New Observational Constraints to MW Chemodynamical models

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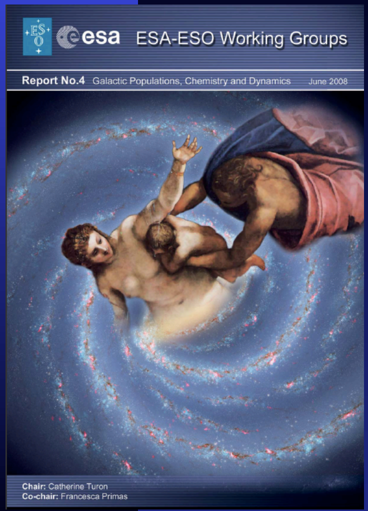
AIP

SDSS III BRAZILIAN PARTICIPATION GROUP

LIneA Laboratório Interinstitucional de e-Astronomia

Nice June 2014

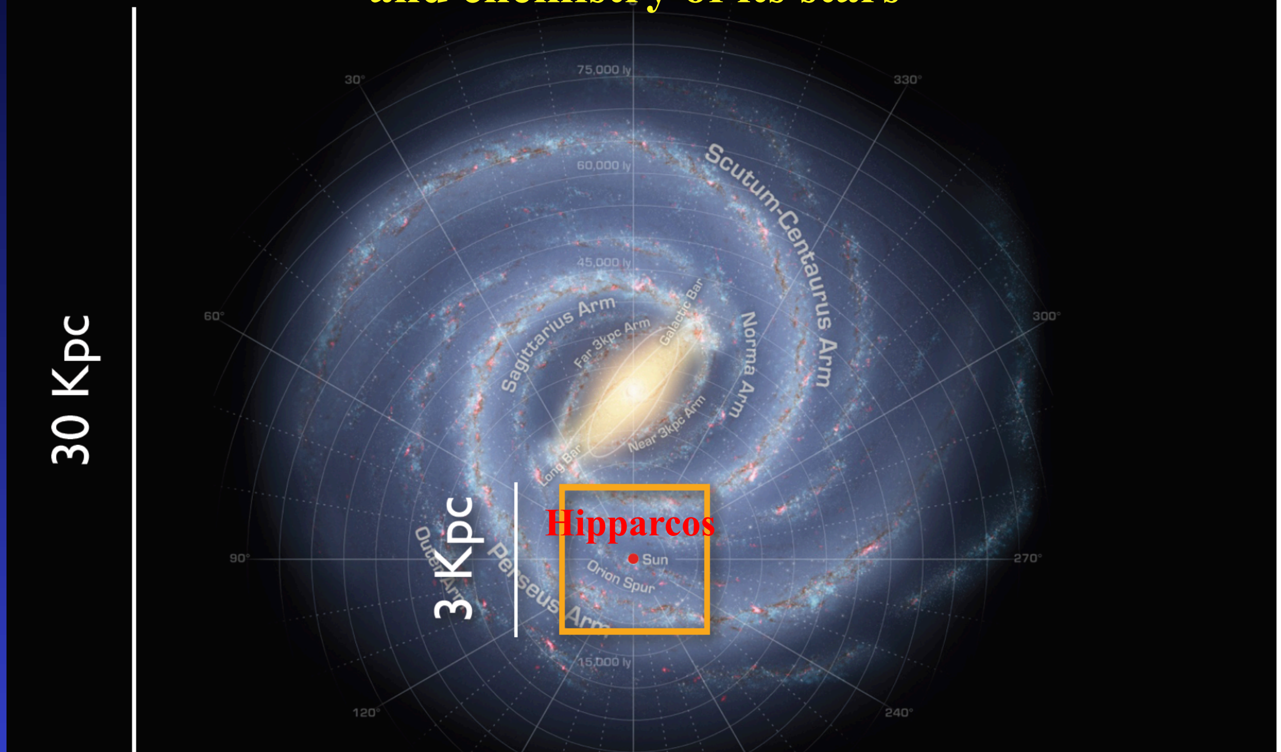
Milky Way Assembly & Evolution



Turon, Primas, Binney, Chiappini, Drew, Helmi, Robin, Ryan 2008

GREAT Chemo-dynamical Survey 2010, C. Babusiaux, A. Bragaglia, A. Brown, C. Chiappini, S. Feltzing, U. Heiter, A. Helmi, V. Hill, A. Lanzafame, A. Recio-Blanco, N. Walton

The mechanism of formation and evolution of the Milky Way are encoded in the location, kinematics and chemistry of its stars



Galaxy shaped by several processes: gas accretion & chemical enrichment, mergers, radial migration

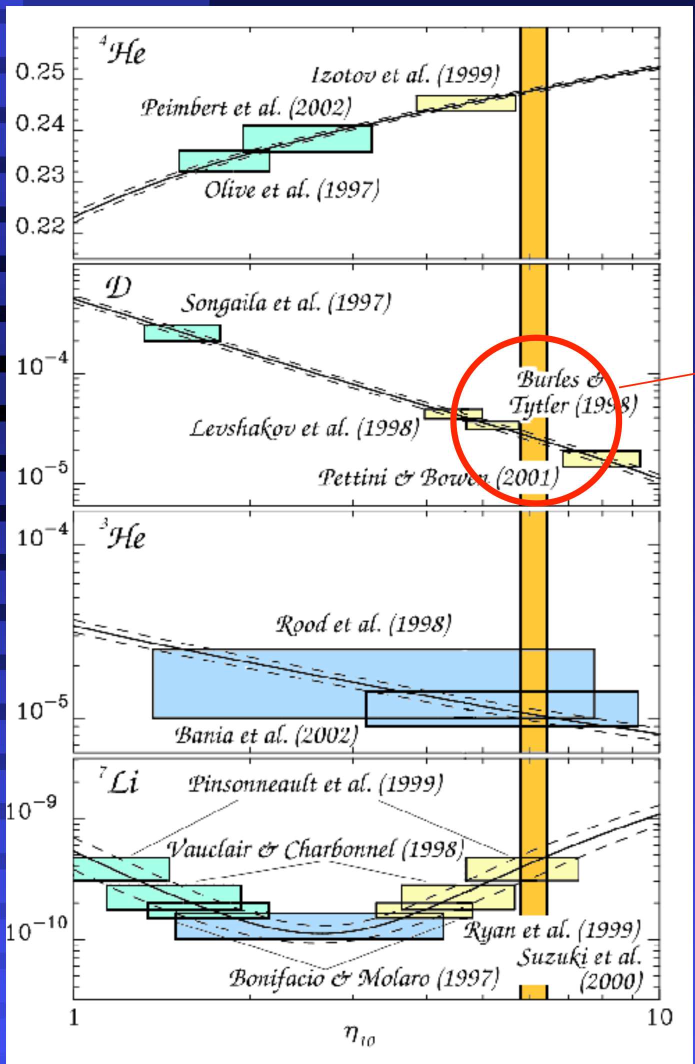
Are they all important? Which one dominates? When?

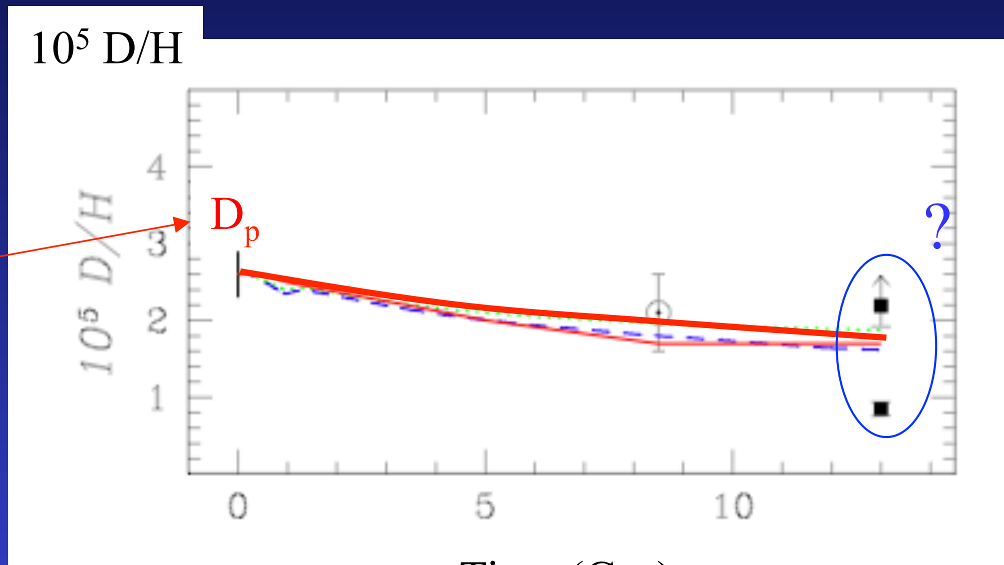
1. Need for Infall

The D Evolution

Deuterium destroyed in stellar interiors → Its quantity in the ISM decreases from its primordial value to the current values measured recently by FUSE

Big Bang Nucleosynthesis





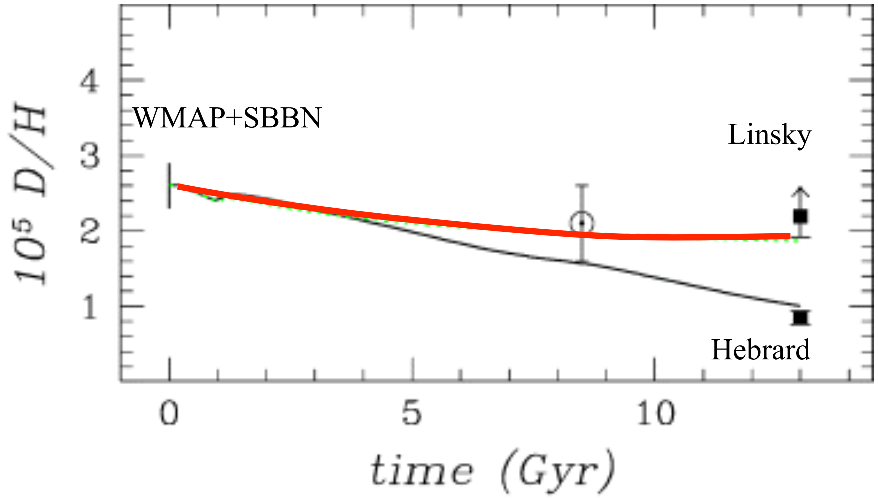
Romano et al. 2006

Before WMAP: Measuring primordial abundances of ^{4}He, D, ^{3}He and ^{7}Li to constrain the cosmic baryon density
After WMAP: We know primordial abundances

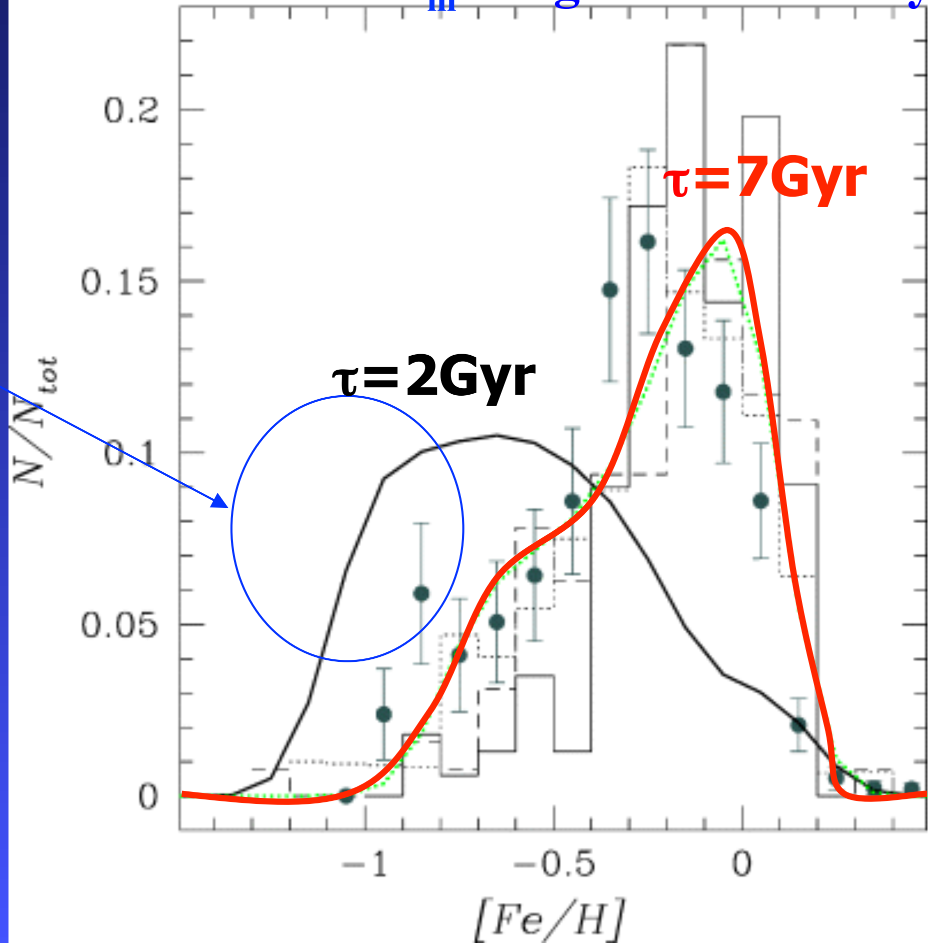
Infall needed to explain D/H and the metallicity distribution of long living stars

$$f = A\exp(-t/\tau)$$

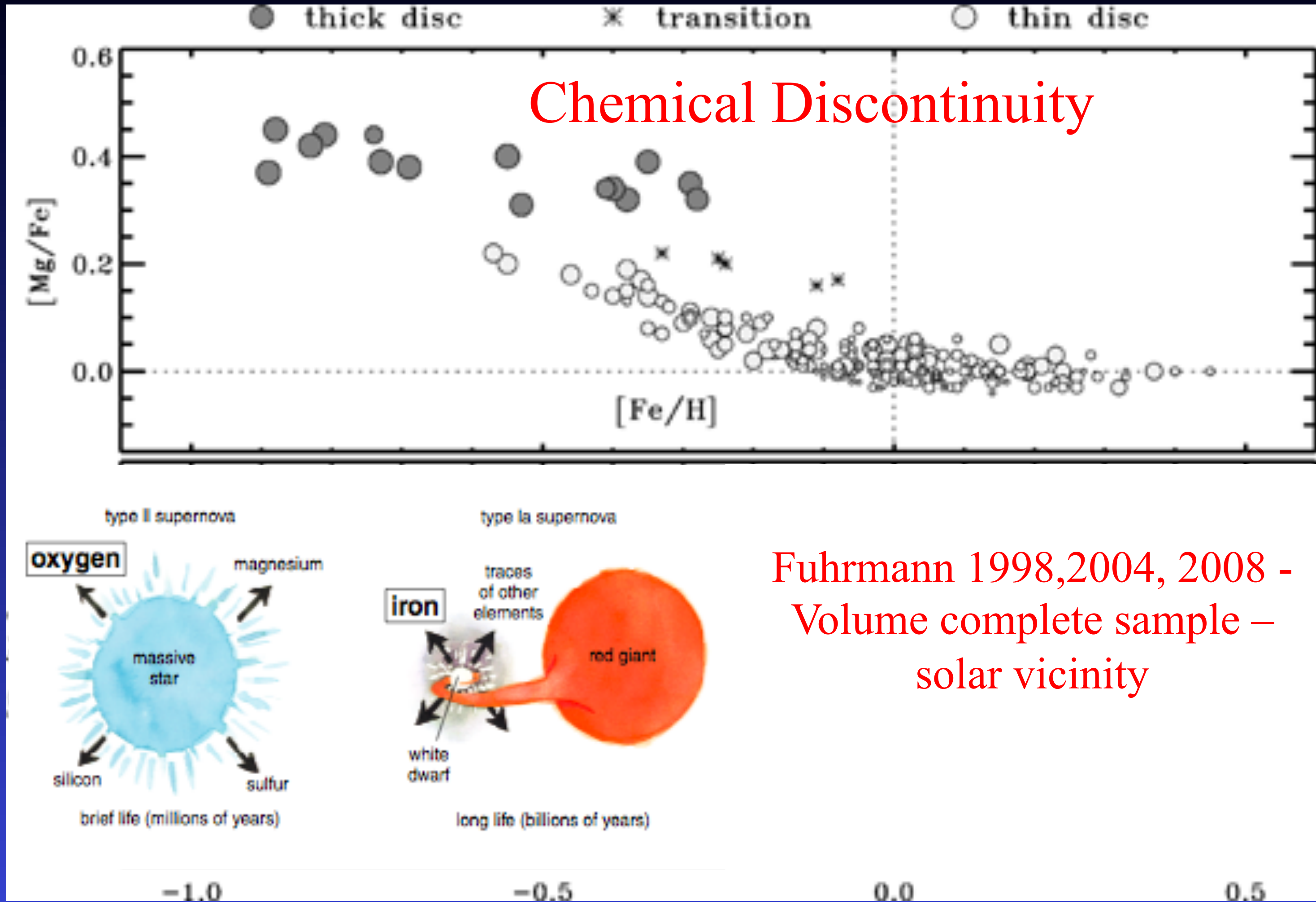
G-dwarf Problem: Simple model and/or fast accretion predicts too many metal poor stars, not observed



Stars with τ_m > Age of the Galaxy



2. Discontinuity in the Abundance Ratios

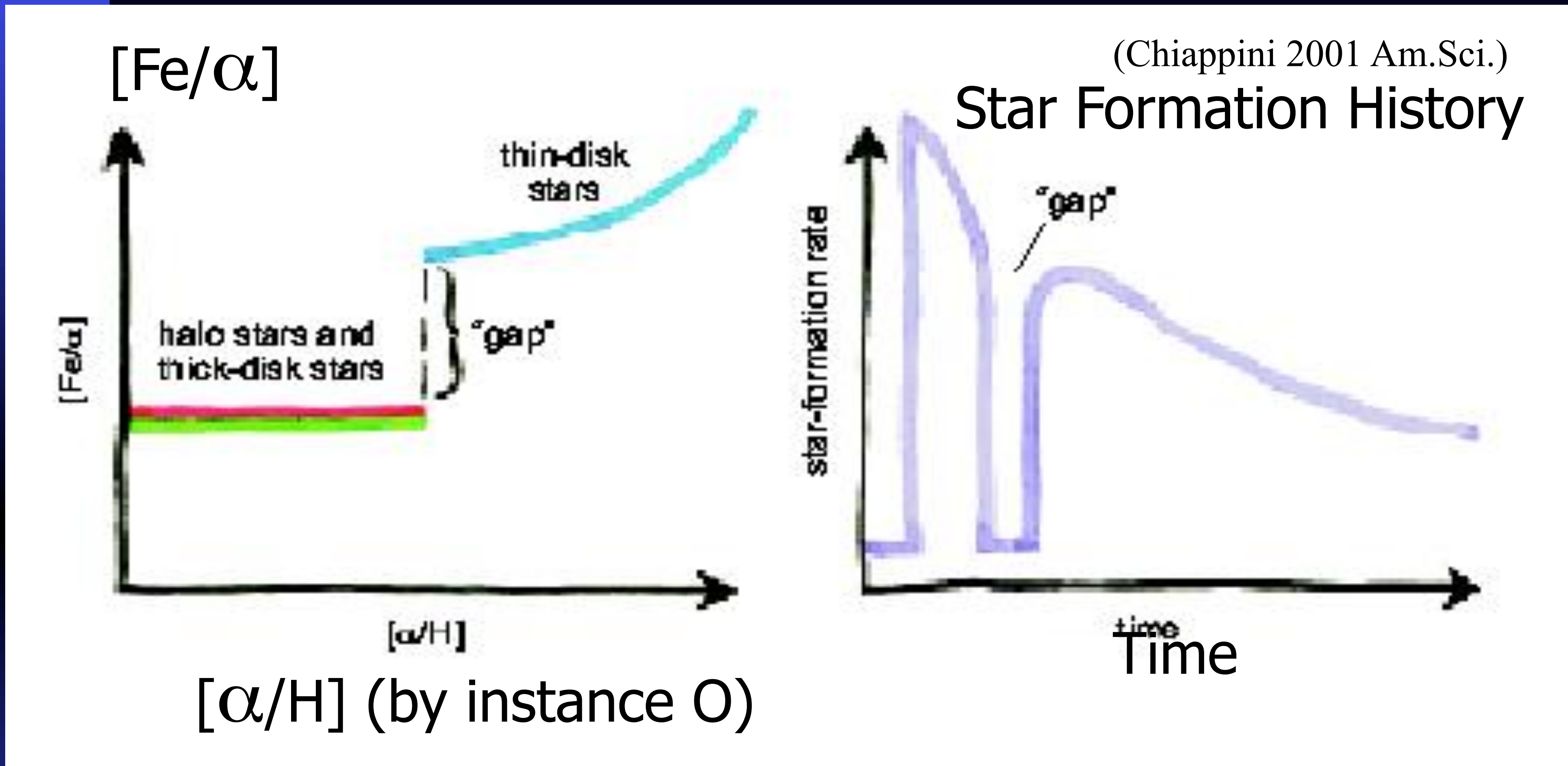


Lack of scatter (10000 lower than metallicity range!)

Halo, Thick disk, Thin disk: cannot have been made by uncorrelated systems

Suggestions of an age gap between thick disk and oldest stars in thin disk

(Chiappini et al. 1997; Liu & Charboyer 2000, Sandage et al. 2003, Bernkopf & Furhmann 2006)

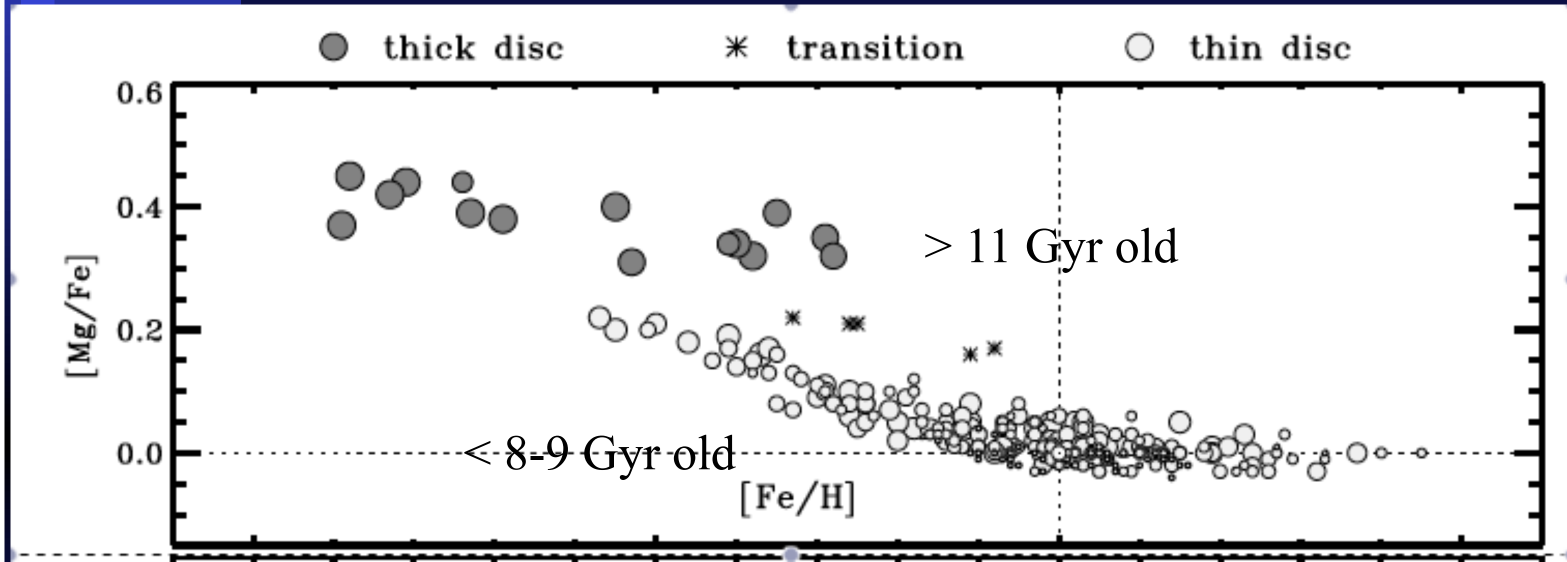


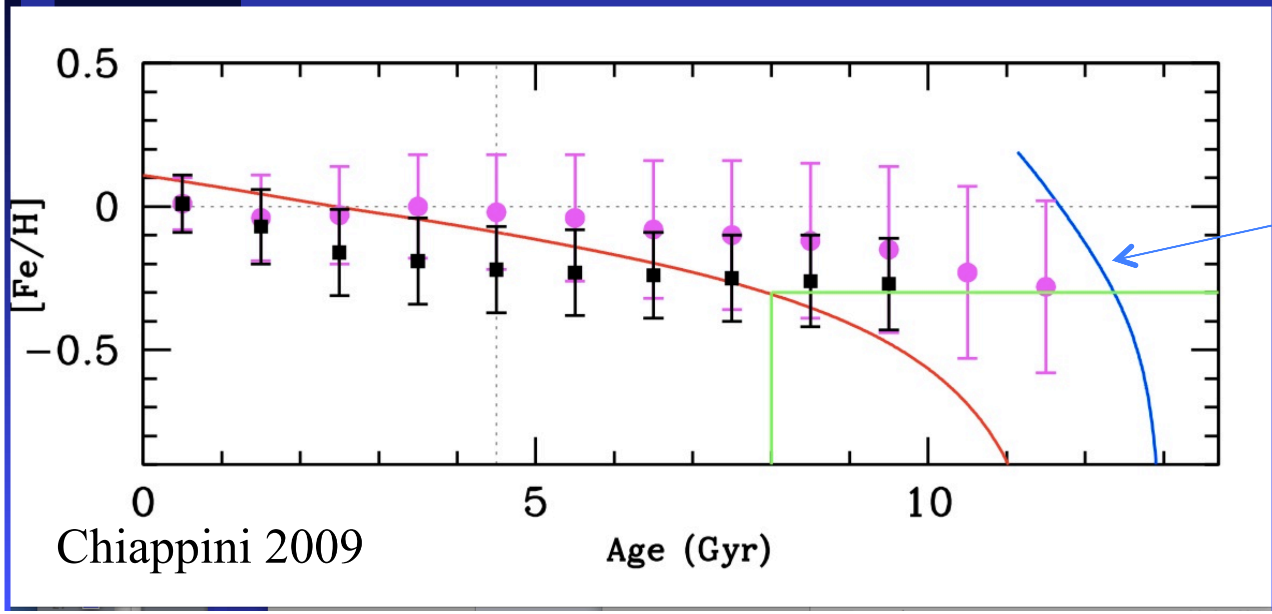
This behaviour is expect to show up more clearly for a ratio between an element restored on long timescales to the ISM (e.g. Fe, C) and an element ejected in short timescales (e.g. O)

(Chiappini et al. 2003 a,b)

AMR from thin + thick

" This chemical map portrays the imprint of a huge SF gap" (Fuhrmann 2011)





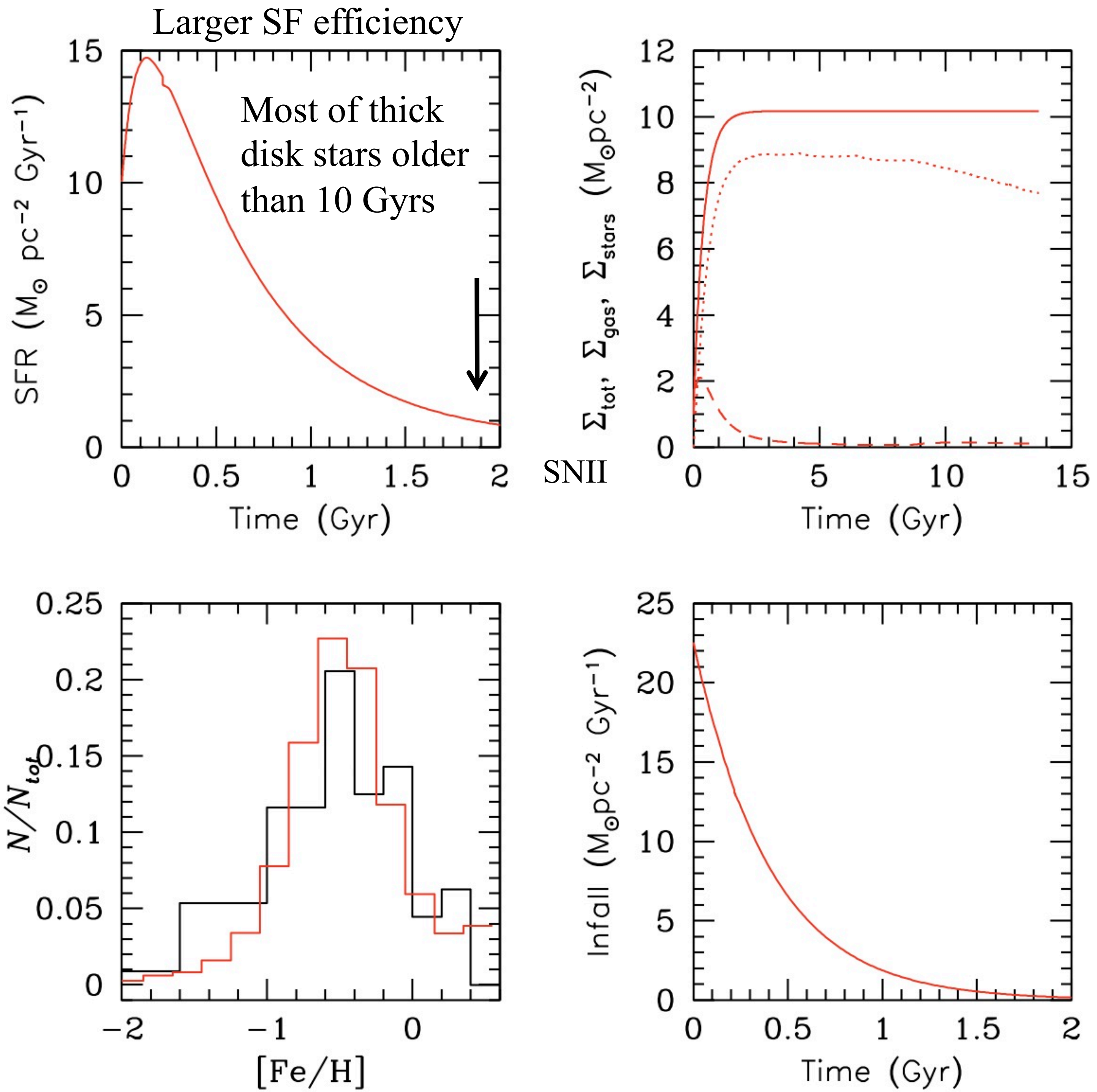
Compatible with AGES from Fuhrmann 2011

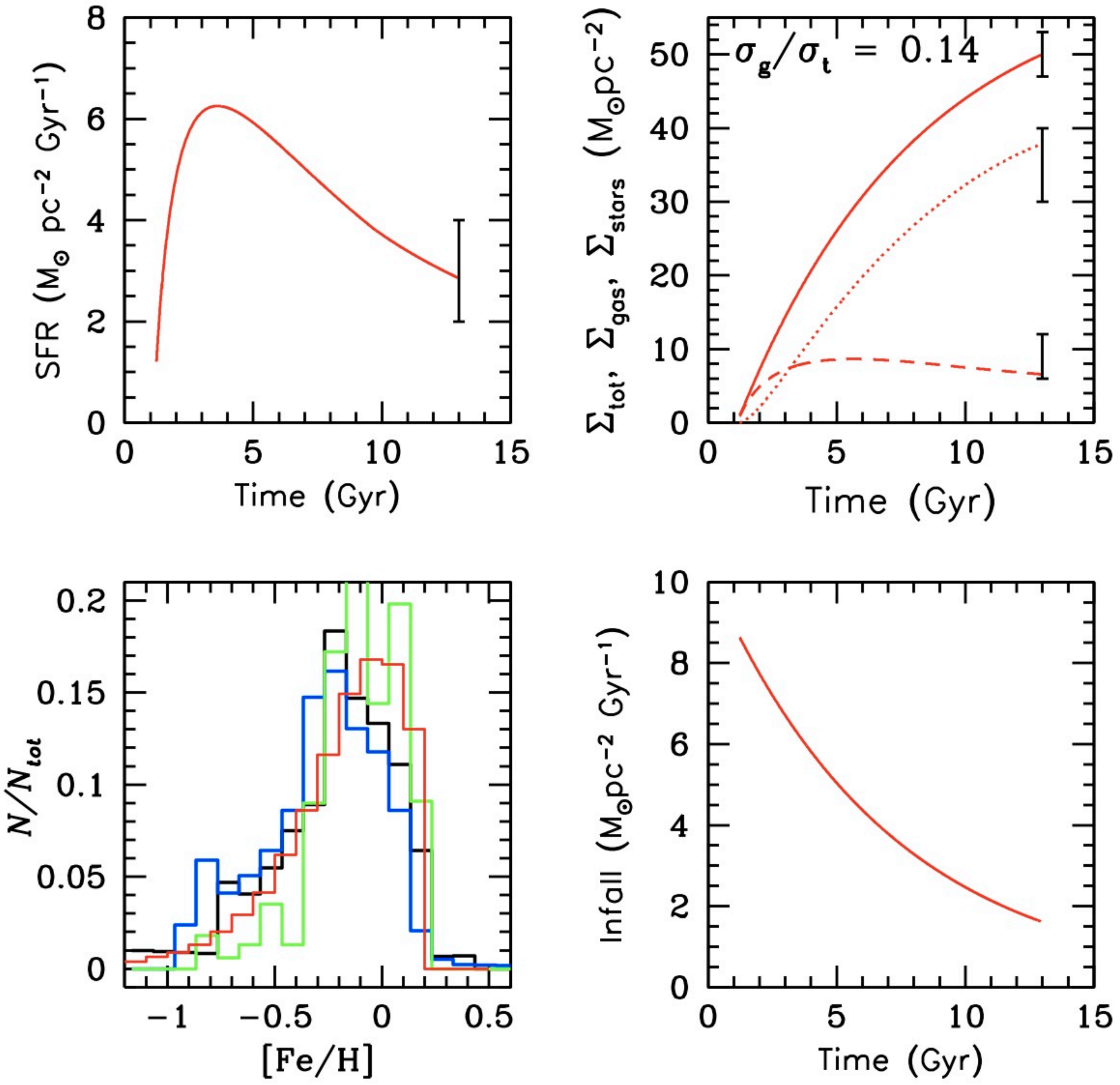
Burst SF -> can reach high [Fe/H] in 1-2 Gyrs

Soubiran et al. (2008)
(thick disk candidates removed)
da Silva et al. (2006)

Thick Disk

f = A exp(-t/τ)
τ < 0.4 Gyr

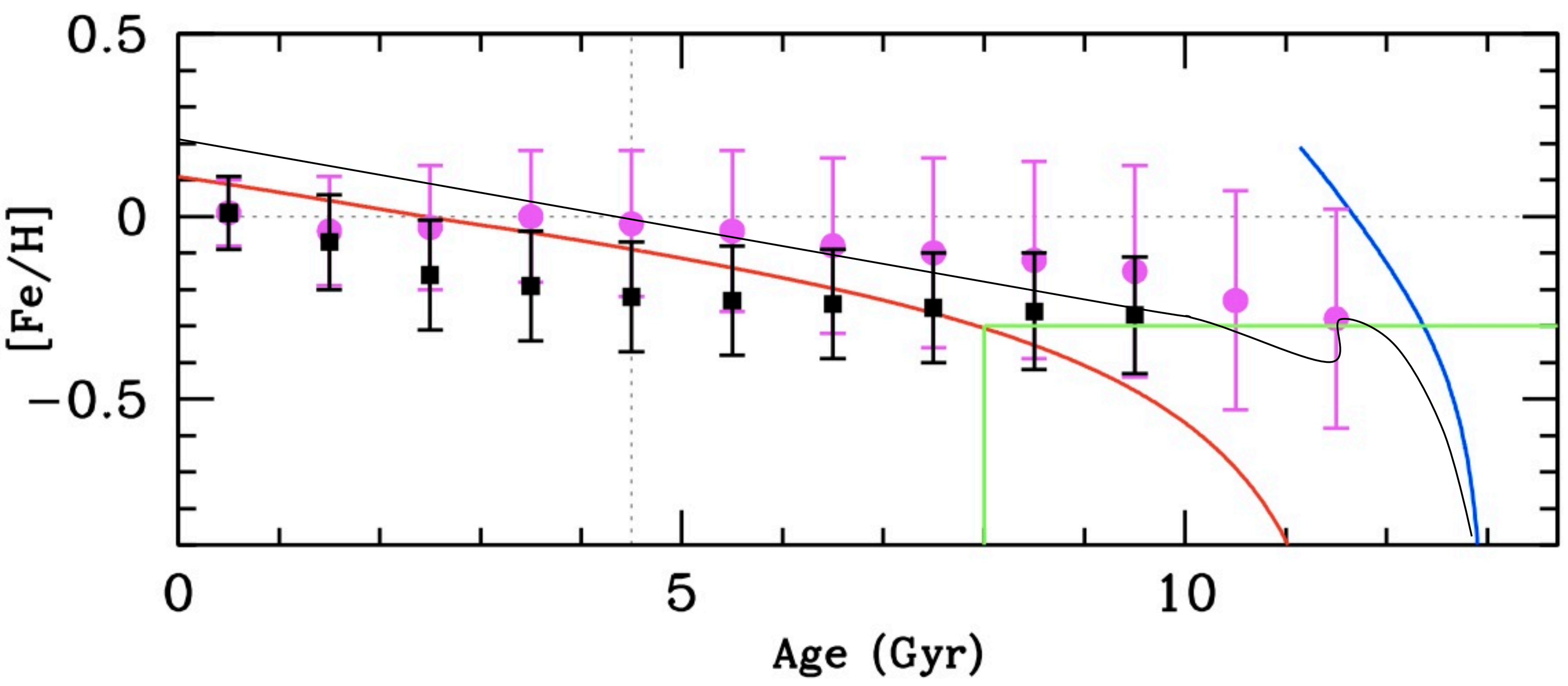




Thin Disk

f = A exp(-t/τ)
τ (R_sun)= 7 Gyr

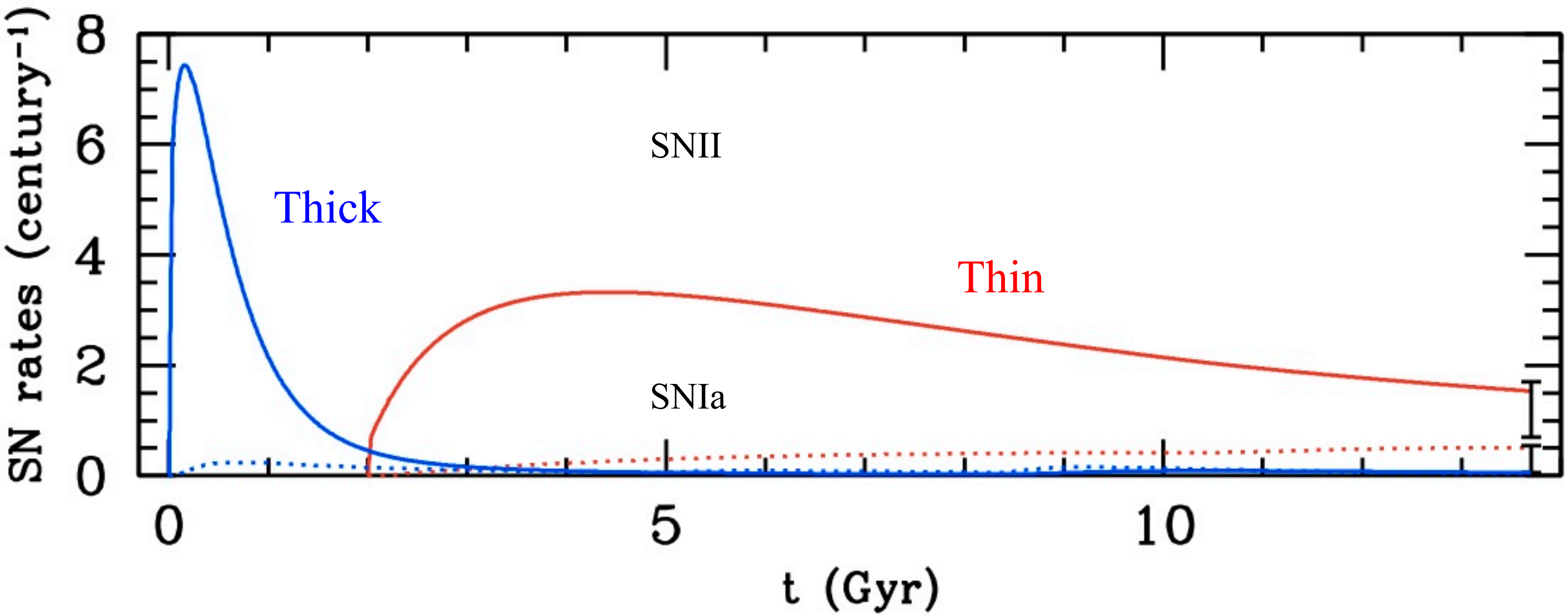
Dispersion increases with ages:
Age errors + mix populations (radial mixing + thick/thin stars) contribute to flattening/scatter



Da Silva et al. 2006: Giants – good for young ages/ larger errors for old ages
scatter 0.1 dex = errors in last 4 Gyrs – mild CE last 4.5 Gyrs

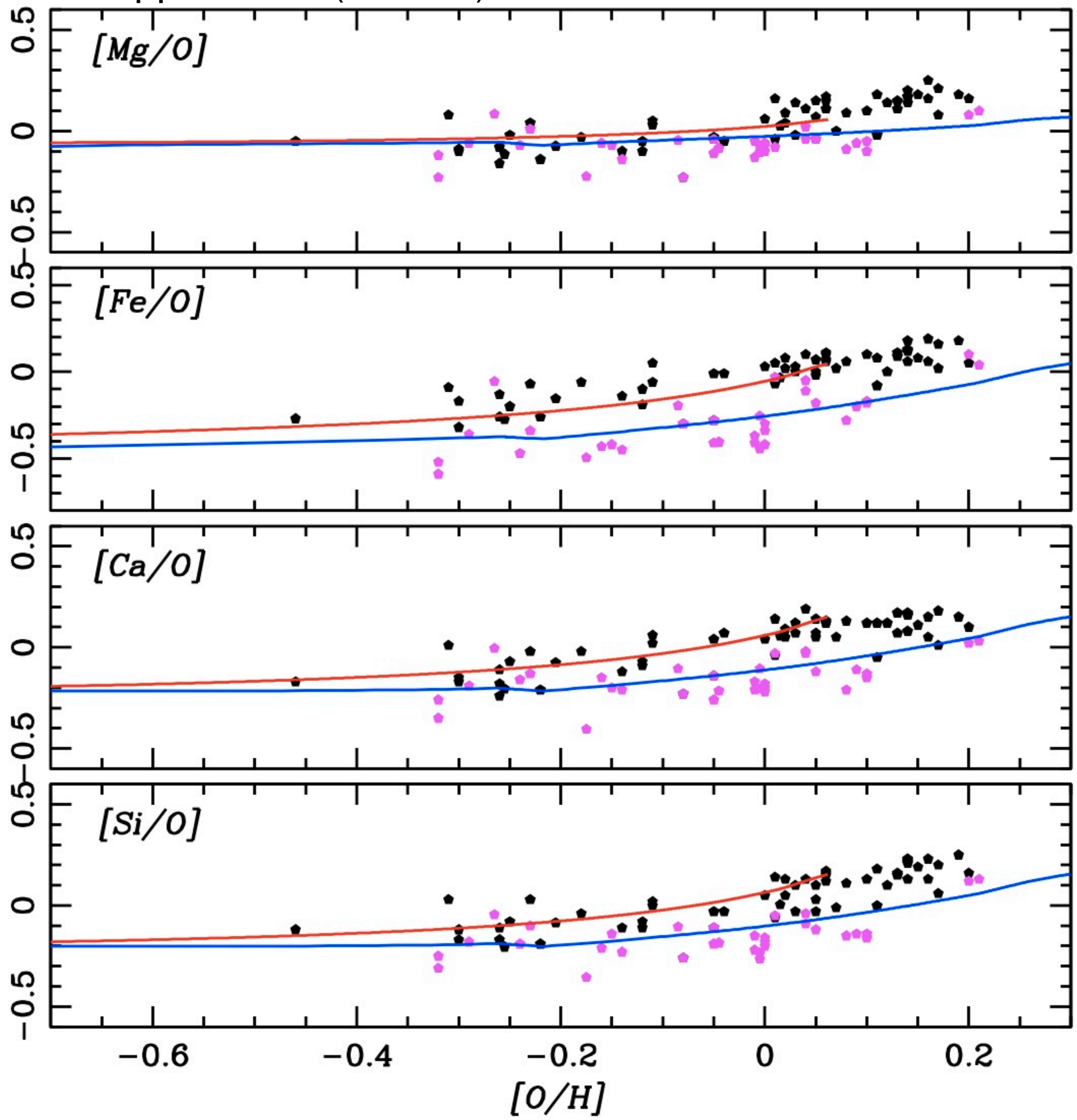
Soubiran et al. 2007: Clump stars - tried to avoid thick disk stars (only thin)
AMR less flat at old ages

Predicted SN rates



AT IAU 254

Chiappini 2008 (IAU 254)



Models:
THICK
THIN

Data (Feltzing & collab.):
THICK
THIN

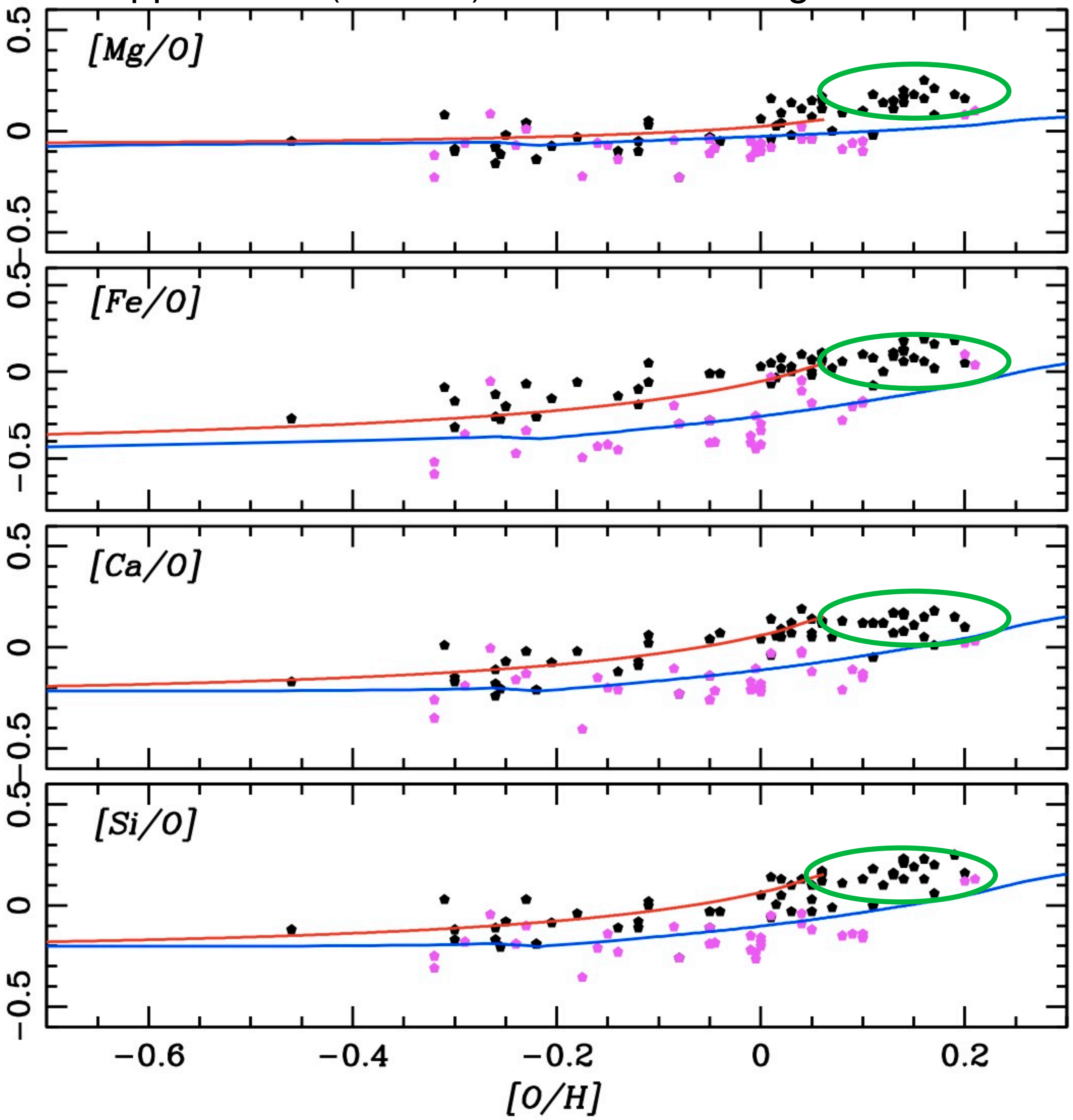
BUT…

We see stars here that are not born here

Stars more metal rich than young stars & ISM

Stellar Migration

Chiappini 2008 (IAU 254) – Need radial migration



Bulge? (Grenon 1989)
Inner disk (radial migration?)

Models:
THICK
THIN

Data (Feltzing & collab.):
THICK
THIN

Open questions:

- Biased HR samples -> is gap real?
- Could radial migration alone make thick disk? And is the apparent “gap” just an effect of SNIa/SNII timescales + migration ? (Schoenrich & Binney 2009)
- AMR flat + scatter due to radial migration (SB, and others)

How to proceed?

Answers require work in two directions:

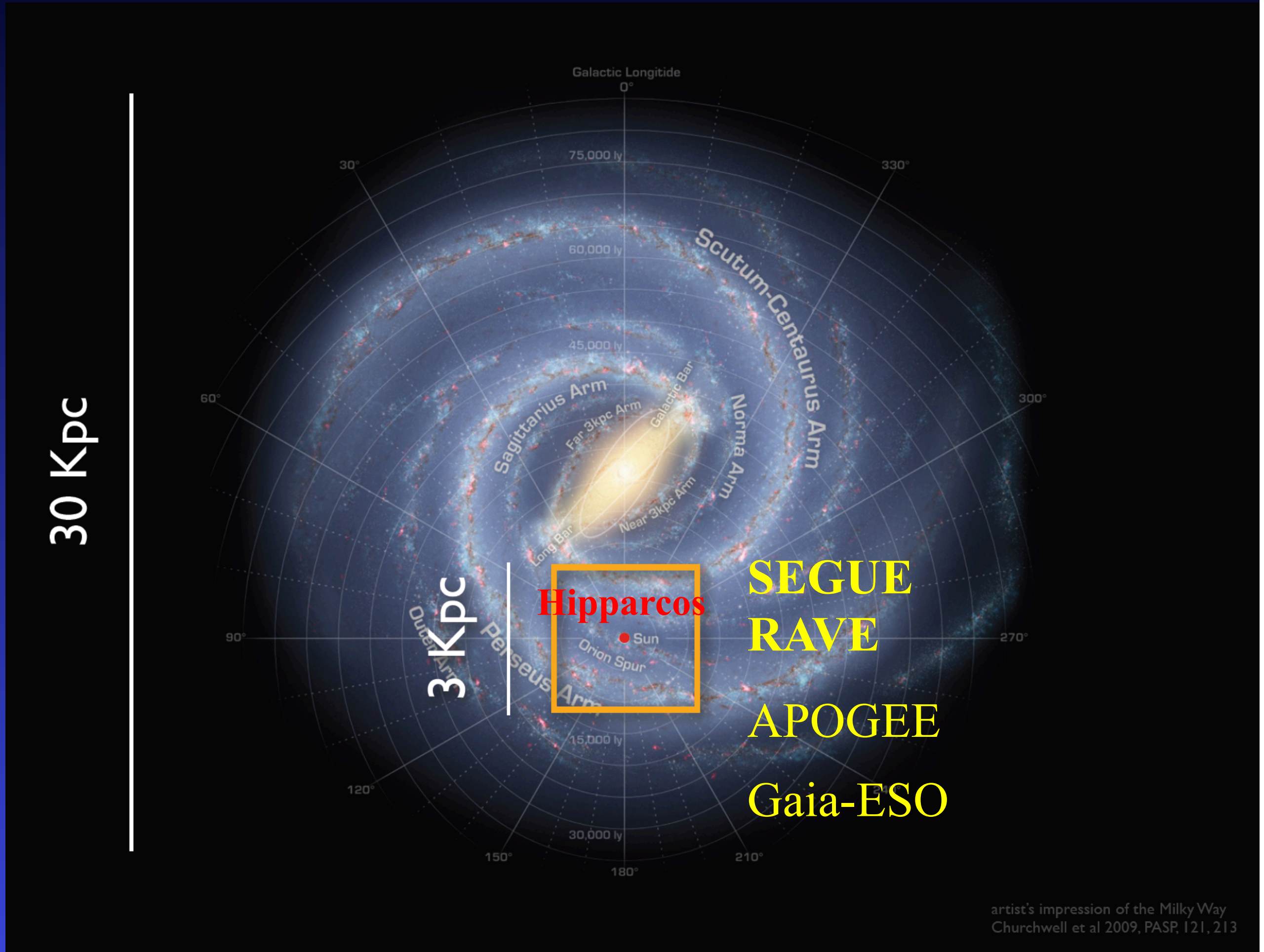
A. Unbiased samples (large ones, for larger volumes)

B. Chemodynamical model (within the cosmological framework) to see what is possible in terms of thick disk formation and if one simple disk can produce a gap in the abundance diagrams.

A Leaving the Hipparcos volume…

Spectroscopic Surveys:

RAVE – R ~ 7000
SEGUE – R ~ 2000
APOGEE – IR – R ~ 20 000
Gaia-ESO – FLAMES & UVES



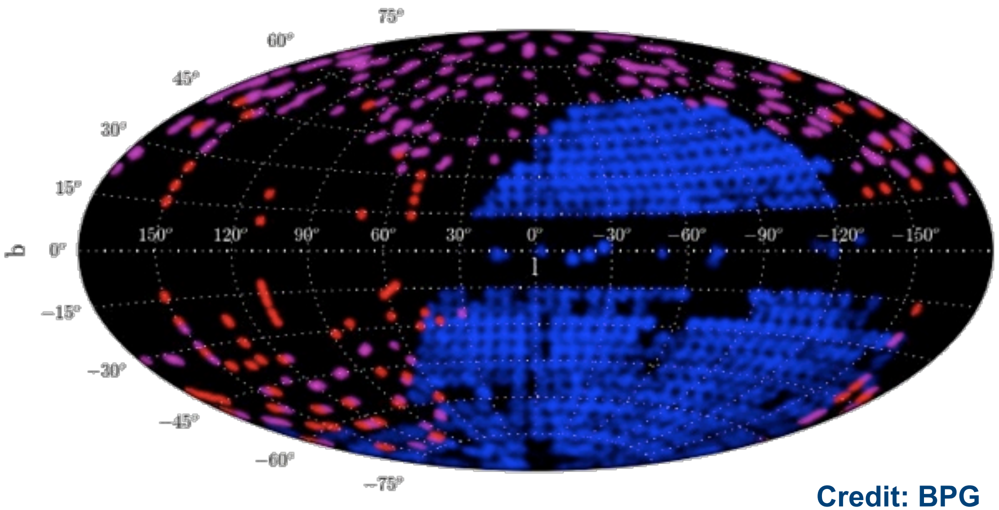
Spectrophotometric Distances – Uncertainties ~ 20-30% (Santiago, Brauer, Anders, Chiappini et al. 2014 Schultheis et al. 2014; Binney et al. 2014)

APOGEE Red Clump Catalog – Uncertainties ~10 % (Bovy et al 2014, submitted)

More constraints with RAVE + SEGUE

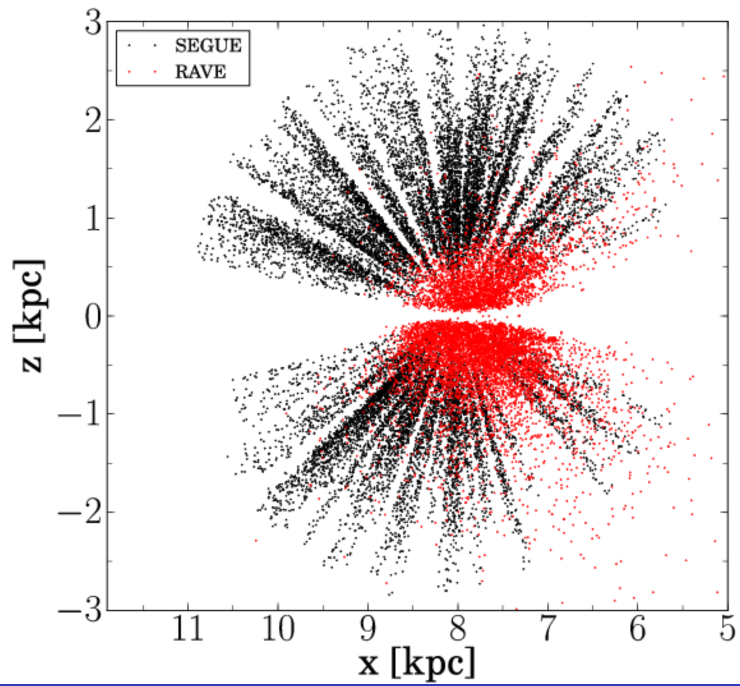
RAVE SEGUE SEGUE-2

Moderate – low resolution



Credit: BPG

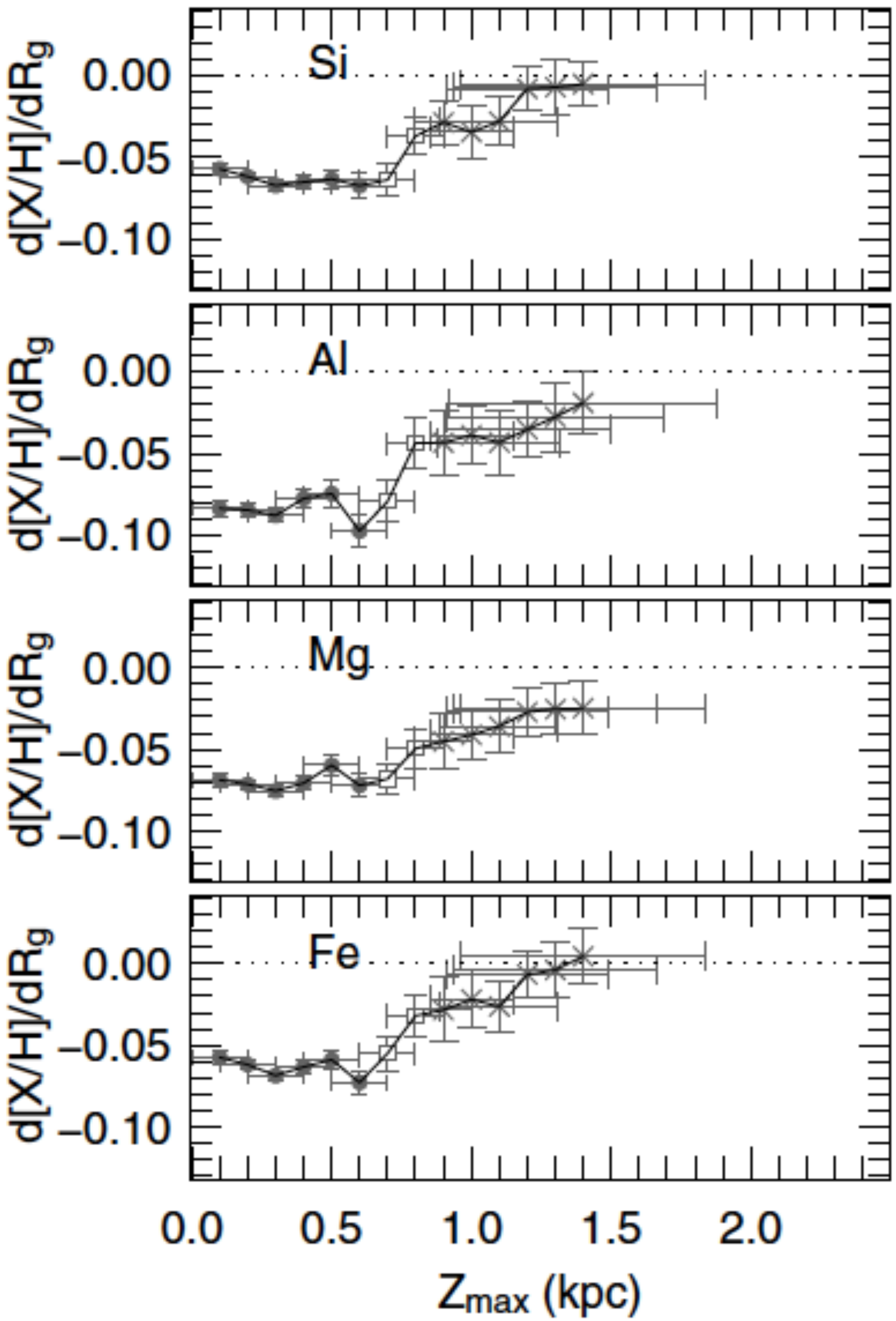
Credit: D. Brauer



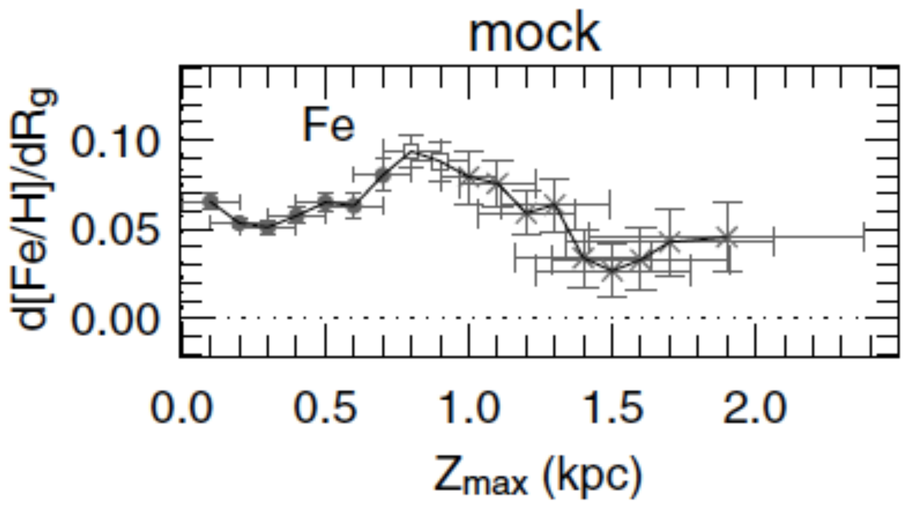
RAVE giants (red) sample a similar volume as SEGUE dwarfs (black)

Boeche, Chiappini + RAVE collaboration 2013, MNRAS
Brauer, Chiappini, + SDSSIII-BPG (in preparation)
Minchev, Chiappini, Martig + RAVE collaboration 2014, ApJ Letters
Boeche et al. 2013, 2014 (RAVE gradients dwarfs & giants)

RAVE – individual abundances -First time that abundance gradients to such a large dataset!



Discrepancy caused by the lack of correlation between metallicity and tangential velocity (or angular momentum) in models (e.g. Besancon, Trilegal).

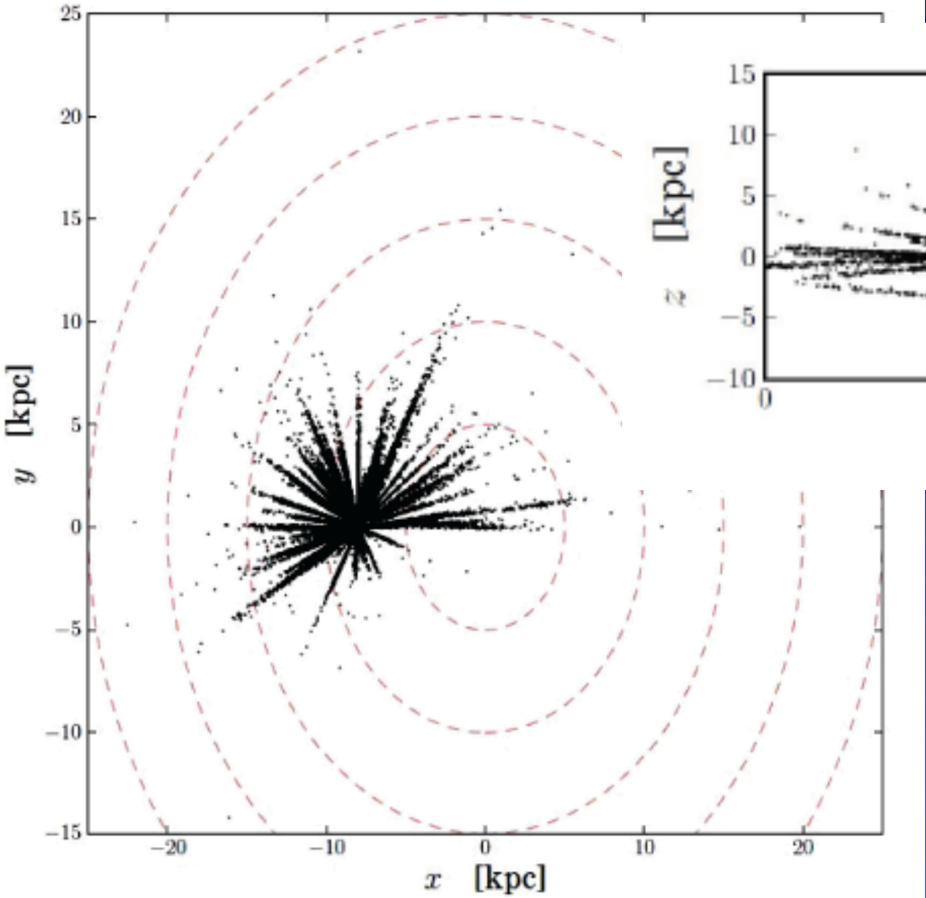


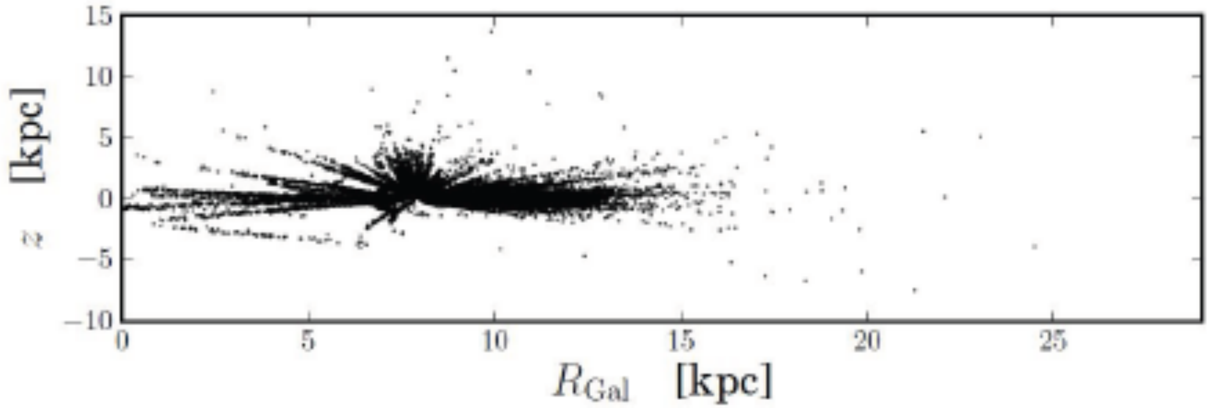
A&A 564, A115 (2014)

Chemodynamics of the Milky Way

I. The first year of APOGEE data★

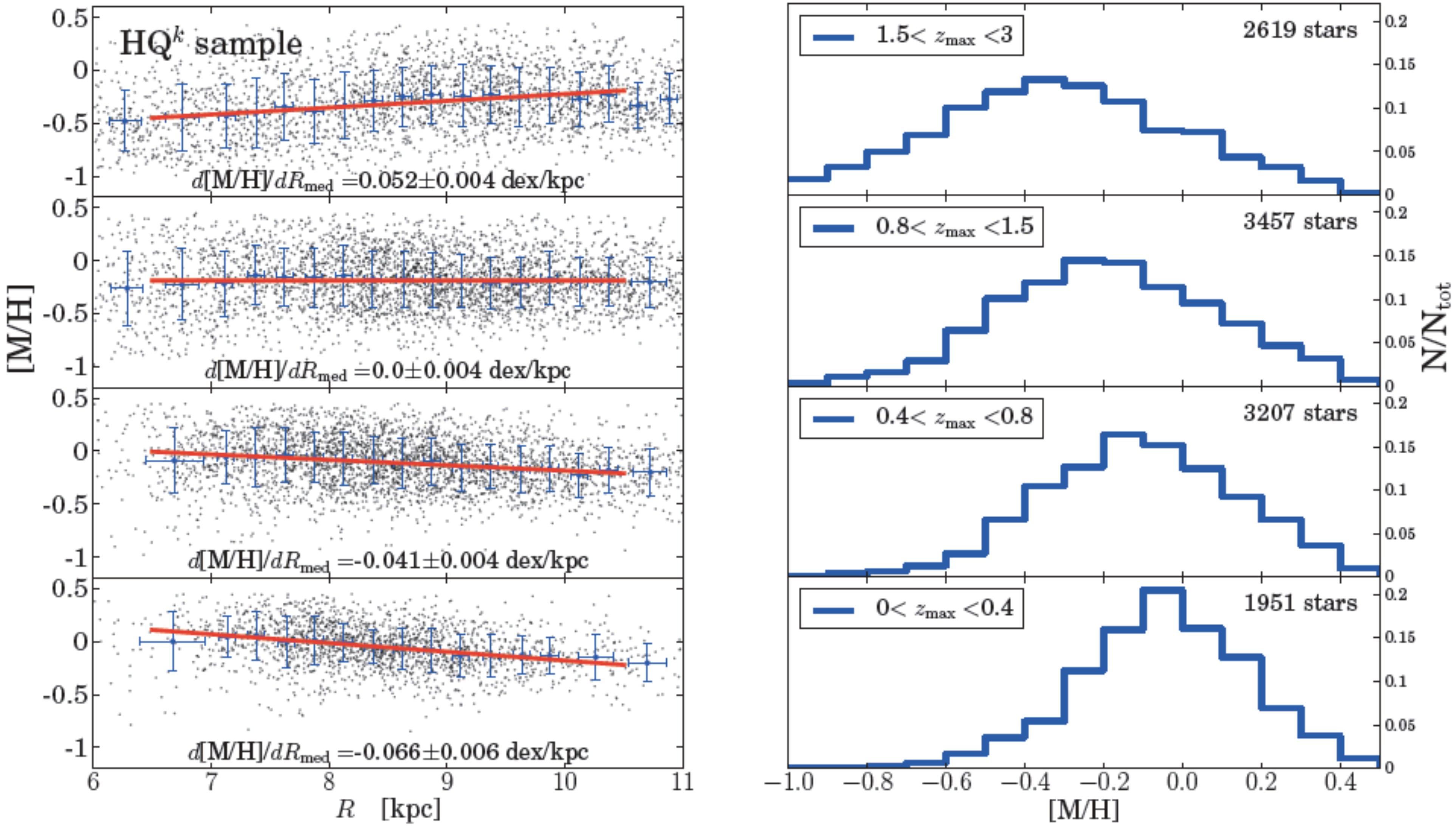
F. Anders[1,2], C. Chiappini[1,3], B. X. Santiago[3,4], H. J. Rocha-Pinto[3,5], L. Girardi[3,6], L. N. da Costa[3,7], M. A. G. Maia[3,7], M. Steinmetz[1], I. Minchev[1], M. Schultheis[8], C. Boeche[9], A. Miglio[10], J. Montalbán[11], D. P. Schneider[12,13], T. C. Beers[14,15], K. Cunha[7,16], C. Allende Prieto[17], E. Balbinot[3,4], D. Bizyaev[18], D. E. Brauer[1], J. Brinkmann[18], P. M. Frinchaboy[19], A. E. García Pérez[20], M. R. Hayden[21], F. R. Hearty[20,12], J. Holtzman[21], J. A. Johnson[22], K. Kinemuchi[18], S. R. Majewski[20], E. Malanushenko[18], V. Malanushenko[18], D. L. Nidever[23], R. W. O'Connell[20], K. Pan[18], A. C. Robin[24], R. P. Schiavon[25], M. Shetrone[26], M. F. Skrutskie[20], V. V. Smith[14], K. Stassun[27], and G. Zasowski[28]





ADDING INFORMATION AT
LOW GALACTIC LATITUTES!

APOGEE Gradients & MDF (raw)

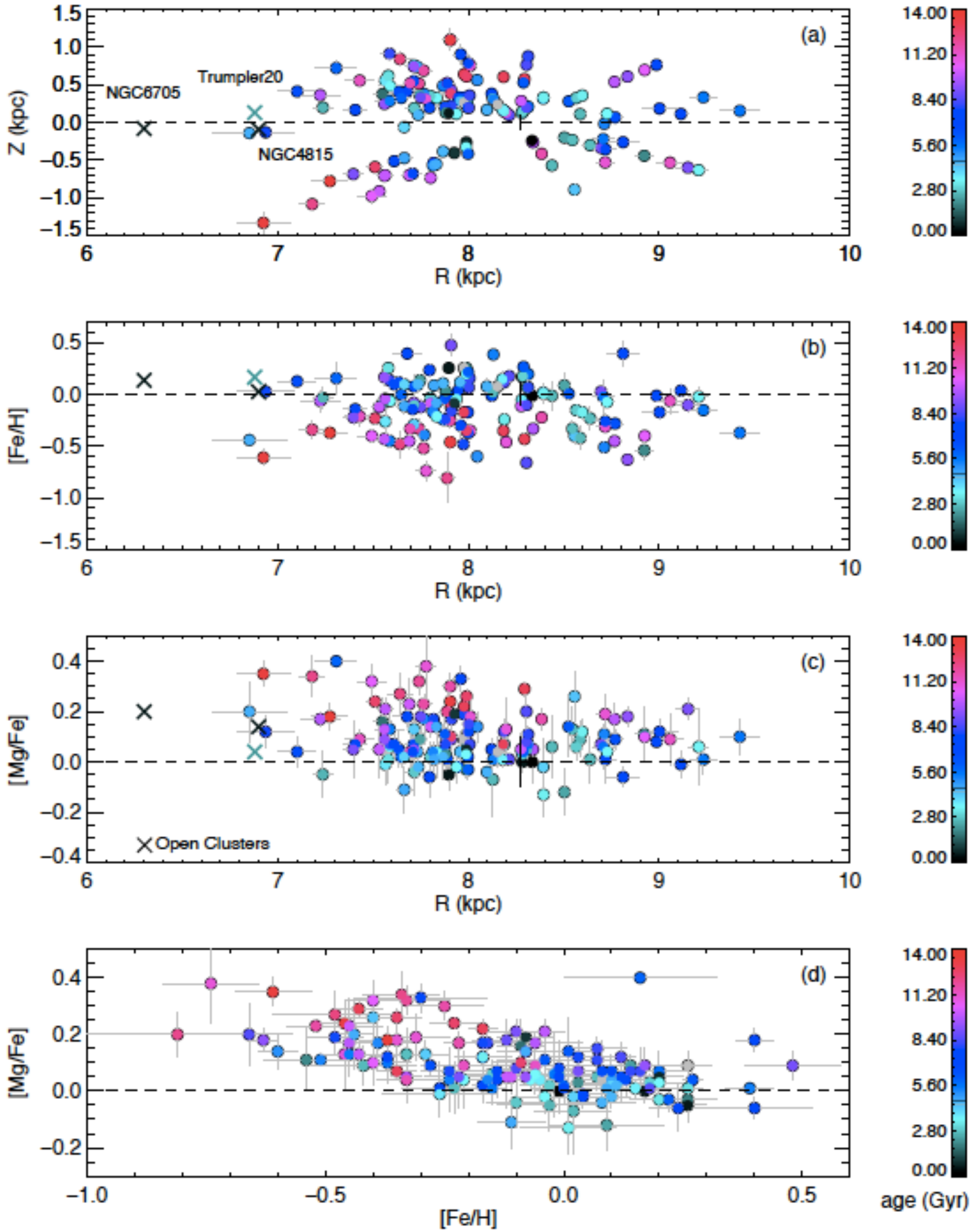


Anders, Chiappini et al. 2014

Gaia ESO - UVES

Bergmann et al. 2014

- 144 stars
- ages 0.5 – 13.5 Gyr
- 6 < R (kpc) < 9
- 0 < |Z| < 1.5 kpc

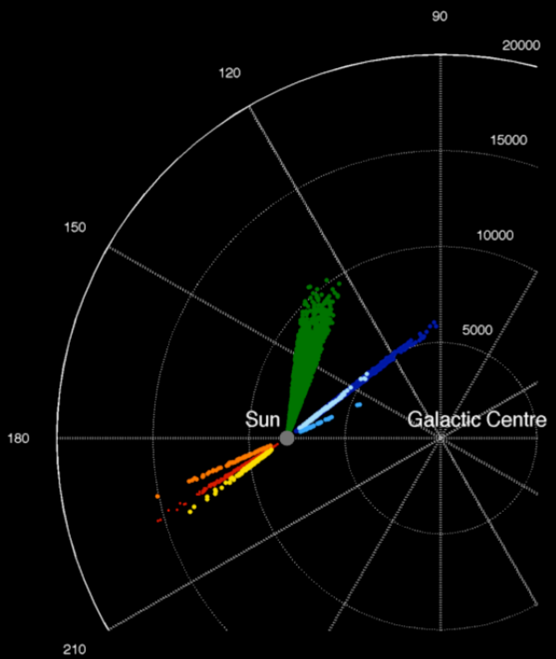


Asteroseismology: Constraints at larger distances!

CoRot & Kepler

Crucial role played by solar-like pulsating RGs:

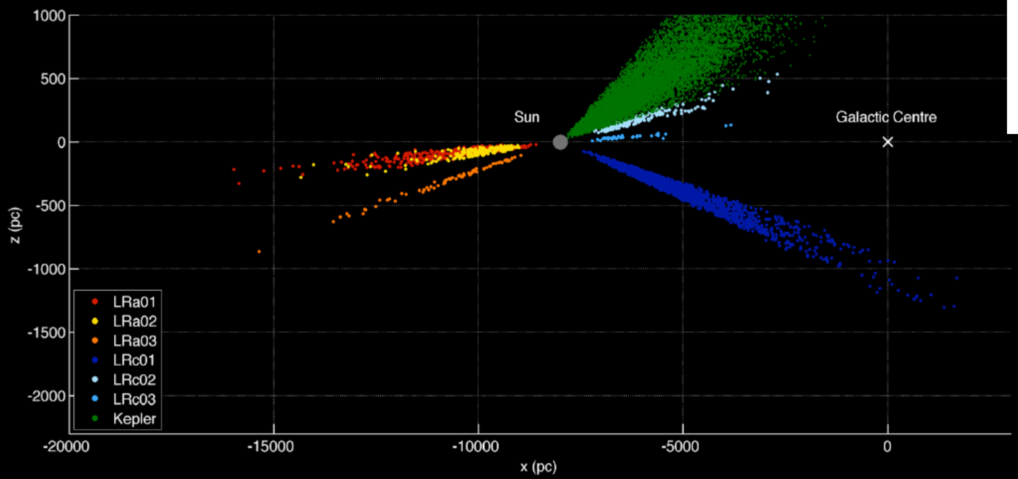
- well-populated class of accurate distance indicators
- spanning a large age range
- probe large distances



Distances and age

$$\frac{M}{M_\odot} \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right)^3 \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-4} \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{3/2}$$

$$\frac{R}{R_\odot} \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right) \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2} \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{1/2}.$$



- Uncertainty on M ~ 10%
- Uncertainty on R ~ 3%

Stepping out with Asteroseismology

- Uncertainties in distances ~ 15 %; <5% for high quality data

$$\log d = 1 + 2.5 \log \frac{T_{\rm eff}}{T_{\rm eff,\odot}} + \log \frac{\nu_{\rm max}}{\nu_{\rm max,\odot}} + \\ -2 \log \frac{\Delta\nu}{\Delta\nu_\odot} + 0.2(m_{\rm bol} - M_{\rm bol,\odot}),$$

d is expressed in pc, $m_{\rm bol}$= apparent bolometric magnitude, $M_{\rm bol,\odot}$= absolute solar bolometric magnitude.

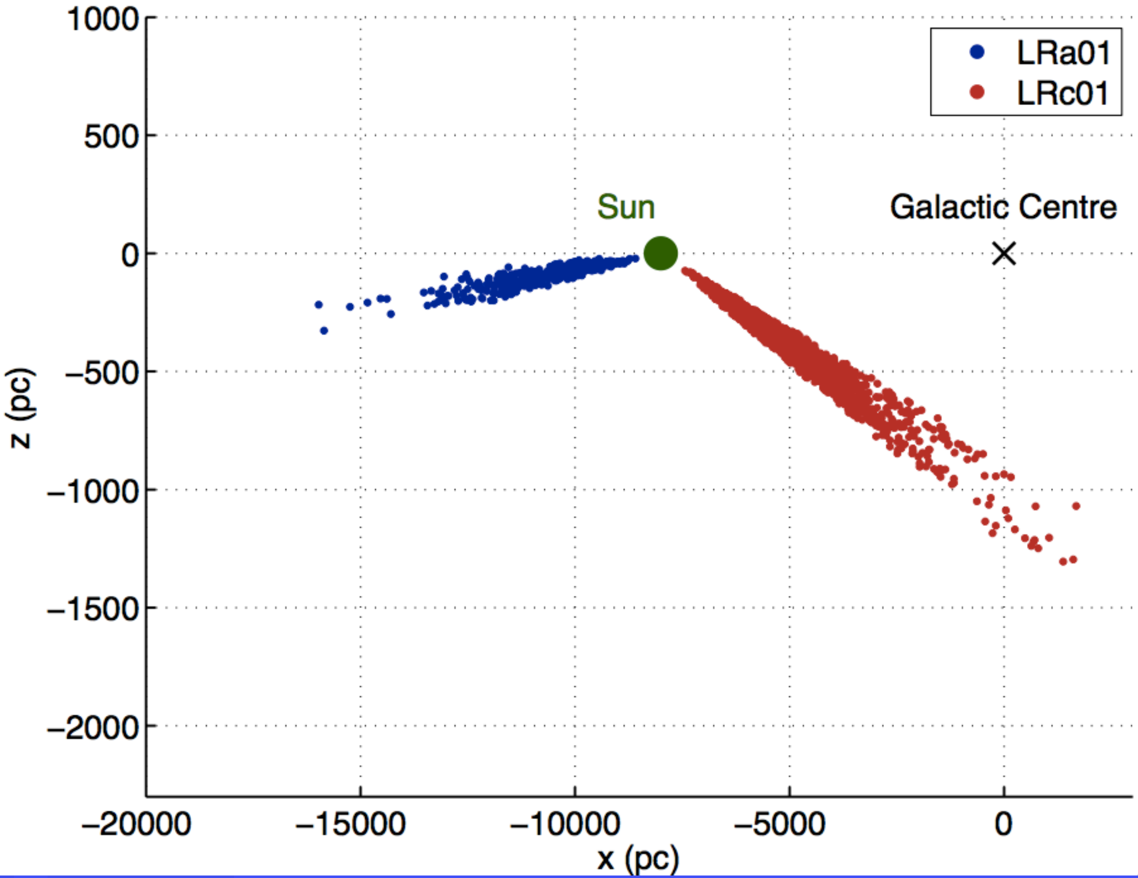
- Seismic log g -> uncertainty of 0.03 dex

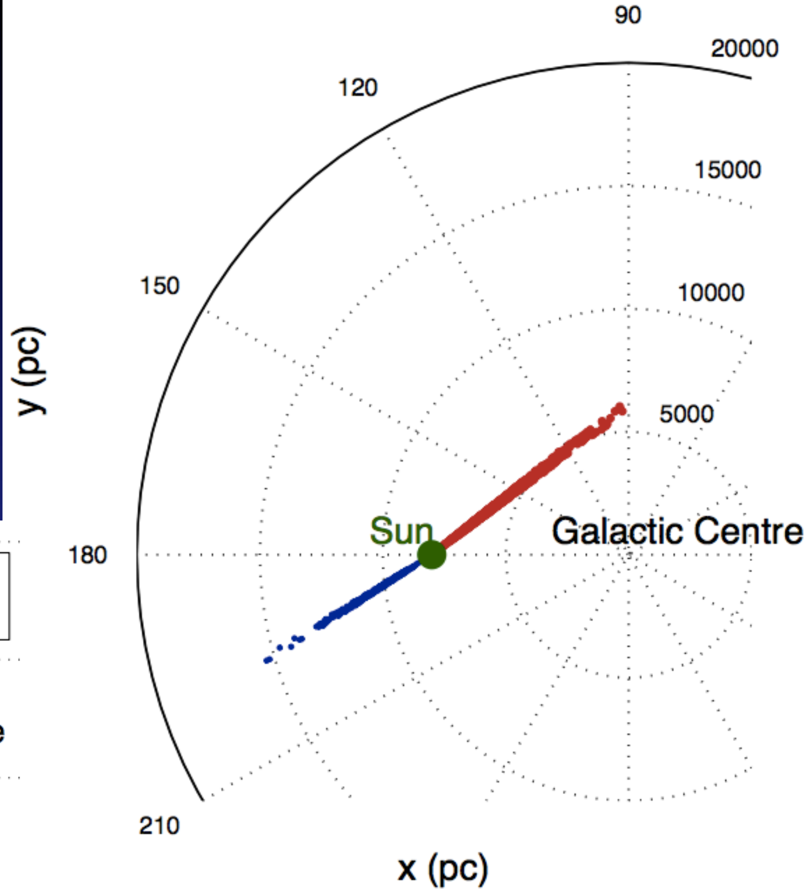
[spectroscopic usually 0.1-0.3 dex!]

$$\log g = \log g_\odot + \log \left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right) + \frac{1}{2} \log \left(\frac{T_{\rm eff}}{\mathrm{T}_{\rm eff,\odot}}\right)$$

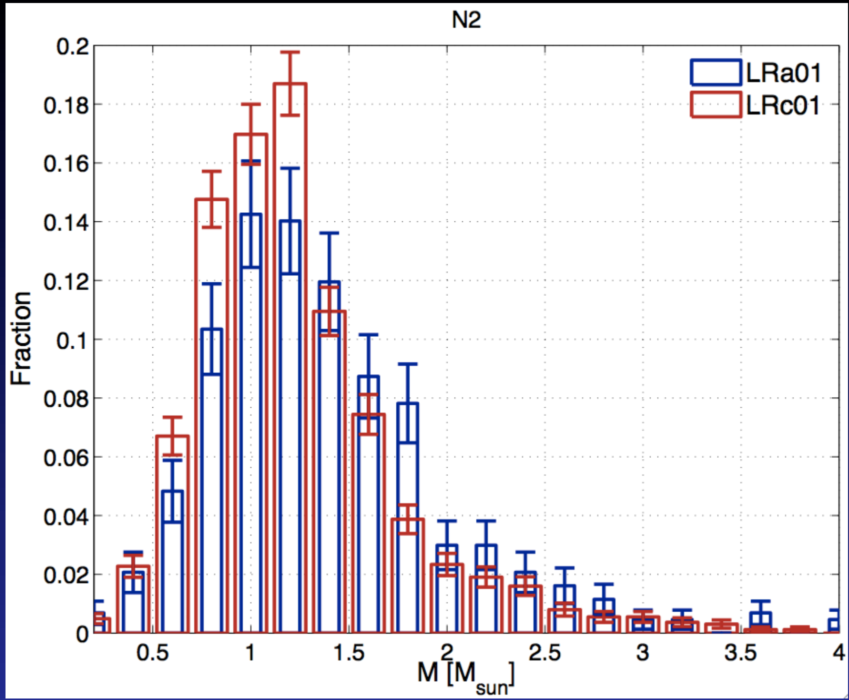
CoRoT

First use of asteroseismology to determine precise distances for a large (~2000) sample of field stars (giants) spread across nearly 15 kpc of the Galactic disc, exploring regions which are a long way from the solar neighbourhood.

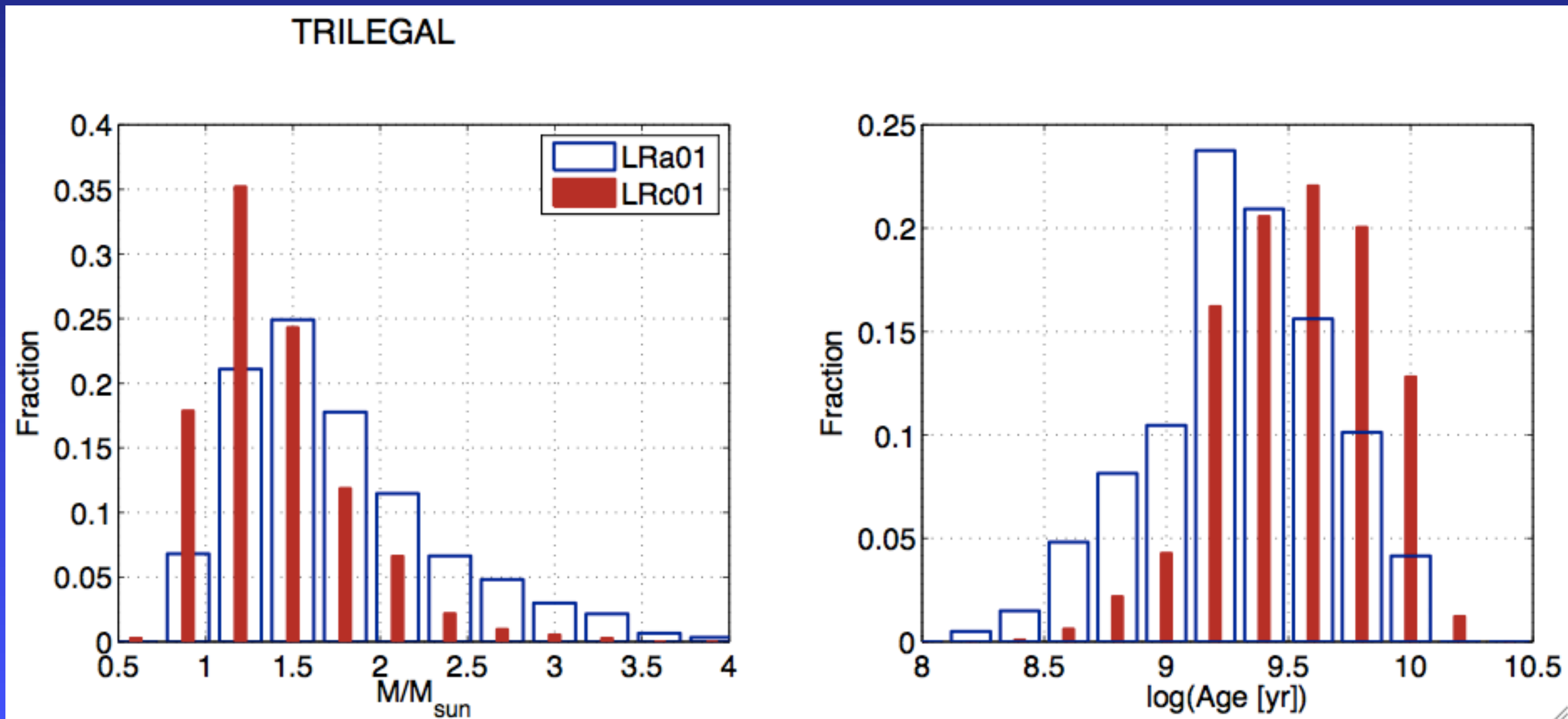




Miglio, Chiappini, Morel, Barbieri, Chaplin, Girardi, Montalban, Noels, Valentini, Mosser, Baudin, Casagrande, Fossati, Silva Aguirre & Baglin 2013, MNRAS 429, 423
[LRa01+Lrc01 analysis]



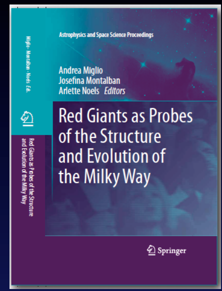
We find significant differences in the mass distributions of these two samples which, by comparison with predictions of synthetic models of the Milky Way (TRILEGAL), we interpret as mainly due to the vertical gradient in the distribution of stellar masses (hence ages) in the thin disc.



- Age
- Distances

- Gaia
- Asteroseismology (CoRoT & Kepler & PLATO)

Mass, Radius & Evolutionary Stage



- Stellar parameters, metallicities
- [alpha/Fe] and detailed abundances

+

- Ground-based spectroscopic Surveys needed
  - APOKASC -> Extinctions & distances for ~2000 stars; 0.5 < d (kpc) < 5kpc; Current uncertainty < 2% ! (Rodrigues et al. 2014 – BPG/SDSSIII – in preparation)
  - CoRoT follow-up with Gaia-ESO -> data in hands UVES + FLAMES-GIRAFFE – Valentini et al. - in preparation)

On going follow up of LRa01 by APOGEE; LRc01 by GAIA-ESO, Kepler targets by APOGEE
More Kepler observations – some with RAVE info

Workshop: "Reconstructing the Milky Way's history: spectroscopic Surveys, Asteroseismology and chemodynamical models", June 1-5 2015
Physics Center Bad Honnef - Bonn – Germany

A

Chemodynamical models

N-body Simulations: Why?

- N-body simulations are the appropriate technique to treat time-dependent non-axisymmetric systems such as our barred galaxy
- 3D self-gravitating systems with large dynamic range in temporal scales, involving both gas and collisionless matter (stars) – TreeSPH codes, AMR, Voronoi
- Gas - Increases complexity due to star formation and energy feedback ⟷ **Chemistry/Mass return**
- The role of the bar in radial migration cannot be ignored (Minchev et al. 2010, Brunetti, Chiappini & Pfenniger 2011)

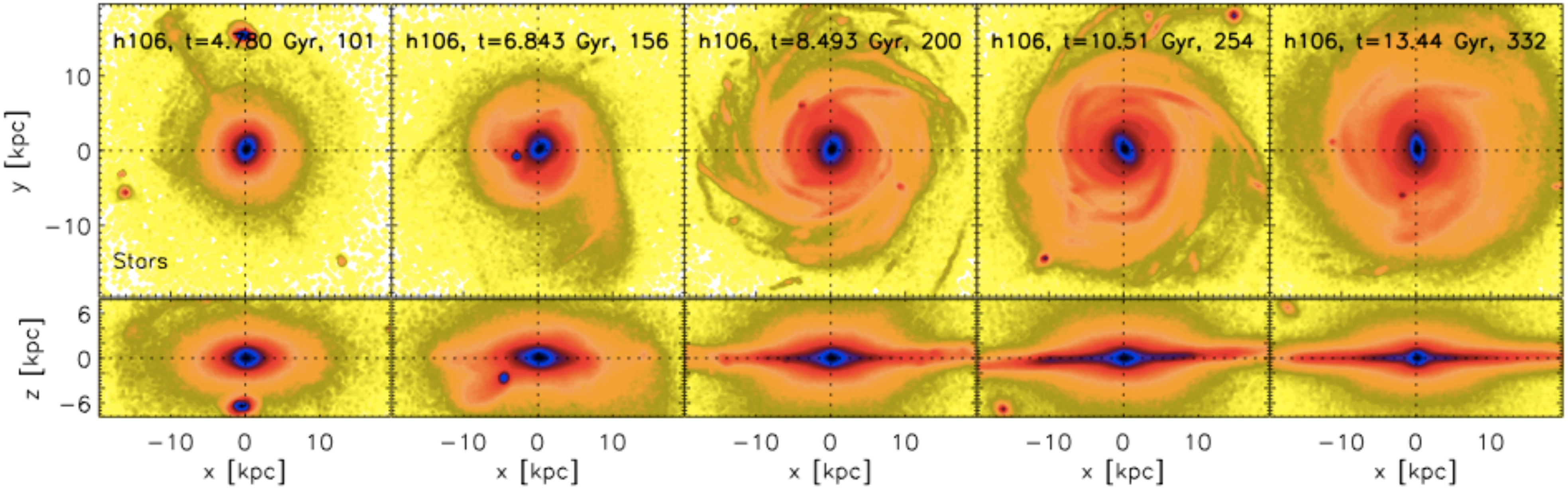
Caveat: non-physical effects (e.g. overcooling, overmerging, angular momentum loss) when trying to describe sub-grid physics governing galaxy evolution (Star formation, feedback, magnetic fields..)

New Approach "Surrogate galaxies"

Minchev, Chiappini, Martig 2013 I. A&A 558, id.A9 (MCM Model)
Minchev, Chiappini, Martig 2014 II. A&A (submitted)

- Choose a high-resolution simulation in the cosmological framework that meet the following MW properties :
  - a bar
  - gas accretion – disk grows inside-out (gas from filaments + mergers)
  - early mergers – merger activity decreases toward redshift zero
  - lasts for at least 10 Gyrs
- Disk Properties at redshift zero => consistent with dynamics & morphology of MW: Presence of a MW size bar; small bulge
- We place the "solar radius" (8 kpc) just outside the 2:1 outer Lindblad resonance (OLR) of the bar, as is believed to be the case for the MW (e.g., Dehnen 2000; Minchev et al. 2007)
- We resample the disk's SFH appropriate for the chemical evolution model
- Use a pure thin disk chemical evolution model (from the point of view of star formation history) – the simplest case, no SFR threshold, no pre-enrichment
- We extract self-consistent dynamics: radial migration from internal perturbations + mergers

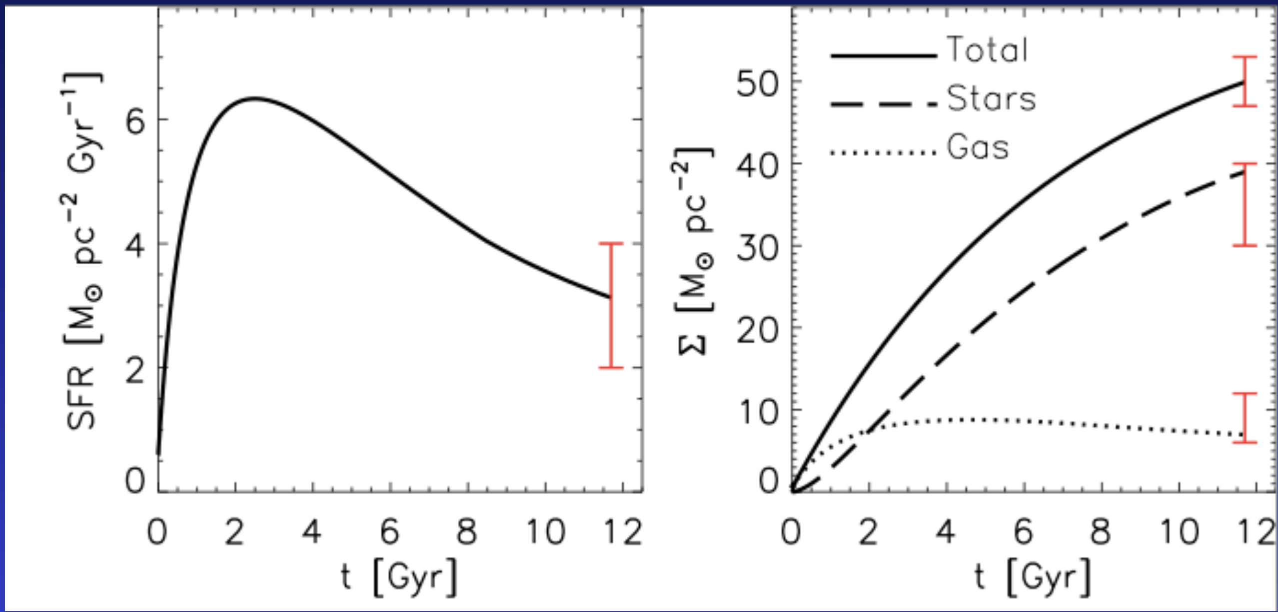
Input Dynamics Martig et al. 2012



We can now look for the contamination (from migration) to the input chemical model

Input Chemistry

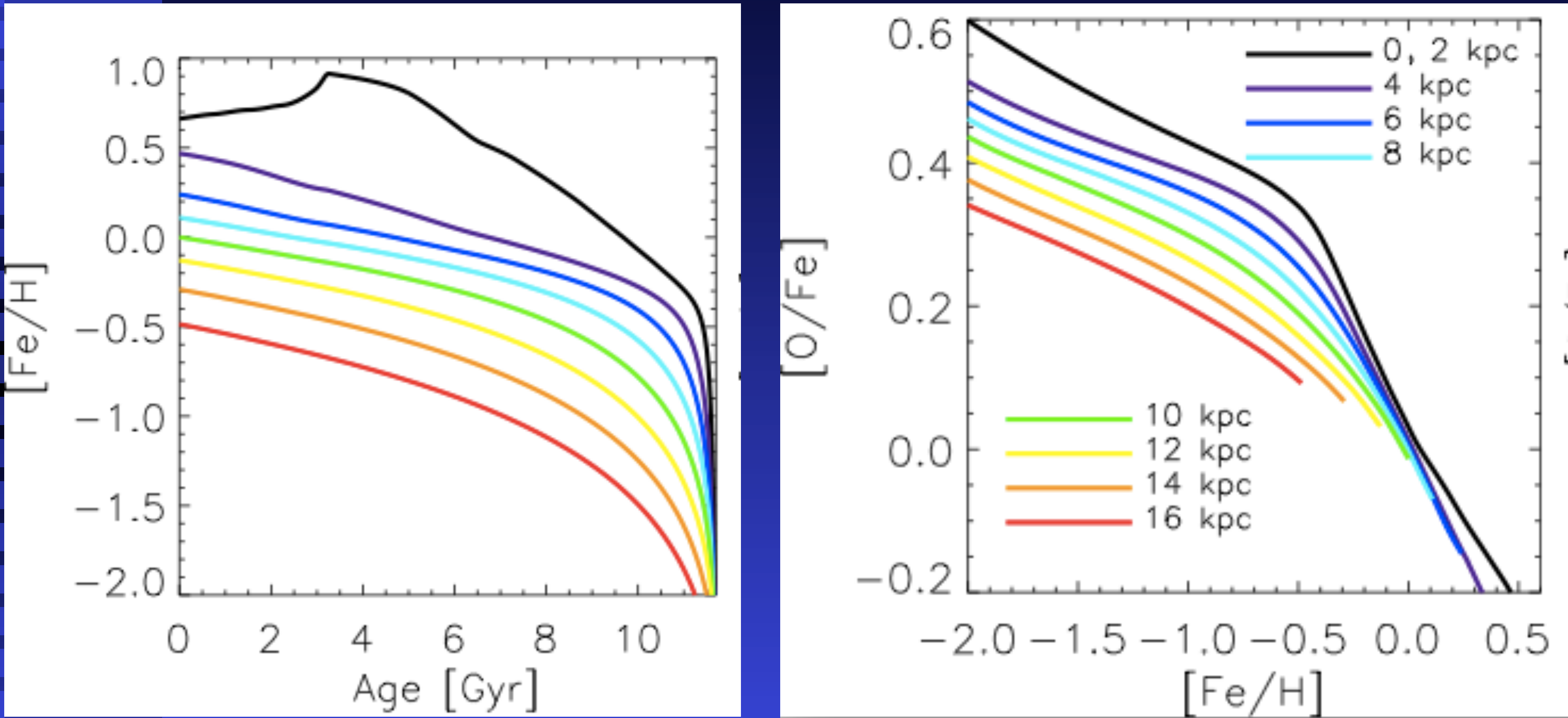
Pure Thin Disk Solar Vicinity



Chiappini 2009 IAU 254

Matching several observational constraints in the MW, some of them not affected by migration (e.g., deuterium)

Pure Thin Disk

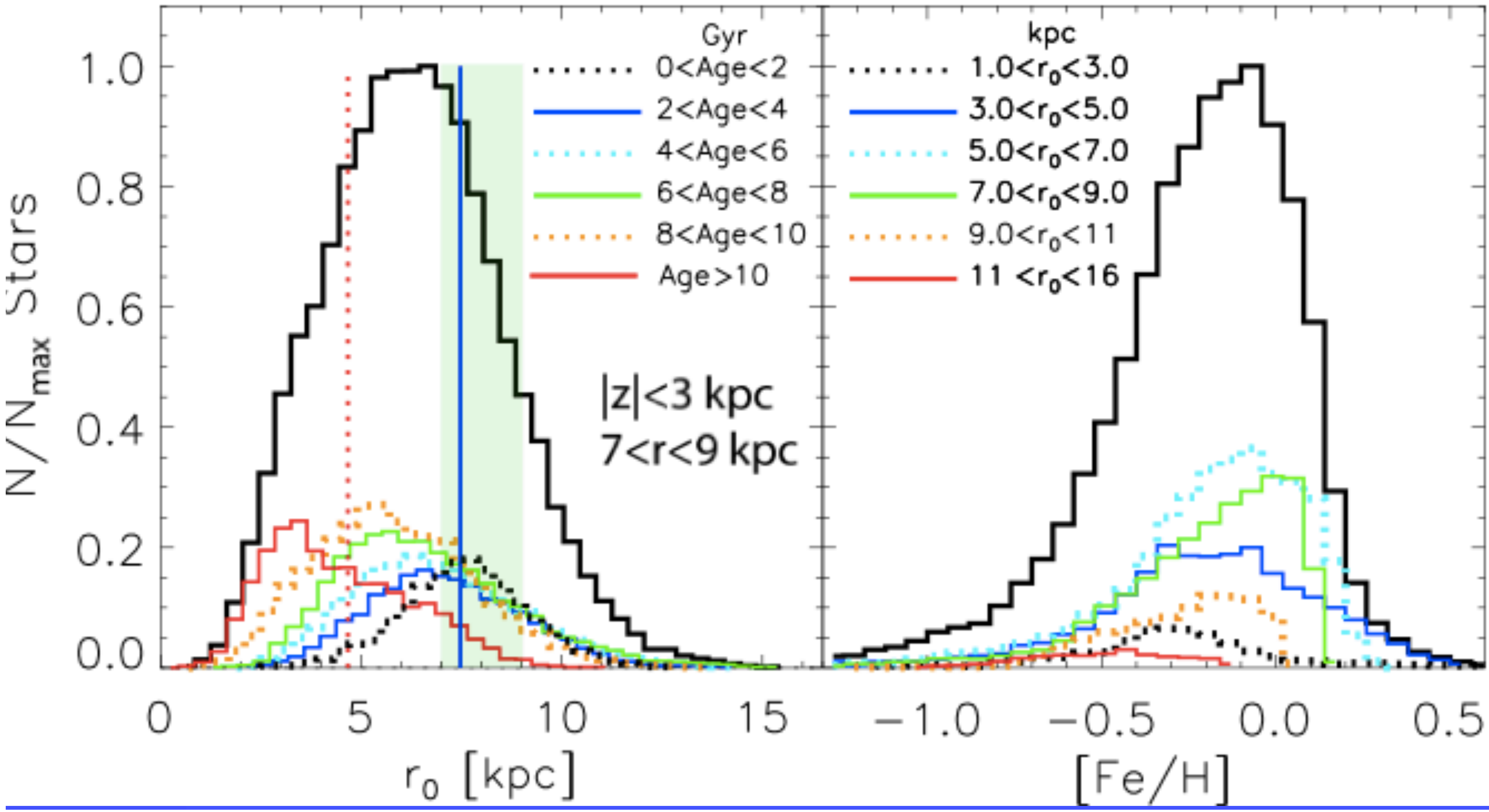


Using τ(r) from Chiappini et al. 2001
But assuming something "ad hoc" for r < 4 kpc
(in this region, not clear what happens to abundance gradients/bulge)

Metallicity Distribution at Solar Vicinity

Mosaic of stars born at different $R_{initial}$ at different times

r_0 = Birth Radii in kpc



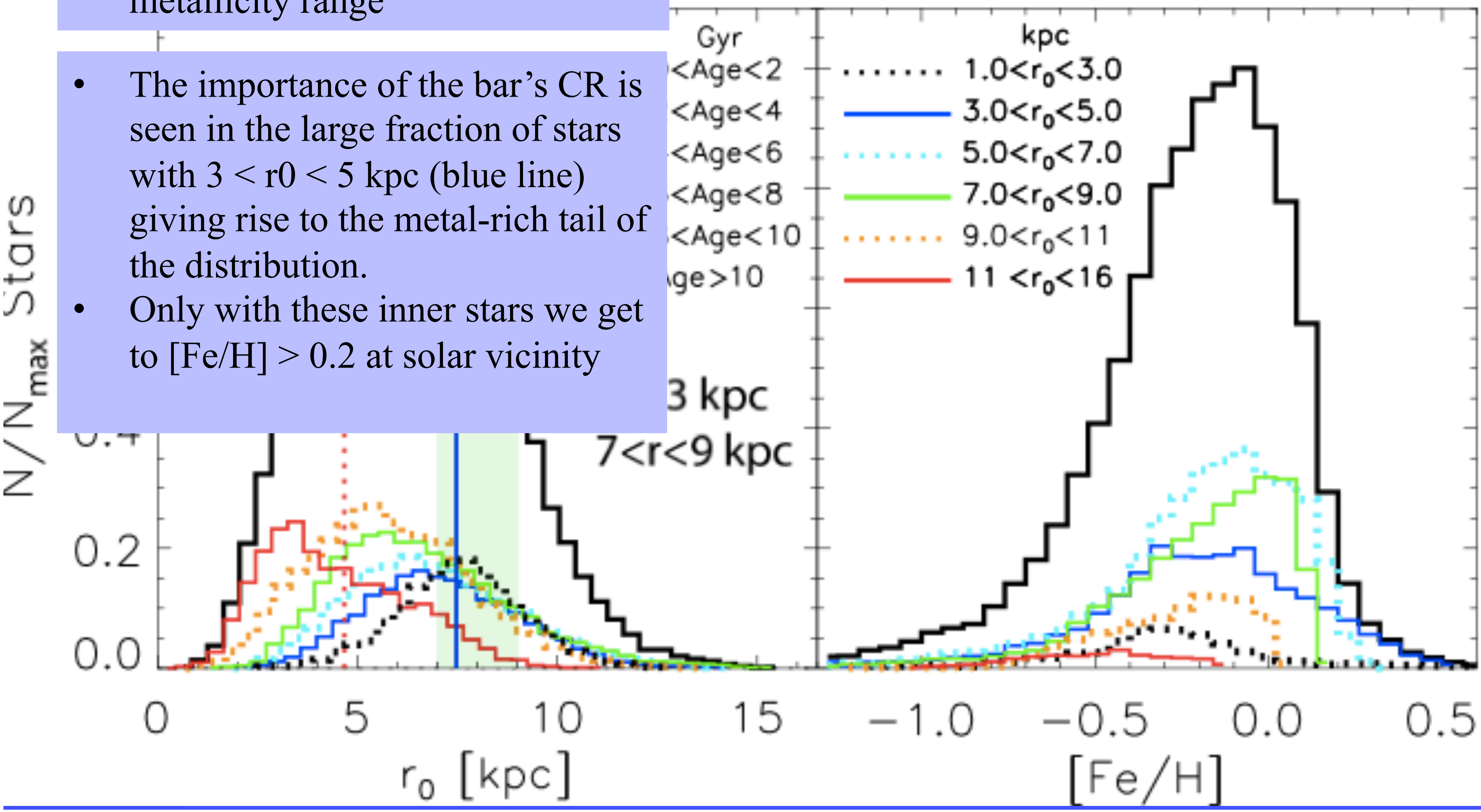
Metallicity Distribution at Solar Vicinity

Mosaic of stars born at different $R_{initial}$ at different times

r_0 = Birth Radii in kpc

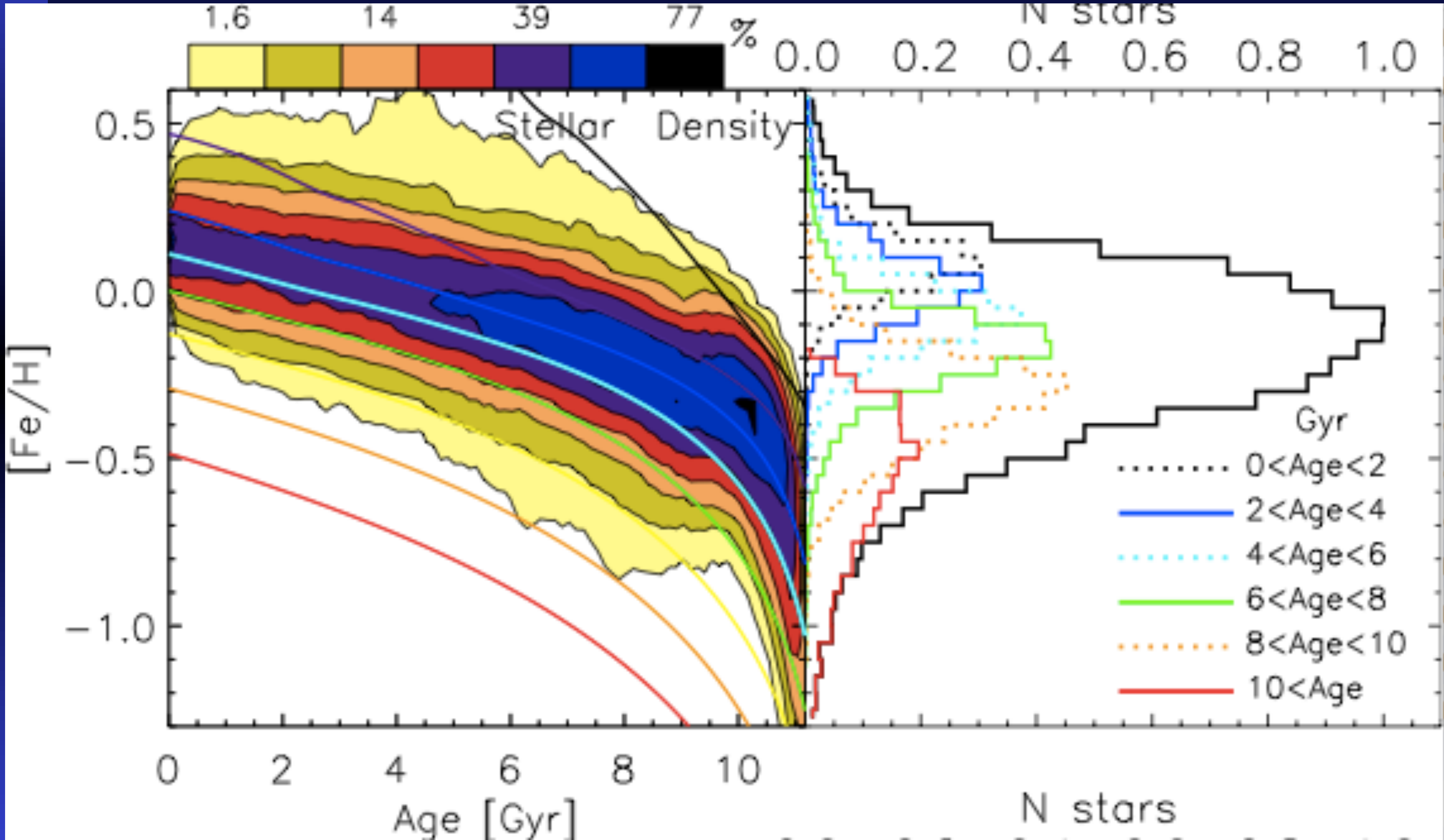
- Old stars sample a broad metallicity range

- The importance of the bar's CR is seen in the large fraction of stars with 3 < r0 < 5 kpc (blue line) giving rise to the metal-rich tail of the distribution.
- Only with these inner stars we get to [Fe/H] > 0.2 at solar vicinity



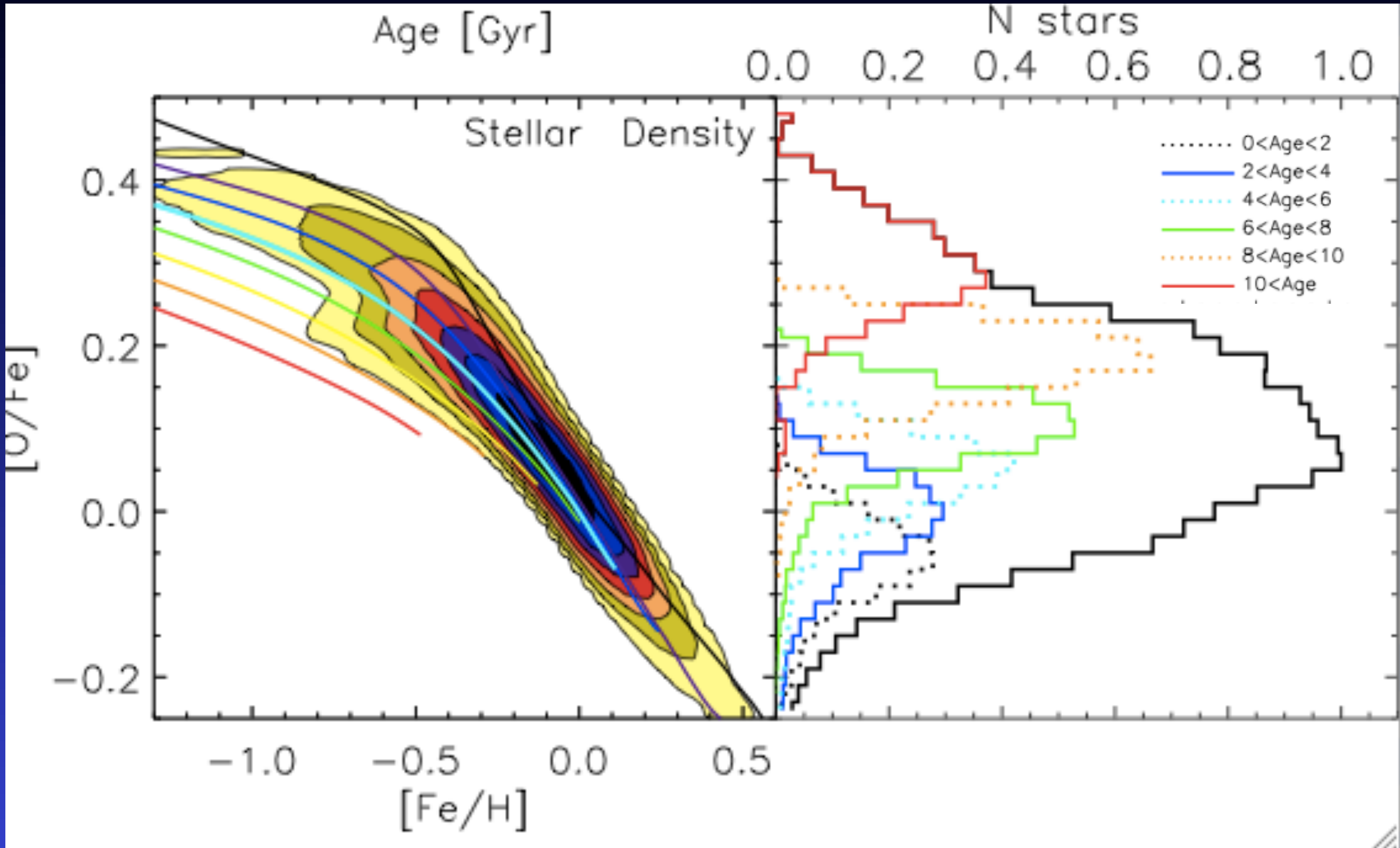
Radial migration produces scatter in AMR
But some trend is preserved

(the mean is close to the R=8kpc curve – cyan)



AGES!

Strong radial migration – but not much scatter in [O/Fe]

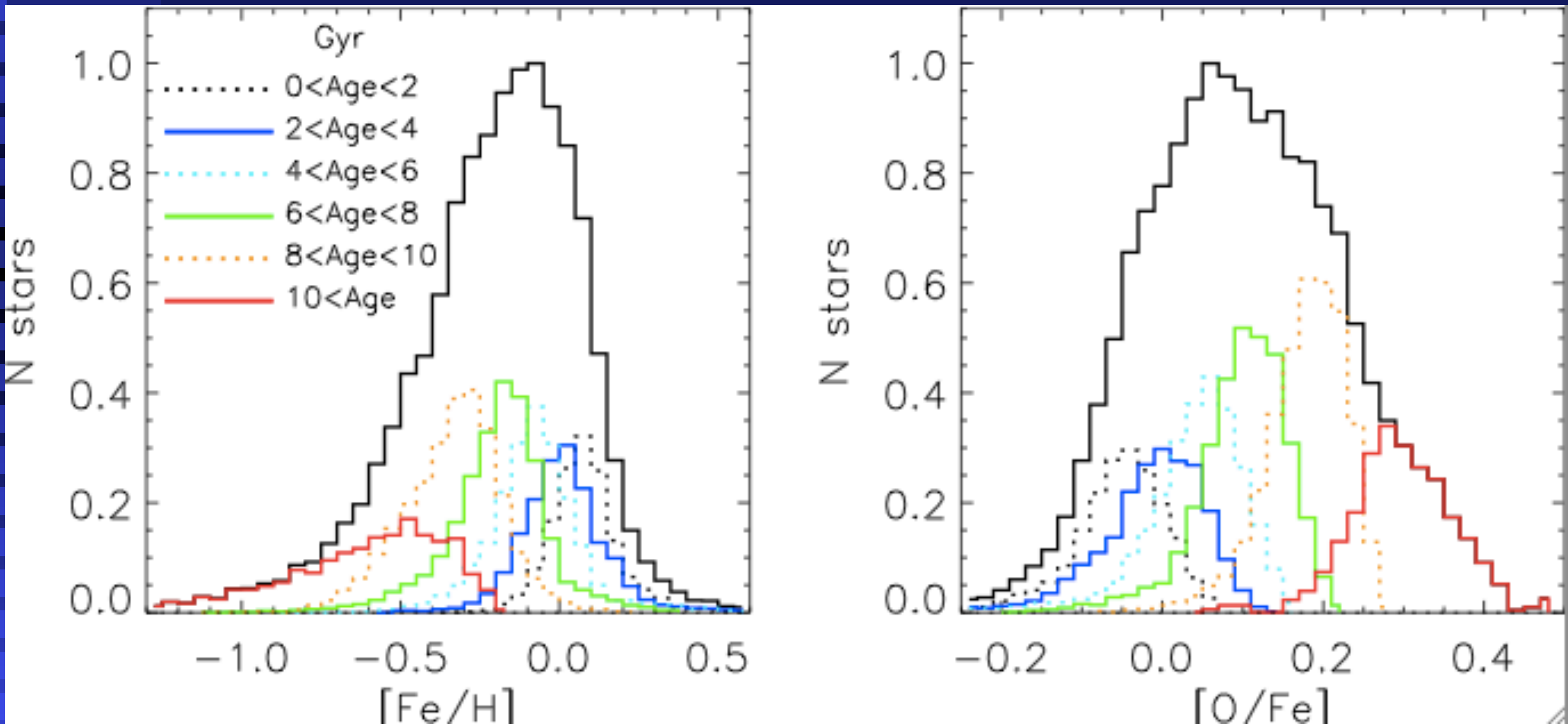


AGES!

Close look at properties of the oldest population (red):

Is this the Thick disk?????

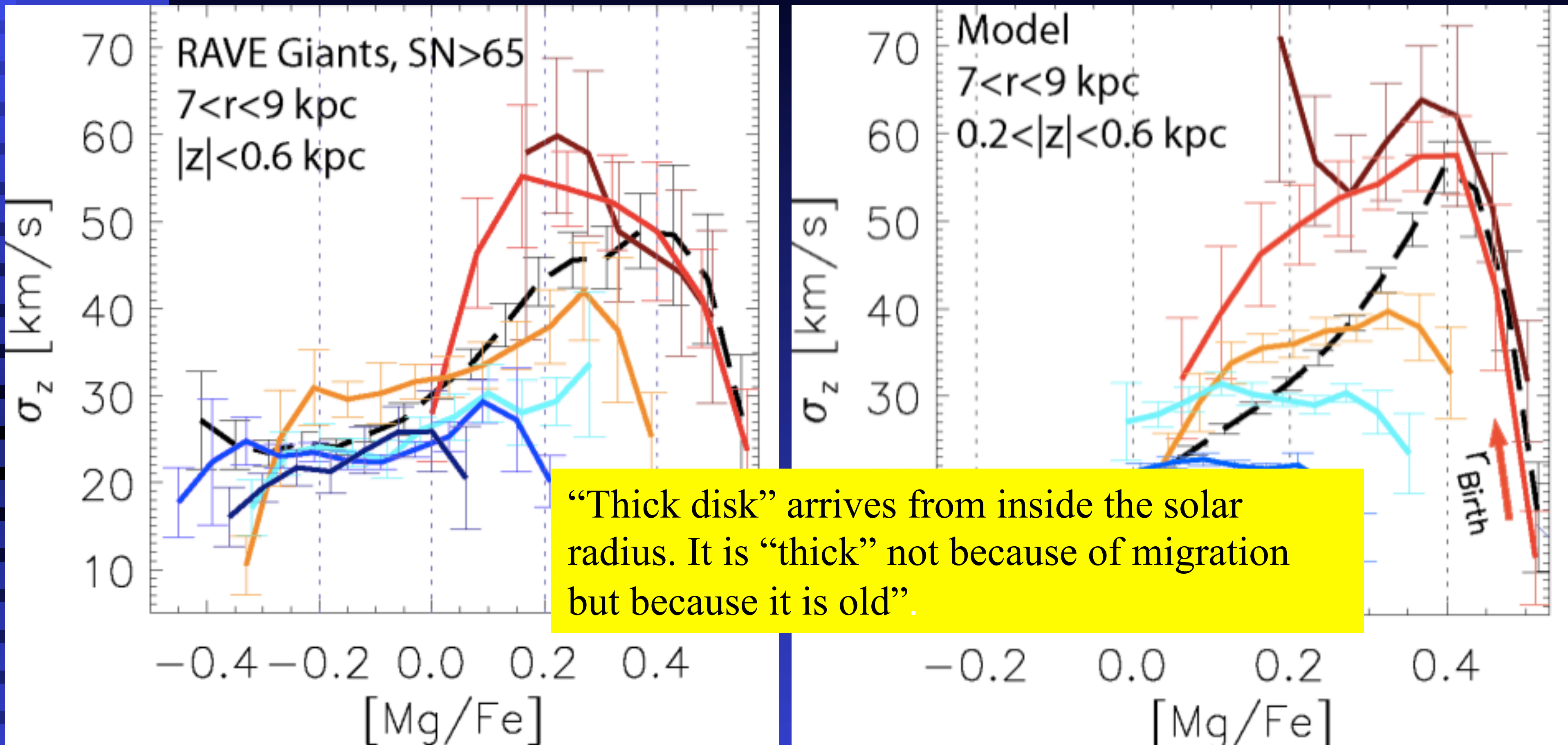
- Have thick disk like ages
- Have thick disk like MDF
- Have thick disk like [O/Fe]
- Lag the "thin disk" by ~50 km/s



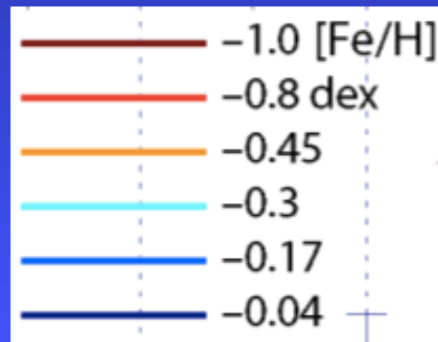
AGES!

RAVE

MCM MODEL



"Thick disk" arrives from inside the solar radius. It is "thick" not because of migration but because it is old".



We found unexpected behavior in the velocity dispersion of a sample of RAVE giants: it decreases strongly for stars with [Mg/Fe]~0.4 dex (i.e., those that formed in the first Gyr of the Galaxy's life).

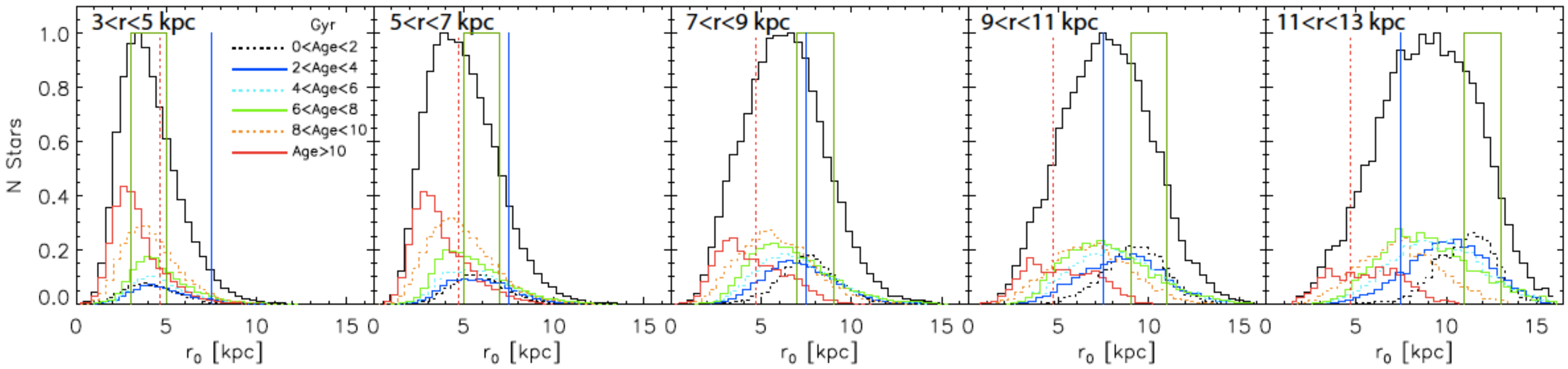
Minchev, Chiappini, Martig +R AVE collaboration, ApJL 2014

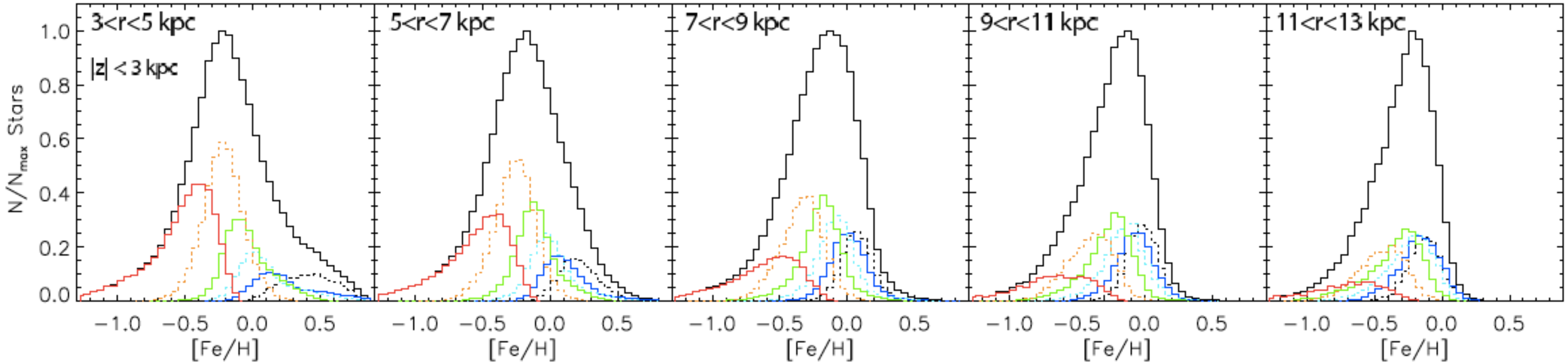
The properties at different places in the disk

The R_{birth} mix

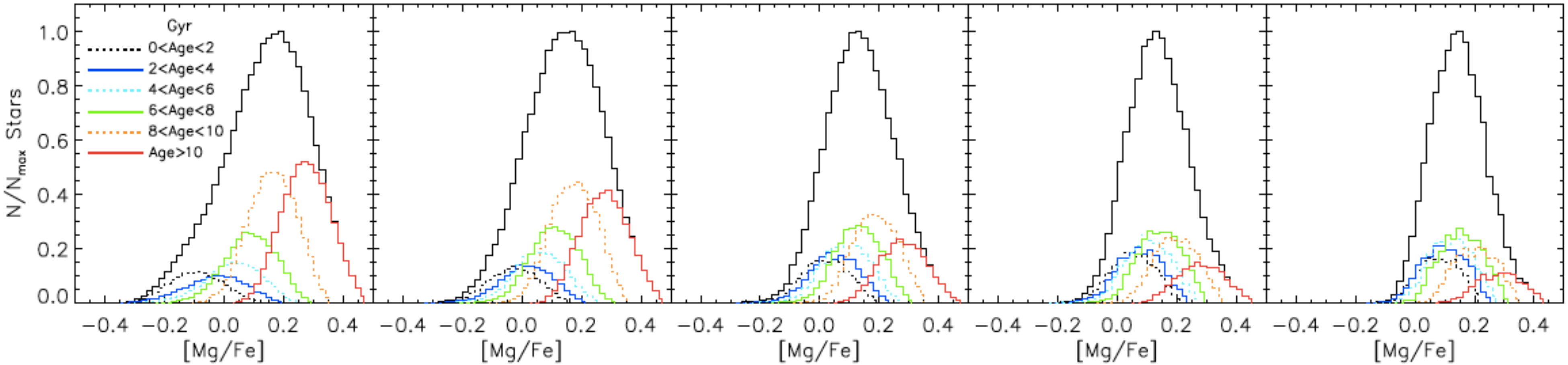
Stars that today are in the indicated bin, came from different R0

Minchev, Chiappini, Martig 2014, A&A (submitted) – MCM II



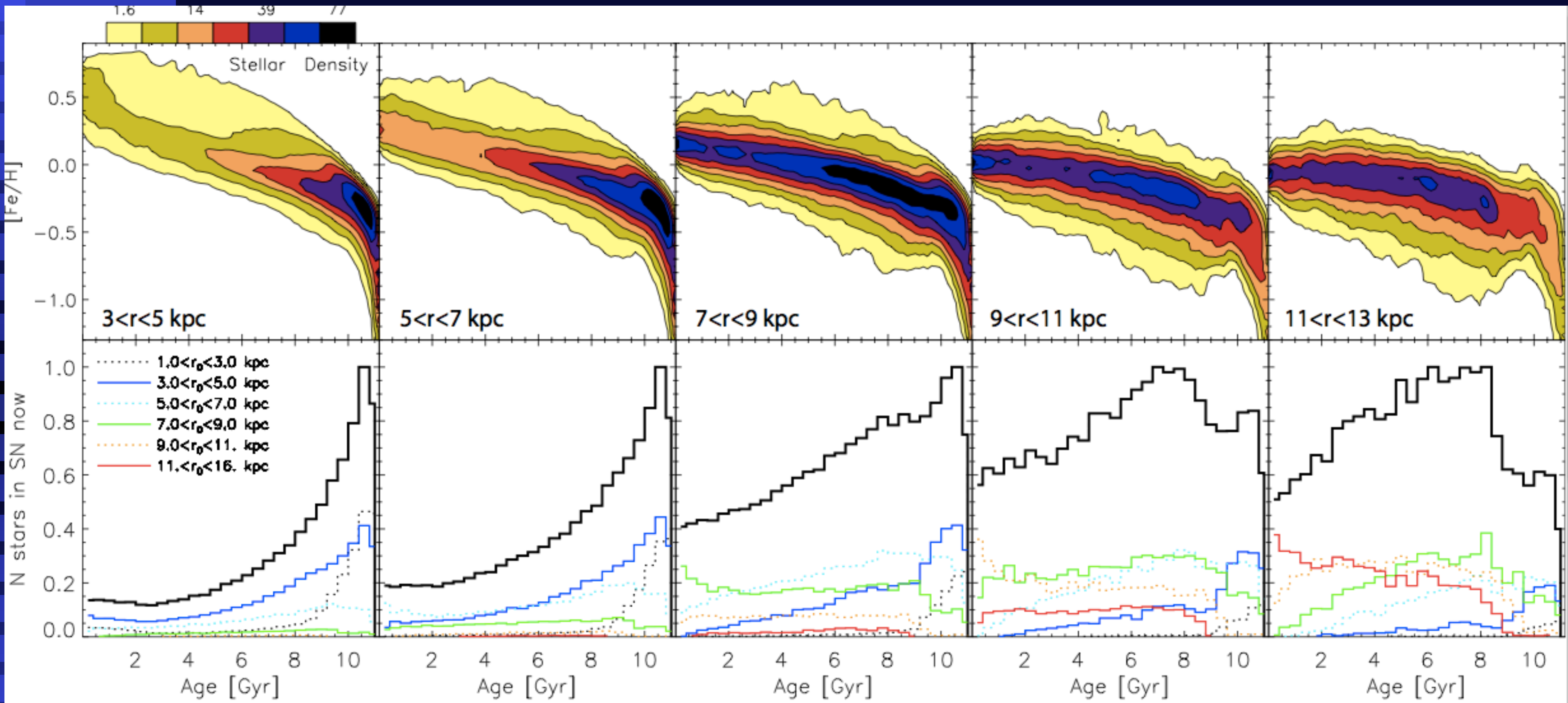


MDF gets narrower towards outer disk – lost of metal rich tail
Peak does not change much, age populations overlap towards outer disk



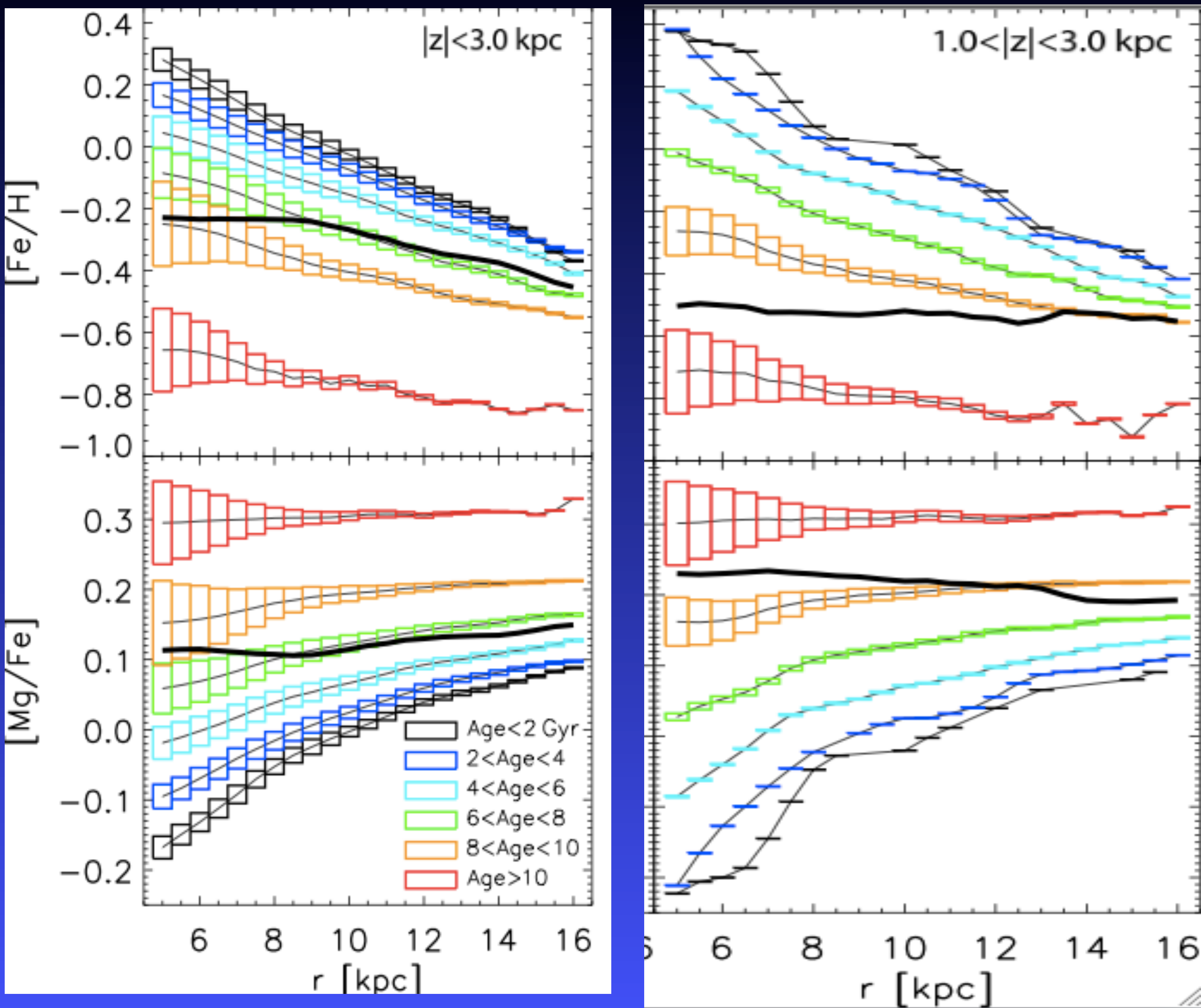
“high-alphas” contribution decreases towards outer disk

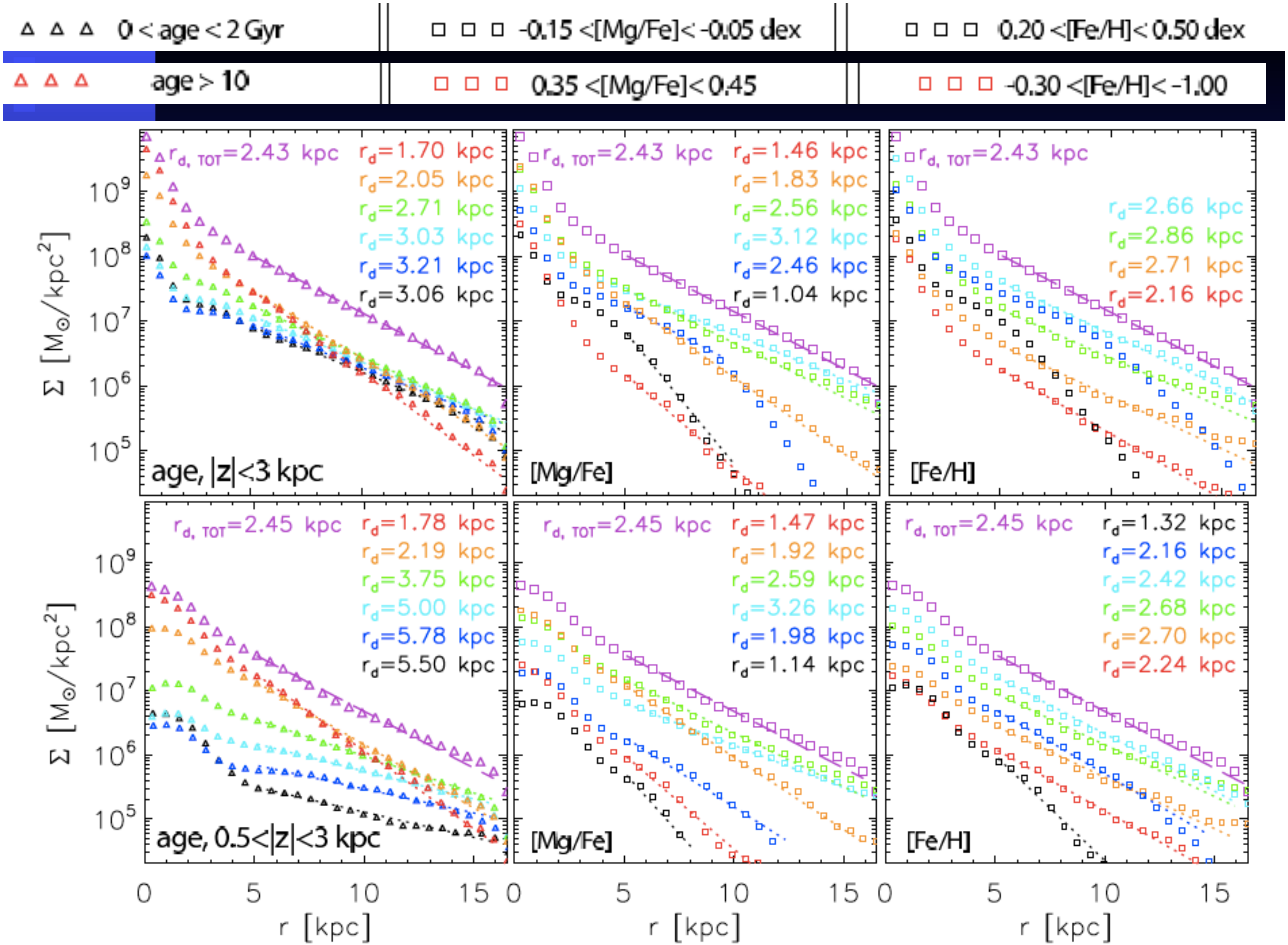
The properties at different places in the disk: AMR



Prediction: AMR Scatter increases towards outer regions

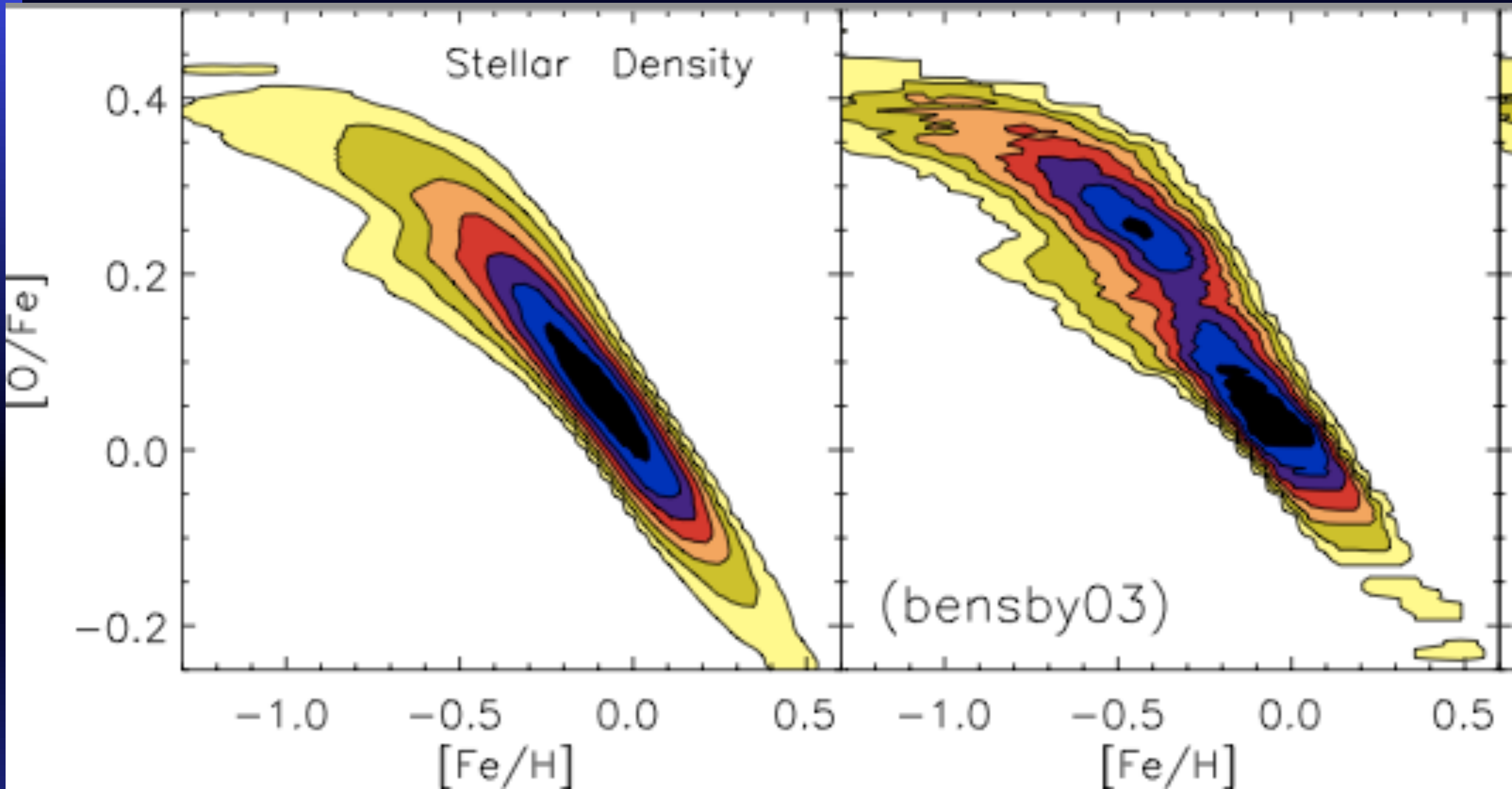
Gradients – Model Prediction





0 < age < 2 Gyr
age > 10
-0.15 <[Mg/Fe]< -0.05 dex
0.35 <[Mg/Fe]< 0.45
0.20 <[Fe/H]< 0.50 dex
-0.30 <[Fe/H]< -1.00
r_d, TOT=2.43 kpc
r_d=1.70 kpc
r_d=2.05 kpc
r_d=2.71 kpc
r_d=3.03 kpc
r_d=3.21 kpc
r_d=3.06 kpc
age, |z|<3 kpc
r_d, TOT=2.43 kpc
r_d=1.46 kpc
r_d=1.83 kpc
r_d=2.56 kpc
r_d=3.12 kpc
r_d=2.46 kpc
r_d=1.04 kpc
[Mg/Fe]
r_d, TOT=2.43 kpc
r_d=2.66 kpc
r_d=2.86 kpc
r_d=2.71 kpc
r_d=2.16 kpc
[Fe/H]
r_d, TOT=2.45 kpc
r_d=1.78 kpc
r_d=2.19 kpc
r_d=3.75 kpc
r_d=5.00 kpc
r_d=5.78 kpc
r_d=5.50 kpc
age, 0.5<|z|<3 kpc
r_d, TOT=2.45 kpc
r_d=1.47 kpc
r_d=1.92 kpc
r_d=2.59 kpc
r_d=3.26 kpc
r_d=1.98 kpc
r_d=1.14 kpc
[Mg/Fe]
r_d, TOT=2.45 kpc
r_d=1.32 kpc
r_d=2.16 kpc
r_d=2.42 kpc
r_d=2.68 kpc
r_d=2.70 kpc
r_d=2.24 kpc
[Fe/H]
Σ [M⊙/kpc²]
10⁹
10⁸
10⁷
10⁶
10⁵
0
5
10
15
r [kpc]

Selection effects can create discontinuity in [O/Fe] plot

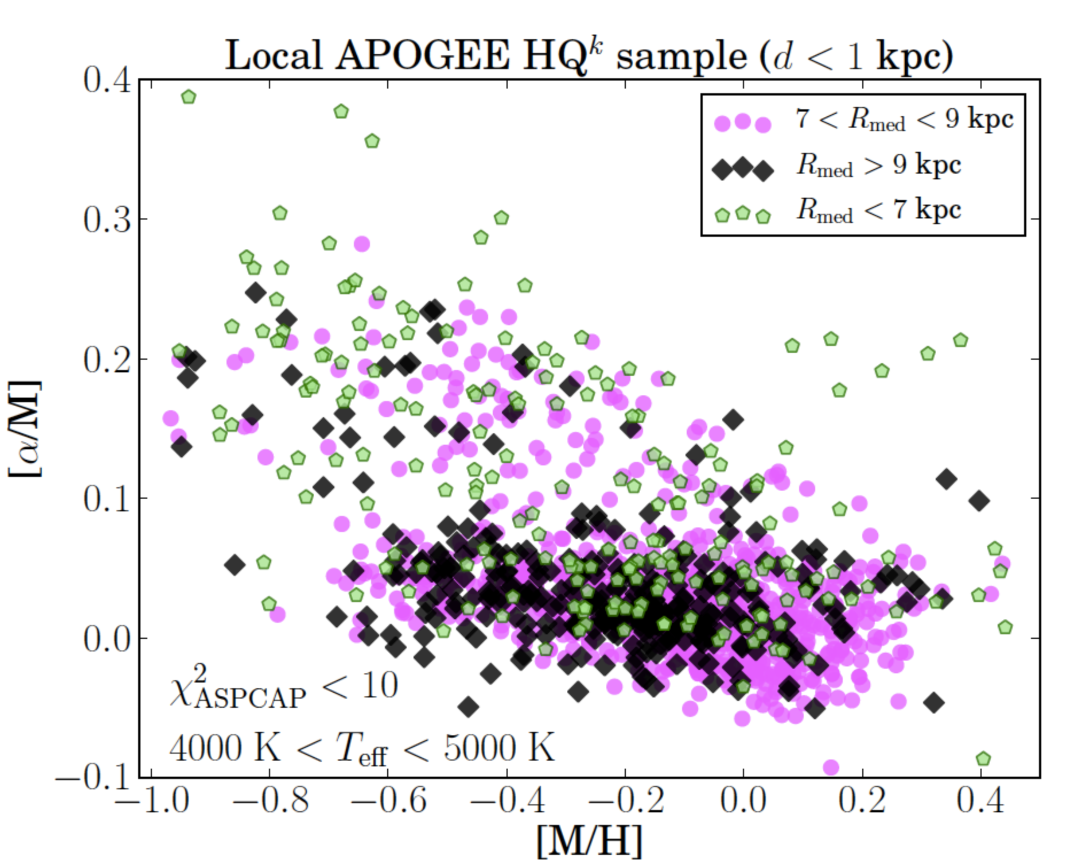


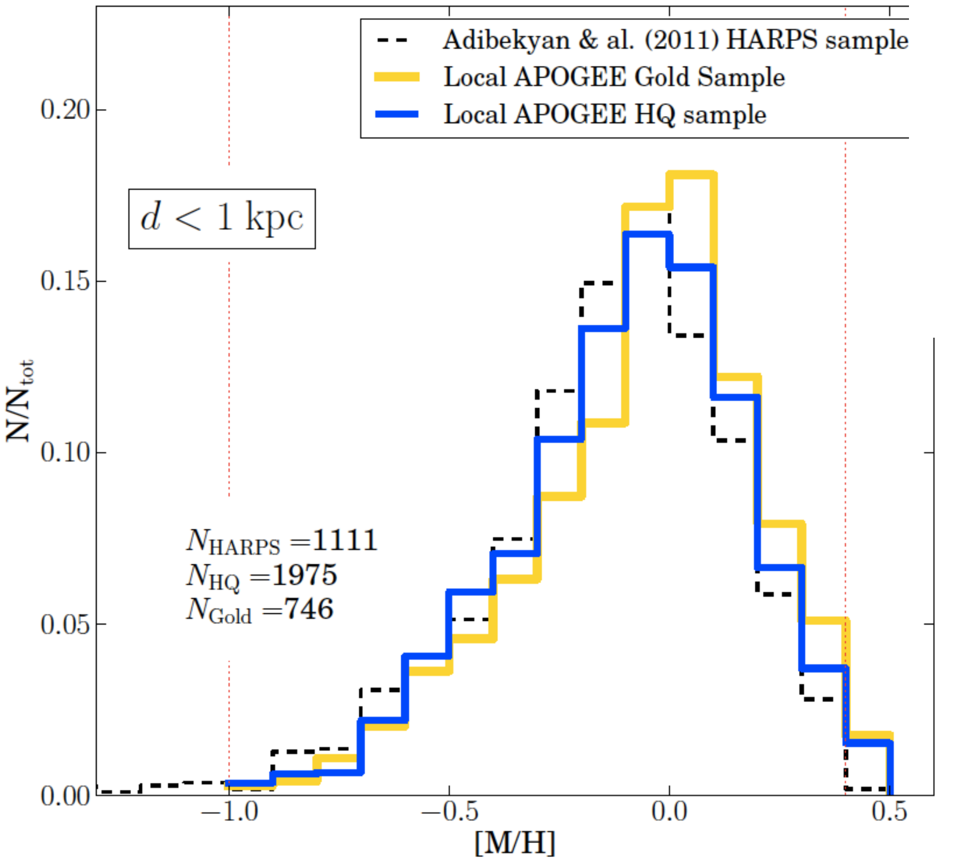
Probability membership to either "Thick" and "Thin" velocity ellipsoids

Is the bimodality in the [Fe/H]-[O/Fe] plane due to selection effects?

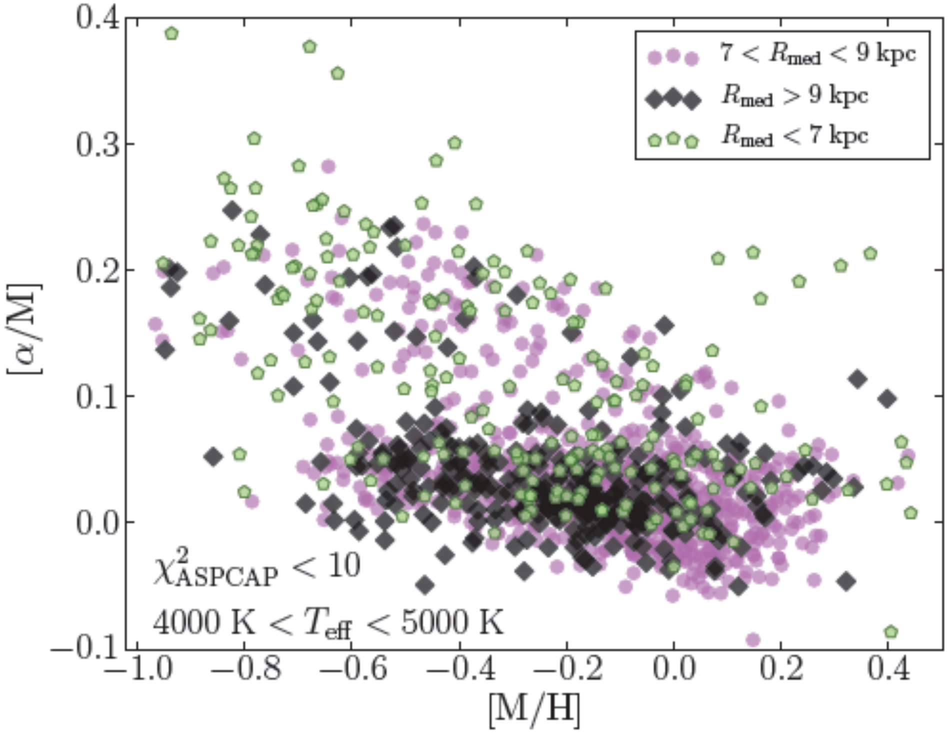
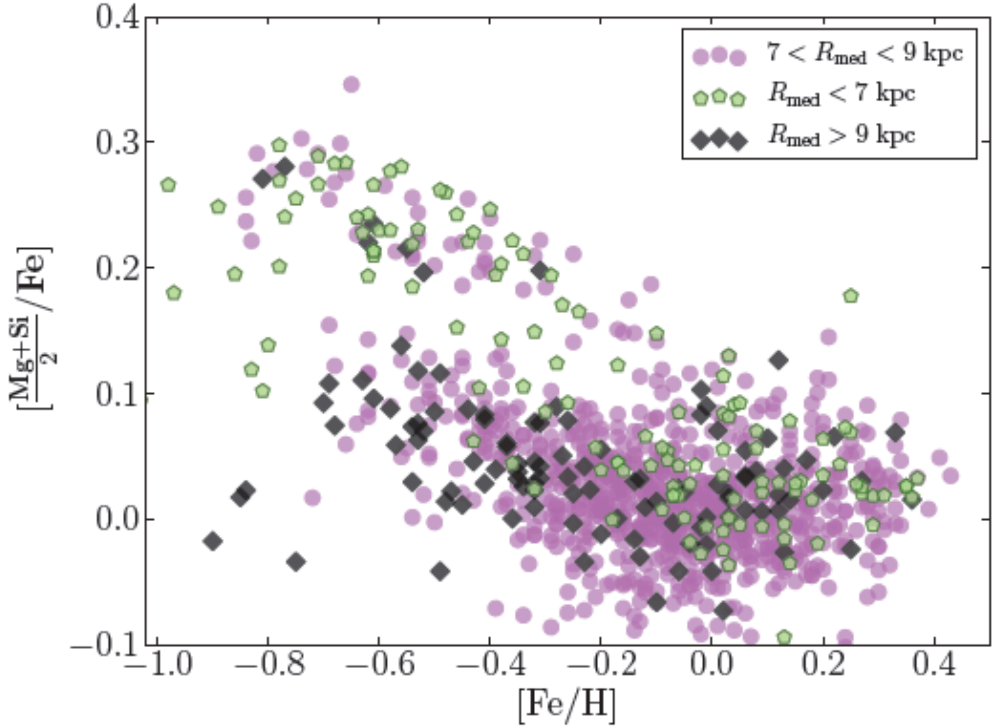
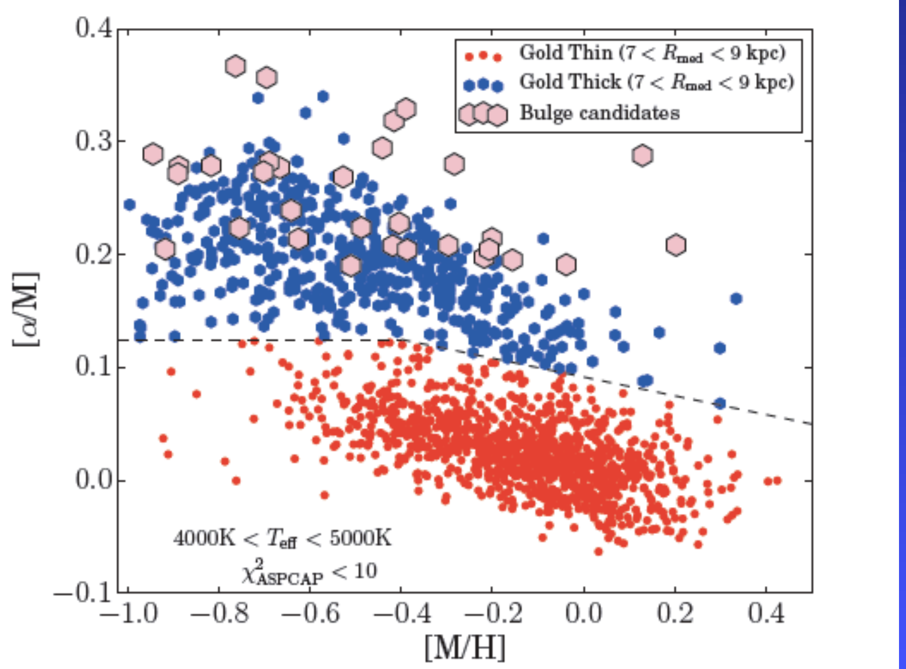
Local Volume as seeing by APOGEE
Comparison with HARPS sample

Despite different selection biases, optical v.s IR, both are similar

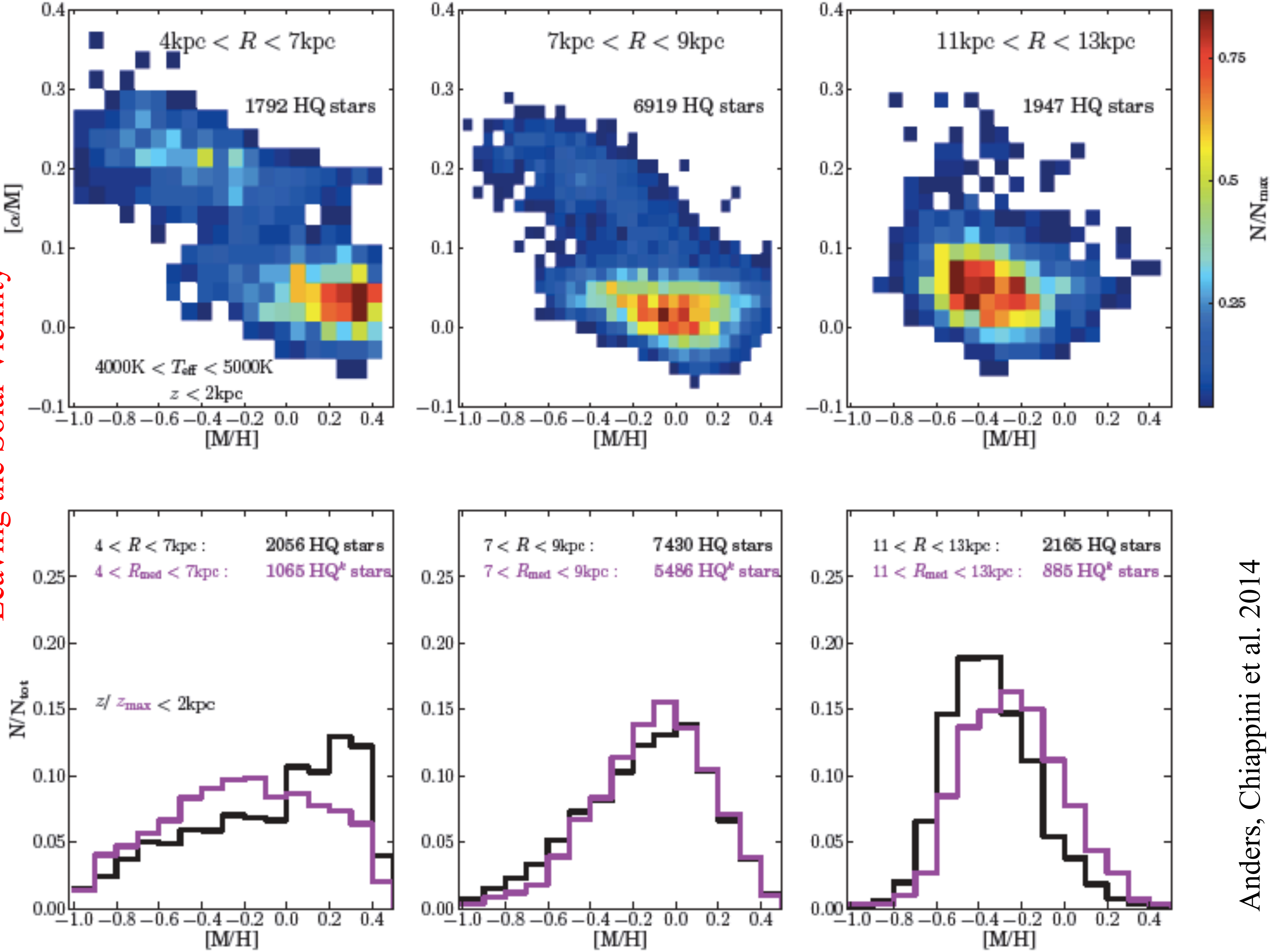




Anders, Chiappini et al. 2014

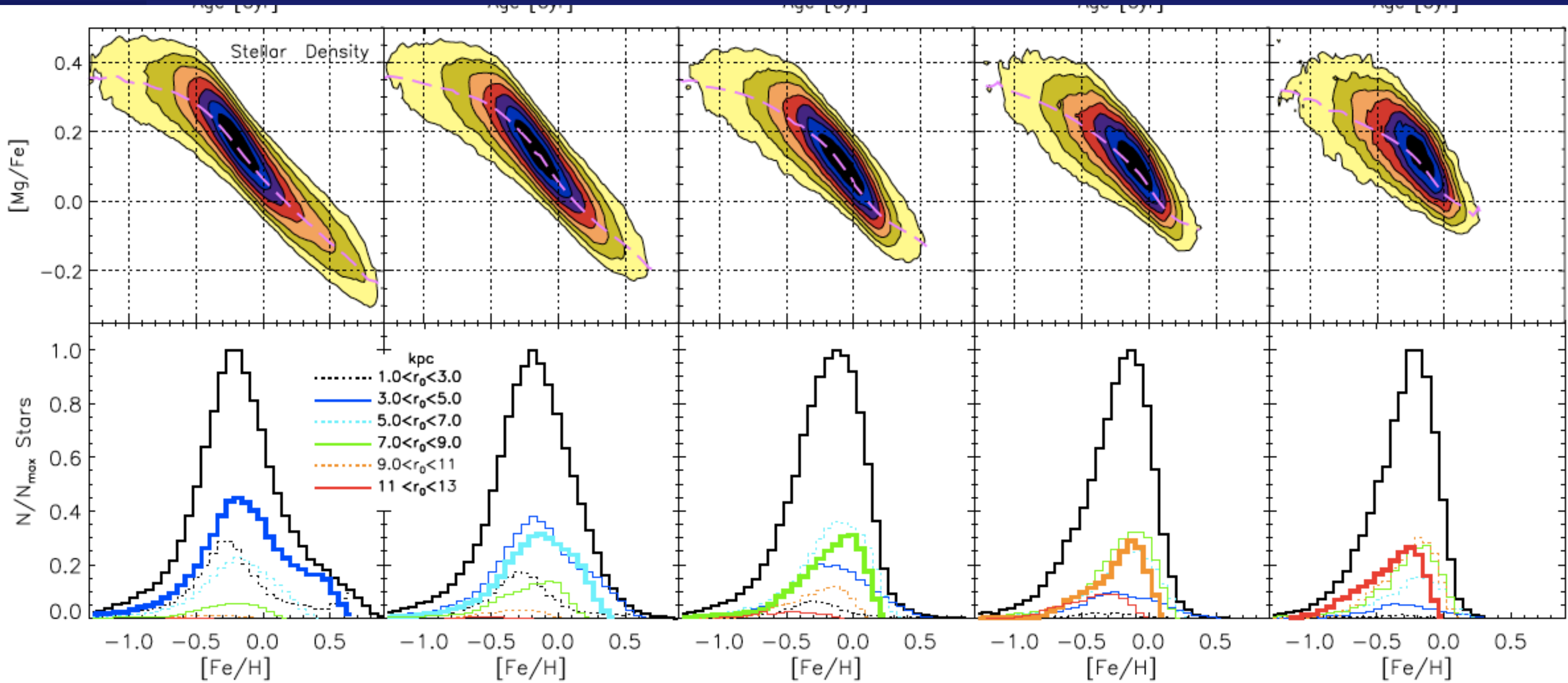

$7 < R_{\rm med} < 9$ kpc
$R_{\rm med} > 9$ kpc
$R_{\rm med} < 7$ kpc
$\chi^2_{\rm ASPCAP} < 10$
4000 K $< T_{\rm eff} <$ 5000 K
[α/M]
[M/H]

$7 < R_{\rm med} < 9$ kpc
$R_{\rm med} < 7$ kpc
$R_{\rm med} > 9$ kpc
$[\frac{\rm Mg+Si}{2}/\rm Fe]$
[Fe/H]

Gold Thin ($7 < R_{\rm med} < 9$ kpc)
Gold Thick ($7 < R_{\rm med} < 9$ kpc)
Bulge candidates
4000K $< T_{\rm eff} <$ 5000K
$\chi^2_{\rm ASPCAP} < 10$
[α/M]
[M/H]

Leaving the Solar Vicinity



Anders, Chiappini et al. 2014

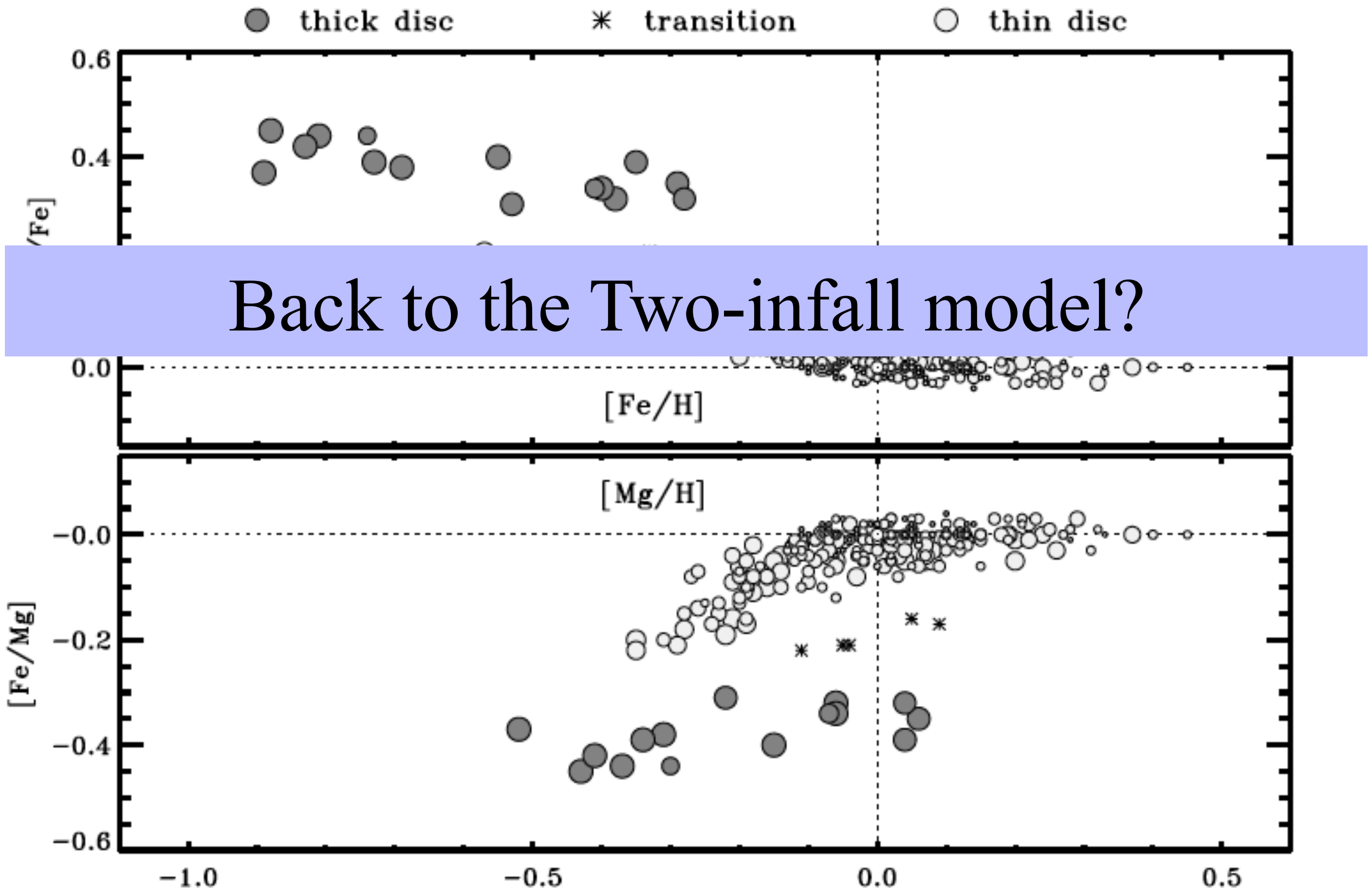
But no gap?



Stellar Density
[Mg/Fe]
N/N$_{max}$ Stars
kpc
1.0<r$_0$<3.0
3.0<r$_0$<5.0
5.0<r$_0$<7.0
7.0<r$_0$<9.0
9.0<r$_0$<11
11 <r$_0$<13
[Fe/H]

If not all samples are biased, is the gap real?!

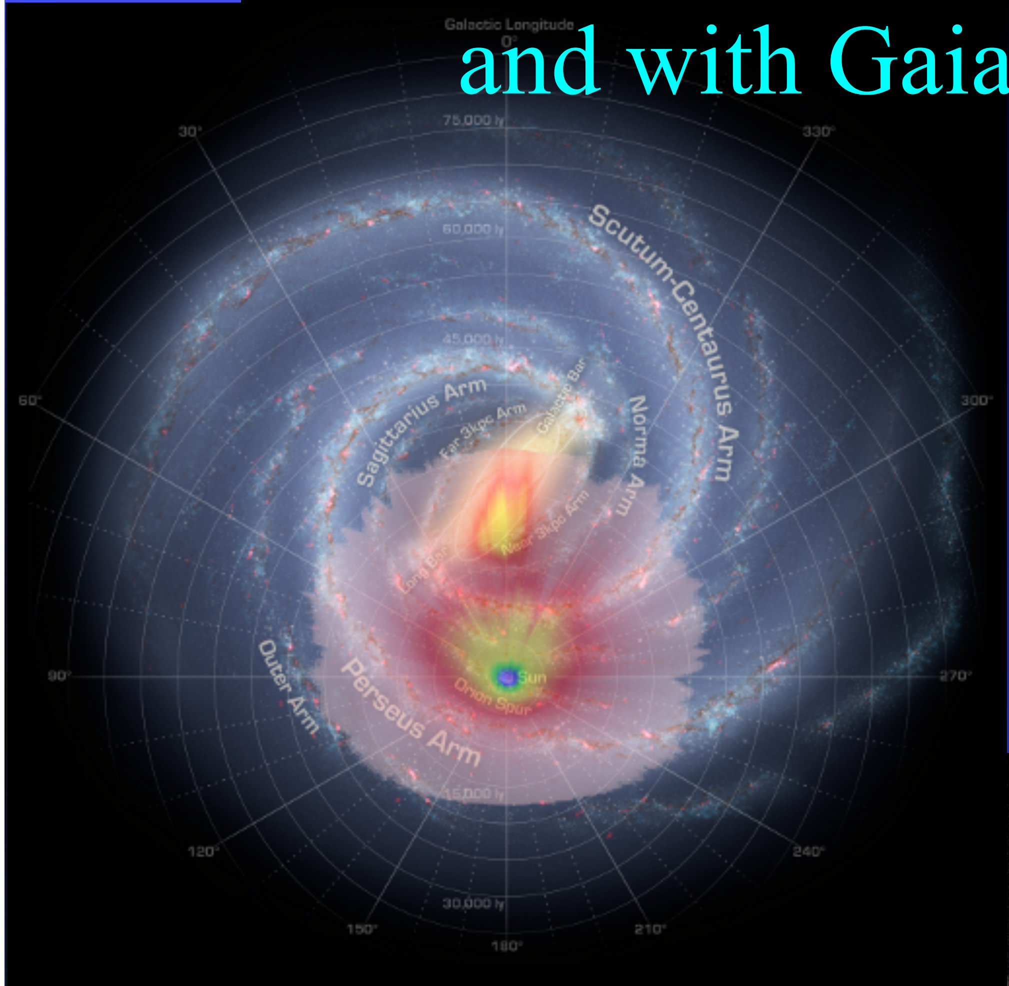
Fuhrmann 2011



Back to the Two-infall model?

Figure 15. The local, volume-complete perspective on the magnesium and iron abundances of 271 F-, G- and K-type stars. Upper panel: [Mg/Fe] versus [Fe/H]; lower panel: the same data, but with the α-chain element magnesium as reference. Circle diameters are in proportion to the stellar age estimates. This chemical map portrays the imprint of a huge star formation gap that subdivides the extremely old ($\tau \geq 12$ Gyr) thick-disc stars in a fairly flat abundance distribution from the much younger and well-displaced thin-disc stars ($\tau \leq 8$ Gyr) in a curved string-of-pearl-like distribution. Only five objects dubbed as transition stars display intermediate characteristics.

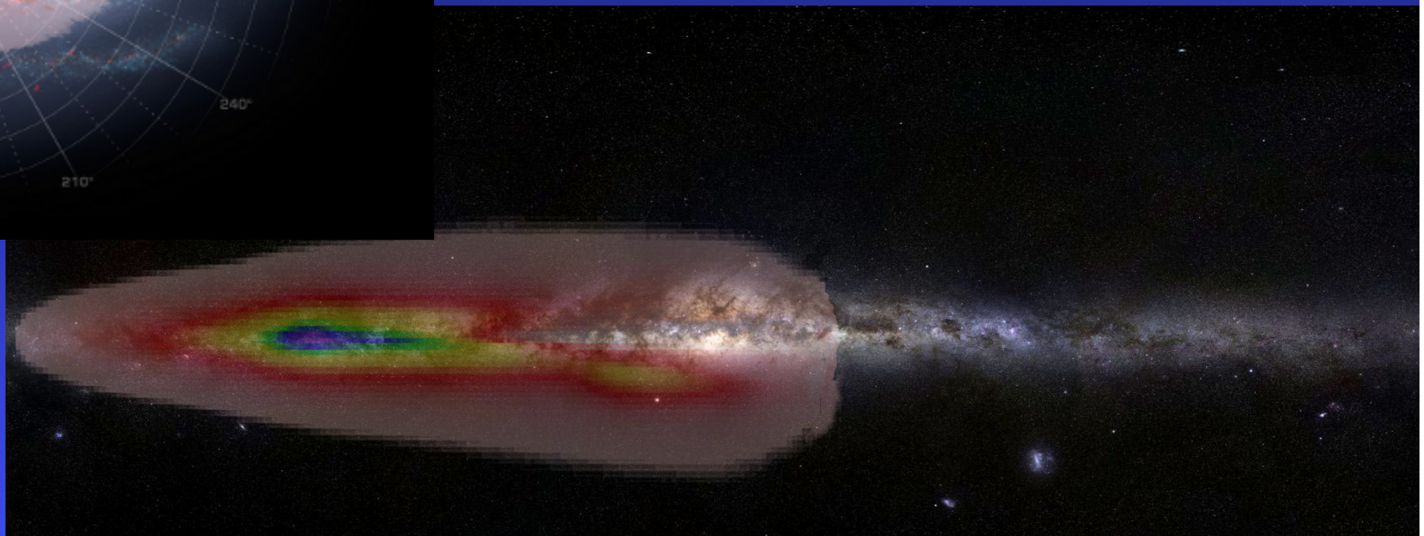
and with Gaia & 4MOST…



PI. R. de Jong (AIP)

Chiappini: Project Scientist (2011-2013)
Now: Sofia Feltzing + Richard MacMahom

Chiappini et al. 2013, Science Report (~90pp)



- 4MOST Phase A Review (May 2013); Approved for Phase B (mid-2013)
- First light 2020 -> > 10 million targets in the disk!

Take home message:

GOLD ERA FOR GALACTIC ARCHAEOLOGY: NEAR FIELD COSMOLOGY

- Stars observed "here" are combination of stars born hot + radial migration bringing contribution of old stars from inner radii
- The MW "thick disc" emerges naturally from (i) stars born with high velocity dispersions at high redshift, (ii) stars migrating from the inner disc early on due to strong merger activity, and (iii) further radial migration driven by the bar and spirals at later times
- The older population has the properties of what has been called "thick disk", but not a clear gap in chemical plane
- If you apply to the particles similar "observational biases" you get chemical discontinuity, but there are samples that seem to be free of biases and still show a gap! (e.g. Fuhrmann's, Gaia-ESO, HARPS, APOGEE)
- For now we are using [alpha/Fe] as proxy for age. Tighter constraints will come once we could use ages, even just in large bins (asteroseismology)
- Plan: to use all these new constraints to improve models, make mocks with the N-body simulation as "seen" by the different surveys

Workshop: “Reconstructing the Milky Way’s history: spectroscopic Surveys, Asteroseismology and chemodynamical models”, June 1-5 2015
Physics Center Bad Honnef - Bonn – Germany

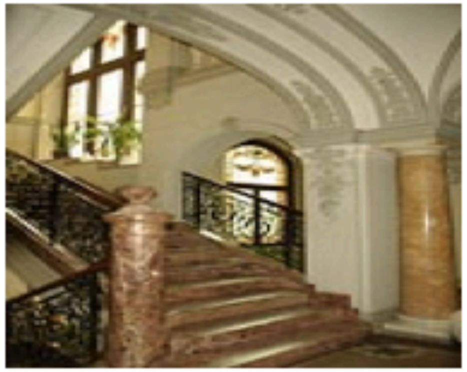








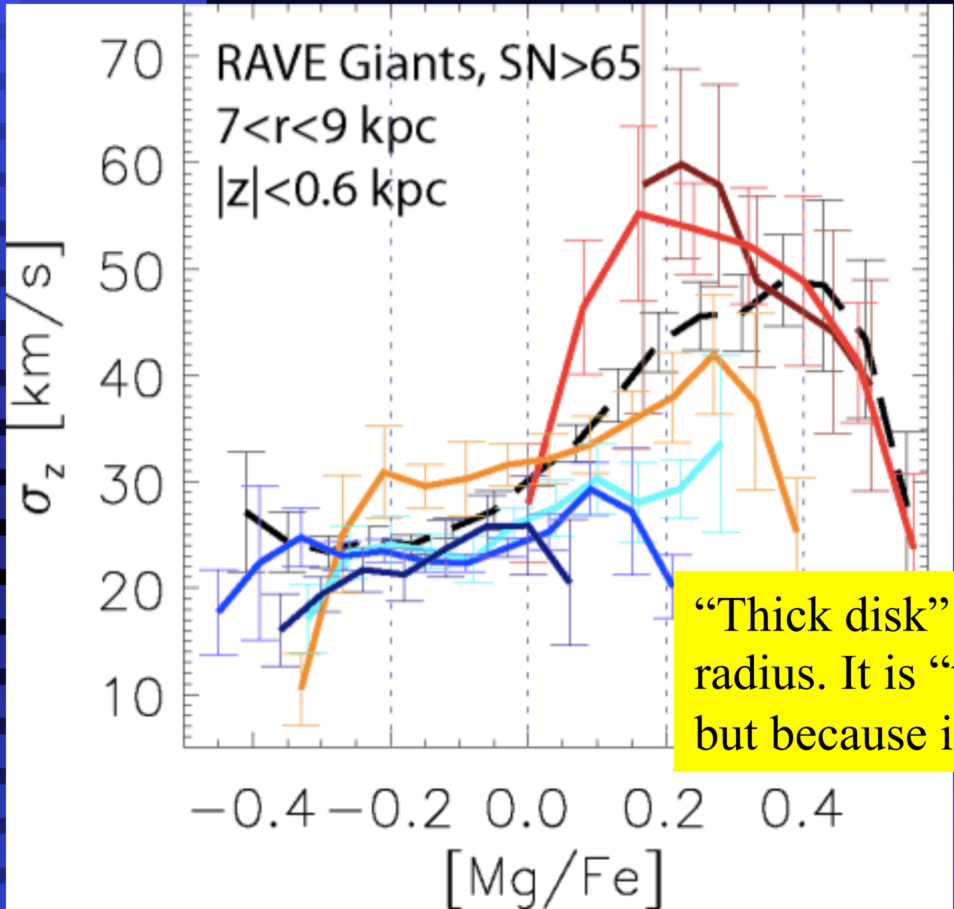


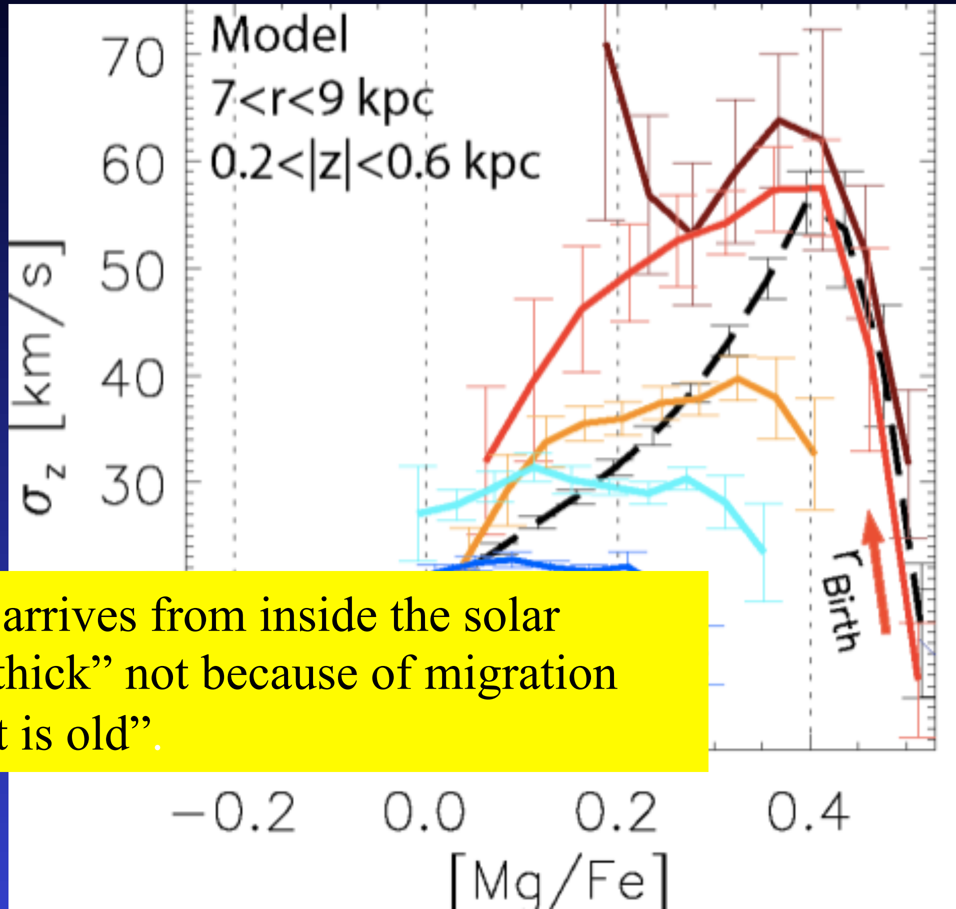



EXTRAS

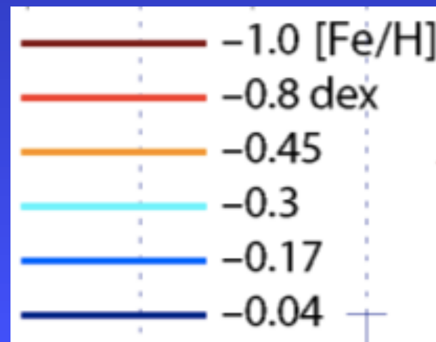
RAVE

MCM MODEL



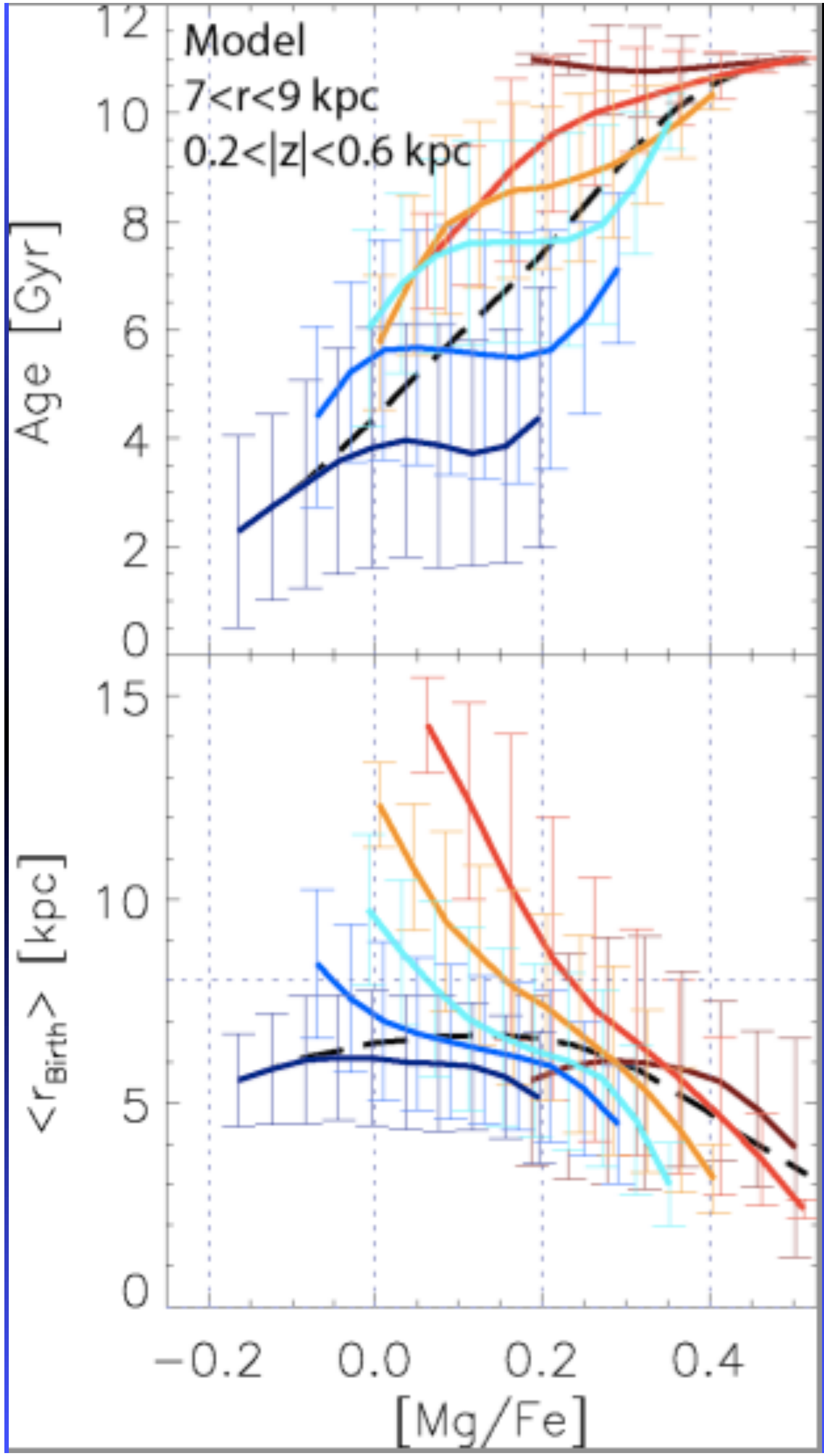


"Thick disk" arrives from inside the solar radius. It is "thick" not because of migration but because it is old".



We found unexpected behavior in the velocity dispersion of a sample of RAVE giants: it decreases strongly for stars with [Mg/Fe]~0.4 dex (i.e., those that formed in the first Gyr of the Galaxy's life).

Minchev, Chiappini, Martig +R AVE collaboration, ApJL 2014



These findings can be explained by perturbations from massive mergers in the early Universe and the subsequent radial migration of stars with cooler kinematics from the inner disc:

During mergers (early on) stars migrating outwards arrive significantly colder than the in-situ population

How much enrichment from t_{sun} to t_{now}?

Table 5: Comparison of the proto-solar abundances from the present work and Grevesse & Sauval (1998) with those in nearby B stars and H II regions. The solar values given here include the effects of diffusion (Turcotte & Wimmer-Schweingruber 2002) as discussed in Sect. 3.11. The H II numbers include the estimated elemental fractions tied up in dust; the dust corrections for Mg, Si and Fe are very large and thus too uncertain to provide meaningful values here. Also given in the last column is the predicted Galactic chemical enrichment (GCE) over the past 4.56 Gyr.

Elem.	Sun[a]	Sun[b]	B stars[c]	H II[d]	GCE[e]
He	10.98 ± 0.01	10.98 ± 0.01	10.98 ± 0.02	10.96 ± 0.01	0.01
C	8.56 ± 0.06	8.46 ± 0.05	8.32 ± 0.03	8.66 ± 0.06	0.06
N	7.96 ± 0.06	7.87 ± 0.05	7.76 ± 0.05	7.85 ± 0.06	0.08
O	8.87 ± 0.06	8.74 ± 0.05	8.76 ± 0.03	8.80 ± 0.04	0.04
Ne	8.12 ± 0.06	7.98 ± 0.10	8.08 ± 0.03	8.00 ± 0.08	0.04
Mg	7.62 ± 0.05	7.62 ± 0.04	7.56 ± 0.05		0.04
Si	7.59 ± 0.05	7.55 ± 0.04	7.50 ± 0.02		0.08
S	7.37 ± 0.11	7.19 ± 0.04	7.21 ± 0.13	7.30 ± 0.04	0.09
Ar	6.44 ± 0.06	6.44 ± 0.13	6.66 ± 0.06	6.62 ± 0.06	
Fe	7.55 ± 0.05	7.55 ± 0.04	7.44 ± 0.04		0.14

[a] Grevesse & Sauval (1998) [b] Present work [c] Przybilla, Nieva & Butler (2008), Morel et al. (2006), Lanz et al. (2008) [d] Esteban et al. (2005, 2004), García-Rojas & Esteban (2007) [e] Chiappini, Romano & Matteucci (2003).

Asplund et al. 2009

Chemical gradients in the Milky Way from the RAVE data

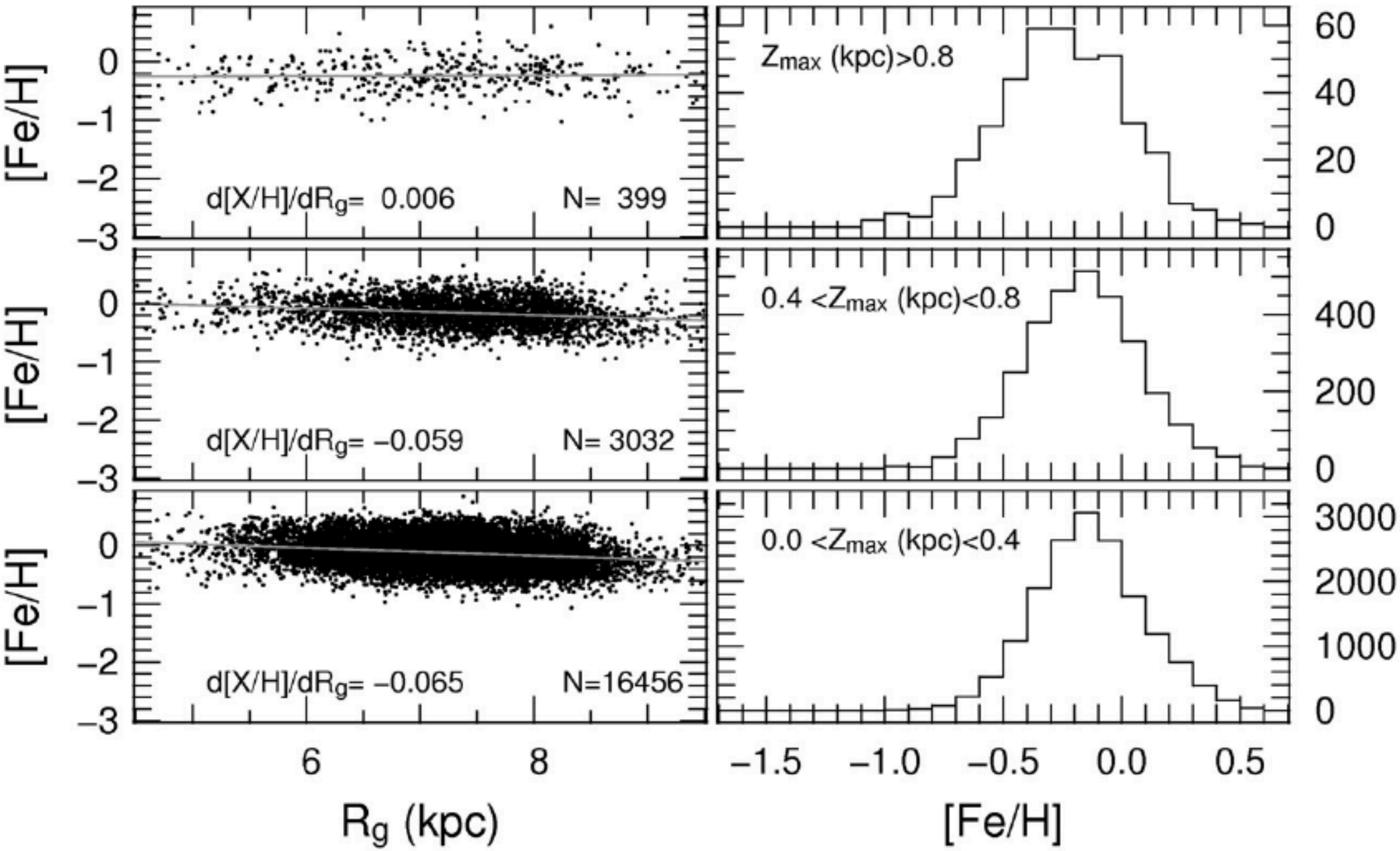
I. Dwarf stars

A&A 559, A59 (2013)

C. Boeche[1,2], A. Siebert[3], T. Piffl[2], A. Just[1], M. Steinmetz[2], S. Sharma[4], G. Kordopatis[5], G. Gilmore[5], C. Chiappini[2], M. Williams[2], E. K. Grebel[1], J. Bland-Hawthorn[4], B. K. Gibson[6,7], U. Munari[8], A. Siviero[9,2], O. Bienaymé[3], J. F. Navarro[10], Q. A. Parker[11,12,13], W. Reid[12], G. M. Seabroke[14], F. G. Watson[13], R. F. G. Wyse[15], and T. Zwitter[16,17]

RAVE

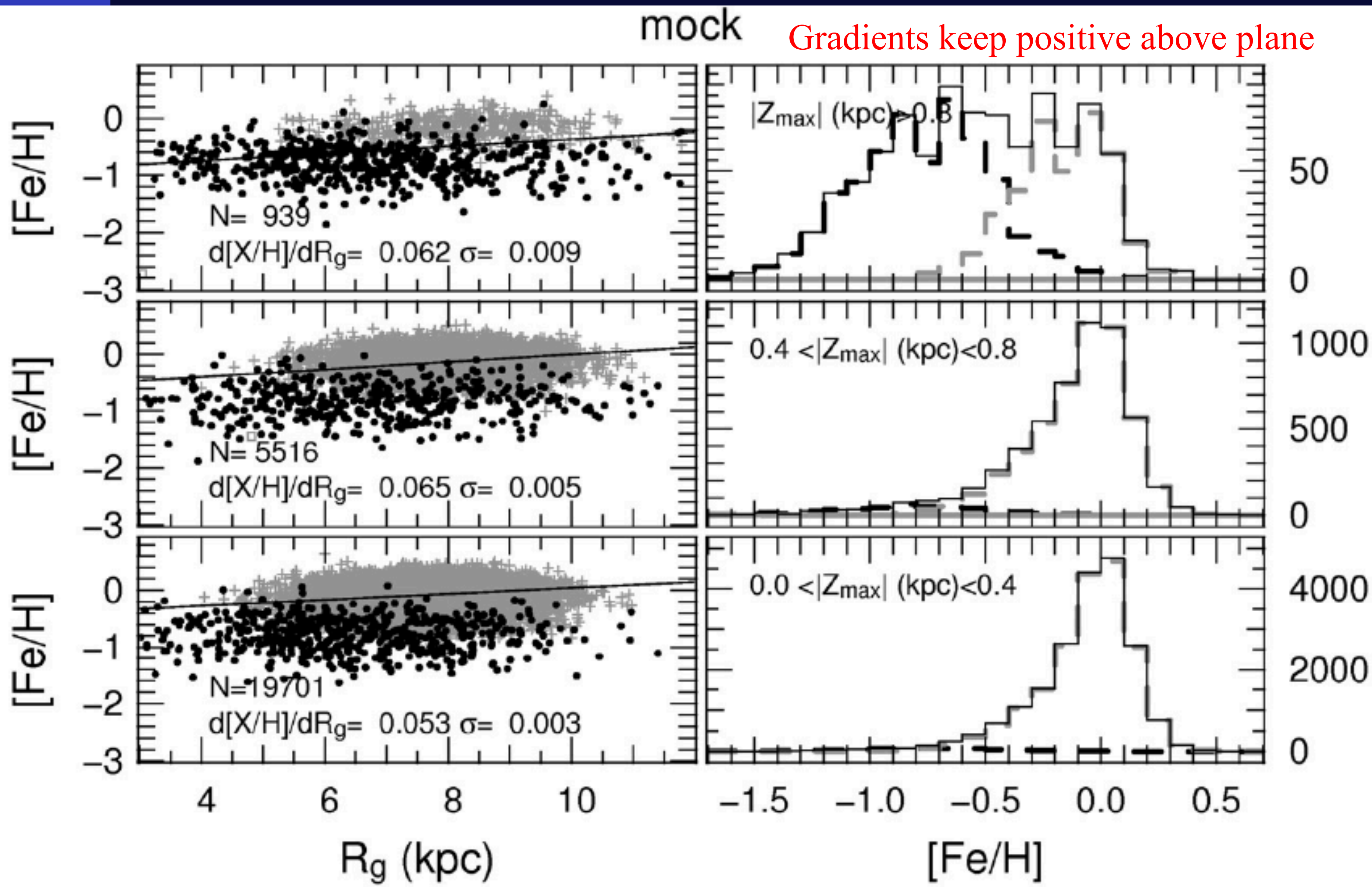
Gradients flatten with height above plane



Mock Sample – with GALAXIA-Besancon

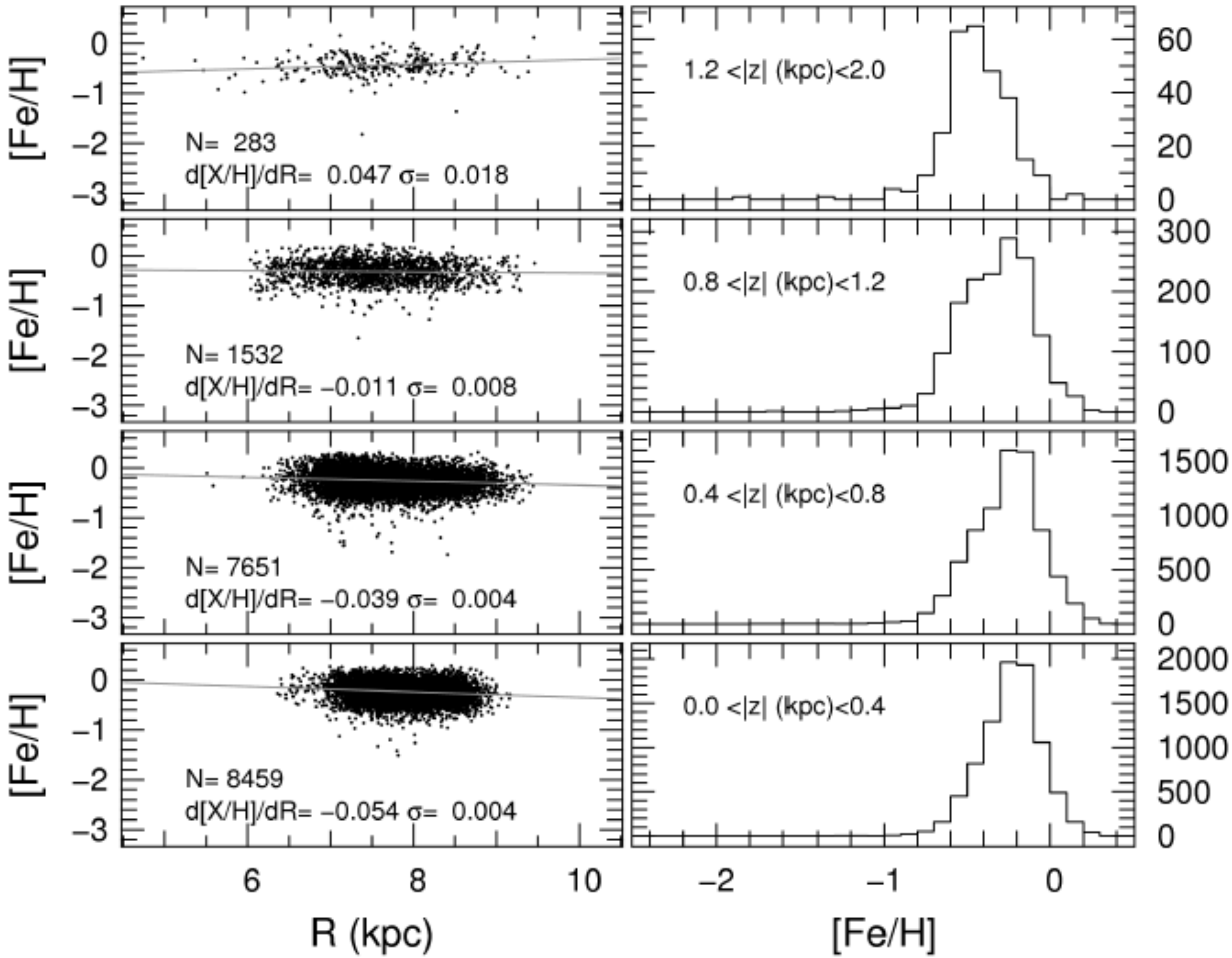
These huge datasets offer important constraints both for synthetic models and chemodynamical models
But in synthetic models -> lack correlation between chemistry and kinematics

Gradients keep positive above plane



Chemical gradients in the Milky Way from the RAVE data.
II. Giant stars

Boeche et al. (A&A Submitted)



Mock Sample – with GALAXIA-Besancon

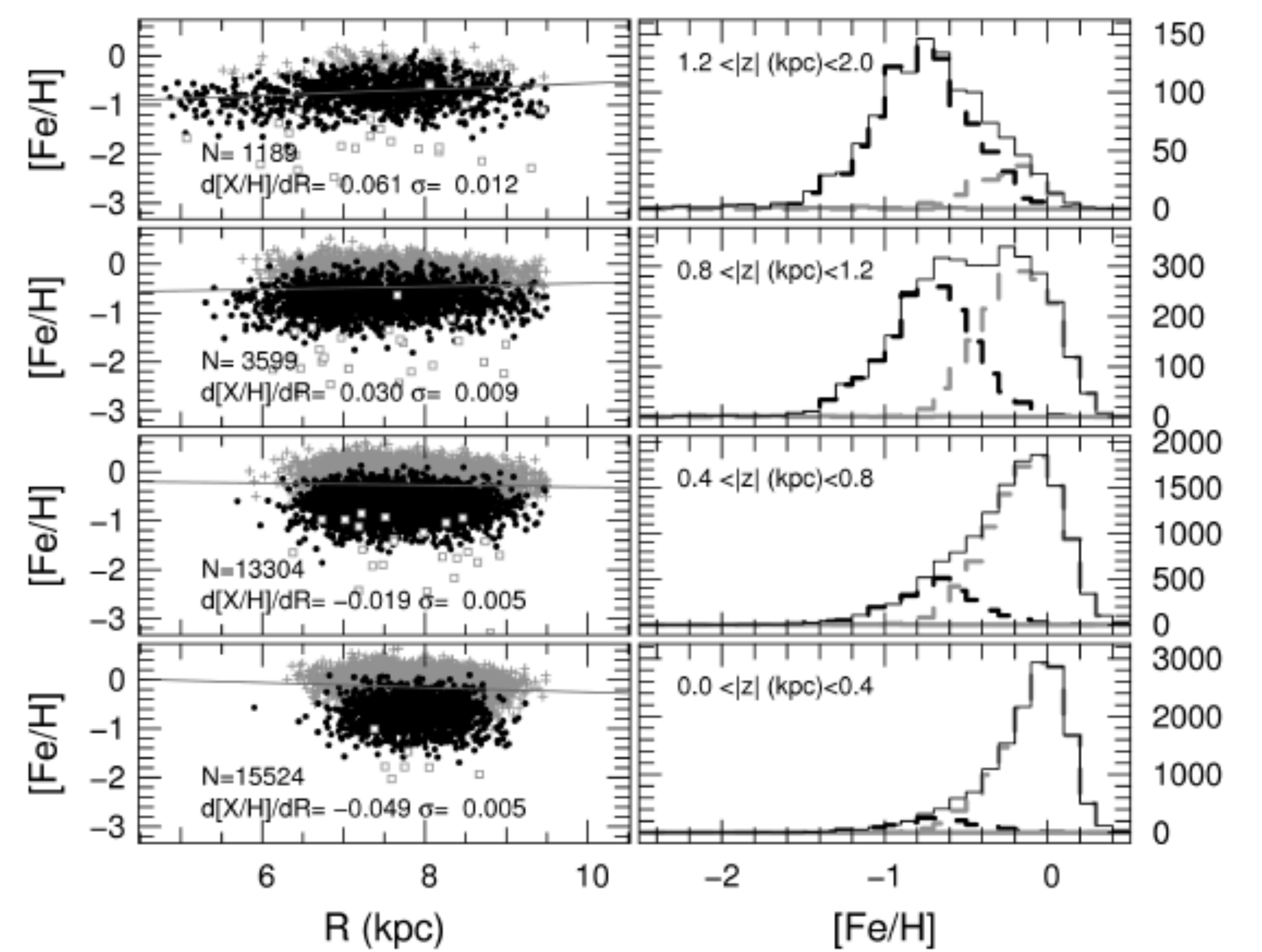


Table 3. Radial [Fe/H][a] gradients with respect to the orbital guiding radius[b] in the range $6 < R_g < 11$ kpc, for four ranges of z_{max}.

$\frac{d[Fe/H]}{dR_g}$ [dex/kpc]	APOGEE HQ[k]	APOGEE Gold	GCS dwarfs[c]	RAVE dwarfs[a]
$0.0 \le z_{max}$ [kpc] < 0.4	-0.066 ± 0.006	-0.074 ± 0.010	-0.043 ± 0.004	-0.065 ± 0.003
$0.4 \le z_{max}$ [kpc] < 0.8	-0.041 ± 0.004	-0.038 ± 0.008	-0.008 ± 0.011	-0.059 ± 0.005
$0.8 \le z_{max}$ [kpc] < 1.5	$+0.000 \pm 0.004$	$+0.026 \pm 0.008$	$+0.056 \pm 0.019$	$+0.006 \pm 0.015$
$1.5 \le z_{max}$ [kpc] < 3.0	$+0.052 \pm 0.004$	$+0.049 \pm 0.008$	–	–

Table 4. Radial [α/Fe][a] gradients with respect to the orbital guiding radius[b] in the range $6 < R_g < 11$ kpc, for four ranges of z_{max}.

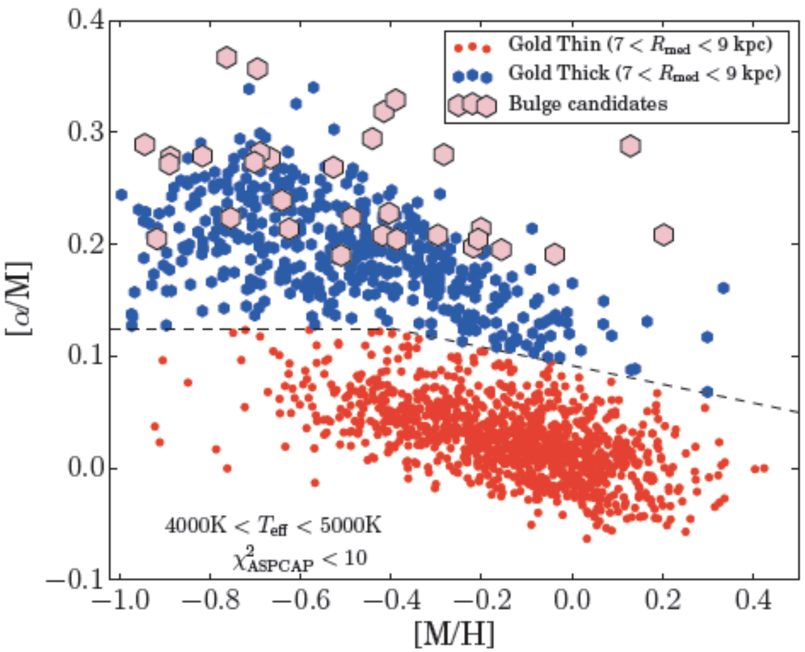
$\frac{d[\alpha/Fe]}{dR_g}$ [dex/kpc]	APOGEE HQ[k]	APOGEE Gold	GCS dwarfs[c]	RAVE dwarfs[a]
$0.0 \le z_{max}$ [kpc] < 0.4	-0.005 ± 0.001	-0.005 ± 0.002	$+0.010 \pm 0.002$	-0.004 ± 0.001
$0.4 \le z_{max}$ [kpc] < 0.8	-0.009 ± 0.001	-0.007 ± 0.002	-0.006 ± 0.005	-0.005 ± 0.002
$0.8 \le z_{max}$ [kpc] < 1.5	-0.019 ± 0.001	-0.022 ± 0.002	-0.023 ± 0.007	-0.020 ± 0.005
$1.5 \le z_{max}$ [kpc] < 3.0	-0.031 ± 0.001	-0.023 ± 0.002	–	–

Anders, Chiappini et al. 2014

RAVE GIANTS – Boeche et al. 2014 (submitted)

	$\frac{d[Fe/H]}{dZ}$	$\frac{d[Mg/H]}{dZ}$	$\frac{d[Al/H]}{dZ}$	$\frac{d[Si/H]}{dZ}$	$\frac{d[Ti/H]}{dZ}$	$\frac{d[Fe/H]}{dZ}$ (mock)
$0.0 < \lvert Z\rvert$ (kpc)≤ 0.4	-0.050 ± 0.027	$+0.019 \pm 0.022$	$+0.045 \pm 0.030$	-0.088 ± 0.030	$+0.081 \pm 0.023$	-0.373 ± 0.031
$0.4 < \lvert Z\rvert$ (kpc)≤ 0.8	-0.087 ± 0.030	$+0.022 \pm 0.025$	-0.027 ± 0.034	-0.117 ± 0.033	$+0.076 \pm 0.023$	-0.409 ± 0.038
$0.8 < \lvert Z\rvert$ (kpc)≤ 1.2	-0.148 ± 0.073	-0.031 ± 0.061	-0.124 ± 0.075	-0.197 ± 0.078	$+0.010 \pm 0.055$	-0.536 ± 0.085
$1.2 < \lvert Z\rvert$ (kpc)< 2.0	-0.199 ± 0.070	$+0.041 \pm 0.096$	$+0.031 \pm 0.104$	-0.140 ± 0.096	-0.086 ± 0.068	-0.338 ± 0.083

	$\frac{d[Fe/H]}{dR}$	$\frac{d[Mg/H]}{dR}$	$\frac{d[Al/H]}{dR}$	$\frac{d[Si/H]}{dR}$	$\frac{d[Ti/H]}{dR}$	$\frac{d[Fe/H]}{dR}$ (mock)
$0.0 < \lvert Z\rvert$ (kpc)≤ 0.4	-0.054 ± 0.004	-0.034 ± 0.004	-0.035 ± 0.005	-0.064 ± 0.005	$+0.008 \pm 0.004$	-0.049 ± 0.006
$0.4 < \lvert Z\rvert$ (kpc)≤ 0.8	-0.039 ± 0.004	-0.031 ± 0.004	-0.032 ± 0.005	-0.046 ± 0.004	-0.005 ± 0.003	-0.019 ± 0.005
$0.8 < \lvert Z\rvert$ (kpc)≤ 1.2	-0.011 ± 0.008	-0.023 ± 0.007	-0.027 ± 0.009	-0.028 ± 0.008	-0.015 ± 0.006	$+0.030 \pm 0.009$
$1.2 < \lvert Z\rvert$ (kpc)< 2.0	$+0.047 \pm 0.018$	$+0.025 \pm 0.015$	$+0.060 \pm 0.022$	$+0.009 \pm 0.018$	$+0.032 \pm 0.017$	$+0.061 \pm 0.012$



Anders, Chiappini et al. 2014