Future of GALAH + related surveys (observational surveys of stars in the Milky Way)

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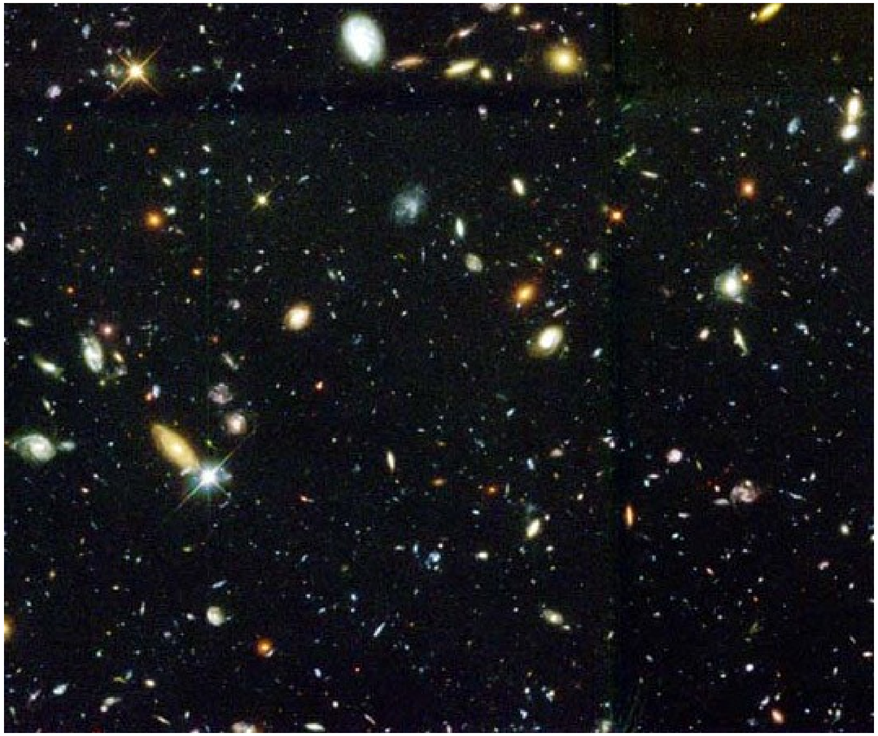
Milky Way a laboratory for understanding galaxy formation.

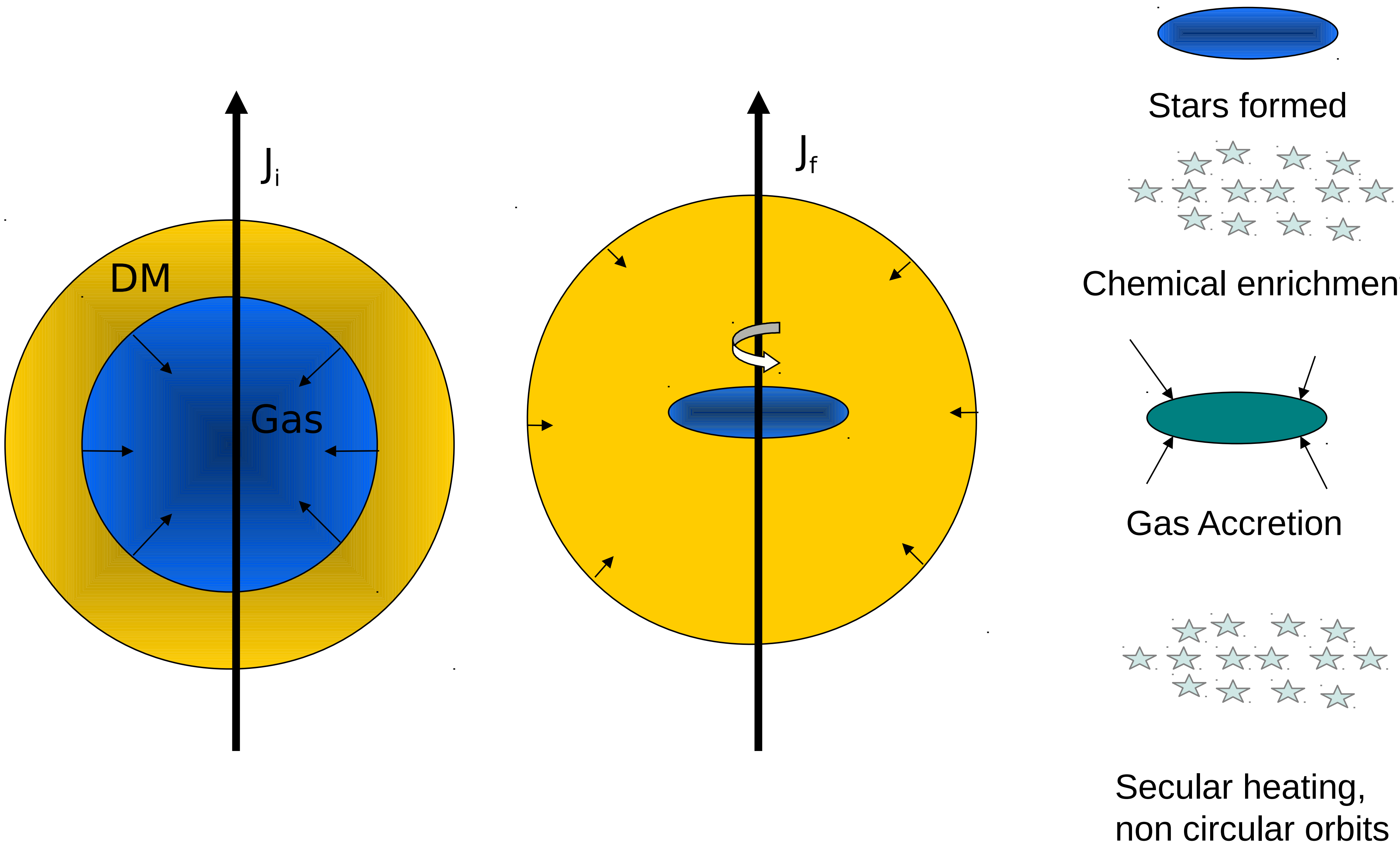
- Future in the context of understanding the formation and evolution of the MW.
- For distant galaxies we can only get gross properties as individual stars are difficult to resolve.
- Milky Way stars are nearby, so we can in principle get (x,v), [Fe/H], X/Fe, age, mass.
- With this we can test galaxy formation theories.

Image: Michael Goh

Image: Hubble Deep Field

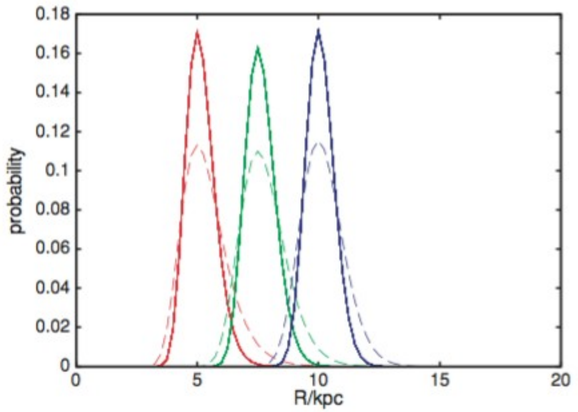


How was Milky Way formed?

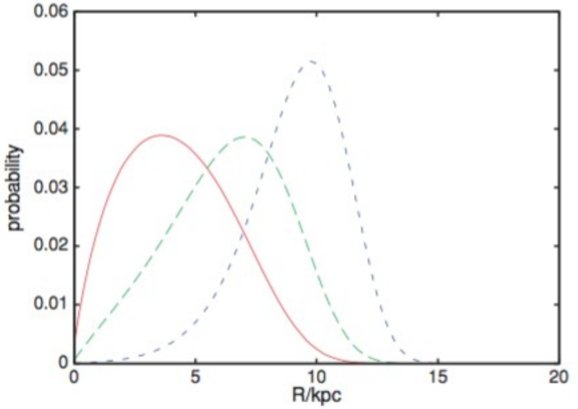


Blurring and Churning

- Blurring:
  - Disc heating makes orbits elliptic.
  - energy added but ang mom remains same.



- Churning:
  - Scattering at orbital resonance.
  - Changes the angular momentum causes radial migration



Schonrich 2009

Age metallicity

- Z(t,R)
- Effect of churning and blurring
- Wide range of age and metallicity in solar neighborhood.

Schonrich 2009

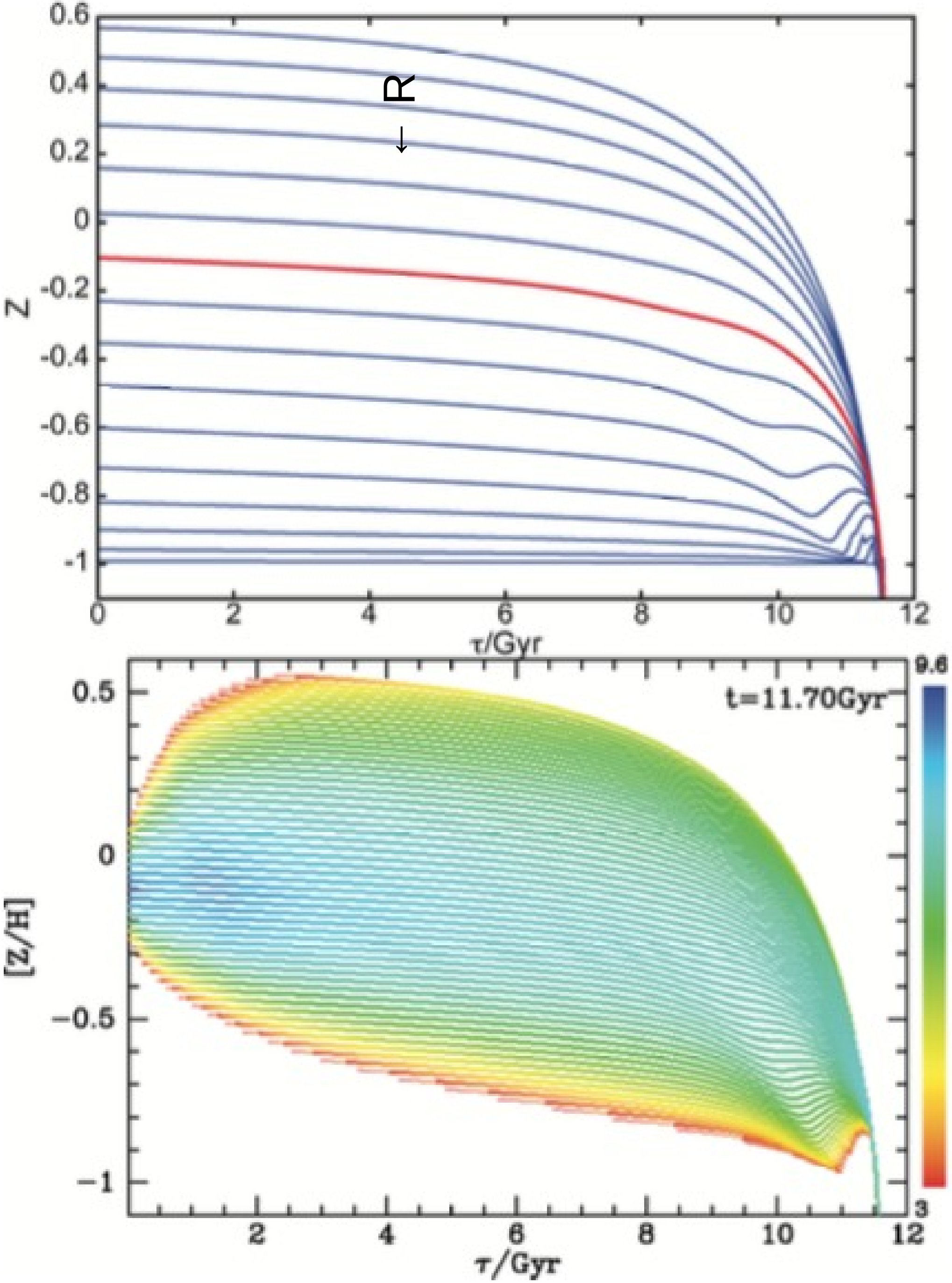


Figure 6. Upper panel: the metallicity of the cold ISM in each annulus as a function of lookback time showing each fifth ring. The curve for the solar annulus is red. Lower panel: the present density of solar-neighbourhood stars in the age–metallicity diagram. The colours encode the logarithm of the density of stars.

We only have the present snapshot, cannot go back in time to unravel the formation history.

What information do we have?

Large observational surveys of the Milky Way.

- Astrometric:
  - **l, b, μ_l, μ_b.** Angular position and angular velocity/proper motion
  - HIPPARCOS, UCAC4, PPMXL, HSOY, UCAC5, [GAIA]
- Photometric:
  - **B,V,u,g,r,i** , Color and magntiude of stars
  - **d, T_{eff},**
  - 2MASS, SDSS, APASS, SkyMapper, [LSST]
- Spectroscopic:
  - **V_r** , radial velocity, **d, T_{eff}, logg, [Fe/H], [X/Fe]**,(mass, age)
  - GCS, SEGUE, RAVE, APOGEE, Gaia-ESO, LAMOST, GALAH [Funnel Web, SDSS V, 4MOST, WEAVE, DESI]

Machinery to interpret observations

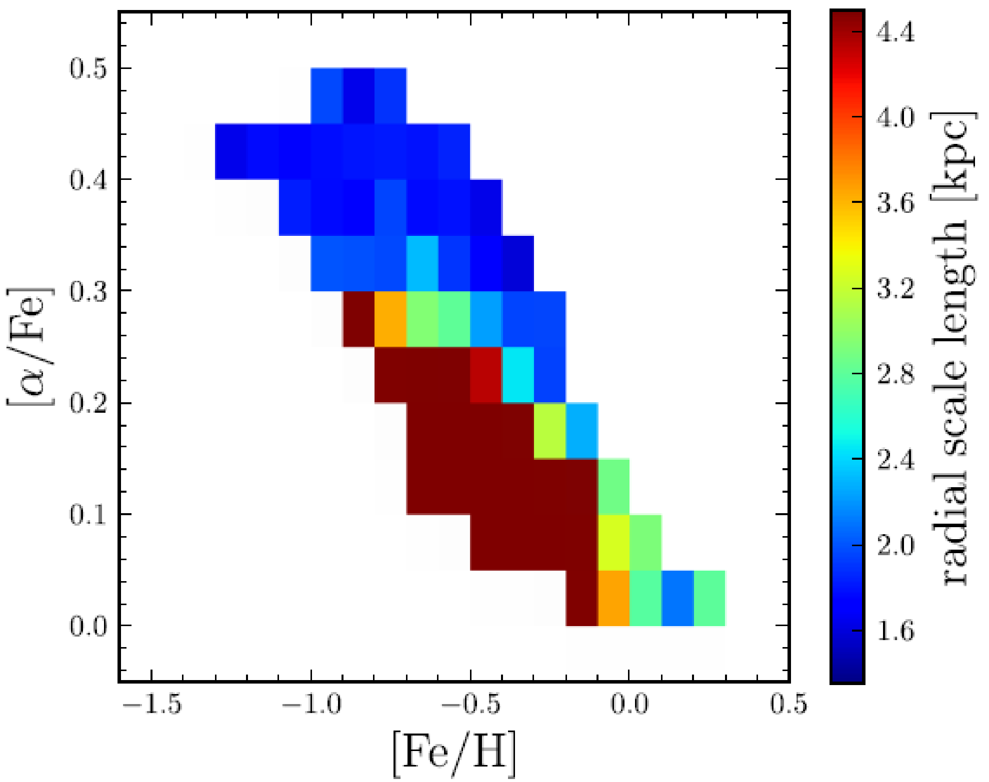
- Forward modelling. From models to data.
  - $(x, v) \rightarrow (x_{obs}, v_{obs})$
- Equilibrium models, semi analytic
  - N body simulations too computationally expensive to fit data
- $f(x,v,\tau)$ to $f(J,\tau)$ (Binney 2010-2015)
  - $J(x,v|\Phi)$ constants of motion actions, Reduces problem from 6d to 3d
- $p(x_{birth}, v_{birth}, \tau, [\alpha/Fe], [Fe/H]) \rightarrow p(x_{now}, v_{now}, \tau, [\alpha/Fe], [Fe/H])$
  - N-body simulations

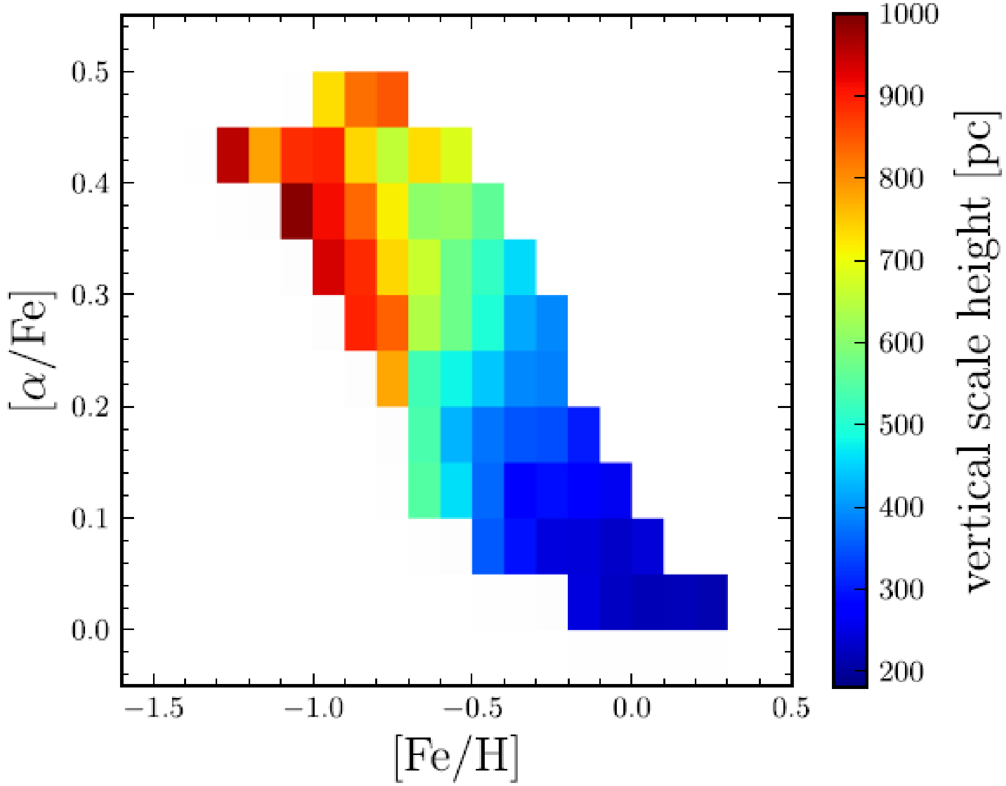
- **p(x, v, t, [α/Fe], [Fe/H])** – chrono-chemo-dynamic
- **p(x, v, [α/Fe], [Fe/H])** – chemo-dynamic
- **p(x, [α/Fe], [Fe/H])** – chemo-spatial
  - **p(R,z | [α/Fe], [Fe/H])** p([α/Fe], [Fe/H]) (MAP)
    - [Bovy et al. 2012, SEGUE]
  - **p([α/Fe], [Fe/H] | R,z)** p(R, z)
    - [Hayden et al.2015, APOGEE]

- **p(R,z, [α/Fe], [Fe/H], t)** – chrono-chemo-spatial (MAAP)
  - **p(R,z | [α/Fe], [Fe/H], t)** p([α/Fe], [Fe/H],t)

Mono abundance populations (MAP)

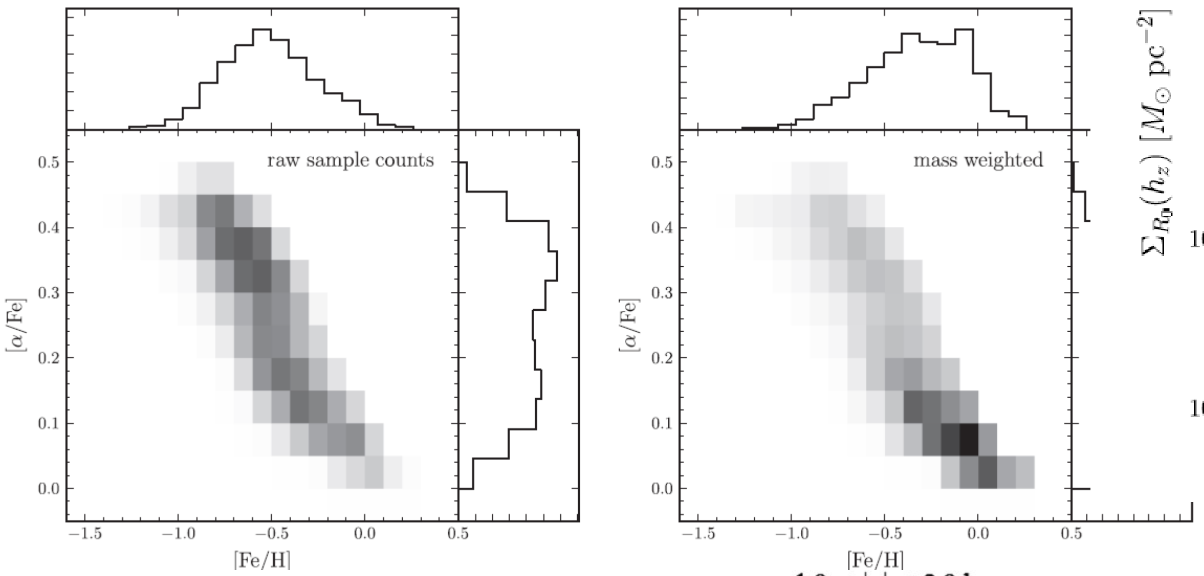
- SEGUE data 23,000 G dwarfs.
- **p(R,z | [α/Fe], [Fe/H])**

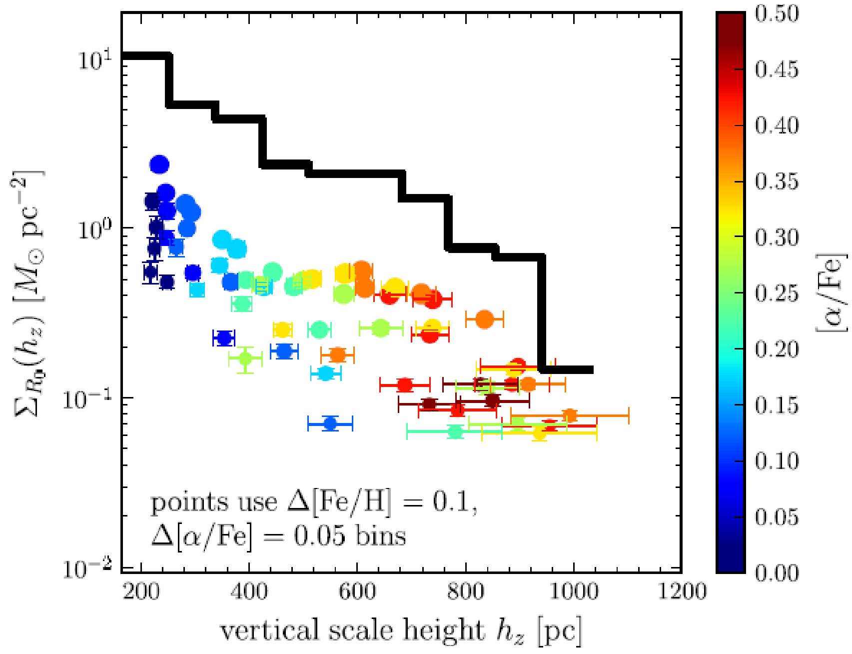




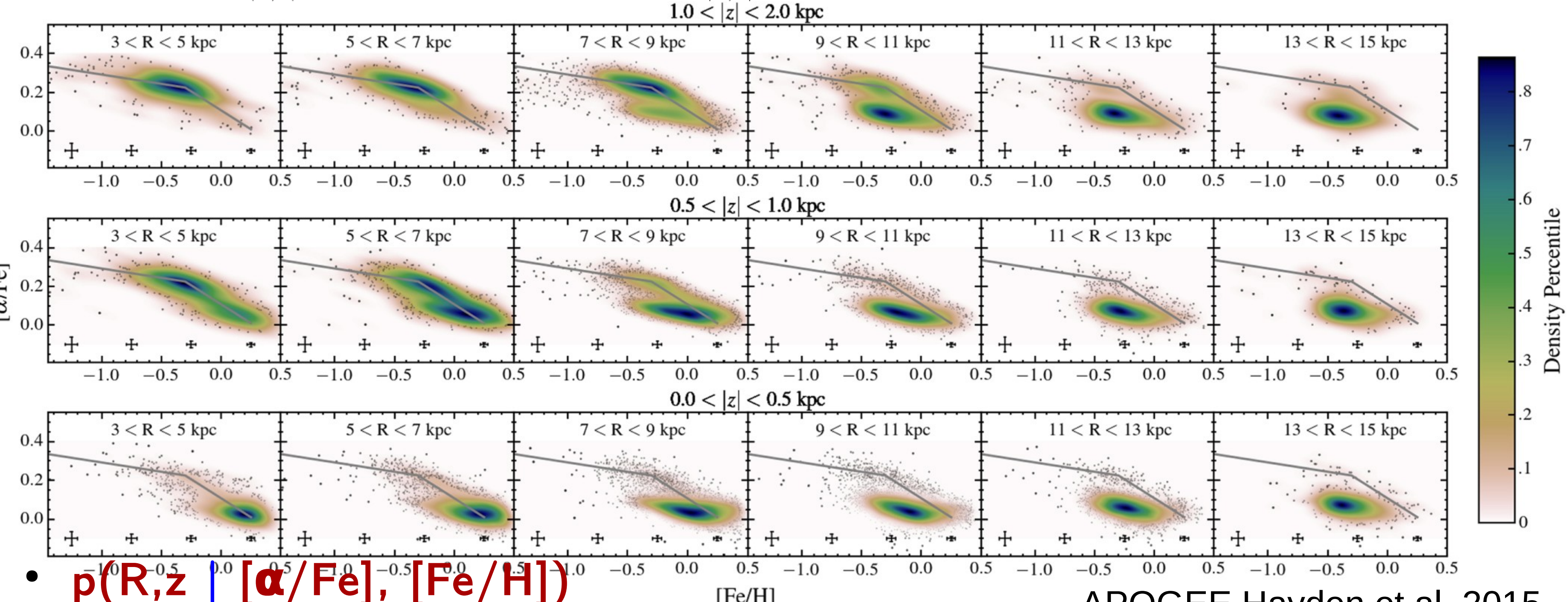
Bovy et al. 2012

Distinct thick disc or not?





Bovy et al. 2012



- **p(R,z | [α/Fe], [Fe/H])**

APOGEE Hayden et al. 2015.

- **p(x, v, t, [α/Fe], [Fe/H])** – chrono-chemo-dynamic
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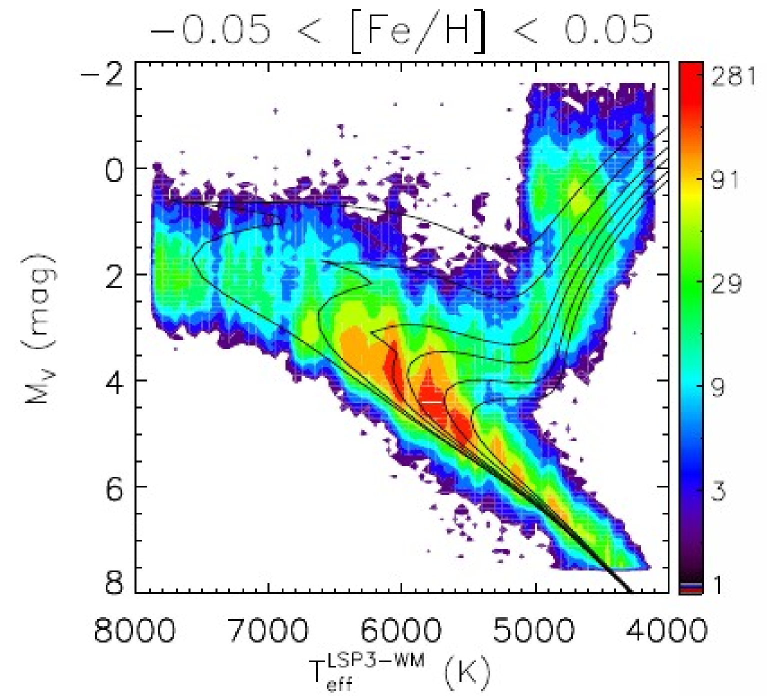
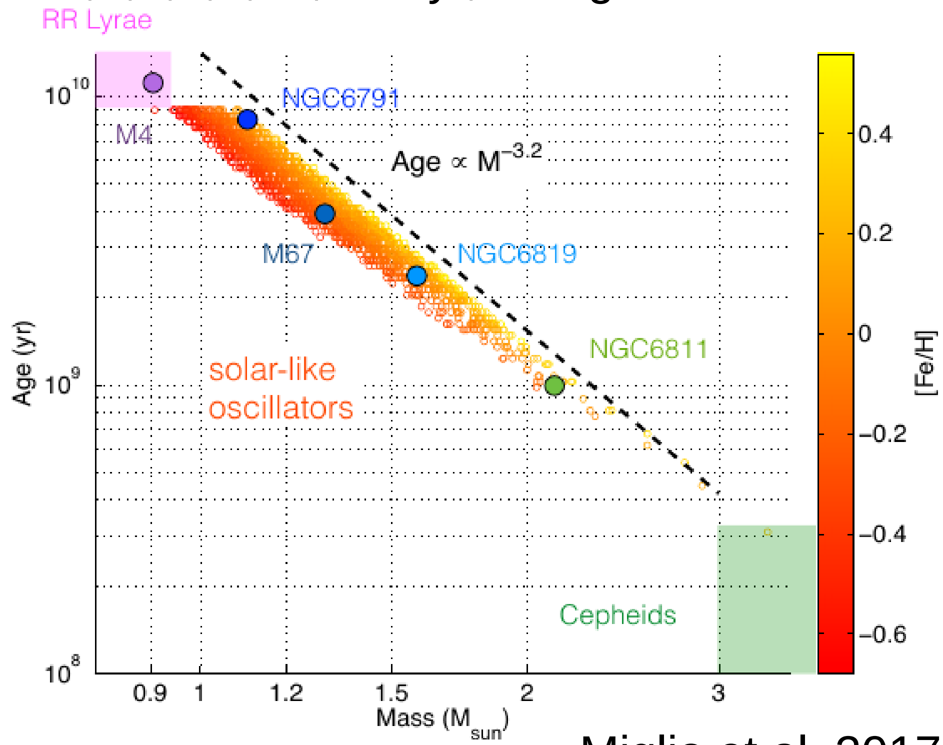
- **p(R,z, [α/Fe], [Fe/H], t)** – chrono-chemo-spatial (MAAP)
  - **p(R,z | [α/Fe], [Fe/H], t)** p([α/Fe], [Fe/H],t)

How can we get ages.

- Main sequence turn off and subgiants
  - log g, Teff, [Fe/H]
  - parallax, log g, Teff, [Fe/H]
  - (M_V, Teff, [Fe/H])
    - Machine learning,
      - Xiang et al. 2017
- Giants
  - Asteroseismology
  - ν_{max}, $\Delta\nu$, Teff, [Fe/H]
  - C/N, H-alpha
    - Machine learning,
      - Ness et al. 2015, Martig et al. 2016



1,2,4,6,8,10,14 Gyr, Xiang et al. 2017



Miglio et al. 2017

Rise of the machines

- Train → Learn → Predict

- Input: Spectra with stellar parameters/labels
  - Labels = **{T_{eff}, log g, [Fe/H], Mass, Age, M_V}**

- New spectra → Output stellar parameters

- ***The Cannon*** (Ness et al , Casey et al, Ting et al)

- ***KPCA*** (Kernel principal component analysis)
  - Xiang et al (LAMOST)

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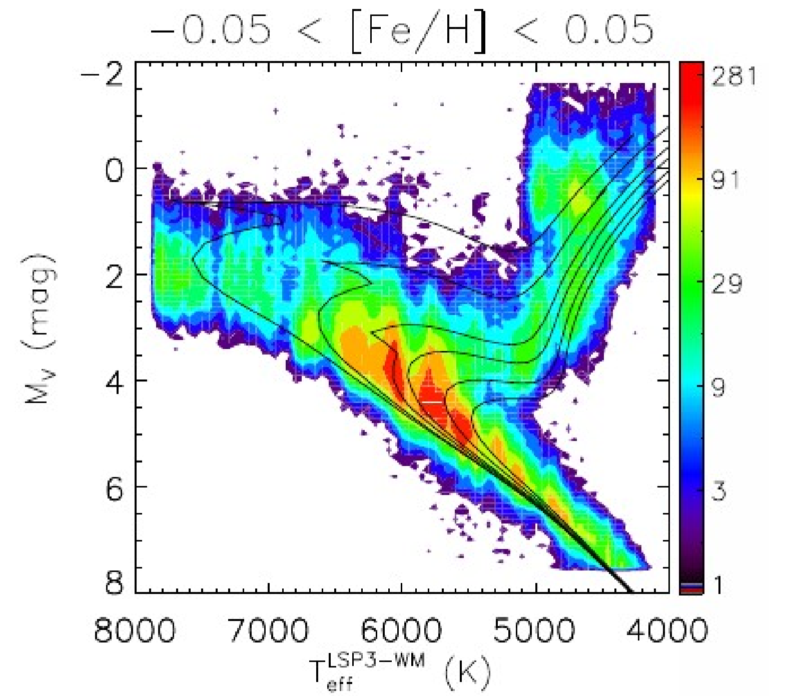

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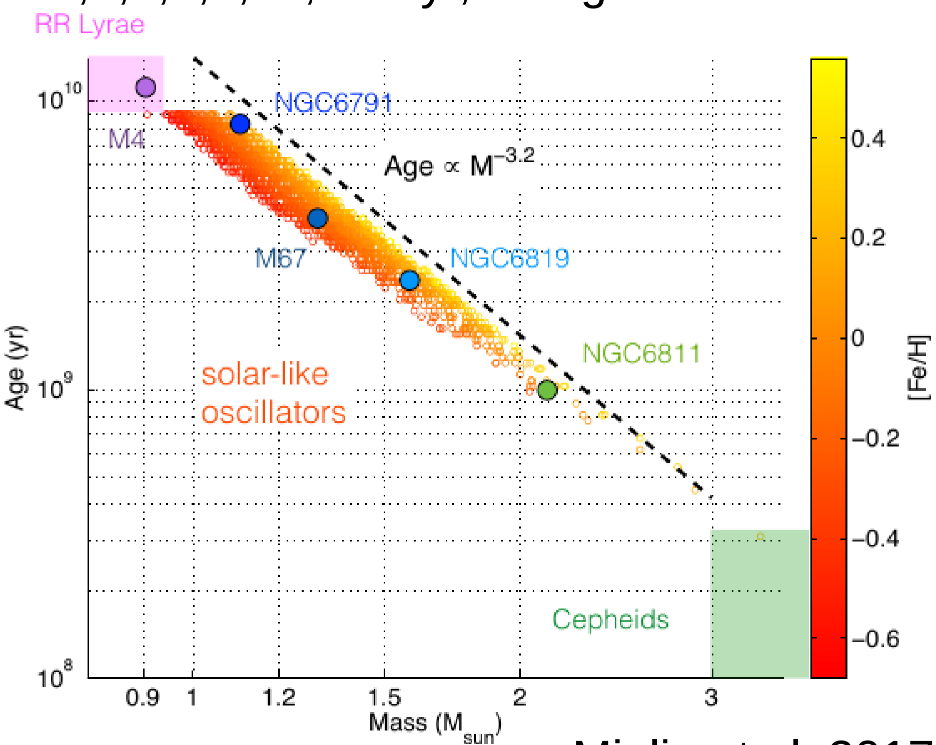
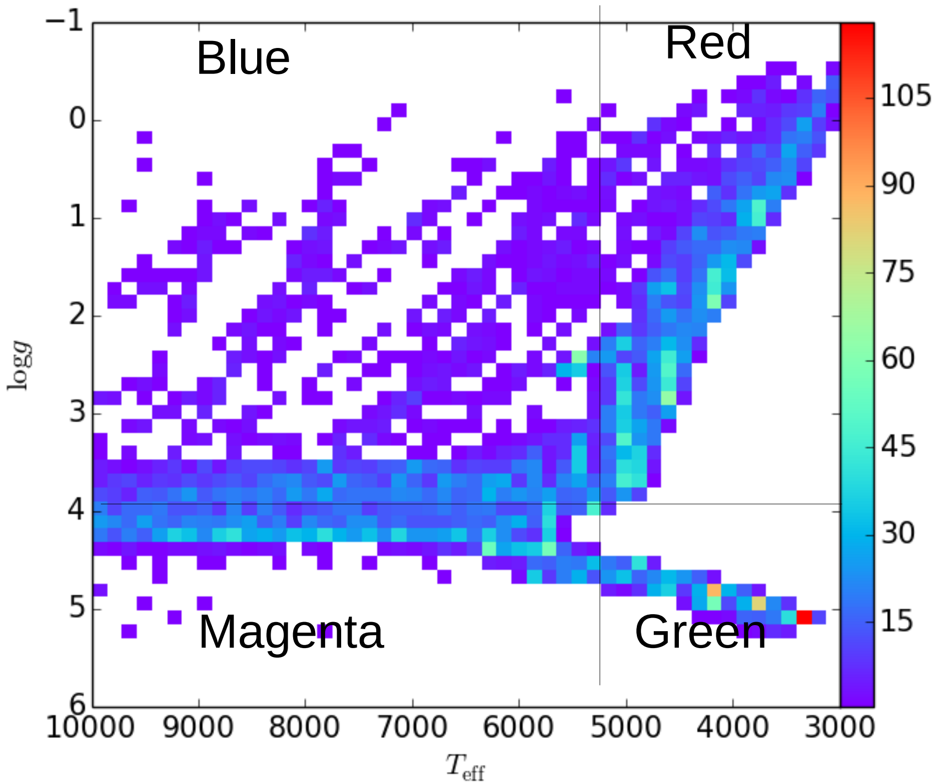
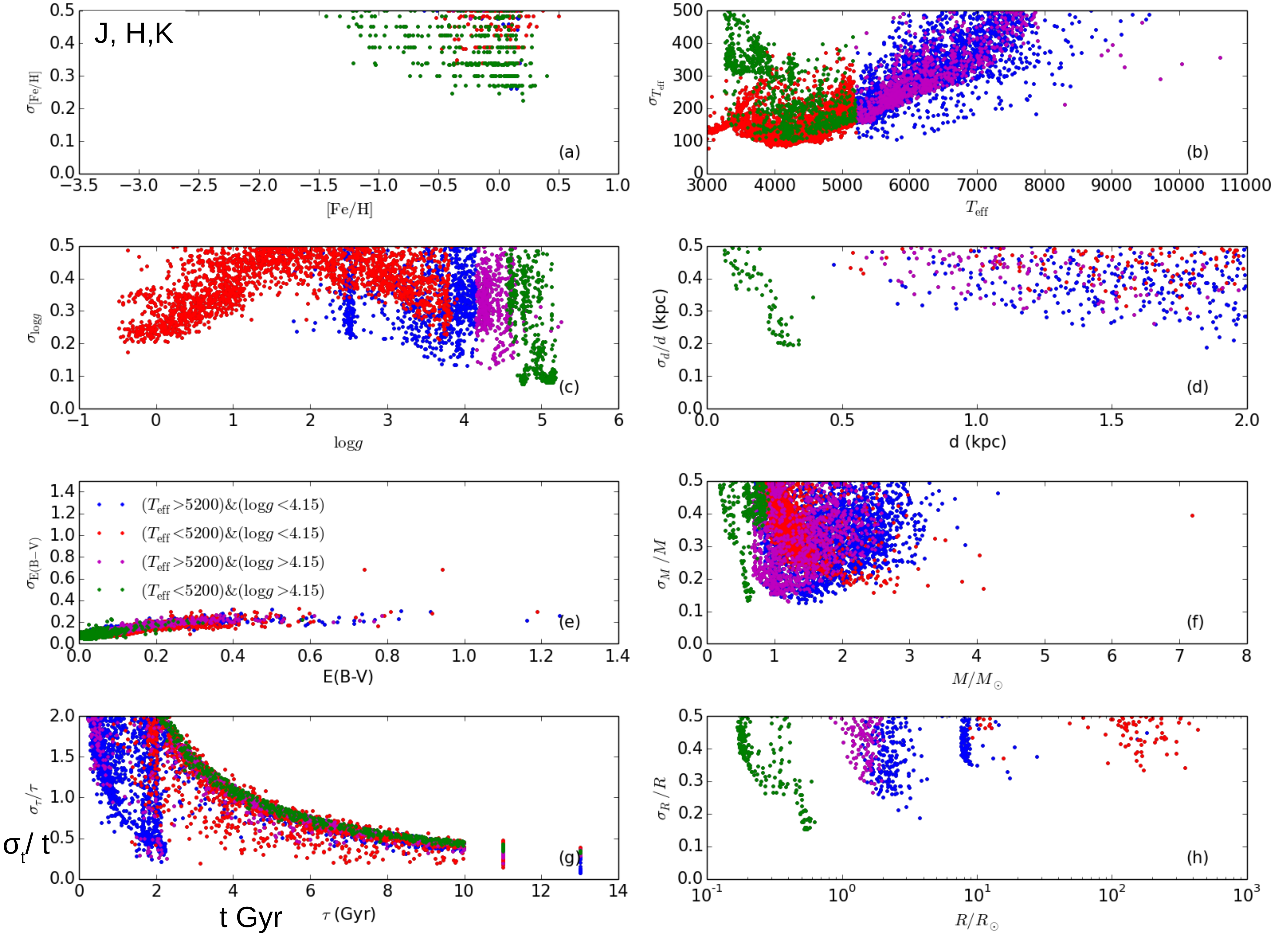


Miglio et al. 2017

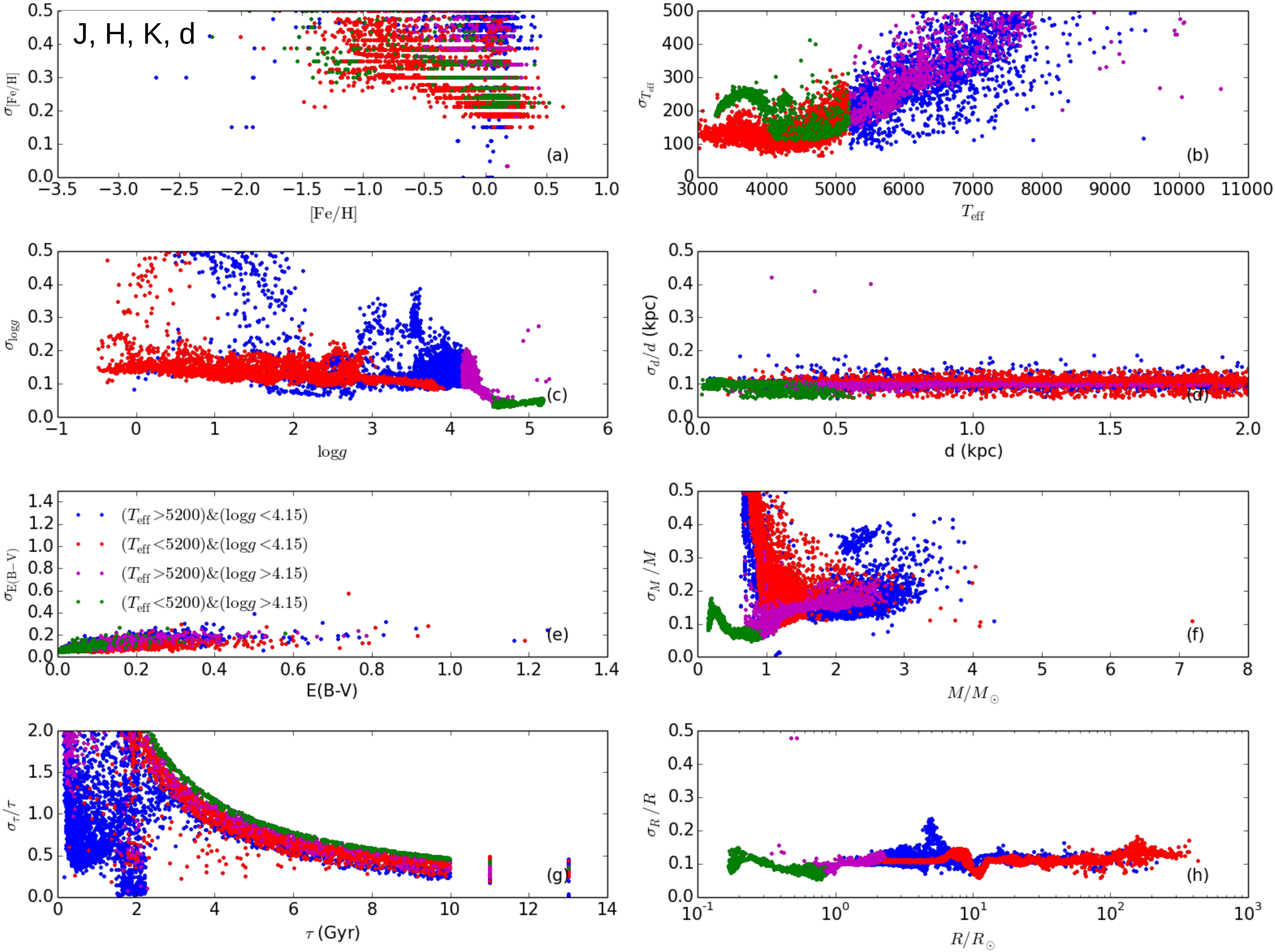
How can we get ages?

- BSTEP (Sharma et al 2018).
- Take 10,000 stars from a synetheic catalog and see how well we can recover the stellar properties
- Evenly sampled across (log g, Teff) plane.
- distance:10%,
- T_{eff}: 0.01 dex,
- Logg: 0.08
- [Fe/H]: 0.05
- (J,H,K): 0.02





J, H,K
$\sigma_{[Fe/H]}$
[Fe/H]
(a)
$\sigma_{T_{eff}}$
T_{eff}
(b)
$\sigma_{\log g}$
log$g$
(c)
σ_d/d (kpc)
d (kpc)
(d)
$\sigma_{E(B-V)}$
E(B-V)
(T_{eff} >5200)&(log$g$ <4.15)
(T_{eff} <5200)&(log$g$ <4.15)
(T_{eff} >5200)&(log$g$ >4.15)
(T_{eff} <5200)&(log$g$ >4.15)
(e)
σ_M/M
$M/M_\odot$
(f)
σ_τ/τ
σ_t/ t
τ (Gyr)
t Gyr
(g)
σ_R/R
$R/R_\odot$
(h)


J, H, K, d
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
[Fe/H]
$\sigma_{[Fe/H]}$
T_{eff}
$\sigma_{T_{eff}}$
log$g$
$\sigma_{\log g}$
d (kpc)
σ_d/d (kpc)
E(B-V)
$\sigma_{E(B-V)}$
$M/M_\odot$
σ_M/M
τ (Gyr)
σ_τ/τ
$R/R_\odot$
σ_R/R
$(T_{eff}>5200)\&(\log g<4.15)$
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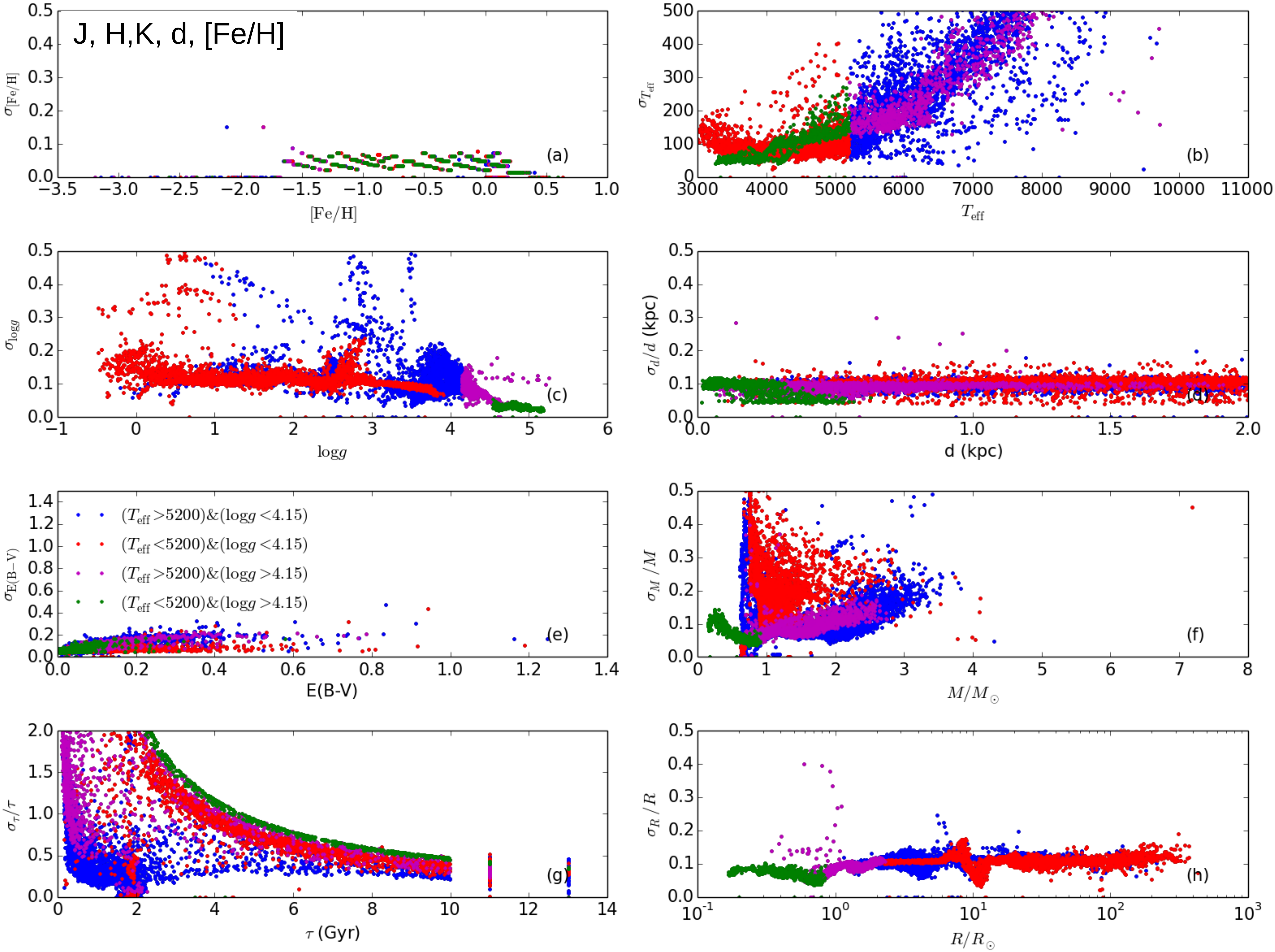
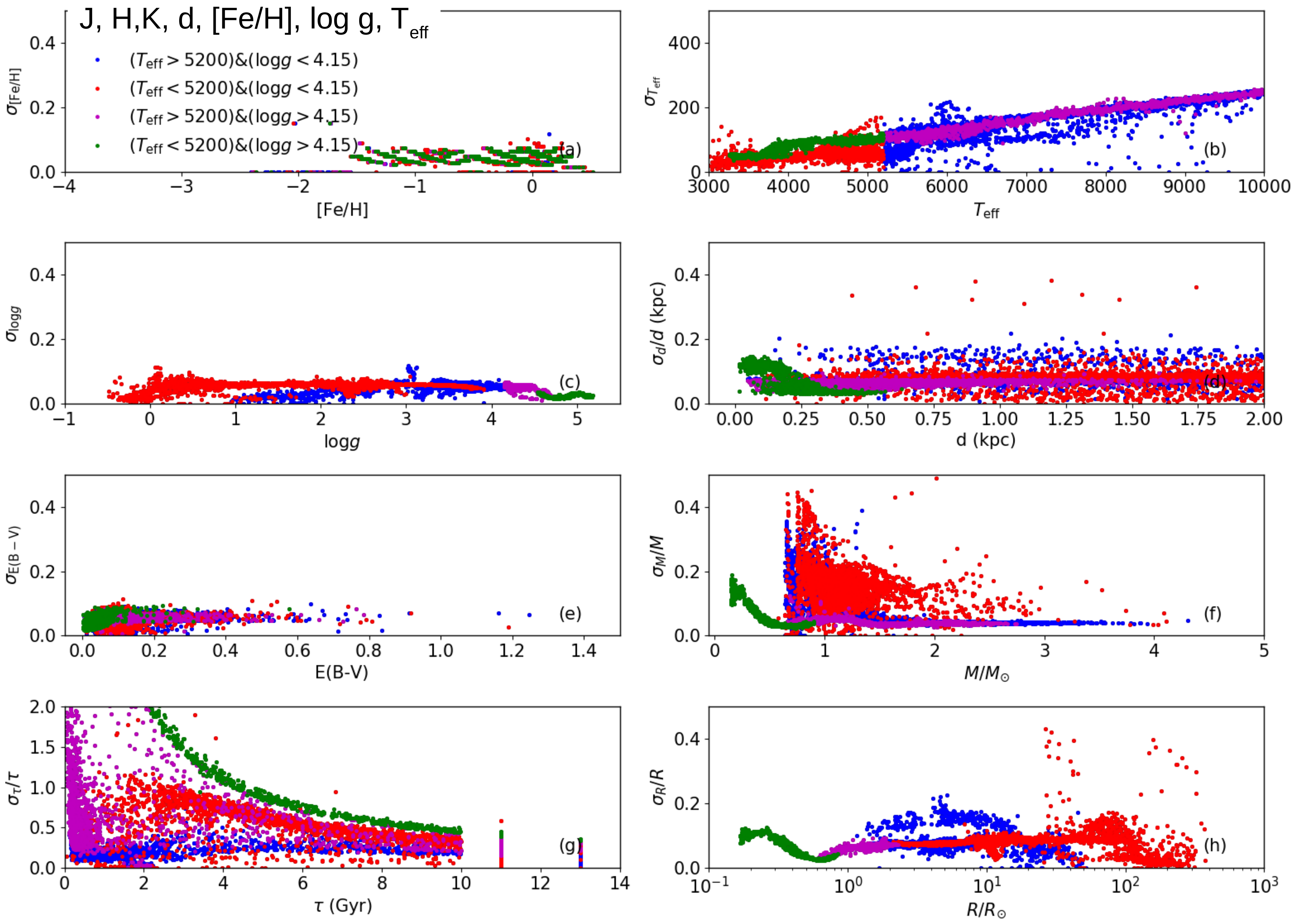
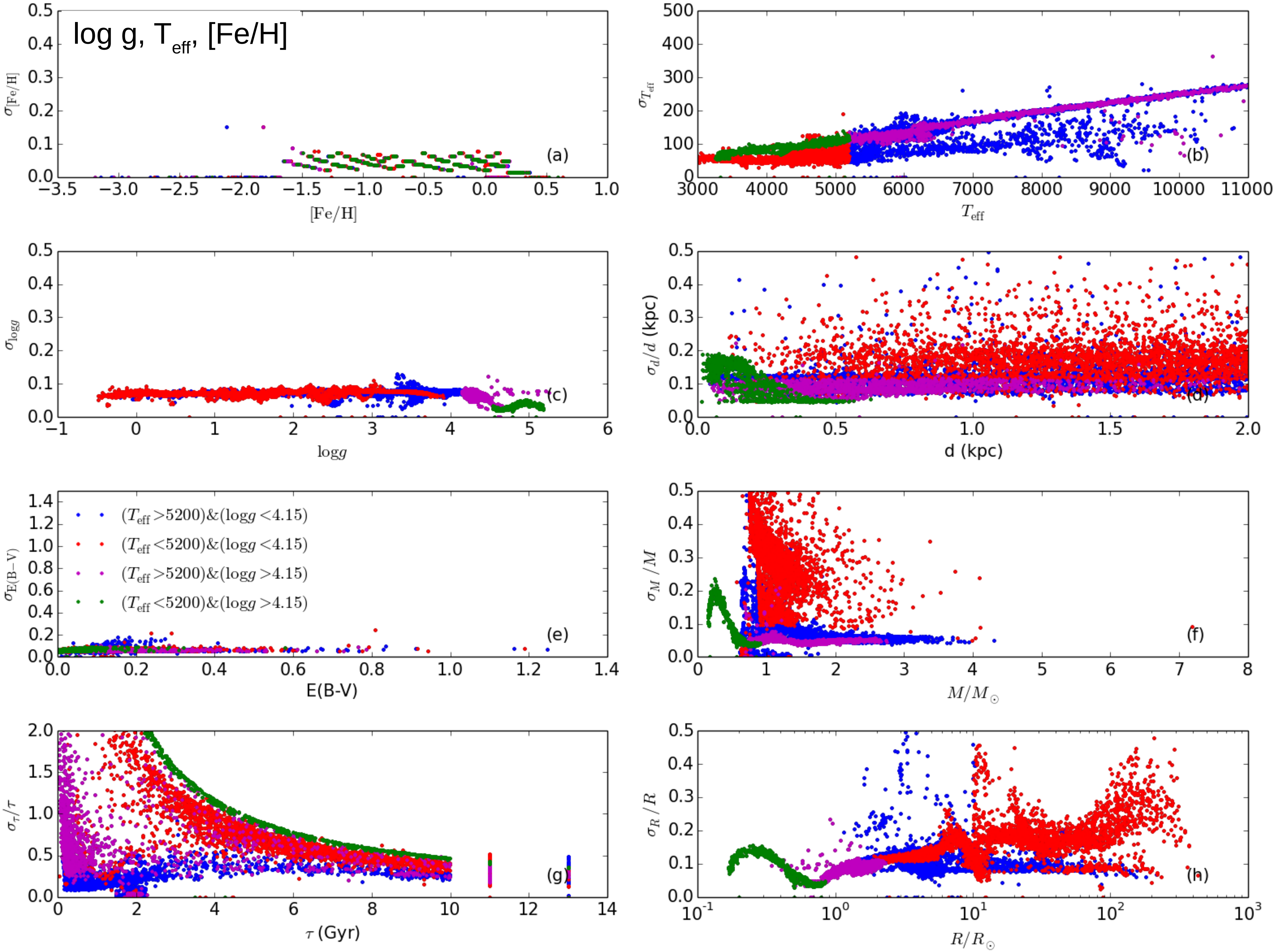


J, H,K, d, [Fe/H]
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
$\sigma_{[Fe/H]}$
[Fe/H]
$\sigma_{T_{eff}}$
T_{eff}
$\sigma_{\log g}$
$\log g$
σ_d/d (kpc)
d (kpc)
$\sigma_{E(B-V)}$
E(B-V)
$(T_{eff}>5200)\&(\log g<4.15)$
$(T_{eff}<5200)\&(\log g<4.15)$
$(T_{eff}>5200)\&(\log g>4.15)$
$(T_{eff}<5200)\&(\log g>4.15)$
σ_M/M
$M/M_\odot$
σ_τ/τ
τ (Gyr)
σ_R/R
$R/R_\odot$

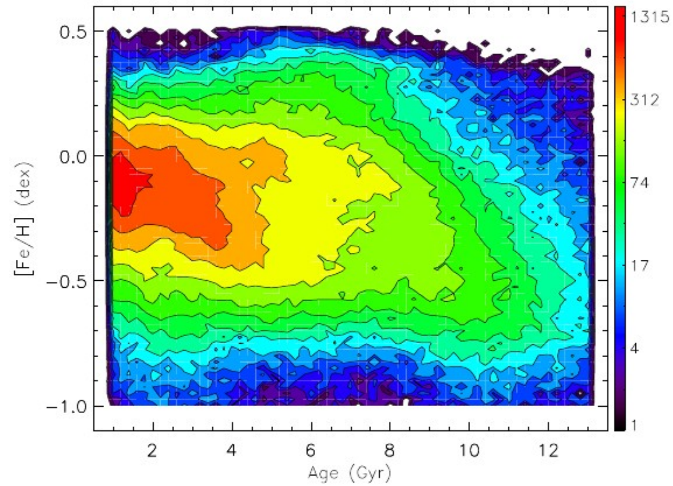


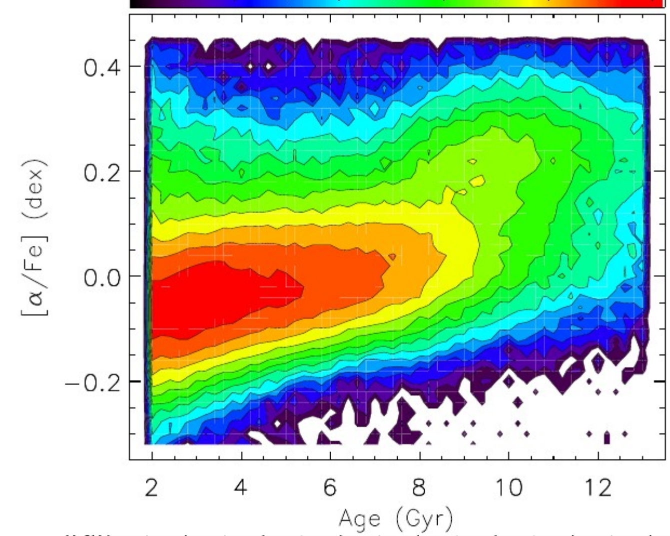
J, H,K, d, [Fe/H], log g, T_{eff}
$(T_{eff} > 5200)\&(\log g < 4.15)$
$(T_{eff} < 5200)\&(\log g < 4.15)$
$(T_{eff} > 5200)\&(\log g > 4.15)$
$(T_{eff} < 5200)\&(\log g > 4.15)$
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
$\sigma_{[Fe/H]}$
[Fe/H]
$\sigma_{T_{eff}}$
T_{eff}
$\sigma_{\log g}$
$\log g$
σ_d/d (kpc)
d (kpc)
$\sigma_{E(B-V)}$
E(B-V)
σ_M/M
$M/M_{\odot}$
σ_τ/τ
τ (Gyr)
σ_R/R
$R/R_{\odot}$



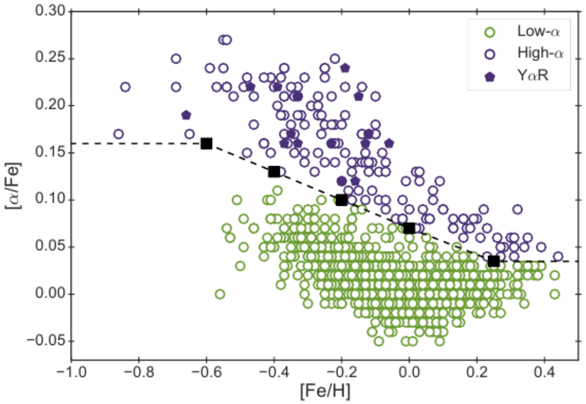
log g, T_eff, [Fe/H]
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
[Fe/H]
σ_[Fe/H]
T_eff
σ_T_eff
log g
σ_log g
d (kpc)
σ_d/d (kpc)
E(B-V)
σ_E(B−V)
(T_eff > 5200)&(log g < 4.15)
(T_eff < 5200)&(log g < 4.15)
(T_eff > 5200)&(log g > 4.15)
(T_eff < 5200)&(log g > 4.15)
M/M_⊙
σ_M/M
τ (Gyr)
σ_τ/τ
R/R_⊙
σ_R/R

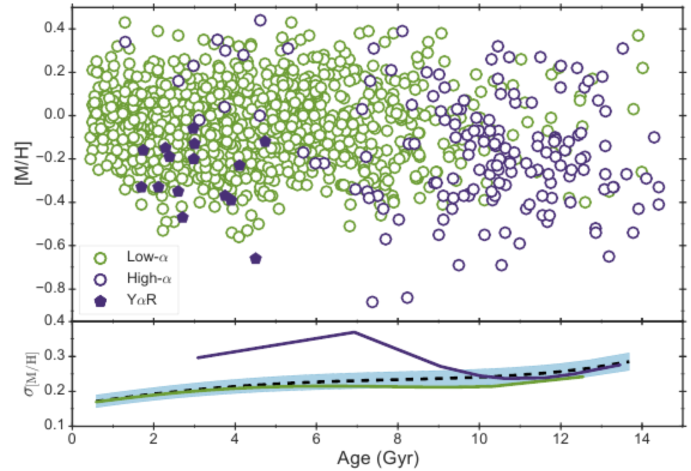
LAMOST
Xiang et al. 2017
Machine learning
(Mv,Teff, [Fe/H], [α/Fe])
1 Million MSTO, SG

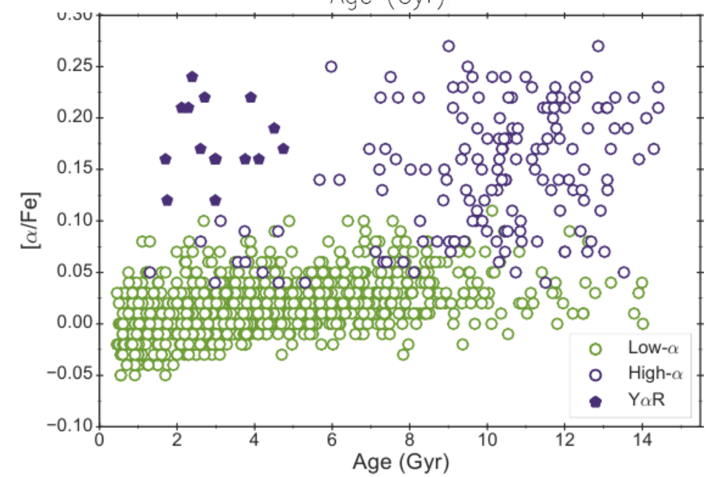




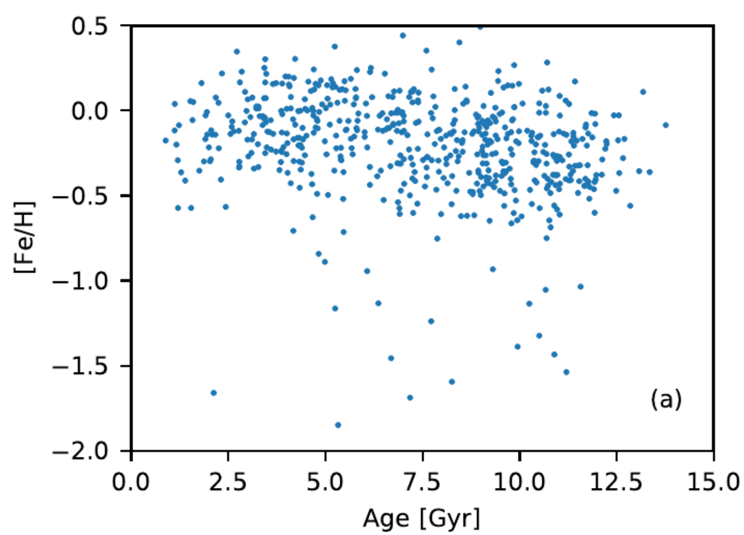
KEPLER-APOGEE
Silva Aguirre et al. 2017

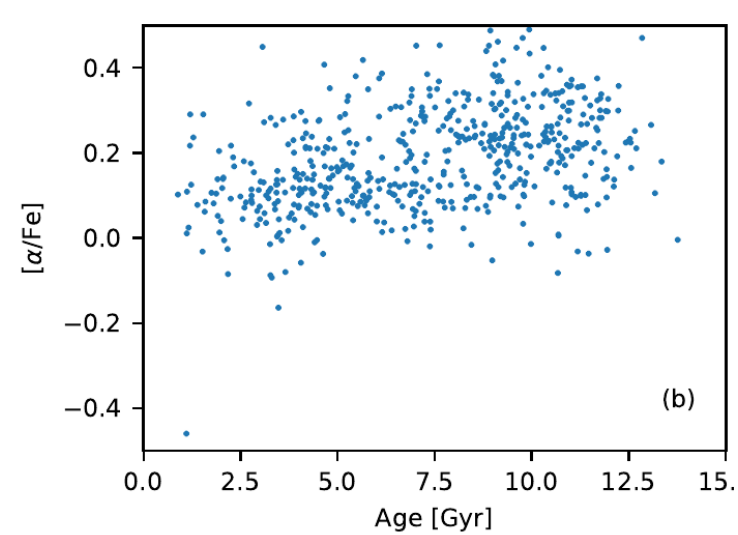




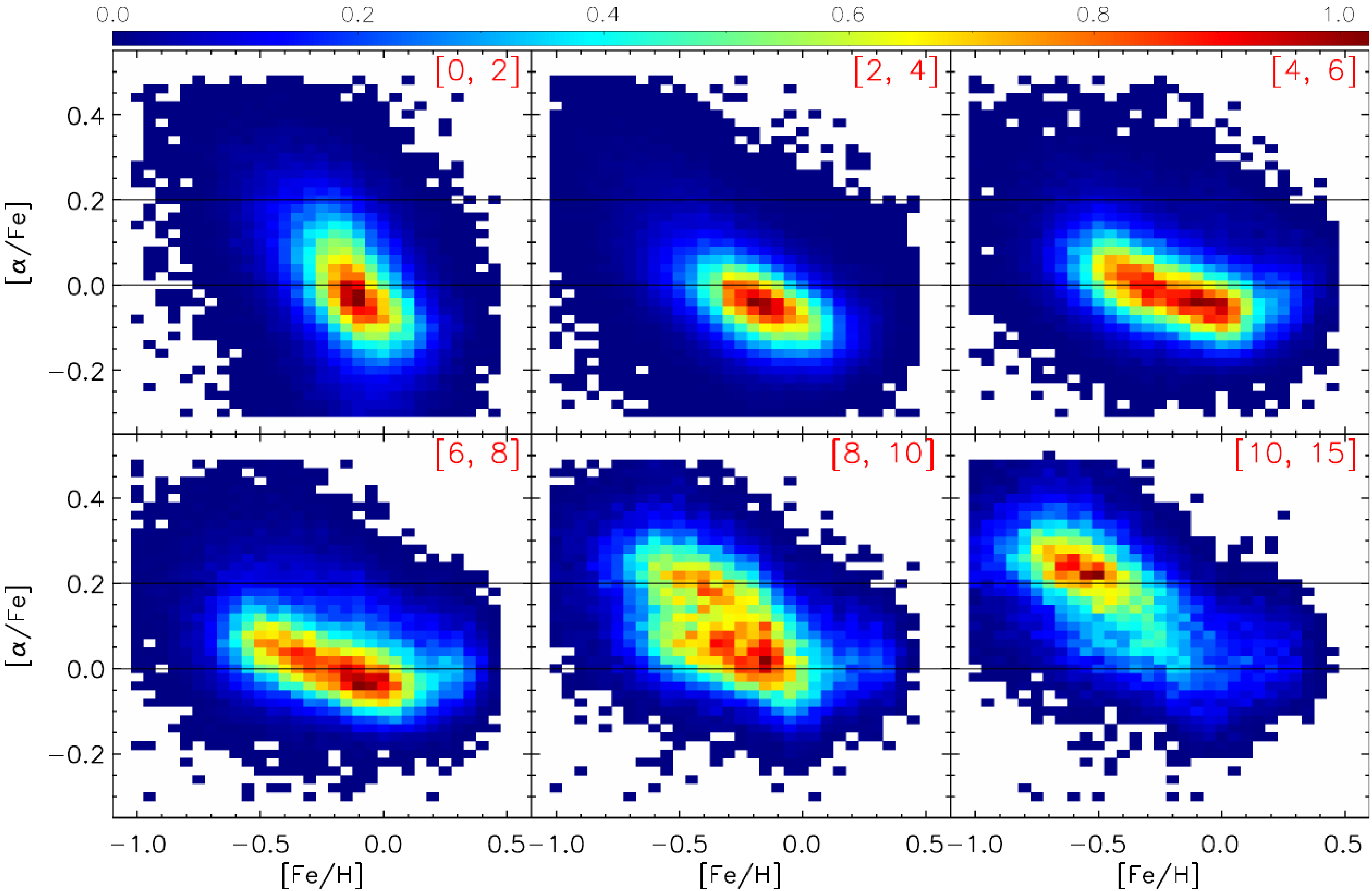


K2-HERMES/ GALAH
Sharma et al. (in prep)

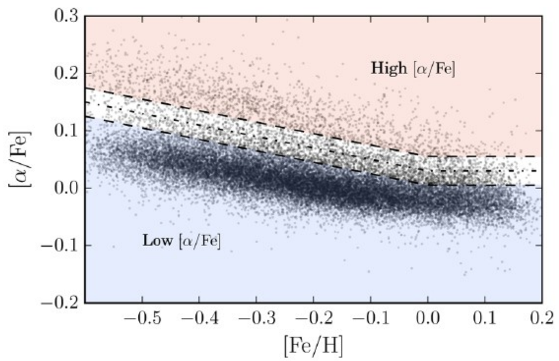


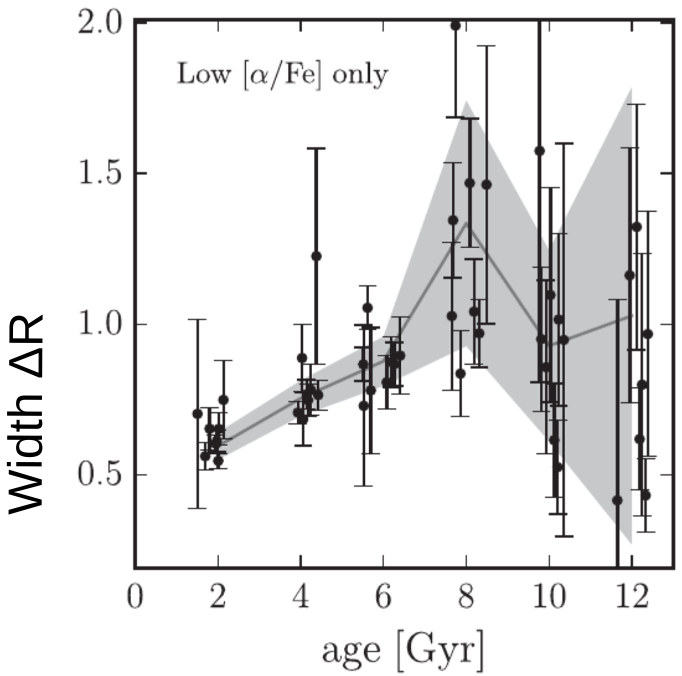


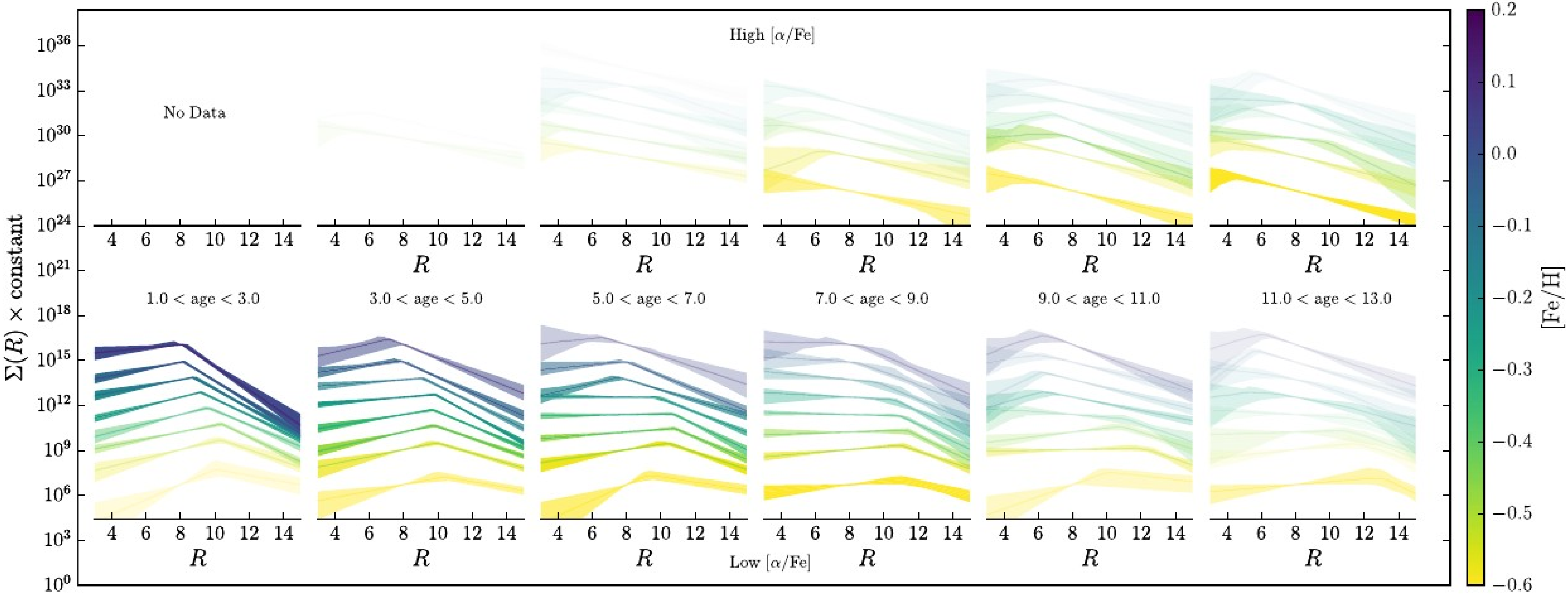
Xiang et al. 2017



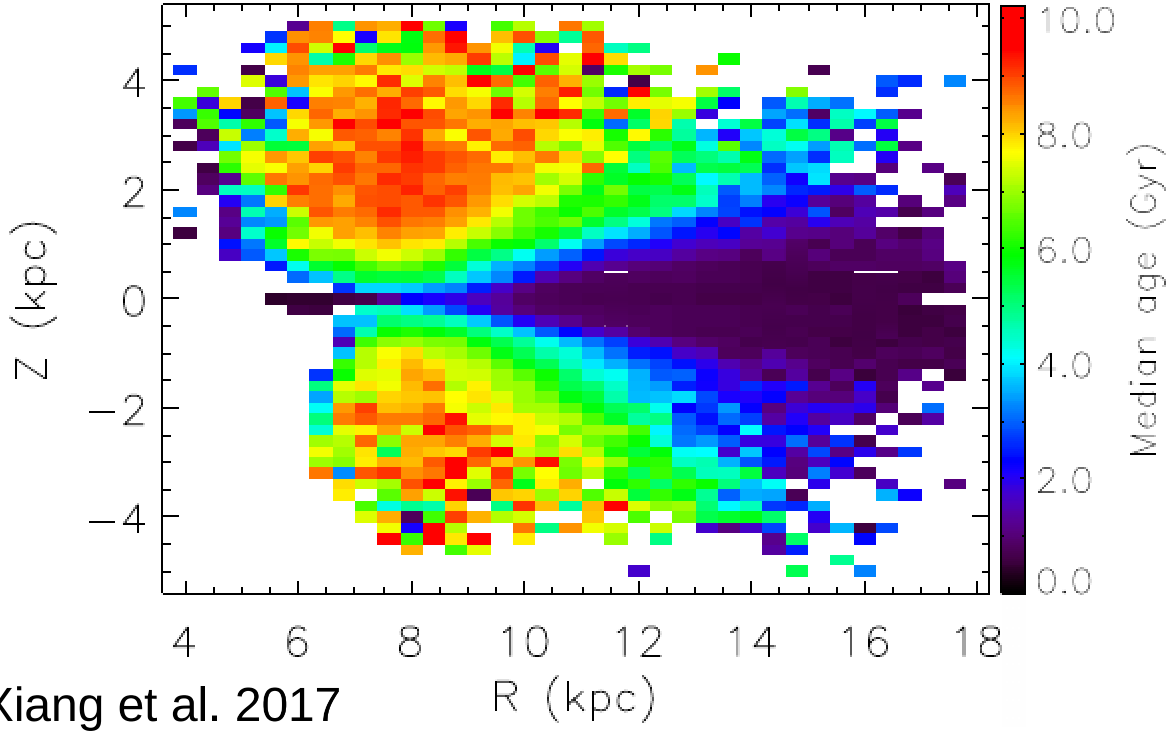
- Mackereth et al. 2017
- Giants, Spectroscopic Ages using C/N ratio
- Mono-abundance and mono-age
- **p(R,z | t, [α/Fe], [Fe/H])**





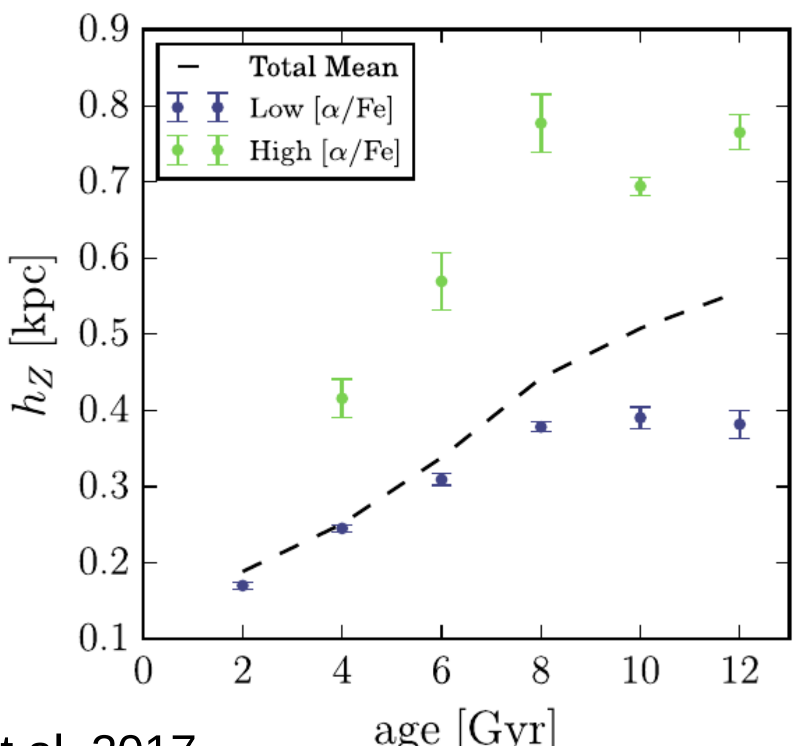


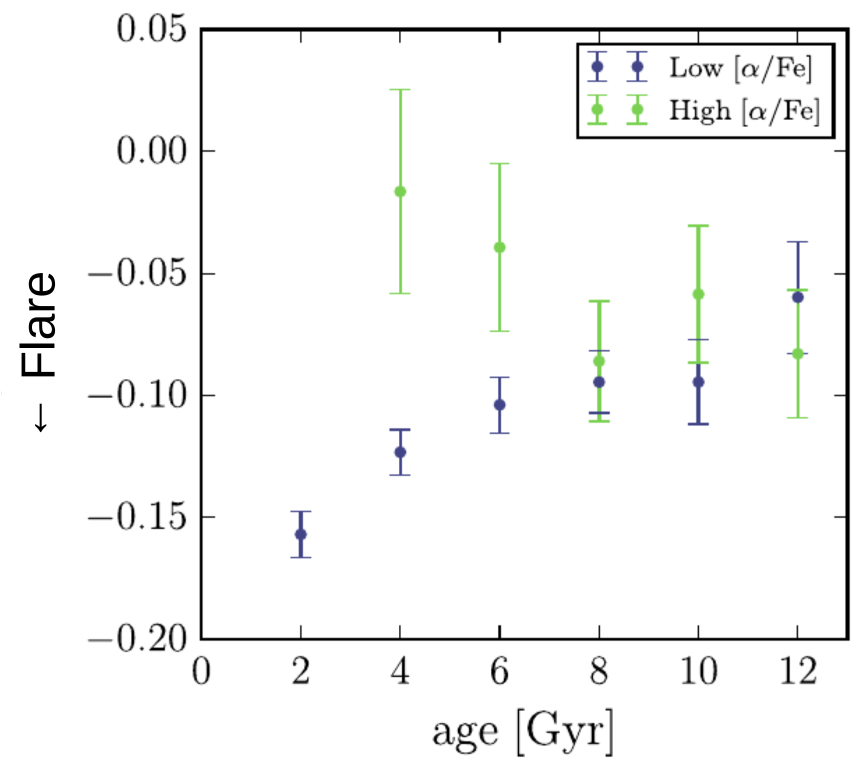
Age →



Xiang et al. 2017

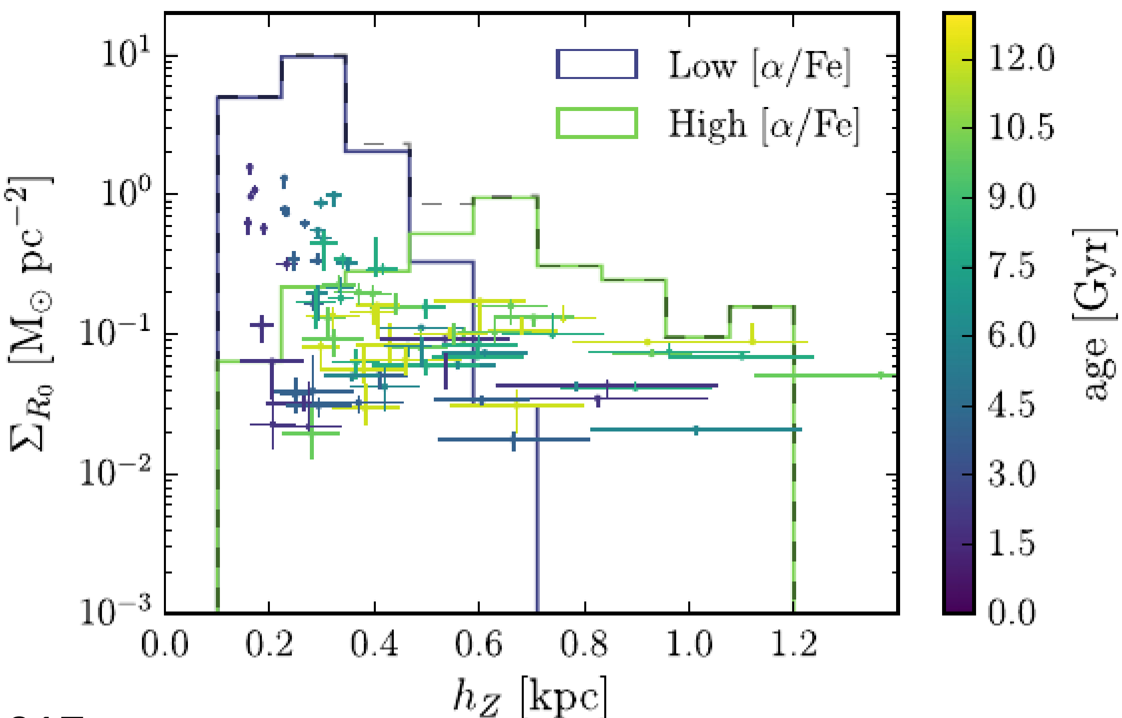
- Oldest pop are thicker, least flared
- Young are thin and most flared





Mackereth et al. 2017

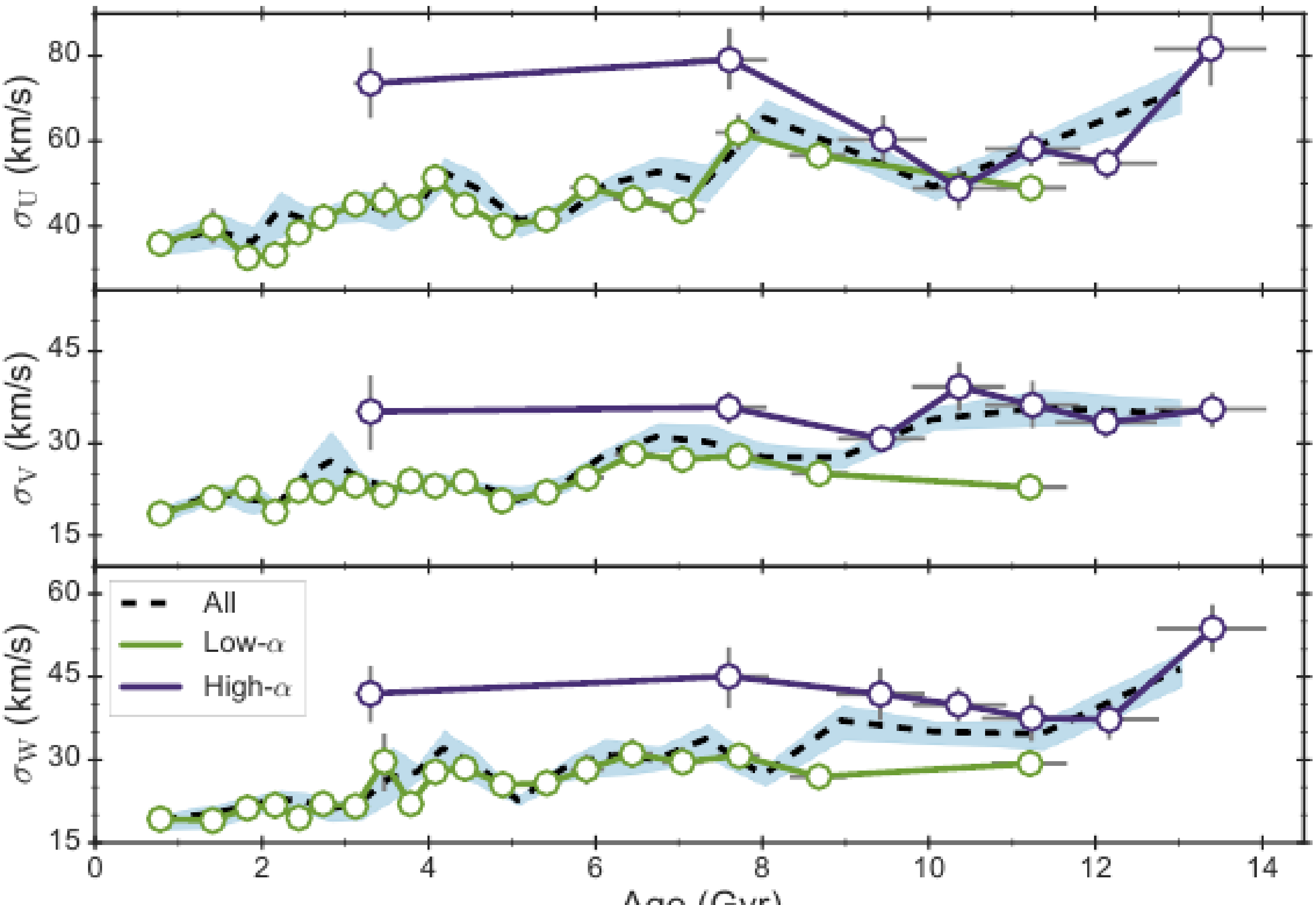
- No bimodality in $p(h_z)$



Mackereth et al. 2017

Age-velocity dispersion

- However, thick disc has distinct σ_W



KEPLER-APOGEE
Silva Aguirre et al. 2017

Uncertainties in (age, [Fe/H], [α/Fe]) not taken into account.

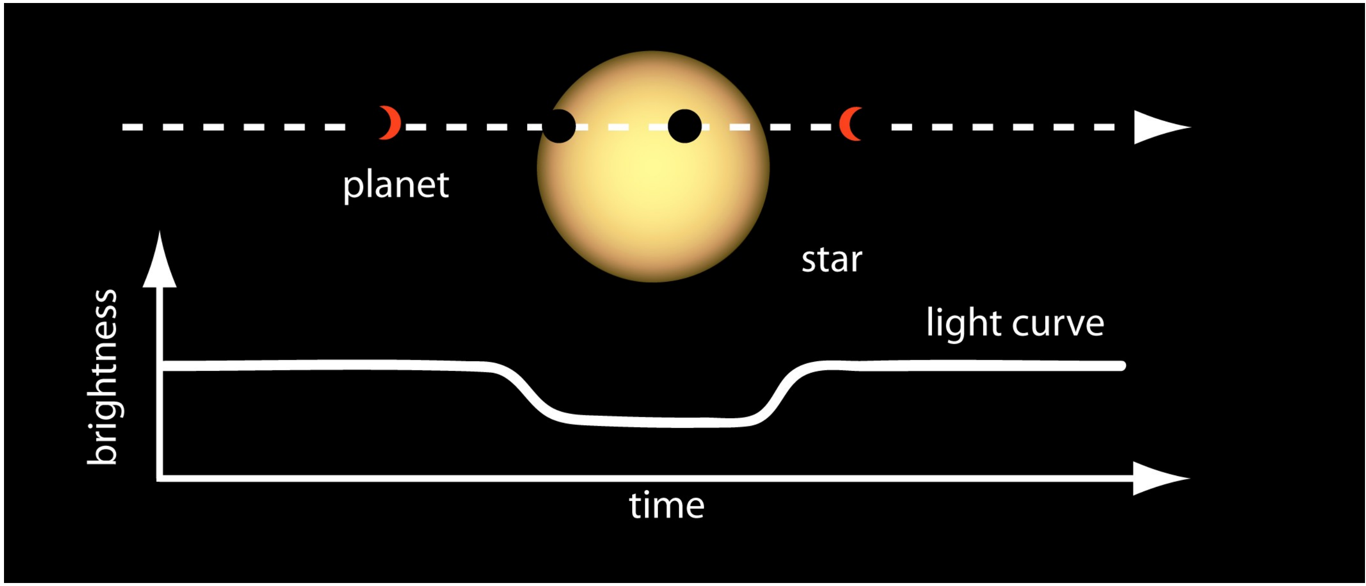
Trends are not intrinsic.

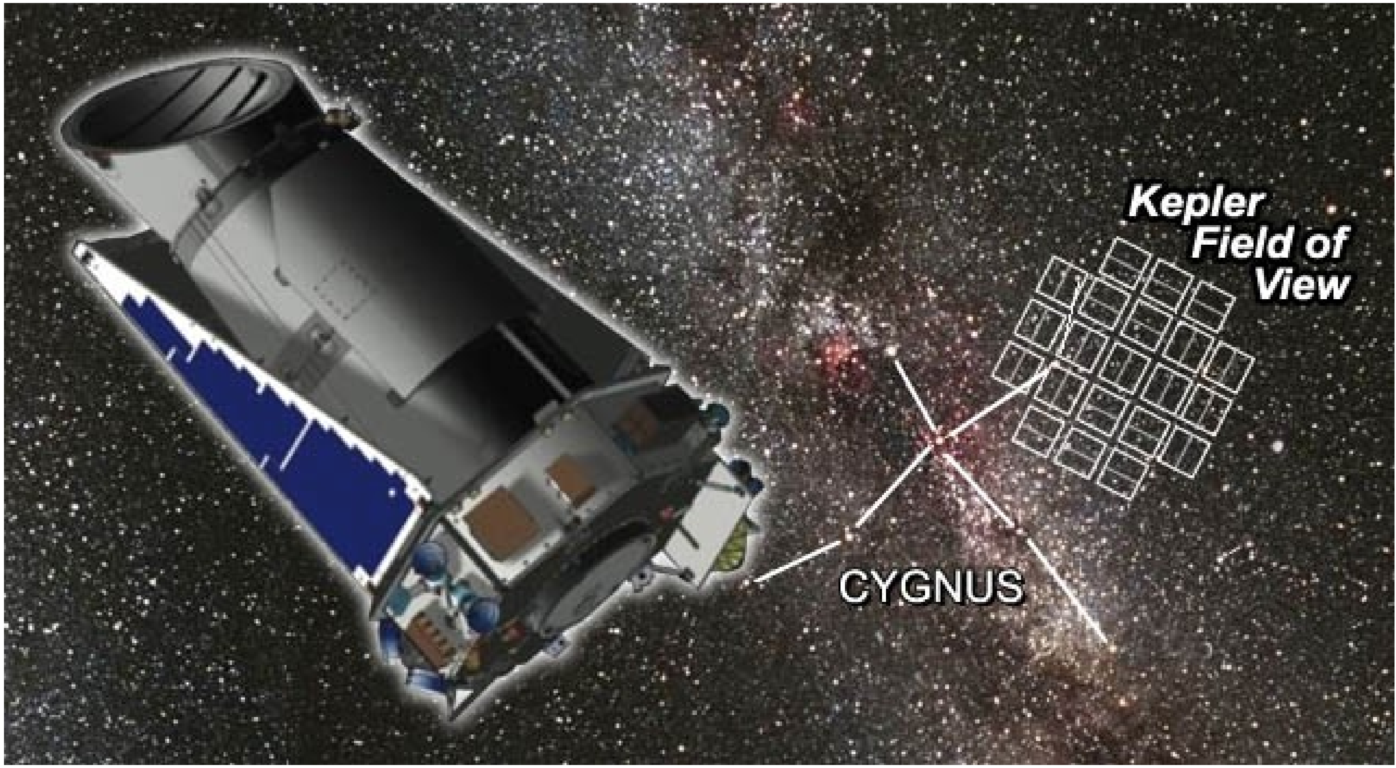
Extinction mapping

- Photometry → 3D Extinction
  - Galactic models are used as priors.
- Photometry, Spectroscopy → 3D Extinction
  - Possible even with low res spectra.
  - Spectroscopic survey with full 3d coverage, but not necessarily complete would be ideal.
  - Hierarchical modelling.
- Photometry color → T_{eff}, distance
  - For all Gaia stars
- Photometry, parallax → T_{eff}, age
  - Ages for all Gaia MSTO stars with good parallax.

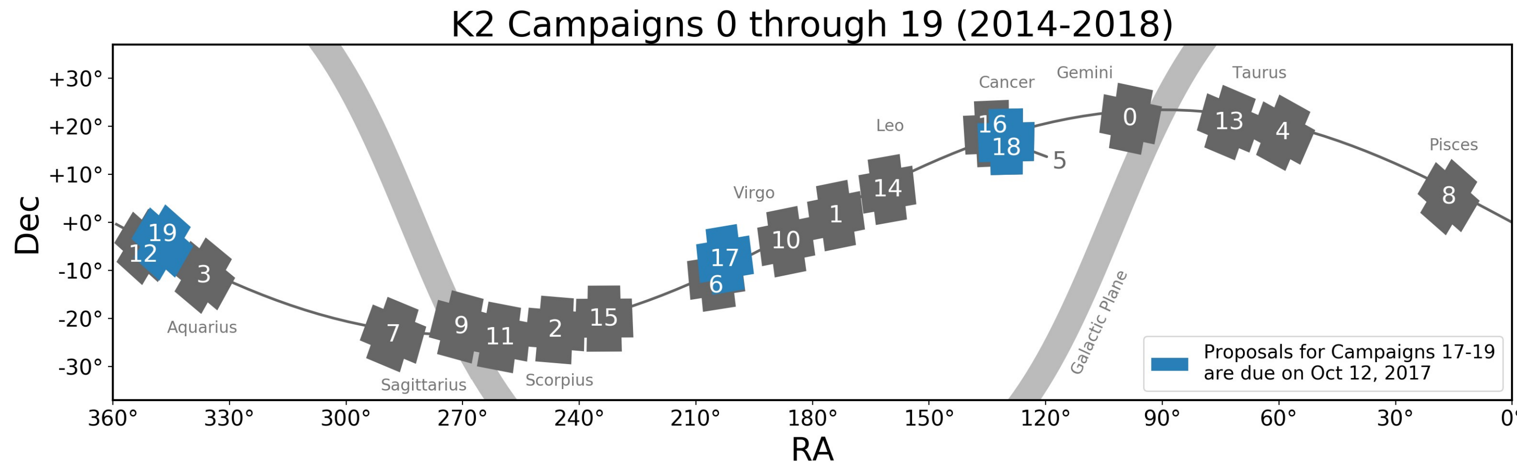
KEPLER

- Continuous monitoring of 150,000 stars.
- 8 deg radius

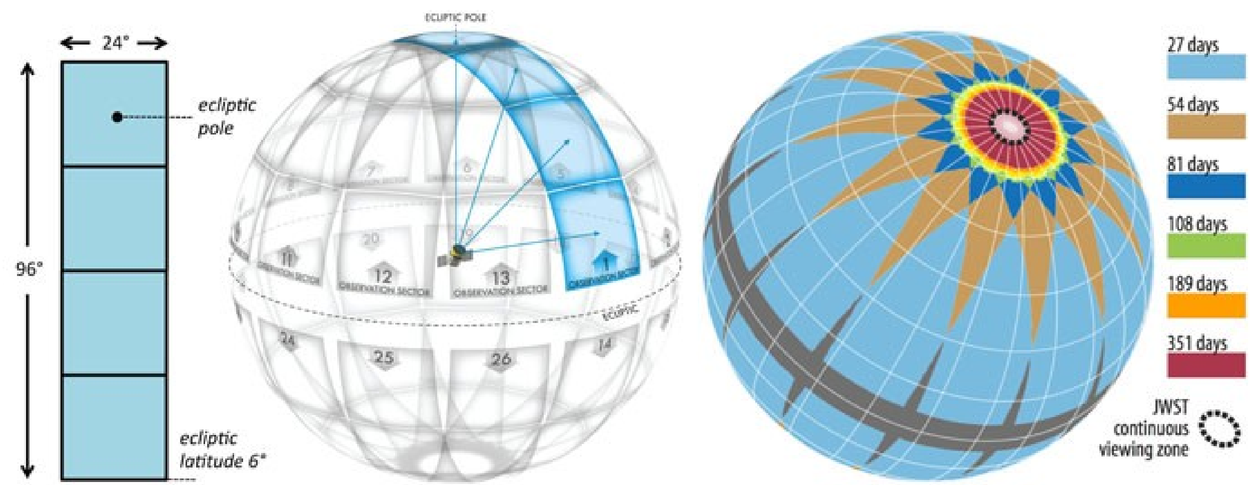




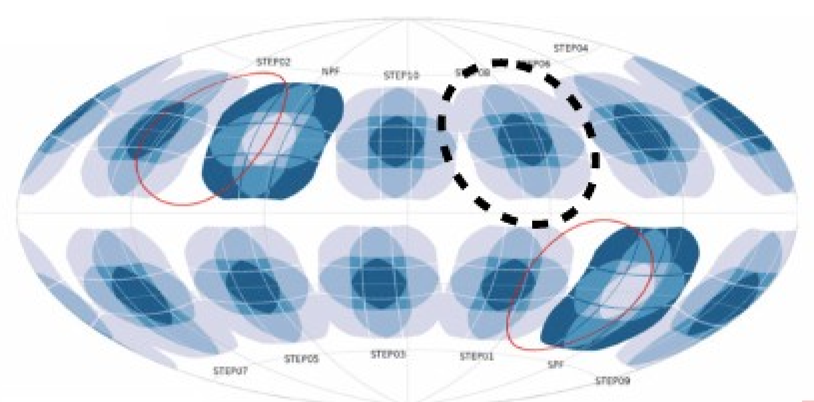
K2,
115x19 sq deg
8 deg
22 k
V ~ 14

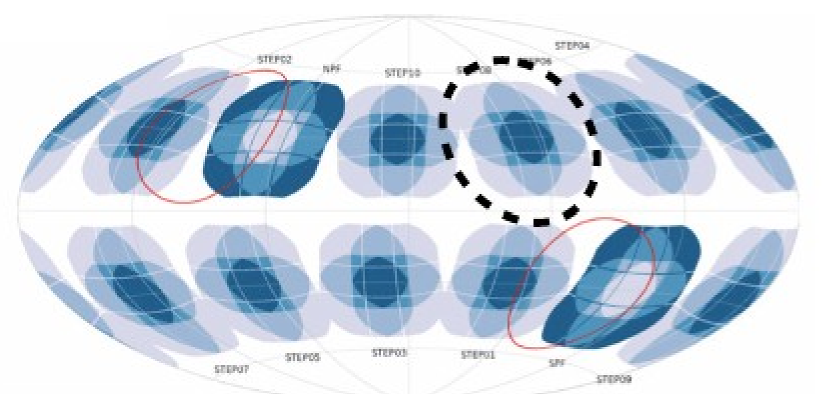


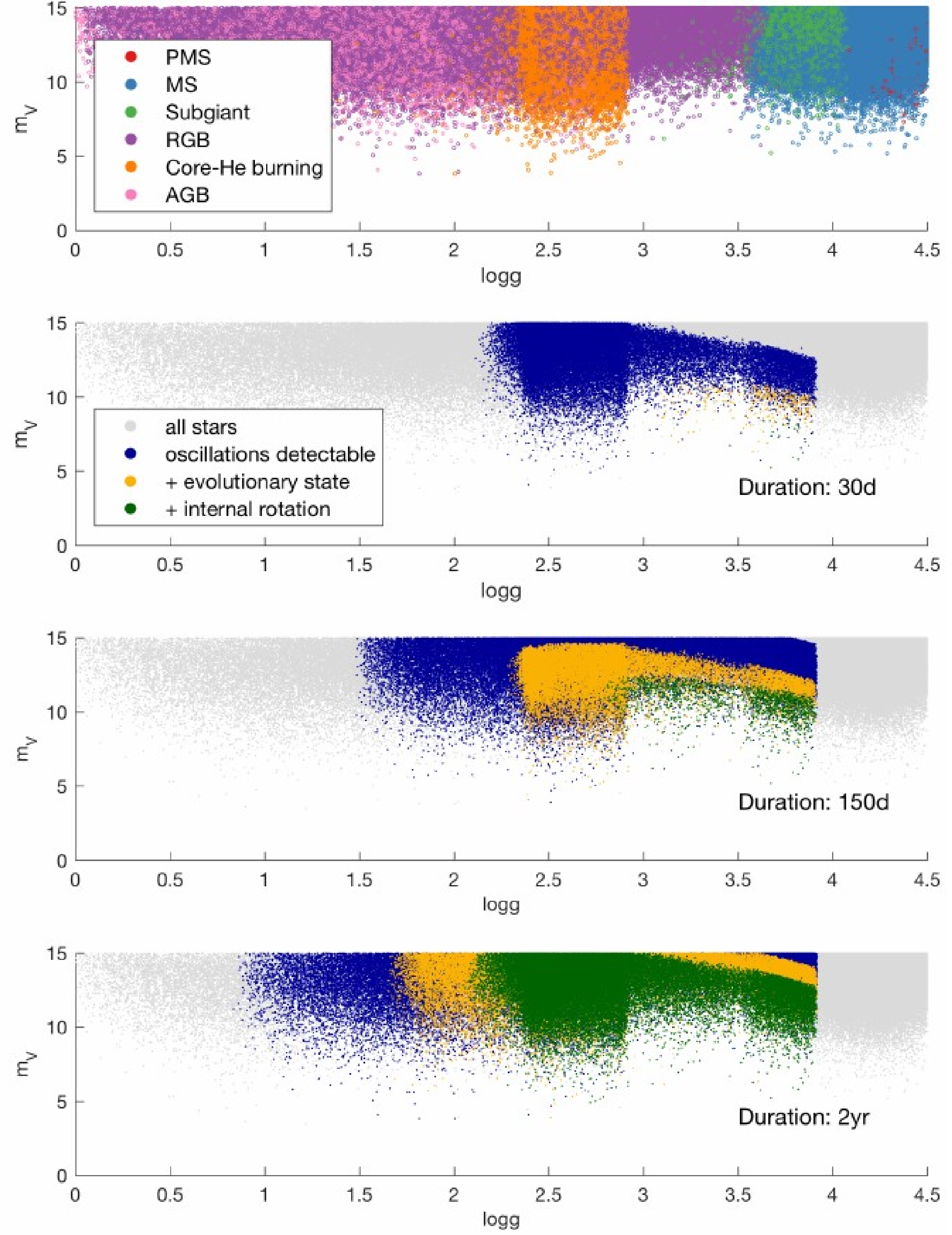
TESS
All sky,
CVZ 12deg
V~13, 2.5 kpc



PLATO
1600 sq degx12, Launch 2025
2 LD 2yr,
12 step-and-stare 1 month
22.5 deg
V~15, 6.3 kpc







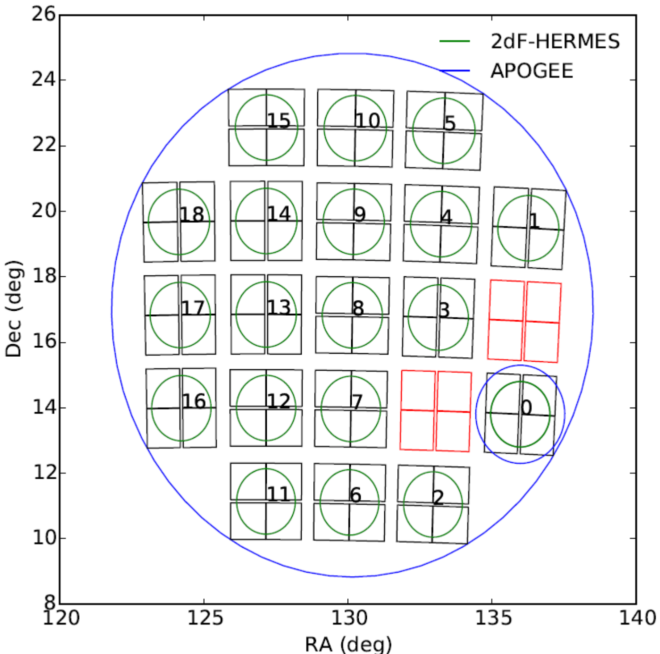
Miglio et al 2017

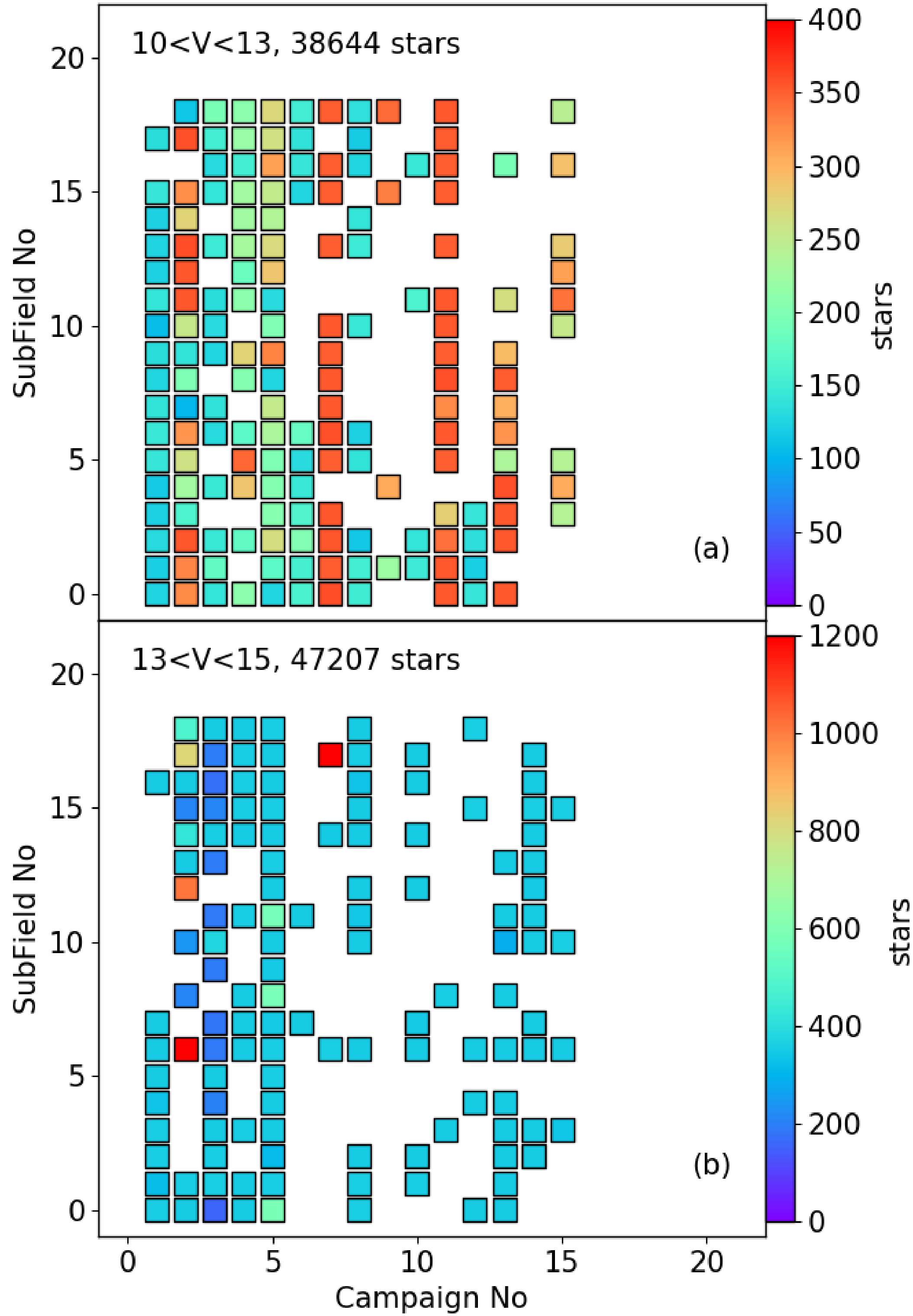
K2-HERMES survey

PI: Sanjib Sharma , CoIs: Dennis Stello, Rob Wittenmyer, Joss Bland-Hawthorn, Martin Asplund, Ken Freeman, Sven Buder, Janez Kos, Ly Duong, Jane Lin, Karin Lind, Melissa Ness, Tomaz Zwitter, Daniel Huber, Tim Bedding, Gregor Traven, Sarah Martell, Gayandhi De Silva, Jeffrey Simpson, Borja Anguiano, Andrew Casey, Luca Casagrande, Aaron Dotter, James Esdaile, Marc Hon, Prajwal Kafle, Michael Ireland, David Nataf, Shourya Khanna, Hafiz Saddon, Duncan Wright, Daniel Zucker

K2-HERMES

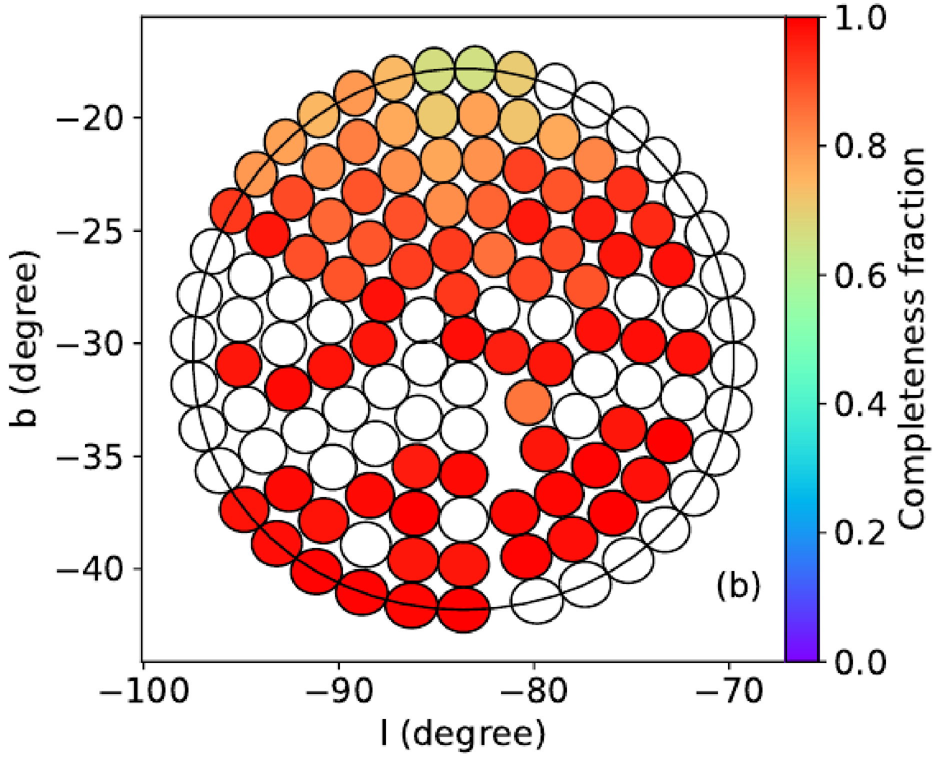
- Current status of observations.
- DR1
  - (Sharma et al. 2018 in prep)

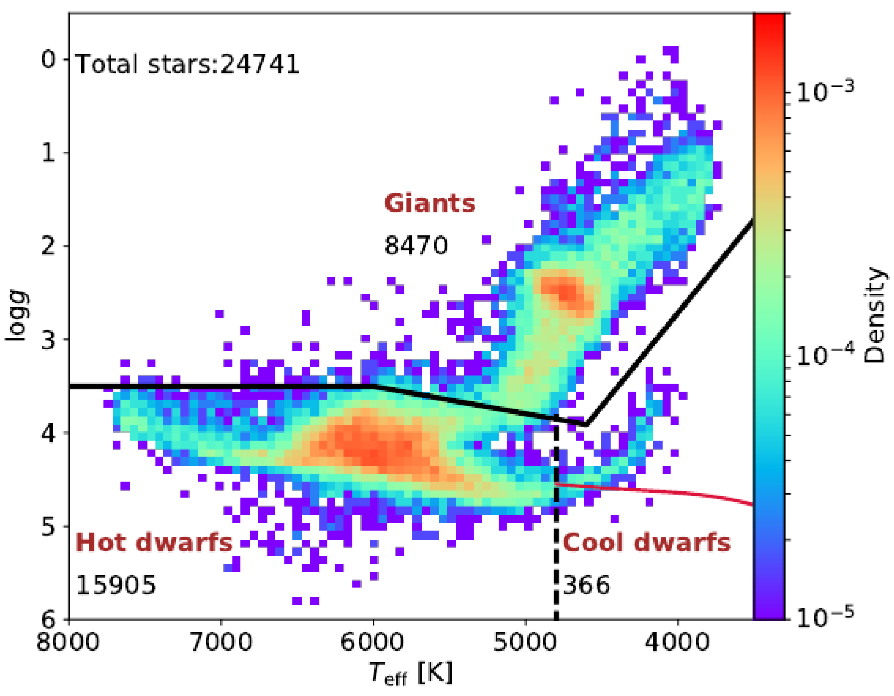




TESS-HERMES (DR1, Sharma et al. 2018)

- http://www.physics.usyd.edu.au/tess-hermes/
- MAST (NASA archive)





Future Spectroscopic surveys

- Why do we need ?
  - (Age, abundance)
- How many stars do we need?
  - (x, v, t, Fe/H, [α/Fe]) space 9 dims
  - (J(x,v), t, Fe/H, [α/Fe]) space 6 dims
  - 10 bins per dim → 10^9 cells)
  - 10 stars per cell → 10^{10} stars (10^7 using J).

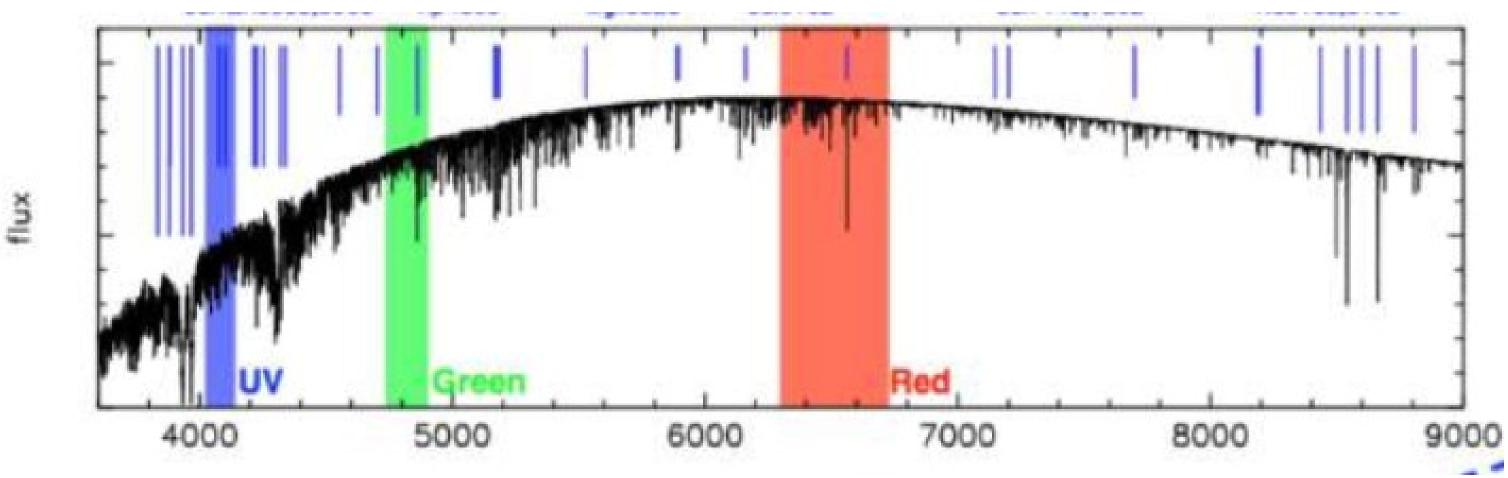
- What coverage do we need?
  - All sky (Full sampling of (R,z) space)
- How faint?
  - For disc 5-8 kpc
  - For bulge 8-10 kpc
  - For halo 20-80 kpc
  - MSTO M_v=4, Gaints M_v=1
  - V=17.5, d_{MSTO}= 5 kpc , d_{Giant}= 20 kpc
  - V=20.5, d_{MSTO}= 20 kpc , d_{Giant}= 80 kpc

Design of spectroscopic surveys

- Multiplexing
  - high >1000
- FOV
  - Large > 1 deg diamter
- Telescope diameter
  - Large 4m, 8m, 12m.
- Multi or single epoch.
- Wavelength range and Resolution

Wavelength range and resolution

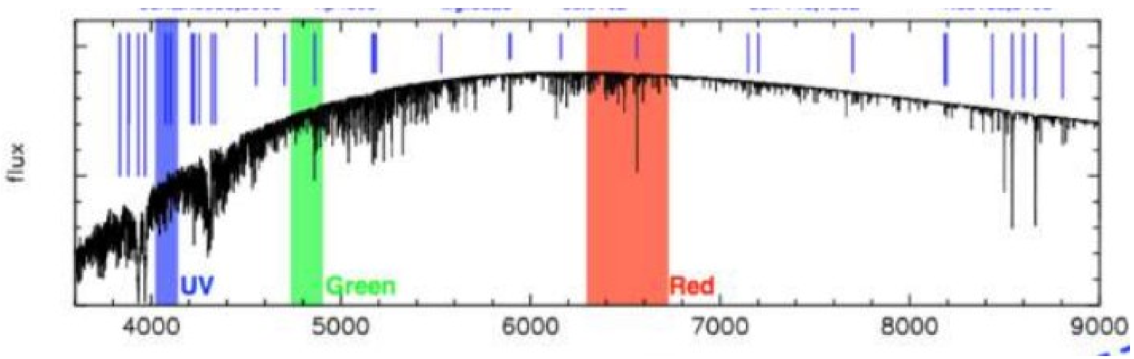
- LR 1000-5000, full optical 360nm-980nm
  - Driven by need for extragalactic science
  - SEGUE, RAVE, LAMOST, PFS, DESI, WEAVE, 4MOST
- HR 20000-50000, only windows
  - APOGEE, GALAH, 4MOST, WEAVE, LAMOST,MSE



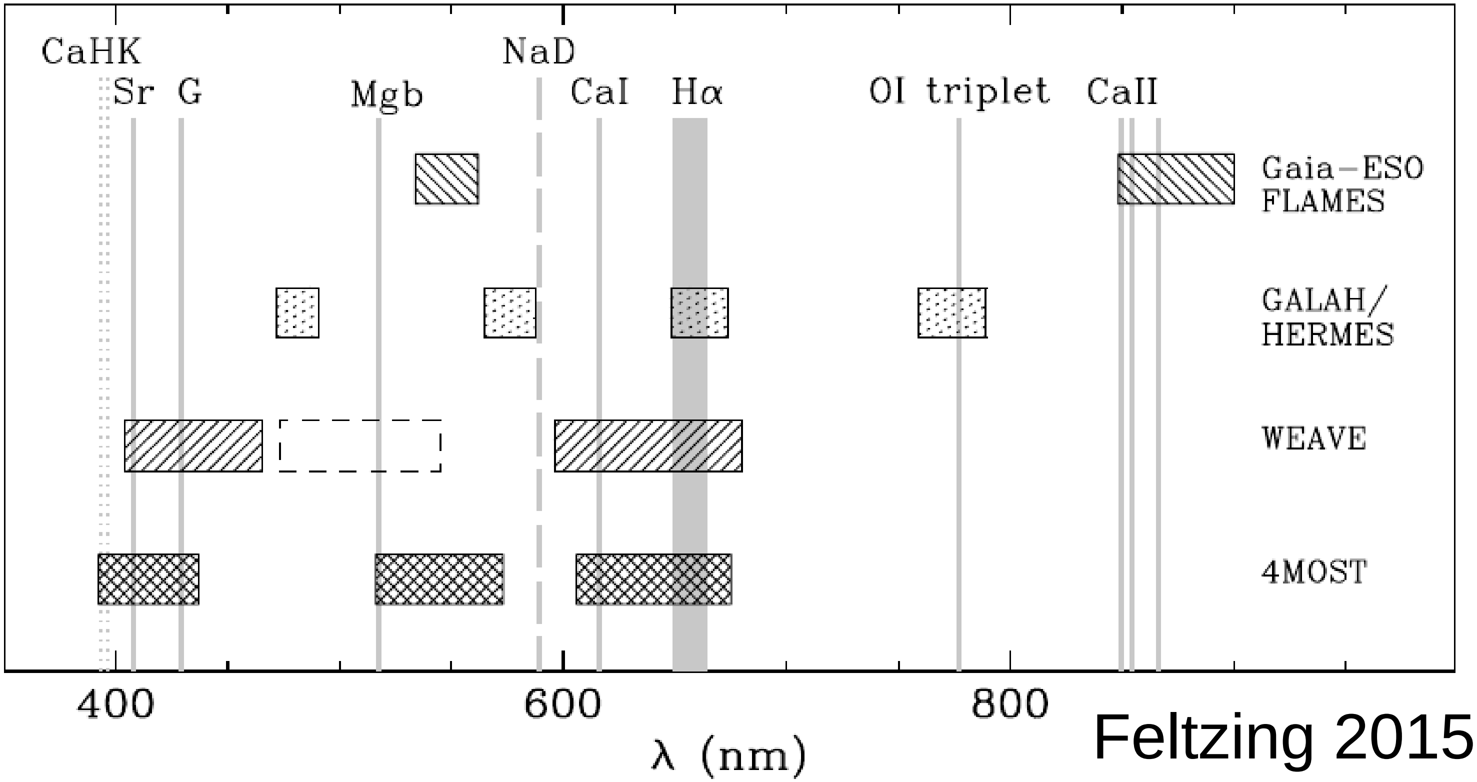
McConnachie et al. 2016

What wavelength windows?

- Blue < 450 nm, for heavy elements, metal poor stars, CH, Ca HK,SrII, BaII, Y
- Red for in plane to avoid extinction APOGEE
- Radial Vel- Mgb, CaII
- Gravity sensitive
  - CaI, CaII, Mgb,
- Interstellar- NaD
- Machine Learning age sensitive features



McConnachie et al. 2016



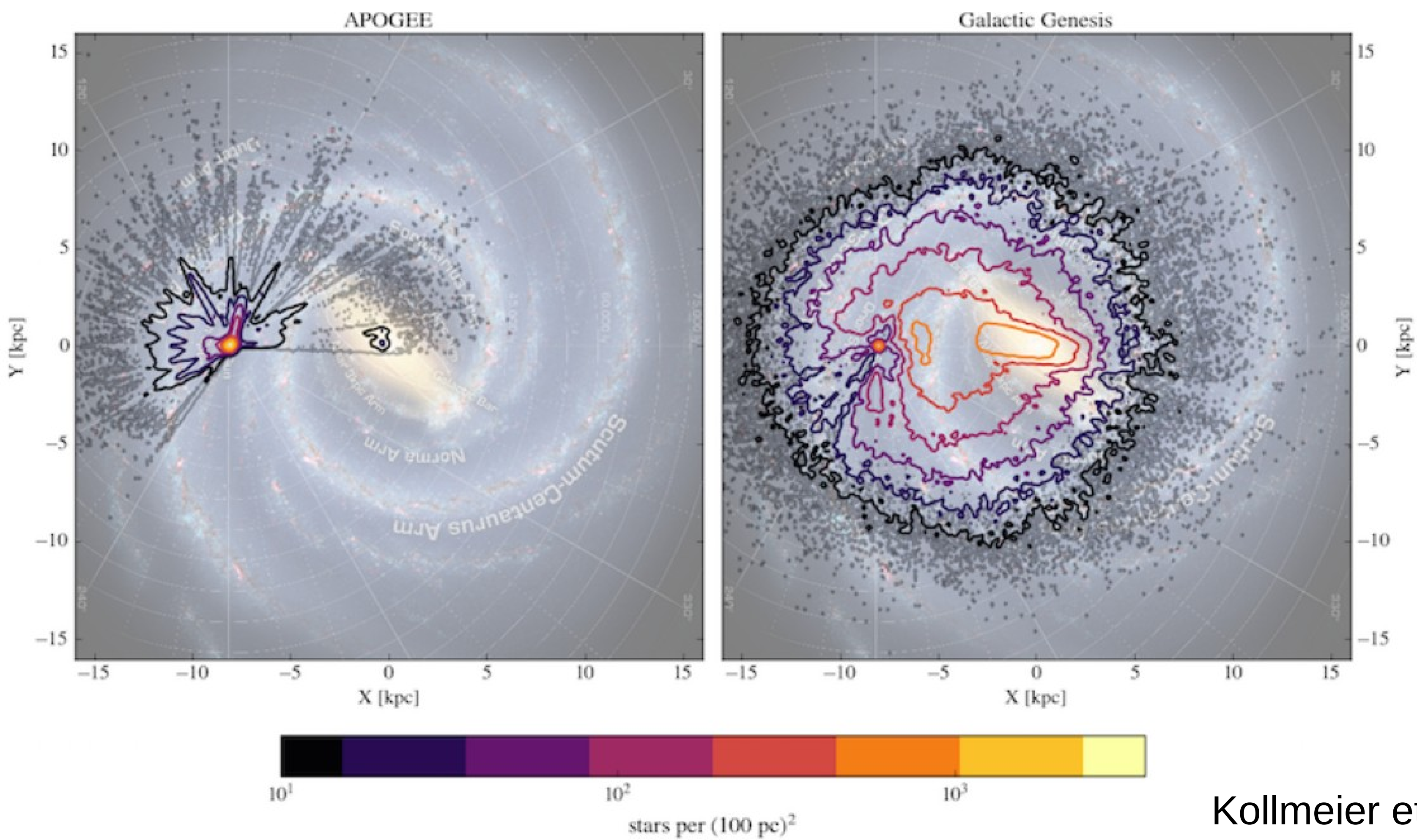
Feltzing 2015

Facility / Instrument	*First light (anticipated)*	*Aperture (M1 in m)*	*Field of View (sq. deg)*	*Etendue*	*Multiplexing*	*Wavelength coverage (um)*	*Spectral resolutio (approx)*
SDSS I - IV	Existing	2.5	1.54	7.6	640	0.38 - 0.92	1800
Guo Shoujing / LAMOST	Existing	4	19.6	246	4000	0.37 - 0.90	1000 - 10000
AAT / HERMES	2015	3.9	3.14	37.5	392	windows	28000, 50000
WHT / WEAVE	2017	4	3.14	39.5	1000	0.37 - 1.00	5000
						windows	20000
VISTA / 4MOST	2017	4	2.5	31.4	2400	0.39 - 0.95	5000
						windows	18000
Mayall / DESI	2018	4	7.1	89.2	5000	0.36 - 0.98	4000
VLT / MOONS	2018	8.2	0.14	7.4	1000	0.8 - 1.8	4000
						windows	20000
Subaru / PFS	2019	8.2	1.25	66	2400	0.38 - 1.26	2000
						0.71 - 0.89	5000
MSE	2024	11.25	1.5	149	3468	0.36 - 1.8	3000
						0.36 - 0.95 50% coverage	6500
						windows	40000

McConnachie et al. 2016

SDSS-V (2020-2024)

- 6M stars, APOGEE IR spectrograph
- Time domain spectroscopy (20 min to 20 yrs), (Alice Quillen poster)
- IFU 3300 sq deg, R 5000, 360nm-1000nm
  - ISM, stellar populations



Kollmeier et al. 2017

Future of surveys

- We can understand the formation of the Milky Way, with accurate ages and abundance for large number of stars spread all over the Galaxy.

Spectroscopic Survey Facilities by 2020–2025								
Survey (facility)	$N_{\rm target}$	$R_{\rm spectra}$	$N_{\rm multi}$	$\lambda\,[\mu m]$	$\Omega_{\rm sky}$	$N_{\rm epoch}$	Timeframe	$m_{\rm primary}$
SDSS-V	7×10^6	**22,000** **2,000**	**500**	**1.51–1.7** **0.37–1.0**	4π	**1–174**	**2020–2024**	$m_H \lesssim 13.4$ $m_i \lesssim 20$
Gaia (RVS)	8×10^6	11,000	—	0.85–0.87	4π	$\sim$60	2013–2020	$m_G \lesssim 12$
Gaia-ESO	0.1×10^6	17,000	140	0.55 & 0.85	0.02π	$\sim$1	2013–2018	$m_G \lesssim 17$
GALAH	0.8×10^6	28,000	400	0.40–0.85	π, $\lvert b\rvert \geq 10$	$\sim$1	2015–2020	$m_G \lesssim 13$
WEAVE	0.8×10^6	5,000 20,000	1000	0.37–0.9	$\sim\pi$	$\sim$1–2	2018–2023	$m_G \lesssim 19$
DESI	4×10^7	3,000	5000	0.36–0.98	1.35π, $\lvert b\rvert \geq 25^\circ$	1–4	2019–2024	$m_r \lesssim 23$
LAMOST	8×10^6	1,800	4000	0.4–0.9	0.5π	$\sim$1	2010–2020	$m_G \lesssim 16$
4MOST	10×10^6	5,000 20,000	1600 800	0.4–0.9	1.5π	1–2	2023–2028	$m_r \lesssim 22$ $m_V \lesssim 16$
APOGEE-1& 2	5×10^5	22,000	300	1.51–1.7	0.5π	$\sim$1–30	2011–2019	$m_H \lesssim 12.2$
PFS	1×10^6	3,000	2400	0.4–1.6	0.05π	1	2018–2021	$m_i \lesssim 23$
MOONS	2×10^6	5,000 20,000	1000	0.6–1.8	0.05π	1	2020–2025	$m_g \lesssim 22$ $m_H \lesssim 17$

Kollmeier et al. 2017