AIP

Galactic archaeology with the RAdial Velocity Experiment

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& RAVE collaboration
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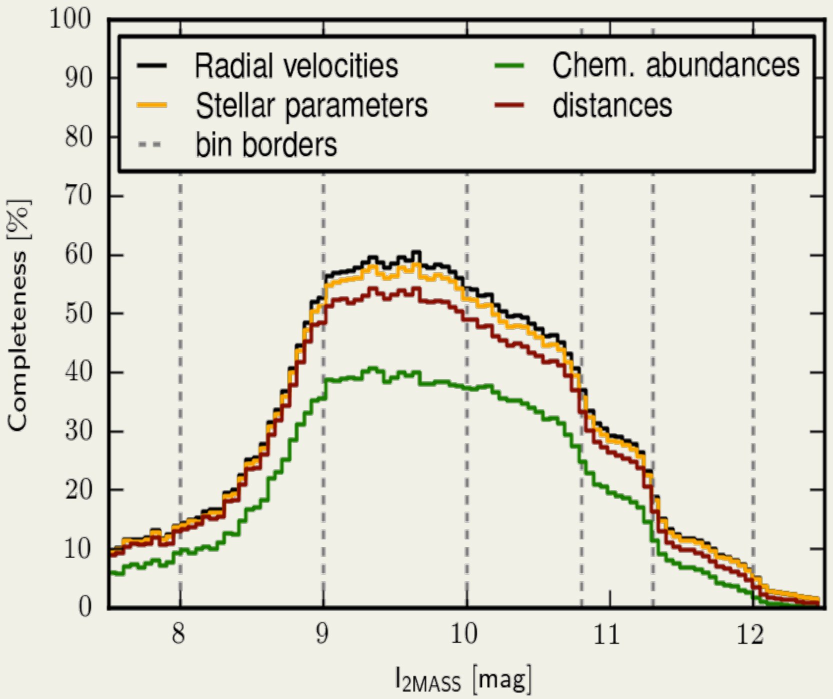
Multi-Object Spectroscopy in the next decade: Big questions, large surveys and wide fields

RAVE: 4th public data release

Kordopatis+ 2013b

- Intermediate resolution (R~7500)
- 425 561 stars,
- 482 430 spectra *(DR3: 77 461 stars)*
- 9 <I< 12 mag



Database:

- ✓ **Radial velocities**
- ✓ **Spectral morphological flags**
- ✓ **T_{eff}, logg, [M/H]**
- ✓ **Line-of-sight Distances**
- ✓ ***Mg, Al, Si, Ti, Ni, Fe***
- ✓ **Photometry**:
  DENIS, USNOB, 2MASS, APASS
- ✓ **Proper motions:**
  UCAC4, PPMX, PPMXL, Tycho-2, SPM4

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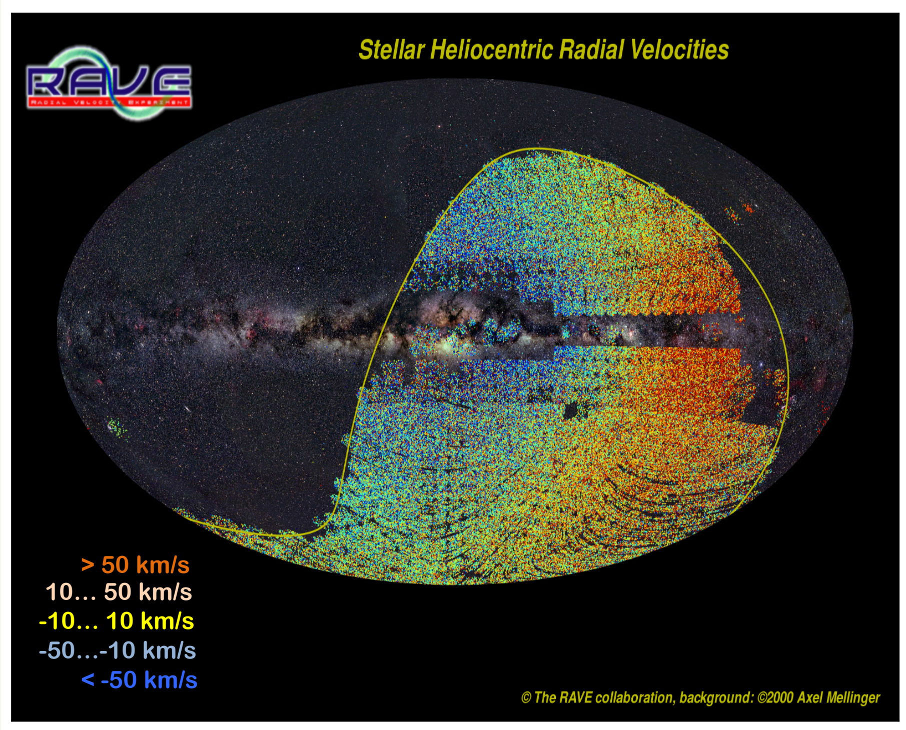

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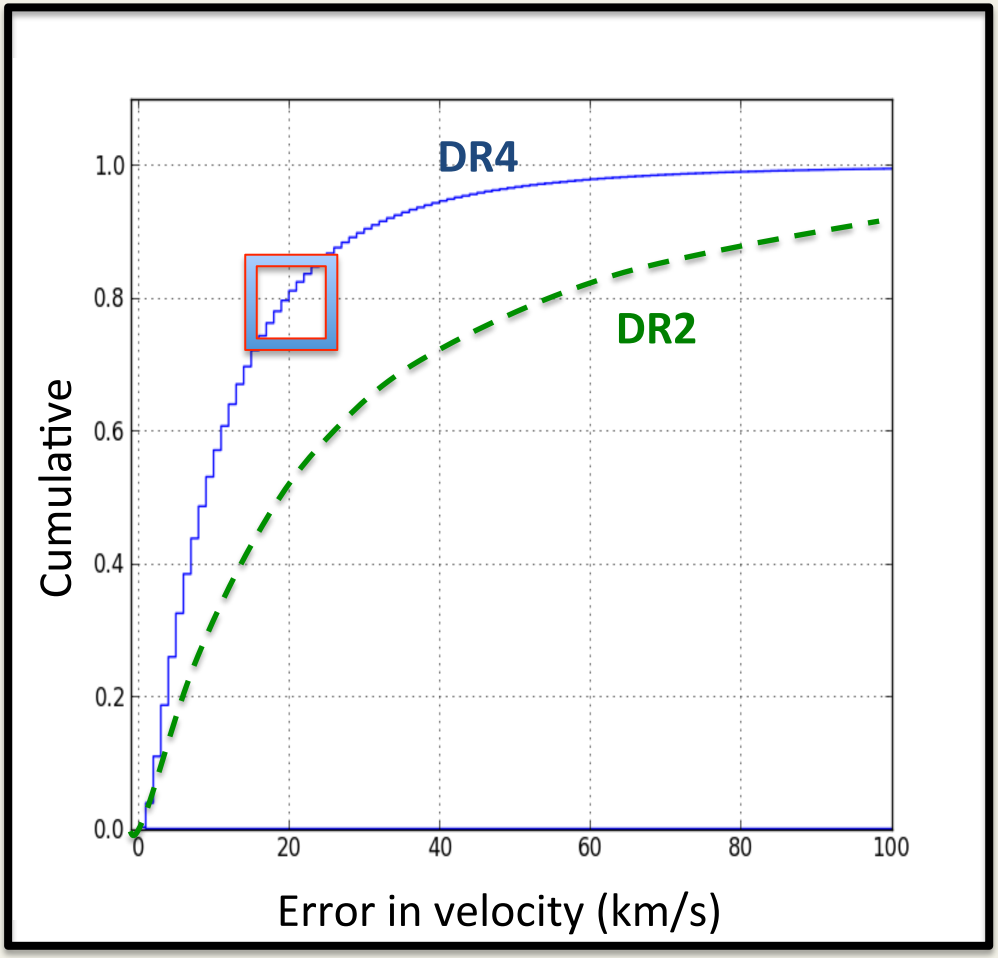
- ✓ **Photometry**: *DENIS, USNOB, 2MASS, APASS*
- ✓ **Proper motions:** *UCAC4, PPMX, PPMXL, Tycho-2, SPM4*

RAVE's Galactic 3D velocity errors



Combination of:

Distance errors (<30%)

+Errors in RV

(95% of the stars $\Delta V_{rad} < 4$ km s^{-1})

+Errors in proper motions

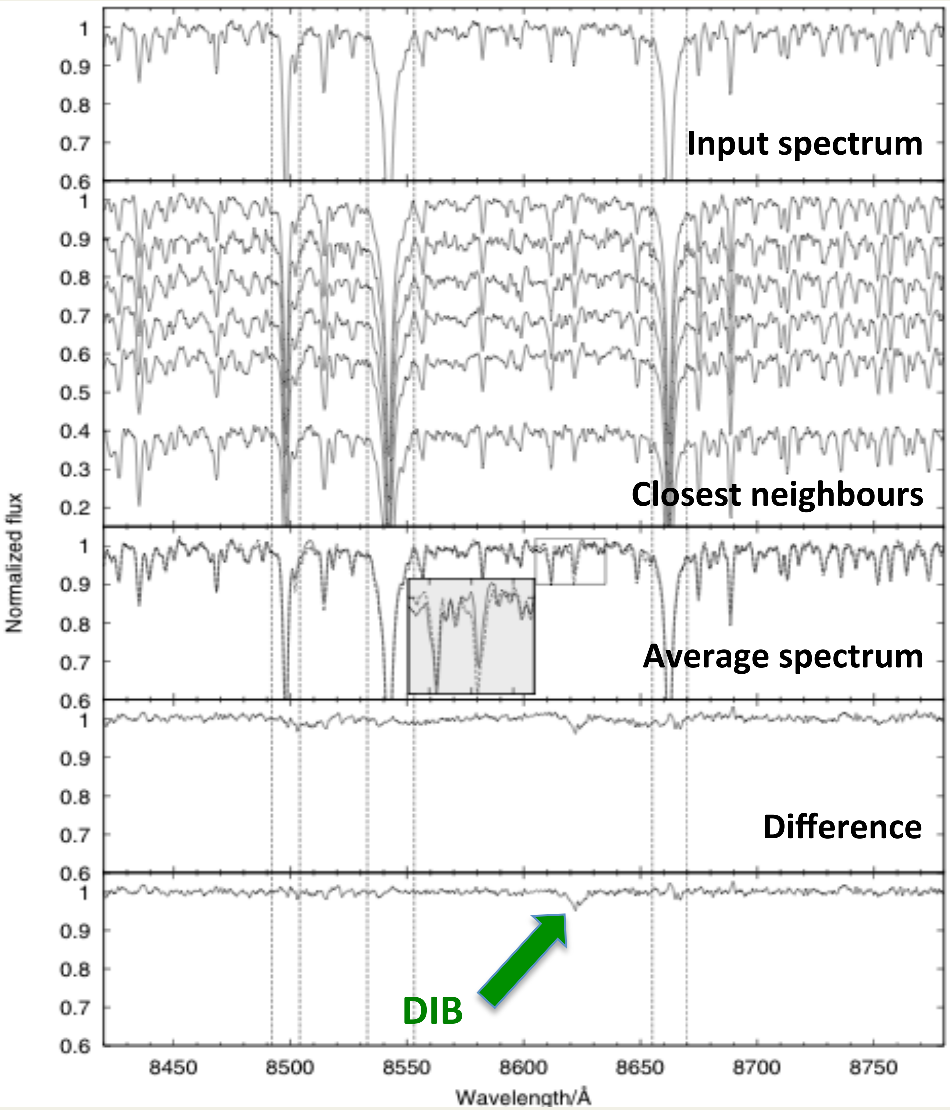
(~3 mas yr^{-1})

80 % of the stars with $\Delta V < 20$ km s^{-1}

Science?

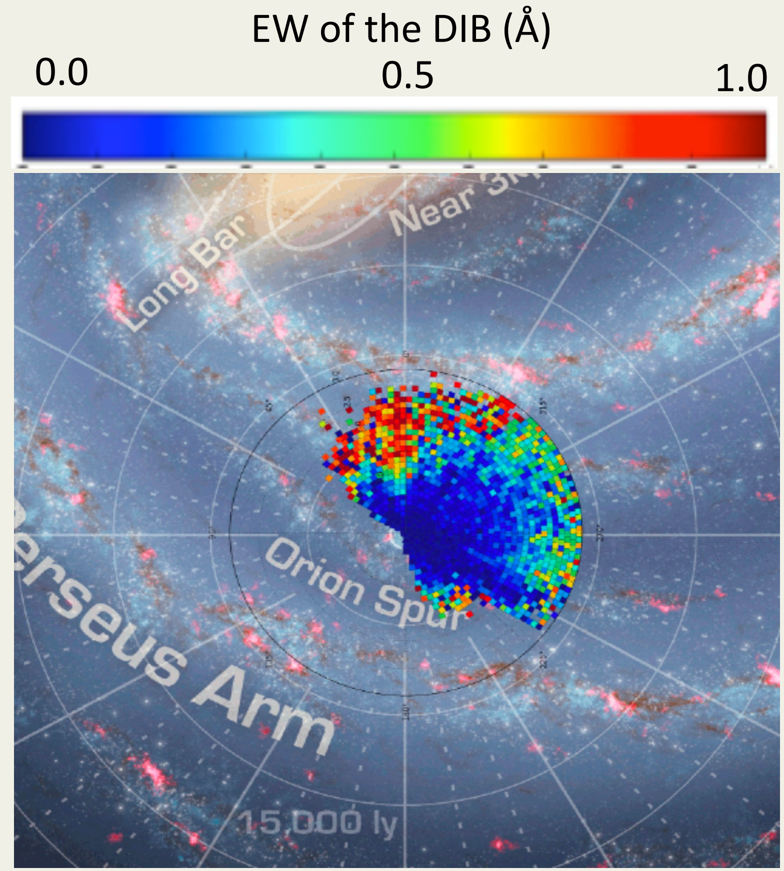
- **DR4 has led to >20 publications:**
  - Structure and kinematics of the Milky Way
  - Accretion events
  - Moving groups
  - Evolution of the discs
  - Mapping of the Diffuse Interstellar bands
  - …

Interstellar matter



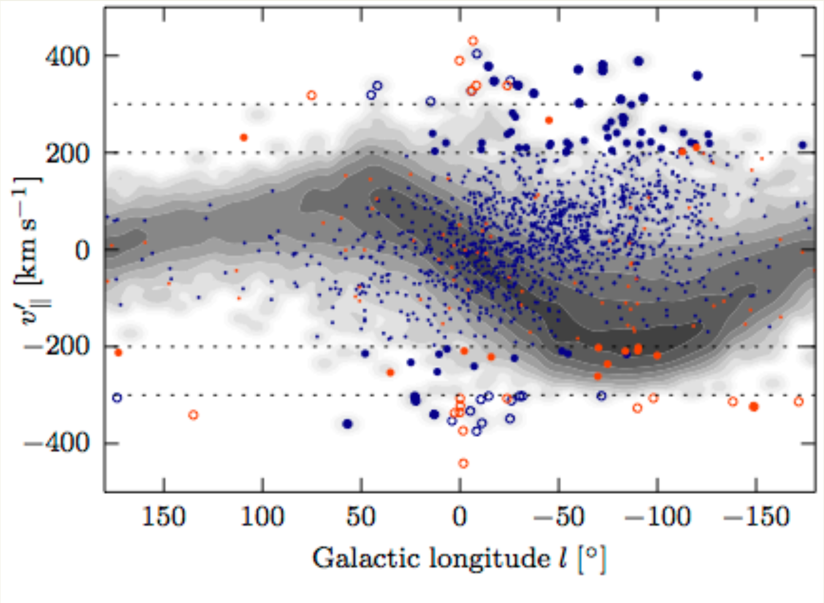
Kos+ 2013,2014

Mapping
of the Diffuse Interstellar Band

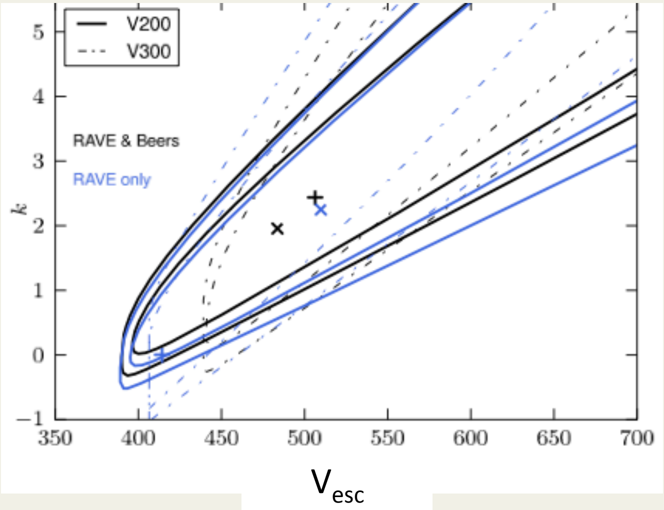


Galactic escape speed

Piffl+ 2014



Sample selection:
90 Counter-rotating halo stars with
$v_{||} > 200$ km s^{-1} or $v_{||} > 300$ km s^{-1}

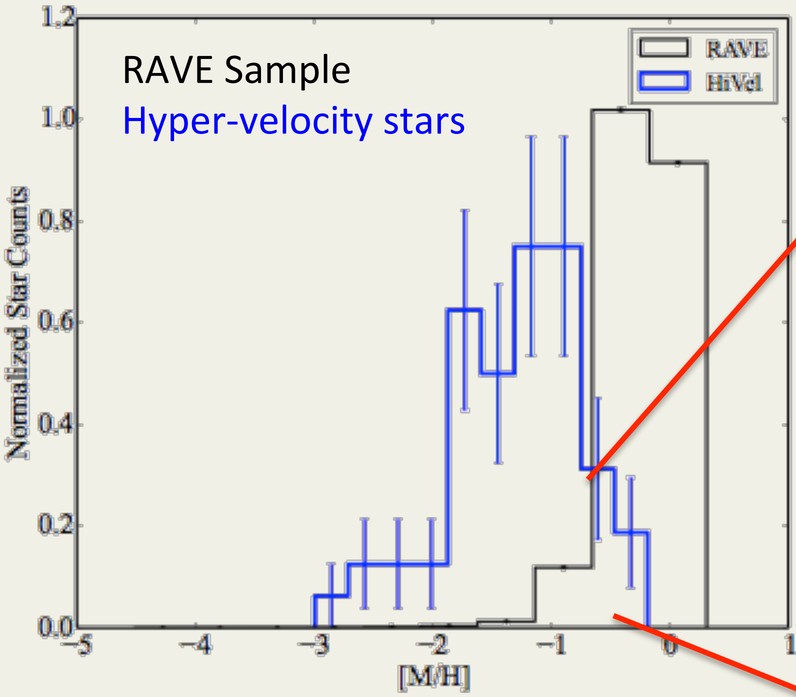


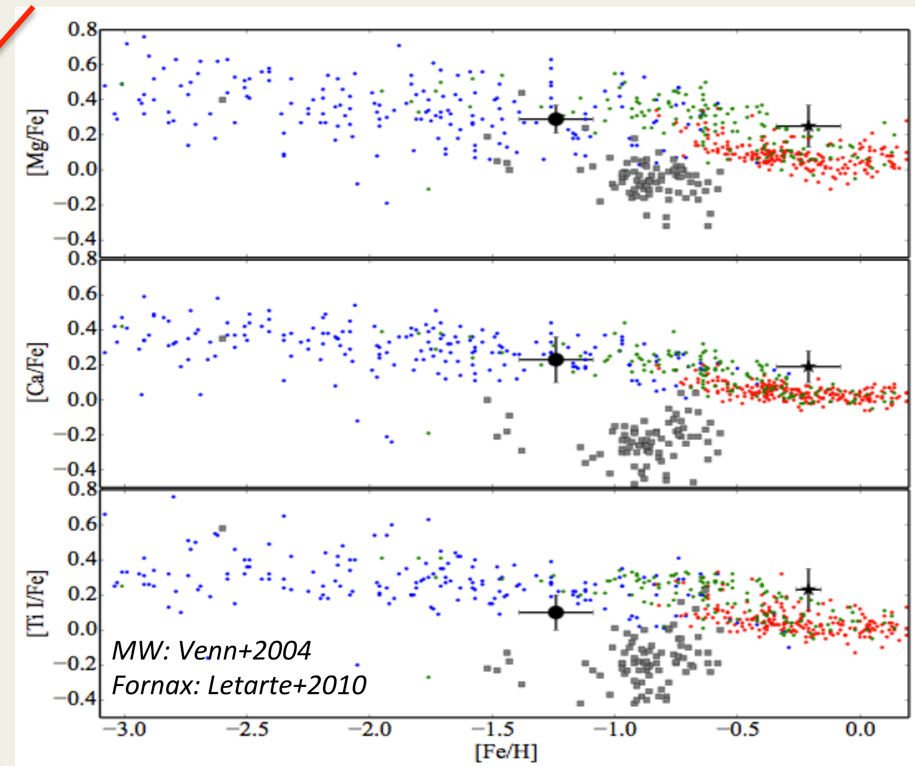
Density of stars: *f*(escape speed):
$n(v) \sim (v_{esc} - v)^k$ *(Leonard & Tremaine, 1990)*

$V_{esc} = 533$ km s^{-1}
$\Rightarrow M = 1.3 \times 10^{12}\ M_\odot$ *($\Phi(R) = -0.5 * V_{esc}^2$)*

Hyper-velocity stars

Hawkins+ 2015

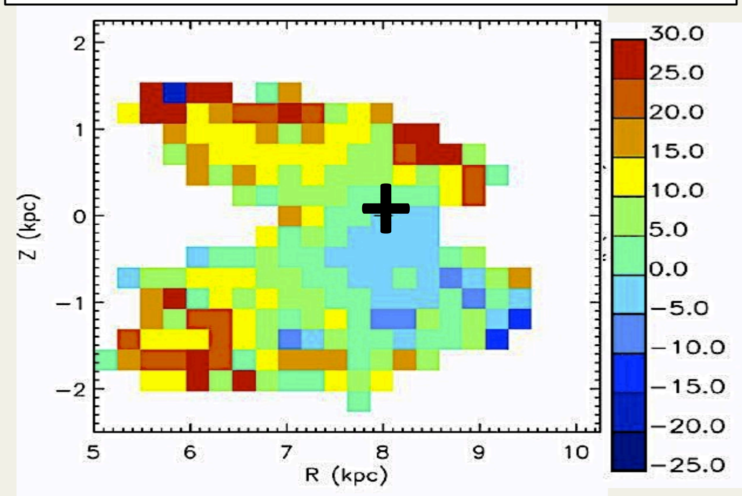




Discovery of a dynamically ejected thick disc star

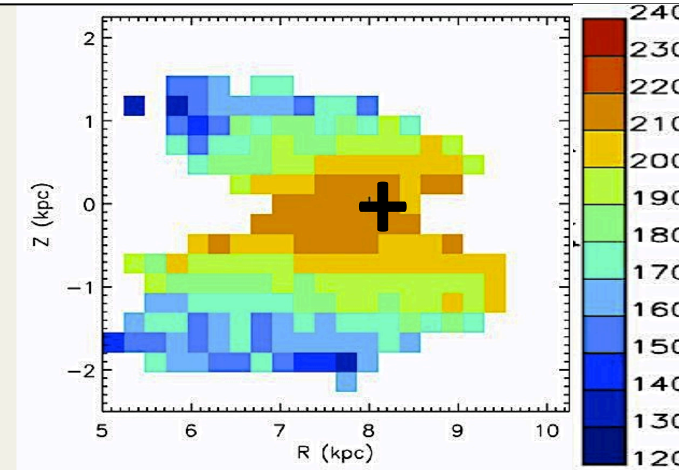
Velocity maps

Galactocentric radial velocity

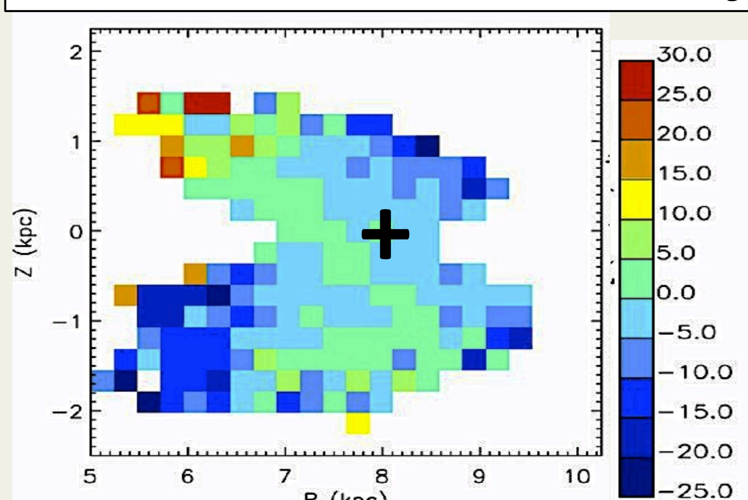


Kordopatis+ 2013c

Galactocentric azimuthal velocity



Galactocentric vertical velocity



Velocity maps

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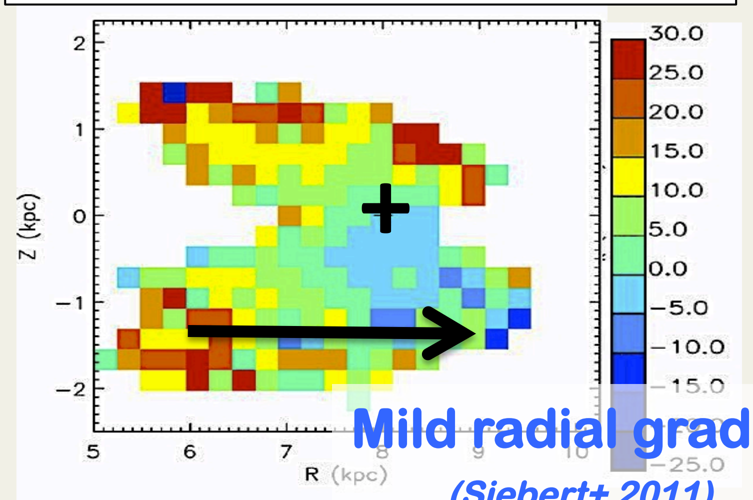
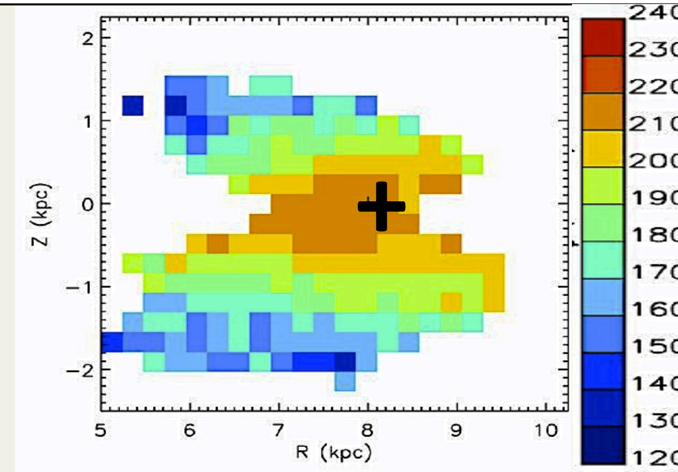


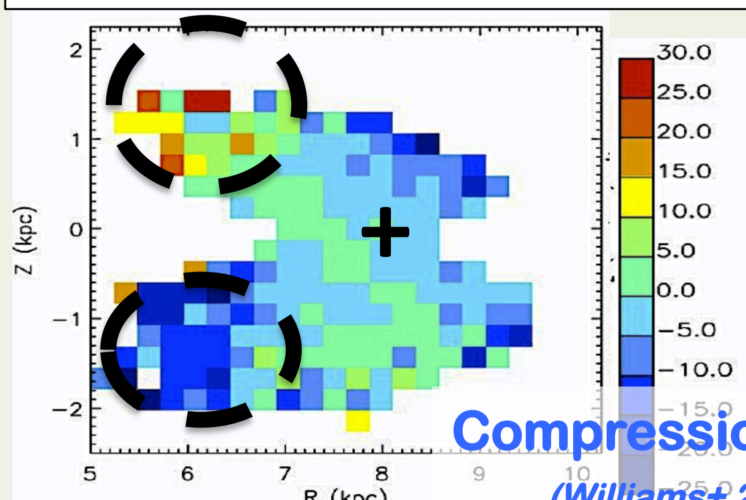
Mild radial gradient in V_R

(Siebert+ 2011)

Galactocentric azimuthal velocity



Galactocentric vertical velocity

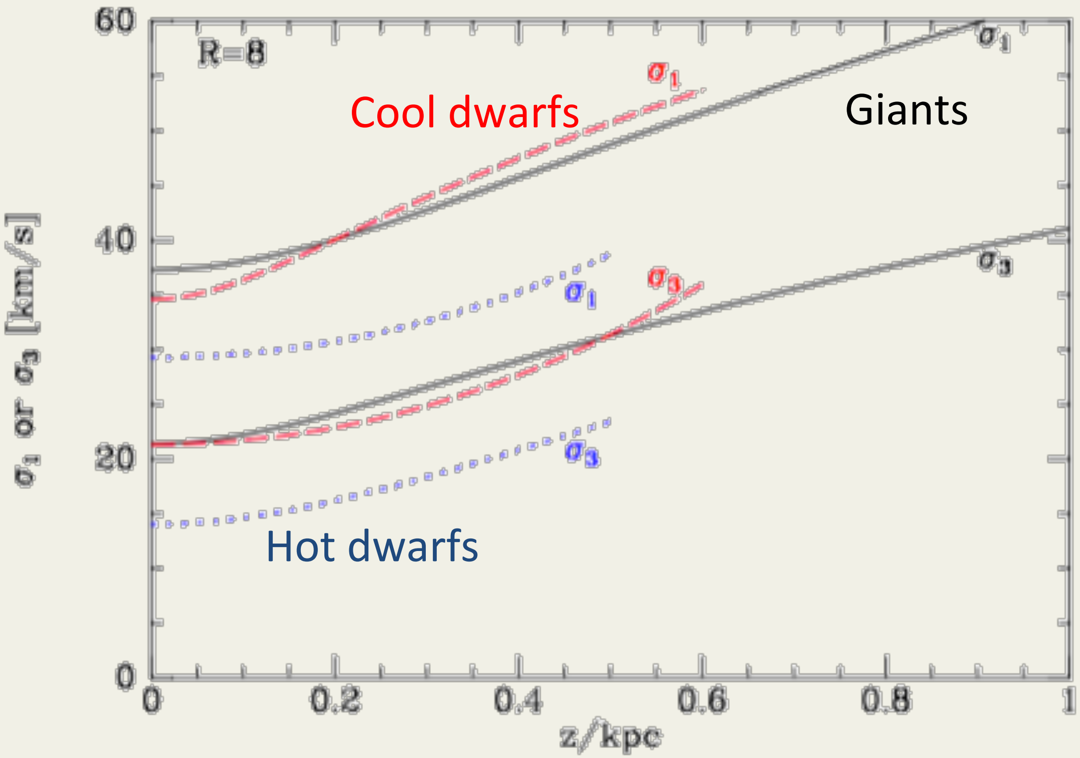


Compression-rarefaction pattern

(Williams+ 2013)

Stellar dynamics

Binney+ 2014



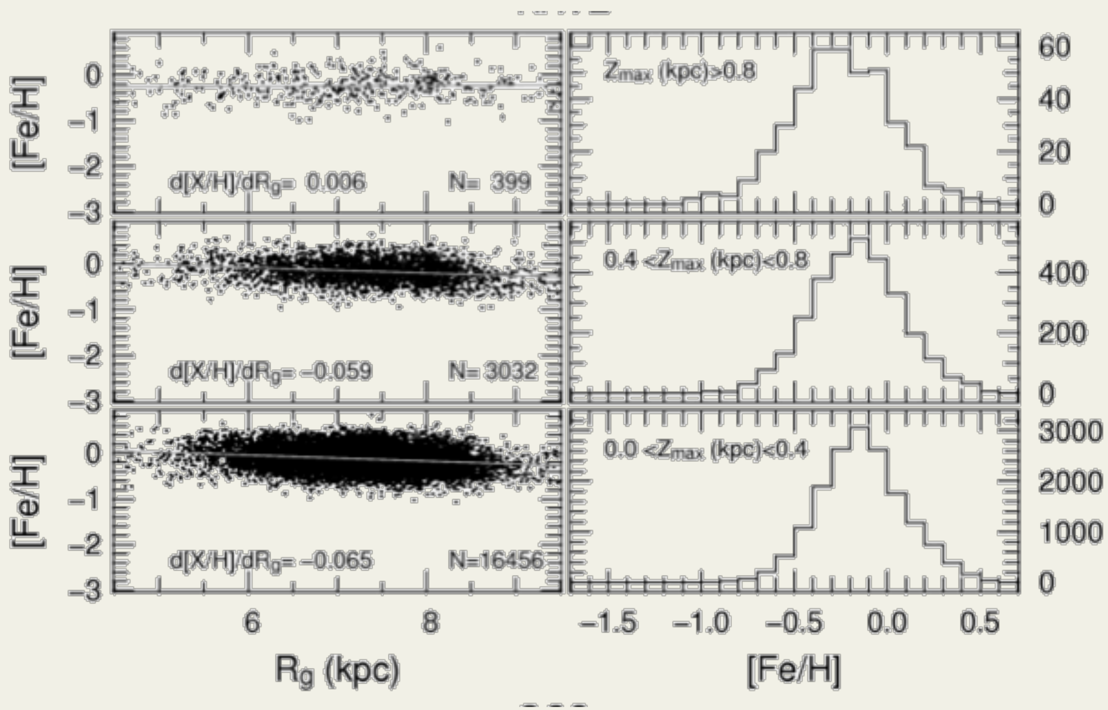
Cool dwarfs and giants agree, except near the plane where σ-dwarfs is lower

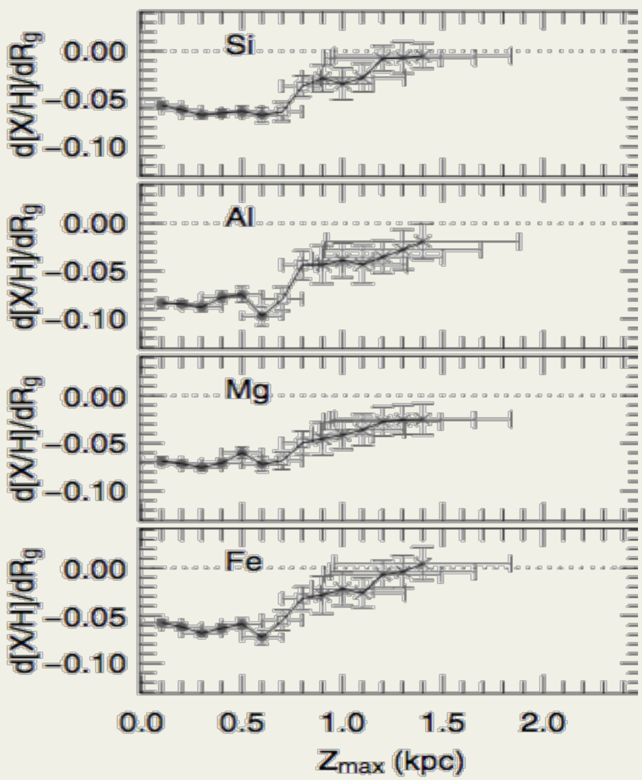
σ for hot dwarfs significantly lower (younger stars)

Milky Way potential at R~8 dominated by the disc potential

Radial Chemical gradients in the disc: [M/H] & [X/Fe]

Boeche+ 2013,2014

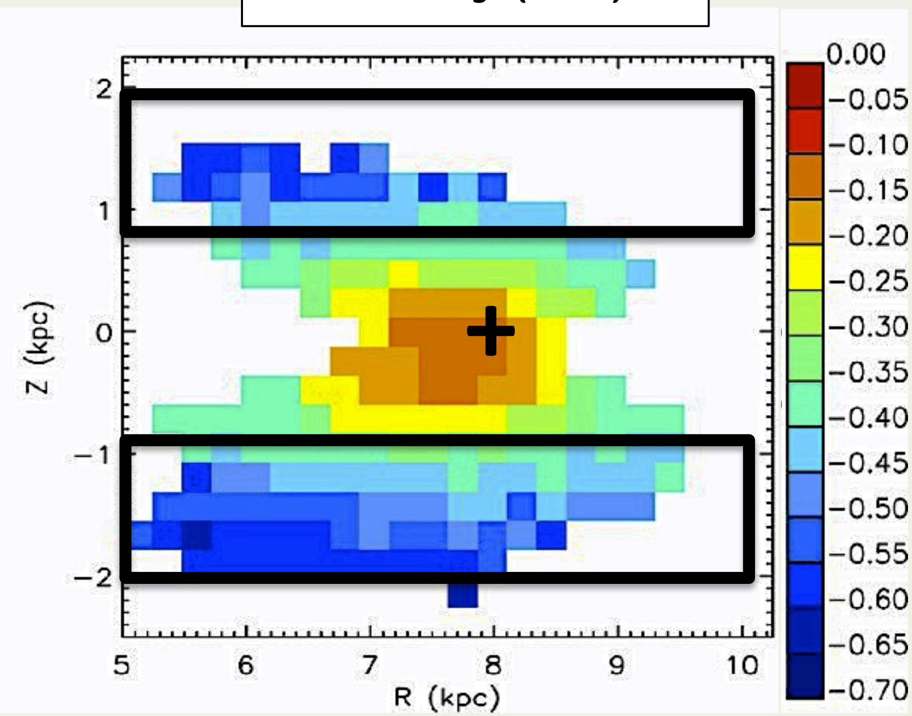


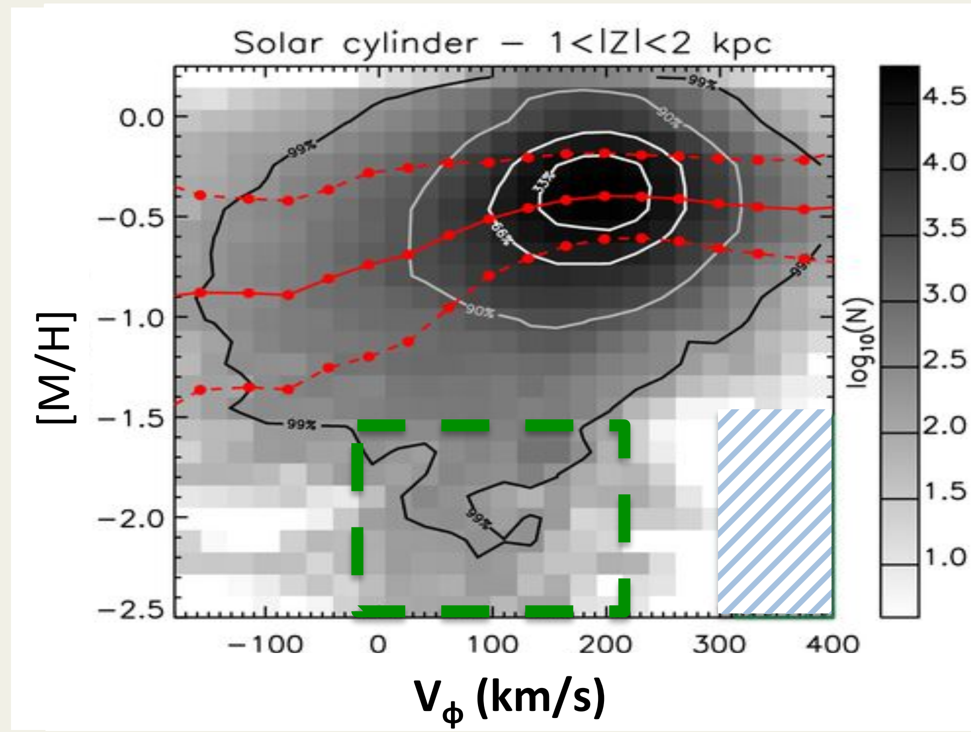


Constraints on Disc formation & Radial migration of stars

Metal-weak thick disc

Kordopatis+ 2013c





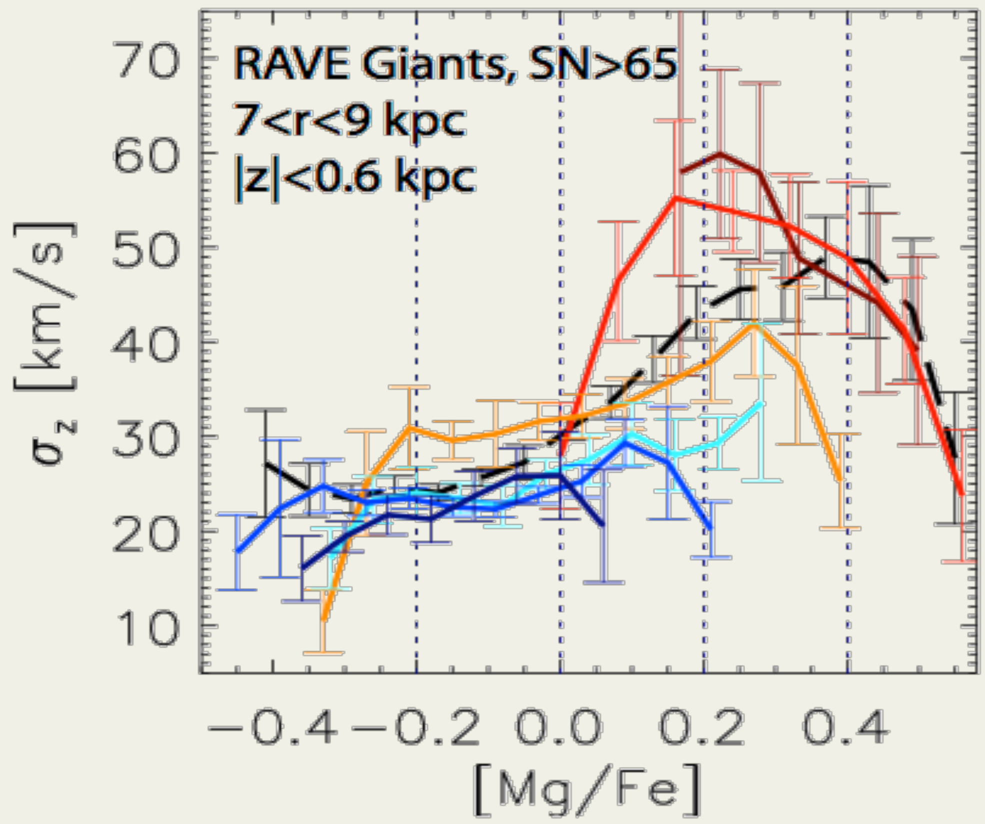
"Disc component" at V_ϕ ~ 100 km/s & [M/H] <-1.5 dex
MWTD reaches [M/H]<-2 dex and represents ~5% of the canonical Thick disc

⇒ Correlation between V_ϕ and [M/H] confirmed
⇒ Extra-galactic origin?

Signatures for a violent origin?

Minchev+ 2014

[Fe/H]= -1.00 dex
[Fe/H]= -0.80 dex
[Fe/H]= -0.45 dex
[Fe/H]= -0.30 dex
[Fe/H]= -0.17 dex
[Fe/H]= -0.04 dex



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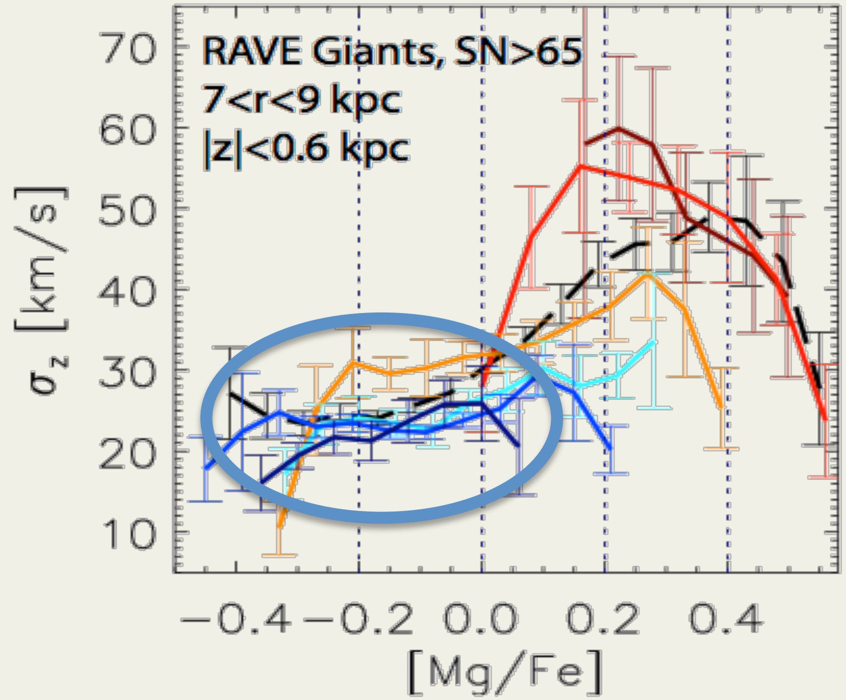
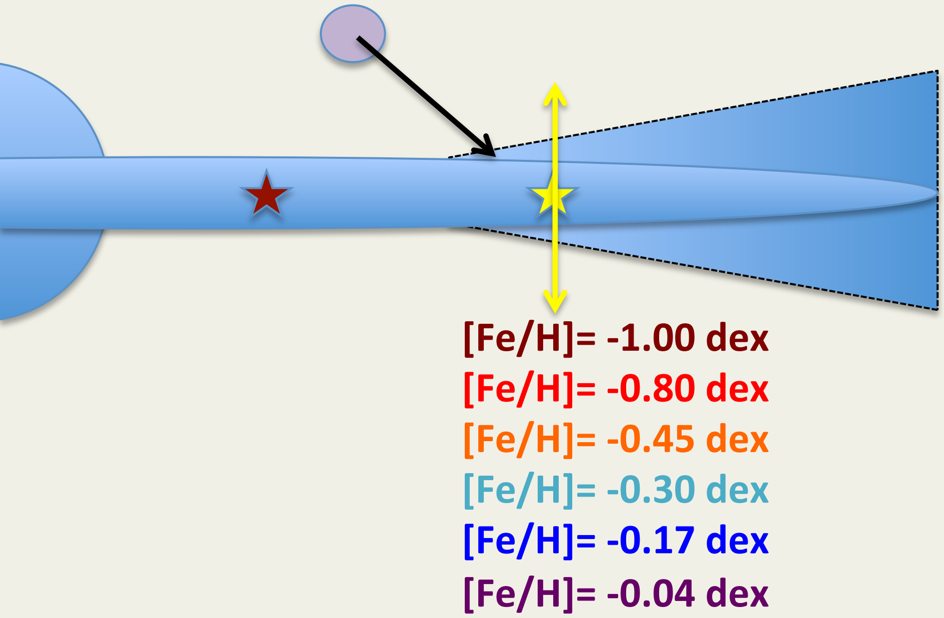
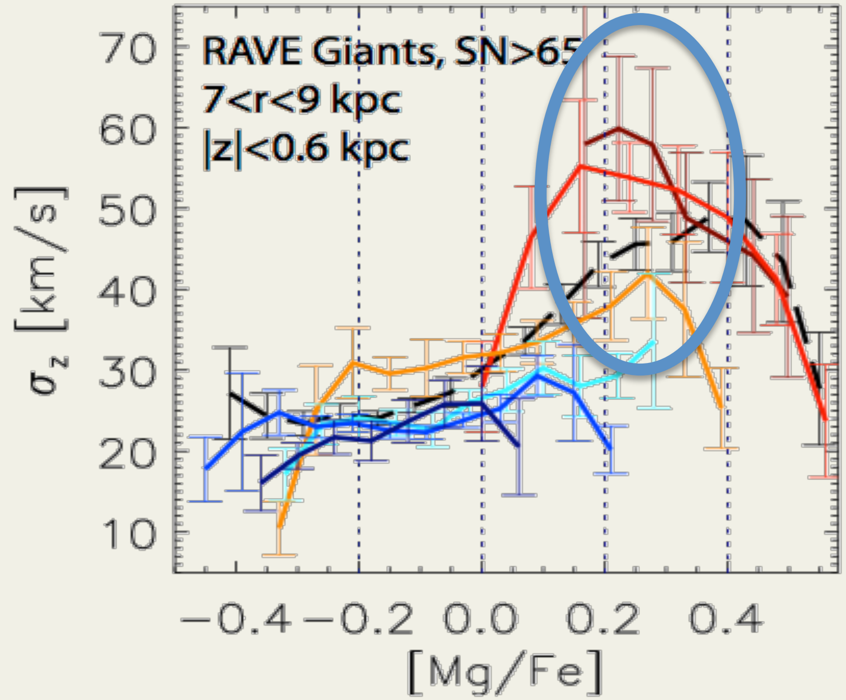


1 - Normal disc evolution:
Stars migrate and gain random energy (kinematically hotter)

Signatures for a violent origin?

Minchev+ 2014

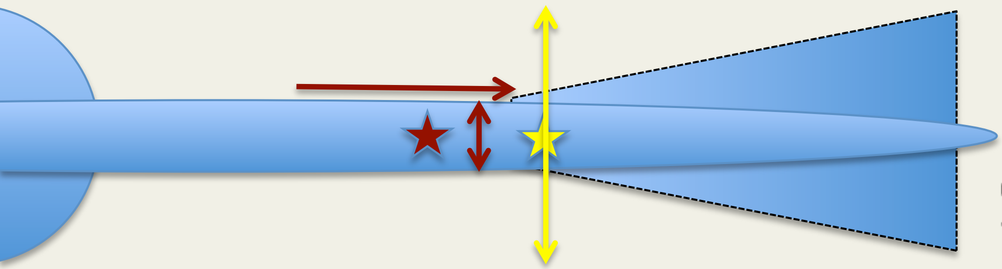




2- Massive merger at [Mg/Fe]~0.3 dex:
Stars gain a vertical velocity dispersion and cannot migrate as efficiently as before because they spend less time on the plane

Signatures for a violent origin?

Minchev+ 2014



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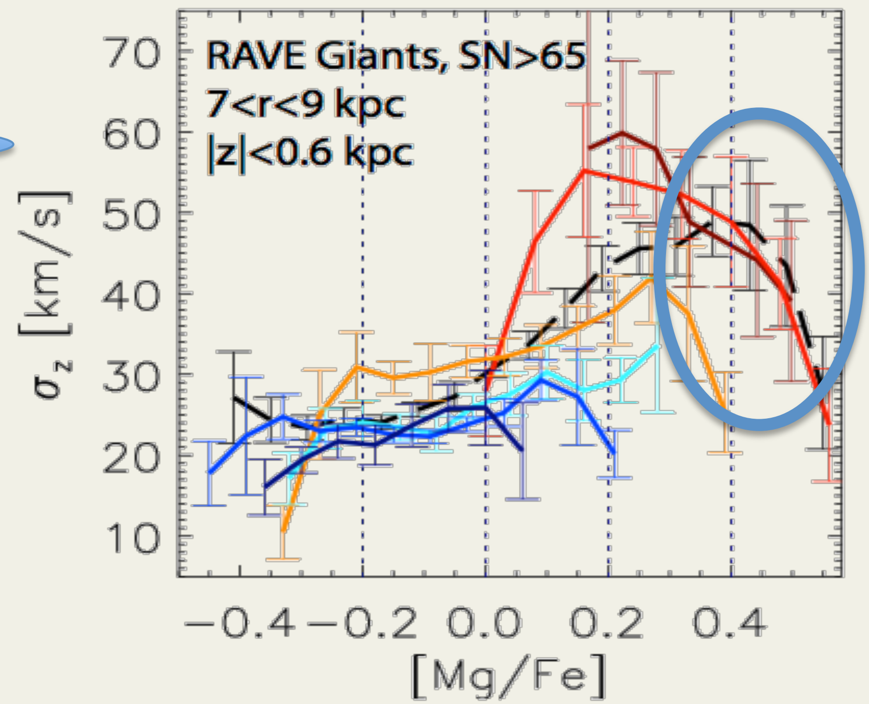
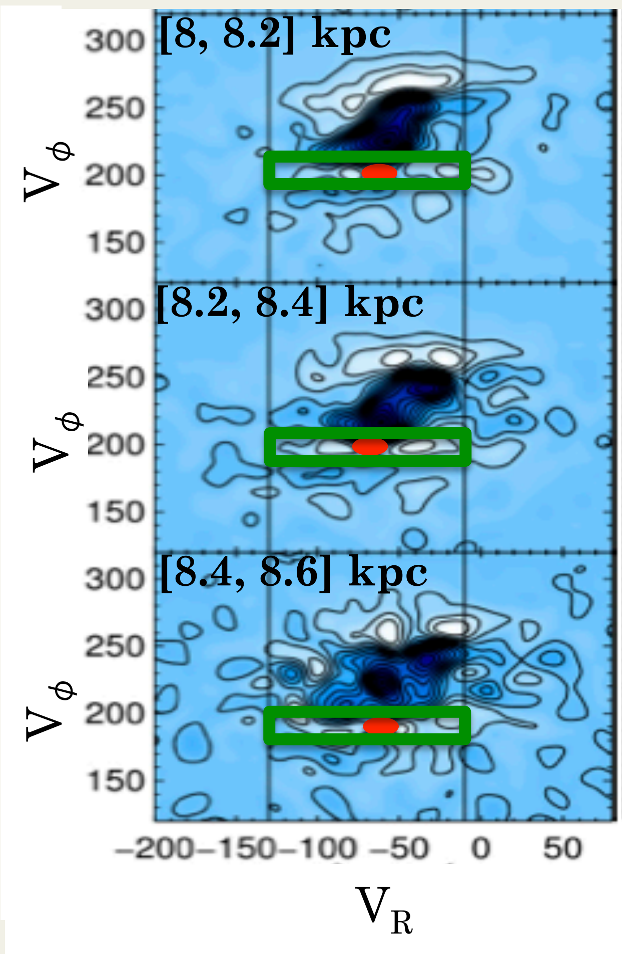


3- Older stars from small guiding radii migrate
Stars with smaller guiding radii migrate to the Solar neighbourhood, having cooler kinematics than the locally born stars

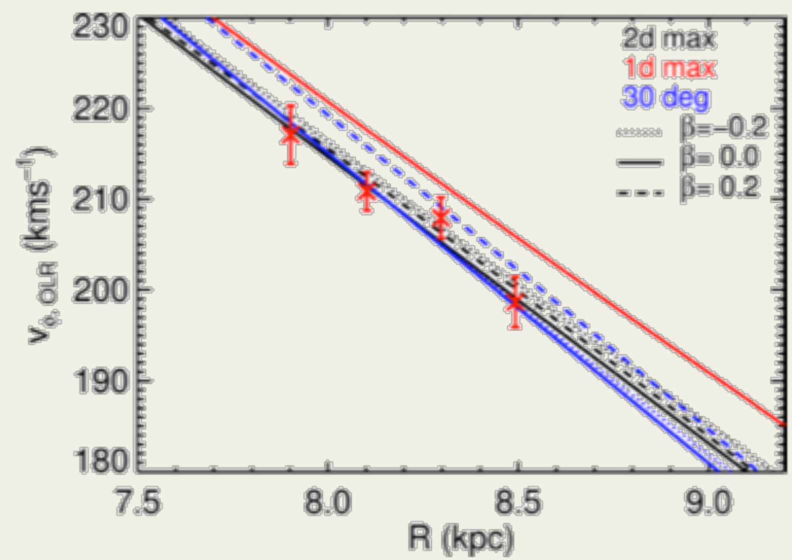
Galactic bar & Moving groups

Antoja+ 2014

Identification of the Hercules stream at different radii
Saddle point position ≈ f(pattern speed, orientation of the bar).



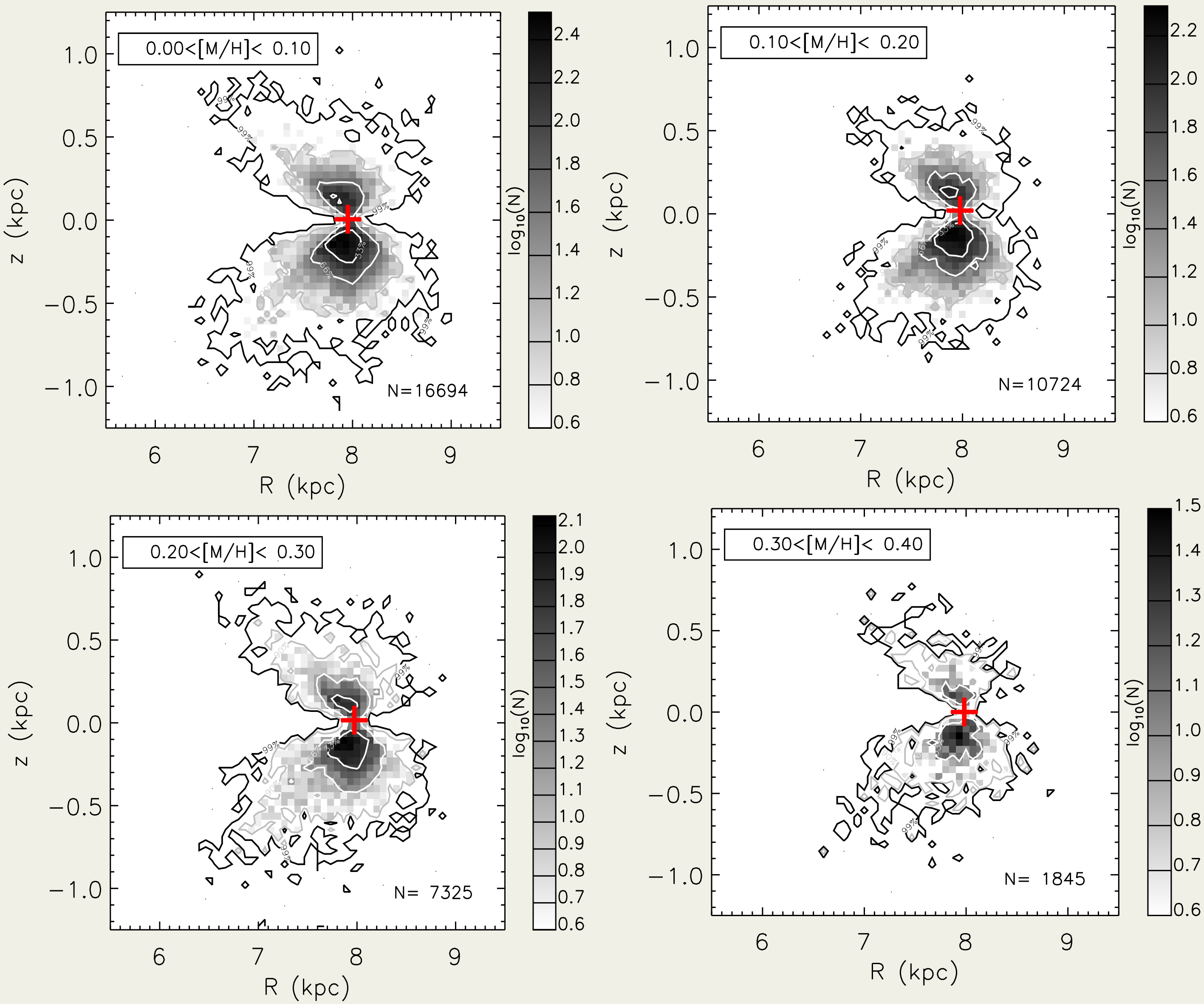
$$v_{\phi,\mathrm{OLR}}(R) \approx a\, v_0\,(R/R_0)^{\beta}\,\frac{1+\beta}{1-\beta}\left[1-\frac{\Omega_b R}{v_0(R/R_0)^{\beta}}\,\frac{1}{1+\sqrt{(1+\beta)/2}}\right] -(b+c\beta-1)\,v_0\,(R/R_0)^{\beta}.$$



Bar's pattern speed:
$51 < \Omega_b < 56$ km s $^{-1}$ kpc^{-1} for $10^o < \Phi_b < 45^o$

Super-Solar metallicity stars

Kordopatis et al., 2015, MNRAS, 447, 3526



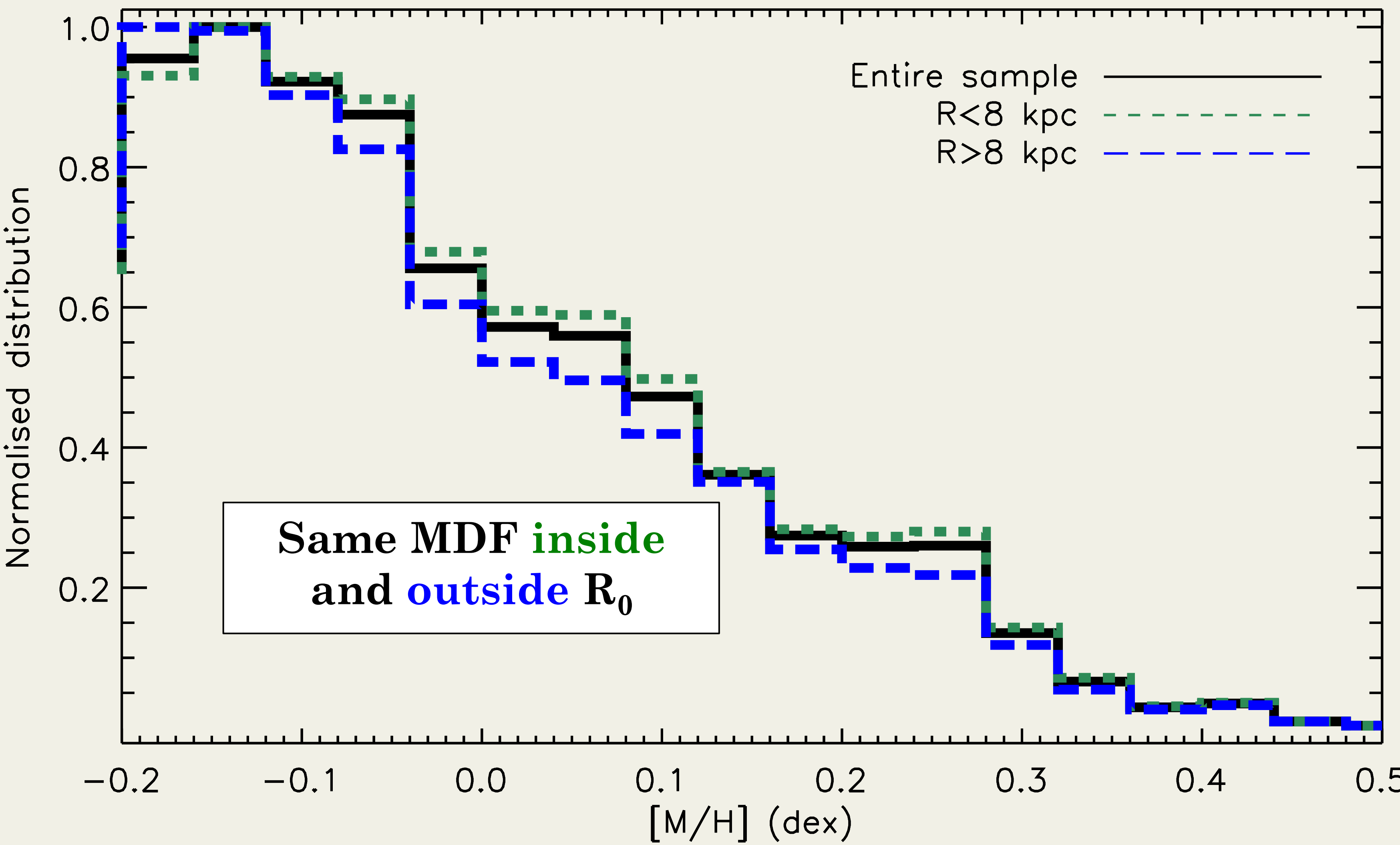
Stars mainly located close to the plane.

➢ **But also:**

Fair amount of stars between 0.4 < z < 1 kpc

Super-Solar metallicity stars
1) R separation

Kordopatis et al., 2015, MNRAS, 447, 3526



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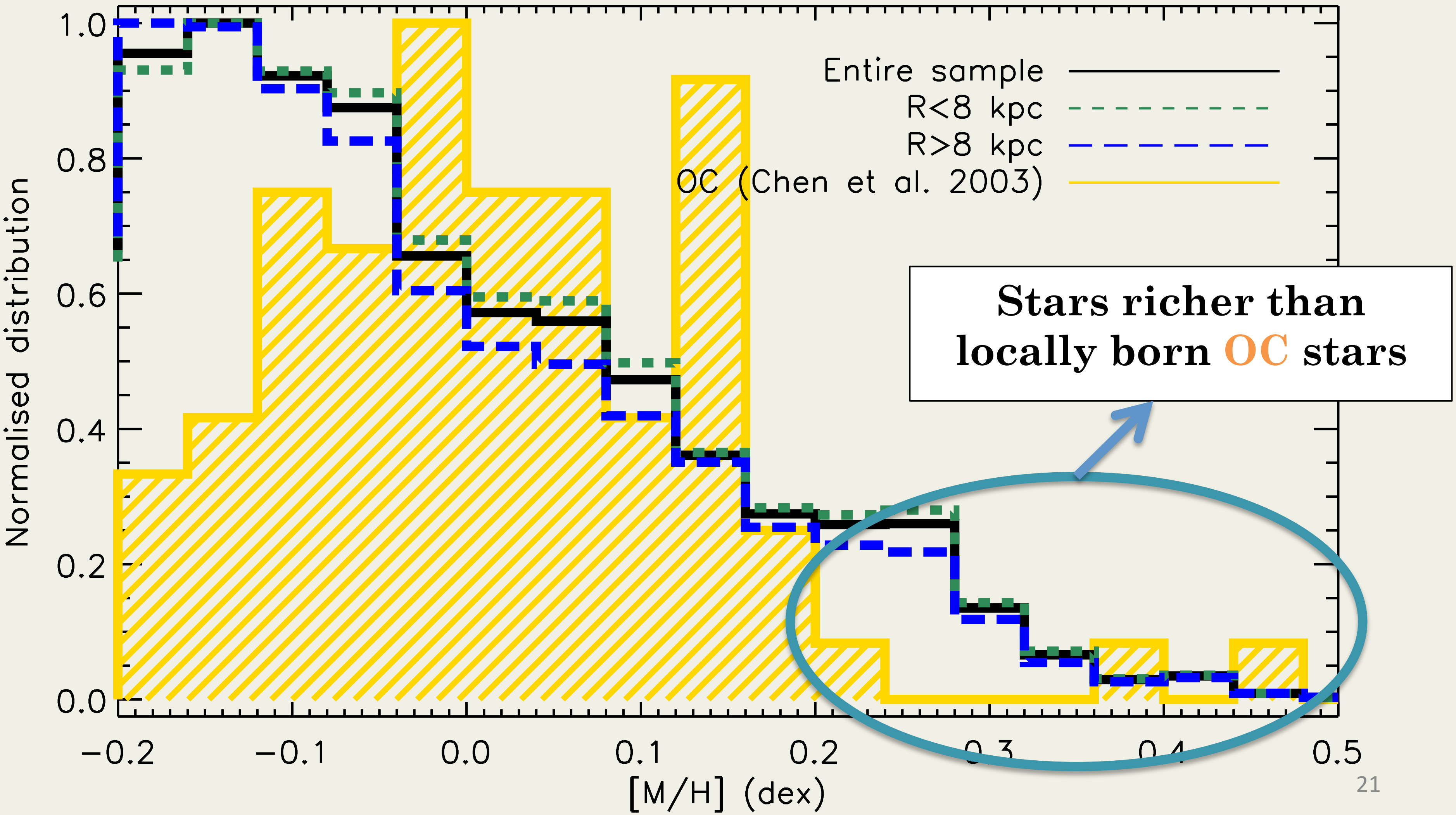

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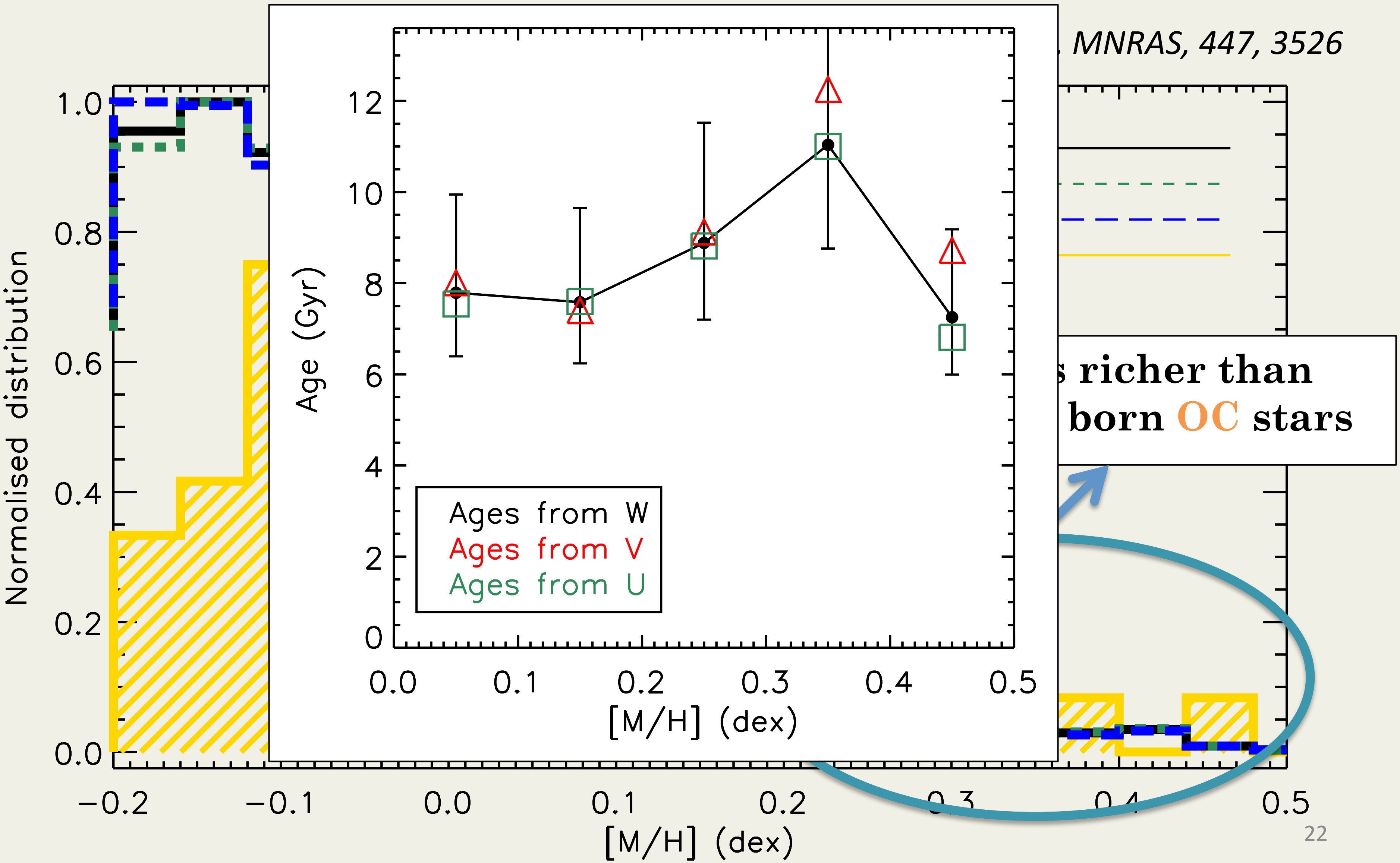
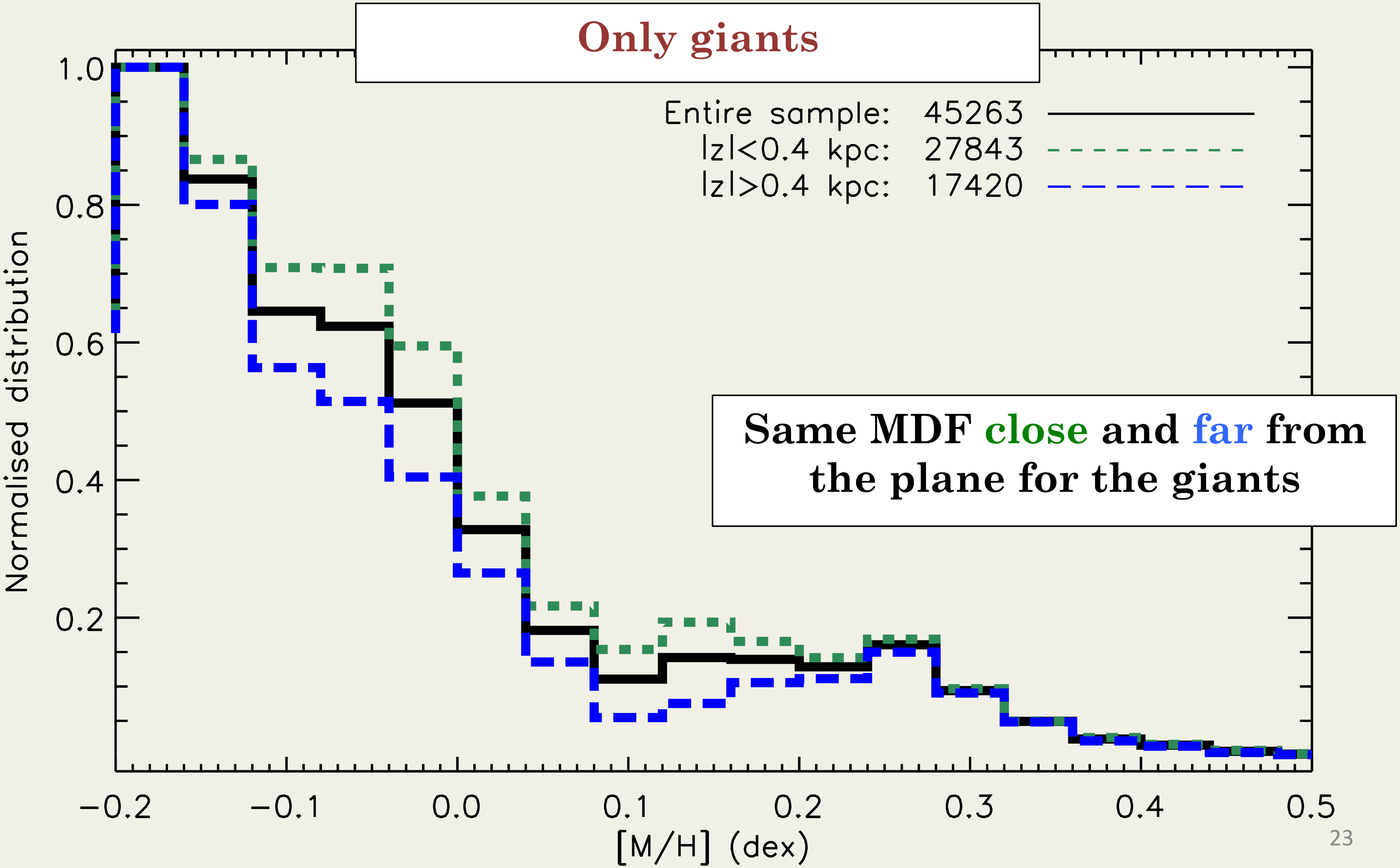


Super-Solar metallicity stars
2) Z separation



Super-Solar metallicity stars →Eccentricity determination

Kordopatis et al., 2015, MNRAS, 447, 3526

3 discs:

$$\rho(R,z) = \frac{\Sigma_0}{2z_d} \exp\left[-\left(\frac{R_h}{R} + \frac{R}{R_d} + \frac{|z|}{z_d}\right)\right]$$

2 spheroids:

$$\rho(R,z) = \frac{\rho_0}{m^{\gamma}(a+m)^{\beta-\gamma}} \exp[-(mr_0/r_{cut})^2]$$

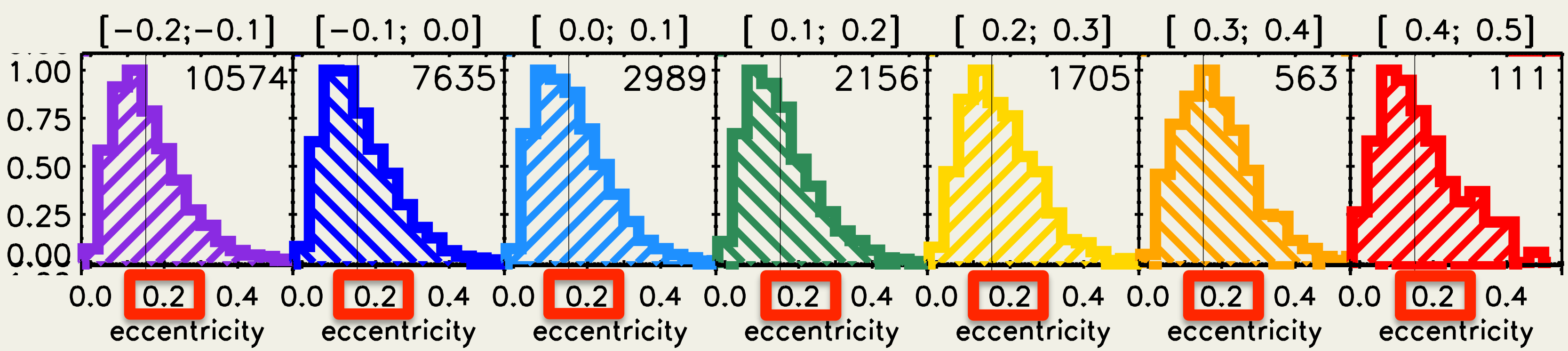
$$m(R,z) \equiv \sqrt{(R/r_0)^2 + (z/qr_0)^2}$$

Table 1. Parameters for the adopted mass model of the Milky Way.

Disc	Thick	Thin	Gas
Σ_0 ($M_\odot\,kpc^{-2}$)	7.30×10^7	1.11×10^9	1.14×10^8
R_d (kpc)	2.4	2.4	4.8
z_d (kpc)	1.0	0.36	0.04
R_h (kpc)	0	0	4
Spheroid	Dark halo	Bulge	
ρ_0 ($M_\odot\,kpc^{-3}$)	1.26×10^9	7.56×10^8	
q	0.8	0.6	
γ	−2	1.8	
β	2.21	1.8	
r_0 (kpc)	1.09	1	
r_{cut} (kpc)	1000	1.9	

(Dehnen & Binney 98, Binney12)

Solar neighbourhood:



Super-Solar metallicity stars →Spiral history of the MW

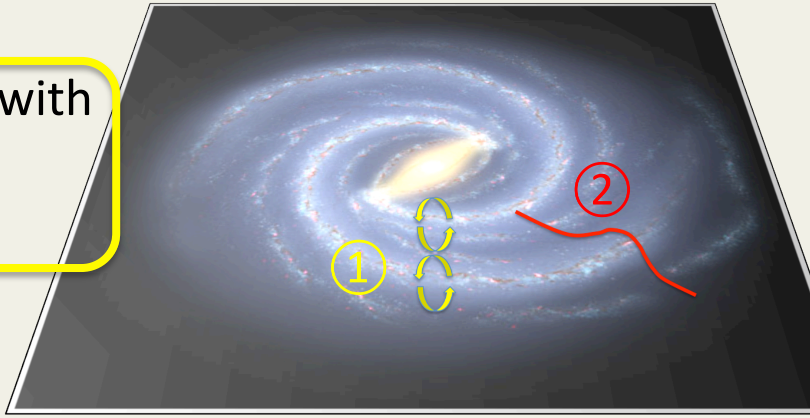
Kordopatis et al., 2015, MNRAS, 447, 3526

~Observation

- Given ISM's metallicity gradient:
  $\partial[M/H]/\partial R \sim -0.06$ dex kpc^{-1} *(Smartt & Rolleston97; Balser+11…)*
  - **Stars born well inside R_o.**
    Stars with [M/H]=0.2 dex: $R_{birth} < 6$kpc
    Stars with [M/H]=0.4 dex: $R_{birth} \sim 2$kpc

Theory

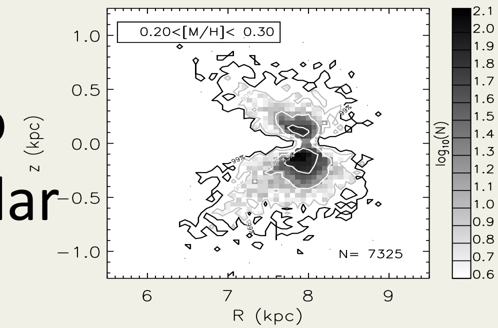
- Radial migration: *(Sellwood&Binney02…)*
  1. Churning: Co-rotation resonances with spirals
     - **Δe/Δt ~ 0**
  2. Blurring: Lindblad resonances
     - **Δe/Δt ≠ 0**



Super-Solar metallicity stars →Spiral history of the MW

~Observation

- *"Radially migrated stars seen >0.8kpc*
  - Radial migration probability is insensitive to the extent of a star's excursions perpendicular to the plane

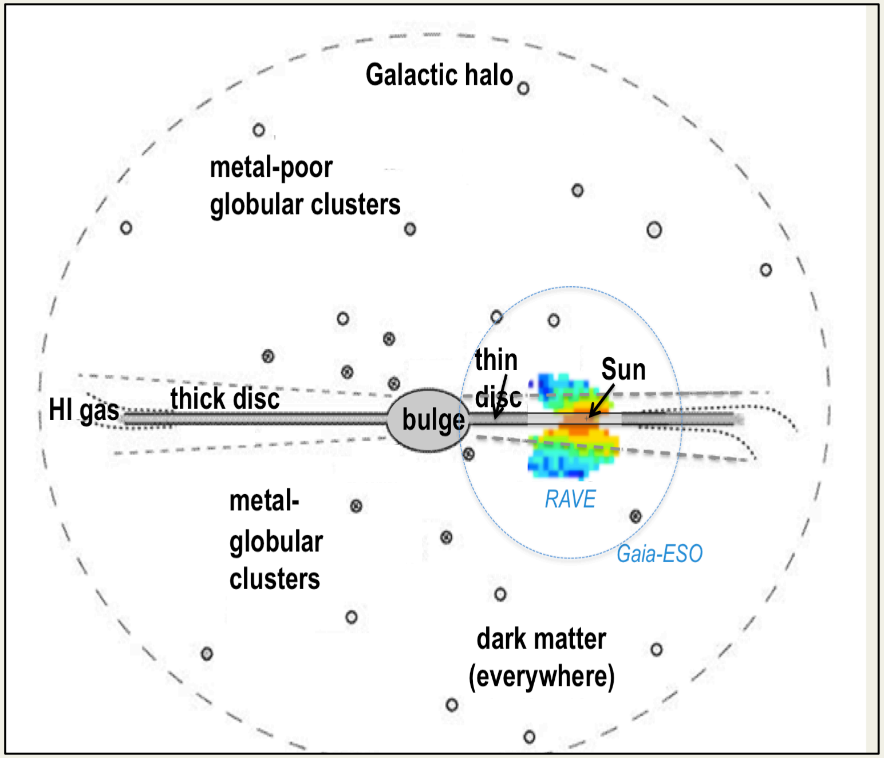


Theory

- *Binney & Tremaine08*: "The gravitational field of a spiral structure with radial wavenumber k varies with exp(−k|z|)"
  - ➢ Influence of a wave on stars: < 1/k from the plane

➢ **The radial wavelength of spiral structure is no smaller than ~1kpc**

Conclusions / Perspectives



- 4MOST / WEAVE: larger samples, higher resolutions
- Gaia release scenario:
  - Spectral parameters available in 2018
- Galactic chemo-dynamics with Gaia is possible from 2016!
- Until then: use of RAVE parameters with Gaia's proper motions/ parallaxes/flags/parameters from BP/ RP
- DR5: Improved parameters and abundances

RAVE vs Gaia

- Intermediate resolution (R~7 500)
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Gaia:

R~11 500
Same λ coverage (CaII triplet)
~10^7-10^8 targets with spectra

Database:

✓ Radial velocities => ~same accuracy
✓ Spectral morphological flags => Coming from the CUs
✓ T_{eff}, logg, [M/H] => same precision (RVS) + BP/RP
✓ *Mg, Al, Si, Ti, Ni, Fe* => Similar
✓ Line-of-sight Distances **=> Parallaxes!**
✓ Photometry:
DENIS, USNOB, 2MASS, APASS => BP/RP
✓ Proper motions:
UCAC4, PPMXL, Tycho-2, SPM4 **=> high precision!**

RAVE vs Gaia

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DENIS, USNOB, 2MASS, APASS

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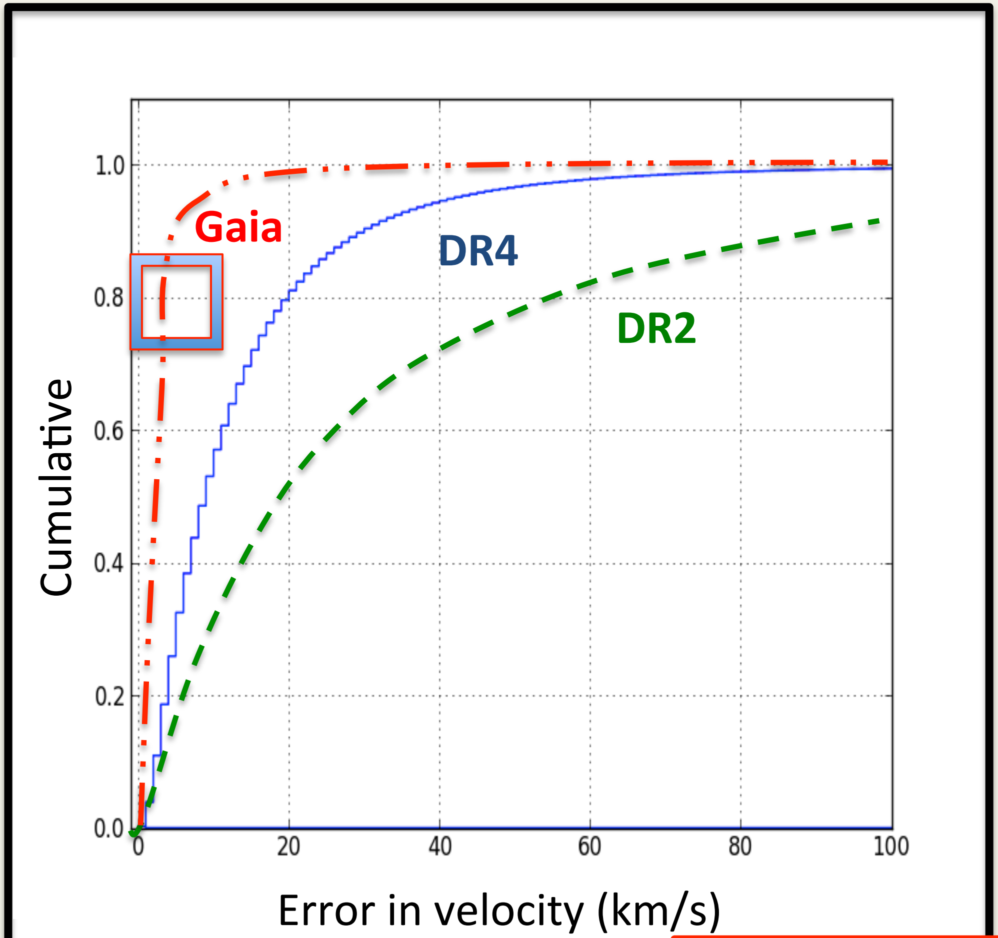
UCAC4, PPMXL, Tycho-2, SPM4

~~RAVE's~~ Gaia's Galactic 3D velocity errors



Combination of:

Distance errors ~~(<30%)~~ **(<10%)**

+Errors in RV

(95% of the stars $\Delta V_{rad} < 4$ km s^{-1})

+Errors in proper motions

~~(~3 mas yr^{-1})~~ **50 µas yr^{-1}**

80 % of the stars with $\Delta V < 5$ km s^{-1}

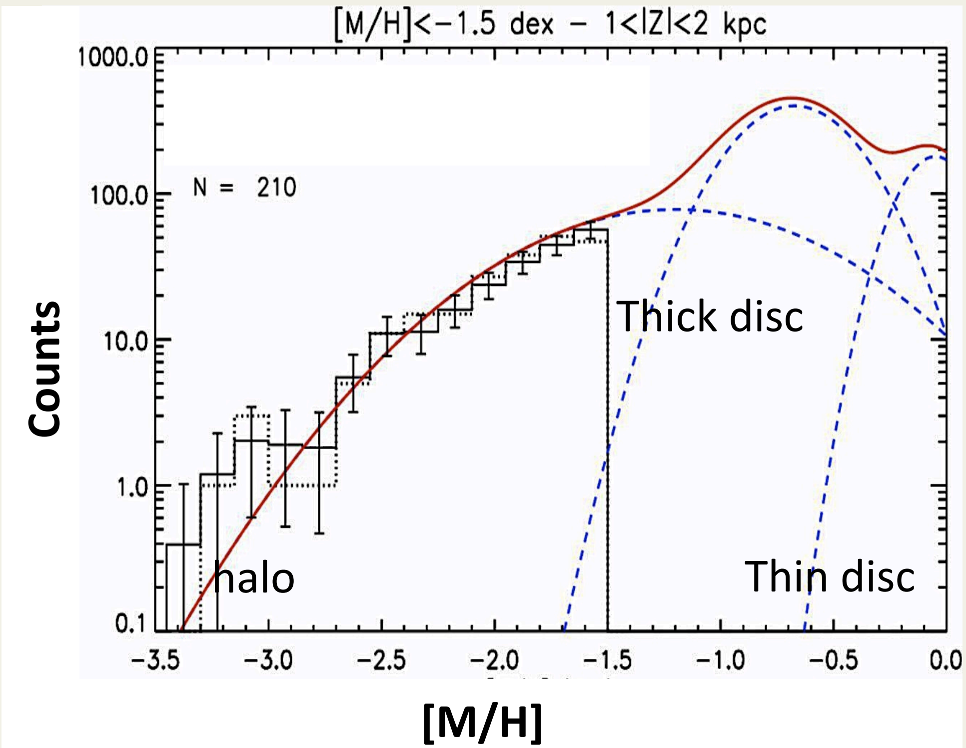
Papers

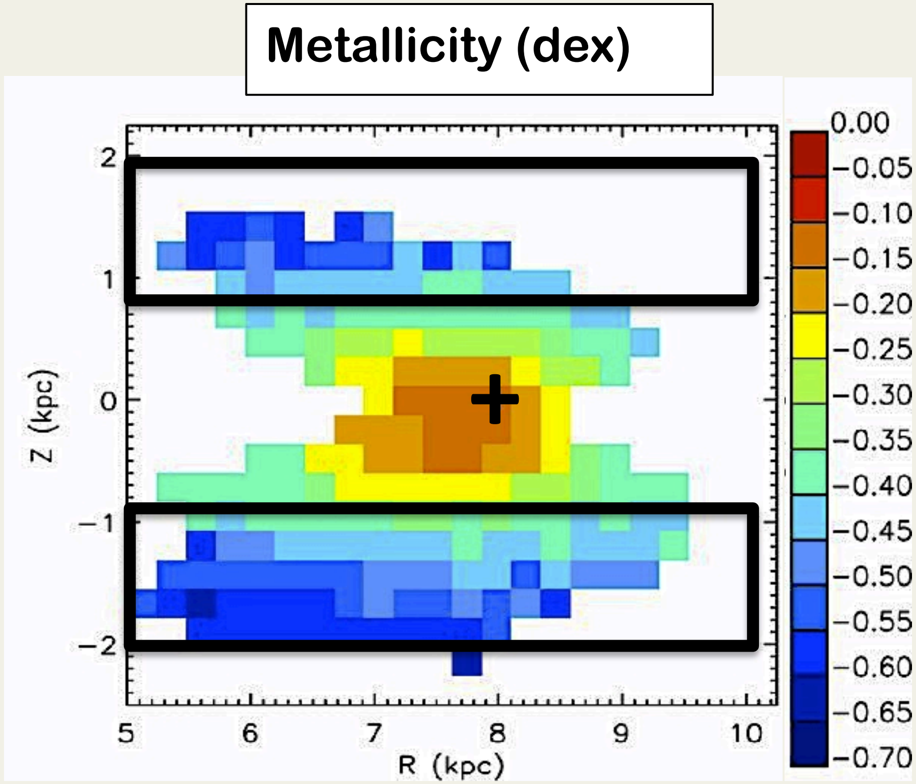
- DR4 (Kordopatis et al.)
- Distances (Binney et al.)
- Radial migration (Kordopatis et al.)
- Dynamics (Binney et al.)
- Gradients (Boeche et al.)
- Clusters (Conrad et al.)
- History (Minchev et al.)
- Metal-weak thick disc (Kordopatis et al.)
- MW escape speed & mass (Piffl et al.)
- DIB (Kos et al.)
- Chromospherically active stars (Zerjal et al.)
- Galactic bar (Antoja et al.)
- ….

THANK YOU

Metal-weak thick disc

Kordopatis et al. 2013c





Selection: 1<|Z|<2 kpc & [M/H] < -1.5 dex

Thick disc not expected

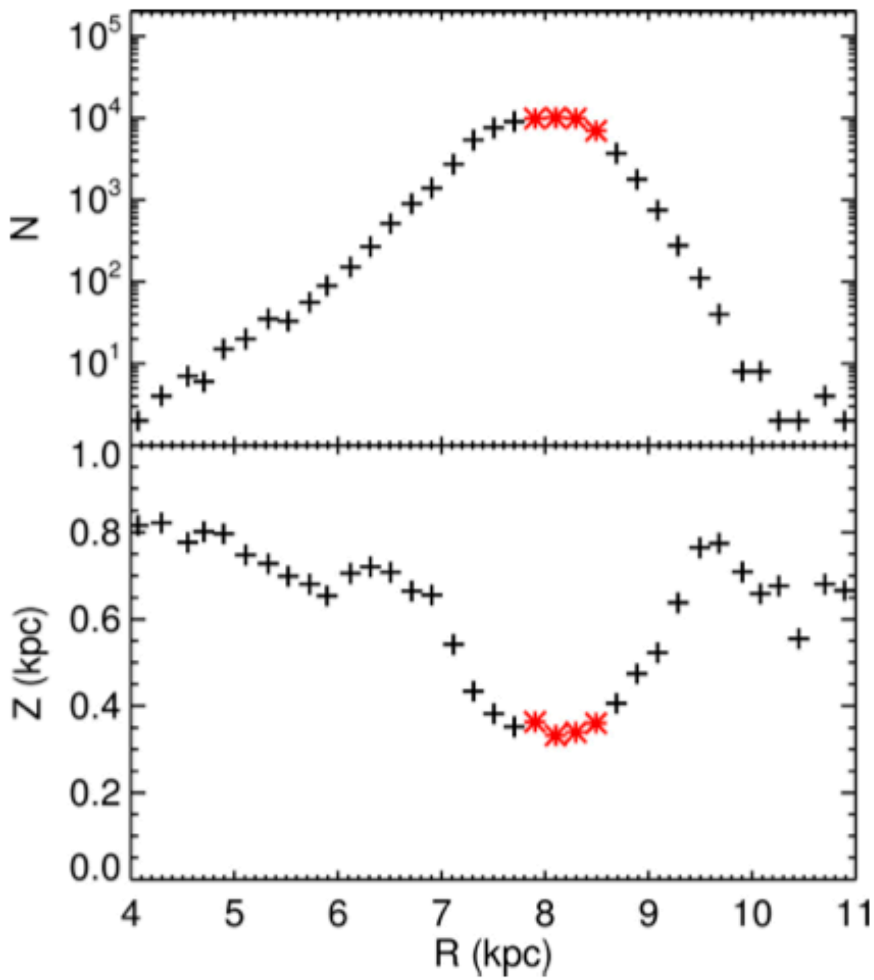


Fig. 9. Number of stars per bin in R (*top*) and median Z coordinate (*bottom*) as a function of R for the band selected in the RAVE DR4. The red asterisks are the bins used in our analysis.

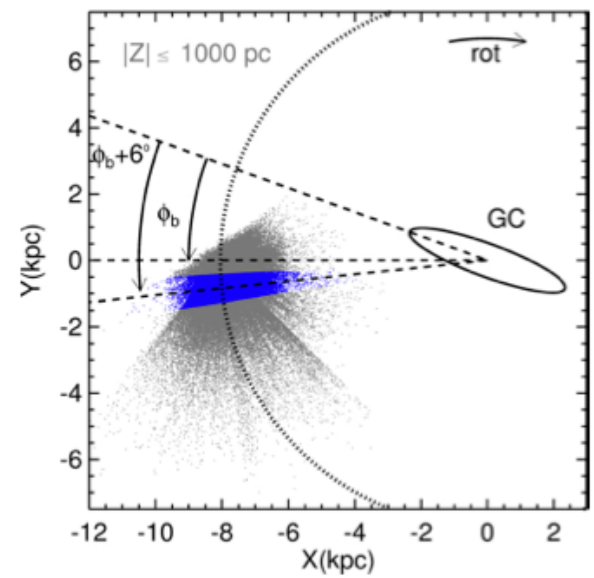
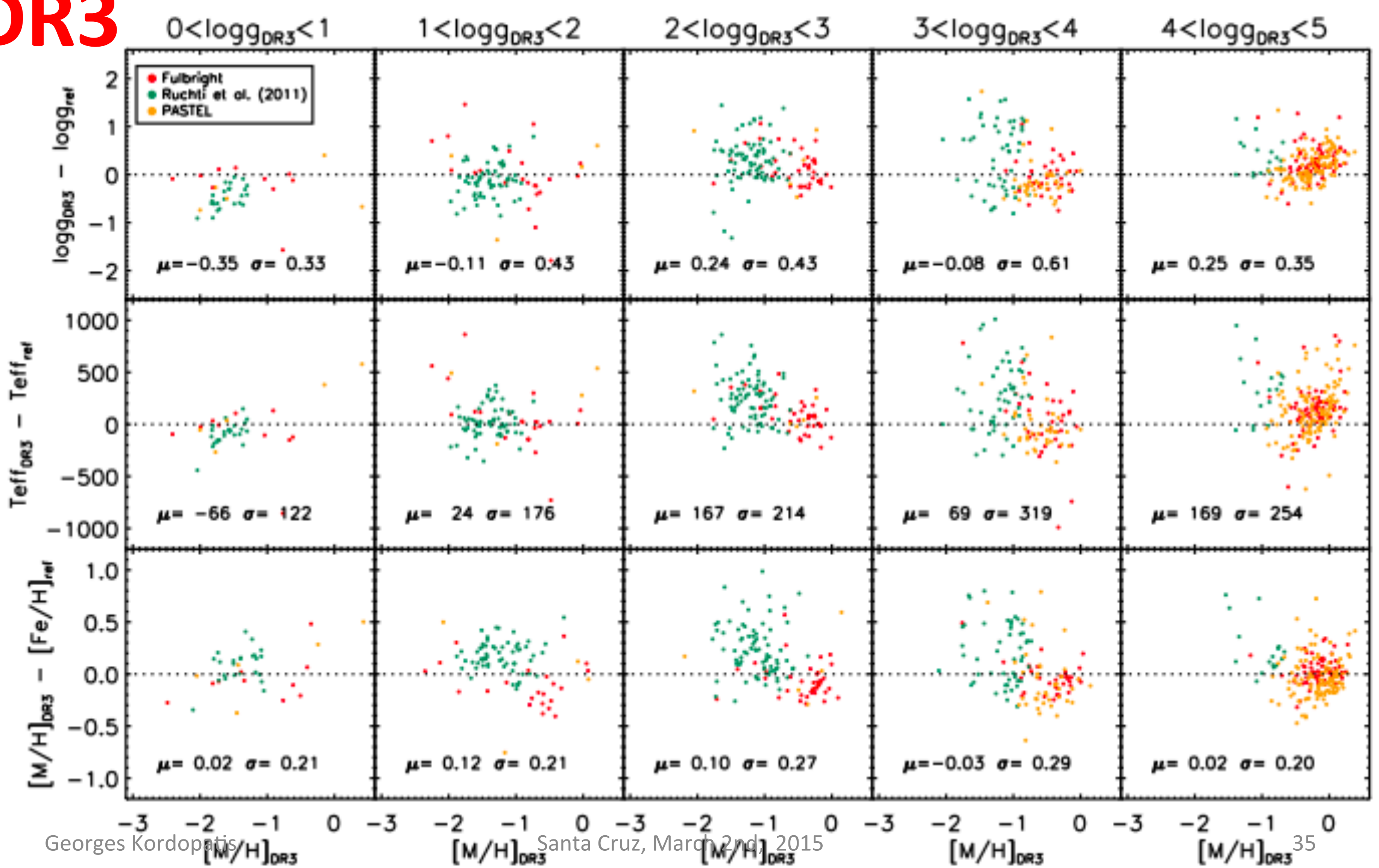


Fig. 8. Positions of the RAVE DR4 stars selected with $|Z| \leq 1$ kpc (grey dots) together with the stars selected in the band at $\phi_b + 6$ deg with respect to the bar (blue dots). The Sun is at $X = -8.05$ and $Y = 0$. A schematic bar with an (arbitrary) orientation of $\phi_b = 20$ deg is also shown.

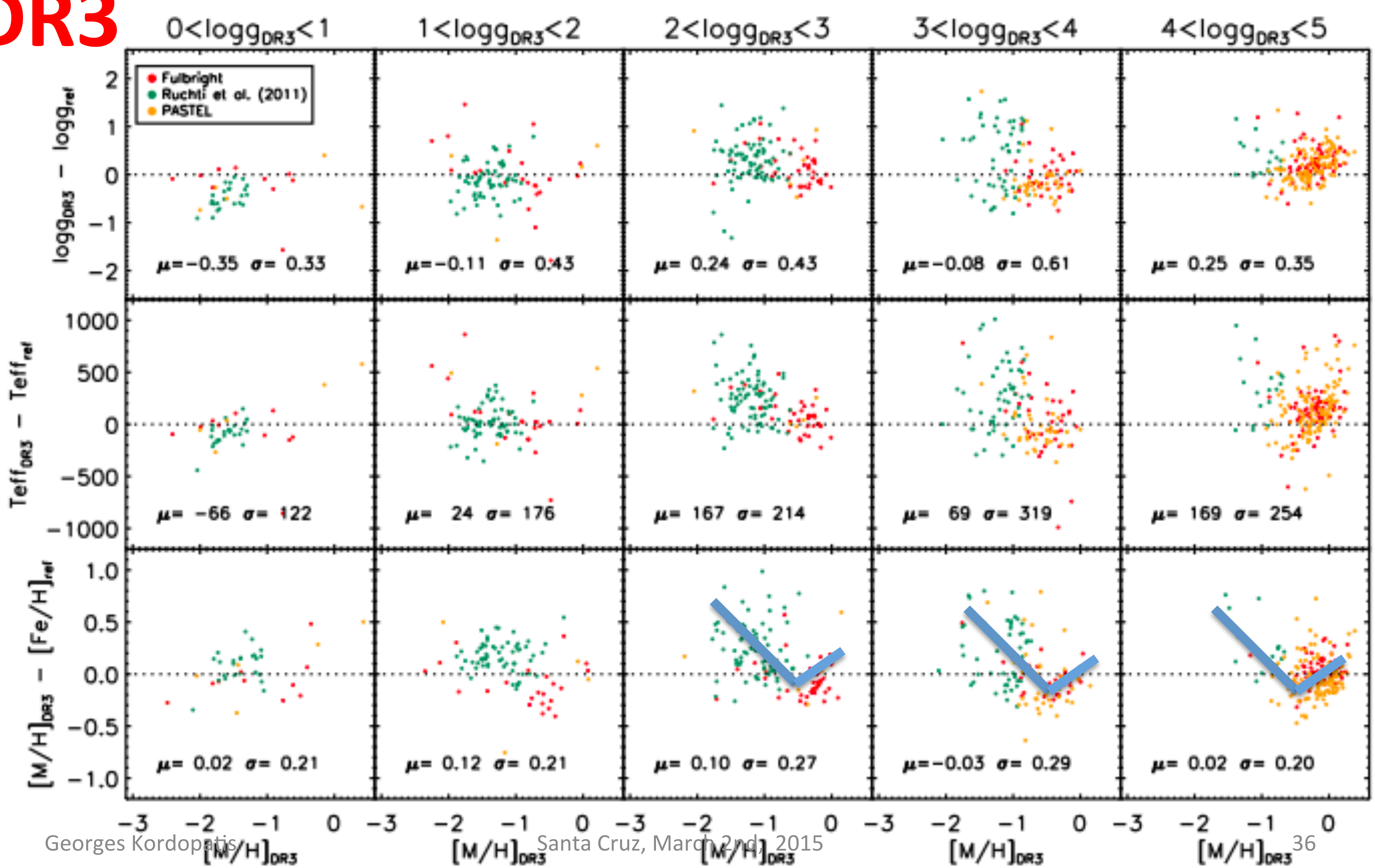
calibration issues & presence of biases

DR3

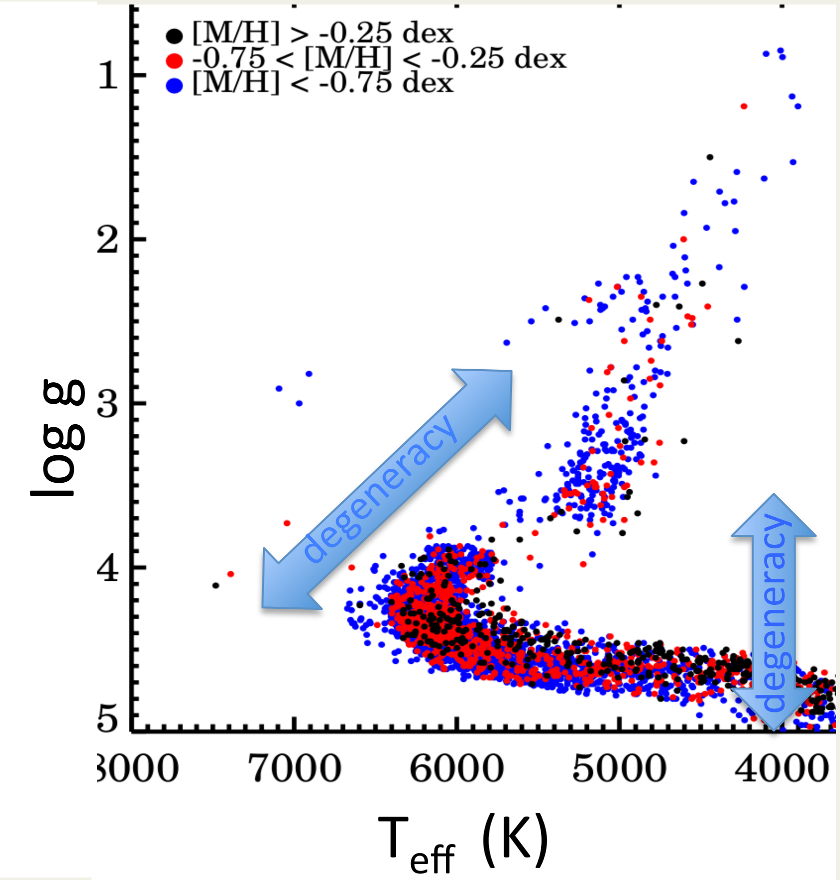


calibration issues & presence of biases

DR3



We want to minimise the effect of the degeneracies



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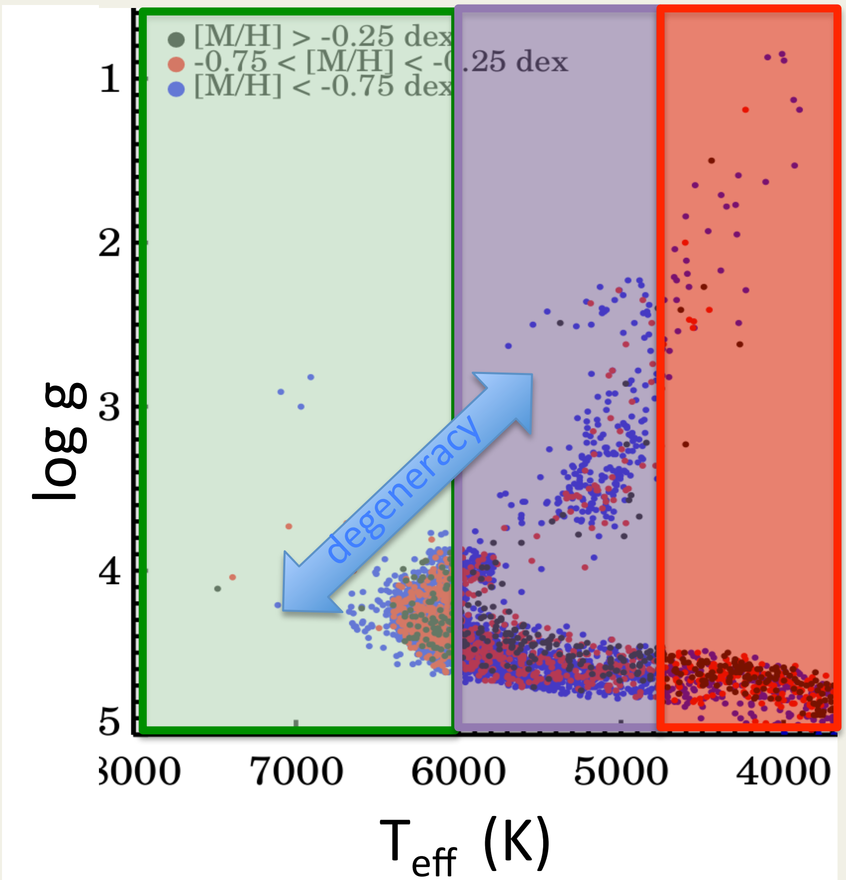
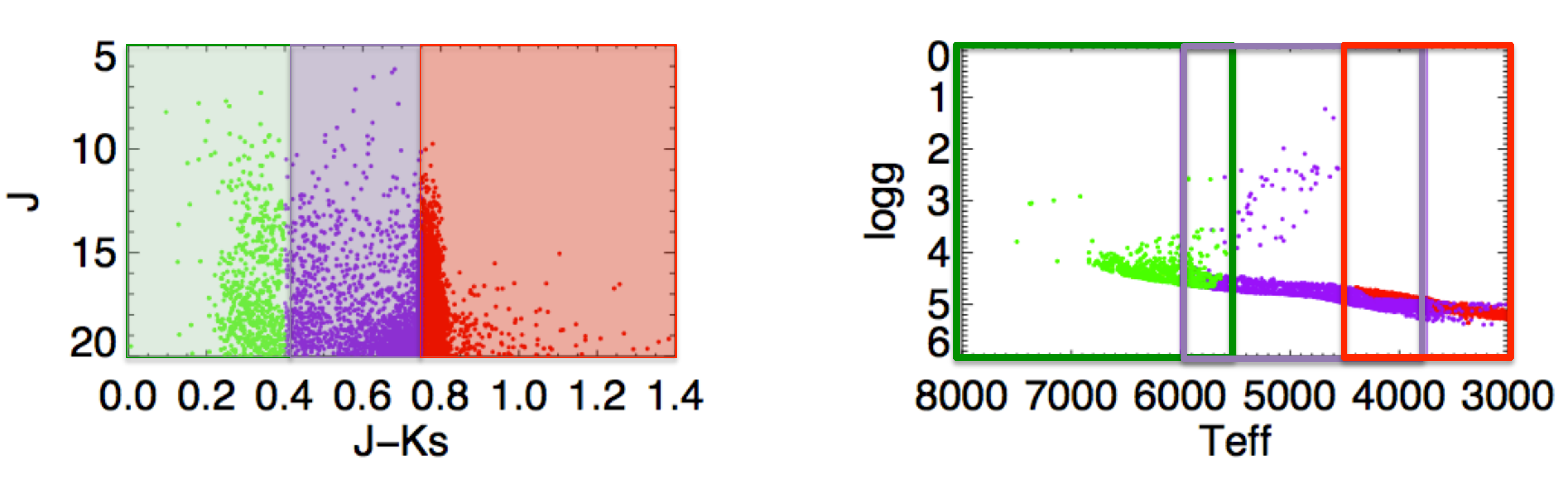


Goal:
Reduce the parameter space where the solution is searched

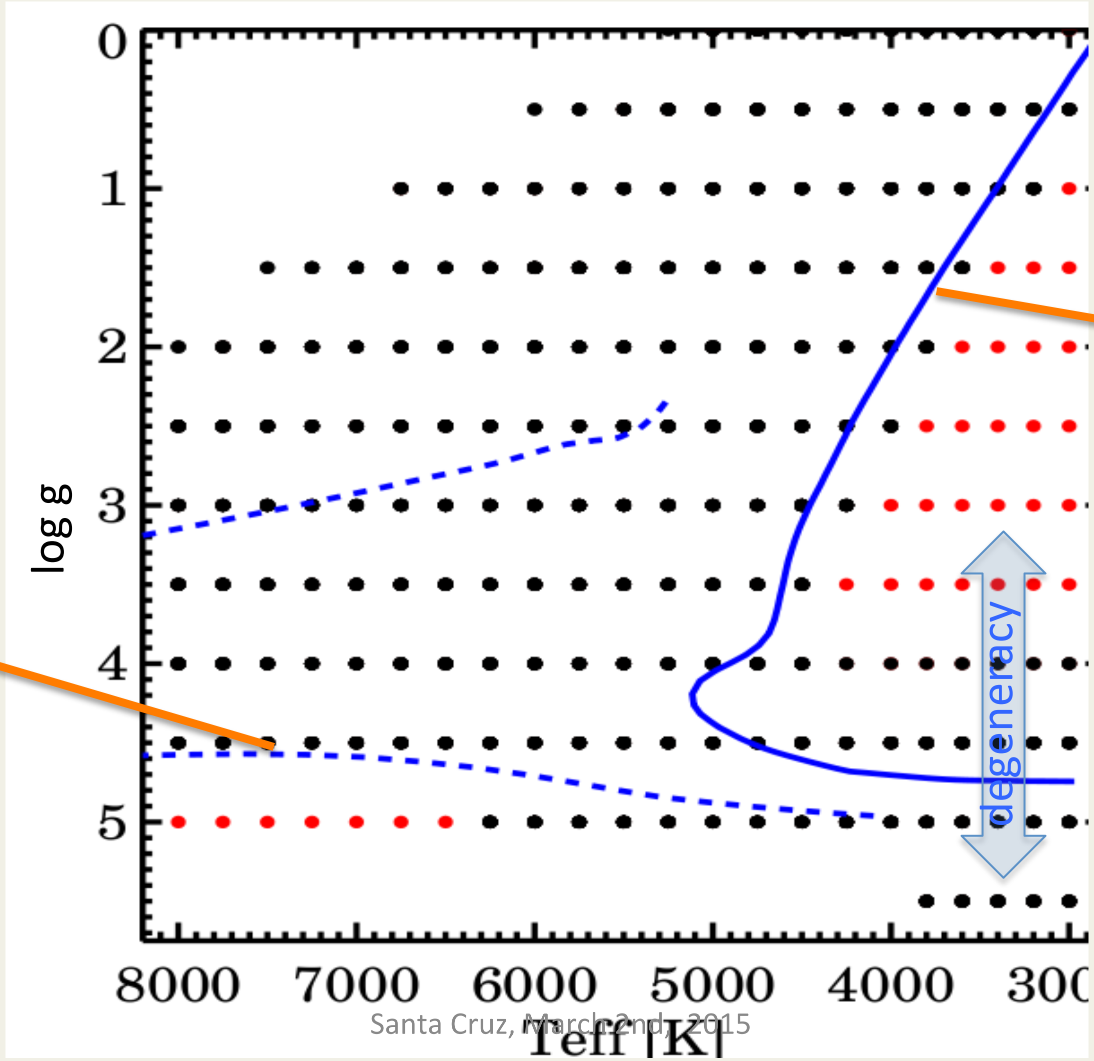
Reduce the parameter space => 1) Photometric prior

2MASS photometric temperature priors



- $(J\text{-}K_s) > 0.75$ ➔ $T_{eff} < 4500$ K
- $0.4 < (J\text{-}K_s) < 0.75$ ➔ $3750 < T_{eff} < 6000$ K
- $(J\text{-}K_s) < 0.4$ ➔ $T_{eff} > 5250$ K

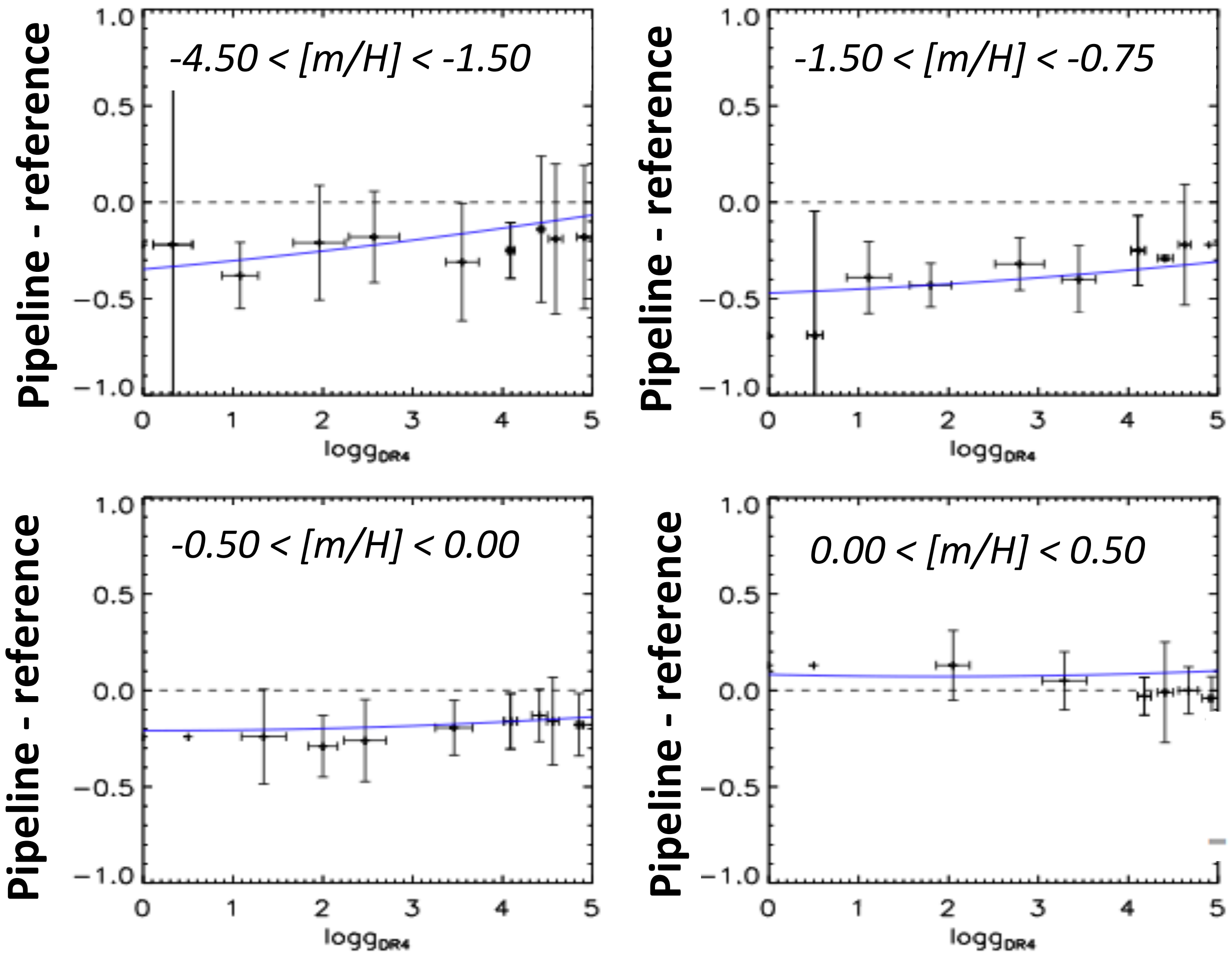
Reduce the parameter space => 2) non physical combinations



Age=14 Gyrs
[Fe/H]=0.3 dex

Age=0.3 Gyrs
[Fe/H]=-3 dex

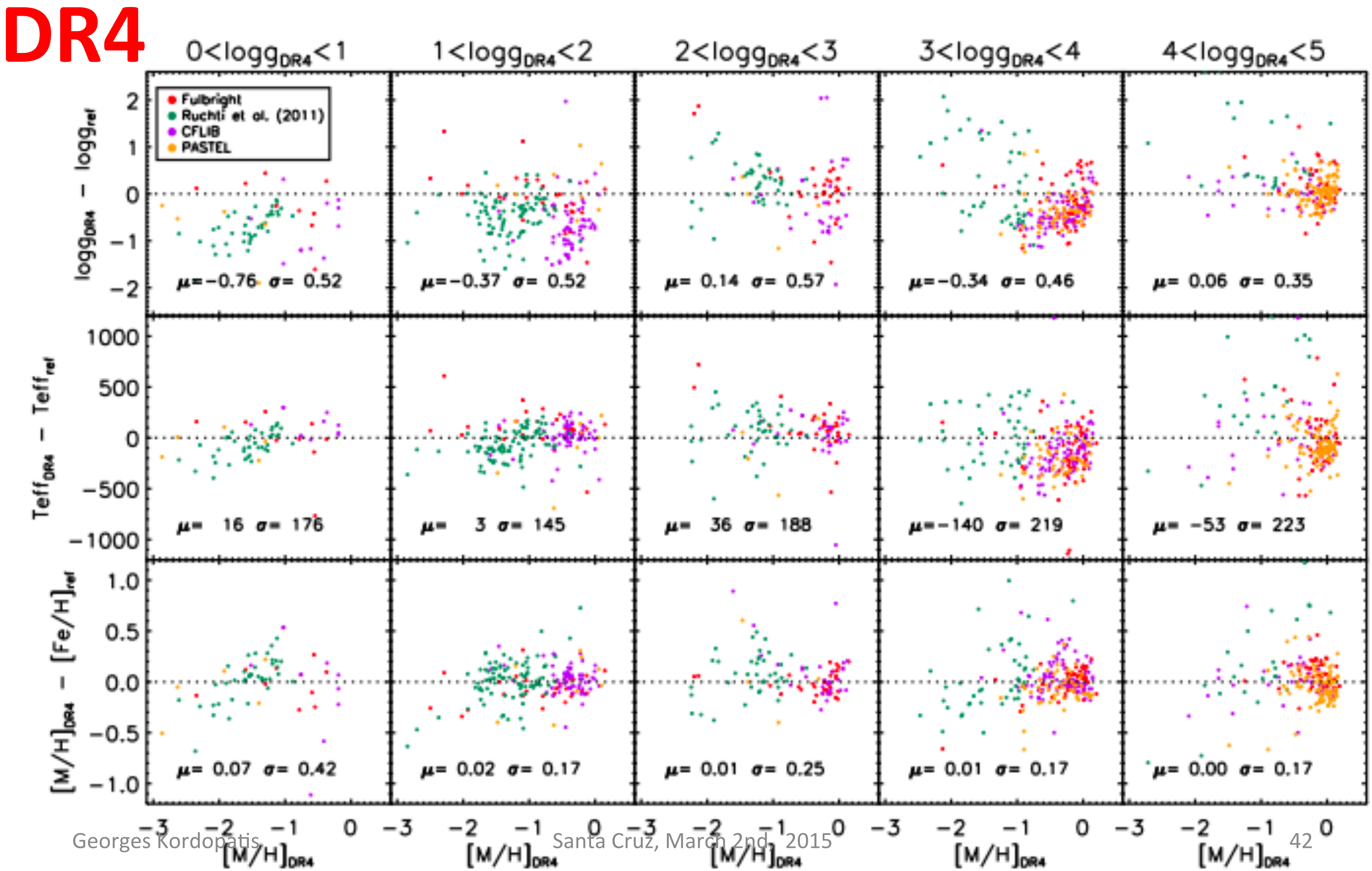
Calibration of the [M/H]



Calibration relation:

$$[\mathrm{m/H}]-[\mathrm{M/H}]_{\mathrm{ref}} = -0.076-0.006*\log g+0.003*\log^2 g$$
$$-0.021*[\mathrm{m/H}]*\log g+0.582*[\mathrm{m/H}]+0.205*[\mathrm{m/H}]^2.$$

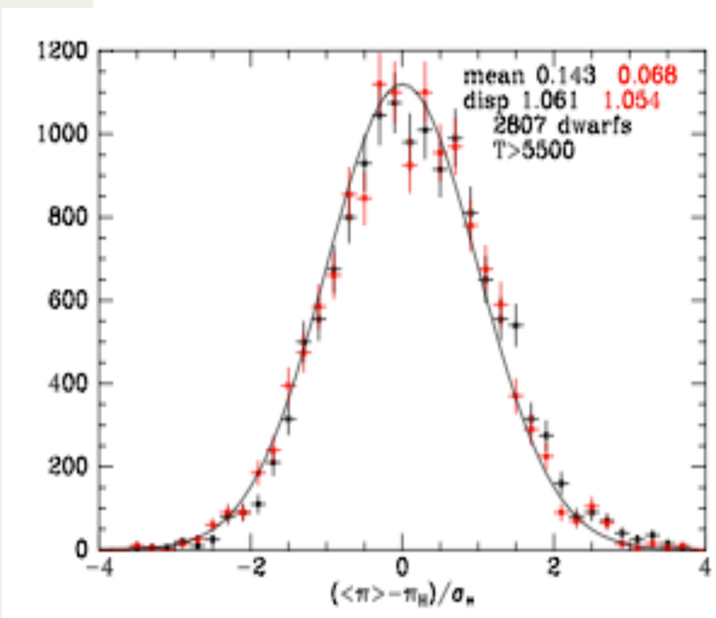
Validation of the calibration

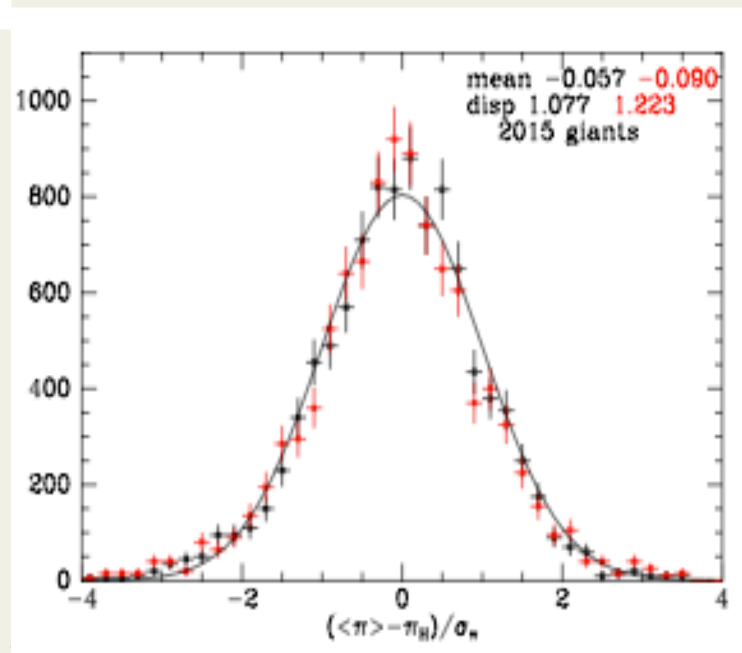


Stellar distances

- Bayesian projection of the Teff, logg, [M/H] on isochrones

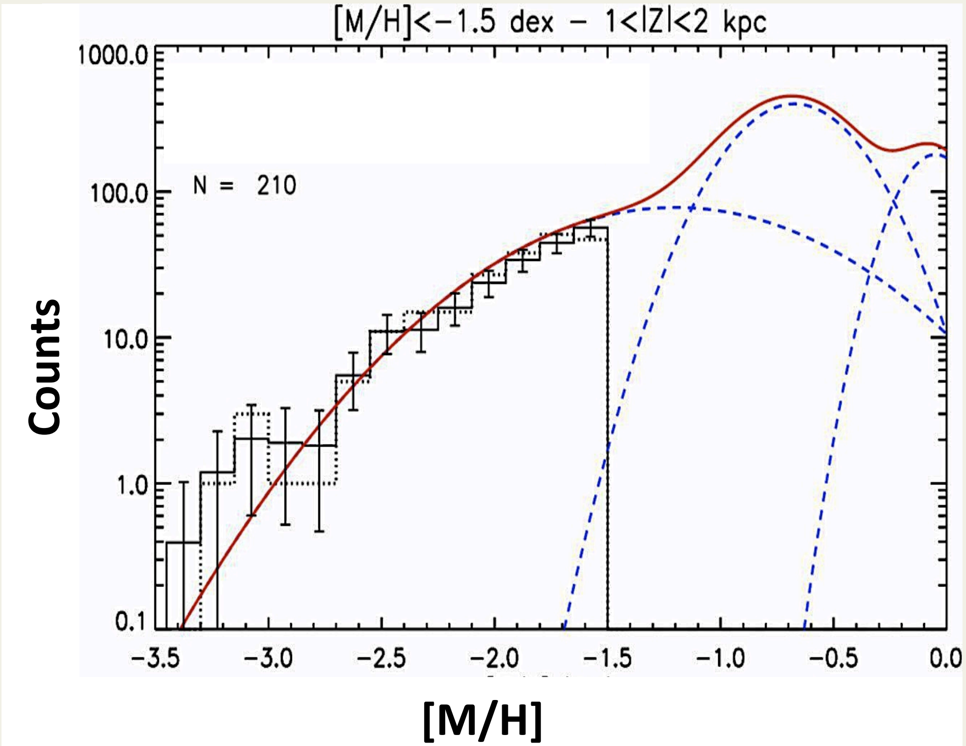
$$p(\text{model}) = p(\mathcal{M}) \sum_{i=1}^{3} p_i([M/H])\, p_i(\tau)\, p_i(\boldsymbol{r}),$$

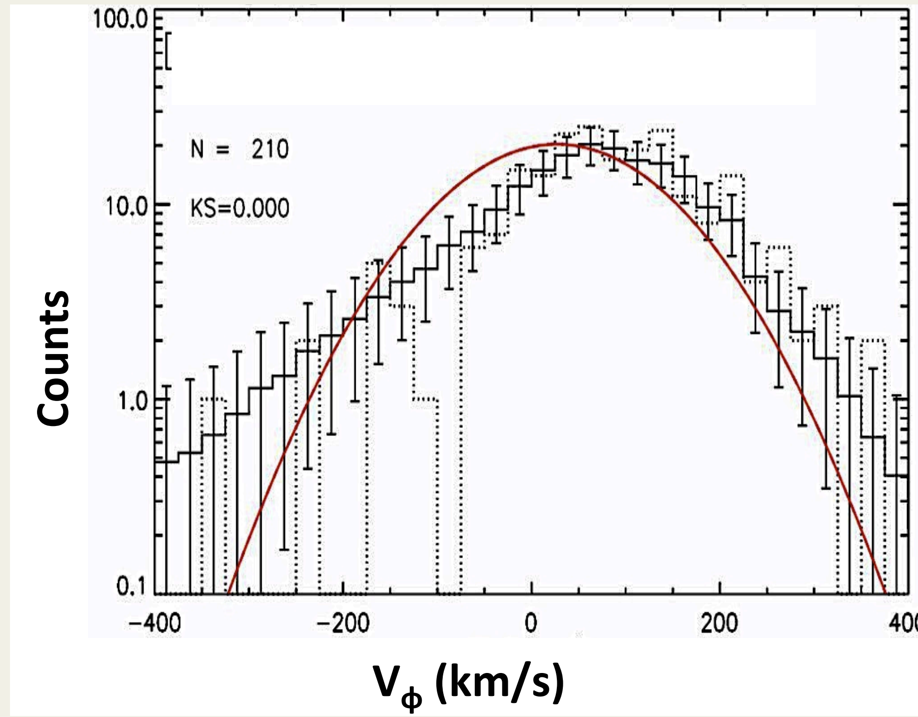




Metal-weak thick disc

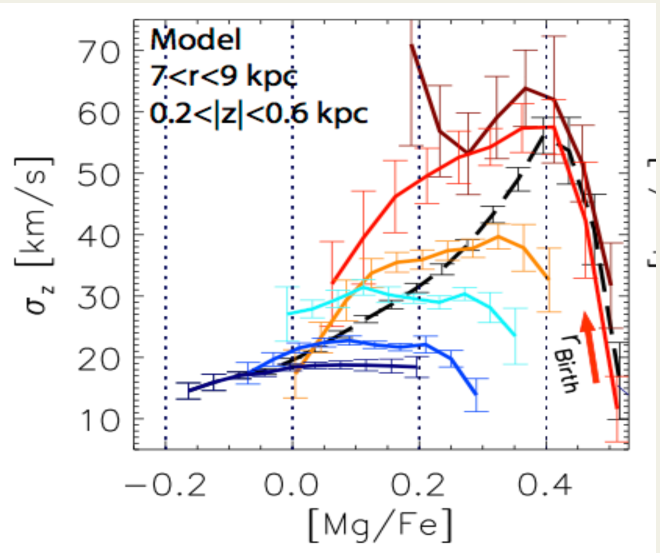
Kordopatis et al. 2013a,c





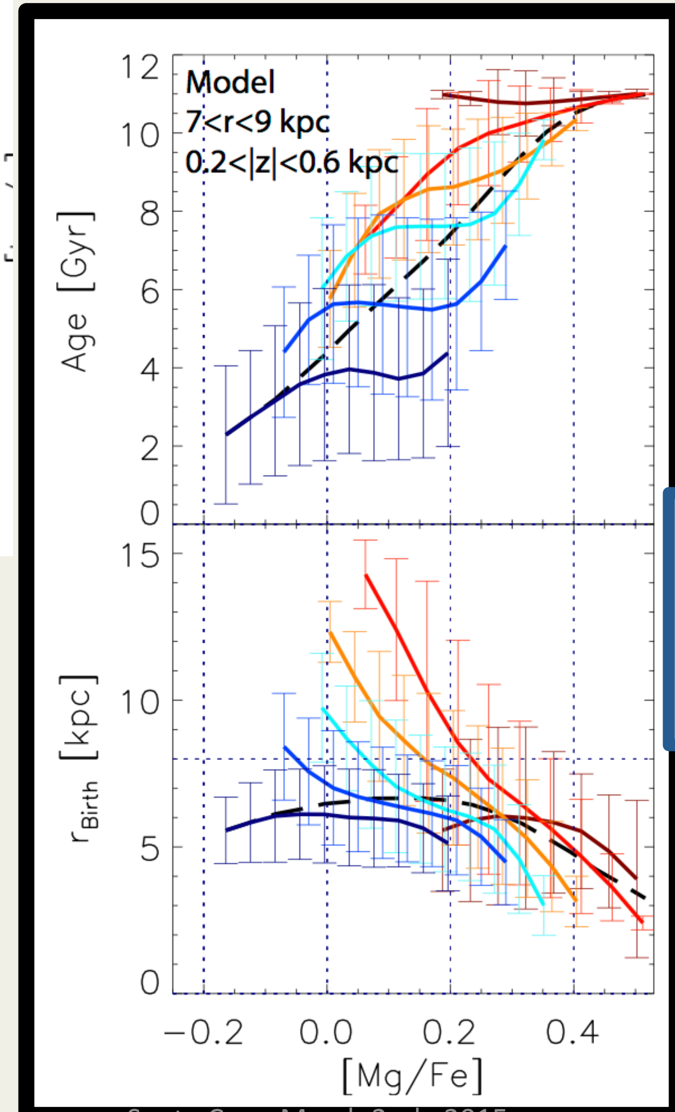
The halo alone <u>cannot</u> fit the data correctly

Signatures for a violent origin?



Minchev et al. 2014

[Fe/H]= -1.00 dex
[Fe/H]= -0.80 dex
[Fe/H]= -0.45 dex
[Fe/H]= -0.30 dex
[Fe/H]= -0.17 dex
[Fe/H]= -0.04 dex



The stars come progressively from small radii while having similar ages

Galactic escape speed

Piffl et al. 2014

Asymptotic behaviour of the stellar density of the high velocity stars (Leonard & Tremain 1990)

$$n(v) \propto (v_{\rm esc} - v)^k$$

$$\begin{aligned} n_{||}(v_{||} \mid \boldsymbol{r}, k) &\propto \int \mathrm{d}\boldsymbol{v}\, n(\boldsymbol{v} \mid \boldsymbol{r}, k)\delta(v_{||} - \boldsymbol{v} \cdot \hat{\boldsymbol{m}}) \\ &\propto \left(v_{\rm esc}(\boldsymbol{r}) - |v_{||}|\right)^{k+1} \end{aligned}$$