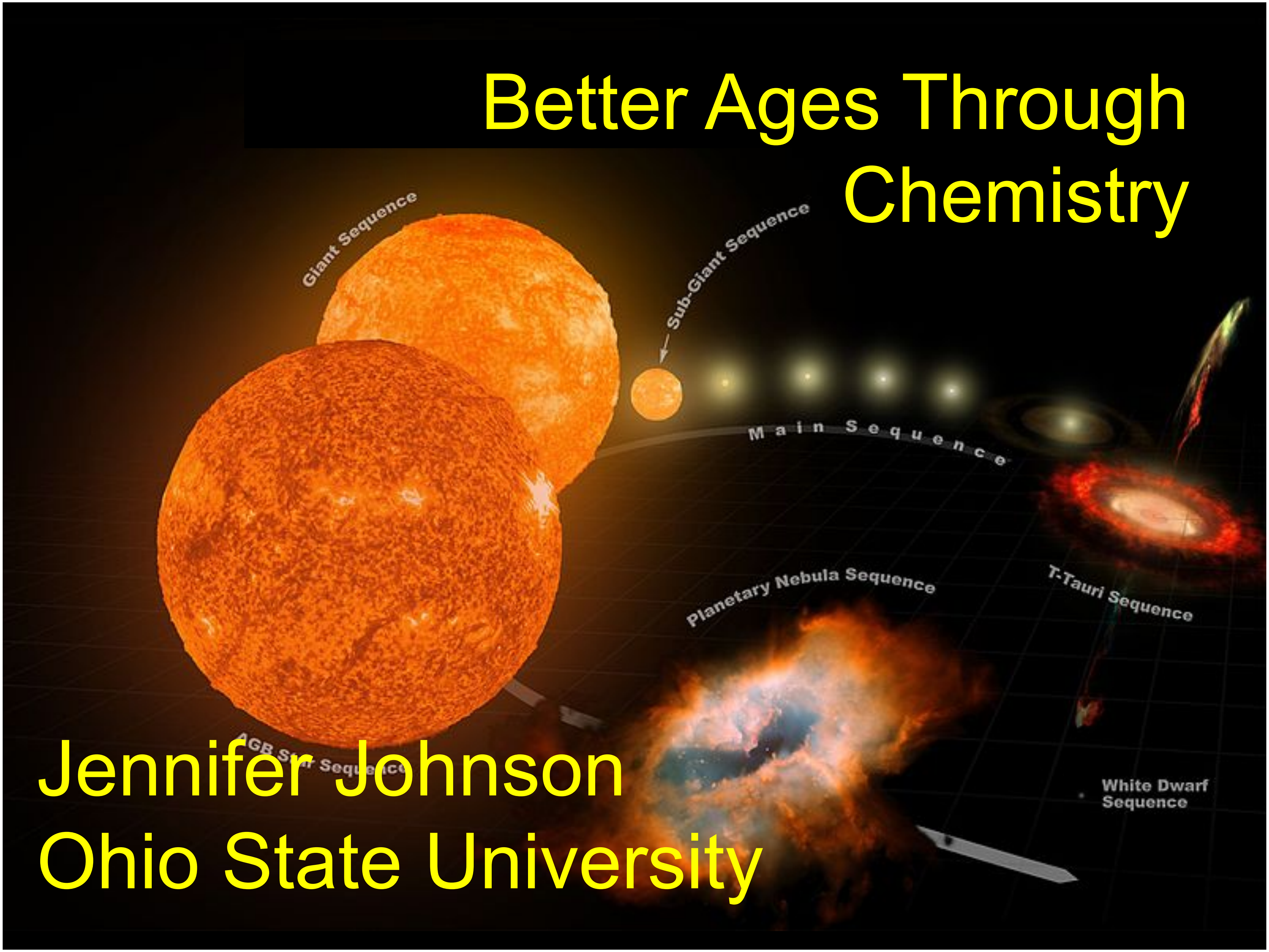
Better Ages Through Chemistry

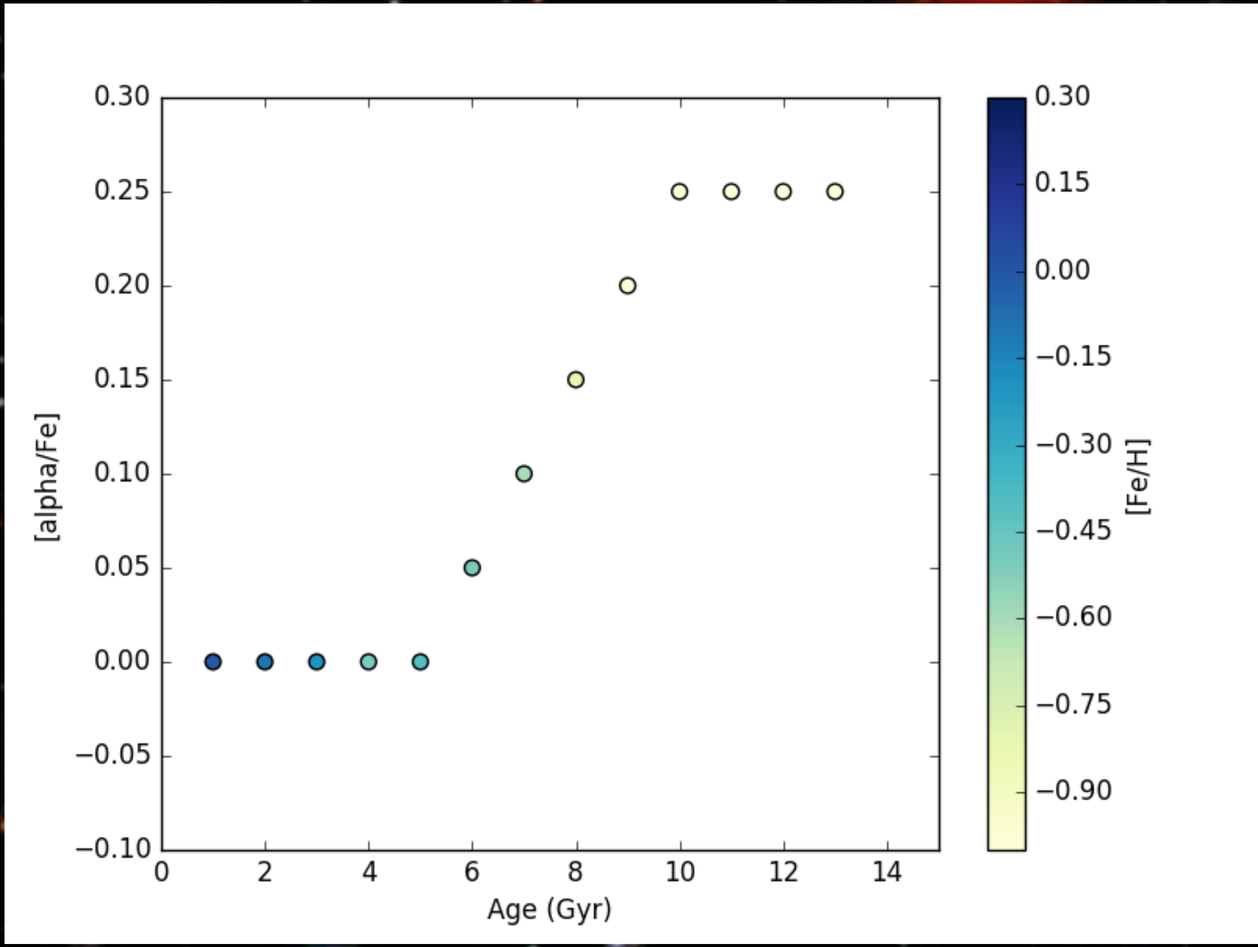


Jennifer Johnson
Ohio State University

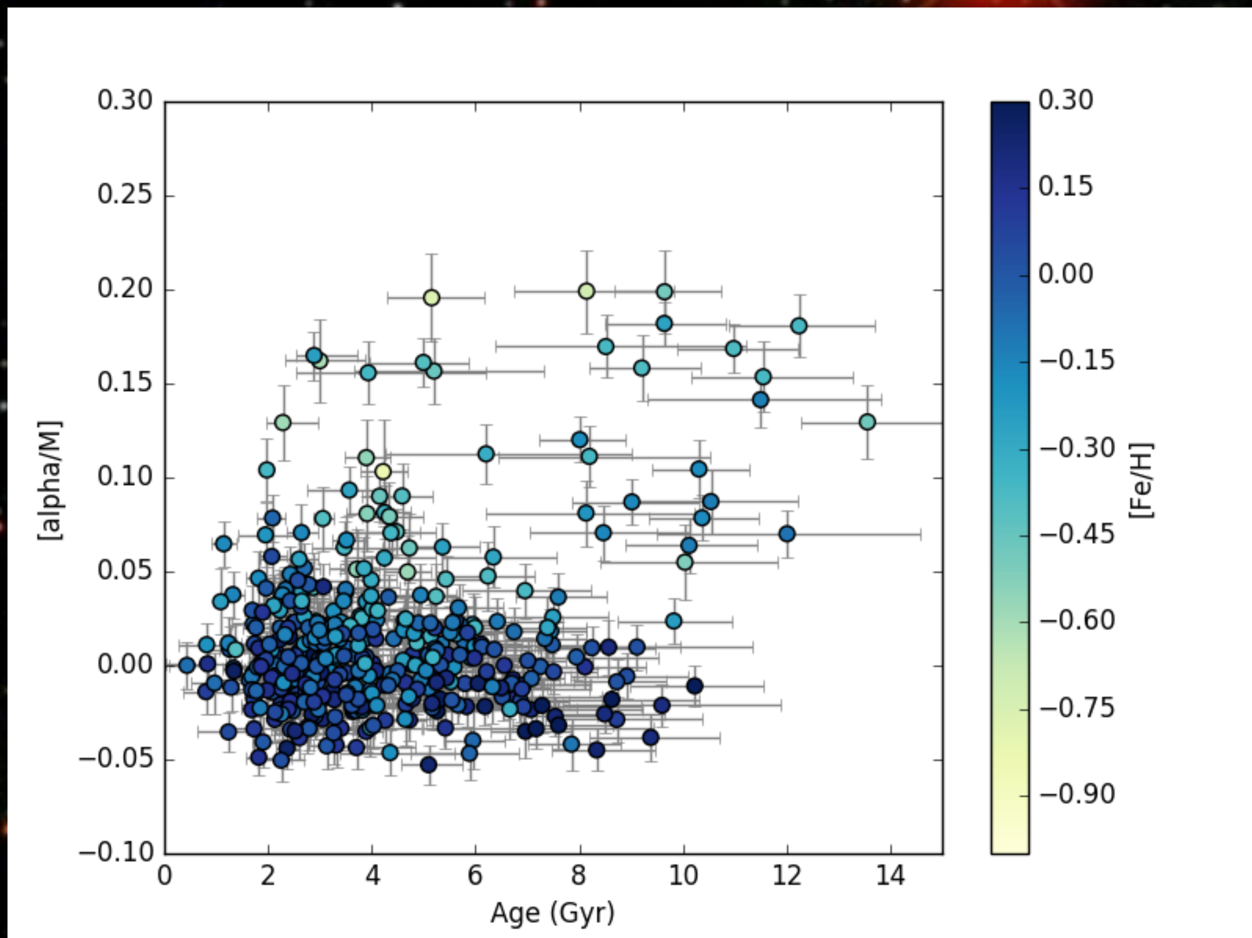
Stellar Ages are Important.....

- Ages of planetary systems
- Star formation history of the Milky Way
- Inside-out, upside-down galaxy formation
- Origin of the thick disk
- Age-metallicity relationship
- Amount of radial mixing in the disk of the Milky Way

A Simple View of the Solar Neighborhood

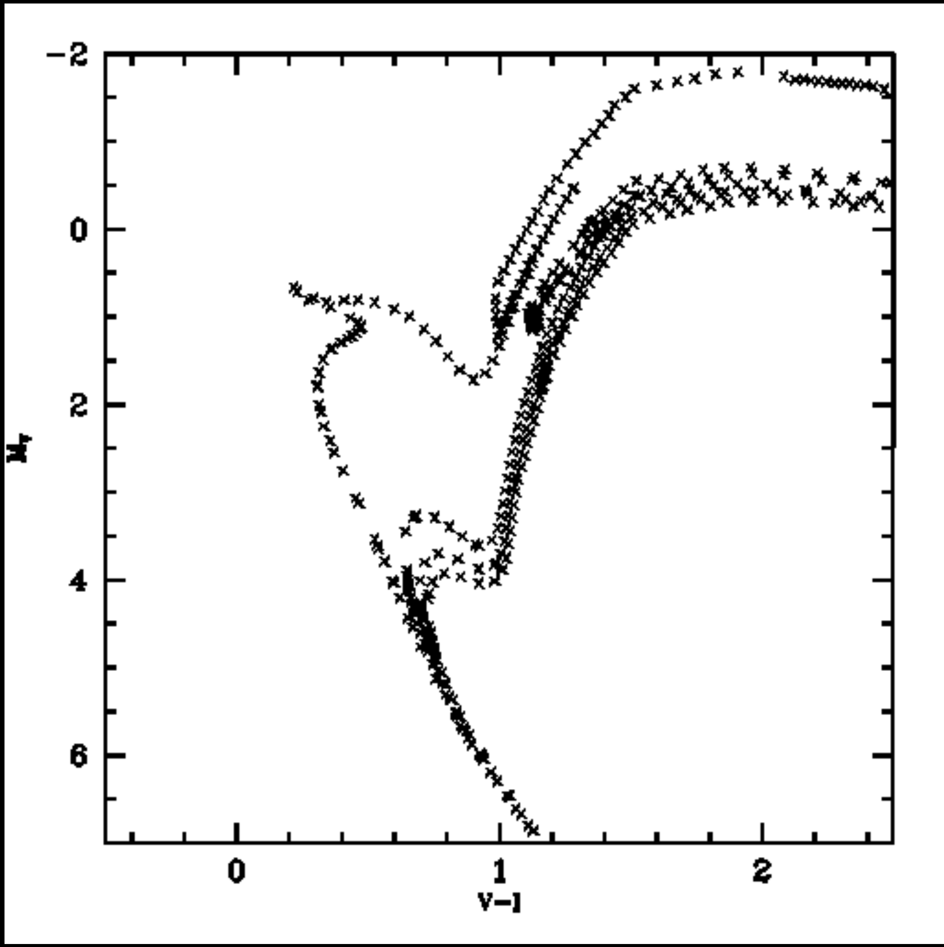


The Actual View of the Solar Neighborhood

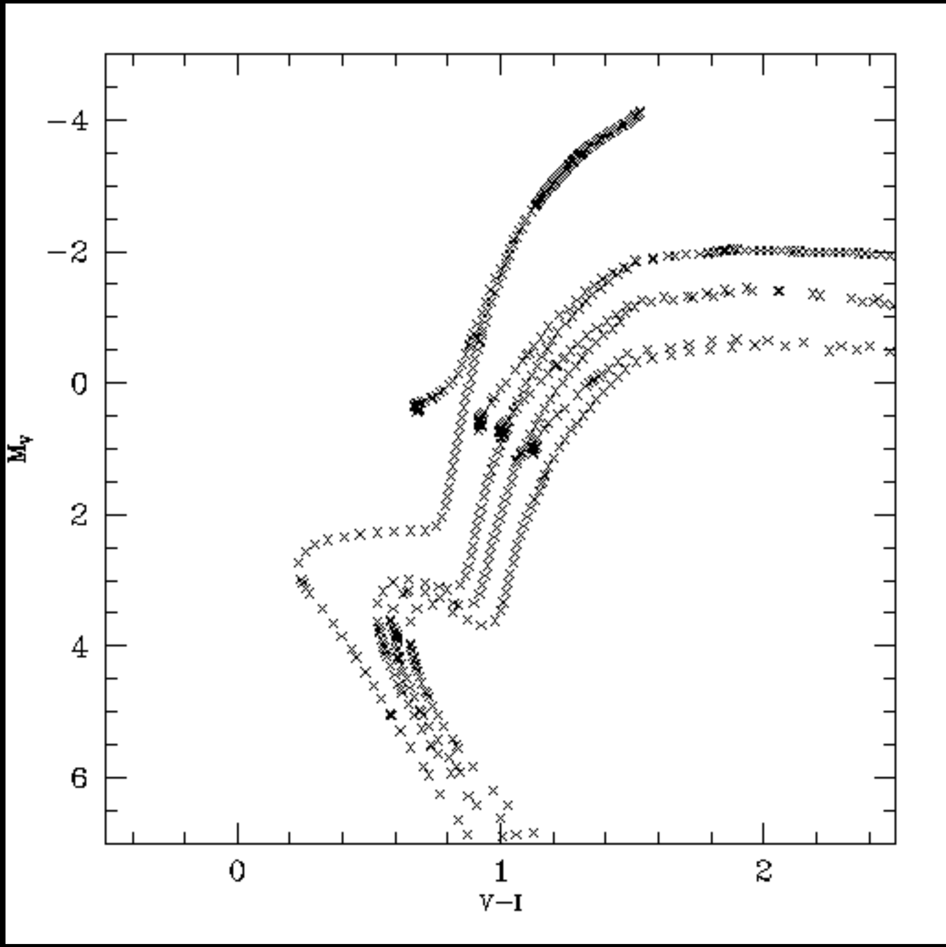


APOKASC dwarf catalog – Serenelli et al, 2018

……But Hard to Measure

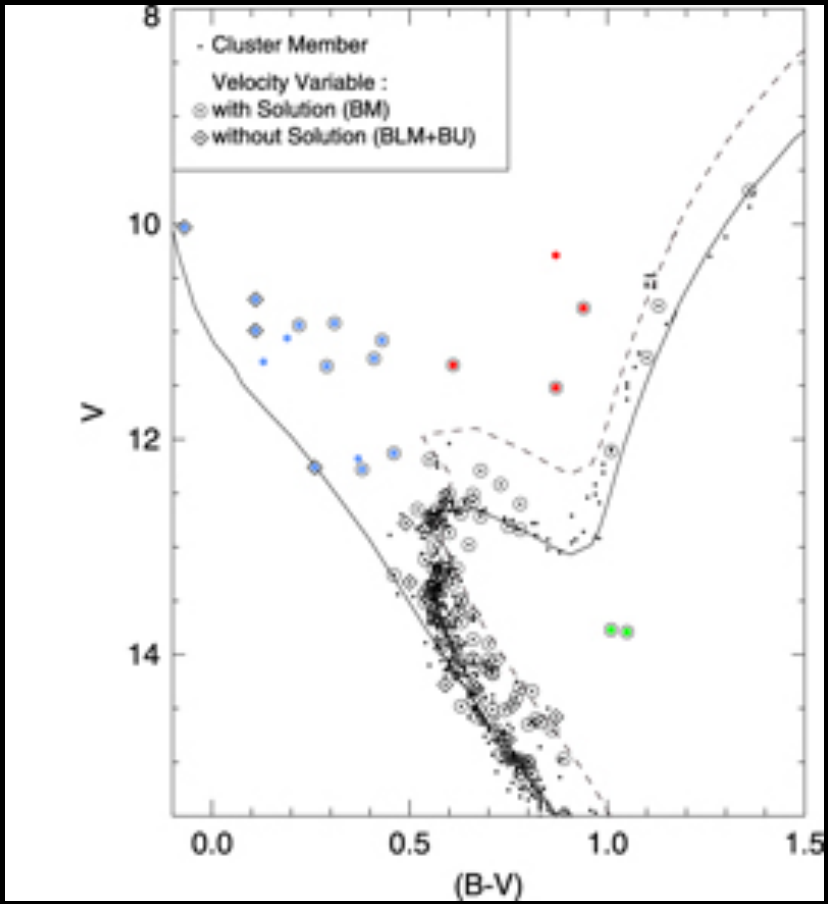


Composition Matters



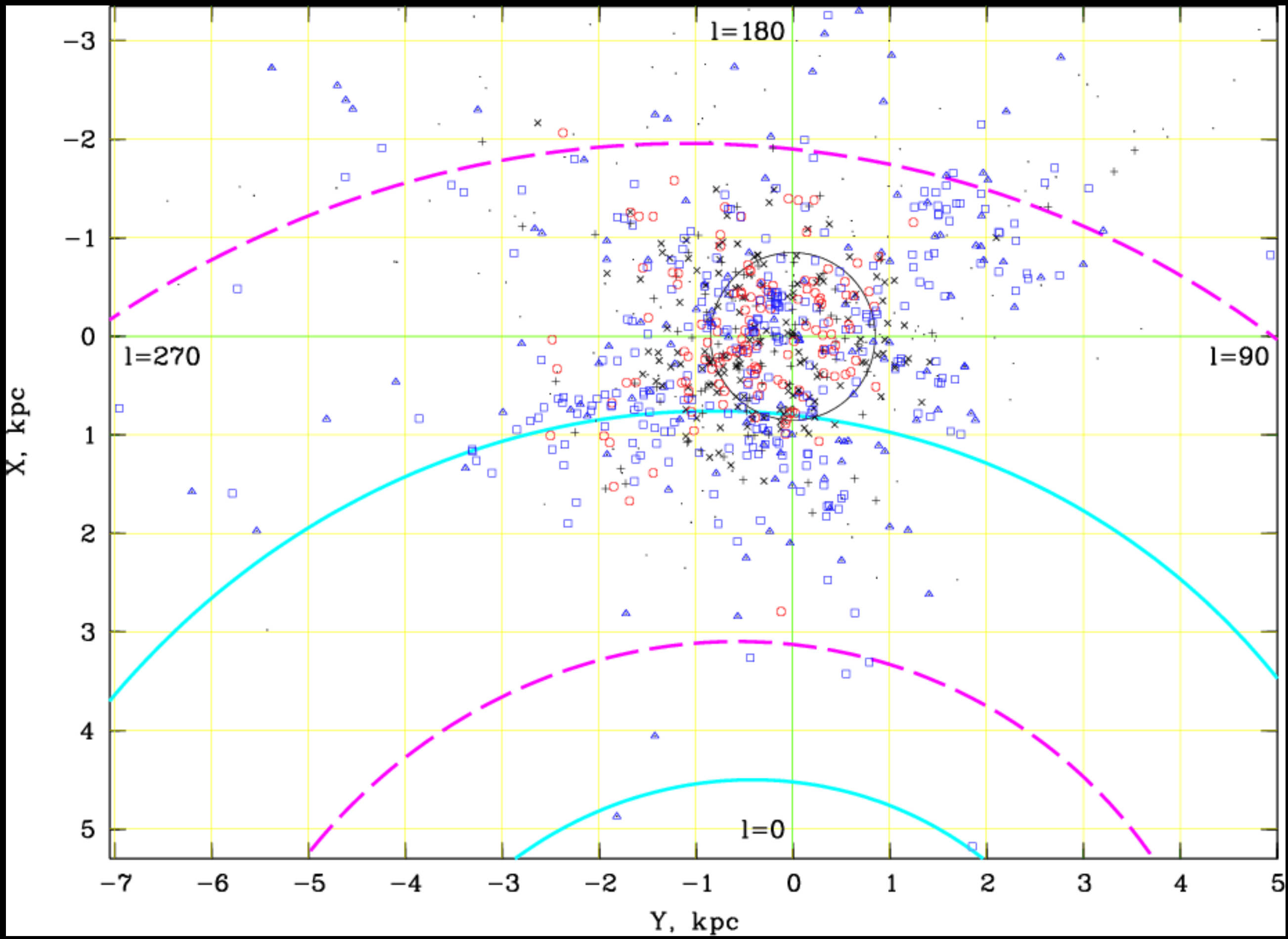
Open clusters to the rescue

Waid Observatory



Geller et al. 2015 (WOCS)

Open Clusters (somewhat) to the rescue



Piskunov et al. 2006

The Key Role of Turnoff Stars

Hydrogen exhaustion timescale

Mass + composition of evolved stars → age

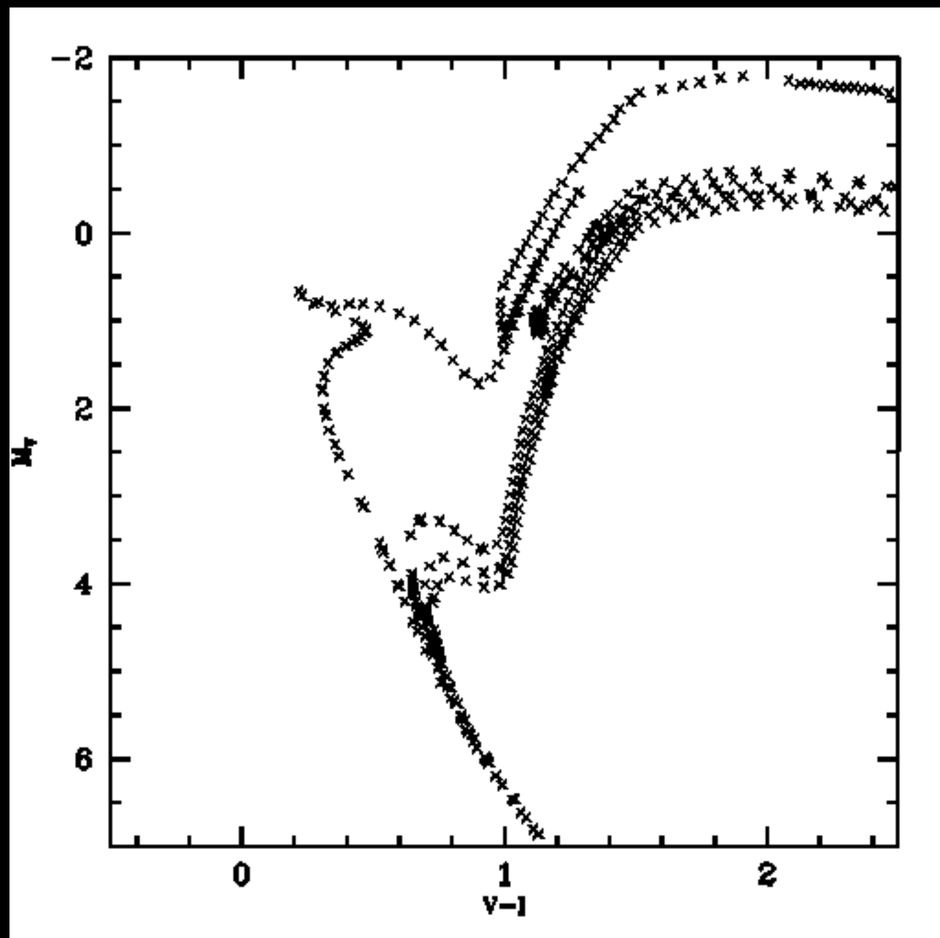
Ages for Luminous Red Giants

Asteroseismology

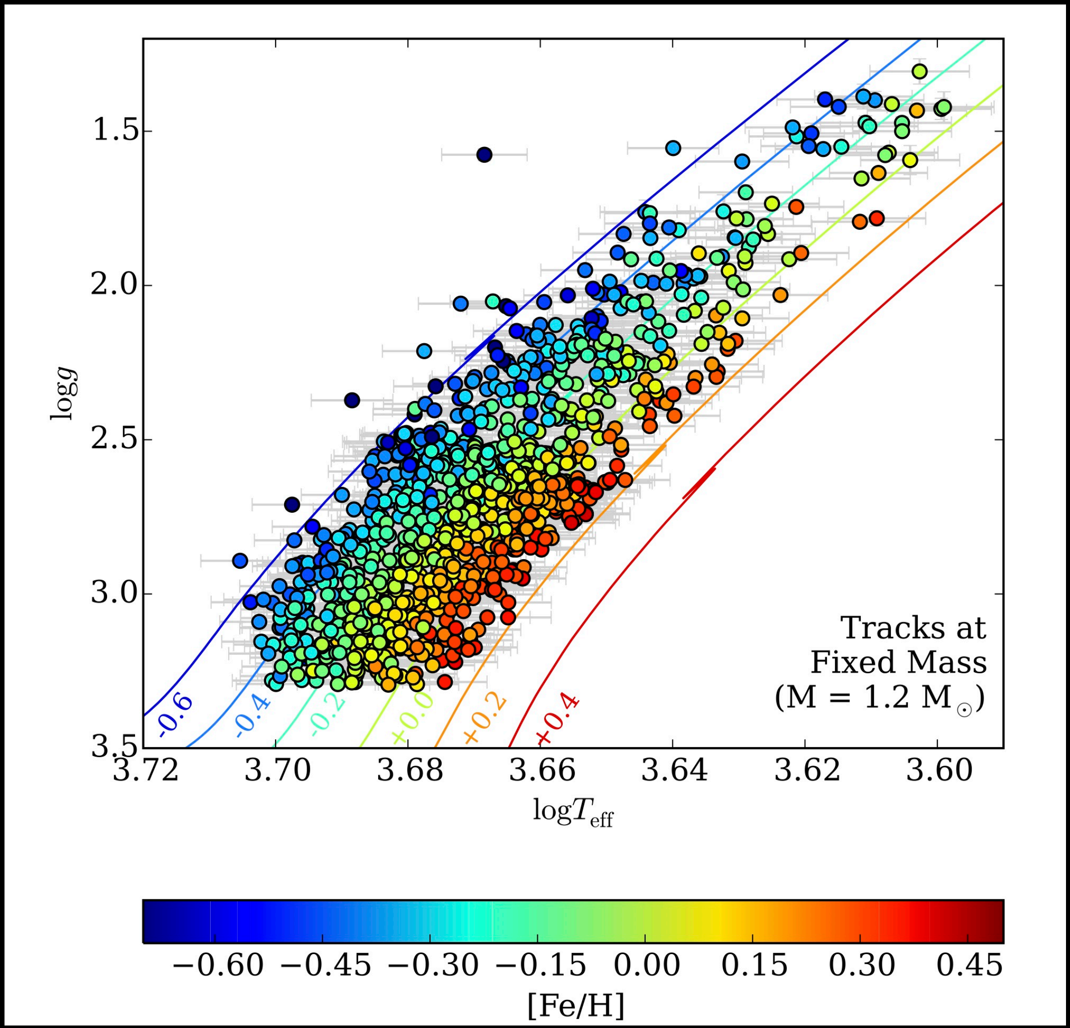
Carbon and Nitrogen Measurements

Gaia parallaxes

Gaia alone will not save us..

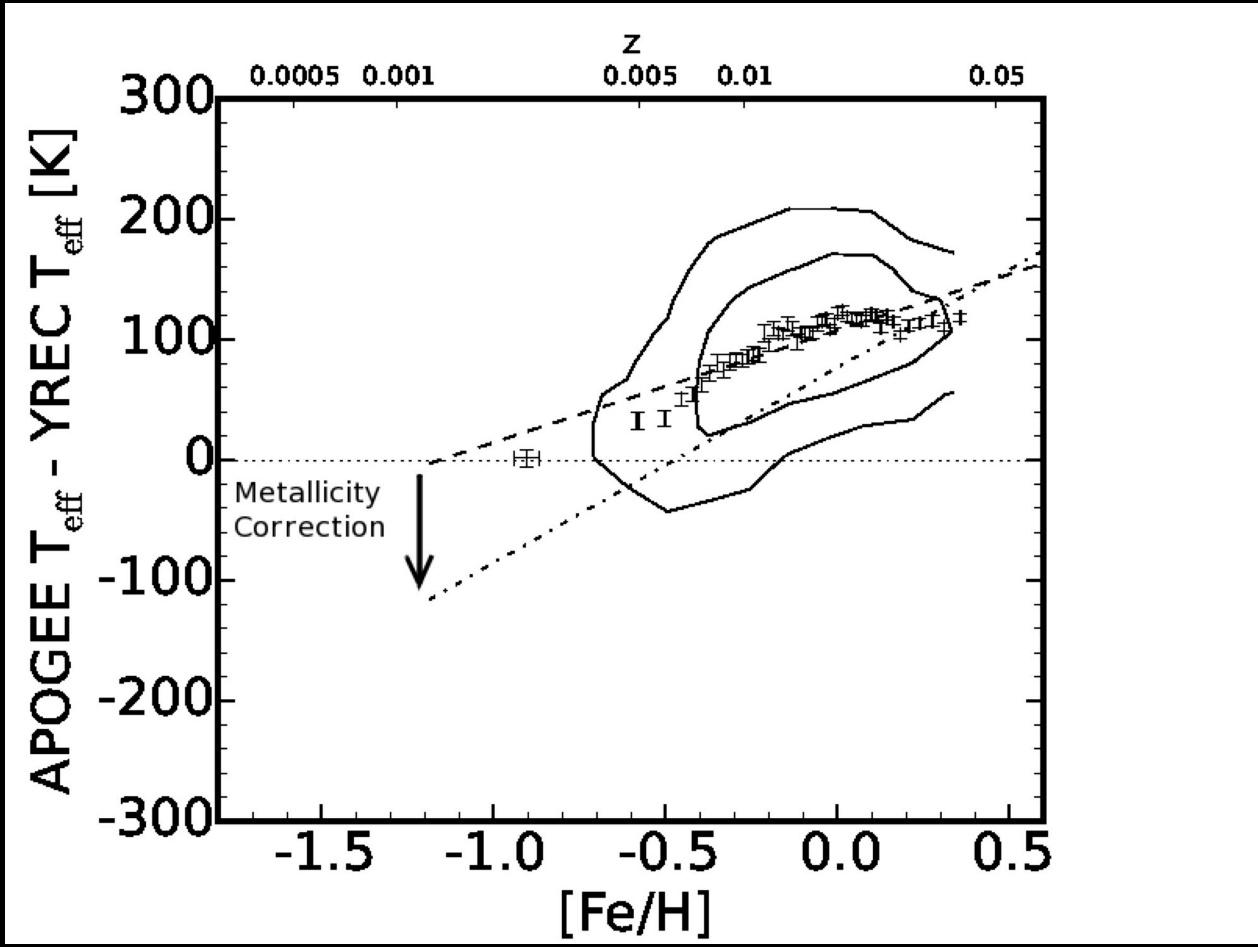


Red Giant Branch Models Currently Fail



Tayar et al. 2017

Possible Explanation – Mixing Length



Tayar et al. 2017

APOKASC Collaboration

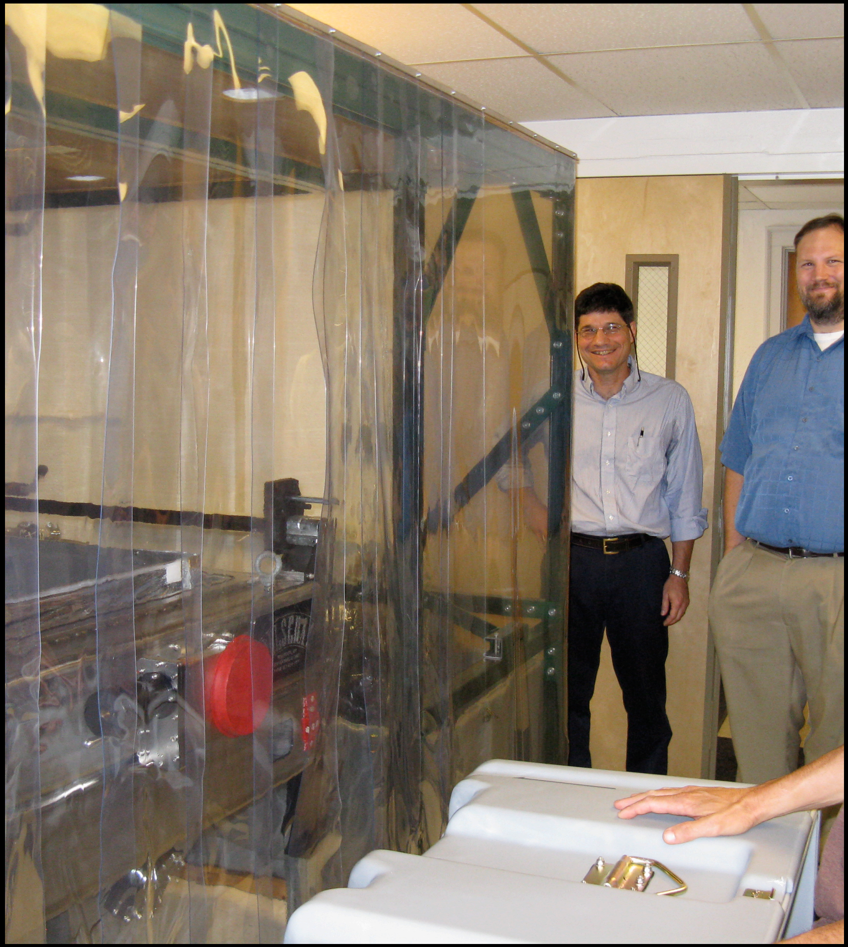
- Marc H. Pinsonneault, Yvonne Elsworth, Courtney Epstein, Saskia Hekker, Sz.Meszaros, William J. Chaplin, Rafael Garcia, Jon Holtzman, Savita Mathur, Ana Garcıa Perez, Sarbani Basu, Leo Girardi, Victor Silva Aguirre, Matthew Shetrone, Dennis Stello, Carlos Allende Prieto**1**, Deokkeun An, Paul Beck, Dmitry Bizyaev, Jo Bovy, Katia Cunha, Joris De Ridder, D.A. Garcia-Hernandez, Ronald Gilliland, Fred R. Hearty, Daniel Huber, Inese Ivans, Thomas Kallinger, Steven R. Majewski, Marie Martig, Andrea Miglio, Benoit Mosser, David L. Nidever, Aldo Serenelli, Verne V. Smith, Jamie Tayar, Olga Zamora, Gail Zasowski

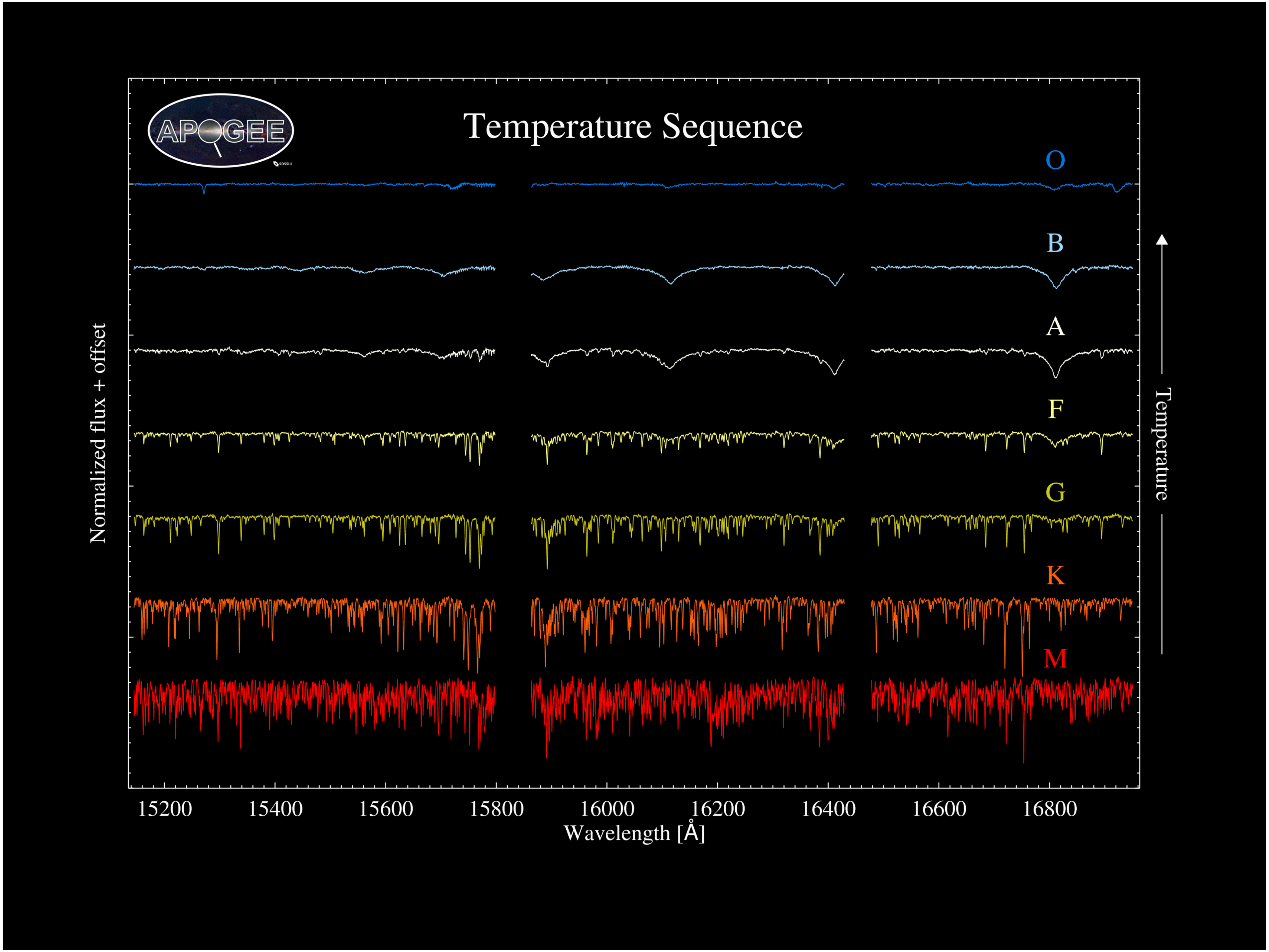
APOGEE

- High-resolution H-band spectroscopic survey
- Stellar parameters determined by chi^2 minimization to a grid of synthetic spectra
- ~10,000 stars observed in the *Kepler* field, mostly red giants
- First APOKASC catalog reporting $\Delta\nu$, $\nu_{max,}$ M, R, Teff, …. (Pinsonneault et al. 2014)
- 2nd catalog coming soon coming soon, including empirical calibration

Sloan Digital Sky Surveys: APOGEE

- H-band survey of Galactic populations
- 250,000 stars (80% red giants)
- R~22,500
- >15 elements – including C, N, O, Na, Mg, Ca, Mn, Fe, Co, Ni
- Targeted from 2MASS
- Compliments optical surveys such as Gaia-ESO, Galah

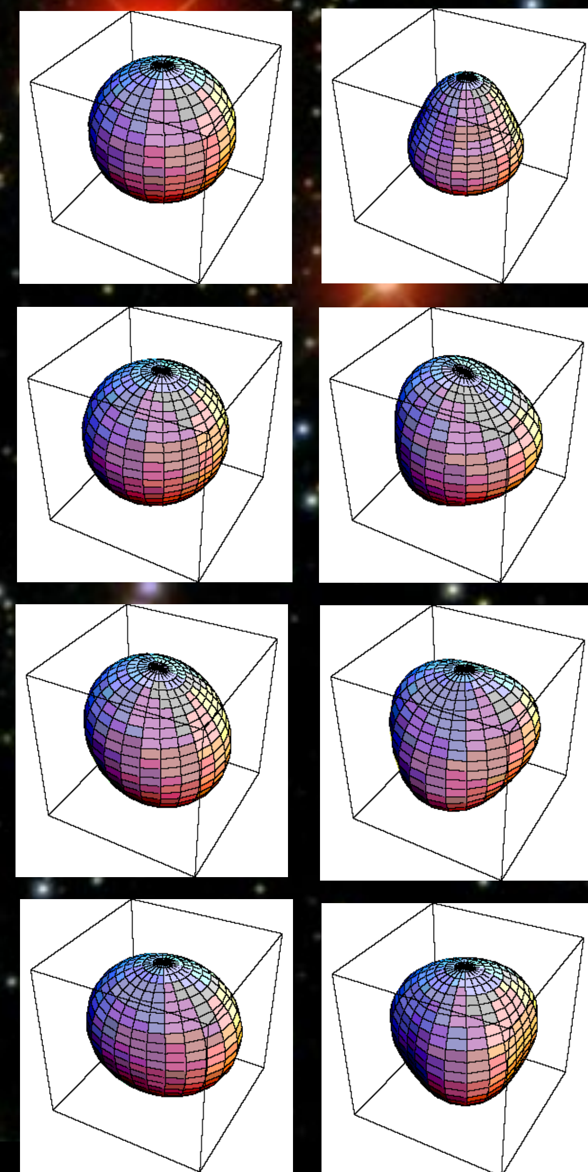




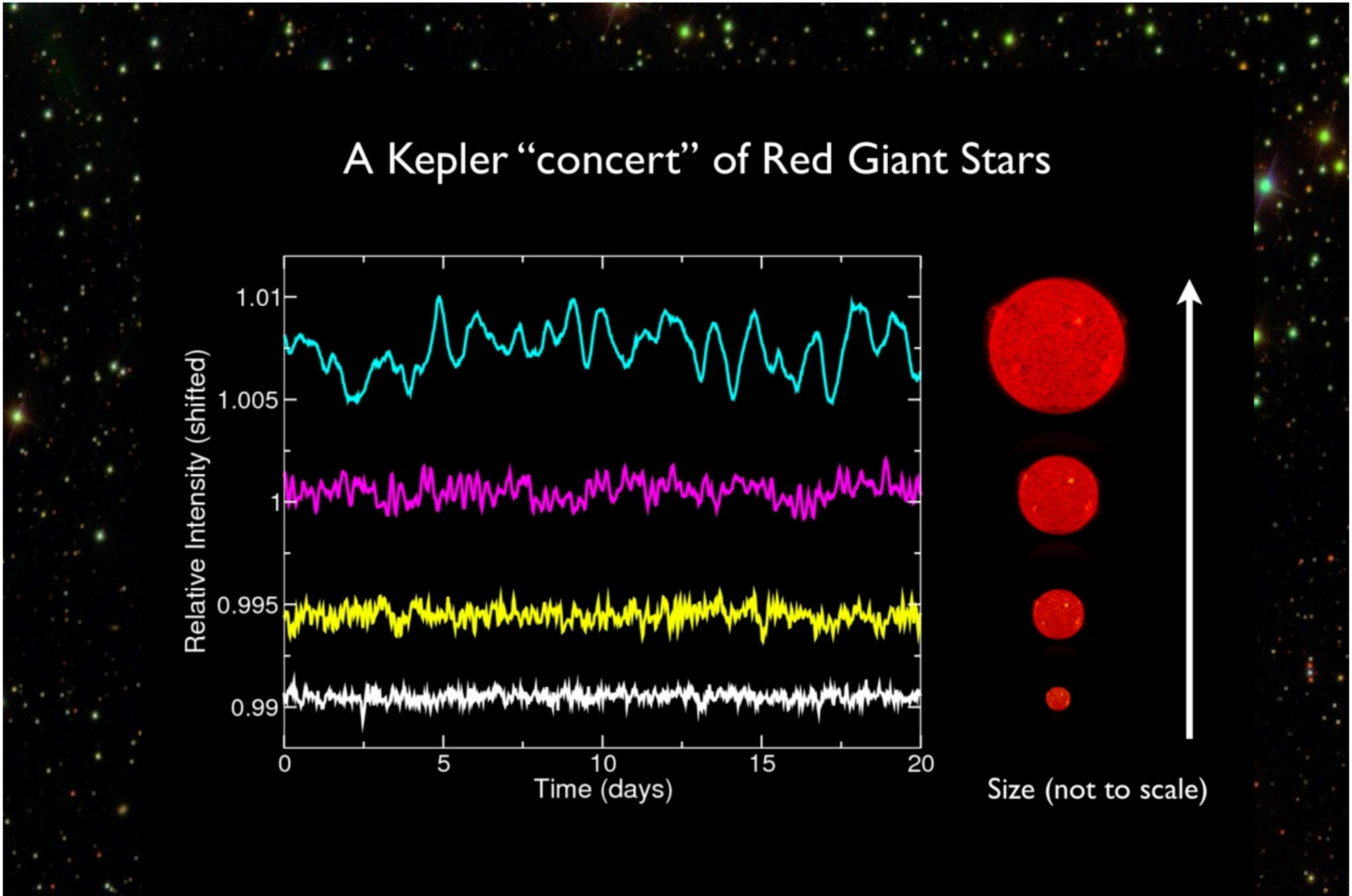
APOGEE
Temperature Sequence
O
B
A
F
G
K
M
Normalized flux + offset
Temperature
15200
15400
15600
15800
16000
16200
16400
16600
16800
Wavelength [Å]

Observing oscillation modes

- Modes excited in the convection zone propagate through the stars
- Oscillations cause the brightness of the star to change
- Low-order modes are visible with high-precision photometry

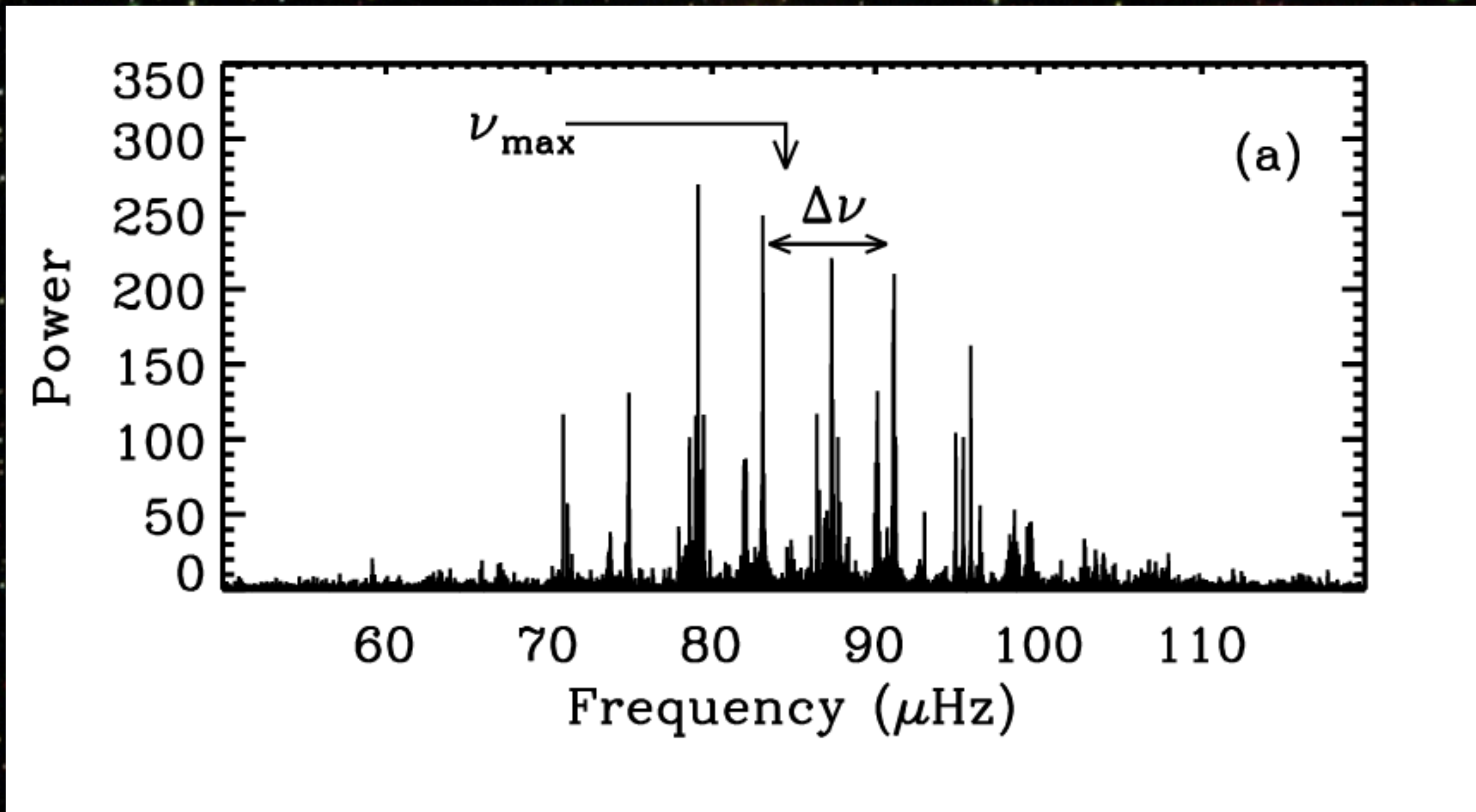


Slide from Stello, KASC 6 presentation



Slide from Kepler Asteroseismic Science Consortium/D. Stello/NASA

Key Frequencies



Stello et al. 2013

Physics of Key Frequencies

$$\nu_{\mathrm{max}} \approx \frac{M}{R^2 \sqrt{T_{\mathrm{eff}}}} \approx \frac{g}{\sqrt{T_{\mathrm{eff}}}}$$

$$\Delta\nu \approx \sqrt{\frac{M}{R^3}} \approx \sqrt{\frac{g}{R}} \approx \sqrt{\bar{\rho}}$$

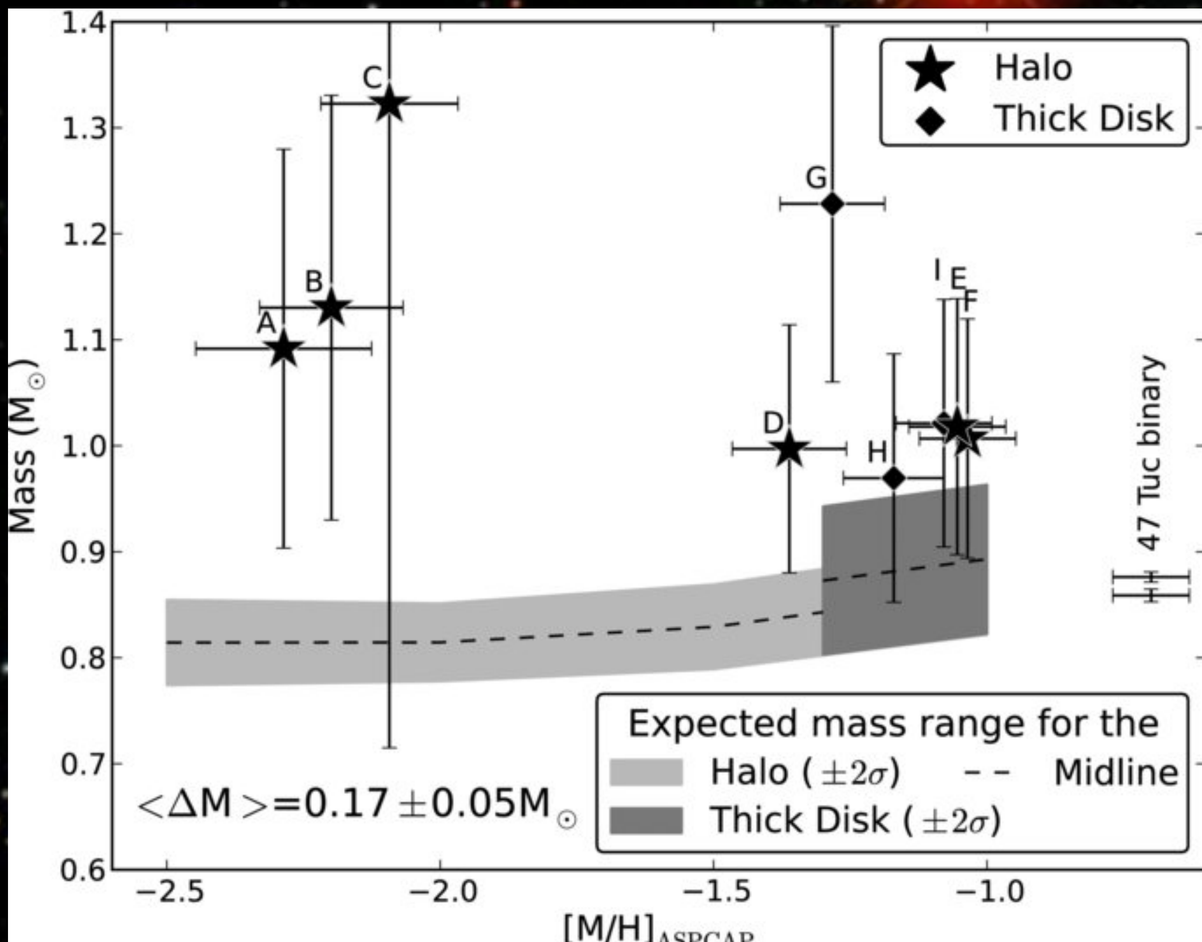
Scaling Relations

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

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

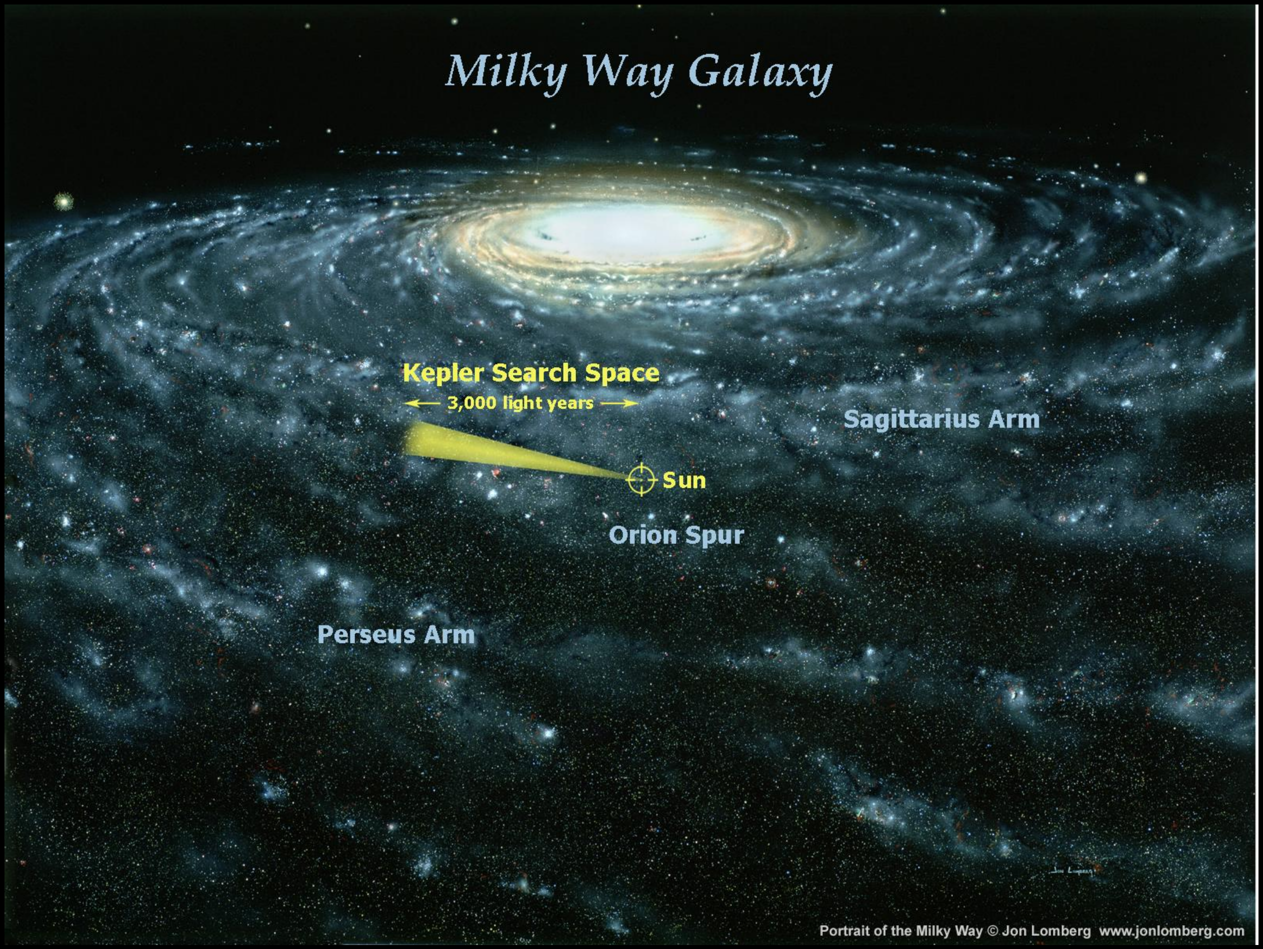
Red Giants are not homologous with the Sun

Towards Absolute Ages

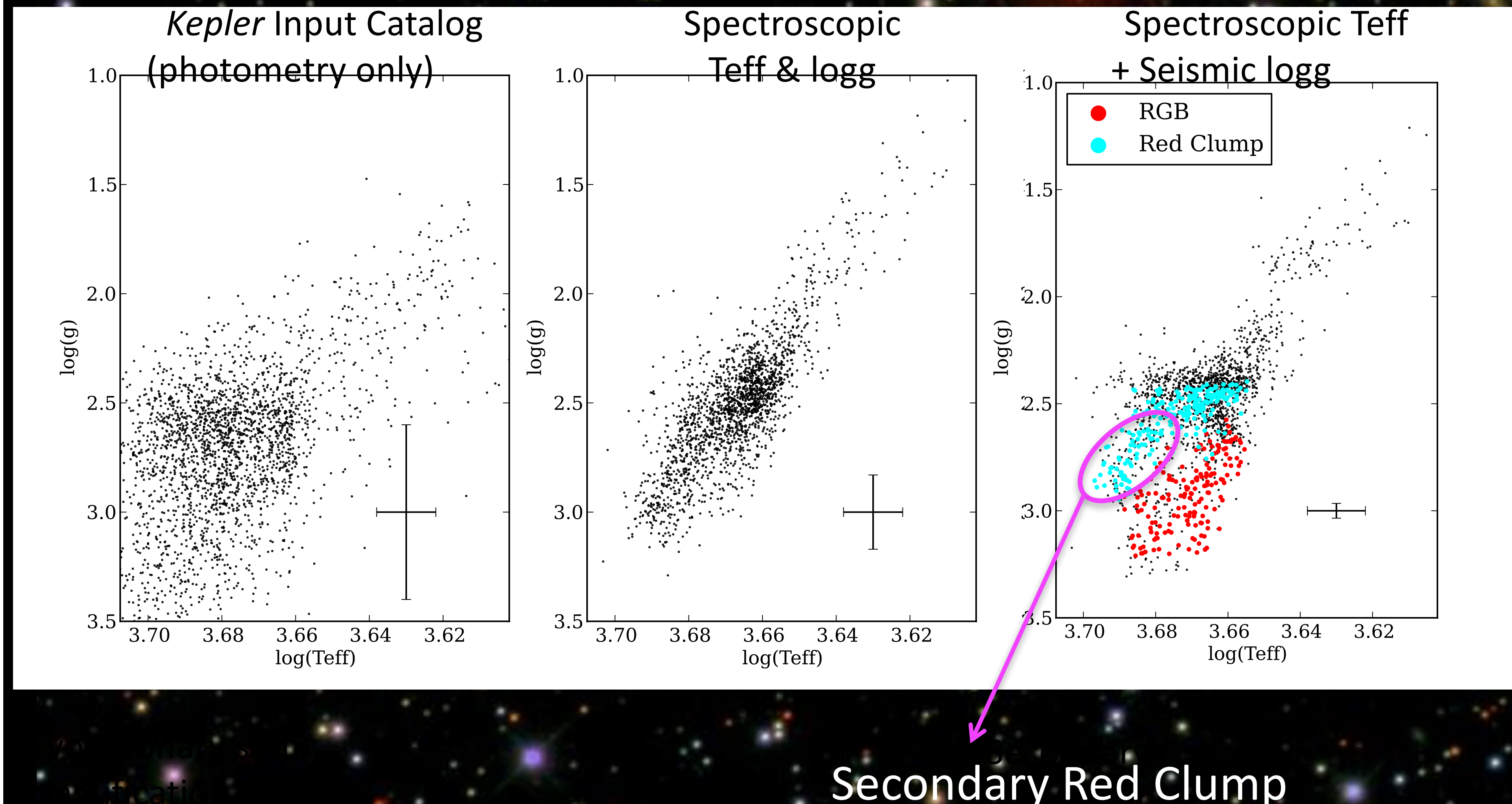


Epstein et al. 2014

The *Kepler* Field in the Galaxy



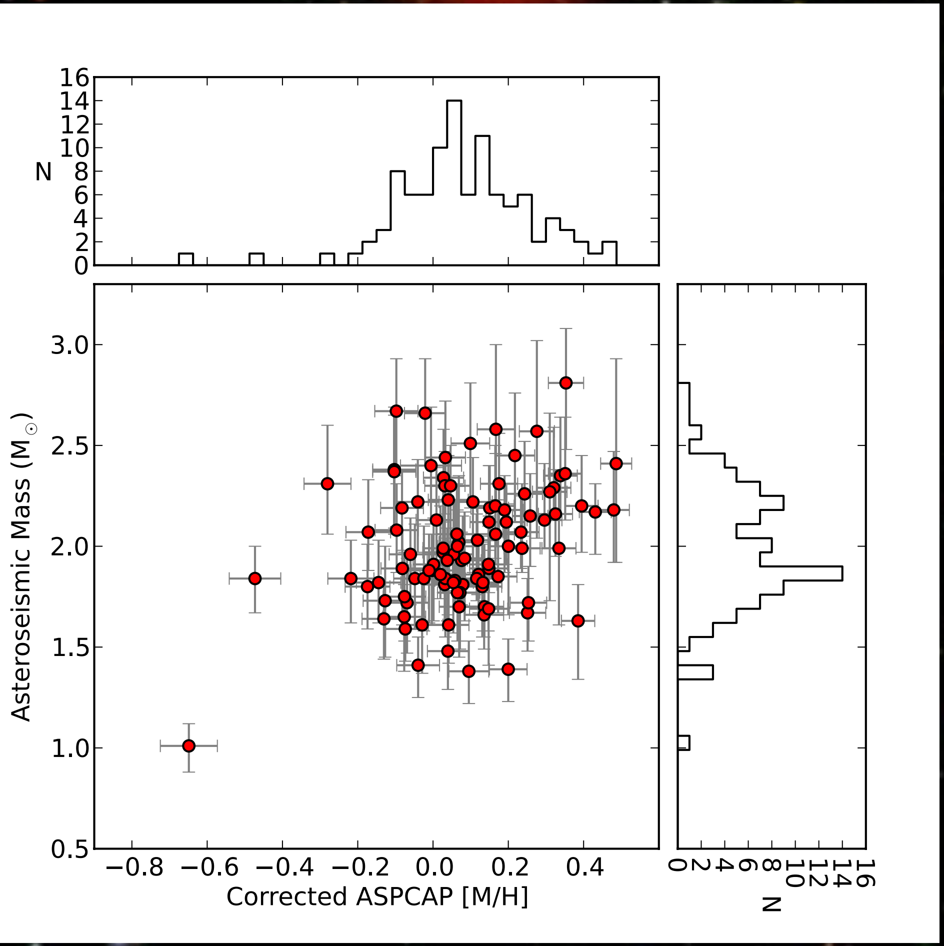
H-R Diagram in the *Kepler* Field



Mass-Metallicity Distribution for Secondary Red Clump

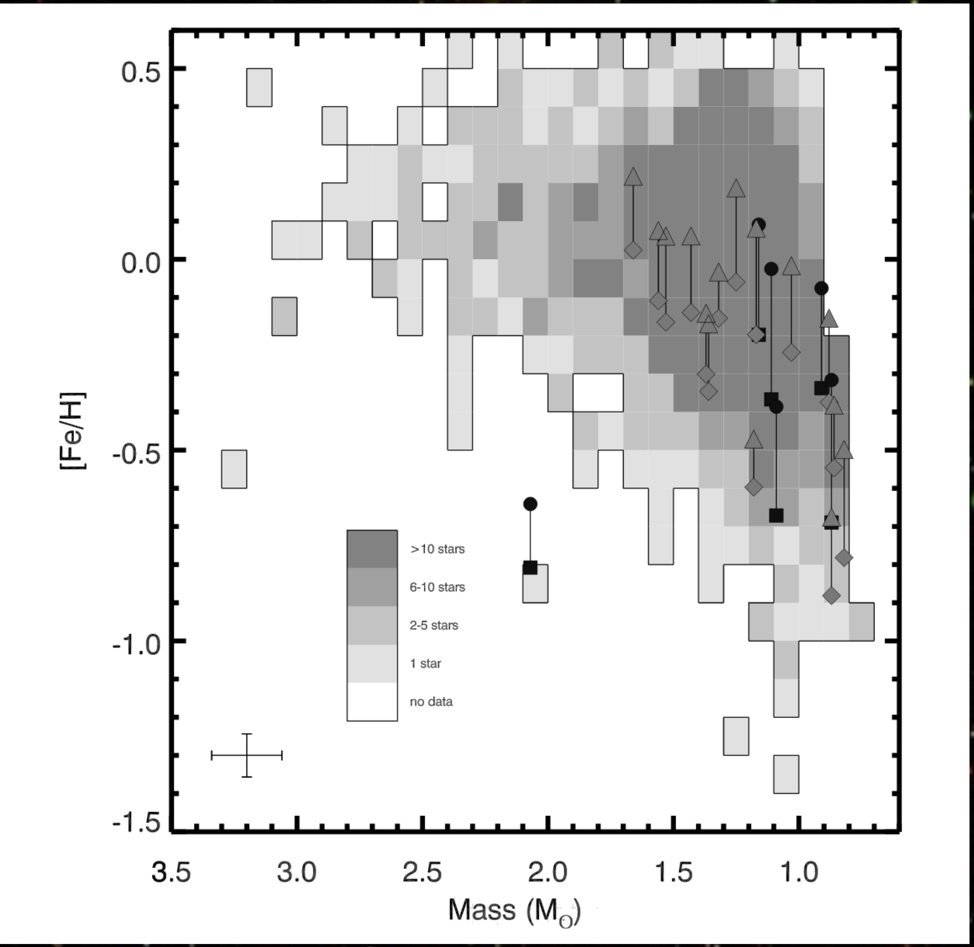
Stars in the secondary red clump have ages of ~1.5 +/- 0.5 Gyr

Not a complete MDF, but a clear spread in metallicty



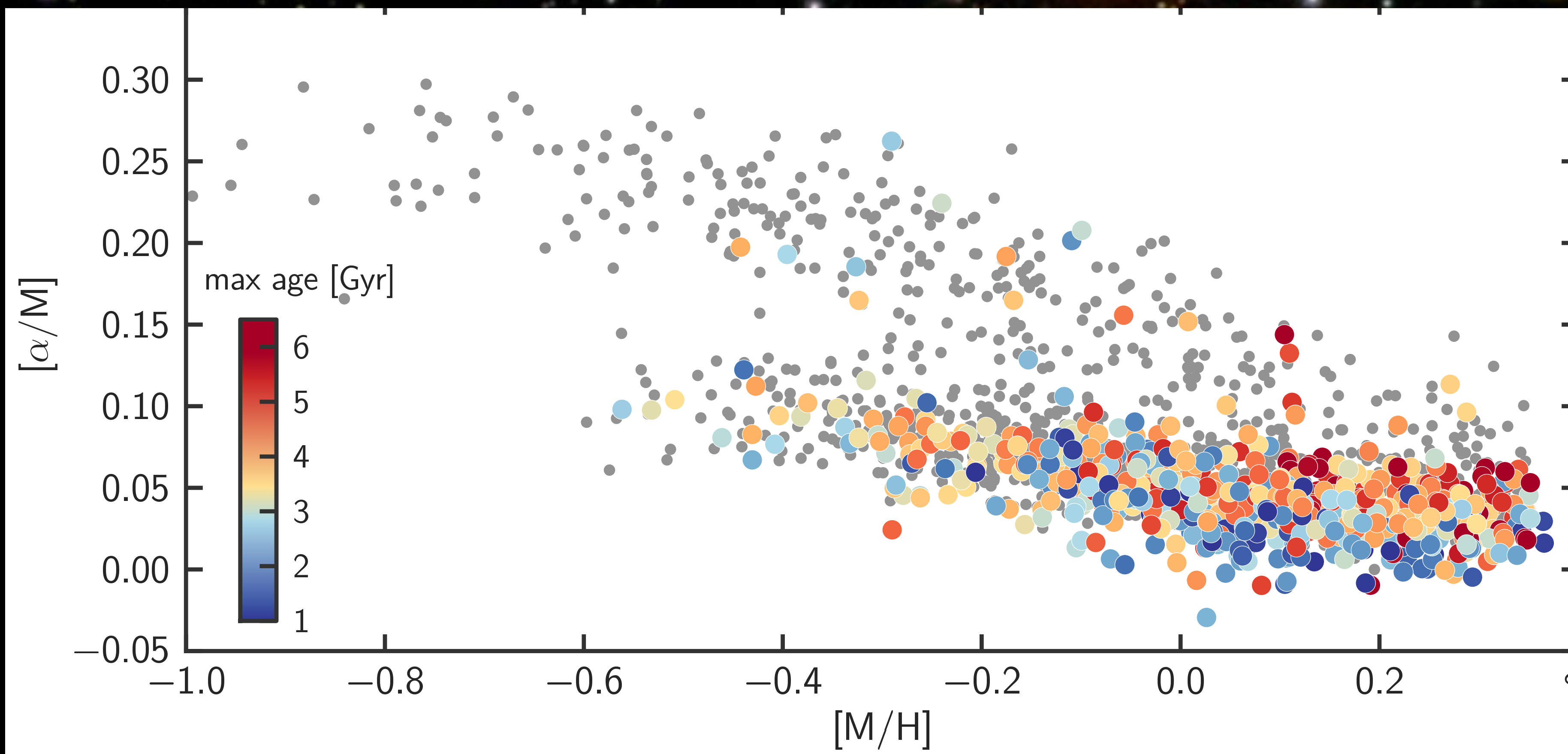
Epstein, Girardi, et al , in prep

Finding a Descendent of a Blue Straggler



Tayar et al. 2015

Young Alpha-rich stars



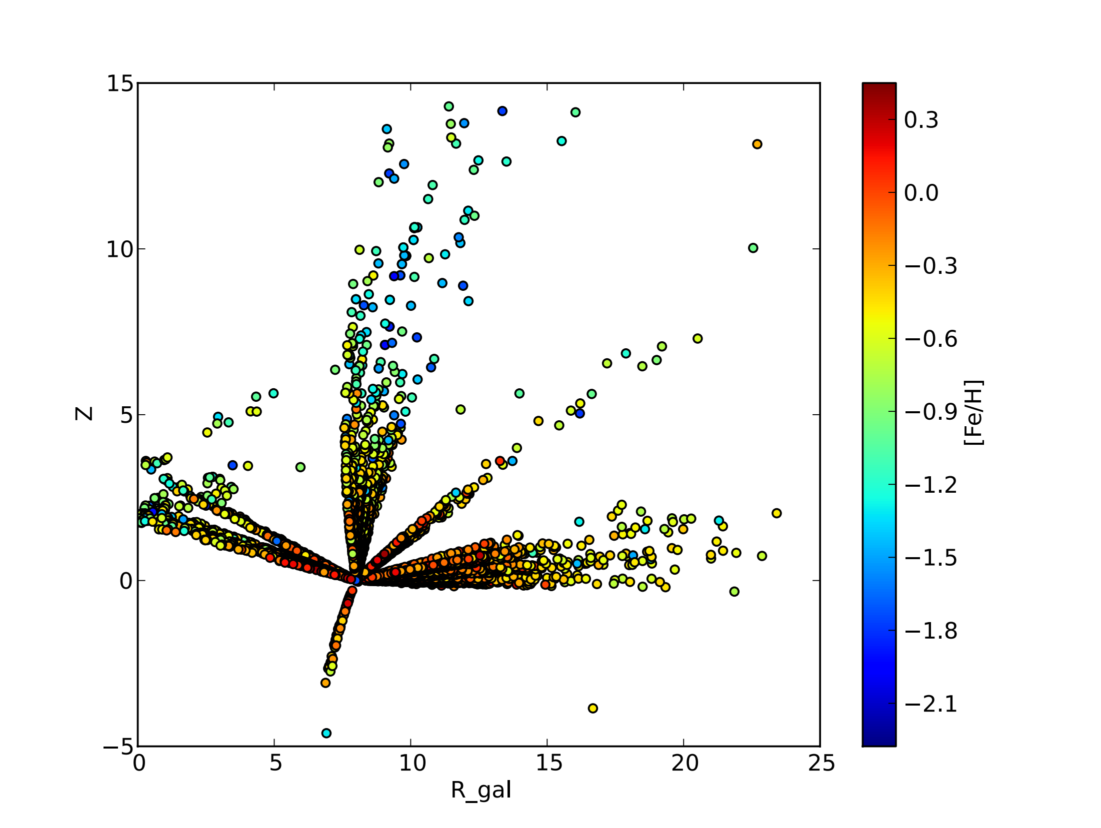
Martig et al. 2015

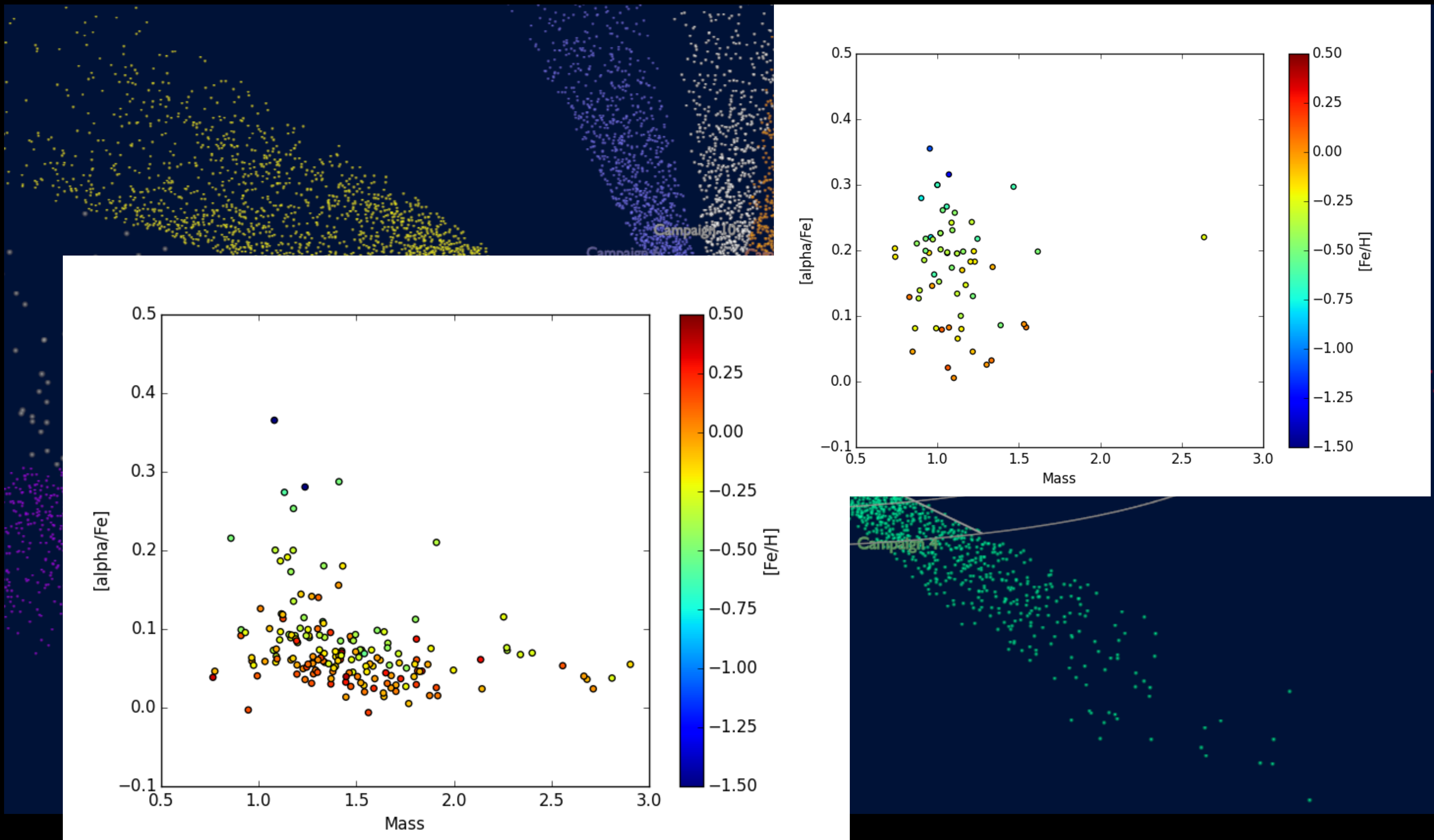
For CoRoT data: Chiappini et al. 2015

K2 & Galactic Archaeology

Animation from AIP

Stellar Pops Across the Galaxy

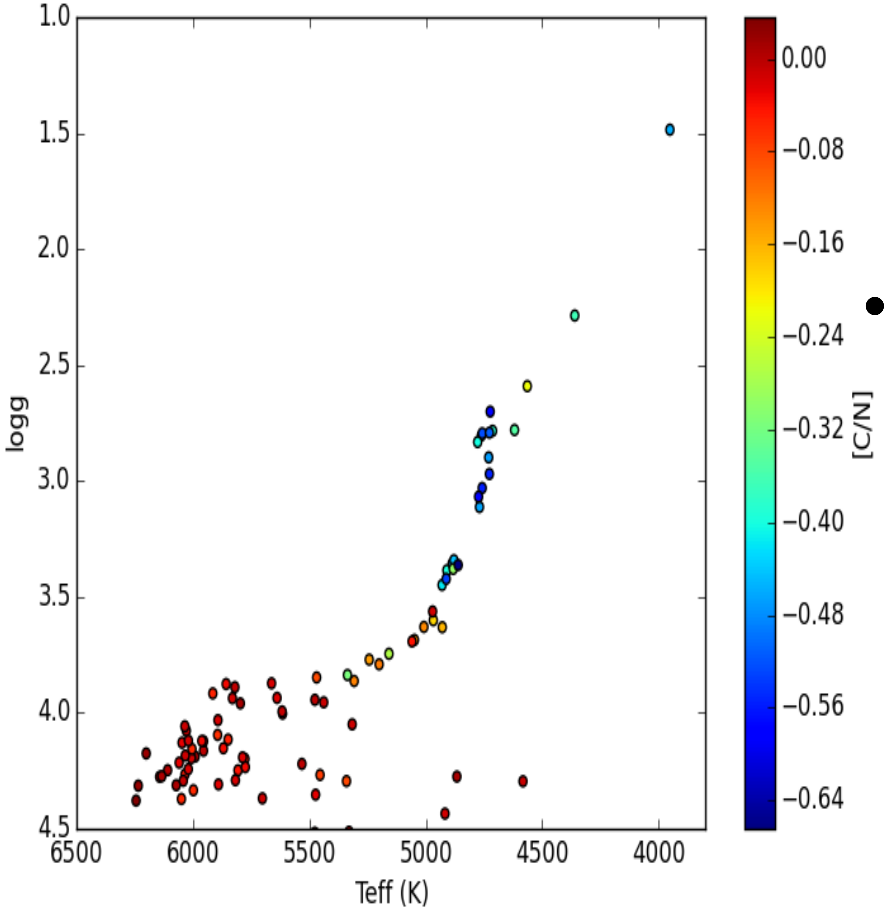




K2 map from K2 GAP (Stello) & AIP, C4 BAM parameters

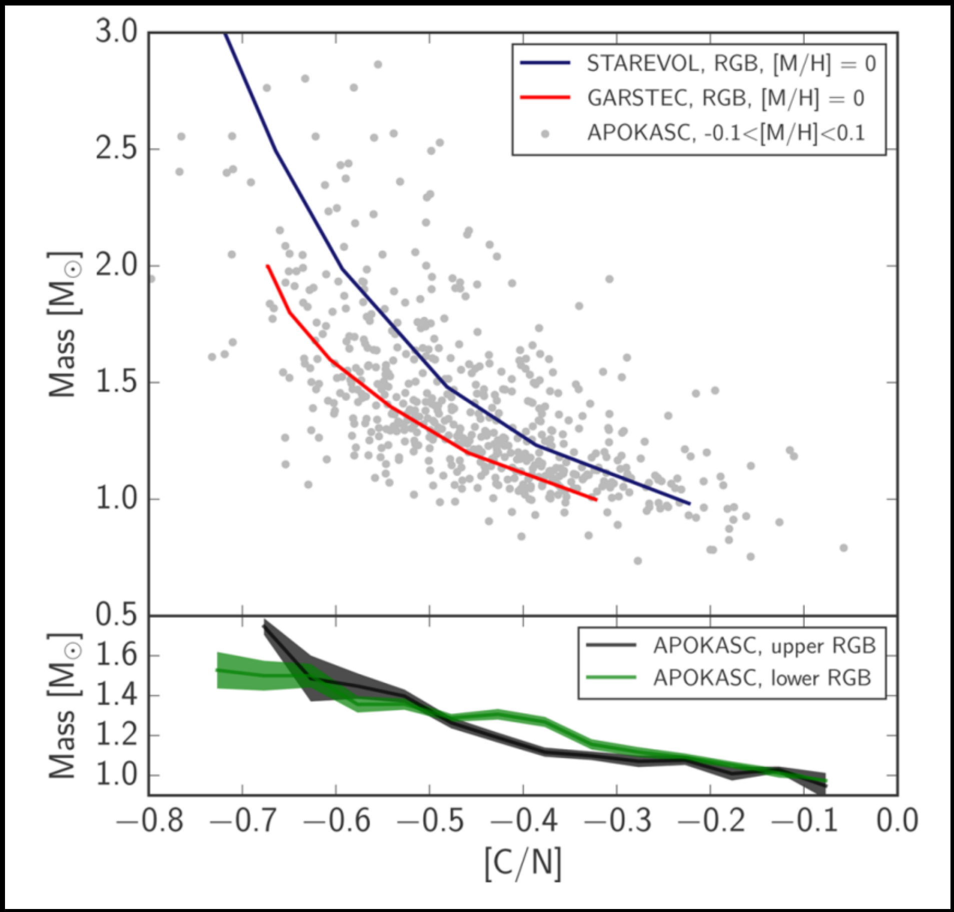
The First Dredge-Up

APOGEE DR13 C/N in M67 Members



- Nuclear burning products in the interior will appear at the surface on the red giant branch
- This 1st **Dredge-up** is sensitive to mass, composition, and any extra internal main sequence mixing

C/N as a Mass Diagnostic

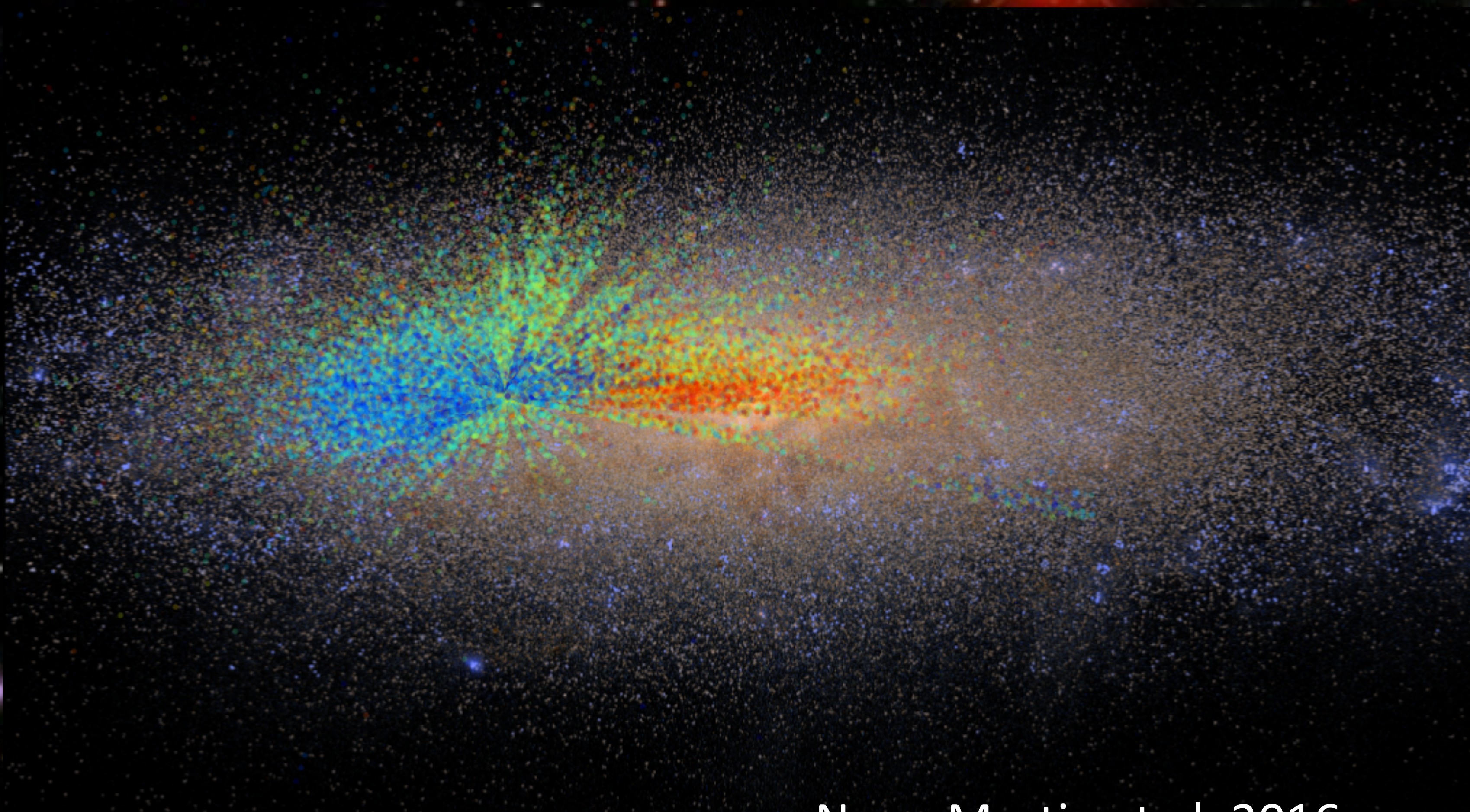


Masseron et al. 2015

Martig et al. 2016

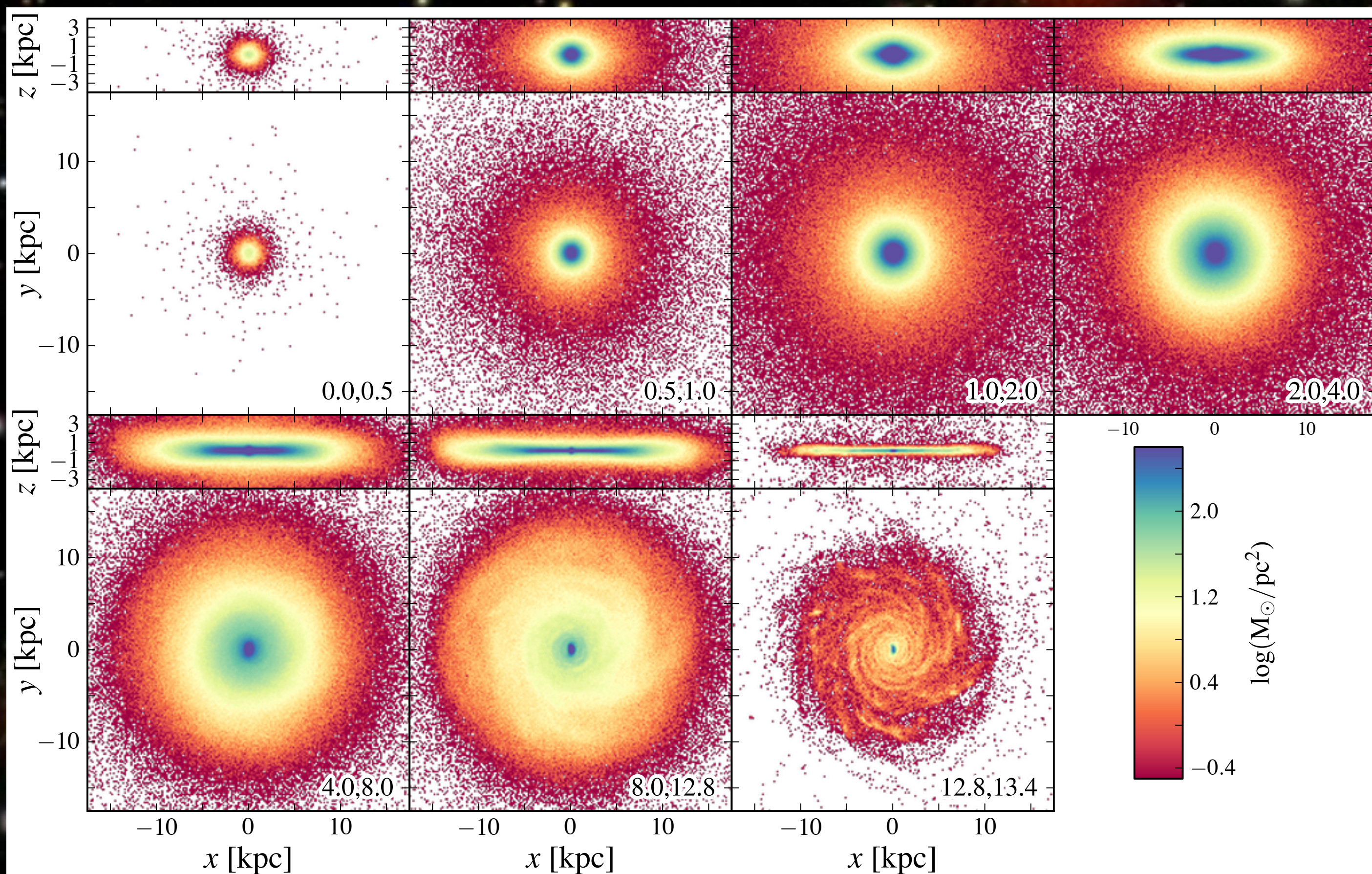
Ness et al. 2016

Age Map of Milky Way



Ness, Martig et al. 2016

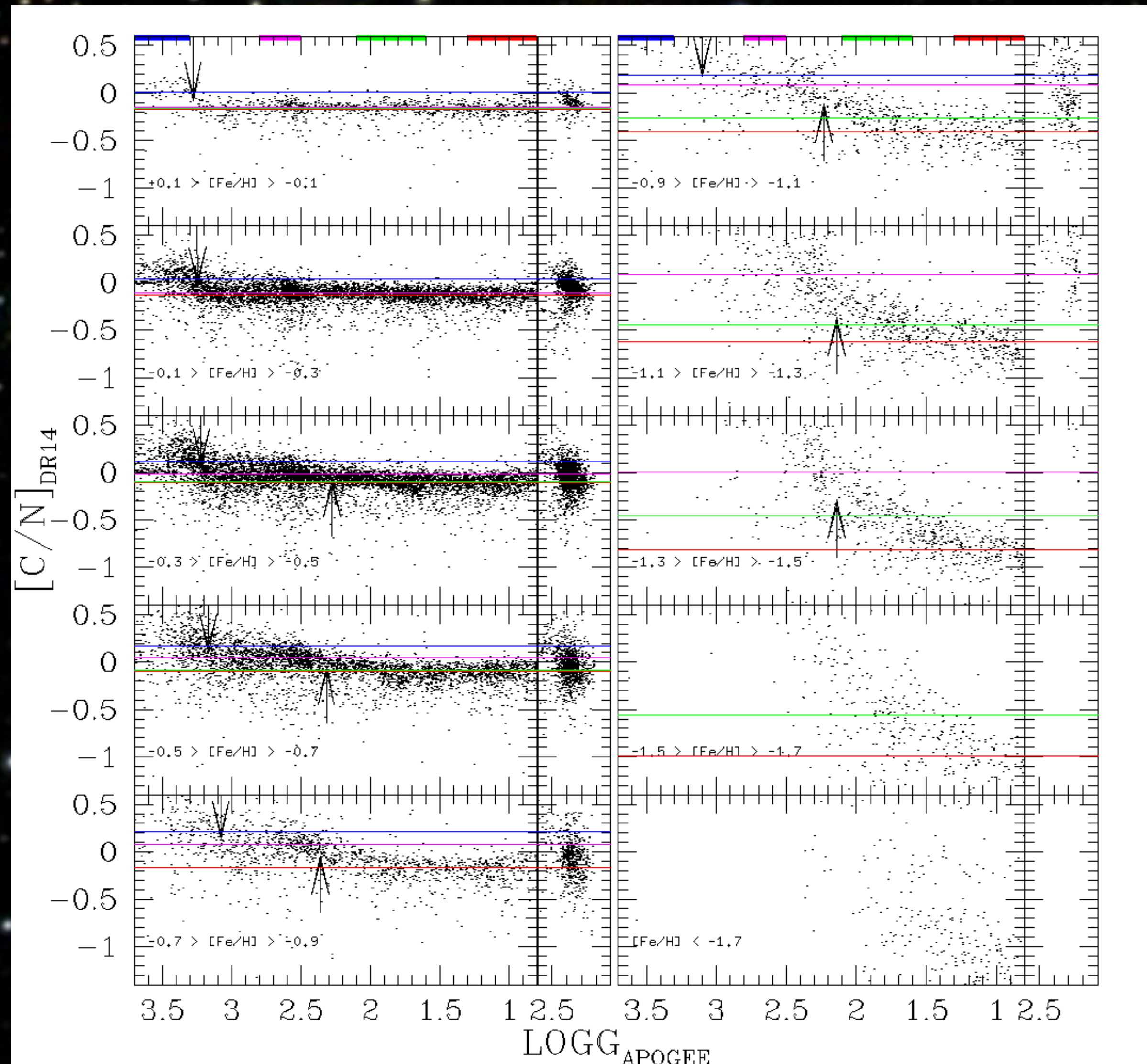
Building a Galaxy



Bird et al. 2013

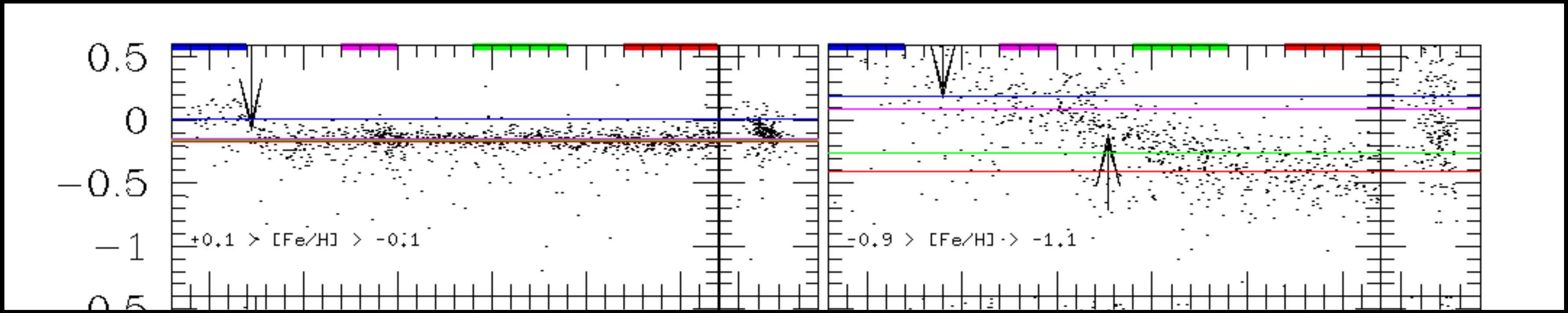
C/N and its discontents

- Chemical evolution
- Extra-mixing



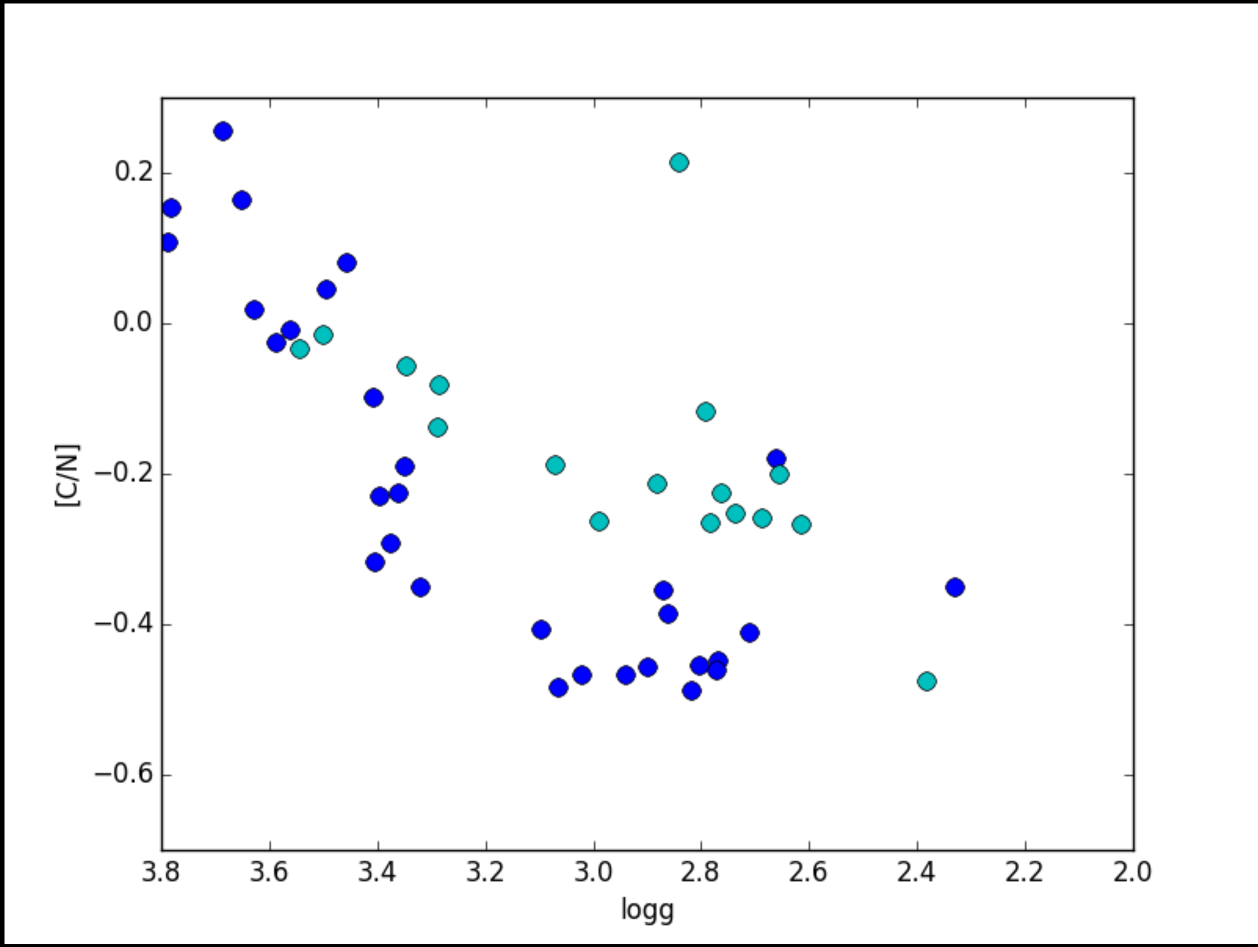
Shetrone, Tayar, et al., in prep

Extra-mixing & Chemical Evolution

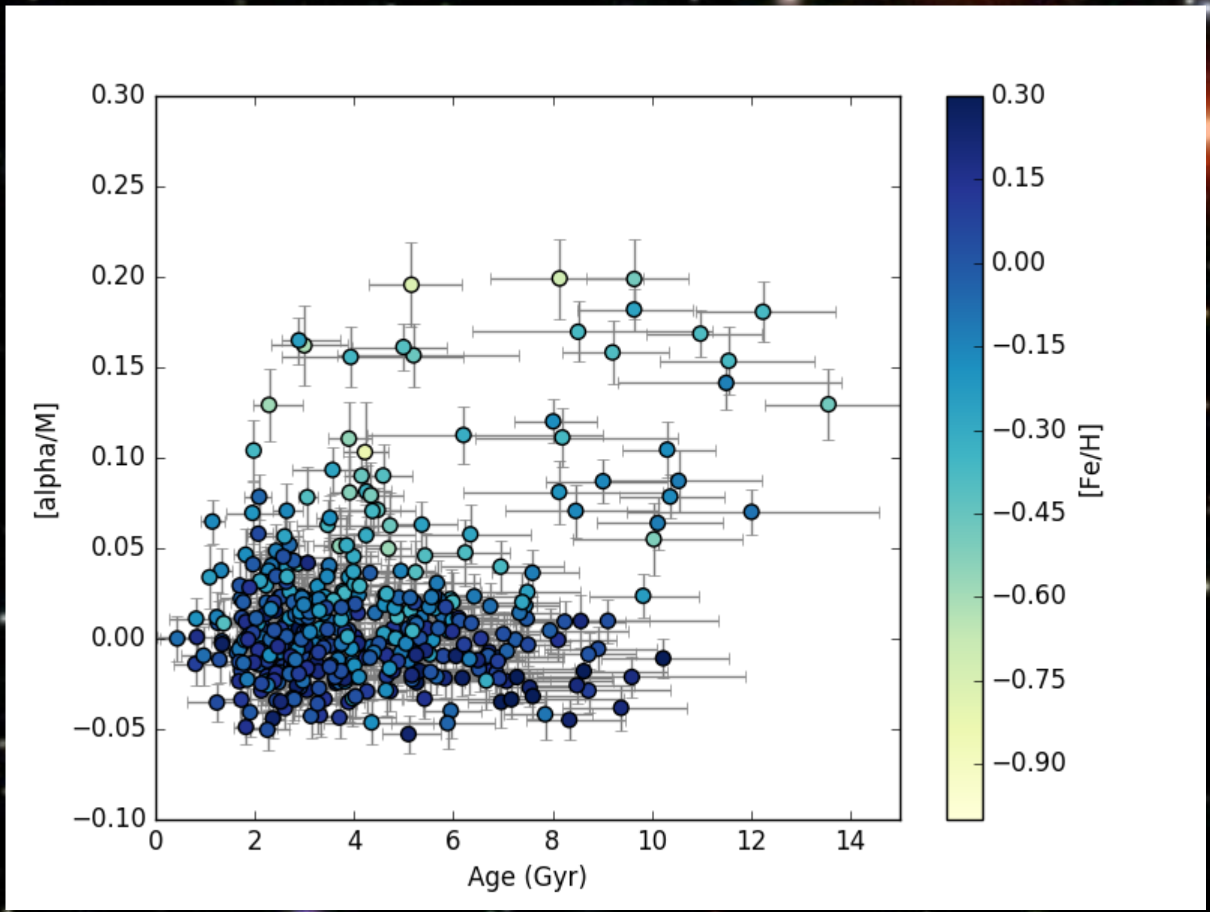


Shetrone, Tayar, et al., in prep

Calibration: M 67 and NGC 188



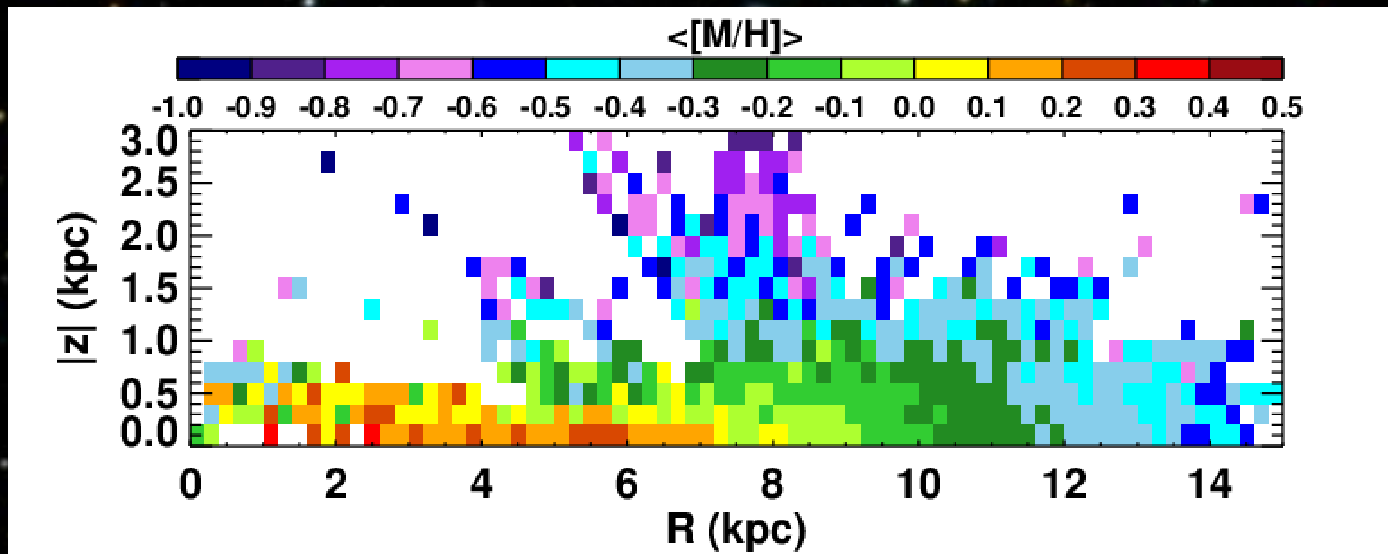
Age-Metallicity Relation & Radial Mixing



APOKASC dwarf catalog – Serenelli et al, submitted

Wandering Stars

Favored idea to explain age-metallicity spread – radial mixing (e.g. Schoenrich & Binney 2009) Mechanism would need to operate on short timescales! *Does it also explain the ages?*



Hayden et al. 2014

[α/Fe] vs. age

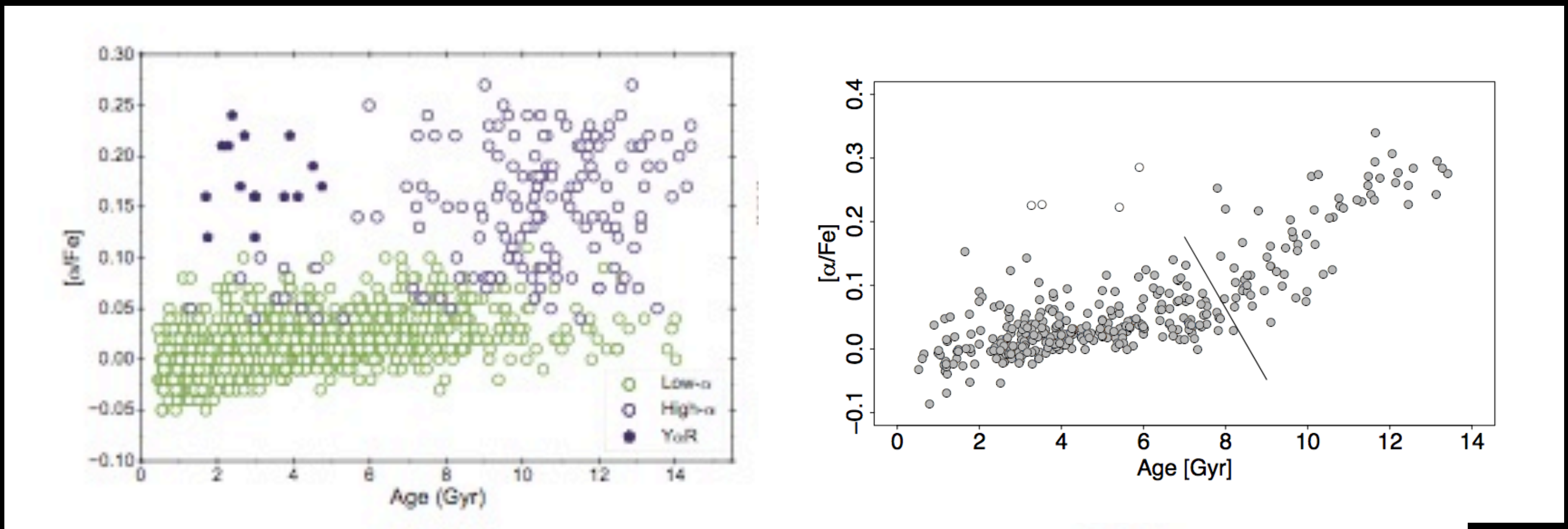


Figure 10. Relations between age and chemistry for the sample of giants. *Left* α-abundances as a function of age for the chemically

Haywood et al. 2013

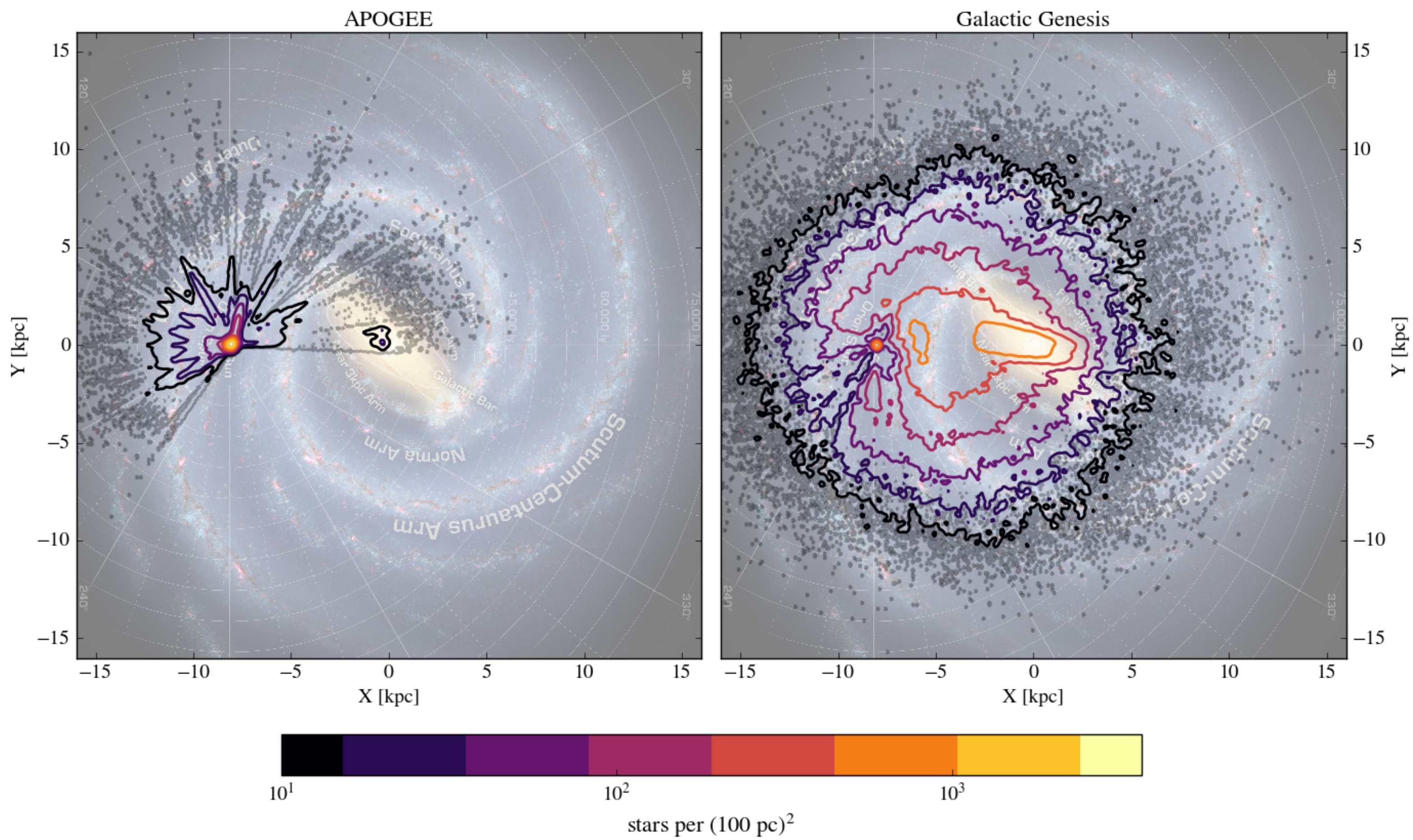
Silva Aguirre et al. 2017 submitted

Galactic Archaeology Summary

- C/N provides good relative ages for bulk populations
  - Deviations from scaling relations for seismic calibrators
  - Extra-mixing corrections
- Inside-out/upside down Milky Way formation
- Radial mixing can qualitatively explain the old, metal-rich stars in the solar neighborhood
  - Does it work quantitatively?
  - Does it explain the young alpha-rich stars?

The Future & SDSS-V

Milky Way Mapper – Galactic Genesis



~5 million stars with H < 11 mag, G-H > 3.5 mag, S/N > 40

Figure by J. Bird

Orion

- M42 0.07 pc / spaxel
- APOGEE stars (yellow)
- Combine information from gas and stars to map the interaction between stars and ISM
- Have Teff, L, Z, [X/H], f_{UV}, (age) for each star
- Gas: temperature, density, kinematics, abundances

Images: ESO 2.2m

Milky Way Mapper – Stellar Astrophysics

AS4's all-sky multi-epoch spectroscopy is an awesome machine for stellar science. Hundreds of thousands of stars in each category:

- Synergy with asteroseismology & transit studies with TESS & PLATO
- RVs across the HR diagram for binary studies at all masses
- IR spectra for census in SF regions & tie to ISM
- Age info for evolved stars in binaries/white dwarfs/& red giants (core of GG proposal)

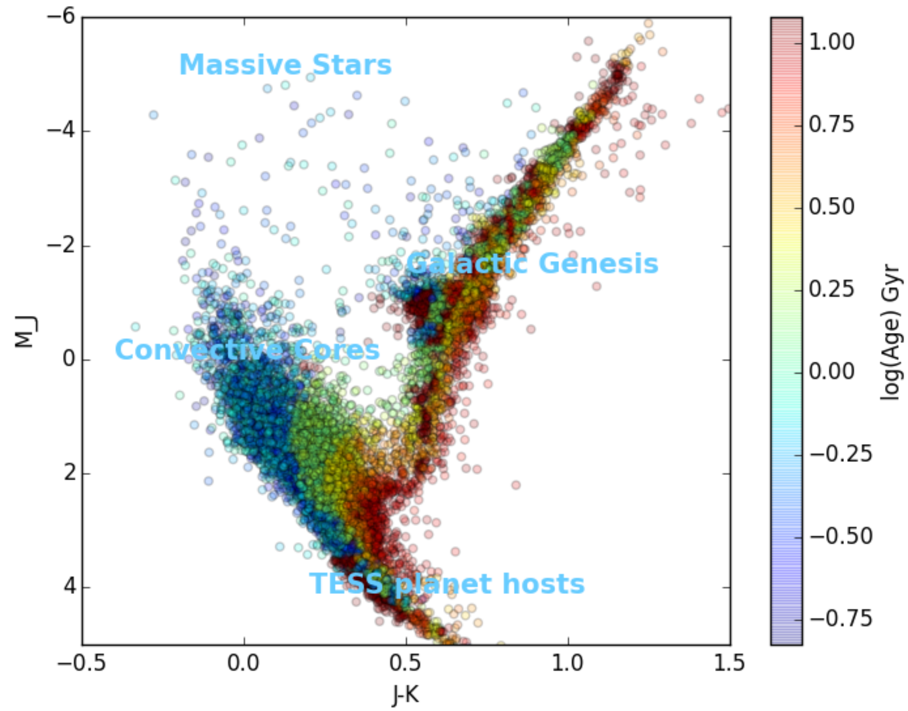


Figure by L. MacArthur/D. Hogg/J. Johnson

Milky Way Mapper – Binary Studies

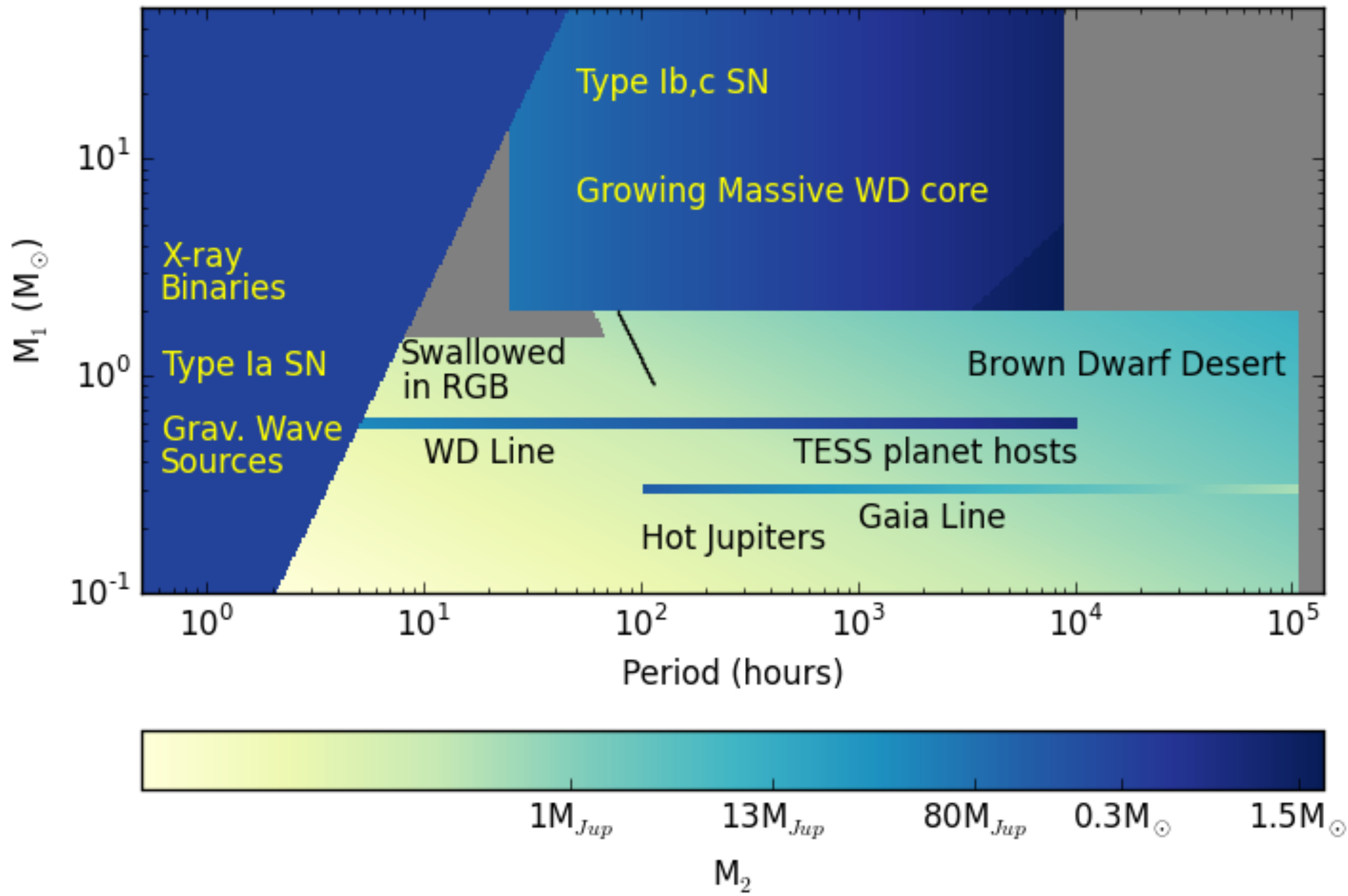
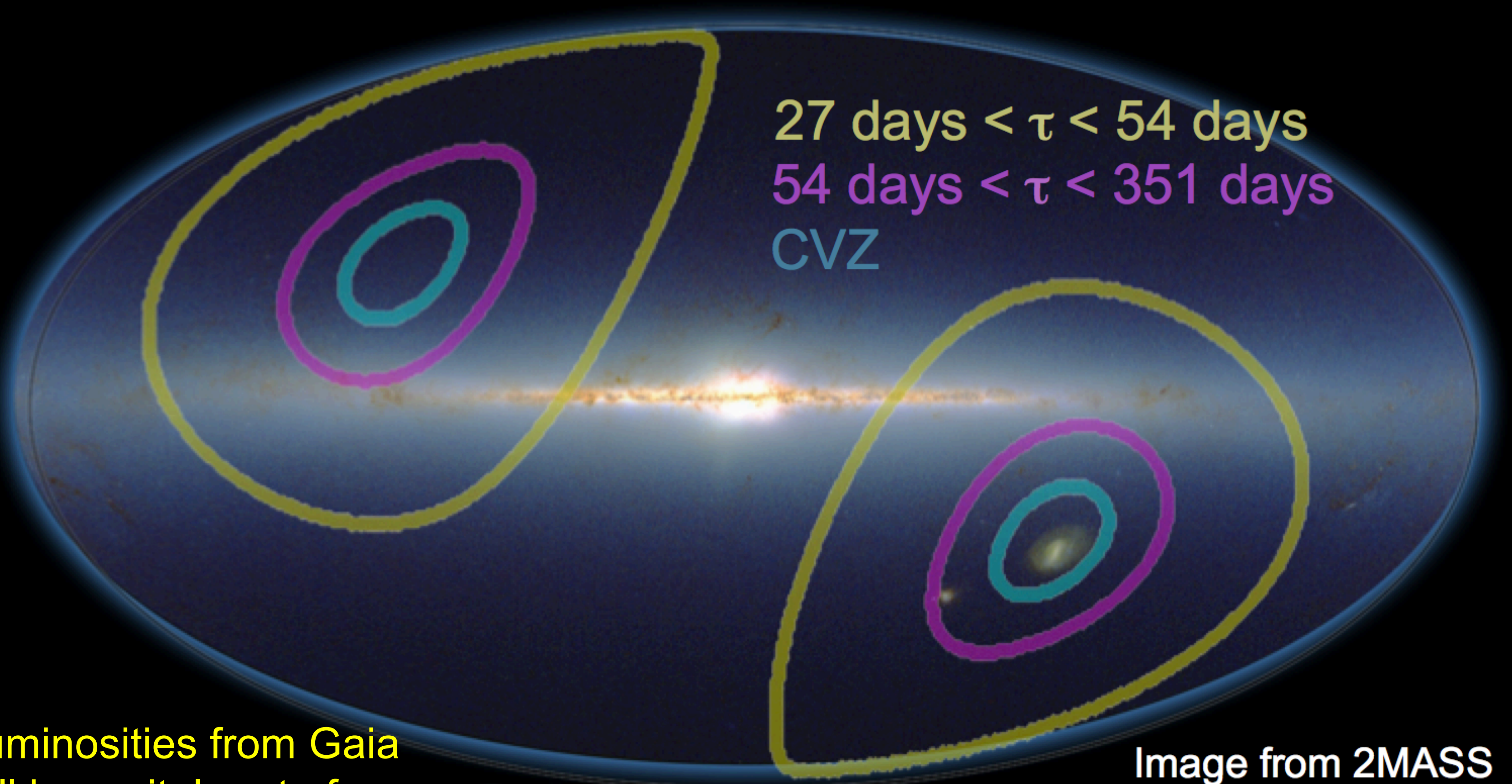


Figure by J. Johnson

TESS & Galactic Archaeology



Luminosities from Gaia will be a vital part of understanding these data.

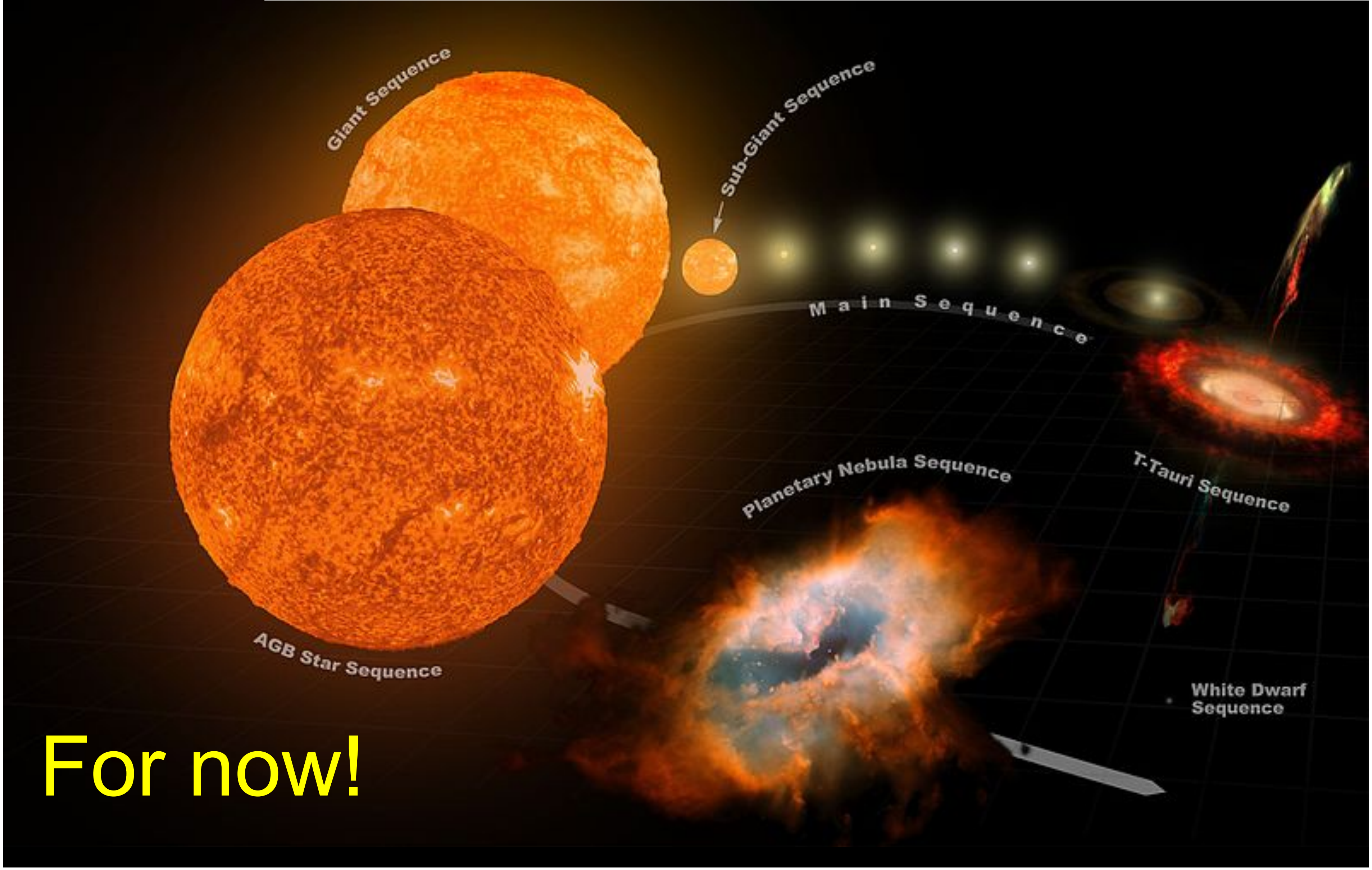
~~Golden~~ Age of Galactic Archaeology

~~Astatine~~ Iridium!

New tools for making progress on some long-standing fundamental issues in galaxy formation

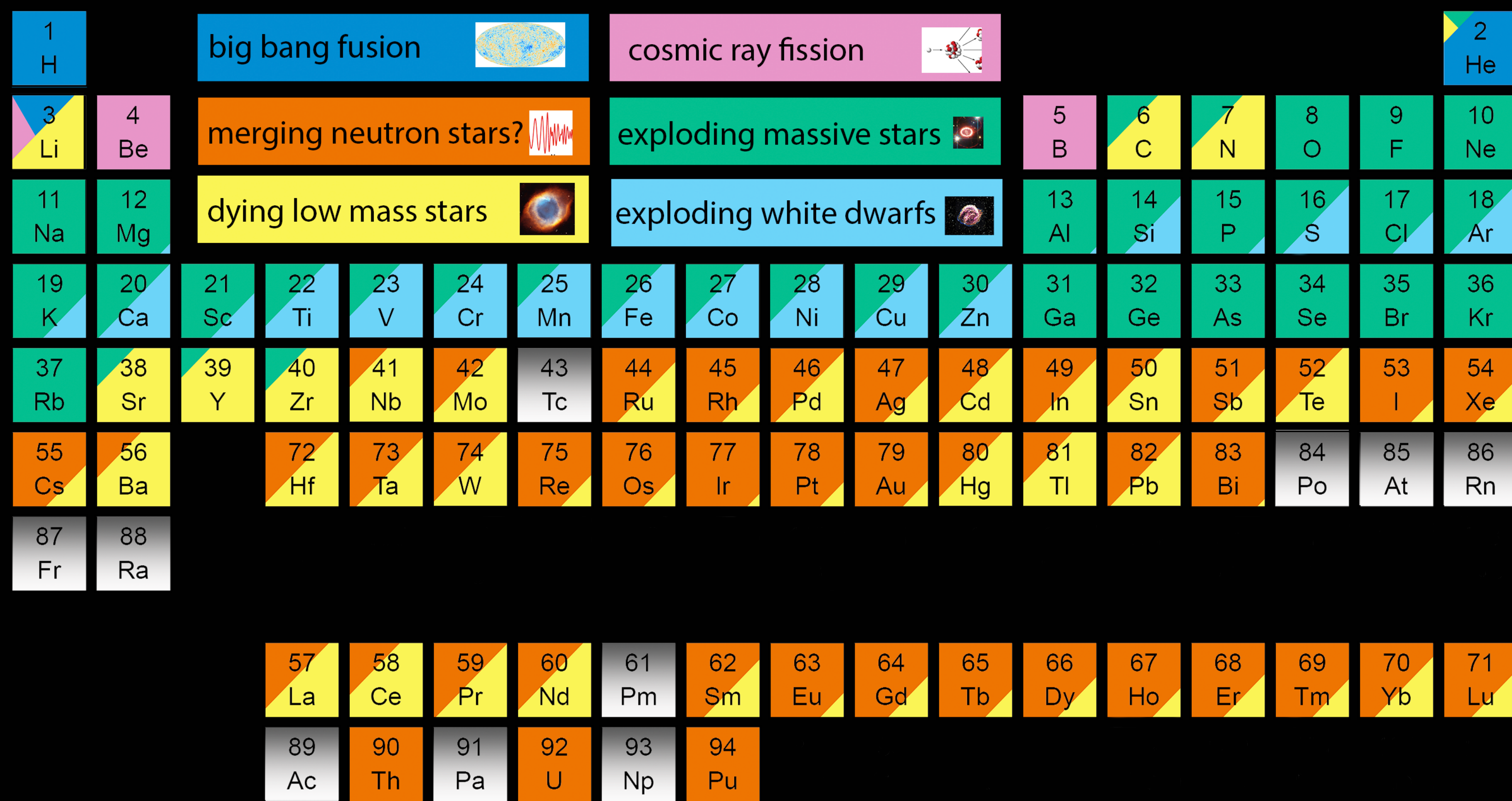
- Origin of the thick disk
- Radial mixing in the disk
- Star formation history of Milky Way
- Age-metallicity relation
- Timescales for chemical evolution
- What this all means for ROCKY PLANETS

The End



For now!

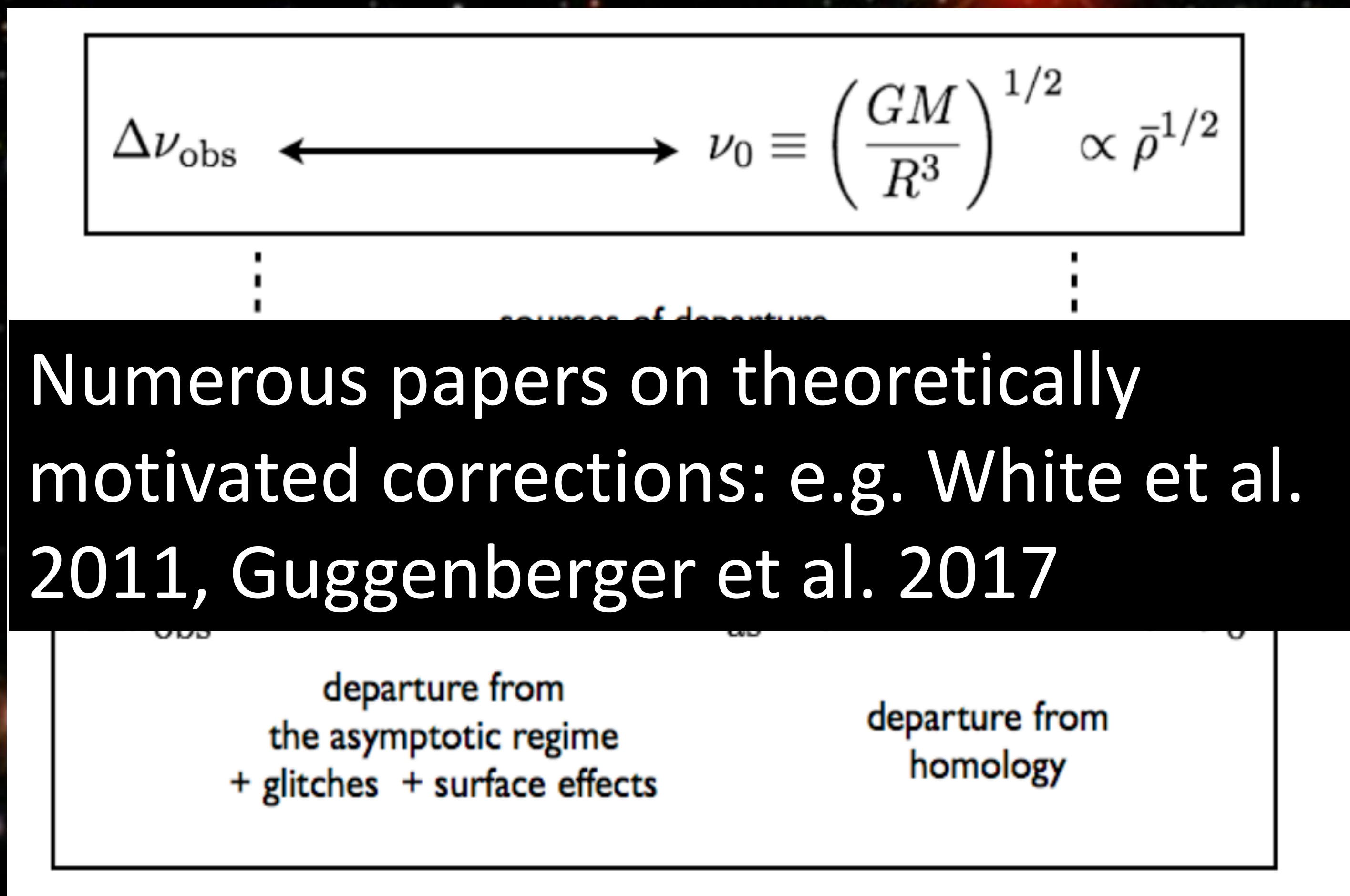
The Origin of the Solar System Elements



Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

Astronomical Image Credits:
ESA/NASA/AASNova

Towards Absolute Ages --theory



Numerous papers on theoretically motivated corrections: e.g. White et al. 2011, Guggenberger et al. 2017

Belkacem 2013