Observations of Thick Disks (Stellar)

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Exponential Disks, Flagstaff, October 7, 2014

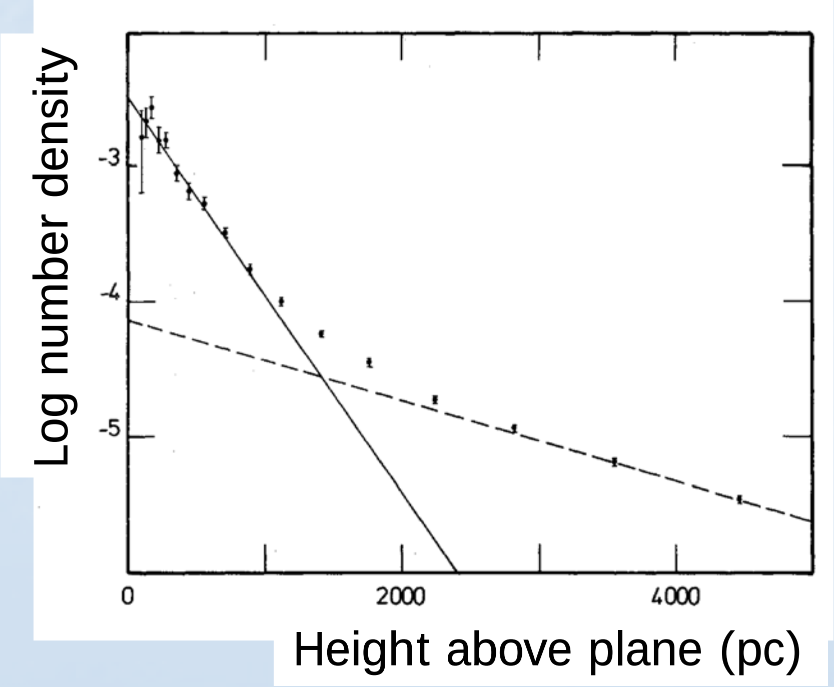
What can we learn?

- Thin stellar disks are fragile and can be disturbed by external influences such as companion galaxies and mergers, and internal perturbations such as spiral arms, bars and Giant Molecular Clouds
  - Stellar systems are collisionless and cannot ‘cool’ once heated, unlike gas
    - Vertical structure contains imprints of past heating and of star formation during dissipational settling
  - Radial structure contains imprints of angular momentum distribution/re-arrangement
- Properties of thin and thick stellar disks constrain
  - Merger/accretion, infall history
  - star formation rate vs dissipation rate
  - Internal secular processes

Thick Stellar Disks

- Identified first as third component in surface brightness profile in external S0 galaxies – bulge, thin disk plus an additional exponential vertical fall-off (Burstein 79, Tsikoudi 79)
- Star counts at the Galactic Poles fit by two exponentials

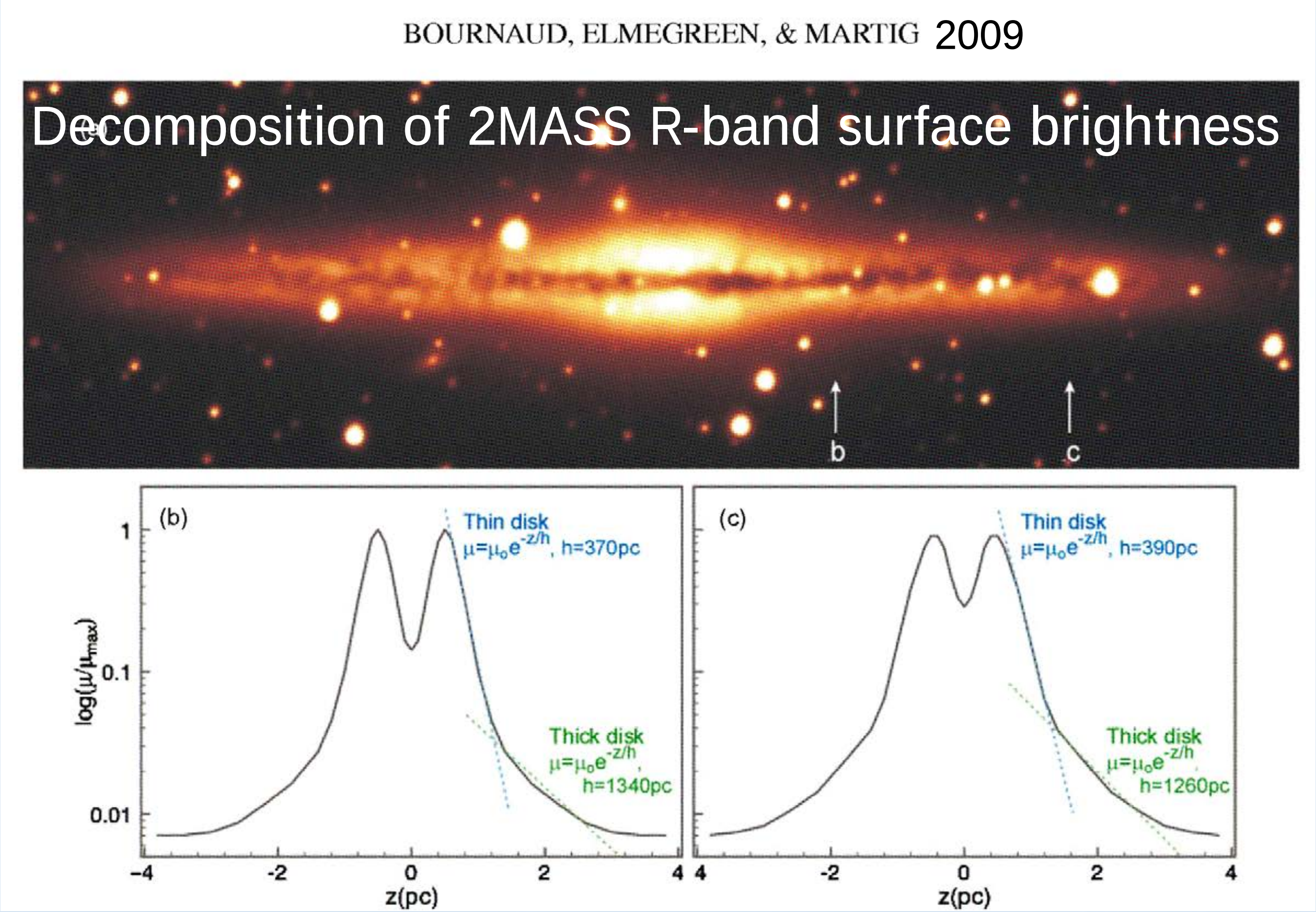
Gilmore & Reid (1983)
see also Yoshii (1982)



Thick Disks in External Galaxies

- Most external (edge-on) disk galaxies have vertical surface brightness profiles better fit by two components - exponentials or isothermal disks (e.g. Comerón et al 2011; 2013) - with the higher scale-height thick disk being old(er) (e.g. Yoachim & Dalcanton 2008; Mould 2005)
  - A few are counter-rotating ➔ external origin?
- Derived thin and thick disks have comparable scale-lengths and scale-heights different by a factor of around 4, each approximately constant with radius (e.g. Comerón et al 2011)
- Mass ratio of thick to thin disk higher at lower circular velocity (Comerón et al 2011; Yoachim & Dalcanton 2006)
- Ratio of mass in thick disk plus 'bulge' to mass in thin disk approximately constant (Comerón et al 14 + Salo + Comerón talks)

Milky Way analogue, NGC 891



HST star-count analysis gives similar results (Ibata et al 2009)

Milky Way Thick Disk

- Stars studied mostly within few kpc of the Sun
- Kinematics intermediate between thin disk and halo, mean rotation velocity lags thin disk by ~ 50km/s, vertical velocity dispersion ~ 40km/s ➔ thick, with scale height of ~1kpc
  - Higher than extrapolation of thin disk age-velocity dispersion
- Mean metallicity ~ -0.6 dex (0.25 solar value)
- Elemental abundances ‘alpha-enhanced’ $[\alpha/Fe] > 0$
- Most thick disk stars are old, ~ 10 Gyr
- Derived mass ~ 20% of thin disk mass i.e. ~ $10^{10}\ M_\odot$
- Thick disk appears distinct but distributions overlap with those of other stellar components and often non-Gaussian: how best to define the thick disk?

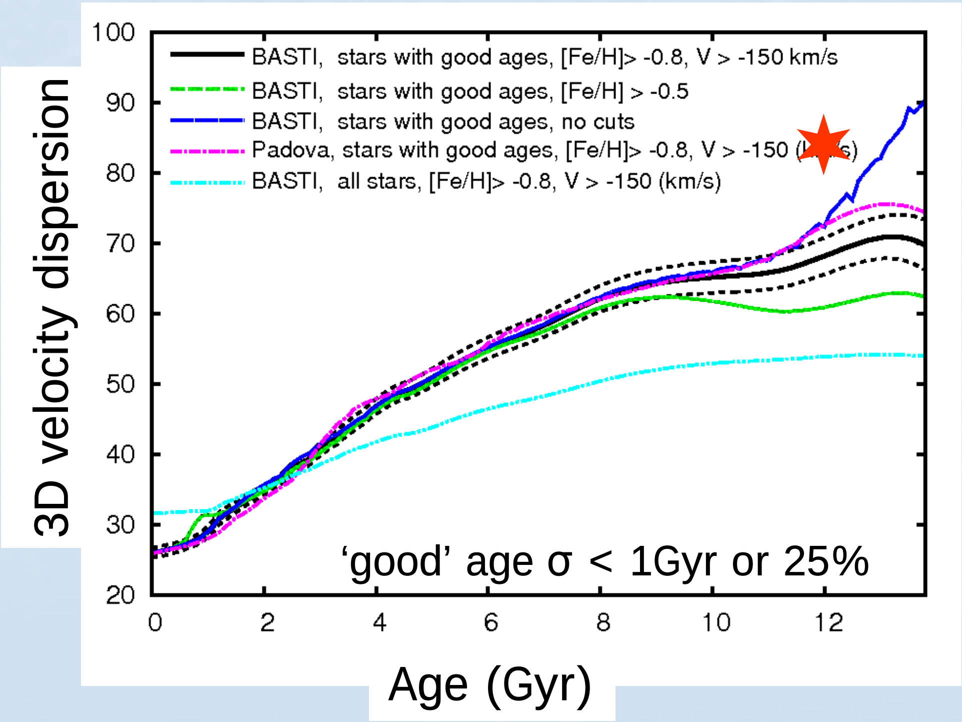
e.g. Wyse 2009

Milky Way Galaxy Thin Disk

- Local thin disk stars show age-velocity dispersion relationship : older stars are 'hotter'
- Exact trend difficult to define (age uncertainties, plus substructure in planar velocities – effect of bar plus spirals?)

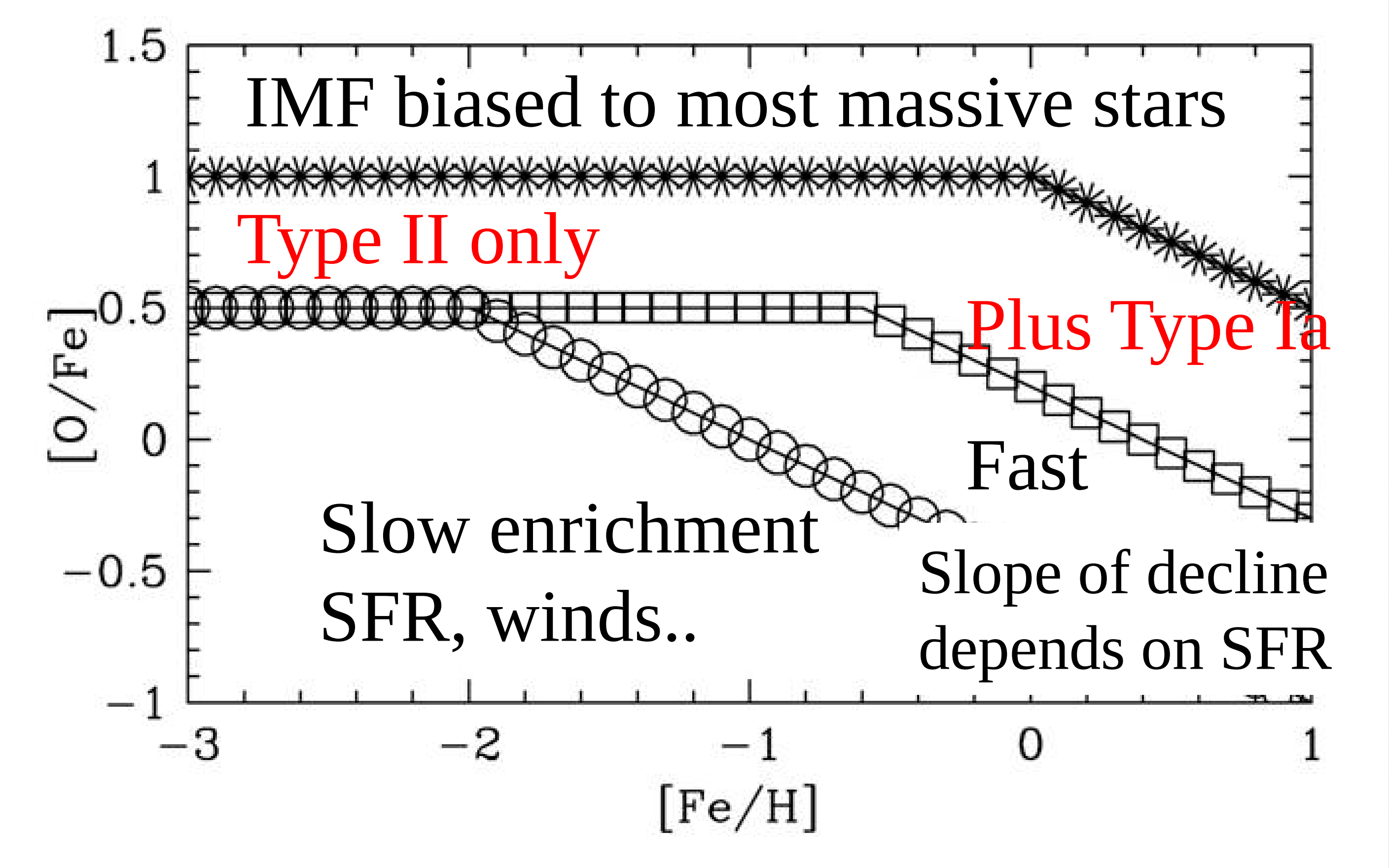
Casagrande et al 2011, analysis of the Geneva-Copenhagen Survey (Nordstrom et al 2004), F/G stars within ~ 100pc

✶ thick disk



Elemental Abundances: beyond metallicity

Alpha element and iron



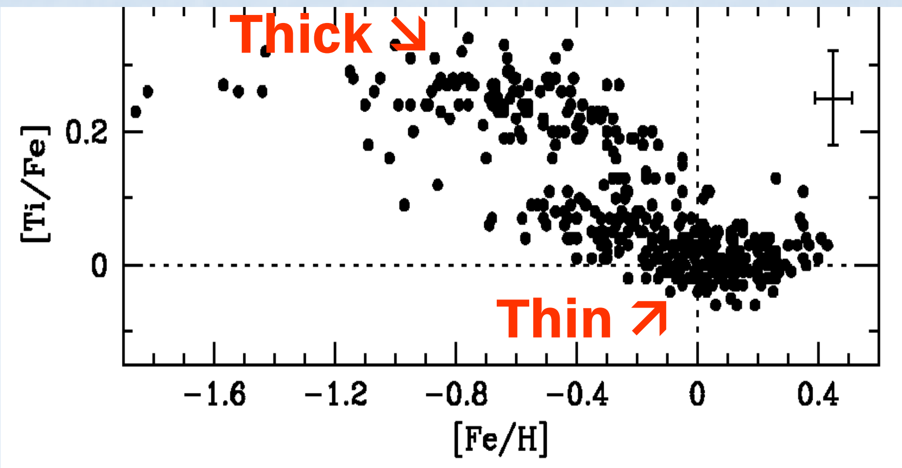
Self-enriched star forming region.

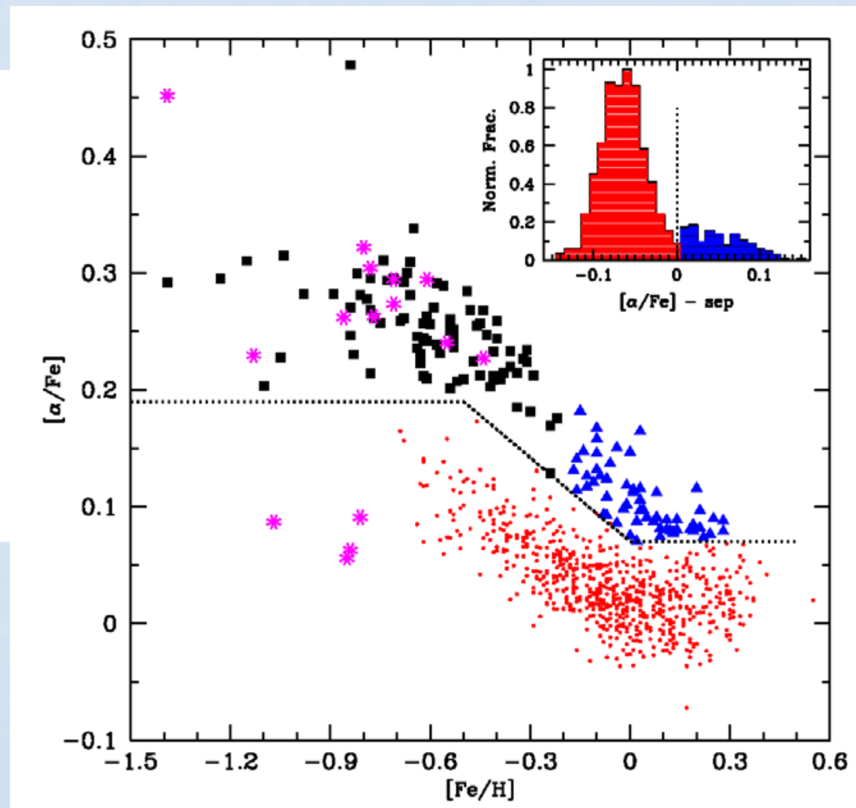
Wyse & Gilmore 1993

This model assumes good mixing so IMF-average yields

Very Local Galaxy

- Thick and Thin disks separated by elemental abundance pattern, obtained from high resolution spectra ➔ distinct star-formation and enrichment histories





Bensby et al 14

Adiekyan et al 13

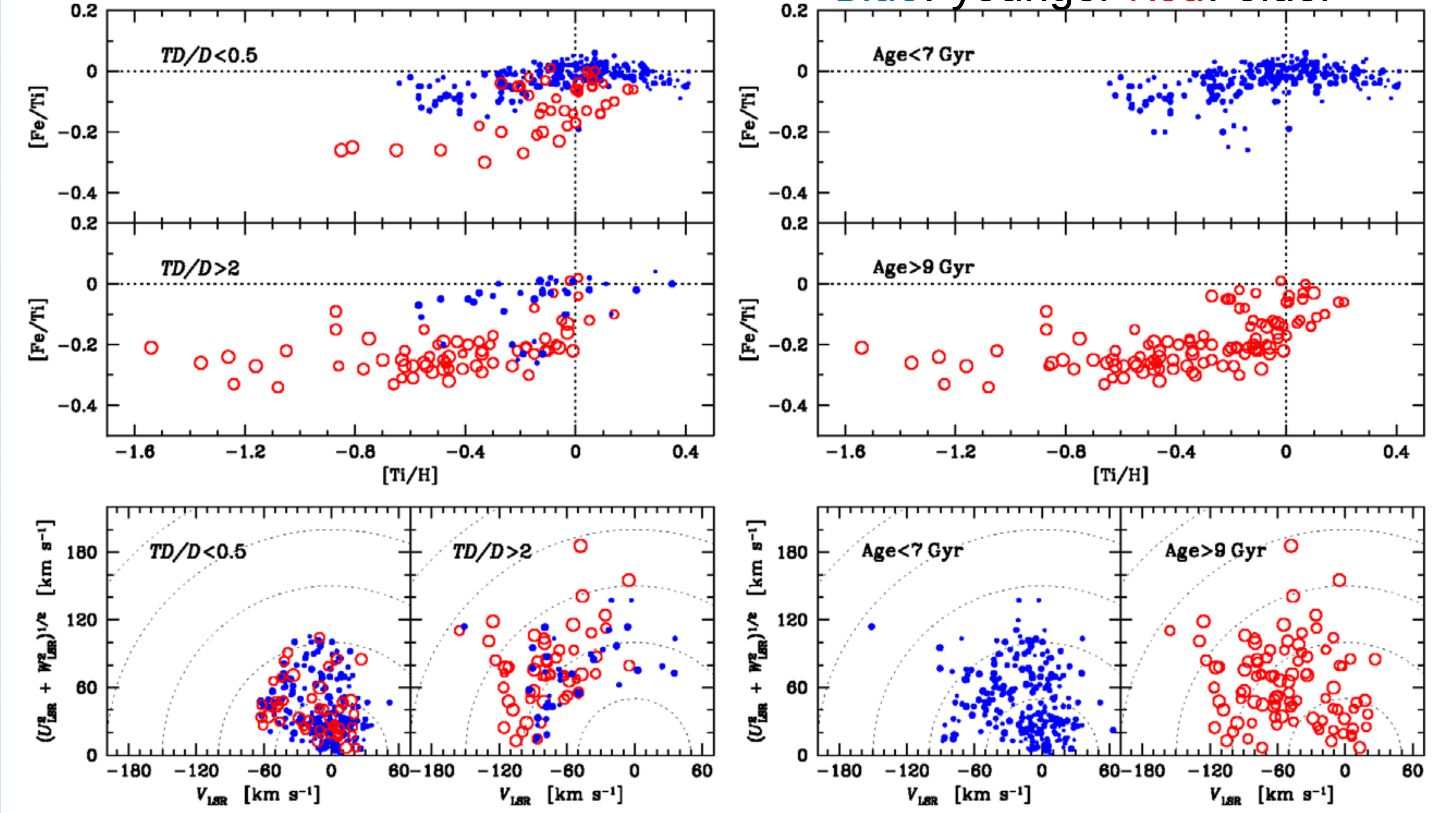
FG(K) stars within 100pc

Local Thick and Thin Disks

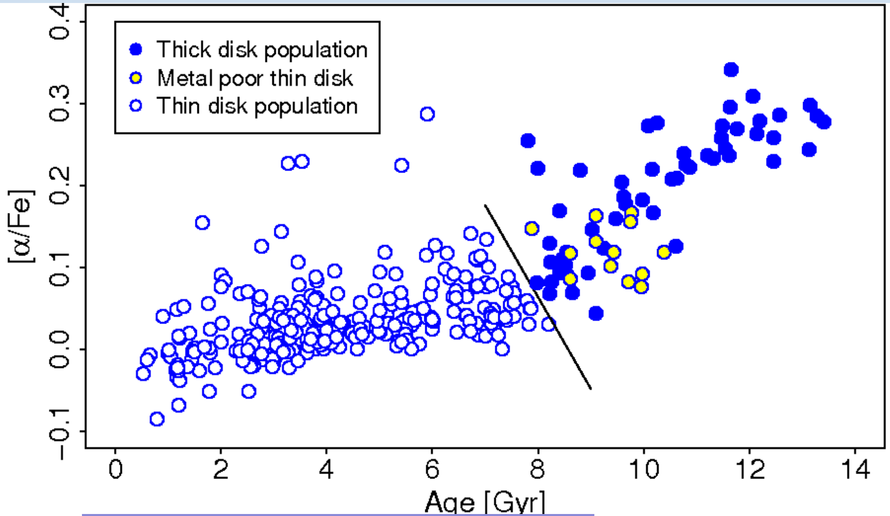
Kinematics-based definition

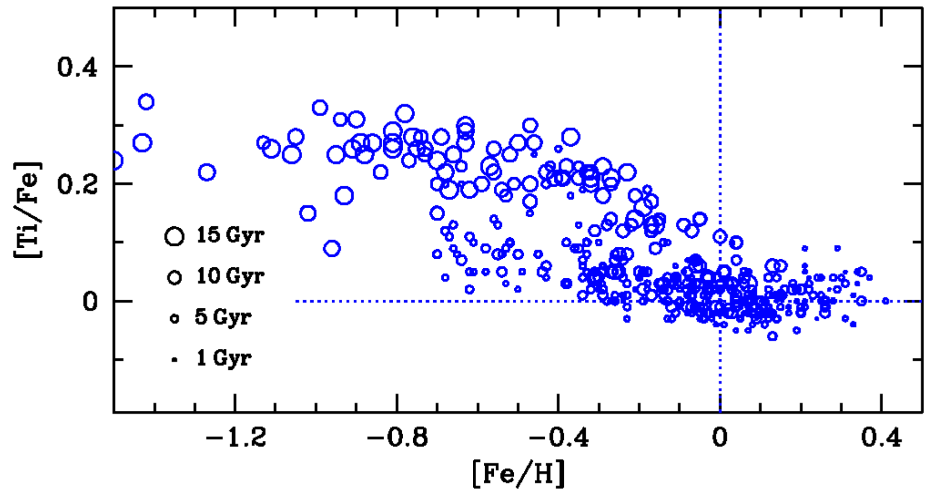
Age-based definition

Blue: younger Red: older

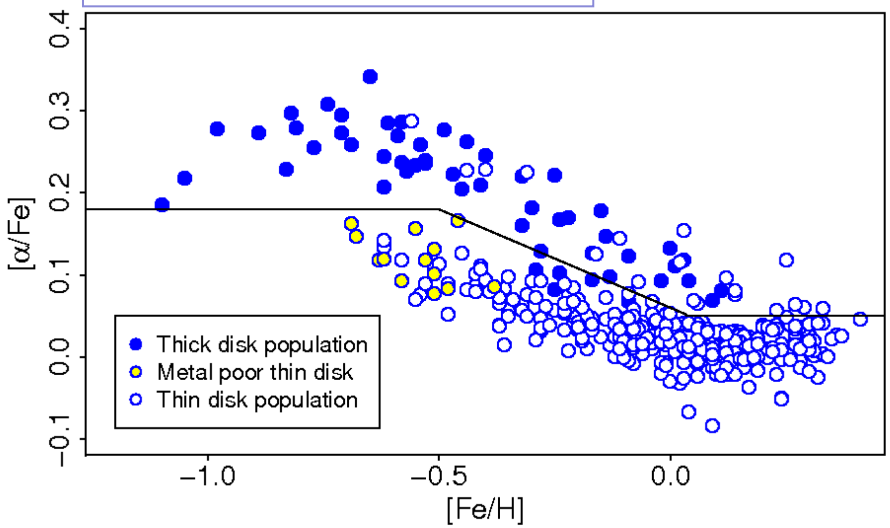


Bensby, Feltzing & Oey 2014





Haywood et al 2013



Bensby et al 2014

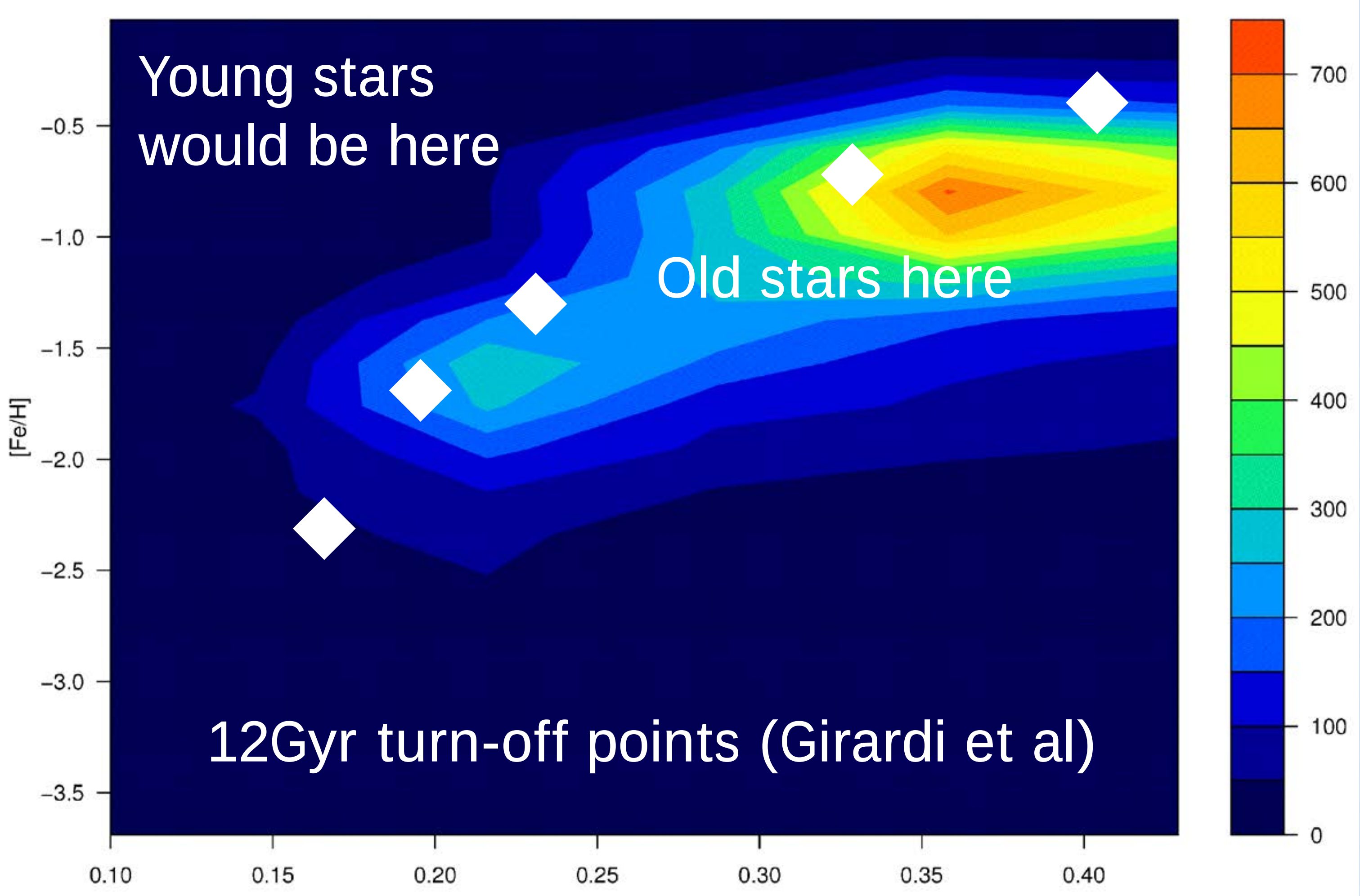
Adding ages to the local HARPS sample of Adibekyan et al 2013

- ➔ Thick disk is old and 'alpha-enhanced'
- ➔ Formed from gas predominantly enriched by core-collapse Sne
- ➔ Consistent with old age of turnoff, dominant population (Wyse et al 09)

Thick disk has OLD turnoff

Gilmore & Wyse 1985
Carney et al 1989……

[Fe/H]



$(g\text{-}r)_o$

Wyse, Gilmore, Norris

8,600 faint F/G dwarfs, several kpc above the plane, spectroscopic metallicities from AAOmega/AAT data

Non-Local Samples: SEGUE

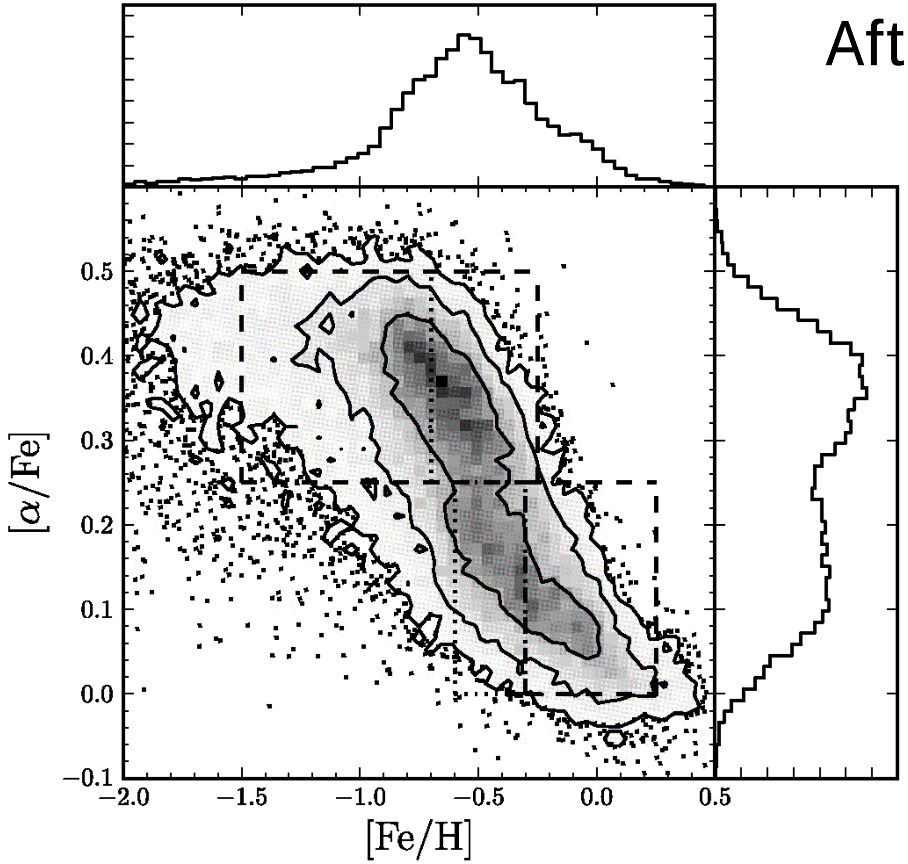
SDSS Segue survey, ~20,000 G dwarf stars several kpc distant

spectral resolution $\mathcal{R} \sim 2{,}000$ Not ideal for elemental abundances!

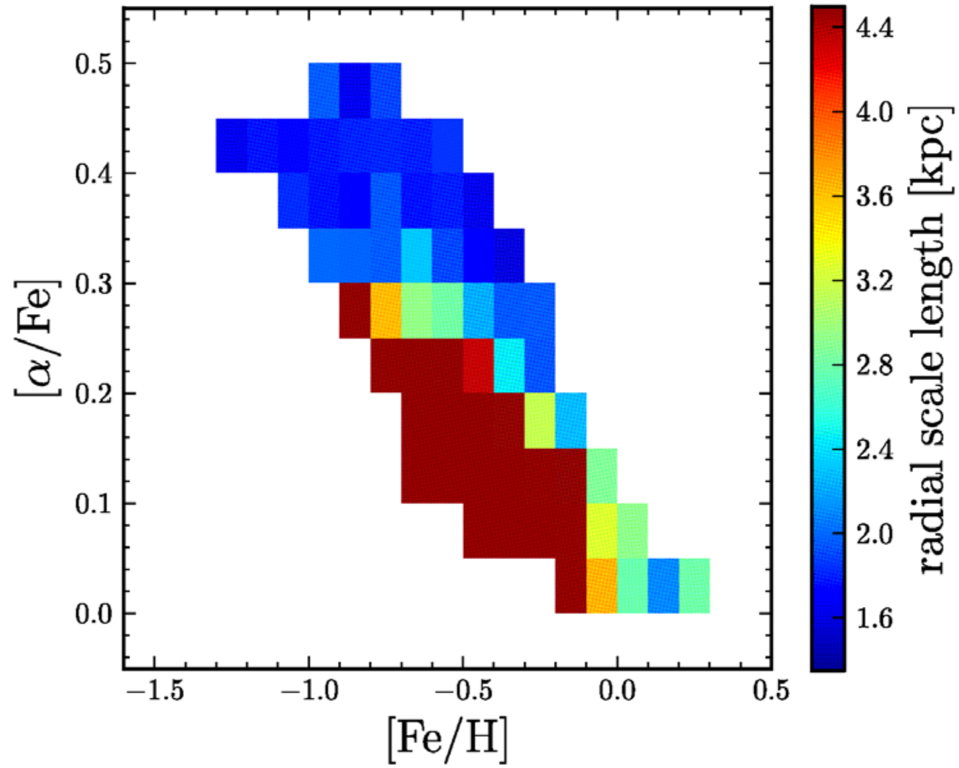
Bovy et al 2012

'The Milky Way has no thick disk'

Observed distribution

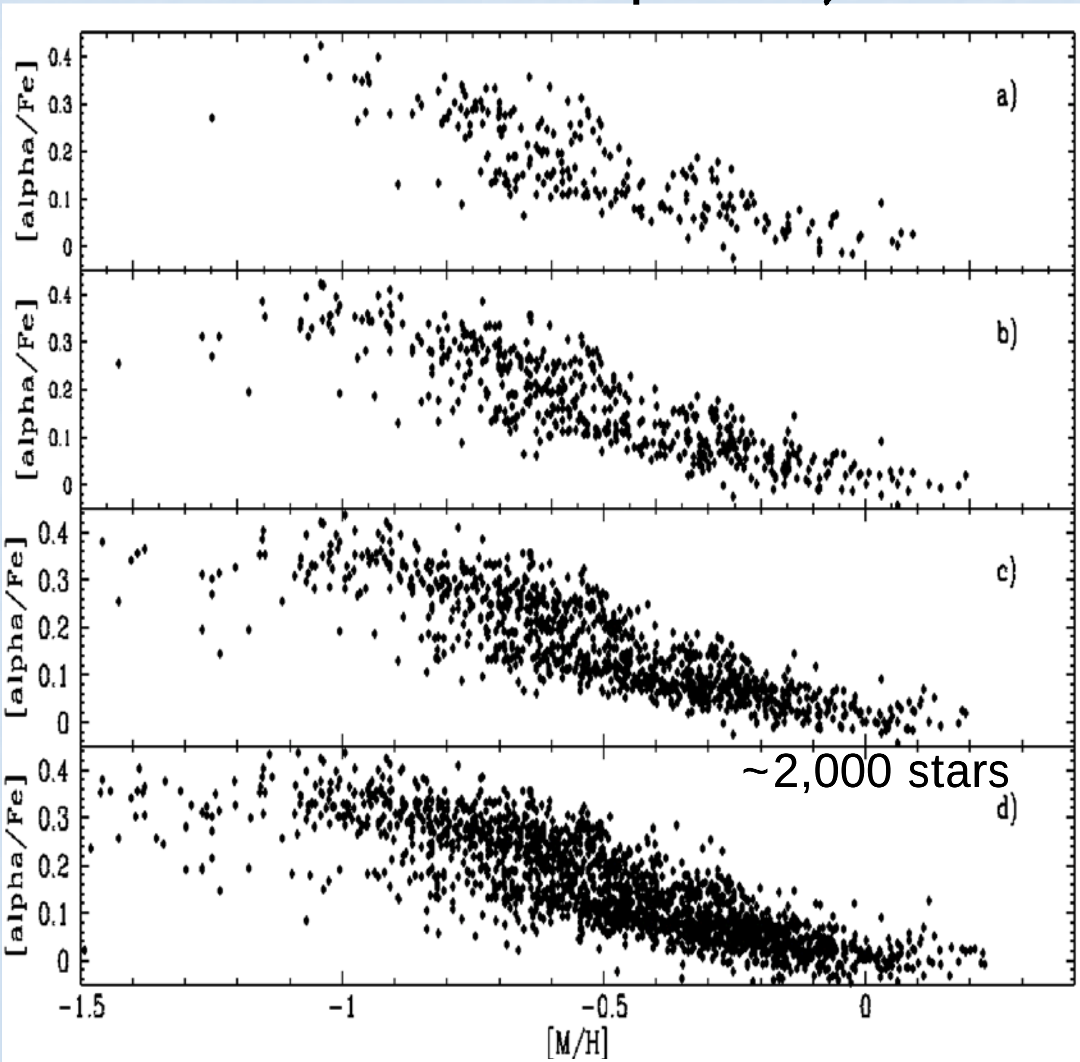


After correction for selection function



Non-Local Samples: GES

Gaia-ESO survey, FG dwarf stars several kpc distant (r < 18), VLT Flames/Giraffe spectra $\mathcal{R} \sim 20{,}000$



Errors increase a) (0.05 in [alpha/Fe]) → d)

Two sequences separated by low-density region: distinct thick disk.

Recio-Blanco et al (inc RW), 2014

300 VLT nights over 5 years
100,000 stars + clusters
PIs Gilmore & Randich
Started 12/2011

Also Ruchti & Bensby talks

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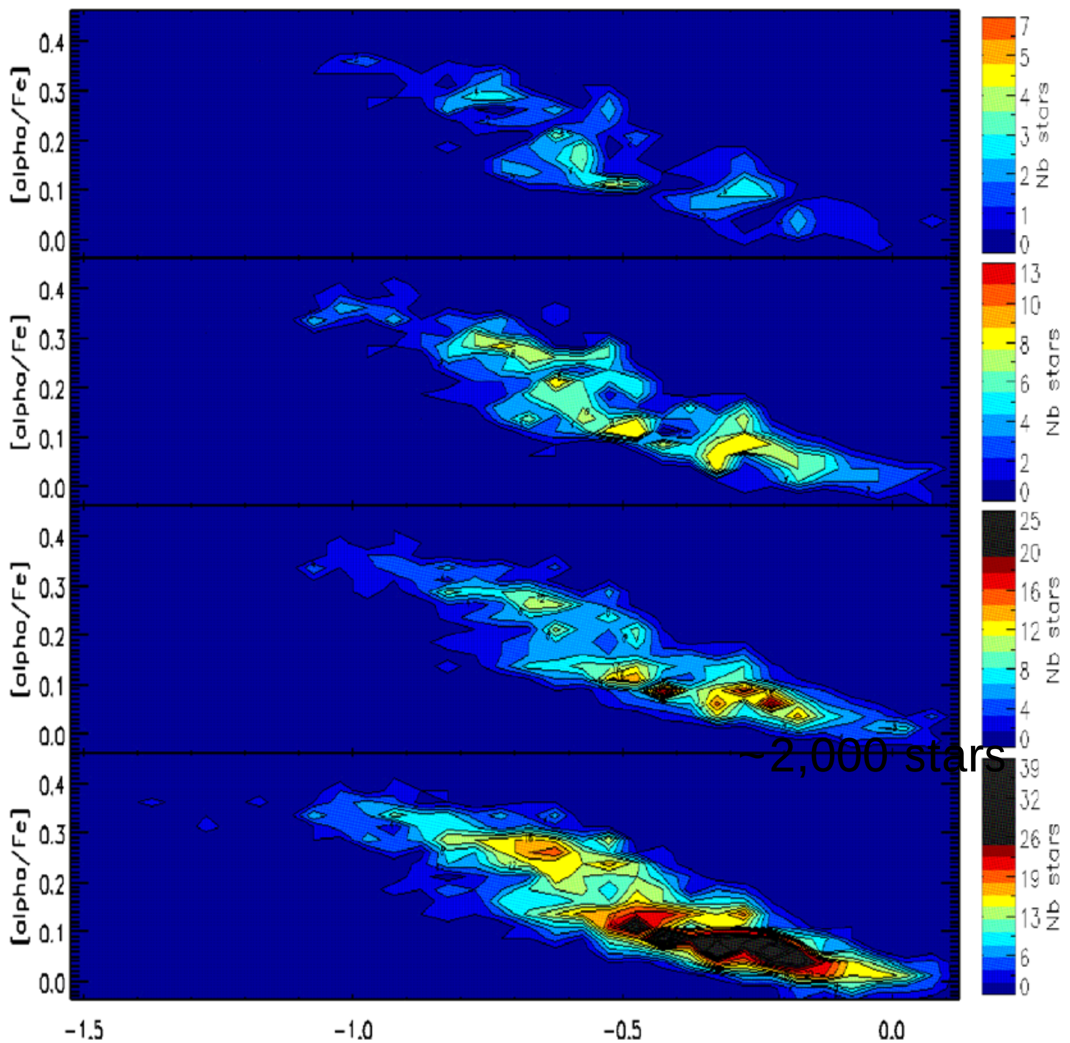

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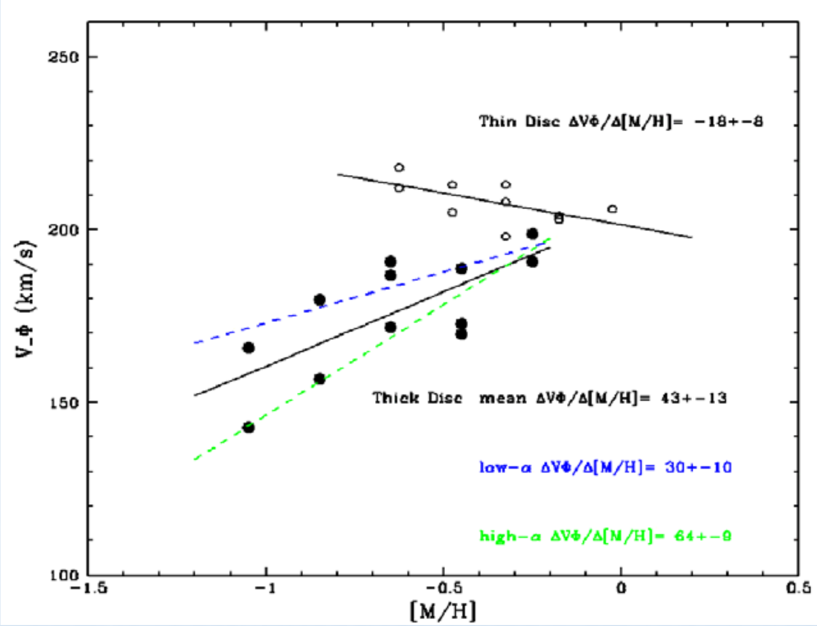
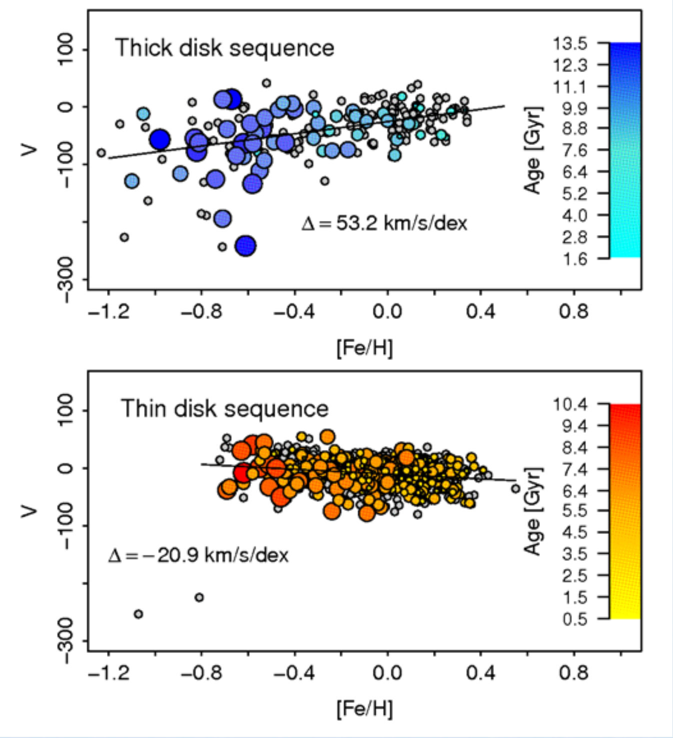
Opposite rotational velocity gradients for thin and thick disks:



Recio-Blanco et al 2014

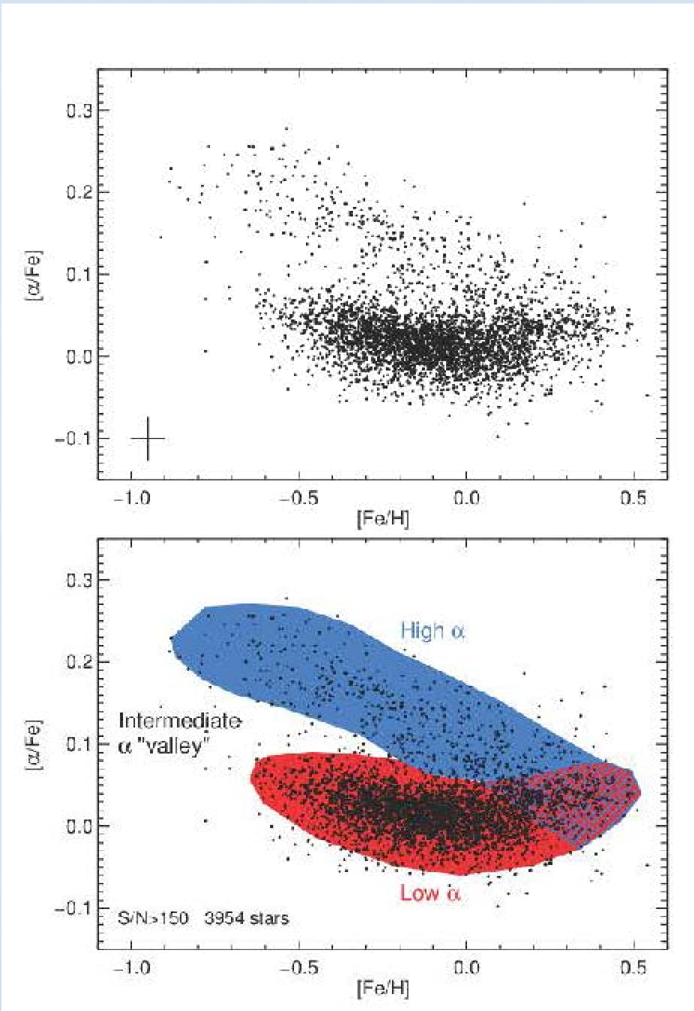


Haywood et al 2013

Qualitatively consistent with trends obtained by Bovy et al (2012) of increasing scale-length with increasing [Fe/H] for ‘high-alpha’ stars, and decreasing scale-length with increasing [Fe/H] for ‘low-alpha’ stars: scale-length should increase with increasing rotational velocity (for fixed velocity dispersions).

Non-Local Samples: APOGEE

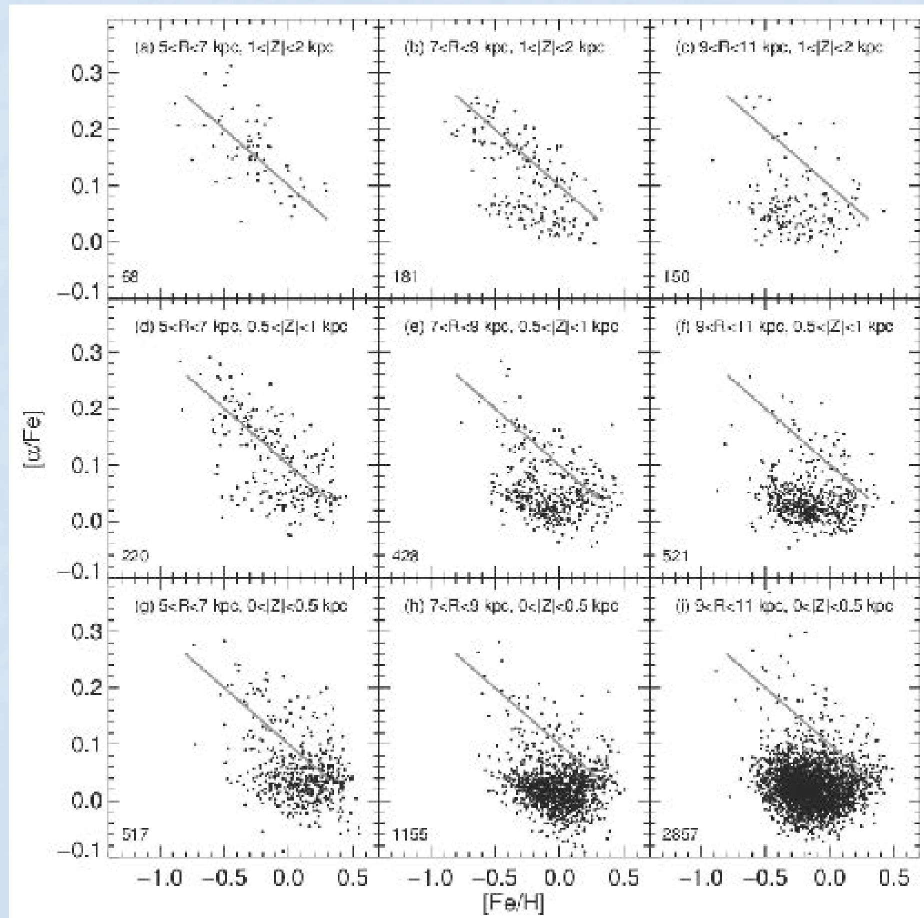
Nidever et al 2014



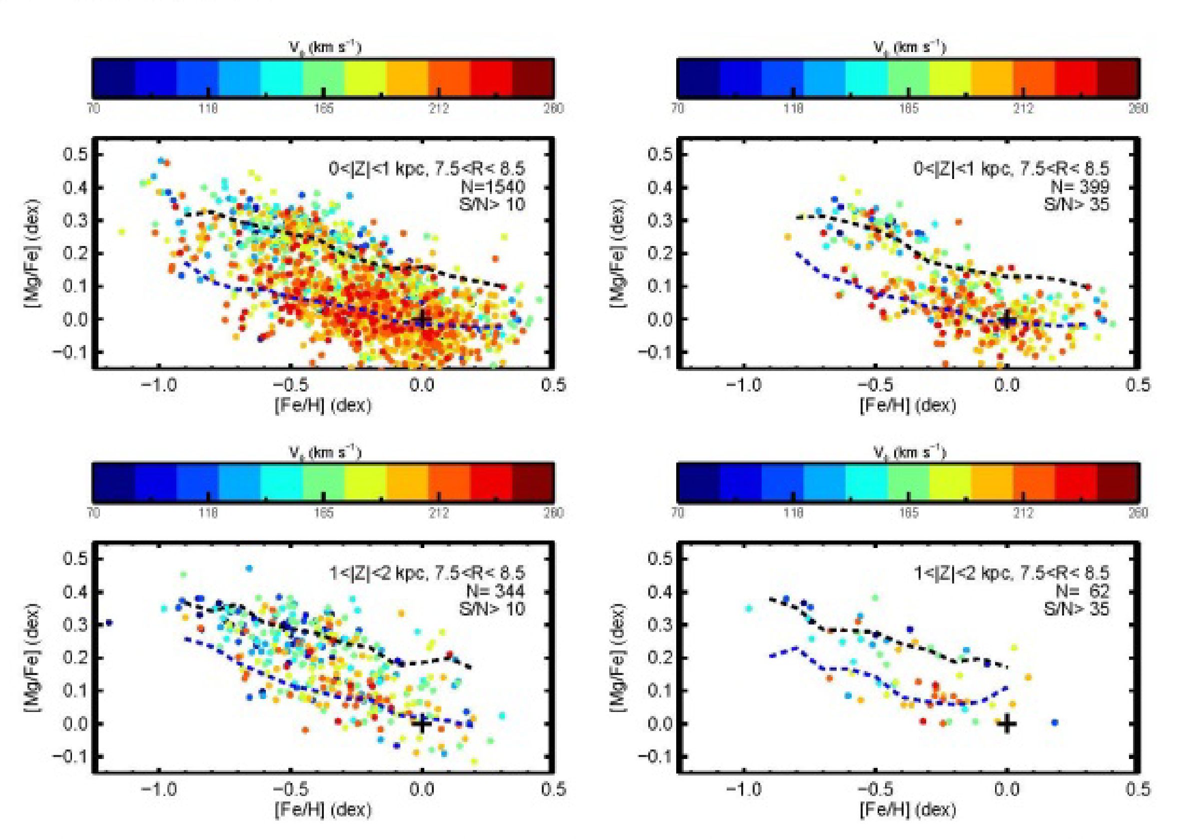
Thick disk sequence constant

Thin disk sequence changes with R,Z

➔ Varying star formation efficiency/outflow



Non-Local Samples: GES



Kordopatis, Wyse et al in prep

See also Bensby talk

- Distances of a few kpc
- Invariant thick disk sequence, changing thin disk (cf APOGEE)
- Investigating as function of kinematics, e.g. orbital rotational velocity

Distinct Galactic Thick Disk

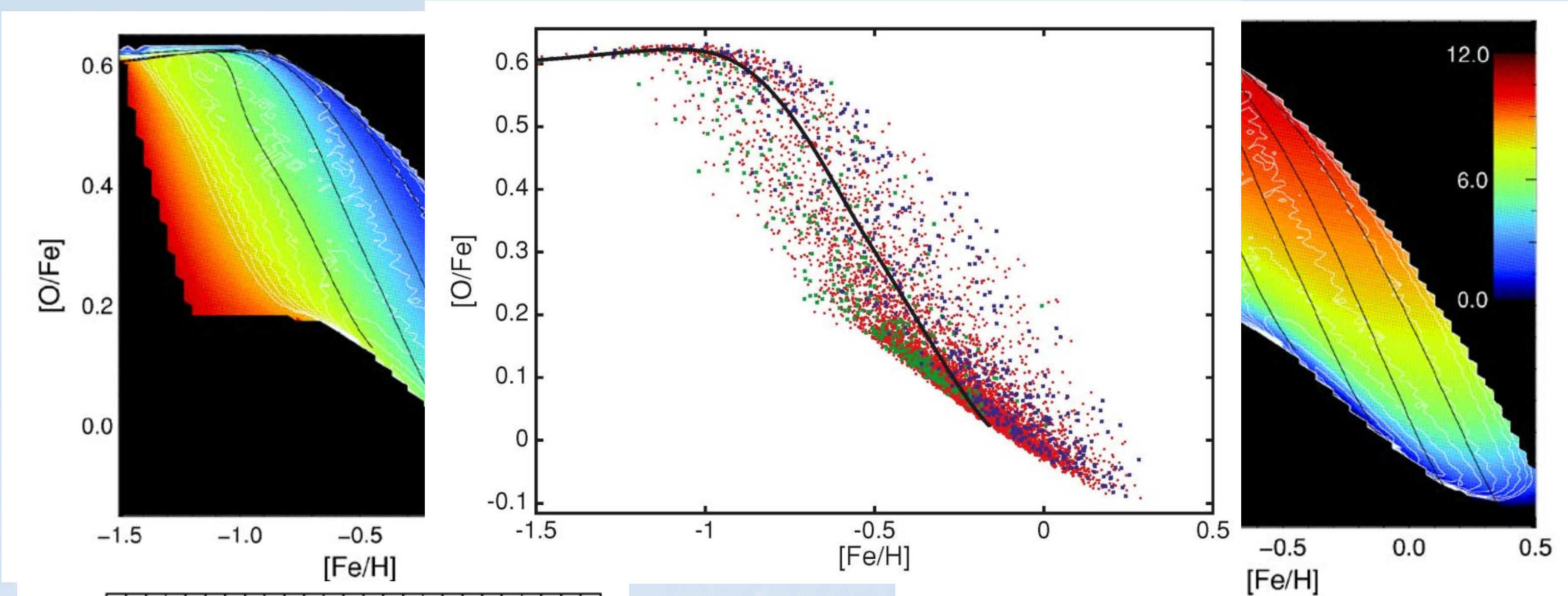
- Selection by kinematics, or age, or distance from the plane, or metallicity, or elemental abundance at given metallicity (best separation) gives broadly similar samples of 'thick disk' stars: distinct from thin disc ➔ can talk about 'the thick disk'
- Metal-weak thick disk has thick-disk kinematics (e.g. Kordopatis et al. inc RW 2013 – data from RAVE; Beers et al 14)
  - Metal-weak thick disk does have enhanced elemental abundances equal to those of stellar halo – invariant IMF (Ruchti, Fulbright, Wyse et al. 2010, 2011 – stars selected from RAVE)
- Similar stellar age distribution as bulge ➔ same event/mechanism? (Wyse, 2001; Comerón et al 2014)

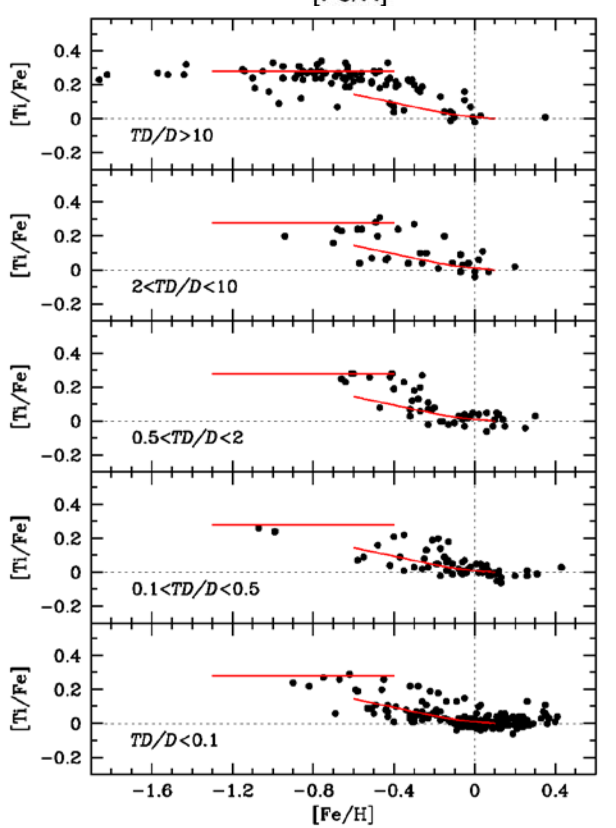
Internal, Secular Evolution

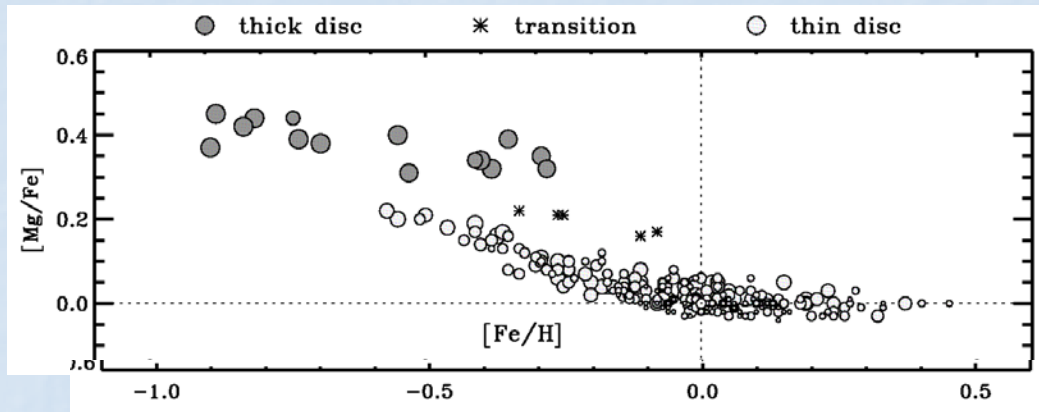
- Heating by in-plane spirals and GMC in present thin disk apparently insufficient to form thick disk, but play major role in thin-disk age-velocity dispersion relation
- Mixing from increased epicyclic excursions insufficient to provide observed scatter in age-metallicity relationship (for realistic metallicity/age gradients)
- **Radial migration** (Sellwood & Binney 2002) can move stars over ~ 2kpc while maintaining orbital circularity: acts at co-rotation resonance, needs many transient spirals of different pattern speeds to affect the entire disk
  - More effective for stars on close to circular orbits, less for populations of significant velocity dispersion, but also depends on spiral pattern (Vera-Ciro et al 2014; Solway et al 2012; Daniel & Wyse, in prep)
  - Be careful of usage of term ‘radial migration’ – heating or not?

Radial Migration to Form Thick Disk?

- Velocity dispersion of thin disk stars increases towards the central regions, as surface density increases; stars migrating outwards expected to reach higher scale-heights than local thin disk i.e. form a thick(er) disk (Schonrich & Binney 2009)
- Inner disk stars are older (inside-out formation?)
  ⇨ old(ish) thick disk, but expect age range to result
- Concept valid, importance not yet established quantitatively
  - Vertical energy not conserved (Solway et al 2012; Minchev et al 2012; Roskar et al 2013) so not so thick
  - Effectiveness of migration decreases with random motions (possible signature detected, decrease in velocity dispersion for highest [Mg/Fe] stars at high [Fe/H], Minchev et al, RAVE, 2014)
  - Chemical evolution model needs development
- Apparently plays important role in simulations but complicated (e.g. Bird et al 2012, 2013; Roskar et al 2012, talks here...)







Upper panels: Chemical evolution with radial migration, Schonrich & Binney 2009

Lower panels: (left) local stars sorted by Kinematics, Bensby et al. 2014; (right) symbol size scaled by age, Fuhrmann 2011

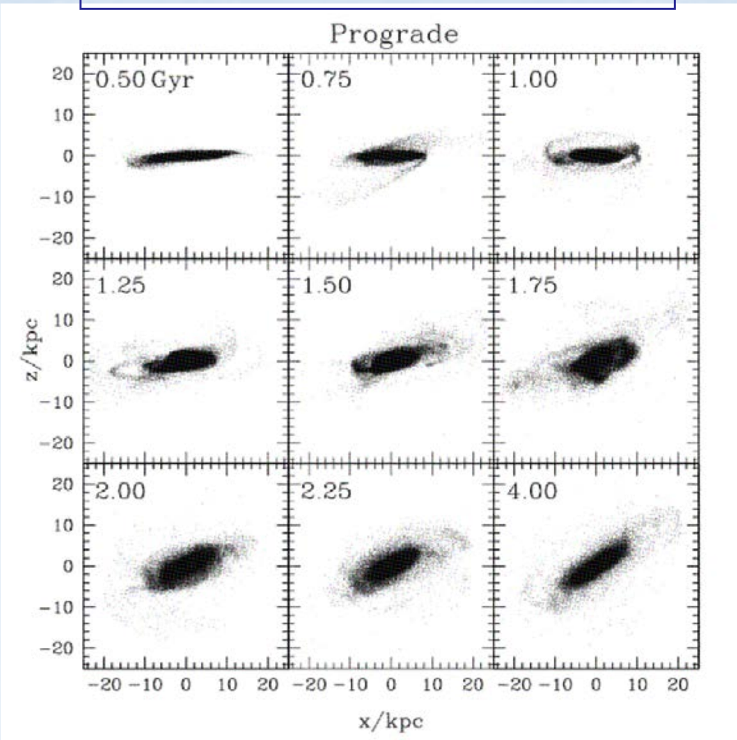
- Trends not well matched

Thick Disks through Minor Mergers

- Initially thin stellar disk; after merging orbital energy is absorbed into internal degrees of freedom of the disk, increasing vertical velocity dispersion and scale-height ➔ thick stellar disk.
  $\Delta\sigma^2 \sim v_{orbit}^2 \, M_{sat}/M_{gal}$ (Ostriker 1990, Gilmore & Wyse 1985)
- Orbital angular momentum gives tilt.
- Satellite debris spread through galaxy
- Thick disk will be compressed and heated by accretion of gas to re-form thin disk
- Re-start chemical evolution, form second sequence in elemental abundances (?)
  e.g. Snaith et al 2013

Villalobos & Helmi 2008

1:5 mass-ratio satellite (collisionless)

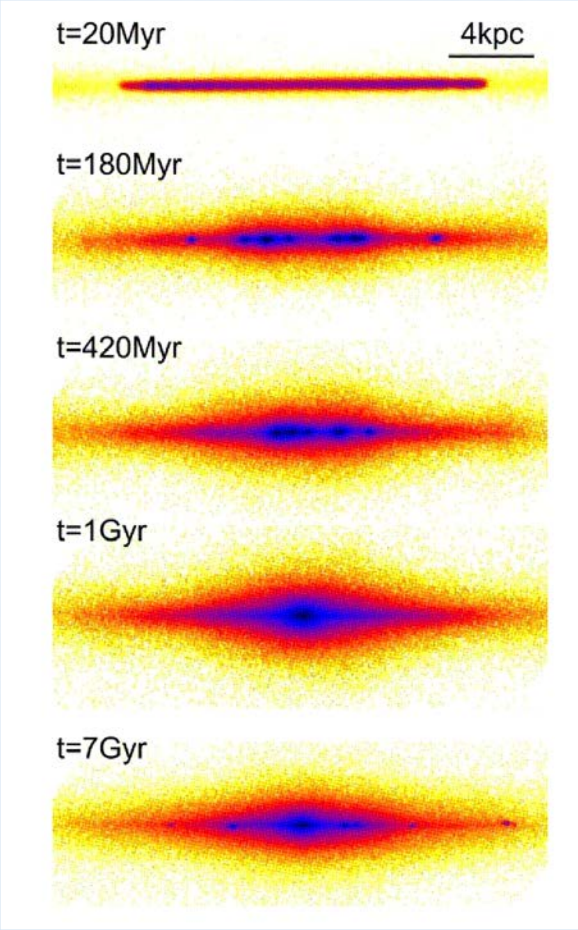


Including gas causes less heating/thickening (radiate energy); more mergers cause more heating ➔old age limits mergers to early times redshift > 2. Hierarchical clustering of ΛCDM generically leads to late mergers and broad range of ages in thick disk (and bulges)

Thick Disks without Mergers: Evolution of Clumpy Turbulent Disks at z~ 2?

- Gravitational instabilities form massive clumps, $M \gtrsim 10^8 M_\odot$, rapid star-formation plus scattering creates thick disk (Bournaud, Elmegreen & Martig 09)
- Early thick disks will be compressed and heated by accretion/re-formation of thin disk (Ostriker 1990; Elmegreen & Elmegreen 2006)
  - Adiabatic growth would lead to

$$\Delta H/H \sim -\Delta M_{gas}/M_{disk} \;\; ; \;\; \Delta\sigma^2/\sigma^2 \sim -2\,\Delta H/H$$



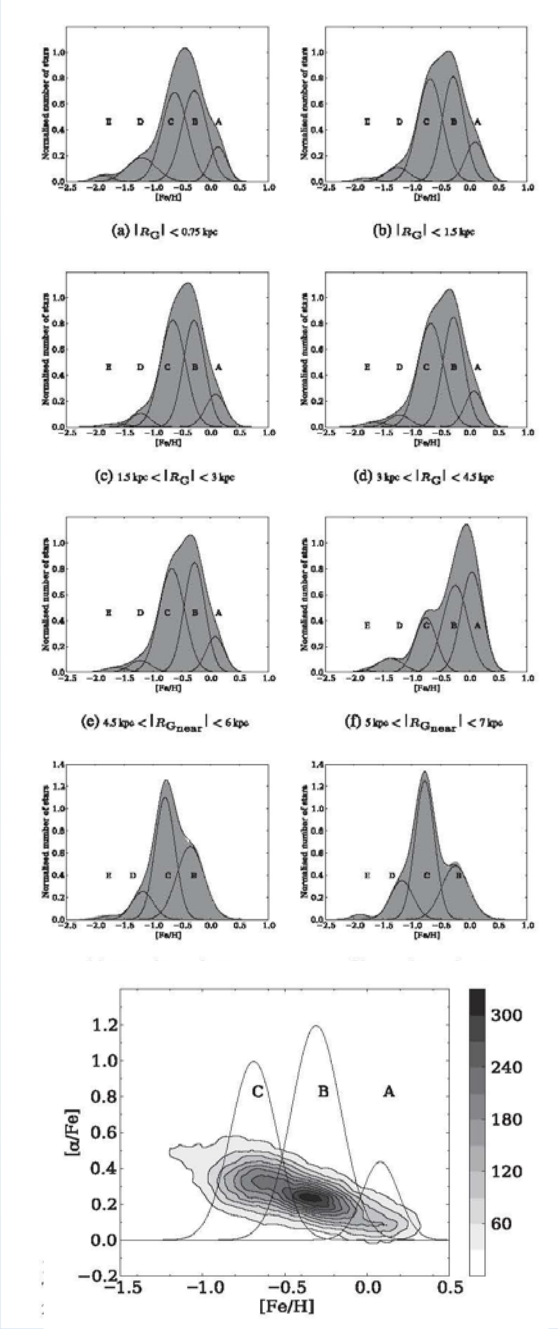
- Clumps alternatively/also form bulges
- Star formation during dissipative settling from thick to thin disk (Burkert et al 92) would form vertical metallicity gradient in thick disk
  ➔ hints of gradient, e.g. Reico-Blanco et al 14
- Would subsequent thin disk have separate elemental abundance pattern ?
- Mergers would reheat – need very quiescent (Bird's talk – no significant merger since redshift of 3)

Relation to bulge?

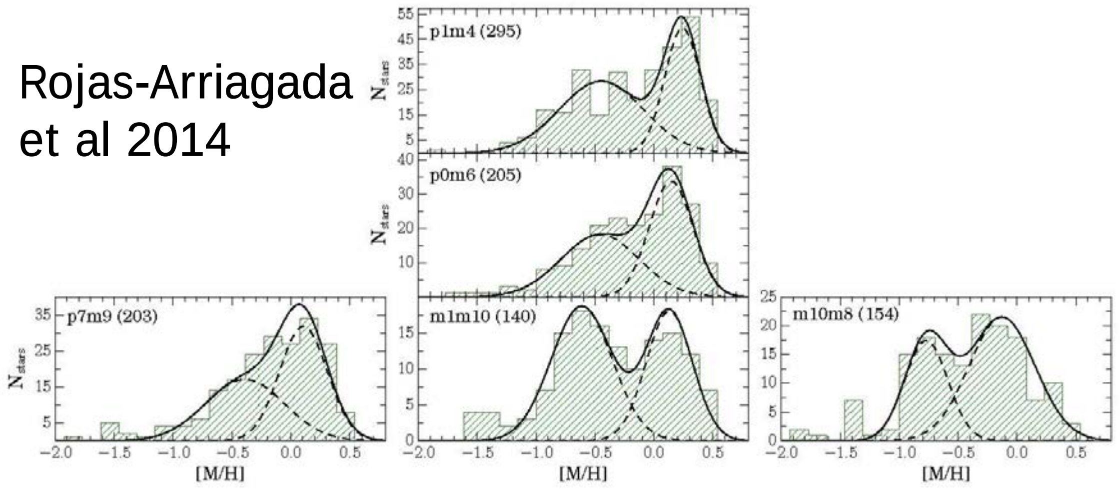
- Both Galactic thick disk and Galactic bulge dominated by old population
- Mean metallicity of local thick disk lower than that of bulge (factor 1.5 – 2) – need data for inner disks
- Changes in stellar metallicity distributions in lines-of-sight to bulge can be modelled as changing mix of populations (Ness et al 2013; Rojas-Arriagada et al, inc RW, 2014)

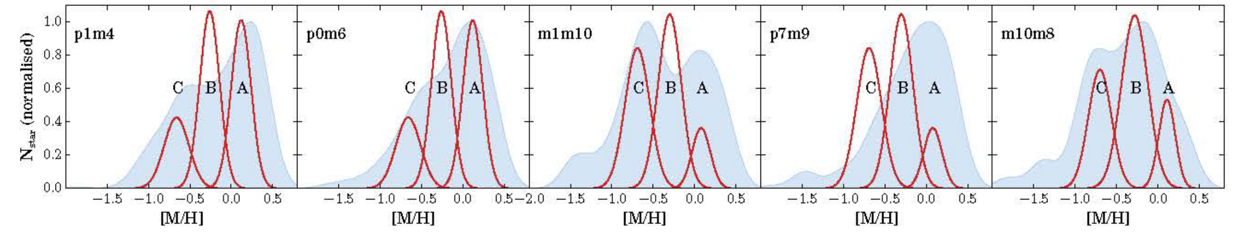
  – what are they?
- Elemental abundance patterns merge (Melendez et al 2008; Ness et al 2013)
- More data (APOGEE, GES, HERMES..) and modelling (e.g. Immeli et al 2004) are needed!

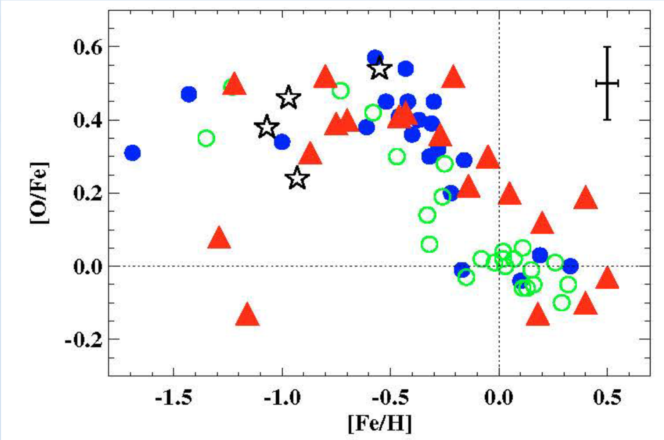
Ness et al 2013



Rojas-Arriagada et al 2014







Melendez et al 08

● - thick disk

☆ - halo

▲ - bulge

o – thin disk

Conclusions

- Thick disks and their relation to thin disks lie at the core of nature vs nurture, internal vs external influences on galaxy evolution
  - Galactic thick disk appears distinct from thin disk
  - Old, little merging since redshift of > 2
  - Unusual in ΛCDM (few percent only of mass of Milky Way!), but selected for 'zoom-ins' of Milky Way analogues
- Ongoing massive spectroscopic surveys should elucidate connections among stellar components

  → How the Milky Way evolved - a typical disk galaxy

- Great complementarity between study of old nearby resolved stars and direct study of systems forming at high redshift: will only improve as new facilities and capabilities become realized