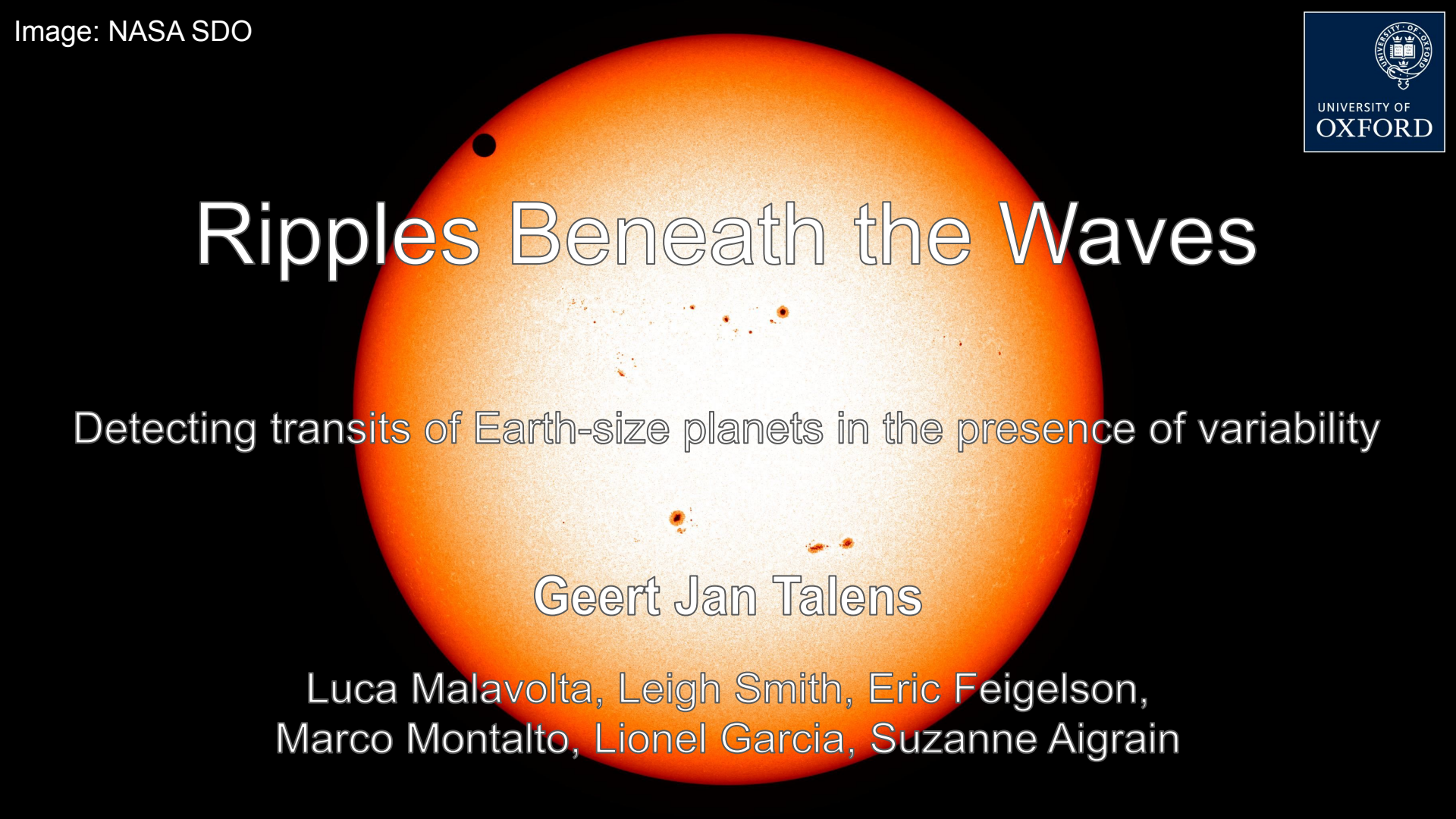
Image: NASA SDO



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Ripples Beneath the Waves

Detecting transits of Earth-size planets in the presence of variability

Geert Jan Talens

Luca Malavolta, Leigh Smith, Eric Feigelson,
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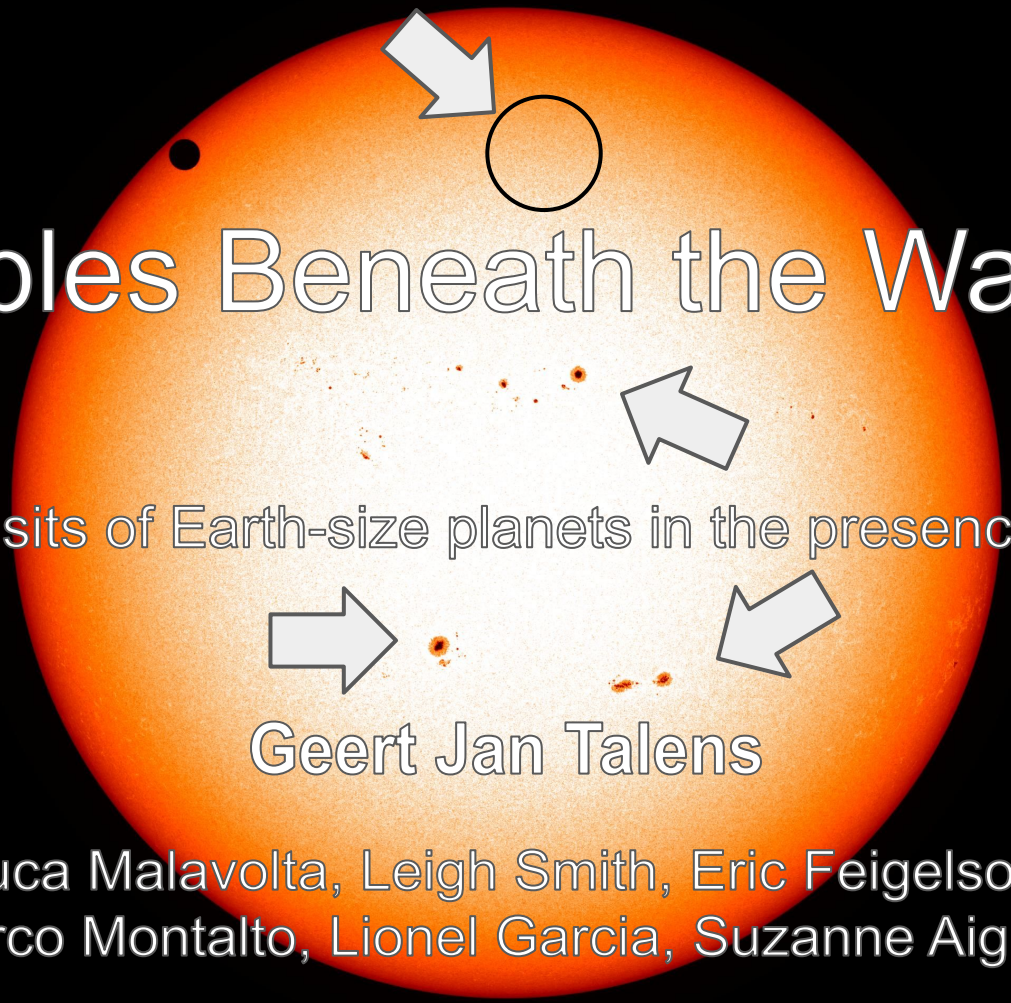

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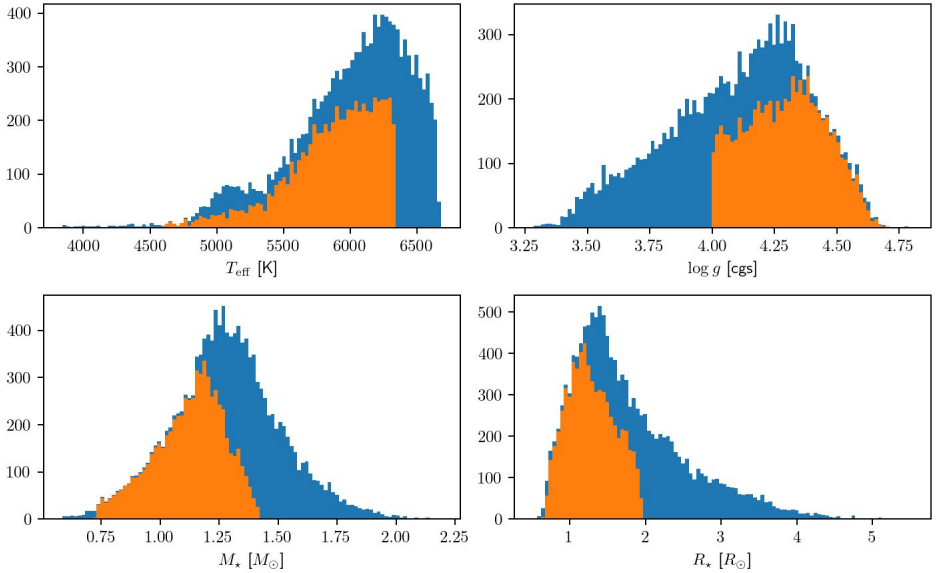
Aim

Compare different lightcurve filter and transit search algorithms to provide recommendations for the EAS.

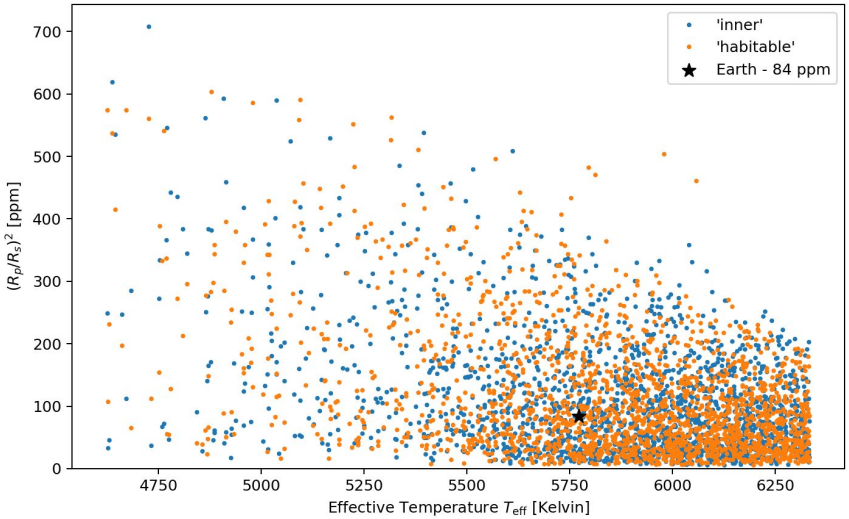
Simulations - Stars

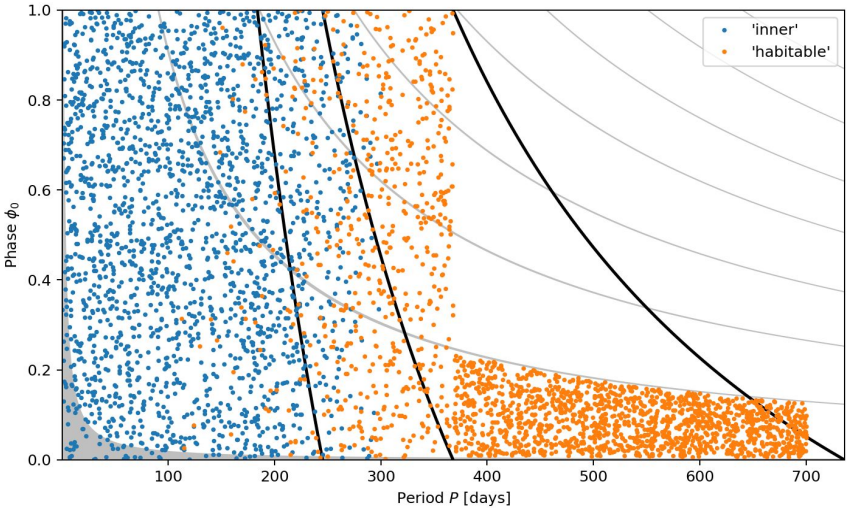
- Selected from PIC 2.1 P1 + P2.
- Applied cuts:
  - log g > 4
  - 4595 K < T_{eff} < 6334 K
  - V > 8
- Simulated 2000 stars.
- Using PSLS V1.8:
  - Poisson noise, systematics.
  - Granulation, oscillations.
  - Irregular quarter lengths.
  - Quarter gaps, momentum gaps.
- Using pyspot:
  - Out-of-transit spot modulations.



Simulations - Planets

- 2 possible transit signals:
  - ‘inner’: Period interior to the habitable zone.
  - ‘habitable’: Period inside the habitable zone for MS stars. For evolved stars orbits may be interior to the HZ.
- Transit parameters:
  - $0.5\ R_e < R_p < 2.0\ R_e$ (uniform).
  - T_0 constrained to prevent mono-transits.

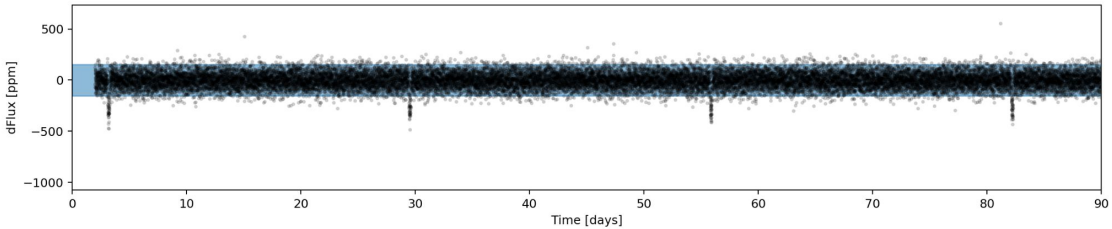




Ripples and Waves

- Transit + Noise

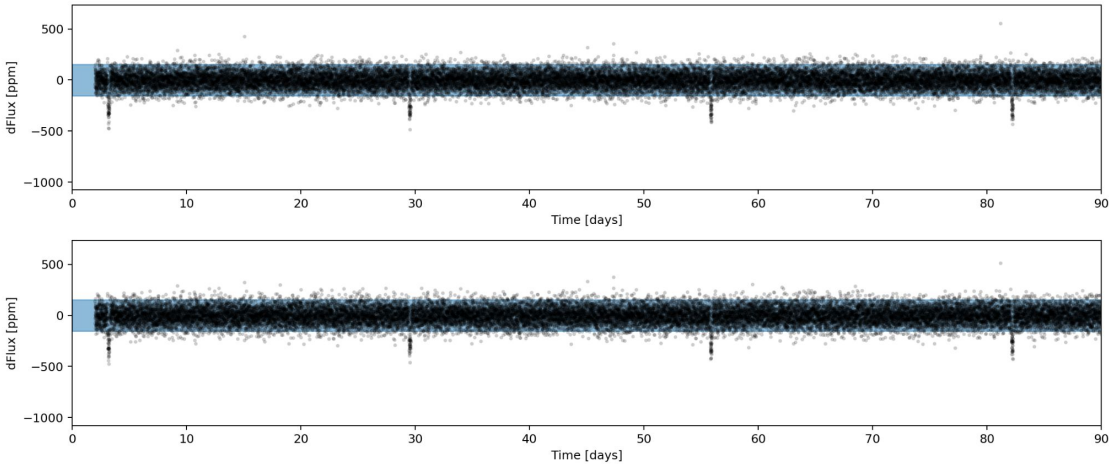
$R_s = 0.7\ R_{sun}$ $R_p = 1.2\ R_{earth}$



Ripples and Waves

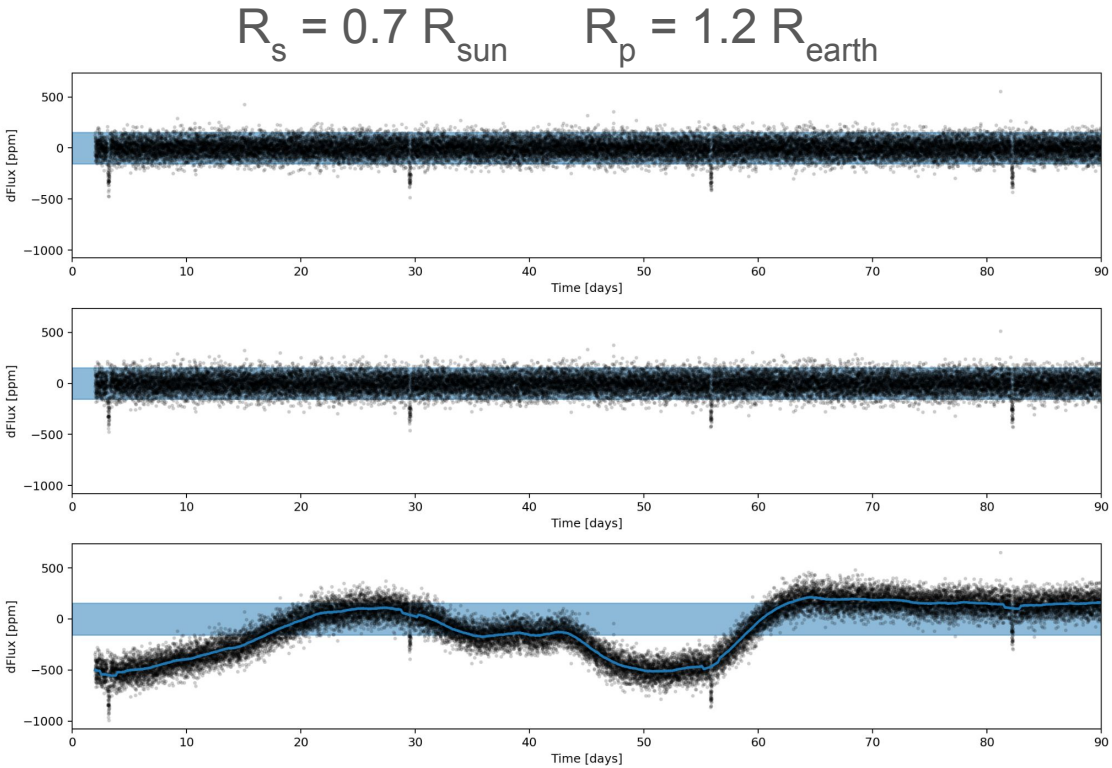
- Transit + Noise
- Granulation + Oscillations

$R_s = 0.7\ R_{sun}$ $R_p = 1.2\ R_{earth}$



Ripples and Waves

- Transit + Noise
- Granulation + Oscillations
- Spots + Systematics



Ripples and Waves

- Transit + Noise
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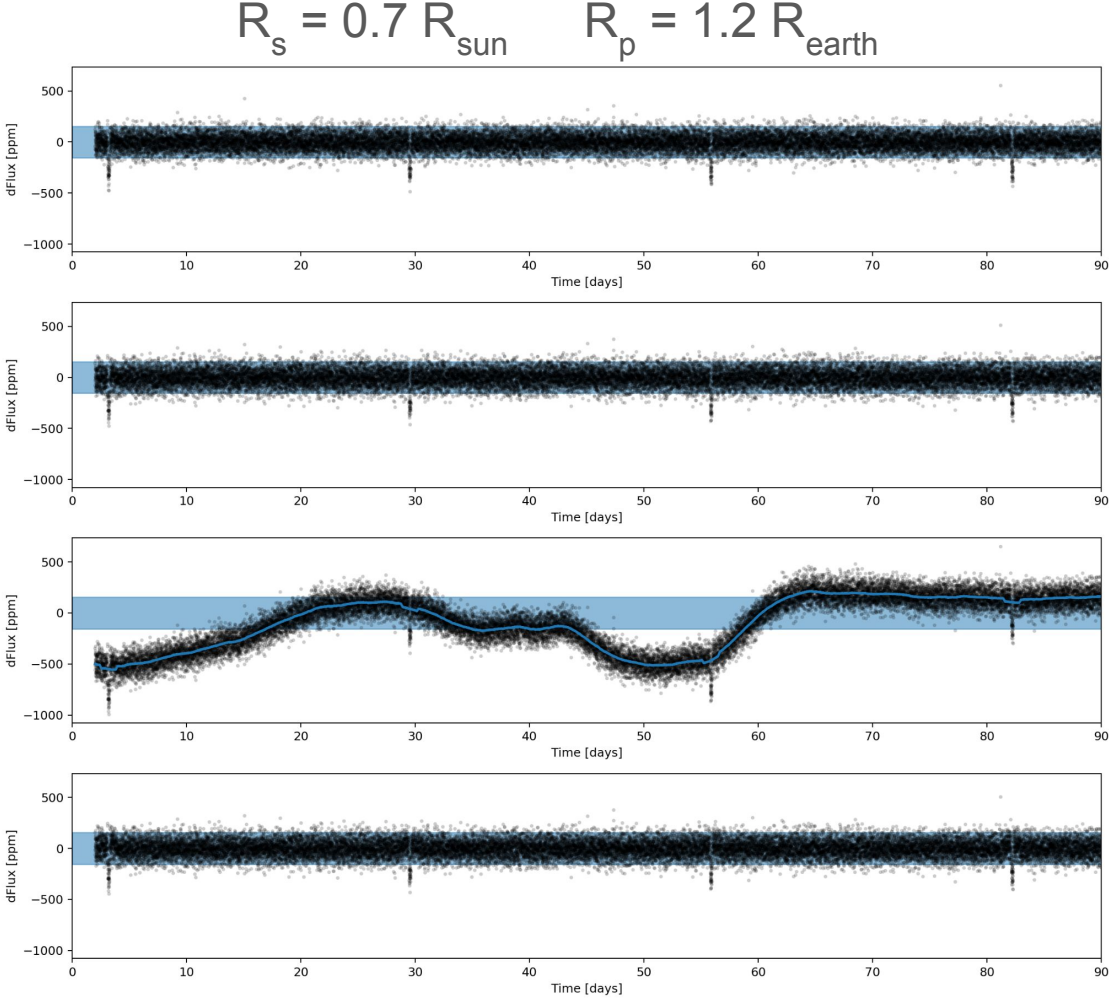

Lightcurve Filters

Biweight (wotan)

Huber spline (wotan*)

Lowess (wotan*)

YSD-Lowess (*Battley et al. 2020*)
- Custom implementation using wotan Lowess.

ARFIMA (*Feigelson et al. 2018*)
- Part of the AutoRegressive Planet Search (ARPS).

**modified for stability*

Continuing from Canocchi et al. 2023

Lightcurve Filters

Biweight (wotan)

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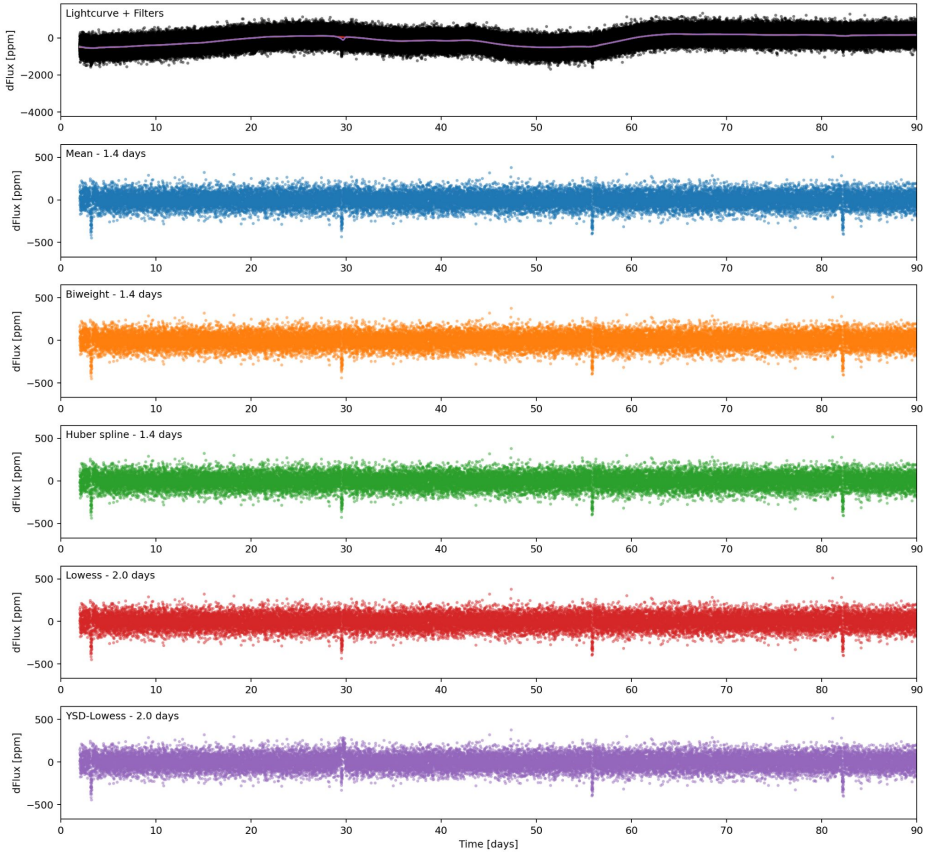
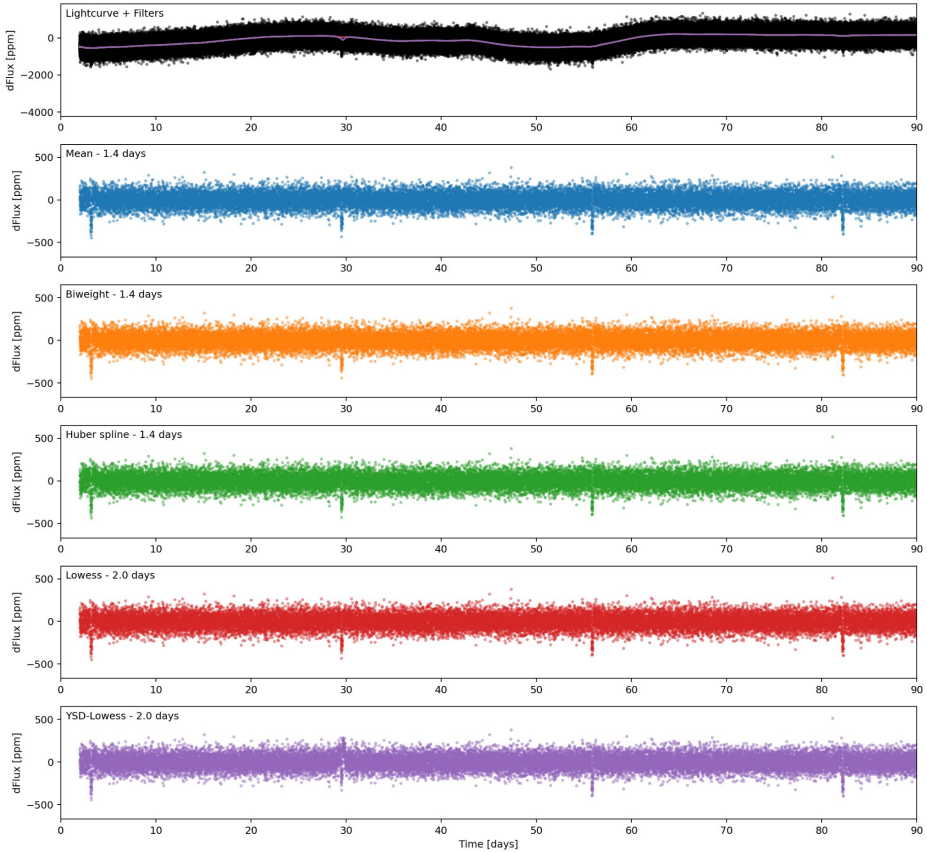
ARFIMA (*Feigelson et al. 2018*)
- Part of the AutoRegressive Planet Search (**ARPS**).
- Produces the filtered lightcurve derivative.

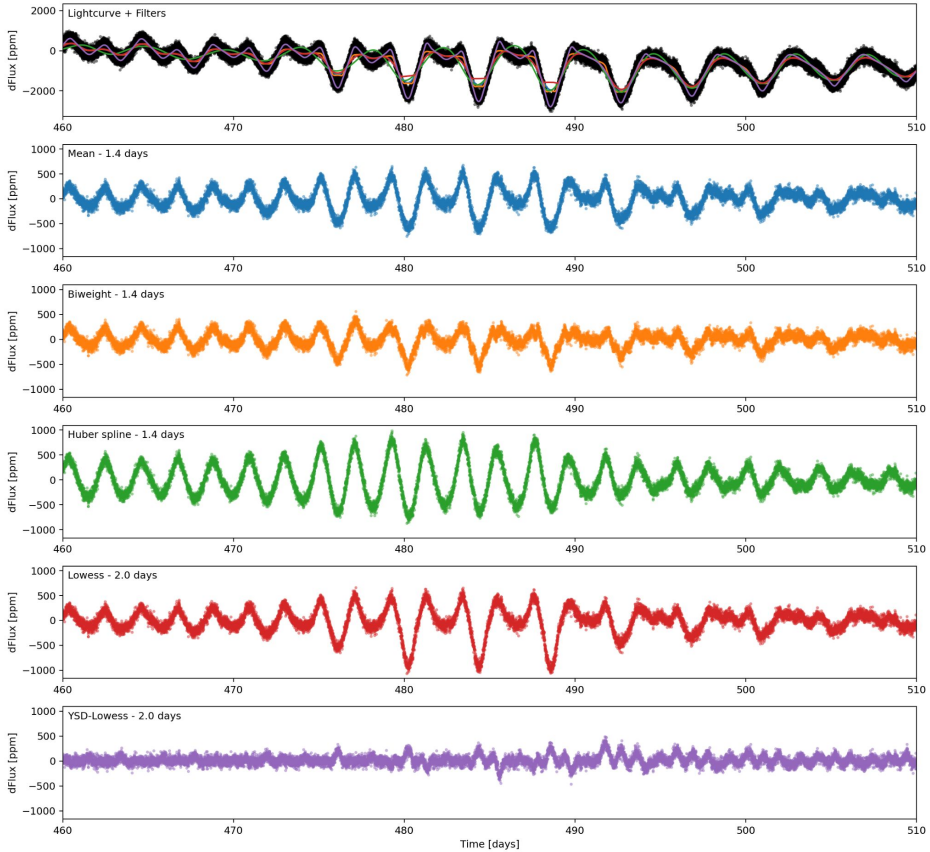
**modified for stability*

Lightcurve Filters: Mean, Biweight, Huber spline, Lowess, YSD-Lowess



Lightcurve Filters: Mean, Biweight, Huber spline, Lowess, YSD-Lowess





Search Algorithms

Transit Least Squares (*Hippke et al. 2019*)
- Including some bug fixes.

CETRA (*Smith et al. 2025*)
- GPU implementation of TLS.
- EAS default.

Warped Least Squares
- Custom implementation of TLS.
- Uses filter-modified transit shapes.

TCF (*Caceres et al. 2019*)
- Part of the AutoRegressive Planet Search (ARPS).
- Searches the filtered lightcurve derivative.

nuance (*Garcia et al. 2024*)
- Uses simultaneous GP for the filter.

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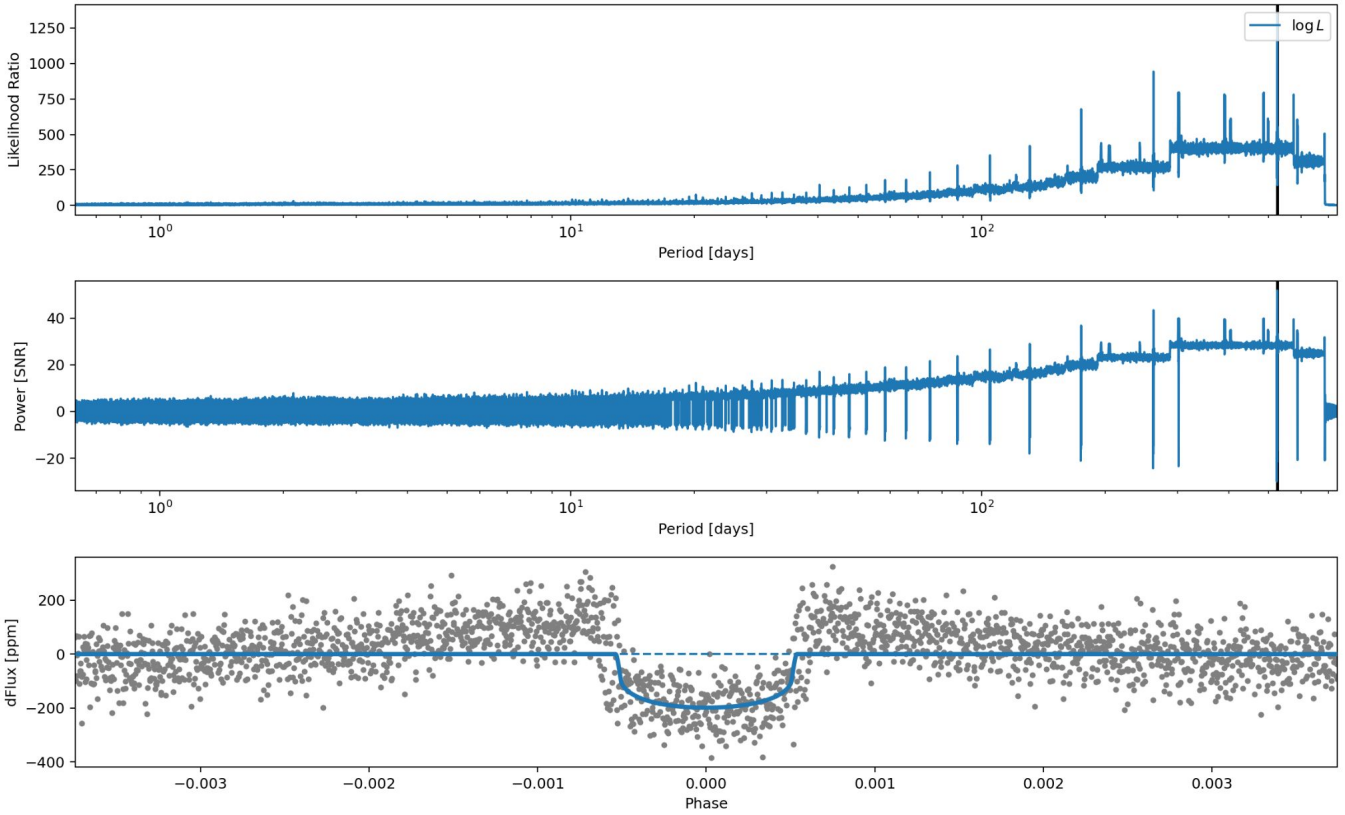
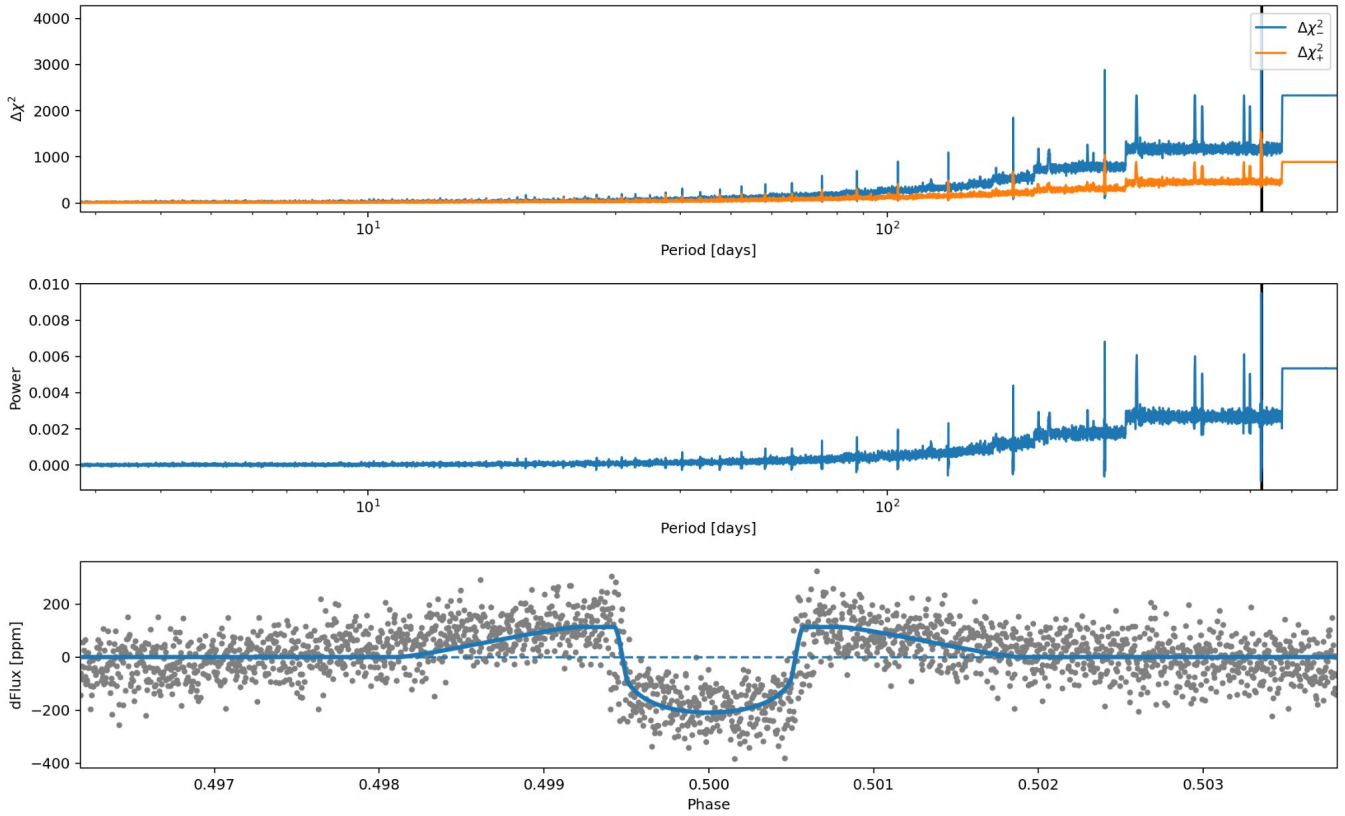
CETRA


log L
Likelihood Ratio
1250
1000
750
500
250
0
10^0
10^1
10^2
Period [days]
Power [SNR]
40
20
0
−20
10^0
10^1
10^2
Period [days]
dFlux [ppm]
200
0
−200
−400
−0.003
−0.002
−0.001
0.000
0.001
0.002
0.003
Phase

Warped Least Squares



ARPS

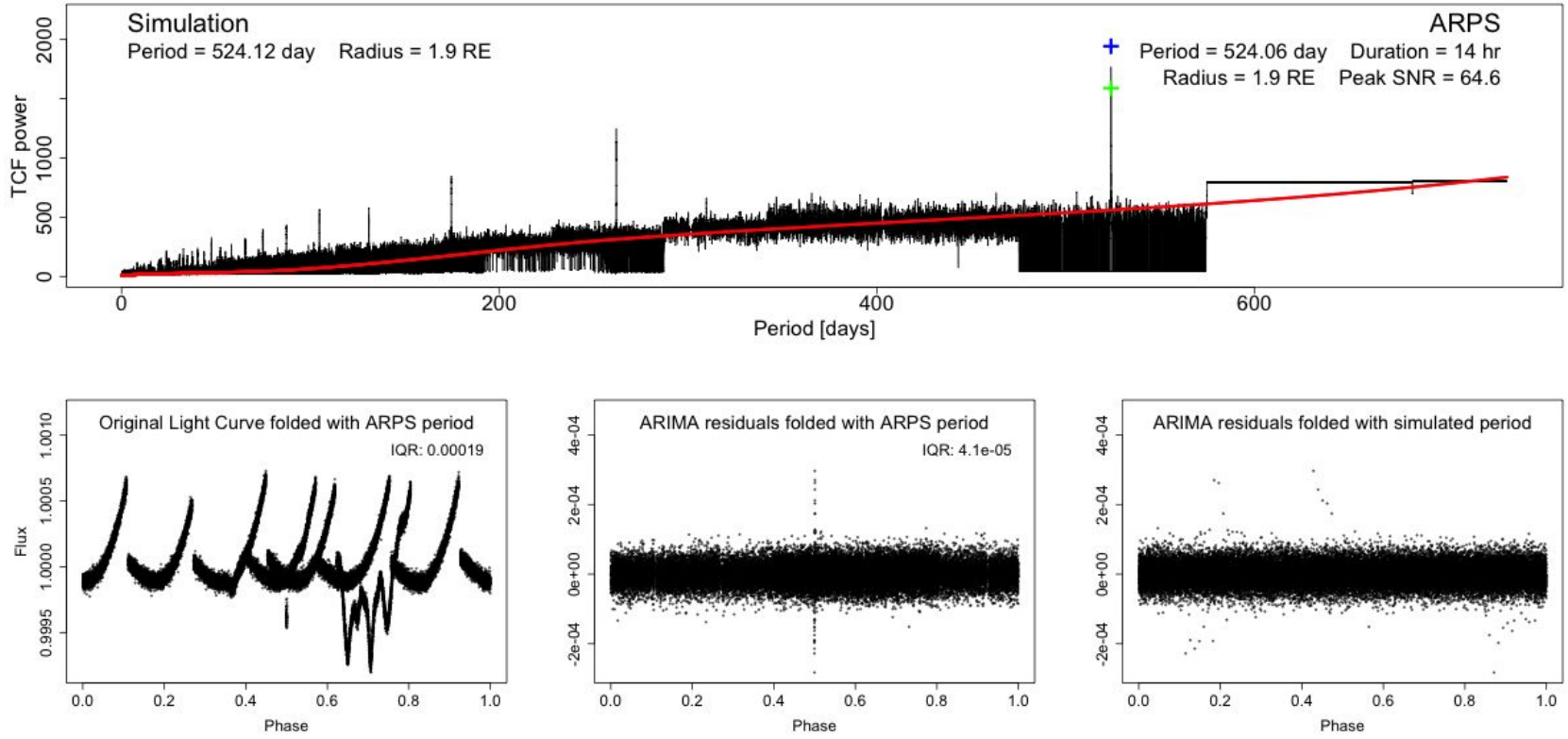


Figure: Montalto et al. in prep.

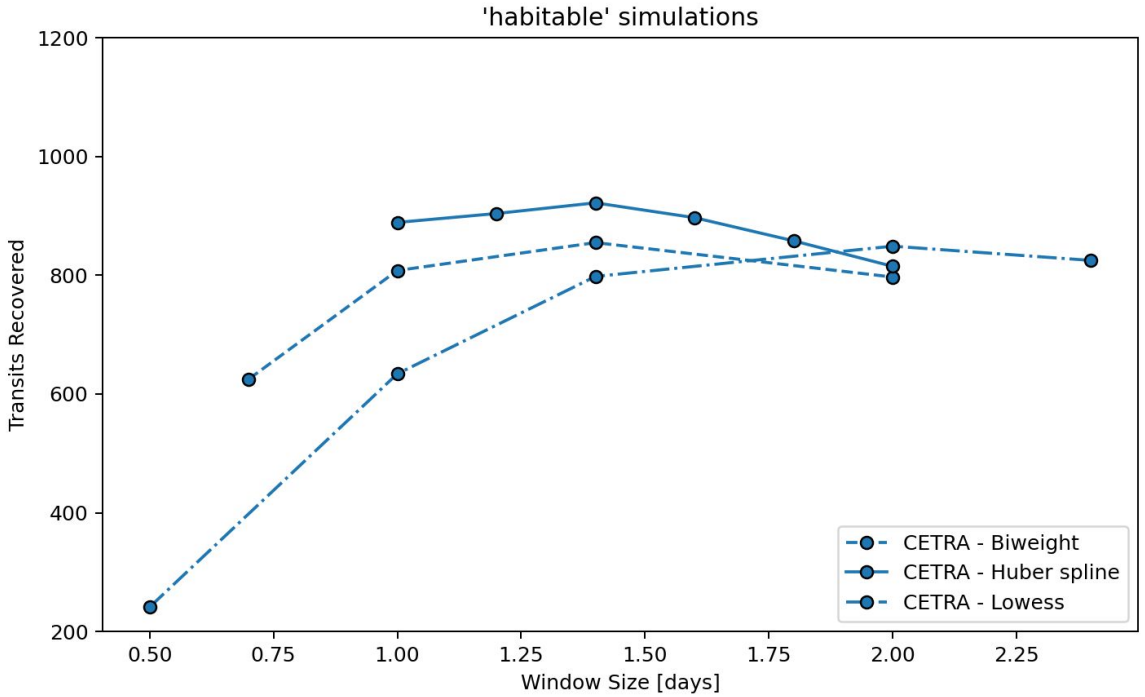
What I call a recovery

- Periodic matches:
  - $(P - P_{rec}) \times N_{tr} < 0.5 \times T_{14}$
  - $(P - 0.5 \times P_{rec}) \times N_{tr} < 0.5 \times T_{14}$
  - $(P - 2.0 \times P_{rec}) \times N_{tr} < 0.5 \times T_{14}$
  - $(P - 3.0 \times P_{rec}) \times N_{tr} < 0.5 \times T_{14}$

- Non-periodic matches:
  - $N_{tr} = 1, (T_0 - T_{rec}) < 0.5 \times T_{14}$
  - $N_{tr} = 2, (T_0 - T_{rec}) < 0.5 \times T_{14}$
  - $N_{tr} = 2, (T_0 + P - T_{rec}) < 0.5 \times T_{14}$

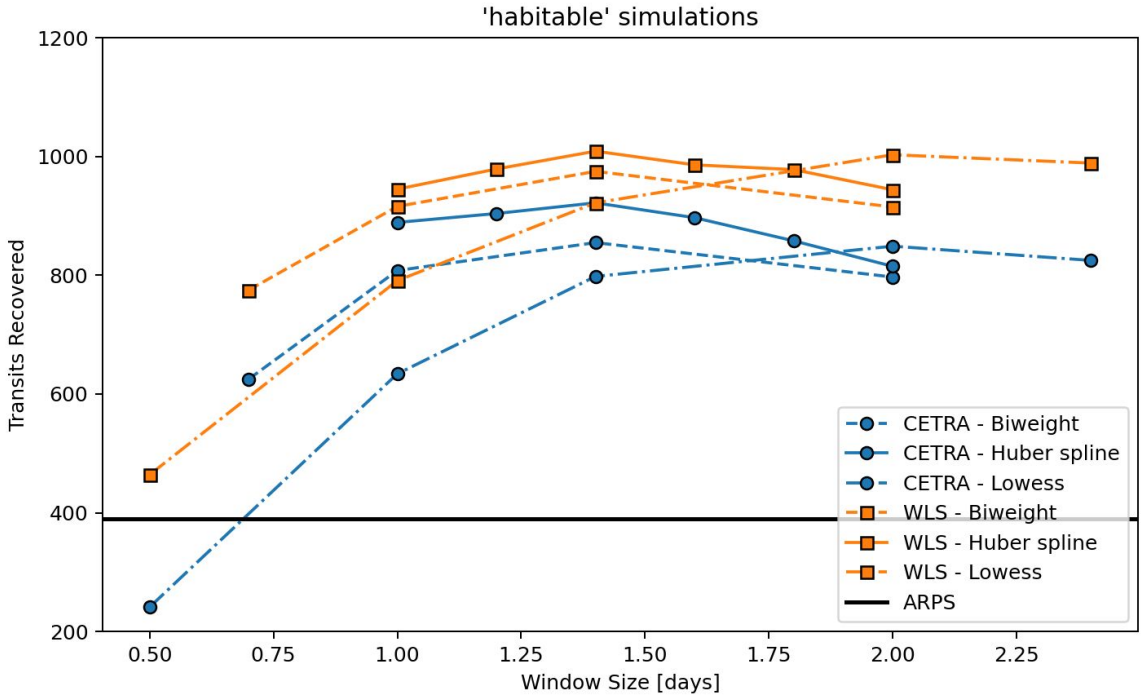
Results

- Huber spline



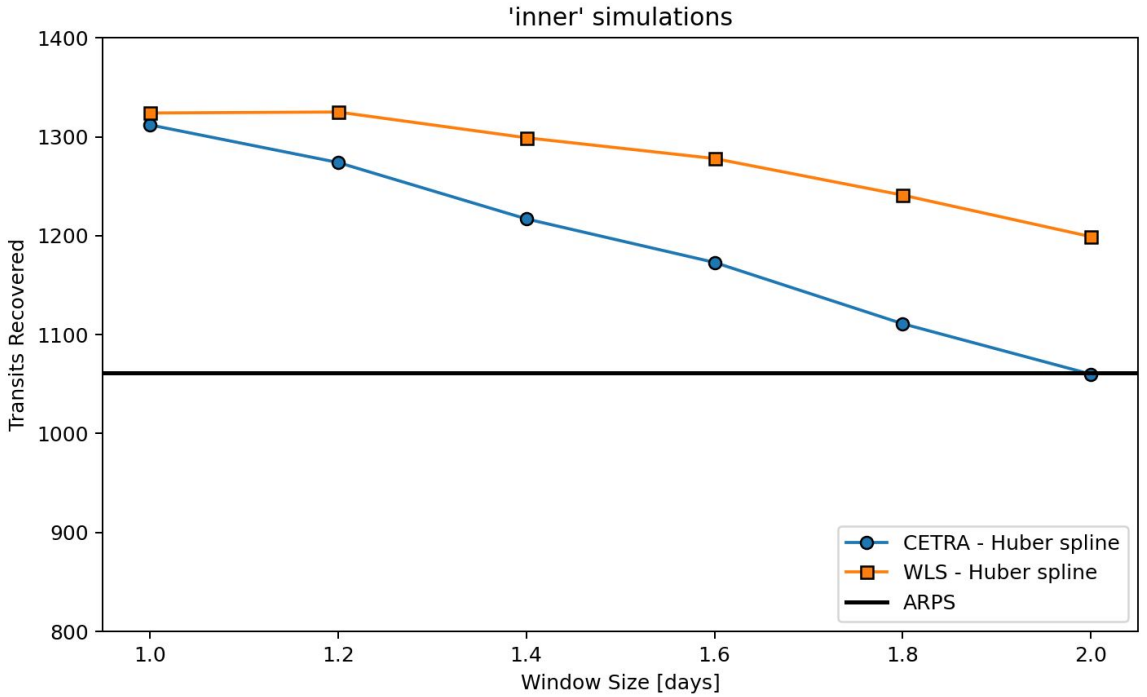
Results

- Huber spline
- Warped models



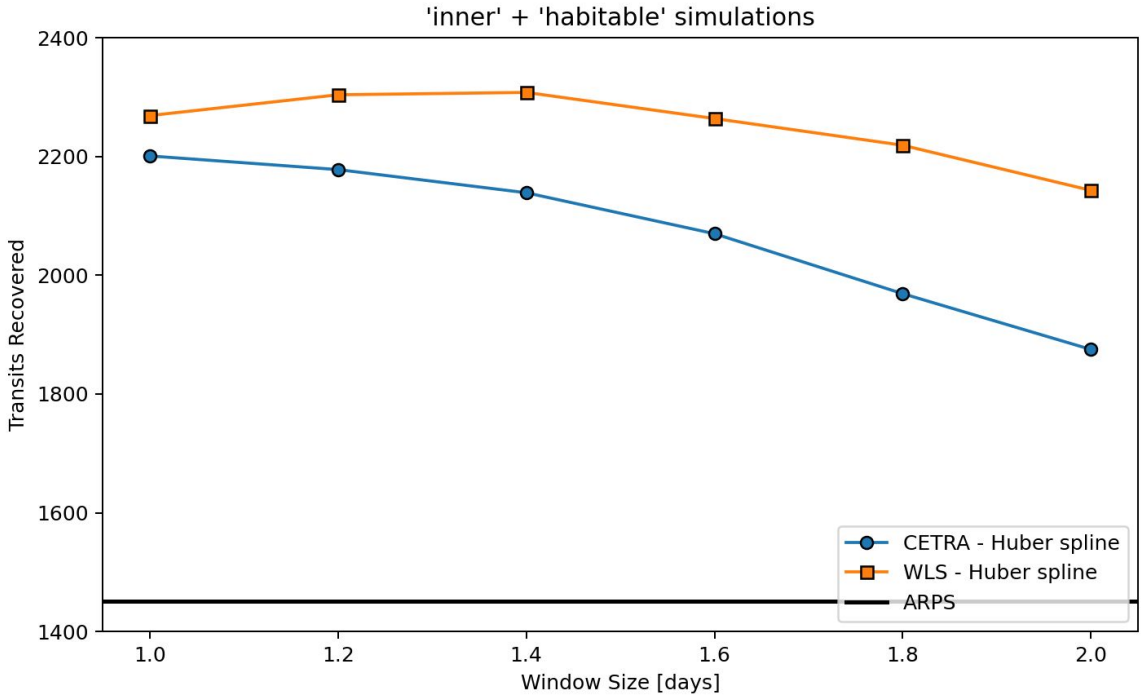
Results

- Huber spline
- Warped models
- Test shorter windows



Results

- Huber spline
- Warped models
- Test shorter windows
- Window size unclear

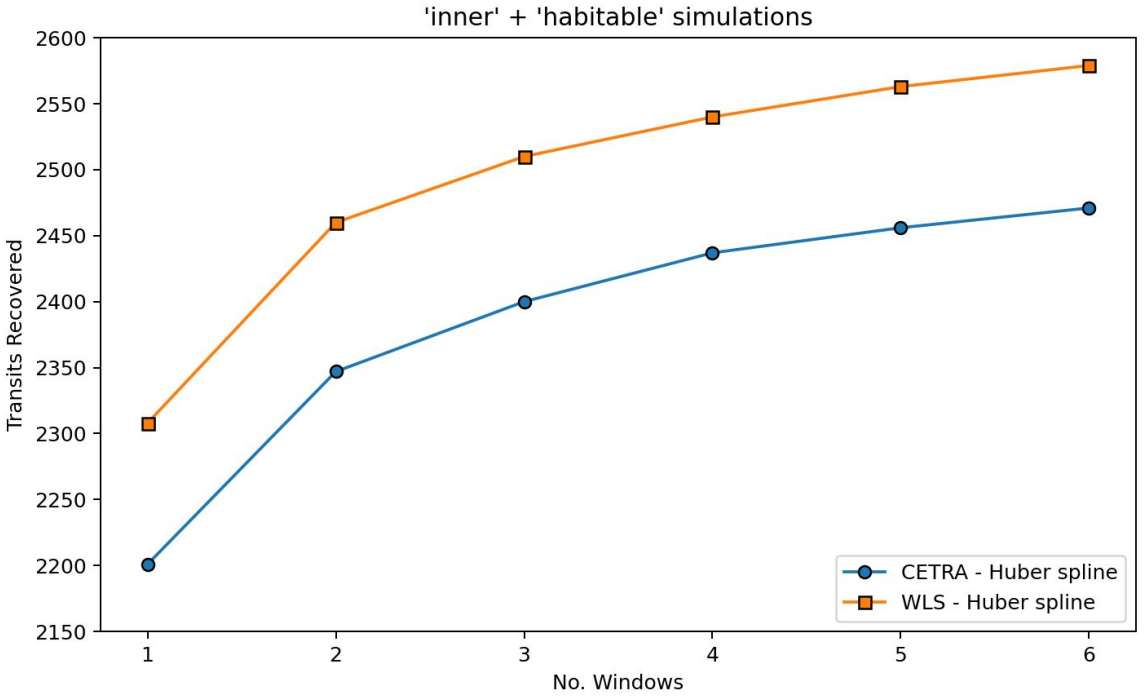


Results

Best single window:

CETRA
- 1.0 day
- 2201 of 4000 signals

WLS
- 1.4 day
- 2308 of 4000 signals

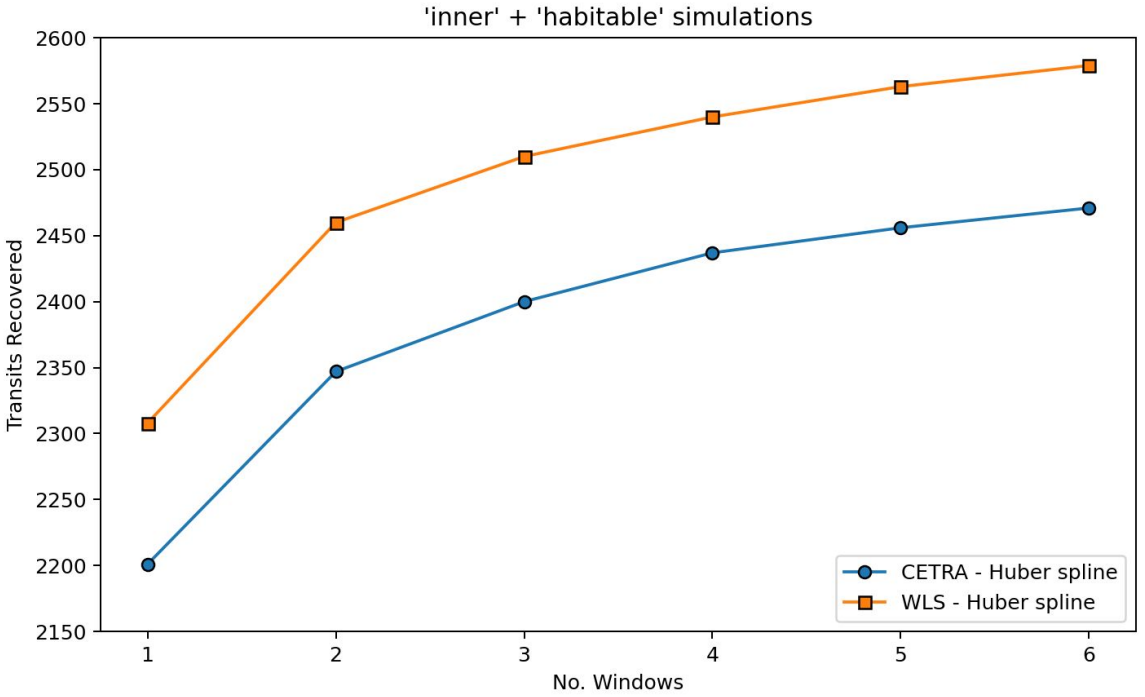


Results

Best three windows:

CETRA
- 1.0, 1.4, 1.8 days
- 2400 of 4000 signals

WLS
- 1.0, 1.4, 1.8 day
- 2510 of 4000 signals



Next steps

- Run/analyse additional filters.
- Comparison with nuance.
- Test the effect of binning.
- Investigate the effect of SDE/SNR cuts.
- Tests with high impact parameter searches.

Conclusions

- The best filter to use (so far) is a **Huber spline**.
  - The optimal window may be dependent on the algorithm.
  - Combining filters sees meaningful gains in recovered signals.

- **Warping** the transit signal to match the filter sees significant gains.
  - Ongoing work to implement and test this in CETRA.

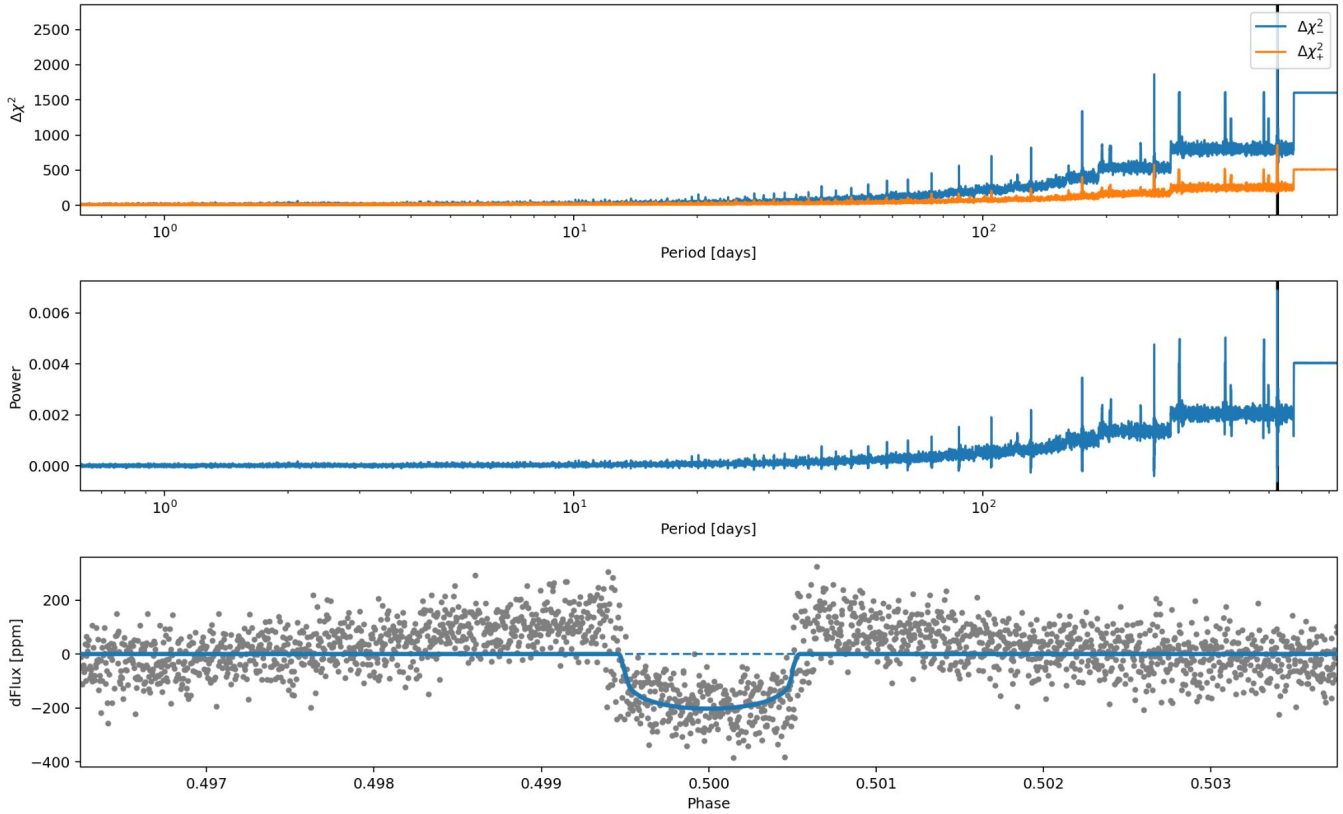
- **Transit depth** drives missed signals, followed by **impact parameter**.
  - Only 50-60% of ‘habitable’ sample is recovered.
  - Around 70% of ‘inner’ signals are recovered.

Bonus Slides

(Un)Warped Least Squares

882 of ‘habitable’ transits recovered.

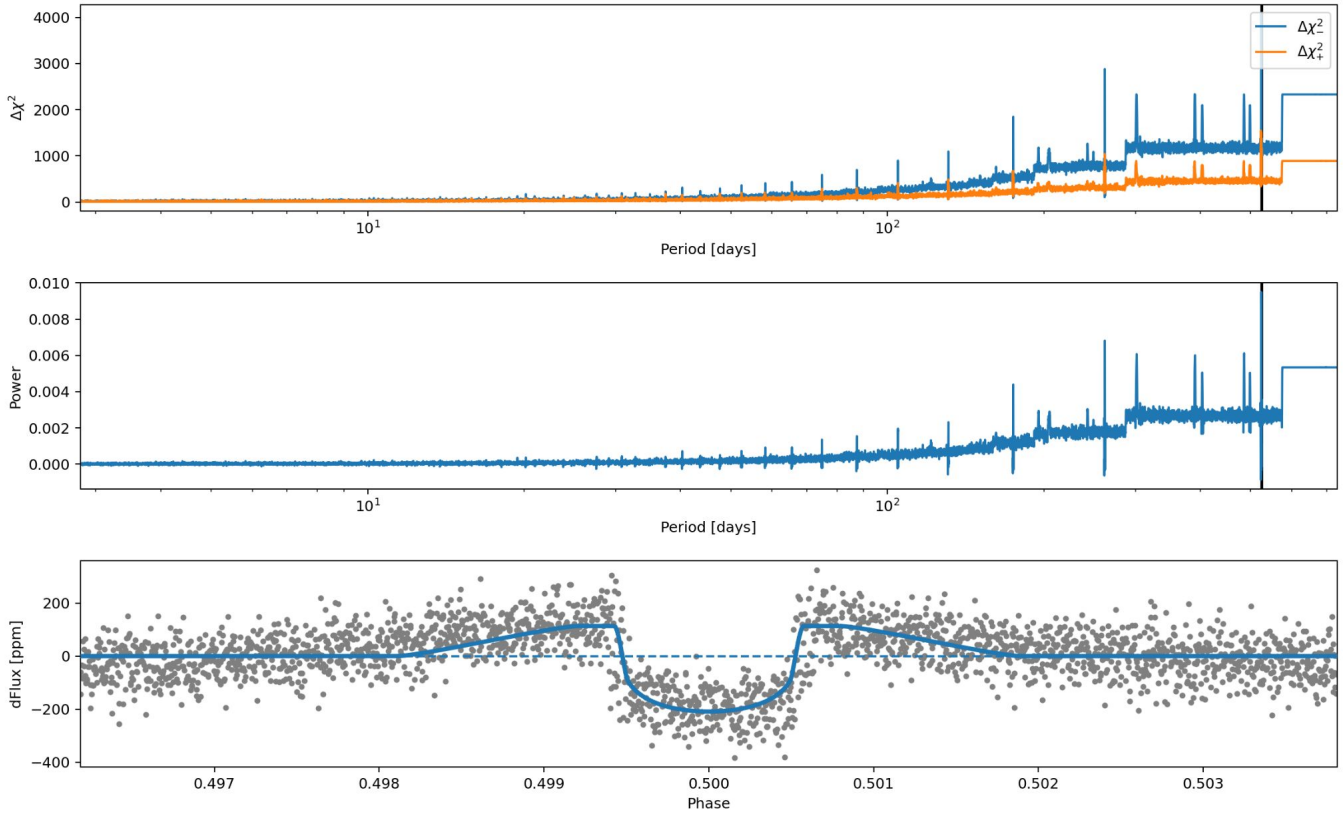
CETRA: 922

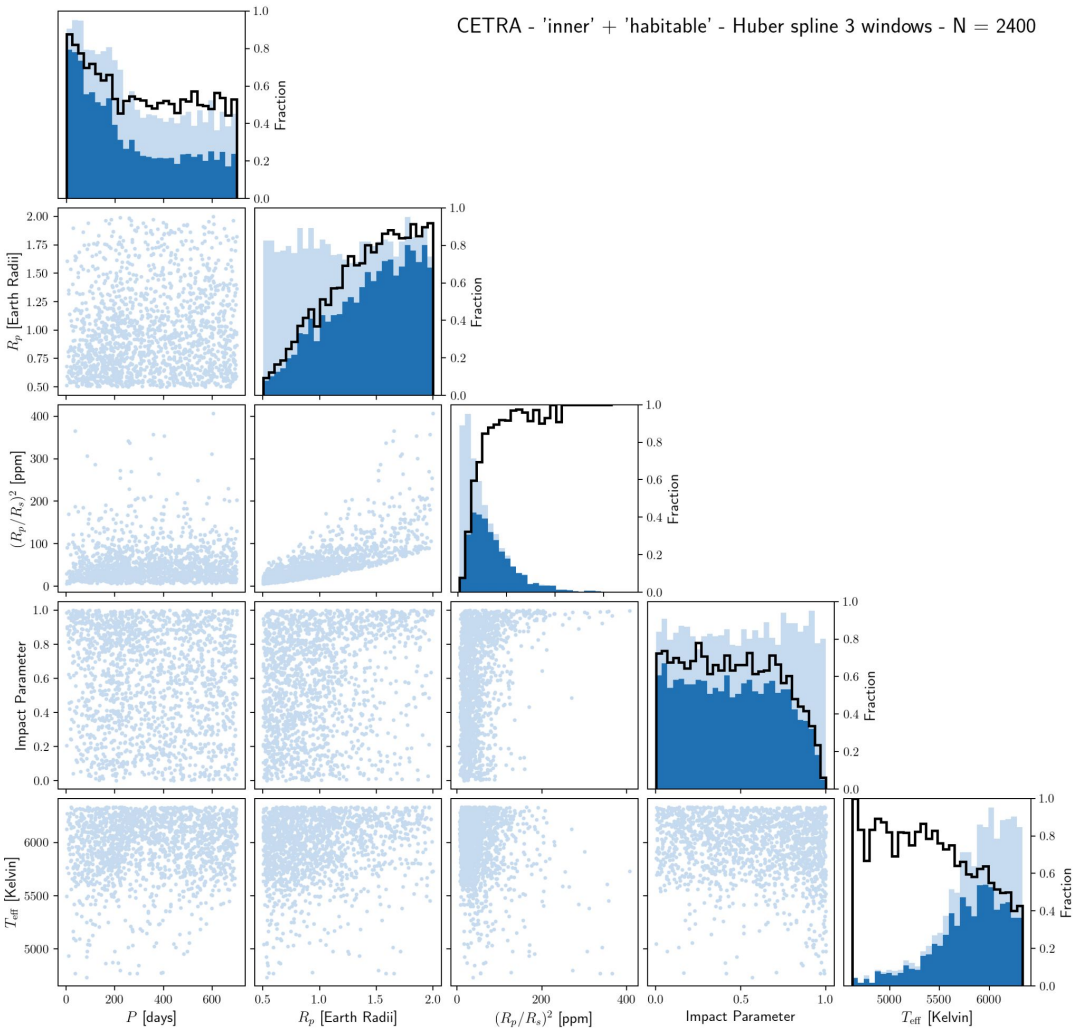


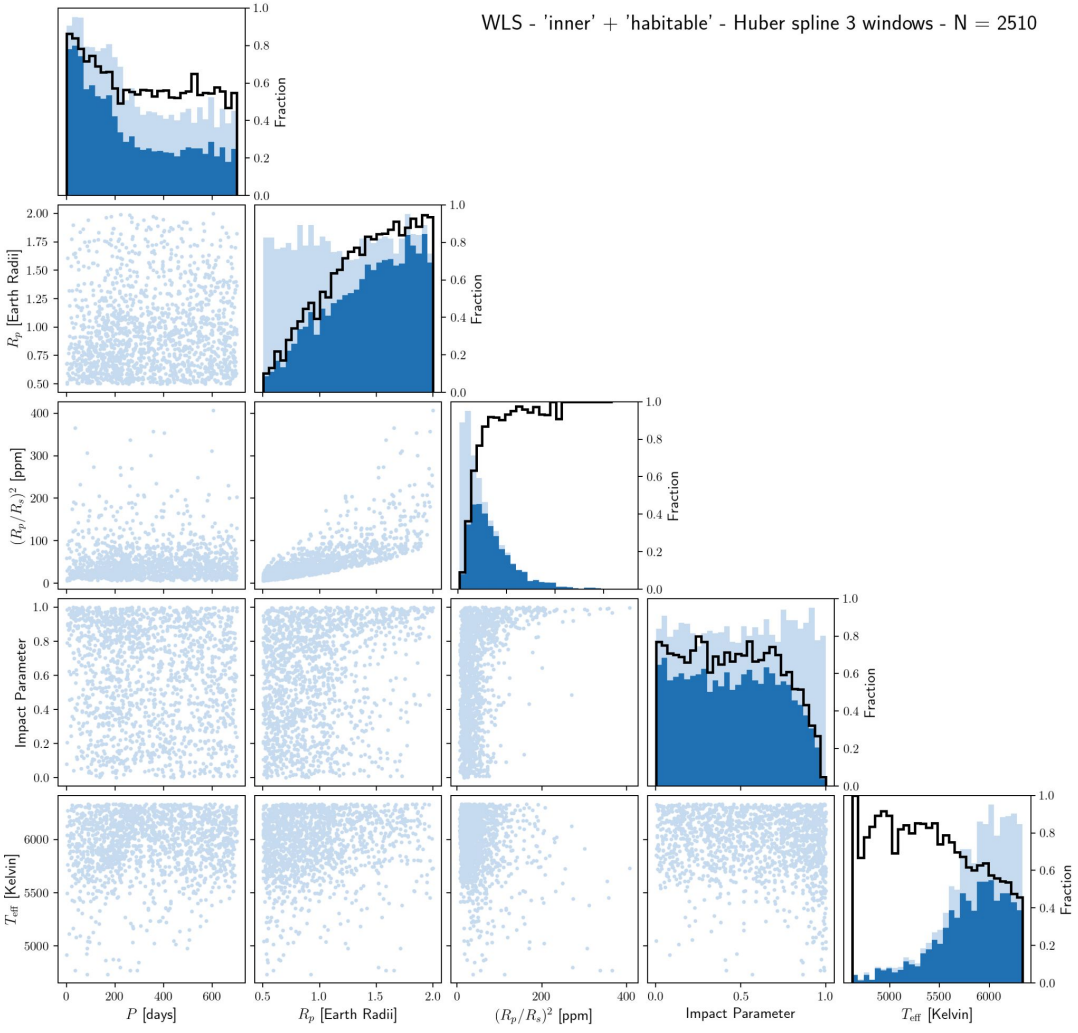
Warped Least Squares

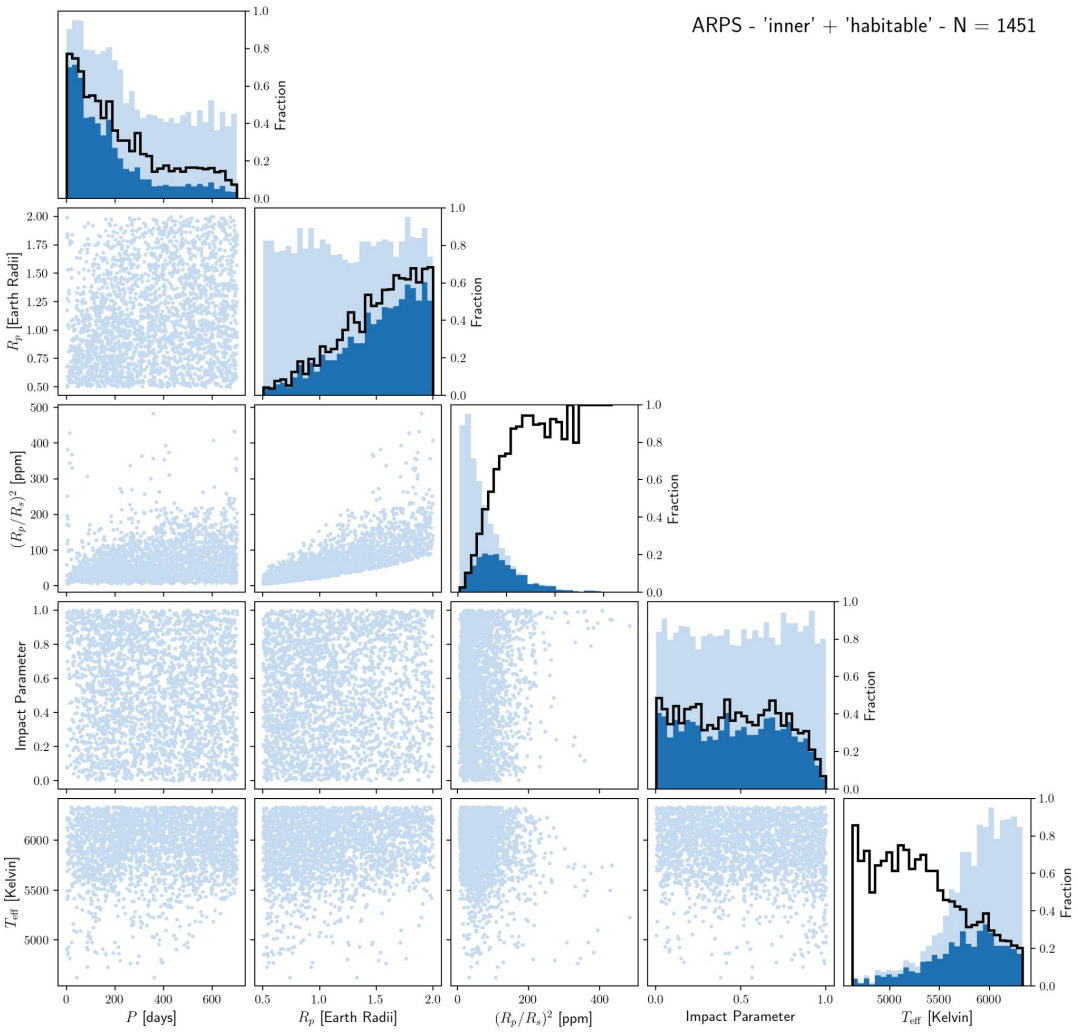
1009 of ‘habitable’ transits recovered.

CETRA: 922




CETRA - 'inner' + 'habitable' - Huber spline 3 windows - N = 2400
Fraction
R_p [Earth Radii]
$(R_p/R_s)^2$ [ppm]
Impact Parameter
$T_{\rm eff}$ [Kelvin]
P [days]


WLS - 'inner' + 'habitable' - Huber spline 3 windows - N = 2510
Fraction
R_p [Earth Radii]
$(R_p/R_s)^2$ [ppm]
Impact Parameter
$T_{\rm eff}$ [Kelvin]
P [days]
R_p [Earth Radii]
$(R_p/R_s)^2$ [ppm]
Impact Parameter
$T_{\rm eff}$ [Kelvin]


ARPS - 'inner' + 'habitable' - N = 1451
Fraction
R_p [Earth Radii]
$(R_p/R_s)^2$ [ppm]
Impact Parameter
$T_{\rm eff}$ [Kelvin]
P [days]
R_p [Earth Radii]
$(R_p/R_s)^2$ [ppm]
Impact Parameter
$T_{\rm eff}$ [Kelvin]

WLS Power

GLS, BLS/TLS (+ empirical scaling)

$\Delta\chi(P) = \chi_0 - \chi(P)$

$\mathbf{P} = \Delta\chi(P)/\chi_0$

WLS

$\Delta\chi(P) = \chi_+(P) - \chi_-(P)$

$\mathbf{P} = \Delta\chi(P)/\chi_+(P)$

Search speed