Galactic Archaeology: Current Surveys and Instrumentation

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The Fossil Record

- Studying low-mass old stars nearby allows us to do cosmology locally.
  - There are copious numbers of stars nearby that have ages $\gtrsim$ 10 Gyr : formed at redshifts > 2
  - Retain memory of initial/early conditions: chemical abundances, orbital angular momentum/integrals (modulo torques)
- Complementary approach to direct study of galaxies at high redshift
  - Snapshots of different galaxies vs evolution of one
- Can derive metallicity independent of age
  - Break degeneracy of integrated light

Clues from the Fossil Record

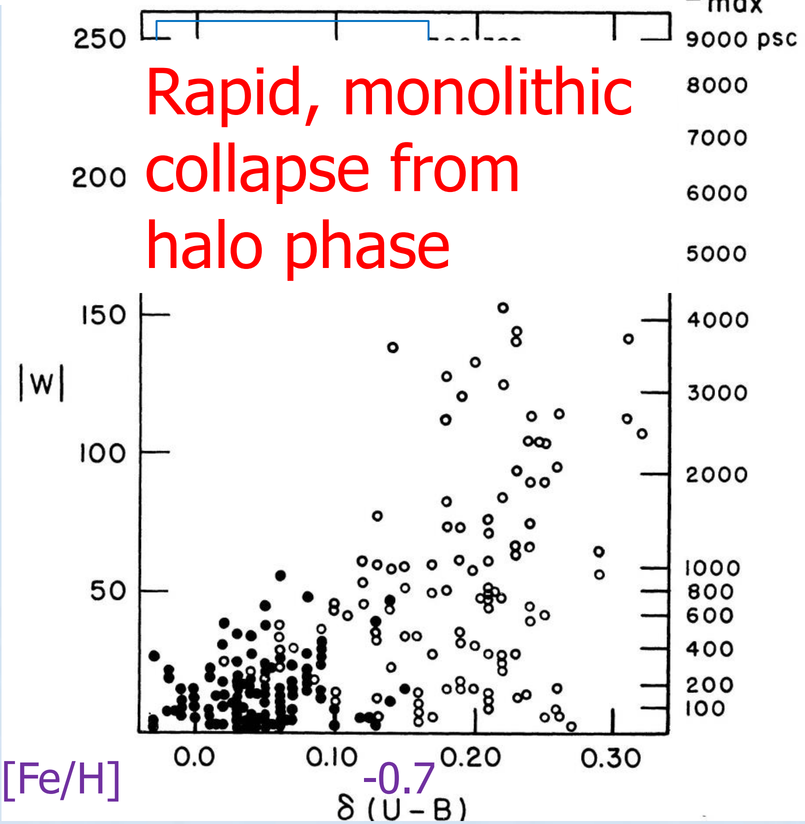
- Merging history: nature of Dark Matter
- Star formation history
  - Mass assembly/star formation may be different
- Chemical evolution: ‘feedback’
- Dissipative gas physics vs dissipationless
- Stellar Initial mass function at low and high redshift
- Mass profile: kinematics to dynamics, DM
  - Smooth profile of Milky Way dark halo plus substructure
  - Also within satellites: mass function

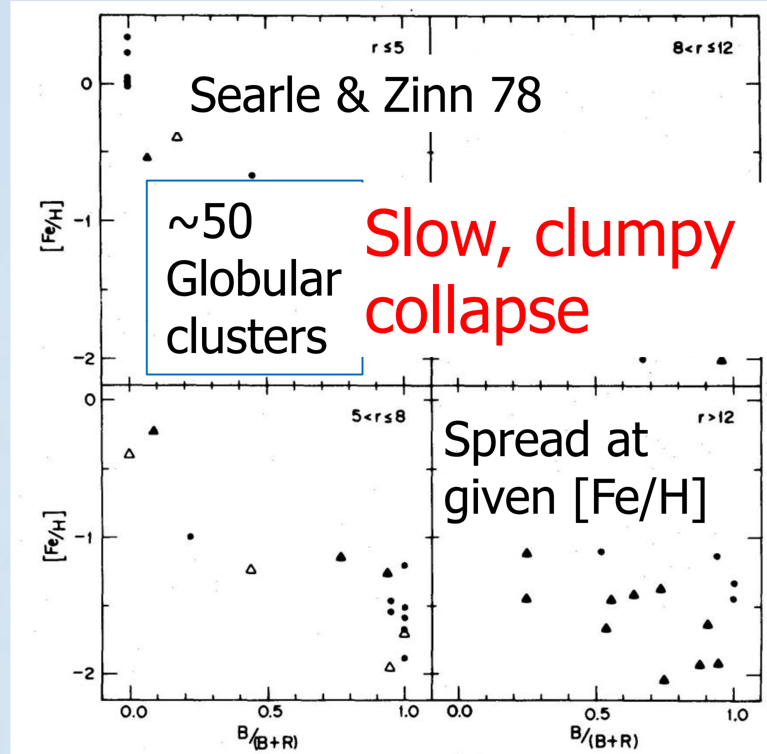
Survey of Surveys

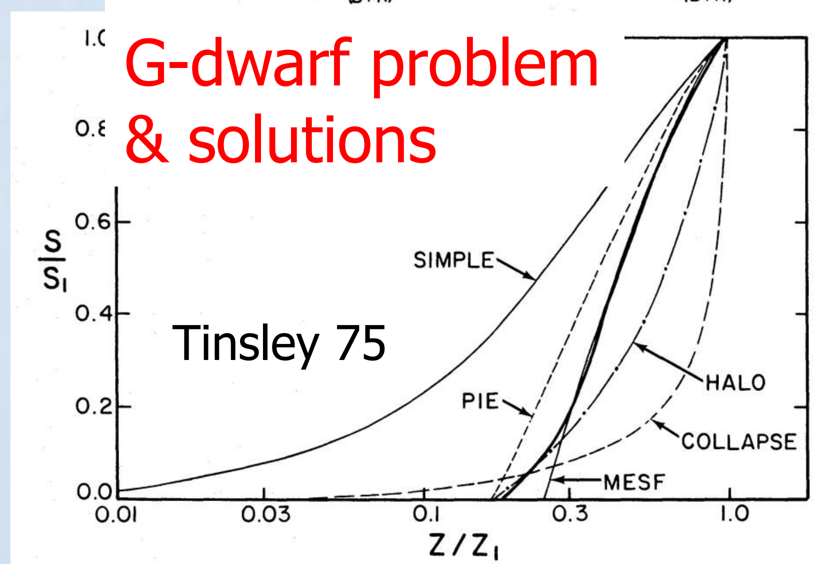
- Many stellar surveys with same `big picture' science goals: decipher the evolutionary history of the Milky Way (many described in later talks, apologies for not including here)
  - Target different components with different tracers e.g. clusters, turn-off stars, red giant stars
  - Differ in which phase-space coordinates can be studied: kinematic, spatial, chemical
    - Ideally as many as possible
  - Differ in quality and quantity of data
    - Much physics in detailed shapes of distributions
    - Need to understand and minimise uncertainties
  - Will focus on disk(s)

Context: precursors led the way

Eggen Lynden-Bell & Sandage 62



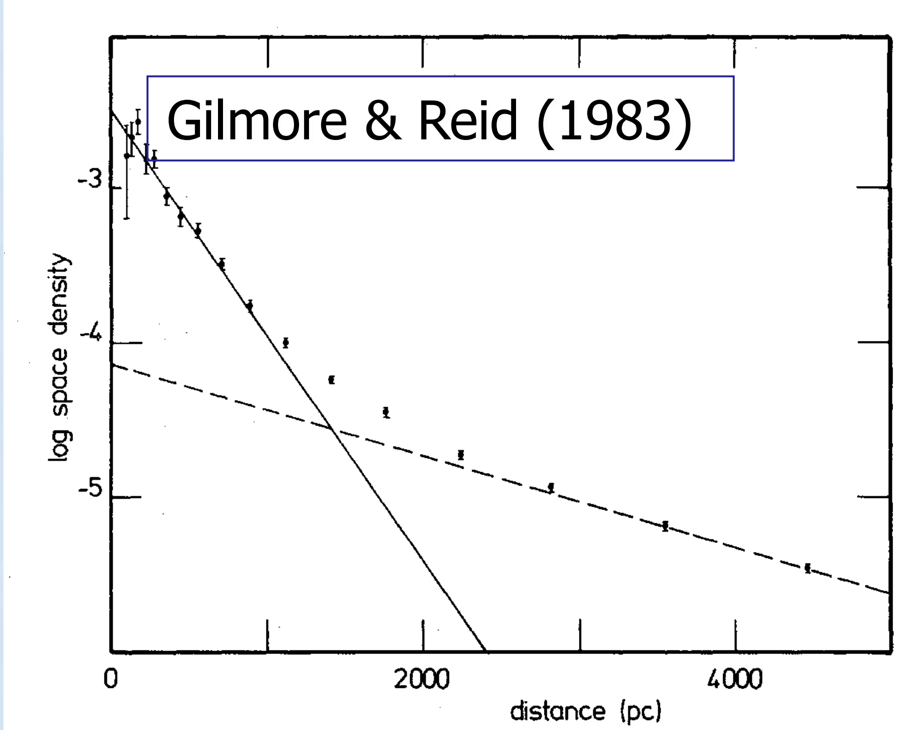




'Large' samples were hundreds, limited to photometric metallicity and very nearby stars, distant globular clusters

Moving beyond solar neighbourhood

- Star counts at the Galactic Poles fit by two exponentials: Thick Disk
- Thought initially to be part of stellar halo – later characterized as distinct in kinematics and metallicity from both halo and thin disk (e.g. Zinn 85; Wyse & Gilmore 1986; Ratnatunga & Freeman 89)

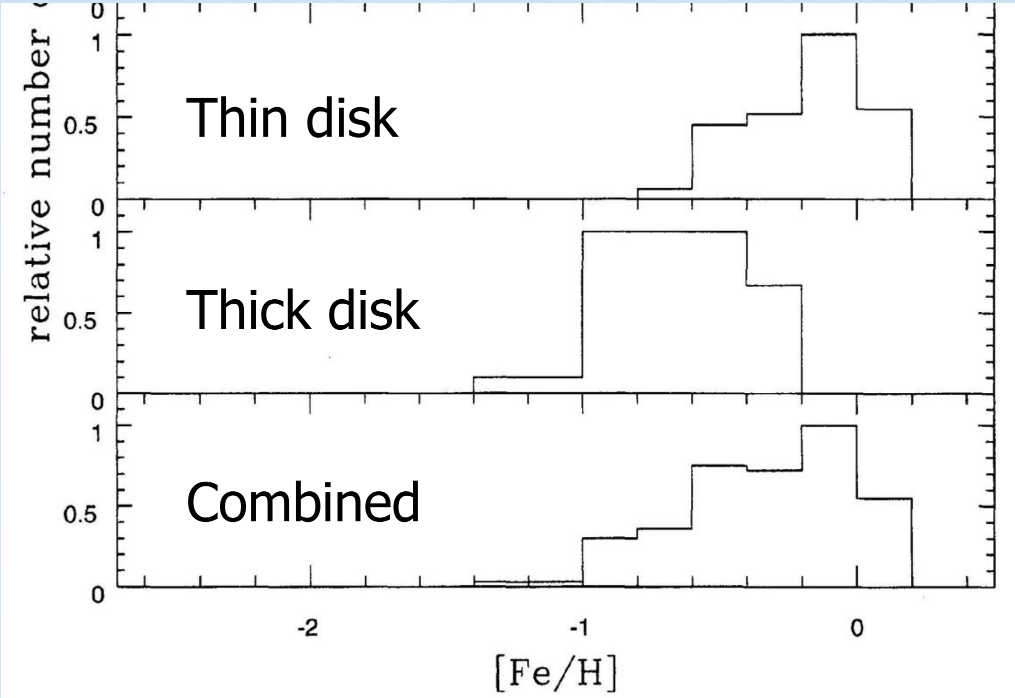


- Earliest phase of disk
  -Solves 'G-dwarf problem' ?

Near and Far

Wyse & Gilmore 95

- Combination of local F/G sample with stars several kpc away, with both kinematics and metallicity, (still only hundreds of stars) allows decomposition into thick and thin disks where distributions overlap



➔ identifies metal-poor thin disk and metal-rich thick disk

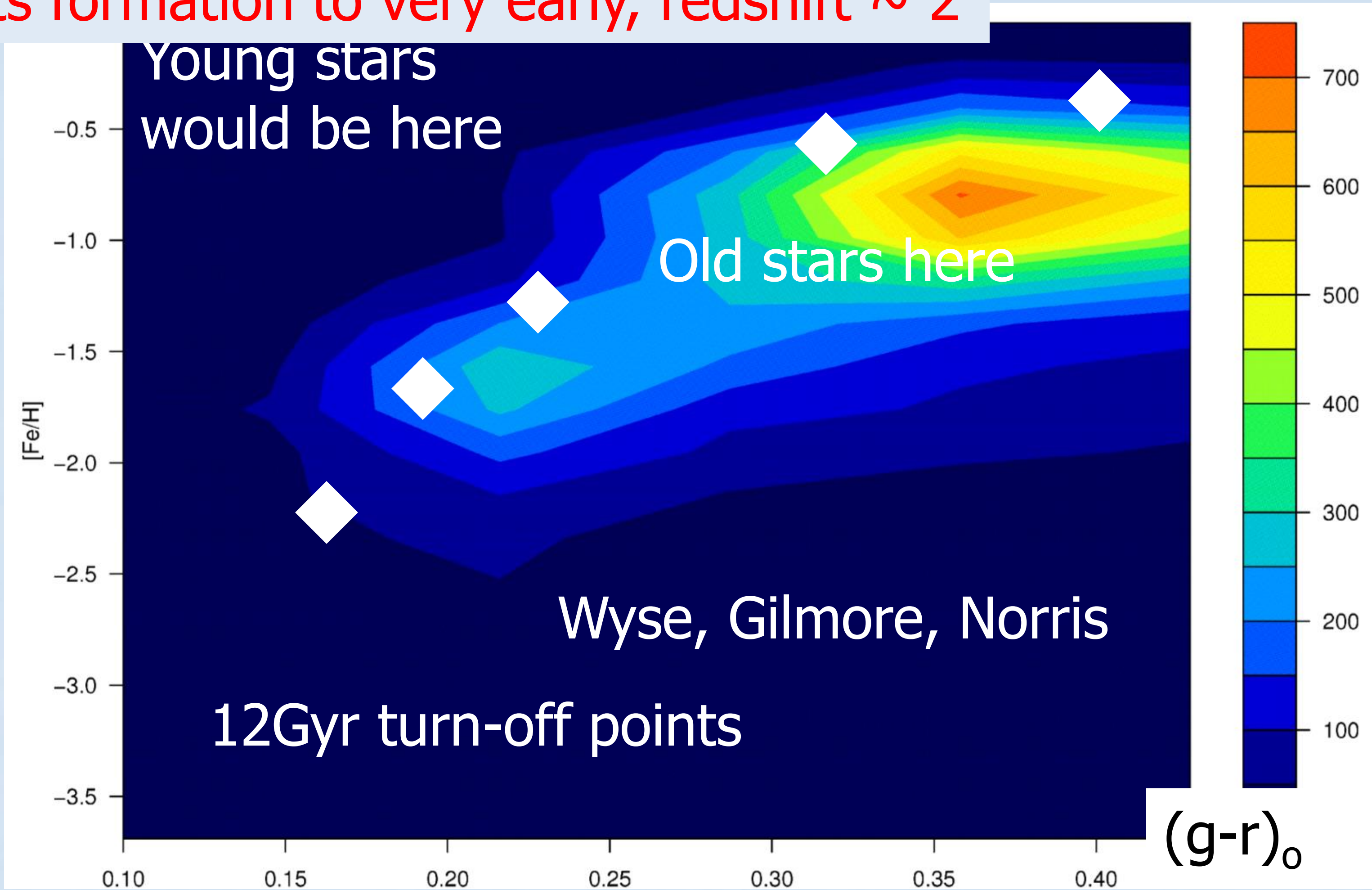
➔ Important constraints on models of formation

➔ Colours and metallicities provide constraints on age of population: thick disk predominantly old, 10-12Gyr (same as 47 Tuc, ‘thick disk’ globular)

Thick disk has OLD turnoff

Gilmore & Wyse 1985
Carney et al 1989……

➔limits formation to very early, redshift ~ 2

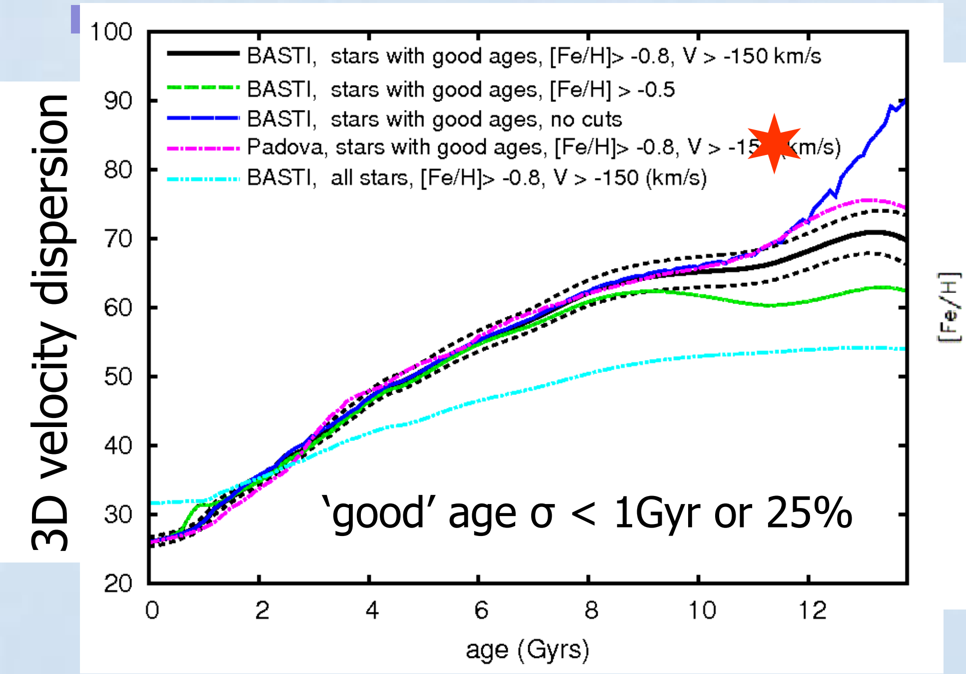


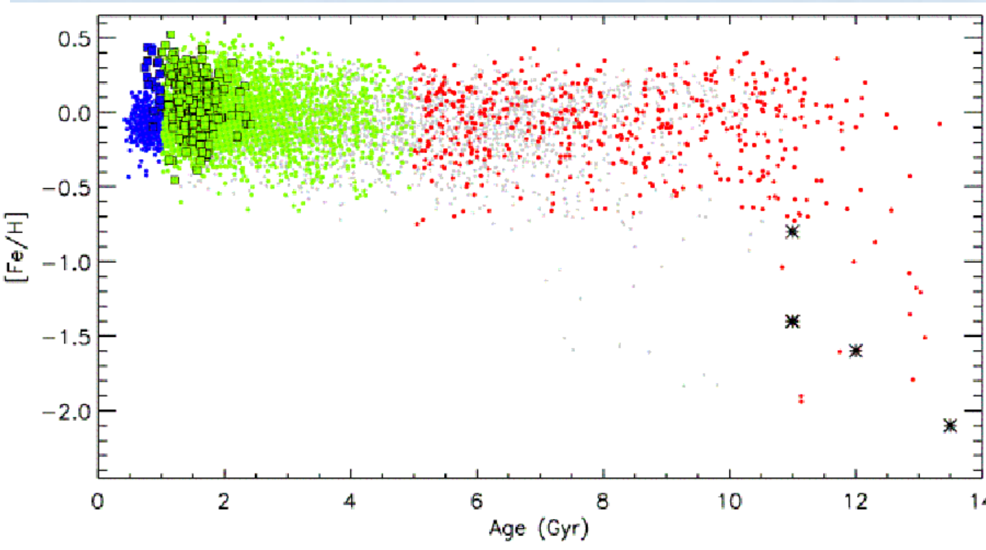
8,600 faint F/G dwarfs, several kpc above the plane, fields along SDSS equatorial stripe ($\mathcal{R}$ ~ 6000, includes CaK line and G-band, 400 fibre 2dF AAOmega/AAT) see Jayaraman et al 2013

GCS: Photometric Parameters, Large Sample
Strömgren, Nordström et al, Casagrande et al

- Local thin disk stars (14,000 F/G stars within ~ 40pc) show age-velocity dispersion relationship
- Age-metallicity more scatter than trend

➔ lots of old stars nearby

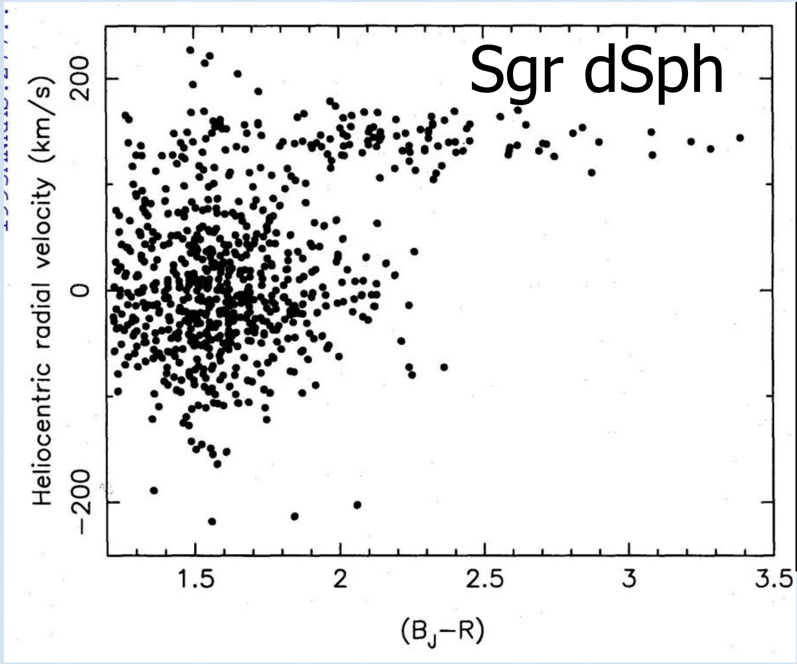


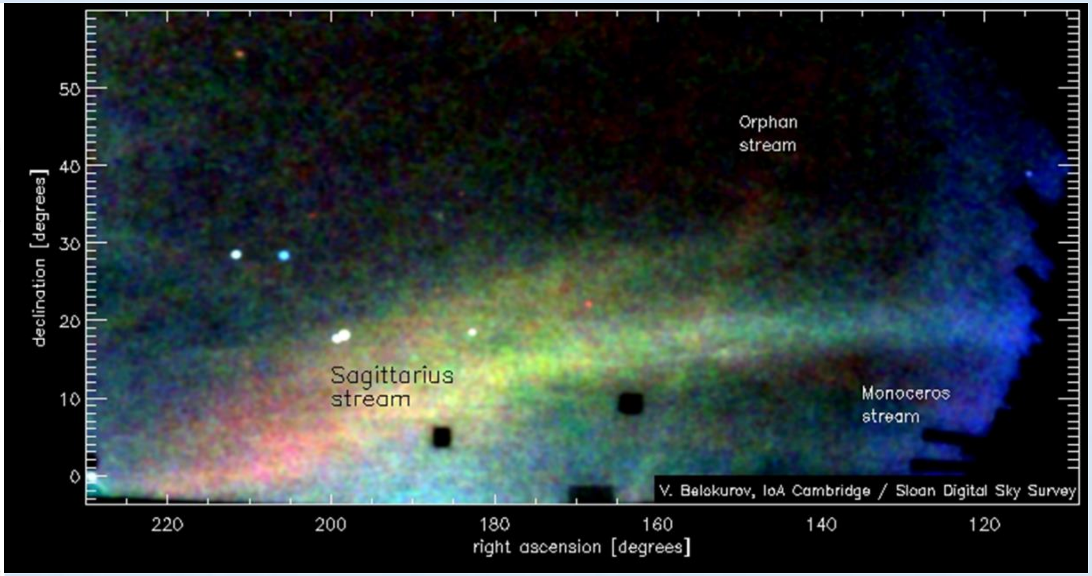


✶ thick disk

Substructure

- Larger samples allow identification and characterization of substructure in phase space
- Imaging surveys play crucial role





Ibata, Gilmore & Irwin 95

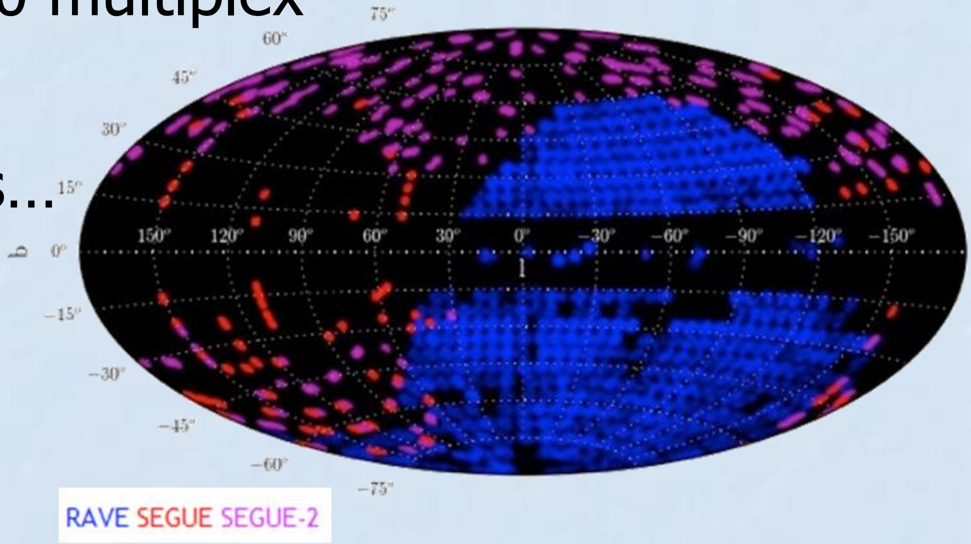
Belokurov et al 2006

MOS survey of Galactic Bulge, ~1500 stars in 6 fields

SDSS Segue-1 and -2:
A Spectroscopic Survey of >240,000 Stars

Yanny et al 2009; Eisenstein et al 2011

- Sparse sampled on the sky, low spectral resolution, wide wavelength coverage, ~600 multiplex
- Several stellar targets
  - G dwarfs, BHB, K Giants…
- Metallicity, radial velocity, [α/Fe]
- Determine large-scale and small-scale gradients
  - Further characterize thick and thin disks (e.g. Cheng et al)
- Halo substructure e.g. Newberg et al
- RAVE: ~500,000 stars – Kordopatis talk



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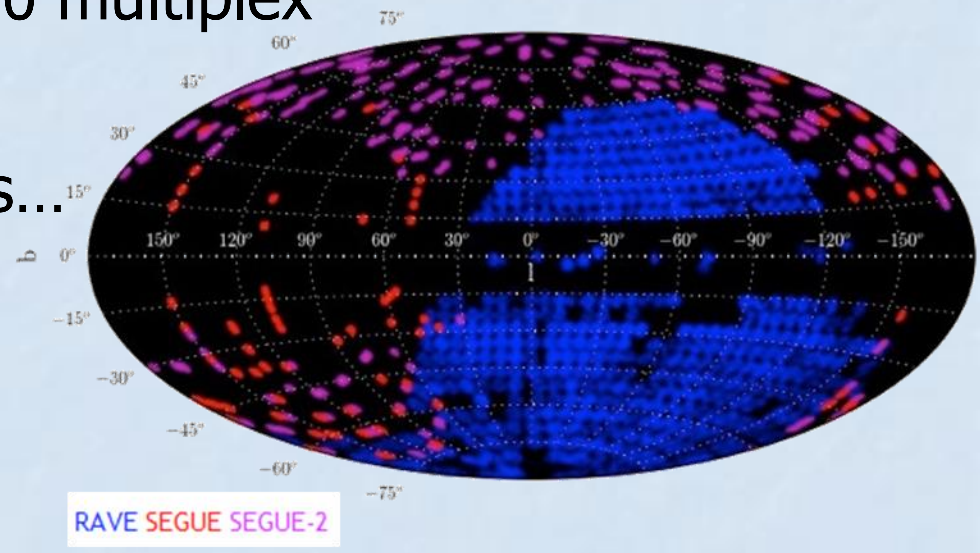
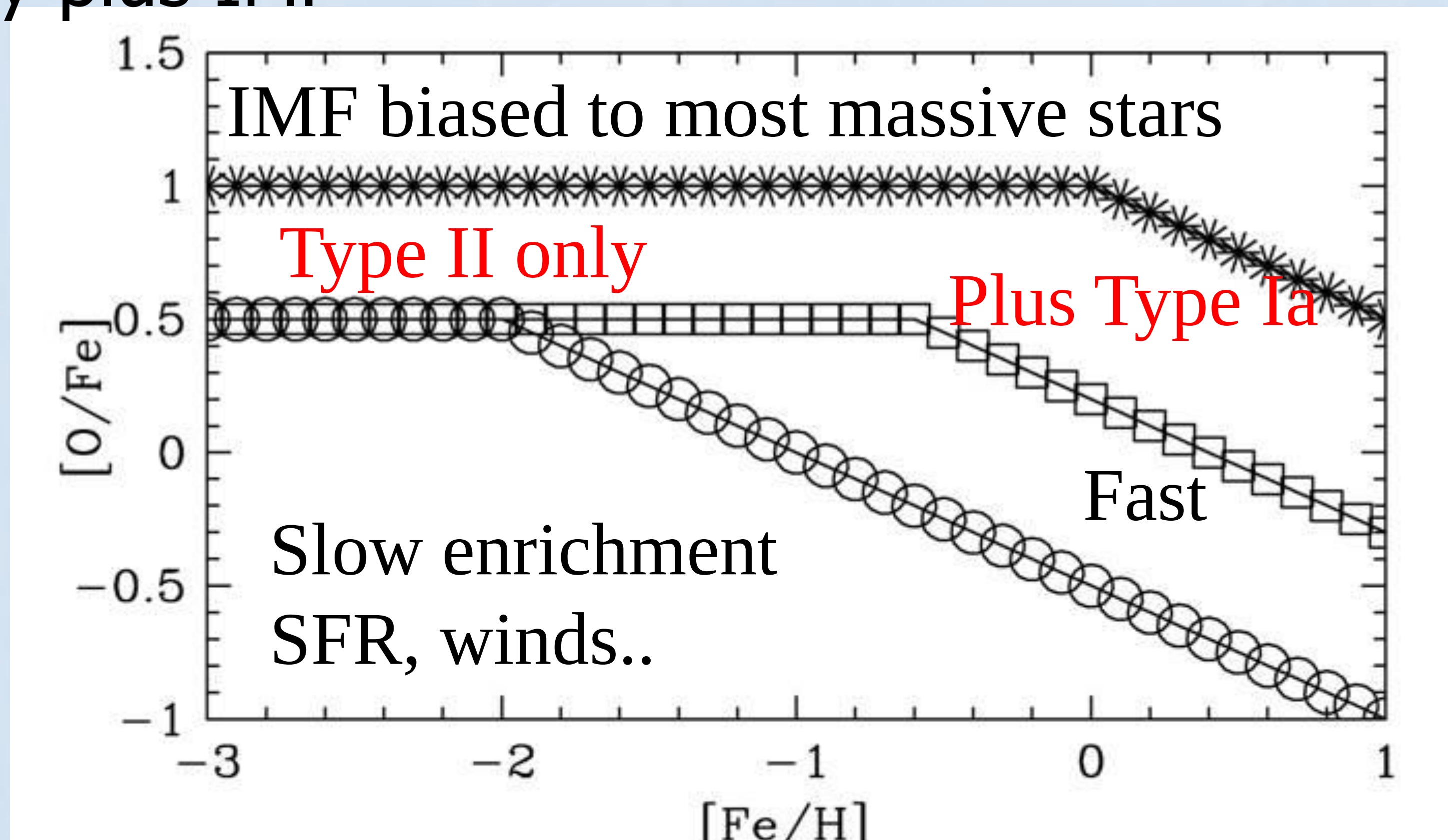


Elemental Abundances: beyond metallicity

Alpha element and iron: Star Formation/Enrichment History plus IMF



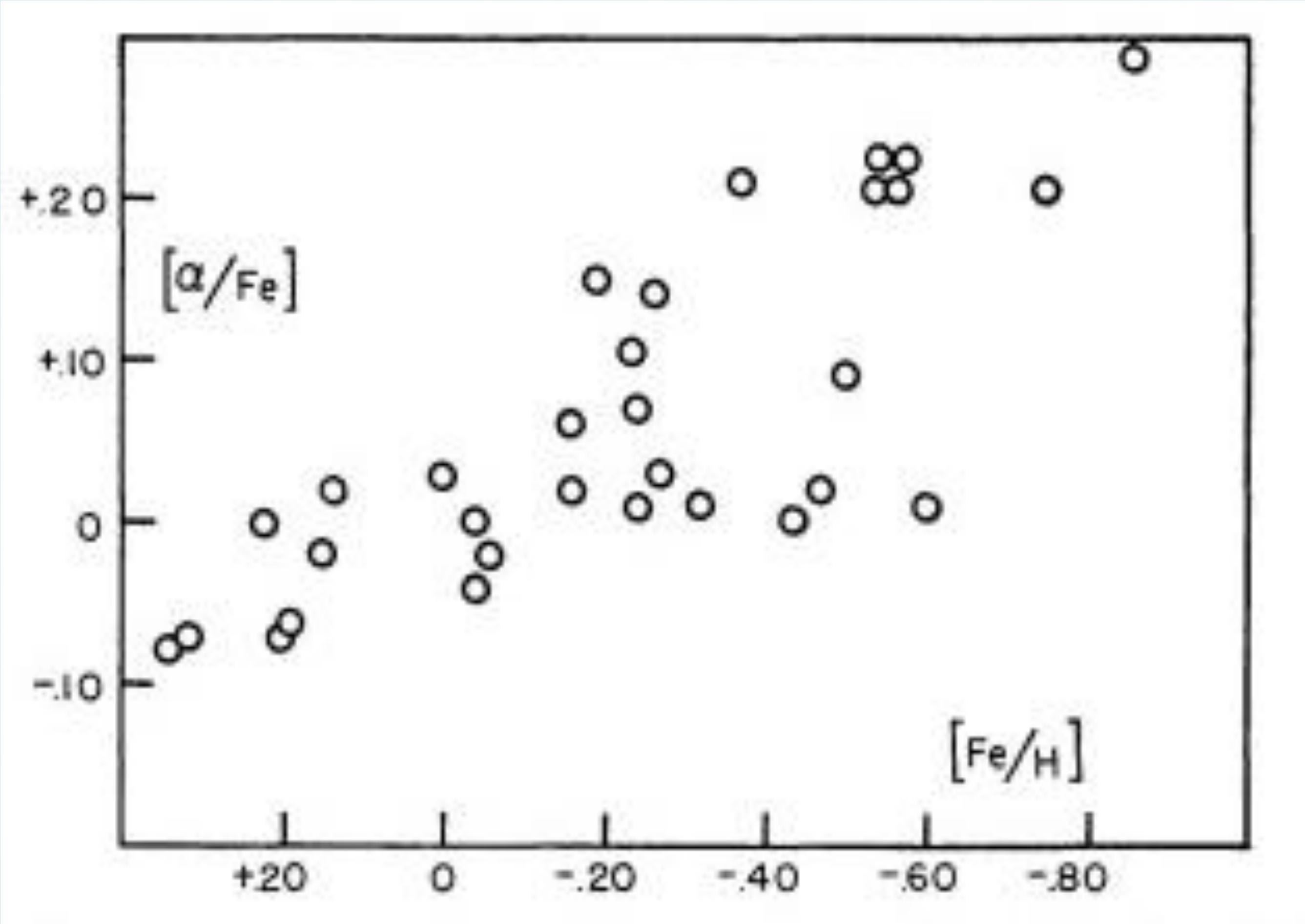
Wyse & Gilmore 1993

Self-enriched star forming region.

This model assumes good mixing so IMF-average yields

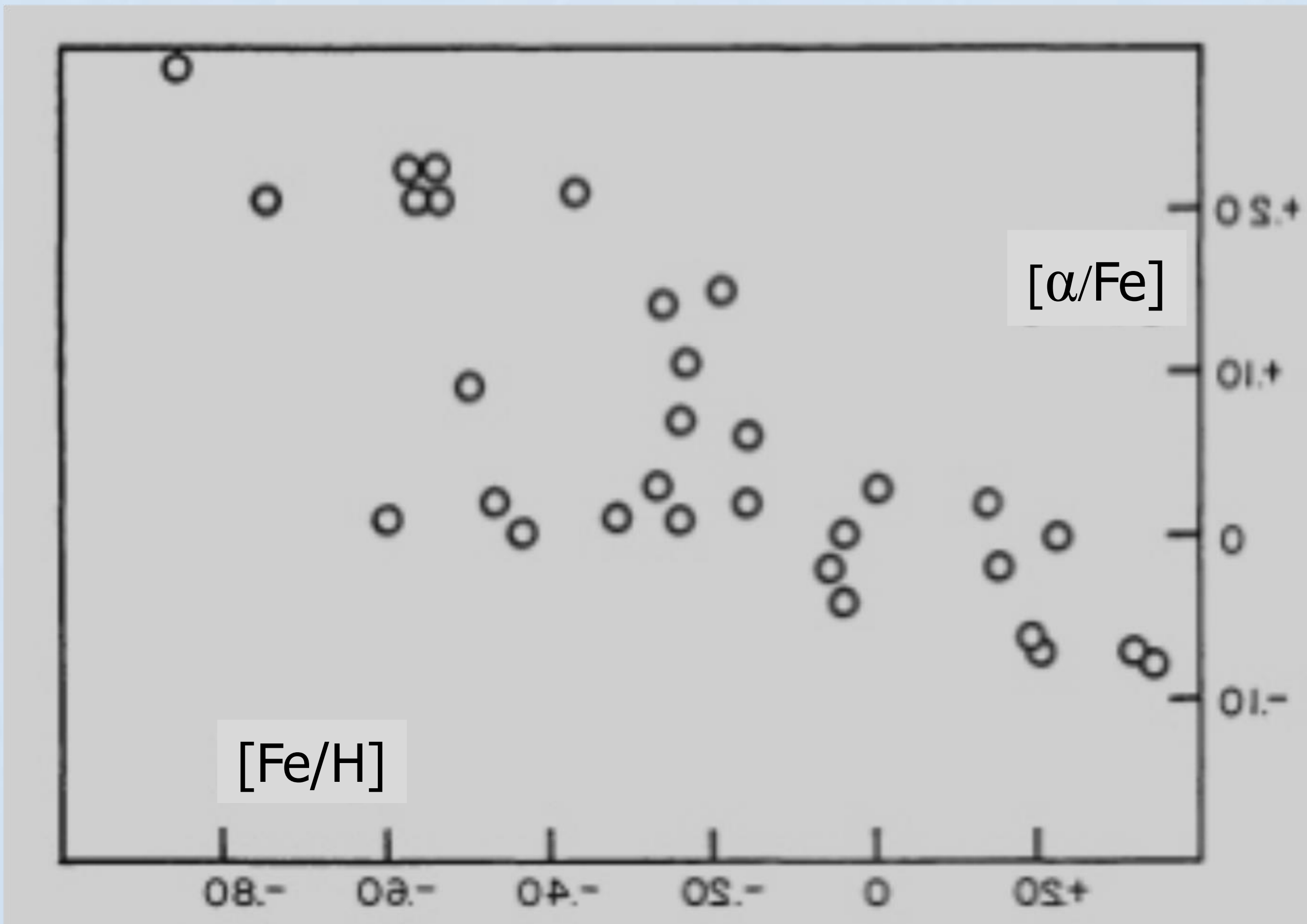
Elemental Abundances
Nearby Stars

Wallerstein 1962



Elemental Abundances
Nearby Stars

Wallerstein 1962

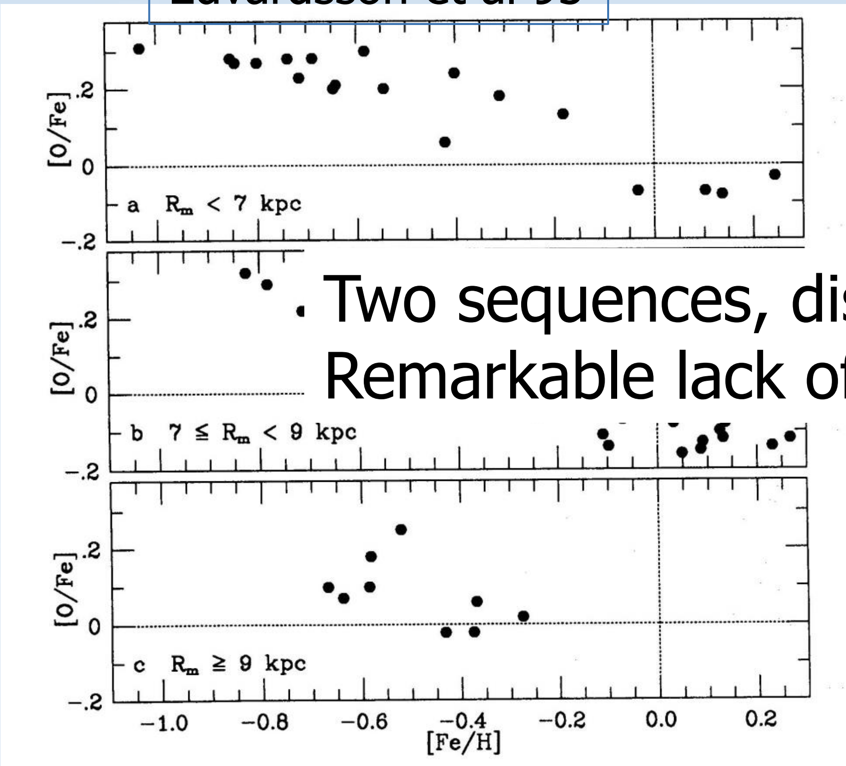


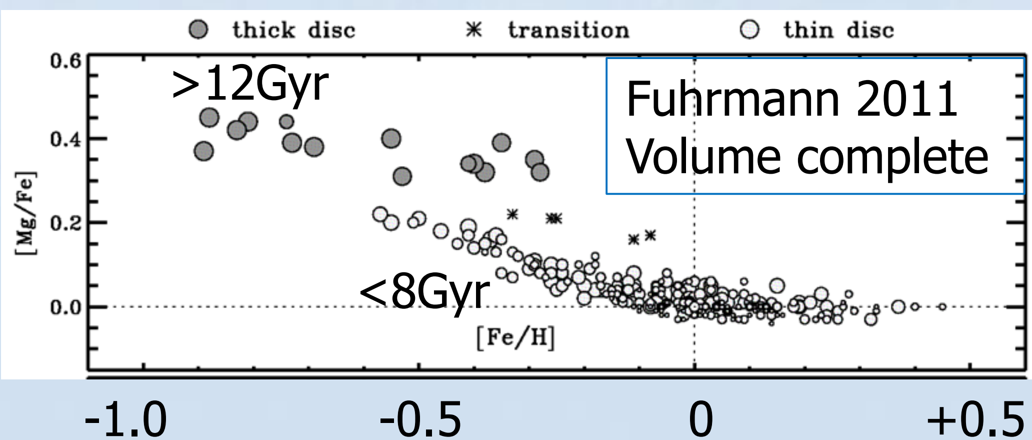
Elemental Abundances: Nearby Stars

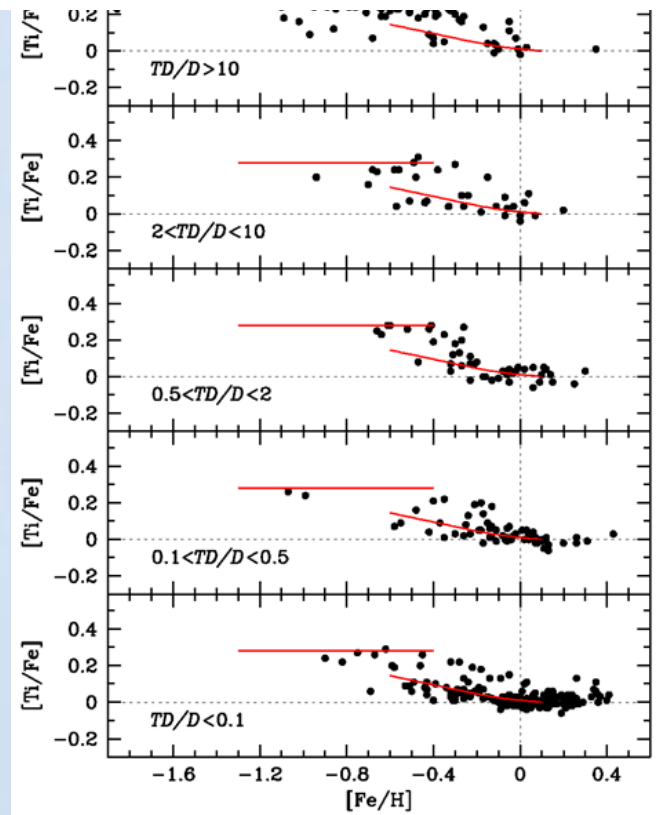
Elemental abundance patterns by
- Mean orbital radius
- Kinematics
- Age (bigger symbols are older)

Two sequences, distinct thick and thin disks
Remarkable lack of scatter: invariant IMF, mixing

Edvardsson et al 93







Non-Local Samples

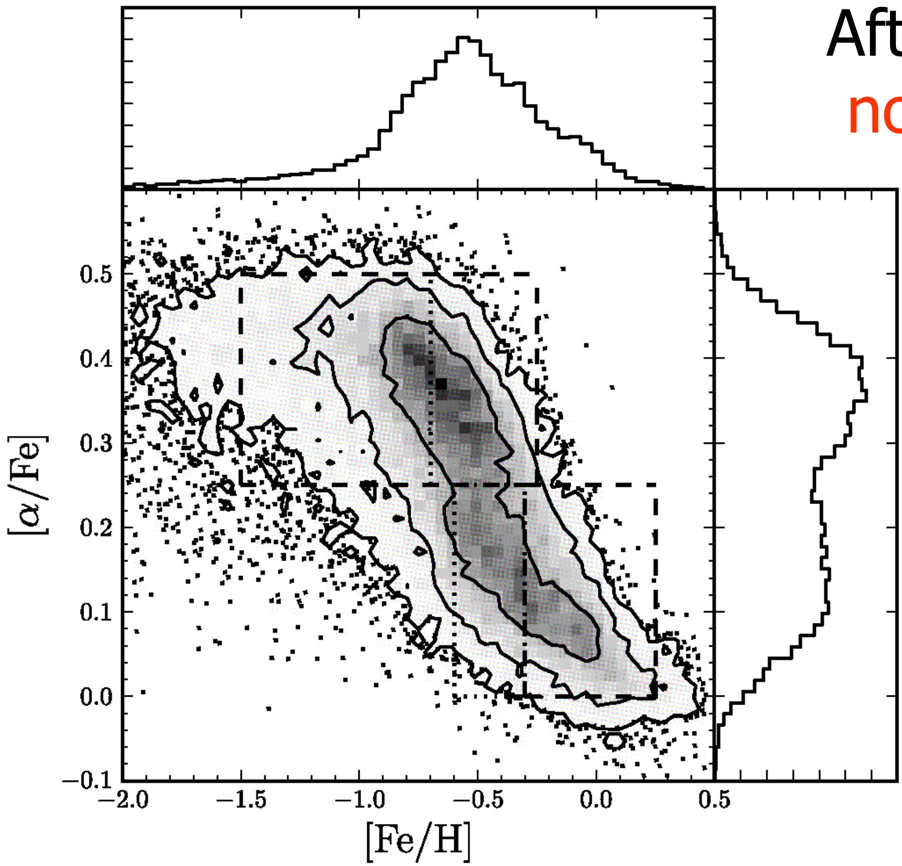
SDSS Segue survey, ~20,000 G dwarf stars several kpc distant

low spectral resolution $\mathcal{R} \sim 2{,}000$

Bovy et al 2012

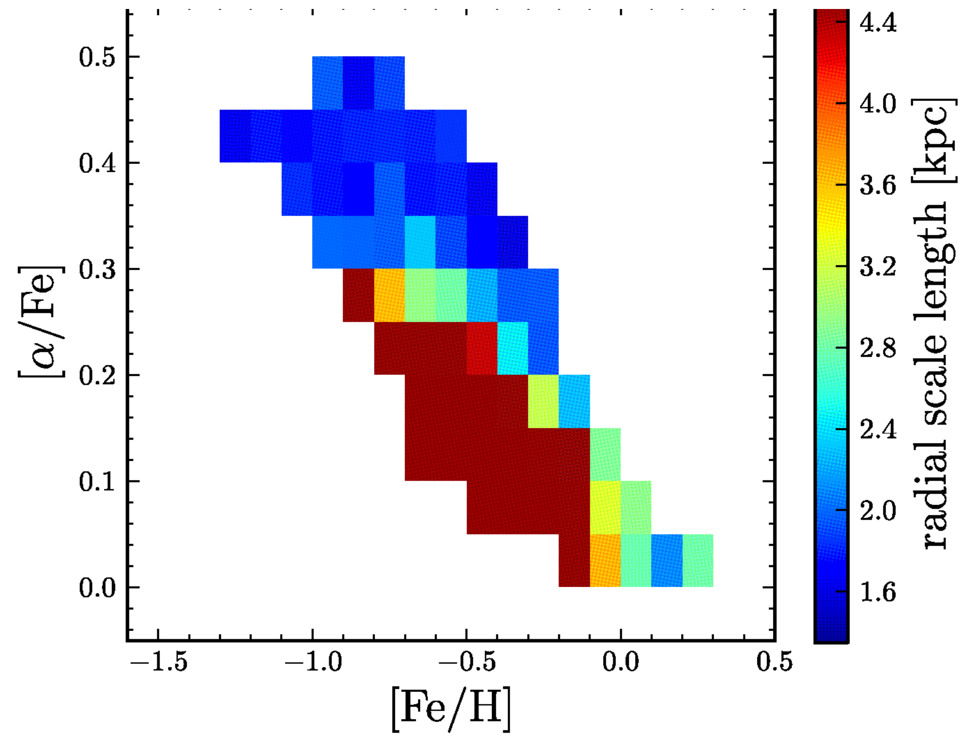
Not ideal for elemental abundances!

Observed distribution



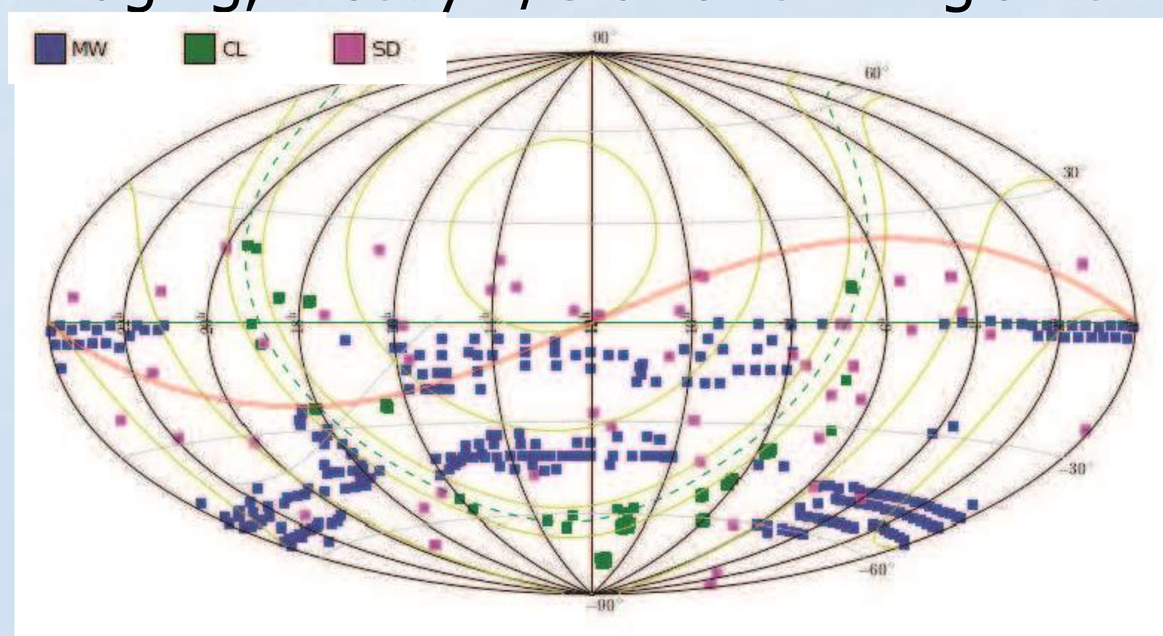
After correction for selection function

no distinct thick disk?



Gaia-ESO Public Survey

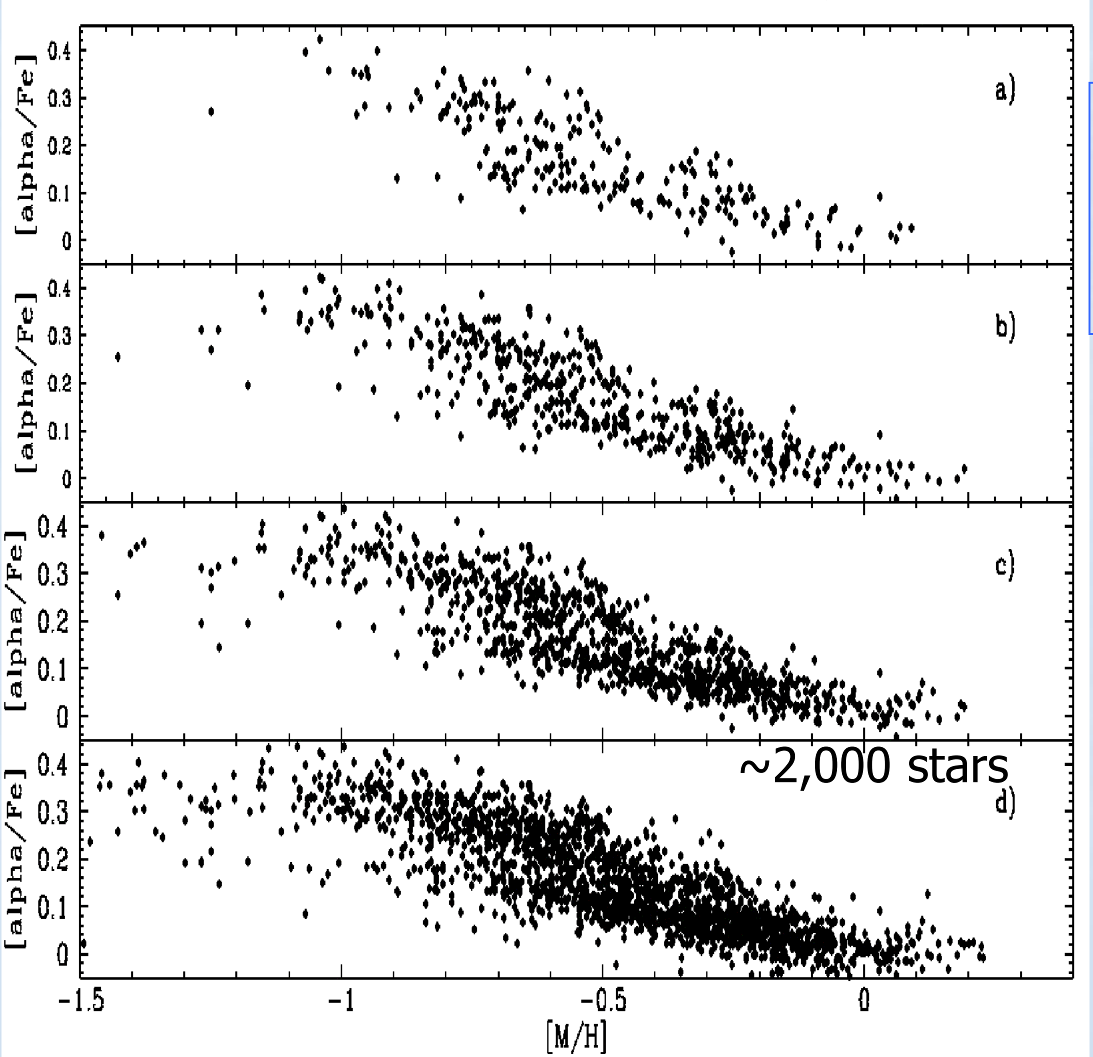
- Allocated 300 nights over 5 years (started 1/2012) on VLT to obtain ($\mathcal{R}$ > 16,000) spectra (mostly GIRAFFE, subset UVES) and hence radial velocities and stellar parameters, including elemental abundances, for ~100,000 faint field stars (typically r ~ 18), all major stellar components plus star clusters (PIs Gilmore & Randich; Gilmore et al. inc RW 12)
- Selected from VISTA imaging, mostly F/G dwarfs + K giants
- Complements Gaia's astrometric data



167/200 nights,
~85,000 Giraffe
(110 fibres, 25′ FoV)
~25,000 UVES

Non-Local Samples

Gaia-ESO survey, FG dwarf stars several kpc distant (r < 18), VLT Flames/Giraffe spectra $R \sim 20{,}000$; initial sample size 5,000



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

Gaia-ESO: 300 VLT nights over 5 yr ➔ 100,000 stars (field) + open clusters
PIs Gilmore & Randich
Started 1/2012

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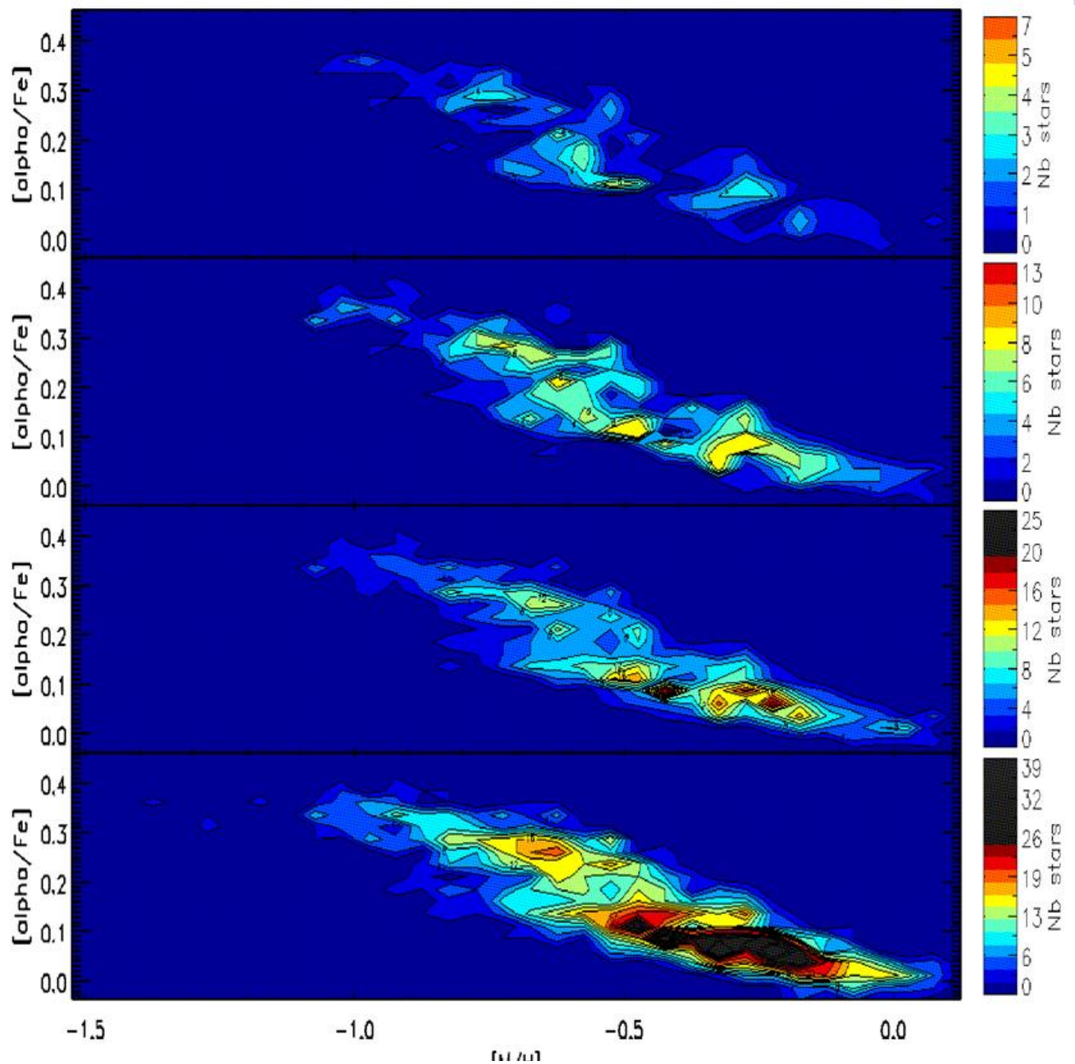

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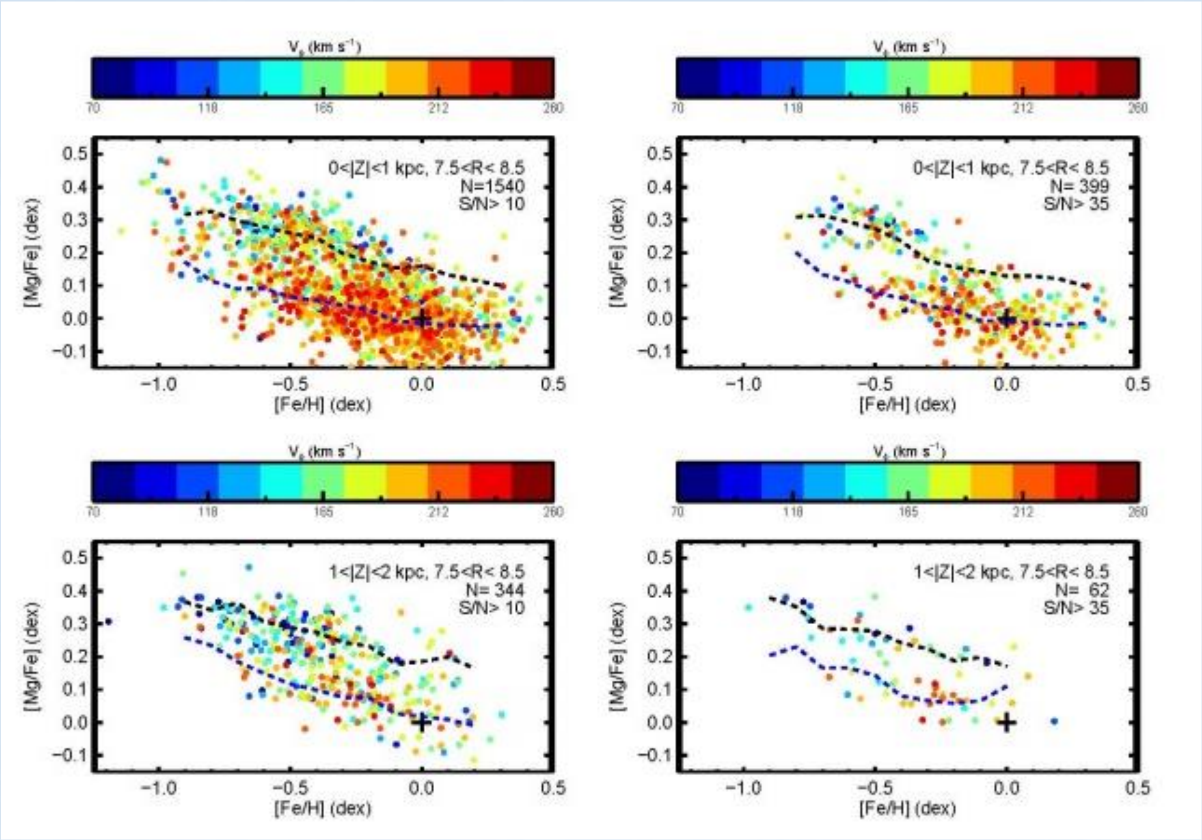
Non-Local Samples: GES



Kordopatis, Wyse et al in prep

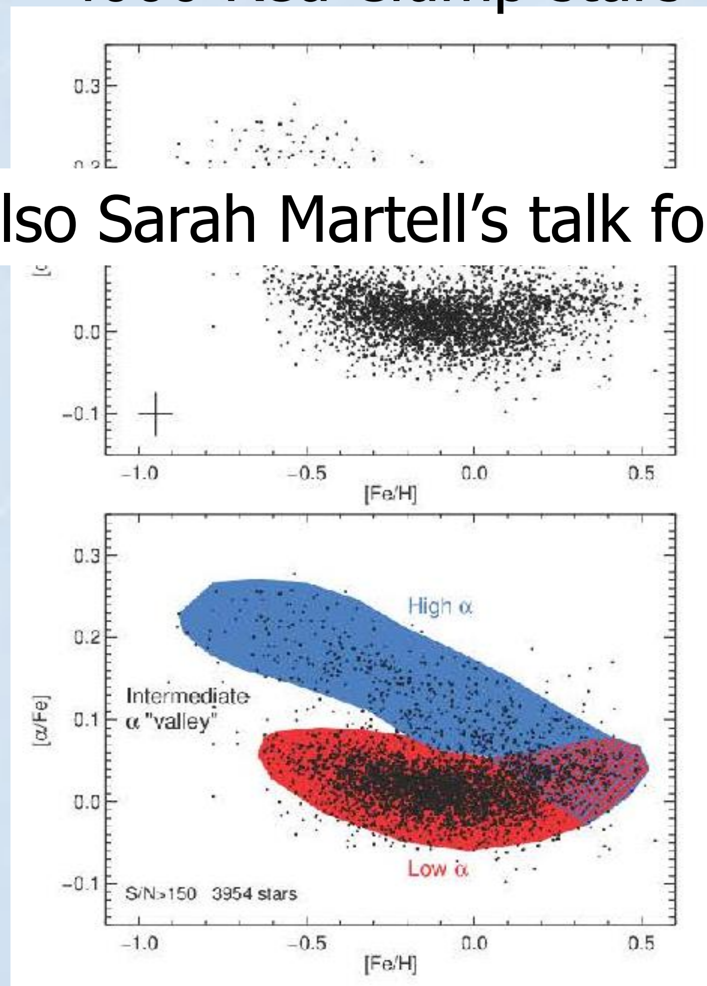
- Elemental abundance sequences separated by kinematics also – will be more robust with Gaia data

Non-Local Samples: APOGEE

Nidever et al Carlos Allende Prieto's talk ~30000

~4000 Red Clump stars

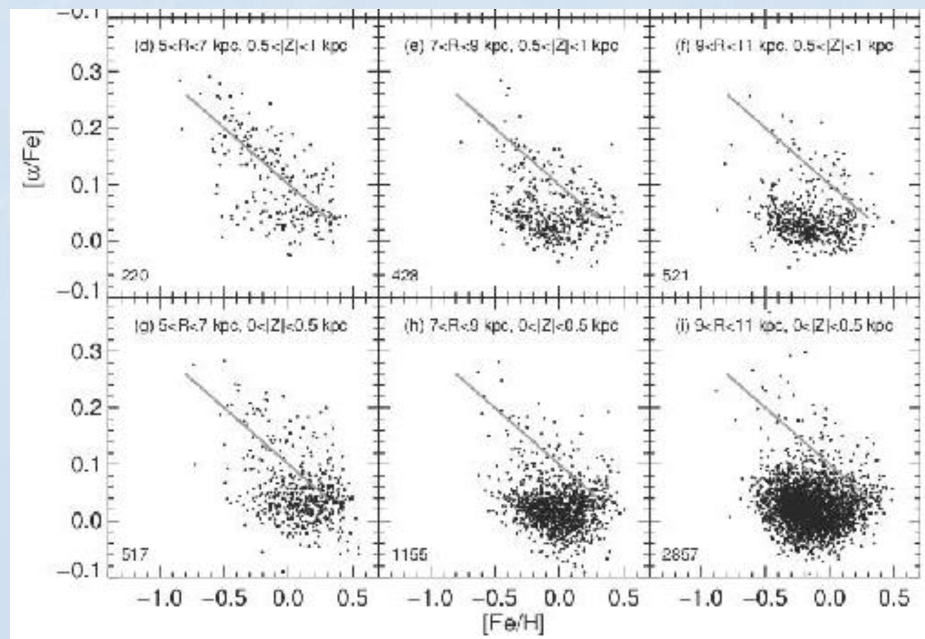
Also Sarah Martell's talk for more detailed elemental abundances



Distinct thick and thin disks

Thin disk sequence changes with R,Z

➔ Varying star formation efficiency/outflow



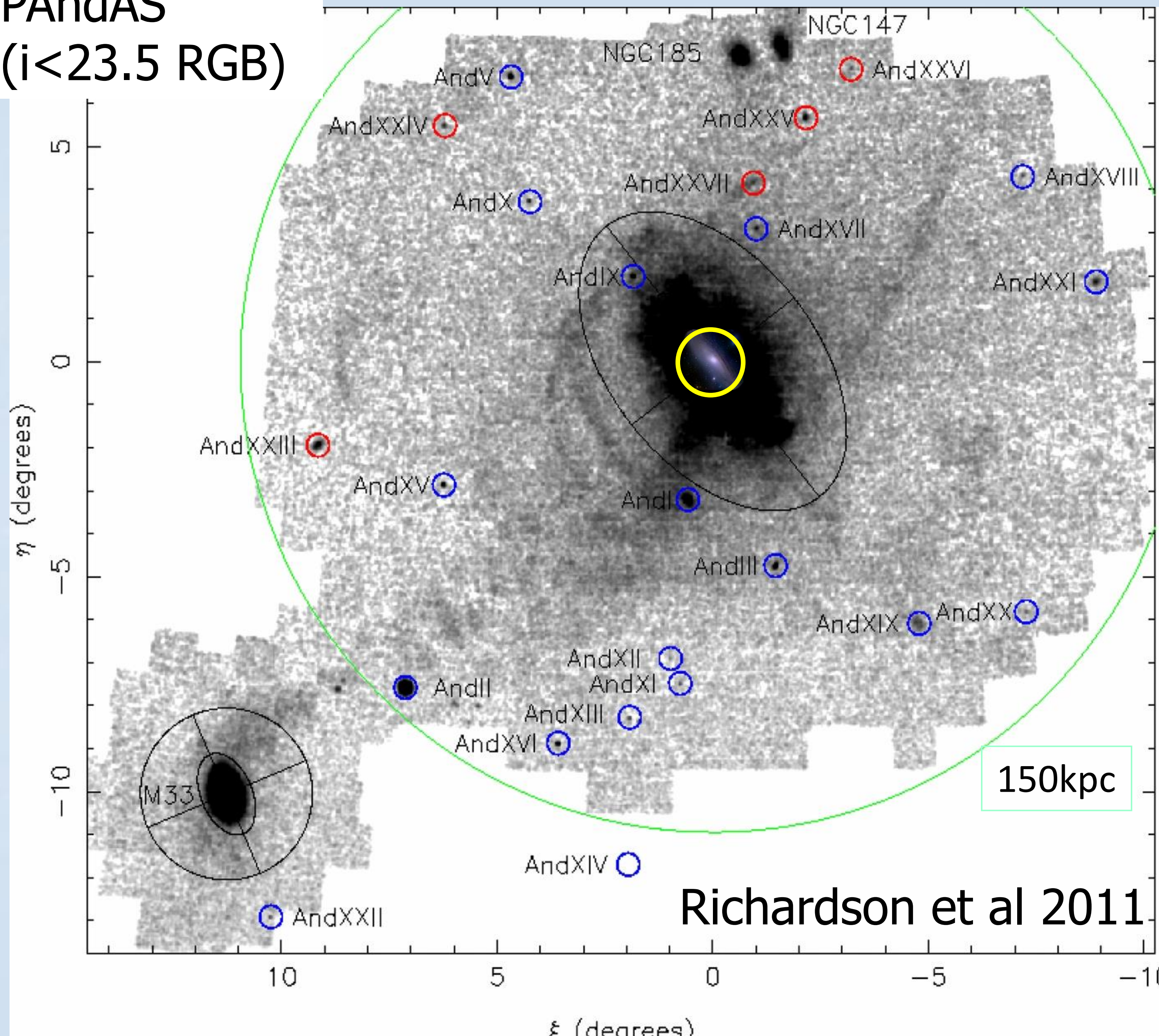
Subaru Prime Focus Spectrograph GA Survey

- 8m telescope, wide FoV (1.3deg) and > 2,000 fibres (see Takada et al 2014)
- 3-arm (blue, red, near IR) low-resolution spectrograph ($\mathcal{R} \sim 2000$)
  - Velocity, Iron, Carbon
- Medium resolution ($\mathcal{R} \sim 5000$) mode for red arm
  - [α/Fe] (Kirby)
- Northern hemisphere ➔ outer disk(s), M31, many dSph satellite galaxies
  - HyperSuprimeCam narrow-band (pre)imaging for dwarf/giant separation
- Start ~ 2019

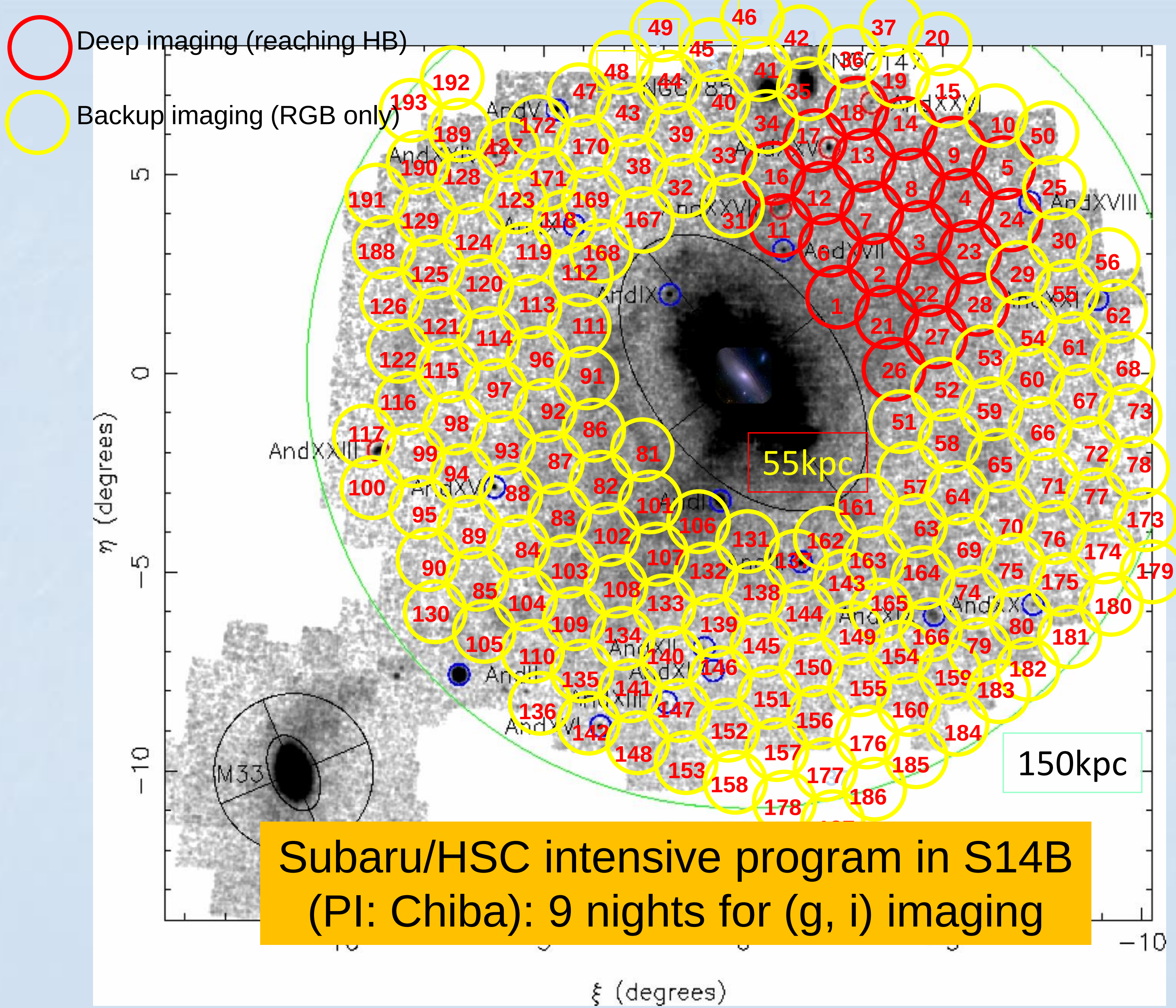
Subaru Prime Focus Spectrograph Survey

- Field stars in disks, halo – complement Gaia
  - [α/Fe] for brighter stars, V < 20
  - Phase-space substructure in fainter stars
  - Outer disk (cf LAMOST, Zhao)
- M31: obtain spectroscopic metallicities and velocities for large sample of individual stars, selected after pre-imaging
  - cf Gilbert et al (2014) SPLASH survey, used photometric metallicities for kinematically selected M31 stars
  - Ibata et al (2014)- redder RGB stars contaminated with MW stars, underestimated metal-rich end of M31 metallicity distribution
  - Extract true halo substructure ➔ merger history
- dSph: obtain velocities and [α/Fe] across full extent
  - Improved constraints on dark matter, tidal effects, baryonic feedback etc

PAndAS
(i<23.5 RGB)



Richardson et al 2011



Subaru/HSC intensive program in S14B (PI: Chiba): 9 nights for (g, i) imaging

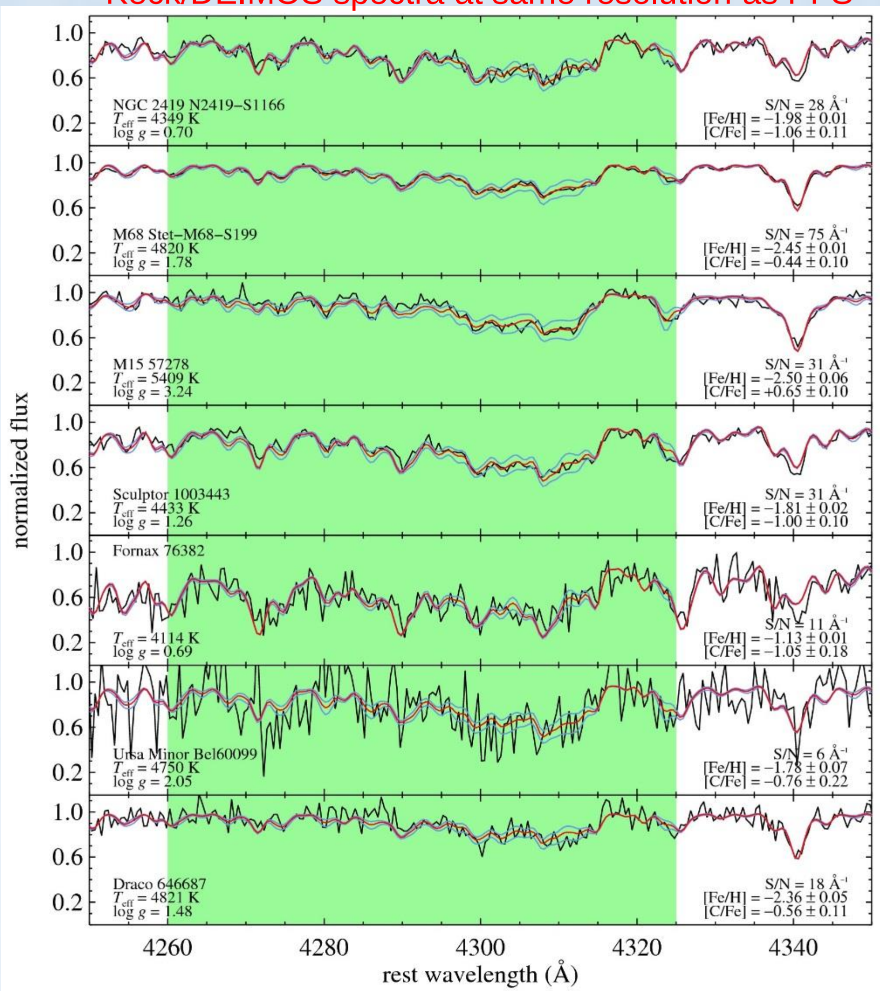
Concluding Remarks

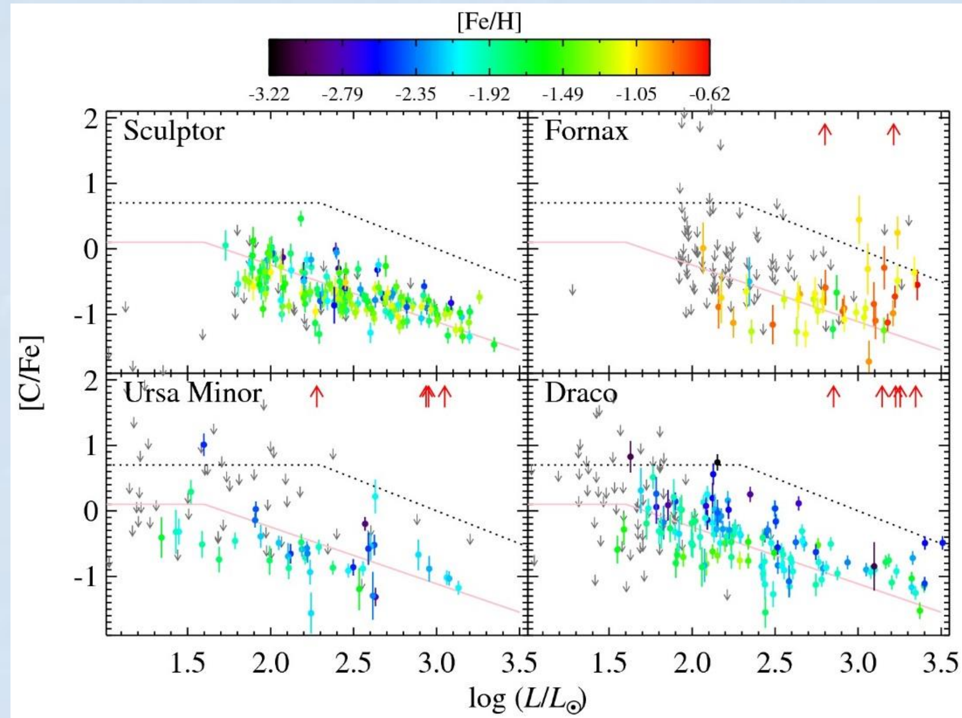
- Exciting times to be studying low-mass stars
  - Ongoing/imminent surveys, complementary and competitive, (will) provide transformative datasets to decipher how normal disk galaxies form and evolve, yield insight into the nature of dark matter
  - High-redshift surveys are quantifying the stellar populations and morphologies of galaxies at high look-back times
  - Large, high-resolution simulations of structure formation are allowing predictions of Galaxy formation in a cosmological context, ready for testing
  - LHC re-start!

Carbon in PFS spectra

Kirby et al 2015

Keck/DEIMOS spectra at same resolution as PFS





[C/Fe] can be precisely determined (dredge-up effect in upper RGBs)

Systematic changes with L and [Fe/H]

→ Use PFS for a large number of stars in dSphs and field halo stars in the MW

Kirby, Cohen, et al., ApJ, submitted

Original GA Survey Plan (to be revised)

Survey	Mode	Mag. Range (mag)	Exp. (sec)	No. Fields	Survey (nights)	Comments
Bright time:						
MW thick disk	MR + LR	V < 19	2700	208	20	Thick disk:
MW thick disk	MR LR(blue)					b=-30, 60 < l < 120
Grey time:						
MW halo	MR + LR(b	V < 21	7200	40	10	Halo: 270
MW disk	LR					)
MW stream	LR	V < 22	7200	24	6	'Field of Stream'
MW dSph	MR + LR(blue)	V < 21	7200	28	7	Frx, Scl, LeoI, Umi & Dra
Dark time:						
MW dSph	MR					
M31 halo	LR	21.5<V<22.5	18000	50	31	HSC sample
dIrr	LR	V < 22.5	18000	4	3	N6822, IC10, WLM
Total				456	96	

MW bright thick-disk stars (25 nights)

MW faint halo/disk stars (28 nights)

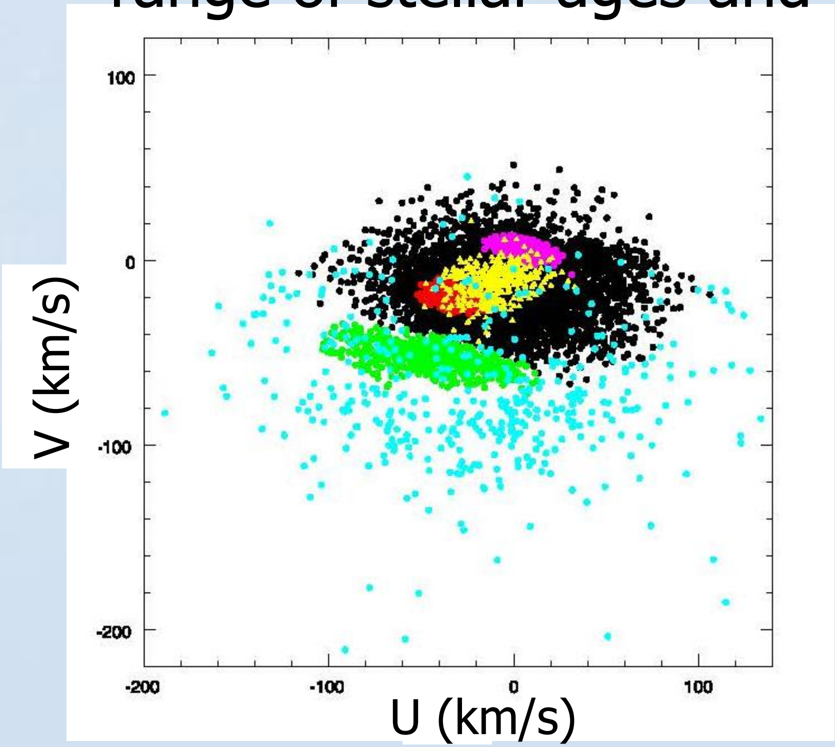
MW dSph + M31 halo stars(43 nights)

The Milky Way - a Typical Disk Galaxy
What can we learn?

- Thin stellar disks 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 and cannot ‘cool’ once heated, unlike gas
  - Vertical structure contains imprints of past heating/cooling
  - 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 processes
- Bulge – classical or pseudo? Connection to disk or halo?

Thin disk substructure

- Spiral arms can cause significant disturbances in stellar kinematics that persist after arm perturbation has gone (e.g. de Simone et al 2004)
  - Also can have coherent induced motions due to Bar resonances
- The source of 'moving groups' and 'streams' with large range of stellar ages and metallicities



Famaey et al 05; cf Dehnen 1998
Local sample - ~6000 Hipparcos giants with 3D space motions

Gaia

- Successfully launched in 2013 Dec.
- Some degradation at the faint limit now
  - Astrometry: 200-300μas -> 540μas for V=20mag
  - Radial velocity: ΔVr=15km/s for V=16mag -> 15mag

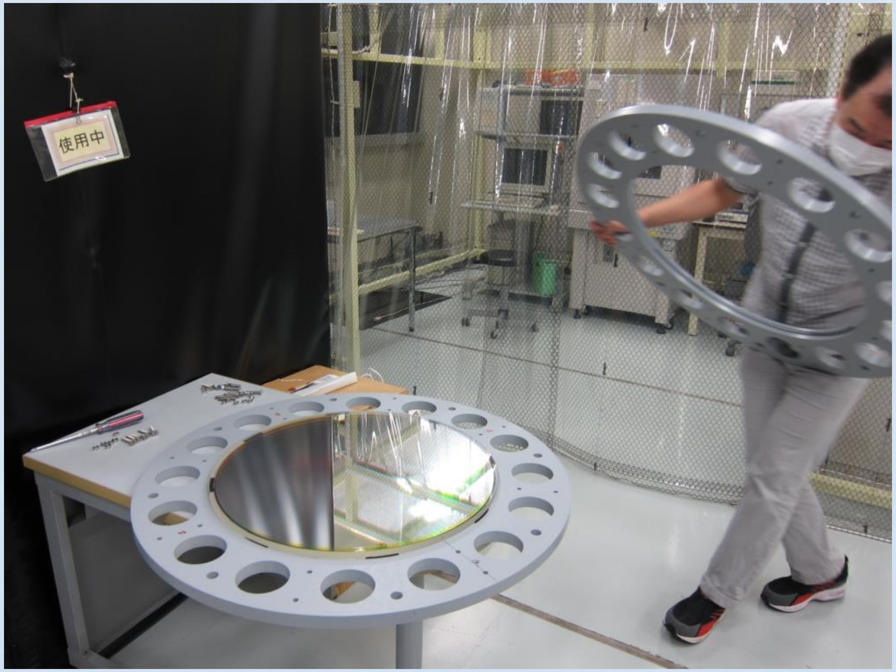
  More weight on brighter stars (advantage for 4m projects!?)

  but anticipated mission extension of 2-2.5 years would bring the uncertainties back down to the planned values
- Data release schedule
  - DR1 (summer 2016): positions and G-mags
  - DR2 (early 2017): astrometric data, mean RVs
  - DR3 (2017/2018), DR4 (2018/2019): variables, binaries
  - Final release (2022)

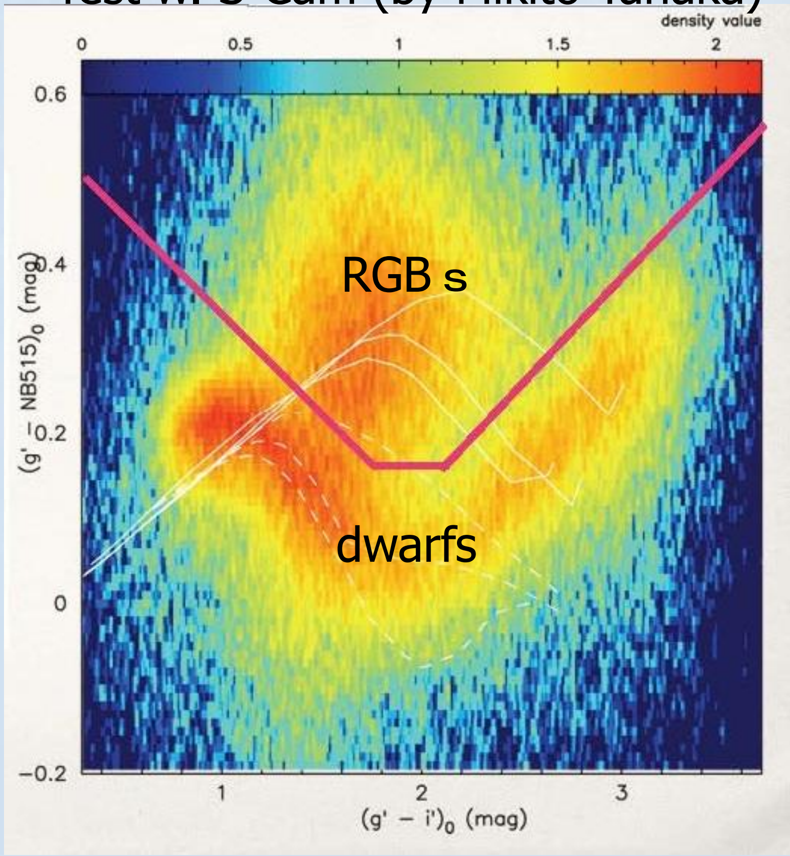
NB515 filter for HSC

NB515 (CW: 515 nm, FWHM: 8nm) (from S15A)
Separation of <u>RGB</u> stars in <u>M31 halo</u> + <u>MW satellites</u> from the foreground MW dwarfs

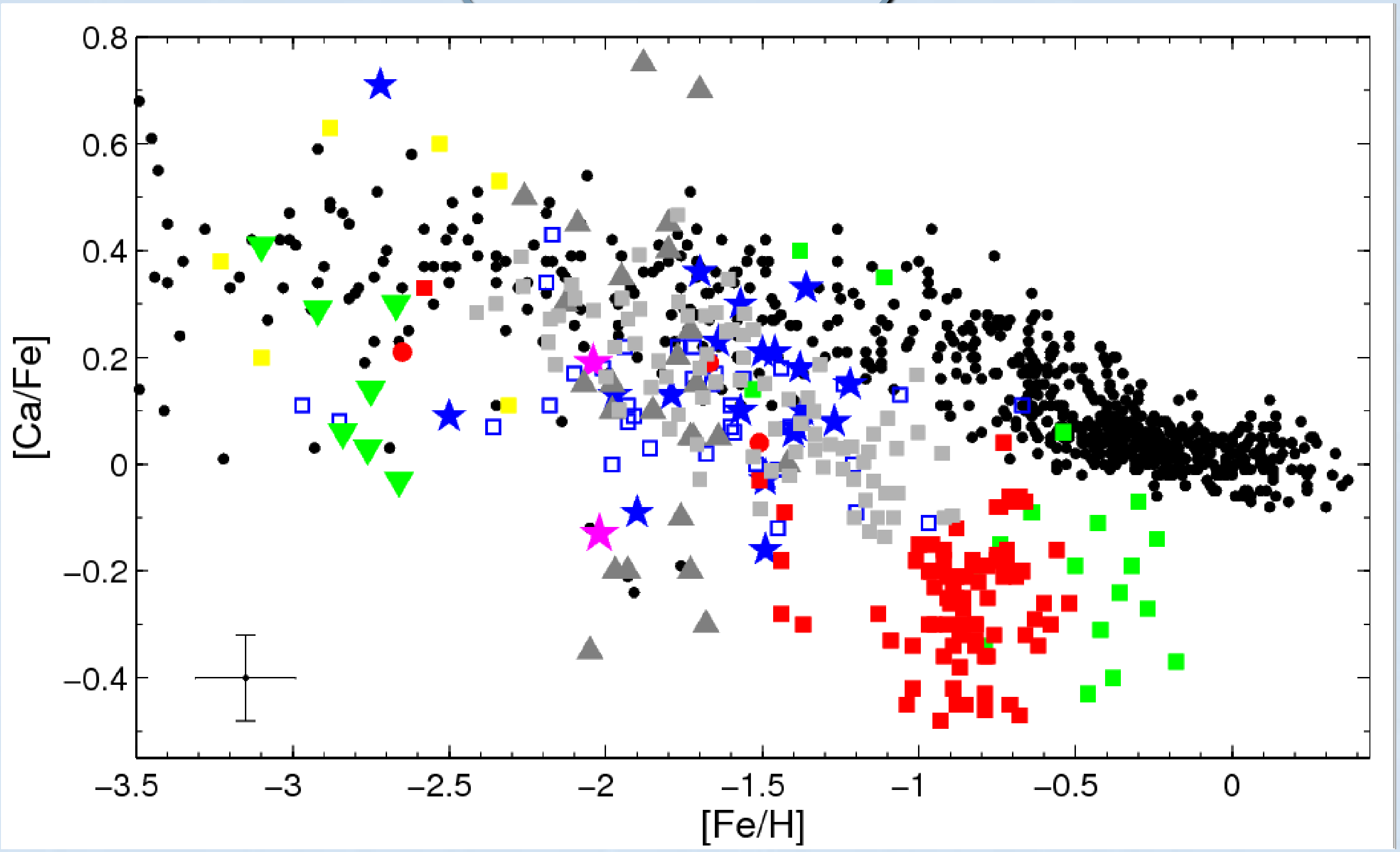
Aug 28, 2013



Test w. S-Cam (by Mikito Tanaka)



dSphs vs. MWG abundances
(from A. Koch)



Shetrone et al. (2001, 2003): 5 dSphs

Sadakane et al. (2004): Ursa Minor

Monaco et al. (2005): Sagittarius

Koch et al. (2006, 2007): Carina

Letarte (2006): Fornax

Koch et al. (2008): Hercules

Shetrone et al. (2008): Leo II

Frebel et al. (2009): Coma Ber, Ursa Major

Aoki et al. (2009): Sextans

Hill et al. (in prep): Sculptor

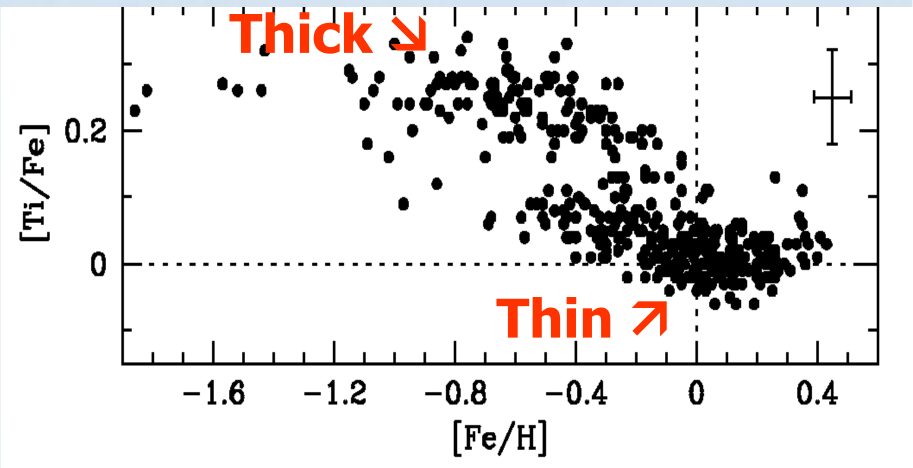
Galactic dSph sample for PFS-MR survey

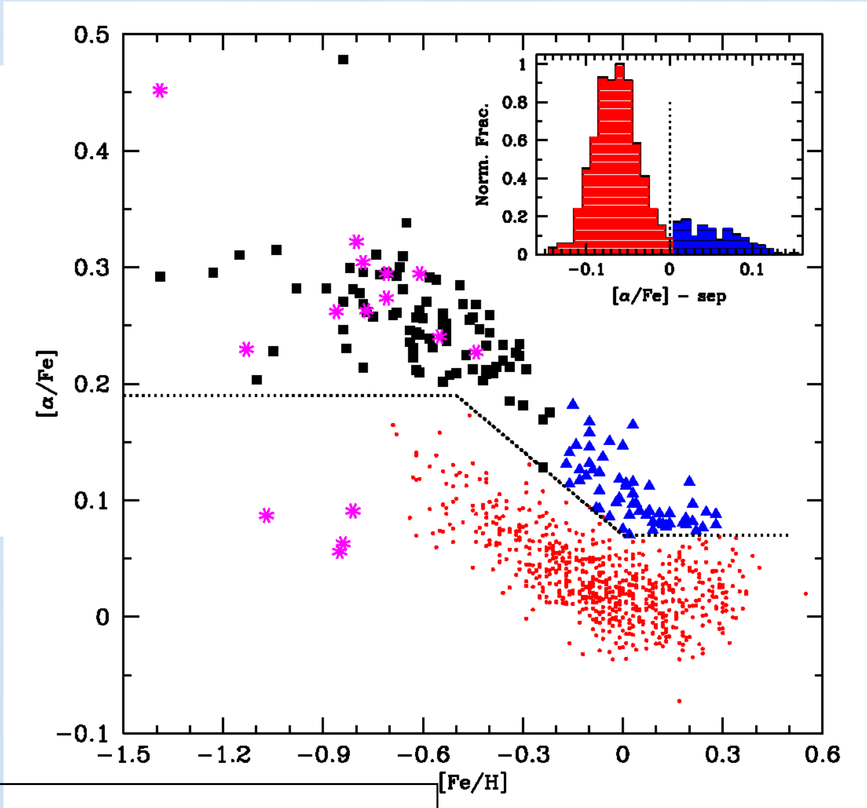
Object	RA	DEC	D (kpc)	r_c (arcmin)	Tidal radius (arcmin)	Number of PFS pointings
Fornax	02h 40m	-34° 27'	138	14	71	4 x 2 = 8
Sculptor	01h 00m	-33° 43'	87	6	76	4 x 2 = 8
Sextans	10h 13m	-01° 37'	88	17	160	4 x 2 = 8
Draco	17h 20m	+57° 55'	84	9	28	1 x 2 = 2
Leo I	10h 08m	+12° 18'	247	3	13	1 x 2 = 2
Ursa Minor	15h 09m	+67° 13'	69	16	51	4 x 2 = 8

(Irwin & Hatzidimitriou 1995)

Back to the Galaxy

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





Bensby et al 14

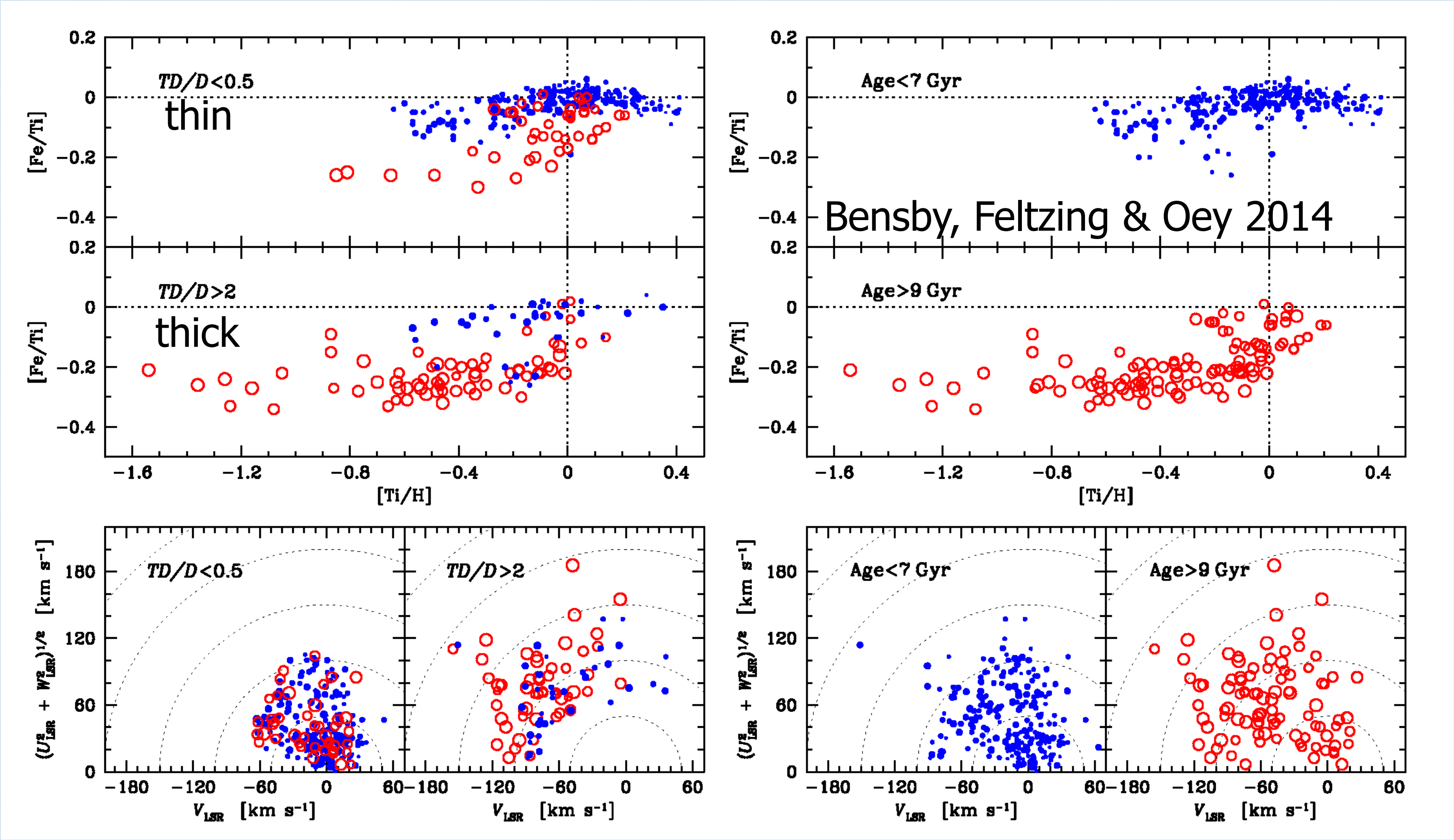
Adiekyan et al 13

Very nearby FG(K) stars: not volume complete

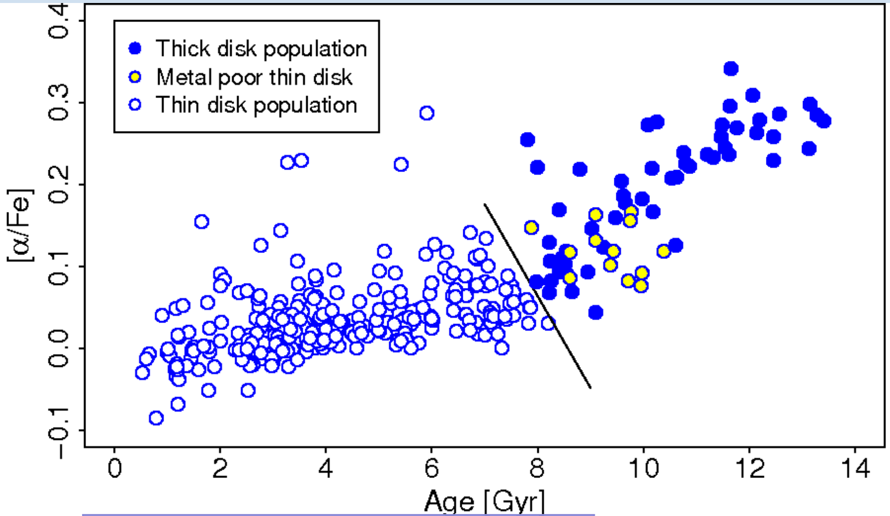
Local Thick and Thin Disks

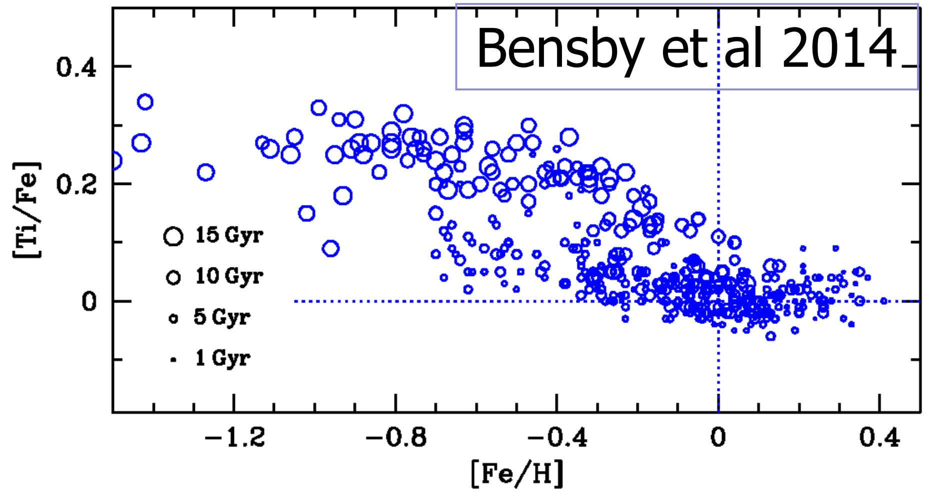
Kinematics-based definition

Age-based definition

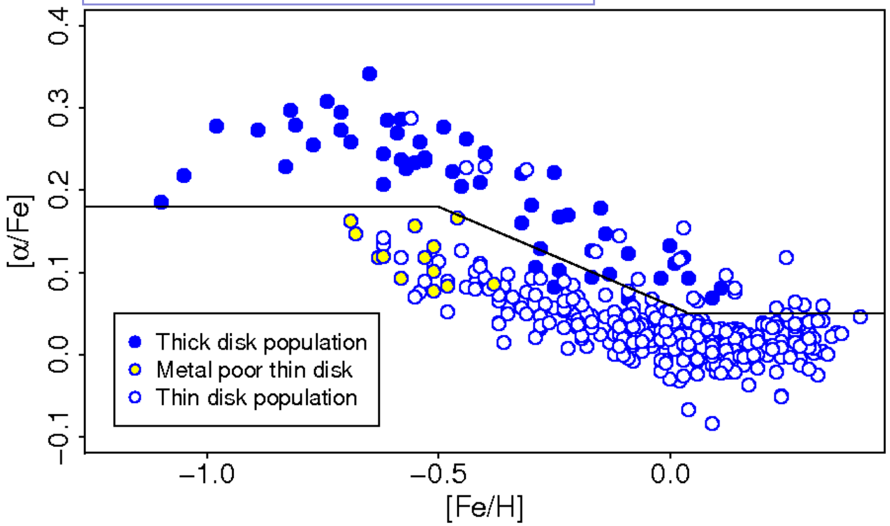


Heterogeneous selection function





Haywood et al 2013



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

Thick disk is old and 'alpha-enhanced'

➔Formed early, from gas predominantly enriched by core-collapse Sne

NB Peak iron abundance of thick disk at ~-0.6 dex: old

Forming a disk galaxy like the MW in ΛCDM

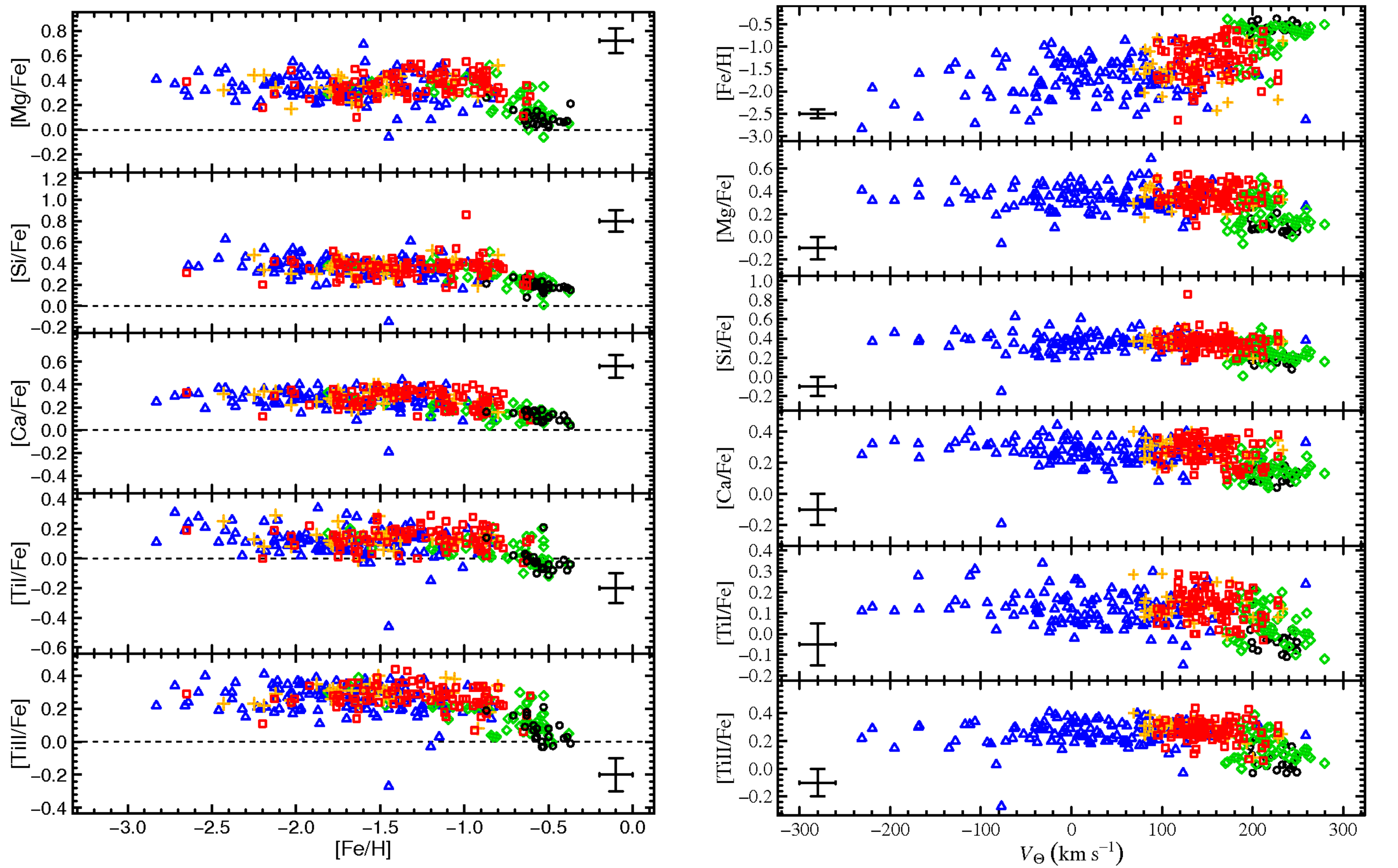
- Generic massive disk galaxy in ΛCDM has large bulge-disk ratio and active merging history
- However, old age of thick disk stars, combined with continuous star formation in thin disk, limits last significant merger to a look-back time corresponding to age of 'heated' stars: 10Gyr-old thick disk constrains mergers since redshift of 2 to have been only very minor: unusual in ΛCDM (Wyse 2001; Stewart et al 2008)

  ➔ Need to select atypical Galaxy-mass halo with very quiet merger history e.g. no significant (1:10) merging after redshift 3 (11.5Gyr) (Guedes et al 11; Bird et al 2013)

  - Fewer than 1% of halos of this mass
  - But late-type (Sb/Sbc) disk galaxies are not rare
  - Old thick disks are not rare
- Need also careful treatment of SFR and feedback

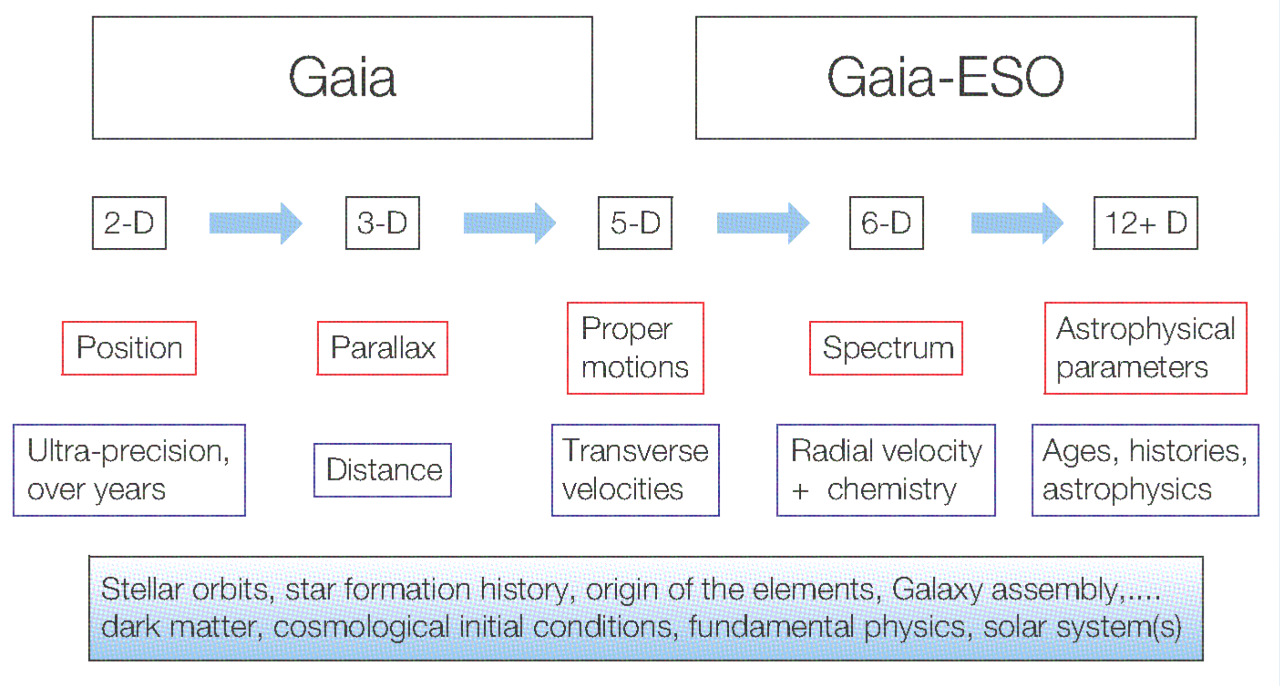
Metal-weak thick disk stars have same enhanced [α/Fe] as halo: Same massive-star IMF, well-mixed to show IMF average yield & formed early

Ruchti, Fulbright, Wyse et al 2011



Gaia-ESO Public Survey

- Complements Gaia astrometric satellite
- Allocated 300 nights over 5 years (started 1/2012) on VLT to obtain ($\mathcal{R}$ > 16,000) spectra and hence radial velocities and stellar parameters, including elemental abundances, for ~100,000 faint field stars (typically r ~ 18), at intermediate latitudes (plus star clusters) (Gilmore et al. inc RW 2012)



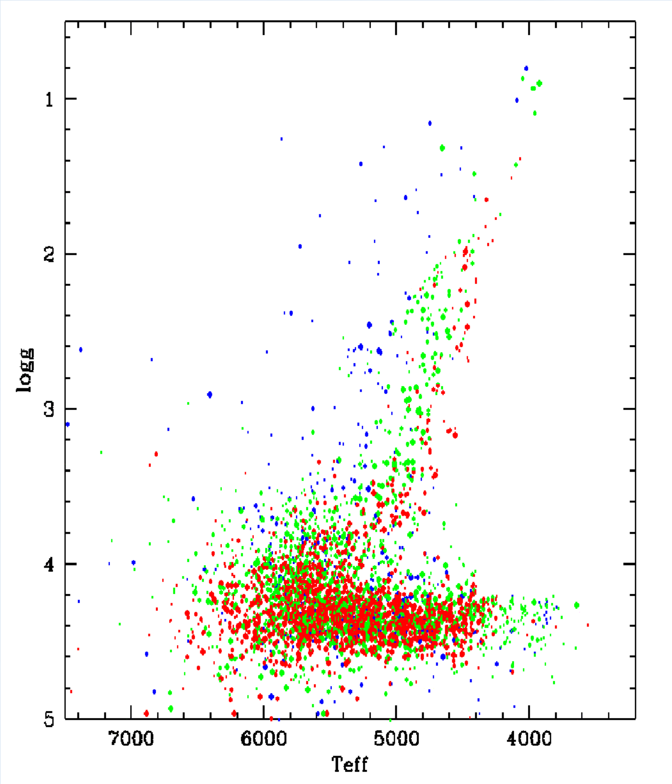
Elemental Abundances

- Type II supernovae have progenitors > 8 $M_{\odot}$ and explode on timescales ~ 10^7 yr, less than typical duration of star formation
  - Main site of α-elements, e.g. O, Mg, Ti, Ca, Si
- Low mass stars enriched by only Type II SNe show enhanced ratio of α-elements to iron, with value dependent on mass distribution of SNe progenitors – if well-mixed system, see IMF-avg.
- Type Ia SNe produce very significant iron, on longer timescales, few x 10^8 – several 10^{10}yr (WD in binaries) after birth of progenitor stars

Thin to Thick Disk Transition

Recio-Blanco et al., 2014

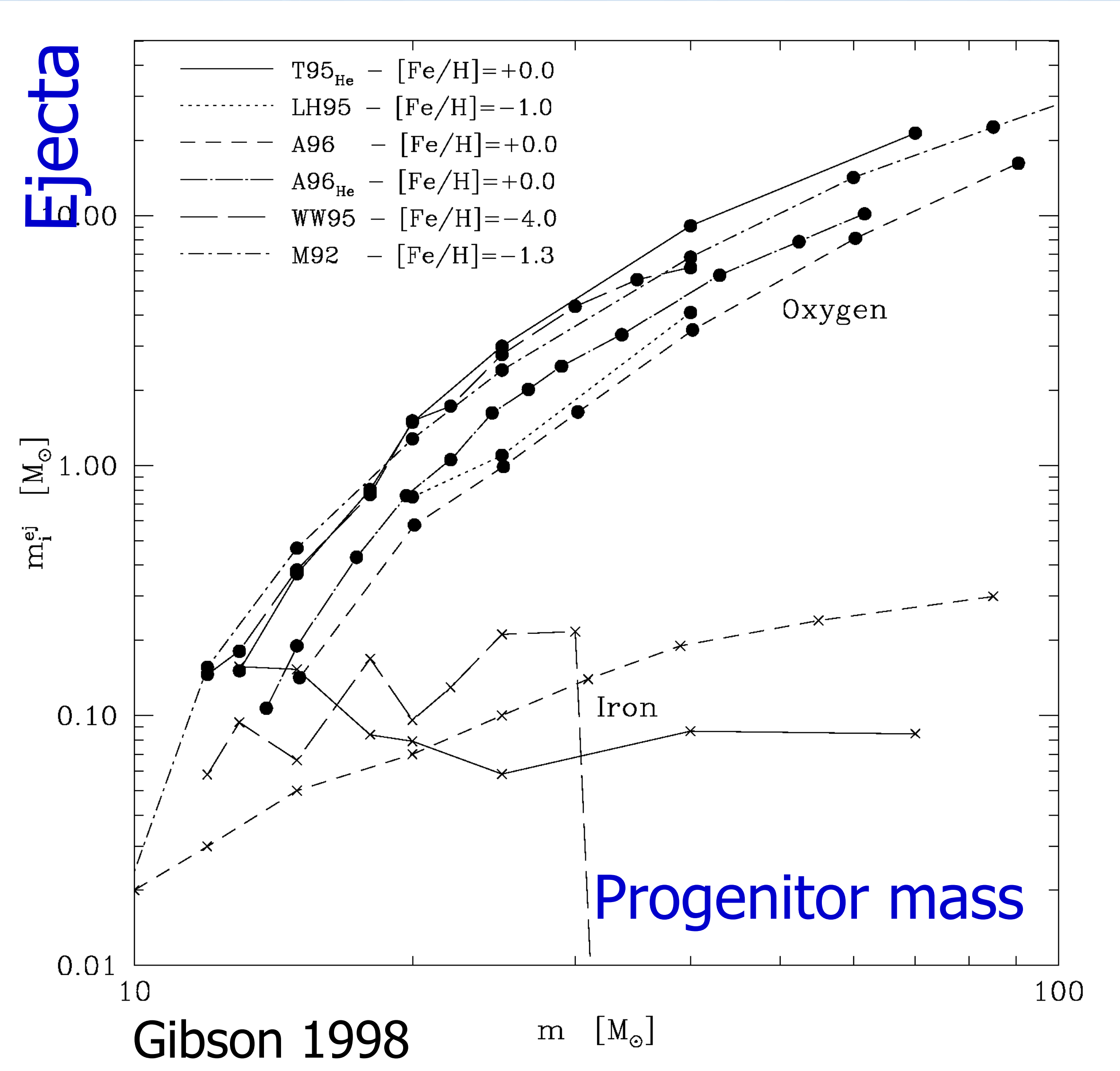
- Analyse ~5,000 disk stars
- Thin disk distinct from thick disk in elemental abundance pattern
- Also in terms of rotational velocity gradients



Color-code: metallicity
Red: [M/H] > -0.5 dex
Green: -1 < [M/H] ≤ -0.5
Blue: [M/H] ≤ -1 dex

Radial velocity error ~ 0.3km/s
[M/H] error ~ 0.1 dex
[α/Fe] error ~ 0.05 dex
Distance error ~ 20-30%
PM error ~ 8 mas/yr

IMF dependence due to different nucleosythetic yields of Type II progenitors of different masses



Salpeter IMF (all progenitor masses) gives [α/Fe] ~ 0.4; Change of IMF slope of ~1 gives change in [α/Fe] ~ +0.3

➔Detectable

(Wyse & Gilmore 92)

Galaxy-scale Challenges for CDM

- On galaxy scales there is an opportunity to learn some (astro)physics:
  - Large galaxies of old stars, small galaxies of young (plus old) stars →'downsizing'
  - Massive pure-thin-disk galaxies exist: None should since mergers heat and puff-up disks, create bulges
  - The MWG has a thick disk, and these stars are old, as in the bulge. This seems common but implies little merging since early times, to build them up
  - Sgr dSph in the MWG proves late minor merging happens, but is clearly not dominant process in evolution of MWG except the outer halo, $R_{GC} \gtrsim 25$ kpc
  - The 'feedback' requirement: otherwise gas cools and stars form too efficiently, plus angular momentum transported away from gas in mergers: stellar disks are too massive and compact
  - The substructure problem – how to hide them?

Wyse & Gilmore 1992

TABLE 1. Woosley data: Dependence of the elemental yields and [O/Fe] on the slope of the IMF.

Main Sequence Mass ($M_\odot$)	10	12	15	20	25	35	50	100
Oxygen Produced ($M_\odot$)	0.1	0.5	0.5	1.5	3	6.5	12	30
Iron Produced ($M_\odot$)	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
IMF Slope	−2.3		−1.5		−1.5		−1.1	
Δ[O/Fe]		0.2				0.1		
				0.3				

TABLE 2. Thielemann *et al.* data: Dependence of the elemental yields and [O/Fe] on the slope of the IMF.

Main Sequence Mass ($M_\odot$)	13	15	20	25	40	100
Oxygen Produced ($M_\odot$)	0.22	0.43	1.5	3	20	20
Iron Produced ($M_\odot$)	0.24	0.15	0.075	0.05	0.05	0.05
IMF Slope	−2.3		−1.5	−1.5		−1.1
Δ[O/Fe]		0.3			0.15	
			0.45			

Salpeter IMF slope: -1.35

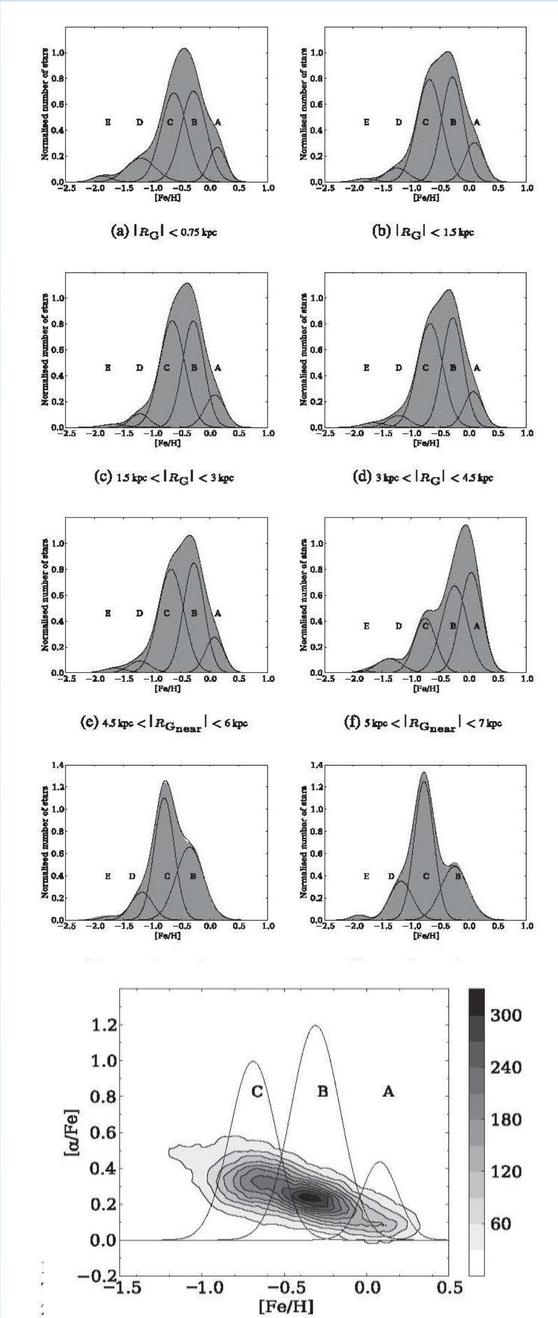
Scalo: -1.5

Matteucci for Bulge: -1.1

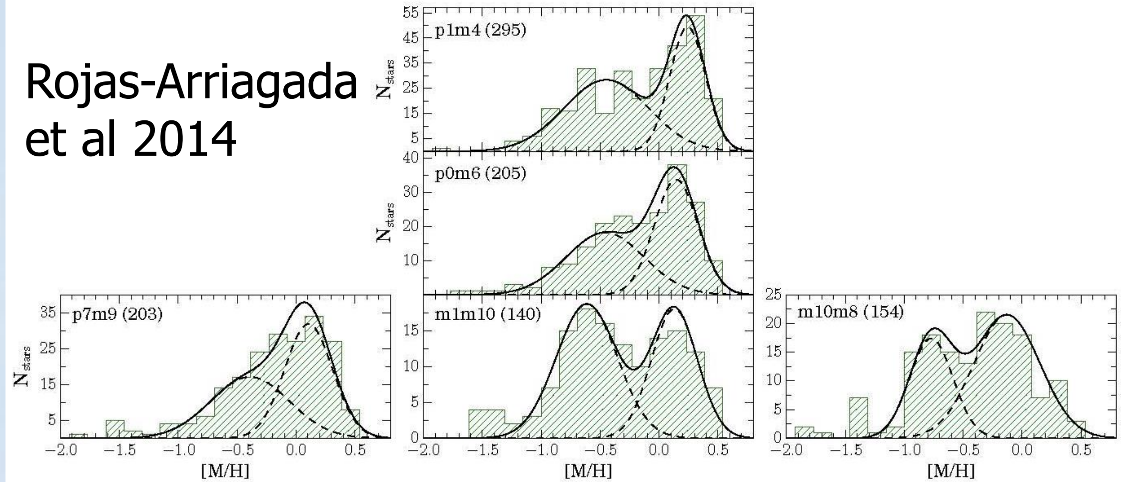
Relation to bulge?

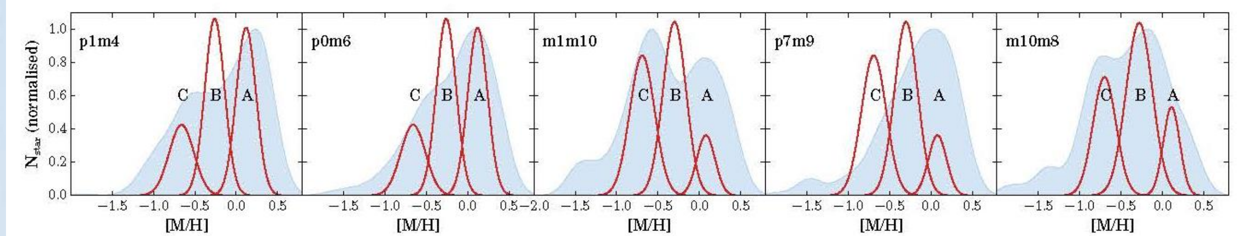
- Both Galactic thick disk and Galactic bulge dominated by old population
- Mean metallicity of local thick disk lower than that of bulge (factor 1.5 – 2) – need data for inner disks
- Changes in stellar metallicity distributions in lines-of-sight to bulge can be modelled as changing mix of populations (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!

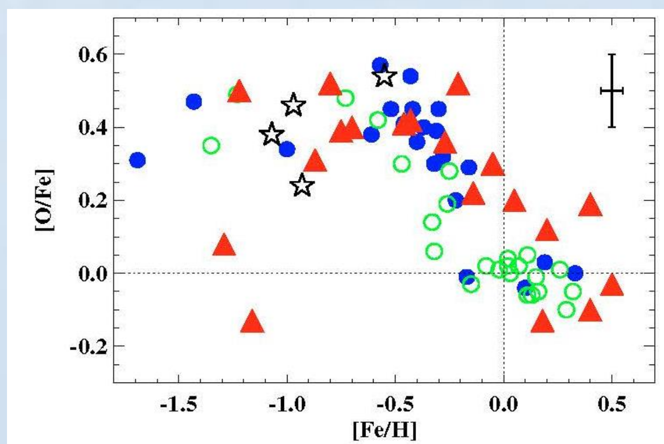
Ness et al 2013



Rojas-Arriagada et al 2014







Melendez et al 08

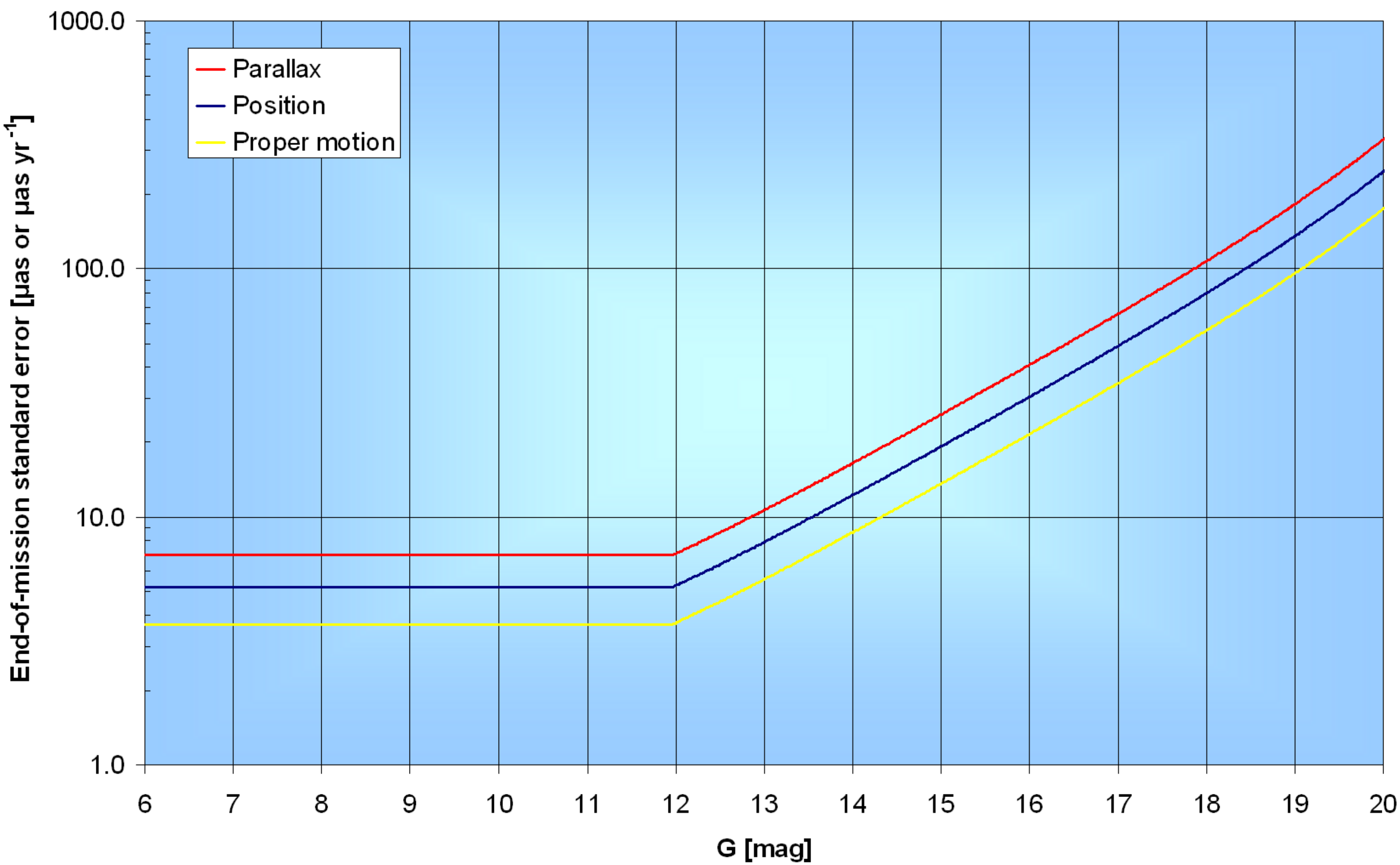
● - thick disk
☆ - halo
▲ - bulge
o – thin disk

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

Gaia



Parallax
Position
Proper motion
1000.0
100.0
10.0
1.0
End-of-mission standard error [µas or µas yr-1]
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
G [mag]