ARCHITECTURES OF ROTATING STAR-PLANET SYSTEMS:

COMPARING THEORETICAL PREDICTIONS TO OBSERVATIONS

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AIM, CEA, CNRS, Université Paris-Saclay, Université de Paris, Sorbonne Paris Cité

In collaboration with:

Breton, S.N., Ahuir, J., Mathur, S., Brun, A.S., Delsanti, V., Mathis, S., Santos, A.R.G.

HOW DOES A PLANET AFFECT THE EVOLUTION OF THE STAR?

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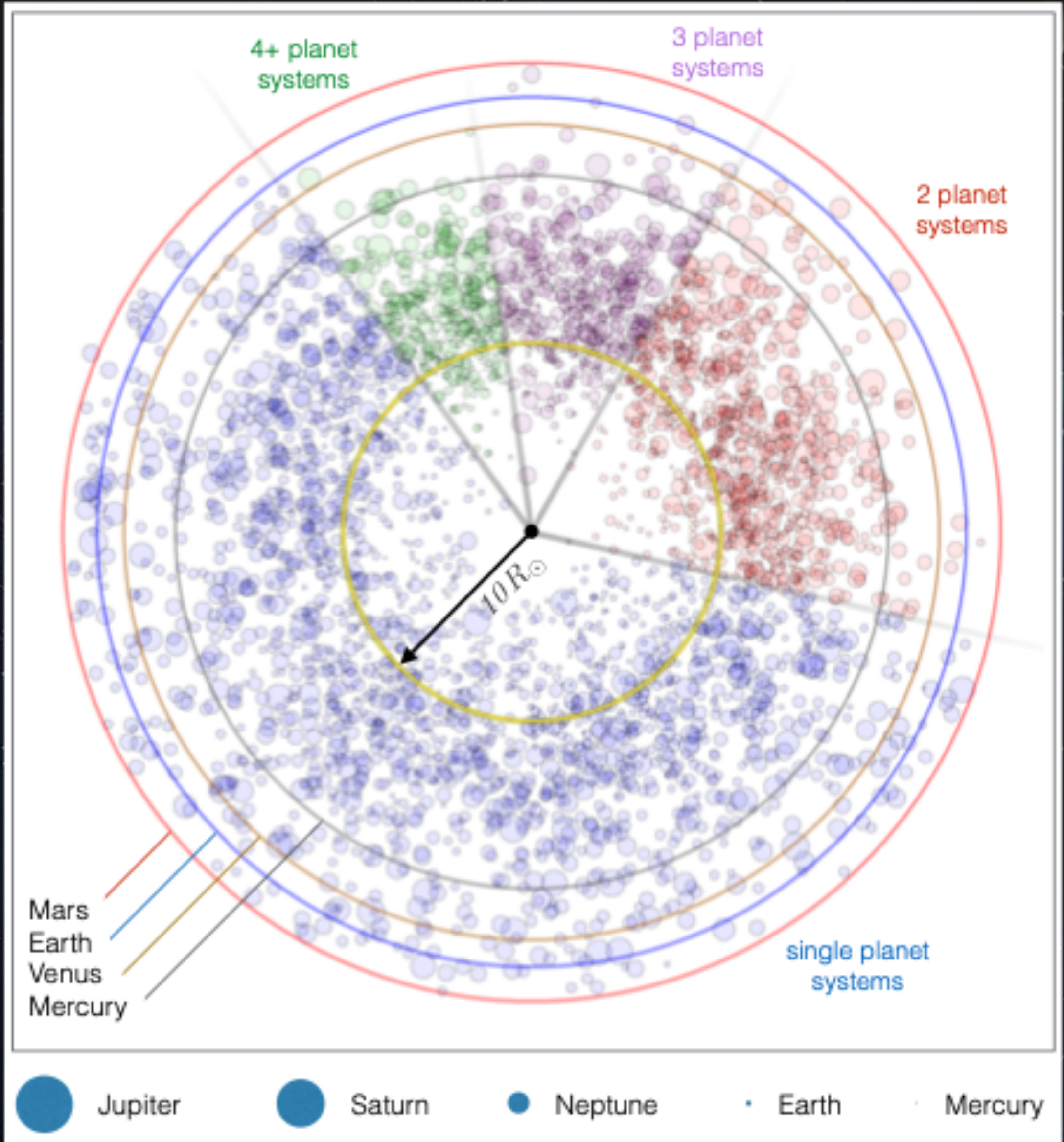
SUMMARY

- I- Introduction
  - Architecture of the exoplanet systems: P_{orb} vs P_{rot}
- II- Data analysis
  - Determination of P_{rot}
- III- Modelling
  - ESPEM
- Comparing the distribution of planets produced
  - By the Model to confirmed distribution of planets
- Conclusion & Perspectives

I-Introduction:

P_{rot} vs P_{orb}

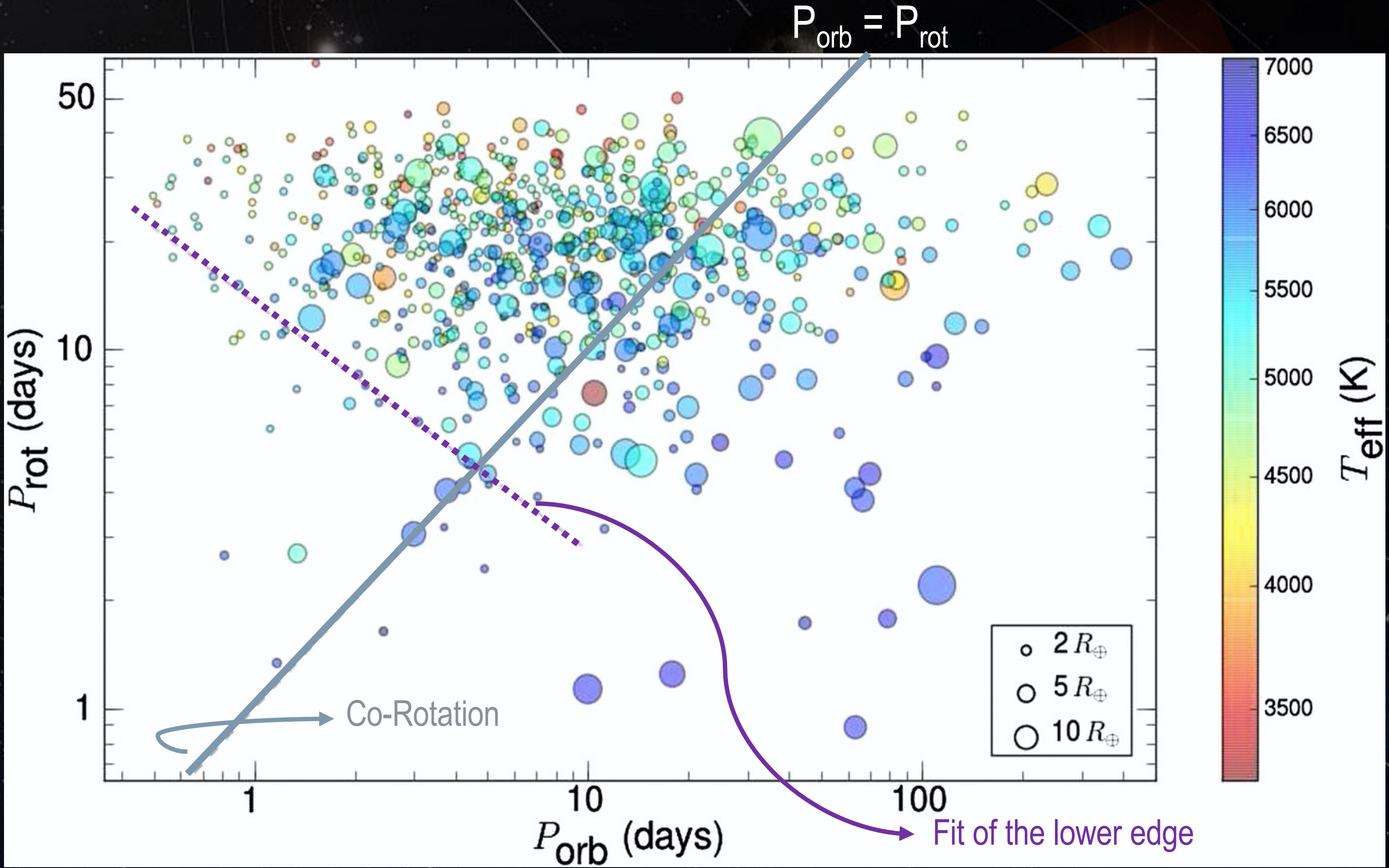
I-INTRODUCTION



- ~4560 planets discovered
- ~ 1 planet per star in average
- Close-in systems
  - observational bias
- Need to better understand simultaneously:
  - Influence of activity and stellar winds of the host stars.

[Batygin & Laughlin 15]

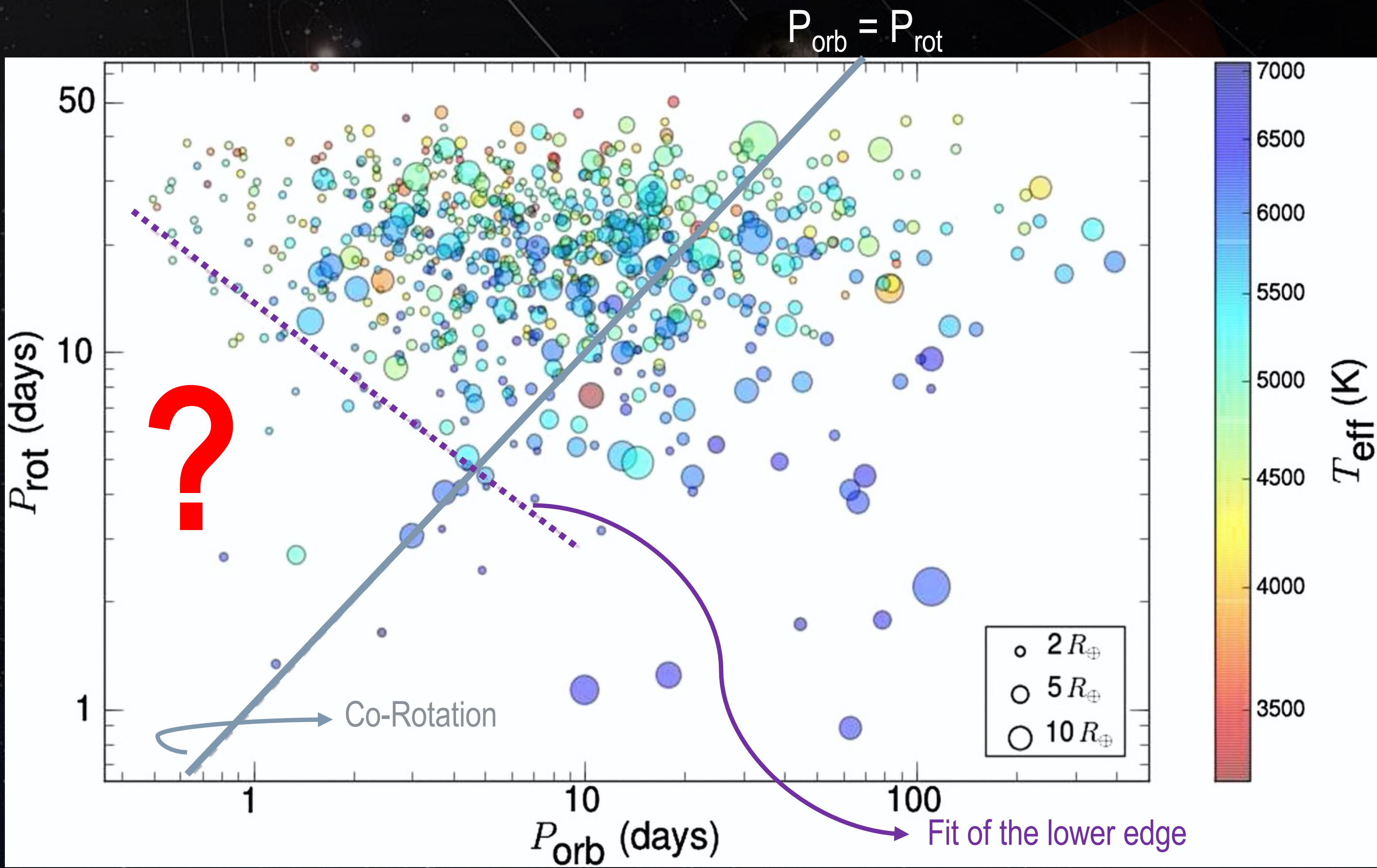
I-INTRODUCTION



[McQuillan, Mazeh & Aigrain 2013 (MMA)]
[see also e.g., Teitler & Königl 14, Lanza & Shkolnik 14, Strugarek+ 14, O'Connor & Hansen 18, Heller 19]

- Relation between stellar P_{rot} with planetary P_{orb}
- 1919 Main Sequence KOIs only 737 with robust P_{orb} with Q3-Q14
  - Confirmed and candidate planets in single or multiple systems

I-INTRODUCTION



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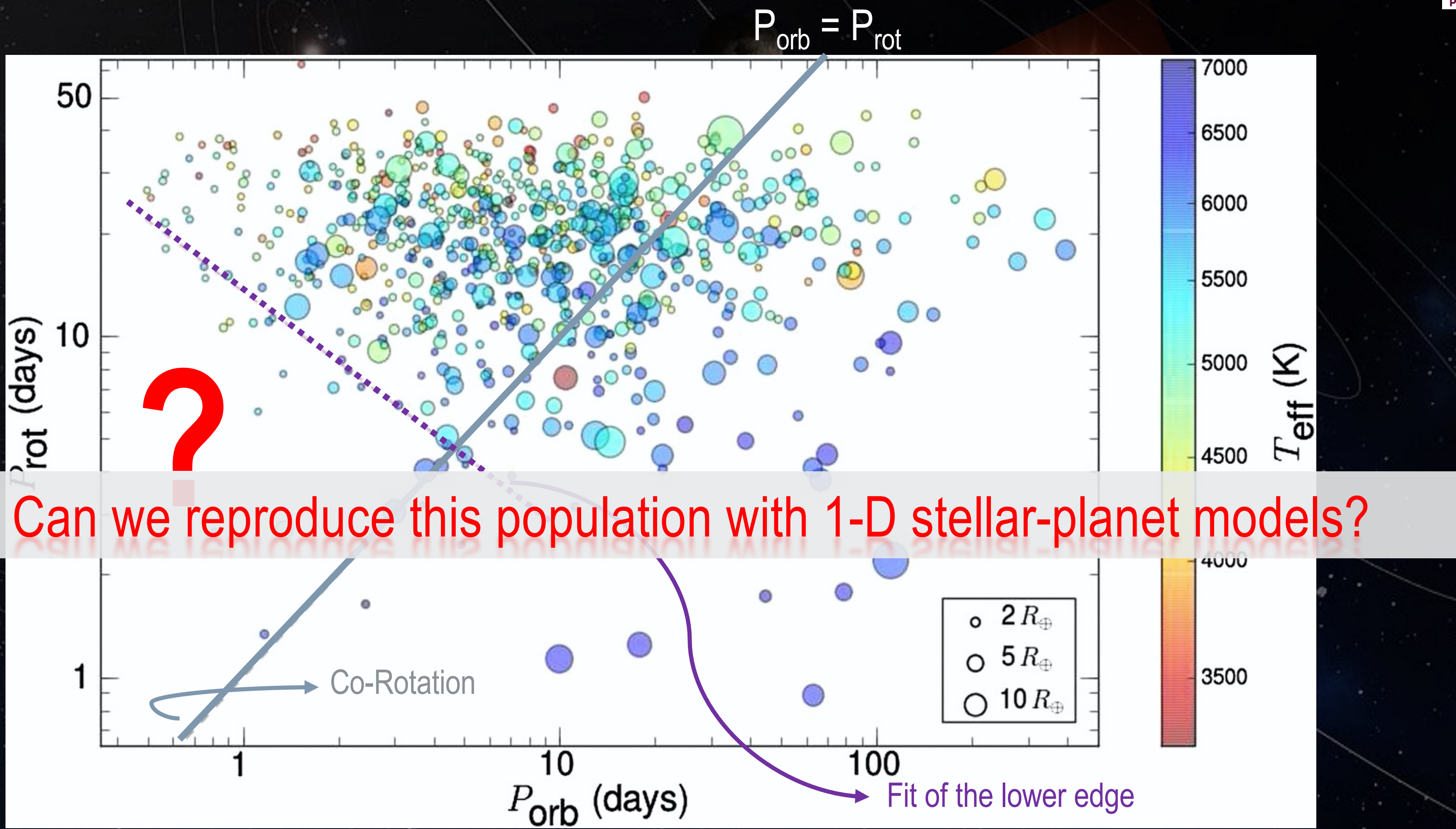
- Dearth of close-in planets around fast rotators
  - only slowly spinning stars, P_{rot} >5–10 days, host planets on P_{orb} < 3 days

I-INTRODUCTION



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- Dearth of close-in planets around fast rotators
  - only slowly spinning stars, P_{rot} >5–10 days, host planets on P_{orb} < 3 days

I-INTRODUCTION

How is the evolution of the stellar rotation impacted by the presence of a planet?

Can we explain the dearth of exoplanets around fast-rotating stars?

- Objectives of this work ***(…IN PROGRESS !!!!!)***

Introduce ab initio prescriptions of tidal, magnetic, and braking torques simultaneously to improve our understanding of underlying physics.

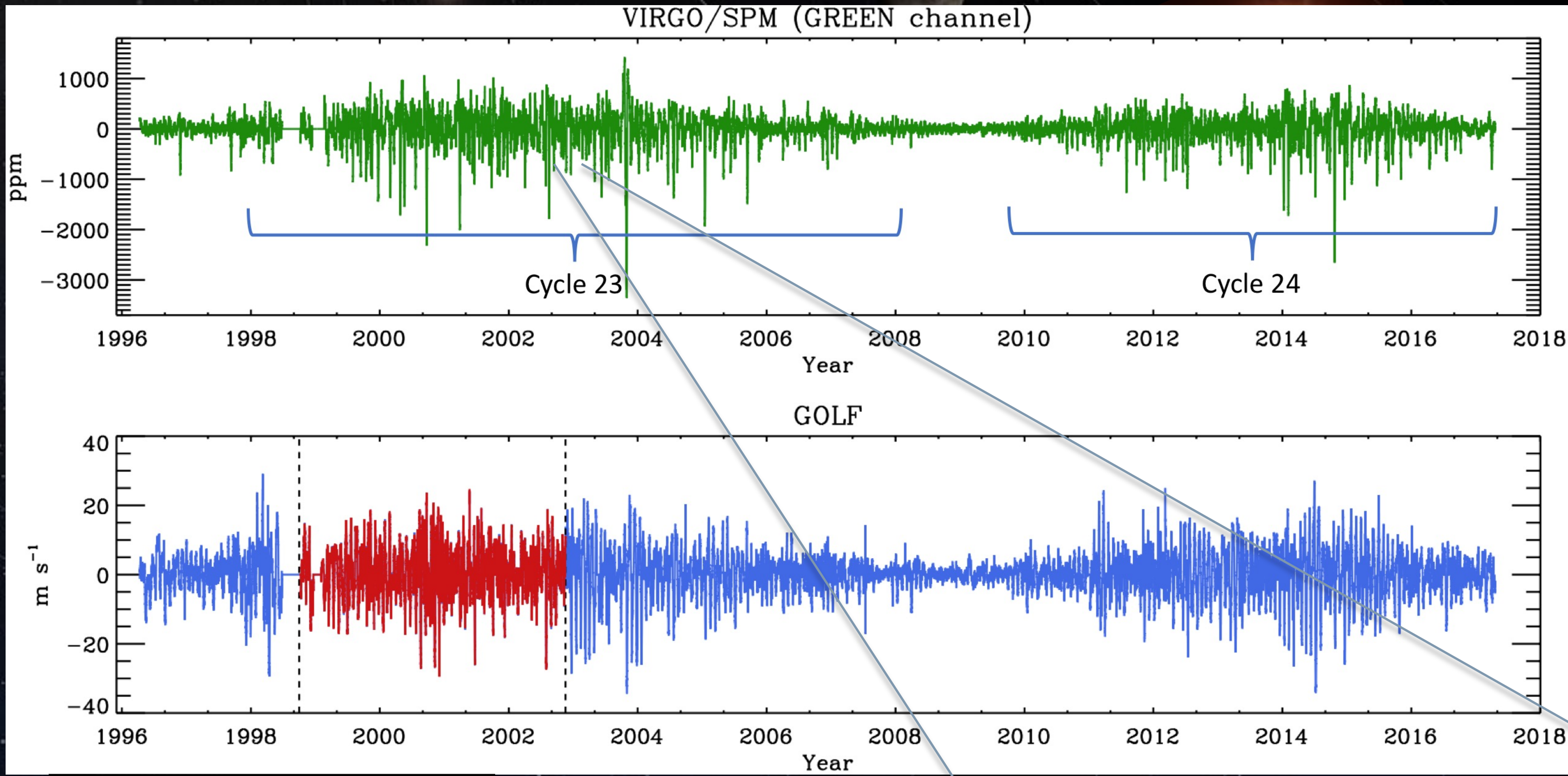
- To do so:
  - Use only confirmed planets
  - Excluding all non-yet confirmed ones
  - Exclude all multi systems
    - Because our model
      - only deals with 1 planet orbiting the host star
    - Problem:
      - Detecting one single planet in a system
        - Cannot exclude the presence of other planets
  - Use the full *Kepler* (main mission) dataset (Q0-Q17)
    - Extension to K2 planets on going

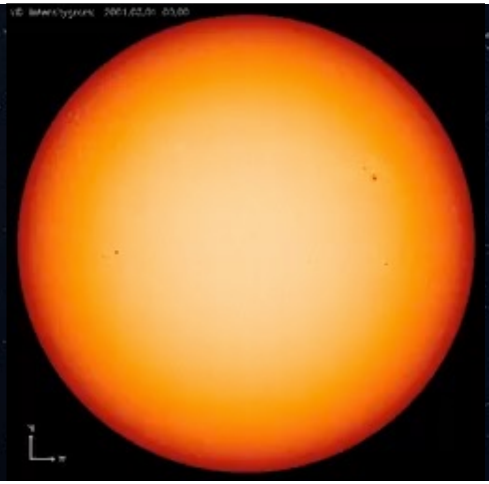
II- Data analysis :

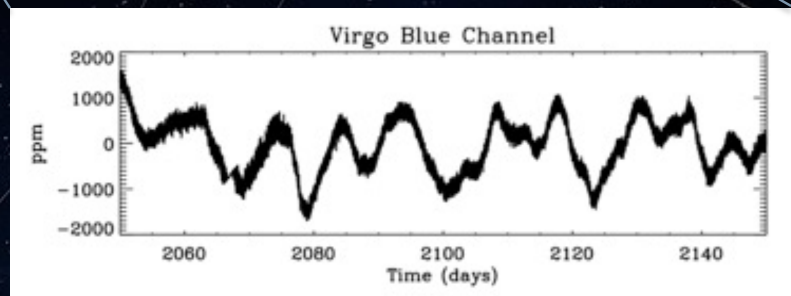
Extracting P_{rot}

II-DATA ANALYSIS

For solar-Like stars with external convective envelopes







[Salabert, García+2018]

Hotter stars: Also showing spots [e.g. Balona+2011,2013]

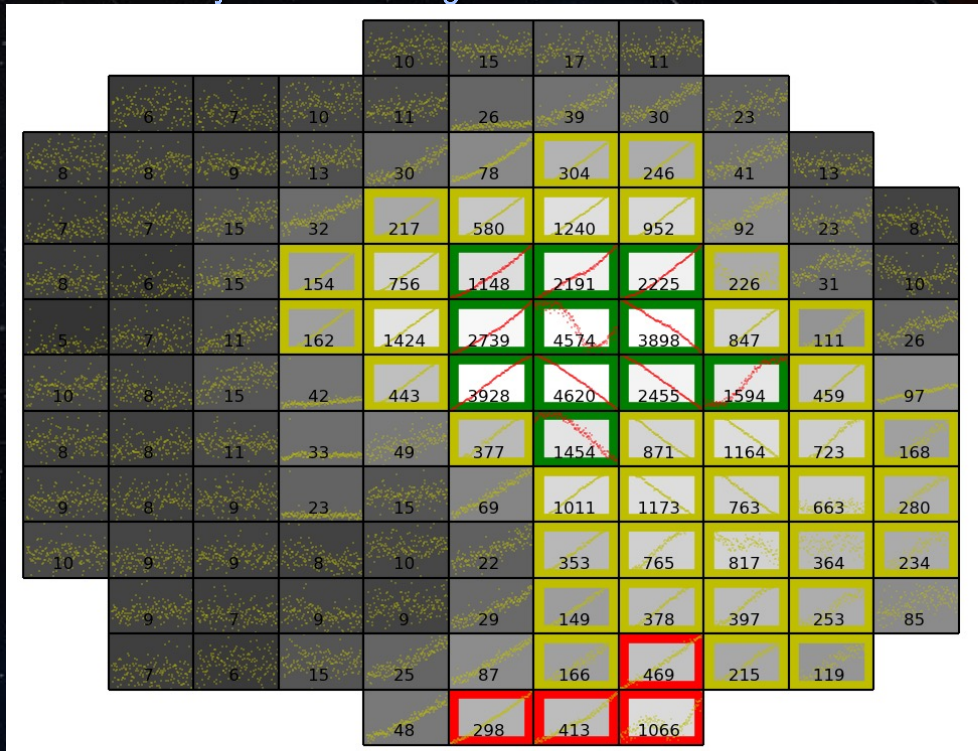
II-APERTURE PHOTOMETRY

- Data preparation
  - Larger aperture photometry

    Limit threshold of 100 e-/s

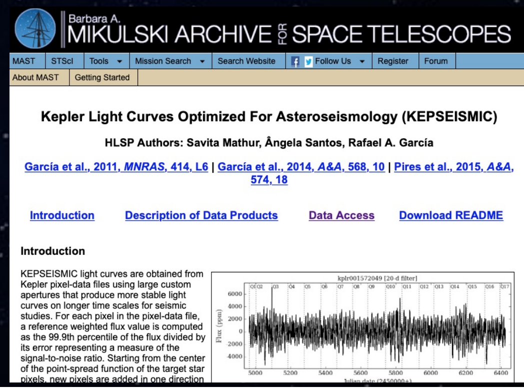
    Negative gradient from the center

    Better stability with less long instrumental trends



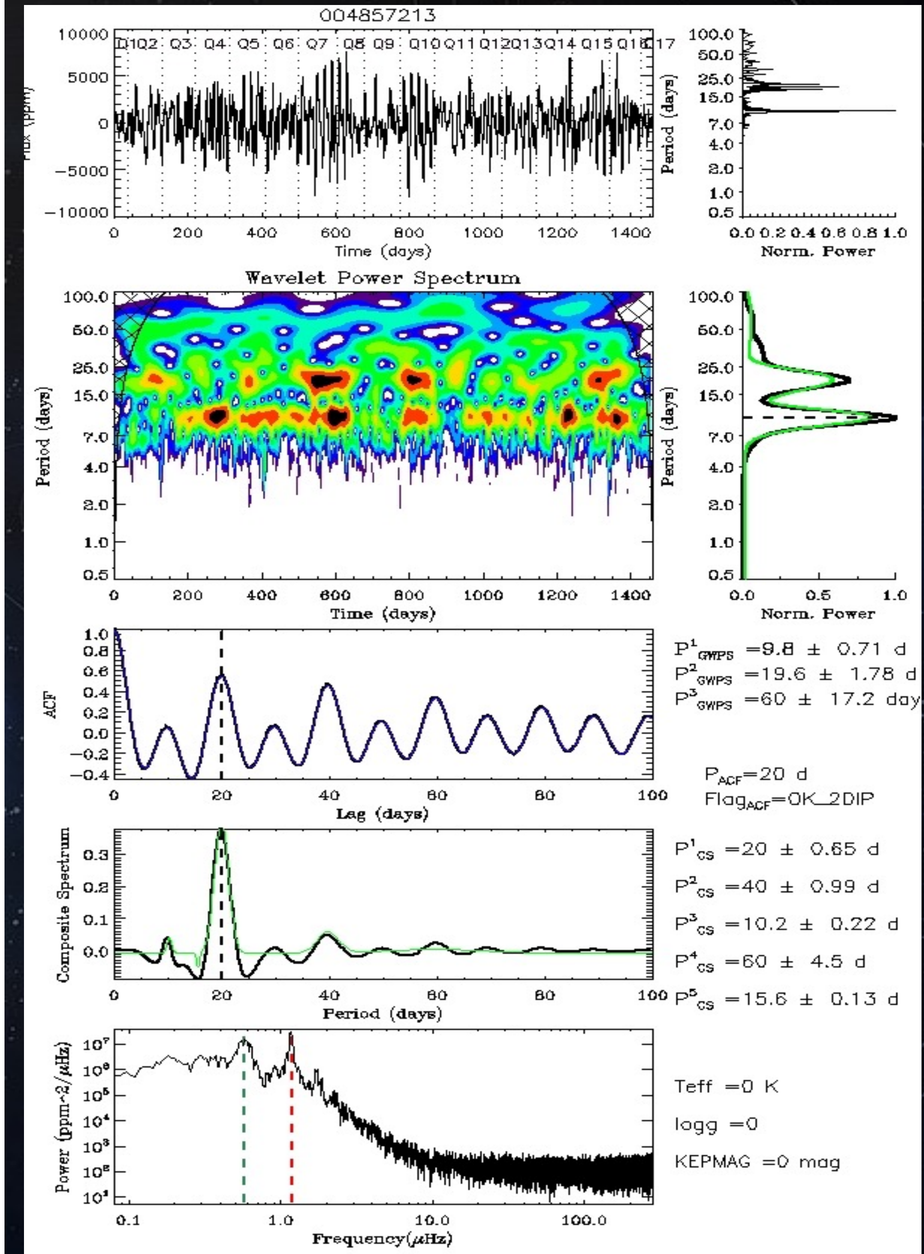
- KEPSEISMIC datasets [1]
  - 3 high-pass filters at 20, 55 and 80 days

[García+ 2011]



[1]https://archive.stsci.edu/prepds/kepseismic/

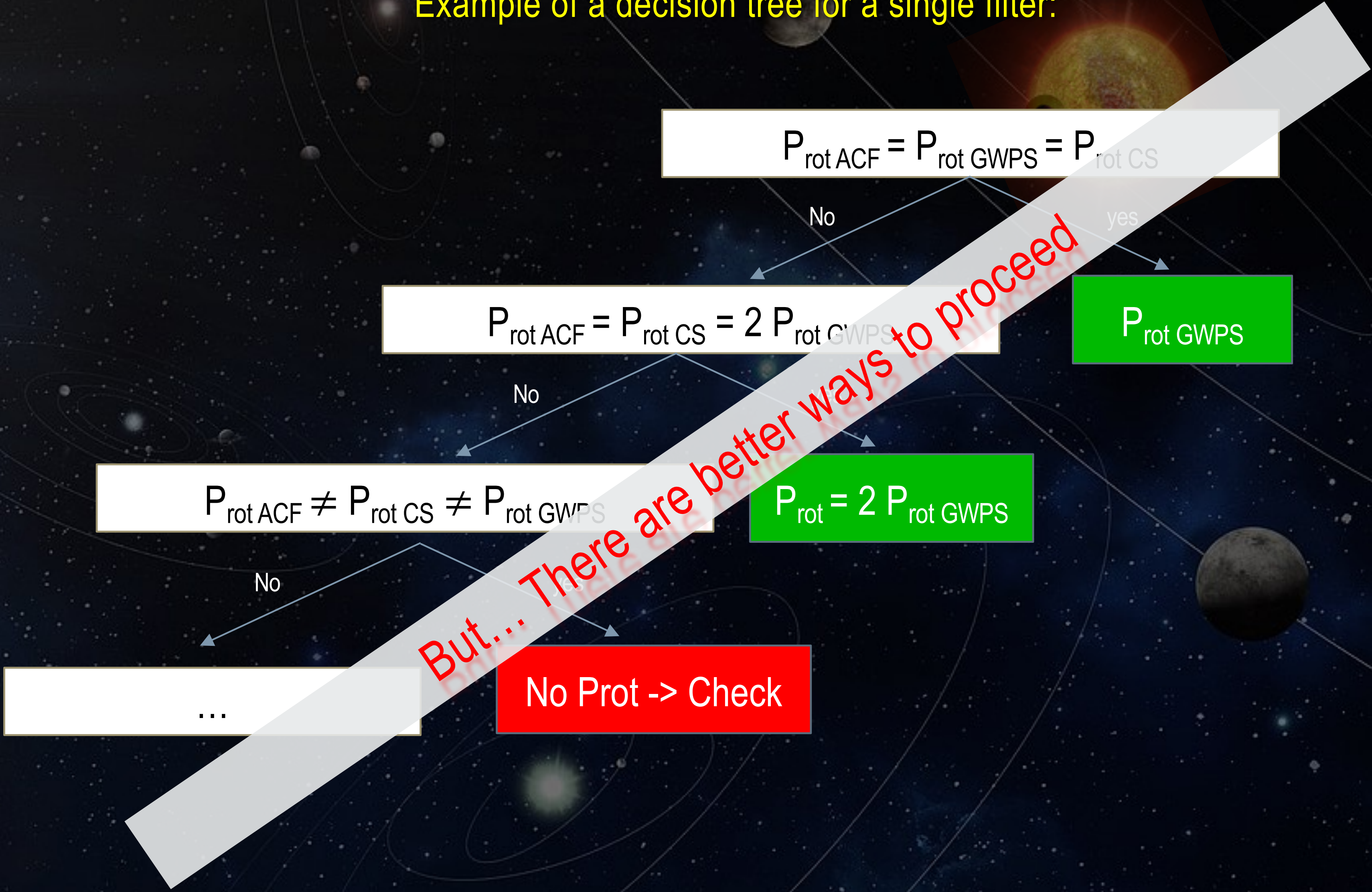
II-EXTRACTING P_{ROT} (I)



- 3 LCs are prepared
  - With 3 different high-pass filters
    - 20, 55, and 80d
    - For visual inspection
      - Also checked PDC-MAP
- For each filter P_{rot} is obtained using:
  - 2 independent methods
    - GWPS from wavelet analysis
      - Useful to check instrumental problems [e.g. Mathur+ 2010]
    - ACF [e.g. McQuillan+ 2013,2014; García+ 2014]
  - Combined metric : Composite Spectrum [Ceillier+ 2016]
- Combining different methods with data preparation:
  - 9 different P_{rot} estimation
  - Improve ***completeness*** and ***reliability*** [Aigrain+ 2015]
- Final P_{rot}:
  - Using a simple decision tree [García+ 2014; Ceillier+2017; Santos+2019]

DECISION TREE

Example of a decision tree for a single filter:



II- ROOSTER (ML) ALGORITHM

- Extend the decision tree philosophy to Random Forrest Classifiers
  - Allow to extend the number of input parameters to $9P_{rot}$ + 150 more (e.g. Sph, Teff, …)

1

Known label for each element of the training set

2

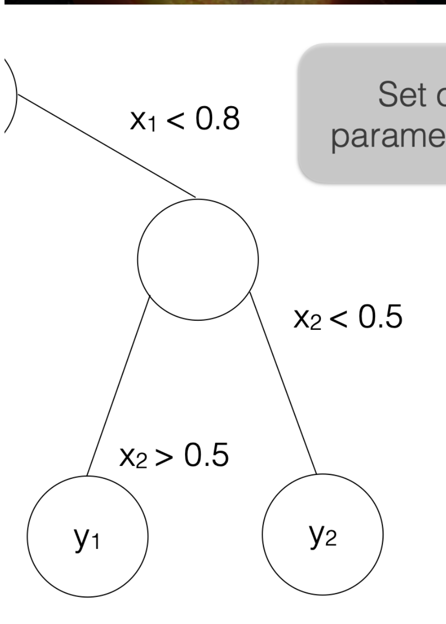
The training set is divided in sub-samples in order to build the forest

3

Test set (known labels) : **classifier accuracy check**

Table B.1. 159 input parameters used to train the RF classifiers.

ACF_ER_SPH_20	ACF_ER_SPH_55	ACF_ER_SPH_80
BAD_Q_FLAG	CS_CHIQ_20	CS_CHIQ_55
CS_CHIQ_80	CS_GAUSS_1_1_20	CS_GAUSS_1_1_55
CS_GAUSS_1_1_80	CS_GAUSS_1_2_20	CS_GAUSS_1_2_55
CS_GAUSS_1_2_80	CS_GAUSS_1_3_20	CS_GAUSS_1_3_55
CS_GAUSS_1_3_80	CS_GAUSS_1_4_20	CS_GAUSS_1_4_55
CS_GAUSS_1_4_80	CS_GAUSS_1_5_20	CS_GAUSS_1_5_55
CS_GAUSS_1_5_80	CS_GAUSS_2_1_20	CS_GAUSS_2_1_55
CS_GAUSS_2_1_80	CS_GAUSS_2_2_20	CS_GAUSS_2_2_55
CS_GAUSS_2_2_80	CS_GAUSS_2_3_20	CS_GAUSS_2_3_55
CS_GAUSS_2_3_80	CS_GAUSS_2_4_20	CS_GAUSS_2_4_55
CS_GAUSS_2_4_80	CS_GAUSS_2_5_20	CS_GAUSS_2_5_55
CS_GAUSS_2_5_80	CS_GAUSS_3_1_20	CS_GAUSS_3_1_55
CS_GAUSS_3_1_80	CS_GAUSS_3_2_20	CS_GAUSS_3_2_55
CS_GAUSS_3_2_80	CS_GAUSS_3_3_20	CS_GAUSS_3_3_55
CS_GAUSS_3_3_80	CS_GAUSS_3_4_20	CS_GAUSS_3_4_55
CS_GAUSS_3_4_80	CS_GAUSS_3_5_20	CS_GAUSS_3_5_55
CS_GAUSS_3_5_80	CS_NOISE_20	CS_NOISE_55
CS_NOISE_80	CS_N_FIT_20	CS_N_FIT_55
CS_N_FIT_80	CS_SPH_ER_20	CS_SPH_ER_55
CS_SPH_ER_80	END_TIME	F_07
F_20	F_50	F_7
GWPS_CHIQ_20	GWPS_CHIQ_55	GWPS_CHIQ_80
GWPS_GAUSS_1_1_20	GWPS_GAUSS_1_1_55	GWPS_GAUSS_1_1_80
GWPS_GAUSS_1_2_20	GWPS_GAUSS_1_2_55	GWPS_GAUSS_1_2_80
GWPS_GAUSS_1_3_20	GWPS_GAUSS_1_3_55	GWPS_GAUSS_1_3_80
GWPS_GAUSS_1_4_20	GWPS_GAUSS_1_4_55	GWPS_GAUSS_1_4_80
GWPS_GAUSS_1_5_20	GWPS_GAUSS_1_5_55	GWPS_GAUSS_1_5_80
GWPS_GAUSS_2_1_20	GWPS_GAUSS_2_1_55	GWPS_GAUSS_2_1_80
GWPS_GAUSS_2_2_20	GWPS_GAUSS_2_2_55	GWPS_GAUSS_2_2_80
GWPS_GAUSS_2_3_20	GWPS_GAUSS_2_3_55	GWPS_GAUSS_2_3_80
GWPS_GAUSS_2_4_20	GWPS_GAUSS_2_4_55	GWPS_GAUSS_2_4_80
GWPS_GAUSS_2_5_20	GWPS_GAUSS_2_5_55	GWPS_GAUSS_2_5_80
GWPS_GAUSS_3_1_20	GWPS_GAUSS_3_1_55	GWPS_GAUSS_3_1_80
GWPS_GAUSS_3_2_20	GWPS_GAUSS_3_2_55	GWPS_GAUSS_3_2_80
GWPS_GAUSS_3_3_20	GWPS_GAUSS_3_3_55	GWPS_GAUSS_3_3_80
GWPS_GAUSS_3_4_20	GWPS_GAUSS_3_4_55	GWPS_GAUSS_3_4_80
GWPS_GAUSS_3_5_20	GWPS_GAUSS_3_5_55	GWPS_GAUSS_3_5_80
GWPS_NOISE_20	GWPS_NOISE_55	GWPS_NOISE_80
GWPS_N_FIT_20	GWPS_N_FIT_55	GWPS_N_FIT_80
GWPS_SPH_ER_20	GWPS_SPH_ER_55	GWPS_SPH_ER_80
G_ACF_20	G_ACF_55	G_ACF_80
H_ACF_20	H_ACF_55	H_ACF_80
H_CS_20	H_CS_55	H_CS_80
LENGTH	N_BAD_Q	Prot_ACF_20
Prot_ACF_55	Prot_ACF_80	Prot_CS_20
Prot_CS_55	Prot_CS_80	Prot_GWPS_20
Prot_GWPS_55	Prot_GWPS_80	START_TIME
Sph_ACF_20	Sph_ACF_55	Sph_ACF_80
Sph_CS_20	Sph_CS_55	Sph_CS_80
Sph_GWPS_20	Sph_GWPS_55	Sph_GWPS_80
Teff	kepmag	logg



Set of elements **x** with parameters $\{x_i\}$ with labels y_i

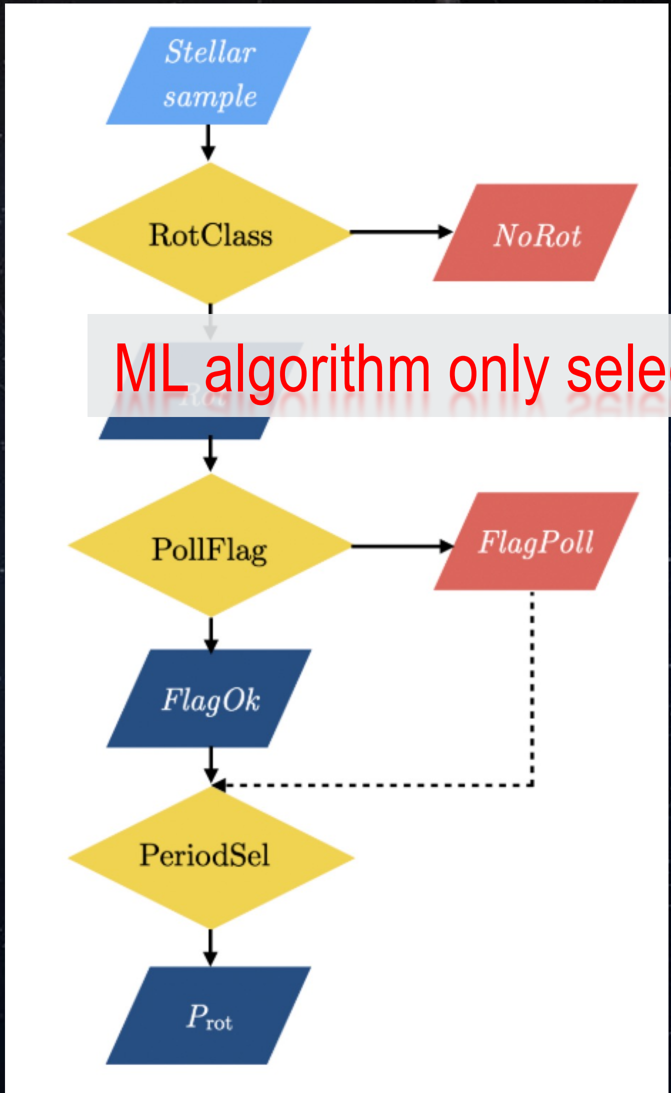
training parameters: outputs from F, CS methods + stellar parameters

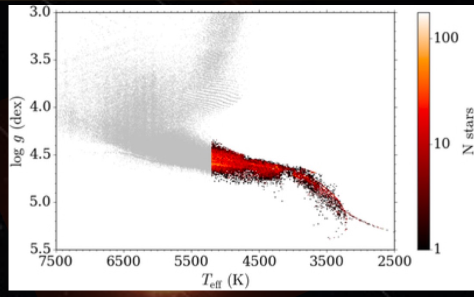
159 input parameters

[Breton+ 2021]

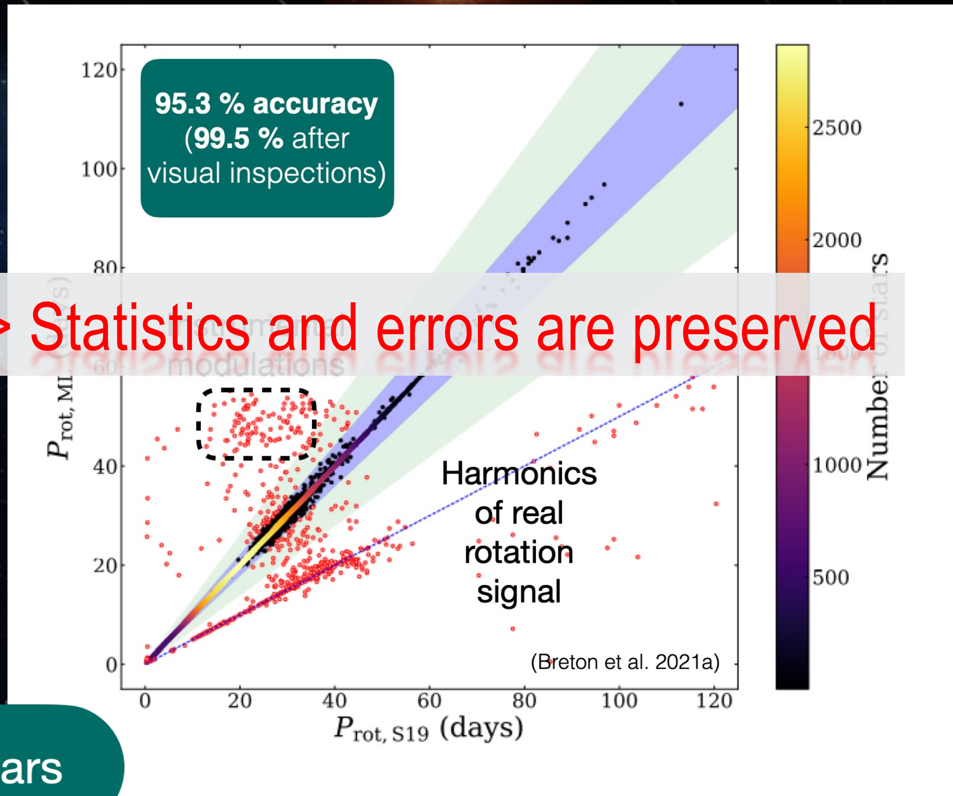
II- ROOSTER (ML) ALGORITHM

- 3 independent classifiers
  - Training & validation sample from
    - K, M dwarfs [Santos+2019]





ML algorithm only selects the P_{rot} => Statistics and errors are preserved



~ 14,500 stars

691 stars with more than 10% difference between ROOSTER and S19

[Breton+ 2021]

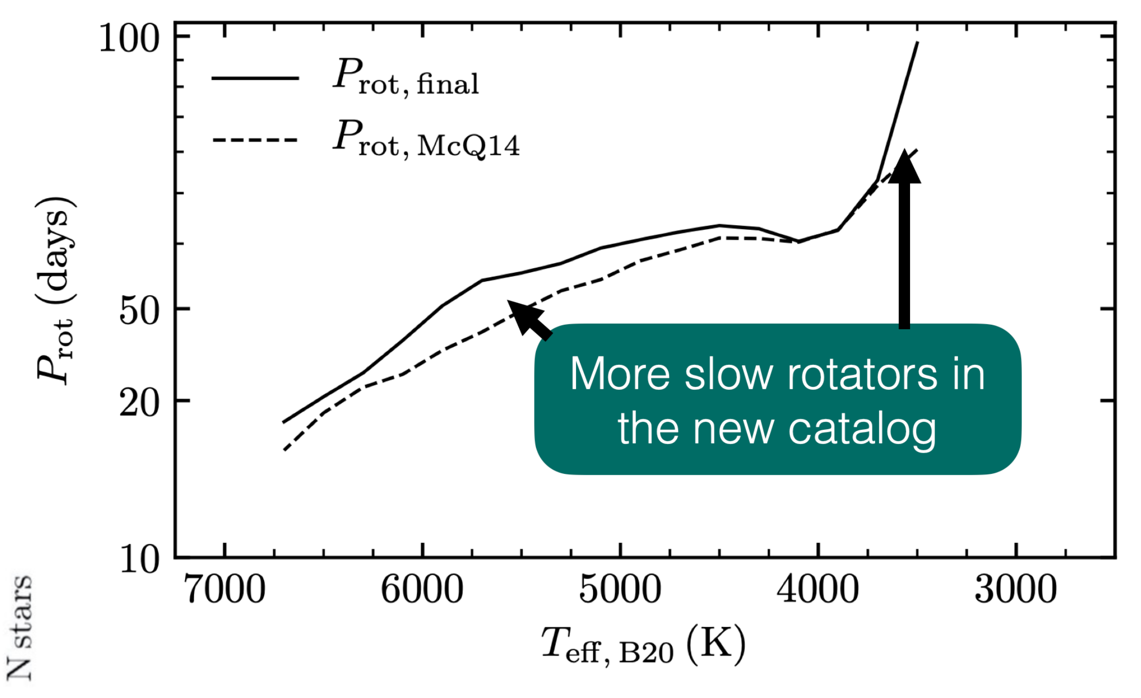
https://gitlab.com/sybreton/pushkin; https://gitlab.com/sybreton/ml_surface_rotation_paper.

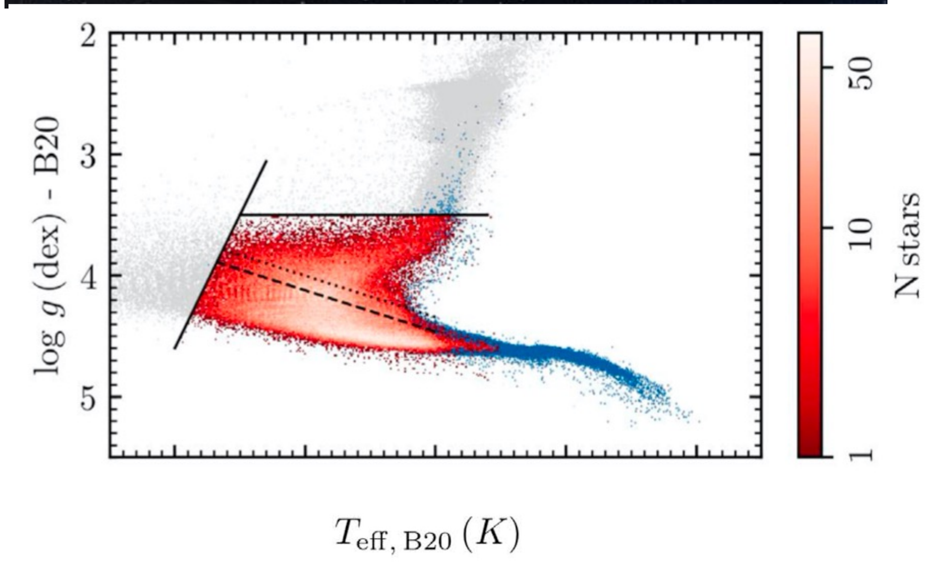
COMMERCIAL BREAK

New *Kepler* rotation catalog

[Santos+2021*]

55,232 stars with P_{rot}
(24,182 new detections in comparison with McQuillan et al. 2014)

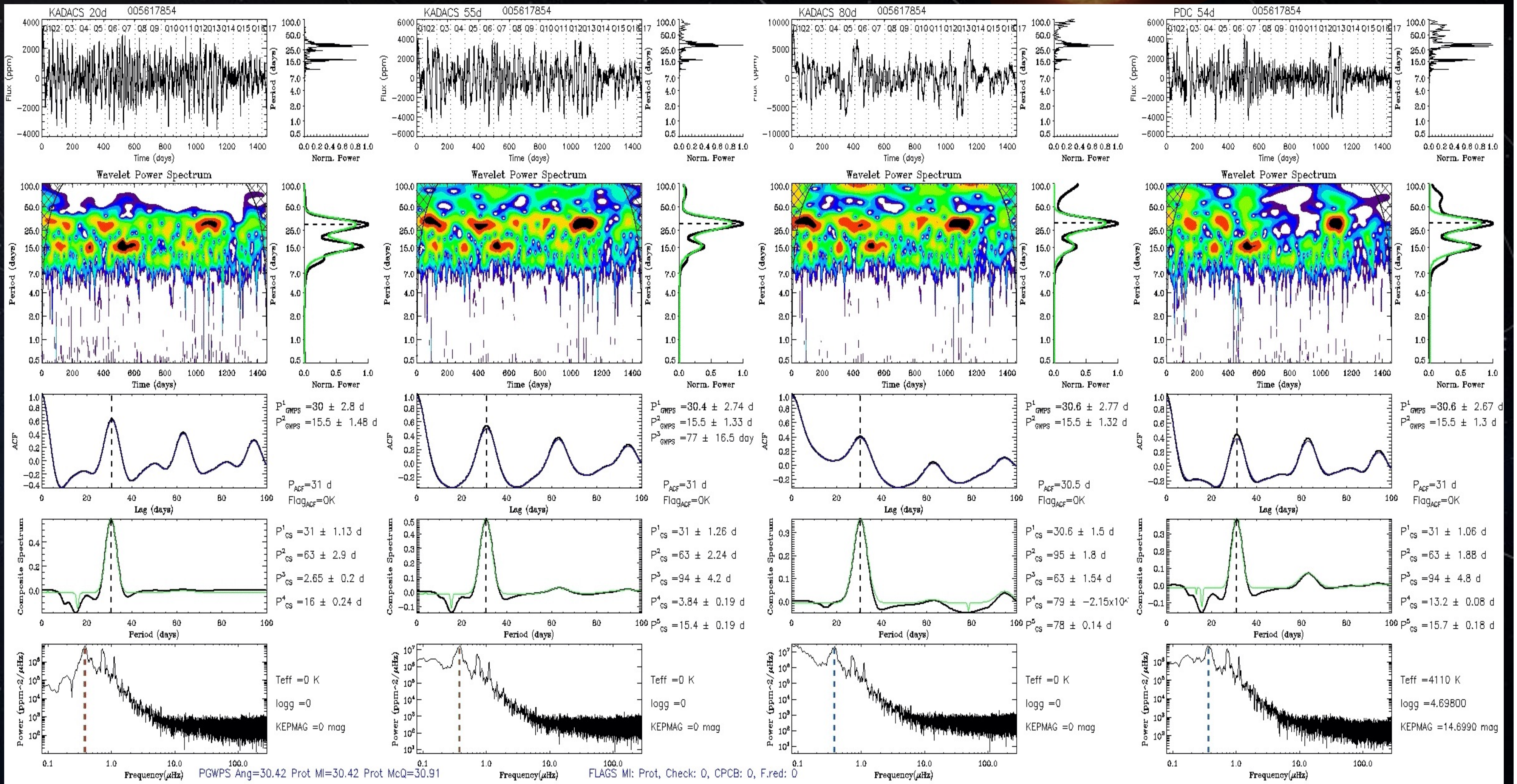




*https://iopscience.iop.org/article/10.3847/1538-4365/ac033f

II-EXAMPLE OF VETTING PROCEDURE

- PDC-MAP data is used in the vetting procedure
  - But caution is needed because it can filter trully stellar signal in random quarters



II- CONFIRMED *KEPLER* PLANET HOSTS

NASA EXOPLANET ARCHIVE
NASA EXOPLANET SCIENCE INSTITUTE

https://exoplanetarchive.ipac.caltech.edu

Summary Counts

All Exoplanets	4566
Confirmed Planets Discovered by Kepler	2402
Kepler Project Candidates Yet To Be Confirmed	2361
Confirmed Planets Discovered by K2	476
K2 Candidates Yet To Be Confirmed	889
Confirmed Planets Discovered by TESS [1]	169
TESS Project Candidates Integrated into Archive (2021-11-10 13:00:02) [2]	4682
Current date TESS Project Candidates at ExoFOP	4682
TESS Project Candidates Yet To Be Confirmed [3]	3125

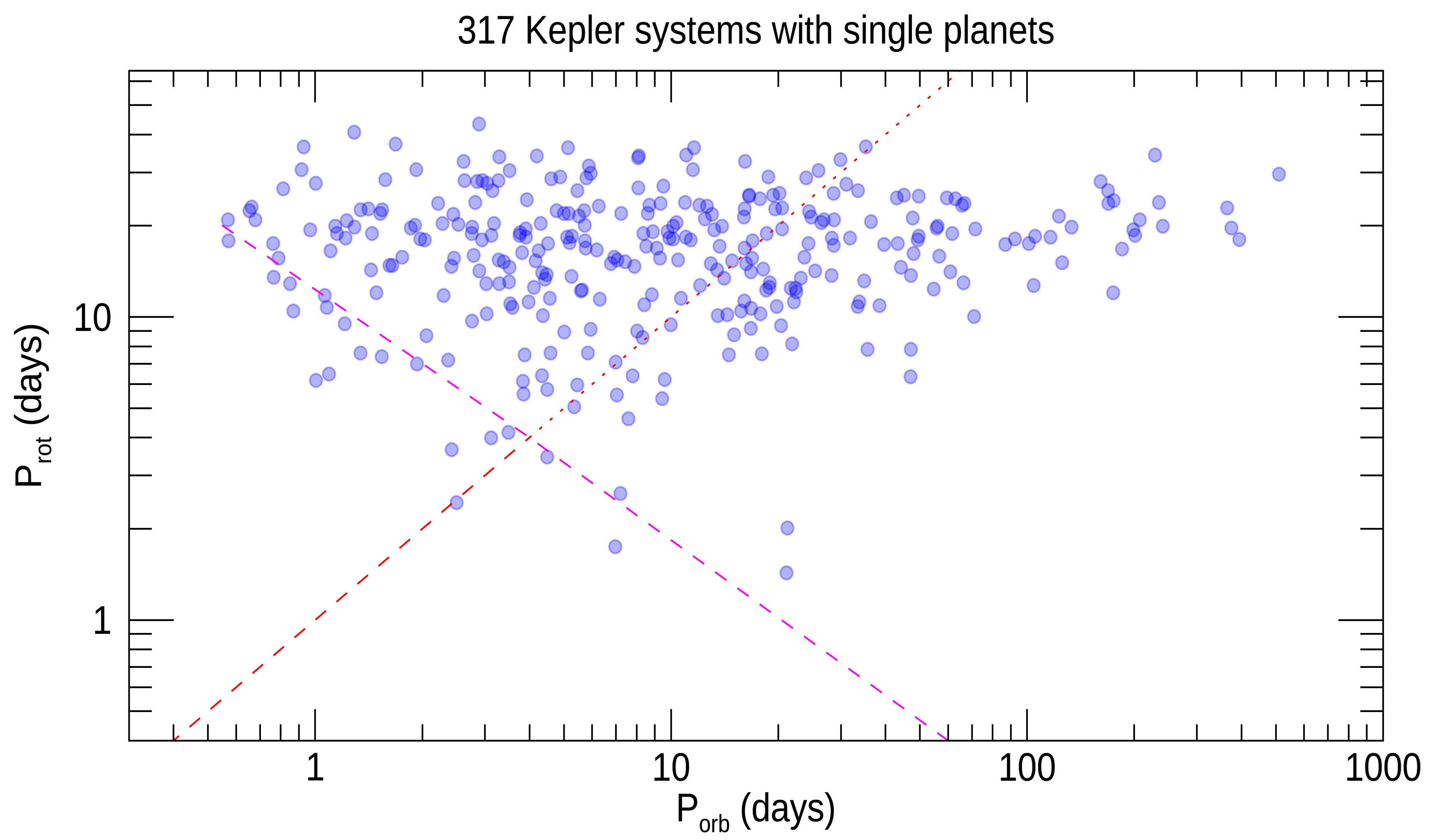
- 4566 total confirmed planets
  - 2402 are confirmed planets discovered by *Kepler* and 476 in K2
  - 4 more have *Kepler* data
  - 1704 independent systems (planet hosts) in *Kepler* and 258 in K2
- Preliminary results using:
  - Only *Kepler* results from the automatic vetting by ROOSTER (double checked by eye)

	In *Kepler*	P_{rot} (Us / McQ+2013)
Planets	2424	674
Systems	1704	453 (528)
Singles	1240	317 (356)

Problem with CB Flag

Only 222 Confirmed systems in common

II- CONFIRMED *KEPLER* PLANET HOSTS



III-Modelling:

ESPEM*

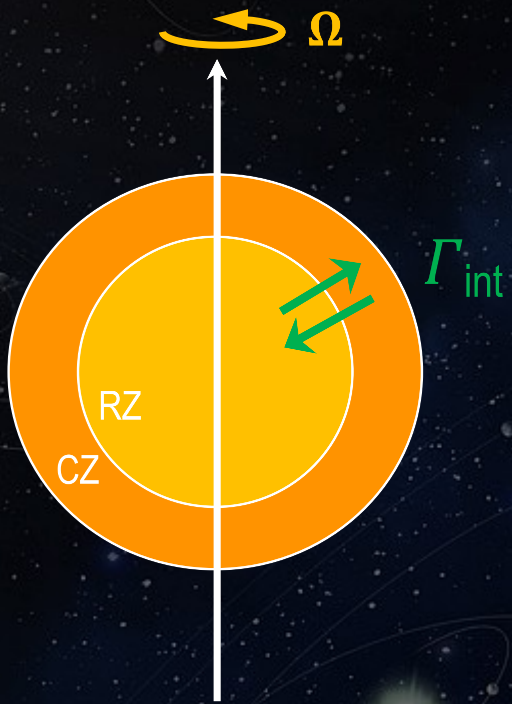
**Évolution des Systèmes Planétaires Et Magnétisme*

III- ESPEM: STAR

- Schematic view of ESPEM:
  - Star made with a two layer's mode

$M_\star < 1.2\ M_\odot$

Γ_{int} : internal coupling. Interaction between the envelope and the radiative zone



III- ESPEM: STAR

- Schematic view of ESPEM:
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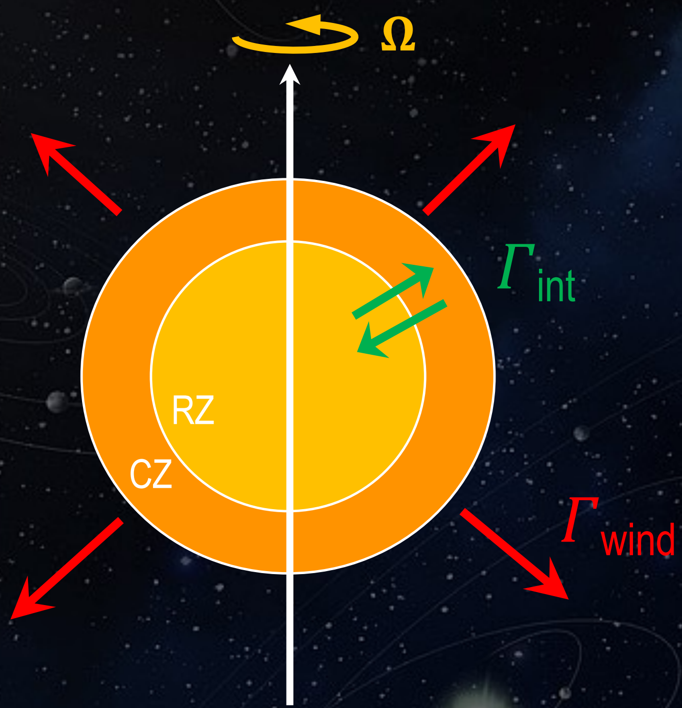
$M_\star < 1.2\ M_\odot$

Γ_{int} : internal coupling. Interaction between the envelope and the radiative zone

Γ_{wind} : braking of the envelope by the wind



III-STAR-PLANET MAGNETIC INTERACTION REGIMES

III- ESPEM: STAR + PLANET

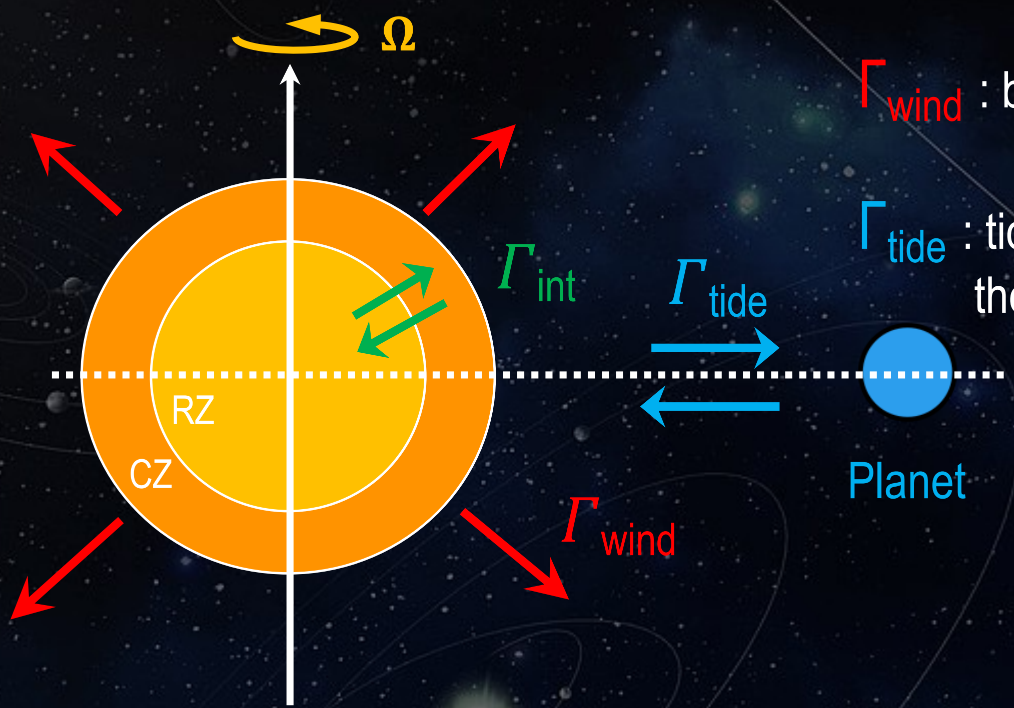
- Schematic view of ESPEM:
  - Star made with a two layer's mode
  - Planet is a single point

$M_\star < 1.2\, M_\odot$

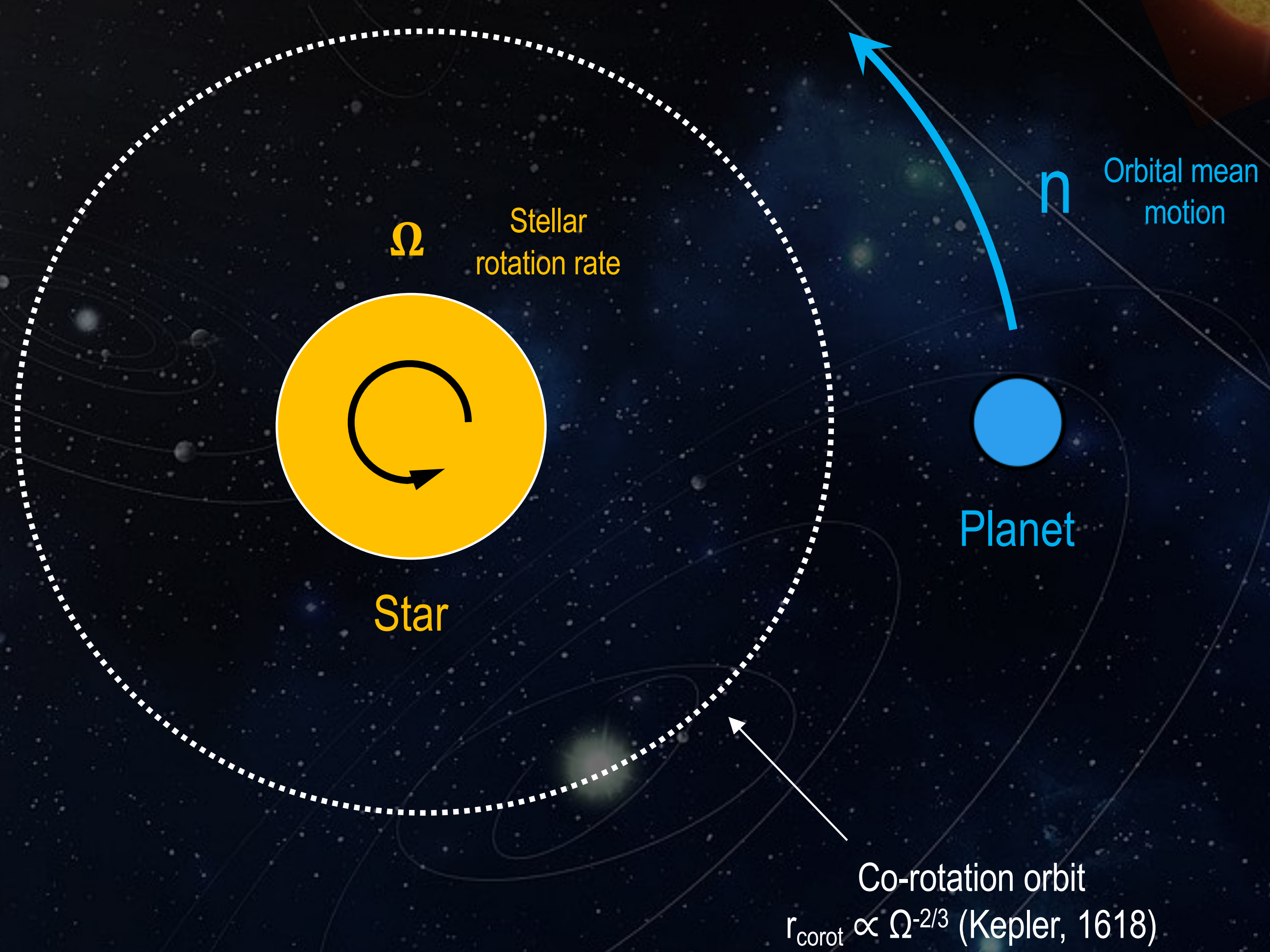
Γ_{int} : internal coupling. Interaction between the envelope and the radiative zone

Γ_{wind} : braking of the envelope by the wind

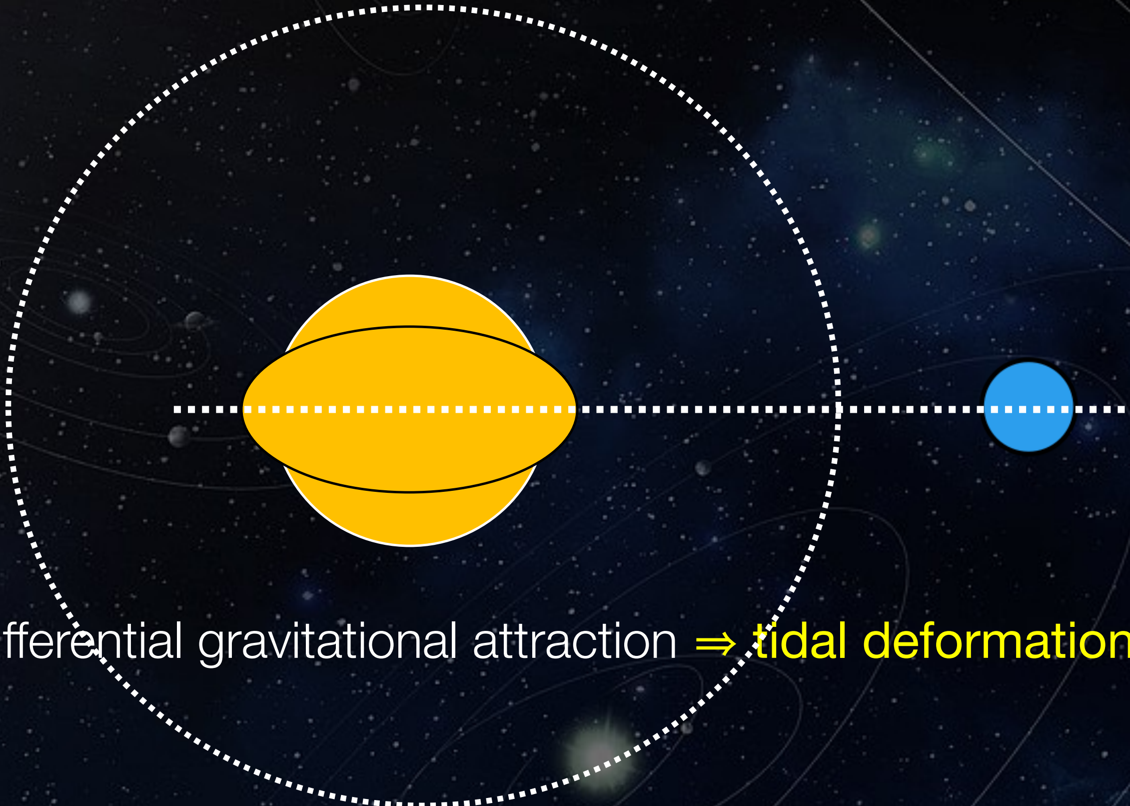
Γ_{tide} : tidal dissipation. Interaction between the envelope and the orbit.



III-TIDAL DISSIPATION



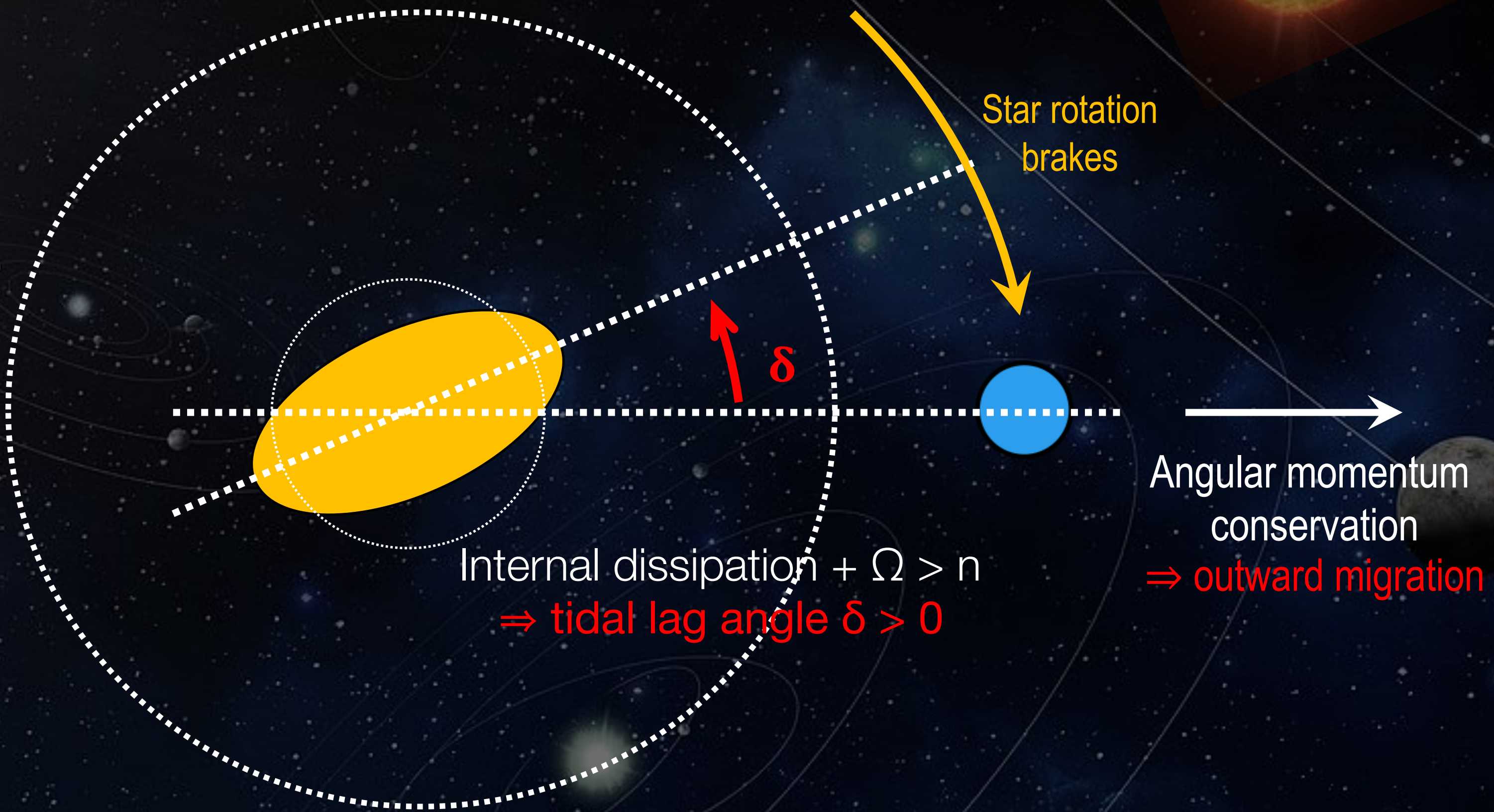
III-TIDAL DISSIPATION



Differential gravitational attraction ⇒ tidal deformation

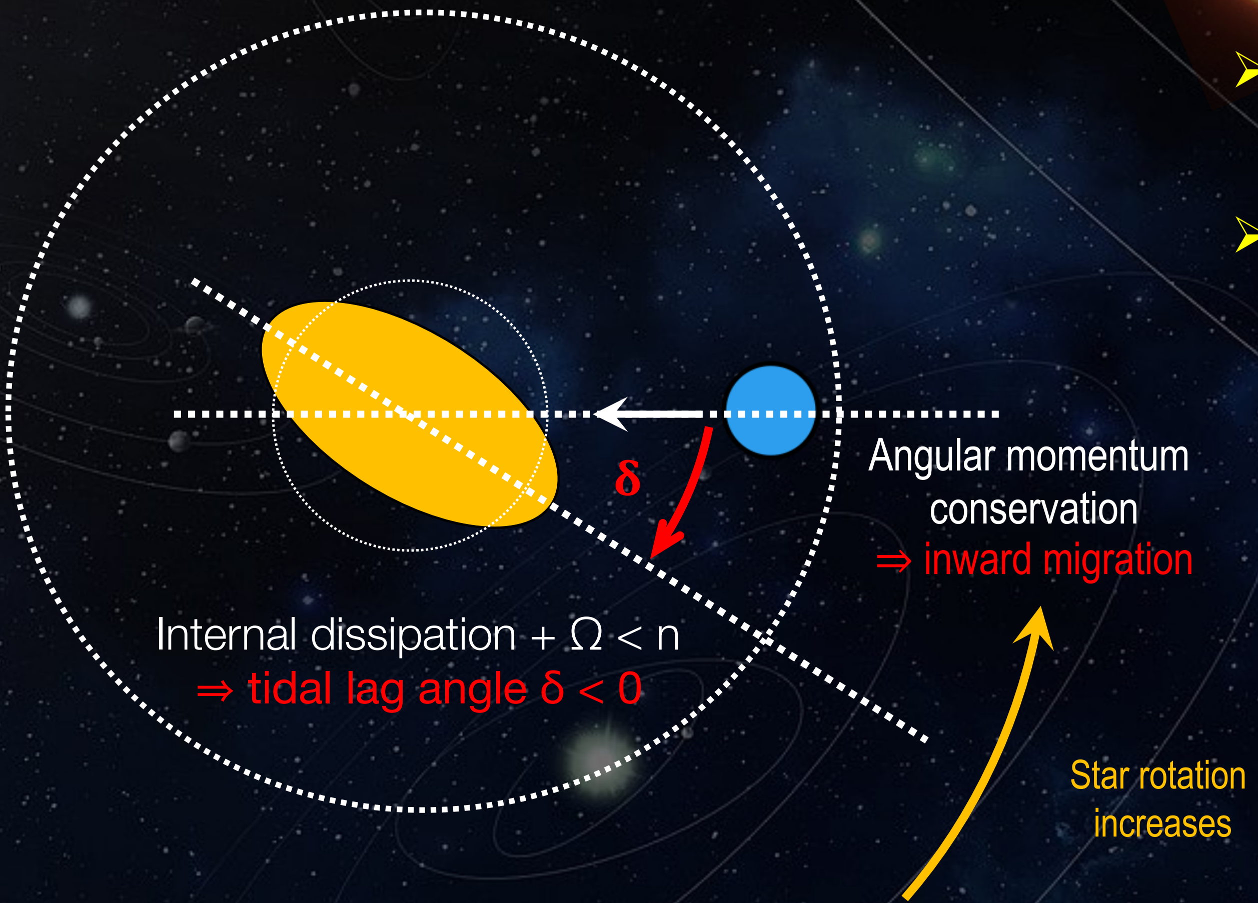
III-TIDAL DISSIPATION

Case 1: $\Omega > n$



III-TIDAL DISSIPATION

Case 2: $\Omega < n$

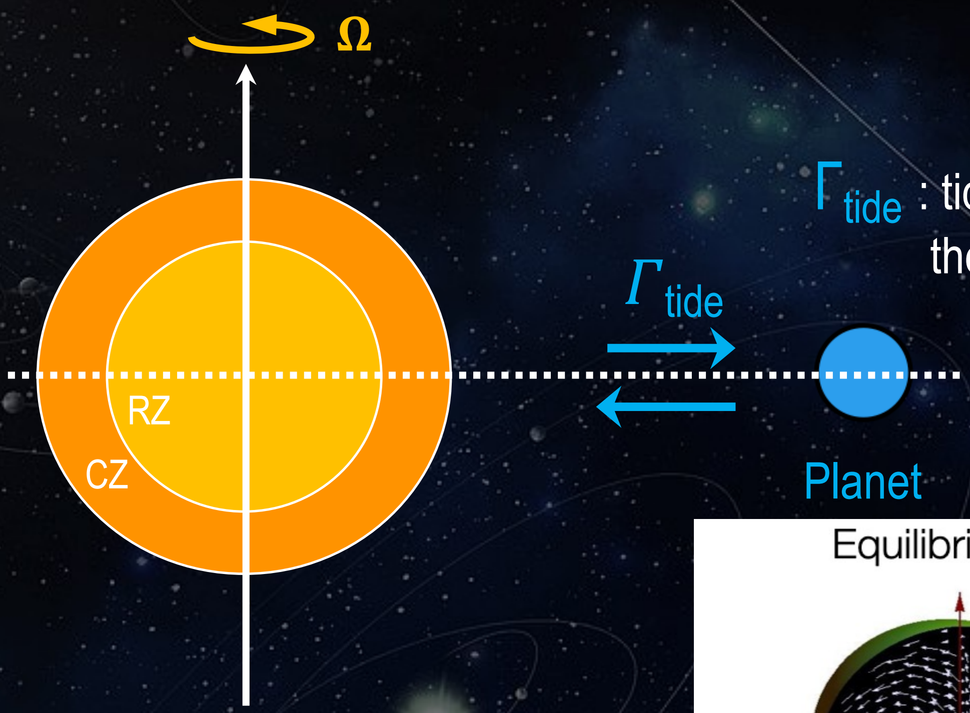


- If $L_{orb} > 3\ L_{star}$
  - Stable equilibrium
- If $L_{orb} < 3\ L_{star}$
  - Spiral towards the star

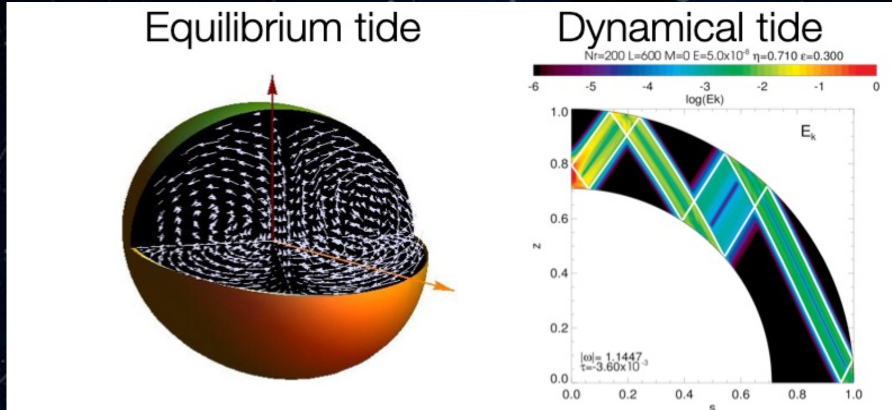
III- ESPEM: TWO TIDES CONSIDERED

$M_\star < 1.2\, M_\odot$

- Schematic view of ESPEM:
  - Star made with a two layer's mode
  - Planet is a single point



Γ_{tide} : tidal dissipation. Interaction between the envelope and the orbit.



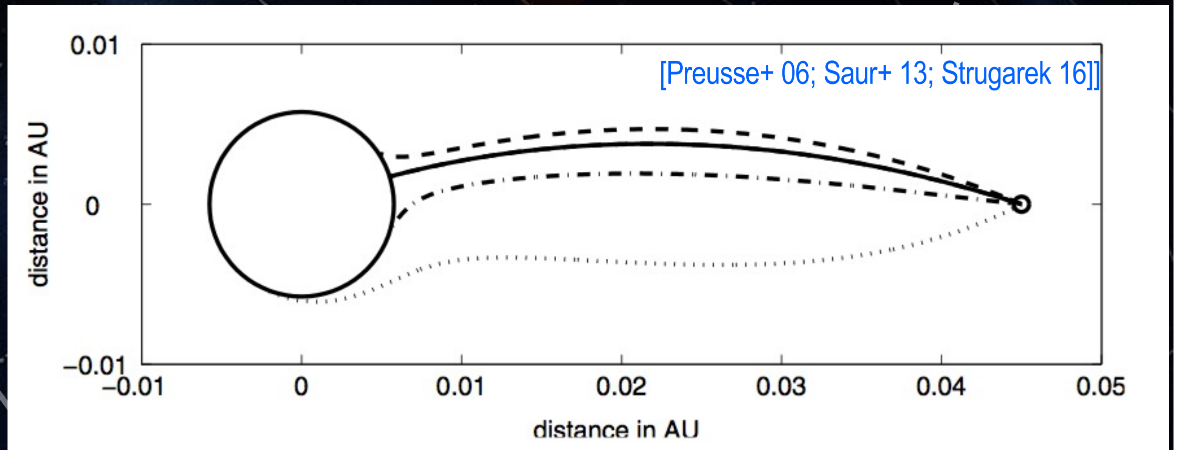
Velocity field associated to the deformation. Remus, Mathis & Zahn 12

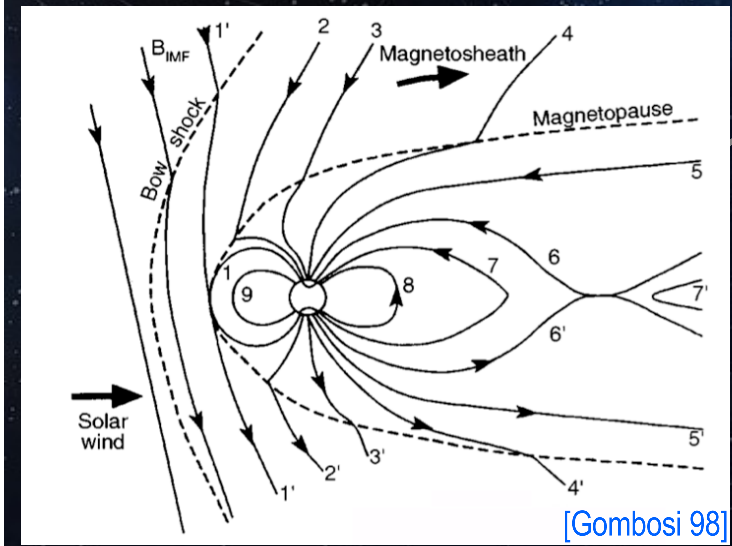
Inertial waves. Guenel+ 16

III-STAR-PLANET MAGNETIC INTERACTION REGIMES

Star

- **Sub**-Alfvénic interaction:
  - star-planet **connection**





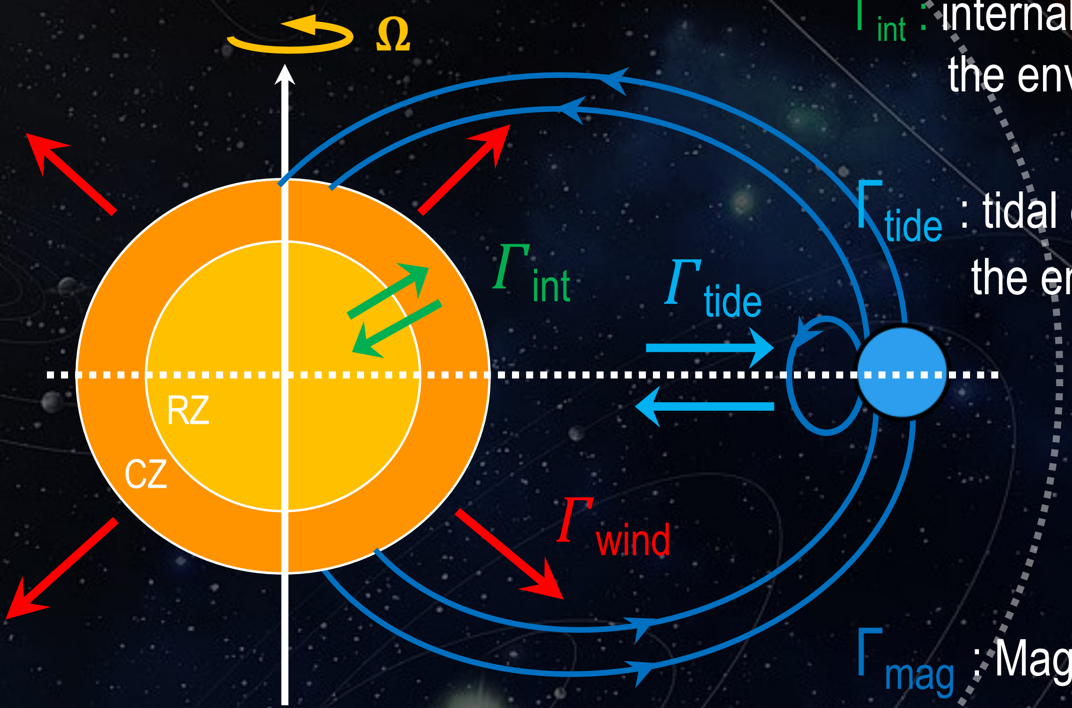
Alfvén radius

Super-Alfvénic interaction:
shock formation

III- ESPEM: STAR + PLANET

- Schematic view of ESPEM:
  - Star made with a two layer's mode
  - Planet is a single point

$M_\star < 1.2\ M_\odot$



Γ_{wind} : braking of the envelope by the wind

Γ_{int} : internal coupling. Interaction between the envelope and the radiative zone

Γ_{tide} : tidal dissipation. Interaction between the envelope and the orbit.

Γ_{mag} : Magnetic field effect

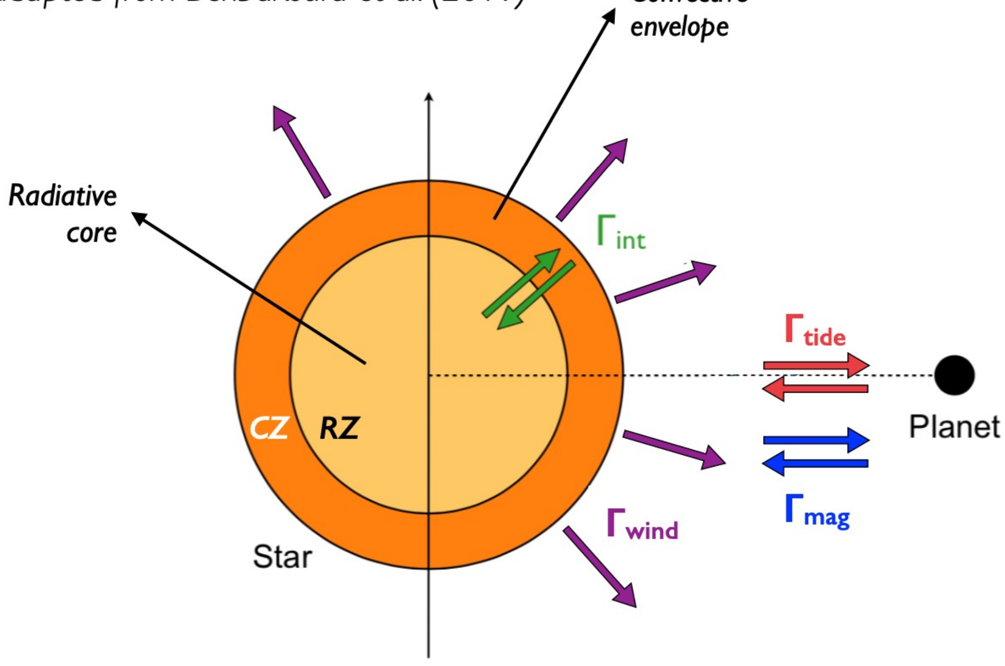
- Tidal torques dominate for G-type stars with hot Jupiters
- Magnetic torques dominate for M-dwarfs with Earth-mass planets
- In young systems, a case-by-case discussion is needed…

III-ESPEM CODE: SUMMARY

ESPEM : a 1D numerical model → Coplanar circular star-planet system

→ Secular evolution of the semi-major axis and the stellar rotation rate

adapted from Benbakoura et al. (2019)



Equilibrium tide

Dynamical tide

(inertial waves in the convective zone)

Two bodies, multiple interactions

Equations for the angular momentum evolution (uniform rotation both in RZ and in CZ):

$$\frac{dL_{orb}}{dt} = -\Gamma_{tide} - \Gamma_{mag}$$

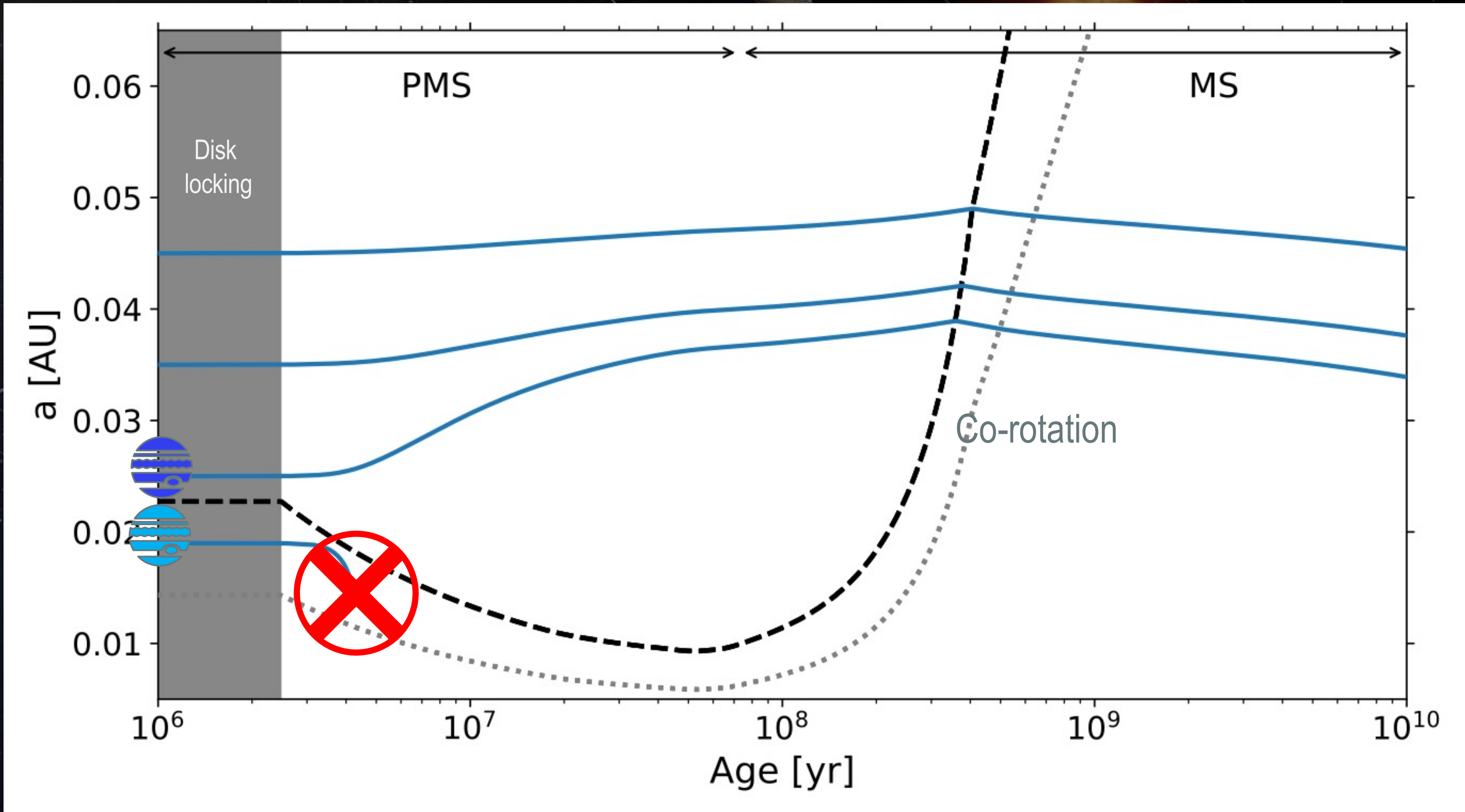
$$\frac{dL_c}{dt} = \Gamma_{int} + \Gamma_{tide} + \Gamma_{mag} - \Gamma_{wind}$$

$$\frac{dL_r}{dt} = -\Gamma_{int} + \Gamma_{tide}$$

Requires a 1D MHD wind

III-ESPEM: MIGRATION

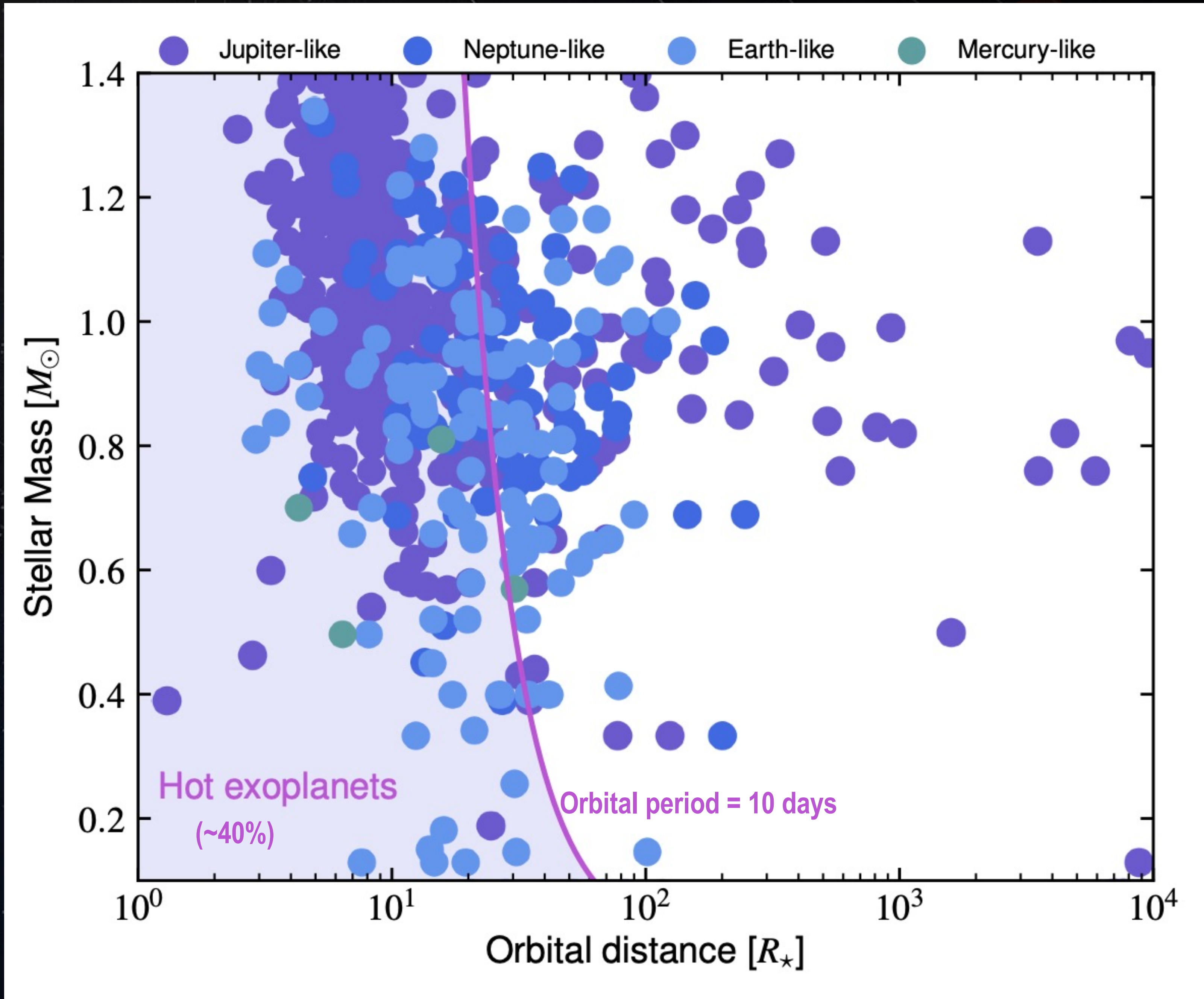
- Close-in planets migration due to tidal and magnetic torques



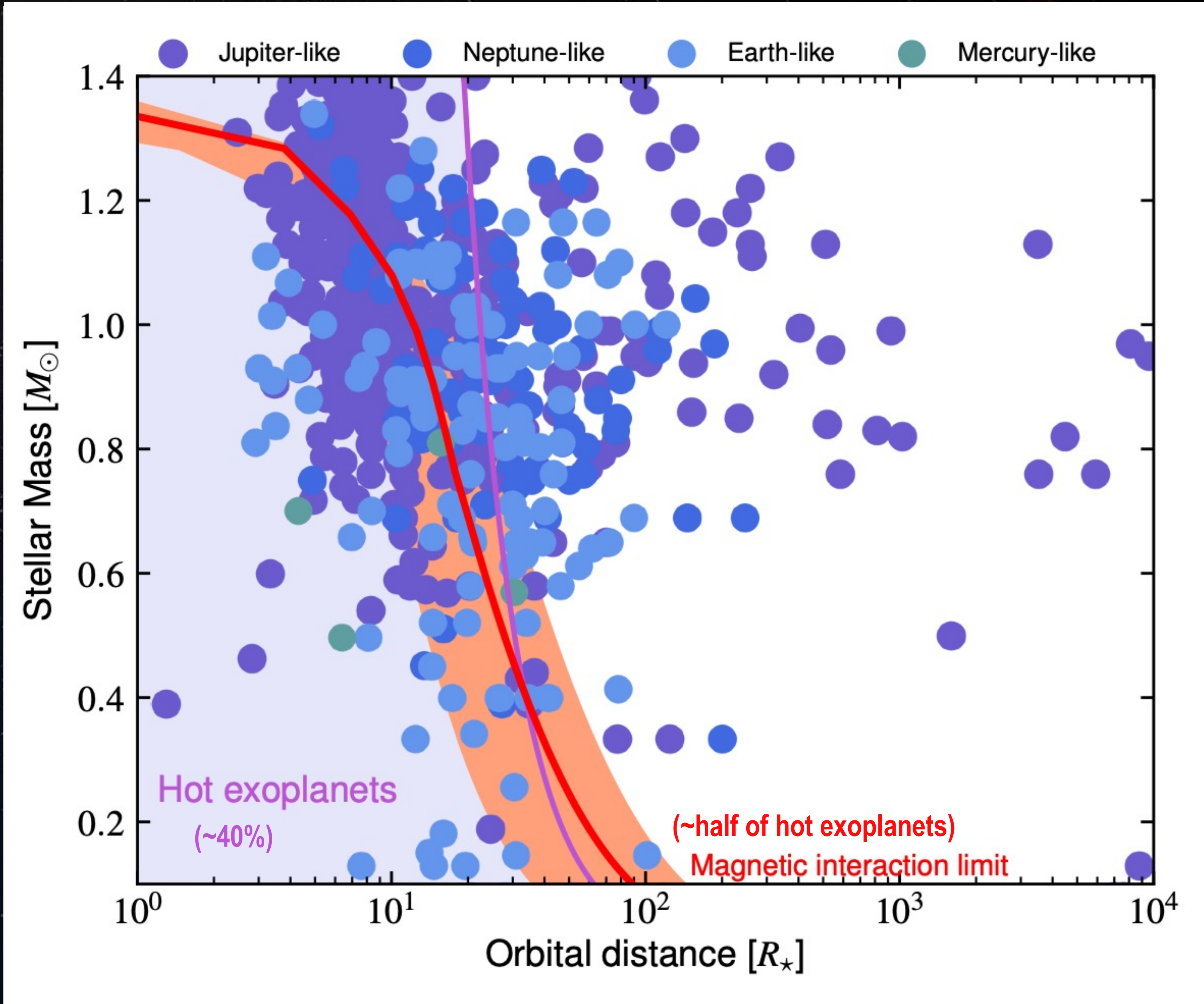
[Benbakoura+ 2019, Ahuir+ 2021]

- The fast migration phase is dominated by the dynamical tide
- After co-rotation, the magnetic torque is responsible to the migration towards the star

III-OBSERVATIONAL BIAS



III-EFFECT OF THE MAGNETIC TORQUE



IV-Comparing

Model to observations

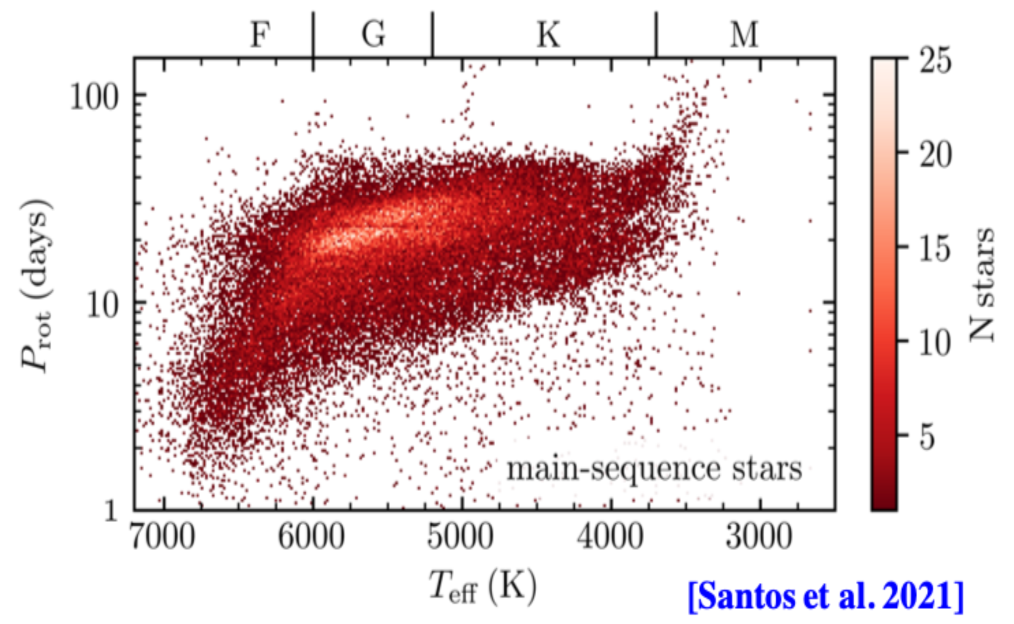
III-SIMULATING KEPLER POPULATION WITH ESPEM

- Generation of a synthetic population
  - 7000 ESPEM models

- Initial Stellar and planetary conditions:

Paramètre	Plage de valeurs	Distribution
Etoile.		
$M_\star$ [$M_\odot$]	0.5 – 1.1	Uniforme
$P_{rot,ini}$ [jours]	1 – 10	Uniforme
$T_{eff}[K]$	3700-6000	-
$\log g$	4.25-5.07	-
Planète.		
a_{ini} [AU]	5×10^{-3} – 0.2	Uniforme en logarithme
M_p [$M_\oplus$]	0.5 – 1589 (= 5 M_{Jup})	Uniforme en logarithme
B_p [G]	$0^{(a)}$, 1, 10	-
P_{orb} [jours]	0.12 - 46	-
R_p [$R_\oplus$]	0.8-12.7	-

[Ahuir 2021]

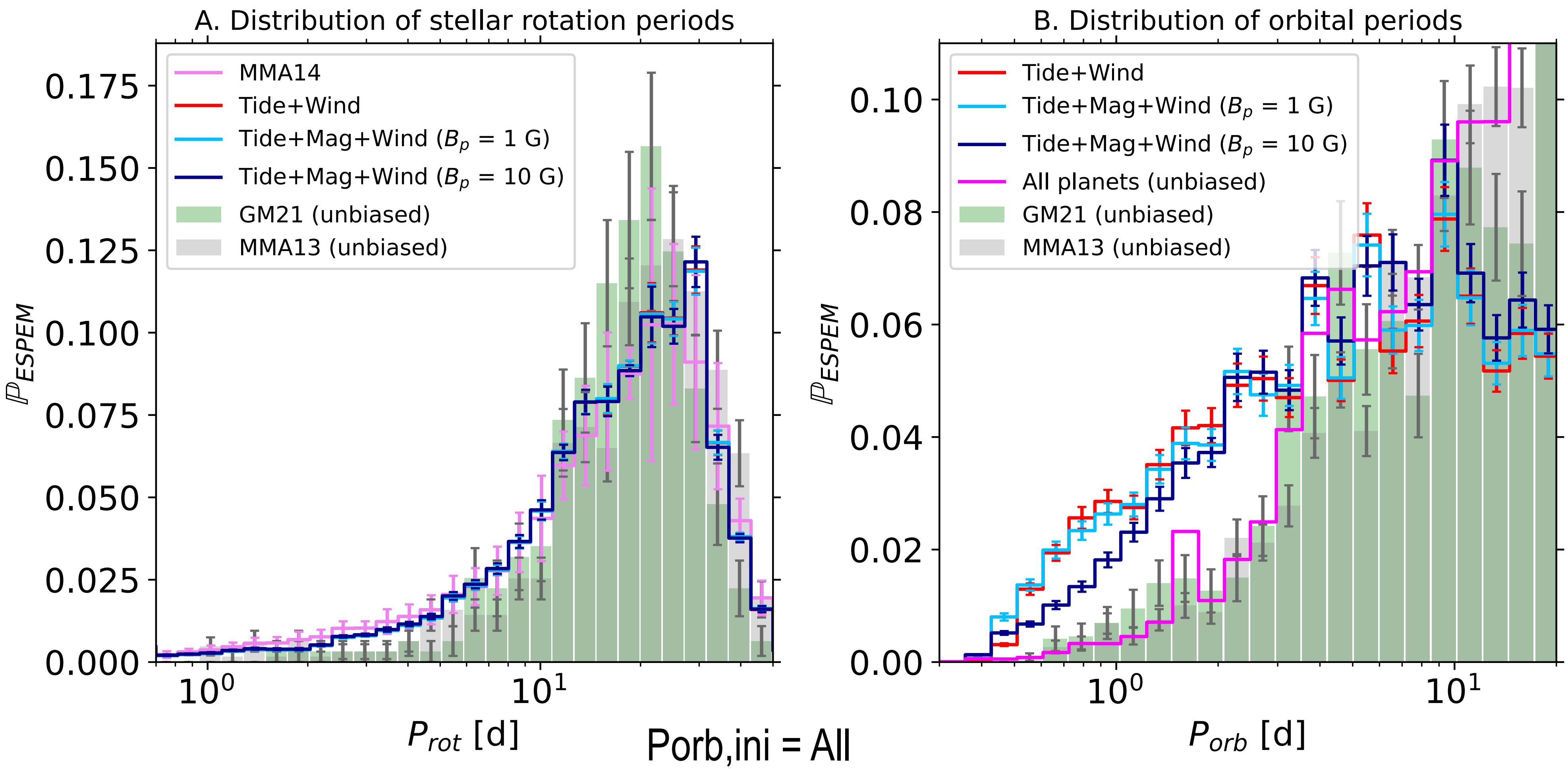


[Santos et al. 2021]

- Results are then "biased" to follow planets observed by *Kepler*
  - Same P_{rot}-T_{eff} distribution

Stellar age   Stellar age & Mass

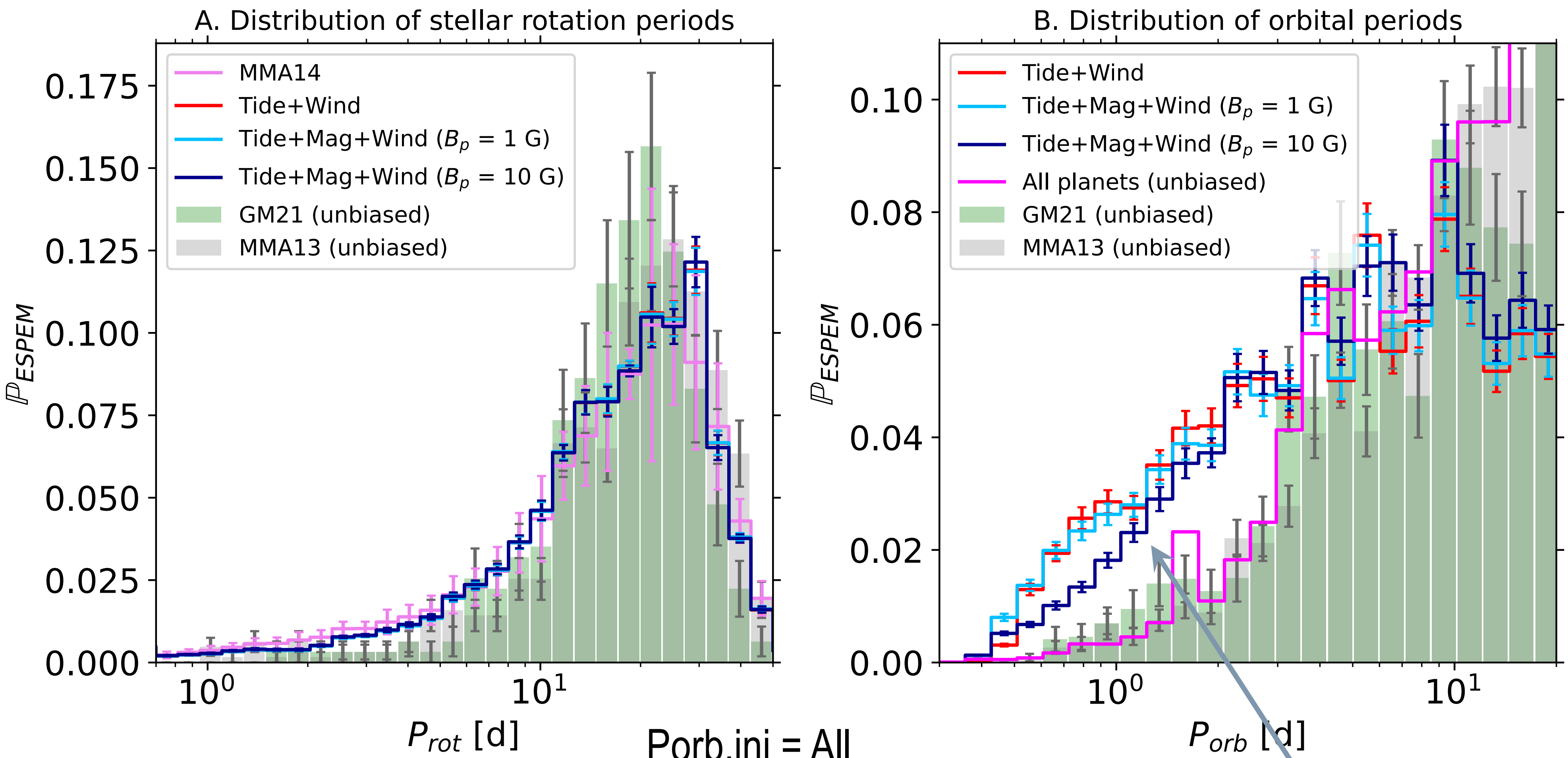
III-COMPARING THE RESULTS



Porb,ini = All

- Unbiased *Kepler* distributions:
  - Corrected for the probability of a transit to be observed.
- Tide + Wind and Tide + wind + Mag (Bp =1G) very similar

III-COMPARING THE RESULTS



Porb,ini = All

- Unbiased *Kepler* distributions:
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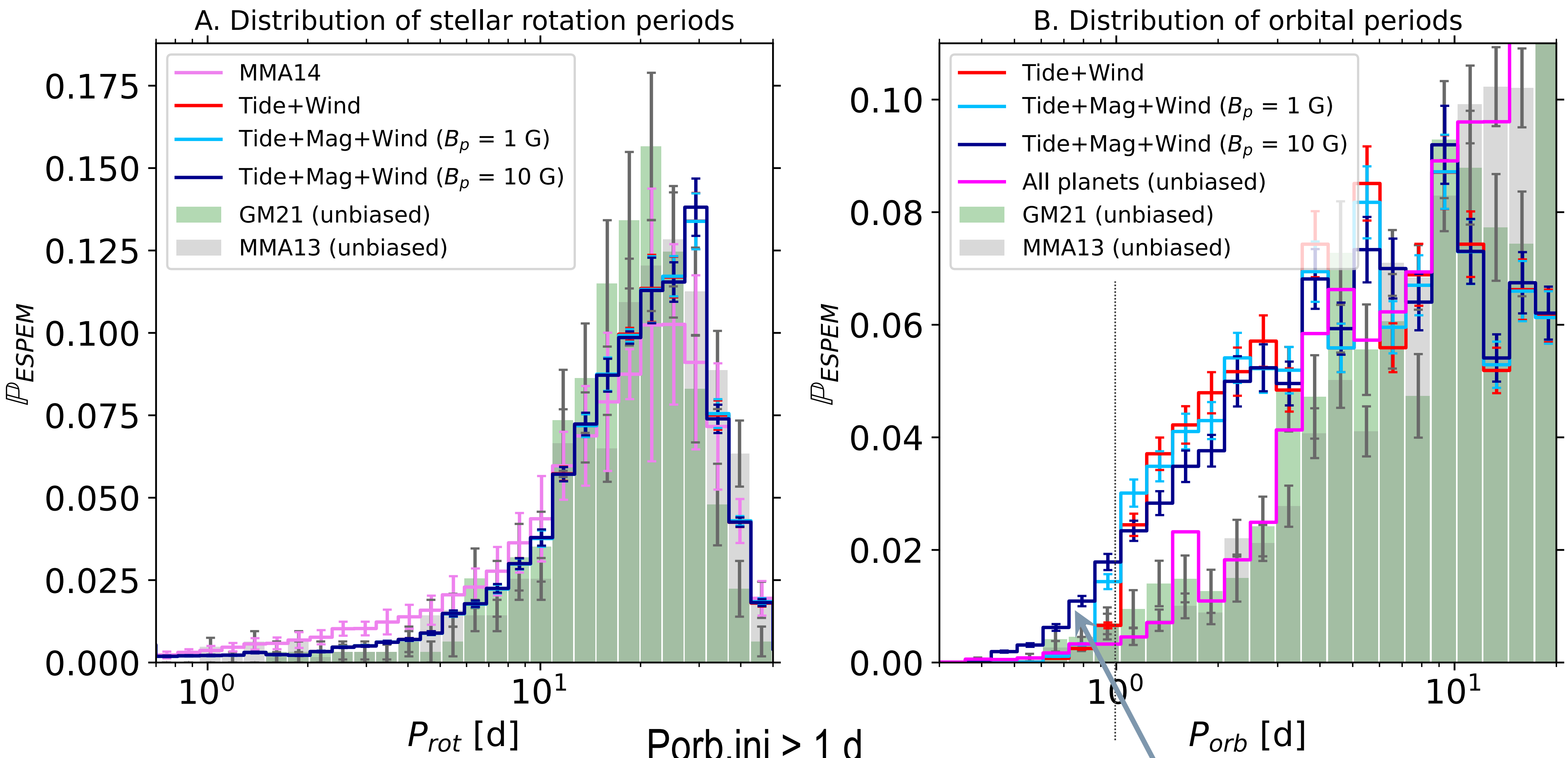
Excess of close-in planets

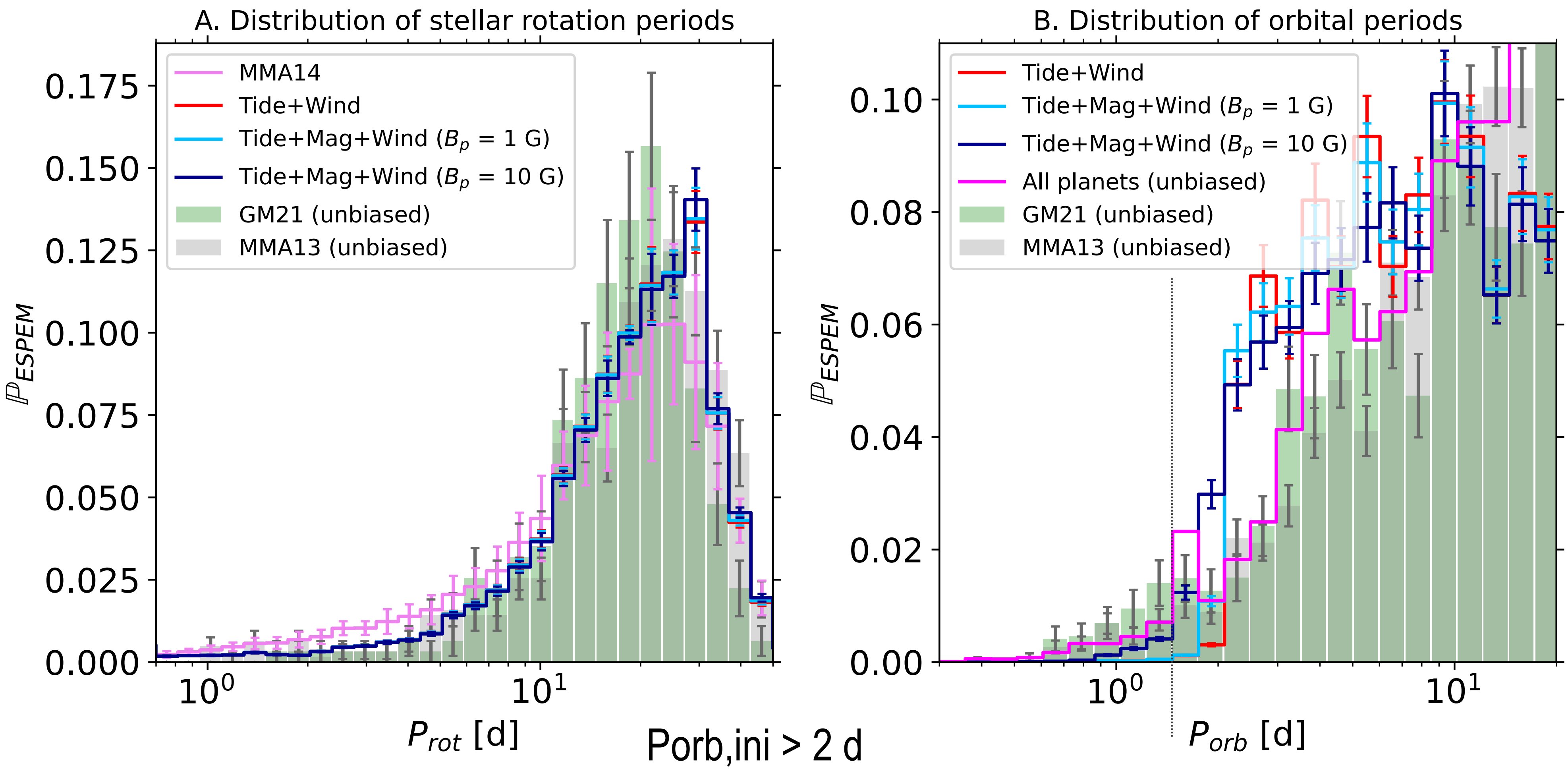
III-COMPARING THE RESULTS



Porb,ini > 1 d

Fill-in only if Bp >>

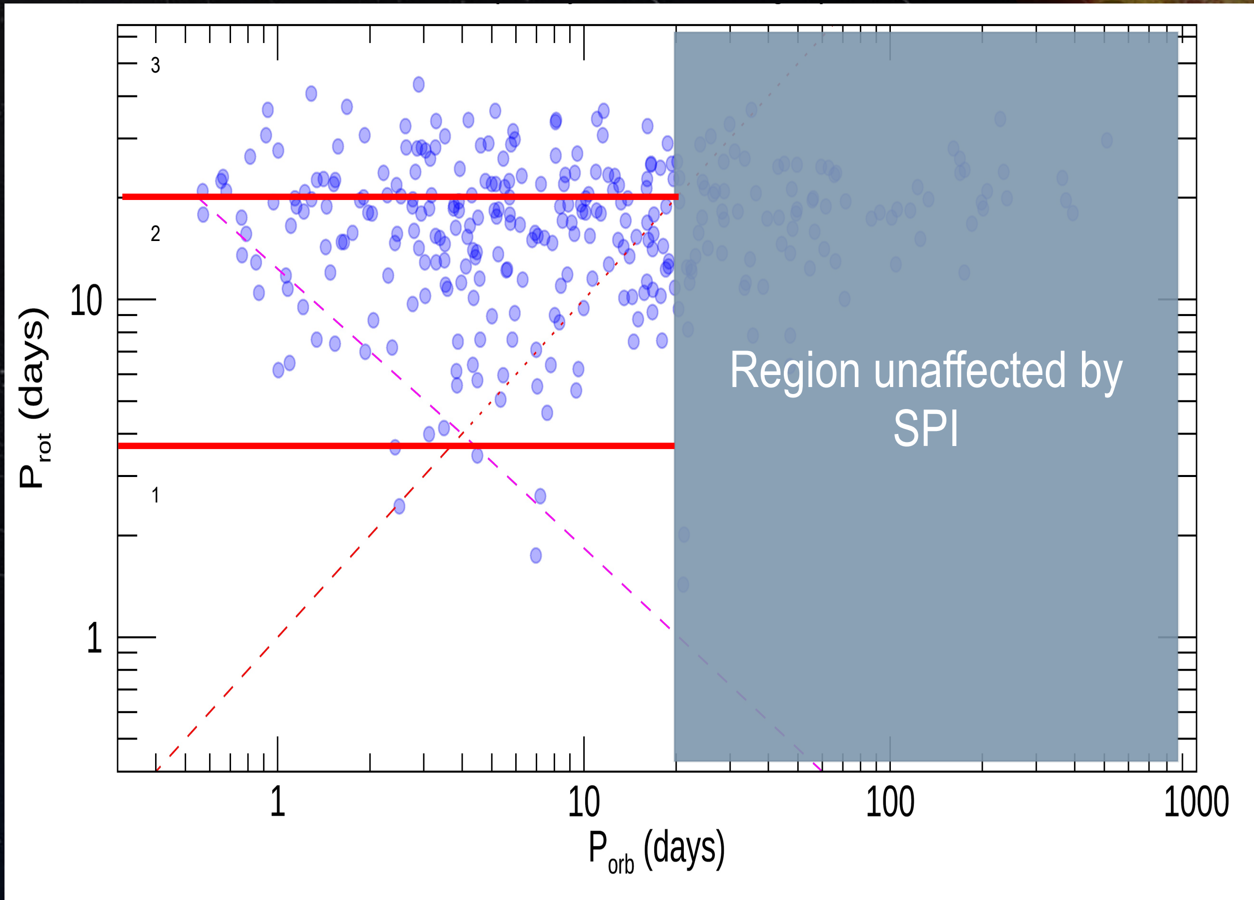
III-COMPARING THE RESULTS



Porb,ini > 2 d

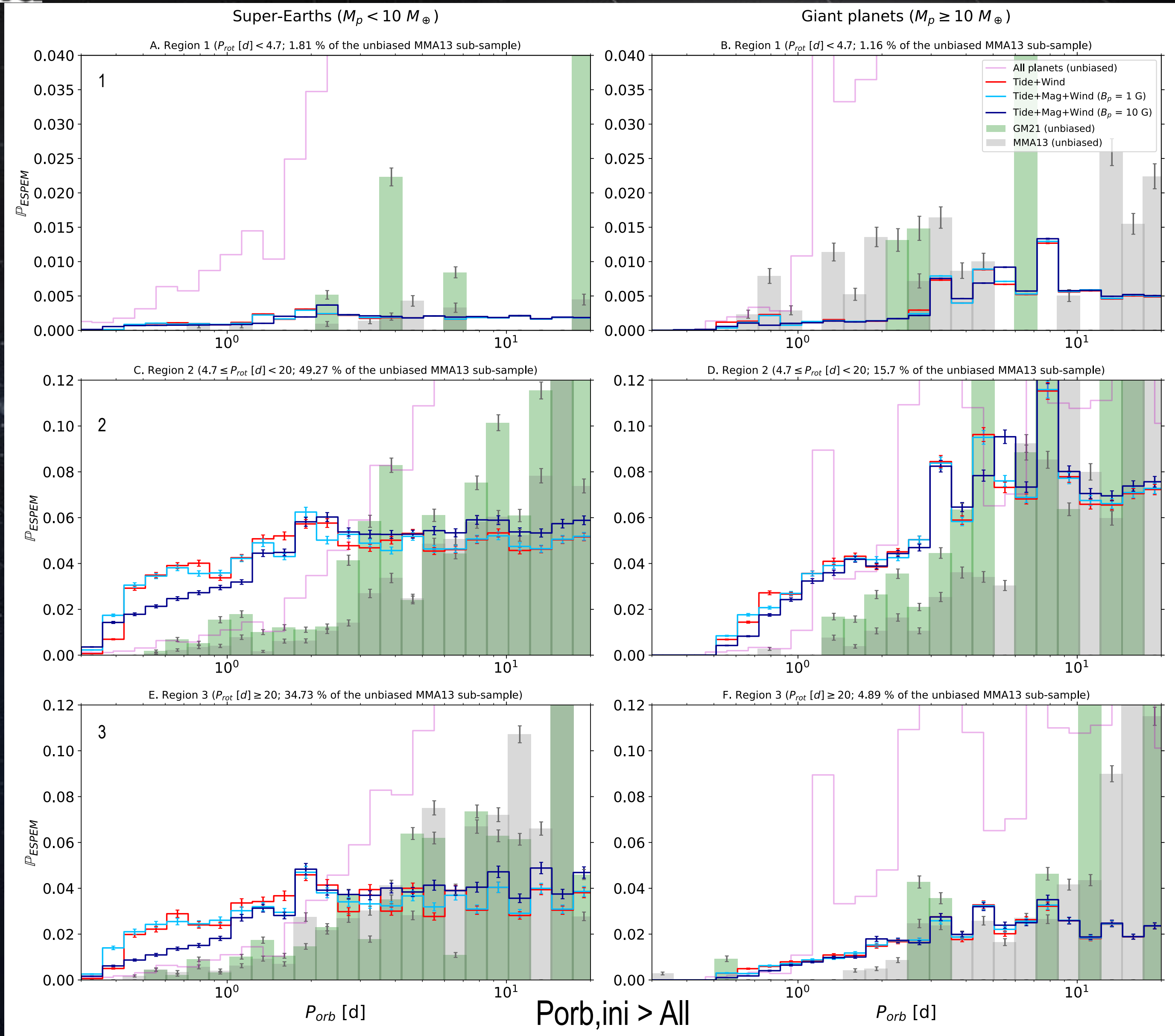
III-M_P AND P_{ROT}

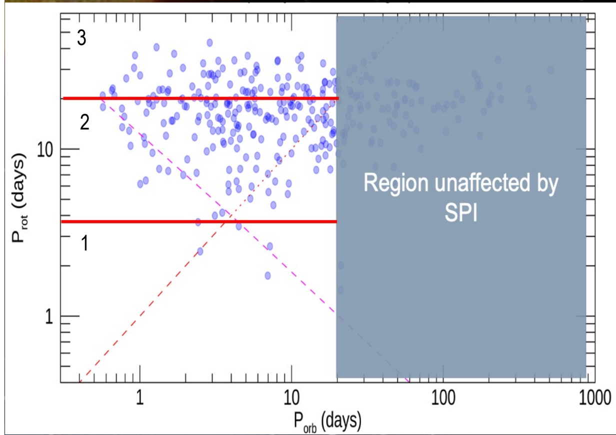
Compare the distributions as a function of M_p and P_{rot}



Porb,ini > All

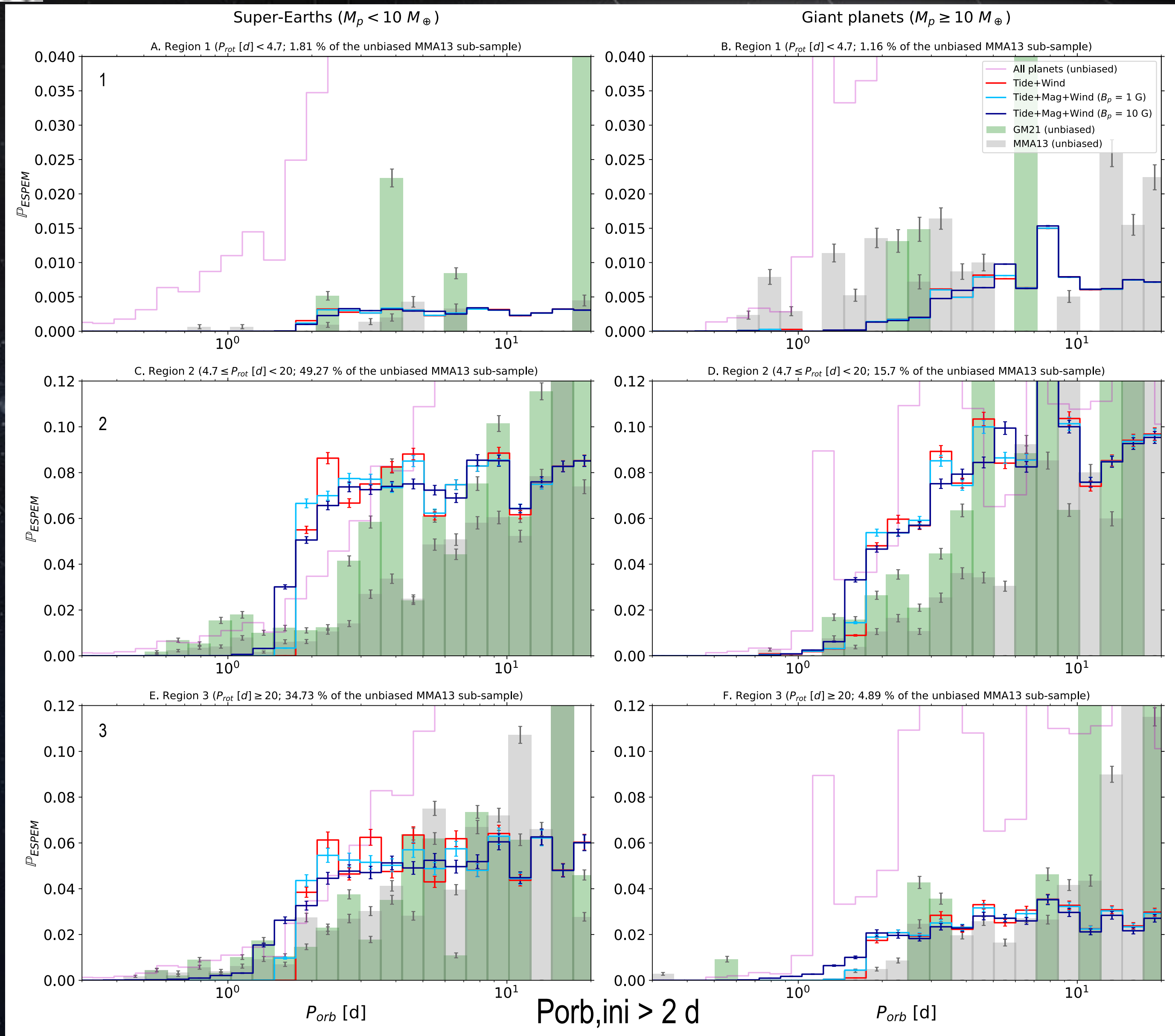
III-Mp AND PROT



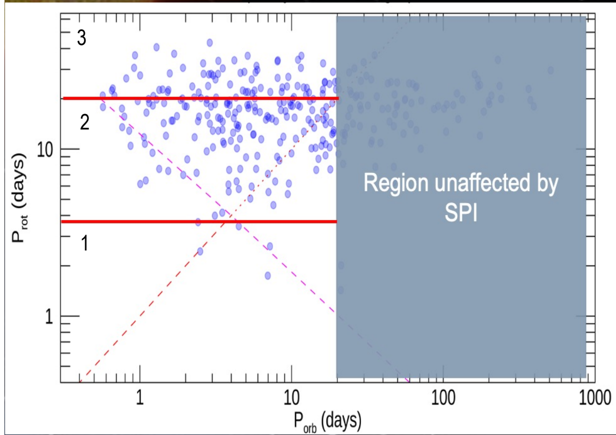


- For Super-Earth planets:
  - Magnetic Torque shape the distribution
- For Massive planets:
  - Tidal effects dominates the distribution

III-M_P AND P_{ROT}



Porb,ini > 2 d



- **For Super-Earth planets:**
  - Magnetic Torque shape the distribution
- **For Massive planets:**
  - Tidal effects dominates the distribution

IV-Conclusions

& Perspectives

IV-CONCLUSIONS & PERSPECTIVES

- Study of the architecture of the confirmed planets
  - Re-analysis of *Kepler* & K2 is on going
- Dearth of close-in planets around fast rotators is still there
- ESPEM: Evolution model of a two-layer's star with single point planet
  - Star-Planet interactions including
    - Stellar wind, internal interaction, tidal (equilibrium and dynamic), and magnetic torques
  - Challenges:
    - Still a lot of close-in planets in the simulations
    - Improvement when removing $P_{orb,\ ini} < 2d$
- Open questions to reduce planet migration for close-in planets:
  - Extreme planetary dynamo?
  - Initial conditions of planetary formation?
  - Any additional star-Planet interaction?