Exocomets

Challenges in detection of exocomets as monotransit

Alain Lecavelier des Etangs
(Institut d'Astrophysique de Paris - CNRS)

With inputs from
Pierre Dumond and Théo Vrignaud

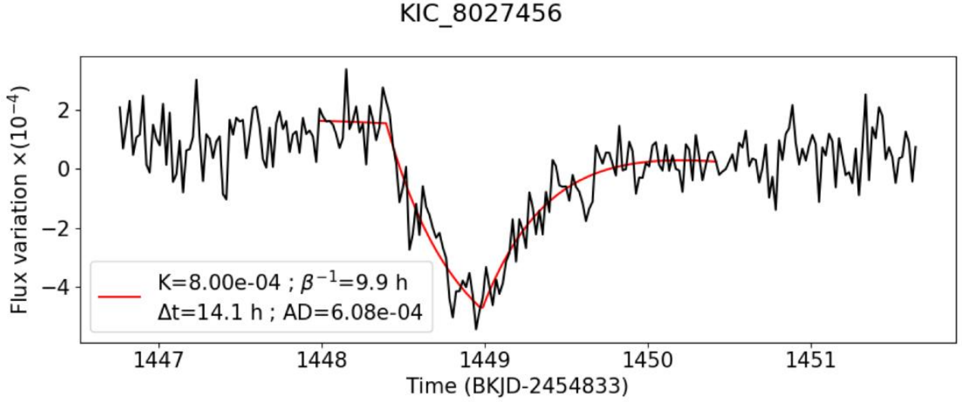
Search for exocomets transits in Kepler light curves

Ten new transits identified

P. Dumond[1,2], A. Lecavelier des Etangs[1], F. Kiefer[1,3], G. Hébrard[1], and V. Caillé[1,4]

Submitted to A&A on June, 20, 2025

- Using **neural network trained on a library of theoretical transit light curves**
- Analysis of 171,359 Kepler light curves
- ➔ Output : List of 17 high-confidence exocometary transits,
  - 7 previously reported events
  - **10 new exocomets transits**



Detection of small bodies as comets

- Comets = small bodies with evaporation signature

(evaporation of volatile, from a body on an eccentric orbit)

➔ Small bodies can be detected when they are comets !!

- Detection of the coma and/or tail
    - ➔ up to several millions kilometers in size
    - ➔ detection through **transit observations** in extrasolar systems

Detection of small bodies as comets

- Detection
  of the two components

  – Gas (spectroscopy)

  – Dust (photometry)

- Exocomets can be detected in **spectroscopy** through **<u>the transit signature of the gaseous coma</u>**
- Exocomets can be detected in **photometry** through **<u>the transit signature of the dust tail</u>**

Transits of exocomets

- Exocomets can be detected in **spectroscopy** through **<u>the transit signature of the gaseous coma</u>**

- Exocomet can be detected in **photometry** through **<u>the transit signature of the dust tail</u>**

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Discovery of the 1st exocomets

Ferlet et al. (1987); Lagrange et al. (1988) Beust et al. (1990-2004)

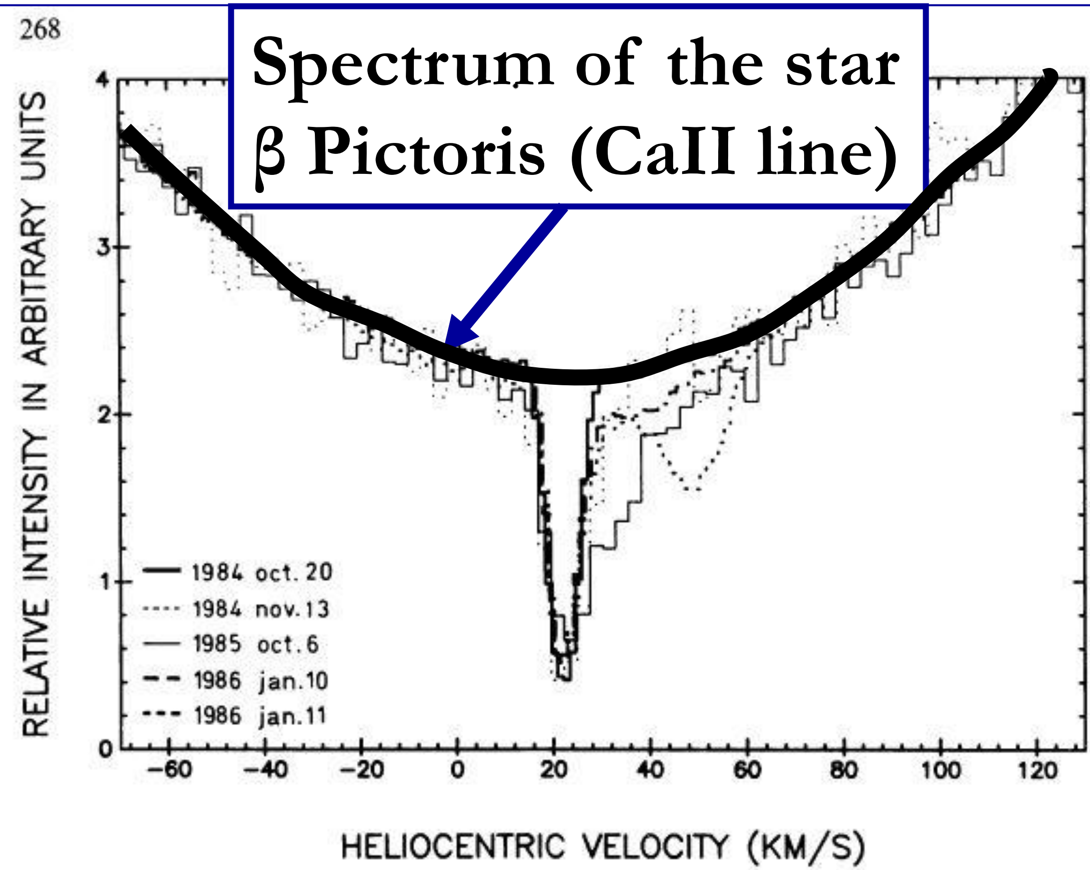

Fig. 1. Enlarged spectra of *β* Pic in the region of the circumstellar Ca II-K line, in an heliocentric velocity scale. They have been normalized in order for the "continua" (the stellar line widened by rotation) to coincide. To avoid confusion due to its much lower signal to noise ratio, the 1985, March 9 spectrum has not been plotted. Variations during 1986, January 17 are studied in Fig. 2

(Ferlet et al. 1987)

Spectroscopic transits of exocomets
in the young planeary system of β Pictoris

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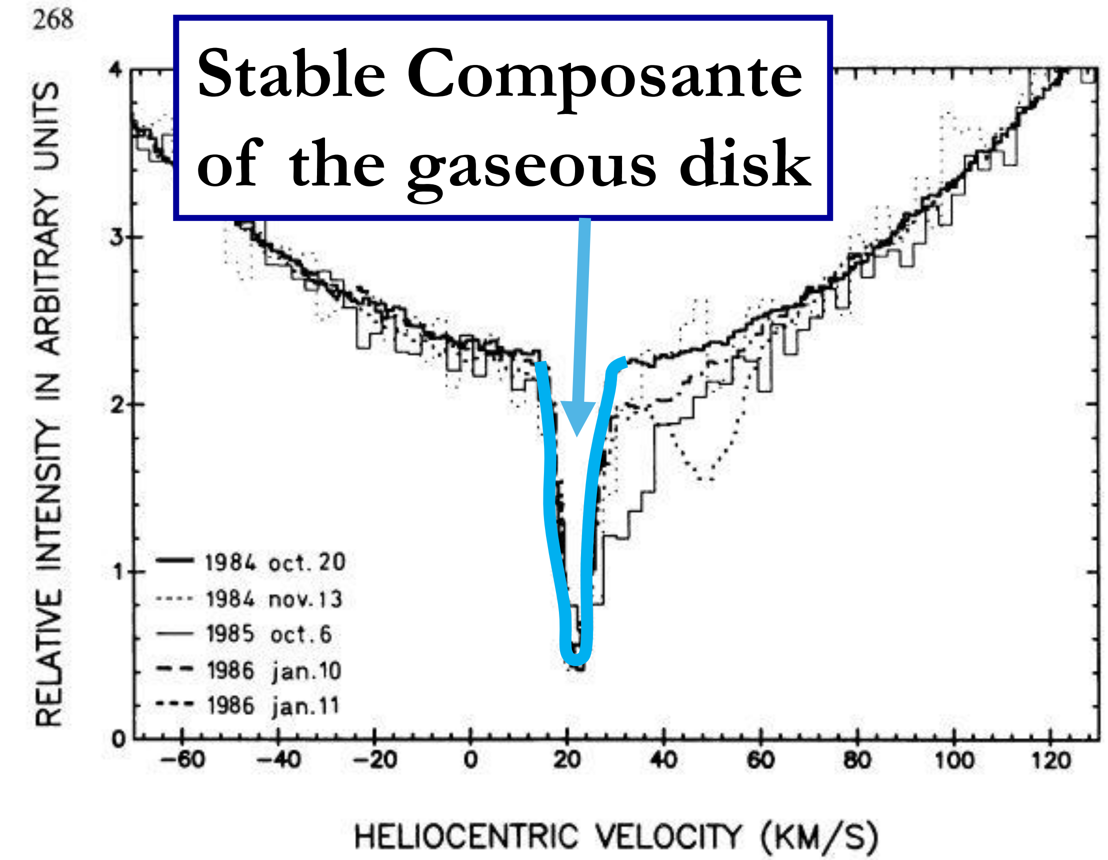

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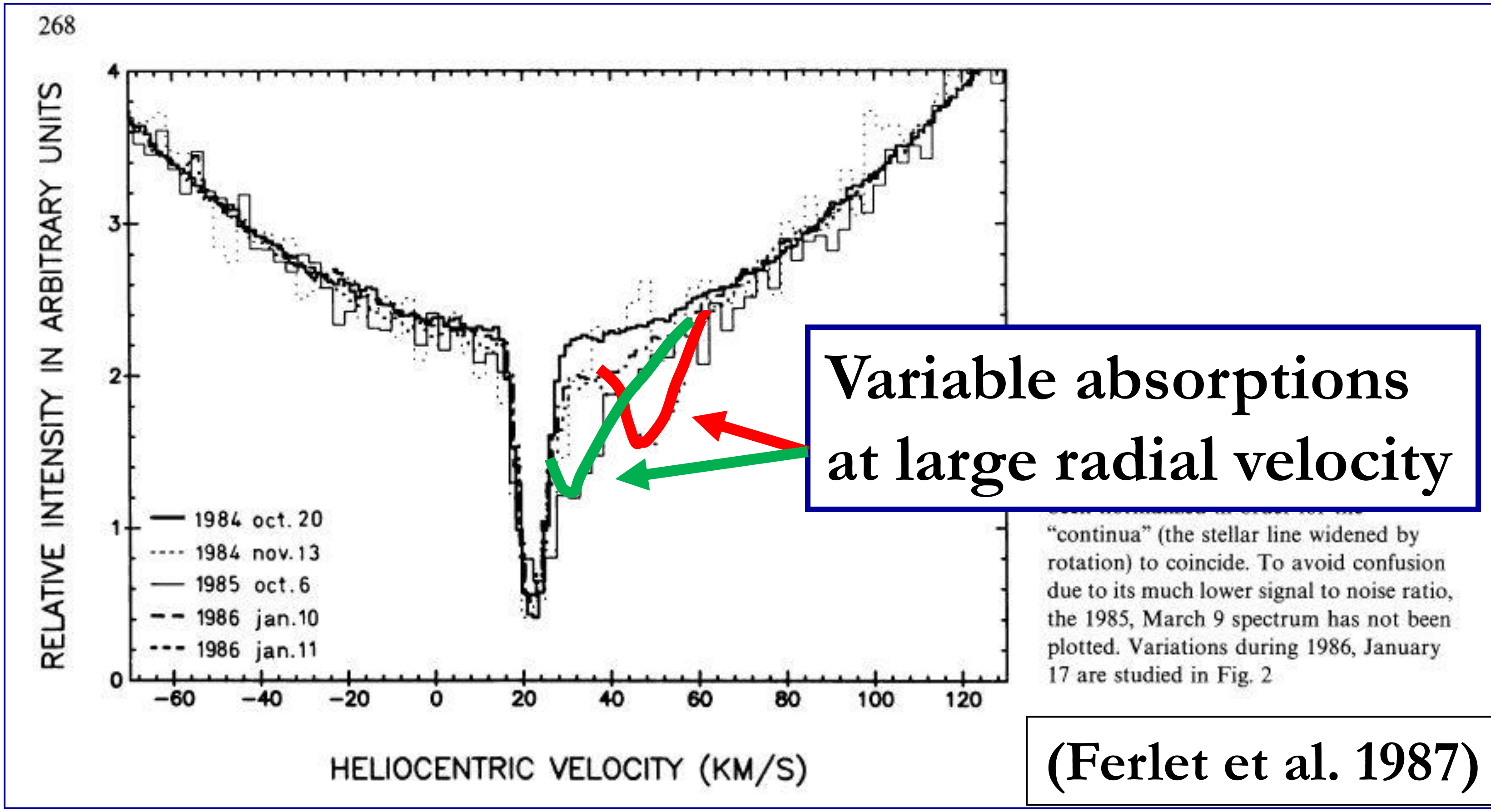
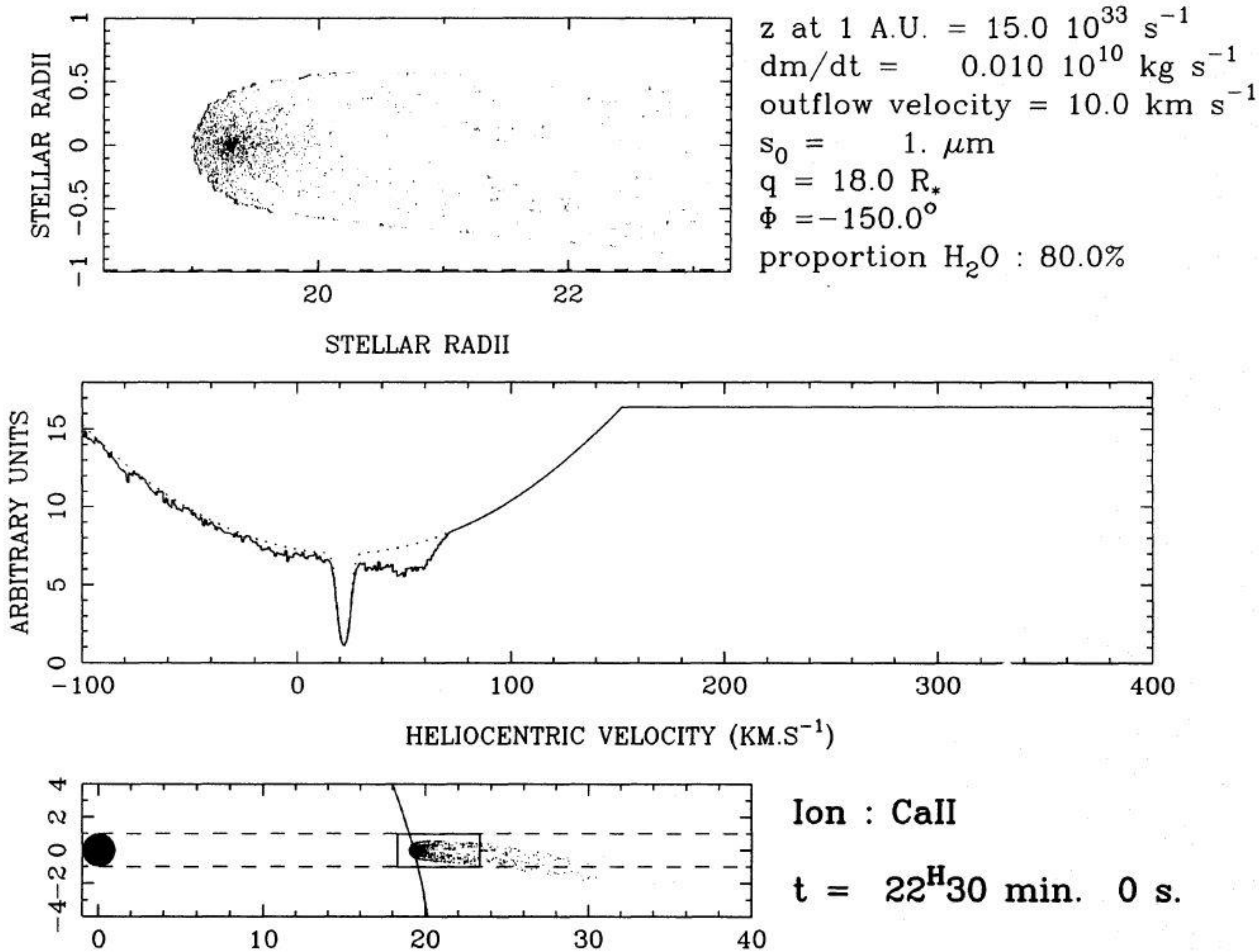


Spectroscopic transits of exocomets
in the young planeary system of β Pictoris

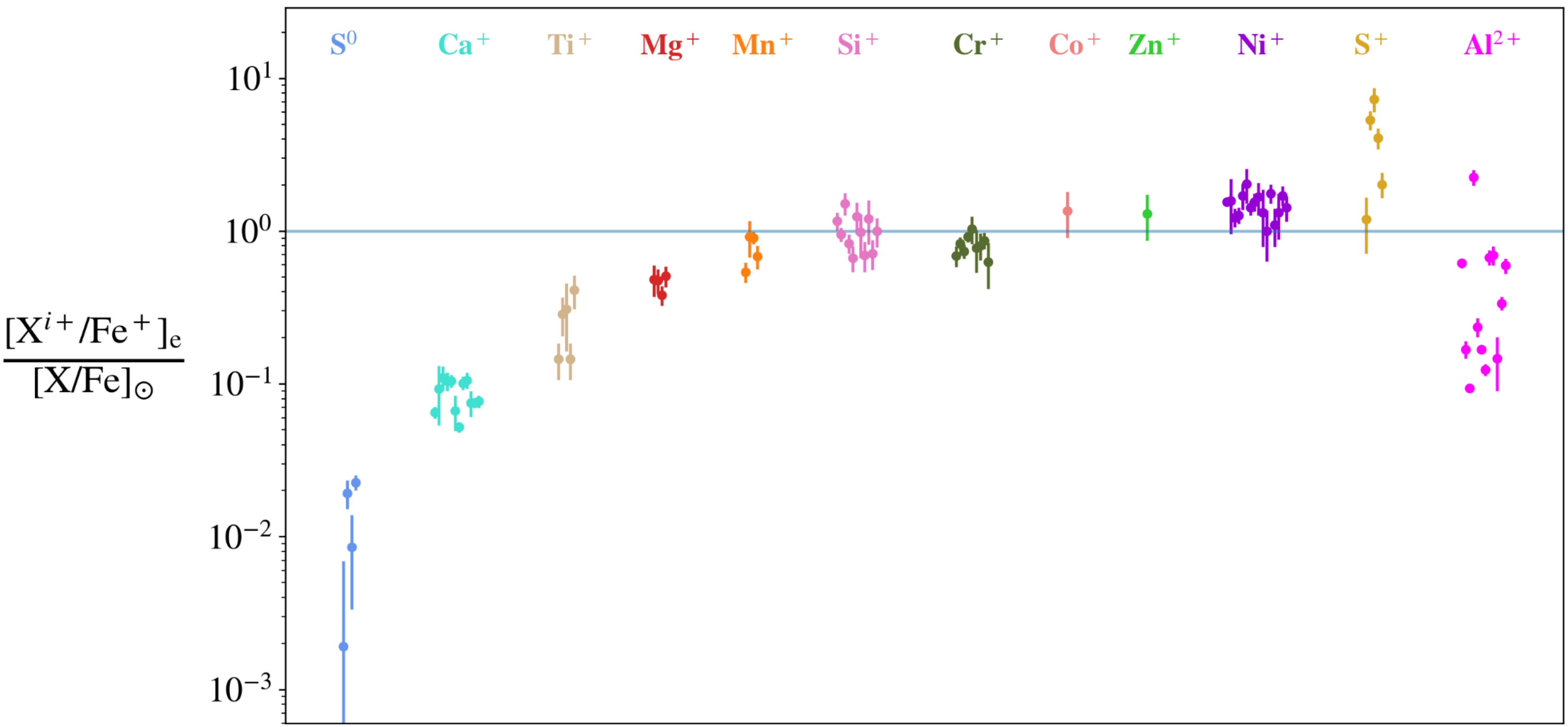
Numerical simulations of exocomets transits

(Beust et al. 1990-2004)



Toward composition measurement

Ions abundance in 30 β Pic exocomets
(Vrignaud & Lecavelier 2025)



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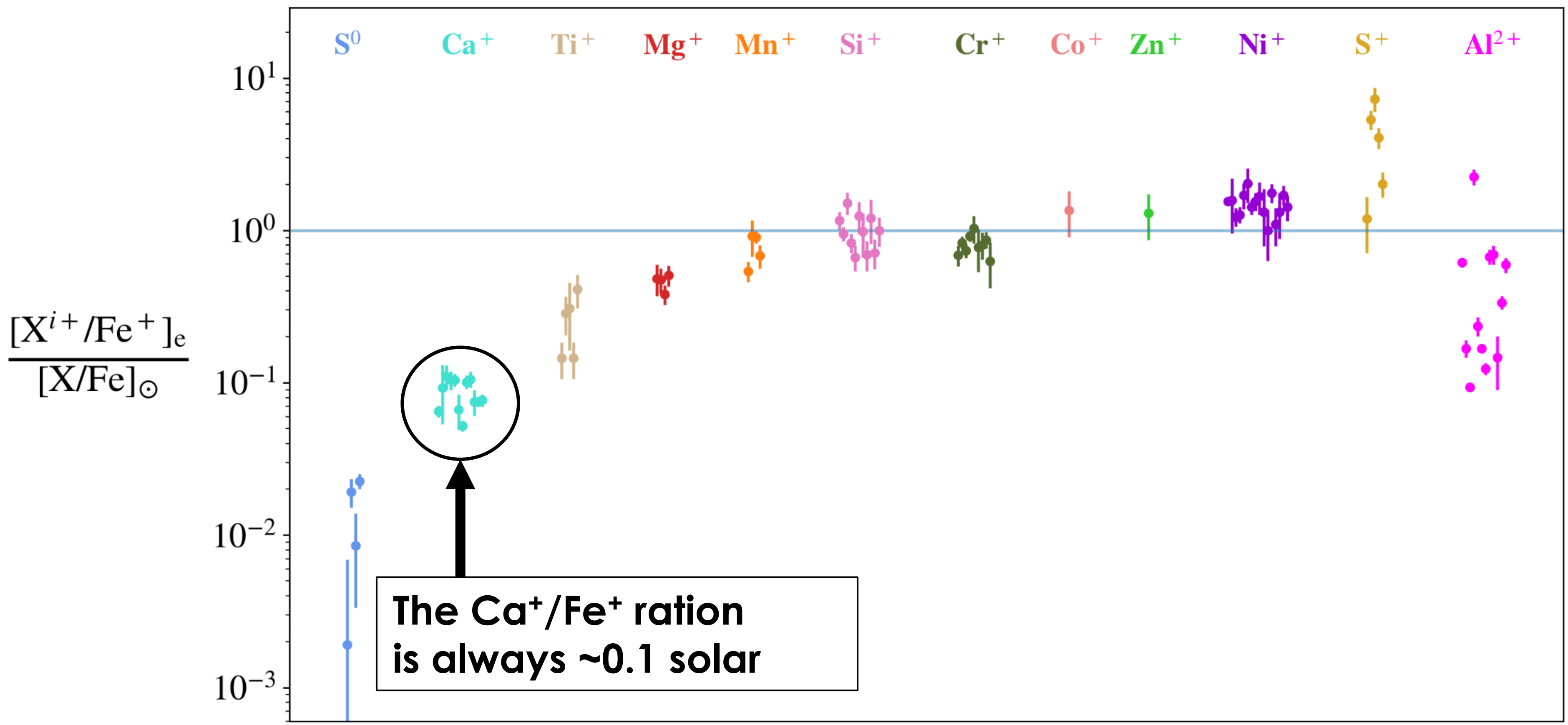

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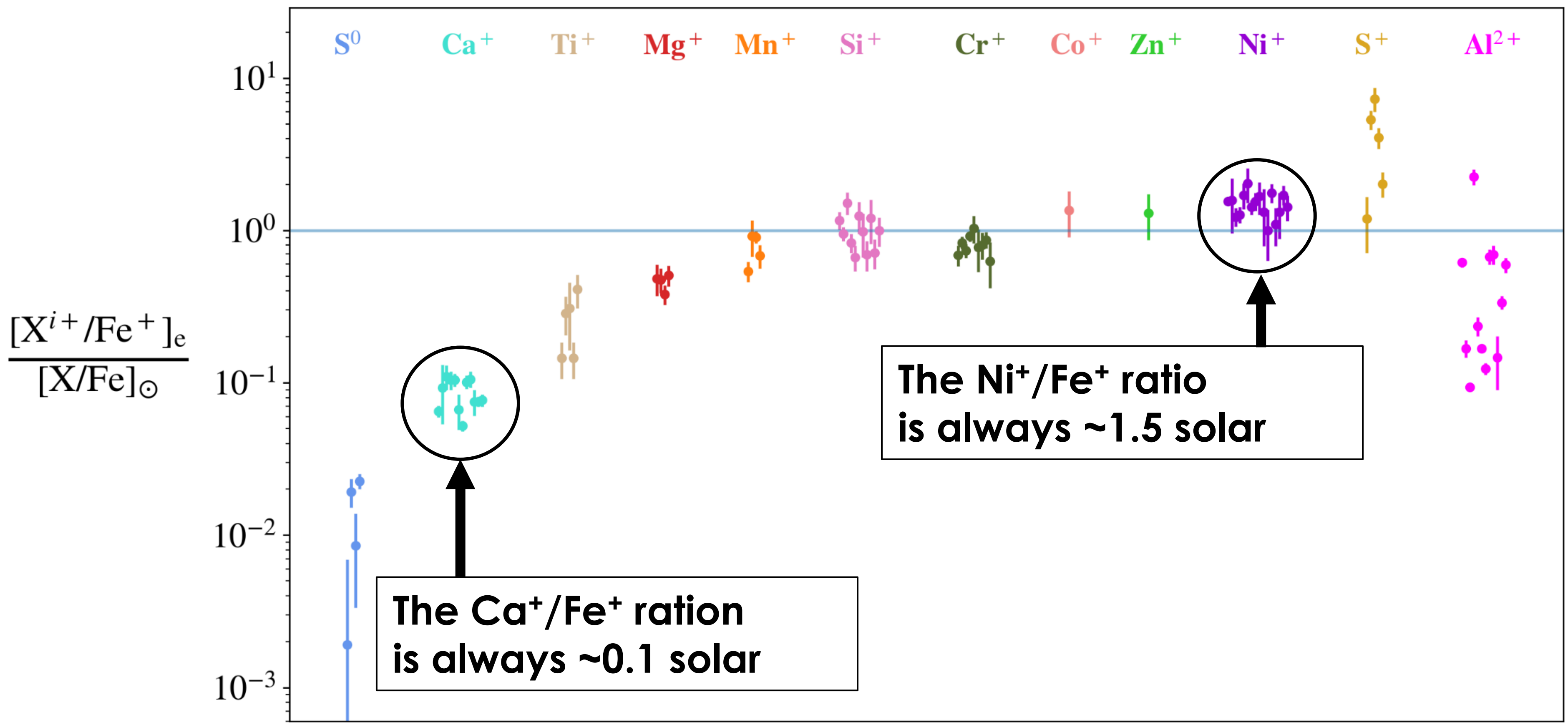

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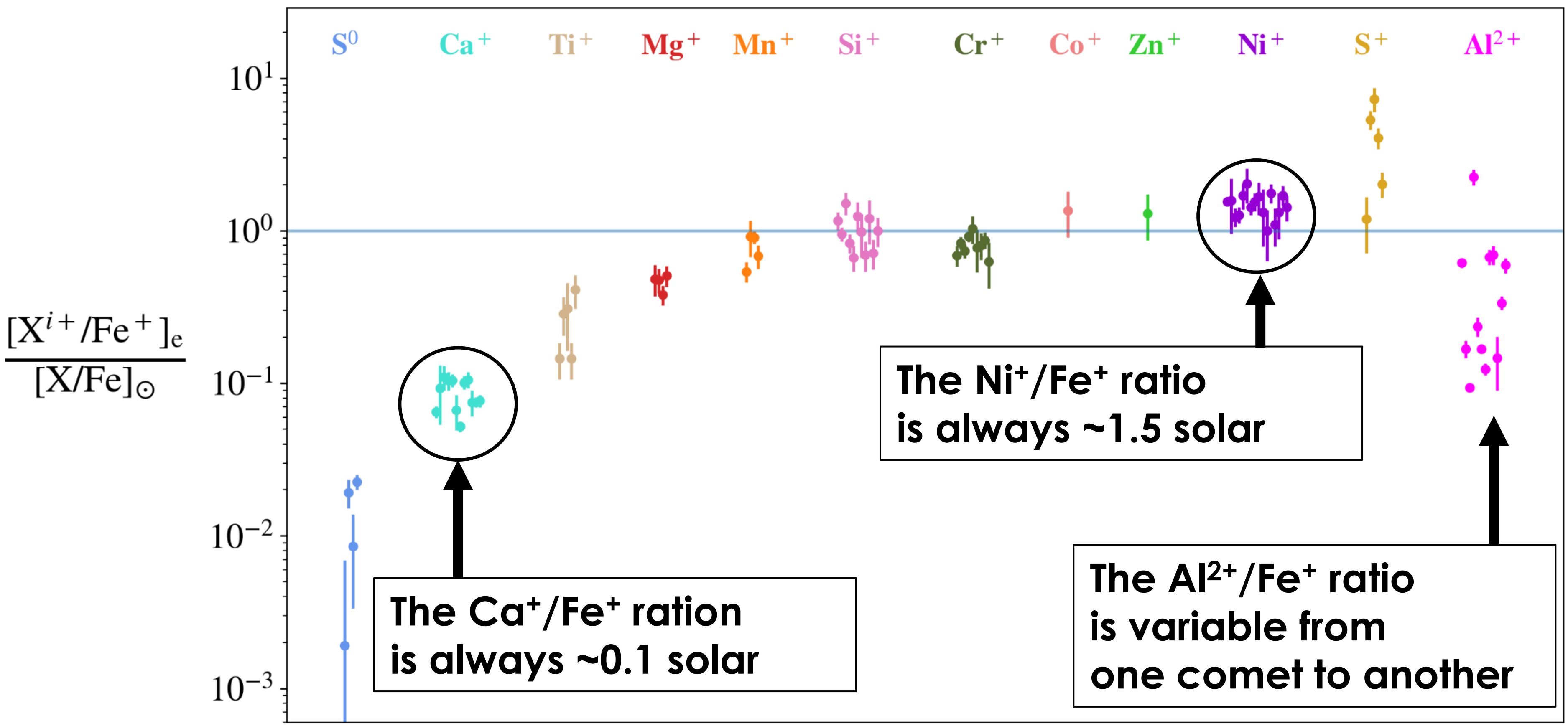

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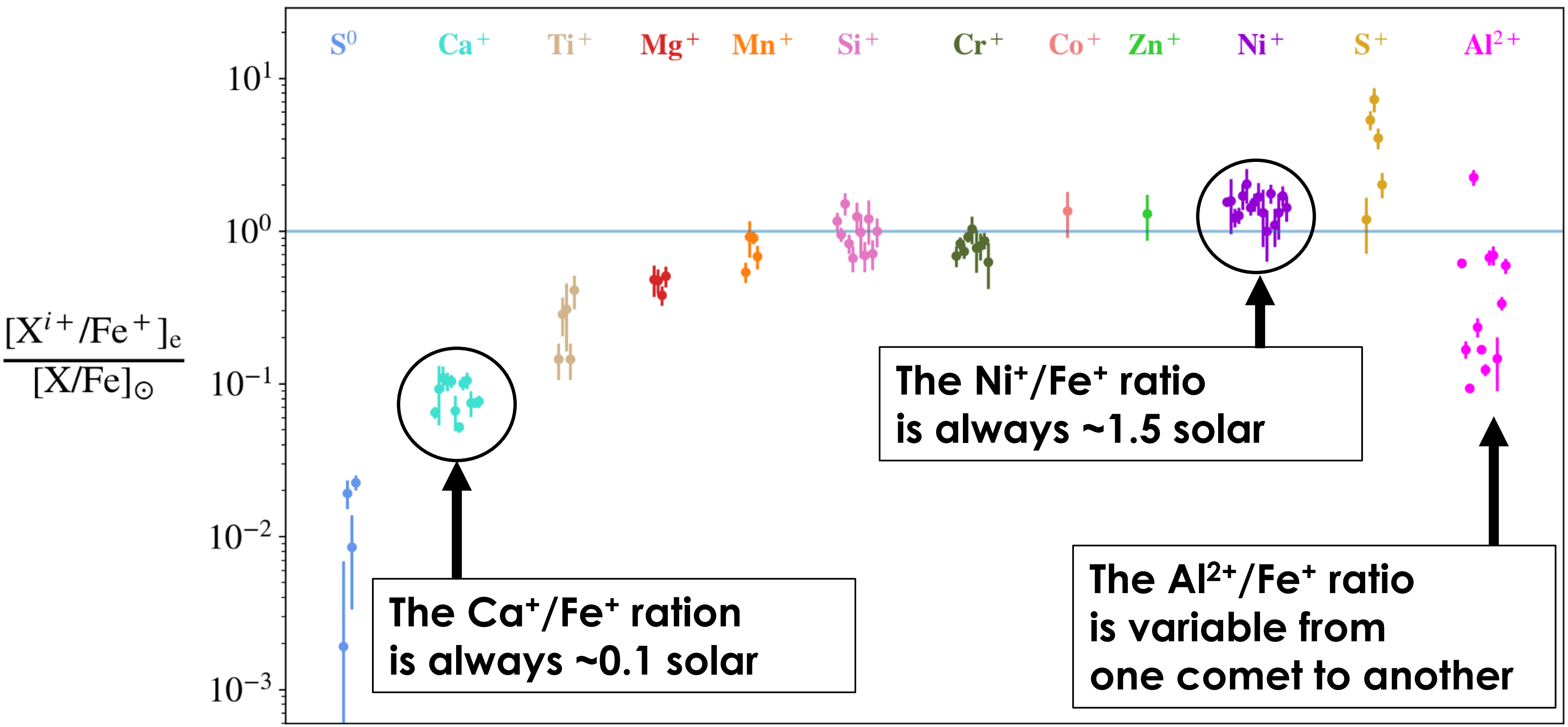

➔ Cycle 32 HST program to obtain exocomet spectra on wide wavelength range

Transits of exocomets

- Exocomets can be detected in **spectroscopy** through **the transit signature of the gaseous coma**

- Exocomet can be detected in **photometry** through **the transit signature of the dust tail**

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Photometric detection of exocomets

Lecavelier, Vidal-Madjar & Ferlet (1999) ; Lecavelier (1999)

Astron. Astrophys. 343, 916–922 (1999)

ASTRONOMY AND ASTROPHYSICS

Photometric stellar variation due to extra-solar comets

A. Lecavelier des Etangs, A. Vidal-Madjar, and R. Ferlet

Institut d'Astrophysique de Paris, CNRS, 98bis Boulevard Arago, F-75014 Paris, France

ASTRONOMY & ASTROPHYSICS SUPPLEMENT SERIES

NOVEMBER II **1999**, PAGE 15

Astron. Astrophys. Suppl. Ser. **140**, 15–20 (1999)

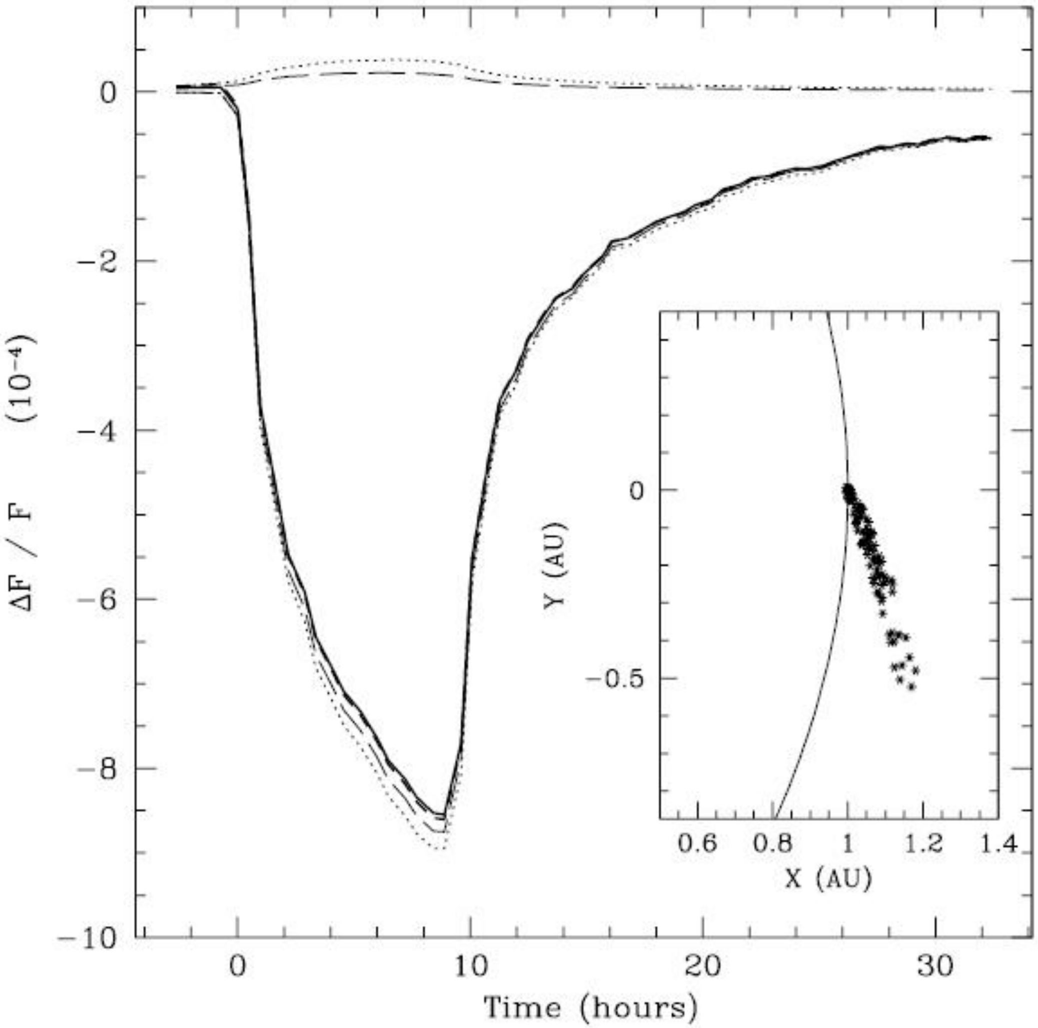
A library of stellar light variations due to extra-solar comets

A. Lecavelier des Etangs[1]

Institut d'Astrophysique de Paris, CNRS, 98bis Boulevard Arago, F-75014 Paris, France

Photometric detection of exocomets

Lecavelier et al. (1999)



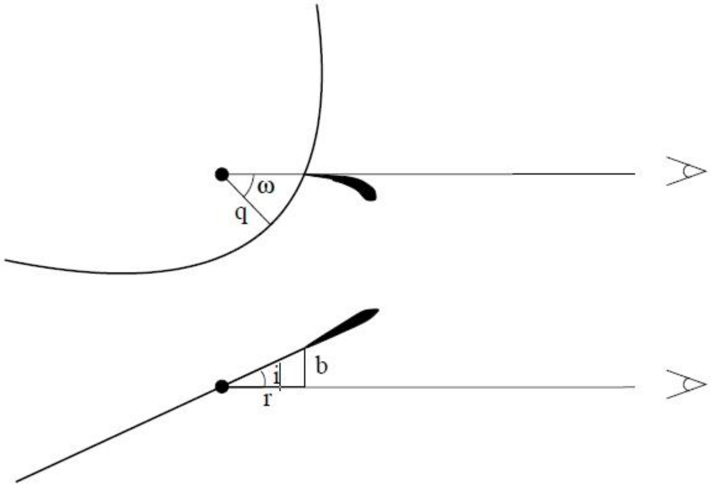
Simulation with production rate P = $2 \cdot 10^6$ kg/s and periastron q = 1 ua

A library of exocomets photometric transits

(Lecavelier 1999b)

$$P = P_0 \left(\frac{r}{r_0}\right)^{-2} \left(\frac{L_*}{L_\odot}\right)$$

$\log(P_0/\text{kg s}^{-1}) = 2, 3, 4, 5, 6$

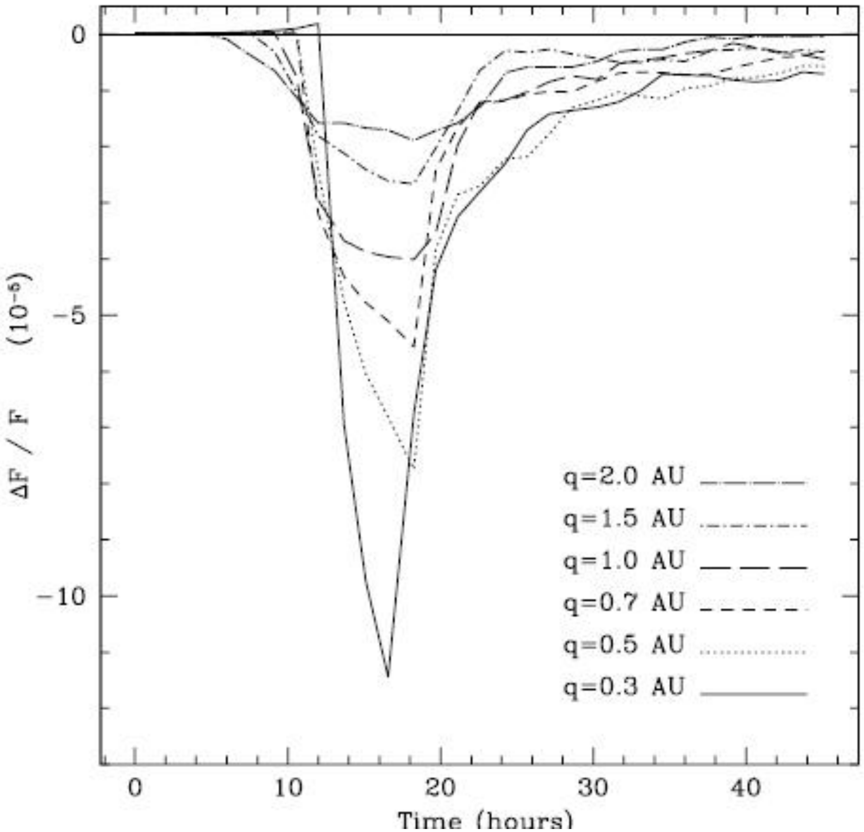


$$dn(s) = \frac{(1 - s_0/s)^m}{s^n} \quad (1)$$

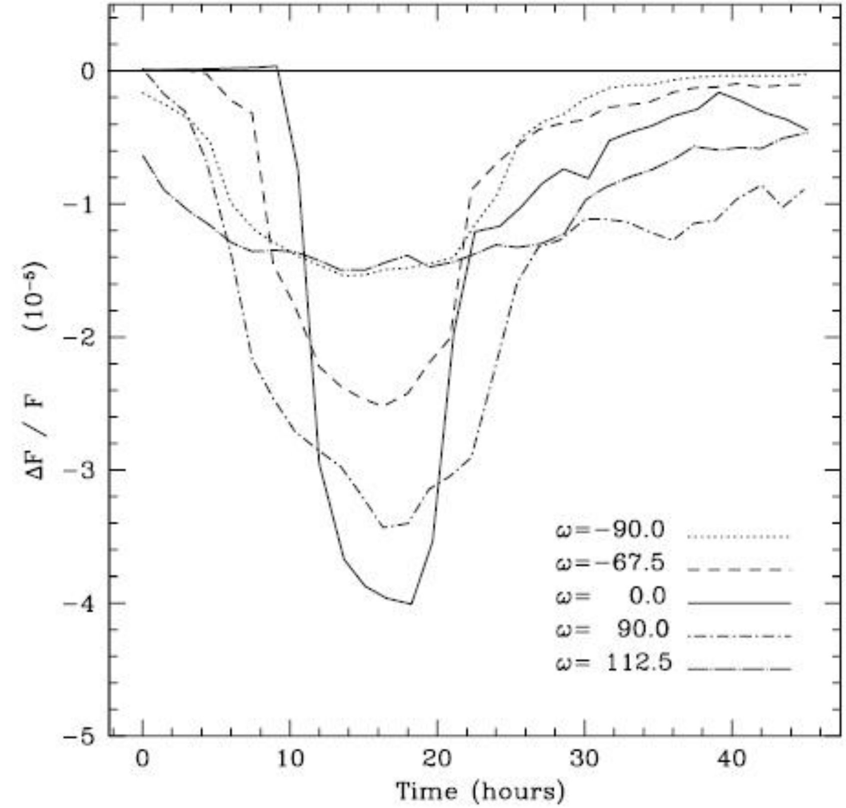
as observed in the solar system, where s is the dust size. We take $s_0 = 0.1\mu\text{m}$, $n = 4.2$, $m = n(s_p - s_0)/s_0$, and $s_p = 0.5\ \mu\text{m}$

Size distribution		Stellar type	Production		Periastron		ω				Impact parameter	
	name	name	(kg s^{-1})	name	(AU)	name	(°)	name	(°)	name	(R_*)	name
$s_p = 0.20\ \mu m$	20	M	10^2	20	0.3	03	−157.5	m7	157.5	p7	0	00
$s_0 = 0.05\ \mu m$, $n = 4.2$		K	10^3	30	0.5	05	−135.0	m6	135.0	p6	0.33	03
		G	10^4	40	0.7	07	−112.5	m5	112.5	p5	0.66	06
$s_p = 0.25\ \mu m$	25	F	10^5	50	1.0	10	−90.0	m4	90.0	p4	1.00	10
$s_0 = 0.1\ \mu m$, $n = 4.2$		A	10^6	60	1.5	15	−67.5	m3	67.5	p3	1.33	13
					2.0	20	−45.0	m2	45.0	p2	1.66	16
$s_p = 0.50\ \mu m$	50						−22.5	m1	22.5	p1		
$s_0 = 0.1\ \mu m$, $n = 4.2$							0.0	00				

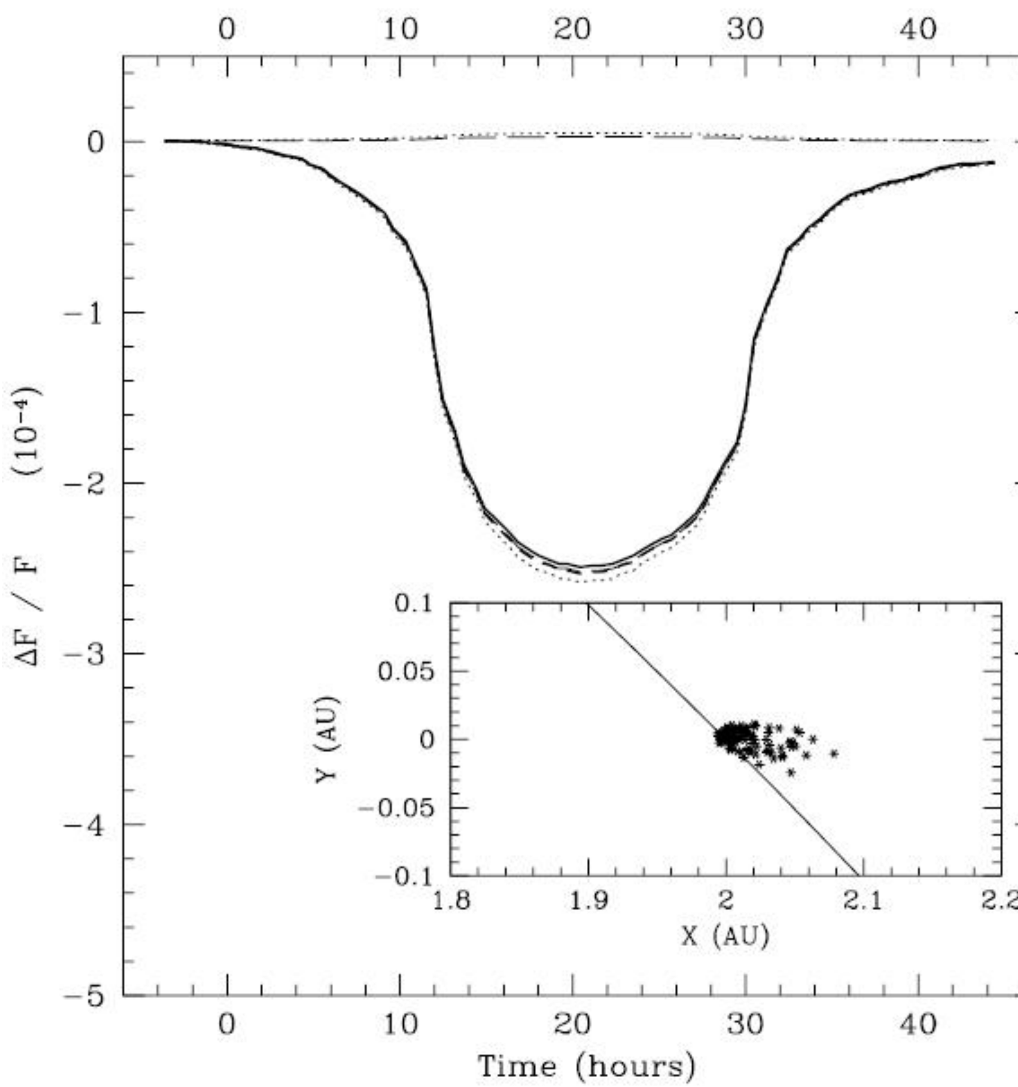
A library of exocometary transits



As a function of periastron

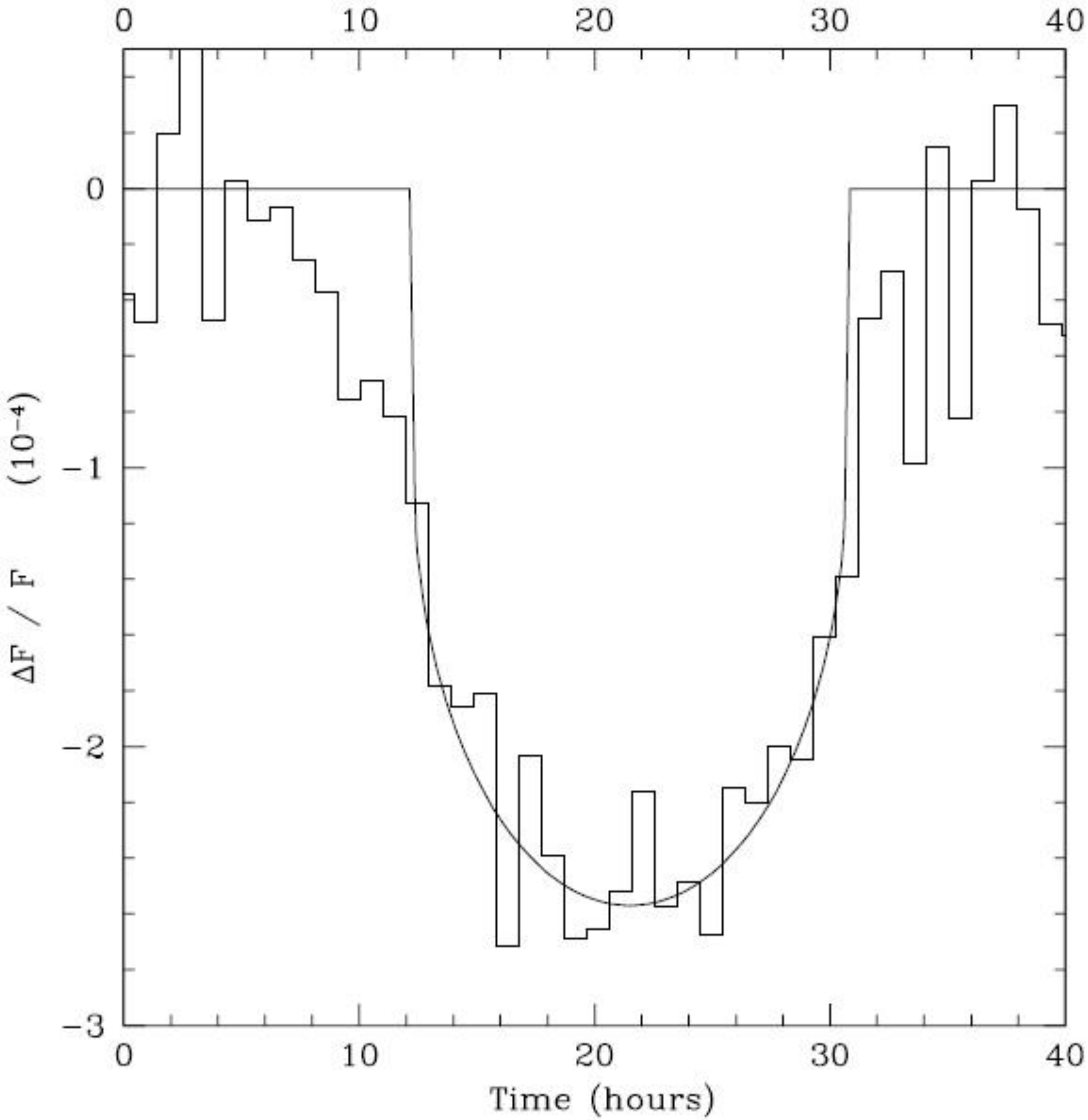


As function of longitude of periastron



Transit for P = 5 x10^5 kg/s

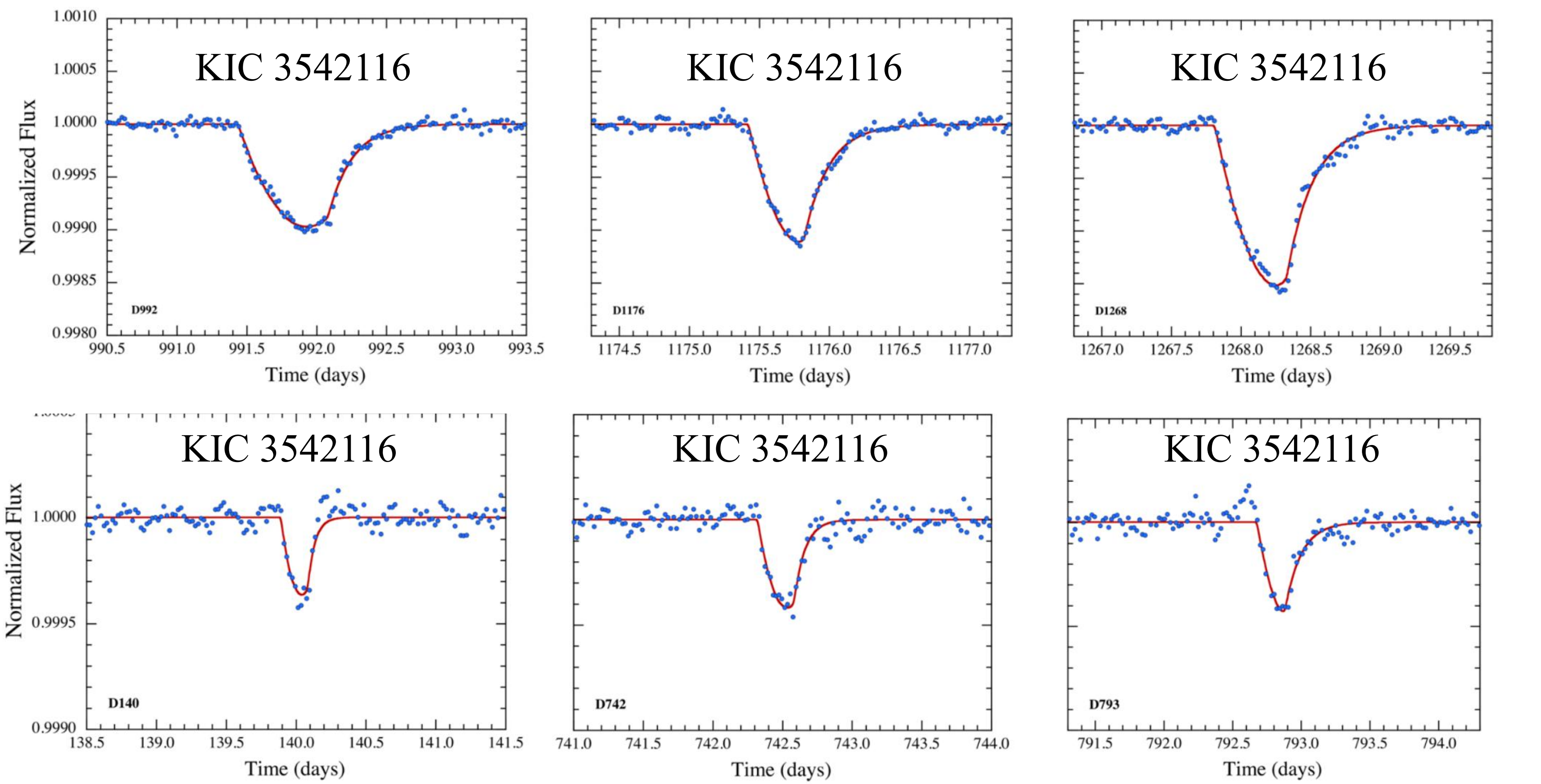
at q = 2 UA and ω=90°



Transit for P = 5 x10^5 kg/s at q=2 UA, ω=90°, 3σ = 10^{-4} for t_{exp}=1h
Planetary fit : a = 2 AU ; R_p= 9000 km

Detection of exocomets with Kepler in KIC 3542116 and KIC 11084727

Rappaport et al. (2018)



Photometric detection with TESS

Zieba et al. (2019)

Letter to the Editor

Transiting exocomets detected in broadband light by TESS in the β Pictoris system★

S. Zieba[1], K. Zwintz[1], M. A. Kenworthy[2], and G. M. Kennedy[3]

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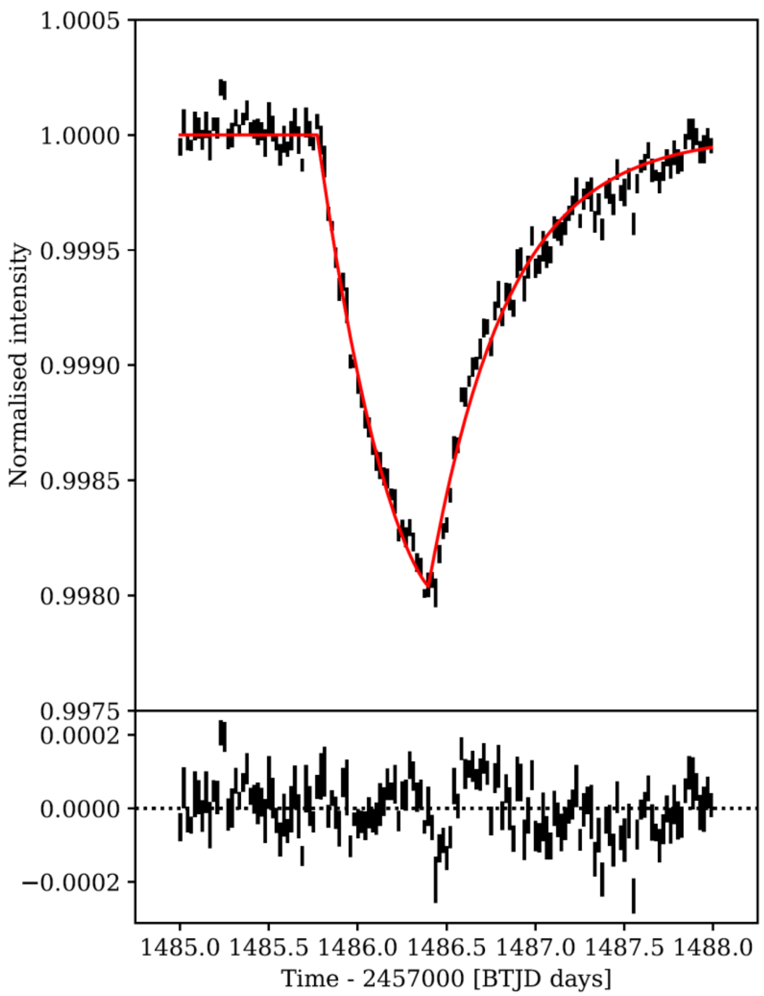
ABSTRACT

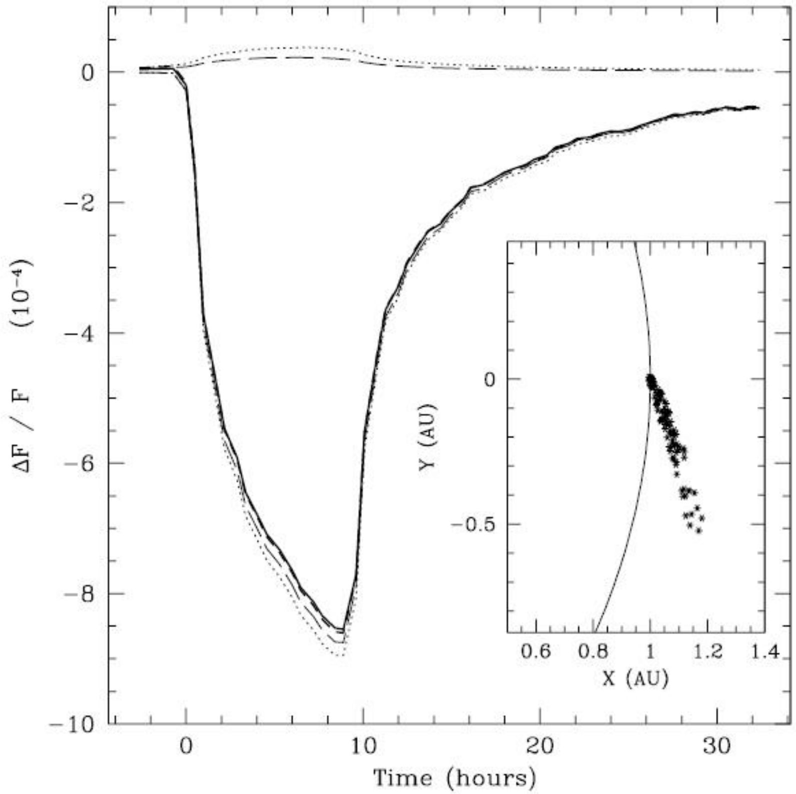
Aims. We search for signs of falling evaporating bodies (FEBs, also known as exocomets) in photometric time series obtained for β Pictoris after fitting and removing its δ Scuti-type pulsation frequencies.
Methods. Using photometric data obtained by the TESS satellite we determined the pulsational properties of the exoplanet host star β Pictoris through frequency analysis. We then pre-whitened the 54 identified δ Scuti p-modes and investigated the residual photometric time series for the presence of FEBs.
Results. We identify three distinct dipping events in the light curve of β Pictoris over a 105-day period. These dips have depths from 0.5 to 2 millimagnitudes and durations of up to 2 days for the largest dip. These dips are asymmetric in nature and are consistent with a model of an evaporating comet with an extended tail crossing the disc of the star
Conclusions. We present the first broadband detections of exocomets crossing the disc of β Pictoris, complementing the predictions made 20 years earlier by Lecavelier Des Etangs et al. (1999, A&A, 343, 916). No periodic transits are seen in this time series. These observations confirm the spectroscopic detection of exocomets in calcium H and K lines that have been seen in high resolution spectroscopy.

Photometric detection with TESS



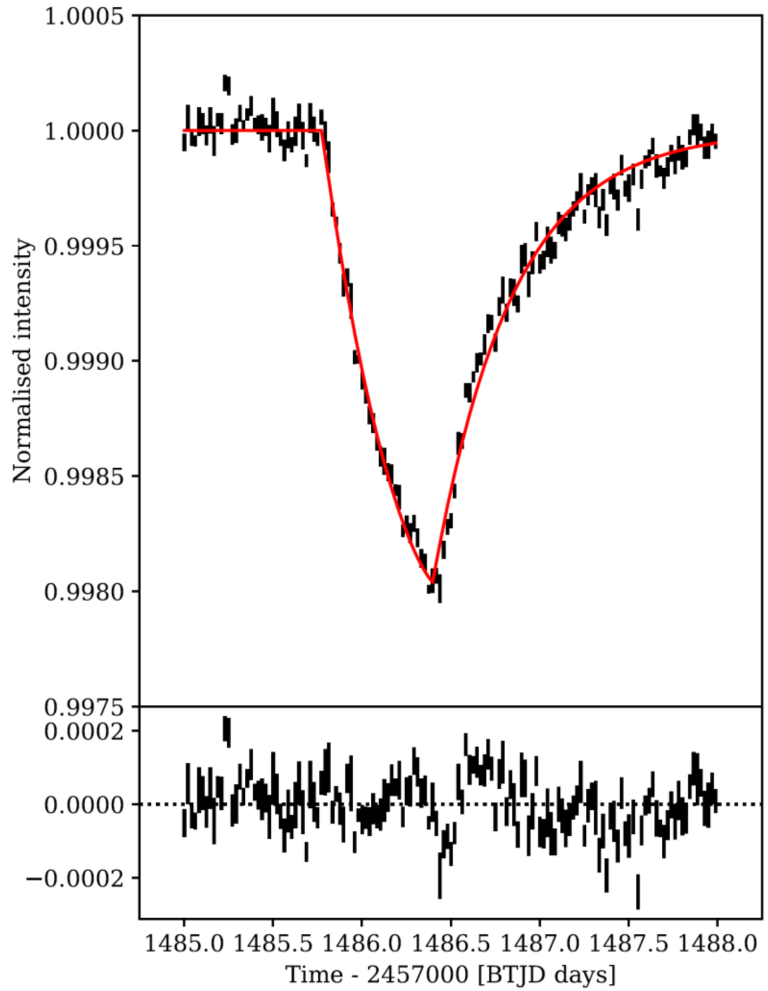
TESS Observation (2019)

Photometric detection with TESS



Simulation (1999)

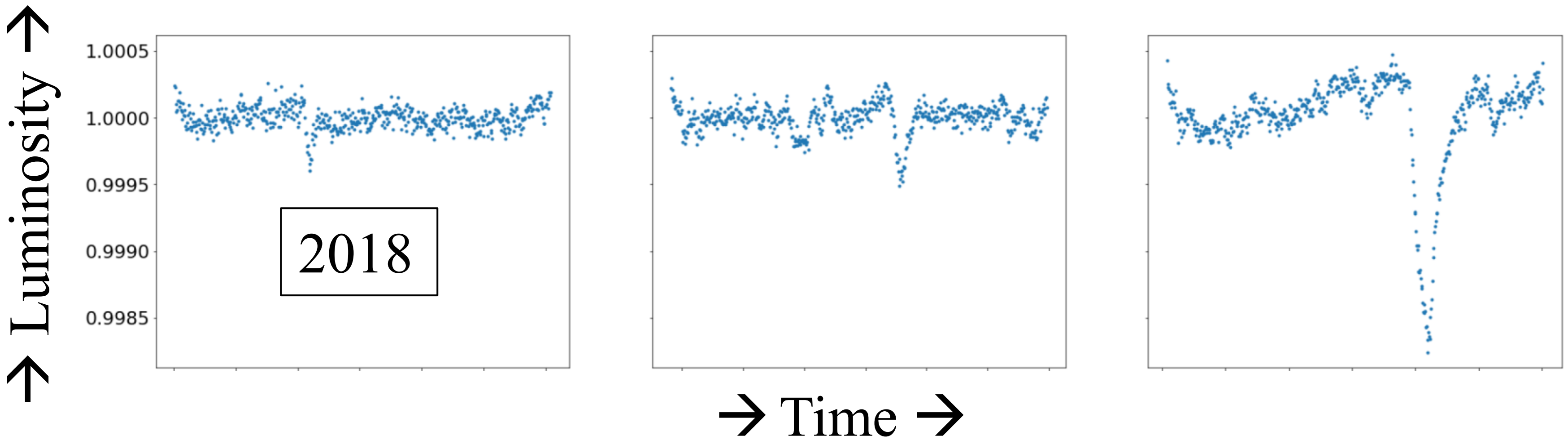
with $P = 2 \cdot 10^6$ kg/s and $q = 1$ ua



TESS Observation (2019)

New exocomets discovered with TESS observations

Lecavelier et al. (2022), see also Pavlenko et al. (2022)



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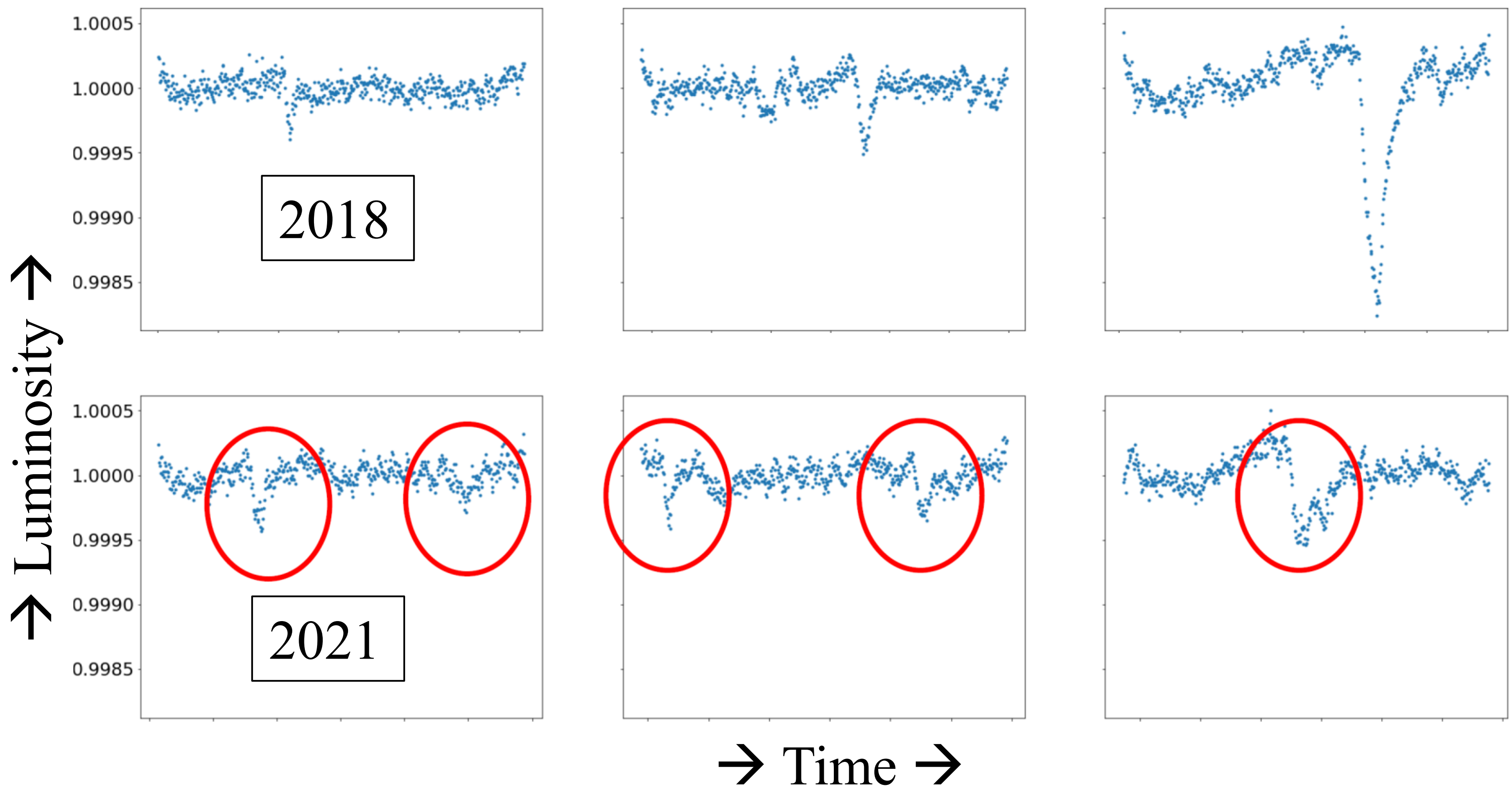

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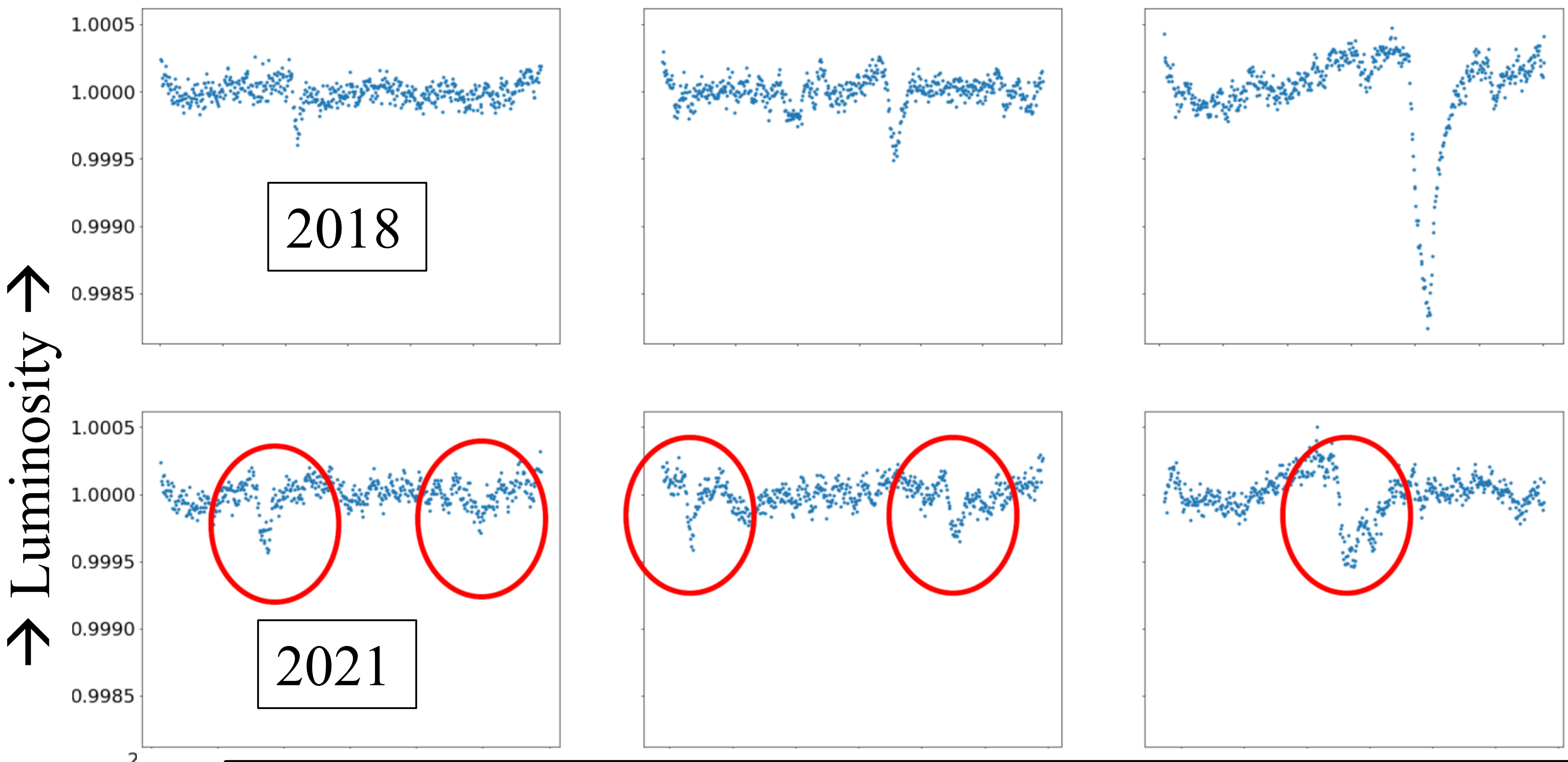
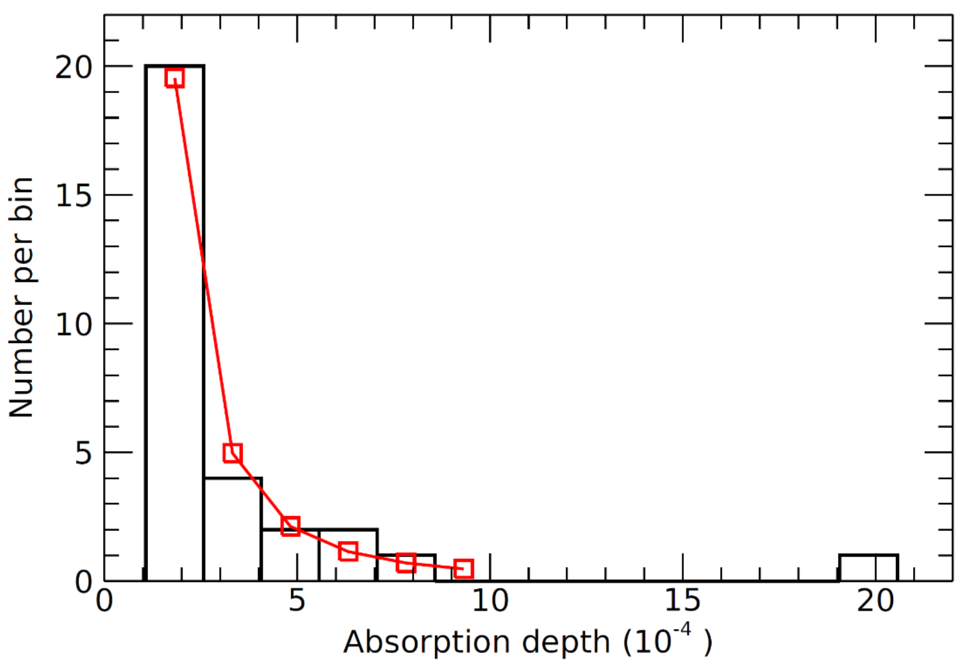


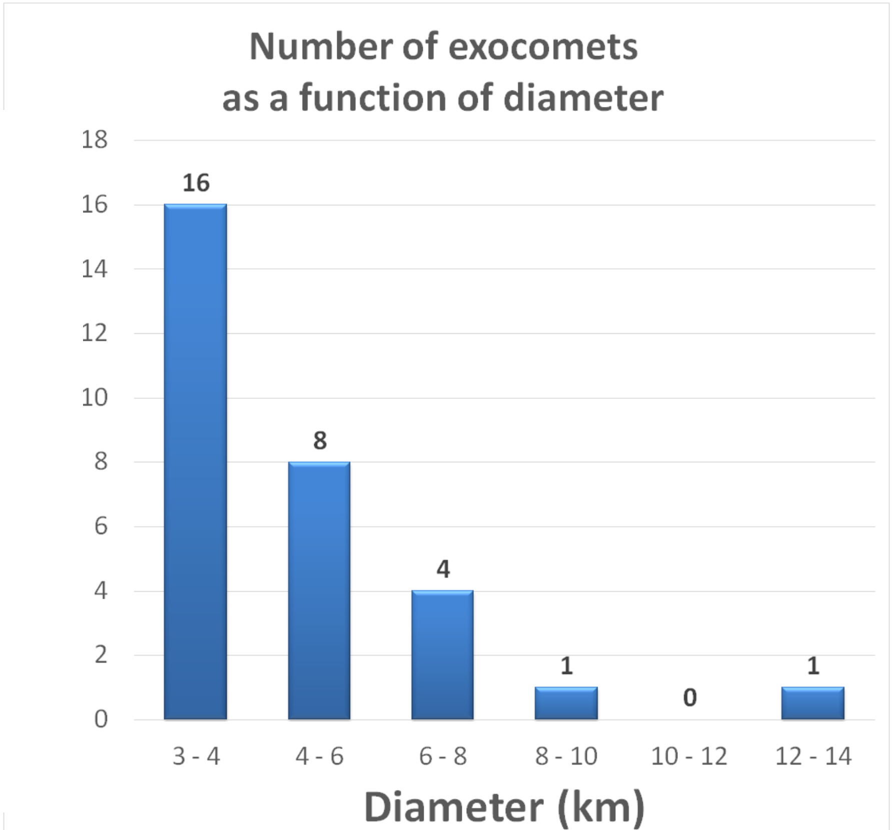
Detection de 30 exocomets in 156 days of observations

Exocomets size distribution in the β Pictoris planetary system

Lecavelier, Cros, Hébrard et al. (2022)

30 exocomets detected in 156 days of TESS observations





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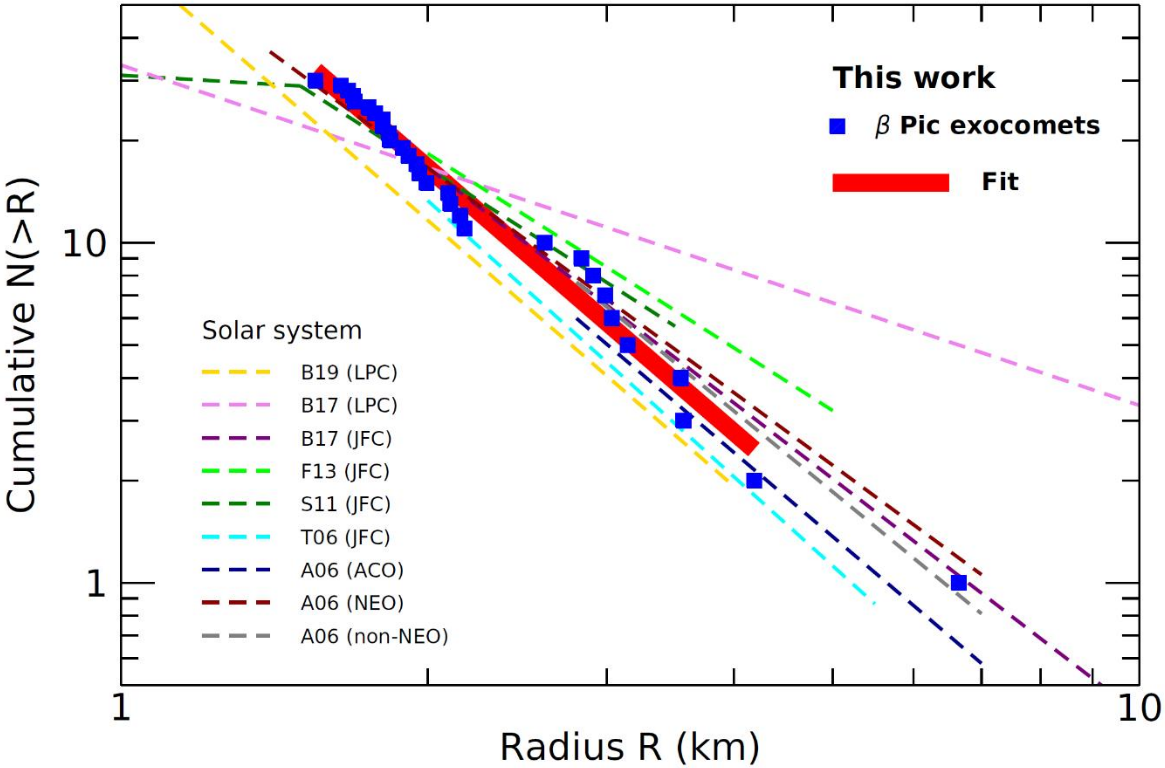
Exocomets size distribution in the β Pictoris planetary system

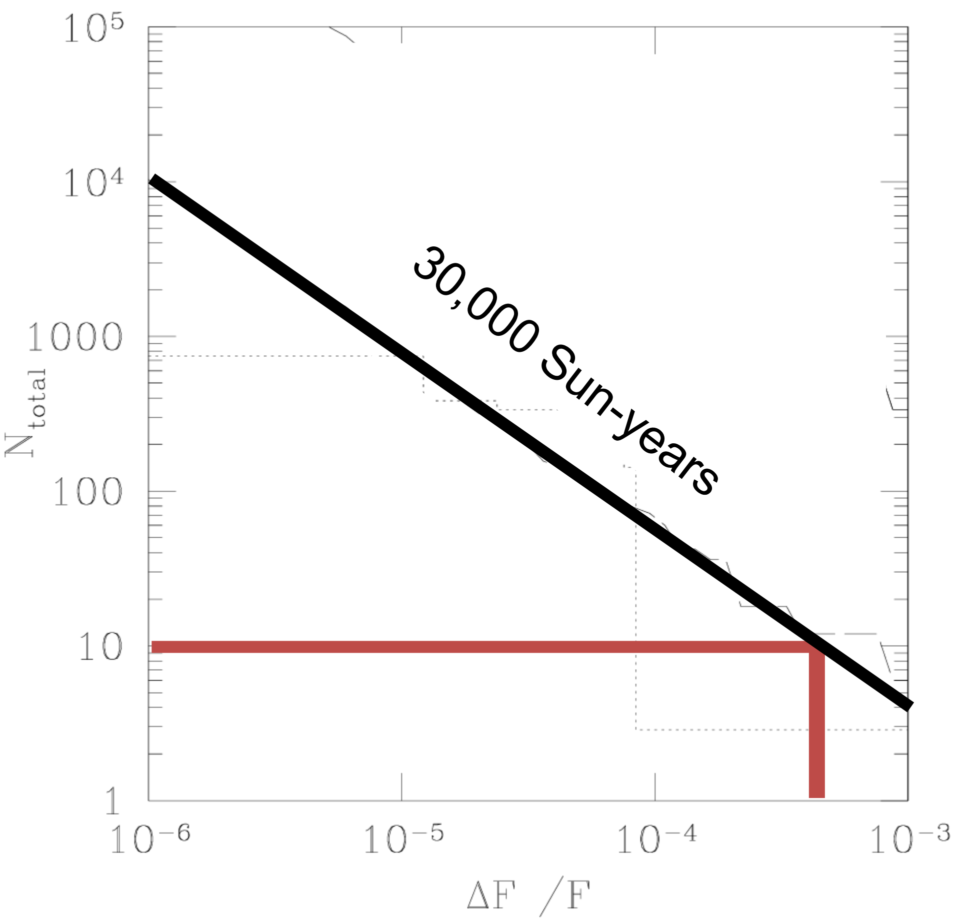
Alain Lecavelier des Etangs[1], Lucie Cros[1,2], Guillaume Hébrard[1,3], Eder Martioli[1,4], Marc Duquesnoy[5], Matthew A. Kenworthy[6], Flavien Kiefer[1,5], Sylvestre Lacour[5], Anne-Marie Lagrange[5], Nadège Meunier[7] & Alfred Vidal-Madjar[1]

- Size distribution : $dN(R) \propto R^{-3.6}$
- Same as in Solar System !
- Signature of collisional history



A new search for exocomet in Kepler data

Previous searches in Kepler data (Rappaport et al. 2018, Kenedy et al. 2019) yielded 3 exocometary systems



At a few 10^{-4} accuracy,
~10 detections for 30,000 star-years observation of solar type systems.

➔ Kepler (600,000 star-years) should yield ~200 exocomets transits.

(Lecavelier et al. 1999)

A new library of exocomets photometric transits

Lecavelier et al.

Astron. Astrophys. Suppl. Ser. **140**, 15–20 (1999)

A library of stellar light variations due to extra-solar comets

A. Lecavelier des Etangs[1]

NEW SIMULATIONS ::

- Higher accuracy
- Better sampling of *Production rates* and parameters space
- Kepler time cadence and Kepler photometric band

Size distribution	name	Stellar type name	Production $(\mathrm{kg\ s^{-1}})$	name	Periastron (AU)	name	ω (°)	name	ω (°)	name	Impact parameter (R_*)	name
$s_\mathrm{P} = 0.20\ \mu$m	20	M	10^2	20	0.3	03	−157.5	m7	157.5	p7	0	00
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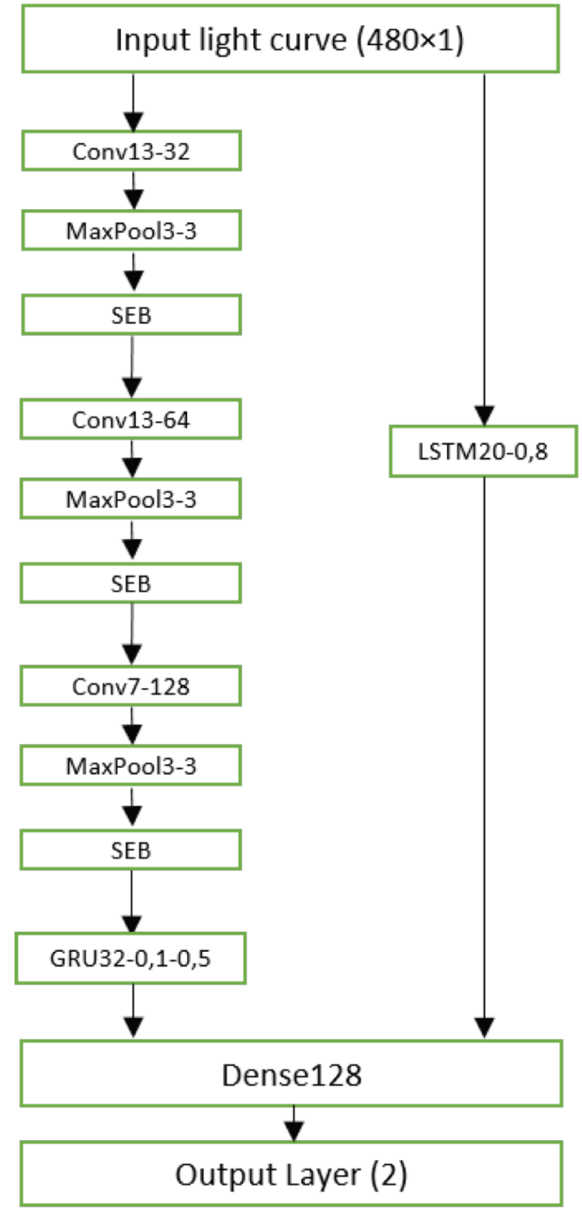
$s_\mathrm{P} = 0.50\ \mu$m	50						−22.5	m1	22.5	p1		
$s_0 = 0.1\ \mu$m, $n = 4.2$							0.0	00				

A new search for exocomet in Kepler data

- **Implementation of a neural network**

→ Input : 10-days Kepler light curve segment

→ Output : 1) probability of detection
2) time of the transit on the LC



A new search for exocomet in Kepler data

- Implementation of a neural network

- **Training using the theoretical light curves and Kepler light curves**
  (labeled light curves with and without theoretical transits)

  → supervised learning

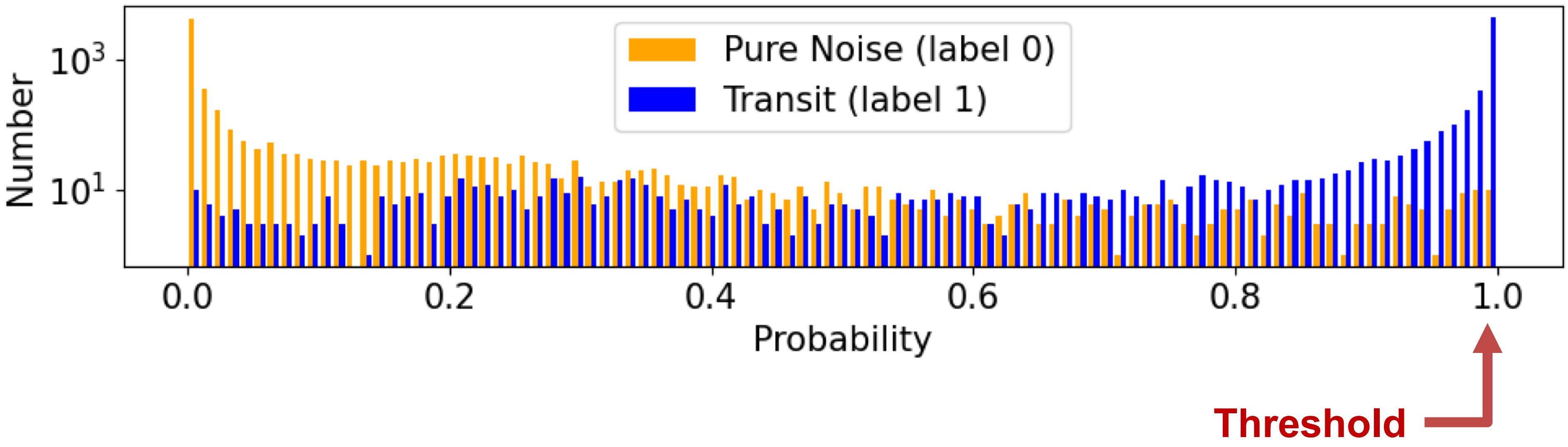
A new search for exocomet in Kepler data

- Implementation of a neural network
- Training using the theoretical light curves and Kepler light curves (labeled light curves with and without theoretical transits)
- **With a threshold of 0.99**

  the "precision" (true positive rate) is 99.8%, FPR ~ 1 – 2 ‰

  the "recall" (efficiency of finding real transits) is 79,1%

  ➔ loss of ~20%



A new search for exocomet in Kepler data

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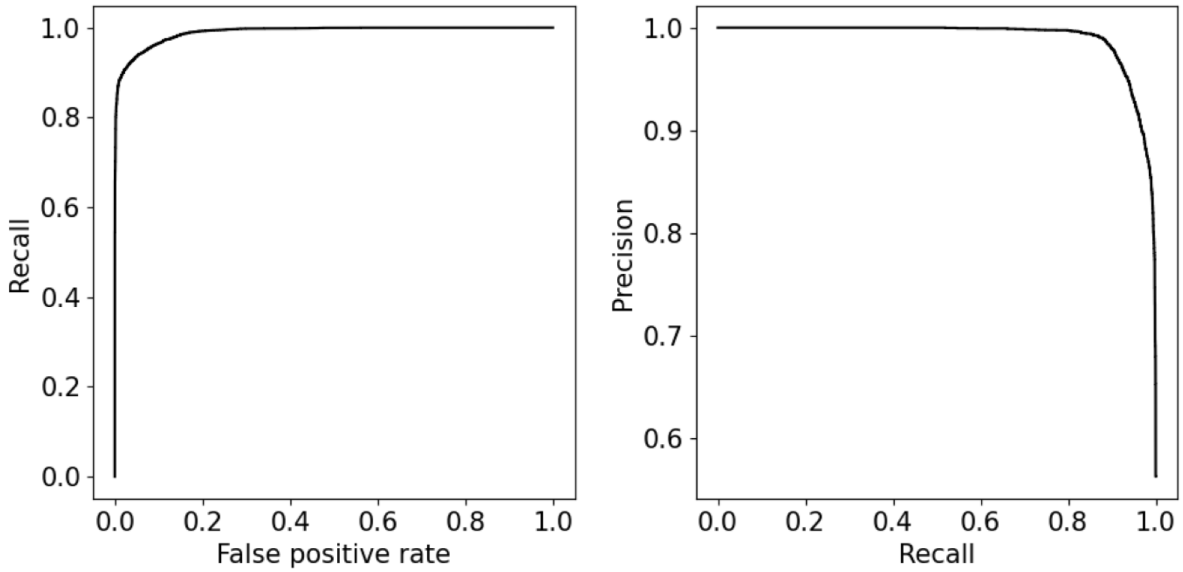


AUC = 0.986 to 0.994

A new search for exocomet in Kepler data

- Implementation of a neural network

- Training using the theoretical light curves and Kepler light curves (labeled light curves with and without theoretical transits)

- With a threshold of 0.99

  the "precision" (true positive rate) is 99.8%, FPR ~ 1 – 2 ‰

  the "recall" (efficiency of finding real transits) is 79,1%

  ➔ loss of ~20%

- About 10^6 "10-days" light curves per quarter (with ~10 real transits)

  ➔ **10^3 candidate detections per quarter**

  ➔ Need for further selection criteria :

  - Shape of the light curve fitted with exocomet model
  - Detection of extra noise using RMS, …

  ➔ ~ 50 – 100 candidates per quarter

  ➔ Final validation through visual inspection

A new search for exocomet in Kepler data

After visual inspection to eliminate obvious false positives,

→ 1st -Tier (best) catalog of 17 exocomets transits,
10 new detections

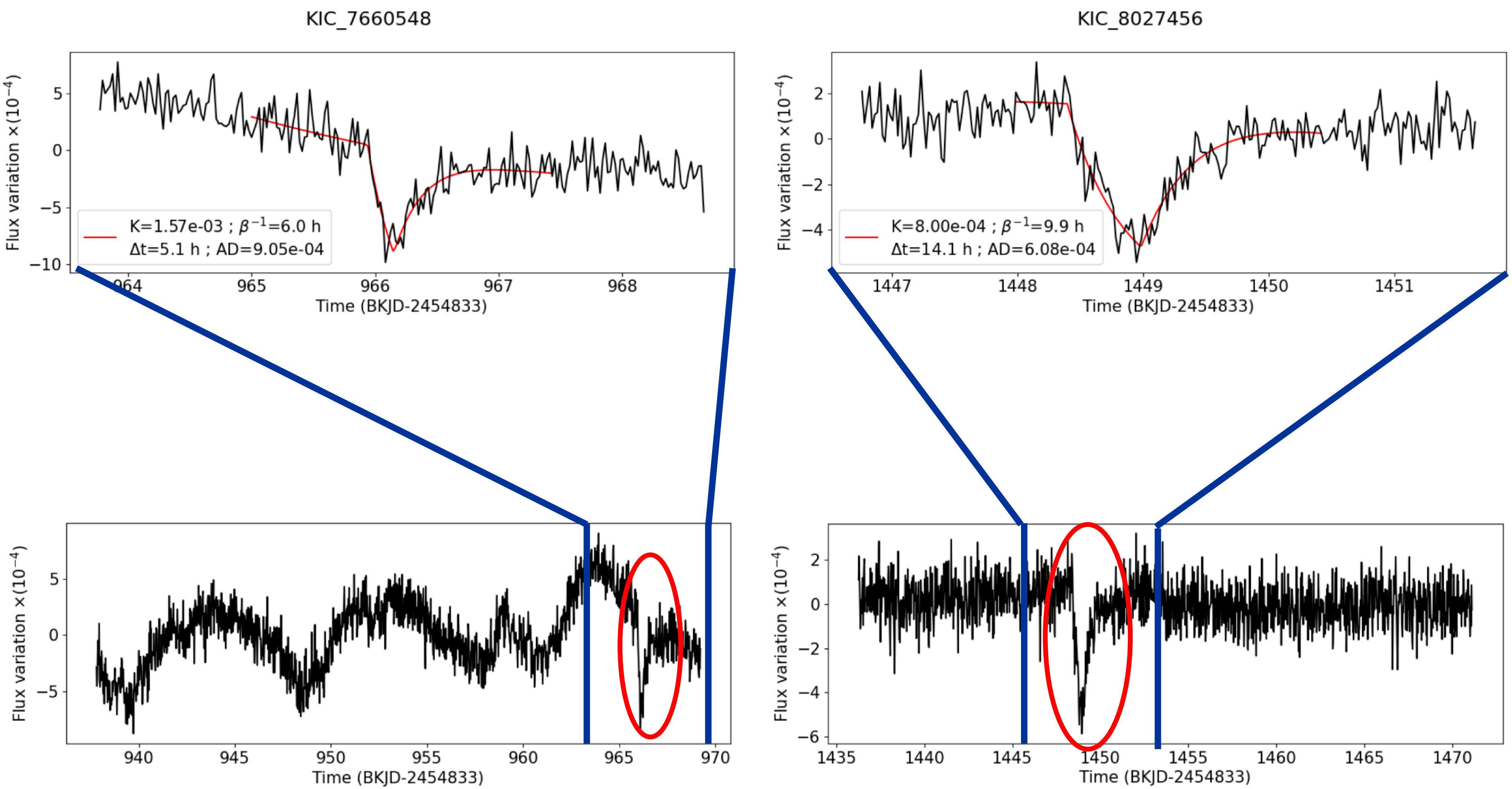
→ 2nd -Tier (good) catalog of 40 exocomets transits

→ 3rd -Tier catalog of 49 symmetric transits
that can be fitted by exocometary or exoplanetary single transit.

→ **To be compared to the ~200 exocomets transits in Kepler data**

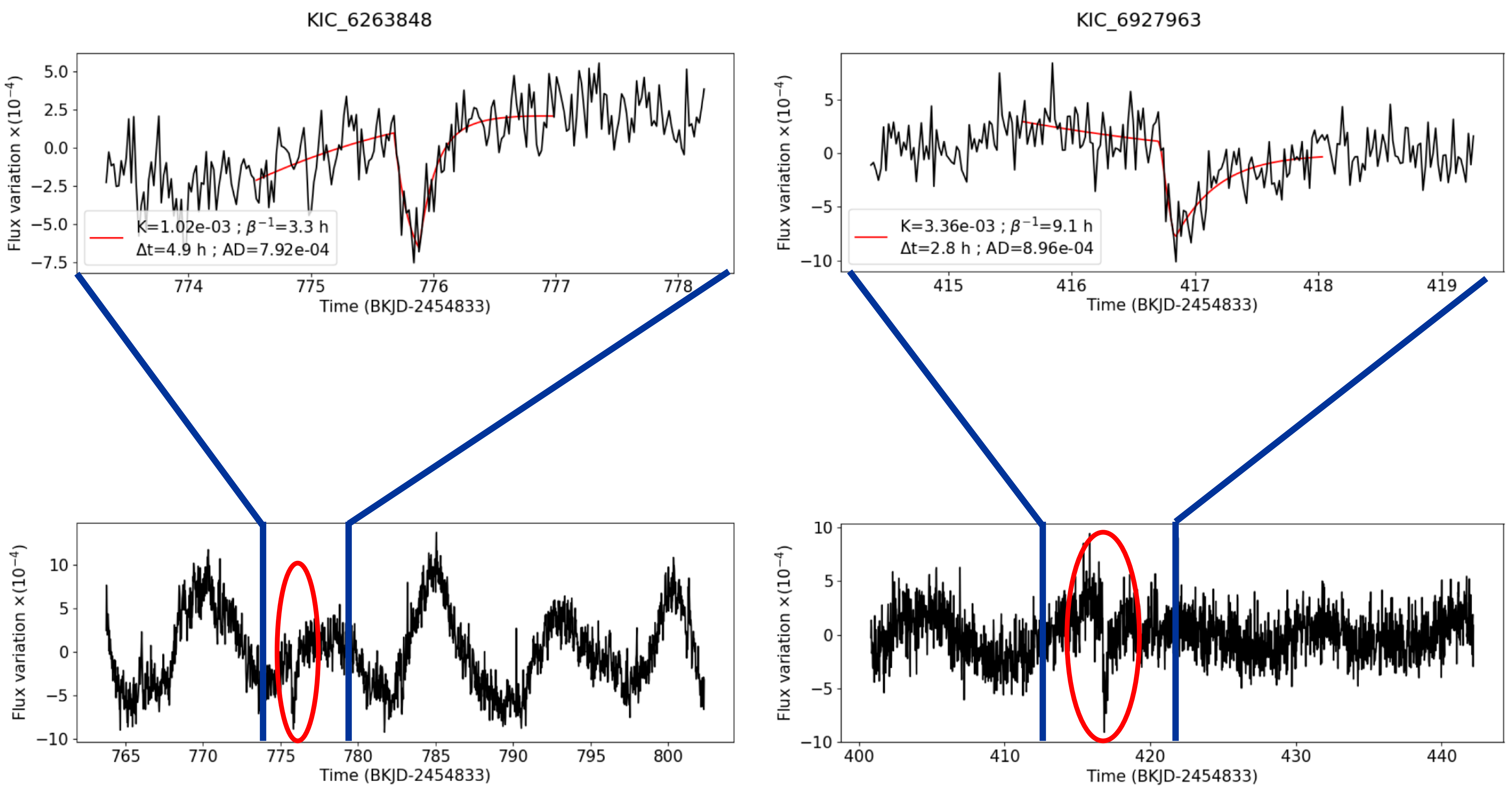
A new search for exocomet in Kepler data

➔ 1st -Tier (best) catalog of 17 exocomets transits, 10 new detections



A new search for exocomet in Kepler data

➔ 2nd -Tier (good) catalog of 40 exocomets transits



Application to PLATO data

PLATO will provide 245,000 stars over >4 years in the P5 sample

➔ 10^6 star-years at ~100 ppm

➔ 2000 – 3000 exocomets transits (if solar activity)

➔ **PLATO will be a game-changer in exocomets studies**


Thank you !

The end


Thank you !


Thank you !
Thierry Lombry