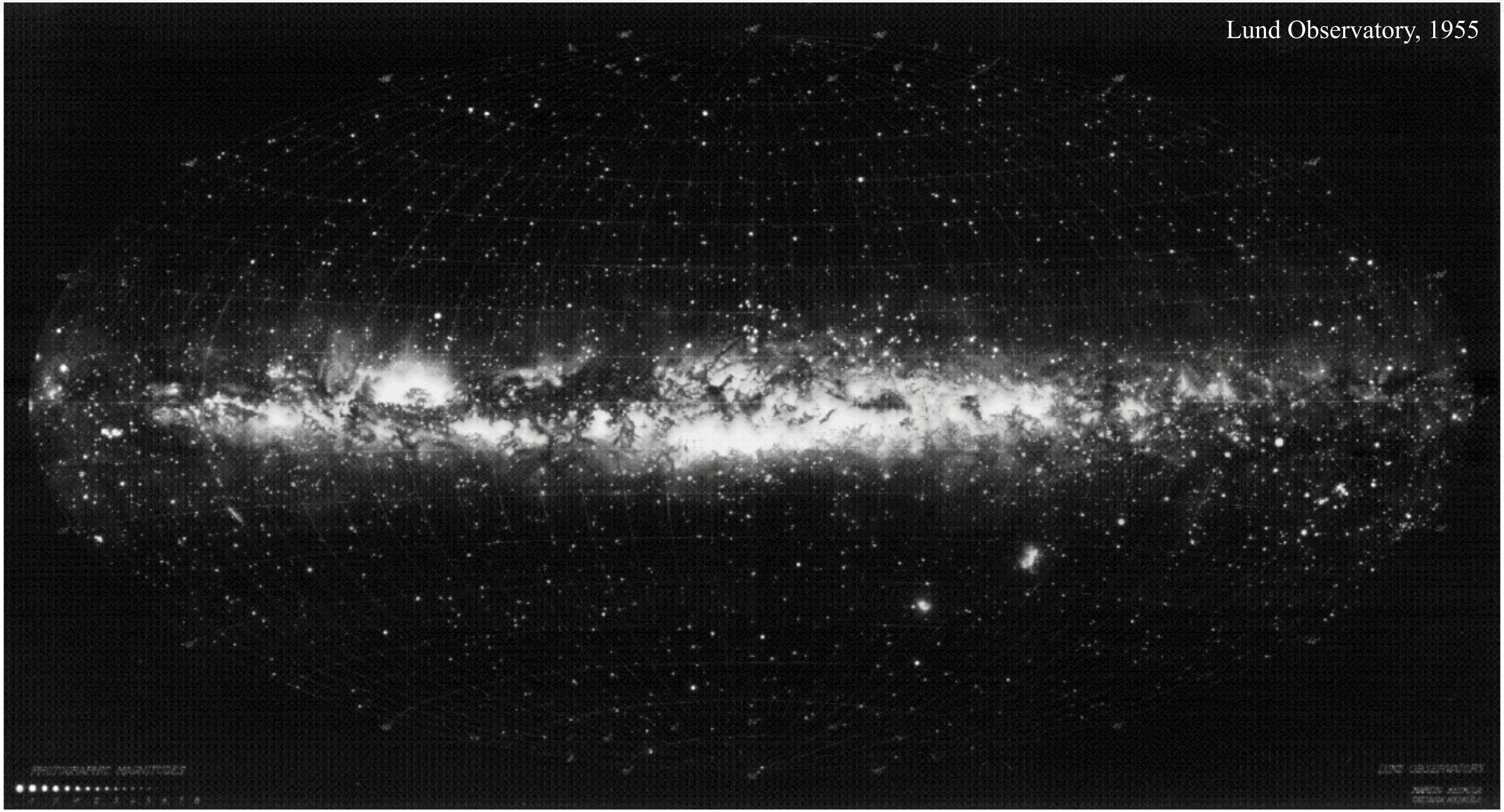
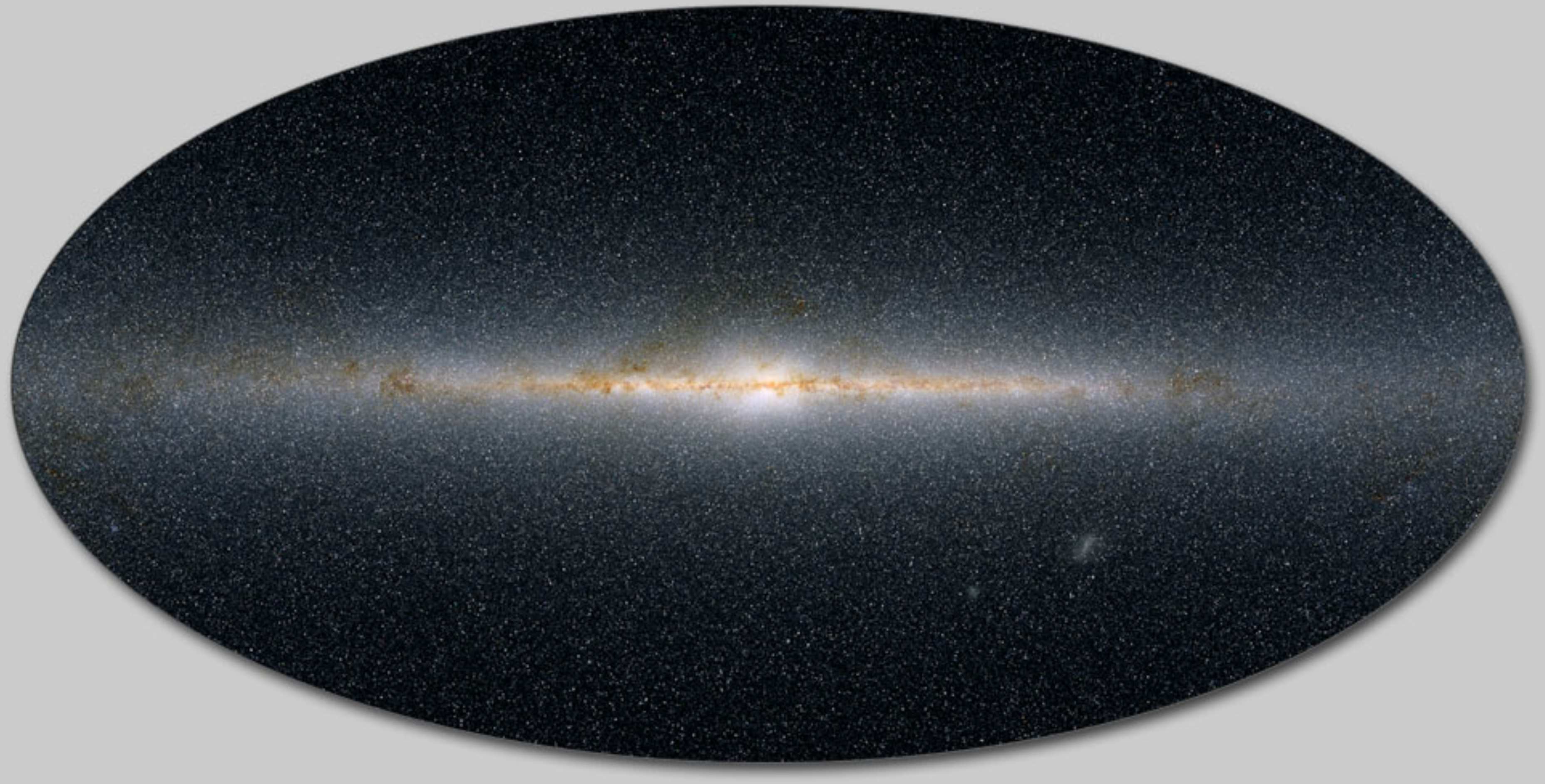
The Milky Way Galaxy



Marina Rejkuba, ESO, Garching

2MASS Showcase

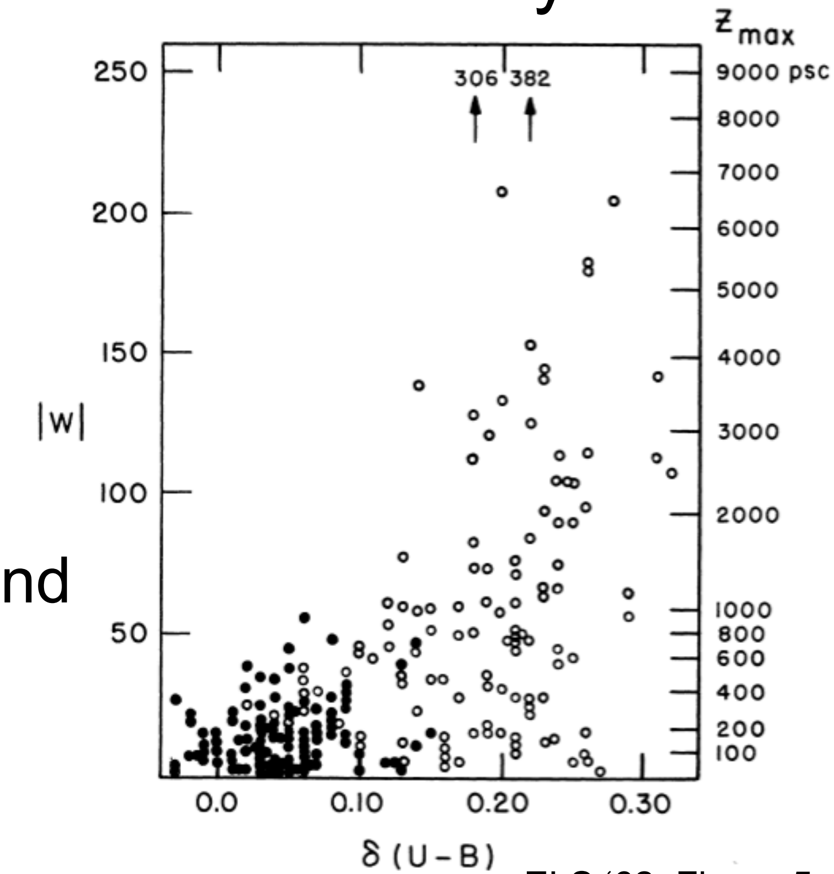


The Infrared Milky Way This map of the infrared sky includes the light of a half billion stars

Two Micron All Sky Survey Image Mosaic: Infrared Processing and Analysis Center/Caltech & University of Massachusetts

50 years from ELS

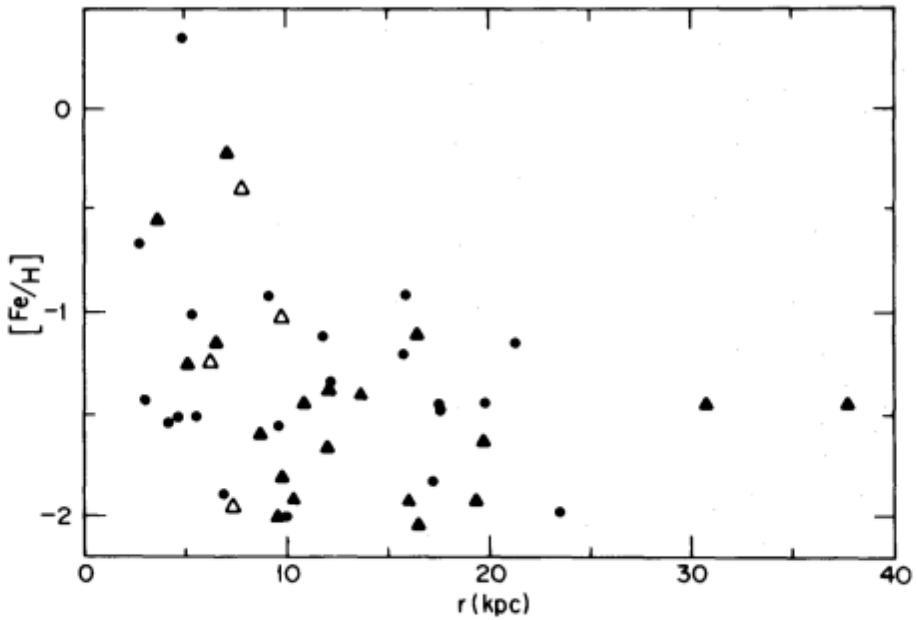
- Eggen, Lynden-Bell & Sandage 1962: “Evidence from the motions of old stars that the Galaxy collapsed”
  - “… the oldest objects were formed at almost any height above the galactic plane, whereas the youngest were formed very near the plane.”
  - “The process was very rapid and consumed a time span of not more than a few times 10^8 yr.”
  - metallicity gradient



ELS ‘62, Figure 5

Searle 1977, Searle & Zinn '78

- Lack of metallicity gradient for outer halo globular clusters



Searle & Zinn 1978, Fig.9

  - ➢ halo built up over an extended period (after the collapse of the central regions of the Galaxy have been completed) from independent protogalactic fragments with masses ~10^8 $M_\odot$

Milky Way is a spiral galaxy

- Disk → defines the plane and extends to ~15 kpc
  - ¾ of the baryonic mass – $5 \times 10^{10}\ M_{\odot}$
  - Thin disk Hz~300 pc, Thick disk Hz~900 pc (old, α-enhanced)
  - Normalization thick/thin disk~2-20%
- Bulge→ central component extending to ~3kpc
  - Dominated by the bar – peanut shape (COBE/DIRBE)
  - ¼ of the baryonic mass
  - Old, α-enhanced
- Halo → nearly spherical extending to ~100kpc
  - 1% of the baryonic mass; local normalization ~1/1000
  - Old, α-enhanced, sub-structure
- Dark matter halo: $1\text{-}3 \times 10^{12}\ M_{\odot}$

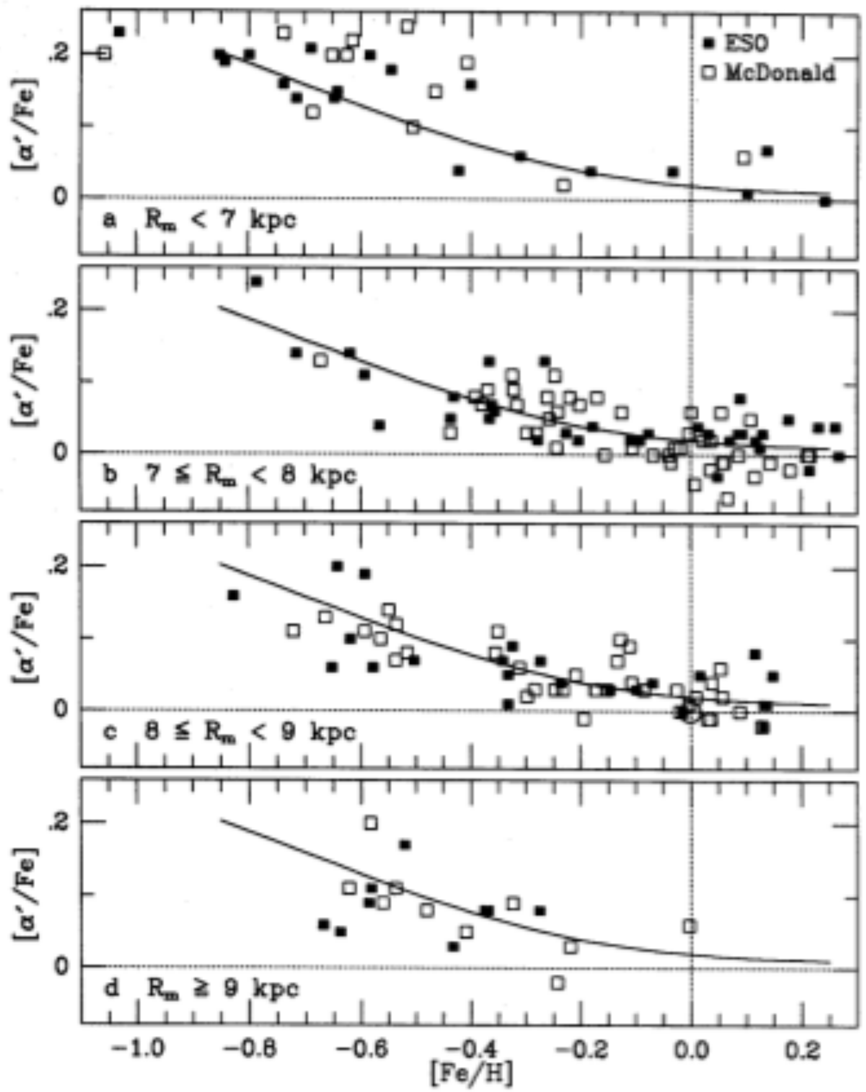
Large area surveys

- Stellar counts studies & large surveys
  - UK Schmidt Telescope → Thick disk (Gilmore & Reid 1983), Sagittarius dwarf (Ibata et al. 1994, 1995)
  - Palomar Observatory Sky Survey (POSS) → asymmetries in the disk counts (Larsen & Humphreys 1996, Parker+2003)
  - Hipparcos → SFH in the solar neighbourhood (Hernandez & Valls-Gabaud '00)
  - Two Micron All Sky Survey (2MASS) → Sgr dwarf (Majewski+2003), streams and sub-structure (Rocha-Pinto et al. 2003, 2006)
  - Sloan Digital Sky Survey (SDSS) and Sloan Extension for Galactic Understanding and Exploration survey (SEGUE) → disk and halo structure, streams, metallicity distribution (Ivezic+2008, Juric+2008, Carollo+2007, Belokurov et al. 2006, 2007, 2010…)
  - The Radial Velocity Experiment (RAVE) → kinematic groups (Antoja+2012)

Edvardsson et al. 1993

- 189 nearby field F & G dwarf stars selected from Strömgren photometry (Olsen 1977, 1983 – La Silla Danish 50cm, KPNO)
- S/N~200 spectra from ESO 1.4m ESO Coude Auxiliary Telescope (60 usable nights 1983-1986) & 2.7m McDonald Observatory (1982-1988)
- First systematic homogeneous analysis (>1450 citations)
  - Abundances of 13 elements based on new generation of model atmospheres
  - Kinematics → orbital properties
  - Photometric ages

Edvardsson et al. 1993



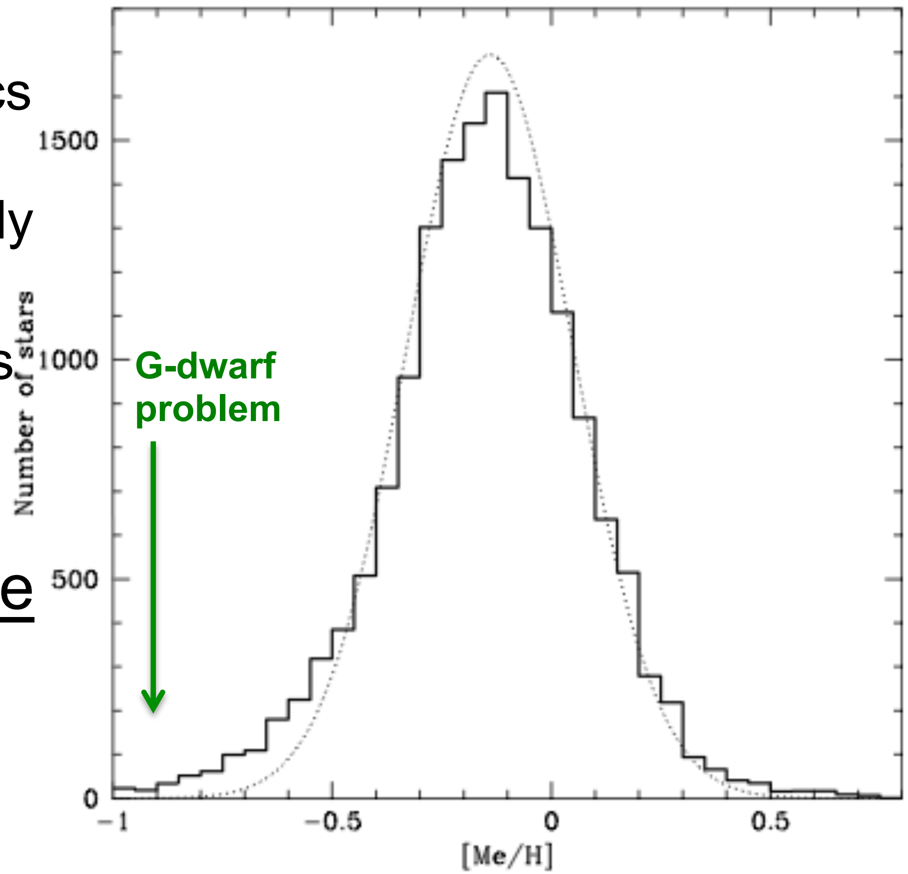
Edvardsson et al. 1993, Fig 20

- [Fe/H] vs age very flat with a large scatter in metallicity at all ages
- Remarkably little scatter in abundance ratio of elements
- Galactic abundance gradient confirmed ~0.1 dex/kpc
- Galactic chemical evolution requires complex models

Geneva-Copenhagen Survey (GCS)

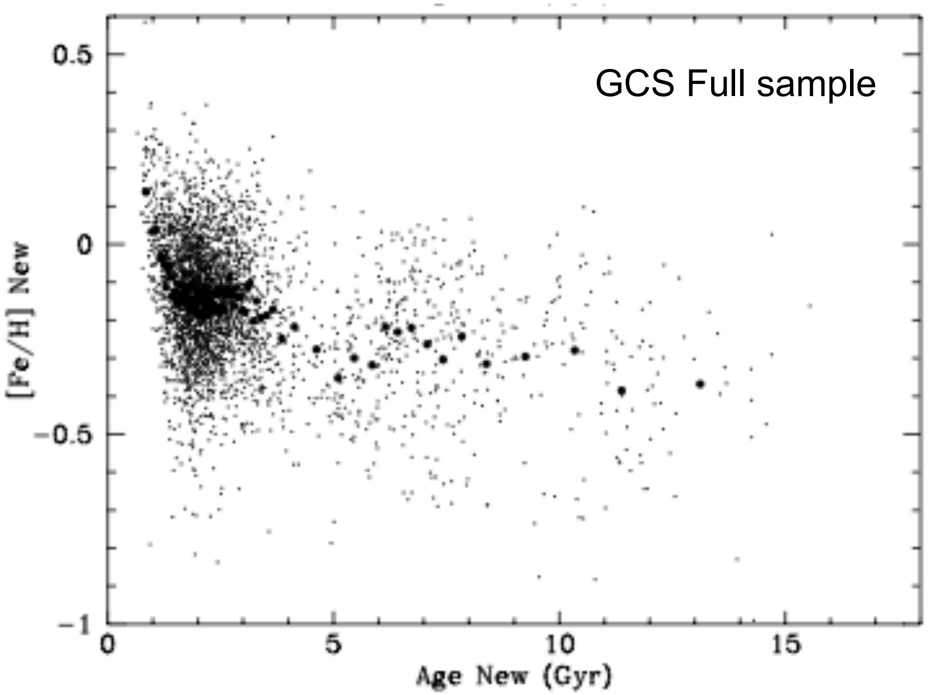
- Nordström et al. (2004), Holmberg et al. (2007)
  - Metallicity, rotation, age, kinematics and Galactic orbits for a complete, magnitude-limited and kinematically unbiased sample
  - 16 682 nearby F and G dwarf stars (Strömgren *uvbyβ*)
- CORAVEL: Danish 1.5m in La Silla & Swiss 1m at Observatoire de Haute-Provence:
  - "60476 CORAVEL observations have been made of 12 941 of the programme stars … some 1000 nights' worth of data."

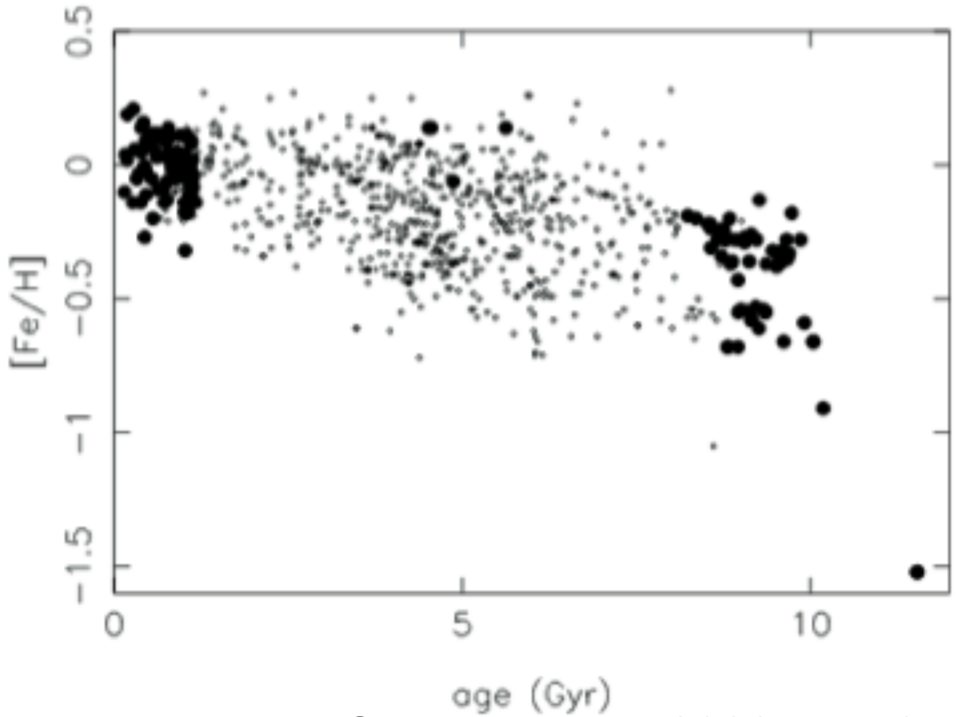
Thin disk MDF
Mean [Fe/H] = -0.14, σ=0.19 dex



Nordström et al. 2004, Fig. 9

Age Metallicity Relation?





Soubiran et al. 2008, Fig. 9
See also Rocha-Pinto et al. 2006
AMR present

- Holmberg et al. 2007 Fig. 23b
  - Little or no variation in mean metallicity with age
  - Large and real scatter in [Fe/H] at all ages (see also Feltzing et al. 2001)

mean [Fe/H] = -0.21 and standard deviation σ = 0.21 dex

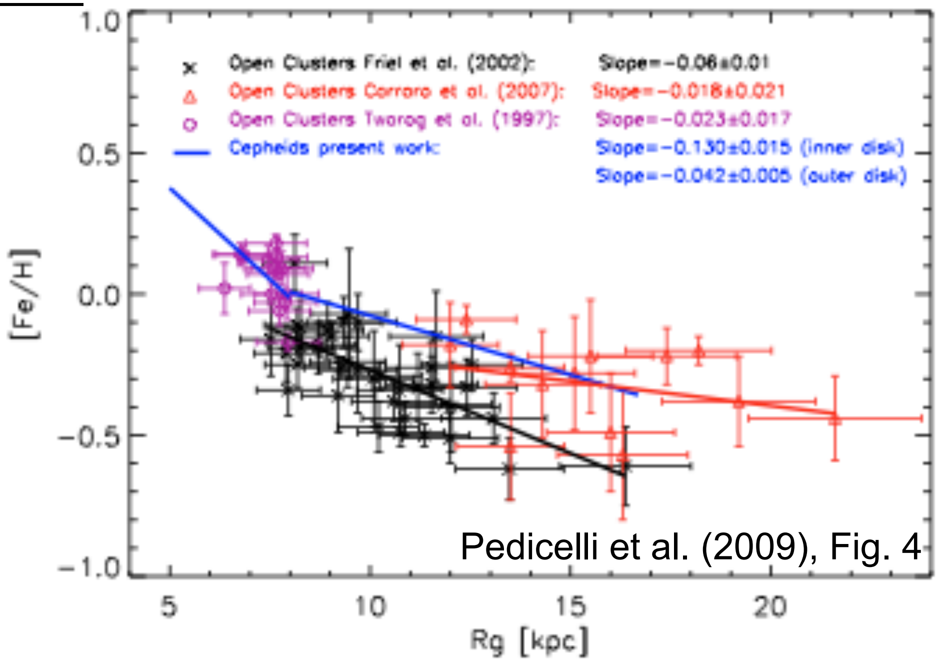
- da Silva et al. 2012 – large underlying complexity in [X/Fe] vs. age

Stellar ages are difficult to measure

- Cosmocronometry – age dating from relative abundances of radioactive isotopes
  - Hill et al. 2002: The extreme r-element rich, iron-poor halo giant CS 31082-001 observed with UVES@UT2 (within "First Stars" LP) → age = 14 ± 2.4 Gyr
- From white dwarf mass distribution
  - Kalirai 2012: comparison of inner halo WD masses selected from SPY survey (UVES LP by PI: Napiwotski) with M4 & disk WDs
    - M4 WDs $M=0.529\pm0.012\ M_{\odot}$, age=12.5±0.5 Gyr
    - Inner halo WDs $M=0.551\pm0.005\ M_{\odot}$, age=11.4±0.7 Gyr
    - Disk WDs $M=0.613\pm0.126\ M_{\odot}$ (SDSS)
- Asteroseismology
- Isochrone fitting in the HR diagram

Thin disk: metallicity gradient

- Metallicity gradient steeper in the inner disk
- Open clusters:
  - “Bologna Open Cluster Chemical Evolution” (BOCCE) project (Carretta+’04, ‘05, ‘07, Bragaglia+2008) – FLAMES@UT2
  - Carraro+2007, Sestito+2008, Magrini+2010 – FLAMES@UT2
  - Friel et al. 2002 – CTIO+KPNO
- Cepheids:
  - Pedicelli et al. 2009 (compilation incl. ESO data)
- Red clump giants:
  - Hill et al. 2012– FLAMES



Pedicelli et al. (2009), Fig. 4

Thick disk

- Gilmore & Reid 1983:

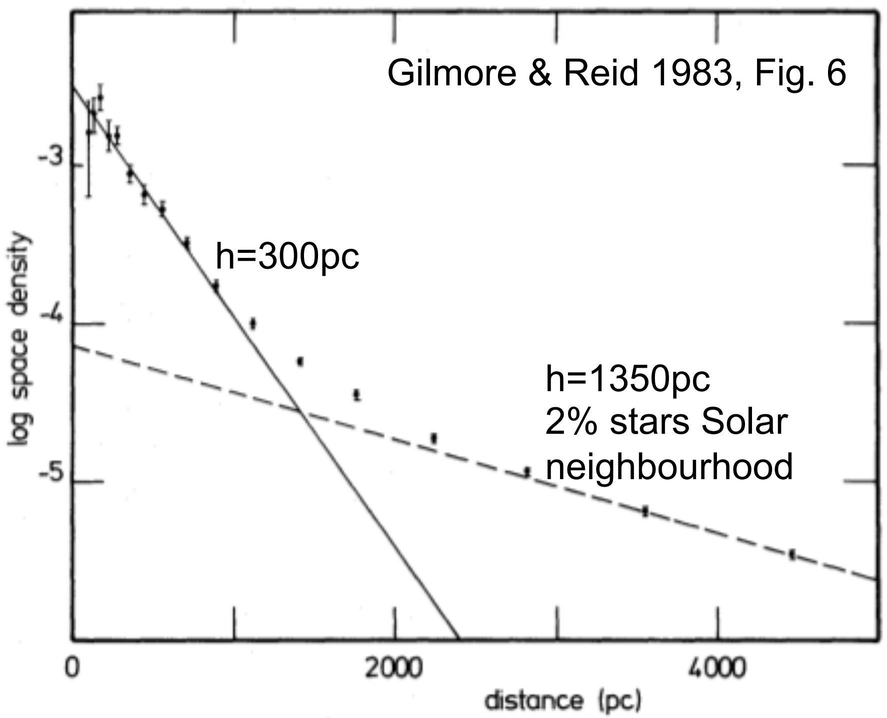
Thick disk discovery – star counts from photographic <u>UK Schmidt telescope</u> plates pointing near South Galactic Pole

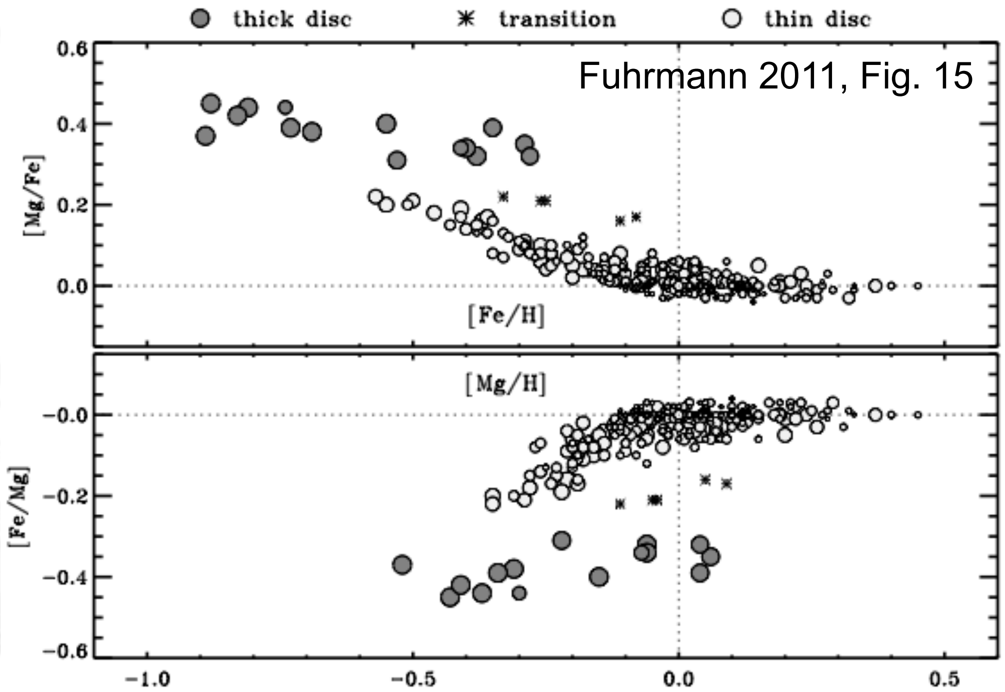
- Fuhrmann 1998-2011

Volume complete sample d<25 pc from <u>FOCES at Calar Alto Observatory</u>

thin vs. thick disk dichotomy

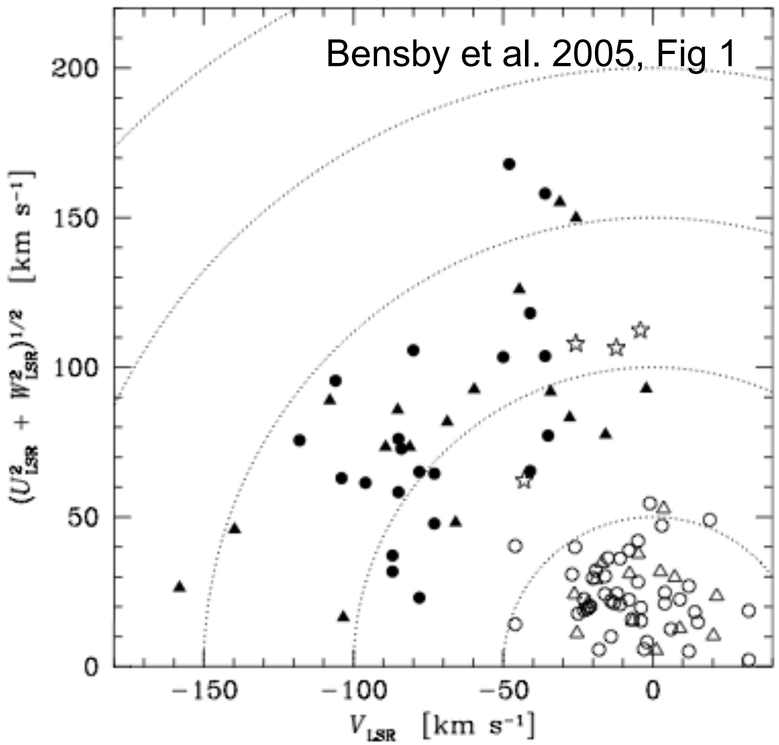
Thick disk is massive; 20% local stars

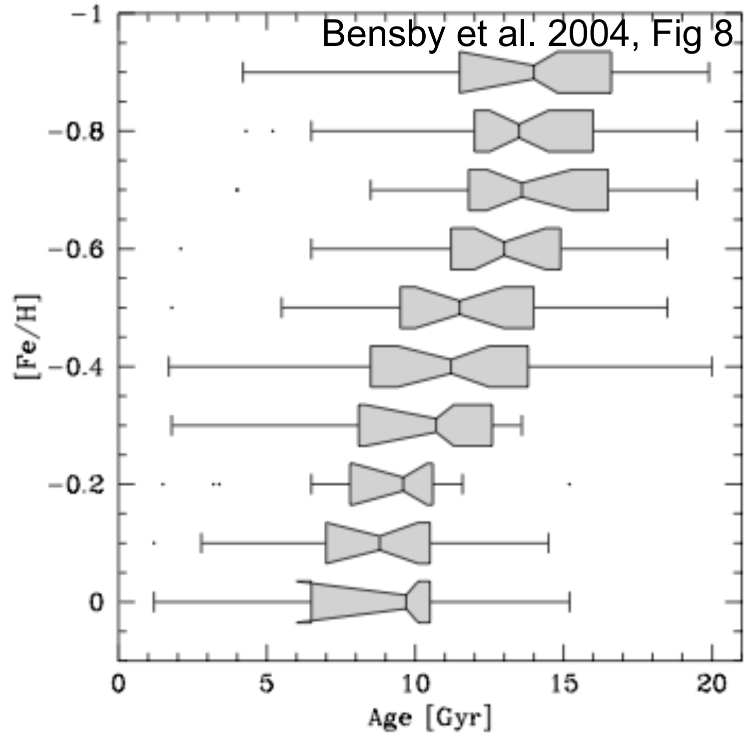




Thick disk characterisation

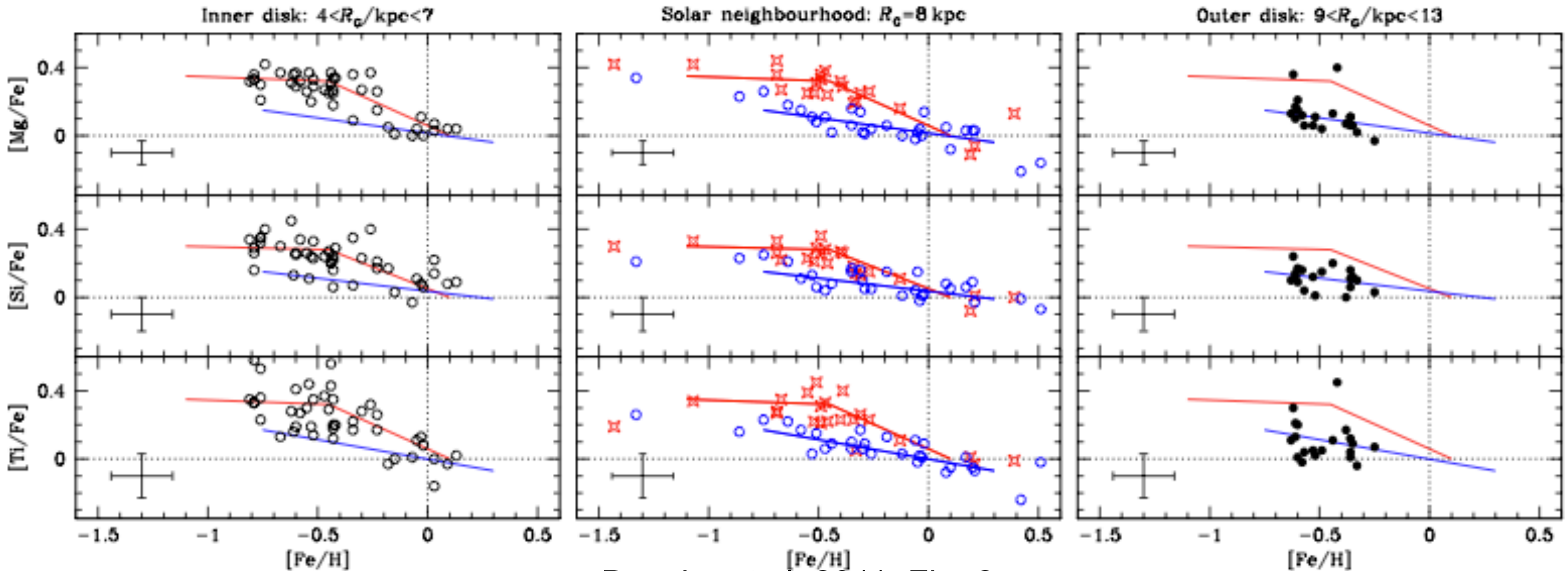
- Bensby et al. 2003, 2005, 2007, 2010, 2011
  - FEROS@1.5m + UVES@UT2 ESO + SOFIN@NOT+ MIKE@Magellan highres spectra of F & G dwarfs
  - Stellar parameters and abundances for 14 elements





Thick disk characterisation: Bensby et al. 2003-2011

- Thick disk extends to solar [Fe/H] – early and fast enrichment
  - Flat [α/Fe]=0.3-0.4 until [Fe/H]=-0.4 dex then decrease (SNIa)
- Average age: thin 4.9±2.8 Gyr, thick 11.2±4.3 Gyr
- Scale length L_{thick}=2 kpc, L_{thin}=3.8 kpc
- metal-poor bulge – thick disk similar: ages, MDF, flat radial abundance gradient (stellar radial migration)

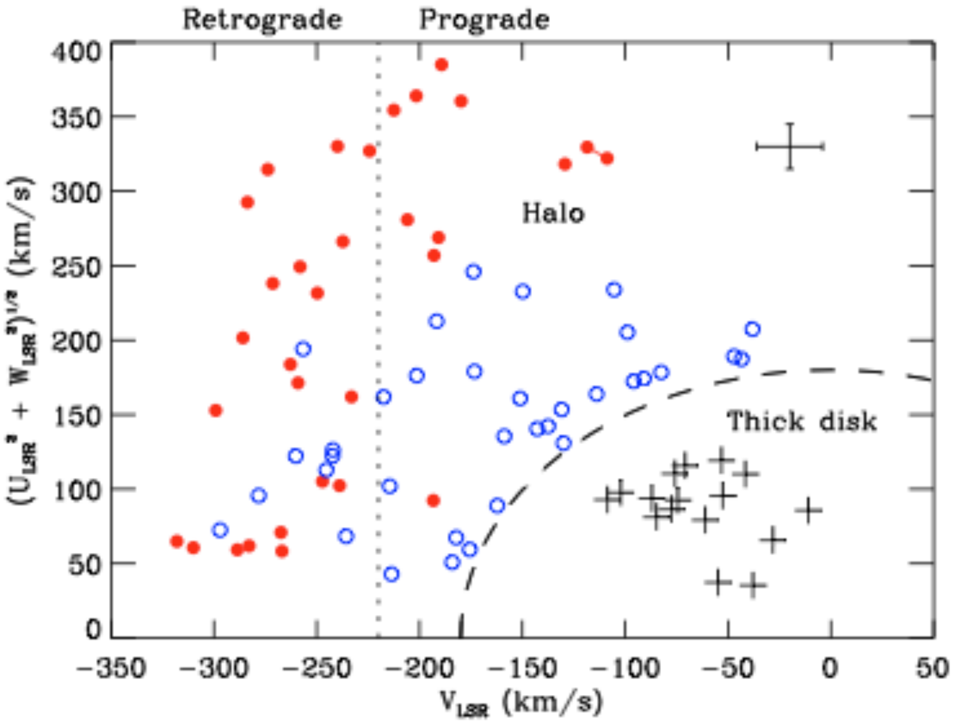


Bensby et al. 2011, Fig. 2

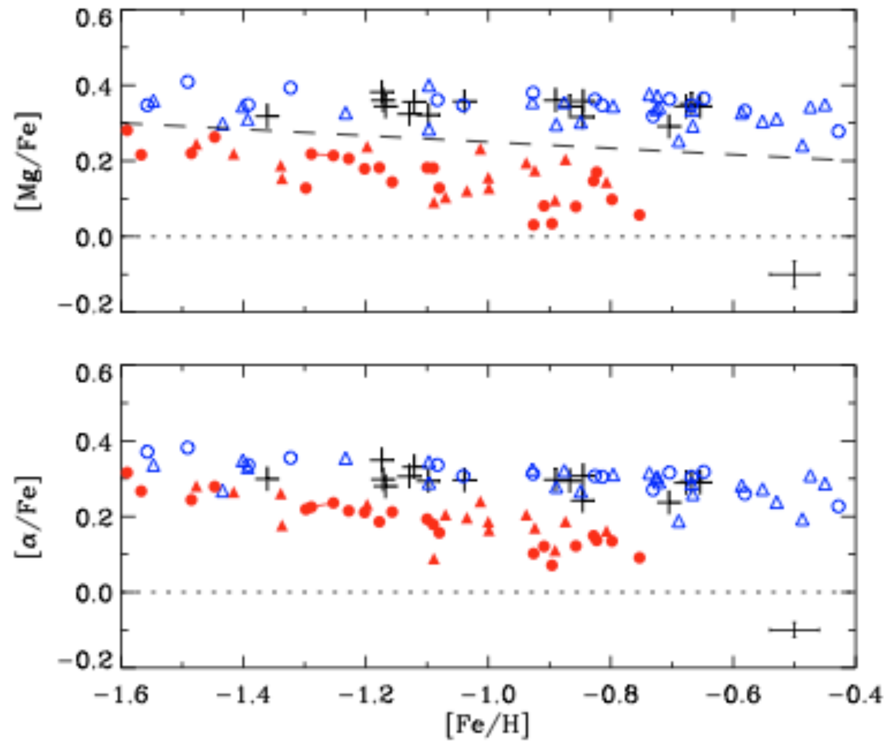
Two distinct halo populations

- SDSS: kinematics + metallicity distributions (Carollo+2007)
- Schuster & Nissen 1997, 2010, 2011, 2012: EMMI@NTT, UVES@VLT Archive + FIES@NOT spectra
  - low-α halo population accreted → ω Cen as progenitor?

Schuster & Nissen 2010, Fig. 3



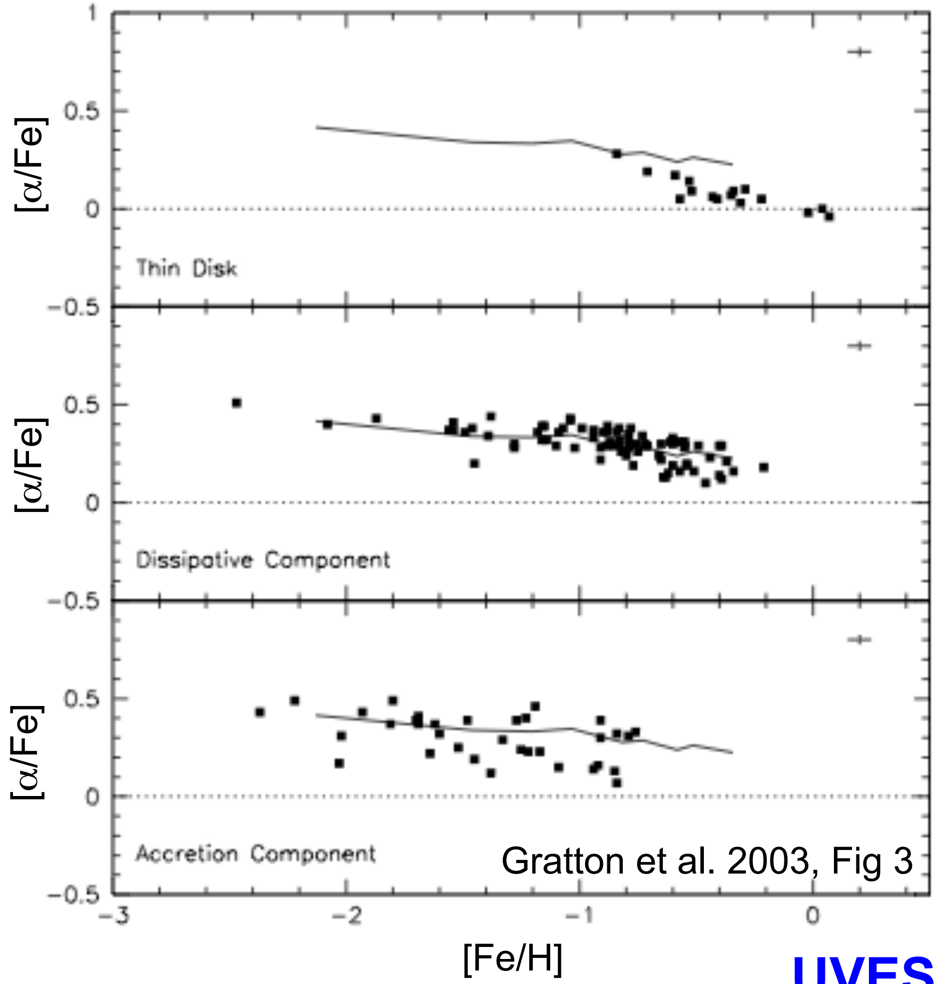
Schuster & Nissen 2010, Fig. 1



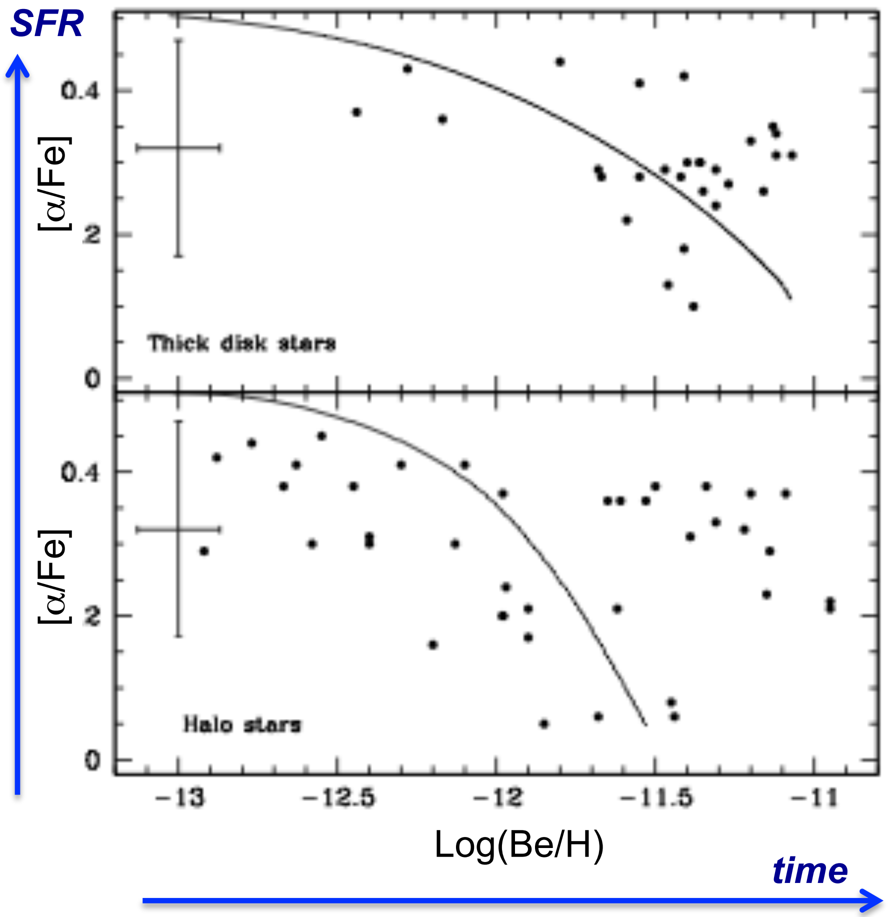
Halo: two populations?

Gratton et al. 2003: 150 field subdwarfs and subgiants with accurate parallaxes (Hipparcos)
halo: dissipative vs. accretion component

Be as a cosmochronometer?
→ Distinct populations in the halo
→ Thick disk – homogeneous population



Gratton et al. 2003, Fig 3



Smiljanic et al. 2010, Fig. 17

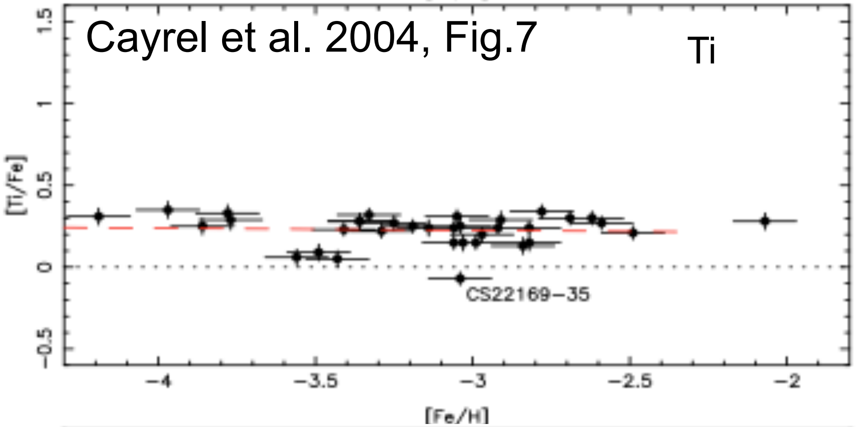
UVES data

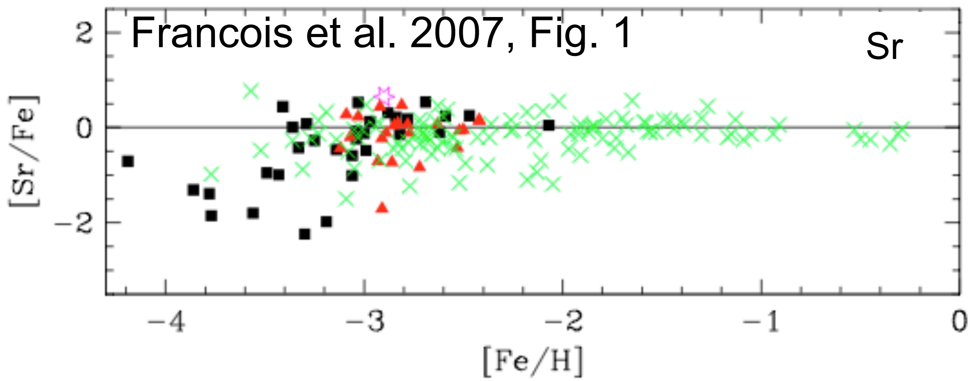
Metallicity Distributions and the search for metal-poor stars

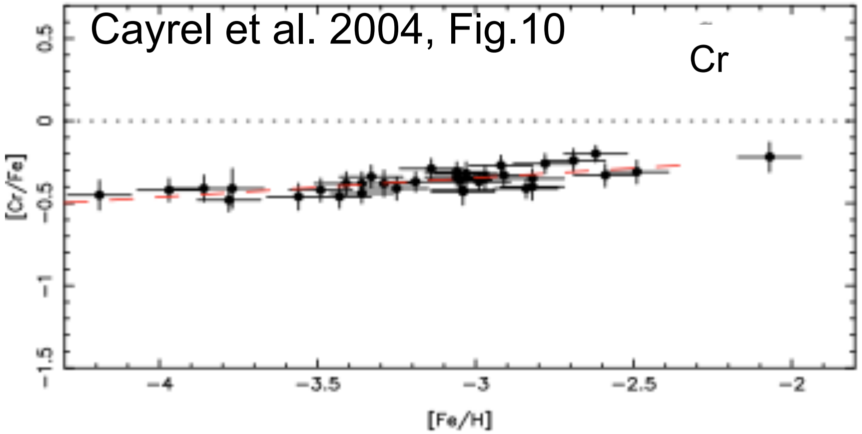
- HK survey (Beers et al.)
  - Objective prism H & K lines of CaII
- Hamburg/ESO (HES) survey (Christlieb et al.)
  - ESO 1m Schmidt telescope
  - HERES (Hamburg ESO R-process Enhanced Stars) – UVES LP (PI: Christlieb) + many different 4m telescopes
- SDSS
  - Follow-up SEGUE (Carollo et al. 2007, Ivezic et al. 2008)
- UVES search for extremely metal-poor stars (Cayrel et al. 2004, Francois et al. 2007 (First Stars UVES LP), Bonifacio et al. 2009, 2012)
- X-SHOOTER as the new tool (Caffau et al. 2012; LP)

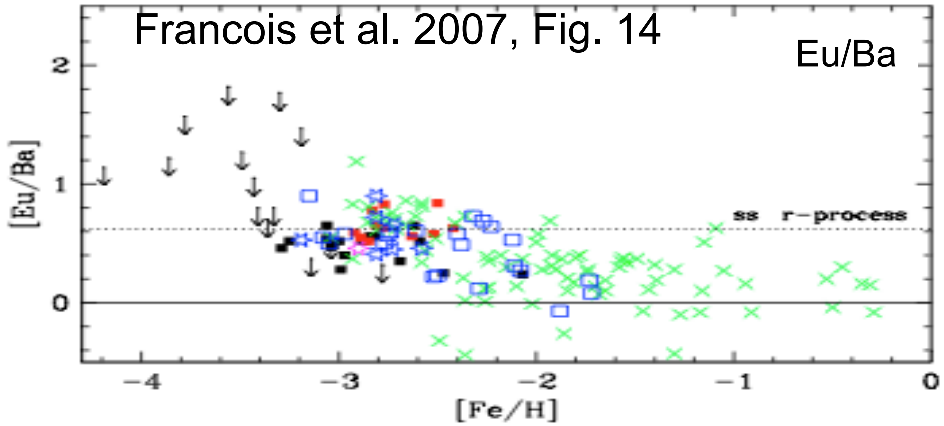
UVES Large Program “First Stars” (PI: Cayrel)

- 35 very metal-poor stars with very high quality spectra: UVES@UT2
  - Precise determination of 33 elemental abundances
  - High uniformity for α and Fe-peak elements, larger scatter for n-capture
  - Reaching primordial yields and probing early enrichment events

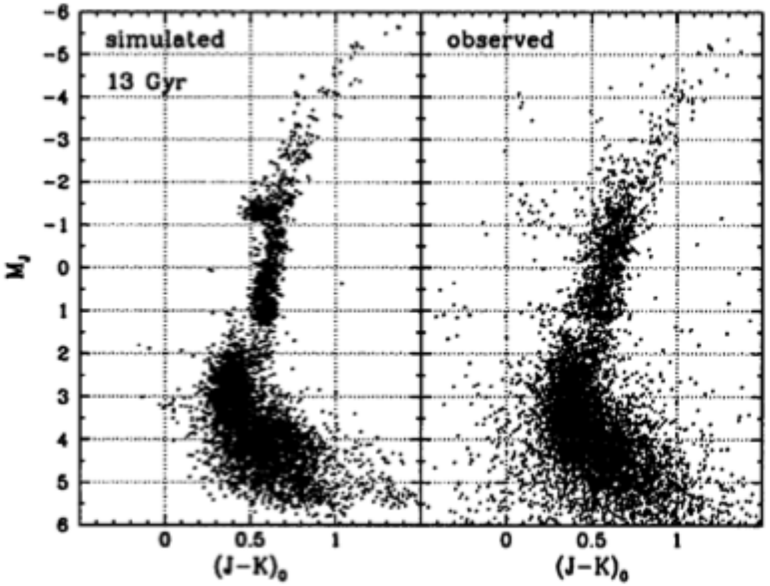




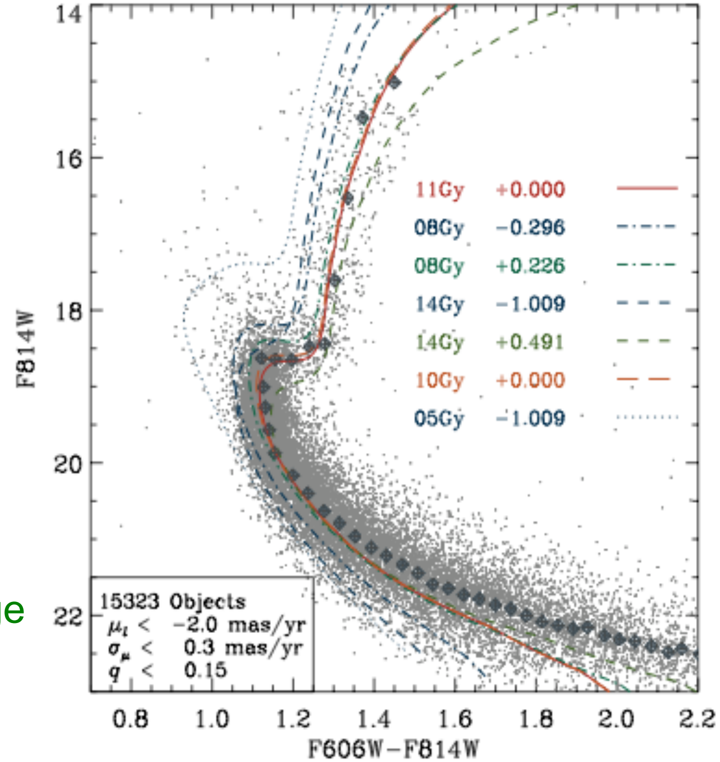




Bulge age



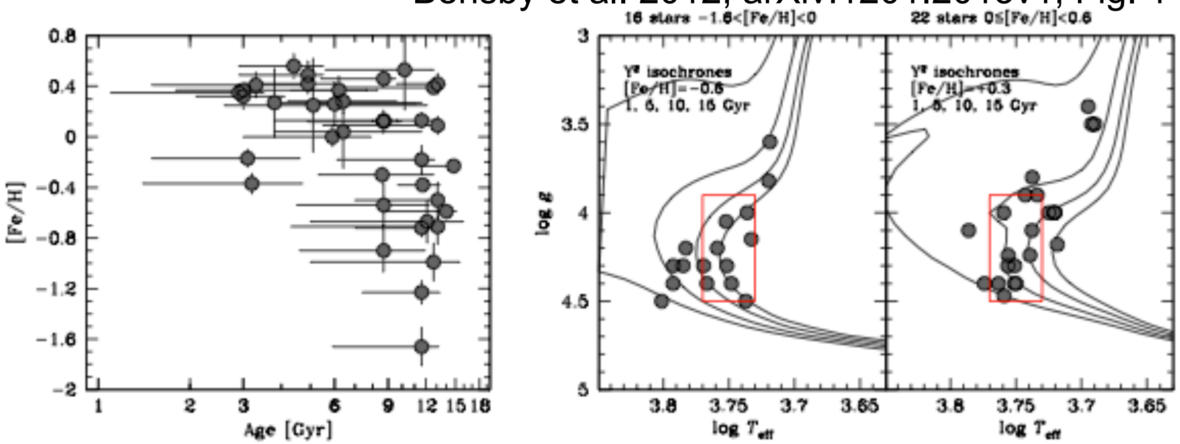
- Old bulge:
From deep CMDs turn-off >10Gyr (Zoccali et al. 2003, Fig 20: SOFI@NTT)



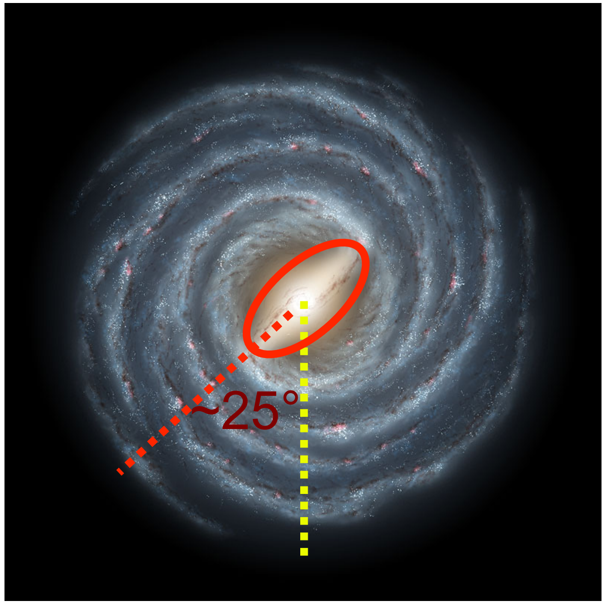
- Old bulge:
Proper motion cleaned deep HST CMD
Clarkson et al. 2008, Fig 20

- Bensby et al. (2011, 2012) find evidence for an intermediate age population in a sample of 38 microlensed dwarfs, 16 (40%) are younger than 7 Gyr

Bensby et al. 2012, arXiv:1201.2013v1, Fig. 1



Bulge: structure



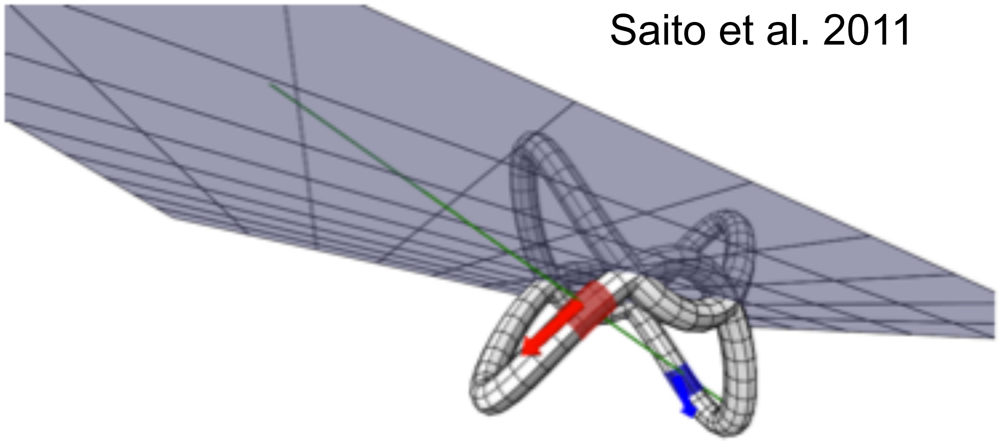
- Bar: ~25° , 1:0.35:0.26

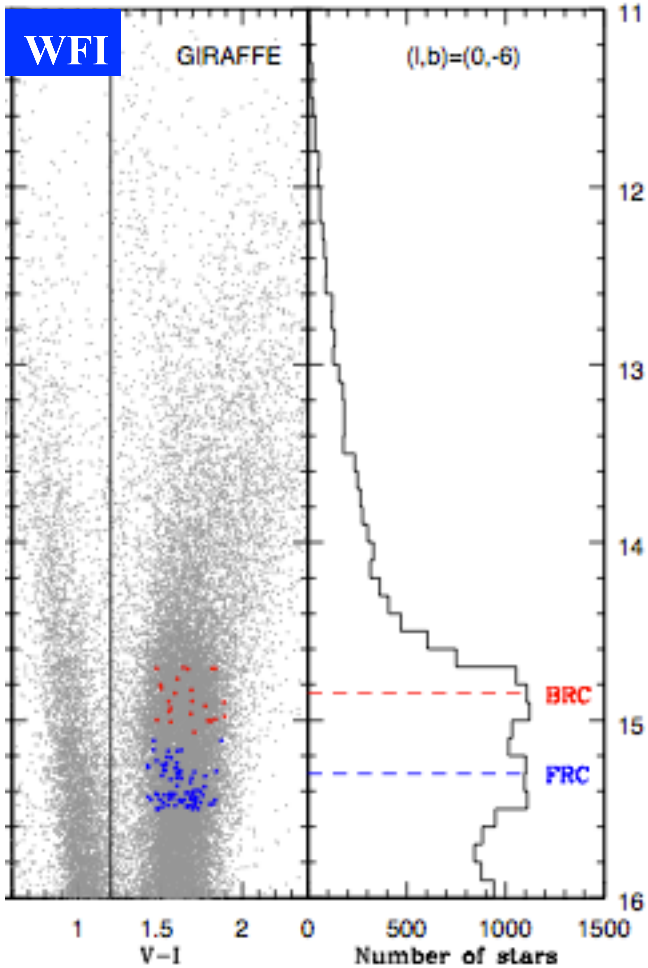
Bissantz & Gerhard '02
Babusiaux & Gilmore '05
Cabrera Lavers et al. '08
...

NEW:

- X-shape:
  red clump splits along minor axis, |b|>5°
- Two overdense regions along the line of sight

McWilliam & Zoccali 2010
Nataf et al. 2010
Saito et al. 2011





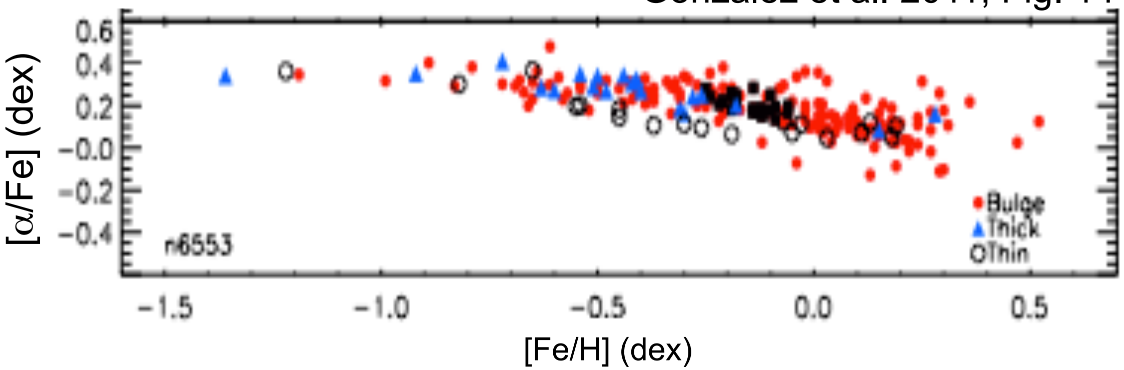
Vasquez, Zoccali et al. 2012, submitted

Bulge: populations & origin

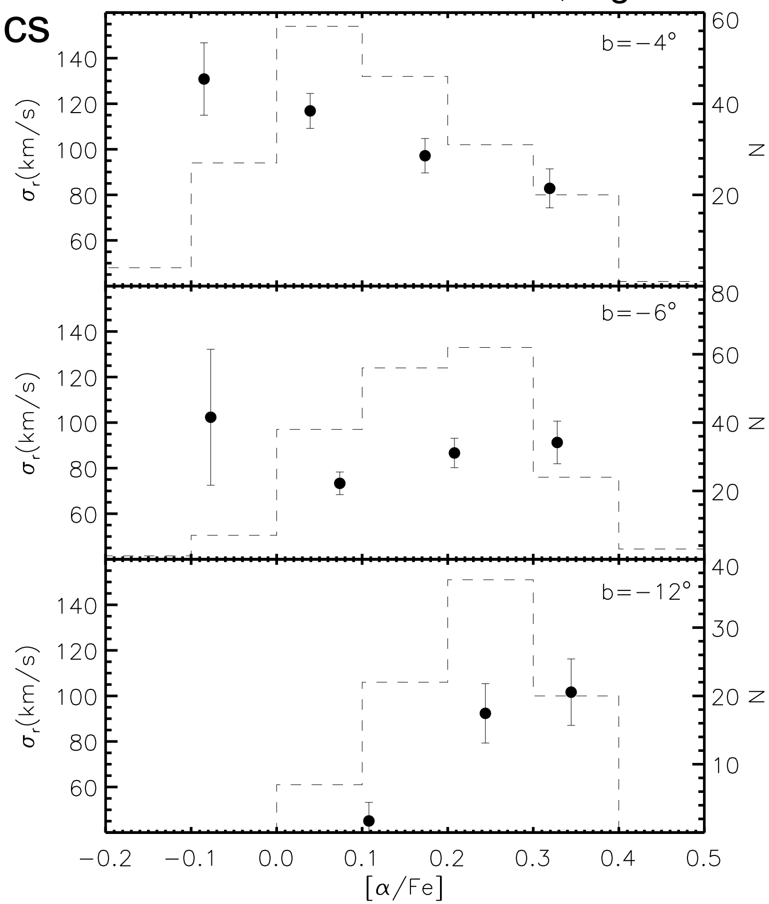
Zoccali et al. 2008, Babusiaux et al. 2010, Gonzalez et al. 2011, Hill et al. 2011 FLAMES spectra of ~800 K-giants in the bulge

- Metal-rich component (low α) – disk/bar kinematics
- Metal-poor component (α-enhanced) – spheroid kinematics
- Gradient: [Fe/H] & [α/Fe] – metal-rich (low α) component disappears at higher b (minor axis)
- Bulge and thick-disk chemically similar (Melendez+2008, Alves-Brito+2010, Bensby+2010, Gonzalez+2011, Trevisan+2011)

Gonzalez et al. 2011, Fig. 14



Gonzalez et al. 2011, Fig. 17



VVV: The VISTA Variables in the Via Láctea

- **PIs: D. Minniti, P. Lucas**

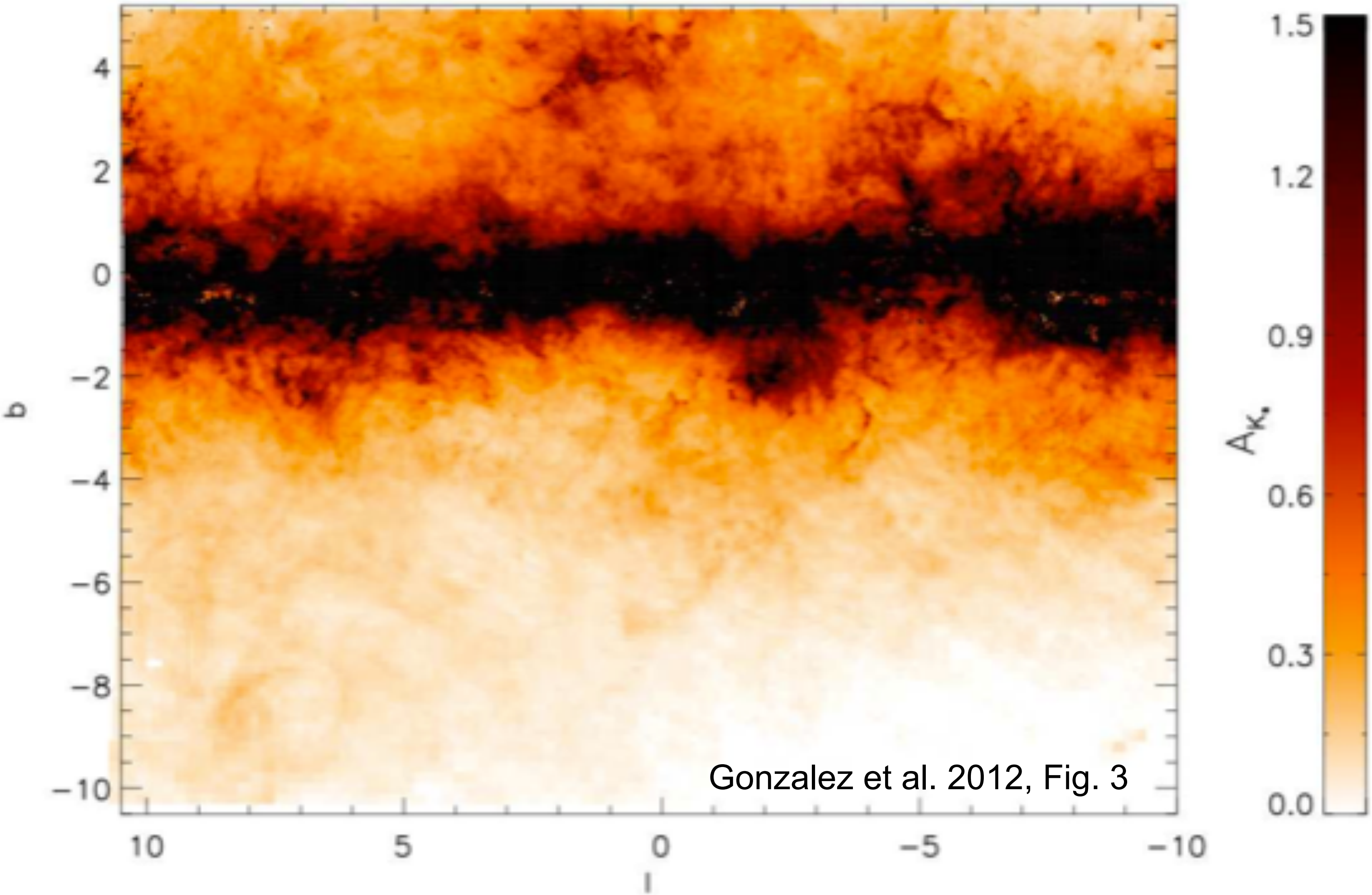
DR1: http://archive.eso.org/cms/eso-data/eso-data-products (Saito et al. 2012)

- **300 deg^2 bulge:** $-10° < l < +10°$ $-10° < b < +5°$ (Minniti et al. 2010)
- **220 deg^2 disk:** $295° < l < 350°$ $-2° < b < +2°$

- Y, Z, J, H, Ks filters – ~4mag deeper than 2MASS
- **~100 epochs in Ks – variability campaign started**

VVV: BEAM Calculator

BEAM Calculator: http://mill.astro.puc.cl/BEAM/calculator.php

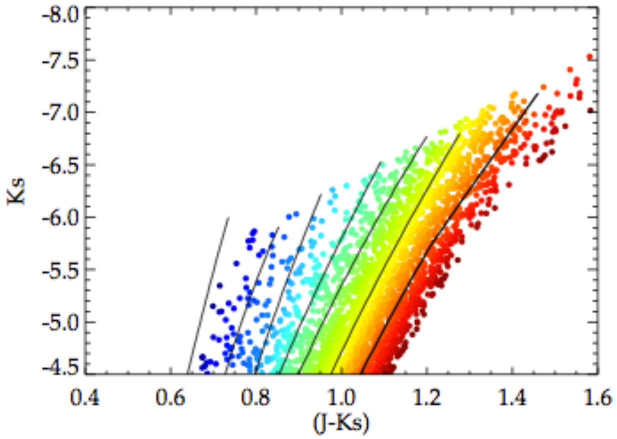


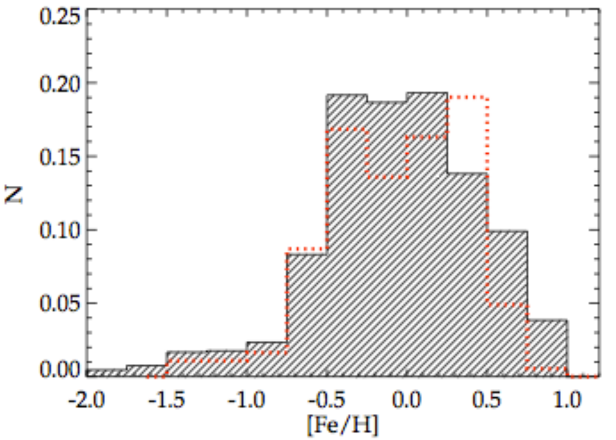
Gonzalez et al. 2012, Fig. 3

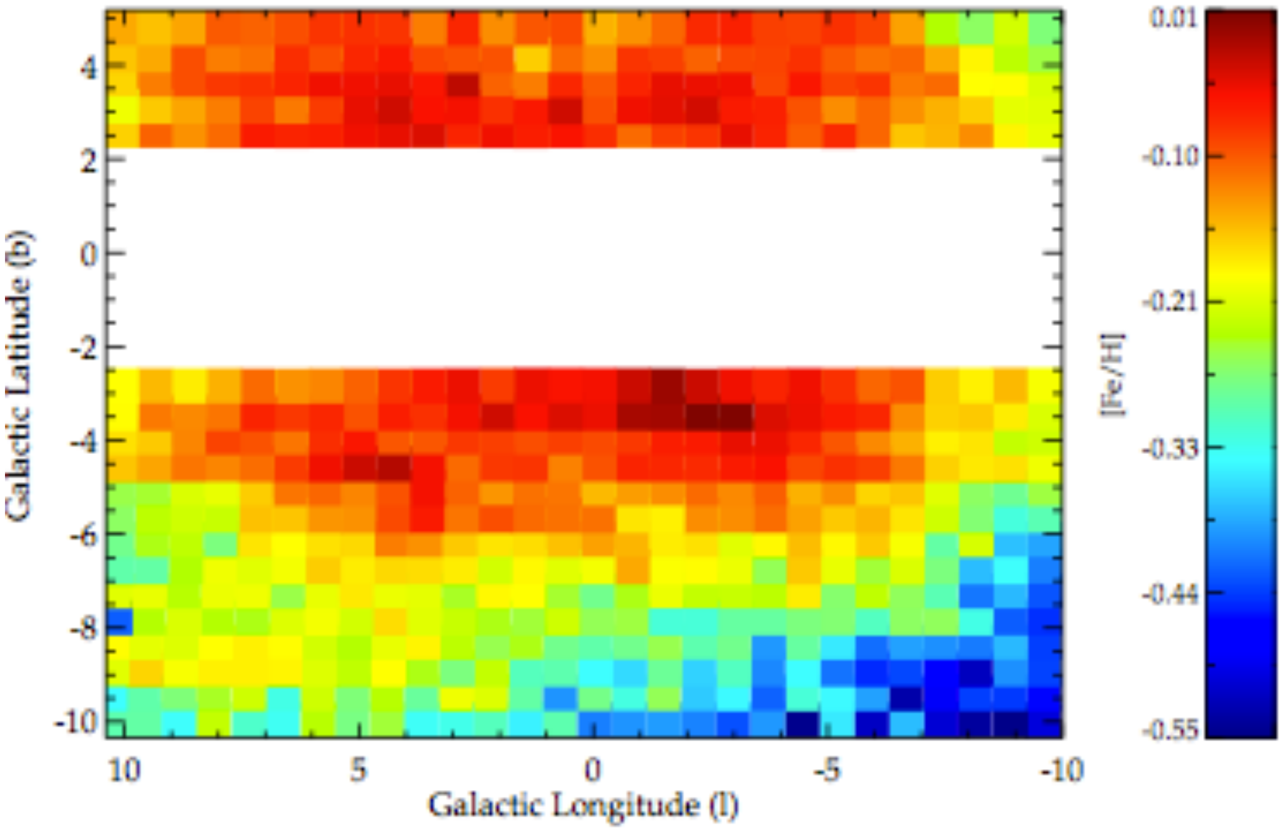
VVV: BEAM Calculator

The complete (photometric) metallicity map of the MW bulge

BEAM Calculator: http://mill.astro.puc.cl/BEAM/calculator.php







Gonzalez et al. 2012, in prep

Galaxy formation sequence

(Inner) halo collapse → thick disk & bulge → accretion of the outer halo & thin disk formation

- Inner halo 2-3 Gyr older & higher α-enhancement than outer halo (Schuster & Nissen 2012)
- Outer halo substructure (2MASS, SDSS; Belokurov et al. 2006) – early accretion due to higher α-element abundances than current dSph (Tolstoy)
- Thick disk is old, α-enhanced – fast formation (Bensby et al., Fuhrmann)
- Similarity of inner disk to bulge/bar population (Melendez et al., Bensby et al., Gonzalez et al., Hill et al.)
- Thin disk – long formation time-scale (>6-7Gyr) → radial migration, vertical heating; gas infall → narrow MDFs (G-dwarf problem)

2008 ESA–ESO Report: Galactic Populations, Chemistry and Dynamics

- Gaia data volume and quality of data → revolution

- Large statistically significant samples → surveys
  - dynamical, kinematic and compositional studies

Turon & Primas, eds.
2008 ESA-ESO Report No. 4

- ESO: follow-up & complementarity
  - High & medium-resolution spectroscopy
  - Multi-object IR spectrograph
  - High multiplex optical/blue spectrograph

- Improvements in theory, modeling and analysis techniques

ESO contribution to understanding MW galaxy

- Past:
  - Major role in high-resolution spectroscopy

- Recent/Ongoing:
  - Starting to take lead also in photometric surveys: VISTA & VST
  - VVV → Bulge stellar populations, 3D structure
  - VHS → Halo sub-structure, satellites
  - VST – VPHAS+ → disk and 3D extinction mapping, spiral structure
  - Gaia-ESO survey (Gilmore & Randich) → high-resolution spectroscopy: 10^5 MW stars in the field and open clusters

- Future:
  - 4MOST / MOONS → high-multiplex spectrographs
  - Gaia follow-up