Galactic Archaeology: The formation and evolution of the Milky Way using large observational surveys

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Large observational surveys of the Milky Way.

- Astrometric:
  - **l,b, μ_l,μ_b.** Angular position and angular velocity/proper motion
  - UCAC4, PPMXL, HIPPARCOS (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)
  - APOGEE, Gaia-ESO, GALAH,(RAVE, SEGUE, LAMOST) [4MOST]
- Asteroseismology:
  - Kepler mission, K2, TESS

Chemical abundance and age is important? Life long tags

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

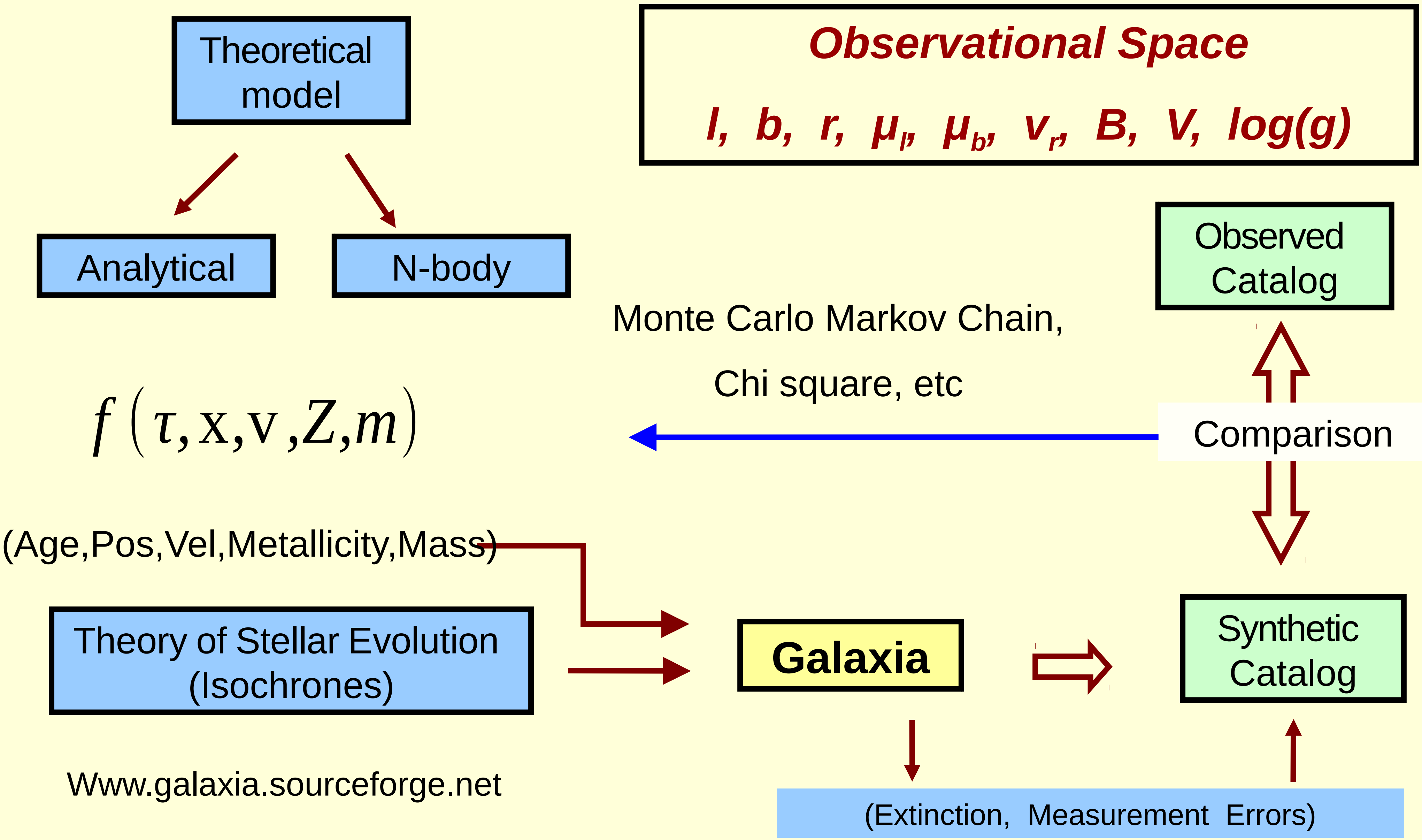
- This is what makes it challenging.
- High resolution spectra crucial.

Machinery to interpret observations

- Forward modelling. From models to data.
- N body simulations
- Equilibrium models
- f(x,v|τ) to f(J|τ) or f(J|Z)   (Binney 2010-2015)
  - J(x,v| Φ) constants of motion
  - Reduce problem from 6d to 3d
  - Pseudo isothermal DF
  - Extended distribution function (Sanders & Binney 2015)
-

Galaxia: galaxia.sourceforge.net

- A framework to compare theoretical models of our Galaxy wit observations.

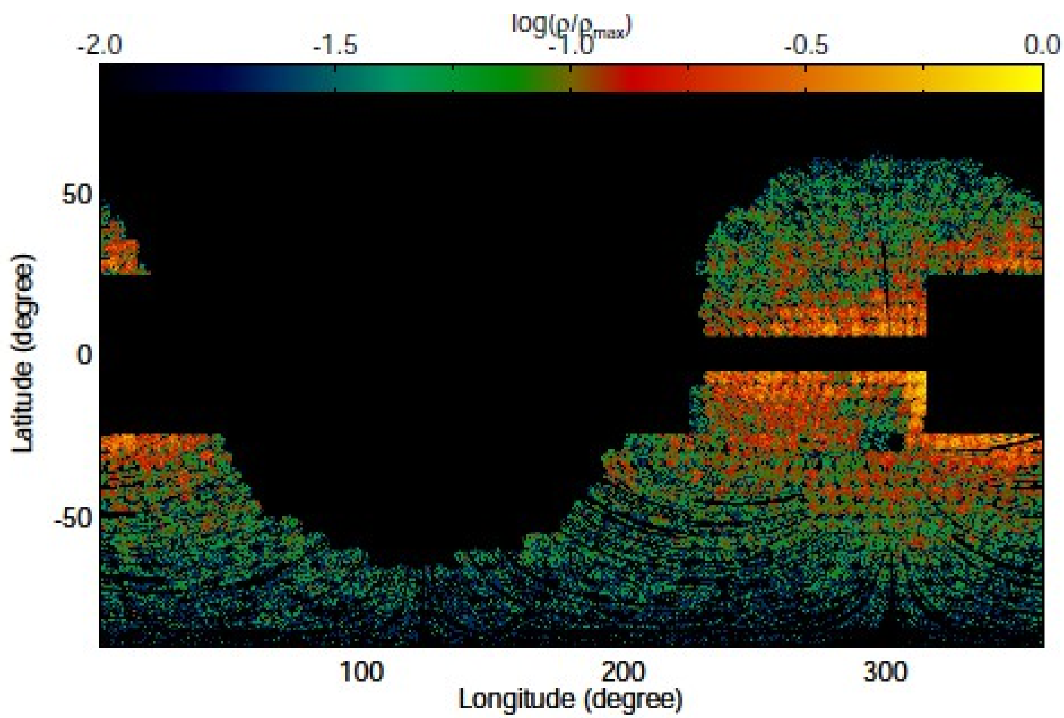


Www.galaxia.sourceforge.net

Kinematic analysis using RAVE and GCS

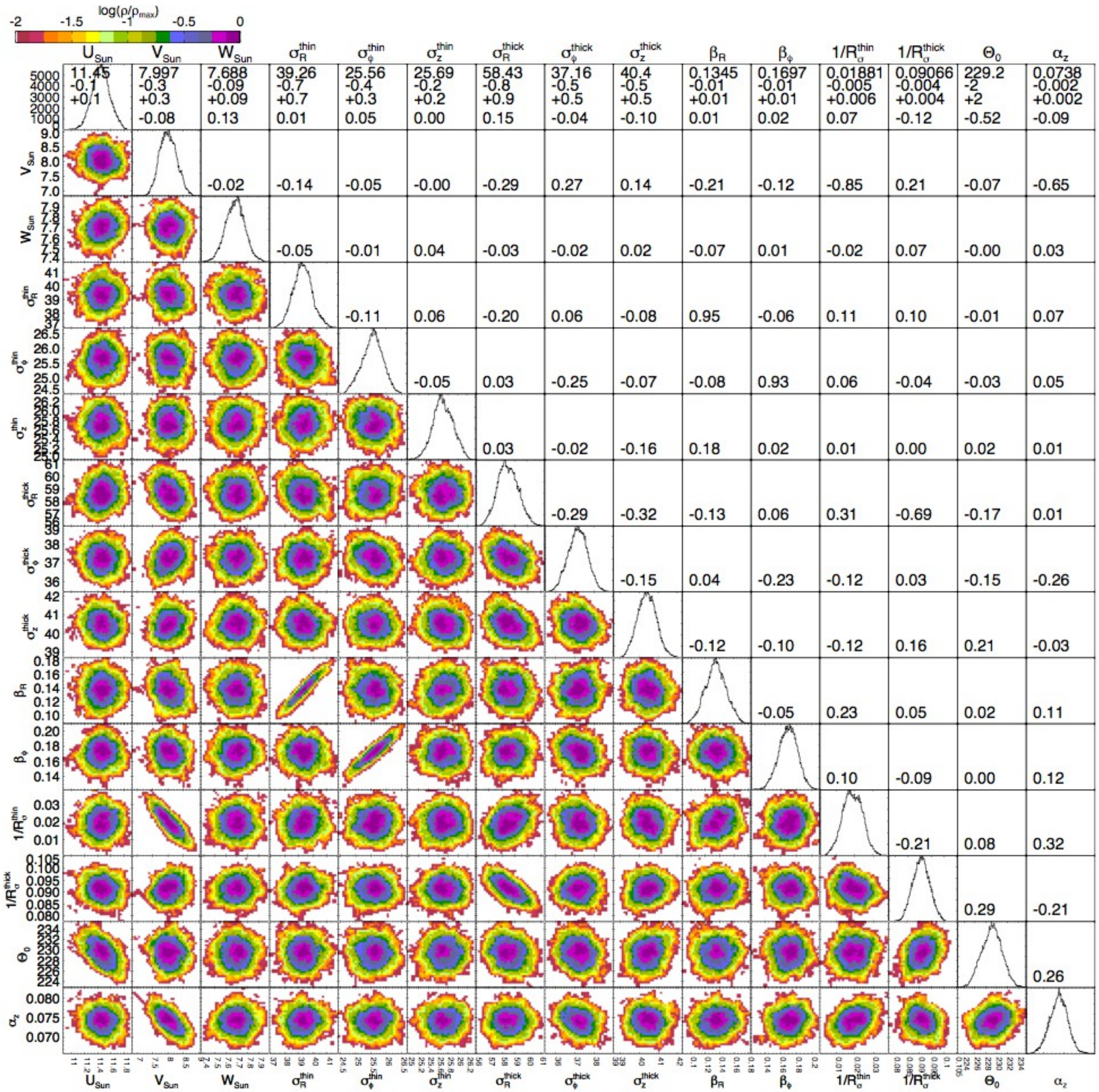
- GCS: A color magnitude limited sample of stars with (x,
  Very local 120 pc. (about 5000 stars)

RAVE a spectroscopic survey of about 500,000 stars with accurate, (l,b,v_{los}). 1- 2kpc. **$p(\theta \mid l,b,v_{los})$**



RAVE-GAUSS

- Marginalised posterior distribution of model parameters.
- The anti-correlation of R_σ^{thin} and $V_\odot$ sun can be seen
- $V_\odot$ and v_c affected by α_z



Sharma et al. 2014

Best fit parameters for the Shu model

Model	RAVE SHU	RAVE SHU	GCS SHU
$U_\odot$	$11.2^{+0.13}_{-0.13}$	$10.92^{+0.13}_{-0.14}$	$10.16^{+0.39}_{-0.4}$
$V_\odot$	$9.71^{+0.12}_{-0.11}$	$7.53^{+0.16}_{-0.16}$	$9.81^{+0.28}_{-0.28}$
$W_\odot$	$7.536^{+0.085}_{-0.086}$	$7.542^{+0.089}_{-0.093}$	$7.13^{+0.18}_{-0.19}$
$\sigma_R^{\rm thin}$	$42.37^{+0.61}_{-0.66}$	$39.78^{+0.81}_{-0.73}$	$39.99^{+0.91}_{-0.91}$
$\sigma_z^{\rm thin}$	$26.85^{+0.85}_{-0.92}$	$24.7^{+0.66}_{-0.66}$	$23.63^{+0.85}_{-0.8}$
$\sigma_R^{\rm thick}$	$38.84^{+1.2}_{-0.96}$	$42.31^{+1}_{-0.9}$	$45.9^{+1.8}_{-1.8}$
$\sigma_z^{\rm thick}$	$29.15^{+0.87}_{-0.79}$	$34.66^{+0.61}_{-0.58}$	$32.6^{+2.3}_{-2.2}$
β_R	$0.236^{+0.011}_{-0.011}$	$0.198^{+0.014}_{-0.014}$	$0.237^{+0.013}_{-0.013}$
β_z	$0.398^{+0.03}_{-0.029}$	$0.328^{+0.027}_{-0.024}$	$0.366^{+0.021}_{-0.021}$
$1/R_\sigma^{\rm thin}$	$0.0673^{+0.0028}_{-0.0028}$	$0.0722^{+0.0035}_{-0.0032}$	0.073
$1/R_\sigma^{\rm thick}$	$0.1555^{+0.0046}_{-0.0064}$	$0.1335^{+0.0046}_{-0.0056}$	0.132
Θ_0	$212.6^{+1.4}_{-1.3}$	$232.8^{+1.7}_{-1.6}$	232
R_0	8	8	8
α_z	0	$0.048^{+0.0019}_{-0.0018}$	0.0471
α_R	0	0	0
$\chi^2_{\rm red}$ RAVE	1.52	1.43	1.80
$\chi^2_{\rm red}$ GCS	5.15	5.57	3.86

α_z free makes v_c go up.

232.8+7.53=240.33 km/s.

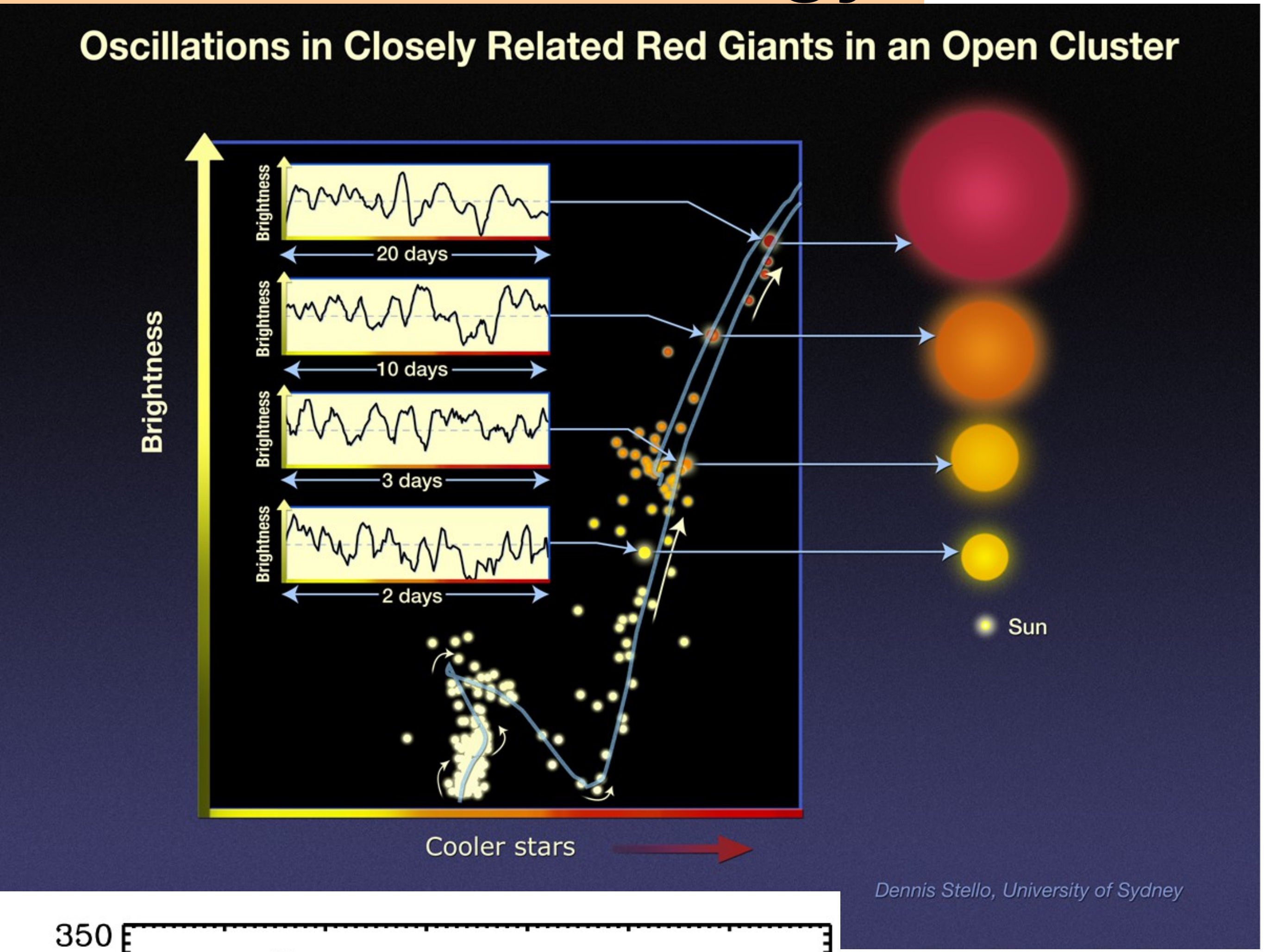
GCS and RAVE also match,

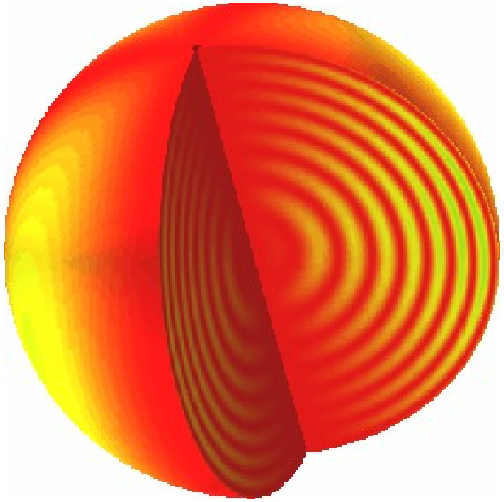
σ_R similar for thin and thick

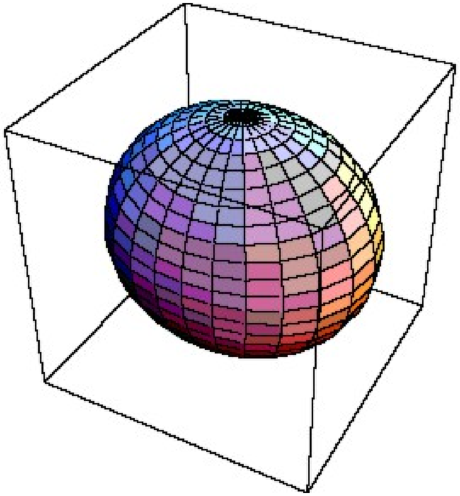
Sharma et al. 2014

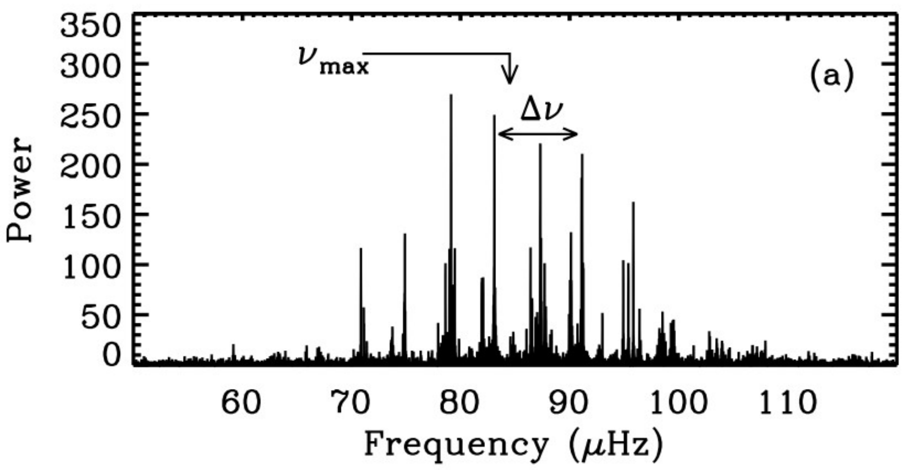
Quantities in magenta were kept fixed during fitting. Units are in km/s and kpc

Asteroseismology



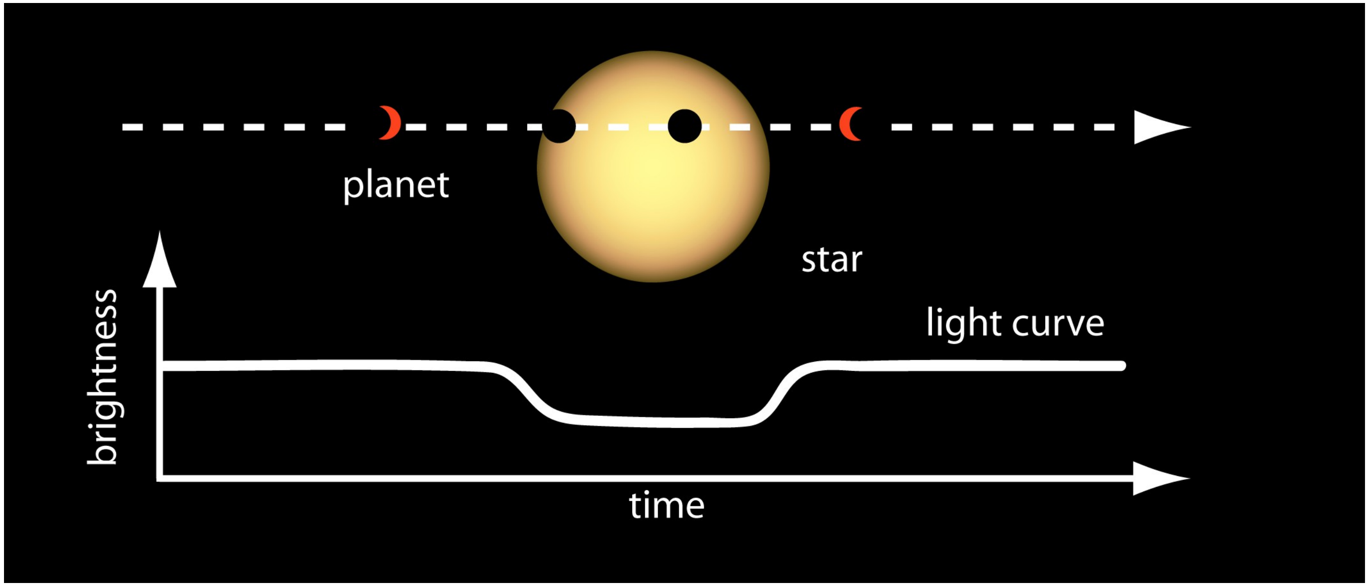


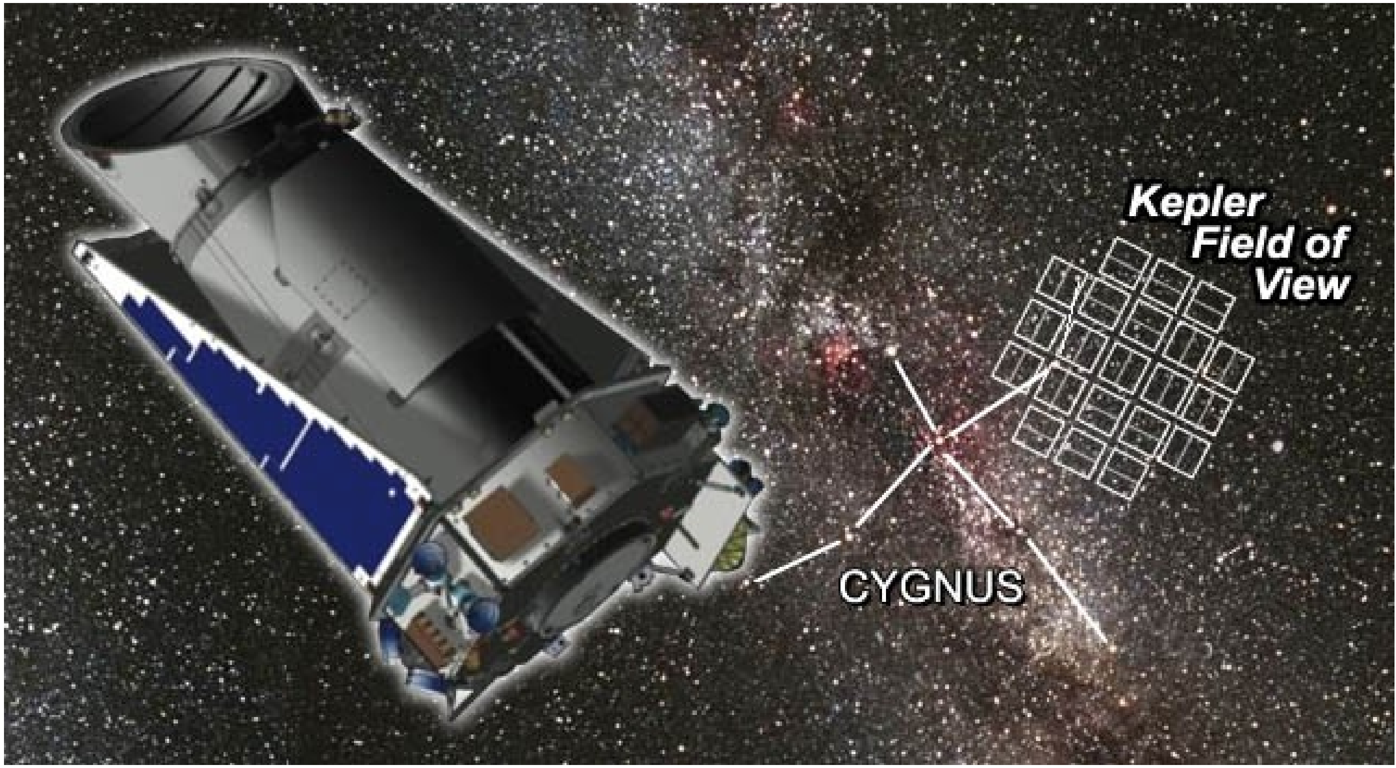




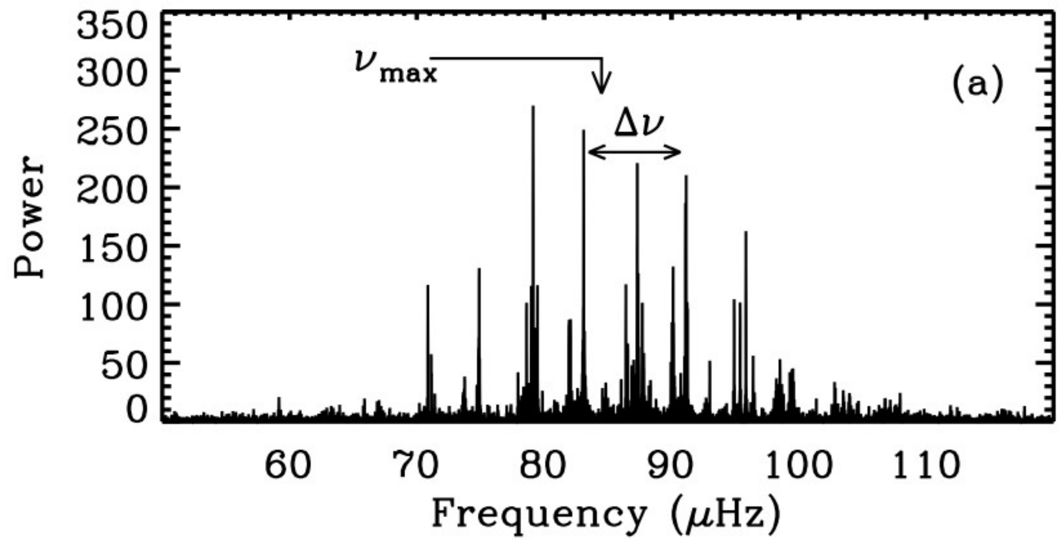
KEPLER

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





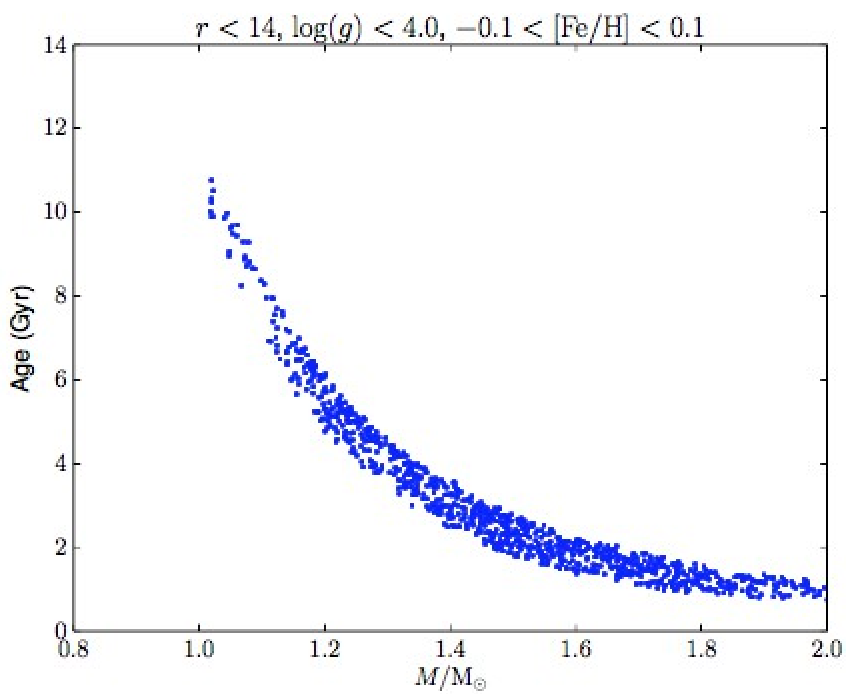
Galactic archeology with Asteroseismology



- Vmax(g) then M(dnu,numax)
- Gives mass and radius and potentially age.Age crucial for GA.
- Kepler, K2, CoRoT, TESS.
- Kepler did not have well defined selection function.

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

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

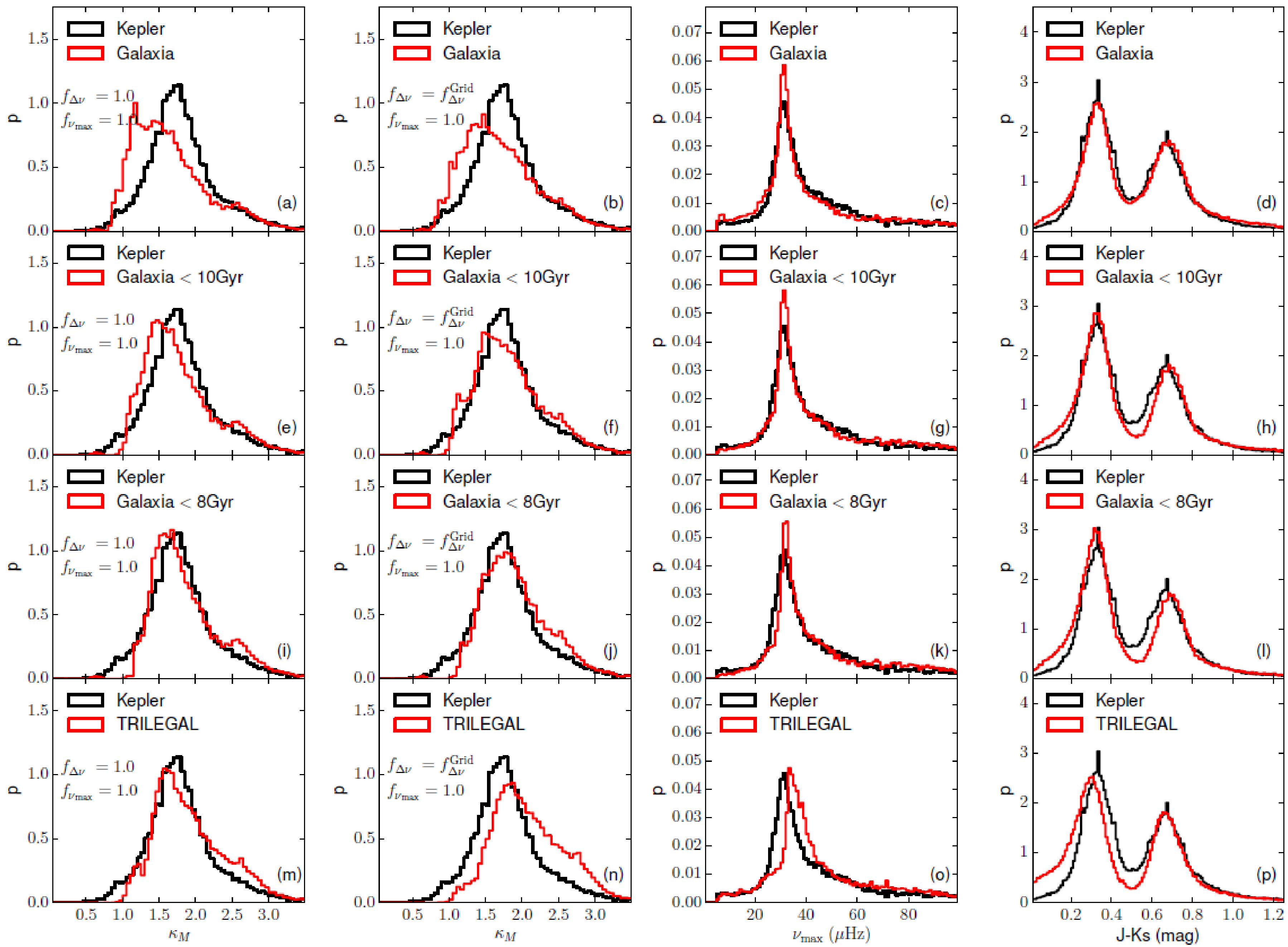


Sharma et al. 2016 (AN)

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

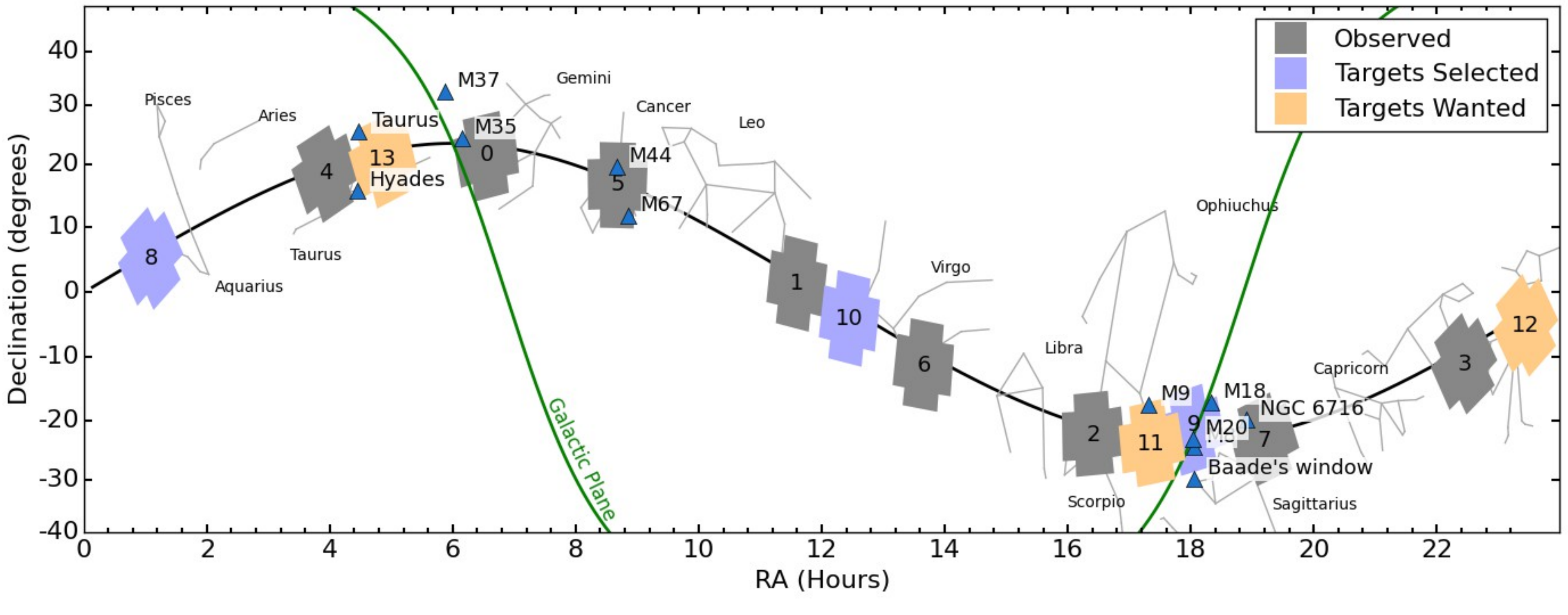
$$\left(\frac{M}{M_\odot}\right) \simeq \left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right)^3\left(\frac{\langle \Delta\nu_{nl}\rangle}{\langle \Delta\nu_{nl}\rangle_\odot}\right)^{-4}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{1.5}$$

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



K2 mission

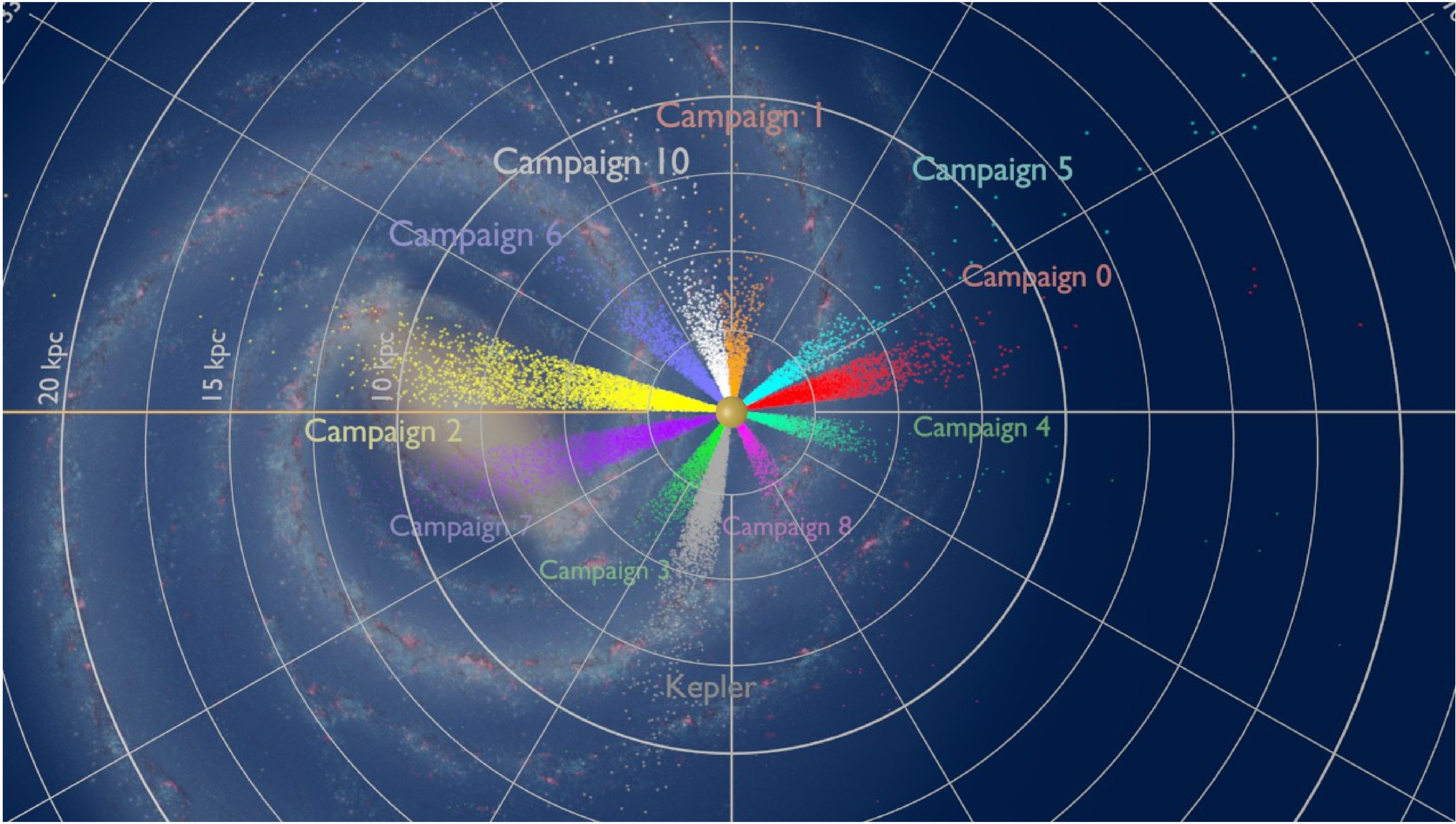
- In May 2013, of the four reaction wheels, two stopped working.
- June 2014 Kepler repurposed as K2 mission.
  - per campaign: 3 months, 20,000 targets.



K2GAP

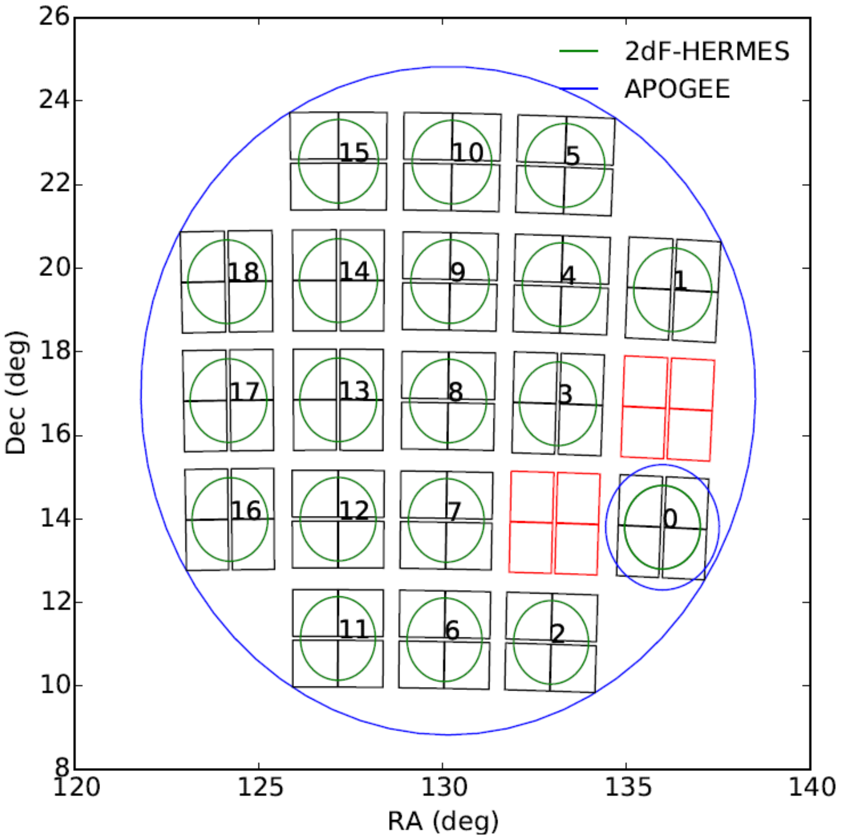
www.physics.usyd.edu.au/k2gap

- Galactic archaeology program with K2.
  - Dennis Stello (PI), Sanjib and Asteroseismic commun
- Very well defined selection function, avoiding SF mistake made in KEPLER mission.
  - (J-K)>0.5 upto V ~ 14 or 15
- 40% of targets allocated via this program.
- Among the top two programs.


Campaign 1
Campaign 10
Campaign 5
Campaign 6
Campaign 0
20 kpc
15 kpc
10 kpc
Campaign 2
Campaign 4
Campaign 7
Campaign 8
Campaign 3
Kepler

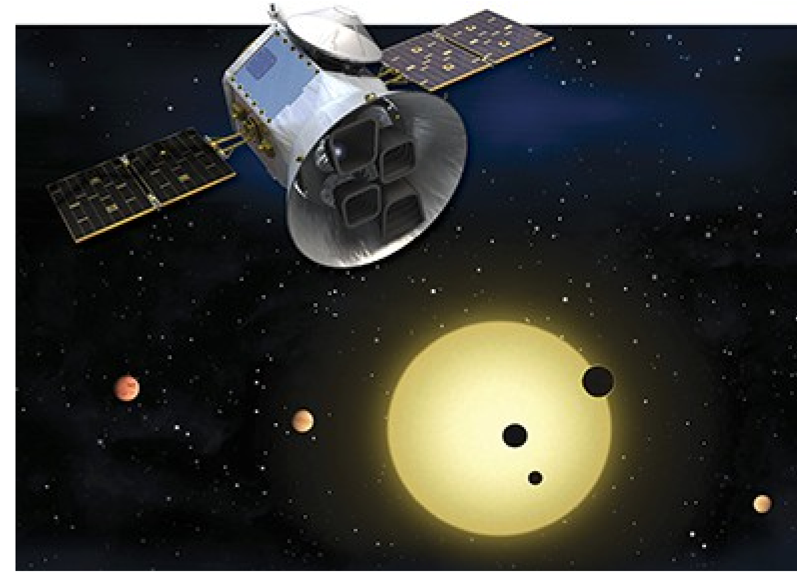
K2-HERMES program (59 nights)

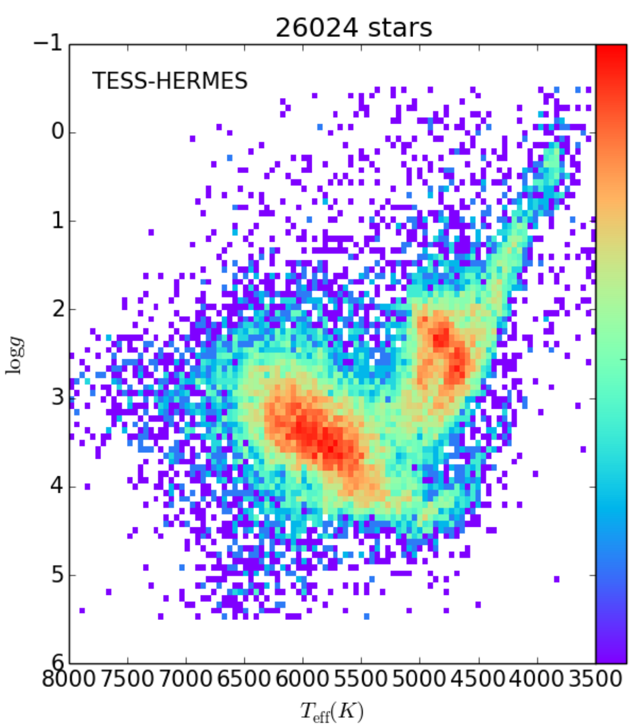
- Program to follow up K2 targets with **HERMES at AAT**.
  - Precise abundaces, accurate asteroseismic information.
  - Goldmine for galactic archaeology.
- 10<V<13, 13<V<15,
- **60,000** stars.
- Priority to K2 targets
- SF and Completeness:
  - 10<V<13
  - (13<V<15)&((J-K)>0.5)

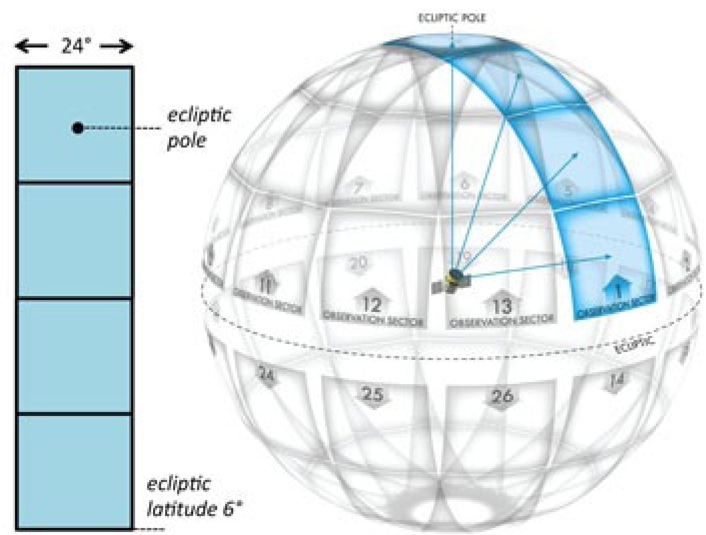


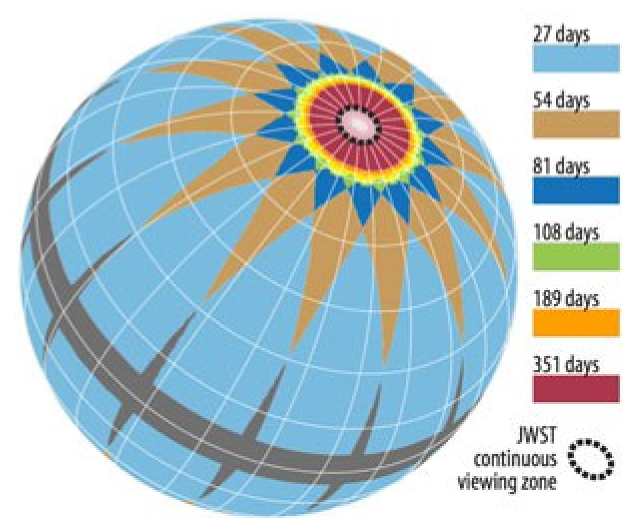
TESS HERMES program

- Launch date June 2018
- Full frame images for
- CVZ 12 degree radius
- Oscillations in RG should be detectable till I<12 (V<13)
- 17 nights at AAT, (10<V<13)



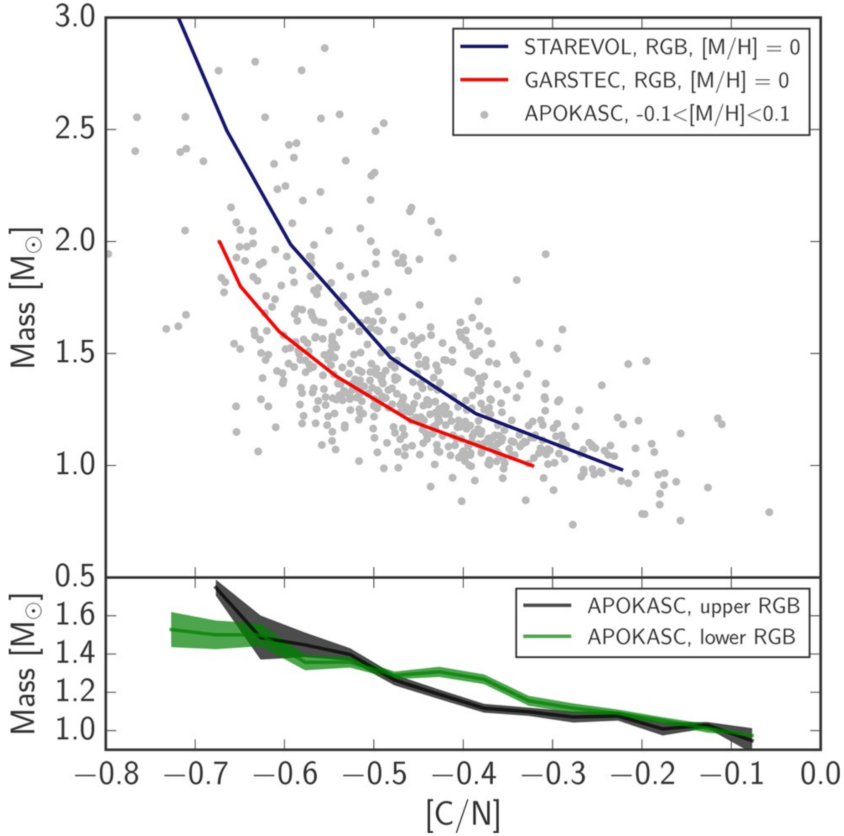


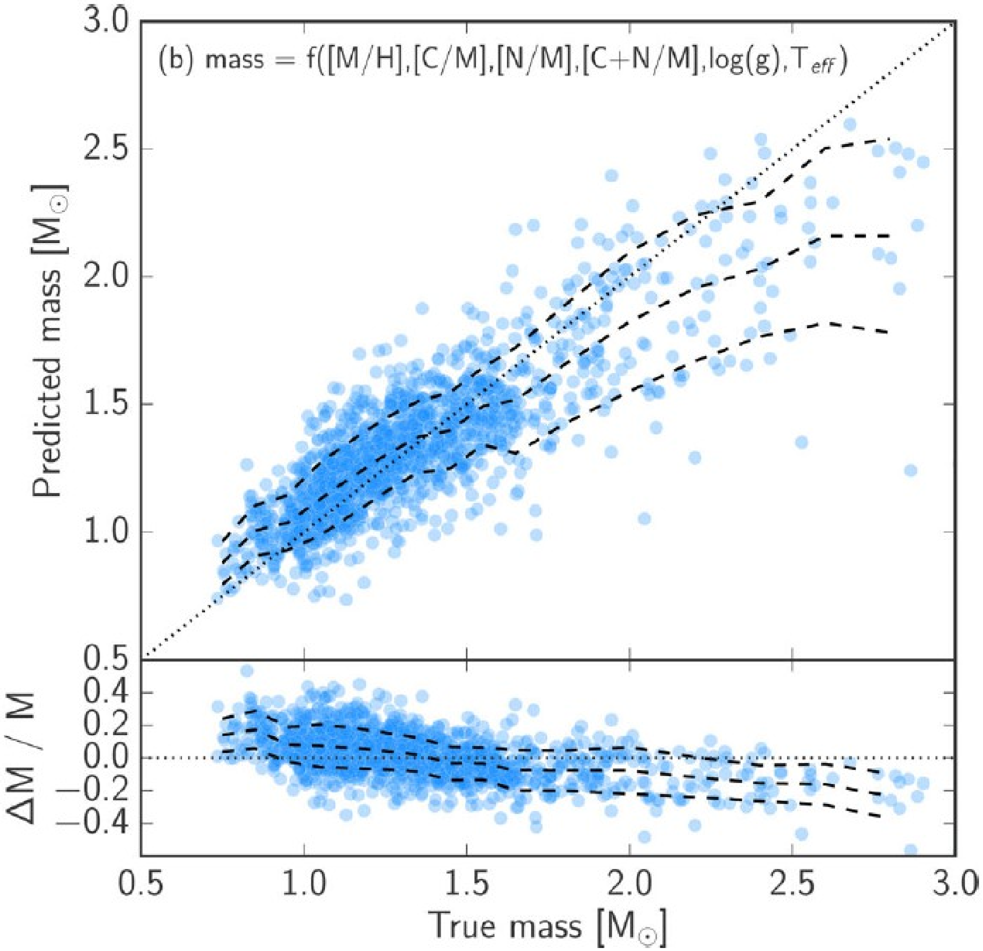




Spectroscopic determination of Mass

- Martig et al. 2016, Ness et al. 2016
- 14 % accuracy

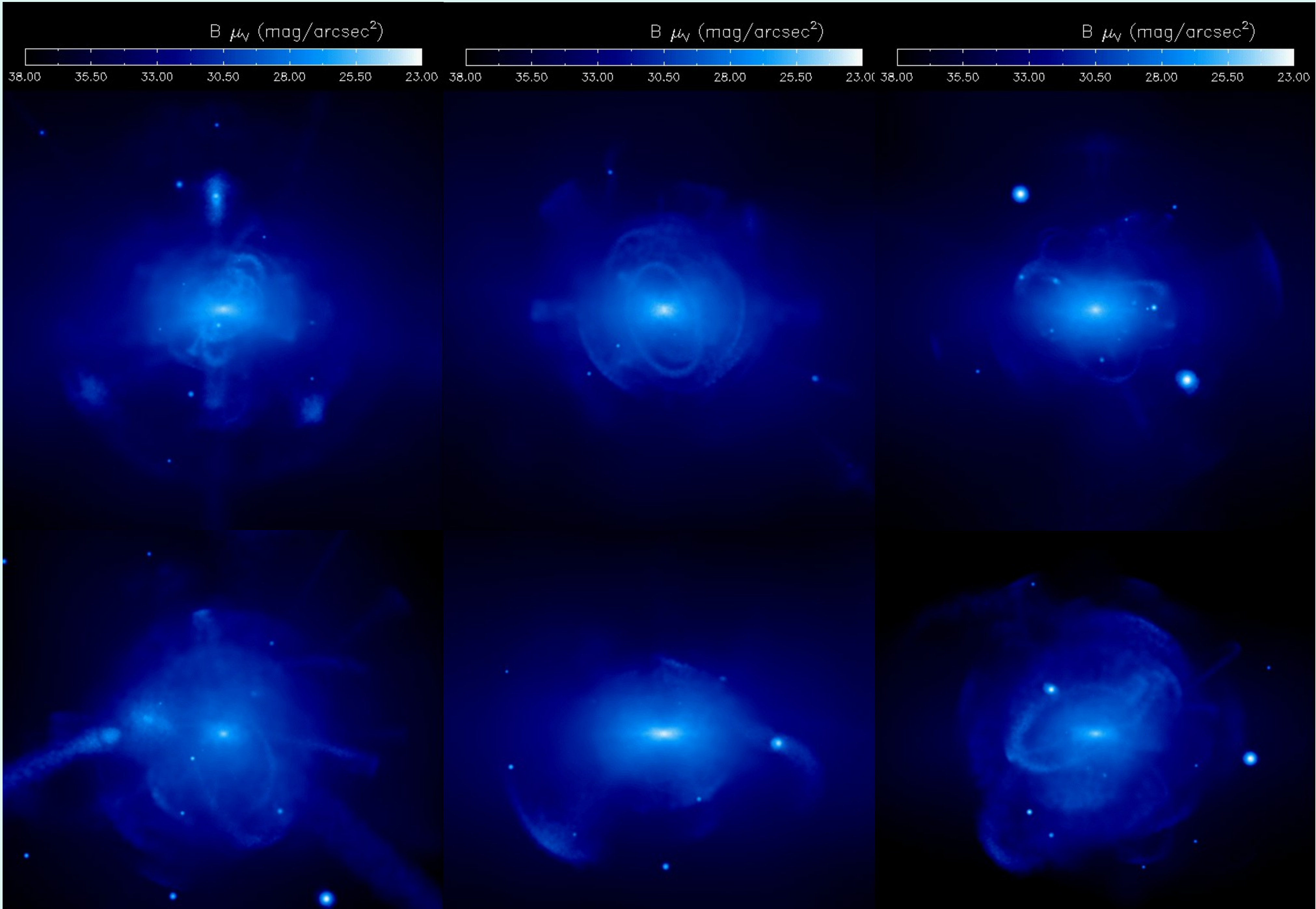




Subaru and Galactic Archaeology

- With PFS, low-res spectra can we get C/N or other mass markers.
- Strength is fainter stars, wide area.
- Milky Way Halo ideal candidate.

Structures as fossils of accretion events (3d space)



LCDM halos μ_V (mag/arcsec^2) Bullock & Johnston 2005

Structures are related to accretion history

Radial Circular | Old Young | HighL LowL

Non-LCDM halos

Rad: *ε<0.2*

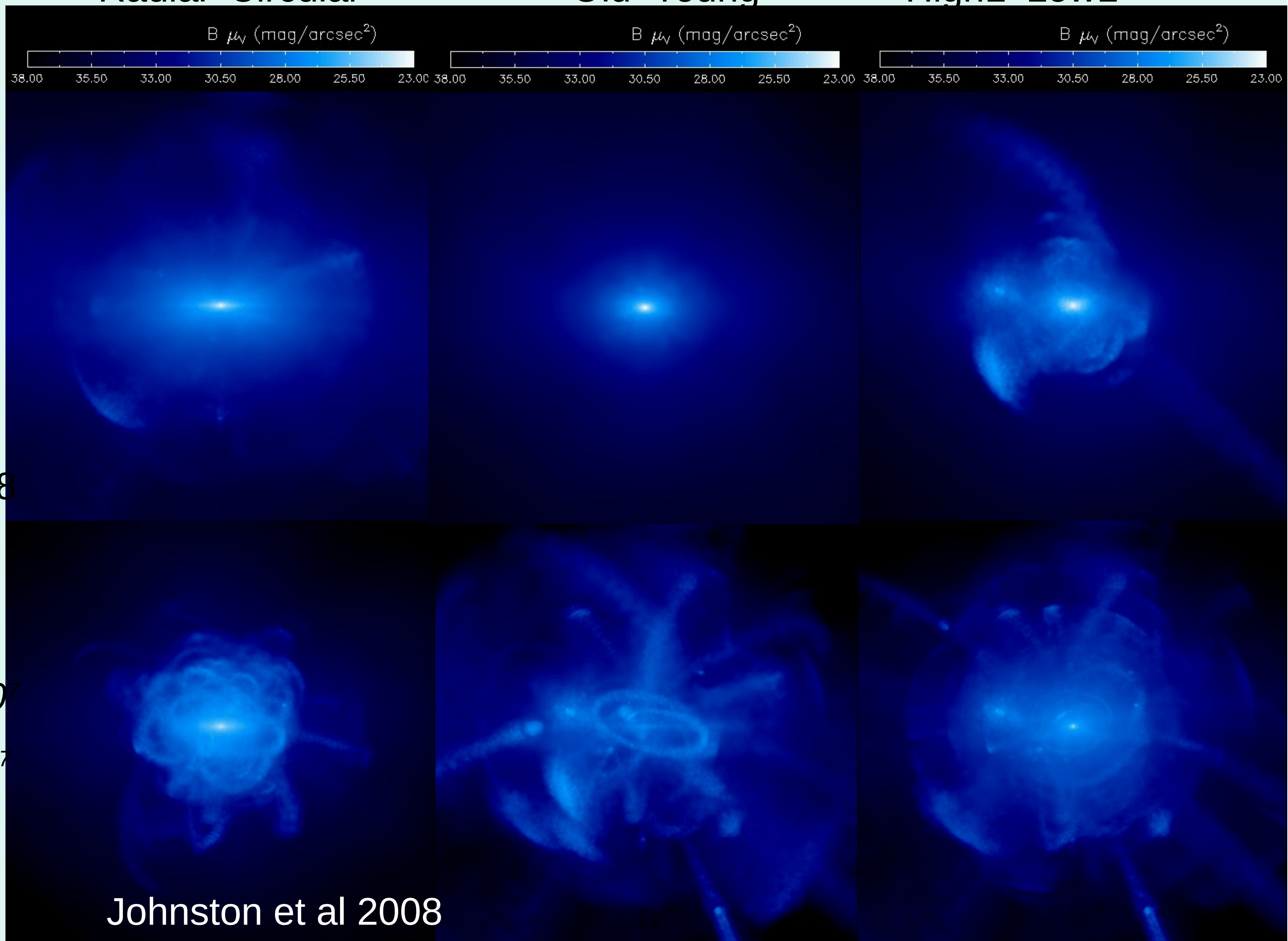
Circ: *ε>0.7*

Old: $t_{acc}>11$

Young: $t_{acc}<8$

HighL: $L>10^7$

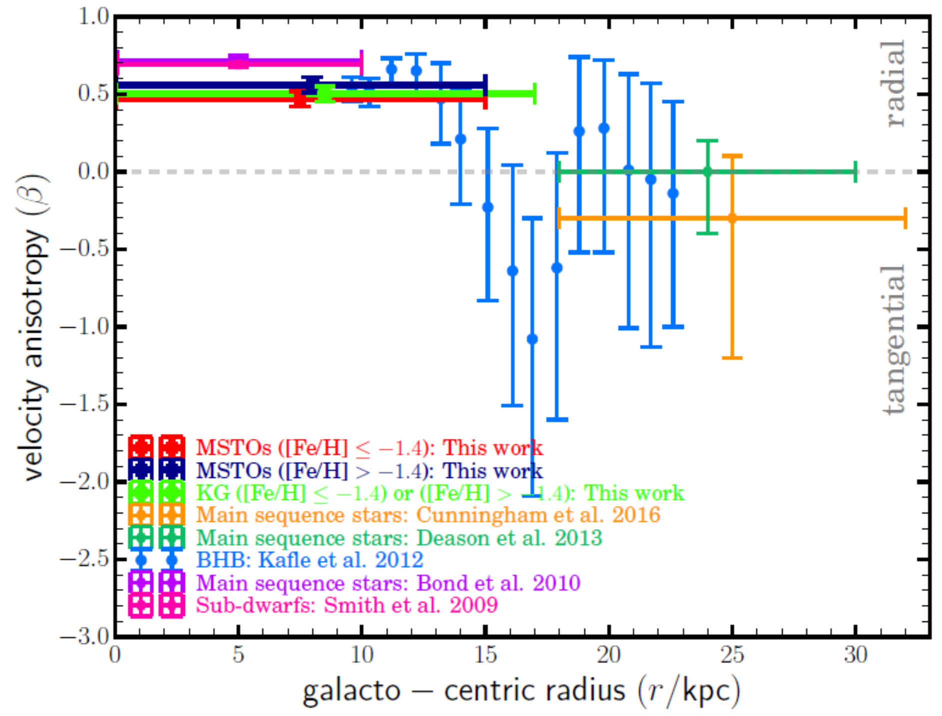
LowL: $L<10^7$



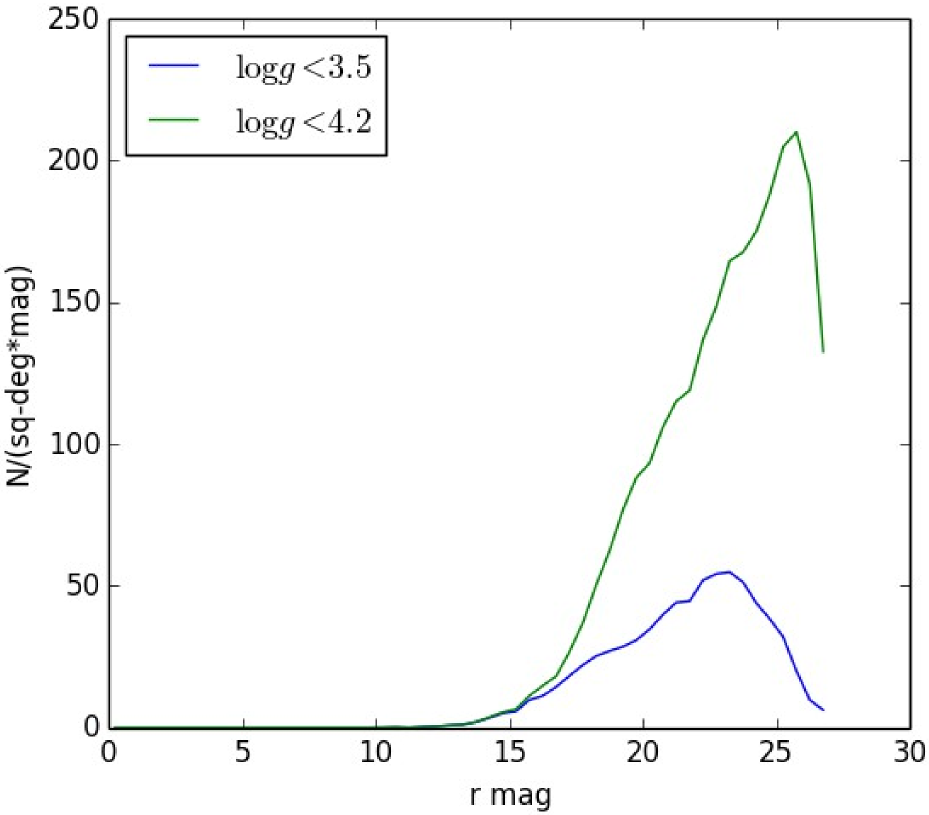
Johnston et al 2008

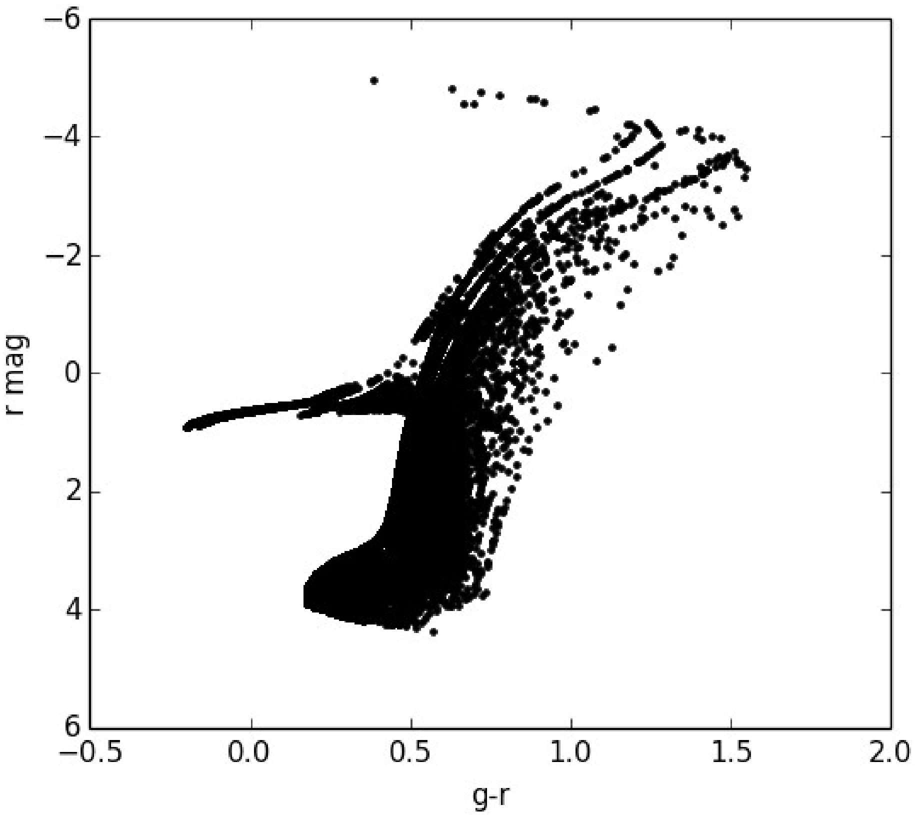
Kafle et al 2013,2014

- Kinematic properties of halo using SEGUE BHB stars
  - (r< 15 kpc, |z|> 4 kpc).
- Dip in anisotropy profile.
- Rotation depends on metallicity.



Density of halo stars (*Galaxia*) preliminary





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