The Structure and Substructure of the Milky Way Galaxy Discs

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The Fossil Record: Galactic Archaeology

- Studying low-mass old stars ➔ near-field cosmology
  - There are copious numbers of stars nearby that have ages $\gtrsim$10 Gyr : formed at redshifts > 2 - thin disc, thick disc, bulge, halo, satellite galaxies
  - Retain memory of initial/early conditions: elemental abundances, orbital angular momentum/integrals – modulo torques - kinematic and chemical phase space structure
- Break degeneracy of integrated light
  - Can derive metallicity independent of age, dust etc
  - Stellar Initial Mass Function – count stars for low-mass end; elemental record for high-mass end
- Panoramic photometric, astrometric and spectroscopic surveys are transforming (and will transform) the field

What can we learn from disc stars?

- Thin stellar discs are fragile and can be disturbed by external influences such as companion galaxies and mergers, in addition to internal perturbations such as spiral arms, bars and Giant Molecular Clouds
- Stellar systems are collisionless - cannot ‘cool’ once heated, unlike gas
  - Vertical structure: heating/merging/dissipational settling
  - Radial structure: inside-out growth, imprints of angular momentum distribution/re-arrangement

➔ Thin disc/thick disc dichotomy: earliest phases of disc, heating history, timescales

➔ Stellar Radial Migration within thin disc: size evolution, onset of star formation in outer regions

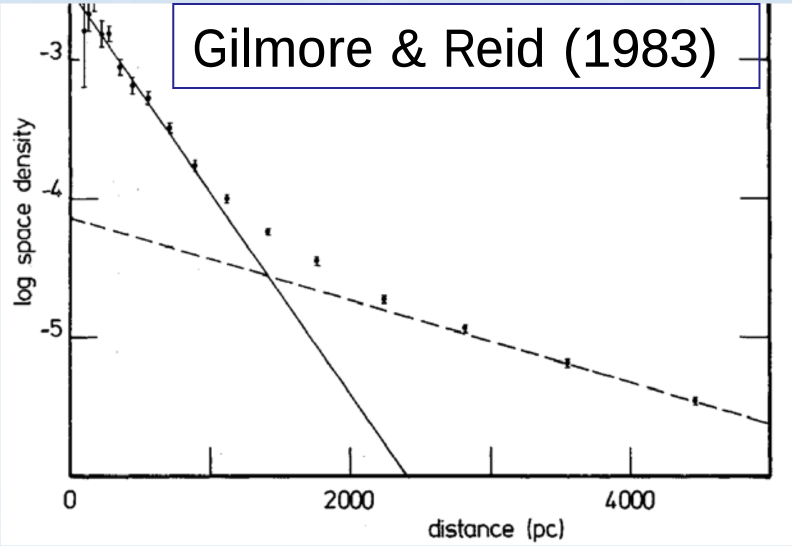
➔ Bending modes in thin disc: internal, not external substructure

Star Counts: Thick/Thin Discs

- Thick discs identified first in surface brightness profile in S0 galaxies – bulge, thin disc plus an additional exponential vertical fall-off, constant scale-height with radius (Burstein 79, Tsikoudi 79)
- Detected in many disc galaxies (van der Kruit 80s; Comeron et al 12
- Star counts at the Galactic Pole fit by two exponentials
- Kinematic and metallicity data characterized as old and distinct from halo and thin disc (e.g. Wyse & Gilmore 1986, 95; Ratnatunga & Freeman 89)
- Or continuous with thin disc ? (e.g. Norris 87; Bovy et al 2012)
- Newer data → distinct

→ oldest disc stars - earliest phases of disc

Gilmore & Reid (1983)



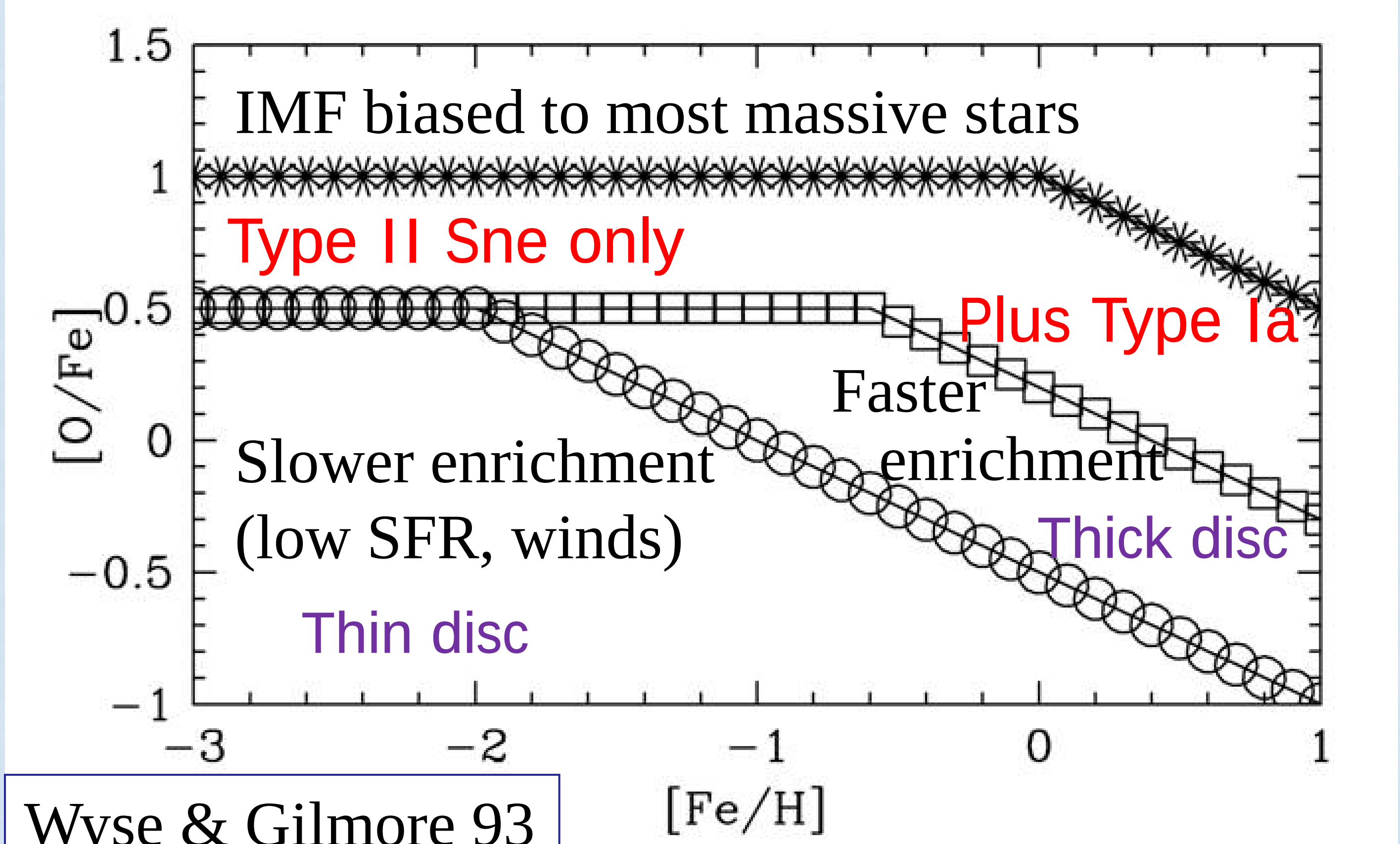
Local Milky Way Thick Disc

- Kinematics intermediate between thin disc and halo
  - mean rotation velocity lags thin disc by ~ 50km/s, vertical velocity dispersion ~ 40km/s ➔ thick, with scale height of ~1kpc
    - too hot to result from internal disk heating e.g. spiral, GMCs
    - Discontinuous trend with thin disc ➔ Exceptional event?
- Mean metallicity ~ -0.5 dex
- Elemental abundances 'alpha-enhanced' ([α /Fe] > 0)
  - Discontinuous trend with thin disc ➔ distinct component
- Most thick disc stars are old, ~ 10-12 Gyr → redshift > 2
  - Strong constraint on merger history, disc heating and radial mixing
- Derived mass > 20% (50%?) of thin disc mass i.e. > 10^{10} $M_\odot$
  - Mass and inferred SFR similar to star-forming discs at redshift ~ 2
  - Turbulent gas - need stellar data!

Freeman, Norris, Morrison, Rockosi, Carney, Majewski, Gilmore, Wyse....

Elemental Abundances: star formation history and enrichment history

Alpha element (core-collapse SNe) and iron (Type Ia SNe)

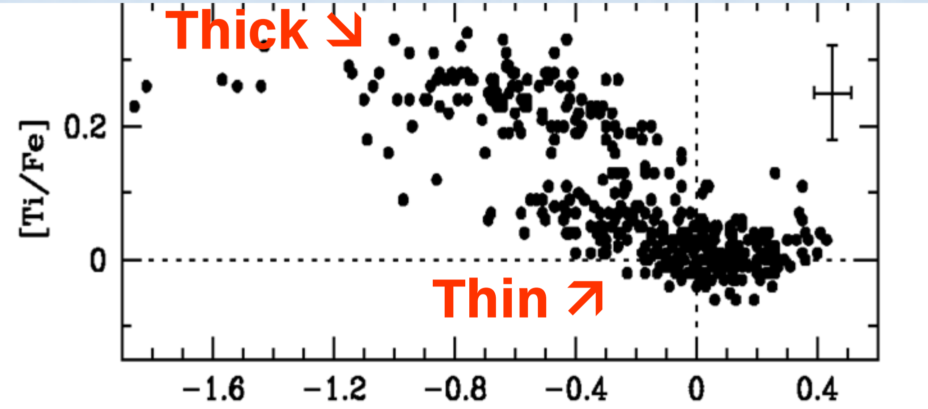


Wyse & Gilmore 93

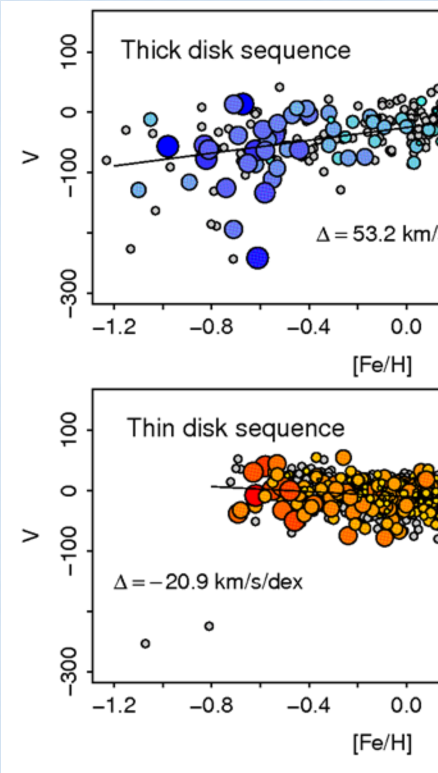
Self-enriching star-forming region, non-bursty star formation.
Model assumes massive-star IMF average yields

Very Local Thick and Thin Discs

- Very local Thick and Thin discs separated by elemental abundance patterns, obtained from high resolution spectra ➔ distinct star-formation and enrichment histories
- 'High-alpha' sequence is old, has 'hot' kinematics: thick disc



Bensby et al 2014

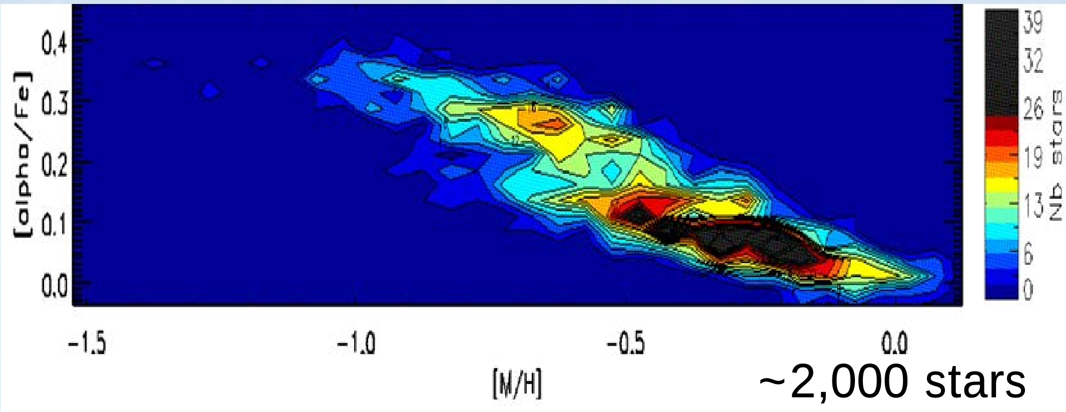


Haywood et al 2013

Very nearby FG(K) stars: not volume complete

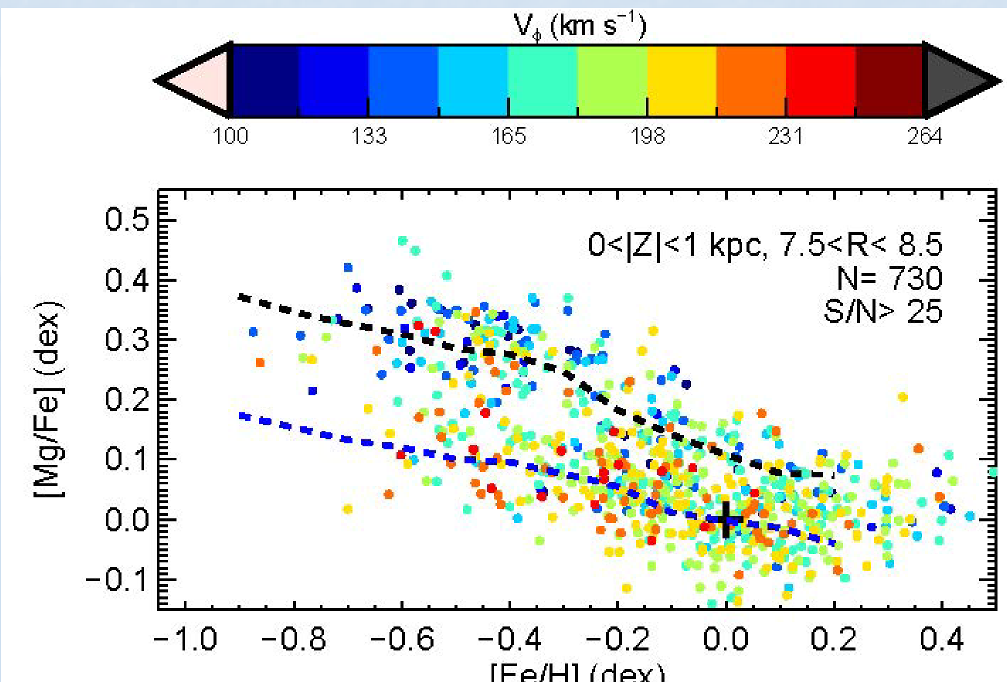
Non-Local Samples

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



~2,000 stars

Two sequences separated by low-density region: distinct thick disc (Recio-Blanco et al inc RW 2014)

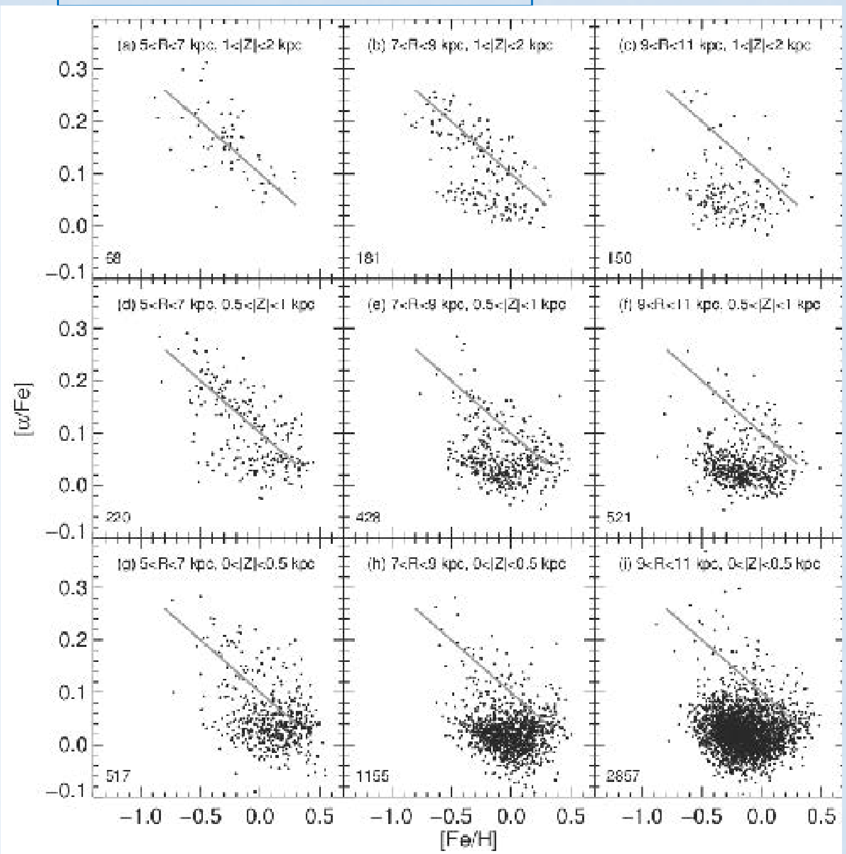


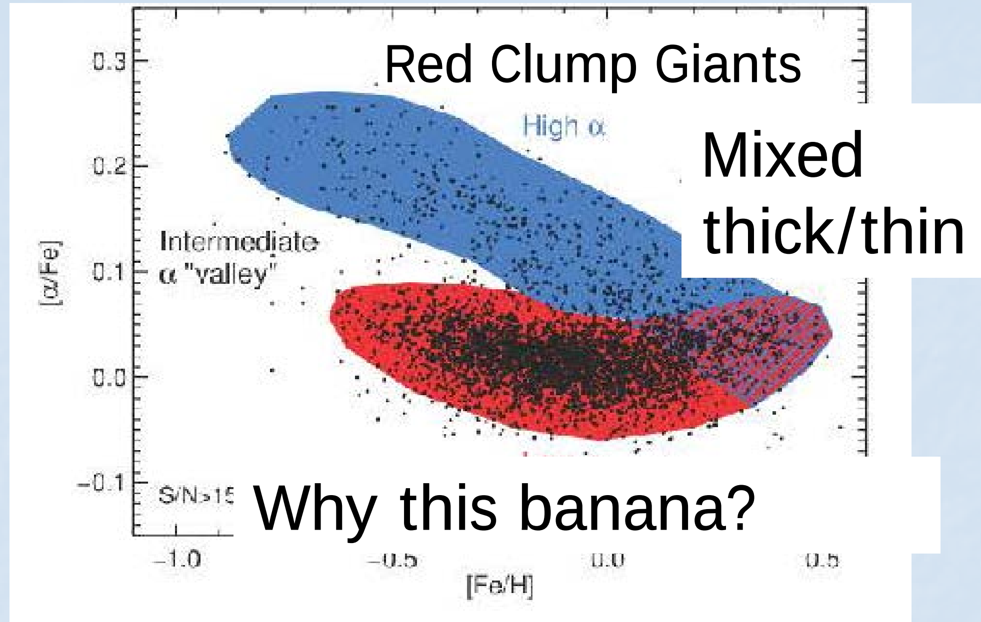
Different orbital rotation velocity distributions; thick disc stars lag behind thin disc (Kordopatis, RW et al 15)

Gaia-ESO: 300 VLT nights over 5+ years (end 2017), 100,000 field stars + open clusters PIs Gilmore & Randich

Non-Local Samples: APOGEE

Nidever et al 2014

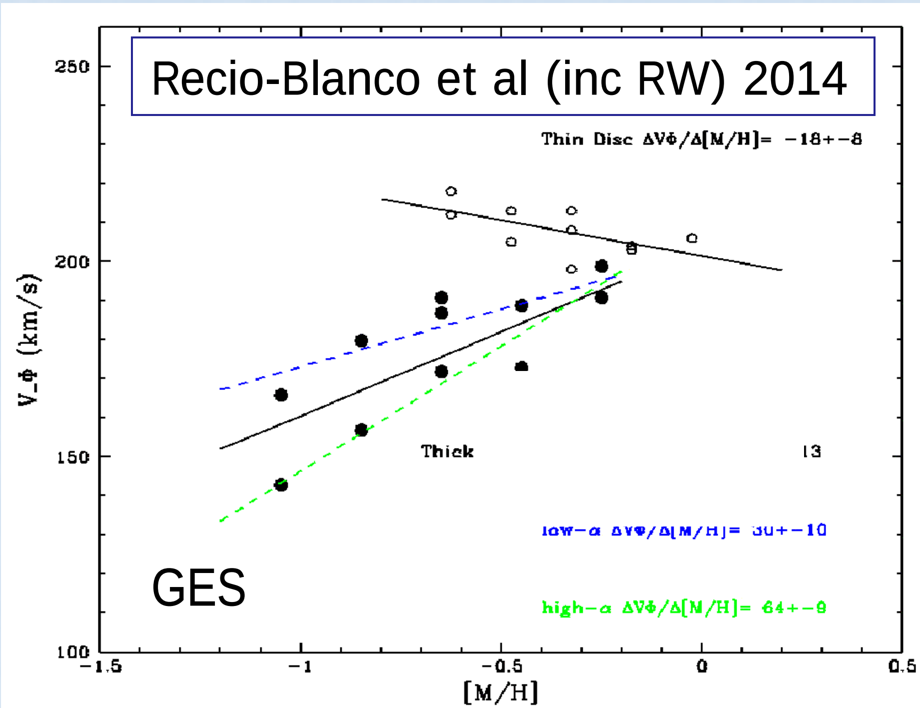


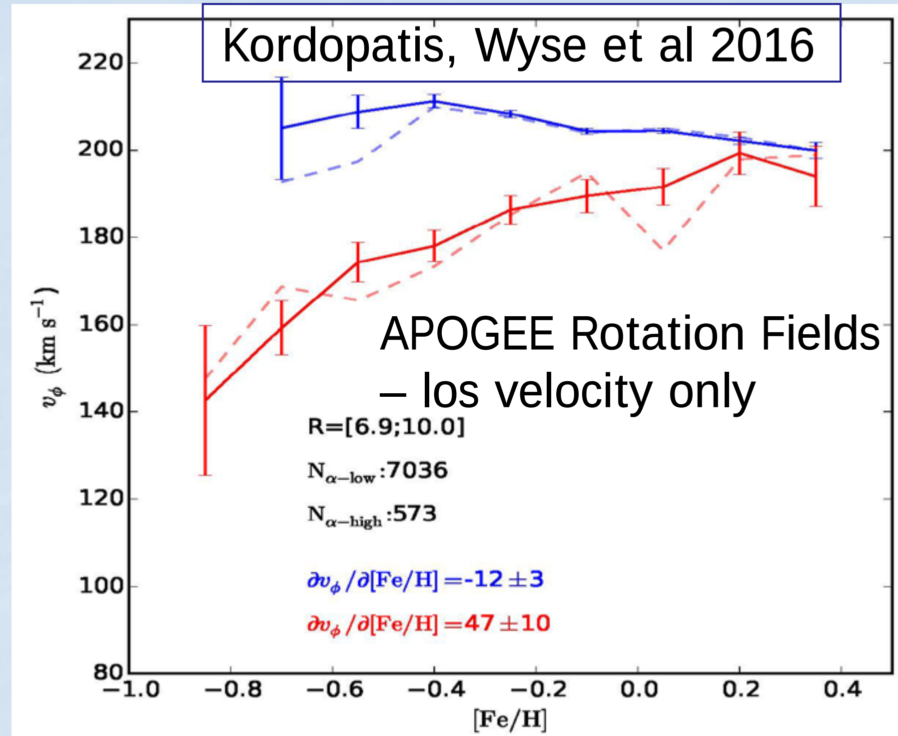


- Distinct thick and thin discs
  - Thick disk sequence invariant
  - Thin disk sequence changes with R,Z
    - ➔ Varying star formation efficiency

- Short thick disc scale-length
  - How to reconcile with star-counts and external galaxies? Flaring, mixture of components? (Minchev et al 2015; Ness talk)

Adding kinematics Very different rotational velocity trends for thin and thick discs:

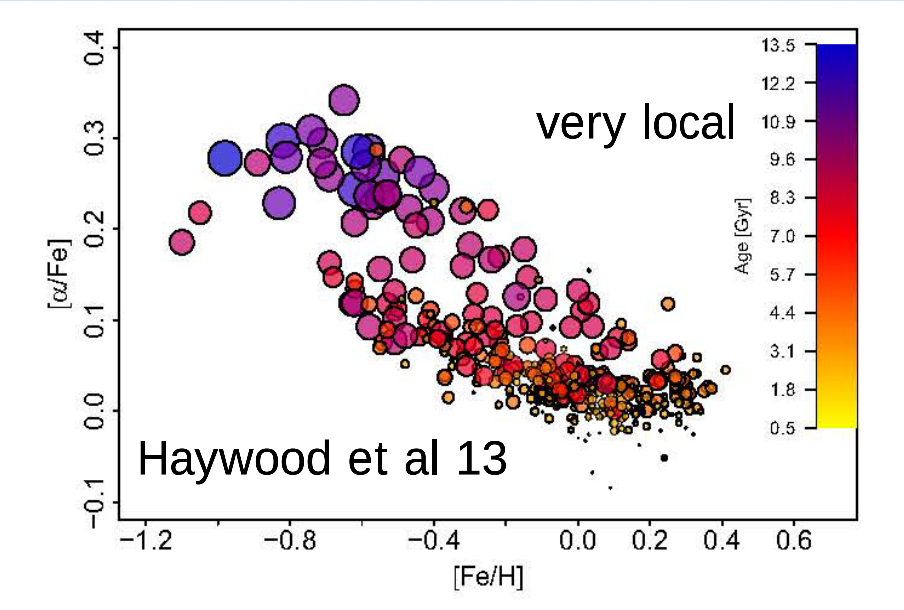


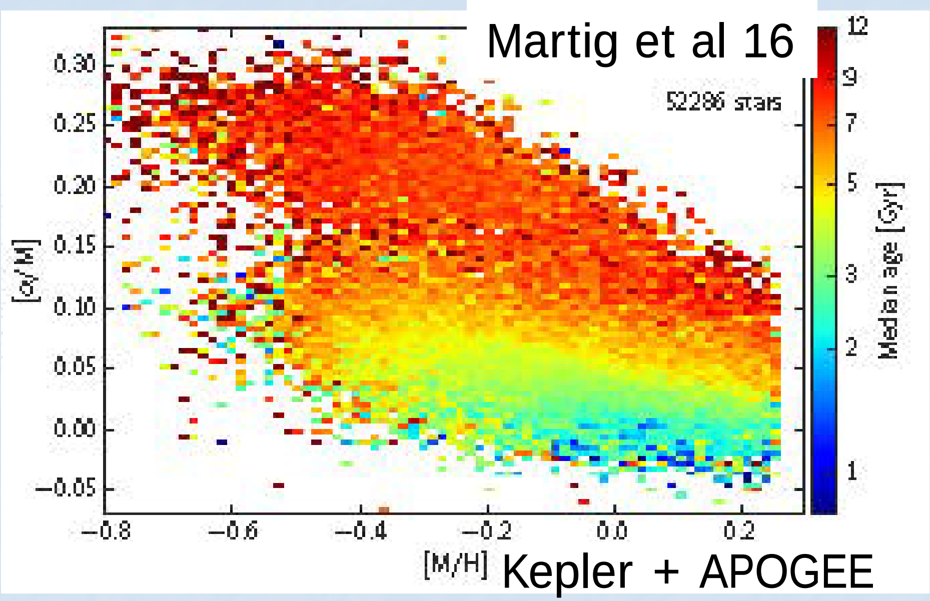


- Qualitatively consistent with dynamical equilibrium (radial Jeans equation) and scale-length - metallicity – [α/Fe] trends (cf Bovy et al 2012) ➔ needs quantitative analysis and models
- Dissipational collapse and spin-up of proto-thick disc? But shallow radial and vertical metallicity gradients (Hayden et al 14)

- Thick disc stars are old – as are some thin disc stars

NB: Thick disc peak [Fe/H] ~ -0.5





Age-metallicity-[α/Fe] relation in local thick disk

APOGEE DR12: Obtain mass estimate from C/N ratio, calibrated by ~ 1500 stars with asteroseismology data from Kepler ➔ ages

See Melissa Ness talk

Old Age of Thick Disc Stars Limits Merger History

- Thick disc (likely) forms prior to equilibrium/virialization of halo ➔ while active assembly/mergers, turbulent gas
- Mergers heat the thin disc and input stars formed up to that epoch into the thick disc
- There are stars of all ages in the thin disc, reflecting continuous star formation since early times
- Dominant old age of thick disc implies no significant merger since redshift at which look-back time age of thick disc
  - Quiescent merger history since redshift $\gtrsim$ 2 (Wyse 2001)
- Active merger history would also build-up (classical) bulge
- Minor mergers/interactions e.g. Sagittarius dwarf affect outer thin disc (flare, warp..)

Accurate and precise (old) stellar ages are crucial

Internal, Secular Evolution to Re-arrange Discs?

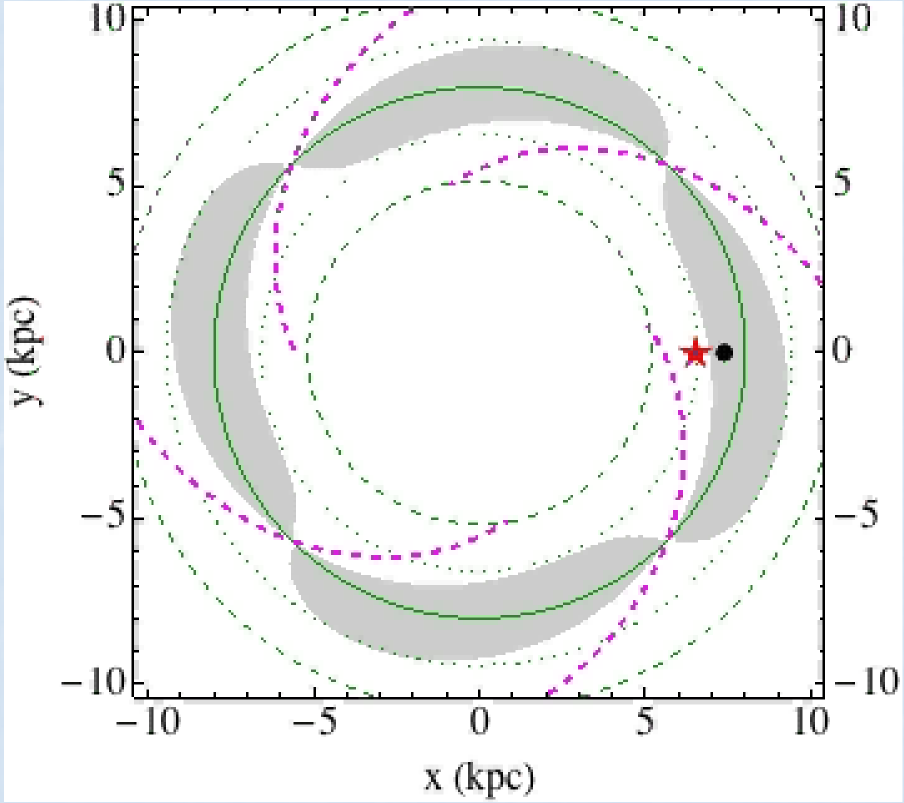
- **Radial migration** (Sellwood & Binney 2002) can move stars of order the disk scale-length during lifetime of disk, without associated kinematic heating (maintaining orbital circularity): acts for stars captured at co-rotation resonance of transient spiral pattern and needs many transient spiral arms of different pattern speeds to affect the entire disk
  - More effective for stars on closer-to-circular orbits, less so for populations of higher velocity dispersion/lower angular momentum orbits (e.g. Solway et al 2012; Vera-Circo et al 2014, Daniel & Wyse 2015, 2016)
  - Efficiency depends on parameters of spiral pattern – amplitude, duty cycle, wave number, number of arms etc

Being Trapped at Corotation Resonance is First Step in Radial Migration

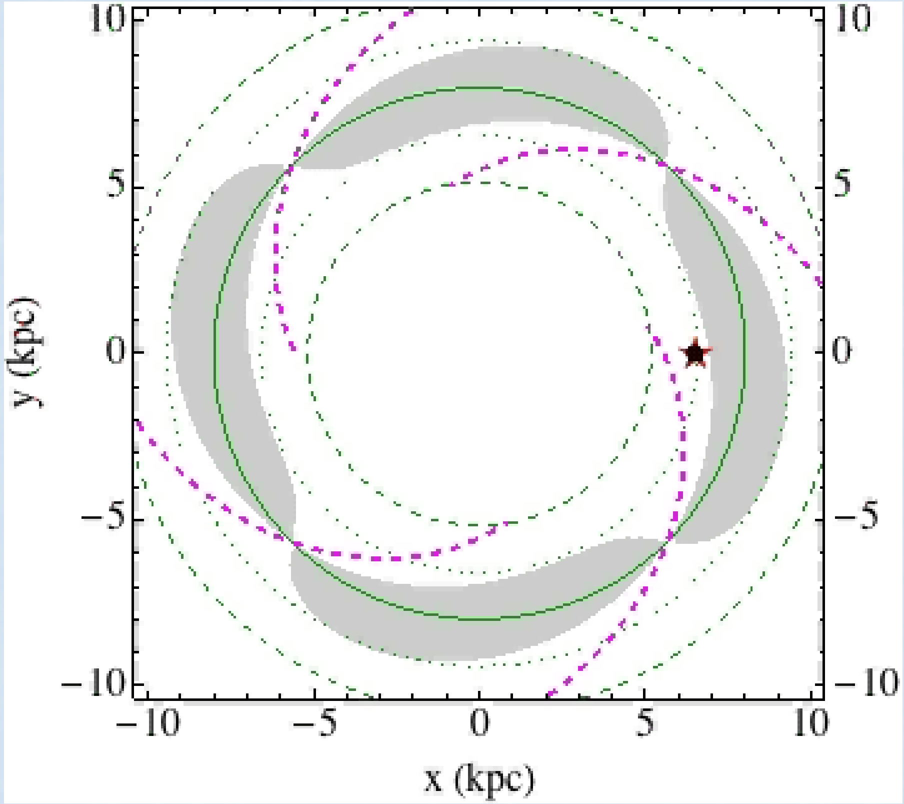
Frame Rotating with Spiral Pattern

Daniel & Wyse 2015

Trapped



Not Trapped



★ position of star ● guiding centre ; Green circle is corotation radius
Grey denotes region of trapping defined by Jacobi Integral (conserved in rotating frame), determined chiefly by angular momentum (guiding centre)

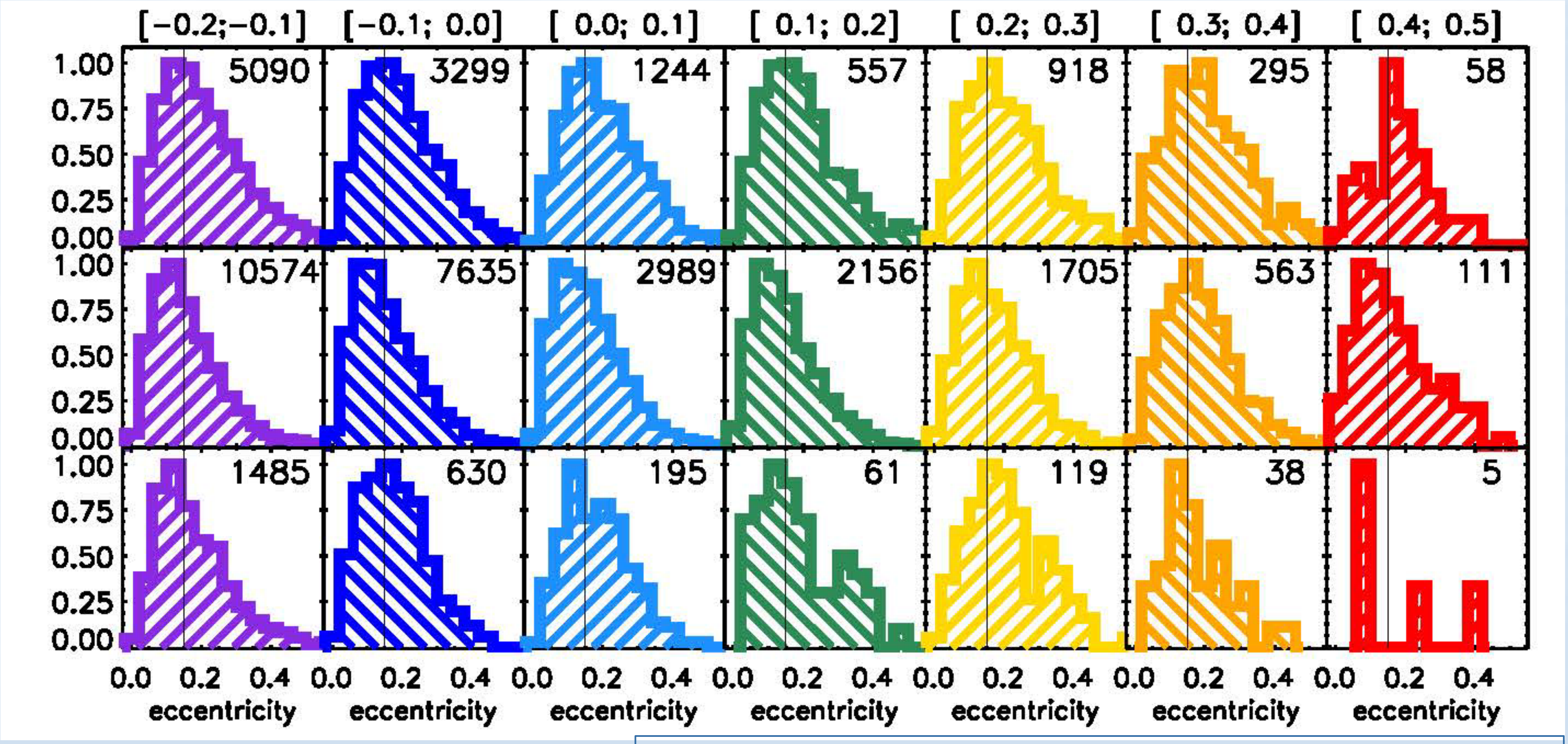
- Physics of radial migration solid – importance less clear
- Large scatter in age-metallicity relation for thin disc could arise from radial mixing between regions of different enrichment and star-formation histories (Sellwood & Binney 02)
- Apparent role in simulations e.g. to build-up outer disc, ‘stars’ move from birth radius - but details lacking (e.g. Bird et al 12, 13; Roskar et al 12; Vera-Ciro et al 14; Grand et al 16; Loebman et al 16)
- Lower restoring force in lower surface density outer regions, plus ‘hotter’ inner disc, led to suggestions that migration important in formation of thick disc (e.g. Schonrich & Binney 2009; Loebman et al 2011)
  - Not likely since old age limits process to early epochs only, distinct elemental abundance pattern, steep trend of rotational velocity with metallicity, plus insufficient thickening (e.g. Aumer, Binney & Schonrich 2016)

Radial Migration into the Solar Neighbourhood?

- Young (OB) stars locally have mean metallicity ~ solar with small scatter ~ 10% (Nieva & Przybilla 2012)
  - → Older local thin disk stars > solar metallicity formed elsewhere?
- Test with large sample of stars, straightforward selection function, robust kinematic and stellar parameters, for statistical analysis: RAVE (DR6, ~460,000 stars, Kunder et al. inc RW 2016)
  - → Kinematics and vertical distributions of local super-solar metallicity stars and solar metallicity stars are the same, super-solar stars could have formed in inner disk and migrated several kpc outwards, with little kinematic heating (Kordopatis, Binney, Gilmore, Wyse et al 2015)
- 60% of RAVE stars (over 250,000) are in Gaia DR1 → improved orbital parameters and ages, quantification of importance of radial migration ongoing

Derived orbital eccentricity distributions: 7 metallicity bins (columns) from 2/3 solar (left) to 3x solar (right) and 3 radial bins (rows, upper 6.5 < R(kpc) < 7.5; middle 7.5 < R < 8.5; lower 8.5 < R < 9.5):

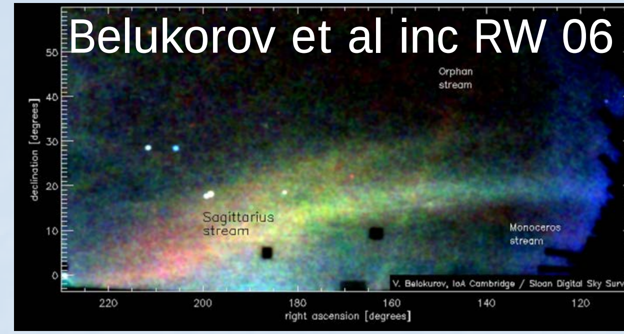
No obvious differences. Mostly close to circular orbits ➔ super-solar stars are not just passing through on eccentric orbits

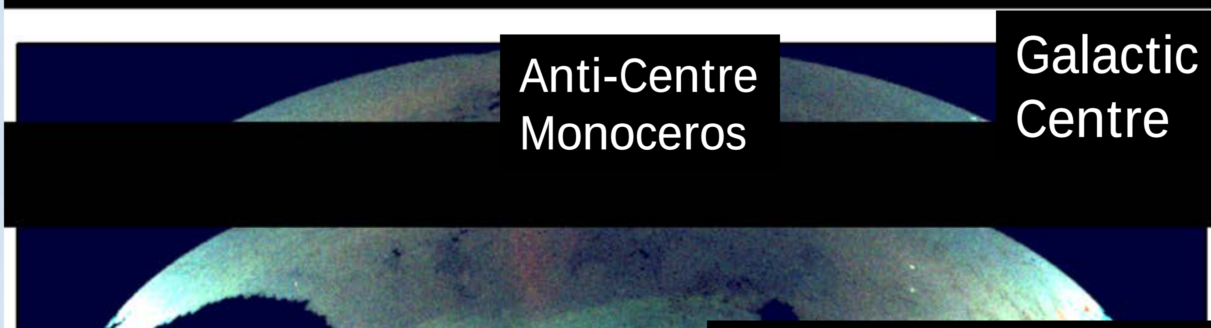


Kordopatis, Binney, Gilmore, Wyse et al 2015

Outer Disk with Pan-STARRS

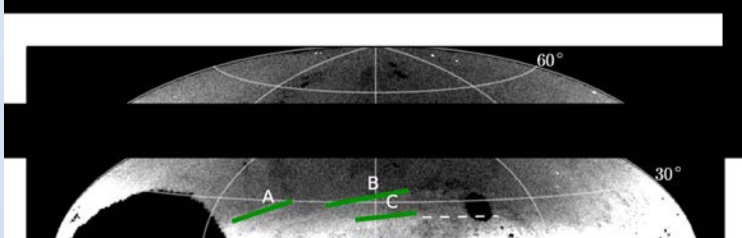
Low-latitude 'field of streams'





Slater et al (inc RW) 14

Complex structure!



7.5-11 kpc 'Monoceros Ring'
Complex Structure
Sharp Features

5-6.5 kpc

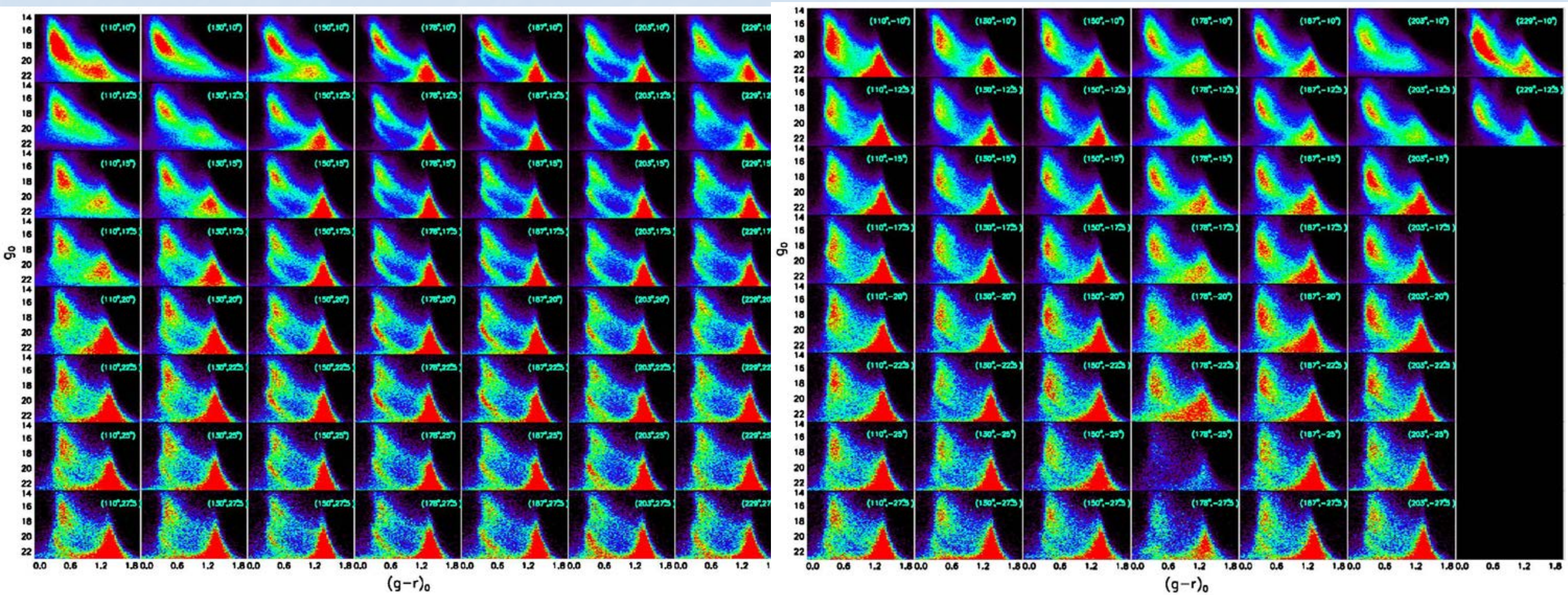
14.5-17.5 kpc
Sgr Stream

MSTO stars, $0.2 < (g-r)_0 < 0.3$

Outer Disk with SDSS

Hess Diagrams $(g\text{–}r)_0$ vs g_0

Xu, Newberg et al 2015



North (left) and South (right) of the Galactic Plane

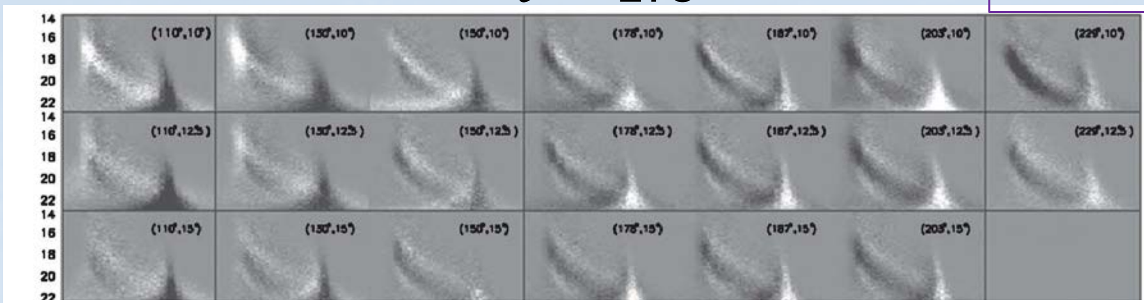
$2.5^o \times 2.5^o$ bins in (ℓ, b), Col: constant ℓ; Row: constant b

Anti-centre fields: $110^o < \ell < 229^o$, $10^o < |b| < 30^o$

Residuals from North – South of the Galactic Plane

ℓ = 178°

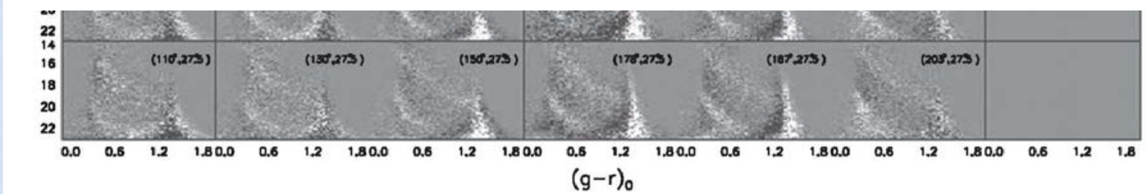
Xu, Newberg et al 2015



$|b|$ = 20°

More stars in the north at distances of ~2kpc
More stars in the south at distances of 4-6kpc
More stars in the north at distances of 8-10kpc

'Monoceros' one of several oscillatory overdensities
(More stars in the south at distances of 12-16kpc)



Anti-centre fields

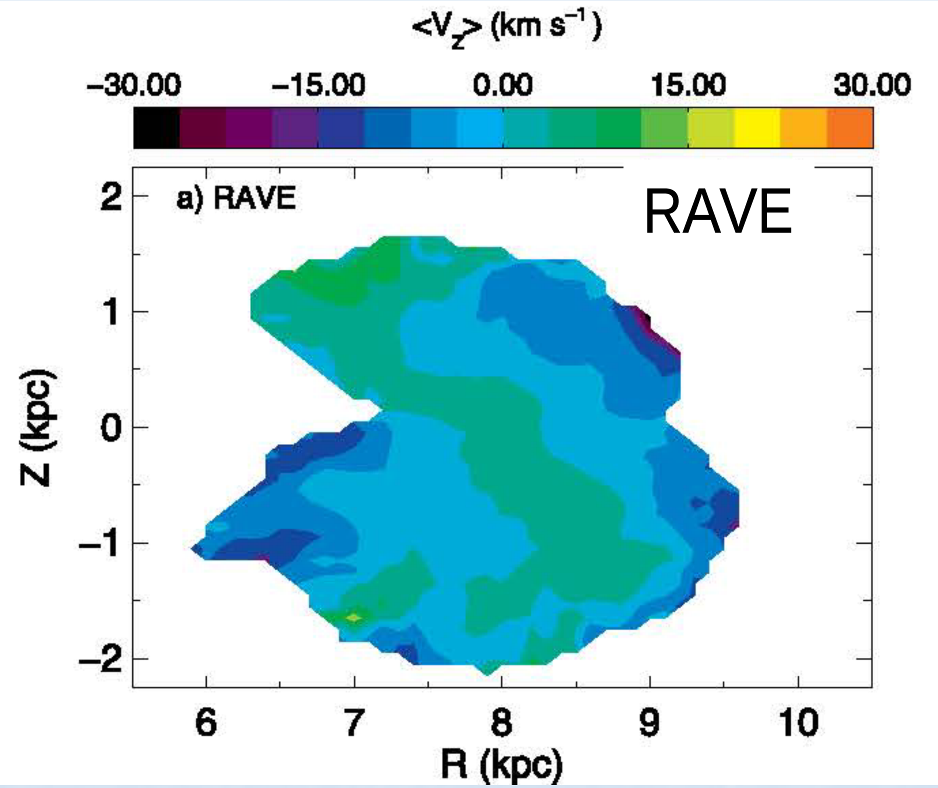
2.5° x 2.5°
bins in $(\ell, |b|)$

Col: fixed ℓ

Row: fixed $|b|$

➔ main sequences stars show alternating white/black stripes as a function of apparent magnitude (distance), factor of $\lesssim 2$ variations : Rings? Coherent vertical oscillations in disk?

Oscillatory kinematics



Systematic variations – oscillatory patterns - in mean vertical motions seen in three large spectroscopic surveys: SDSS/SEGUE (Widrow et al 12), RAVE (Williams et al, inc RW, 2013) and LAMOST (Carlin et al 2014)

➔ Breathing/bending modes of thin disc (disc metallicities)

- Due to bar/spirals (Debattista 14) and/or due to satellite (Sgr? Gomez et al 13; Widrow et al 14) - but overdensities are not necessarily debris from satellite

Concluding remarks

- Thick disc is a separate component of the Milky Way
  - Dominant old age, enhanced elemental abundances: stars formed in early, compact phase of high star-formation rate
    - Similar to inferences from surveys at redshifts > 2
  - Merger limit from old age makes Milky Way unusual in ΛCDM ➔ need improved merger statistics and stellar ages
- Internal secular processes, such as radial migration, play a role in thin disc evolution, particularly in bringing metal-rich older stars to outer regions
  - Quantification of global importance needed
- Thin discs can respond to gravitational perturbations with collective modes – lumps, moving groups, oscillations
- Massive surveys of disc stars (e.g. PFS!) will enable us to decipher the history of a typical galaxy