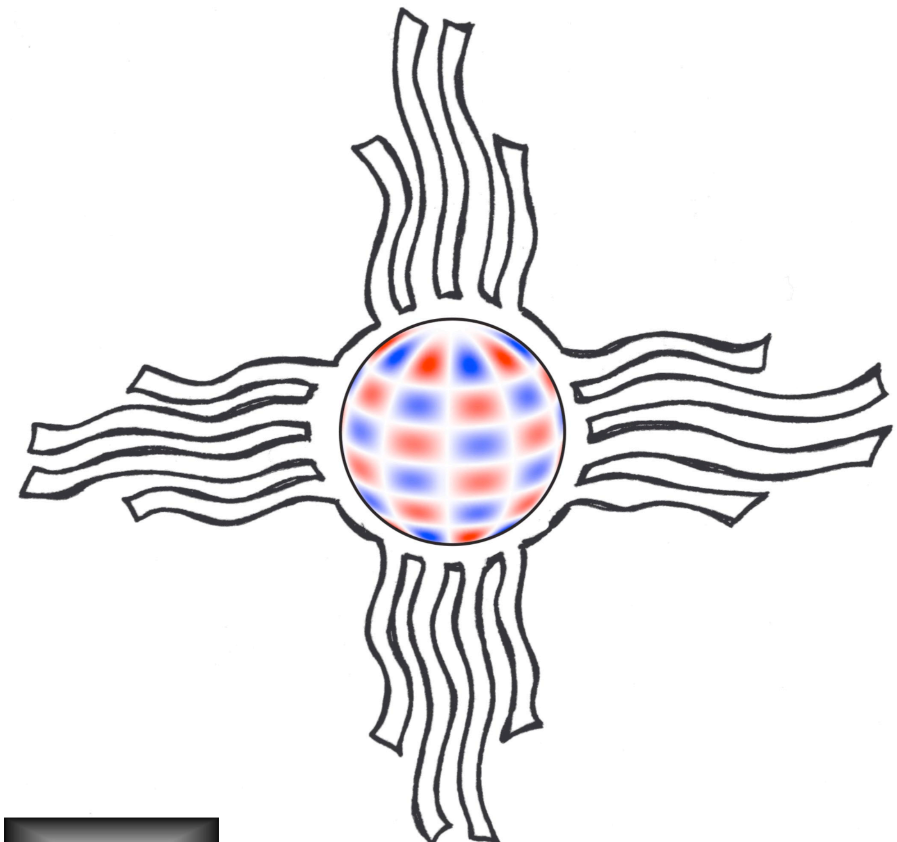
Studying Hybrid gamma Doradus/ delta Scuti Variable Stars with Kepler



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Los Alamos National Laboratory

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HYBRID γ DORADUS – δ SCUTI PULSATORS:

NEW INSIGHTS INTO THE PHYSICS OF THE OSCILLATIONS FROM *Kepler* OBSERVATIONS

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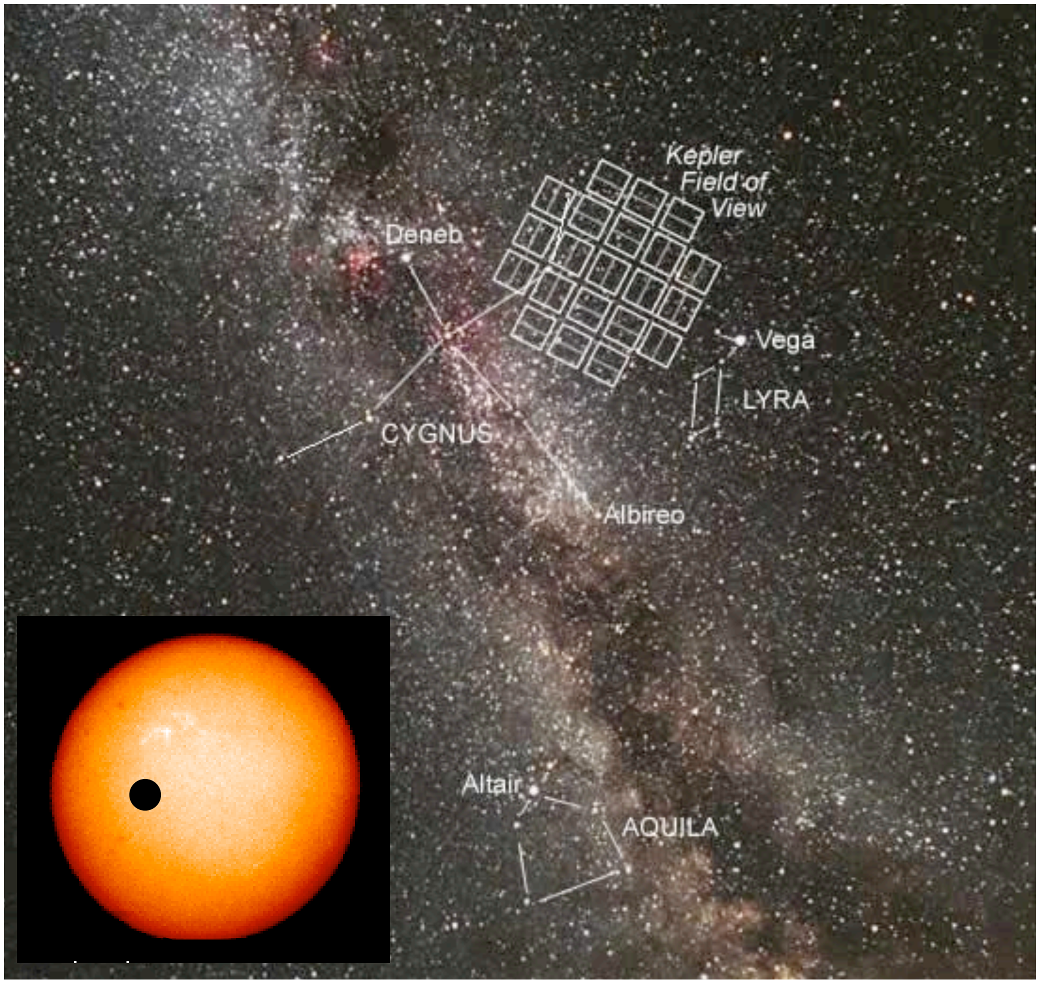
ABSTRACT

Observations of the pulsations of stars can be used to infer their interior structure and test theoretical models. The main sequence γ Doradus (Dor) and δ Scuti (Sct) stars with masses 1.2-2.5 $M_\odot$ are particularly useful for these studies. The γ Dor stars pulsate in high-order g modes with periods of order 1 day, driven by convective blocking at the base of their envelope convection zone. The δ Sct stars pulsate in low-order g and p modes with periods of order 2 hours, driven by the κ mechanism operating in the He II ionization zone. Theory predicts an overlap region in the Hertzsprung-Russell diagram between instability regions, where 'hybrid' stars pulsating in both types of modes should exist. The two types of modes with properties governed by different portions of the stellar interior provide complementary model constraints. Among the known γ Dor and δ Sct stars, only four have been confirmed as hybrids. Now, analysis of combined Quarter 0 and Quarter 1 *Kepler* data for hundreds of variable stars shows that the frequency spectra are so rich that there are practically no pure δ Sct or γ Dor pulsators, i.e. essentially all of the stars show frequencies in both the δ Sct and γ Dor frequency range. A new observational classification scheme is proposed that takes into account the amplitude as well as the frequency, and is applied to categorize 234 stars as δ Sct, γ Dor, δ Sct/γ Dor or γ Dor/δ Sct hybrids.

http://arxiv.org/abs/1001.0747

The NASA Kepler Mission



- Launched March 6, 2009
- Search for habitable planets
- High-precision CCD photometry to detect planetary transits
- Secondary mission to monitor variability of over 100,000 stars for asteroseismology

http://kepler.nasa.gov

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γ Dor and δ Sct hybrids are ideal candidates for asteroseismology

- Pulsate in many simultaneous radial and nonradial modes.
- Similarities with solar like stars, so can build on experience with the Sun
- Slightly more massive than Sun (1.4-1.6 M_{sun})
- Convective cores, shallower convective envelope
- Exhibit modes found in both types of variables that are sensitive to the structure of different regions of the stellar interior.

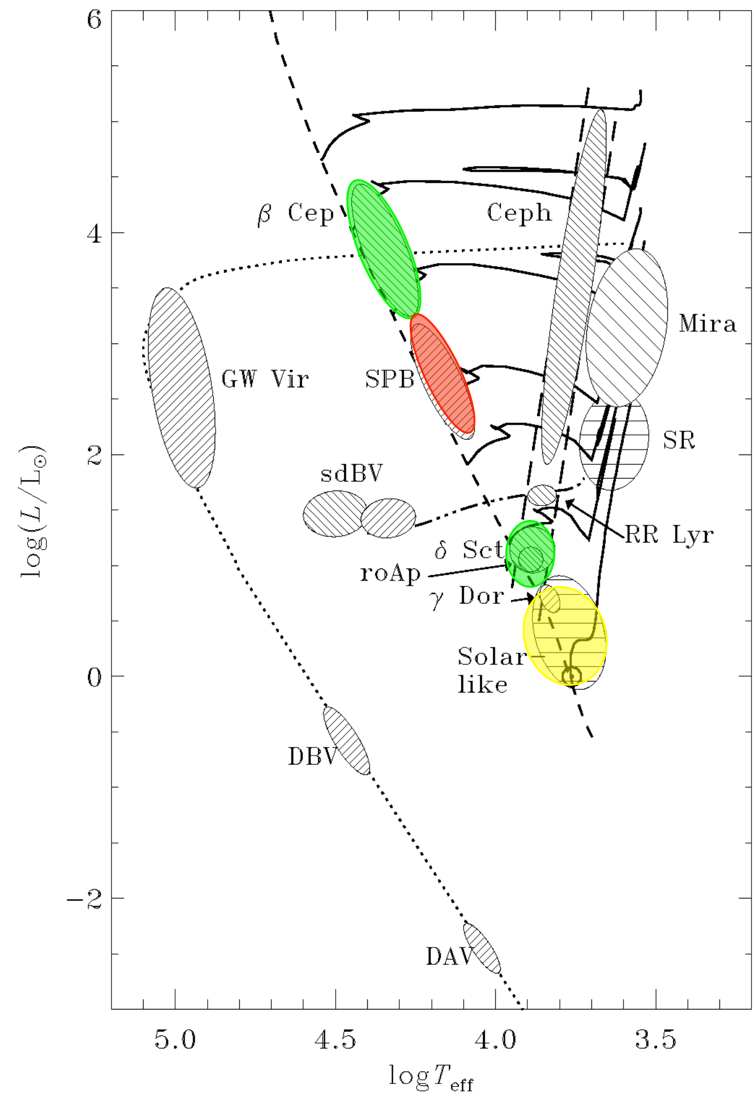
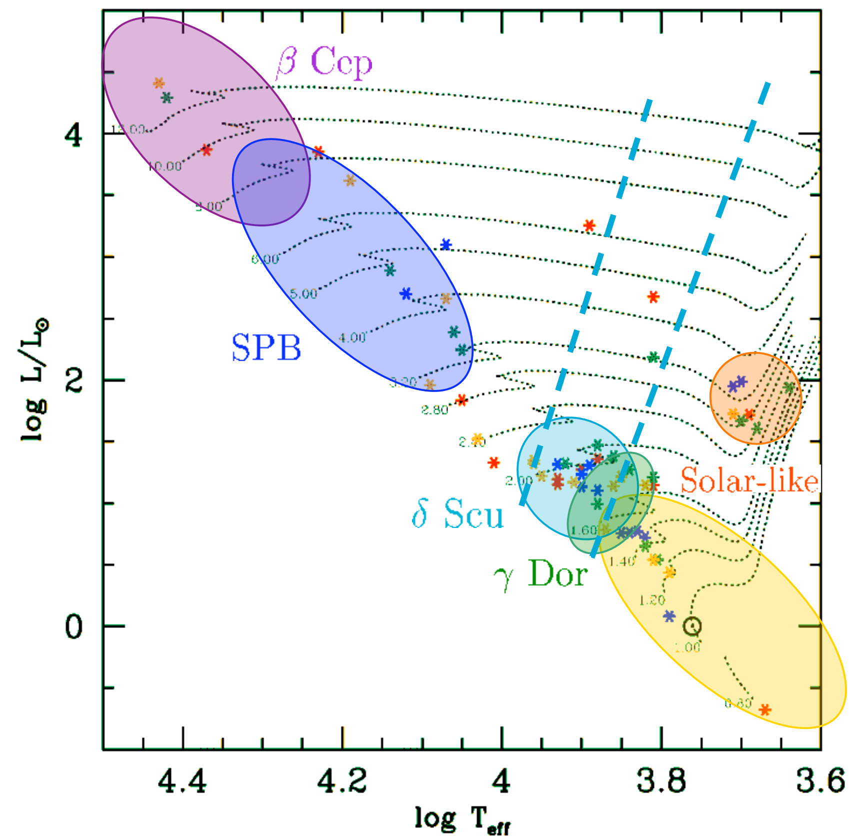


Figure from J. Christensen-Dalsgaard

Properties of γ Doradus Variables

- Pulsating late A-F stars
- On or near main sequence
- Periods ~ 0.3 - 3 days
- Multiple photometric (a few mmag) and spectroscopic variables (up to 4 km s^{-1})
- Undergo gravity-mode pulsations of high radial order (*n*) and low-degree (ℓ)
- More than 60 bona fide current members

  (Henry, Fekel, Henry 2007)



(from Pollard 2009)

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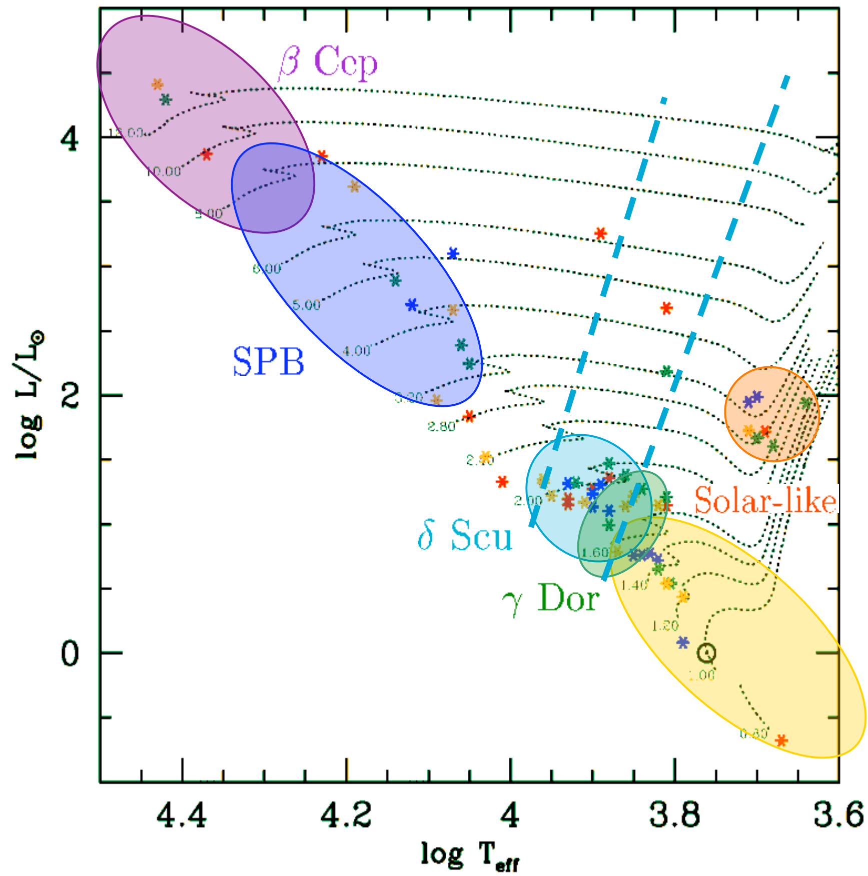
Properties of δ Scuti Variables

- Pulsating A-early F stars
- On or near main sequence
- Periods ~ 2 hours
- Observed in pressure-mode or mixed p- and g-mode pulsations of low-degree (ℓ)
- Hundreds known (Rodriguez et al. 2000)



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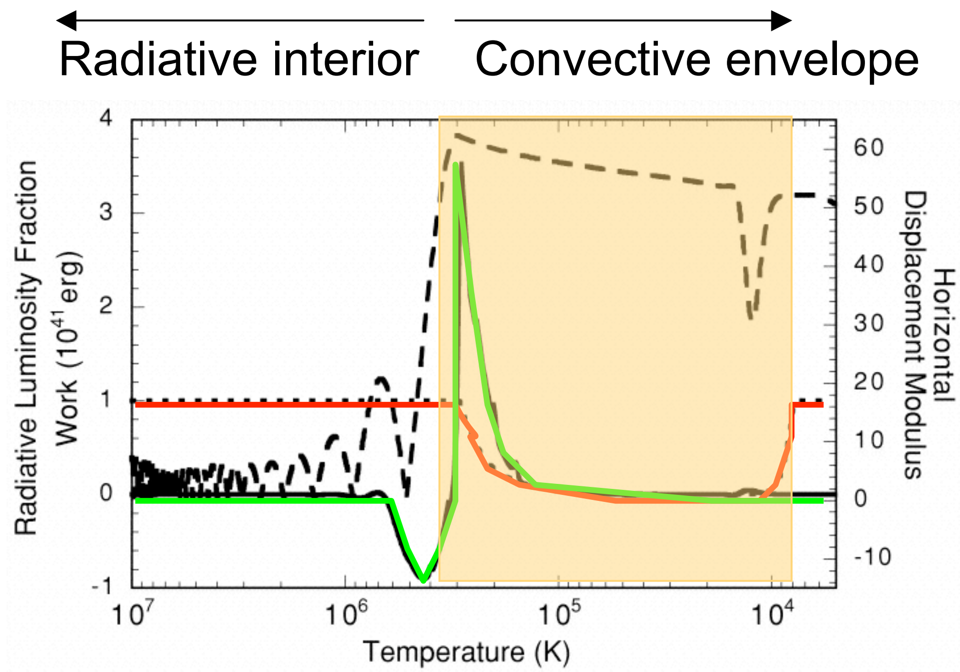
The γ Dor g-modes were theoretically explained by a convective blocking mechanism at the base of the envelope convection zone



Luminosity fraction transported by radiation (red), work driving and damping (green), and modulus of nonadiabatic horizontal displacement (dashed line) vs. Temperature.

(Guzik et al. 2000)

The δ Sct p-modes, however, are driven by kappa-effect from second ionization of of helium in the envelope at about 50,000 K (Chevalier 1971)

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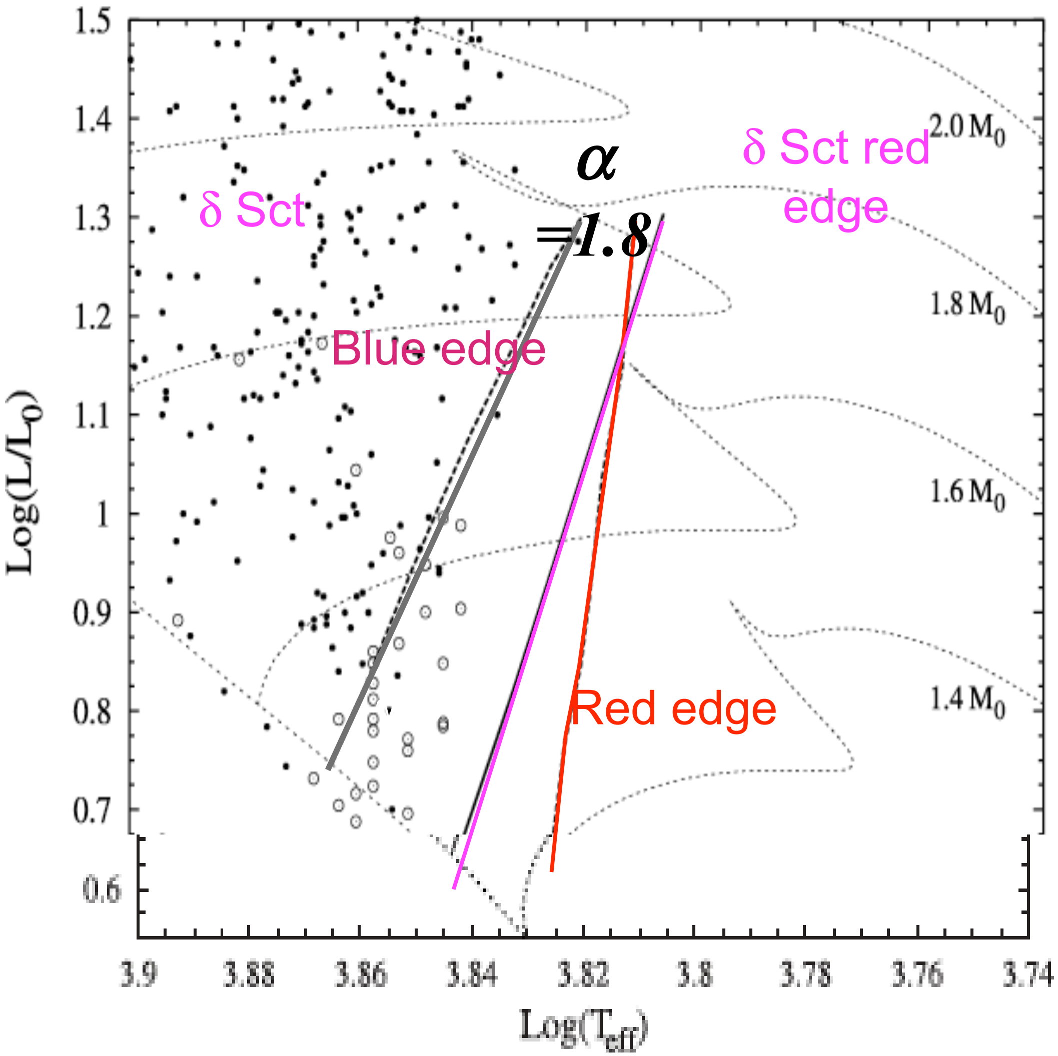
Hybrid stars are predicted by theory to exist only in a small overlap region of the two instability strips



(Dupret et al. 2005)

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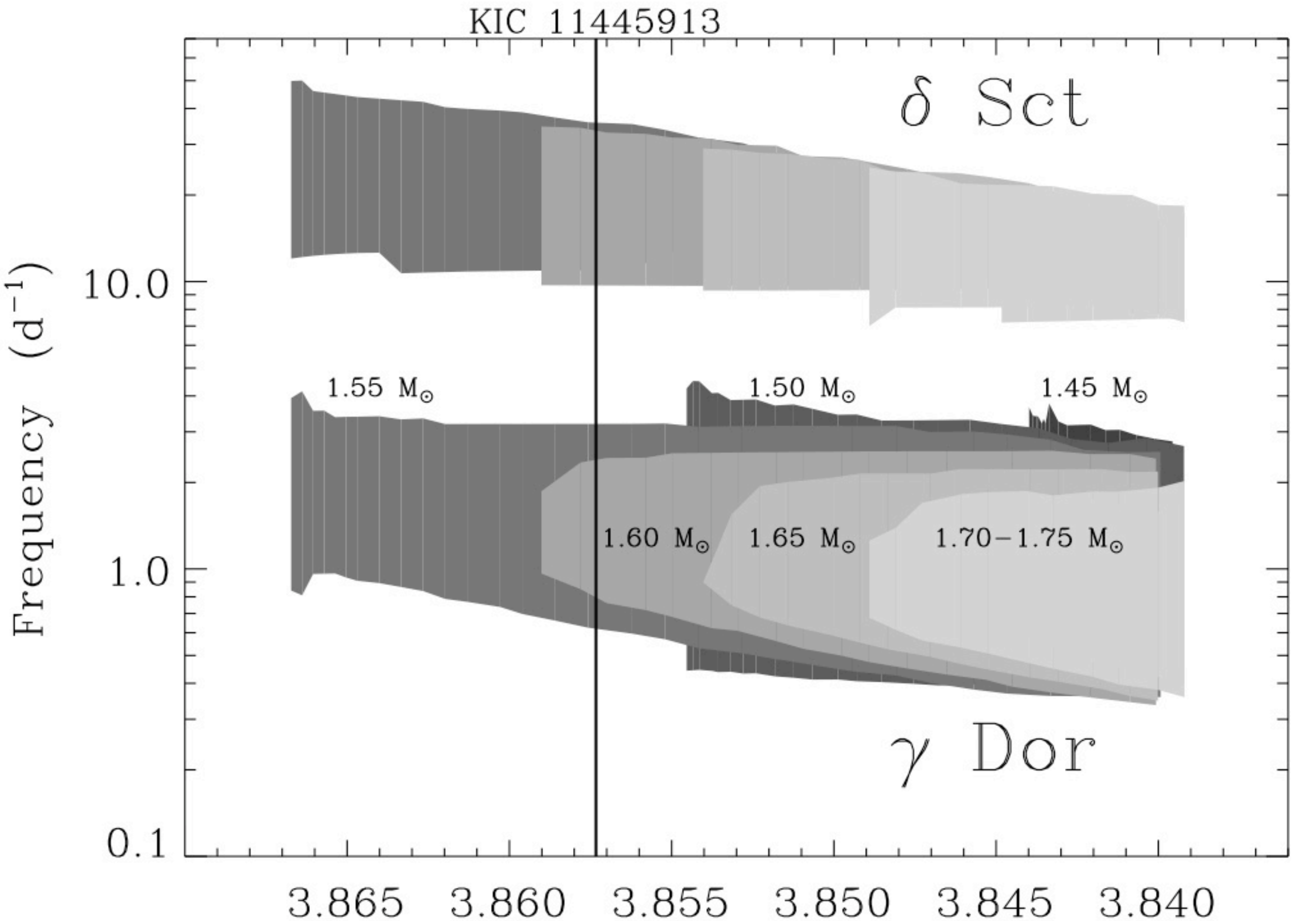
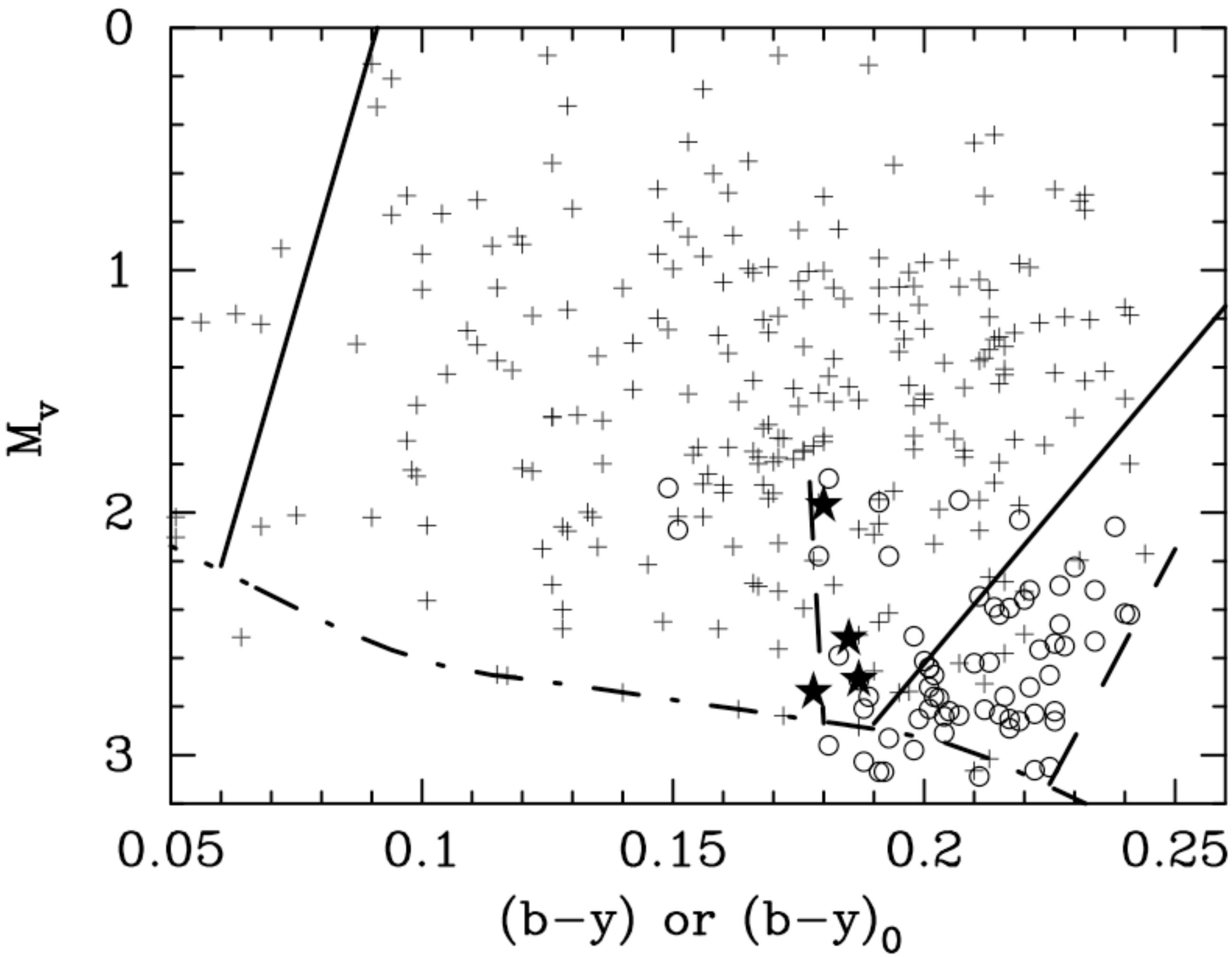
Theoretical models predict hybrids in a narrow temperature range (3.84 < T_{eff} <3.87) , and a frequency gap at about 5-10 cycles/day



(Grighacène 2009)

FIG. 2.— Hybrid theoretical instability domain for $\ell = 0-3$ g and p modes. Models have: $Z = 0.02$, $\alpha_{\rm MLT} = 2.0$, $\alpha_{ov} = 0.2$. The vertical line corresponds to the effective temperature of the *Kepler* target: KIC 11445913 ($T_{\rm eff} = 7200 \pm 200$ K).

Four previously-known hybrids are located in the expected region among γ Dor and δ Sct stars



+ δ Sct

○ γ Dor

(From Handler 2009)

FIG. 1.— Color-Magnitude diagram of δ Sct (plus signs, Rodríguez et al. 2000), γ Dor (open circles, Henry et al. 2007) and stars that show both types of pulsation (star symbols, Henry & Fekel 2005; Rowe et al. 2006; Uytterhoeven et al. 2008; Handler 2009, Rowe, priv. comm.). The Zero-Age Main Sequence (dashed-dotted line, Crawford 1979) as well as the observed borders of the δ Sct (solid lines, Rodríguez & Breger 2001) and γ Dor (dashed lines, Handler & Shobbrook 2002) instability strips, are indicated. Lines on the left indicate blue edges while those on the right give the red edges of the Instability Strips.

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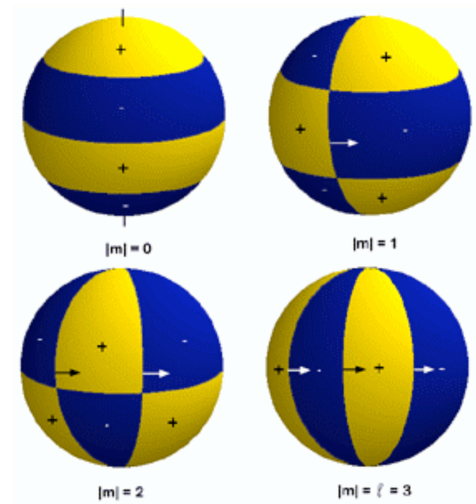
Uytterhoeven et al. 2008 confirmed HD49434 as a hybrid in ground-based spectroscopy

Freq (d^{-1})		*l*	*m*
0.234185			
1.2732			
1.4831	γ Doradus	[4,6]	[0,4]
1.734820	frequency		
2.666	range		
5.3311		[6,8]	[0,4]
5.583			
9.3070	δ Scuti	[4,6]	[0,4]
6.6841/7.6841	frequency	[3,5]	[0,4]
10.1527/9.1527	range	[6,8]	[0,4]
12.0332/11.0332		[6,8]	[0,2]



Non-radial modes described by *spherical harmonics* *l, m*

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Kepler light curve and periodogram for 50 days of data for KIC9775454

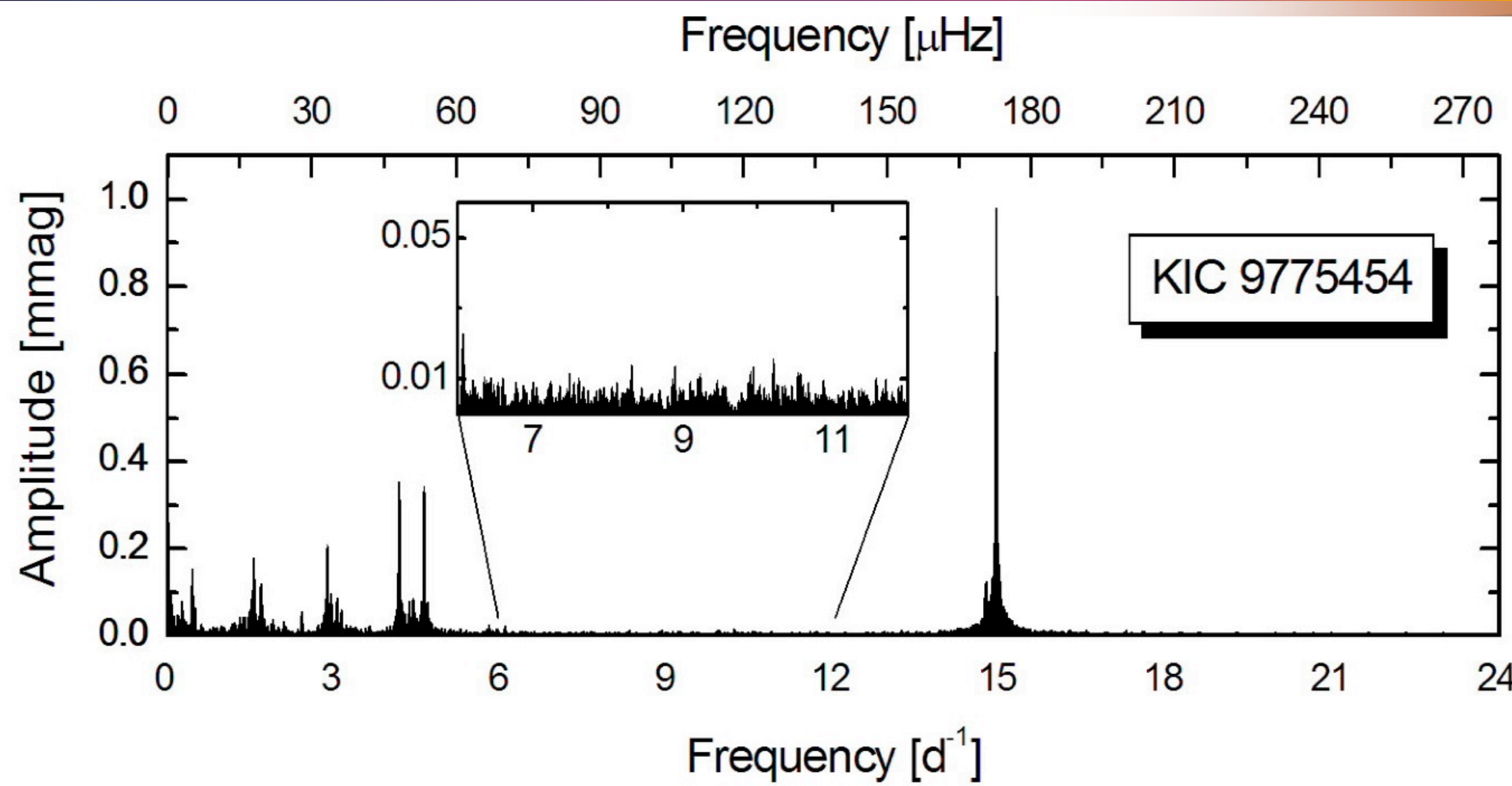
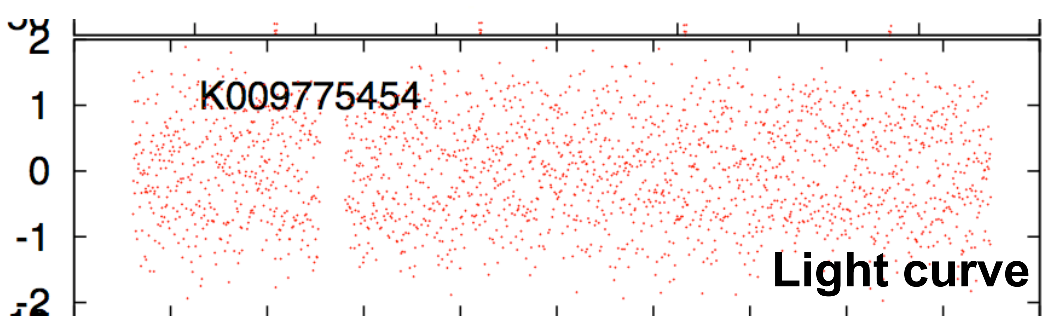
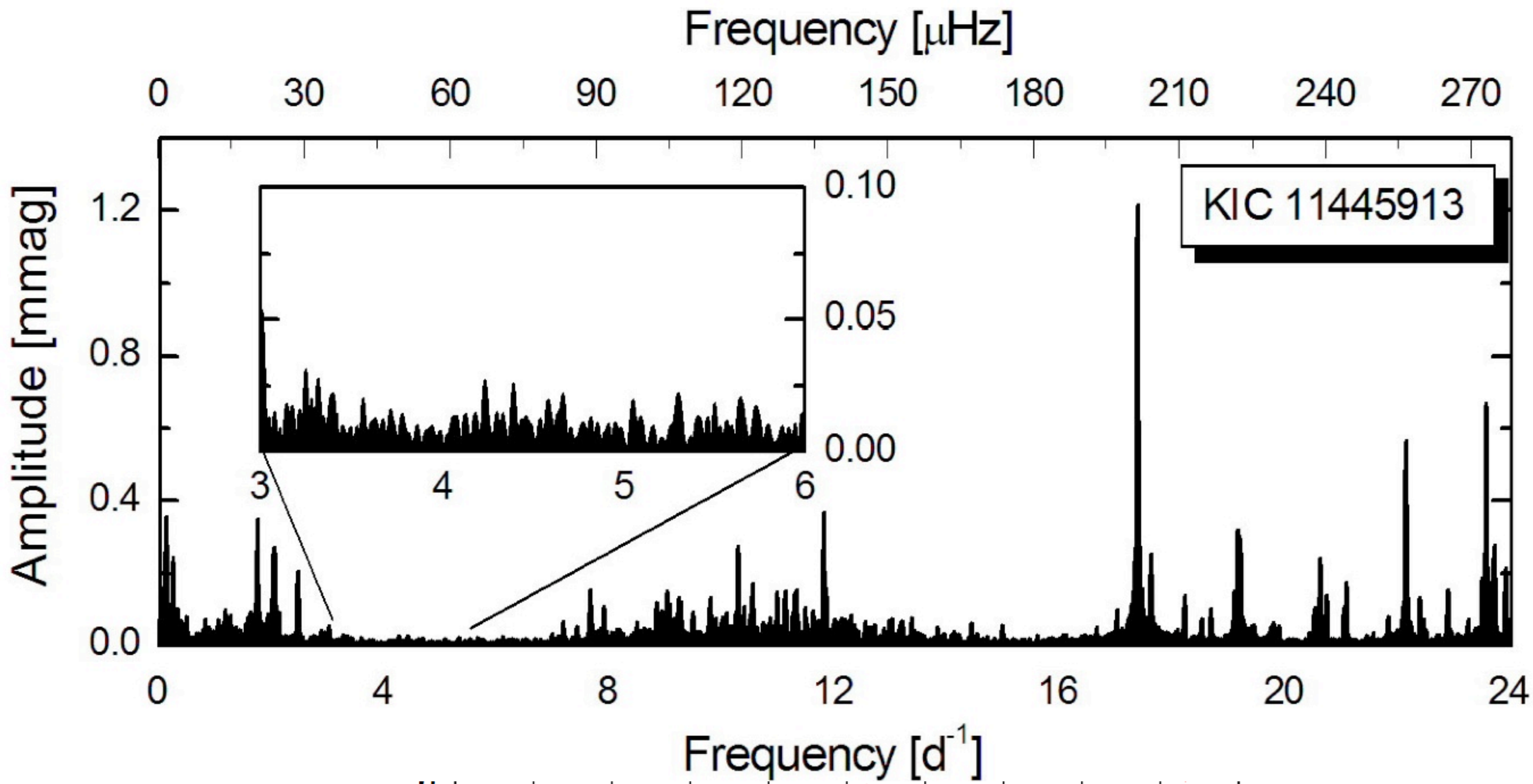
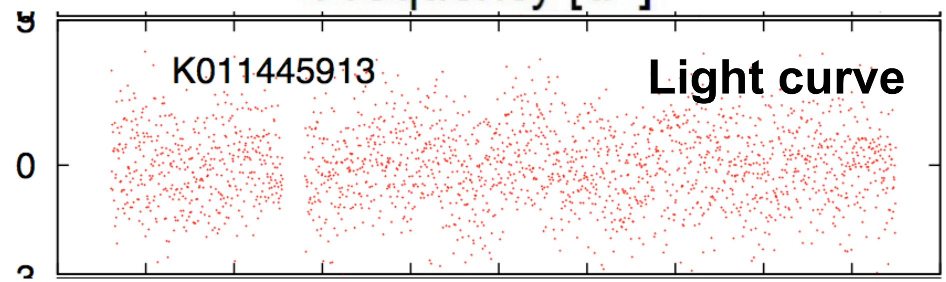


FIG. 4.— Frequency spectra of the long-cadence data obtained by *Kepler* for the stars KIC 9775454 and KIC 11445913 that display hybrid pulsations in the γ Dor region (below 5 d^{-1}) and in the δ Sct region (above 12 d^{-1}). The details of the spectra at higher frequencies require short-cadence data to be confirmed and analyzed.



Kepler light curve and periodogram for 50 days of data for KIC11445913





Because all of the γ Dor and δ Sct stars observed by Kepler turned out to be hybrid candidates, we proposed a new categorization scheme based on both amplitude and frequency

- δ Sct: most of the frequencies are $\geq 5\ \mathrm{d}^{-1}$, and the lower frequencies are of relatively low amplitude;
- δ Sct/γ Dor hybrid: most of the frequencies are $\geq 5\ \mathrm{d}^{-1}$, but there are some lower frequencies which are of comparable amplitude;
- γ Dor/δ Sct hybrid: most of the frequencies are $\leq 5\ \mathrm{d}^{-1}$, but there are some higher frequencies which are of comparable amplitude;
- γ Dor: most of the frequencies are $\leq 5\ \mathrm{d}^{-1}$, and the higher frequencies are of relatively low amplitude.

The new categorization scheme gives the following breakdown of 234 stars

TABLE 1
NUMBER OF STARS AND PERCENTAGE IN EACH CLASS. FOR EACH CLASS THE MEAN VALUES OF THE EFFECTIVE TEMPERATURE IS GIVEN.

Class	Number	Percent	$< \log T_{\rm eff} >$
δ Sct	67	27	3.885 ± 0.003
δ Sct/γ Dor	32	14	3.883 ± 0.006
γ Dor/δ Sct	19	9	3.868 ± 0.006
γ Dor	116	50	3.853 ± 0.005

Table 1 represents 234 out of 554 stars studied by Kepler that showed frequencies in the γ Dor or δ Sct region

The stars in the four categories are not cleanly separated in the HR diagram

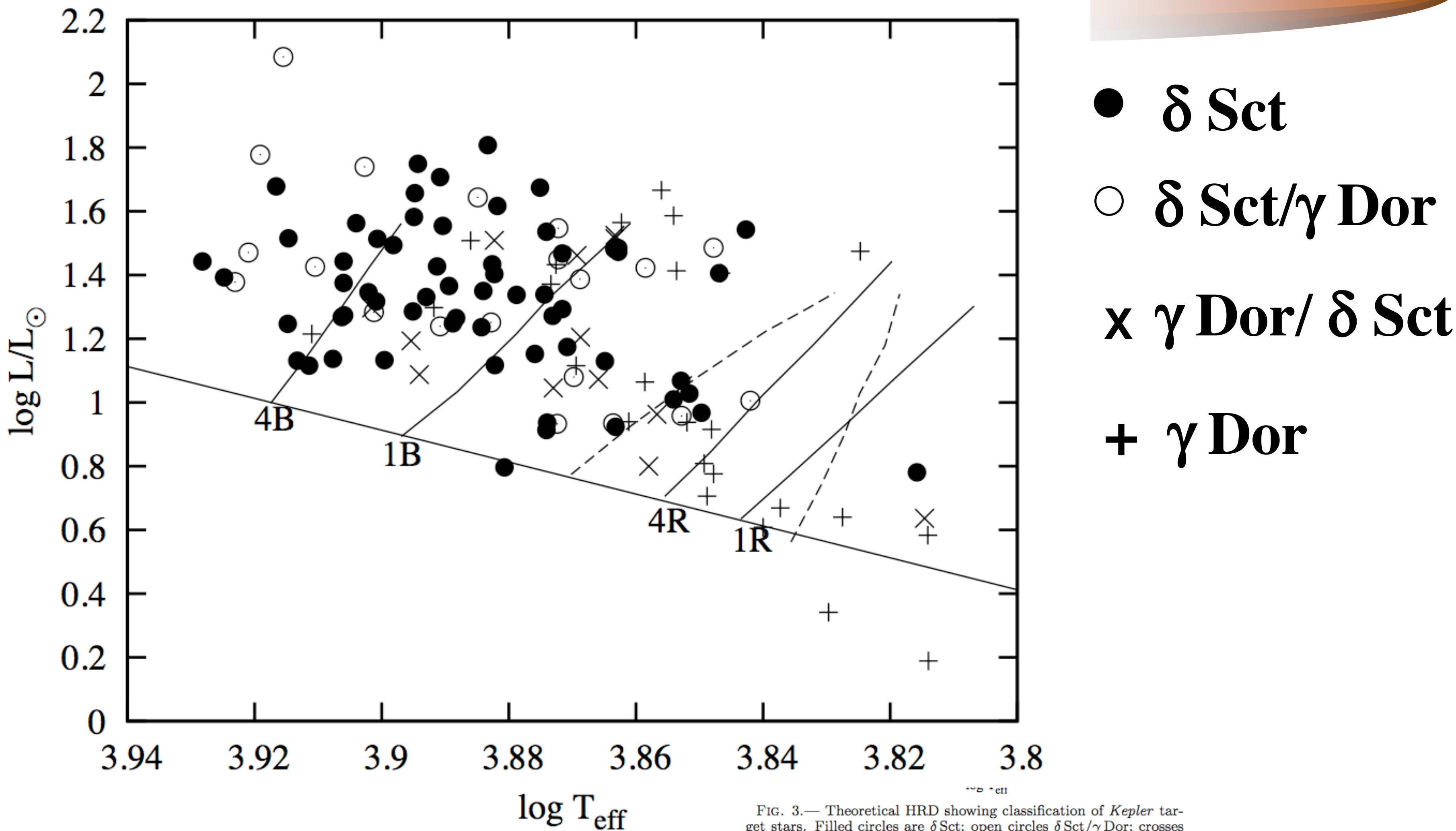


FIG. 3.— Theoretical HRD showing classification of *Kepler* target stars. Filled circles are δ Sct; open circles δ Sct/γ Dor; crosses γ Dor/δ Sct and plus signs γ Dor. The solid lines show the Zero-Age Main Sequence and the radial fundamental red and blue edges (1R, 1B) and the 4-th overtone radial red and blue edges (4R, 4B) (Dupret et al. 2005). The dashed lines are the red and blue edges of the γ Dor instability strip ($\ell = 1$ and mixing length $\alpha_{MLT} = 2.0$) (Dupret et al. 2005).

The Kepler results generate many questions . . .

- Why have Kepler (and CoRoT) detected so many hybrids while theory predicts their existence in only a small overlapping region of the instability strips?
- Are some modes driven by an additional pulsation mechanism, e.g. the stochastic excitation as in solar-like stars?
- Why are modes observed in the gap predicted between the δ Sct and γ Dor frequency range?
- Is Kepler detecting higher-degree ($\ell > 3$) modes usually not visible in ground-based photometry that could fill in the frequency gap?
- Why is there so much variety of amplitudes and frequency spectra among similar stars?
- Why are some of the stars located in the instability strips observed to be essentially constant (not pulsating?)
- Is there a connection between the Am spectral peculiarity and the hybrid phenomenon?

It is exciting that now we have so many hybrid candidates for asteroseismological studies

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