Asteroseismology in action

I: From data to science

Dr. Cole Johnston

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Radboud University

Asteroseismology

Image credit: atesevich/DepositPhotos

Asteroseismology

Stars pulsate at every corner of the HRD!

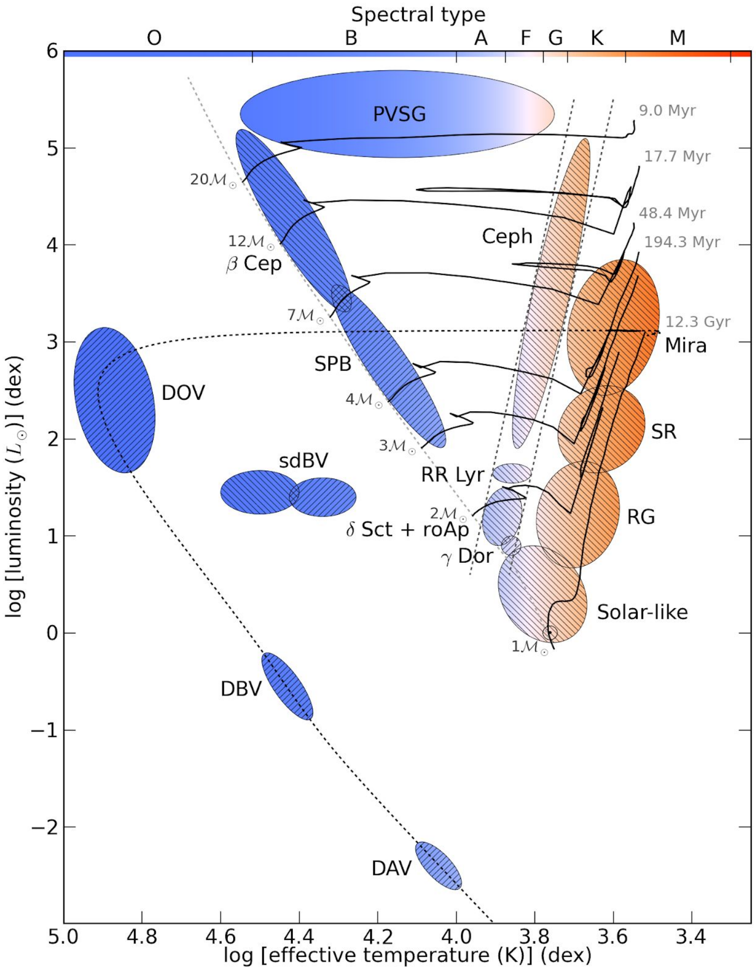

Image credit: Dr. P. Papics

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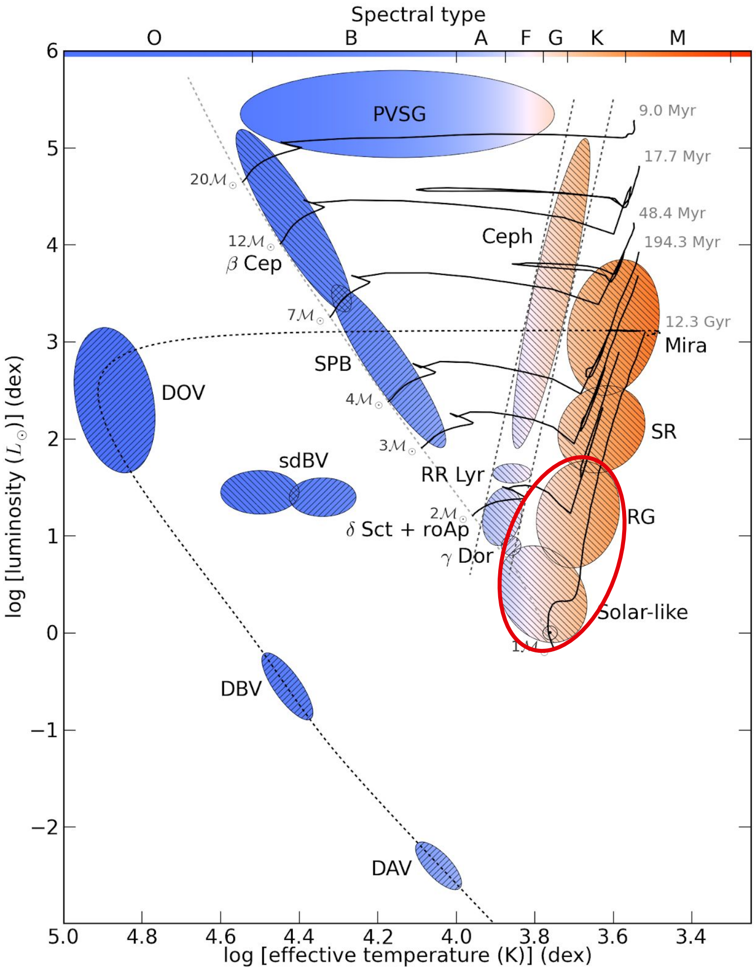

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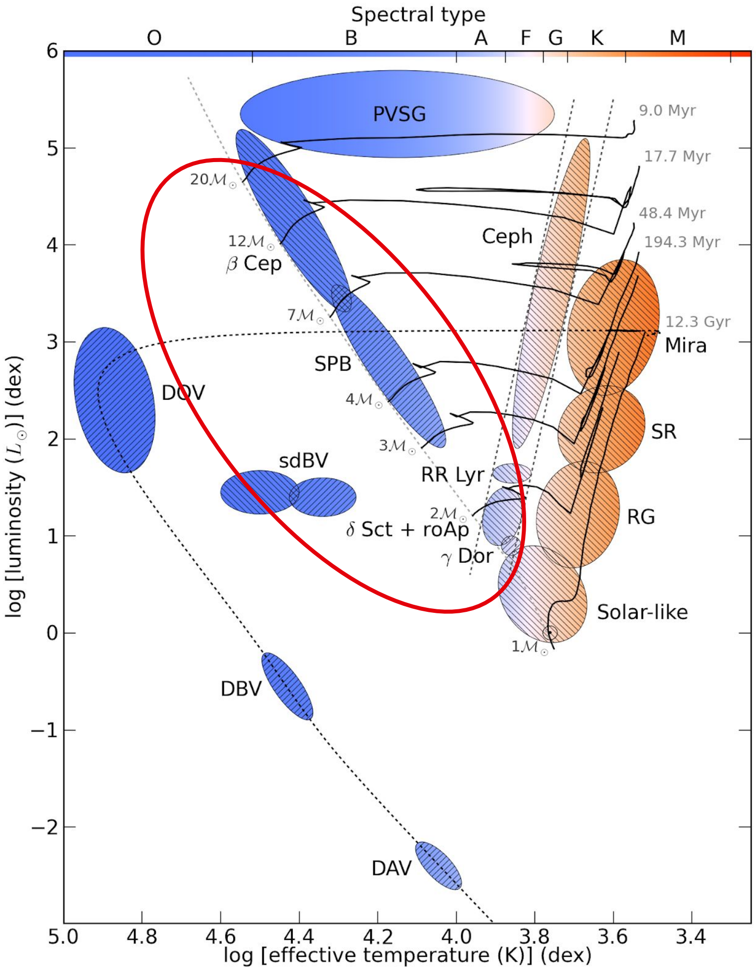

Image credit: Dr. P. Papics

How do we go from data to science

Pulsation frequencies are the fundamental data of asteroseismology

$$\xi(r,\theta,\phi,t) = [(\xi_{r,n,\ell}\,\hat{e}_r + \xi_{h,n,\ell}\,\nabla_h)Y_\ell^m(\theta,\phi)]\exp(-i\omega t)$$

We need to identify (*n,l,m*)

How do we go from time-series observations to modelling?

<u>Time</u>-space → <u>Frequency</u> space

How do we go from data to science

Pulsation frequencies are the fundamental data of asteroseismology

We need to identify (*n*,*l*,*m*)

What are **(*n*,*l*,*m*)**?

$n \rightarrow$ number of radial nodes

$l \rightarrow$ number of surface nodal lines

$m \rightarrow$ number of longitudinal surface nodal lines

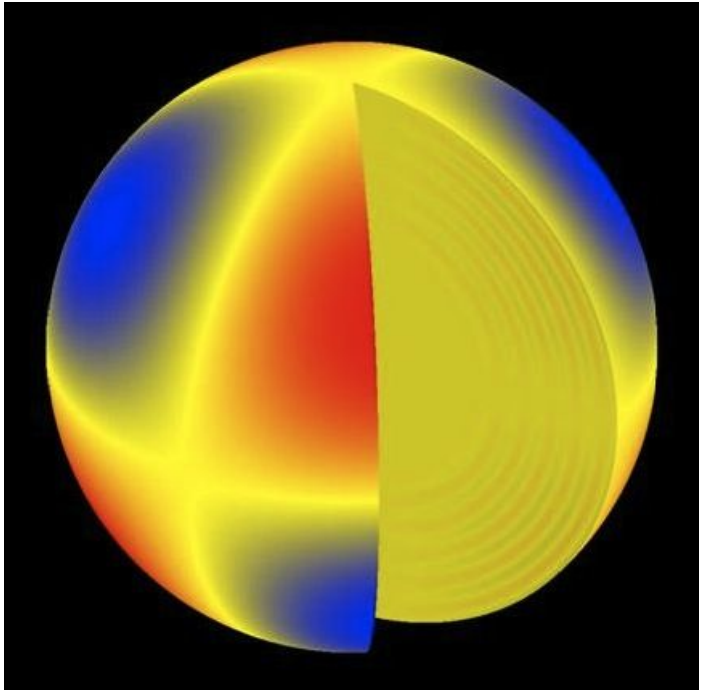

Image credit: NASA

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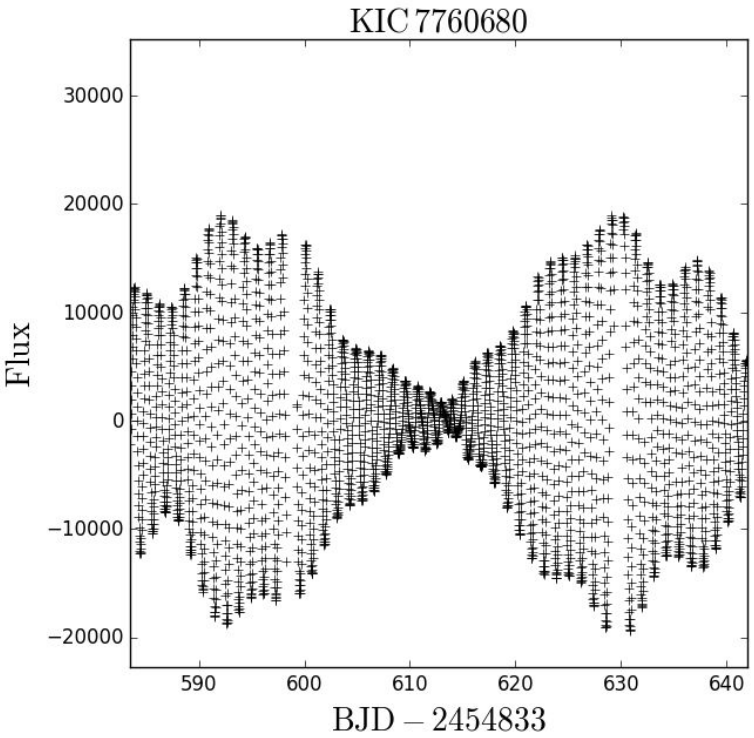

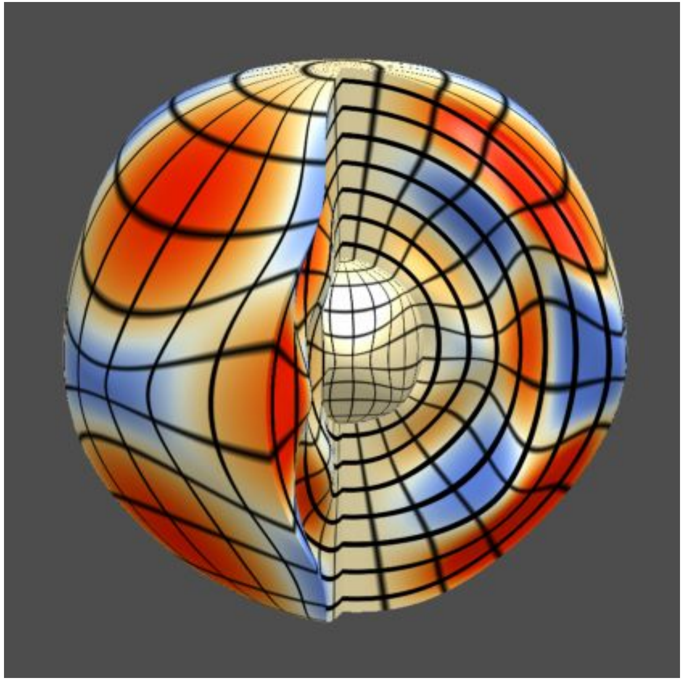

Image Credit: Rich Townsend

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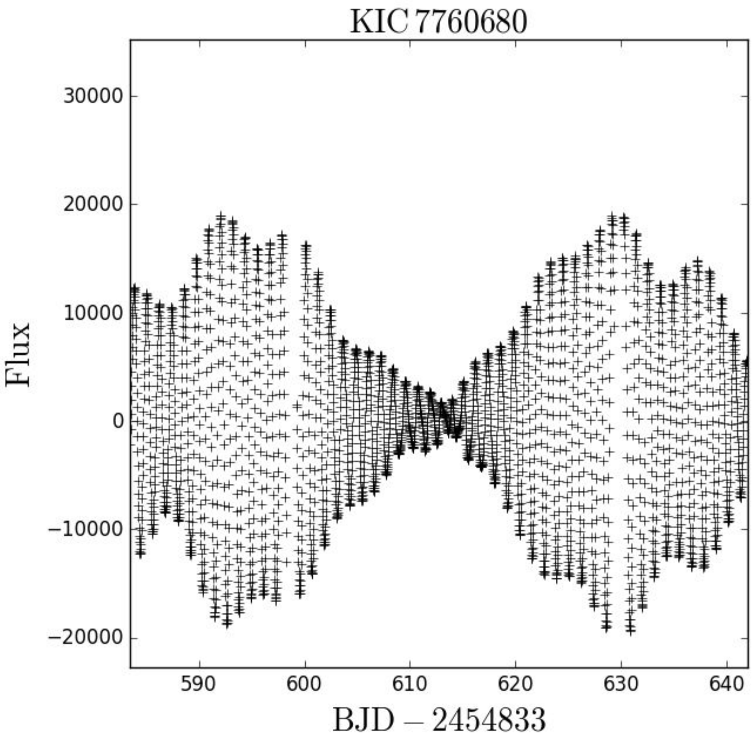
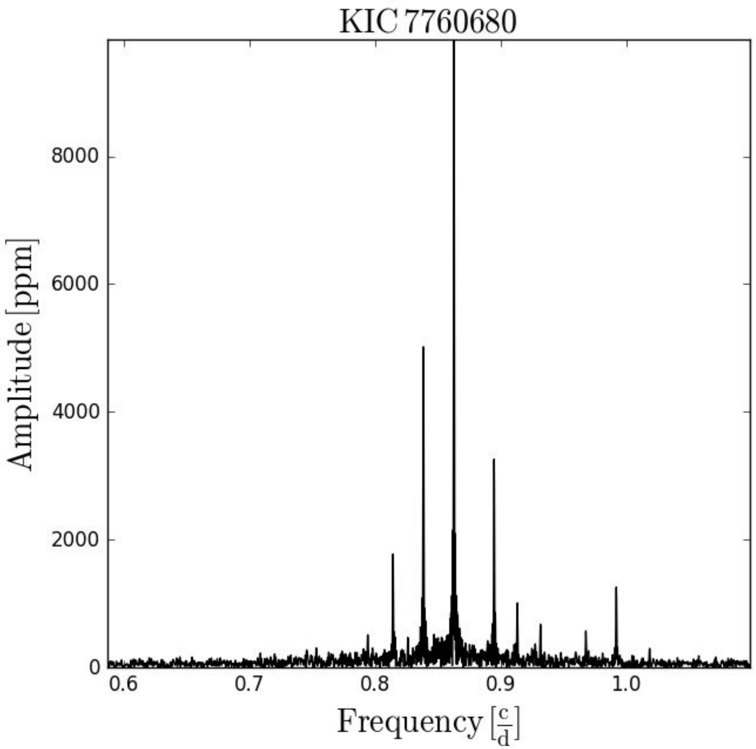
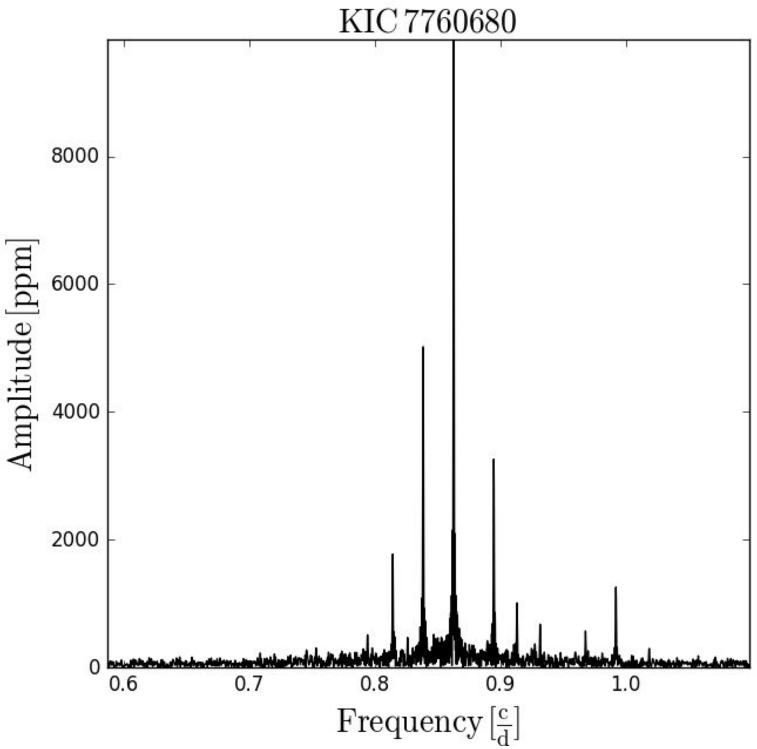




How do we go from data to science

What does a periodogram do:

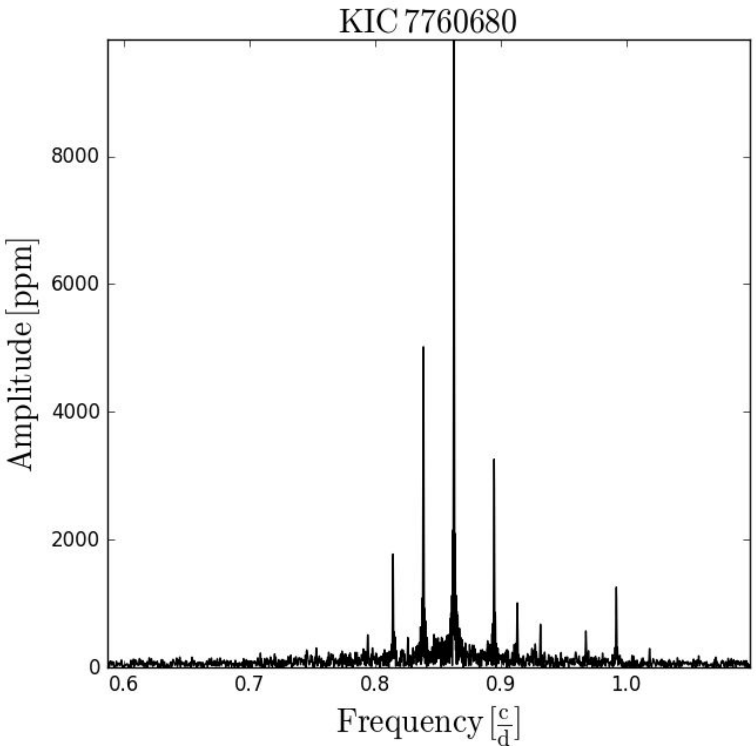
- Picks a range of frequencies
- Make a sine-wave for each frequency
- If the sine-wave matches the data, it has a high amplitude at that frequency



How do we go from data to science

Periodogram options:

- Period04
- Lightkurve
- pythia
- astropy
- numpy
- etc.



Data Considerations

<u>Things to consider</u>:

- Time-span
- Integration time
- Cadence
- Duty-cycle
- Filter(s)
- Number of data points
- Sources of noise

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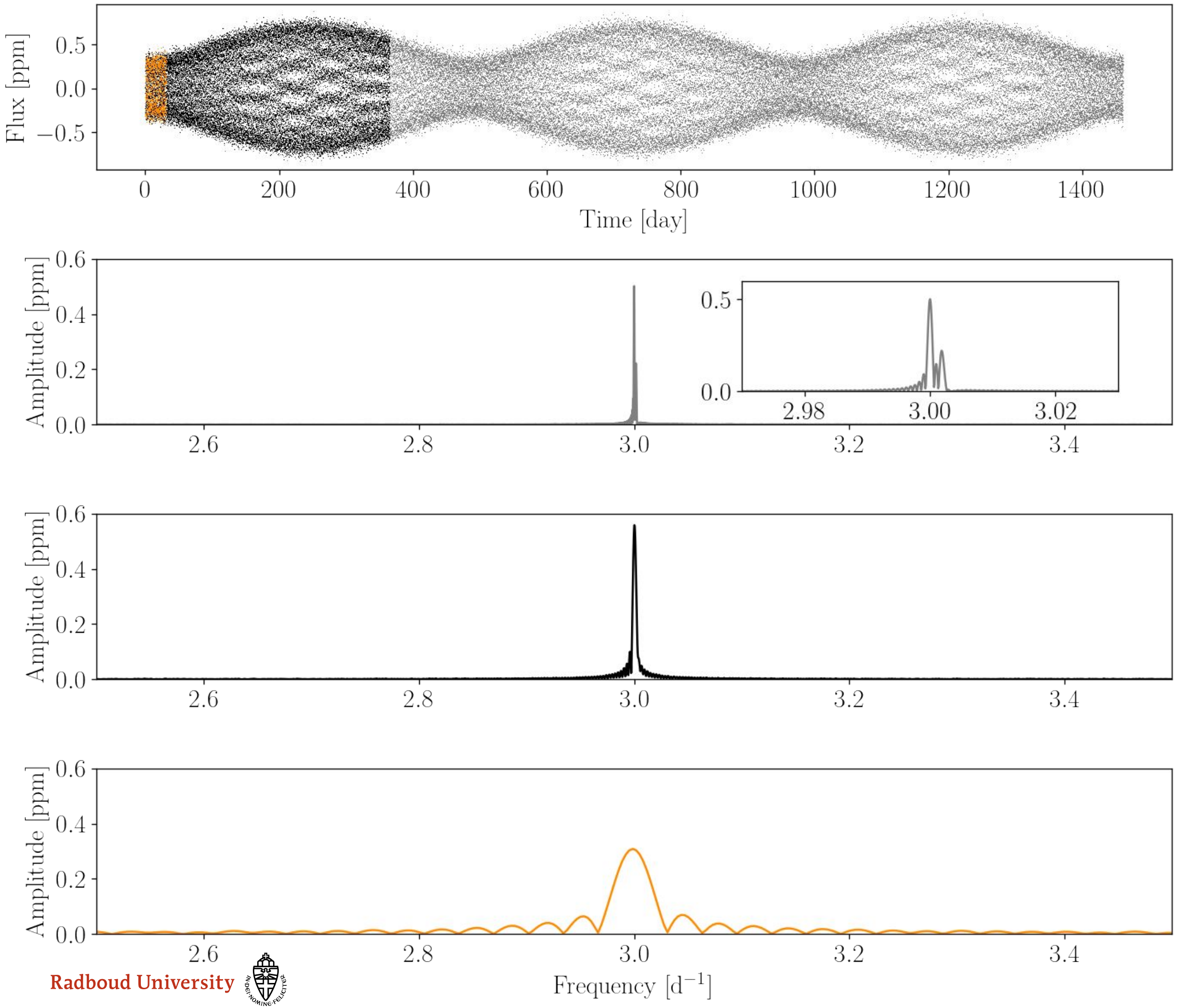
$$\boxed{\Delta f = \frac{1}{max(t) - min(t)}}$$



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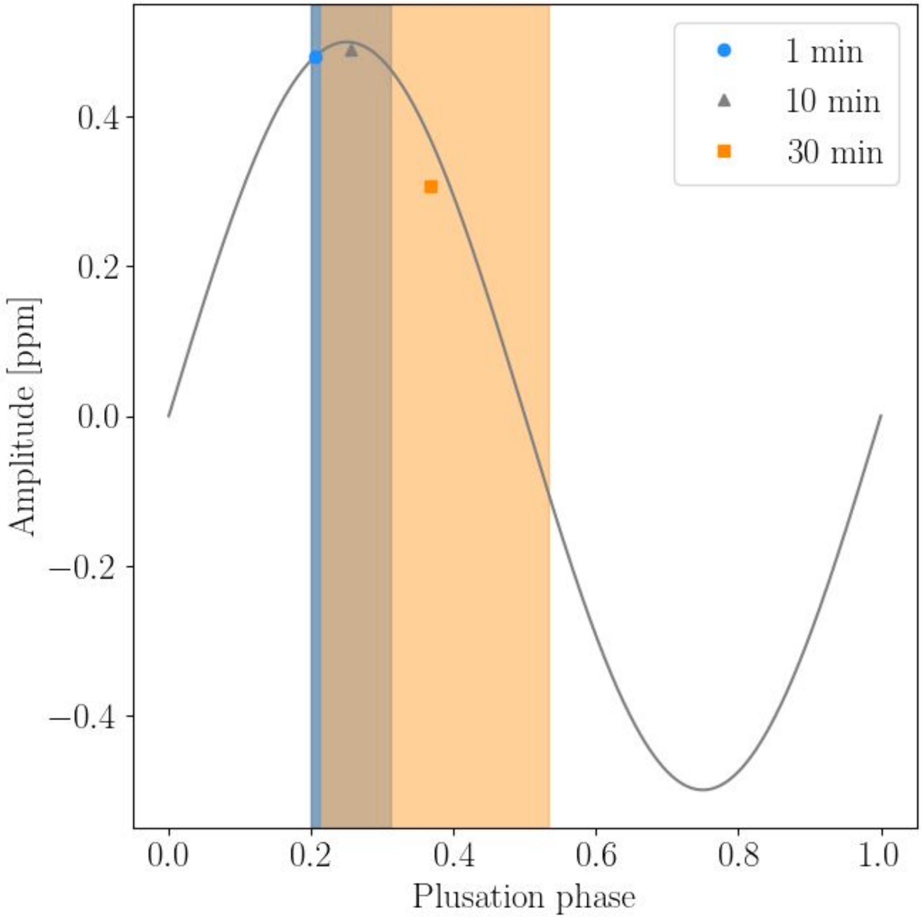

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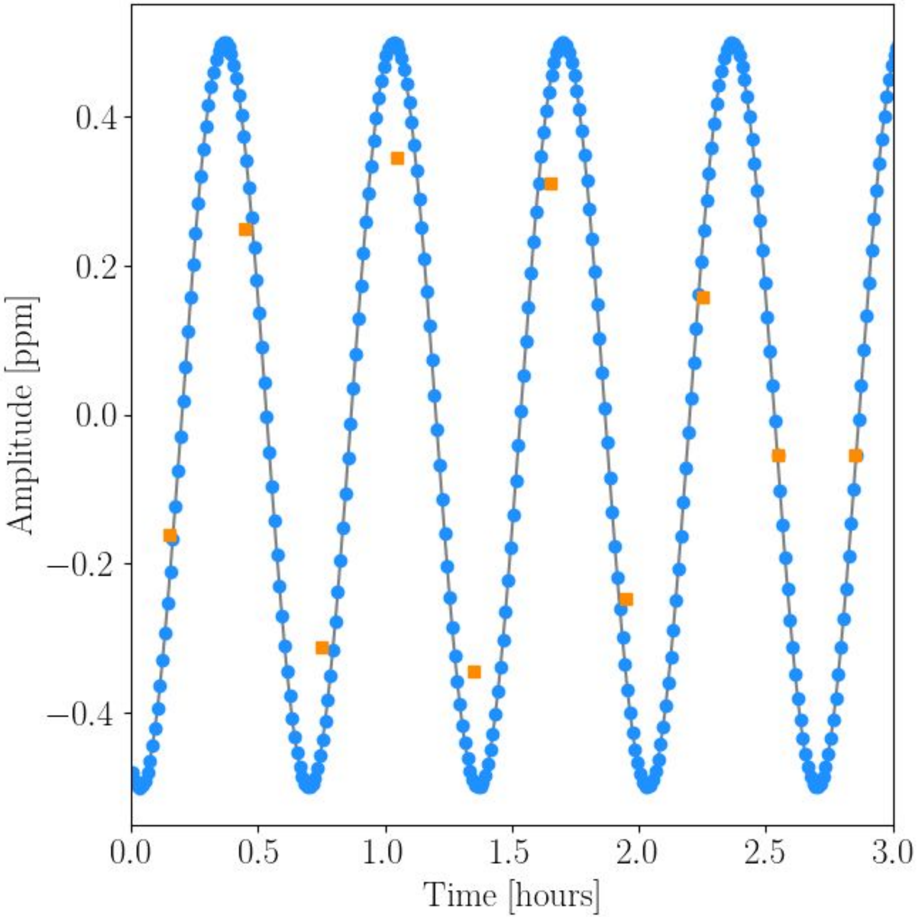

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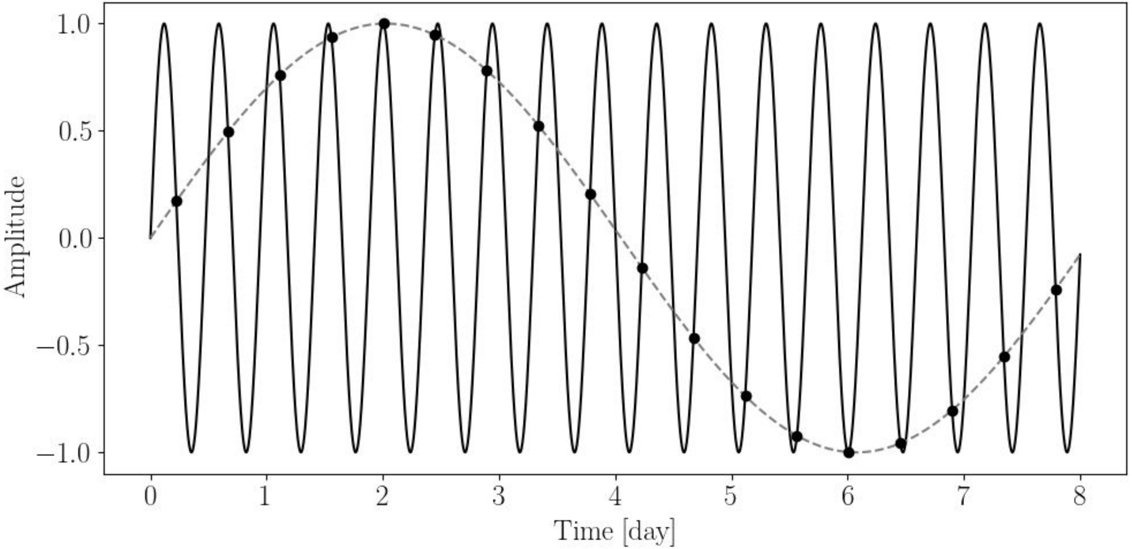

$$f_{\mathrm{nyq}} = \frac{1}{2\Delta t}$$

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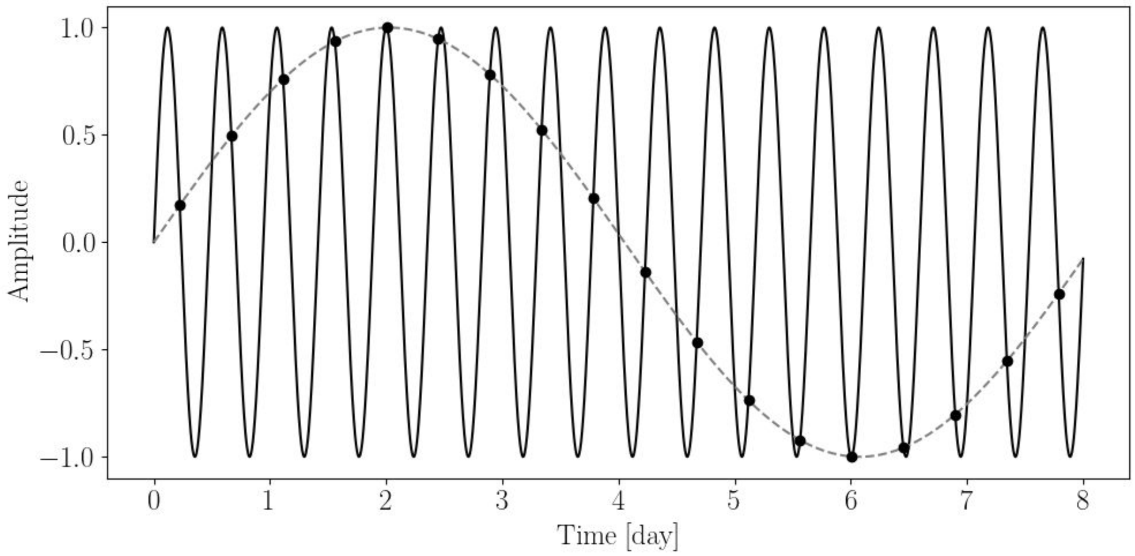

$$f_{\rm nyq} = \frac{1}{2\Delta t}$$

* * Does not strictly apply to un-evenly sampled data**

Data Considerations

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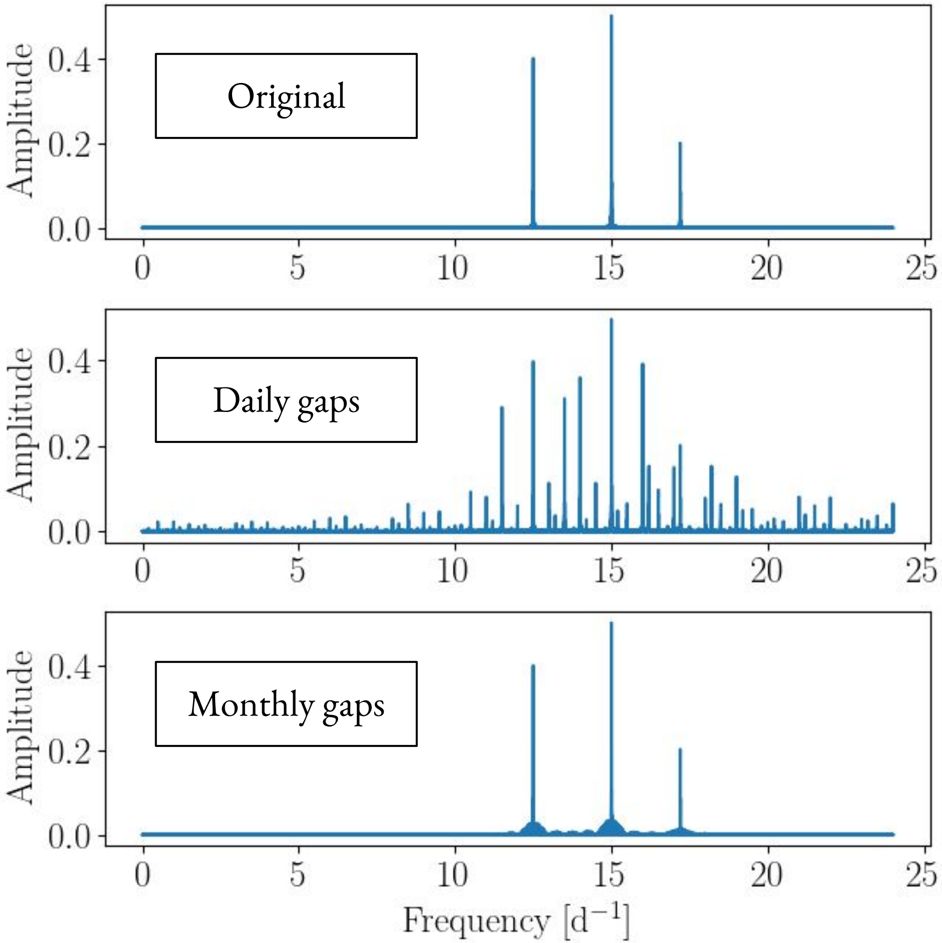

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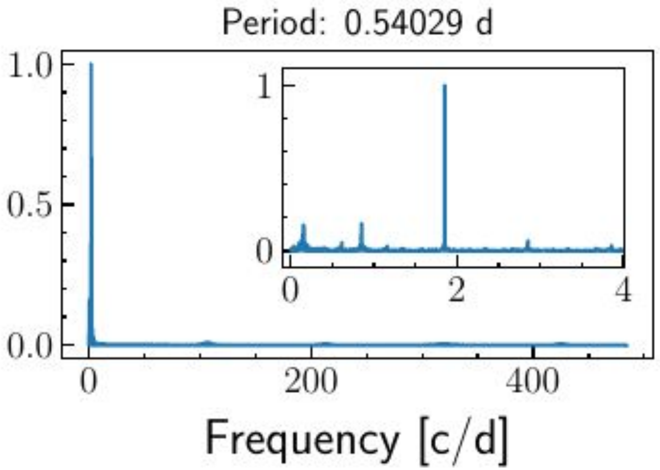

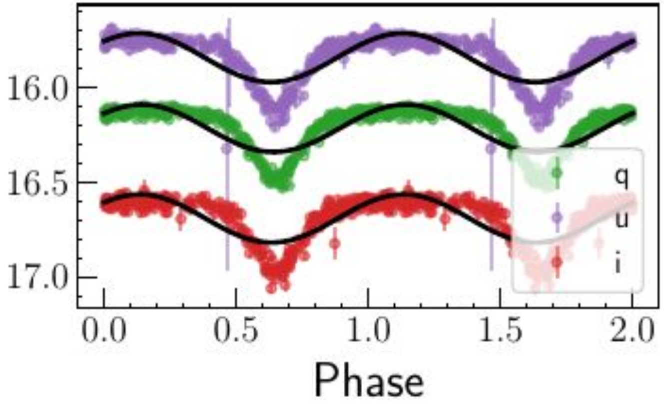

Data Considerations

<u>Things to consider</u>:

- Time-span
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- Sources of noise

$$\sigma_\nu = \frac{\sqrt{6}\,\sigma_N}{\pi\sqrt{N}\;A\;T}, \quad \sigma_A = \sqrt{\frac{2}{N}}\,\sigma_{\mathrm{N}}$$

$$\sigma_\delta = \frac{\sigma_N}{\pi\,\sqrt{2N}\;A}$$

Data Considerations

Ground based

Space based

Things to consider:

- Time-span
- Integration time
- Cadence
- Duty-cycle
- Filter(s)
- Number of data points
- Sources of noise

Ground based:

- Clouds
- Atmosphere
- Air-mass
- CCD sensitivity
- Non-linearity
- Thermal issues
- Trailing issues

Space based:

- Scattered light
- Pointing loss
- Thermal issues
- CCD sensitivity
- Jitter
- Correlated noise

Both:

- Crowding
- Third light
- Background subtraction

How do we go from data to science

Pulsation frequencies are the fundamental data of asteroseismology

How do we go from observations to modelling?

- Photometry
- Spectroscopy

How do we go from data to science

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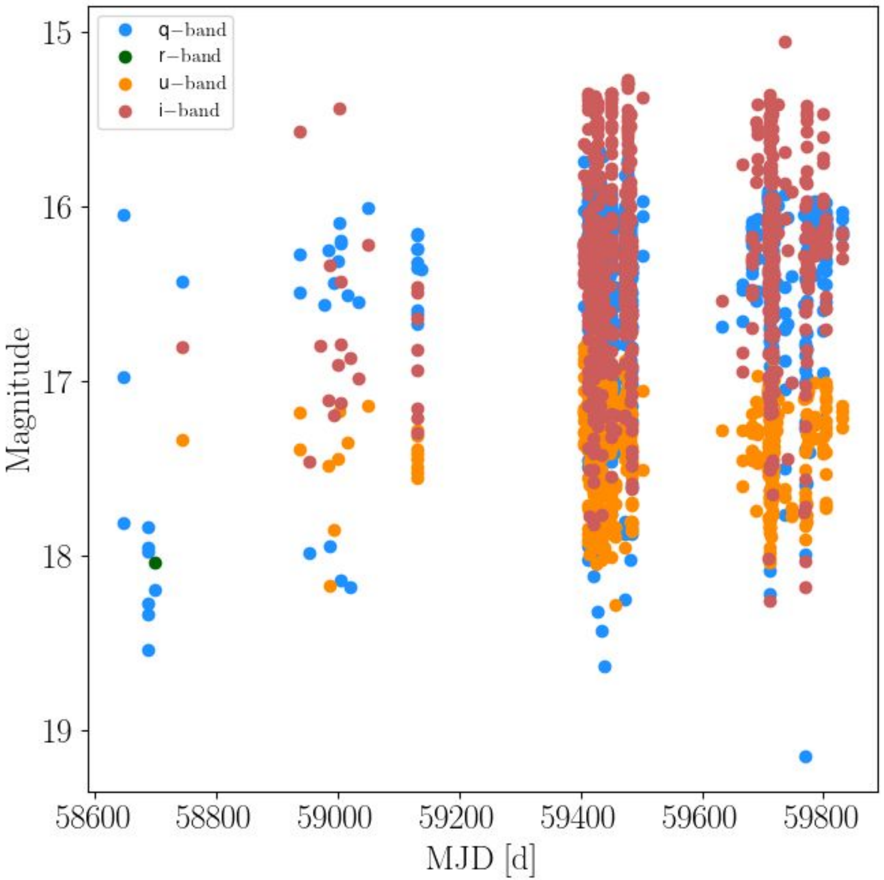
How do we go from observations to modelling?

- **Photometry**
- Spectroscopy

How do we go from data to science

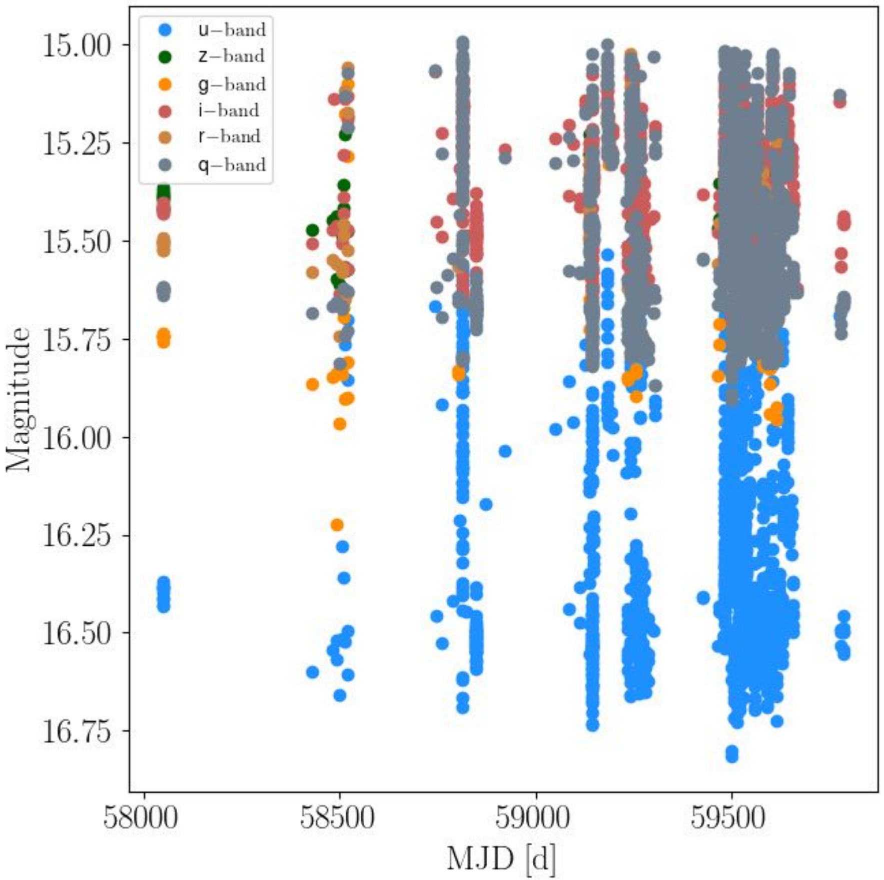
What do we need to consider?



How do we go from data to science

What do we need to consider?

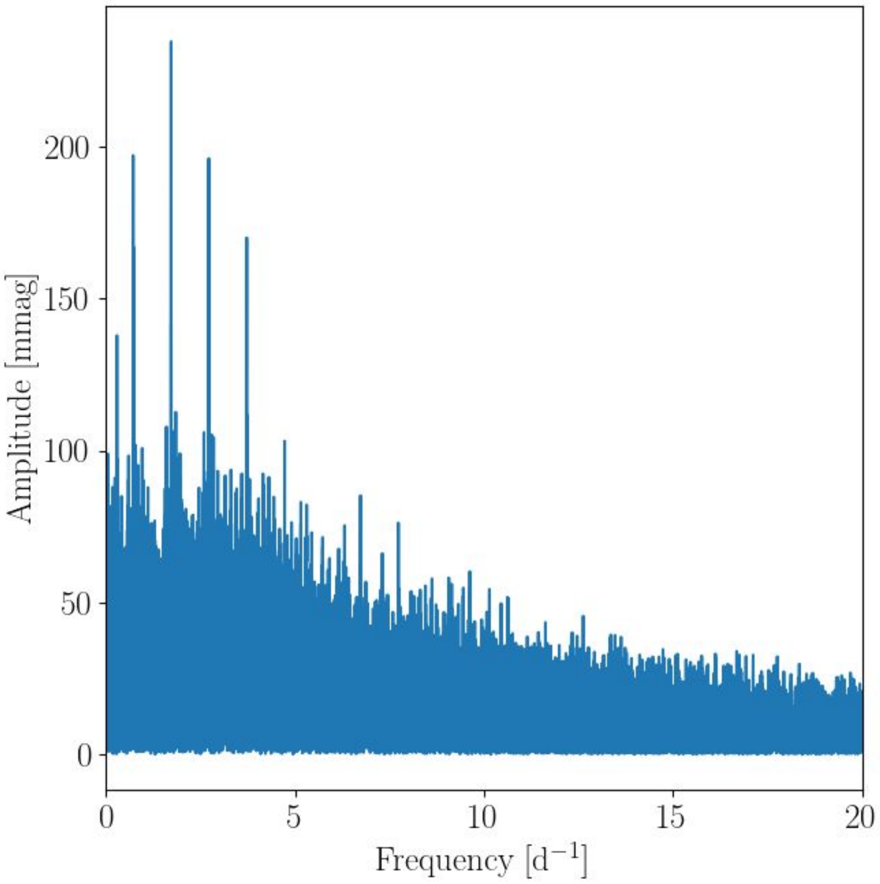
- 6 filters (technically)
- 60 sec exposures
- u has 1419 data points
- i has 1405 data points
- q has 1677 data points
- g,r,z have 99 data points each
- Time-base = 1737.11 days
- df = 0.0006 c/d
- Very, very irregular sampling



How do we go from data to science

What do we need to consider?

- 6 filters (technically)
- 60 sec exposures
- q-band: 808 points
- u-band: 635 points
- q-band: 717 points
- Time-base = 1181.92 days
- df = 0.0009 c/d
- Very, very irregular sampling

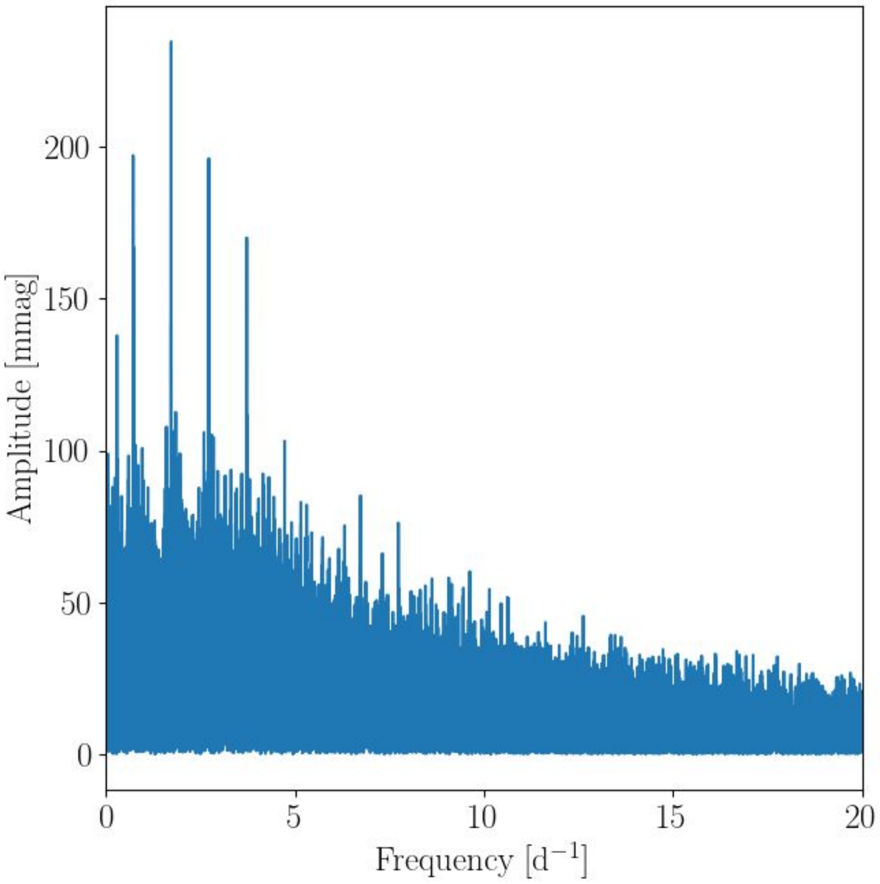


How do we go from data to science

Are there 8 independent frequencies?

$$F_N(\nu) = (F * W_N)(\nu)$$

$$\left| W_N\left(\nu + \frac{n}{\Delta t}\right) \right| = |W_N(\nu)|$$



How do we go from data to science

Check the window function!!

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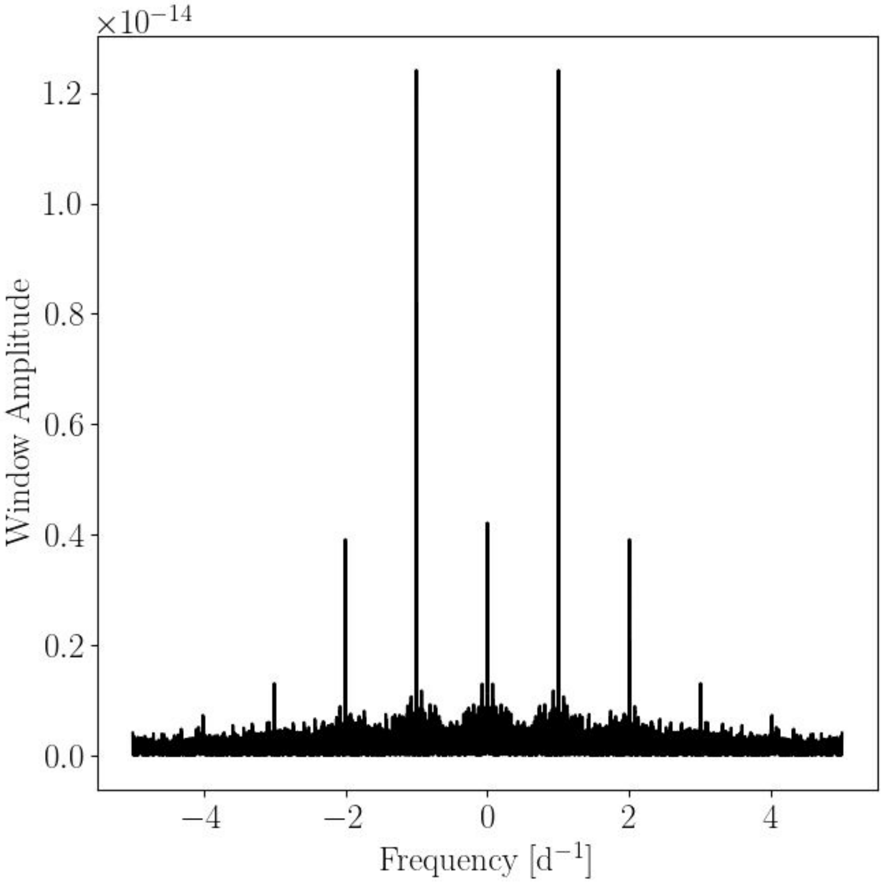


How do we go from data to science

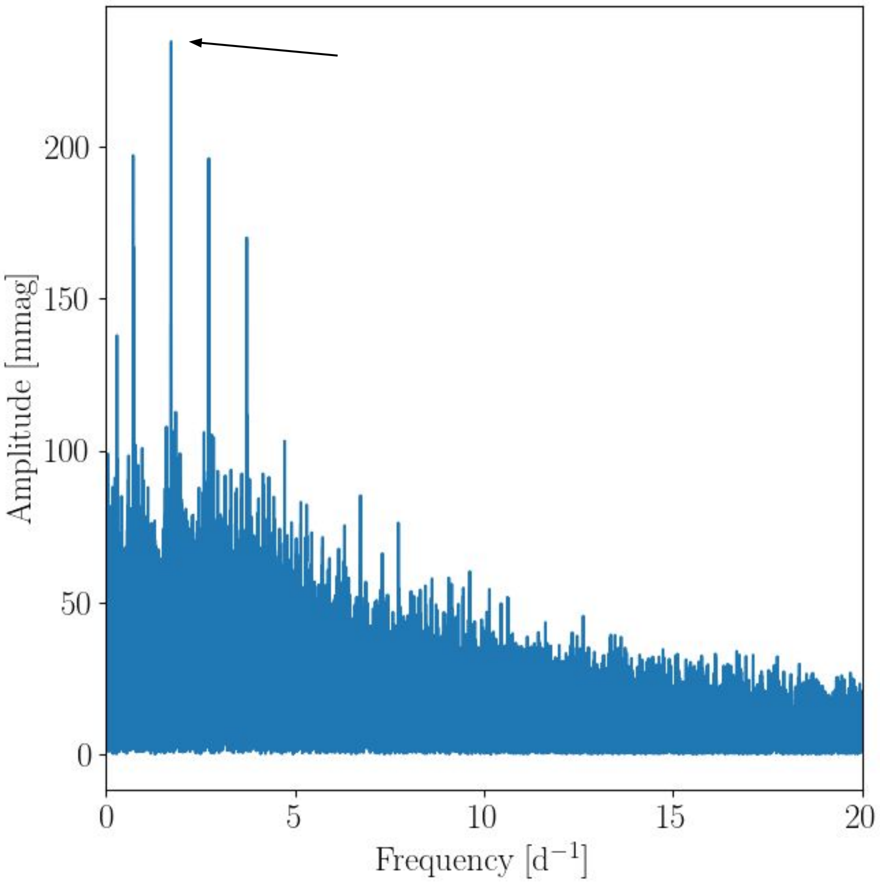
Pick the highest amplitude signal

Phase fold:

$((t-t_0)/P_{orb}) \bmod 1$

Frequency: 1.717794 c/d

Period: 0.582142 d



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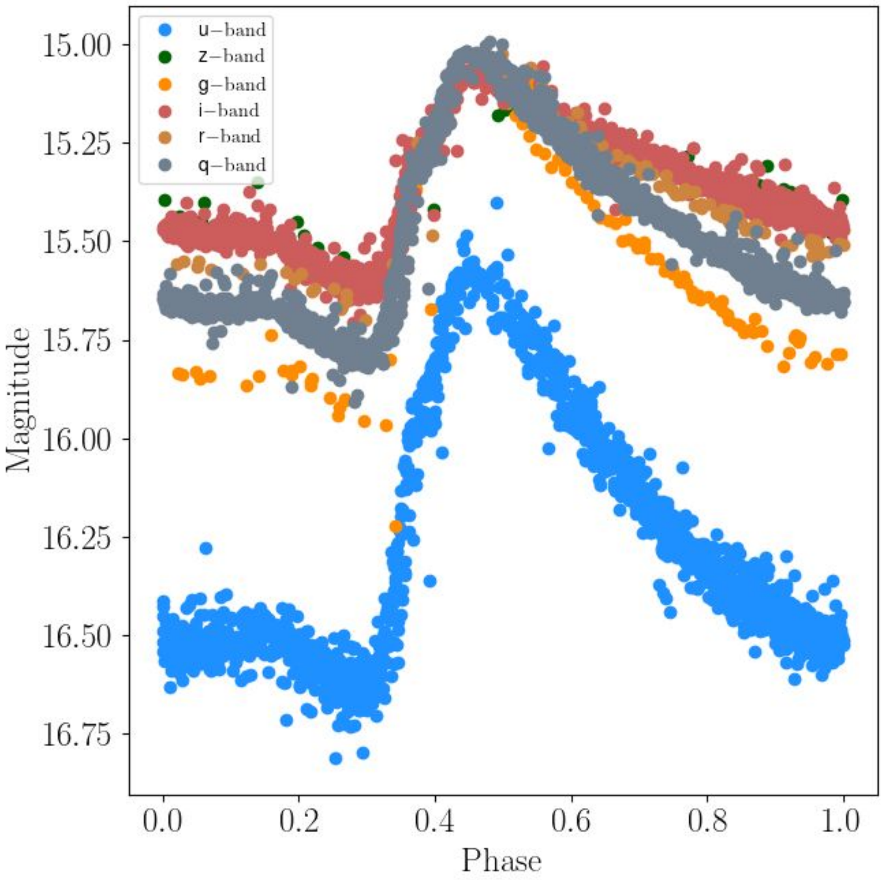


How do we go from data to science

Let's look from space

KIC 9751996

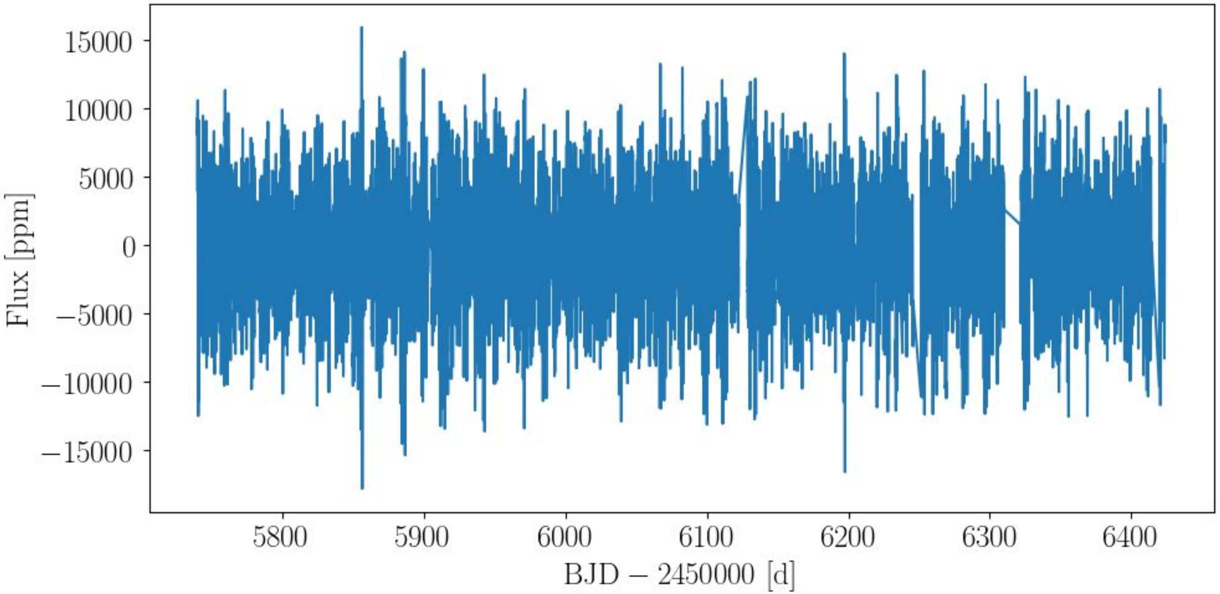
γ Doradus pulsator

$\Delta T = 684.16$ d

$\delta f = 0.0015$

$\delta t = 29.4$ min

$f_{nyq} = 24\ d^{-1}$



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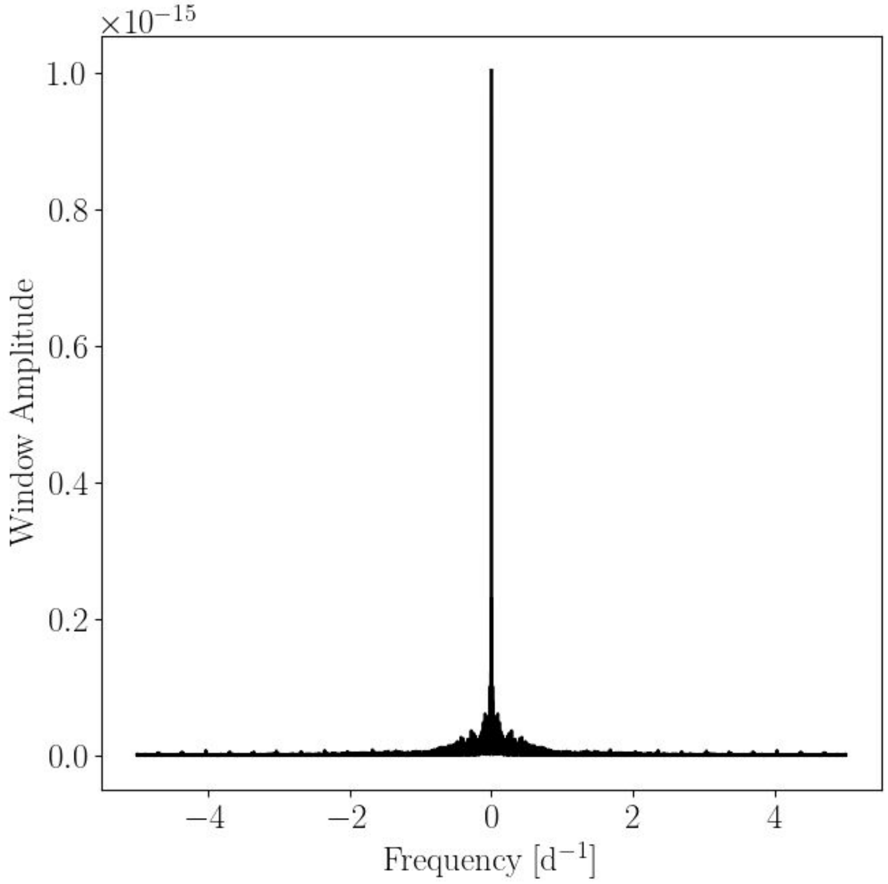

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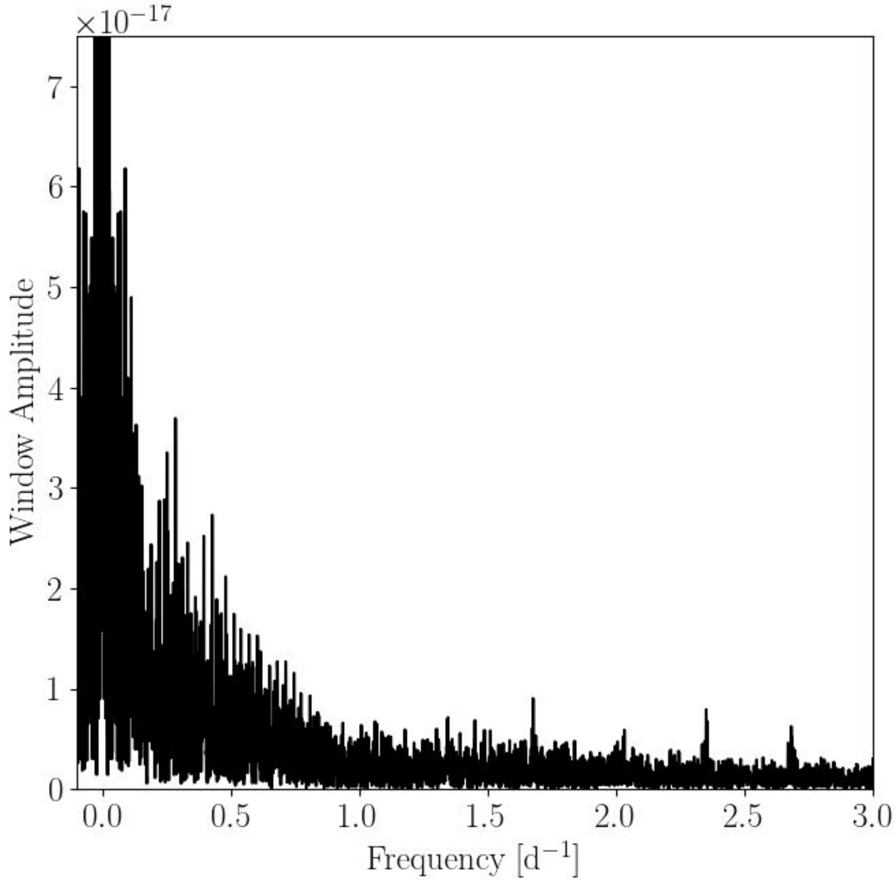

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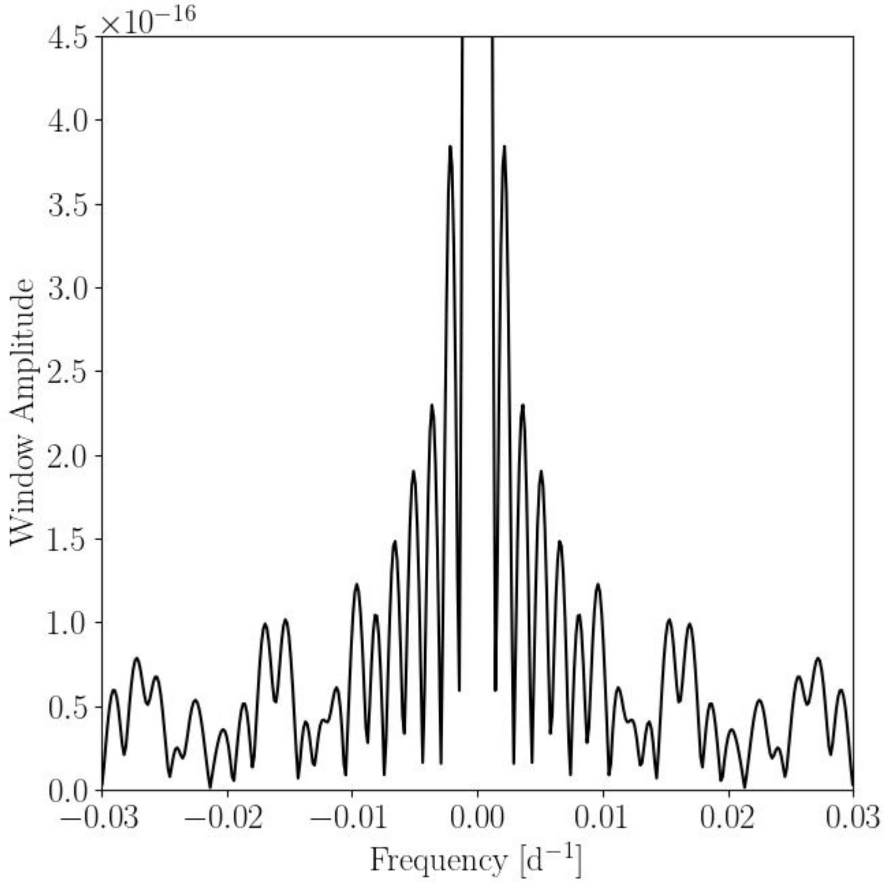

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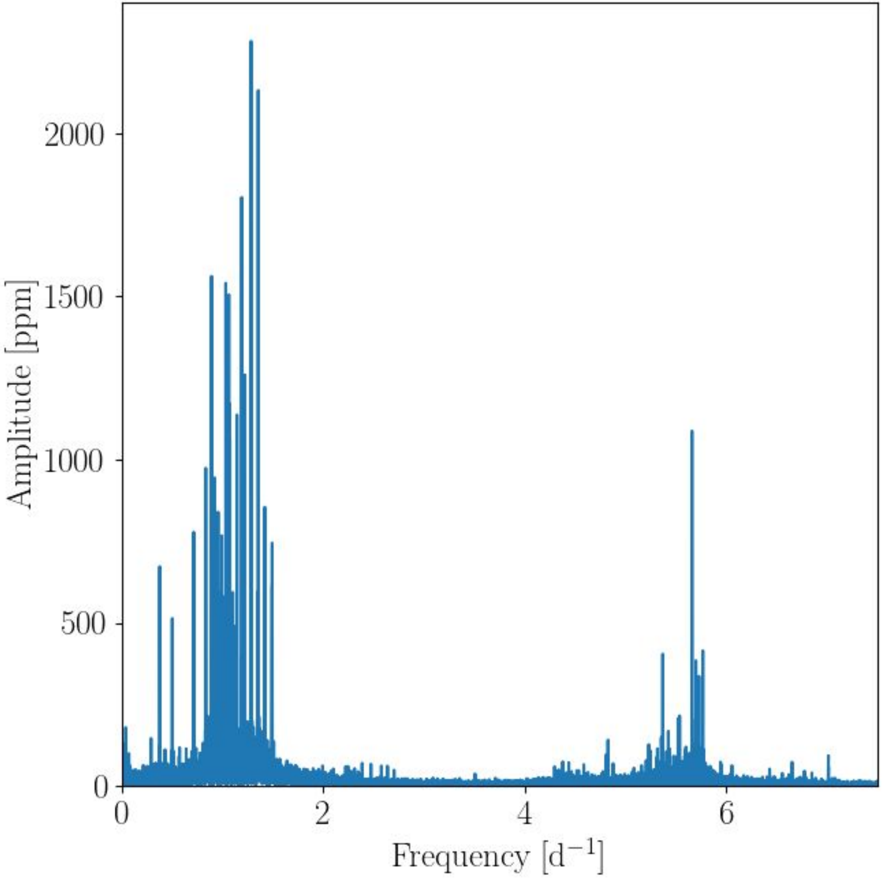

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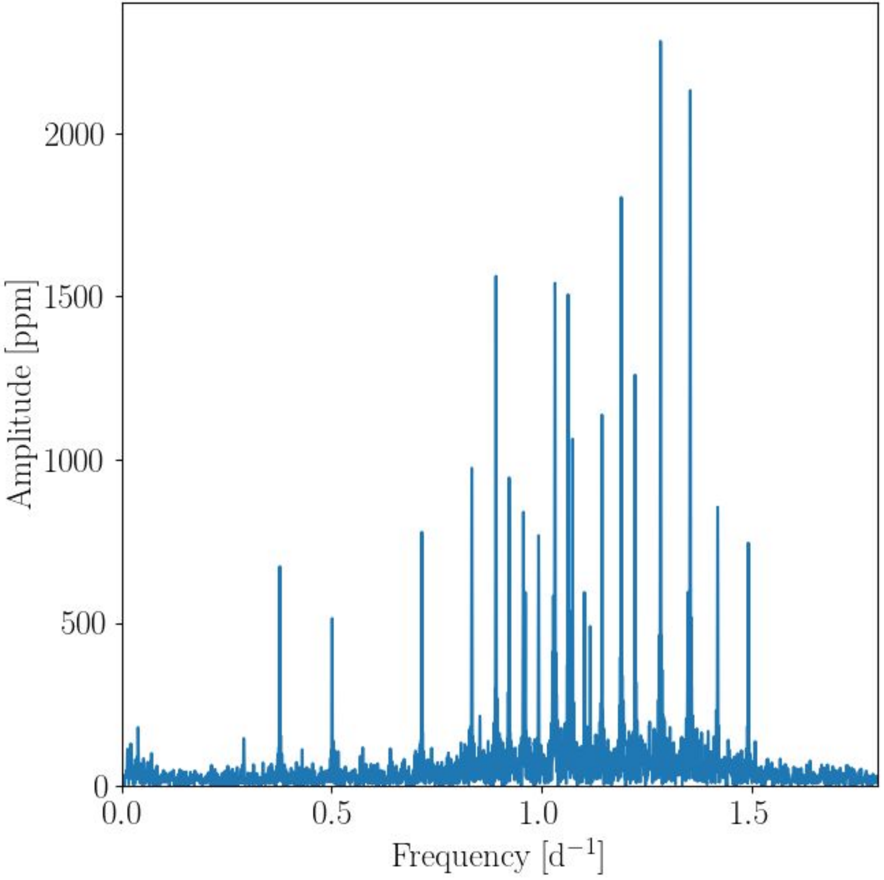
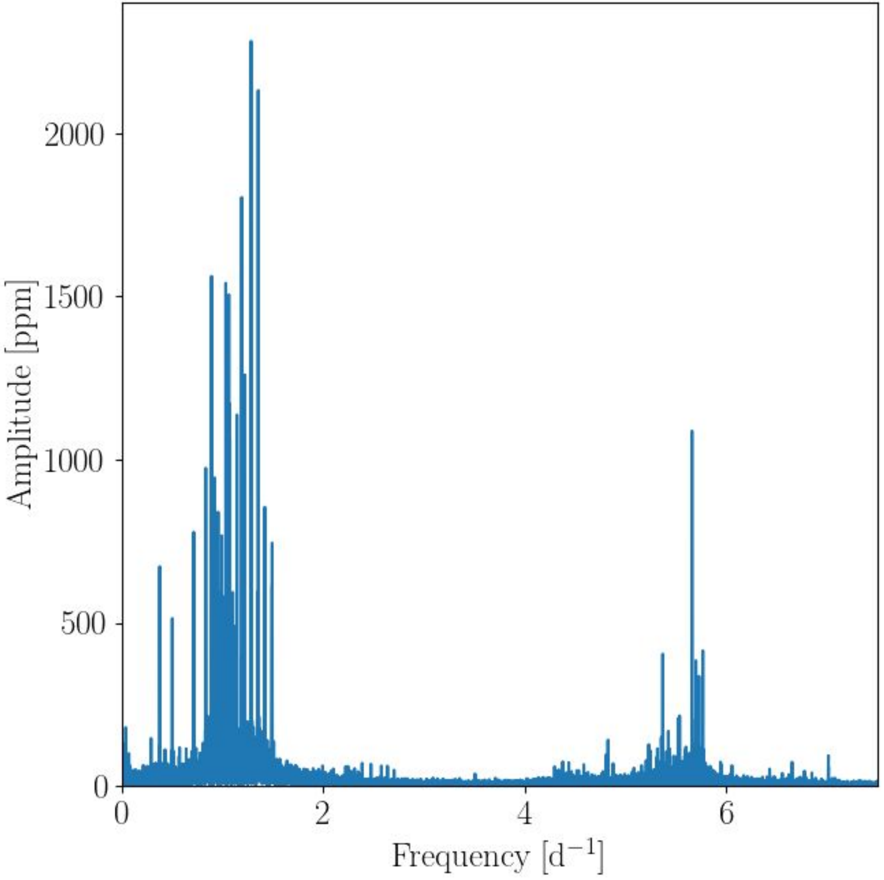


Iterative pre-whitening

You want to extract all **significant** pulsation frequencies.

How do you go about doing this?

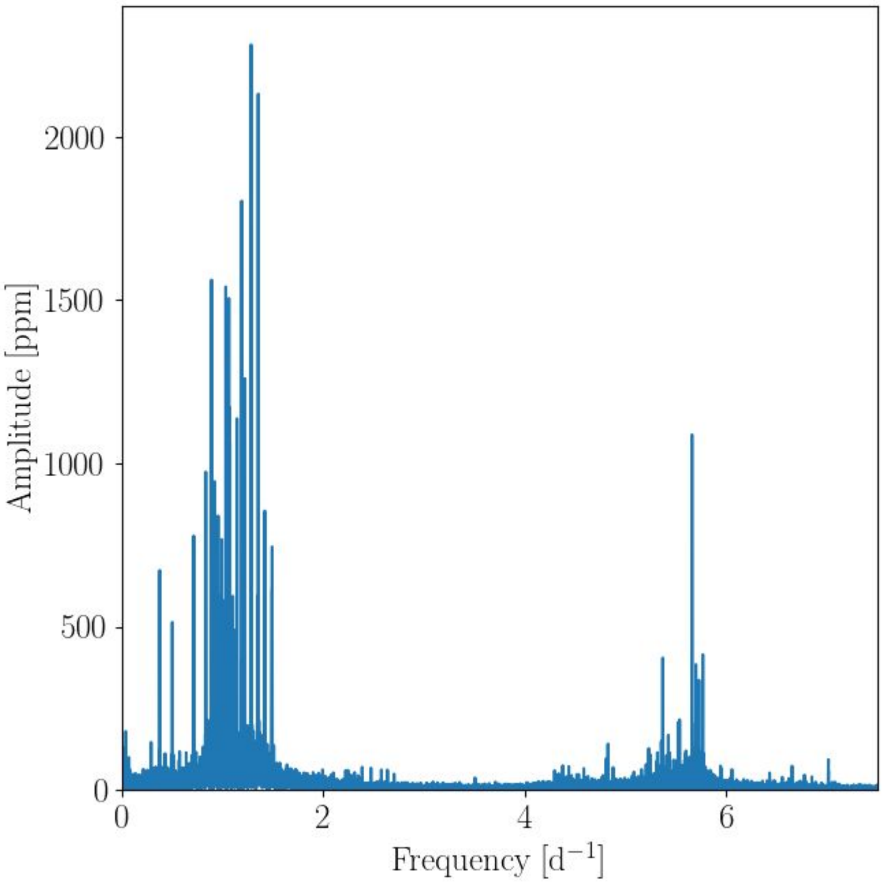


Iterative pre-whitening

Consider a time series as:

$$F\left(t_i\right) = C + \sum_{j}^{N} A_j \sin\left(2\pi f_j t_i + \phi_j\right)$$

- Pick a frequency
- Fit a sinusoid with amplitude A, frequency f, and phase ϕ
- Subtract sinusoid
- Repeat until stopping criterion



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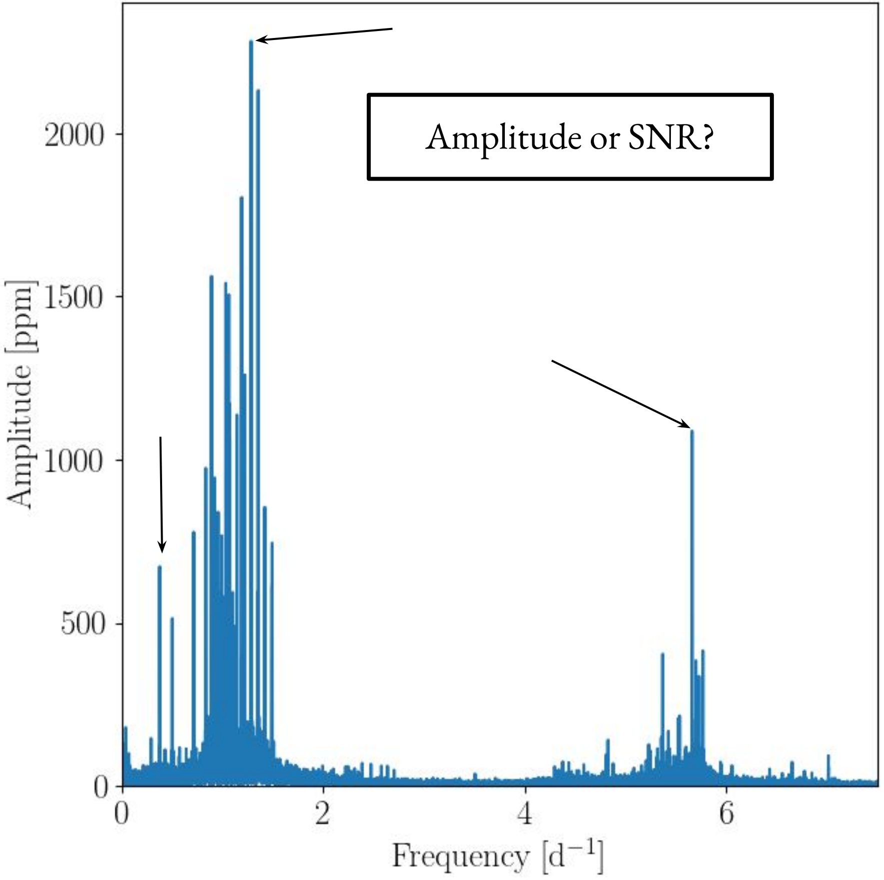

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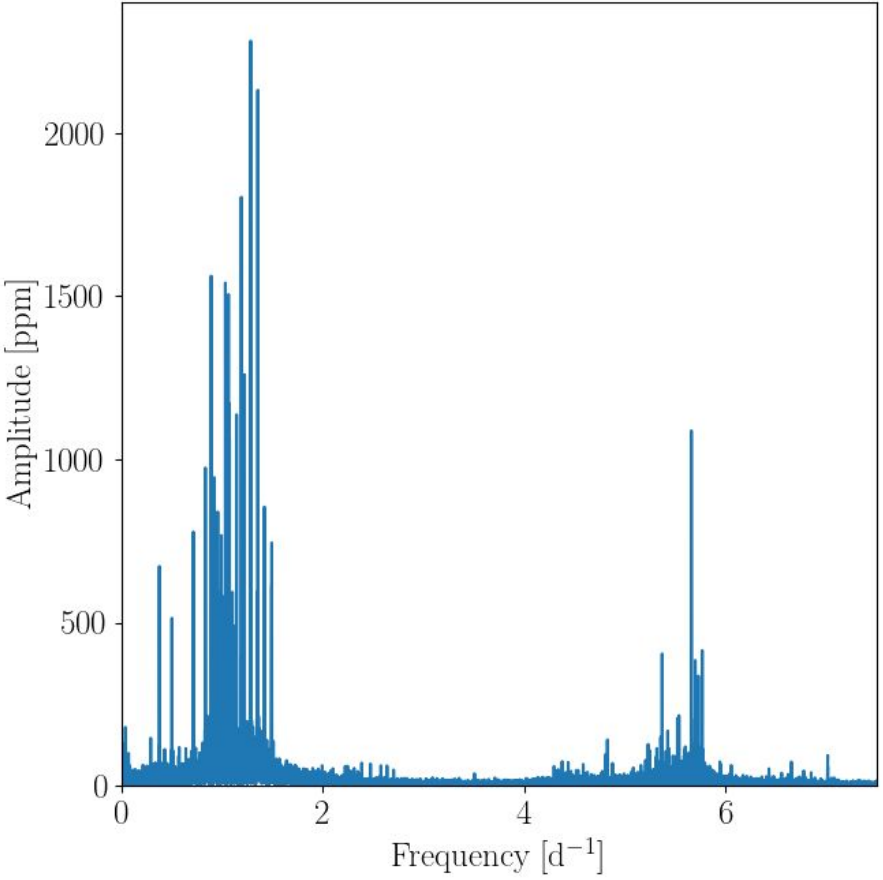

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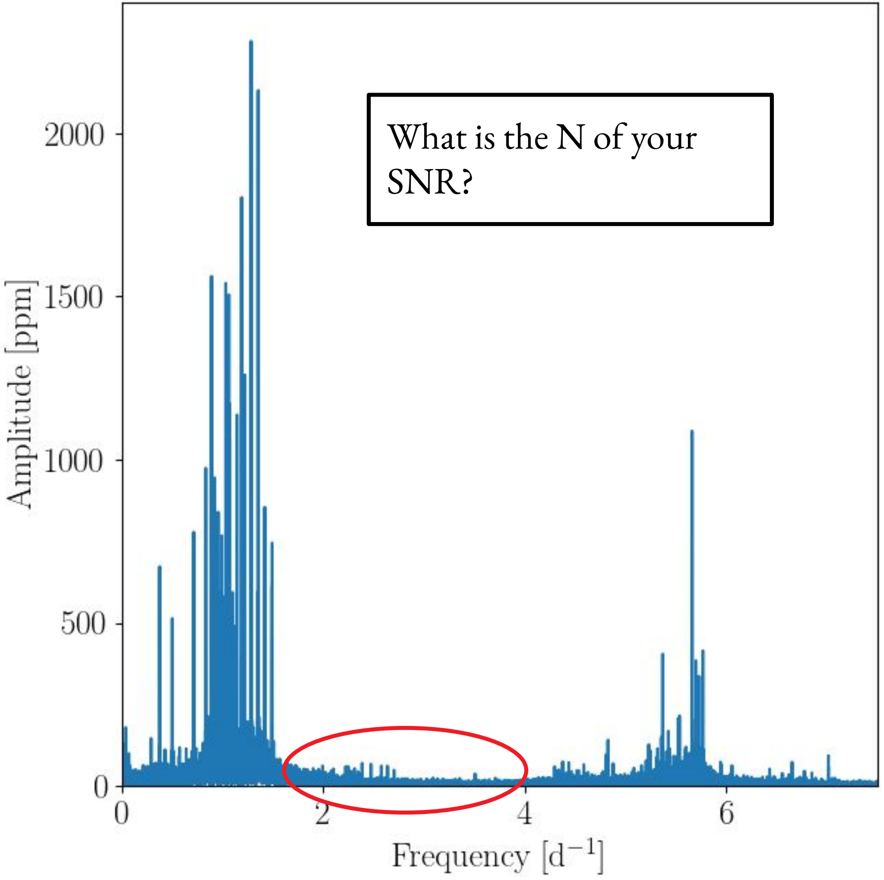
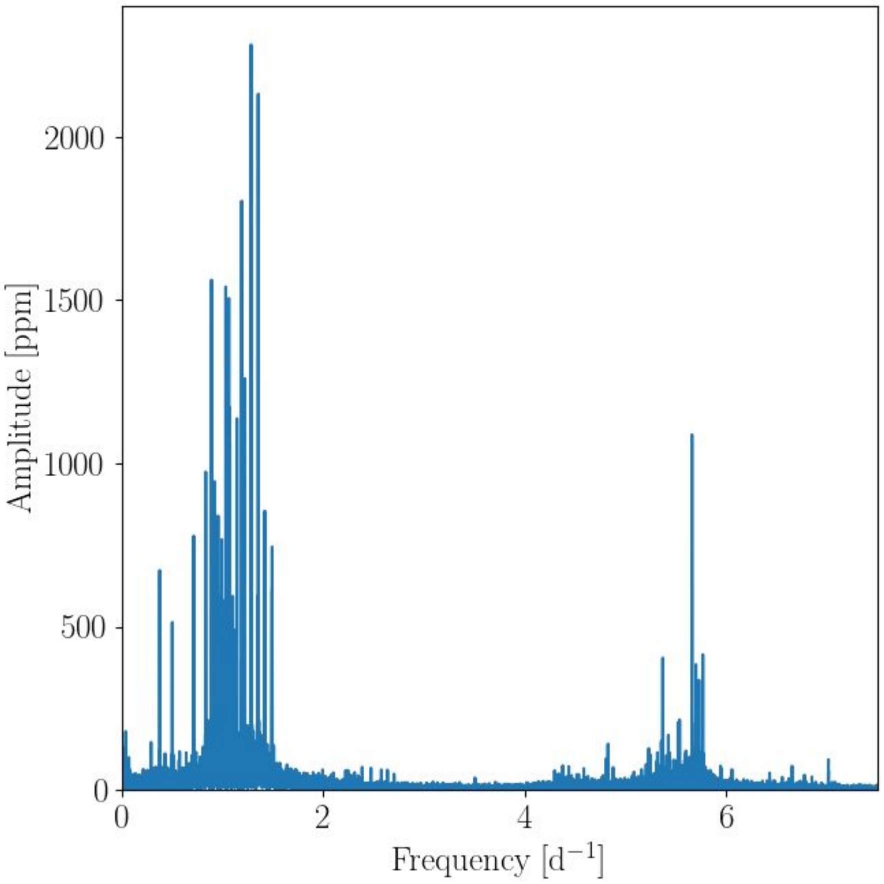


Iterative pre-whitening

You have a list of frequencies ;
what next?

- Final NLLS optimisation
- Check frequency resolution
- Check for combination frequencies
- Re-calculate SNR



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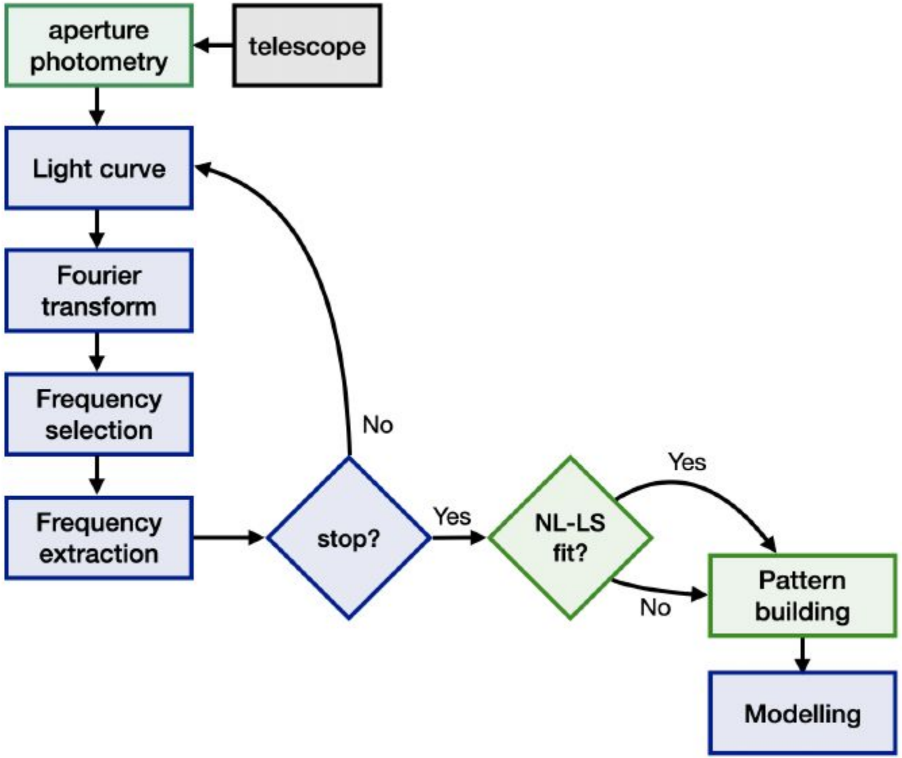

Bowman & Michielsen 2021

Iterative pre-whitening

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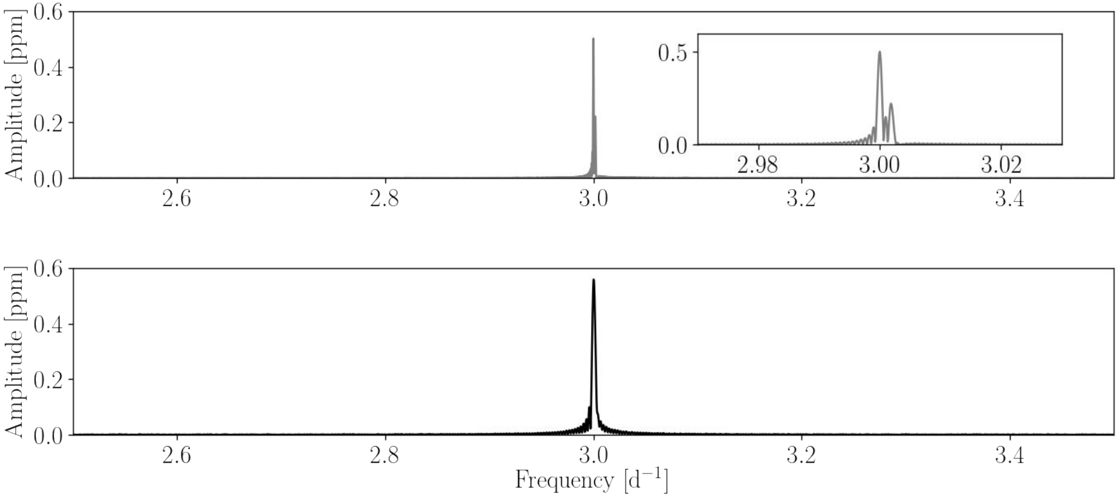

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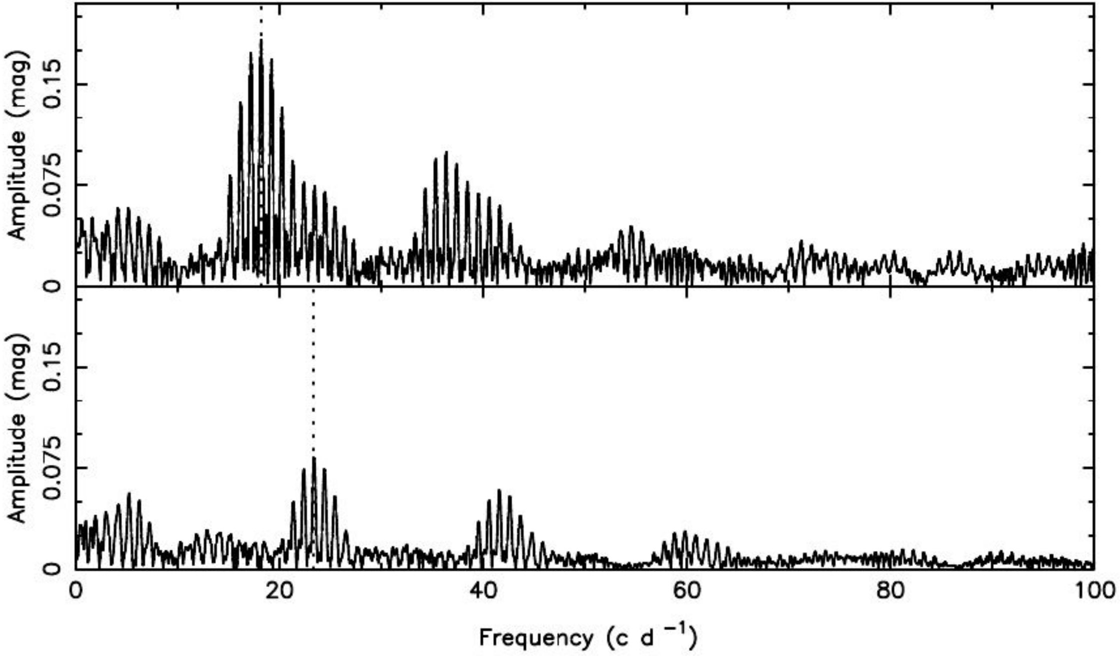
$$\sigma(\nu) = \frac{3}{2}\frac{1}{\Delta T}$$

Loumos & Deeming 1978; de Groote 2010

Iterative pre-whitening

Window functions are a mess

But they do go away if you remove the right frequency



Aerts et al. 2010