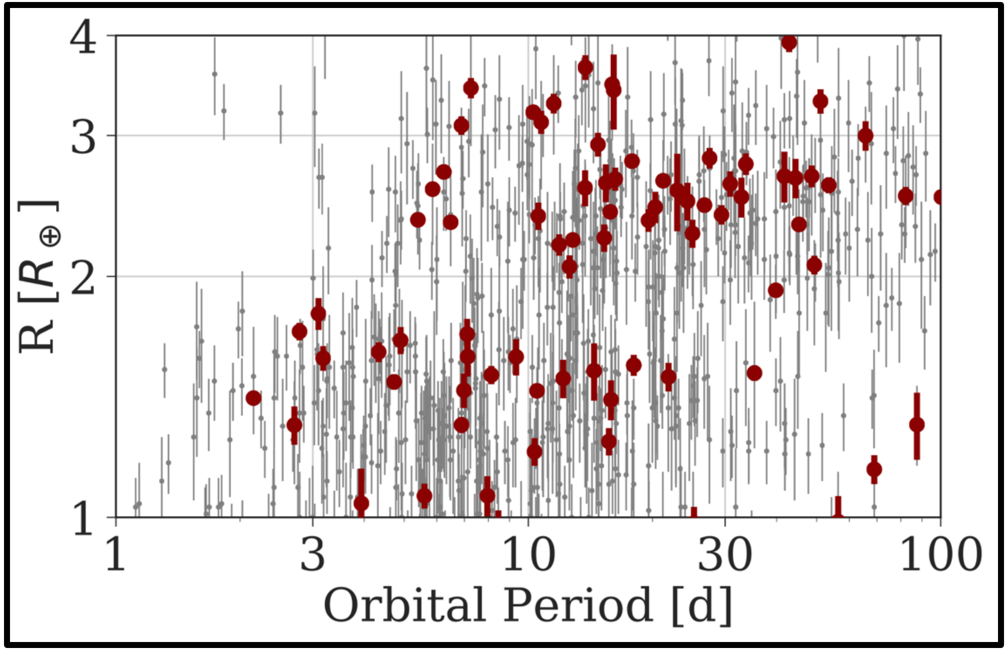
Should We Trust the Asteroseismic Scaling Relations?

Tim Bedding (Univ. Sydney)

The radius valley

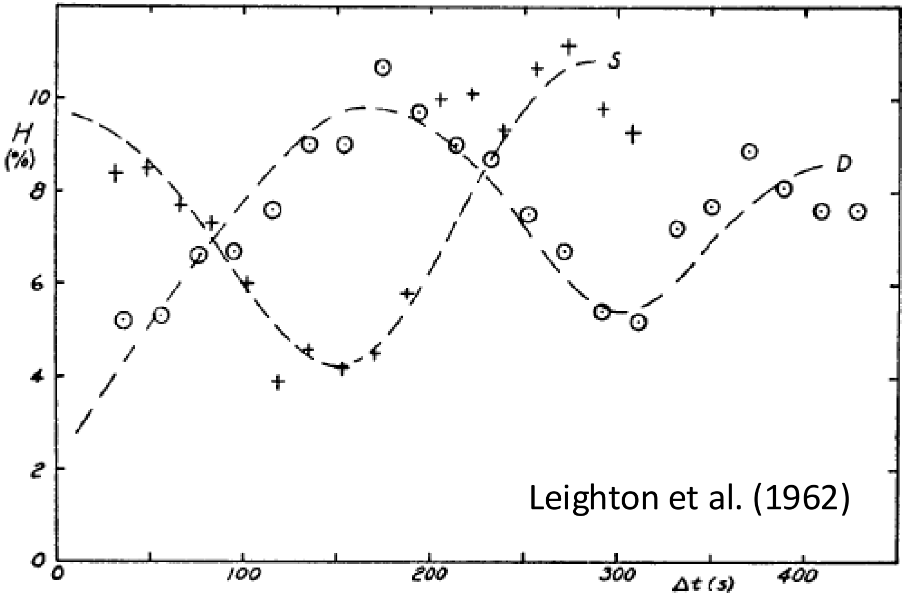


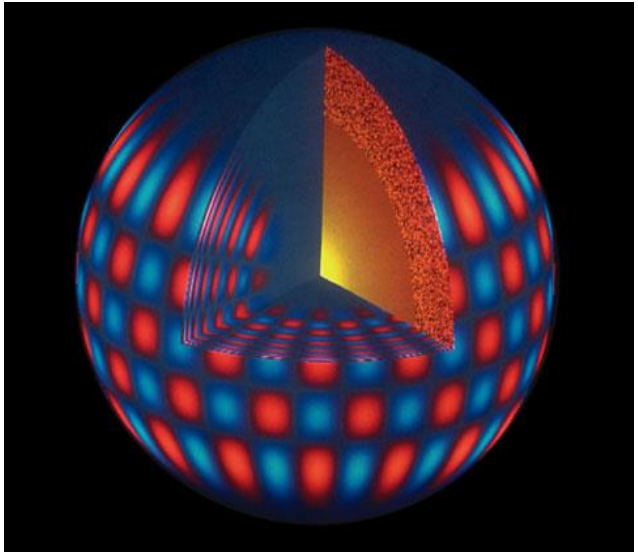
Van Eylen et al. (2017)

The discovery of 5-minute oscillations in the Sun

VELOCITY FIELDS IN THE SOLAR ATMOSPHERE
I. PRELIMINARY REPORT*

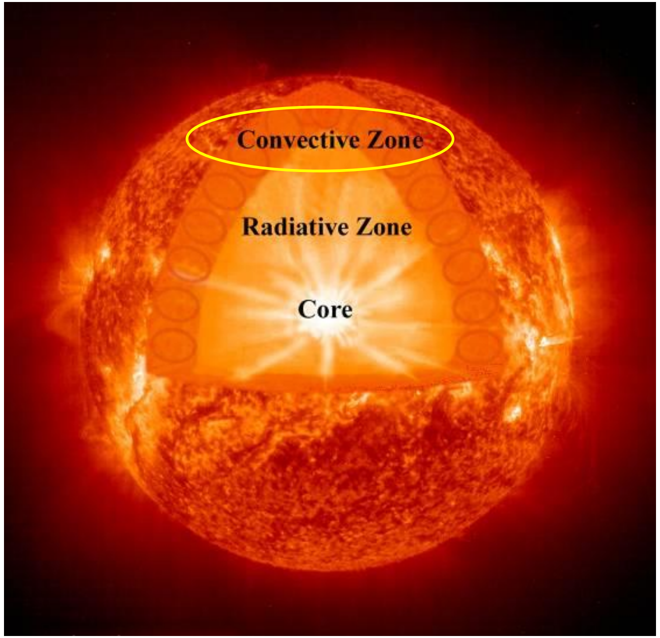
ROBERT B. LEIGHTON, ROBERT W. NOYES, AND GEORGE W. SIMON
California Institute of Technology, Pasadena, California



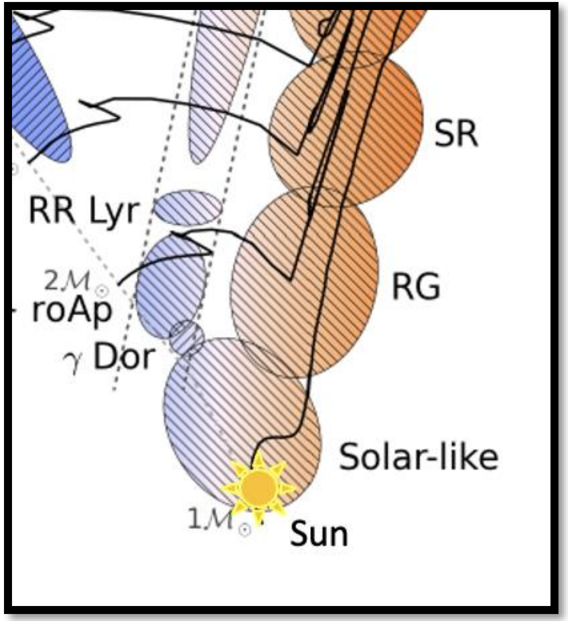


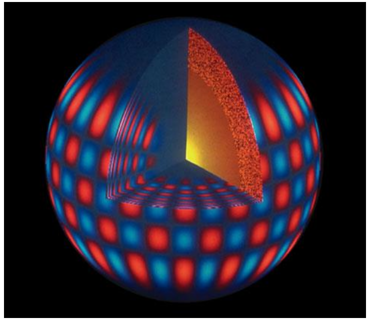
a high-degree mode (ℓ=20)

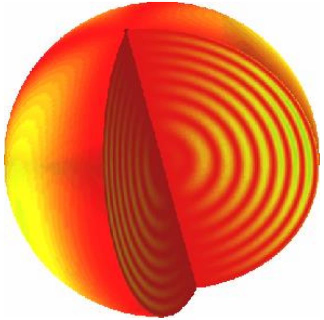
What drives solar-like oscillations?



Convection excites many standing sound waves (stochastic process)



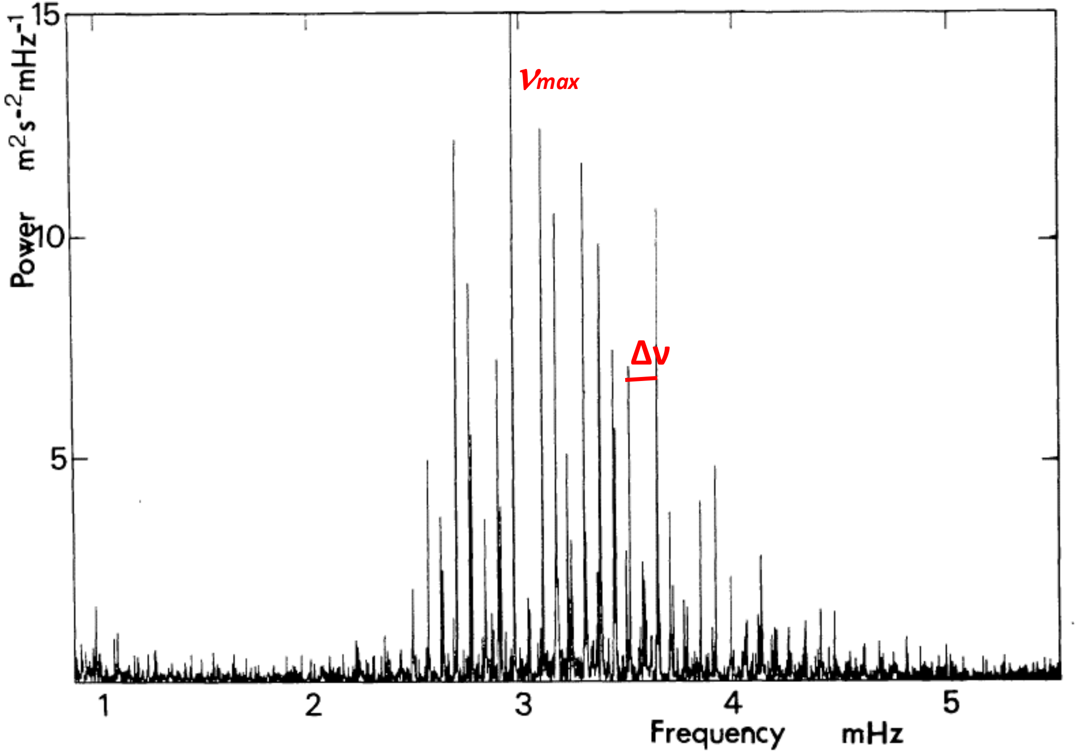


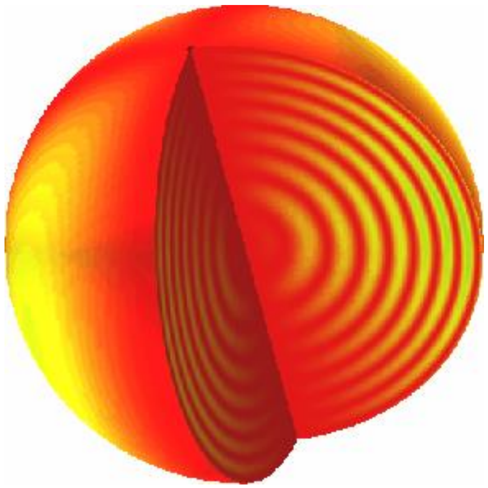


Sun-as-a-star helioseismology

FULL-DISK OBSERVATIONS OF SOLAR OSCILLATIONS FROM THE GEOGRAPHIC SOUTH POLE: LATEST RESULTS*

Grec et al. (1983)



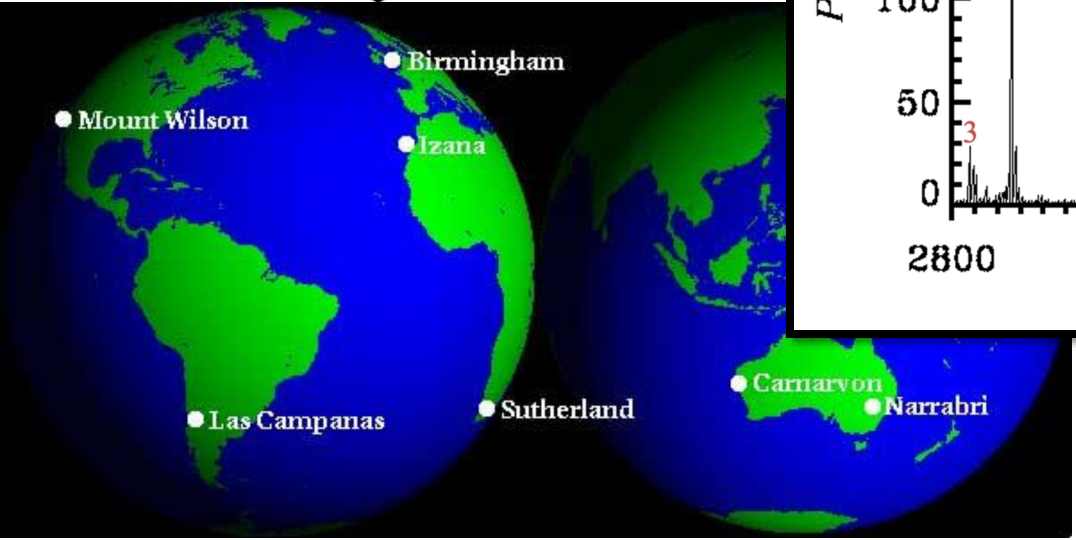


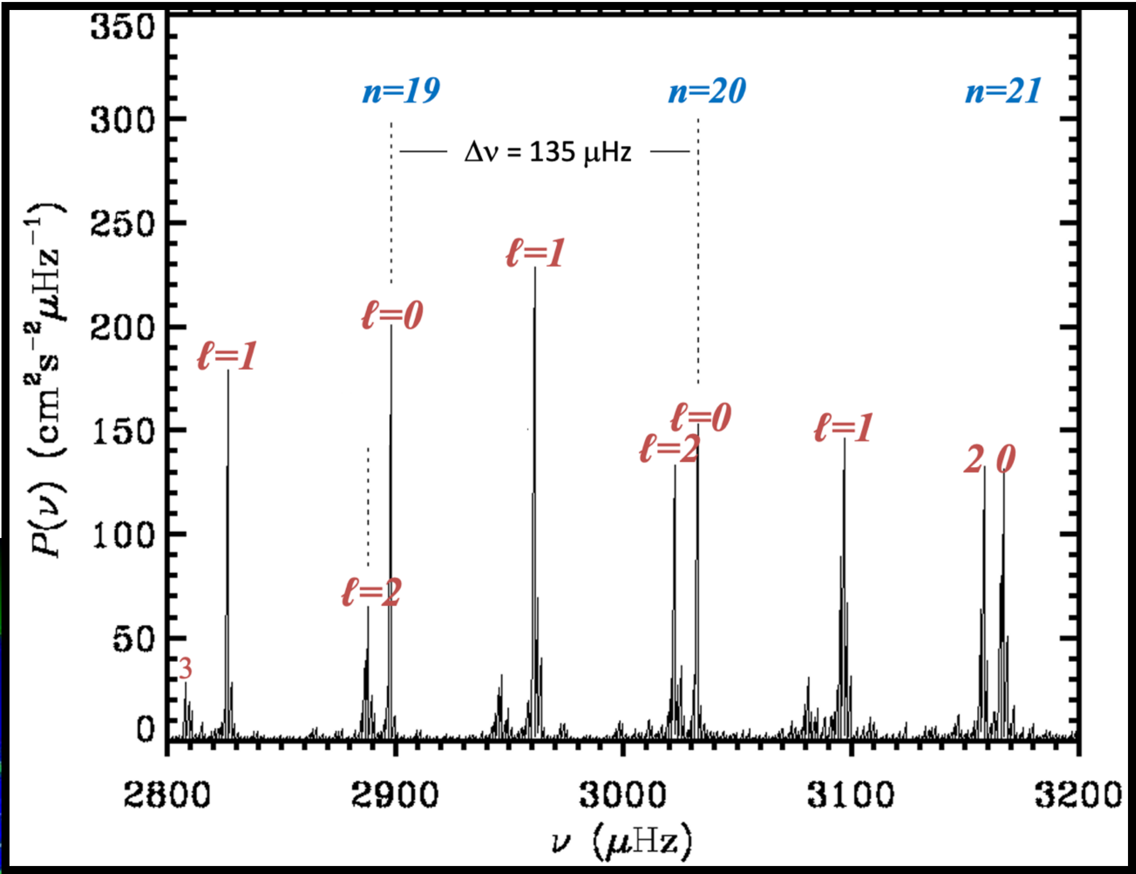
a low-degree mode (ℓ=2)

The Sun

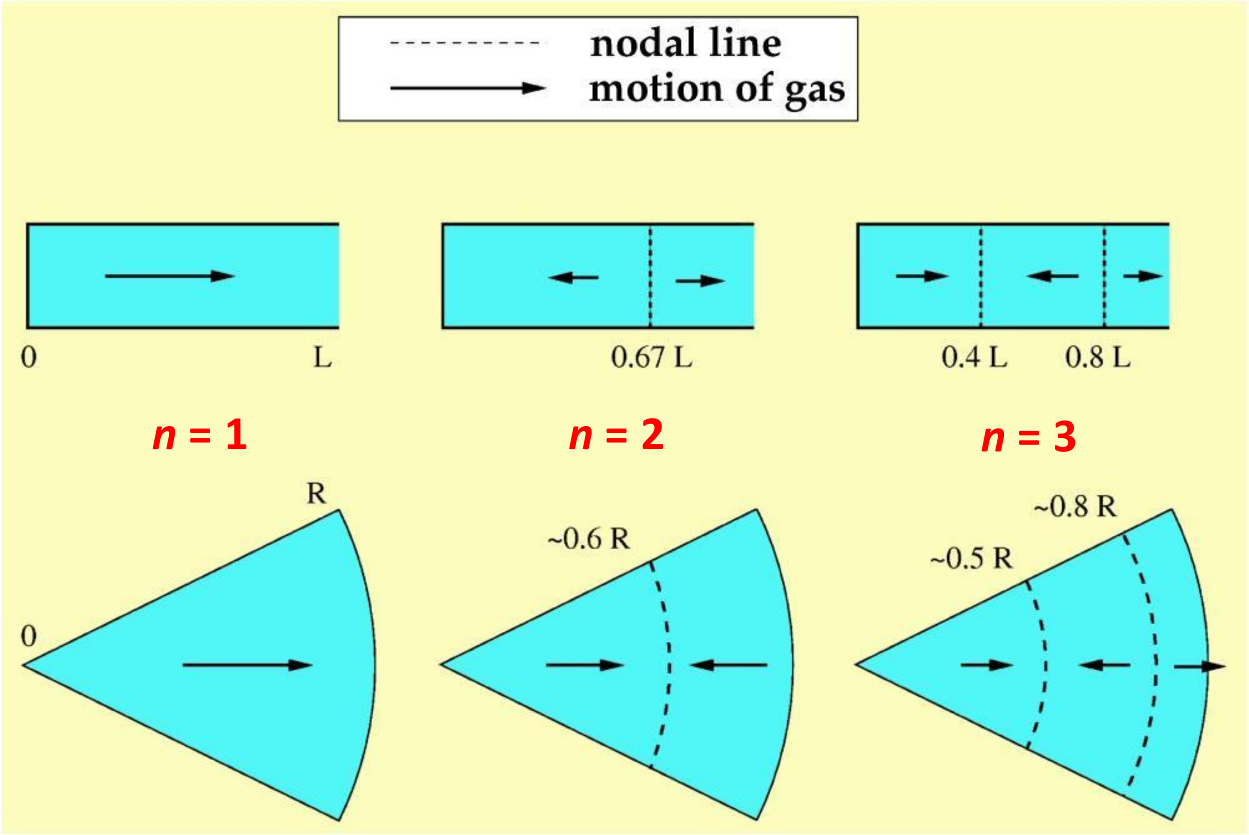
Birmingham Solar Oscillations Network
BiSON

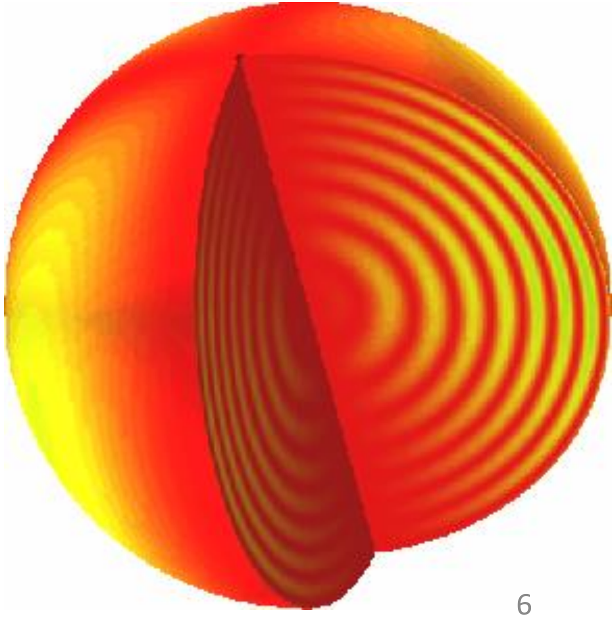
UNIVERSITY OF BIRMINGHAM



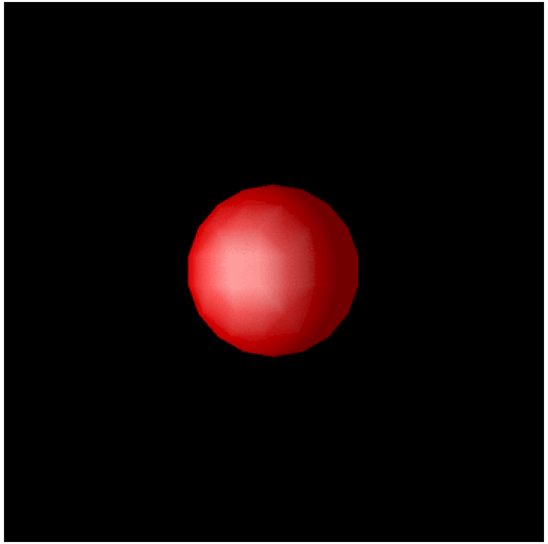


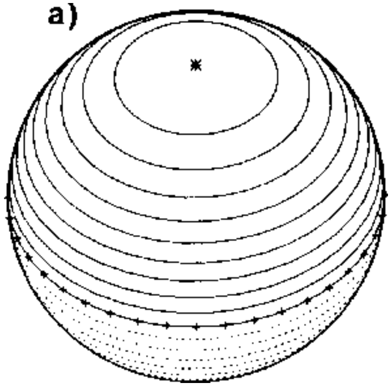
p-mode oscillations are standing sound waves

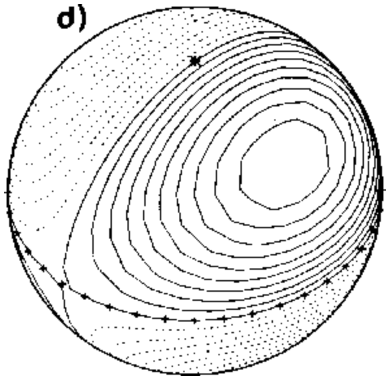




n is the *radial order* of the overtone ℓ =0 (radial modes)

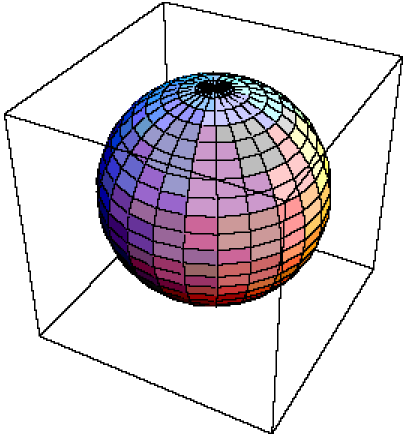


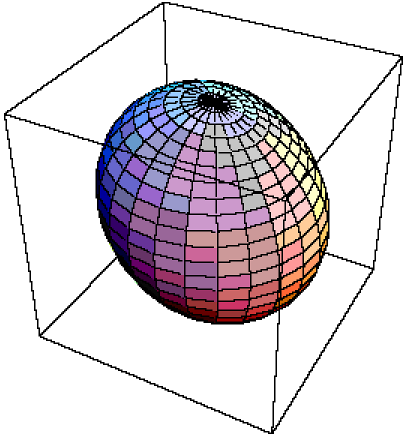




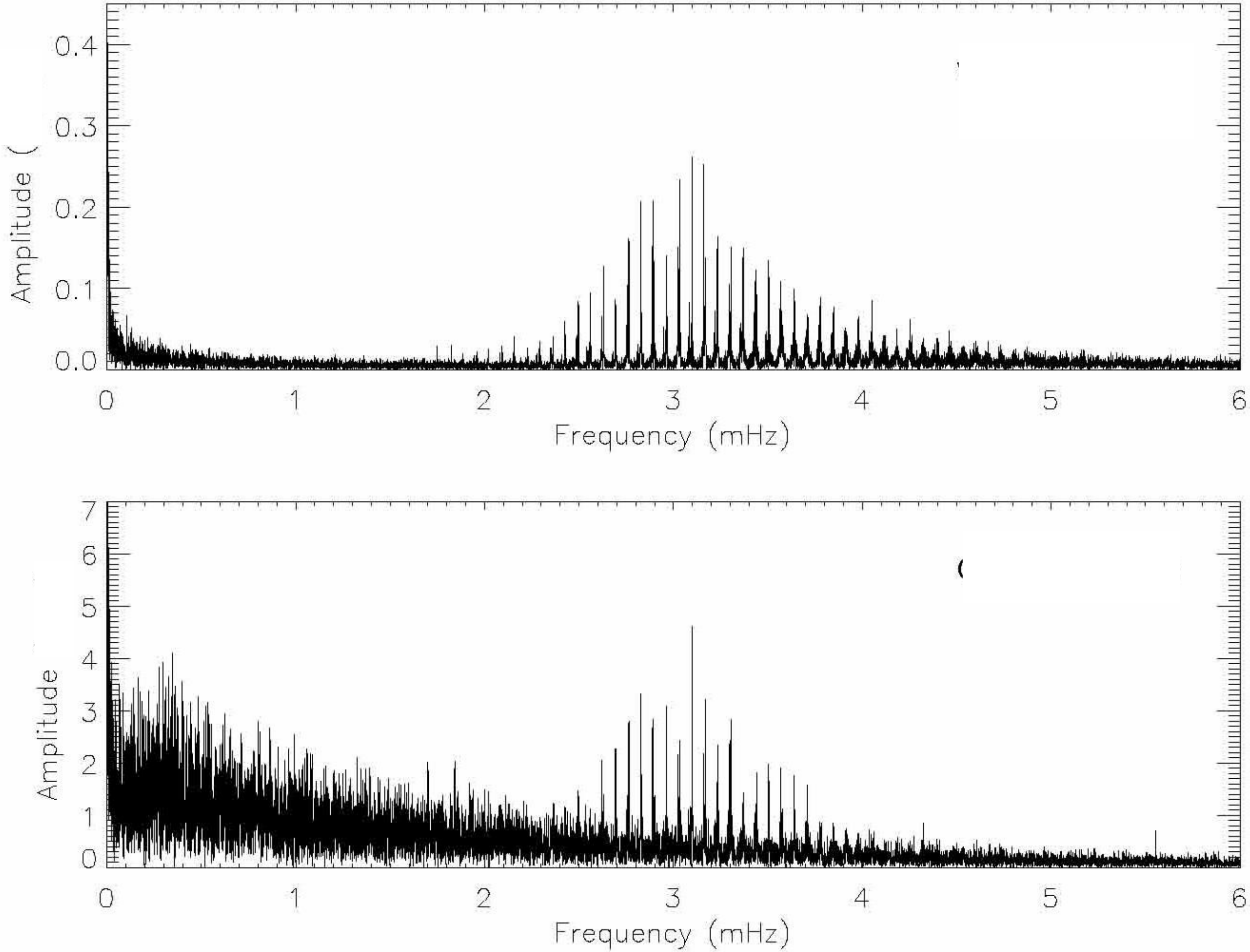
ℓ=1

ℓ= 2

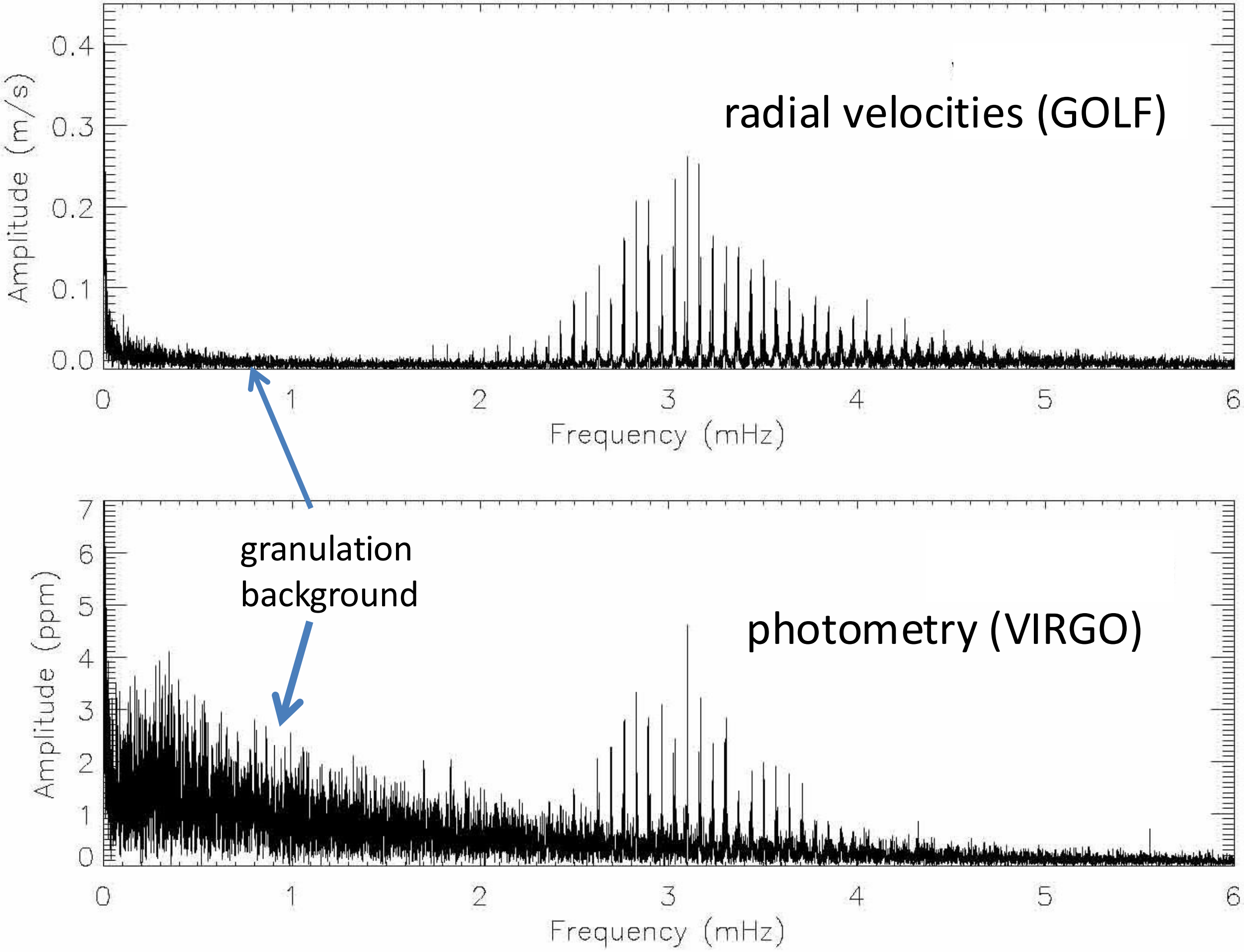




Sun (20 days with SOHO)



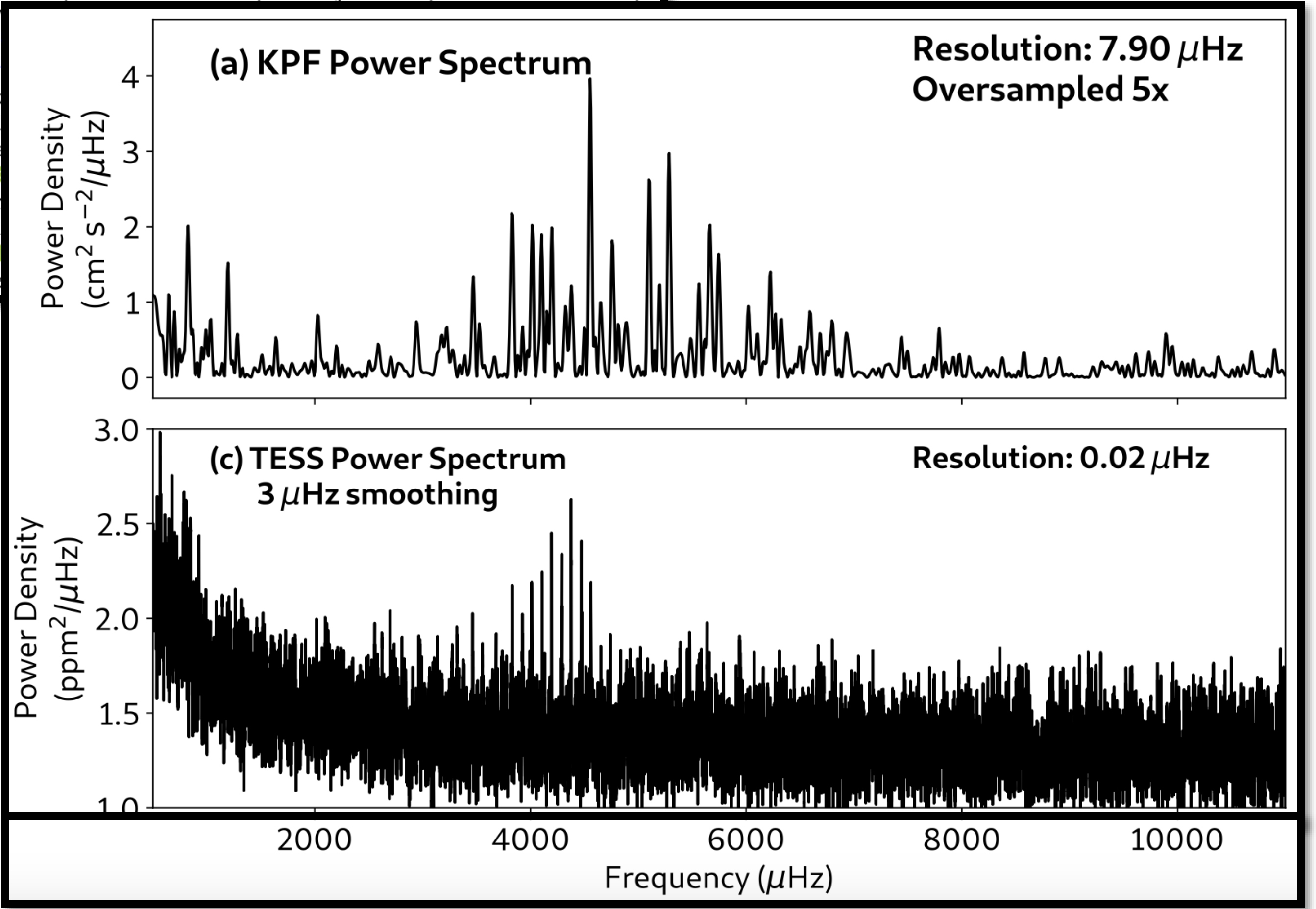
Sun (20 days with SOHO)

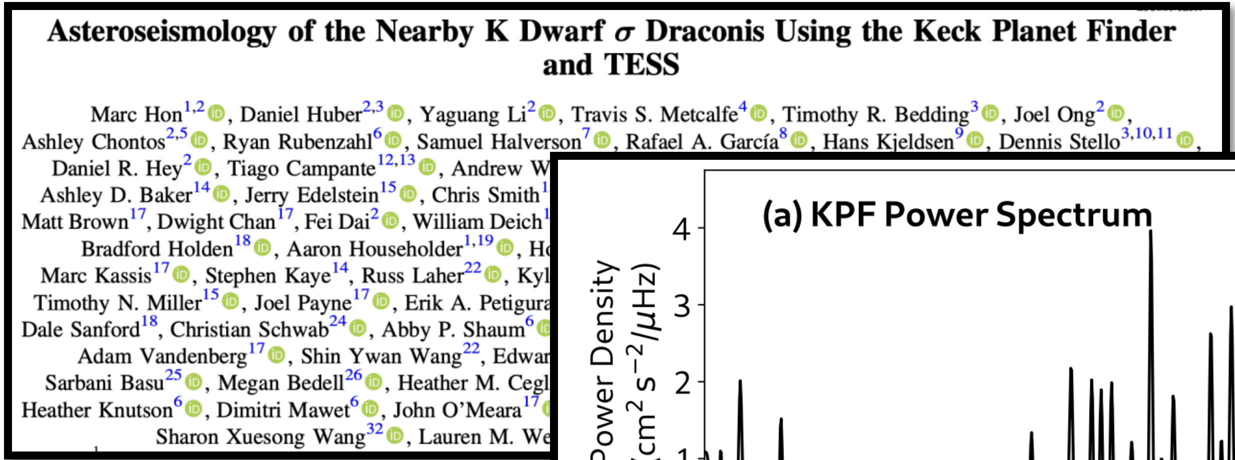


Asteroseismology of the Nearby K Dwarf σ Draconis Using the Keck Planet Finder and TESS

(2024)

Marc Hon[1,2], Daniel Huber[2,3], Yaguang Li[2], Travis S. Metcalfe[4], Timothy R. Bedding[3], Joel Ong[2],
Ashley Chontos[2,5], Ryan Rubenzahl[6], Samuel Halverson[7], Rafael A. García[8], Hans Kjeldsen[9], Dennis Stello[3,10,11],
Daniel R. Hey[2], Tiago Campante[12,13], Andrew W
Ashley D. Baker[14], Jerry Edelstein[15], Chris Smith[1
Matt Brown[17], Dwight Chan[17], Fei Dai[2], William Deich[1
Bradford Holden[18], Aaron Householder[1,19], Ho
Marc Kassis[17], Stephen Kaye[14], Russ Laher[22], Kyl
Timothy N. Miller[15], Joel Payne[17], Erik A. Petigura
Dale Sanford[18], Christian Schwab[24], Abby P. Shaum[6]
Adam Vandenberg[17], Shin Ywan Wang[22], Edwar
Sarbani Basu[25], Megan Bedell[26], Heather M. Cegl
Heather Knutson[6], Dimitri Mawet[6], John O'Meara[17]
Sharon Xuesong Wang[32], Lauren M. We

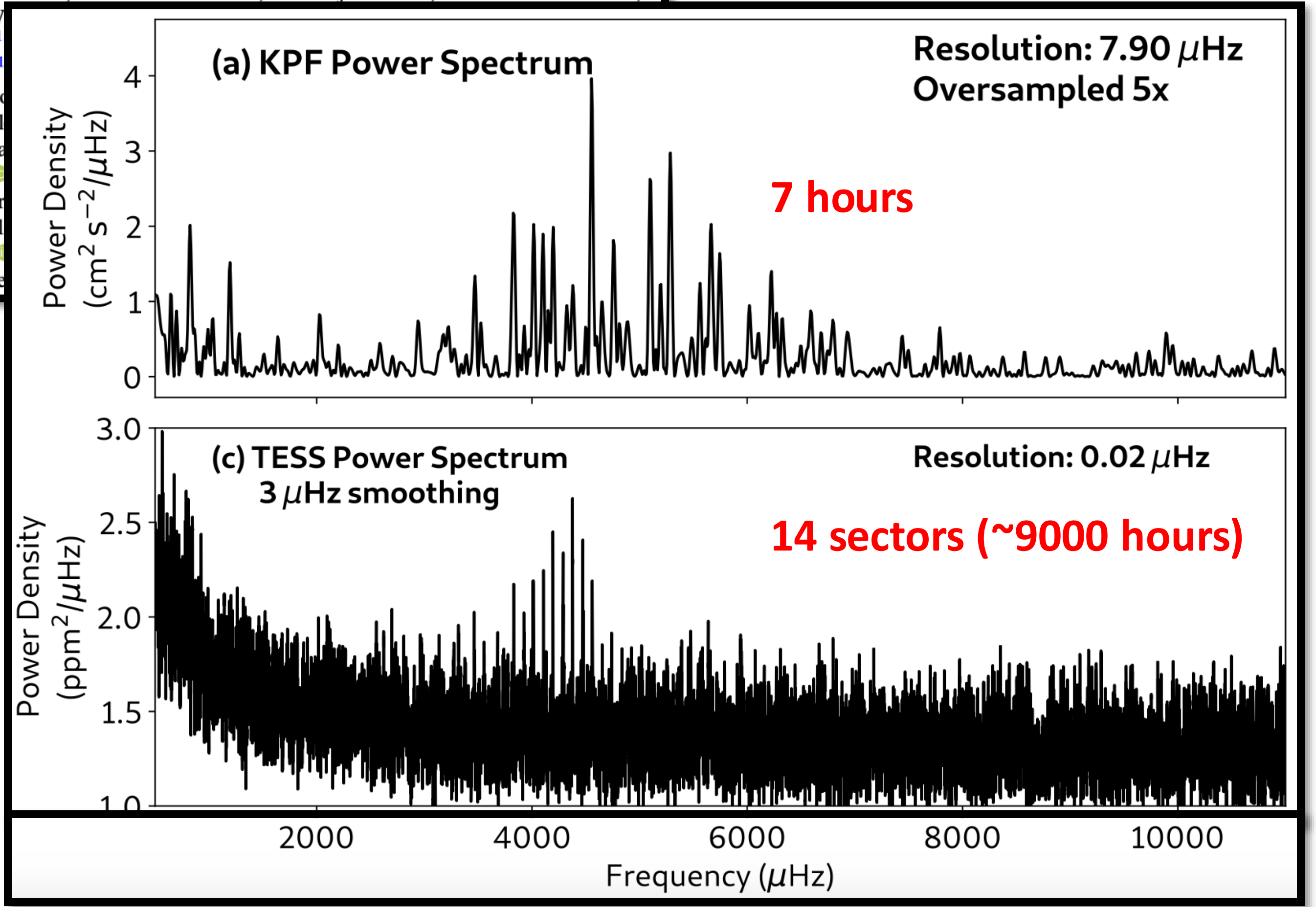




Asteroseismology of the Nearby K Dwarf σ Draconis Using the Keck Planet Finder and TESS

Marc Hon[1,2], Daniel Huber[2,3], Yaguang Li[2], Travis S. Metcalfe[4], Timothy R. Bedding[3], Joel Ong[2],
Ashley Chontos[2,5], Ryan Rubenzahl[6], Samuel Halverson[7], Rafael A. García[8], Hans Kjeldsen[9], Dennis Stello[3,10,11],
Daniel R. Hey[2], Tiago Campante[12,13], Andrew W
Ashley D. Baker[14], Jerry Edelstein[15], Chris Smith[1
Matt Brown[17], Dwight Chan[17], Fei Dai[2], William Deich[1
Bradford Holden[18], Aaron Householder[1,19], Ho
Marc Kassis[17], Stephen Kaye[14], Russ Laher[22], Kyl
Timothy N. Miller[15], Joel Payne[17], Erik A. Petigura
Dale Sanford[18], Christian Schwab[24], Abby P. Shaum[6]
Adam Vandenberg[17], Shin Ywan Wang[22], Edwar
Sarbani Basu[25], Megan Bedell[26], Heather M. Cegl
Heather Knutson[6], Dimitri Mawet[6], John O'Meara[17]
Sharon Xuesong Wang[32], Lauren M. We

(2024)



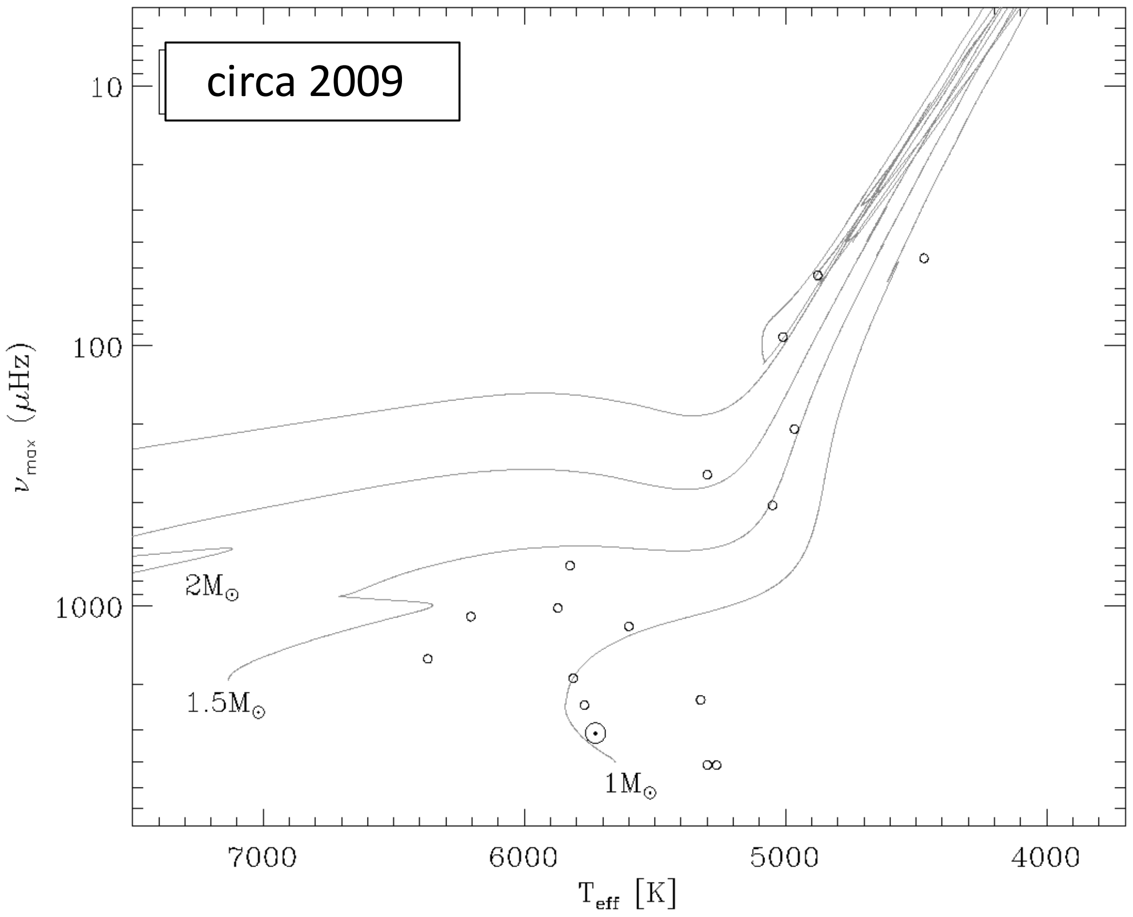
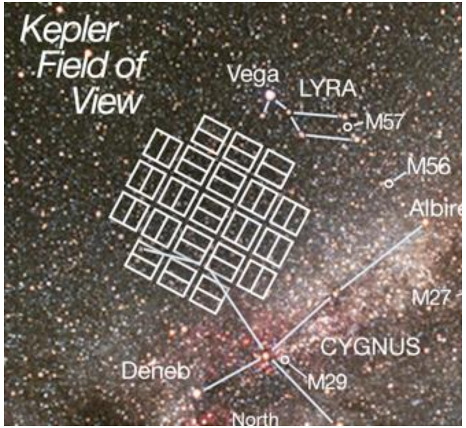
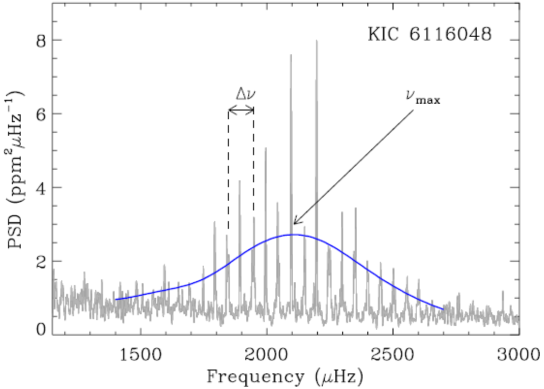
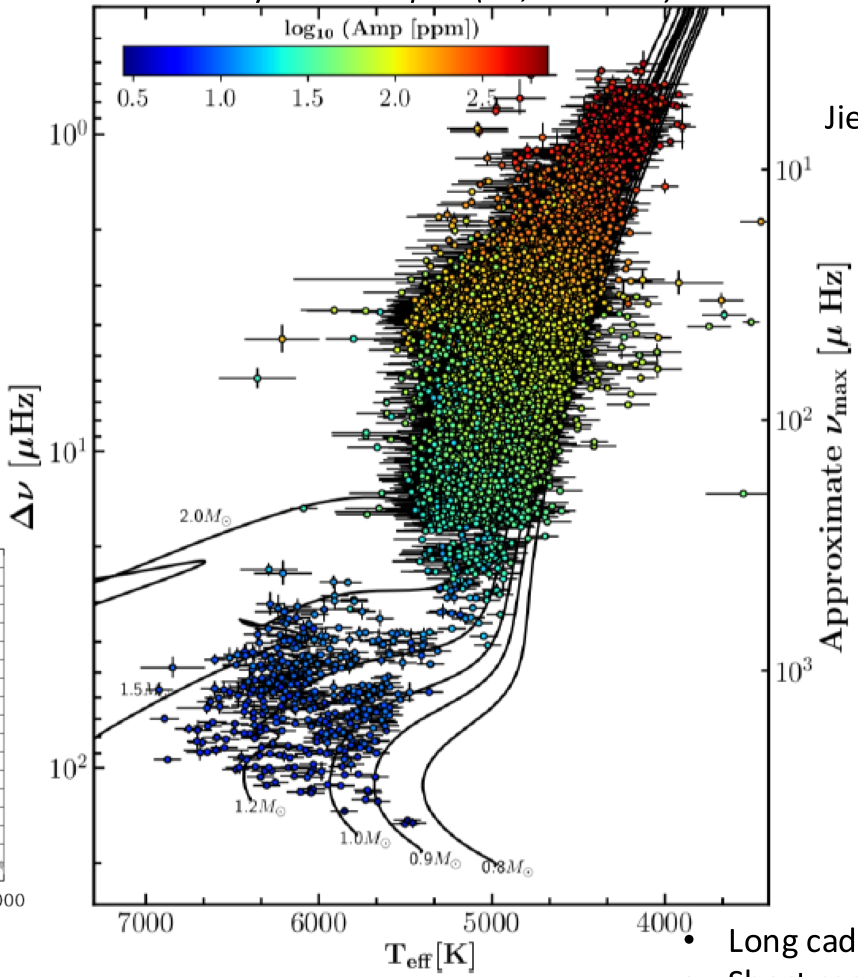


figure by Daniel Huber





after 4 years of *Kepler (16,000 stars)*

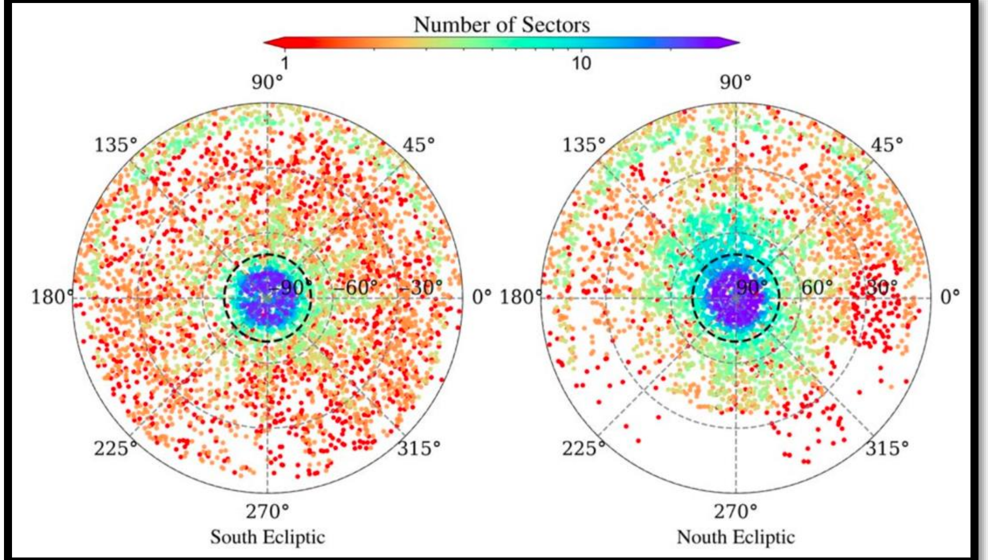


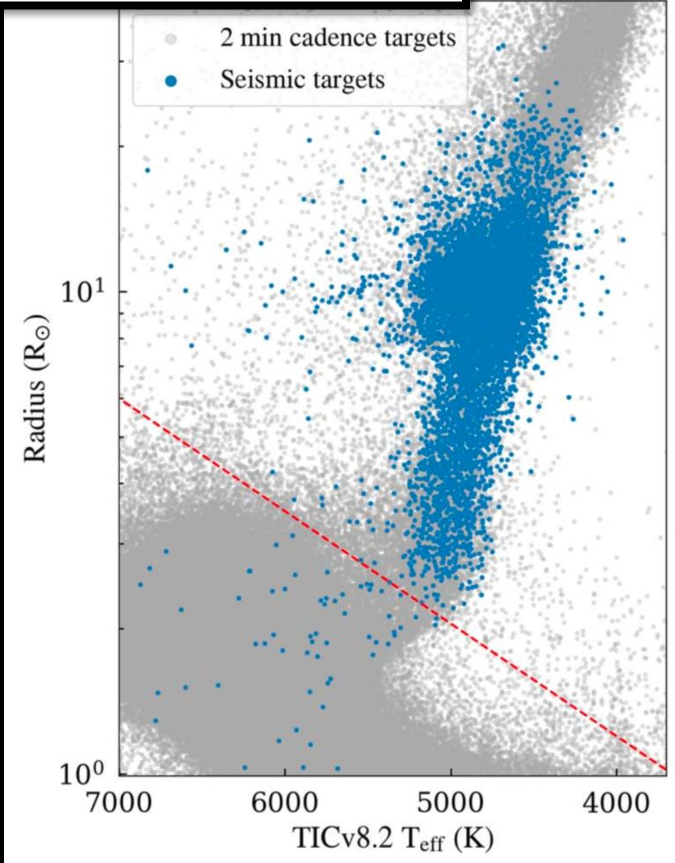
Jie Yu et al. (2017, 2018ab)

- Long cadence (29.4 minutes) – 150,000 stars
- Short cadence (1 minute) – 512 stars

Detection of Solar-like Oscillations in Subgiant and Red Giant Stars Using 2 minute Cadence TESS Data (2024)

Jianzhao Zhou[1,2], Shaolan Bi[1,2], Jie Yu[3,4,5,6], Yaguang Li[7,8], Xianfei Zhang[1,2], Tanda Li[1,2,9], Liu Long[1,2], Mengjie Li[1,2], Tiancheng Sun[1,2], and Lifei Ye[1,2]





TESS solar-like oscillations:

Campante et al. (2019)
Mackereth et al. (2021)
Hill et al. (2021)
Grunblatt et al. (2021, 2022)
Hon et al. (2021, 2022)
Stello et al. (2022)
Hatt et al. (2023)
Malla et al. (2024)
Ong et al. (2024)
Pope et al. (2024)
Sreenivas et al. (submitted)

Asteroseismic scaling relations:

1. ν_{max} depends on surface properties (excitation & damping of modes):

$$\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}} \approx \frac{g}{g_\odot}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{-1/2}$$

2. $\Delta\nu$ scales with sqrt[mean density] (sound travel time across star):

$$\Delta\nu \propto \left(\frac{M}{R^3}\right)^{1/2}$$

Asteroseismic scaling relations:

1. ν_{max} depends on surface properties (excitation & damping of modes):

$$\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}} \approx \frac{g}{g_\odot} \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{-1/2}$$

2. $\Delta\nu$ scales with sqrt[mean density] (sound travel time across star):

$$\Delta\nu \propto \left(\frac{M}{R^3}\right)^{1/2}$$

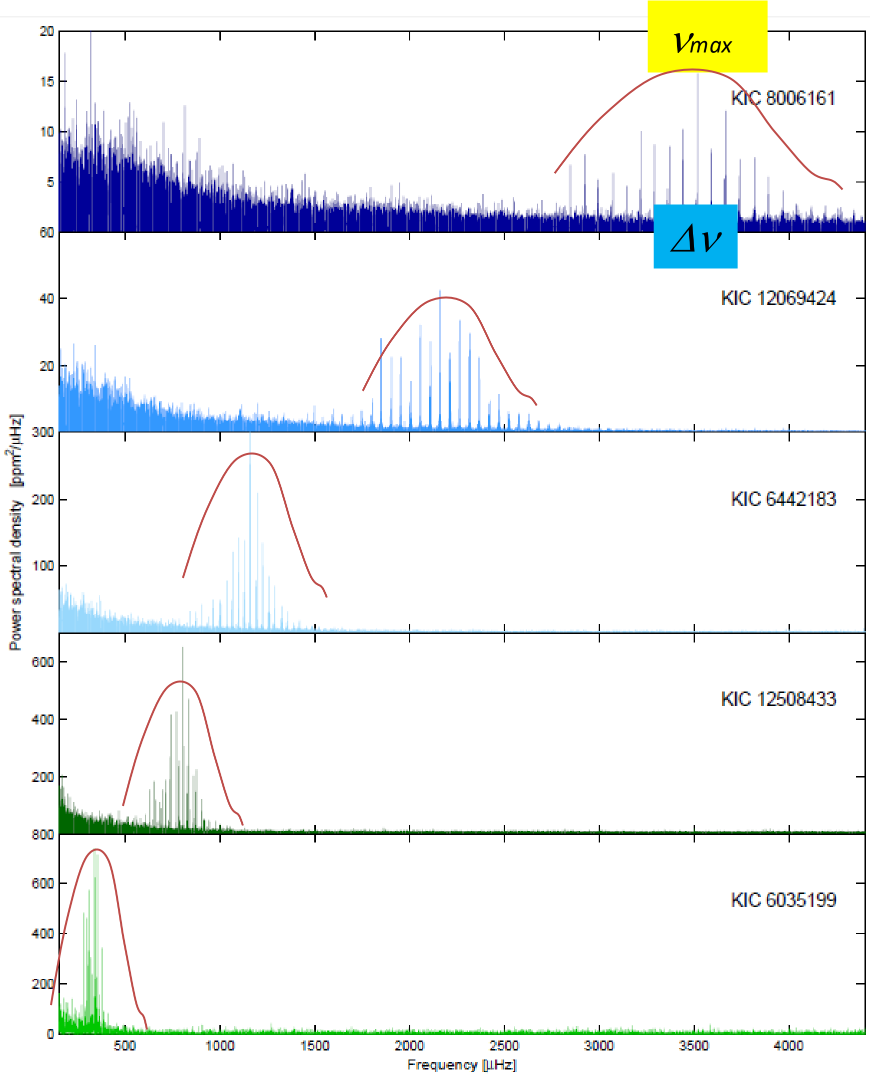
Solve to get mass and radius:

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

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

Stello et al. (2008; ApJL 674, L53)
Kallinger et al. (2010; A&A 509, A77)

for uncertainties on Teff see, e.g., Tayar et al. (2022)



Chaplin & Miglio (2013, ARAA)

1. The ν_{max} scaling relation

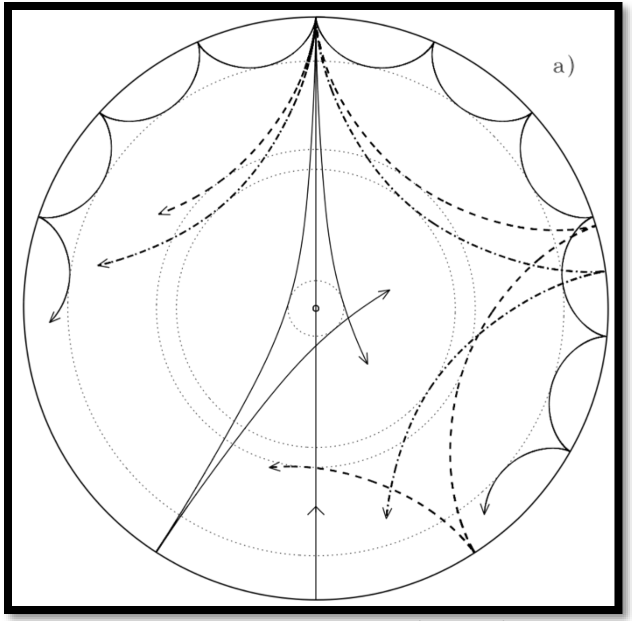
$$\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}} \approx \frac{g}{g_\odot}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{-1/2}$$

1. The ν_{max} scaling relation

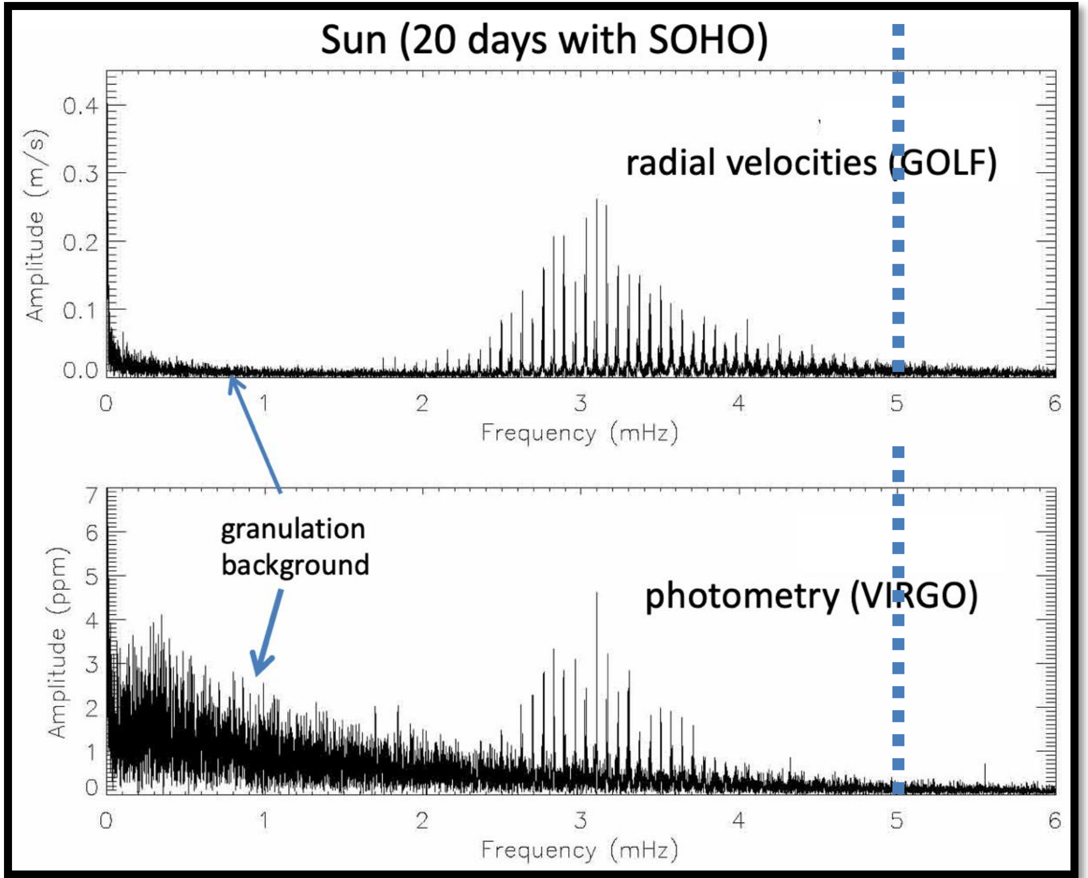
$$\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}} \approx \frac{g}{g_\odot}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{-1/2}$$

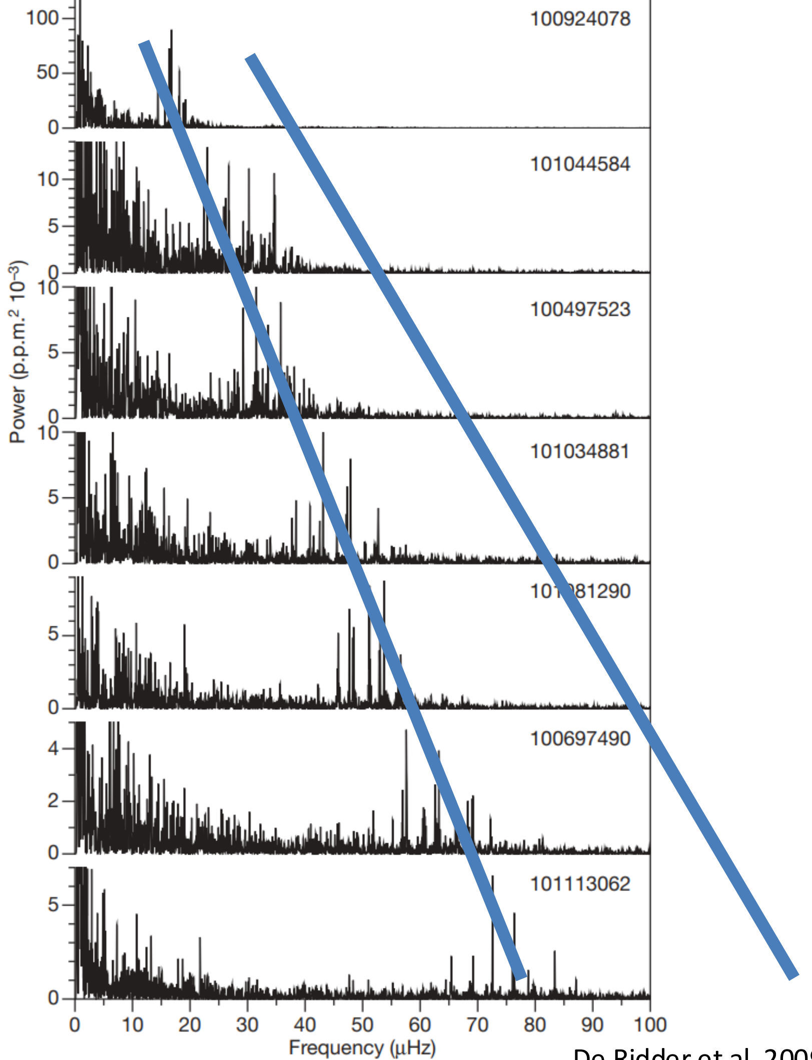
$$\nu_{\rm ac} \propto g/\sqrt{T_{\rm eff}}$$

Brown et al. (1991);
Kjeldsen & Bedding (1995)



Aerts et al. (2011)





De Ridder et al. 2009

We extrapolate from the Sun, assuming ν_{max} is a *fixed fraction* of the acoustic cutoff frequency (~0.6).

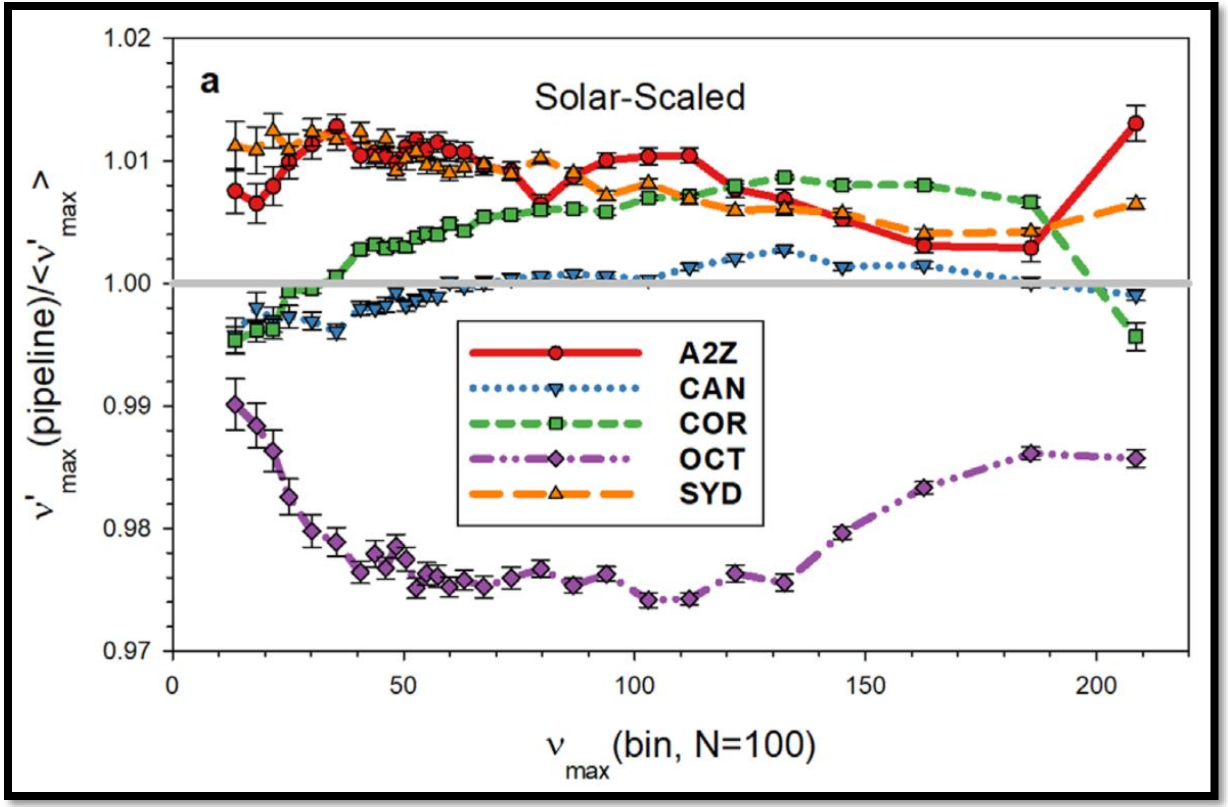
$$\nu_{\rm max} \propto \nu_{\rm ac} \propto g/\sqrt{T_{\rm eff}}$$

Brown et al. (1991);
Kjeldsen & Bedding (1995)

Introduced to *predict* ν_{max}.

see e.g.,
Belkacem et al. (2011; A&A)
Bedding (2014; arxiv:1107.1723)
Chaplin & Miglio (2013, ARAA)
Hekker (2019; *Frontiers*)
Yaguang Li et al. (2021)

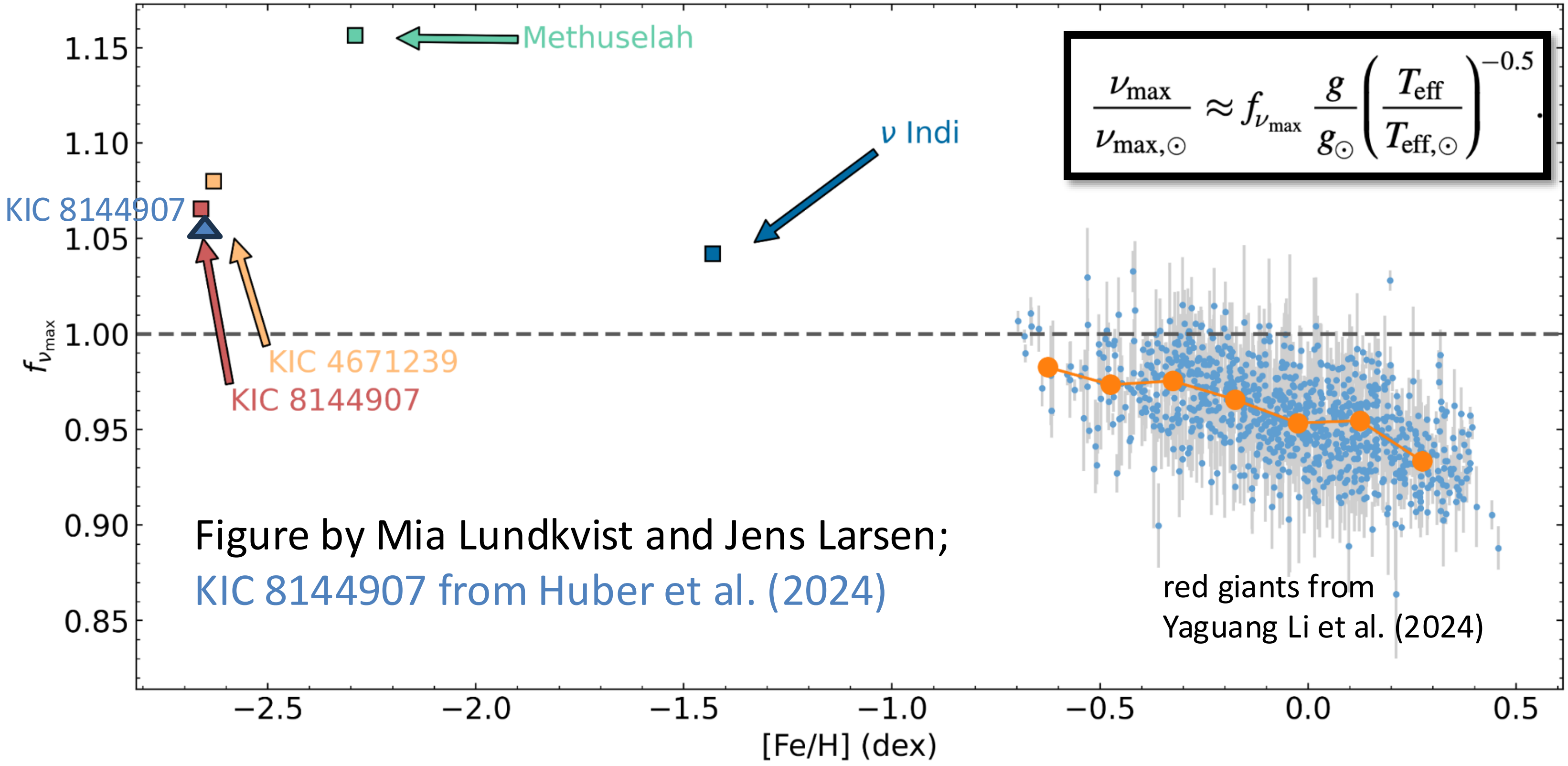
ν_{max} depends on how you measure it



For red giants (APOKASC; Pinsonneault et al. 2018)

Same is true for dwarfs (e.g., Verner et al. 2011)

The ν_{max} scaling probably depends on metallicity



see also Vianni et al. (2017); Yixiao Zhou et al (2024)

Asteroseismic scaling relations:

1. ν_{max} depends on surface properties (excitation & damping of modes):

$$\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}} \approx \frac{g}{g_\odot}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{-1/2}$$

2. $\Delta\nu$ scales with sqrt[mean density] (sound travel time across star):

$$\Delta\nu \propto \left(\frac{M}{R^3}\right)^{1/2}$$

Solve to get mass and radius:

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

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

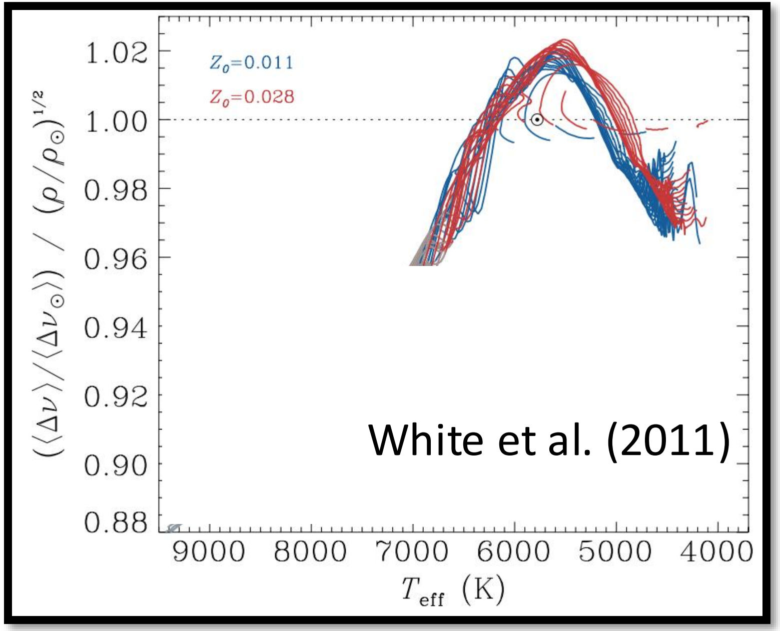
Stello et al. (2008; ApJL 674, L53)
Kallinger et al. (2010; A&A 509, A77)

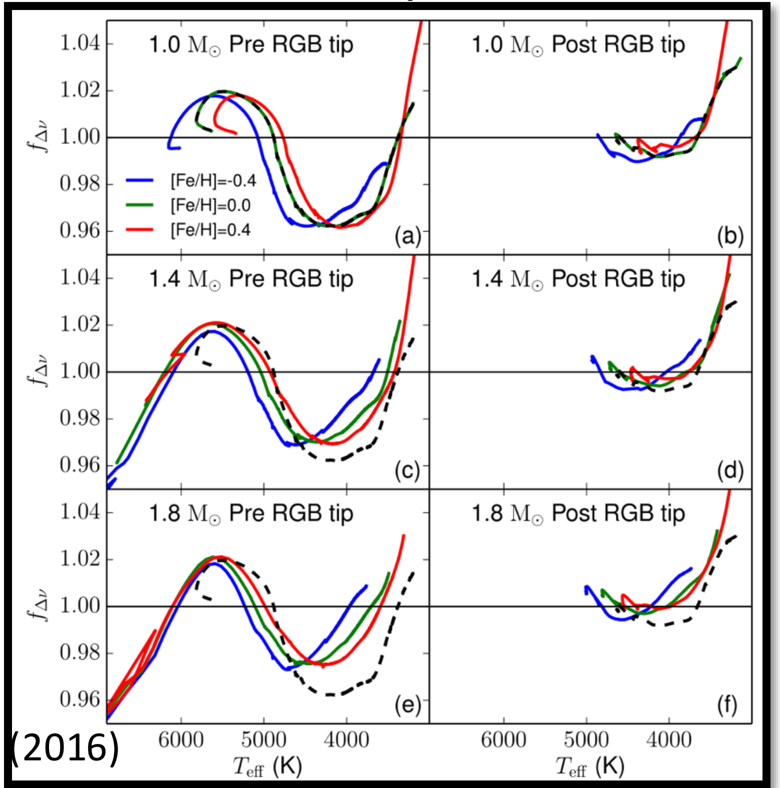
for uncertainties on Teff see, e.g., Tayar et al. (2022)

2. The $\Delta\nu$ scaling relation

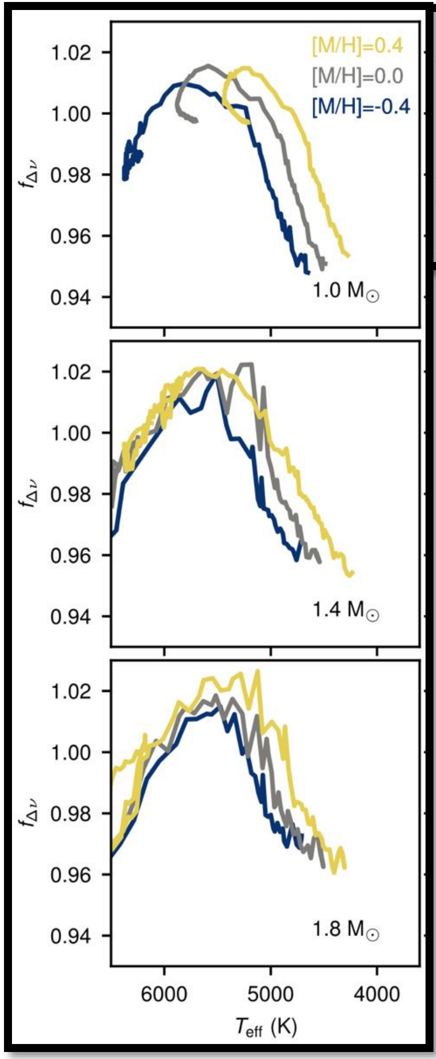
$$\left(\frac{\Delta\nu}{\Delta\nu_{\odot}}\right) = f_{\Delta\nu}\left(\frac{\rho}{\rho_{\odot}}\right)^{0.5}$$

- relies on solid theory (we can compute oscillation frequencies using models)





Sharma et al. (2016)



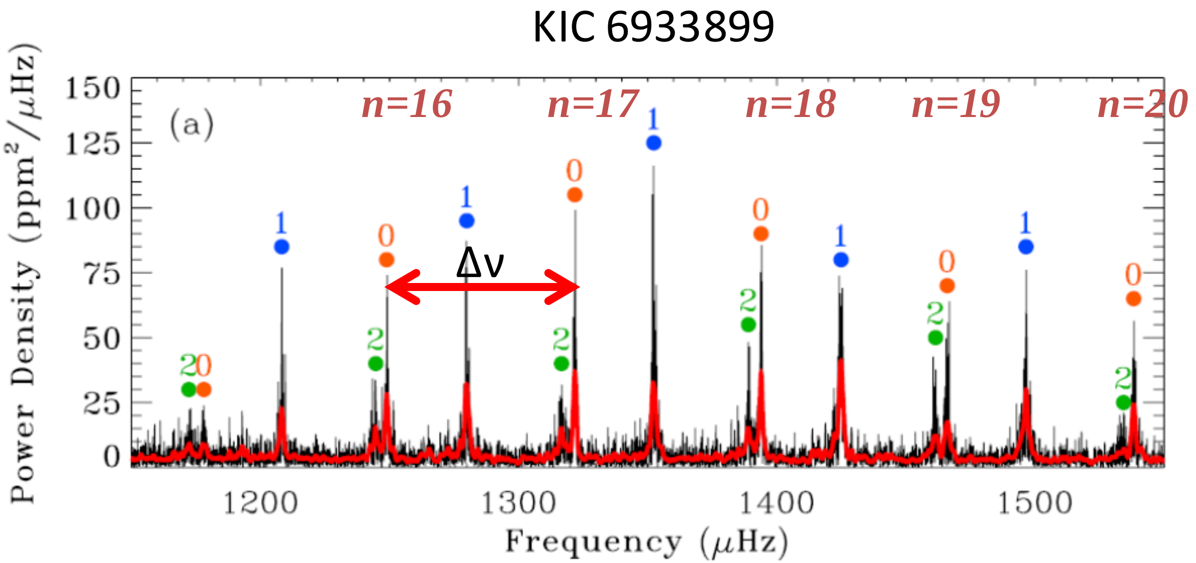
A prescription for the asteroseismic surface correction (2023)

Yaguang Li, (李亚光)[1★] Timothy R. Bedding[1] Dennis Stello,[1,2,3] Daniel Huber,[4] Marc Hon[4], Meridith Joyce,[5] Tanda Li, (李坦达)[6] Jean Perkins,[7] Timothy R. White[1] Joel C. Zinn[8], Andrew W. Howard,[9] Howard Isaacson,[10] Daniel R. Hey[4] and Hans Kjeldsen[3]

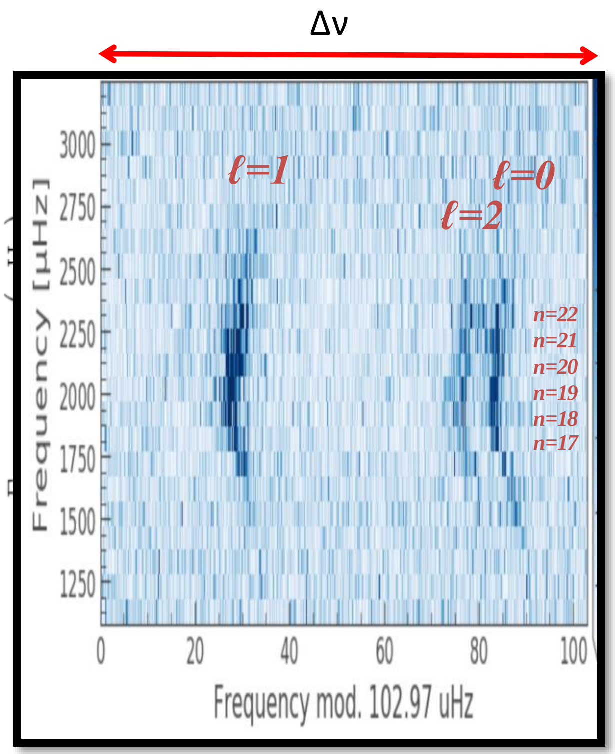
$$\left(\frac{\Delta\nu}{\Delta\nu_\odot}\right) = f_{\Delta\nu}\left(\frac{\rho}{\rho_\odot}\right)^{0.5}$$

$$\begin{aligned} f_{\Delta\nu} = {} & \beta_0 + \beta_1 \log_{10}(\nu_{\rm max}/3090\ \mu{\rm Hz}) \\ & + \beta_2 \log_{10}(\Delta\nu/135.1\ \mu{\rm Hz}) \\ & + \beta_3 (T_{\rm eff}/5777\ {\rm K}) \\ & + \beta_4 (T_{\rm eff}/5777\ {\rm K})^2 \\ & + \beta_5 (T_{\rm eff}/5777\ {\rm K})^3 \\ & + \beta_6 [{\rm M/H}], \\ & \text{for } 0.8 < M/{\rm M}_\odot < 2.2,\ -0.8 < [{\rm M/H}] < 0.5, \\ & \text{and pre-RGB tip } (\Delta\nu > 2.0\ \mu{\rm Hz}). \end{aligned} \tag{16}$$

Better to make full use of *all* the mode frequencies



White et al. (2012)



échelle diagram

Summary

- ν_{max} scaling relation is surprisingly good (few percent), but has metallicity dependence (and value depends on method)
- $\Delta\nu$ scaling relation is very good with theoretical corrections (including the surface correction; see Yaguang Li et al. 2023)
- Best practice: fit the individual mode frequencies (and maybe include ν_{max} as an extra constraint)