The definition of the Galactic thick disk

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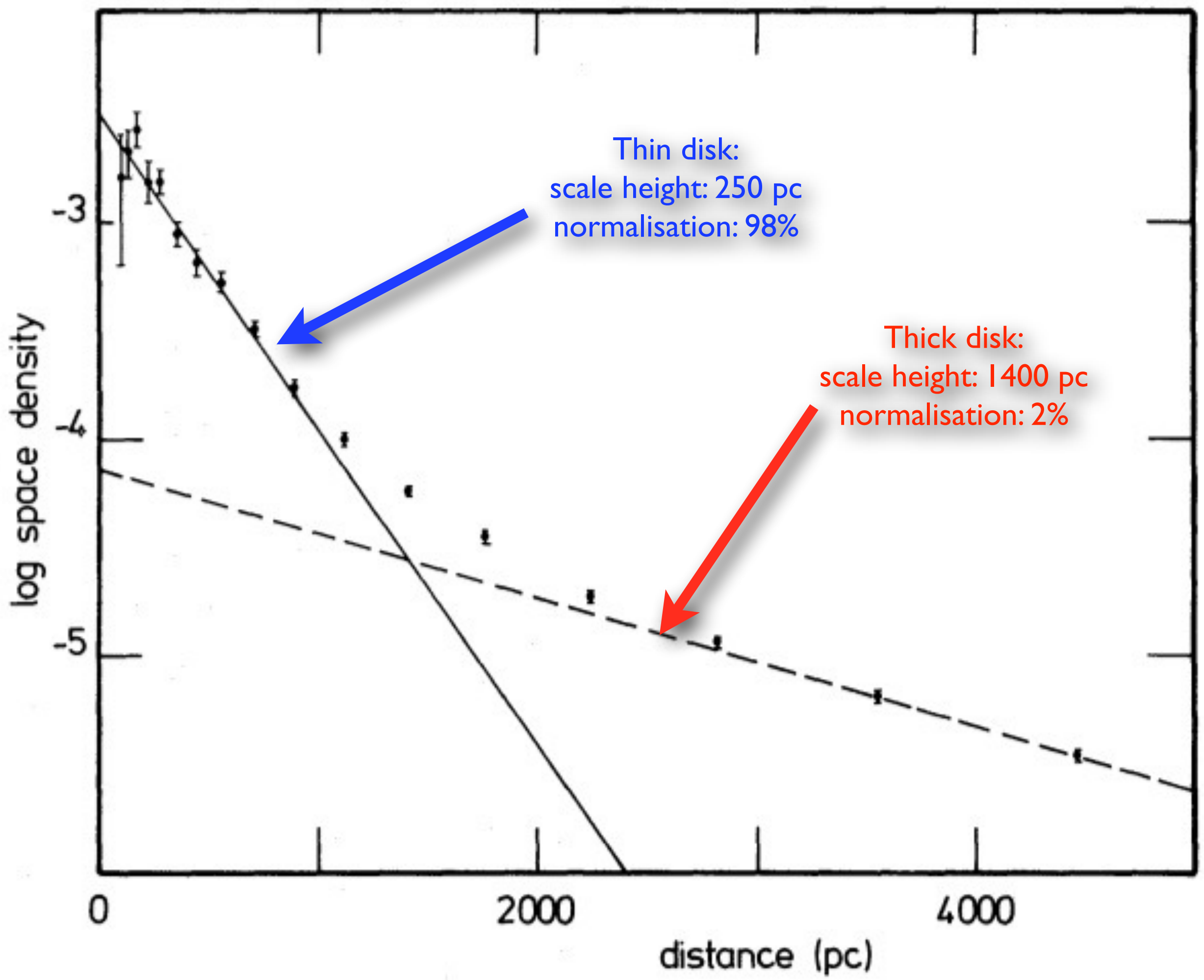
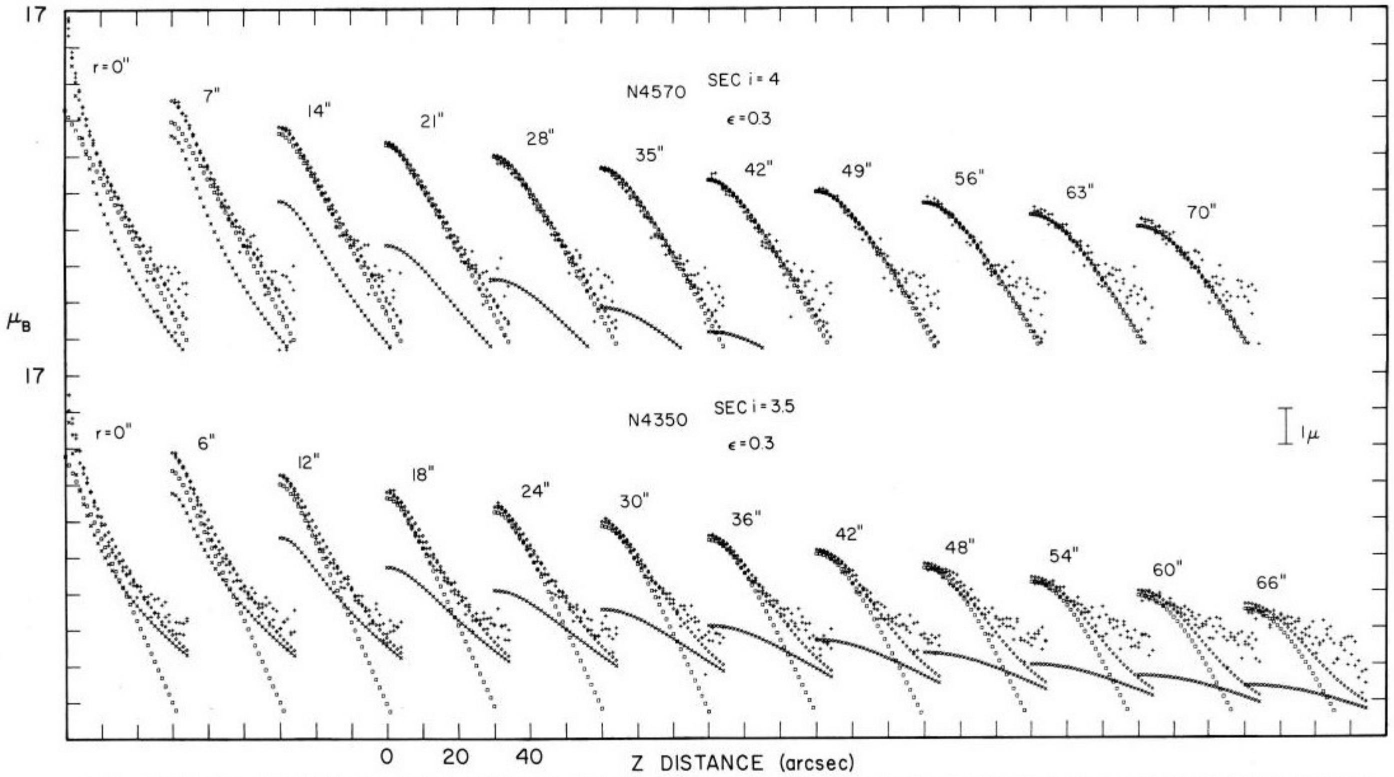
The Milky Way has two disk populations



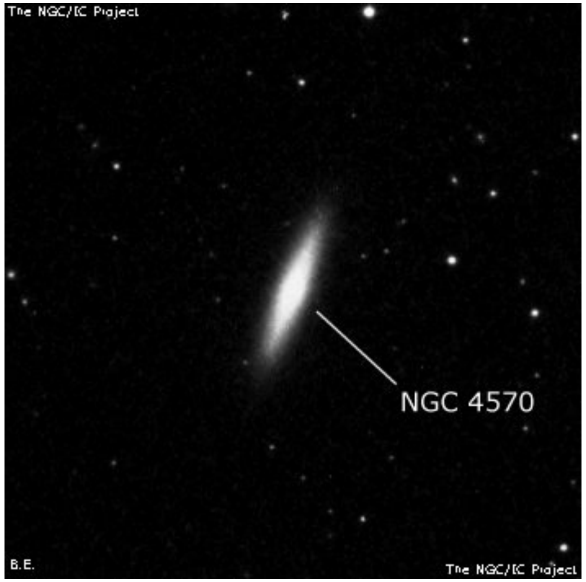
(Gilmore & Reid, 1983, MNRAS, 202, 102)

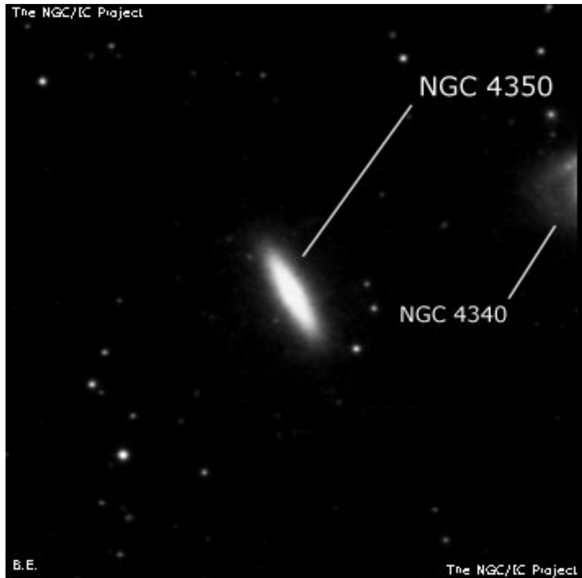
Thick disks in external galaxies

Burstein et al. (1979, ApJ, 234, 829)

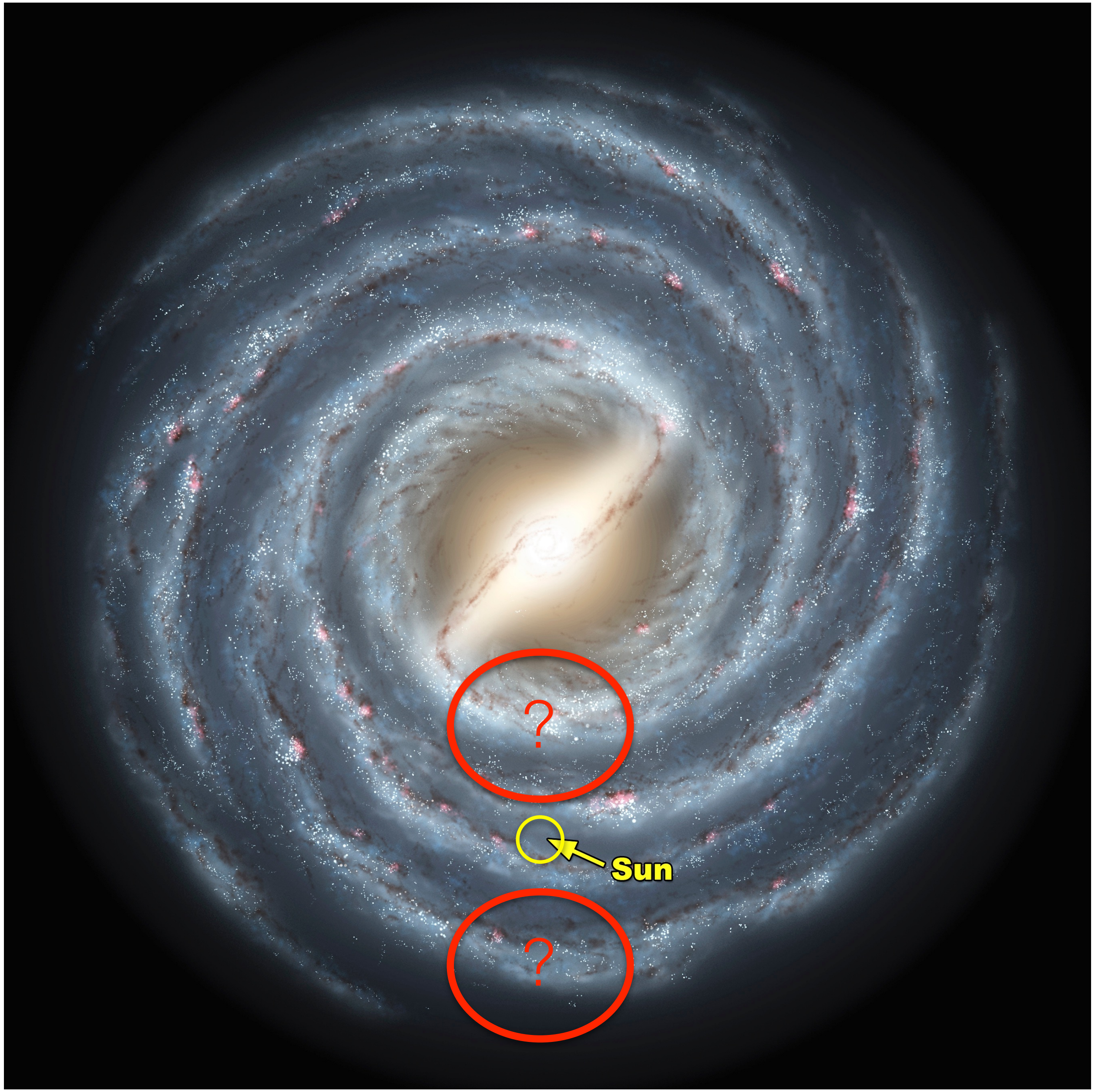


Bulge and thin disk profiles shown, however a third diffuse component is needed to fit the luminosity distribution perpendicular to the plane, named the "Thick disk".





The Milky Way as a benchmark galaxy



Why does the Milky Way have two disk populations?

Need to characterize them in terms of

- velocities
- abundances
- ages

Not only in the solar neighbourhood, but throughout the Milky Way galaxy

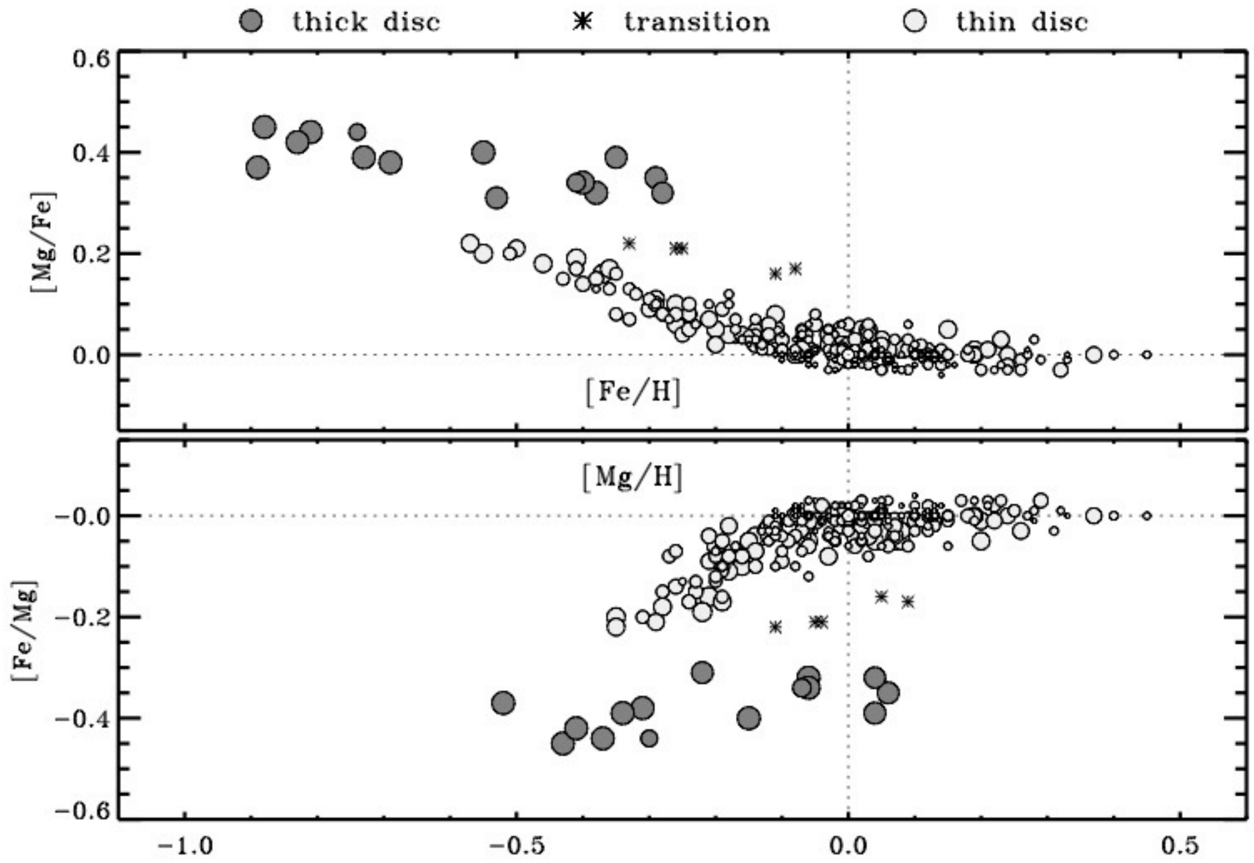
Nearby stars - no selection

- Fuhrmann's study is 85% volume complete for all mid-F type to early K-type stars down to Mv=6.0, north of dec=-15°, within a radius d<25pc from the Sun

- Two types of stars:

  1. Old stars with high [Mg/Fe] ratios

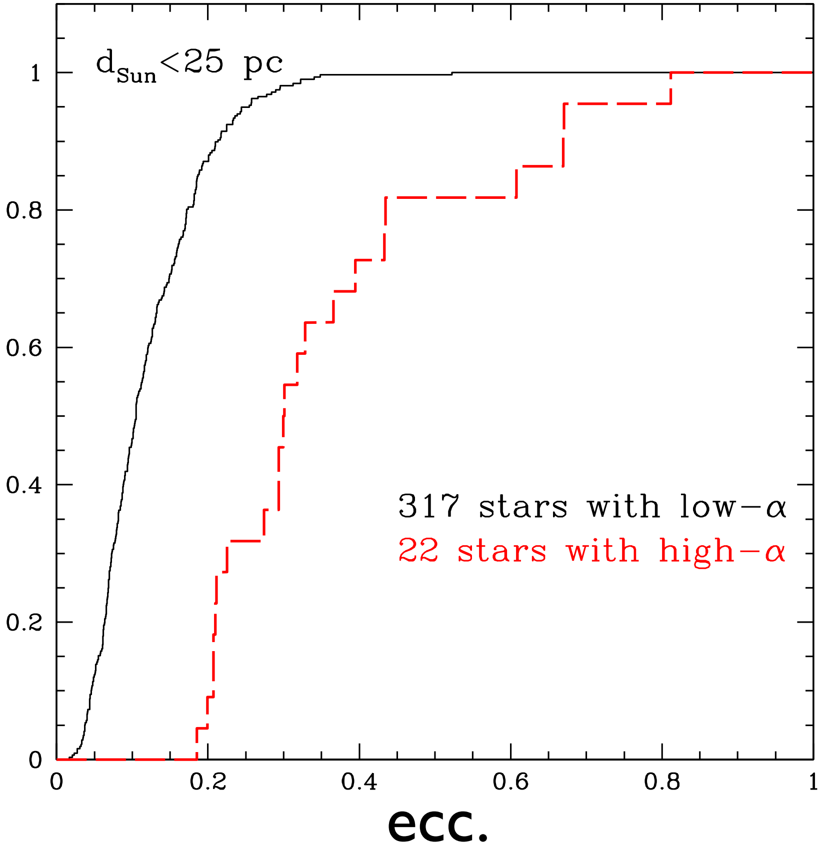
  2. Young stars with low [Mg/Fe] ratios

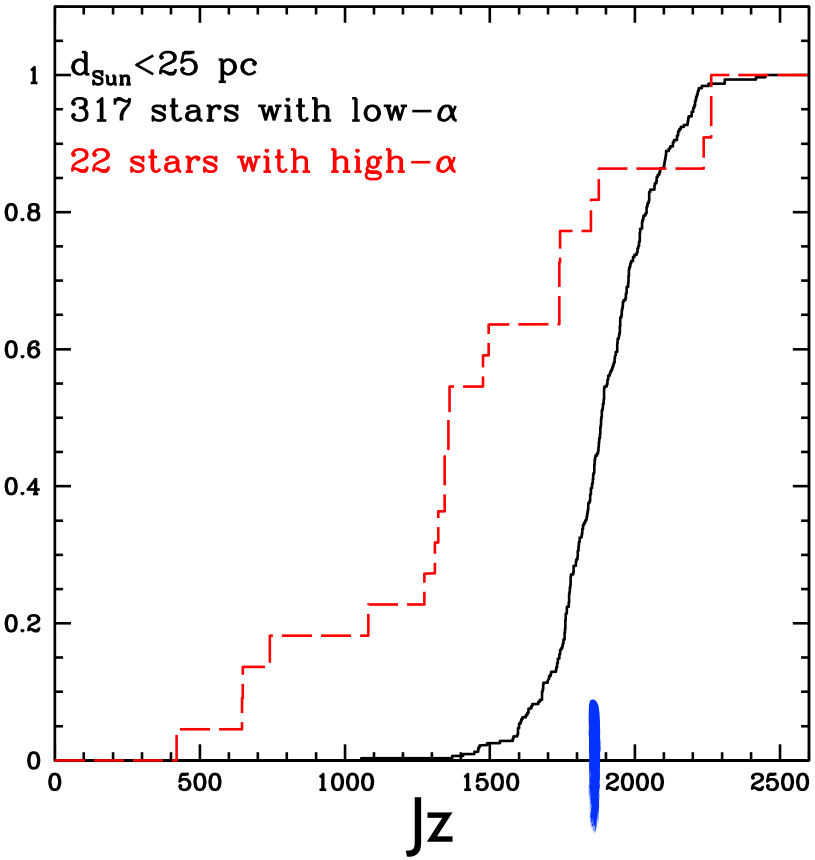


Fuhrmann (1998, 2000, 2004, 2008, 2011)

Two types of stars - high-alpha & low-alpha

(data from Fuhrmann's papers)

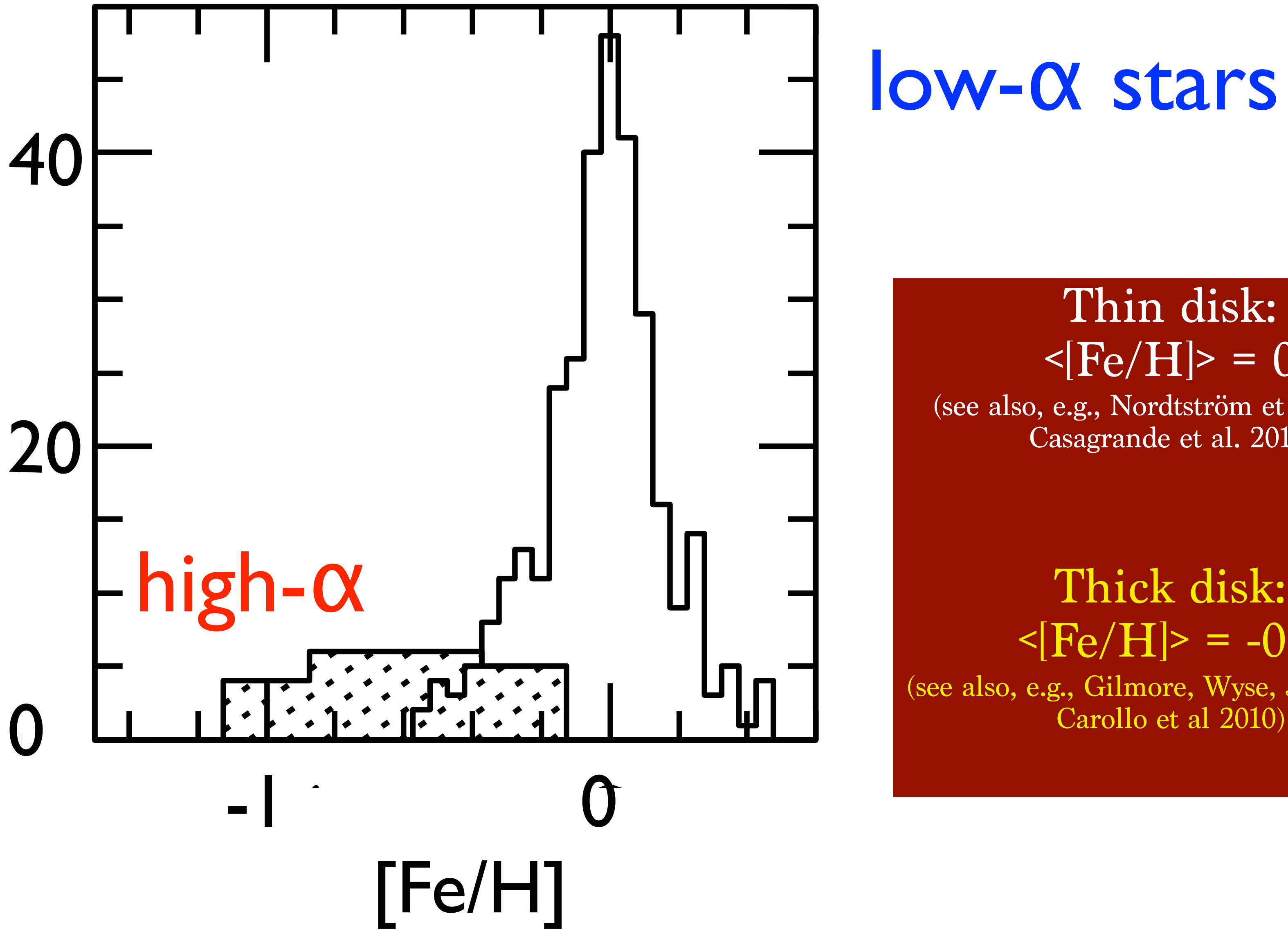




Two very different distributions of eccentricity and Jz for low- and high-α stars

Metallicities

(data from Fuhrmann's papers)



Thin disk:
<[Fe/H]> = 0
(see also, e.g., Nordtström et al., 2004, Casagrande et al. 2011)

Thick disk:
<[Fe/H]> = -0.6
(see also, e.g., Gilmore, Wyse, Jones, 1995; Carollo et al 2010)

Kinematical criteria to select nearby thick disk stars

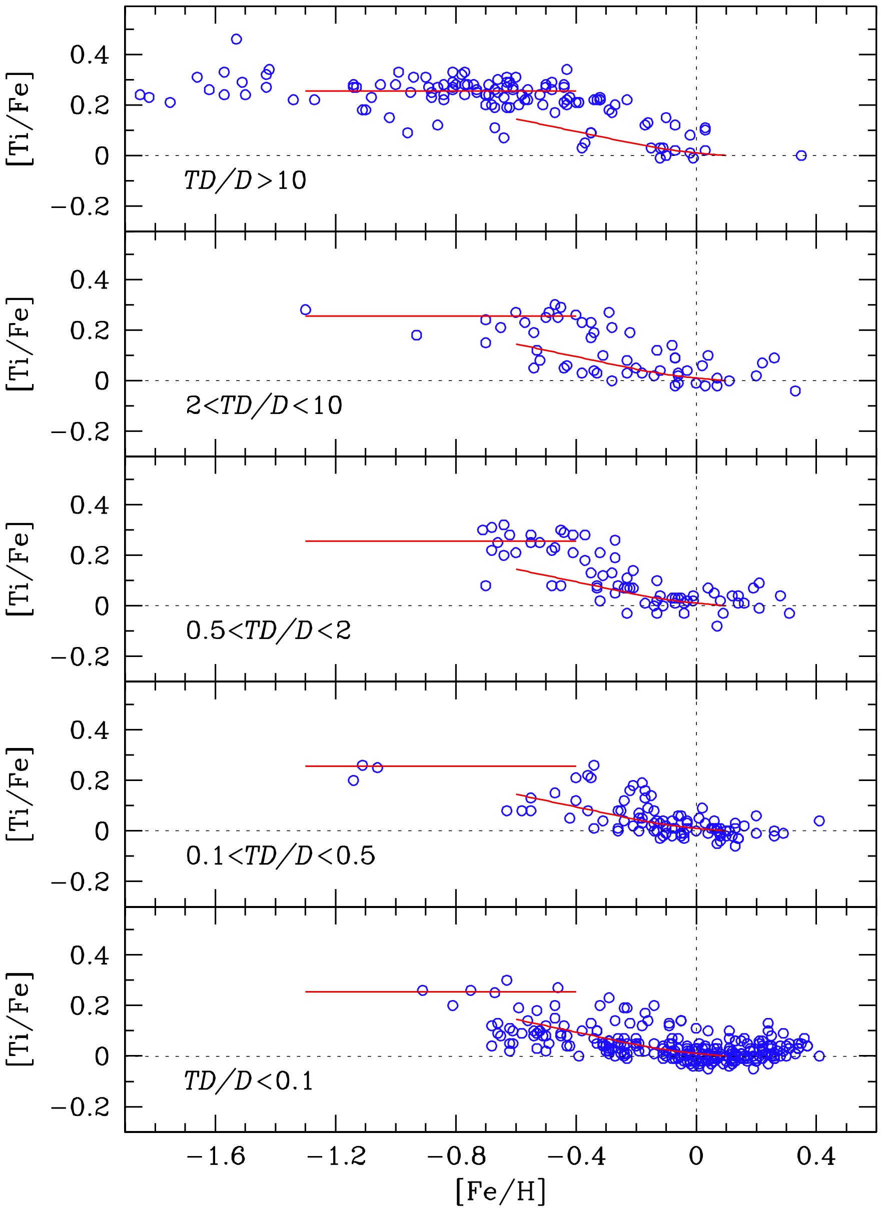
$$P = X \cdot k \cdot \exp\left(-\frac{U_{\rm LSR}^2}{2\sigma_{\rm U}^2} - \frac{(V_{\rm LSR} - V_{\rm asym})^2}{2\sigma_{\rm V}^2} - \frac{W_{\rm LSR}^2}{2\sigma_{\rm W}^2}\right) \qquad k = \frac{1}{(2\pi)^{3/2}\sigma_U\sigma_V\sigma_W}$$

	$\sigma_{\rm U}$	$\sigma_{\rm V}$	$\sigma_{\rm W}$	$V_{\rm asym}$
	[km s^{-1}]			
Thin disk (*D*)	35	20	16	−15
Thick disk (*TD*)	67	38	35	−46
Halo (*H*)	160	90	90	−220

Gaussian velocity distributions, *X* is normalisation in solar neighbourhood (~90% thin, ~10% thick)

Probability ratios: *P*(TD/D)>1 is more likely to be a thick disk star

Kinematics



714 nearby dwarfs from Bensby et al, (2014)

Kinematics:

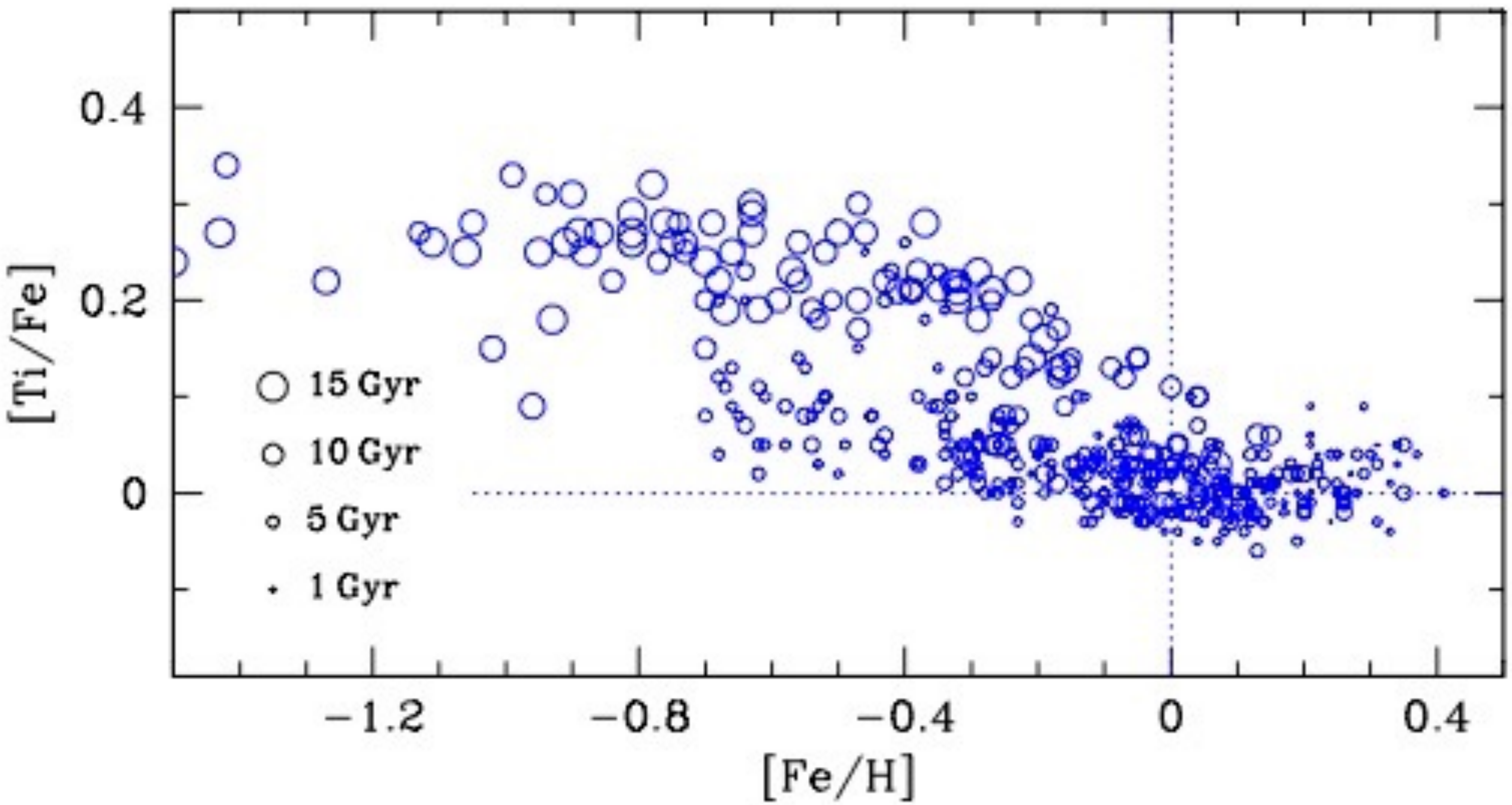
Using Gaussian velocity ellipsoids to calculate probabilities that the stars belong to either the thin or the thick disks

TD/D = 1, equal probabilities
TD/D>1, more likely to be thick disk
TD/D<1, more likely to be thin disk

Chemistry of the Solar neighbourhood

Bensby et al. (2014, A&A, 562, A71)

712 F and G dwarf stars in the Solar neighbourhood

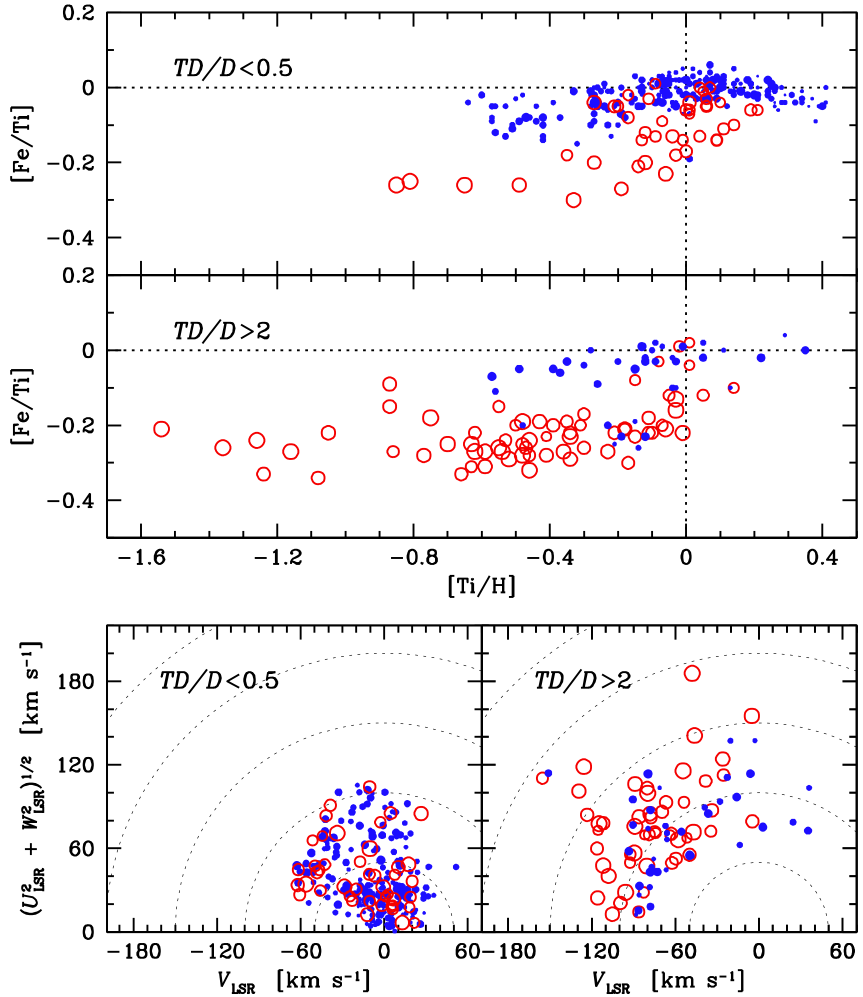


A clear dichotomy:

- **An old and alpha-enhanced population**
- **Less alpha-enhanced young population**

Similar dichotomy seen in many other Solar neighbourhood studies, e.g.,
Reddy+2003,2006, Adibekyan+2012, Fuhrmann 1998,2001,2004,2008,2011, and others.....

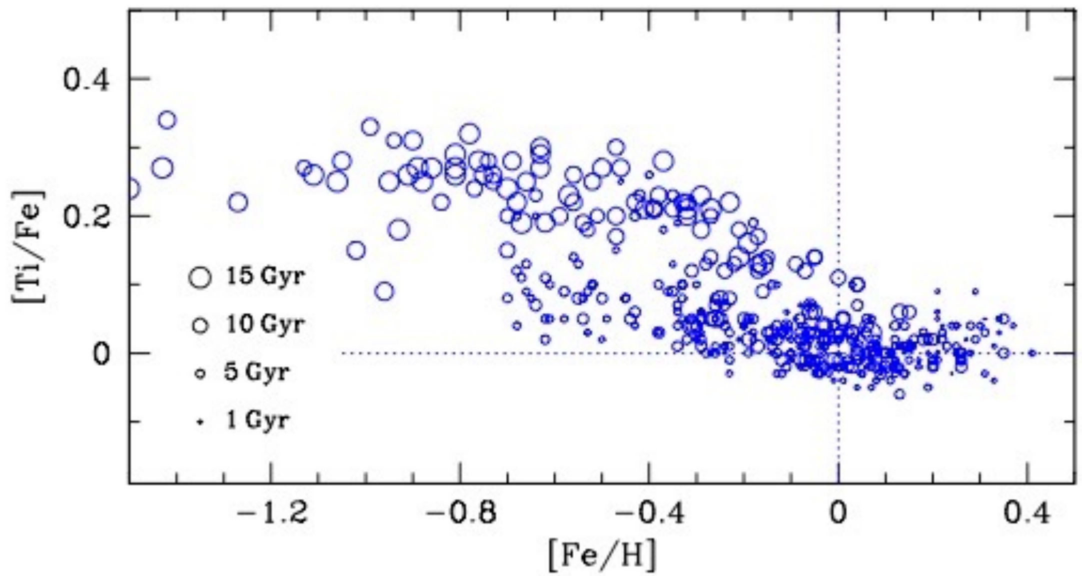
Kinematic confusion



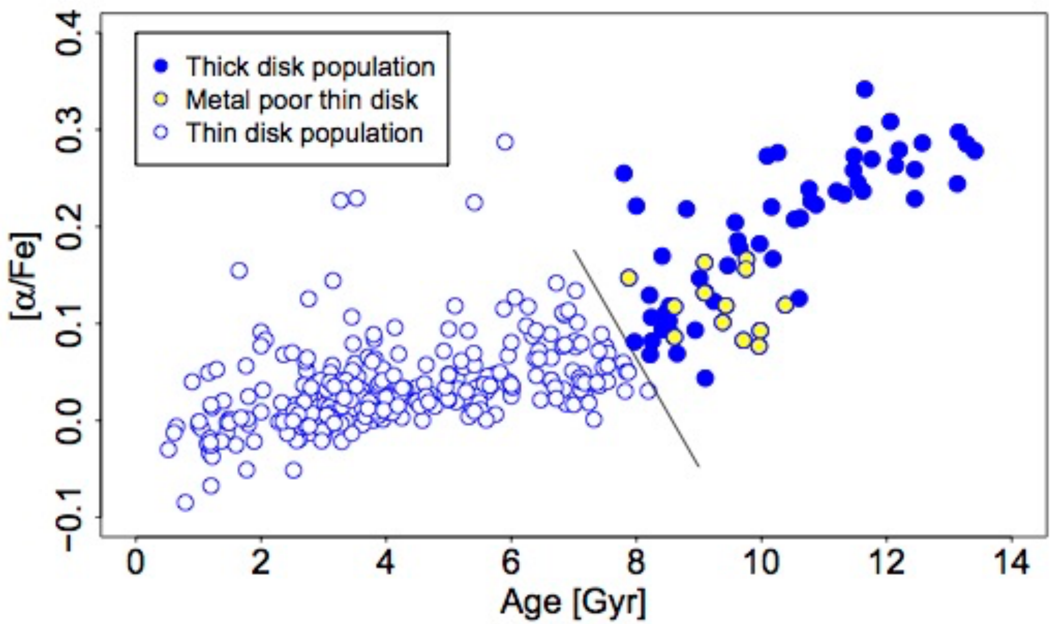
Two well-defined, but not perfectly clear trends

714 nearby dwarfs from Bensby et al, (2014)

Ages

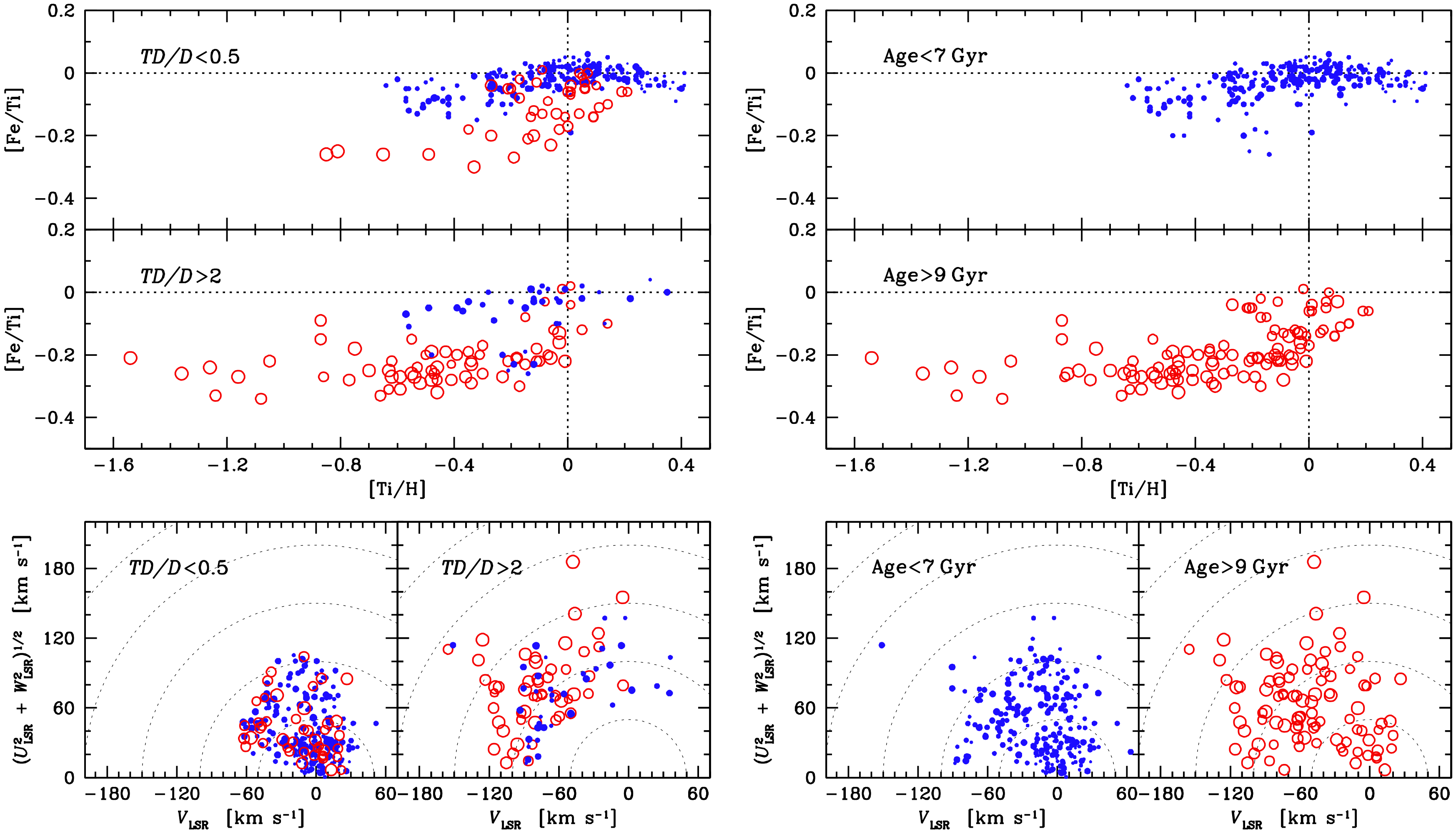


Bensby et al, (2014)



Haywood et al, (2011)

Kinematic confusion

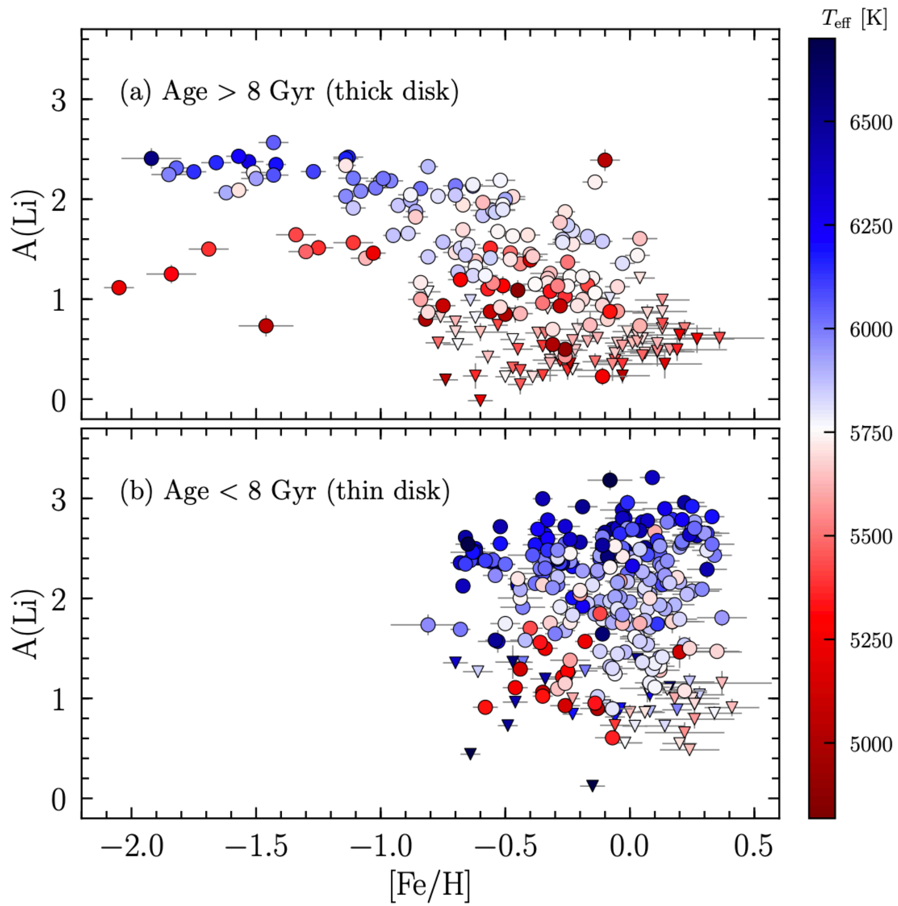


Ages seem to better discriminator between thin and thick disk, but ages are rarely available and very difficult to determine

714 nearby dwarfs from Bensby et al, (2014)

Lithium in the Galactic disk

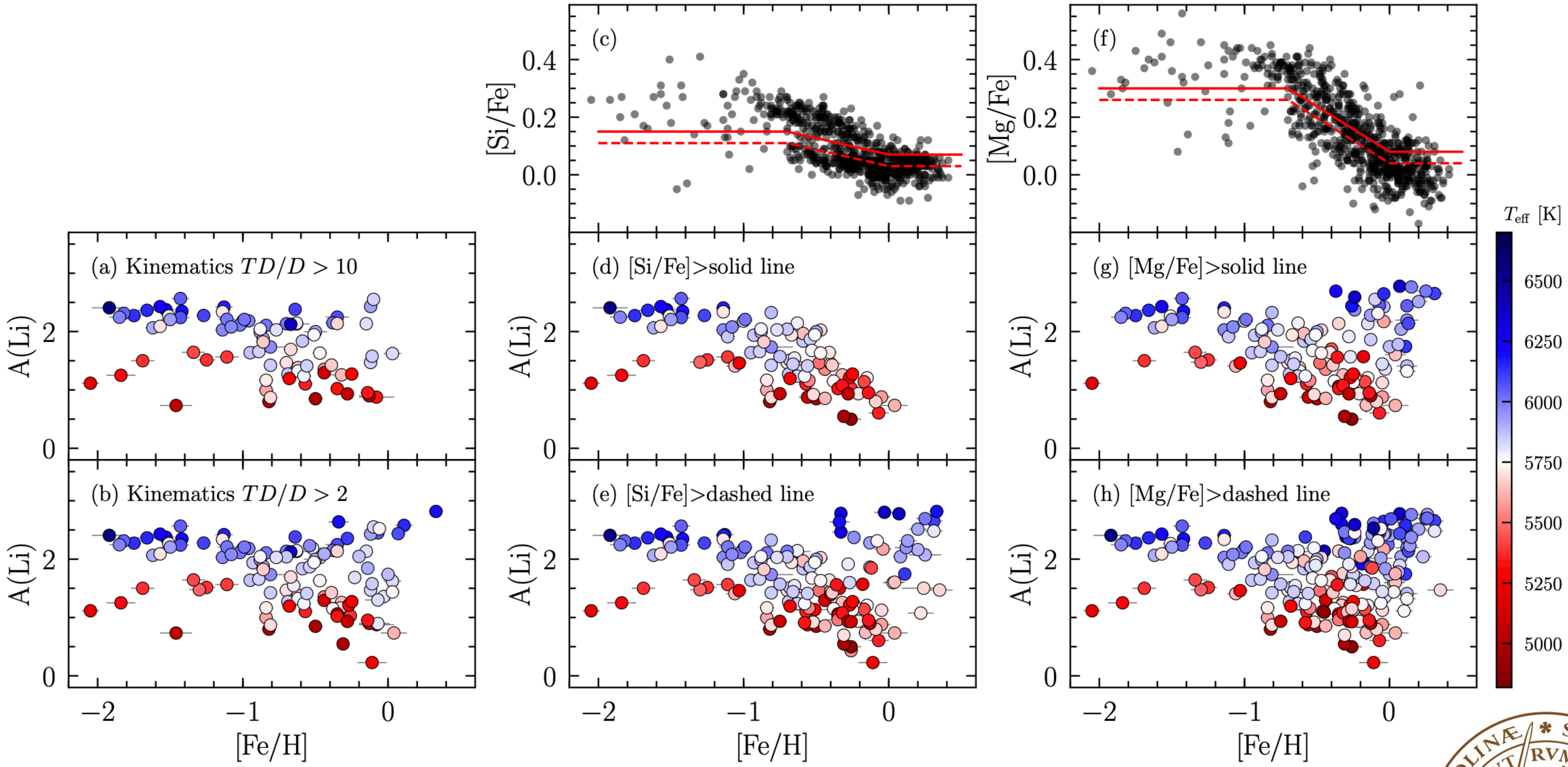
Disk separation based on ages



Bensby & Lind (2018)

Lithium in the Galactic disk

Thick disk definition based on kinematics (left) or alpha-enhancement (right)



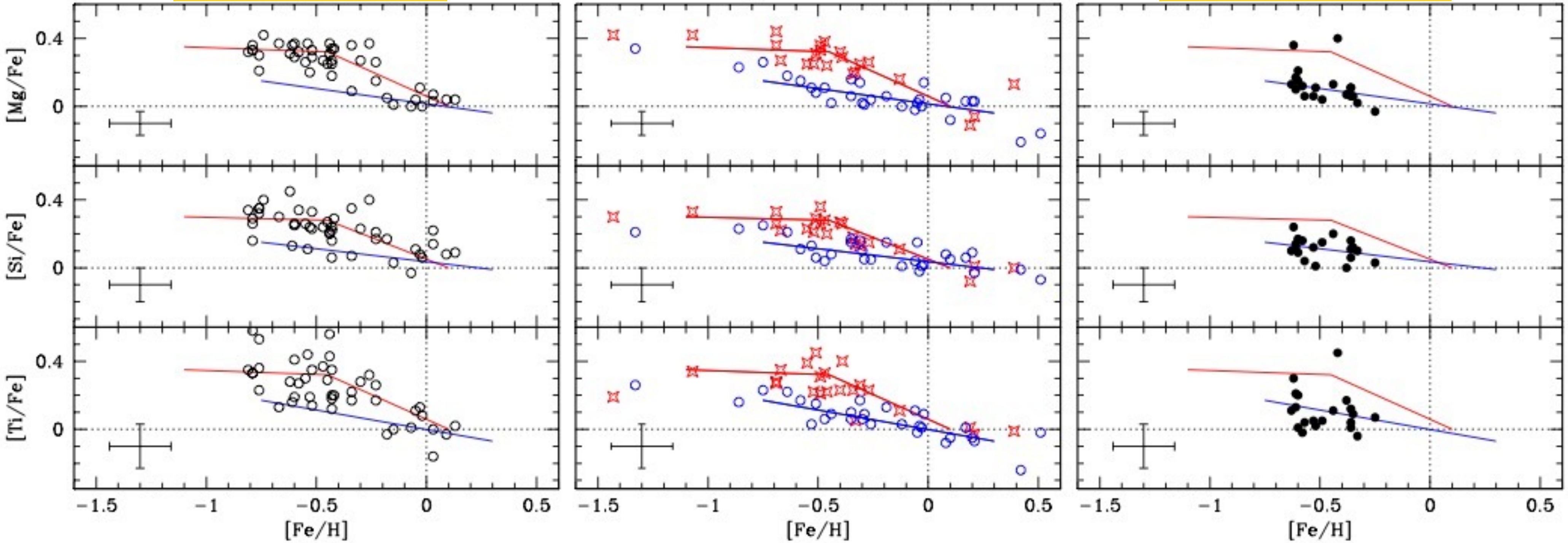
Bensby & Lind (2018)

A bit further away

Inner disk
4 < R_g < 7 kpc

Solar neighbourhood

Outer disk
9 < R_g < 13 kpc



Bensby, Alves-Brito, Oey, Yong, & Melendez, 2010, A&A, 516, L13

Alves-Brito et al. (2010)

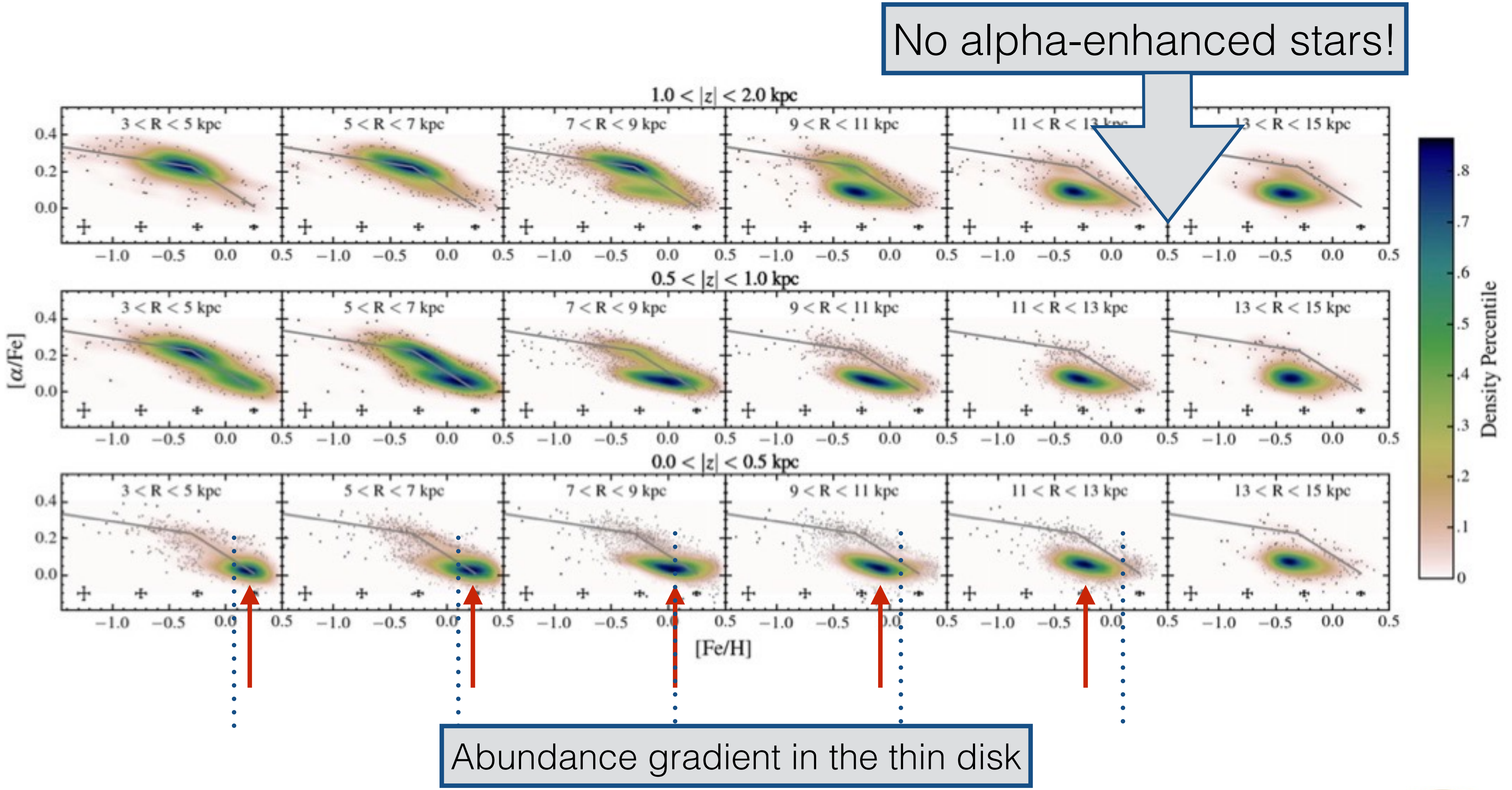
Bensby, Alves-Brito, Oey, Yong, & Melendez, 2011, ApJ, 735, L46

N<u>o</u> alpha-enhanced stars in the outer disk

=> Short scale-length for the thick disk !

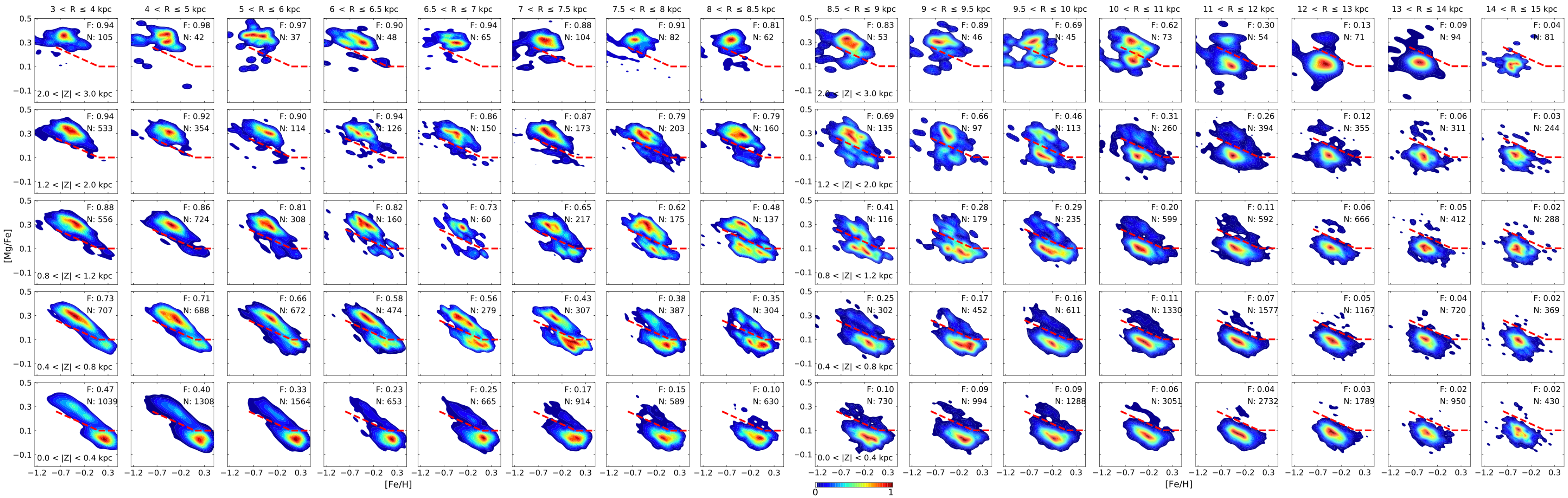
See also, e.g., Cheng et al. (2012), Bovy et al. (2012)

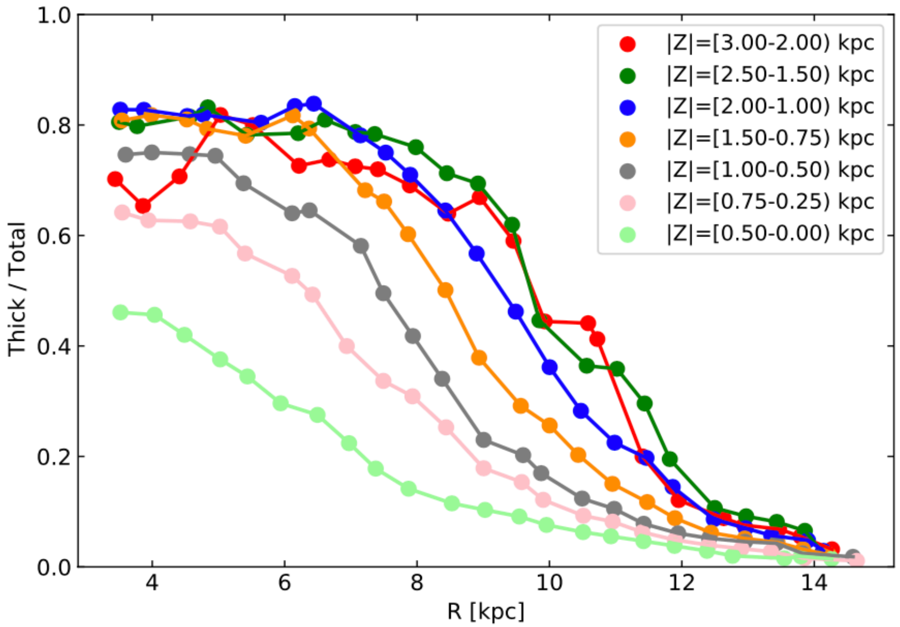
Further away and larger samples - APOGEE



- Hayden et al. (2015), based on red giants from APOGEE DR12

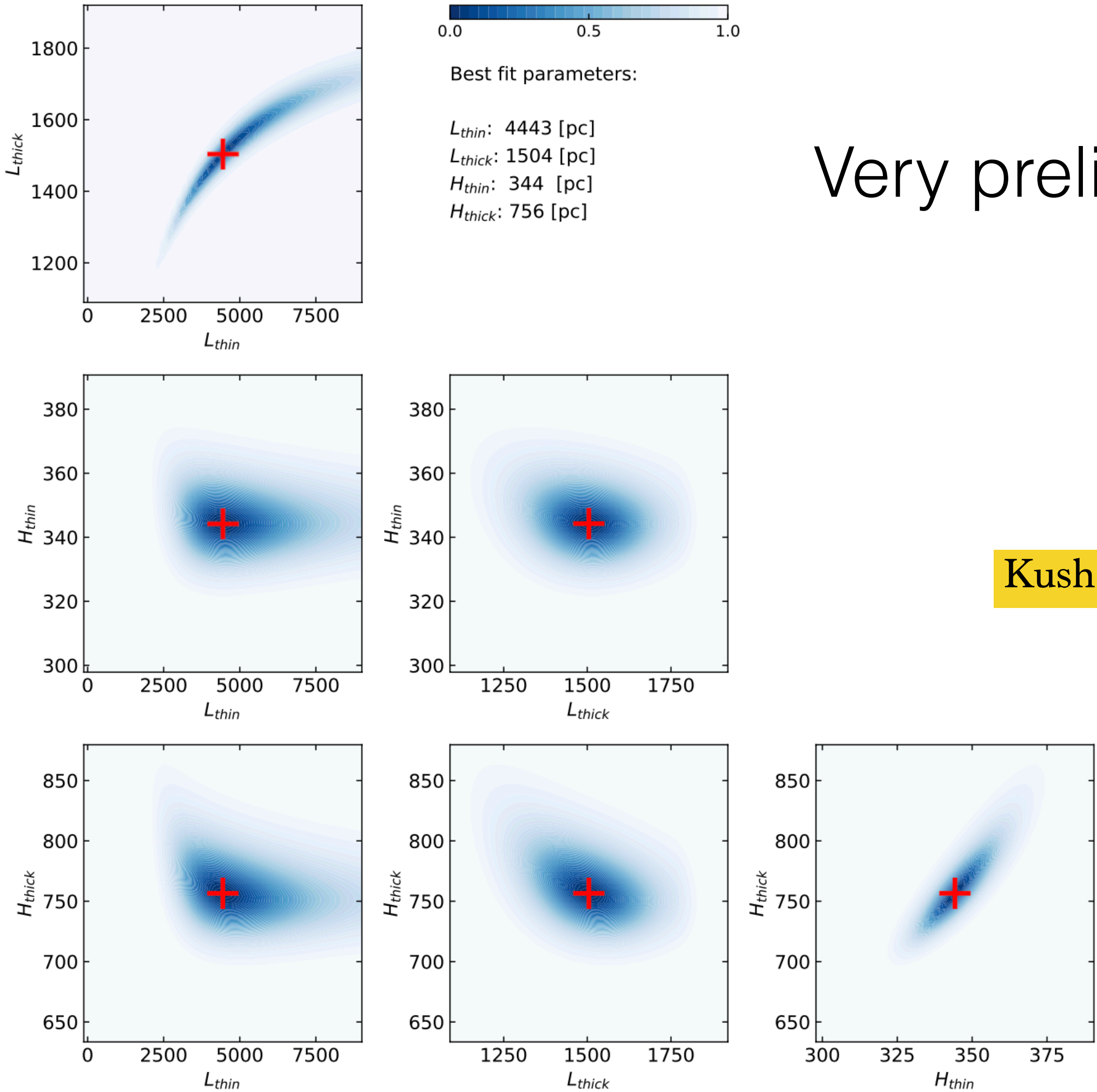
Scalelengths based on APOGEE and Gaia





Kushniruk & Bensby (in prep)

Scalelengths based on APOGEE and Gaia



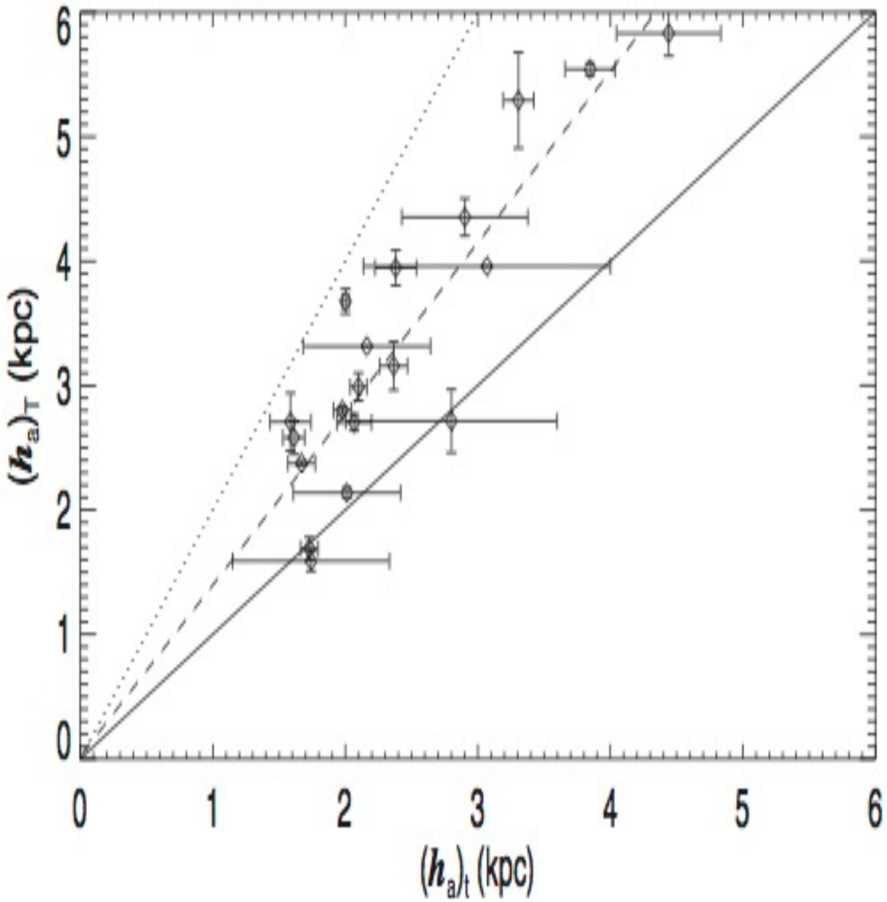
Very preliminary numbers!

Kushniruk & Bensby (in prep)

Scale-lengths in external galaxies

Comeron et al. (2012, ApJ, 759, 98)
Luminosity profile fitting

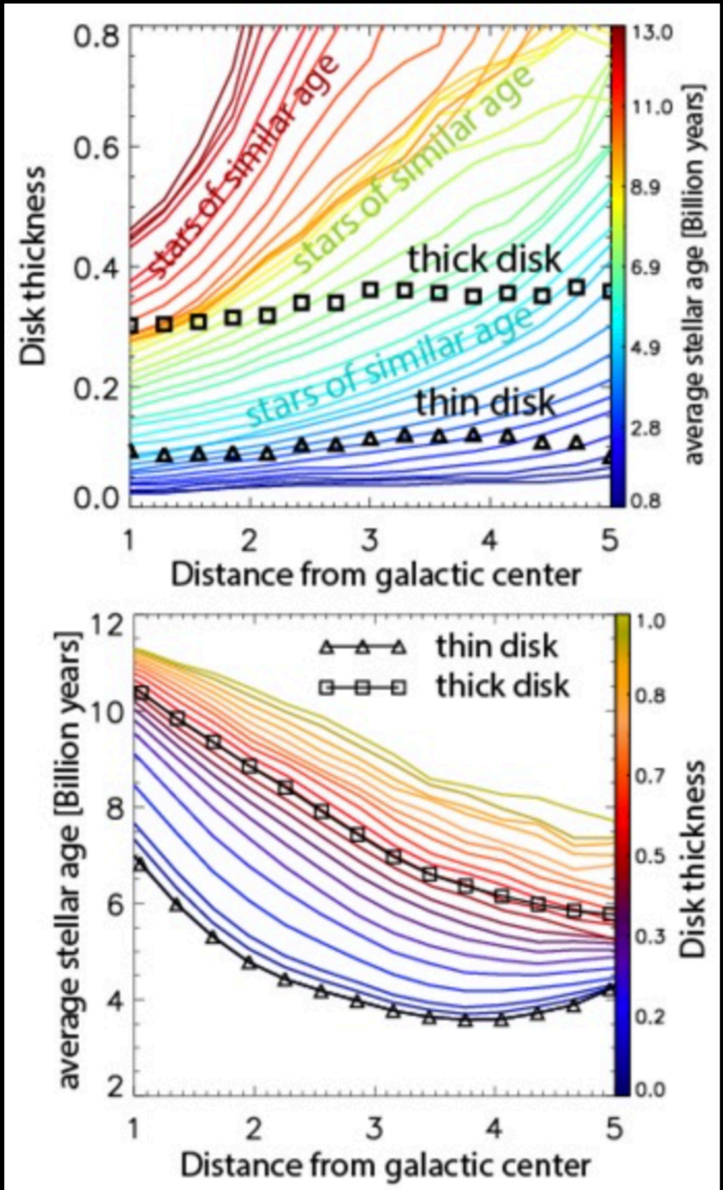
Thick disk scale-length



Thin disk scale-length

Thick disk scale-lengths are longer than thin disk scale-lengths!

Ivan's mono-age populations



Mono-age groups of stars always flare (increase thickens with galactic radius), unless just born. The primary reason for that is the dynamical effect of infalling satellites throughout the disk lifetime.

However, if the disk forms inside-out, then older populations dominate in the inner disk and younger ones in the outer disk.

Therefore, when the total stellar population (all ages) is decomposed into thin + thick disks, the flaring disappears (or is strongly reduced)!

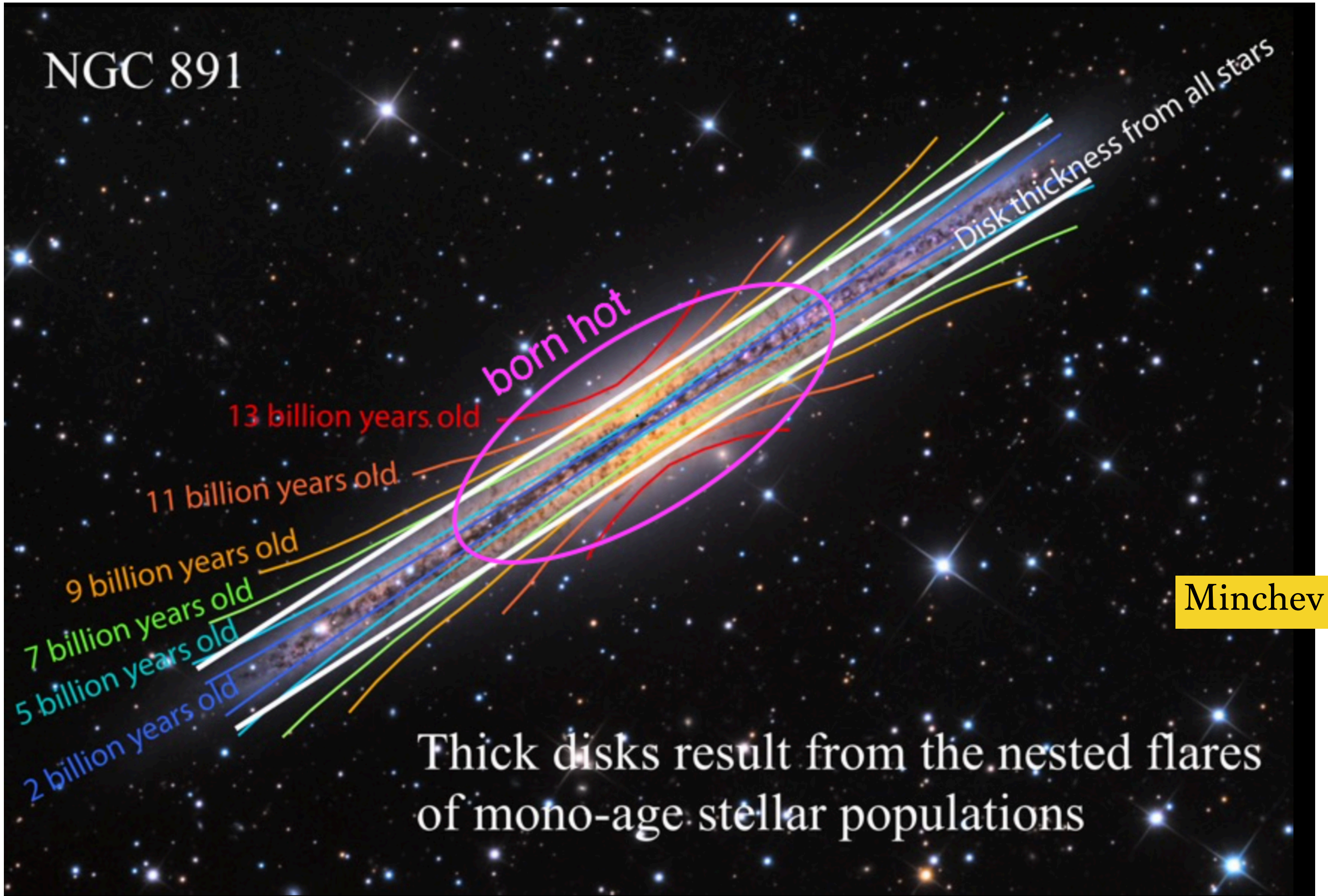
Minchev et al. (2017)

Age gradient in (morphological) thick disk predicted

Chemical thick disk ≠ Morphological thick disk

https://www.pas.rochester.edu/~iminchev/NGC891.html

Ivan's mono-age populations



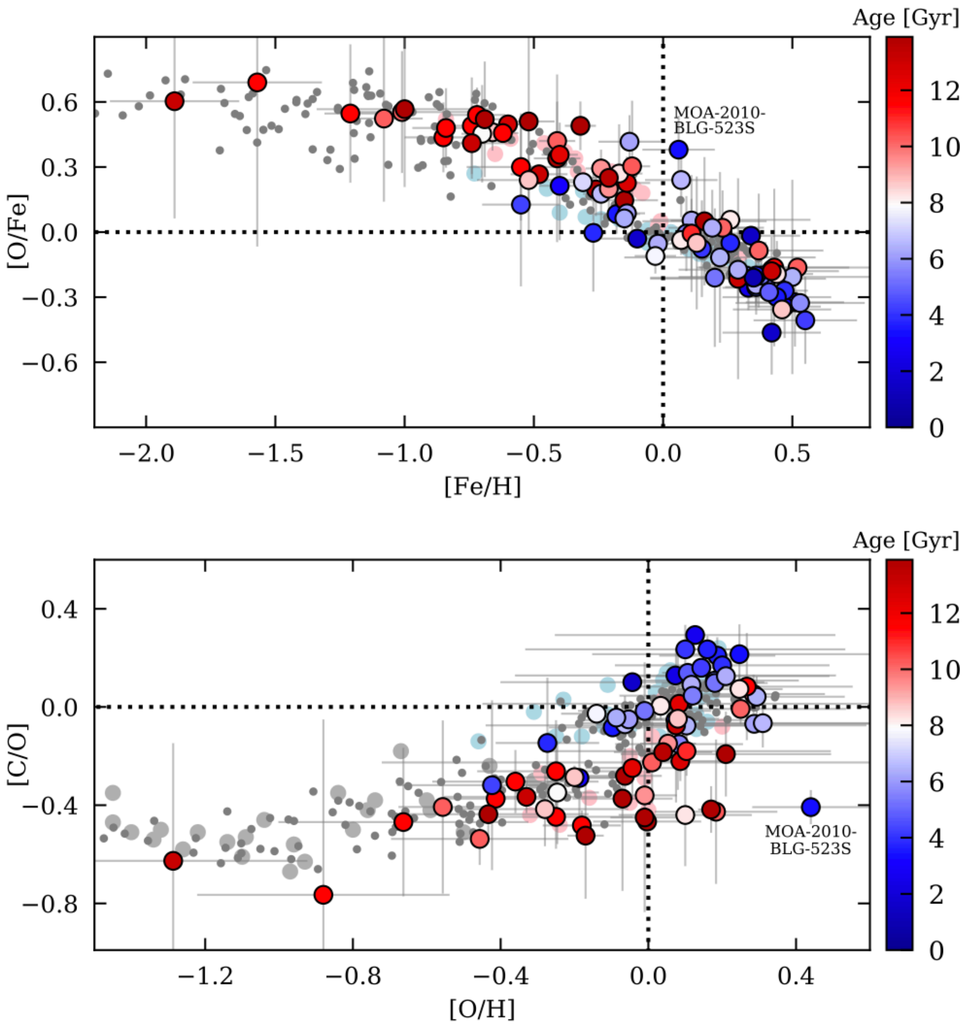
The Milky Way analog galaxy, NGC 891. Overlaid are color curves that show the flares from groups of stars with similar ages. When all stars are put together, the disk has constant thickness, shown by the straight white lines. (Credit: Adam Block, Mt. Lemmon SkyCenter, University of Arizona / Ivan Minchev, AIP)

Minchev et al. (2017)

https://www.pas.rochester.edu/~iminchev/NGC891.html

The thick disk in the Galactic bulge?

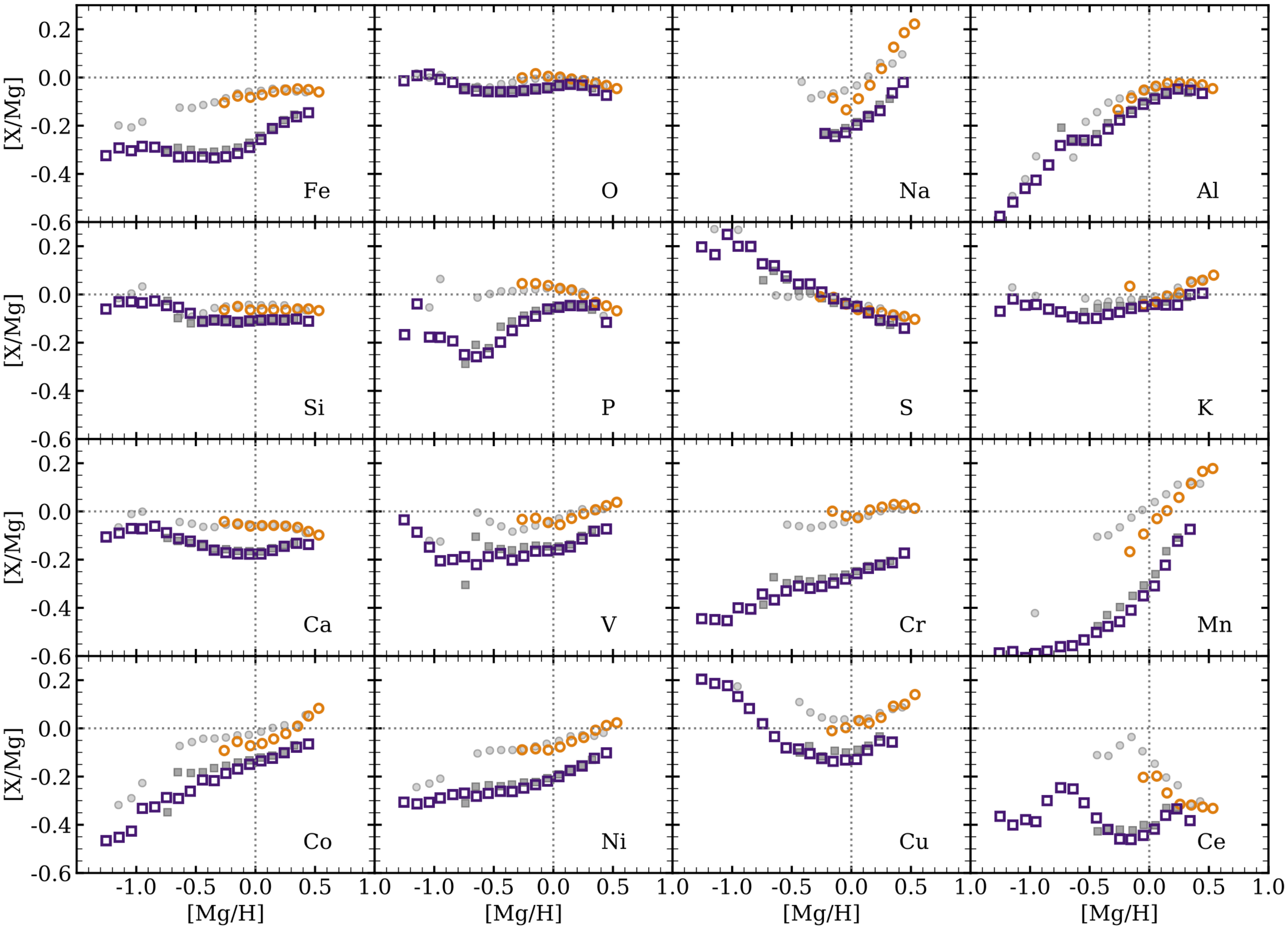
A short thick disk scale-length implies that it becomes the dominating disk population in the inner region of the Galaxy………



Microlensed bulge dwarfs in great agreement with the Solar neighbourhood thin and thick disks

Bensby et al. (2021)

The thick disk vs Galactic bulge



APOGEE DR-17 data

Griffith et al. (2021)

Summary

- No matter if we use kinematical, chemical, or age criteria, Milky Way appears to have two distinct disk populations.
- While there is some kinematical and chemical confusion, the two disks appear to show the cleanest separation using ages
- The thick disk has a short scale-length (based on chemistry)
- Scale-lengths in external galaxies, based on morphology, can be understood in terms of mono-abundance populations, and might not be contradictory……

Summary

- Revise how we see the MW populations

- The thick (old) and thin (young) disks could be seen as evolutionary sequences in the history of the MW and shows a lot of overlap in terms of abundances and kinematics

- The bulge maybe should be considered to be a region rather than a population, where the other MW populations reside, perhaps together with a small classical bulge component

Congratulations Ken!

Found on the internet: https://blog.csiro.au/three-astronomers-walked-into-a-pub/

In the Coonabarabran Bowling Club in northwest NSW during an event the Science in the Pub — a special session held as part of Coonabarabran's annual Starfest, a celebration of matters astronomical.

When discussion got under way, two of the participants claimed to be the Prince of Darkness. They both had pretty good grounds.