Measuring Stellar Parameters

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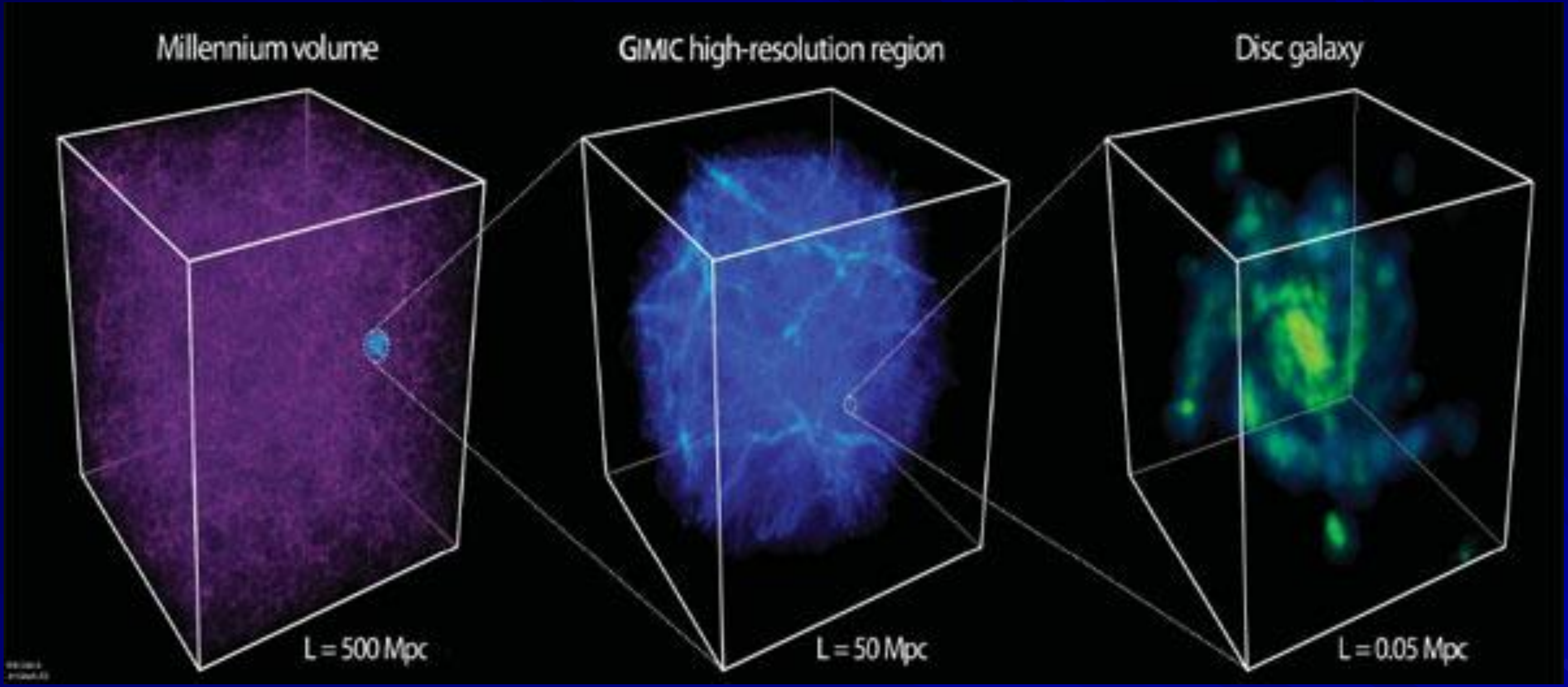
Galactic Archeology



We can test the formation history of the Milky Way if we can precisely measure stellar ages and abundances.

PROBLEM: Are our tools up to the task?

Overall Picture

- Equations of Stellar Structure
- Mass, Composition, Age (plus rotation and magnetic fields) specify the properties of a star
- Classic Observables: L, R, Teff, log g, kinematics
- New (Seismic) Observables: Core properties; surface CZ depth

Global Stellar Properties & Their Dynamic Ranges

- Energy output (L) is related to the surface temperature and radius through

  $L = 4\pi R^2 \sigma T_{eff}^4$

  Where T_{eff}^4 is the flux per unit area that a blackbody would have

- $L_{sun} = 3.844 \times 10^{33}$ erg/s
- **For normal stars $10^{-4}\ L_{sun} < L < 10^{6}\ L_{sun}$**

Luminosity

Historical Path

- Measure Fluxes
- Correct for Extinction
- Infer Distance

- *All of these methods scale well to surveys*

Complications

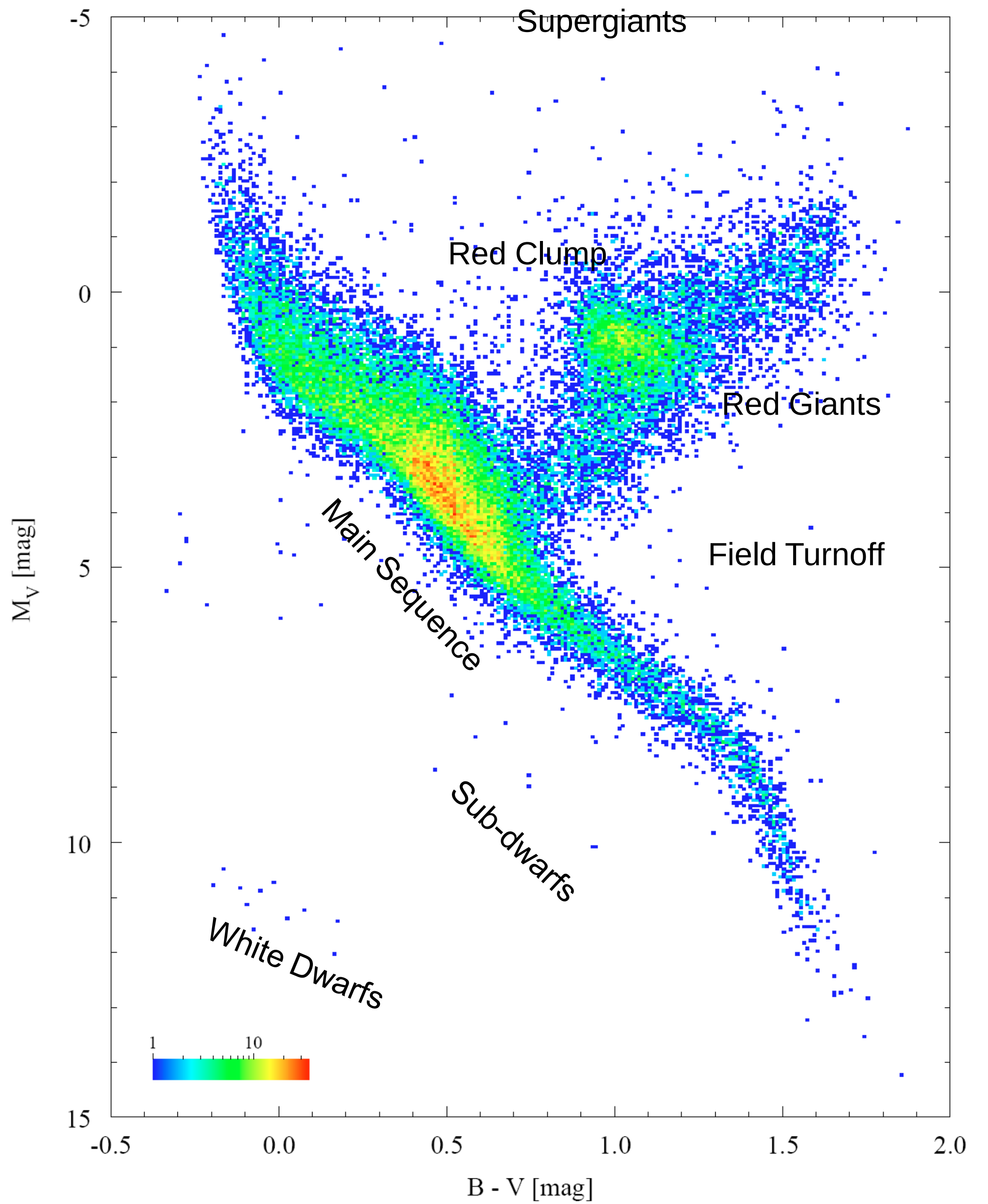
- *Absolute photometry is astonishingly difficult to do well*
- Blends (esp. binaries) affect fluxes and colors
- Reconstructing the SED is quite model dependent
- Extinction is important

Key Future Development: Gaia

The HR Diagram

- Distinct Populations
- Important features give information about galactic populations and relative timescales

Hipparcos CMD, $\sigma < 20\%$



Gaia and Hipparcos

- Hipparcos:

10^5 stars

σ=1 mas

- Gaia:

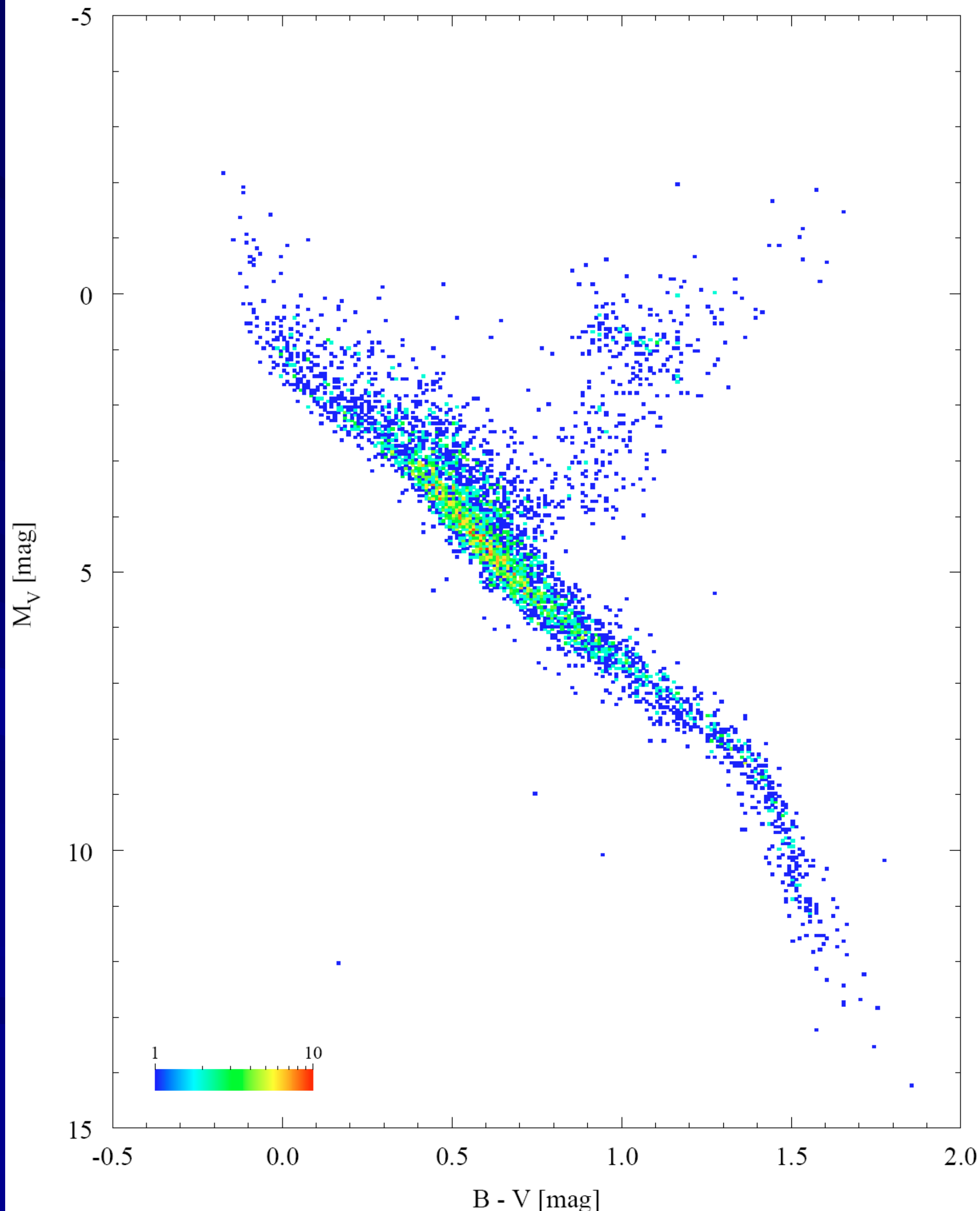
10^9 stars

σ=0.003 mas (12)

σ=0.01 mas (15)

σ=0.2 mas (20)

Hipparcos CMD, σ < 5%



Binaries are Fundamental Astrophysical Calibrators

- EB are efficiently found in time domain surveys
- VB – Gaia!

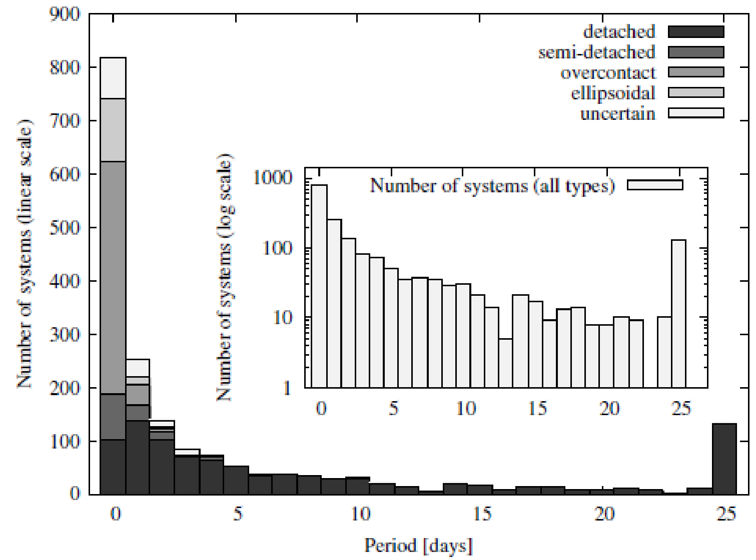


Figure 11. Distribution of periods for all the stars identified as eclipsing binaries in the *Kepler* Q1 data set. The baseline was 34 days (44 with Q0). The bars are stacked by morphology types (detached, semi-detached, overcontact, ellipsoidal, and uncertain). The inlet depicts the number of systems in log scale.

- Complications:
- Detectability – Visual
- Detectability – Eclipsing
- Labor and Resource Intensive Followup
- Difficult to measure composite properties
- Peculiar Systems

Prsa et al. 2011

The Binary M-R Relationship

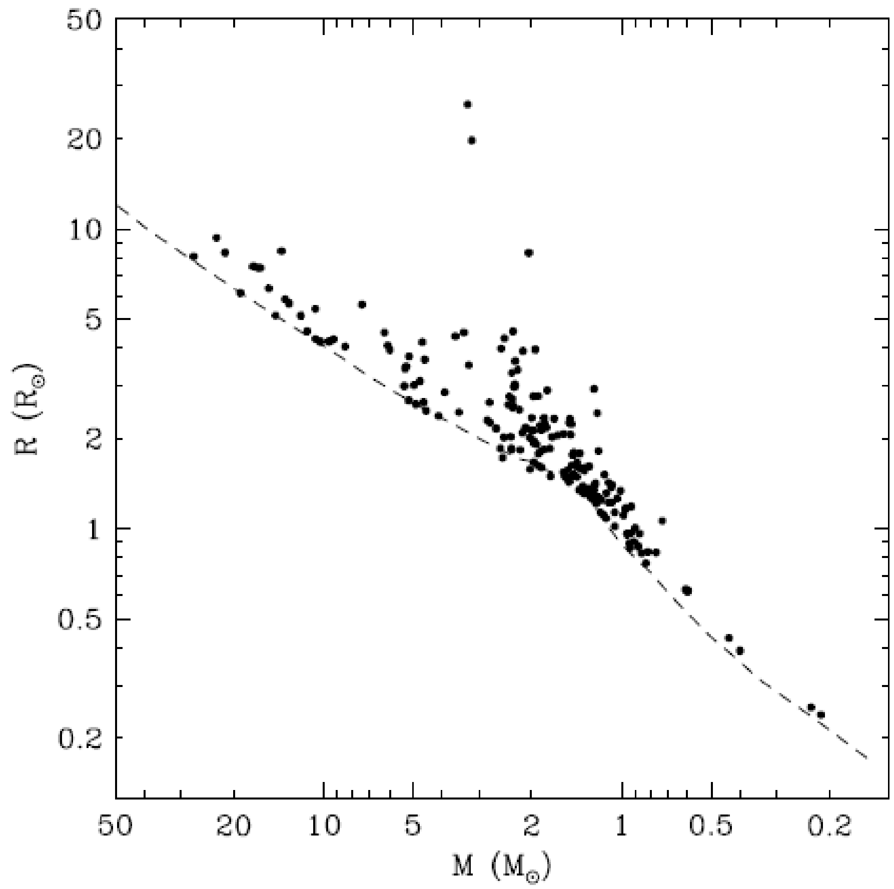


Fig. 2 R vs. M for the stars in Table 2; error bars are smaller than the plotted symbols. A theoretical zero-age main sequence (ZAMS) for solar metallicity from Girardi et al. (2000) is shown by the dashed line.

Torres, Anderson & Gimenez 2009

The Fundamental Mass-Luminosity Relationship

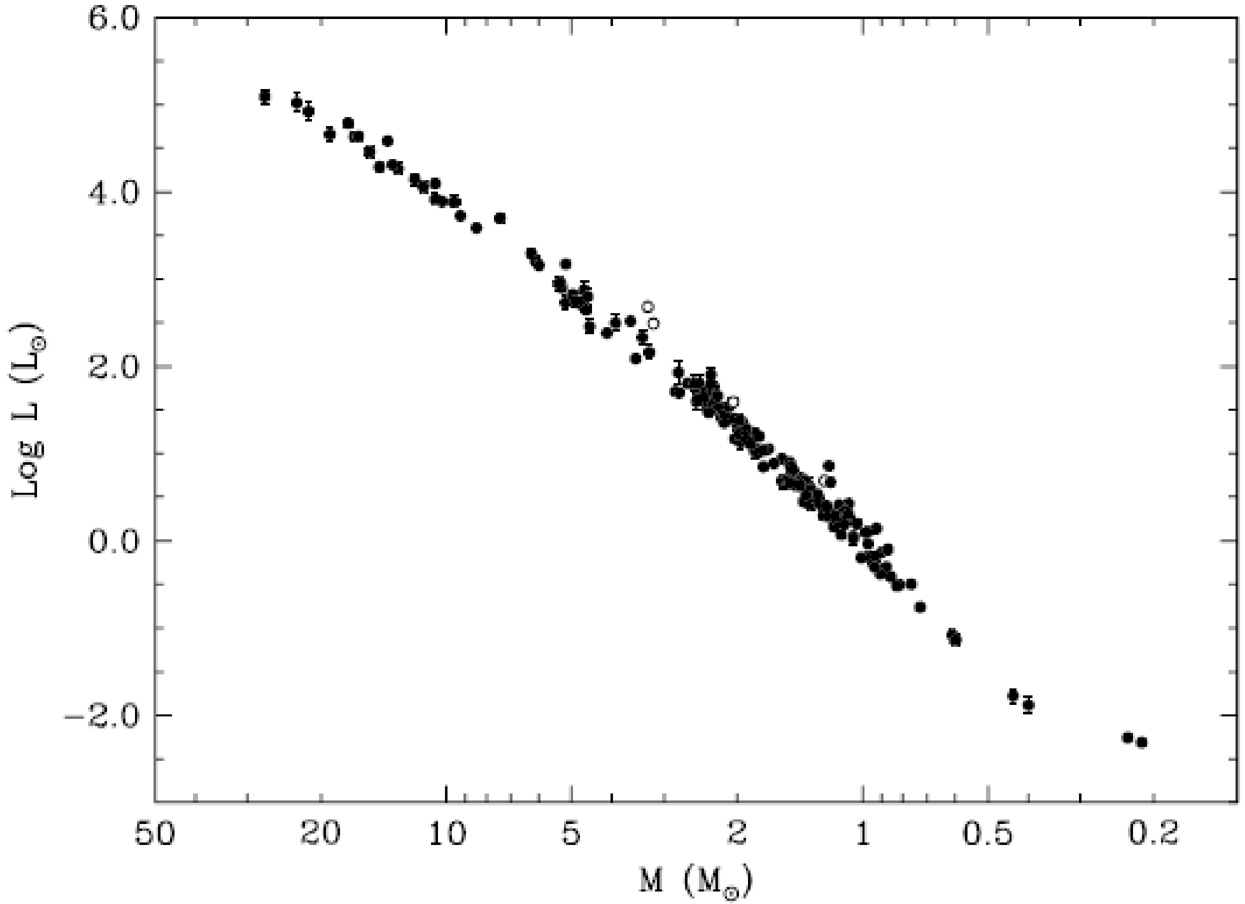


Fig. 5 The mass-luminosity relation for the stars in Table 2. Error bars are shown, and stars classified as giants are identified by open circles. See Sect. 6 for a discussion of the effects of evolution in this diagram.

Scatter in the HR Diagram is real and tied to composition

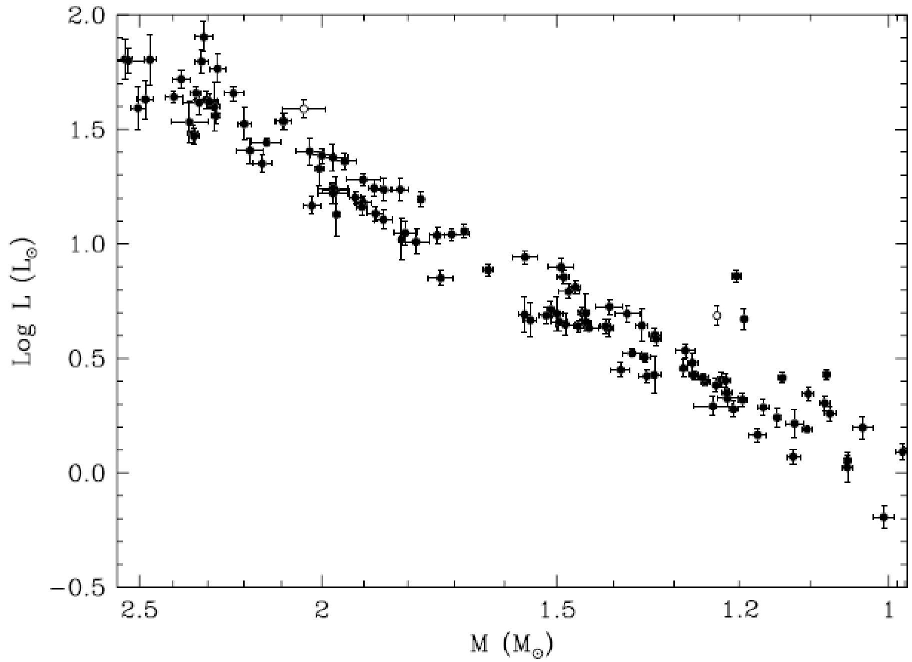
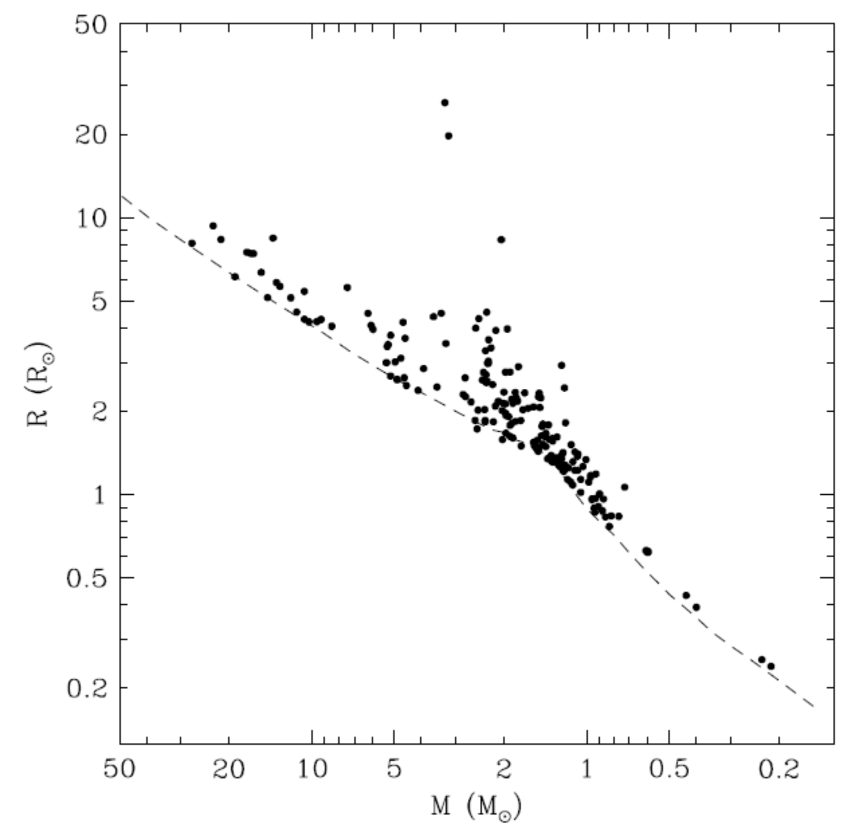
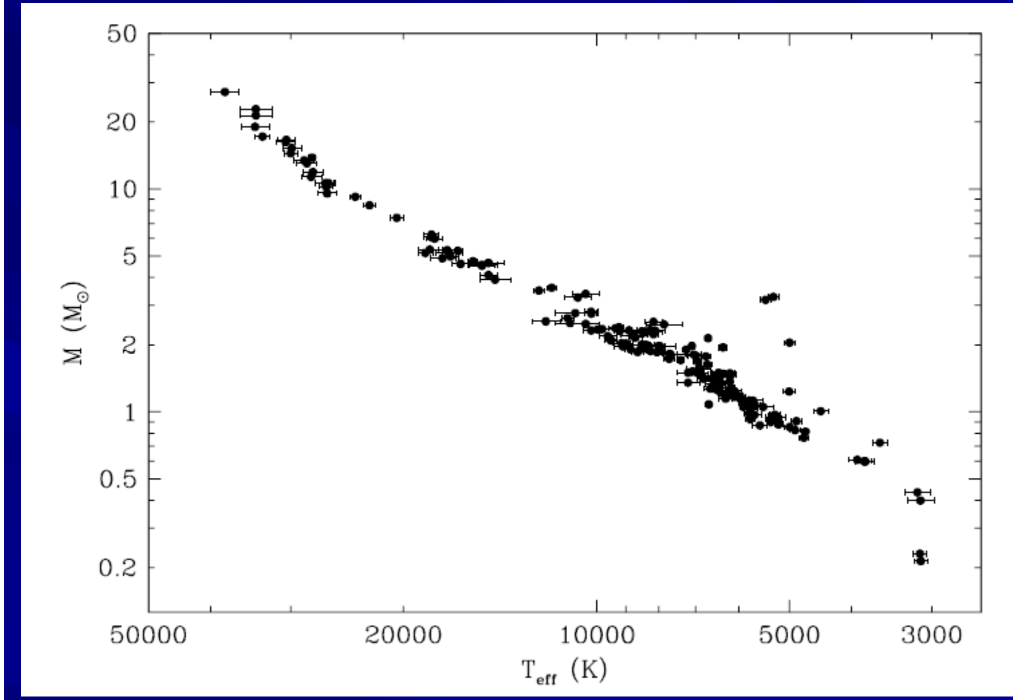


Fig. 6 Close-up of the 1–2.5 $M_\odot$ range of the mass-luminosity relation in Fig. 5. The very significant scatter in log L at each mass value is due to the combined effects of stellar evolution and abundance differences (see text). Open circles: stars classified as giants.

There are also strong M-R and M-Teff relationships





Note: Radii exhibit evolutionary effects

Effective Temperature

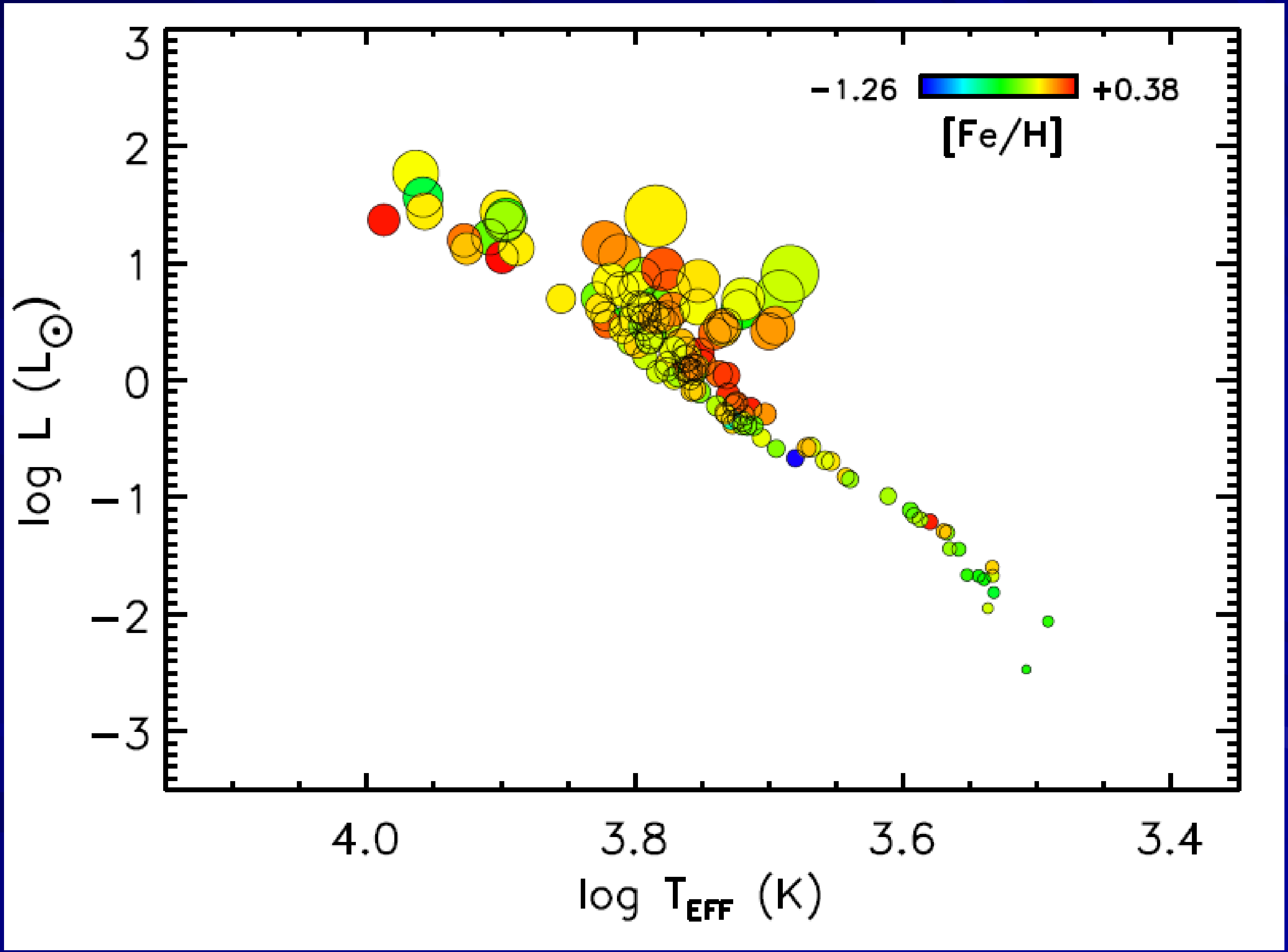
- $L = 4\pi R^2 \sigma T_{eff}^4$ **defines** the effective temperature
- The effective temperature scale is defined rigorously only for stars of known R.
- Calibrated relationships that are commonly used:
  - – Photometric estimates based on colors (Wien's law) or SED fitting; IRFM
  - – Spectroscopic estimates based on stellar absorption lines (Boltzmann/Saha equations)
- Solar Teff = 5,770 K

For normal stars 3,000 K < Teff < 50,000 K

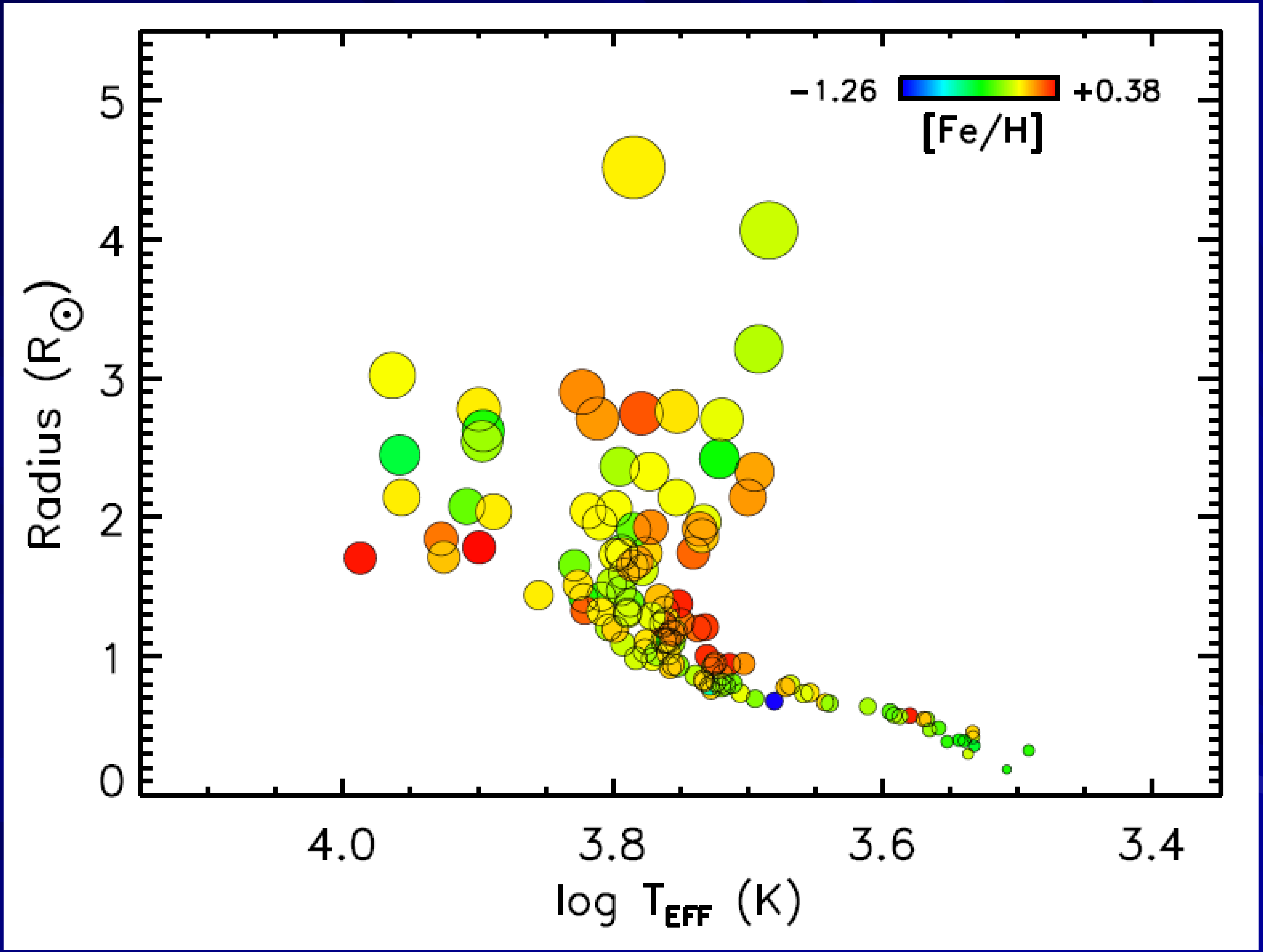
Interferometry and Radius

- With the advent of optical interferometry we can now measure direct angular diameters with uncertainties ~0.05 mas.
- L + R => Teff!

The Interferometric Sample



Boyajian et al. 2013



−1.26
+0.38
[Fe/H]
5
4
3
2
1
0
Radius ($R_\odot$)
4.0
3.8
3.6
3.4
log T_{EFF} (K)

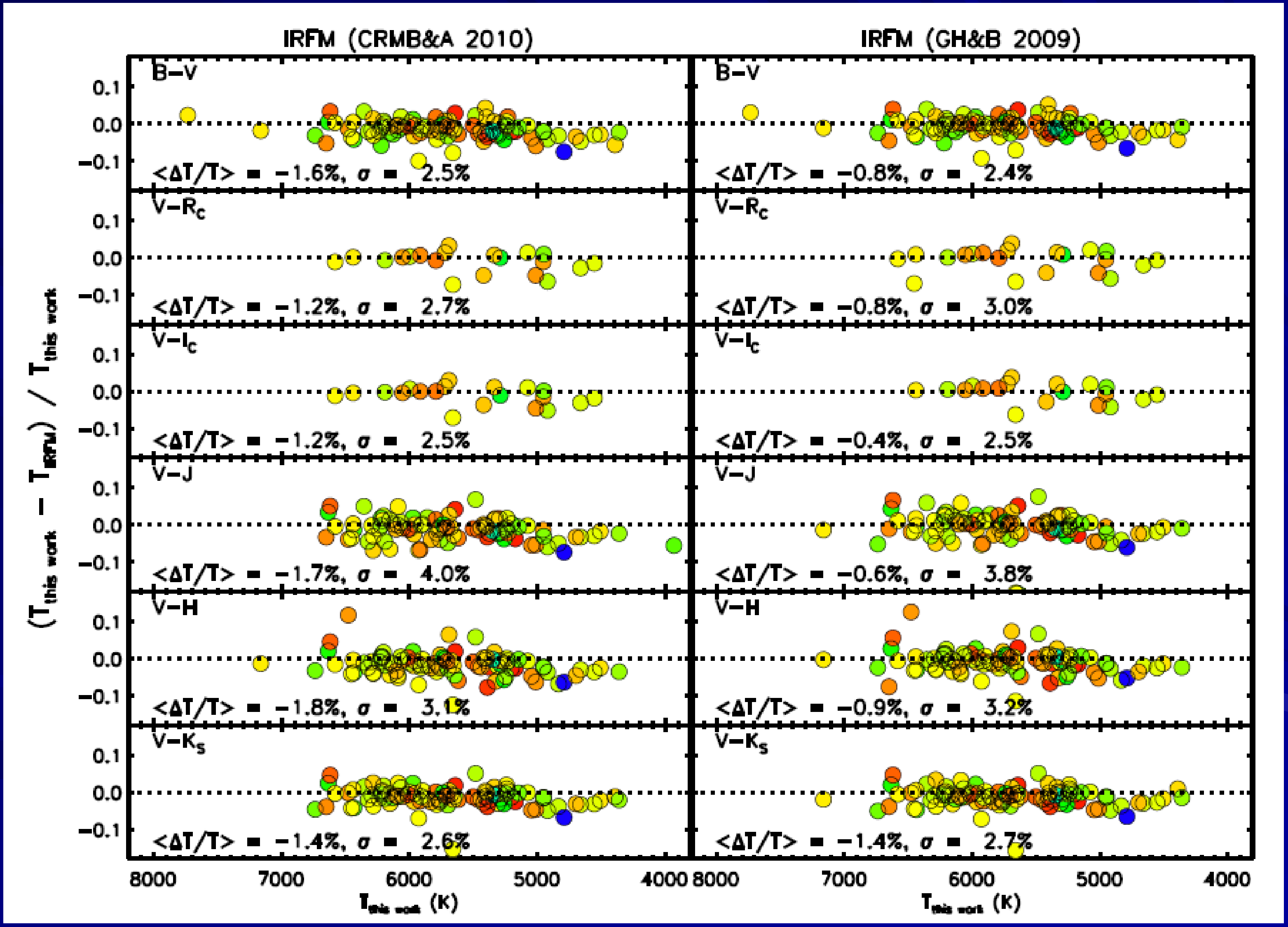
The Temperature Paradox

- Temperature is the single most important determinant of a stars visible properties
- We have numerous and powerful diagnostics testable with fundamental data

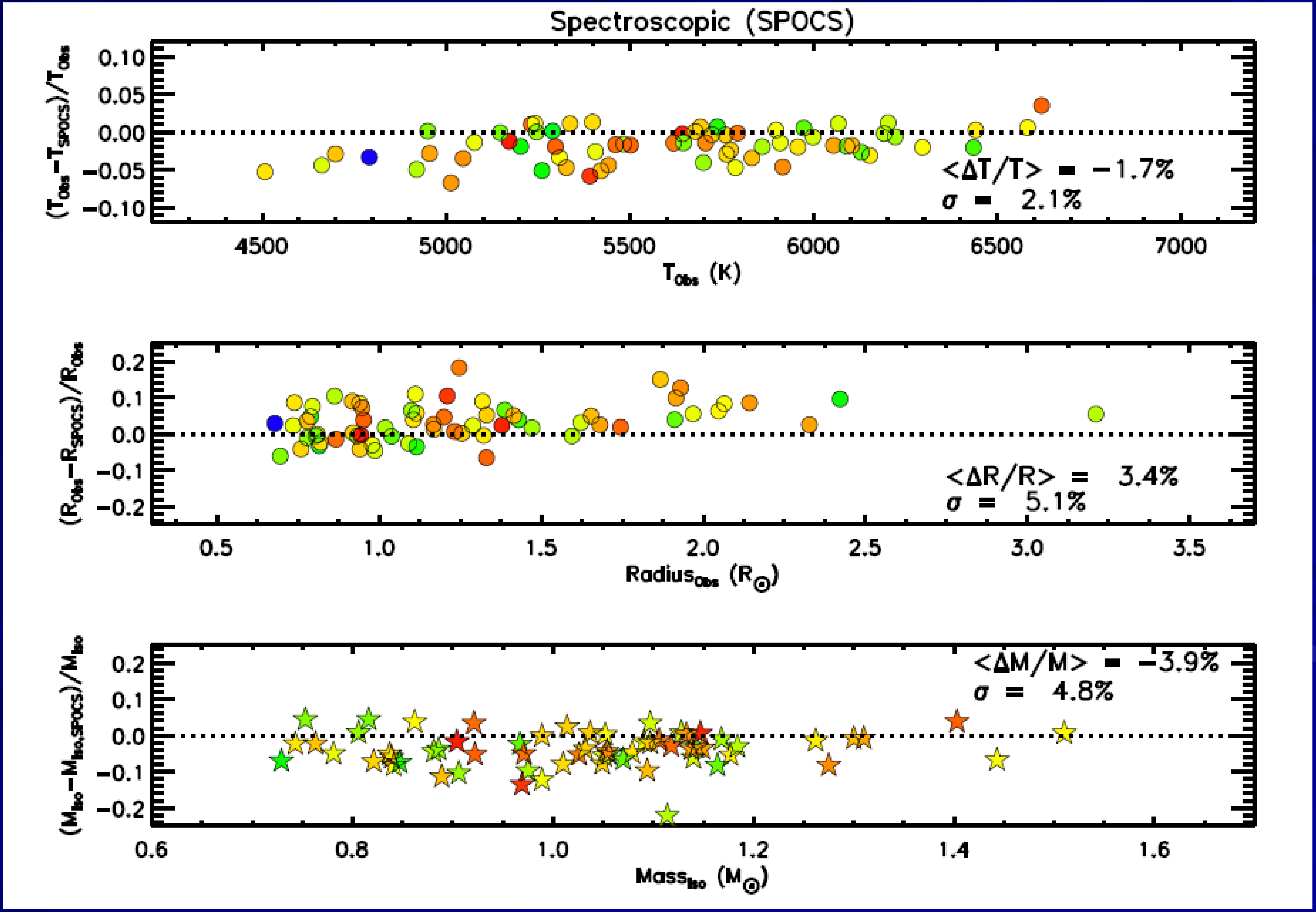
YET

- There are significant disagreements between them that are not resolved

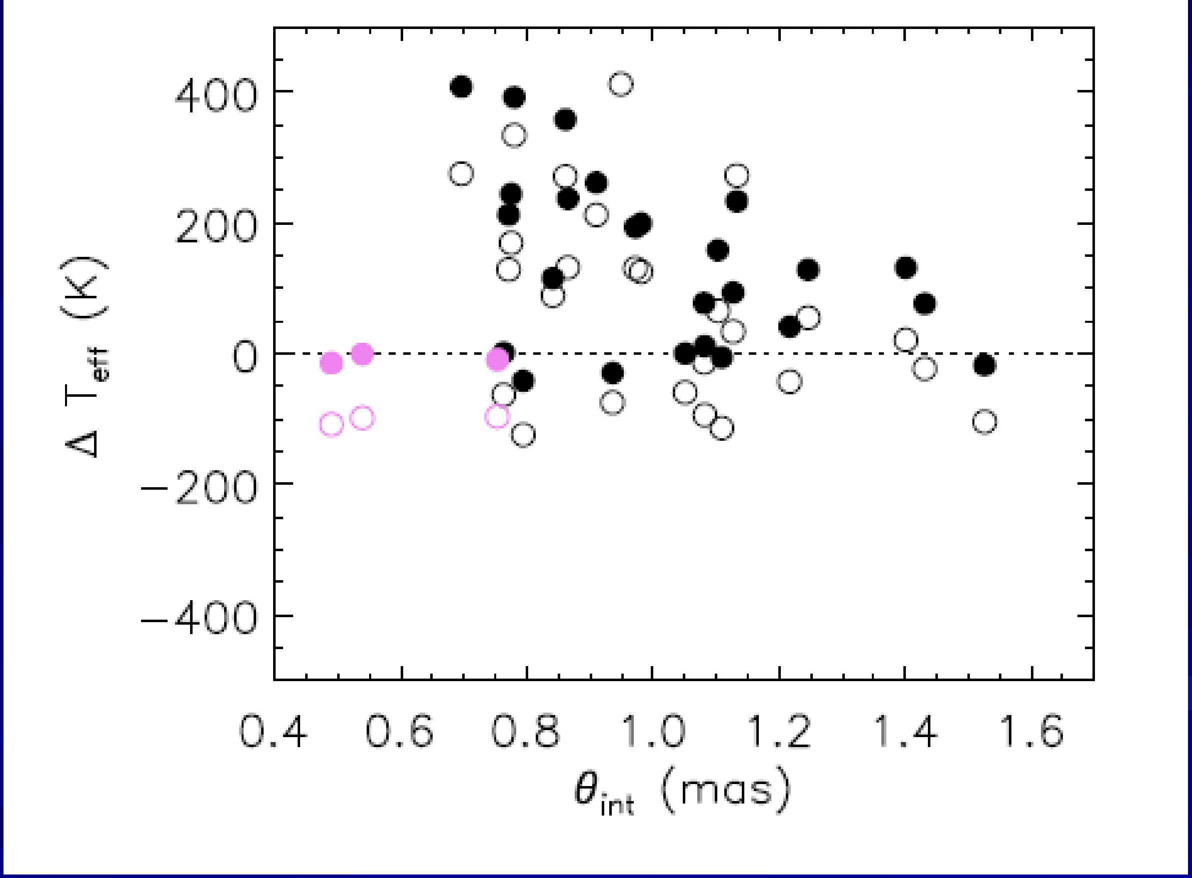
Interferometry Vs. IRFM/Binaries



Interferometry Vs. Spectroscopy

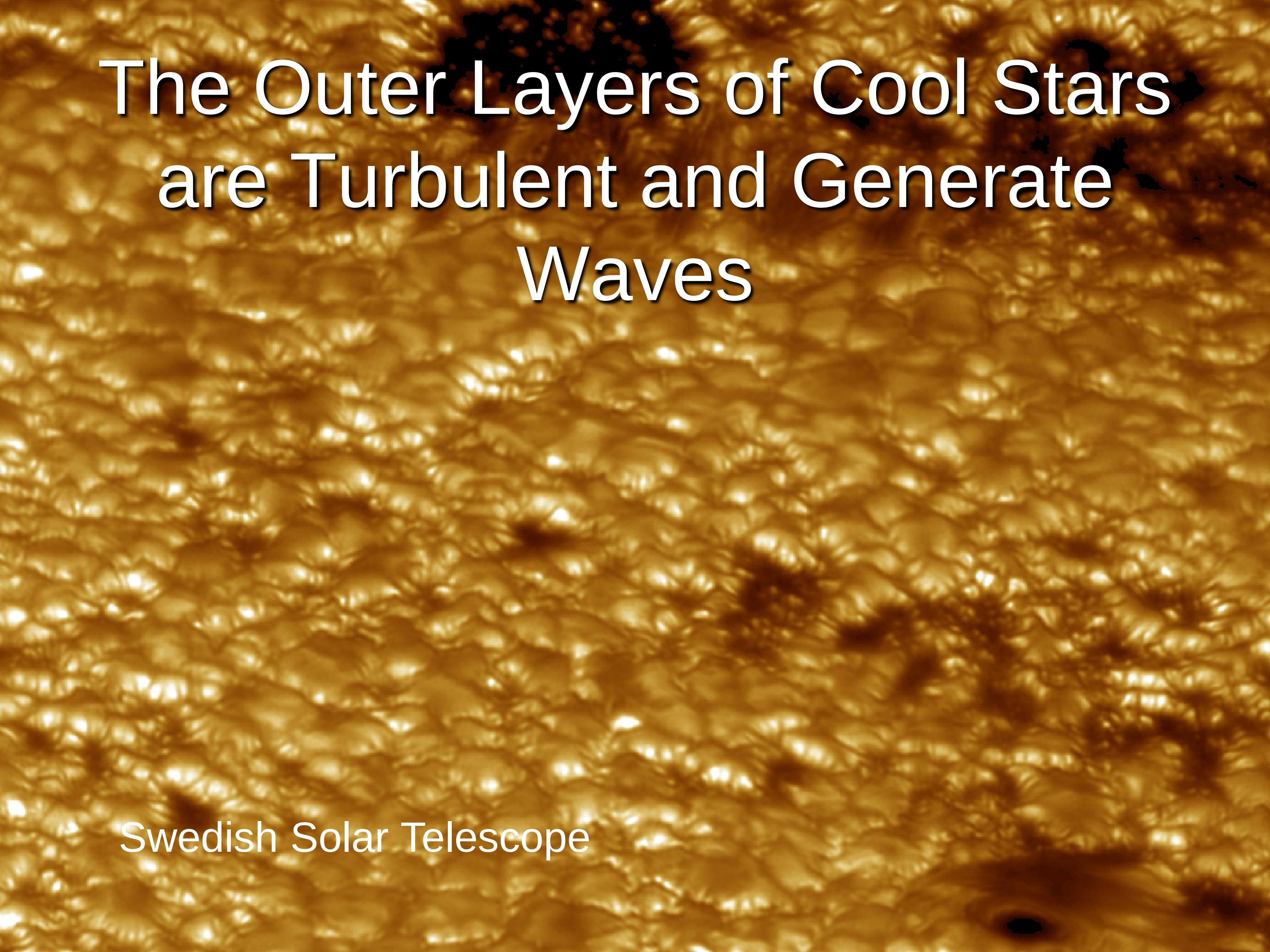


Systematic Errors in Interferometry Data?



Casagrande et al. 2014 (1401.3754)

The Outer Layers of Cool Stars are Turbulent and Generate Waves



Swedish Solar Telescope

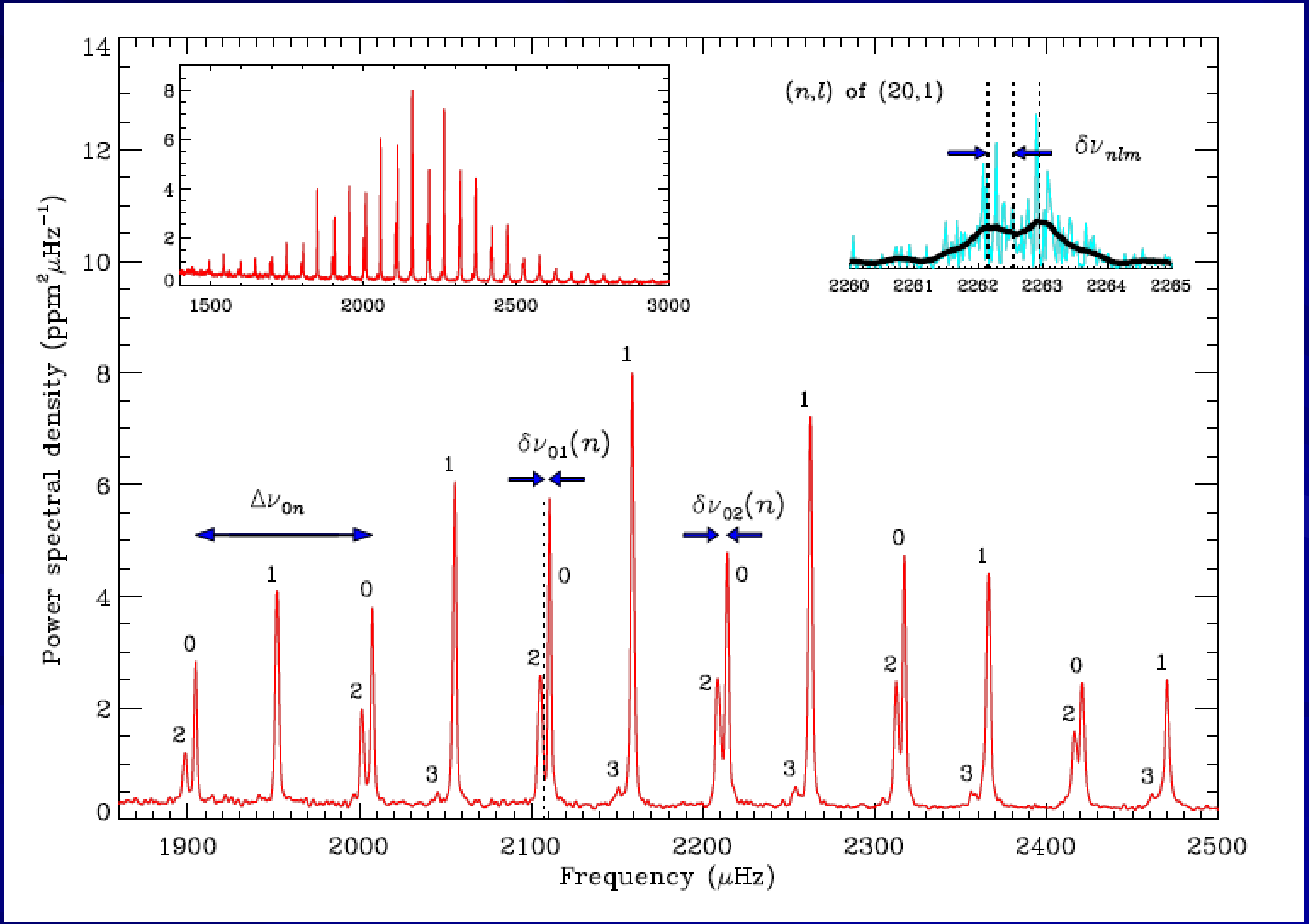
Solar-like Oscillations in Kepler

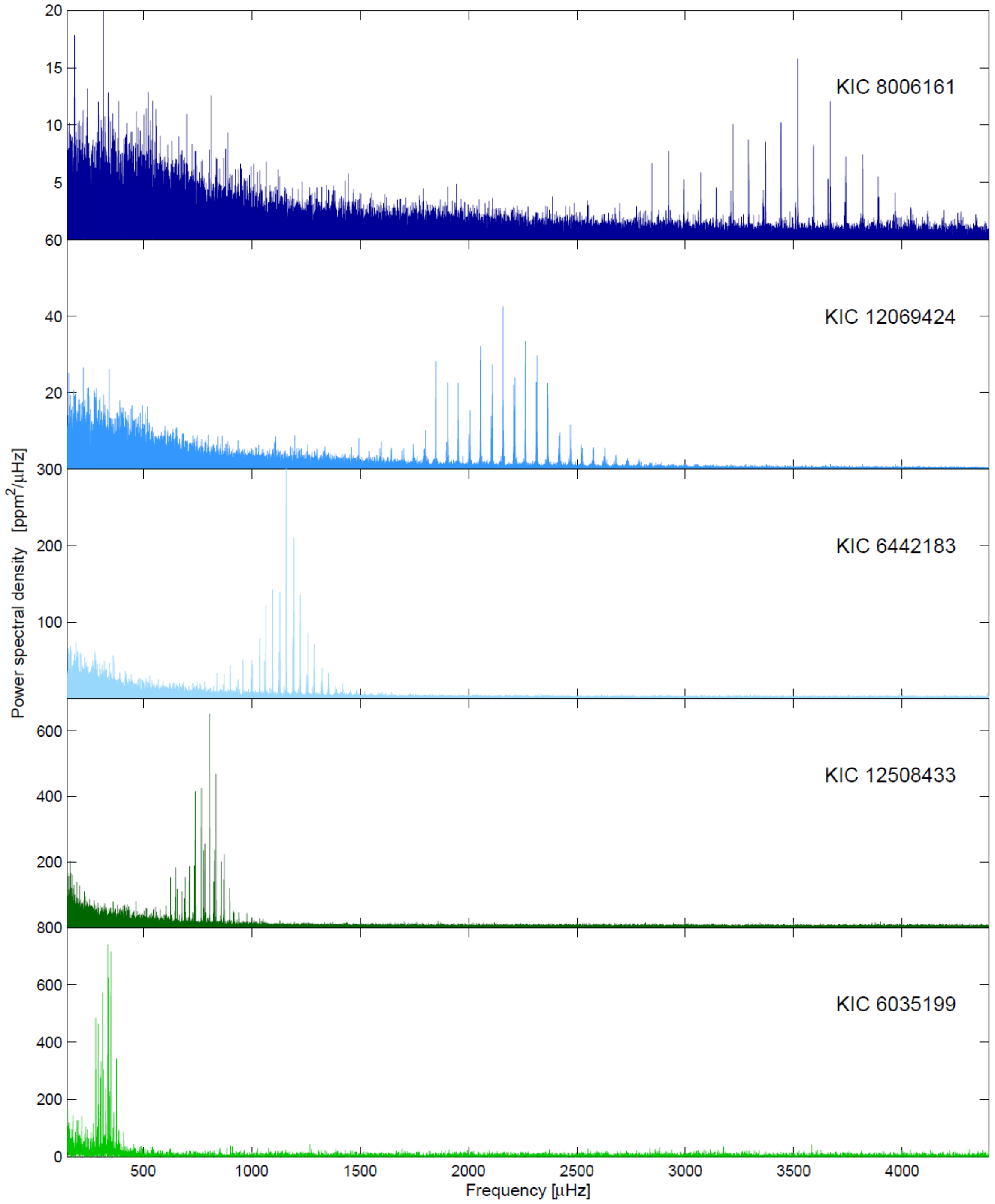
ν_{max}

Rotational Splittings

16 Cyg A
Metcalfe et al. 2012

Pure p-mode pattern





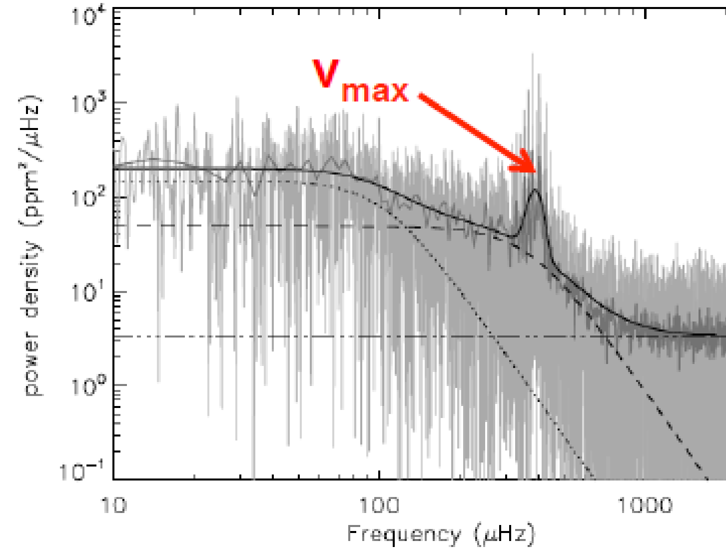
The observed MS pattern is a strong function of log g

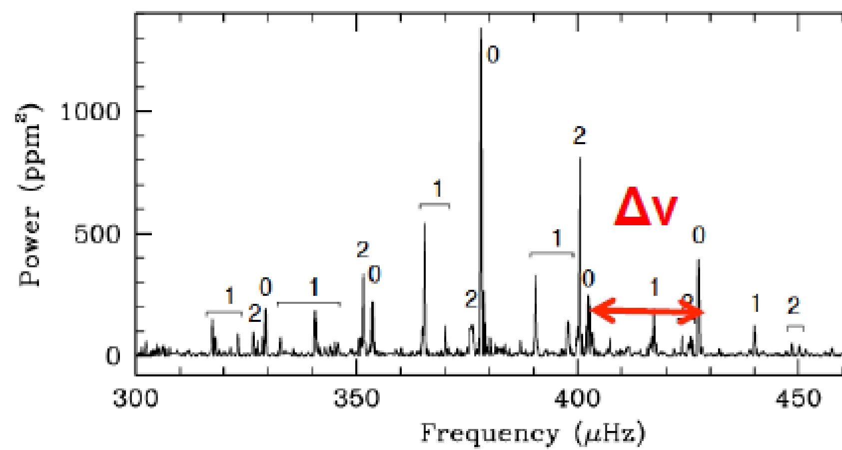
From Chaplin & Miglio 2013

Interiors: What Do We Learn?

$$\frac{\Delta\nu}{\Delta\nu_{\odot}} = \sqrt{\frac{M/M_{\odot}}{(R/R_{\odot})^3}}$$

$$\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}} = \frac{M/M_{\odot}}{(R/R_{\odot})^2\sqrt{(T_{\rm eff}/T_{\rm eff,\odot})}}$$





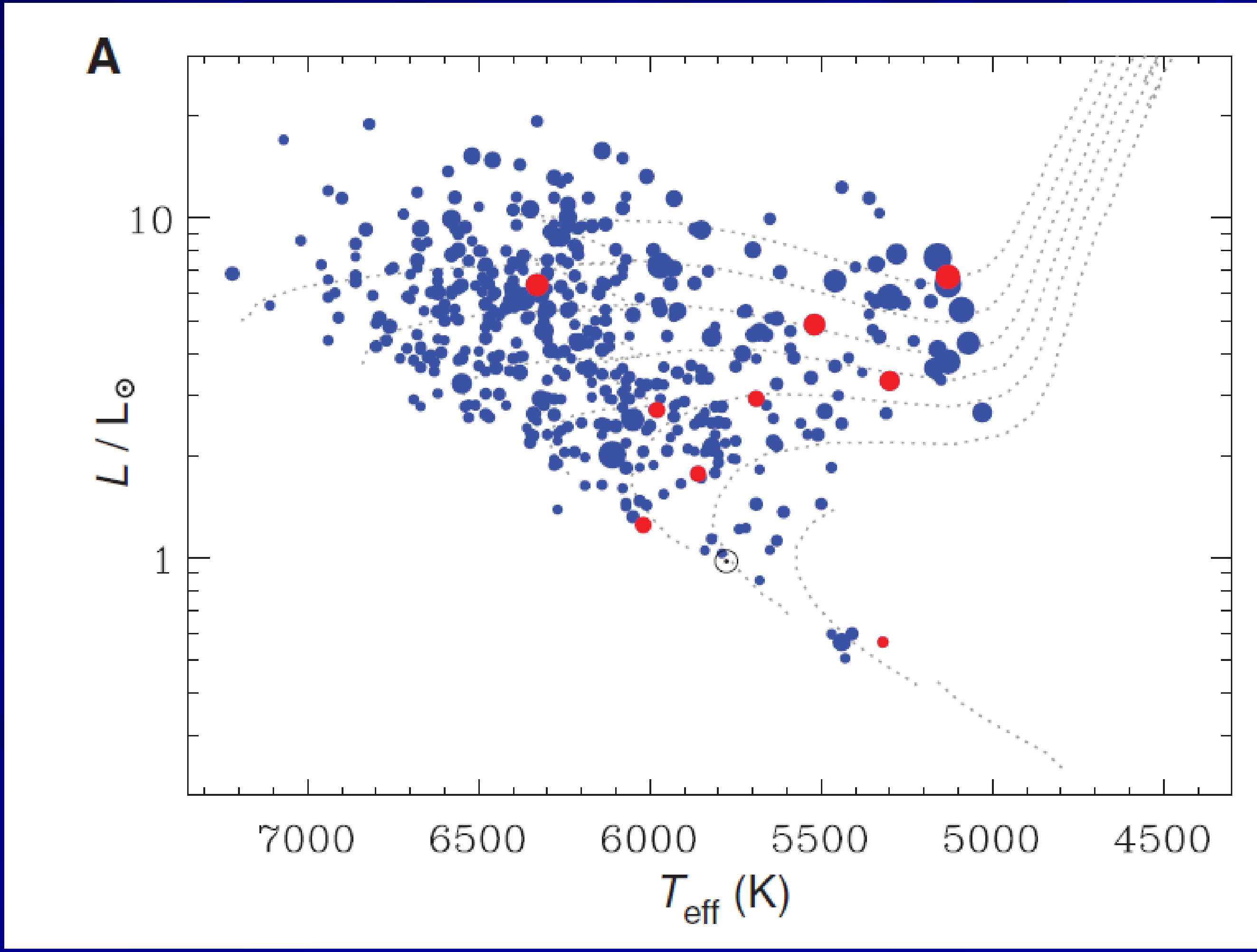
Sample power spectrum of red giant KIC4351319 from Di Mauro et al. (2011)

A Working Tool for Bulk Populations

KASC Spectra

Dwarf stars with detected sun-like oscillations from Kepler

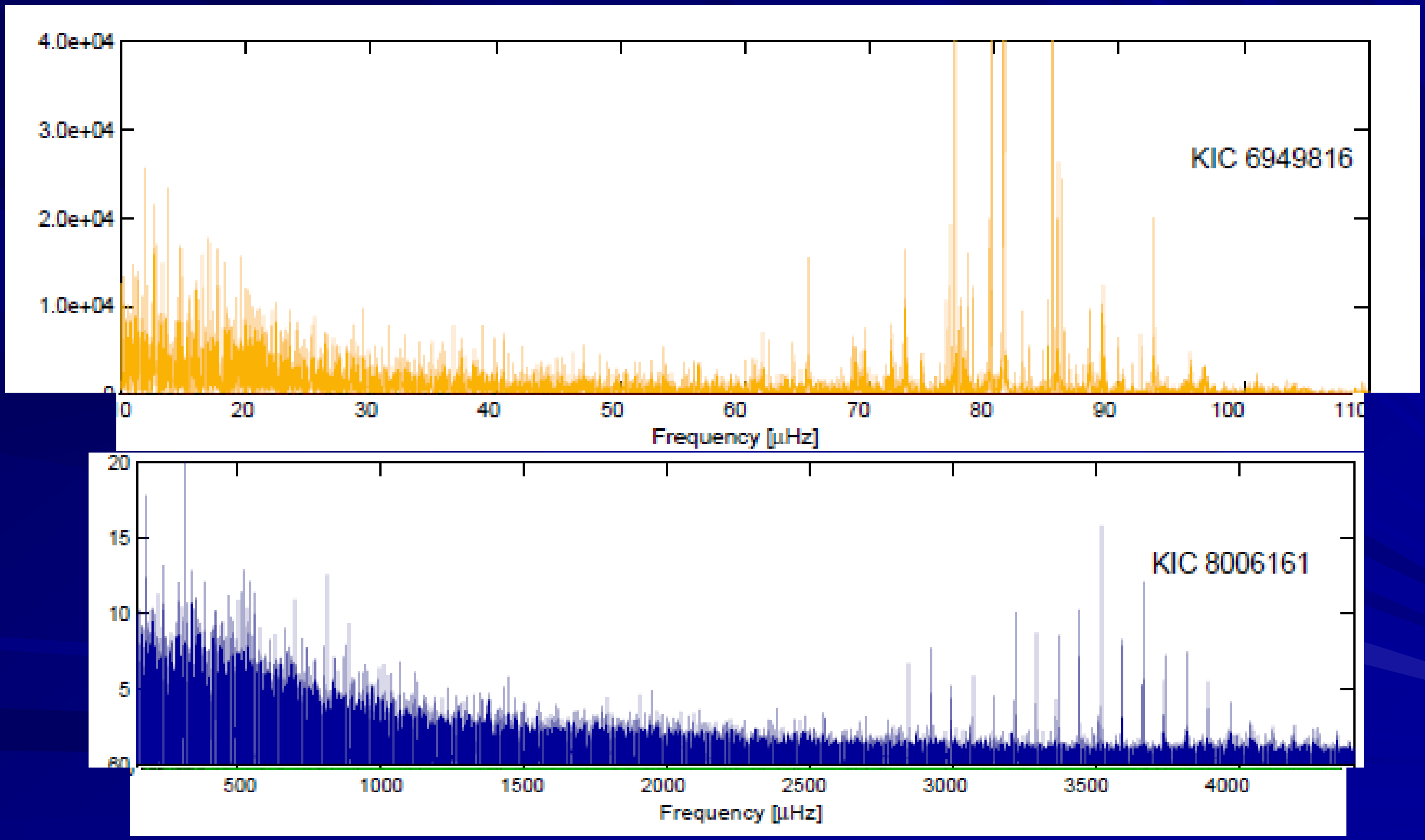
Radius + Independent T_{eff} yields distance and luminosity (Chaplin et al. 2011, 2013)



Giants and Kepler

- Giants are high-amplitude pulsators
  - – Periods of days to months
- Long period is a huge advantage
  - ⇒Accessible with 30 minute cadence
  - ⇒14,000 stars monitored, essentially all detected (Mosser et al. 2009; Hekker et al. 2010)
- Observed frequency pattern is complex!

Giant and Dwarf Frequency Patterns Compared



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13

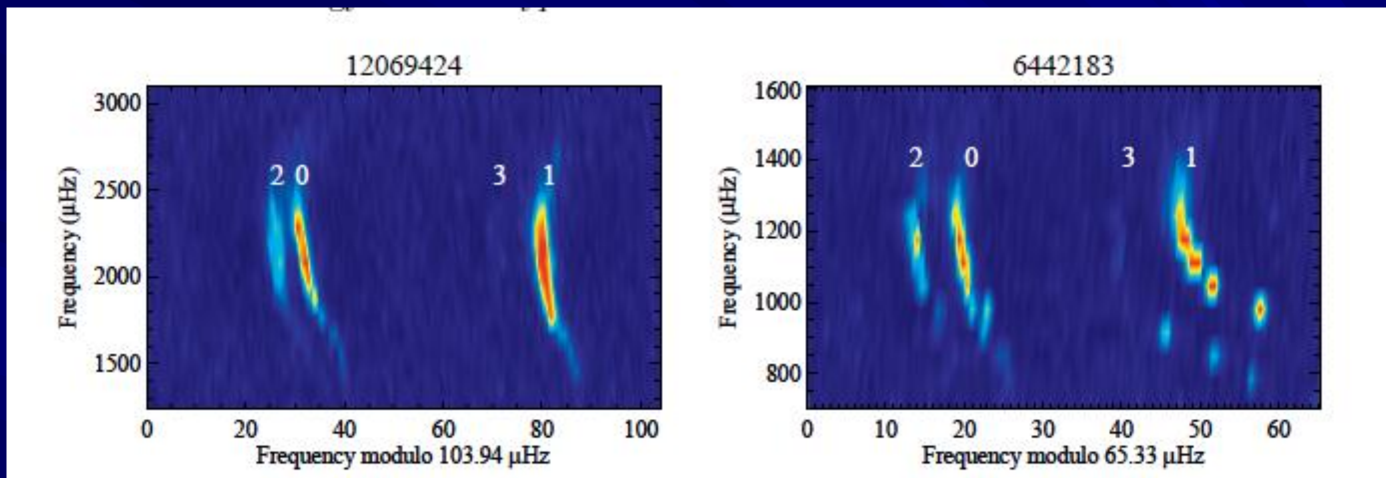
The Complex Giant Pattern is Explained by Mixed Modes

- Mixed modes propagate as p-modes in the convective envelope and g-modes in the deep core; especially strong impact on l=1
- l=0 modes are pure p-modes
- Seen in red giants (Bedding et al. 2010) because the p and g mode frequencies become commensurate
- Comparing the two yields distinct diagnostics of core and envelope properties

Distinct Patterns in Different Evolutionary States

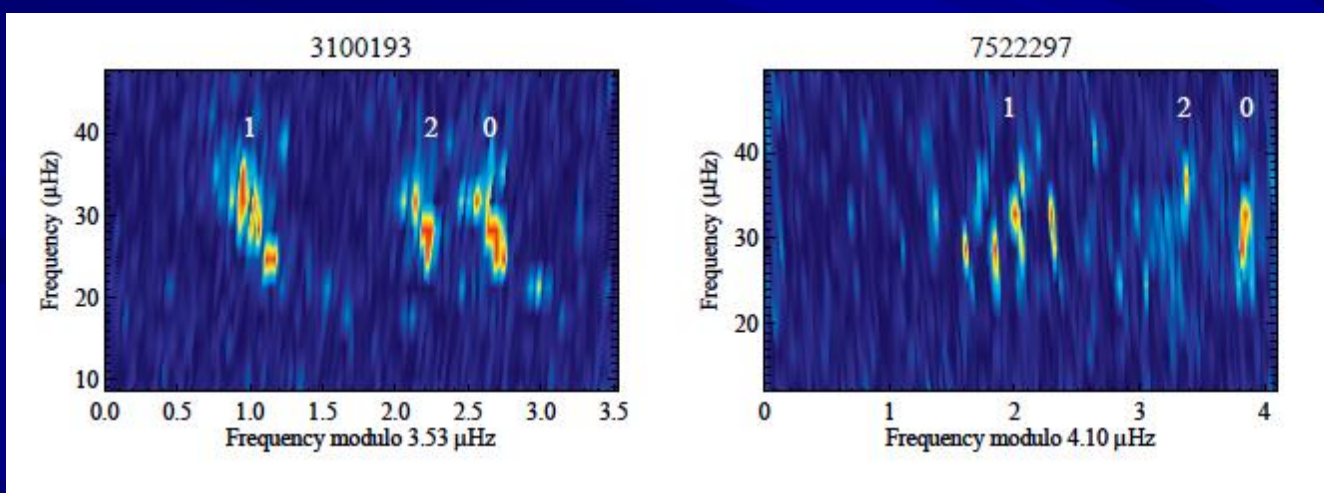
Dwarf

Subgiant



RGB

RC



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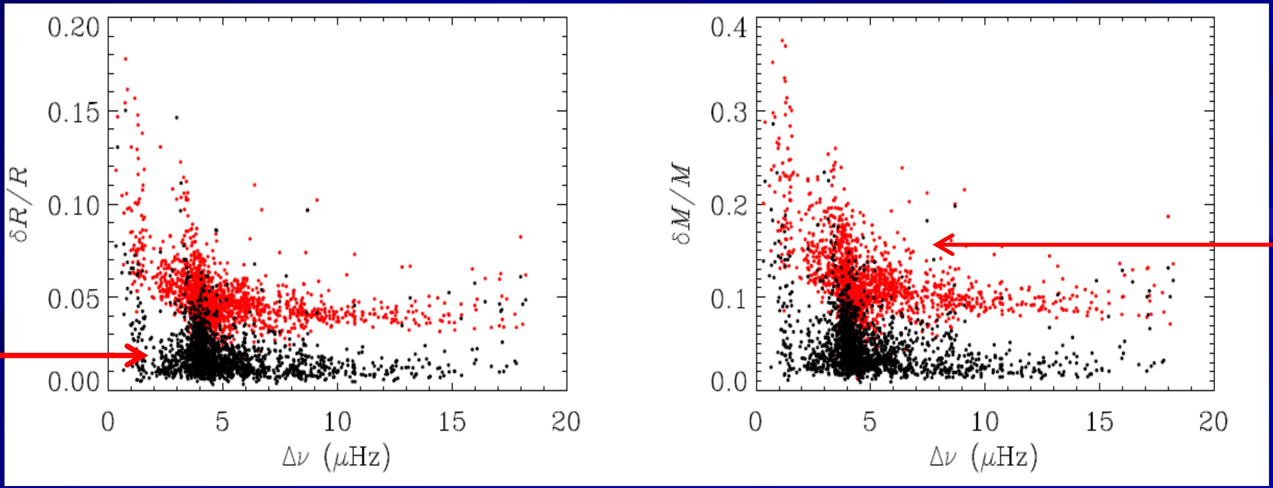
The APOKASC Approach: DR10

- APOGEE sample: ~2,400 Red Giants
  - 1916 stars that pass quality control checks
- Analyze light curves, extract mean asteroseismic properties ($\Delta\nu$, ν_{max})
- R+M from Scaling Relations + Grid-based Modeling



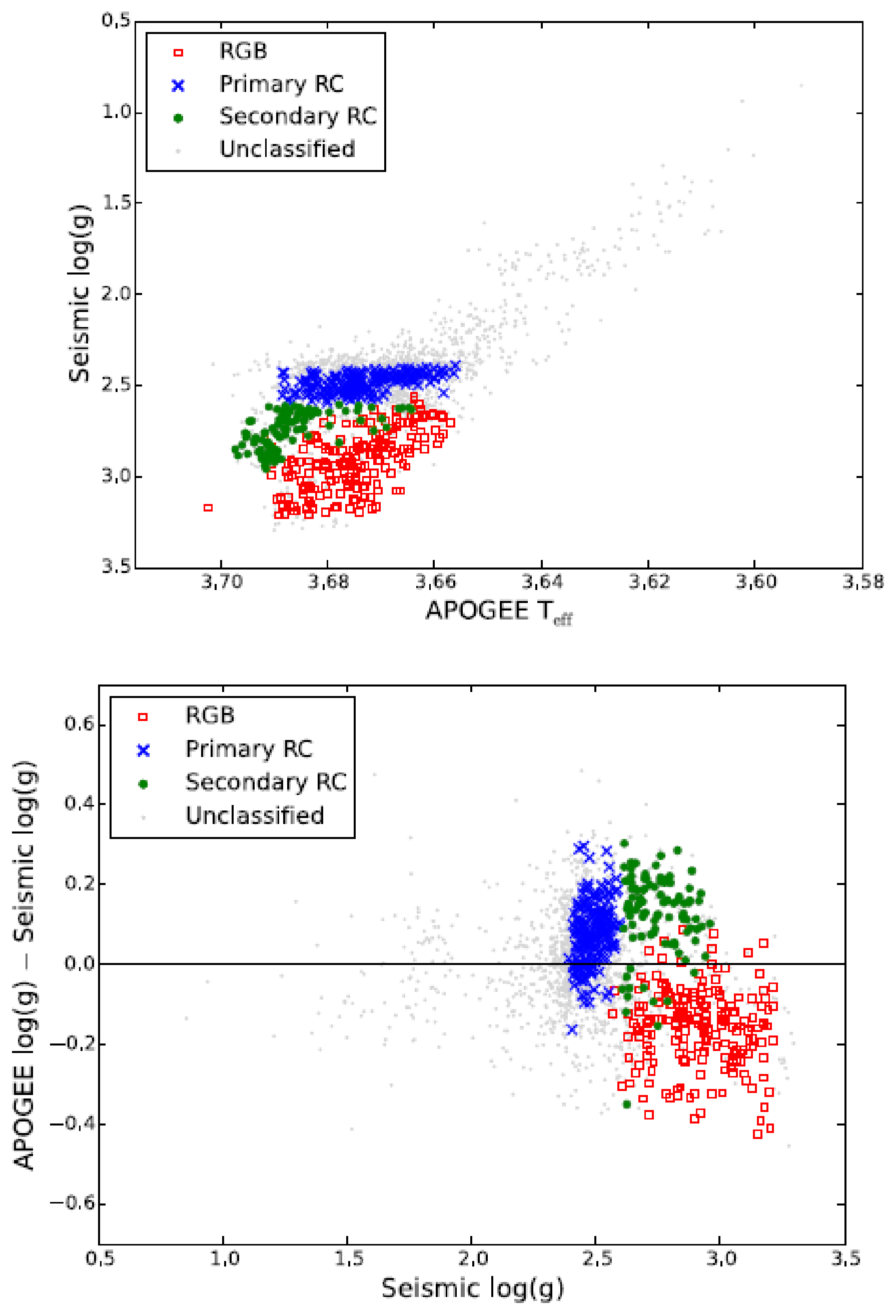
Scatter, Method To Method

Total Error

← Luminosity

A Test of Atmospheres

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



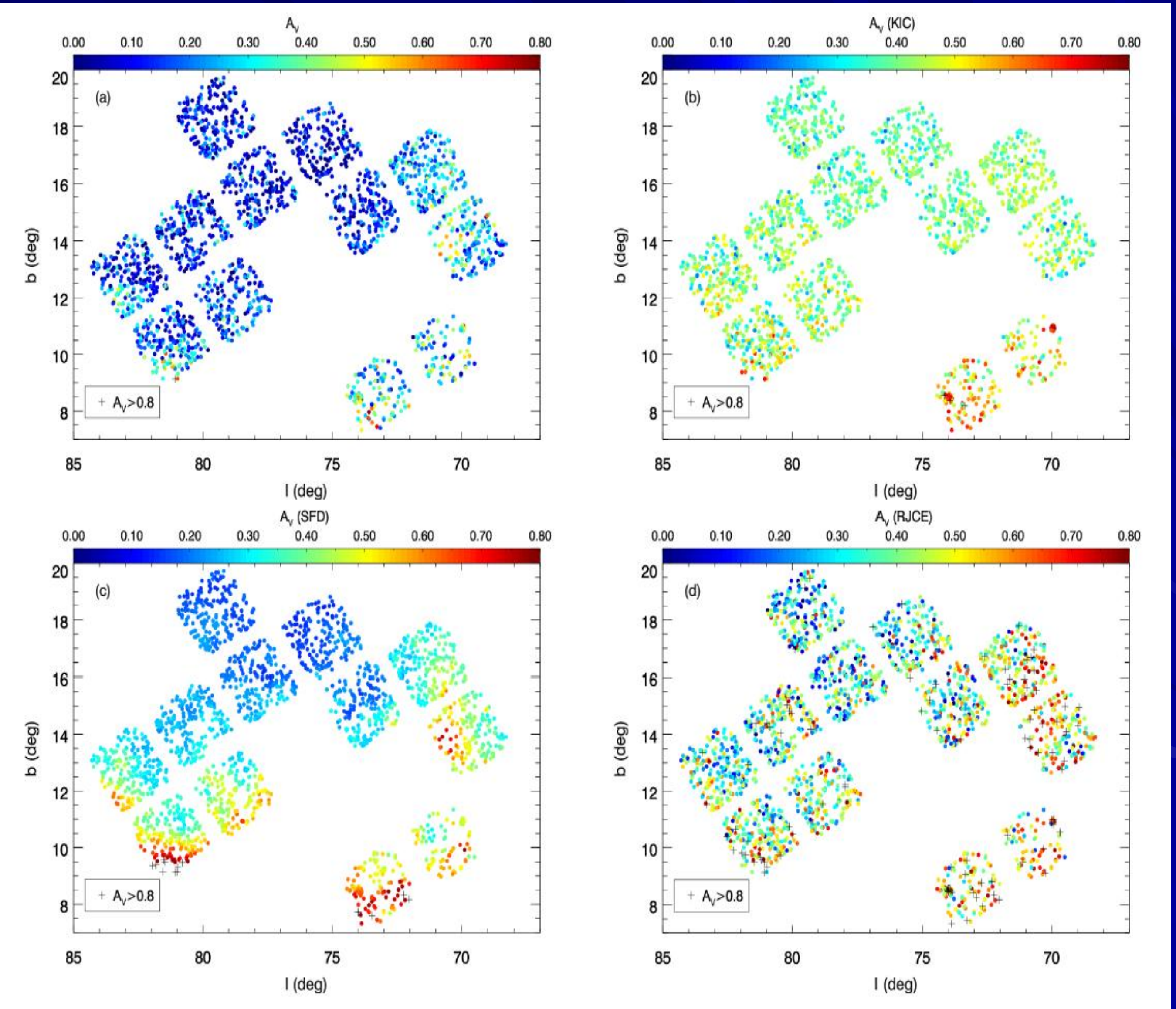
Rodrigues et al. 2014:
SED Fitting and the
KIC Extinction

Rodrigues et al.
Extinction Map

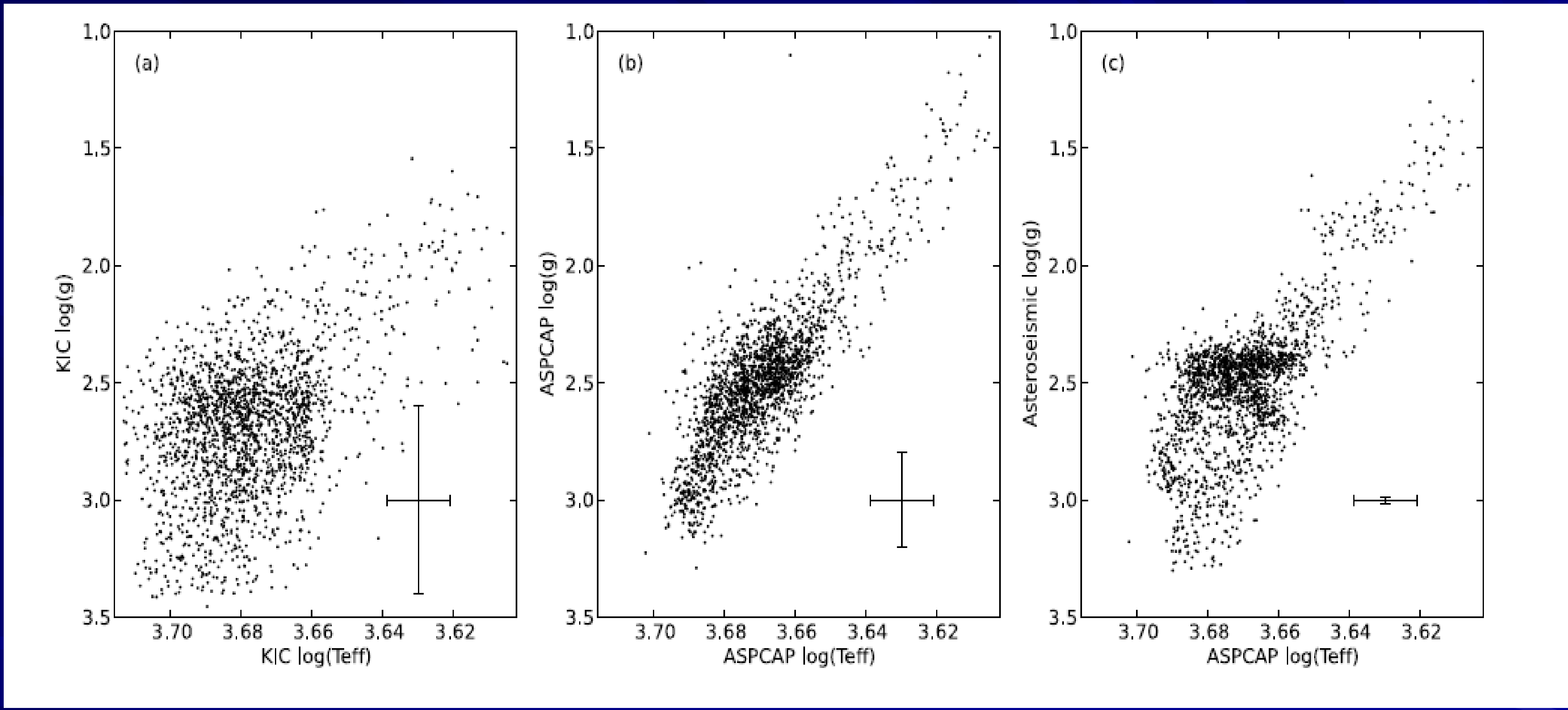
KIC Extinction Map

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

SFD
(Maximum)
Extinction
Map



Results: Snapping Into Focus

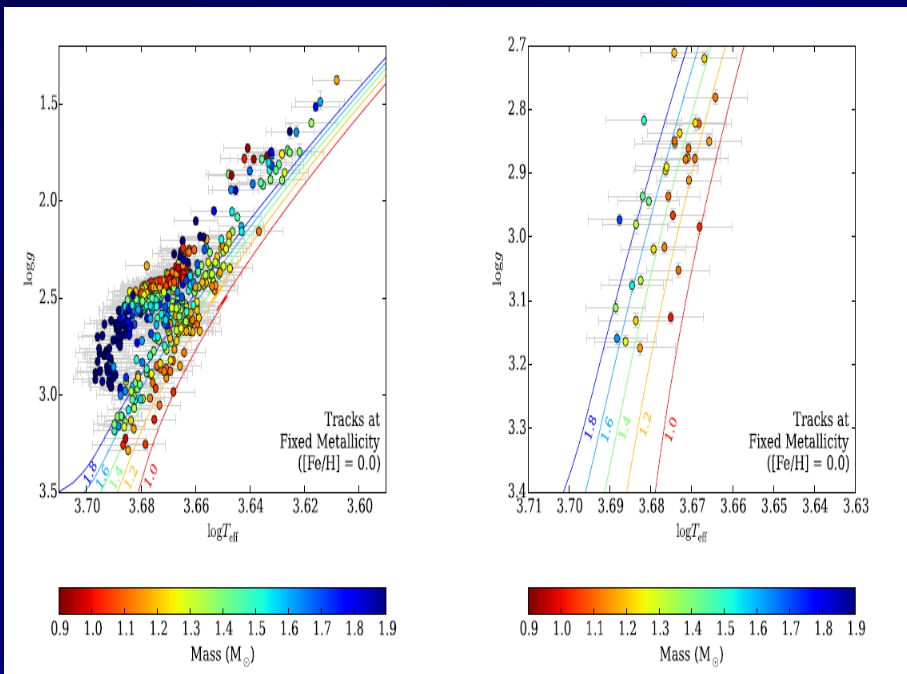


Photometry

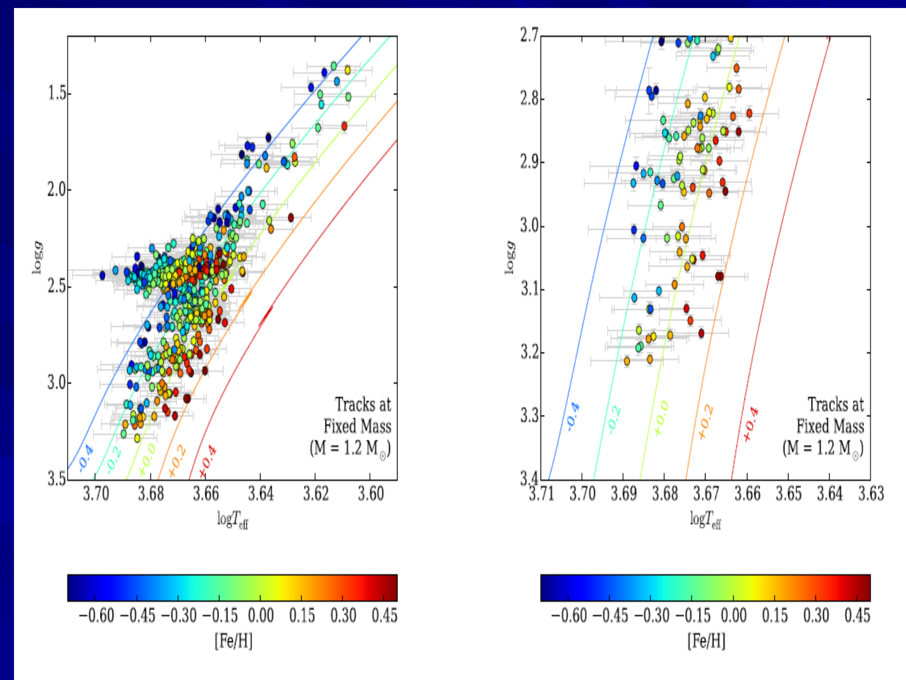
Spectroscopy

Asteroseismology + Spectroscopy

Mass Trends, Fixed [Fe/H]

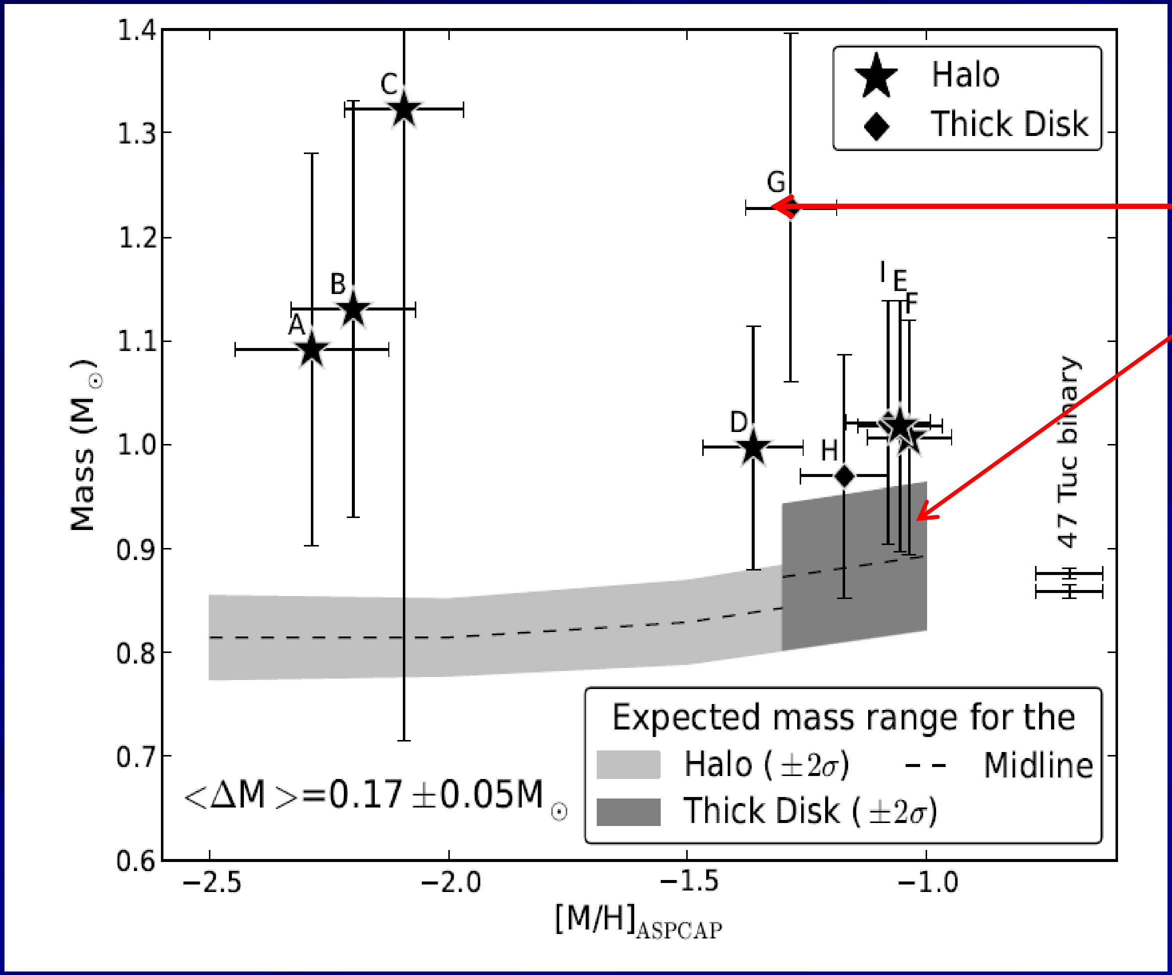


Metallicity Trends, Fixed Mass



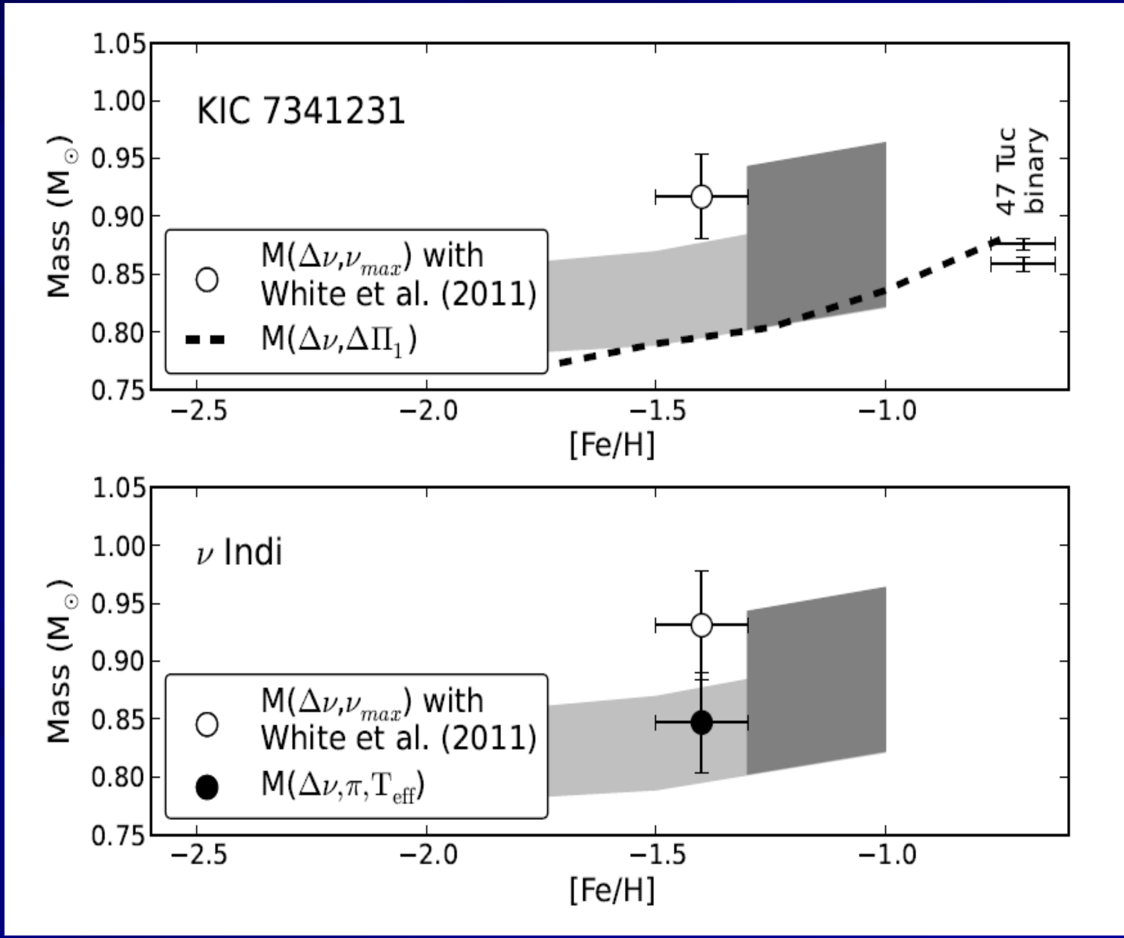
Trouble In Halo-Land

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!