# 1)Kinematic Modelling of the Milky Way using RAVE and GCS.

# 2)Testing of Kepler Asteroseismic results against predictions of a stellar population synthesis based models of the Milky Way


***Sanjib Sharma***

***Joss Bland-Hawthorn***

***Dennis Stello***

***Daniel Huber***

***(University of Sydney, Australia)***

# Basic model of the Milky Way

- Assume galaxy in equilibrium and described by a DF
  - **$f_C$(r,v,t,m,Z)**
- Thin disc, Thick Disc, Stellar Halo, Bar-Bulge.
- **f(r,v,t,m,Z) ∝ p(r,t) p(m|t) p(Z|t) p(v|r,t)**
  - **position-age mass FeH velocity**
- The Besancon model (BGM).
  - **p(r,t) p(m|t) p(Z|t)** the main assumption

# The kinematic model: Gaussian distribution function

$$p(\mathbf{v}|\mathbf{r},\tau) = \frac{1}{\sigma_R\sigma_\phi\sigma_z(2\pi)^{3/2}} \exp\left(-\frac{v_R^2}{2\sigma_R^2}\right) \exp\left(-\frac{v_z^2}{2\sigma_z^2}\right) \times \exp\left(-\frac{(v_\phi - \overline{v_\phi})^2}{2\sigma_\phi^2}\right) \quad (1)$$

## Age Velocity dispersion (AVR)

$$\sigma_{R,\phi,z}^{\text{thin}}(R,\tau) = \sigma_{R,\phi,z,\odot}^{\text{thin}} \exp\left[-\frac{R-R_0}{R_\sigma^{\text{thin}}}\right] \times \left(\frac{\tau+\tau_{\text{min}}}{\tau_{\text{max}}+\tau_{\text{min}}}\right)^{\beta_{R,\phi,z}}$$

$$\sigma_{R,\phi,z}^{\text{thick}}(R) = \sigma_{R,\phi,z,\odot}^{\text{thick}} \exp\left[-\frac{R-R_0}{R_\sigma^{\text{thick}}}\right]$$

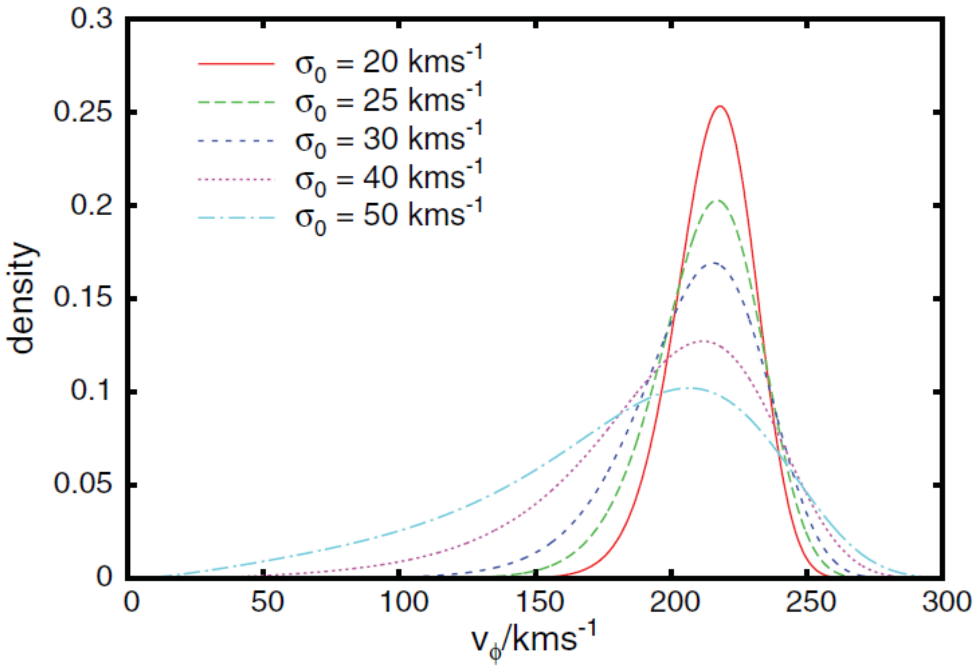
## Asymmetric Drift

$$\overline{v_\phi}^2(\tau,R) = v_{\text{circ}}^2(R) + \sigma_R^2 \times \left(\frac{d\ln\rho}{d\ln R} + \frac{d\ln\sigma_\phi^2}{d\ln R} + 1 - \frac{\sigma_\phi^2}{\sigma_R^2} + 1 - \frac{\sigma_z^2}{\sigma_R^2}\right) (2)$$

# The kinematic model: The Shu distribution function

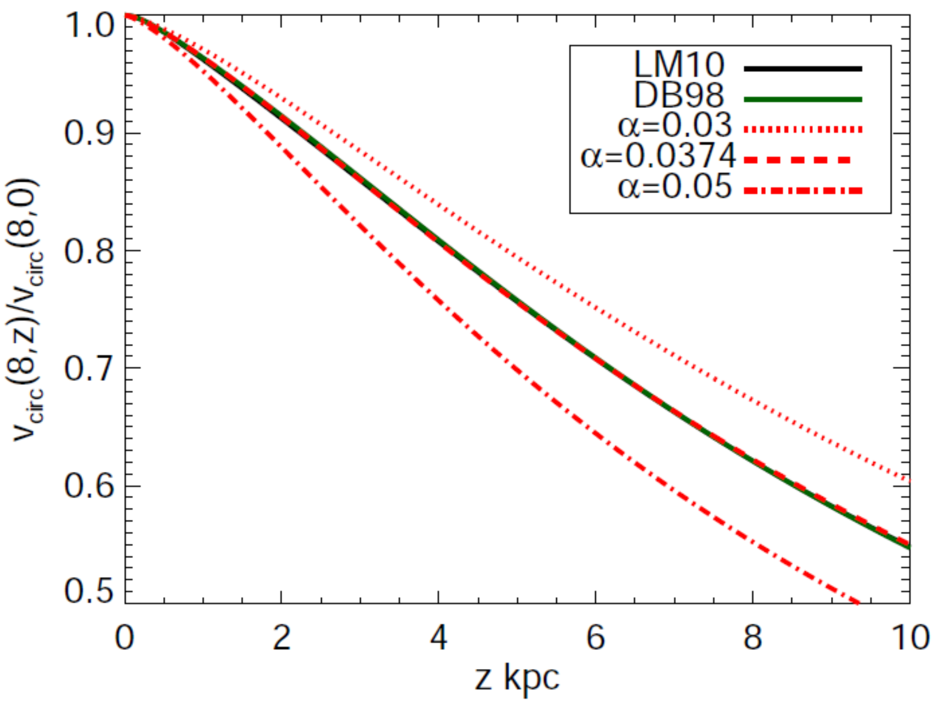
$$f(E_R, L, v_z) = \frac{F(L)}{\sigma^2(L)} e^{-E_R/\sigma^2(L)} \frac{e^{-v_z^2/\sigma_z^2}}{\sigma_z\sqrt{2\pi}}$$

- **$L$** is angular momentum,
- **$E_R = E - E_c(L)$** is the energy in excess of that required for circular motion with a given **$L$**.
- Naturally handles asymmetric distribution.
- Note vertical and planar motion are decoupled, potential separable in **$\Phi(R,z)=\Phi(R)+\Phi(z)$**.



# Vertical dependence of kinematics

- $V_c(R,z)=[v_0+\alpha_R(R-R_\odot)]\,[1/(1+\alpha_z(z/kpc)^{1.34})]$

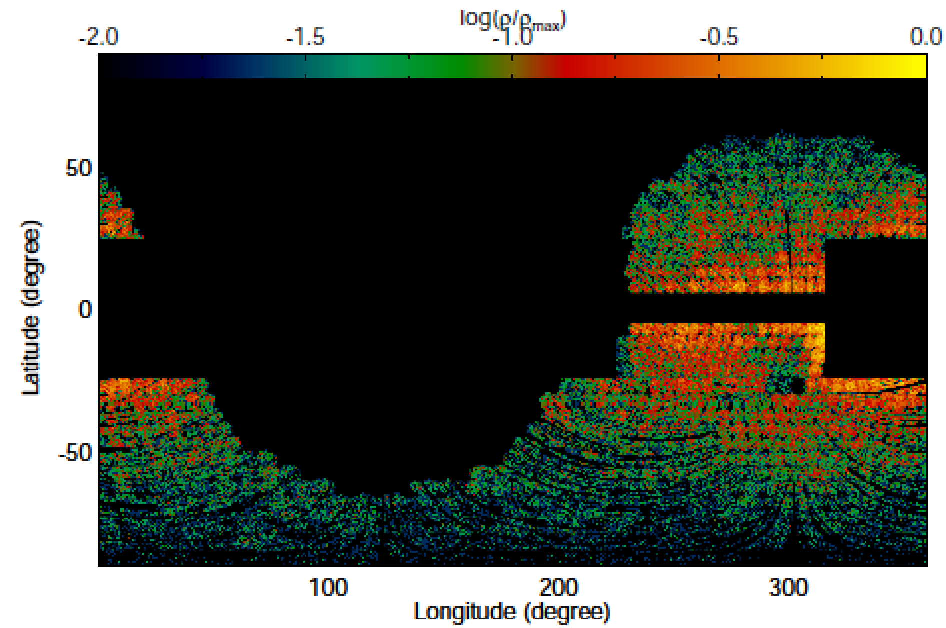



- For circular velocity $V_c$ , models of Milky Way's 3D potential predict **$\alpha_z$ ~ 0.0374**
- Asymmetric drift also has a dependence on **z**.
  - we expect **$\alpha_z$ > 0.0374**

# Kinematic analysis using RAVE and GCS

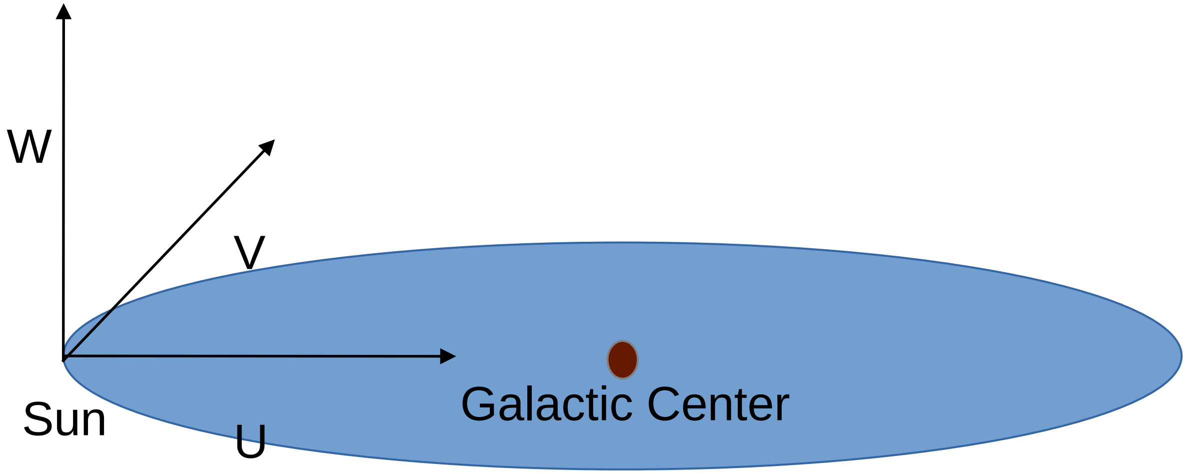
- GCS: A color magnitude limited sample of stars with (x,v).
  - Very local 120 pc. (about 5000 stars)

- RAVE a spectroscopic survey with accurate, $(l,b,v_{los})$.
  - 1- 2kpc (about 500,000 stars)
- $\mathbf{p(\theta \mid l,b,v_{los}) \sim p(l,b,v_{los} \mid \theta)\, p(\theta)}$
- No use of proper motion or distances
- No use of **J-K, $T_{eff}$, log g**



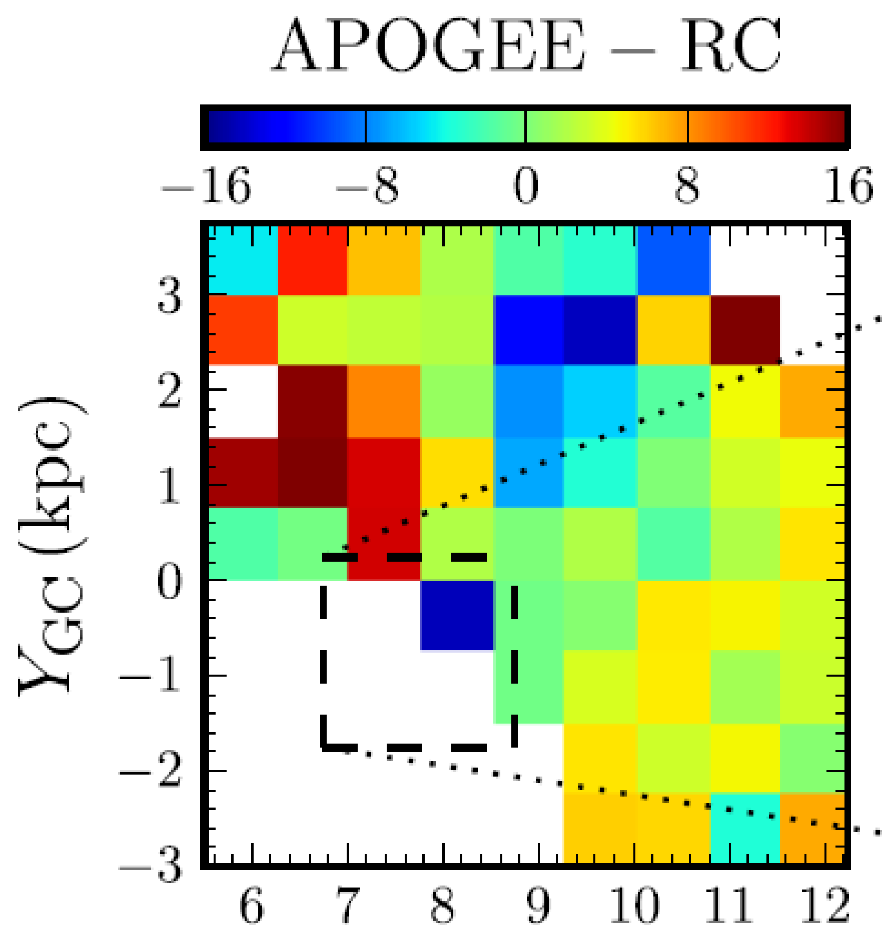
# Questions?

- Is the Gaussian model correct?
- What are the correlations between different parameters?
- Does GCS and RAVE give similar values?
- What are $U_{\odot}, V_{\odot}, W_{\odot}, v_c(R_{\odot})$ ?
- Schonrich et al (2010) (11.1, 12.24, 7.25) km/s, 220+- 30 km/s



# Proper motion of Sgr A*

- $V_c$ , $V_\odot$ and $R_\odot$ are difficult to measure but
  - $\Omega_\odot=(V_c+V_\odot)/R_\odot$ ~ 30.24 km/s/kpc (Reid & Brunthaler 2004).
  - For $R_\odot$=8.0 kpc, $(V_c+V_\odot)$ ~ 242 km/s
- Bovy et al (2012,2014) using APOGEE data find,
  - $V_c$=218 (+- 6) km/s, $V_\odot$ = 26 (+- 3) km/s,
  - $R_\sigma^{thin}$ negative.
  - Since local V ~

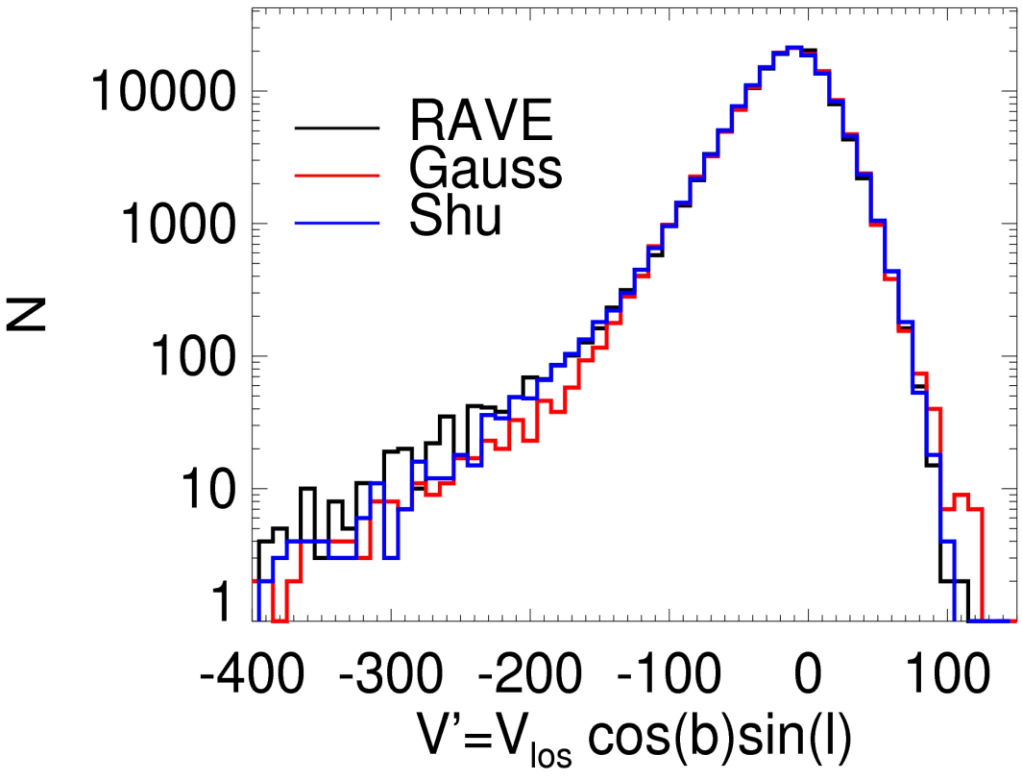



Bovy et al 2014

# Problems with Gaussian models

- In Gaussian models $R_\sigma^{thin}$ is strongly correlated with $V_\odot$.
- Moreover, for RAVE data $R_\sigma^{thin}$ is negative while for GCS data it is positive.
- The Gaussian model gives inconsistent results when applied to RAVE and GCS data sets, because it is not a good description of the data.

The Gaussian model fails to properly fit the wings of the distribution.



# Best fit parameters for the Shu model

| Model | RAVE SHU | RAVE SHU | GCS SHU |
|---|---|---|---|
| $U_\odot$ | $11.2^{+0.13}_{-0.13}$ | $10.92^{+0.13}_{-0.14}$ | $10.16^{+0.39}_{-0.4}$ |
| $V_\odot$ | $9.71^{+0.12}_{-0.11}$ | $7.53^{+0.16}_{-0.16}$ | $9.81^{+0.28}_{-0.28}$ |
| $W_\odot$ | $7.536^{+0.085}_{-0.086}$ | $7.542^{+0.089}_{-0.093}$ | $7.13^{+0.18}_{-0.19}$ |
| $\sigma_R^{thin}$ | $42.37^{+0.61}_{-0.66}$ | $39.78^{+0.81}_{-0.73}$ | $39.99^{+0.91}_{-0.91}$ |
| $\sigma_z^{thin}$ | $26.85^{+0.85}_{-0.92}$ | $24.7^{+0.66}_{-0.66}$ | $23.63^{+0.85}_{-0.8}$ |
| $\sigma_R^{thick}$ | $38.84^{+1.2}_{-0.96}$ | $42.31^{+1}_{-0.9}$ | $45.9^{+1.8}_{-1.8}$ |
| $\sigma_z^{thick}$ | $29.15^{+0.87}_{-0.79}$ | $34.66^{+0.61}_{-0.58}$ | $32.6^{+2.3}_{-2.2}$ |
| $\beta_R$ | $0.236^{+0.011}_{-0.011}$ | $0.198^{+0.014}_{-0.014}$ | $0.237^{+0.013}_{-0.013}$ |
| $\beta_z$ | $0.398^{+0.03}_{-0.029}$ | $0.328^{+0.027}_{-0.024}$ | $0.366^{+0.021}_{-0.021}$ |
| $1/R_\sigma^{thin}$ | $0.0673^{+0.0028}_{-0.0028}$ | $0.0722^{+0.0035}_{-0.0032}$ | 0.073 |
| $1/R_\sigma^{thick}$ | $0.1555^{+0.0046}_{-0.0064}$ | $0.1335^{+0.0046}_{-0.0056}$ | 0.132 |
| $\Theta_0$ | $212.6^{+1.4}_{-1.3}$ | $232.8^{+1.7}_{-1.6}$ | 232 |
| $R_0$ | 8 | 8 | 8 |
| $\alpha_z$ | 0 | $0.048^{+0.0019}_{-0.0018}$ | 0.0471 |
| $\alpha_R$ | 0 | 0 | 0 |
| $\chi^2_{red}$ RAVE | 1.52 | 1.43 | 1.80 |
| $\chi^2_{red}$ GCS | 5.15 | 5.57 | 3.86 |

$\alpha_z$ free makes $v_c$ go up.

232.8+7.53=240.33 km/s.

GCS and RAVE also match,

$\sigma_R$ similar for thin and thick

Quantities in magenta were kept fixed during fitting. Units are in km/s and kpc

# Conclusions

- Deficiency of a Gaussian model is clearly exposed by RAVE data
  - (high $V_{\odot}$ ,negative $R_{\sigma}^{thin}$) upto 5 km/s
- For RAVE, we get $\Omega_{\odot}=(V_c+V_{\odot})/R_{\odot}$ ~ **30.04** km/s/kpc in good agreement with Sgr A* proper motion of **30.24.**

- Neglecting vertical dependence of kinematics can lead to underestimation of $V_c$ by about 20 km/s.

- Using only ($l,b,v_{los}$) data from RAVE survey we obtain
  - good constraints on a number of kinematic parameters of the Milky Way.
- The best fit RAVE model also fits the GCS data well.
- In future, we need a self-consistent dynamical model for more robust analysis.

# Comparing Asteroseismic results of Kepler with theoretical models

- Data:
  - Red Giants sample of 13,000 stars
  - Sub Giant Sample of 400 stars, Chaplin et al (2011)
  - Oscillation frequencies $\nu_{max}$ and $\Delta\nu$
- Model:
  - The **GALAXIA** code (**http://galaxia.sourceforge.net**)
  - Besancon style model
  - Padova Isochrones
- Method:
  - Generate model stars
  - Predict KIC stellar parameters from photometry
  - Apply selection function to sample stars from the model

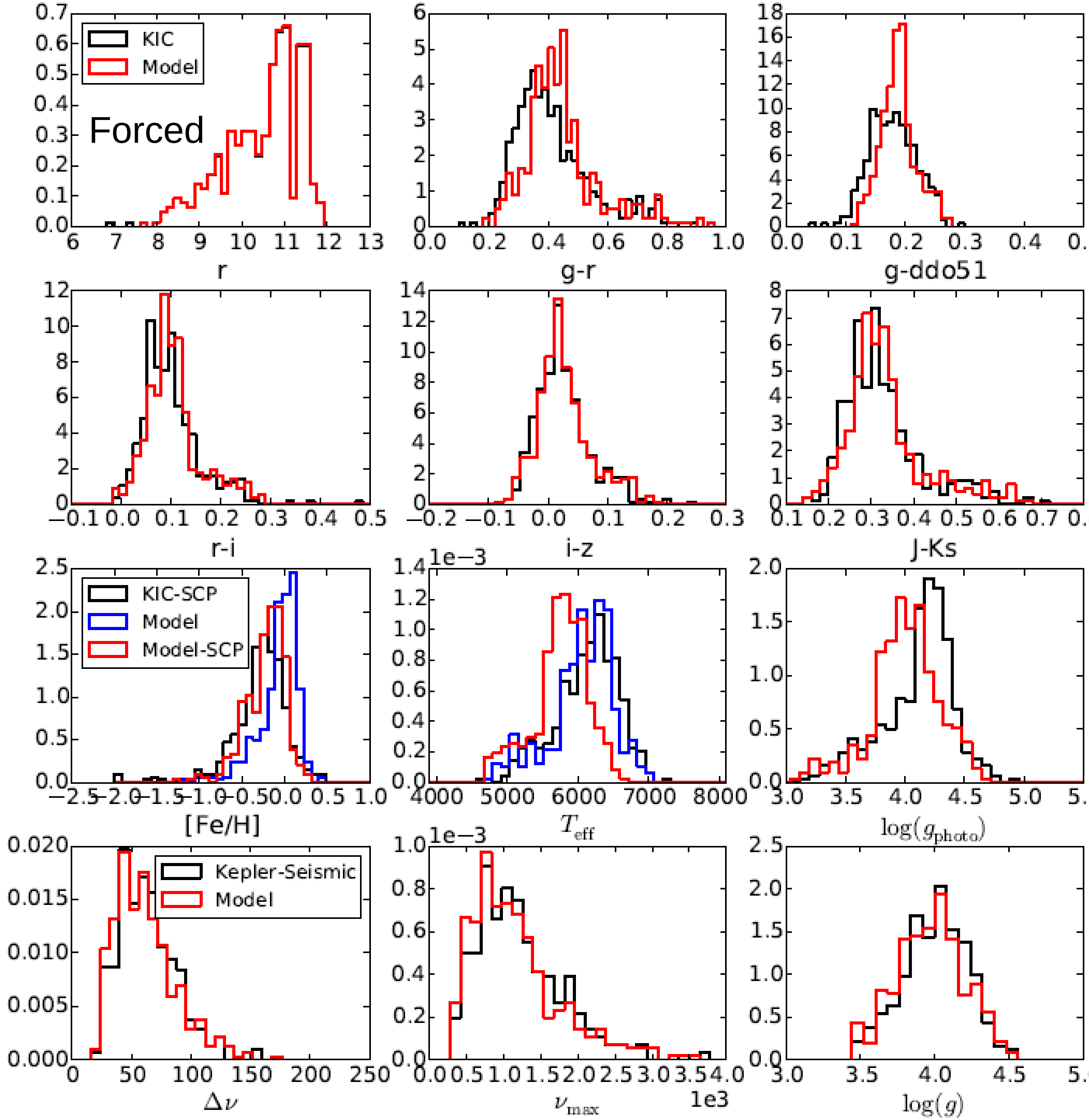
# Sub-giant Sample

Photometry

Photometry

Stellar parameters

Asteroseismic Frequencies



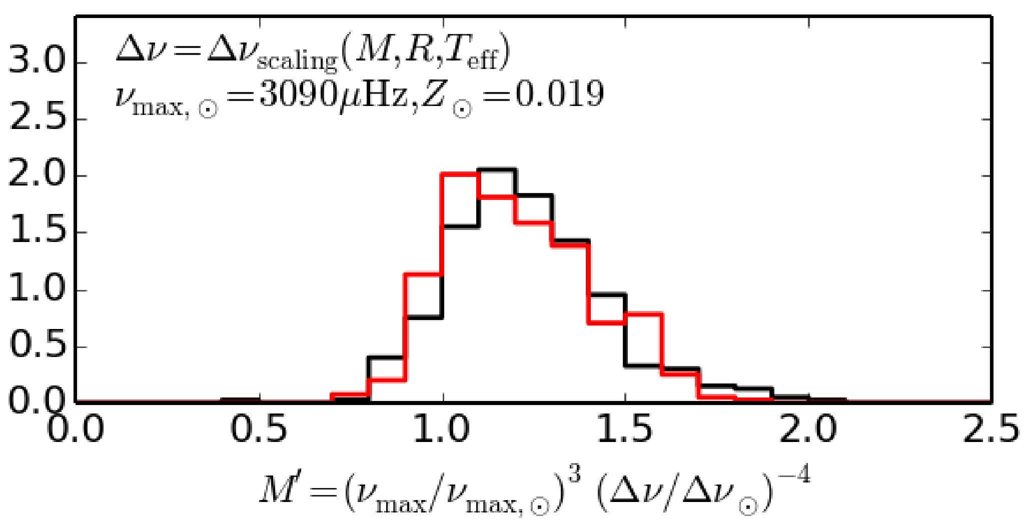

$\Delta\nu$ $\nu_{max}$ $\log g_{seism}$

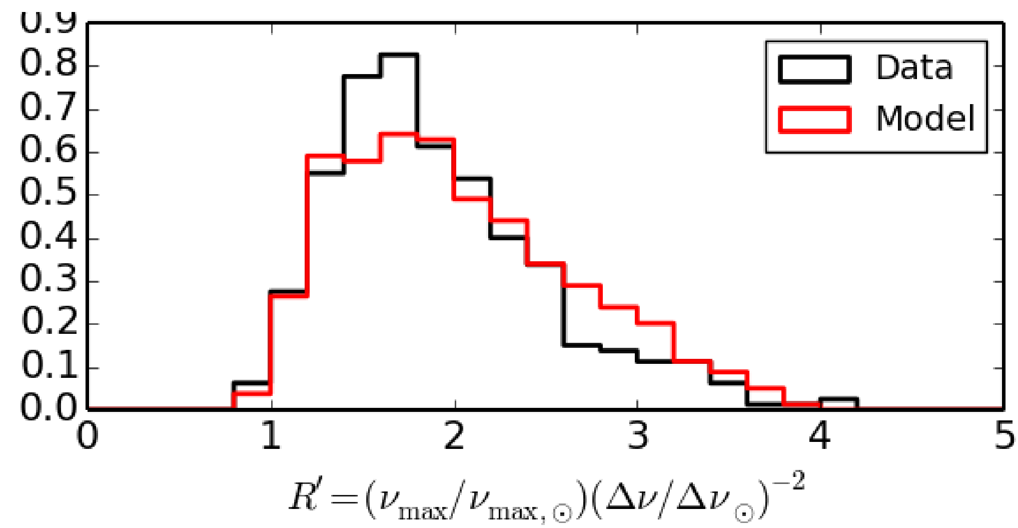
# Distribution of mass M and radius R of sub-giants

Proxy M and R

We do not know $T_{eff}$ of KIC stars.

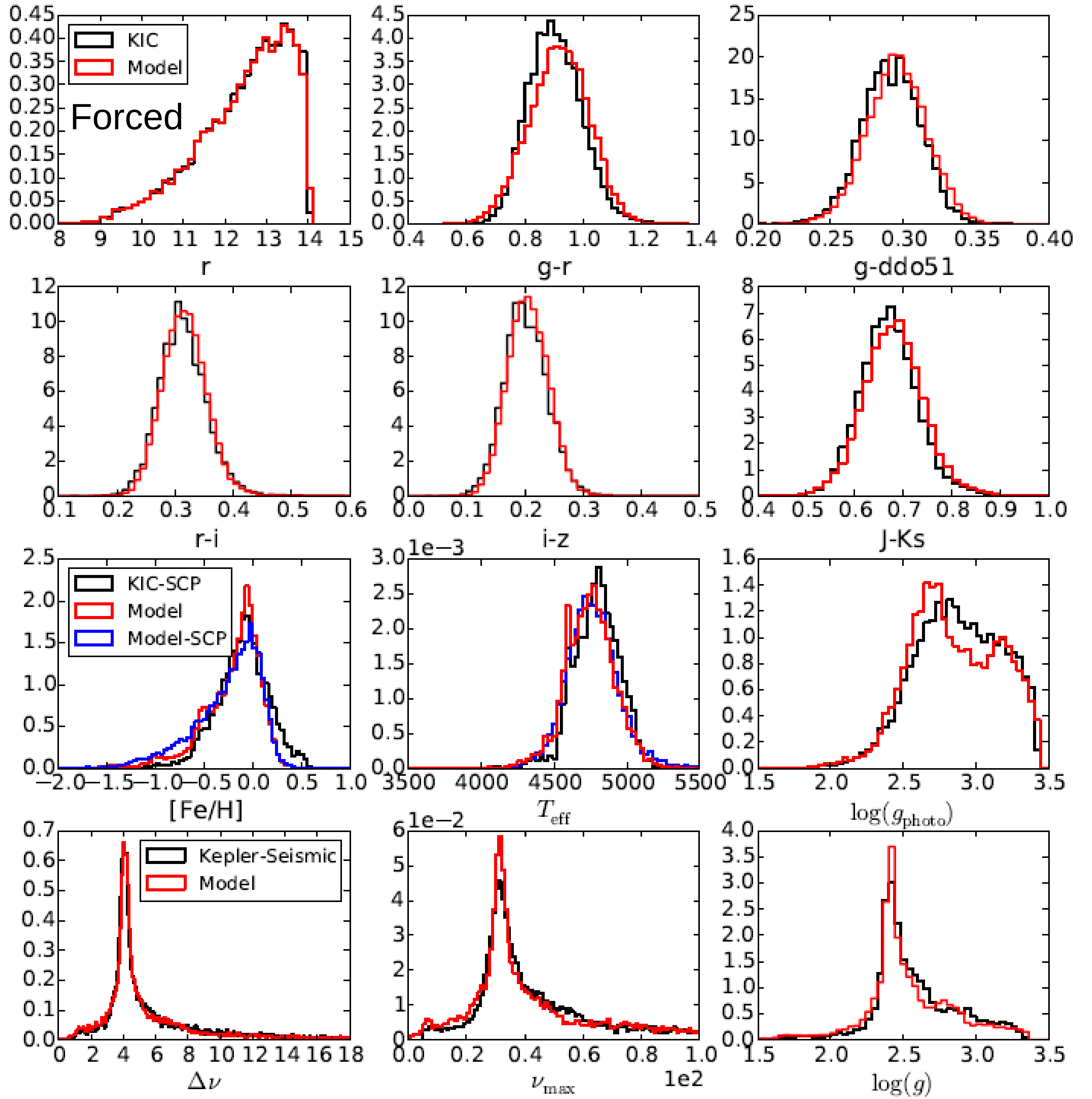
Unlike Chaplin et al (2011) no mismatch of p(m)




$M' = (v_{max}/v_{max,Sun})^3/(\Delta v/\Delta v_{Sun})^4$  $R' = (v_{max}/v_{max,Sun})/(\Delta v/\Delta v_{Sun})^2$

# Red-giant Sample




Photometry

Photometry

Stellar parameters

Asteroseismic Frequencies

$\Delta\nu$ $\quad$ $\nu_{max}$ $\quad$ $\log g_{seism}$

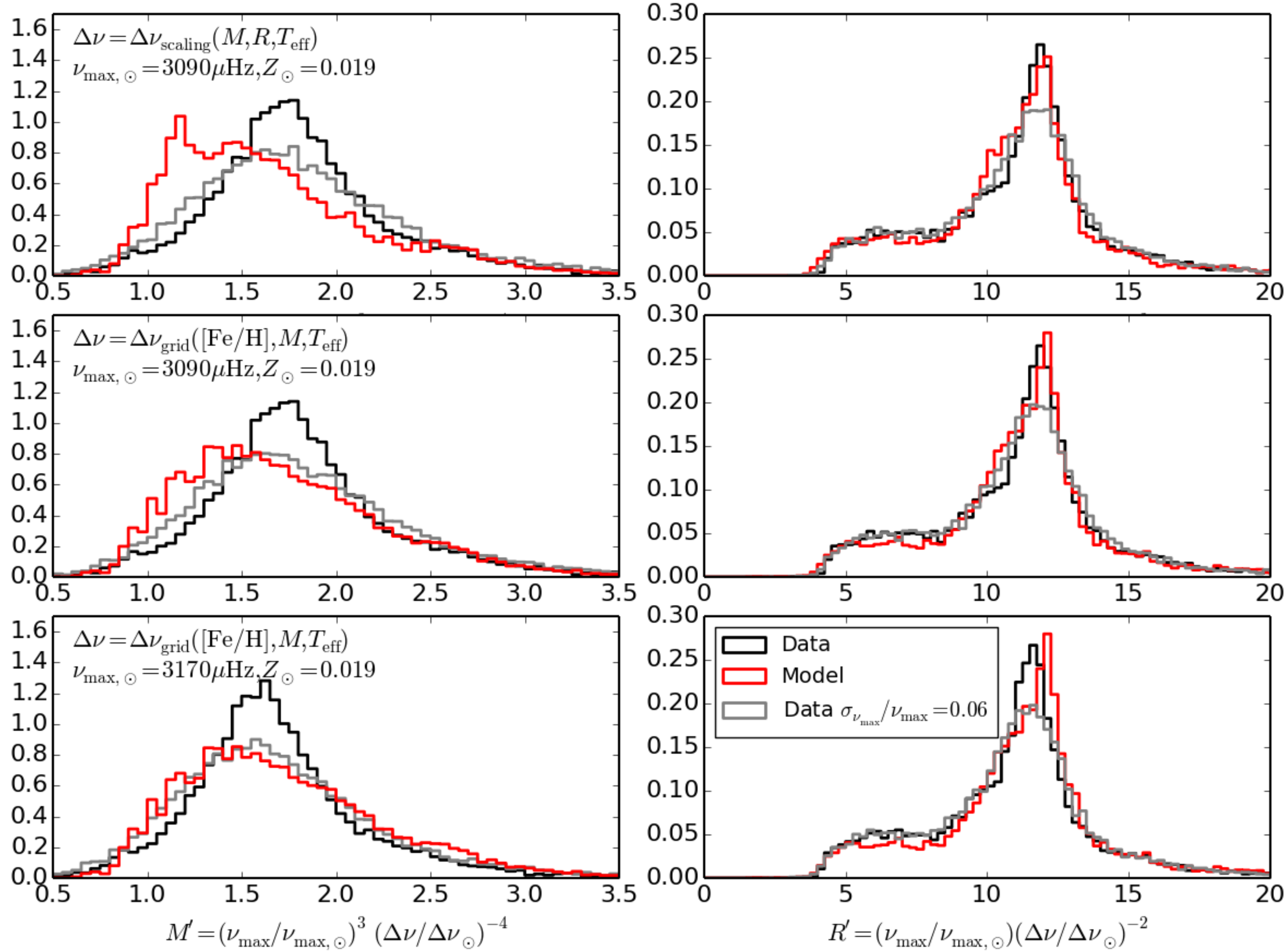
# Distribution of mass M and radius R of Red Giants

($\Delta v$, $v_{max}$)

Scaling Relations

$\Delta v$ theoretical

$v_{max}$ altered




$M' = (v_{max}/v_{max,Sun})^3/(\Delta v/\Delta v_{Sun})^4$ $R' = (v_{max}/v_{max,Sun})/(\Delta v/\Delta v_{Sun})^2$

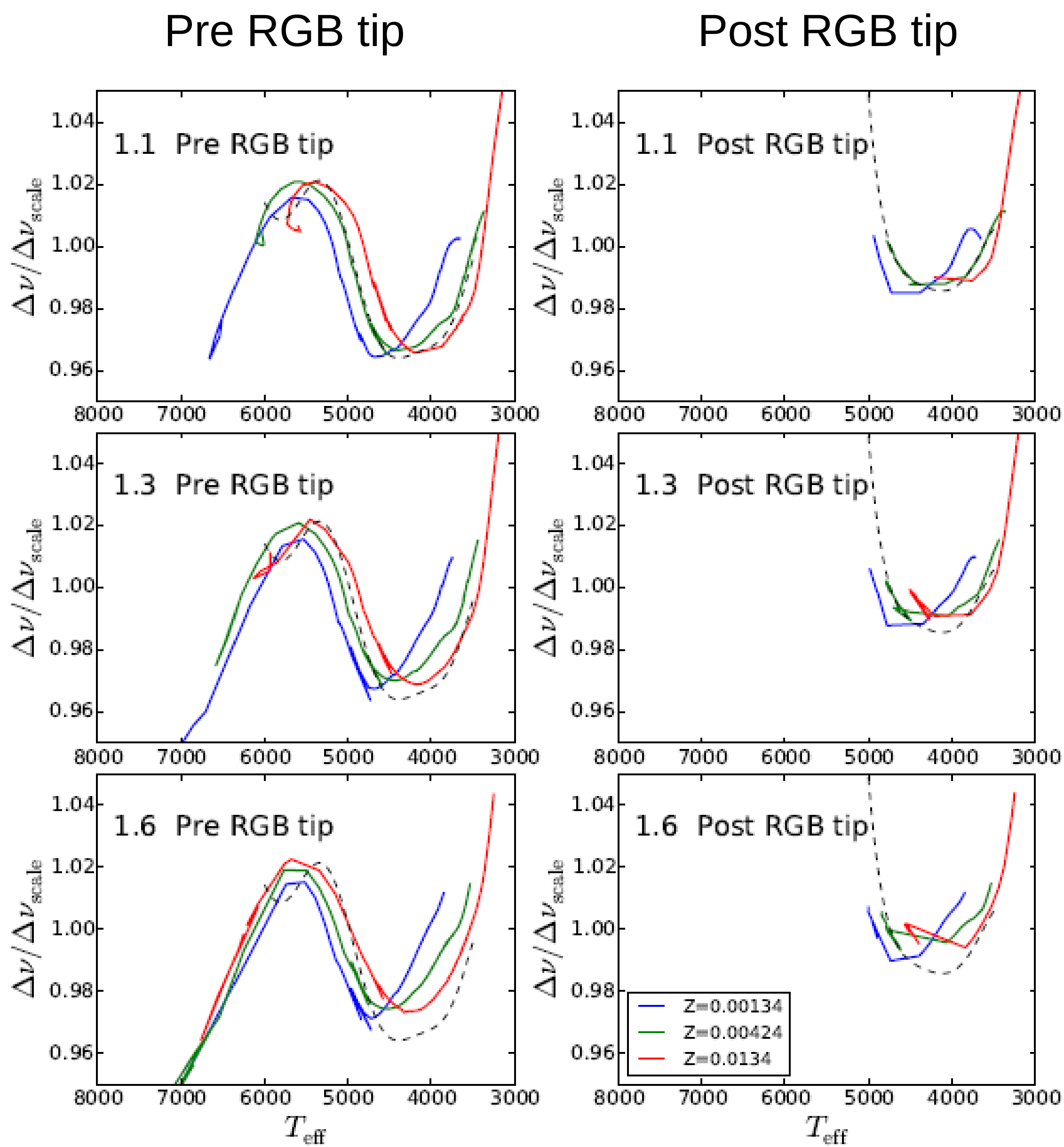
In $v_{max}$, 3% systematic and 5% random error needed to match the model.

# Δv from theory

Scaling relations are not perfect.

Systematics of upto 4% (RGB).

$\Delta\nu_{theory}/\Delta\nu_{scale}$




$T_{eff}$ $T_{eff}$

# Discussion

- If there are streaming motions of the order of 10 km/s on scales > 1kpc.
  - How reliable it is to use equilibrium DF approach to predict $\mathbf{V_c}$ and $\mathbf{V_\odot}$
- Given (M,Z,Age) how accurately can we predict $v_{max}$ and $\Delta v$ from theory.
- More work needed to estimate $v_{max}$ and $\Delta v$ from theory, before we can use astero-seismology for fitting MW models to data, or measure M , R and age.

Publicly available codes that might be of interest to you

**GALAXIA- http://galaxia.sourceforge.net**

**EBF-http://ebfformat.sourceforge.net Efficient Binary data Format**

# Publicly available codes that might be of interest to you

## GALAXIA- http://galaxia.sourceforge.net

Galaxia is a code for generating a synthetic model of the galaxy. The input model can be analytical or one obtained from N-body simulations. The code outputs a catalog of stars according to user specified color magnitude limits.

## EBF-http://ebfformat.sourceforge.net

## Efficient Binary data Format

"*Put fun back into numerical computing, Use EBF*"

>>EBF<<

- A general purpose binary file format publicly available at
- Automatic endian conversion, data type conversion
- Store multiple data items in same file
  - Time to locate an item, almost independent of number of items. Due to use of inbuilt hashtable
- Support for homogeneous multidimensional arrays and structures (also nested structures)
- Not tied to one programming languange.
  - API available in IDL, MATLAB, Python,C,C++, Fortran, Java