The APOKASC Catalog: Spectroscopic, Asteroseismic, ~~and Rotational~~ Data for a Large Sample of Kepler Stars

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The APOKASC Collaboration

The Need for Precision Stellar Astrophysics

- Origins Questions
  - Planet Formation
  - Structure Formation
- Complex Observational Patterns: Things Move!

  ⇒Precise Data Needed

  ⇒Need Better Stellar Physics

APOGEE at a Glance

Slide: GZ

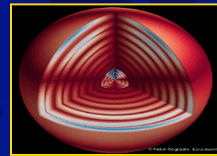
- The Apache Point Observatory Galactic Evolution Experiment
- The 4th (and final) SDSS-III project (2011 – 2014)
- A high-resolution, high signal-to-noise spectroscopic survey
- Operates in the near-infrared (H band): 1.51-1.68 μm
- Targeted ~10^5 RG stars sampling the bulge, disk(s), and halo(es)
- DR10: T_{eff}, [M/H], log g, [a/Fe]; 15 elements in progress

More numbers!

- S/N = 100+/pixel
- R ~ 22,500
- 300 fibers at a time, 7 deg^2 FOV
- RV precision: <0.1 - 0.5 km/s
- Abundance precision: <0.1 dex

S. R. Majewski

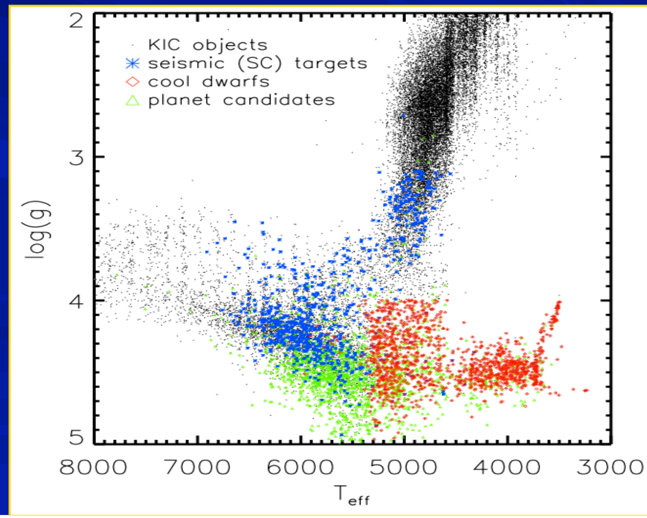
APOGEE + Asteroseismology



- APOGEE-*Kepler* Asteroseismology Collaboration (APOKASC)
  - 10,000 stars: giants with good log(*g*), planet host candidates, cool dwarfs with good rotations, etc.
  - Seismically derived parameters included in DR10!

Slide: GZ

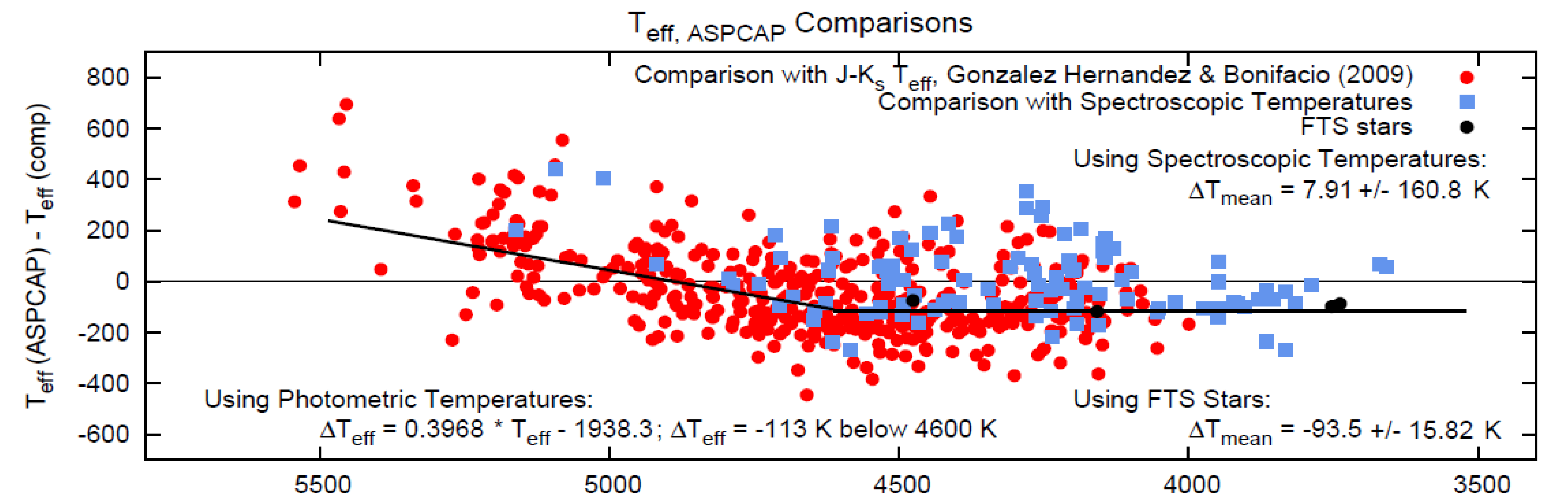
- Also overlap with CoRoT targets



Automated Pipeline Analysis

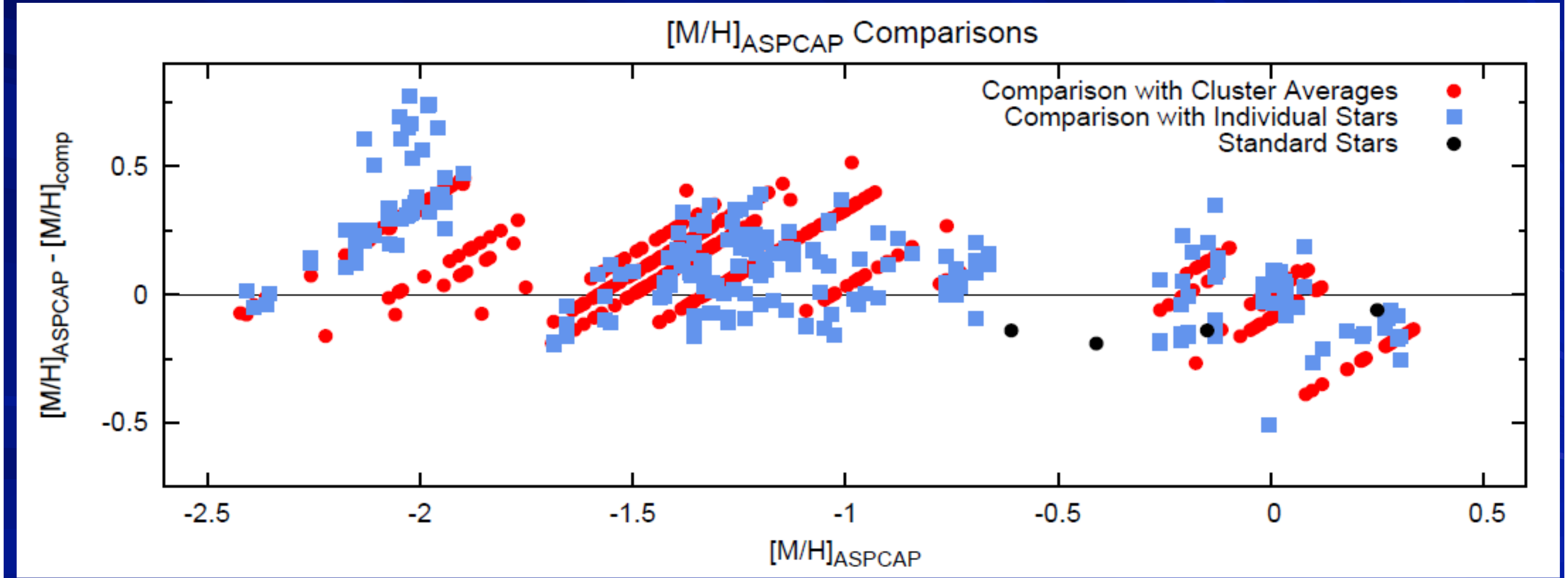
- Boutique analysis of 100,000 targets…NO.
- Automated fitting algorithm (FERRE) for the entire H band spectrum
- Ex post facto calibration of results against independent measurements
  - Star cluster members
  - Asteroseismic log g

Calibrating the Pipeline: Temperatures

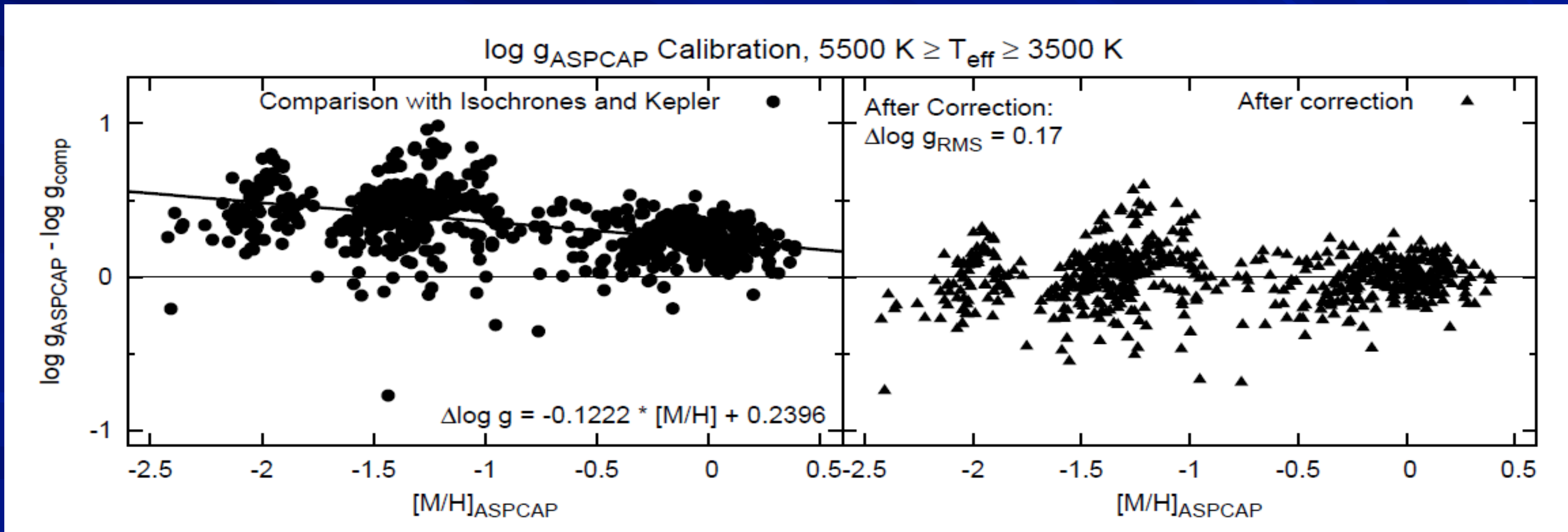


Meszaros et al. (2013)

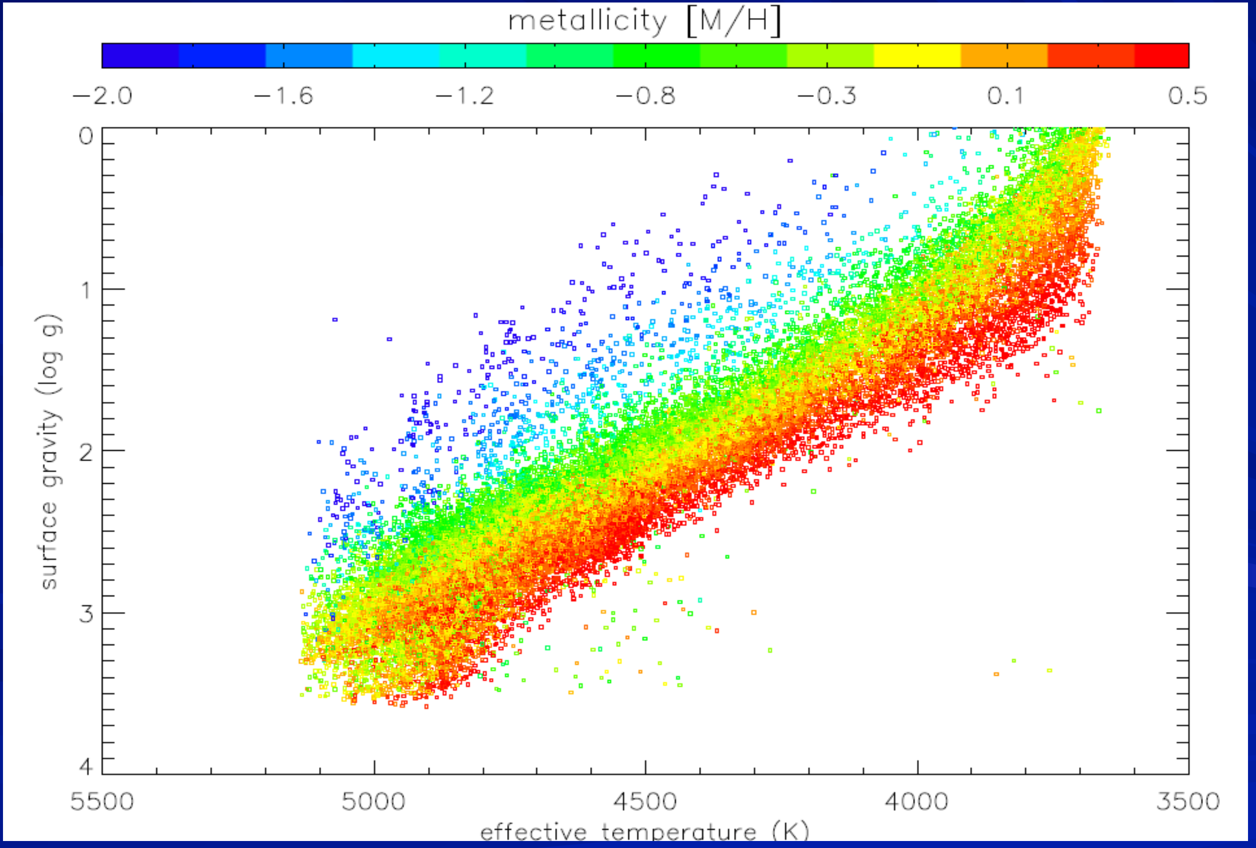
Calibrating the Pipeline: Metallicities



Calibrating the Pipeline: Surface Gravity



APOGEE: 100K Red Giant Spectra

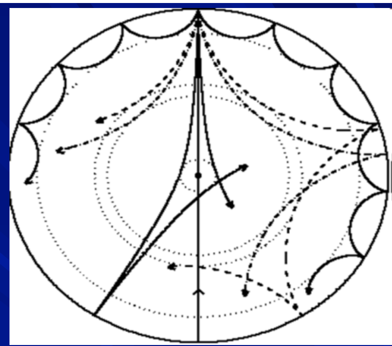


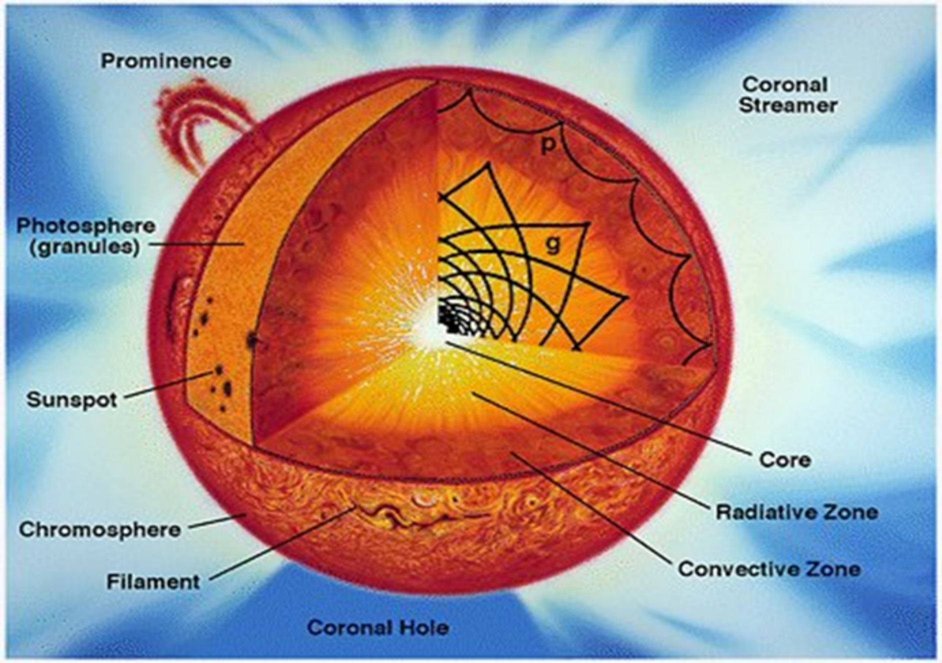
Two Major Impacts of Asteroseismology

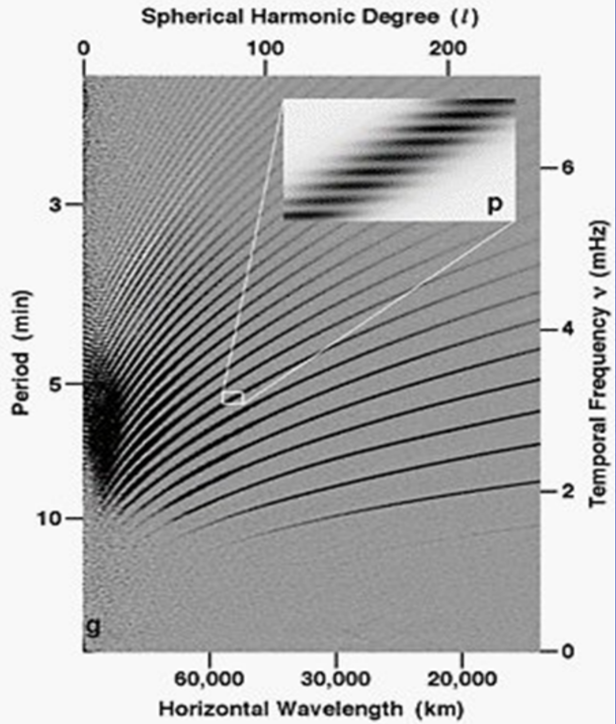
- We can measure fundamental properties (mass, radius, age, rotation) in bulk stellar populations
- Extremely precise surface gravities are a natural product
- We have entirely new categories of stellar observables
  - Surface CZ depth
  - He ionization
  - Core rotation
  - Core mass and density

Spectroscopy + Asteroseismology ♥ 2Gether 4Ever

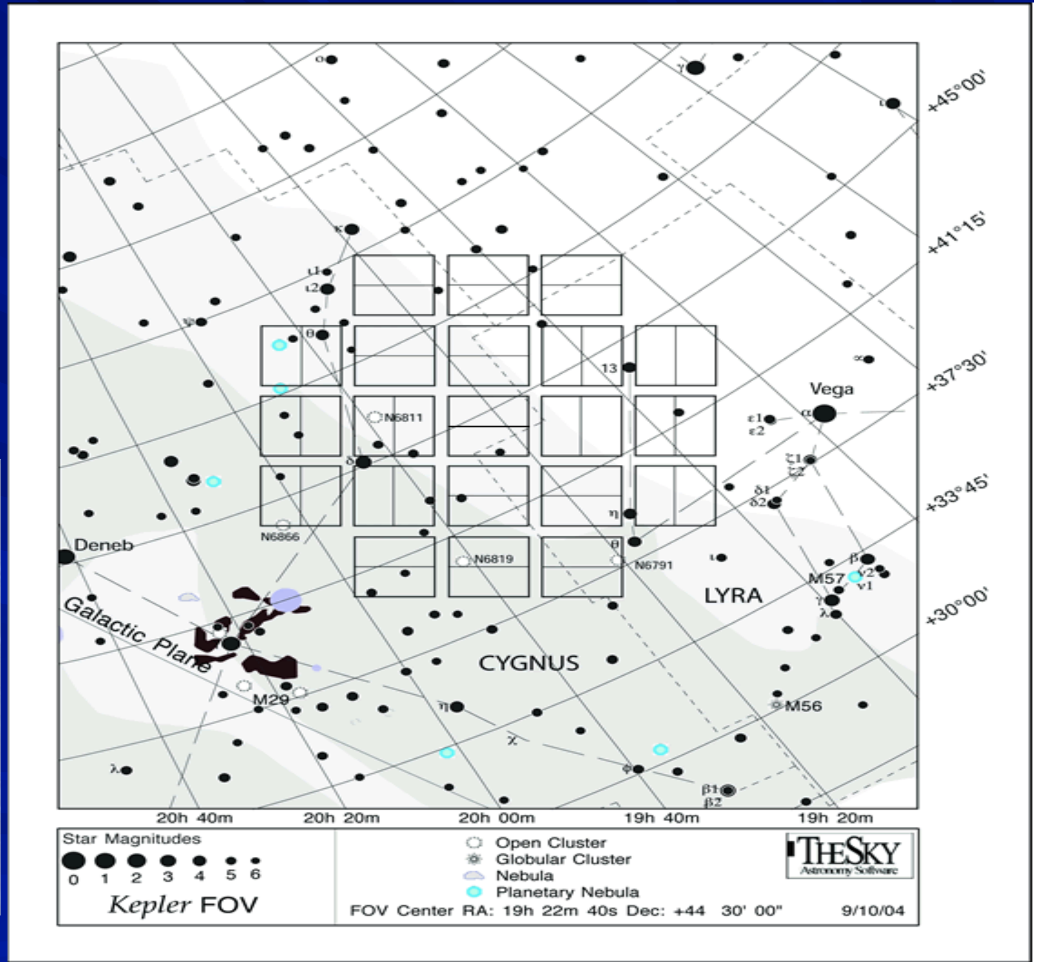
Waves are Generated by Turbulence in Stars







Kepler mission: 150,000 stars monitored



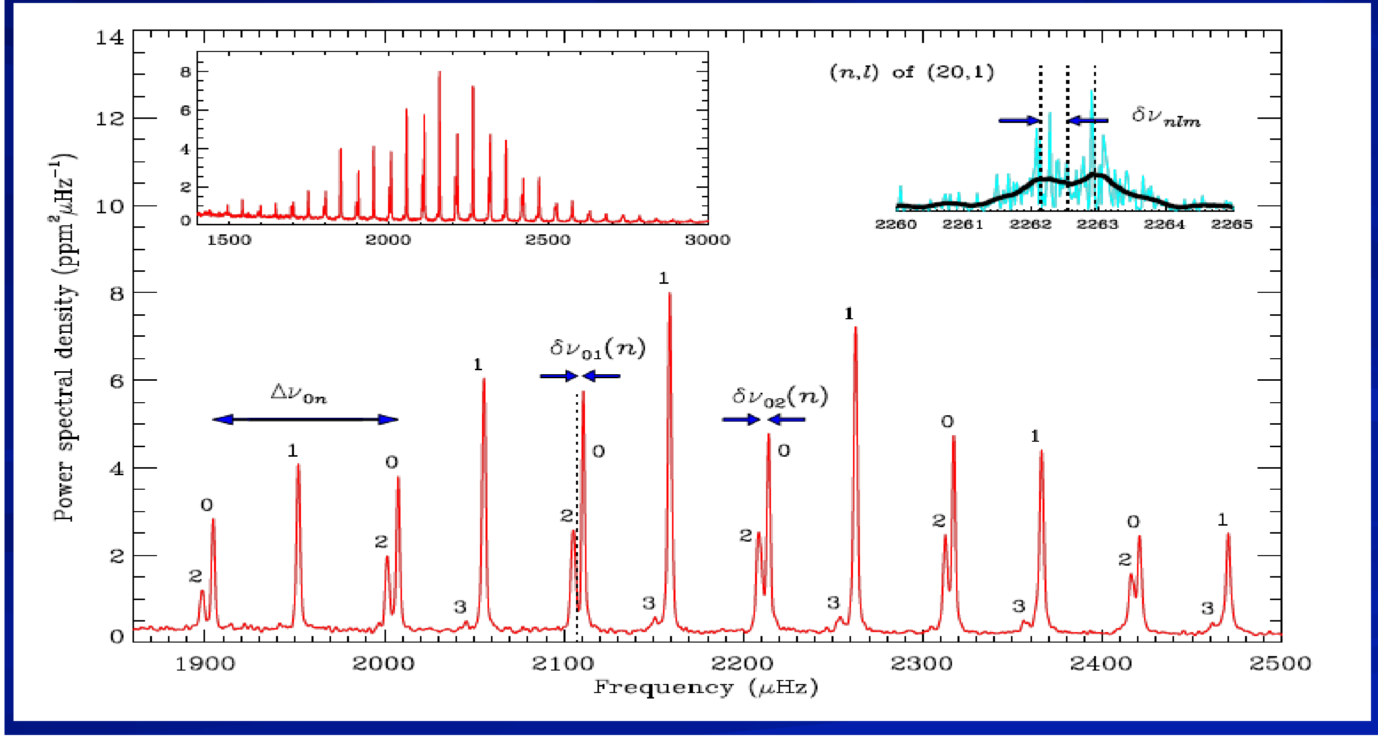
Solar-like Oscillations in Kepler

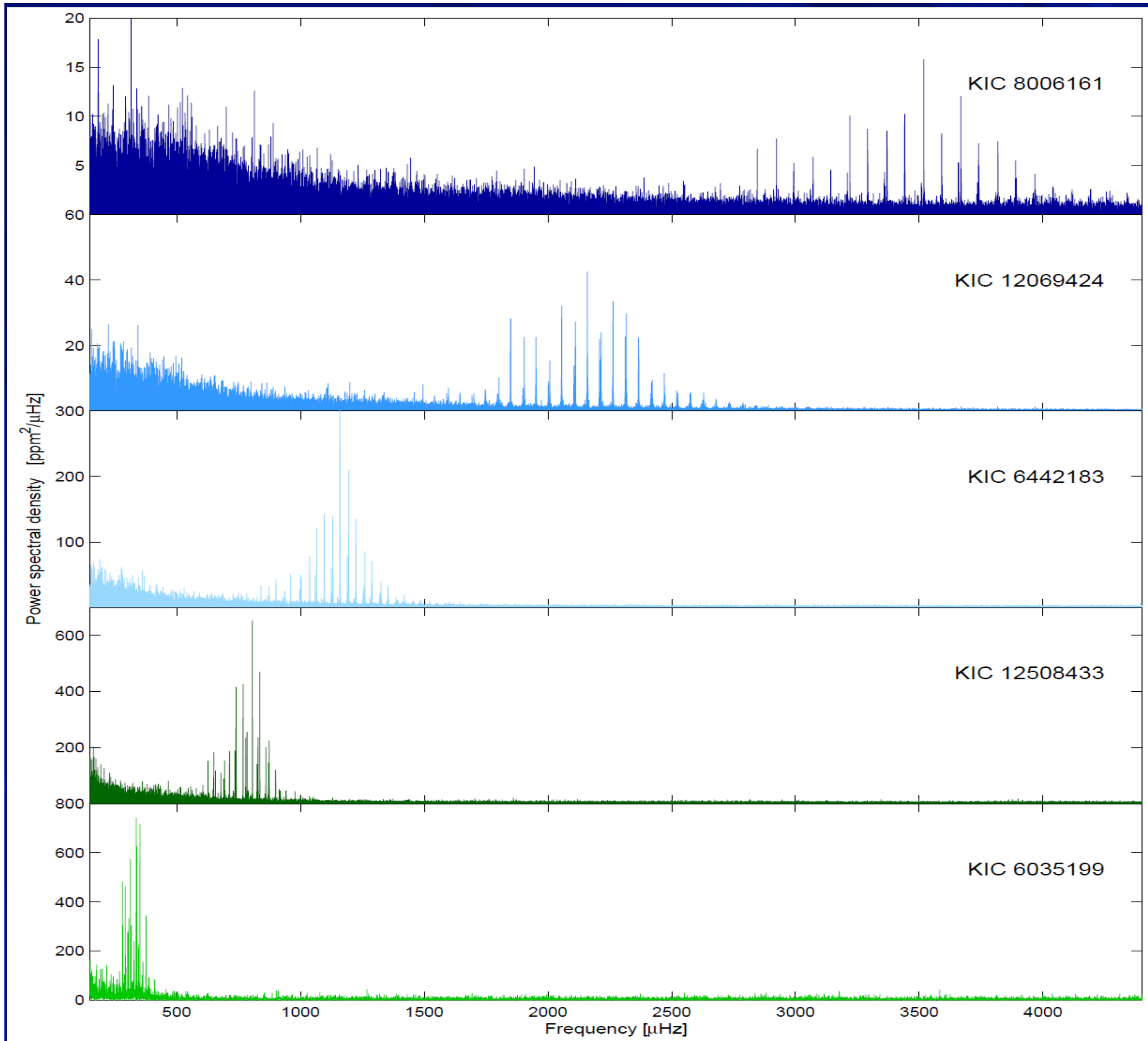
ν_{max}

Rotational Splittings

16 Cyg A
Metcalfe et al. 2012

Pure p-mode pattern



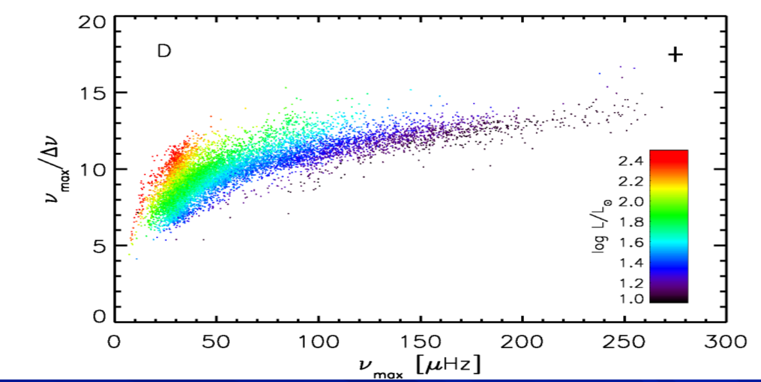


The observed MS pattern is a strong function of log g

From Chaplin & Miglio 2013

Scaling Relations for Bulk Populations

- Two most basic observables:
  - Frequency of maximum power
  - Mean frequency spacing



Hekker et al. 2010 data for Kepler giants

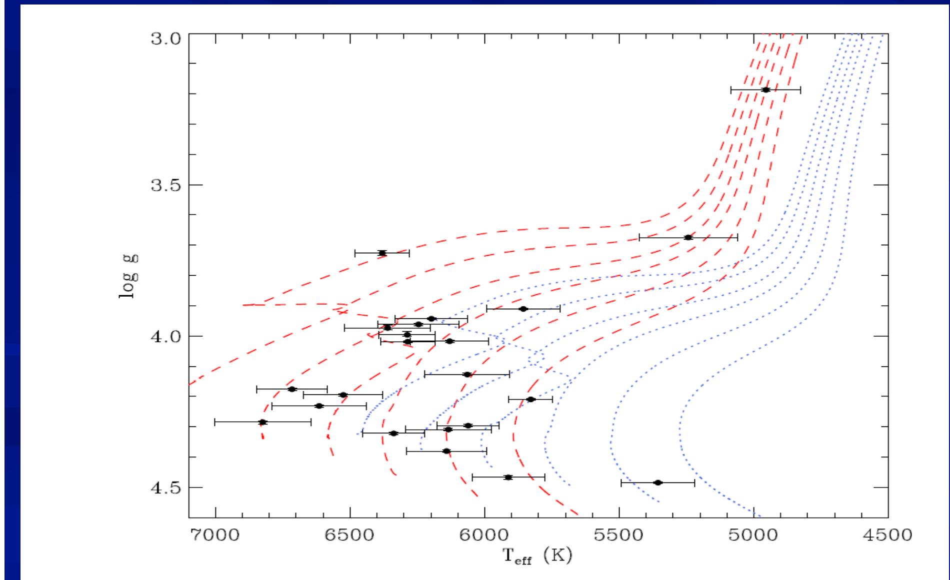
$$\frac{M}{M_\odot} \simeq \left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right)^3 \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-4} \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{3/2}$$

$$\frac{R}{R_\odot} \simeq \left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right) \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2} \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{1/2}.$$

Two Tests of the Radius Scale

Hipparcos Parallaxes + IRFM Teff
⇒Infer R, Compare with Seismology
Aguirre et al. 2012

Interferometric Radii:
Compare with Seismology
Huber et al. 2012



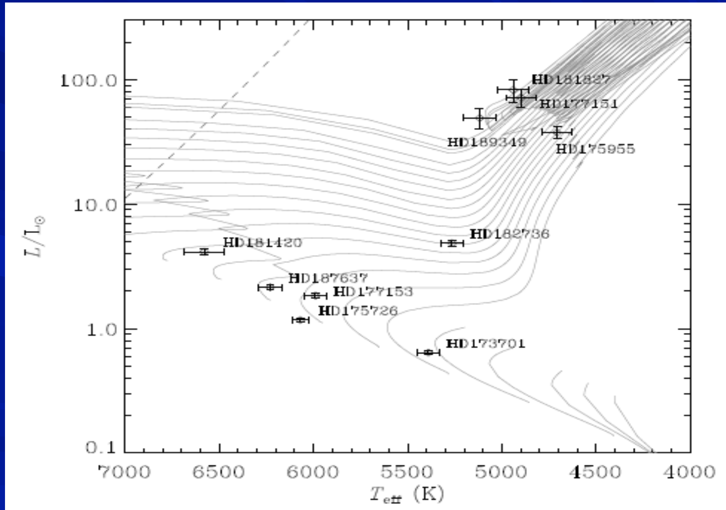
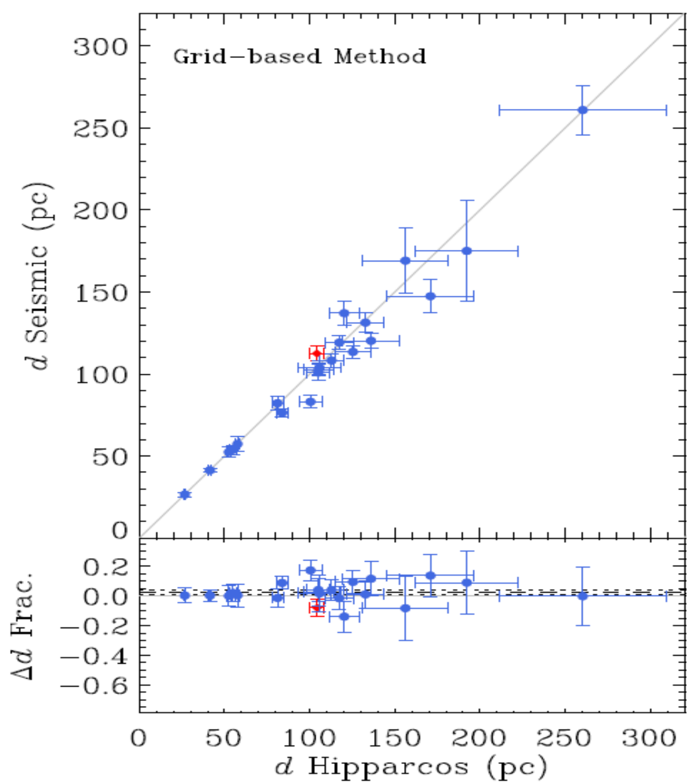


FIG. 1.— H-R diagram with the position of all stars calculated using spectroscopy, photometry and Hipparcos parallaxes. Solar metallicity BaSTI evolutionary tracks from 0.8-2.6 $M_{\odot}$ in steps of 0.01 $M_{\odot}$ are shown as grey lines. The dashed line marks the approximate location of the cool edge of the instability strip.

Good Radius Agreement!



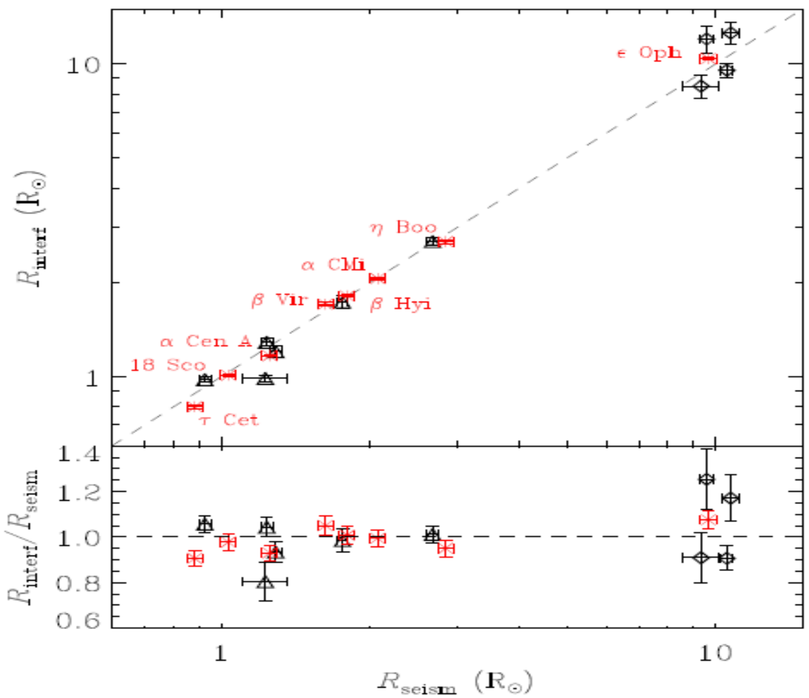
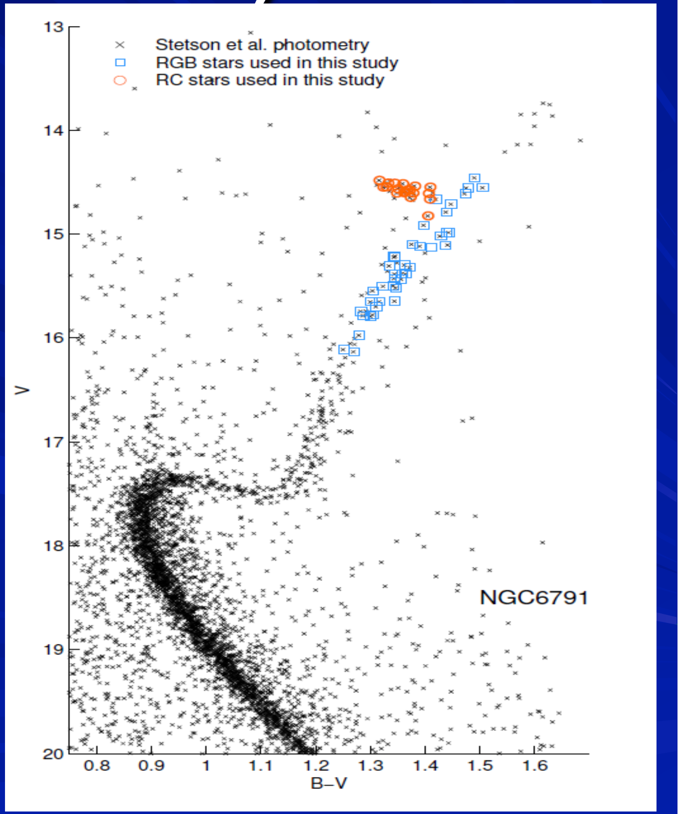


FIG. 7.— Comparison of stellar radii measured using interferometry and calculated using asteroseismic scaling relations. Black diamonds show our *Kepler* and CoRoT sample, and red asterisks show several bright stars as indicated in the plot for comparison. The dashed line marks the 1:1 relation.

Testing the Scaling Relations: NGC 6791 (Miglio et al. 2012)

- We have eclipsing binaries and good abundance constraints
- Lower RGB masses can be predicted from MSTO masses
- Cluster (and EB) distances test radius inferences



Radius and Mass Scaling in Clusters

- Discrepancy for clump giant radii relative to RGB radii (~0.05) tied to structural properties
- Small but real mass difference ~0.06 Msun, RGB vs. that expected from EB constraints on the MS (Brogaard et al. 2012)

Miglio et al. (2012)

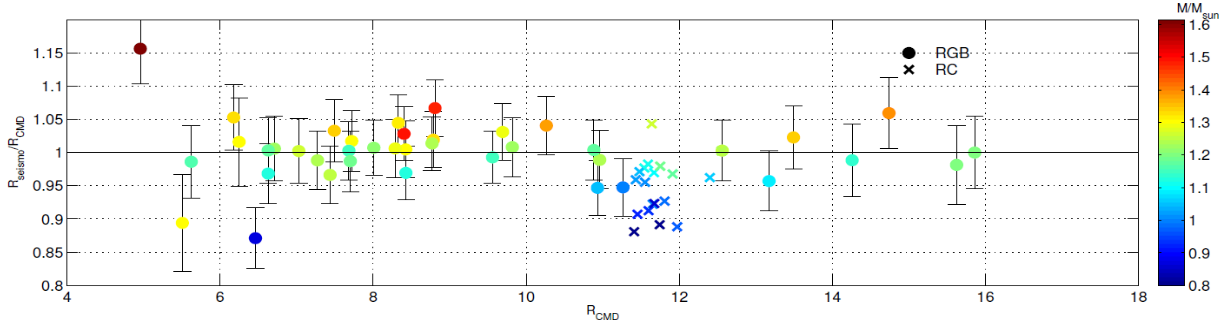
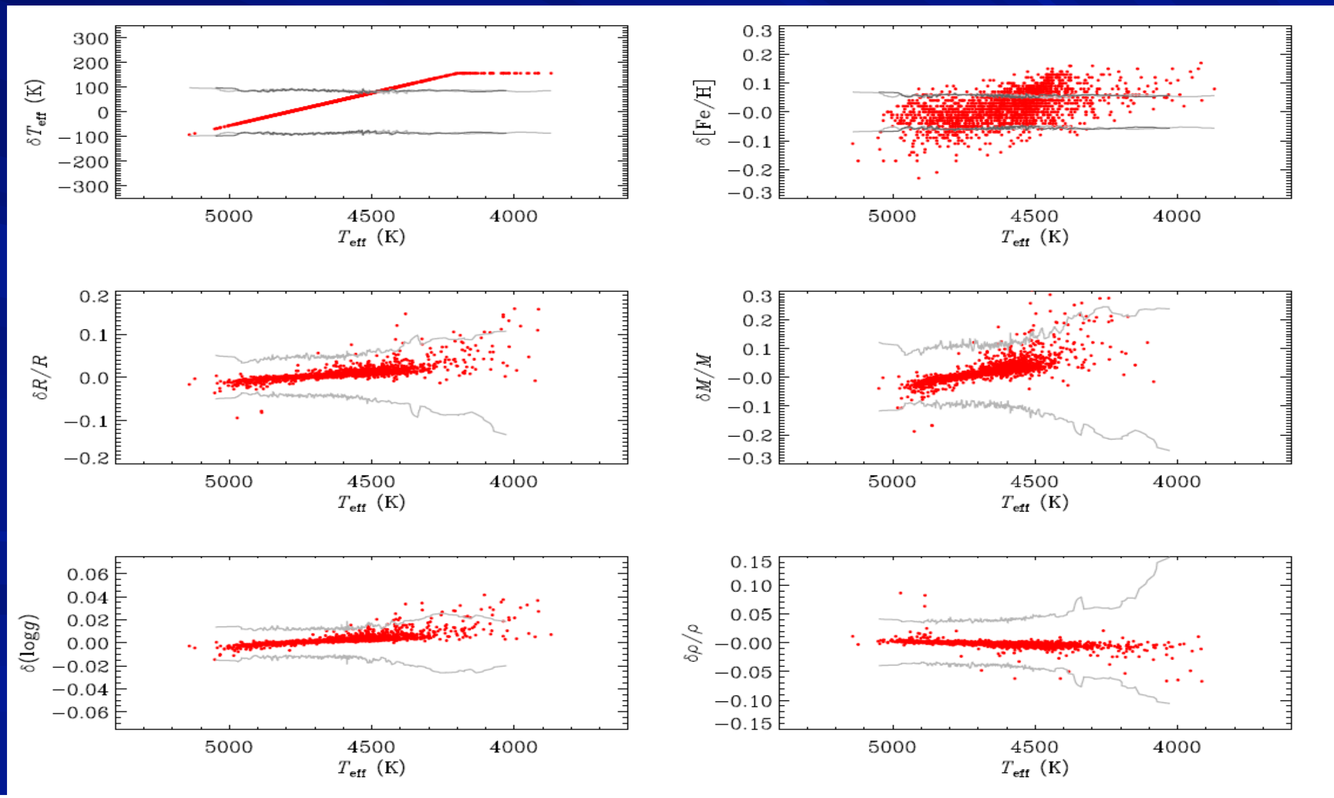


Figure 3. NGC6791: ratio between radii determined using L and $T_{\rm eff}$ ($R_{\rm CMD}$), and those obtained via Eq. 4 ($R_{\rm seismo}$). The mass of each star determined via Eq. 3 is colour coded.

The APOKASC Approach

- APOGEE sample: ~2,400 Red Giants
- Analyze light curves, extract mean asteroseismic properties ($\Delta\nu$, ν_{max})
- 1916 stars that pass quality control checks
- Scaling relations + grid-based modeling
- Check systematics
  - Spectroscopic inputs
  - Multiple pipelines

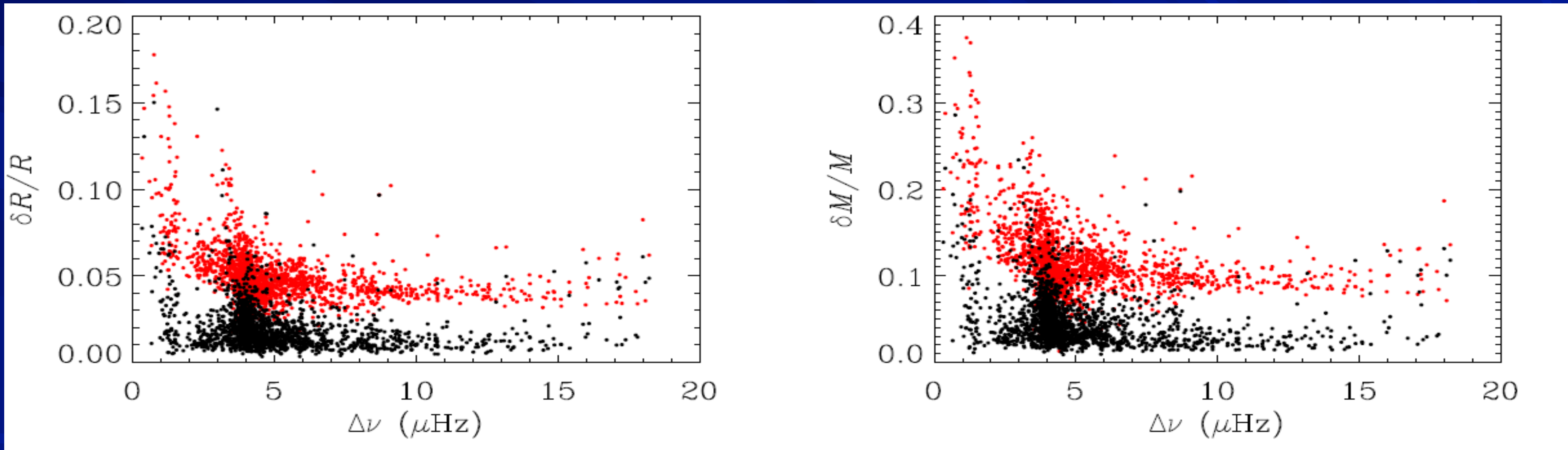
Impact of Systematic Shifts in Spectroscopic Inputs



Significant Impact R, M

Small Impact Log g, <rho>

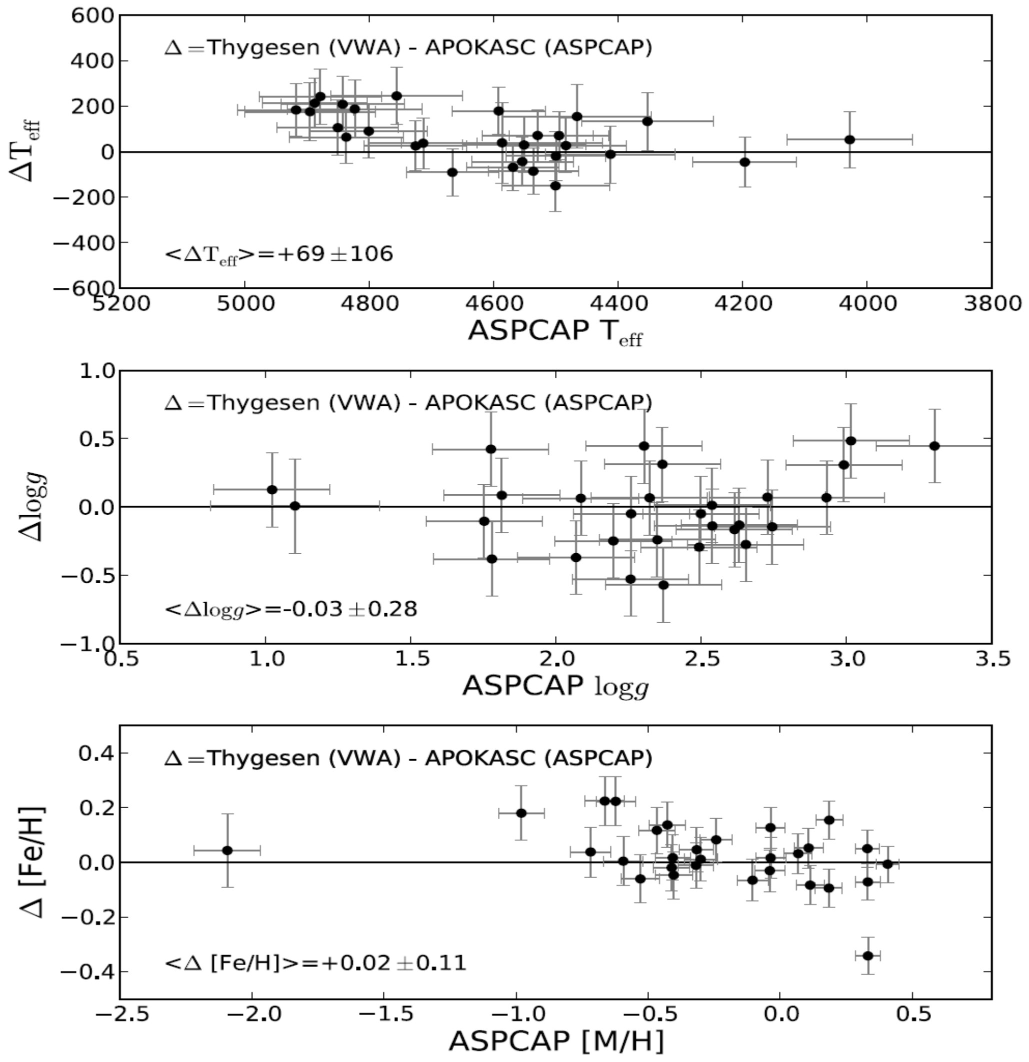
The Bottom Line: Formal Uncertainties in R,M



← Luminosity

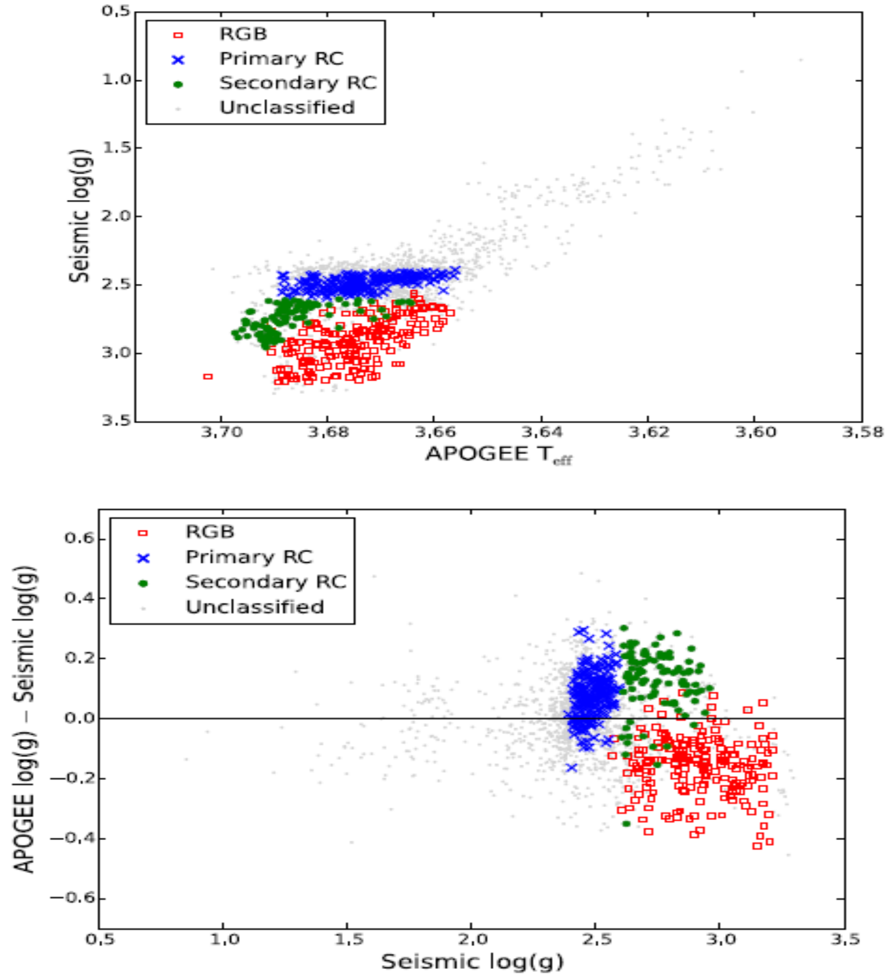
Validation of our Kepler field results

Good Agreement with Optical Spectroscopy of Giants

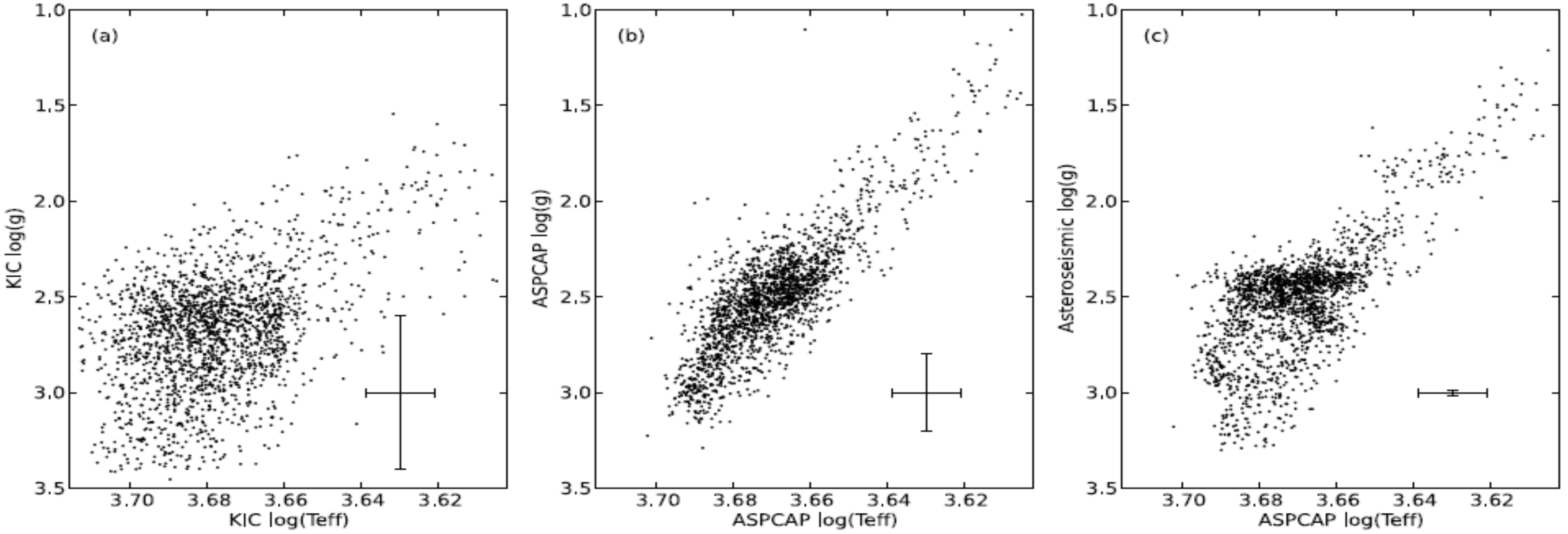


A Test of Atmospheres

- The difference between asteroseismic and spectroscopic log g is different for RC, RGB
- Is this an atmospheres or asteroseismic systematic?



Results: Snapping Into Focus

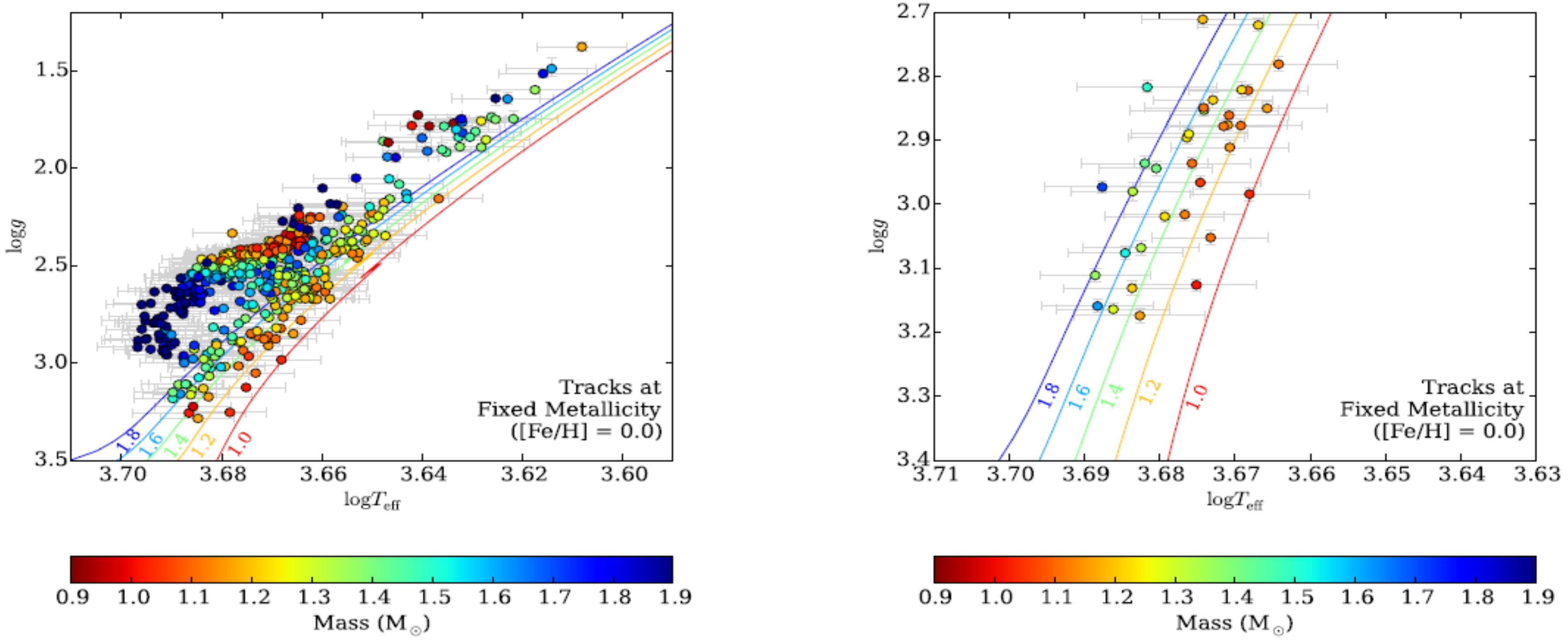


Photometry

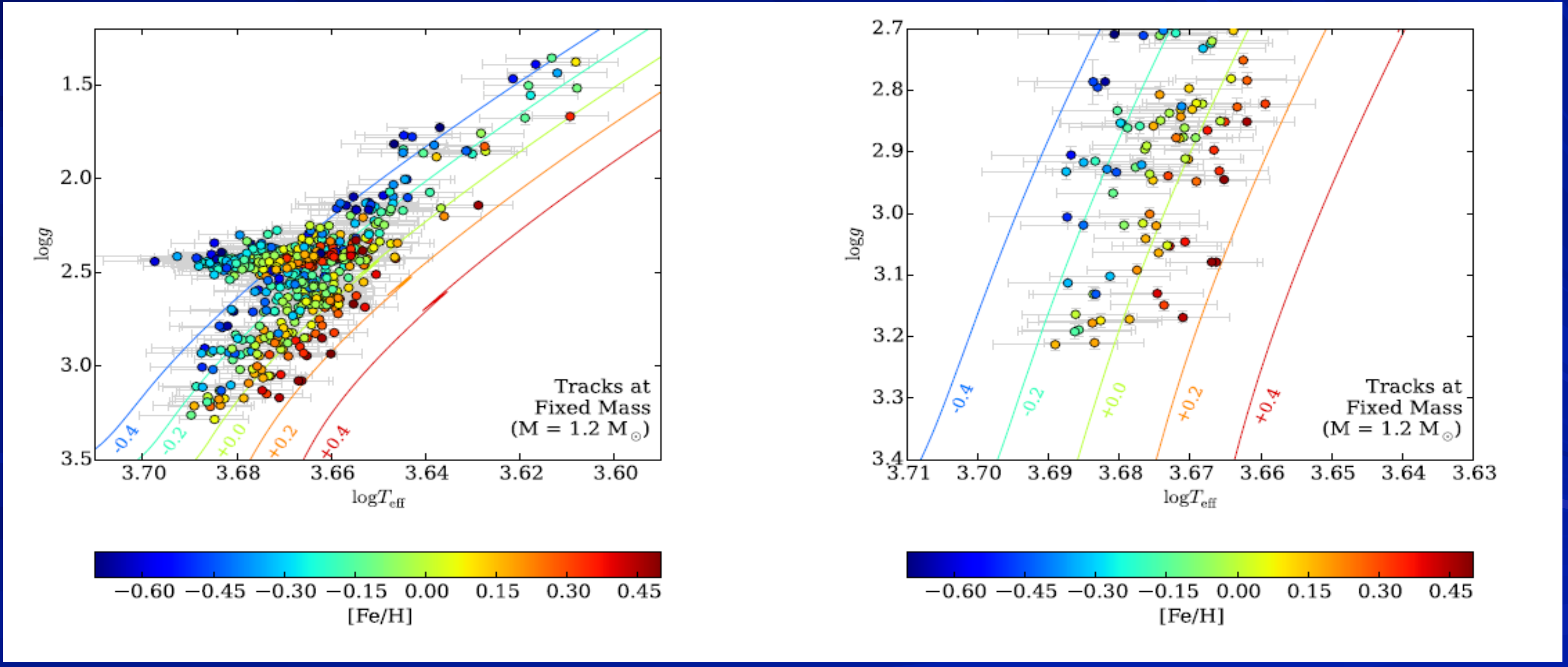
Spectroscopy

Asteroseismology + Spectroscopy

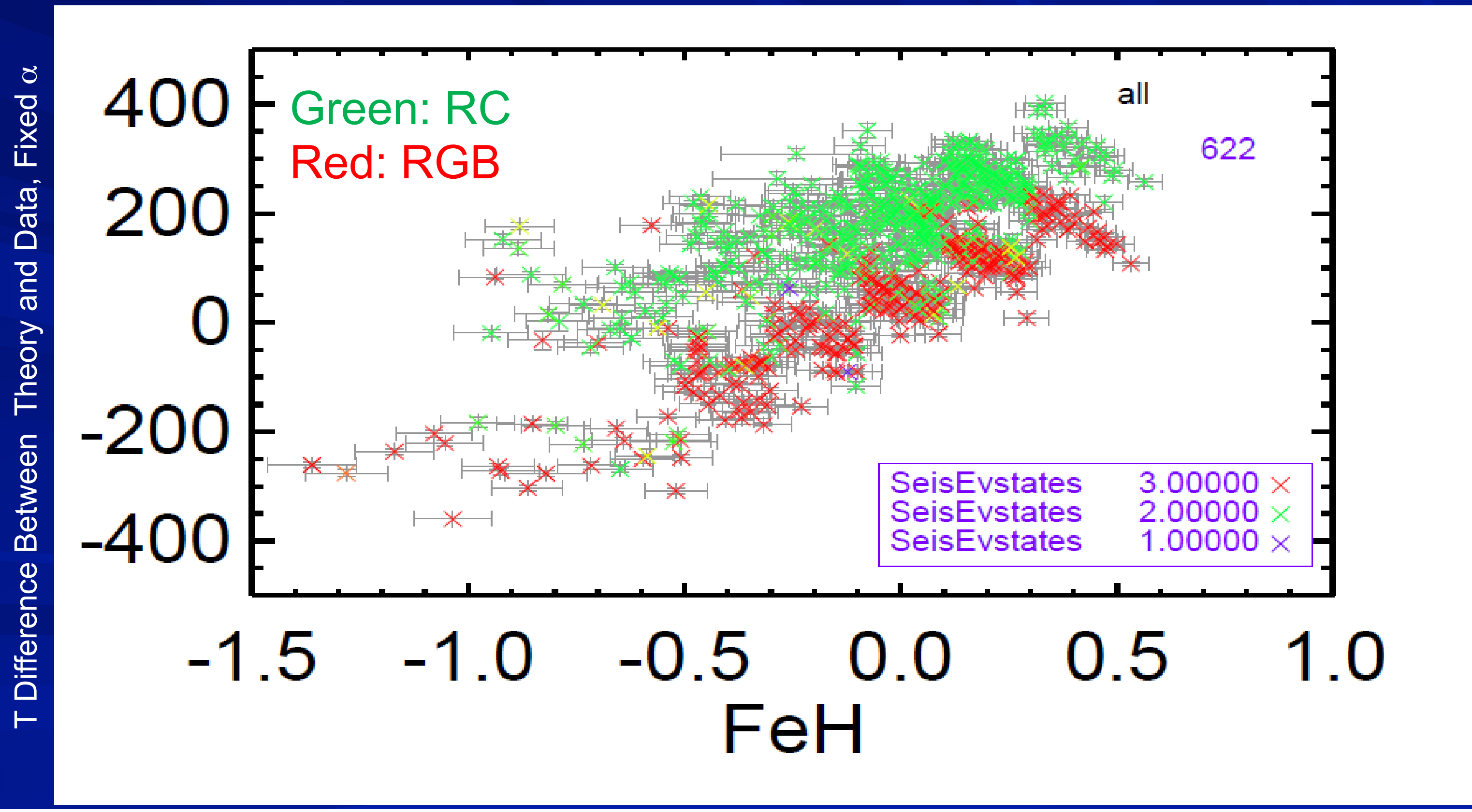
Mass Trends, Fixed [Fe/H]



Metallicity Trends, Fixed Mass



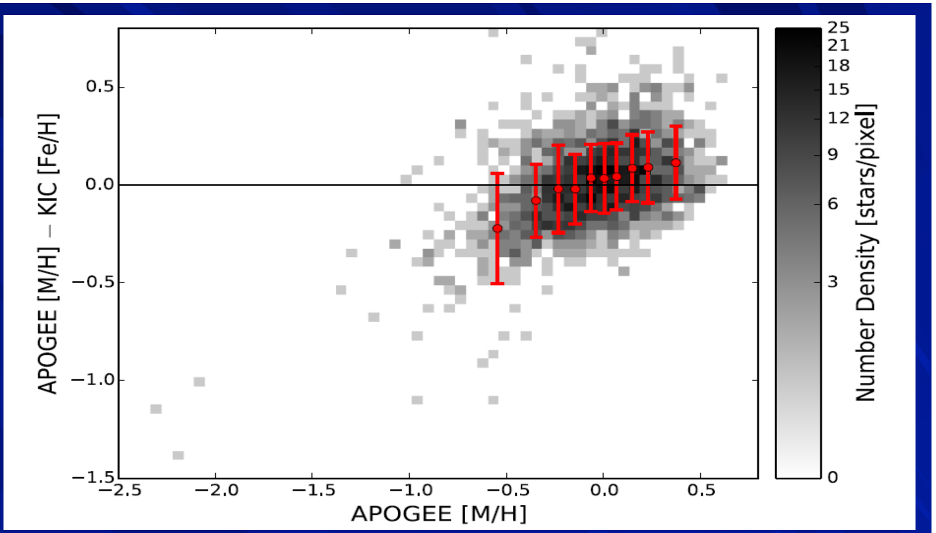
A Metallicity-Dependent Mixing Length?

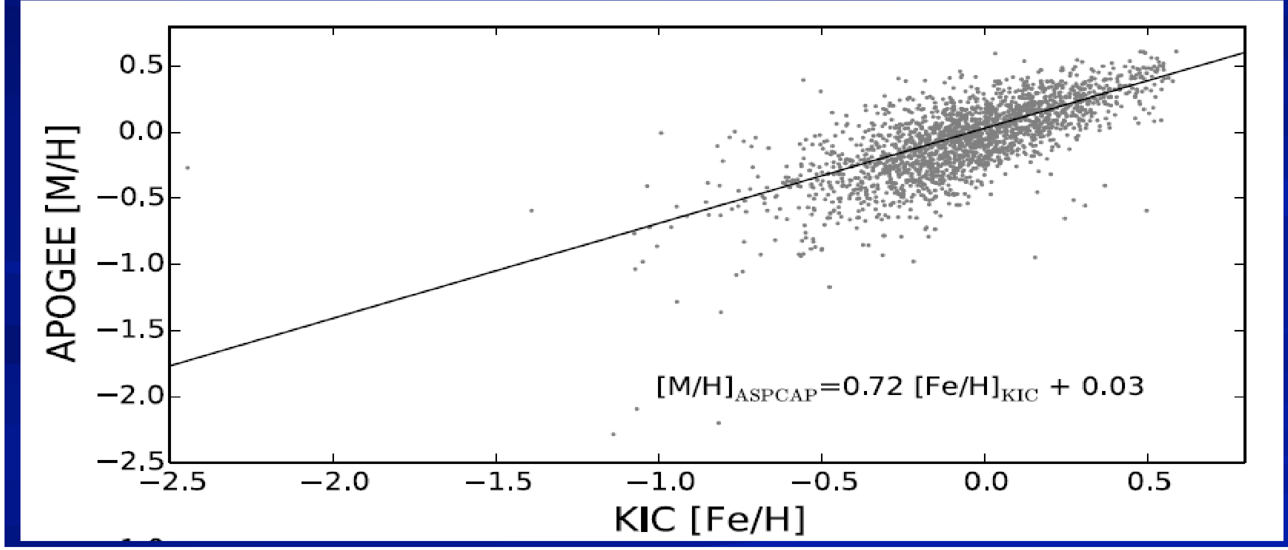


The KIC Re-assessed

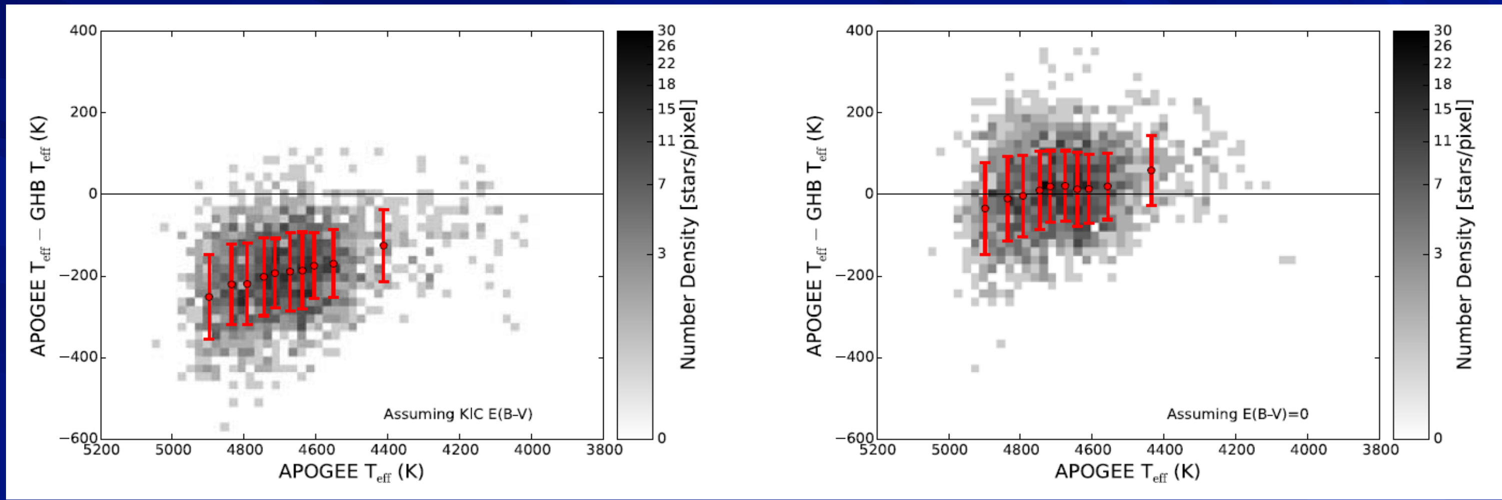
- We can evaluate the underlying stellar parameters against the KIC:
  - T_{eff} (depends on extinction)
  - Log g
  - [Fe/H]

KIC Metallicity *for Giants*: OK!





KIC Temperatures: An Overestimated Extinction

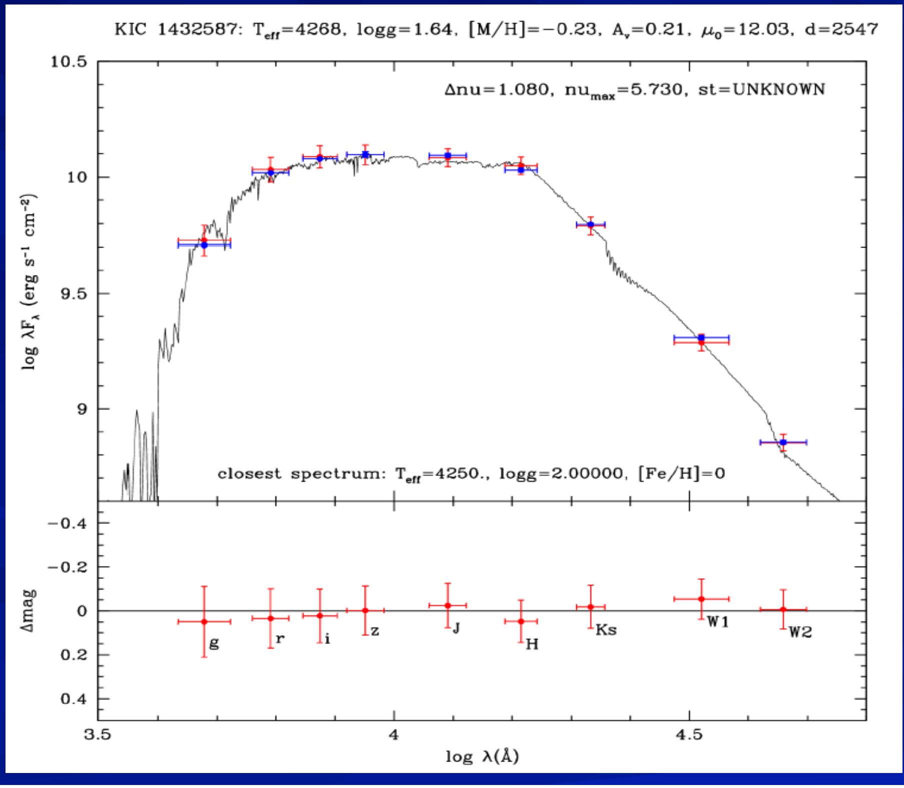


KIC Extinction

Zero Extinction

There is a large offset in T_{eff} between the IRFM and the spectroscopic scale if we adopt the KIC extinction map…

An Independent Test: SED Fitting of Kepler Stars with Asteroseismic log g



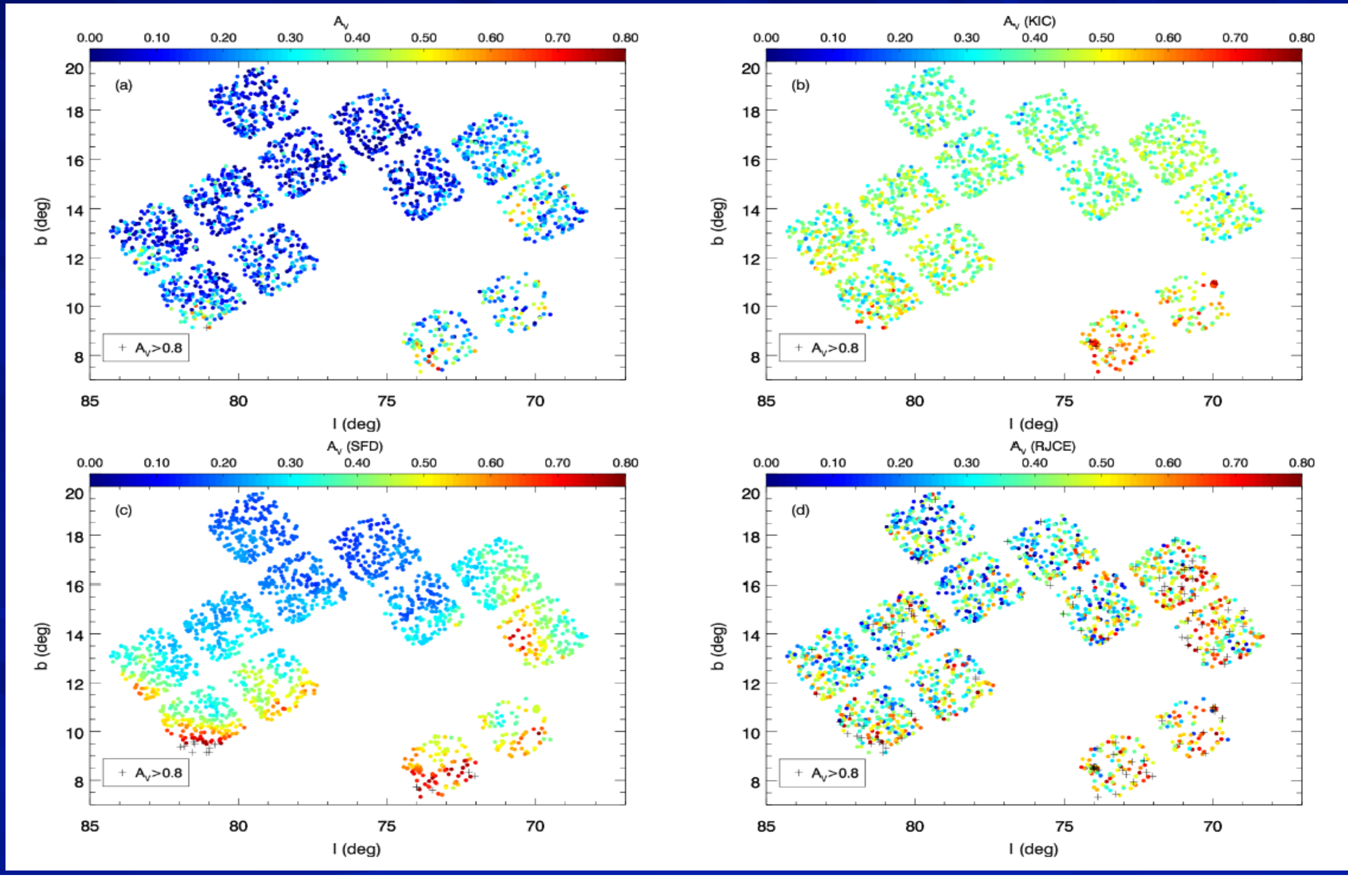
Rodrigues et al. 2014, Submitted ApJ

1916 distances and extinctions for red giants with spectra and asteroseismic log g

Bottom Line:
Inferred extinction
~0.41-0.42 KIC
(also SAGA)

Rodrigues et al.
Extinction Map

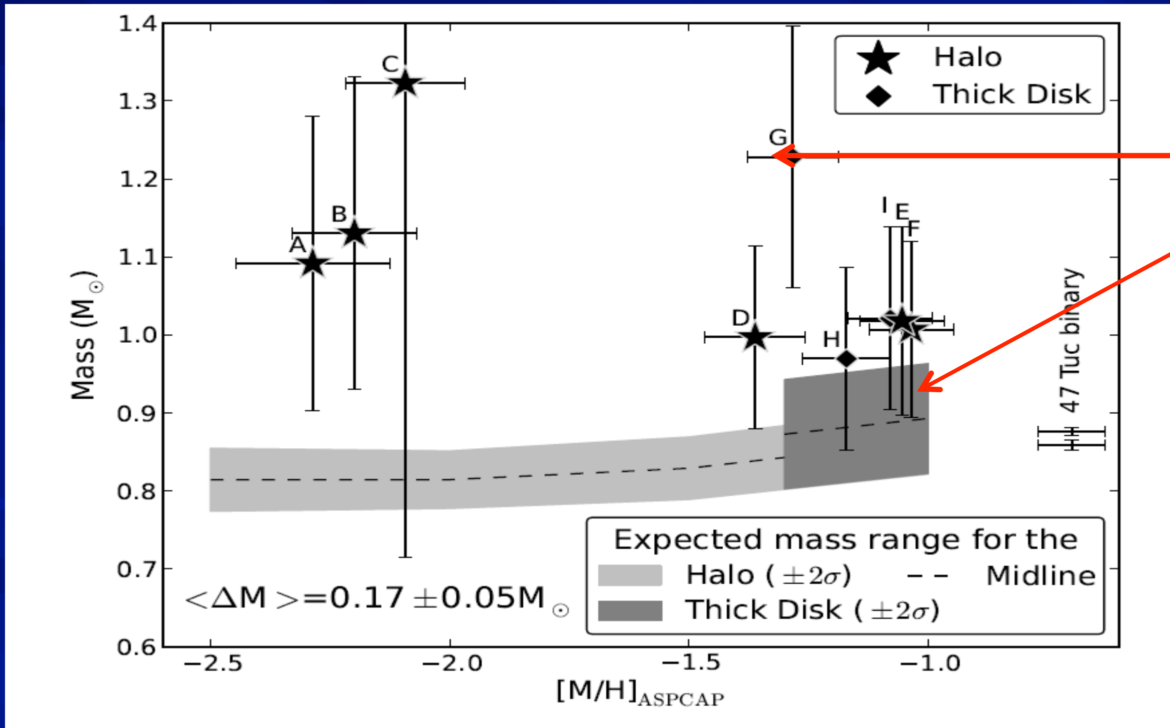
KIC Extinction Map



SFD
(Maximum)
Extinction
Map

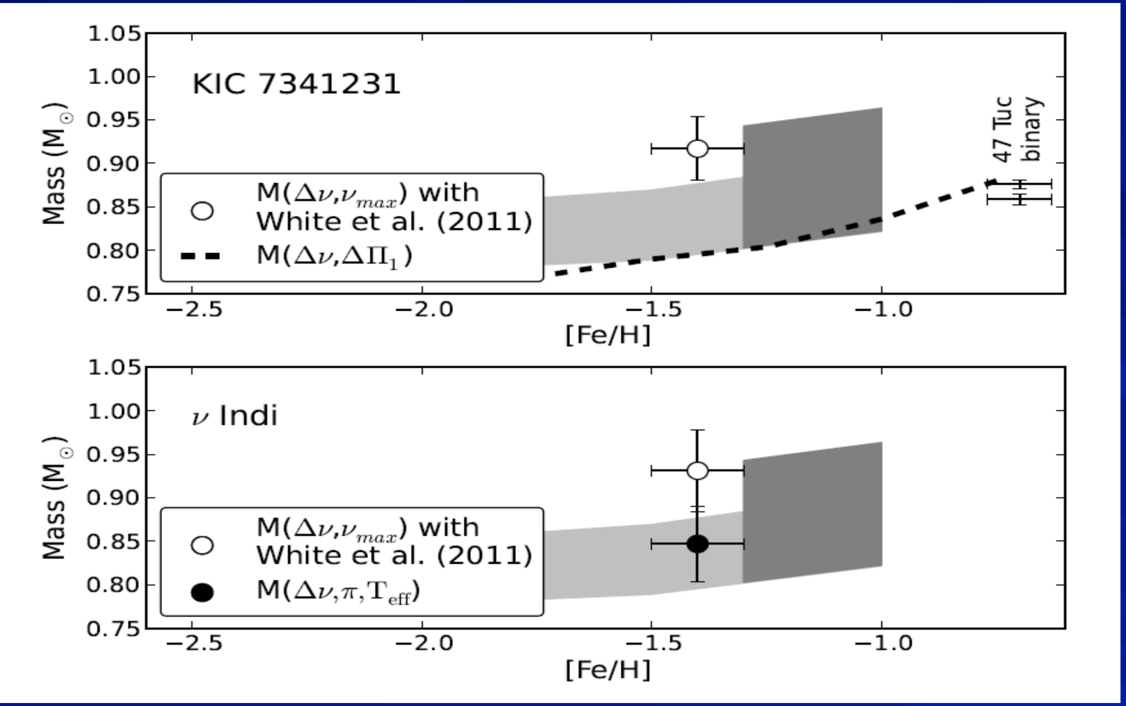
Trouble In Halo-Land

Epstein et al. (2014)



Halo Star Masses From SR Are Well Above Expected Values….

Do We Need to Go Beyond Scaling Relations?

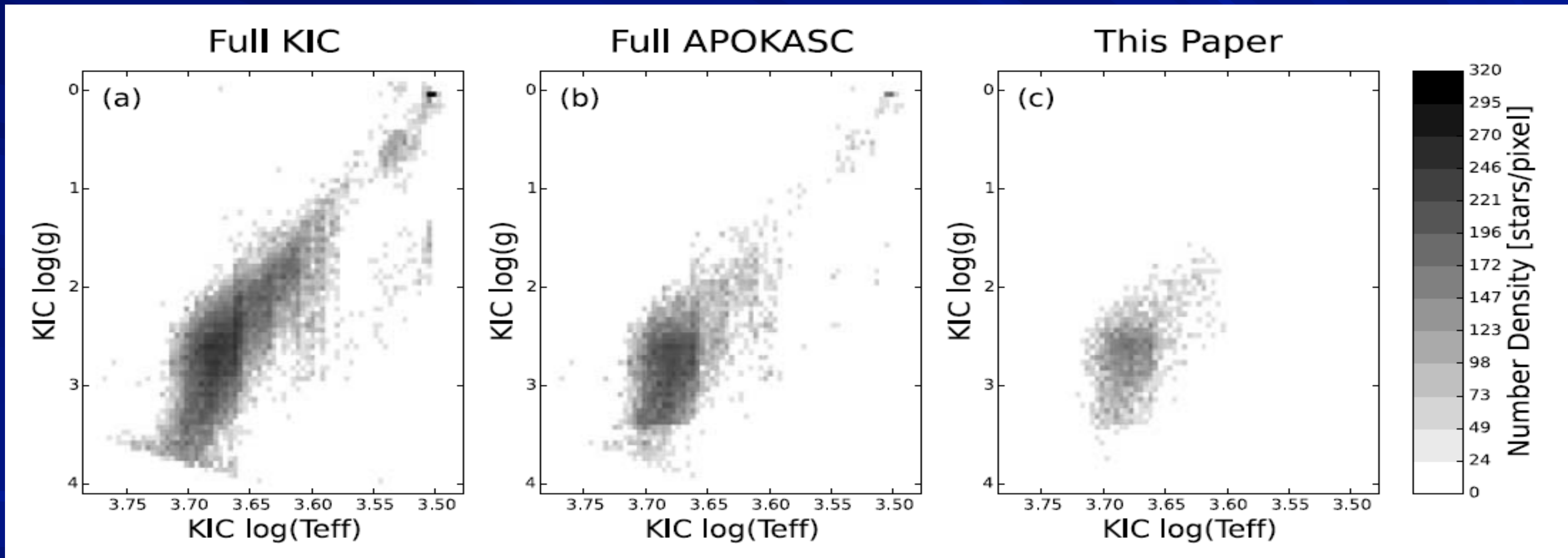


Calibrate…Correct…OR

Boutique Modeling: Reasonable Mass!

Parallax+ $\Delta\nu$: Reasonable Mass!

The Next Step: 10,000 spectra for December 2014



~1,400 "control" dwarfs
~400 asteroseismic dwarfs and subgiants
~8,200 red giants

Future: SDSS-4 + K2

- SDSS-4: will target a full magnitude and color limited Kepler sample

  (T_{eff} < 6500 K, H <11); giants + dwarfs
- K2 – numerous APOGEE targets already in fields, used for targeting. More opportunities possible (ask!)

Moving Forward

Spectroscopy

- Progress in understanding systematic shifts
- Individual abundance measurements
- Tying spectroscopy to the fundamental scale

Asteroseismology

- Evolutionary state diagnostics
- Separating systematic and random errors
- Calibrating against fundamental measurements (frequencies are not masses…)

Sample Selection Biases Must Be Assessed for Population Studies

Conclusions

- Papers submitted – distances, asteroseismology, spectroscopy for large Kepler red giant samples (tables coming)
- KIC performance assessed
- Gaia benchmarks
- Coming soon:
  - Dwarf and Subgiant Catalog
  - Dwarf Metallicity Control Sample
  - CoRoGEE

Upcoming Conferences:

Santa Barbara, CA
The Milky Way and its Stars: Stellar Astrophysics, Galactic Archaeology, and Stellar Populations
Feb 2, 2015 - Feb 6, 2015

Bad Honnef, Germany
Reconstructing the Milky Way History: Spectroscopic Surveys, Asteroseismology and Chemodynamical Models
June 1, 2015- June 5, 2015