What data can do for you

H-W Rix, April 10, 2012

A worked example & a soapbox

- **The Worked Example[*]:**

  How the Galactic disk grew: from '*old, fat and short*' to '*young, thin and long*'

  - You can see it in the data
  - It's hard to resist (over-?)interpretation

- **The Soapbox:** (or: what YOU need to do for the data)

  A) Understanding the selection functions is the limiting factor for doing dynamics of discrete tracers in the Milky Way

  - dynamics links underlying (spatial) densities to kinematics [precision? $1/\mathrm{sqrt}(N_*)$]
  - two options: throw away large fraction of the information, or do hard work

  B) The data themselves are an excellent (self-)calibration source

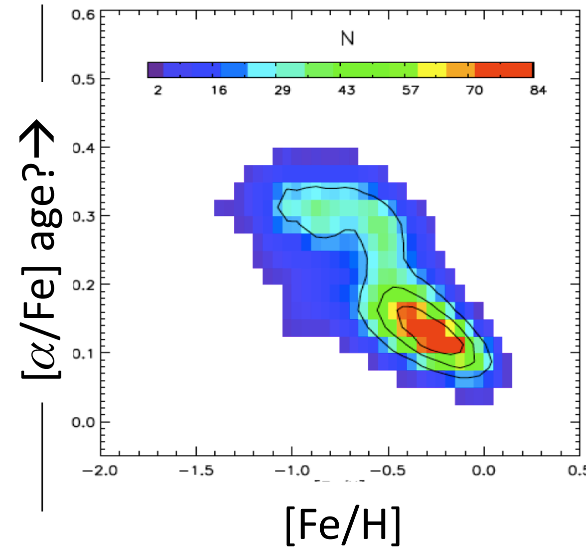
  C) Dynamics tell you the 'now'

  - Qualitative 'formation history' speculation in easy
  - Quantitative 'scenario testing' is very hard

[*] **Bovy, Rix et al 2011/12**

What if you could look at the Milky Way's Disk with Eyes only for Stars of a Certain Age?

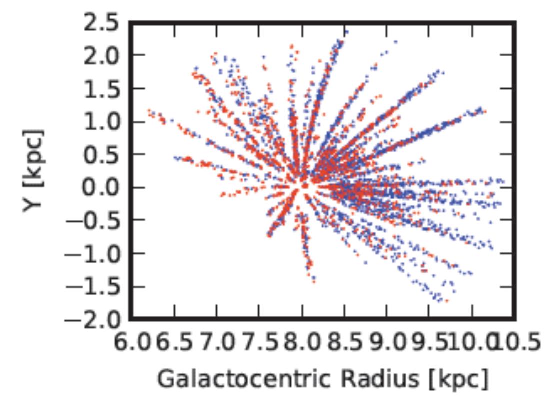
Bovy, Rix, et al 2011a

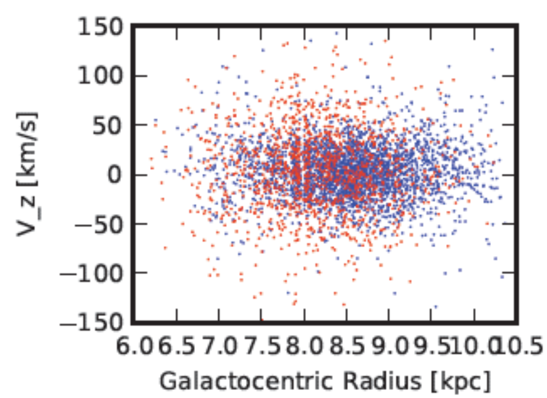


- Accept *mono-abundance* sub-populations in [α/Fe] & [Fe/H] space as proxy for 'mono-age':

  α–enhanced ← → rapid (early?) enrichment,
  best practical 'age tag'?

  What is their ***spatial*** and ***kinematic*** structure?
  - vertically, radially
- Data:
  - SEGUE (Yanny et al 2009): G-dwarf sample
  - Complex spectroscopic selection function
    - Target selection: sample 60 stars/plate in m_r,g-r space
    - To get [a/Fe] → spectral S/N limited
      - Exposure time, airmass, seeing, m_r,g-r
  - Distance, survey volume = f([Fe/H])
    → only known *post-facto* (post-spectro)





- Then 'fit'

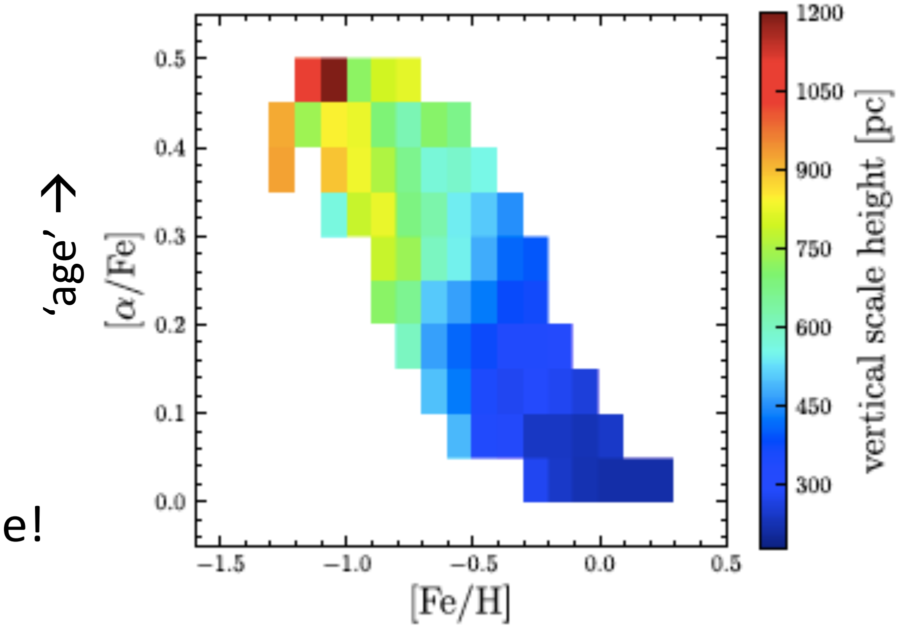
$$\nu_{G-dwarf}(R,z \mid \vec{p}_*([a/Fe],[Fe/H])) = \nu_0 \times e^{-\frac{|z|}{h_z(\vec{p}_*)}} \times e^{-\frac{(R-R_\bullet)}{R_{\exp}(\vec{p}_*)}}$$

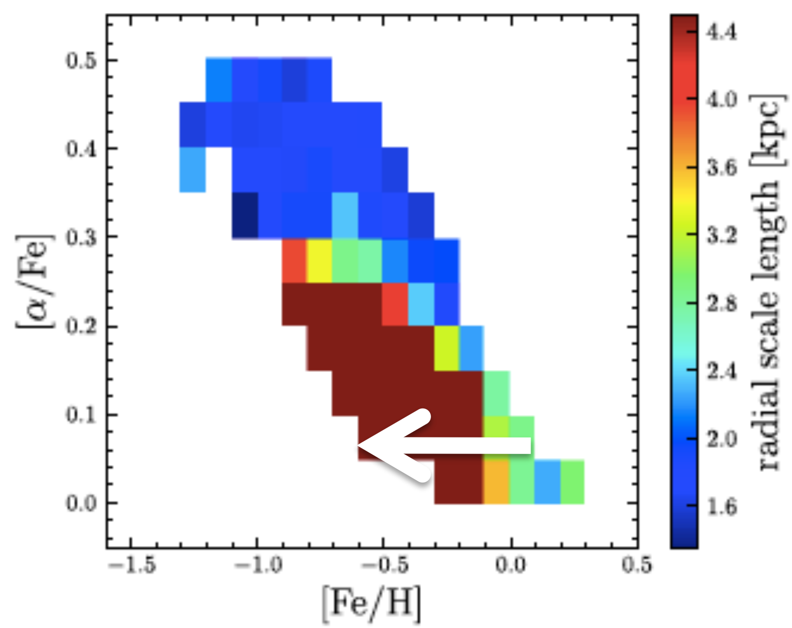
What does the Milky Way's disk look like in stars of a given [α/Fe]-'age'?

- for any given [α/Fe]-[Fe/H], disks are
  - single vertical exponentials (z)
  - single radial exponential (R)

→ mono-abundance components are simple!

- [α/Fe]-old disk components are **thick**
- [α/Fe]-old disk components are **compact**
  - contrary to the geometric decompositions
- At a given [a/Fe]-age, more metal-poor components are more extended!
  - 'outward metallicity gradient'

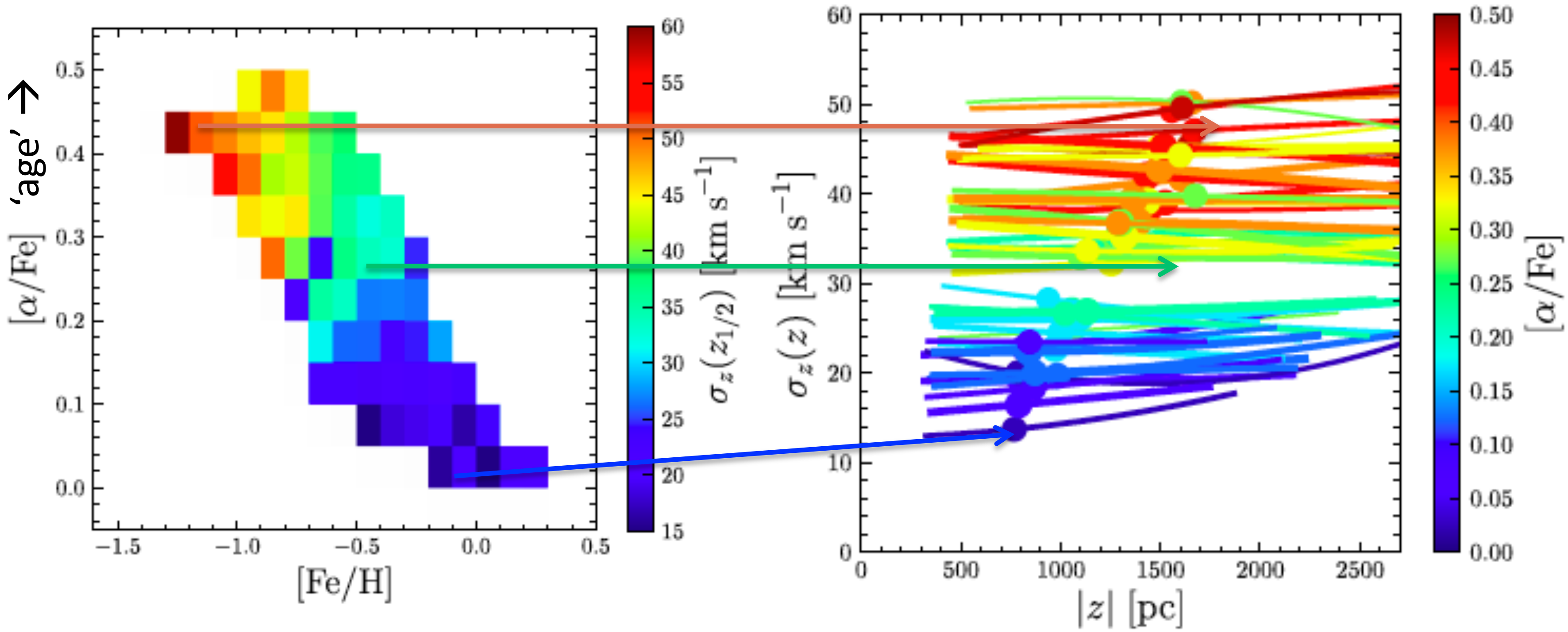




Abundance-dependent kinematics of the MW Disk

Liu & vdVen 2012, Bovy, Rix et al 2012

vertical σ_z dispersion profile



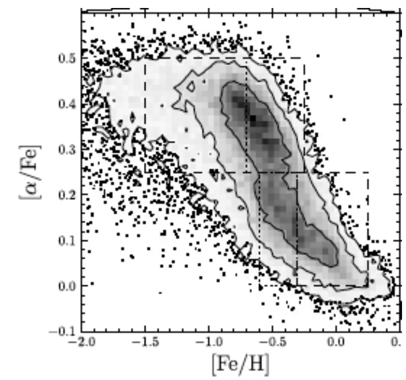
nearly isothermal

Make – and fit – model for velocity dispersion at each [α/Fe], [Fe/H]

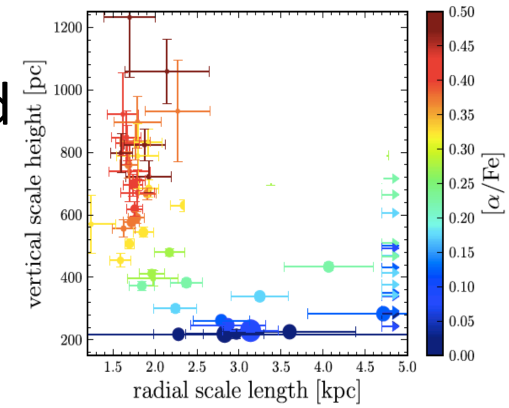
$$\sigma_z(R, z; \theta) = (p_1 + p_2|z| + p_3|z|^2)\ \exp\left(-\frac{R - R_\odot}{R_\sigma}\right)$$

$\sigma_z(R)$ ~exp(-R/7kpc)

Conclusions from the Worked Example



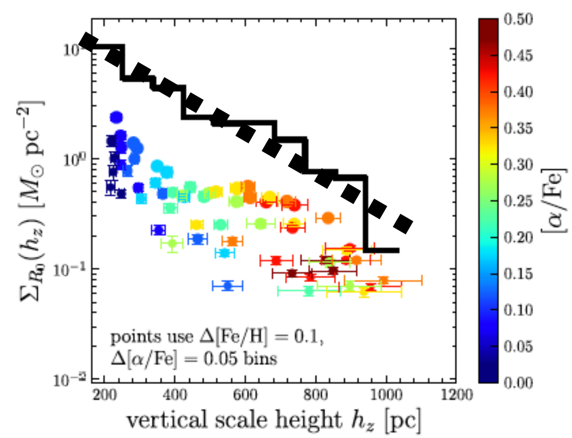
- Looking at the Milky Way in α-age,[Fe/H]-bins slices the stellar disk into 'simple components'



- α-old stars are thickest ***and*** centrally concentrated
  - inside-out growth of the Milky Way disk over ~10Gyrs
- $\Sigma(h_z) \sim e^{-hz}$: data do not support *distinct* thick disk (see Bovy's talk)
  - no inconsistencies with previous claimed 'dichotomies'
- **Qualitatively new constraints for model comparison?**

  → continuous or many-episode disk heating?
  - radial migration explains many aspects

  → oldest stars were never born in a thin,cold disk?



Soap-Box A)

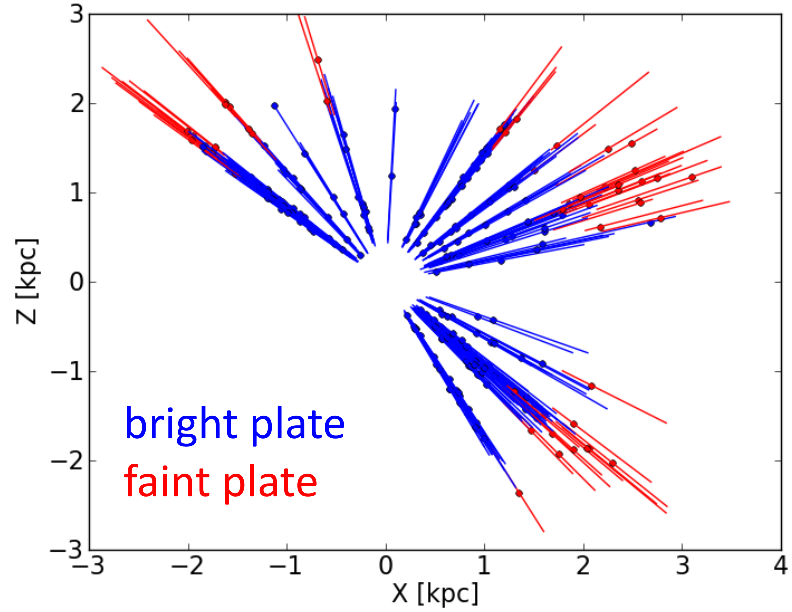
Spatial distribution of spectroscopic samples:

accounting for the sampling function is *key*

For given density model:

$$\nu_{G-dwarf}(R,z \mid \vec{p}_*) = \nu_0 \times e^{-\frac{|z|}{h_z}} \times e^{-\frac{(R-R_\bullet)}{R_{\exp}}}$$

how best to determine the model parameters?

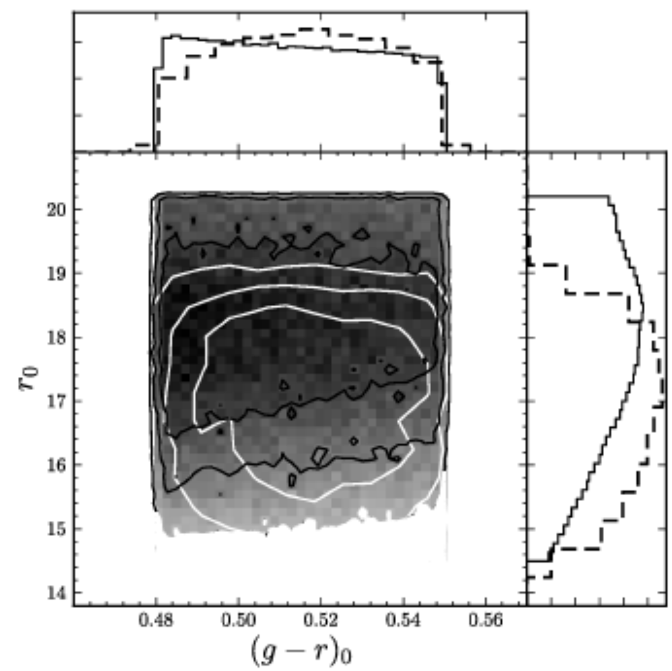


Sub-set of stars (65) targeted in m_r, g-r color-magnitude per (faint/bright) plate

- S/N cut for [a/Fe] determination

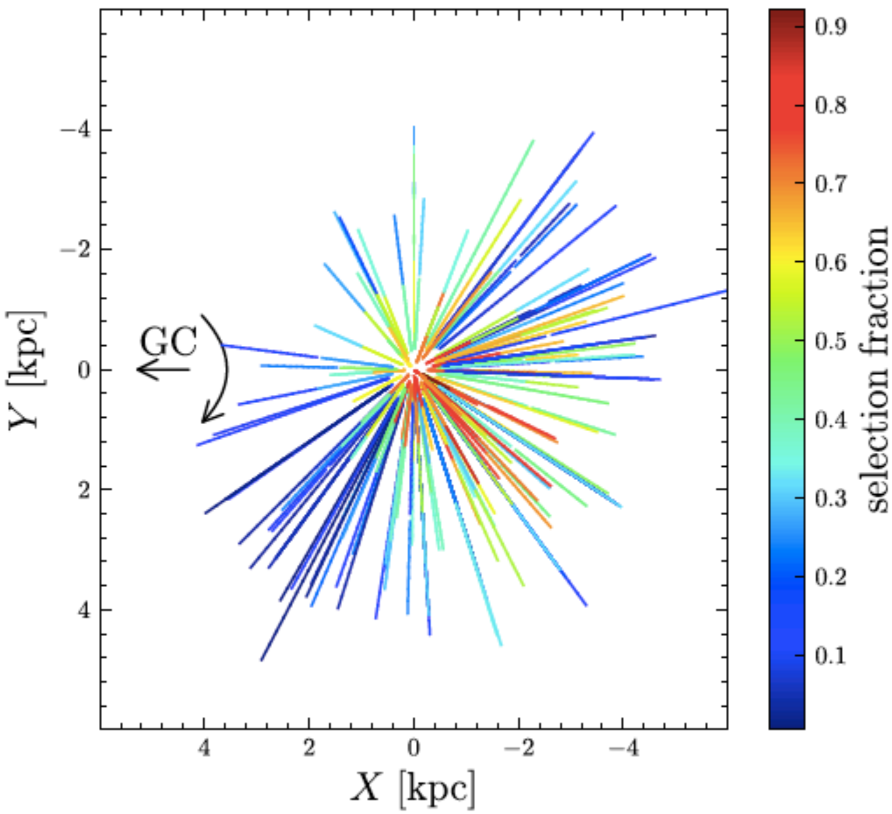
Construct sampling function:

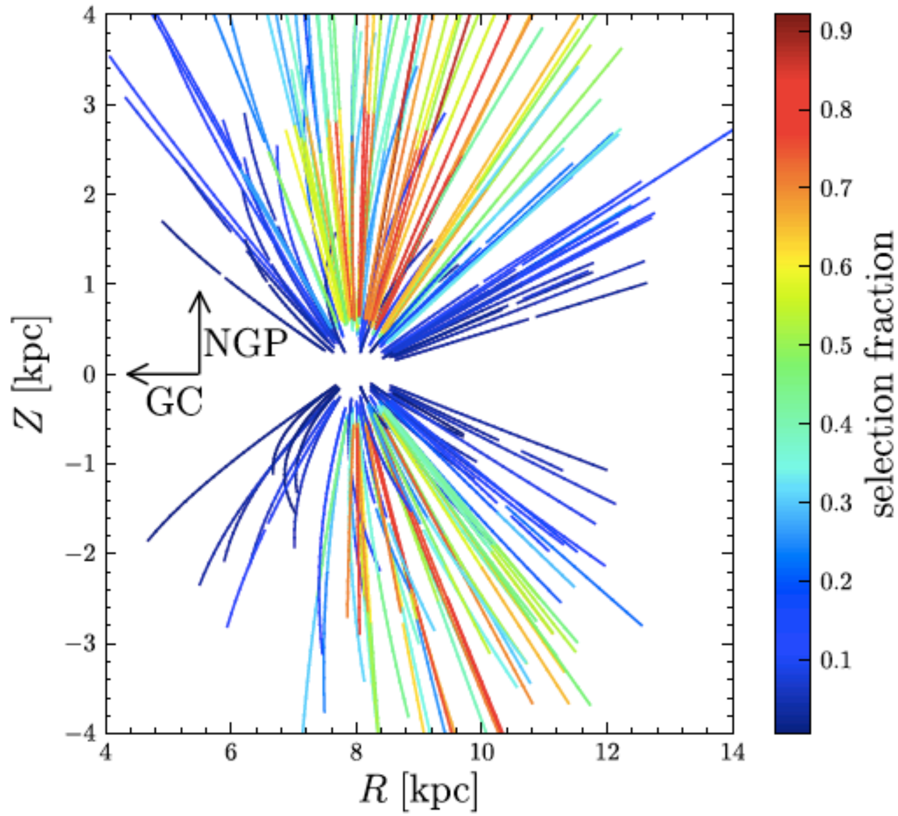
$$w_{spec}(R,z \mid (\mathrm{l,b}),\ \mathrm{m_r},\ \mathrm{g-r},\ \mathrm{[Fe/H]},\ \sigma_{\mathrm{seeing}},\ \mathrm{bright/faint})$$



Bovy, HWR et al 2011a

Which fraction of stars in a (m_r,g-r) bin get targetted by SEGUE?





(Surface)-mass weighting of the abundance distribution in SDSS/SEGUE (at R_0)

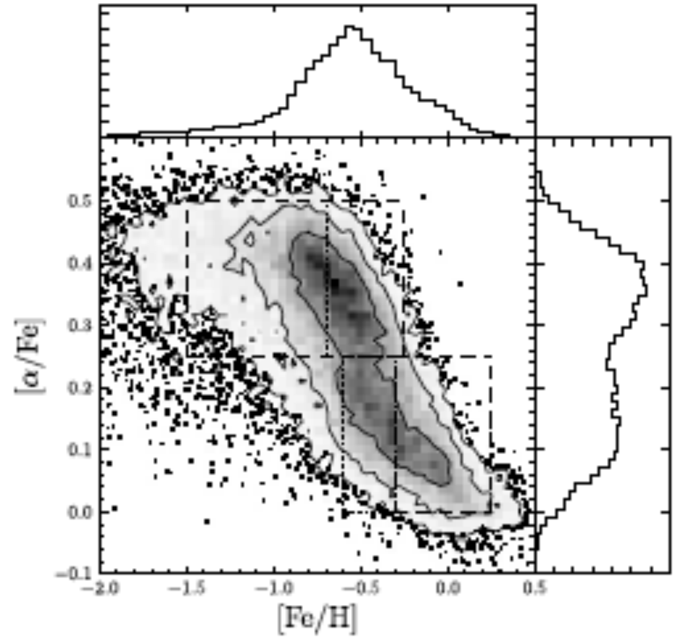
Bovy, Rix & Hogg 2012

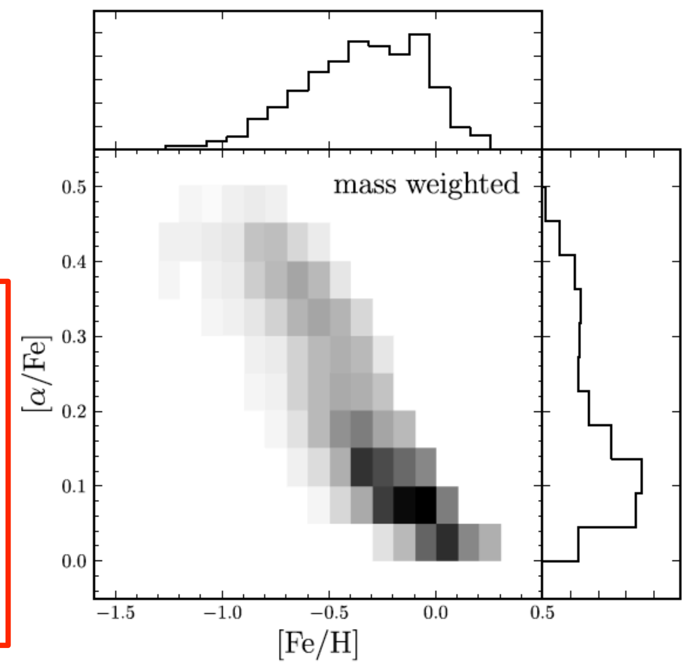
- have fitted n_*(G-dwarfs) of given $[\alpha/Fe]$,[Fe/H]

- Which fraction of the stellar mass of a population with $p(t_{age}|[a/Fe],[Fe/H])$ is contained in 'color-selection box'?

- Assume e.g. Chabrier IMF, $p(t_{age})$ + isochrone and integrate over appropriate color range

  n_*(G-dwarfs) → ρ_*



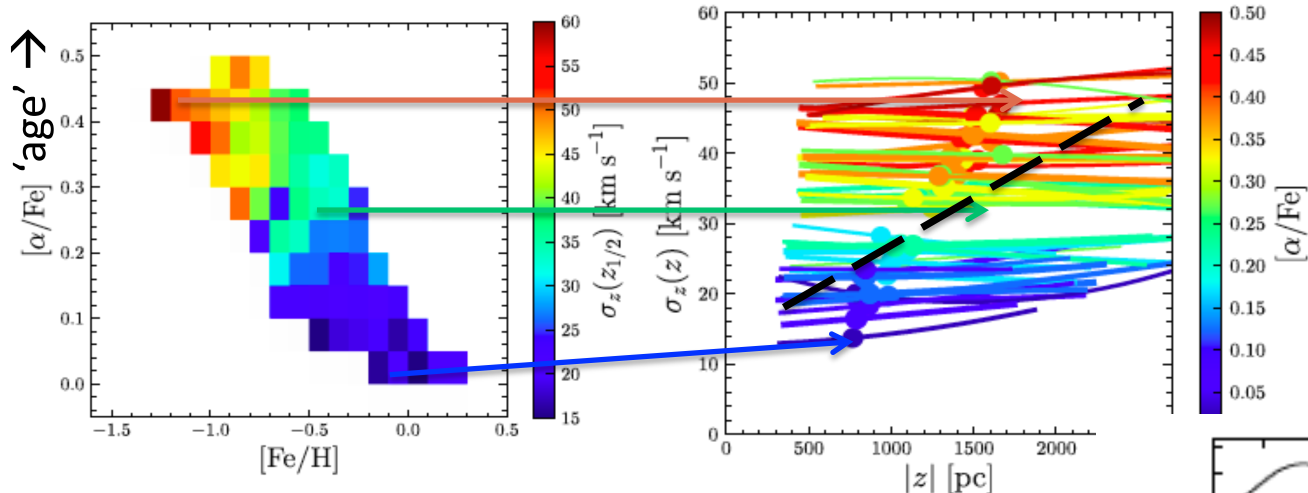


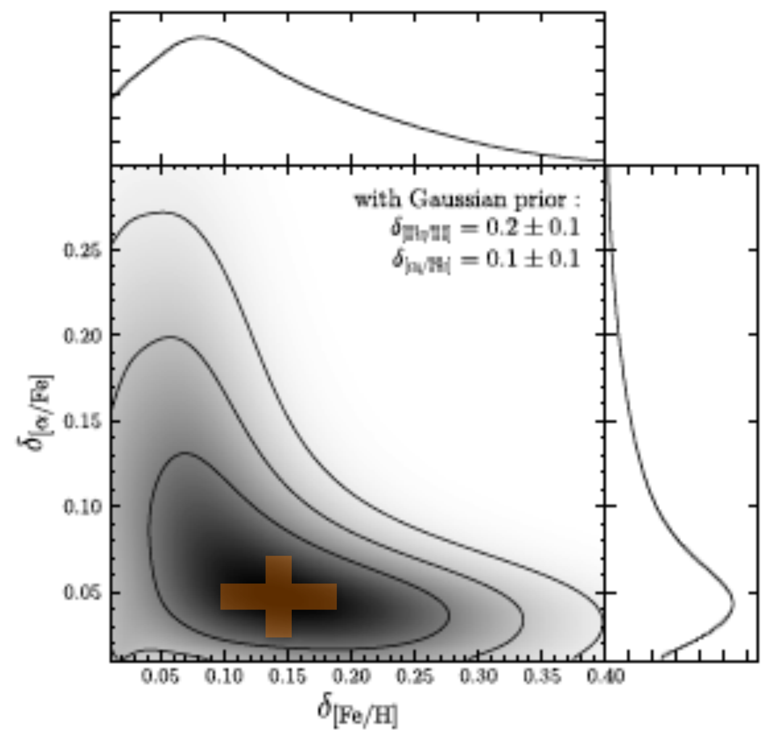
- density & kinematics vary dramatically with sub-population: ~1-10% accurate linkage is hard
- you are never volume-, mass-, etc.. limited, always S/N-limited in some other quantity
- Need 'machinery' like cosmic LSS surveys

Soap-Box B): Exploit Self-Calibration
How precise are the SDSS abundance measurements?

Bovy, Rix et al 2012 (imminent)

vertical σ_z dispersion profile





- σ_z(z | abundance) is nearly isothermal

- but $\langle\sigma_z(z)\rangle$ varies strongly with abundance
  - as does the scale height

→**there cannot be much bin cross-contamination**

What data can do for you

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- **The Soap-Box:**

  A) Understanding the selection functions is the limiting factor for doing dynamics of discrete tracers in the Milky Way

  - dynamics links underlying (spatial) densities to kinematics [precision? 1/sqrt(N_*)]
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  B) The data themselves are an excellent (self-)calibration source

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  - Qualitative 'formation history' speculation in easy
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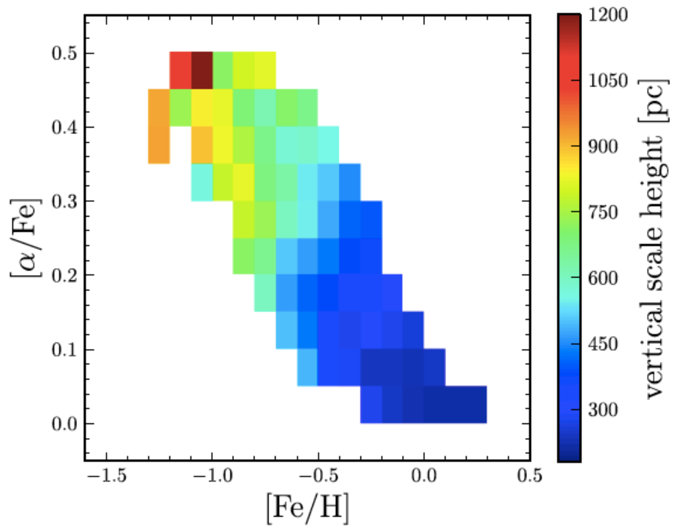
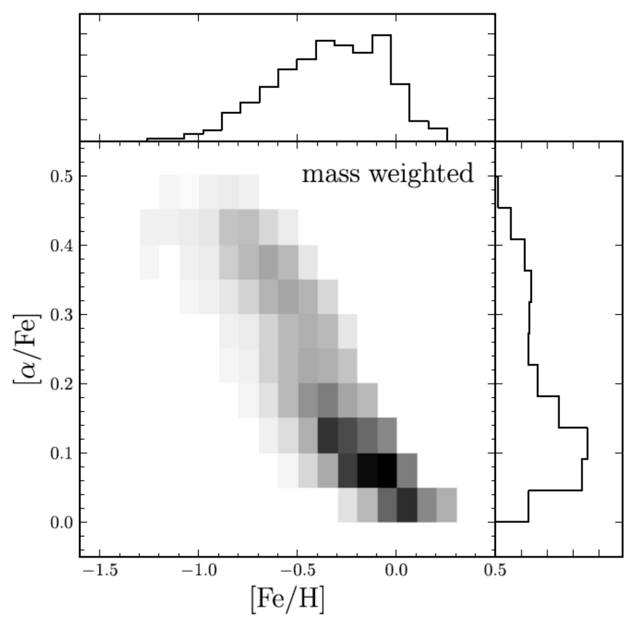
* Bovy, Rix et al 2011/12

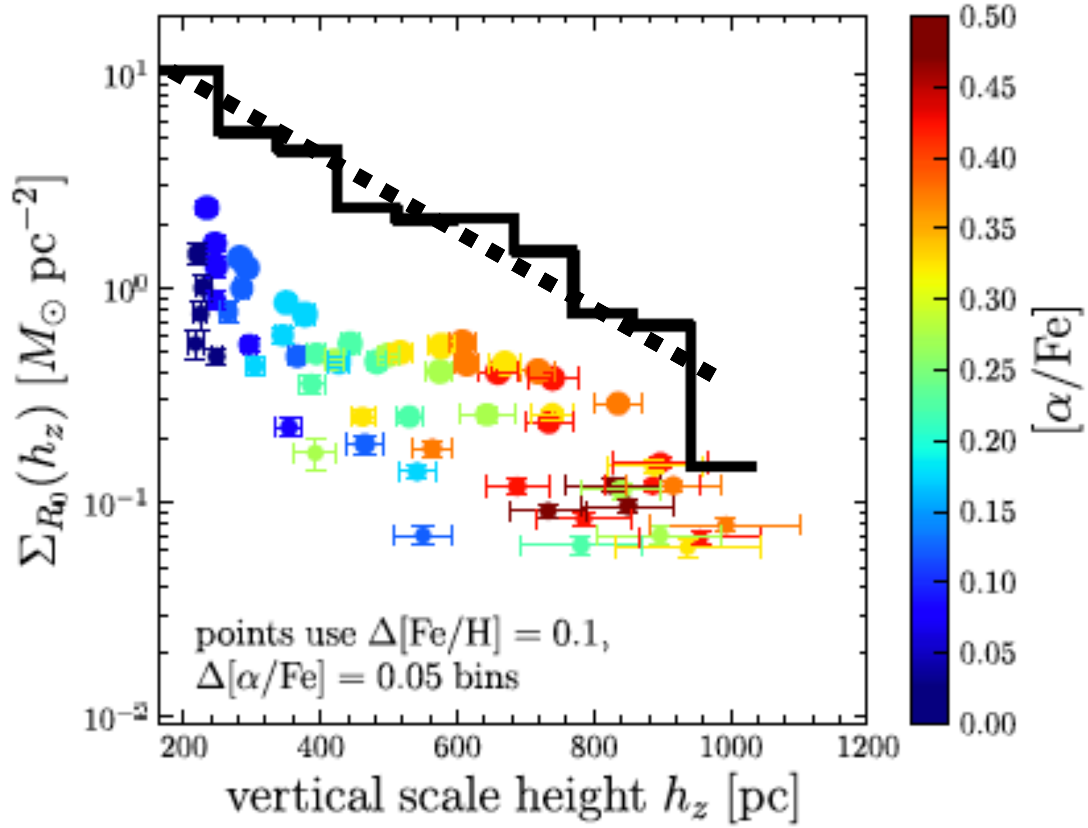
What is the scale-height distribution of stars in the Milky Way's disk?
or Is there a 'Distinct' Thick Disk

1) for each star: [α/Fe],[Fe/H] → h_z
2) for each [α/Fe],[Fe/H] bin → $\Sigma(R_0)$

→ scale height distribution $\Sigma(h_z)$ at R_0





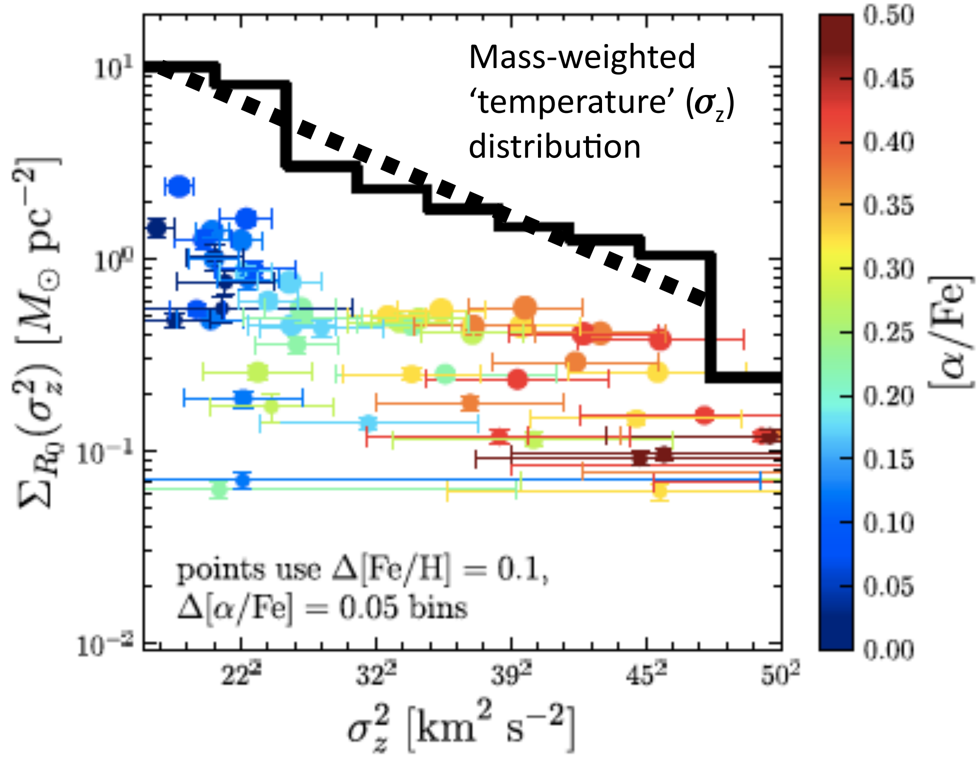


What is the scale-height distribution of stars in the Milky Way's disk?
or Is there a 'Distinct' Thick Disk

- $\Sigma_{R_0}(h_z)$ is NOT bi-modal!

$$\Sigma_{R_0}(h_z) \sim e^{-h_z}$$

$$\Sigma_{R_0}(h_z) \sim e^{-\sigma_z^2} \sim e^{-kT}$$



→ thick disk portions appear as 'thermal tail' of a vertical height/temperature distribution

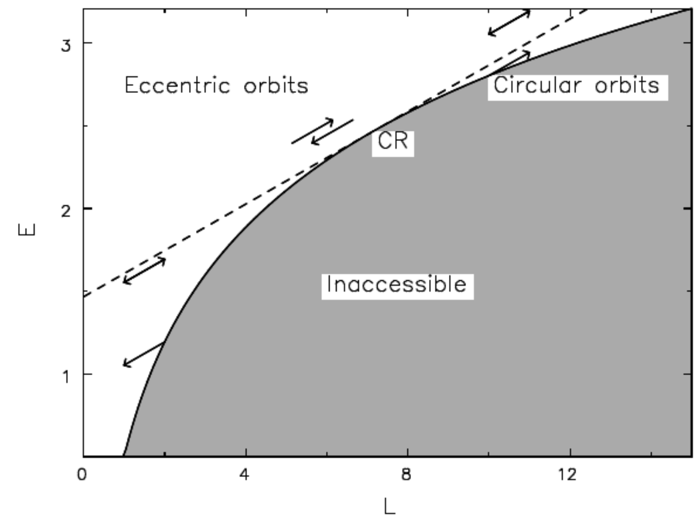
Picture of *distinct* thin/thick disk not supported by data!

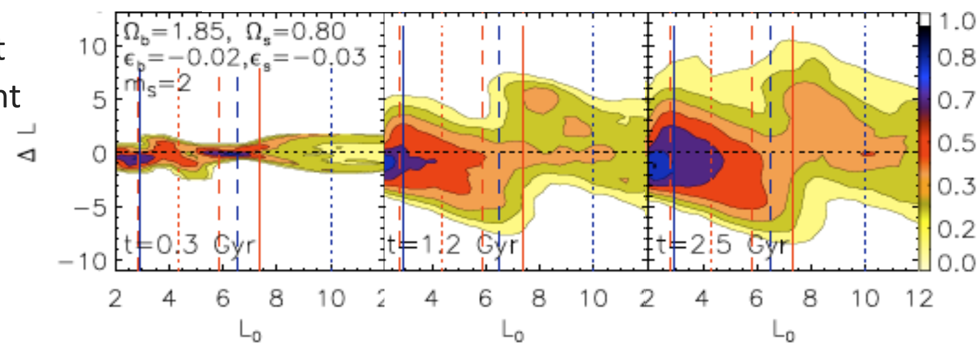
(Stellar) Disk Evolution Processes

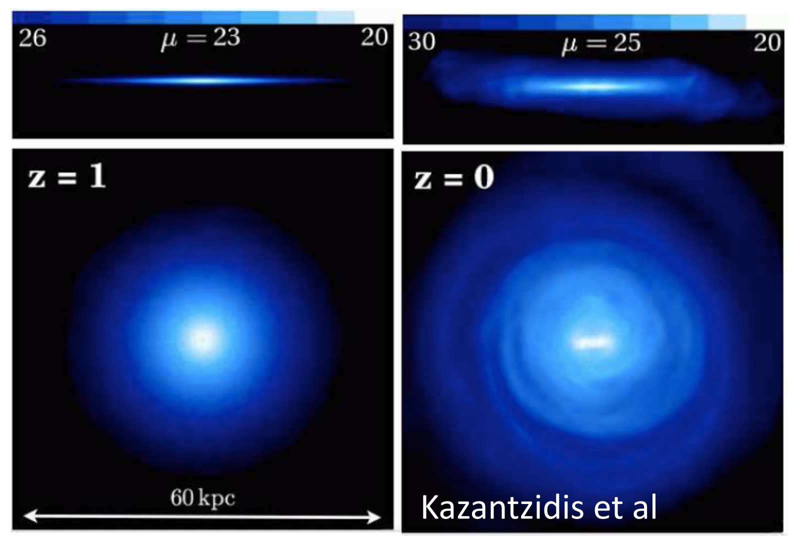
- Gas Infall & Star Formation

- Radial Migration
  (Sellwood & Binney 2002, Minchev et al 2009)
  - Spiral arms, bars change stars' orbits near co-rotation resonance
    - radius changes without eccentricity boost
    - bars/spirals arms are presumably transient → $R_{co\text{-}rot}$ wanders
  - Qualitatively inevitable whenever bars/spirals have been present

- Minor mergers
  - can heat the disk (e.g. Moster et al 2010)
  - can augment the disk (e.g. Abadi et al 2003)
  - Qualitatively inevitable





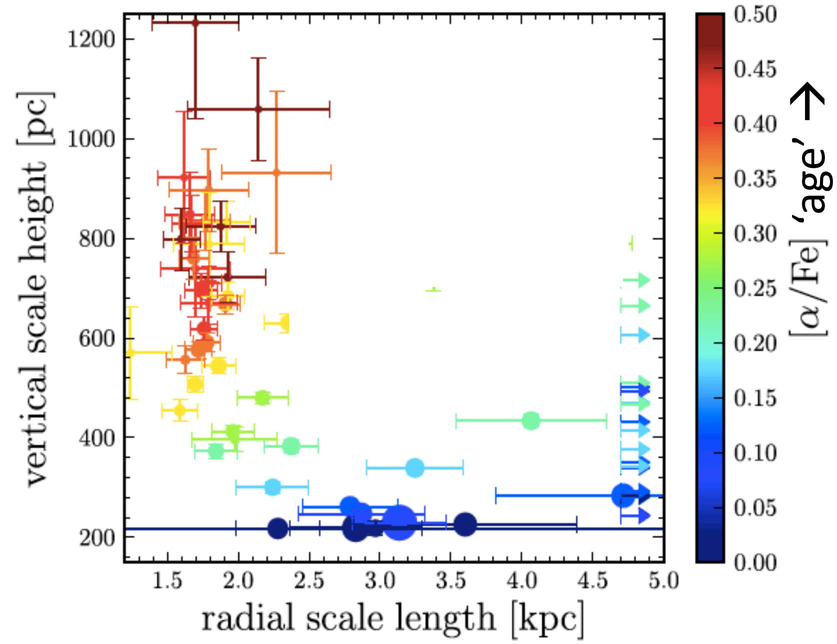


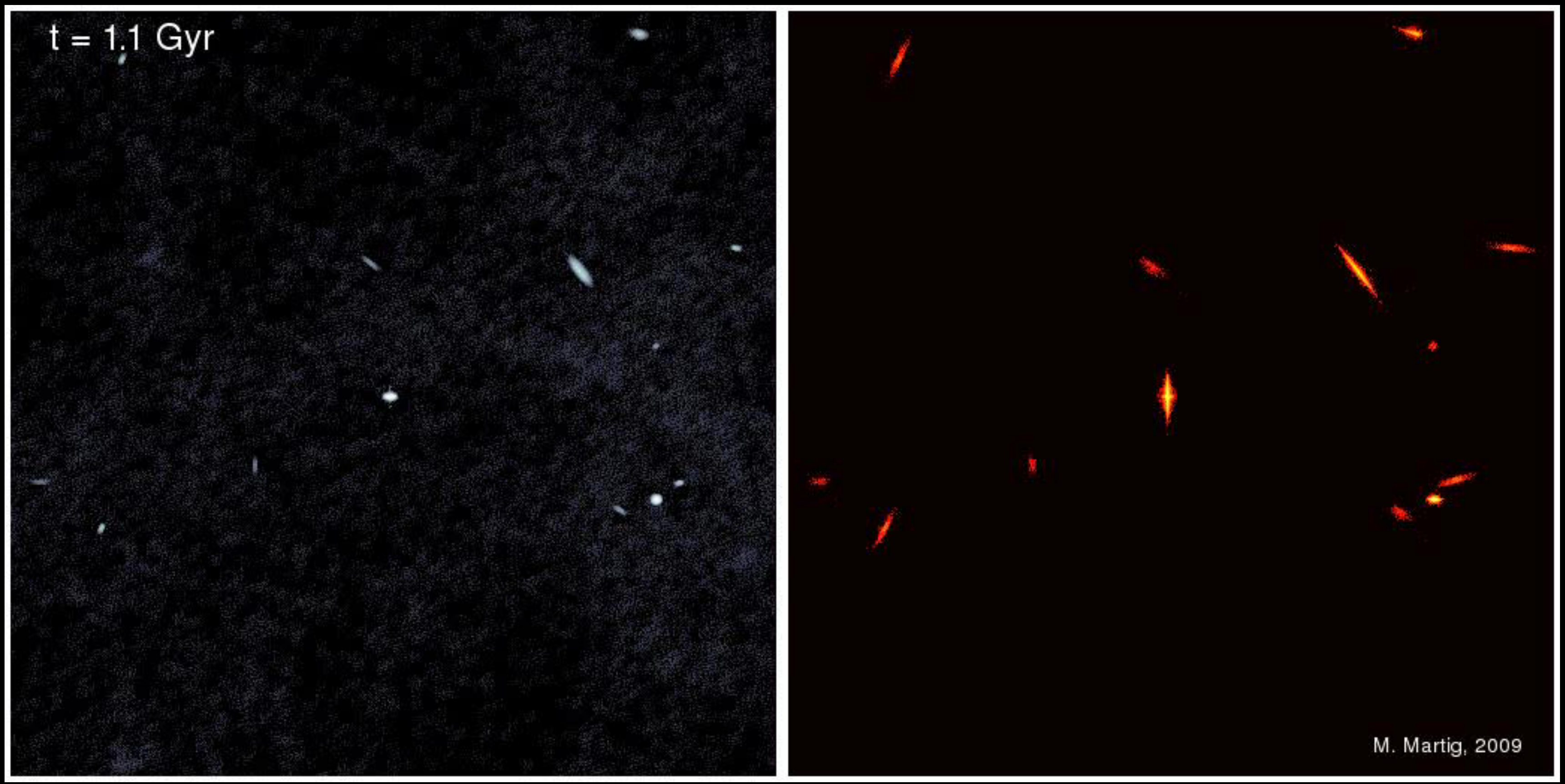
The Geometry of Mono-Abundance Sub-Populations

- Old: thick ←→ compact
  Young: thin ←→ rad. extended

- NB: in a few bins error-induced abundance mixing is important.

- Some abundance bins have effectively flat radial profile at R_0





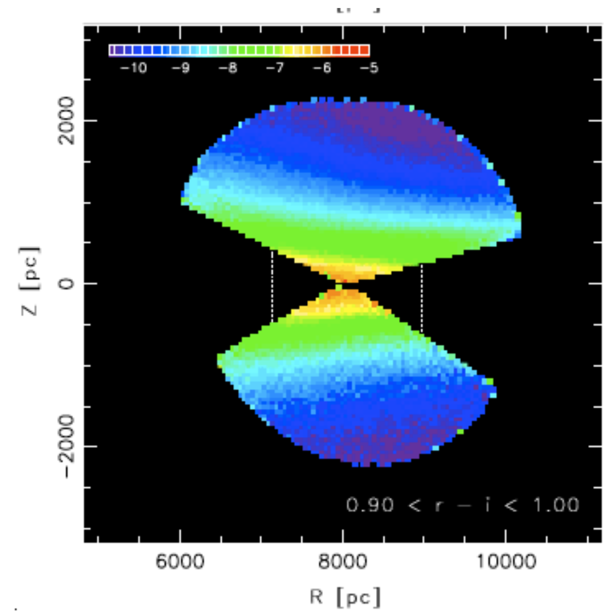
http://www.youtube.com/watch?v=tL4gTINR1Y8

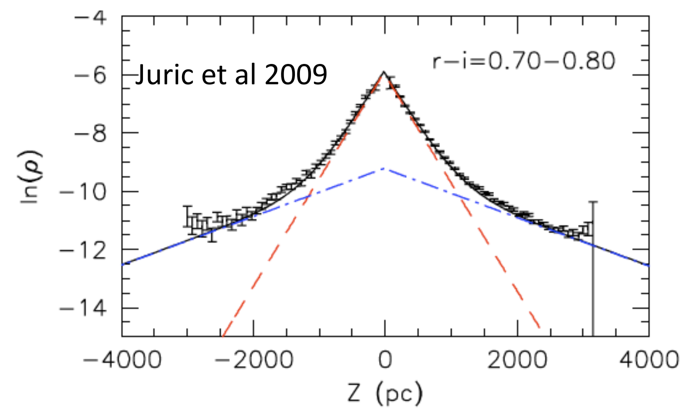
Traditional Characterization of the MW's Stellar Disks(s)

Geometry & Kinematics

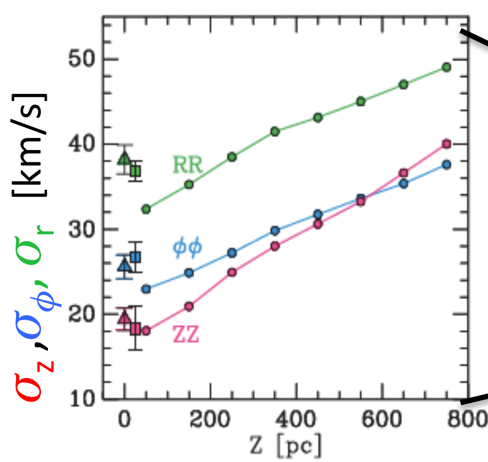
- Stellar Number Density
  - double exponential vertically (thick/thin disk)
  - exponential in radius: thick disk radially extended???
- Stellar kinematics
  - velocity dispersion increases with height
- Two component description sensible

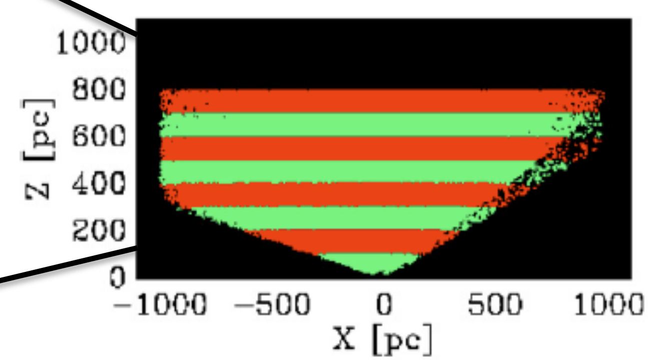
  ..but the geom./kinem. data show no 'breaks'





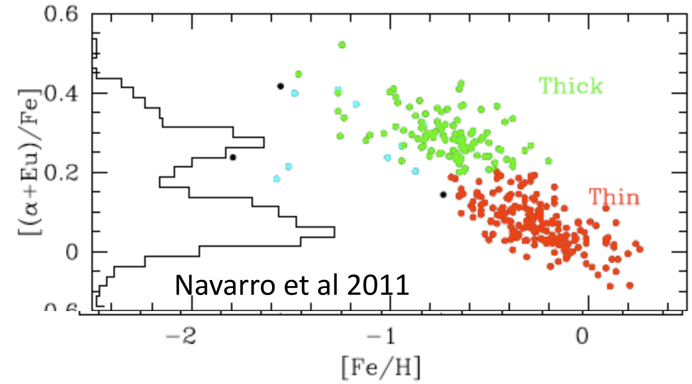
Fuchs, HWR et al 2008



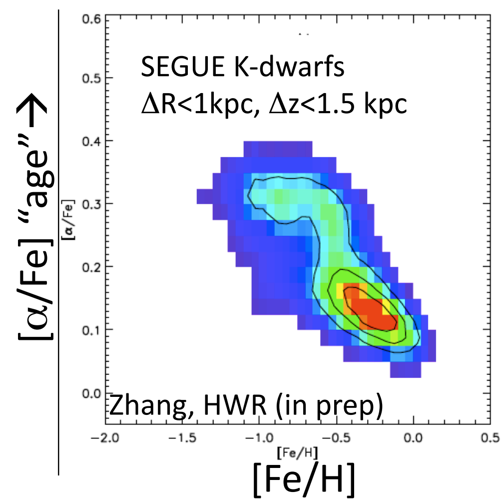


Characterizing the Stellar Disks(s)
Chemo-kinematic

- Bi-modal [α/Fe] distribution
  - Abundances are α-enhanced until after a few Gyrs SN Ia enrichment takes over
  - Lee et al 2011, Navarro et al 2011
  - α–enhanced ← → rapid (early?) enrichment, best practical 'age tag'?



- Strong correlation between kinematics and abundances:
  - more metal-poor: kin. hotter
  - 'thick disk' is α-enhanced [α/Fe]>0.2



- Do the abundances argue for a "distinct thin-thick disk"?

Approaches to Testing Disk Formation/Evolution Scenarios:

- Ideally, we would like to know:
  - How many stars are on which orbits now?

    and how is this related to
  - When and on what orbits were they born?

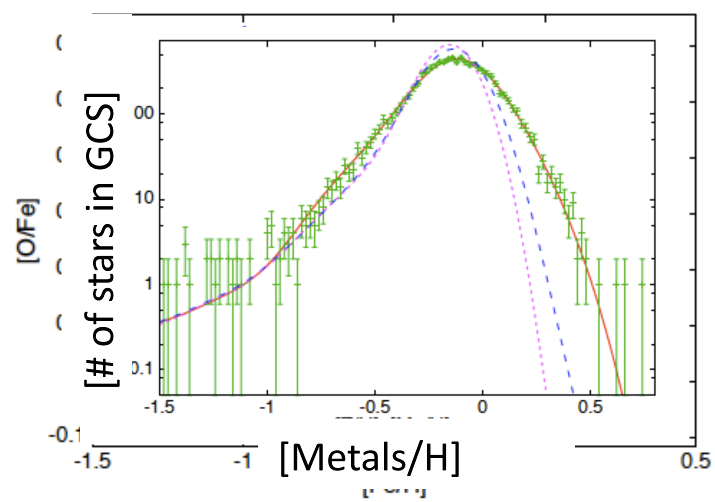
  - Stellar ages are hard to measure → abundance tags, [α/Fe]

- A local (<200 pc) approach to this line of argument
  (e.g. Schoenrich & Binney 2009)

  - [α/Fe] as enrichment age proxy, [Fe/H] birth radius proxy →

  - abundance distribution of stars near the Sun can be explained as a consequence of radial migration

Does that model – tuned to R_o – get things right at other radii?



Questions for this talk

Has the Milky Way disk grown inside out throughout its life?

Does it make sense to view distinct thin & thick disk components?

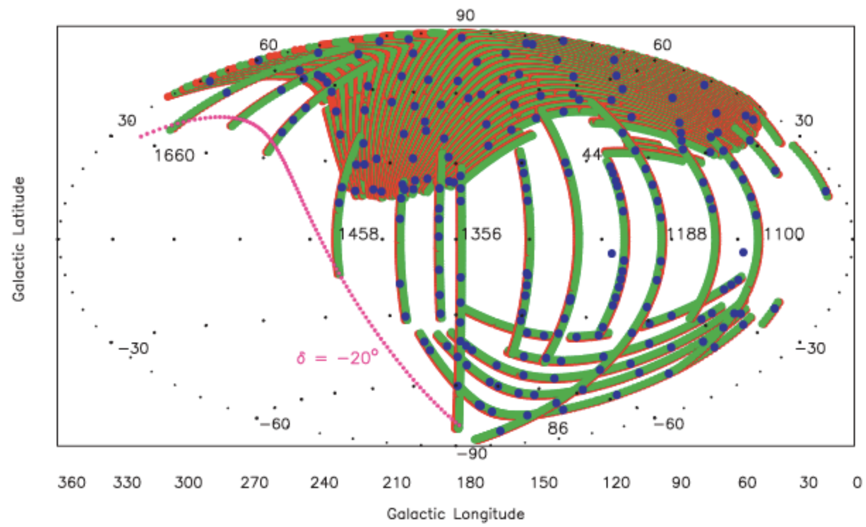
Can one differentiate disk evolution mechanism?

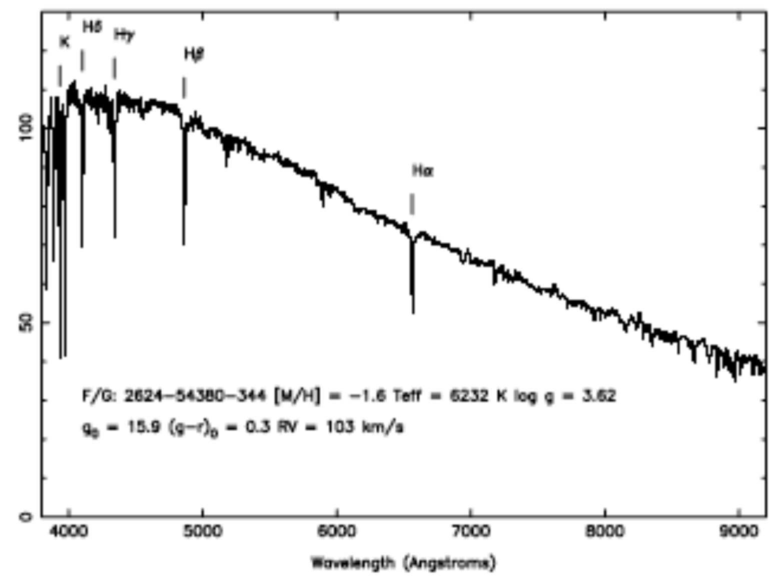
The data: SEGUE

'SDSS spectroscopizes the Milky Way'

Yanny et al 2009; Rockosi: PI

- spectra for 240,000 stars
  - ~10 targeting categories
  - spectral res. R~1800
  - $14 < m_r < 20$
- yielding:
  - T_{eff}, log g
  - [Fe/H] (±0.2 dex), [α/Fe] (0.06dex) (Lee et al 09)
  - (MS) distances to ~7% (An et al 2010)
  - δv ~ 7 km/s ($\delta\mu$ ~ 2.5mas/yr)
- good:
  - radial velocities 'good enough': ~8 km/s
  - distances 'good': ~5-10%
  - two abundance numbers: [Fe/H], [α/Fe]
  - giant/dwarf separation using log g
- less good:
  - mostly high latitude / optical spectra
  - D_{min} = 300-700 pc



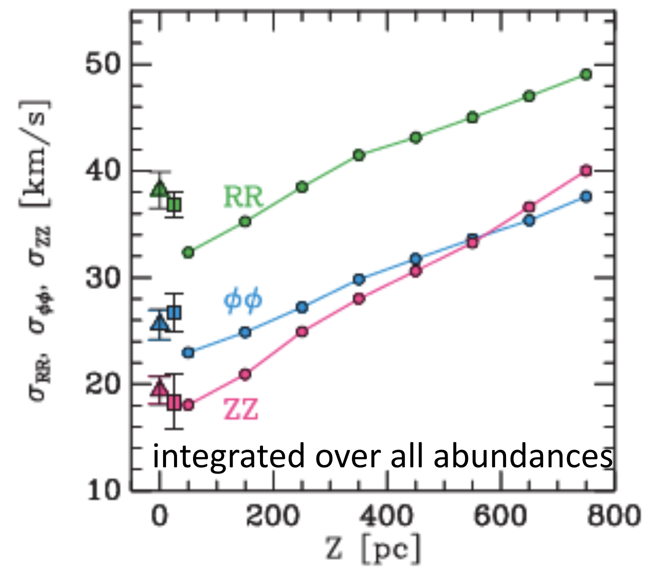


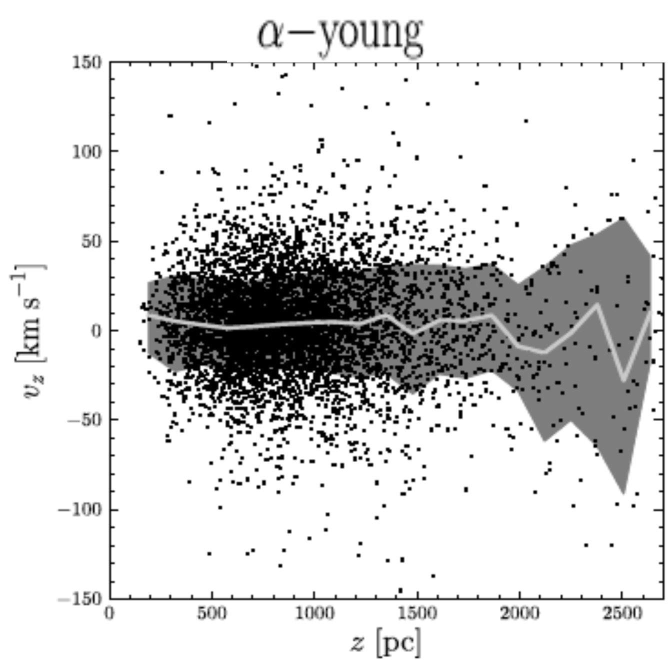
Abundance-dependent kinematics of the MW Disk

Liu & vdVen 2012, Bovy, Rix et al 2012 (imminent)

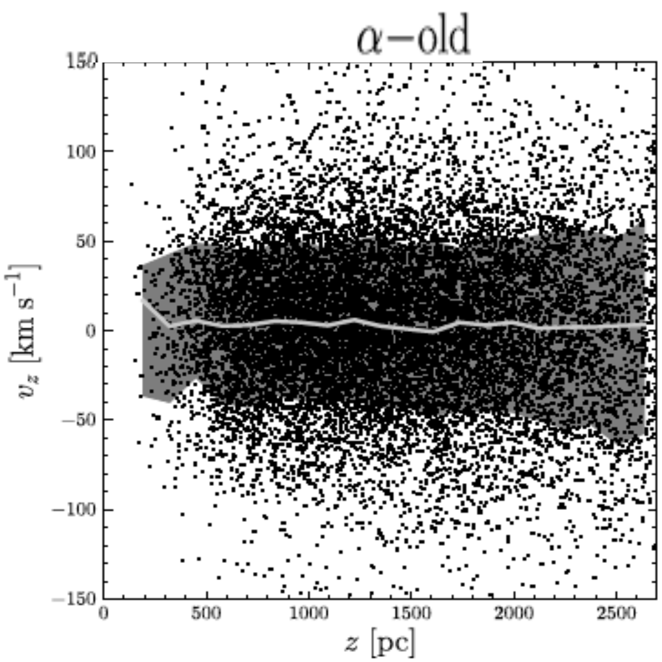
- In general: stars well above the disk plane are ‘hotter’ (larger σ_z)
- What are the kinematics of ‘mono-abundance’ components?

vertical σ_z dispersion profile





vertical velocities [km/s]



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