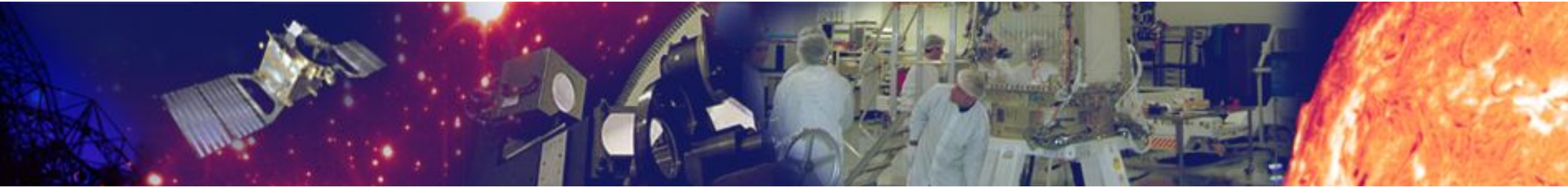
The Stellar Analysis System: weighting, sizing and dating the stars

R-M. Ouazzani, K. Belkacem,
C. Renié, O. Roth, J. Philidet and the WP12



PLATO mission consortium: core stellar science

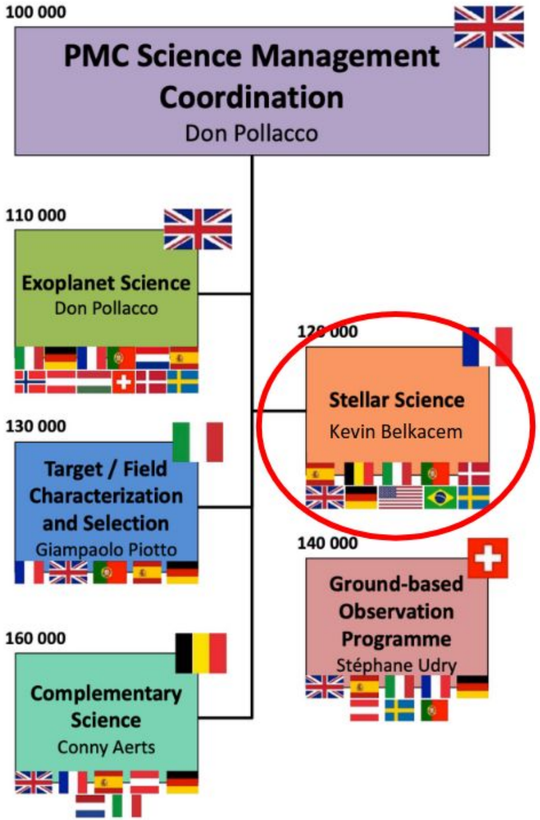
Stellar Science work package (WP12)
255 members

Before operations

- Specifies the Stellar Analyses System pipeline (SAS) (architecture and algorithms)
- Provides external tools (stellar model+frequencies grids, spectroscopic parameter tables, ...)
- Validates the pipeline and evaluates its performances

During operations

- Updates the algorithms specifications and tools
- Validation of mission data-products DP3 to DP5



The PLATO stellar programs

The PLATO Core Program

Designed to fulfill the science objectives of the mission

- FGK dwarfs and subgiants (F5 to K7)
- Cool dwarfs (M)

The Science Calibration and Validation stars (scv)

Designed to test, improve and validate stellar models

- Red giant stars
- γ Doradus stars
- Eclipsing binaries
- Photometrically stable stars

⟶ regimes out of reach by the core program

⟶ Parameters derived using model-independent methods

Complementary Science Program

Designed to serve the wider community with photometric obs^{o}

- Binary and multiple stars
- Pulsating stars (earlier than F5)
- Magnetic stars and rotational variables
- Stars with mass loss
- young stellar objects and stars with debris disks
- Galactic structure
- Transient phenomena and extragalactic science

The core program stellar samples

		P_1	P_2	P_4	P_5	Colour sample
Stars		≥ 15,000 (goal 20000)	≥ 1,000	≥ 5,000	≥ 245,000	300
Spectral type		Dwarf and subgiants F5-K7	Dwarf and subgiants F5-K7	Cool late type dwarfs	Dwarf and subgiants F5-K	Anywhere in the HR diagram
Limit m_V		11	8.5	16	13	-
Random noise (ppm in 1 hour)		≤ 50	≤ 50	-	-	-
Observation phase		LOP	LOP	LOP	LOP	LOP
Observation sampling times	Imagettes	25 s	25 s 2.5 s for a subsample	25 s for > 5,000 targets	25 s for > 9,000 targets	2.5 s
	Light-curves	-	-	-	≤ 600 s	-
	Centroid measurements	-	-	-	≤ 50 s for 5% of targets	-
	Transit oversampling	-	-	-	≤ 50 s for 10% of targets	-
Wavelength		500-1000 nm	500-1000 nm	500-1000 nm	500-1000 nm	Red and blue spectral bands

From ESA-PLATO-ESTEC-SCI-RS-001

P1 sample

FGK dwarfs and subgiants Vmag<11

P2 sample

FGK dwarfs and subgiants Vmag<8.5

P4 sample

M dwarfs Vmag<16

P5 sample

FGK dwarfs and subgiants Vmag < 13

The PLATO data products

Validated imagettes, light curves and centroid curves	DP0	L0	raw data
Calibrated imagettes, light curves and centroid curves	DP1	L1	corrected & calibrated data
Planetary candidate transits and their parameters	DP2	L2	science products
Asteroseismic mode parameters	DP3	L2	science products
Stellar rotation and activity	DP4	L2	science products
Stellar radii, masses, and ages	DP5	L2	science products
Living catalogue of confirmed planetary systems and their characteristics using light curves and transit time variations	DP6	L2	science products
Follow-up ground-based observations		Lg	follow-up data
Living catalogue of confirmed planetary systems and their characteristics using new ground-based follow-up observations (Lg)	DP6+Lg	L3	final catalog

The PLATO data products

Validated imagettes, light curves and centroid curves	DP0	L0
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Follow-up ground-based observations		Lg
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raw data

corrected & calibrated data

stellar science products

follow-up data

final catalog

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Follow-up ground-based observations		Lg	follow-up data
Living catalogue of confirmed planetary systems and their characteristics using new ground-based follow-up observations (Lg)	DP6+Lg	L3	final catalog

\+ **Additional data products:**

- Analyses-ready cleaned light curves
- Additional seismic parameters: splittings, heights, inclination angles, mean density
- Additional stellar parameters: effective temperature, metallicity, abundances, …

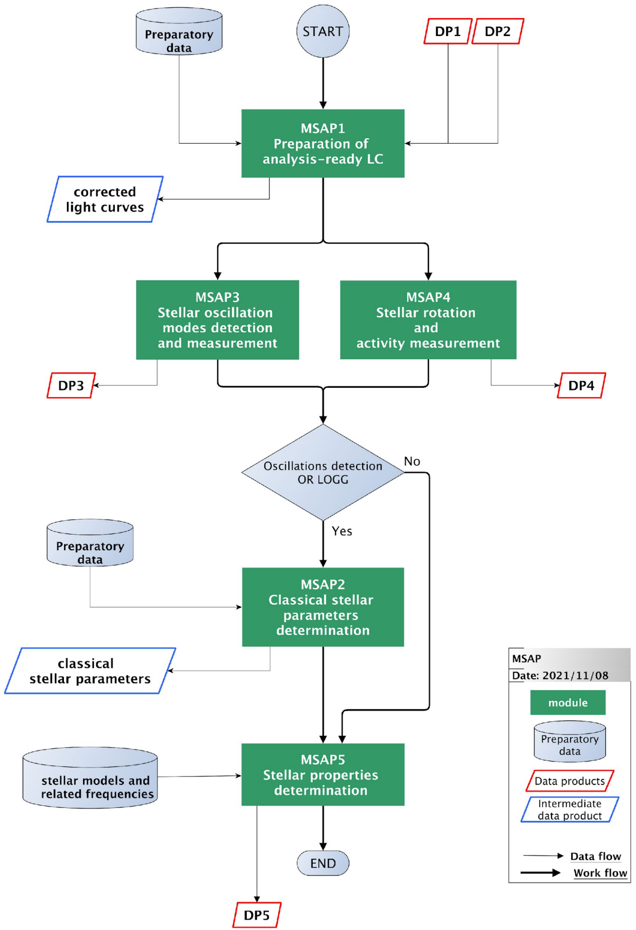
The Stellar Analysis System pipeline (SAS)

Function of the Pipeline

✓ processes DP1 light curves from P1, P2, P4, and P5 samples
✓ produces DP3 (oscillations), DP4 (rotation + activity), and DP5 (mass, radius, age) for all the targets

Science Modules

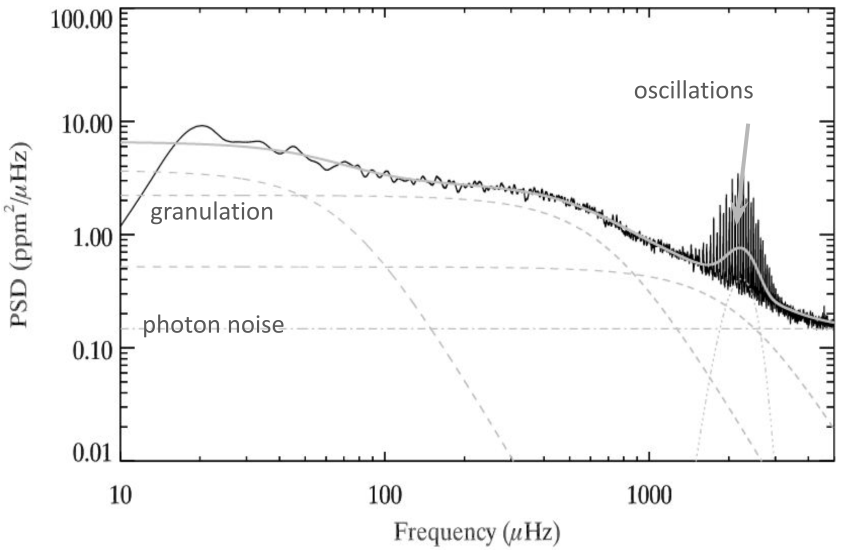
- **MSAP1** « *Preparation of analysis-ready light-curves* »
  Lead: A. Moya & N. Lanza
- **MSAP2** « *Classical stellar parameters determination* »
  Lead: T. Morel
- **MSAP3** « *Stellar oscillation modes detection and measurement* »
  Lead: W.J. Chaplin
- **MSAP4** « *Stellar rotation and activity measurement* »
  Lead: N. Lanza
- **MSAP5** « *Stellar properties determination* »
  Lead: M. Cunha, A. Miglio
- *Grids of stellar models and frequencies* *Lead: A. Palacios*



Expected yield: Asteroseismology

From Goupil et al. (2024), based on PIC 1.1.0

- Estimated number of PLATO seismic targets
- P1, P2 and P5 samples
- Expected performances in terms of mass, radius and age



Mode detection probability

$$P_{\rm det} = \int_{u_0}^{\infty} \frac{1}{\Gamma(N_{\rm b})} \, u'^{N_{\rm b}-1} \, {\rm e}^{-u'} \, {\rm d}u'$$

$$u_0 = \frac{1 + (S/N)_{\rm thres}}{1 + (S/N)_{\rm mod}}$$

N_b Number of independent frequency bins in oscillation envelope band

$(S/N)_{thresh}$ Signal-to-noise ratio for which the false alarm probability is 0.1%

$(S/N)_{mode}$ Signal-to-noise ratio of the oscillations (total oscillation power/total noise power in the same frequency range)

Expected yield: Asteroseismology

From Goupil et al. (2024), based on PIC 1.1.0

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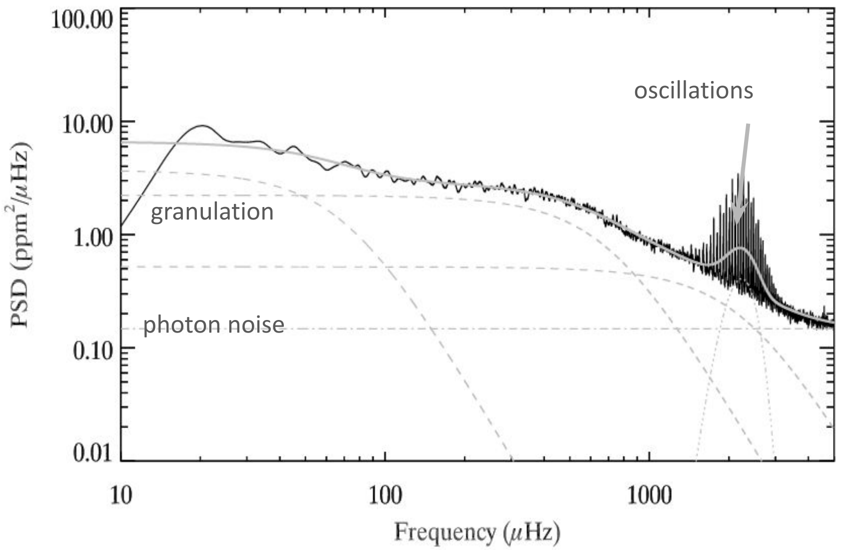

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$$u_0 = \frac{1 + (S/N)_{\rm thres}}{1 + (S/N)_{\rm mod}}$$

N_b Number of independent frequency bins in oscillation envelope band

$(S/N)_{thresh}$ Signal-to-noise ratio for which the false alarm probability is 1%

$(S/N)_{mode}$ Signal-to-noise ratio of the oscillations (total oscillation power/total noise power in the same frequency range)

Expected yield: Asteroseismology P1-P2 samples

Cases	Beginning Of Life PIC 1	End Of Life PIC 1	Beginning Of Life PIC 2
	Goupil et al. (2024) based on PIC 1.1.0		PLATO-LIRA-PSM-TN-0098 based on PIC 2.1.0.1
All stars	5858 (84 %)	5553 (79 %)	8291 (71%)
Main-sequence only	2751	2449	3549
M < 1.6 Msun	4744	4439	
M < 1.6 Msun, MS stars only	2732	2430	
M < 1.2 Msun	1245	1106	
M < 1.2 Msun, MS stars only	1016	830	
R < 1.1 Rsun	269	203	

Expected yield after 2 years for P1 and P2 samples

- Oscillations detected in 71% of P1/P2: 8291 stars
- Oscillations detected in 60-70% of P1-P2 with $M < 1.2\ M_{sun}$

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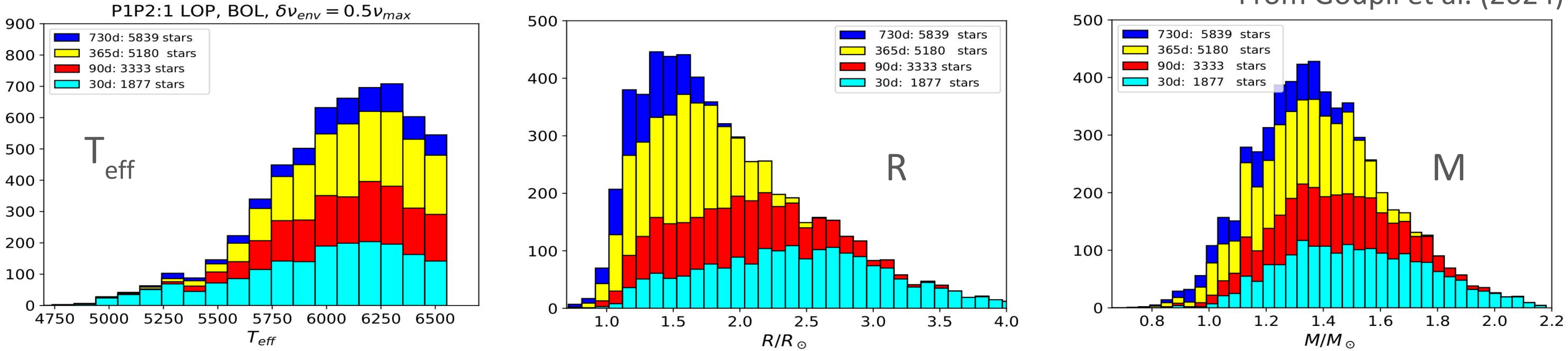

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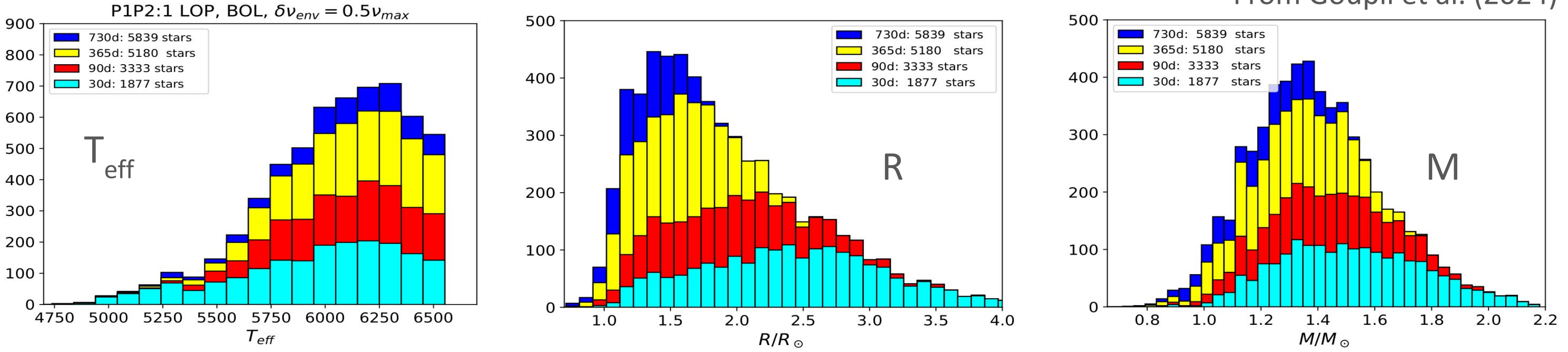
M < 1.2 Msun	1245	1106	
M < 1.2 Msun, MS stars only	1016	830	
R < 1.1 Rsun	269	203	

Expected yield after 4 years for P1 and P2 samples

- Oscillations detected in **79%** of P1/P2: 8685 stars (4220 MS)
- Individual frequencies of oscillations in 8670 stars (4205 MS)

From Goupil et al. (2024)



Expected yield: Asteroseismology P5 sample

Cases	3 months	1 year	2 years PIC 1
All stars	1599 (1 %)	5718 (4 %)	9491 (7%)
Main-sequence only	0	61	584
Subgiants	1599	5657	8877
M < 1.2 Msun	81	392	878
M < 1.2 Msun, MS stars only	1016	43	250

Expected yield after 2 years for P5 sample

- Oscillations detected in 7% of P5: 9491 mostly subgiant stars
- Detection rate of MS stars positive after a year

Expected yield: Asteroseismology P5 sample

Cases	3 months	1 year	2 years PIC 1
All stars	1599 (1 %)	5718 (4 %)	9491 (7%)
Main-sequence only	0	61	584
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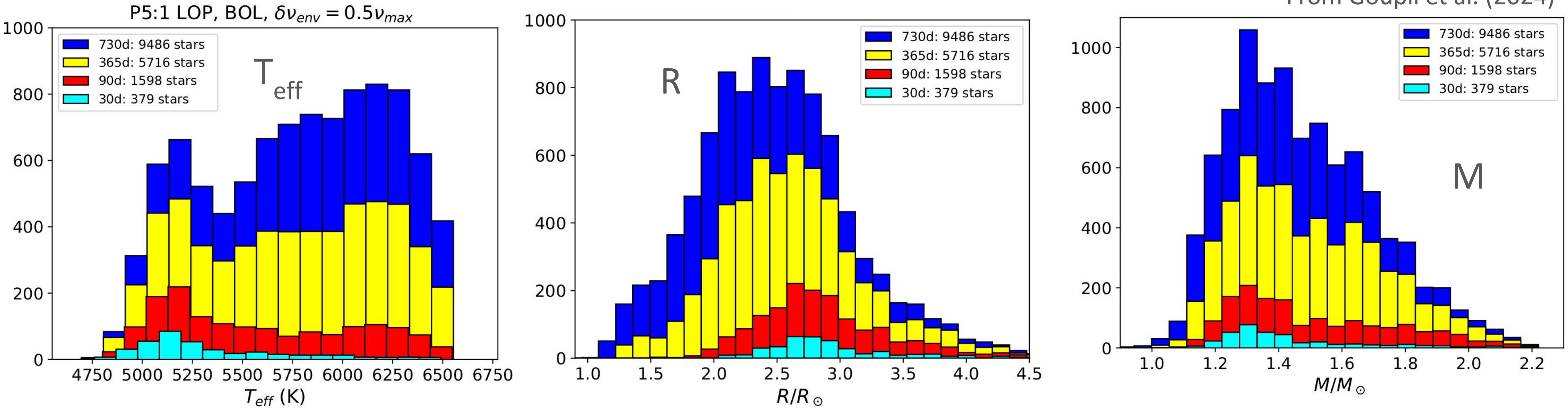
M < 1.2 Msun	81	392	878
M < 1.2 Msun, MS stars only	1016	43	250

Expected yield after 2 years for P5 sample

- Oscillations detected in 7% of P5: 9491 mostly subgiant stars
- Detection rate of MS stars positive after a year

From Goupil et al. (2024)



Expected yield: MRA inference (P1-P2 samples)

PLATO Science Requirements

Mass better than **15%**,
Radius better than **2%**,
Age as low as **10%**

reference star
$1M_{sun}$, $1R_{sun}$ and T_{eff} = 6000K.

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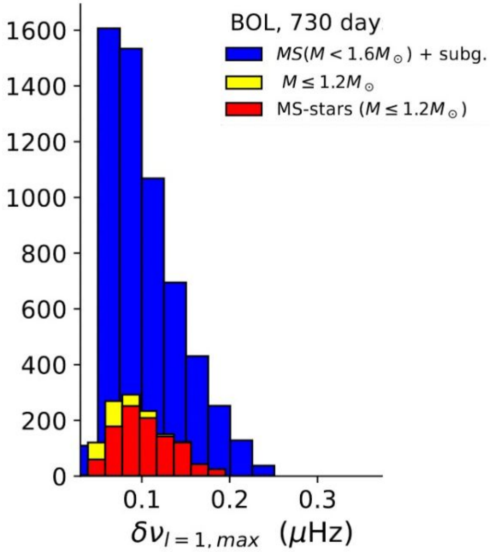
seismic inferences based on measurements of individual modes.
→ δM/M, δR/R and δA/A are directly related to $\delta\nu$



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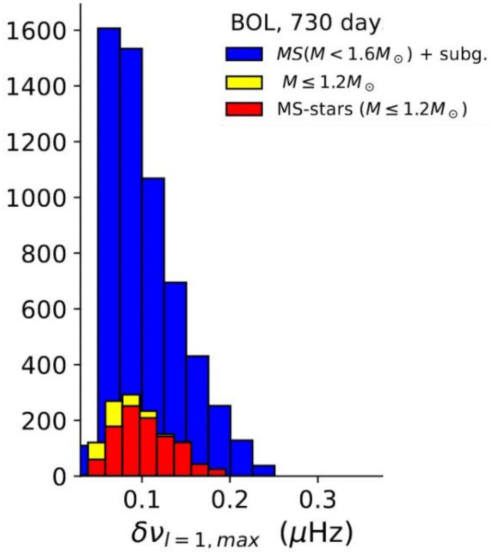
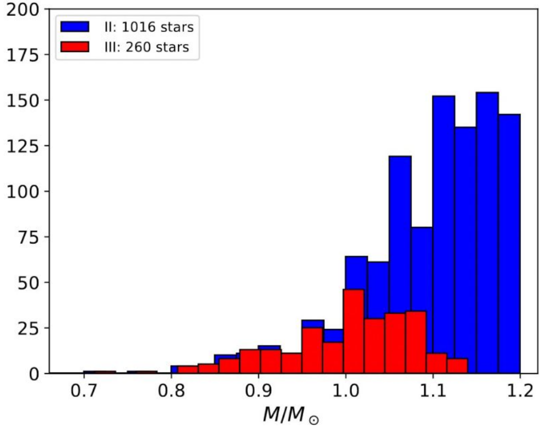
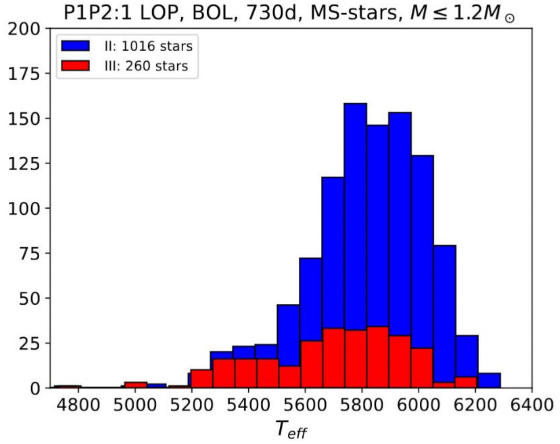
seismic inferences based on measurements of individual modes.
→ δM/M, δR/R and δA/A are directly related to $\delta\nu$

2-year baseline, P1-P2, MS, M< 1.2 Msun

Criterium	BOL	EOL
δM/M < 15% and δR/R < 2%	1016	880
+ δA/A < 10%	1016	880
+ R < 1.1 Rsun	260	195

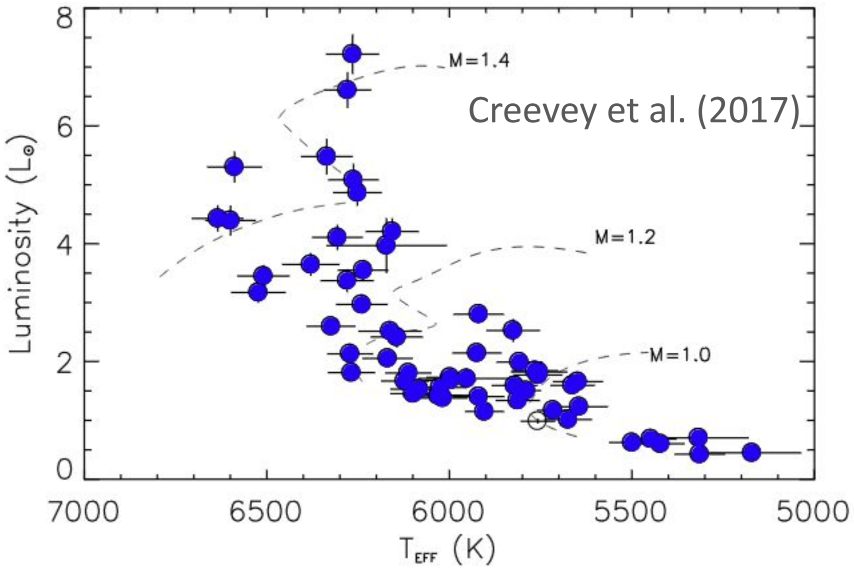


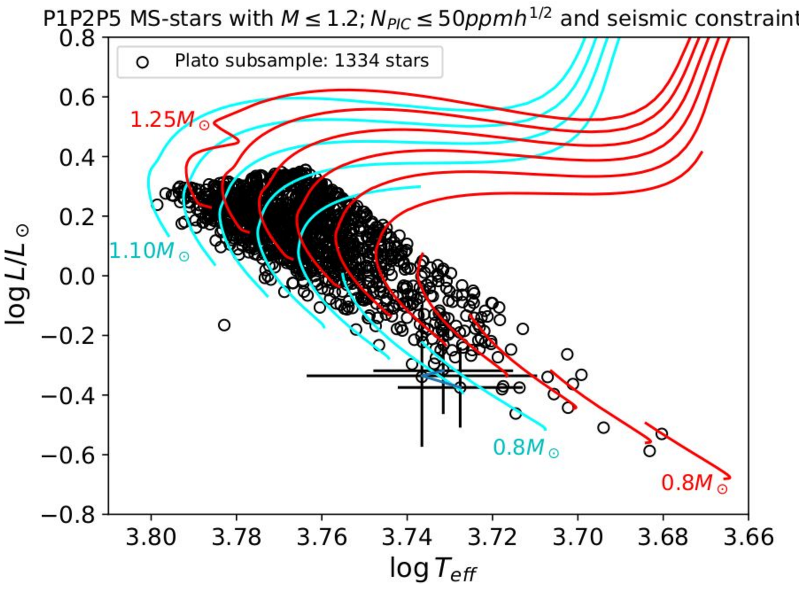




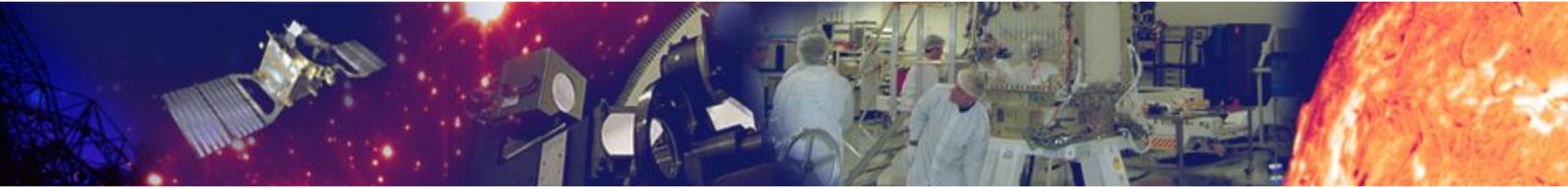
Comparison with Kepler yield

% 67 stars in the Kepler legacy sample





Thank you?

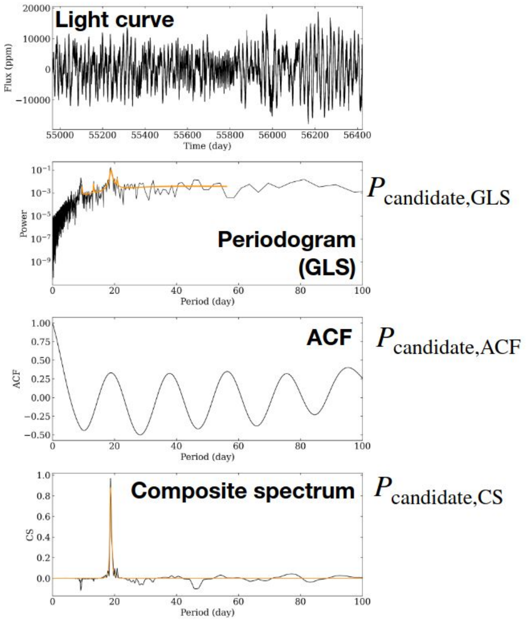


Expected yield: rotation (P1-P2)

MSAP4 output

- Rotation period
- Long term modulation (Sph index, cycle period)
- Granulation
- model-independent log g

For rotation and cycle periods ⟶ ROOSTER

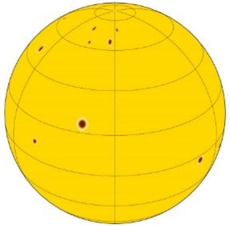


ROOSTER
Random fOrest Over STEllar Rotation
(**Breton** et al. 2021)

⟶ P_{rot} ⟶

The code is open-source and fully modular:
Source code: gitlab.com/sybreton/star_privateer
Documentation: star-privateer.readthedocs.io

star-privateer



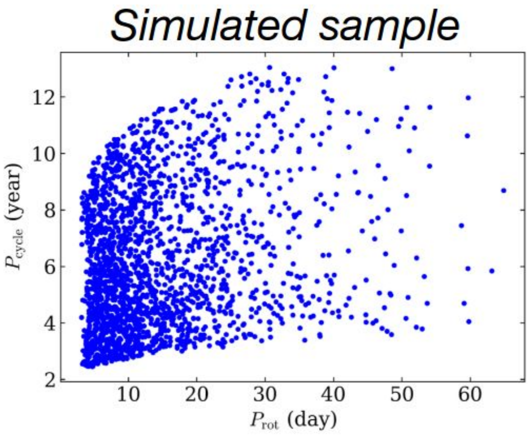
S_{ph}
(photometric **magnetic activity** proxy)
+
Rossby number **Ro** and differential rotation

(Mathur et al. 2014, Noraz et al. 2022)

Expected yield: rotation (P1-P2)

From Breton et al. (2024)

- Simulated light curves for P1-P2 samples (based on PIC 1)
- Estimated recovery rate for rotation and cycle periods



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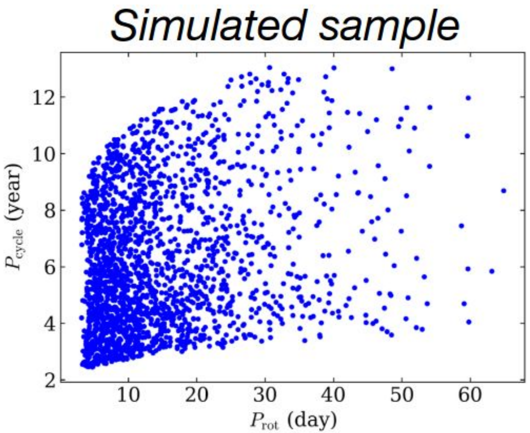
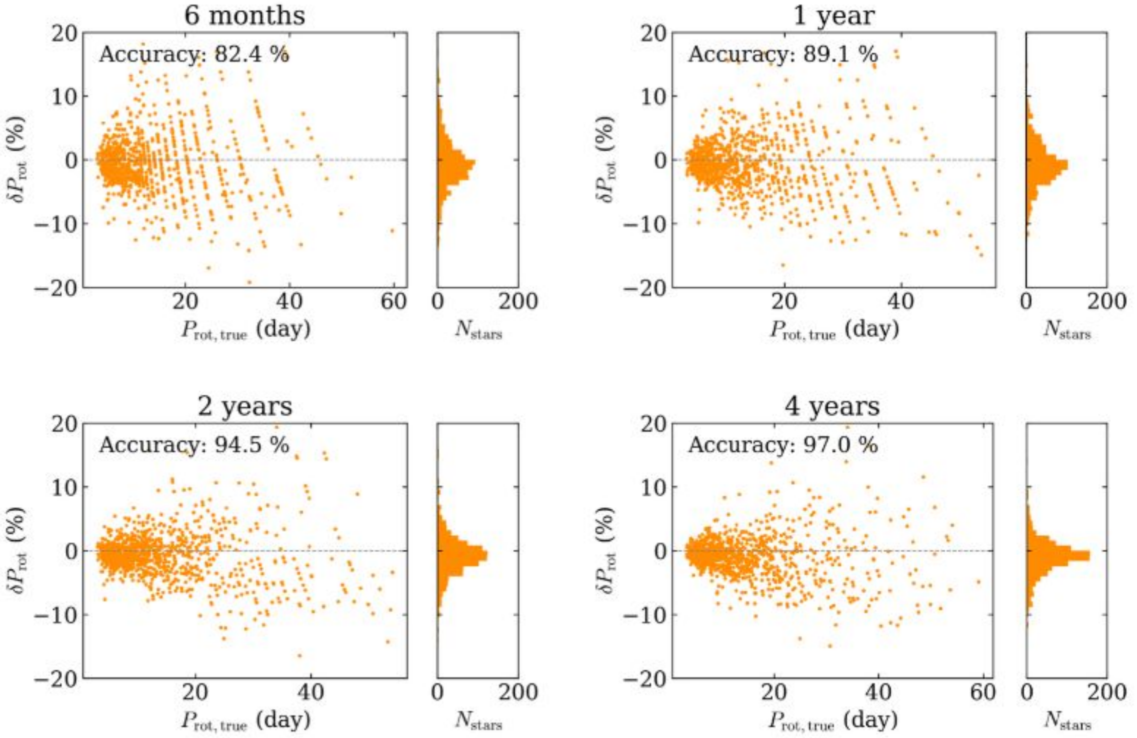




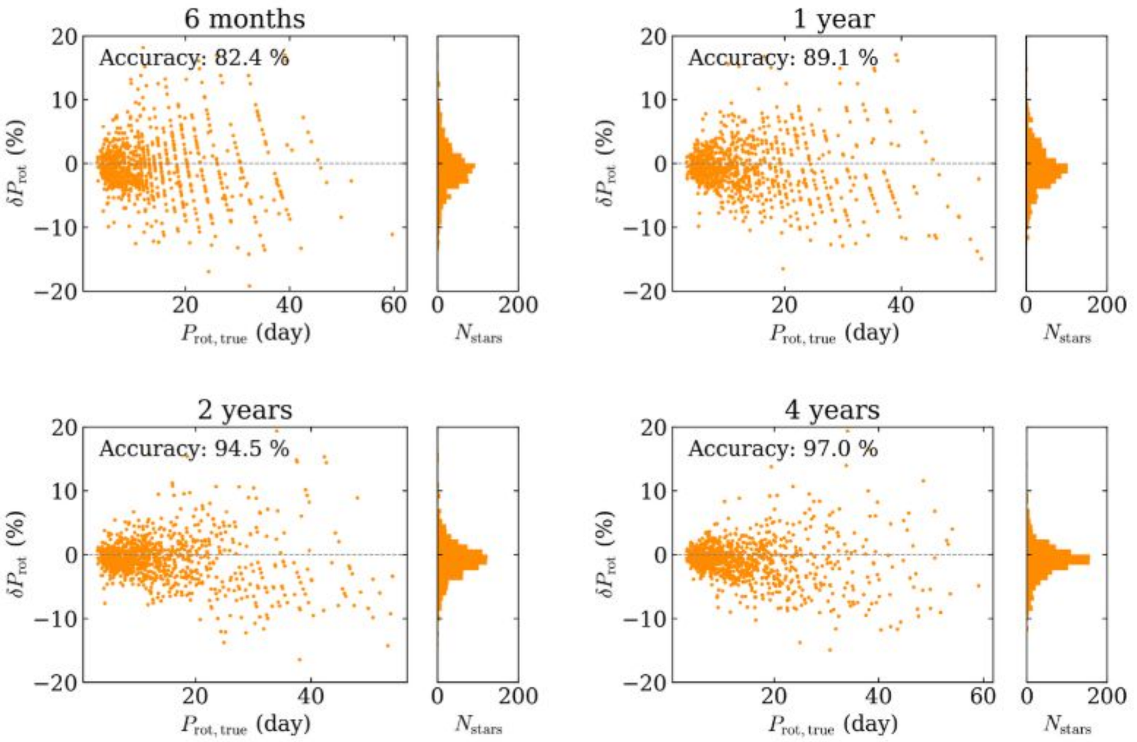
Expected yield: rotation (P1-P2)

From Breton et al. (2024)

- Simulated light curves for P1-P2 samples (based on PIC 1)
- Estimated recovery rate for rotation and cycle periods

Rotation recovery

- Criterium: $\delta P_{rot}/P_{rot} < 10\%$
- Very good recovery rate after 1 or 2 years
- Smaller spread for shorter periods and longer baseline



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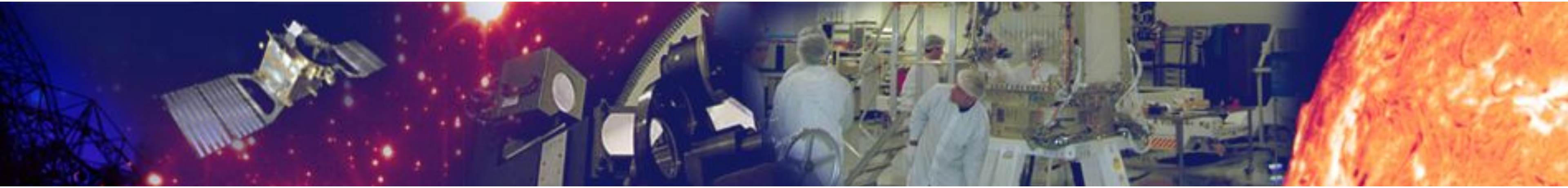


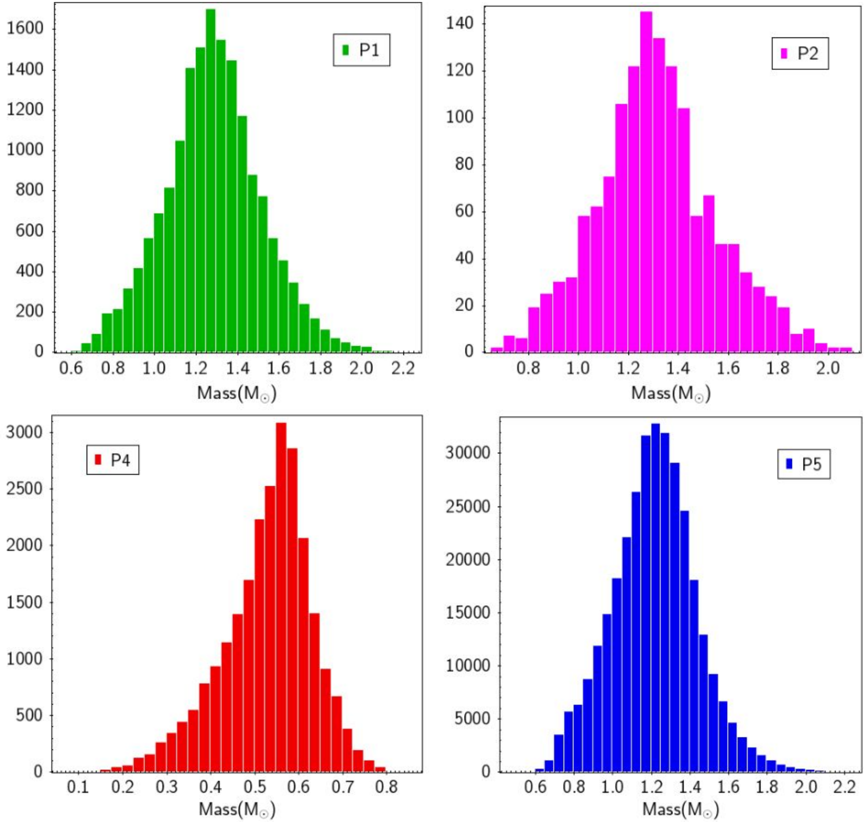
PLATO % TESS

Comparison of PLATO and TESS's design

	PLATO	TESS
Telescope aperture	12cm	10cm
Telescope field of view	1037 deg^2	576 deg^2
Number of telescopes	24	4
Telescope arrangement	Four groups of six. Each group points together. Groups have overlapping fields-of-view.	Adjacent pointing to give strip-like field-of-view
Total field of view (per pointing)	2232 deg^2	2304 deg^2
Time per pointing	2+ years	27 days
Number of pointings	2	30
Pixel size	15 arcseconds	21 arcseconds
Wavelength range	500-1000nm	600-1000nm
Cadence	25s (for main sample, M-dwarfs, brightest stars) 600s (for statistical sample of ≥245,000 stars)	120s (for brightest 200,000 stars) 1800s (full frame images)
Main targets	Bright, Sun-like stars	Bright, M-dwarf stars
Main objective	Earth-sized planets in the habitable zone	Rocky planets
Number of stars	≥265,000	≥500,000
Noise	≤ 50 ppm in 1hr (for main sample) ≤800ppm in 1hr (for M-dwarfs)	≤200ppm in 1hr
Predicted yield	>4,000 planets 2-120 small planets in habitable zone of solar-like stars	~1,700 planets 640-1340 planets around M-dwarfs 1-4 small planets in the habitable zones around M-dwarfs
Nominal mission duration	4 years	2 years
Location	L2 (1.5 million km from Earth)	Orbiting between Earth and the Moon's orbit (384,000km from the Earth)

The PLATO Input Catalog 2.0

Distribution in terms of **mass**



Sample	PIC2.0.0.1-t	Required
P1	16900	15000
P2	1398	1000
P4	24707	5000
P5	313554	245000

From PLATO_SCI_UPD_TN_0020

Predicted seismic yield with PLATO (update with PIC 2.1.0.1)

From Goupil et al. in rev.

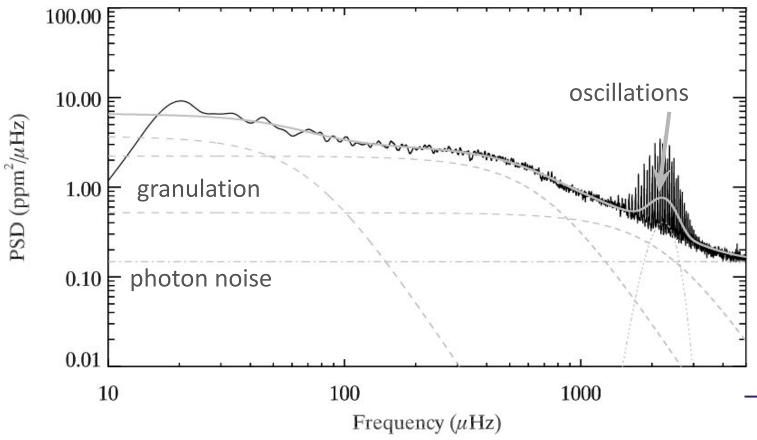
The probability that the power spectrum holds oscillations to a detectable level is given by:

$$P_{\rm final} = \int_y^\infty \frac{\exp(-y')}{\Gamma(N)} y'^{(N-1)}\, dy', \quad \text{avec} \quad y = (1 + {\rm S/N_{thresh}})/(1 + {\rm S/N_{tot}}).$$

${\rm S/N_{thresh}}$ → the S/N threshold above which the probability that the signal is due to noise is lower than 1%.

${\rm S/N_{tot}} = P_{\rm tot}/B_{\rm tot}$ → le global S/N due to the total power in oscillations,

P_{tot} : total power in oscillations B_{tot} : background in the oscillations frequency interval



$B_{tot} = B_{inst} + B_{gran}$

B_{inst} → scaling law: power of ν_{max}

B_{gran} → with PINE for PIC targets

$$P_{\rm tot} \simeq \frac{1}{2} \frac{V_{\rm mod}^2 A_{\rm max}^2}{\Delta\nu}$$ → scaling laws based on stellar parameters

→ Detection probability for samples P_1, P_2 and P_5 targets of the PIC

Predicted seismic yield with PLATO (based on PIC 1.1.0)

PLATO-LIRA-PSM-TN-0098

for 2 instrumental conditions:

Beginning Of Life //

End Of Life (22 cameras only allowing for degradation of the instrument)

cases	BOL	EOL
all	5858	5553
MS-stars	2751	2449
$M < 1.6$	4744	4439
$M < 1.6$, MS-stars	2732	2430
$M \leq 1.2$	1245	1106
$M \leq 1.2$, MS-stars	1016	830
$R \leq 1.1$	269	203

for one LOP:

7 009 stars the P_1-P_2 samples

Samples P_1-P_2

130 140 stars in the P5 sample

From Goupil et al. in rev.