UNIVERSITY OF BIRMINGHAM | SCHOOL OF PHYSICS AND ASTRONOMY

Asteroseismic Peak-Bagging

State of the Art and Planned Development

MILAZZO, MAY 2018

GUY R. DAVIES

Outline of work - Pipeline

WP128

- Identification of eclipse signals
- Modelling and removal of eclipse signals
- Filtering of L1 light curves
- Detection and characterisation of gaps
- Interpolation to fill gaps

- Detection of solar-like oscillations
- Extraction of global asteroseismic parameters
- Preparation for peak-bagging
- Peak-bagging
- Quality control for peak-bagging

e.g., Handberg & Lund 2015

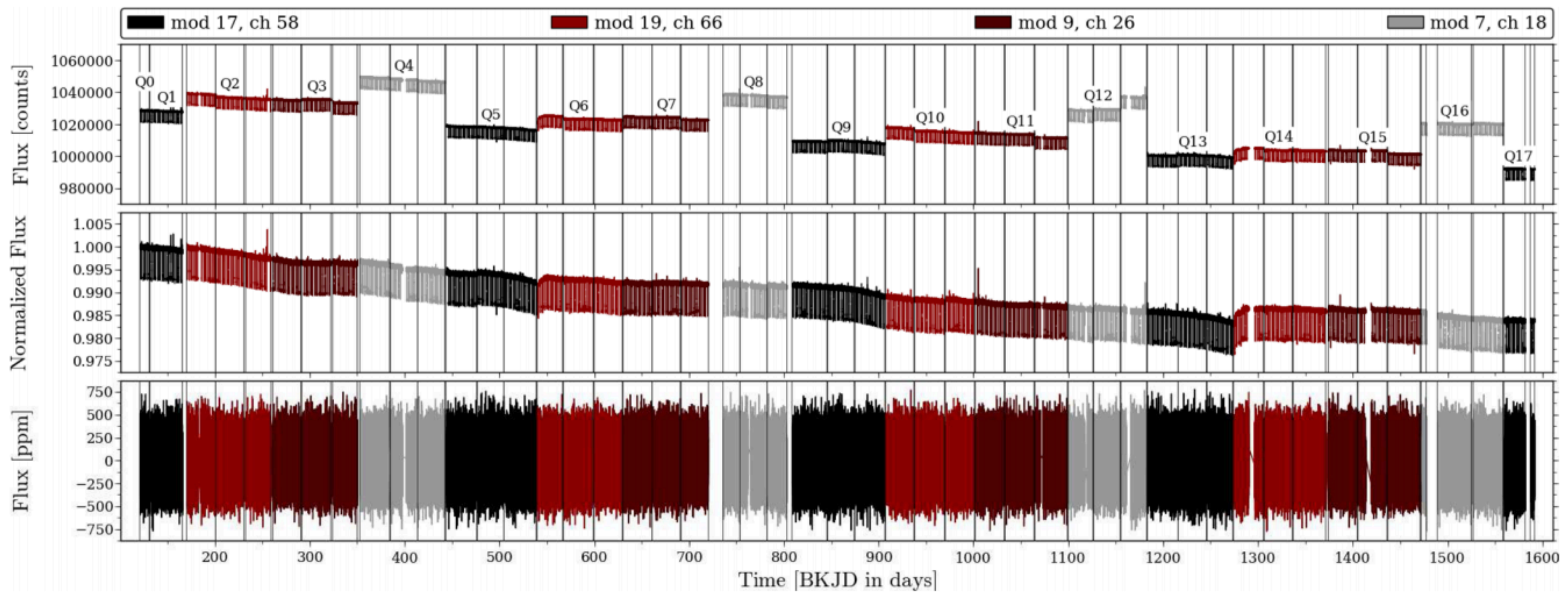
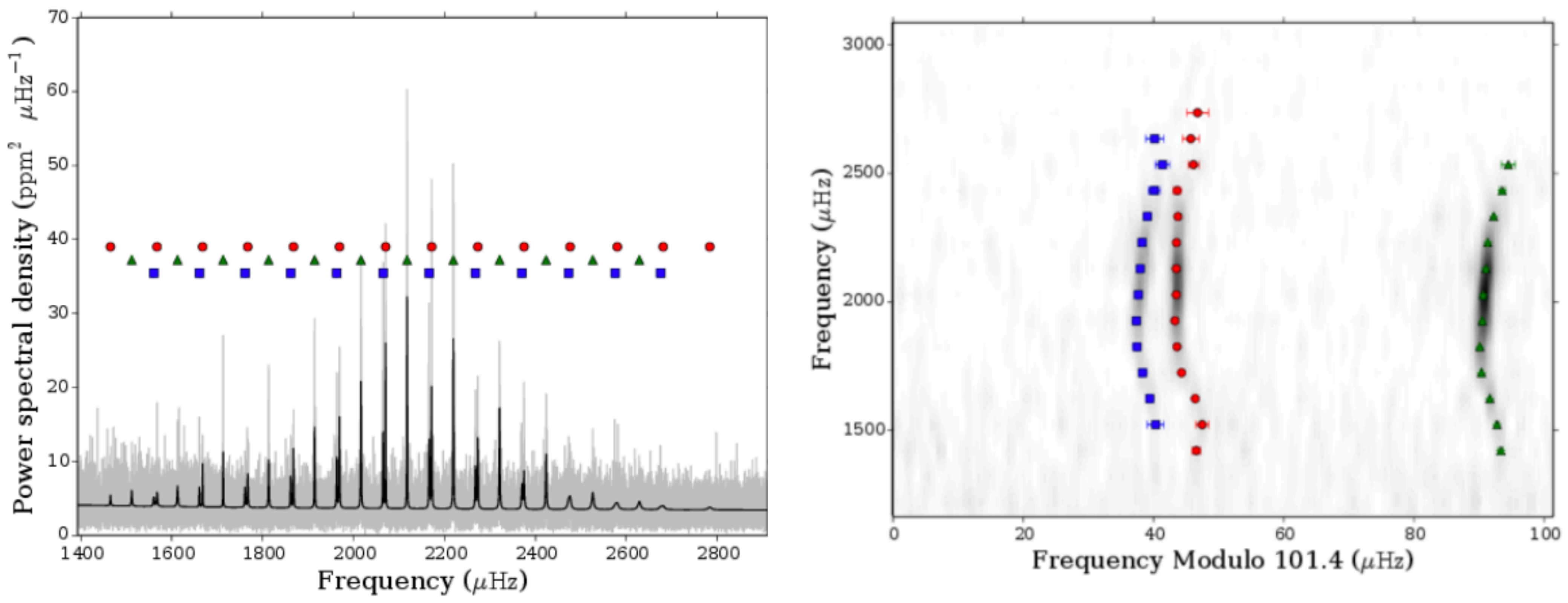


Figure 4. *Kepler* time series for HAT-P-7. Top: initial time series after removal of bad data points. Indicated is the quarter designation with the vertical lines giving the start and end times for the sub-quarters. The different colouring gives the position of HAT-P-7 with respect to the *Kepler* CCD module (mod) and channel (ch). Middle: stitched light curve from following the procedure outlined in Step 3 of Section 2. Bottom: final corrected light curve ready of asteroseismic analysis after applying all steps of Section 2.

e.g., Davies, Silva Aguirre,+ 2016



Calls for participation

WP128

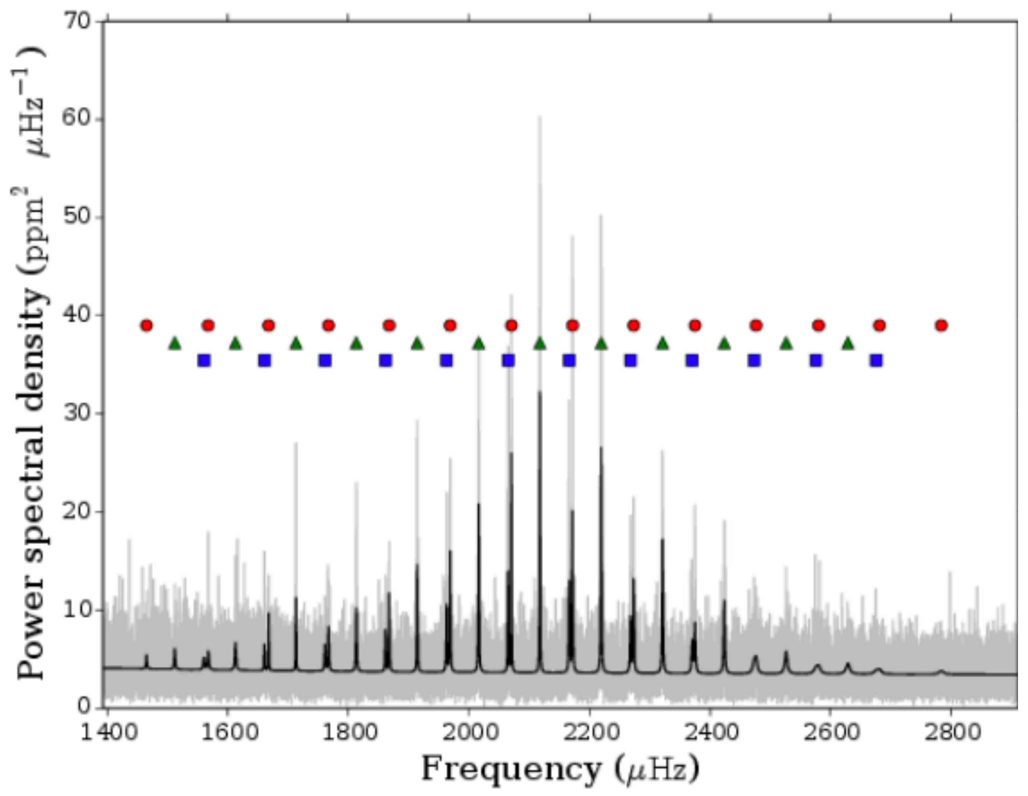
Short Cadence
MS/SG

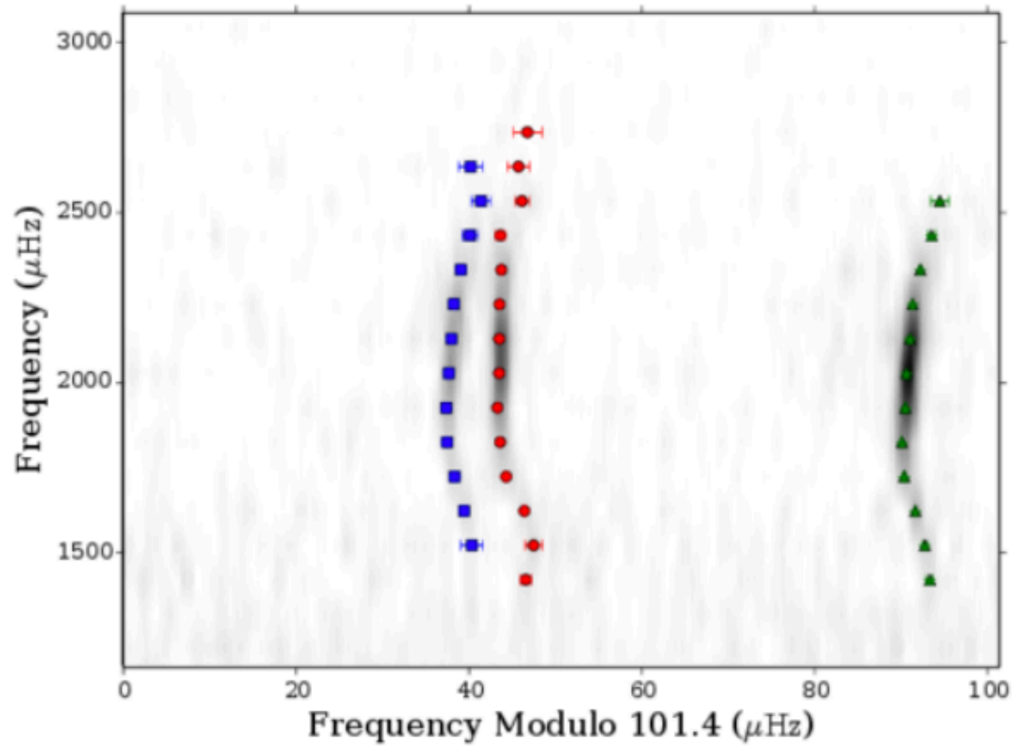
Long Cadence
SG/RG

- Detection of solar-like oscillations
- Extraction of global asteroseismic parameters
- Preparation for peak-bagging
- Peak-bagging
- Quality control for peak-bagging

Part 1 - Participant led analysis on 20 Kepler stars

Part 2 - Automated analysis on 40 Kepler stars





Outline of work - Timeline

WP128

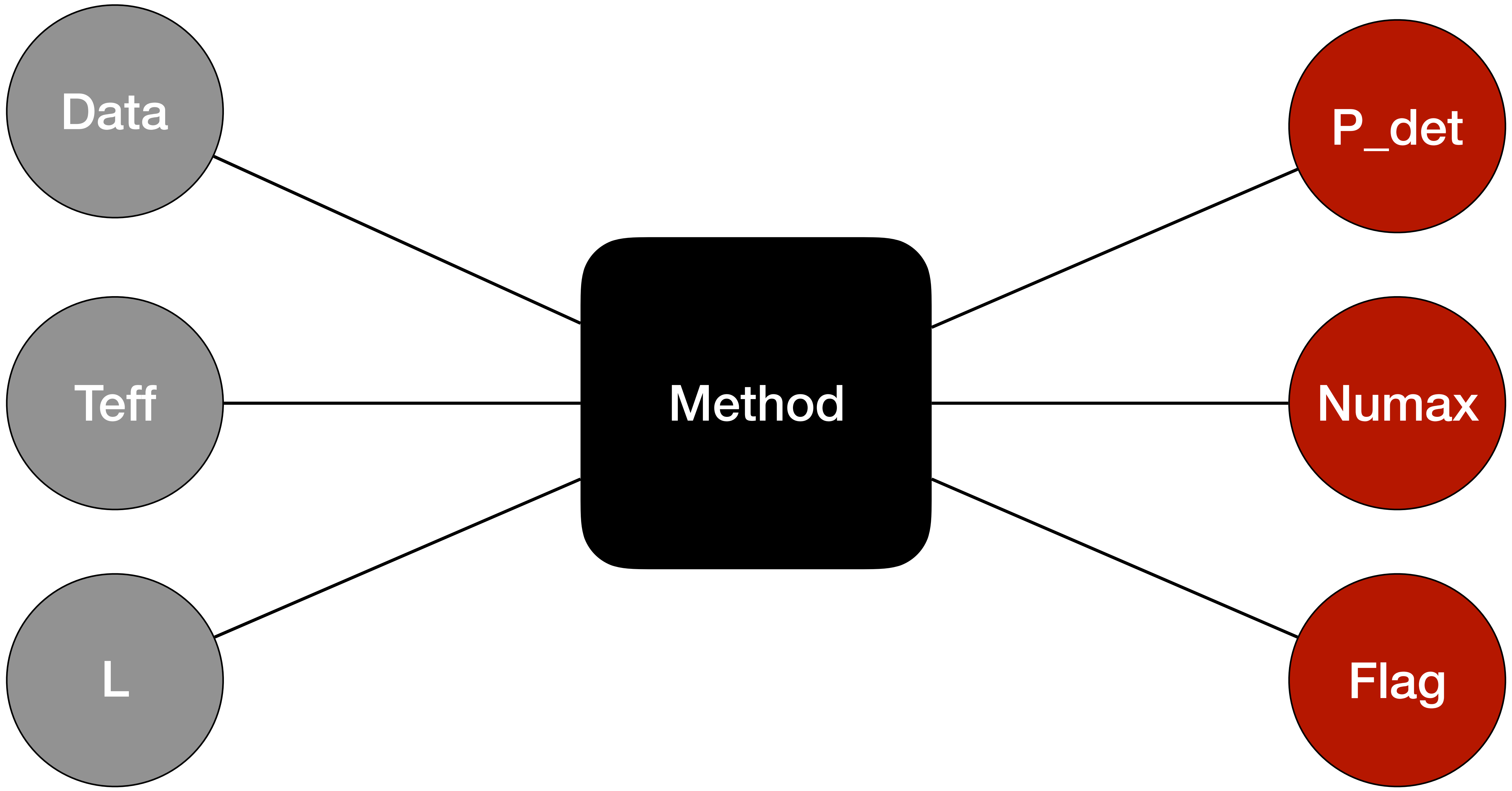
Short Cadence
MS/SG

- i) Announce opportunity to participate and ask for expressions of interest
- ii) Begin Part 1 (June)
- iii) Deadline for Part-1 submission of results (beginning September)
- iv) Deadline for Part-2 submission of codes (beginning September)
- v) Analysis by WP128 leads of Part 1 results (September)
- vi) Preparation for running codes for Part 2 (September)
- vii) Analysis of results from Part 2 (October)
- viii) Engagement/discussion: Feedback on results, lessons learned (November/December)

Long Cadence
SG/RG

Detection of S-L Oscillations

WP128



Detection of S-L Oscillations

WP128

8 HON ET AL.

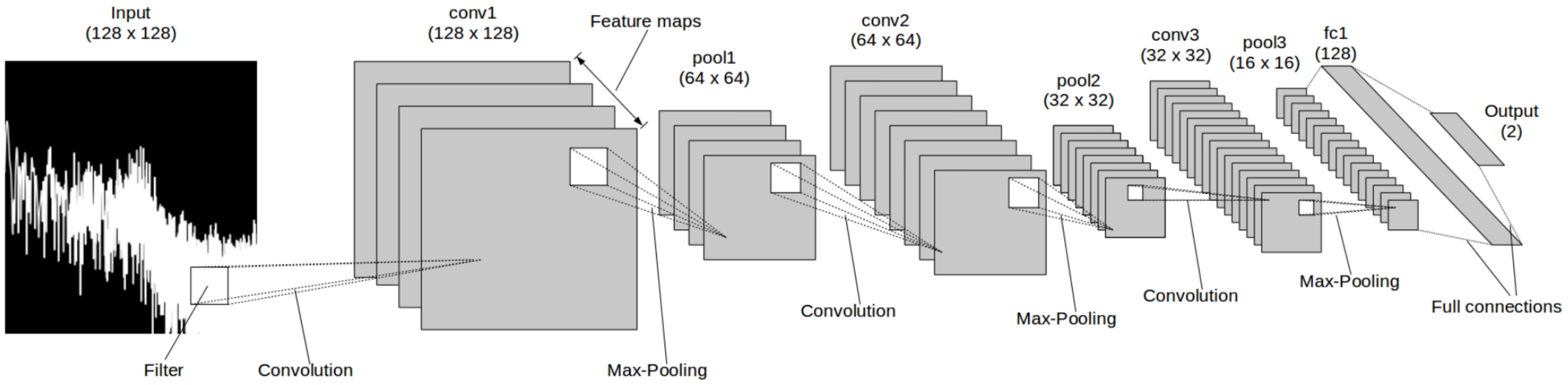
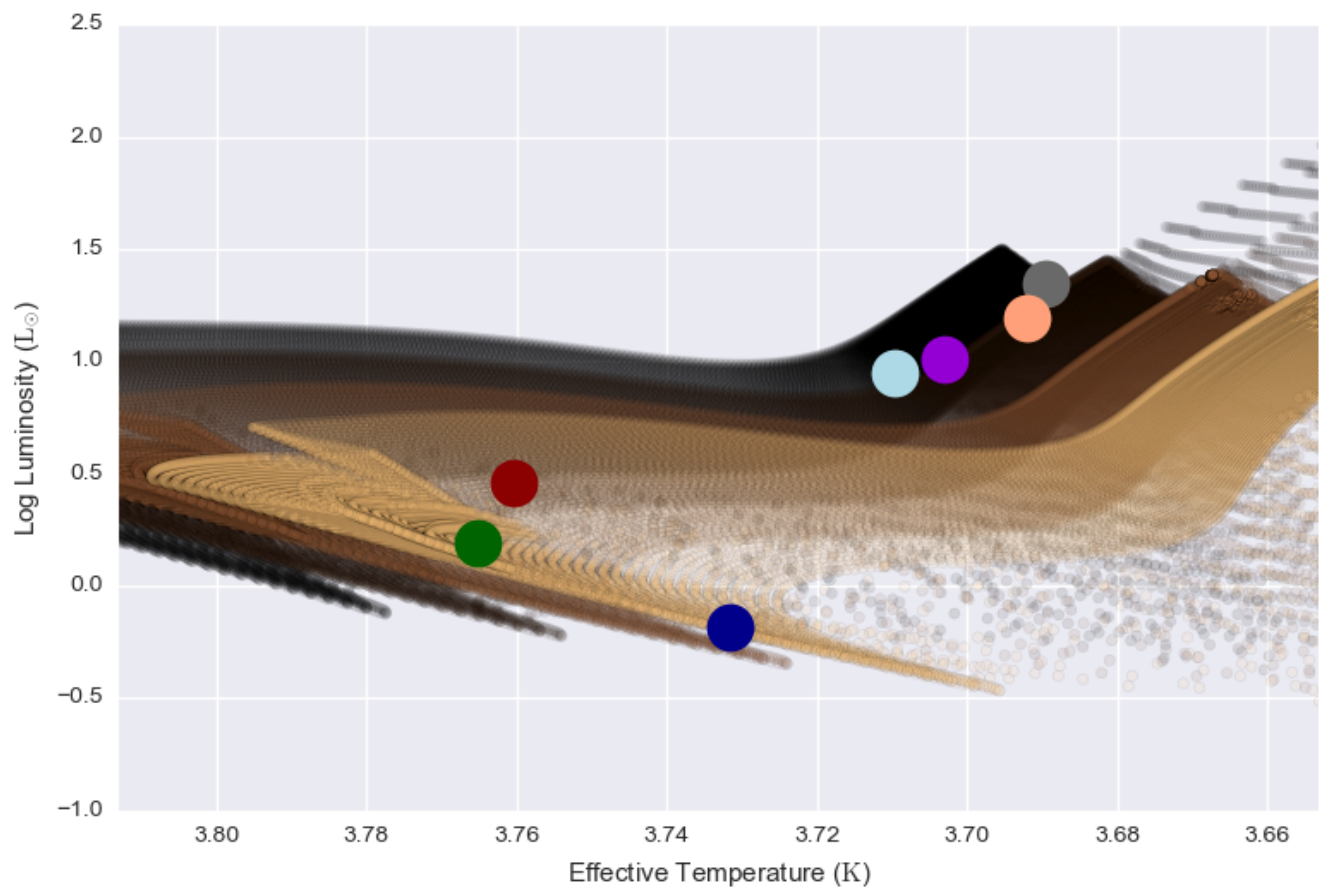
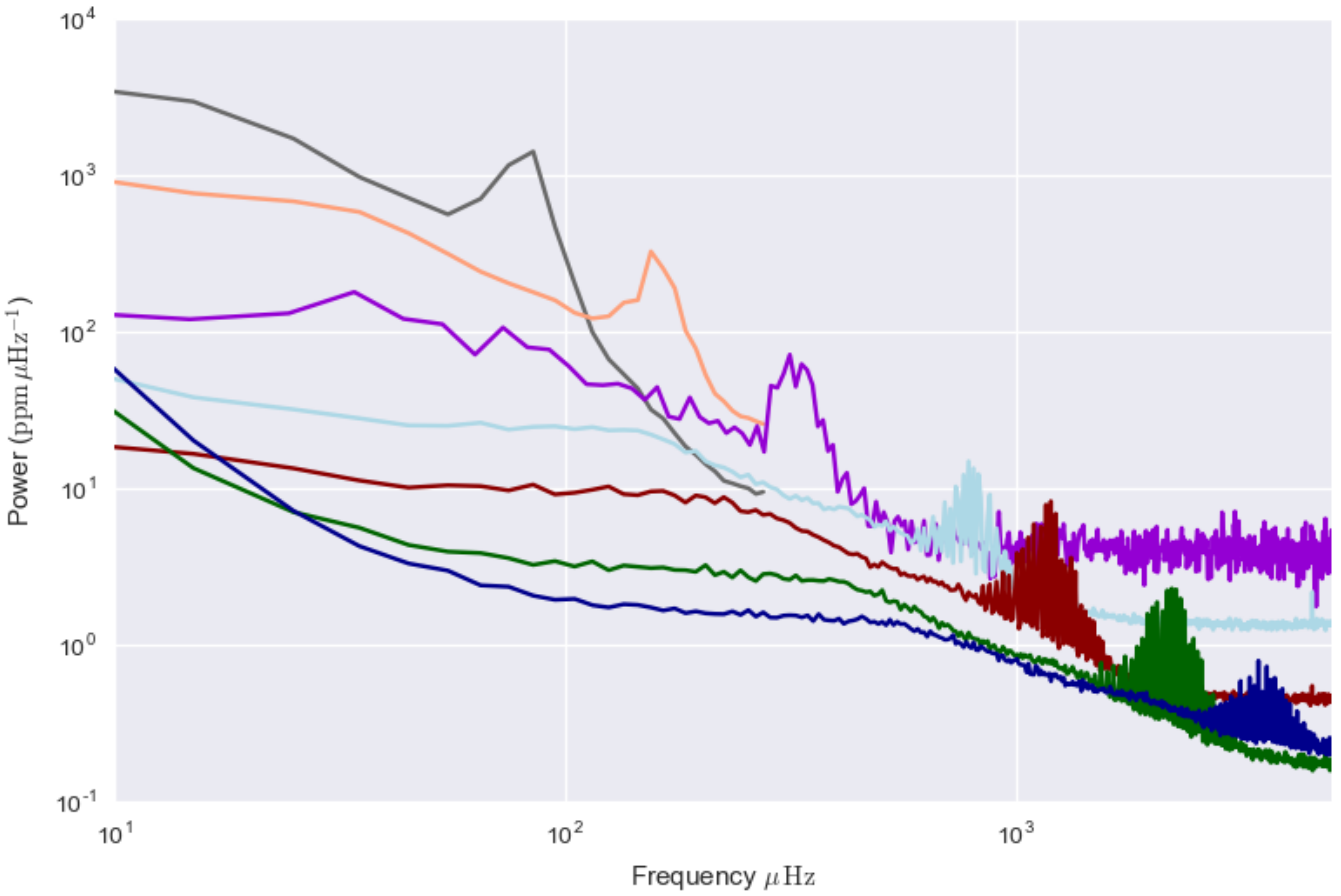


Figure 5. Schematic for the 2D convolutional neural network classifier. For convolutional (conv) and pooling (pool) layers, the values in brackets indicate the dimension of each feature map, while for fully-connected (fc) layers, they indicate the number of neurons within that layer.

Detection of S-L Oscillations

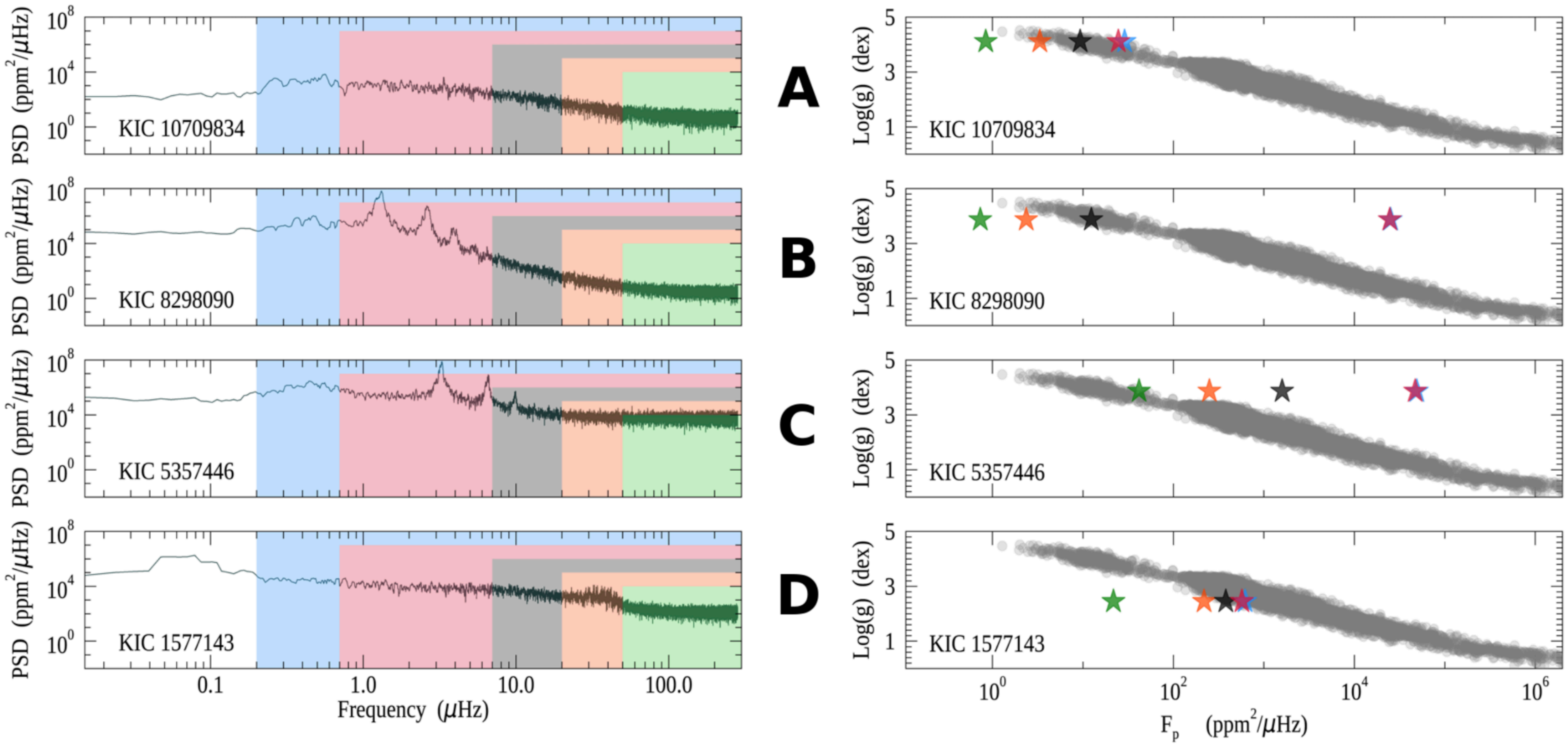
WP128

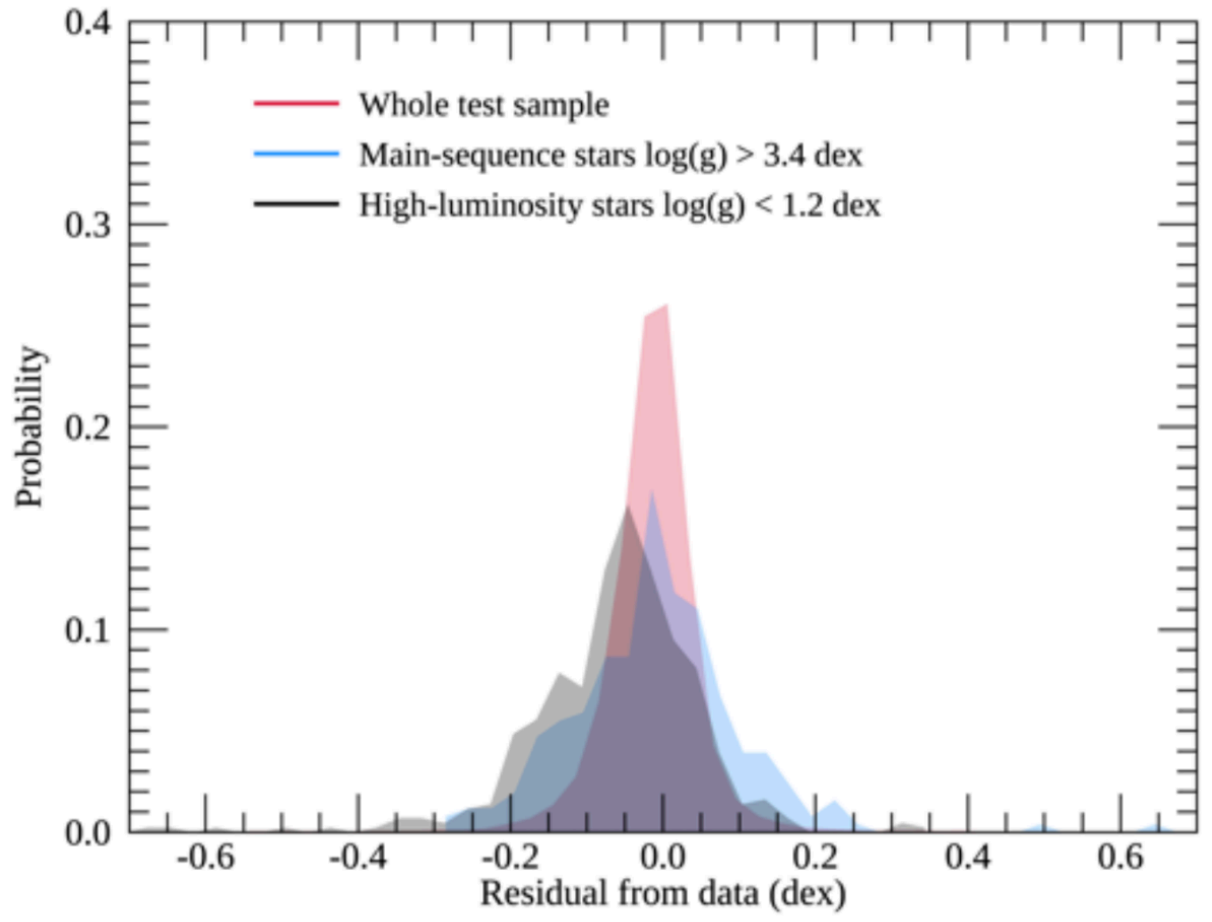




Detection of S-L Oscillations

WP128

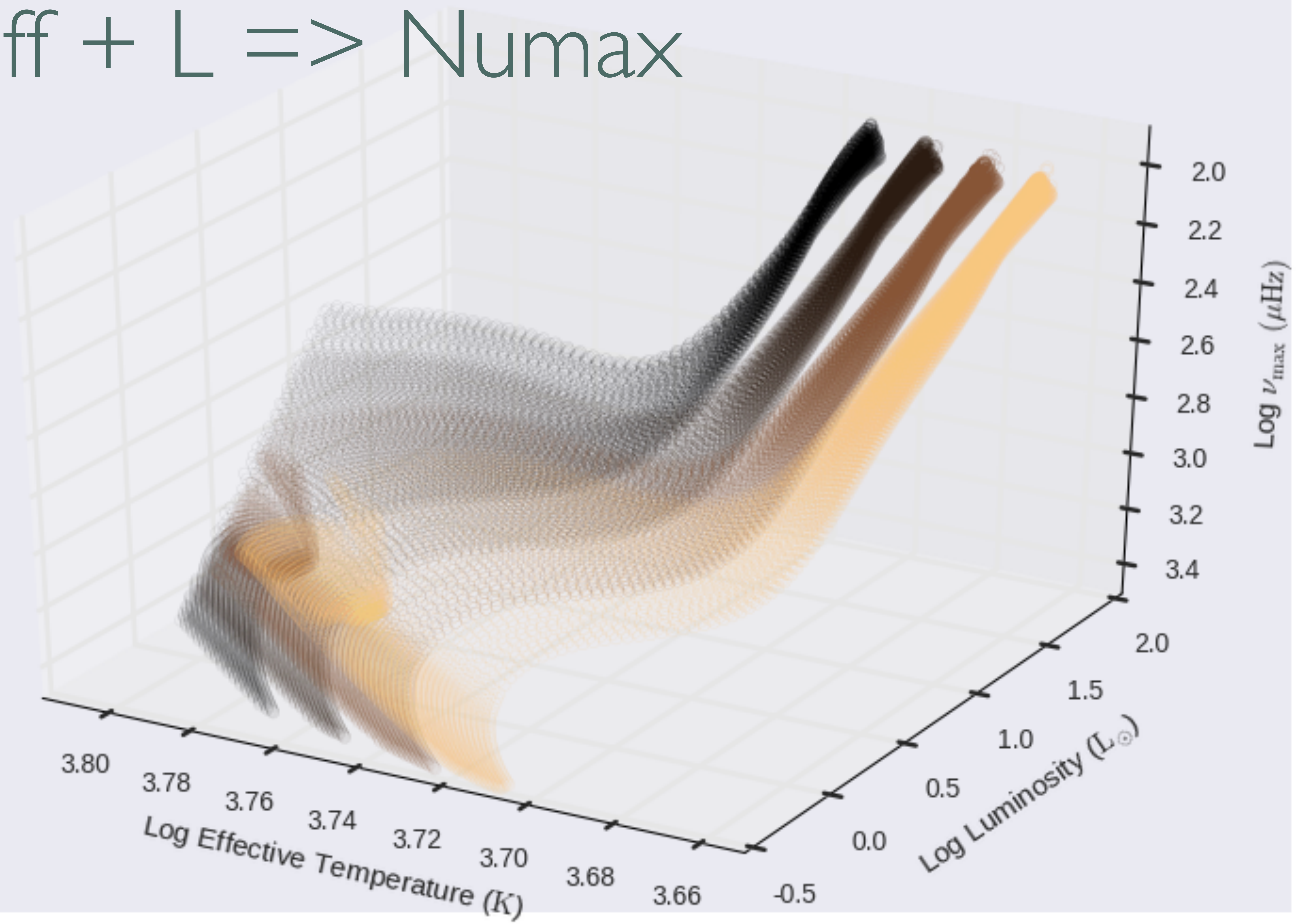




Bugnet, Garcia, Davies, + Submitted

See also, Bastien, Kallinger, Ness, etc

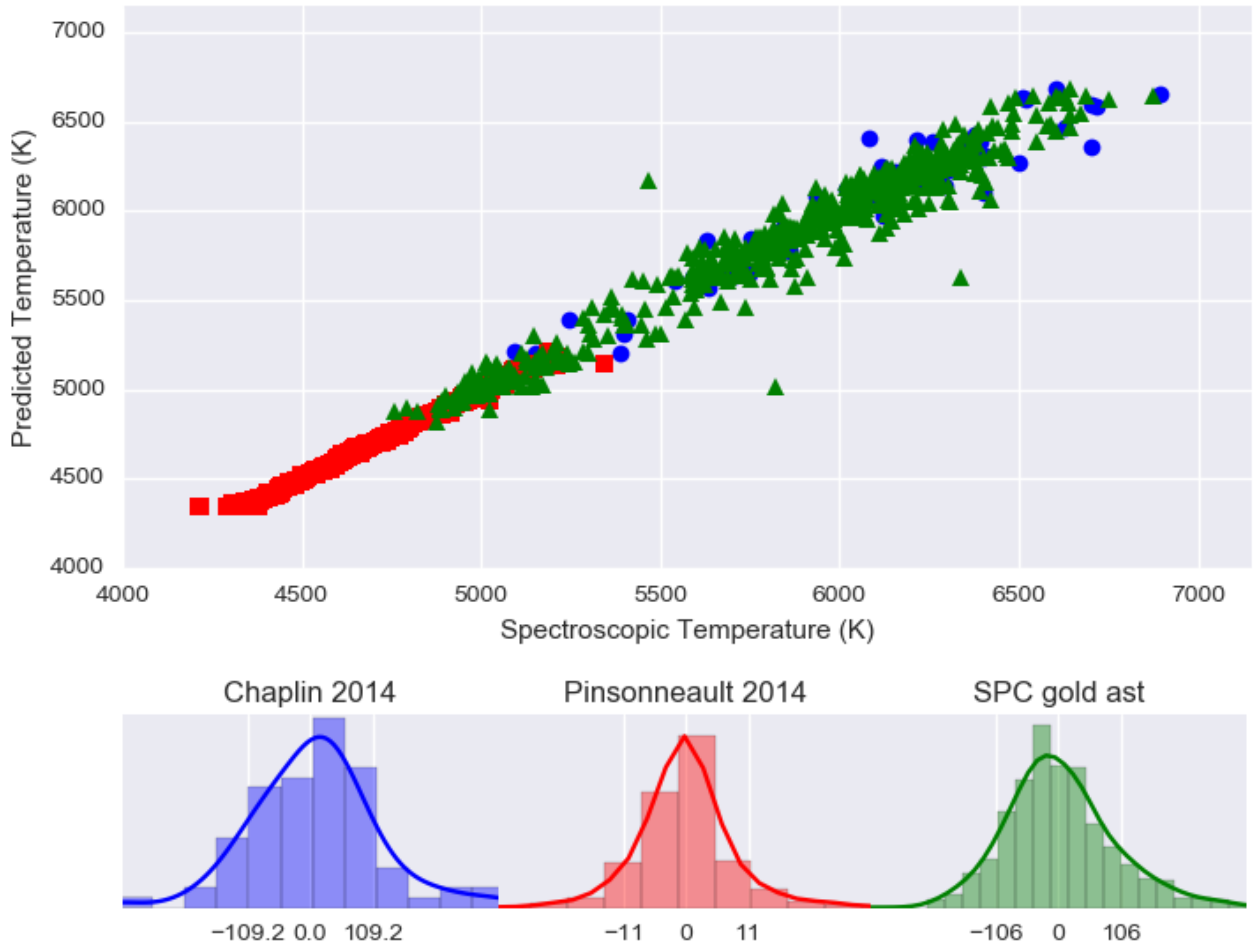
Teff + L => Numax



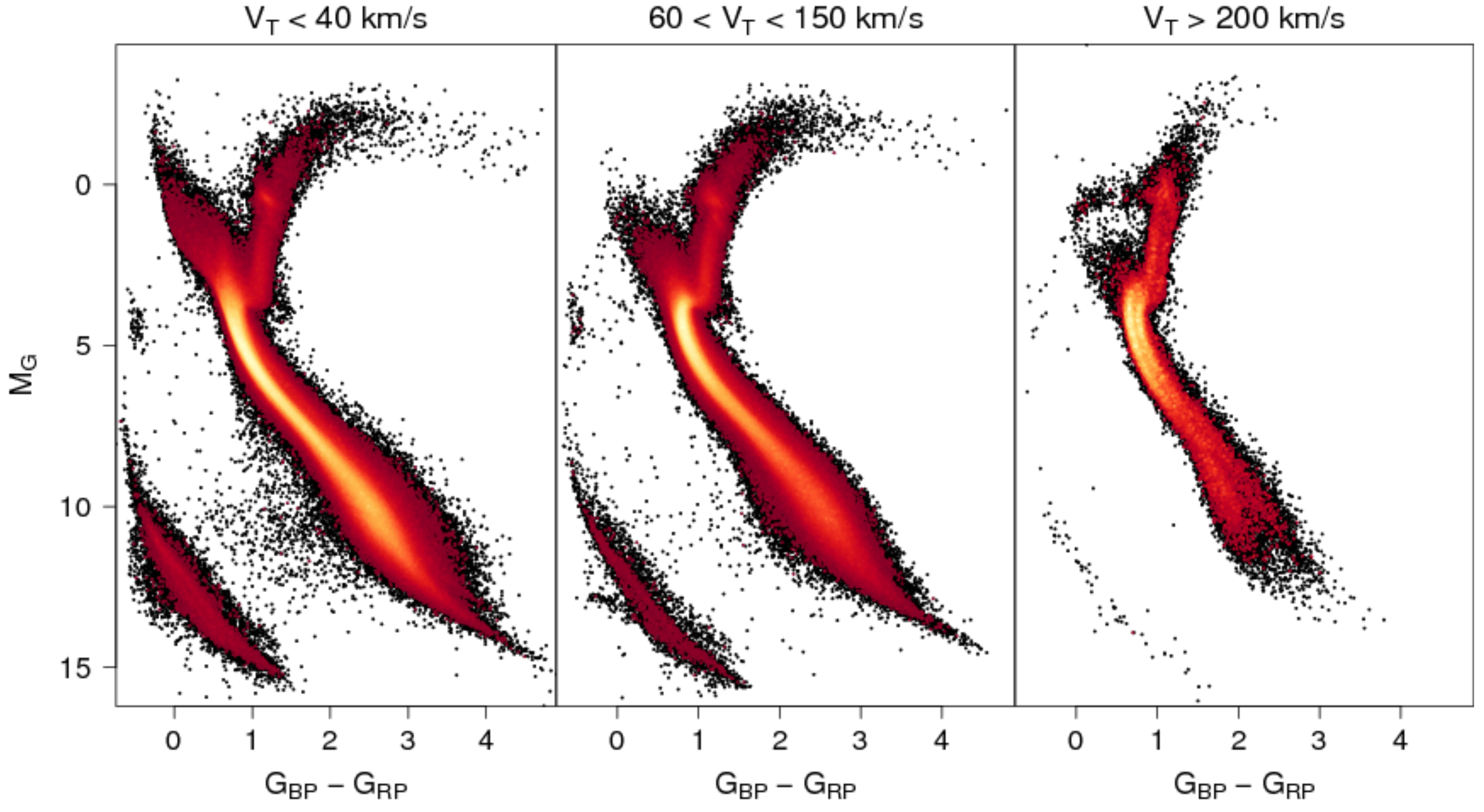
Log ν_{max} (μHz)
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
Log Luminosity ($L_\odot$)
-0.5
0.0
0.5
1.0
1.5
2.0
Log Effective Temperature (K)
3.80
3.78
3.76
3.74
3.72
3.70
3.68
3.66

Temperature

Luminosity



gaia

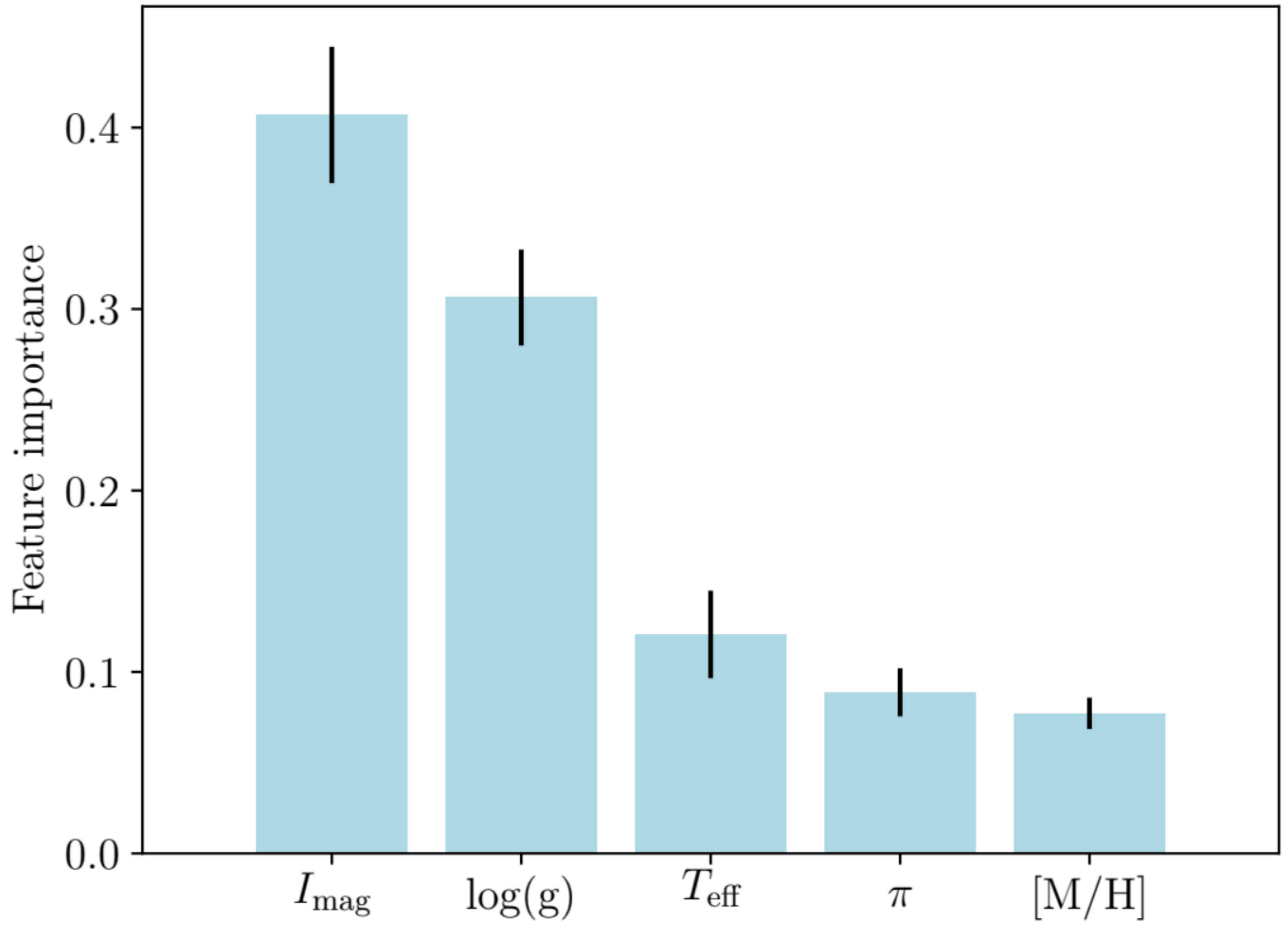


Detection of S-L Oscillations

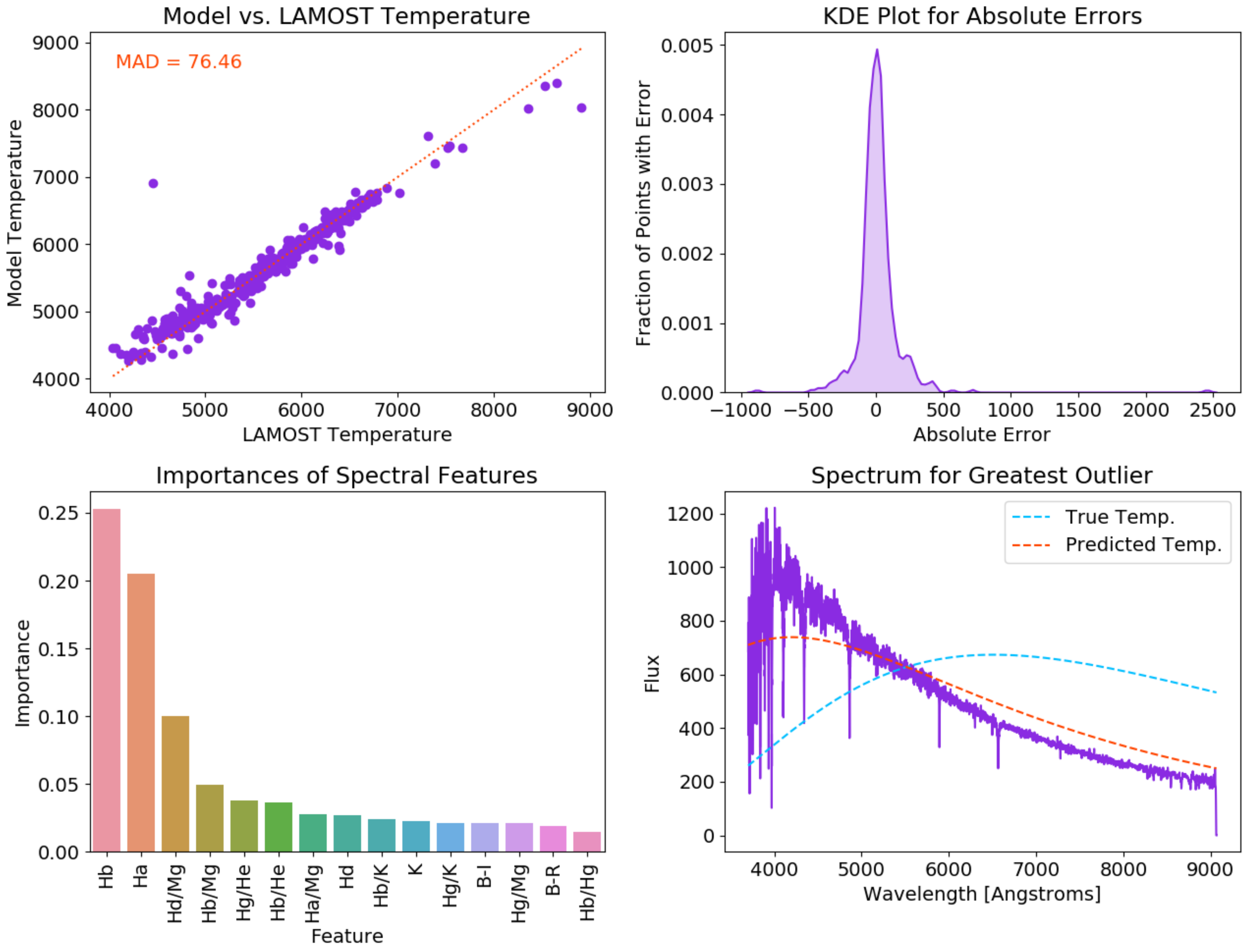
WP128

TESS Asteroseismic Predictions for Red Giants using Machine Learning

M. Schofield[1,2*], G. R. Davies[1,2], W. J. Chaplin[1,2], A. Miglio[1,2], M. F. Randrianandrasana
[1]*Department of Physics and Astronomy, the University of Birmingham, Birmingham B15 2TT, UK*
[2]*Stellar Astrophysics Centre (SAC), Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK-8000 Aarhus C, Denmark*

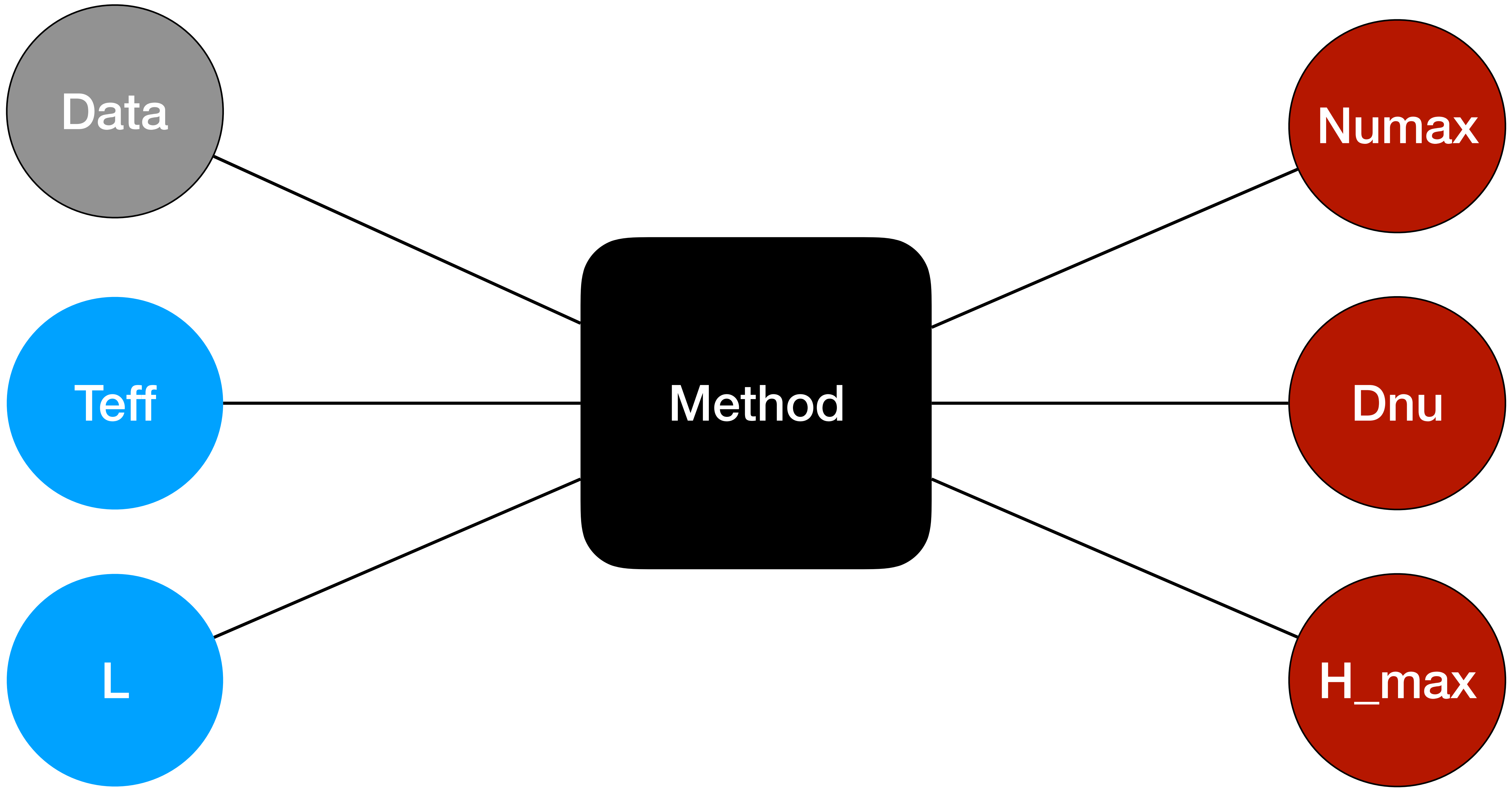


Undergrad project - Mat Scourfield, Chris Burch



Global properties

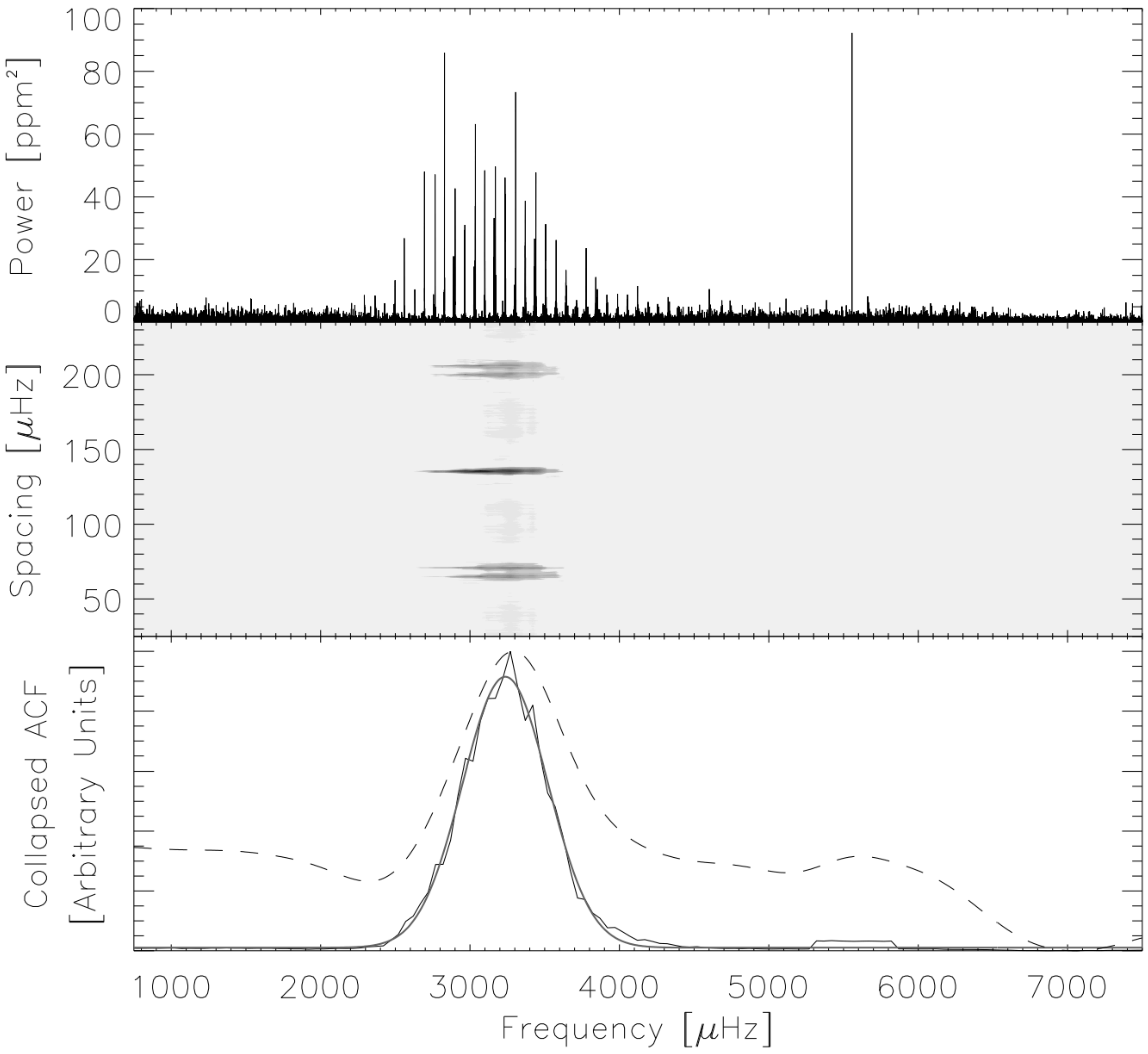
WP128



Global properties

WP128

- Take data from the periodogram
- Use the properties of the repeated pattern
- Left: The ACF of the periodogram
- General: Convolve, search, test, …
- Check the signal is significant
- Return Numax and/or Dnu

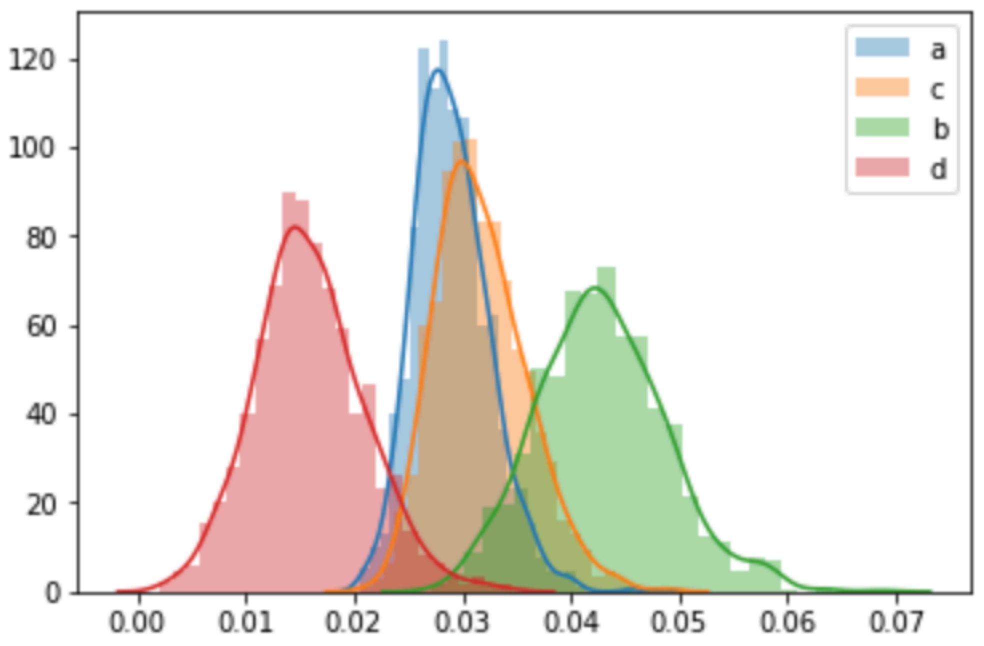


Huber+ 2009

Global properties

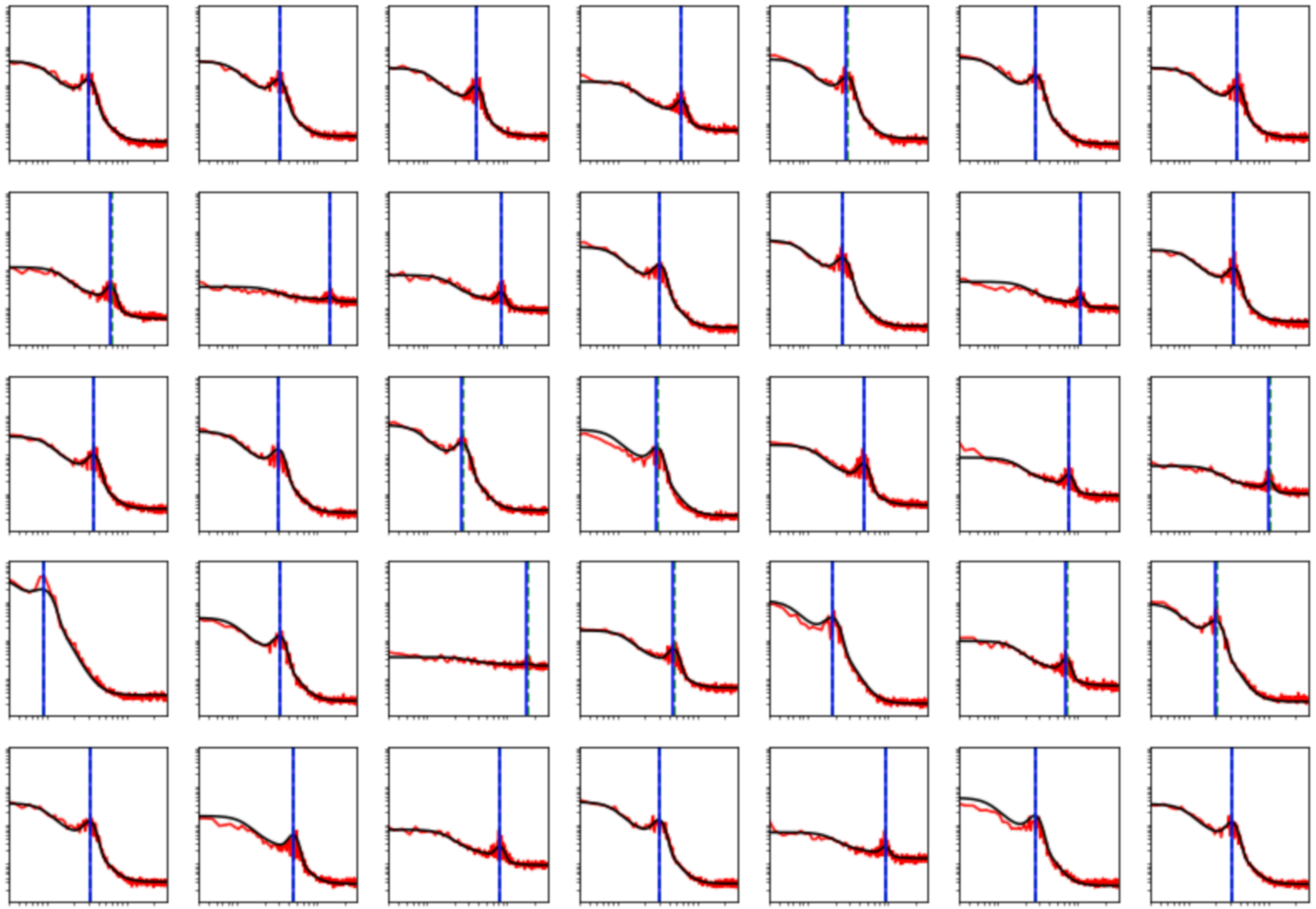
WP128 - Hierarchical Models - A cluster example

- Data from NGC 6791 (Kepler)
- Dimensionality Reduction - 2 parameter's per star
- Latent variable model (Numax, Noise)
- Learn the relationship between parameters
- Relationships are statistical distributions
- Allowance taken for outliers



Spread posteriors

Power

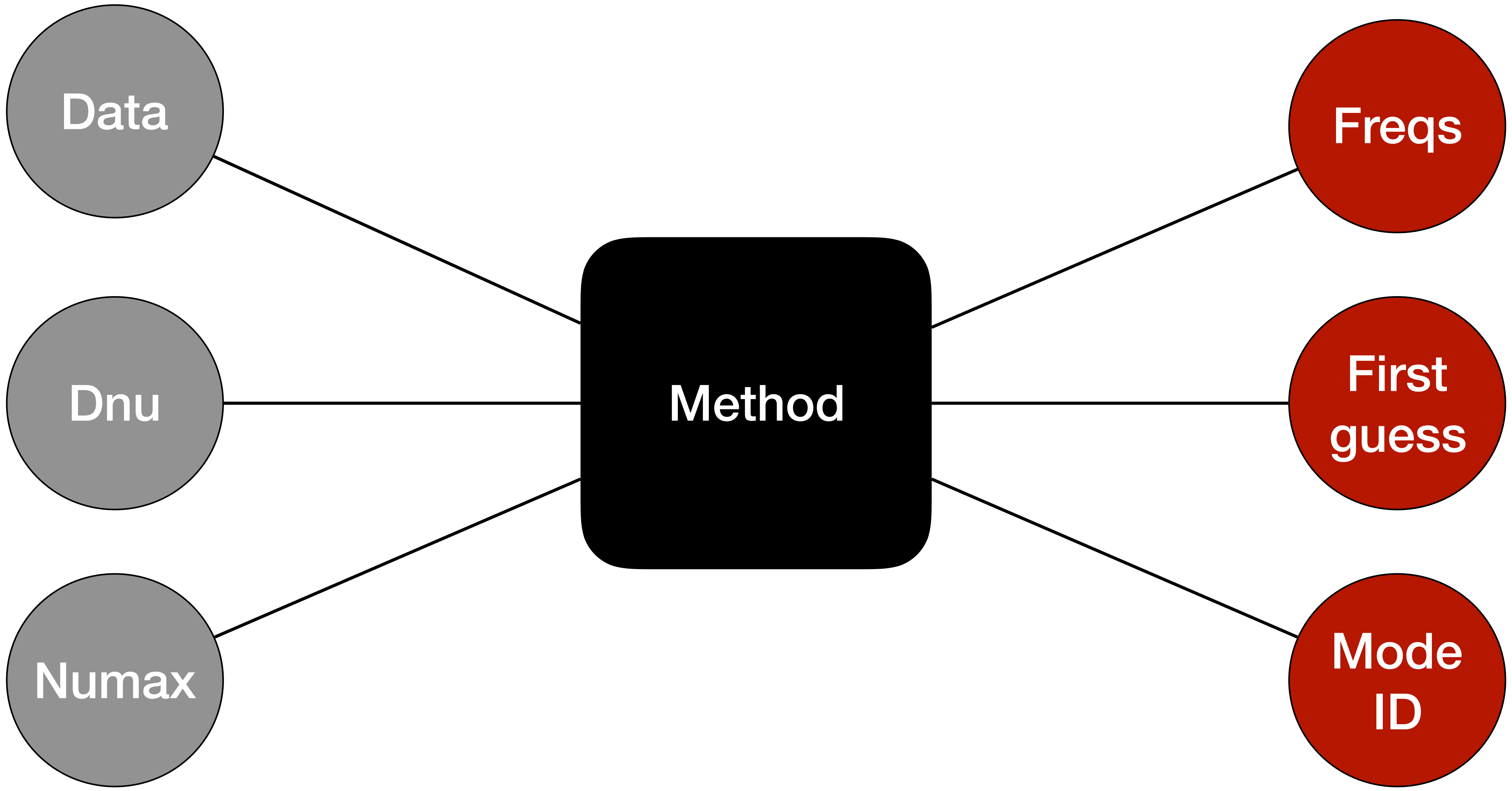


Frequency

Davies+ in prep

Preparation for peak-bagging

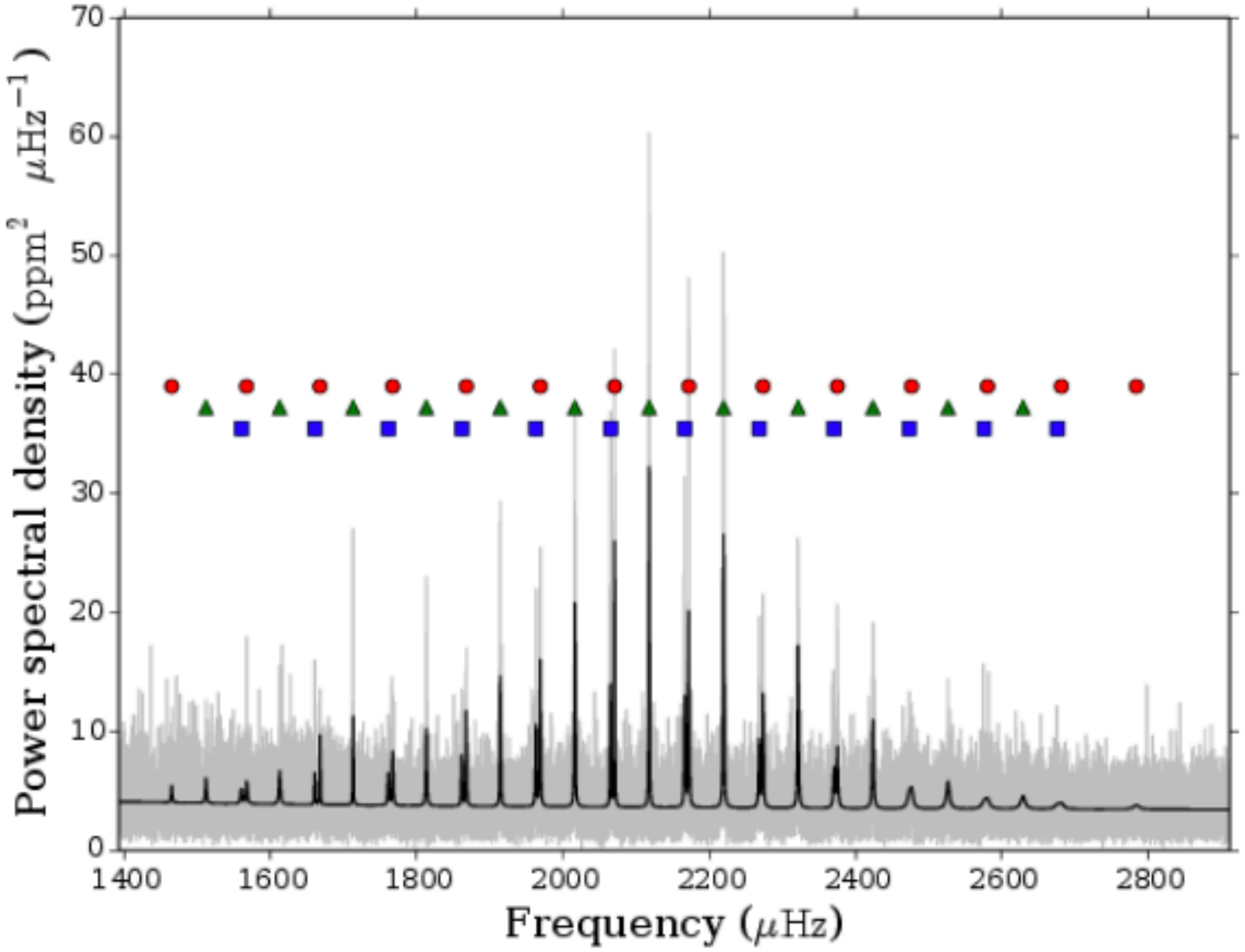
WP128



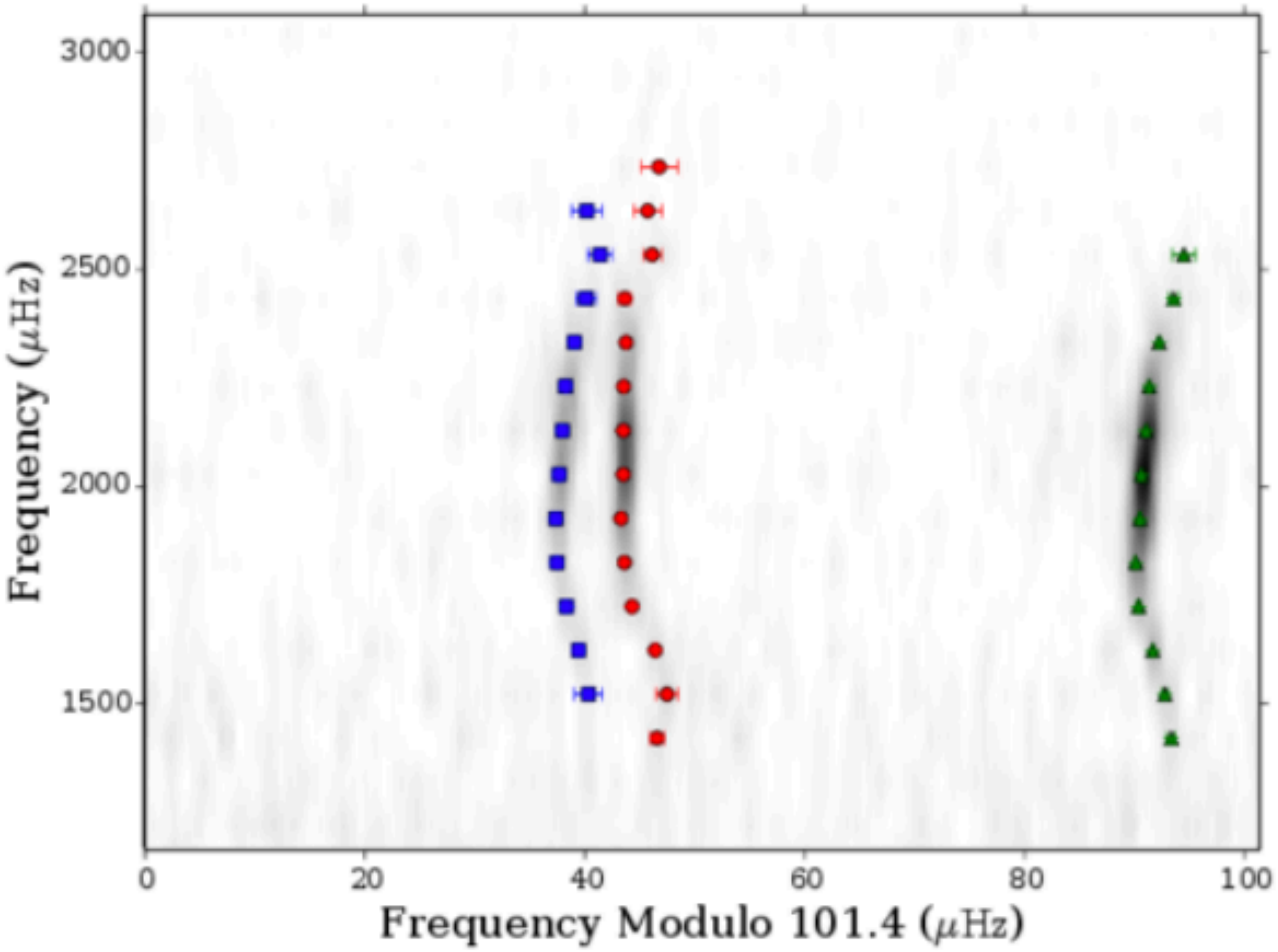
Preparation for peak-bagging

WP128

Simple



Simple



Davies+ 2016

Preparation for peak-bagging

WP128

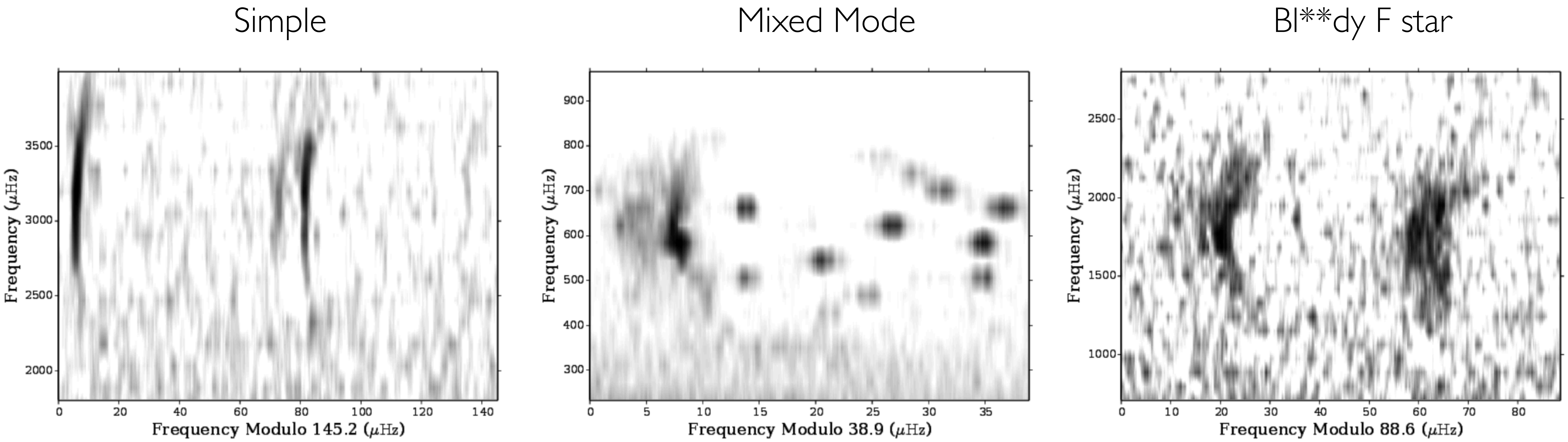
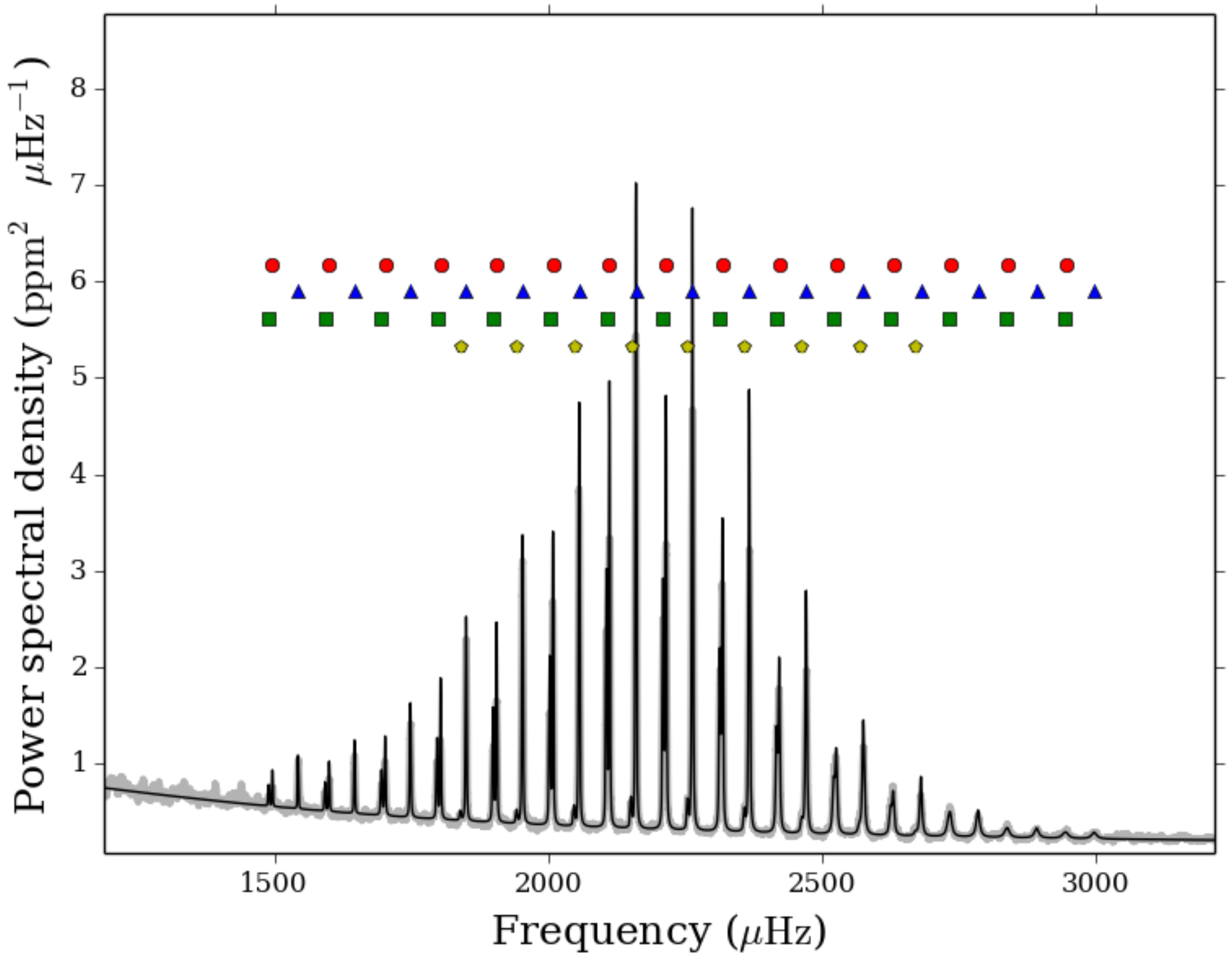


Figure 2. Echelle diagrams for three targets demonstrating the three classifications used. Left: A "simple" star KIC 3544595. Centre: The "mixed mode" star KIC 7199397. Right: The "F-like" star KIC 7670943.

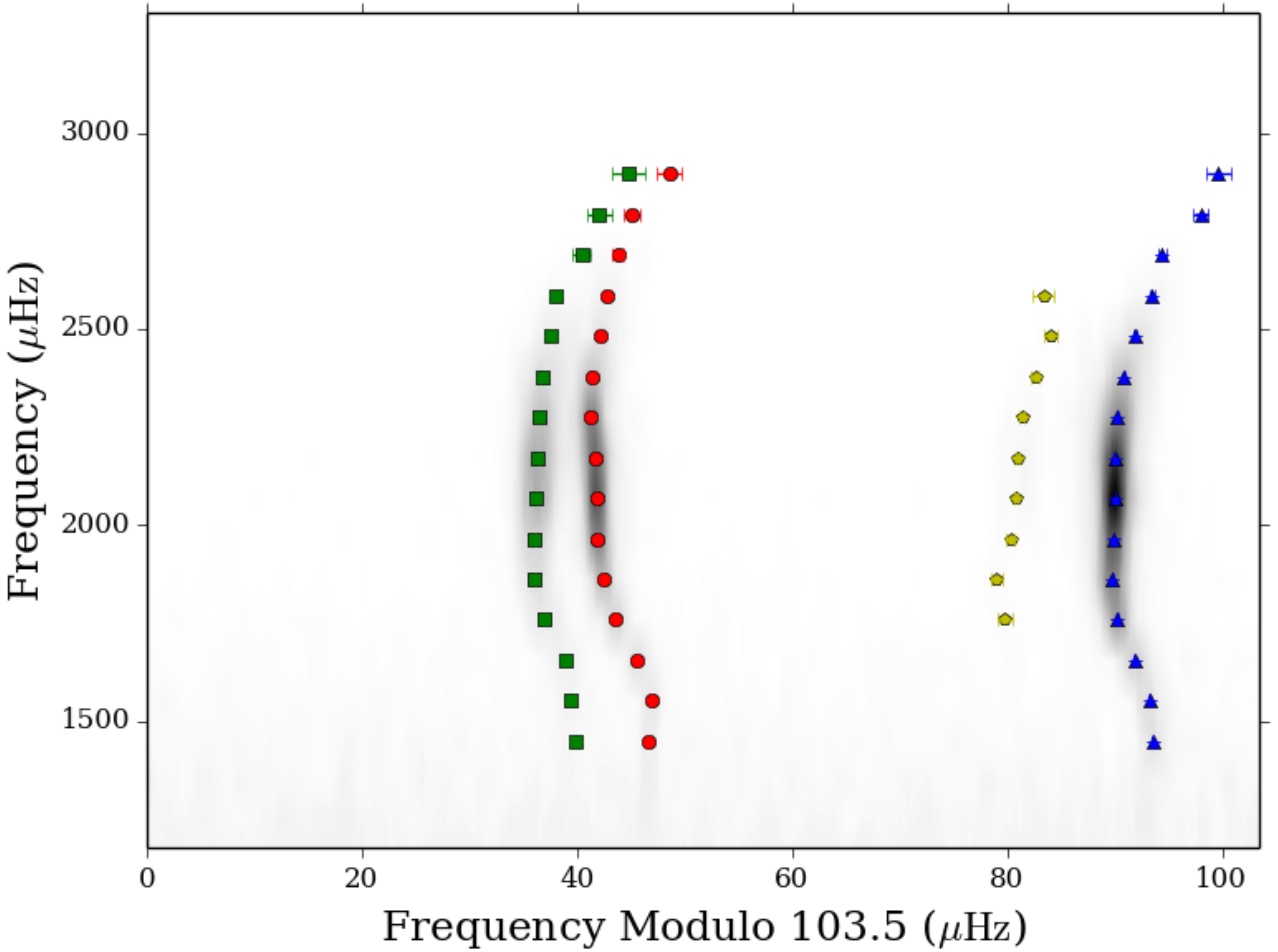
Davies+ 2016

Preparation for peak-bagging

WP128

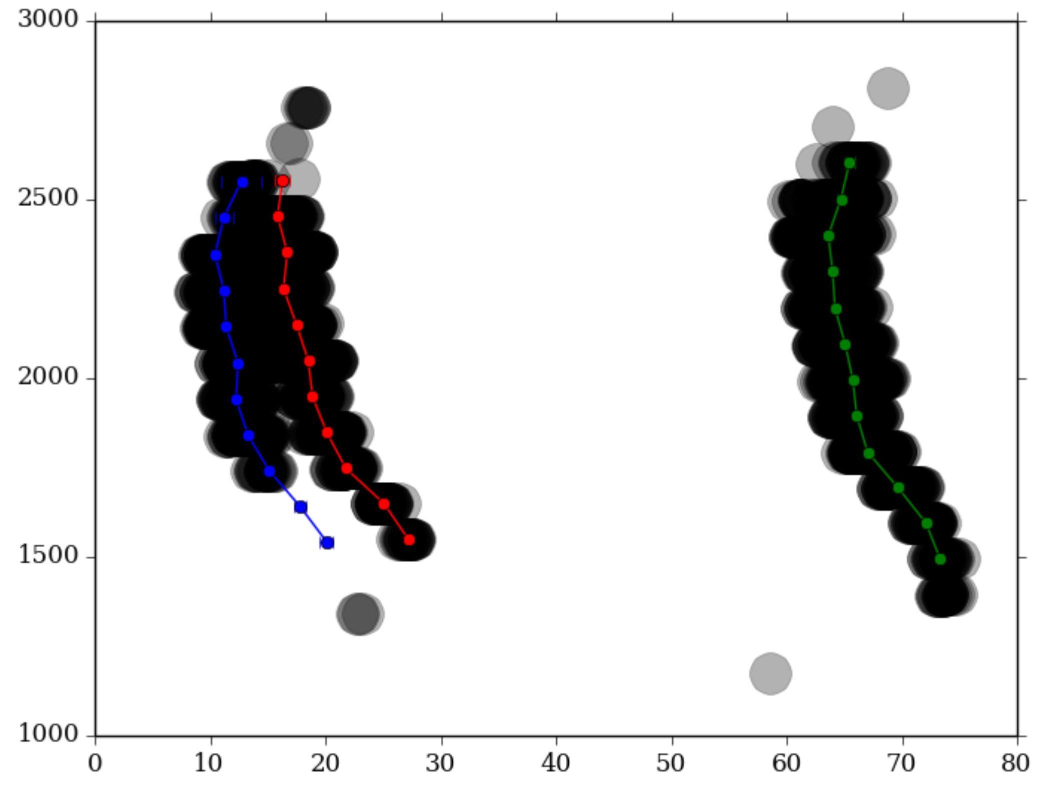


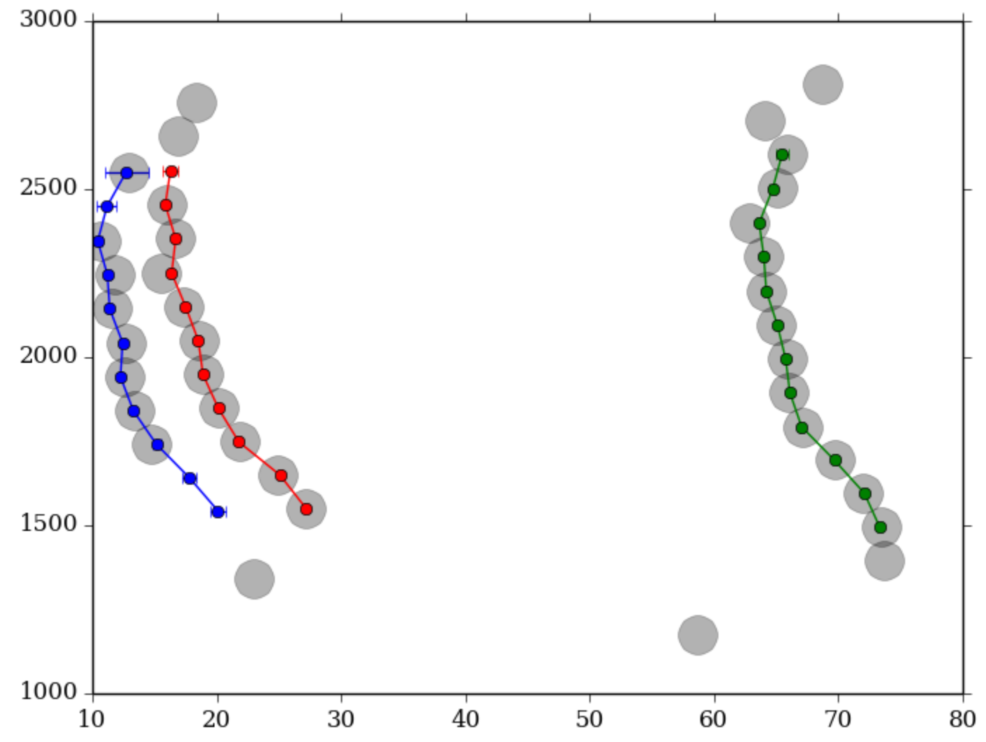
Davies+ 2015

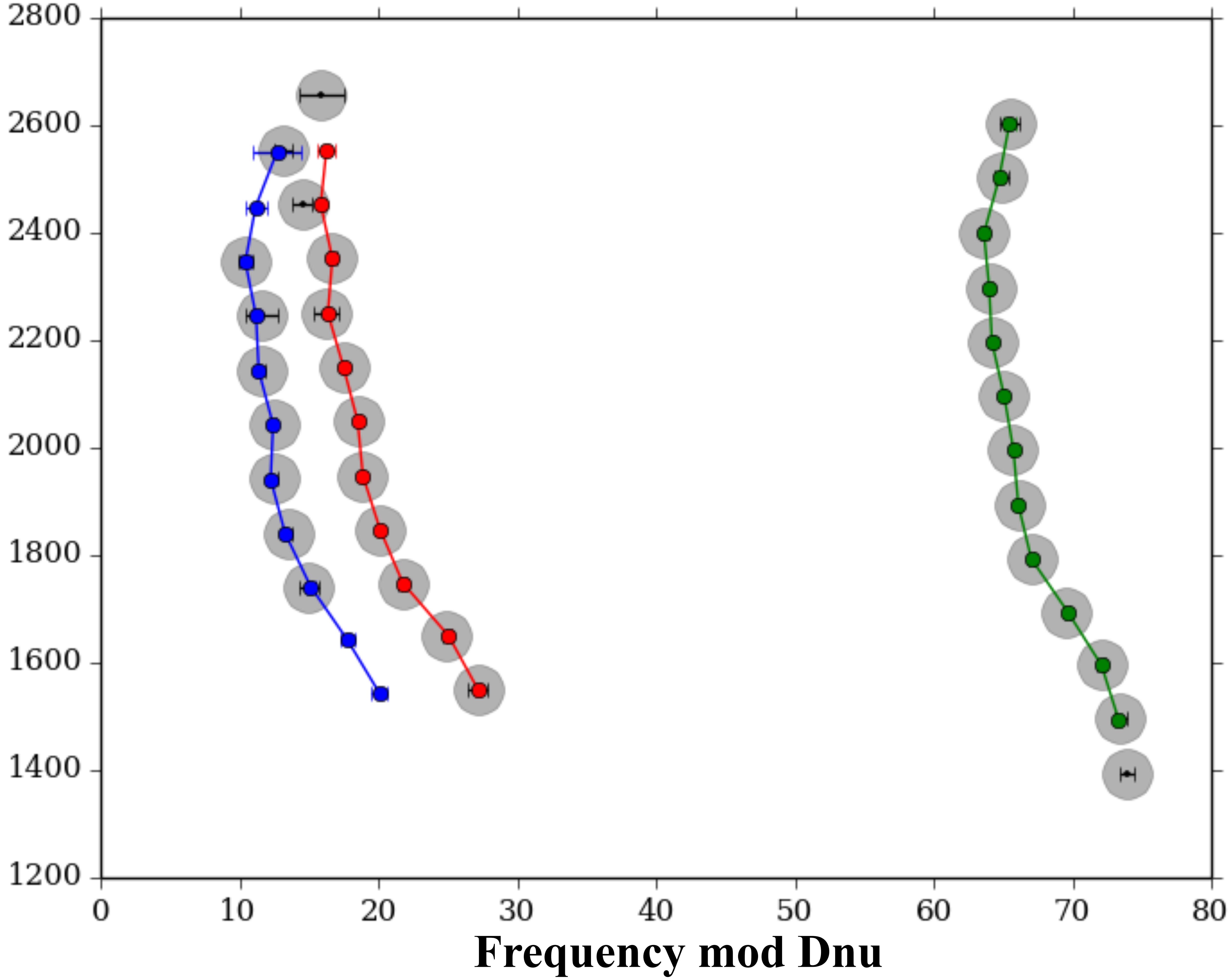


Preparation for peak-bagging

WP128







Preparation for peak-bagging

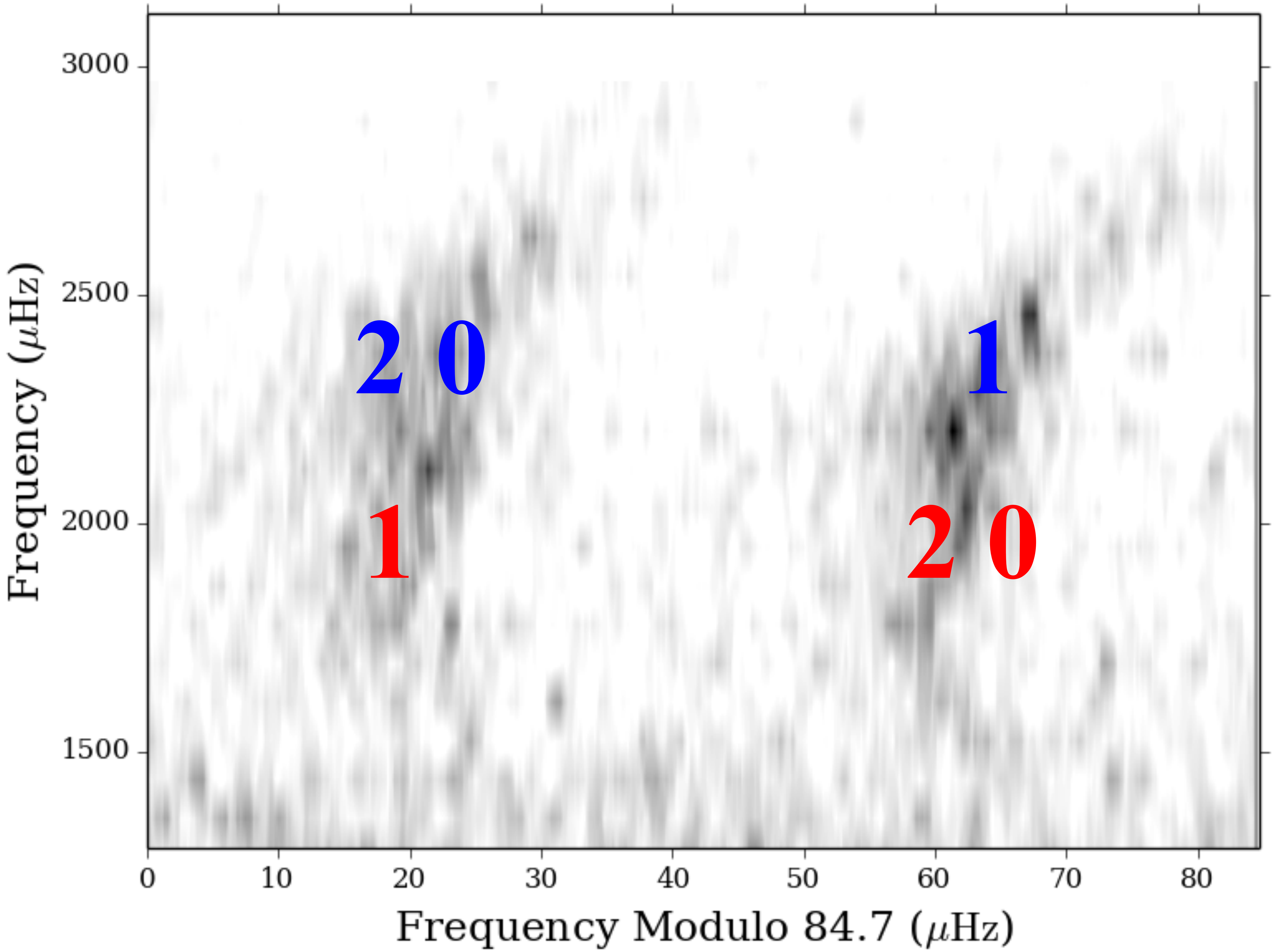
WP128

HD49933

Various references:

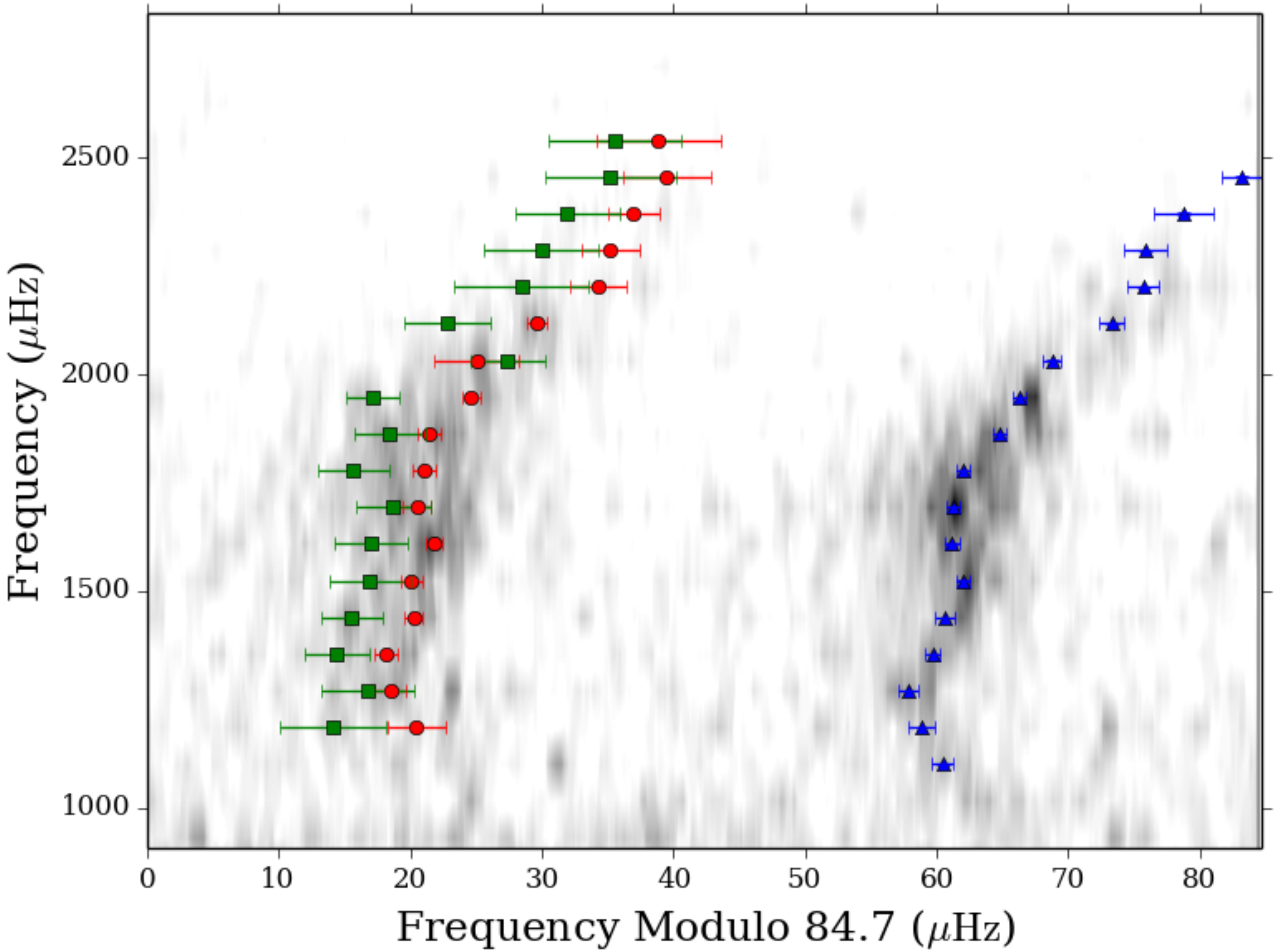
Appourchaux+ 2008
Appourchaux+ 2009
Benomar+ 2009
Gaulme+ 2009
Gruberbauer+ 2009

Confusion between model A and model B



Bayesian model comparison produced unambiguous mode identification.

Benomar+ 2009

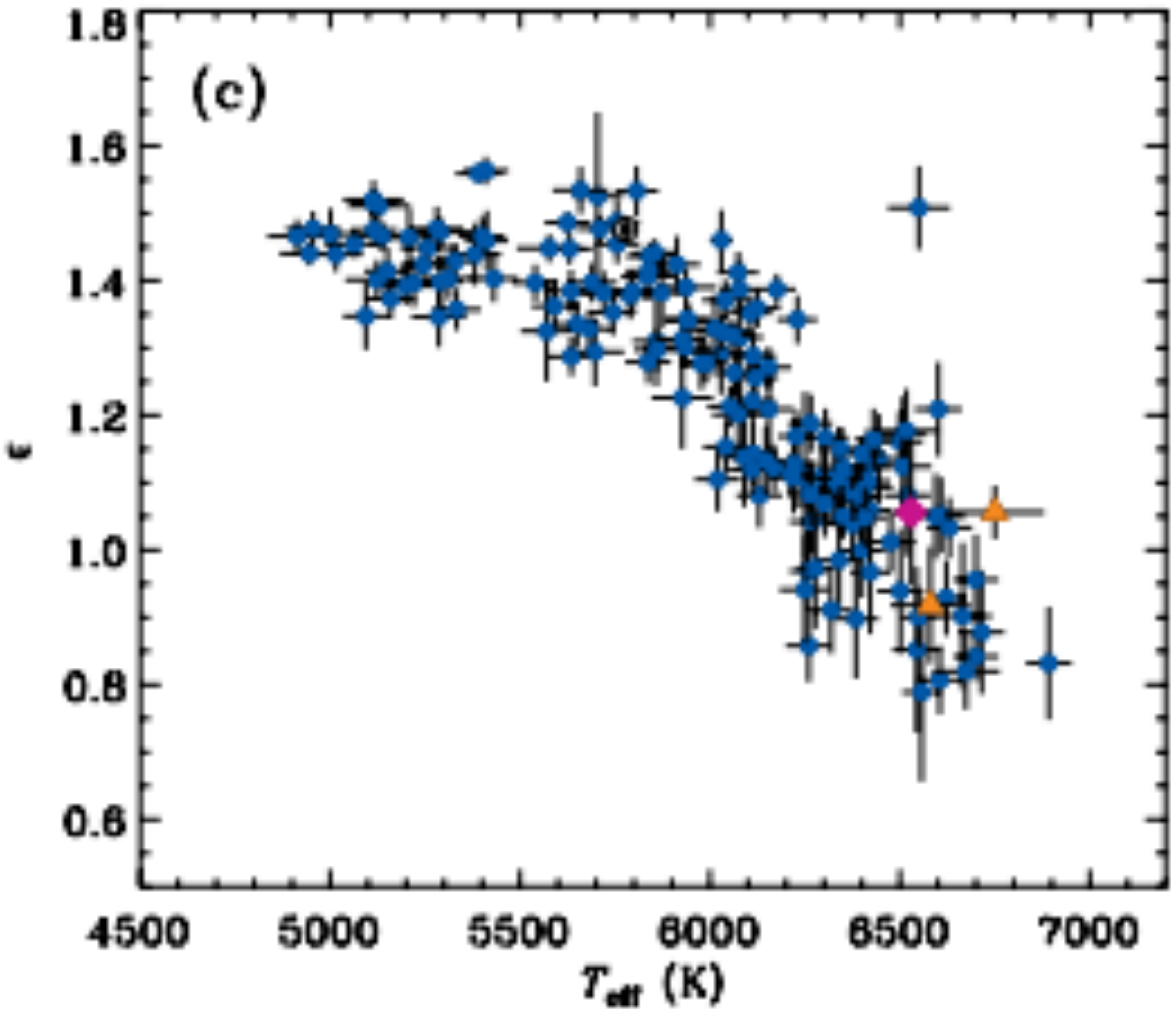


The Astrophysical Journal Letters, 751:L36 (7pp), 2012 June 1
doi:10.1088/2041-8205/751/2/L36

SOLVING THE MODE IDENTIFICATION PROBLEM IN ASTEROSEISMOLOGY OF F STARS OBSERVED WITH *KEPLER*

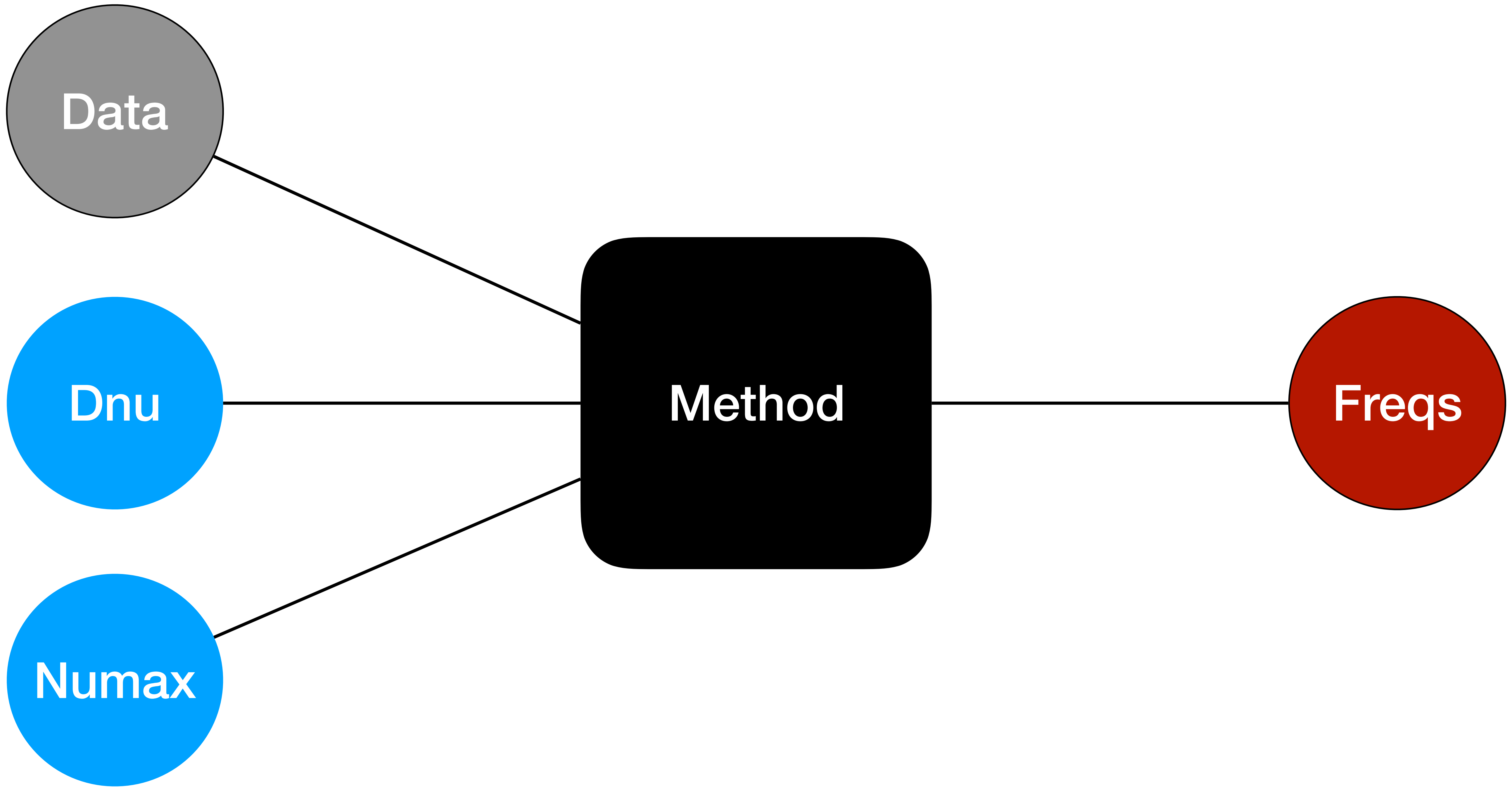
Timothy R. White[1,2], Timothy R. Bedding[1], Michael Gruberbauer[3], Othman Benomar[1], Dennis Stello[1], Thierry Appourchaux[4], William J. Chaplin[5], Jørgen Christensen-Dalsgaard[6], Yvonne P. Elsworth[5], Rafael A. García[7], Saskia Hekker[5,8], Daniel Huber[1,9], Hans Kjeldsen[6], Benoît Mosser[10], Karen Kinemuchi[11], Fergal Mullally[12], and Martin

$$\nu_{n,l} \approx \Delta_l(n)\left(n + \frac{l}{2} + \epsilon\right) - d_{l,l}(n),$$

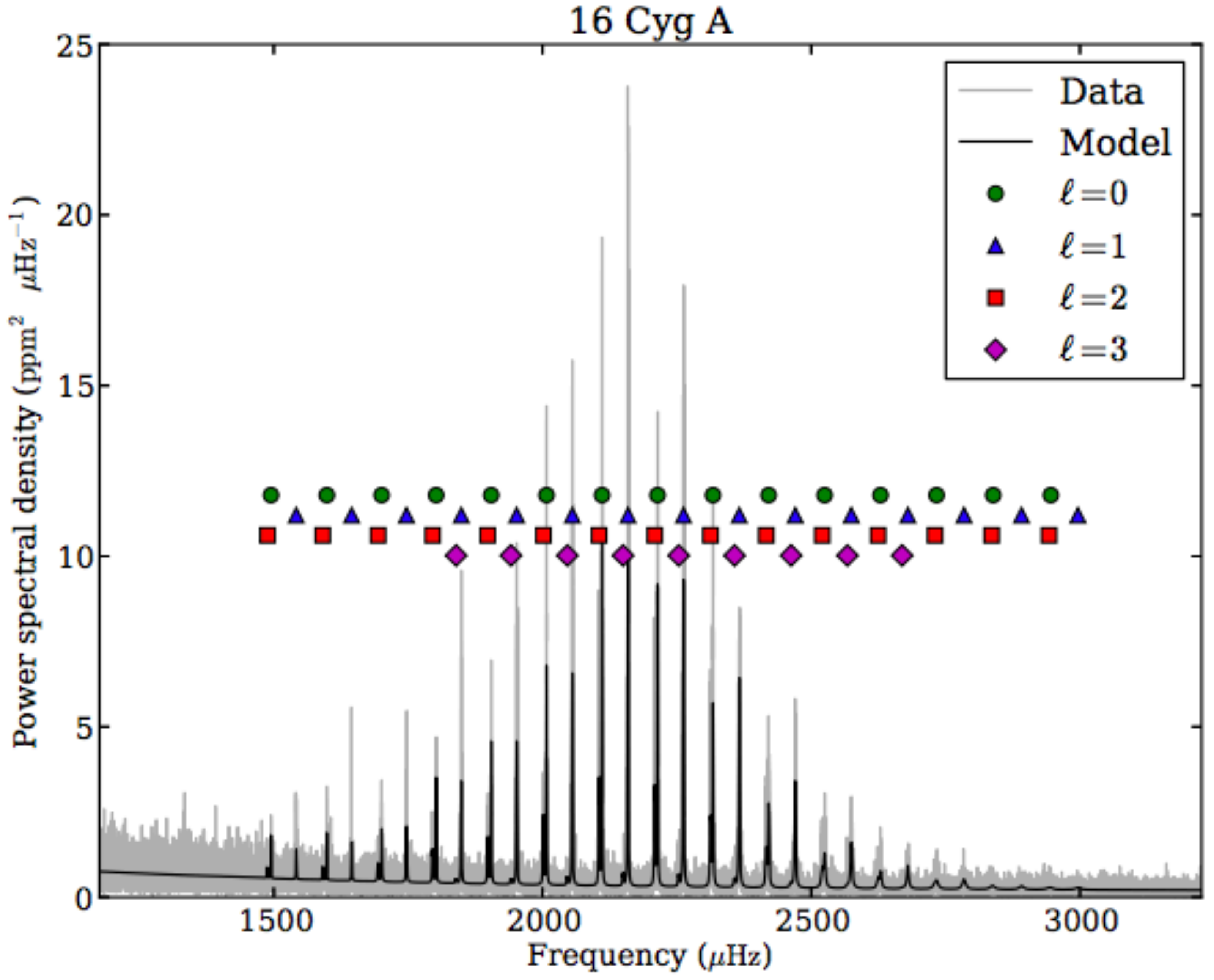


Peak-bagging

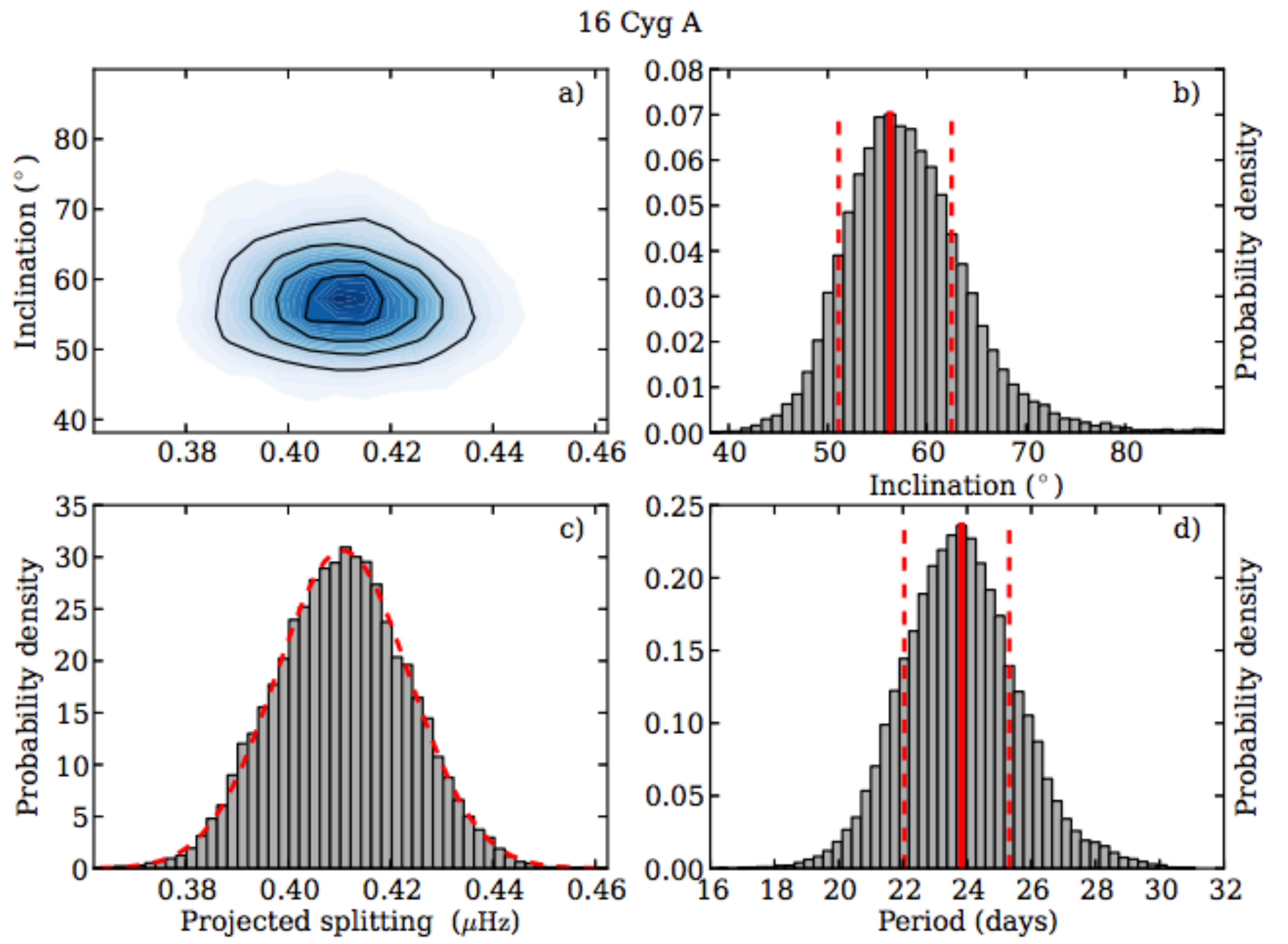
WP128



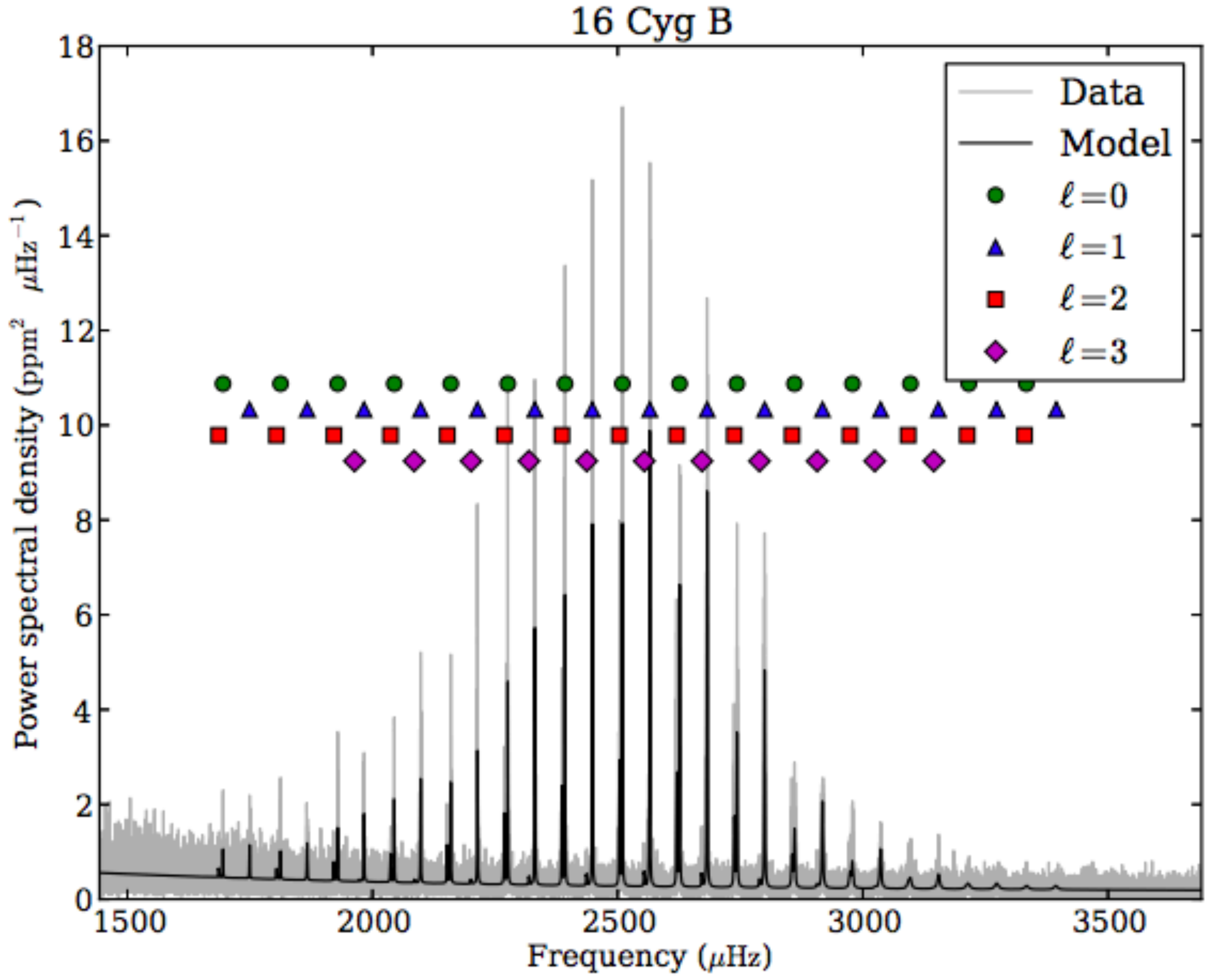
Davies+ 2015



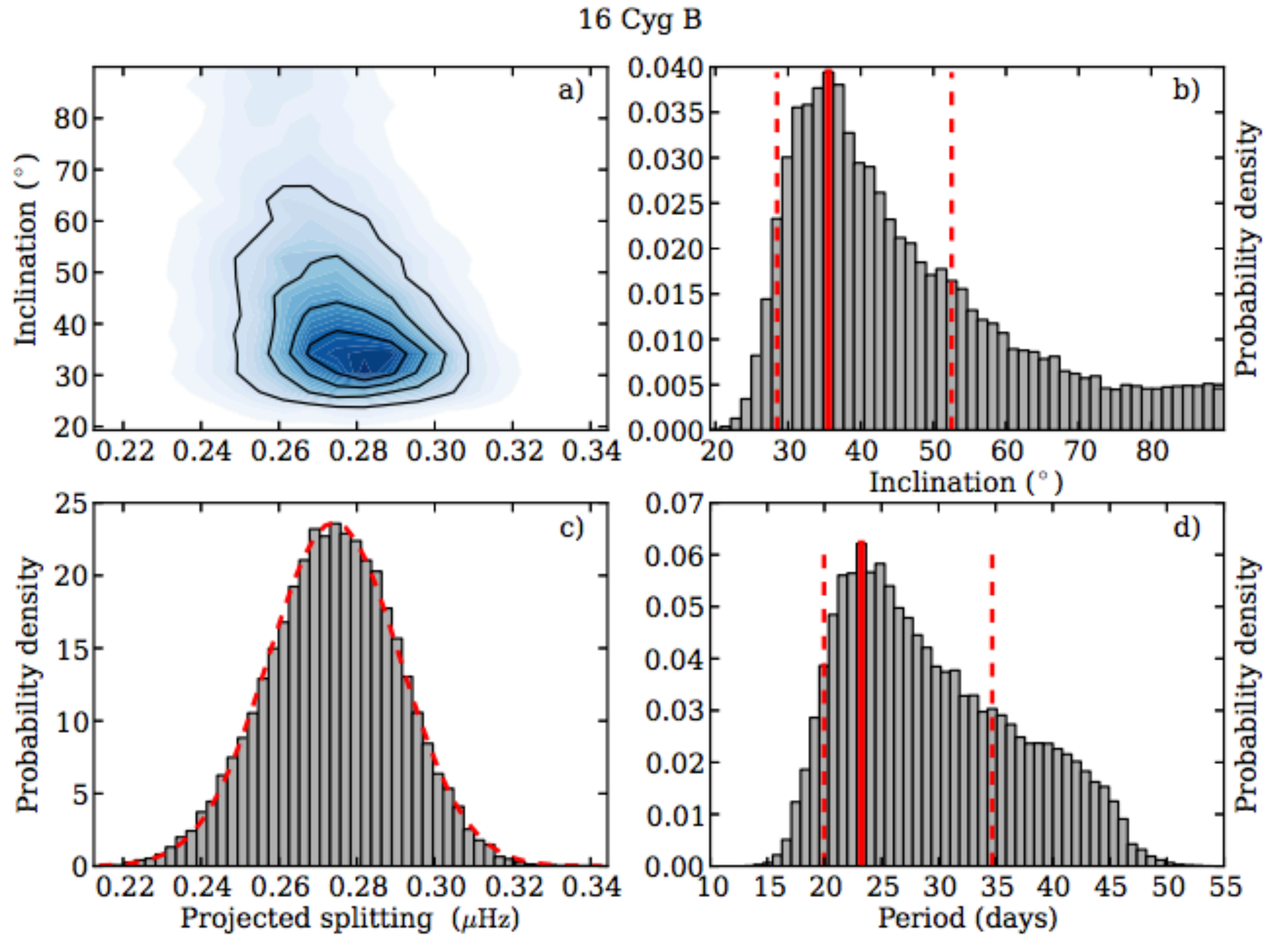
16 Cyg A
Data
Model
ℓ=0
ℓ=1
ℓ=2
ℓ=3
Power spectral density (ppm² μHz⁻¹)
Frequency (μHz)



16 Cyg A
a)
b)
c)
d)
Inclination (°)
Probability density
Projected splitting (μHz)
Period (days)



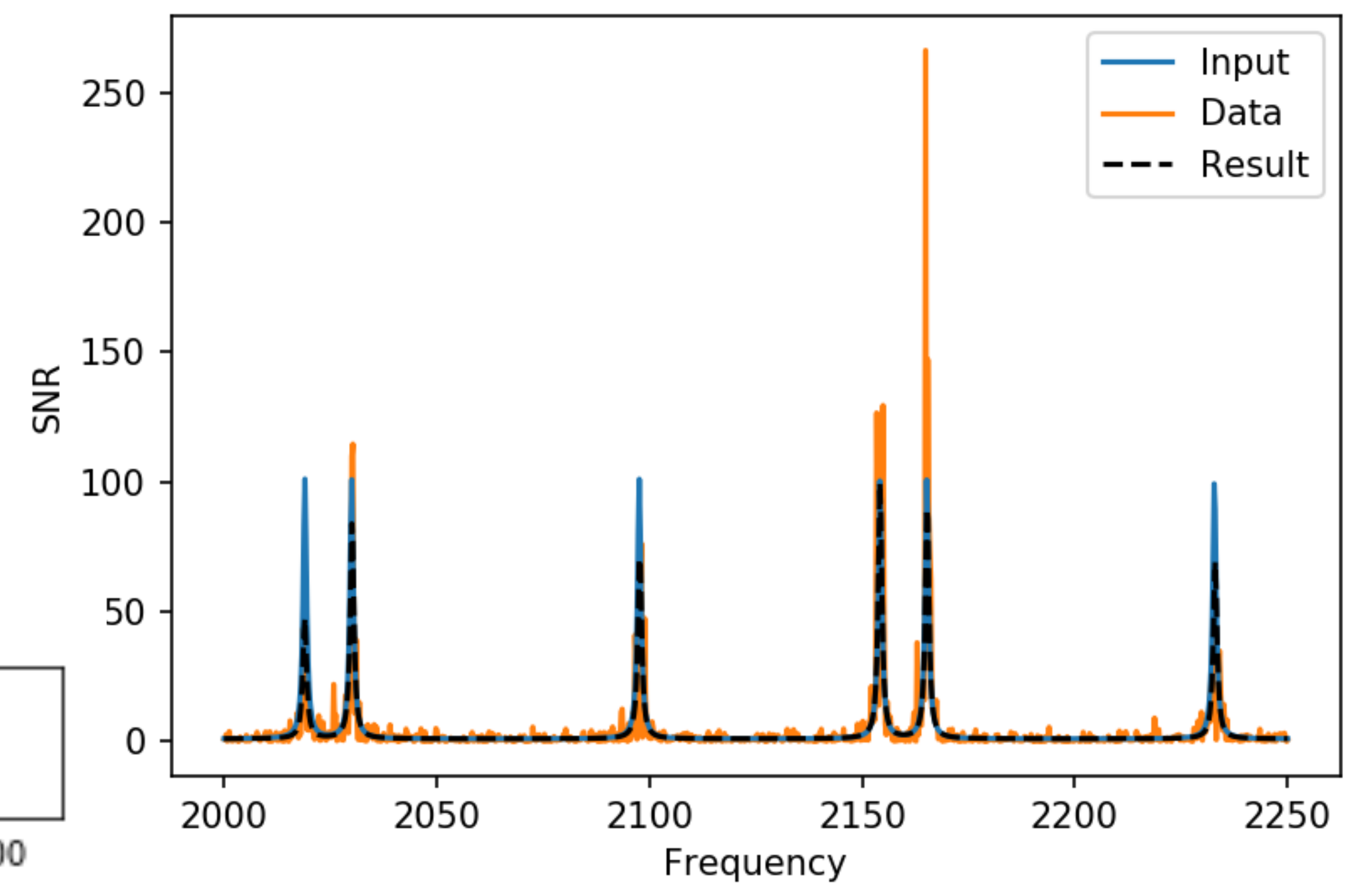
16 Cyg B
Data
Model
ℓ=0
ℓ=1
ℓ=2
ℓ=3
Power spectral density (ppm² μHz⁻¹)
Frequency (μHz)

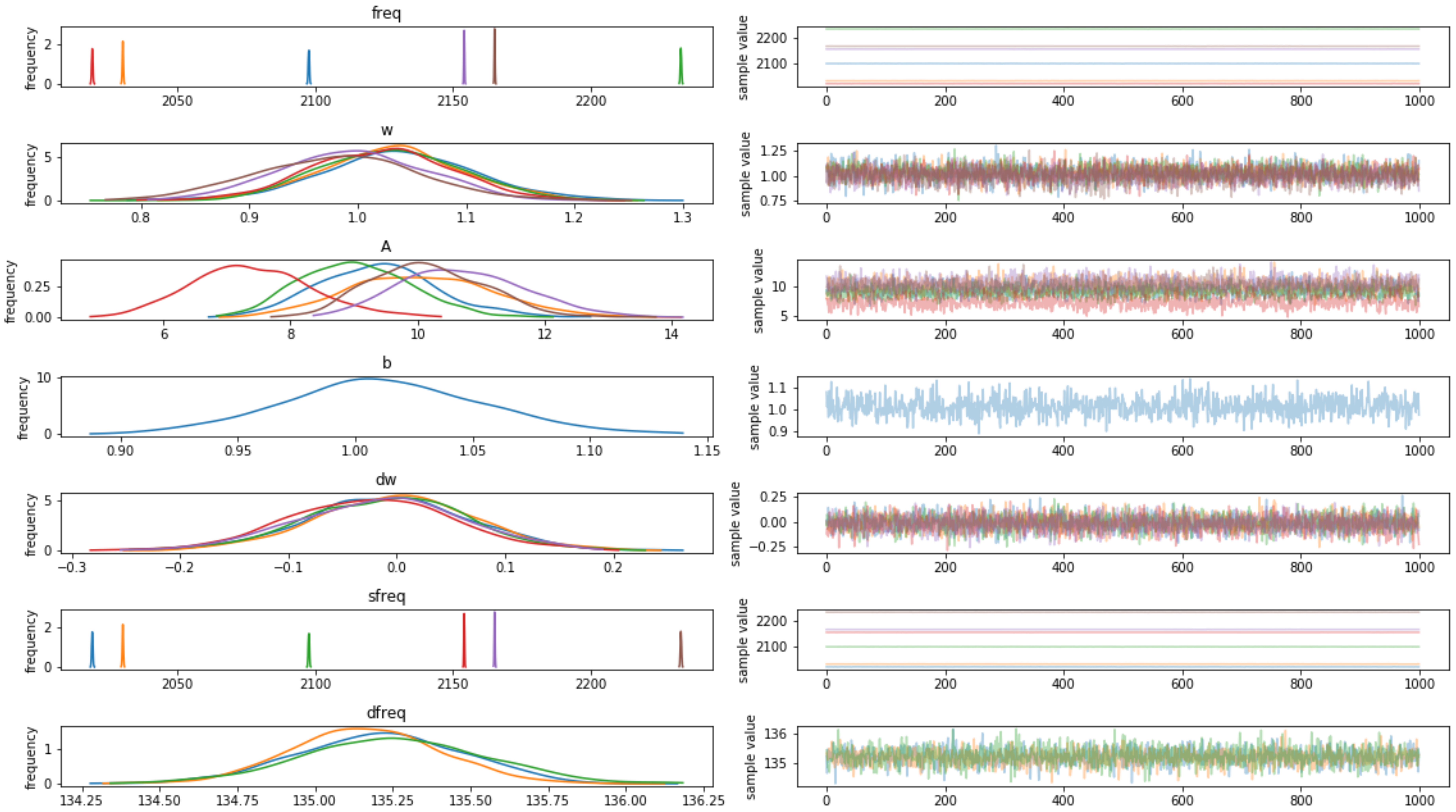


16 Cyg B
a)
b)
c)
d)
Inclination (°)
Probability density
Projected splitting (μHz)
Period (days)

Peak-bagging: No guesses

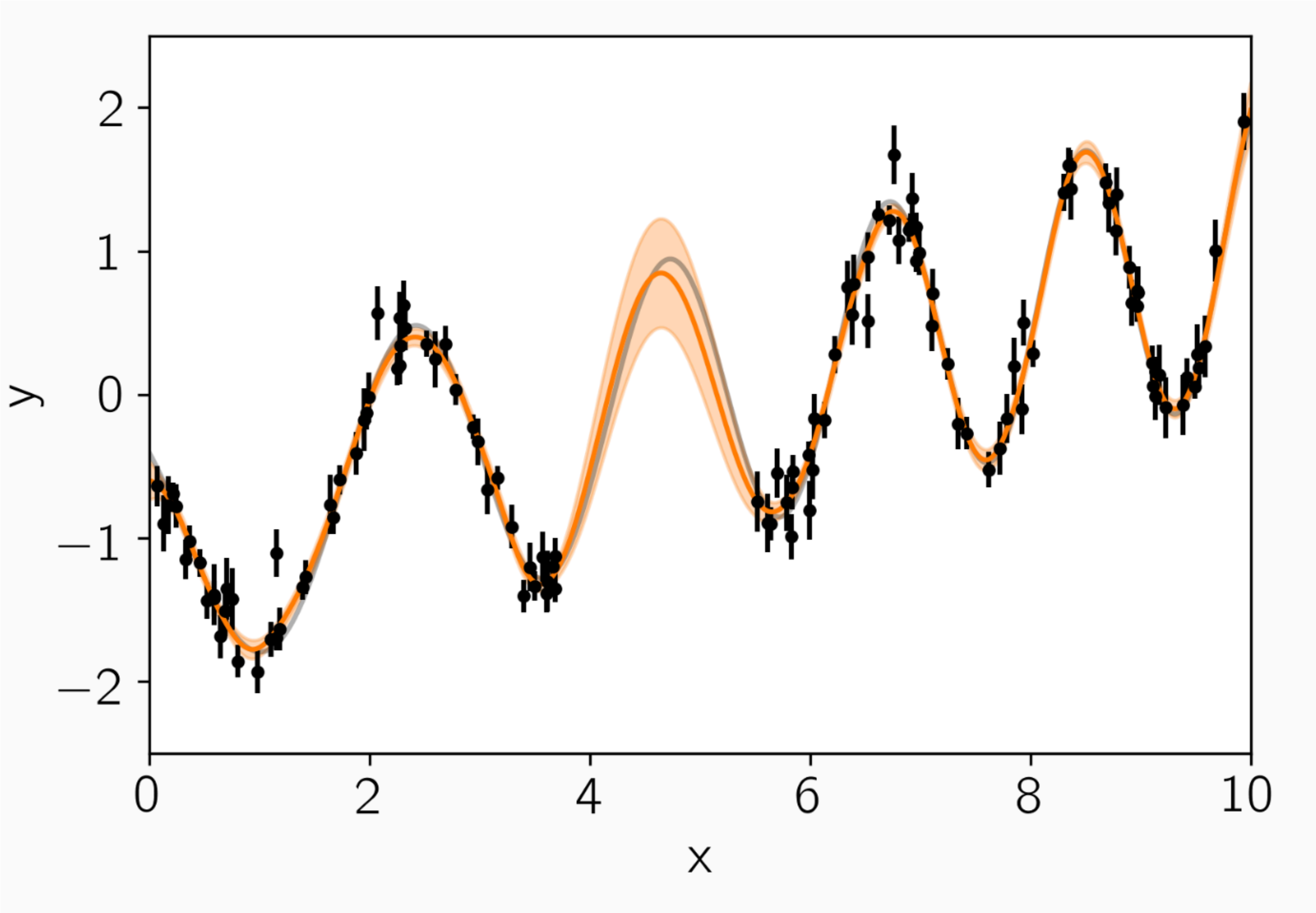
WP128

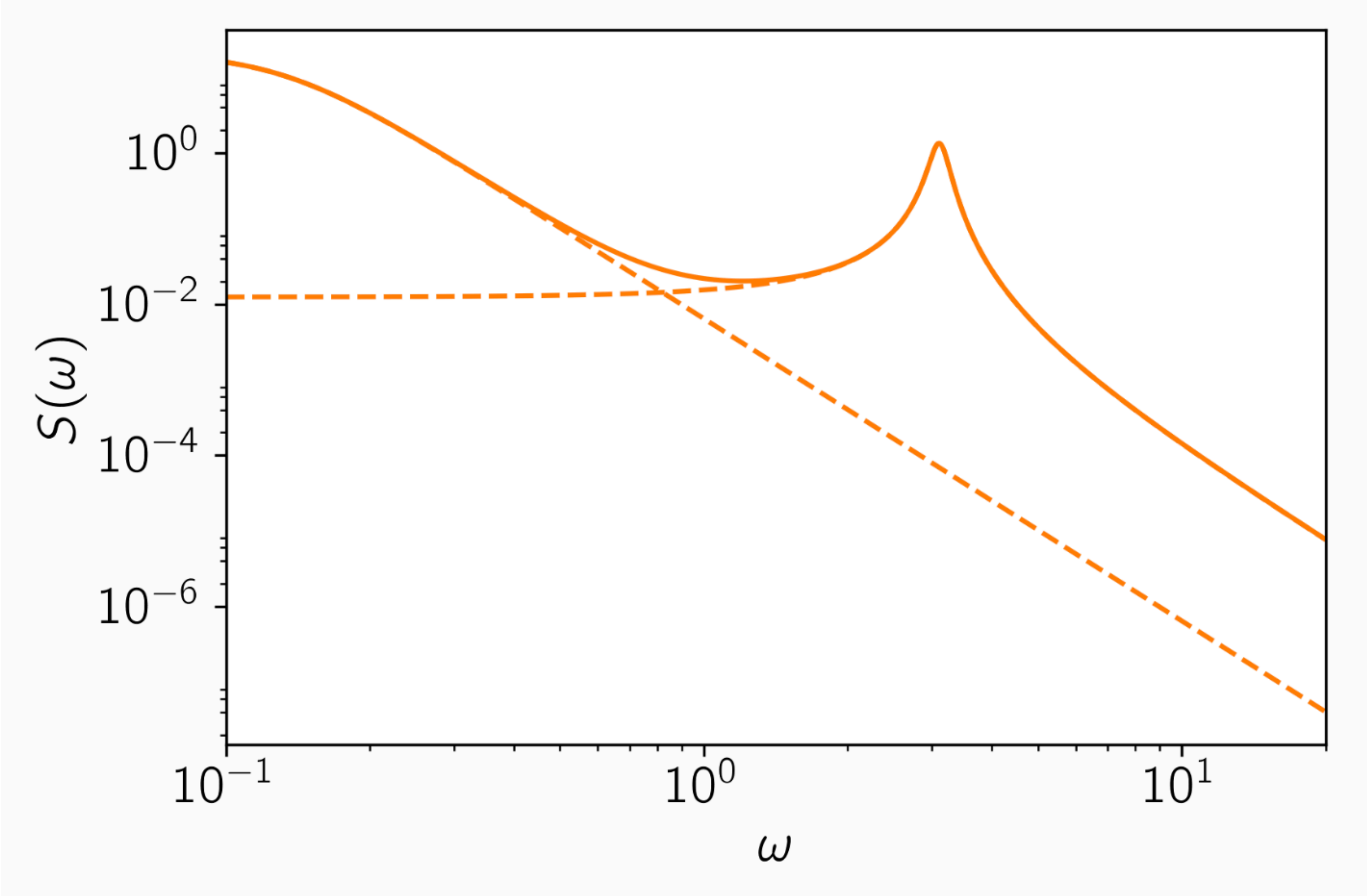




Peak-bagging: Time Domain

WP128



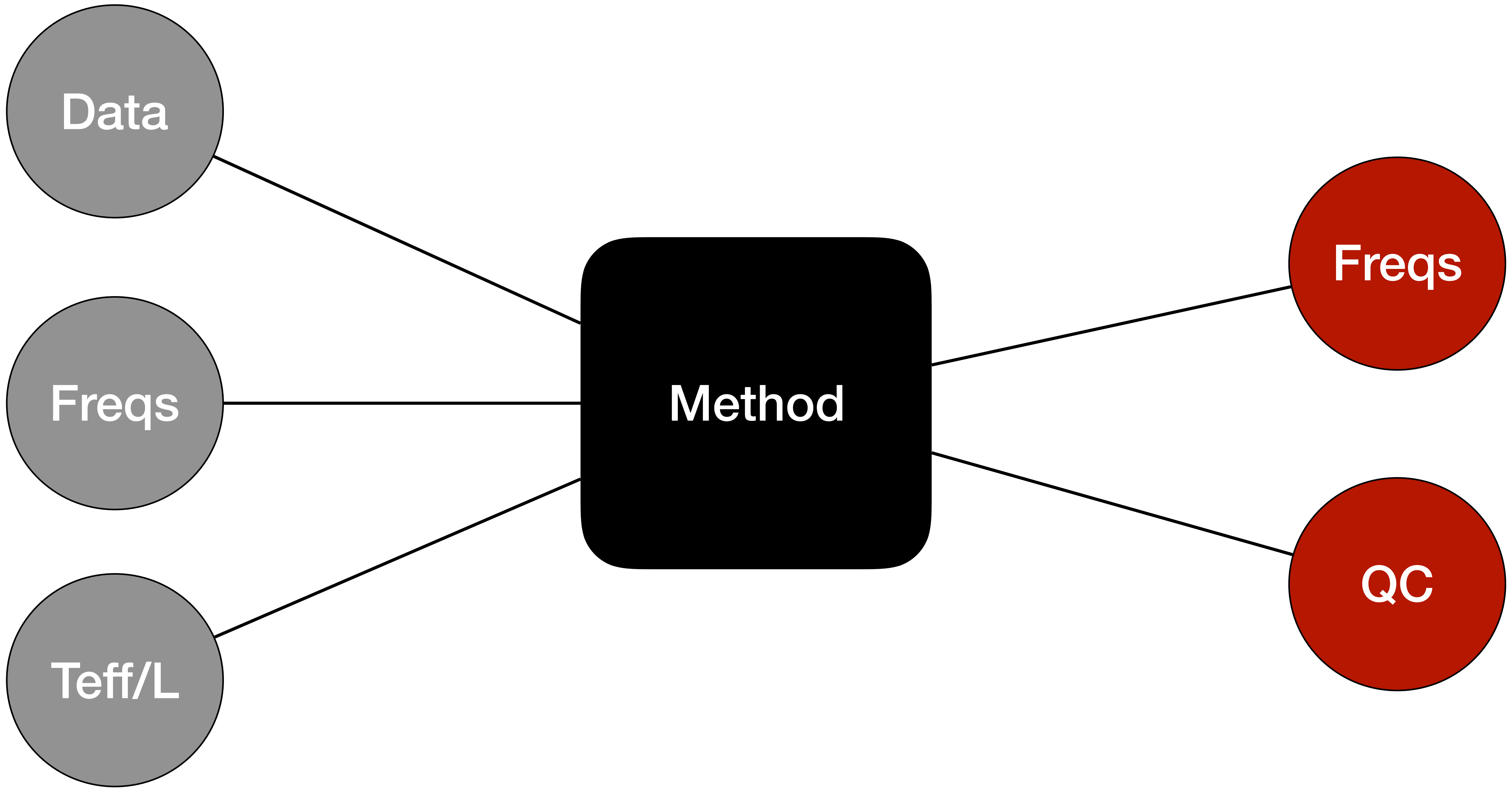


Foreman-Mackay 2017, Farr 2018, Grumblatt 2018

$$\mathcal{O}(N, j^2)$$

Quality Control

WP128



Quality Control

WP128

$$p(D|\vec{\theta}, p_a) = (1 - p_a)\, p(D|H_0, \vec{\theta}) + p_a\, p(D|H_1, \vec{\theta}),$$

Quality Control

WP128

$$p(D|\vec{\theta}, p_a) = (1 - p_a)\, p(D|H_0, \vec{\theta}) + p_a\, p(D|H_1, \vec{\theta}),$$

The likelihood function - the chance of observing the data.

Quality Control

WP128

$$p(D|\vec{\theta}, p_a) = (1 - p_a)\, p(D|H_0, \vec{\theta}) + p_a\, p(D|H_1, \vec{\theta}),$$

The likelihood function

The probability of observing some data given some model multiplied by the probability that the model is correct

Quality Control

WP128

$$p(D|\vec{\theta}, p_a) = (1 - p_a)\, p(D|H_0, \vec{\theta}) + p_a\, p(D|H_1, \vec{\theta}),$$

The likelihood function

The probability of observing some data given some model multiplied by the probability that the model is correct

The probability of observing the same data given some other model multiplied by the probability that this model is correct

Quality Control

WP128

This *or* That

$$p(D|\vec{\theta}, p_a) = (1 - p_a)\, p(D|H_0, \vec{\theta}) + p_a\, p(D|H_1, \vec{\theta}),$$

The likelihood function

The probability of observing some data given some model multiplied by the probability that the model is correct

The probability of observing the same data given some other model multiplied by the probability that this model is correct

Quality Control

WP128

$$p(D|\vec{\theta}, p_{l0}, p_{l0+l2}) = (1 - p_{l0} - p_{l0+l2})\ p(D|H_0, \vec{\theta}) + p_{l0}\ p(D|H_{l0}, \vec{\theta}) + p_{l0+l2}\ p(D|H_{l0+l2}, \vec{\theta}),$$

Bayes factor K,

$$\ln K = \ln p(D|\mathrm{Det}_l) - \ln p(D|H_0). \qquad (35)$$

The reported values then can be qualitatively assessed on the Kass & Raftery (1995) scale, such that:

$$\ln K = \begin{cases} < 0 & \text{favours } H_0 \\ 0 \text{ to } 1 & \text{not worth more than a bare mention} \\ 1 \text{ to } 3 & \text{positive} \\ 3 \text{ to } 5 & \text{strong} \\ > 5 & \text{very strong.} \end{cases}$$

We report all modes that have been fitted. Because we report not only the value and uncertainty for the frequency, but also the probability that we have made a detection, decisions about the use of each mode frequency can be assessed at the stage of detailed modelling.

Davies+ 2016

Table 2. Mode frequencies and statistics for KIC 11295426.

n	l	Frequency (μHz)	68% credible (μHz)	$\ln K$
14	0	1465.55	0.58	1.58
14	1	1512.33	0.4	> 6
14	2	1560.71	1.25	-0.14
15	0	1567.82	0.98	2.46
15	1	1613.09	0.29	> 6
15	2	1661.12	0.17	> 6
16	0	1668.11	0.12	> 6
16	1	1713.36	0.08	> 6
16	2	1761.4	0.19	> 6
17	0	1767.37	0.2	> 6
17	1	1813.43	0.12	> 6
17	2	1861.87	0.15	> 6
18	0	1868.02	0.11	> 6
18	1	1914.52	0.08	> 6
18	2	1963.14	0.14	> 6

Conclusions

WP128

Detection of solar-like oscillations:
Neural Nets, Gaia, Granulation

Extraction of global asteroseismic parameters:
Various existing methods, Development on going

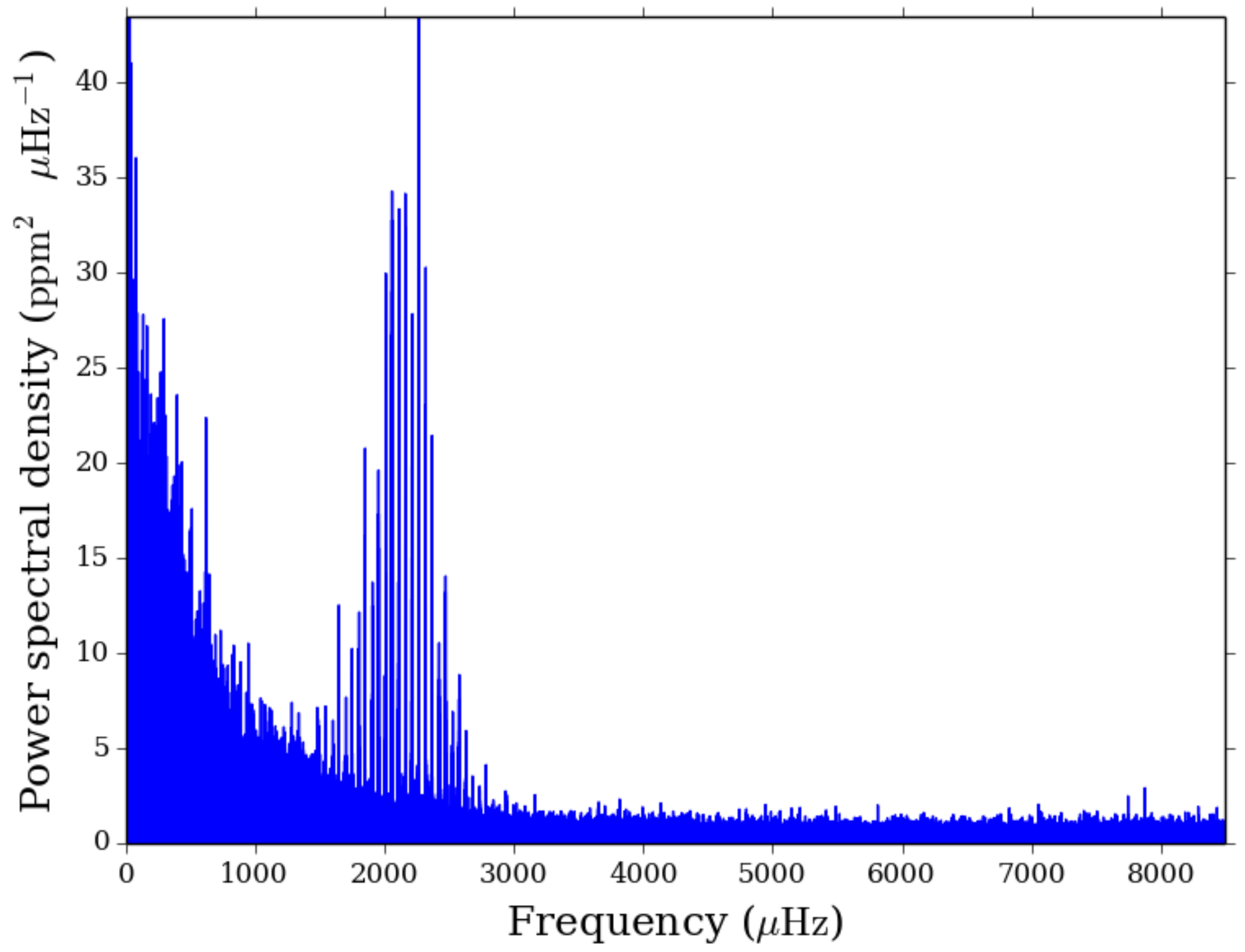
Preparation for peak-bagging:
Categorisation, Mode finding, Mode ID, Development on going

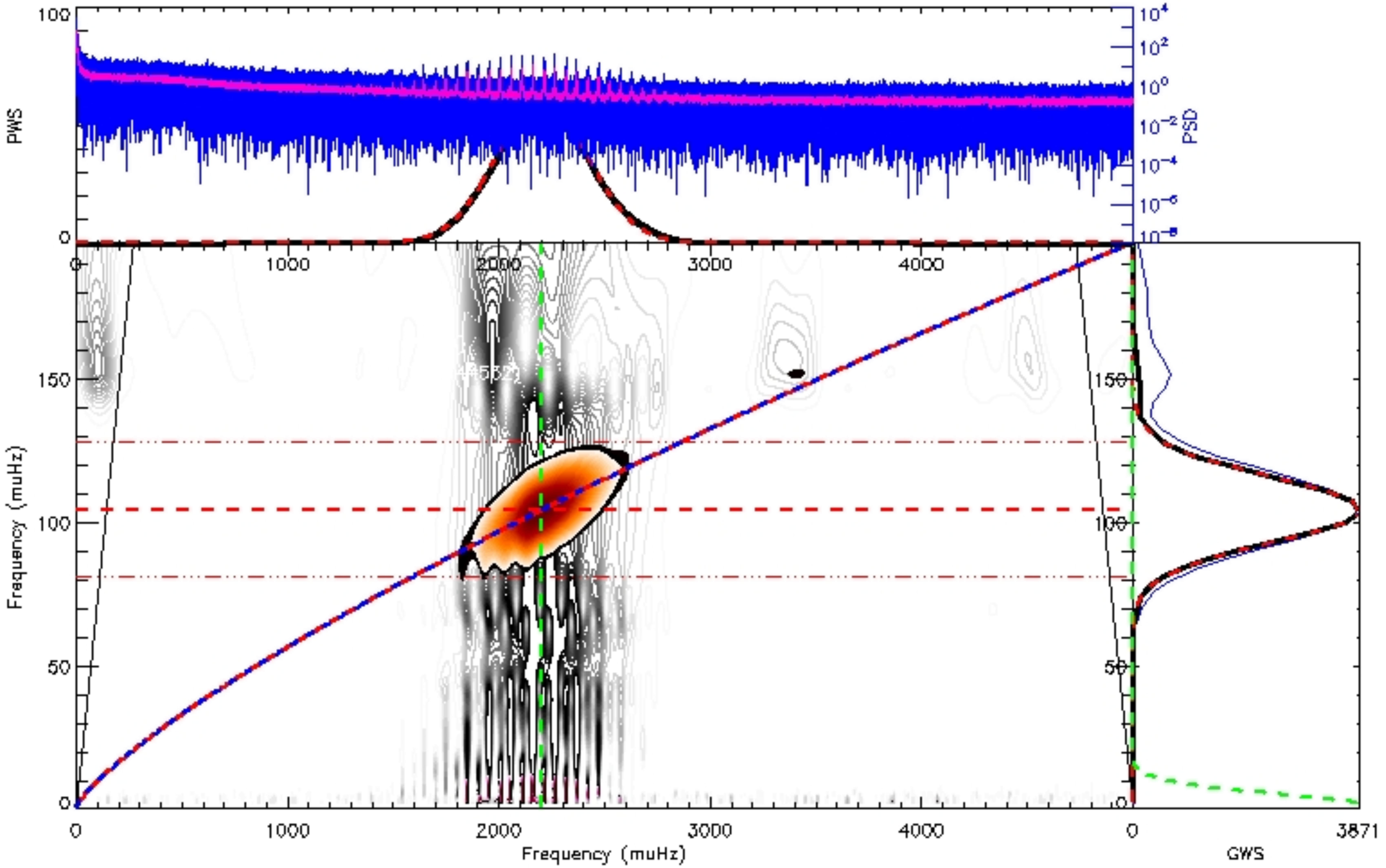
Peak-bagging:
Now just an optimisation problem

Quality control for peak-bagging:
Marginalisation, Mixture models, Development on going

Global properties

WP128





Global properties - Multiple Systems

WP128