kazantzidis et al. 2008

Thick disks are old and ubiquitous

- Thick disk stars are older than ~8 Gyr (Bensby et al. 2004) and serve as a "fossil record" of the early formation of the Galaxy
- Thick disks in external galaxies have similar properties and are likely to be a generic feature of disk galaxies (Dalcanton & Bernstein 2002, Yoachim & Dalcanton 2005, 2006, 2008)
- Kinematics and chemistry
  - Lag in rotation by 20-50 km/s (Chiba & Beers 2000, Soubiran et al. 2003)
  - Metal-poor [Fe/H] ~ -0.5 (Gilmore et al. 1995)
  - α-enhanced, consistent with rapid star formation history (Bensby et al. 2003, 2005)

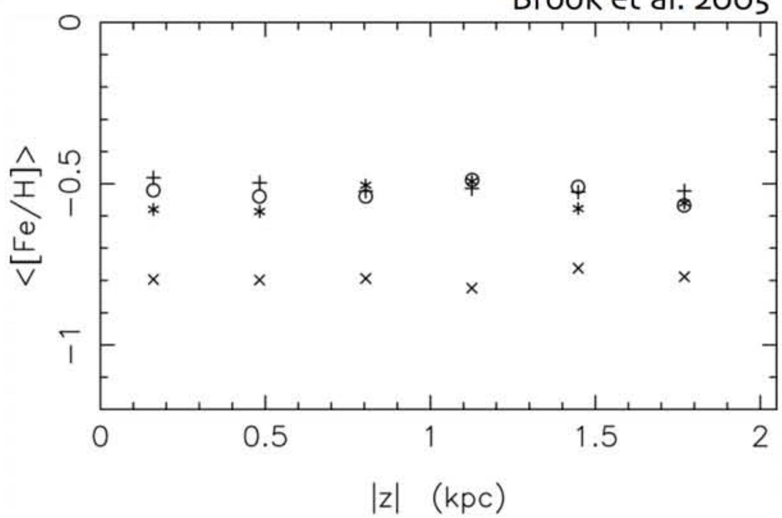
Solar Neighborhood Sample: Bensby et al. 2004



Abundance trends in the thick disk provide hints about its formation

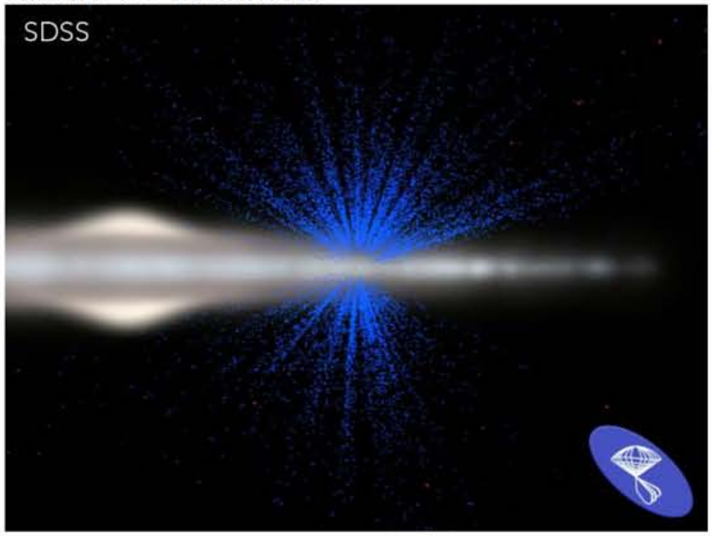
- The presence or lack of abundance gradients can constrain formation scenarios
- A thick disk that formed rapidly at early times will be chemically homogeneous, with no gradient (Brook et al. 2004, 2005)
- A thick disk that forms from an initially thin disk will have no gradient only if radial mixing processes are efficient
  - Disk heating through minor merger (Kazantzidis et al. 2008, 2009, Bird et al. 2011)
  - Resonances with transient spiral arms (Roskar et al. 2008, Schönrich & Binney 2009)

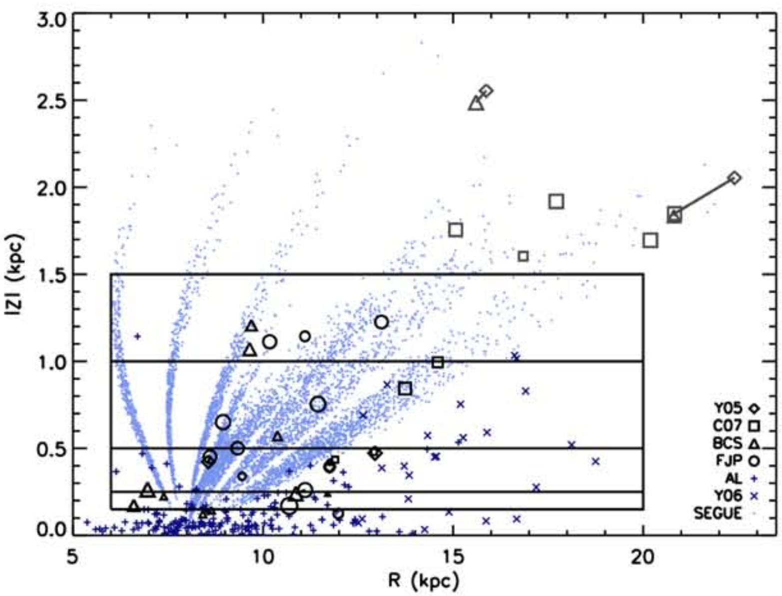
Brook et al. 2005



SEGUE Low Latitude Sample

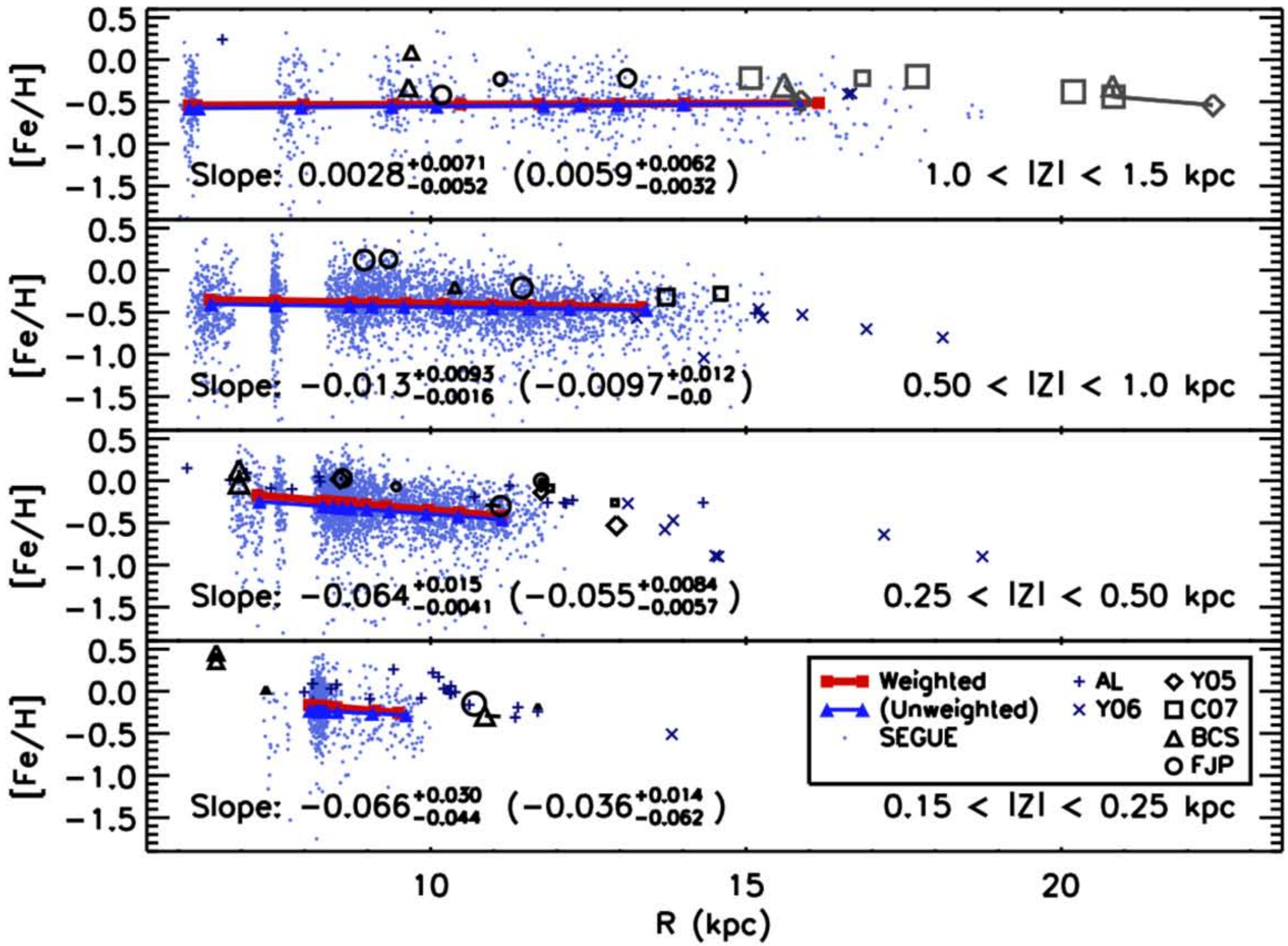
Credit: M. Steinmetz





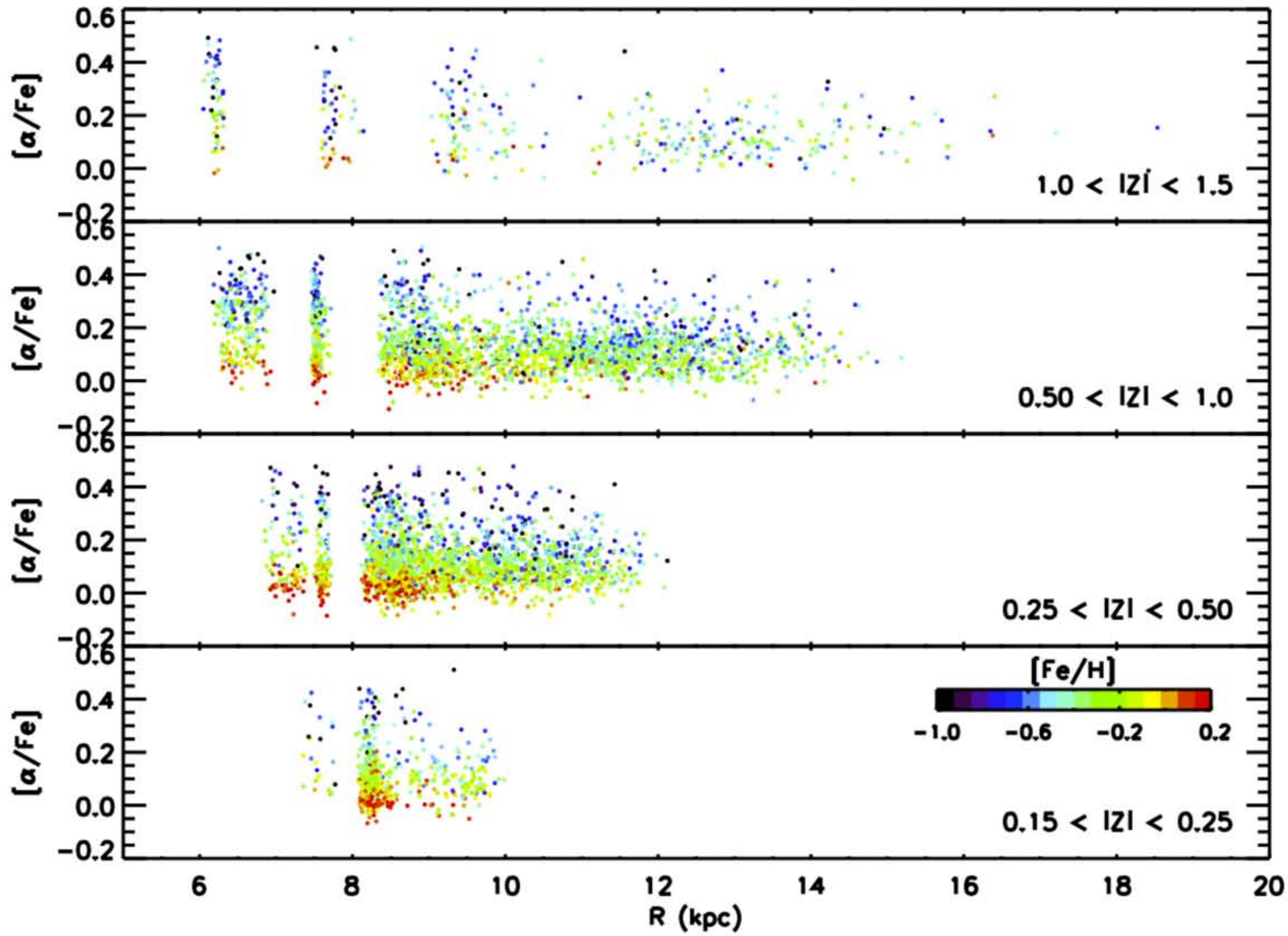
- SEGUE: Sloan Extension for Galactic Understanding and Exploration (Yanny et al. 2009)
  - 360,000 medium resolution (R ~ 2000) spectra of Milky Way stars
  - Large, uniform sample
- ~7000 main sequence turnoff stars
  - 8 < |b| < 16° (low Galactic latitude)
  - 5000 < Teff < 7000 K
  - 6 < R < 16 kpc, 0.15 < |Z| < 1.5 kpc
  - [Fe/H], [α/Fe] from SEGUE Stellar Parameter Pipeline (Lee et al. 2008, 2011)
- Divide sample into bins in R and |Z|, look at trends in [Fe/H] and [α/Fe]

The radial gradient in [Fe/H] becomes flat with increasing |Z|



- → Flat gradient at |Z| > 1.0 kpc
- → Consistent with chemically homogeneous thick disk, as predicted by *in situ* star formation during turbulent clumpy phase
- → Could also indicate that radial mixing processes are strong

Unlike [Fe/H], trends in [α/Fe] are inconsistent with chemical homogeneity



- → Most α-enhanced stars are confined to small radii (R < 10 kpc)
- → Our data are consistent with a short scale length for the high-α population

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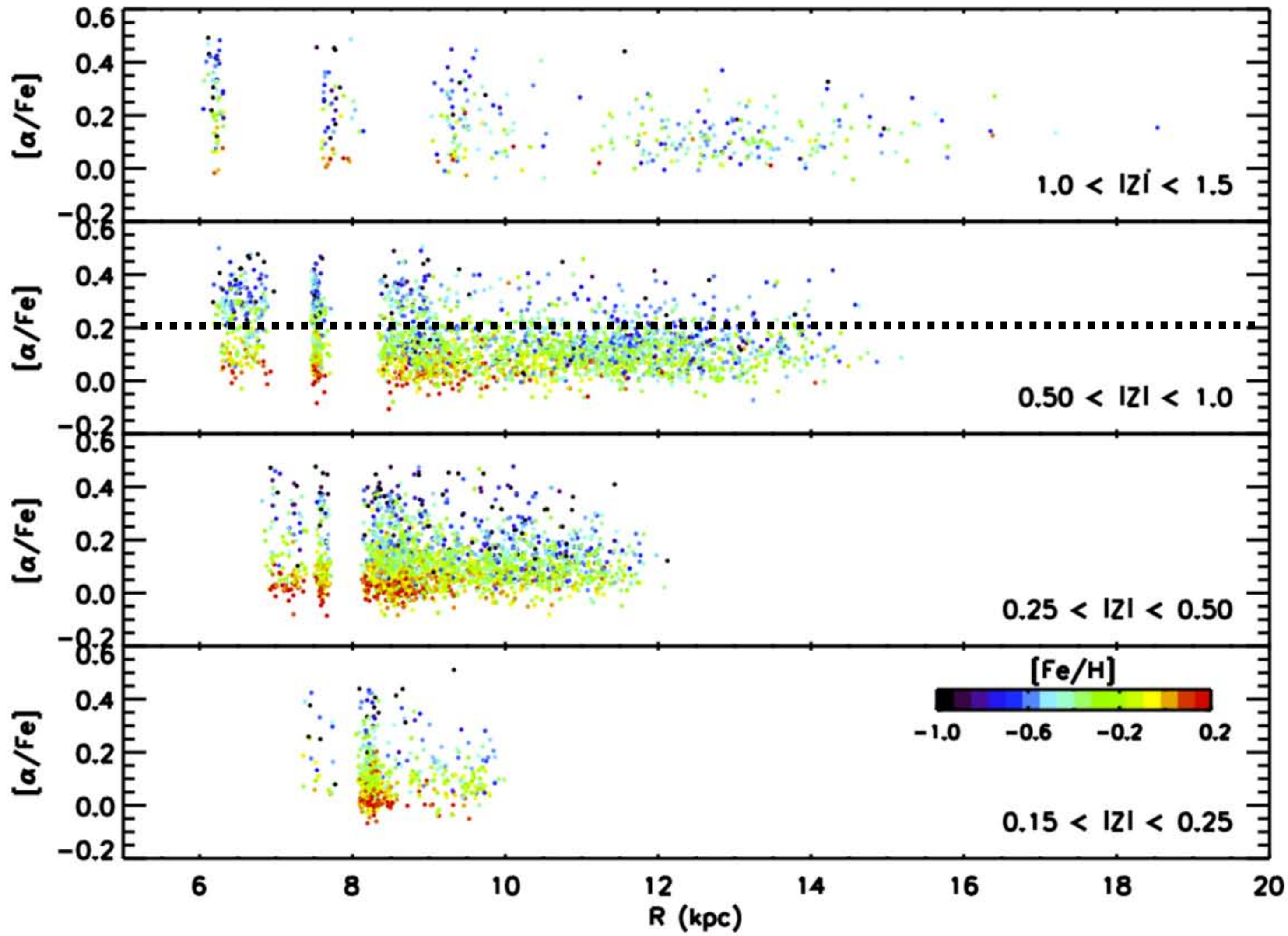

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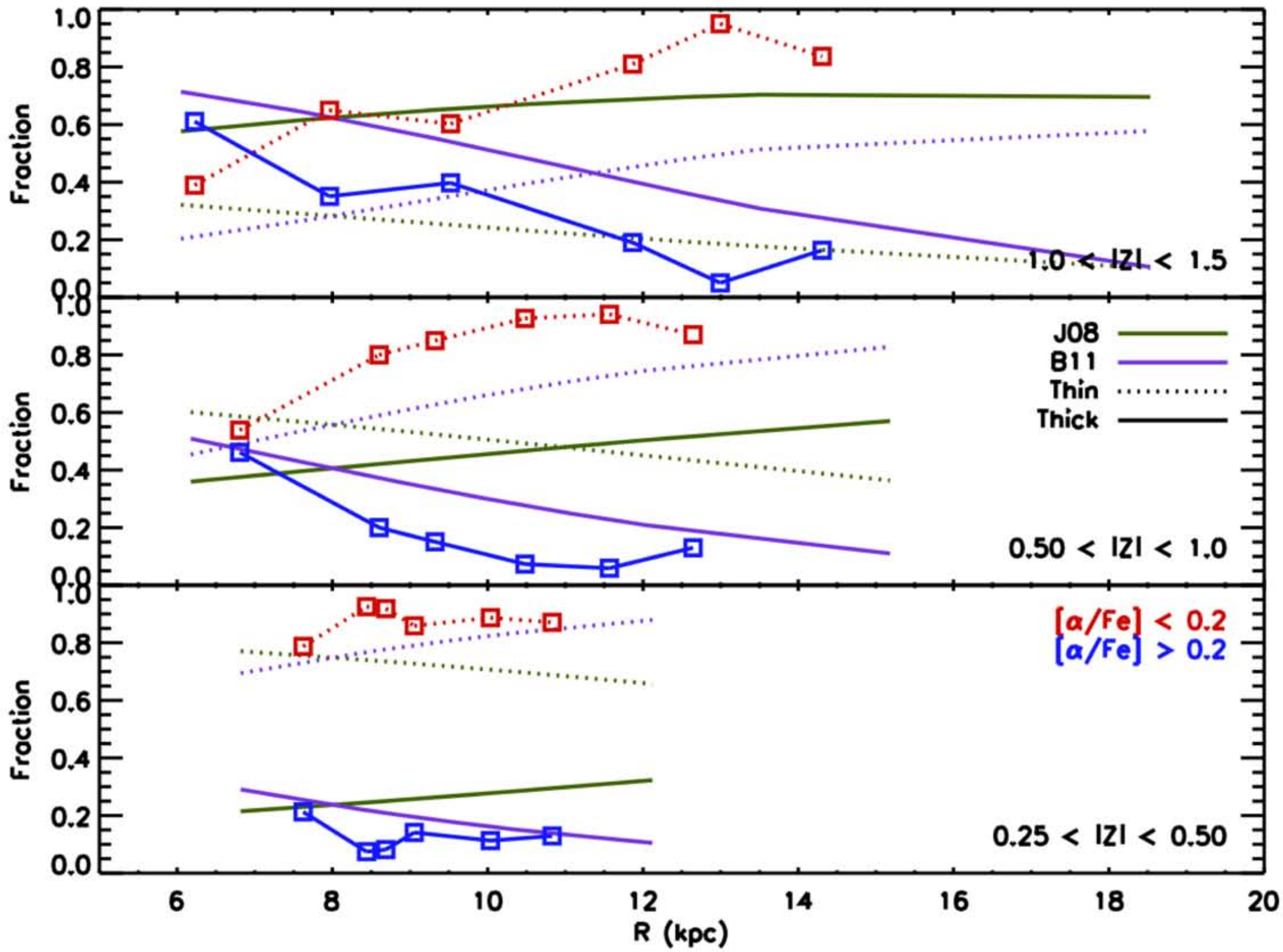
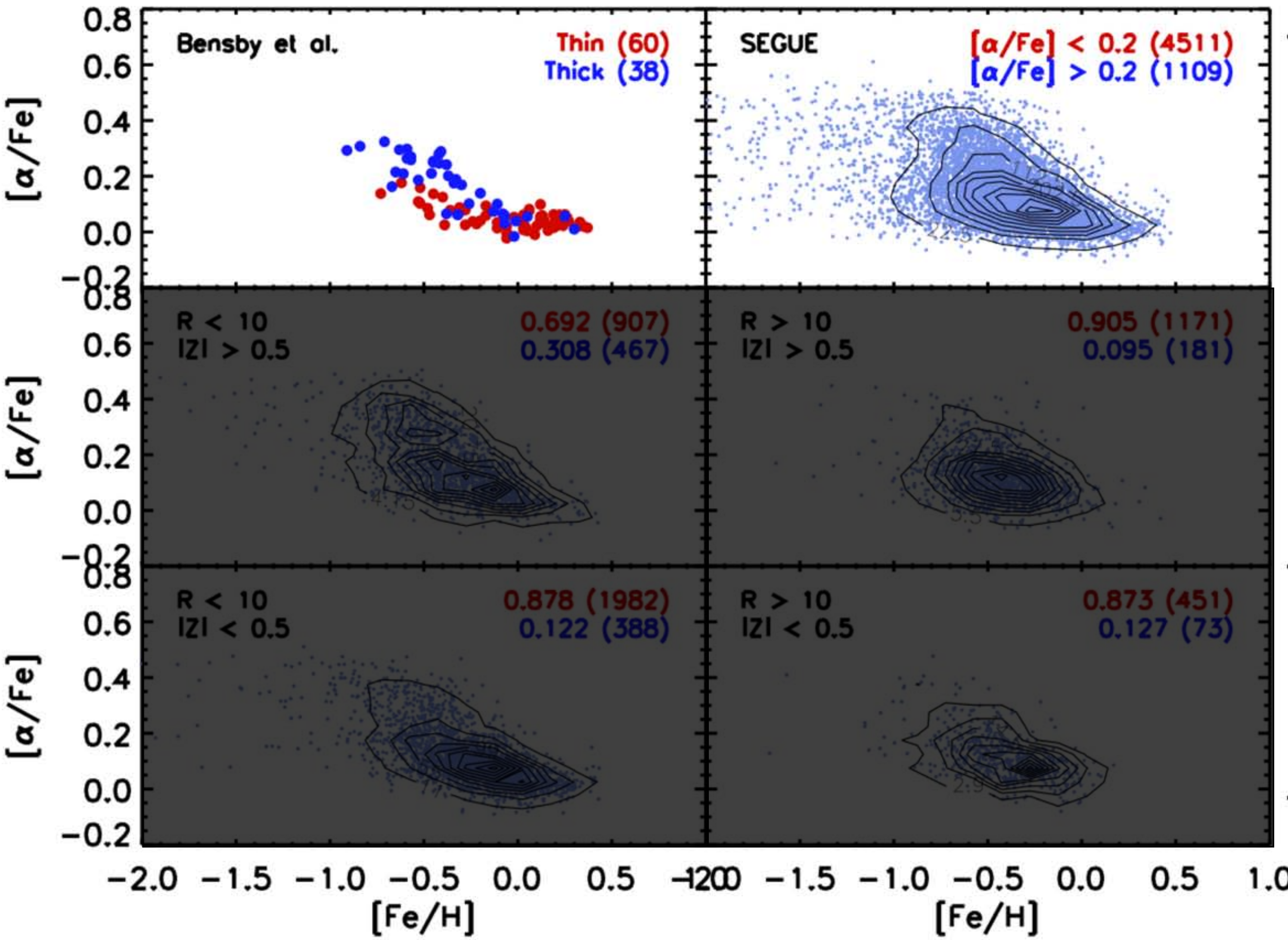


- → Juric et al.
  - ··· L_{thin}=2.6 kpc
  - — L_{thick}=3.6 kpc
- → Bensby et al.
  - ··· L_{thin}=3.8 kpc
  - — L_{thick}=2.0 kpc
- → The inner and outer disks show different vertical abundance trends and kinematic properties

The inner and outer disk show different vertical trends in [α/Fe] vs. [Fe/H]



→ From observations of nearby stars, we expect the fraction of high-α stars to increase as the thick disk becomes the dominant population at large |Z|

→ At small R, the fraction of high-α stars increases at large |Z|

→ At large R, the fraction of high-α stars is low at all |Z|

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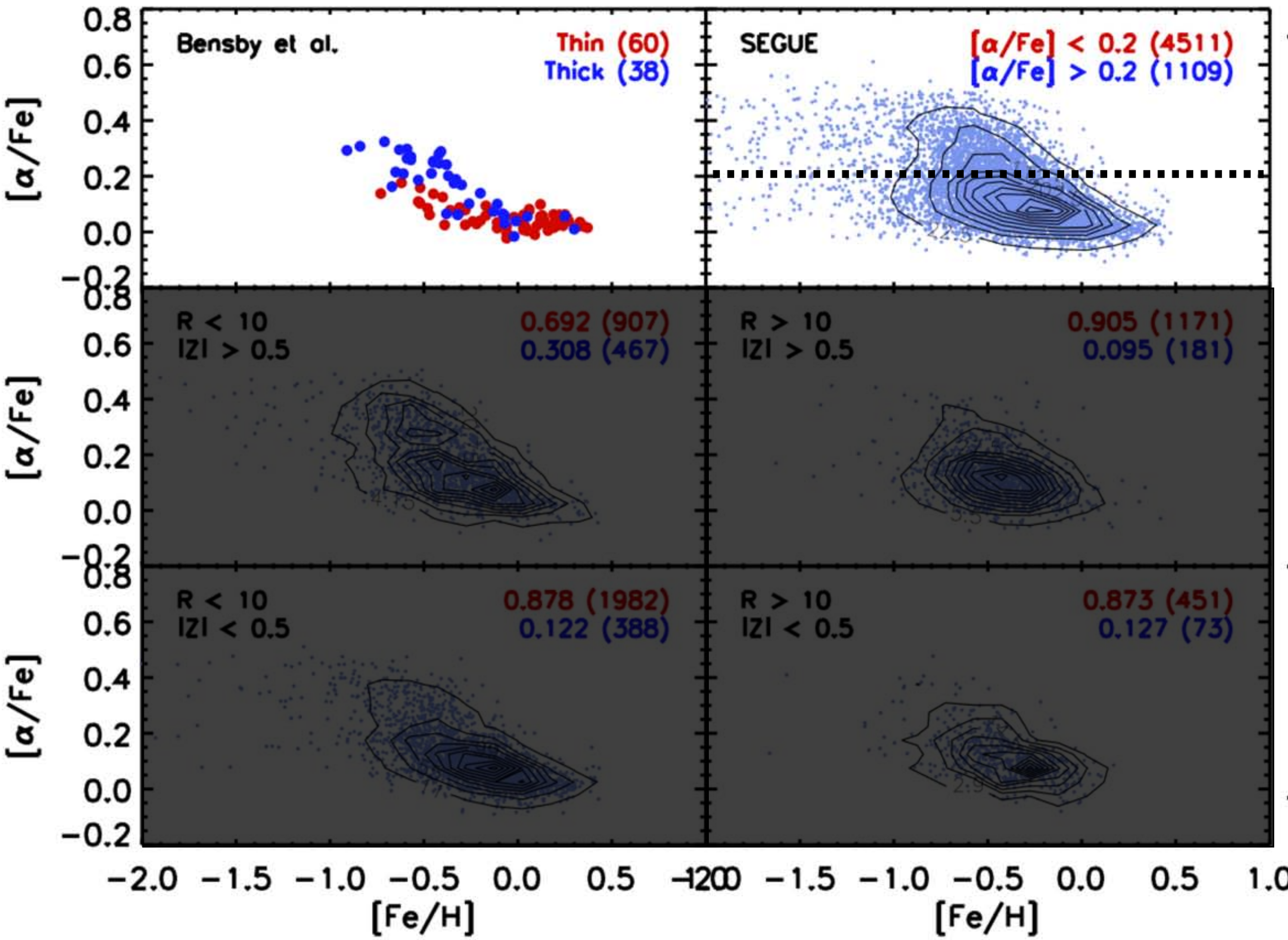

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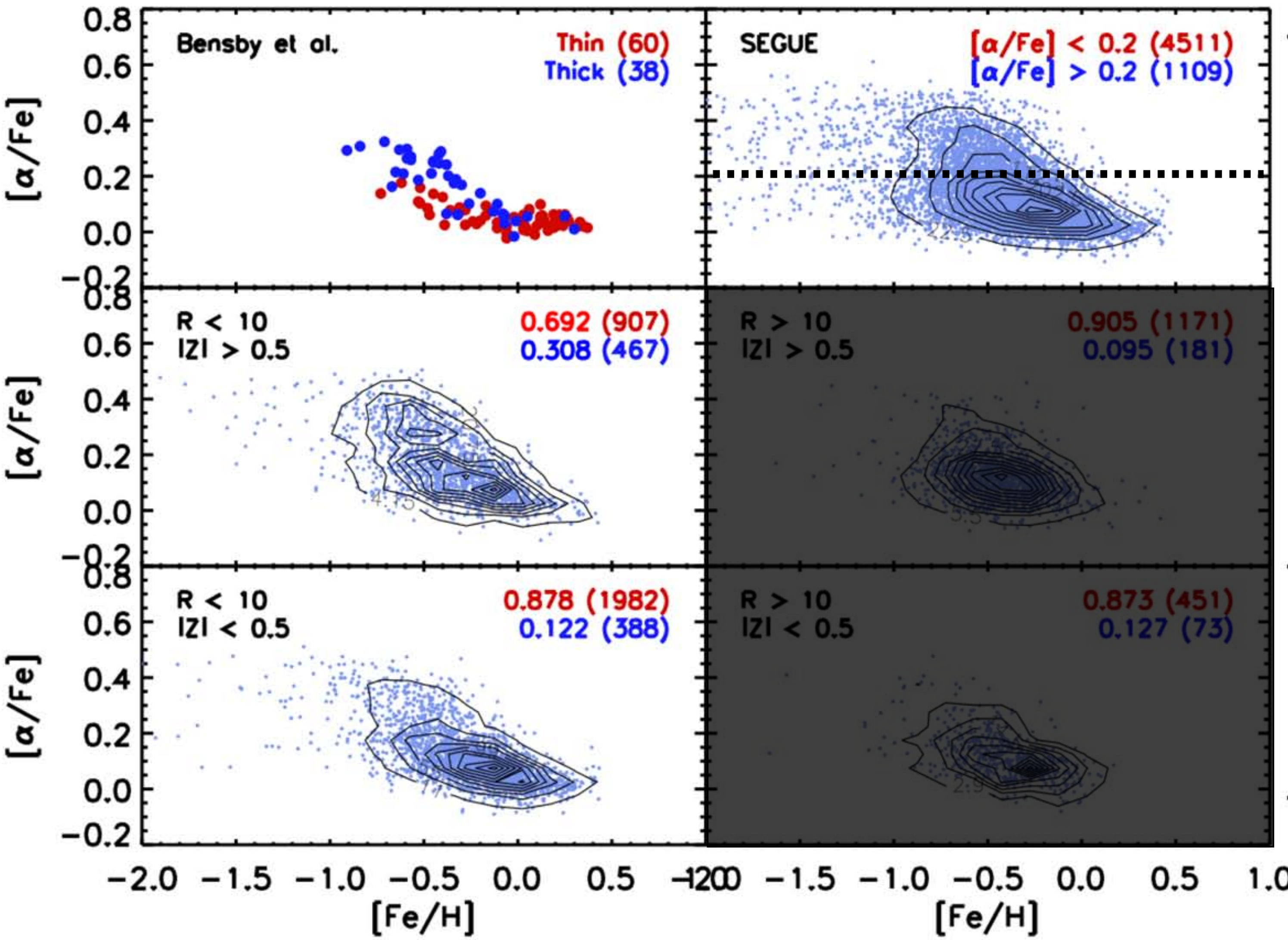

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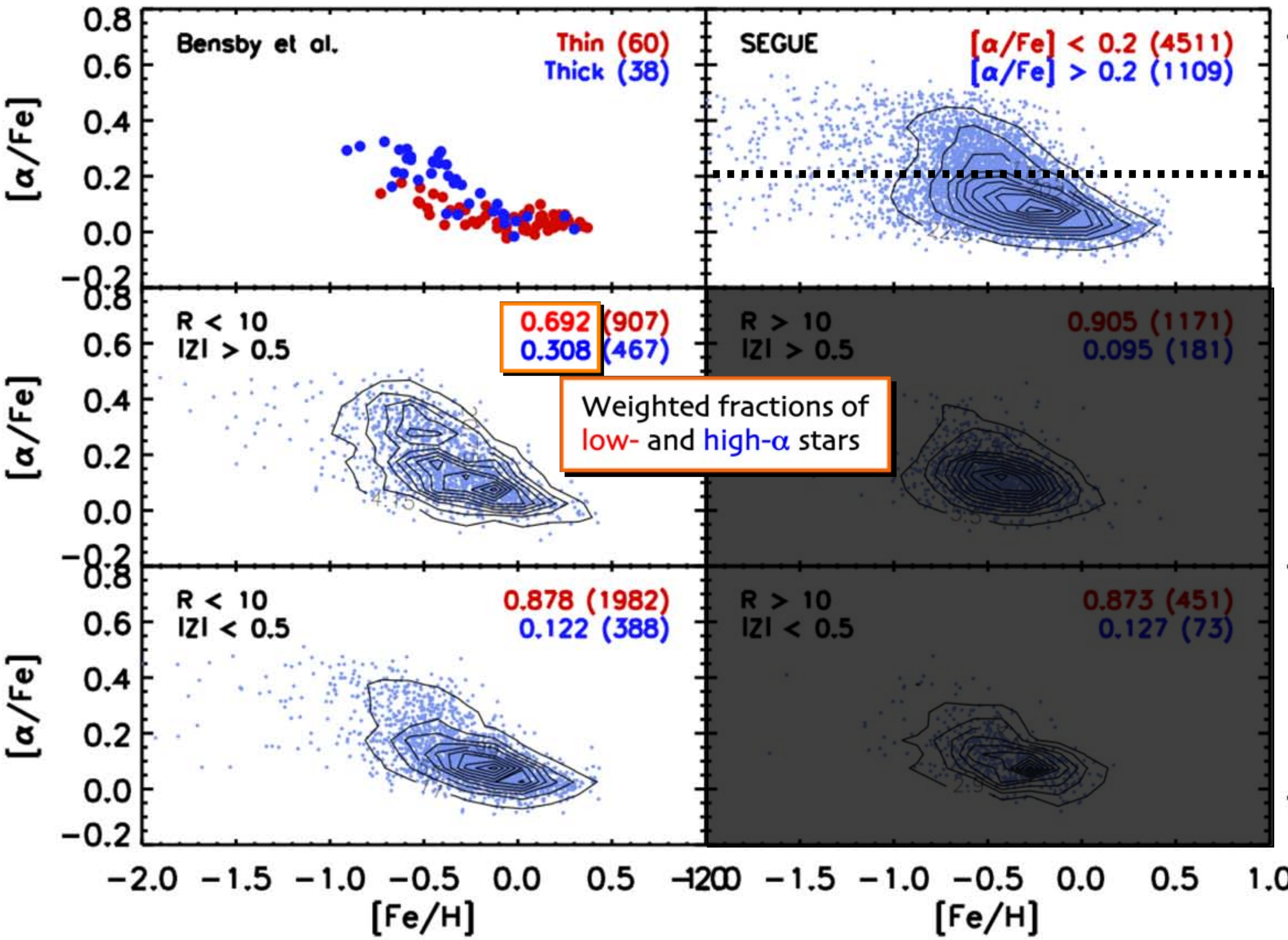

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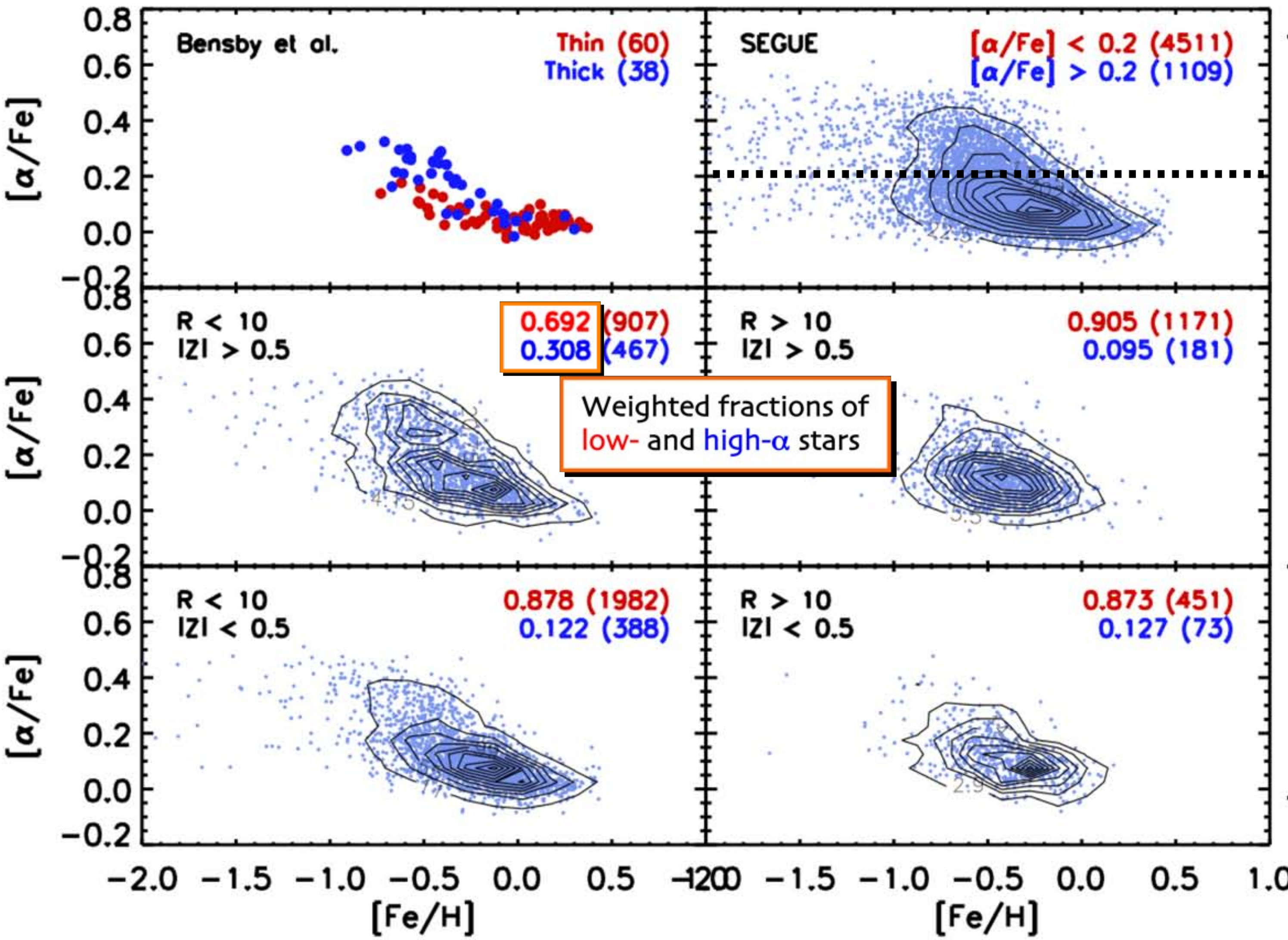

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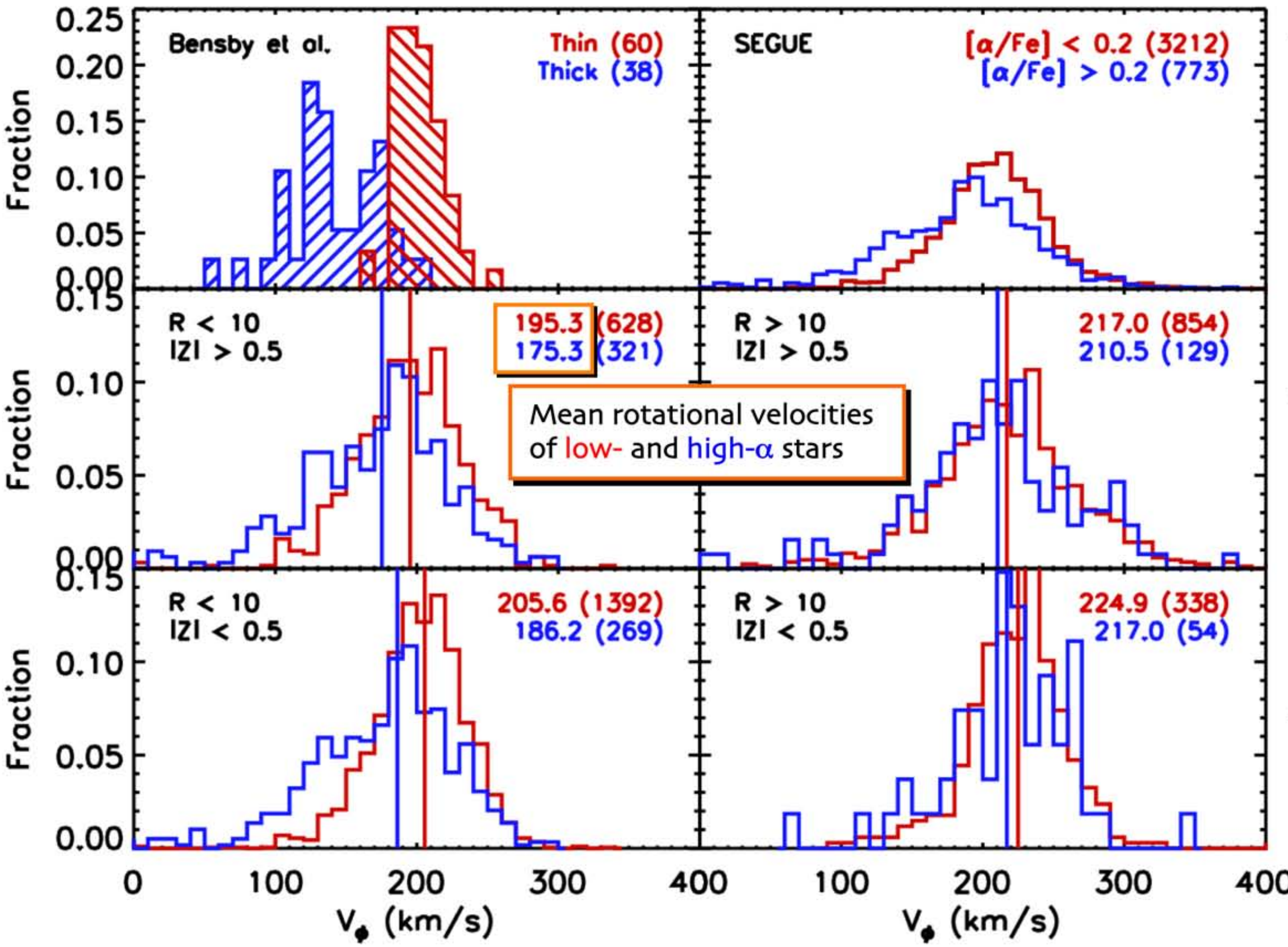
High-α stars in the inner and outer disk have different kinematic properties



- → From observations of nearby stars, we expect a correlation between [α/Fe] and kinematics
- → At small R, high-α stars lag low-α stars by ~20 km/s, similar to observations of nearby stars
- → At large R, high- and low-α stars have similar distributions in rotational velocity

Summary

- Radial gradient in [Fe/H] is flat at |Z| > 1.0 kpc
  - Whatever mechanism takes stars to large |Z| leads to a flat gradient in [Fe/H]
  - Thick disk formed quickly in turbulent disk phase
  - Or radial migration (induced by spiral arms or minor mergers) is strong

- Short scale length for high-α stars
  - At small R, see same chemical and kinematic properties as thin and thick disk stars in solar neighborhood
  - At large R, high-α stars are fewer in number and do not lag behind low-α stars
  - Different populations in inner and outer disk? Different formation mechanisms at work?