The role of stellar populations in making the Milky Way
a testbed for galaxy formation

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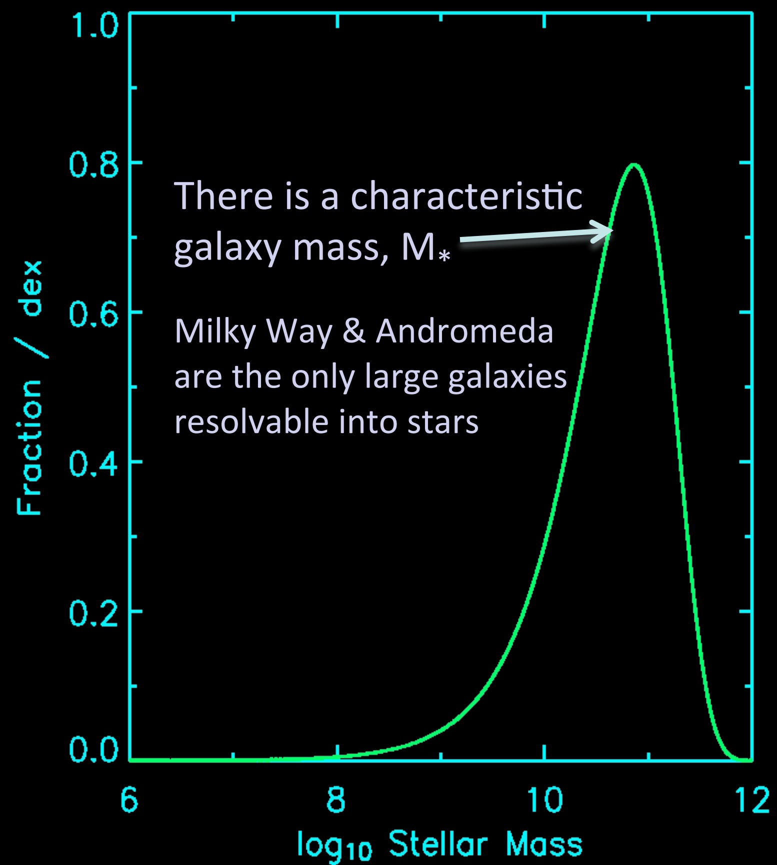
Review reading:

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
  - $6 \times 10^{10} M_{Sun}$ in stars, ¾ in a disk
  - Making 'realistic galaxy disks' in *ab initio* simulations remains difficult

- It's what we got (best)
  - star-by-star in 6+N dimensions

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

Why “galaxy people” need to learn about stars & stellar populations

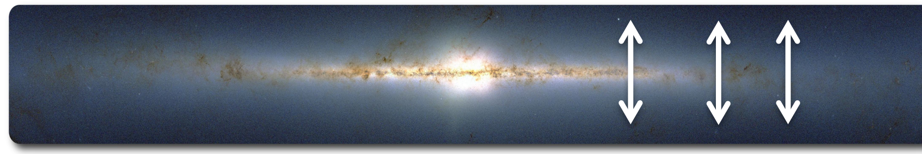
- Stars are the defining constituents of galaxies
- Stars are best probes of the (3D) matter distribution
- The chemo-orbital distribution of stars are the best empirical encoding of a galaxy’s formation history

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

What aspects of (disk) galaxy formation can be uniquely tested/inferred in the Milky Way?

- 3D distribution of the (dark) matter
- What processes create a stellar halo?
  - What processes shape the population of satellite galaxies?
- What (init) conditions & processes set stellar disk structure?
- What processes shape the "innards" (bulge, bar, etc..)?
- How does chemical enrichment "work"?
  - How does gas inflow/accretion & feedback work?
  - Is primeval IMF dramatically different?

3D Mass Distribution in Milky Way



- DM at ***small*** radii:
- Disk self-gravity & dark disk?

  DM cusp/Core in a big galaxy?

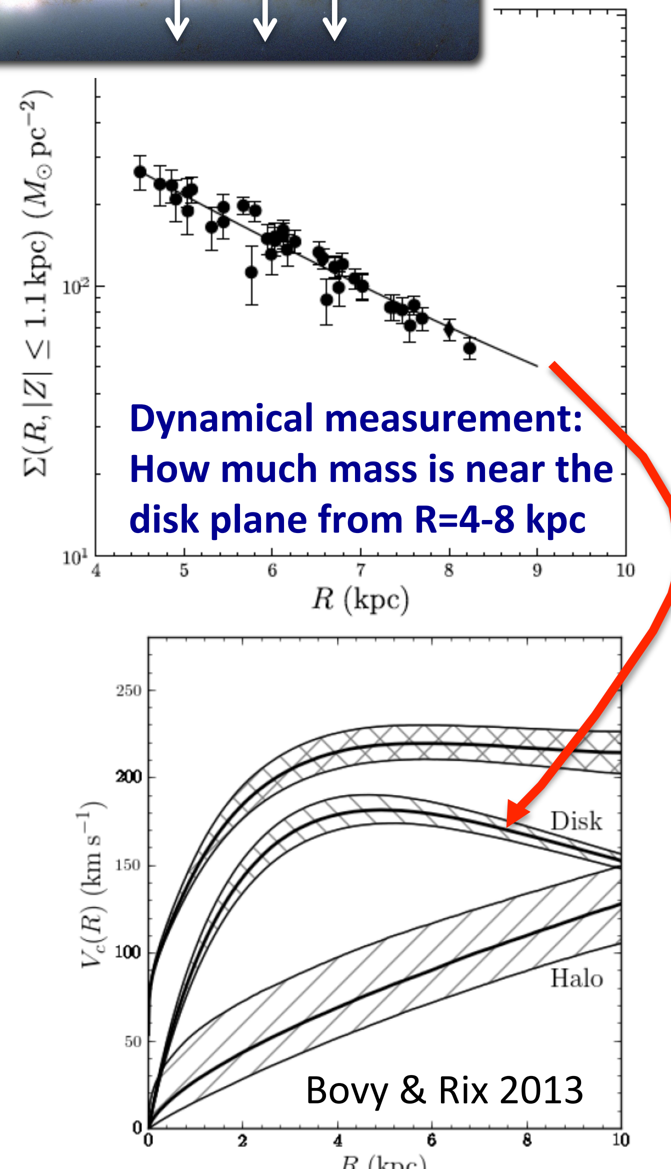
  D: disk and halo dynamics

- "Shape" of the DM halo?

  D: stellar streams and halo stars

- Star-less low-mass DM halos?

  D: bumps in cold stellar streams



D: "Diagnostics"

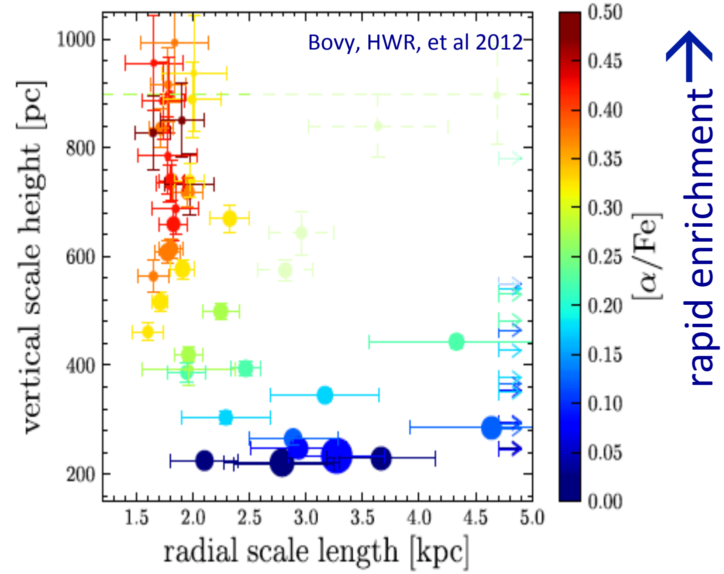
What Factors Set/Shape the Structure of the Disk?

- What matters for the radial profile?
  - initial angular momentum
  - radial migration

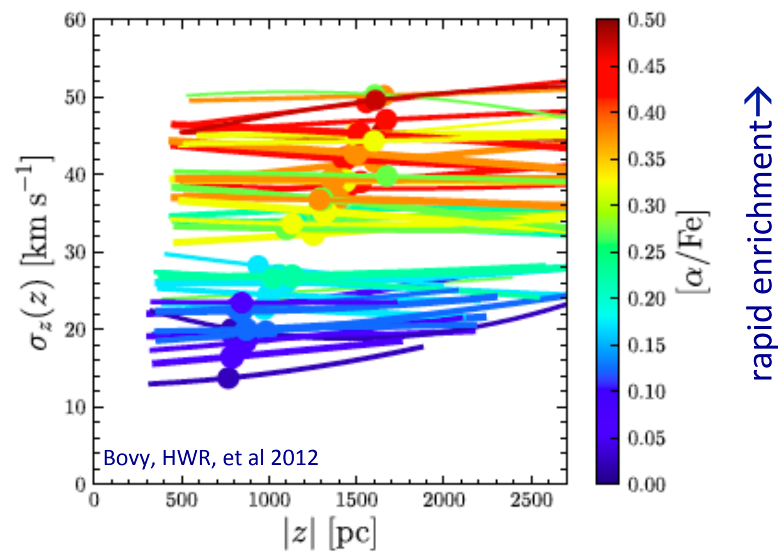
  D: $h_R(t_{age})$, chemical tagging, chemo-dynamical models

- What sets vertical disk structure?
  - (intially) unsettled gas
  - secular heating
  - impulsive heating

  D: $\sigma_z(t_{age})$, satellite-debris in the disk



vertical σ_z dispersion profile



NB: 0.07 syst.err. in [α/Fe] ←→ 25% in σ_z

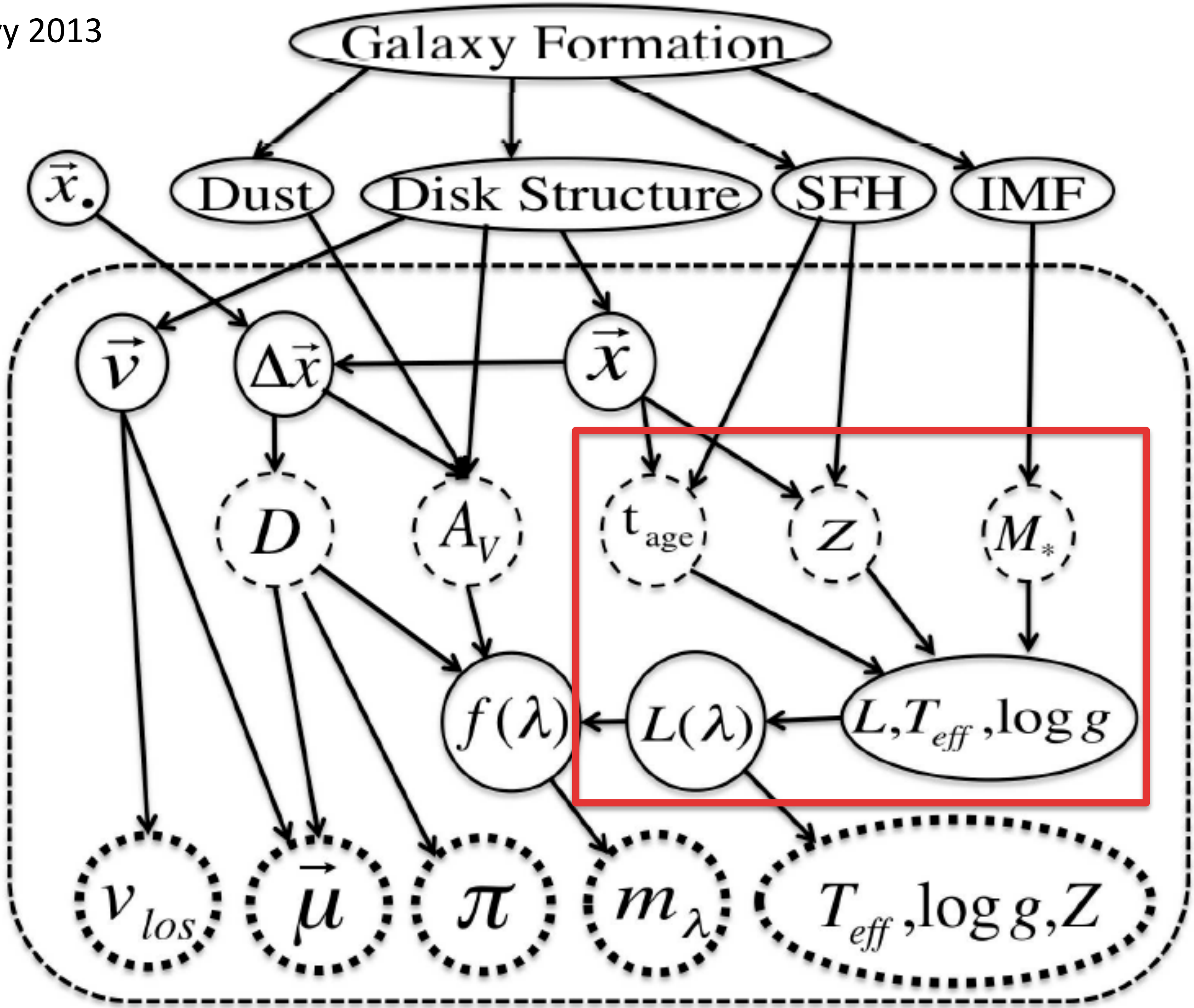
What is the (ideal) set of observables?

- p($\boldsymbol{r},\boldsymbol{v}$, M_*, L_*, log g, T_{eff}, t_{age}, [Fe/H],[α/Fe],[X/H]...)
  - 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!
    - Surveys: SEGUE, RAVE, APOGEE, PanSTARRS, Gaia-ESO,LAMOST, Galah, Gaia, etc..

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

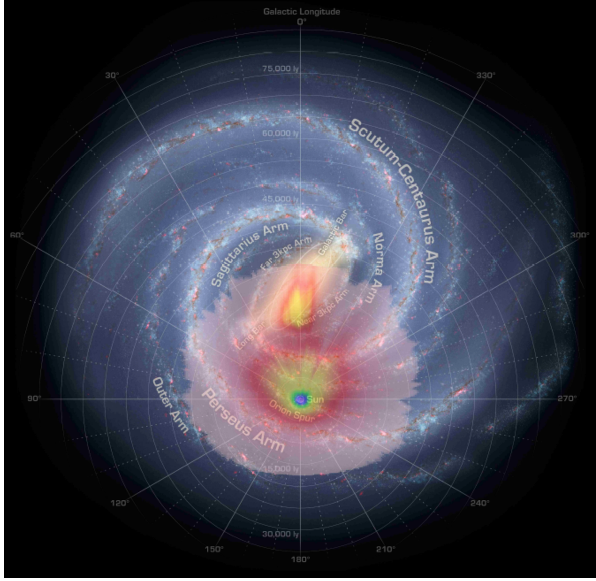
  p(Orbits ($\boldsymbol{r},\boldsymbol{v}$) | f_*, t_{age}, [Fe/H],[α/Fe],...) requires Φ(r)

Rix & Bovy 2013



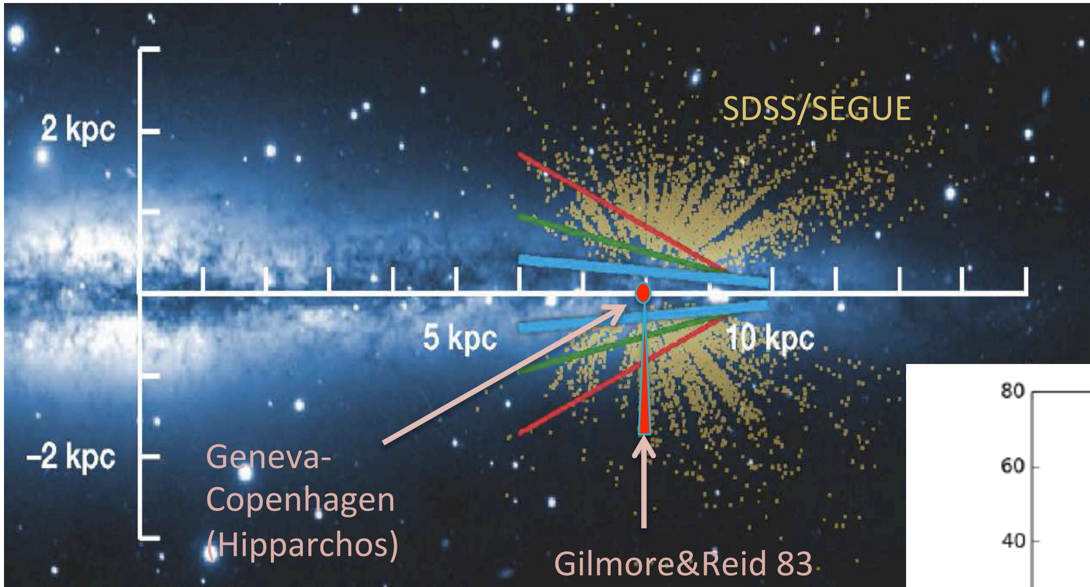
Know thy selection function

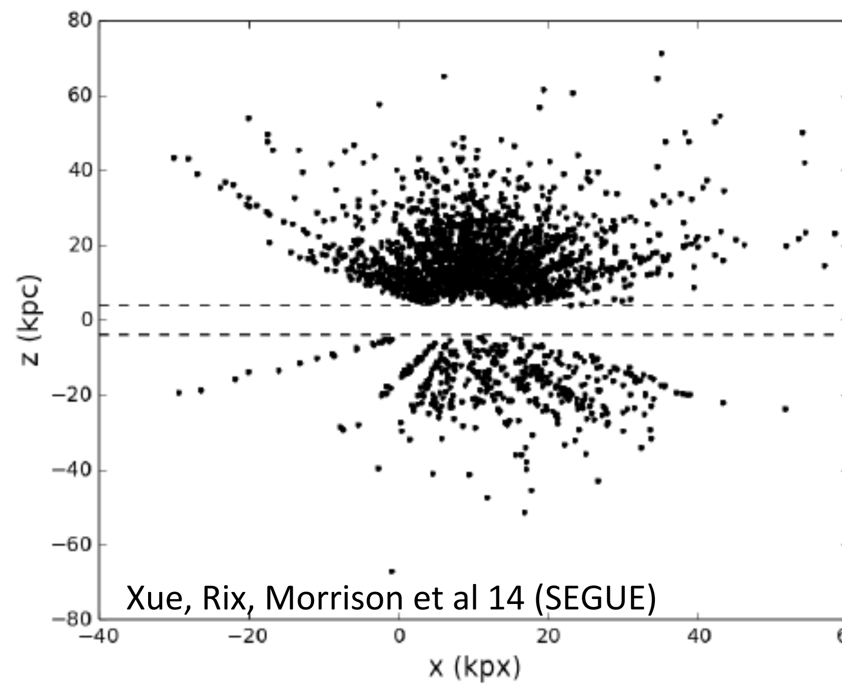
..just having a catalog with perfect entries in not good enough..



$$p_{sample}(\ell, b, D, A_V, L_*, T_{eff}, [Fe/H])$$

Now the Galaxy is being covered systematically with spectra





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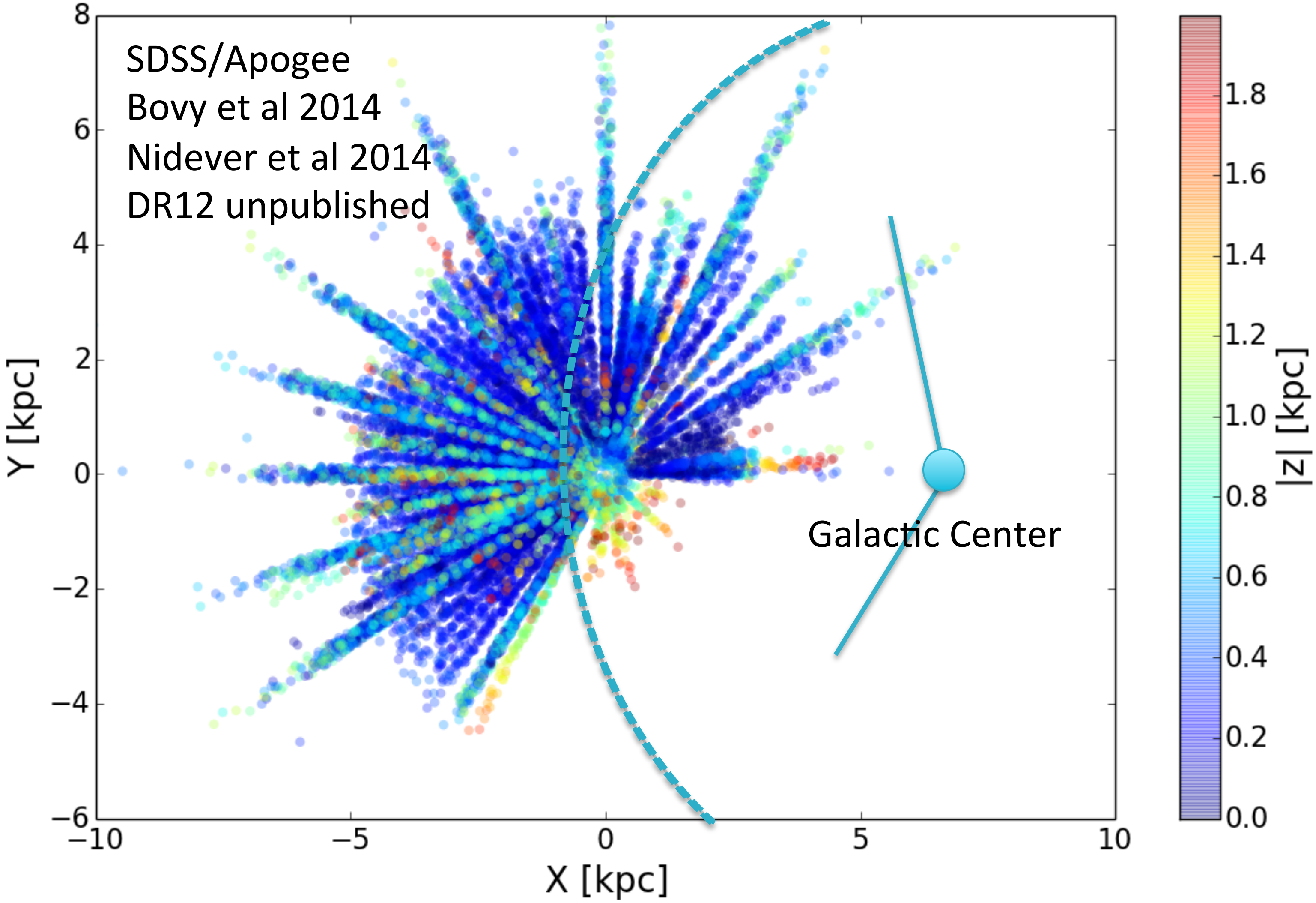
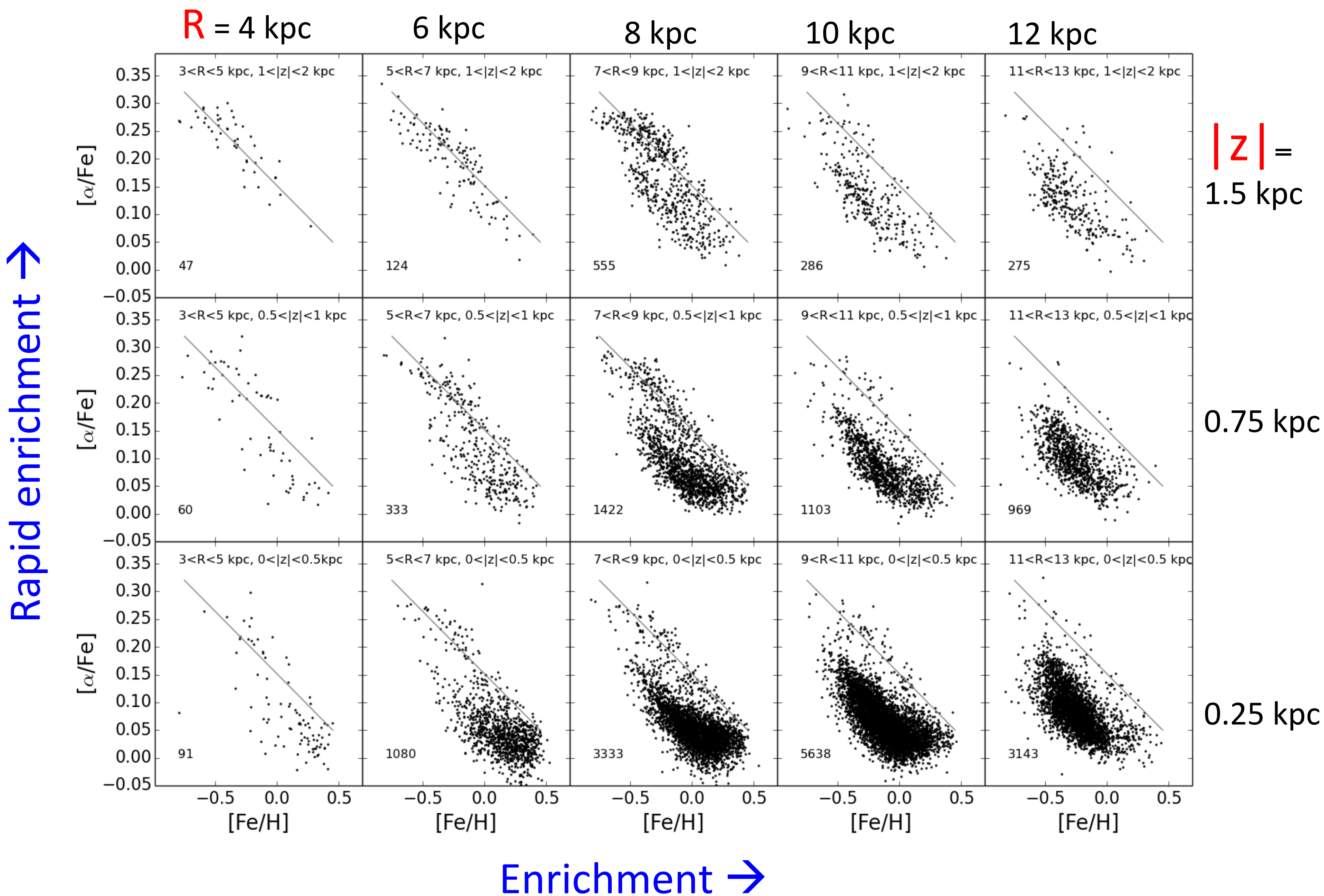
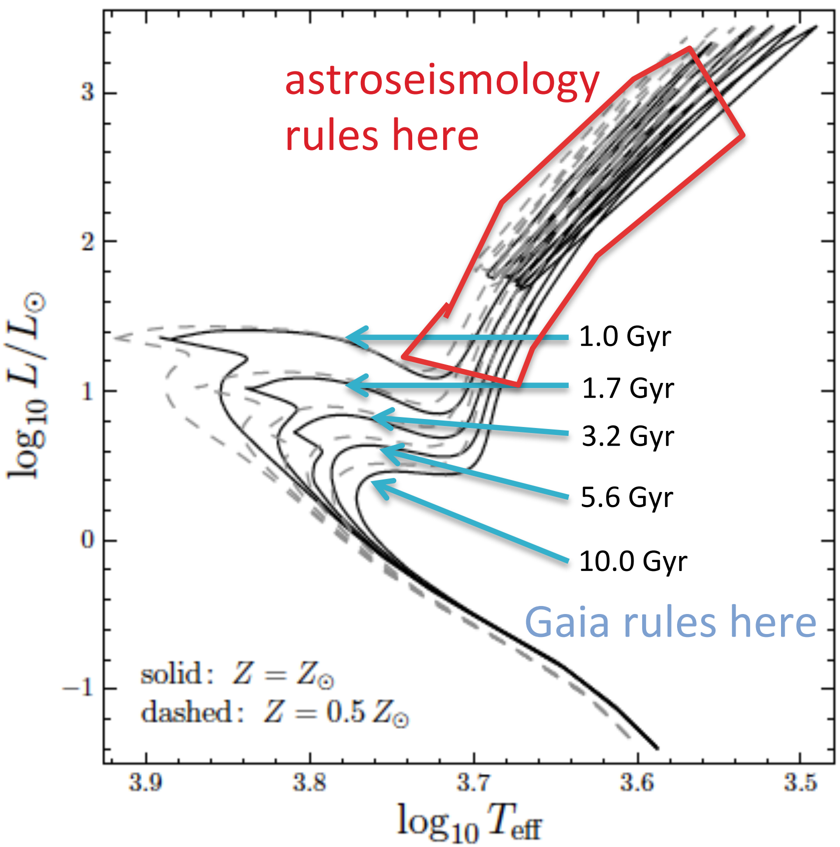
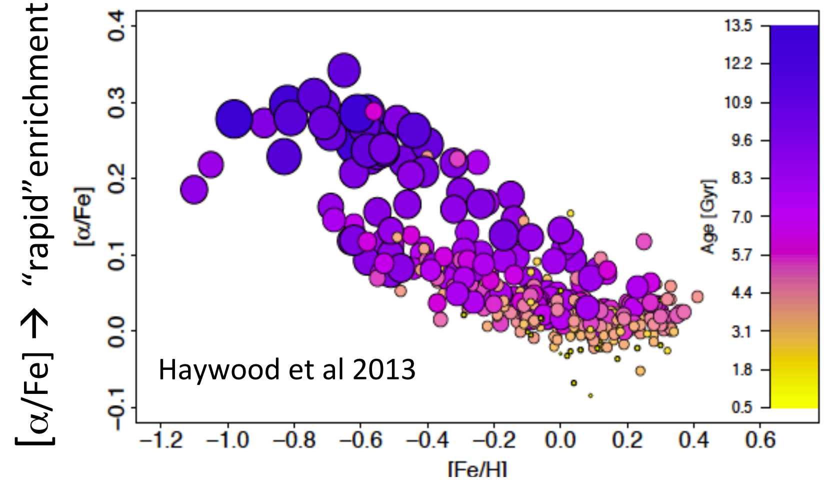




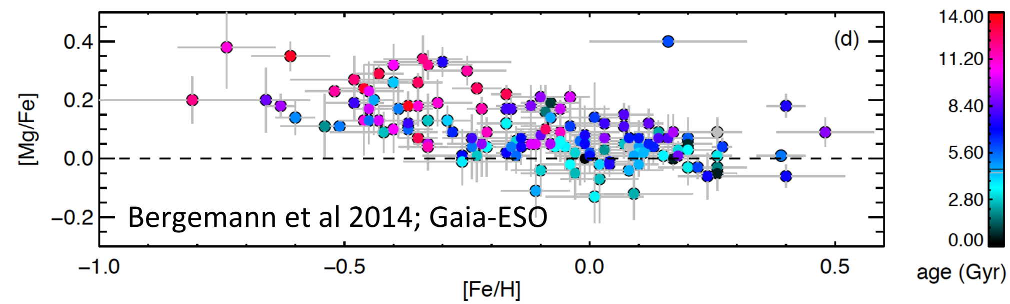
R = 4 kpc
6 kpc
8 kpc
10 kpc
12 kpc
|z| =
1.5 kpc
0.75 kpc
0.25 kpc
3<R<5 kpc, 1<|z|<2 kpc
5<R<7 kpc, 1<|z|<2 kpc
7<R<9 kpc, 1<|z|<2 kpc
9<R<11 kpc, 1<|z|<2 kpc
11<R<13 kpc, 1<|z|<2 kpc
47
124
555
286
275
3<R<5 kpc, 0.5<|z|<1 kpc
5<R<7 kpc, 0.5<|z|<1 kpc
7<R<9 kpc, 0.5<|z|<1 kpc
9<R<11 kpc, 0.5<|z|<1 kpc
11<R<13 kpc, 0.5<|z|<1 kpc
60
333
1422
1103
969
3<R<5 kpc, 0<|z|<0.5kpc
5<R<7 kpc, 0<|z|<0.5 kpc
7<R<9 kpc, 0<|z|<0.5 kpc
9<R<11 kpc, 0<|z|<0.5 kpc
11<R<13 kpc, 0<|z|<0.5 kpc
91
1080
3333
5638
3143
[α/Fe]
[Fe/H]
Rapid enrichment →
Enrichment →

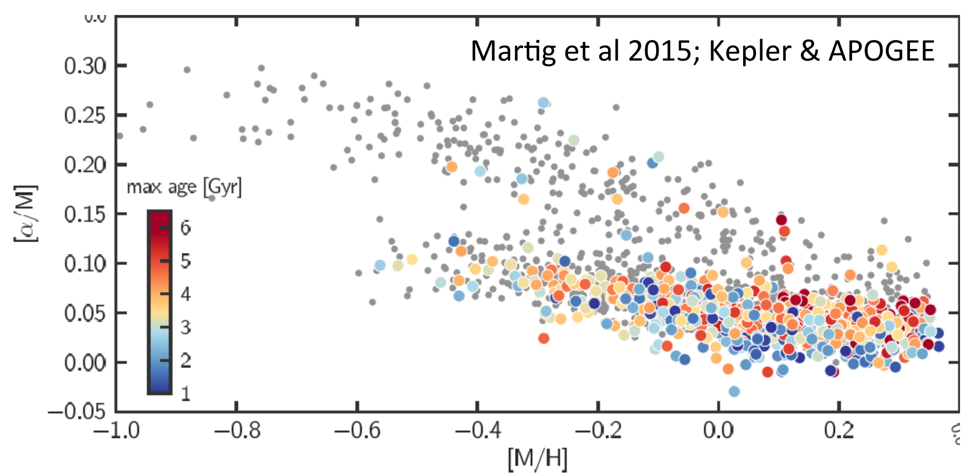
Ages and their "abundances proxies"





[Fe/H] → more prior enrichment





Soderblom 2010 review!

Bringing surveys on the same footing with *The Cannon*[*]

(Ness, Hogg, Rix, Ho, Zasowski, 2015, today's astro/ph)

- for sub-set of *reference objects*, observed in ***two*** surveys, presume we trust their stellar labels (T_{eff},log*g*,[X/H], etc..) from survey A

- Basic assumptions
  - spectra of stars with the same labels look the same
  - spectra change smoothly with label changes

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

[*] Annie Jump Cannon

The (simplistic) Math of *The Cannon*

- Training Step:
  - fix model, **one** pixel at a time with **all** reference stars
  - Labels from survey A, spectra from survey B!

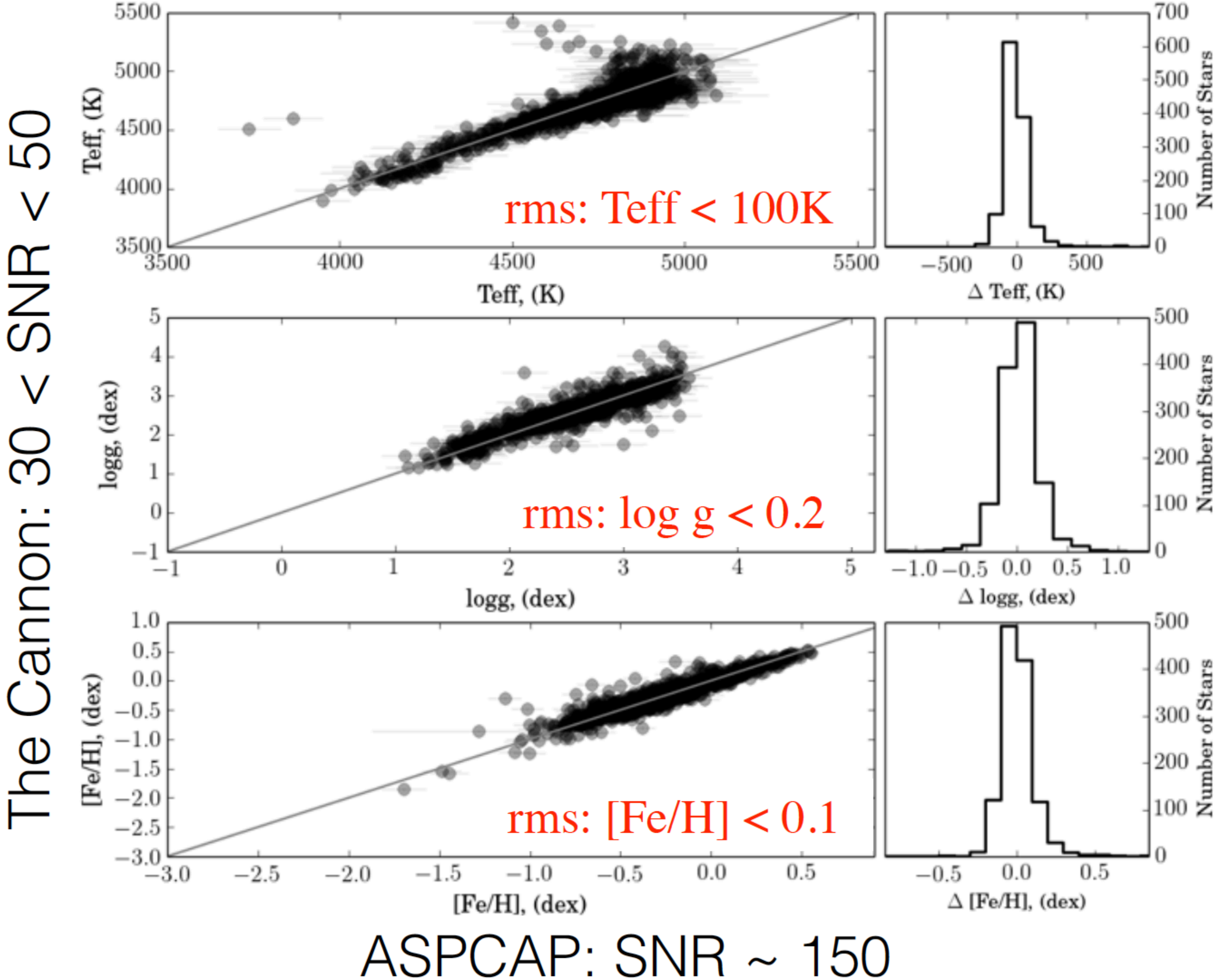
$$f_{n\lambda} = \quad a_\lambda + b_\lambda(\mathrm{Teff})_n + c_\lambda(\mathrm{logg})_n + d_\lambda([\mathrm{Fe/H}])_n + \mathrm{scatter}_\lambda$$

in practice this is a polynomial function of the labels

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

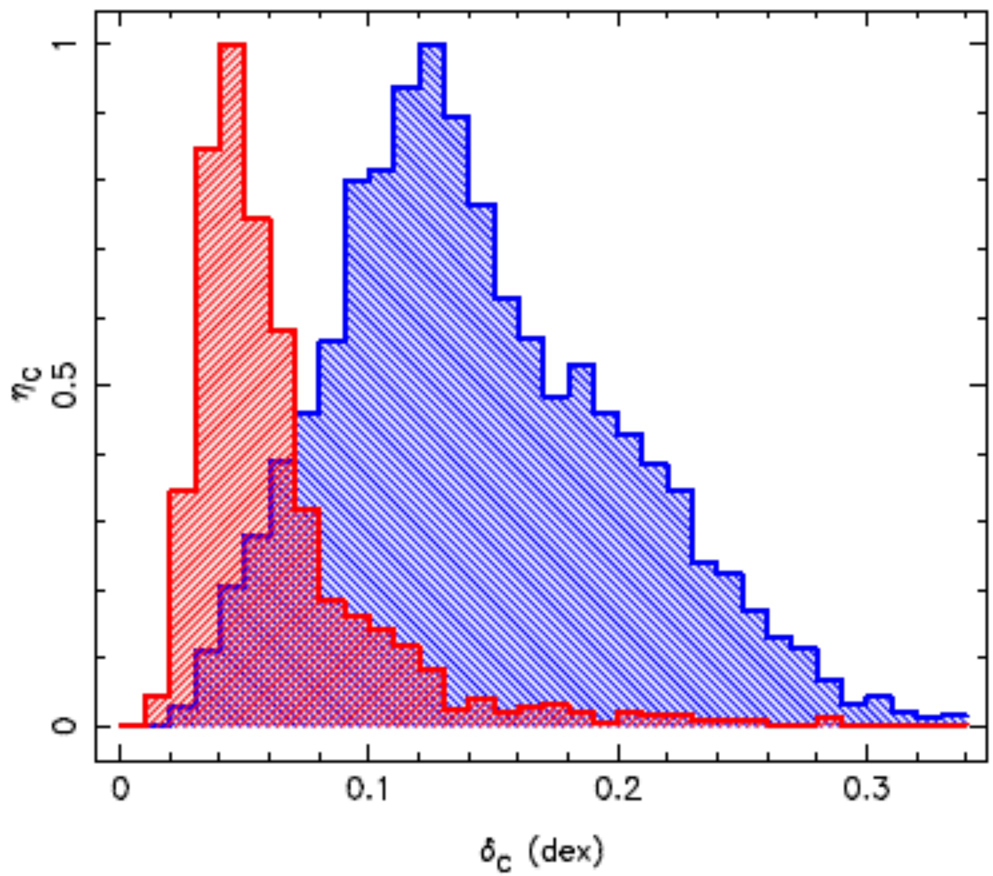
$$f_{m\lambda} = \quad a_\lambda + b_\lambda(\mathrm{Teff})_m + d_\lambda(\mathrm{logg})_m + d_\lambda([\mathrm{Fe/H}])_m + \mathrm{scatter}_\lambda$$

The Cannon @ SNR ~ 40 and ASPCAP @ SNR ~150



So, what's on everybody's plate?

- Wrapping your mind around the imminent Gaia information
- Getting good stellar ages in different parts of the galaxy
- Putting different surveys (stellar parameters & abundances) on the same (and correct) footing
- So, now you have the "ideal" data set
  - What's the best way to do dynamical models
  - What's the best way to test formation history
  - What's the best way to test enrichment processes
  - How is "chemical tagging" put into practice?



1
0.5
0
η_C
0
0.1
0.2
0.3
δ_C (dex)