Leibniz-Institut für
Astrophysik Potsdam

APOGEE, Archaeology, and Asteroseismology

LIneA Webinar, 10.03.2016

Friedrich Anders (AIP)

Cristina Chiappini, Thaíse Rodrigues, Benoit Mosser, Andrea Miglio,
Josefina Montalbán, Léo Girardi, Márica Valentini, Mathias Schultheis,
Basílio Santiago, Matthias Steinmetz,
BPG, APOGEE, & CoRoT collaborations

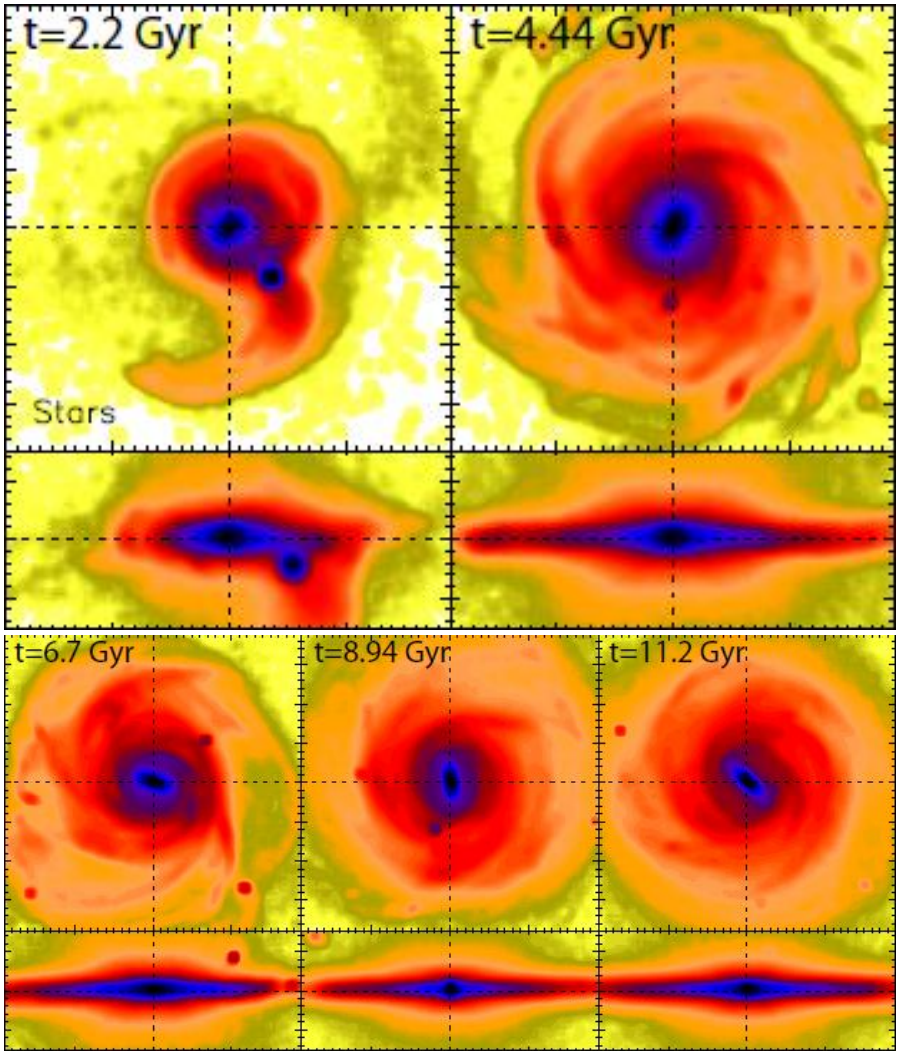
Outline

PhD thesis @ AIP/UP started 09/2013

C. Chiappini

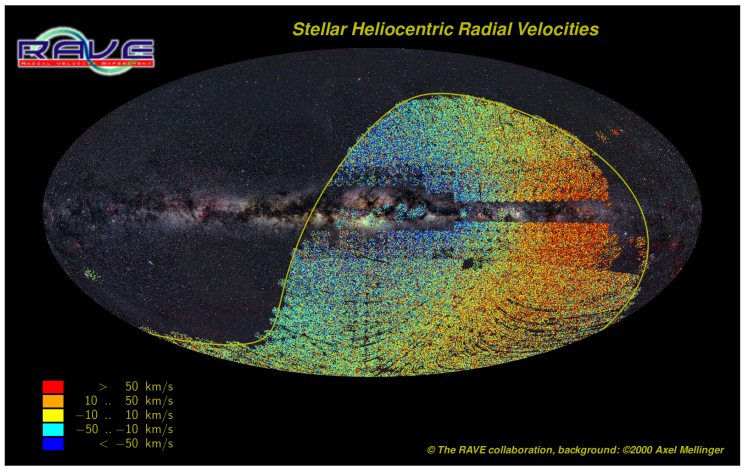
M. Steinmetz

Data vs. modern Milky Way simulations



Minchev, Chiappini, Martig (2013), A&A, arXiv:1208.1506

Radial velocity map from the RAVE survey.



Credit: The RAVE Collaboration; background image by A. Mellinger (2000).

Inside your coffee cup - An analogy

"Galactic Archaeology"

- Combination of Chemical evolution theory with Stellar Dynamics & Cosmology – *how did the MW form?*
- Use (semi-) empirical chemo-kinematical relations as well as forward modelling (Population synthesis, chemical evolution, pure dynamical + full chemodynamical models)
- Make use of spectral analysis, photometry & astrometry
- Main driver: Radial Migration – stars loose dynamical information about their birthplace
  (by interaction with the bar, the spiral arms, merging satellites, internal heating...)

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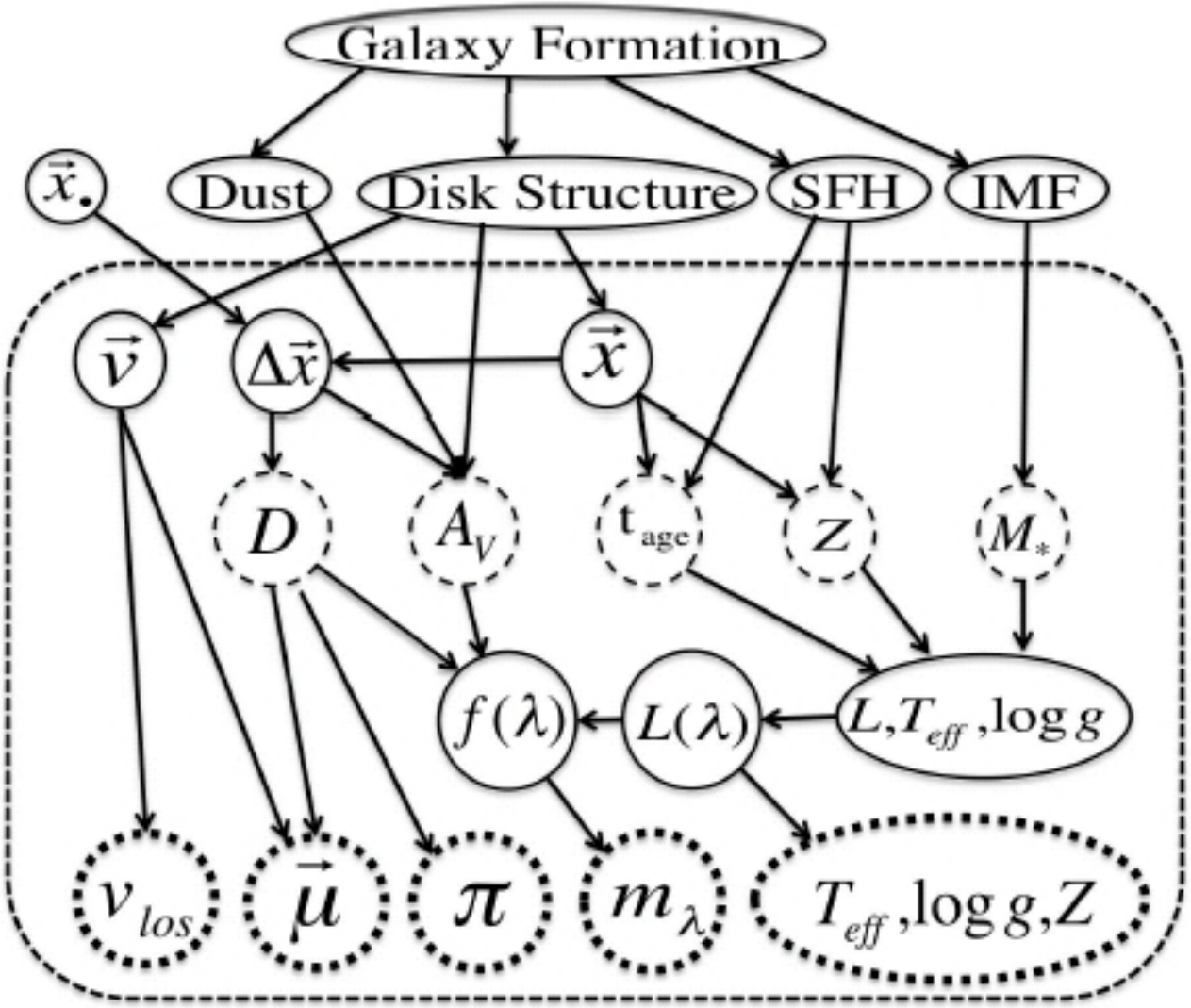
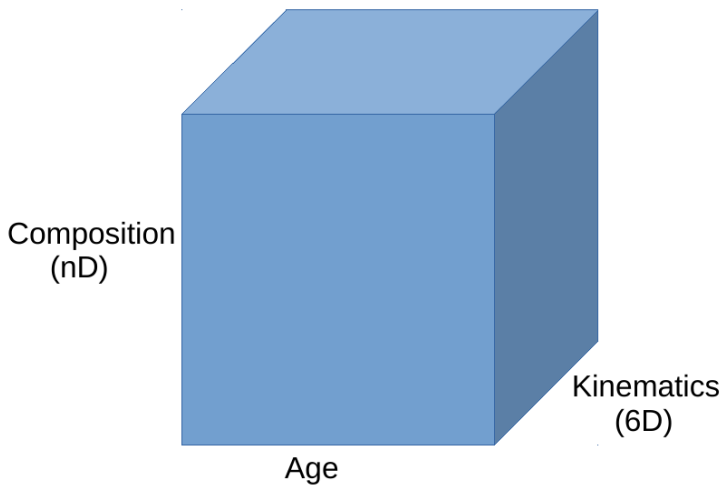
"Galactic Archaeology" – Stars as Time Capsules



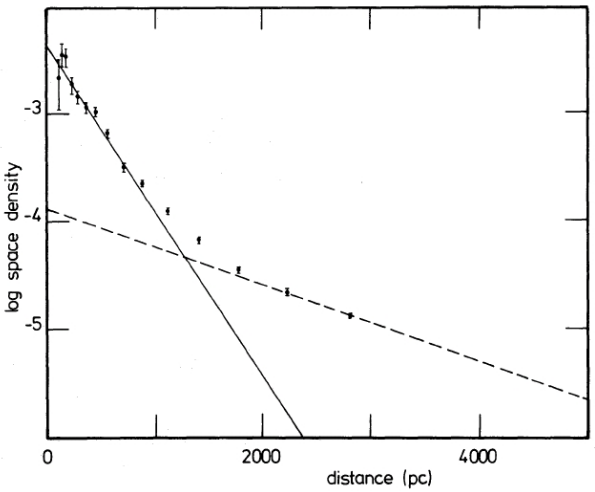
Rix & Bovy 2013, arXiv:1301.3168

Dissecting the Age-kinematics-abundance hypercube

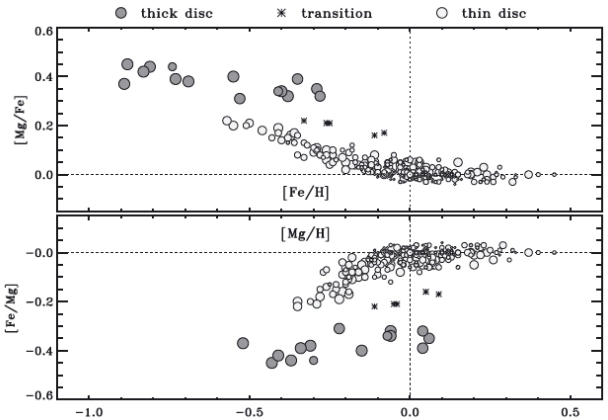


- Galactic models make predictions for the distribution of stars in this multi-dim. space (or its subspaces)
- Basic problem of Galactic Archaeology: dimensionality reduction
- *Look for the most robust and telling slices of this hypercube to constrain models for a given dataset*

Example: Thick & Thin Disc

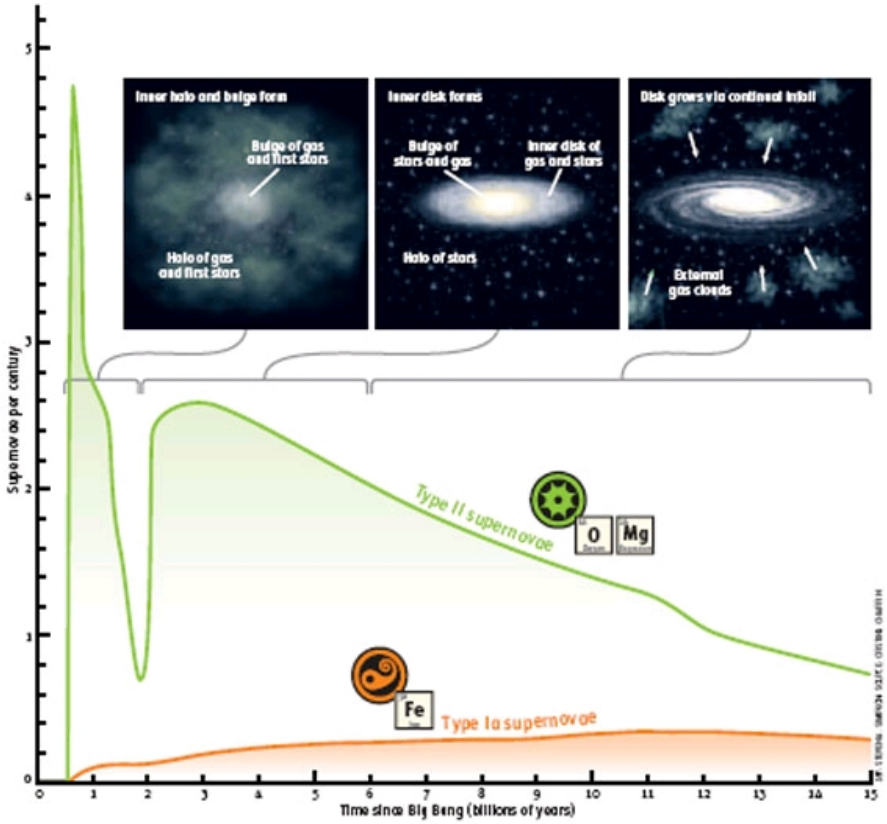


Gilmore & Reid (1983), MNRAS.



Fuhrmann (1998, 2001, 2004, 2005, 2011), MNRAS.

Thin & thick disc as two distinct formation epochs?

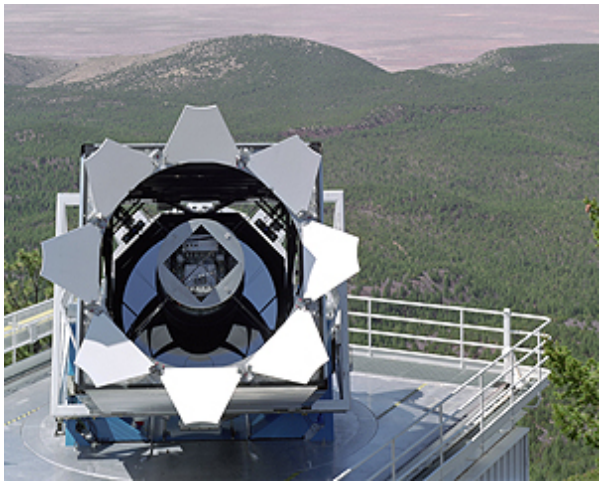


From Chiappini (2004), S&T.

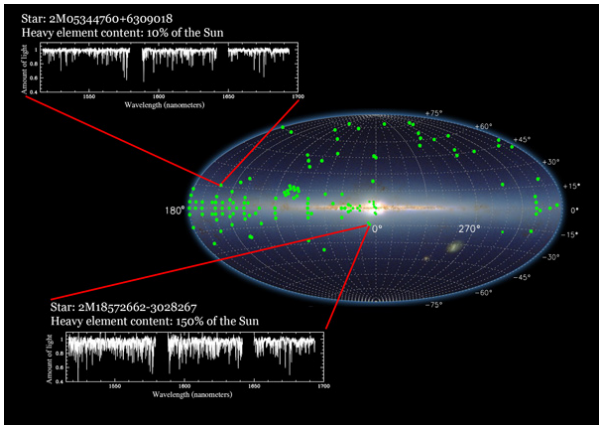
Spectroscopic stellar surveys

Survey	Period	Sky Area	# of Spectra	app. mags	$\sigma(v_{\rm los})$	σ([Fe/H])	char. dist.
GCS	1981-2000	South	16,000	$V \sim 10$	0.5 km/s	indiv.	0.003 kpc
RAVE	2003-2013	South	570,000	$I = 9 - 12$	3 km/s	0.2 dex	0.5 kpc
SEGUE	2004-2009	North	360,000	$g = 15 - 20$	8 km/s	0.2 dex	2 kpc
APOGEE	2011-2014	North	100,000	$H < 13.8$	0.5 km/s	indiv.	10 kpc
Gaia-ESO	2012-2015	South	150,000	$V < 18$	0.5 km/s	indiv.	4 kpc
LAMOST	2012-2018	North	3,000,000	$V < 18$	10 km/s	0.2 dex	4 kpc
Gaia	2013-2018	all sky	50,000,000	$V < 17$	10 km/s	0.25 dex	4 kpc

The SDSS-III/APOGEE survey



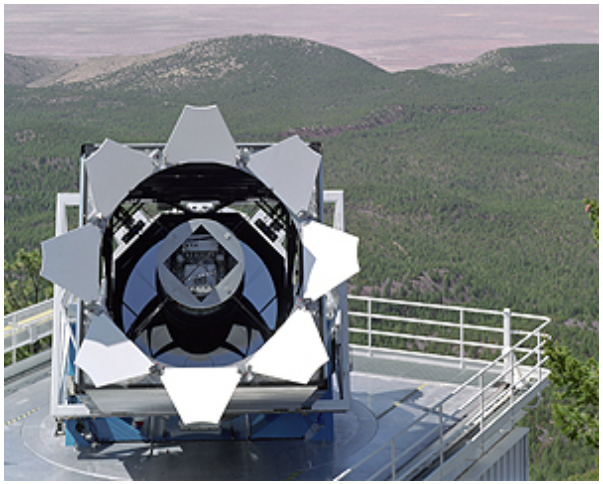
The SDSS Telescope at APO.



SDSS-III/DR10 press release. Credit: R. Schiavon & P. Frinchaboy.

- three-year spectroscopic survey at the 2.5m telescope at Apache Point Observatory
- first multi-object fiber spectrograph in the NIR ever
- high-resolution ($R \sim 22.500$) high signal-to-noise ($S/N \sim 100$ pixel^{-1}) spectra of red giant stars in the H band ($\lambda = 1.5 - 1.7 \mu m$)
- precise (~ 100 m/s) radial velocities & chemical abundances of up to 15 elements (0.1 dex precision)

The SDSS-III/APOGEE survey



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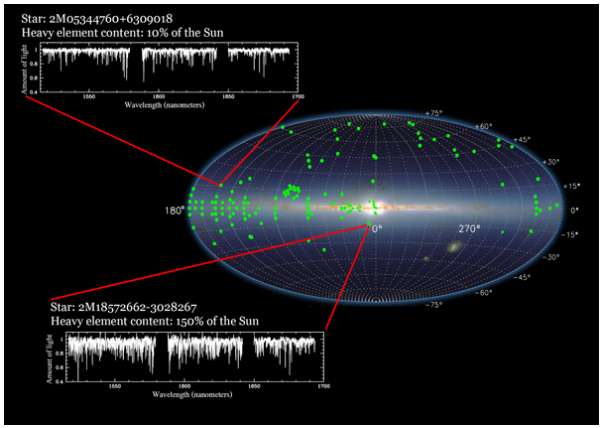

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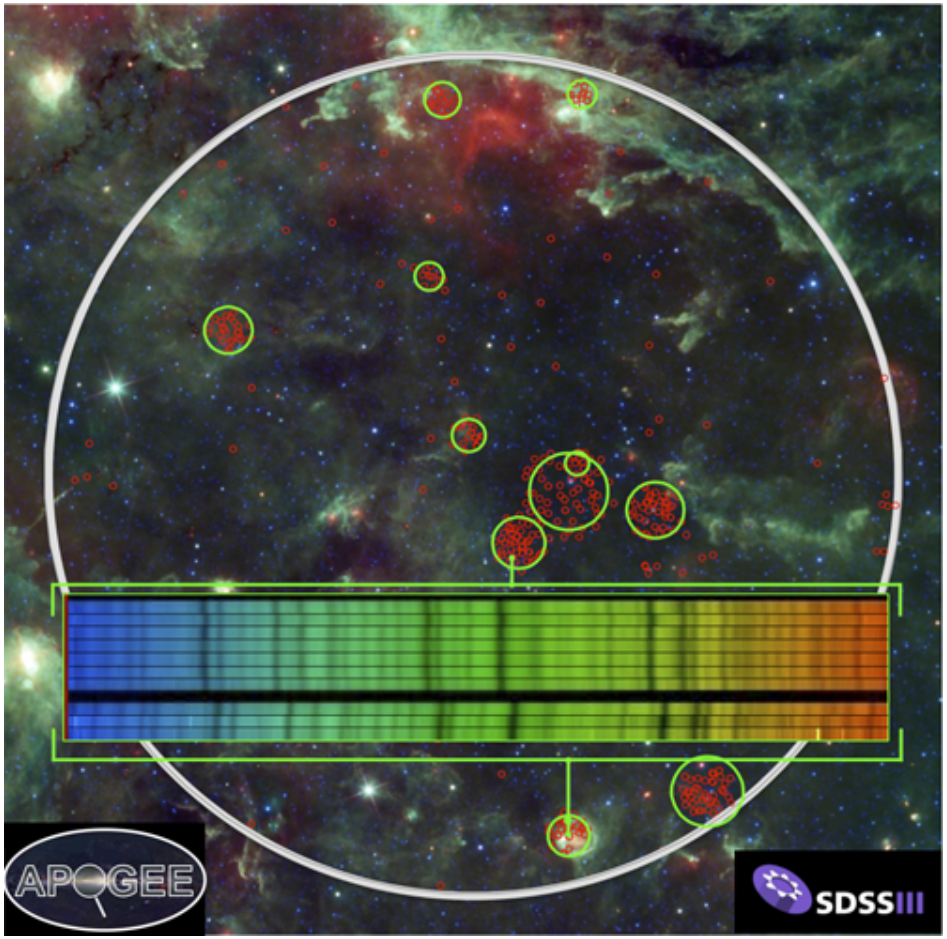
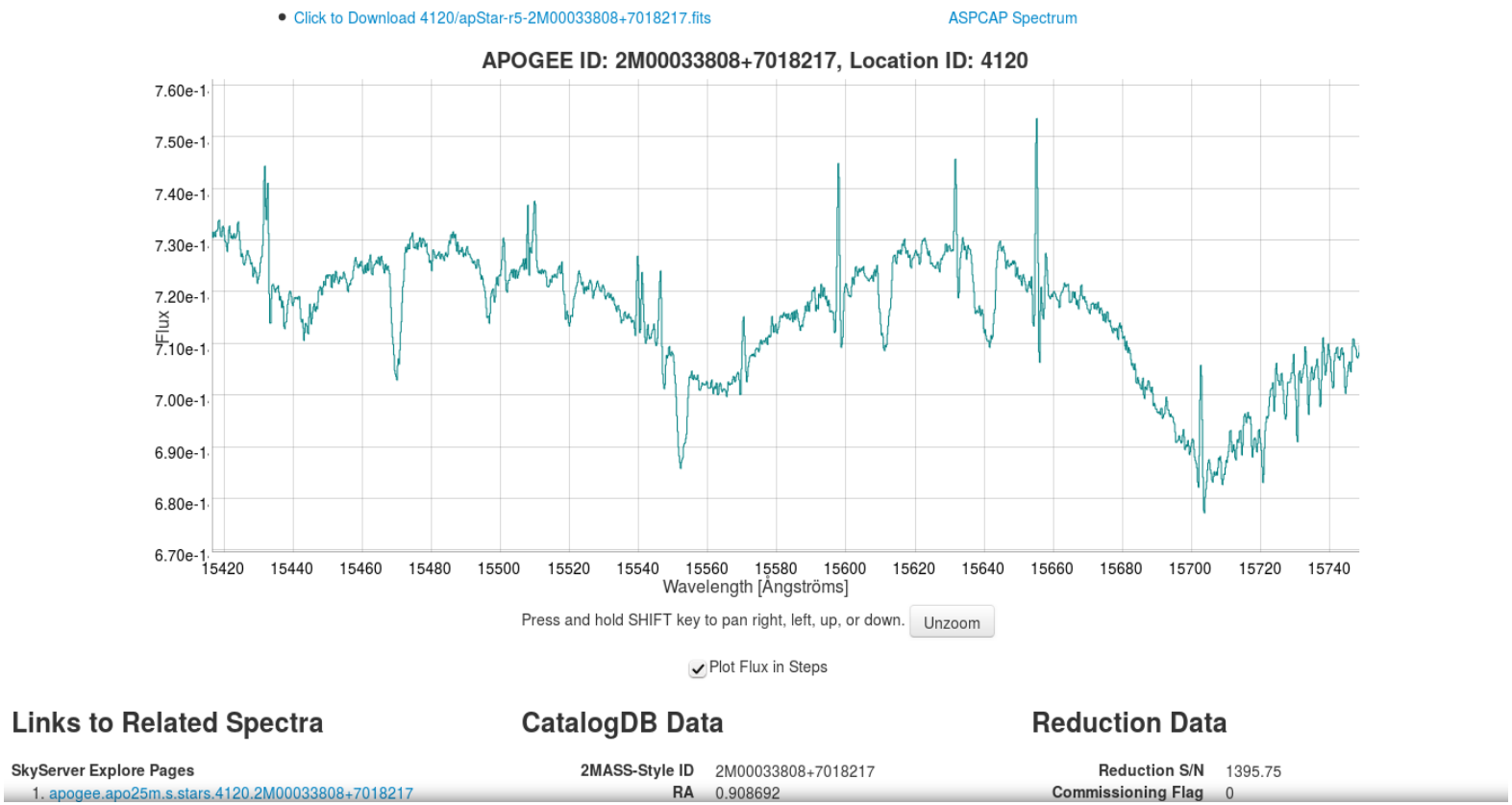


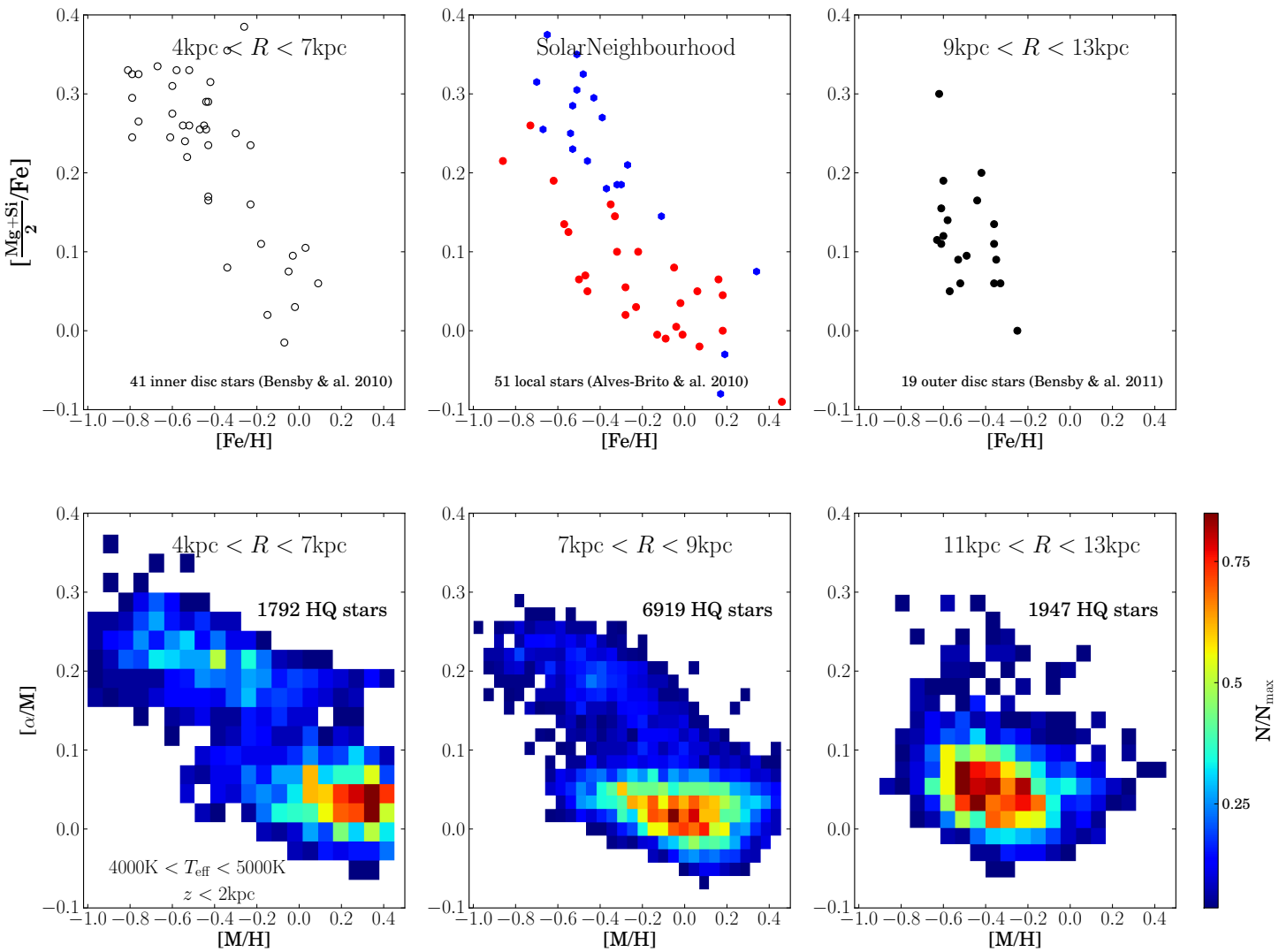
APOGEE's "first light" field. Credit: G. Zasowski.

APOGEE spectra

Basic interactive visualization tools at
http://mirror.sdss3.org/basicIRSpectra

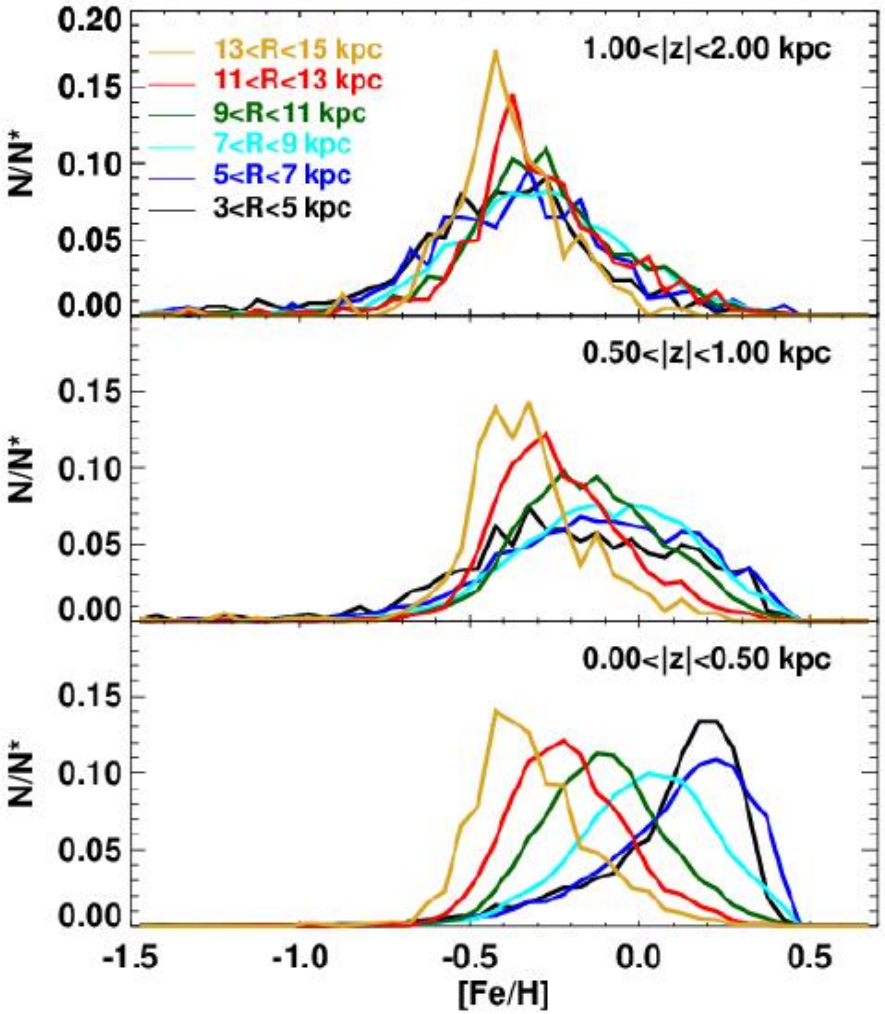


Abundance patterns at different Gal. distances



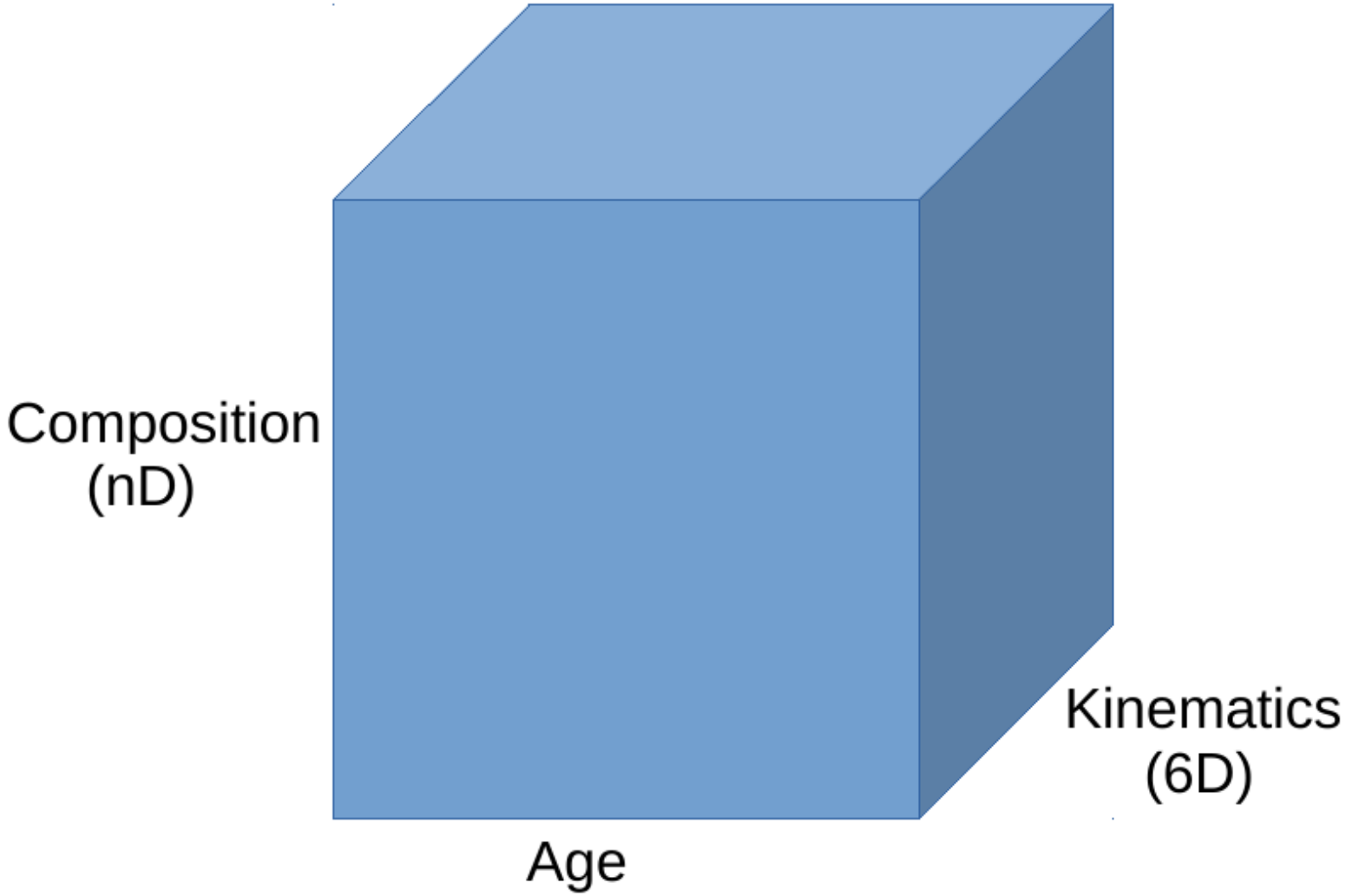
Anders et al. (2014), with data from Bensby et al. (2011).

MDFs at different Gal. distances



Hayden et al. 2015

Ages provide crucial Galaxy model constraints: attack!



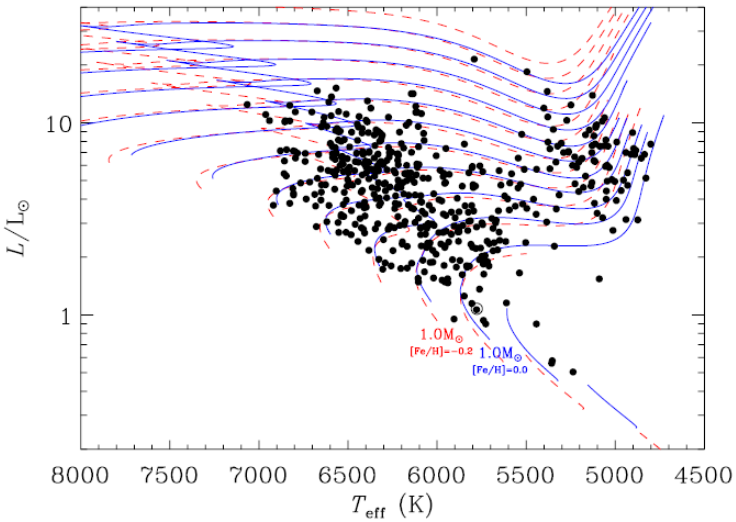
Age-dating stars: methods

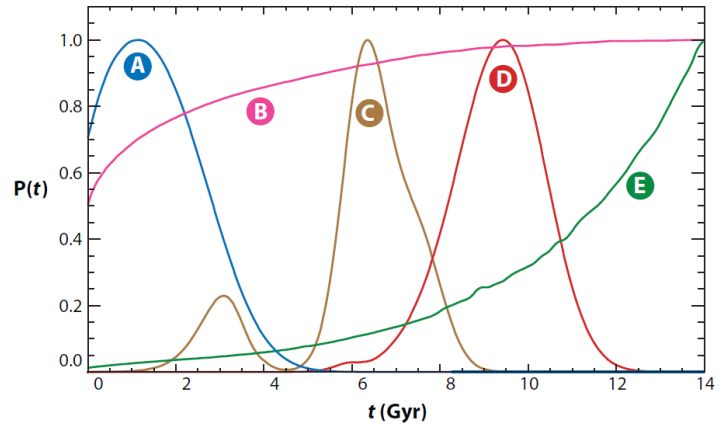
- Stellar activity
- Gyrochronology
- Li depletion boundary
- U/Th decay
- Planetary nebulae
- Stellar kinematics

...

- **HRD/CMD methods**
  - Cluster CMDs
  - WD cooling sequence
  - **Isochrone methods**
  - **Detailed modelling**

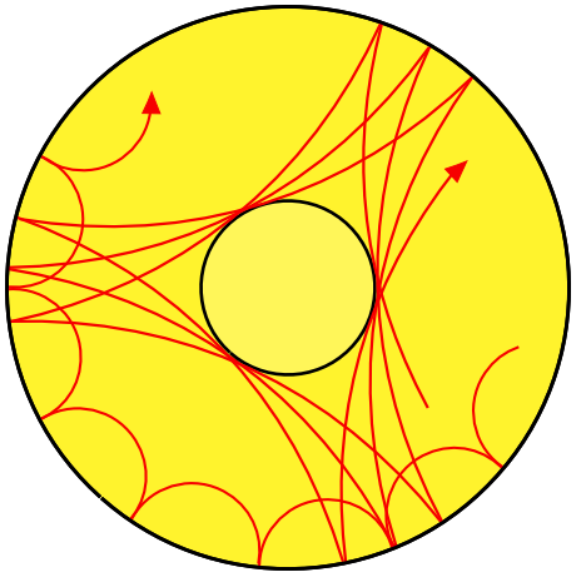
Chaplin et al. (2014)





Soderblom (2010), with data from Takeda et al. (2007)

"Entry-level Asteroseismology" Miglio



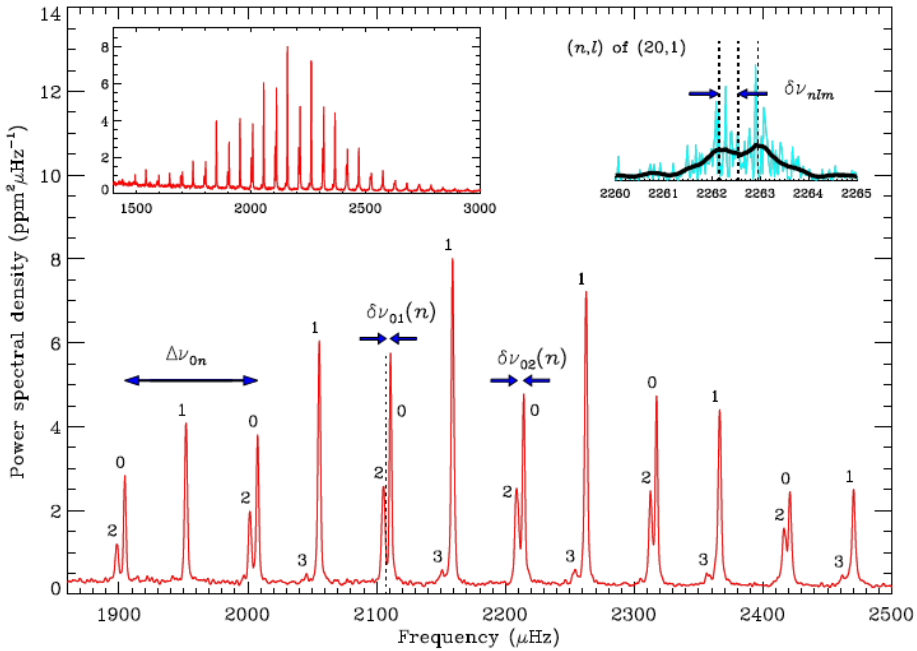
- "Solar-like" oscillations can be detected in stars through ultra-high precision photometry time series
- rich frequency spectra – modes are excited and damped by turbulence in the convective envelope

$$\left(\frac{R}{R_\odot}\right) \simeq \left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right)\left(\frac{\langle\Delta\nu_{nl}\rangle}{\langle\Delta\nu_{nl}\rangle_\odot}\right)^{-2}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{0.5},$$

$$\left(\frac{M}{M_\odot}\right) \simeq \left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right)^{3}\left(\frac{\langle\Delta\nu_{nl}\rangle}{\langle\Delta\nu_{nl}\rangle_\odot}\right)^{-4}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{1.5}$$

$$\left(\frac{\rho}{\rho_\odot}\right) \simeq \left(\frac{\langle\Delta\nu_{nl}\rangle}{\langle\Delta\nu_{nl}\rangle_\odot}\right)^{2}$$

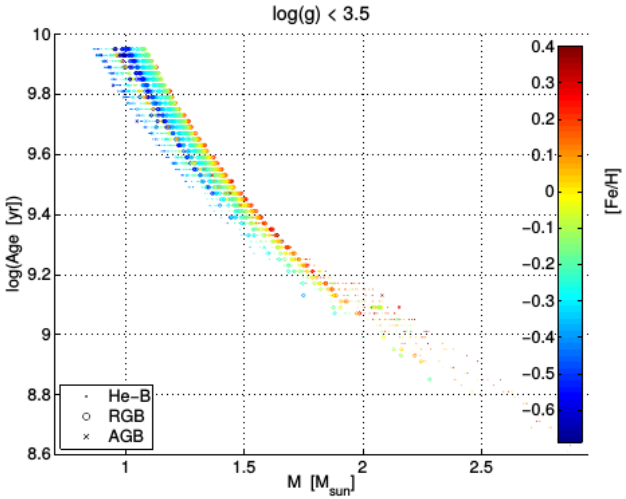
$$\left(\frac{g}{g_\odot}\right) \simeq \left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right)\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{0.5}.$$

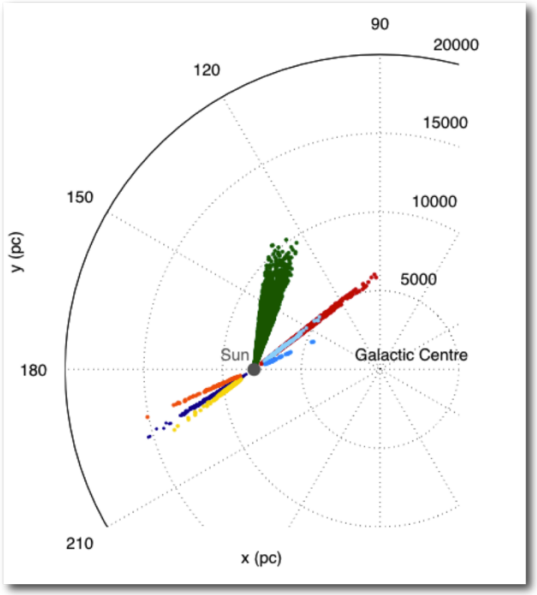


Miglio (2011)

Ensemble/Stellar populations asteroseismology

- **Red giants** most useful through tight age-mass relation
- $\Delta\nu, \nu_{\rm max}$ available for large samples
- $\frac{\Delta R}{R} \sim 5\%, \frac{\Delta M}{M} \sim 10\%$
- $\frac{\Delta \tau}{\tau} \sim 30\% \rightarrow$ ages useful in a statistical sense
- **further improvement by adding spectroscopic constraints** $T_{\rm eff}$, [Fe/H]





Miglio (2011), Miglio et al. (2013)

Leibniz-Institut für Astrophysik Potsdam

Home Science Speakers Registration Participants Contributions Program Venue & Accomodation

592. WE-Heraeus-Seminar – 1st to 5th June 2015

Reconstructing the Milky Way's History: Spectroscopic Surveys, Asteroseismology and Chemodynamical Models

Venue:

Physikzentrum Bad Honnef
Hauptstraße 5
53604 Bad Honnef (near Bonn, Germany)

The *Physikzentrum* (Physics Center) is run by the Deutsche Physikalische Gesellschaft e. V. (DPG) and is jointly supported by the University of Bonn and the state of North Rhine – Westphalia.

Bad Honnef is located near Bonn (15 km) and Cologne (40 km). The stately mansion housing the *Physikzentrum* is surrounded by a park at the foot of the *Siebengebirge* ("The Seven Hills") on the right bank of the Rhine River.

This seminar is generously funded by the Wilhelm und Else Heraeus-Stiftung.

Click here to learn more about the foundation.

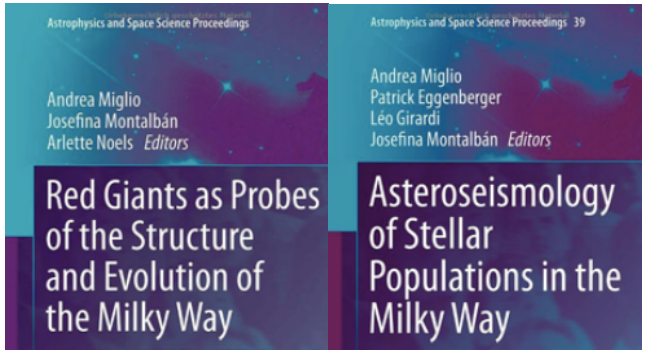
Important Dates:

- Registration closed: 15th March 2015
- List of participants published: 17th April 2015
- Registration Letters and final Abstracts due: 8th May 2015
- **Conference dates: 1-5 June 2015**

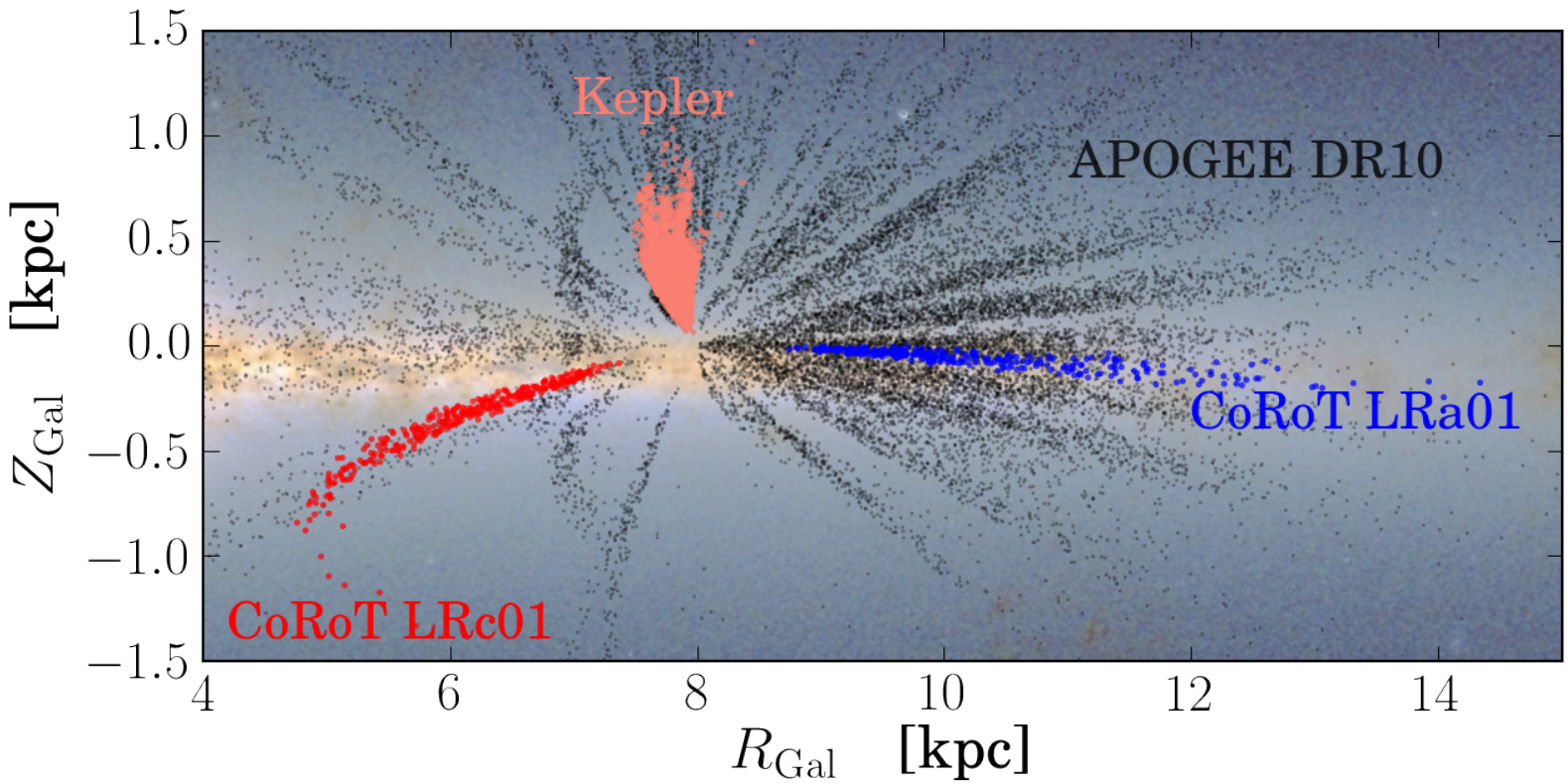
Accomodation and Meals:

- All participants will be hosted in the beautiful Bad Honnef mansion.
- Meals and accomodation will be covered by the organizers.
- Some support is available for travel expenses of *invited speakers*.
- We are allowed a maximum of 70 participants.

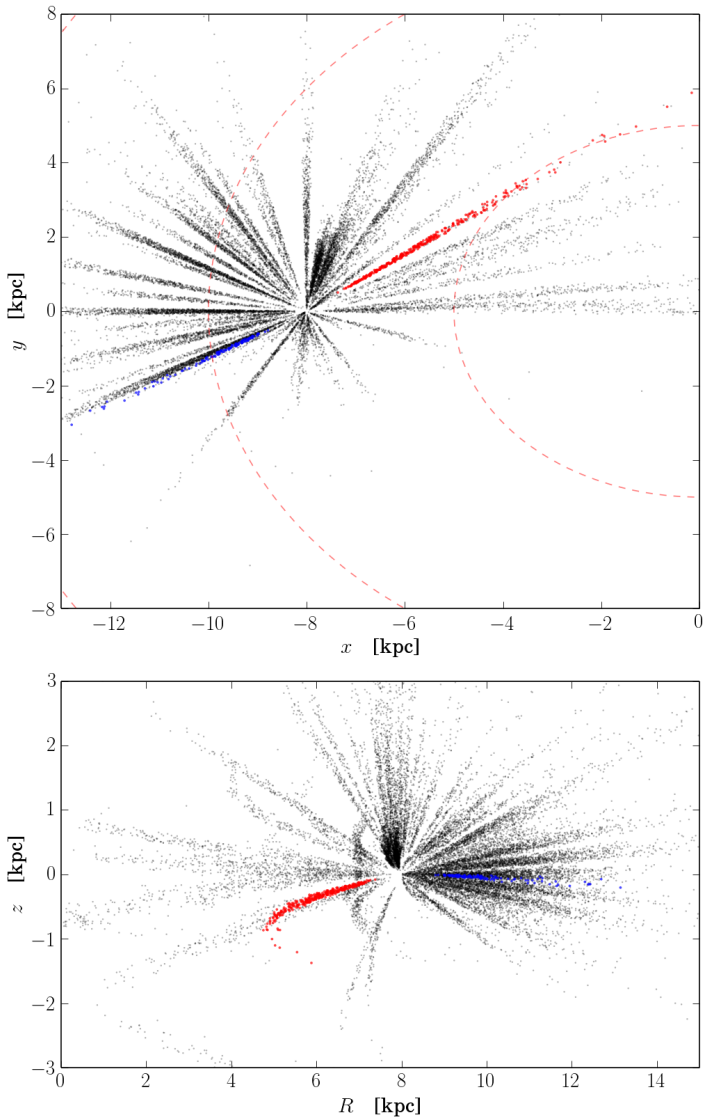
≫ *Time is now ripe to bring together again the representatives from the extensive ground-based surveys, as well as asteroseismology, Galaxy formation and stellar evolution experts to set our roadmap for future endeavors in this field.* ≪



Currently available APOGEE seismic samples



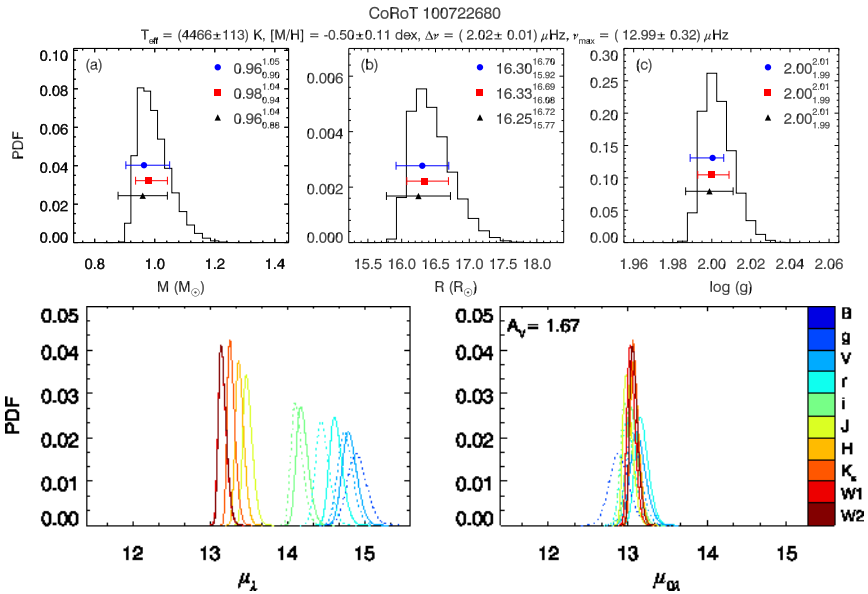
The DR12 CoRoT-APOGEE Sample



CoRoGEE stars	690
with "good" APOGEE results	678
LRa01	333
LRc01	345
PARAM converged	623
Proper motions available	555
Good orbits ($\sigma(v_T) < 20$ km/s)	147

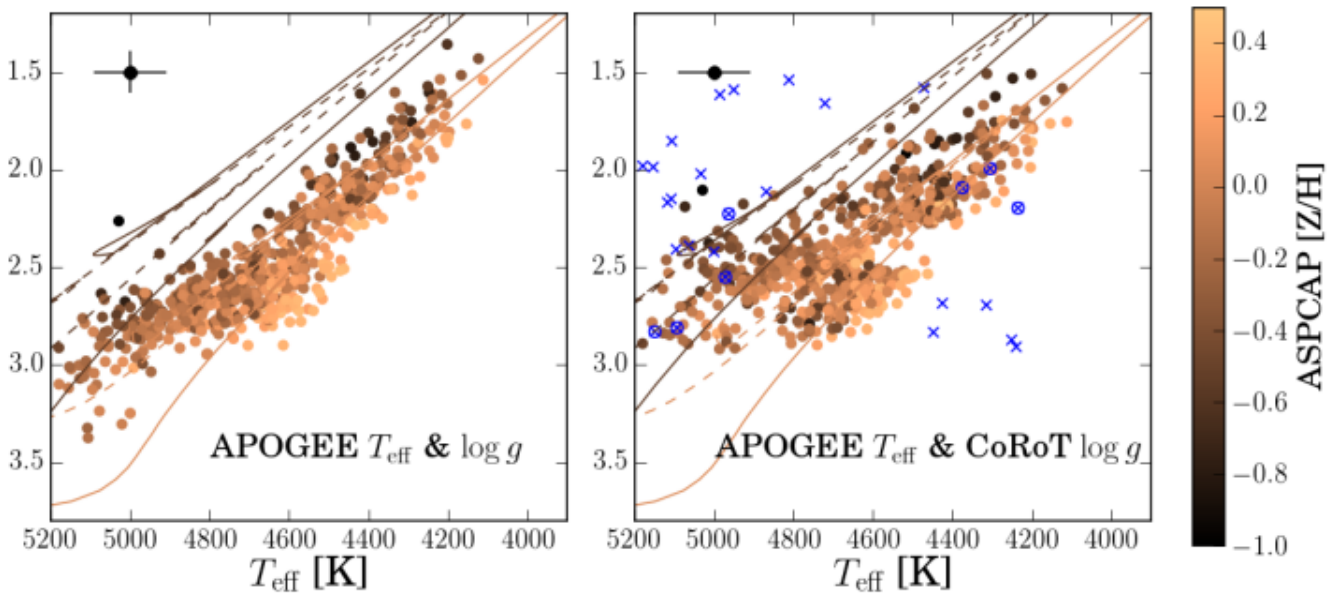
PARAM: Combining asteroseismology and spectroscopy

- $\frac{\Delta R}{R} \sim 3\%, \frac{\Delta M}{M} < 10\%$
- Precise (2%) distances + extinctions
- Typical age uncertainties $\sim 25\%$
- Use of evolutionary stage information possible



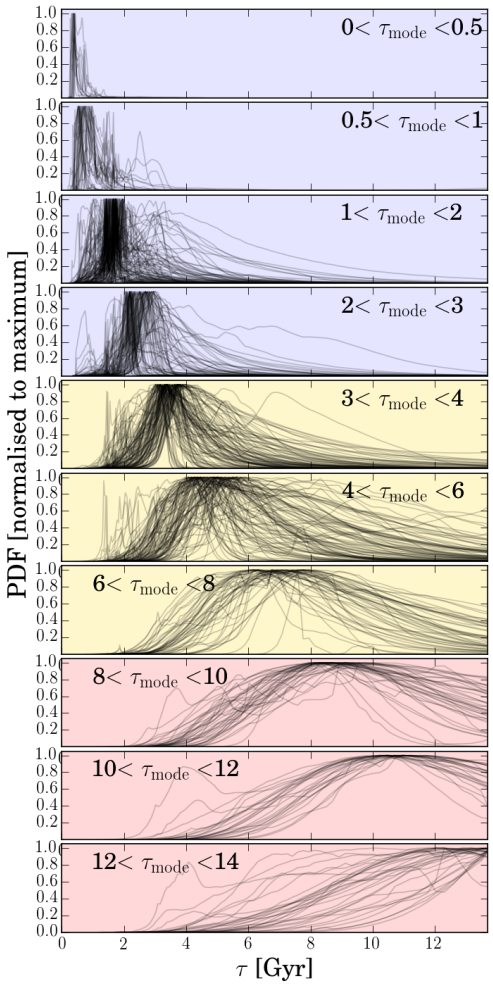
PARAM code: da Silva et al. (2006), Miglio et al. (2012), Rodrigues et al. (2014) Figure courtesy of T.S. Rodrigues

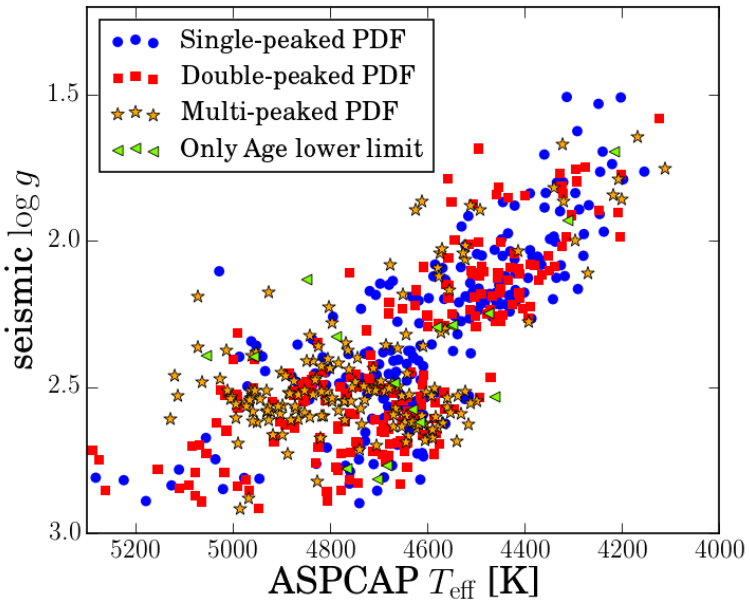
Sanity checks: *HR* diagram



- Combination of asteroseismology and spectroscopy yields more precise HRD
- PARAM detects unphysical stellar parameter combinations

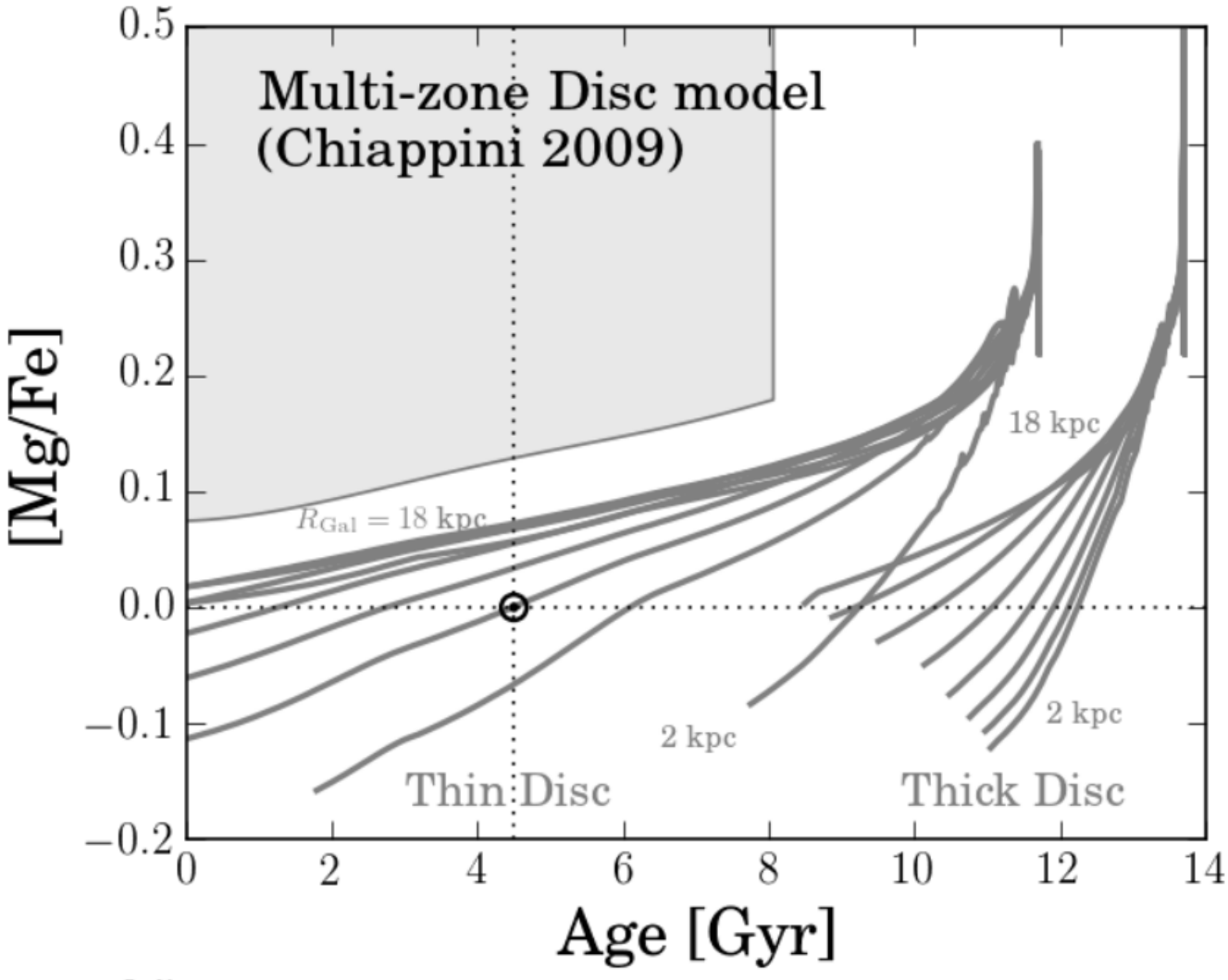
PARAM results: Complex Age PDFs



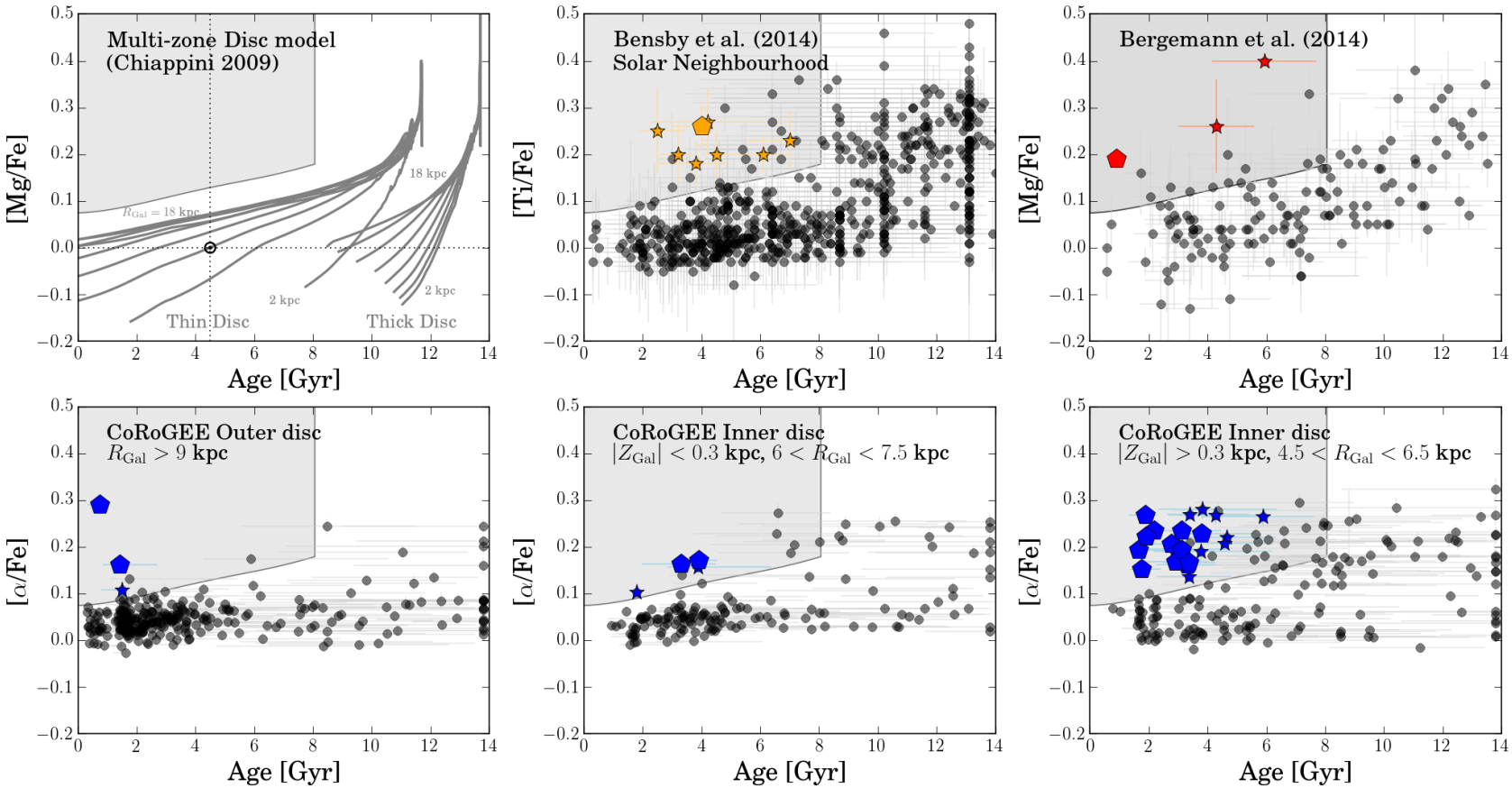


- Age PDFs are typically non-trivial...

What typical models predict for [α/Fe]-vs.-age relation

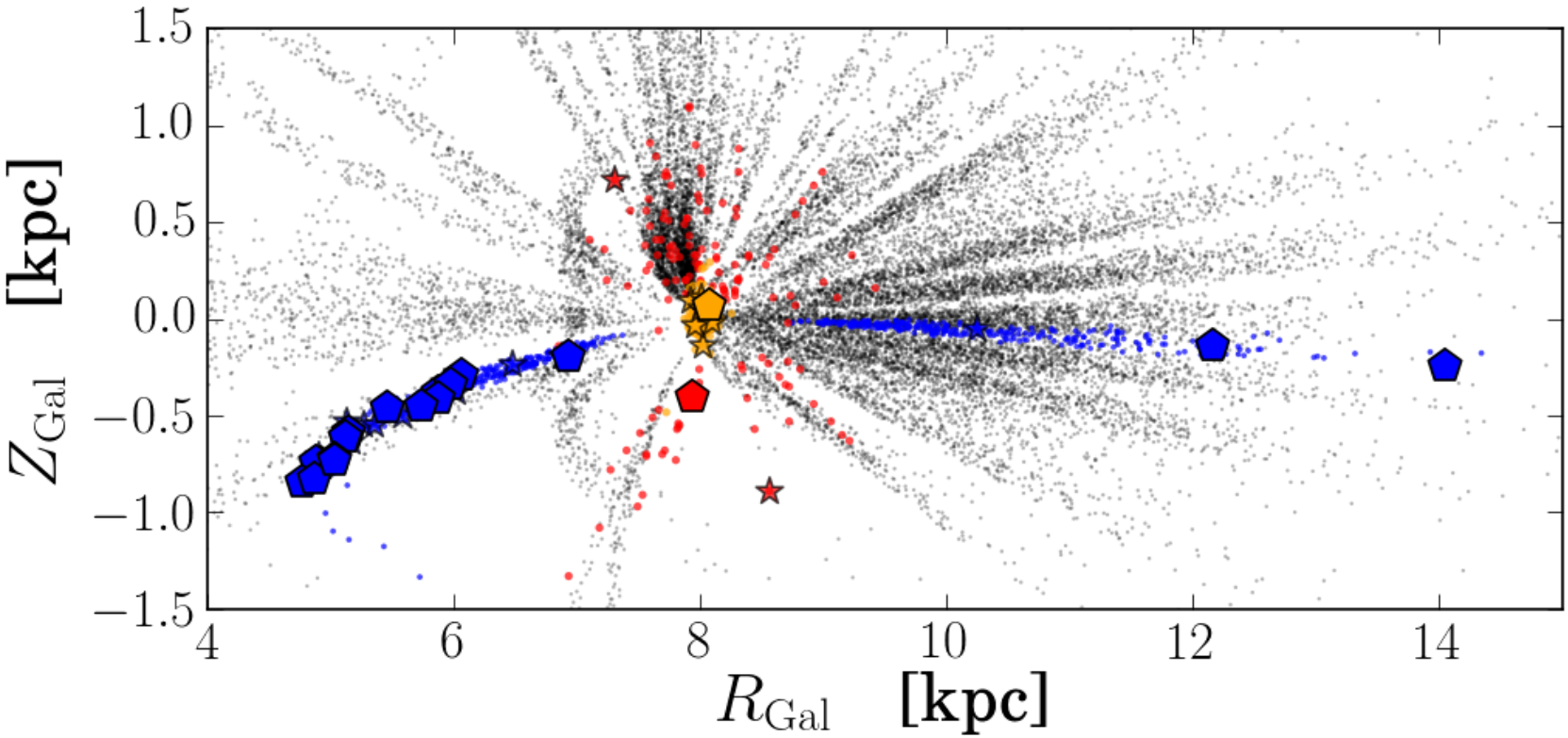


(Apparently) young [α/Fe]-enriched stars in CoRoGEE



- Many more in the inner disc field!

(Apparently) young [α/Fe]-enriched stars



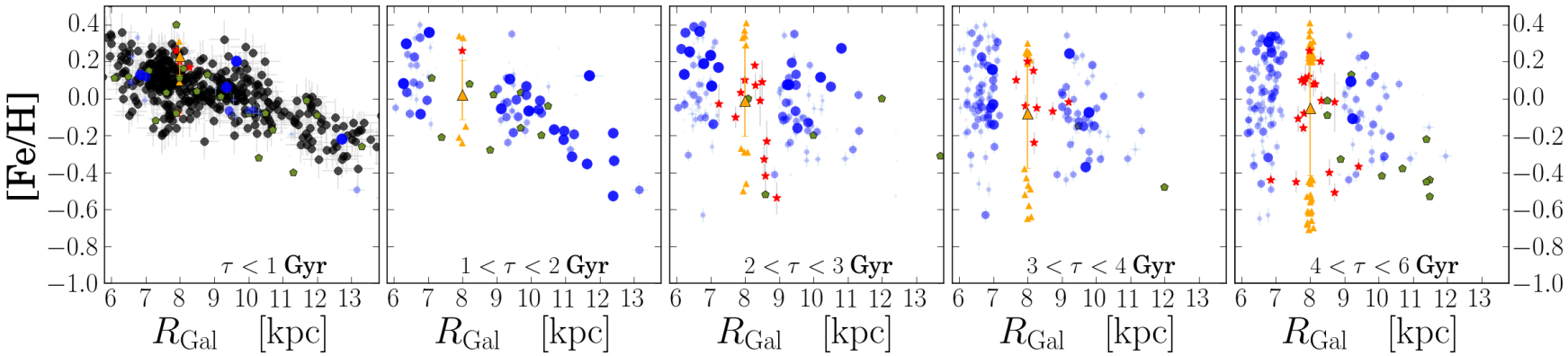
- Many more in the inner disc field!

Young [α/Fe]-enriched stars – Possible explanations

1. Stars for which the scaling relations seem to break (e.g., stellar mergers; NGC 6819 results of Handberg et al., *in prep.*)
2. Close binaries (e.g., evolved blue stragglers) for which the mass-age relation breaks down
3. Massive satellite galaxy debris
4. star-forming bubbles in the inner Galaxy (near the bar corotation)

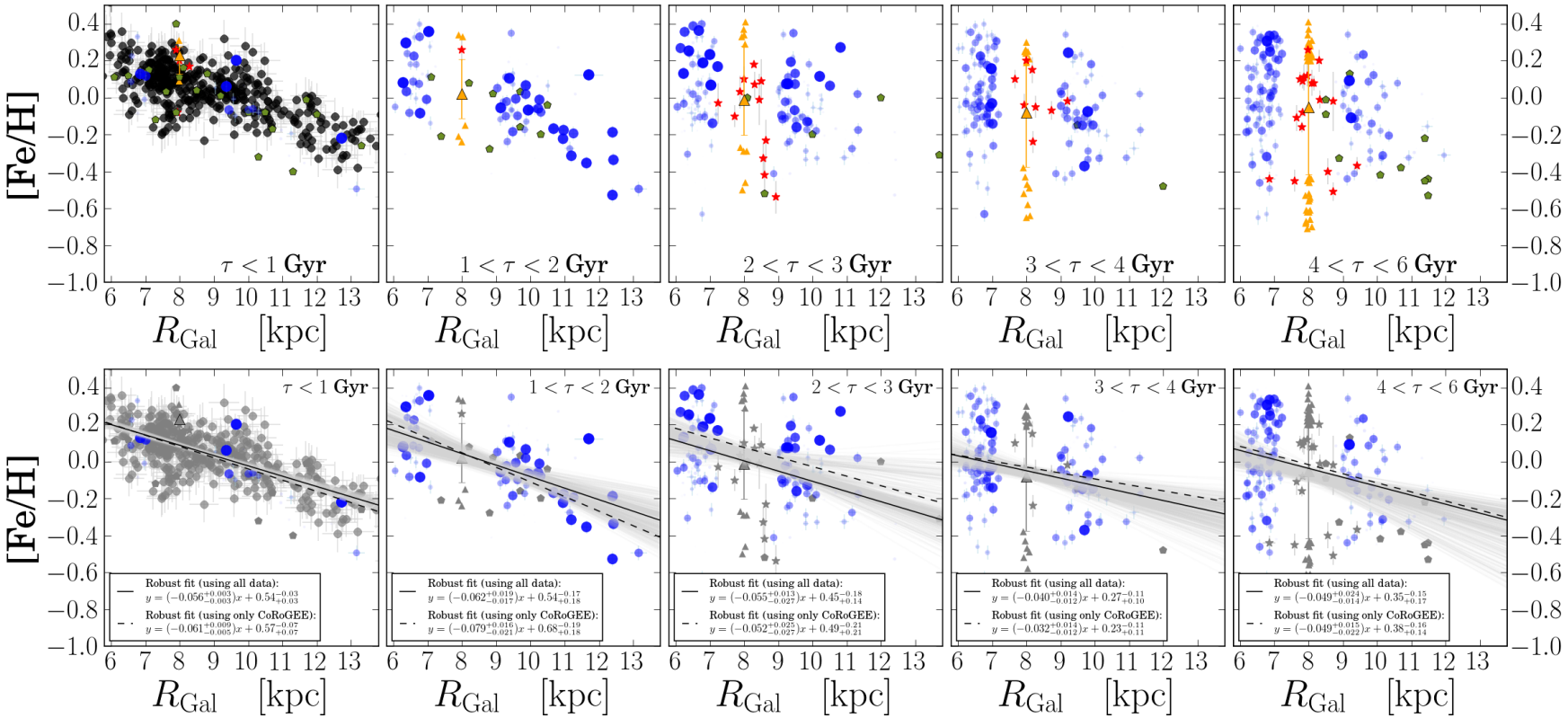
- No conclusive evidence, possibly a mixture of these theories
- More details in Chiappini et al. (2015), Martig et al. (2015)

Time evolution of the radial abundance gradients



- Ideally we want models to fit the full age-$R_{\rm Gal}$-[Fe/H] relation
- but modelling the Age PDFs (and their systematics) is highly non-trivial
- therefore we look at the [Fe/H]-$R_{\rm Gal}$ in wider bins of age

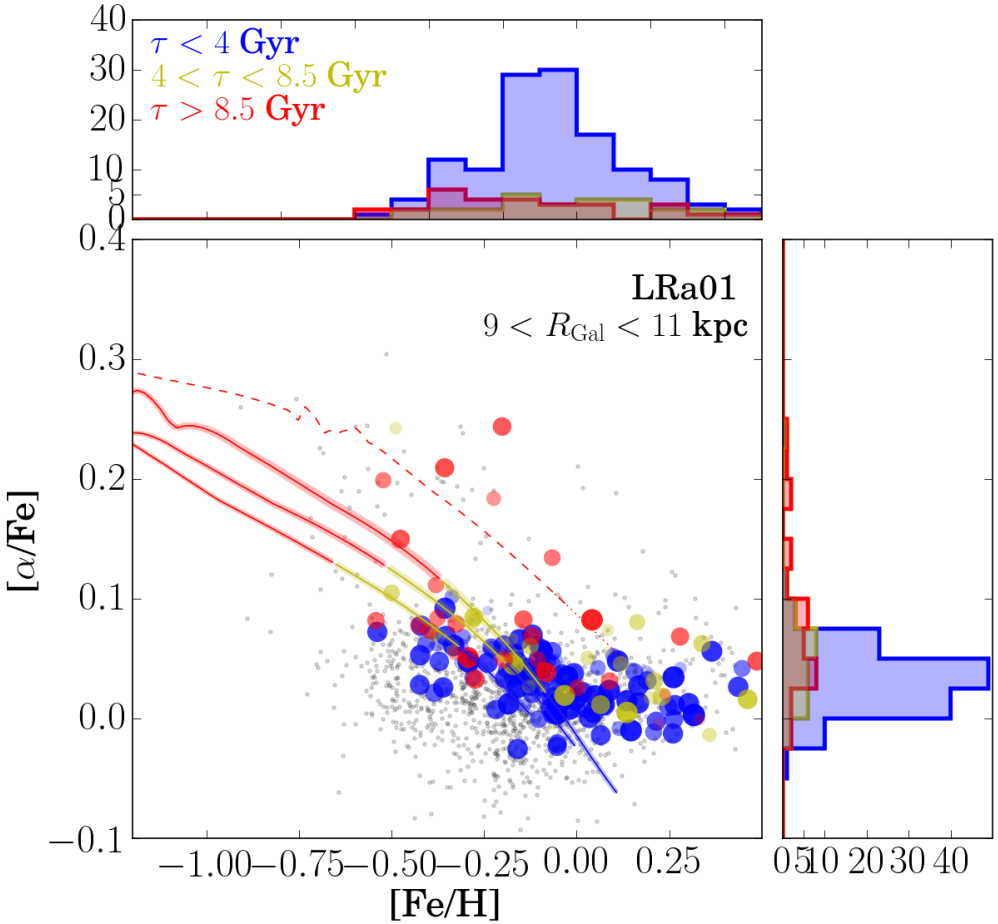
Time evolution of the radial abundance gradients



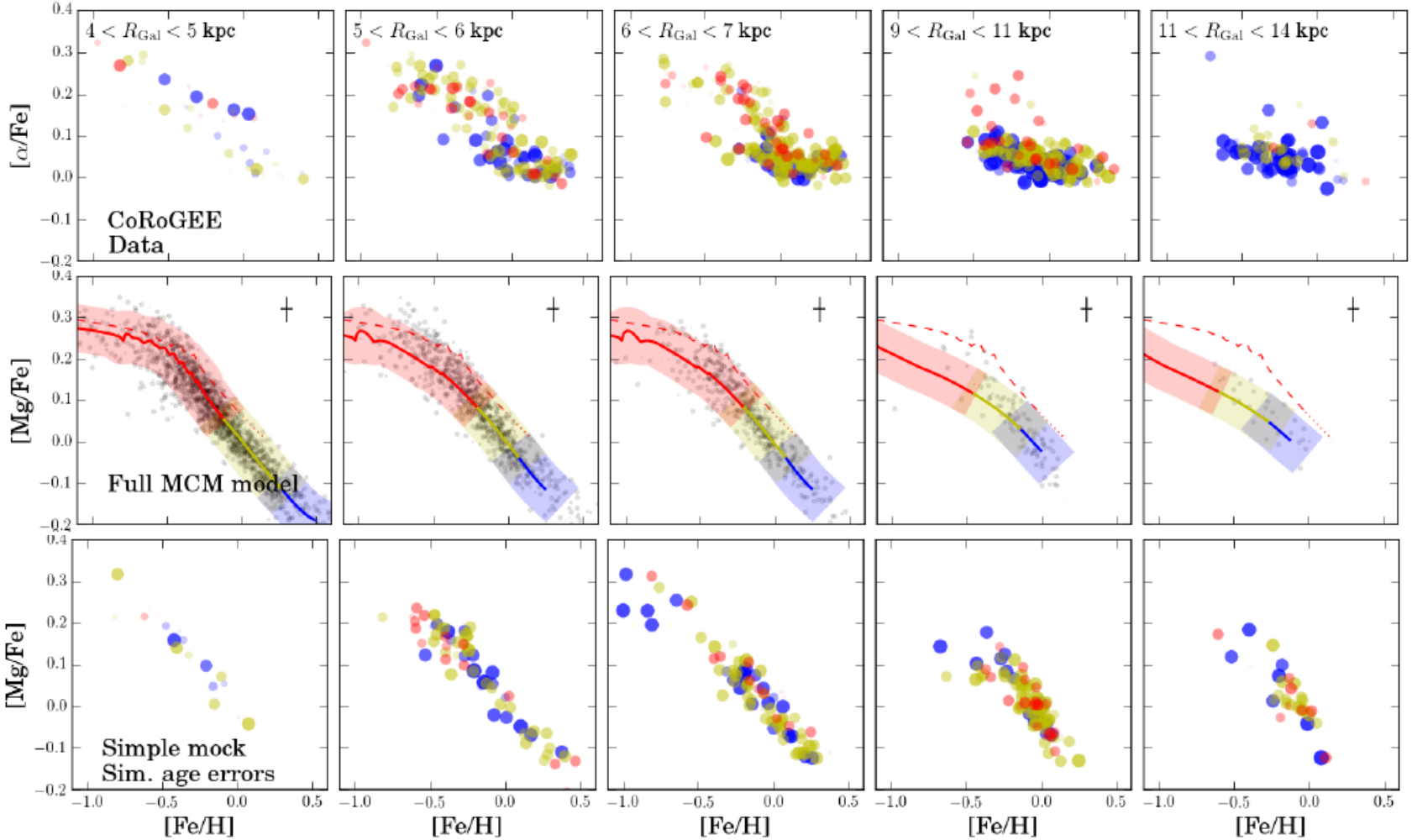
- mean gradient largely constant over the past 5 Gyrs
- more information in the scatter (mixing and migration)

The [α/Fe] vs. [Fe/H] diagram at different Galactocentric Distances

- Trying to find signatures of migration with this diagram
- SMR stars seem to be dominantly young..
- What is the real shape of the [α/Fe] vs. [Fe/H] diagram at super-solar metallicities?



Comparison with a chemodynamical model

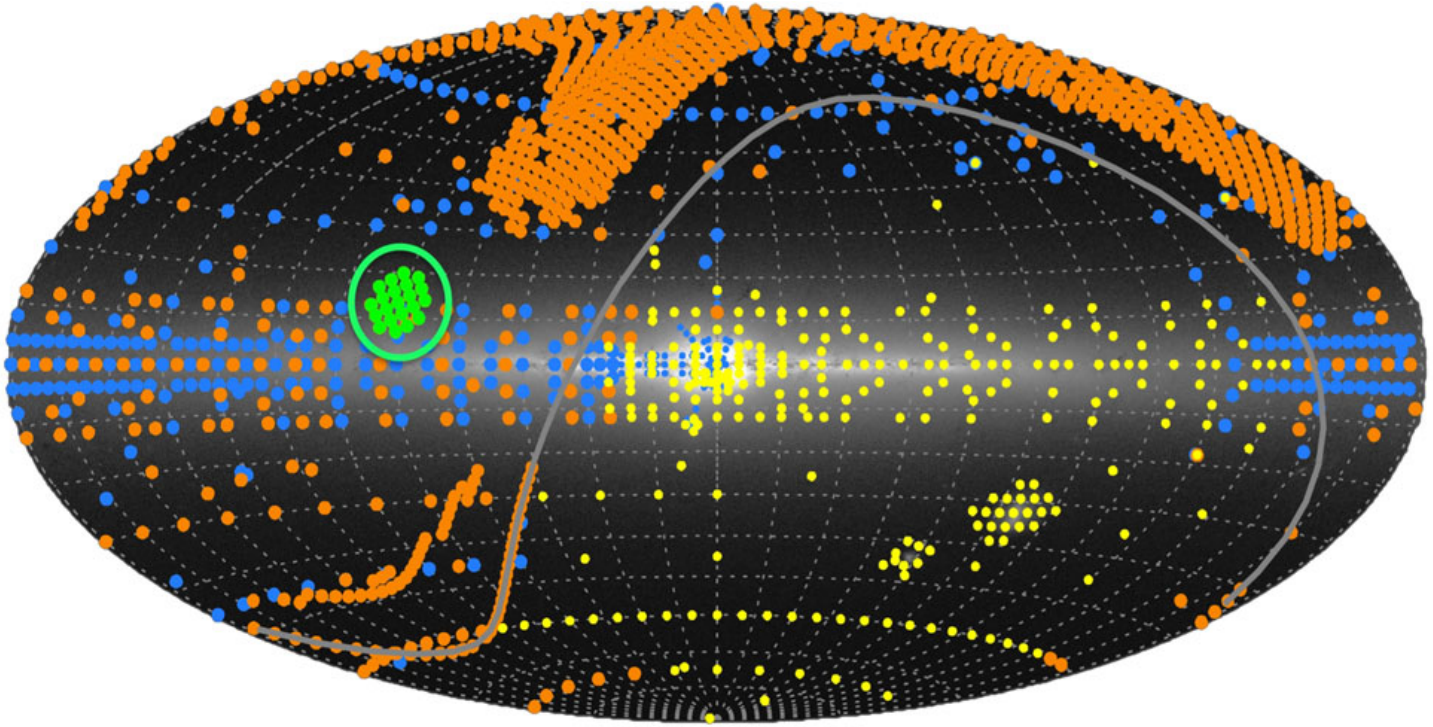


- This comparison begins to show where the model fails!

Summary

- Combining entry-level seismology with spectroscopy brings us one step further in obtaining meaningful ages
- Be very careful when interpreting small subsets
- Still sizeable systematic uncertainties
- New chemodynamical constraints can be formulated over a large range in Galactocentric distance and ages

Future: APOGEE-2

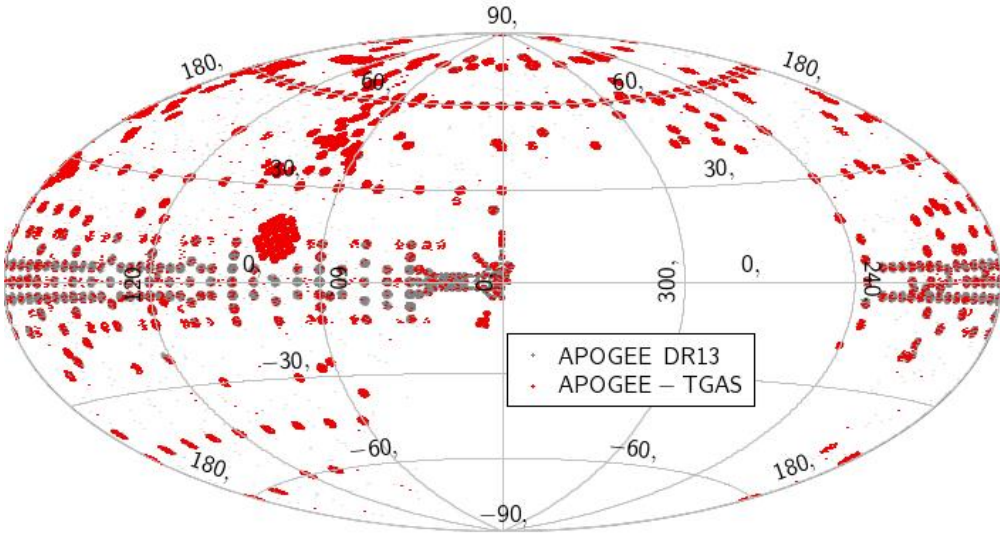


- APOGEE-2N started in autumn 2014
- First data will be released internally with DR13 (July)
- APOGEE-2S is being built up at Las Campanas (3.5 deg^2 FOV plates)

APOGEE-2 BPG/AIP/Brazil Science goals

- ongoing: detailed comparison with (semi-)cosmological N-body simulations using mock observation tools (Anders+)
- K2, *Gaia*, PLATO... (Valentini+)
- make full use of individual element abundances (Cunha+)
- Ultimate goal: constrain MW star formation + radial migration history (Chiappini+)
- Moderately metal-poor bulge in APOGEE (Barbuy+)
- High-res. abundance studies of B stars (Daflon+)
- Constrain stellar pop. models (Girardi+)
- Precisely calibrate spectro-phot. distances (Rodrigues+, Santiago+)
- ....

APOGEE + Gaia

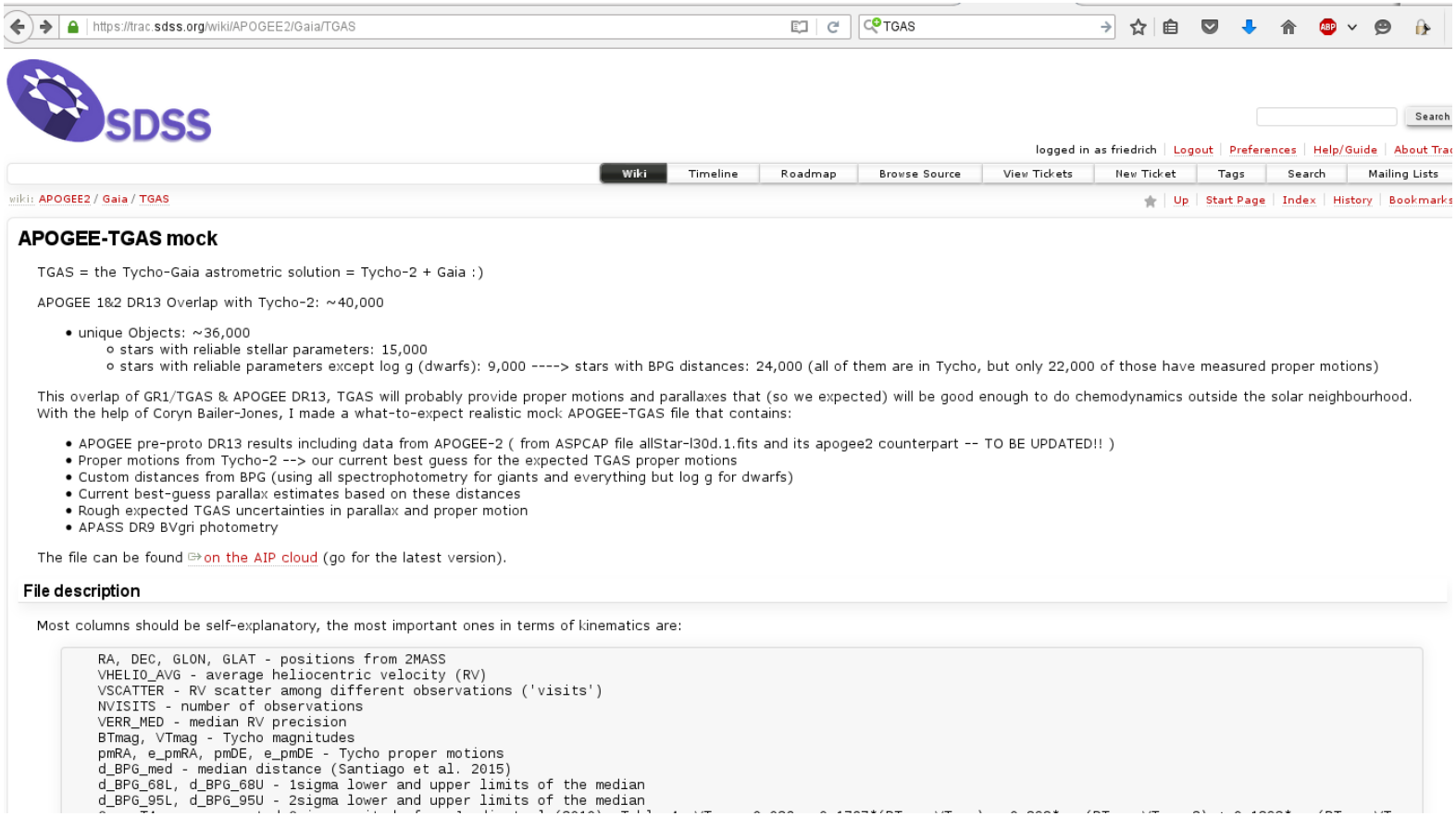


Mag.	Number[a]	Position [μas]	Parallax [μas]	Prop. motion [μas yr^{-1}]
Subset *Tycho* without HIPPARCOS				
6–7	411	244	399	198
7–8	8072	198	348	264
8–9	63 630	191	327	403
9–10	257 243	230	407	680
10–11	686 866	329	601	1145
11–12	993 139	379	722	1522
≥12	302 511	349	702	1615
all (≥6)	2 311 872	332	631	1259

- Gaia DR1 will contain parallaxes and proper motions with Hipparcos-like precision for 2.5 million Tycho stars (Michalik+2015)
- The overlap with APOGEE is $\sim 28,000$ stars
- These can be used to do chemo-kinematics outside the Hipparcos volume
- and also to better test our spectro-photometric distances

APOGEE-TGAS

Test your science ideas using this "pseudo-mock" sample!



https://trac.sdss.org/wiki/APOGEE2/Gaia/TGAS

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APOGEE-TGAS mock

TGAS = the Tycho-Gaia astrometric solution = Tycho-2 + Gaia :)

APOGEE 1&2 DR13 Overlap with Tycho-2: ~40,000

- unique Objects: ~36,000
  - stars with reliable stellar parameters: 15,000
  - stars with reliable parameters except log g (dwarfs): 9,000 ----> stars with BPG distances: 24,000 (all of them are in Tycho, but only 22,000 of those have measured proper motions)

This overlap of GR1/TGAS & APOGEE DR13, TGAS will probably provide proper motions and parallaxes that (so we expected) will be good enough to do chemodynamics outside the solar neighbourhood.
With the help of Coryn Bailer-Jones, I made a what-to-expect realistic mock APOGEE-TGAS file that contains:

- APOGEE pre-proto DR13 results including data from APOGEE-2 (from ASPCAP file allStar-l30d.1.fits and its apogee2 counterpart -- TO BE UPDATED!!)
- Proper motions from Tycho-2 --> our current best guess for the expected TGAS proper motions
- Custom distances from BPG (using all spectrophotometry for giants and everything but log g for dwarfs)
- Current best-guess parallax estimates based on these distances
- Rough expected TGAS uncertainties in parallax and proper motion
- APASS DR9 BVgri photometry

The file can be found on the AIP cloud (go for the latest version).

File description

Most columns should be self-explanatory, the most important ones in terms of kinematics are:

```
RA, DEC, GLON, GLAT - positions from 2MASS
VHELIO_AVG - average heliocentric velocity (RV)
VSCATTER - RV scatter among different observations ('visits')
NVISITS - number of observations
VERR_MED - median RV precision
BTmag, VTmag - Tycho magnitudes
pmRA, e_pmRA, pmDE, e_pmDE - Tycho proper motions
d_BPG_med - median distance (Santiago et al. 2015)
d_BPG_68L, d_BPG_68U - 1sigma lower and upper limits of the median
d_BPG_95L, d_BPG_95U - 2sigma lower and upper limits of the median
```