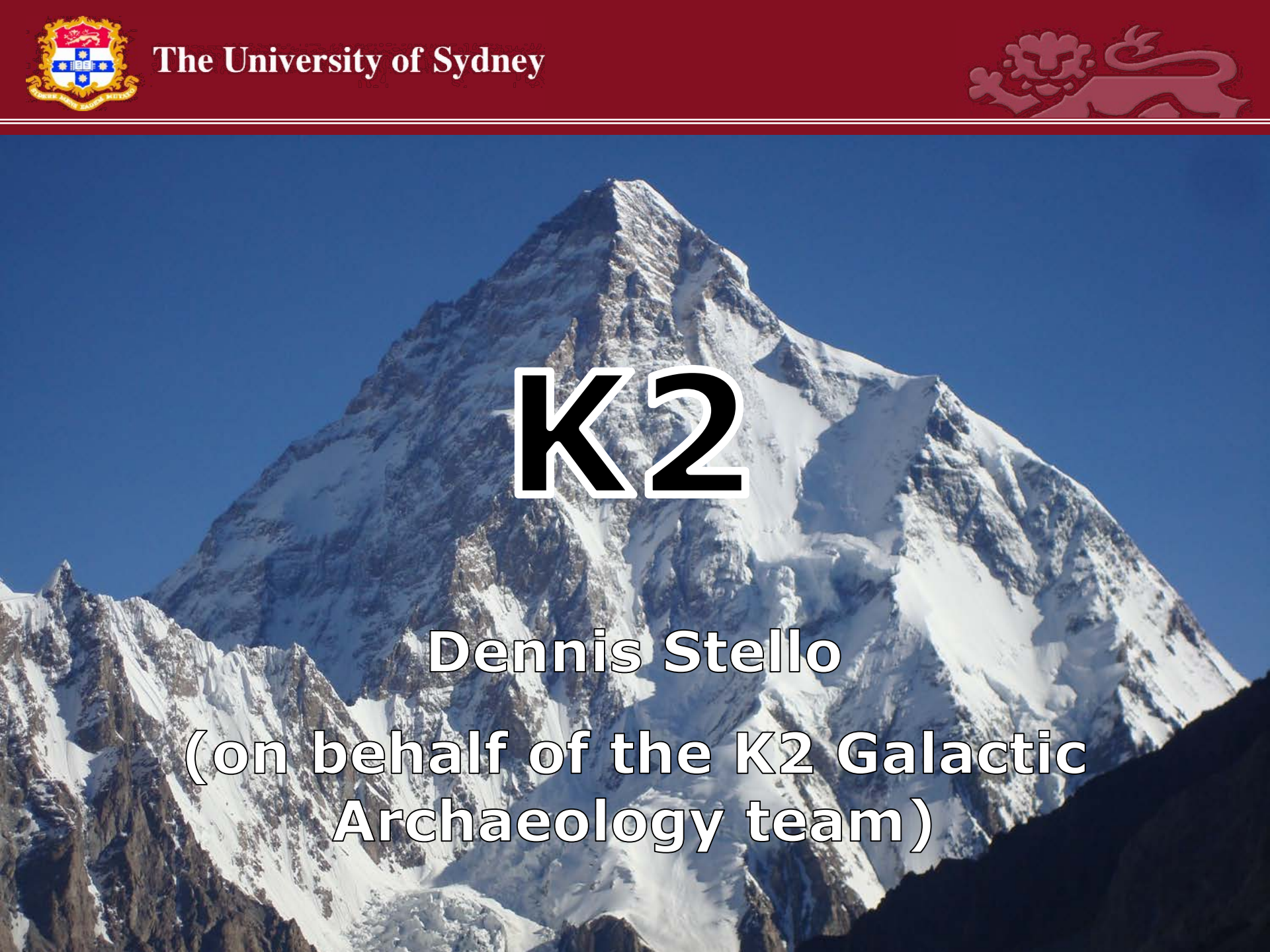
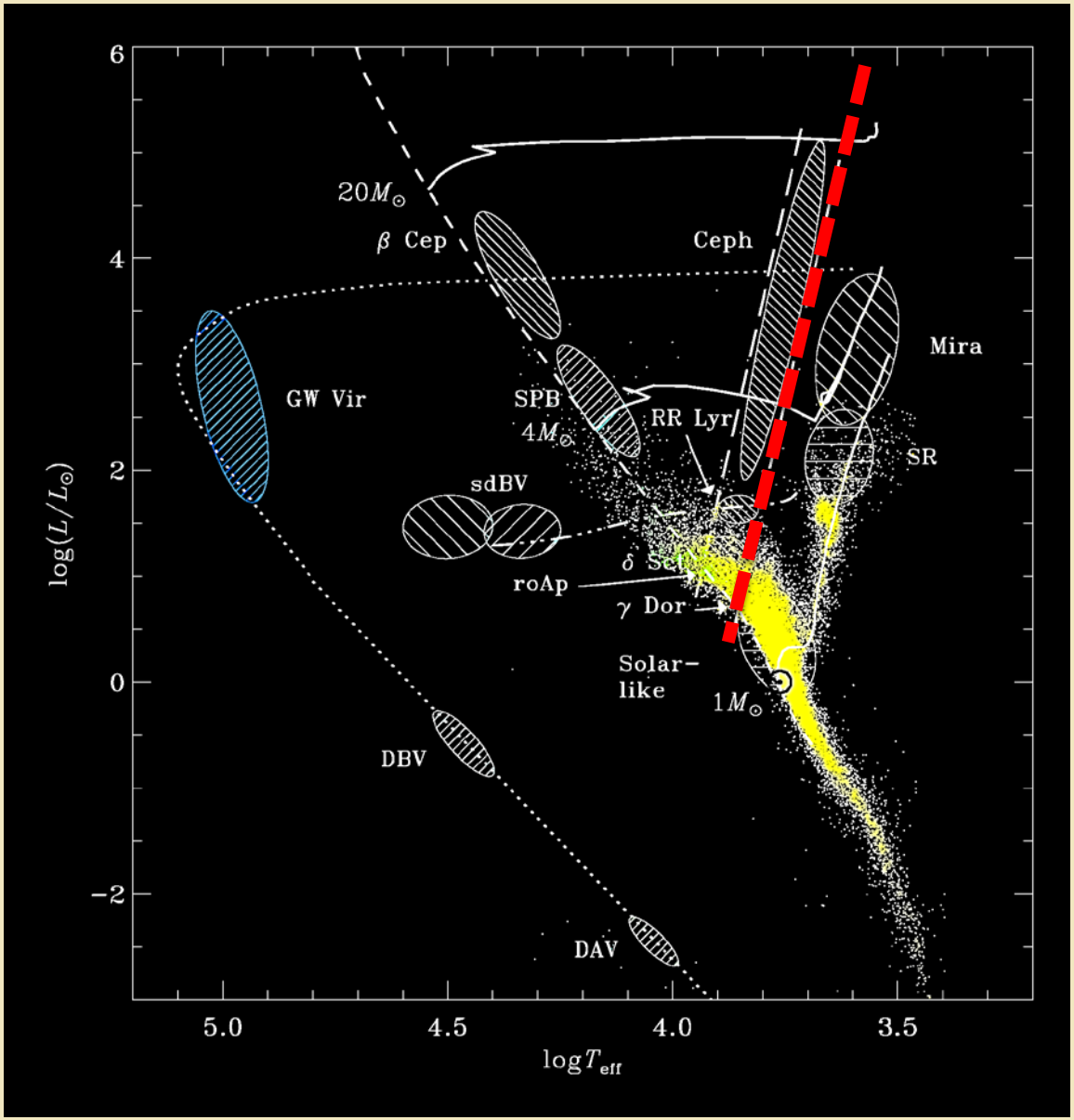
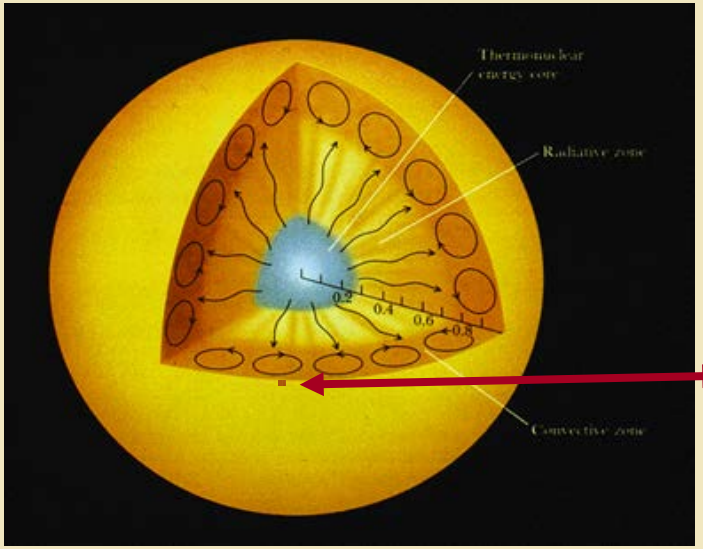
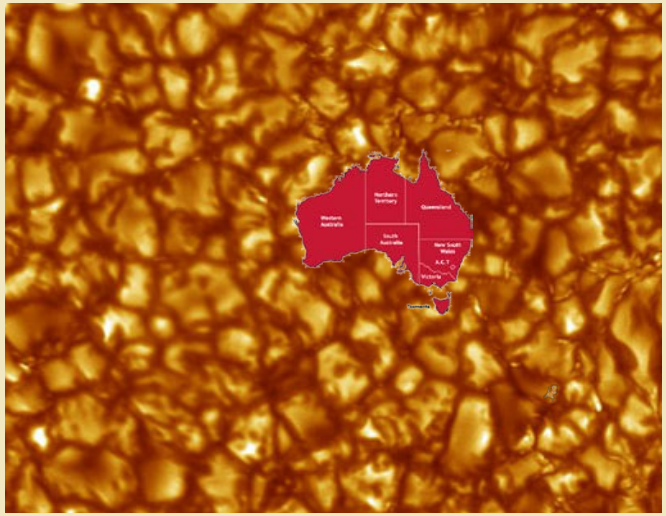

The University of Sydney
K2
Dennis Stello
(on behalf of the K2 Galactic Archaeology team)

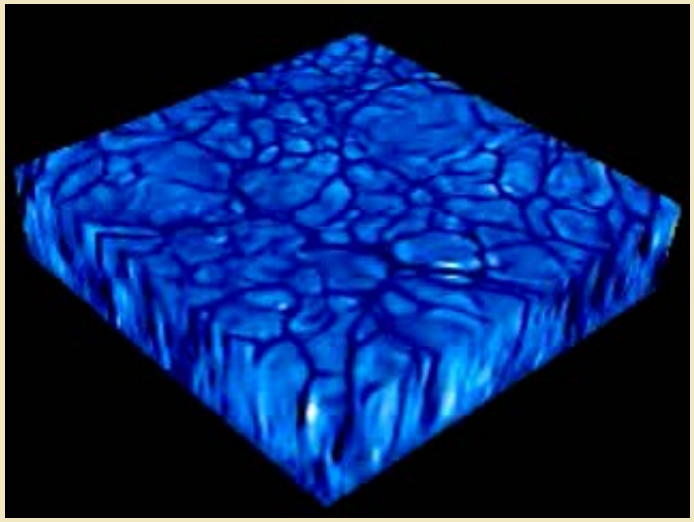
Asteroseismology

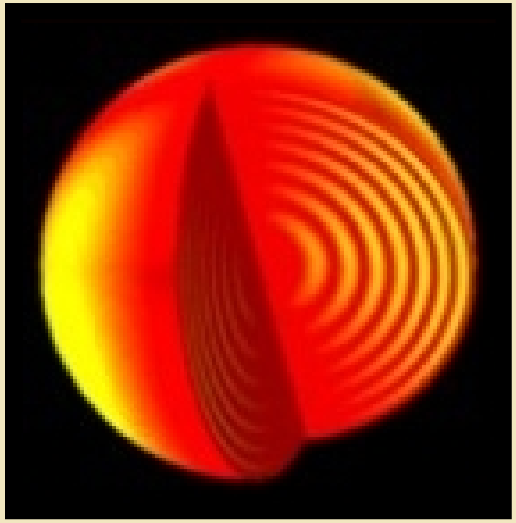


Asteroseismology



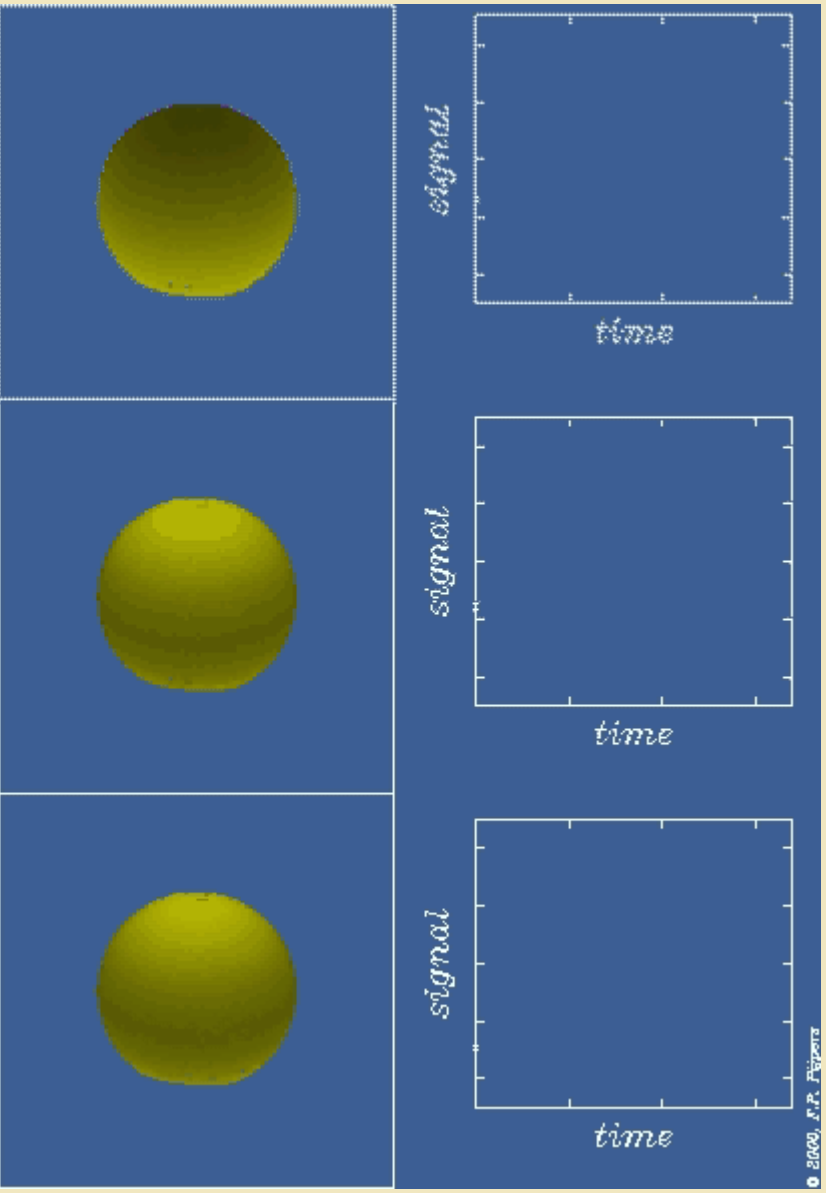


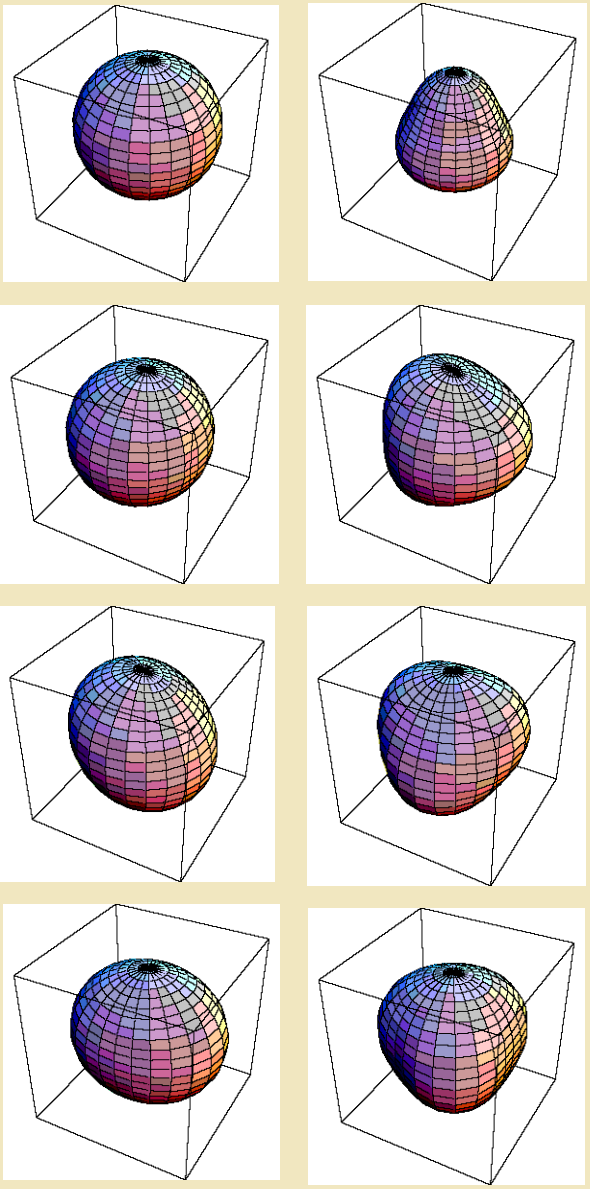




Standing sound waves

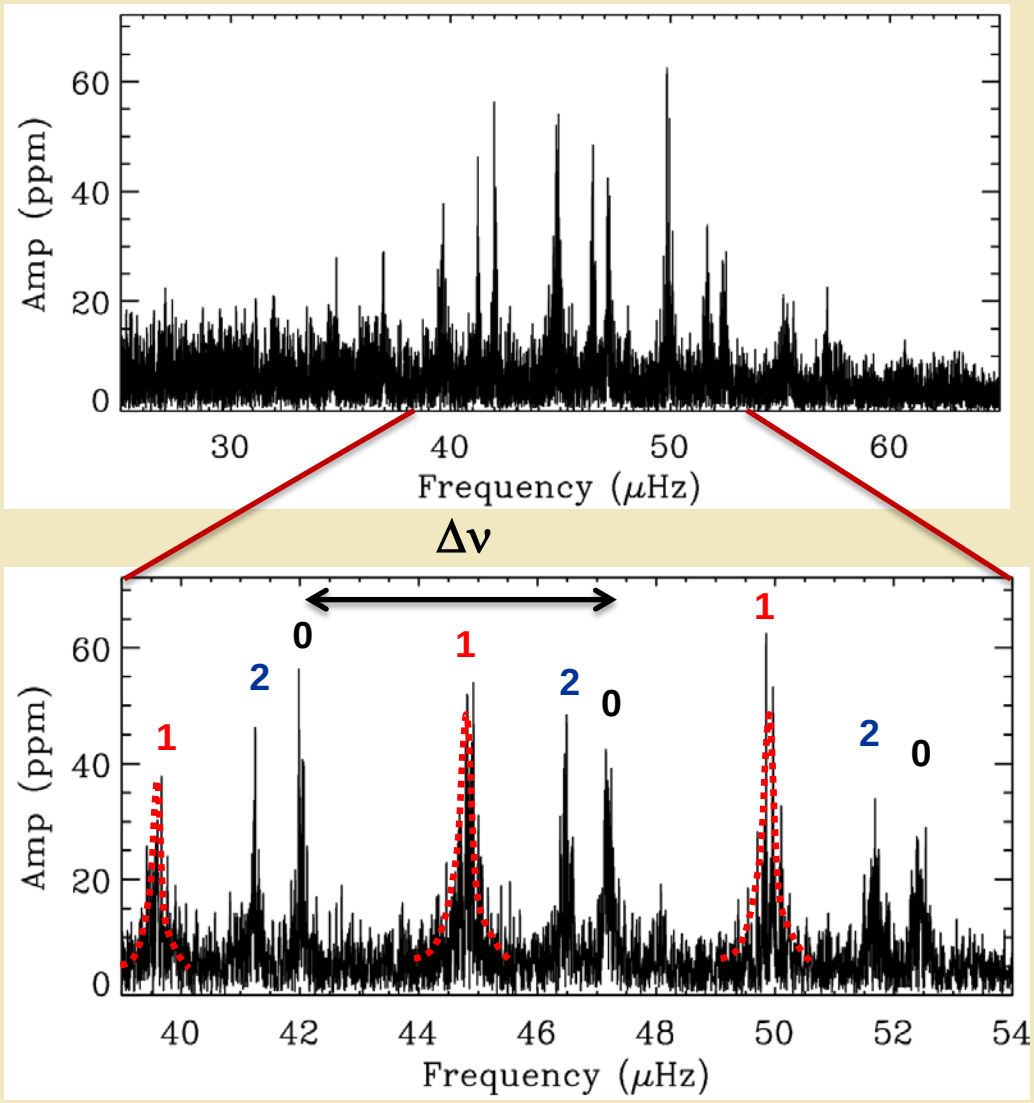
Observing standing waves





The power spectrum

Fourier transform of light curve



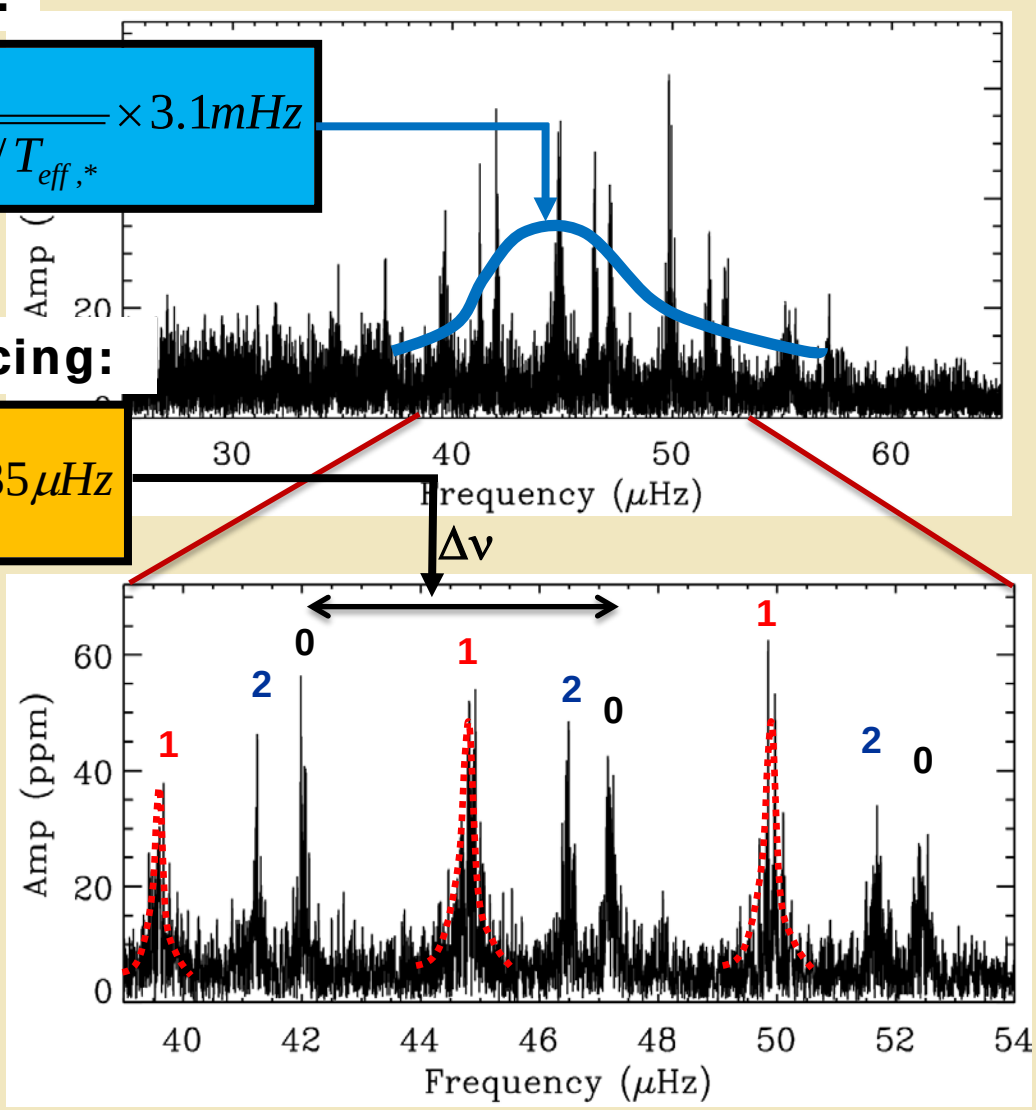
Ensemble seismology: M, R, L

Power location:

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

Frequency spacing:

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



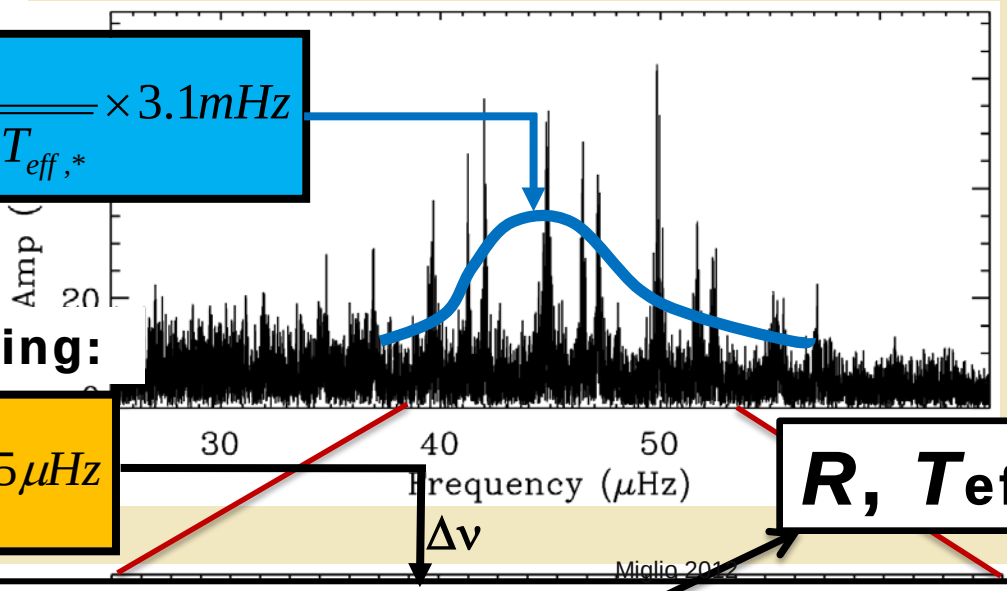
Ensemble seismology: M, R, L

Power location:

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

Frequency spacing:

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



distance

R, Teff → L

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

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

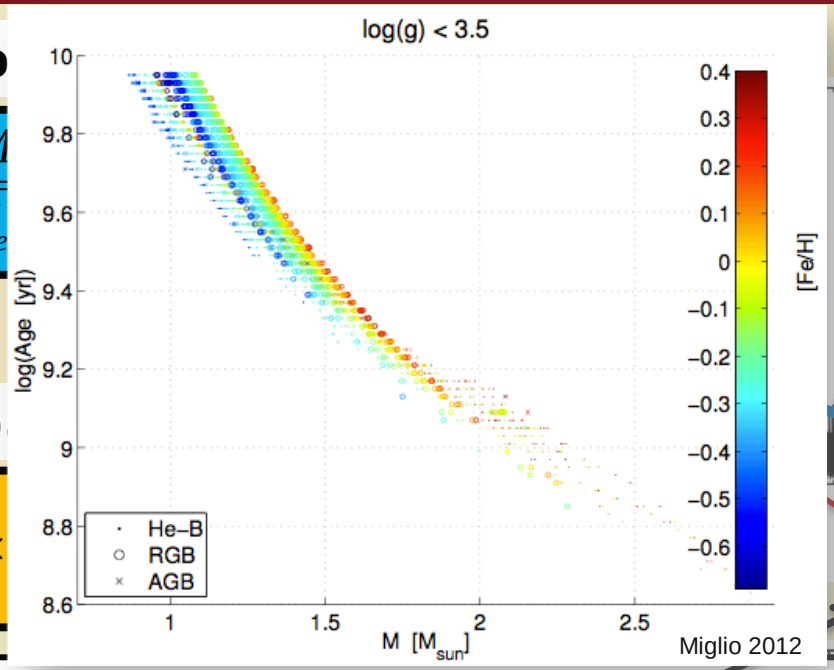
Ensemble seismology: M, R, L

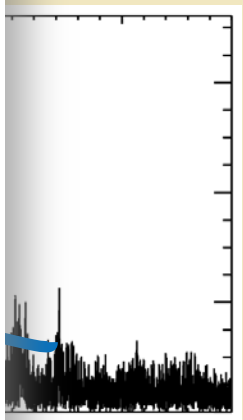
Power locatio

$$\nu_{\max} \cong \frac{M/M_{\odot}}{(R/R_{\odot})^2\sqrt{T_e}}$$

Frequency sp

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





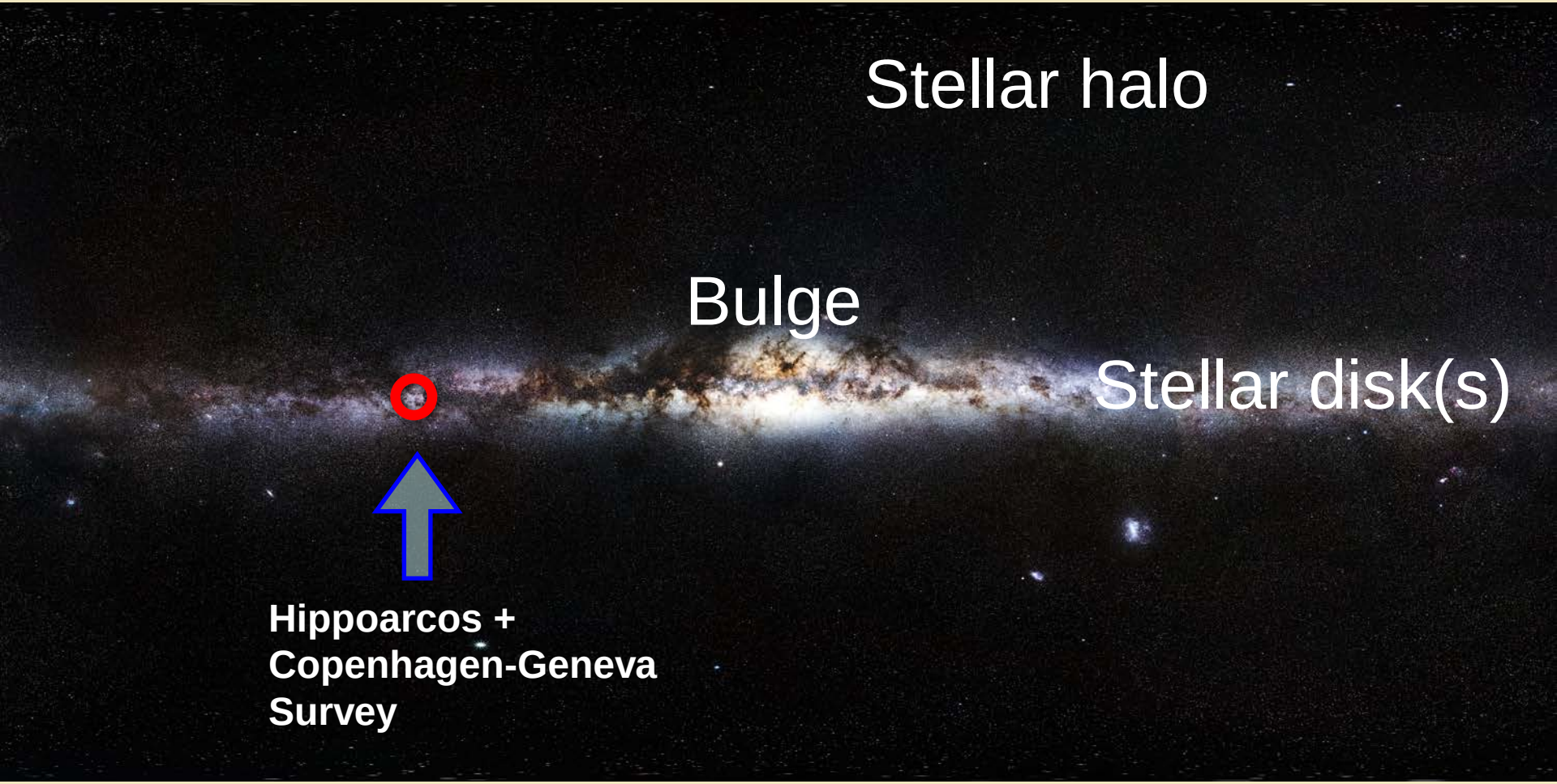
distance

R, Teff → L

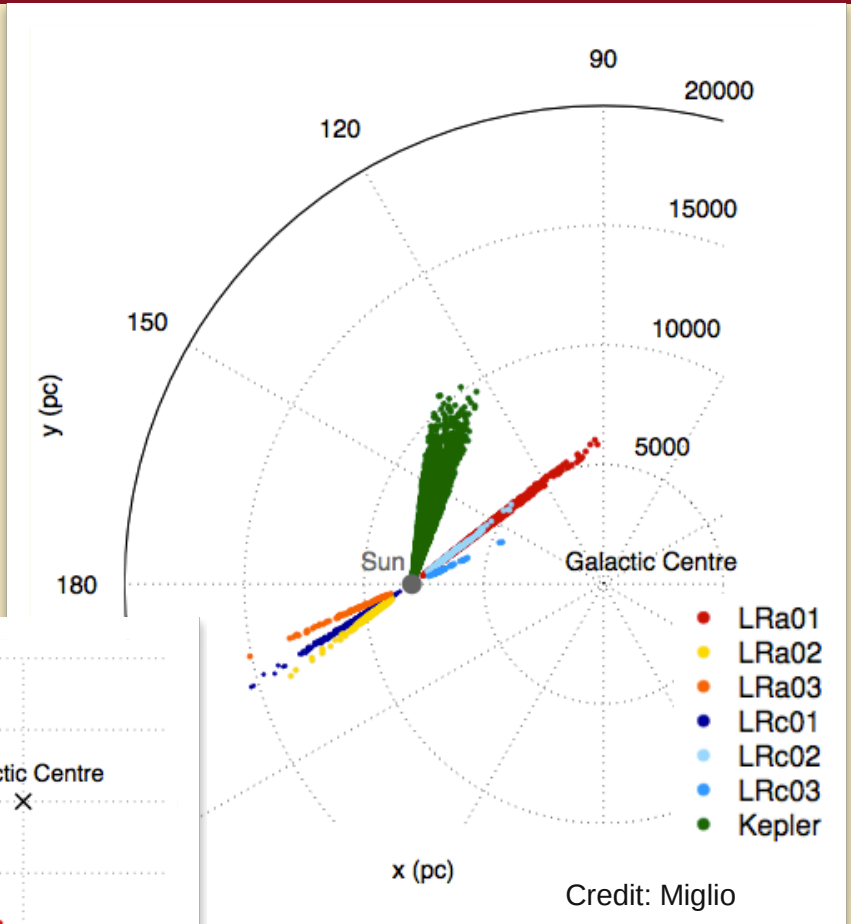
$$\frac{M}{M_{\odot}} \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right)^{3} \left(\frac{\Delta\nu}{\Delta\nu_{\odot}}\right)^{-4} \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{3/2}$$

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

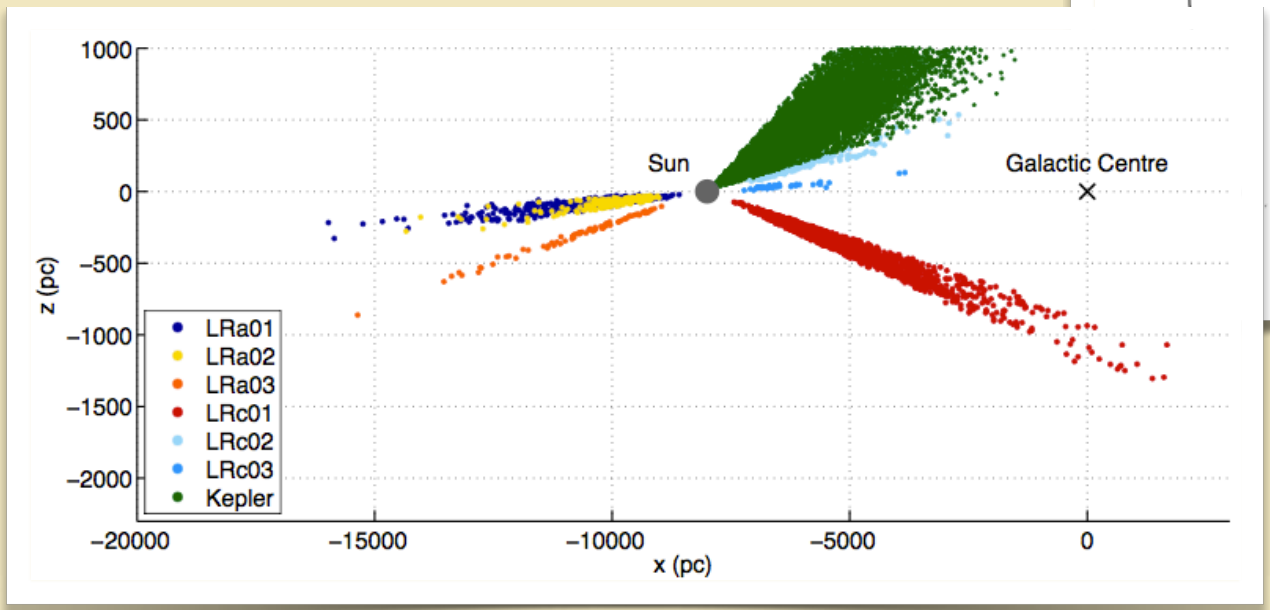
Our Galaxy


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

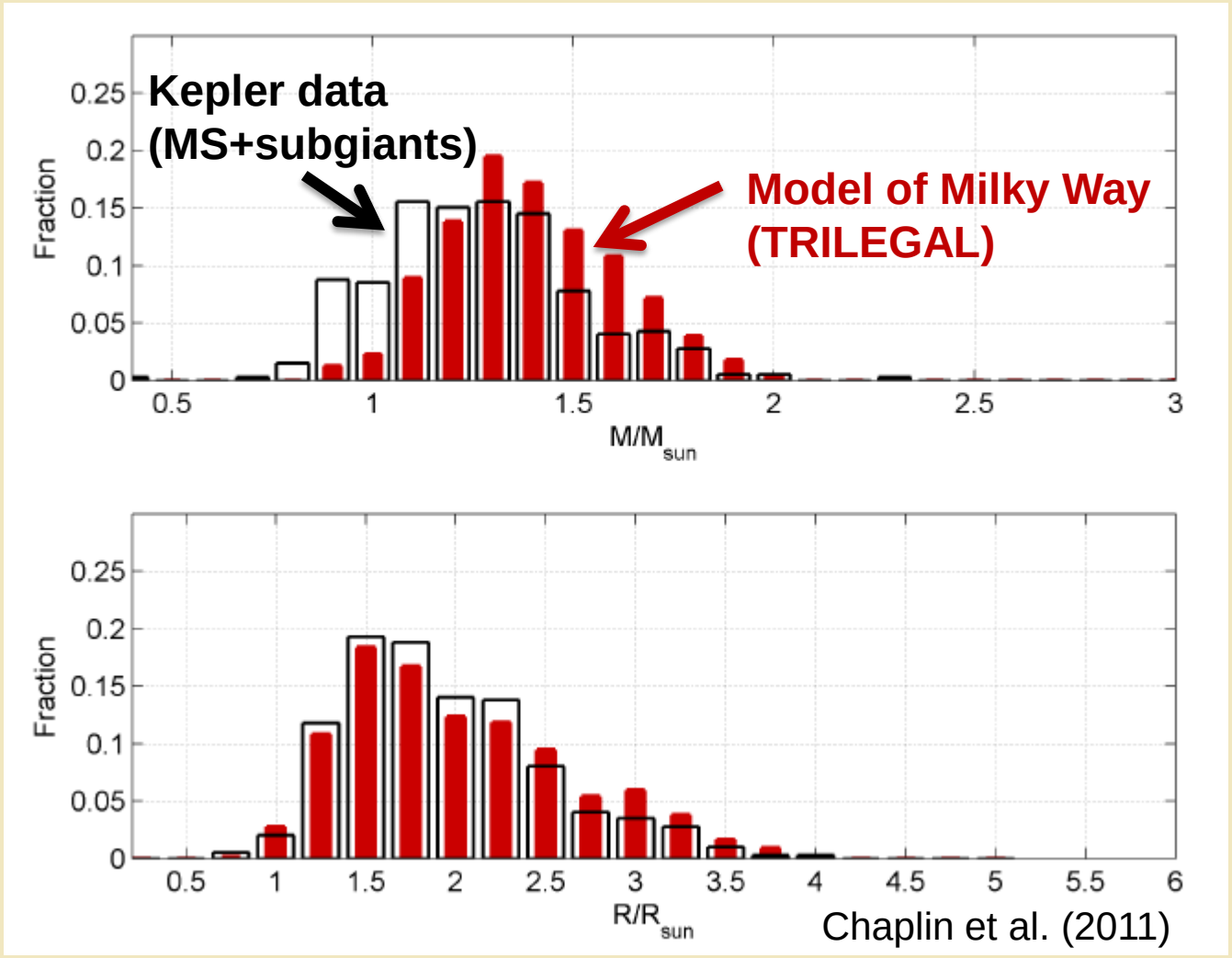
Early results from Kepler and CoRoT



Credit: Miglio



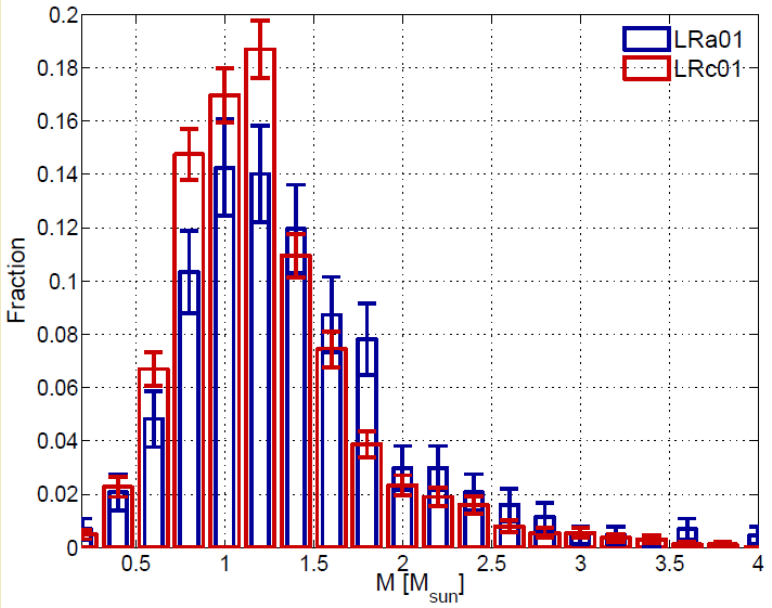
Early results from Kepler and CoRoT

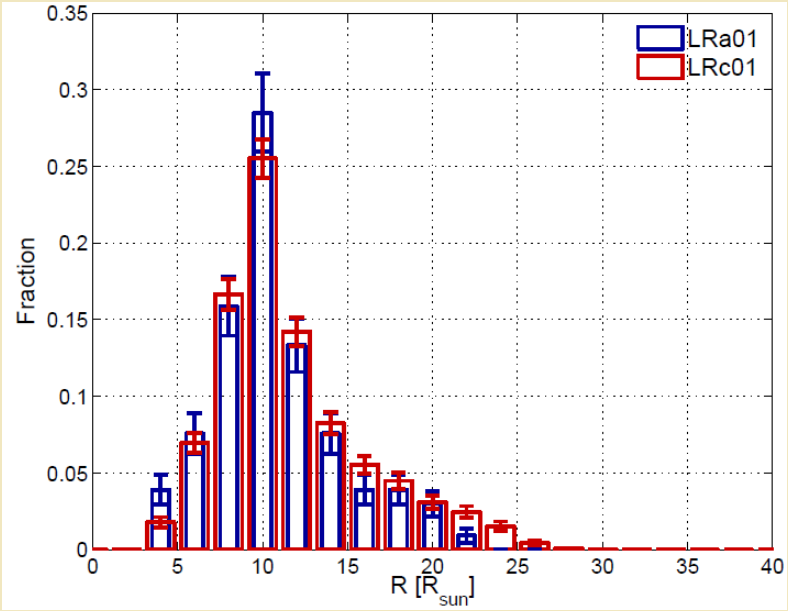


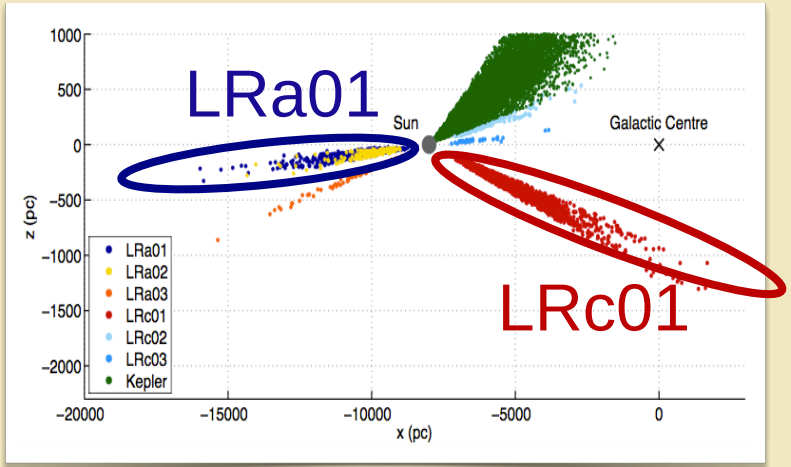
Chaplin et al. (2011)

Early results from Kepler and CoRoT

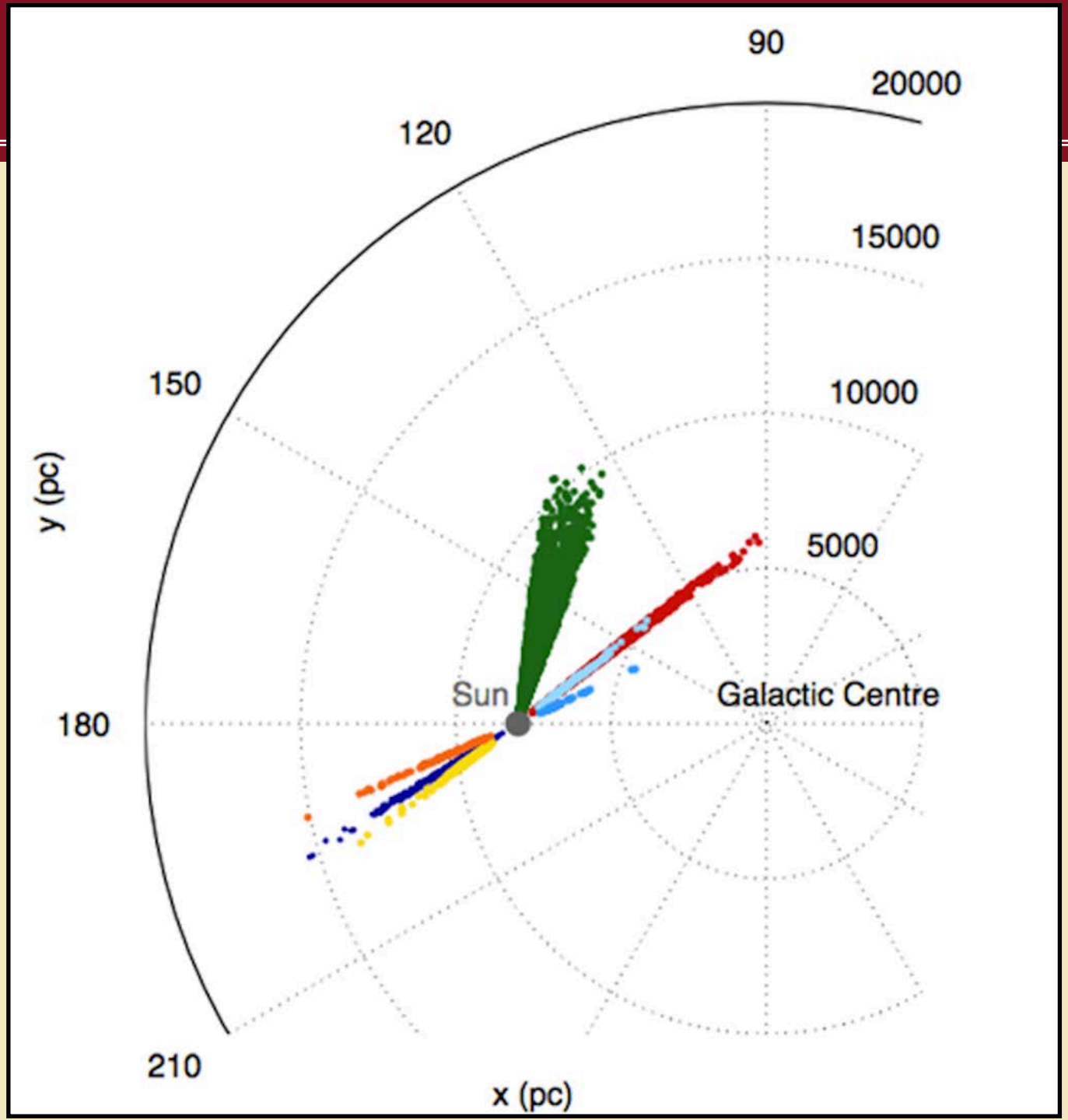
Observed Red giant stars

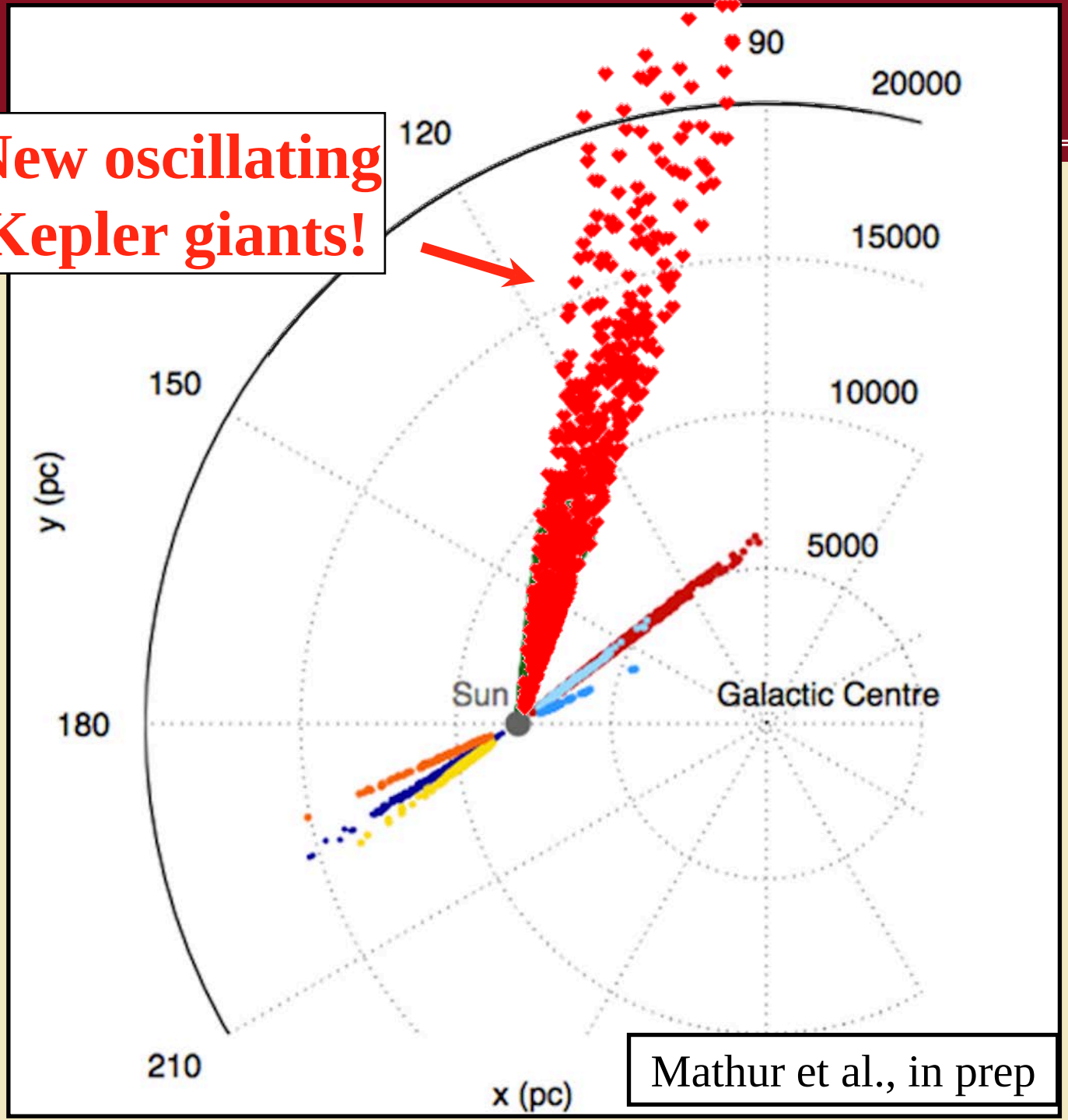






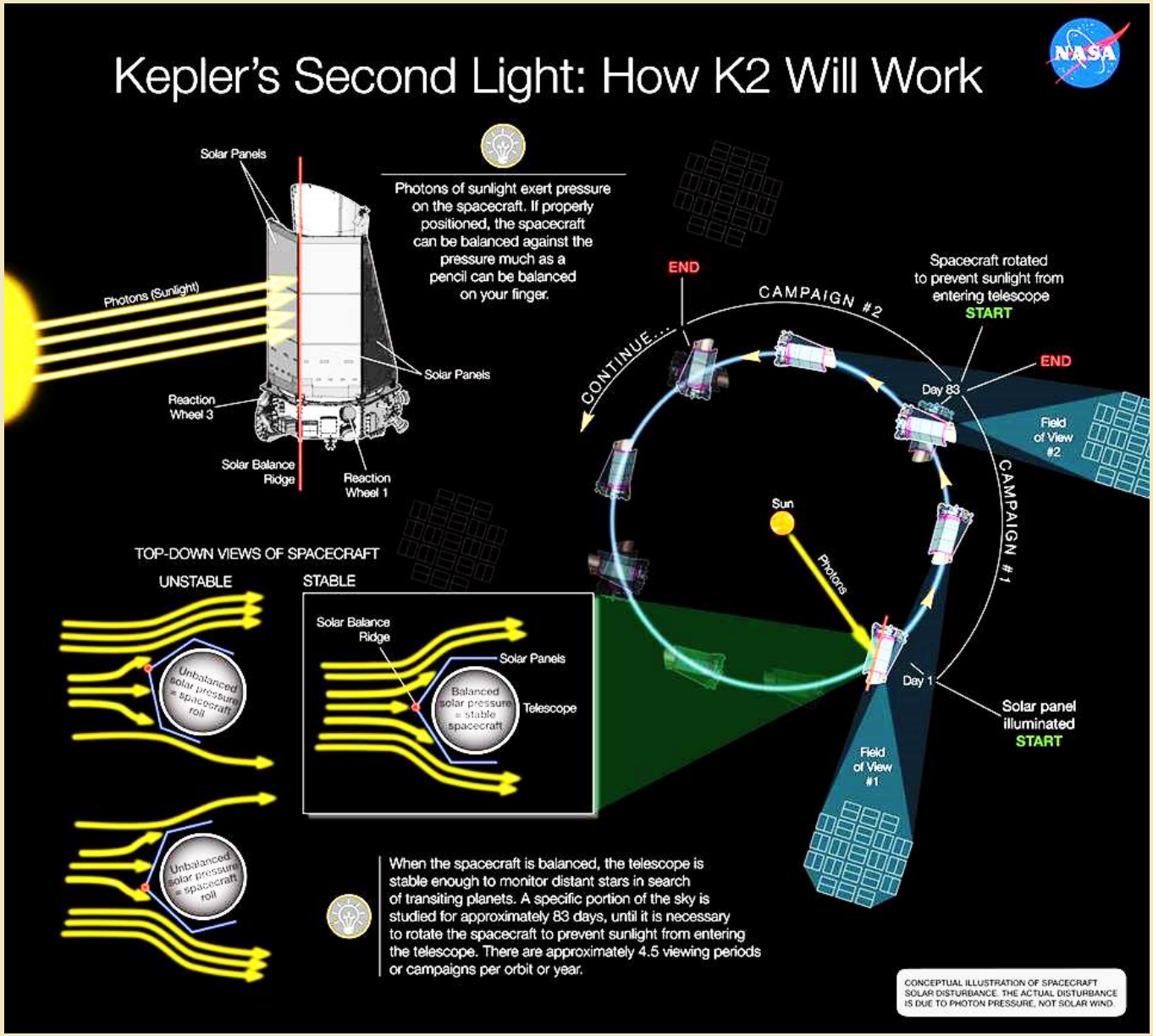
Miglio, Chiappini, Morel et al. 2013


90
20000
120
15000
150
10000
y (pc)
5000
Sun
Galactic Centre
180
210
x (pc)


New oscillating Kepler giants!
90
120
150
180
210
20000
15000
10000
5000
Sun
Galactic Centre
y (pc)
x (pc)
Mathur et al., in prep

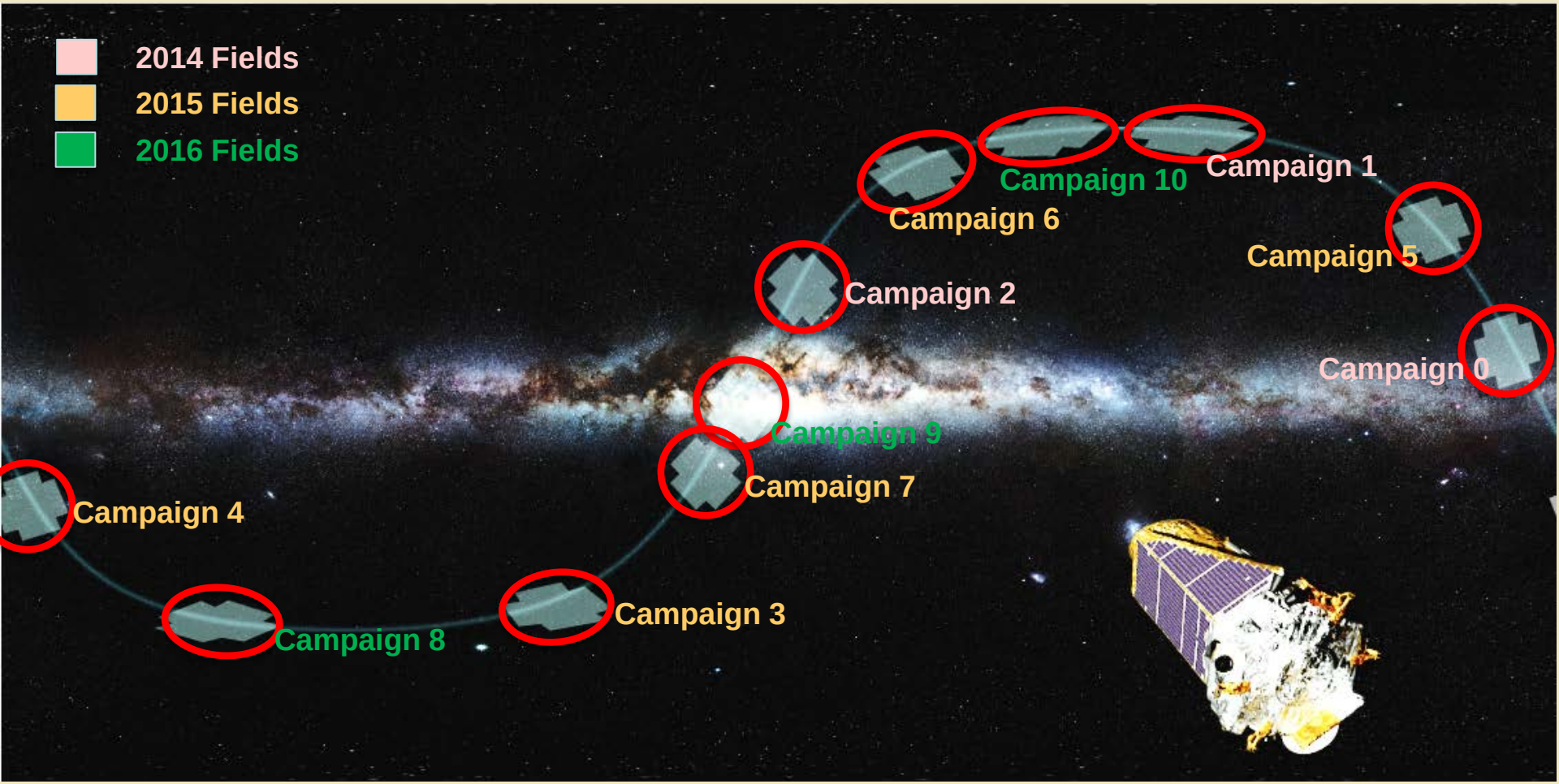
The Kepler mission 2009-2013

K2: The concept

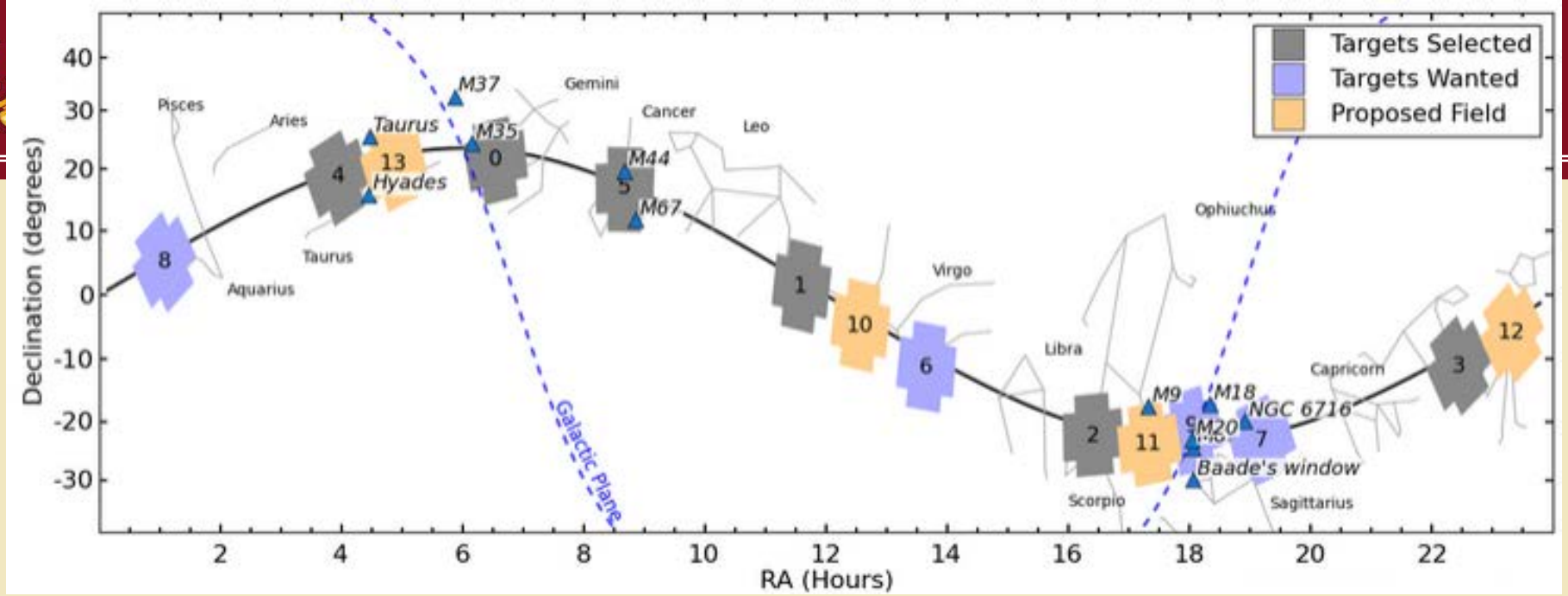


K2: Funded 2 yrs of campaigns

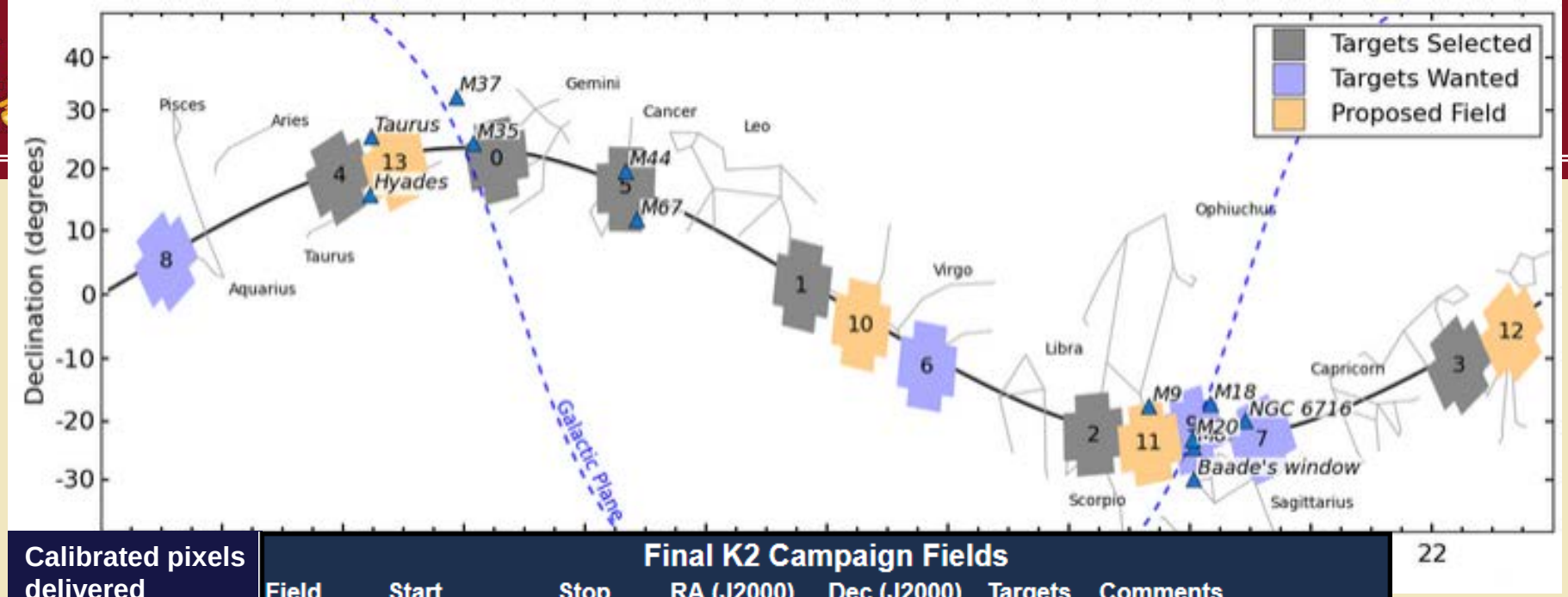
Each campaign field: 10-20K stars observed for ~80 days



"Galactic coordinates"



RA and Dec coordinates



Calibrated pixels delivered

Sep 2014

Dec 2015

Apr 2015

Final K2 Campaign Fields

Field	Start	Stop	RA (J2000)	Dec (J2000)	Targets	Comments
0	2014 Mar 08	2014 May 27	06:33:11.14	+21:35:16.40	✓	Near Galactic Anti-center, M35, NGC 2158
1	2014 May 30	2014 Aug 21	11:35:45.51	+01:25:02.28	✓	North Galactic Cap
2	2014 Aug 23	2014 Nov 13	16:24:30.34	-22:26:50.28	✓	Near Galactic Center, M4, M80, M19, Upr Sco, rho Oph
3	2014 Nov 14	2015 Feb 06	22:26:39.68	-11:05:47.99	✓	South Galactic Cap, Neptune
4	2015 Feb 07	2015 Apr 26	03:56:18.22	+18:39:38.09	✓	M45 (Pleiades), NGC1647, Hyades
5	2015 Apr 27	2015 Jul 13	08:40:37.84	+16:49:46.61		M44 (Beehive), M67
6	2015 Jul 14	2015 Oct 03	13:39:27.61	-11:17:43.29		North Galactic Cap
7	2015 Oct 06	2015 Dec 29	19:11:18.84	-23:21:36.07		Near Galactic Center, NGC 6717
8	2016 Jan 03	2016 Mar 26	01:05:21.12	+05:15:44.45		Uranus
9	2016 Apr 07	2016 Jul 06	18:01:25.08	-21:46:47.32		Galactic Center, Baades Window, M21, M18, M25, M8
10	2016 Jul 06	2016 Sep 21	12:27:07.07	-04:01:37.8		North Galactic cap

K2: Instrument performance

- **Instrument is performing well.**
- Spacecraft has fuel for at least 2 years, perhaps 4+ years.
- Remaining reaction wheels are behaving.
- Initial increase in reaction time for Attitude Control System (ACS) resulted in noise being motion dominated.
- Decrease in ACS reaction time starting in C3 (reduce motion noise by factor 3-4).
  - Kepler : 12mag, 6.5hr 30ppm
  - K2 C0-2: → 60ppm (C0 worst!)
  - K2 C3+ : 40ppm expected

K2: Instrument performance

- Instrument is performing well.
- Spacecraft has fuel for at least 2 years, perhaps 4+ years.
- Remaining reaction wheels are behaving.
- Initial increase in reaction time for Attitude Control System (ACS) resulted in noise being motion dominated.
- Decrease in ACS reaction time starting in C3 (reduce motion noise by factor 3-4).
  - Kepler : 12mag, 6.5hr 30ppm
  - K2 C0-2: → 60ppm (C0 worst!)
  - K2 C3+ : 40ppm expected

The K2 Galactic Archaeology Program (GAP)

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)

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)

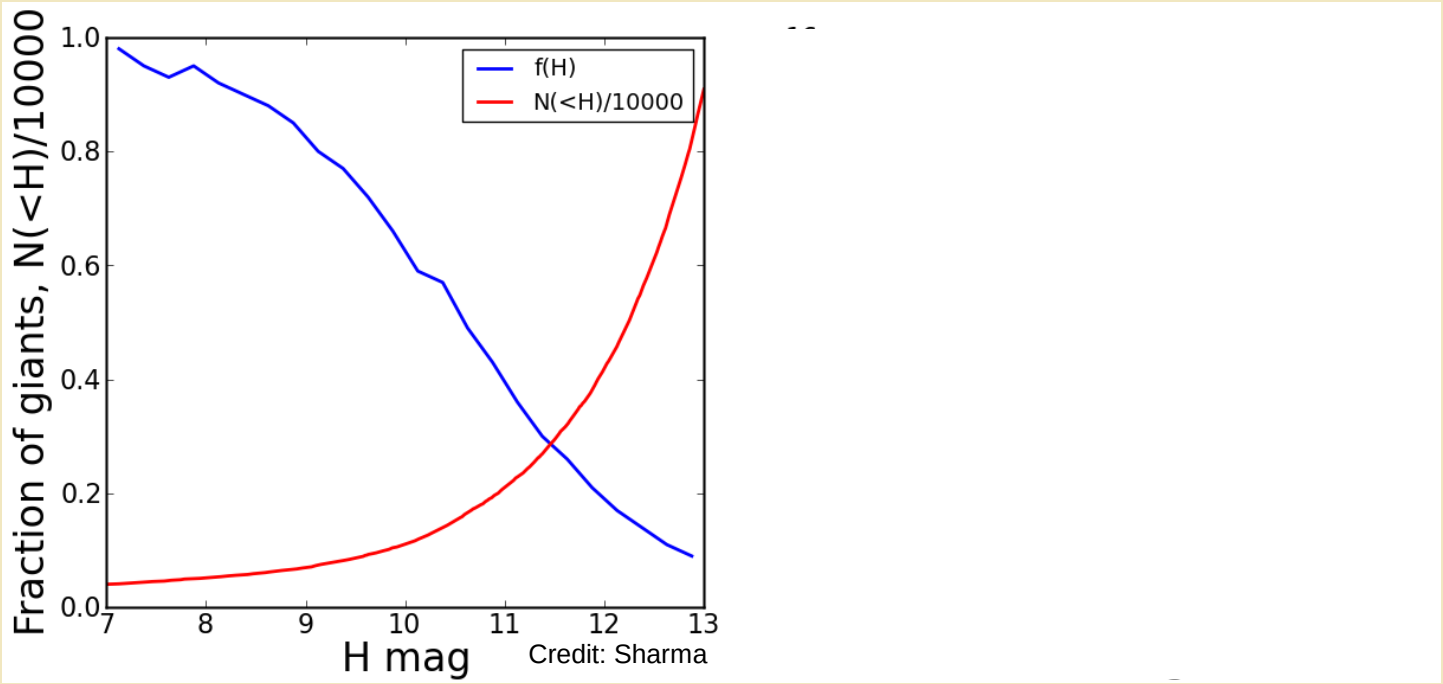
K2 GAP

- **Observational strategy:**
  - **Target 5K-10K stars (~5K red giants) at each campaign**
  - **Use *simple/reproducible section criteria!***

$J–K > 0.5$, $V > 9$ sorted by V (entire field)

or

***$J–K > 0.5$, $9 < V < 13.5$ random by V* (few dense sub-fields)**



K2 GAP

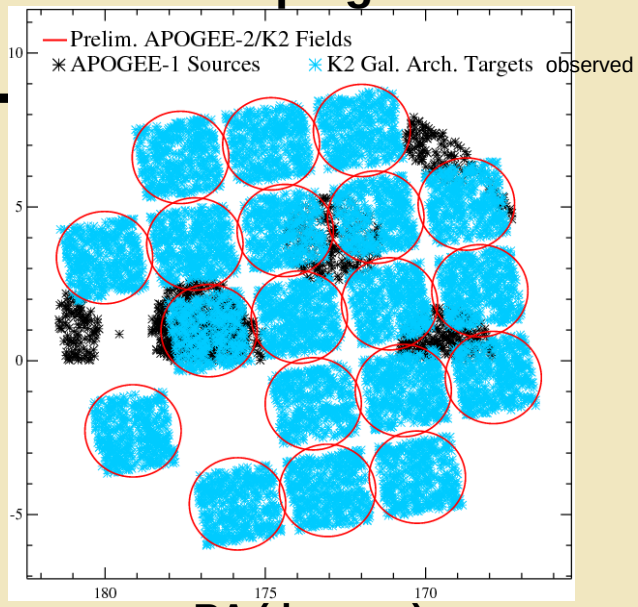
- **Observational strategy:**
  - **Target 5K-10K stars (~5K red giants) at each campaign**
  - **Use *simple/reproducible section criteria!***

***J–K* > 0.5, *V* > 9 sorted by *V* (entire field)**

or

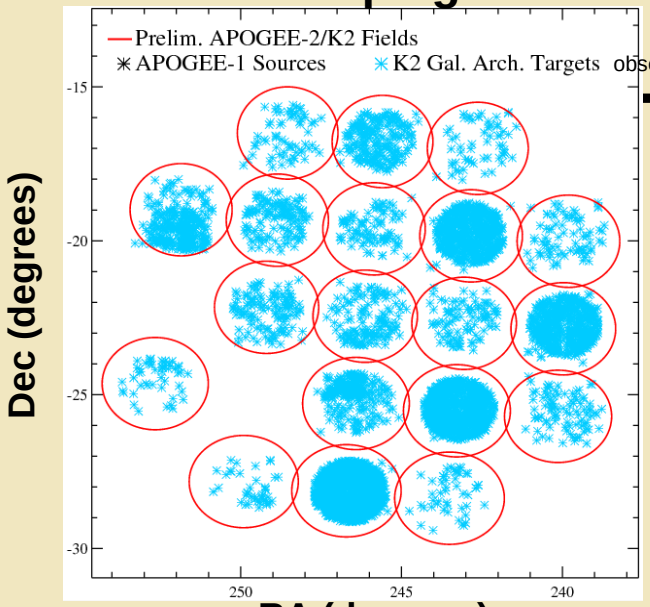
***J–K > 0.5, 9 < V < 13.5 random by V* (few dense sub-fields)**

Campaign-1



Credit: Kevin Covey

Campaign-2



Credit: Kevin Covey

K2 GAP

- **Status of observations:**

Campaign	$N_{targets}$	APOGEE-1	APOGEE-2	GALAH	Gaia-ESO	LAMOST	SAGA
0	452	●	✗	✗	?	○	✗
1	8629	◔	○	○	?	○	○
2	5138	◔	◔	●	few	✗	◔
3	3904	✗	◔	●	?	✗	◔
4	6357	◔	○	●	?	○	○
5	9828	◔	○	●	?	○	○
6+	?	◔	○	○	?	◔	◔

~40% of total K2 capacity

K2 GAP

- **Status of observations:**

Campaign	$N_{targets}$	APOGEE-1	APOGEE-2	GALAH	Gaia-ESO	LAMOST	SAGA
0							✗
1							○
2							○
3							○
4							○
5							○
6+							○

Ground-based coordination:

Sanjib Sharma (GALAH)

Jennifer Johnson (APOGEE)

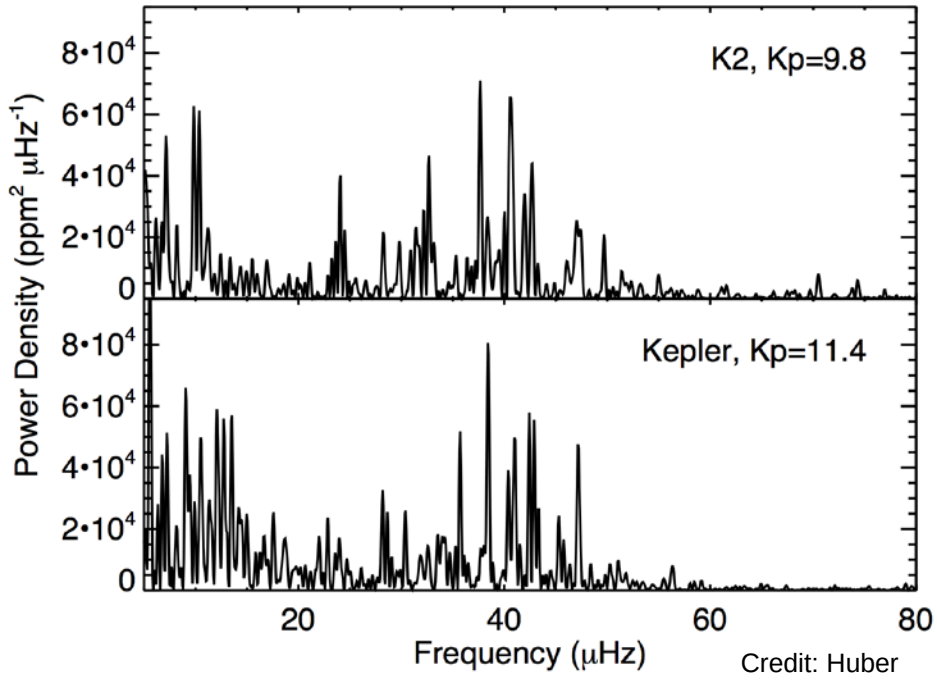
Sofia Feltzing (Gaia-ESO)

Victor Silva Aguirre

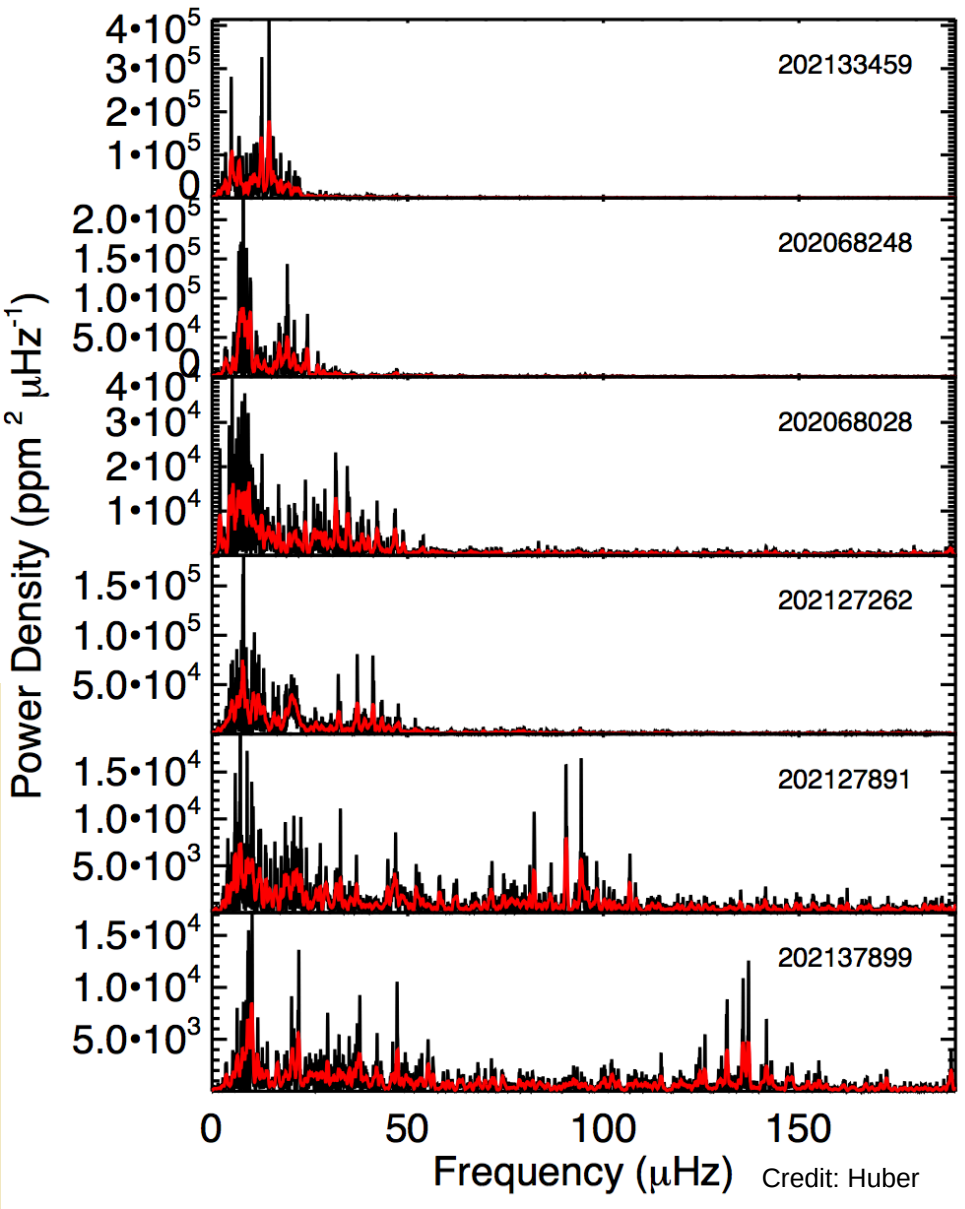
Dennis Stello

- **Don’t forget serendipitous red giants that fall within the pixel stamps of any K2 target => unbiased sample.**

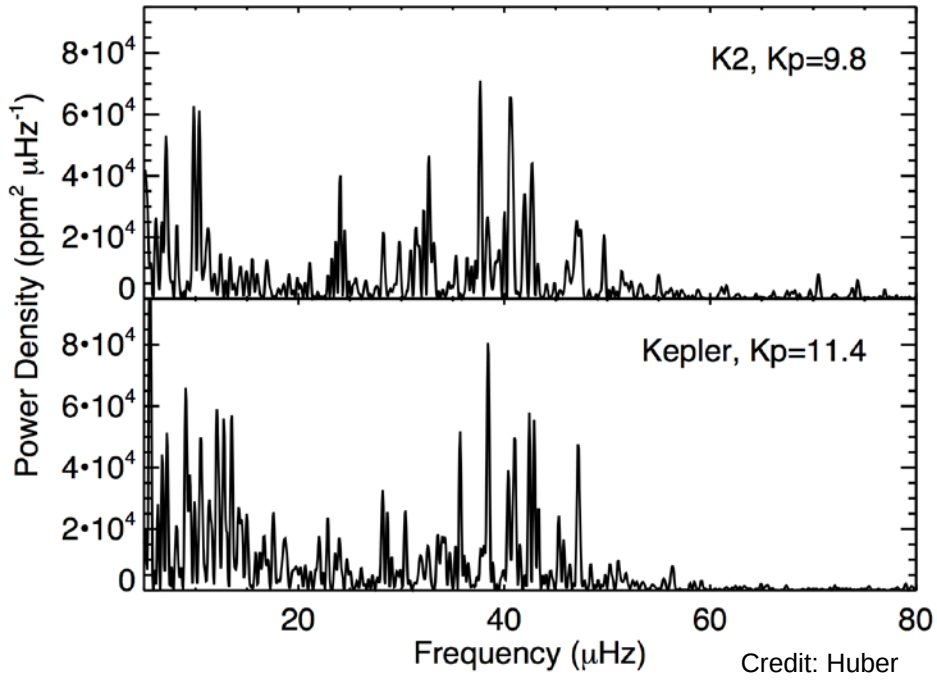
K2 GAP: C0



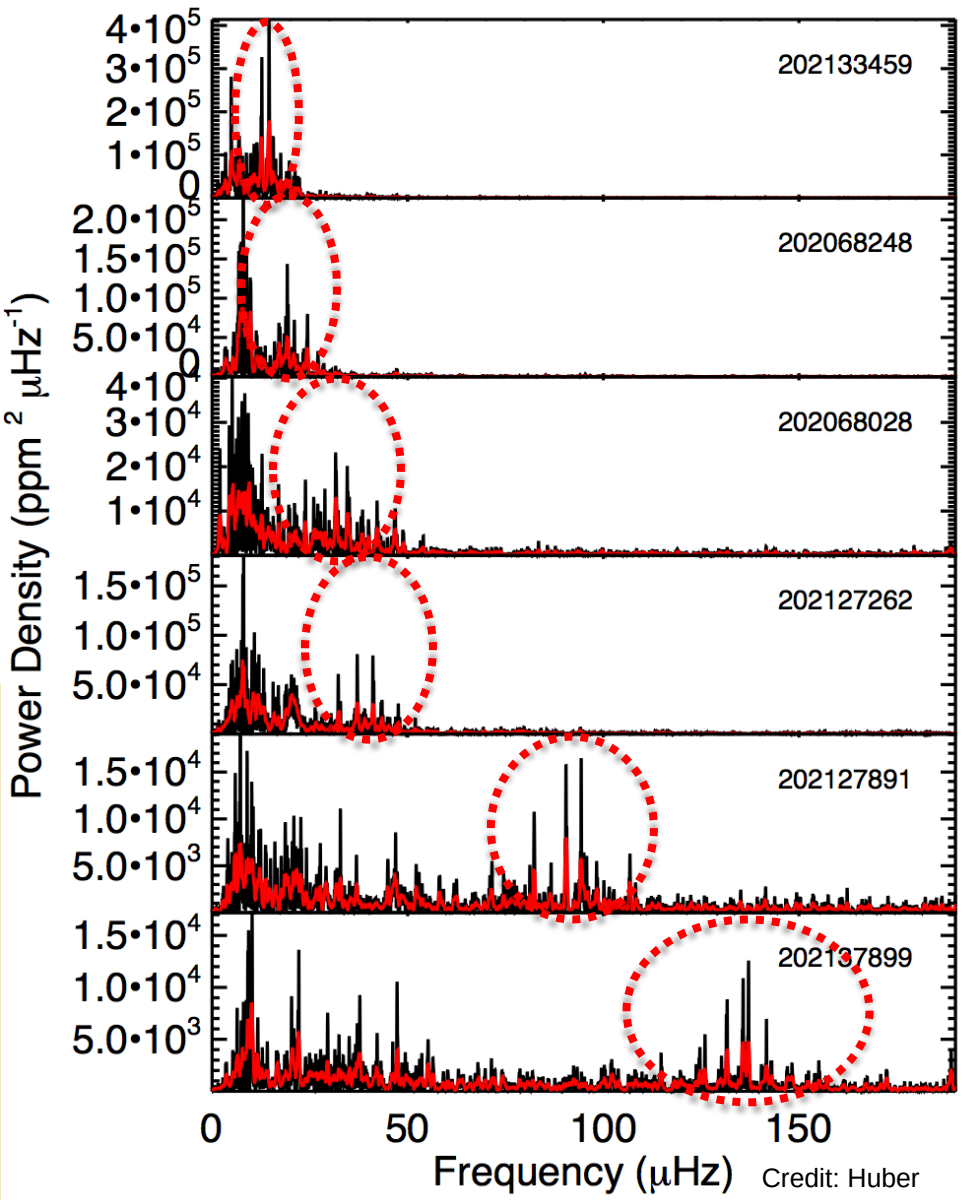
Campaign 0



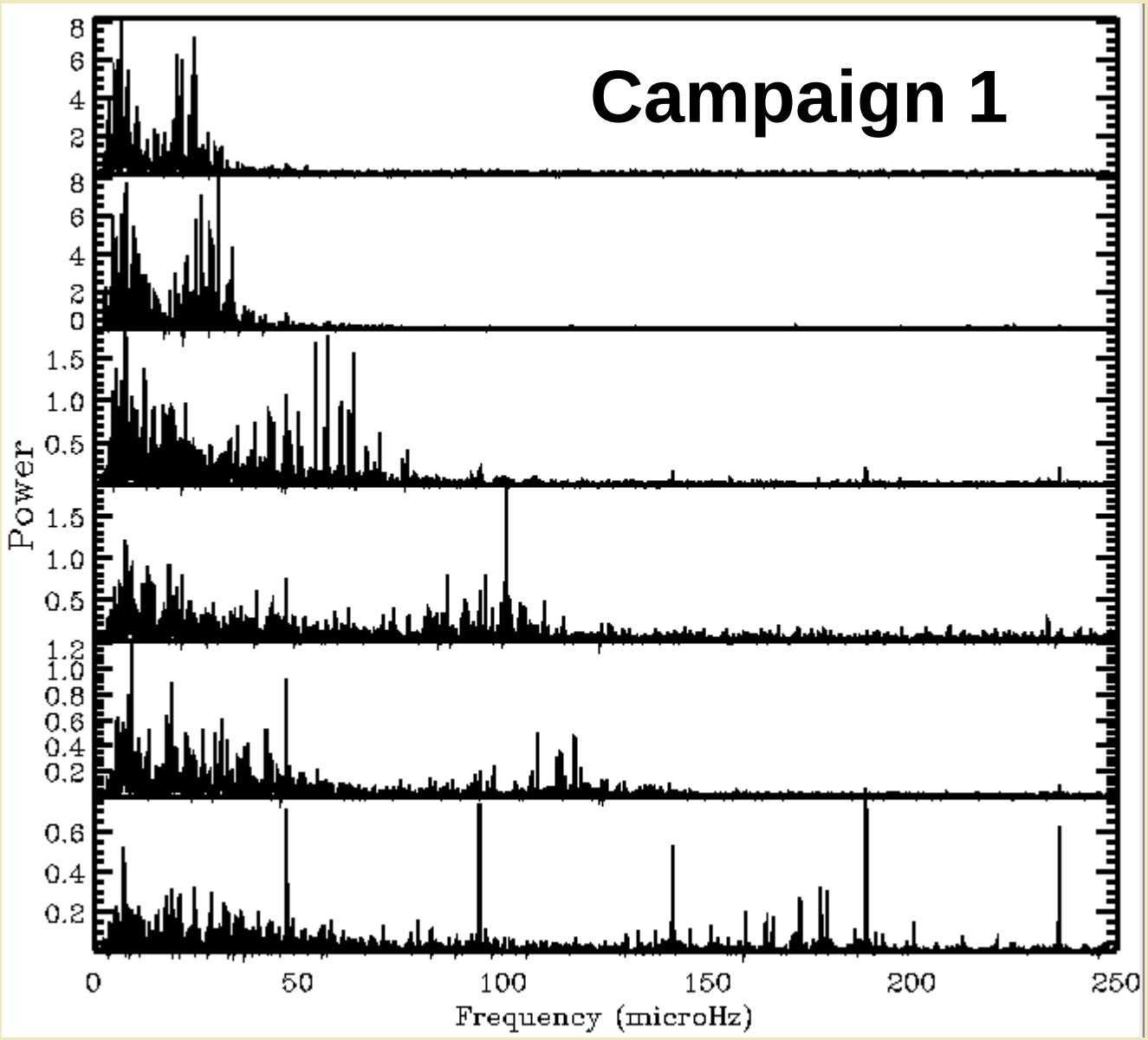
K2 GAP: C0



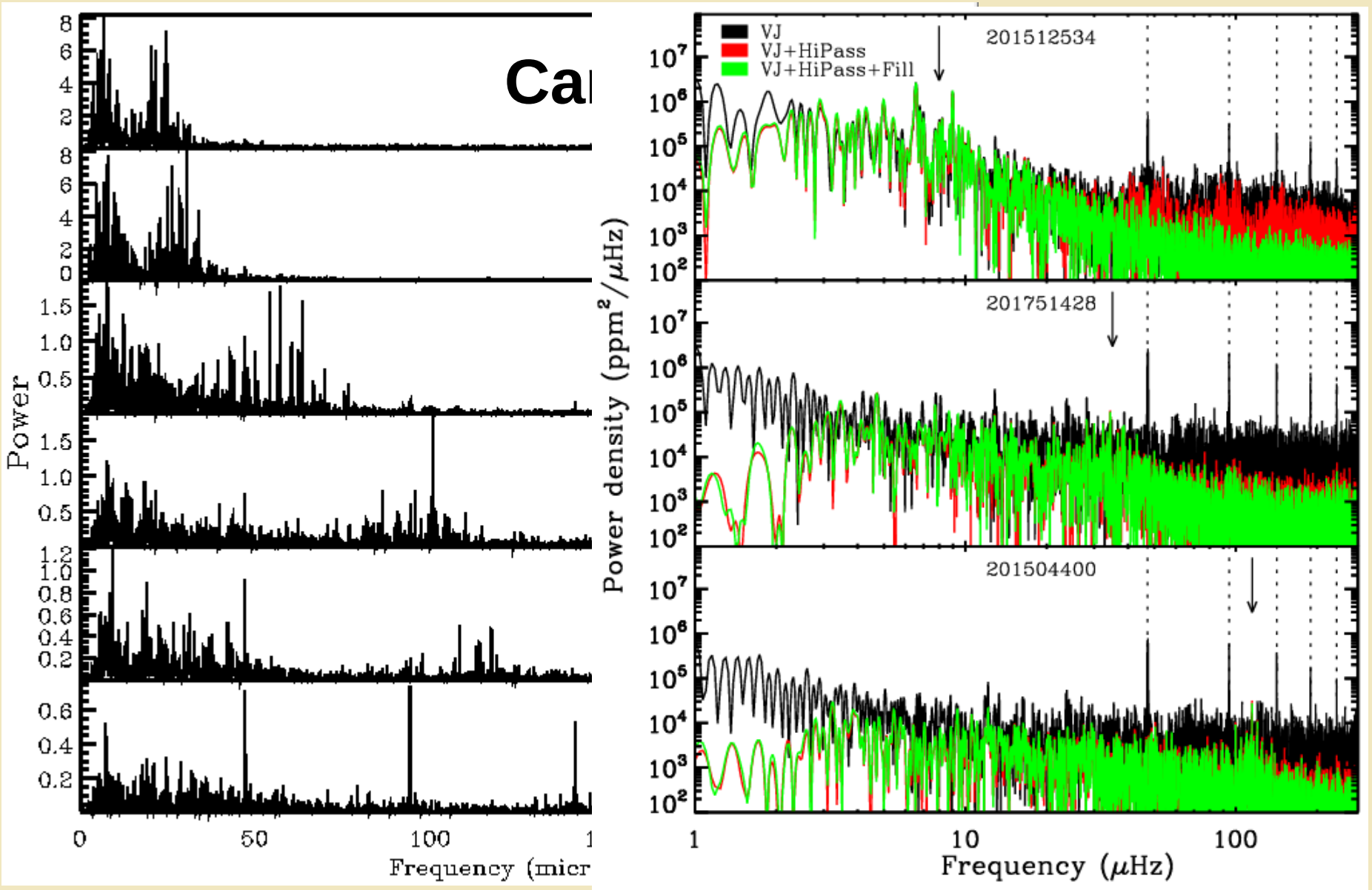
Campaign 0



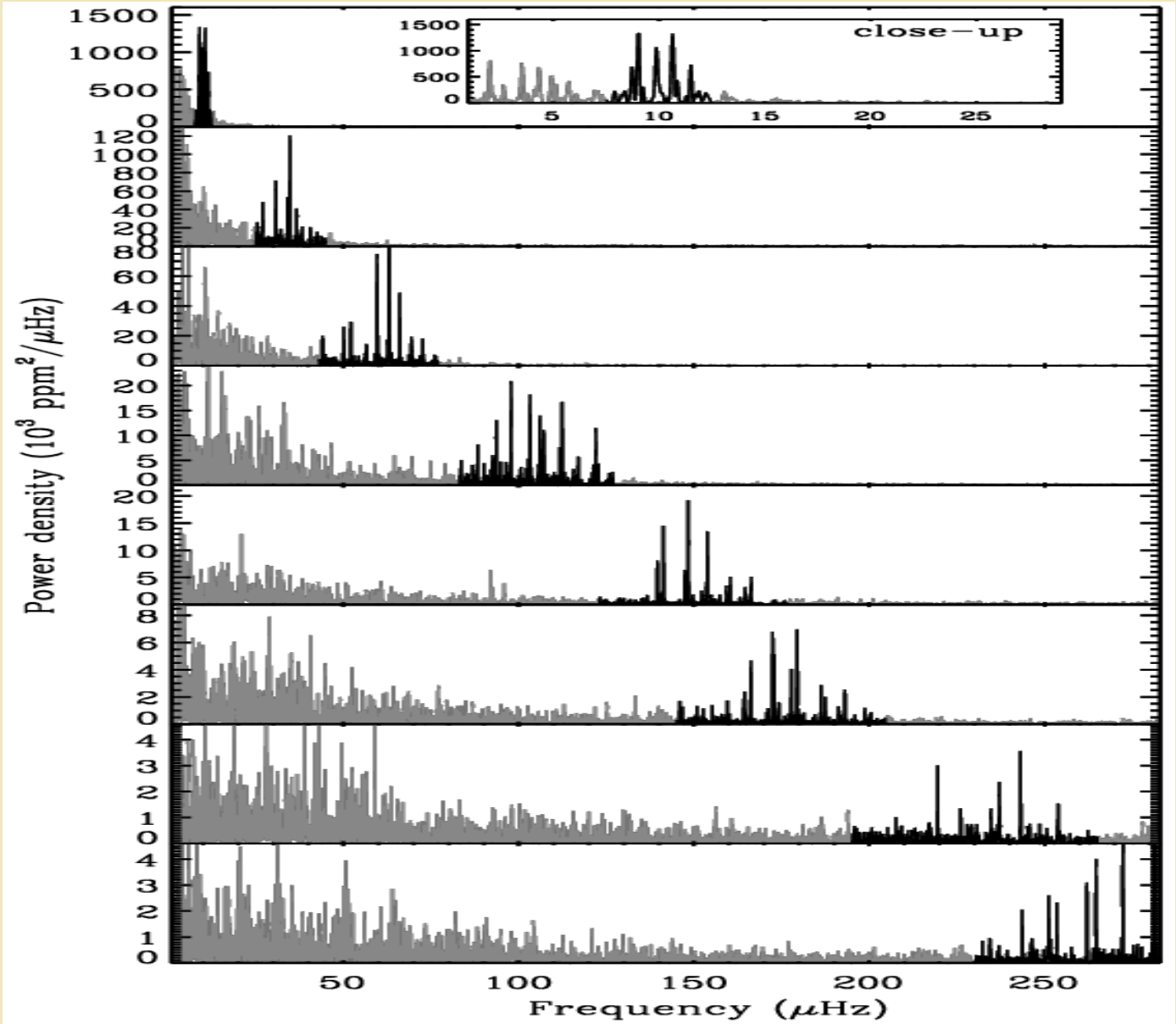
K2 GAP: C1



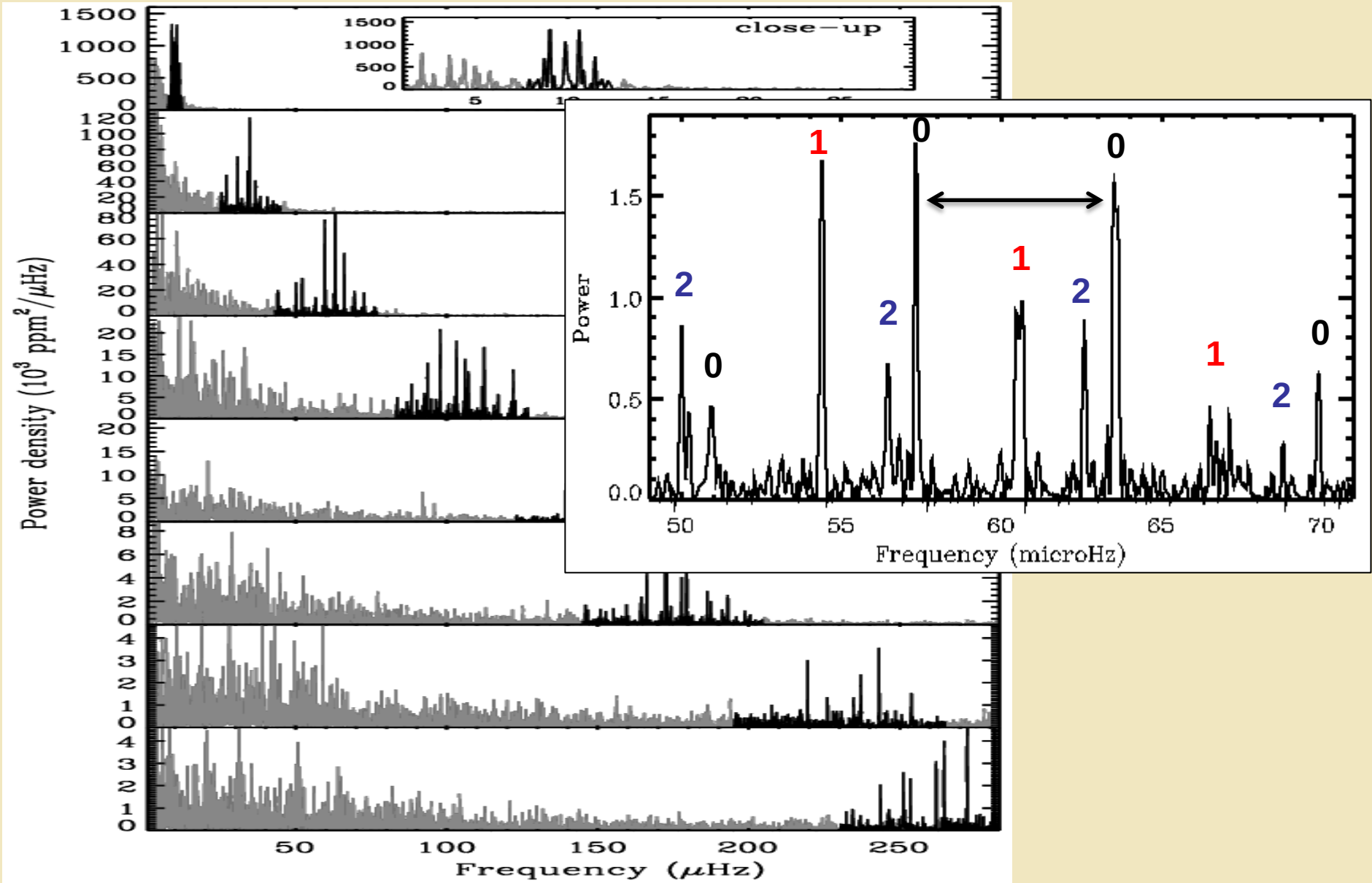
K2 GAP: C1


Power
Frequency (micr
Power density (ppm²/μHz)
Frequency (μHz)
VJ
VJ+HiPass
VJ+HiPass+Fill
201512534
201751428
201504400

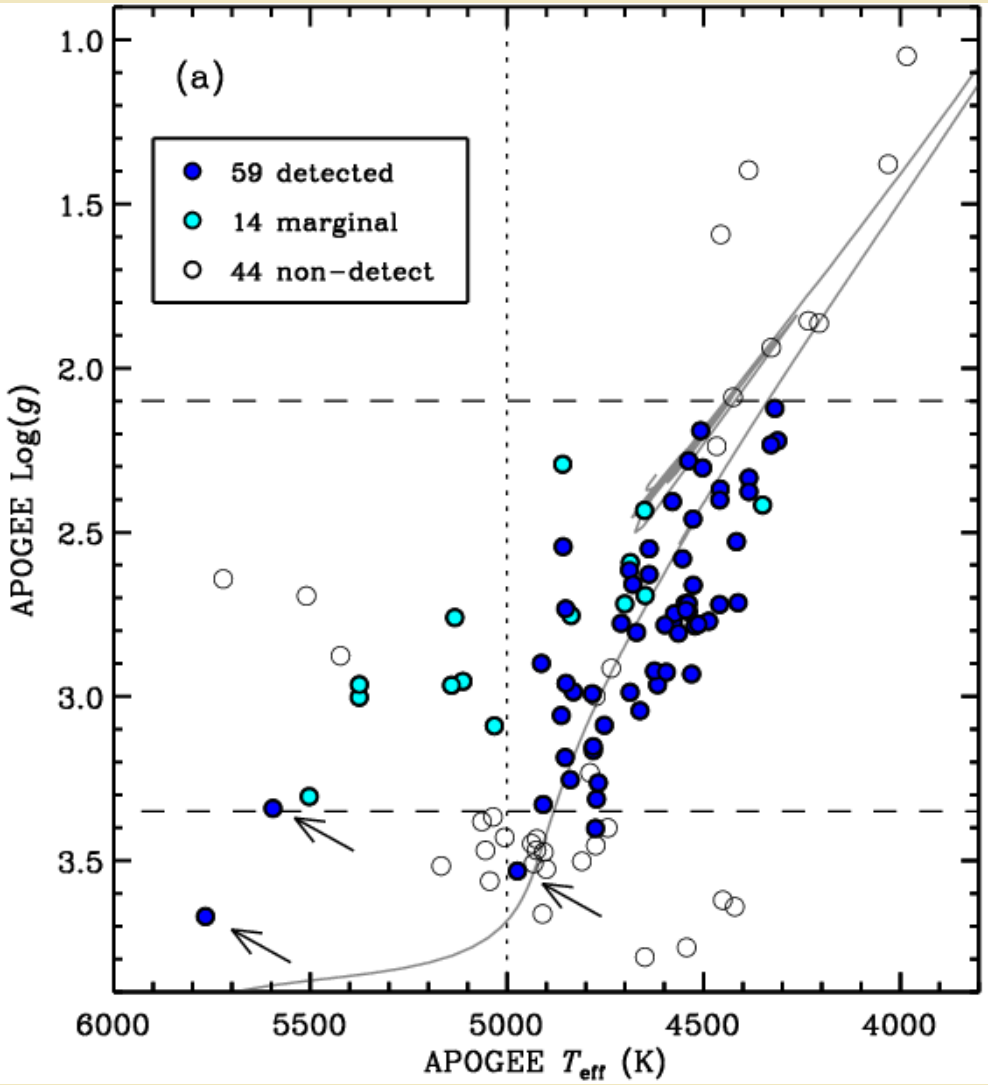
K2 GAP: C1


close−up
Power density (10^3 ppm^2/μHz)
Frequency (μHz)
50
100
150
200
250

K2 GAP: C1

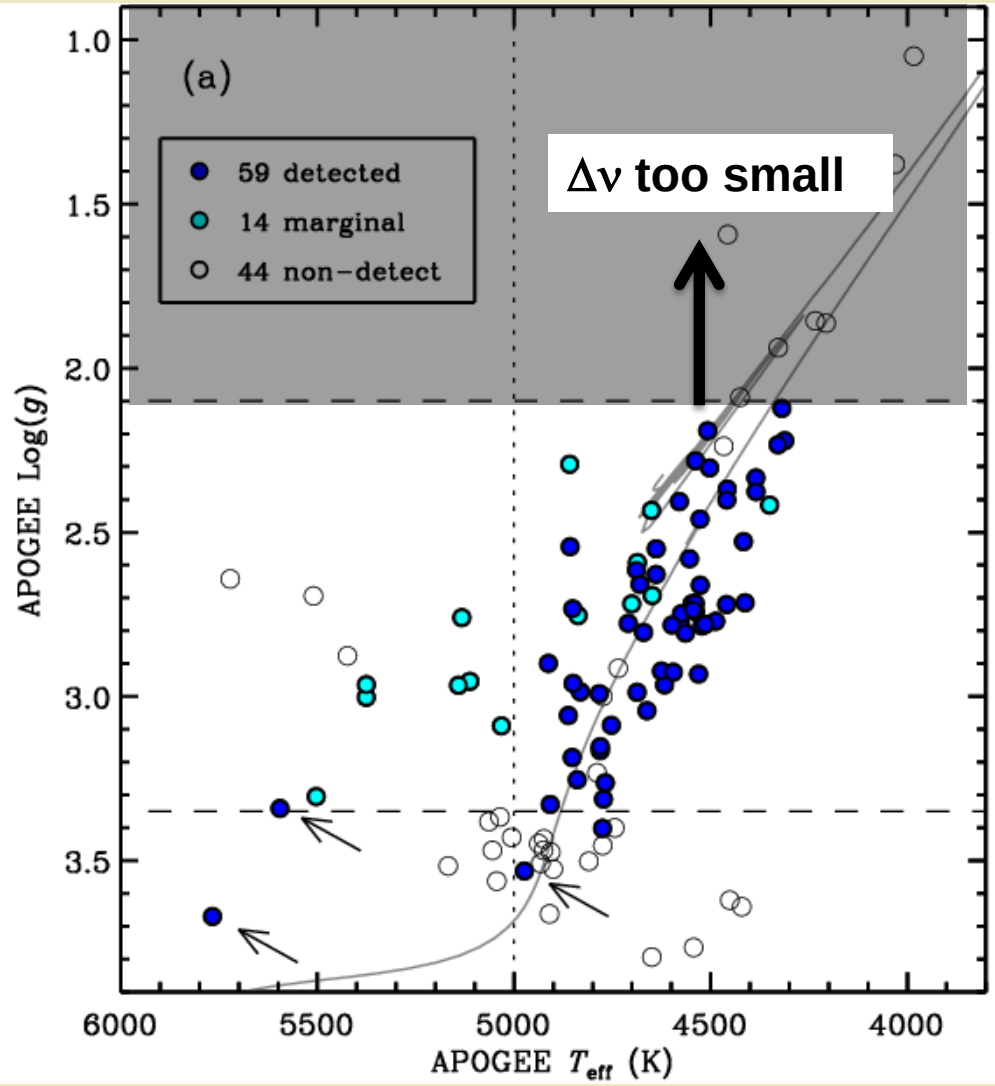

close−up
Power density (10^3 ppm^2/μHz)
Frequency (μHz)
Power
Frequency (microHz)
0
1
2

K2 GAP: C1

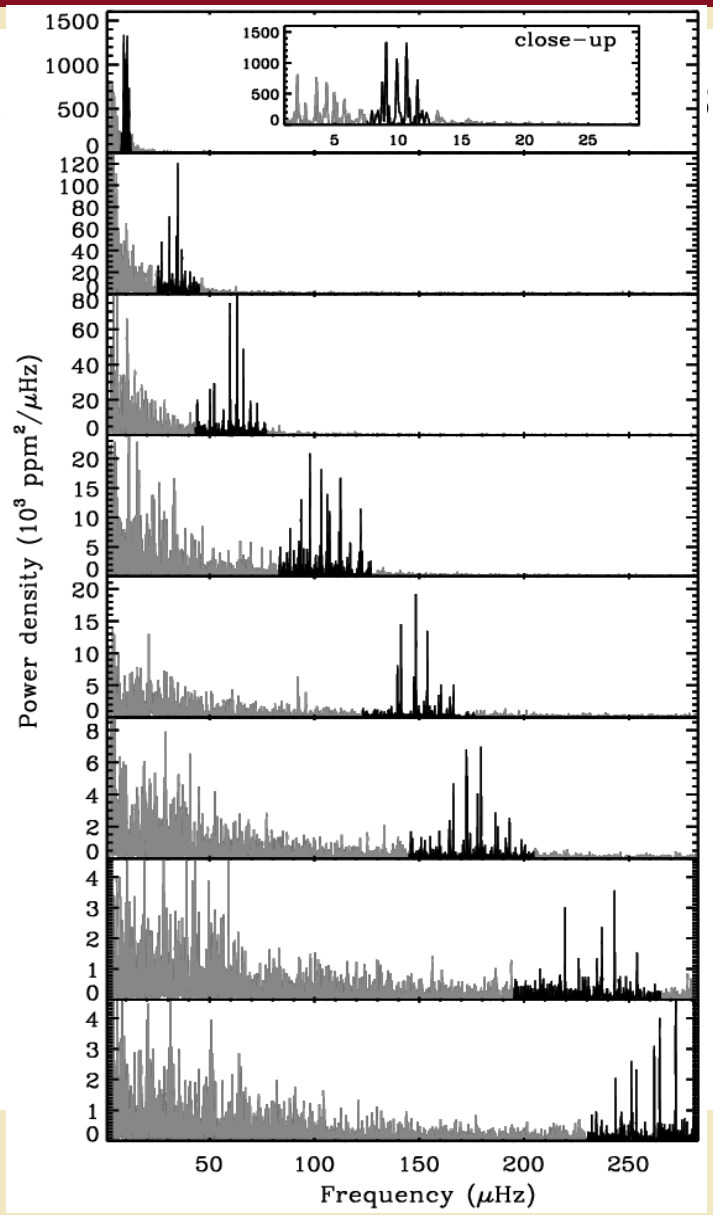


- **117 stars: APOGEE log(g) < 3.8**

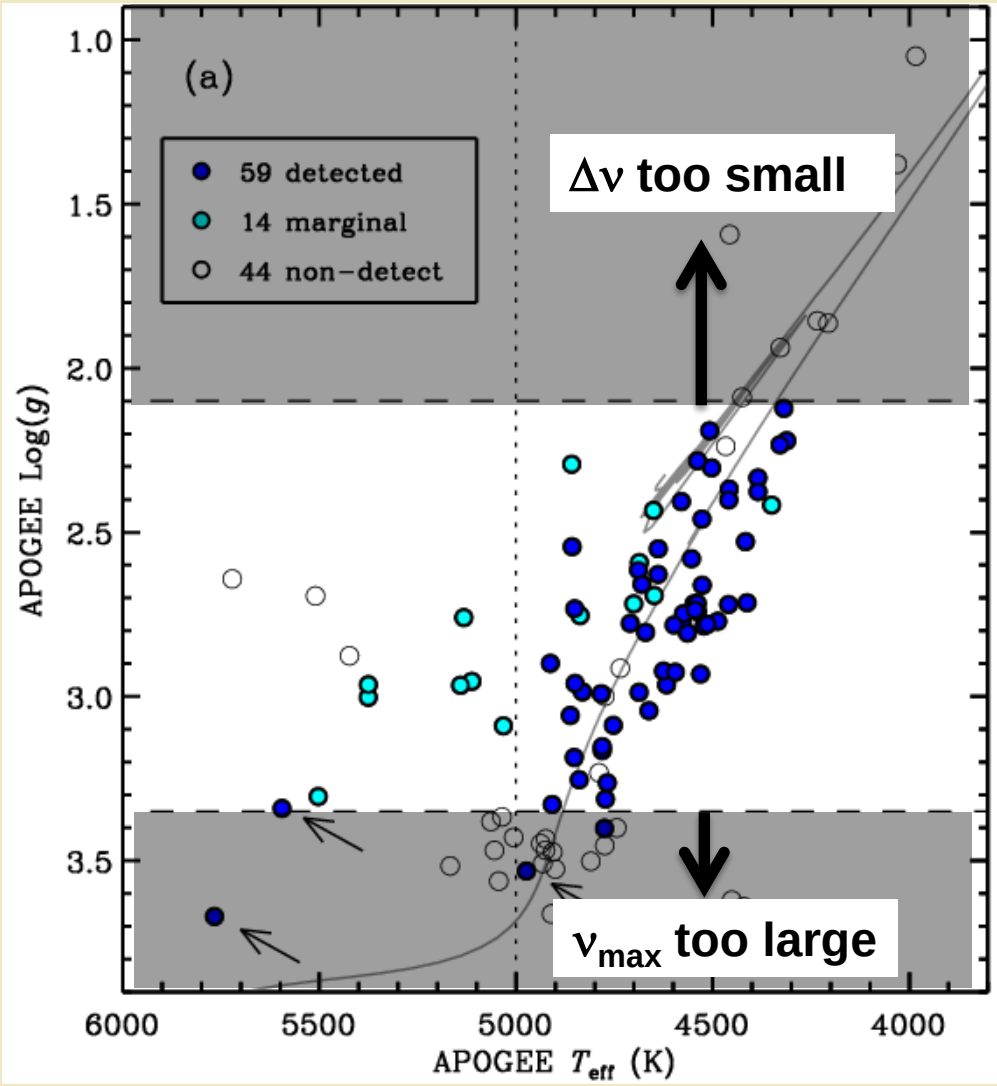
K2 GAP: C1


(a)
59 detected
14 marginal
44 non−detect
Δν too small
APOGEE Log(g)
APOGEE T_{eff} (K)
1.0
1.5
2.0
2.5
3.0
3.5
6000
5500
5000
4500
4000

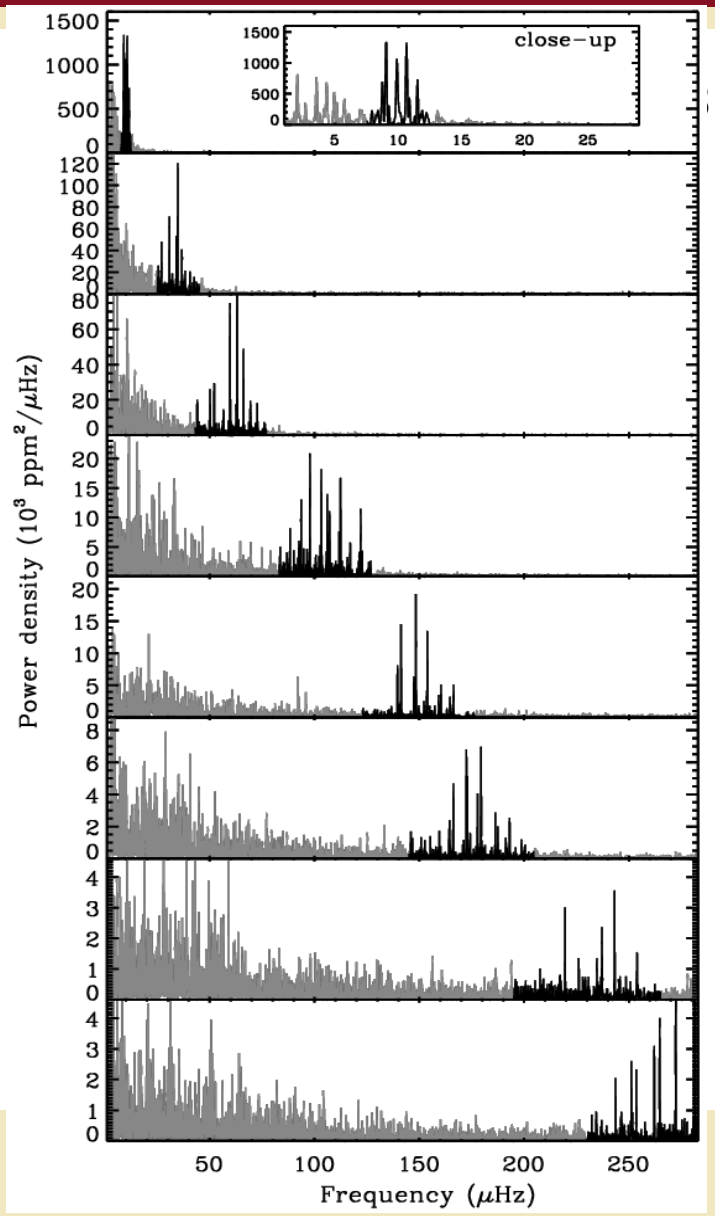
-


close−up
Power density (10^3 ppm^2/μHz)
Frequency (μHz)
50
100
150
200
250

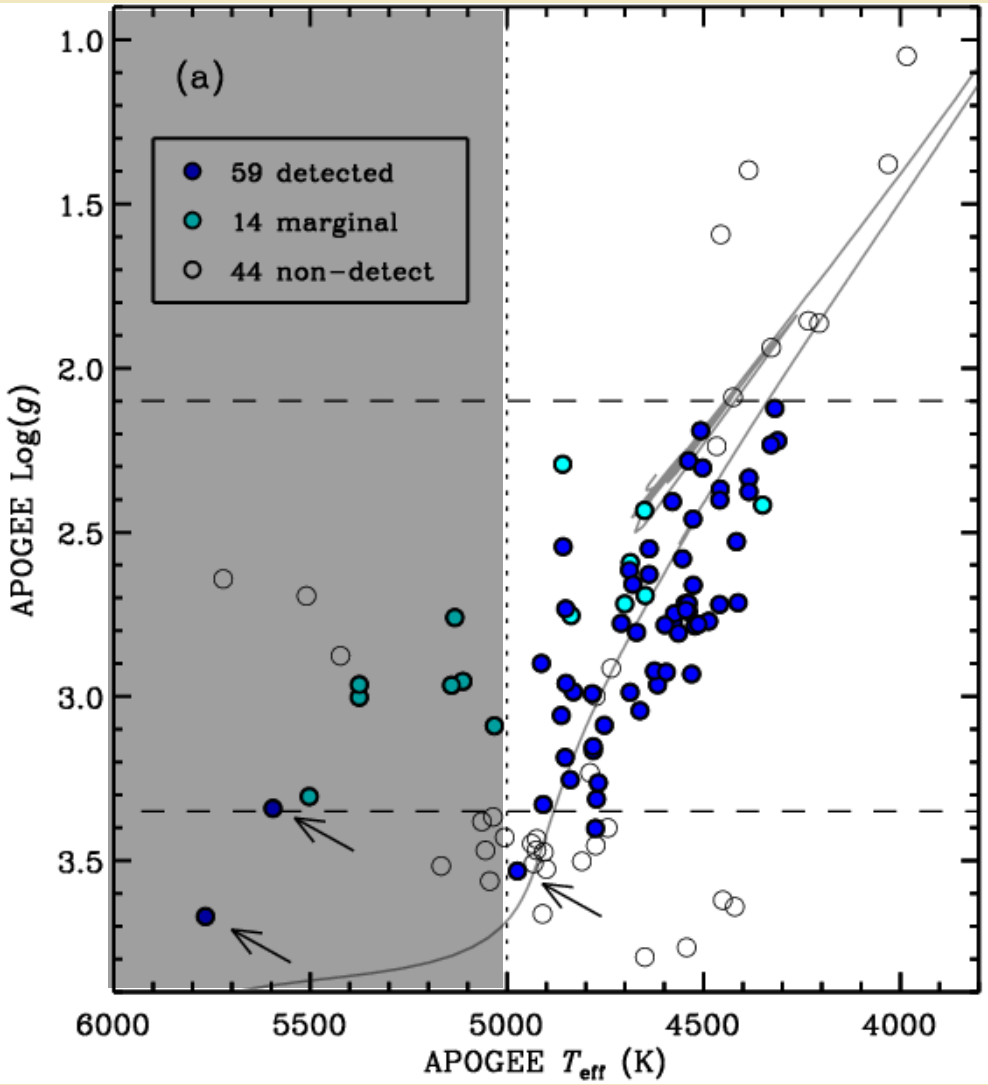
K2 GAP: C1

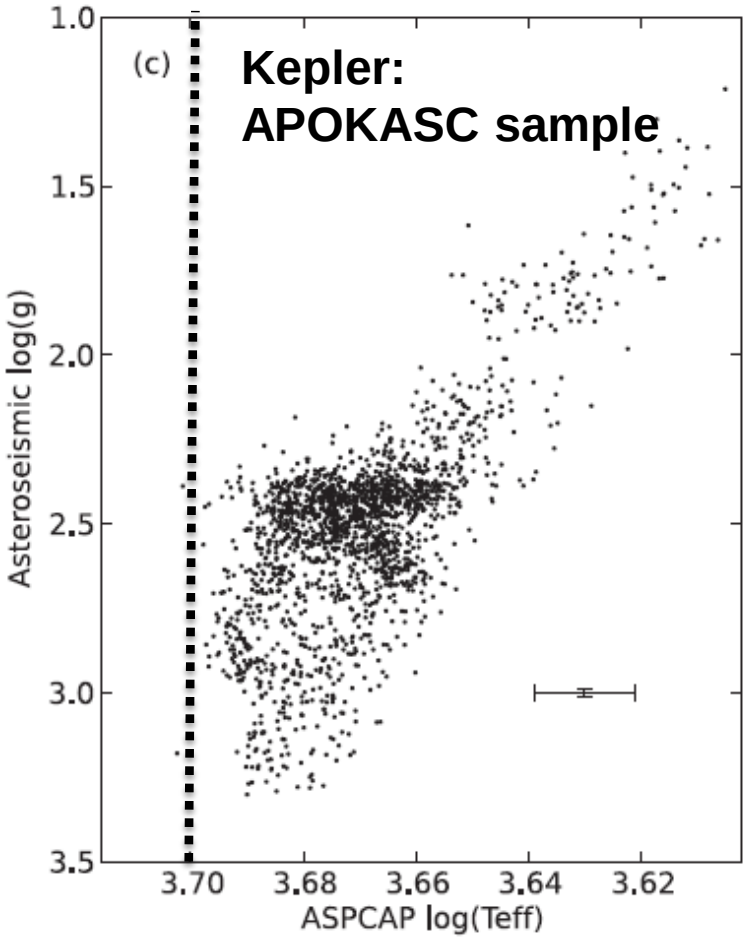

(a)
59 detected
14 marginal
44 non−detect
Δν too small
ν_max too large
APOGEE Log(g)
APOGEE T_eff (K)
1.0
1.5
2.0
2.5
3.0
3.5
6000
5500
5000
4500
4000

-

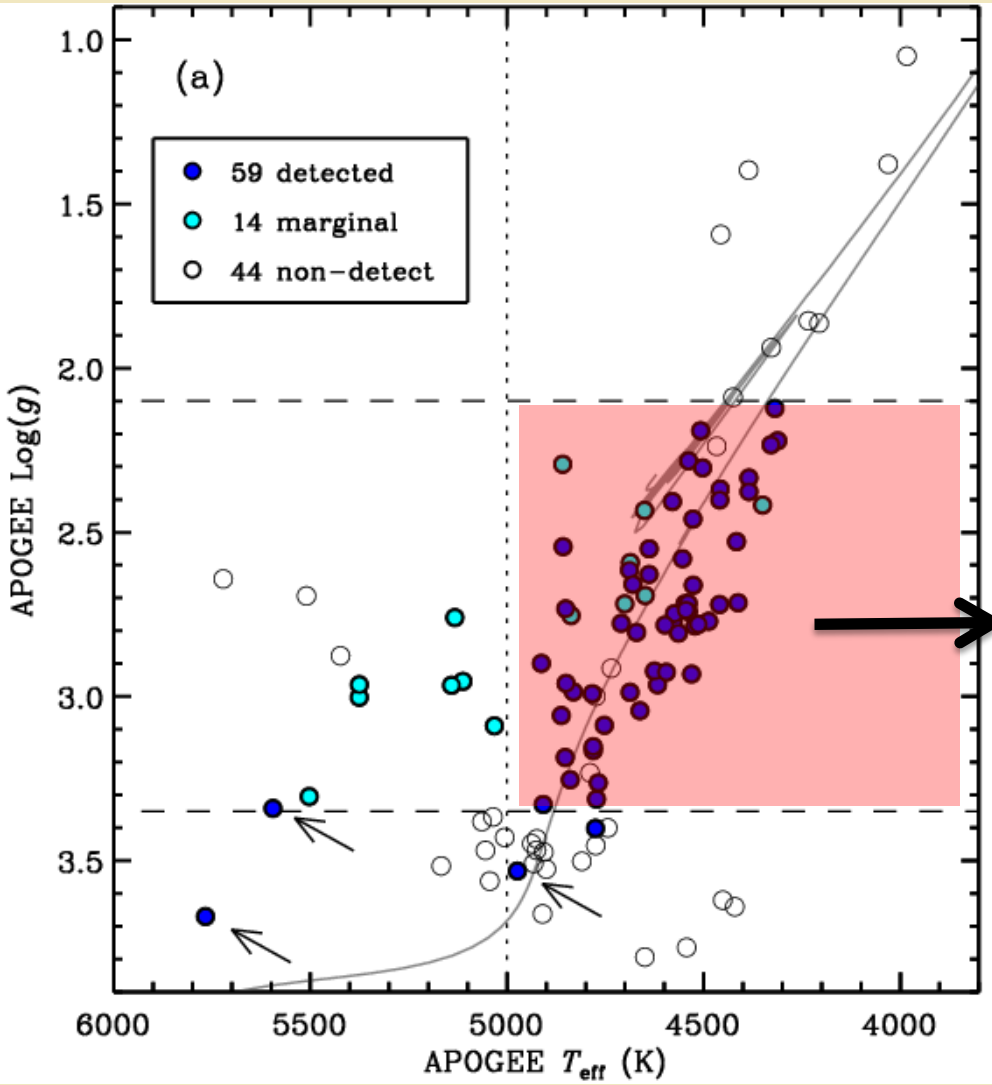

close−up
Power density (10³ ppm²/μHz)
Frequency (μHz)
50
100
150
200
250

K2 GAP: C1


(a)
59 detected
14 marginal
44 non−detect
APOGEE Log(g)
APOGEE T_{eff} (K)
1.0
1.5
2.0
2.5
3.0
3.5
6000
5500
5000
4500
4000

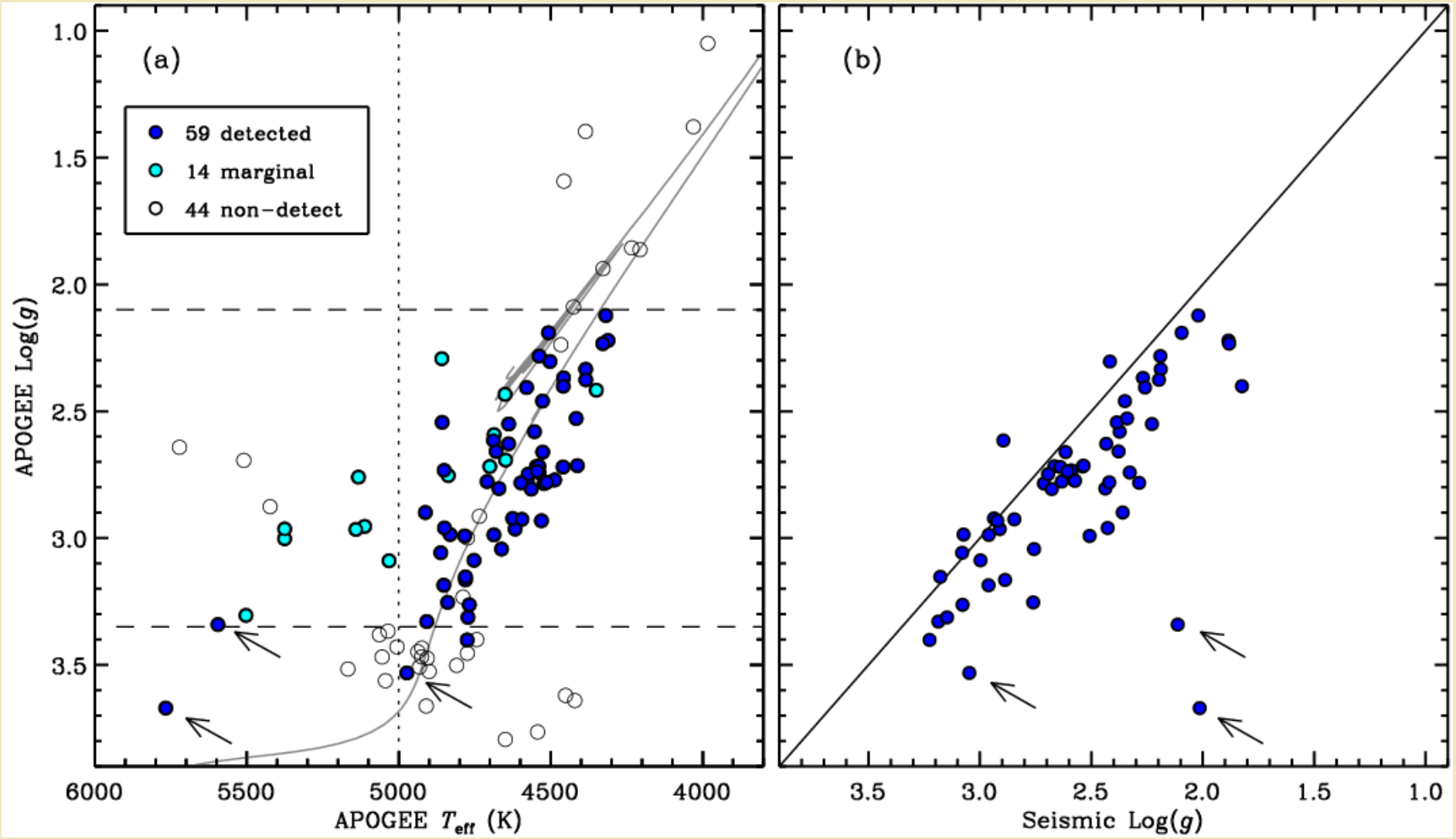

(c)
Kepler:
APOKASC sample
Asteroseismic log(g)
ASPCAP log(Teff)
1.0
1.5
2.0
2.5
3.0
3.5
3.70
3.68
3.66
3.64
3.62

K2 GAP: C1

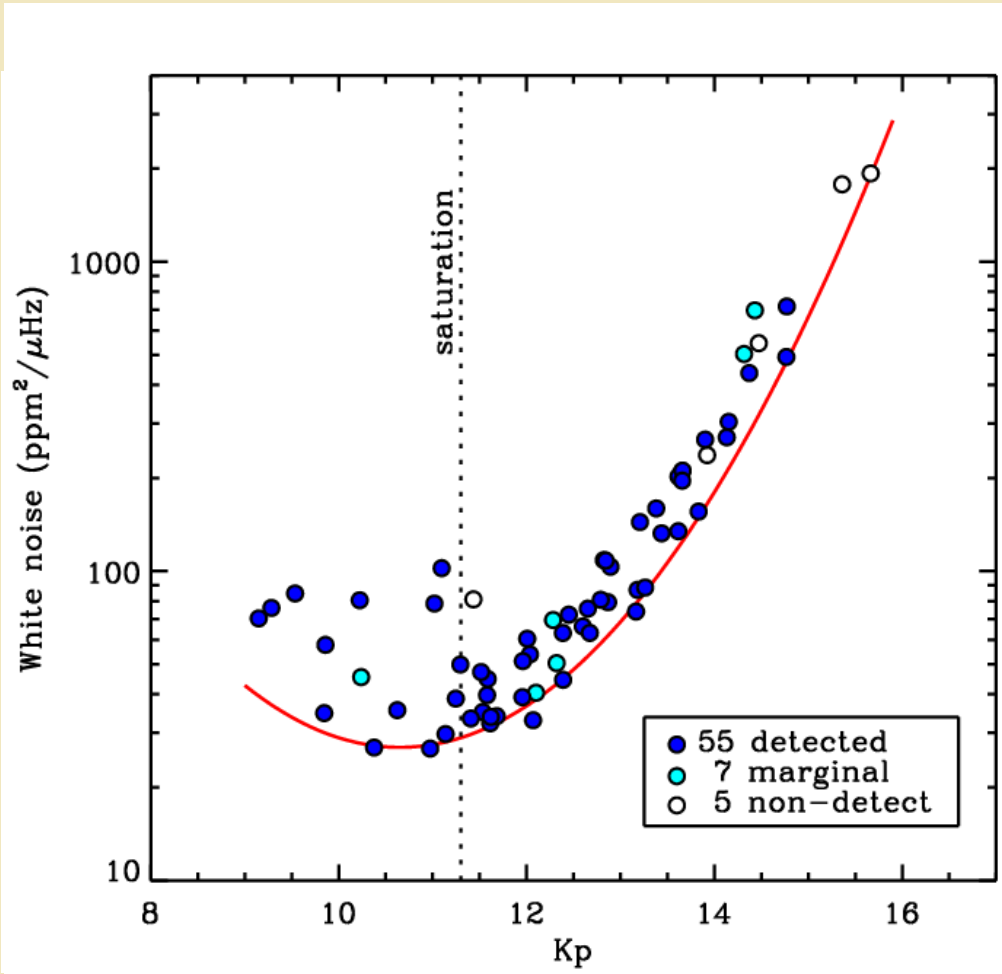


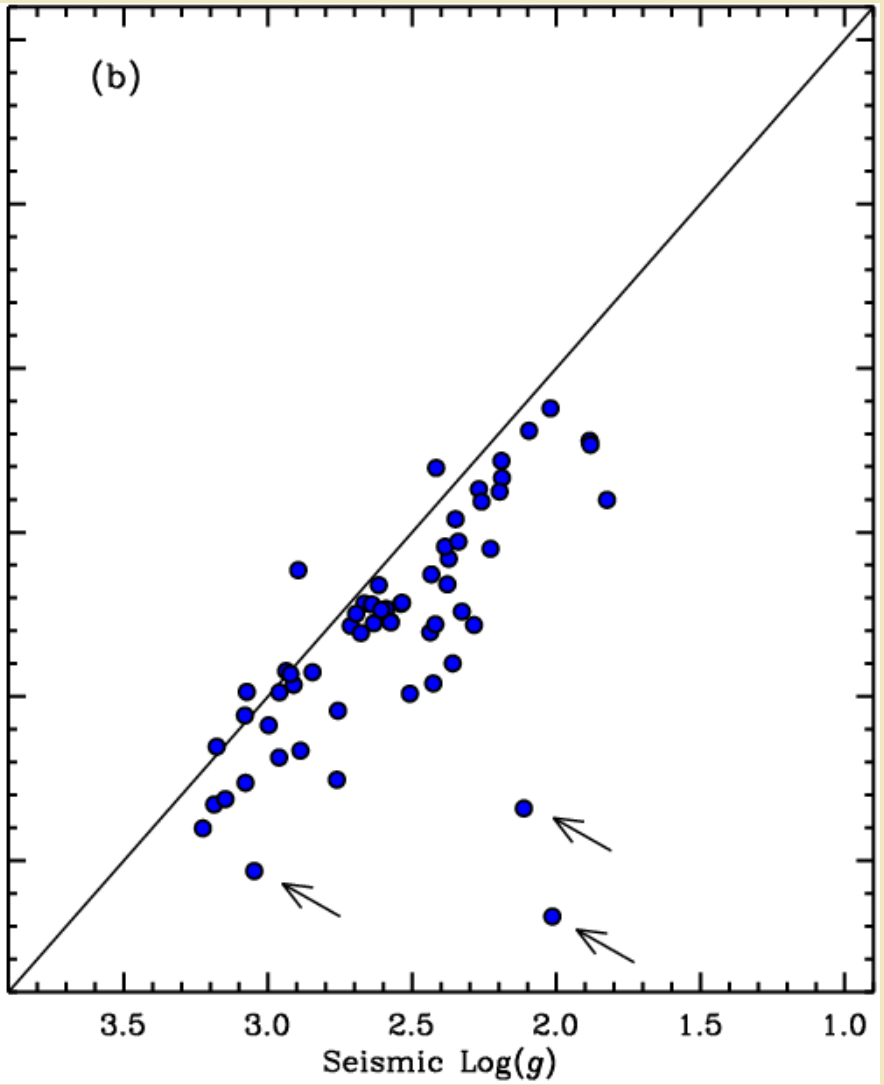
- 67 Stars in total.
- 55 Detected ($\Delta\nu$ and ν_{max}).
- 7 Marginal ($\Delta\nu$ or ν_{max} not clear).
- 5 Non-detected.

K2 GAP: C1

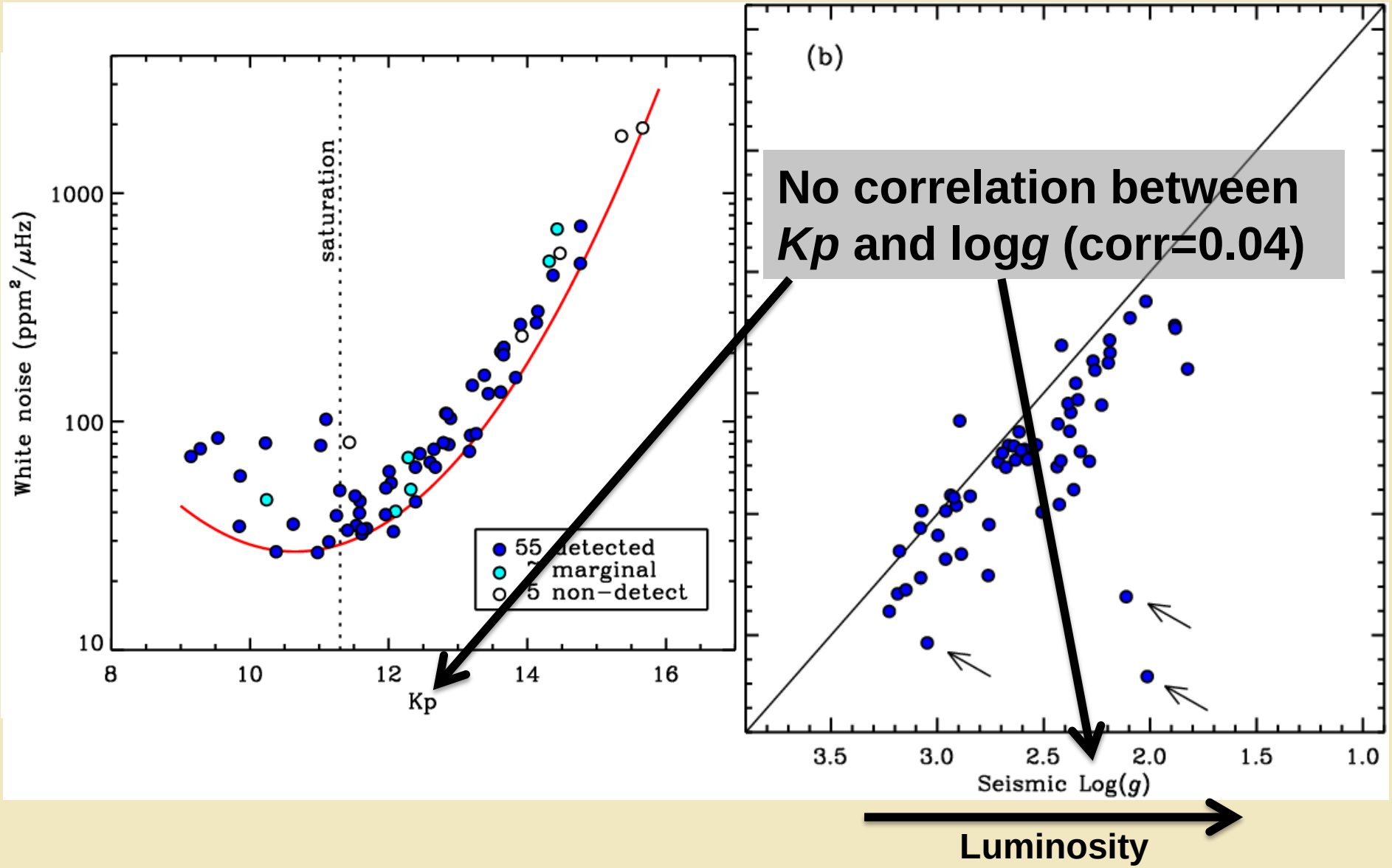

(a)
59 detected
14 marginal
44 non−detect
APOGEE Log(g)
APOGEE T_{eff} (K)
6000
5500
5000
4500
4000
1.0
1.5
2.0
2.5
3.0
3.5
(b)
Seismic Log(g)
3.5
3.0
2.5
2.0
1.5
1.0

K2 GAP: C1

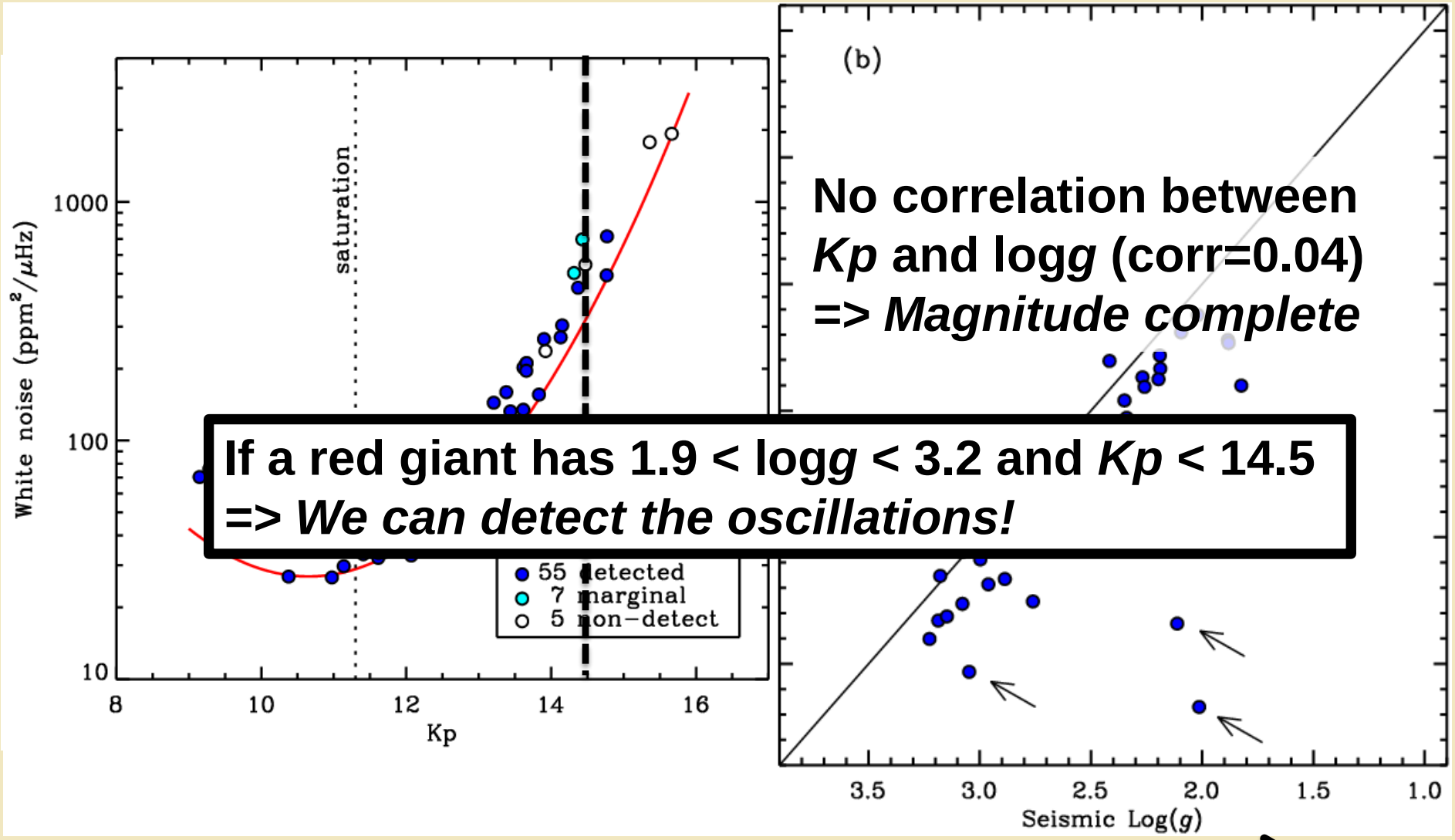

saturation
1000
100
10
White noise (ppm²/μHz)
8
10
12
14
16
Kp
55 detected
7 marginal
5 non−detect


(b)
3.5
3.0
2.5
2.0
1.5
1.0
Seismic Log(g)

K2 GAP: C1


(b)
No correlation between
Kp and log*g* (corr=0.04)
saturation
White noise (ppm²/μHz)
1000
100
10
8
10
12
14
16
Kp
55 detected
marginal
5 non−detect
3.5
3.0
2.5
2.0
1.5
1.0
Seismic Log(g)
Luminosity

K2 GAP: C1



No correlation between *Kp* and log*g* (corr=0.04)
=> *Magnitude complete*

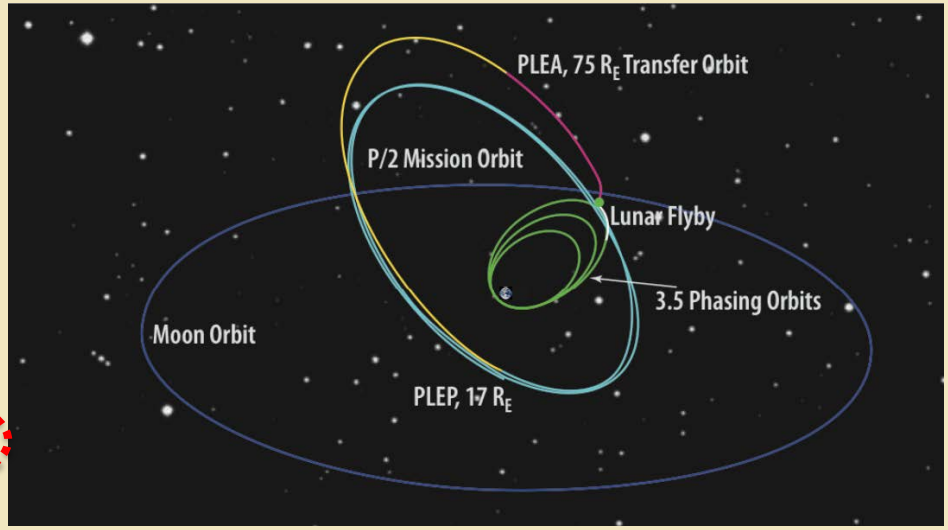
If a red giant has 1.9 < log*g* < 3.2 and *Kp* < 14.5
=> *We can detect the oscillations!*

Luminosity

TESS: 2017-2019+

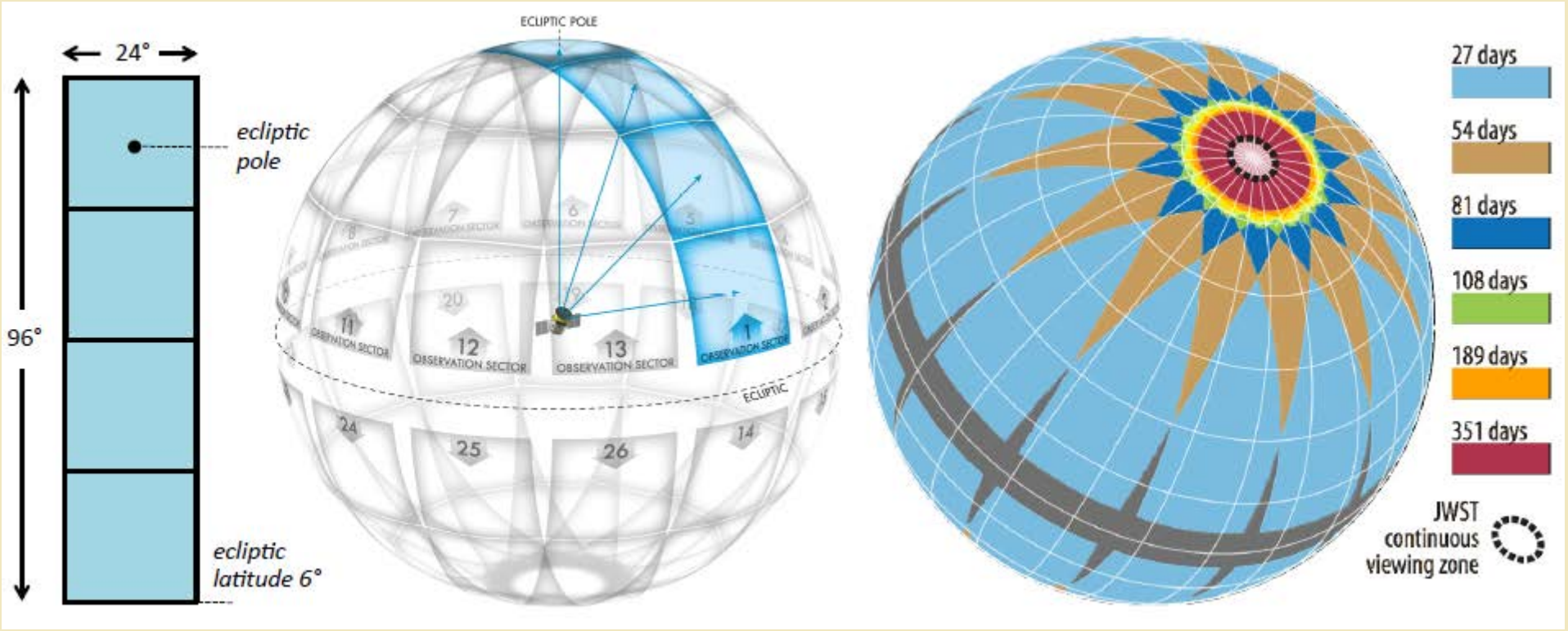
- **Primary Goal:** Discover Transiting Earths and Super-Earths Orbiting Bright, Nearby Stars
  - Rocky Planets & Water Worlds
  - Habitable planets
- Discover the "Best" ~1000 **Small** Exoplanets
  - "Best" means "Readily characterizable"
  - Measurable mass & atmospheric properties

- **Large Area Survey of Bright Stars**
  - F, G, K dwarfs: +4 to +12 magnitude
  - M dwarfs known within ~60 parsecs
  - "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



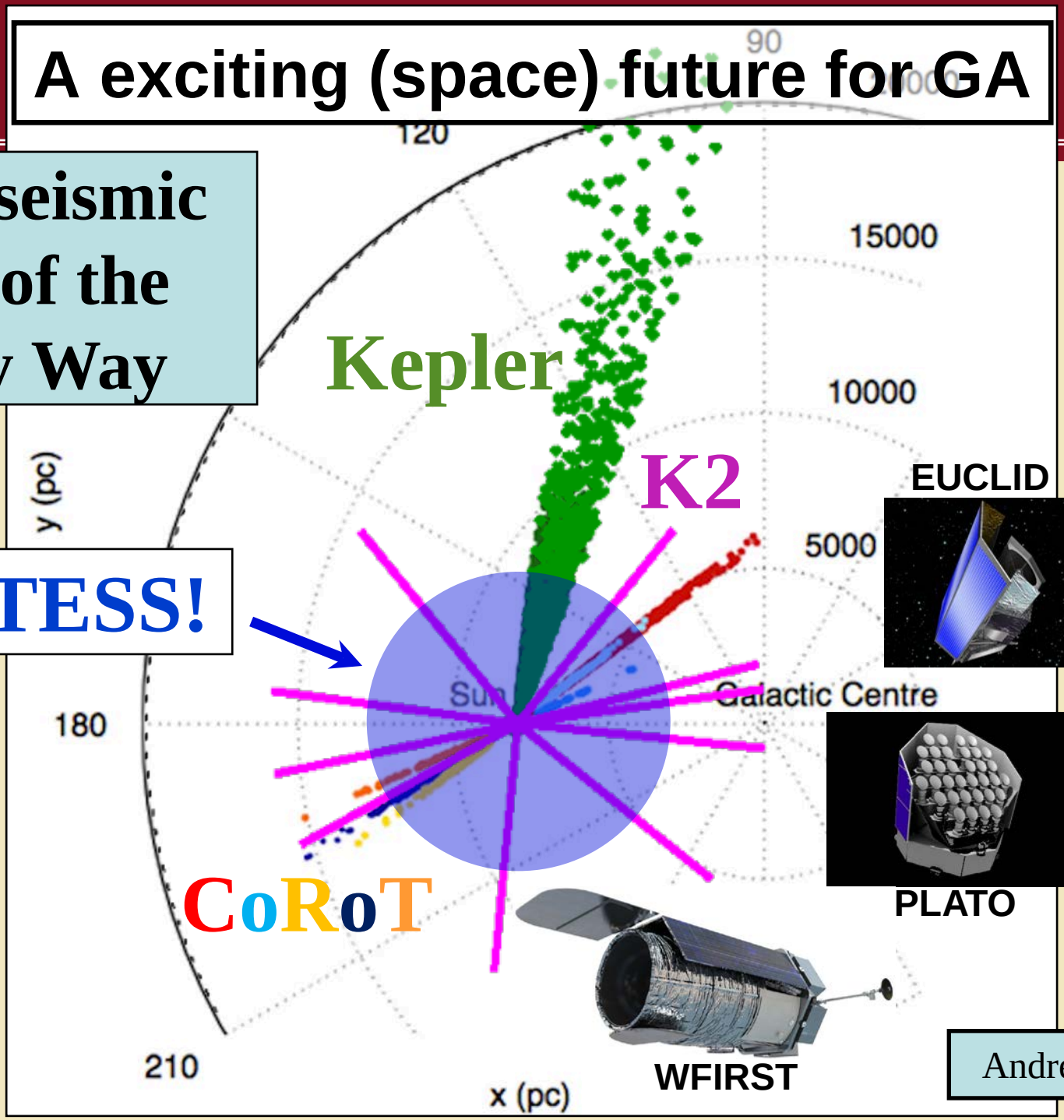
TESS: 2017-2019+

All-sky observing strategy



A exciting (space) future for GA

Asteroseismic View of the Milky Way



Andrea Miglio