Space-Based Asteroseismology across the HR Diagram

Daniel Huber

University of Sydney

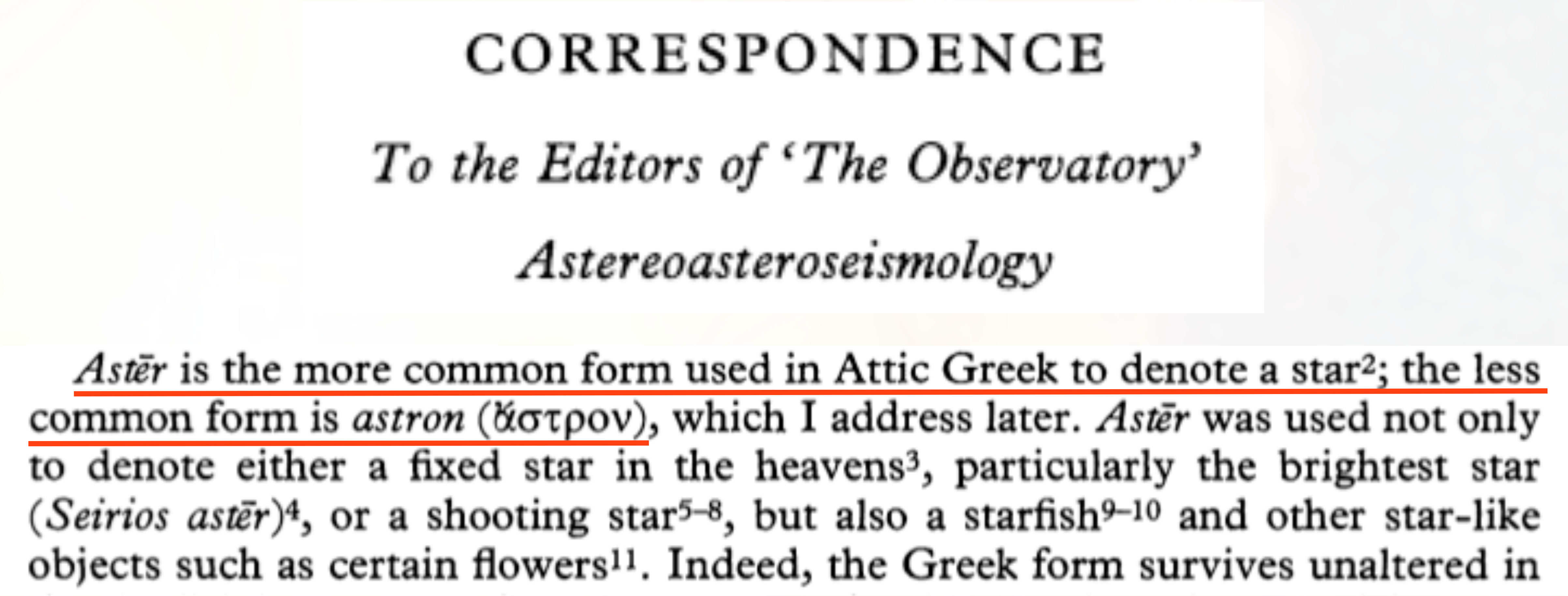
Chaos Among the Stars

August 2015

Asteroseismology in a Nutshell

?

Asteroseismology in a Nutshell

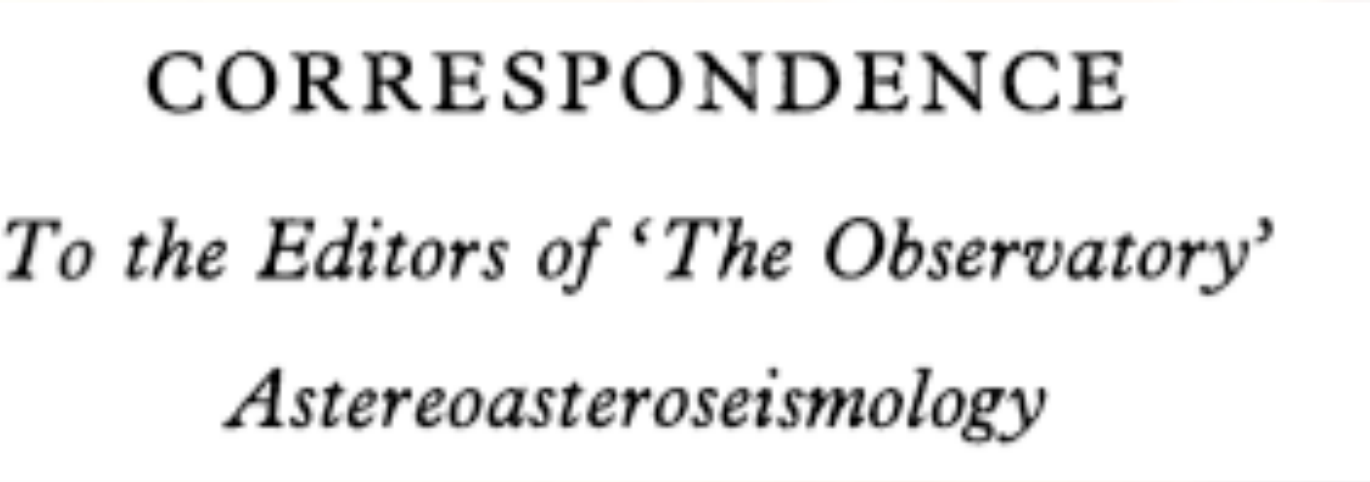


CORRESPONDENCE

To the Editors of 'The Observatory'

Astereoasteroseismology

Astēr is the more common form used in Attic Greek to denote a star[2]; the less common form is *astron* (ἄστρον), which I address later. *Astēr* was used not only to denote either a fixed star in the heavens[3], particularly the brightest star (*Seirios astēr*)[4], or a shooting star[5–8], but also a starfish[9–10] and other star-like objects such as certain flowers[11]. Indeed, the Greek form survives unaltered in



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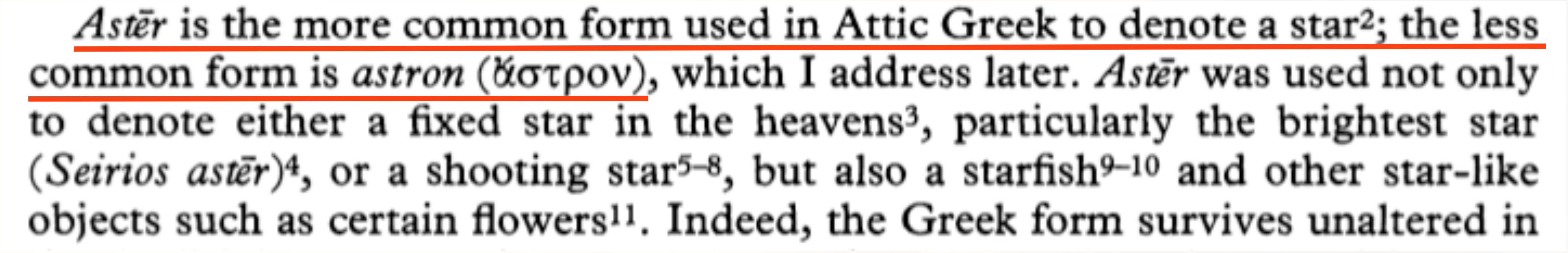

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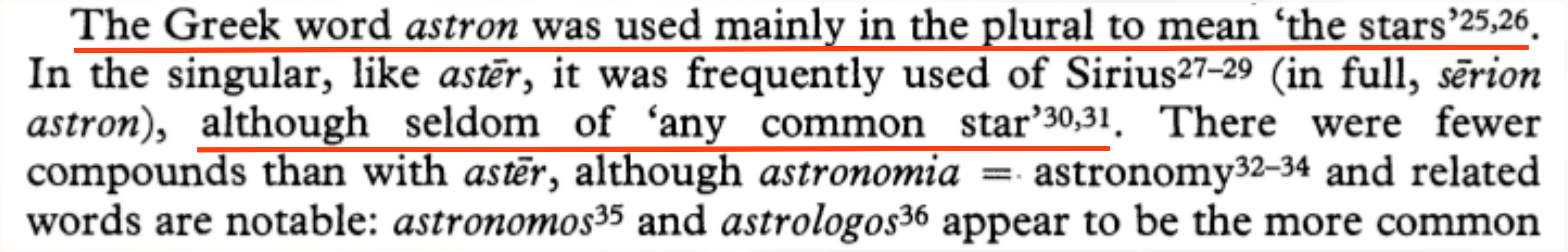
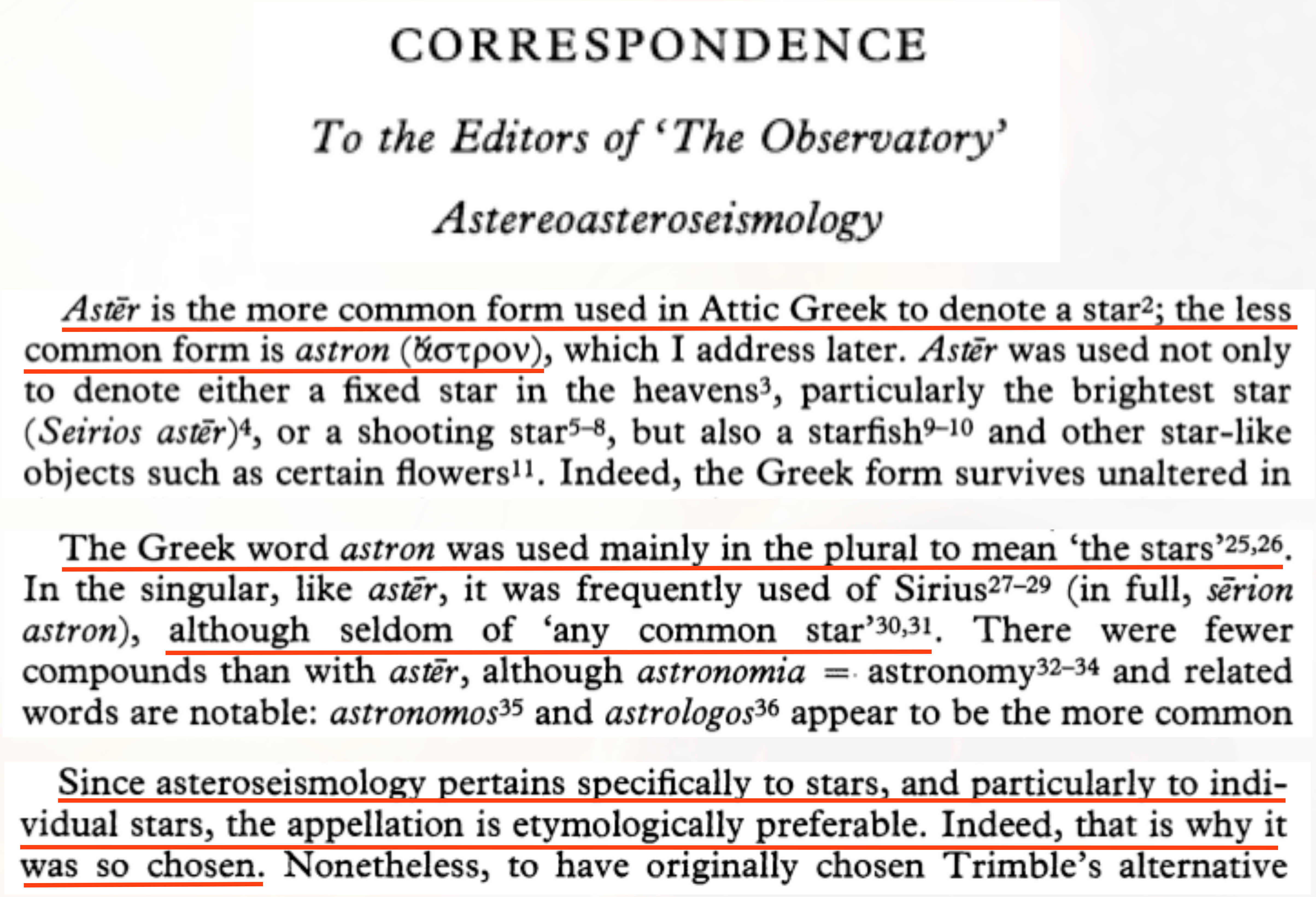


The Greek word *astron* was used mainly in the plural to mean 'the stars'[25,26]. In the singular, like *astēr*, it was frequently used of Sirius[27–29] (in full, *sērion astron*), although seldom of 'any common star'[30,31]. There were fewer compounds than with *astēr*, although *astronomia* = astronomy[32–34] and related words are notable: *astronomos*[35] and *astrologos*[36] appear to be the more common



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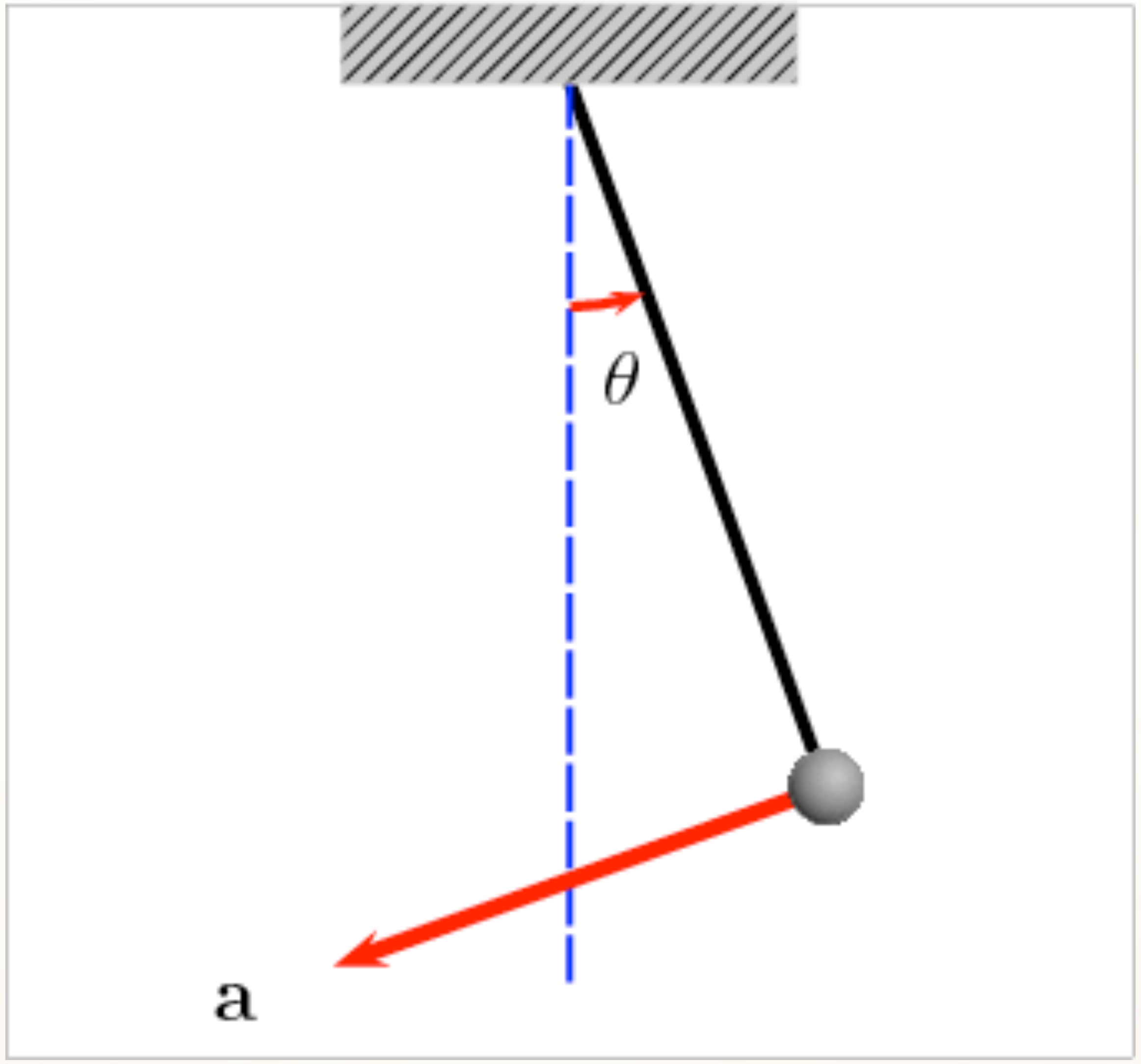
I hope this discussion will dissuade idiosyncratic reviewers of the field from mispronouncing further on our subject in a manner that detracts from its legitimate etymological origins.

Yours faithfully,

Douglas Gough

Oscillating Stars



$$t_{\rm dyn} \simeq \left(\frac{R^3}{GM}\right)^{1/2} \simeq (G\bar{\rho})^{-1/2}$$

dynamical timescale

Oscillation

=

Perturbation

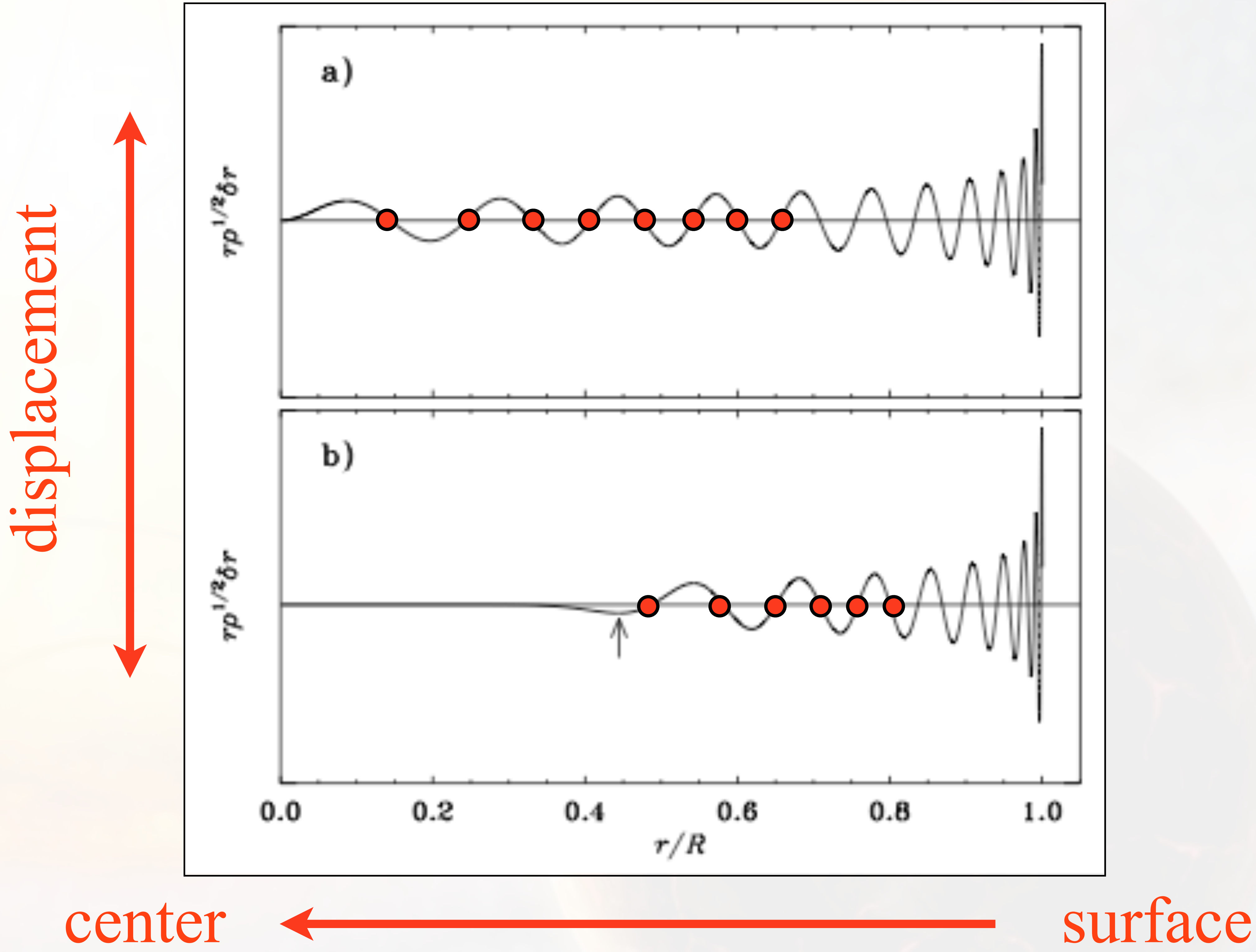
+

Restoring force to bring back to equilibrium

+

Inertia to cause overshoot over equilibrium point

Radial Order *n*



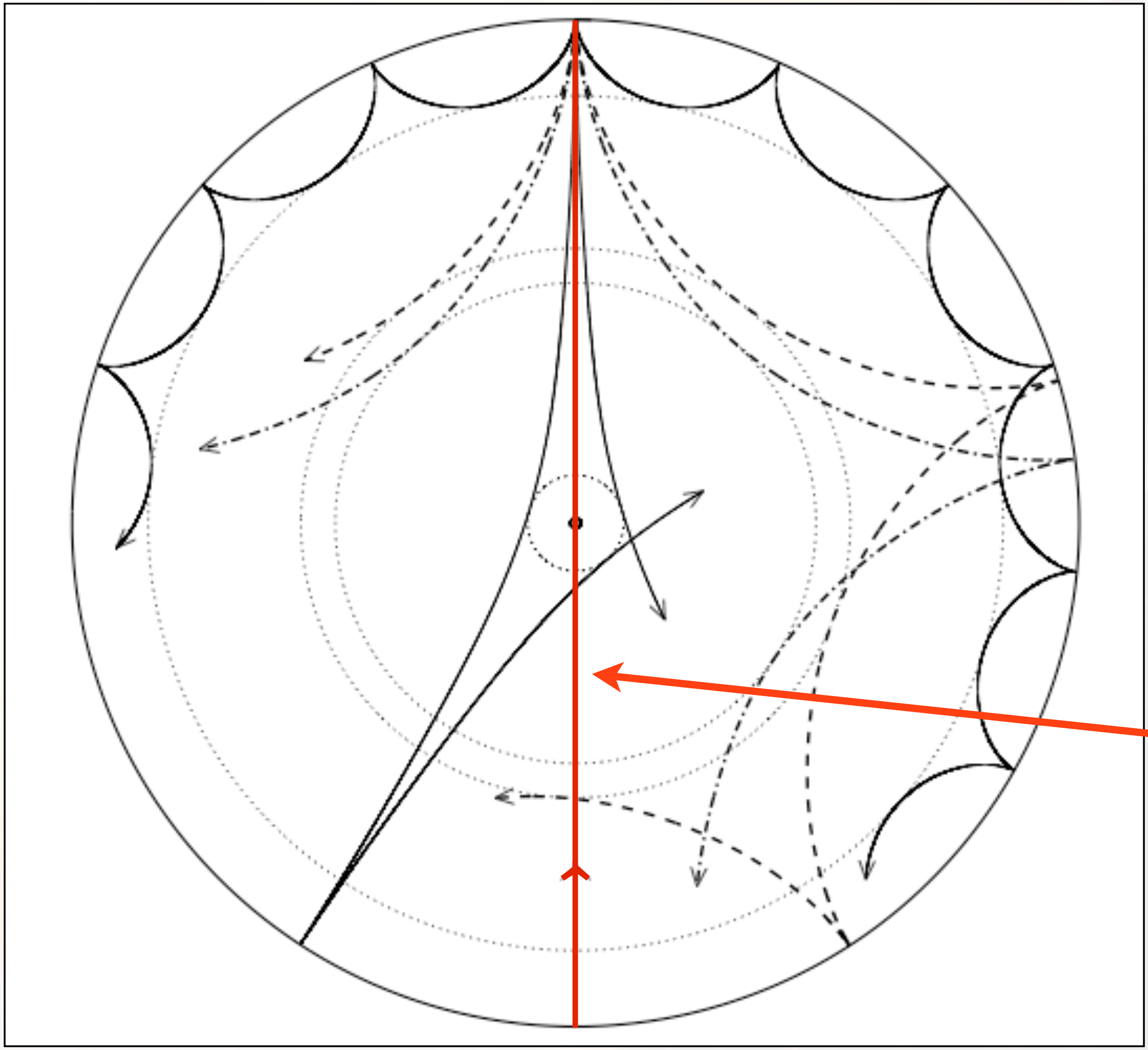
displacement

center

surface

number of nodes from the surface to the center of the star

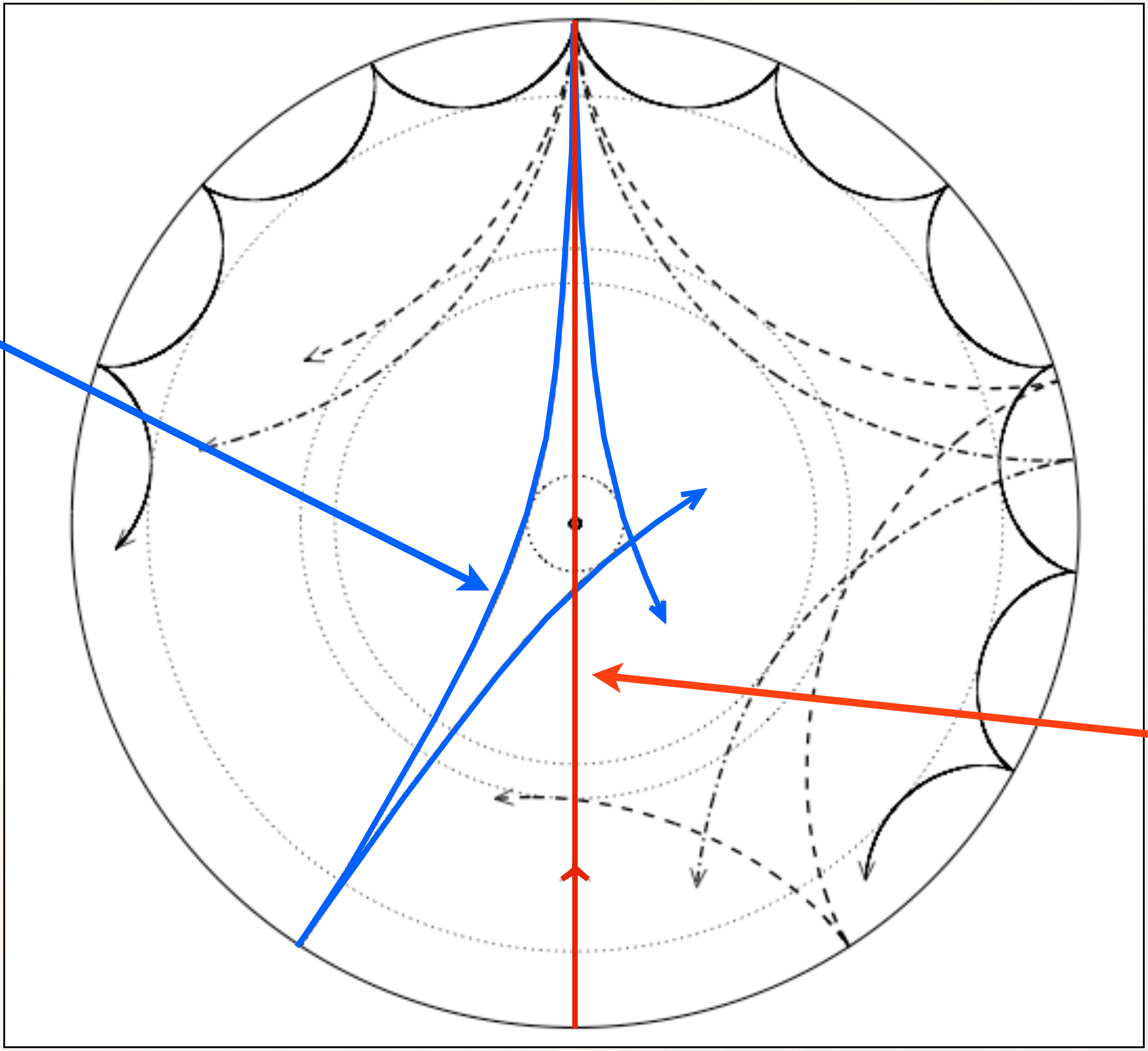
Spherical Degree l



$l = 0$

total number of nodes on surface of the star

Spherical Degree *l*



***l* = 2**

***l* = 0**

total number of nodes on surface of the star

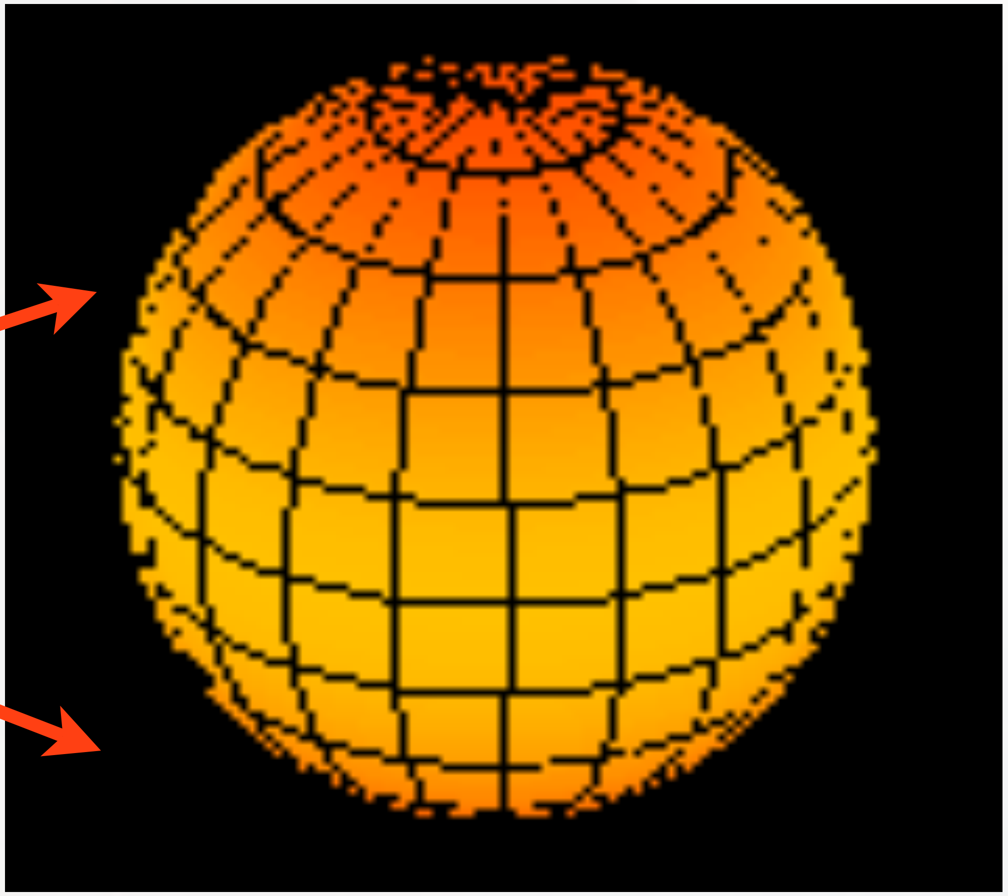
Spherical Harmonics Y_l^m

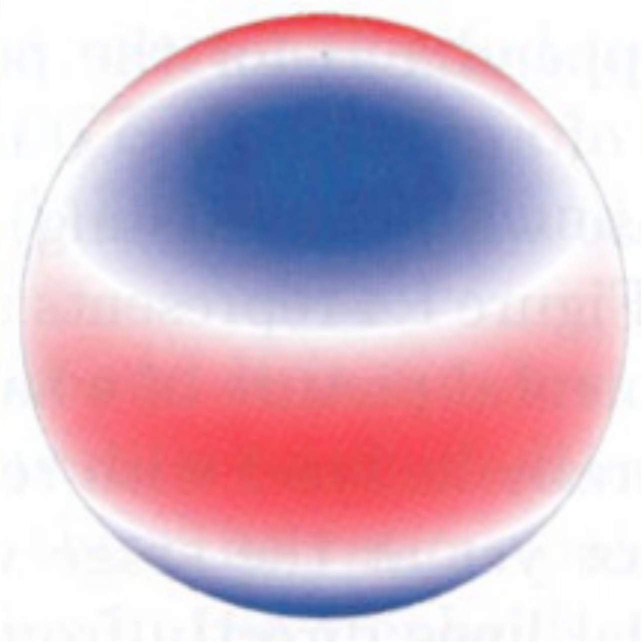
l = spherical degree (total number of surface nodes)

m = azimuthal order (number of nodes through the rotation axis)

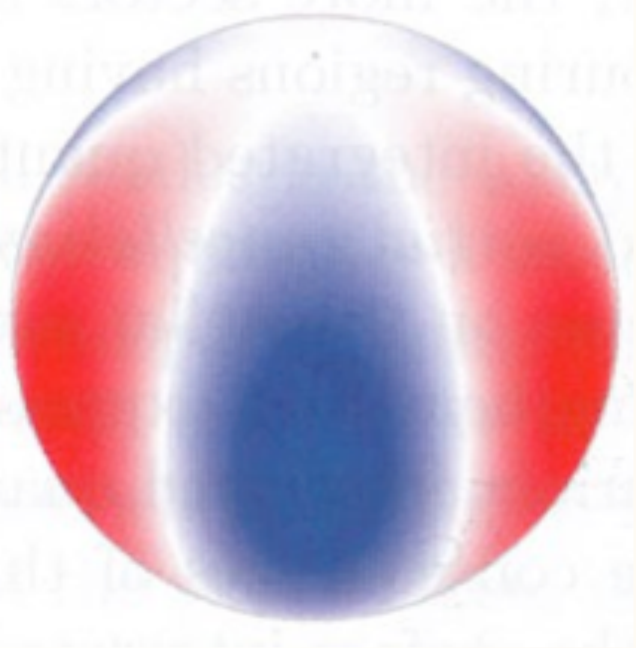
|m| < l

l = 2
|m| = 0





l=3, |m|=1



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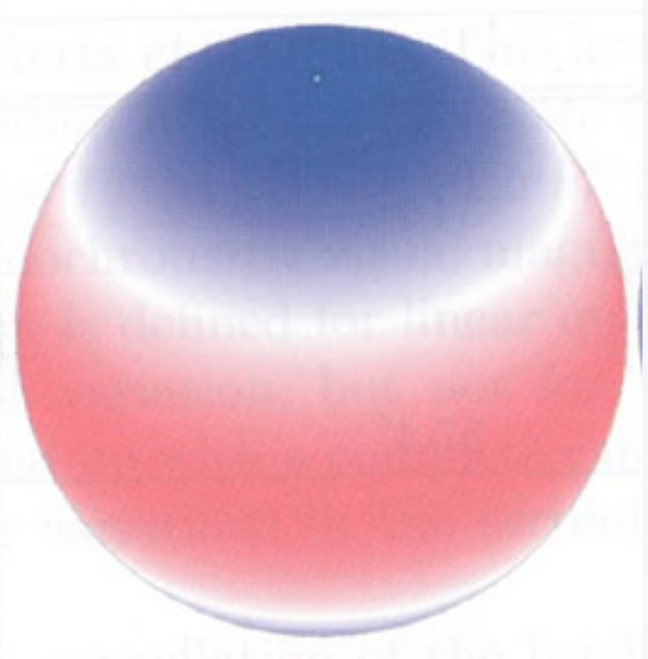
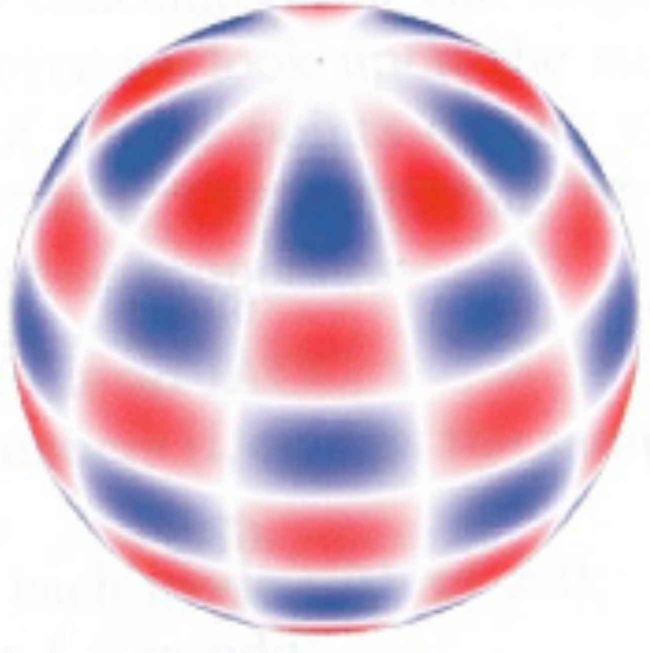
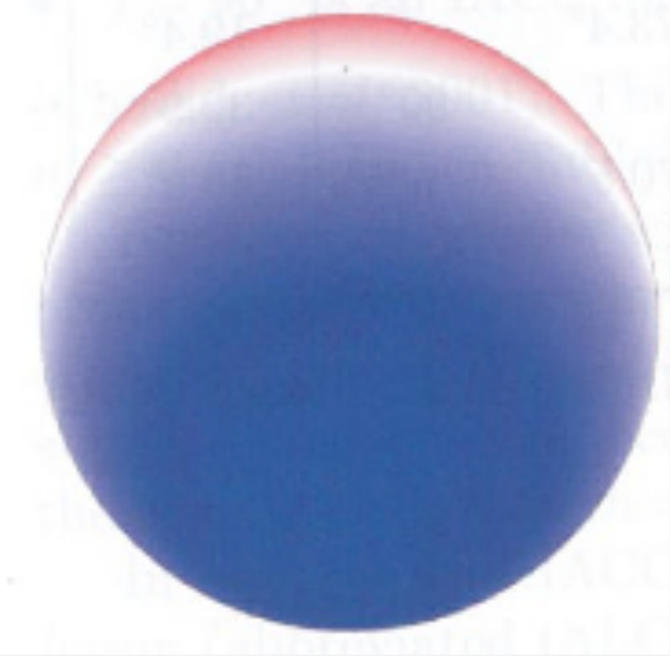


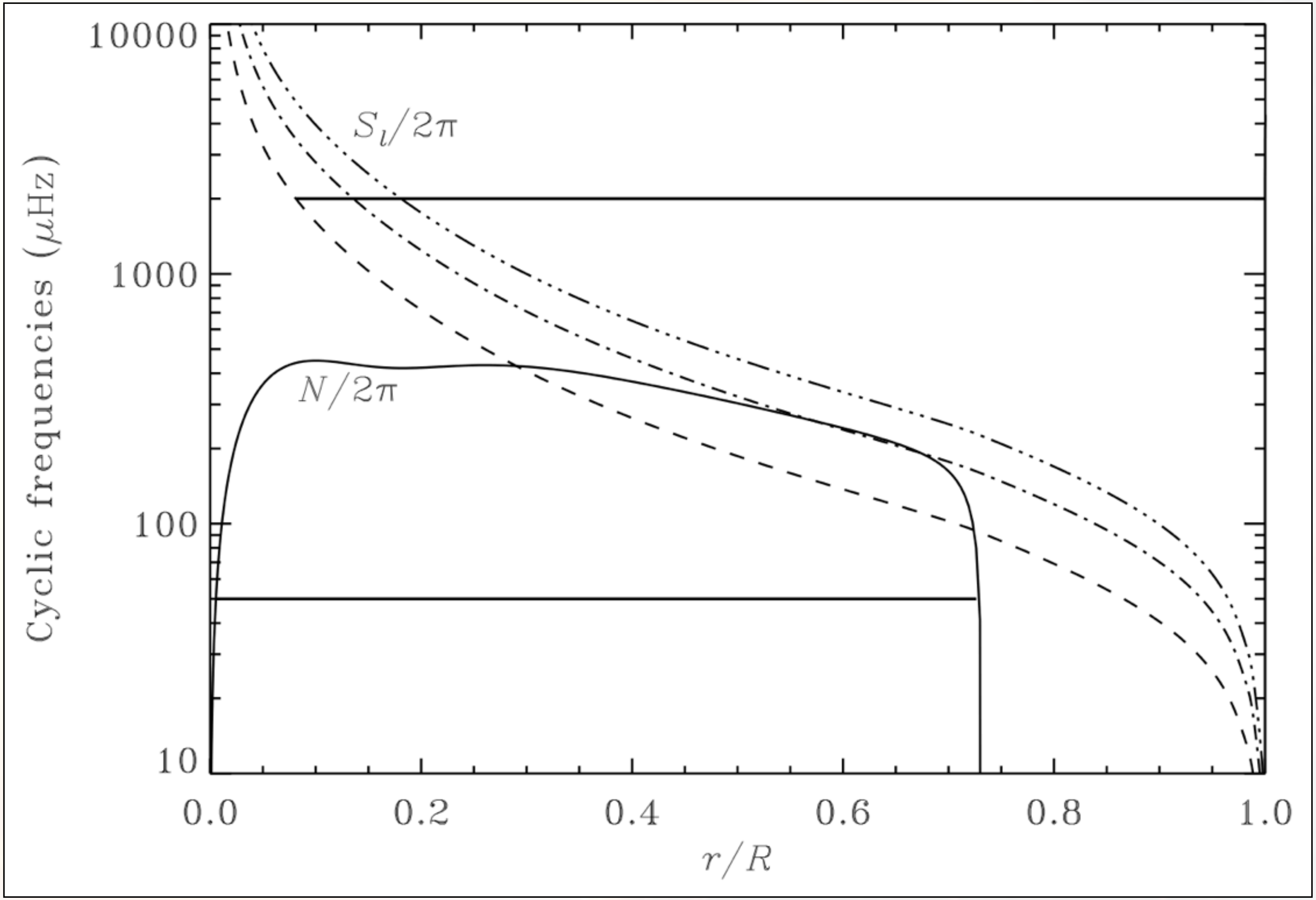
l=2, |m|=0



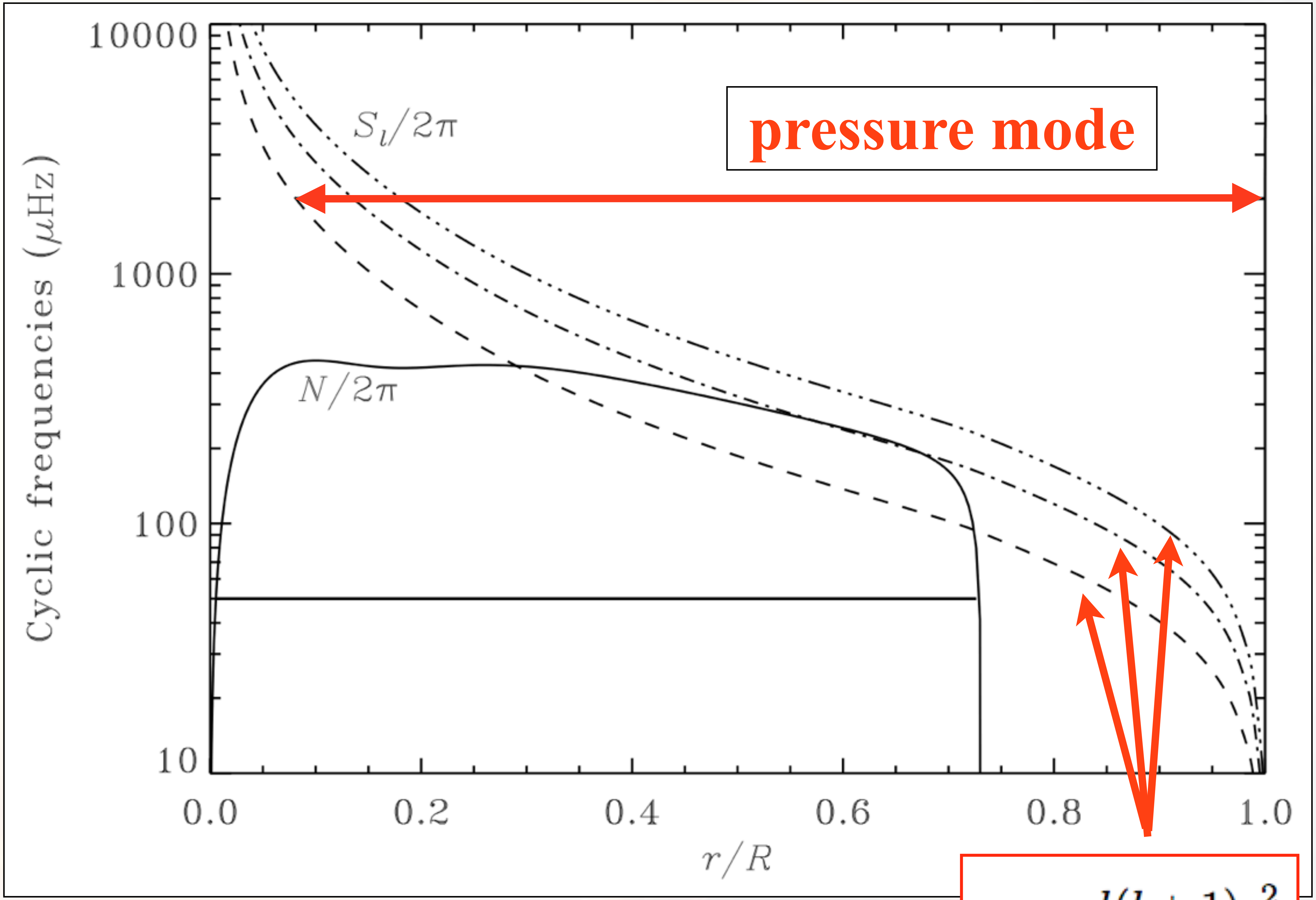
l=10, |m|=5



l=1, |m|=1



Propagation Diagram for the Sun



pressure mode

$$S_l^2 = \frac{l(l+1)c^2}{r^2}$$

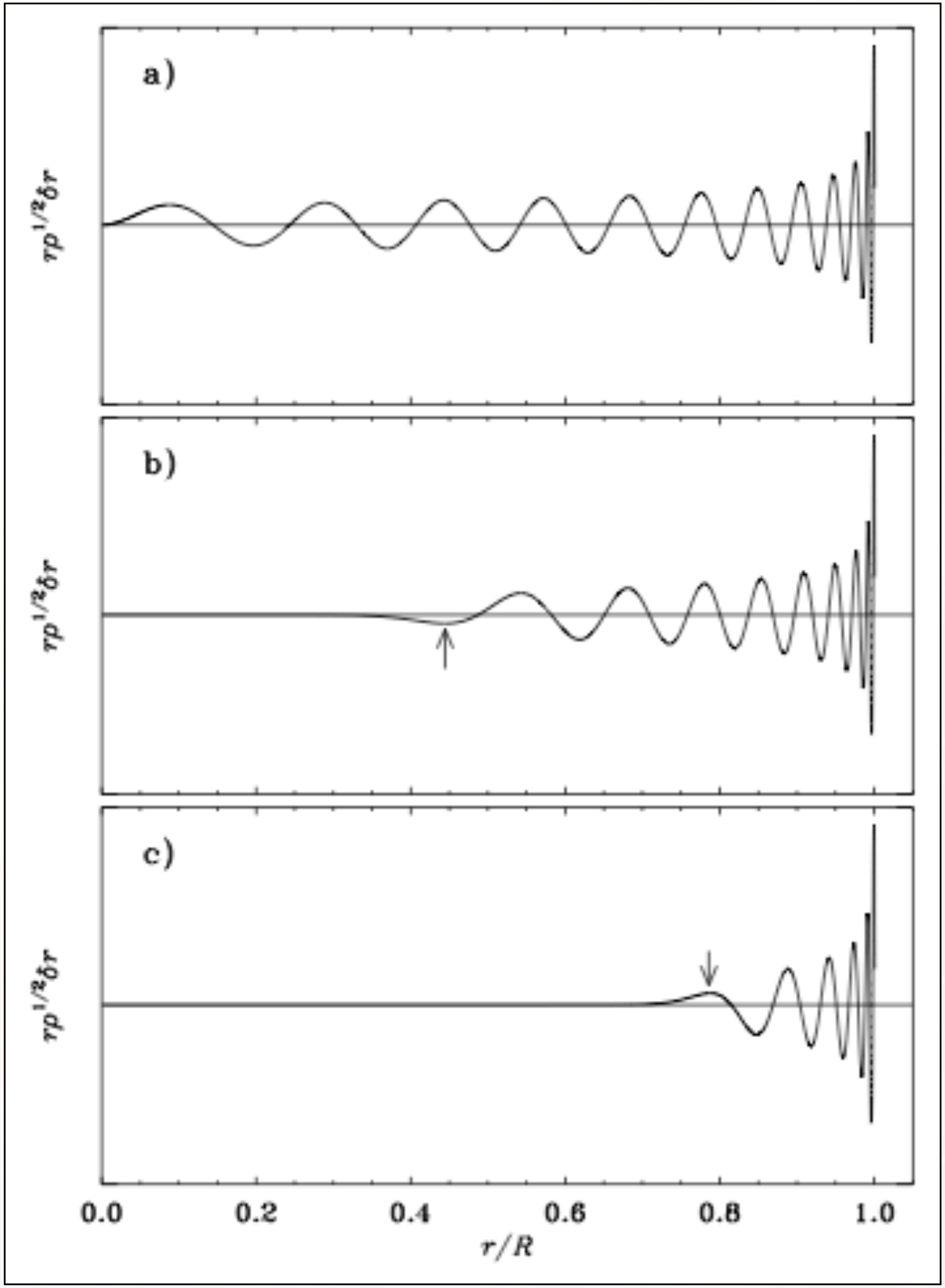
Lamb Frequency

p-modes

$l=0$

$l=20$

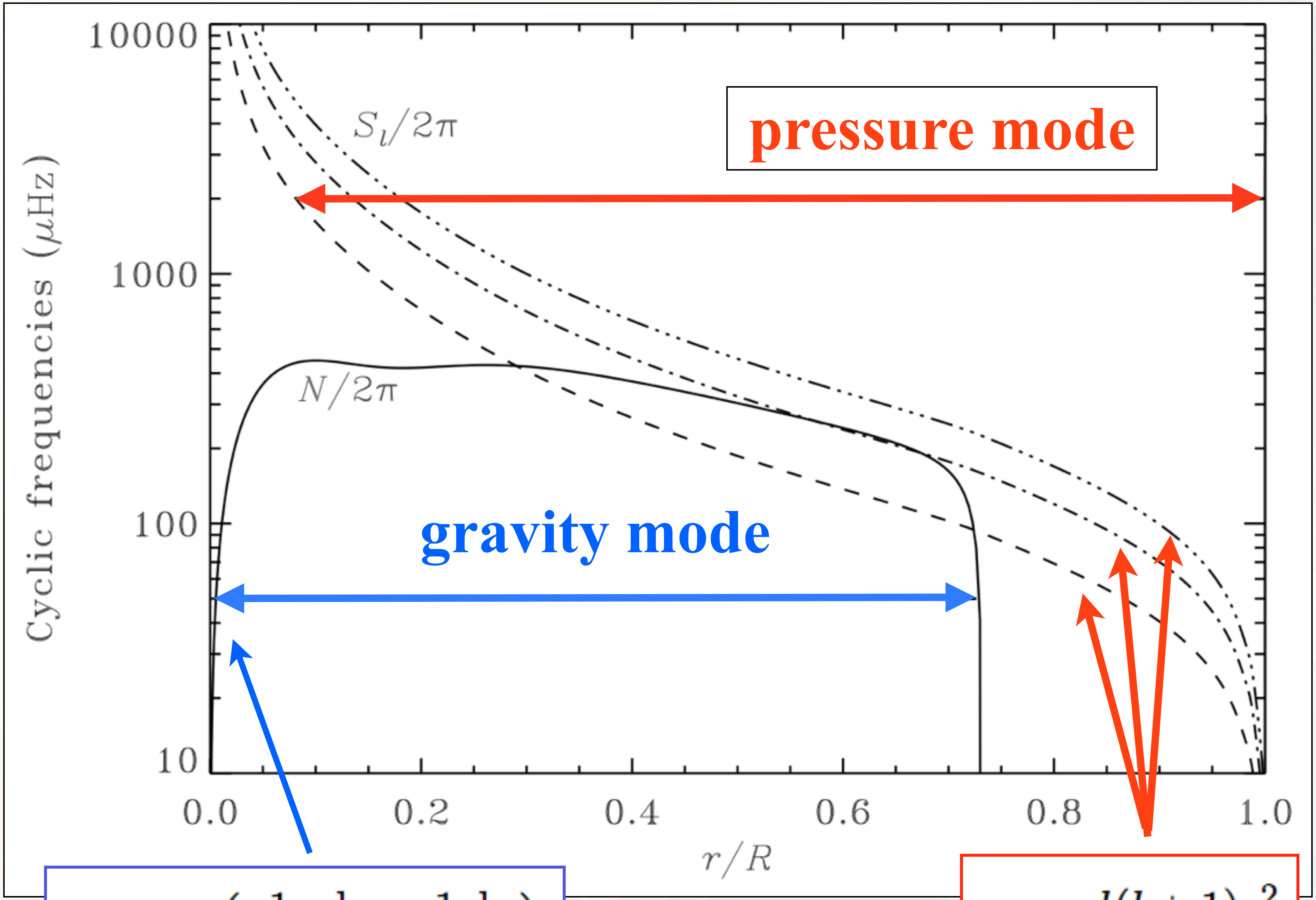
$l=60$



inner turning point depends on l

radial modes travel all the way to center

for fixed l, higher ω means higher n



pressure mode

gravity mode

$$N^2 = g\left(\frac{1}{\Gamma_1 p}\frac{\mathrm{d}p}{\mathrm{d}r} - \frac{1}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}r}\right)$$

Buoyancy Frequency

$$S_l^2 = \frac{l(l+1)c^2}{r^2}$$

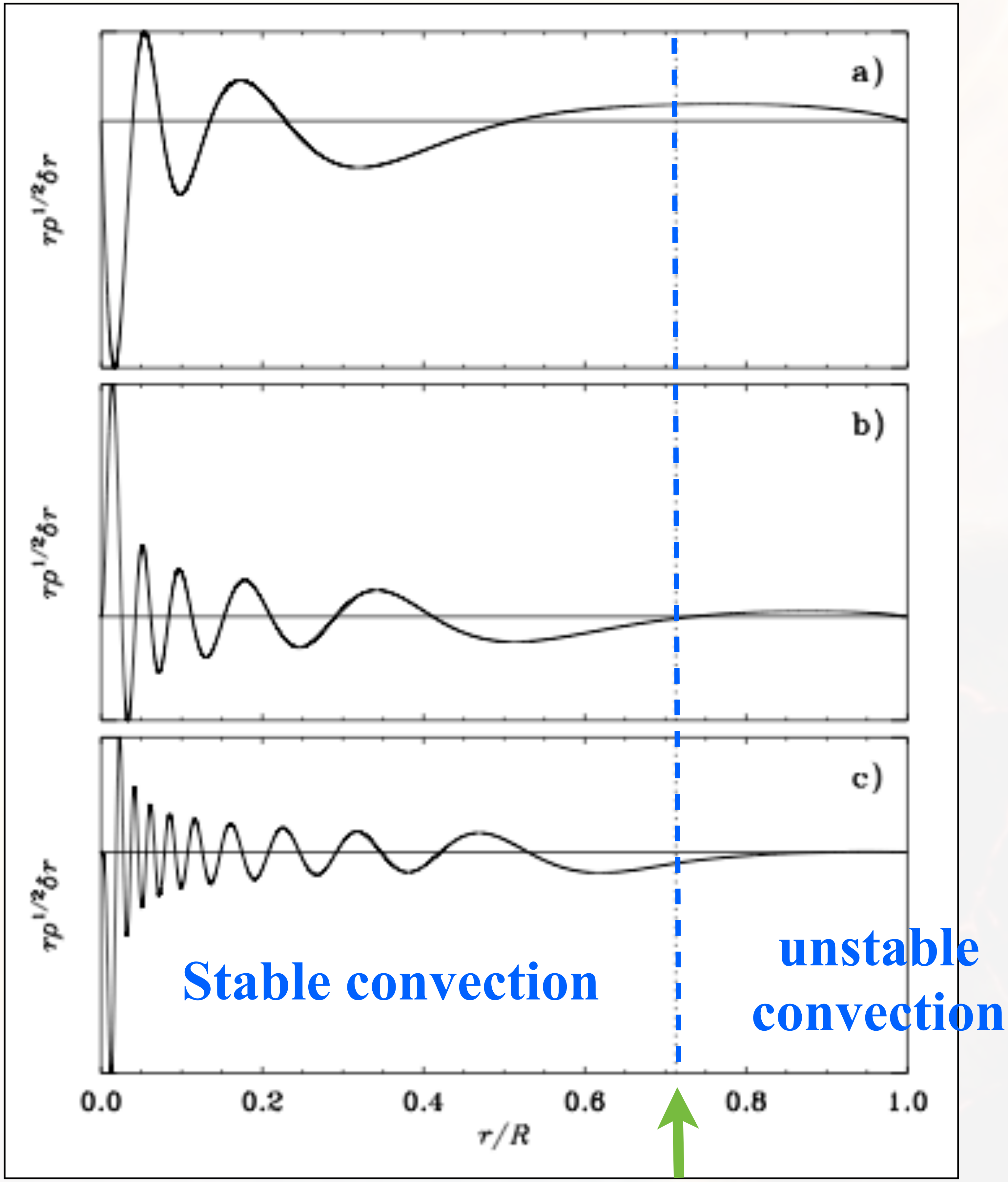
Lamb Frequency

g-modes

l=1

l=2

l=4



Stable convection

unstable convection

Base of the convection zone

turning points are independent of *l*

trapped in interior (for stars with surface convection!)

maximum frequency depends on N

Asymptotic Theory of p- and g-modes

p-modes

$$\omega = \frac{(n + L/2 + \alpha)\pi}{\displaystyle\int_0^R \frac{\mathrm{d}r}{c}} \,.$$

restoring force = pressure

equally spaced in *frequency*

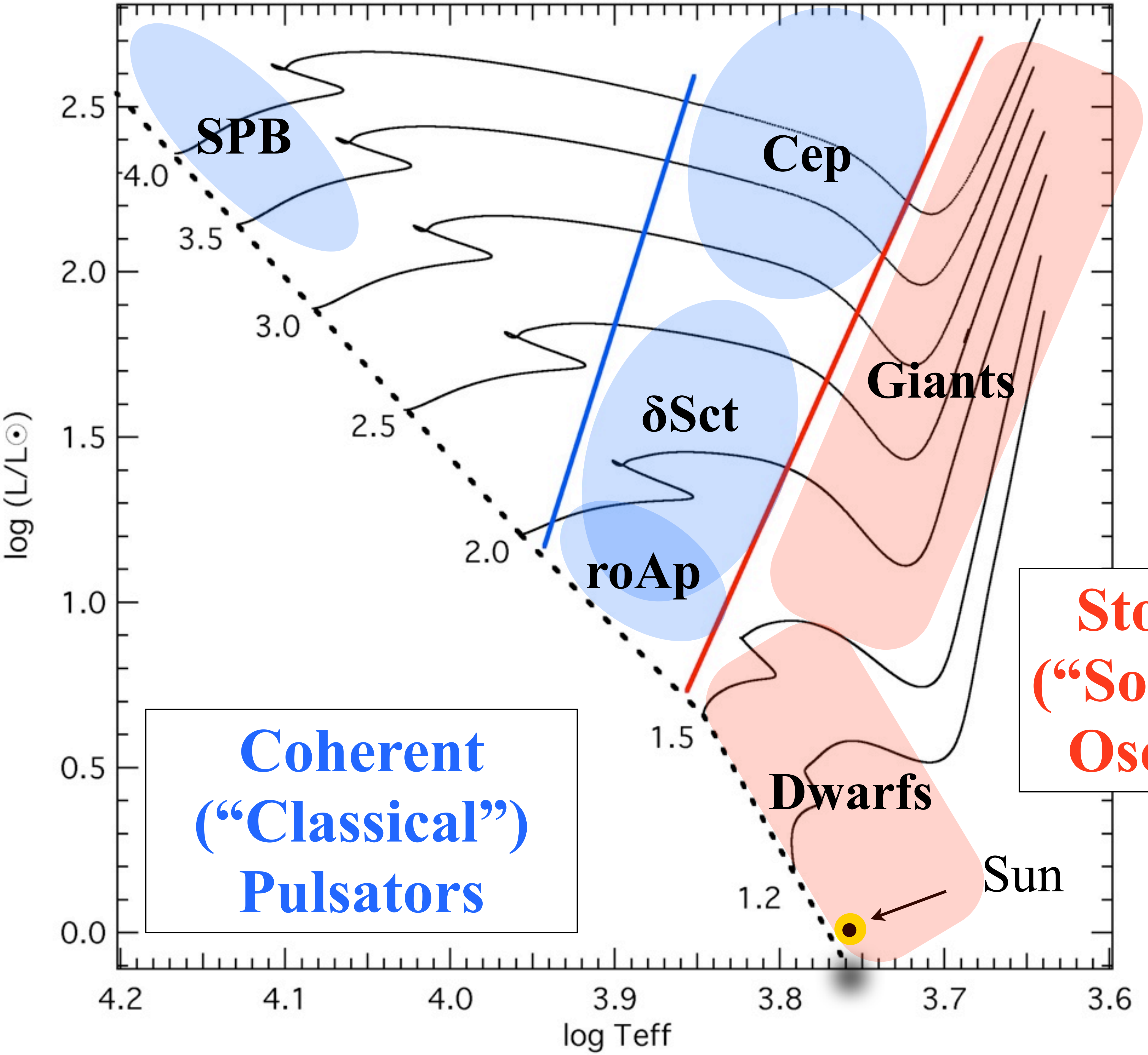
g-modes

$$\omega = \frac{L \displaystyle\int_{r_1}^{r_2} N \frac{\mathrm{d}r}{r}}{\pi(n + l/2 + \alpha_{\mathrm{g}})} \,,$$

restoring force = buoyancy

equally spaced in *period*

for low l and high n



Coherent (“Classical”) Pulsators

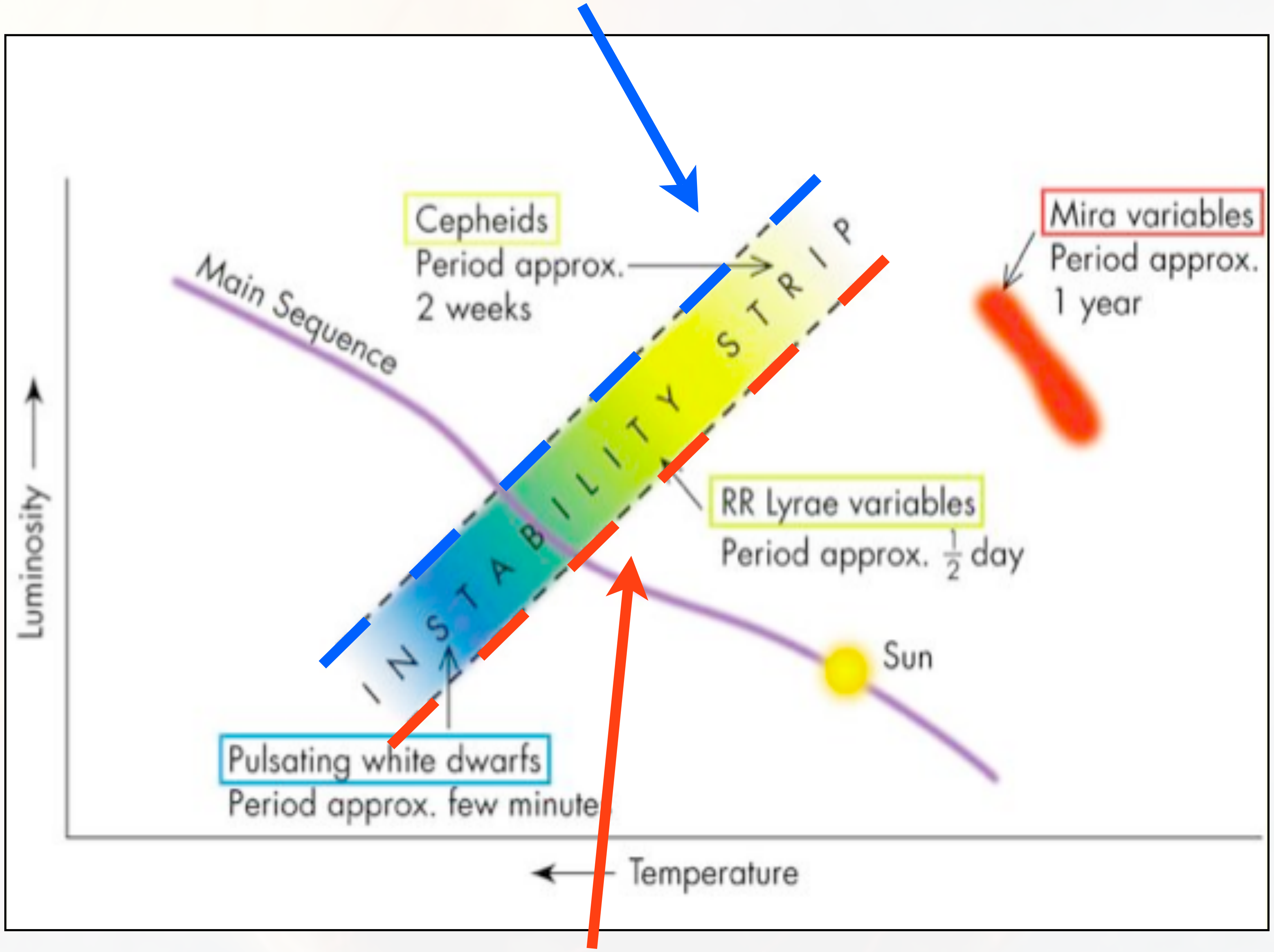
Stochastic (“Solar-like”) Oscillators

Mode excitation: coherent pulsations

Opacity (κ) increases with compression -> **κ-mechanism**

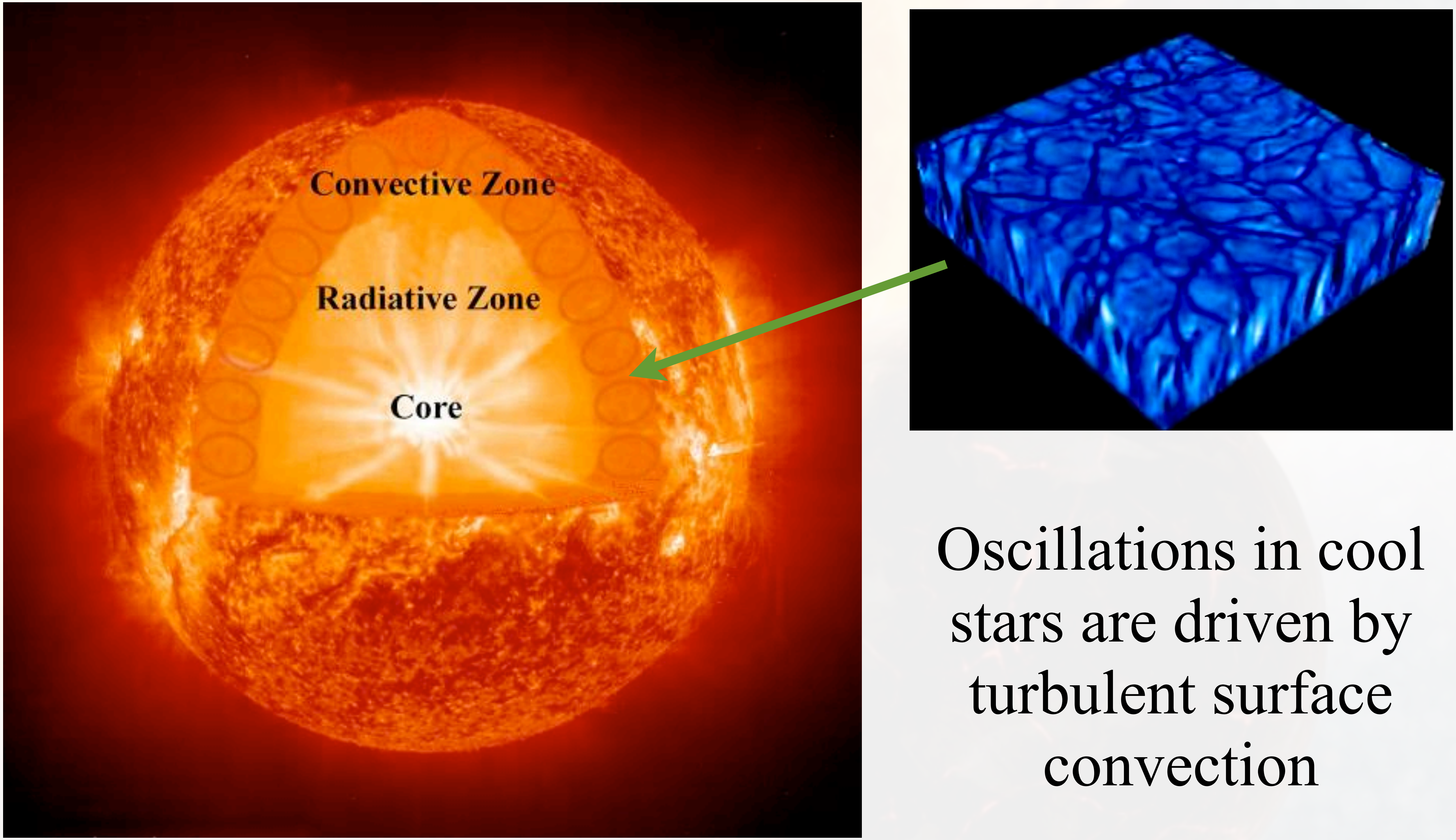
"*classical instability strip*" = κ-mechanism acting in H and He ionization zones

ion. region too close to surface



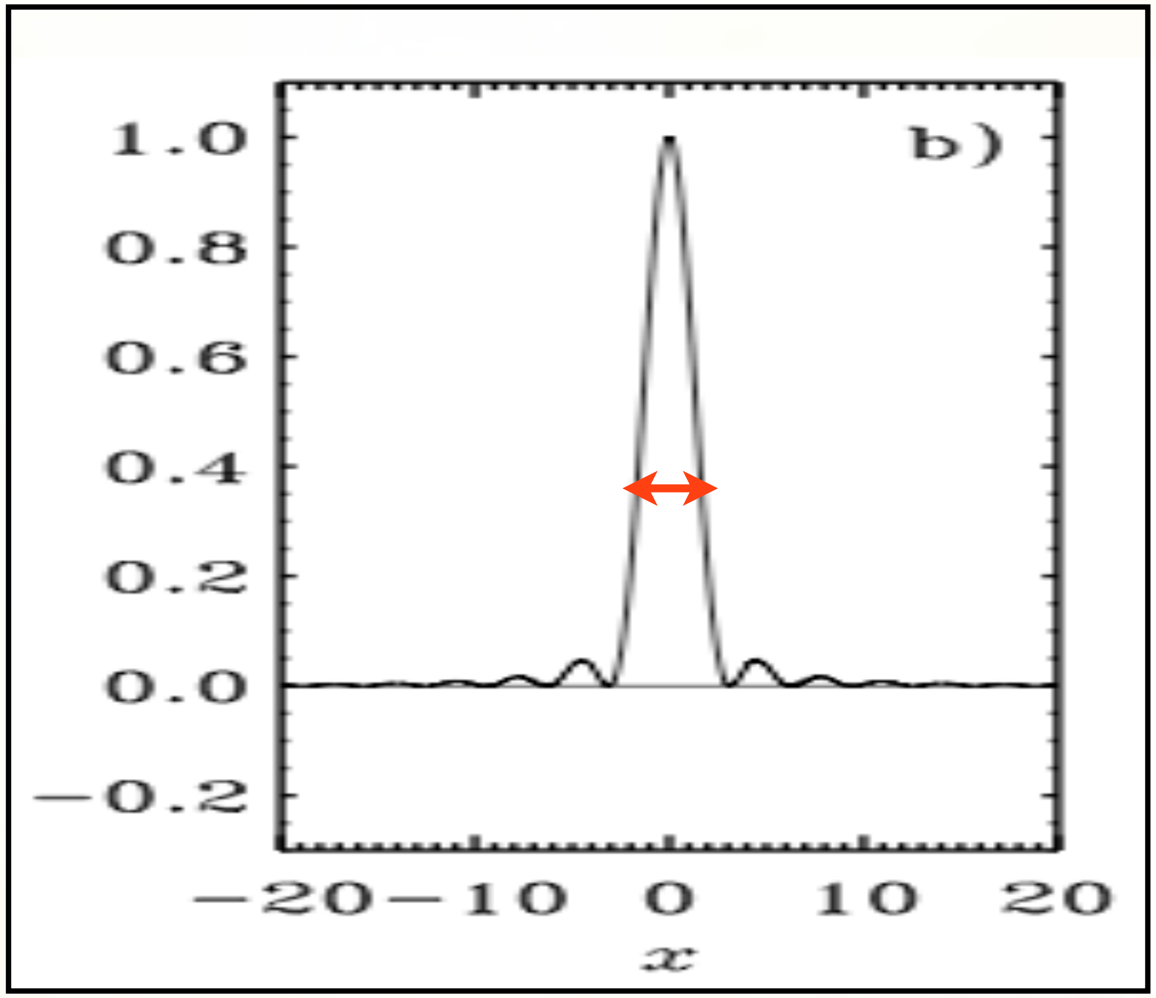
surface convection sets in

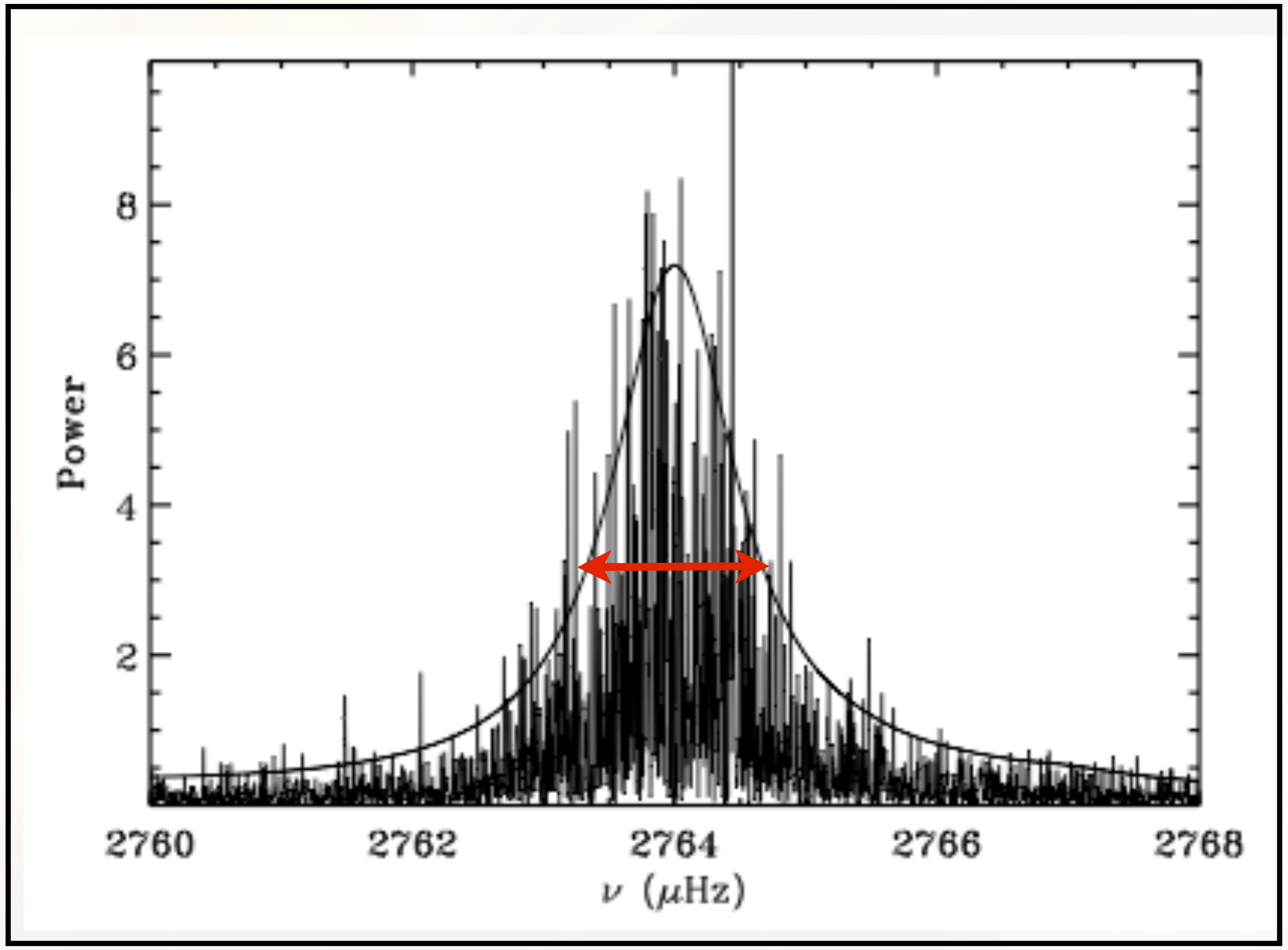
Mode excitation: stochastic oscillations



Oscillations in cool stars are driven by turbulent surface convection

Coherent versus stochastic oscillations





coherent pulsation

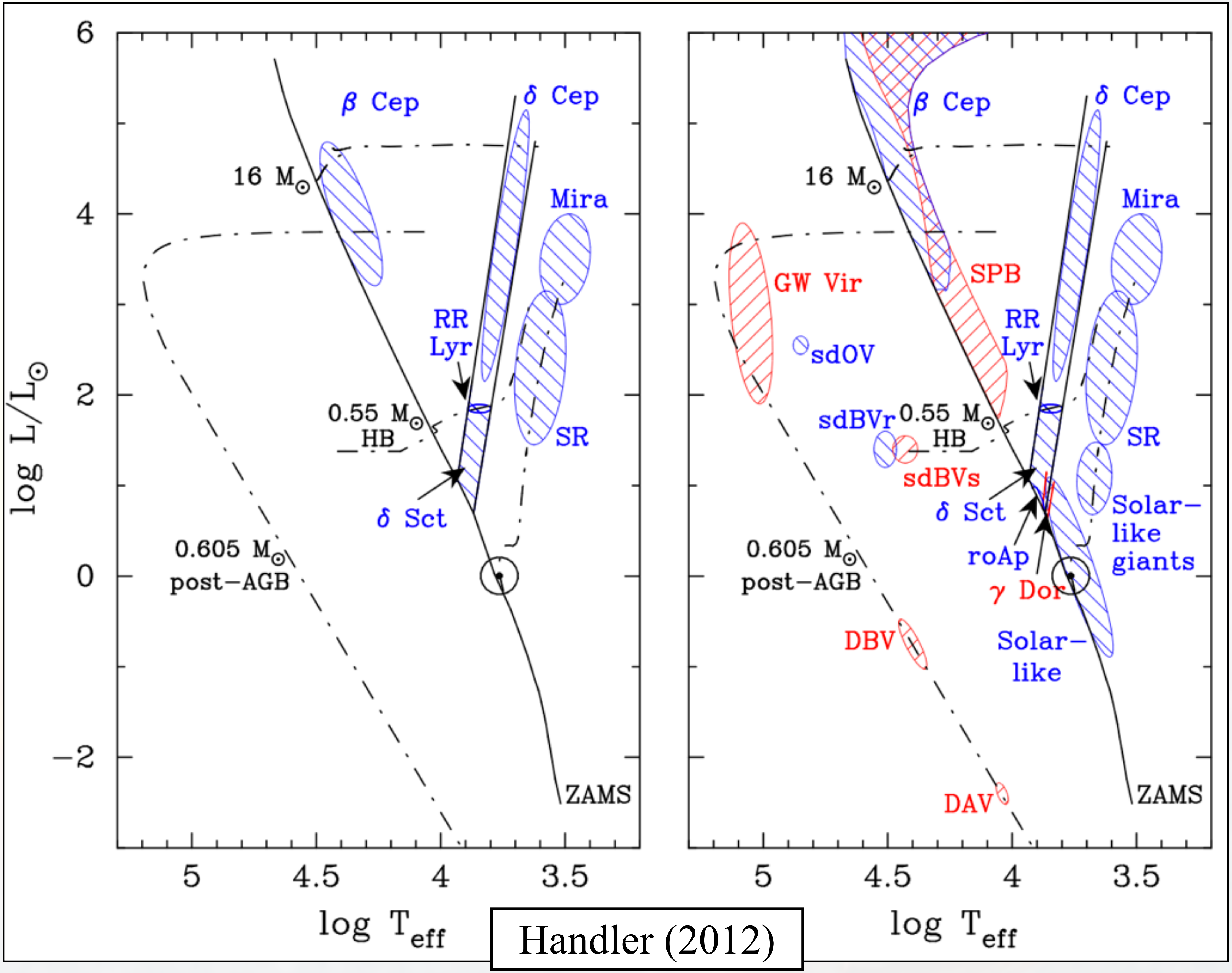
width = length of observation

stochastic oscillation

width = 1/mode lifetime

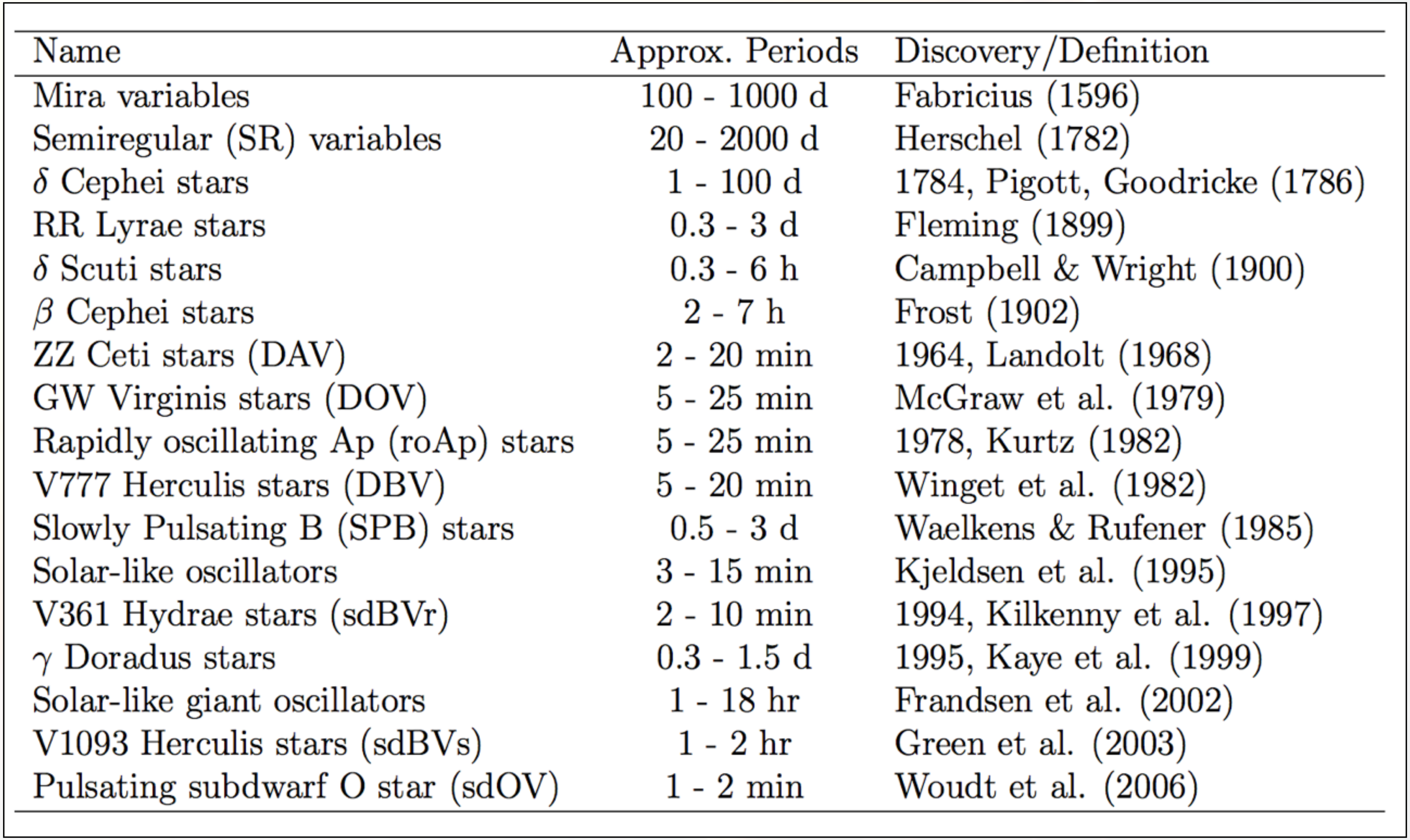
Asteroseismology across the HRD

30 years ago Today



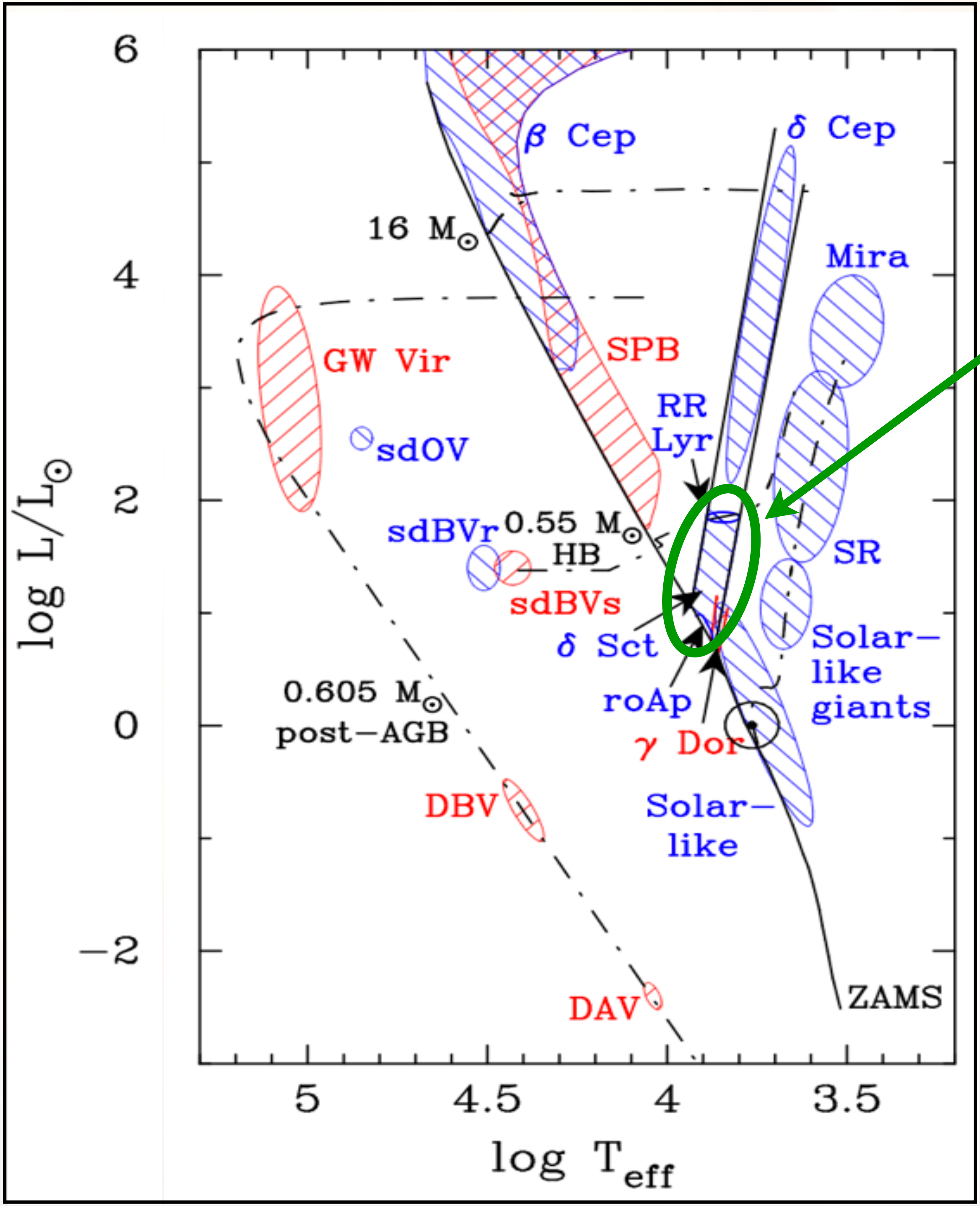
Handler (2012)

Asteroseismology Zoo



Name	Approx. Periods	Discovery/Definition
Mira variables	100 - 1000 d	Fabricius (1596)
Semiregular (SR) variables	20 - 2000 d	Herschel (1782)
δ Cephei stars	1 - 100 d	1784, Pigott, Goodricke (1786)
RR Lyrae stars	0.3 - 3 d	Fleming (1899)
δ Scuti stars	0.3 - 6 h	Campbell & Wright (1900)
β Cephei stars	2 - 7 h	Frost (1902)
ZZ Ceti stars (DAV)	2 - 20 min	1964, Landolt (1968)
GW Virginis stars (DOV)	5 - 25 min	McGraw et al. (1979)
Rapidly oscillating Ap (roAp) stars	5 - 25 min	1978, Kurtz (1982)
V777 Herculis stars (DBV)	5 - 20 min	Winget et al. (1982)
Slowly Pulsating B (SPB) stars	0.5 - 3 d	Waelkens & Rufener (1985)
Solar-like oscillators	3 - 15 min	Kjeldsen et al. (1995)
V361 Hydrae stars (sdBVr)	2 - 10 min	1994, Kilkenny et al. (1997)
γ Doradus stars	0.3 - 1.5 d	1995, Kaye et al. (1999)
Solar-like giant oscillators	1 - 18 hr	Frandsen et al. (2002)
V1093 Herculis stars (sdBVs)	1 - 2 hr	Green et al. (2003)
Pulsating subdwarf O star (sdOV)	1 - 2 min	Woudt et al. (2006)

Handler (2012)



Delta Scuti stars

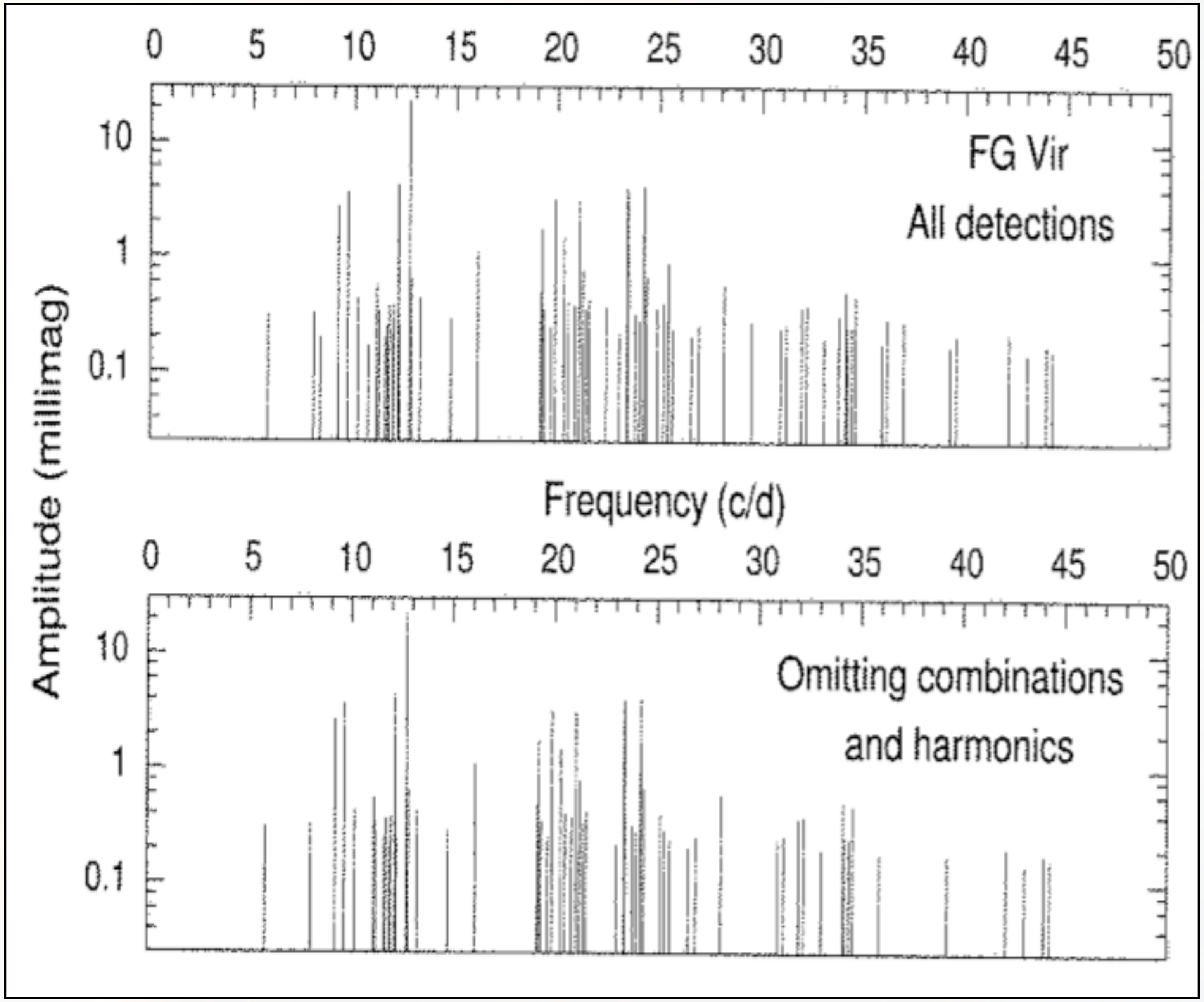
Delta Scuti Stars

Spectral type A-F

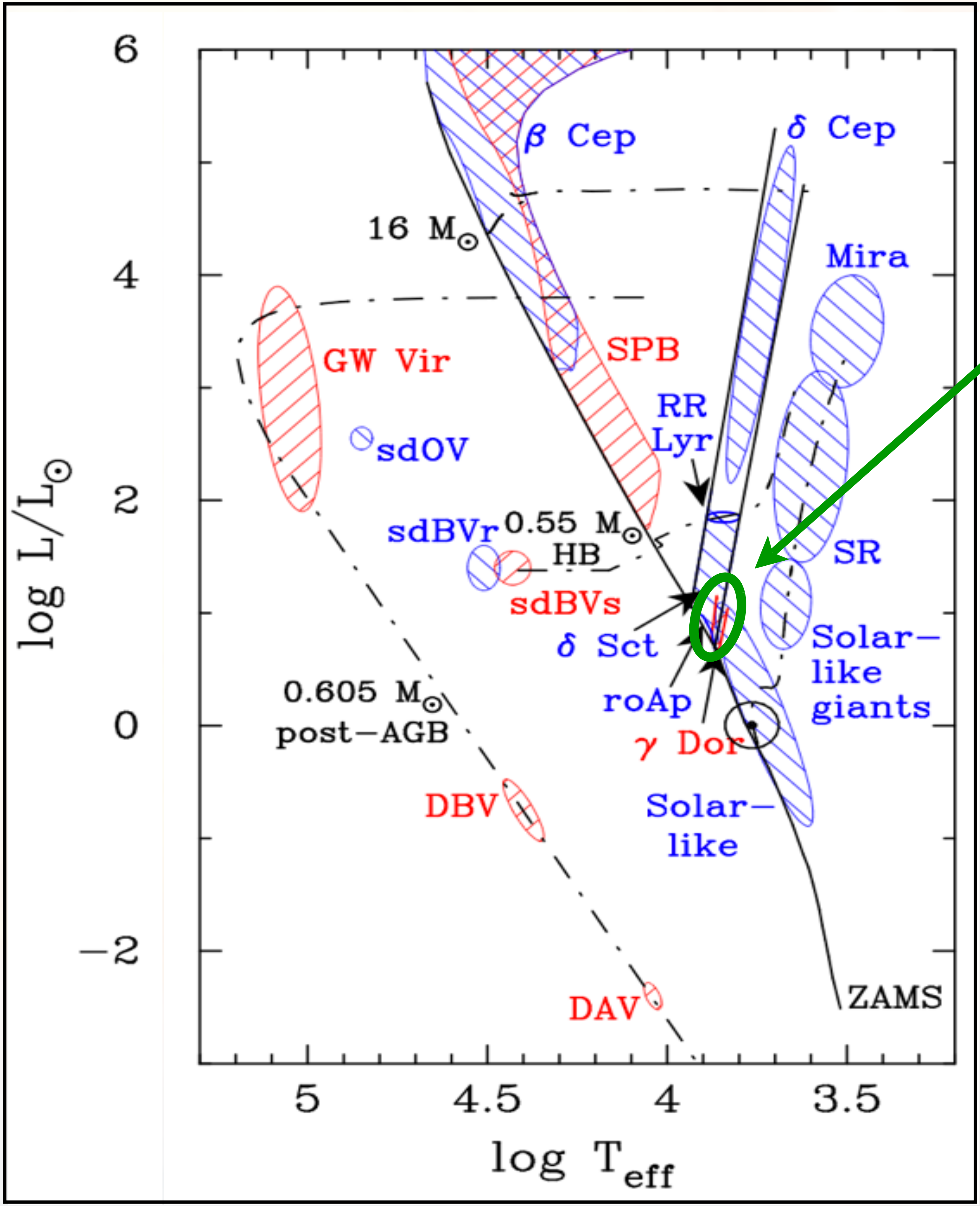
low order radial + non-radial p-mode pulsators

excited by κ mechanism in HeII ionization zone

large population but complex structure of oscillations -> mode identification is difficult!



Breger et al. 2005



gamma Dor stars

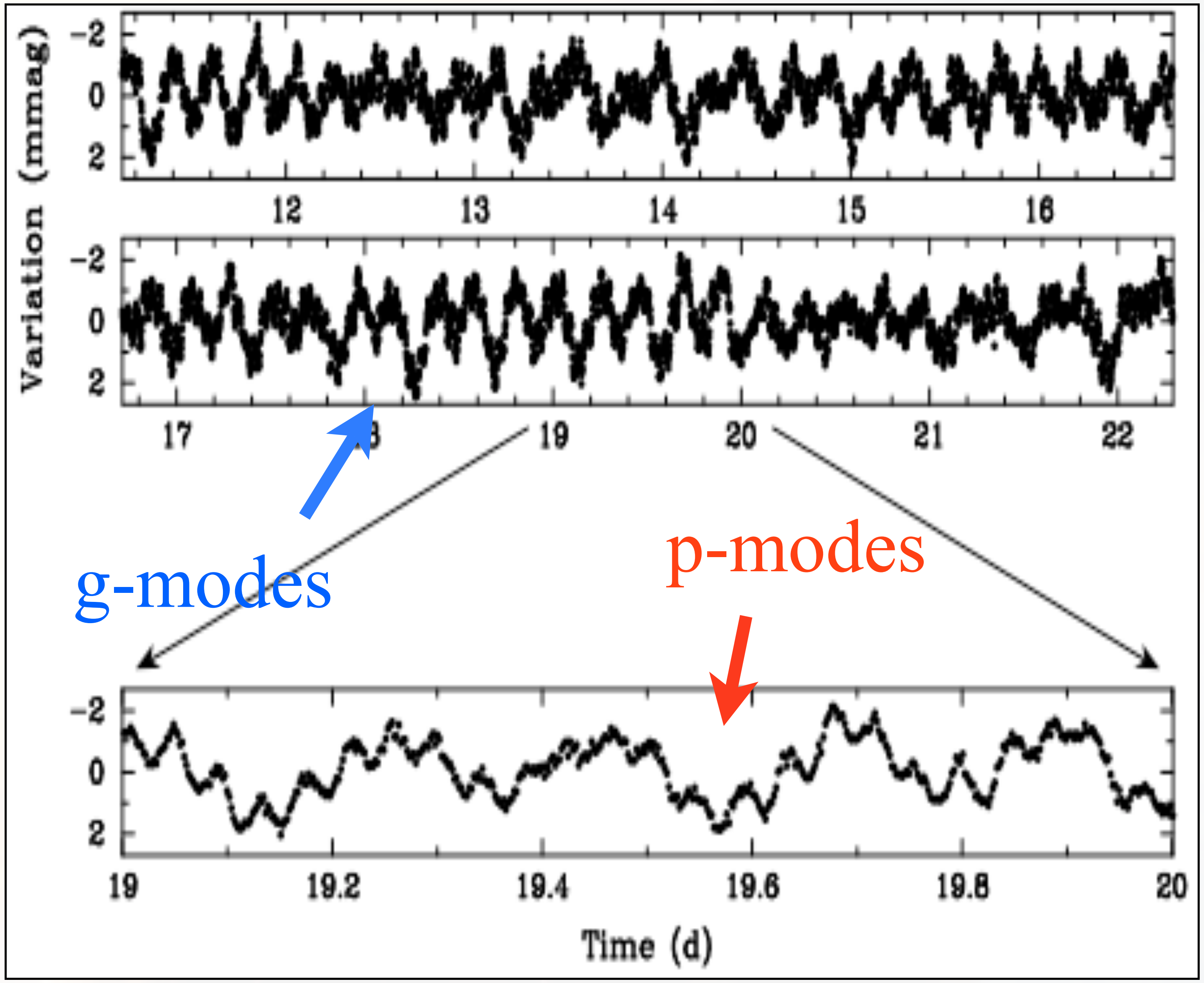
gamma Doradus Stars

Spectral type F

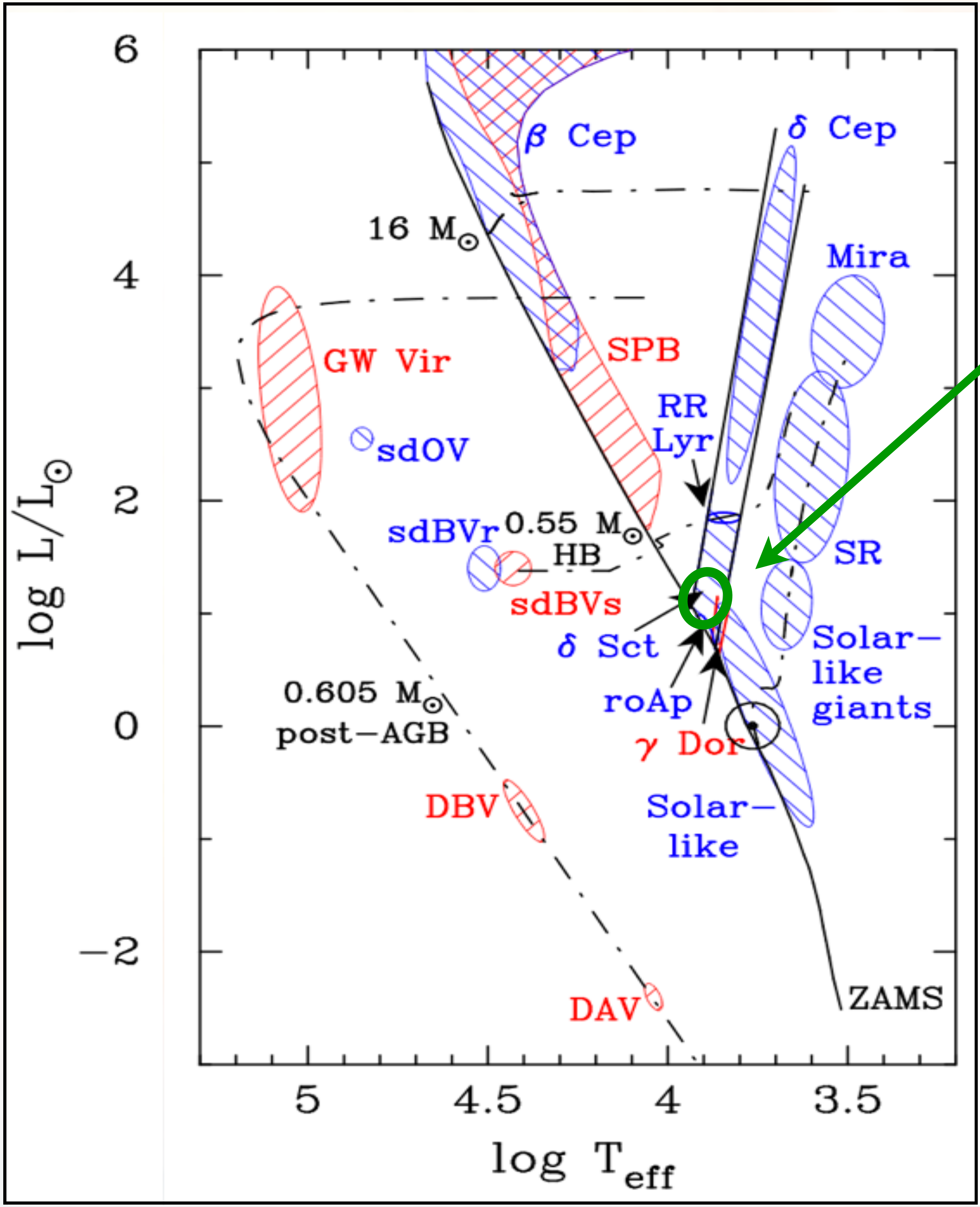
high order g-mode pulsators

no satisfactory explanation for driving; "convective blocking" favored theory

many (or all?) gamma Dor stars show hybrid g-mode and p-mode pulsations → "delgam Scudor" stars



Handler 2012



rapidly oscillating Ap Stars

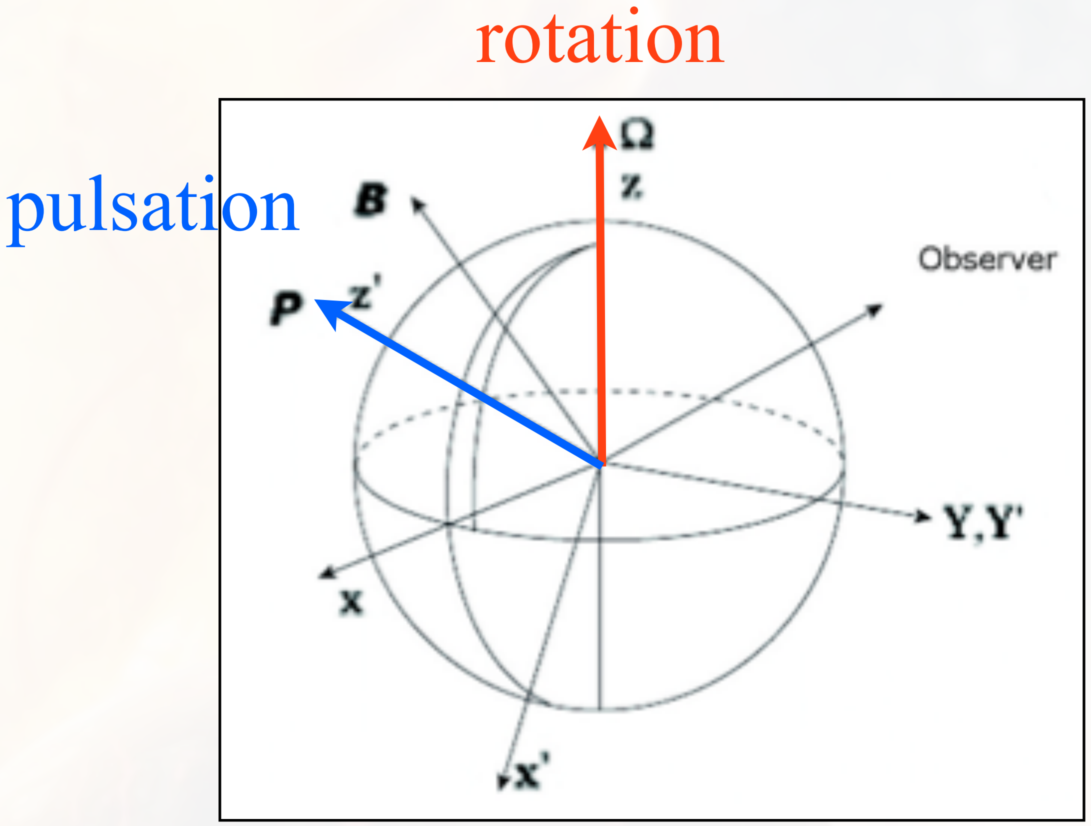
rapidly oscillating Ap Stars

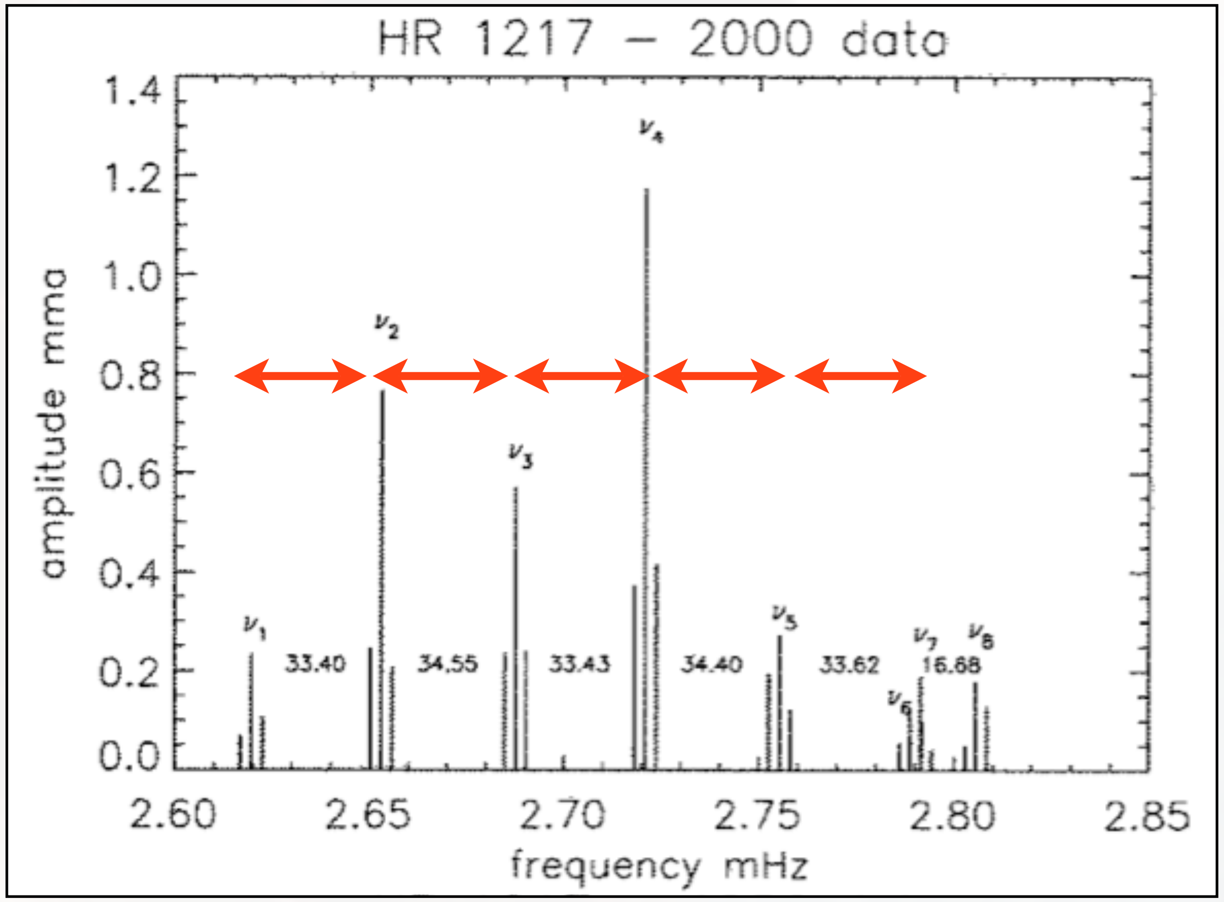
chemically peculiar A stars

high-order non-radial p-mode pulsators

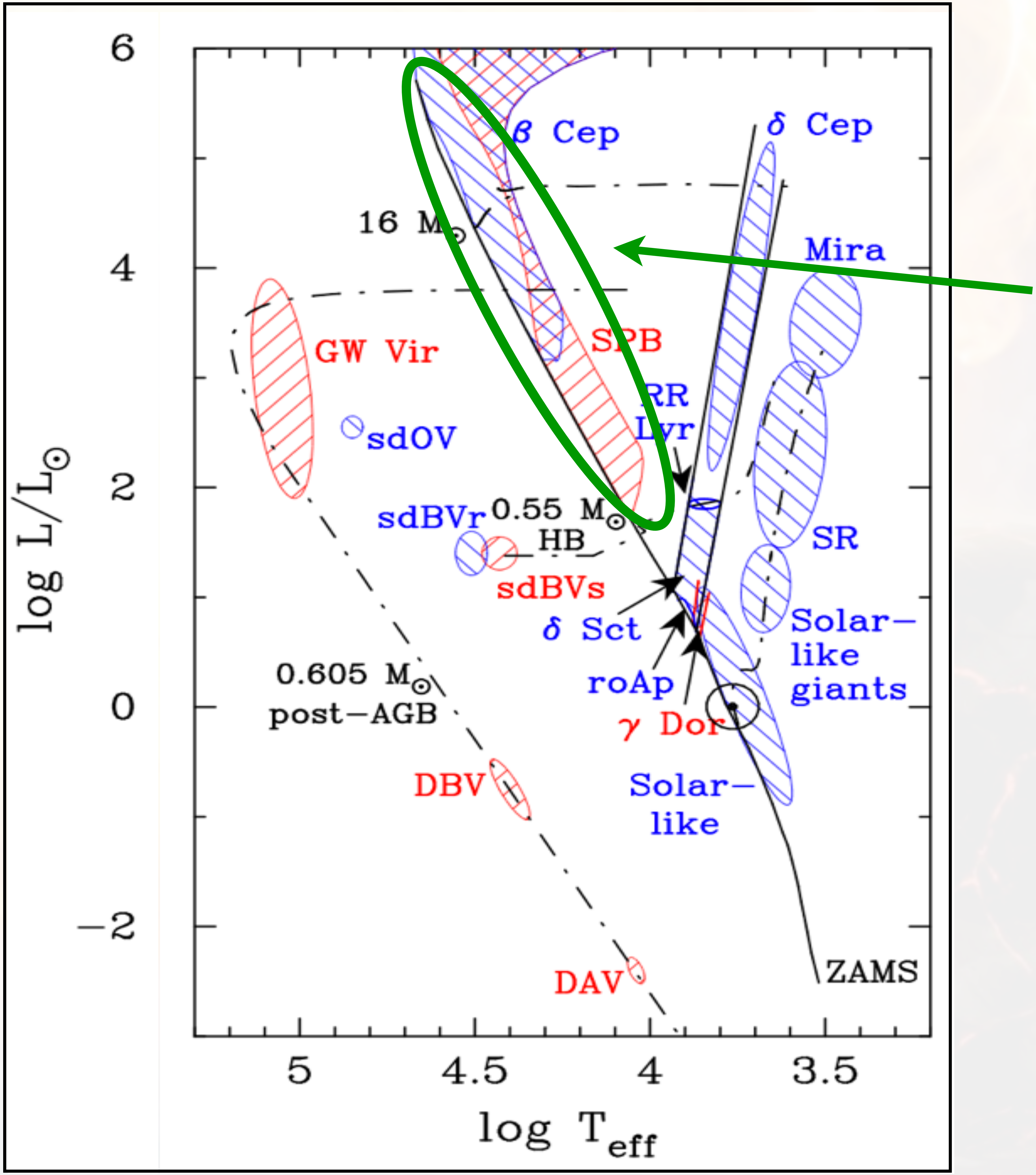
excitation mechanism uncertain, but likely κ -mechanism + magnetic field

Pulsation axis and rotation axis are inclined → *oblique pulsator model*





Kurtz et al. 2005



SPB and beta Cephei Stars

SPB and beta Cephei Stars

SPB = slowly pulsating B stars

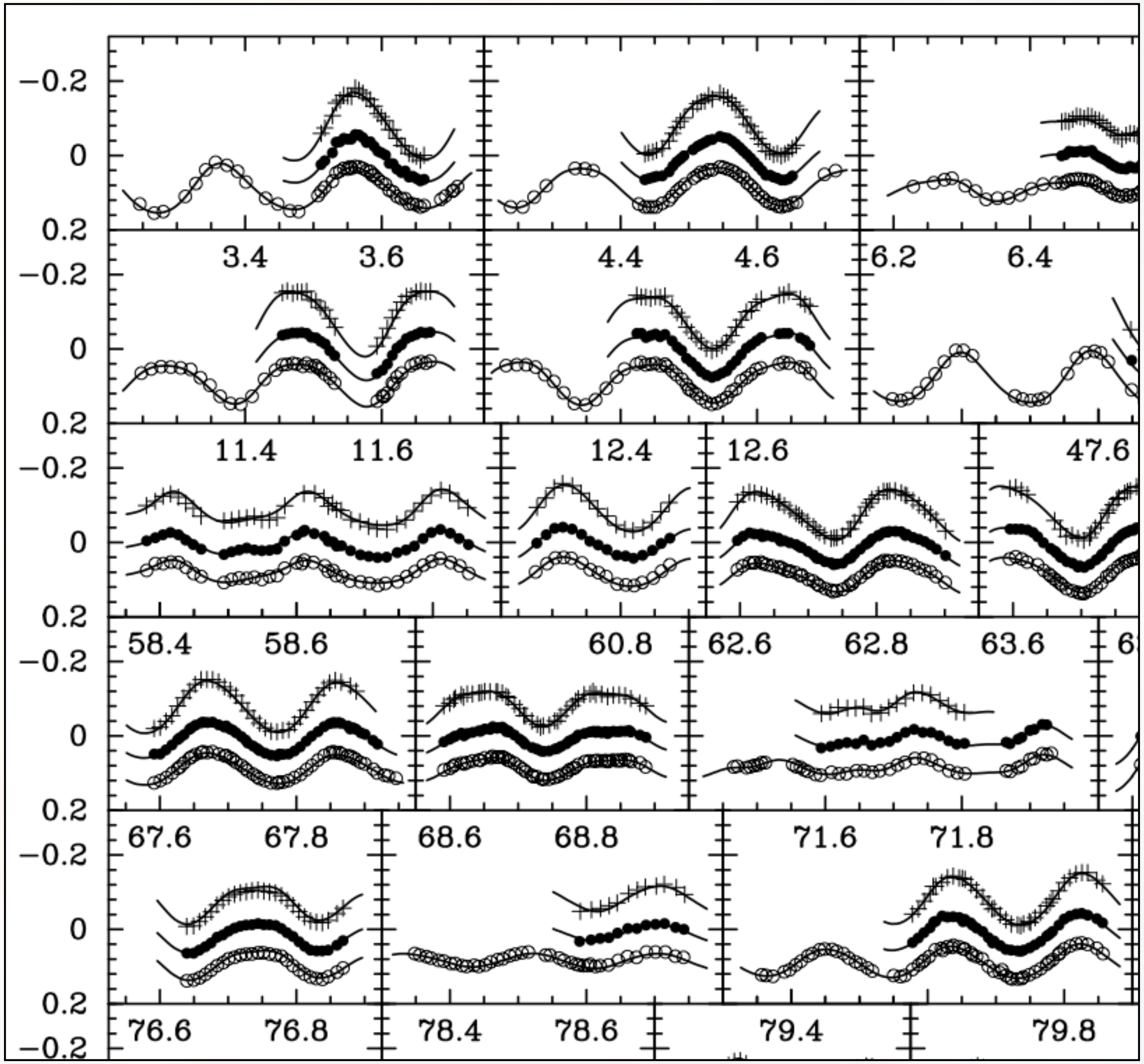
Periods ~ 0.3 - 3 days

non-radial high-order g-modes

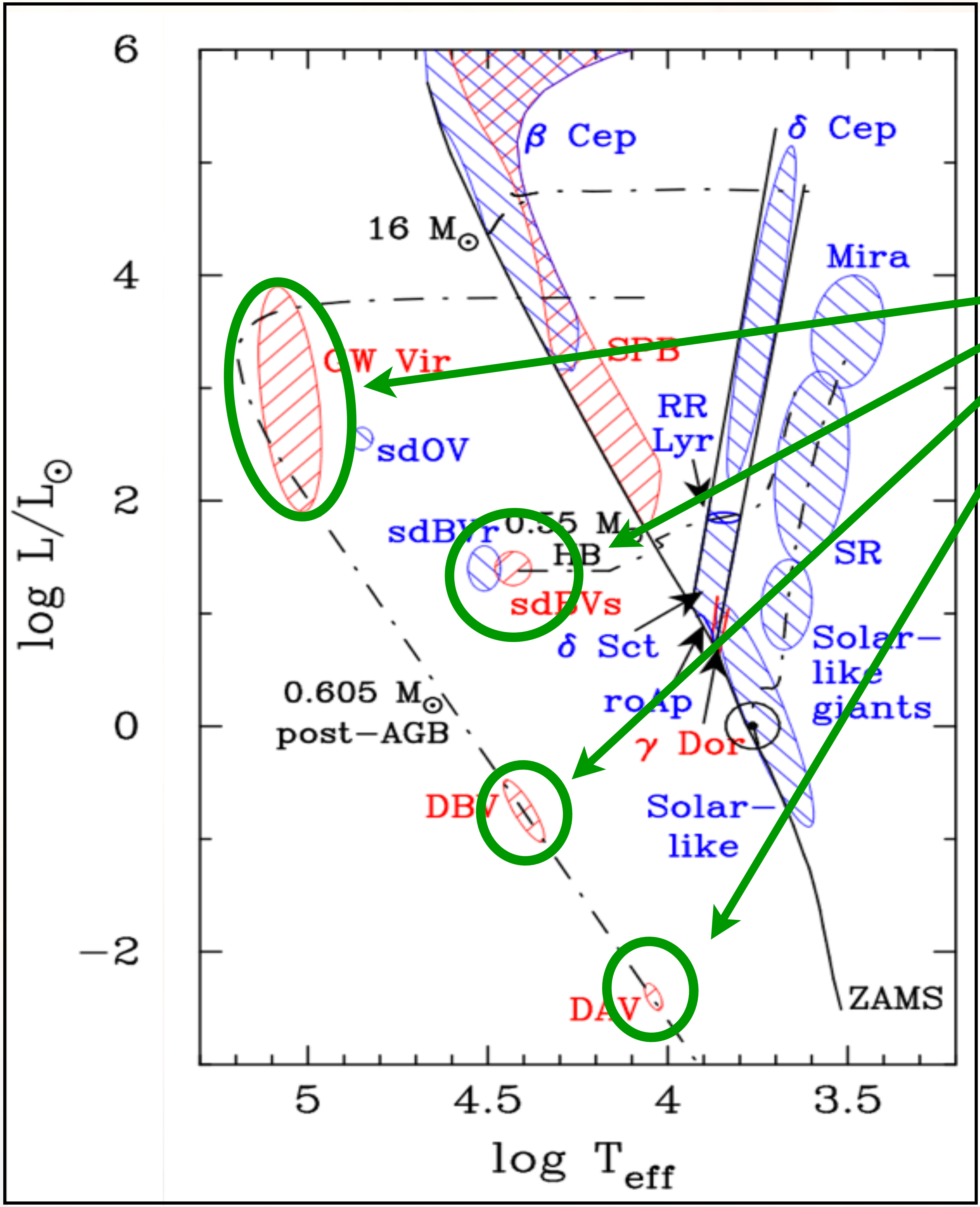
β Cephei stars

Periods ~ 2-8 hours

non-radial low-order p- and g-modes



Handler et al. 2006



Compact Pulsators

Compact Pulsators

high order g-modes ➔
equally spaced in period!

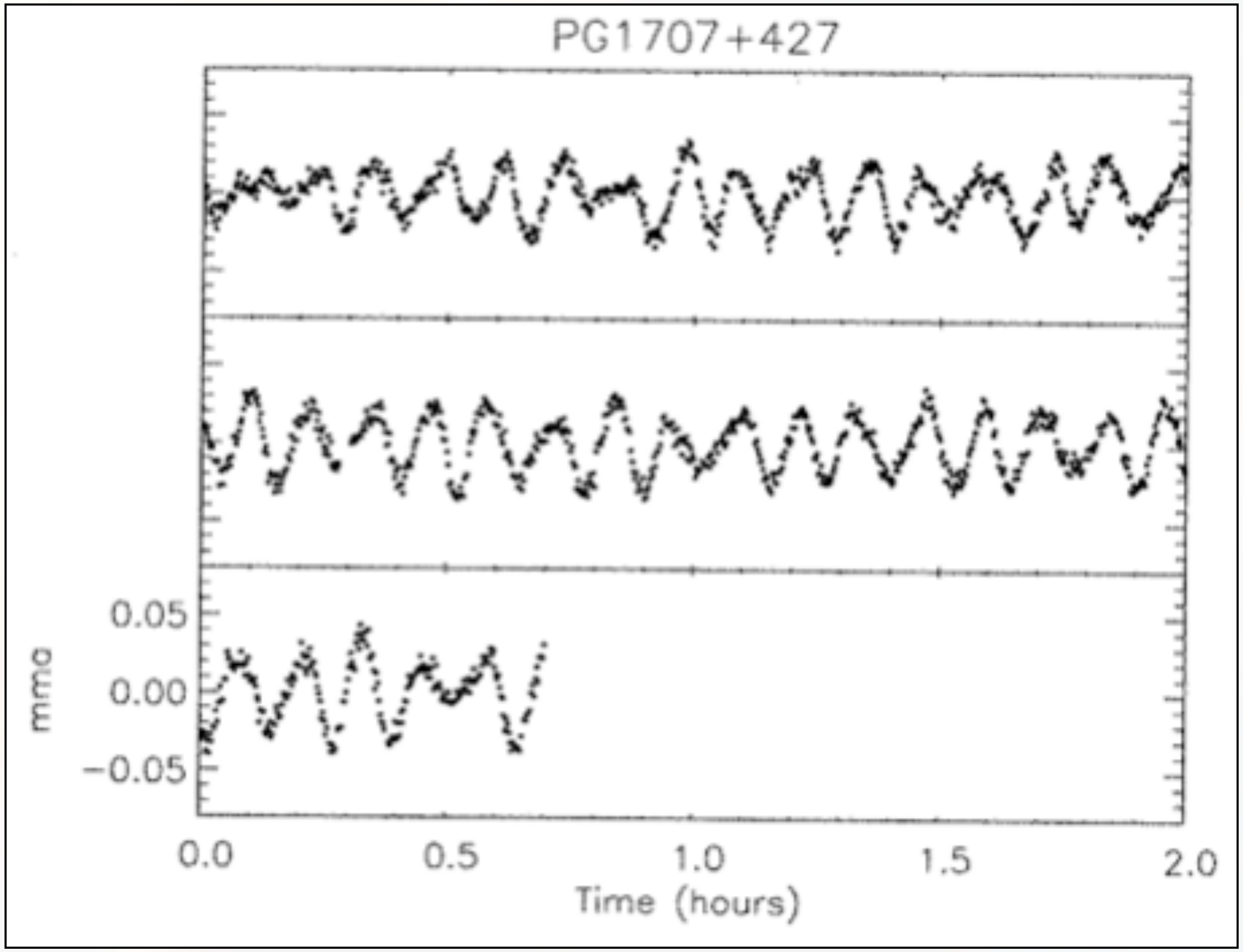
- DAV: H-atmosphere
- DBV: He-atmosphere
- DOV (GW Vir stars)

➔ Neutrino physics
(Winget et al. 2004)

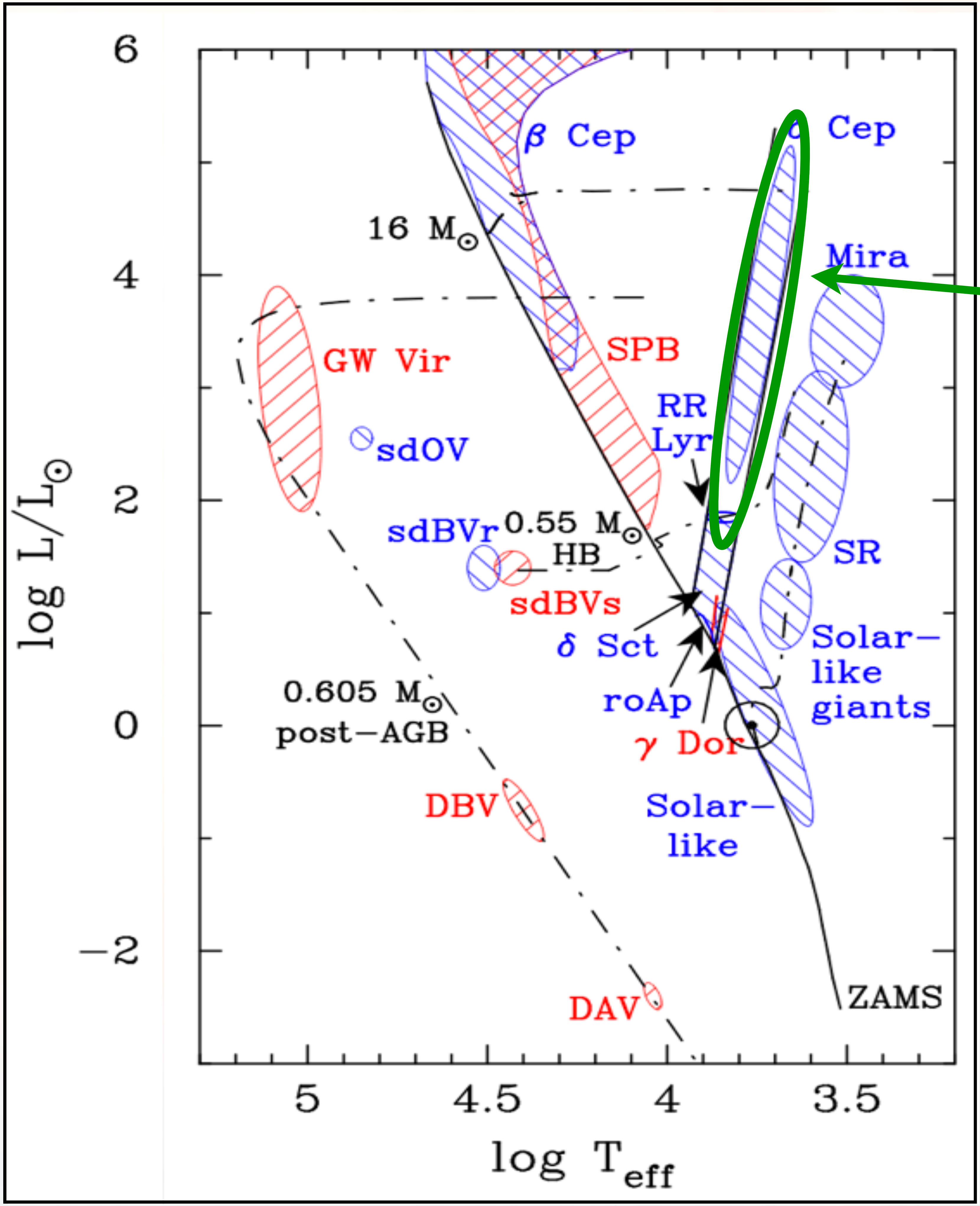
➔ Crystallization
(Metcalfe et al. 2005)

➔ non-linear pulsation
(Montgomery 2005)

pulsating DOV white dwarf



Kawaler et al. (2004)



RR Lyrae & Cepheid Variables

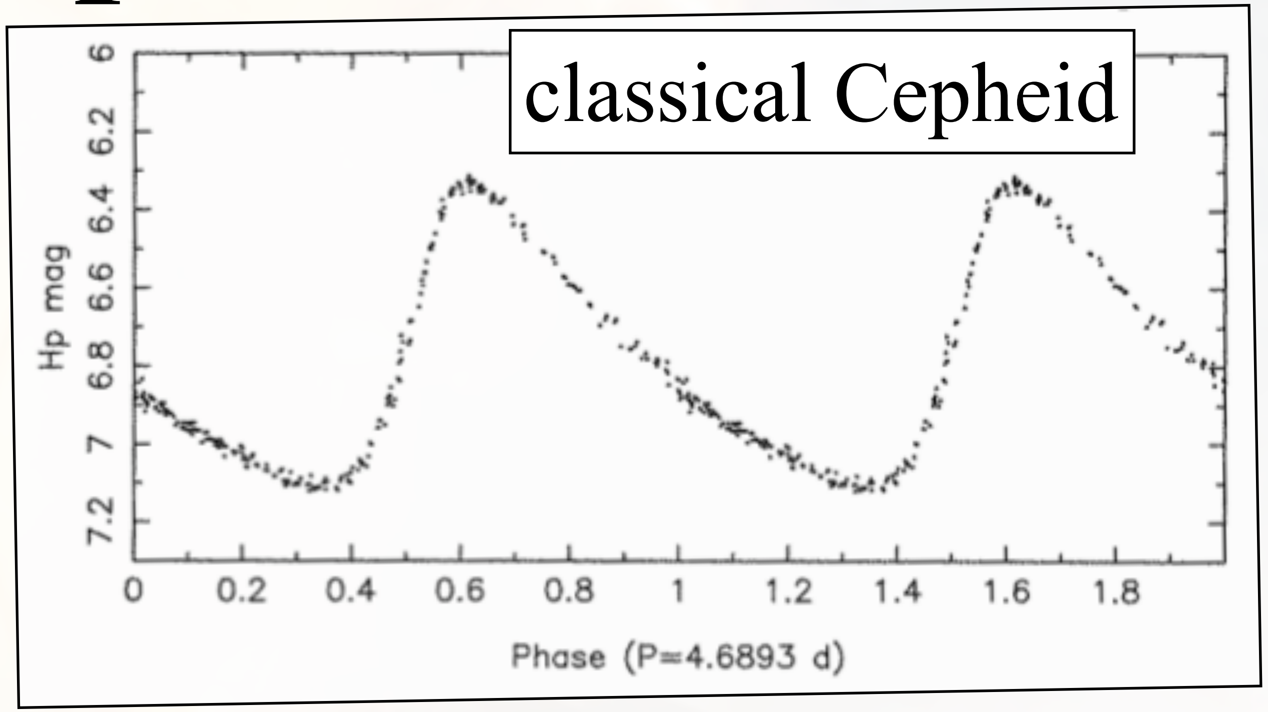
RR Lyrae and Cepheid variables

“classical” radial pulsators

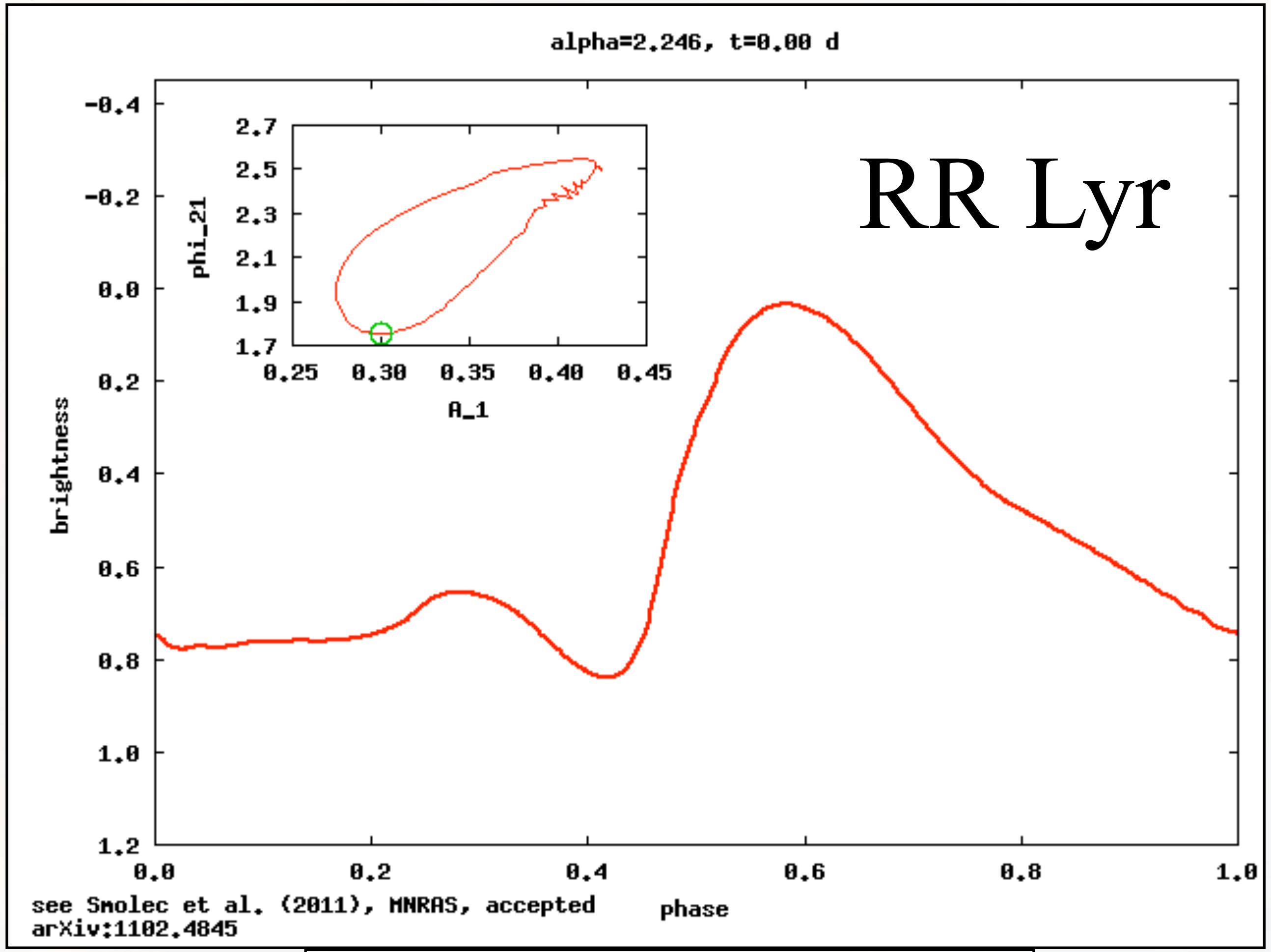
driven by κ-mechanism in He II - He III ionization zone

“standard candles” for distance determinations

RR Lyrae stars show phase-dependent amplitude modulation “*Blazhko effect*”



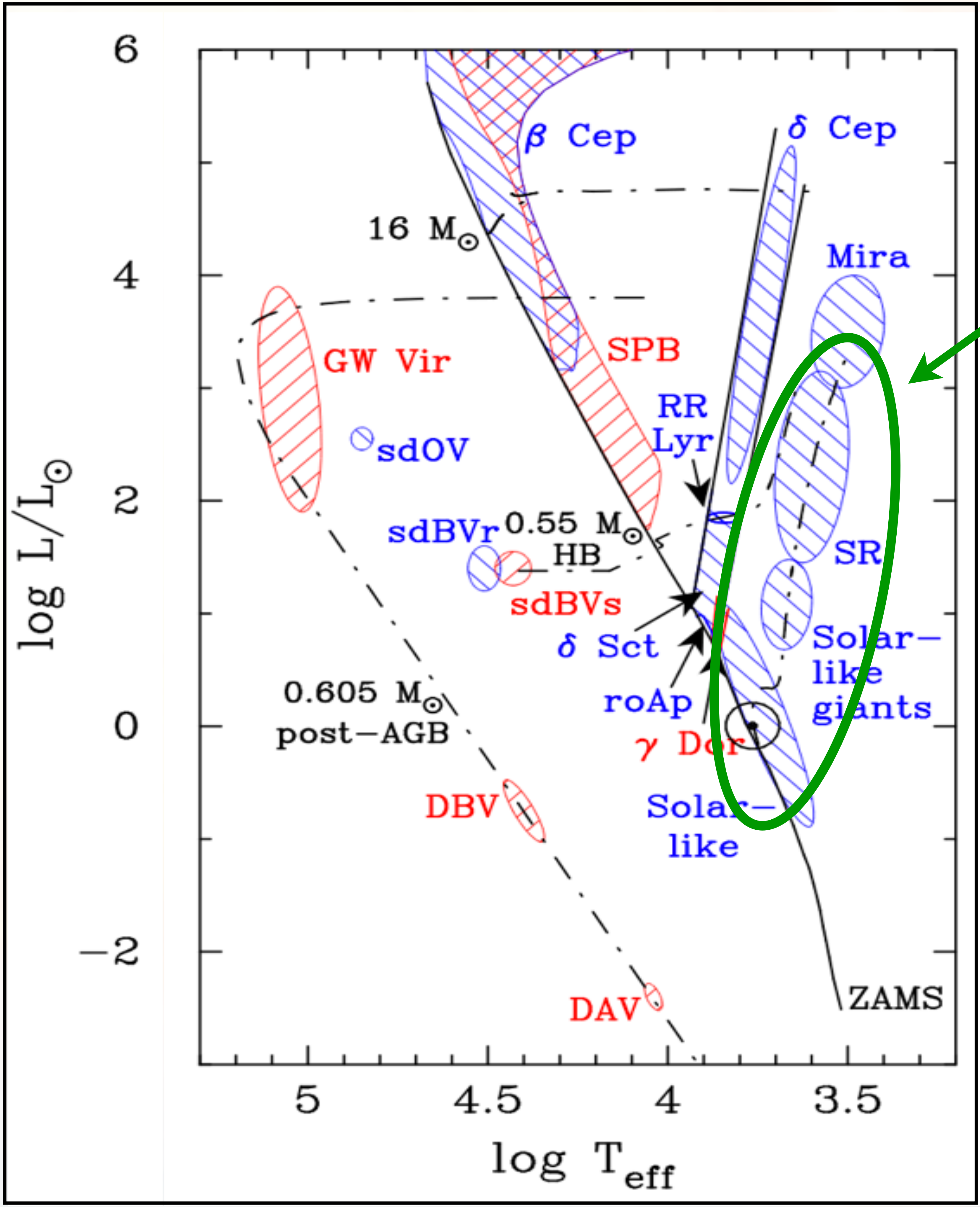
classical Cepheid



RR Lyr

see Smolec et al. (2011), MNRAS, accepted arXiv:1102.4845

Smolek et al. (2011)



Solar-Like Oscillators

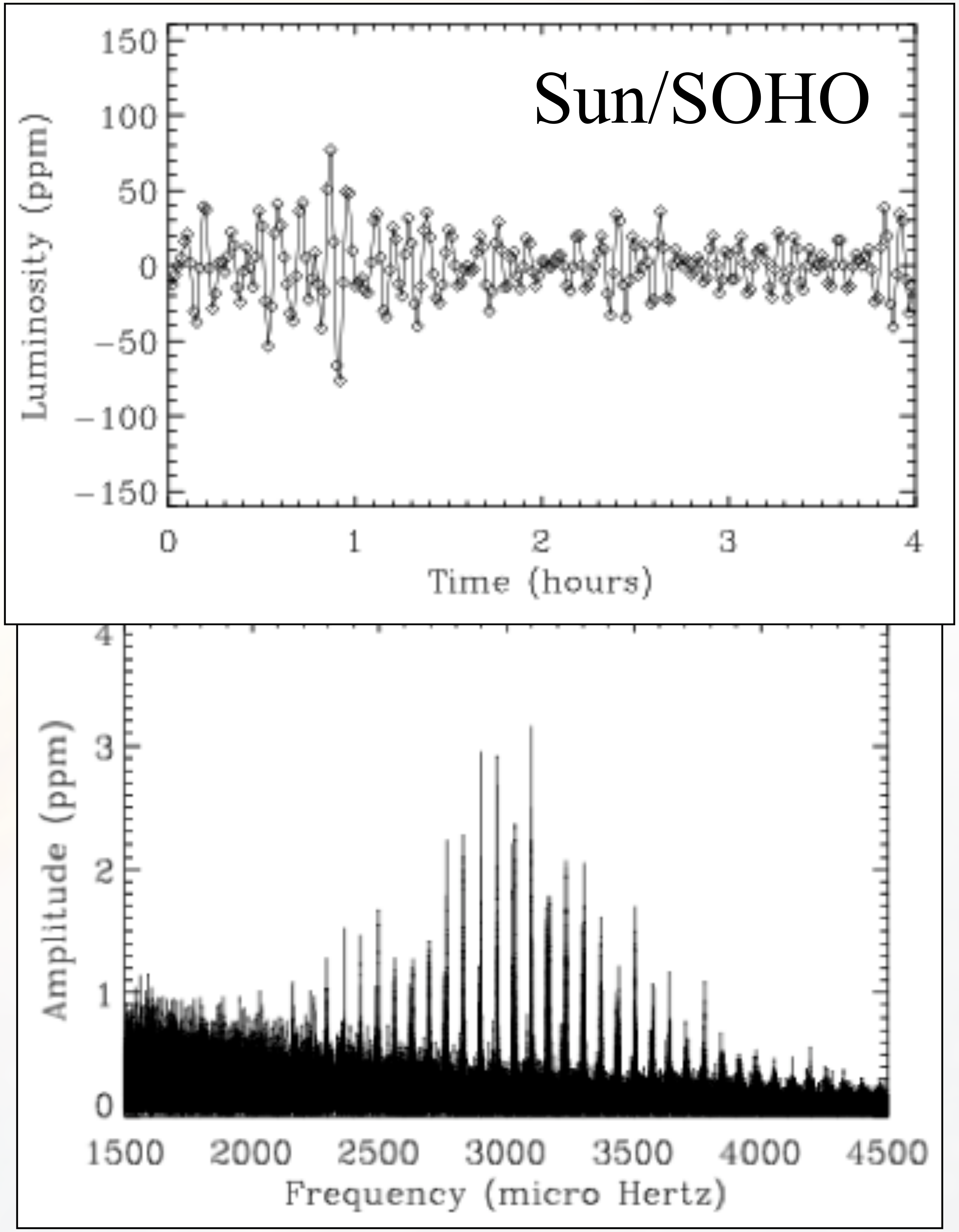
Solar-Like Oscillators

high order p-modes ➔ equally spaced in frequency!

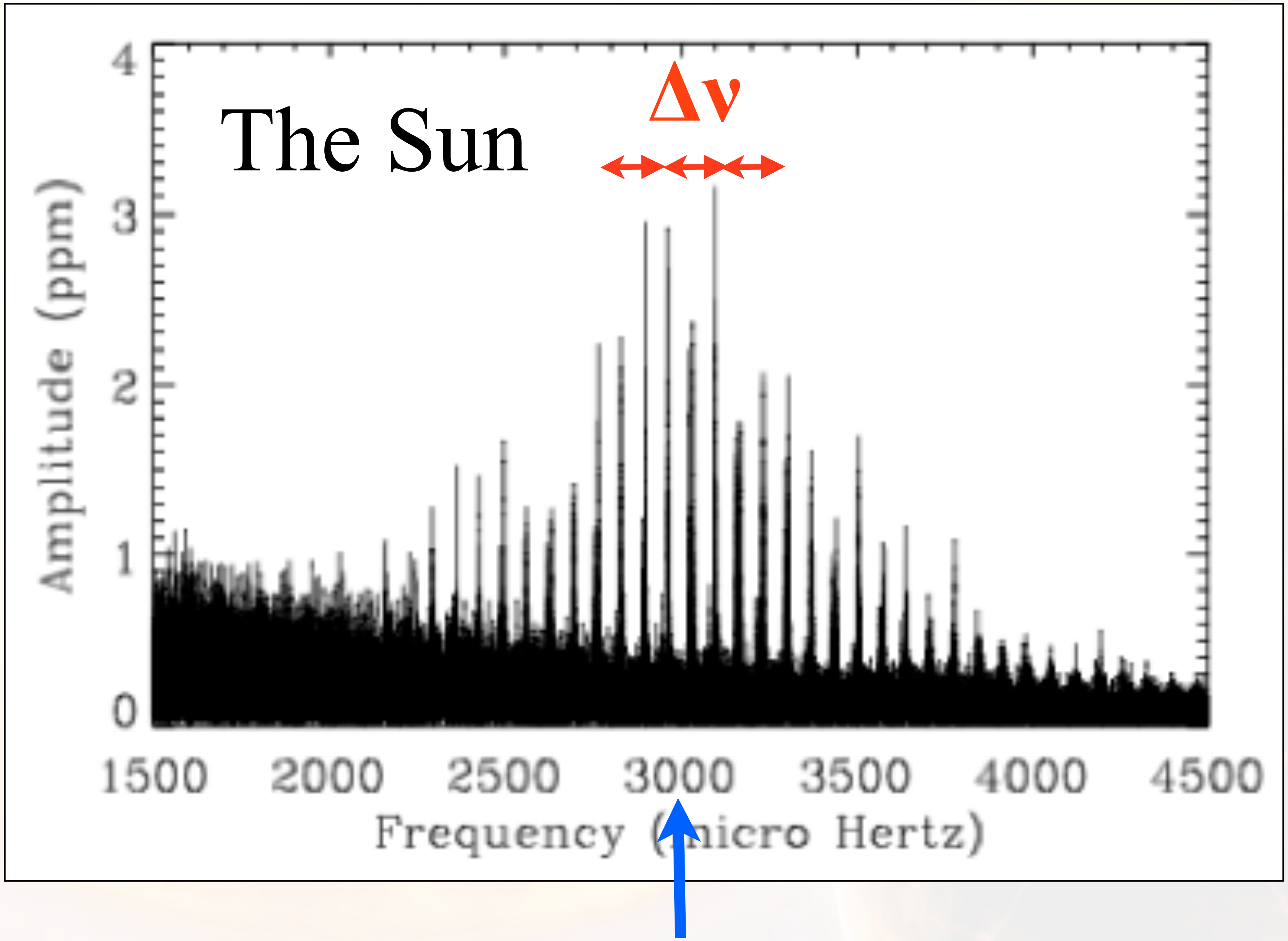
Periods: ~5 mins (Sun) to hours (red giants)

Driven by turbulent surface convection

Small amplitudes!



$\Delta\nu = (2\int dr/c_s)^{-1} \propto (M/R^3)^{1/2}$ (density)



ν_{max}

Scaling Relations

T_{eff}

+

$\Delta\nu$, ν_{max}

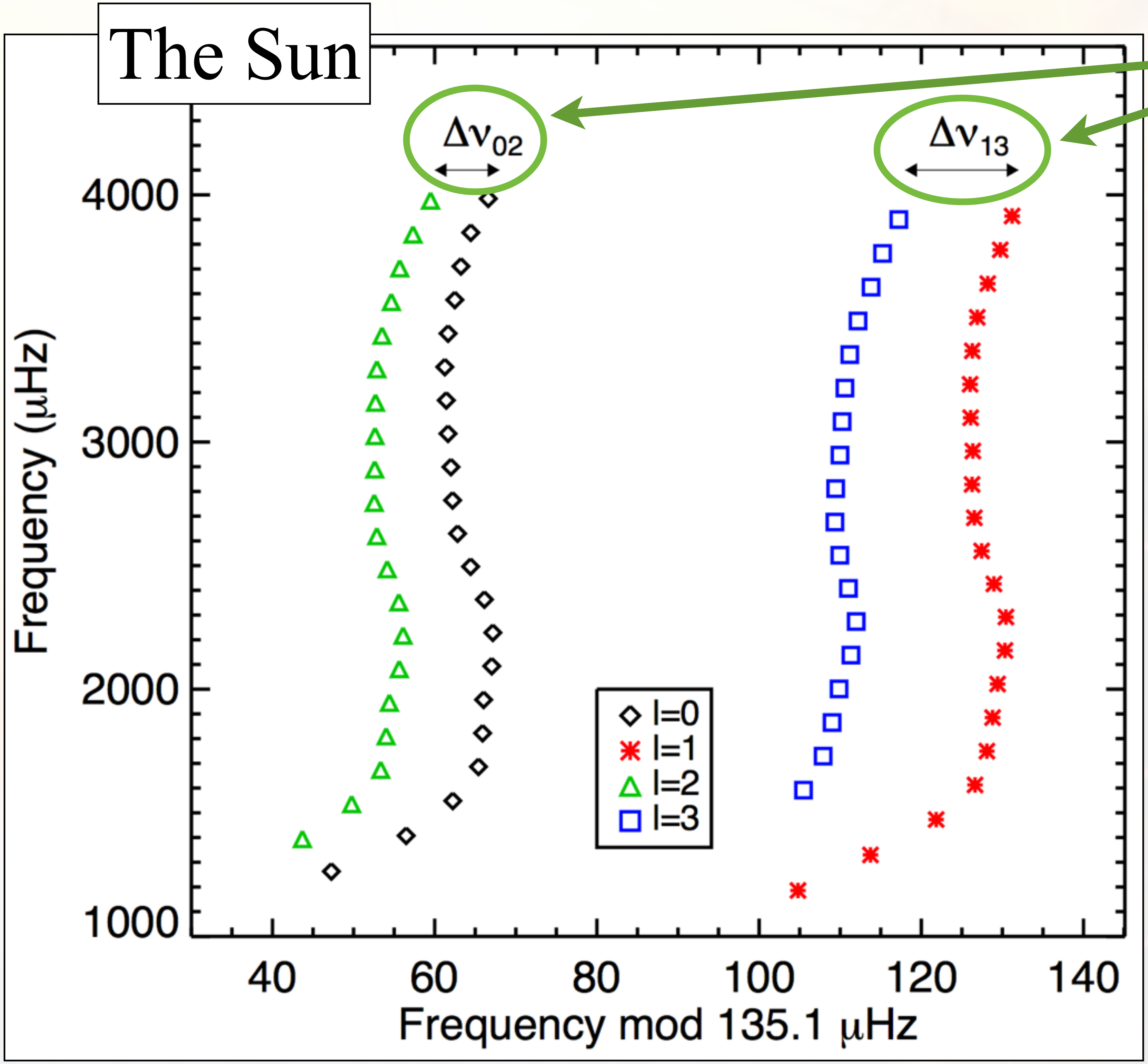
↓

R <~ 5%
M <~ 10%

$\nu_{max} \propto M R^{-2} T_{eff}^{0.5}$ (gravity)

Échelle Diagram

The Sun



$\delta\nu \propto \int dc_s/dr$

(Age)

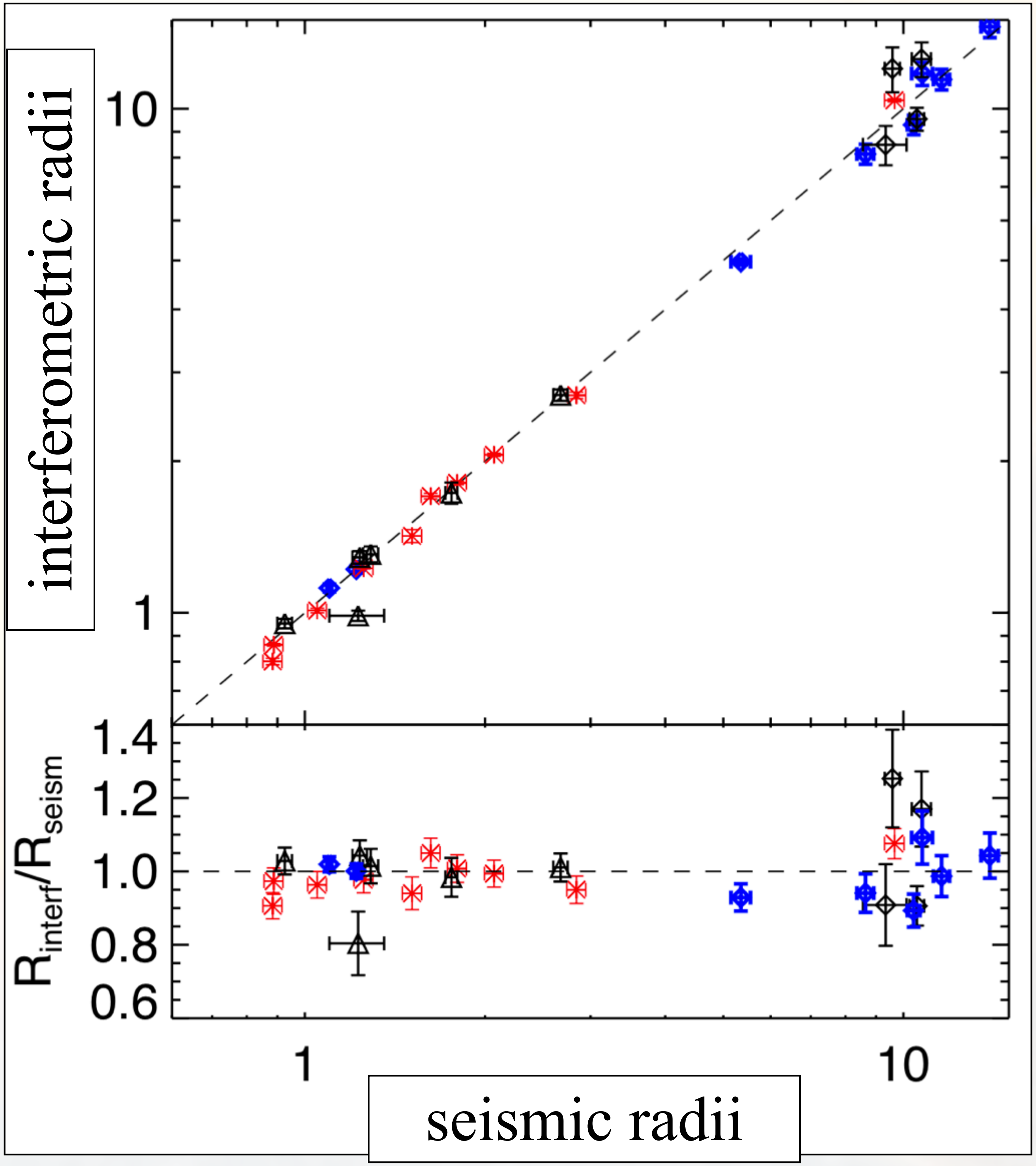
Frequency Modeling

R ~ 1%

M ~ 2%

Age ~ 10%

Does Asteroseismology Work?



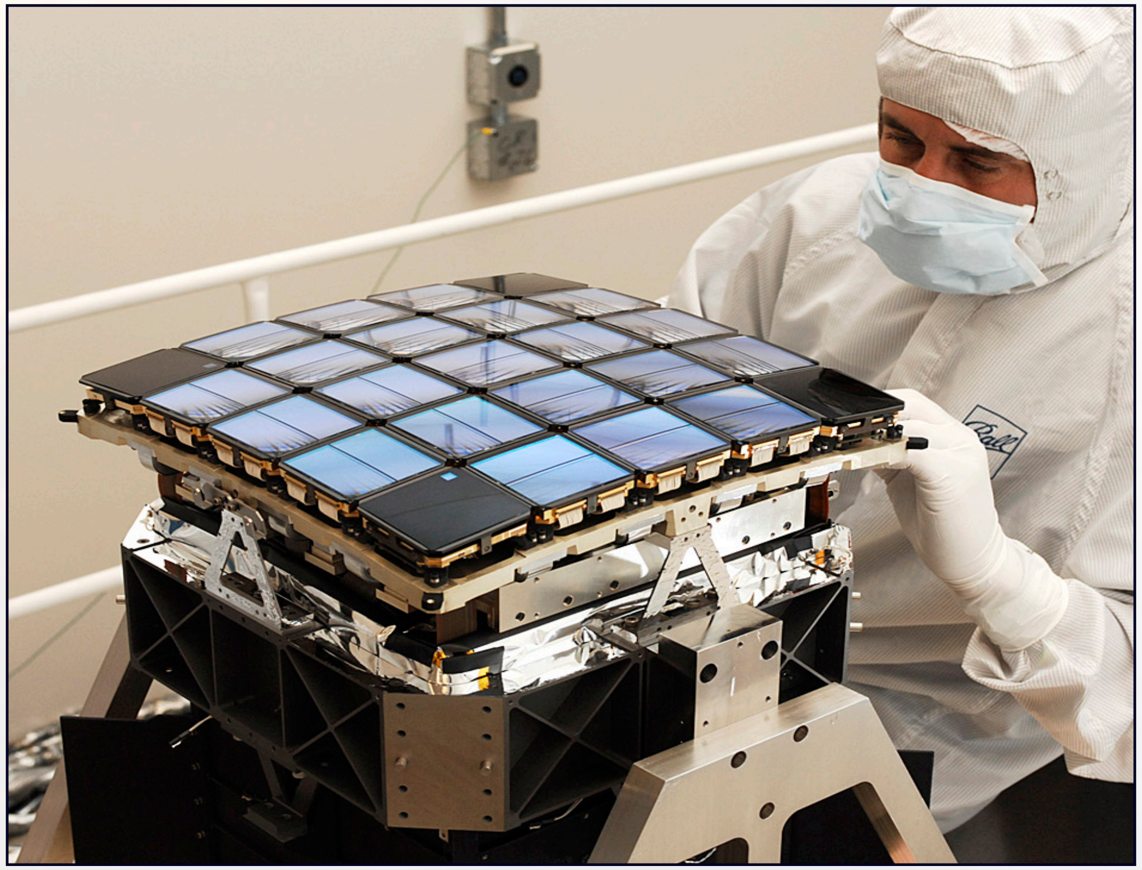
Seismic Radius from simple scaling relations

Huber et al. 2012

White et al., in prep

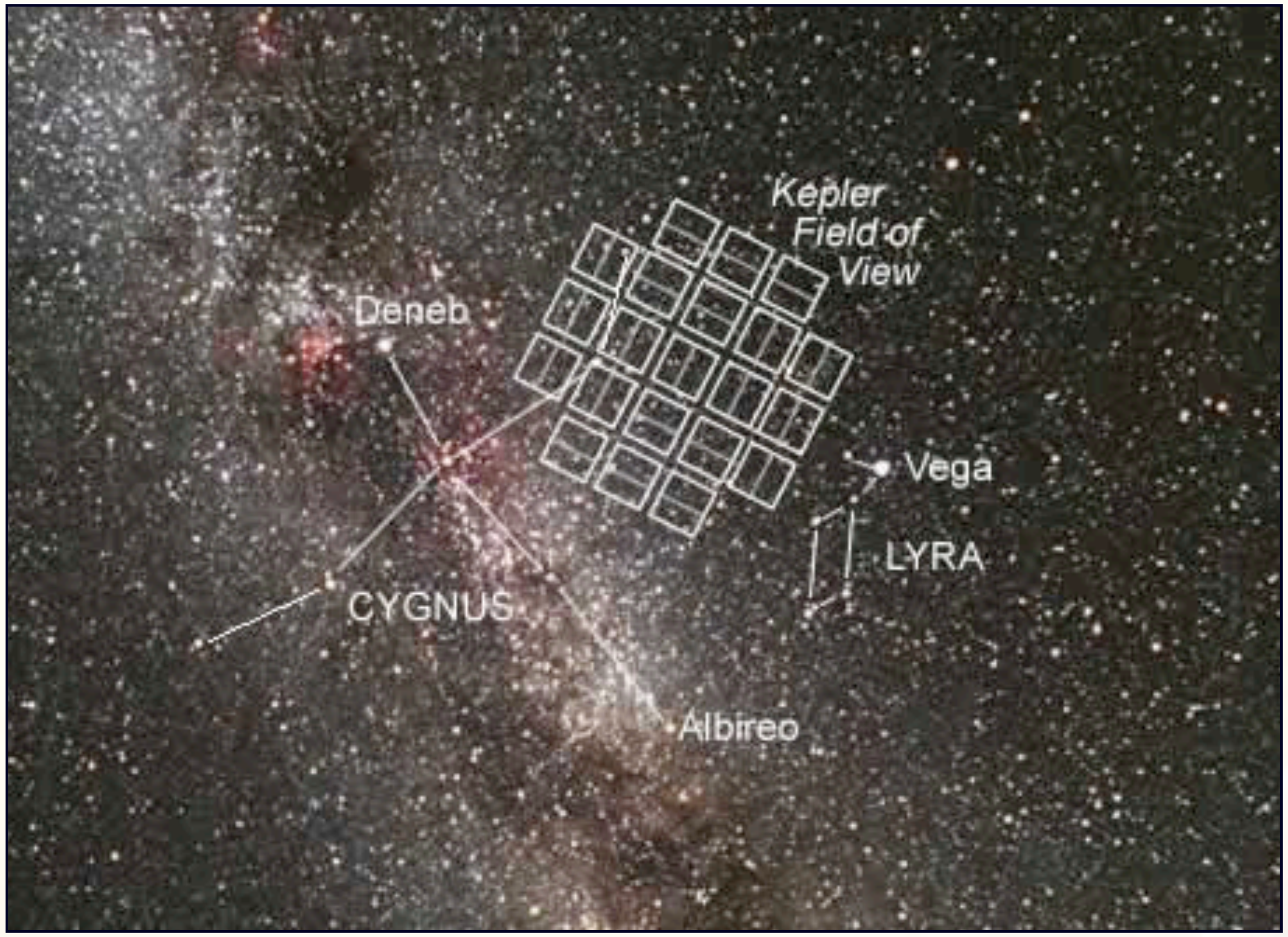
The Space-Photometry Revolution of Asteroseismology

- launched in March 2009
- 0.95 m aperture
- 42 CCD’s , 105 sq deg FOV

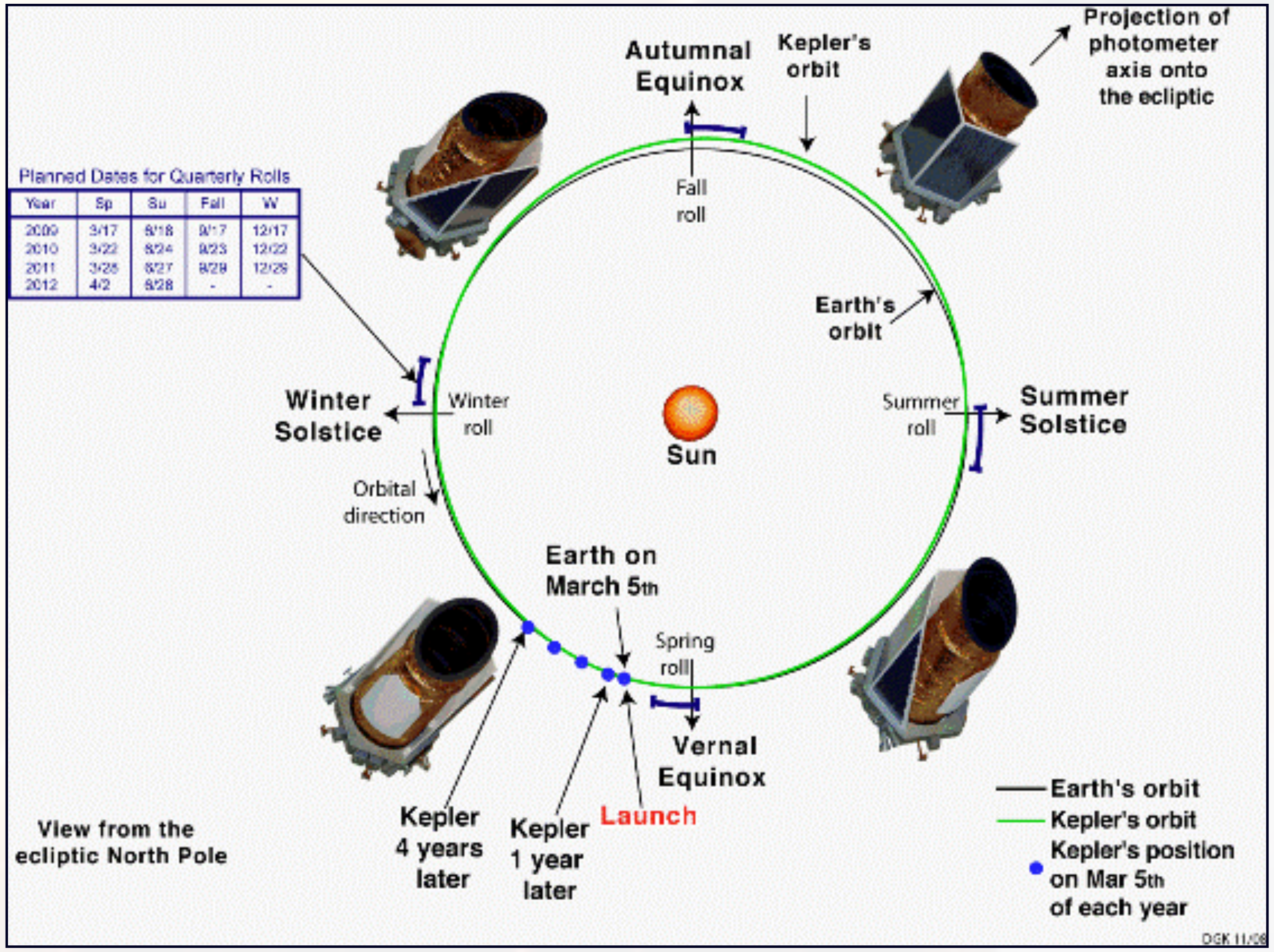


Borucki et al. (2008), Koch et al. (2010)

Kepler Field of View



Kepler Orbit


Planned Dates for Quarterly Rolls

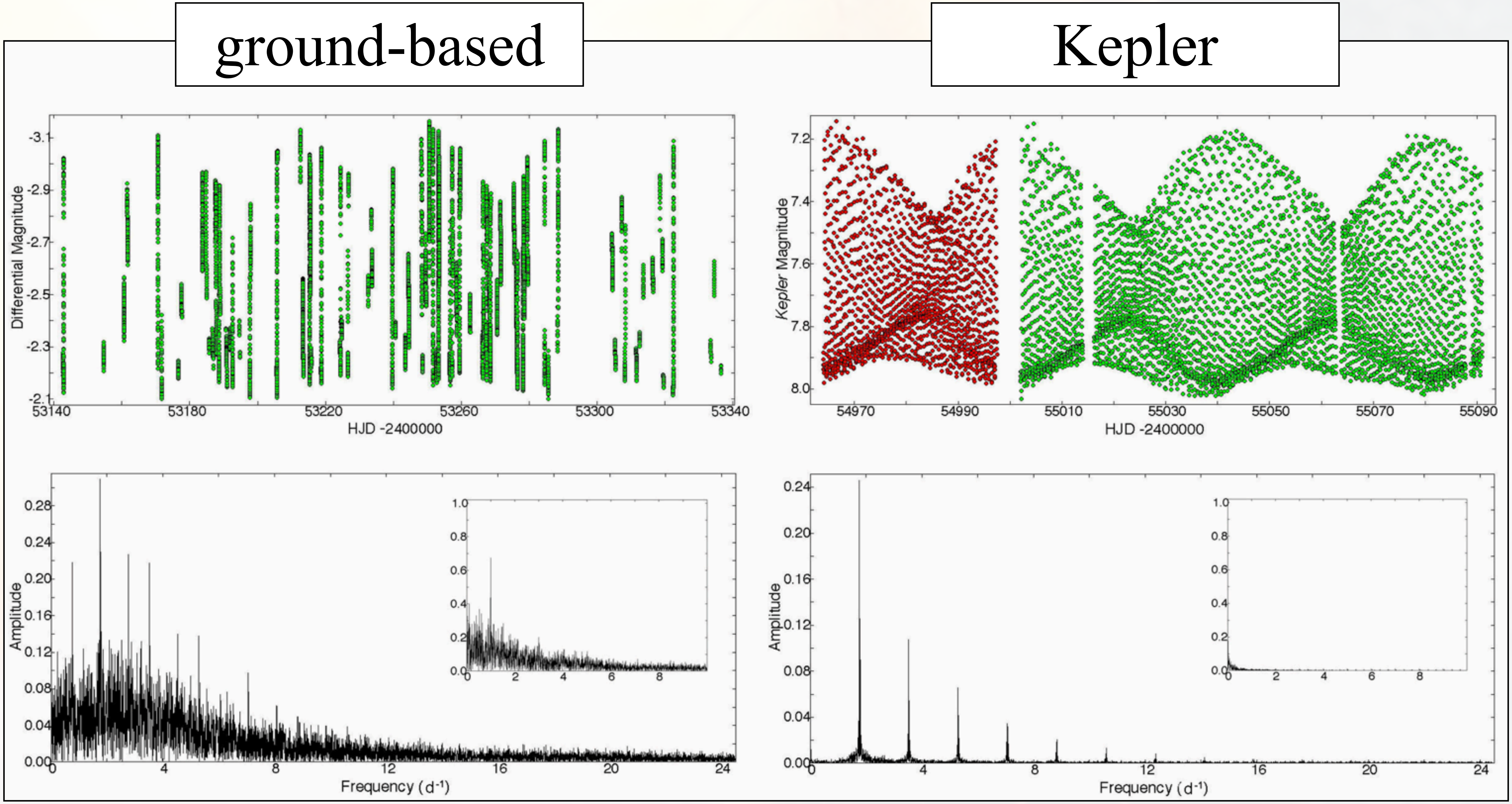
Year	Sp	Su	Fall	W
2009	3/17	6/18	9/17	12/17
2010	3/22	6/24	9/23	12/22
2011	3/25	6/27	9/28	12/26
2012	4/2	6/28	-	-

Kepler obtained uninterrupted high-precision photometry of > 150,000 stars for 4 years to search for transiting exoplanets

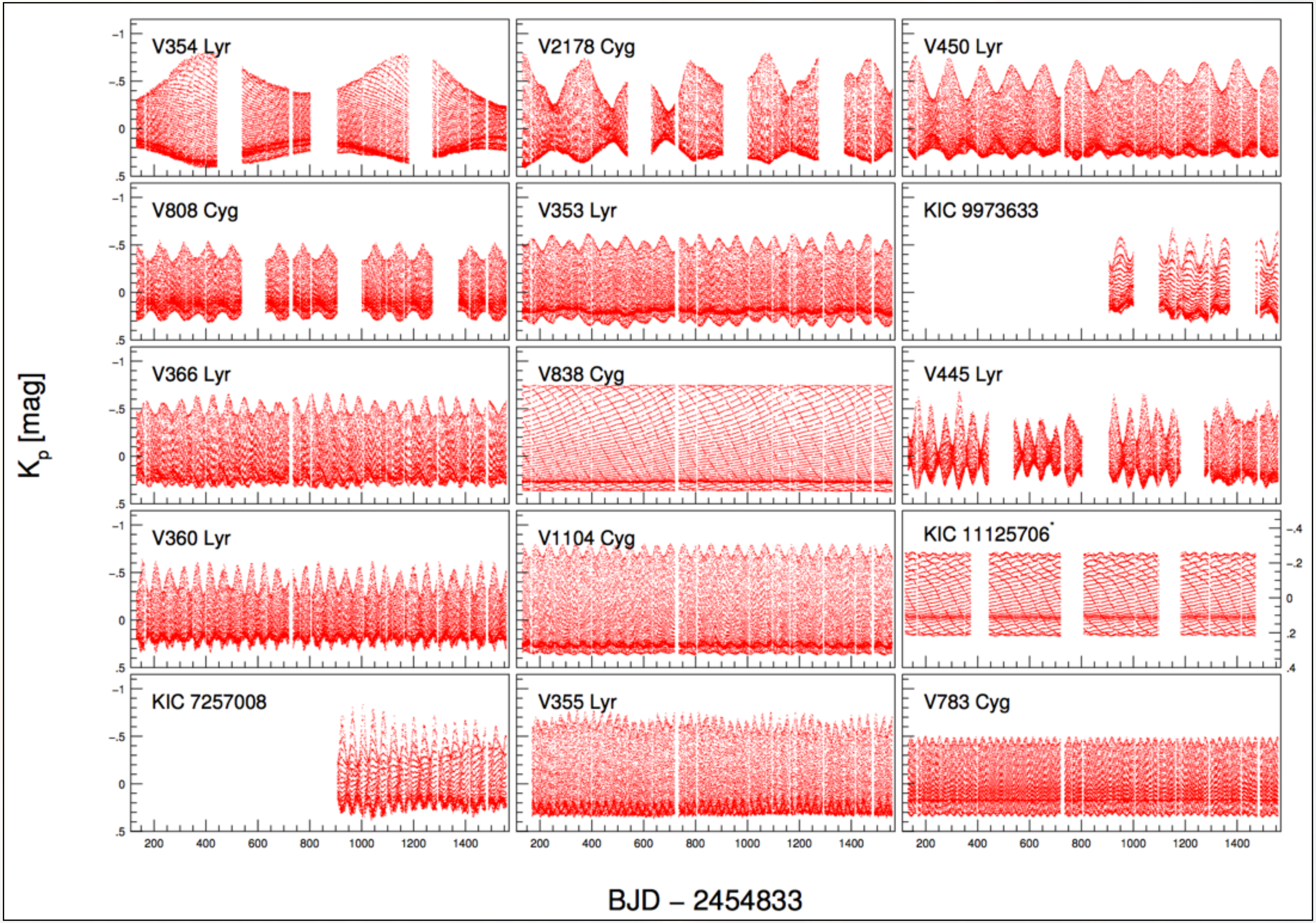
Kepler Revolution of RR Lyrae

ground-based

Kepler

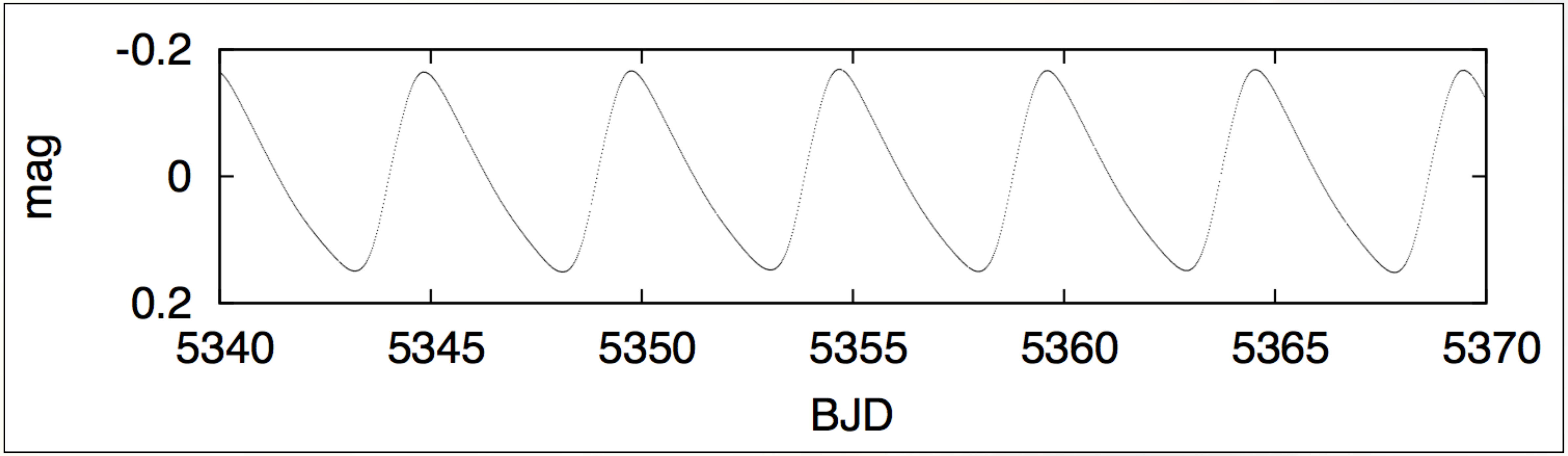


Kolenberg et al. 2011

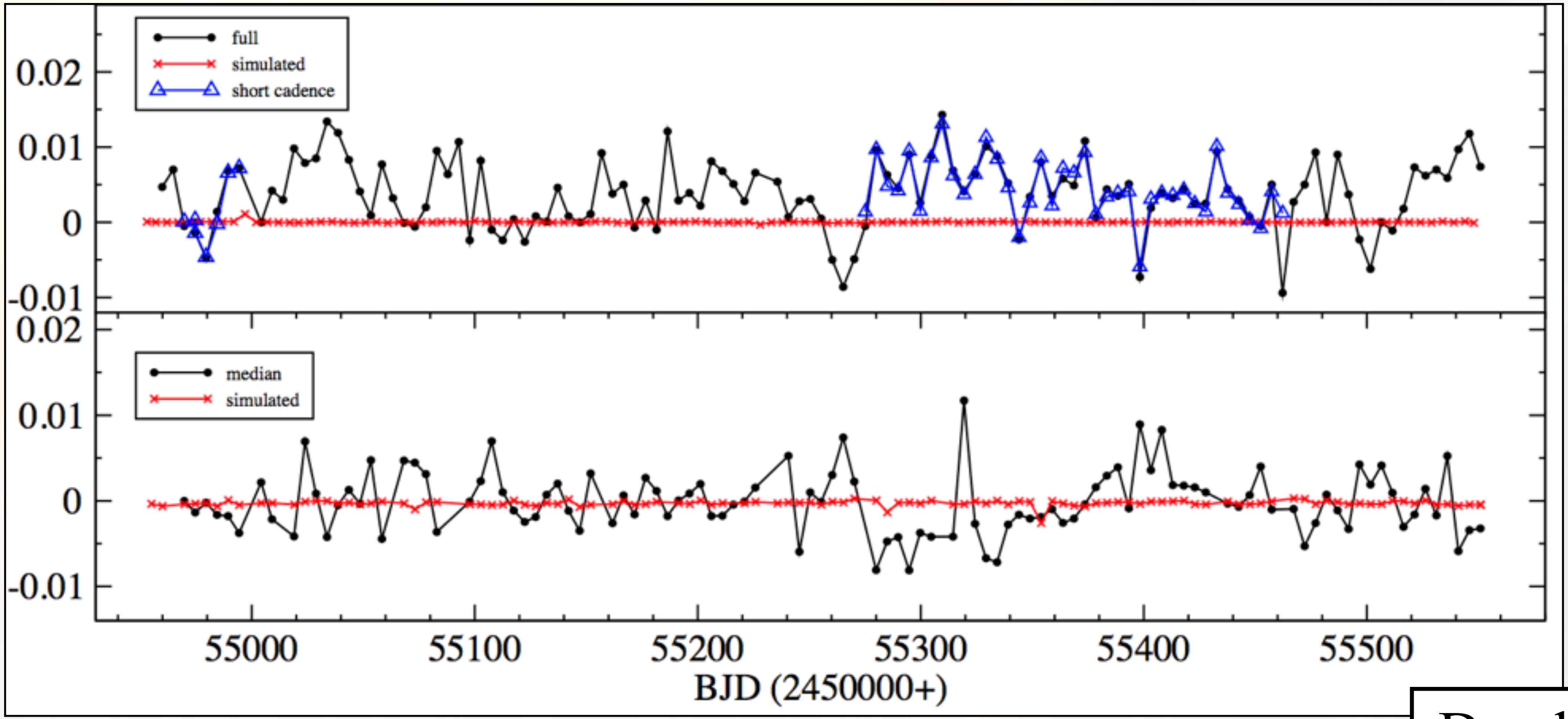


Benko et al. 2014

Kepler & Cepheids

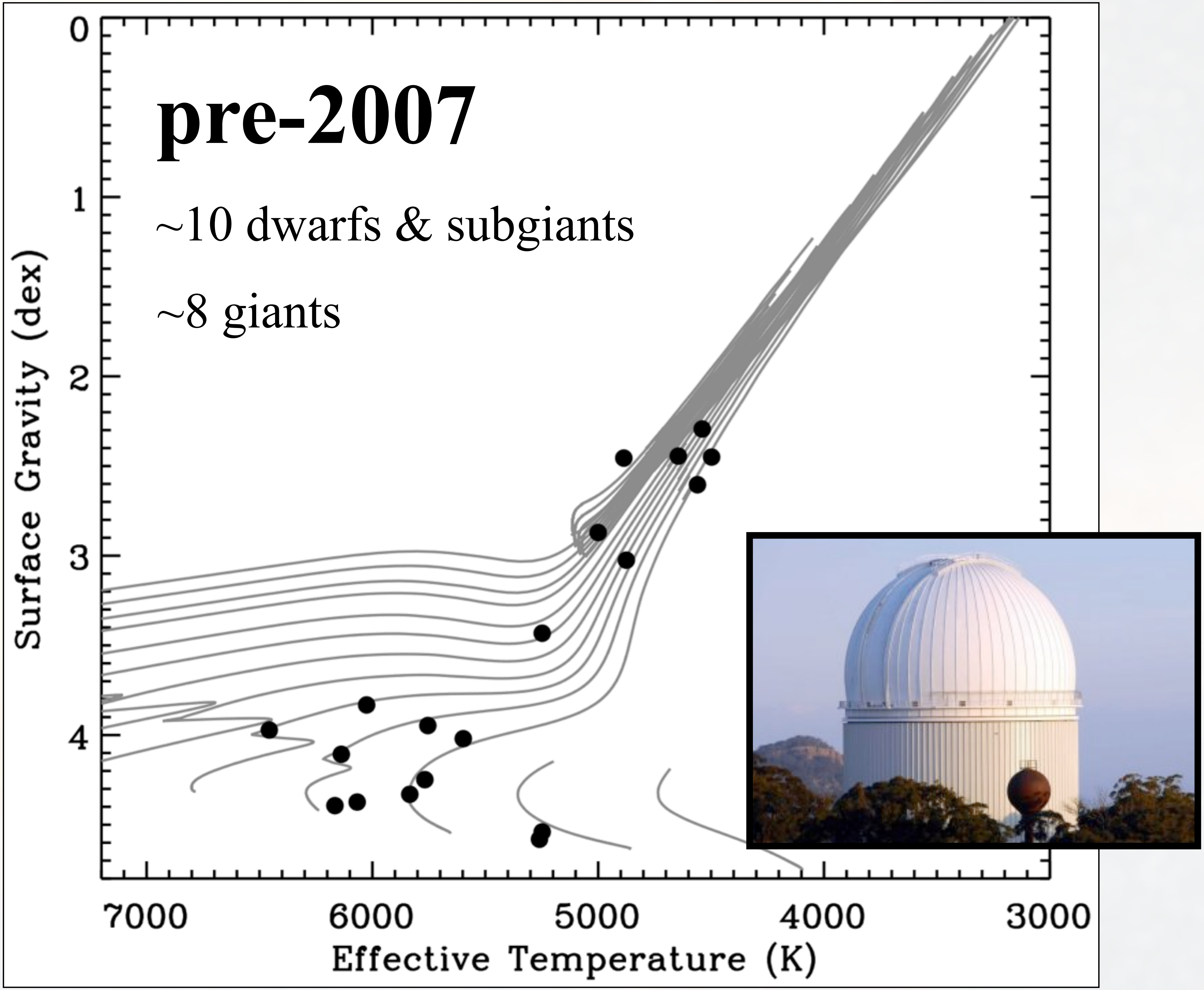


O-C



Period
Jitter

Derekas et al. 2012



pre-2007

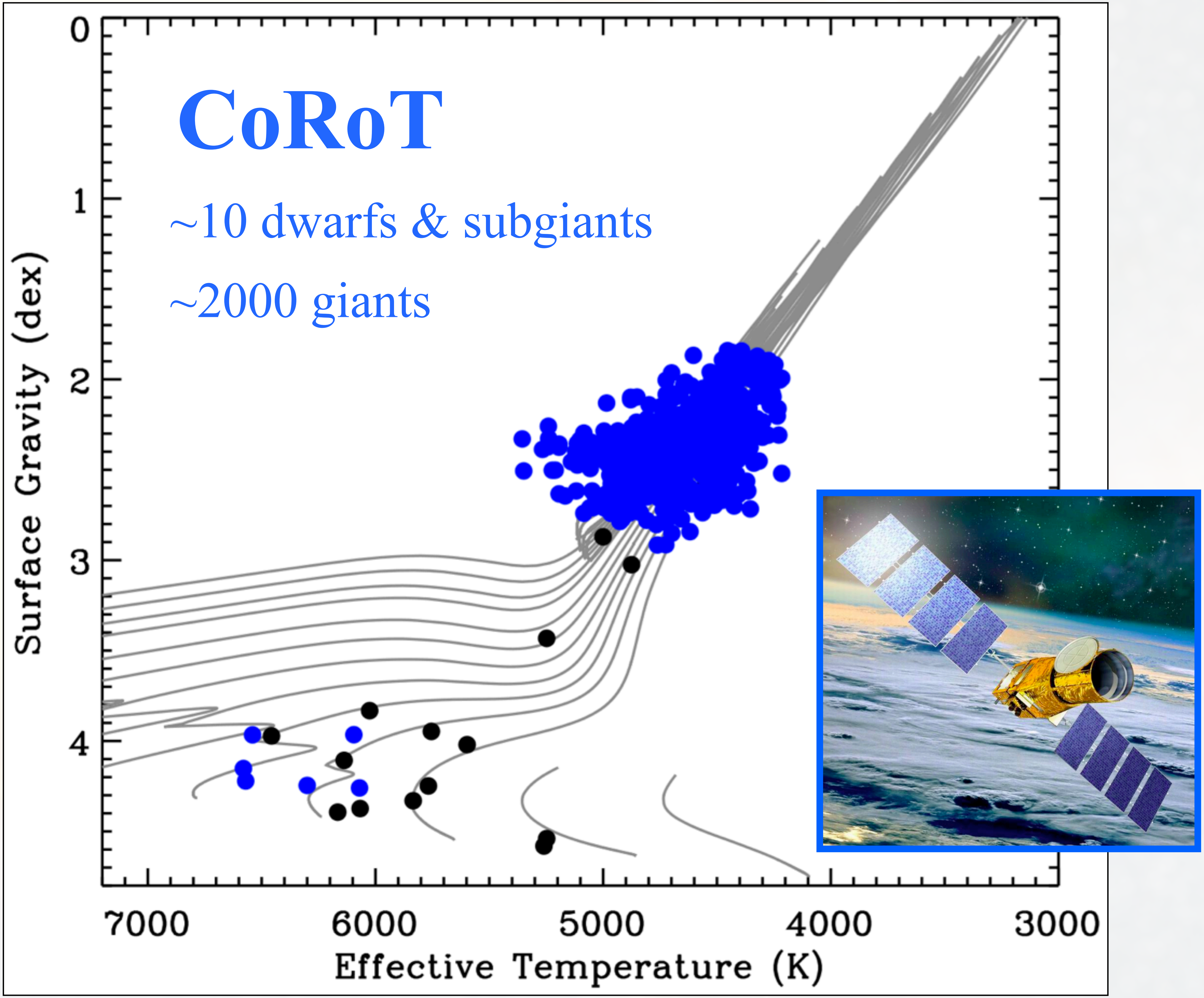
~10 dwarfs & subgiants

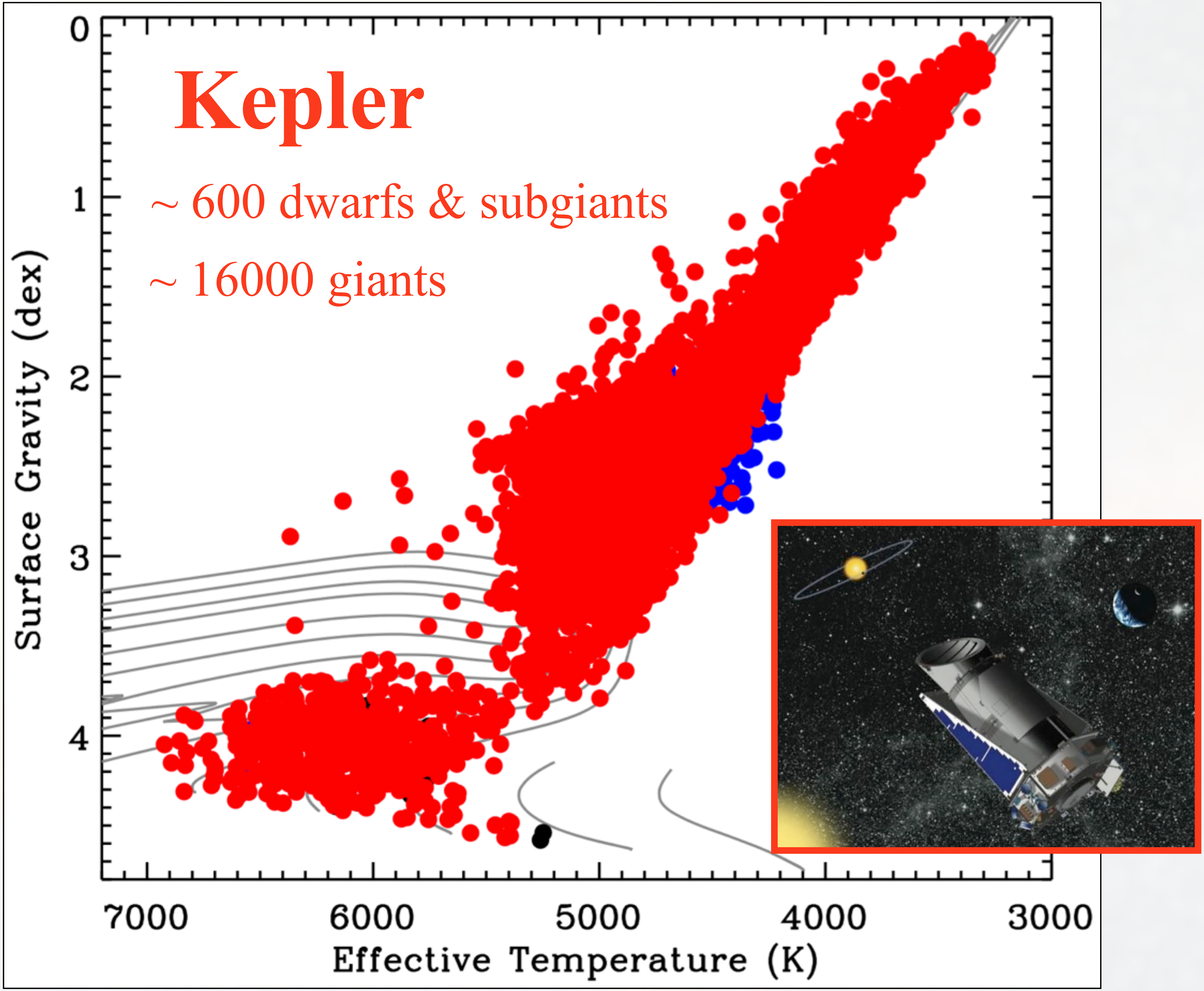
~8 giants

CoRoT

~10 dwarfs & subgiants

~2000 giants

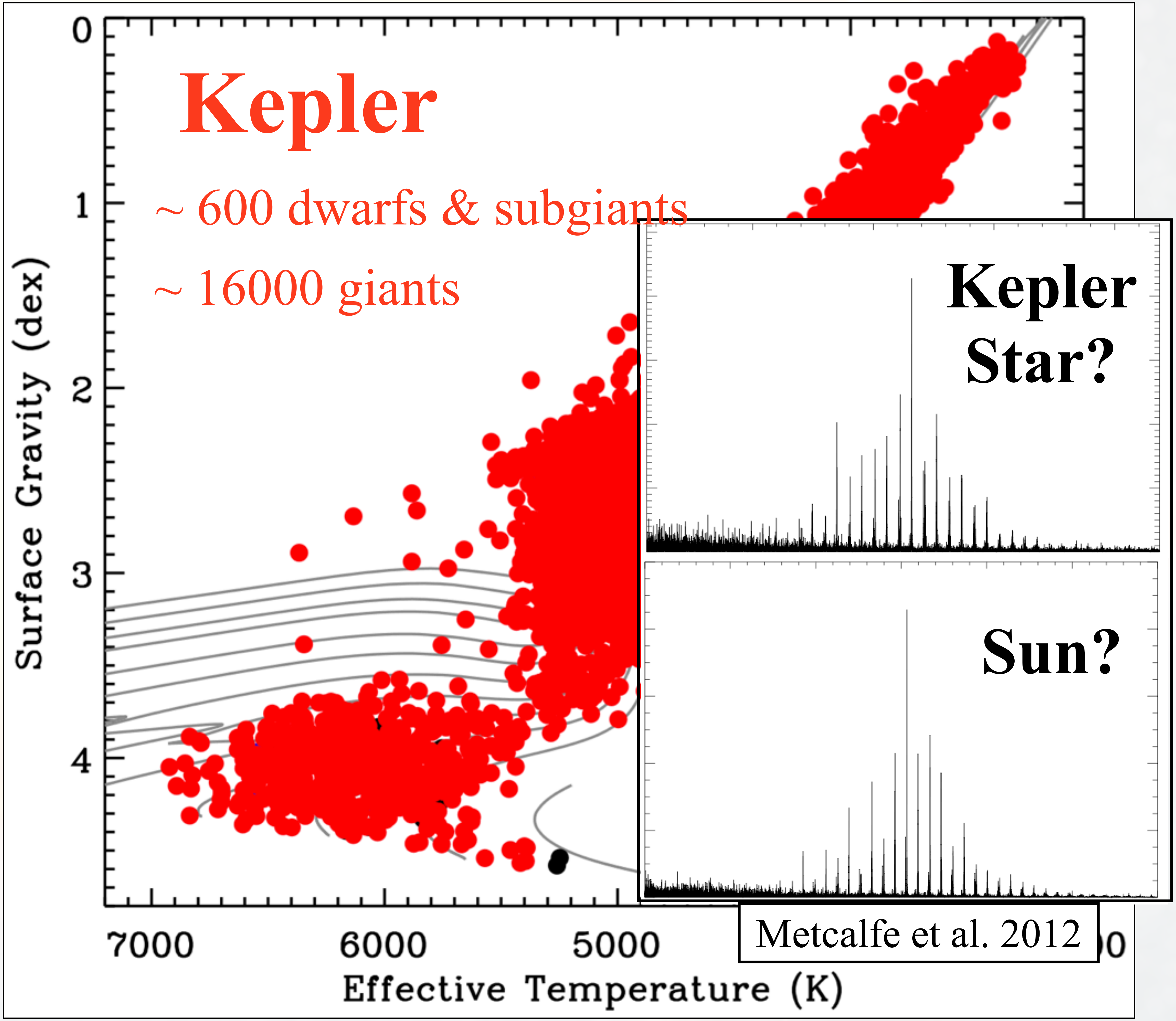




Kepler

~ 600 dwarfs & subgiants

~ 16000 giants



Kepler

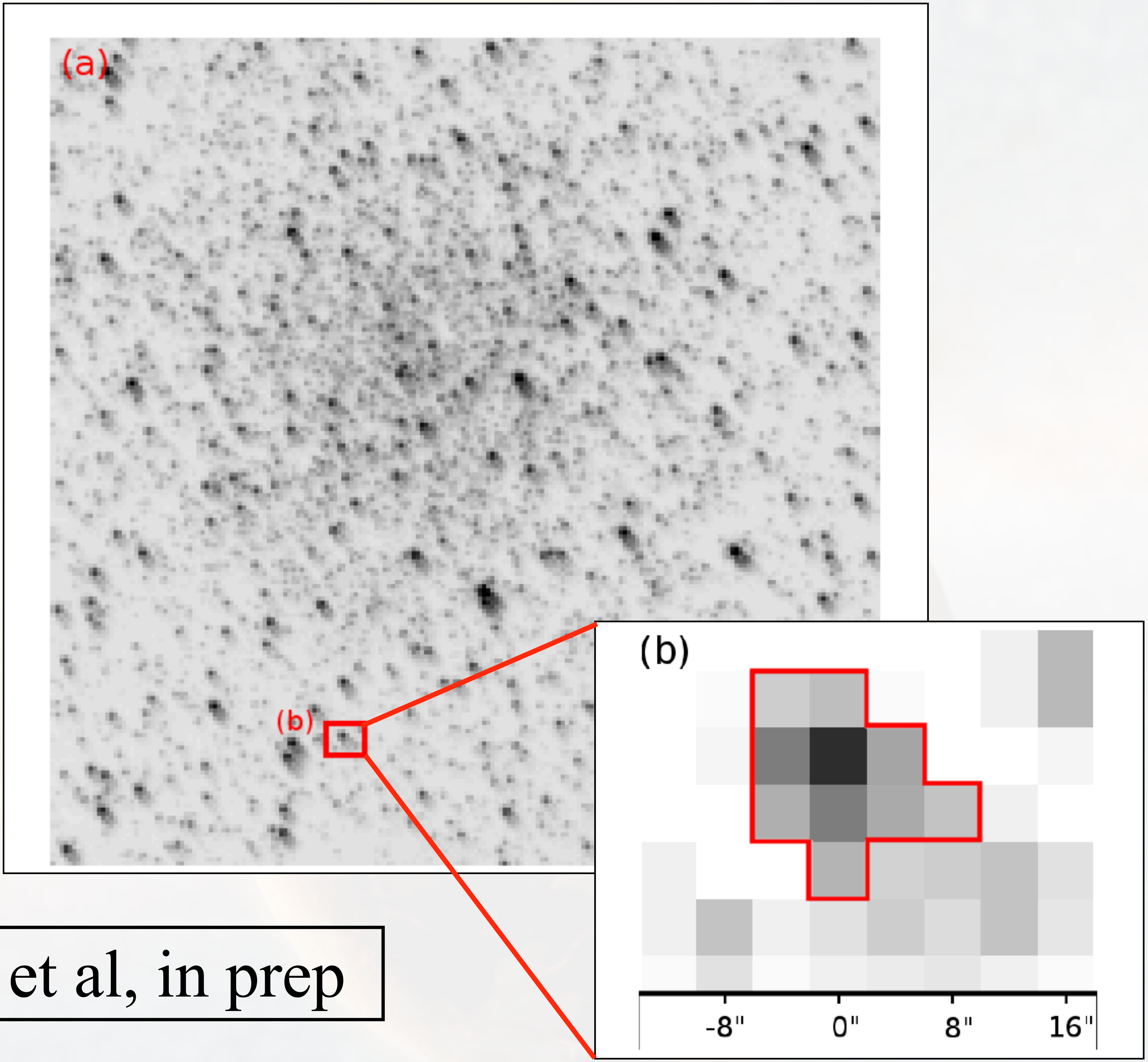
~ 600 dwarfs & subgiants

~ 16000 giants

Metcalfe et al. 2012

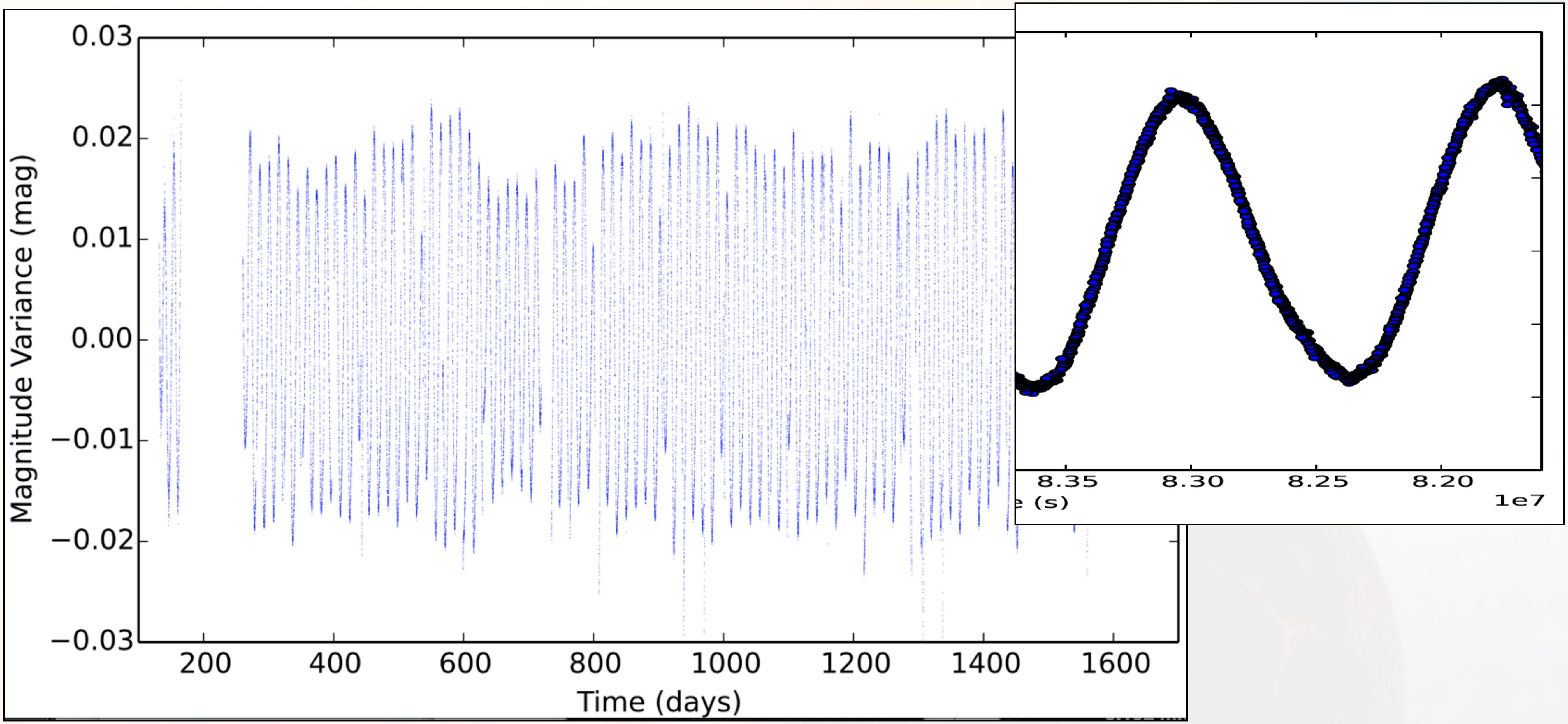
What's next?
Kepler, K2, BRITE, TESS and beyond

Kepler: A second Cepheid!



Jason Drury et al, in prep

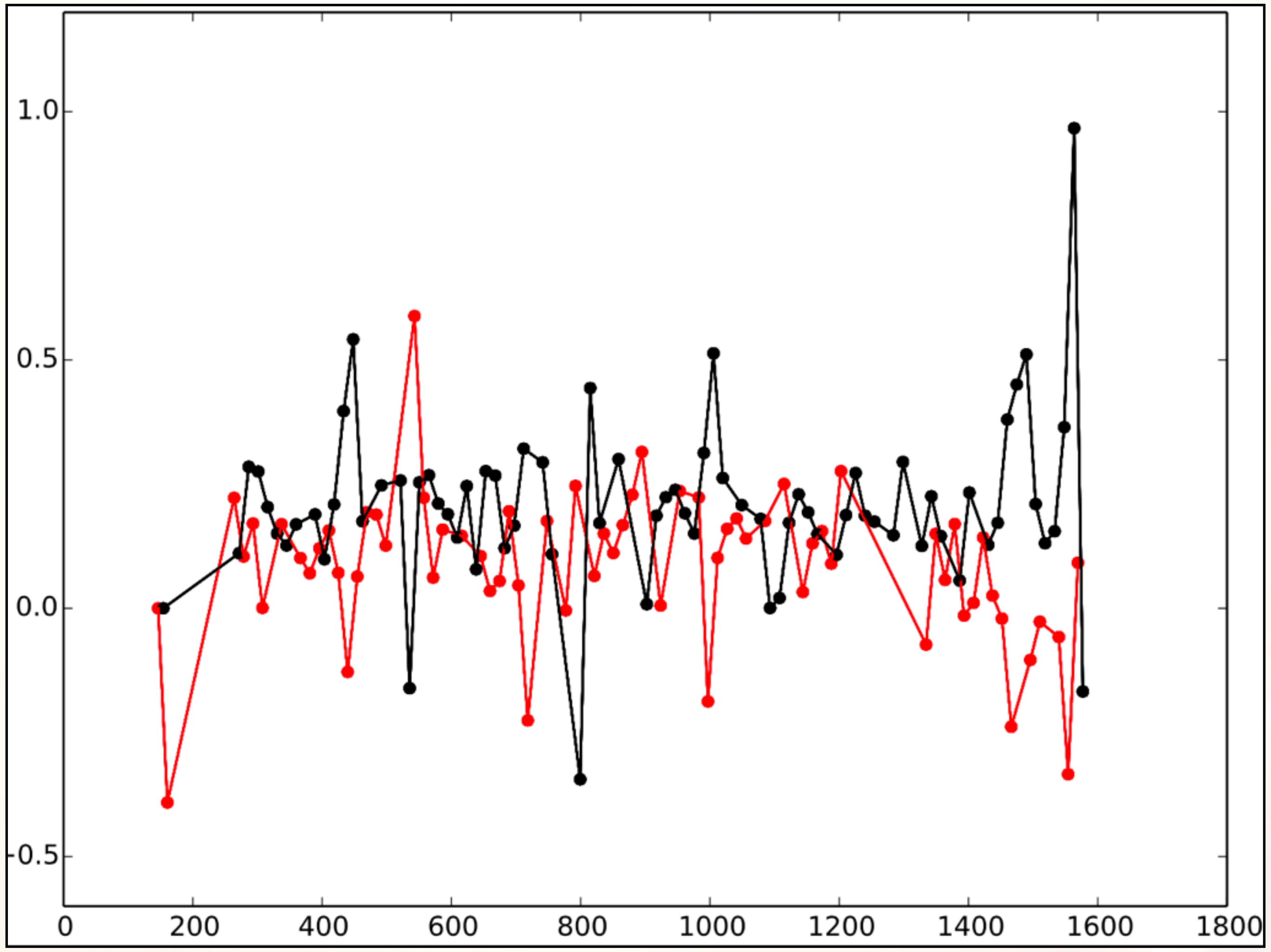
Kepler: A second Cepheid!

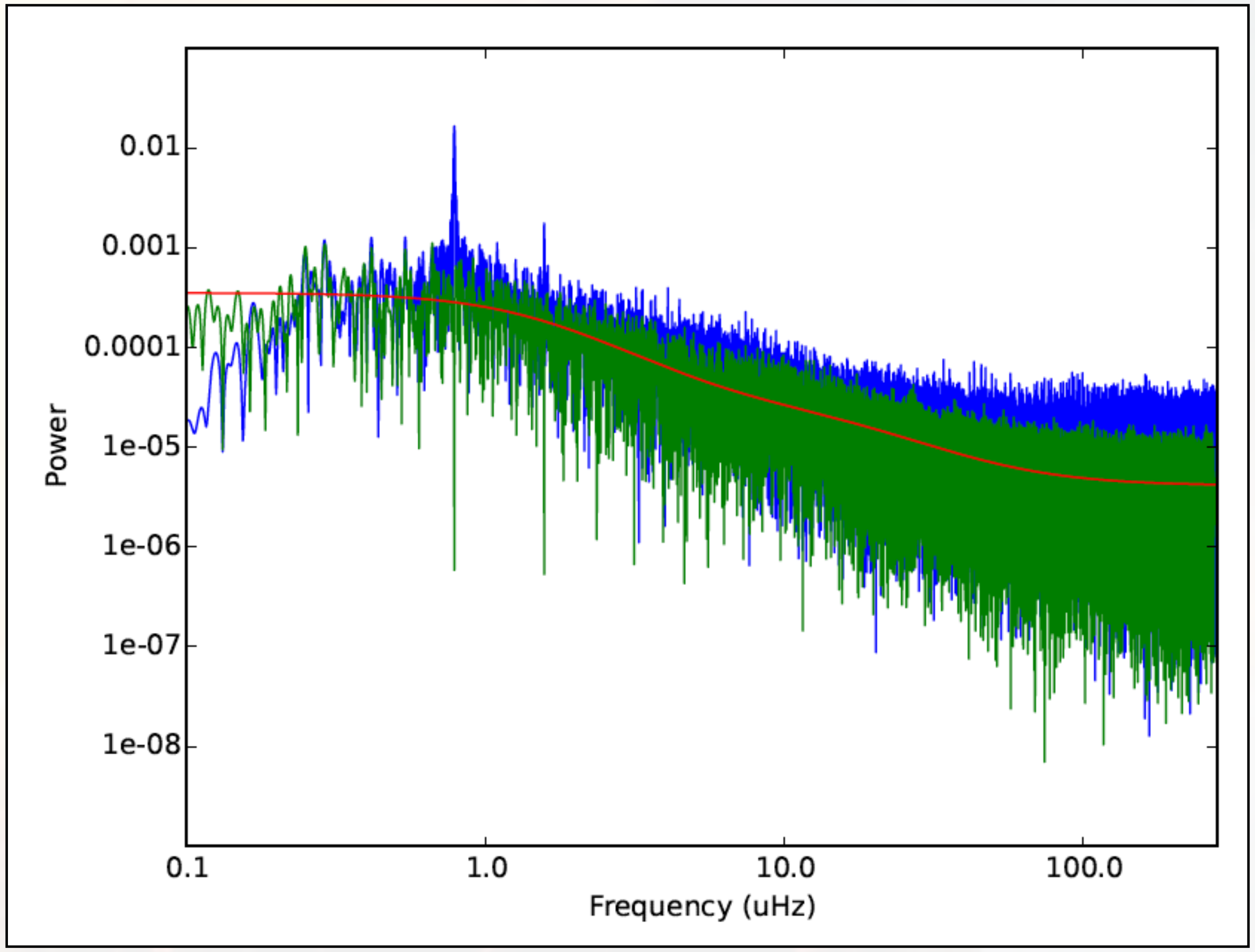


P = 14.7 d Kp = 14.2 B-V = 0.54 d ~ 15 kpc

Jason Drury et al, in prep

Kepler: A second Cepheid!



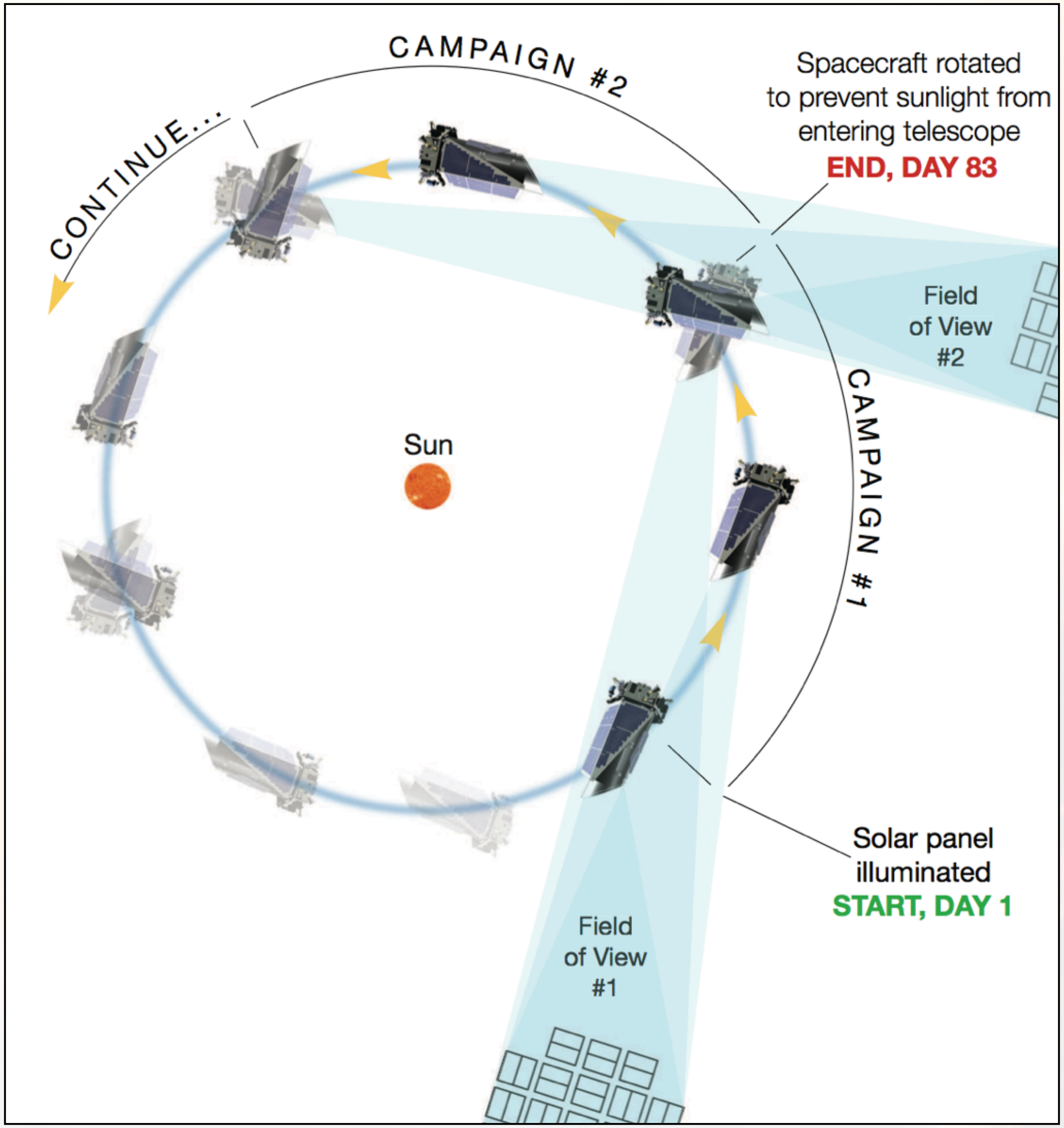


Period Jitter
$\Delta P/P \sim 1.5\text{-}3\%$

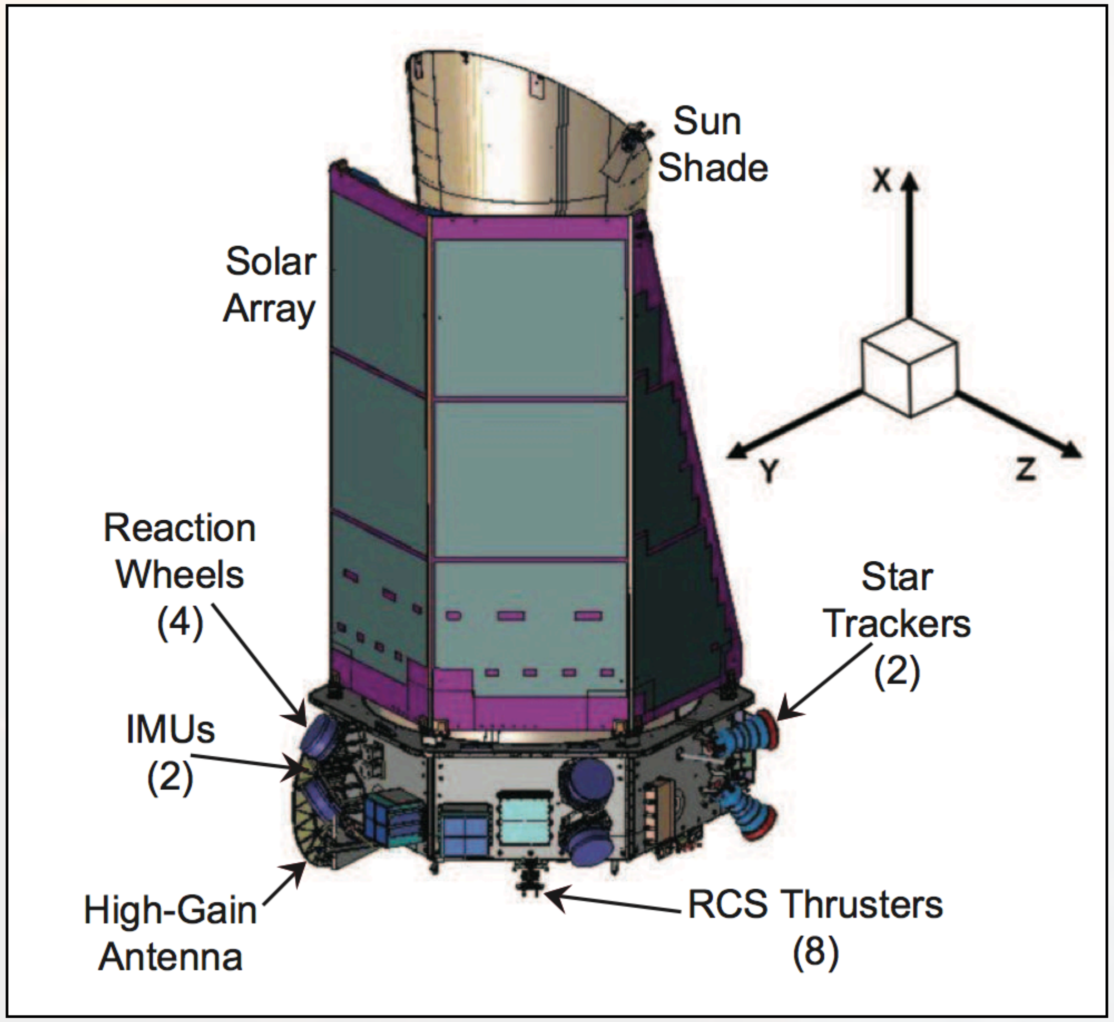
Granulation noise
in a Cepheid?

Jason Drury et al, in prep

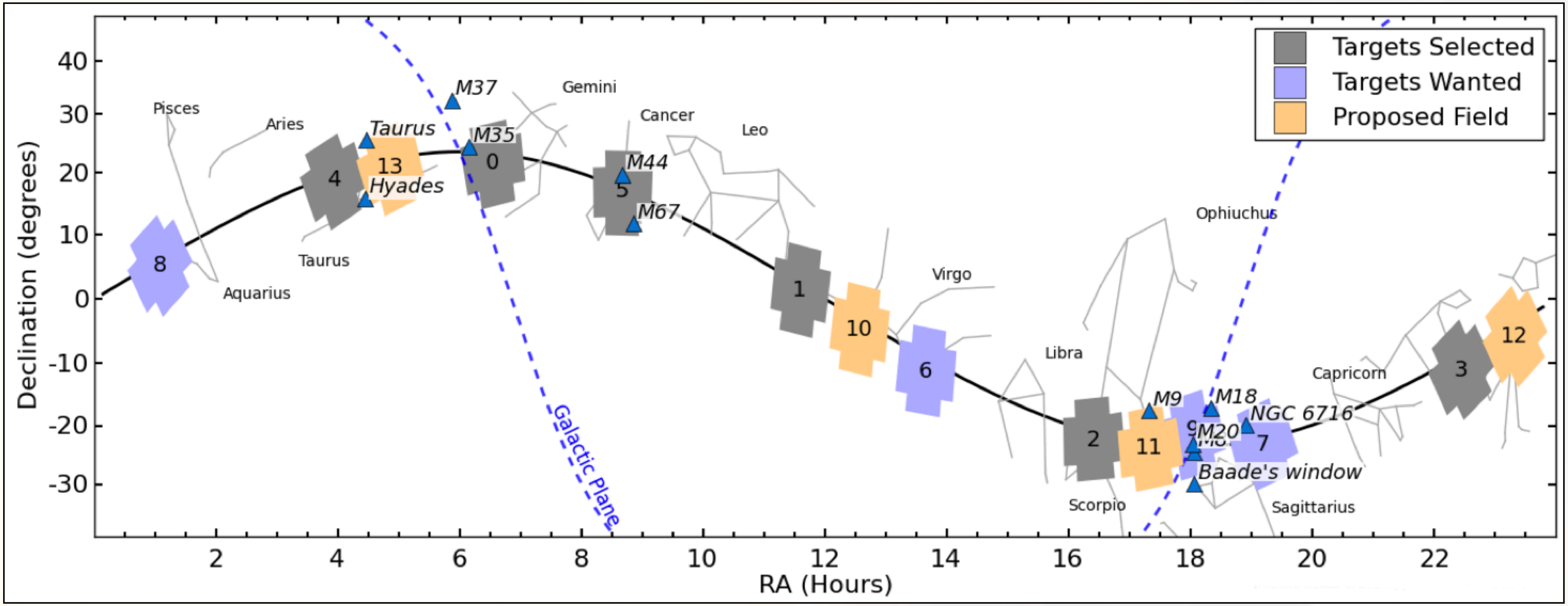
The K2 Mission



~80 day campaigns in each ecliptic field



Howell et al. (2014)

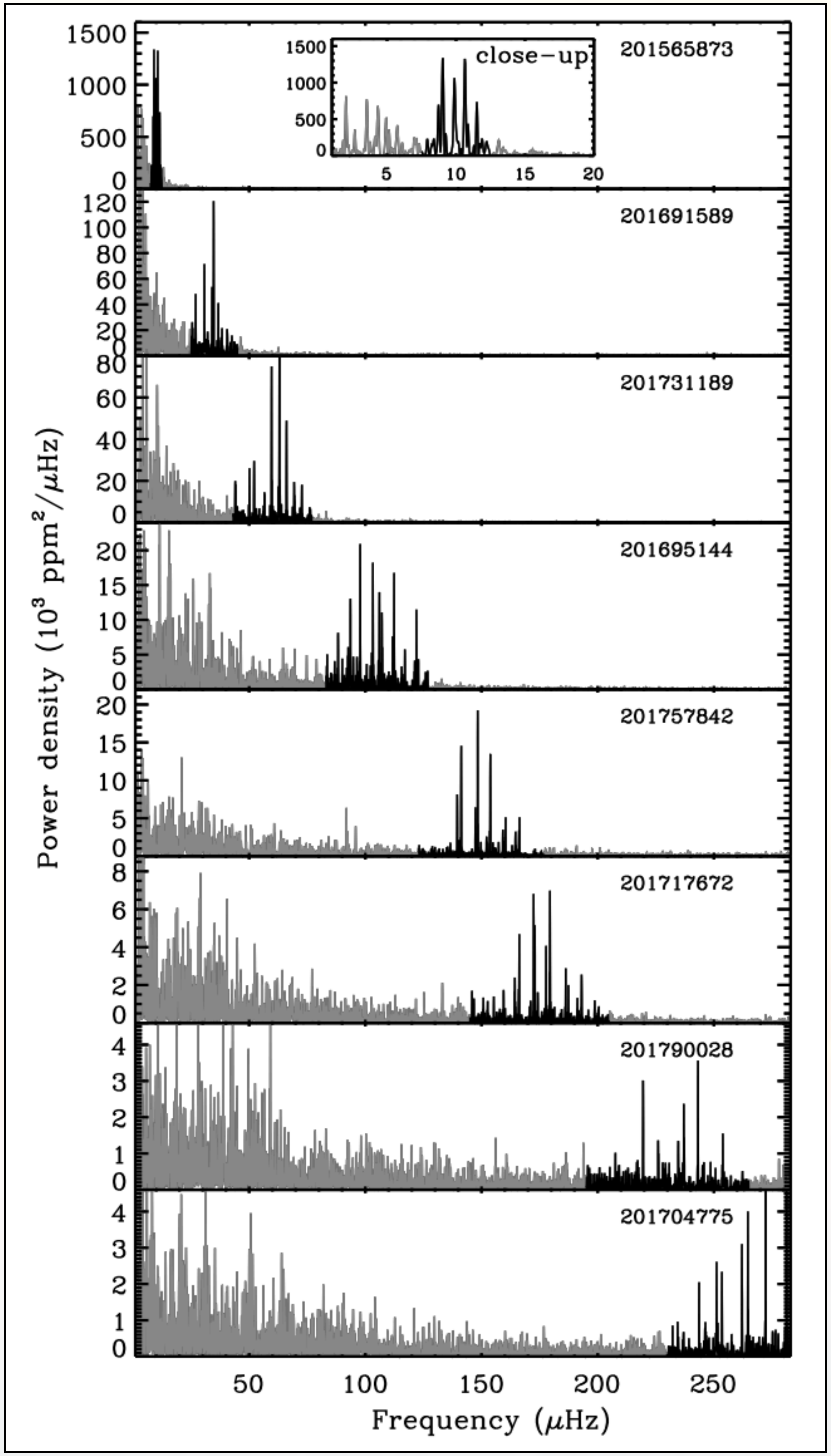


Science: exoplanets, clusters (Pleiades!) & moving groups (upper Sco), galactic fields, etc

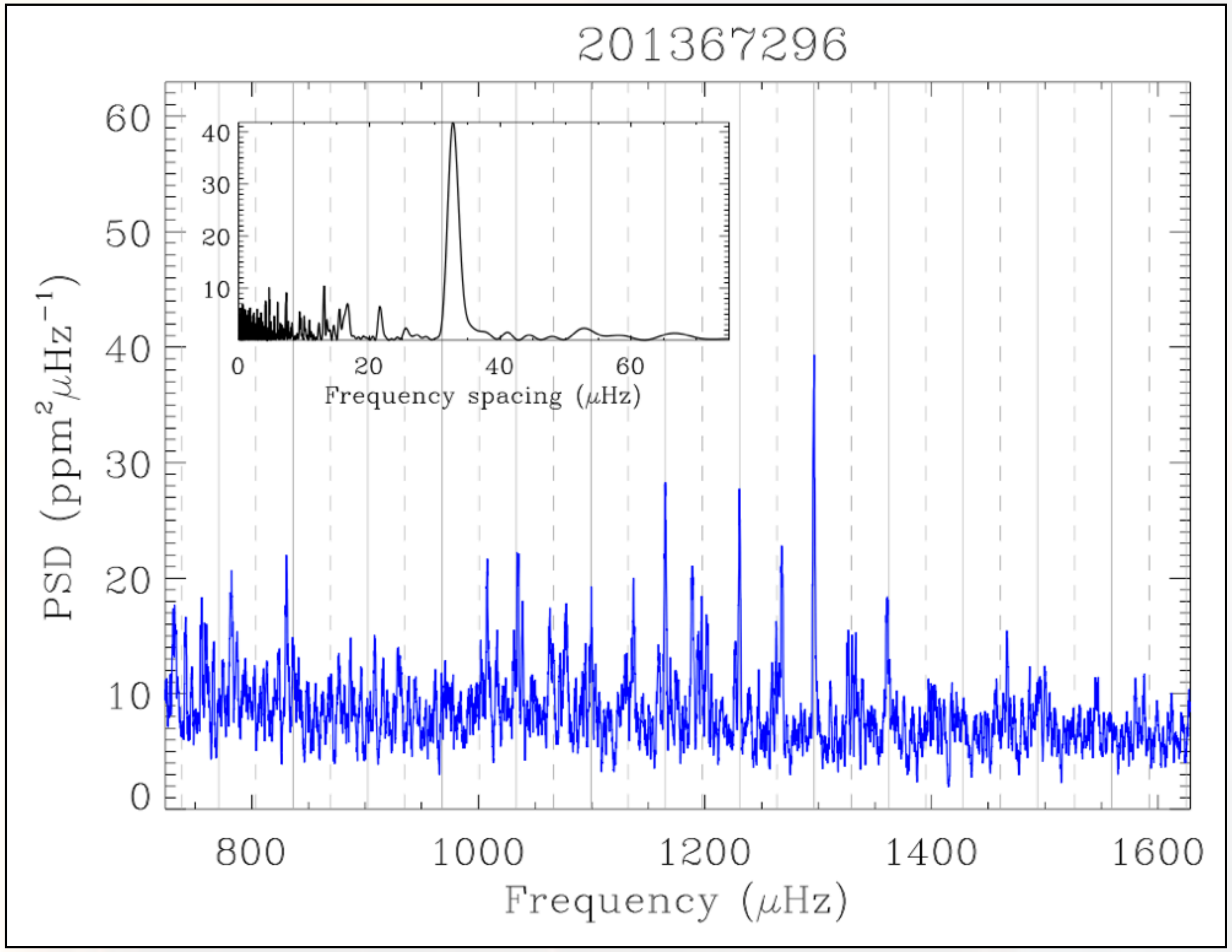
~20000 targets per campaign; **all targets are selected by the community**

http://keplerscience.arc.nasa.gov/K2/

Solar-like Oscillators with K2

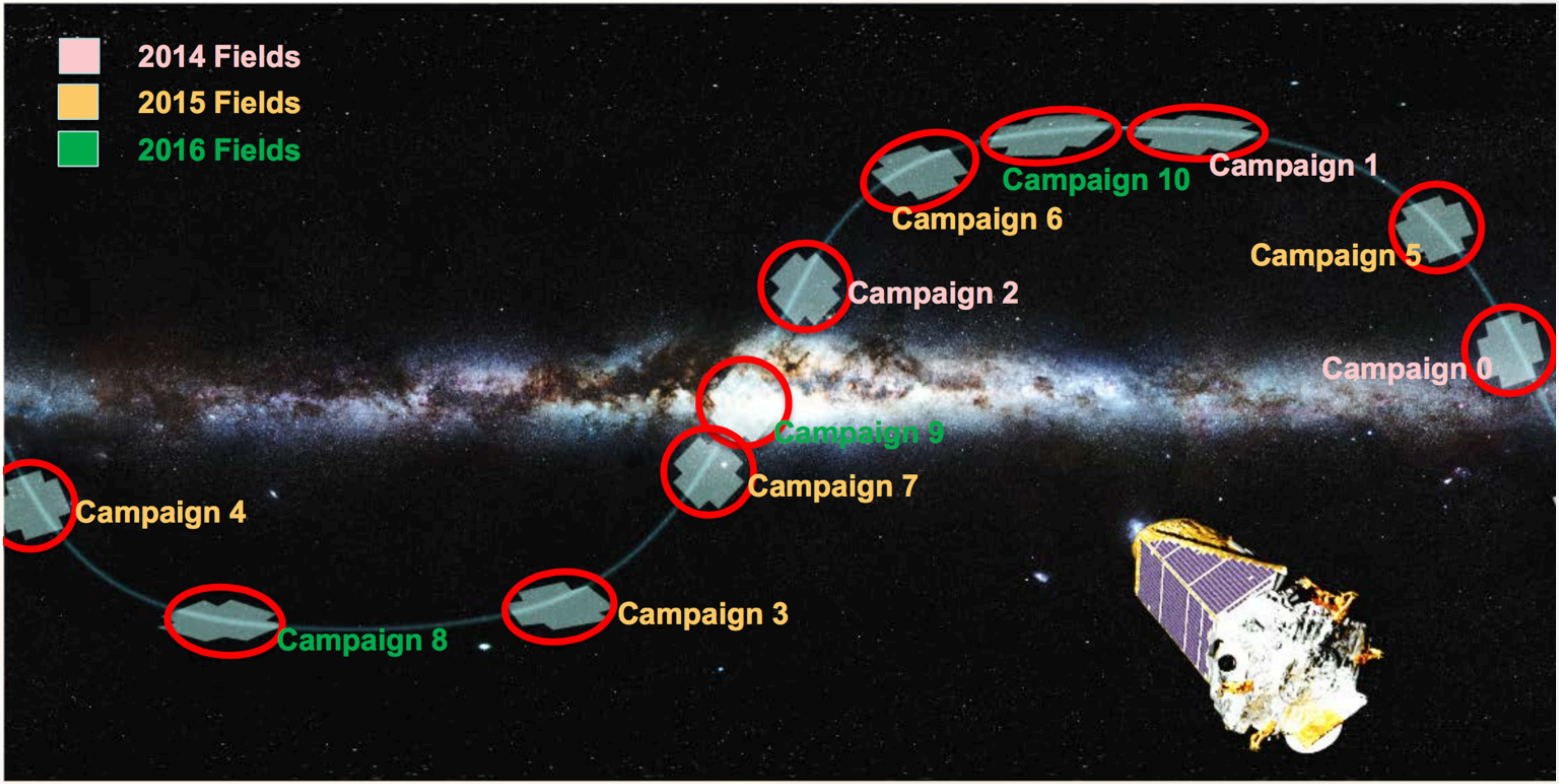


Stello et al. (2015)



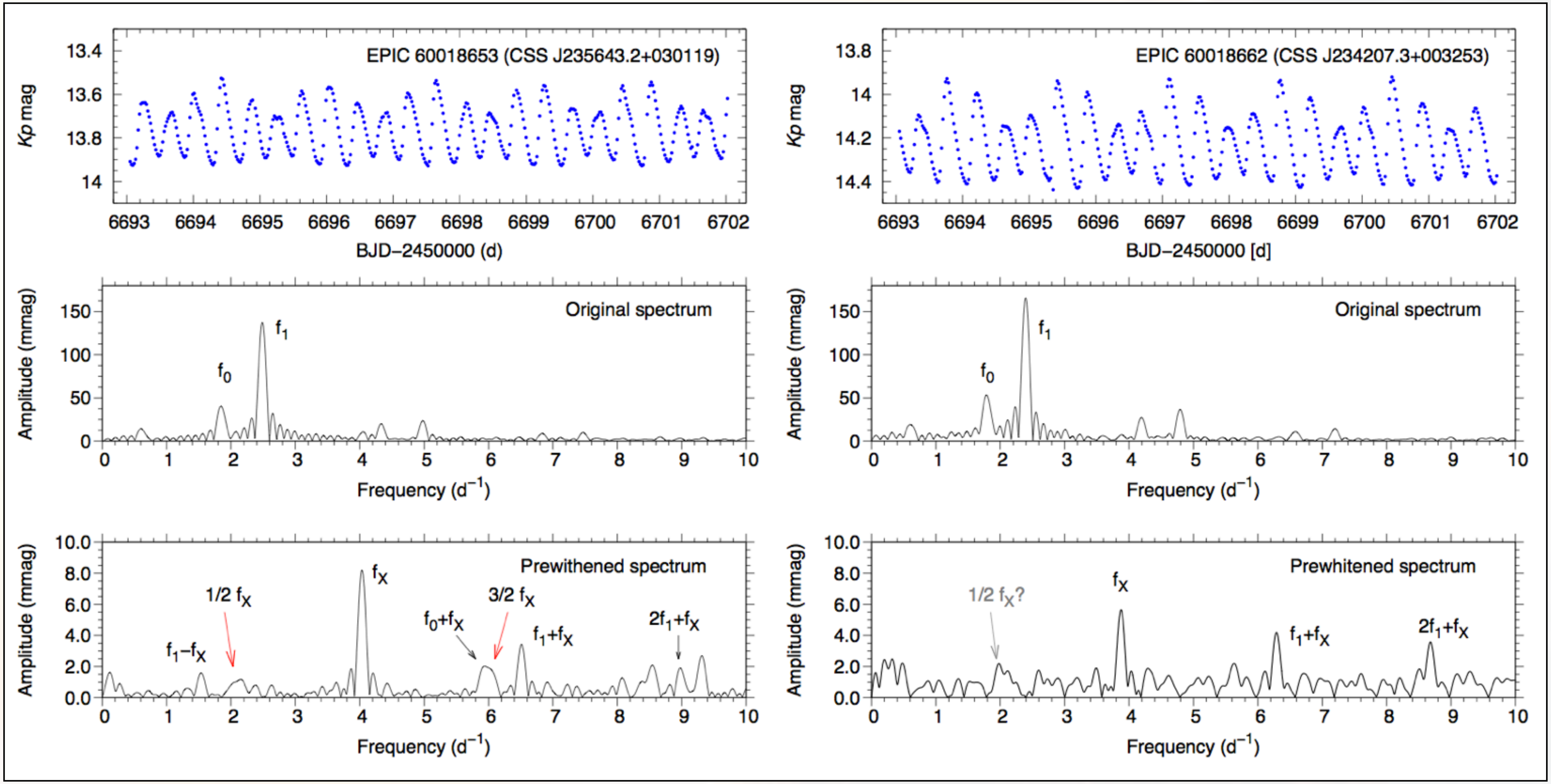
Chaplin et al. (2015)

Galactic Archeology with K2



Stello et al. (2015)

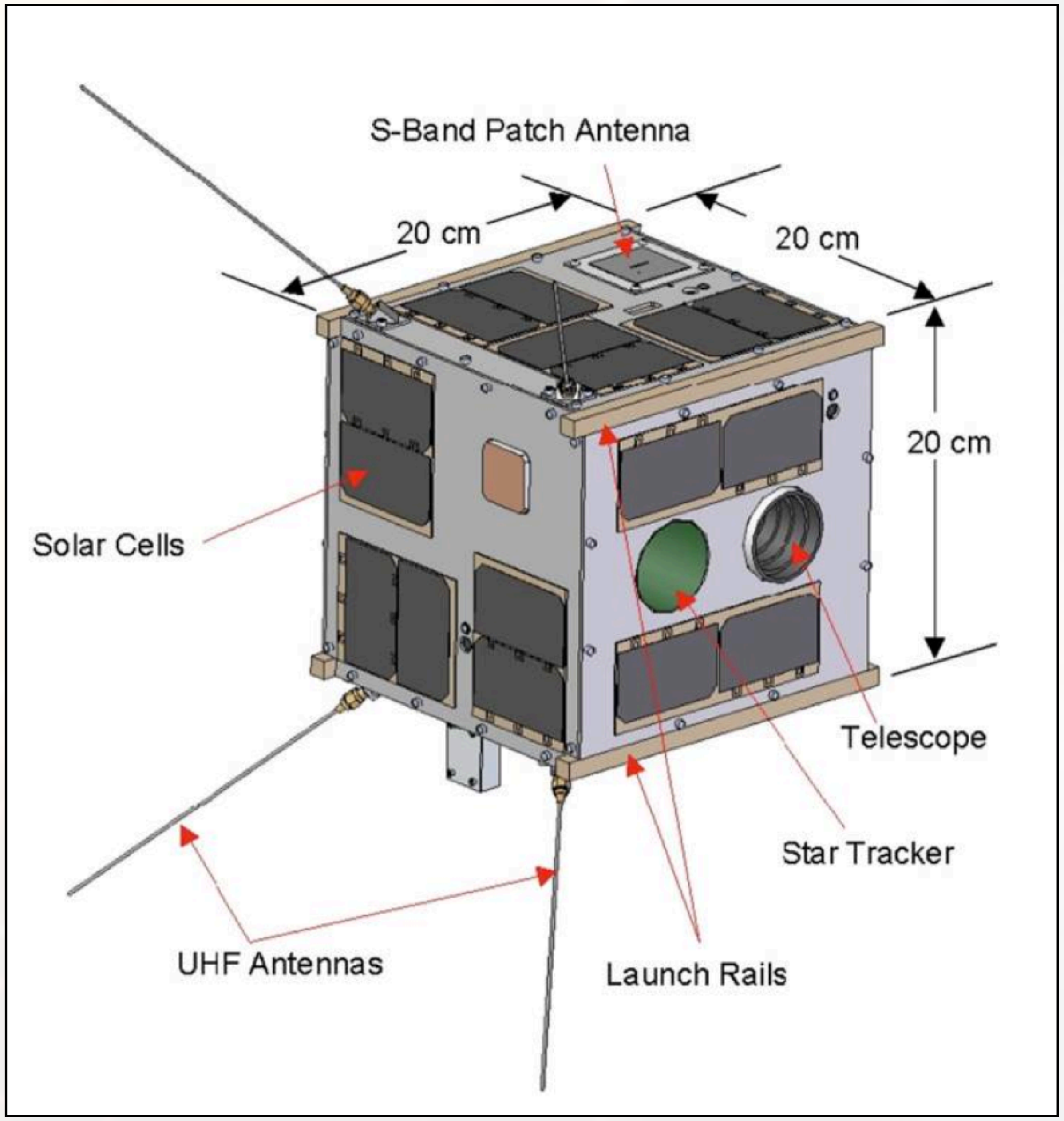
RR Lyrae Stars with K2



10 day engineering campaign!

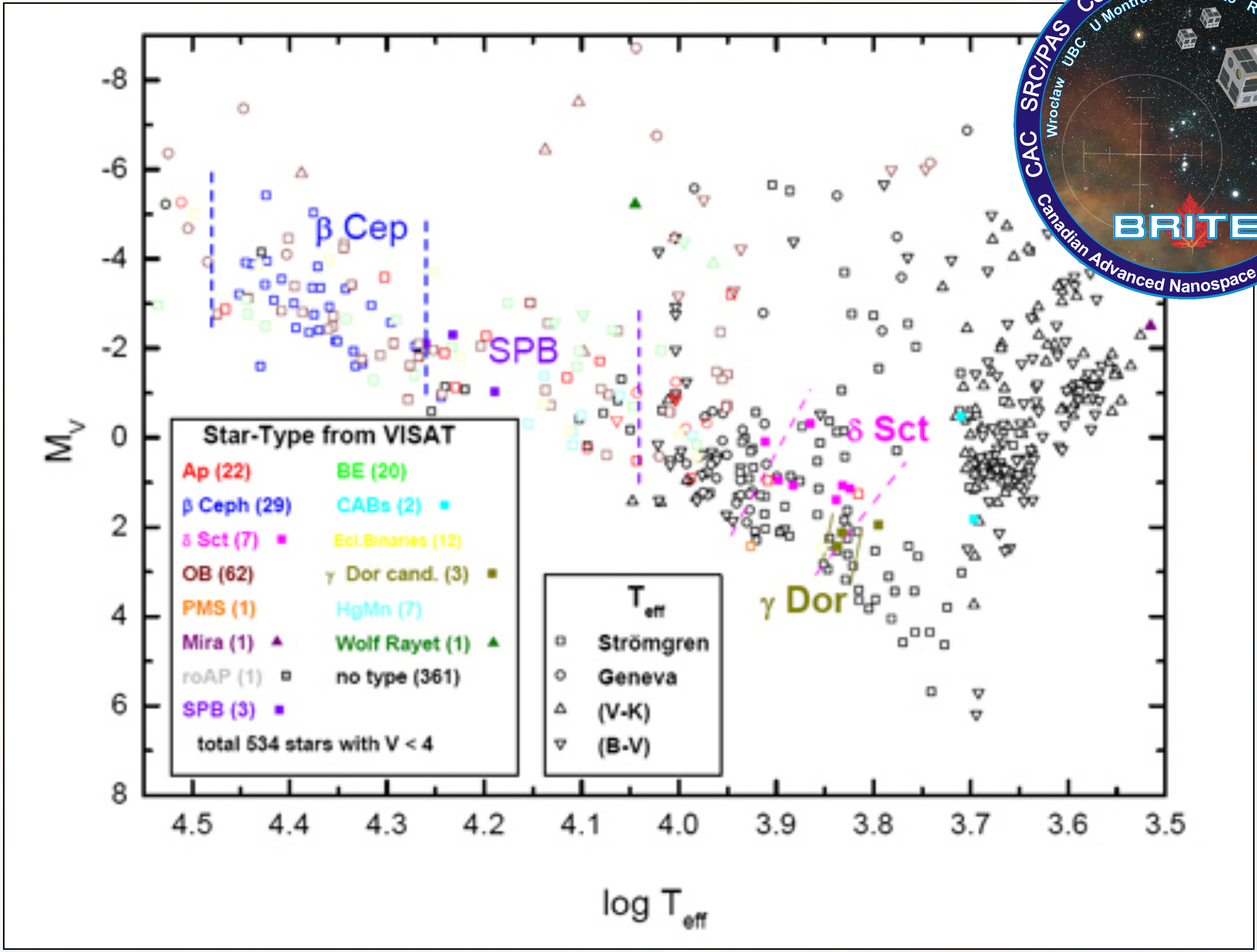
Molnar et al. (2015)

BRITE Constellation

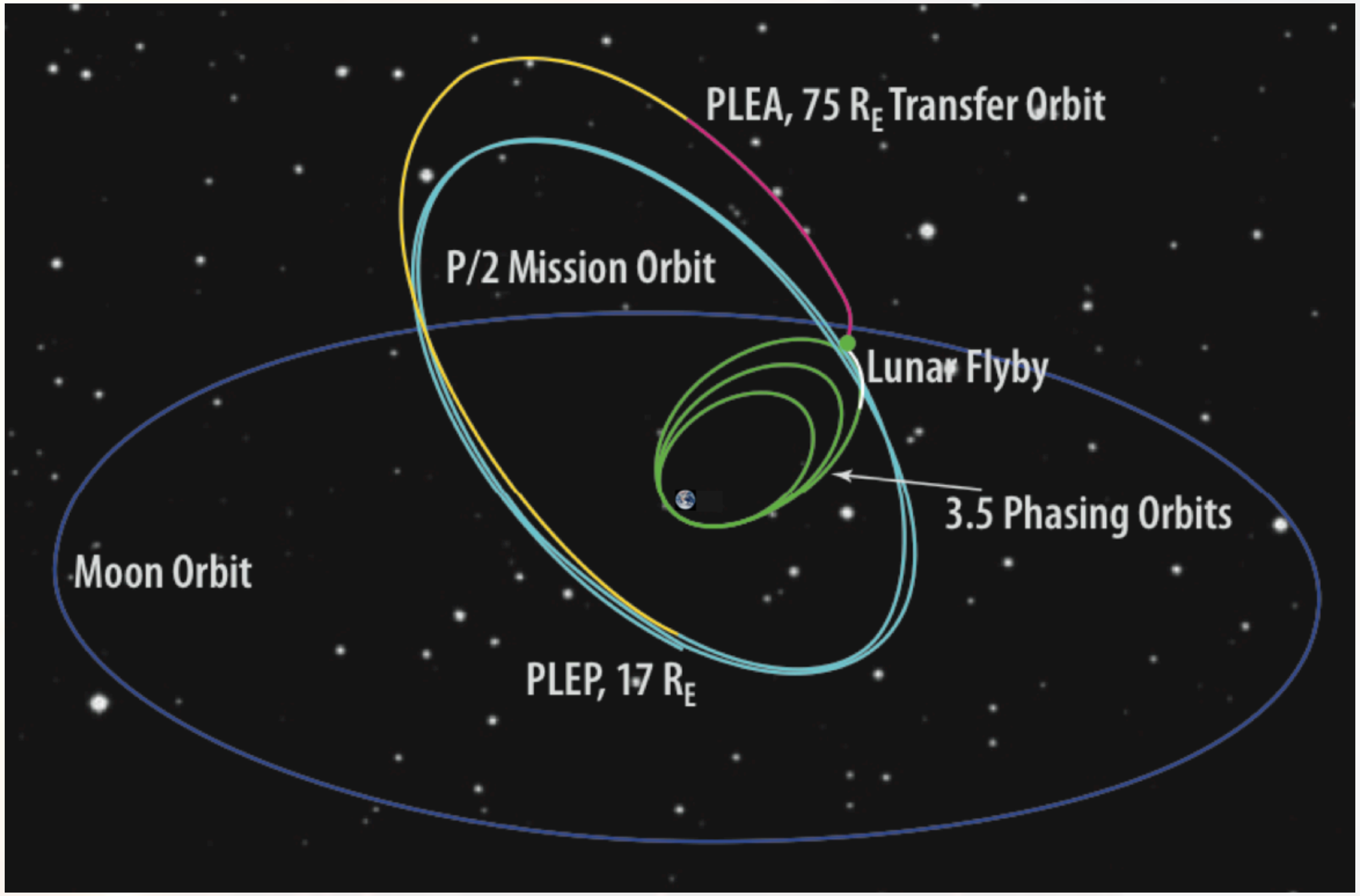


6 Nanosatellites equipped with Red/Blue Filters to observe the brightest (V<6) stars

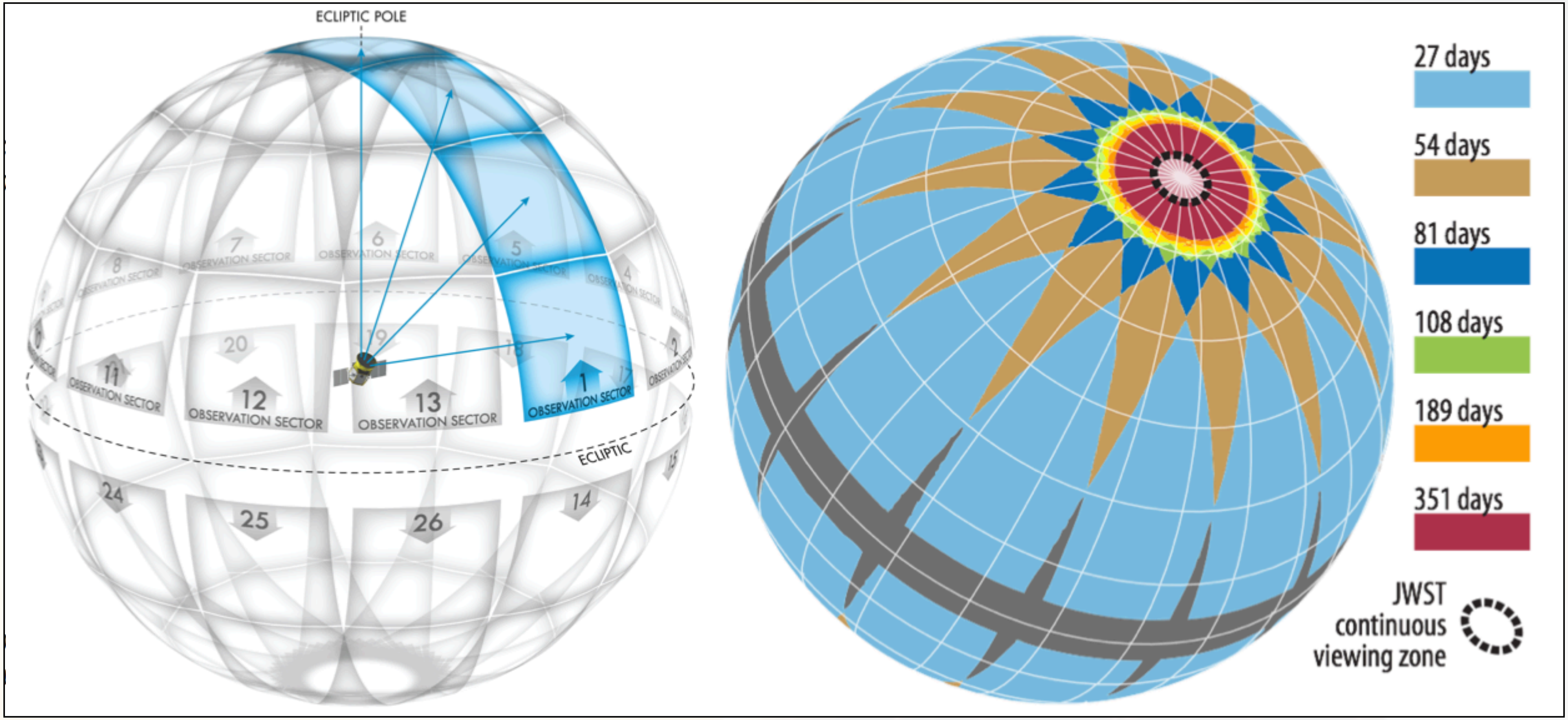
BRITE Targets



Terrestrial Exoplanet Survey Satellite



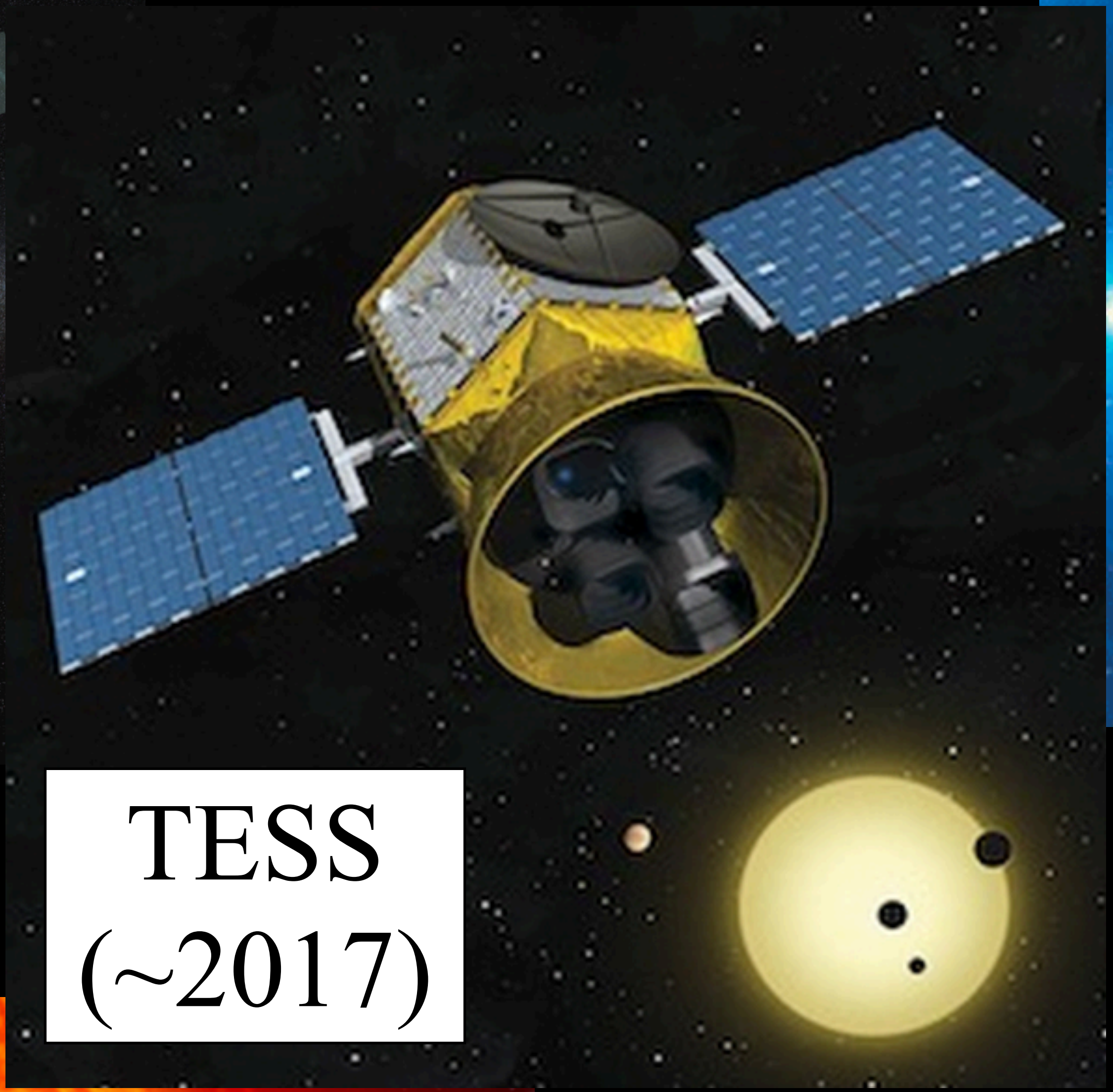
- Photometric Survey to detect transiting habitable zone planets around bright M dwarfs
- Lunar Resonance Orbit, planned launch in 2017



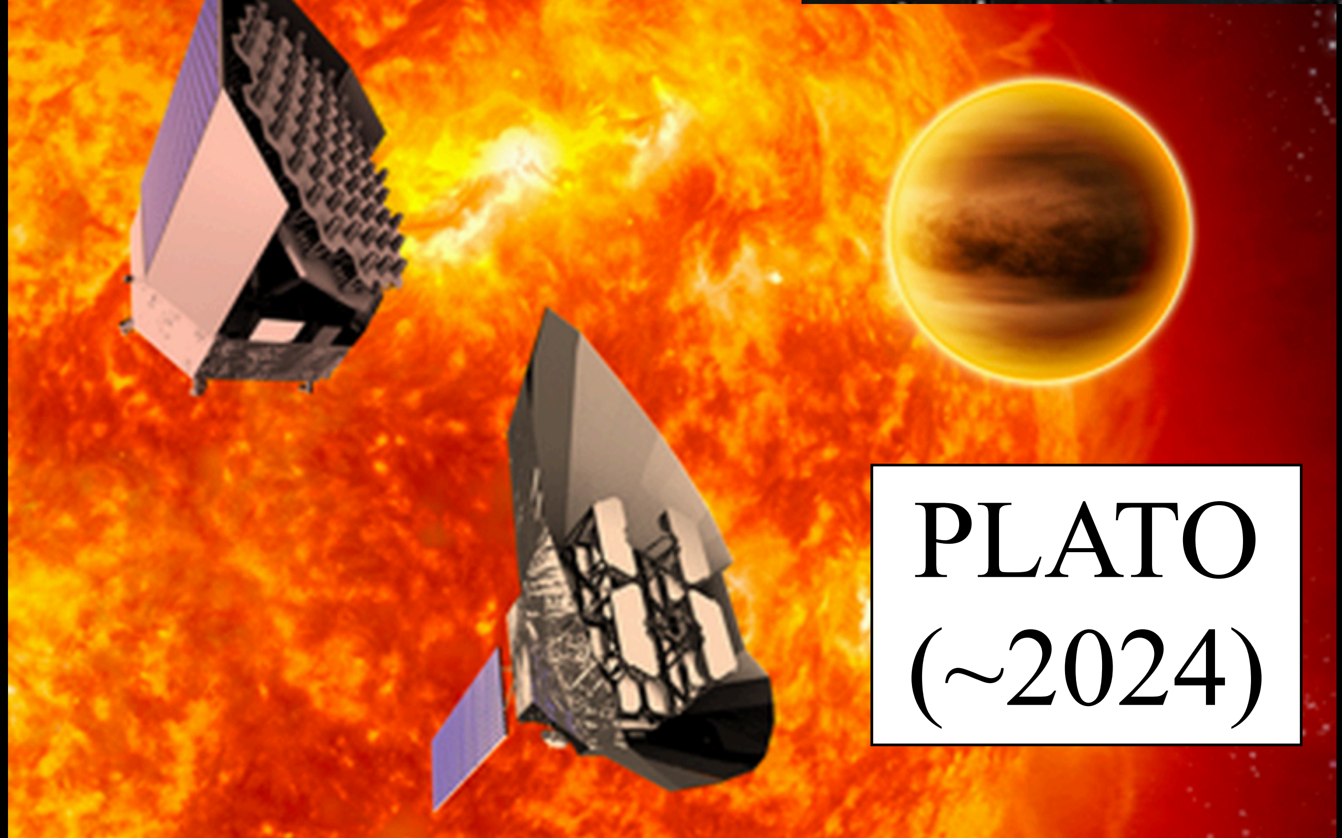
2-min cadence for >200,000 stars

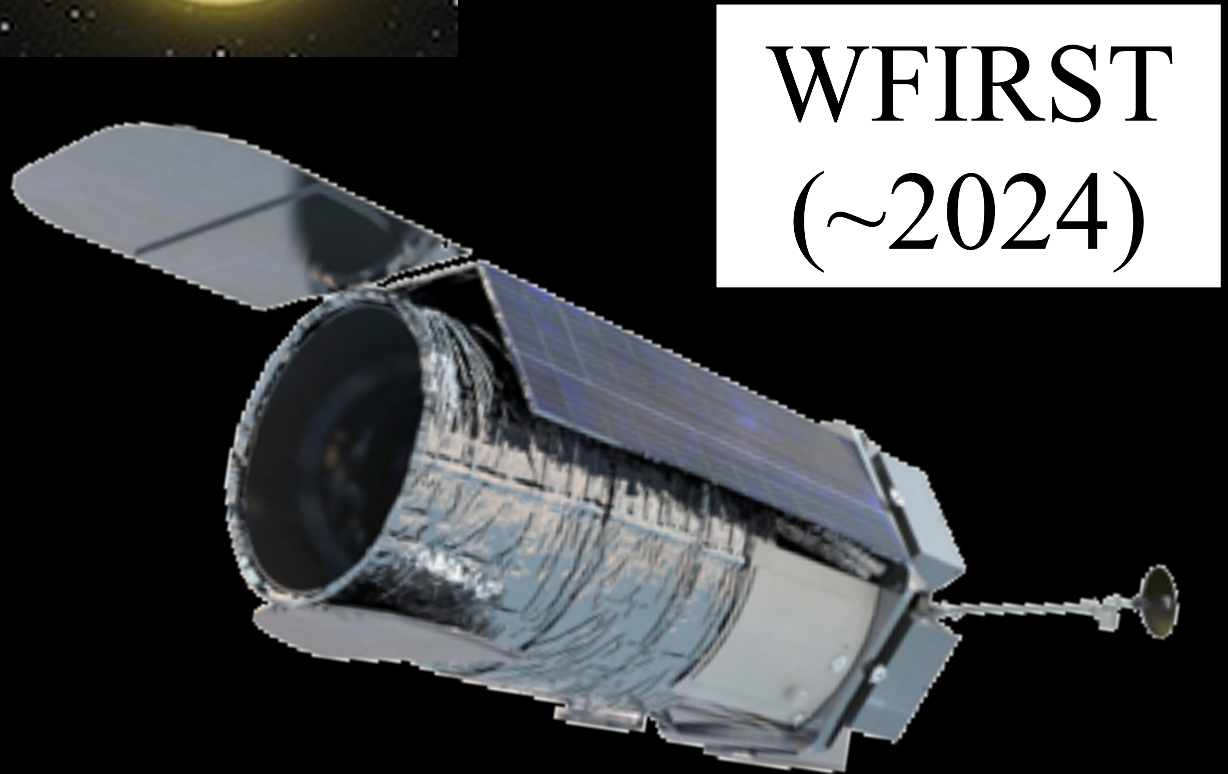
30-min full-frame (!) cadence


Kepler/
K2 (now)


TESS
(~2017)


BRITE
(now)


PLATO
(~2024)


WFIRST
(~2024)