Galactic Archaeology using astero-seismology: Results from Kepler and K2

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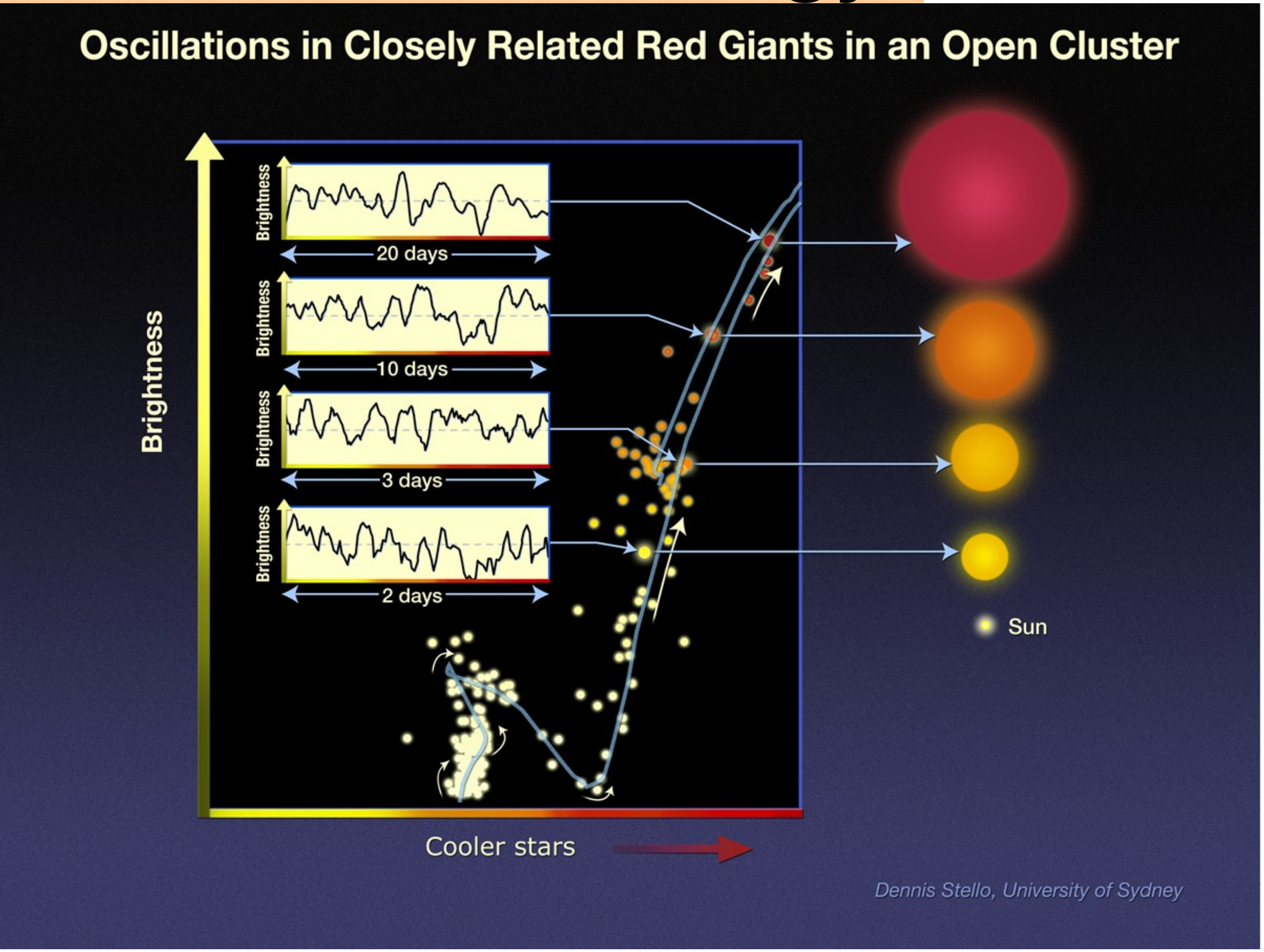
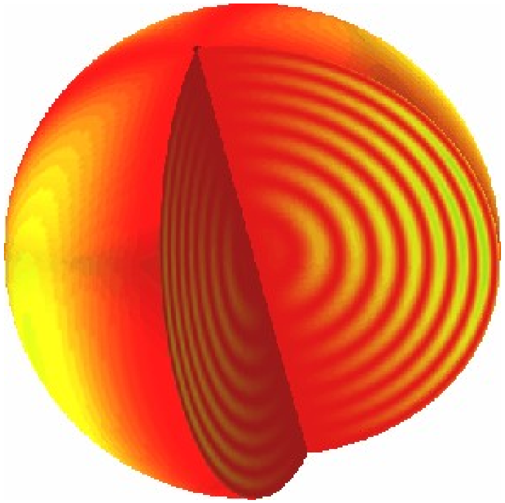
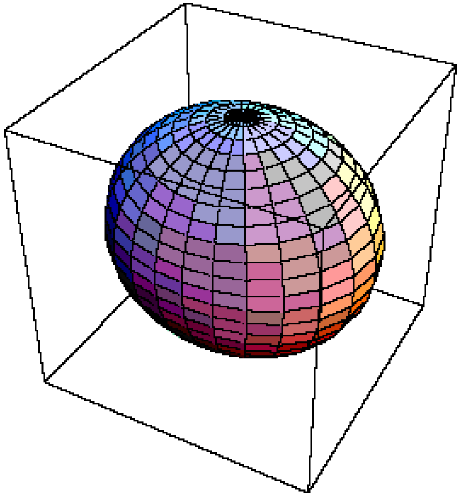
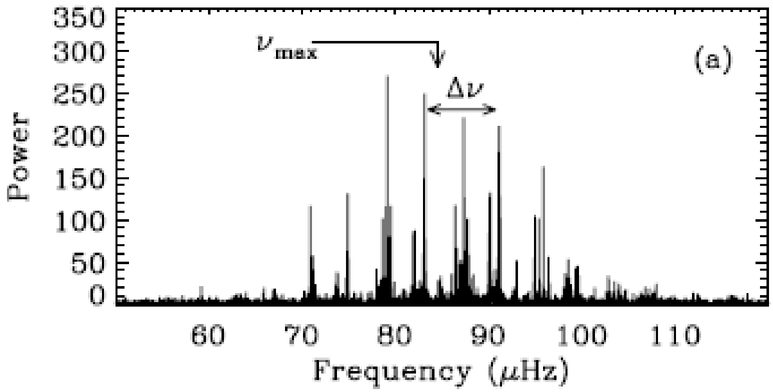
GALAH team.

Asteroseismology



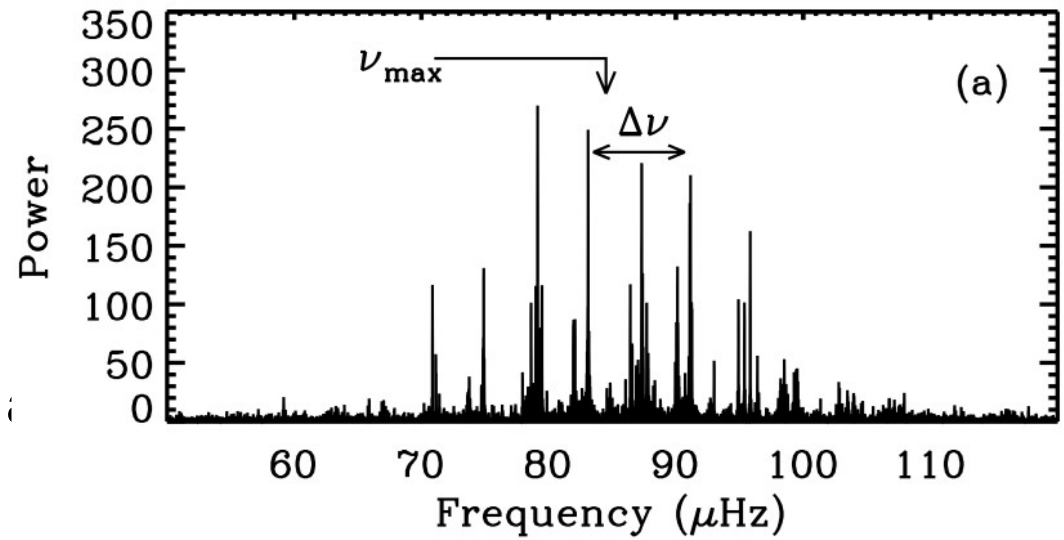






Galactic archeology with Asteroseismology

- $\nu_{max}(g)$, $\Delta\nu(\rho)$ → then $M,R(\Delta\nu,\nu_{max})$
- Gives mass and radius and potentially a
  Age crucial for GA.
- CoRoT, Kepler, K2, TESS, PLATO.
- Kepler did not have well defined selection function.

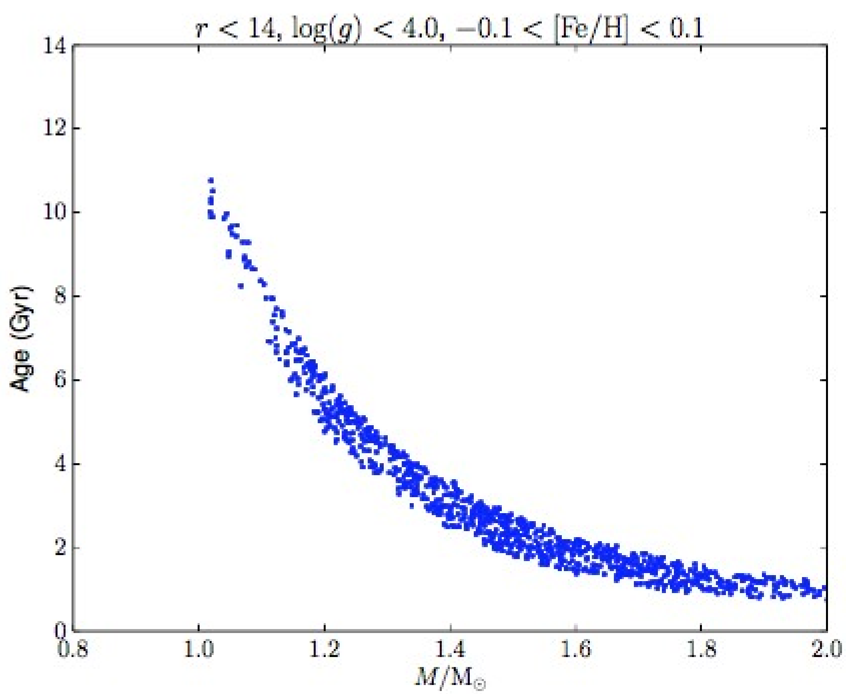


$$\left(\frac{\rho}{\rho_\odot}\right) \simeq \left(\frac{\langle\Delta\nu_{nl}\rangle}{\langle\Delta\nu_{nl}\rangle_\odot}\right)^2,$$

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

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

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

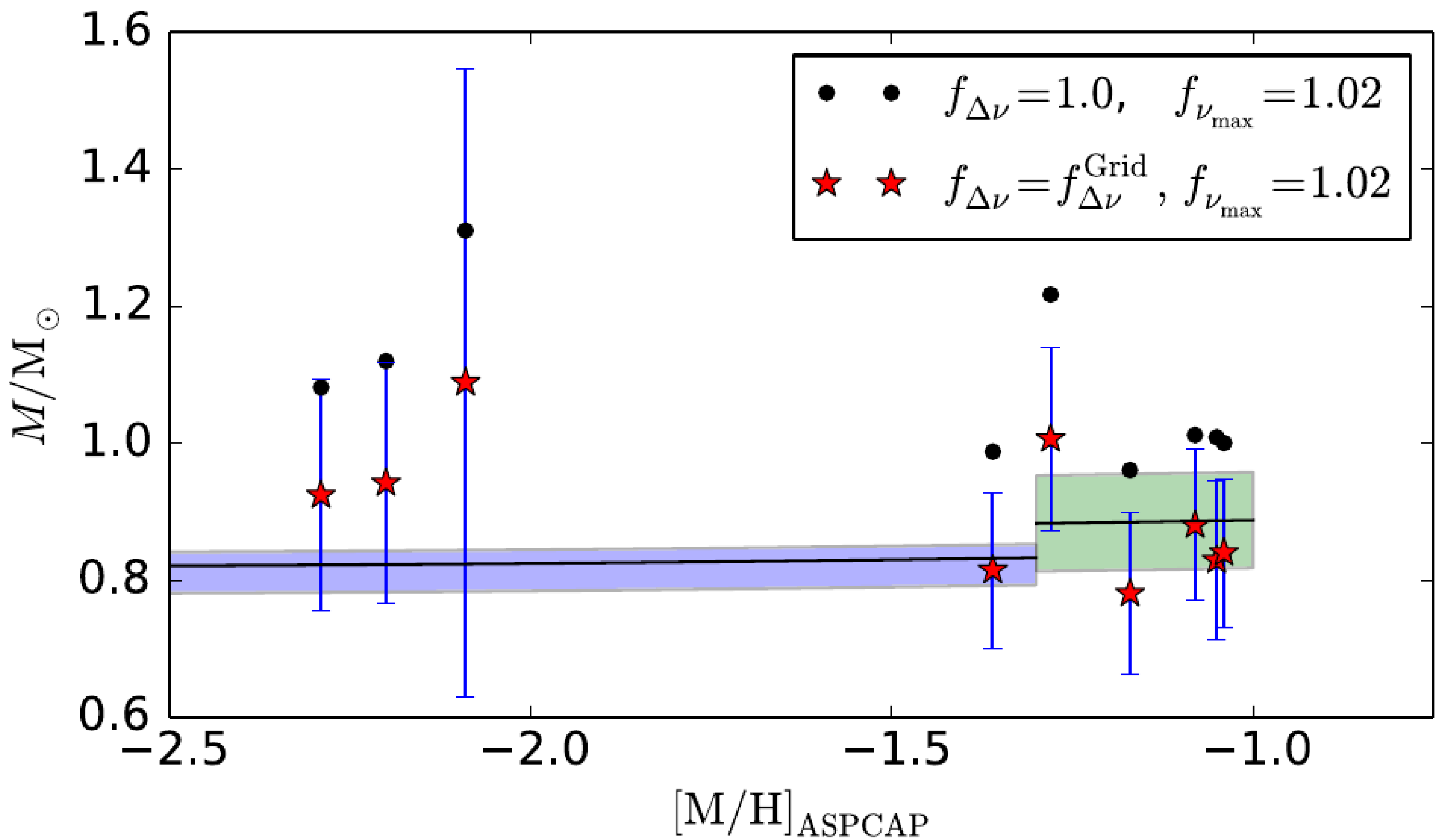


Asteroseismology the good and the bad

- Giants are intrinsically bright
  - can probe the Galaxy deeper for a given apparent magnitude.
- Uncertainty on age is large for old stars.
  - 30-40% for 10 Gyr
- Scaling relations not verified.
  - Asteroseismology overestimates masses
    - Metal poor stars- Epstein et al 2014
    - Eclipsing binaries- Gaulme et al 2017

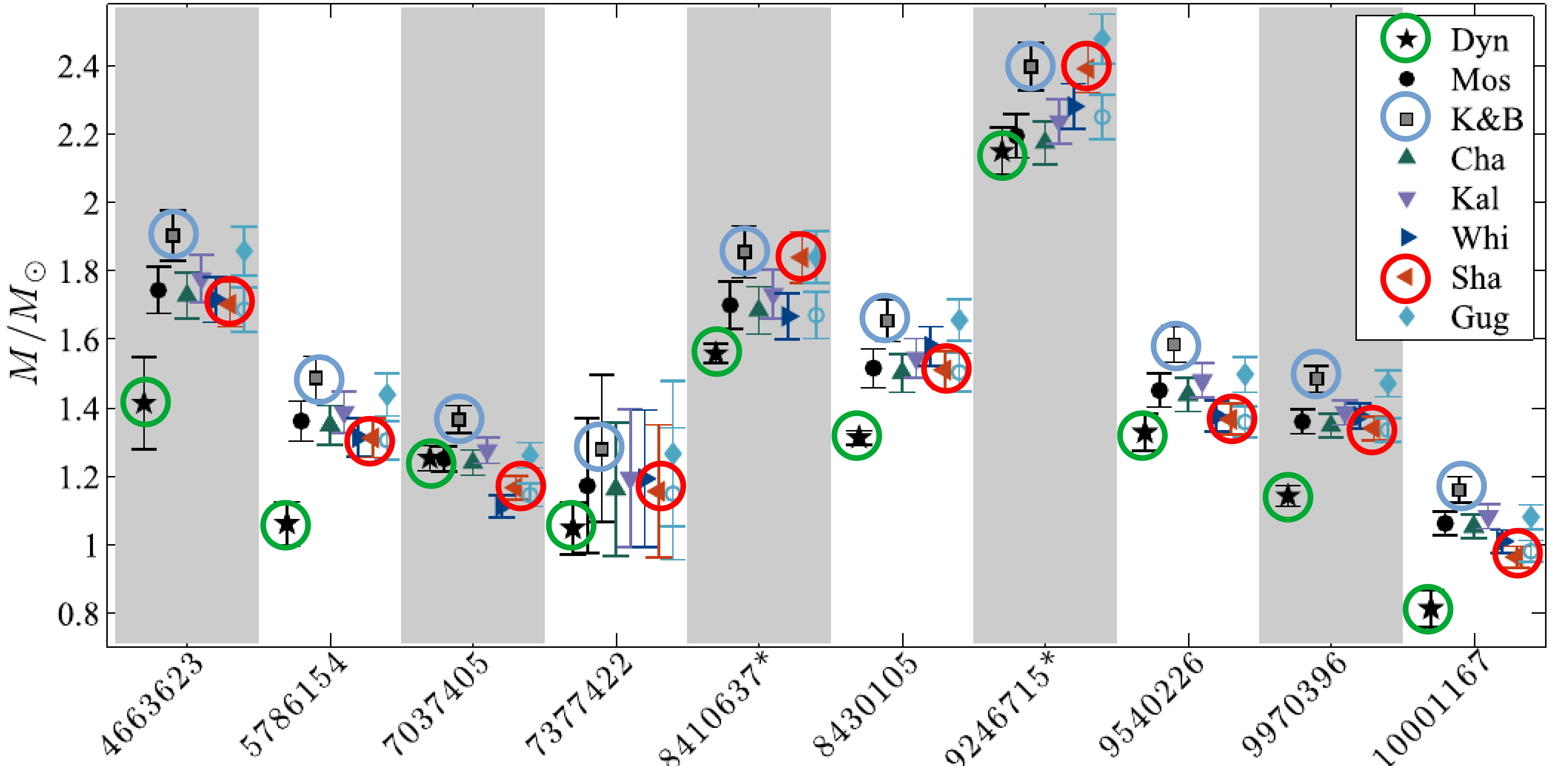
Metal poor stars

- Metal poor stars in APOKASC
  - τ_{thick} =8-13.77 Gyr, $\tau_{stellar\text{-}halo}$=10-13.77 Gyr
- Epstein et al 2014 finds seismology overestimates
- Sharma et al 2016 finds corrections resolve discrepancy.

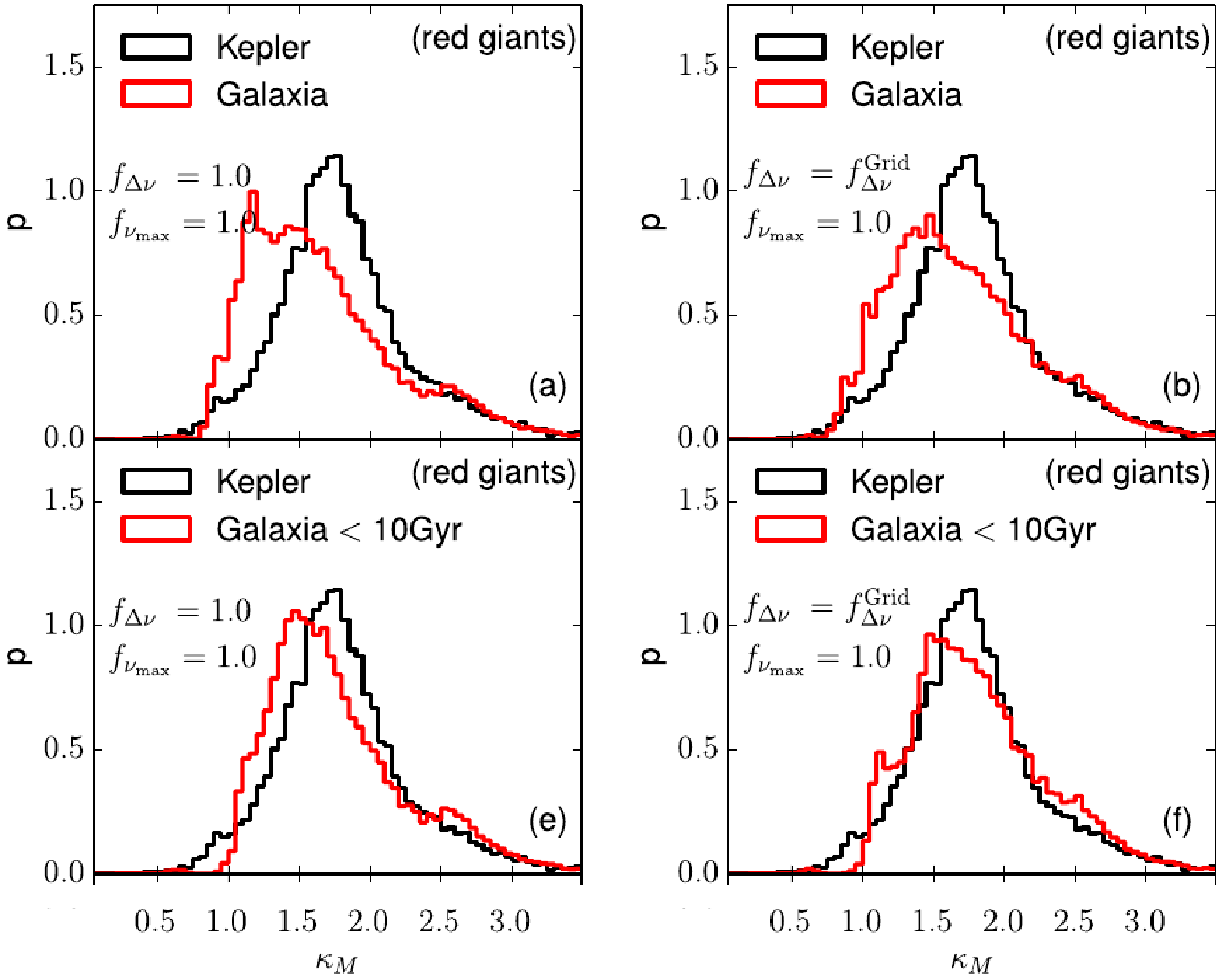


Eclipsing binaries

- Dynamical masses from radial velocity of RG stars in binary systems.
- Gaulme 2017 finds seismology overestimates masses
- Broggard et al 2017 finds 3 of them agree with seismology.



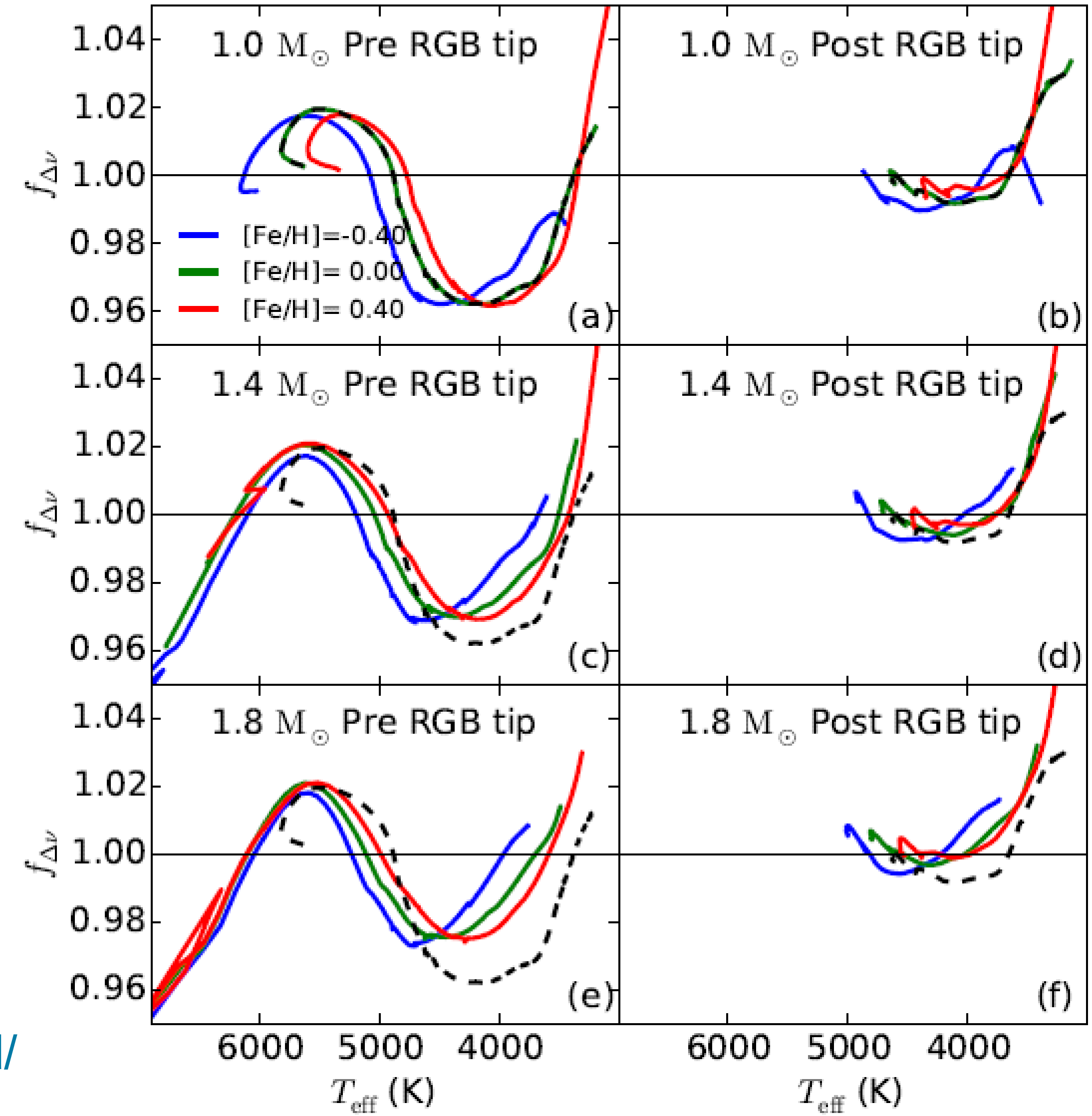
10000 Red giants from Kepler (Sharma et al. 2016)



- Testing predictions of stellar population synthesis Galactic models.
- Besancon model through Galaxia.

Theoretical corrections to Δν from stellar models.

- For giants scaling relations have not been verified.
- Theory predicts corrections for Δν.
- Depends on T_{eff}, [Fe/H], and M.



Sharma et al. 2016

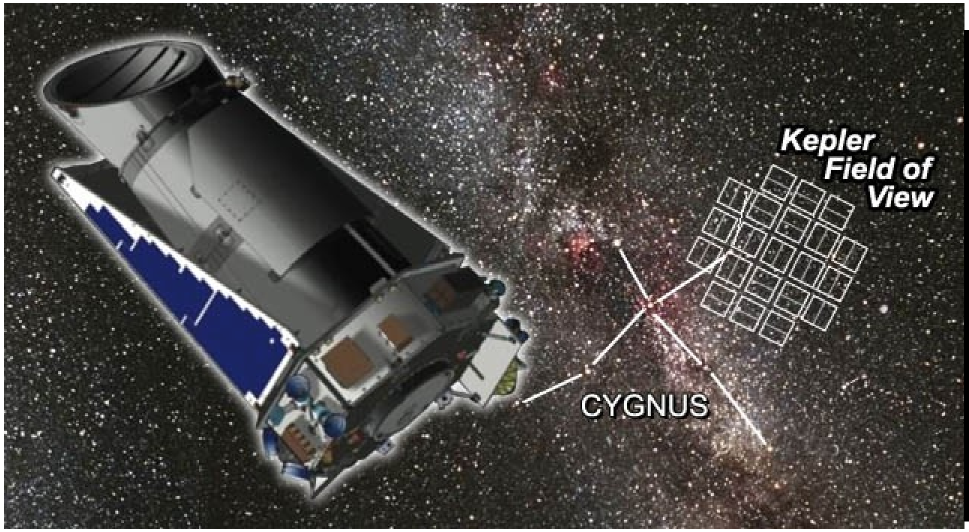
Code and grid to correct the Δν
http://www.physics.usyd.edu.au/k2gap/Asfgrid/

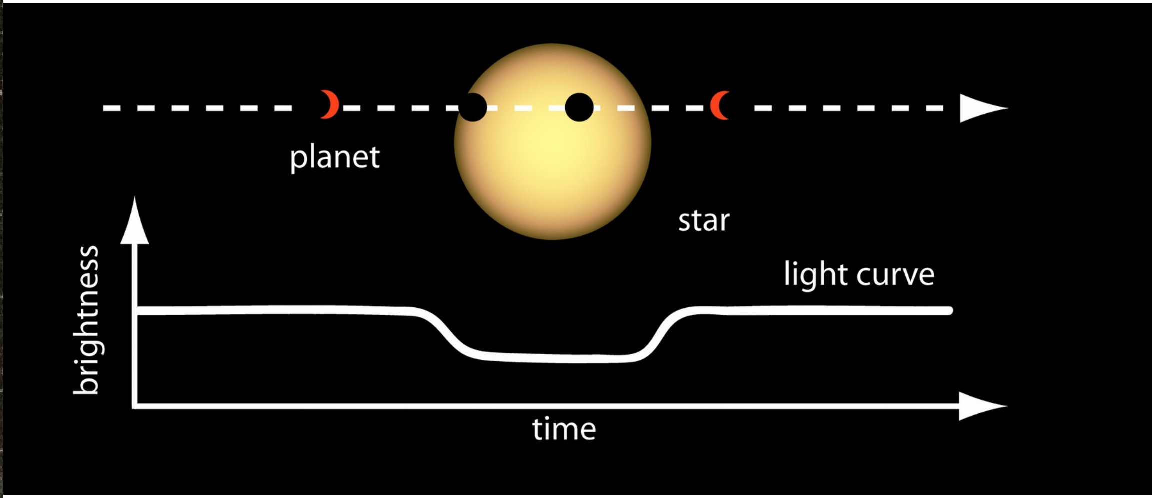
What causes the discrepancy between Galactic models and Kepler?

1)Selection function of Kepler. (Exoplanet misson)

2)Asteroseismic scaling relations.

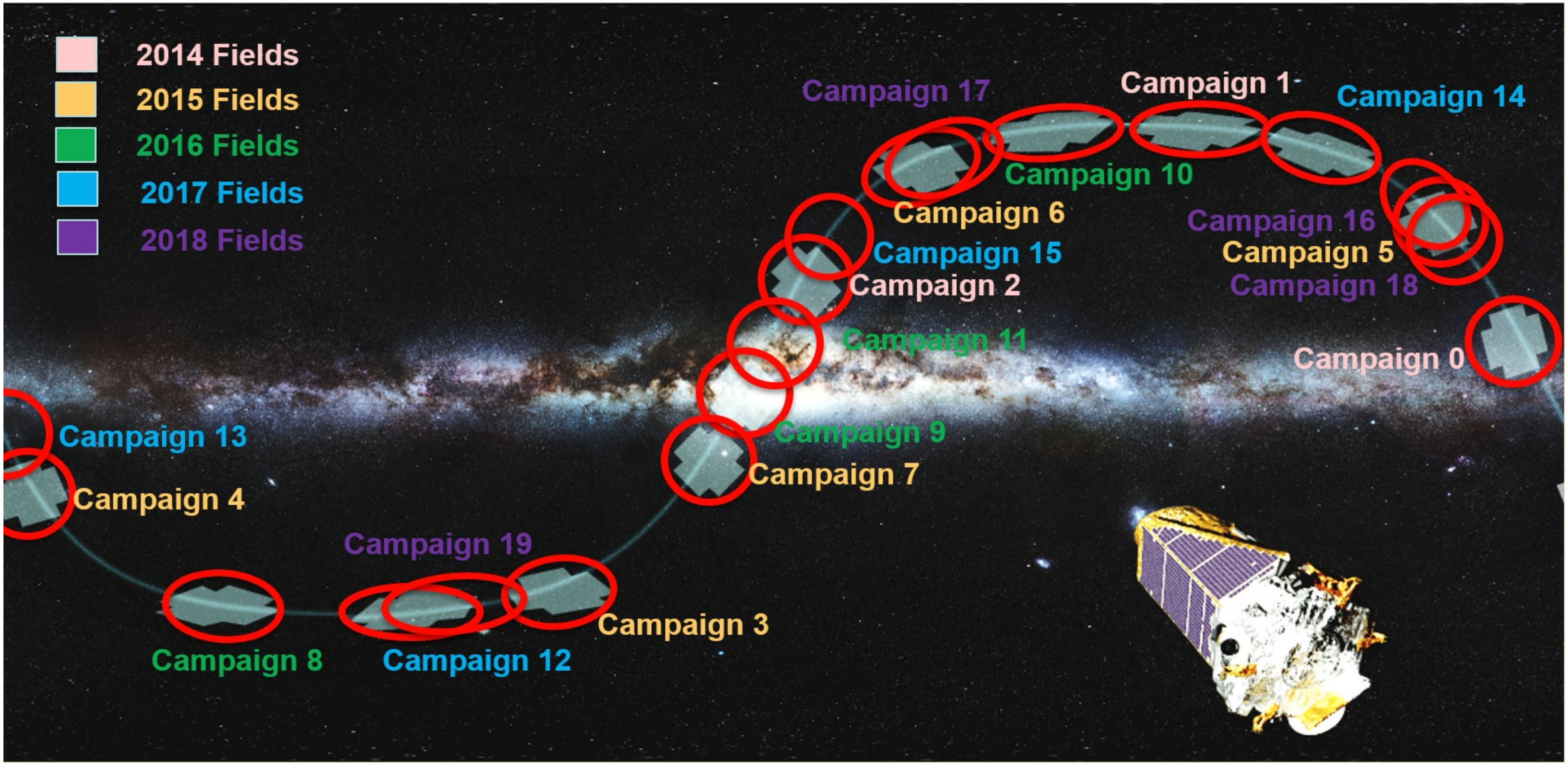
3)Galactic models.





K2 mission

- In May 2013, of the four reaction wheels, two stopped working.
- June 2014 Kepler re-purposed as K2 mission.
  - per campaign: 3 months, 20,000 targets, 19 campaigns



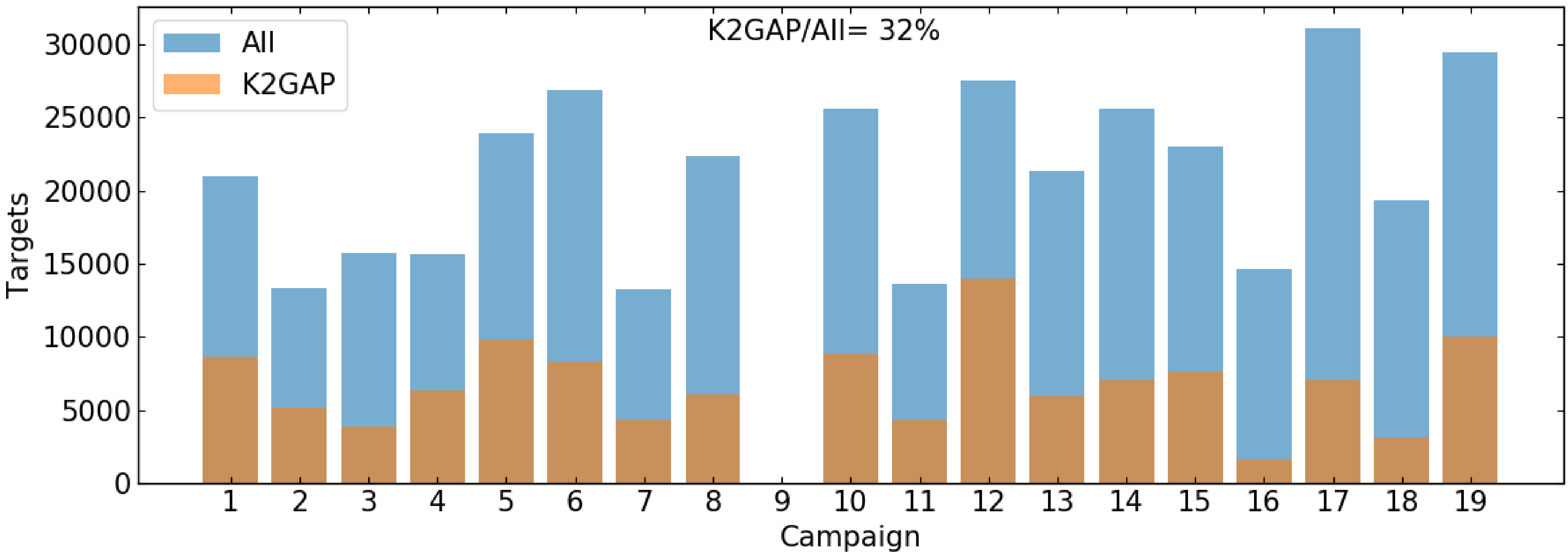
K2GAP

Galactic archaeology program with K2

(*Dennis Stello, Sanjib Sharma and Asteroseismic community*)

www.physics.usyd.edu.au/k2gap

- Very well defined selection function, avoiding SF mistakes made in KEPLER mission.
- 32% of targets allocated via this program.
- Among the top two programs.



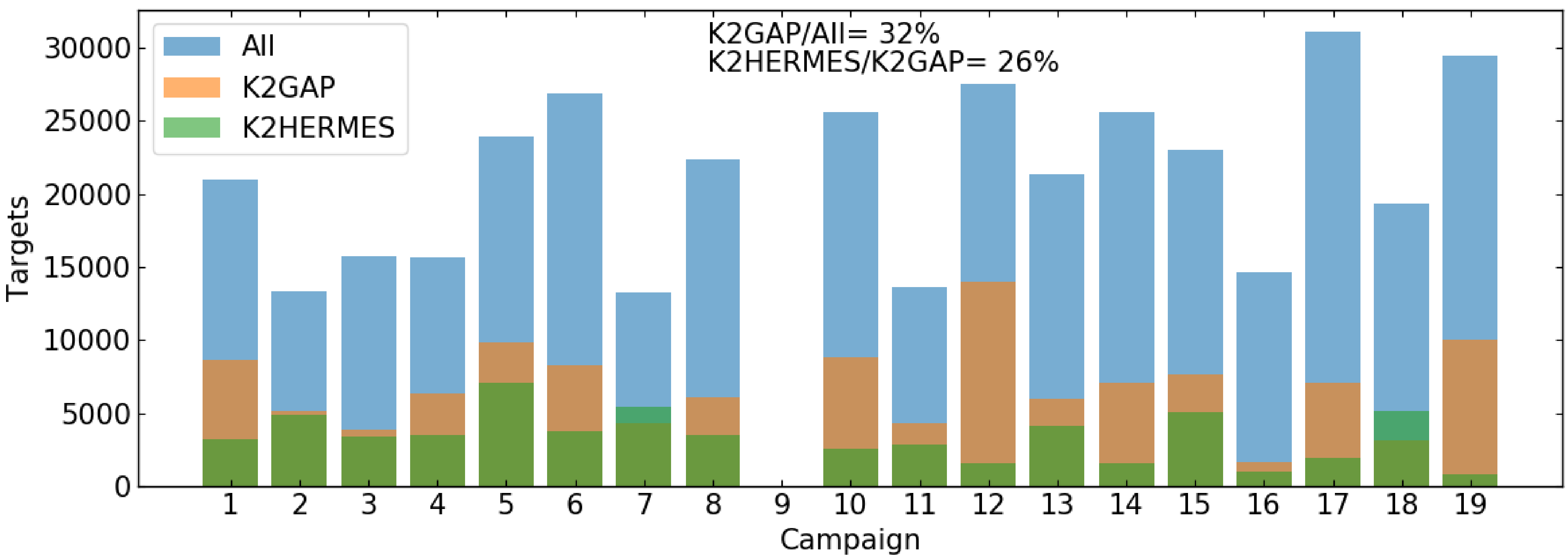
K2-HERMES

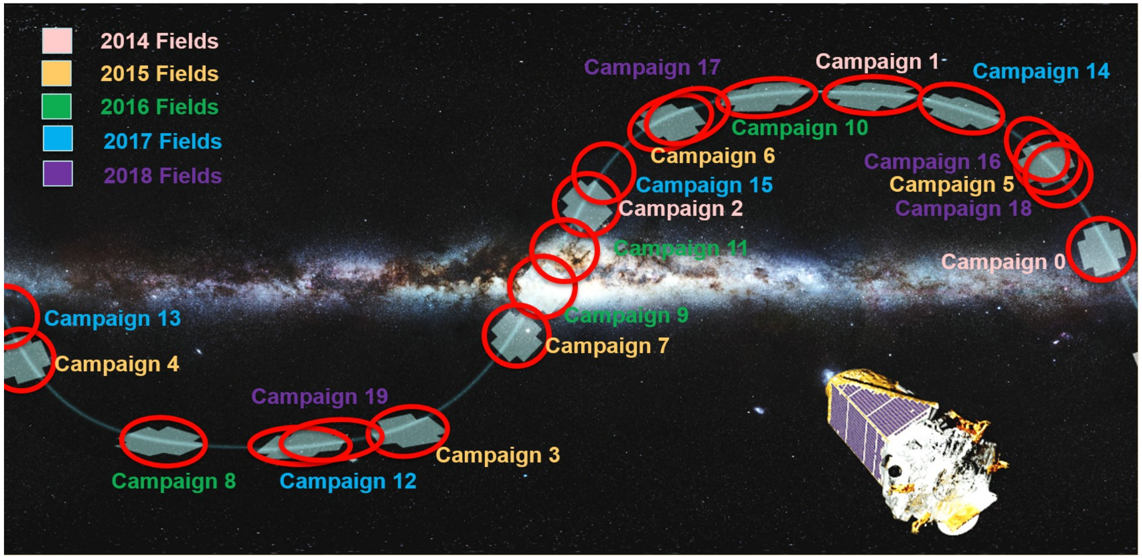
Spectroscopic followup of K2 targets

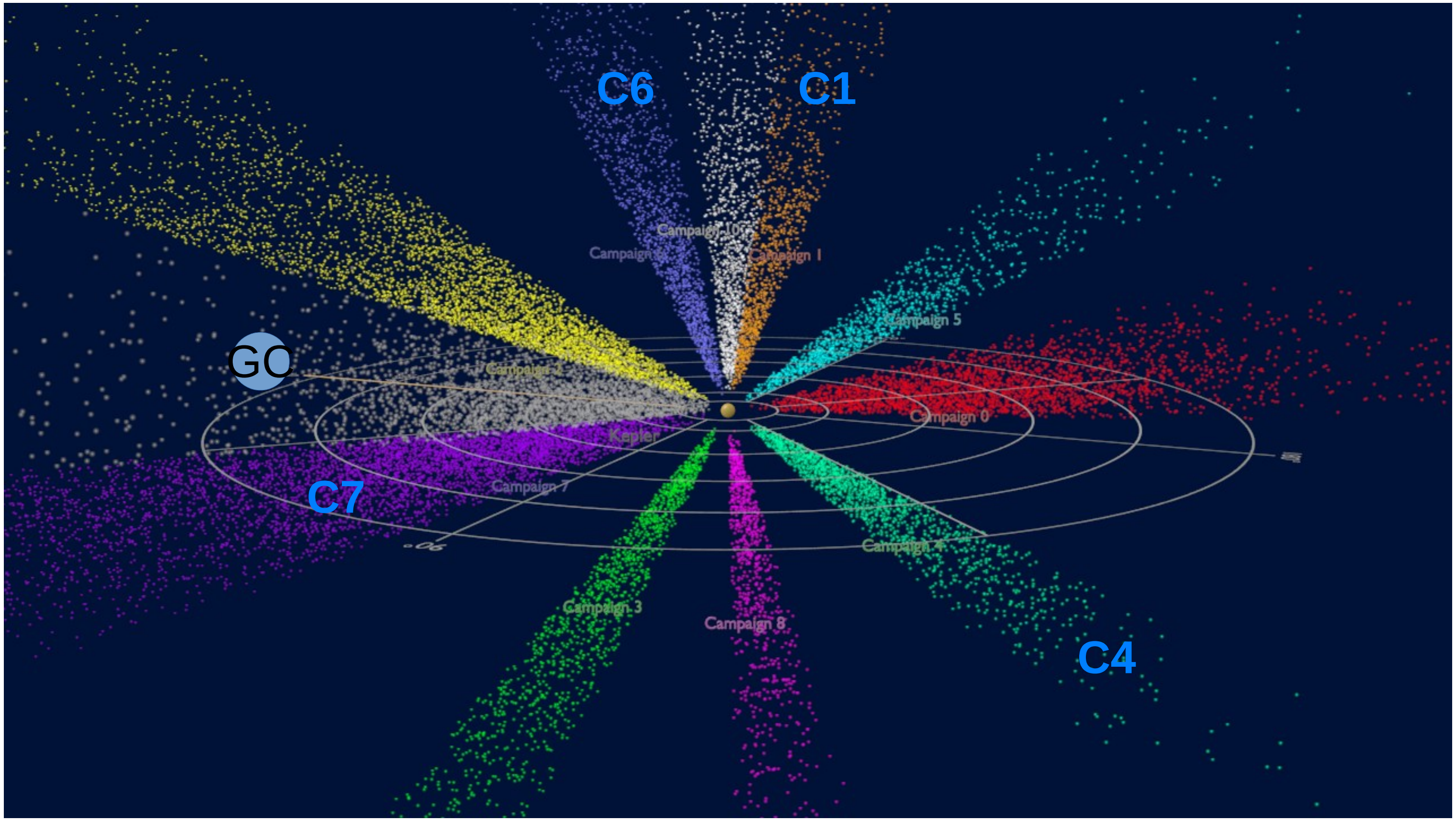
(PI:*Sanjib Sharma and GALAH community*)

www.physics.usyd.edu.au/k2gap

- Well defined selection function.
- 26% of K2GAP targets followed up via this program (plan to do 50%).
- Exoplanet targets are also followed up




2014 Fields
2015 Fields
2016 Fields
2017 Fields
2018 Fields
Campaign 17
Campaign 1
Campaign 14
Campaign 10
Campaign 6
Campaign 16
Campaign 5
Campaign 18
Campaign 15
Campaign 2
Campaign 11
Campaign 0
Campaign 9
Campaign 7
Campaign 13
Campaign 4
Campaign 19
Campaign 3
Campaign 8
Campaign 12

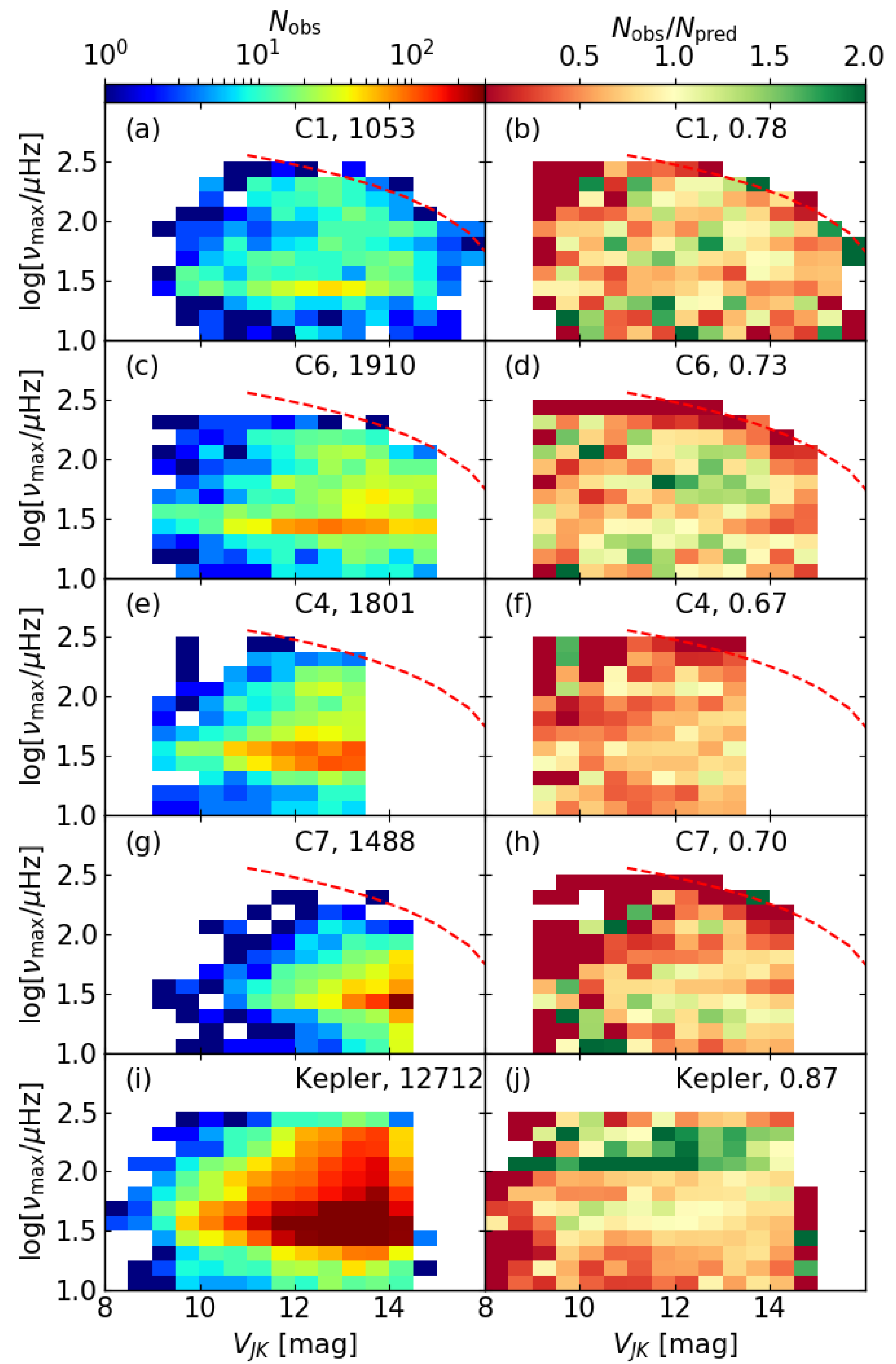

C6
C1
GC
C7
C4

K2 problems

- Only 90 day light curves (Kepler had 3 yrs).
- Photometric precision less than Kepler.
- Pointing accuracy poorer than Kepler.
  - ν_{max} and $\Delta\nu$ cannot be measured for all observed giants.

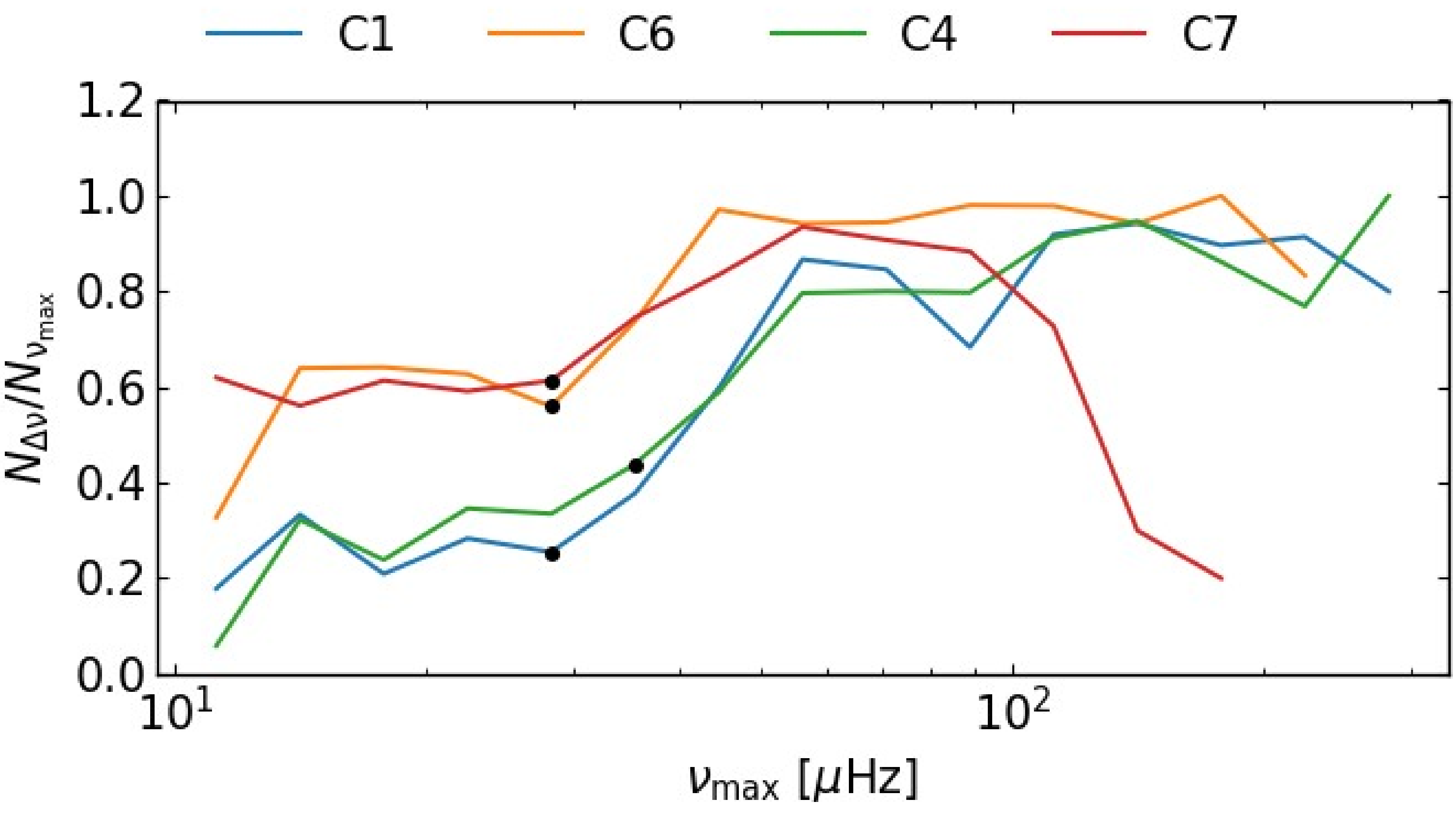
Detection completeness (ν_{max},V).

- Forward modelling.
- Have to match
  - Selection function.
  - Detection probability.



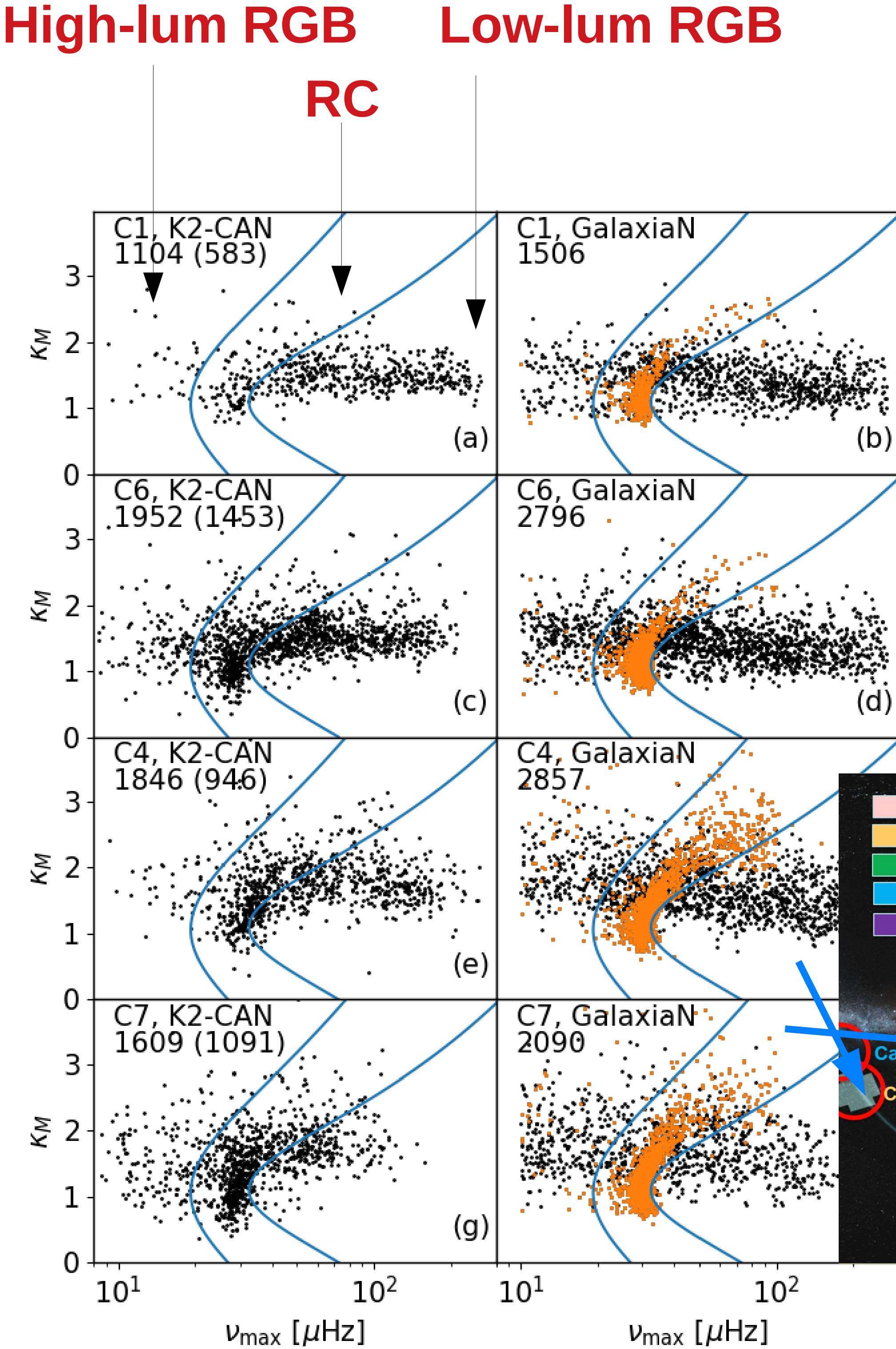
Δν completeness.

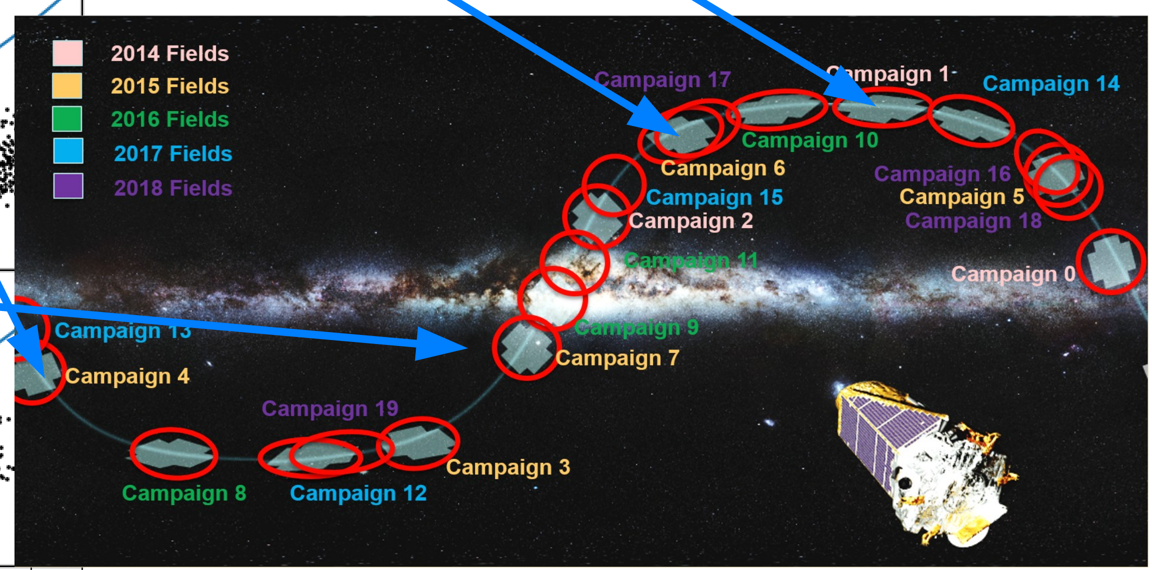
- With data



Separate in 3 classes

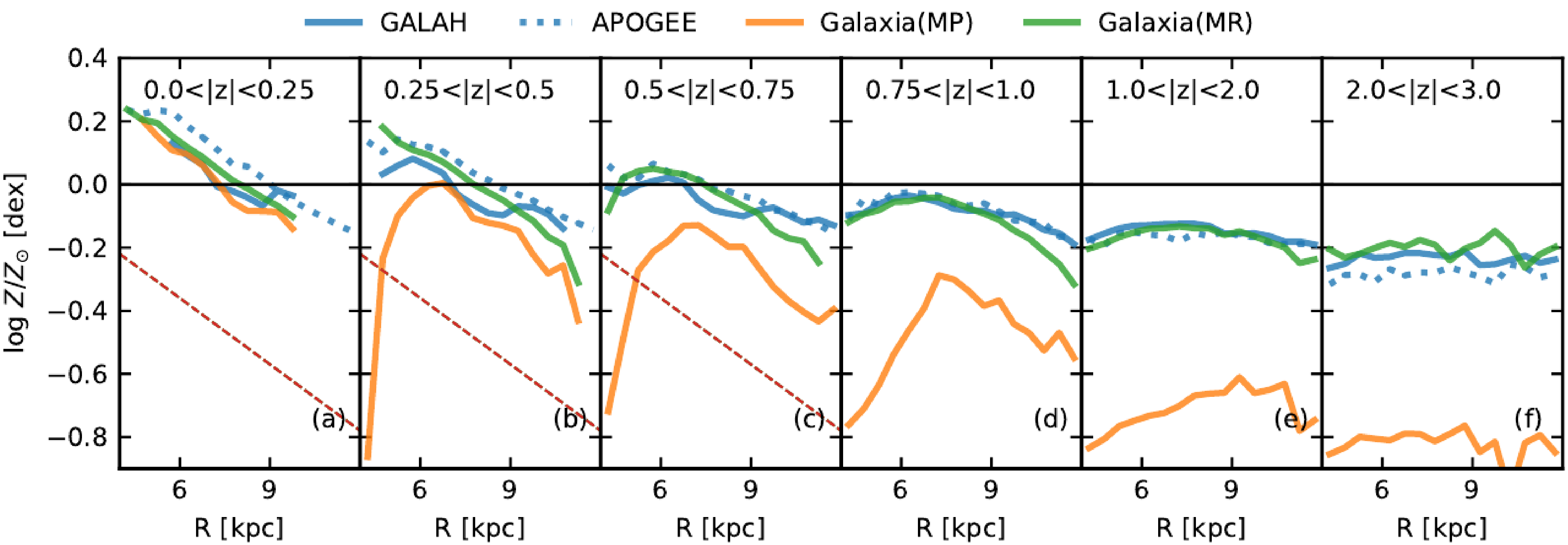
- Each class has its own detection-prob for ν_{max} and $\Delta\nu$, so we need to study them separately.





Metallicity distribution of the Galaxy

- Mass of stars is sensitive to metallicity Z.
- Is our metallicity model correct? Z(R,z)
- $\log(Z/Z_{\odot}) = [Fe/H] + \log(10^{[\alpha/Fe]}\ 0.694 + 0.306)$
  - Salaris & Cassisi 2005

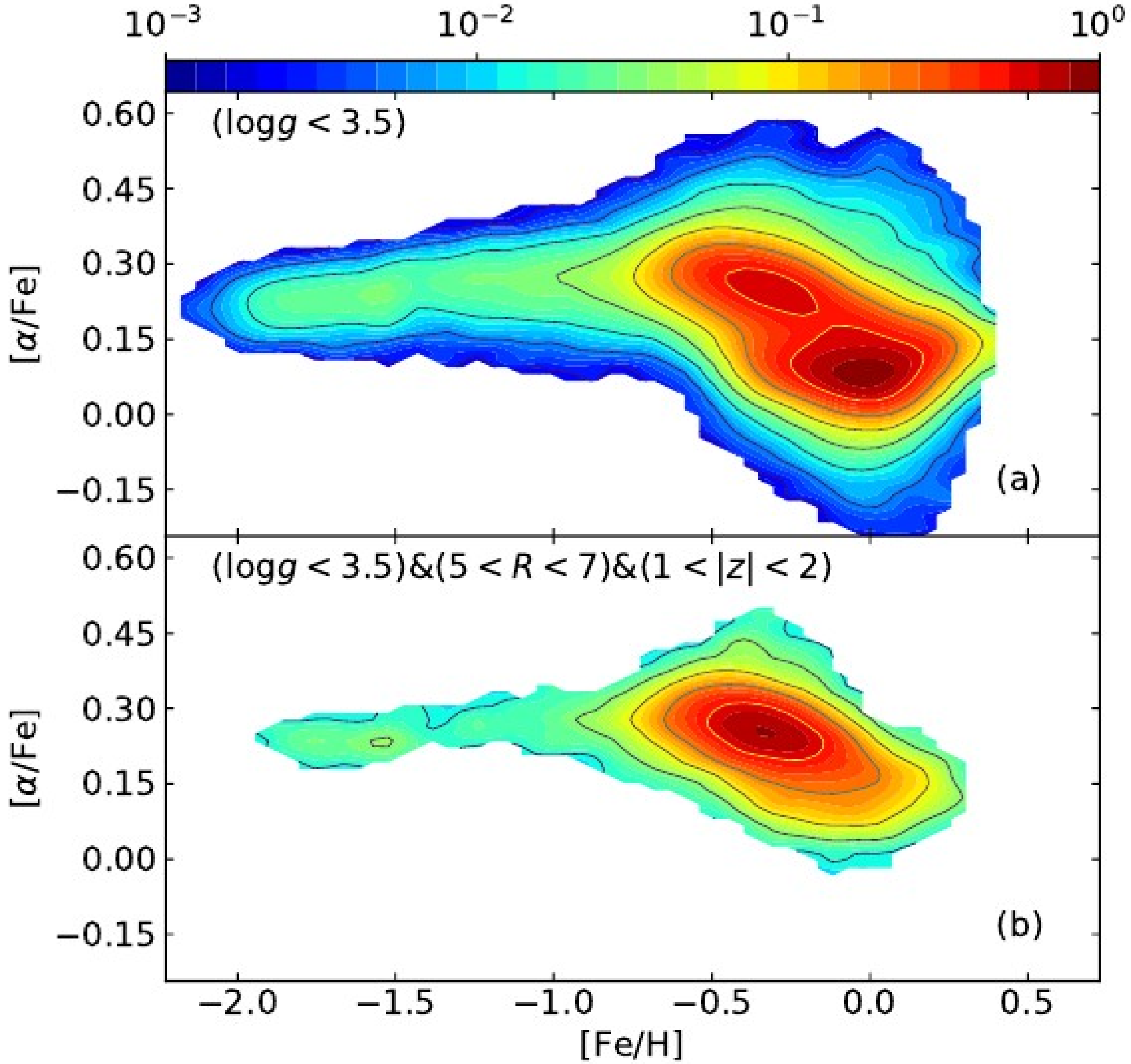


Thick disc with spatial decomposition.

- Besancon used [Fe/H]=-0.78
  - Gilmore 1995
    - Low res spectra
  - Robin 1996
    - UBV photometry

- GALAH gives [Fe/H]=-0.32

- For thick disc alpha enhancement should be taken into account.



We use "importance sampling" to fit a Galactic model

- $E_f[\ S(x)\ ] = E_g[\ S(x)\ \ f(x)/g(x)\ ]$
- $\qquad\qquad = E_g[\ S(x)\ \ w(x)\ ]$
- $\qquad\qquad = (1/N)\sum_i S(x_i)\ w_i(x)$

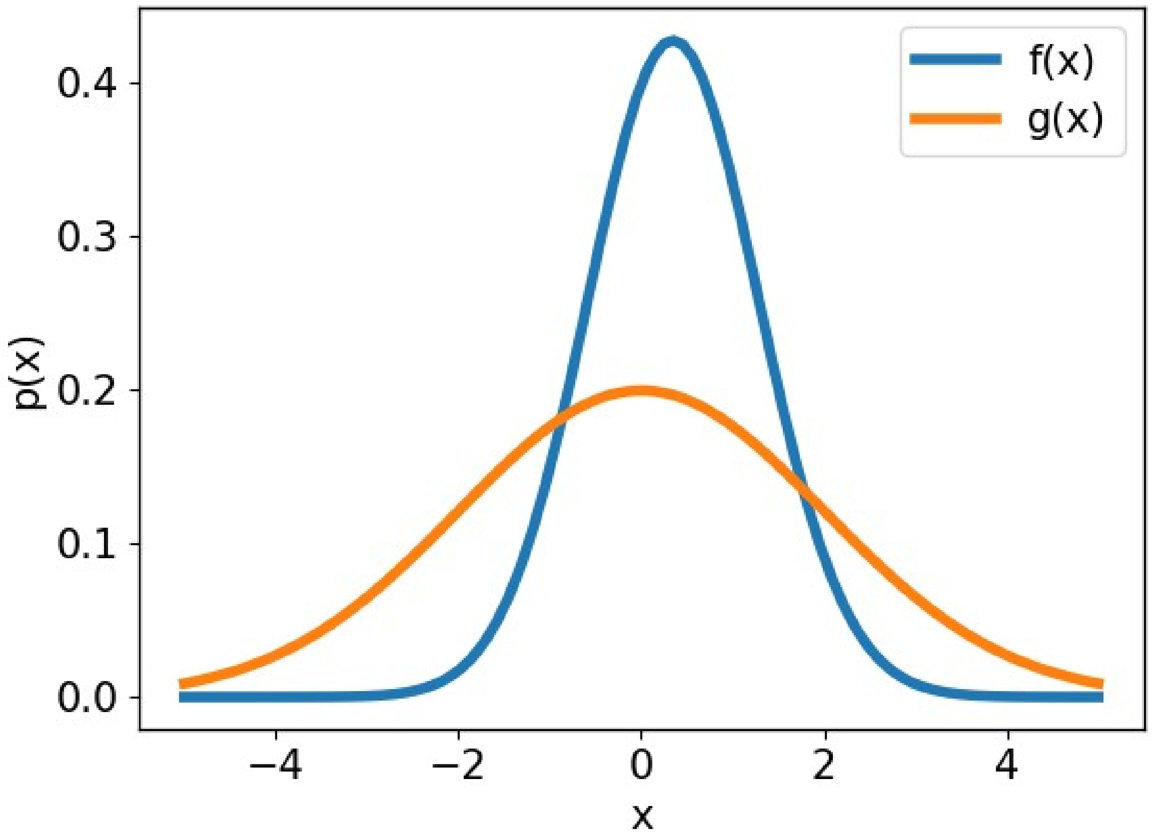


Table 5. Abundance of iron and alpha elements for thick disc stars. Median and standard deviation based on 16-th and and 84-th percentile values are listed. The first four rows show the abundances for stars with $5 < R/\mathrm{kpc} < 7$ and $1 < |z|/\mathrm{kpc} < 2$ and positive rotation about the Galaxy. The last row shows the result obtained by fitting a Galactic model.

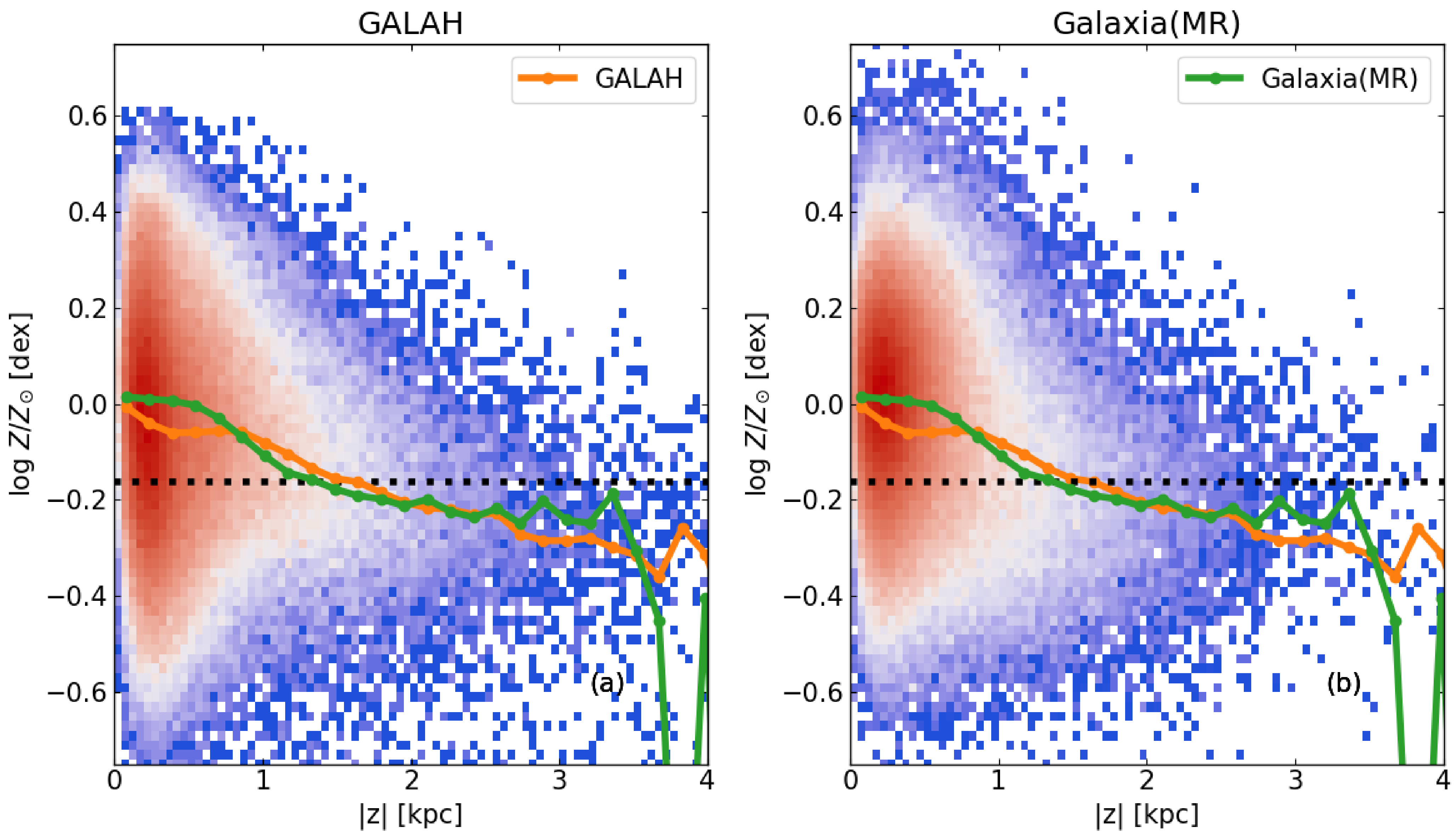
Source	[Fe/H]		[α/Fe]		$\log(Z/Z_\odot)$	
	med	sdev	med	sdev	med	sdev
APOGEE	-0.294	0.28	0.186	0.08	-0.160	0.24
GALAH DR2	-0.367	0.24	0.218	0.08	-0.196	0.21
GALAH DR2c[a]	-0.316	0.21	0.239	0.07	-0.131	0.18
GALAH mock[b]					-0.170	0.25
GALAH DR2c[c]					-0.162	0.17

[a]Calibrated

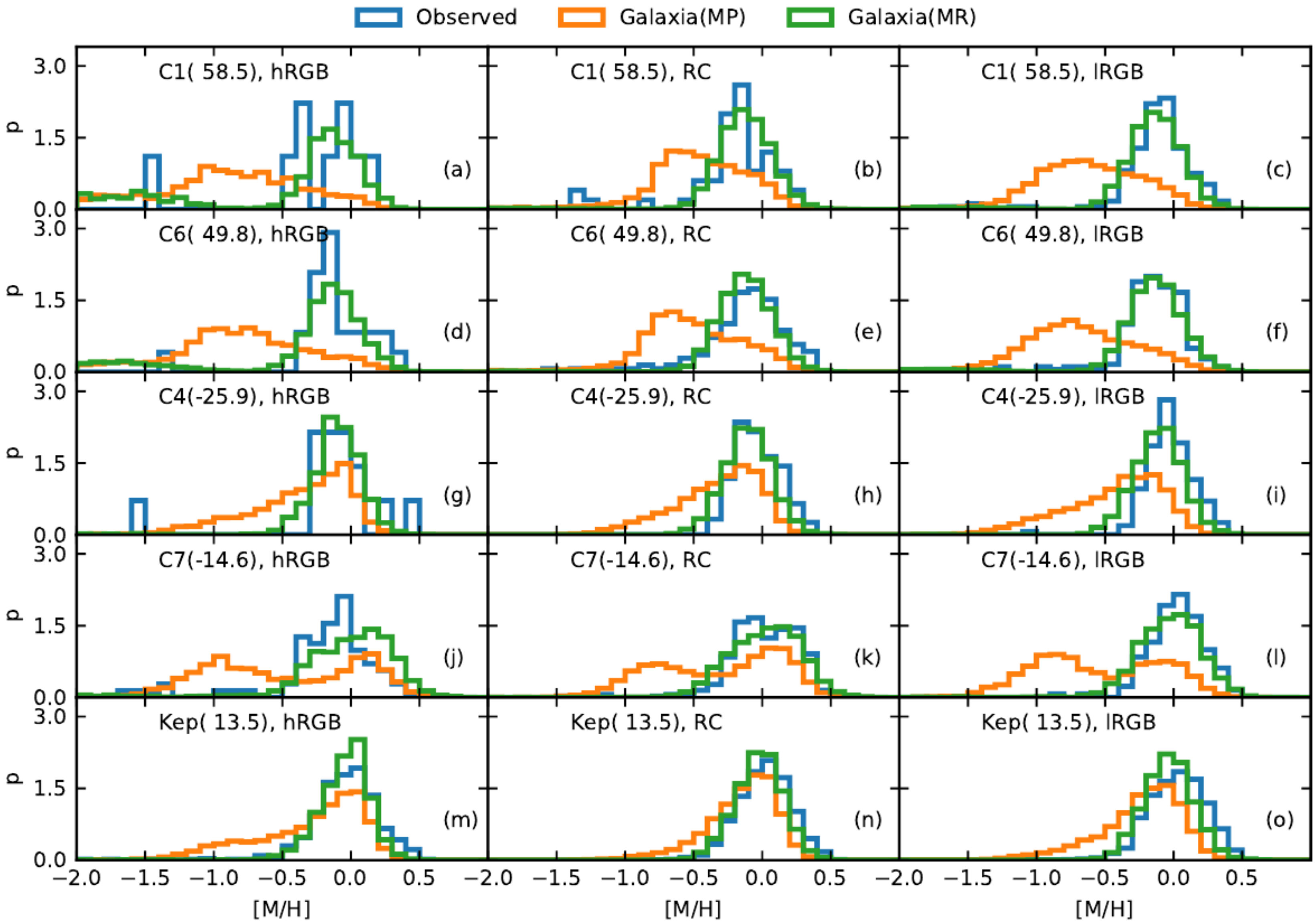
[b]Mock catalog generated by *Galaxia* with $\log(Z/Z_\odot) \sim \mathcal{N}(-0.18, 0.22^2)$ for the thick disc

[c]Fitting a Galactic model to GALAH stars with $5 < R/\mathrm{kpc} < 11$, $1 < |z|/\mathrm{kpc} < 3$, $12 < V_{JK} < 14$, `field_id`<6546 and positive rotation.

- Low metallicity at high z is due to volume incompleteness.

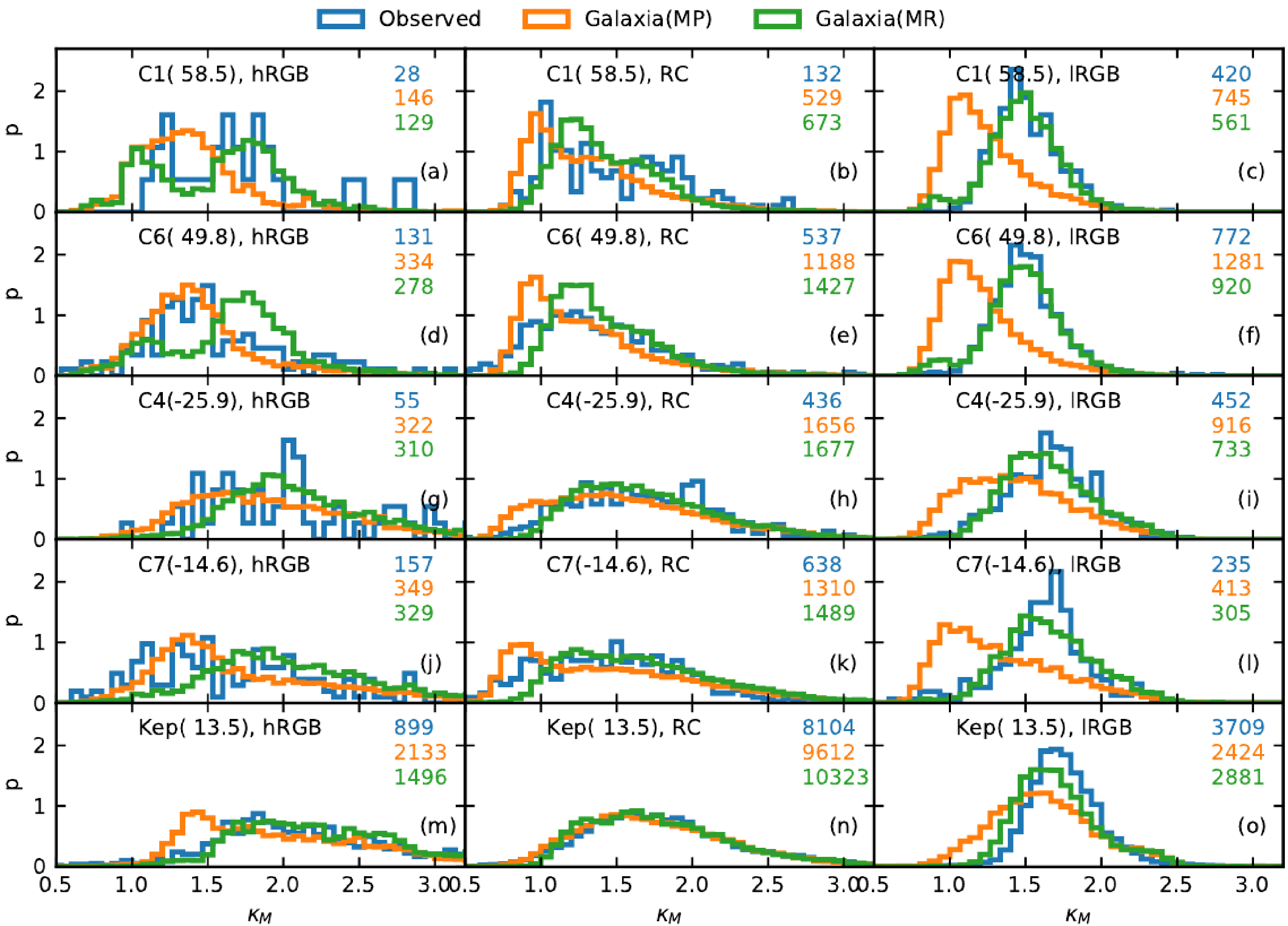


Distribution of [M/H]=log(Z/Z☼)



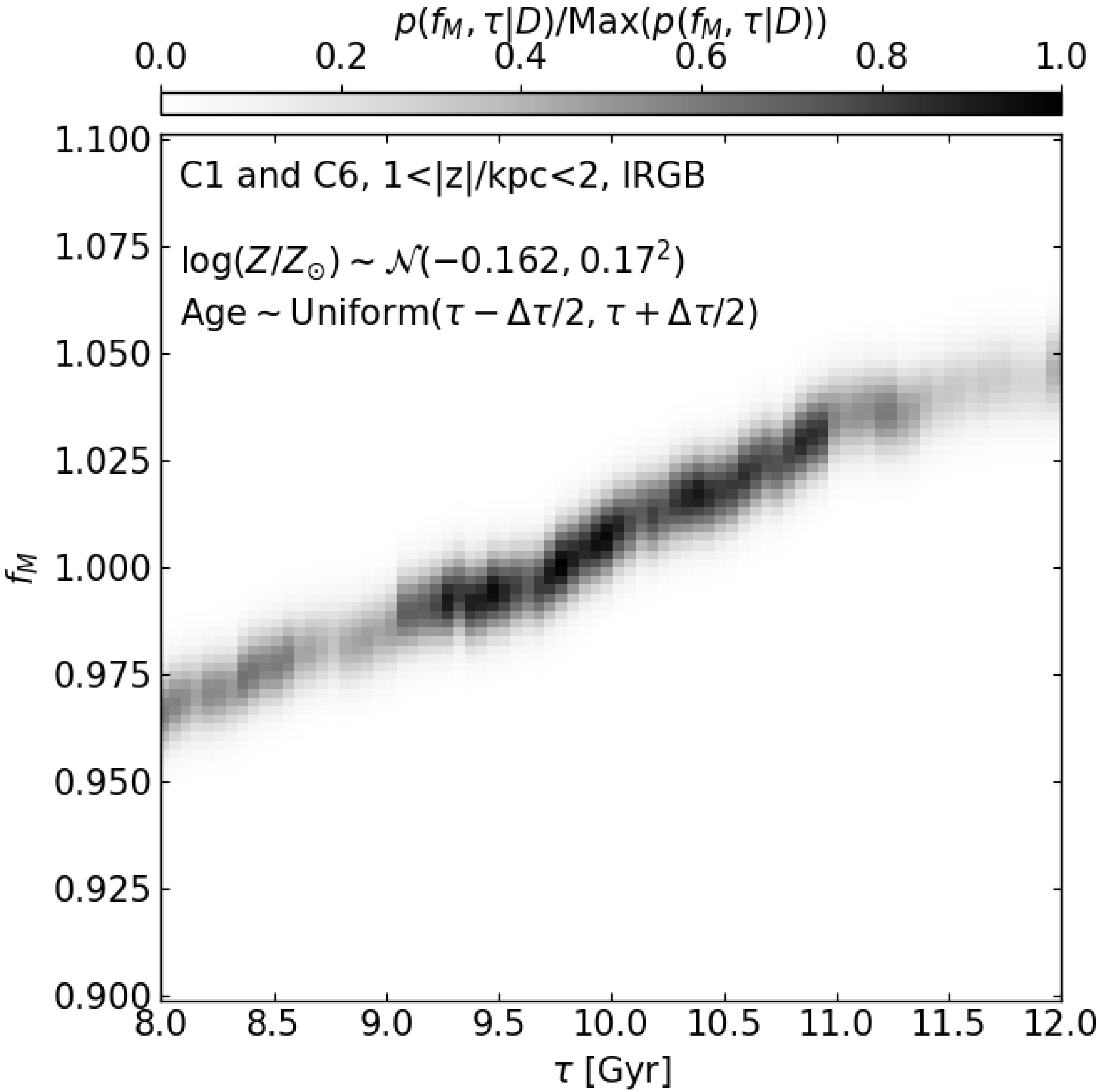
Distribution of seismic mass κ_M

- **Metal poor old thick disc is incompatible with seismic obs.**



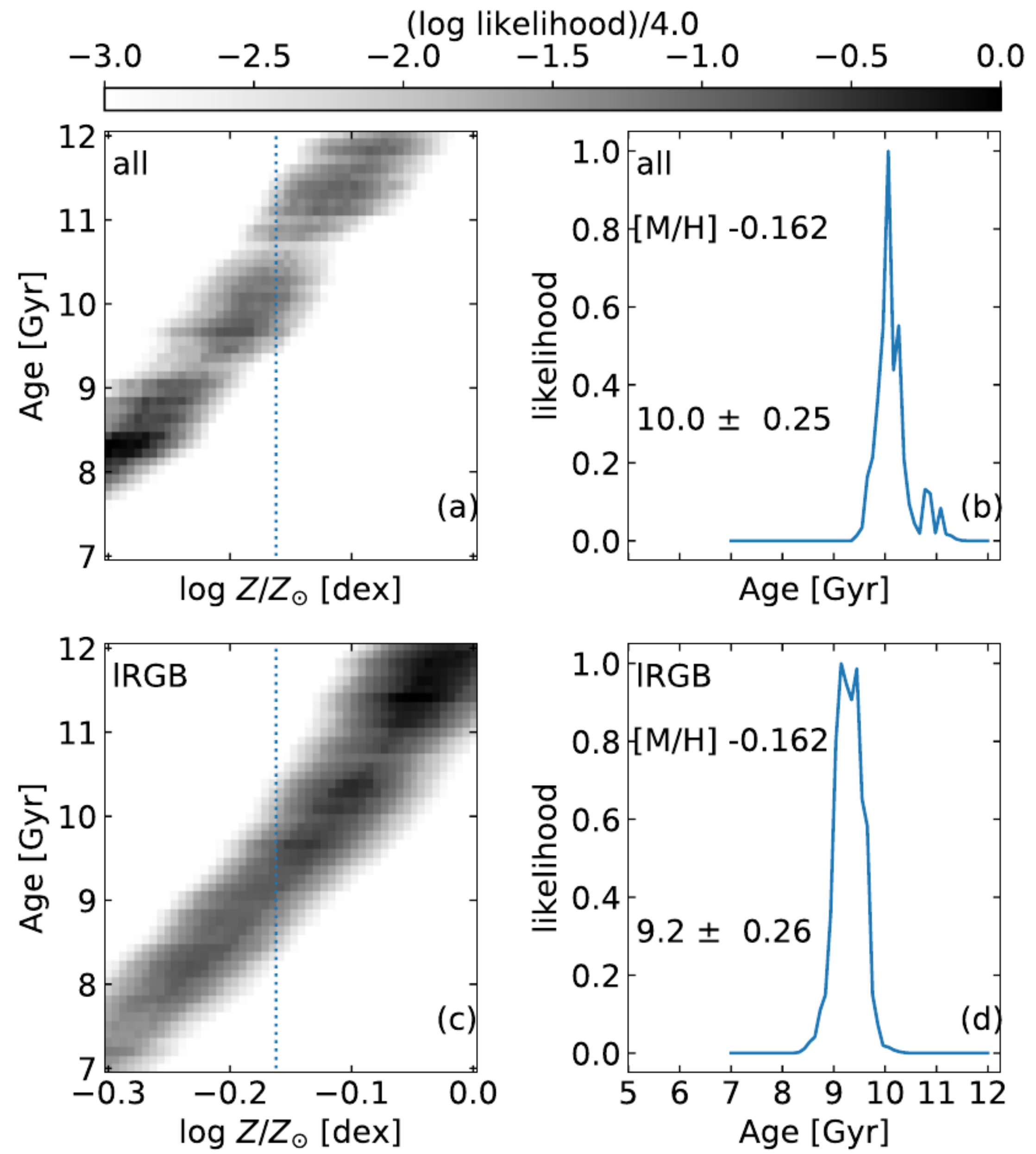
How accurate are seismic relations?

- f_M the factor by which to correct the seismic mass
- Very accurate.



Mean Age of thick disc τ_{thick}

- Degeneracy with age
  - With spectroscopy we can get rid of that.
- Consistent age τ_{thick}.
  - 9.2-10 ±0.2 Gyr
  - 9.5-9.9 ± 0.2 Gyr (WD)
- Systematics in seismic relation are not too large.
- Can use asteroseismology to estimate ages and study the Galaxy.



Age of thick disc from white dwarfs

- Killic et al 2017, τ_{thick} = 9.5-9.9 ± 0.2 Gyr

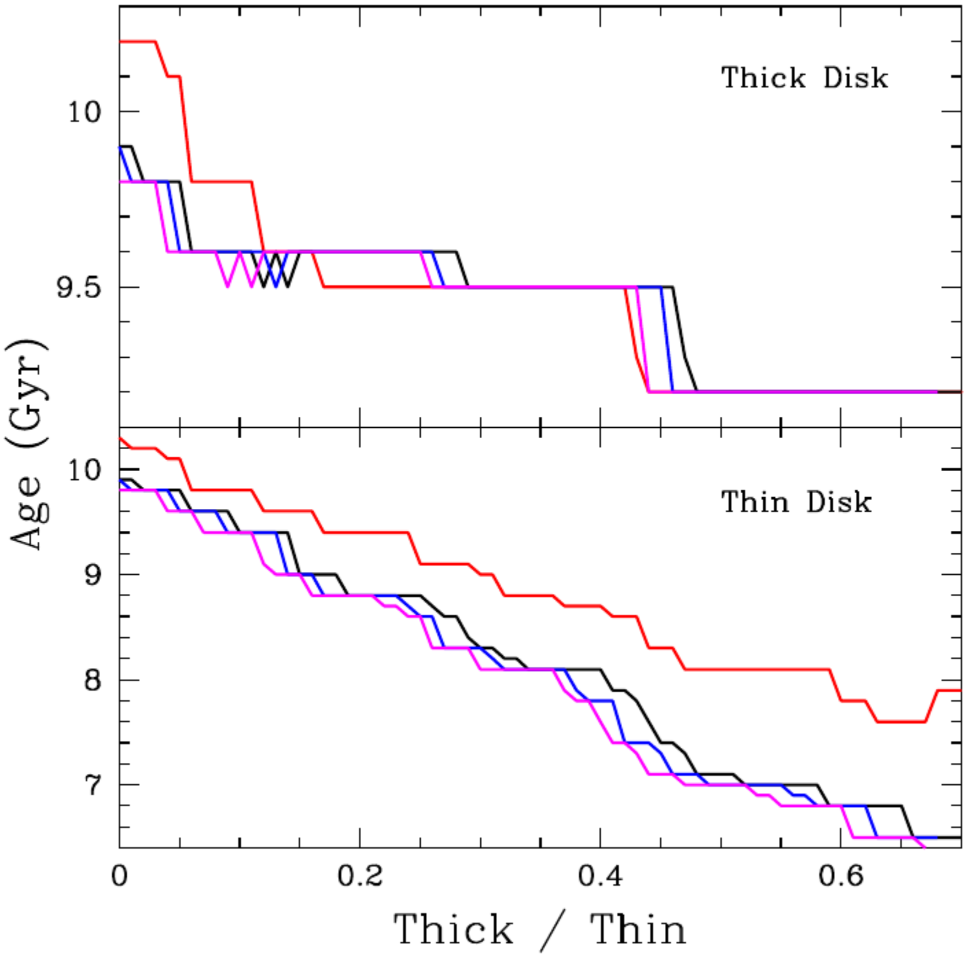


Figure 7. Thin disk and thick disk age constraints as a function of the ratio o thick disk to thin disk white dwarfs. The black, blue, magenta, and red line show the constraints from luminosity functions using the scale heights o 200–900 pc (Bovy et al. 2012), 200–700 pc, 200–500 pc, and 300 pc (Juri et al. 2008), respectively.

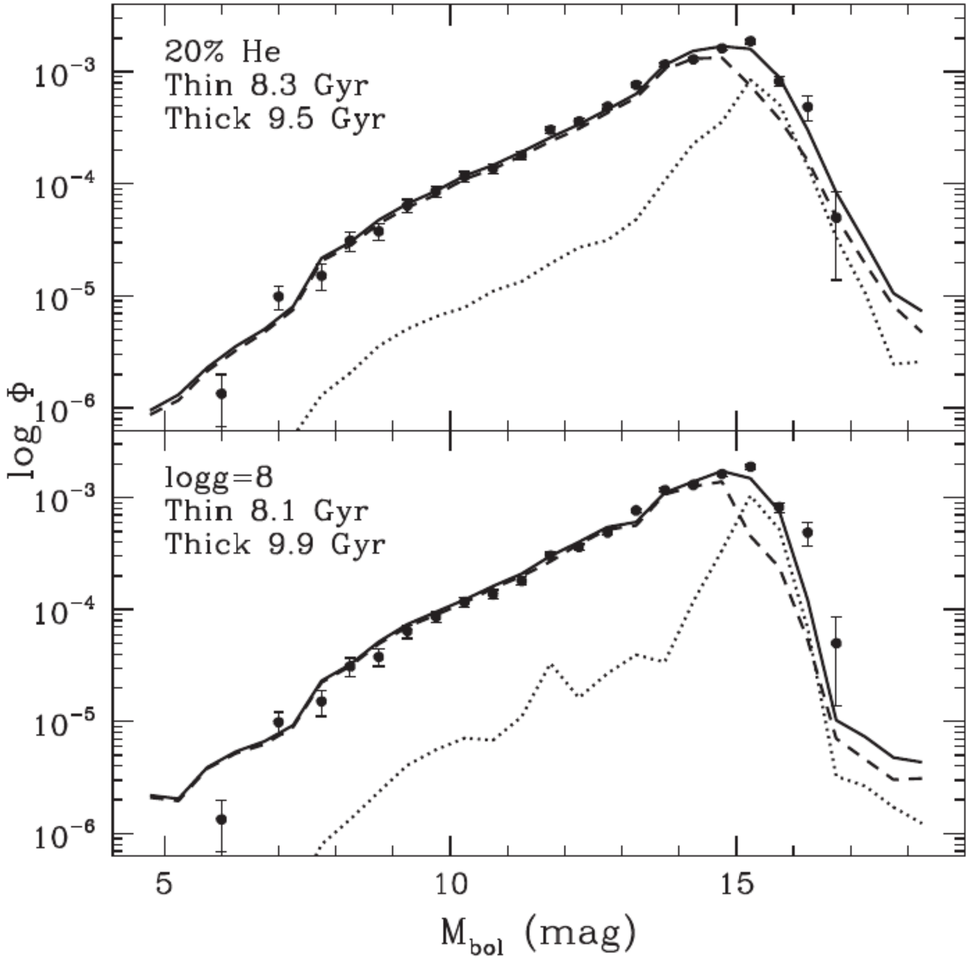


Figure 8. Fits to the disk luminosity function assuming that 20% of the white dwarfs have pure Helium atmospheres (top panel), or 100% of them have $\log g = 8$ (bottom panel). Dashed and dotted lines show the contribution from the thin disk and thick disk white dwarfs, assuming a 35% thick/thin ratio, respectively.

Main conclusions.

- **Metal poor old thick disc is incompatible with seismic obs.**
- **With the revised [M/H] for the first time observed distribution of seismic masses show agreement with theoretical models.**

- **What can we say about the age and the metallicity of the thick disc?**
  - Log $Z/Z_{\odot}$ = -0.16, τ_{thick} =9.2-10 ±0.2 Gyr
  - White dwarfs τ_{thick} =9.5-9.9 ± 0.2 Gyr