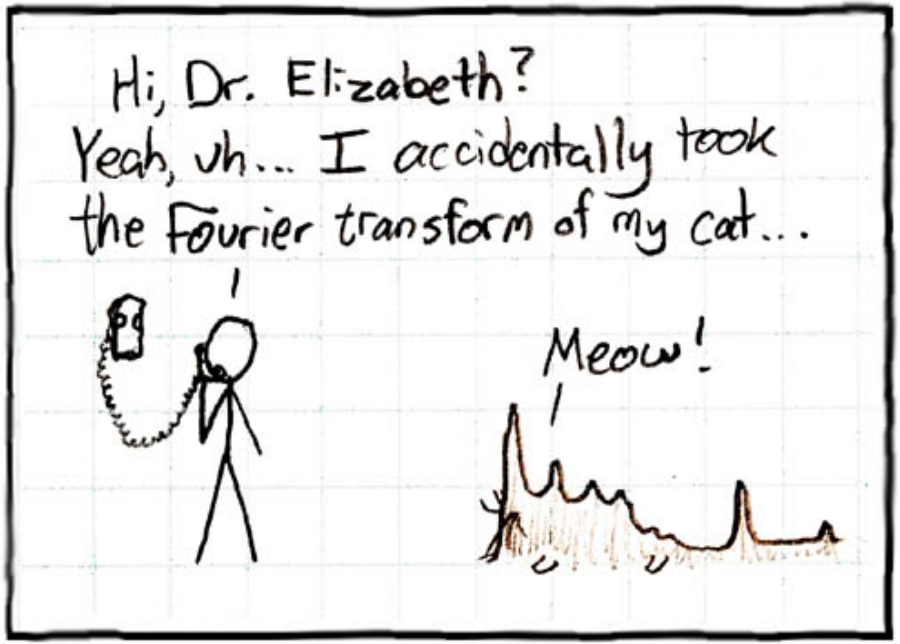
High-frequency δ Scuti stars with TESS

Tim Bedding, Simon Murphy, Daniel Hey,
Daniel Huber, Tanda Li, Gang Li, Yaguang Li,
Barry Smalley, Dennis Stello, Bill Chaplin,
Isabel Colman, Jim Fuller, Eric Gaidos,
Daniel Harbeck, J. J. Hermes, Andrew Mann,
Daniel Reese, Sanjay Sekaran, Tim White, Jie Yu,
Vichi Antoci, Tim Brown, Andrew Howard,
Howard Isaacson, Jon Jenkins, Hans Kjeldsen,
Curtis McCully, Markus Rabus,
George Ricker & Roland Vanderspek

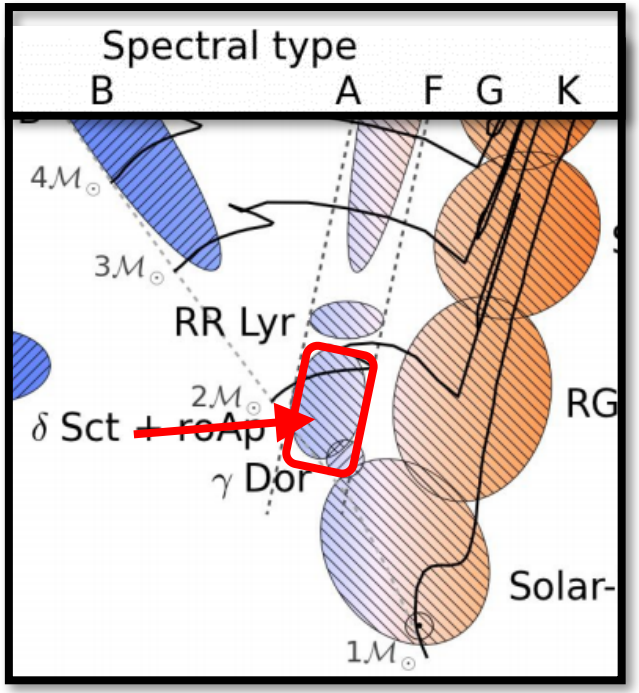


http://xkcd.com/26/

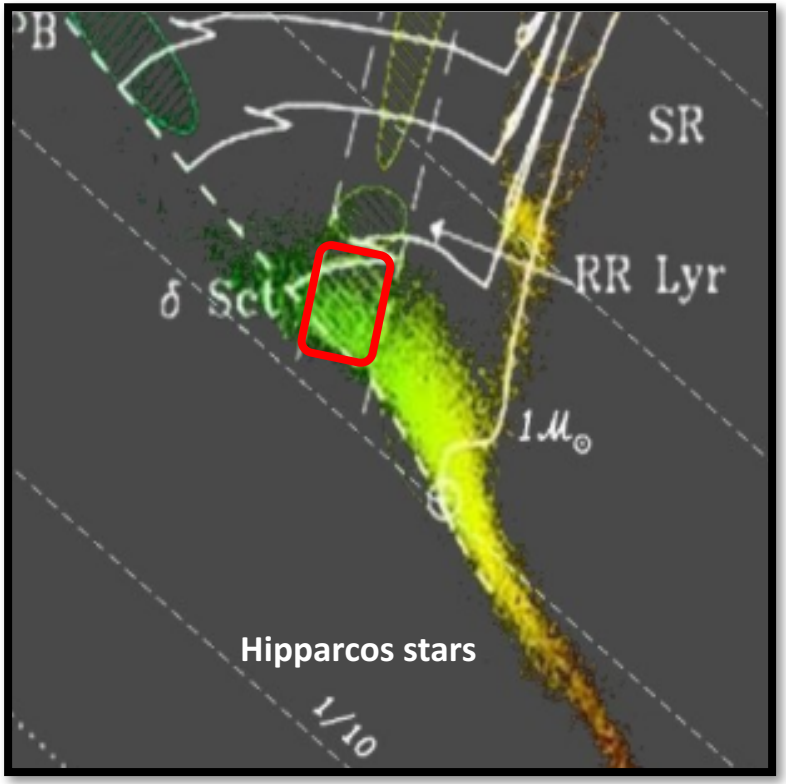
THE UNIVERSITY OF SYDNEY

STELLAR ASTROPHYSICS CENTRE

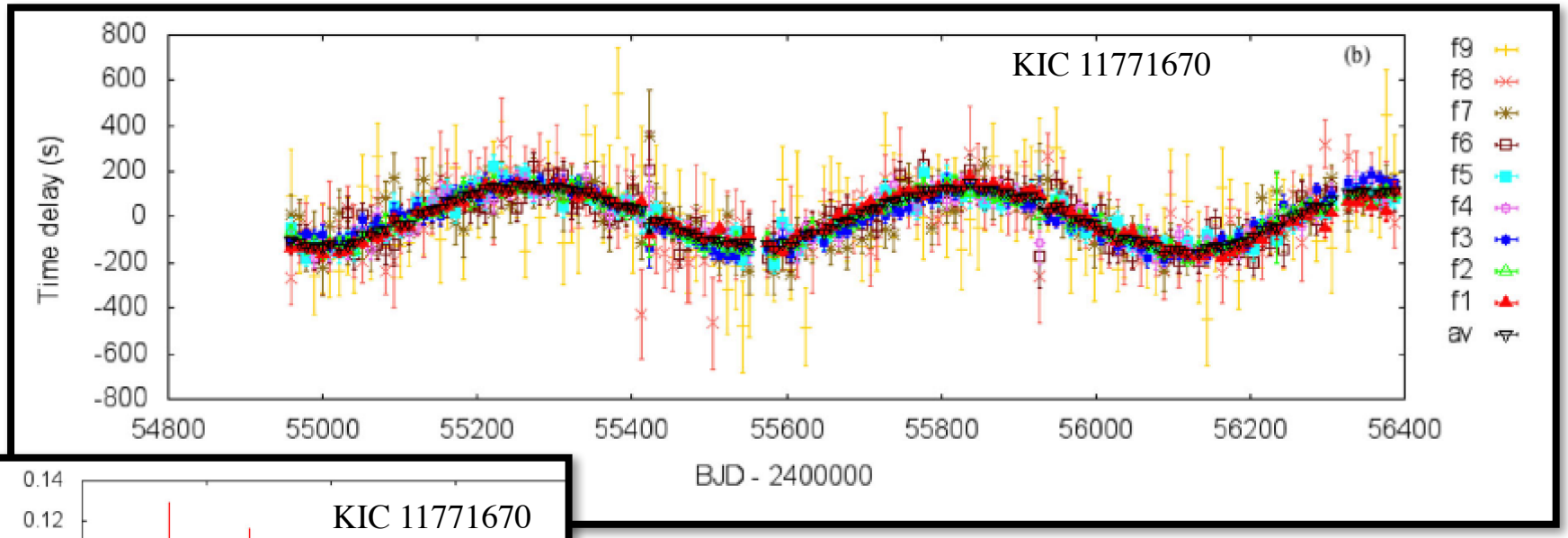
δ Scuti pulsators are common among A-type stars

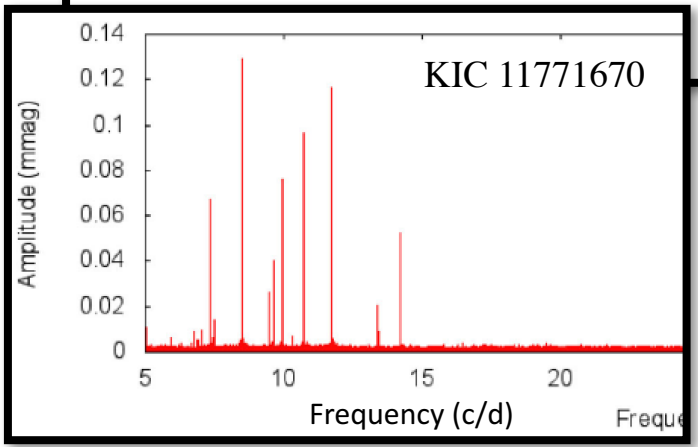


Pápics (2013)



δ Scuti stars are very good clocks!





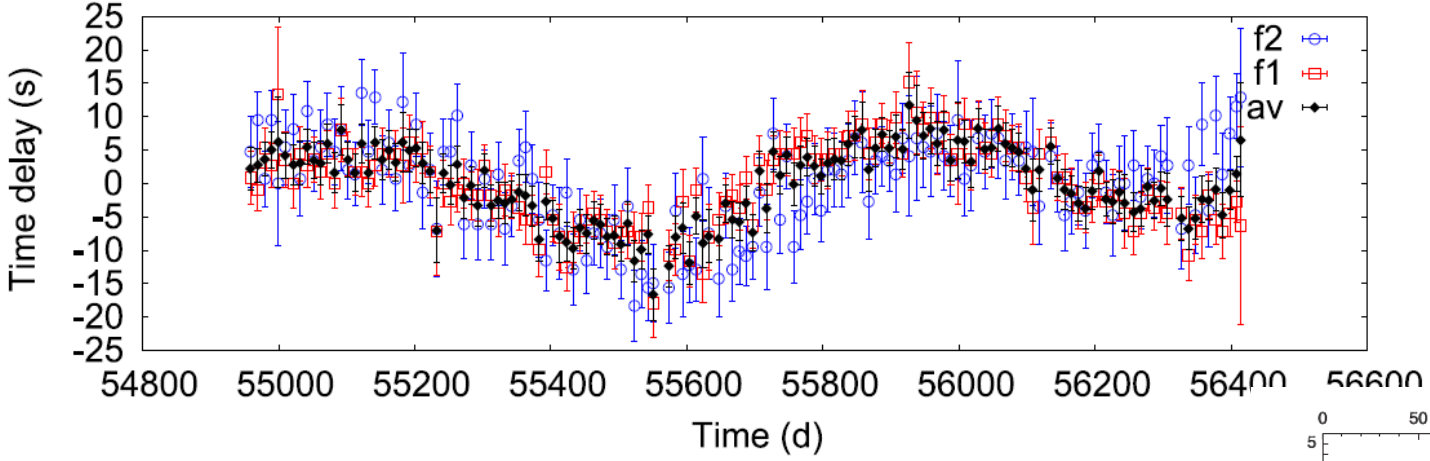
Murphy et al. (2014, 2016a, 2016b, 2018)

The Astrophysical Journal Letters, 827:L17 (4pp), 2016 August 10

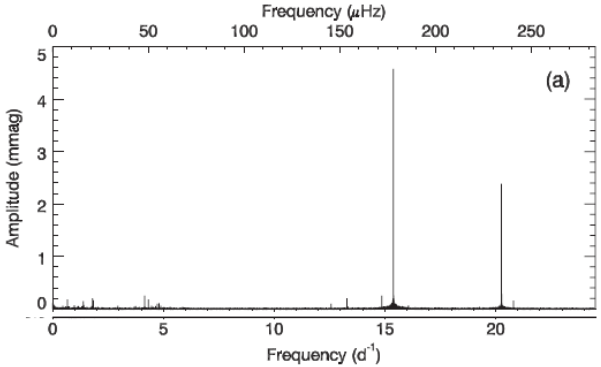
doi:10.3847/2041-8205/827/1/L17

A PLANET IN AN 840 DAY ORBIT AROUND A *KEPLER* MAIN-SEQUENCE A STAR FOUND FROM PHASE MODULATION OF ITS PULSATIONS

Simon J. Murphy[1,2], Timothy R. Bedding[1,2], and Hiromoto Shibahashi[3]

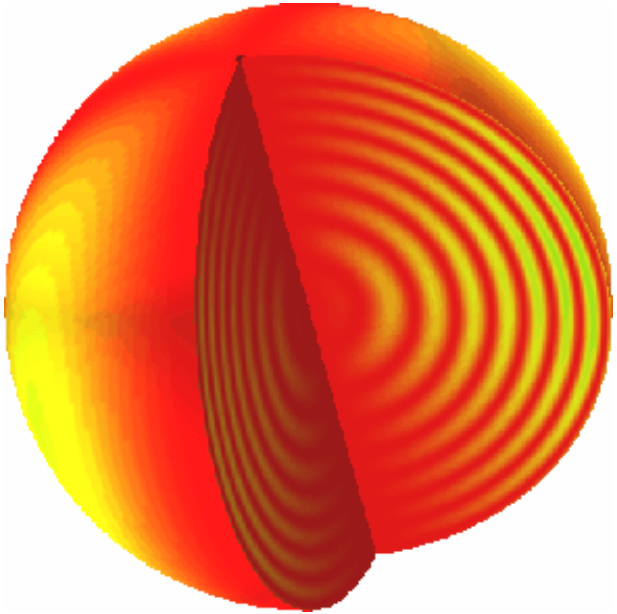


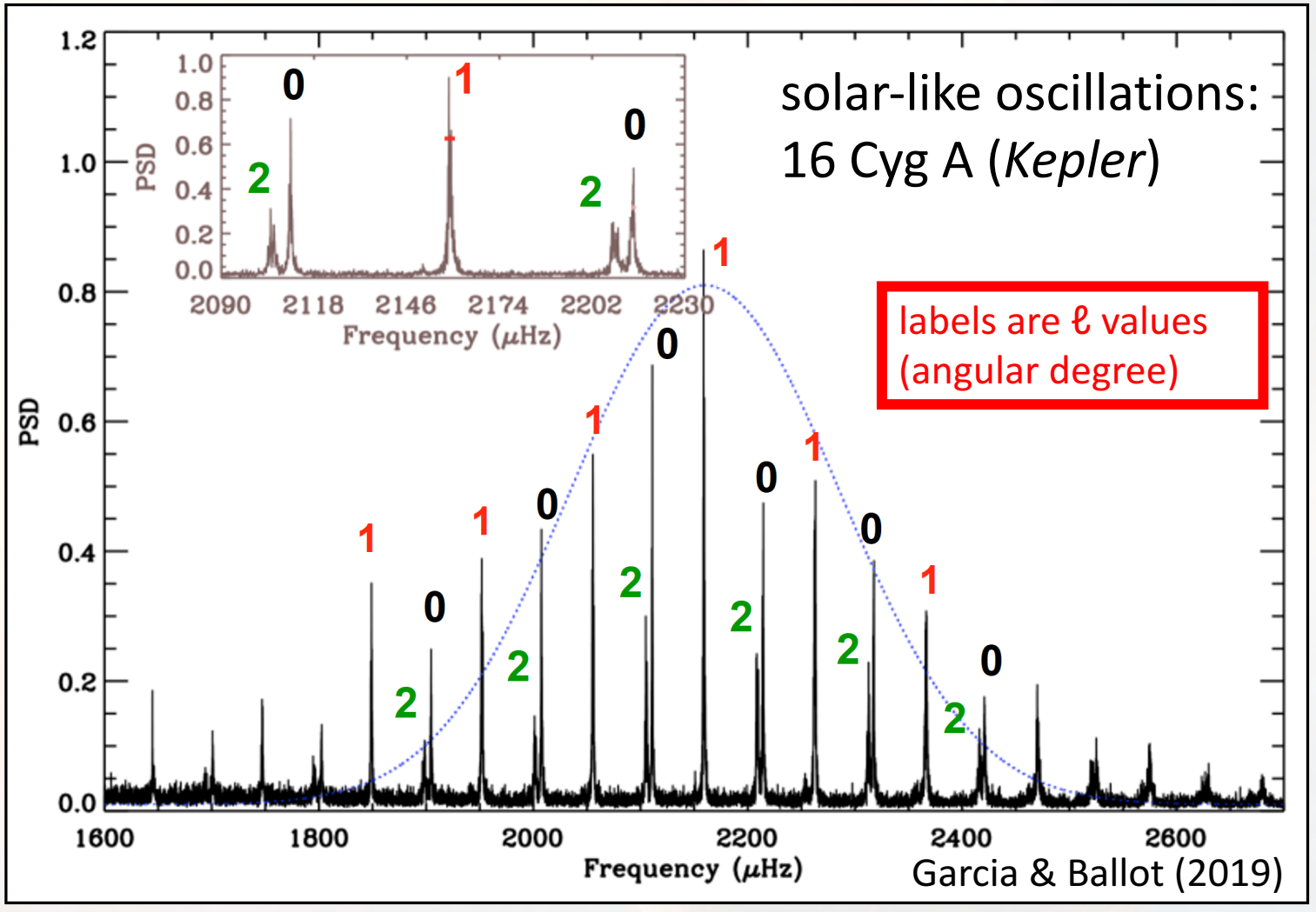
$12\,M_{\rm Jup}$ planet orbiting in or near the habitable zone of a main-sequen



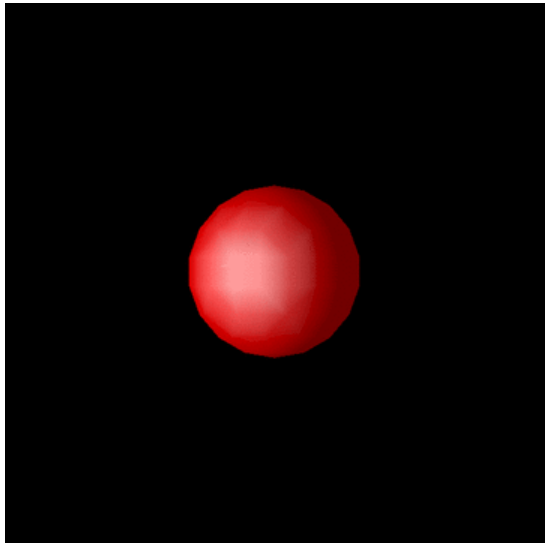
Aims of asteroseismology:

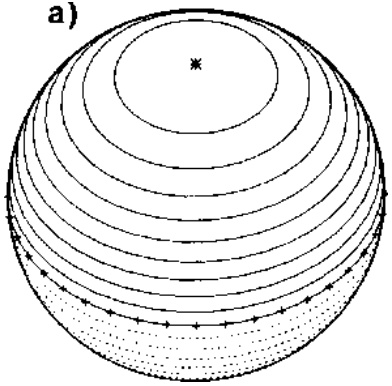
1. fundamental properties of stars (masses, radii, ages)
2. probe stellar interiors in exquisite detail (convective overshoot, nuclear burning, internal rotation, magnetic fields)



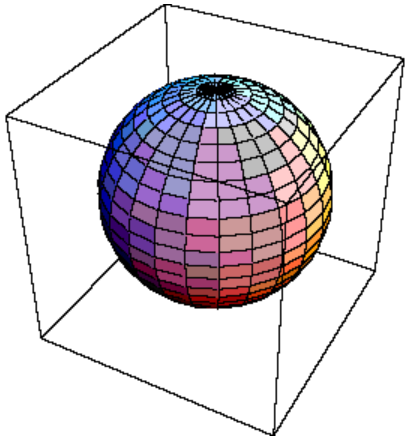

solar-like oscillations:
16 Cyg A (*Kepler*)
labels are ℓ values
(angular degree)
PSD
Frequency (μHz)
Garcia & Ballot (2019)

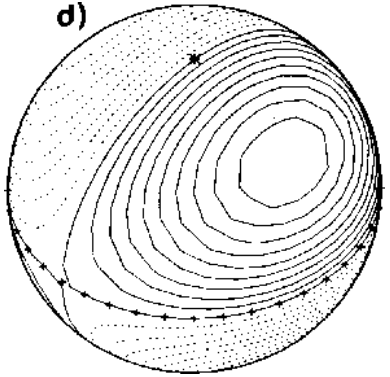
ℓ =0 (radial modes)



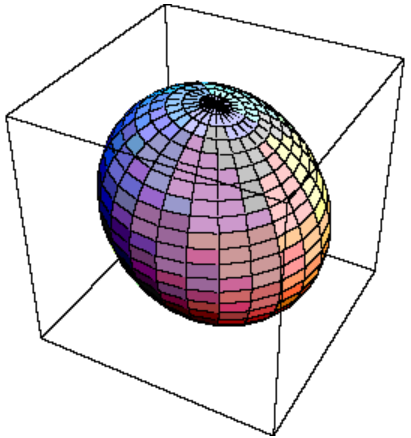


ℓ=1

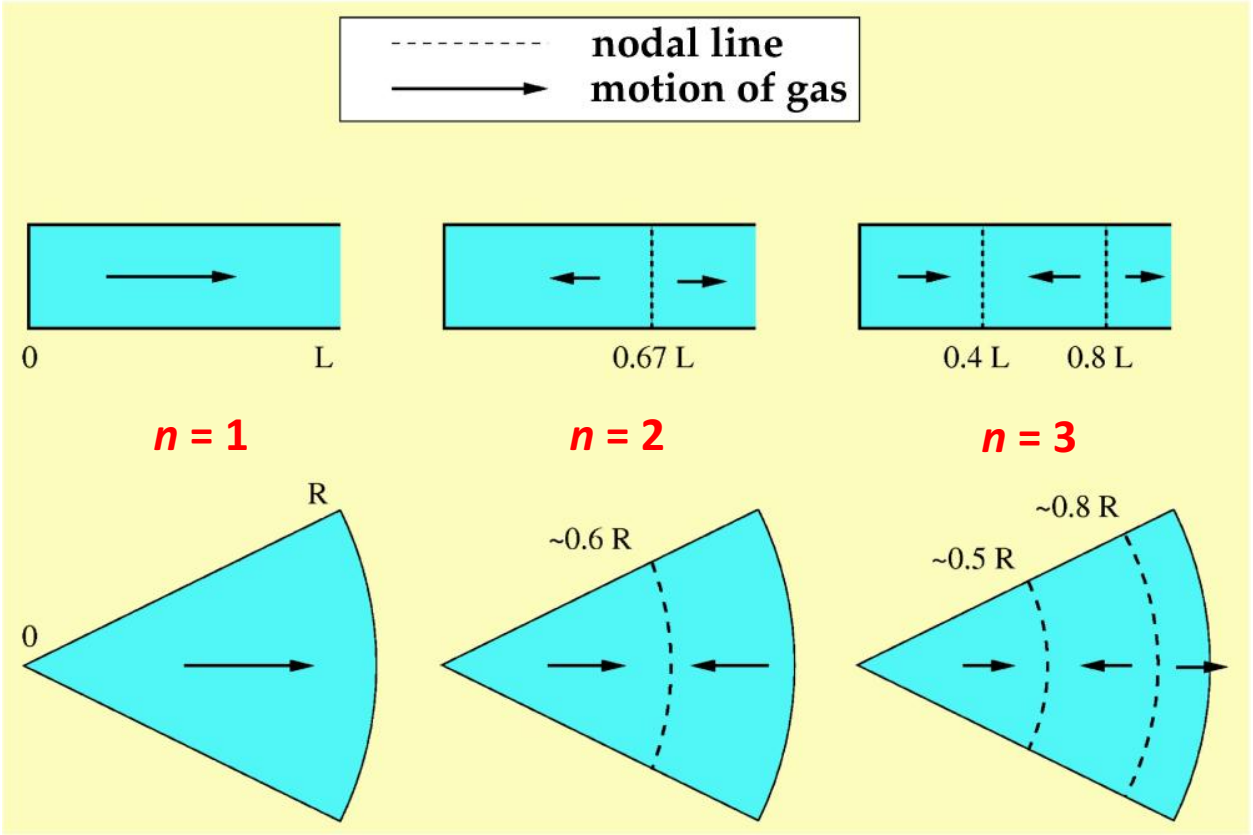




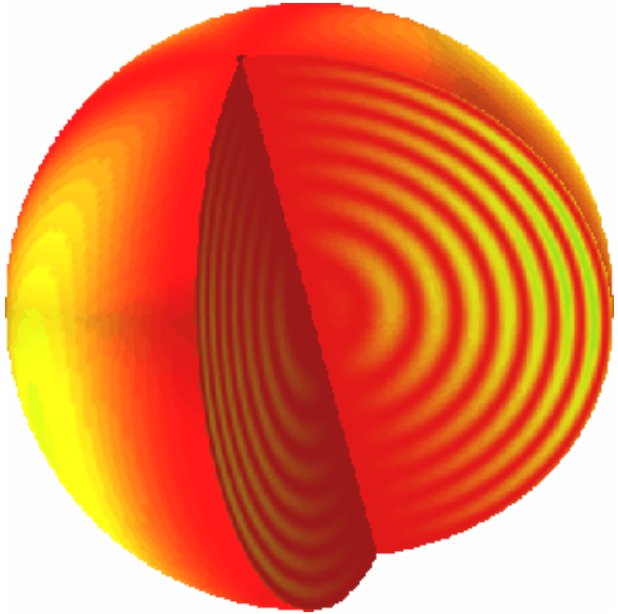
ℓ= 2



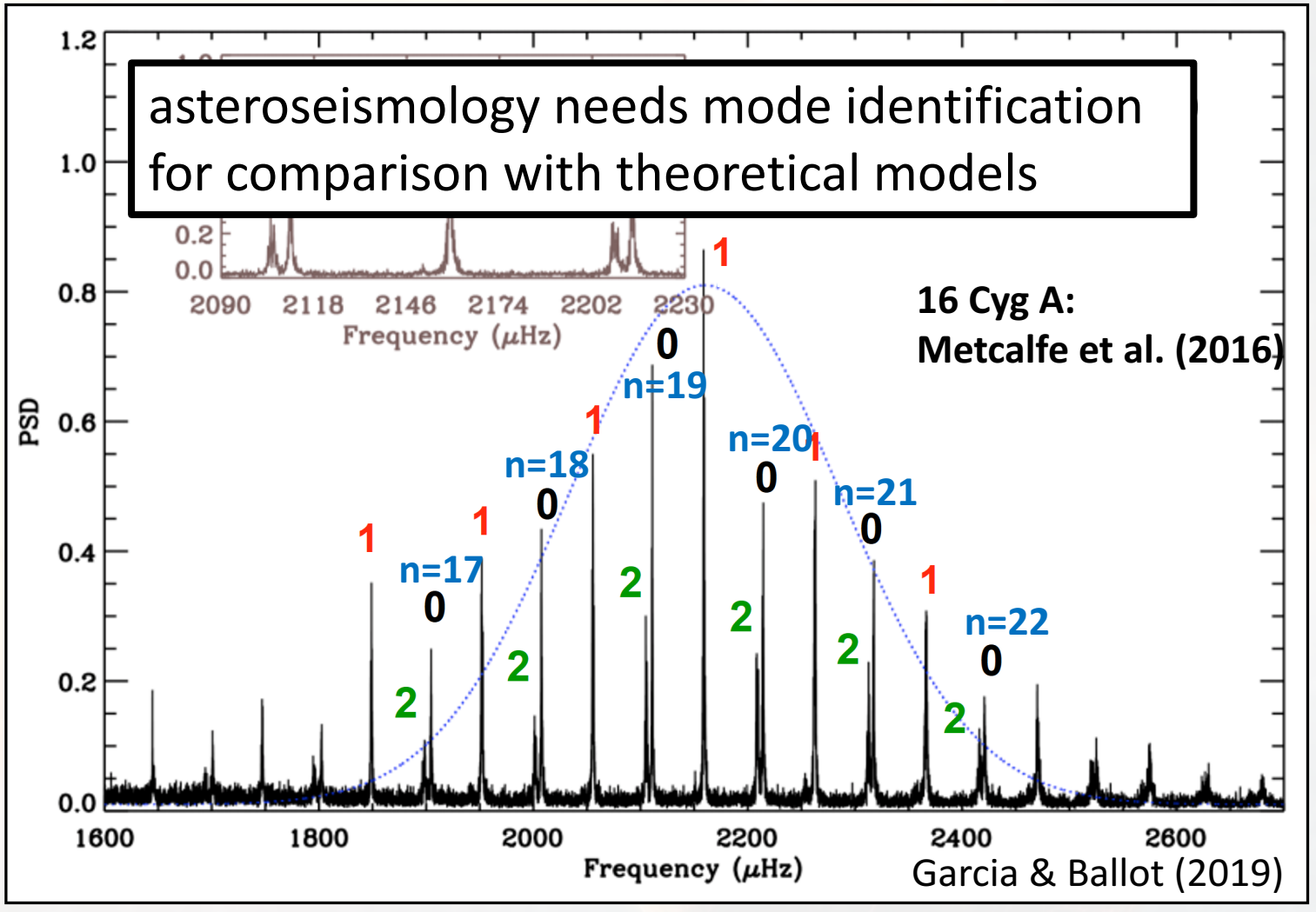
p-mode oscillations are standing sound waves



n = 20

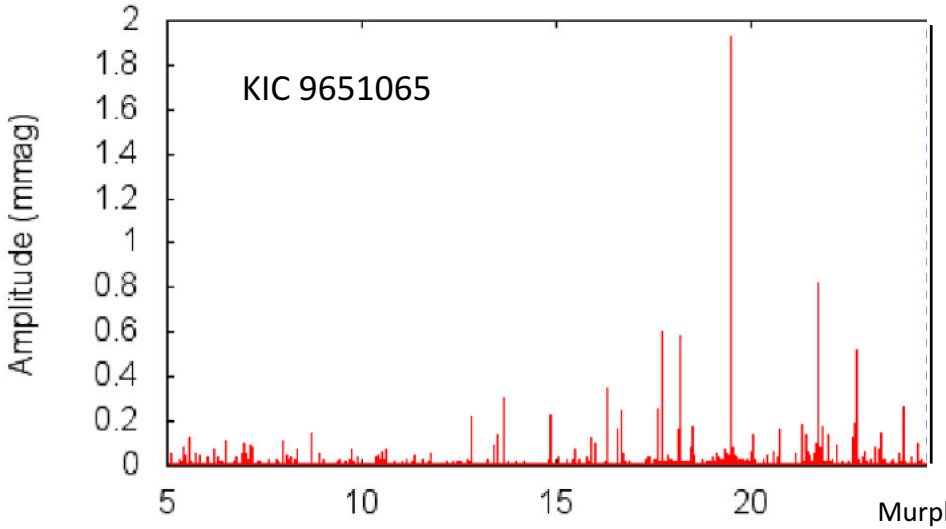


n is the *radial order* of the overtone

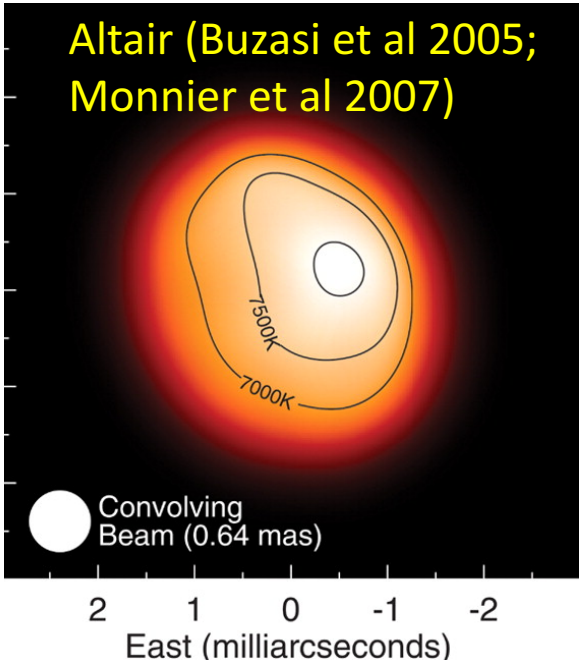

asteroseismology needs mode identification
for comparison with theoretical models
16 Cyg A:
Metcalfe et al. (2016)
Garcia & Ballot (2019)
PSD
Frequency (μHz)
n=17
n=18
n=19
n=20
n=21
n=22

Why is mode identification so difficult in δ Scuti stars?

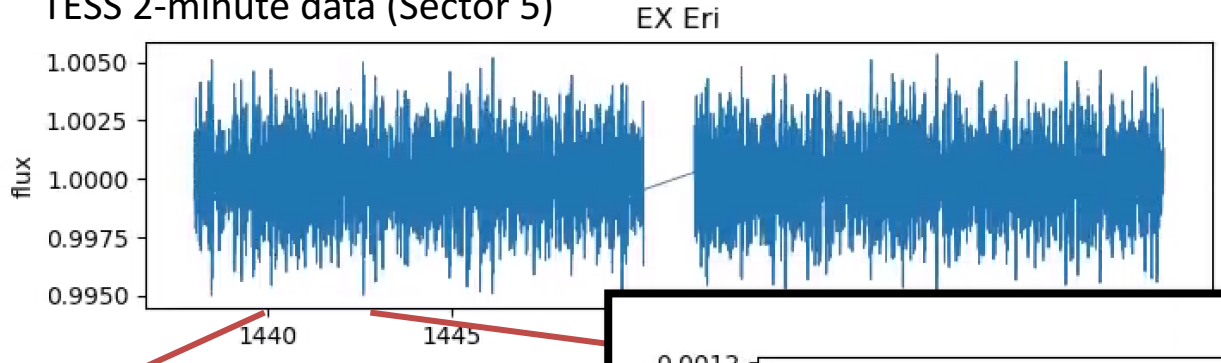
- not all modes excited
- rotation (+ ellipsoidal shape) spoil regular patterns
- (so do avoided crossings of mixed modes)

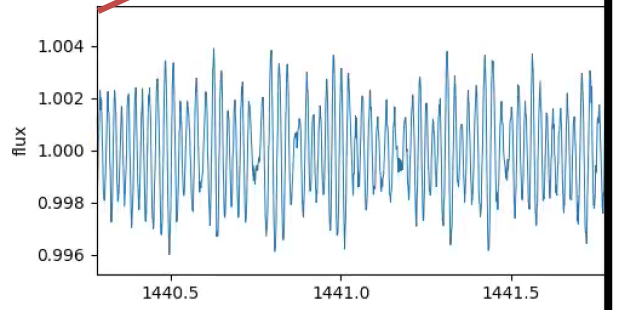


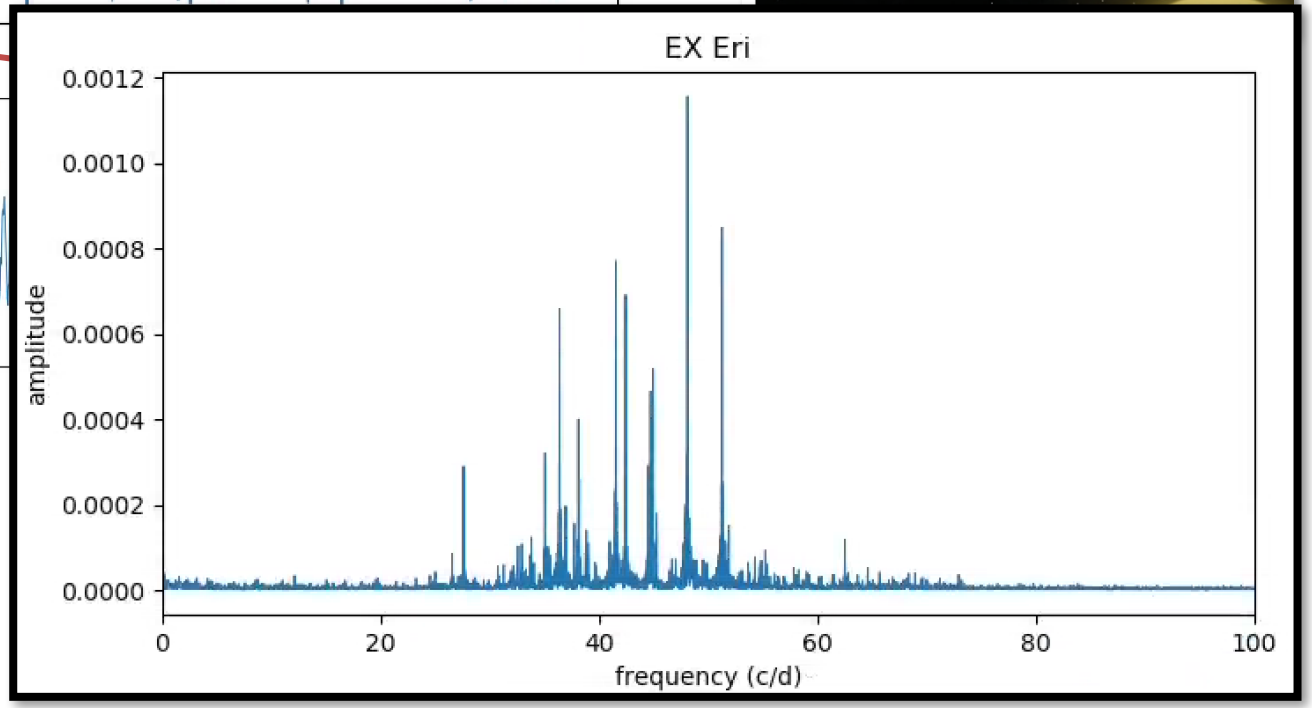
Murphy et al. (2014)



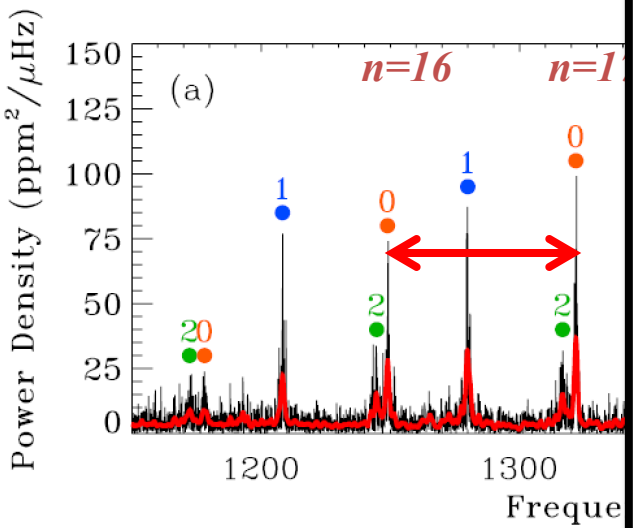
TESS 2-minute data (Sector 5)



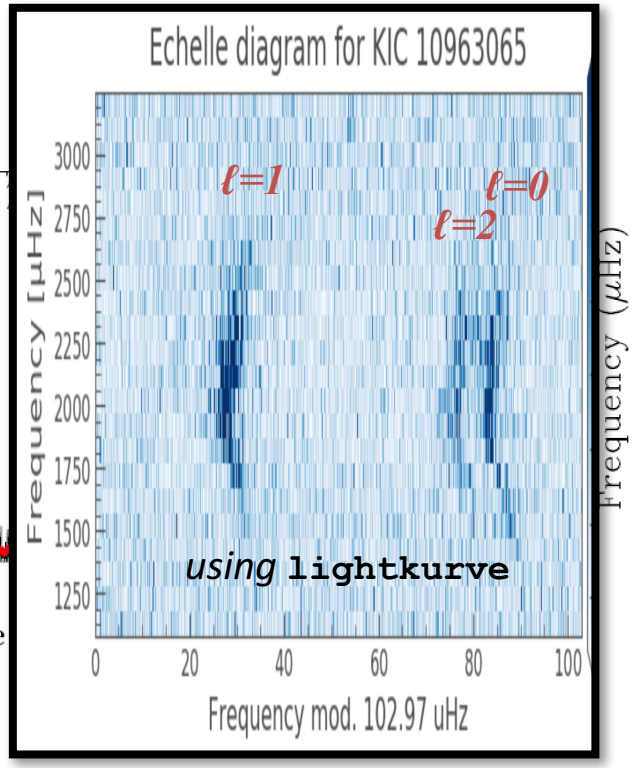


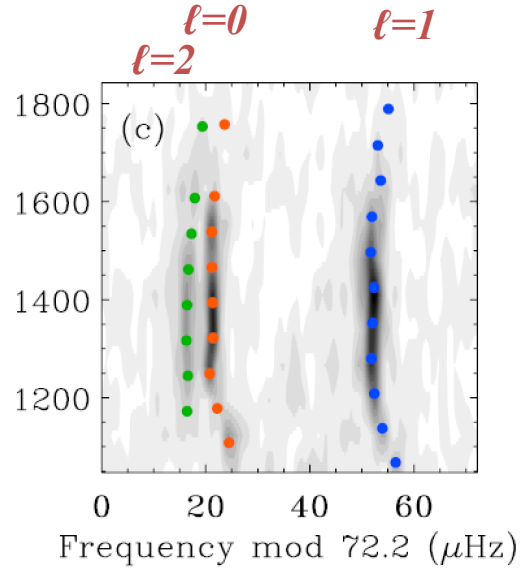


A typical Sun-like star

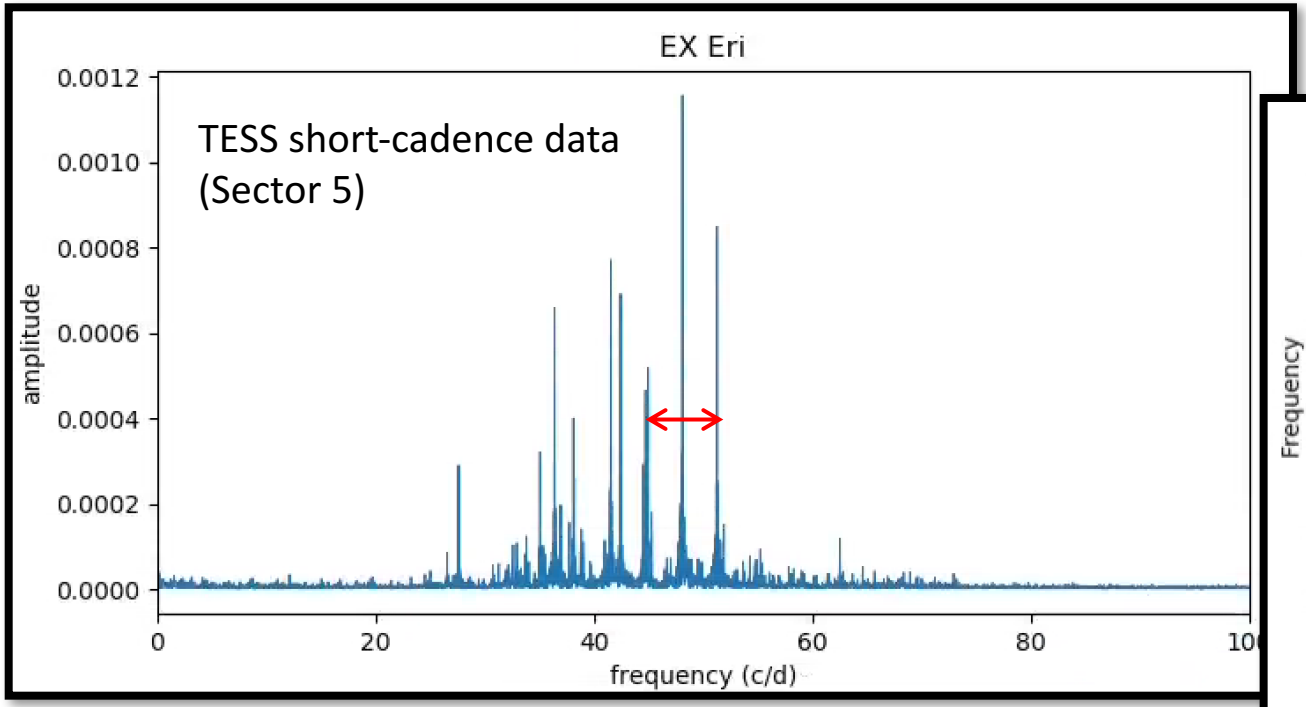


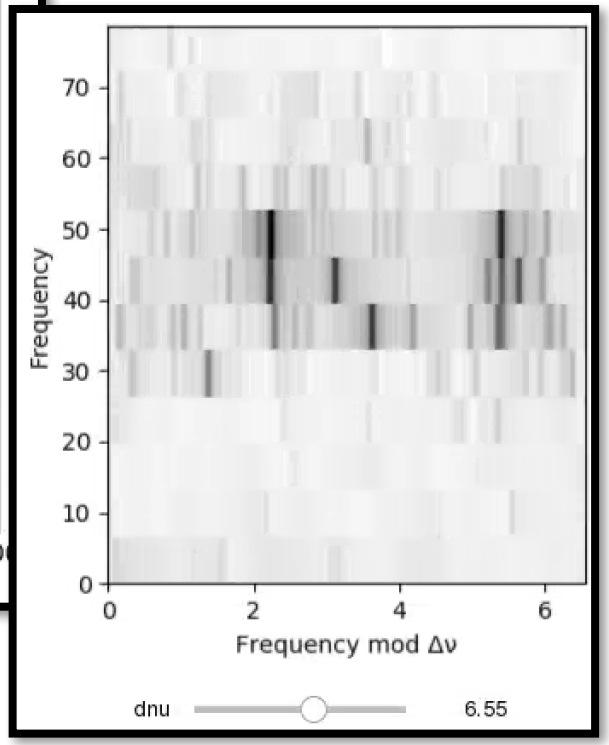
White et al. (2012)





échelle diagram


EX Eri
TESS short-cadence data
(Sector 5)
amplitude
0.0012
0.0010
0.0008
0.0006
0.0004
0.0002
0.0000
0
20
40
60
80
frequency (c/d)


Frequency
70
60
50
40
30
20
10
0
0
2
4
6
Frequency mod Δν
dnu
6.55

Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

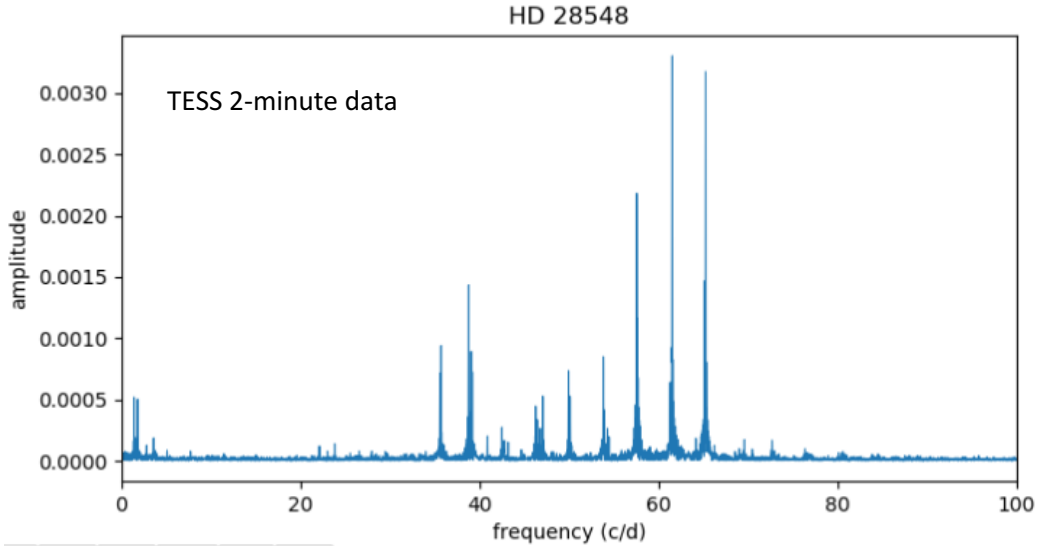
MNRAS **439,** 2078–2095 (2014)
Advance Access publication 2014 February 17

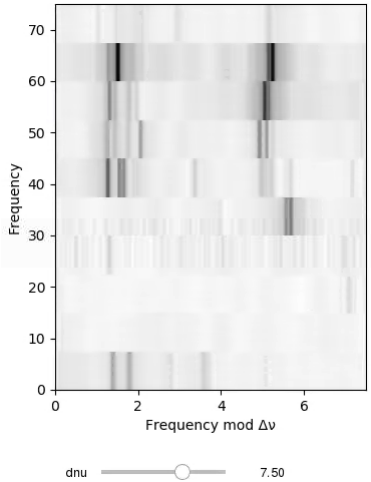
doi:10.1093/mnras/stu09

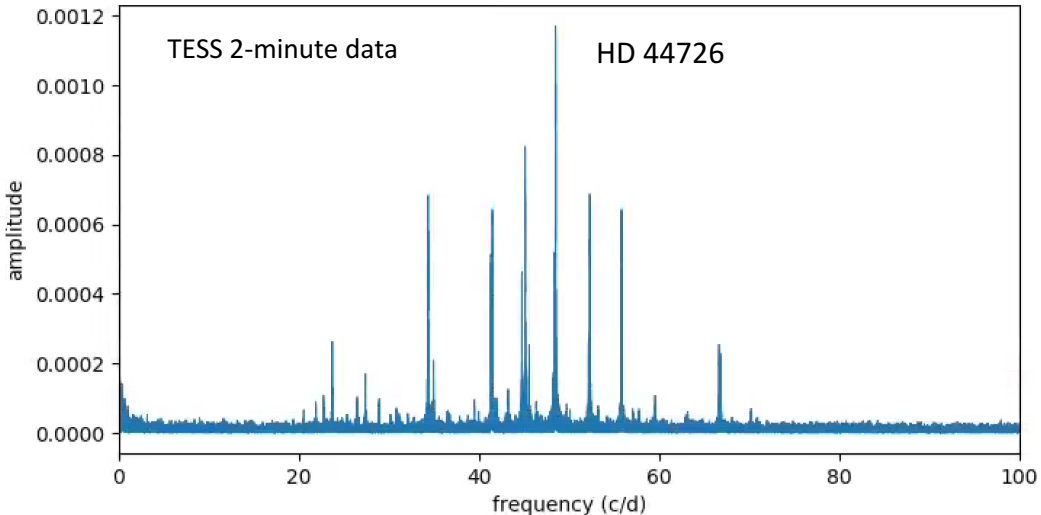
High-frequency A-type pulsators discovered using SuperWASP*†

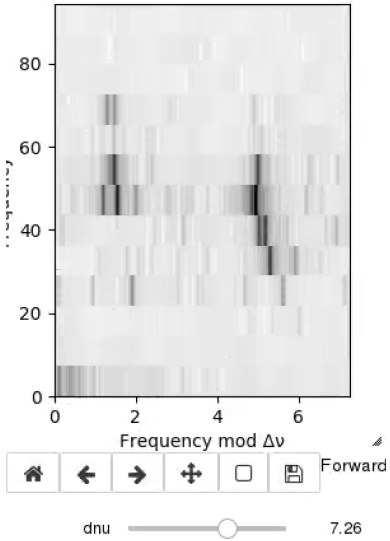
Daniel L. Holdsworth,[1]‡ B. Smalley,[1] M. Gillon,[2] K. I. Clubb,[3] J. Southworth,[1]
P. F. L. Maxted,[1] D. R. Anderson,[1] S. C. C. Barros,[4] A. Collier Cameron,[5] L. Delrez,[2]
F. Faedi,[6] C. A. Haswell,[7] C. Hellier,[1] K. Horne,[5] E. Jehin,[2] A. J. Norton,[7]
D. Pollacco,[6] I. Skillen,[8] A. M. S. Smith,[9] R. G. West[6] and P. J. Wheatley[6]

about 1/3 observed with TESS 2-minute cadence

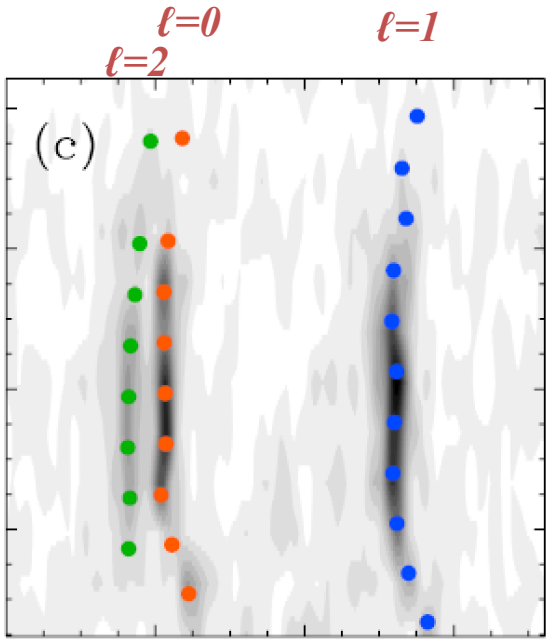

HD 28548
TESS 2-minute data
amplitude
frequency (c/d)


Frequency
Frequency mod Δν
dnu
7.50

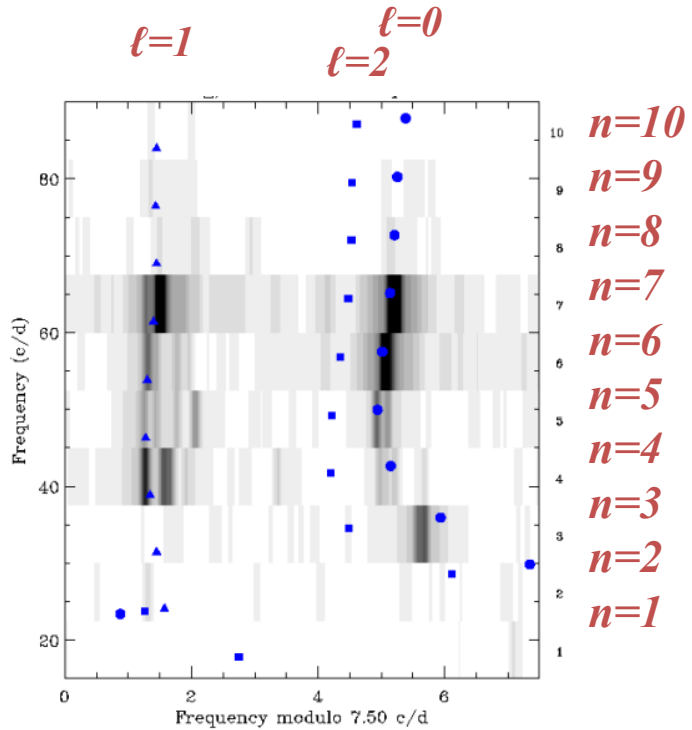

TESS 2-minute data
HD 44726
amplitude
frequency (c/d)


Frequency mod Δν
Forward
dnu
7.26

KIC 6933899 (“Fred”)
Sun-like star



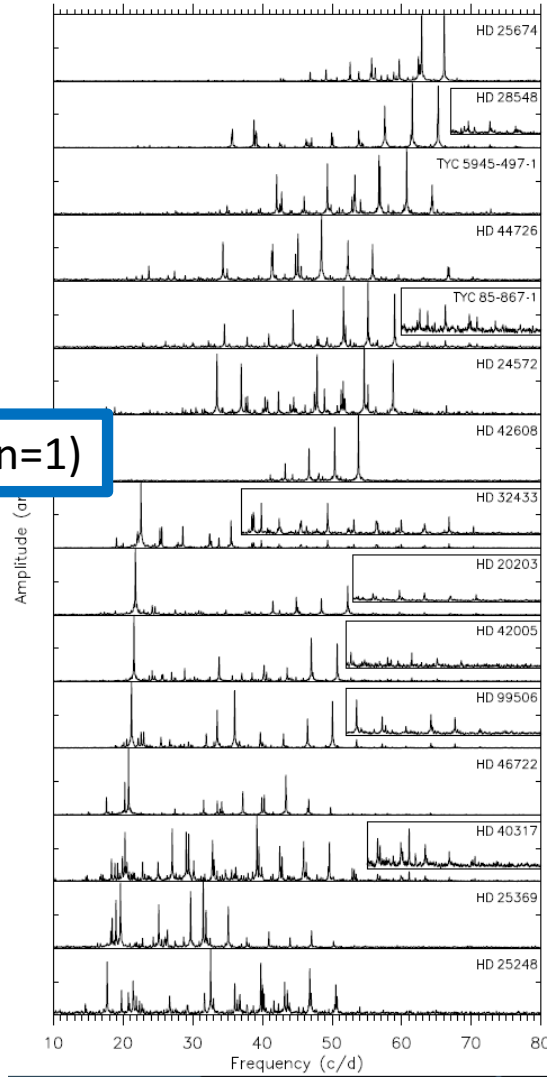
HD 28548
δ Scuti star

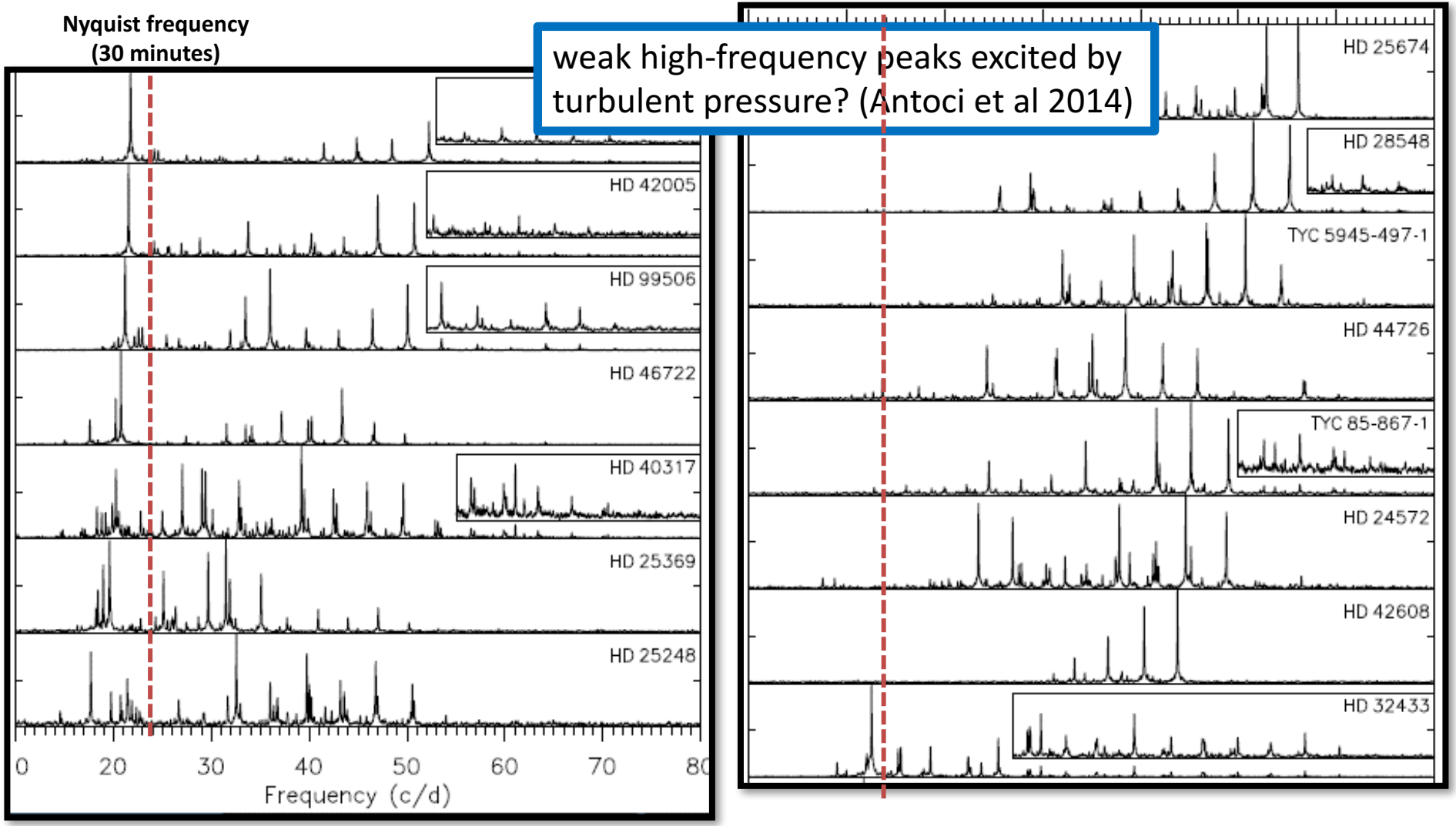


MESA model mass=1.56

we can assign *n* and *l* to the modes ☺

radial fundamental (ℓ=0, n=1)

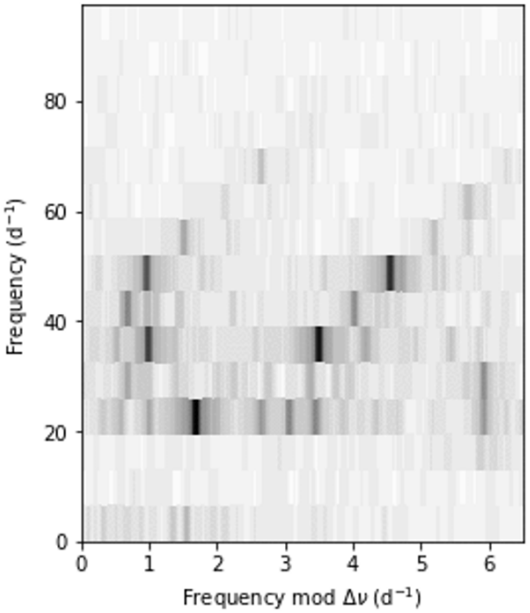


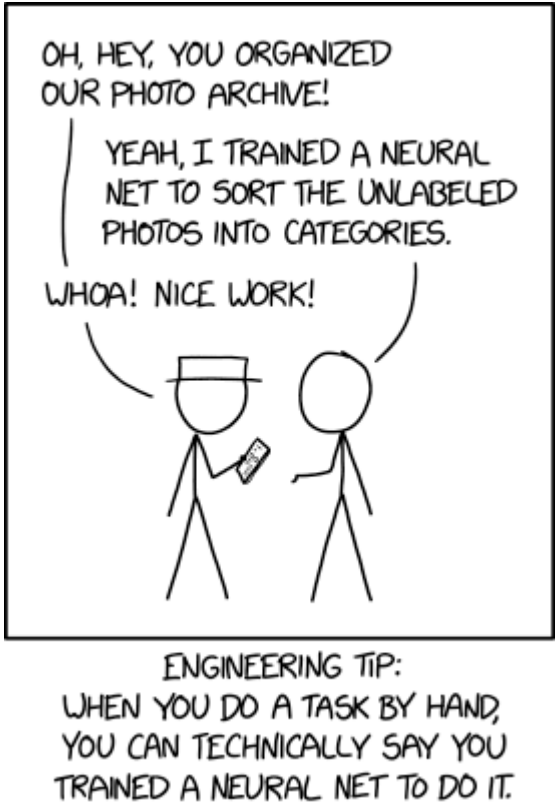

Nyquist frequency
(30 minutes)
weak high-frequency peaks excited by
turbulent pressure? (Antoci et al 2014)
HD 42005
HD 99506
HD 46722
HD 40317
HD 25369
HD 25248
0
20
30
40
50
60
70
Frequency (c/d)
HD 25674
HD 28548
TYC 5945-497-1
HD 44726
TYC 85-867-1
HD 24572
HD 42608
HD 32433

Finding more stars

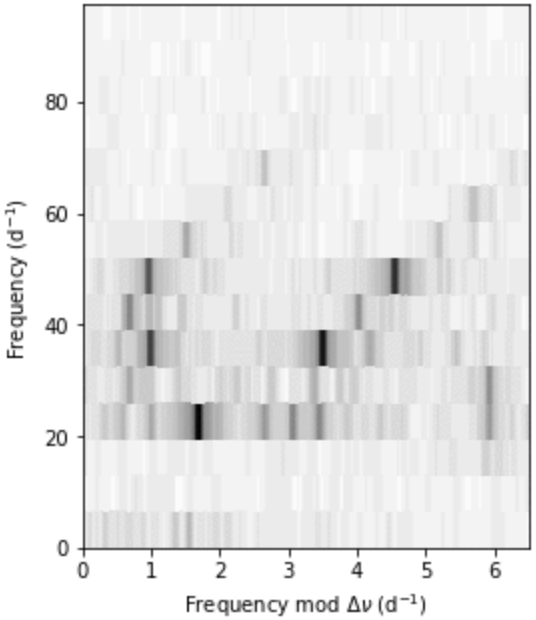
- downloaded all TESS short-cadence data (Sectors 1 to 9; PDC-MAP)
- computed amplitude spectrum
- considered distribution of peak heights above 30 c/d; measure *skewness* (3rd moment; Murphy et al 2019)
- inspected échelle diagrams
- also looked at *Kepler δ* Scutis with short-cadence data
- total 60 stars so far

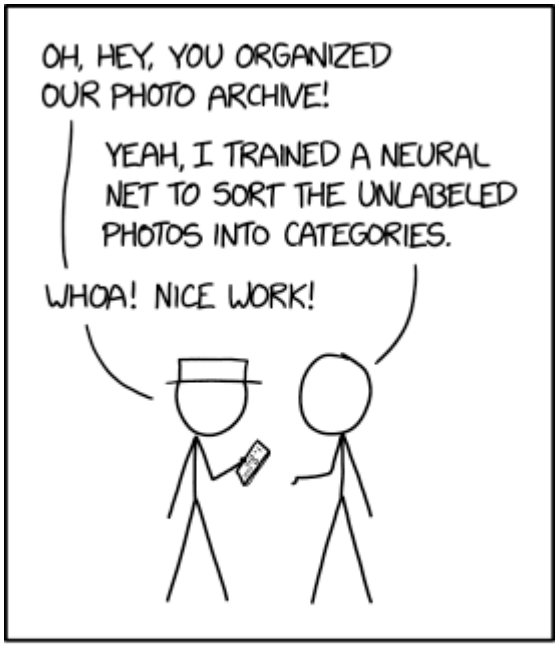
Finding Δν


Frequency (d^{-1})
0
20
40
60
80
0
1
2
3
4
5
6
Frequency mod Δν (d^{-1})
dnu

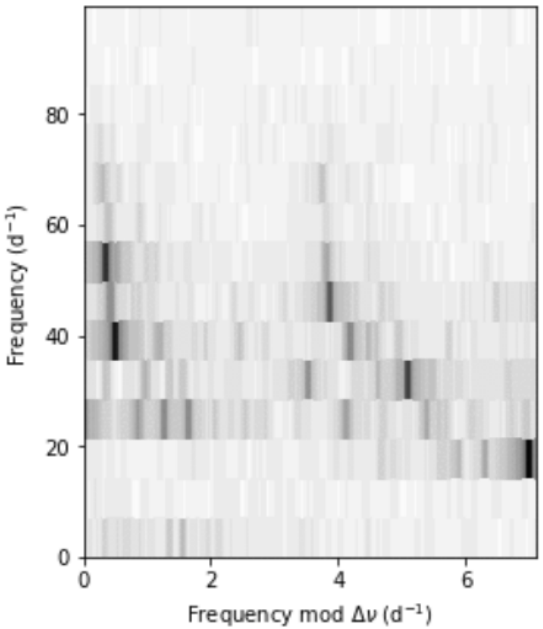

OH, HEY, YOU ORGANIZED OUR PHOTO ARCHIVE!
YEAH, I TRAINED A NEURAL NET TO SORT THE UNLABELED PHOTOS INTO CATEGORIES.
WHOA! NICE WORK!
ENGINEERING TIP:
WHEN YOU DO A TASK BY HAND, YOU CAN TECHNICALLY SAY YOU TRAINED A NEURAL NET TO DO IT.

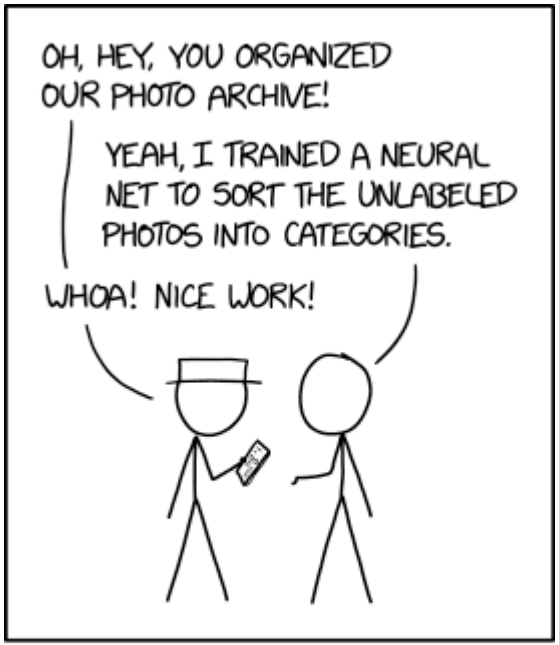
Finding Δv



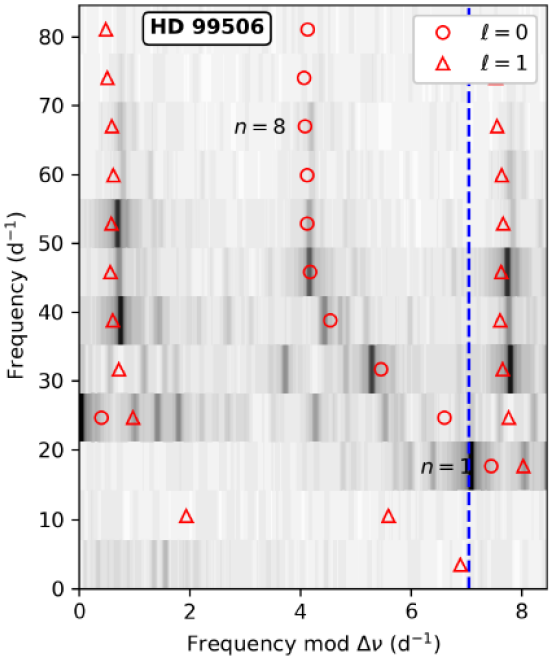


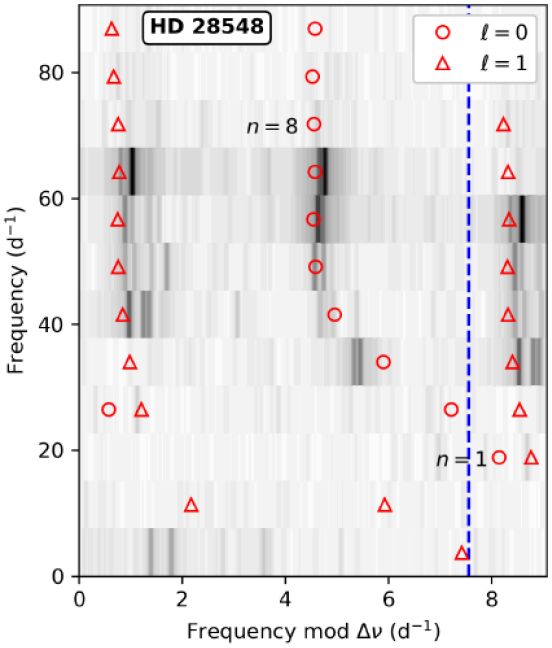
ENGINEERING TIP:
WHEN YOU DO A TASK BY HAND, YOU CAN TECHNICALLY SAY YOU TRAINED A NEURAL NET TO DO IT.

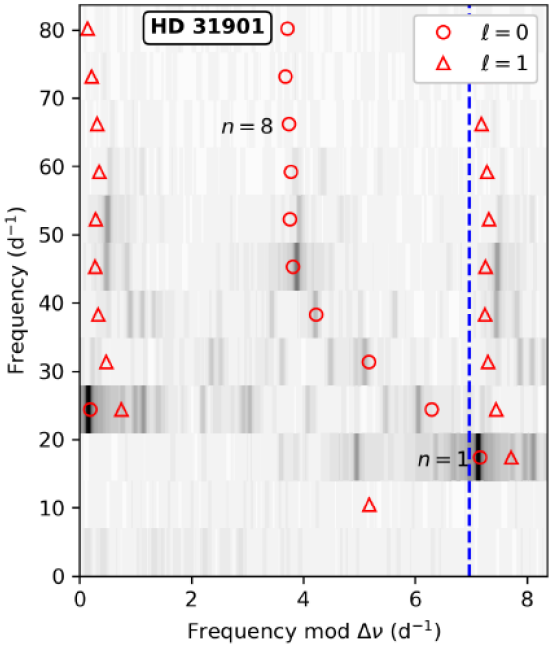




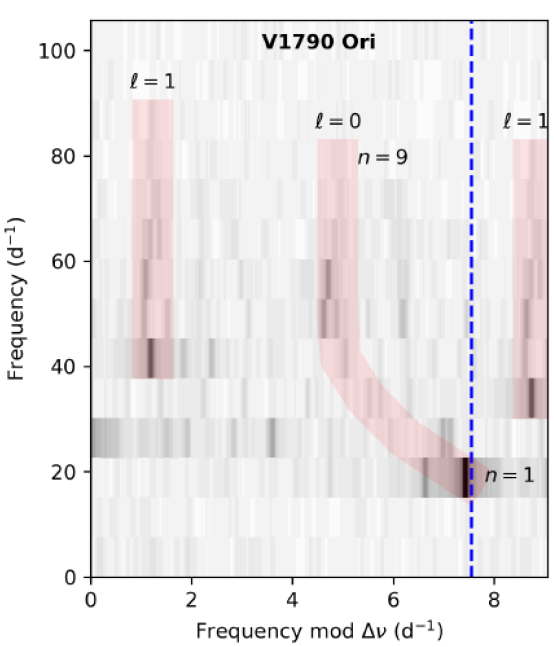
ENGINEERING TIP:
WHEN YOU DO A TASK BY HAND, YOU CAN TECHNICALLY SAY YOU TRAINED A NEURAL NET TO DO IT.

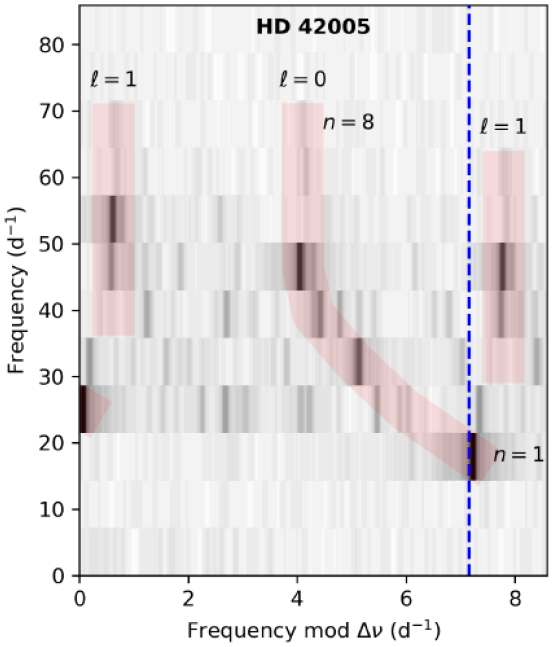


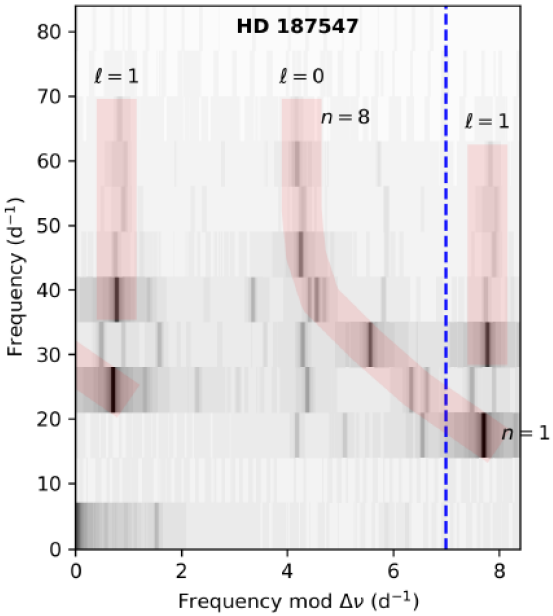


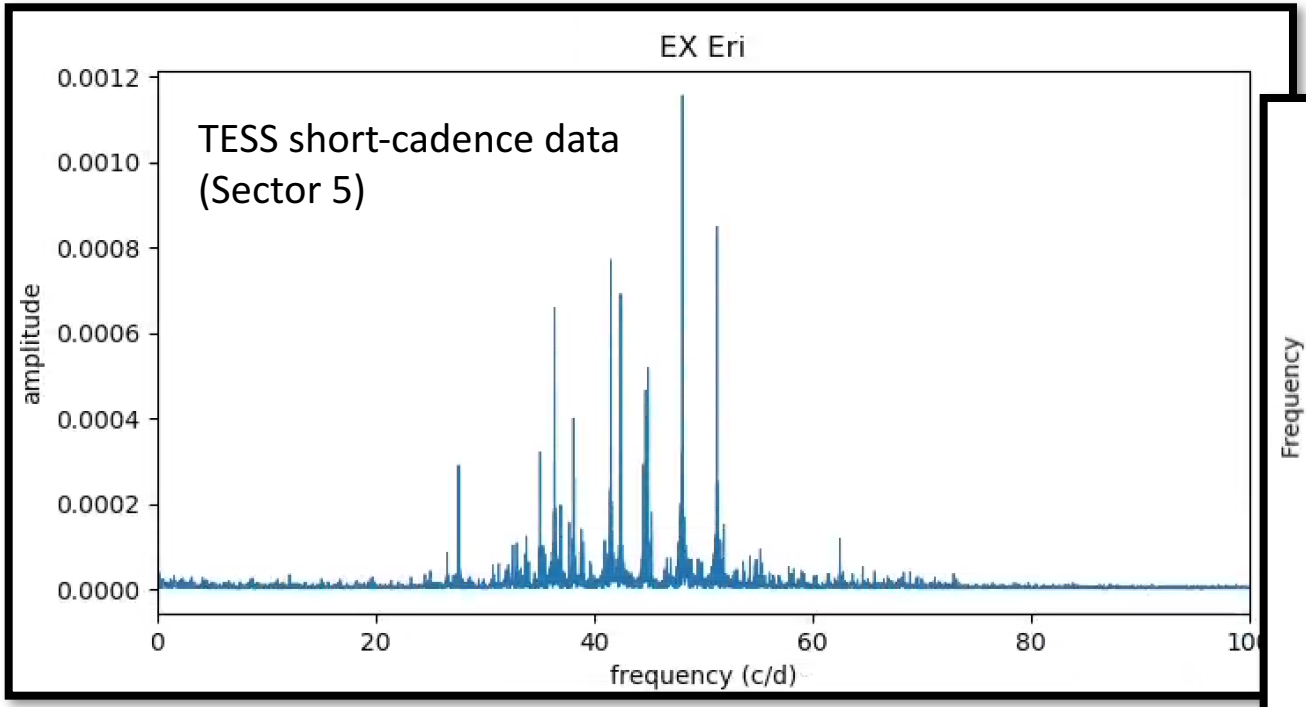


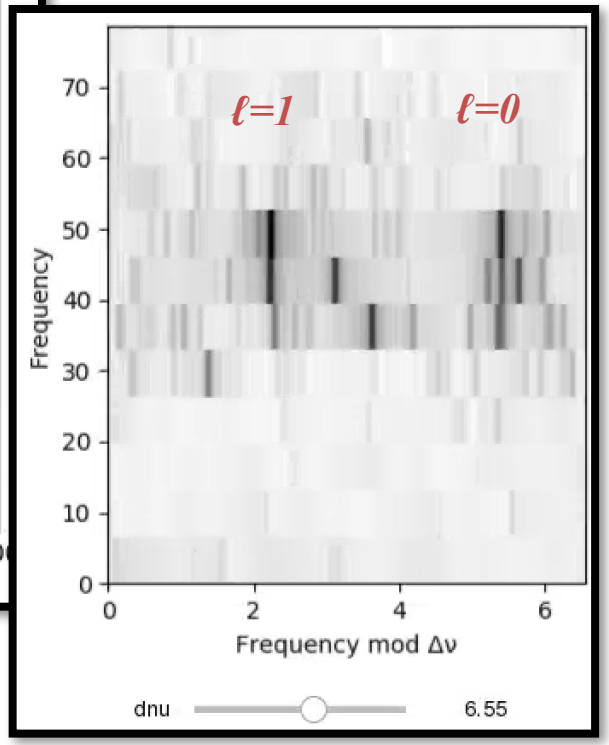
$\Delta\nu$ varies with frequency

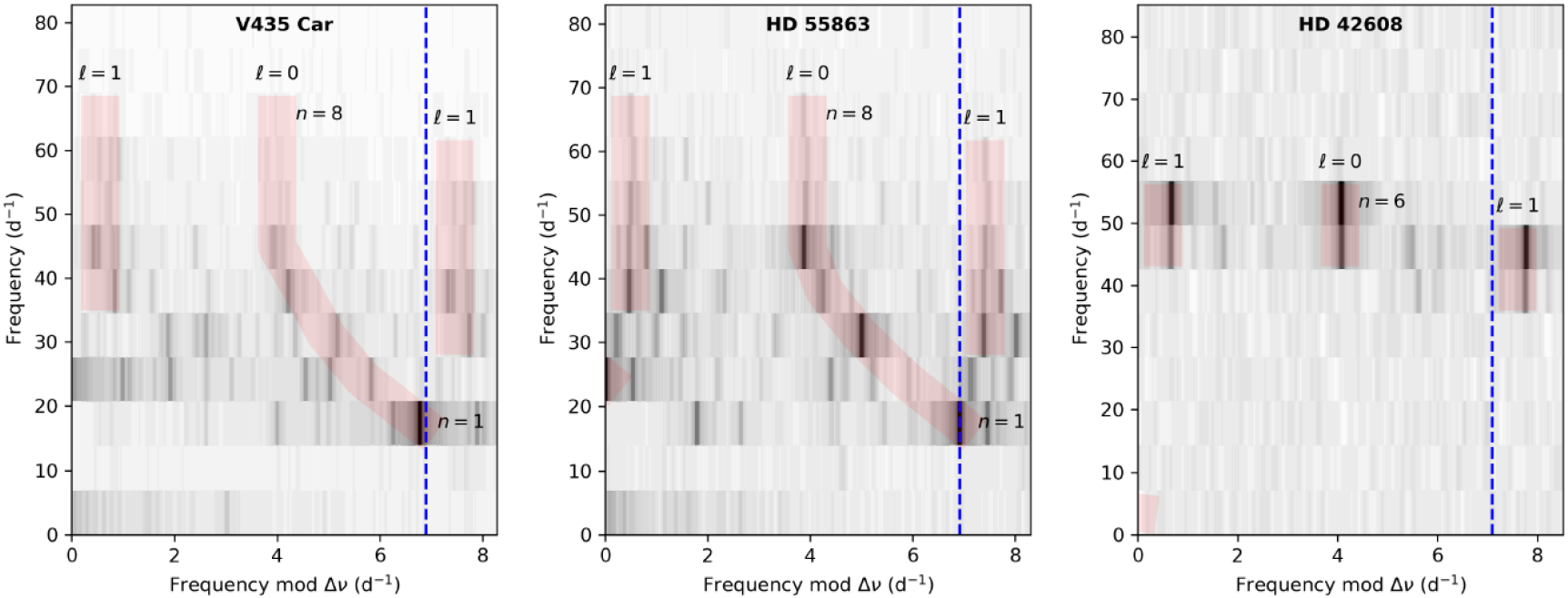

V1790 Ori
$\ell = 1$
$\ell = 0$
$n = 9$
$\ell = 1$
$n = 1$
Frequency (d^{-1})
Frequency mod $\Delta\nu$ (d^{-1})


HD 42005
$\ell = 1$
$\ell = 0$
$n = 8$
$\ell = 1$
$n = 1$
Frequency (d^{-1})
Frequency mod $\Delta\nu$ (d^{-1})

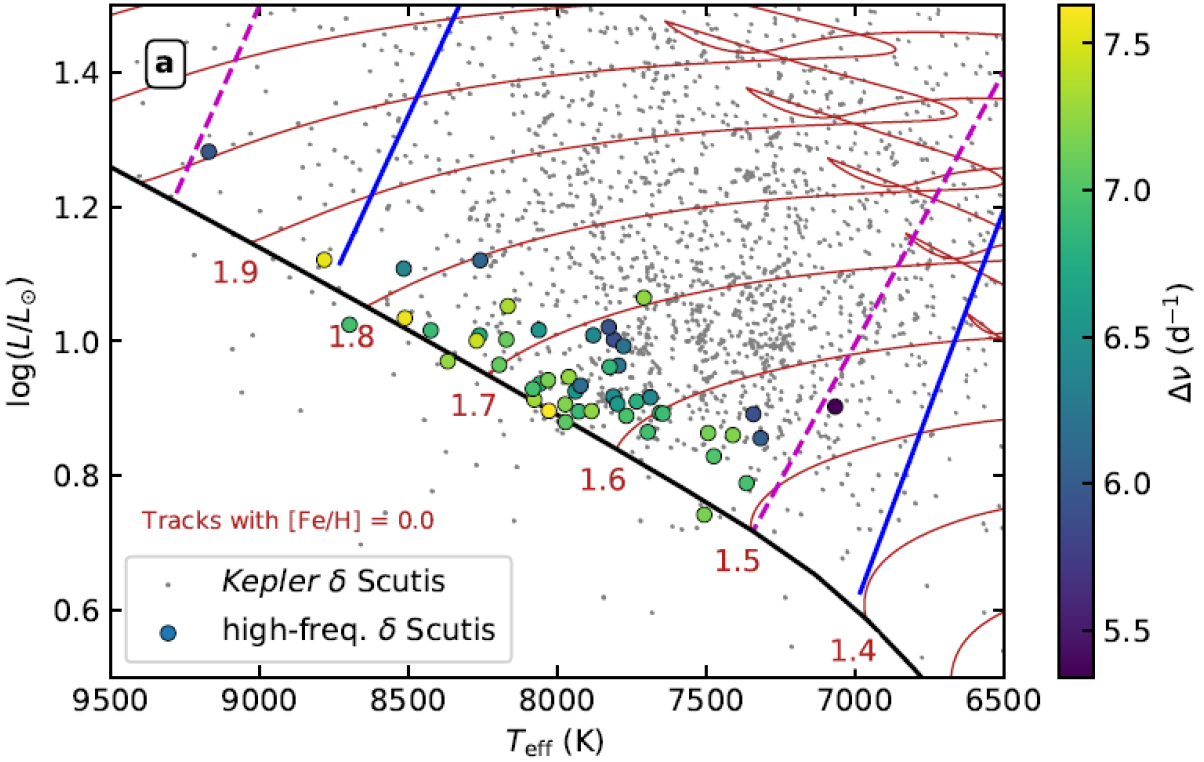

HD 187547
$\ell = 1$
$\ell = 0$
$n = 8$
$\ell = 1$
$n = 1$
Frequency (d^{-1})
Frequency mod $\Delta\nu$ (d^{-1})


EX Eri
TESS short-cadence data
(Sector 5)
amplitude
0.0012
0.0010
0.0008
0.0006
0.0004
0.0002
0.0000
0
20
40
60
80
frequency (c/d)

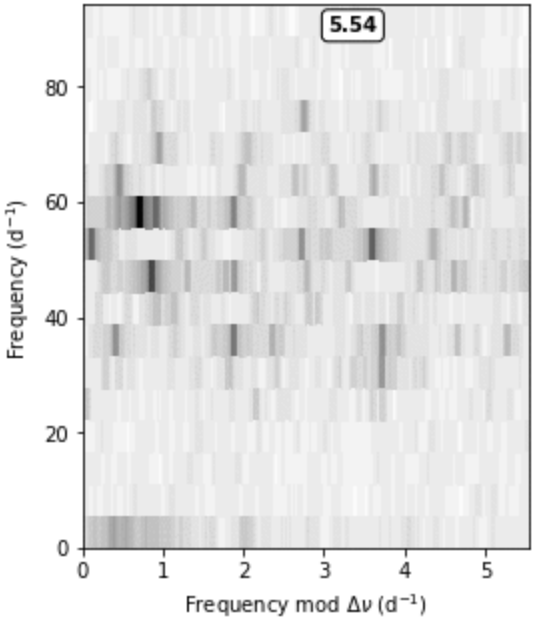

ℓ=1
ℓ=0
Frequency
70
60
50
40
30
20
10
0
0
2
4
6
Frequency mod Δν
dnu
6.55


V435 Car
HD 55863
HD 42608
$\ell = 1$
$\ell = 0$
$n = 8$
$n = 6$
$n = 1$
Frequency (d^{-1})
Frequency mod $\Delta\nu$ (d^{-1})

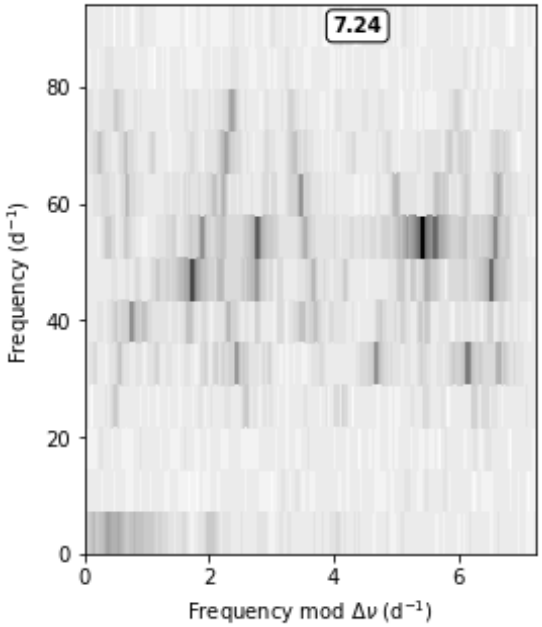
HR diagram (Gaia DR2) – these are young stars



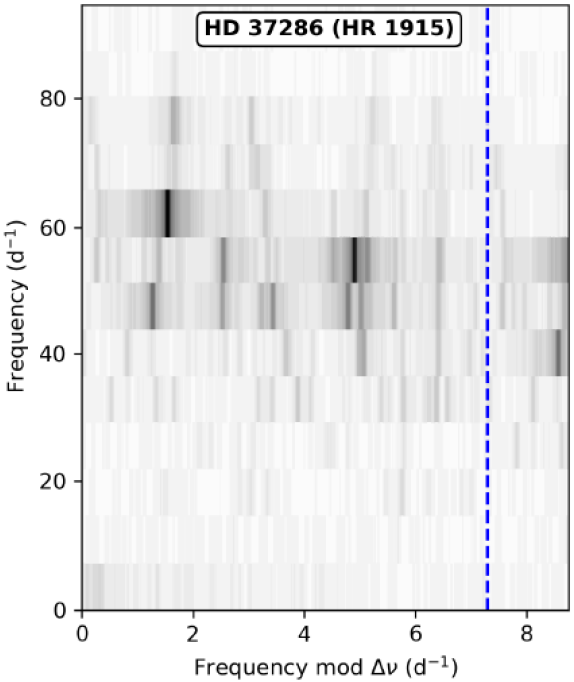
some more complex patterns:

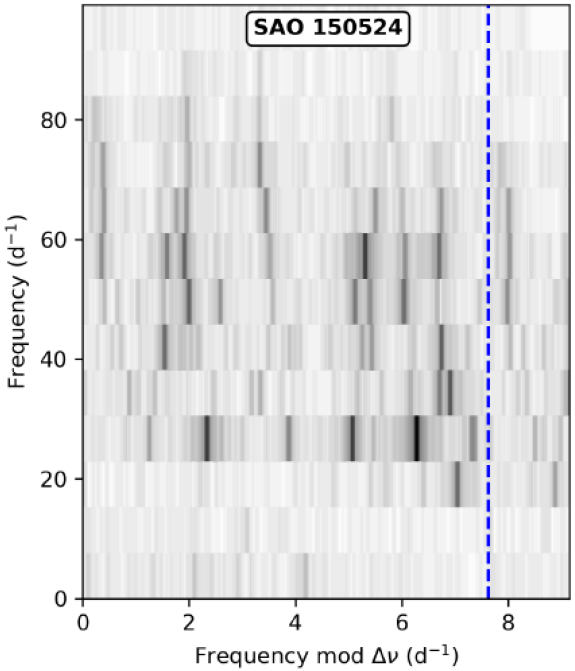


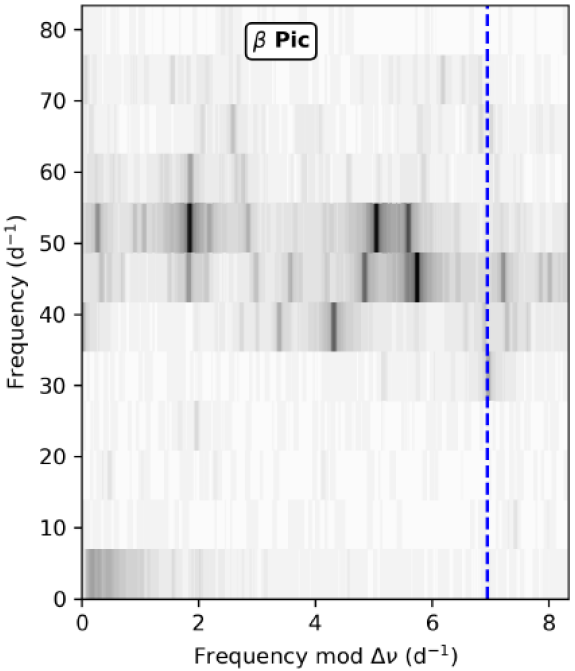
some more complex patterns:



some more complex patterns:



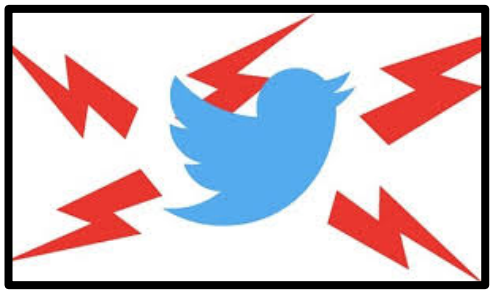




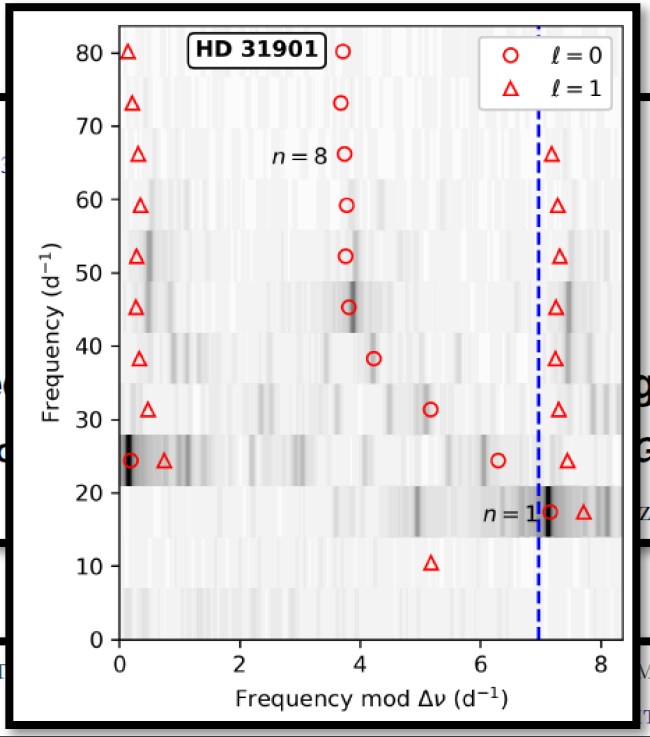
rotation

Young associations

- used *Gaia* DR2 space motions
- cross-matched with known moving groups, clusters and stellar streams:
  - 5 in associations: Octans (3), Cari
  - 1 in moving group: β Pic
  - 1 in stellar stream: Pisces-Eridanae (HD 31901)



Pisces-Eridanae stellar stream



A&A 622, L13 (2019)
https://doi.org/10.1051/0004-6
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Astronomy & Astrophysics

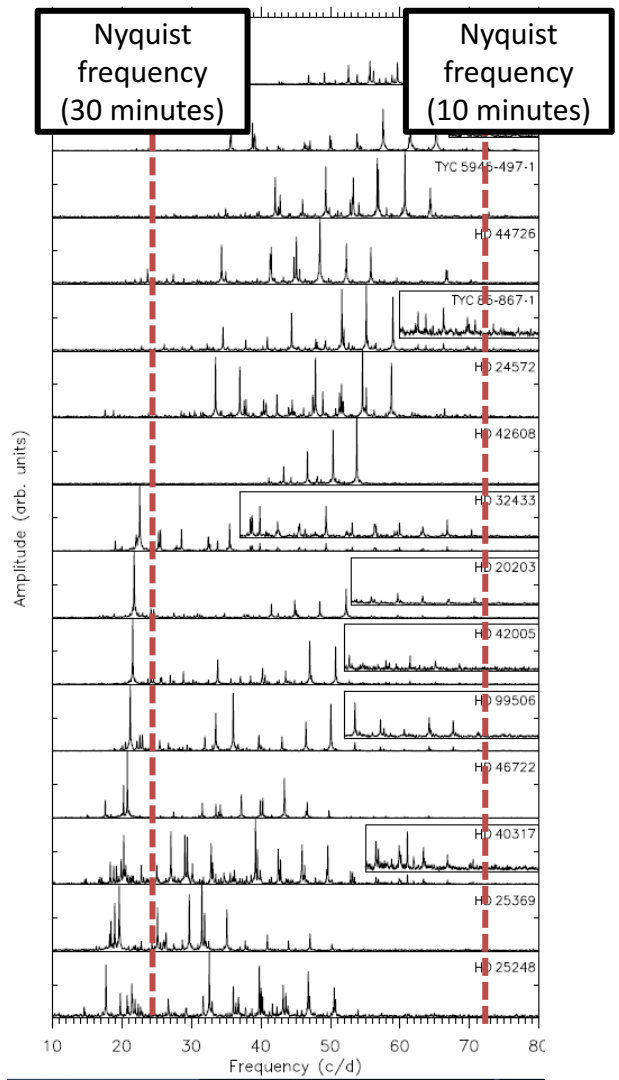
Extende ghborhood

II. Disc *Gaia* DR2★

z[1]

TESS Reveals that M is only 120 Myr Old

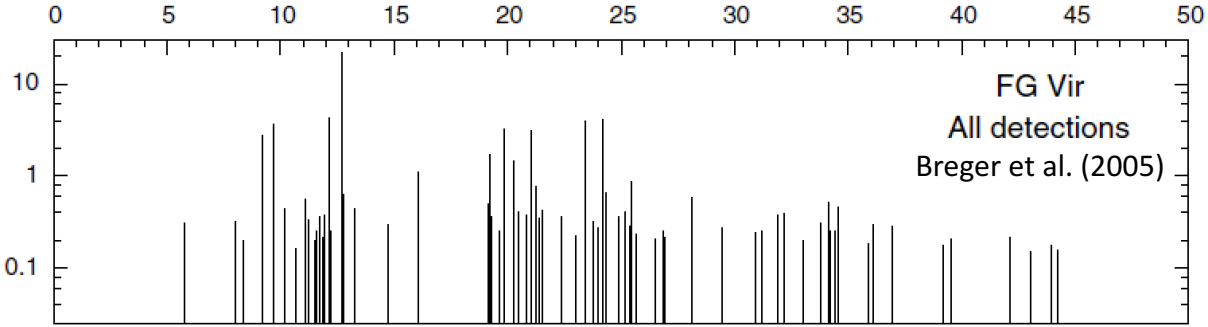
Jason L. Curtis,[1,*] Marcel t,[4] and Jeffrey D. Cummings[5]

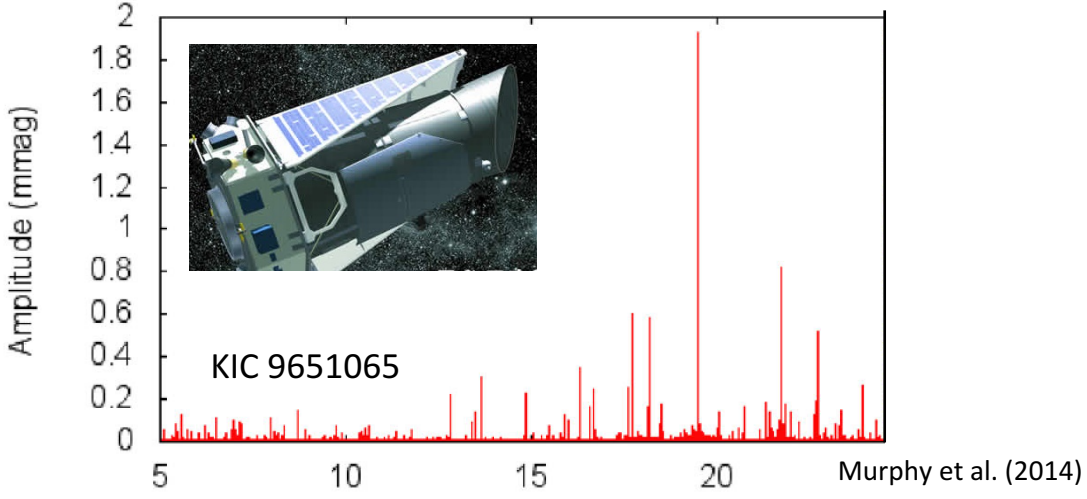


What next?

- can finally do detailed asteroseismology of (some) δ Scuti stars
- compare with models: ages and internal rotation
- TESS is observing many at 2-minute cadence - and even more when FFI long cadence is shortened to 10 minutes

Asteroseismology of δ Scuti pulsators is difficult!

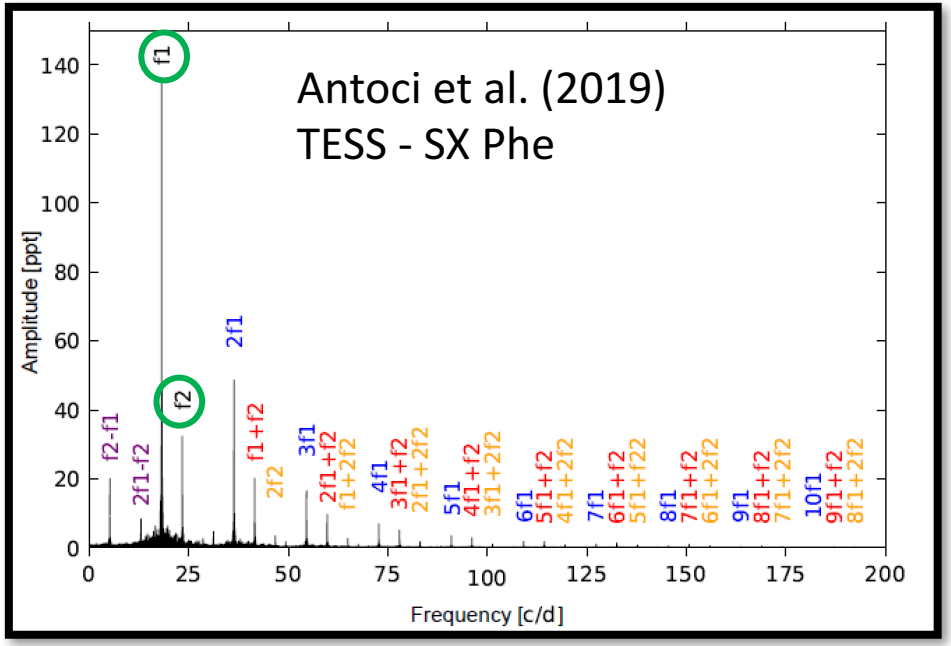


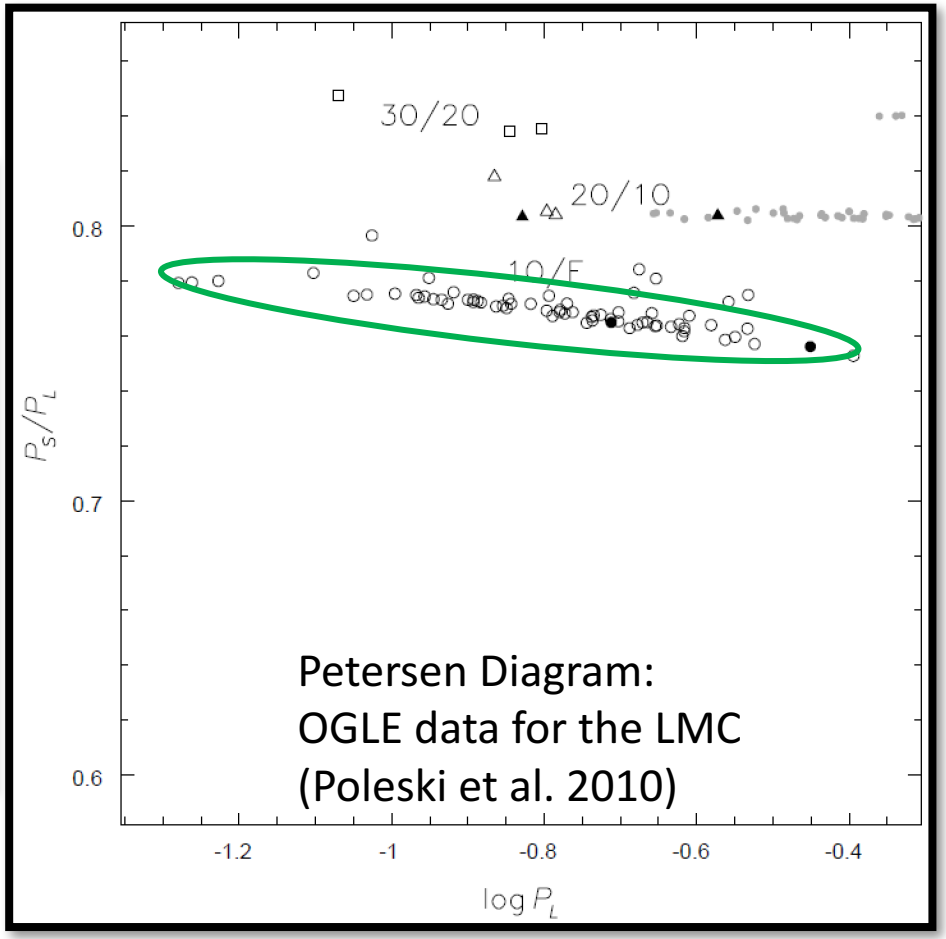


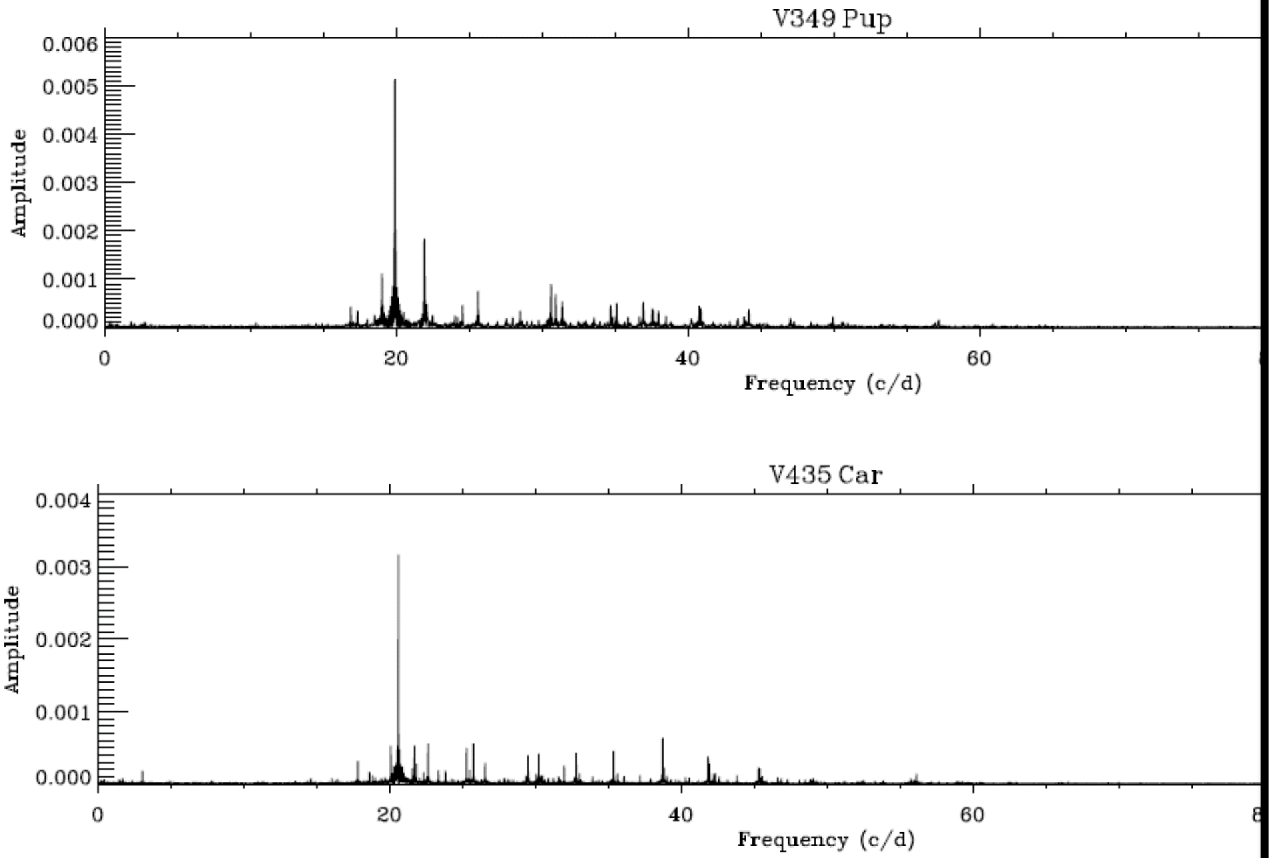
Murphy et al. (2014)

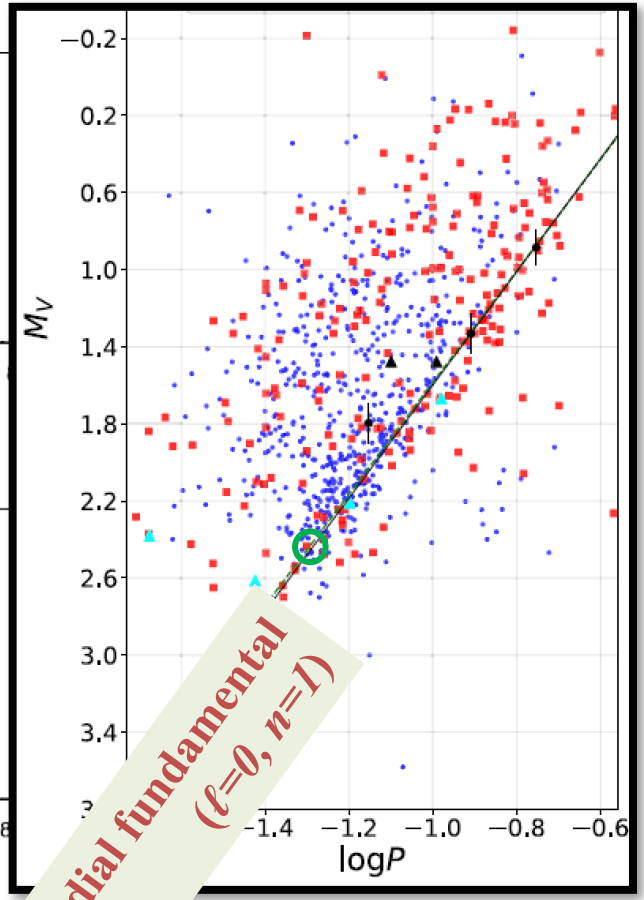
Some δ Scutis are simple

- both radial ($\ell=0$)
- fundamental ($n=1$) & 1st overtone ($n=2$)

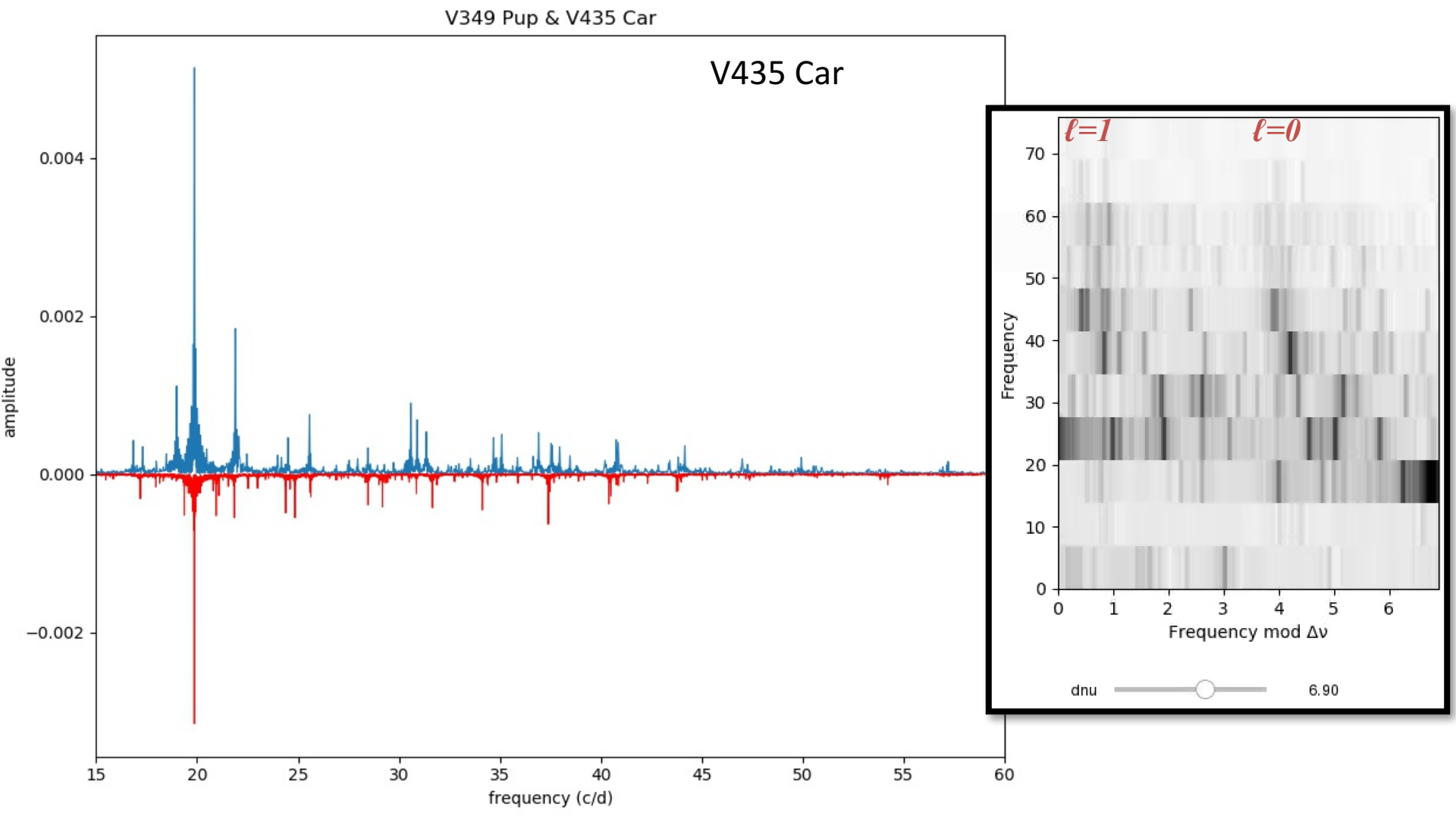


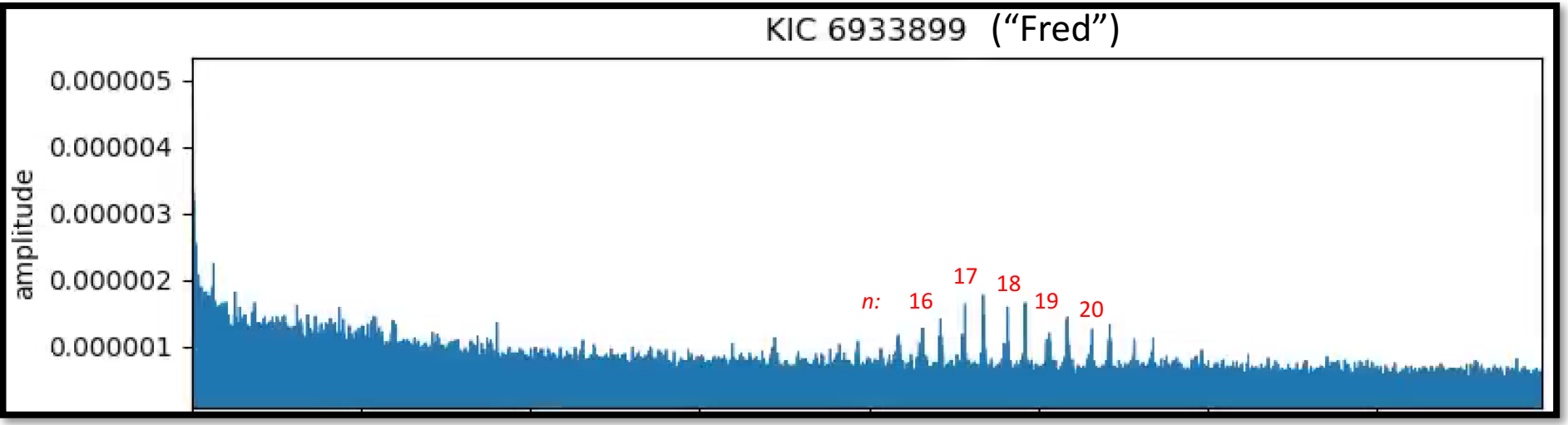


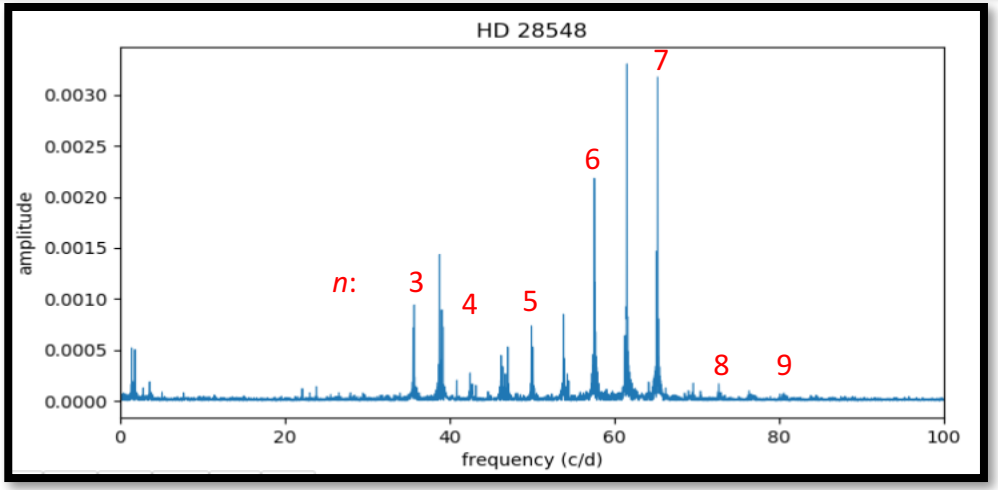




Ziaali et al. (2019)


V349 Pup & V435 Car
V435 Car
0.004
0.002
0.000
−0.002
amplitude
15
20
25
30
35
40
45
50
55
60
frequency (c/d)
ℓ=1
ℓ=0
70
60
50
40
30
20
10
0
Frequency
0
1
2
3
4
5
6
Frequency mod Δν
dnu
6.90

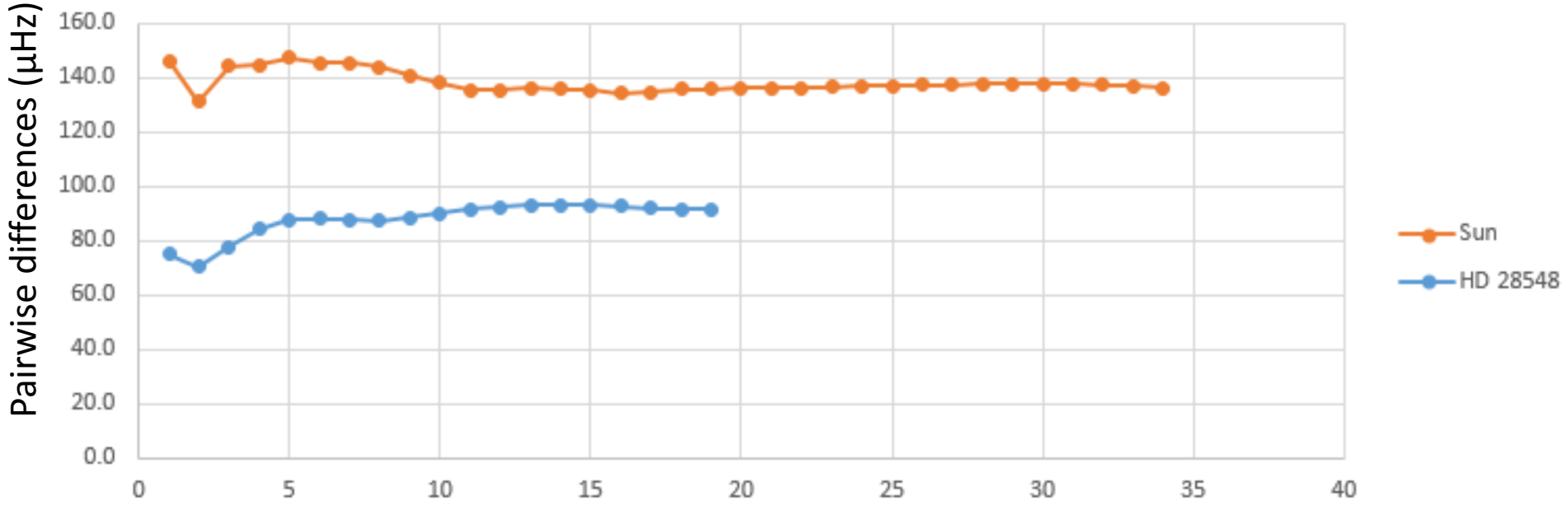


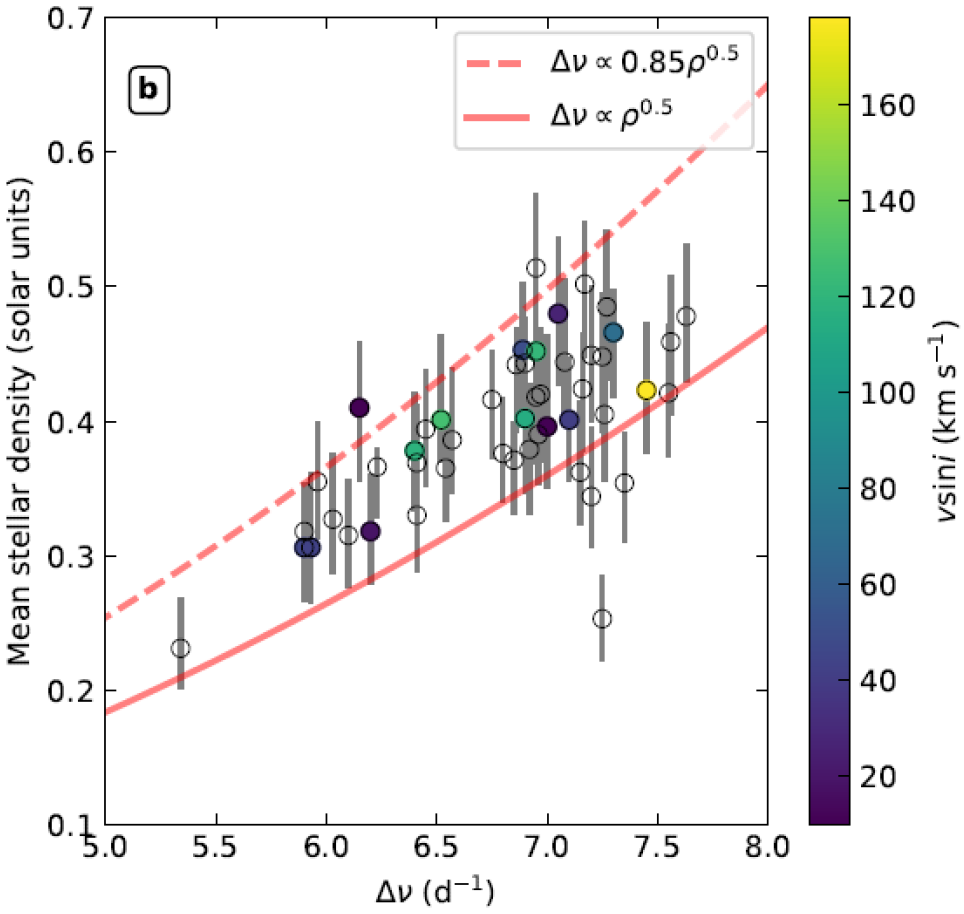


These are *not* solar-like oscillations:

- much higher amplitude
- much lower *n* (do not obey the same ν_{max} scaling relation)

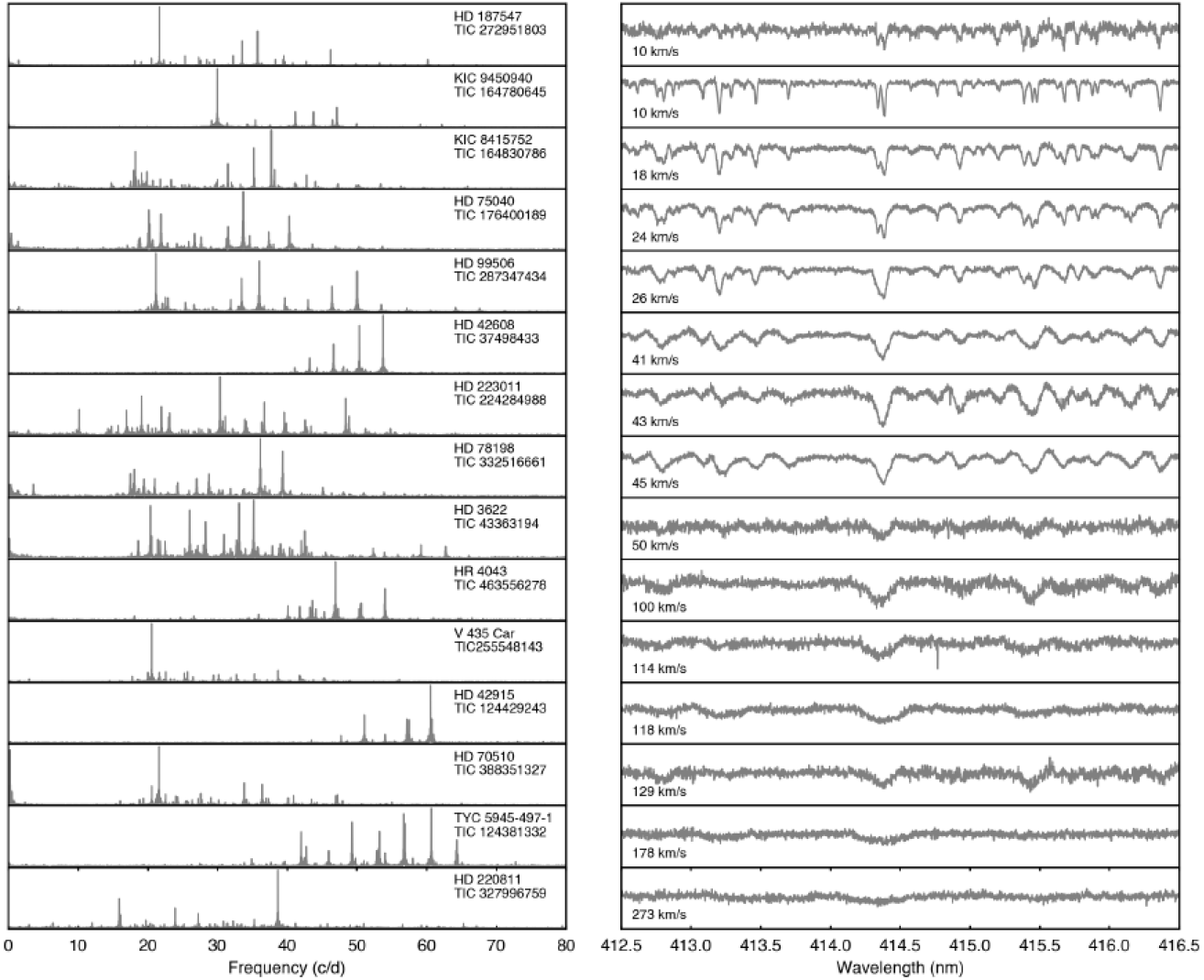
Δν varies with frequency




b
$\Delta\nu \propto 0.85\rho^{0.5}$
$\Delta\nu \propto \rho^{0.5}$
Mean stellar density (solar units)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
5.0
5.5
6.0
6.5
7.0
7.5
8.0
$\Delta\nu$ (d^{-1})
160
140
120
100
80
60
40
20
$v\sin i$ (km s^{-1})

Rotation

- obtained high-resolution spectra of 14 stars with Keck/HIRES and LCO/NRES
- plus published *v* sin *i* for 5 stars
- more than half *v* sin *i* values below 70 km/s
- implies some (but not all) are seen close to pole-on
- also lots are λ Boo stars


HD 187547
TIC 272951803
KIC 9450940
TIC 164780645
KIC 8415752
TIC 164830786
HD 75040
TIC 176400189
HD 99506
TIC 287347434
HD 42608
TIC 37498433
HD 223011
TIC 224284988
HD 78198
TIC 332516661
HD 3622
TIC 43363194
HR 4043
TIC 463556278
V 435 Car
TIC255548143
HD 42915
TIC 124429243
HD 70510
TIC 388351327
TYC 5945-497-1
TIC 124381332
HD 220811
TIC 327996759
0
10
20
30
40
50
60
70
80
Frequency (c/d)
10 km/s
10 km/s
18 km/s
24 km/s
26 km/s
41 km/s
43 km/s
45 km/s
50 km/s
100 km/s
114 km/s
118 km/s
129 km/s
178 km/s
273 km/s
412.5
413.0
413.5
414.0
414.5
415.0
415.5
416.0
416.5
Wavelength (nm)


PRELIMINARY