The ESA PLATO project and its stellar science programs

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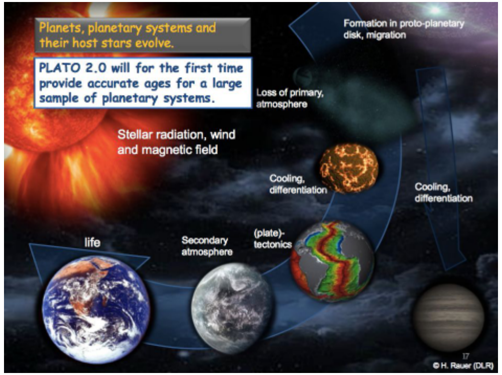
C. Renié, O. Roth, J. Philidet and the WP12

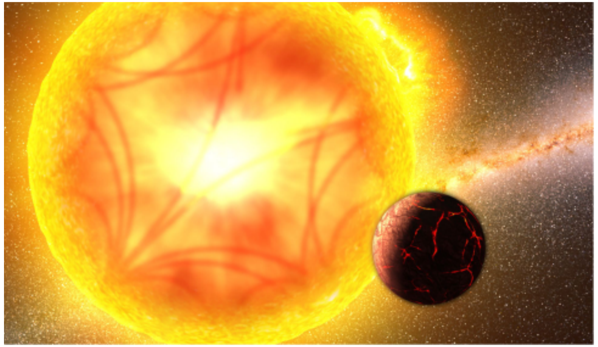
PLATO Science Objectives

Exoplanet Science

- Explore planets diversity
- Characterize terrestrial planet in the HZ around solar-type stars
- Constrain planet formation and evolution processes

→ need for accurate planetary systems **ages**



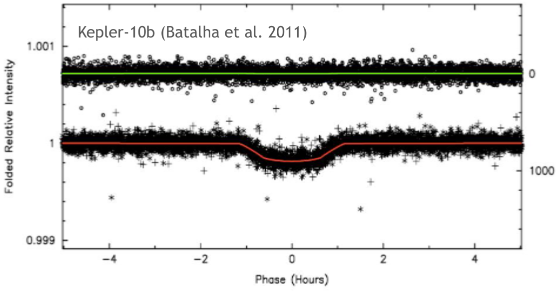


Stellar Science and Asteroseismology

- Perform precise and accurate characterization of stars hosting planets (in particular regarding age)
- Study the internal structure of stars and how it evolves with age.

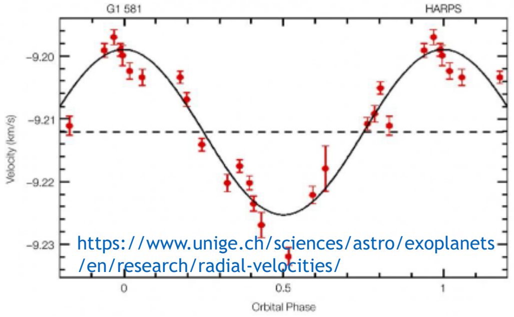
PLATO: a combination of techniques

- Photometric transit



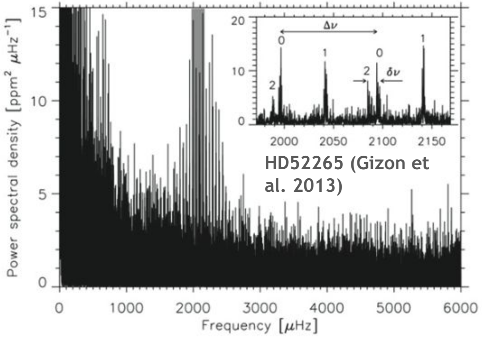
$\rightarrow R_p/R_\star$

- Radial velocities



$\rightarrow M_p/M_\star$

- Asteroseismology



$\rightarrow R_\star, M_\star, \mathrm{Age}, \ldots$

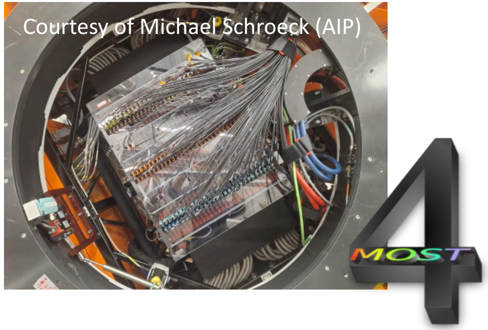
\+

- Astrometry

$\rightarrow L_\star, \ldots$

\+

- Spectroscopy



$\rightarrow T_{\mathrm{eff}}, [F_e/H], \ldots$

Synergies between photometric, spectroscopic, and astrometric observations

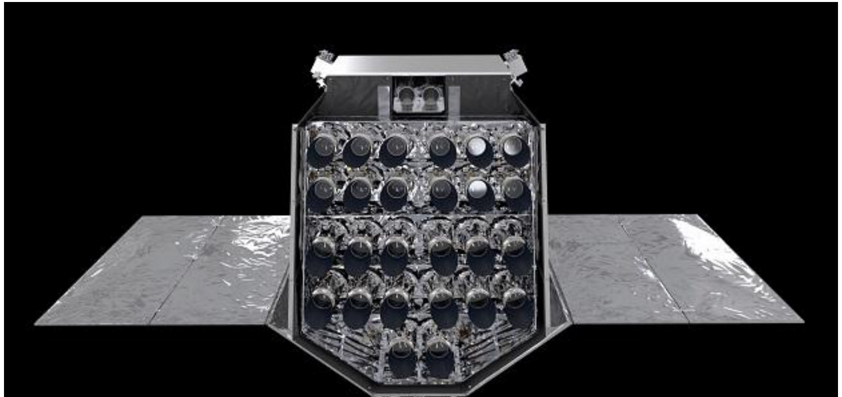
↓

Complete characterization of the observed systems

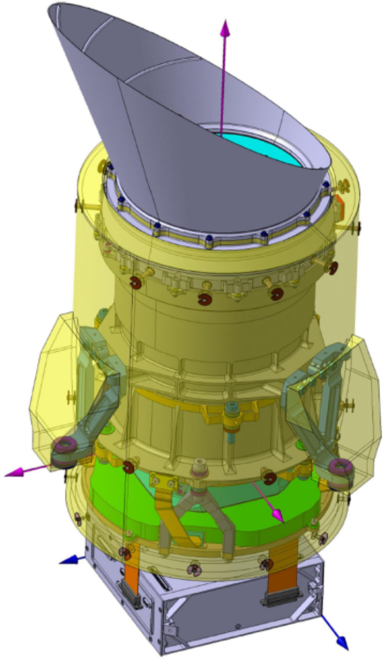
The PLATO instrument

Key figures:

- 24 normal 12cm cameras, cadence 25 s, white light
- 2 fast 12cm cameras, cadence 2.5 s, 2 colors
- 104 CCDs (approximately 8 cm × 8 cm per detector)
- pixel size: 15 arcsec
- Dynamical range: $4 \leq mv \leq 16$



Artist's impression of PLATO.
Credit: ESA/ATG medialab



Schematic figure of one of the cameras of the PLATO spacecraft. *Credit: PMC*

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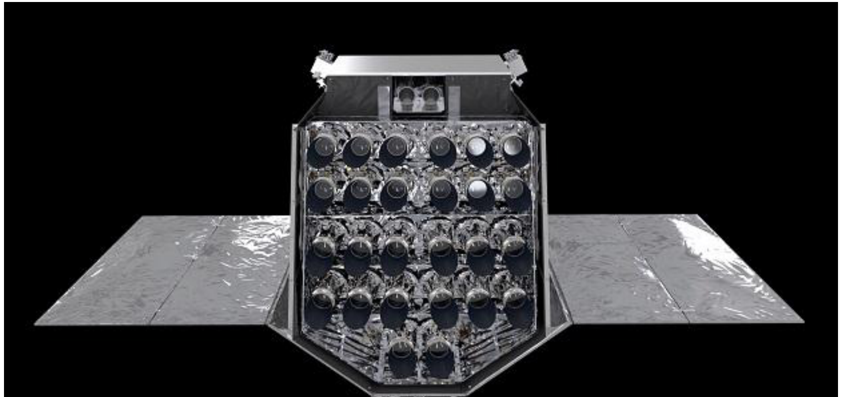

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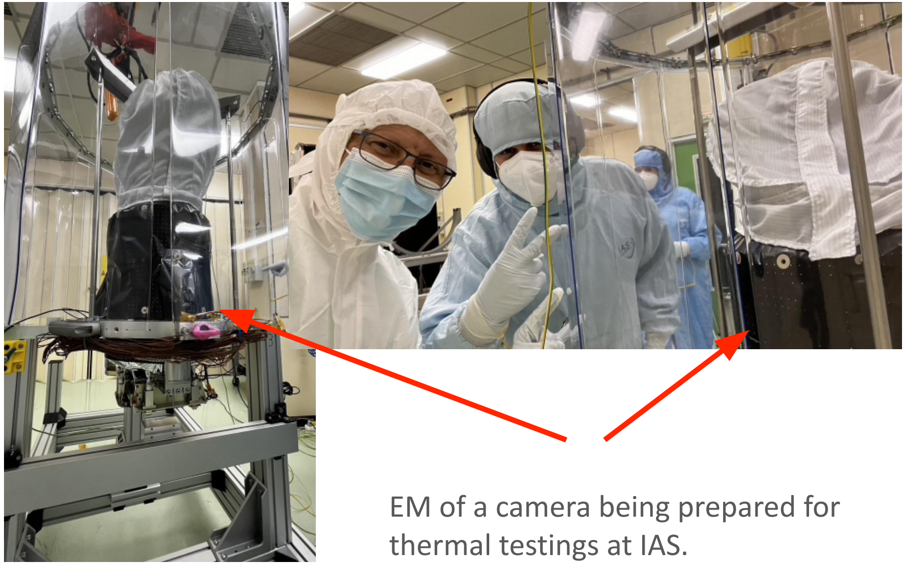
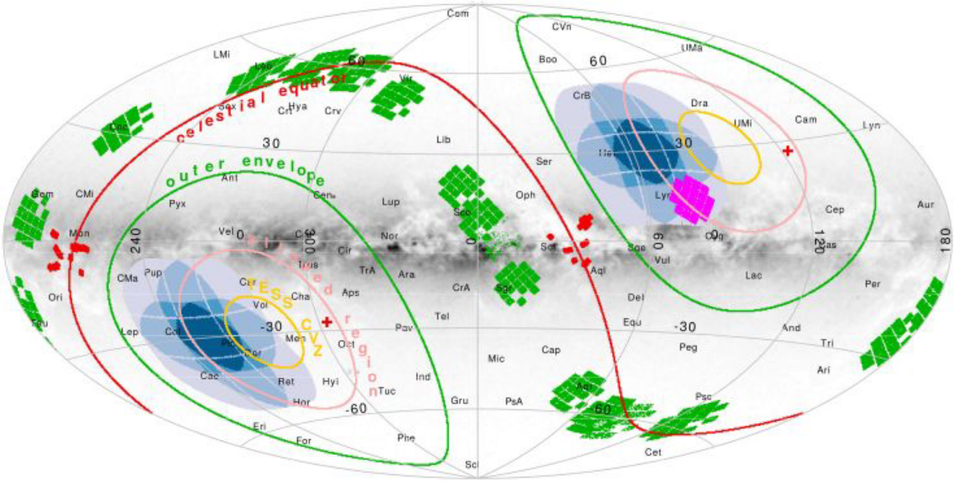
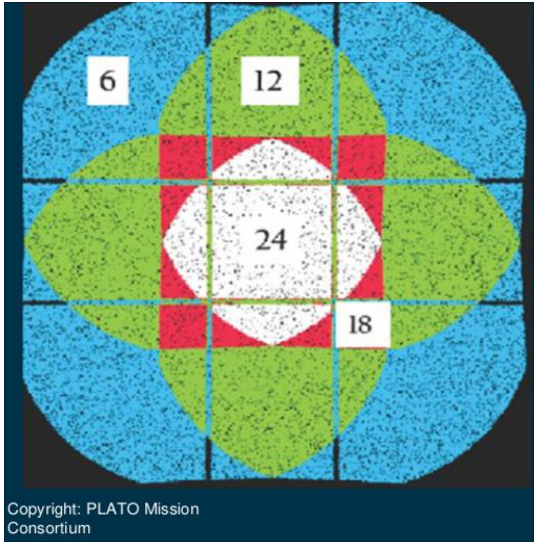


EM of a camera being prepared for thermal testings at IAS.
Courtesy: T. Appourchaux

PLATO observing strategy

- Lifetime: 4 years (extension up to 4.5 years)
- Baseline: 2 long pointings (2yrs+2yrs or 3yrs+1yrs)
- First field (South) selected, second field (North) one year prior to launch





- Total FOV ~ 2232 deg², with 4 groups of cameras ~ 5% of the sky
- PLATO Input Catalogue PIC 1.1.0 based on Gaia DR2 (Montalto et al. 2021, Nascimbeni et al. 2022)
- PIC 2.0.0 based on Gaia DR3 released spring 2023
- Final PIC release based on Gaia DR4 (end of 2025)

The PLATO scientific programs

The PLATO Core Program

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

Designed to fulfill the science objectives of the mission

The Science Calibration and Validation stars (scv stars)

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

Designed to test, improve and validate stellar models

⟶ regimes out of reach by the core program

⟶ Parameters derived using model-independent methods

Complementary Science Program

- 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

Designed to serve the wider community with photometric obs°

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The core program stellar samples

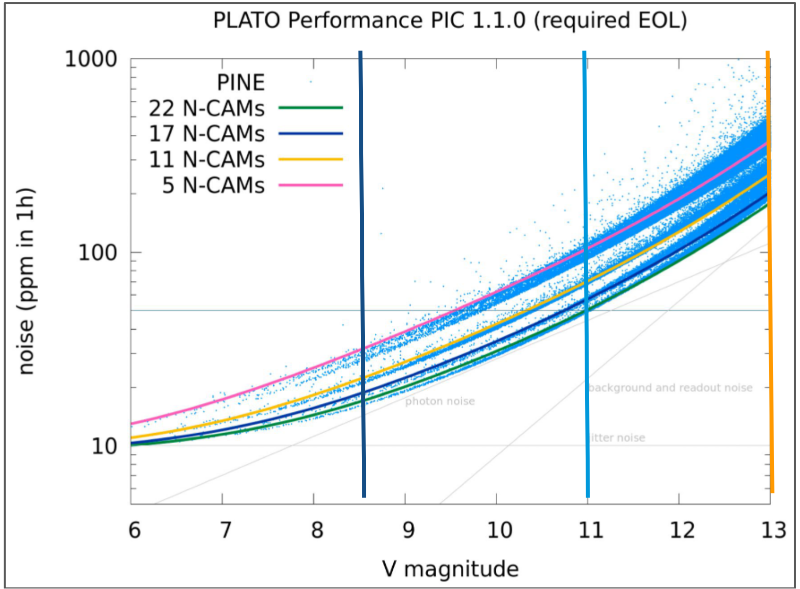
		P_1	P_2	P_4	P_5	Colour sample
Stars		≥ 15,000 (goal 20000)	≥ 1,000	≥ 5,000	≥ 245,000	300
Spectral type		Dwarf and subgiants F5-K7	Dwarf and subgiants F5-K7	Cool late type dwarfs	Dwarf and subgiants F5-K	Anywhere in the HR diagram
Limit m_V		11	8.5	16	13	-
Random noise (ppm in 1 hour)		≤ 50	≤ 50	-	-	-
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

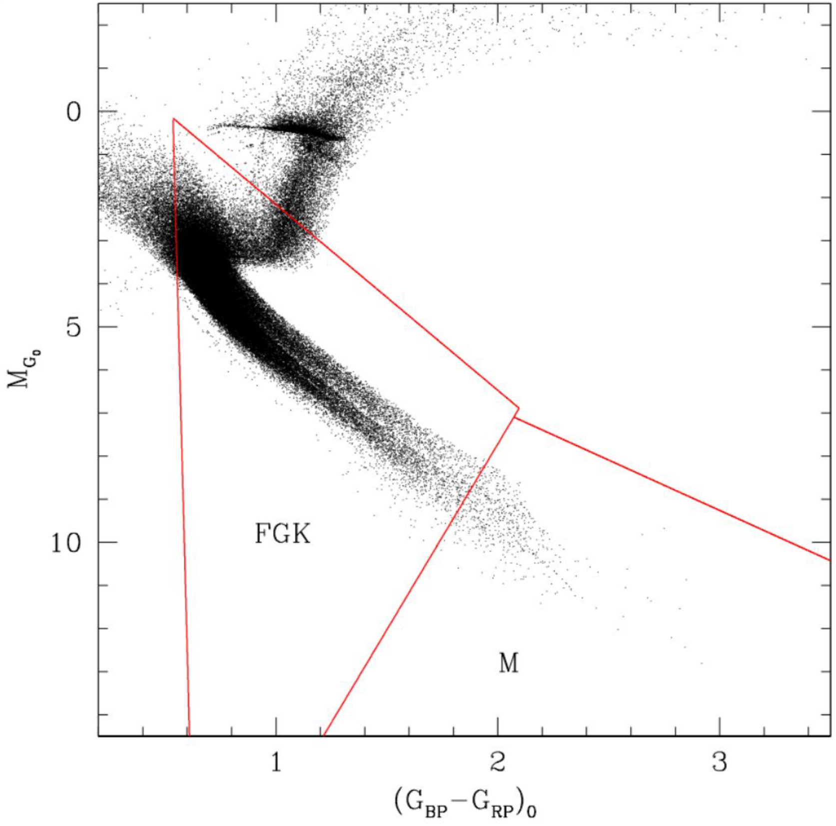
From ESA-PLATO-ESTEC-SCI-RS-001

The PLATO Input Catalog 2.0

- Based on Gaia DR3
- Selection of the samples based on TRILEGAL simulations
- And SNR calculations with PINE (the PLATO Instrumental Noise Estimator, Borner et al. sub)

From Rauer et al. subm.





From PLATO_SCI_UPD_TN_0020

The PLATO Input Catalog 2.0

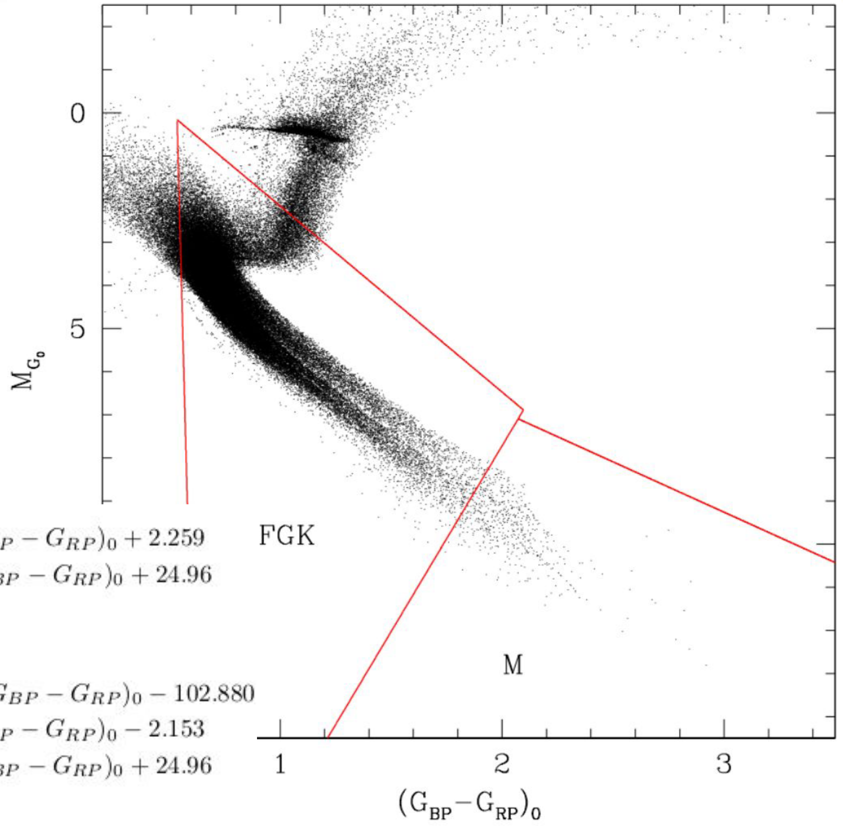
- Based on Gaia DR3
- Selection of the samples based on TRILEGAL simulations
- And SNR calculations with PINE (the PLATO Instrumental Noise Estimator, Borner et al. sub)

$$\text{P1 sample} = \begin{cases} M_{G,0} \leq 192.308\,(G_{BP} - G_{RP})_0 - 102.880 \\ M_{G,0} \geq 4.314\,(G_{BP} - G_{RP})_0 - 2.153 \\ M_{G,0} \leq -8.62\,(G_{BP} - G_{RP})_0 + 24.96 \\ V \leq 11 \\ \mathrm{NSR_{sys}} \leq 50\,\mathrm{ppm\,hr^{-1}} \end{cases}$$

$$\text{P2 sample} = \begin{cases} M_{G,0} \leq 192.308\,(G_{BP} - G_{RP})_0 - 102.880 \\ M_{G,0} \geq 4.314\,(G_{BP} - G_{RP})_0 - 2.153 \\ M_{G,0} \leq -8.62\,(G_{BP} - G_{RP})_0 + 24.96 \\ V \leq 8.5 \\ \mathrm{NSR_{sys}} \leq 50\,\mathrm{ppm\,hr^{-1}} \end{cases}$$

$$\text{P4 sample} = \begin{cases} M_{G,0} \geq 2.334\,(G_{BP} - G_{RP})_0 + 2.259 \\ M_{G,0} > -8.62\,(G_{BP} - G_{RP})_0 + 24.96 \\ V \leq 16 \end{cases}$$

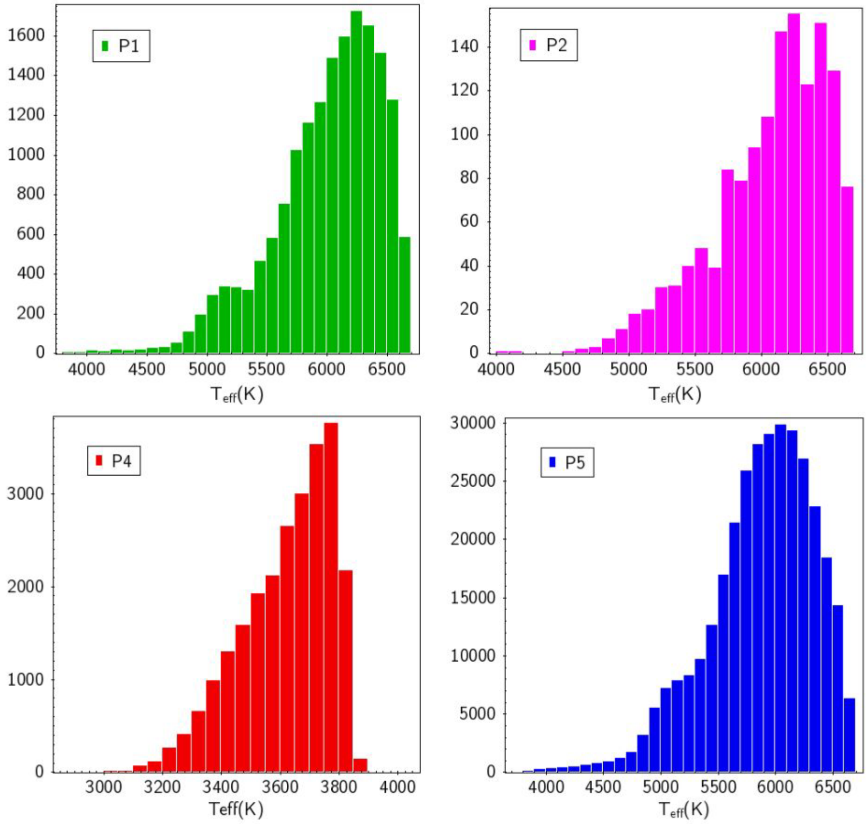
$$\text{P5 sample} = \begin{cases} M_{G,0} \leq 192.308\,(G_{BP} - G_{RP})_0 - 102.880 \\ M_{G,0} \geq 4.314\,(G_{BP} - G_{RP})_0 - 2.153 \\ M_{G,0} \leq -8.62\,(G_{BP} - G_{RP})_0 + 24.96 \\ V \leq 13 \end{cases}$$



From PLATO_SCI_UPD_TN_0020

The PLATO Input Catalog 2.0

Distribution in terms of **Teff**

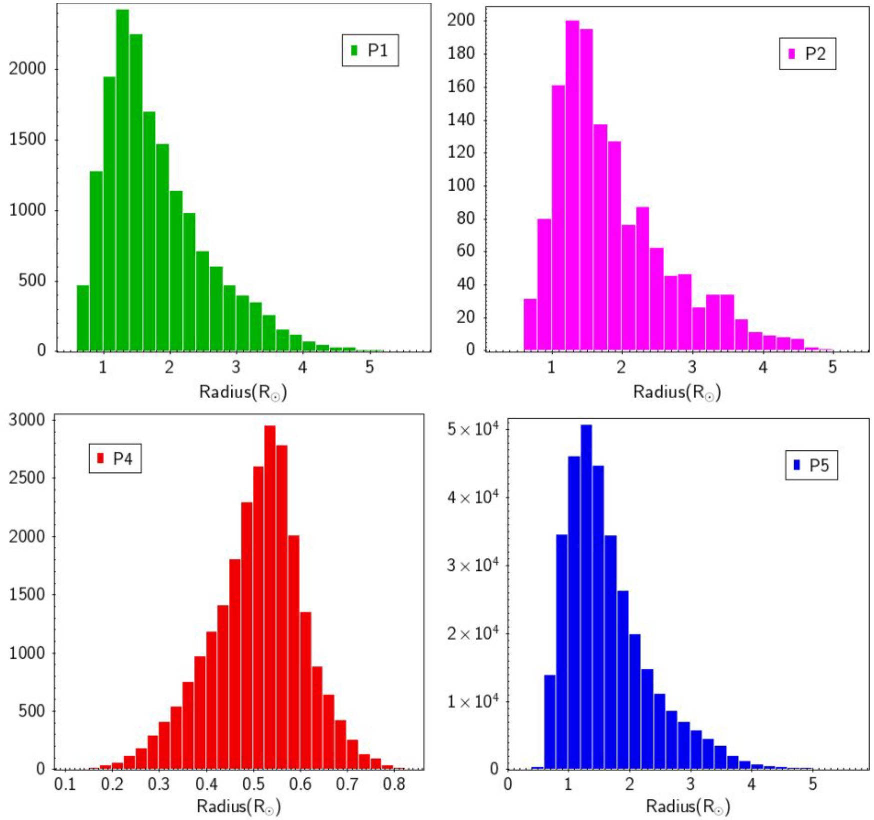


Sample	PIC2.0.0.1-t	Required
P1	16900	15000
P2	1398	1000
P4	24707	5000
P5	313554	245000

From PLATO_SCI_UPD_TN_0020

The PLATO Input Catalog 2.0

Distribution in terms of **radius**



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P2	1398	1000
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P5	313554	245000

From PLATO_SCI_UPD_TN_0020

Predicted seismic yield with PLATO (based on PIC 1.1.0)

From Goupil et al. in rev.

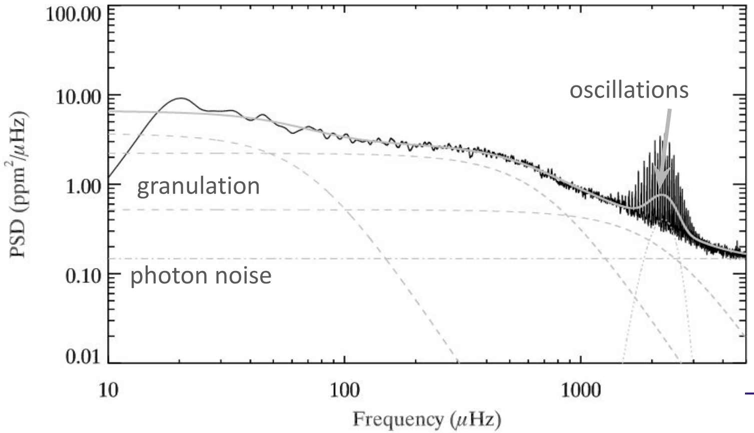
The probability that the power spectrum holds oscillations to a detectable level is given by:

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

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

$\mathrm{S/N_{tot}} = P_{\rm tot}/B_{\rm tot}$ → 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



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

→ scaling law: power of ν_{max}

→ with PINE for PIC targets

$$P_{\rm tot} \simeq \frac{1}{2}\frac{V^2_{\rm mod} A^2_{\rm max}}{\Delta\nu}$$

→ 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)

for one LOP:

7 009 stars the P_1-P_2 samples

130 140 stars in the P5 sample

for 2 instrumental conditions:

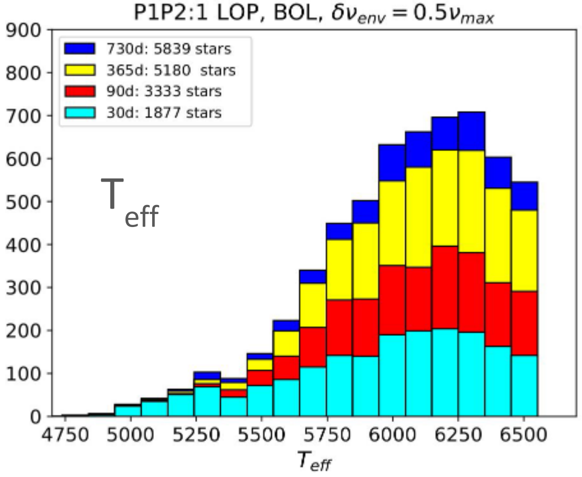
Beginning Of Life //

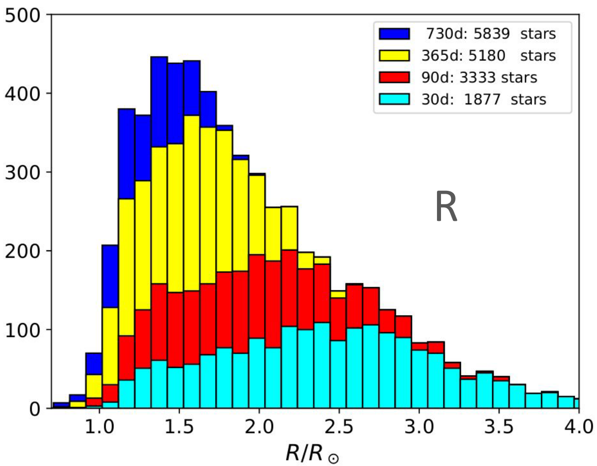
End Of Life (22 cameras only allowing for degradation of the instrument)

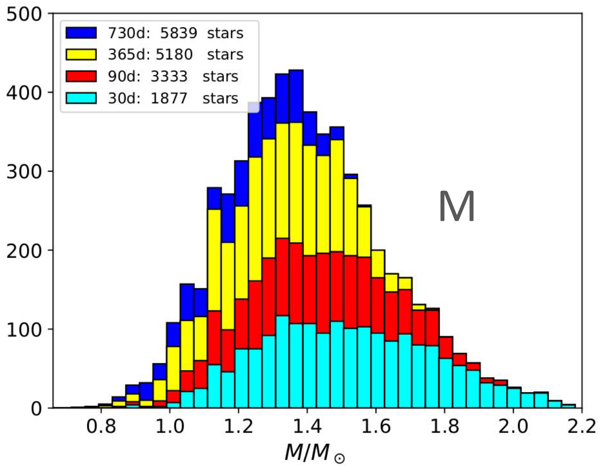
cases	BOL	EOL
all	5858	5553
MS-stars	2751	2449
$M < 1.6$	4744	4439
$M < 1.6$, MS-stars	2732	2430
$M \leq 1.2$	1245	1106
$M \leq 1.2$, MS-stars	1016	830
$R \leq 1.1$	269	203

Samples P_1-P_2

From Goupil et al. in rev.







Predicted seismic yield with PLATO (based on PIC 1.1.0)

for one LOP:

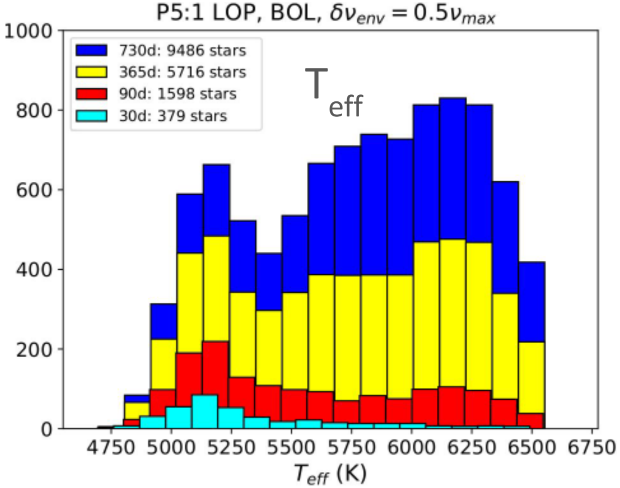
7 009 stars the P_1-P_2 samples

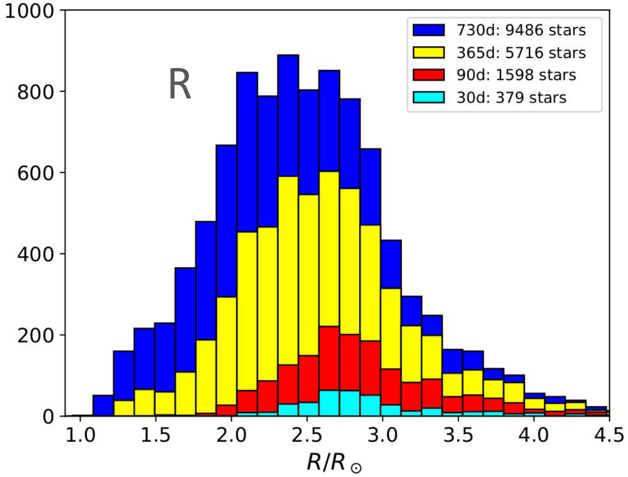
130 140 stars in the P5 sample

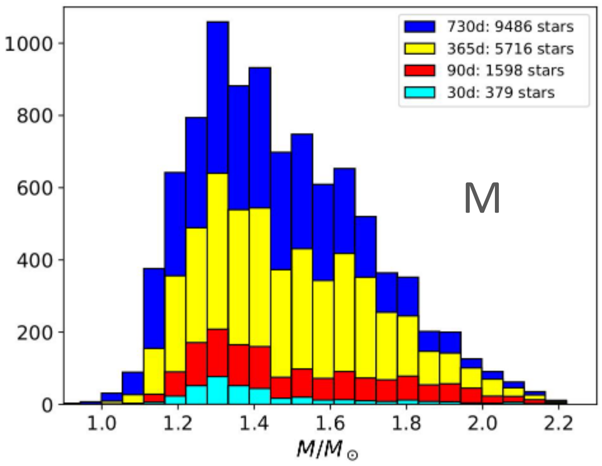
cases	730d	365d	90d
all	9491	5718	1599
MS-stars $M \leq 1.6 M_\odot$ & subgiants of all masses	9486	5716	1599
Subgiants of all masses	8877	5657	1599
$M \leq 1.2$:	878	392	81
MS-stars	250	43	0
subgiants	628	349	81

Sample P_5

From Goupil et al. in rev.







Predicted seismic yield with PLATO (based on PIC 1.1.0)

Theoretical **uncertainties on oscillations** frequencies (Libbrecht 1992):

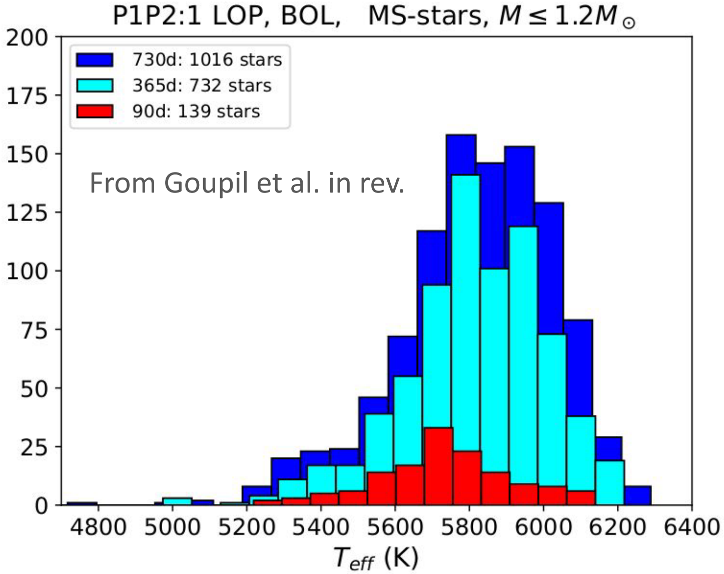
$$\delta\nu_{\ell=1,\max} = \sigma_{\mathrm{Libb},\ell=1,\max}\left(4.89 - 4.18\,\frac{T_{\mathrm{eff}}}{6000}\right)$$

depends on stellar parameters, S/N and observation duration

Uncertainties on M and R
(simulations on grid of stellar models and frequencies + applying seismic inference optimisation):

$$\begin{cases} \delta M/M &= 2.083\ \delta\nu_{\ell=1,max} + 0.046 \\ \delta R/R &= 0.707\ \delta\nu_{\ell=1,max} + 0.149 \end{cases}$$

PLATO Science Requirements:
Mass better than **15%**,
Radius better than **2%**,
Age as low as **10%**
for PLATO reference star
$1M_{sun}$, $1R_{sun}$ and T_{eff} = 6000K.



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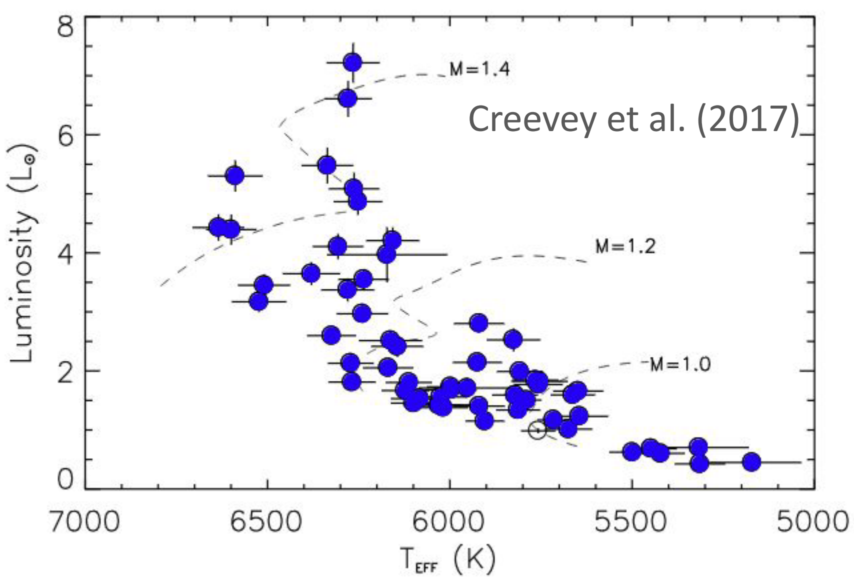
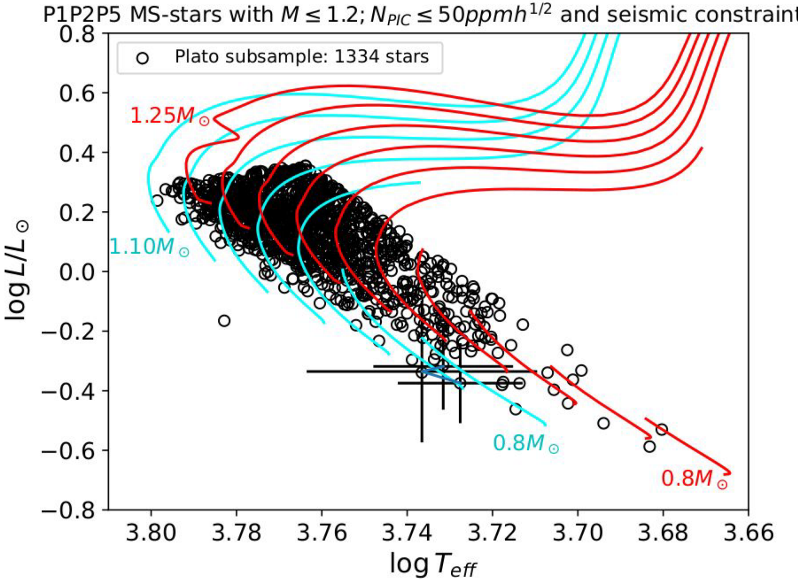
% 67 stars in the Kepler legacy sample

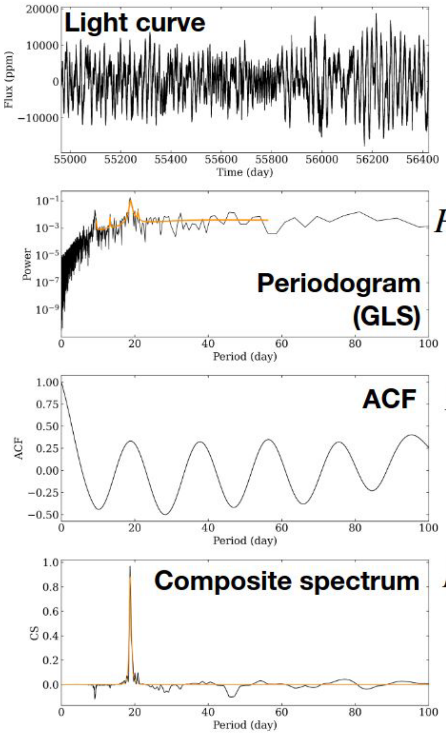




Rotation and activity with PLATO (based on PIC 1.1.0)

MSAP4 stellar rotation and activity measurement: Prot, ΔProt, S_{ph}, long term modulation

Breton et al. (in prep)



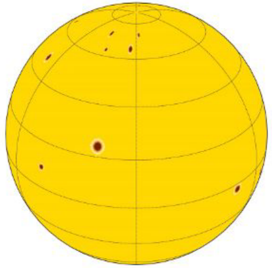
$P_{\mathrm{candidate,GLS}}$

$P_{\mathrm{candidate,ACF}}$

$P_{\mathrm{candidate,CS}}$

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

→ P_{rot} →



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

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

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

star-privateer

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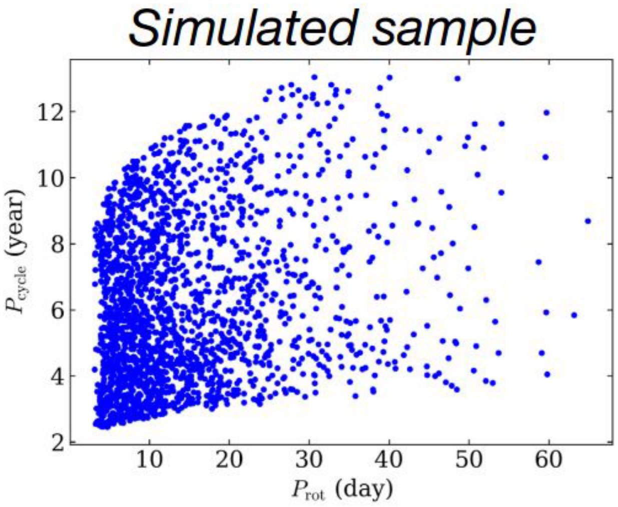

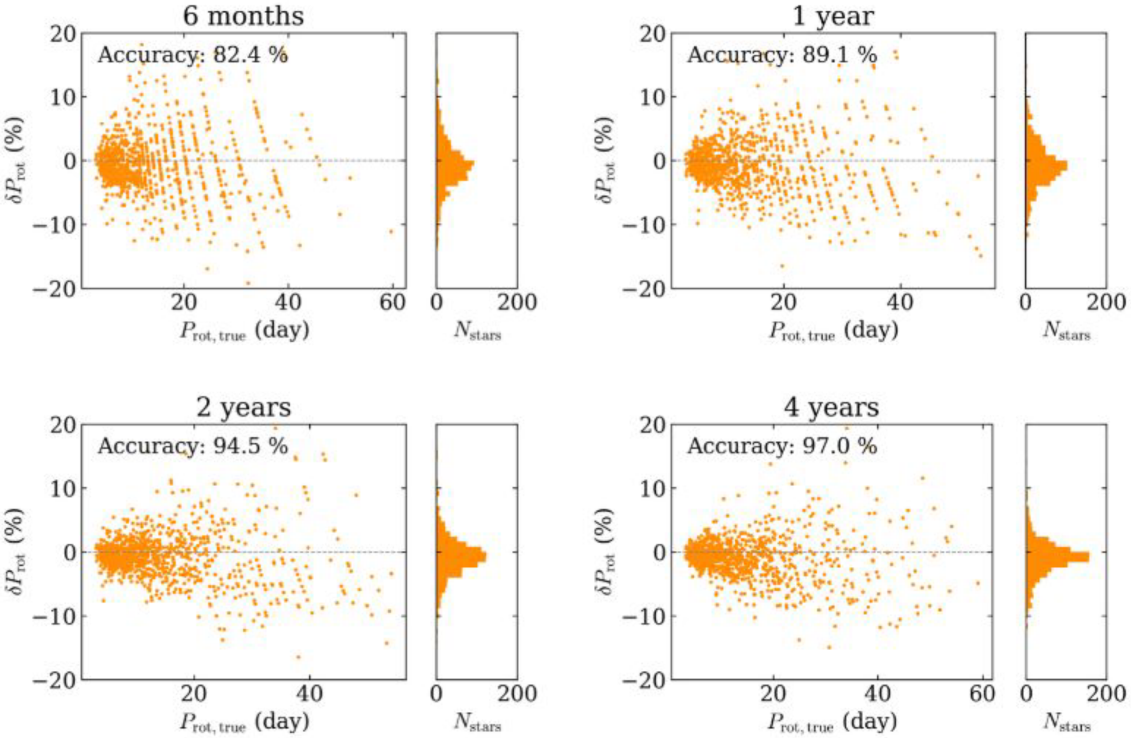

The PLATO data products

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	
Stellar rotation and activity	DP4	L2	
Stellar radii, masses, and ages	DP5	L2	
Living catalogue of confirmed planetary systems and their characteristics using light curves and transit time variations	DP6	L2	
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

+ a large set of additional data products: • analysis ready cleaned lightcurves,
• modes splittings, heights, width, power and peak asymmetry, inclination angles
• seismic log g • flare parameters • effective temperature • metallicity, abundance of alpha elements, …

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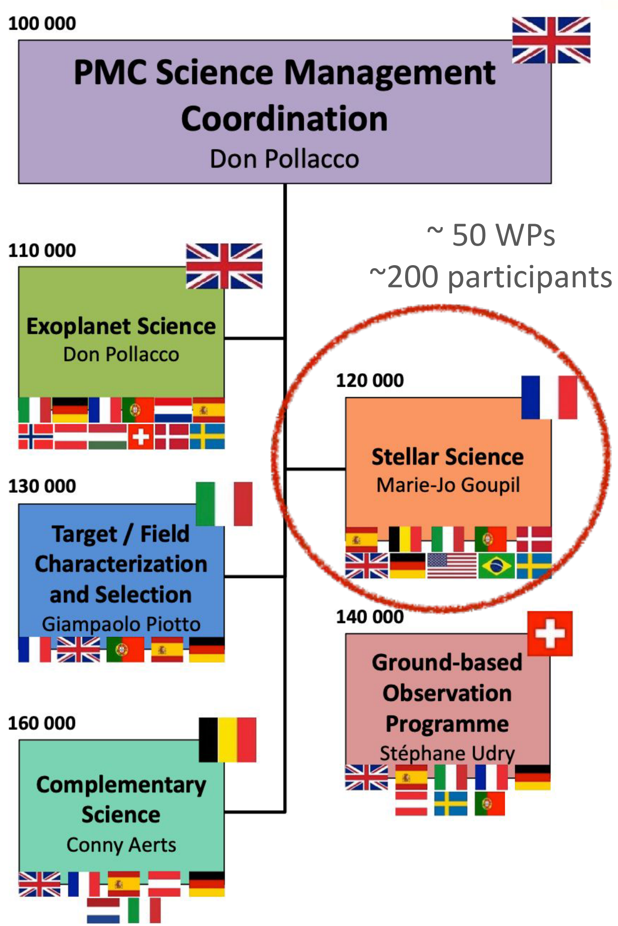
PLATO mission consortium: core stellar science

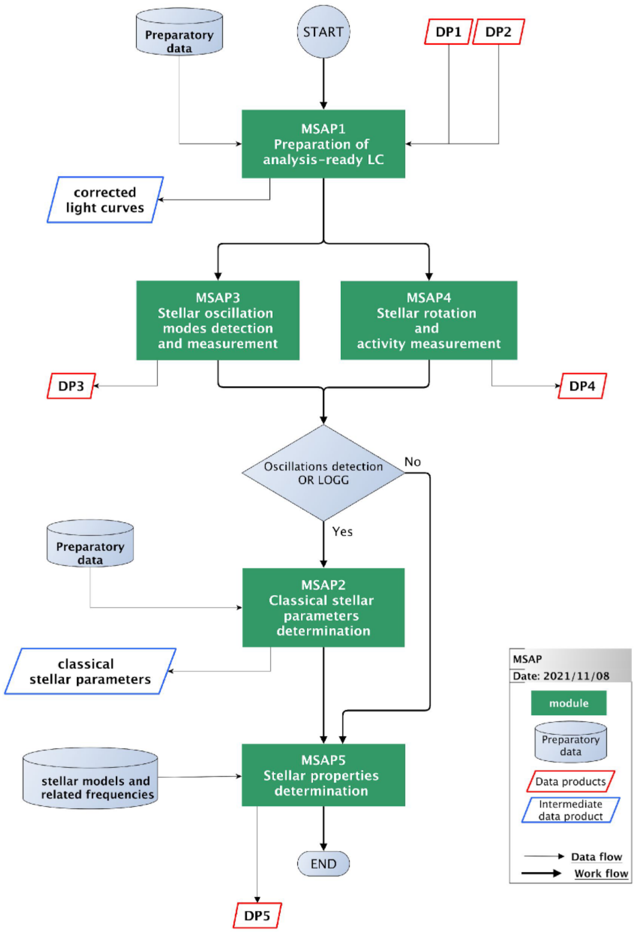
- Stellar science (WP12) duties:
  - L2 stellar pipeline specifications (architecture and algorithms)
  - Provide tools: stellar model/frequencies grids, spectroscopic parameter tables, ...
  - Validation of the pipeline and evaluation of the performances -> test cases, benchmark stars, etc…
  - During implementation and operation phases : updates of algorithms and tools if needed
  - During operations: validation of mission data-products
- If you want to join the Stellar Science PSM (WP12) plato.wp120-office@obspm.fr



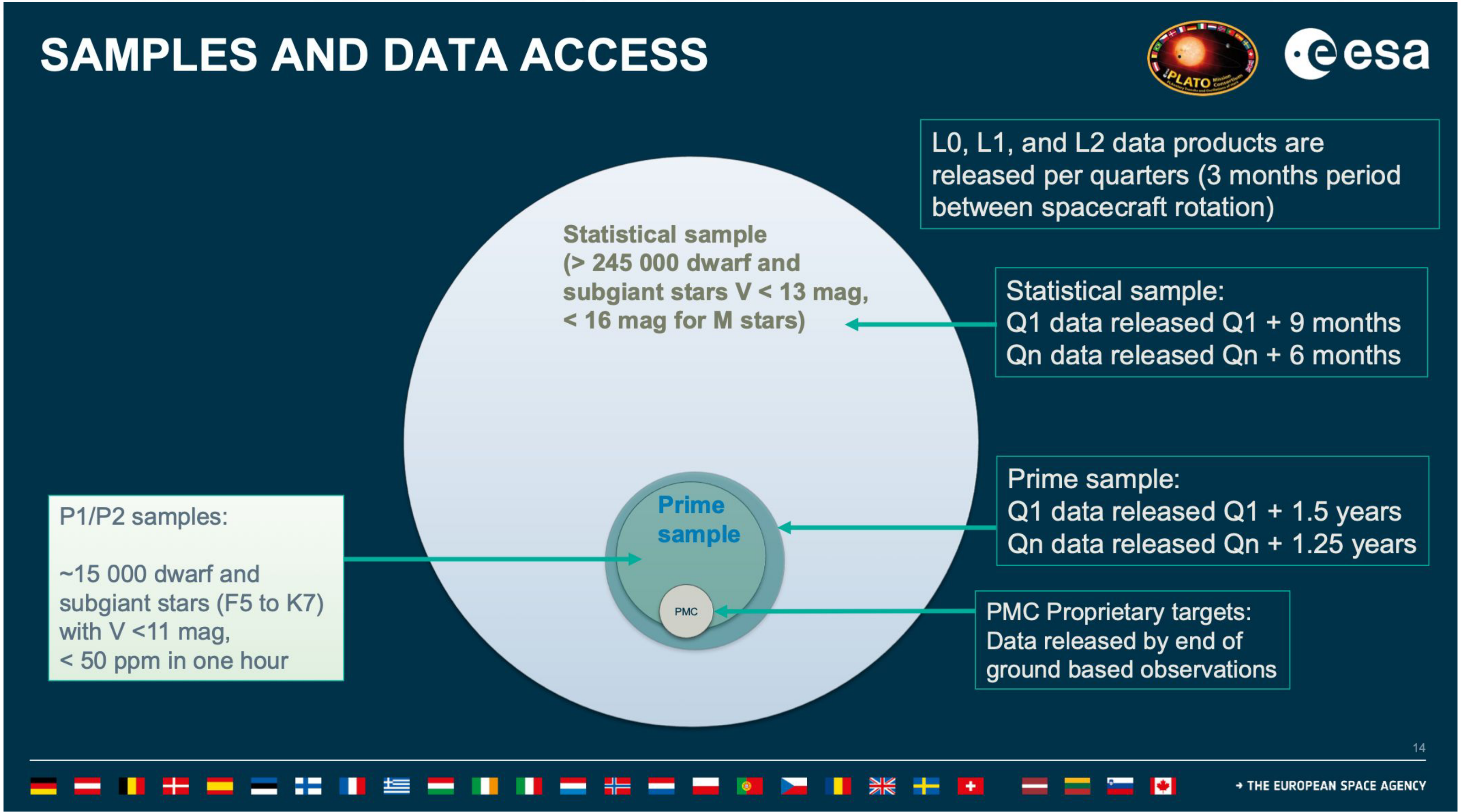
PLATO mission consortium: the stellar pipeline

- ✓ The SAS (Stellar Analysis System) pipeline will process P1, P2, P4, and P5 samples to provide DP3,DP4, and DP5
- ✓ Overall specifications, tests and scientific validation at LESIA Implemention and operation at IAS

- 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, J. Ballot
- *Grids of stellar models and frequencies*
  Lead: A. Serenelli



Data policy for the core program



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The PLATO Core Program

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

Designed to fulfill the science objectives of the mission

The Science Calibration and Validation stars (scv stars)

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

Designed to test, improve and validate stellar models

→ regimes out of reach by the core program

→ Parameters derived using model-independent methods

Complementary Science Program

- 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

Designed to serve the wider community with photometric obs°

PLATO complementary science

Stellar Science → Extragalactic Science → Transient phenomena

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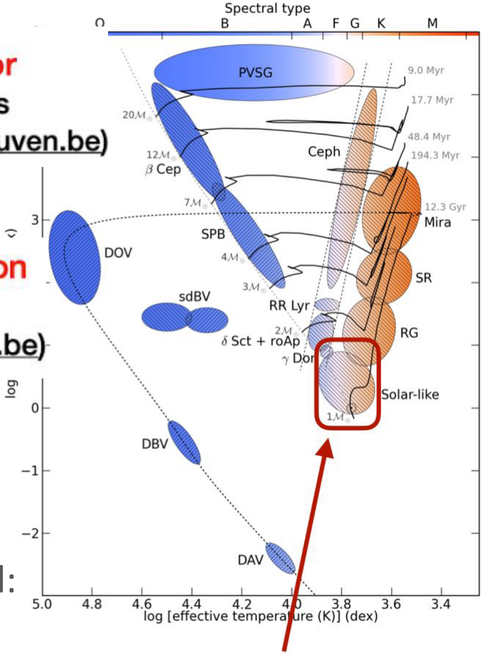
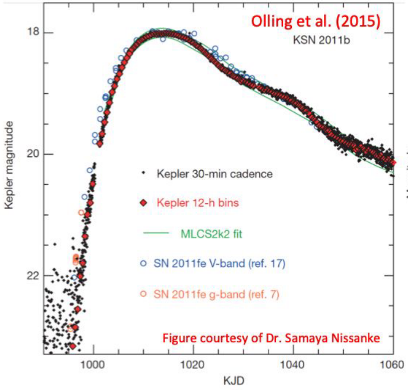
8% of the mission telemetry
2 Guest Observer proposal: 1st one in 2025



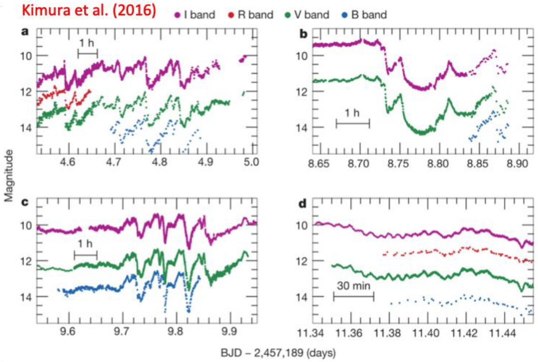
Core Science

Asteroseismology of solar-like pulsators



Extragalactic Science

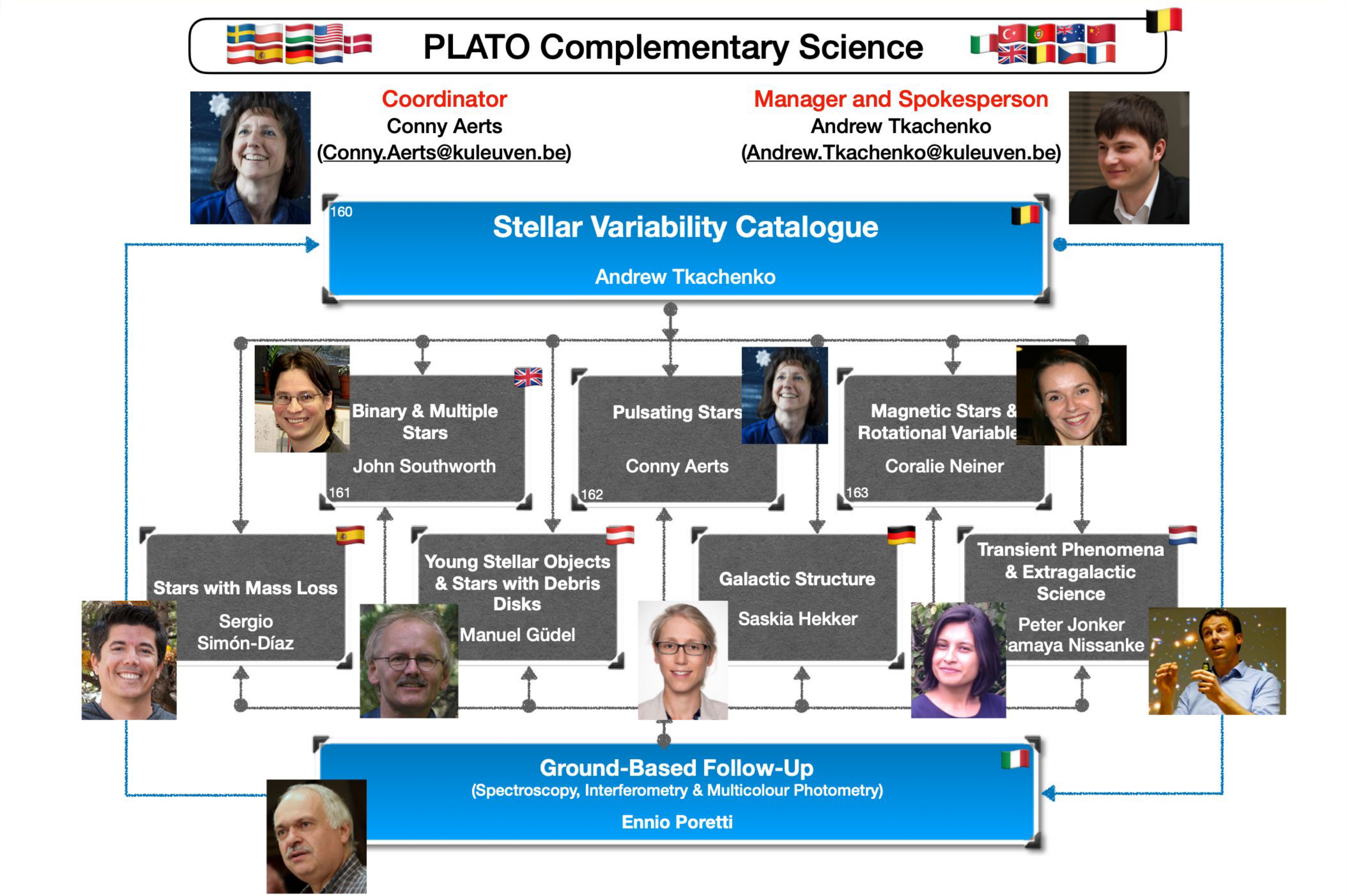
- SNe explosions in distant galaxies: progenitor shock-breakout physics
- Monitoring cores of 1000s AGNs to understand SMBH accretion & variability



Transient Universe

- Mapping and understanding of accretion physics near YSOs
- White dwarfs, black holes, and neutron stars: monitoring in fast cadence asap after transient

PLATO complementary science



Merci de votre attention !