Why and How to "Survey" the Milky Way

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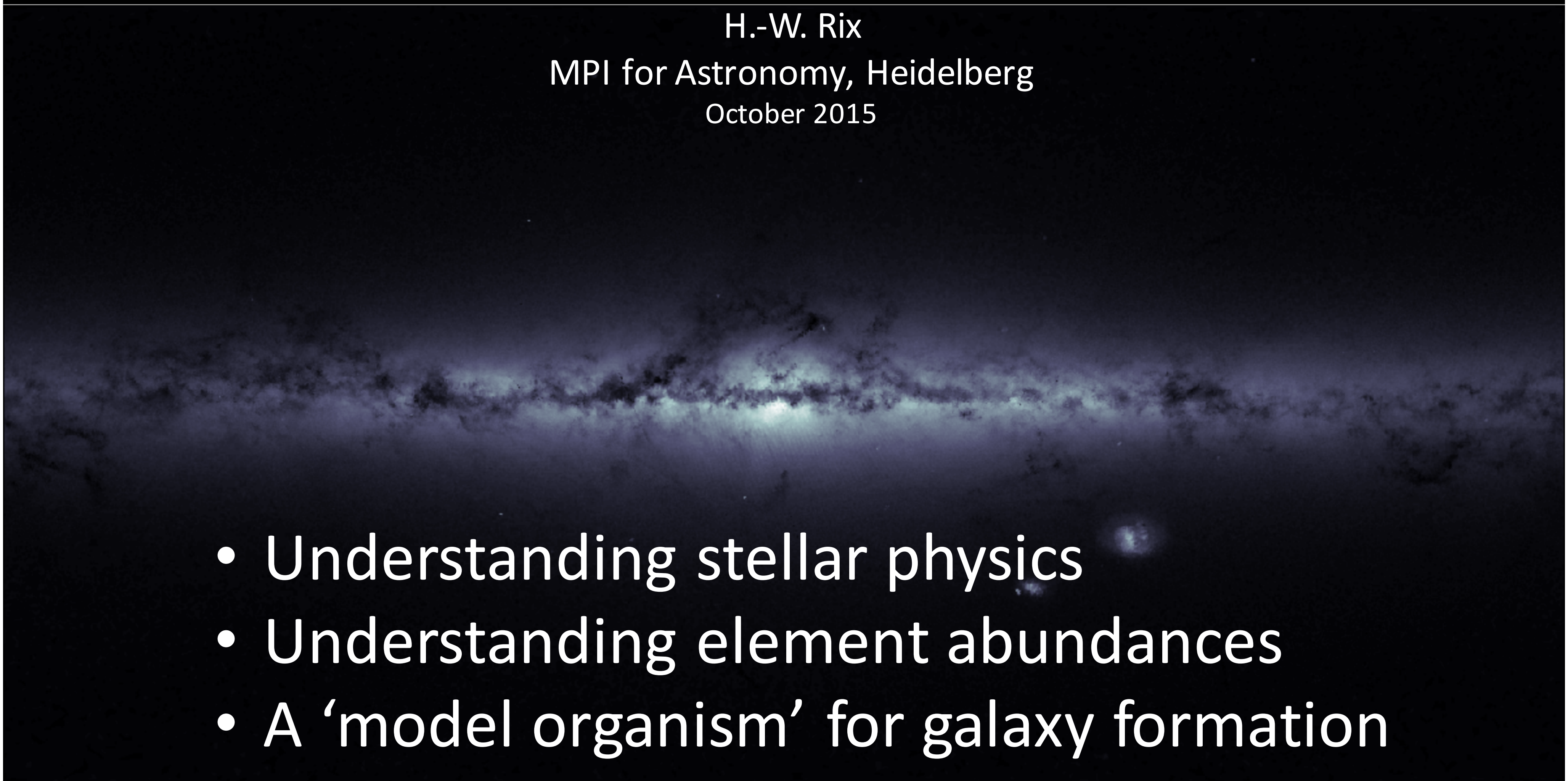
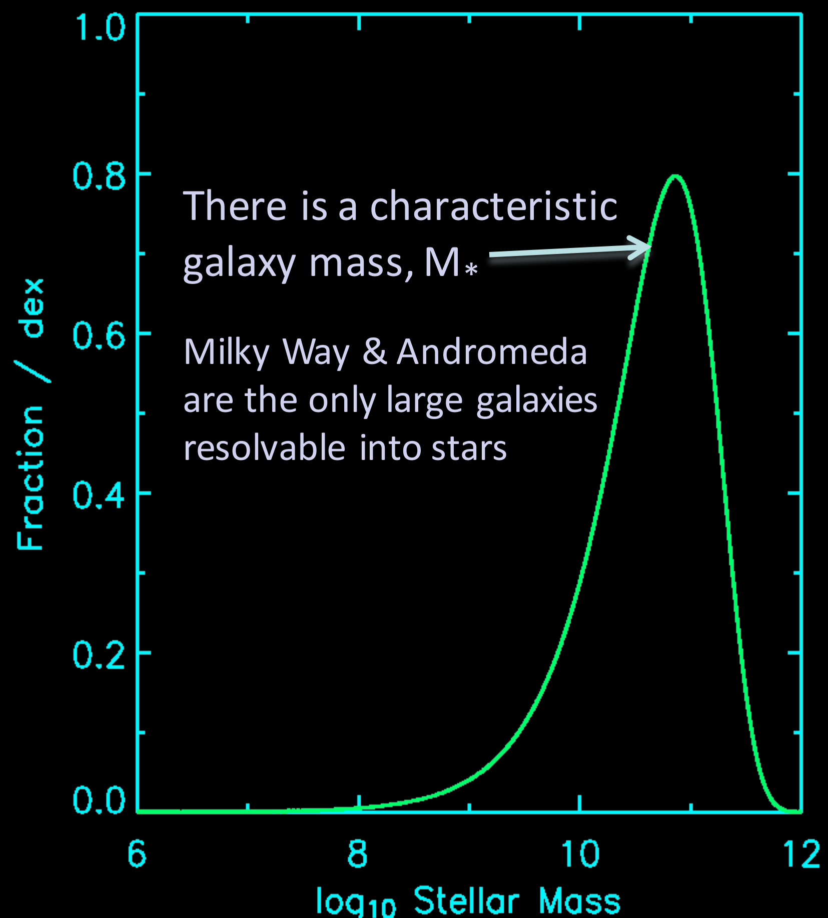


- Understanding stellar physics
- Understanding element abundances
- A 'model organism' for galaxy formation

Review reading: Freeman & Bland-Hawthorn ARAA 2002, Soderblom ARAA 2010, Ivezic, Beers & Juric ARAA 2012 Binney NewAR 2013, Rix & Bovy AARev 2013, Frebel & Norris ARAA 2015

Why might the Milky Way be a good test-bed for galaxy formation?



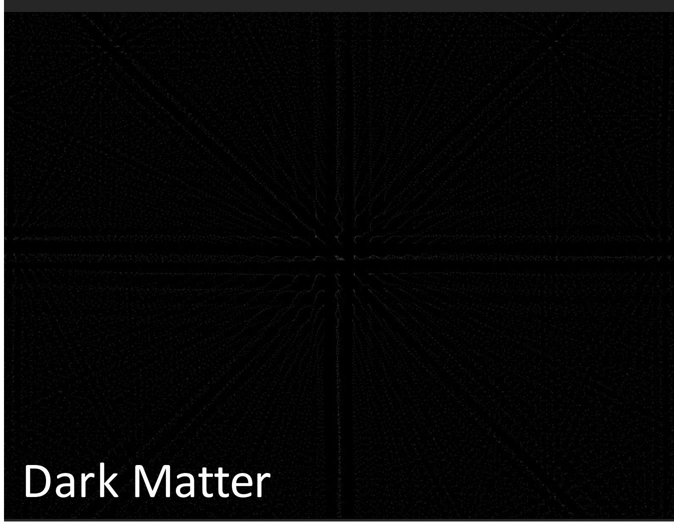
- The Milky Way is an unusually typical galaxy
- It's what we got
  - star-by-star in 6+N dimensions

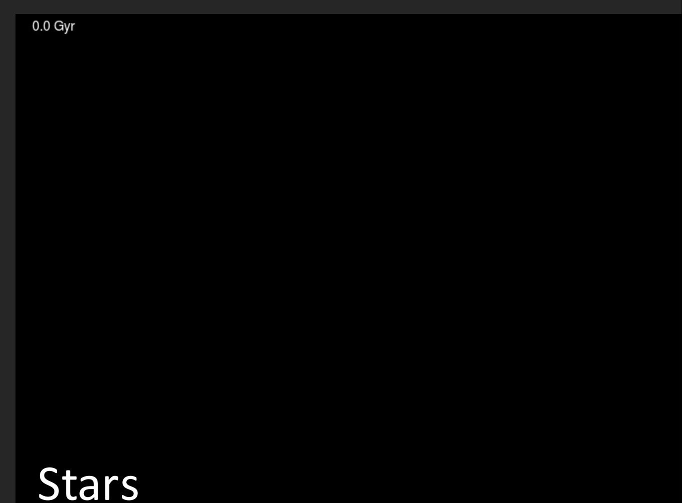
  $p(\boldsymbol{r},\boldsymbol{v},\ M_*,\ L_*, \log g,\ T_{eff},\ t_{age},\ [X/H]\ldots)$

The Milky Way & Galaxy Formation

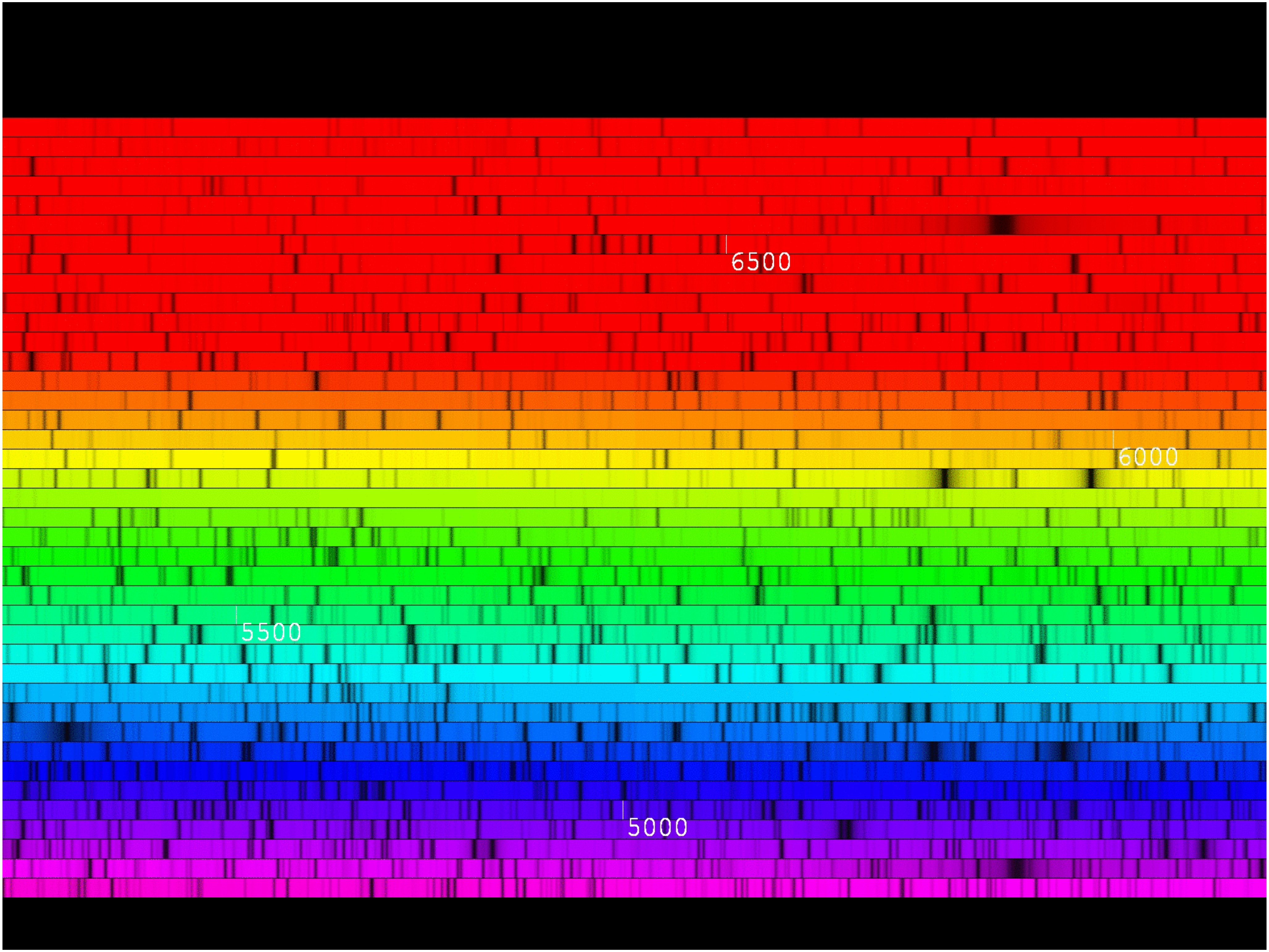
- How much formation memory is in the present-day chemo-orbital distribution of stars?
- What sets the radial and vertical structure of disks?
  - What sets the structure of the spheroid(s)?
- Probing the 3D and small-scale dark matter distribution

Three aspects of simulating a Milky Way-like galaxy (courtesy Stinson et al 2014)





How to answer these questions from 10^{5-7} x this ?


6500
6000
5500
5000

What is the (ideal) set of observables?

- p(***r*,*v***, M_*, L_*,log *g*, T_{eff}, [Fe/H],[α/Fe],[X/H], t_{age}, ...)
  - all these parameters are intricately correlated
    - within a star: stellar physics
    - among stars: galaxy evolution, IMF

- # of stars with such information is e-folding every ~1–2 yrs -- for a decade!
  - high-dimensional space → need very large samples

- separate out ***life-long tags*** of stars:

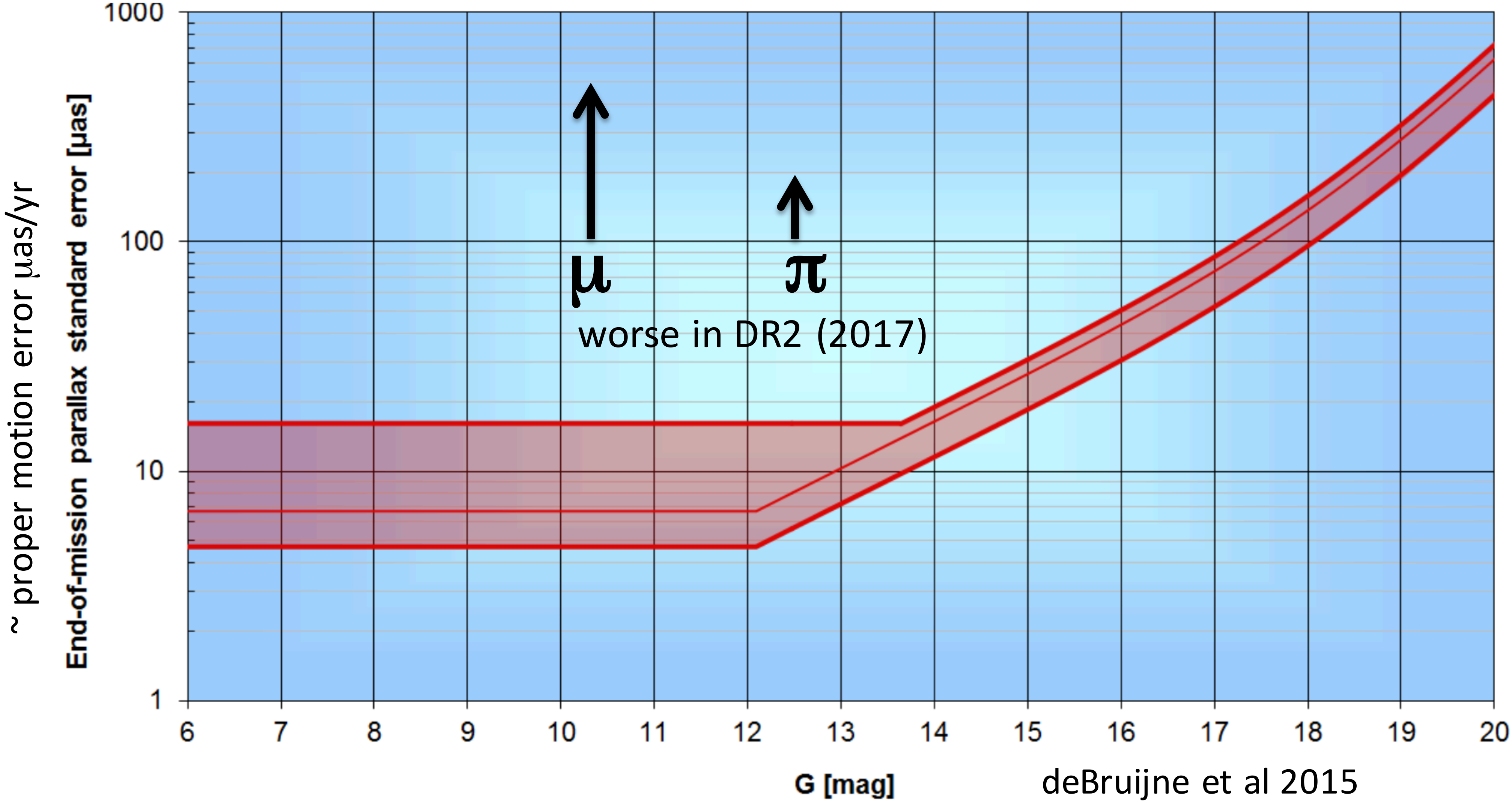
  p($Orbit_{now}$ (***r*,*v***) | t_{age}, [Fe/H],[α/Fe],...) requires Φ(r)

Existing/Ongoing Surveys

gaia

???

Gaia’s immediate impact .. and what’s left to survey?



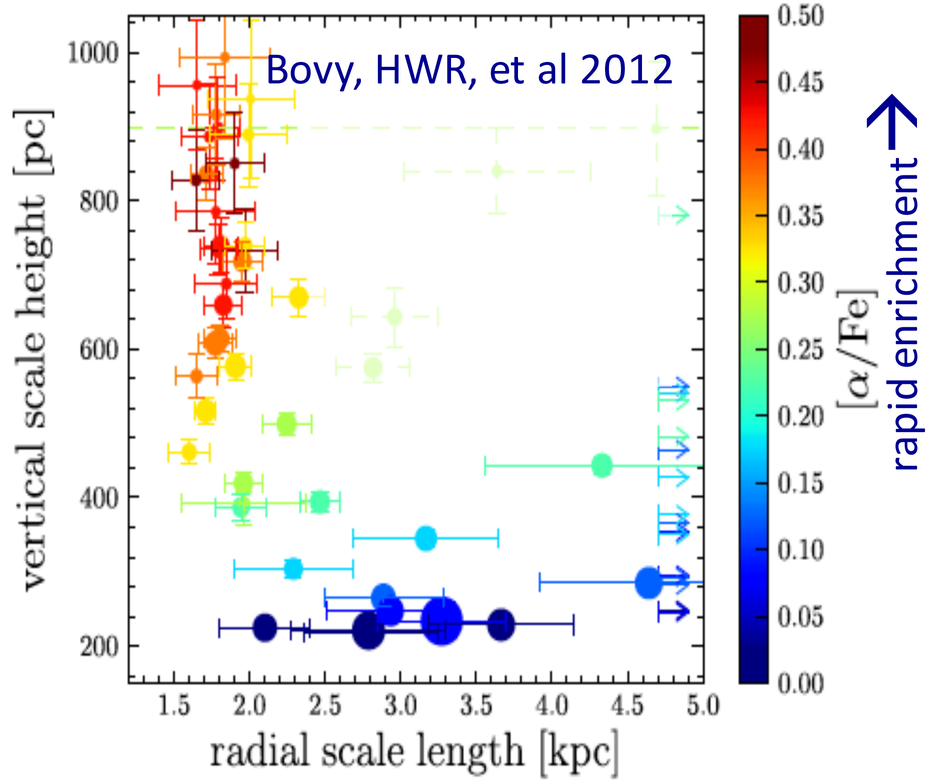
deBruijne et al 2015

What Processes set Disk Structure?

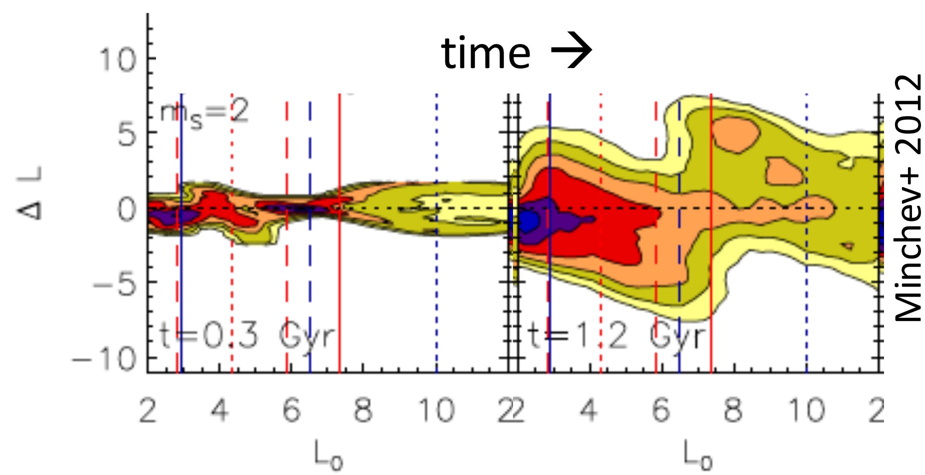
- Stellar disk structure depend strongly on abundances
  (both in ***z*** and ***R***)

  based on analysing mono-abundance populations

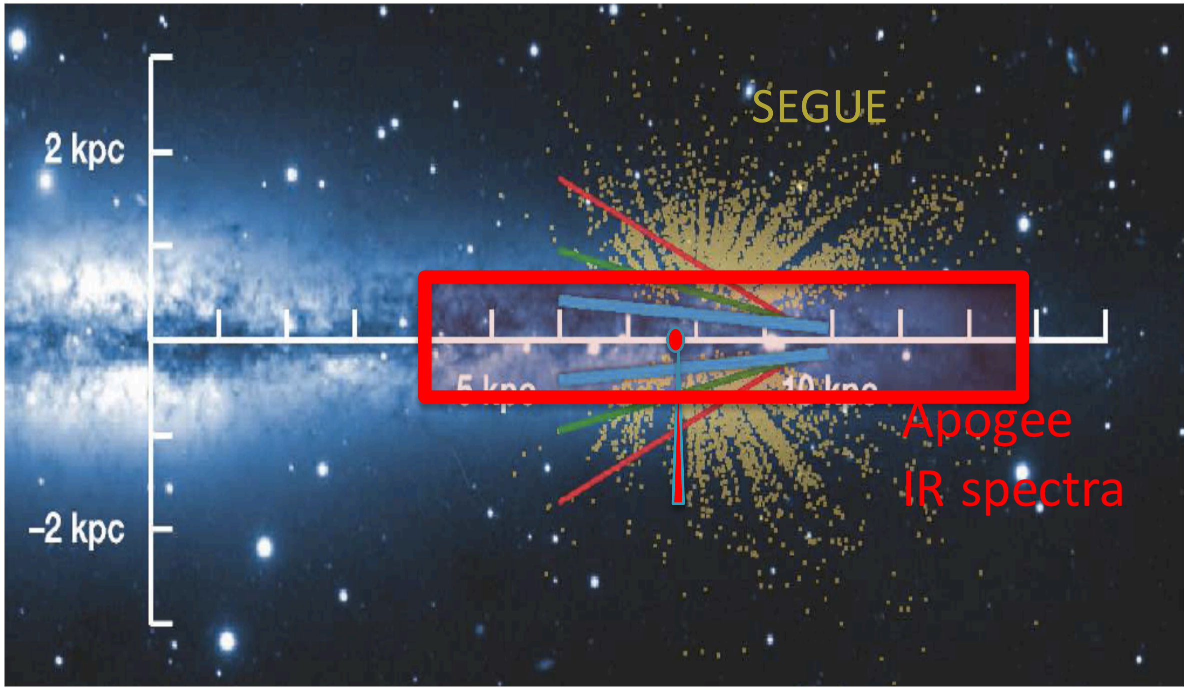
  p(***r,v*** | [Fe/H],[α/Fe])

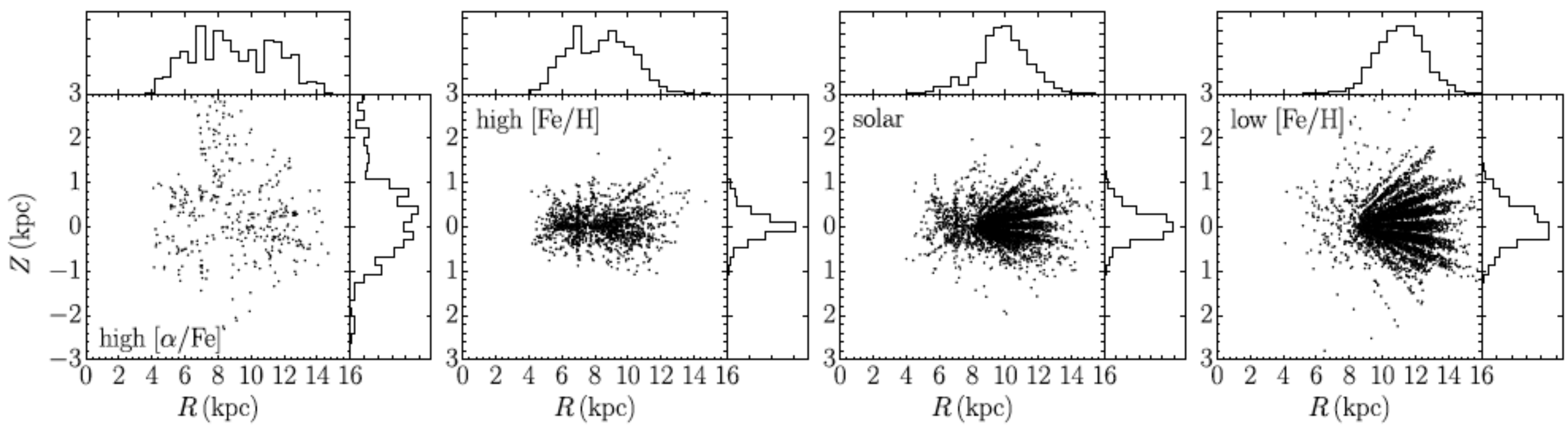


- What determines the orbital radius of a disk star?
  - initial angular momentum
  - radial migration/diffusion
    (Sellwood & Binney 2002)



Limitations of past analyses

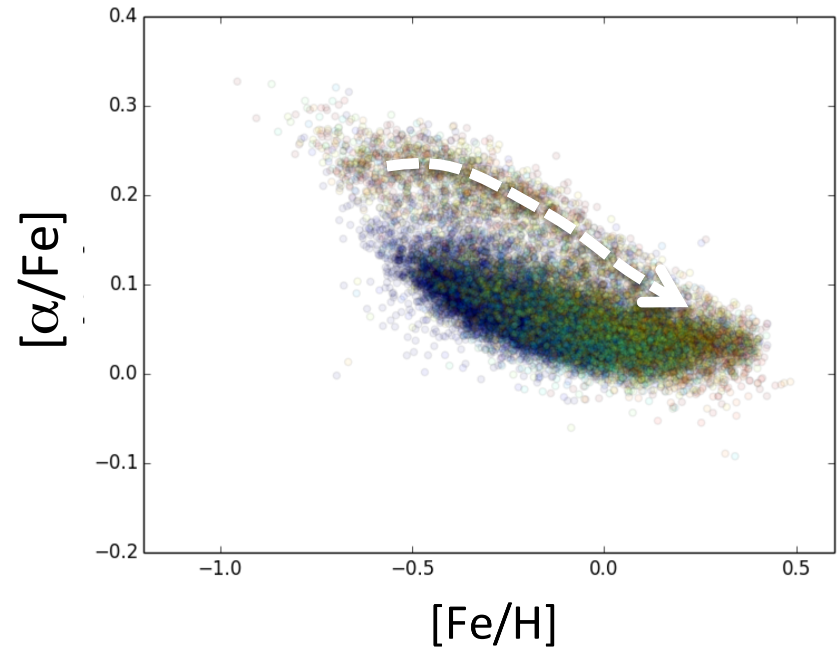


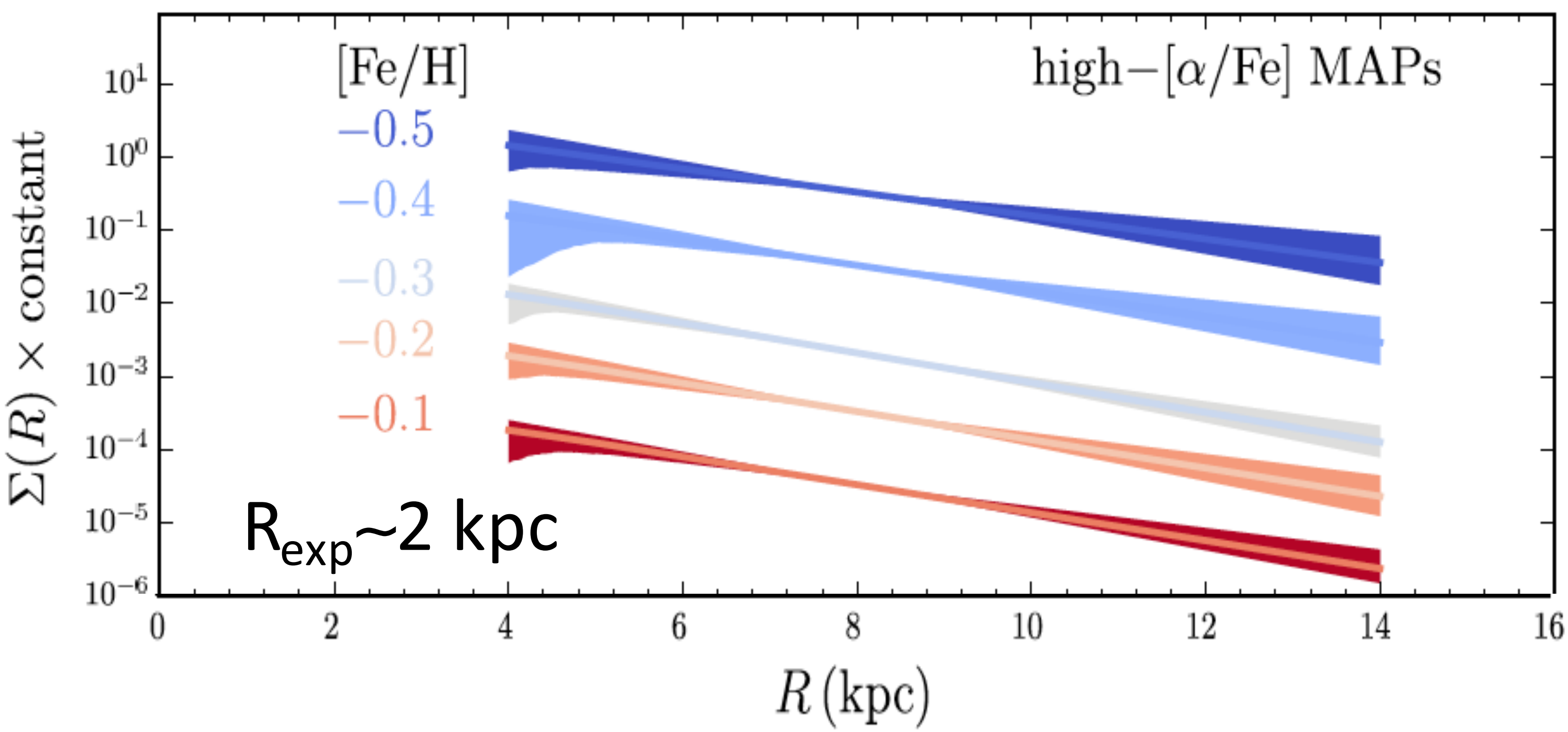


+ selection function & 3D dust map → (R,z) density models

The Structure of Mono-Abundance Populations in the Galactic Disk, as seen by Apogee

Bovy, Rix et al 2015



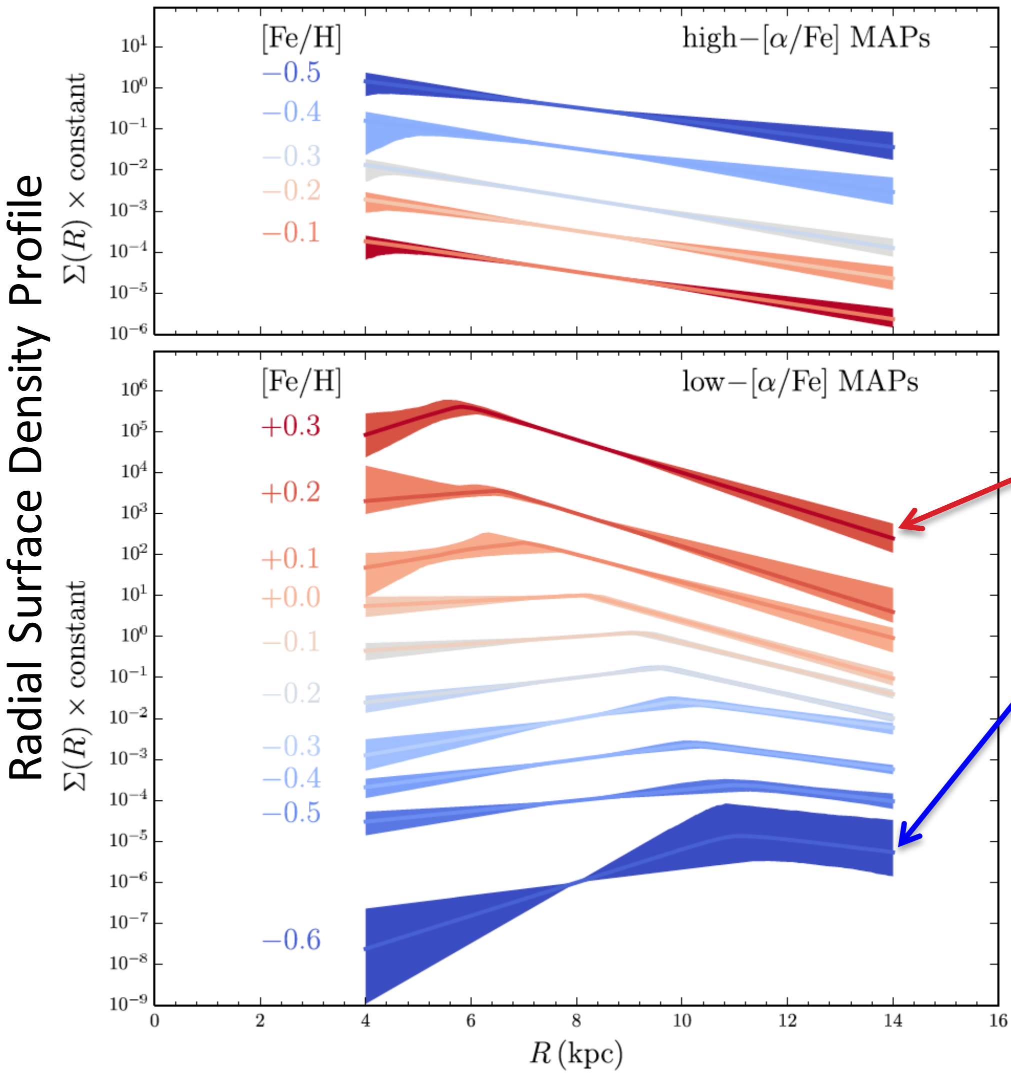


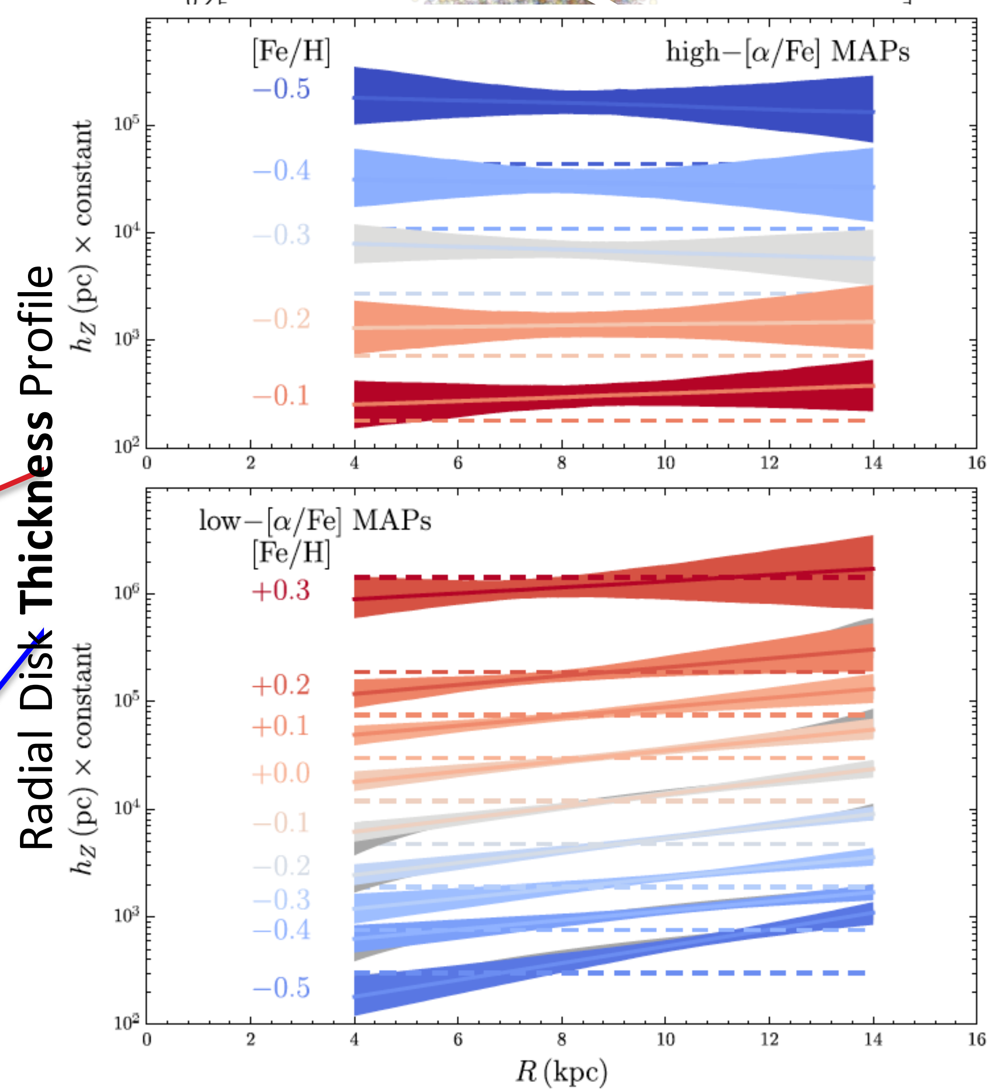
low-α radial profiles rise and fall!

MW disk is a set of donuts!

low-α disk flares/compresses

early/thick disk does not!





Expected from chemical evolution models

e.g. Sanders, Binney, ..2015

What are the next challenges?

[Focus on a disk formation/evolution perspective]

- **Consistent p(orbit,τ_{age},[X/H], ..) throughout the Galaxy**

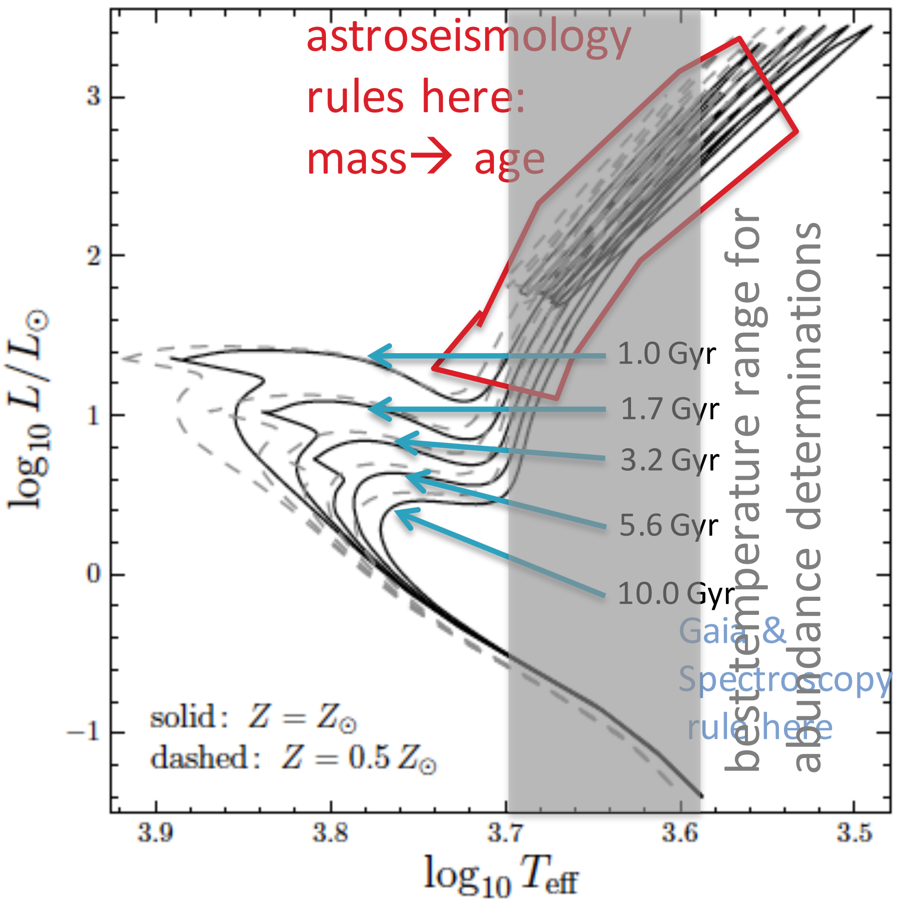
  → put *different* surveys on the same footing

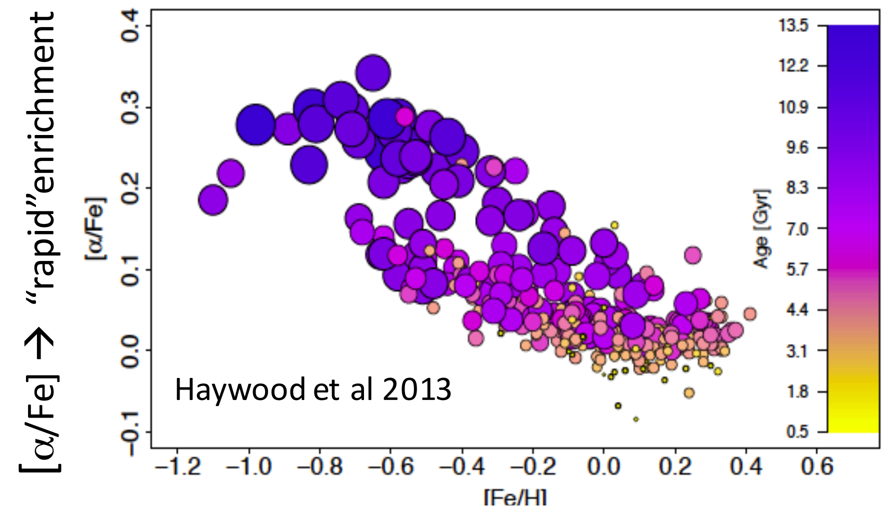
- **Get *ages* for extensive samples of stars!**
  - independent of those "implied" by their [X/H]

- **Understand the complexity of [X/H] space**

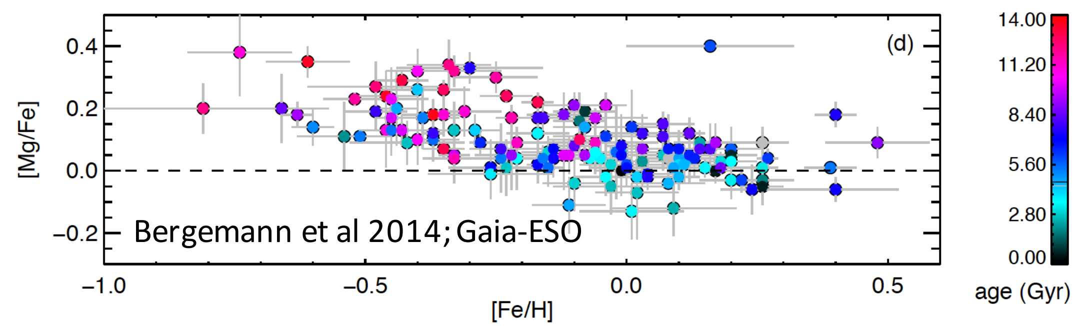
Ages

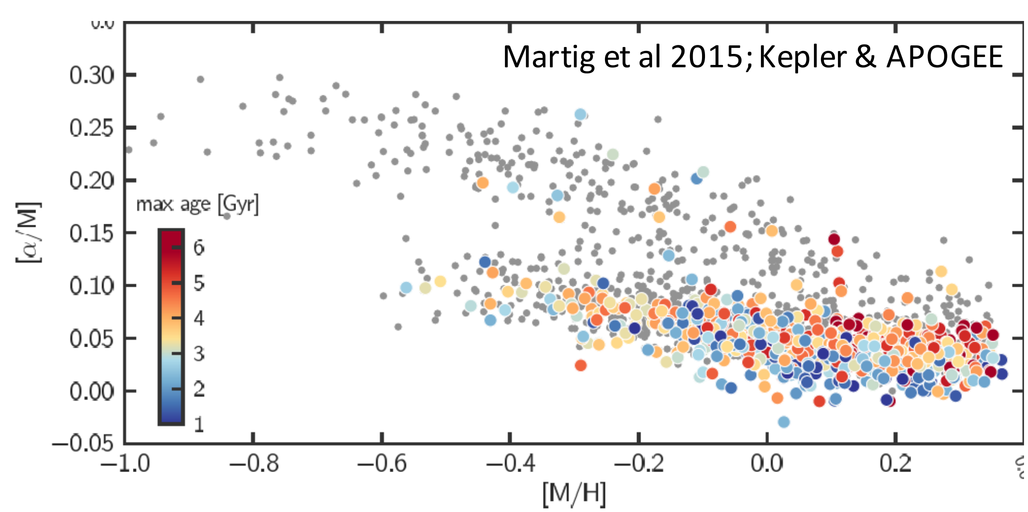
independent of their "abundances proxies"





[Fe/H] → more prior enrichment





Soderblom 2010 review!

Transferring information from one survey to another: *The Cannon**

(Ness, Hogg, Rix, Ho, Zasowski, 2015; A. Ho, Ness et al in prep.)

- Basic assumptions
  - spectra of stars with the same labels (T_{eff},log$g$,[X/H], t_{age},…) look the same
  - spectra change smoothly with label changes

- for sub-set of *reference objects*, observed in ***two*** surveys, presume we trust their stellar labels from survey A

- How can we consistently "transfer (i.e. estimate) labels" to bring survey B onto the same footing?

* Annie Jump Cannon

(Simplified) *Cannon* math for transferring information from one survey to another

Ness,Hogg, HWR et al 2015 & Anna Ho, Melissa Ness, et al in prep.

- Training Step:
  - fix spectrum model, **one** pixel at a time with **all** reference stars
  - Spectra from "new" survey, Labels from "understood" survey A!

spectra in "new" survey **well-understood objects**

$$f_{n\lambda} = a_\lambda + b_\lambda(\mathrm{Teff})_n + c_\lambda(\mathrm{logg})_n + d_\lambda([\mathrm{Fe/H}])_n + \mathrm{scatter}_\lambda$$

- Test Step
  - Take same model coefficients, estimate stellar labels across **all** pixels of **one** survey B object at a time

$$f_{m\lambda} = a_\lambda + b_\lambda(\mathrm{Teff})_m + d_\lambda(\mathrm{logg})_m + d_\lambda([\mathrm{Fe/H}])_m + \mathrm{scatter}_\lambda$$

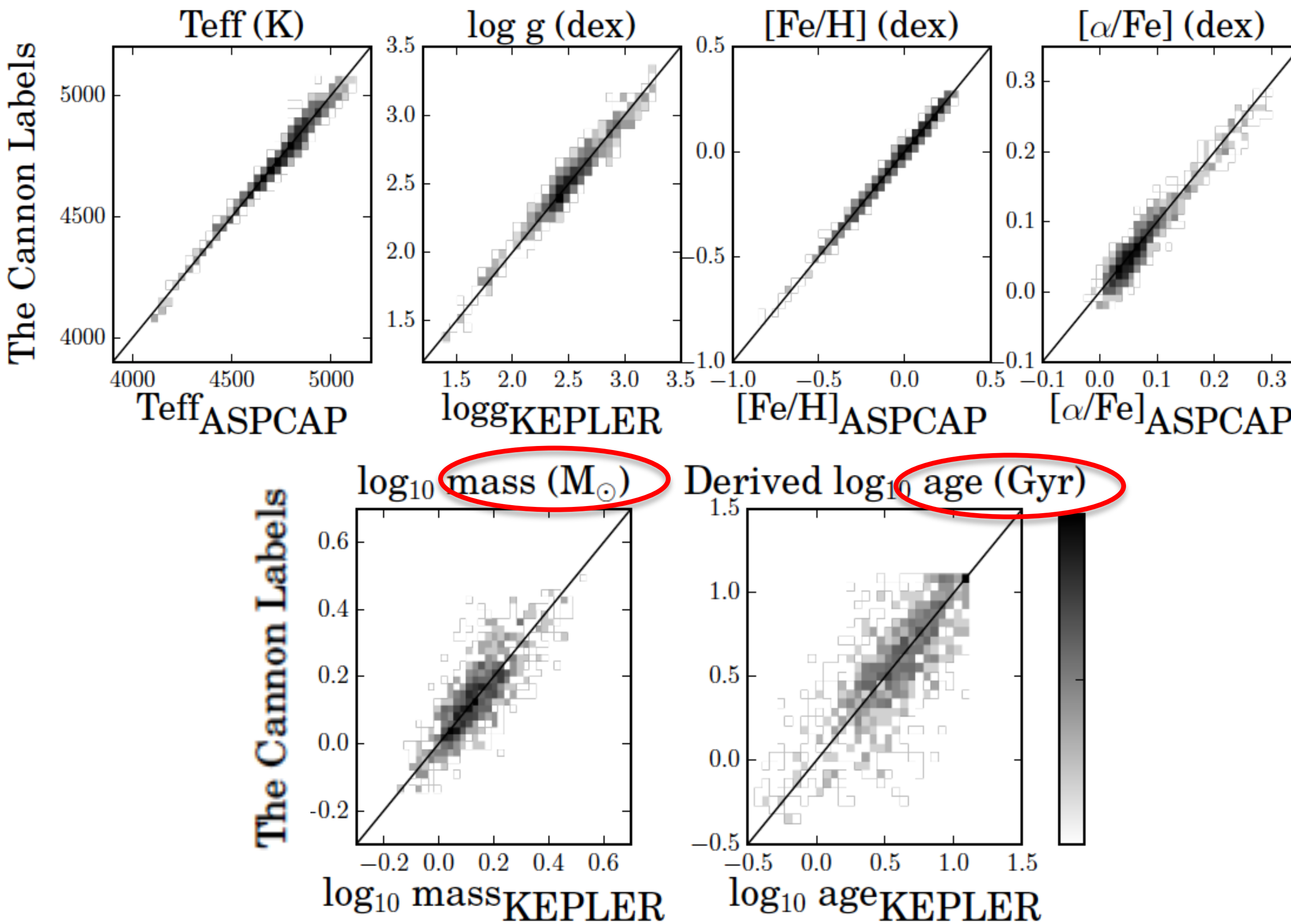
Spectra of new survey objects

→ labels for new survey objects

Spectroscopic age estimates throughout the disk?

Ness, Hogg, HWR et al 2015, Martig, HWR et al 2014 & 2015

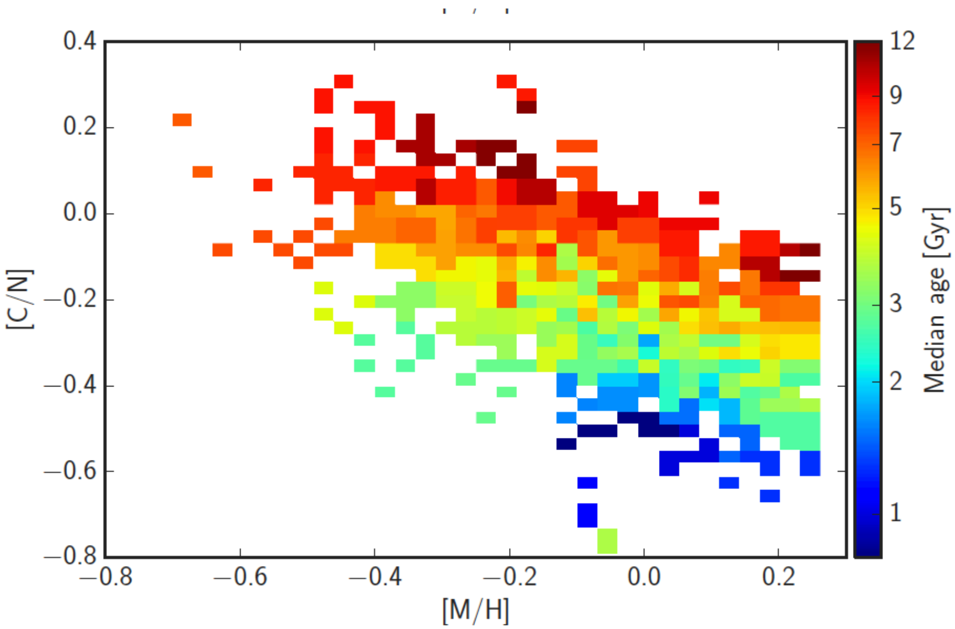
- about 1600 stars with astroseismic mass/age estimates (Kepler) have Apogee spectra…



"leave-one-out" tests

What's "behind" these spectroscopic age estimates for giants?

- Signature is in CN features!
- Why? Mass-dependent dredge-up alters the C & N abundances

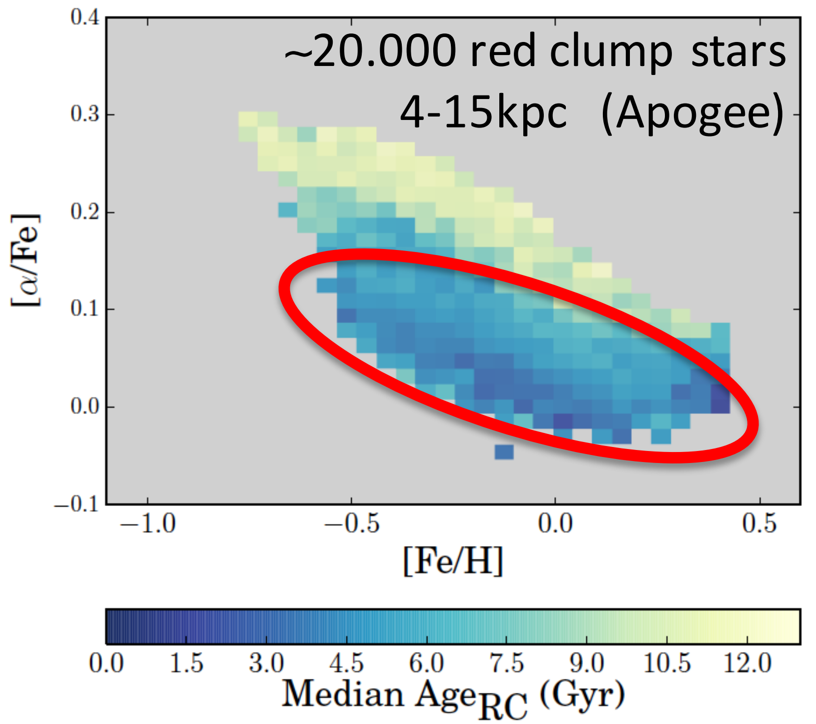


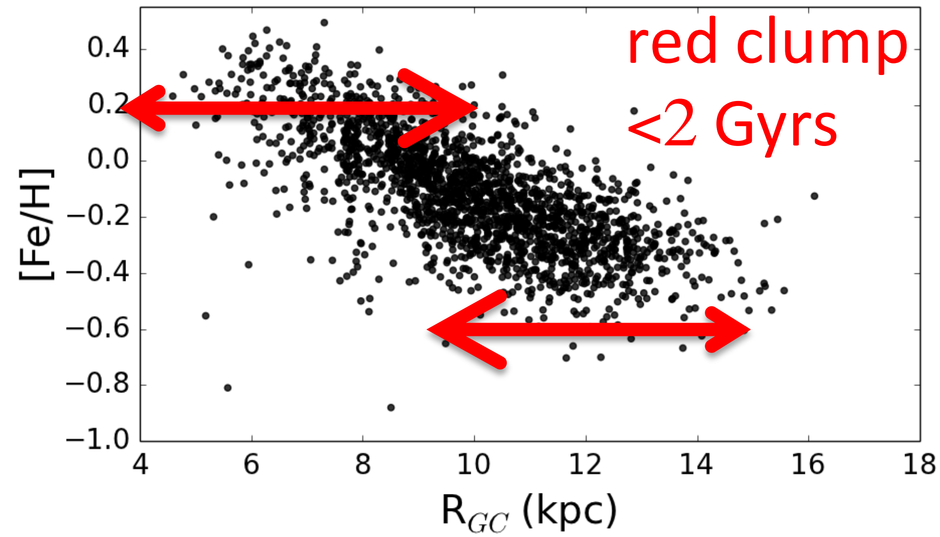
Based on APOGEE spectra:
Martig et al 2015 (submitted); Masseron, Gilmore et al 2015

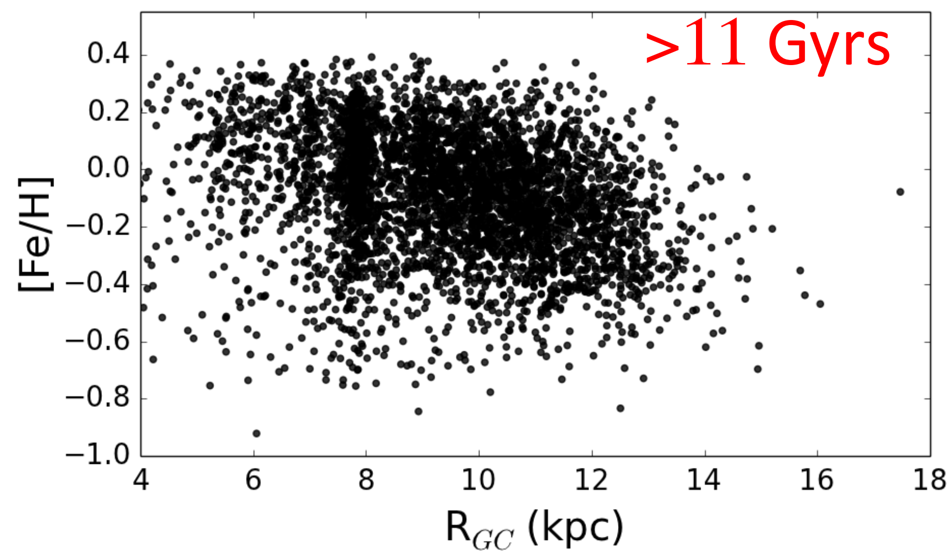
[a/Fe] dependence fitted/marginalized →
age estimate NOT a reflection of birth material composition

Abundance/Age Distribution through the Disk

Ness et al 2015, Martig et al 2015 (submitted)





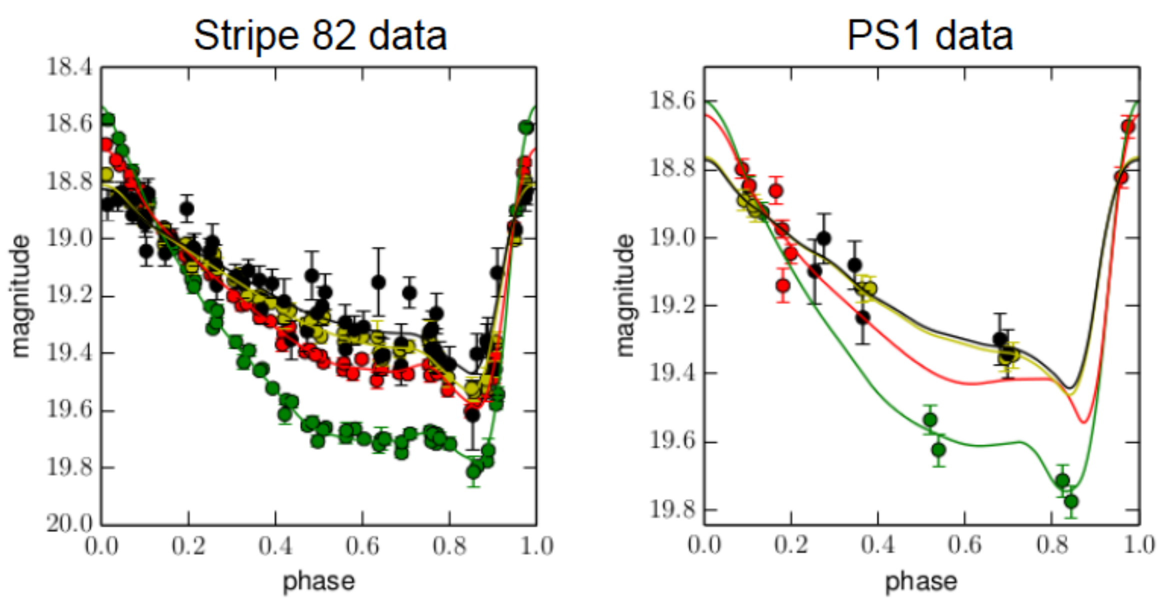


Towards a large-scale test of radial migration efficiency?

Mapping Stars (and Mass) in the Halo

- Gaia can provide proper motions, but no good distances
  → need standard candles

- RR Lyrae from PanSTARRS1 survey (Hernitschek et al, Sesar et al 2015)
  ~35 epochs spread across 5 bands and 3.5 years --- over ¾ of the sky,
  getting periods to 2sec (!!) for 80% of cases

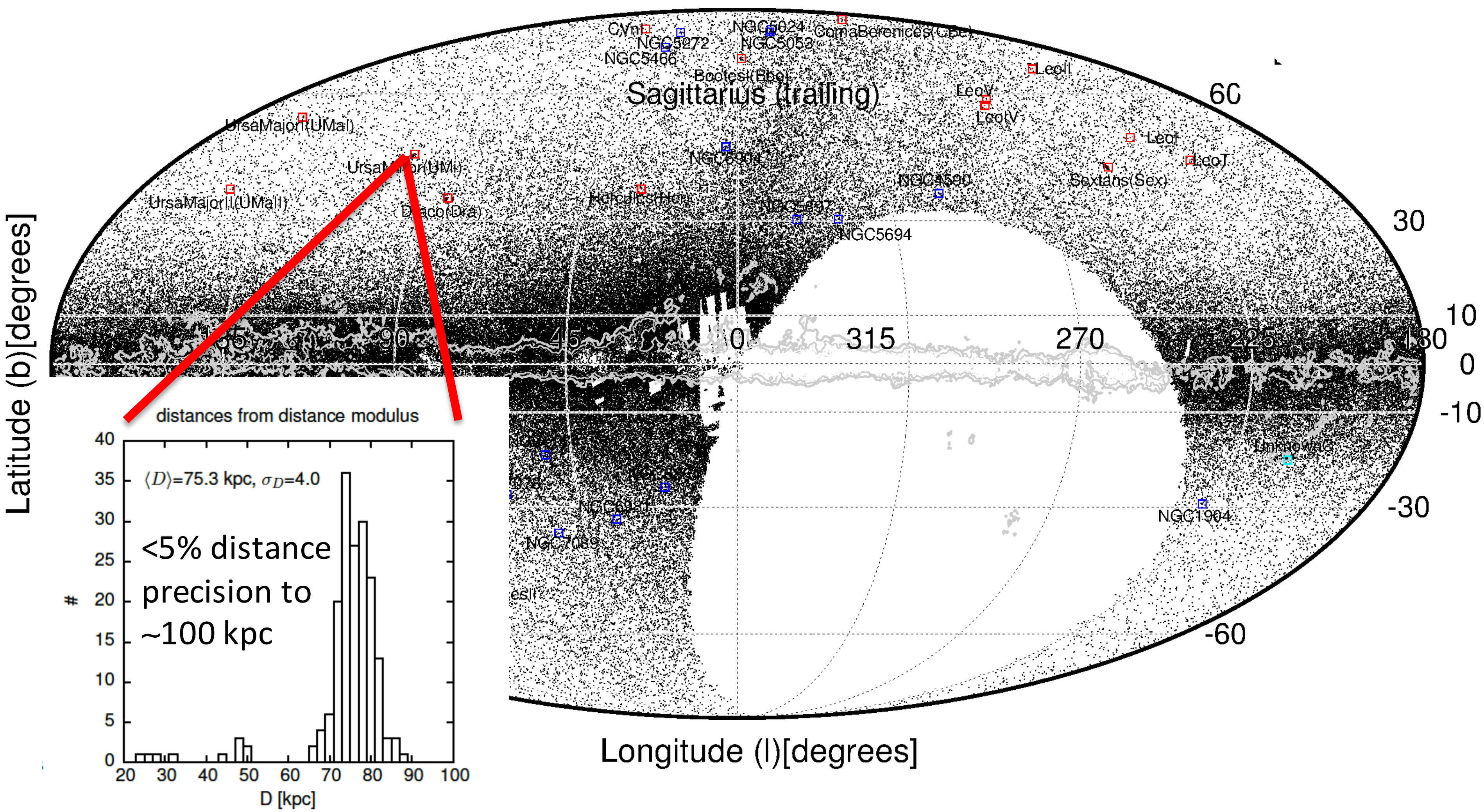


Mapping Stars (and then Mass) in the Halo

Hernitschek, Sesar,HWR et al 2015

200,000 RR Lyrae candidates

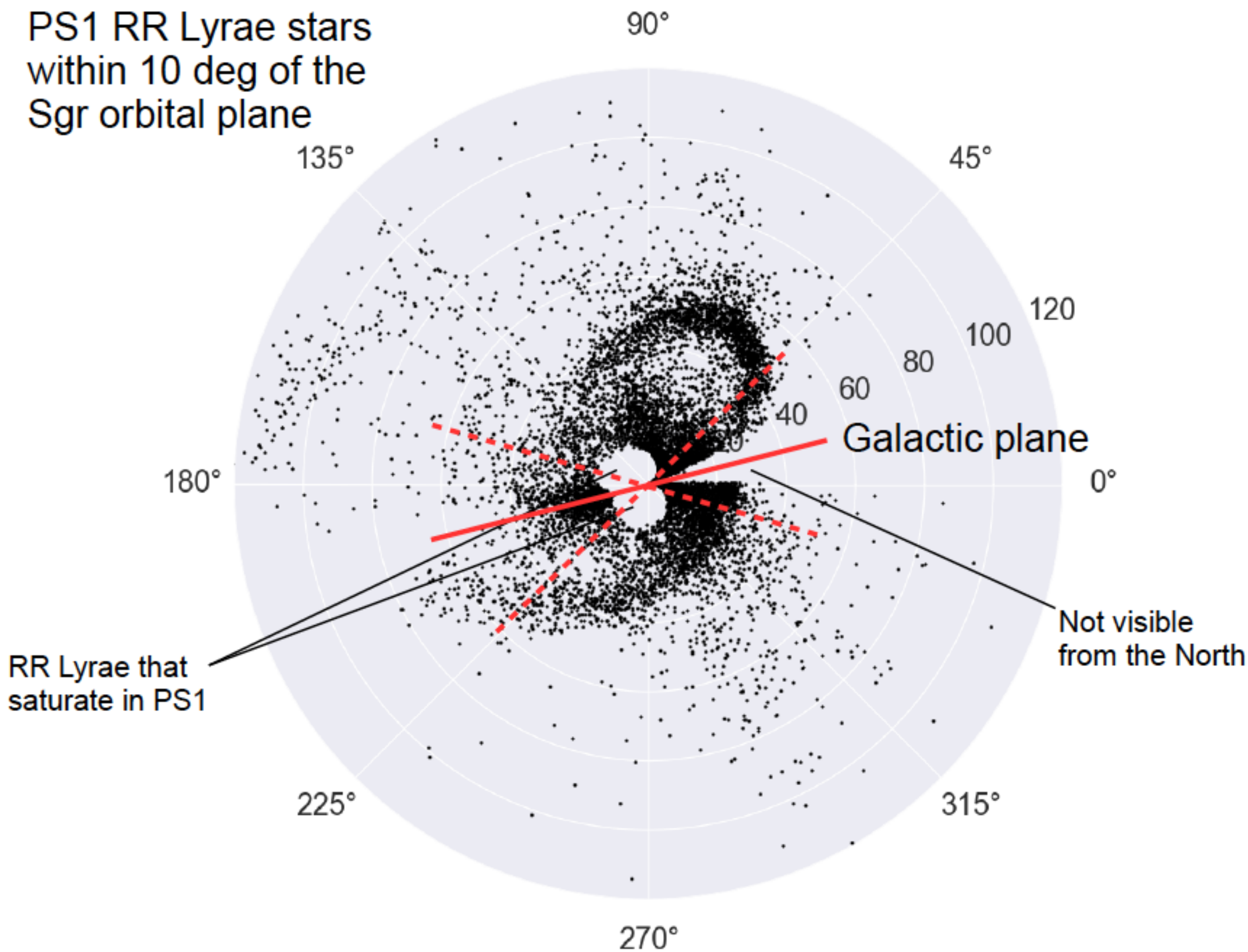
distribution of $p_{RRLyrae}$>0.05 vs. (l,b)



Mapping Stars (and Mass) in the Halo

Orbital plane of the Sgr. stream

(Hernitschek et al, Sesar et al 2015)



Where do we stand?

- Incredibly rich data sets coming together at staggering rate
- **These enable truly different ways to look at the/a Galaxy**
- Enormous amount of technique development still needed
- Gaia is coming!
  - Immediate: calibrating stellar physics and orbits throughout the MW
  - will only enhance the need for Galactic spectroscopy surveys
  - not being part of LSST will hurt