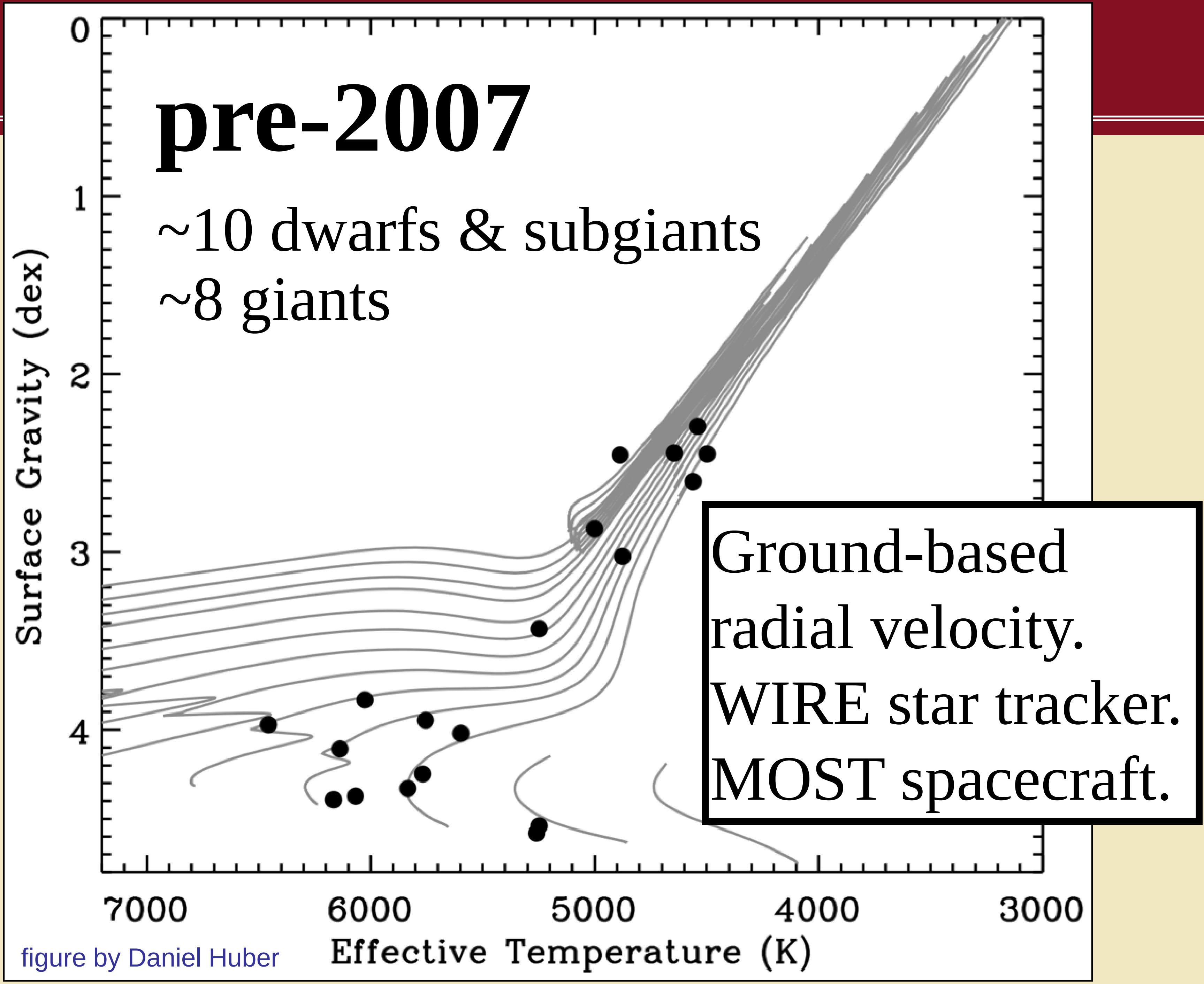
Galah and asteroseismology

Dennis Stello

UNSW SYDNEY | Australia's Global University

The asteroseismic revolution


pre-2007
~10 dwarfs & subgiants
~8 giants
Ground-based radial velocity.
WIRE star tracker.
MOST spacecraft.
Surface Gravity (dex)
0
1
2
3
4
7000
6000
5000
4000
3000
Effective Temperature (K)
figure by Daniel Huber

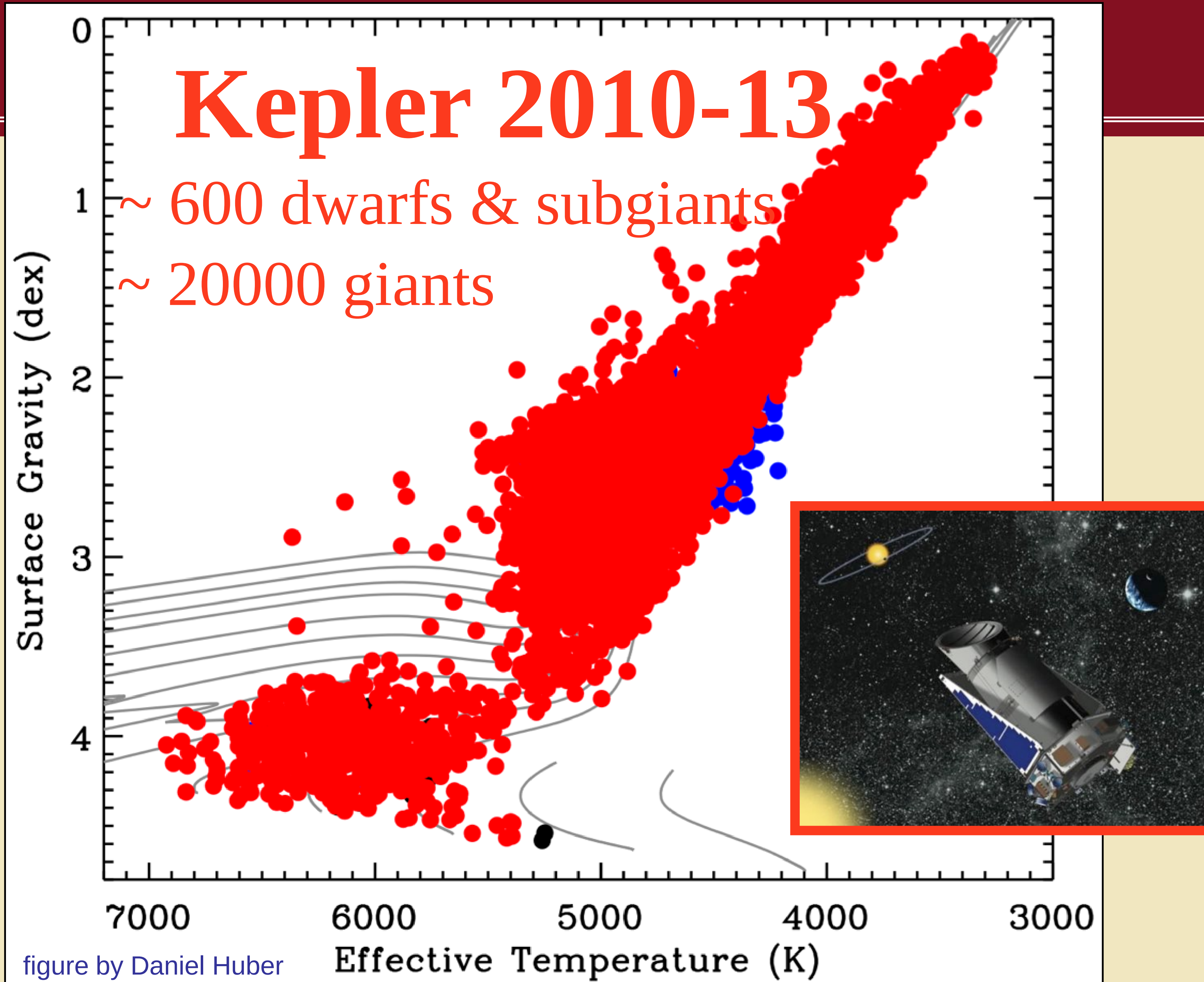
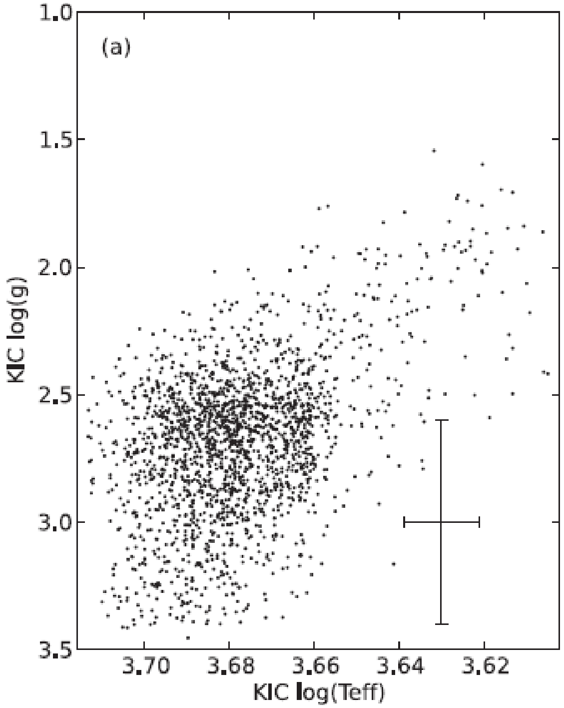


figure by Daniel Huber

Early results from Kepler

Pinsonneault et al. 2016



Log(g)

Teff

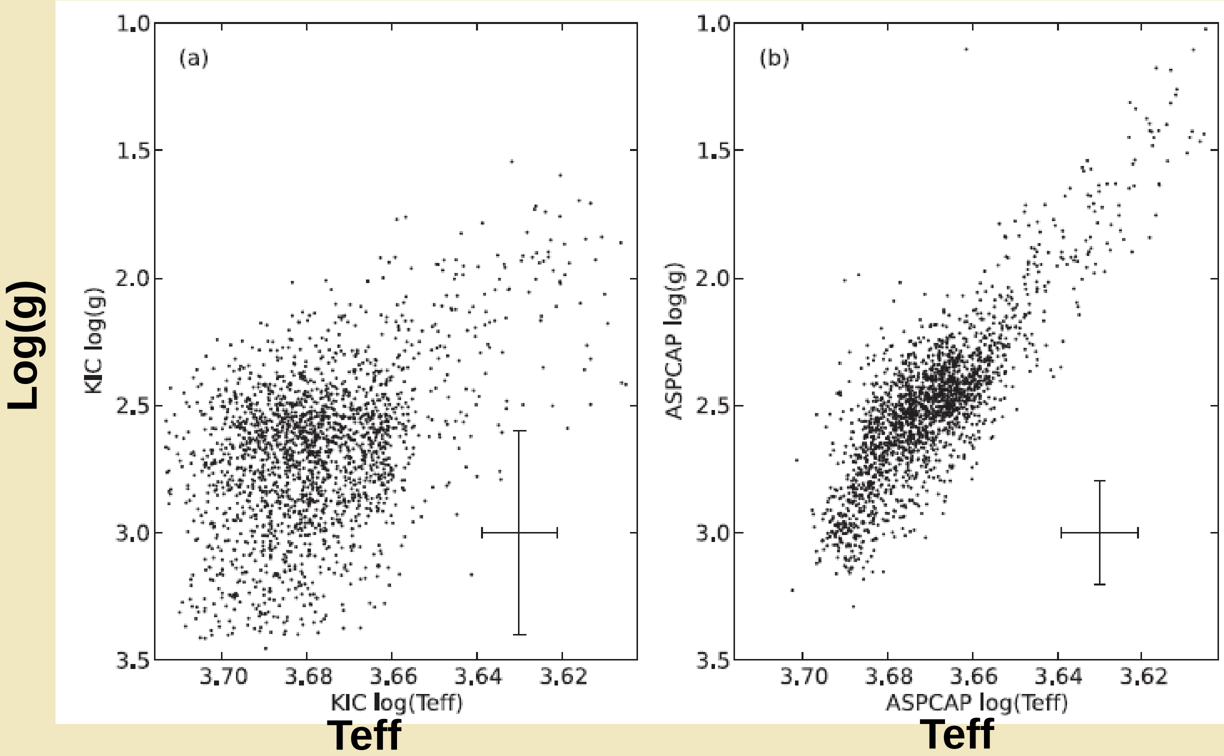
Photometry

APOGEE Red Giants/original Kepler field

Early results from Kepler

Snapping into focus →

Pinsonneault et al. 2016



Photometry **Spectroscopy**

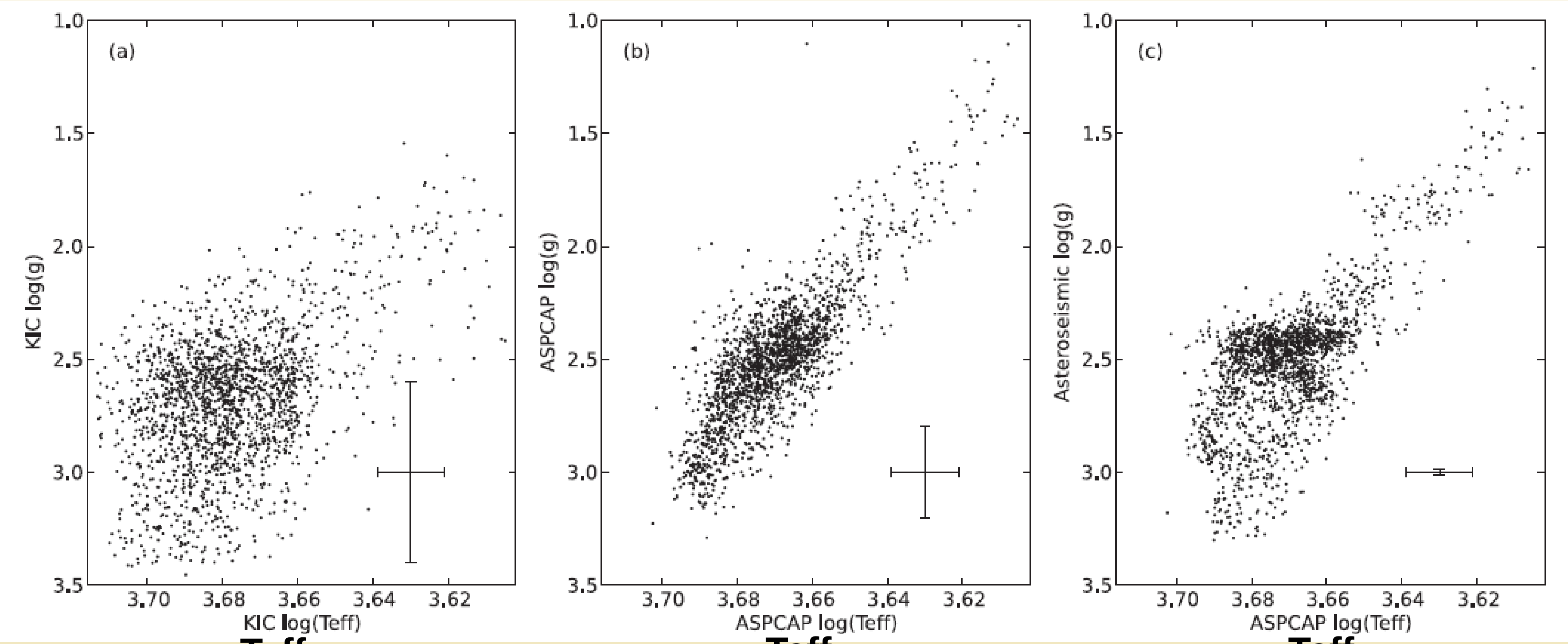
APOGEE Red Giants/original Kepler field

Early results from Kepler

Snapping into focus →

Pinsonneault et al. 2016

Log(g)

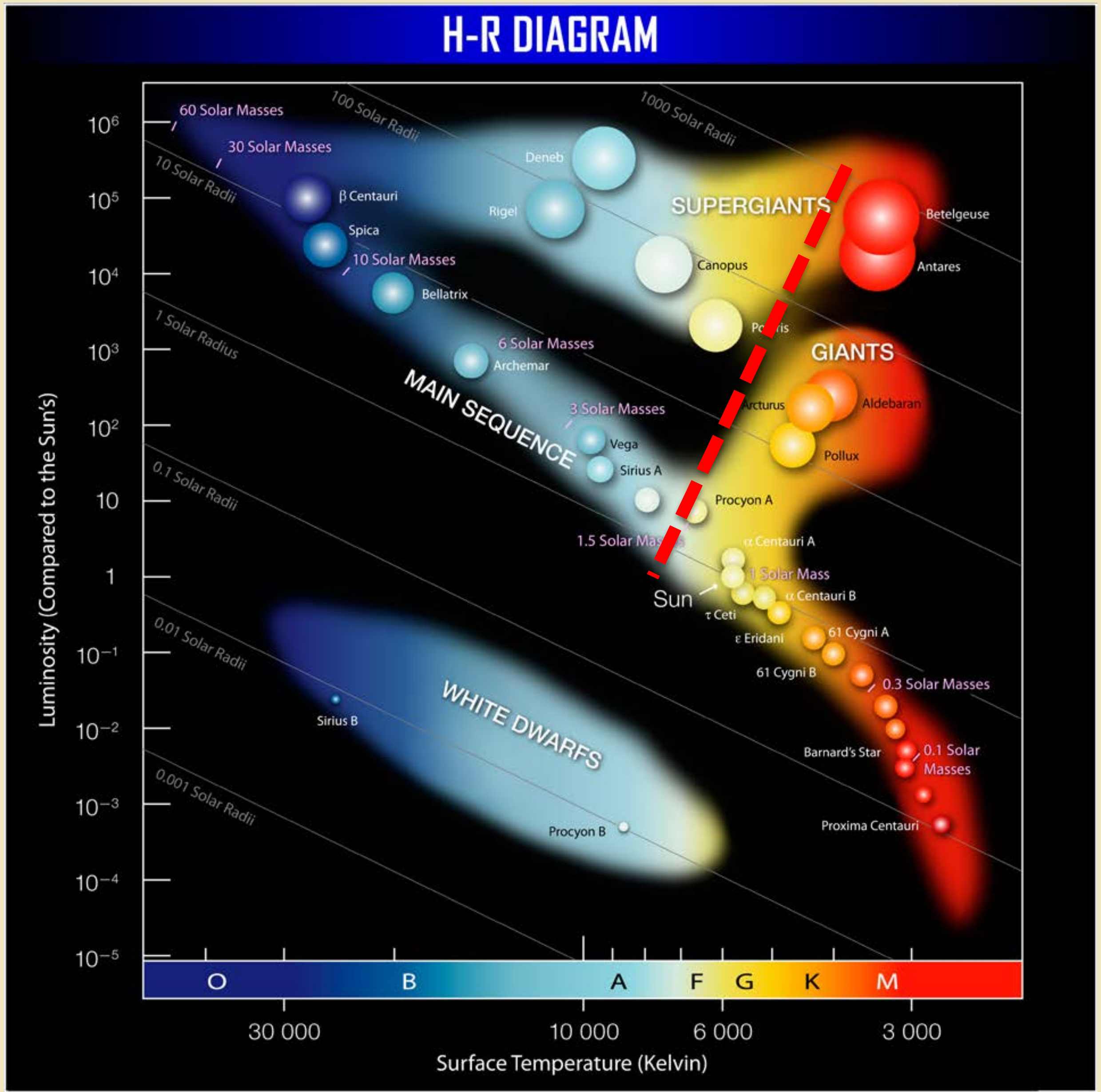


Teff	Teff	Teff
Photometry	**Spectroscopy**	**Spectroscopy + asteroseismology**

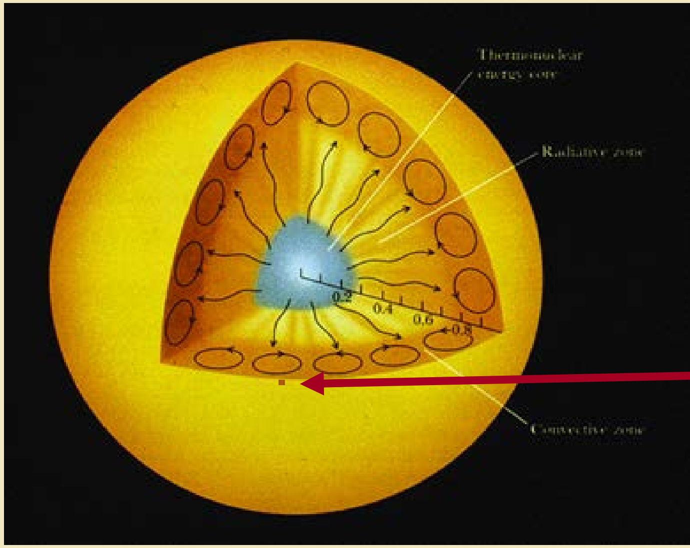
APOGEE Red Giants/original Kepler field

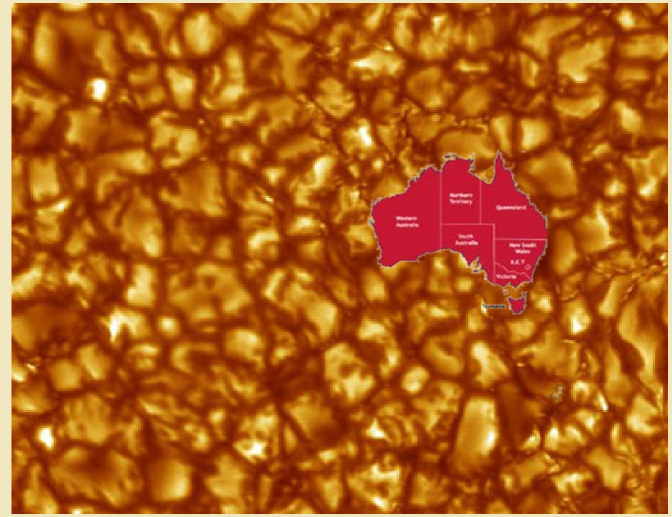
A short introduction to cool-star asteroseismology

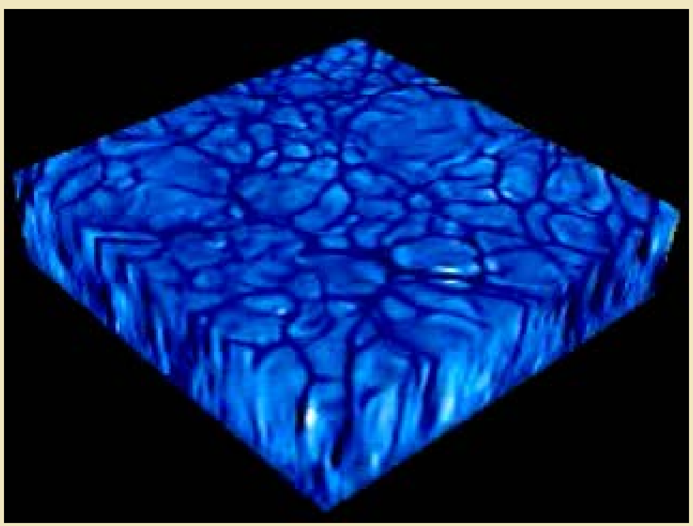
Asteroseismology of cool stars



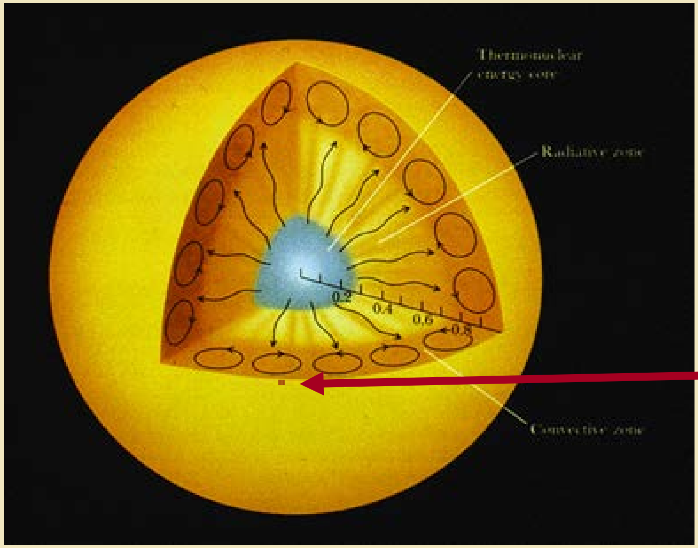
Excitation of solar-like oscillations

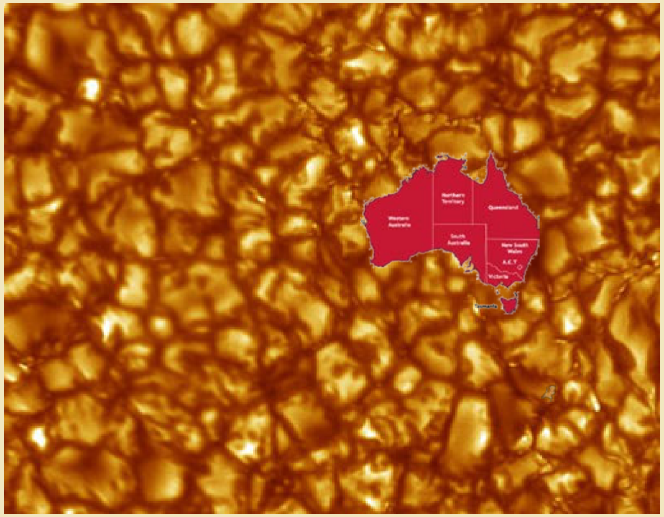


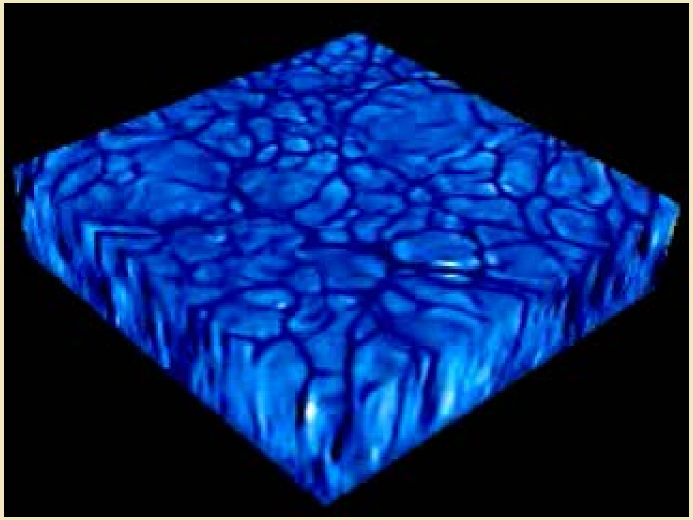




Excitation of solar-like oscillations

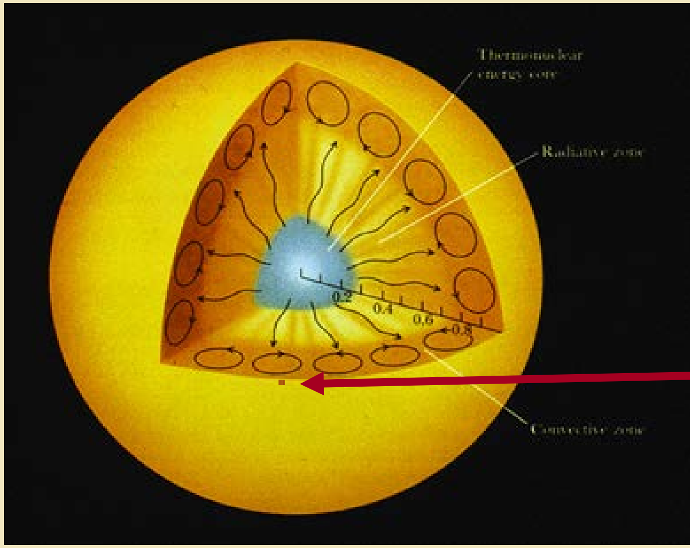


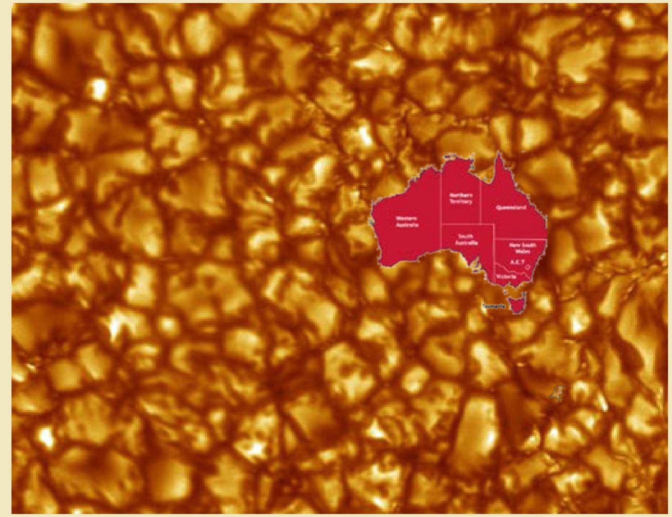




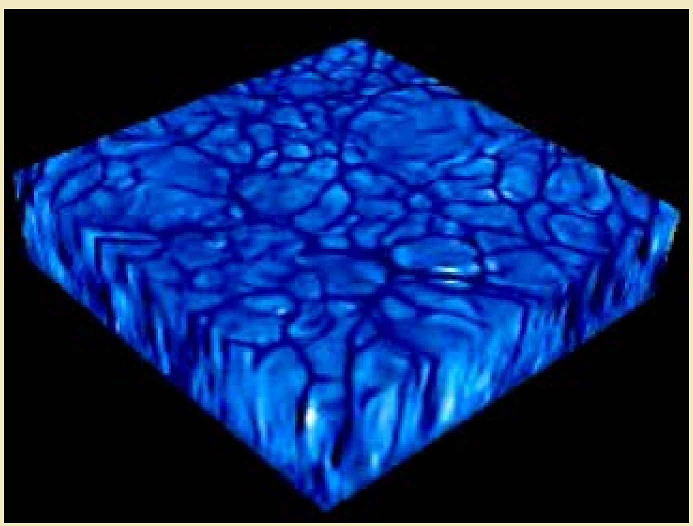
Miso soup

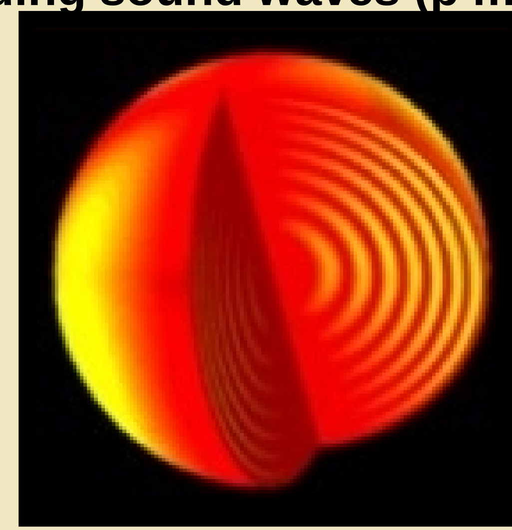
Excitation of solar-like oscillations





Standing sound waves (p modes)





Observing oscillation modes

	Velocity	Brightness
Sun:	20cm/s	4ppm
Red giant:	1-100m/s	30-300ppm

Frequency

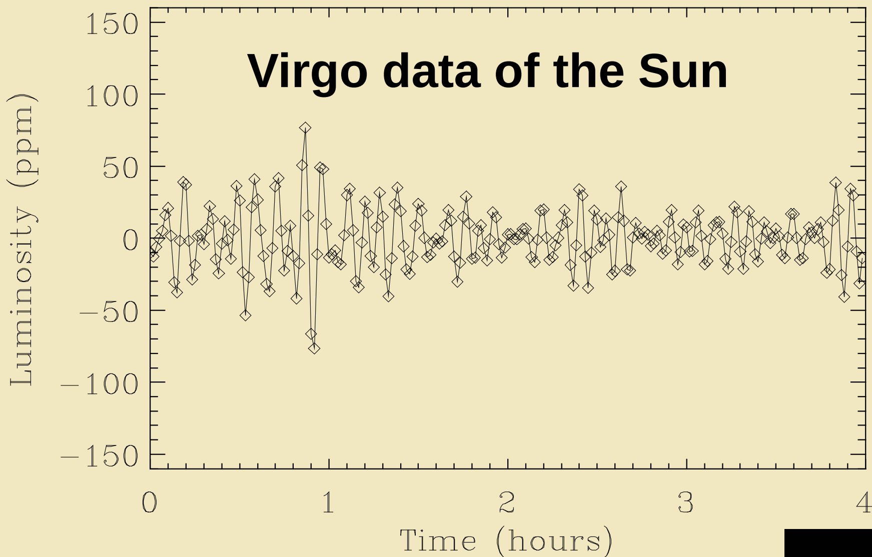
↓

Sound speed

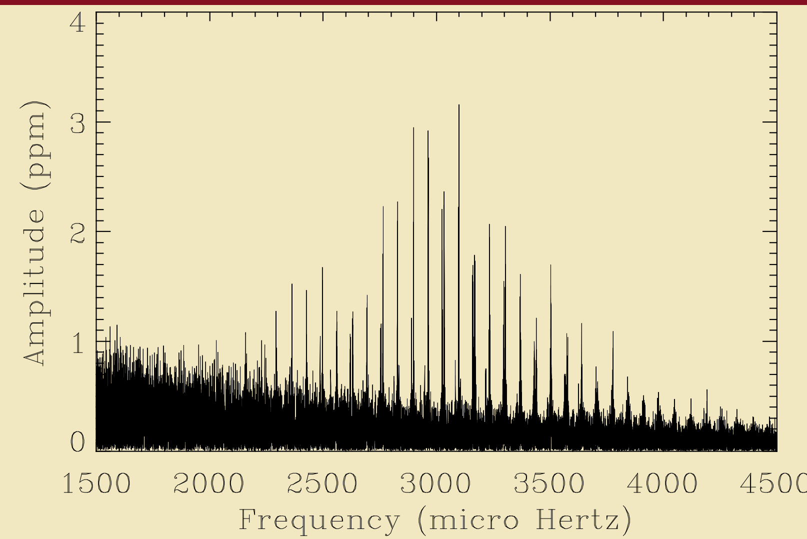
↓

Interior properties

How we do it!

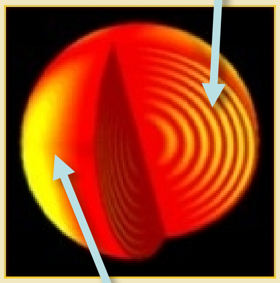


FT

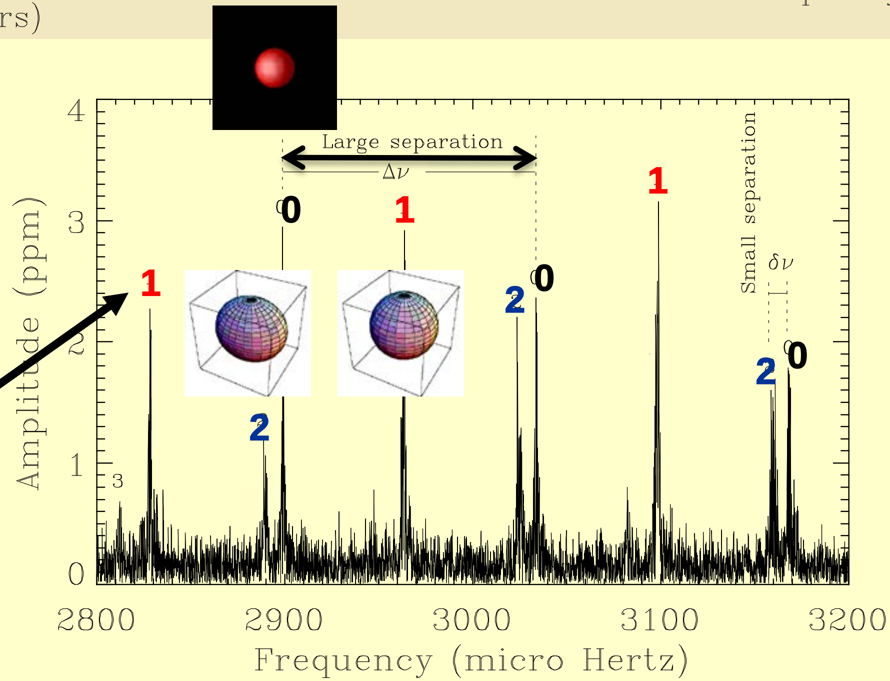


Zoom

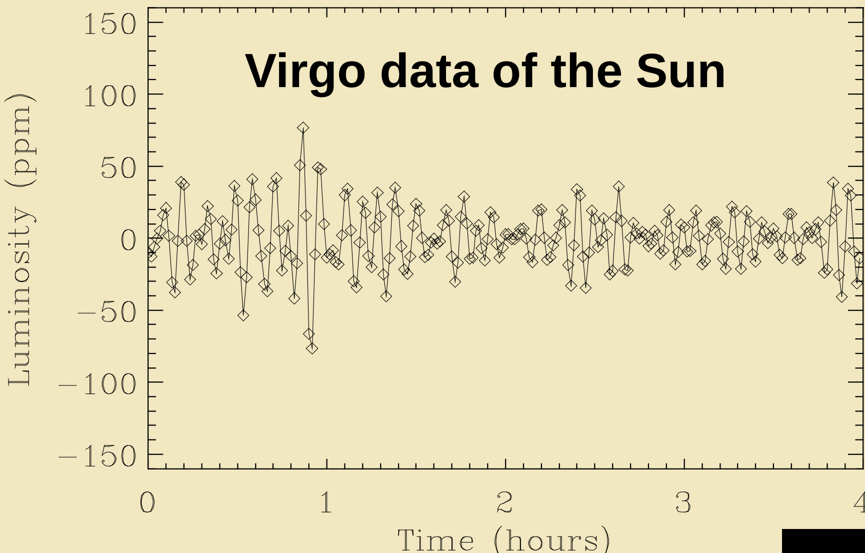
Overtone determined by number of nodes (shells) radially.



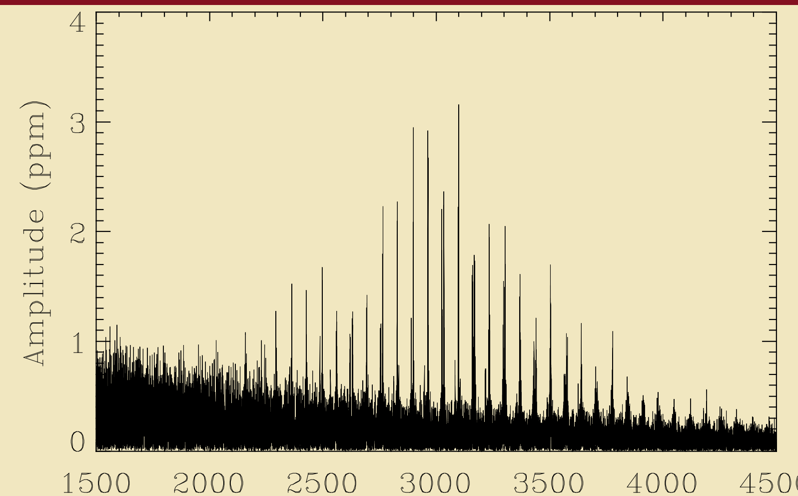
Spherical degree determined by number of `surface' nodal lines.

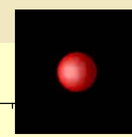


How we do it!



FT

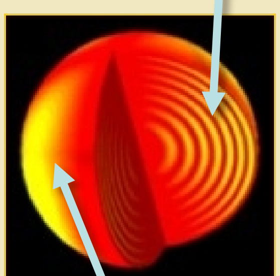




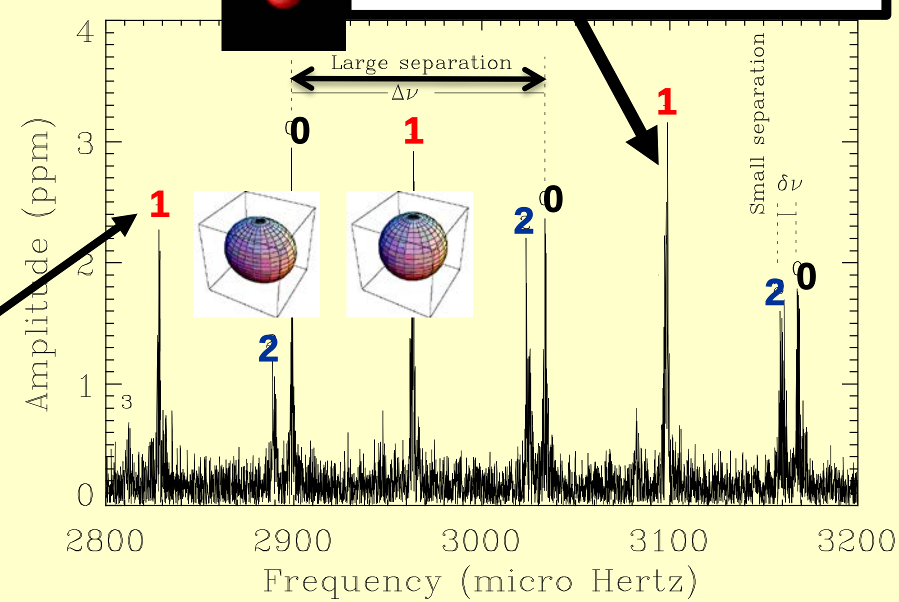
$\delta f/f \sim 10^{-4}\text{-}10^{-6}$

Zoom

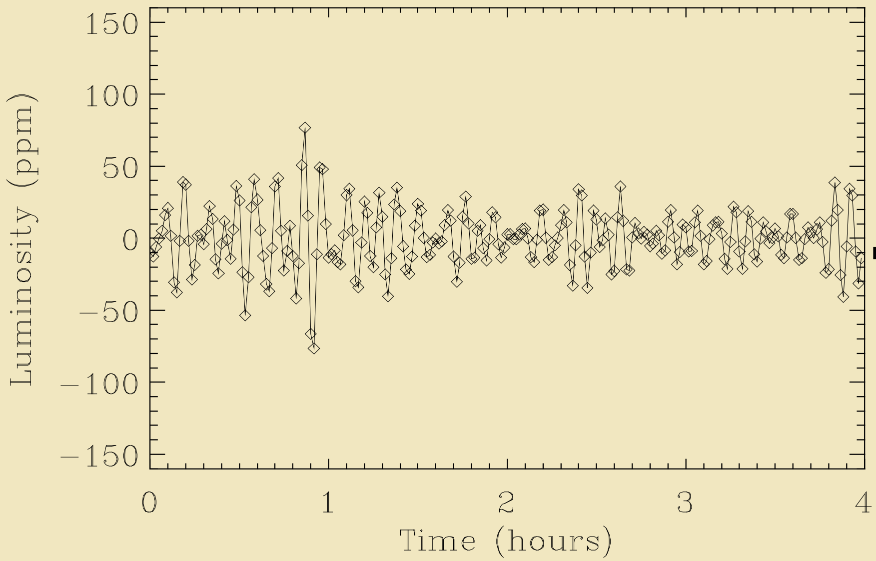
Overtone determined by number of nodes (shells) radially.



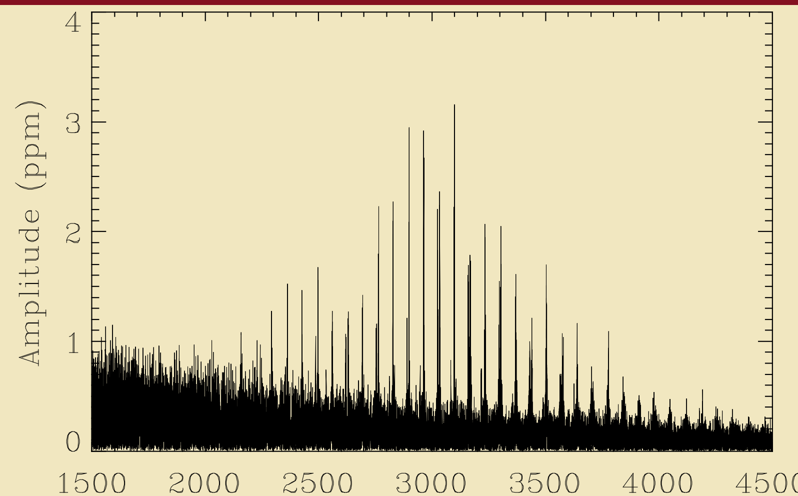
Spherical degree determined by number of \`surface' nodal lines.



What can we measure?

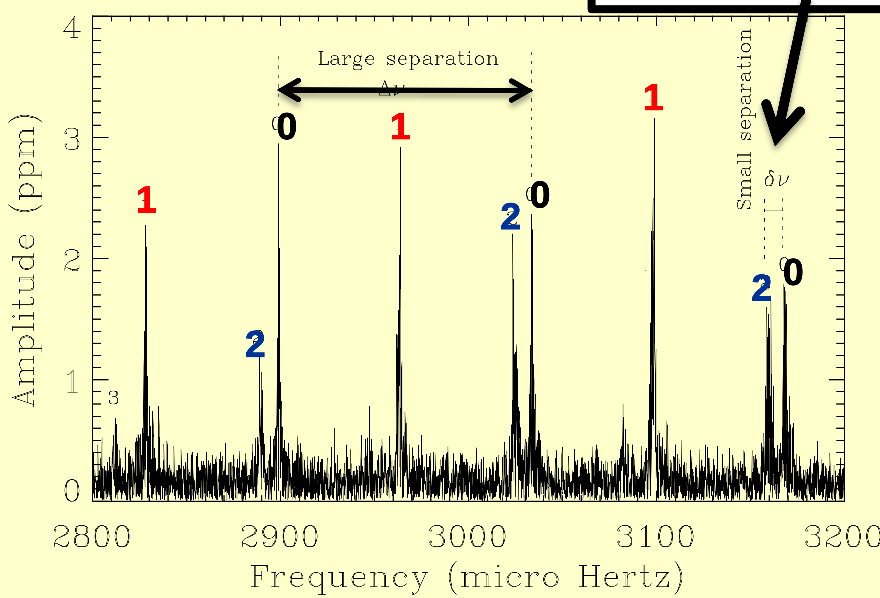


FT

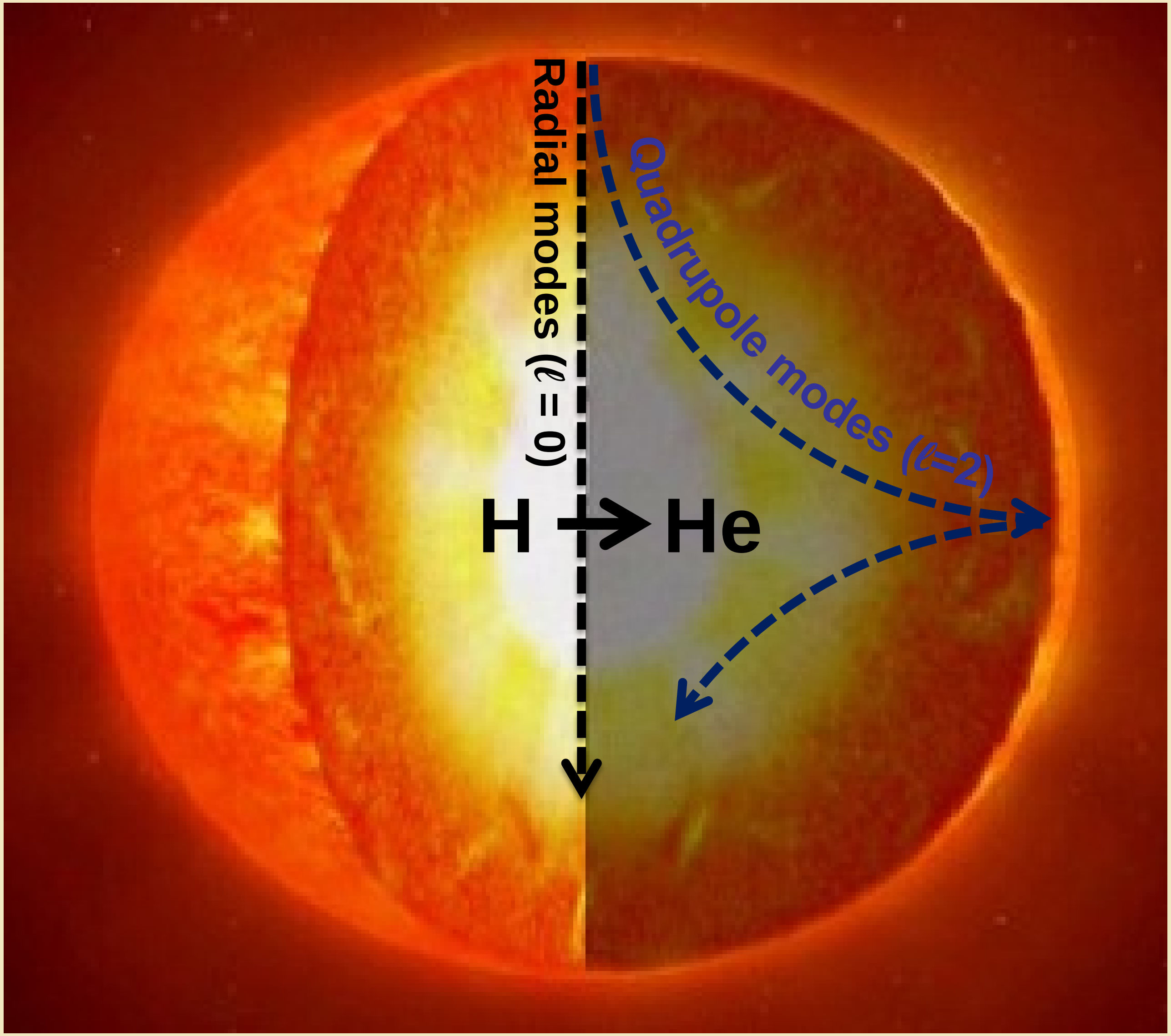


Age of star

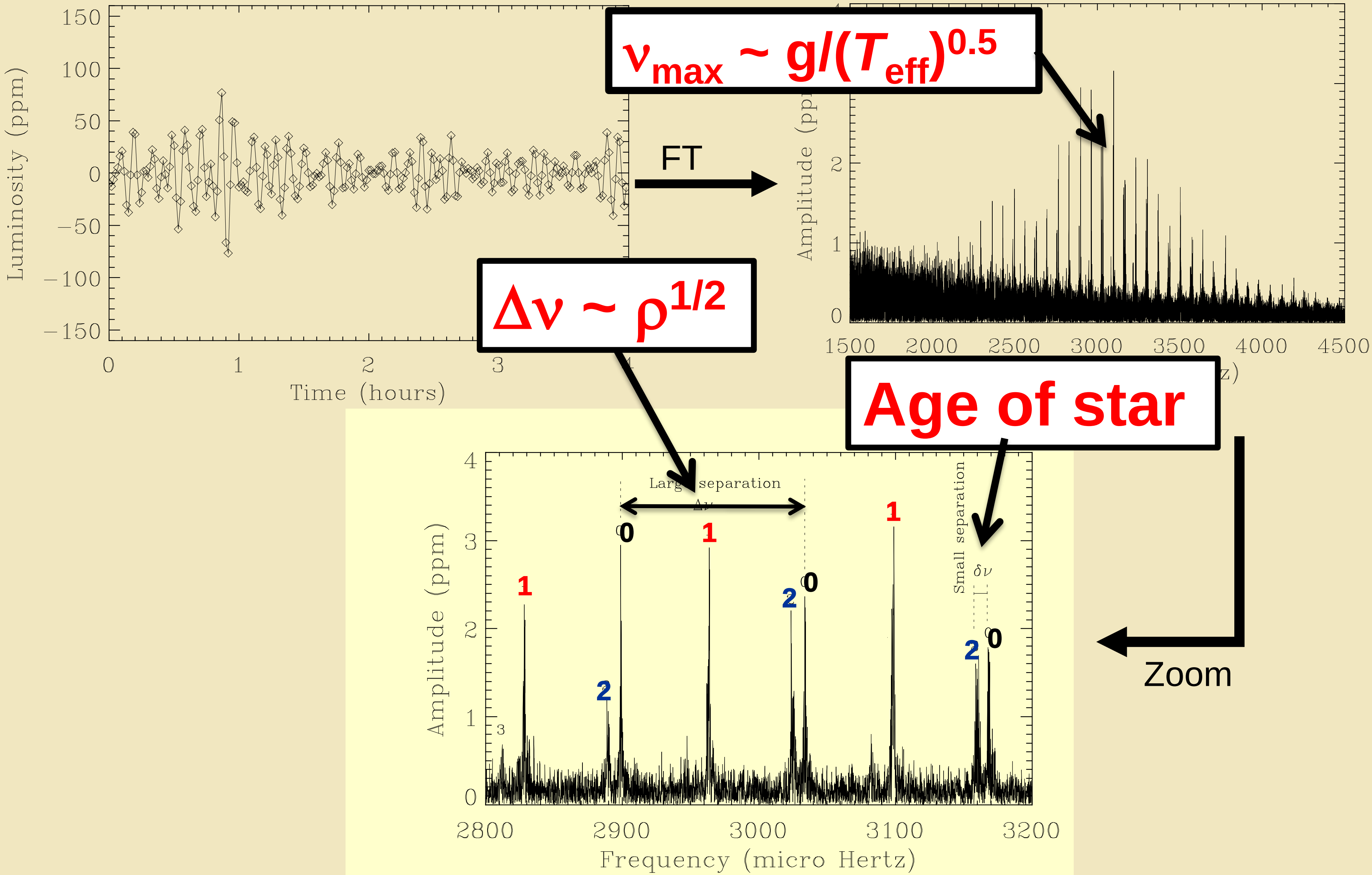
Zoom



Ages of main sequence stars



But there is more

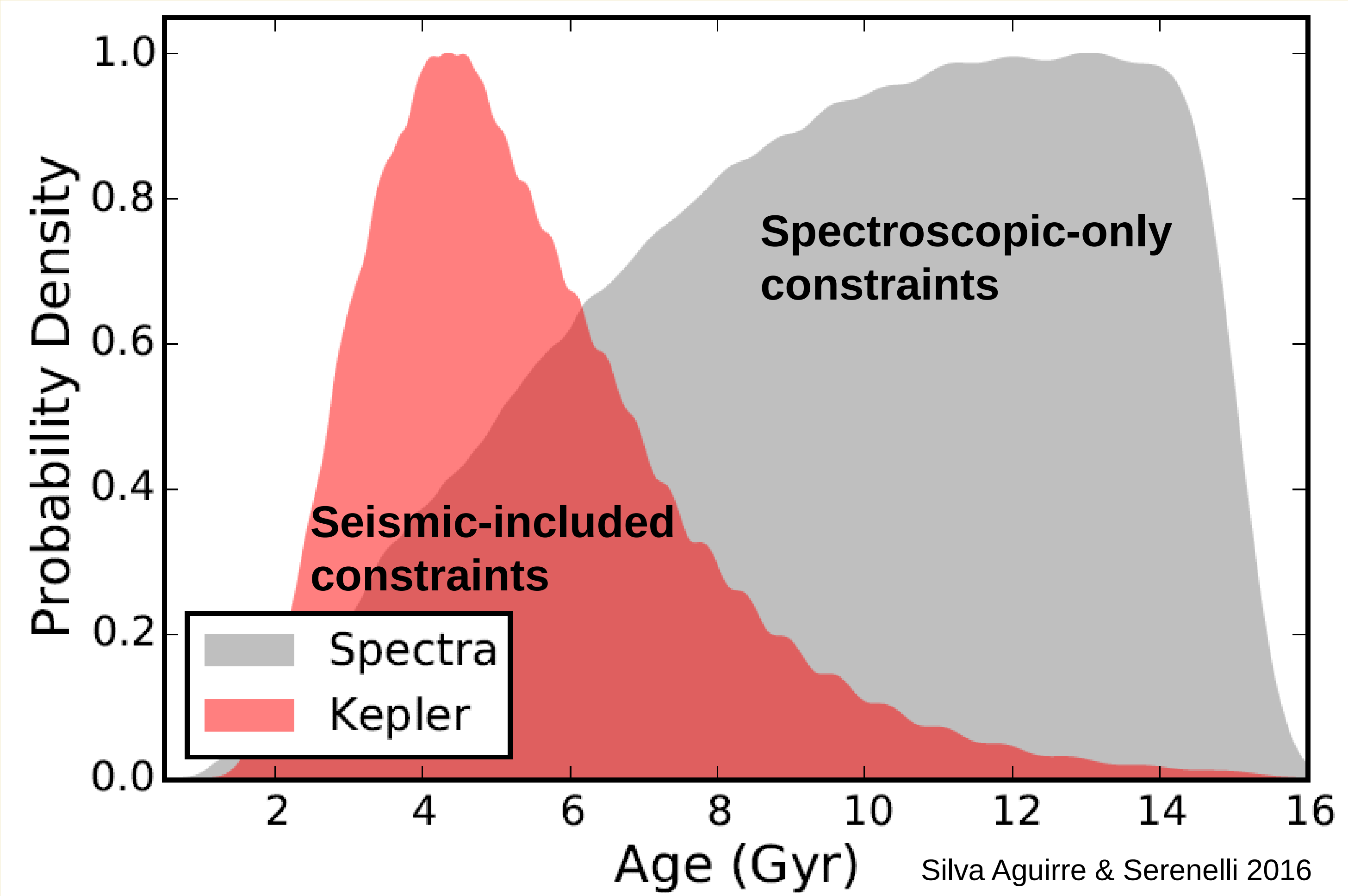


Age precisions

- **Individual mode fitting (or frequency ratios):**
  - Main sequence: ~3% (best, Metcalfe 2015), 5-15% (typical, Metcalfe 2014, Silva Aguirre 2015).
  - Subgiants: ~1% (best, Metcalfe 2010), ~3% (typical, Deheuvels & Michel 2011).
  - Red giants: < 15%(?) (very time consuming)

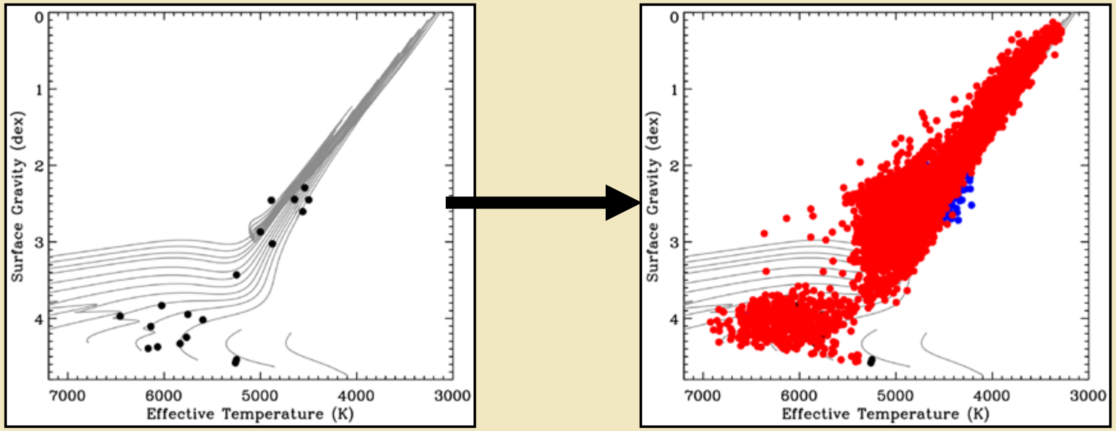
- **$\Delta\nu+\nu_{max}$ (at least one scaling relation):**
  - Main sequence: ~15% – 25% (Chaplin 2014).
  - Subgiants: ~15% – 25% (Chaplin 2014).
  - Red giants: ~15 – 30% (Casagrande 2014).

Ages of red giants

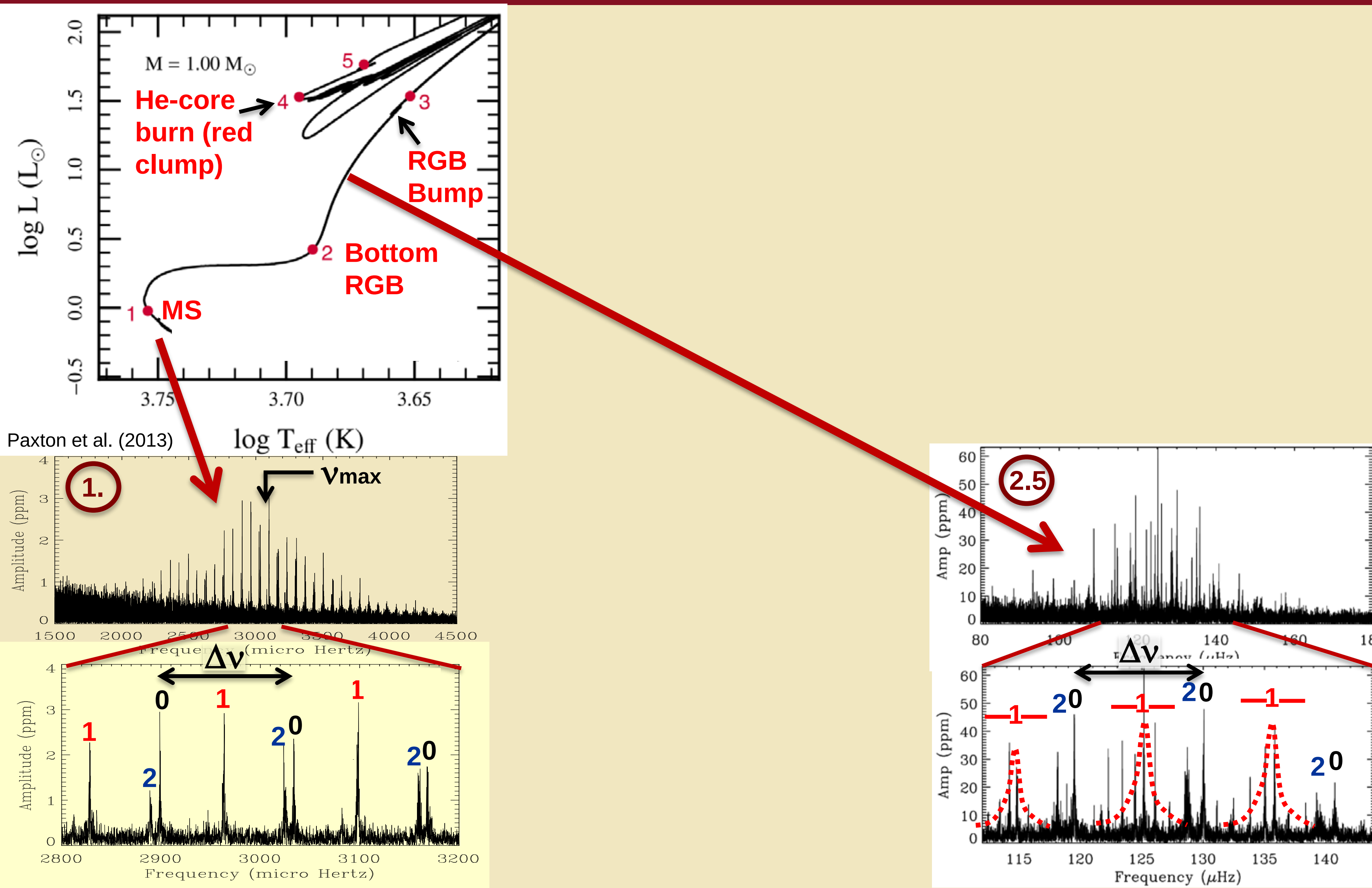


Silva Aguirre & Serenelli 2016

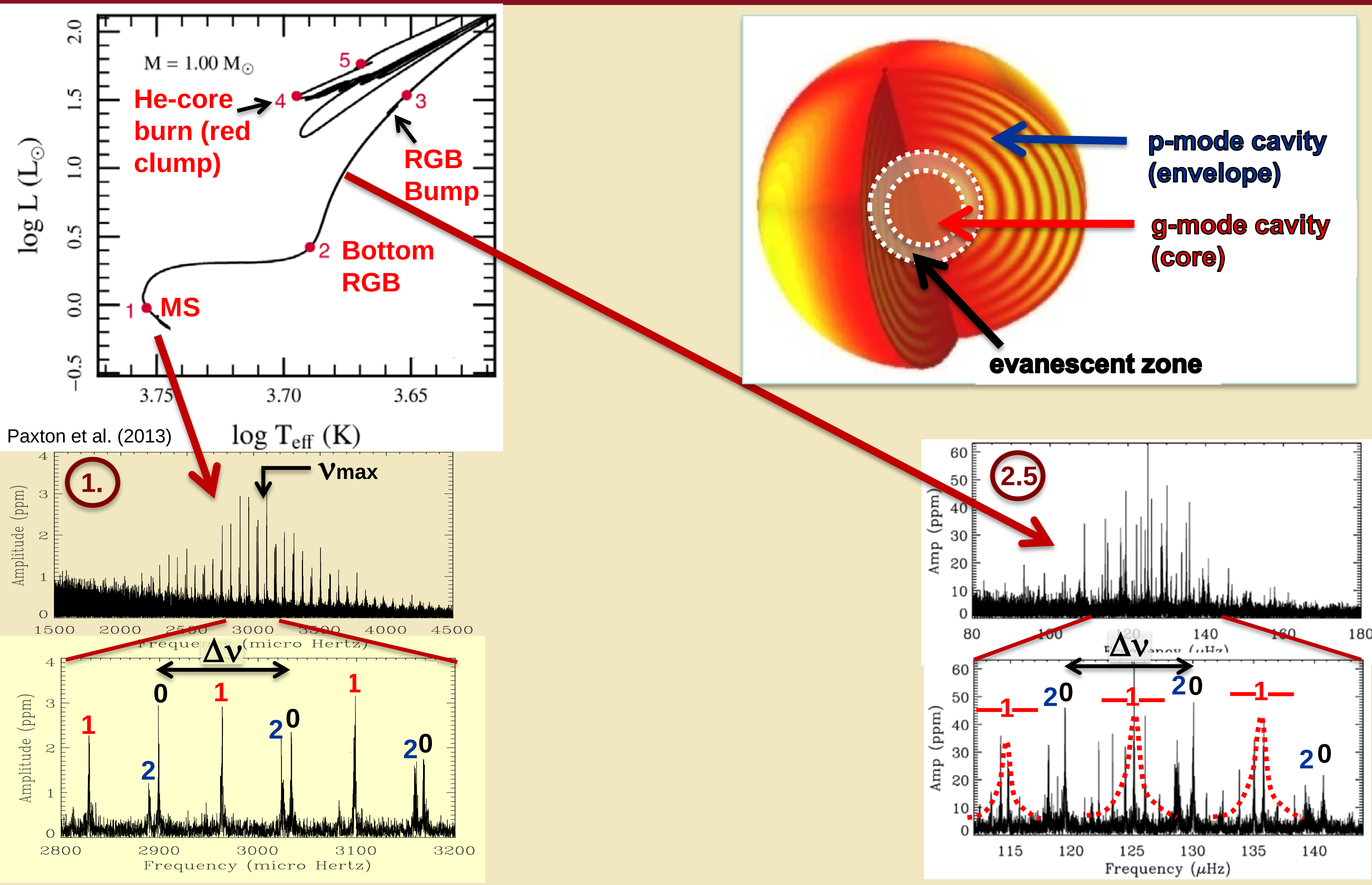
Back to the revolution…what have we learned so far!



Evolution of frequency spectra



Evolution of frequency spectra



Problem!!!

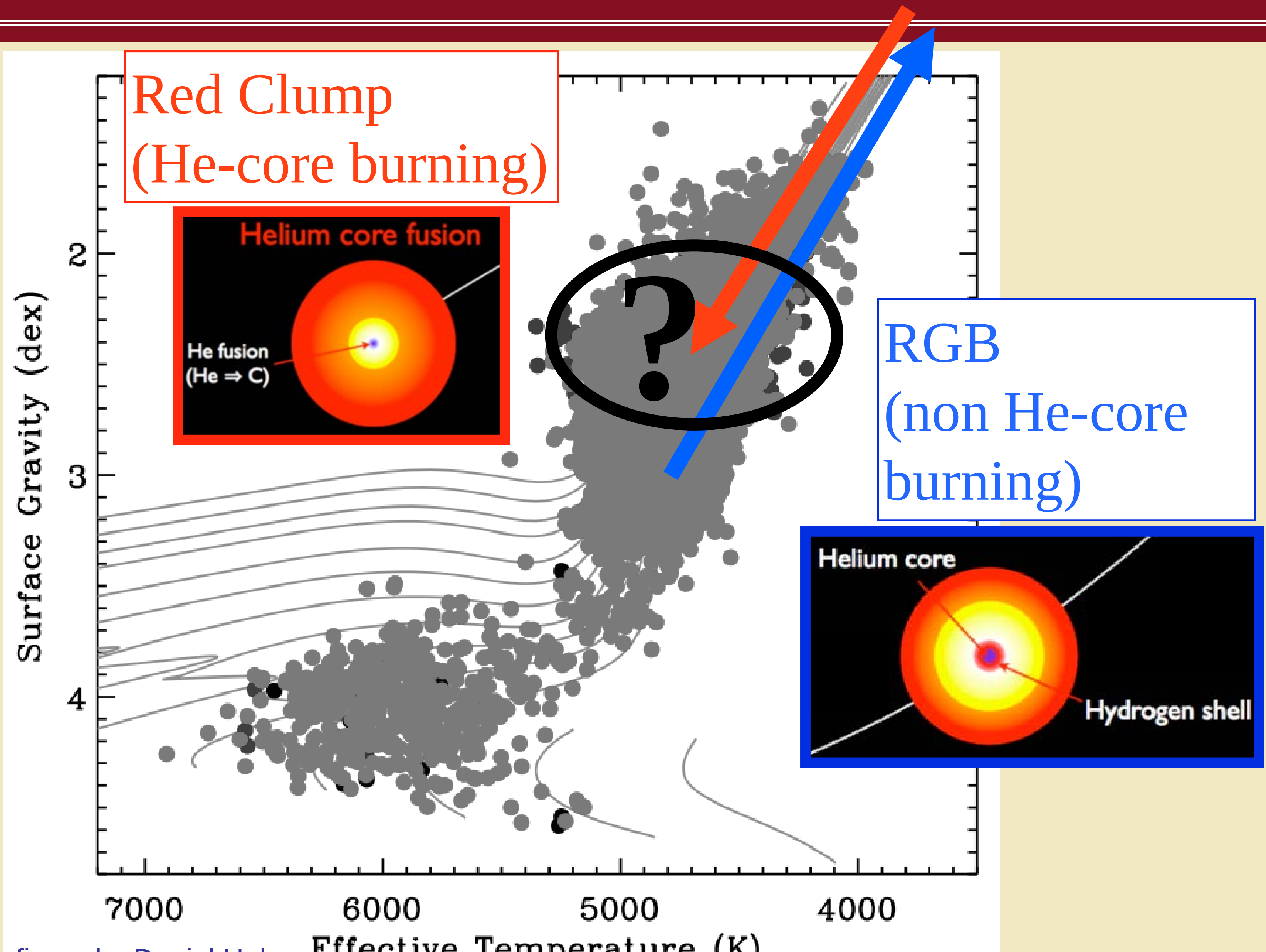
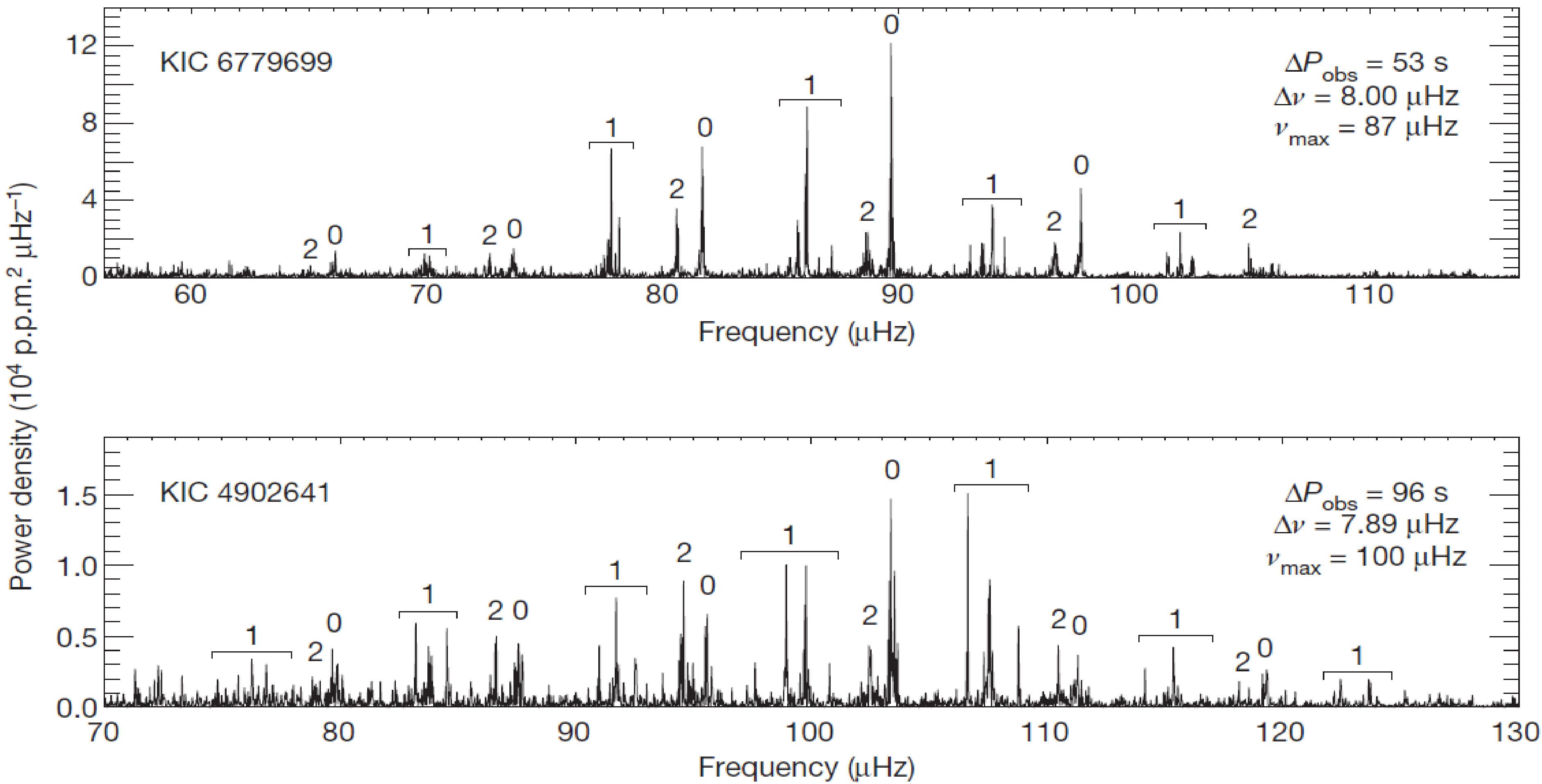


figure by Daniel Huber

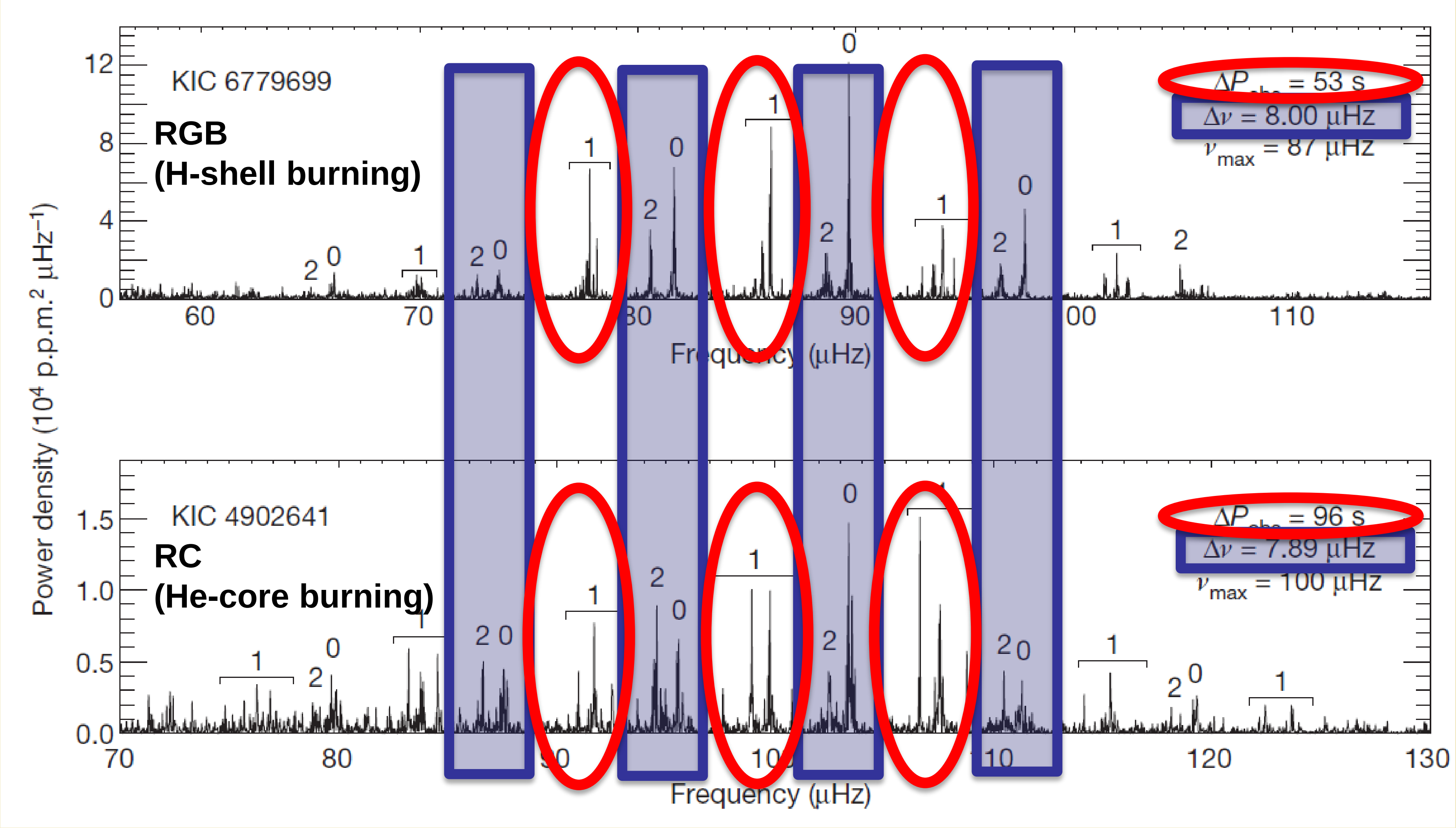
LETTER

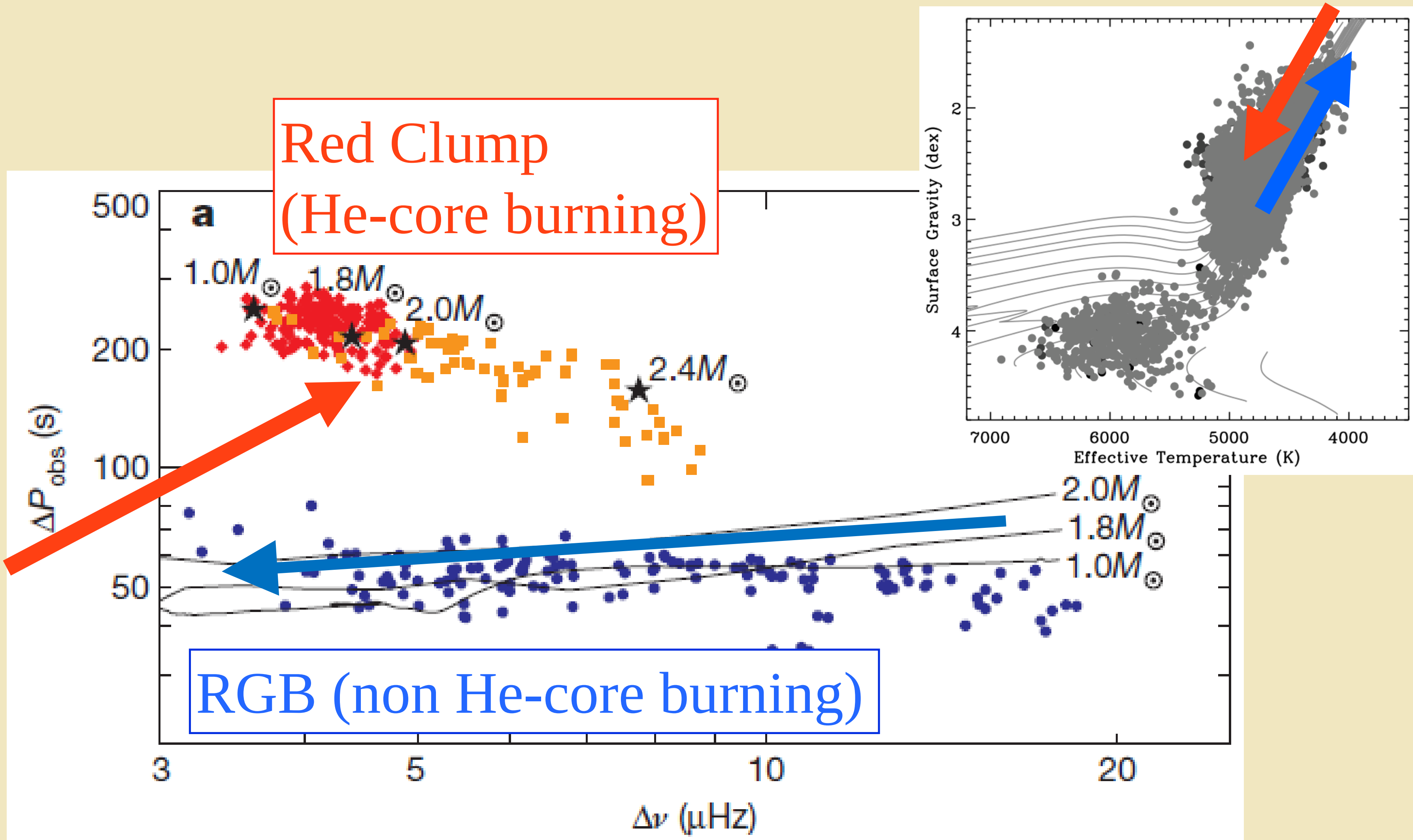
Gravity modes as a way to distinguish between hydrogen- and helium-burning red giant stars

Timothy R. Bedding[1], Benoit Mosser[2], Daniel Huber[1], Josefina Montalbán[3], Paul Beck[4], Jørgen Christensen-Dalsgaard[5], Yvonne P. Elsworth[6], Rafael A. García[7], Andrea Miglio[3,6], Dennis Stello[1], Timothy R. White[1], Joris De Ridder[4], Saskia Hekker[6,8],



RGB/RC stars: seismically different

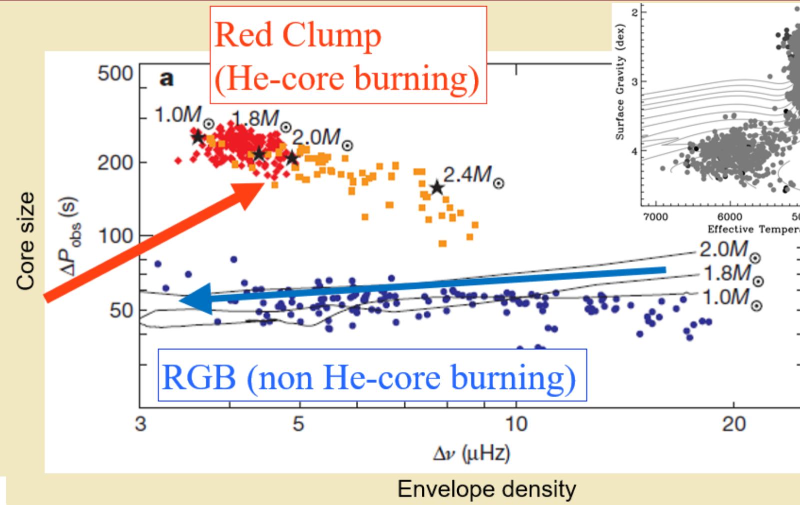


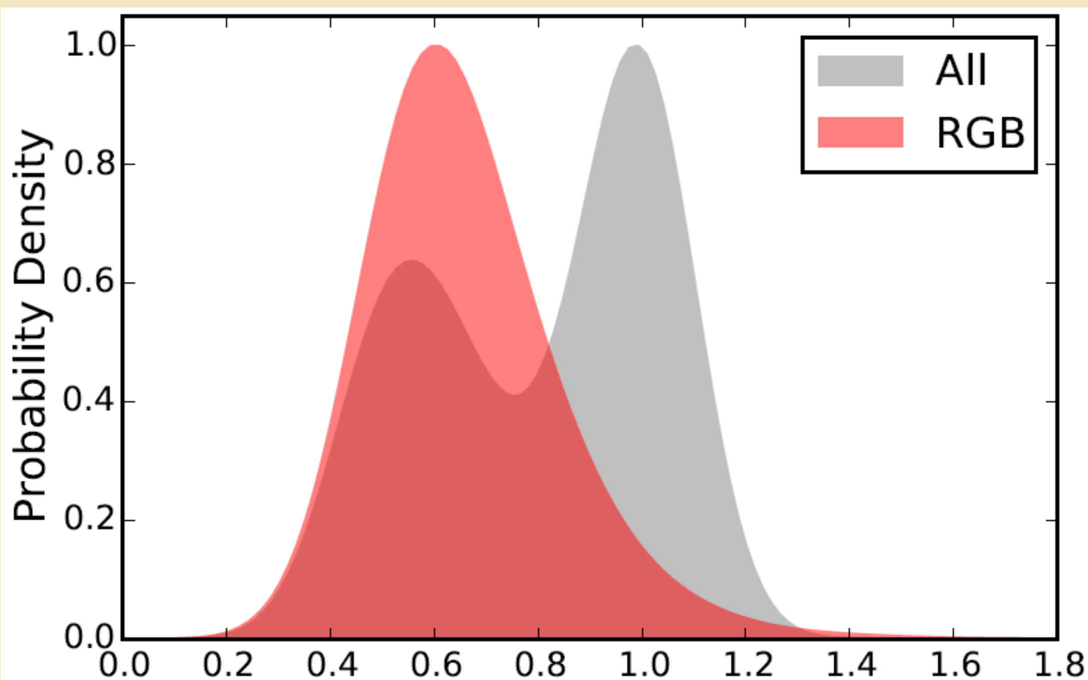


Core size

Envelope density

Ages of red giants

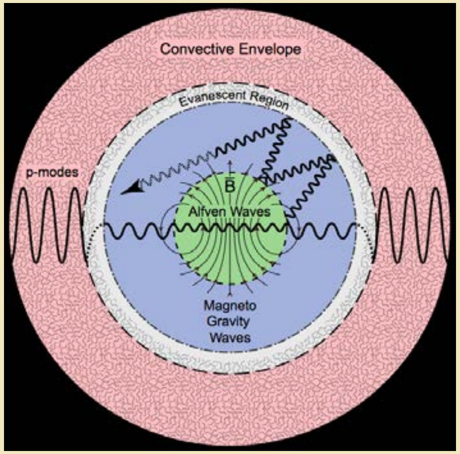




Silva Aguirre & Serenelli 2016

Other breakthroughs!!!

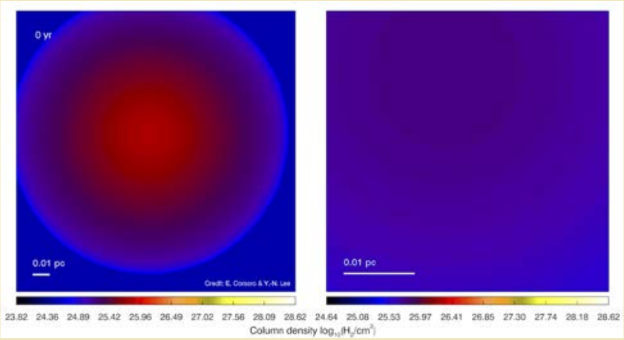
Magnetic green house effect



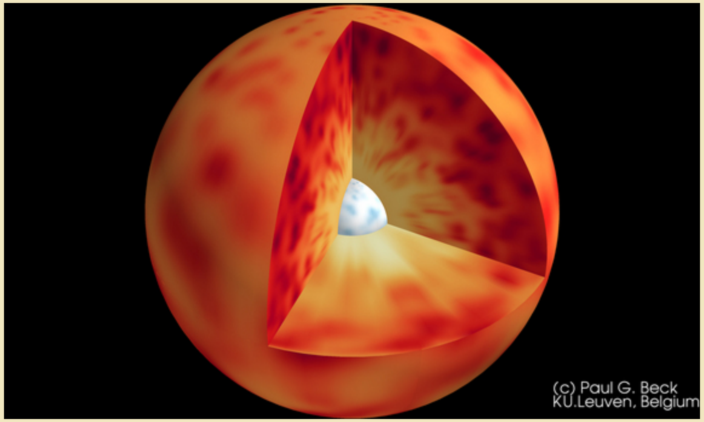
Fuller et al. 2015
(Science)

Stellar inclinations: Do cluster stars' spin align?

Corsaro et al. 2017
(NatureCom)

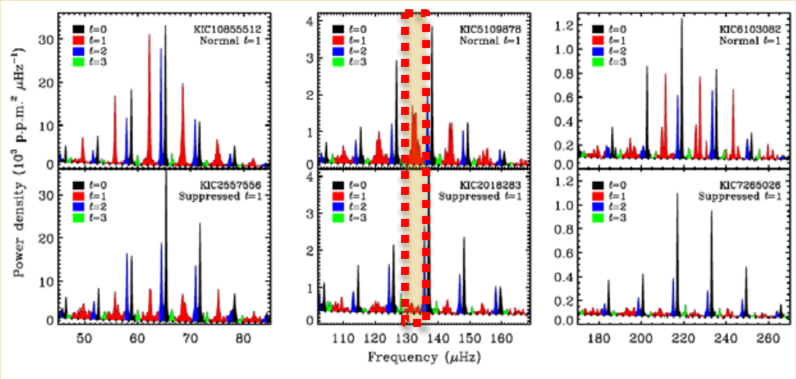


Radial differential rotation and angular momentum transport



Beck et al. 2012 (Nature)
Mosser et al. 2012 (A&A)

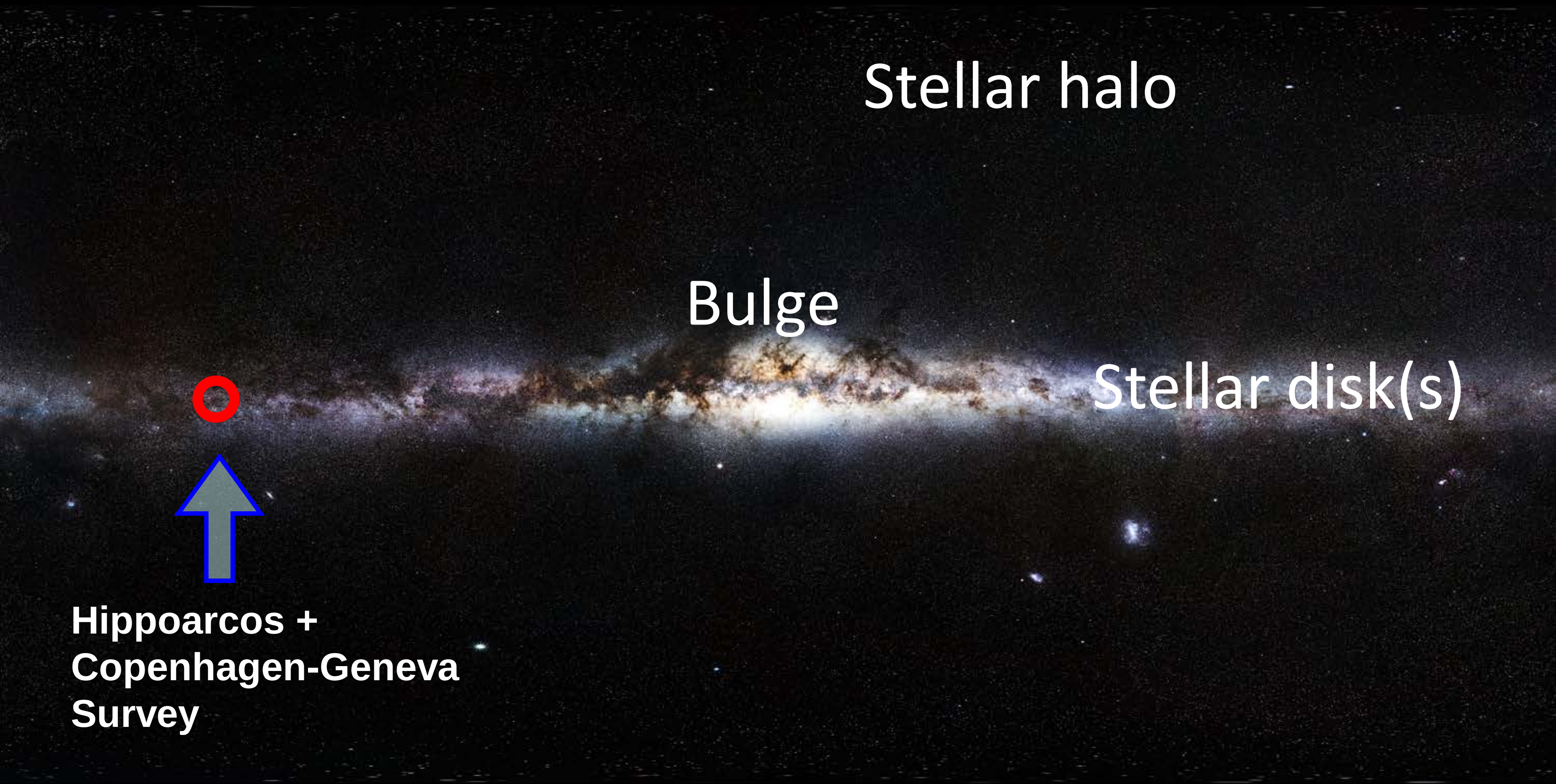
A prevalence of convective core dynamos



Stello et al. 2016
(Nature)

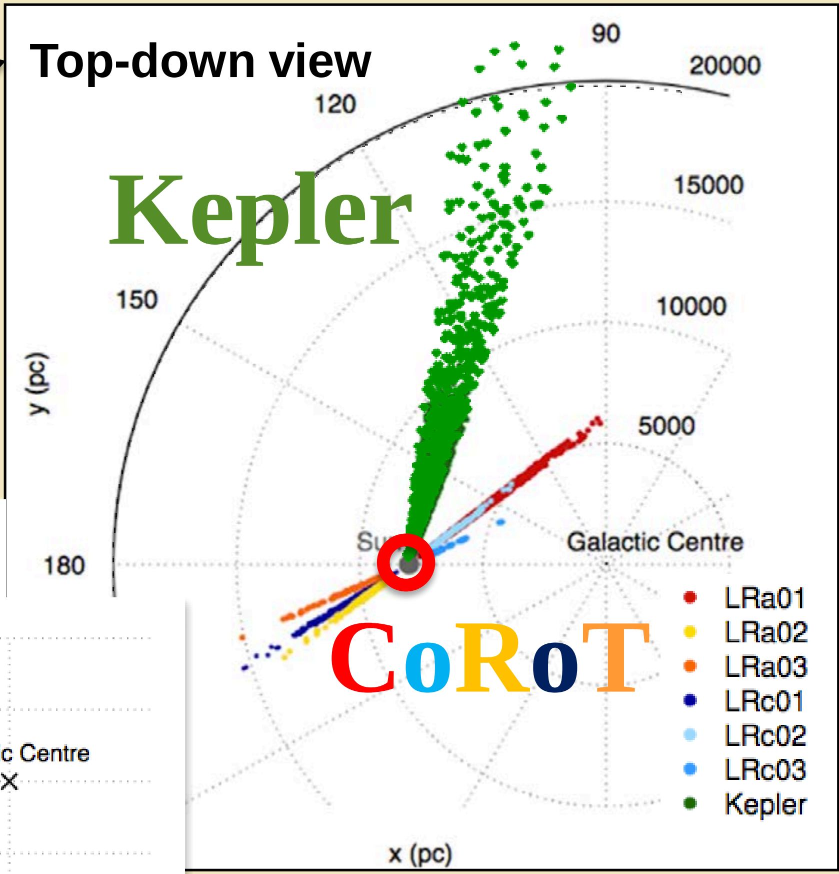
Ensemble seismology:
Probing the structure and evolution of the Milky Way

Our Galaxy

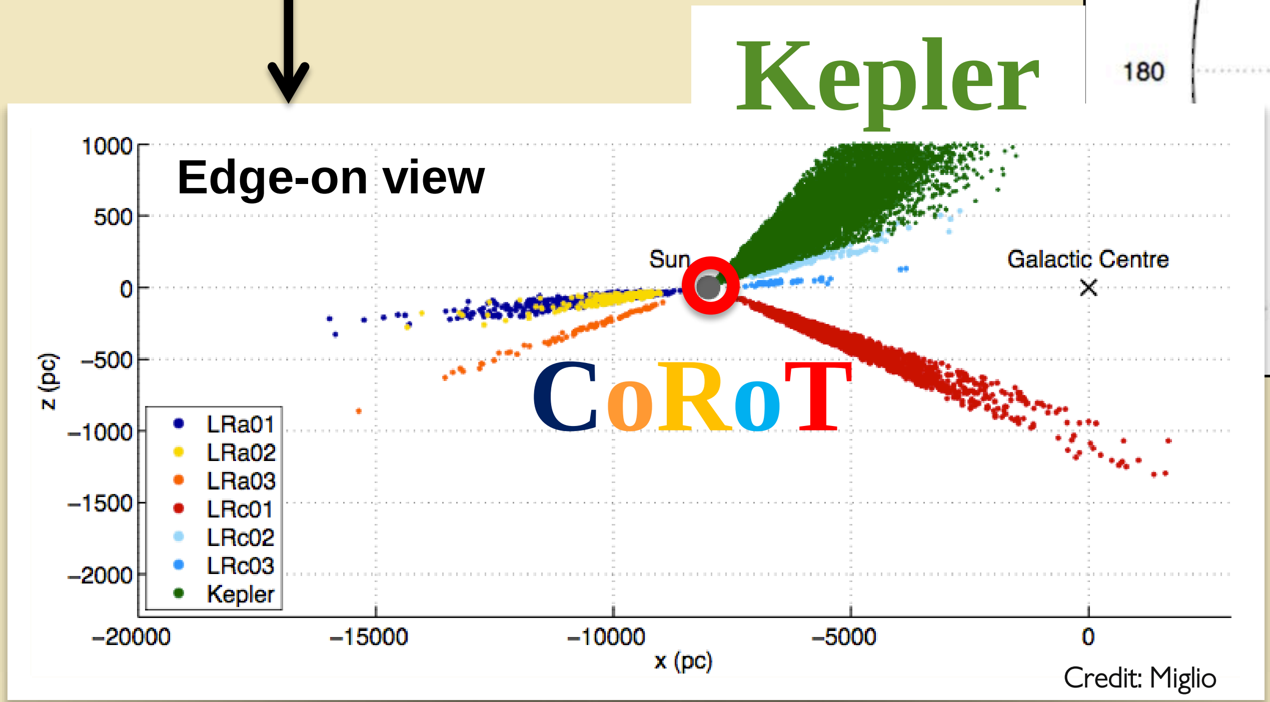

Stellar halo
Bulge
Stellar disk(s)
Hippoarcos +
Copenhagen-Geneva
Survey

Asteroseismic probes of the Galaxy

Probes of the Galaxy



Mathur et al. 2016



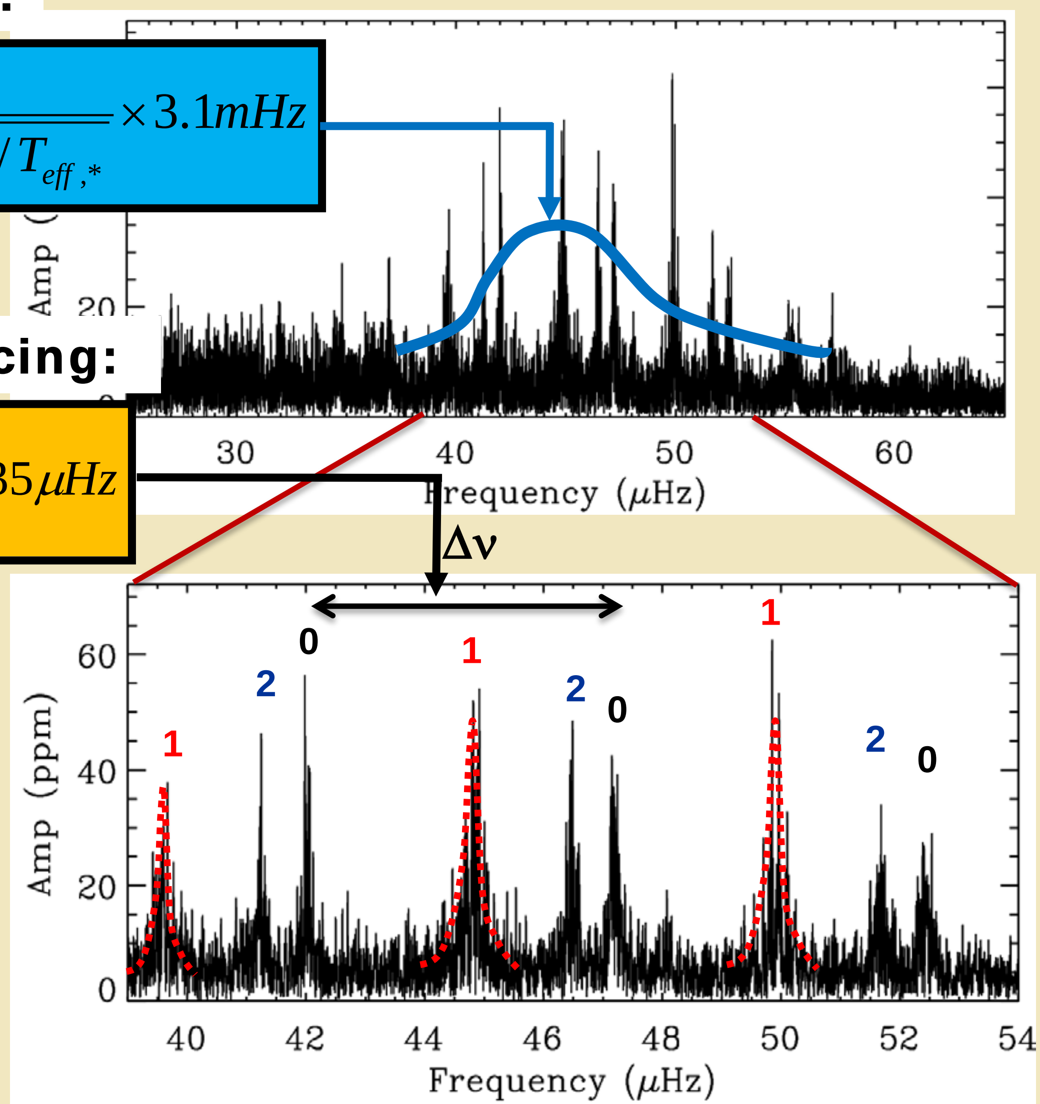
Ensemble seismology: M, R, L

Power location:

$$\nu_{\max} \cong \frac{M/M_*}{(R/R_*)^2\sqrt{T_{eff}/T_{eff,*}}} \times 3.1 mHz$$

Frequency spacing:

$$\Delta\nu \cong \frac{(M/M_*)^{1/2}}{(R/R_*)^{3/2}} \times 135 \mu Hz$$



Ensemble seismology: M, R, L

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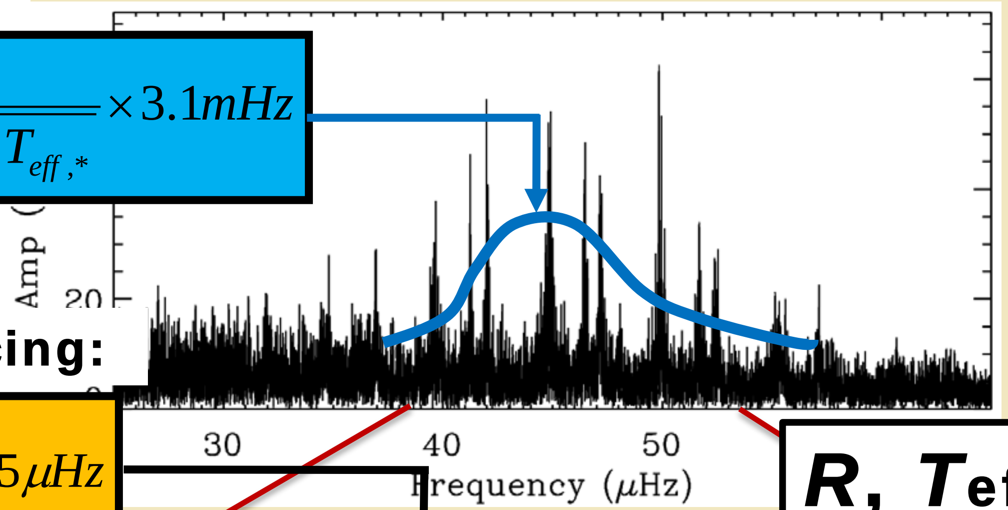
$$\nu_{\max} \cong \frac{M/M_*}{(R/R_*)^2\sqrt{T_{eff}/T_{eff,*}}} \times 3.1 mHz$$



Frequency spacing:

$$\Delta\nu \cong \frac{(M/M_*)^{1/2}}{(R/R_*)^{3/2}} \times 135 \mu Hz$$

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

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

R, Teff → L

distance

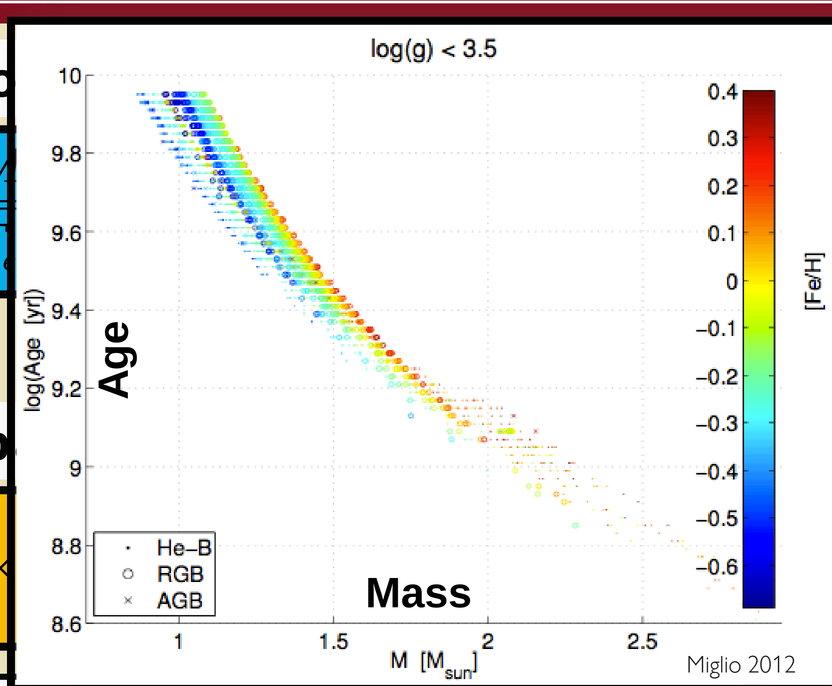
Ensemble seismology: M, R, L

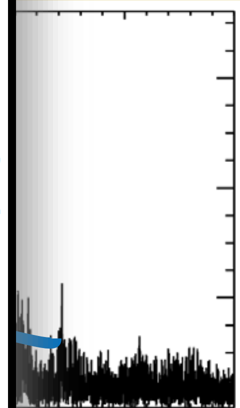
Power locatio

$$\nu_{\max} \cong \frac{M/M}{(R/R_*)^2\sqrt{T}}$$

Frequency sp

$$\Delta\nu \cong \frac{(M/M_*)^{1/2}}{(R/R_*)^{3/2}} \times$$





distance

R, Teff → L

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

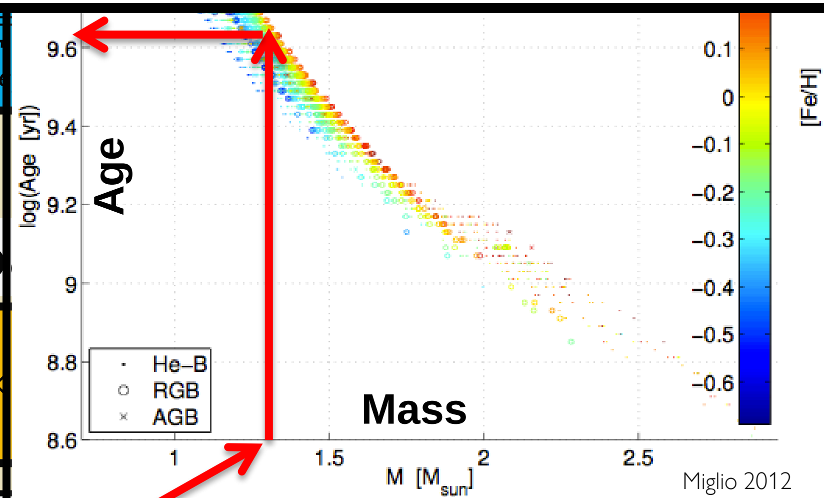
$$\frac{R}{R_\odot} \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right) \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2} \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{1/2}$$

Ensemble seismology: M, R, L

Power l

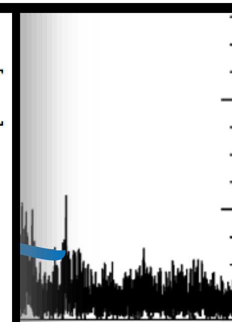
$\nu_{max} \cong \frac{}{(R/R_*)^2 \sqrt{T}}$

Whole-sale seismology!



Frequency sp

$\Delta\nu \cong \frac{(M/M_*)^{1/2}}{(R/R_*)^{3/2}} \times$



distance

R, Teff → L

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

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

Ensemble seismology: M, R, L

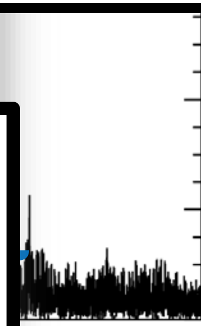
Power l

$$\nu_{max} \cong \frac{\ldots}{(R/R_*)^2\sqrt{T}\ldots}$$

Frequency sp

$$\Delta\nu \cong \frac{(M/M_*)^{1/2}}{(R/R_*)^{3/2}} \times \ldots$$

Whole-sale seismology!



distance

R, Teff → L

Typical precisions:

$\Delta\nu$	0.1-1%
ν_{max}	0.5-2%

Log(g)	0.01-0.03 dex
Radius	2-3%
Mass	6-10%
Age	15-30%
Distance	3-5%

$$\frac{M}{M_\odot} \ldots \left(\frac{T_{eff}}{T_{eff,\odot}}\right)^{3/2}$$

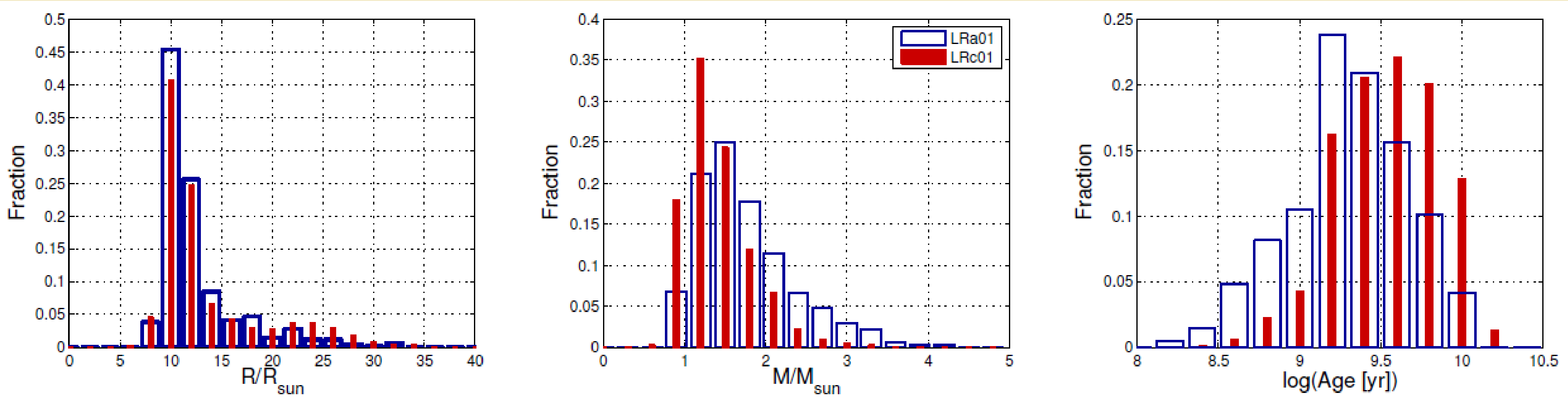
$$\frac{R}{R_\odot} \simeq \left(\frac{\nu_{max}}{\nu_{max,\odot}}\right)\left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{\ldots}\left(\frac{T_{eff}}{T_{eff,\odot}}\right)^{1/2}$$

Frequency (μHz)

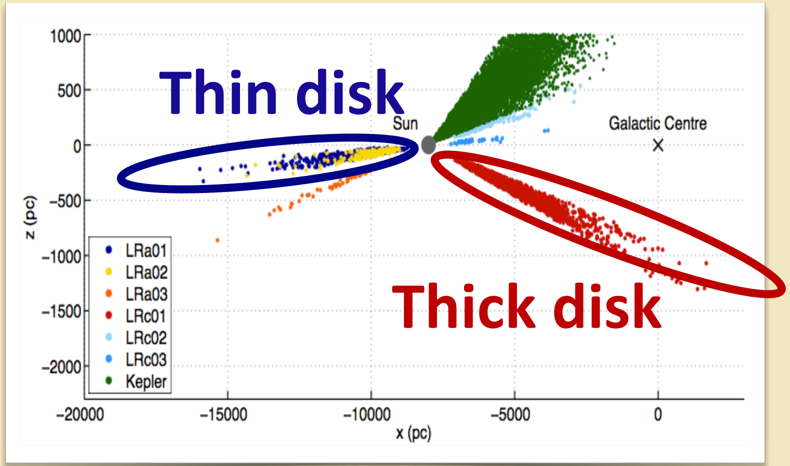
Early results from Kepler and CoRoT

Population synthesis of red giant stars

Radius **Mass** **Age**

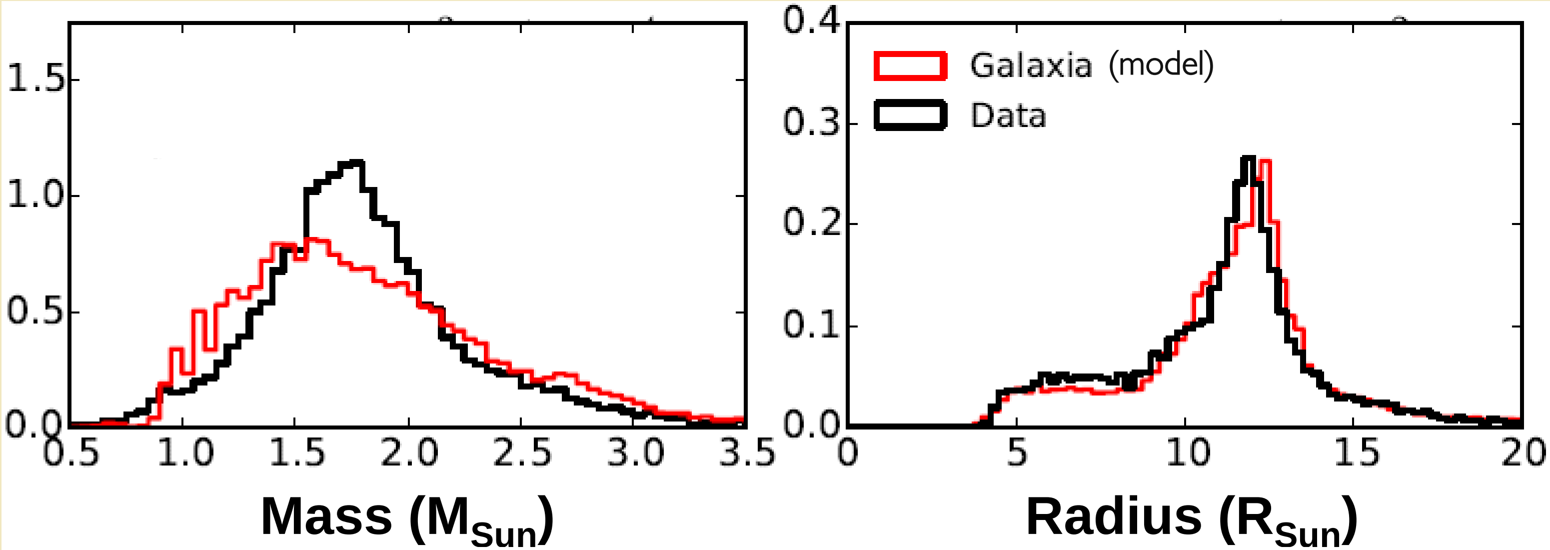


Differential comparison between two fields/populations



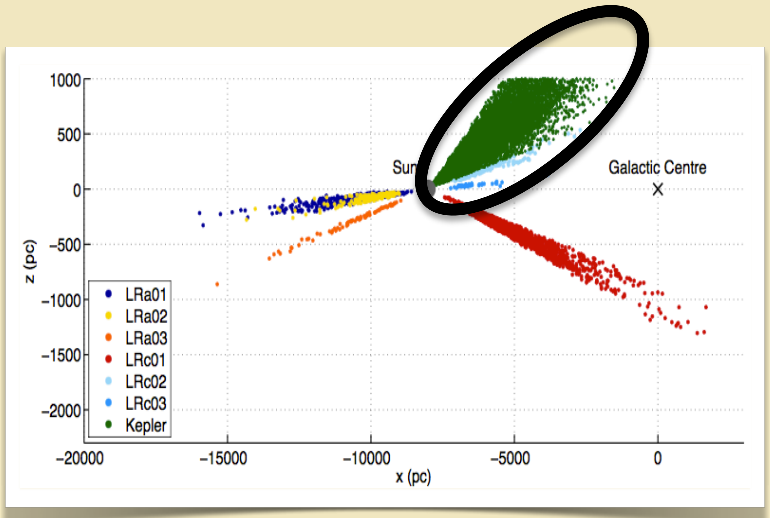
Miglio, Chiappini, Morel et al. 2013

Early results from Kepler and CoRoT

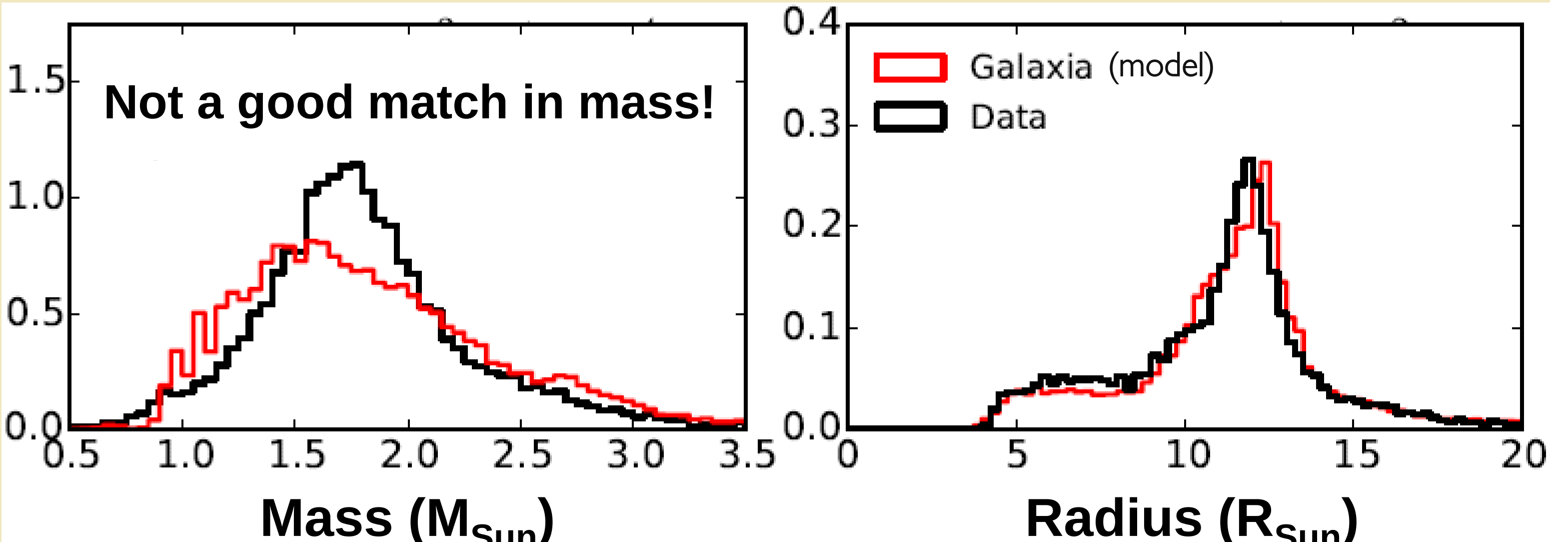


Sharma, Stello, Bland-Hawthorn et al. (2016)

Direct comparison with Galaxy model



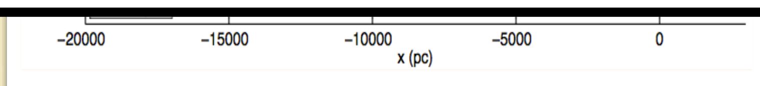
Early results from Kepler and CoRoT



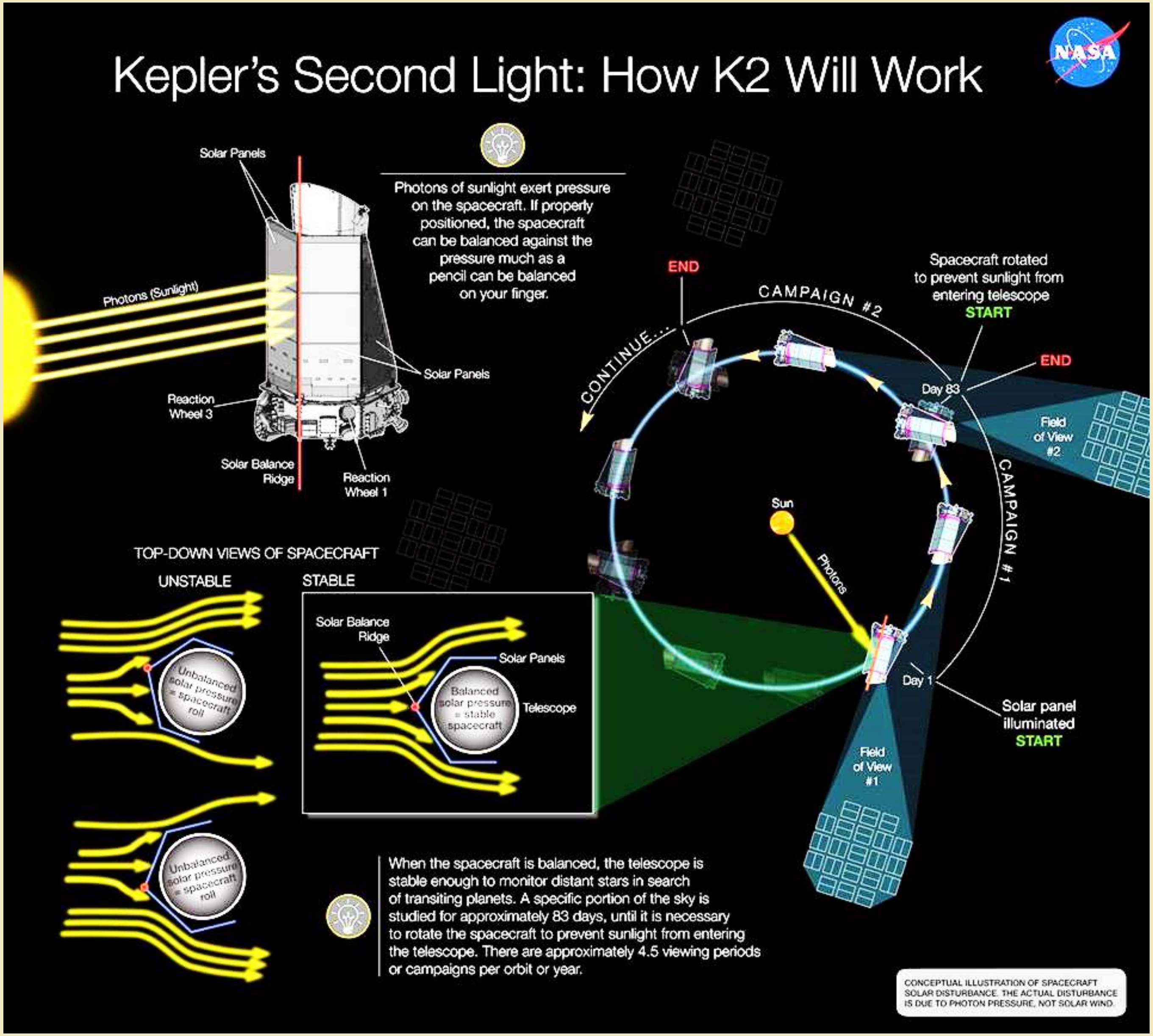
Is this mismatch because of unknown selection effects

OR because our galactic model is inadequate?

Extremely important to understand. Otherwise we can not expect to make useful comparisons!

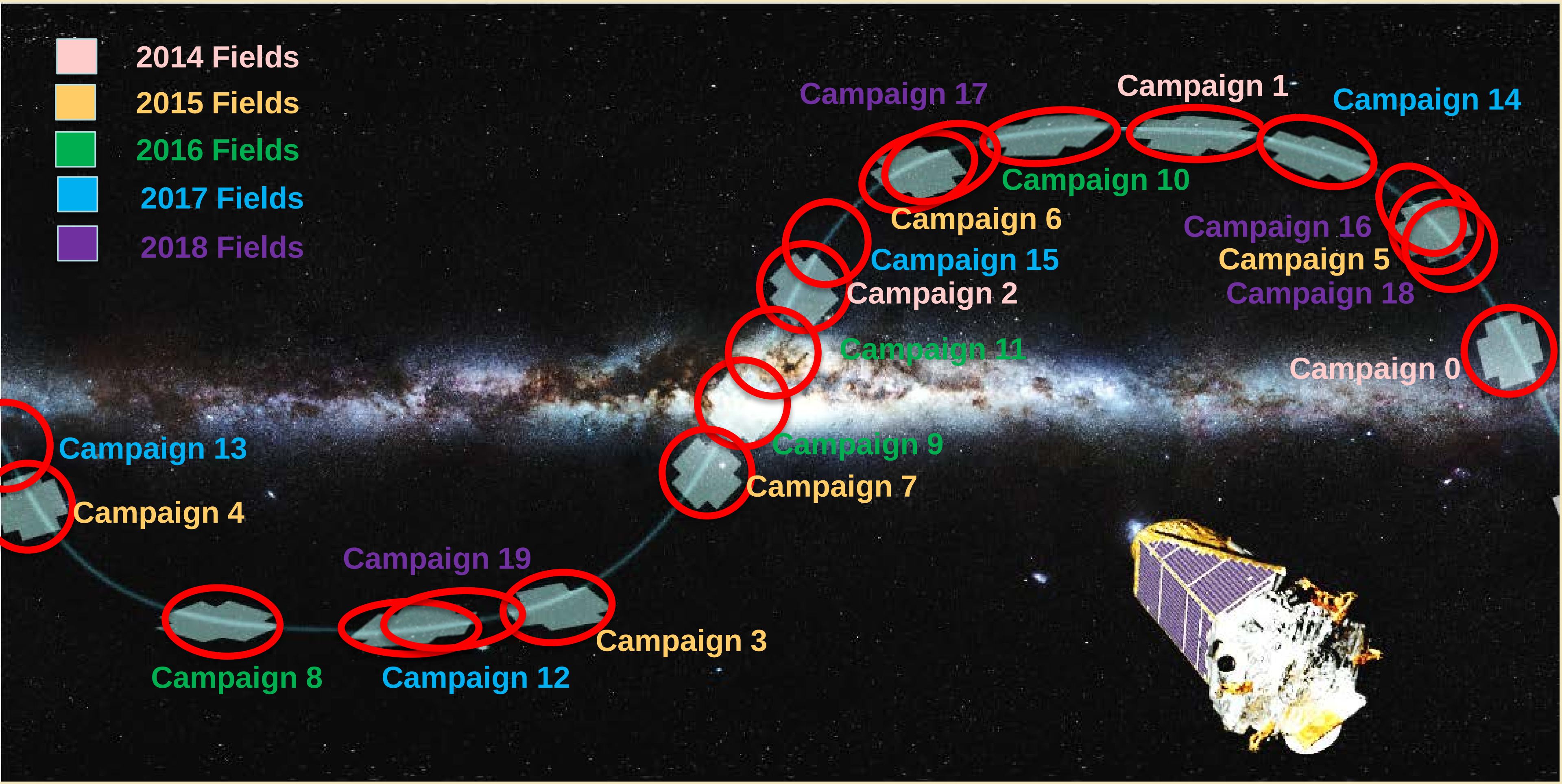


K2: The concept



K2: A new opportunity for Galactic Archaeology

Each campaign field: 10-30K stars observed for ~80 days



The K2 Galactic Archaeology Program (GAP)

The thrust: Use seismology of red giants (K2) combined with T_{eff} and [Fe/H] (ground-based) to probe the structure of the Milky Way

PI: Dennis Stello, CoIs: Derek Buzasi, Ken Freeman, Savita Mathur, Andrea Miglio, Sanjib Sharma, Marc Pinsonneault, Collaborators: Friedrich Anders, Borja Anguiano, Martin Asplund, Sarbani Basu, Paul Beck, Othman Benomar, Maria Bergemann, Joss Bland-Hawthorn, Tiago Campante, Luca Casagrande, Peter De Cat, Márcio Catelan, Bill Chaplin, Cristina Chiappini, Enrico Corsaro, Orlagh Creevey, Eric Depagne, Patrick Eggenberger, Yvonne Elsworth, Jianning Fu, Rafael A. Garcia, Leo Girardi, Jennifer Johnson, Ulrike Heiter, Saskia Hekker, Paola Marigo, Eric Michel, Annie Robin, Maurizio Salaris, Victor Silva Aguirre, Marica Valentini (+ many more)

K2 GAP targets so far

Campaign	$N_{targets}$
0	452
1	8629
2	5138
3	3904
4	6357
5	9828
6	8312
7	4363
8	6185
9	?
10	8947
11	4544
12	14014
13	5974
14	7135
15	7625
16	10672

~30-50% of total K2 capacity

Data download of seismic results:
K2 GAP site: www.physics.usyd.edu.au/k2gap/
MAST: https://archive.stsci.edu/prepds/k2gap/

End of mission (C0-C19): ~30-40k giants with seismic results

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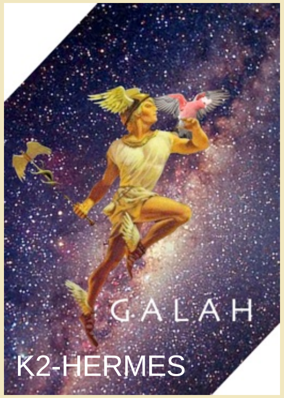
~30-50% of total K2 capacity

Ground-based spectroscopy/photometry (T_{eff}, [Fe/H], Abundances)

APOGEE

RAVE

GaiaESO



LAMOST
(no logo?)

SAGA

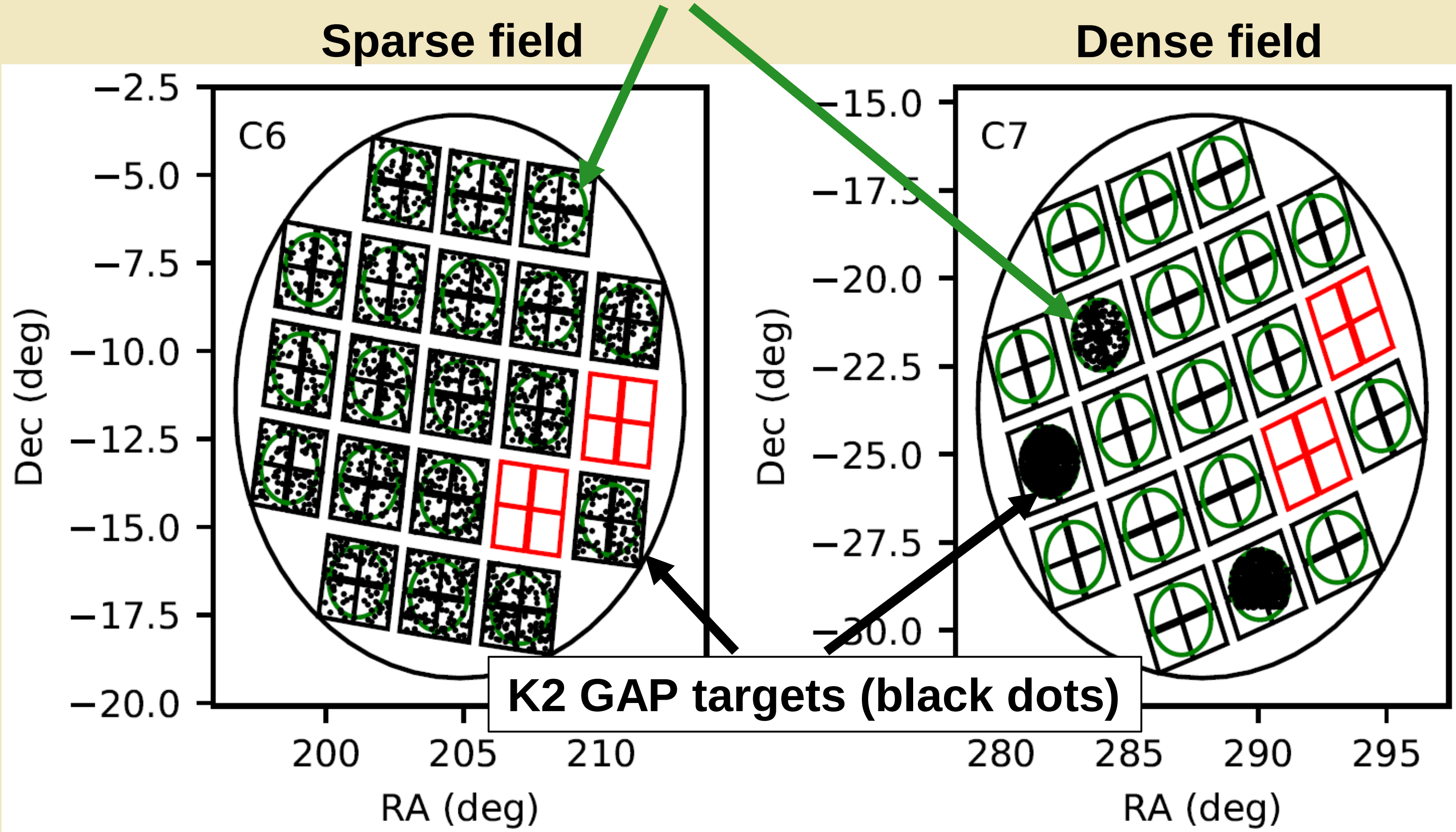
Strömgren survey for Asteroseismology and Galactic Archaeology

End of mission (C0-C19): ~30-40k giants with seismic results

K2-HERMES

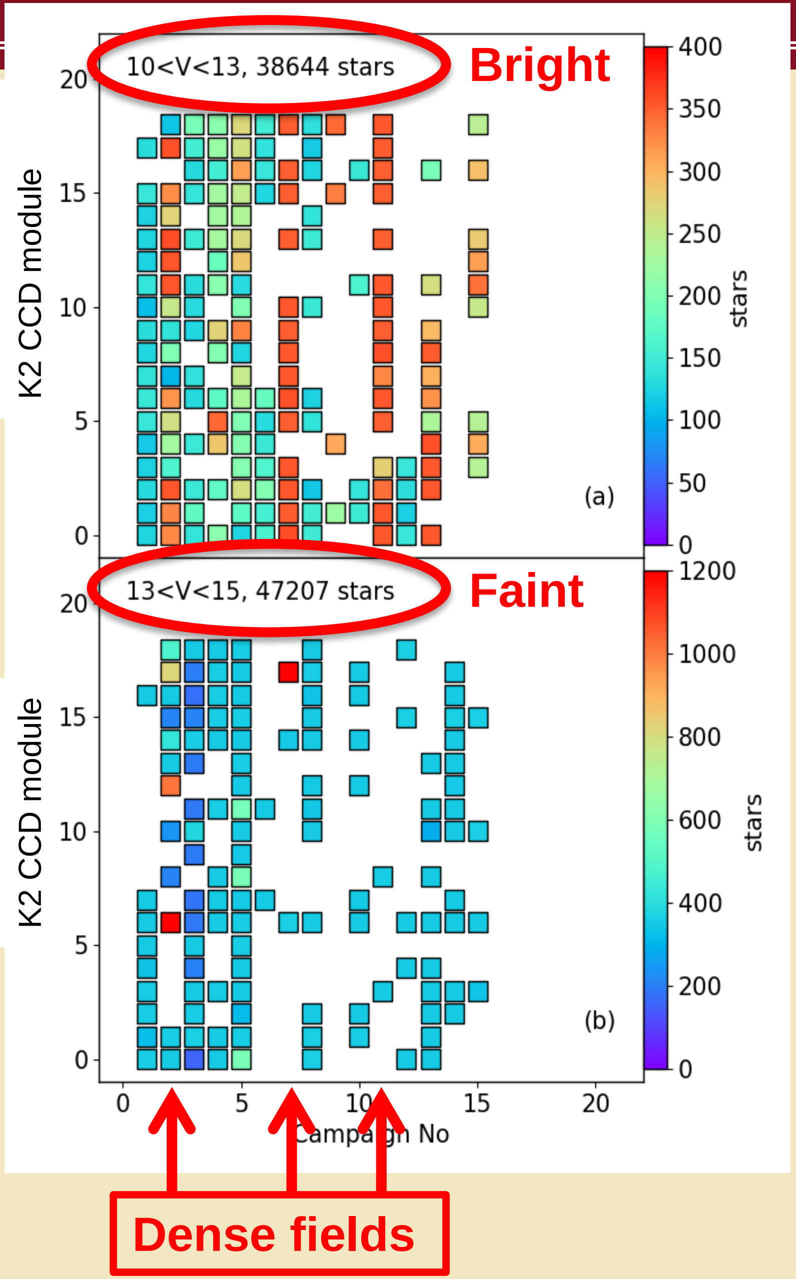
HERMES: A multi-object high-resolution spectrograph on the 4-m AAT (Australia). R=28,000, 350 stars per exposure (2 degree field).

K2-HERMES: Aims to obtain spectra of all stars selected by the `K2 GAP' in the range 9 < V < 15 (within 1 degree of the centres of the K2 CCD modules).



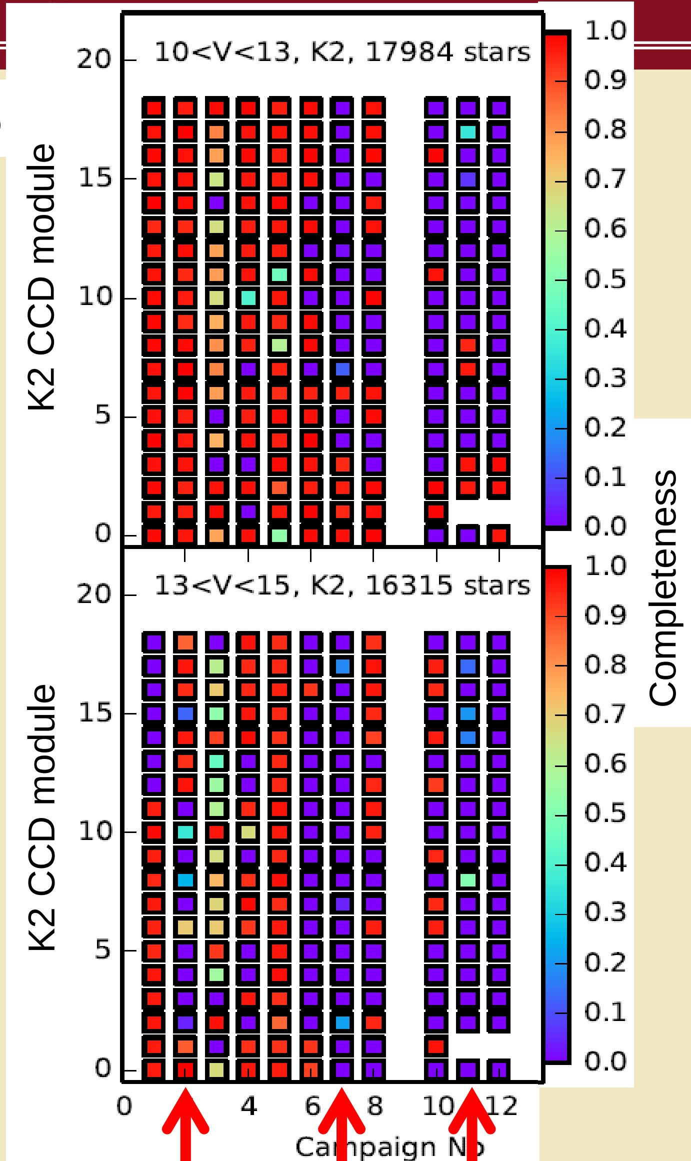
K2-HERMES Status

Jun'17



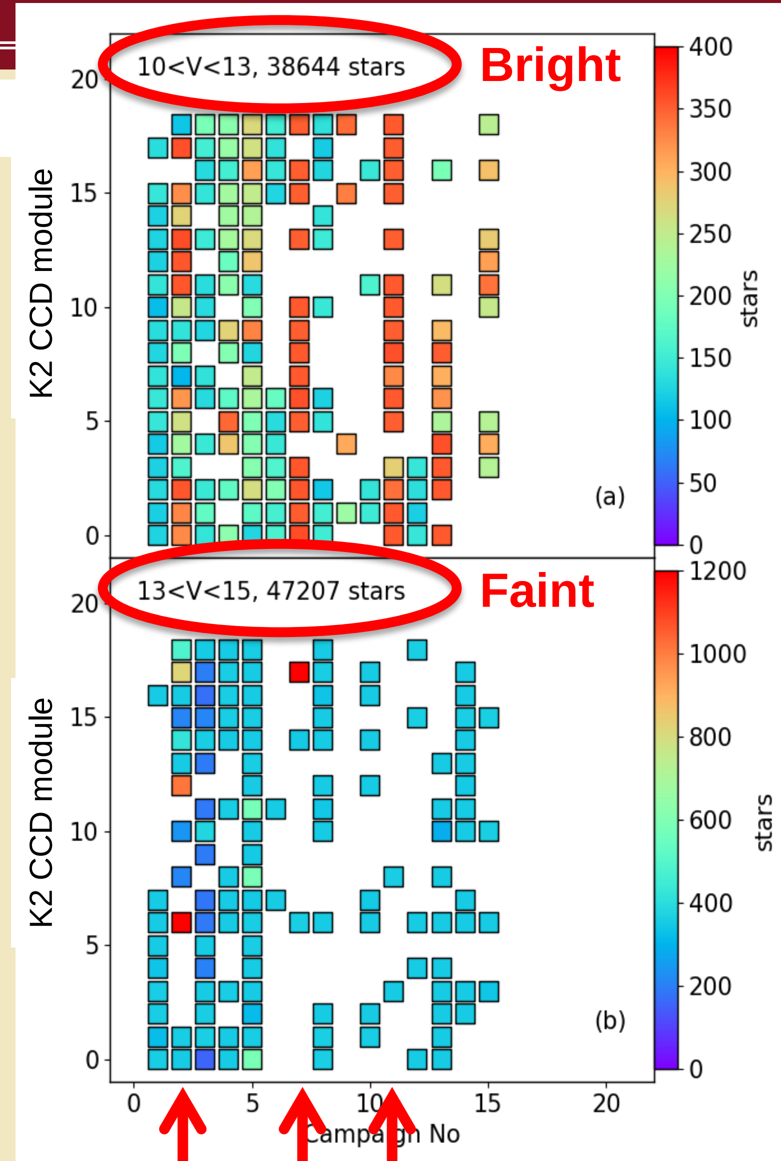
K2-HERMES Status

Dec'16



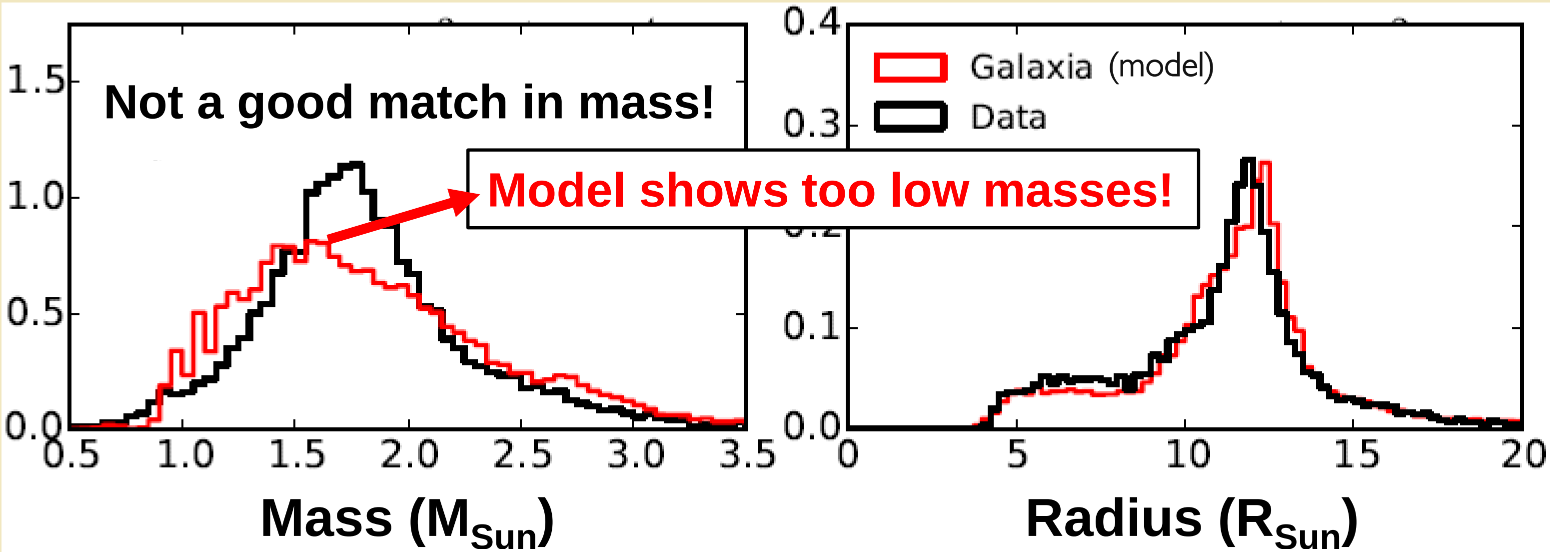
Dense fields

Jun'17



Dense fields

Reminder: What we want to address!



Is this mismatch because of unknown selection effects
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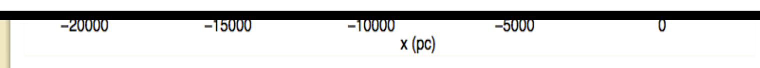
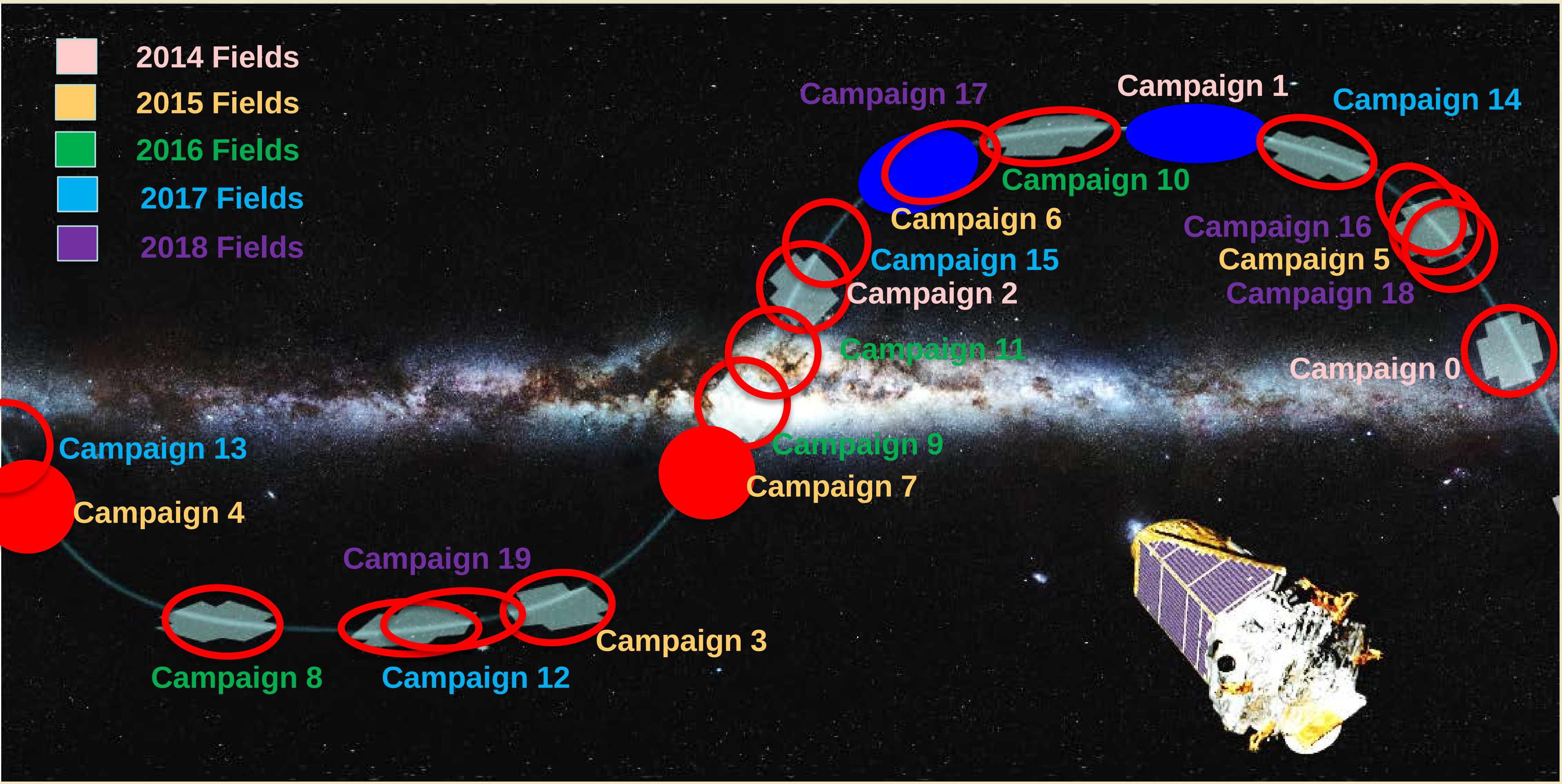
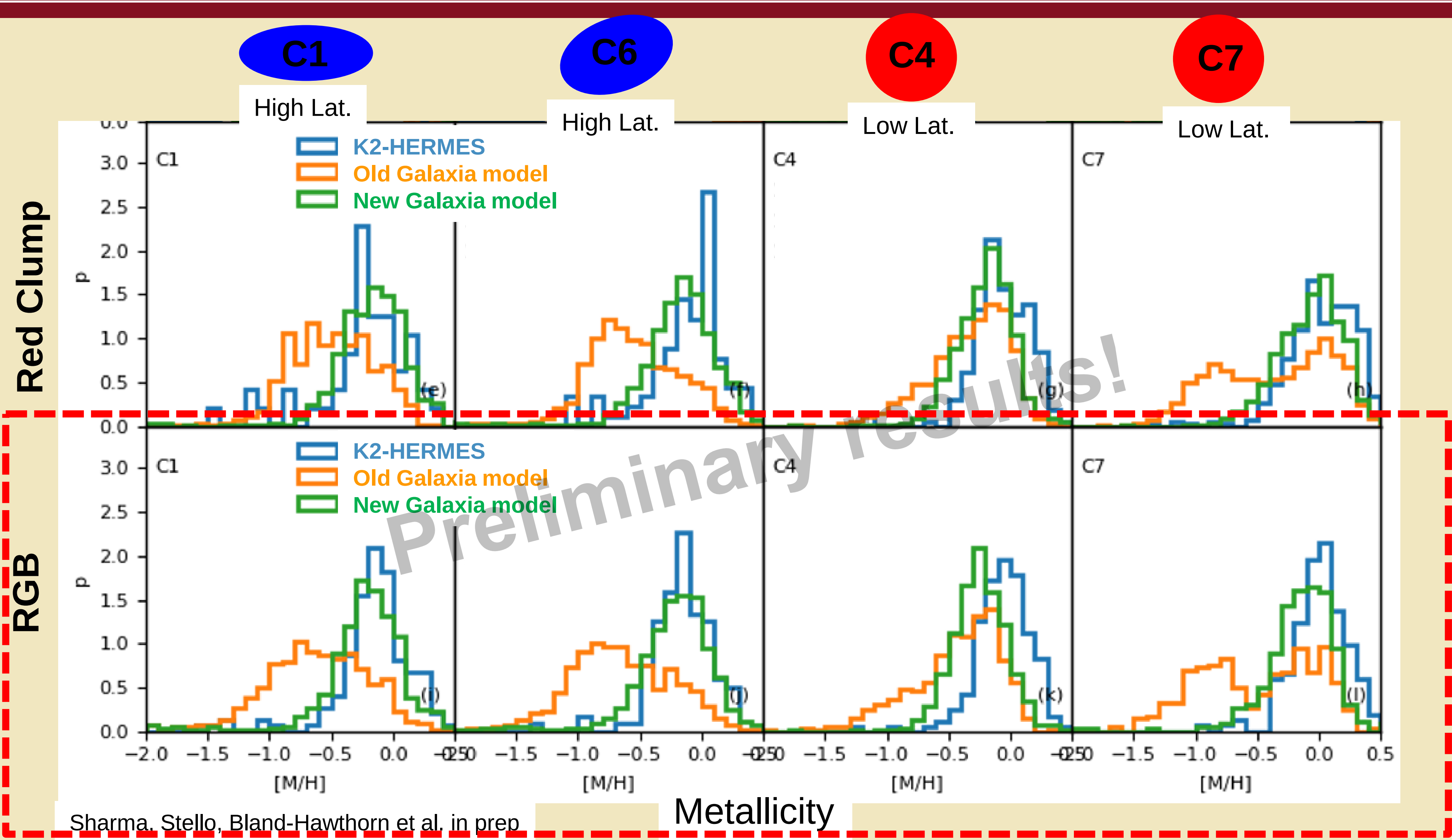


K2-HERMES results!



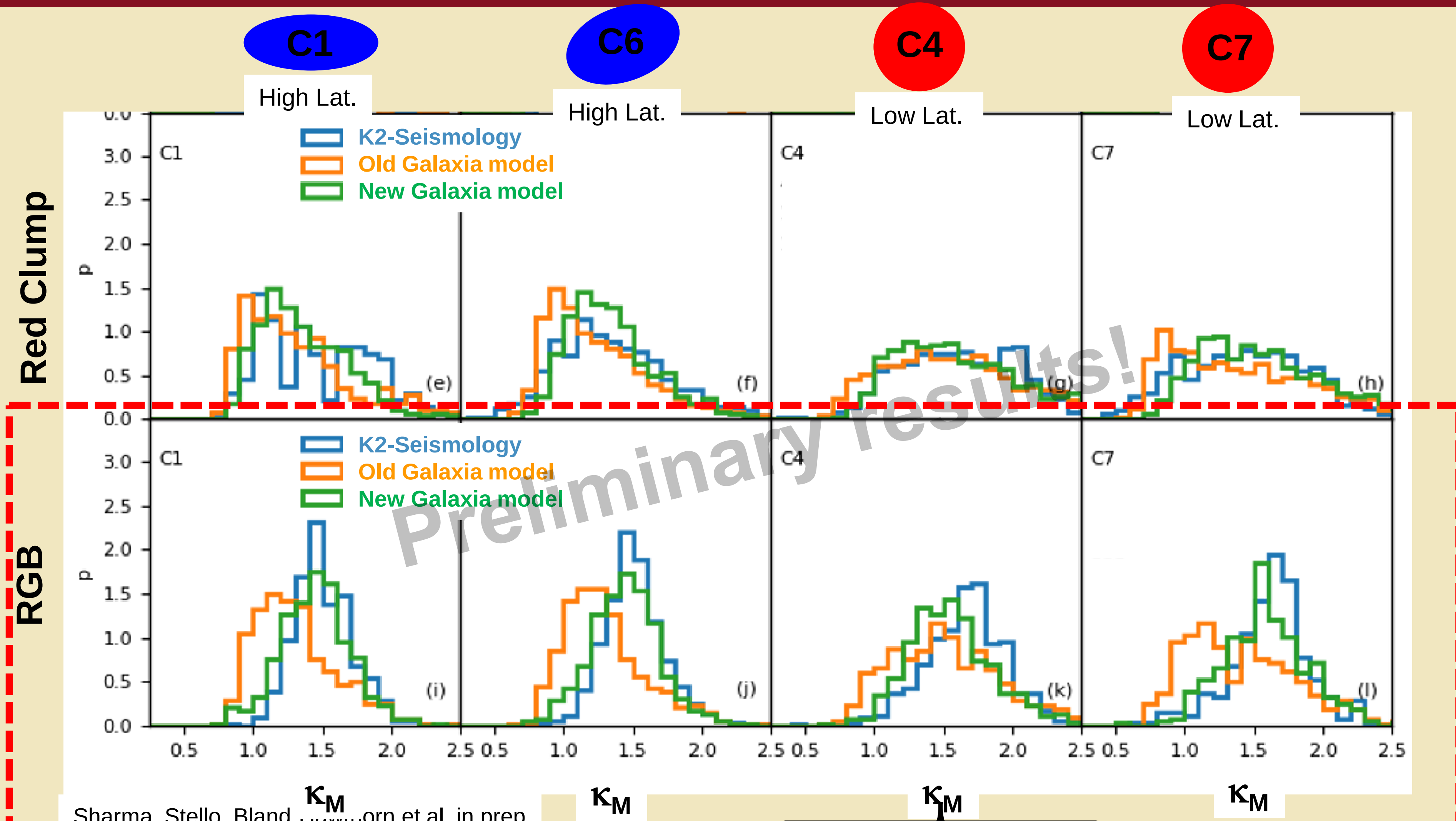
Comparison with Galaxia & K2-HERMES



Sharma, Stello, Bland-Hawthorn et al. in prep

New Galaxia model: Increased thick disk metallicity

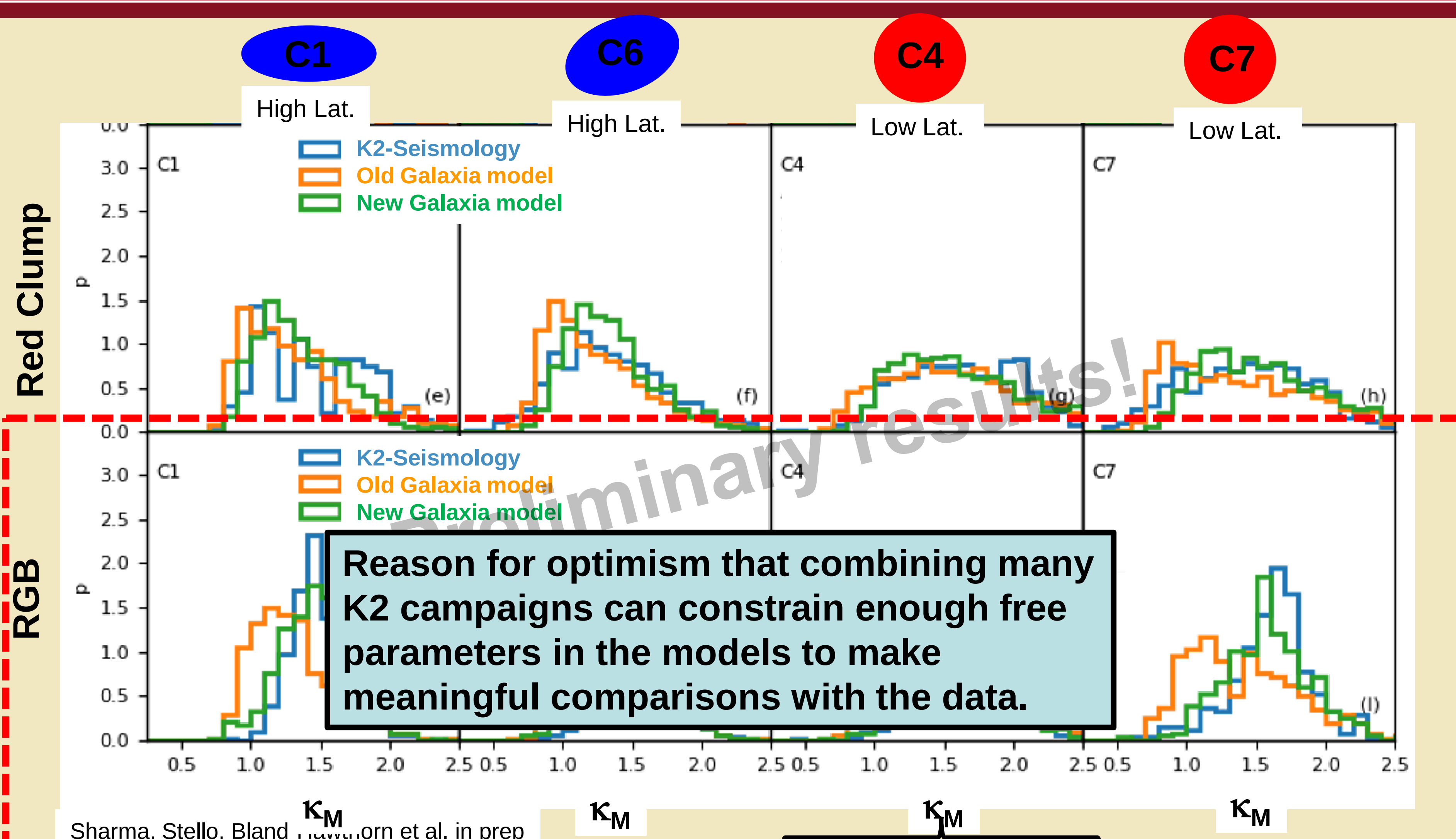
Comparison with Galaxia & K2-HERMES



Sharma, Stello, Bland-Hawthorn et al. in prep

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

Comparison with Galaxia & K2-HERMES

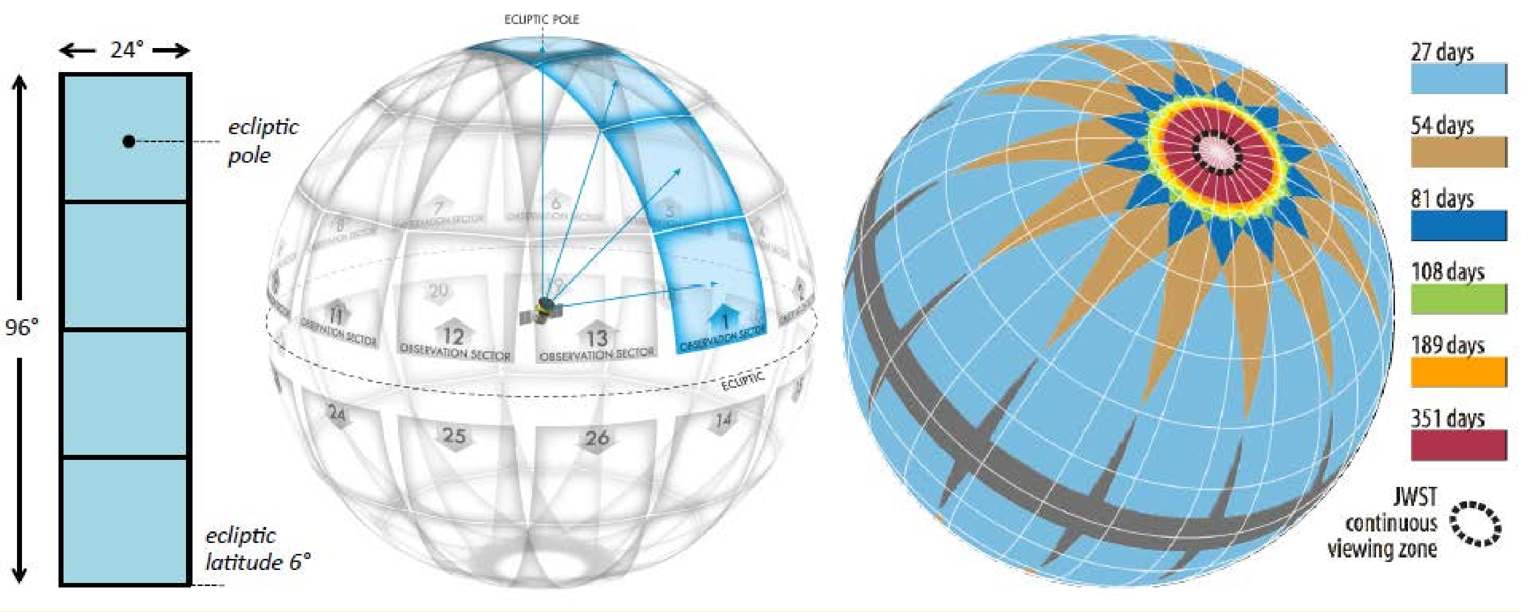


Reason for optimism that combining many K2 campaigns can constrain enough free parameters in the models to make meaningful comparisons with the data.

Sharma, Stello, Bland-Hawthorn et al. in prep

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

TESS: 2018-2020+

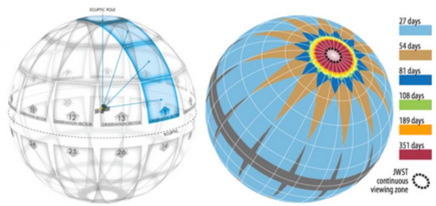


- **Large Area Survey of Bright Stars**
  - F, G, K stars: +4 to +12 magnitude
  - "All sky" observations in 2 years:
    - > 200,000 target stars at <2 min cadence
    - > 20,000,000 stars in full frames at 30 min cadence
    - ~0.5-1.0 mio oscillating red giants

TESS-HERMES Survey

TESS-HERMES site: www.physics.usyd.edu.au/tess-hermes/
MAST: https://archive.stsci.edu/prepds/tess-hermes/

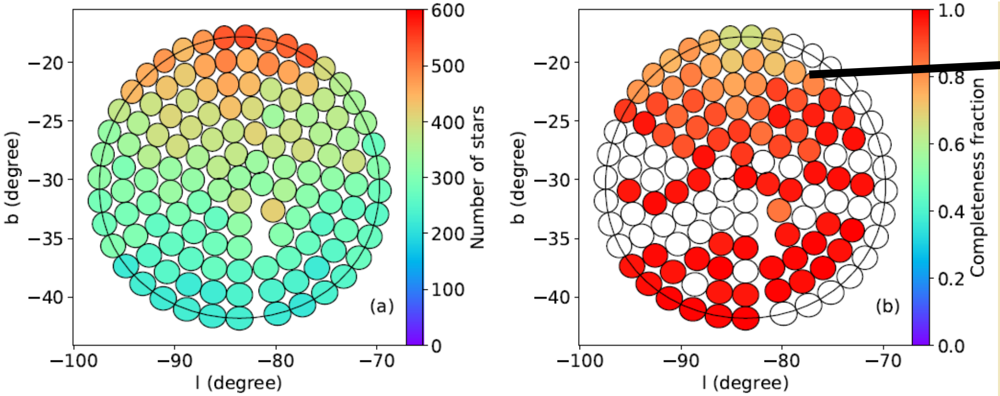
The TESS-HERMES Survey

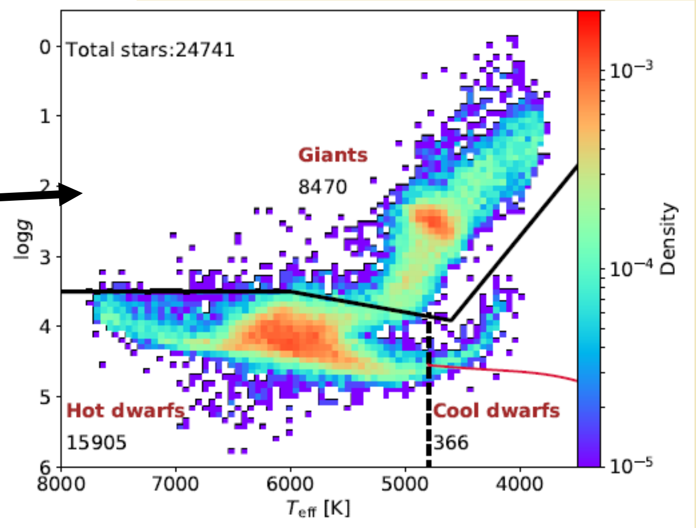


Observes all stars in the TESS continuing viewing zone within $10 < V < 13.1$ using the HERMES spectrograph.

THE TESS-HERMES SURVEY DATA RELEASE 1: HIGH-RESOLUTION SPECTROSCOPY OF THE TESS SOUTHERN CONTINUOUS VIEWING ZONE

SANJIB SHARMA,[1] DENNIS STELLO,[2,3,1] SVEN BUDER,[4,5] JANEZ KOS,[1] JOSS BLAND HAWTHORN,[1] MARTIN ASPLUND,
JANE LIN,[6] KARIN LIND,[4,7] MELISSA NESS,[4] DANIEL HUBER,[8,9,10,11] MARC HON,[2] PRAJWAL R. KAFLE,[12] SHOURYA
HAFIZ SADDON,[2] BORJA ANGUIANO,[13,14] ANDREW R. CASEY,[15] KEN FREEMAN,[6] SARAH MARTELL,[2] GAYANDHI M.
JEFFREY D. SIMPSON,[16] ROB A. WITTENMYER,[17] DANIEL B. ZUCKER,[14,18,16] AND TOMAZ ZWITTER[19]

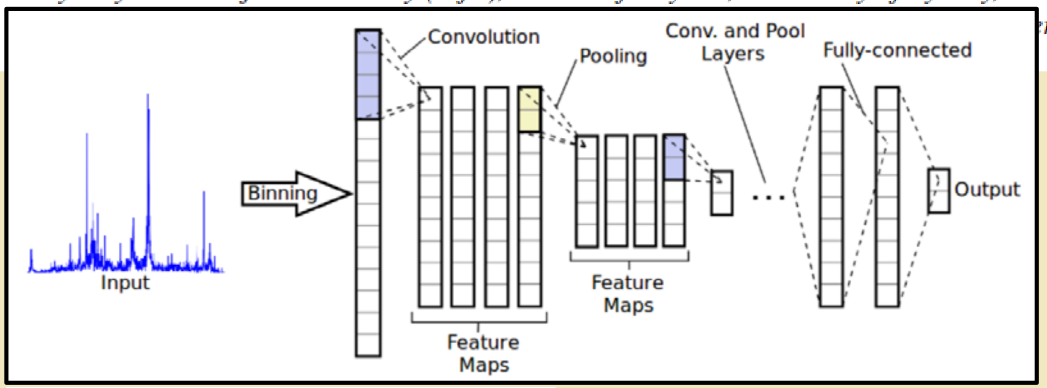


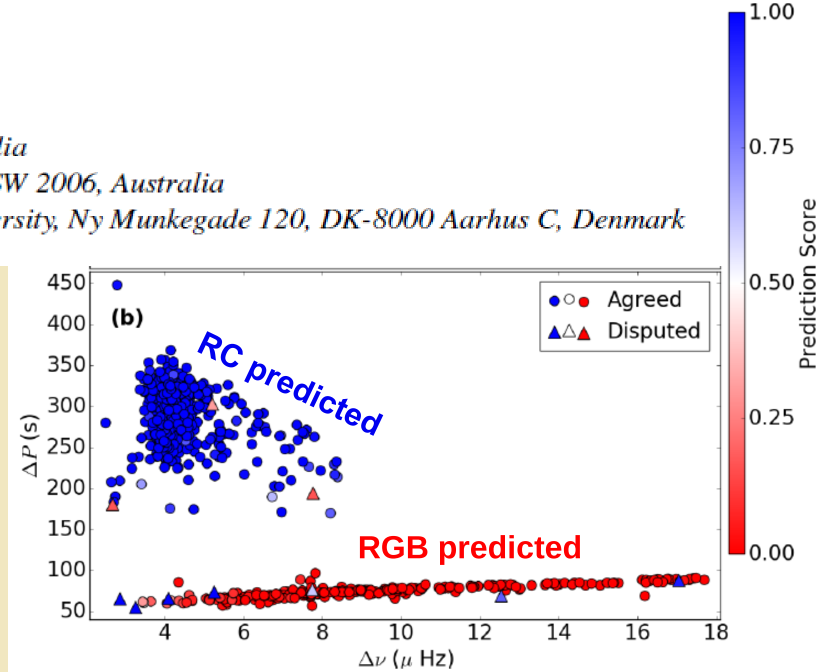


AI-based image recognition

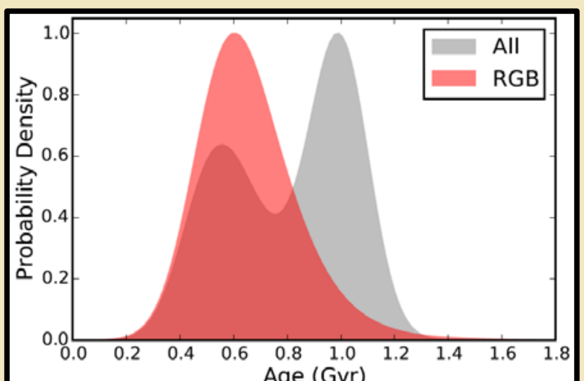
Deep Learning Classification in Asteroseismology

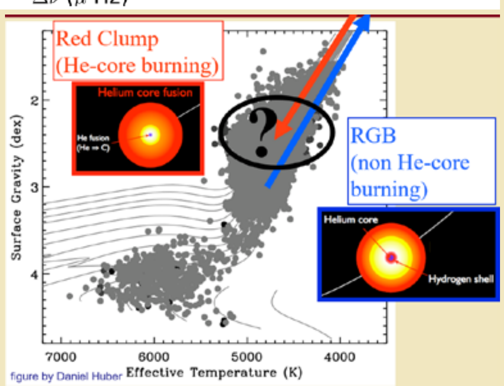
Marc Hon,[1★] Dennis Stello,[1,2,3] and Jie Yu[2]
[1] *School of Physics, The University of New South Wales, Sydney NSW 2052, Australia*
[2] *Sydney Institute for Astronomy (SIfA), School of Physics, University of Sydney, NSW 2006, Australia*
...rsity, Ny Munkegade 120, DK-8000 Aarhus C, Denmark



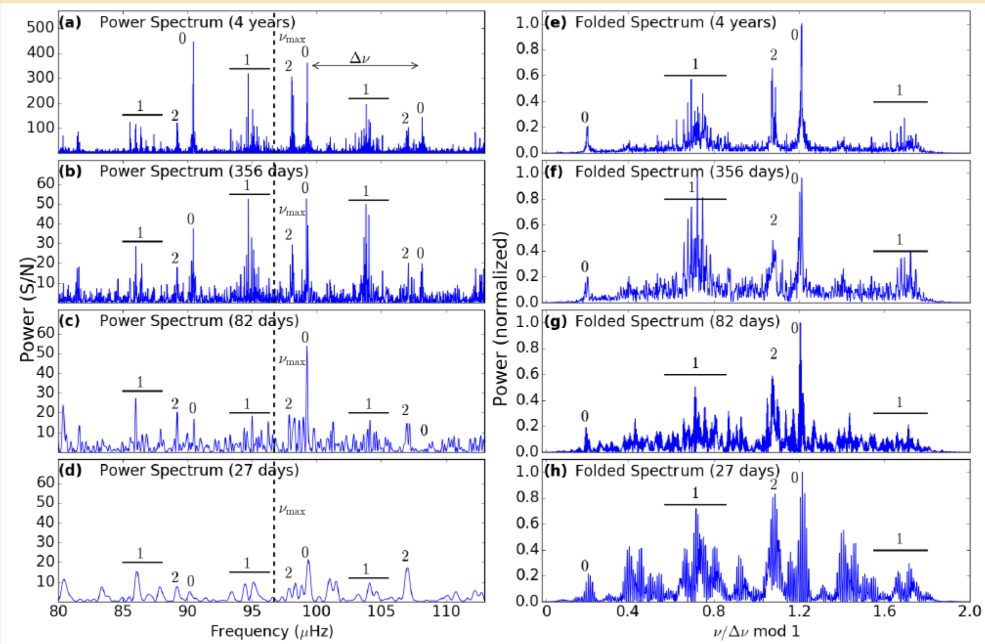


Dataset	CV (±1 std.)	Test
Accuracy	0.982 ± 0.005	0.990
Precision	0.982 ± 0.005	0.990
Recall	0.982 ± 0.005	0.991
F1 Score	0.982 ± 0.005	0.991
ROC AUC	0.998 ±0.002	0.996
Log Loss	0.055 ±0.020	0.044





AI-based classification on K2/TESS



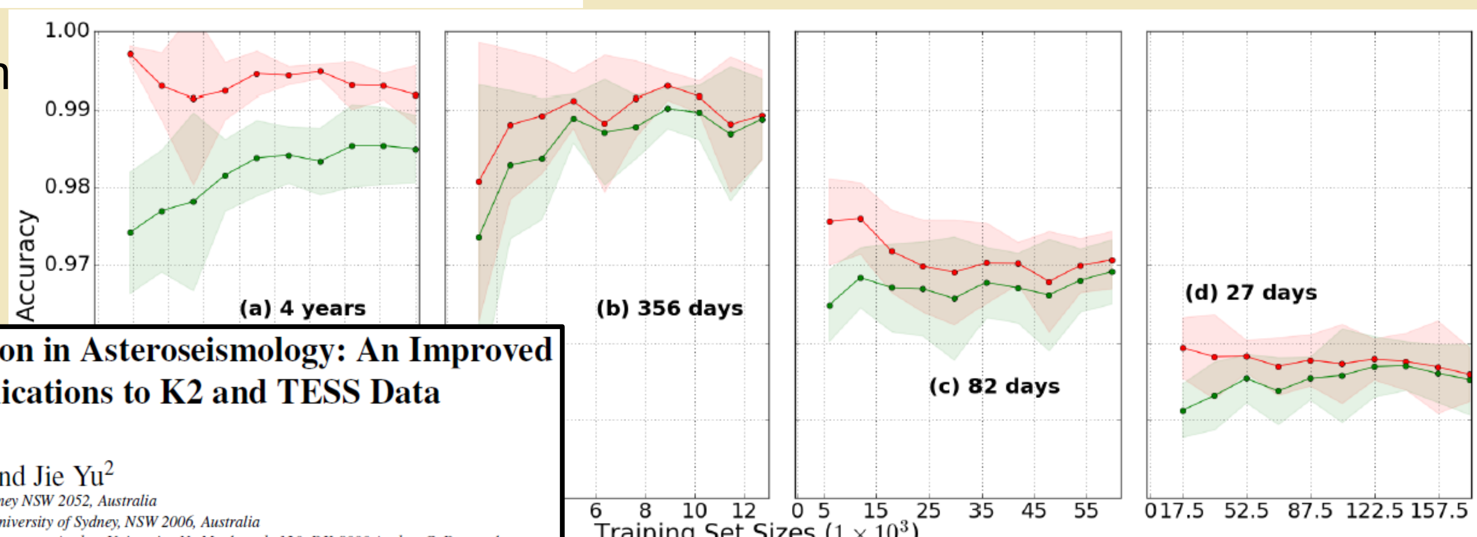
Kepler (4yr)

TESS (1yr, best)

K2/TESS (82days)

TESS (27days, worst)

Changing length of time series



In prep

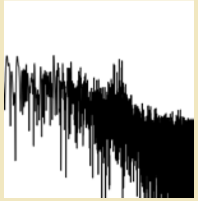
Deep Learning Classification in Asteroseismology: An Improved Neural Network, and Applications to K2 and TESS Data

Marc Hon,[1★] Dennis Stello,[1,2,3] and Jie Yu[2]

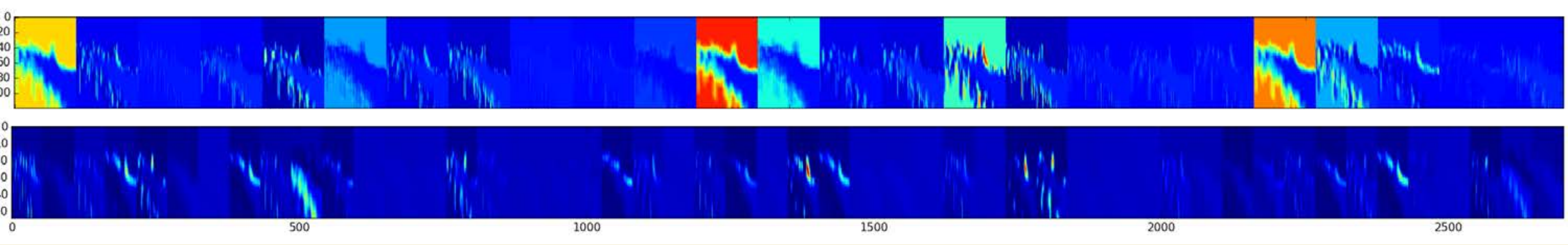
[1] School of Physics, The University of New South Wales, Sydney NSW 2052, Australia
[2] Sydney Institute for Astronomy (SIfA), School of Physics, University of Sydney, NSW 2006, Australia
[3] Stellar Astrophysics Centre, Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK-8000 Aarhus C, Denmark

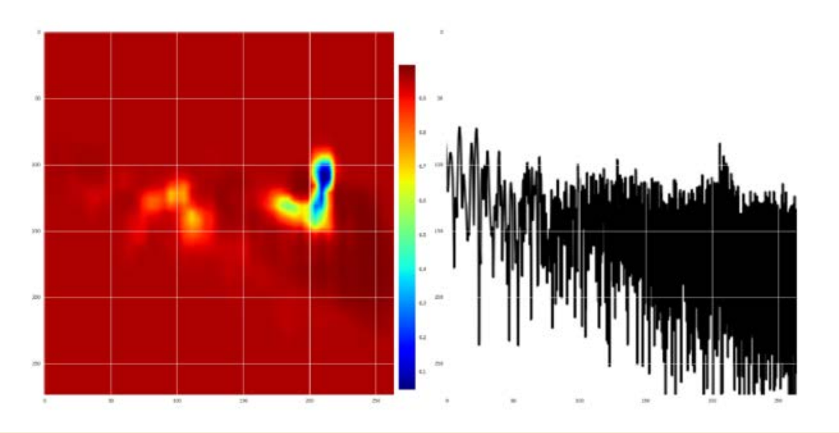
Next up: Detection or not?

Input 2D image



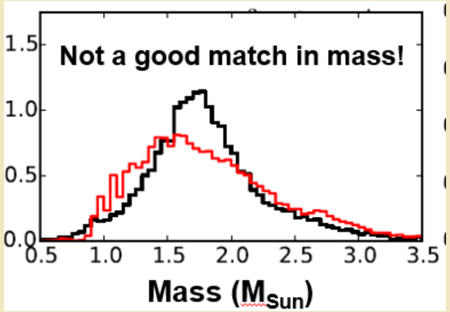
Activation layers





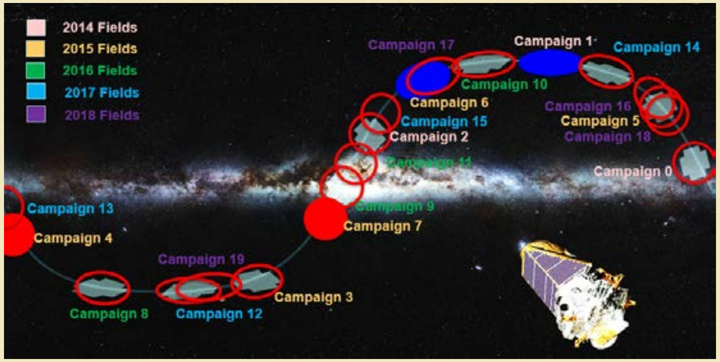
Summary

Kepler



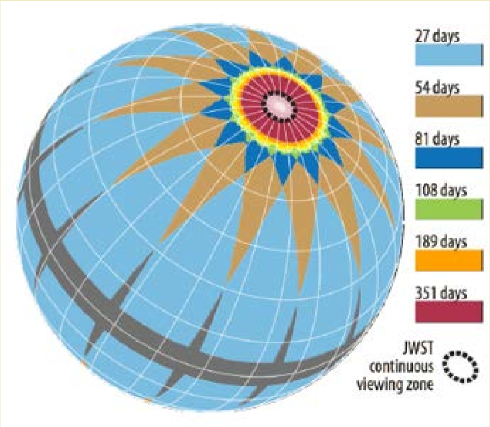
Can we make meaningful comparisons between data and Galaxy models?

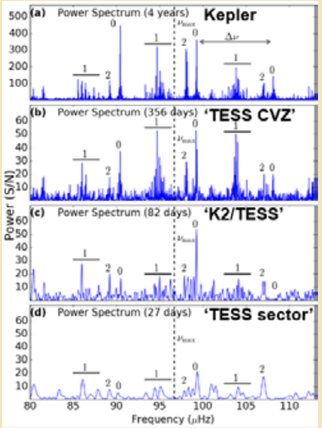
K2



It seems K2/Galah can show a path towards meaningful comparisons.

TESS





RGB/RC classifications works on TESS data; an important step for obtaining precise masses and ages!

A gala(h) of results expected from asteroseismic Galactic archaeology