Ages in the Gaia Sky

MARC PINSONNEAULT

OHIO STATE UNIVERSITY, DEPT. OF ASTRONOMY

Collaborators:
Courtney Epstein
Jamie Tayar
Jennifer van Saders
Joel Zinn

Why Study Ages?

- Ages are crucial for studies of the origin and evolution of planets, stars and galaxies
- Detailed studies of local populations (near-field cosmology) complement high-redshift studies of galaxy formation

The Age Problem

- Intrinsic Model Dependence
- Cannot Be Directly Calibrated
- Indirectly Inferred
- Strong Systematic Errors and Biases

NYTimes:

4 Sisters,
40 Years

The Ecology of Chronology

- Measure Stellar Observables
- Use Models to Relate Observables to Ages
- Apply Population and Selection Corrections

Important Consequence:

Even with Perfect Distances,
Ages Will Be Limited in Precision!

Inferring Errors is Extremely Complex

- When an astronomer says “The age is 100 Myr +/-10…
- Ce n'est pas une incertitude appropriée

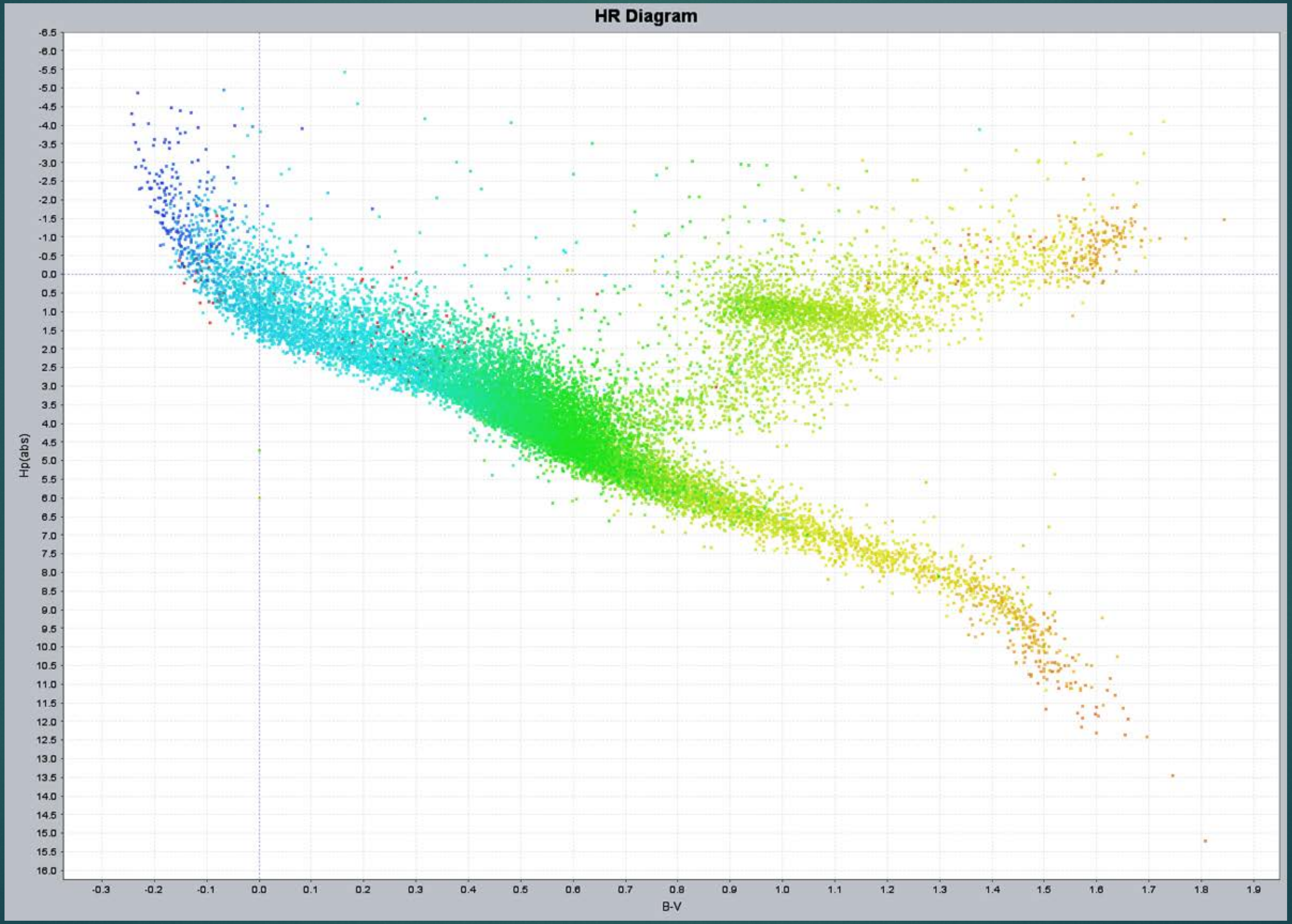
EXAMPLE:

For the upper MS there are 3 age scales

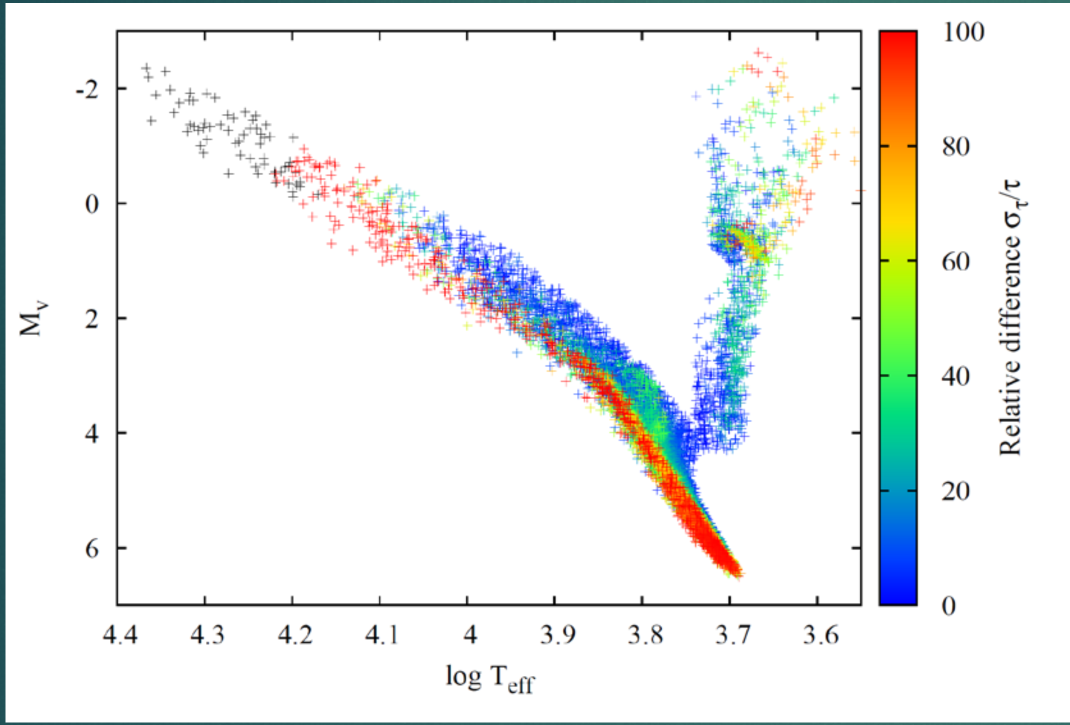
No overshoot or rotation
Overshoot (various amounts)
Rotation

Which produce similar rank-ordering of ages but very different scales…

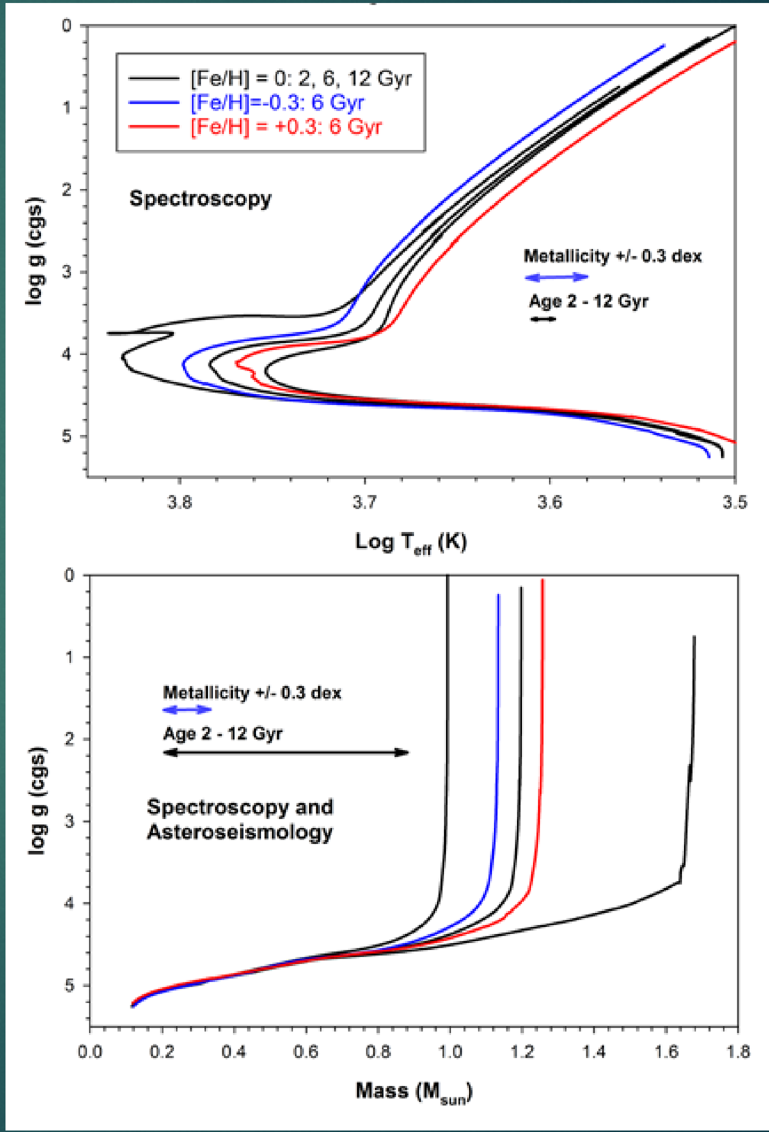
The Revised Hipparcos CMD



Three Domains For Stellar Age Techniques

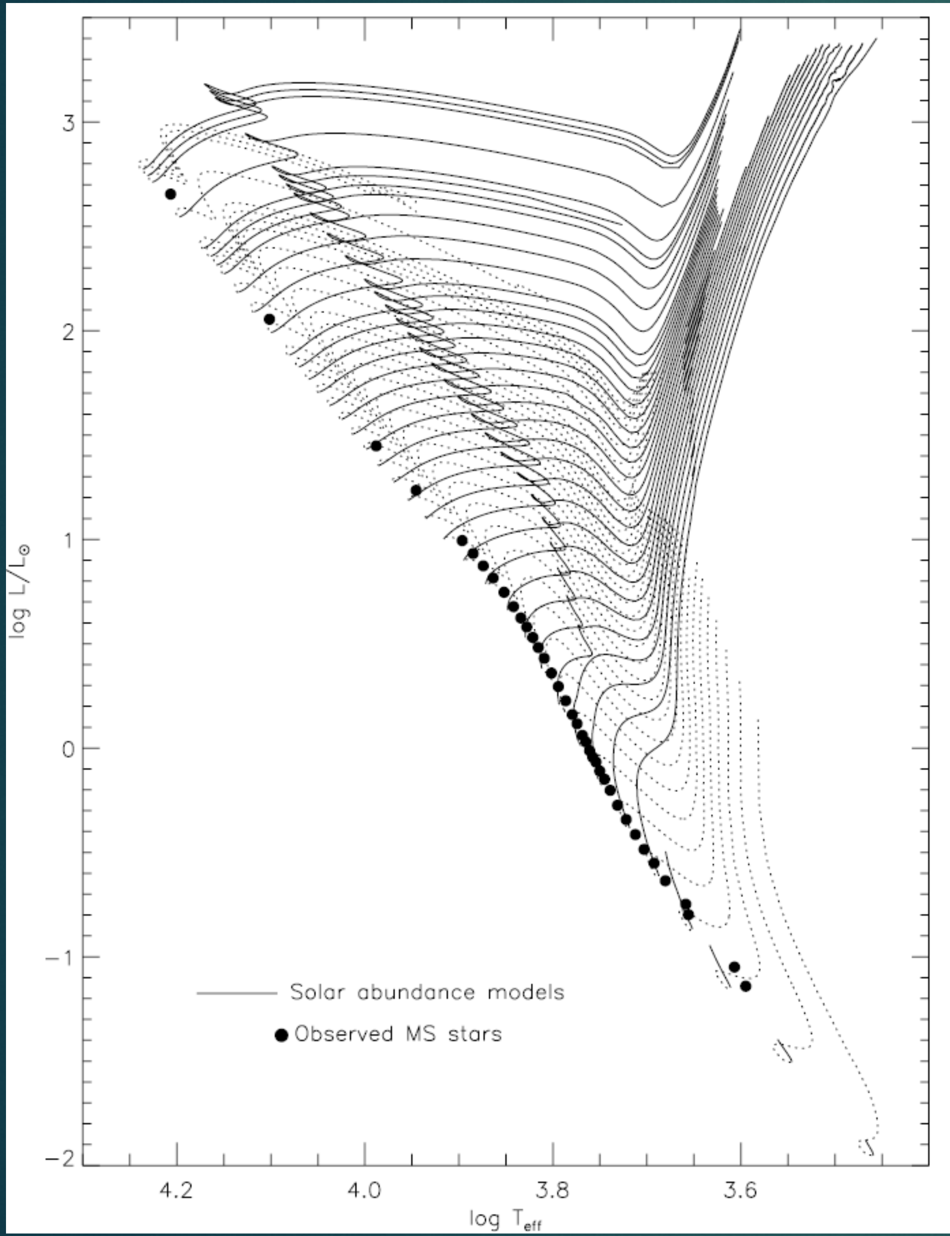


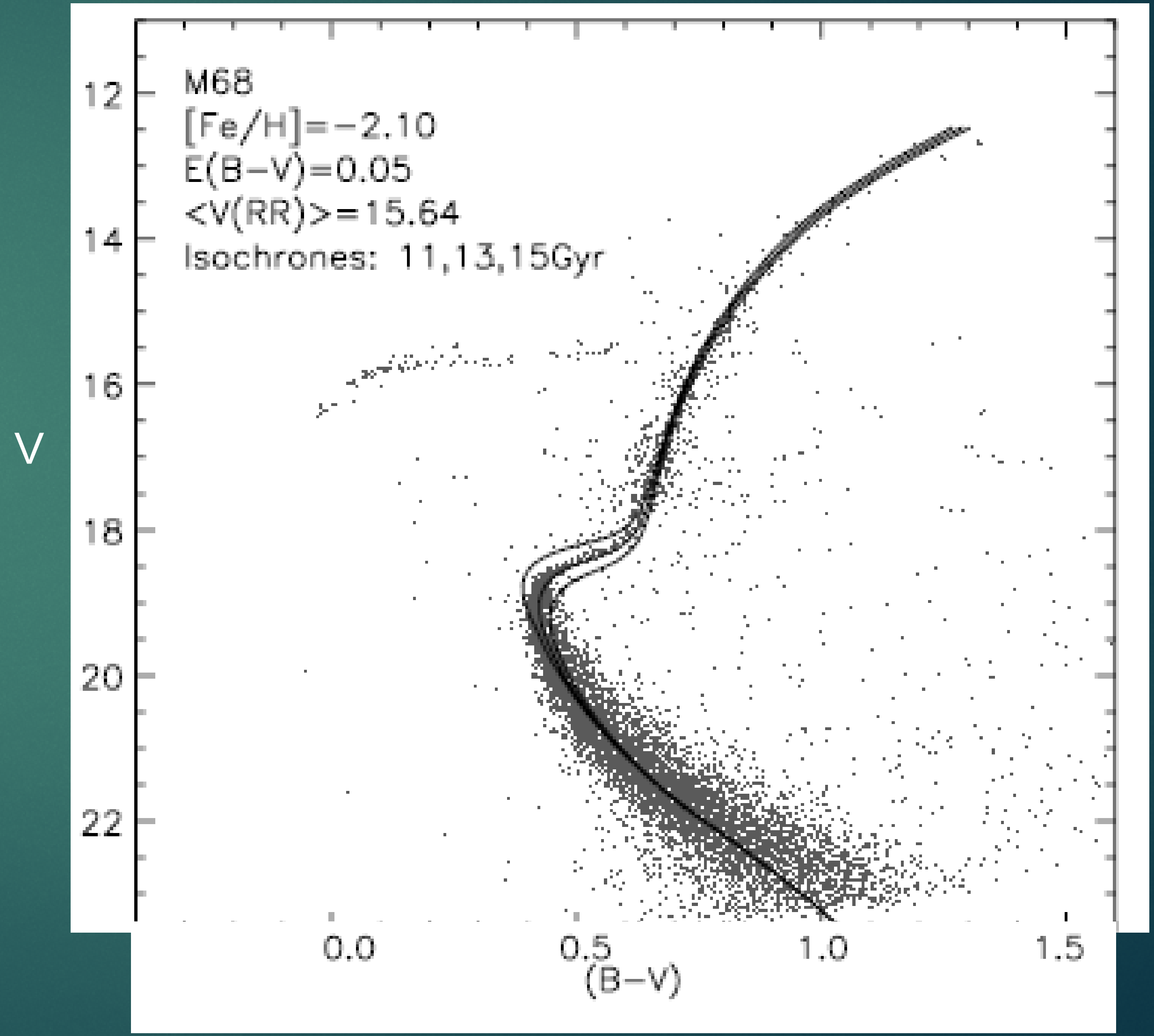
Guede et al. 2015 –
Gaia Age Precision Simulations, D < 1 kpc



The Classic Case: Star Clusters

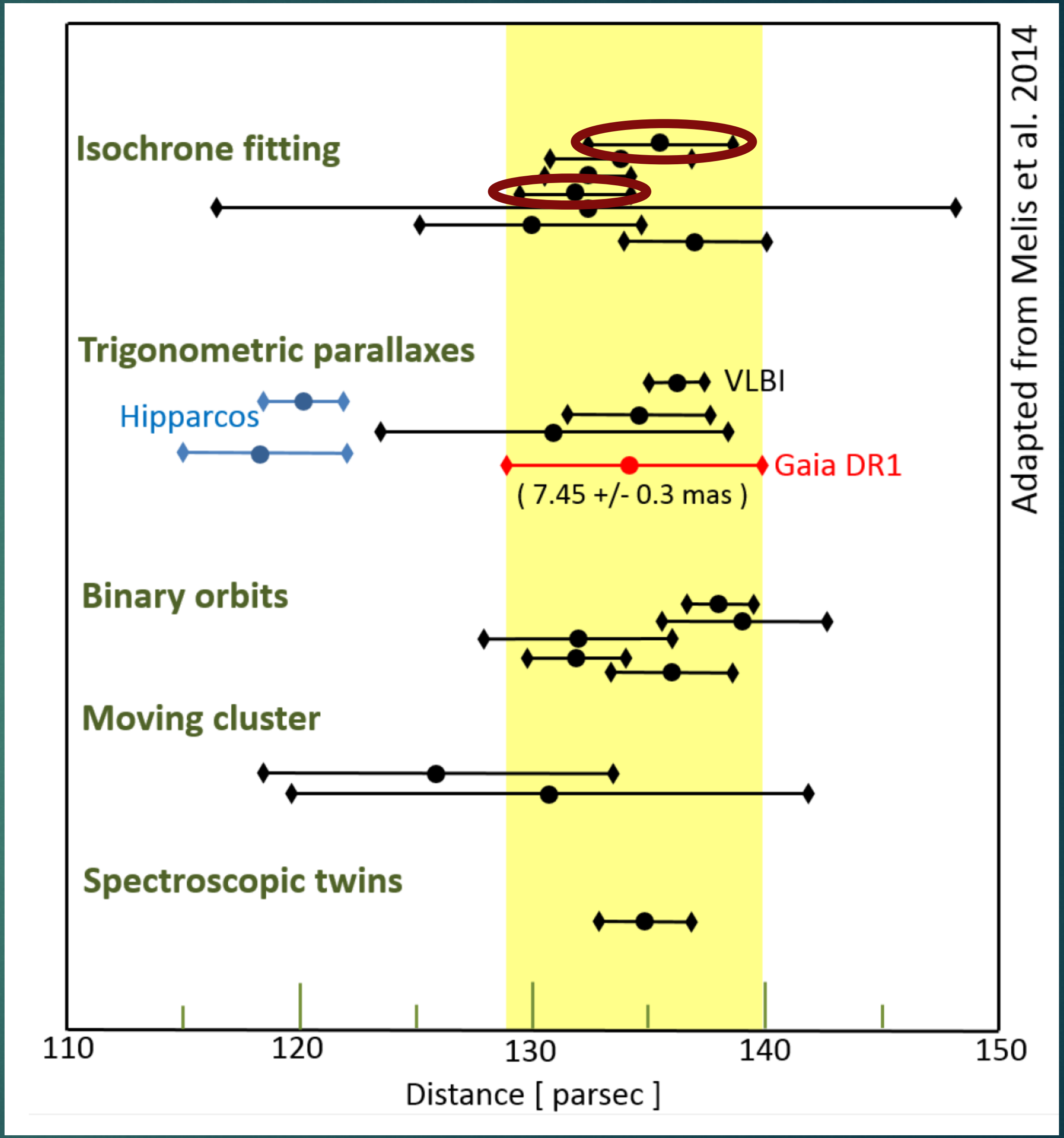
Y^2 Isochrones (Demarque et al. 2001)





The Lesson of the Pleiades and Hipparcos

- We have a rich web of information about stars
- Missions such as Hipparcos & Gaia *add* to our knowledge
- They don't *replace* things that we already knew



Brown+ 2016

The Promise of Gaia

- An enormous increase in the quantity and quality of star cluster data
- Field star ages for bulk populations a realistic prospect…
- TESTS OF MODELS
  - Masses (Binaries, Seismology)
  - Abundances (Spectra)
  - Photometry and Extinction

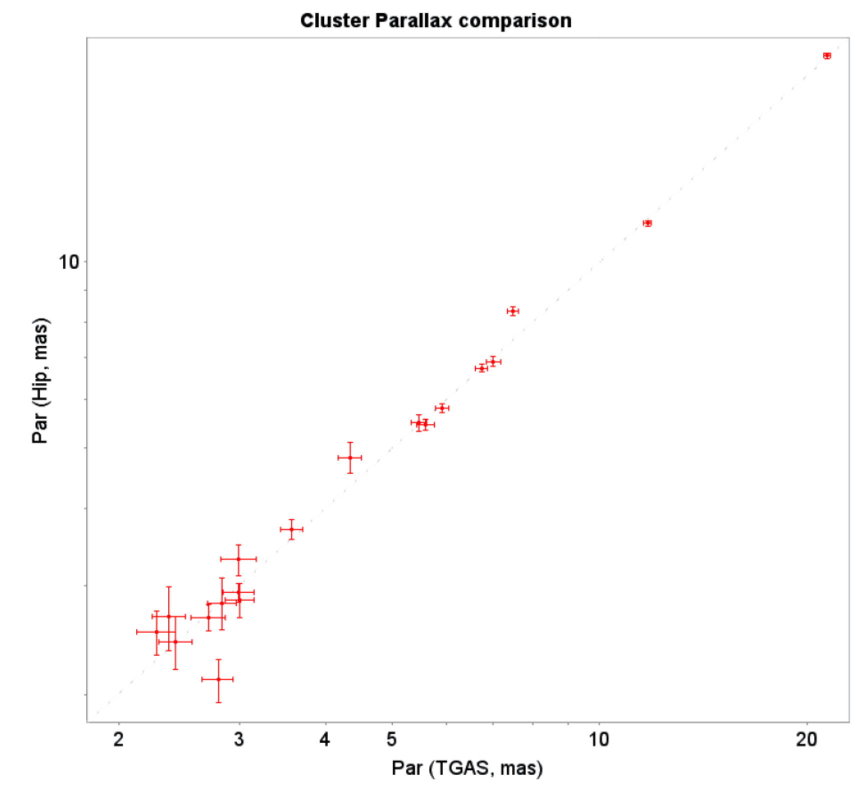


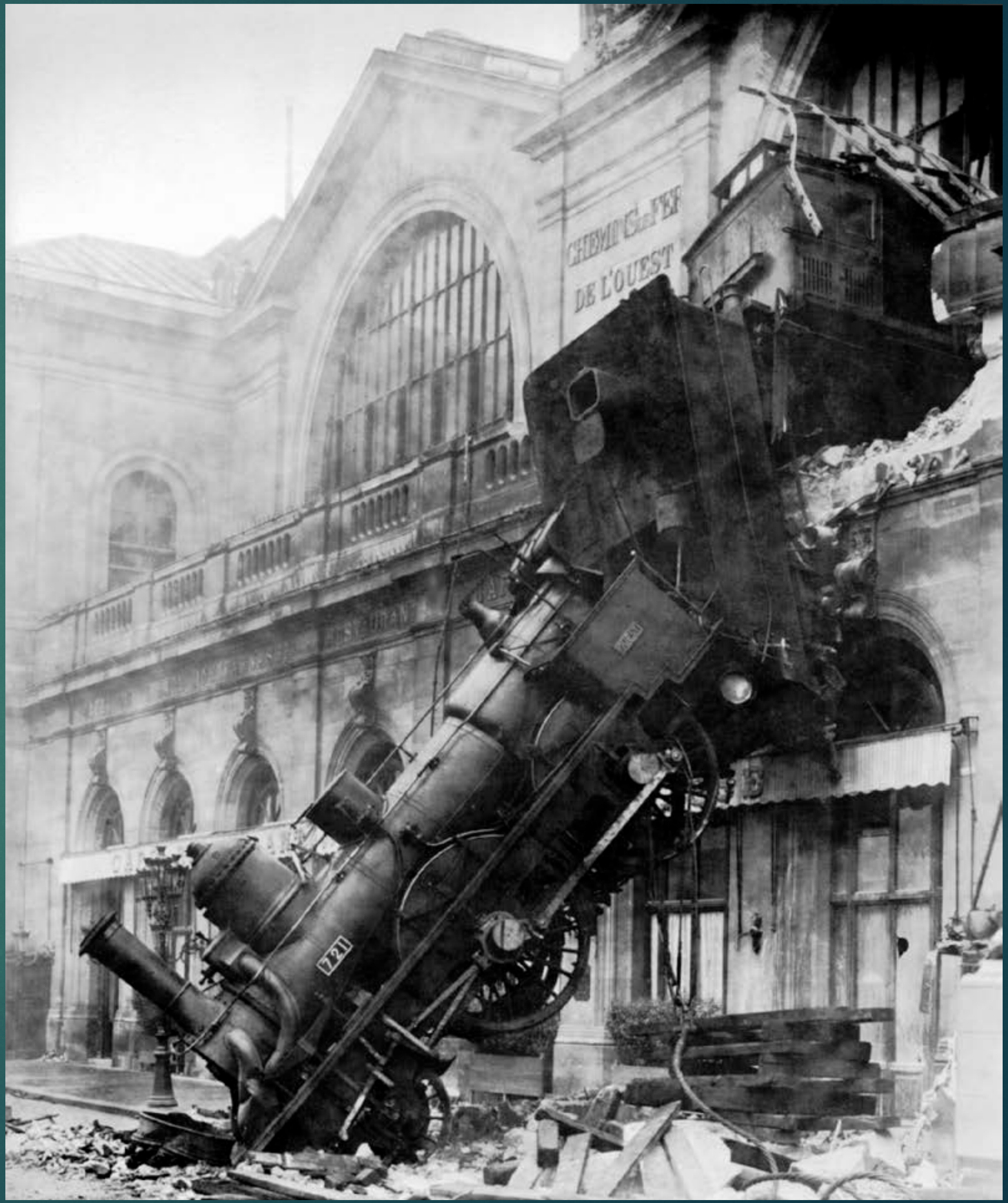
Fig. 34. Comparison between the cluster parallaxes as determined by the HIPPARCOS and TGAS analyses.

Van Leeuwen+2017

BUT: Unlikely to significantly revise inferred properties of well-studied systems

The Most Interesting Failure Modes

- Overshoot vs. Rotational Mixing on the Upper MS
- “Hidden” Chemical Trends
  - Example: Variable He Enrichment or Trends Not Tied to Metals
- Unusual Stellar Evolution Channels (Interacting Binaries)
- Mass Loss



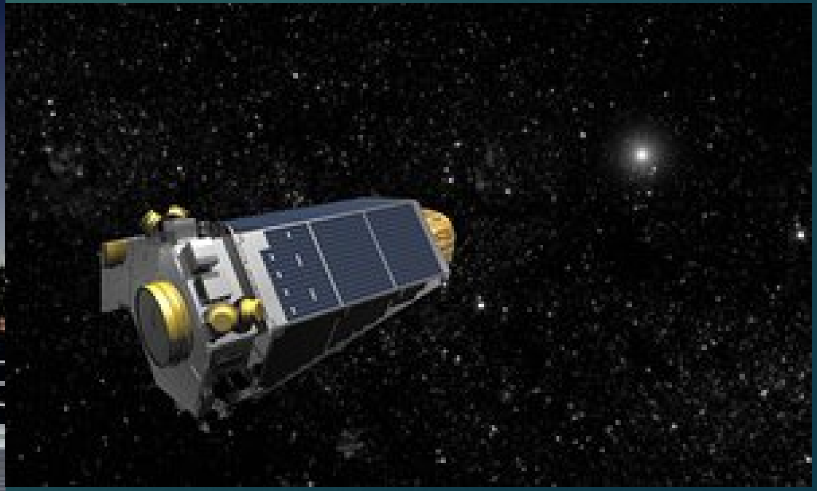
Spectroscopy and Seismology: Perfect Together!

- Stellar pulsation frequencies encode fundamental data about the global and internal properties of stars
- Spectroscopy is uniquely powerful for measuring detailed abundance data AND gives essential T_{eff} + log g + RV data
- **APOGEE-*Kepler* Asteroseismology Collaboration (APOKASC)**
  - DR10: 1,918 giants with spectra and asteroseismic parameters

  PINSONNEAULT+ 2014

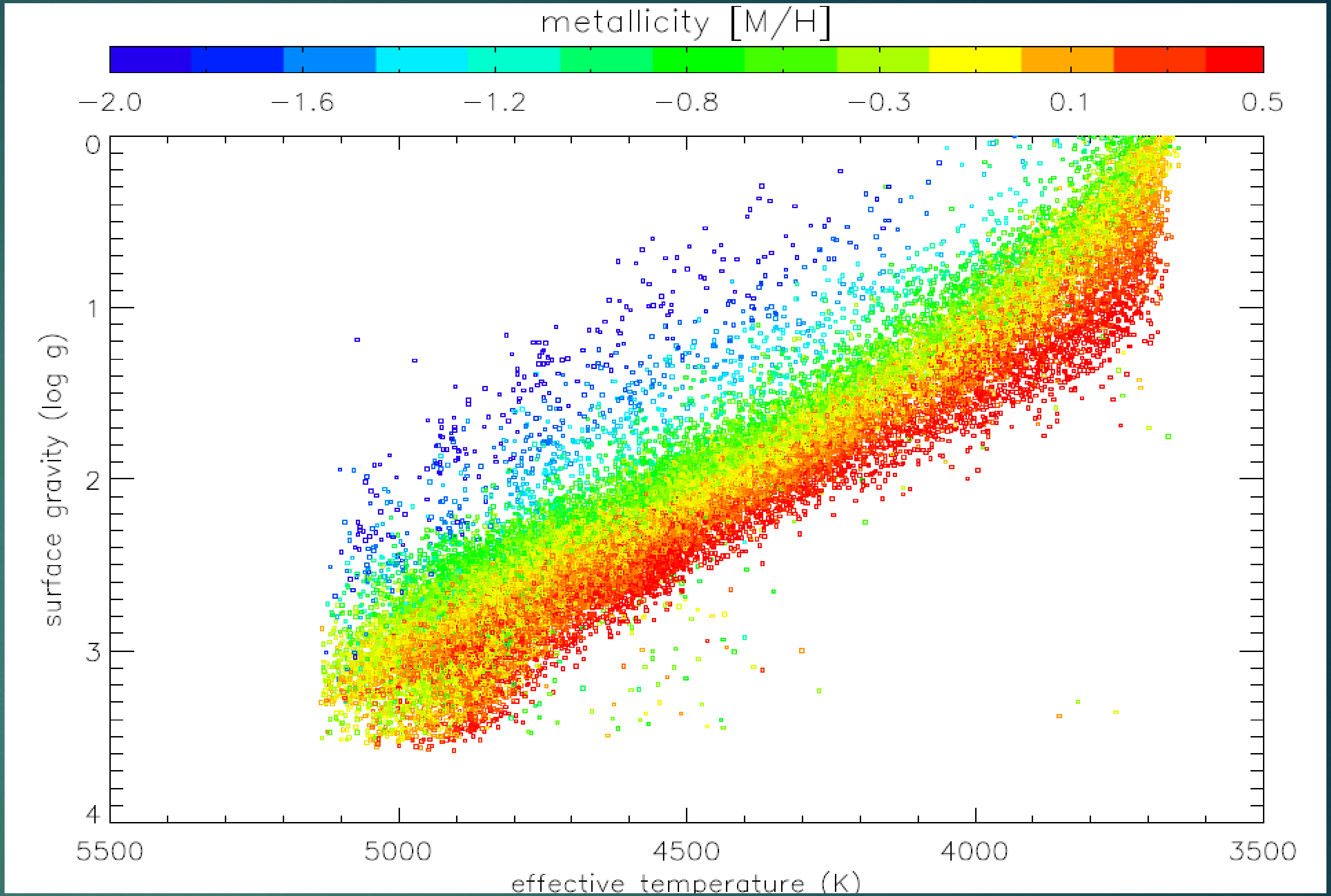
  - DR13: 7,000+ targets

  PINSONNEAULT+2017 (giant catalog)

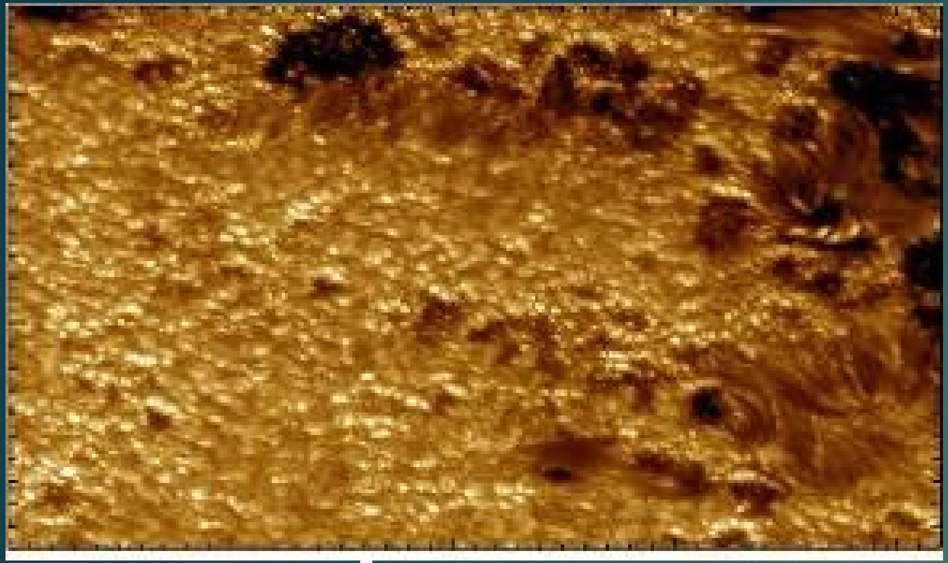


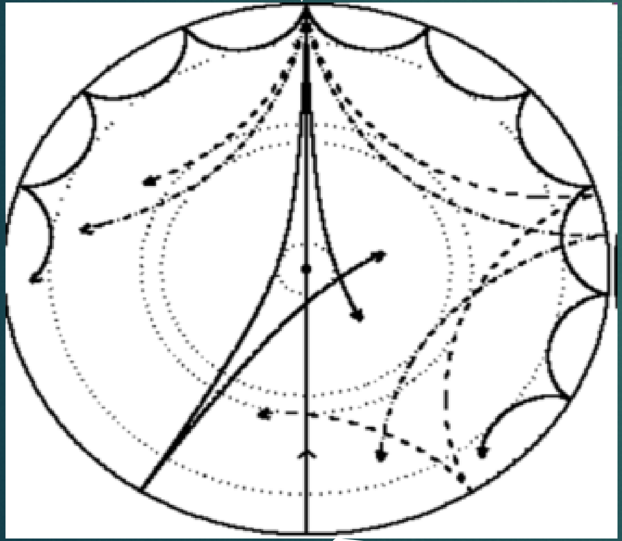
APOGEE

- High resolution (R~22,000) full H-band spectra
- ~230 science fibers per 6 square degree field
- S/N=100 in 3 hrs, H=12.2
- Automated Pipeline Analysis (Garcia Perez et al. 2016, Majewski et al. 2015, Holtman et al. 2015….)

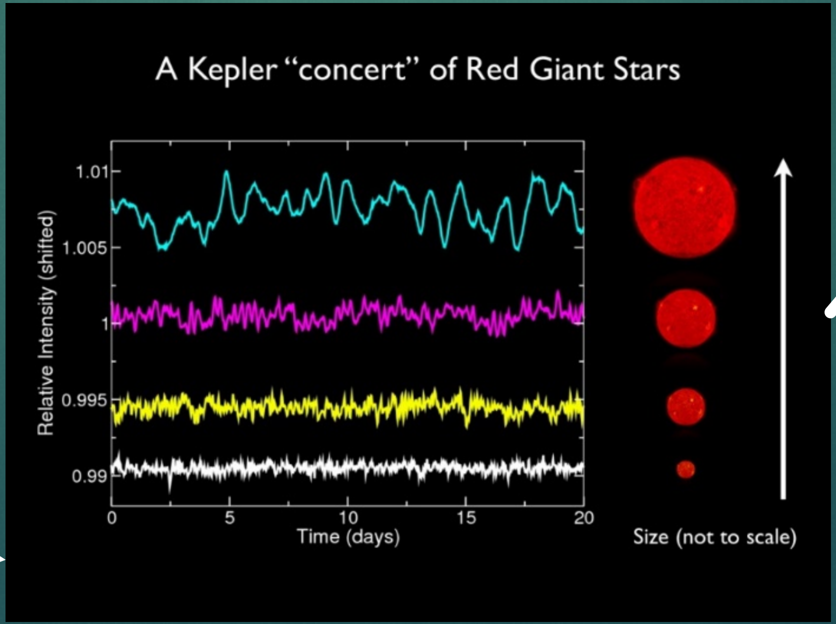


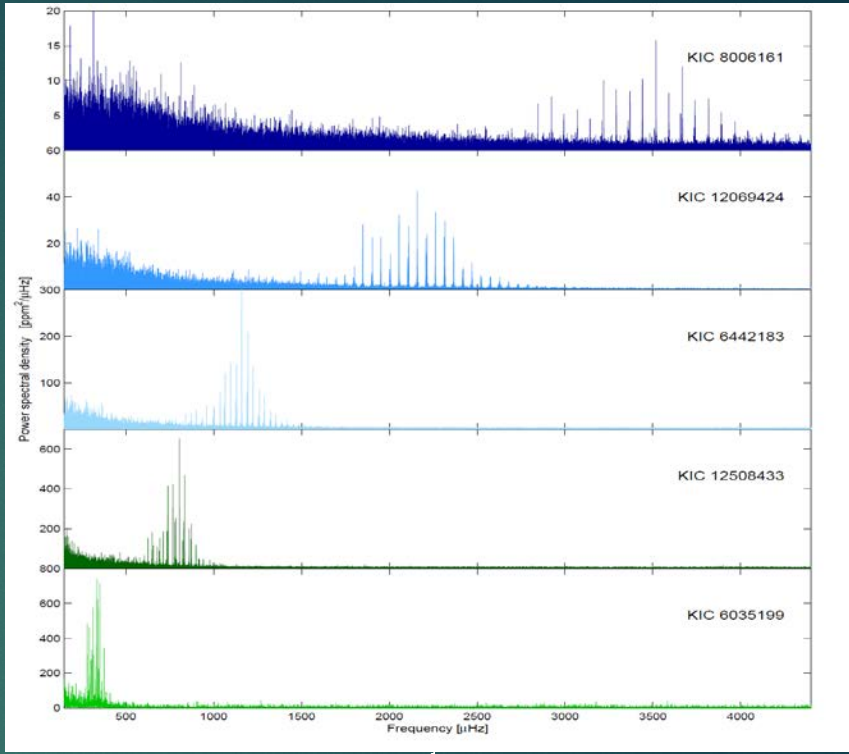
100,000 Abundances From High-Resolution Spectra





Asteroseismology



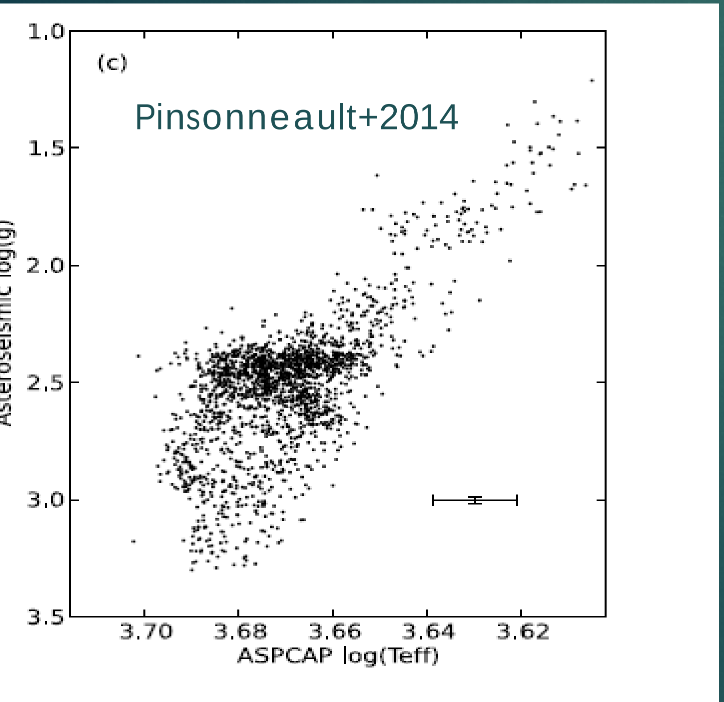


Log g ->

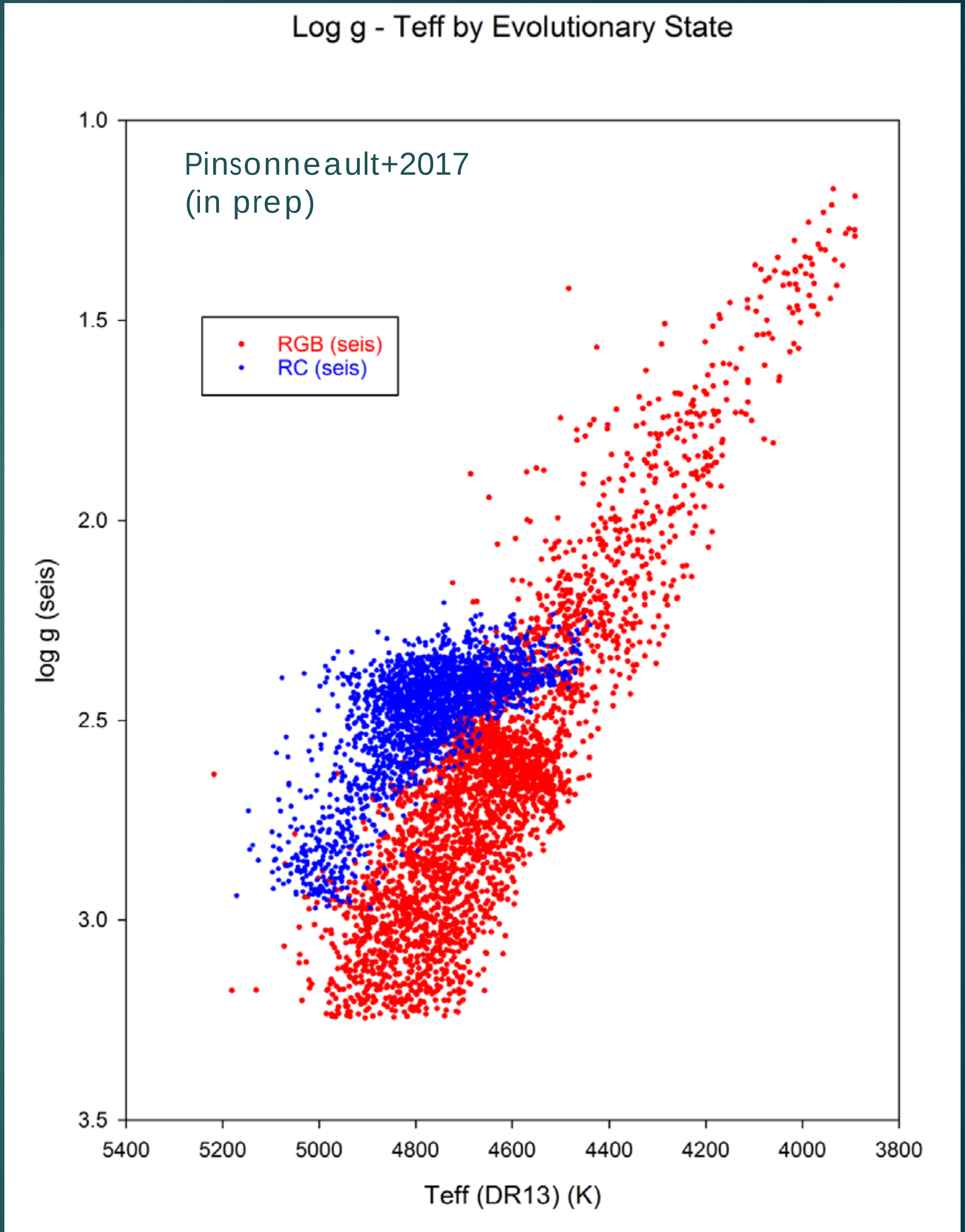
Can be Used to Infer Mass, Radius and Evolutionary State When Combined with Spectroscopy

The *Kepler* Red Giant Population

Asteroseismology
+ Spectroscopy
⇒Log g, Teff, R, M and
Evolutionary State



Powerful
Complement
To Parallaxes:
Mass + HRD
Position



Scaling Relations: Mass from Frequencies

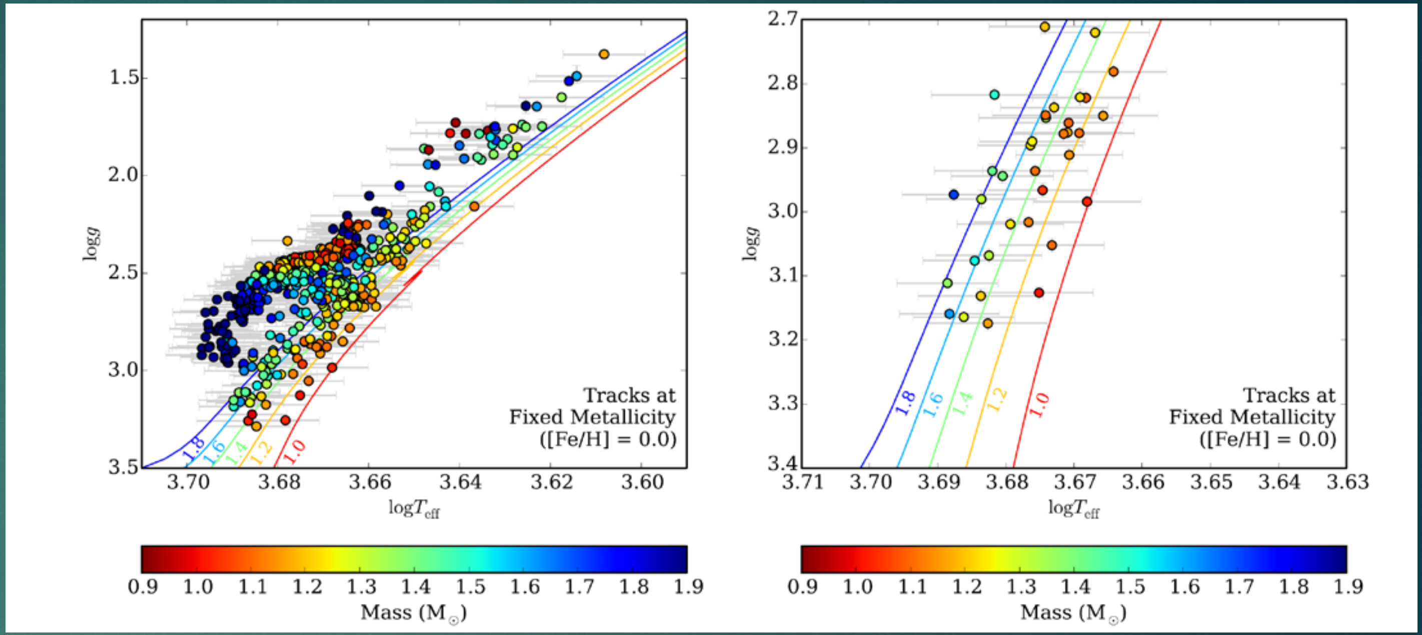
- Two most basic observables:
  - Frequency of maximum power

$\nu_{max} \sim M/R^2$

  - Mean frequency spacing

$\Delta\nu^2 \sim M/R^3$

APOKASC 1 Mass Data in a Narrow Metallicity Range



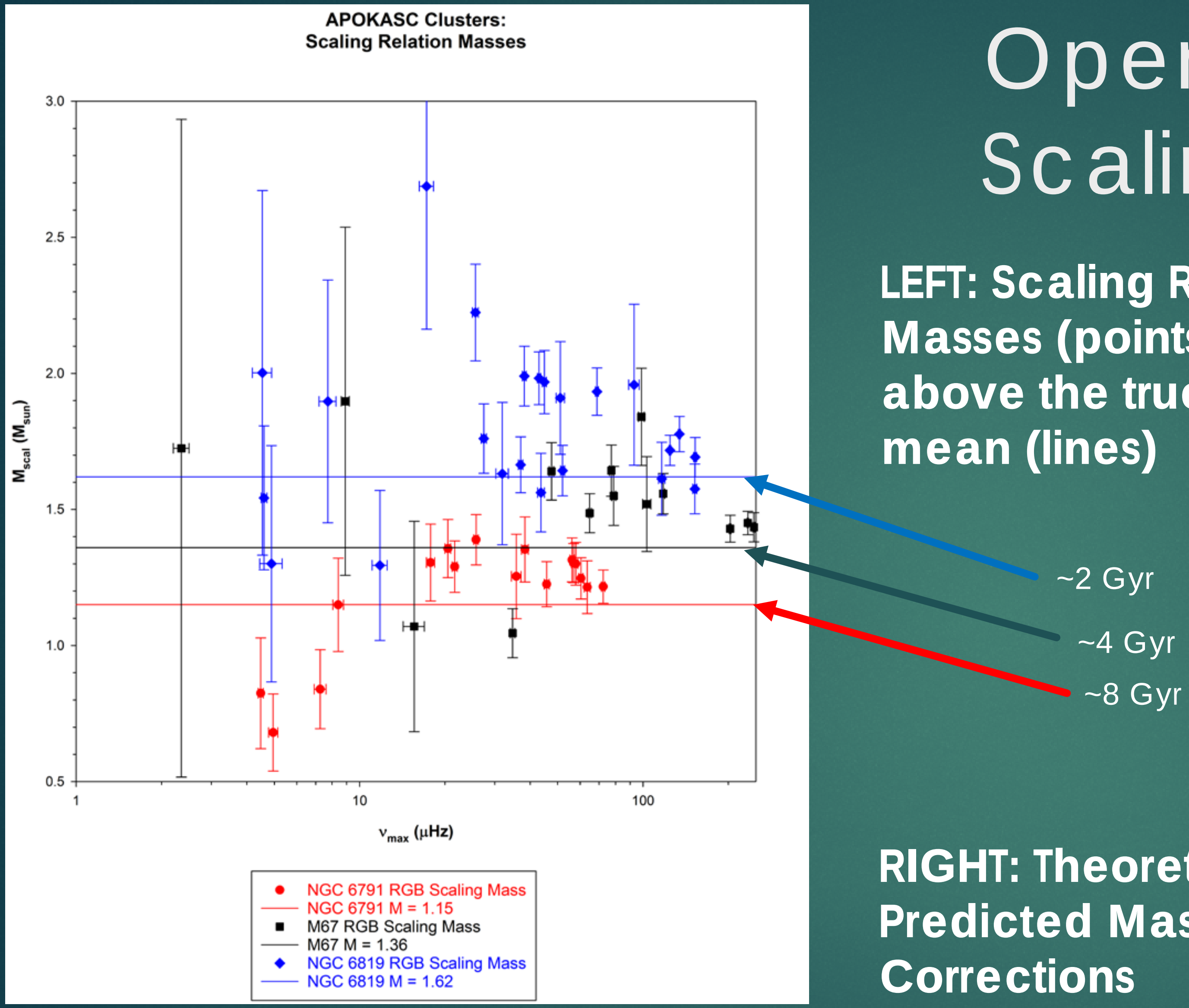
Pinsonneault et al. 2014

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

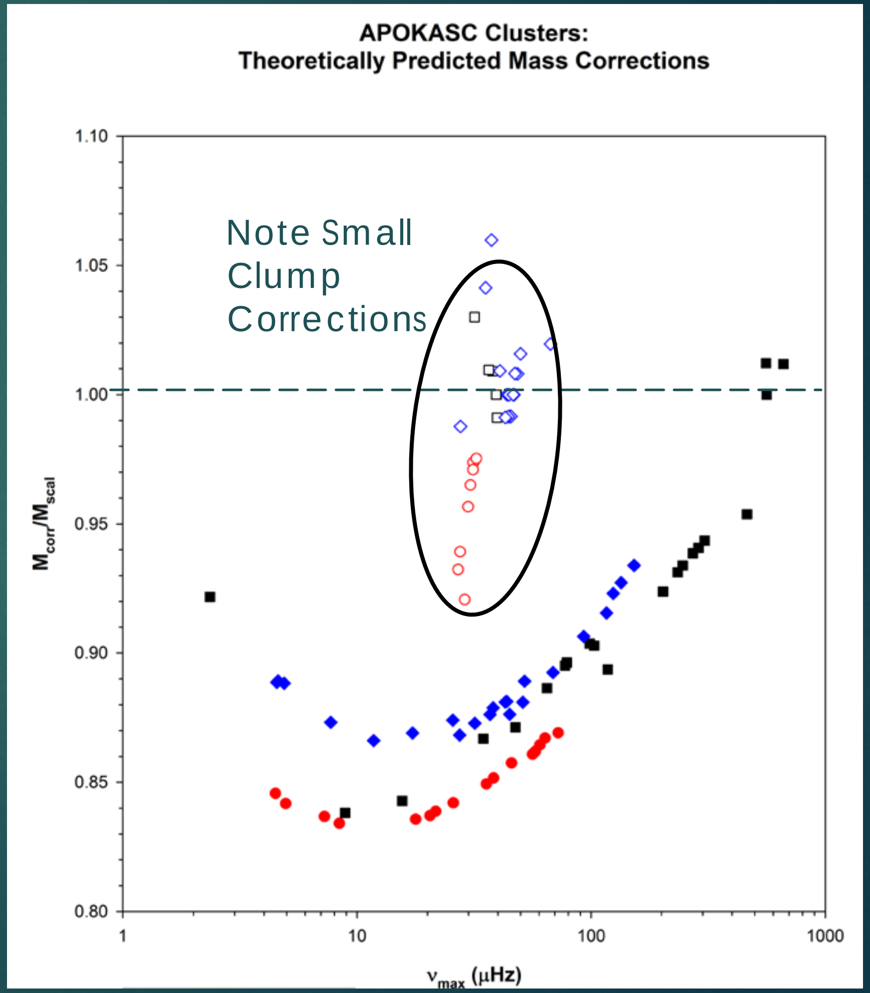
$$\frac{R}{R_\odot} \simeq \left(\frac{\nu_{max}}{\nu_{max,\odot}}\right) \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2} \left(\frac{T_{eff}}{T_{eff,\odot}}\right)^{1/2}.$$

BUT: MASSES NEED TO BE CALIBRATED

Open Cluster Tests of Scaling Relations

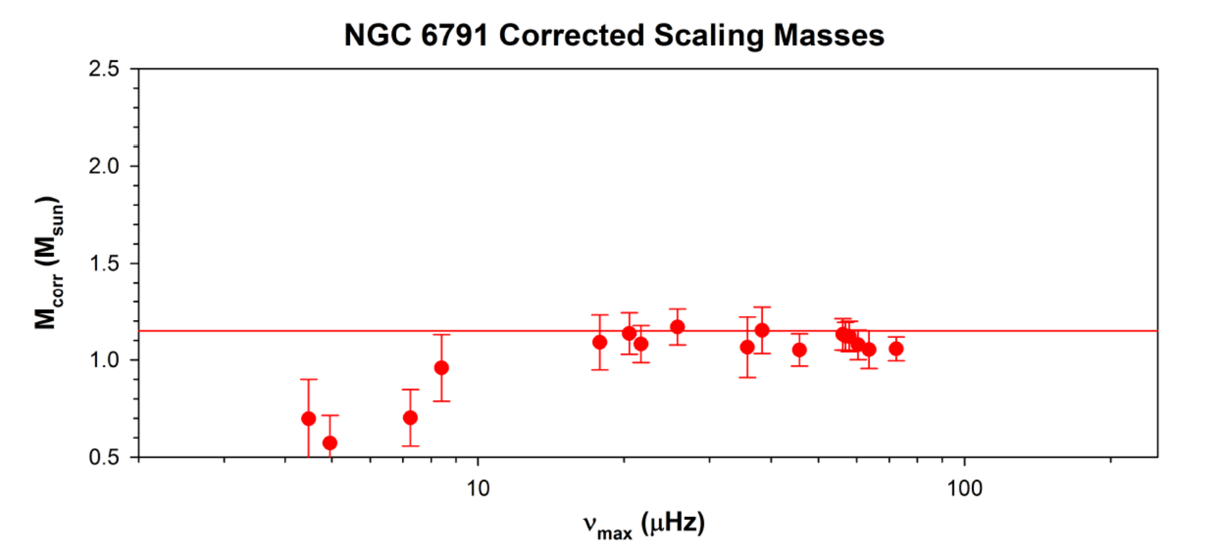


LEFT: Scaling Relation Masses (points) scatter above the true cluster mean (lines)



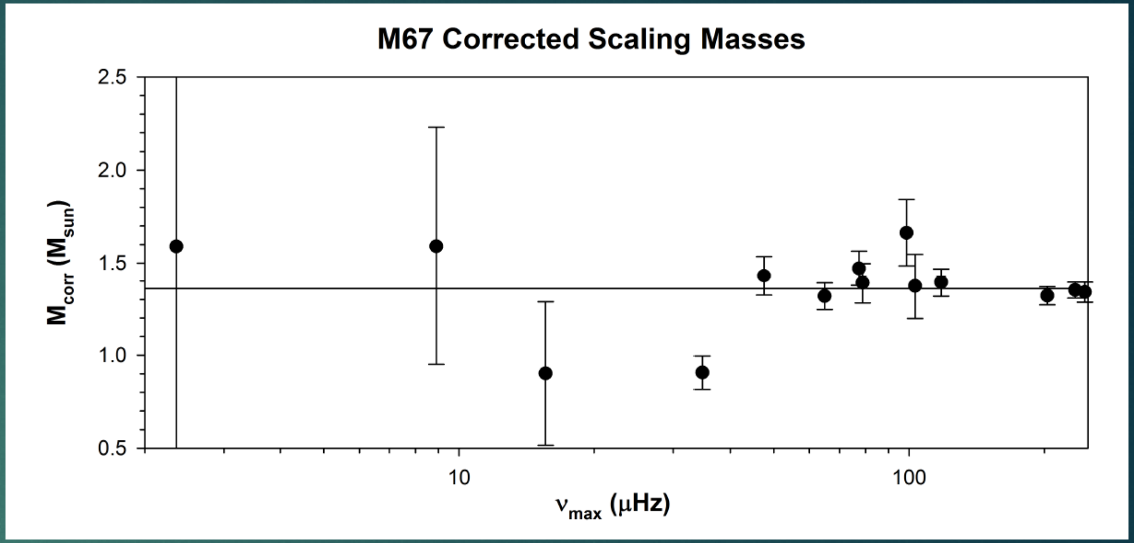
RIGHT: Theoretically Predicted Mass Corrections (Serenelli 2017) Are of the Right Sign and Size

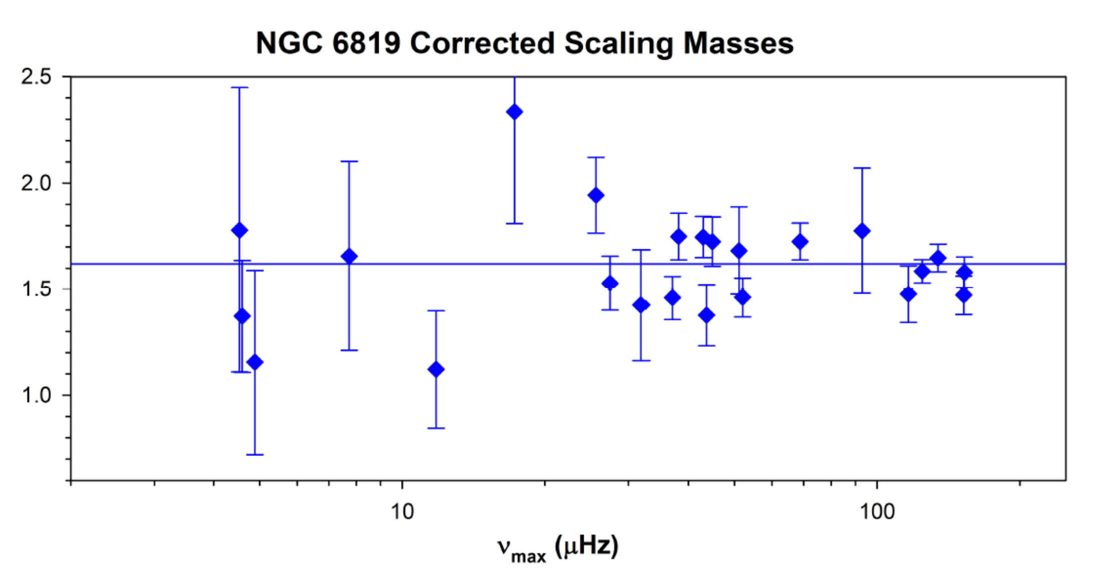
Improved Mass Agreement with Corrections



$$\frac{M_{TRUE}}{M_{SCALING}} = 0.911 +/- 0.016$$

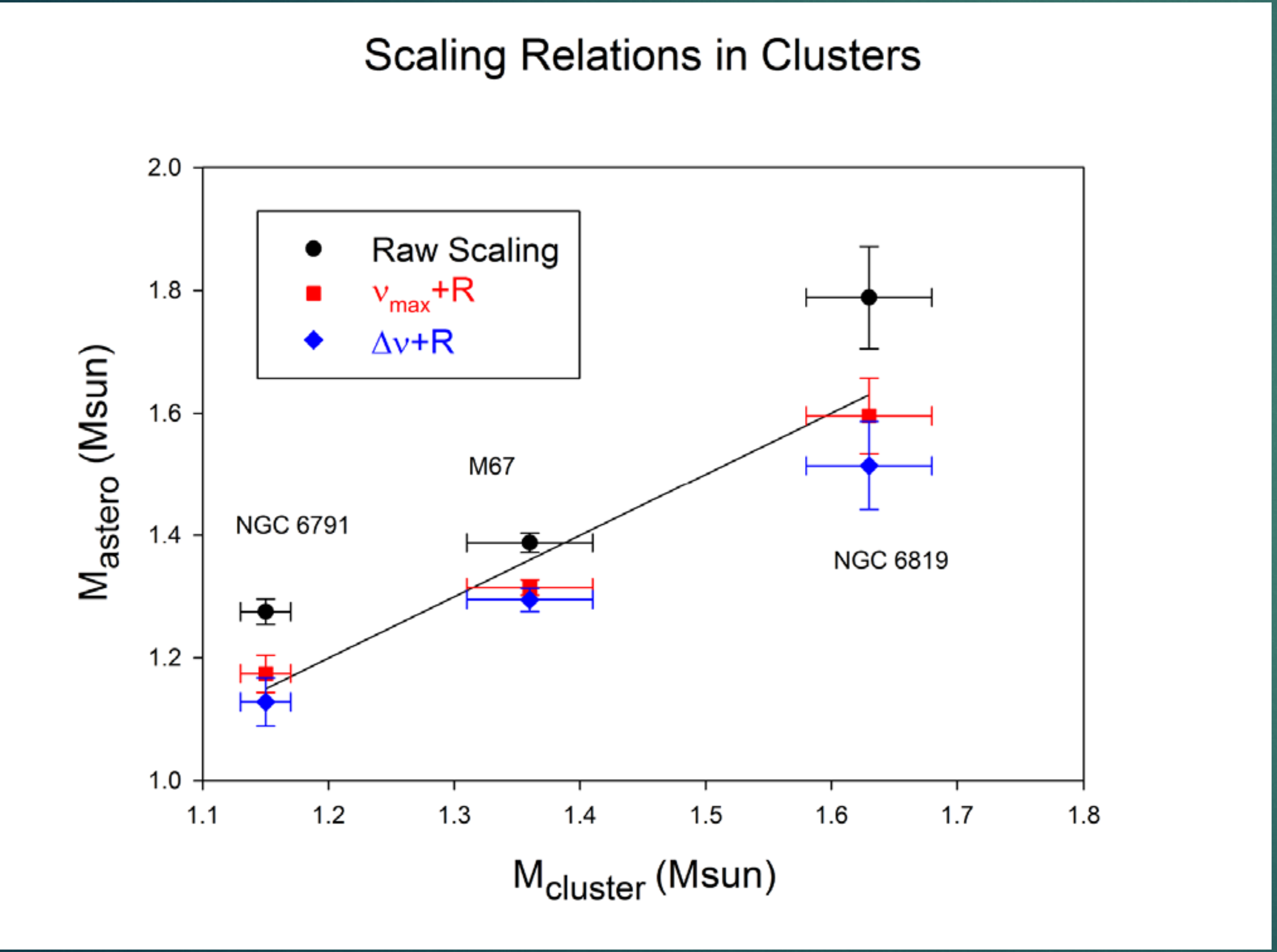
$$\frac{M_{TRUE}}{M_{CORR}} = 1.033+/-0.020$$





CAUTION: Larger Difference with Binaries (Gaulme et al. 2016)

Distance can be used to independently test the two scalings



- For Clusters:
  - $m + (m-M) + A_x = L$
  - $L + T_{eff} = R$

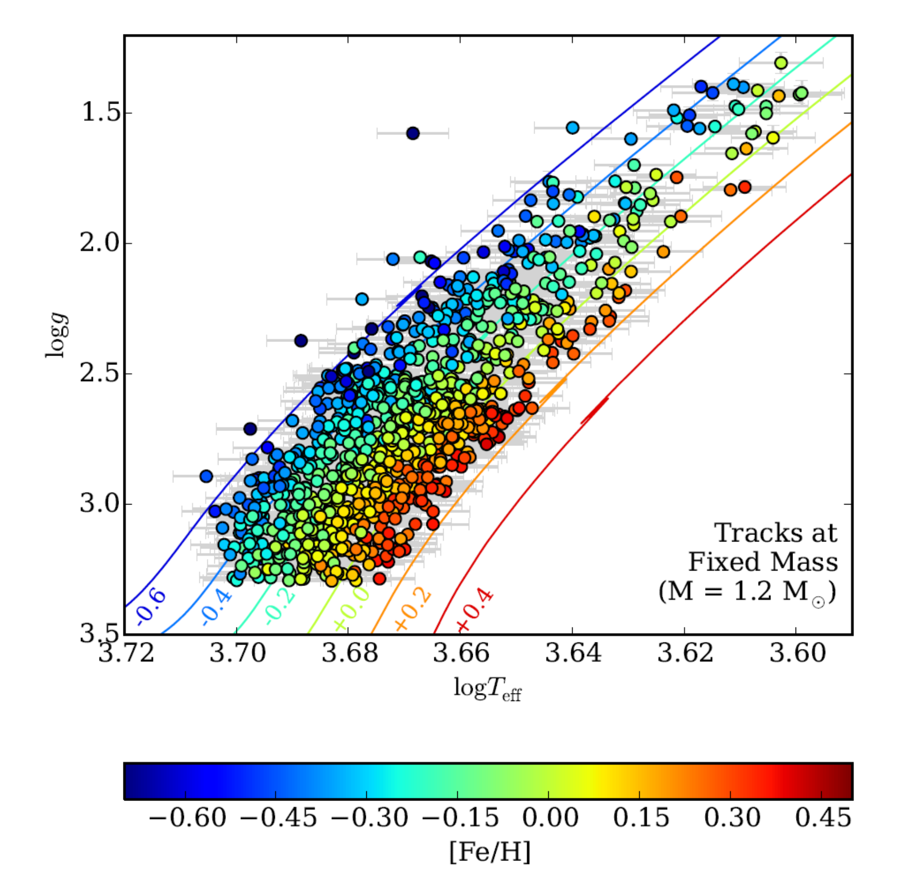
$\Rightarrow M \sim \nu_{max} R^2 T_{eff}^{0.5}$

$\Rightarrow M \sim \Delta\nu^2 R^3$

With Gaia we can do this test for thousands of field giants and with very high precision for clusters….

Asteroseismology Illuminates Defects in Our Isochrones

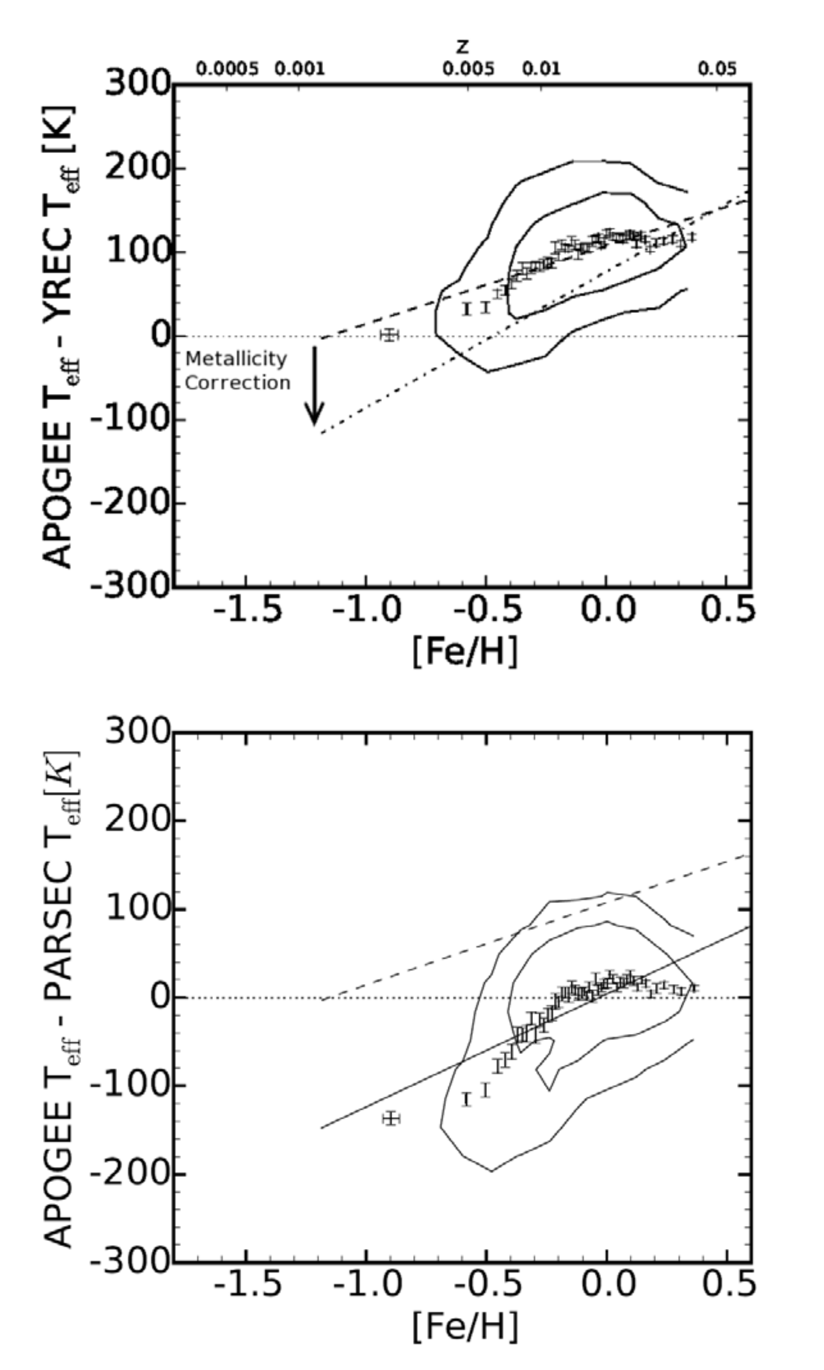
3,000 1st Ascent Giants With Masses



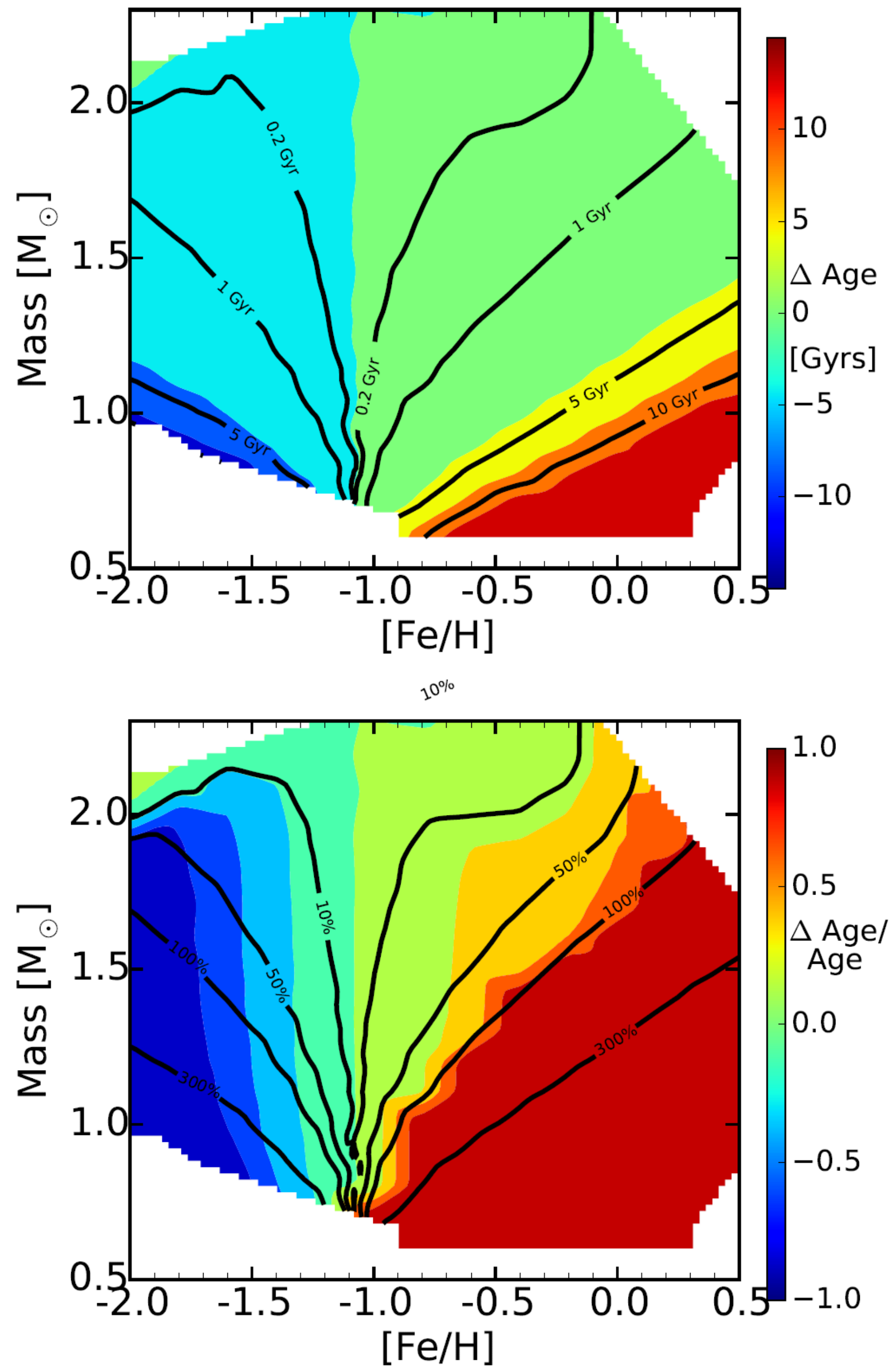
Compare Isochrone-Predicted Teff With Actual Data

Result: A Strong [Fe/H] Dependent Offset

Tayar+ 2017
(astro-ph/1704.01164)

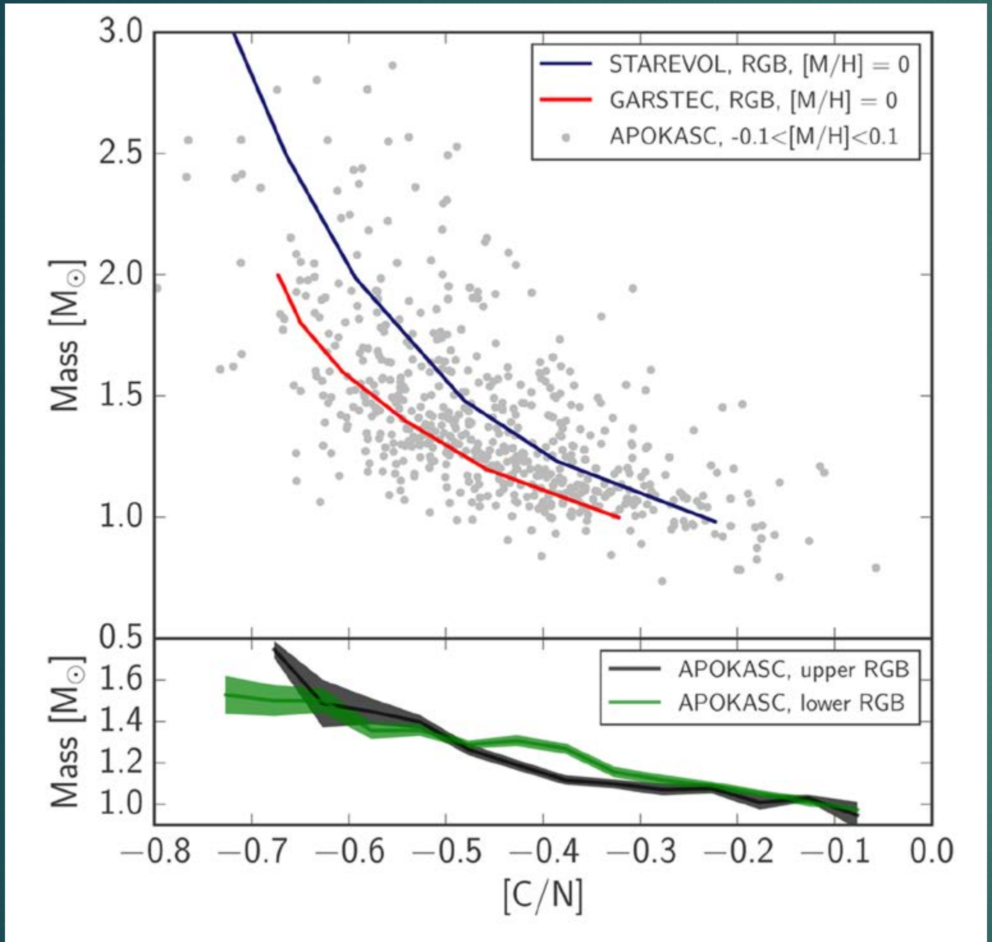


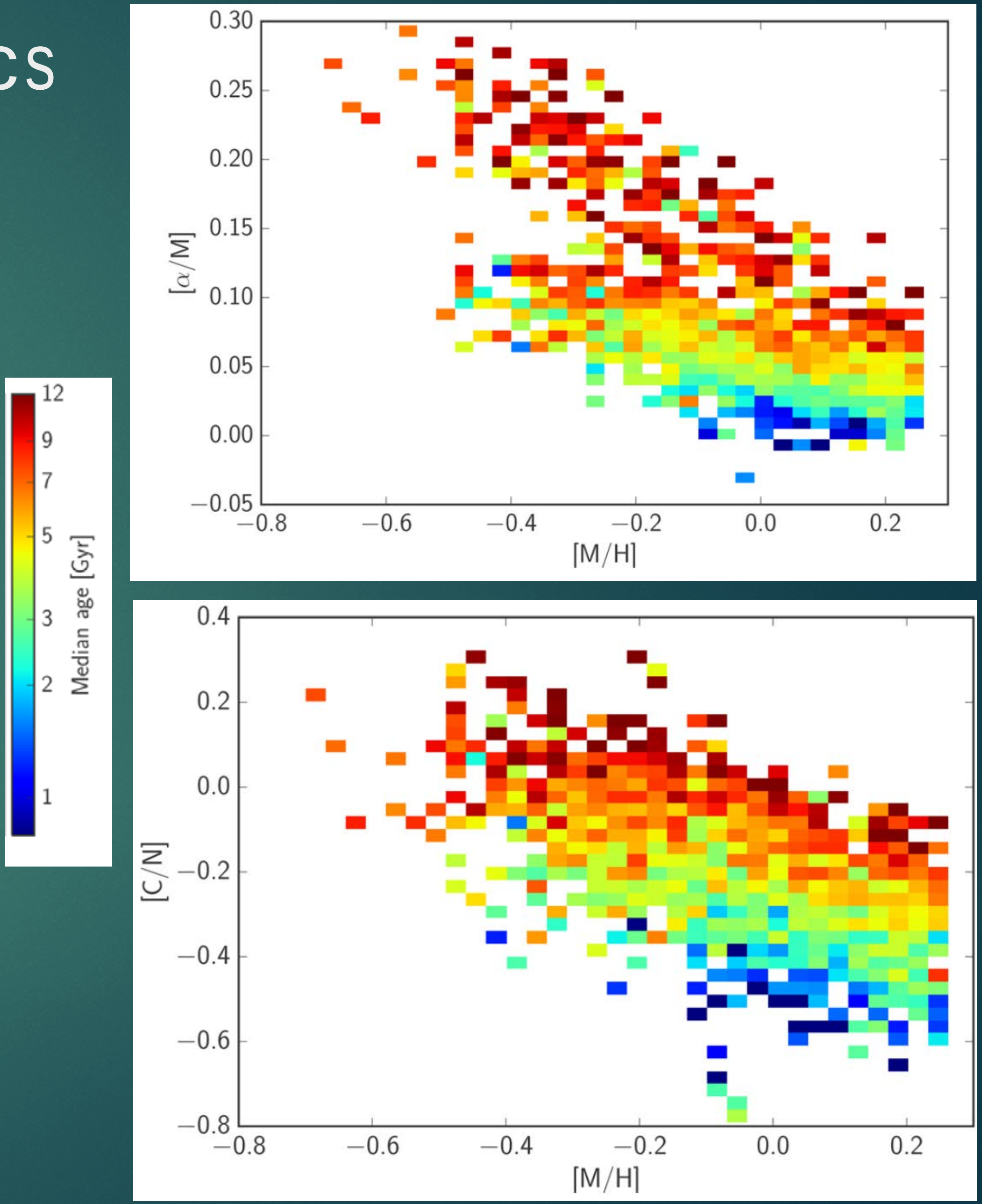
Isochrone Offsets Induce Large Age Shifts in Red Giants



APOKASC Calibrates C/N and Overall Spectra As Mass Diagnostics

Martig+ 2016 Ness+ 2016



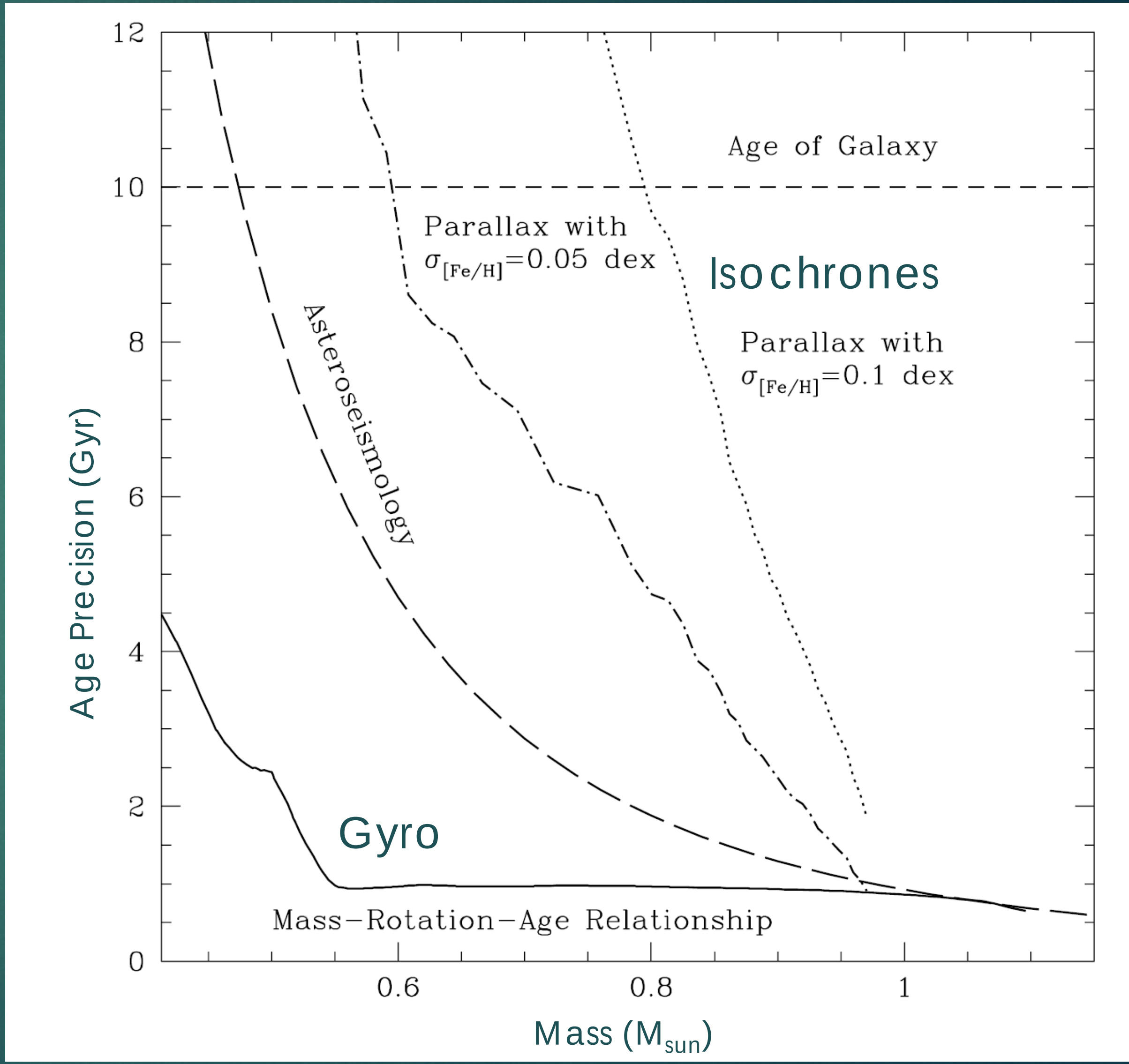


Lower RGB Similar to Upper RGB; Little mixing near solar [Fe/H]

Gyrochronology and Lower MS Ages

- Ages based on nuclear evolution are intrinsically imprecise on the lower main sequence
- Low mass stars spin down as they age:
  - Retains precision even in low mass stars

Epstein & Pinsonneault 2014: Isochrone Vs. Gyro Compared, Lower Main Sequence



Gyrochronology In Theory

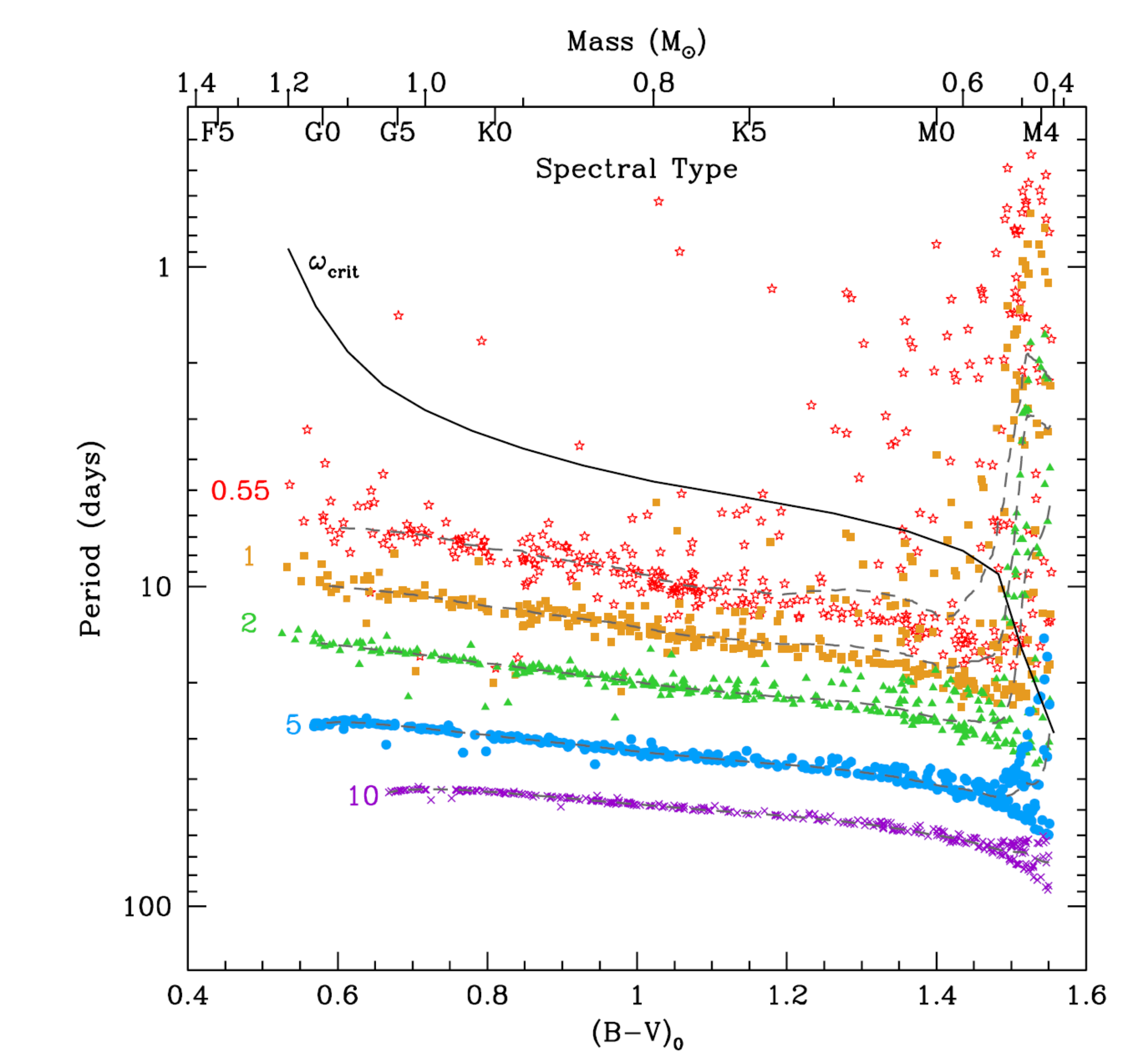
IMPORTANT POINT:

INTRINSICALLY
A SECOND ORDER
AGE DIAGNOSTIC

Rotation Correlated With Age Derived From Other Methods!

Young

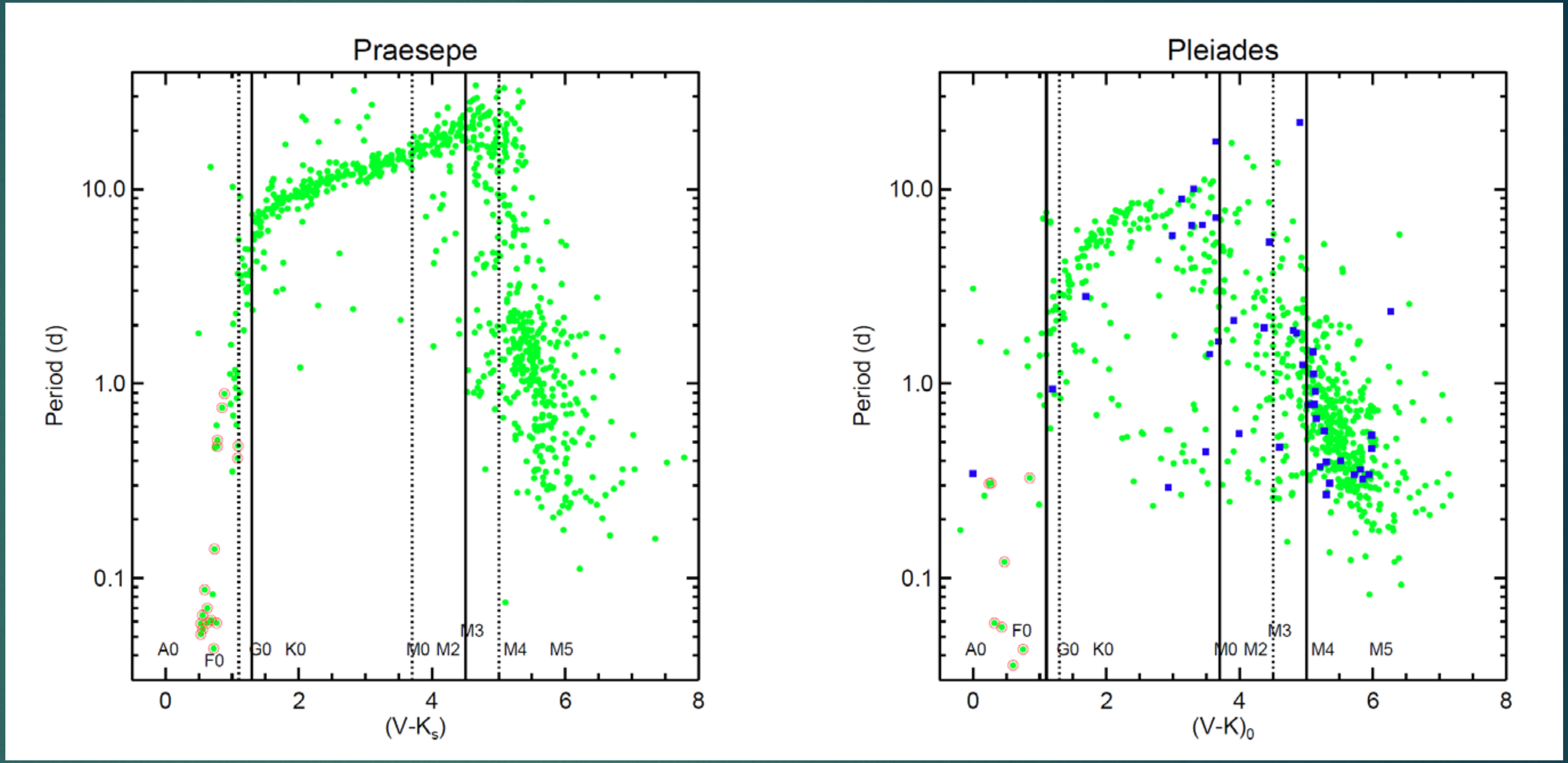
Old



Epstein & Pinsonneault 2014

Gyro In Practice: Promise and Pitfalls

- We have developed an enormous database of rotation periods
- Progress driven by space and ground based transit surveys



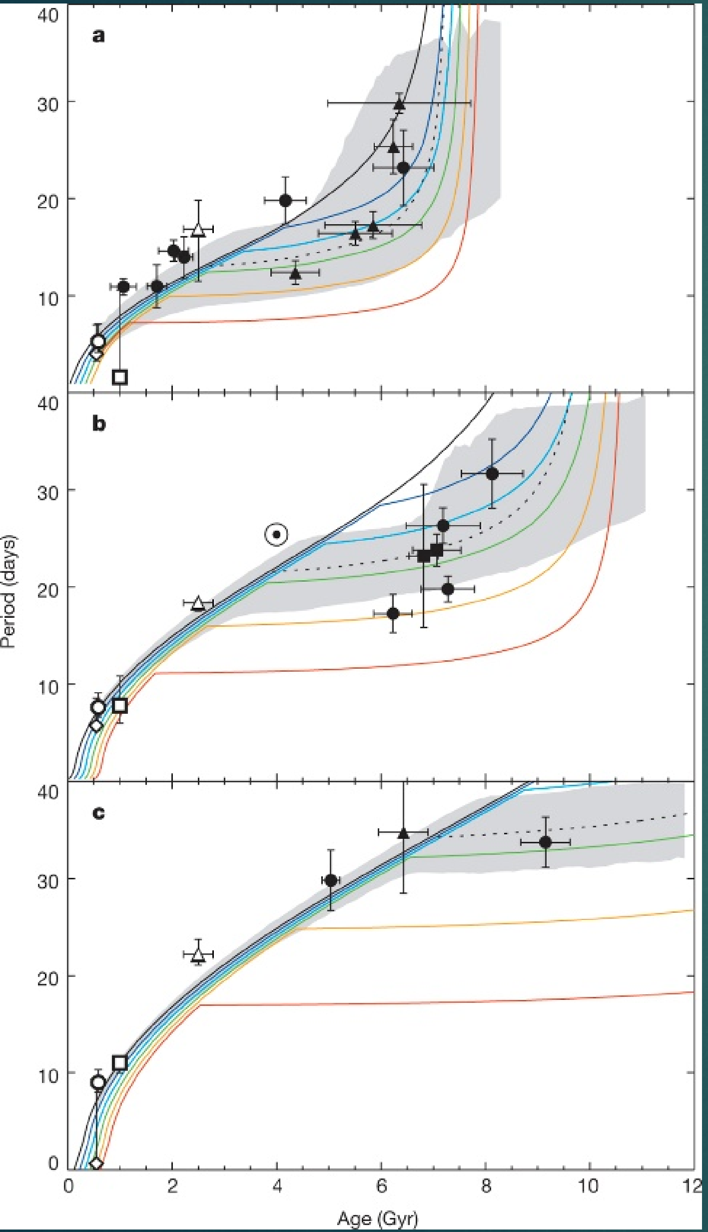
~625 Myr

~125 Myr

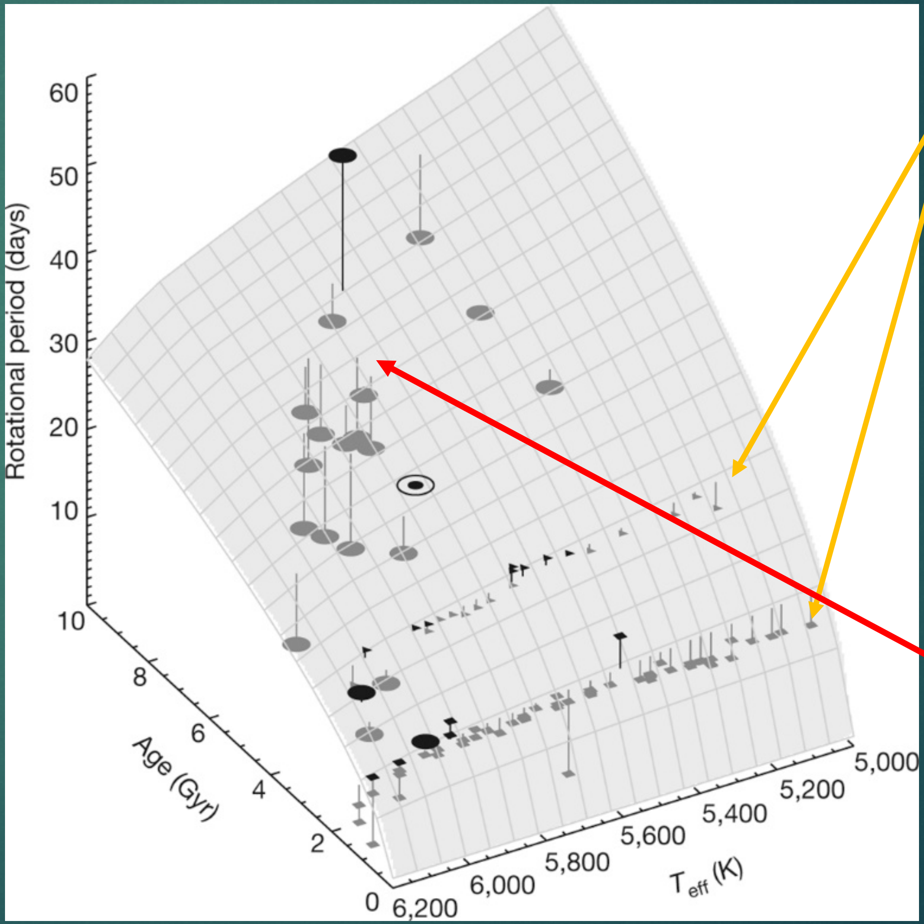
Well-Defined Rotation-Mass-Age Relations, Young Systems (Rebull+ 2016, 2017; Douglas+ 2017)

Clock Stops Earlier At Higher Mass

A Surprise: Spindown Stalls In Old Stars!



The period–age plane as predicted by gyrochronology compared with obserations.



Models Calibrated On Clusters 1-2 Gyr Old…

Predict Rotation Periods Longer Than The Data

van Saders *et al.* 2016 nature

Gaia and Gyrochronology

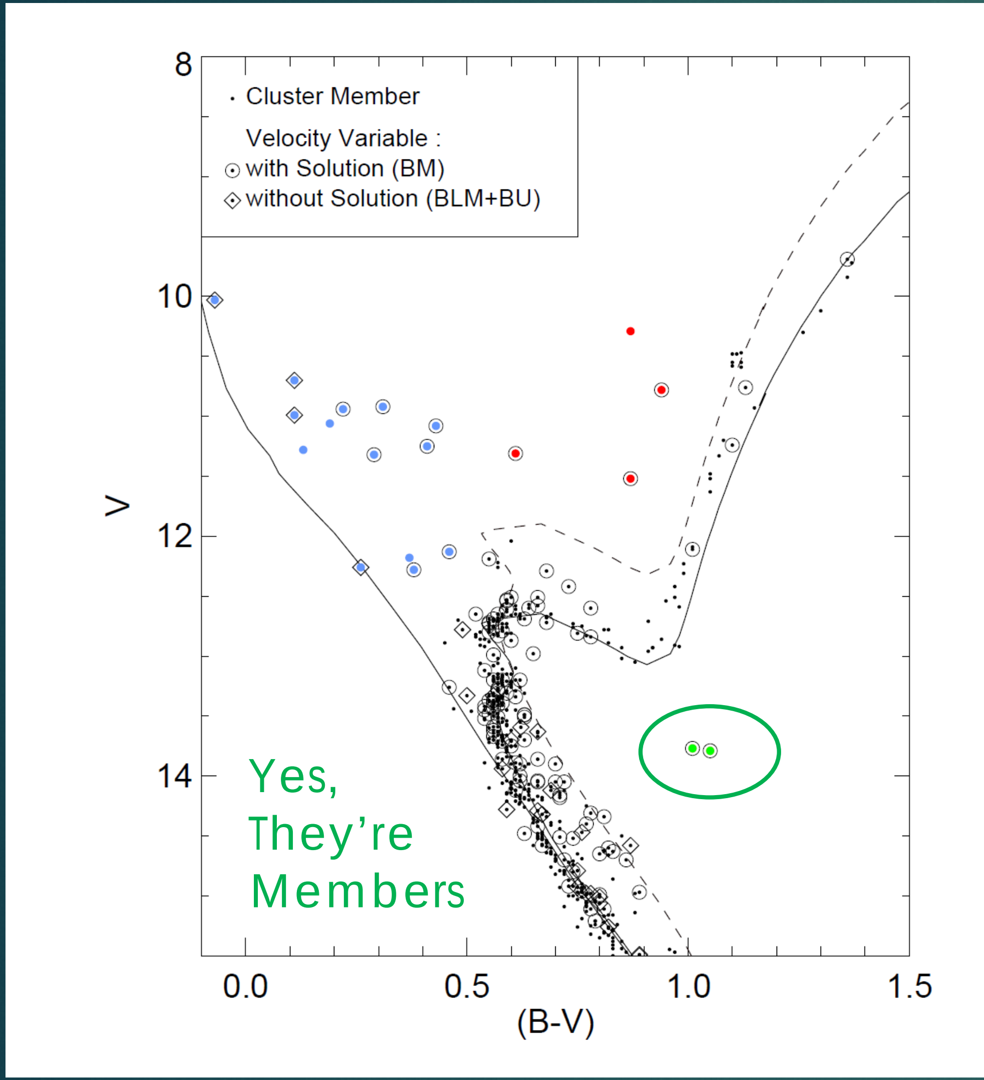
- DIRECT: Young Populations & Binaries
  - Short Period and Active Stars Will Be Detected As Gaia Variable Stars
- INDIRECT: Gaia Radii + TESS/K2/Kepler Seismology and Rotation

  => Large Sample of Direct Age Calibrators for Field Star Gyro
- VERDICT FOR NOW:

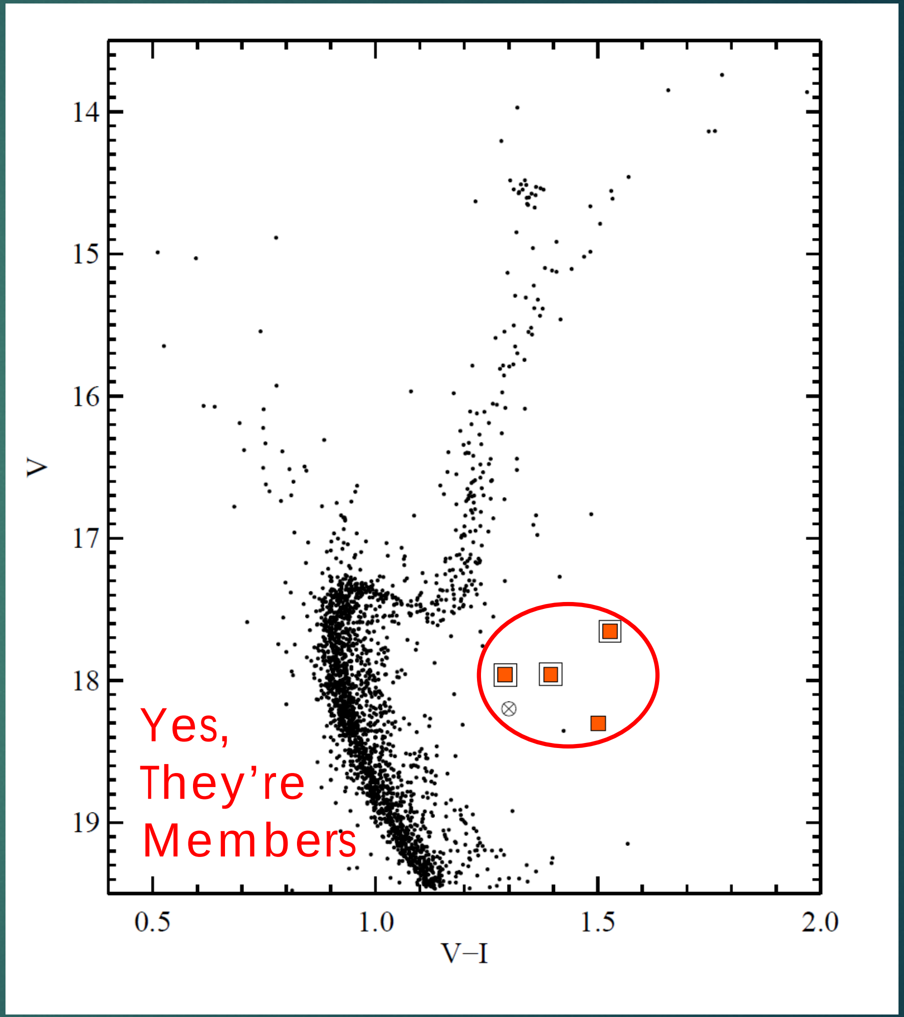
  Useful Age Diagnostic for Stars More Active than the Sun, esp. KM

Binary Star Evolution And Gaia

This is what real Gaia cluster CMDs will look like…

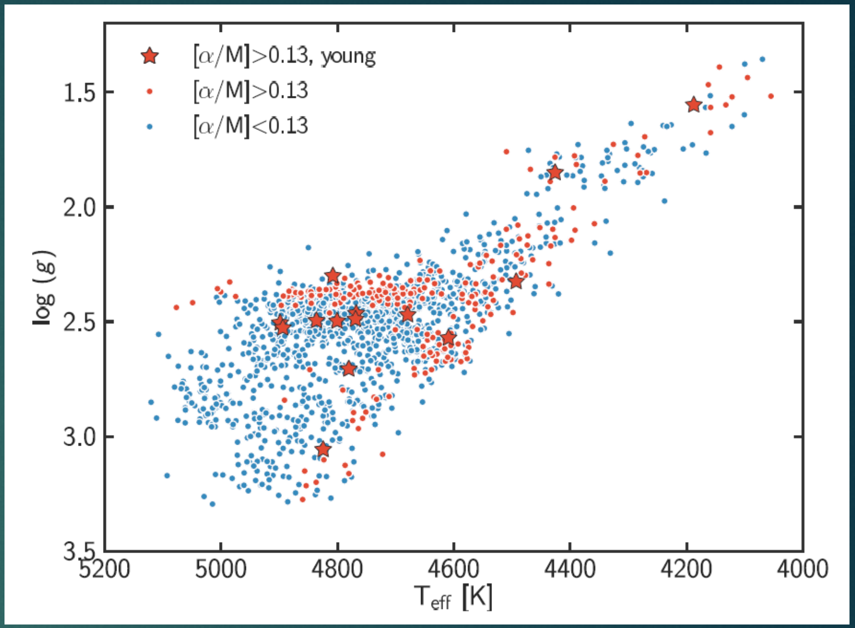


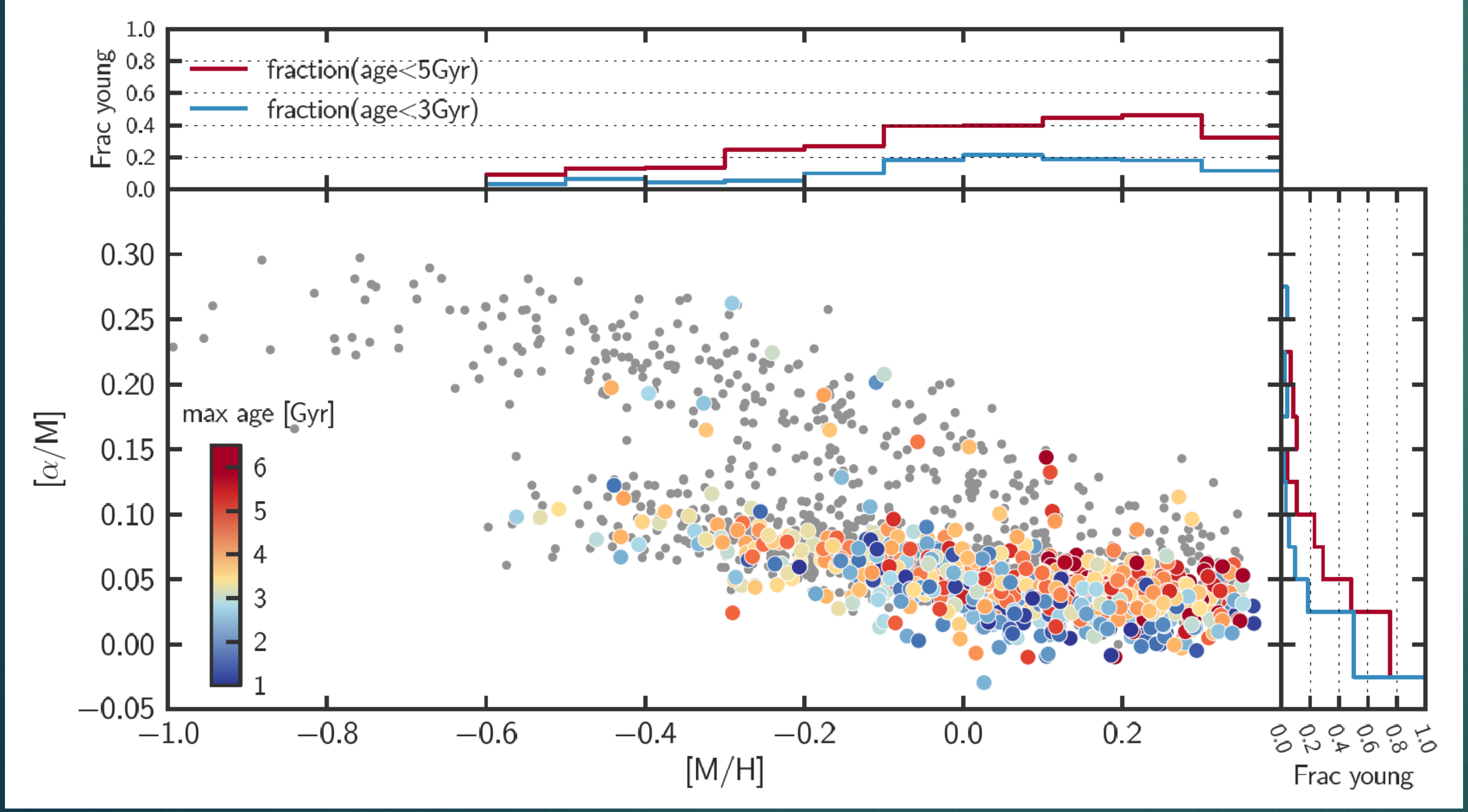
Geller+ 2015: "Oddballs" Are Common in M67



Milliman+ 2016: Numerous Binary Evolution Products in NGC 6791

An Example: Young α-rich giants in the solar neighborhood





- Martig+ 2015: 14/241 high-α stars have ages < 5 Gyr
- Could be evolved blue stragglers…
- But the rate is then high, and must be accounted for in other samples!

CONCLUSIONS

- Stellar Astrophysics is Being Radically Transformed
  - Asteroseismology, Rotation, Large Spectroscopic Surveys
- Gaia will have a profound impact, especially when combined with other constraints
- Seismology can provide masses for large samples of stars
  - POWERFUL combination with Gaia
- Existing isochones will need to be revised
- Stay tuned: we will have a very good idea about the validity of our age framework in ~ 1 year!