Probabilistic modeling and **Inference** in **Astronomy**

Dan Foreman-Mackey
Sagan Fellow, University of Washington
github.com/dfm // @exoplaneteer // dfm.io

Dan Foreman-Mackey

Sagan Fellow, University of Washington

github.com/dfm // @exoplaneteer // dfm.io

I study astronomy.

Photo credit **NASA Ames/SETI Institute/JPL-Caltech**

this isn't what
my data look like

I study astronomy.

Photo credit **NASA Ames/SETI Institute/JPL-Caltech**

Why Astronomy?

simple but interesting physical models

precise open-access data

observational only

Why Astronomy?

simple but interesting physical models

precise open-access data

observational only

no chance of financial gain ever

ex·o·plan·et

ˈ*eksōˌplanət/*

noun. a planet that orbits a star outside the solar system.

Credit **Google**

*How do we **find & study** exoplanets?*

1281 transit

616 radial velocity

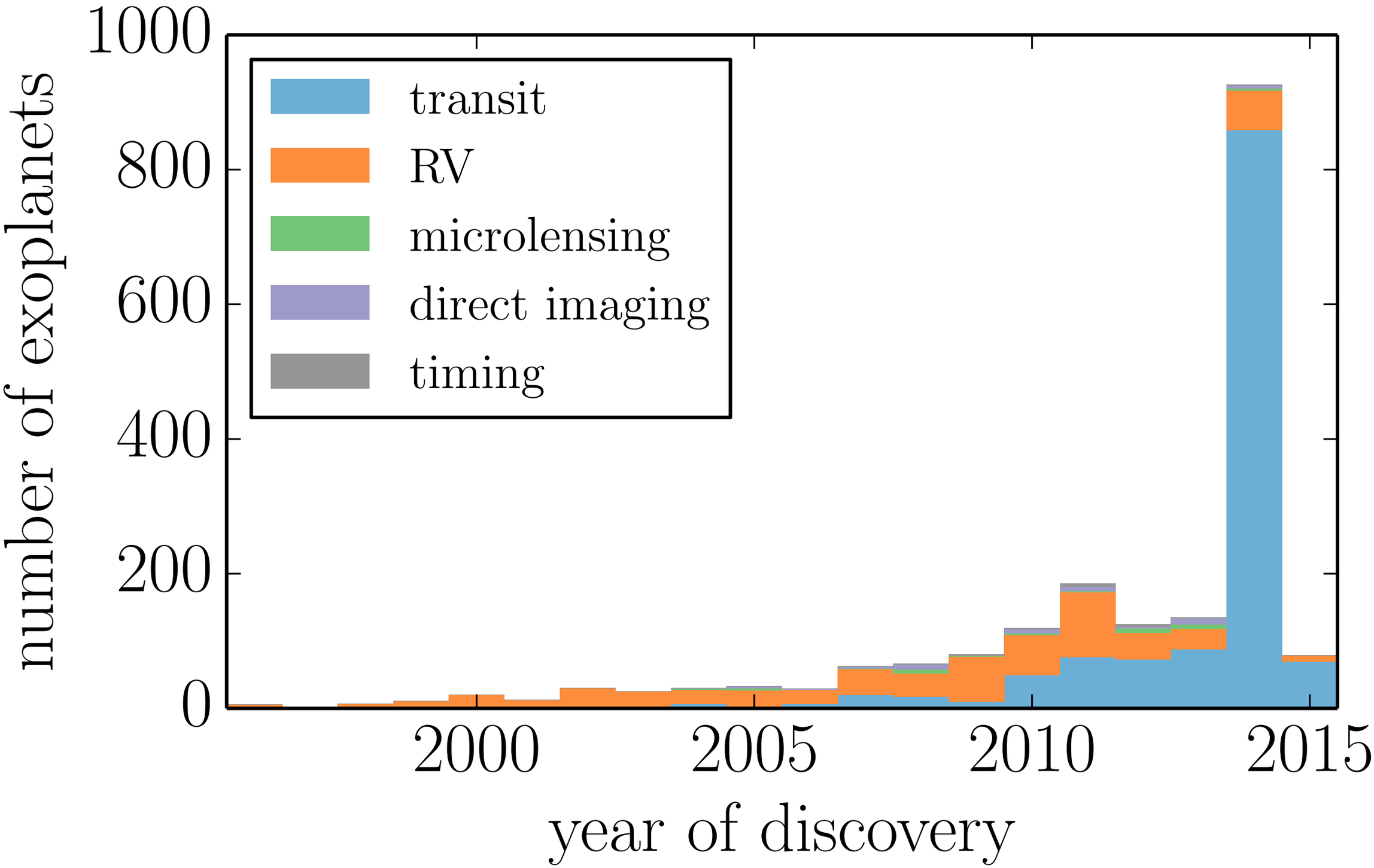
45 direct imaging

32 microlensing

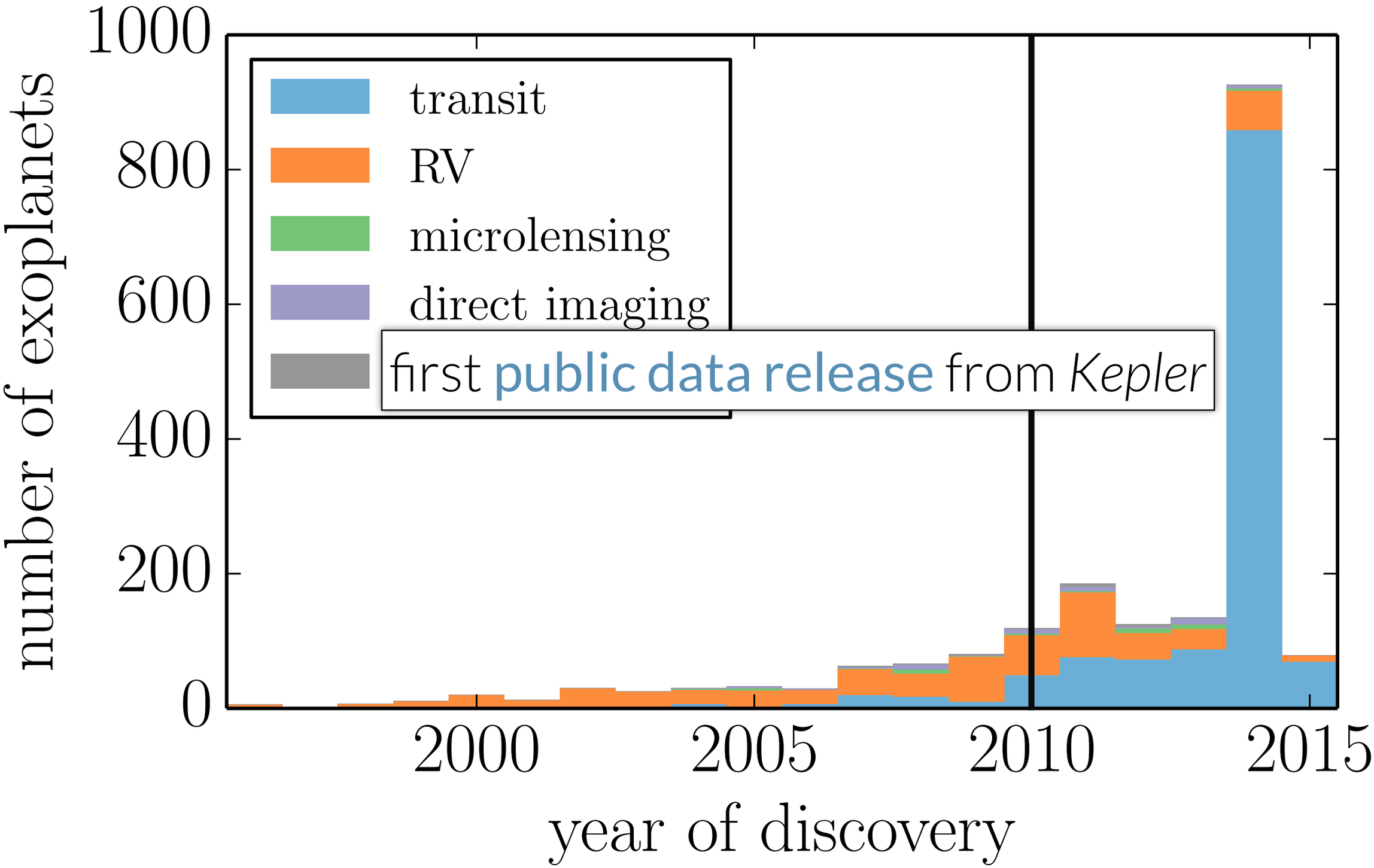
20 timing

0 astrometry

Data from **Open Exoplanet Catalogue**

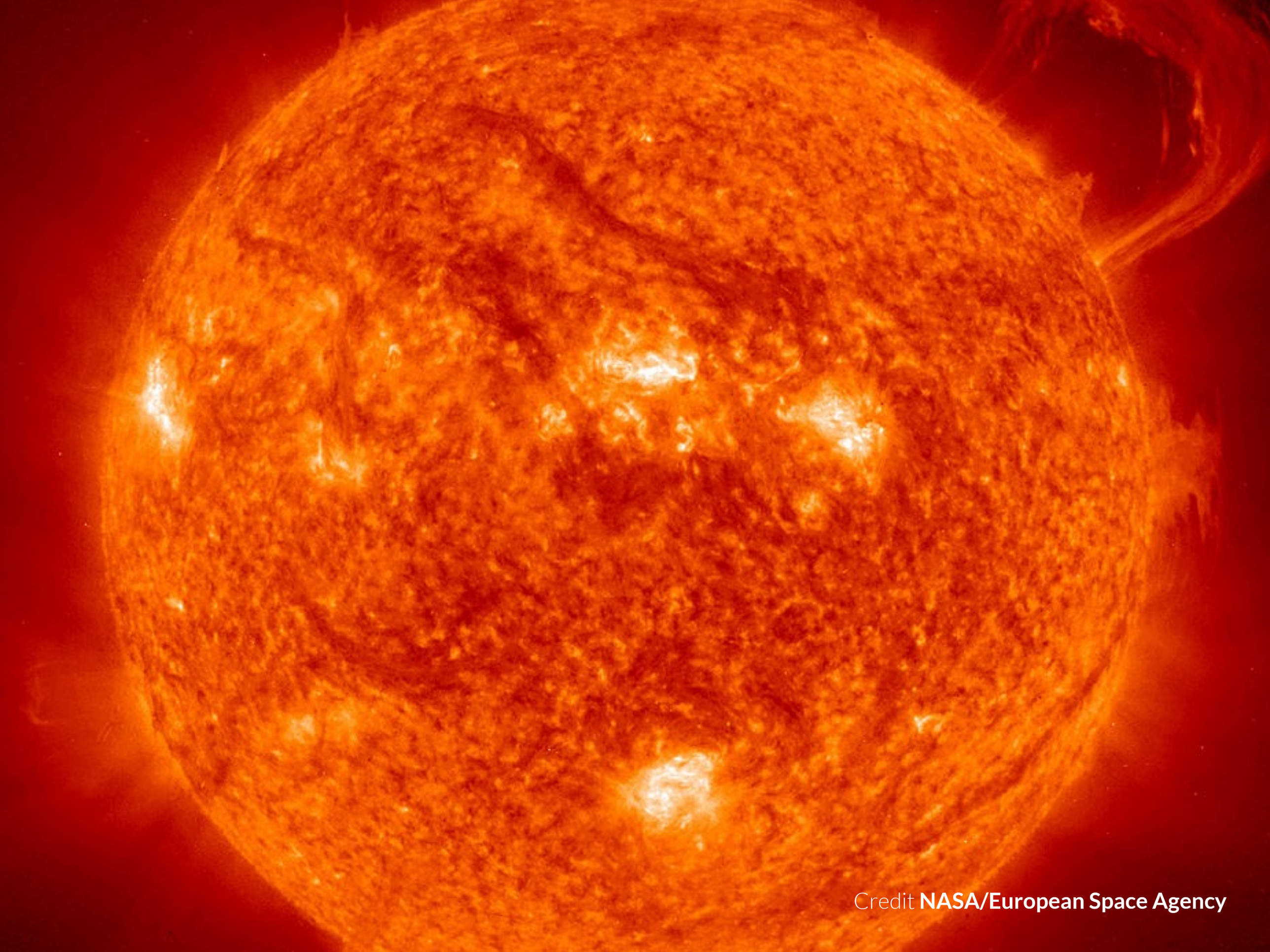


Data from **Open Exoplanet Catalogue**

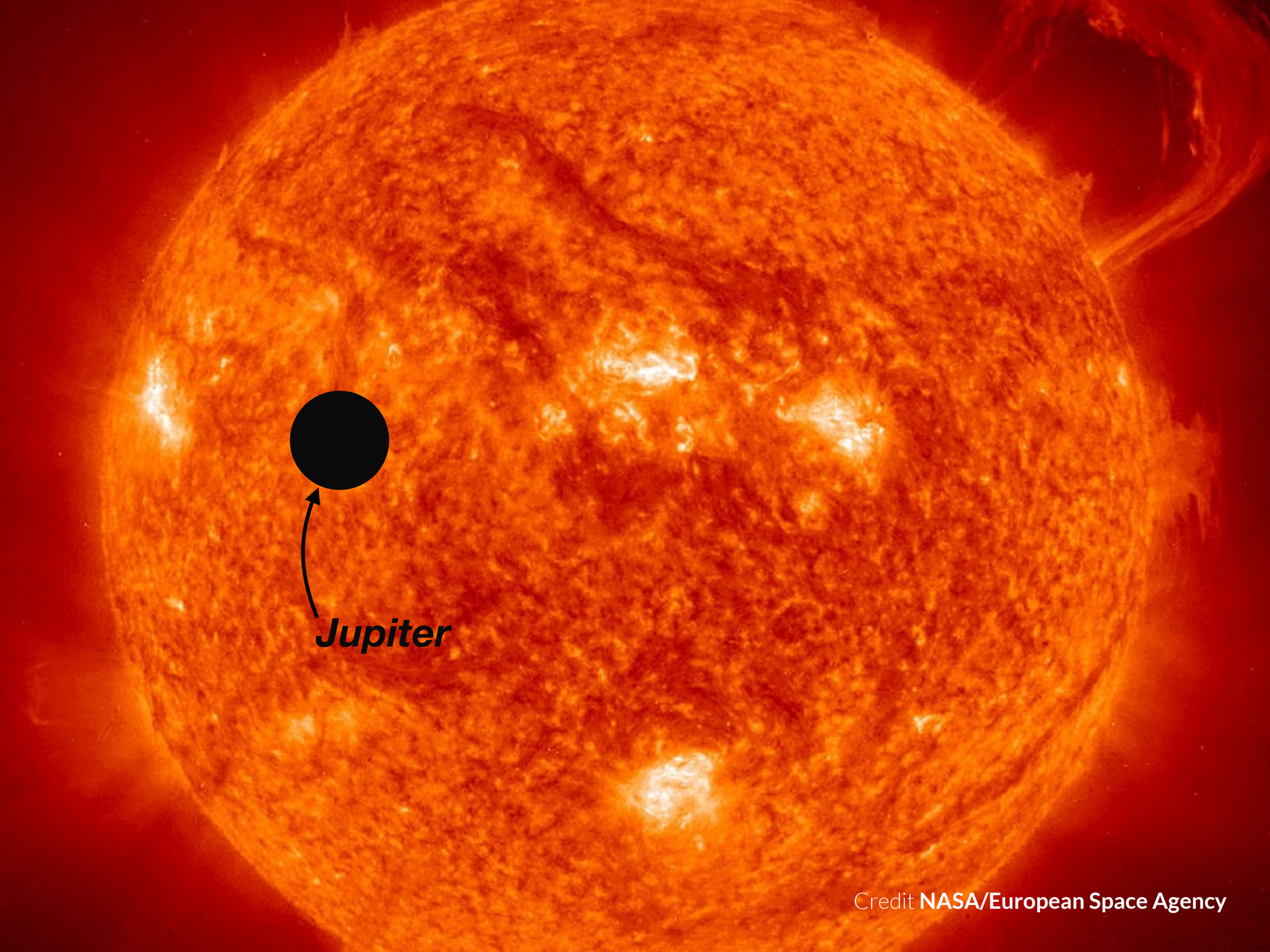


Data from **Open Exoplanet Catalogue**

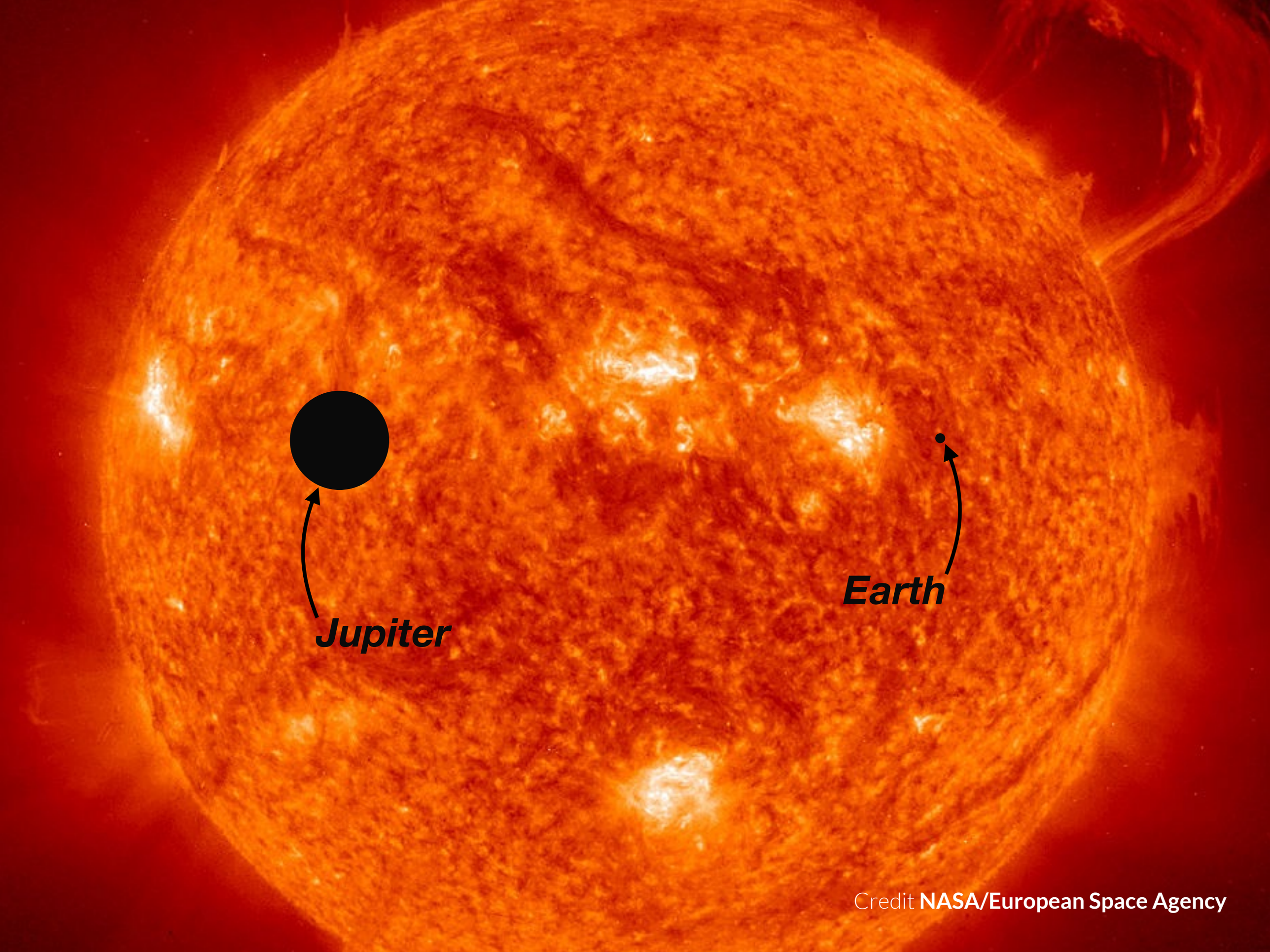
*the **transit** method*



Credit **NASA/European Space Agency**

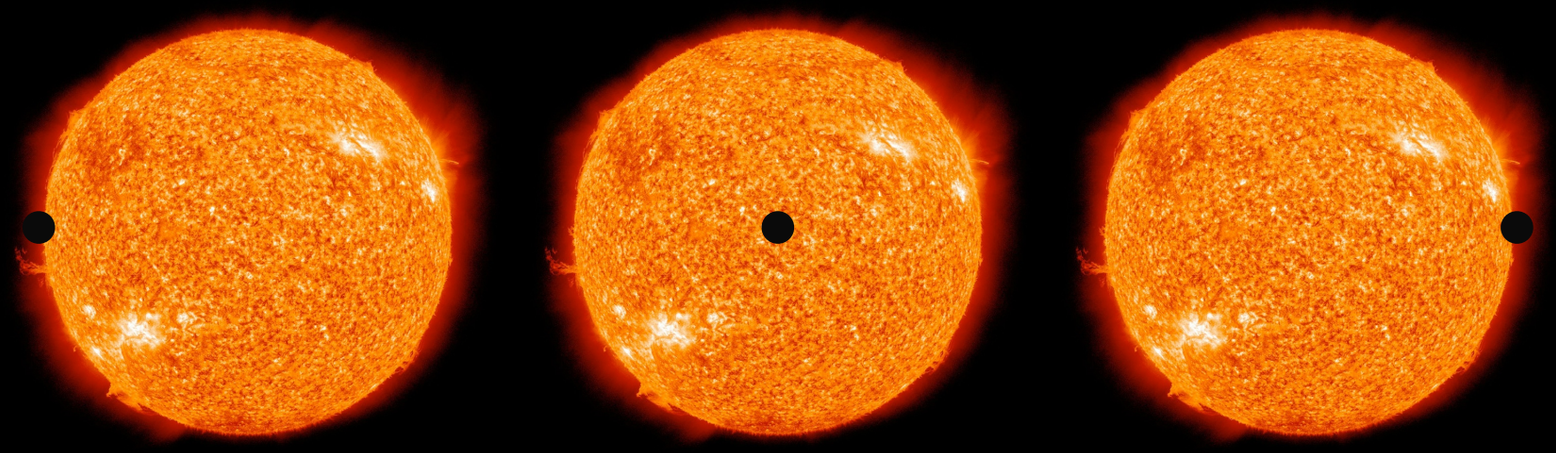


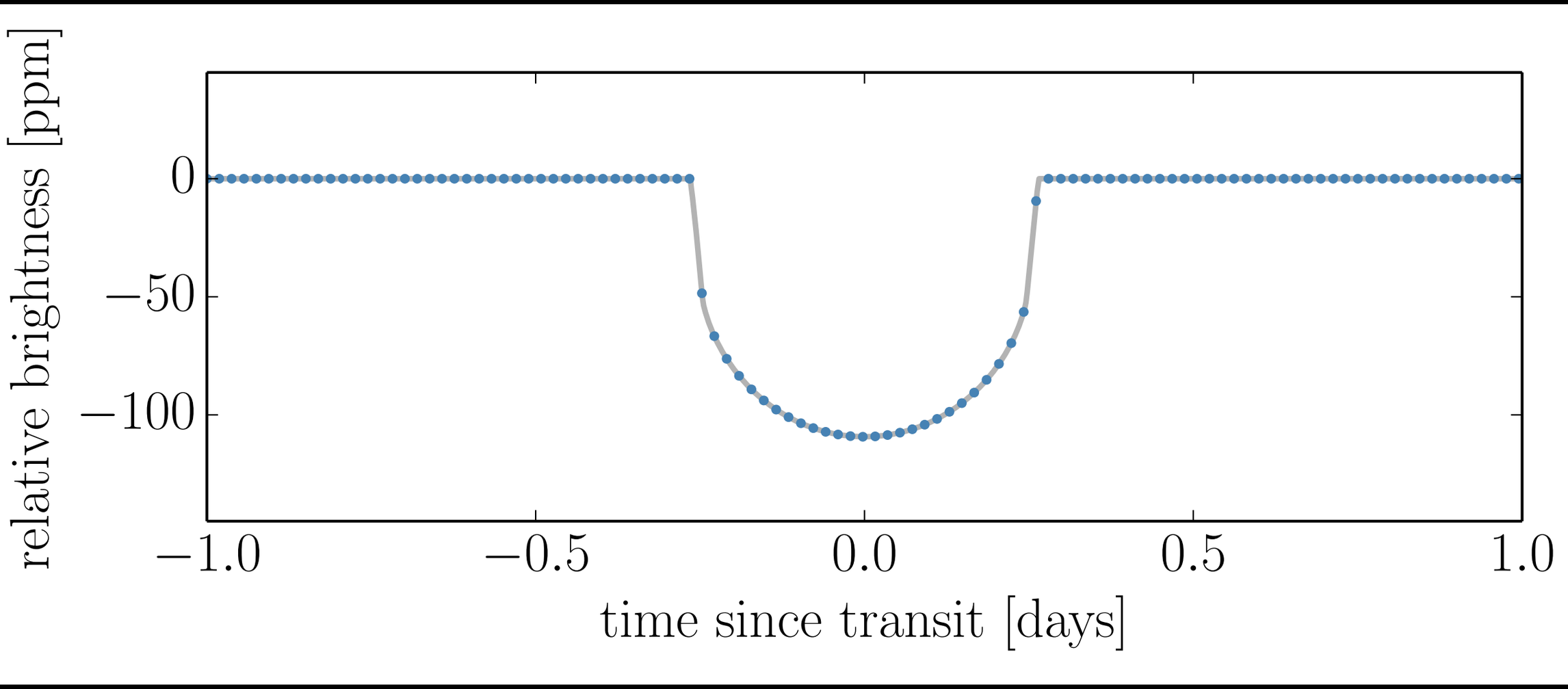
Credit **NASA/European Space Agency**



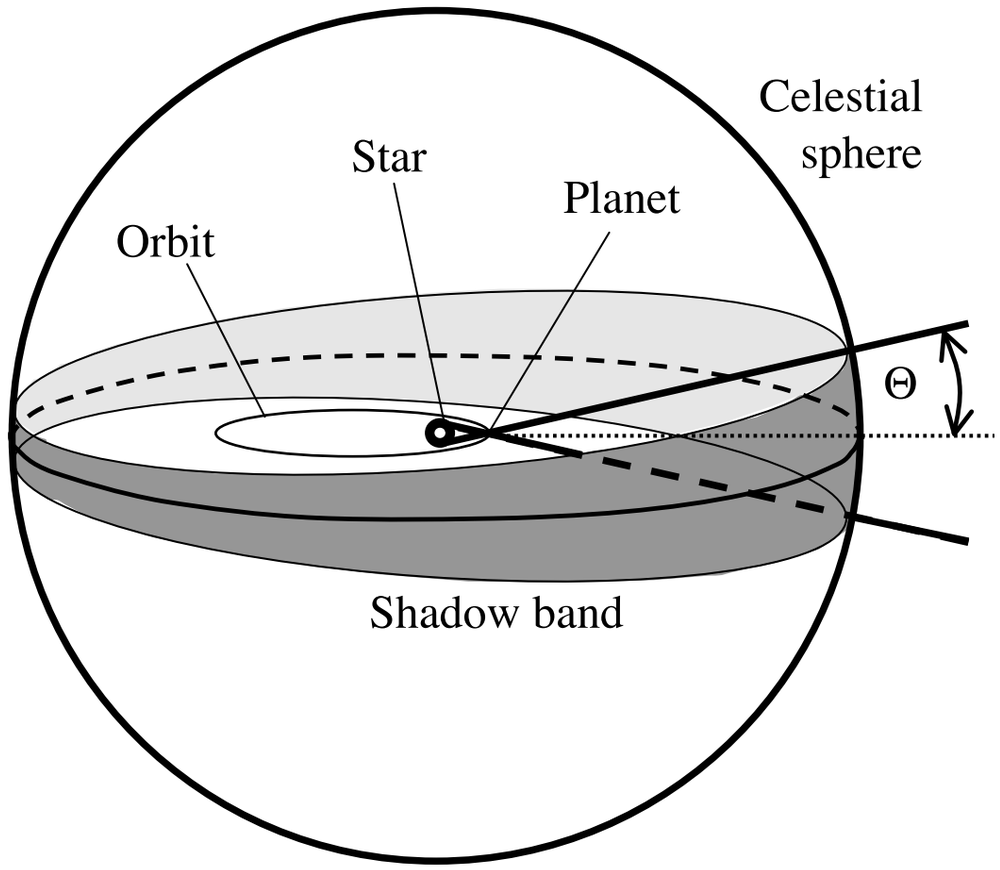
Credit **NASA/European Space Agency**

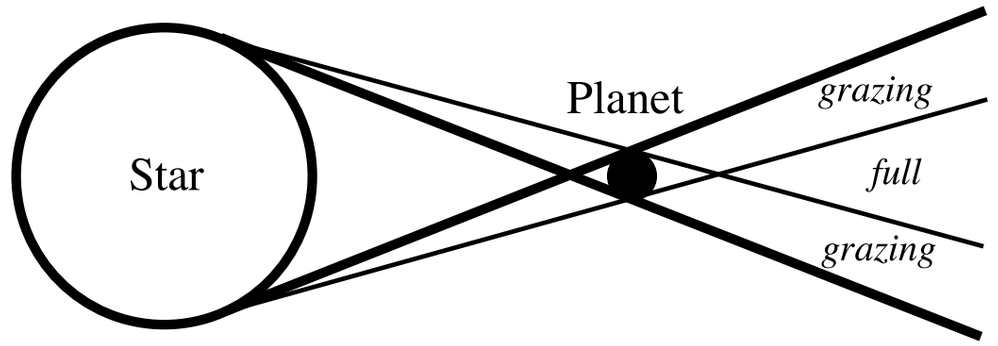
that's not what most stars look like!




relative brightness [ppm]
0
−50
−100
−1.0
−0.5
0.0
0.5
1.0
time since transit [days]

everything is against us!





Close-up

Credit **Winn (2010)**
arXiv:1001.2010

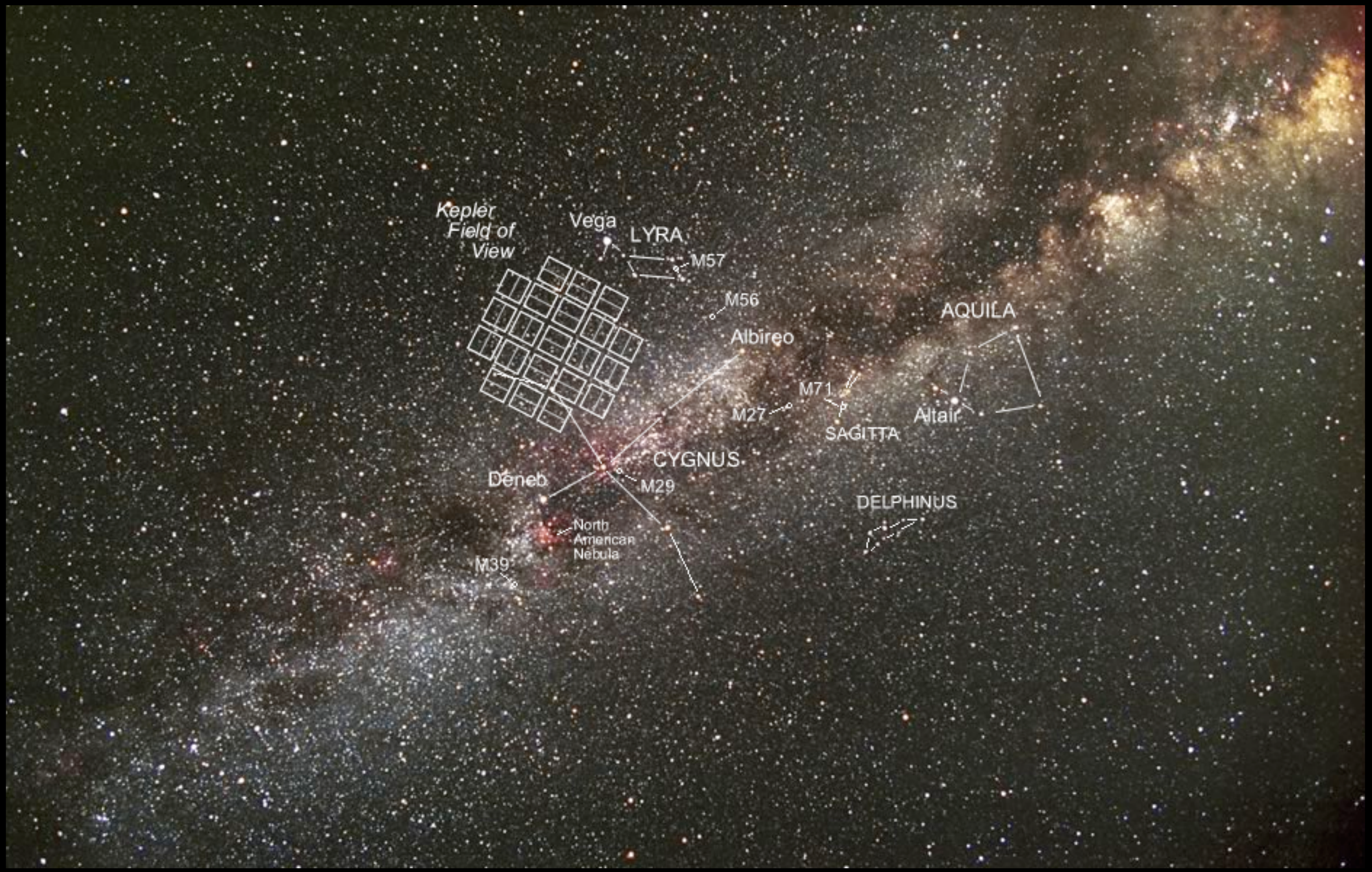
need to look at **the right place**
at **the right time**

and measure
extremely precise
photometry

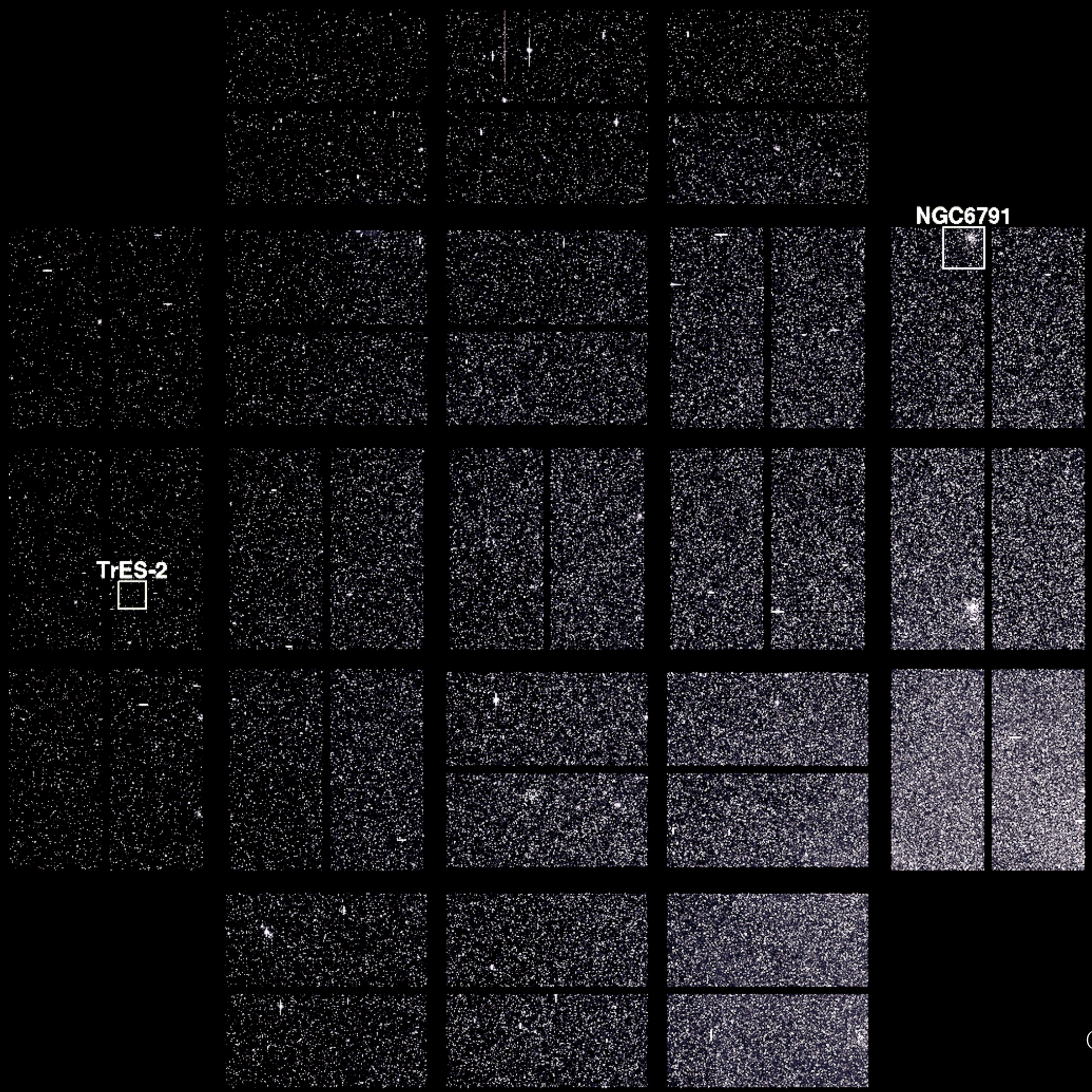
Kepler

Credit **NASA**

Credit **NASA**



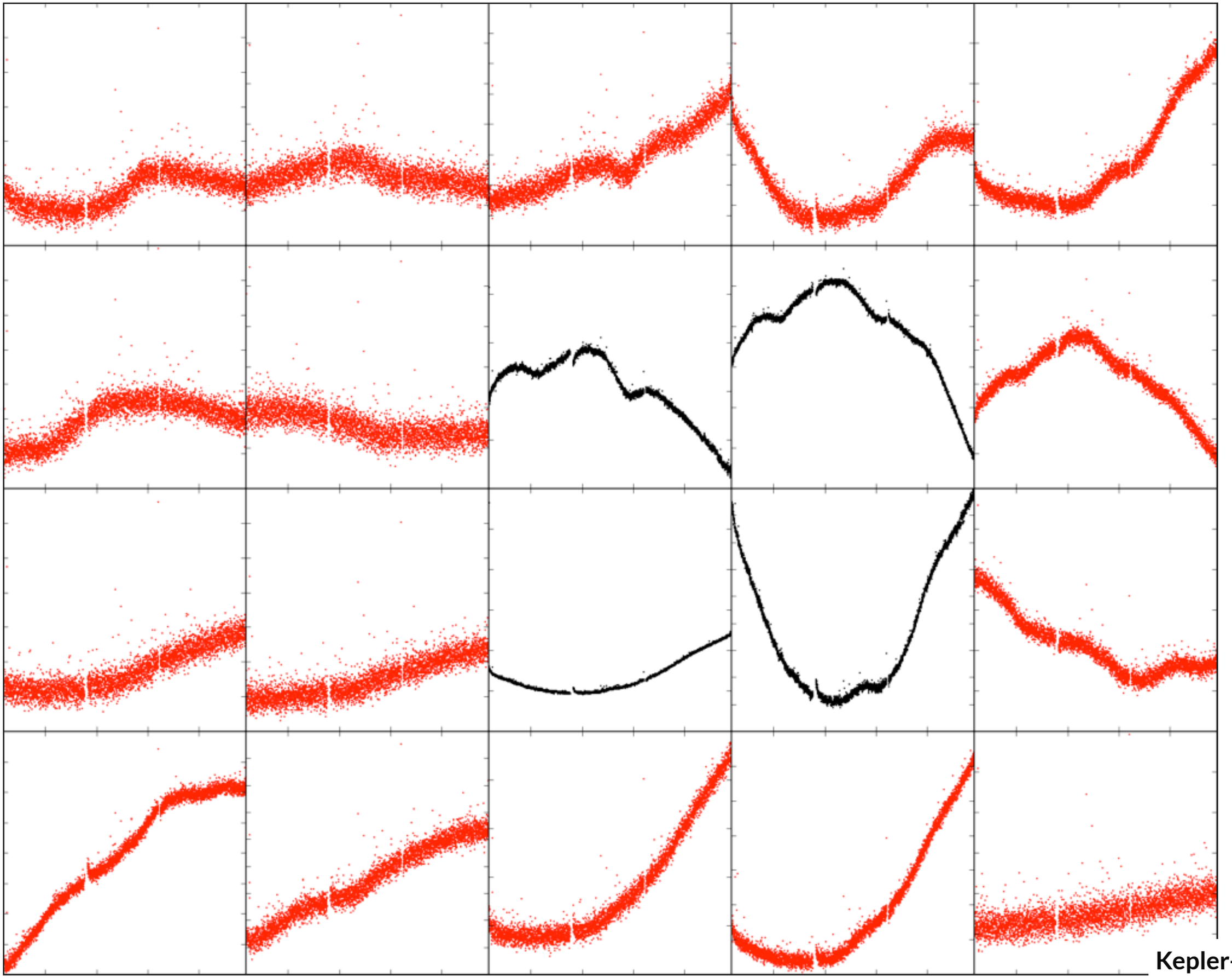
Credit **Carter Roberts**



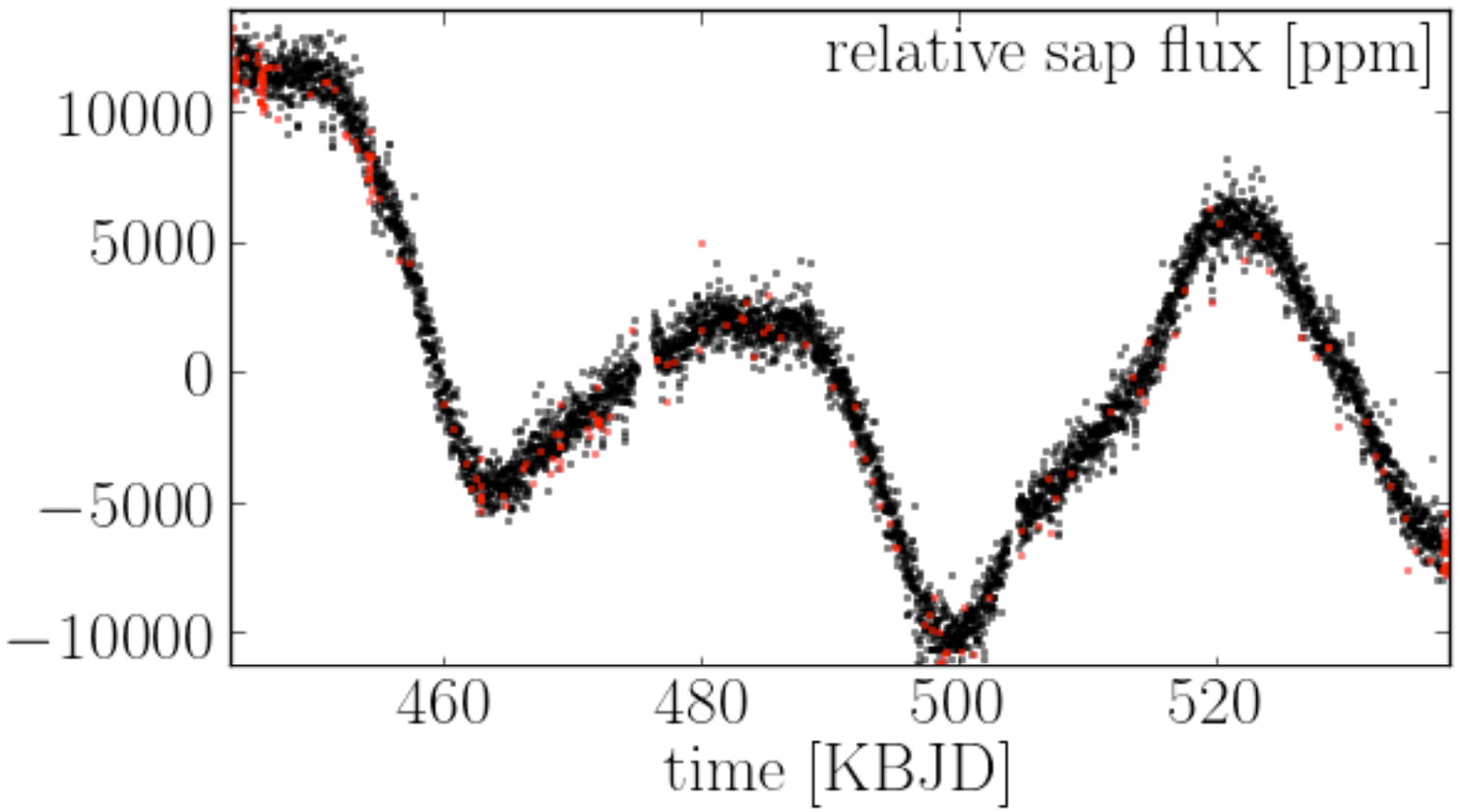
Credit **NASA**

Kepler-32

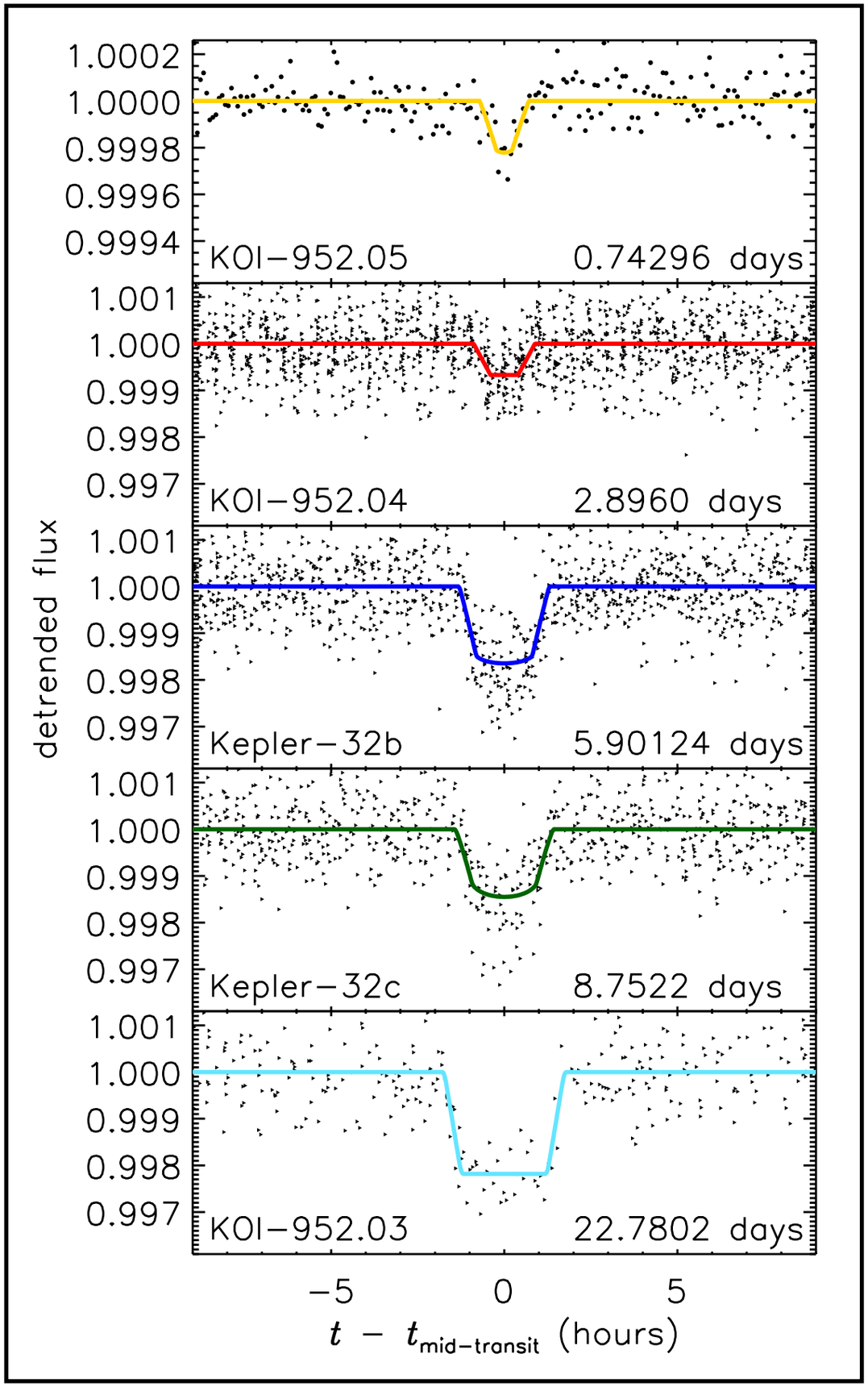
Kepler-32



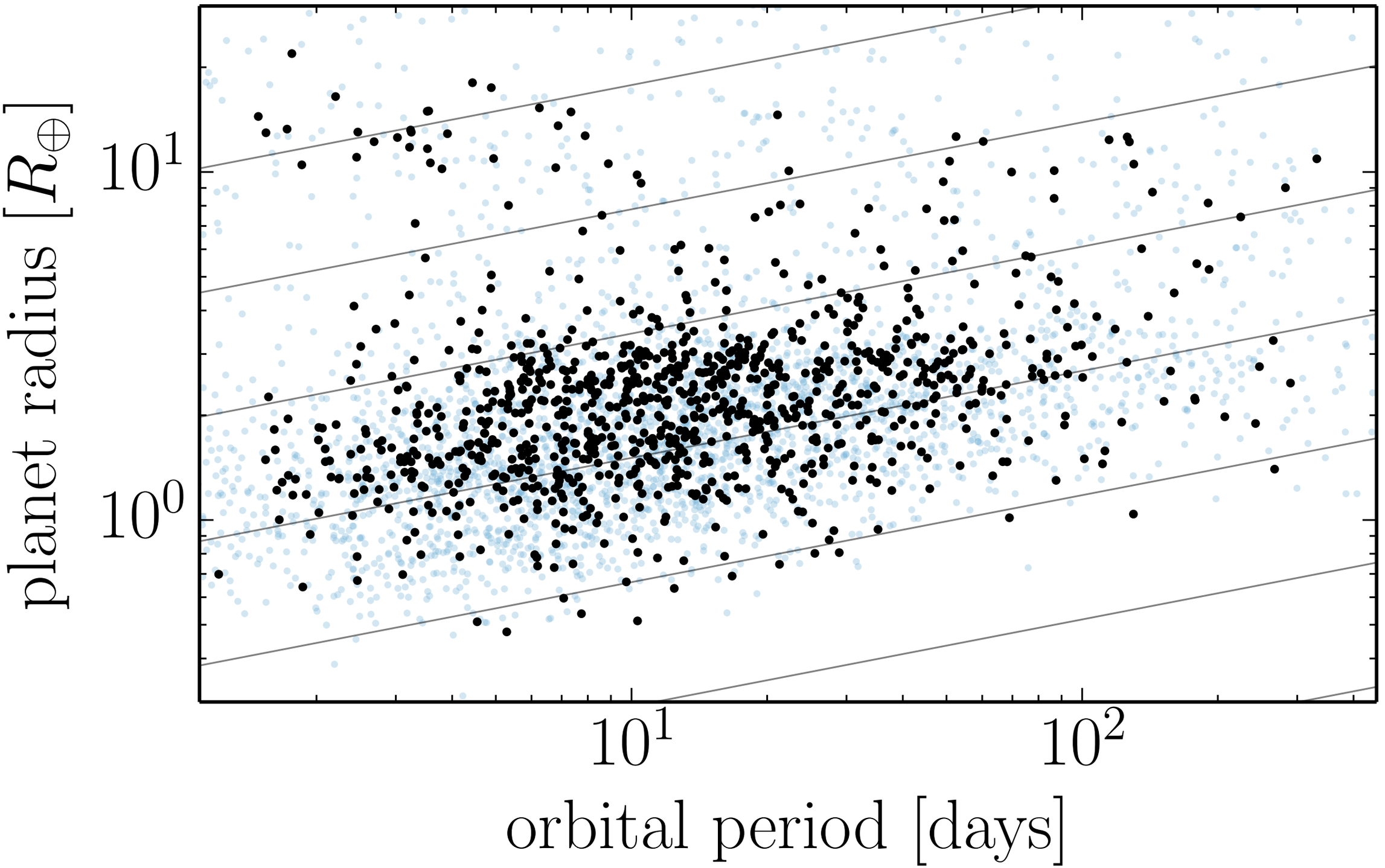
Kepler-32


relative sap flux [ppm]
10000
5000
0
−5000
−10000
460
480
500
520
time [KBJD]

Kepler-32

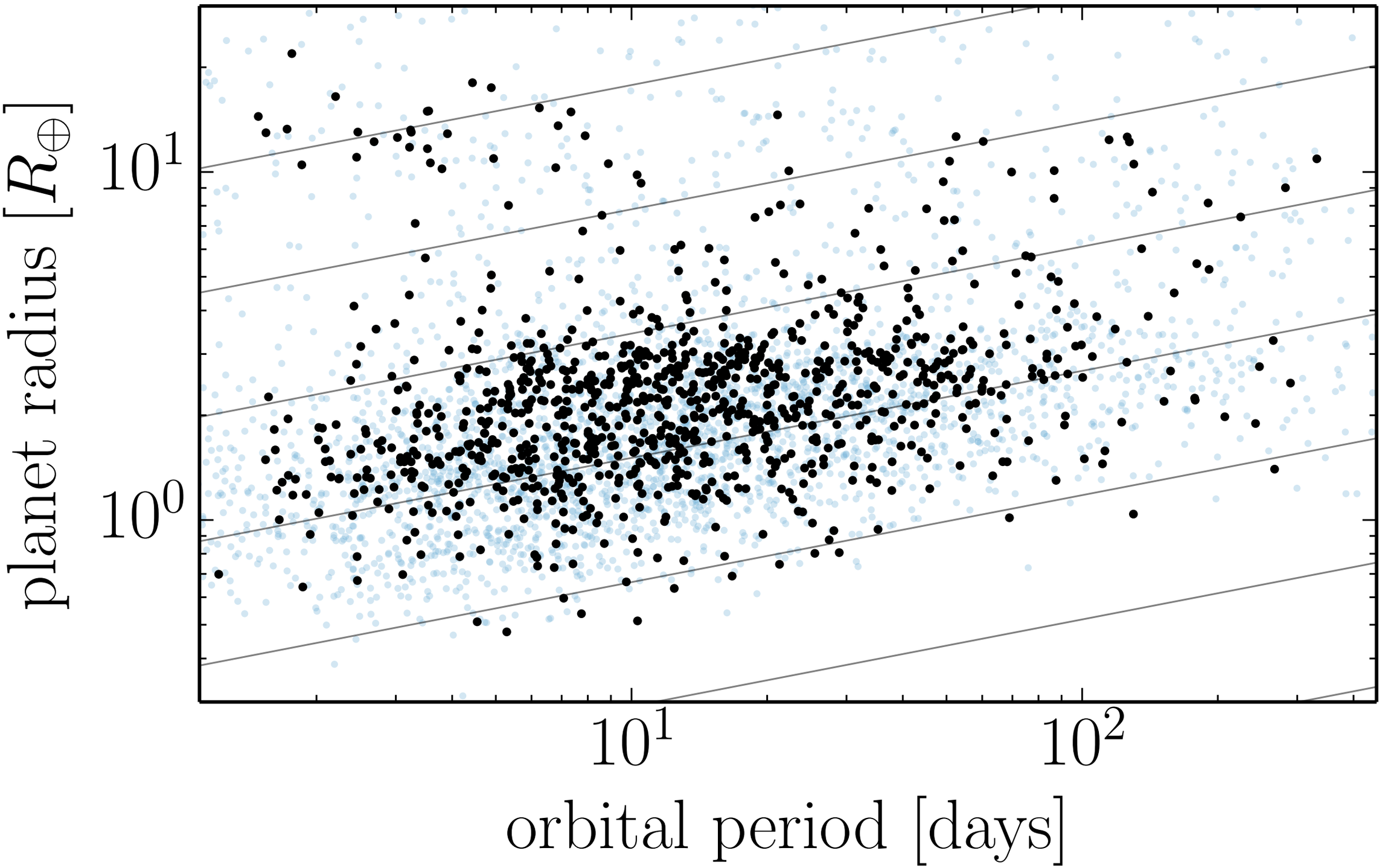


Credit **Fabrycky *et al.* (2012)**

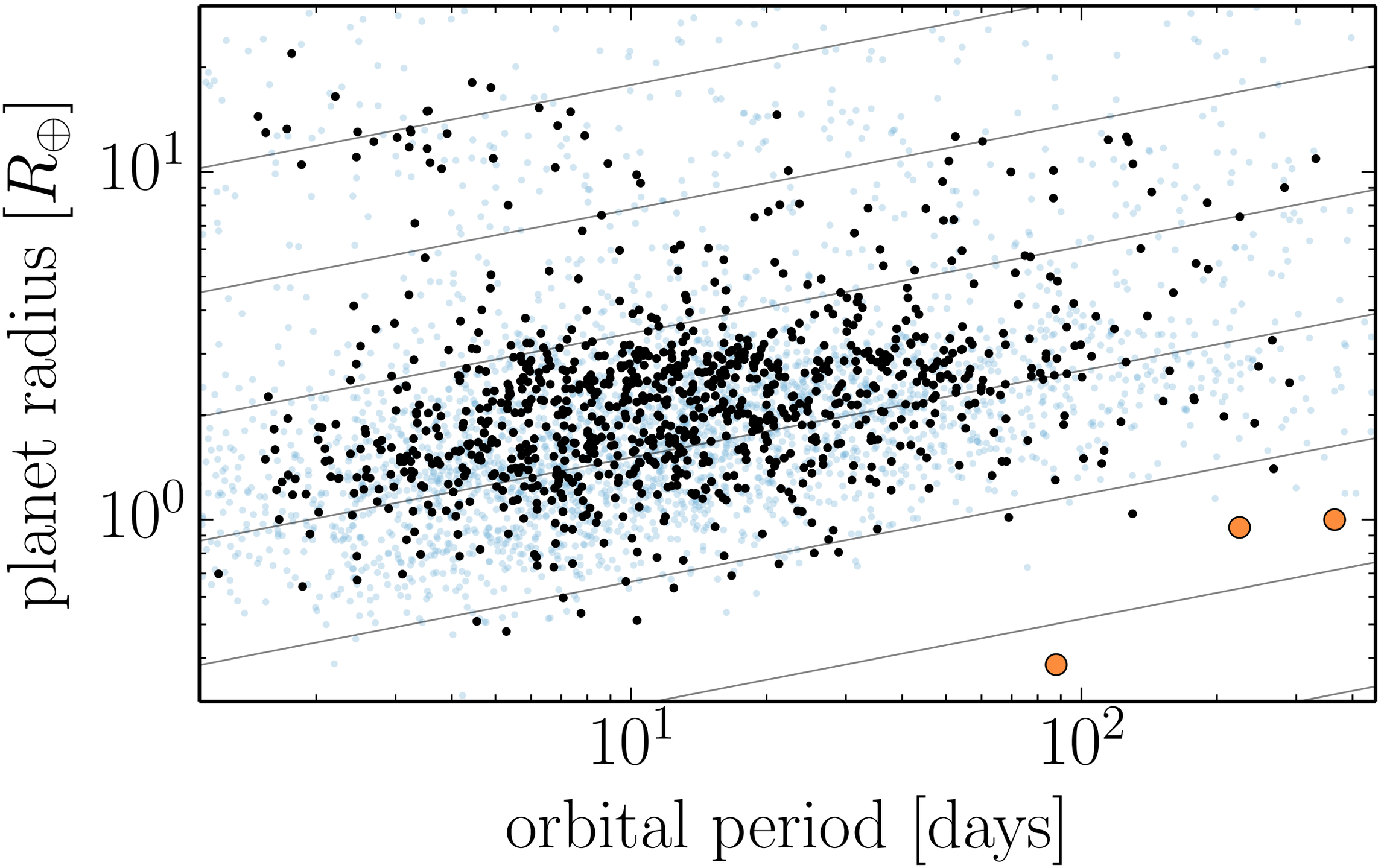


Data from **NASA Exoplanet Archive**

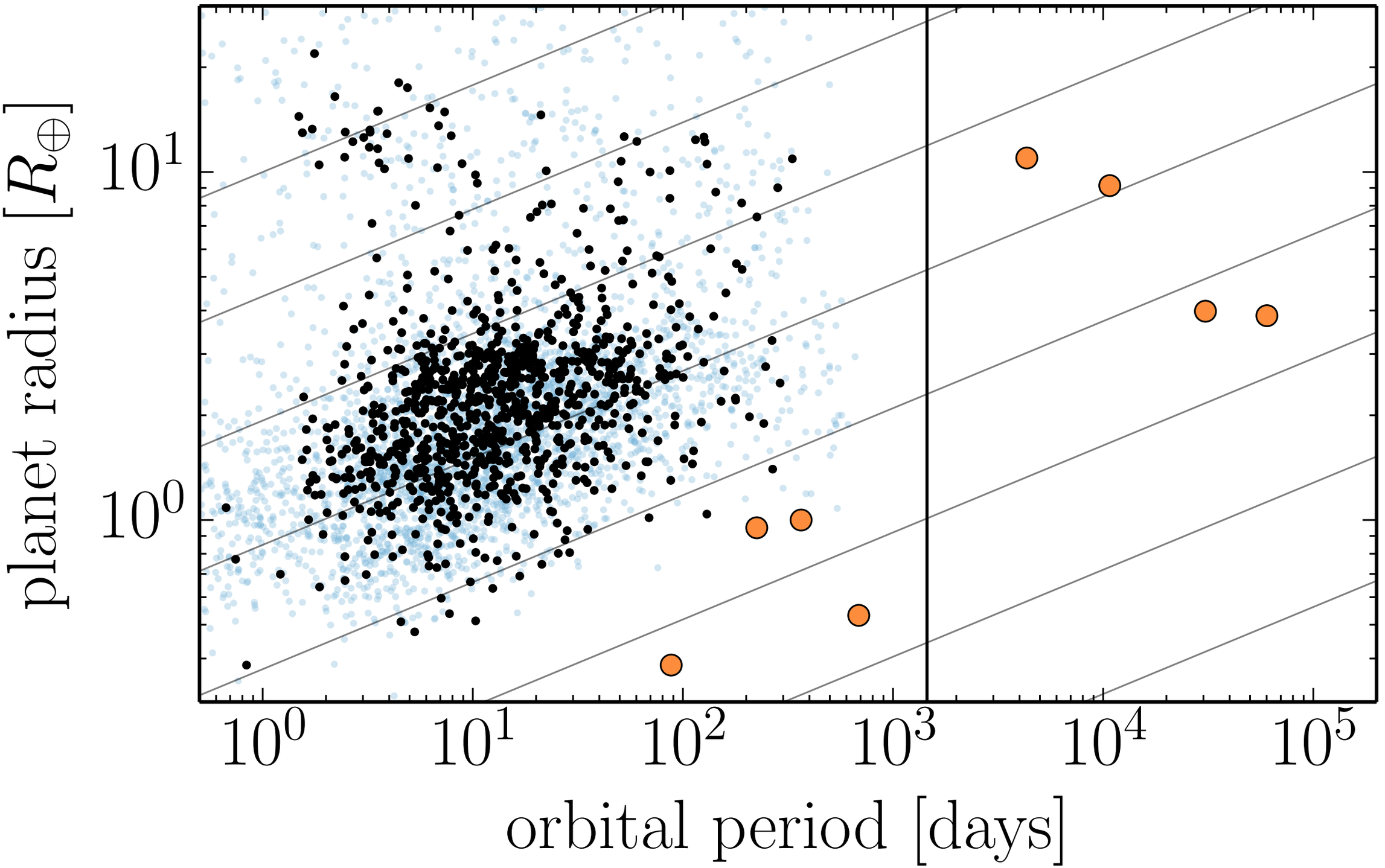
that looks pretty good…



Data from **NASA Exoplanet Archive**



Data from **NASA Exoplanet Archive**



Data from **NASA Exoplanet Archive**

May 2013

The *Kepler Mission* goes up in flames

* not exactly

Kepler

RIP

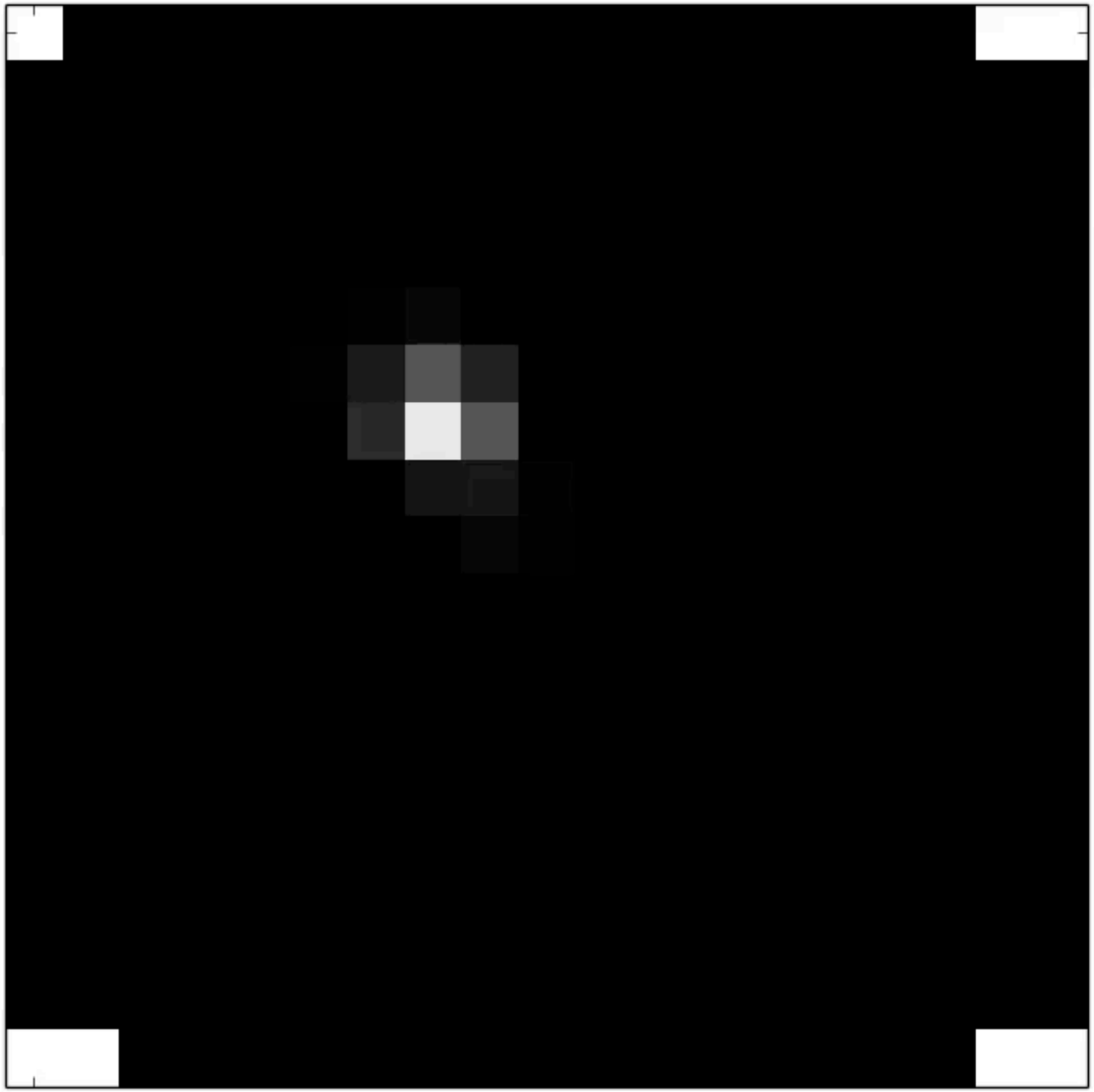
Credit **NASA**

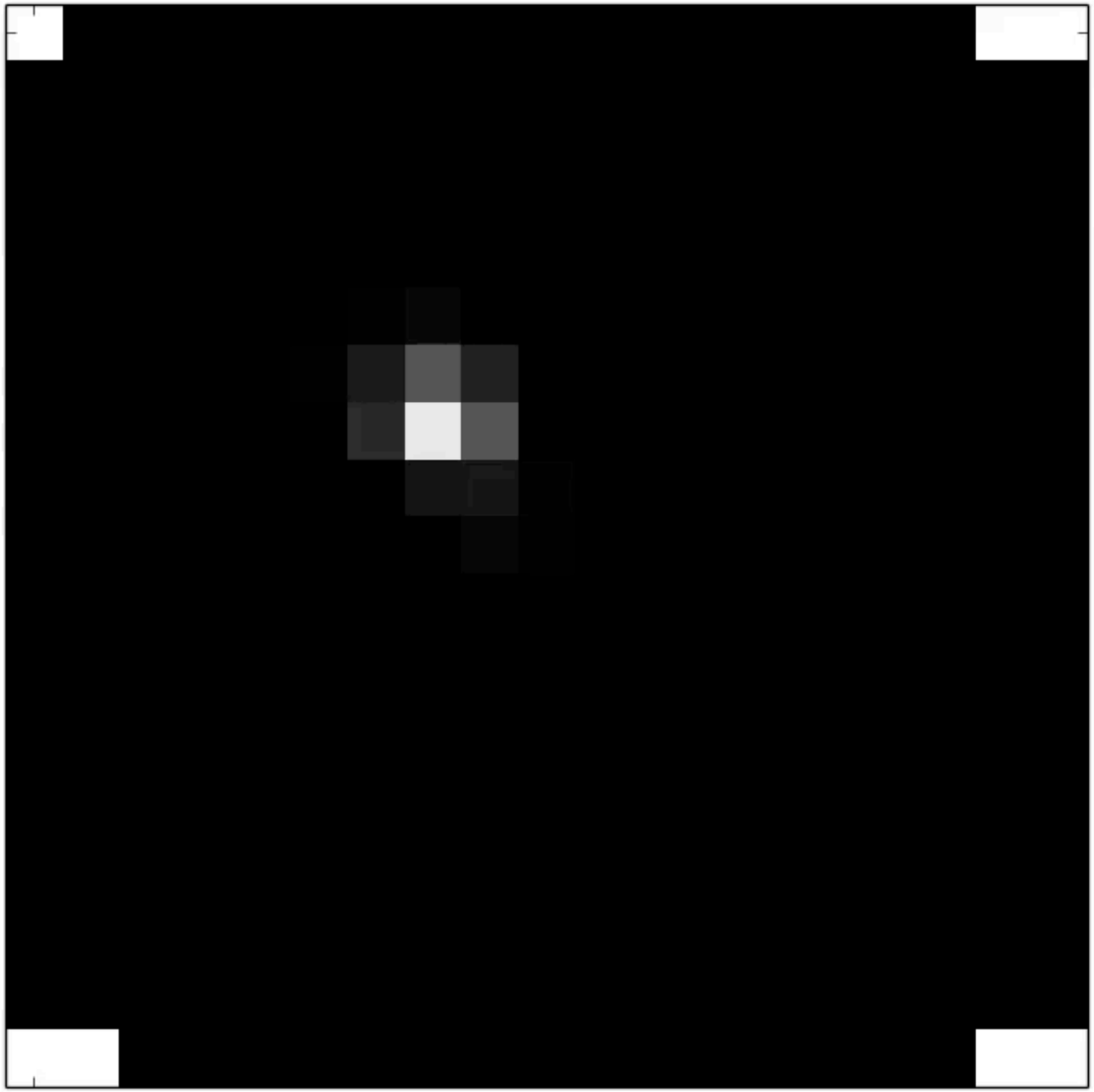
introducing: **K2**

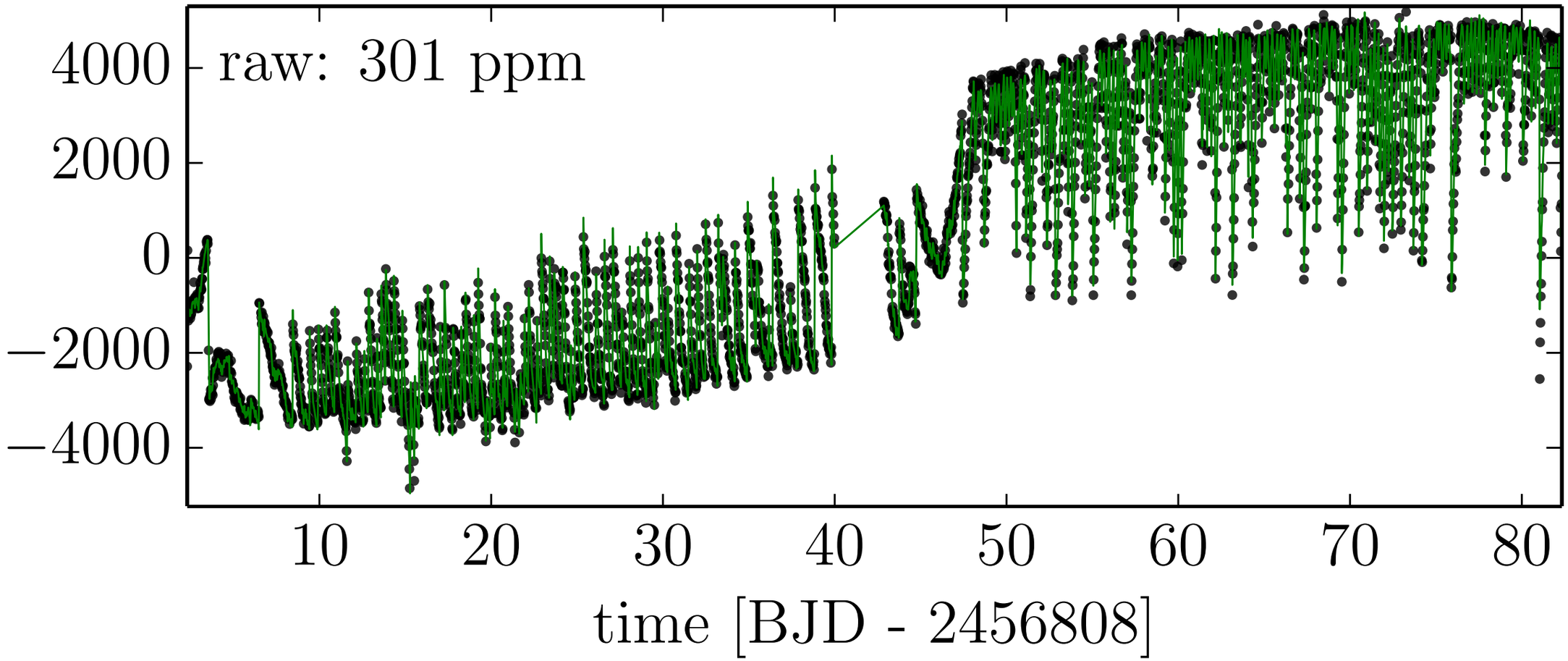
Flickr user **Aamir Choudhry**

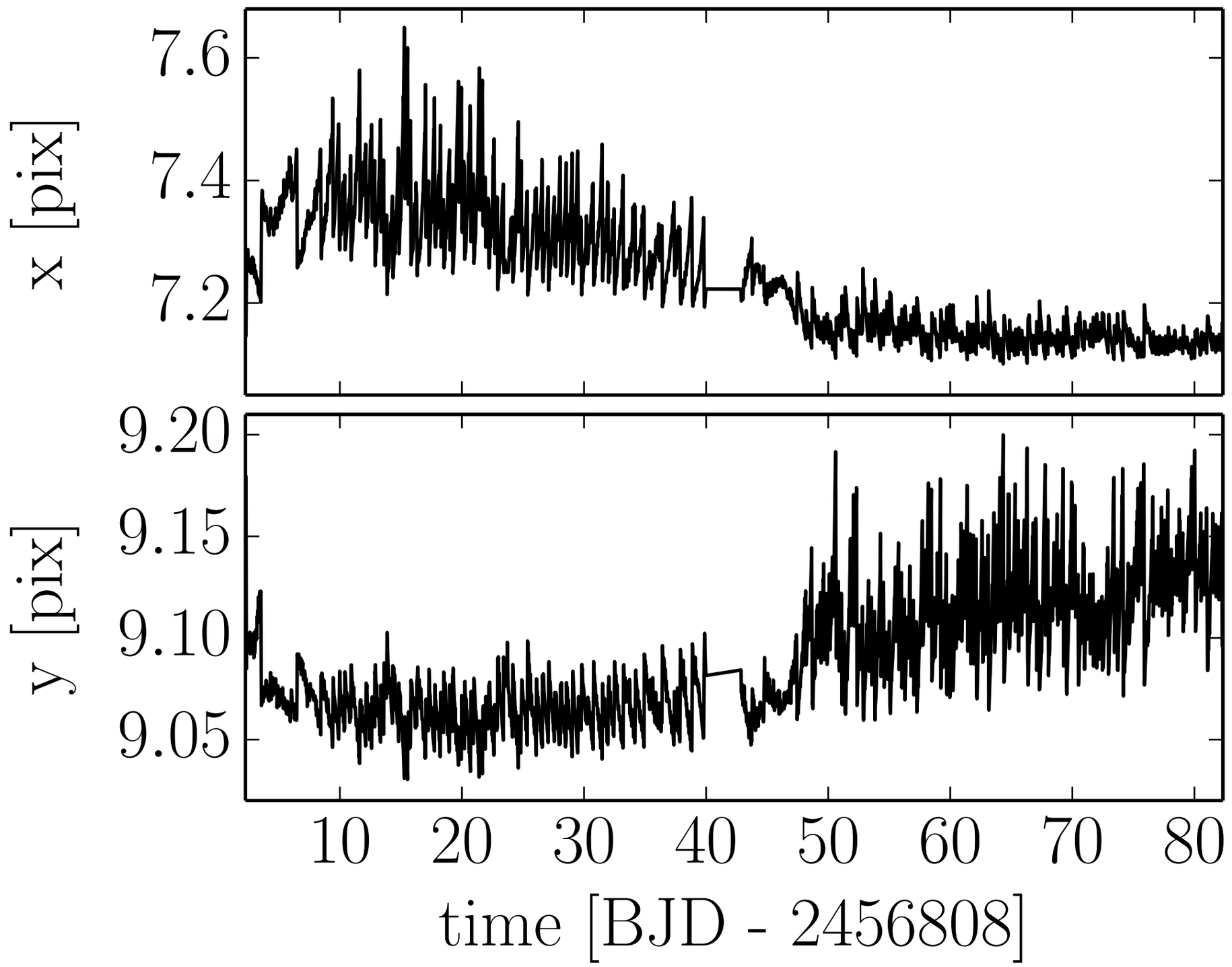
K2

Credit **NASA**



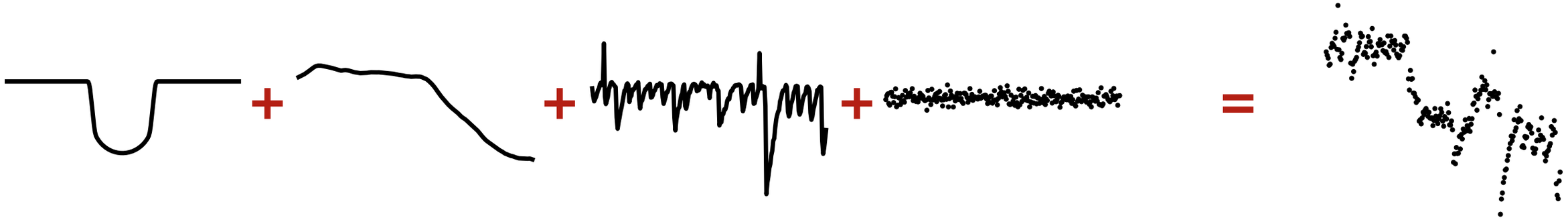



raw: 301 ppm
4000
2000
0
−2000
−4000
10
20
30
40
50
60
70
80
time [BJD - 2456808]


x [pix]
7.6
7.4
7.2
y [pix]
9.20
9.15
9.10
9.05
10
20
30
40
50
60
70
80
time [BJD - 2456808]

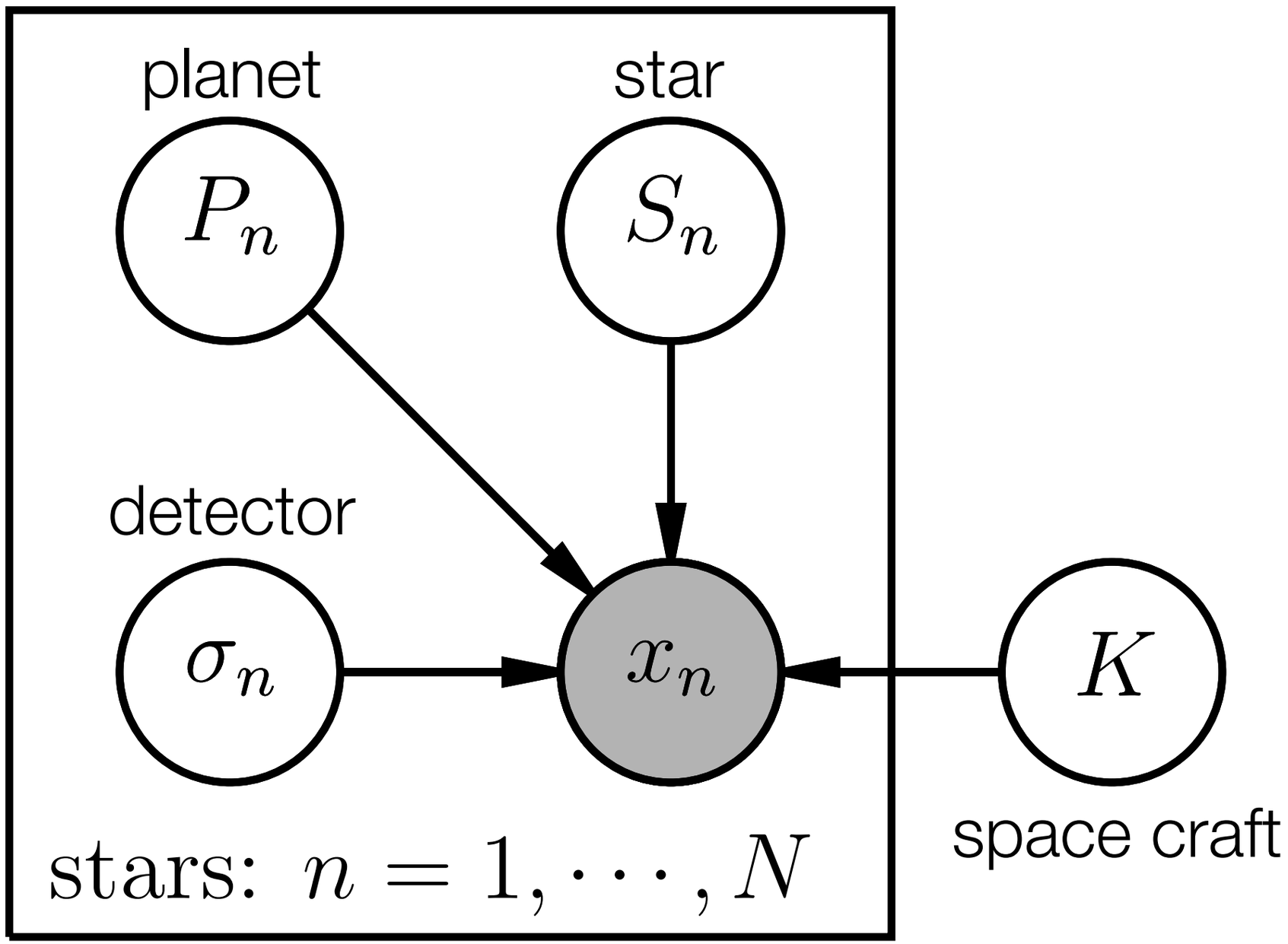
Can we find planets using ***K2***?

Anatomy of a transit signal



planet star space craft detector signal

Designing the probabilistic model



Designing the probabilistic model

representation:

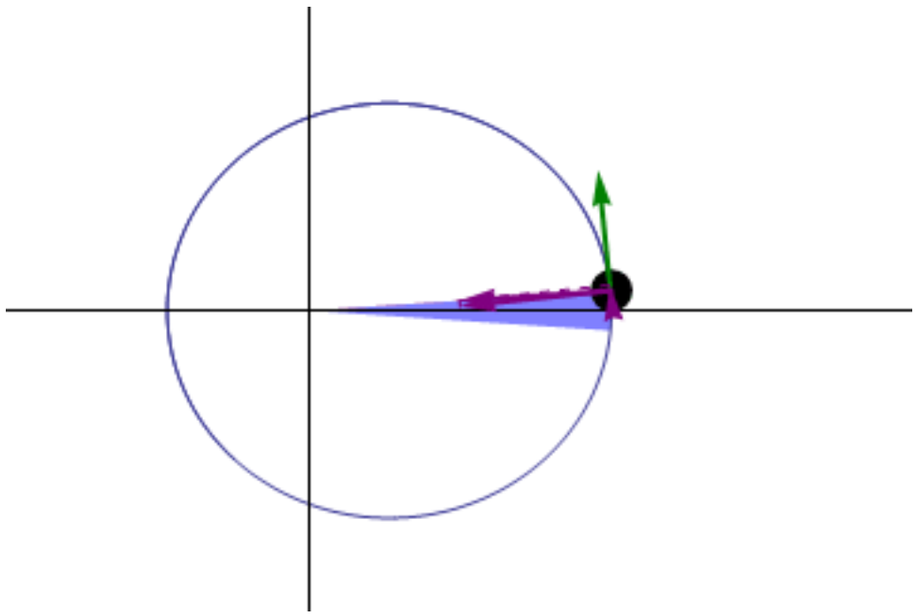
planet: physics and geometry

star: continuous in time → GP

noise: CCD, photon noise → Poisson

space craft: ??

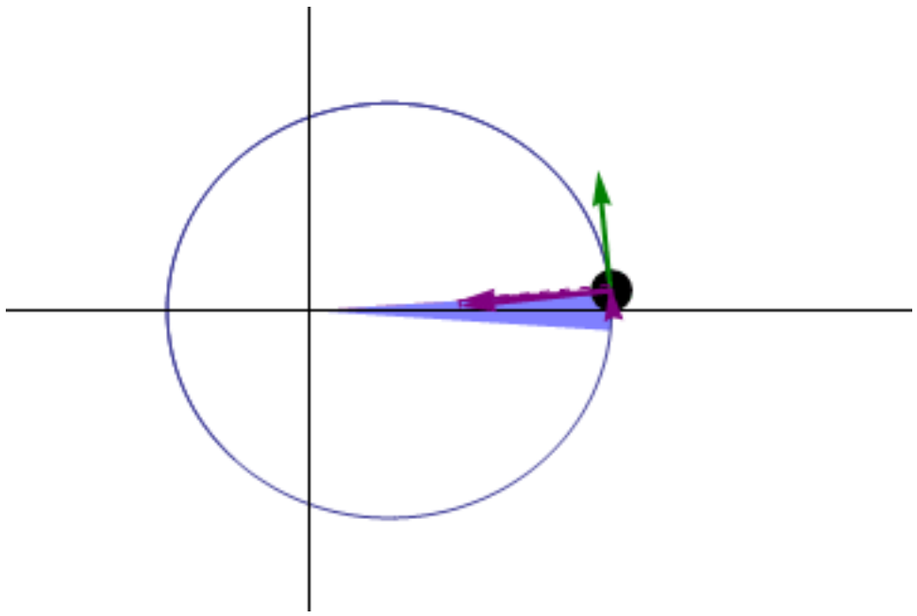
The planet orbit model



Kepler's Laws of Planetary Motion

Wikipedia user **Gonfer**

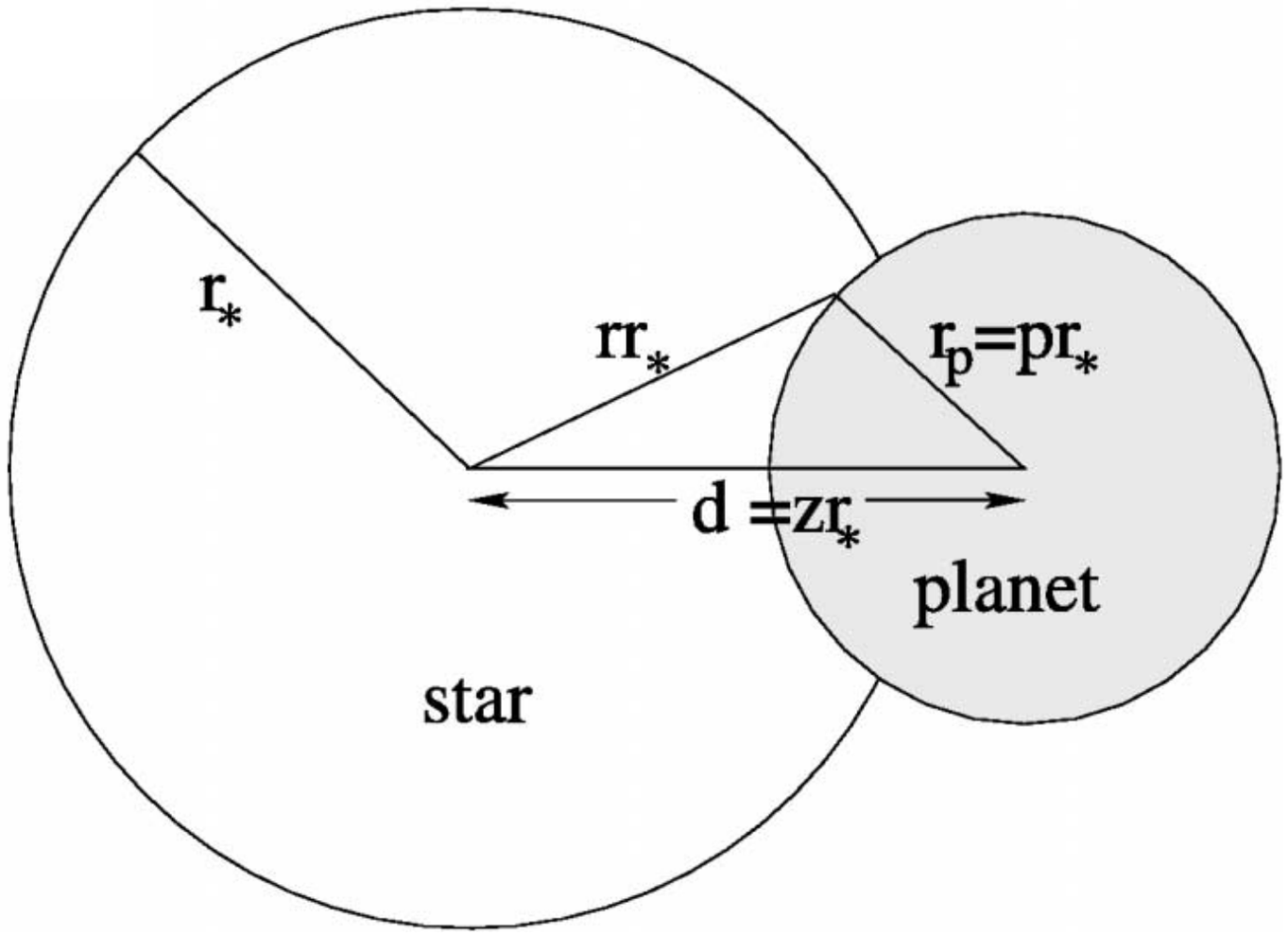
The planet orbit model



Kepler's Laws of Planetary Motion

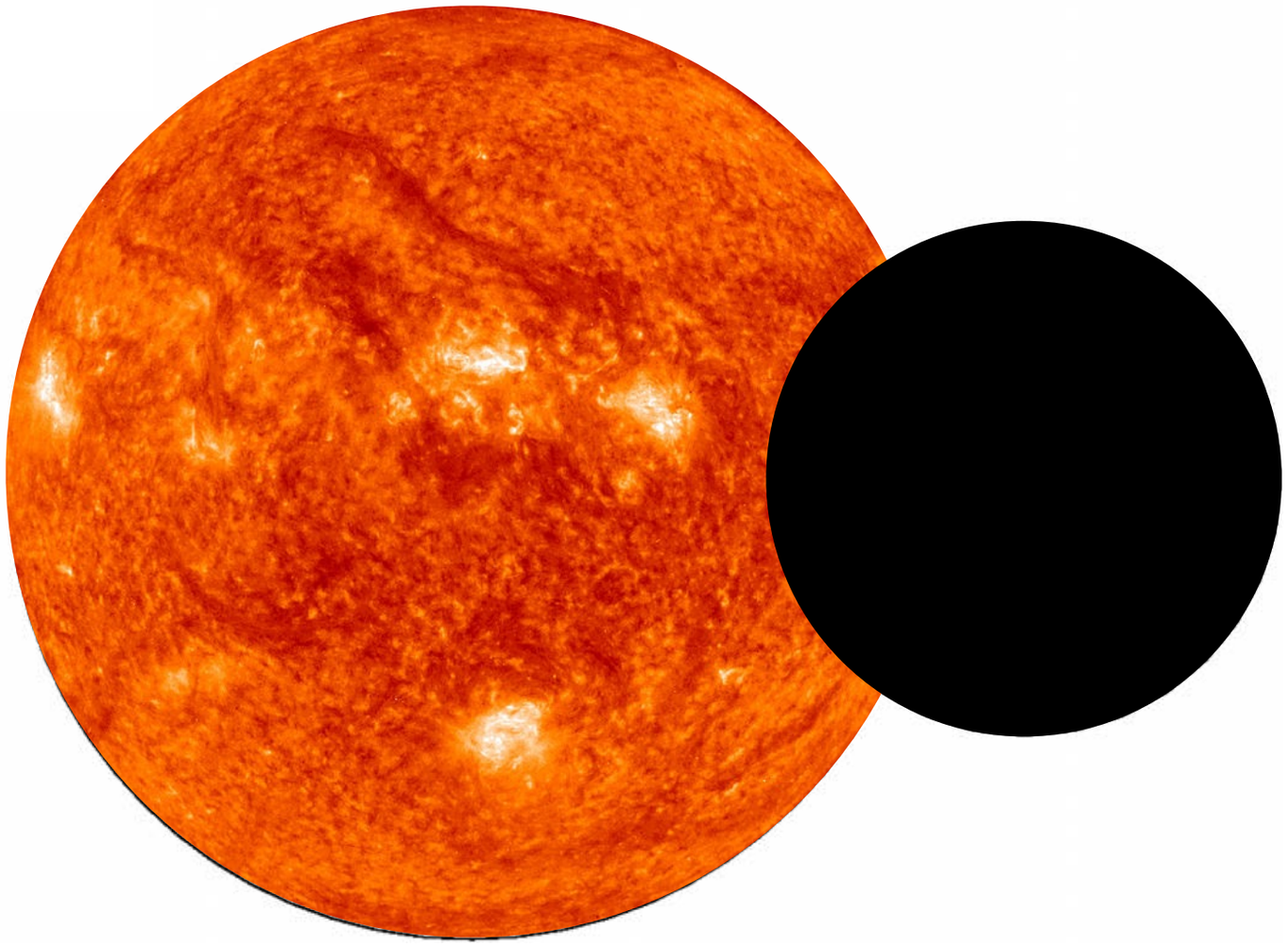
Wikipedia user **Gonfer**

The planet transit model



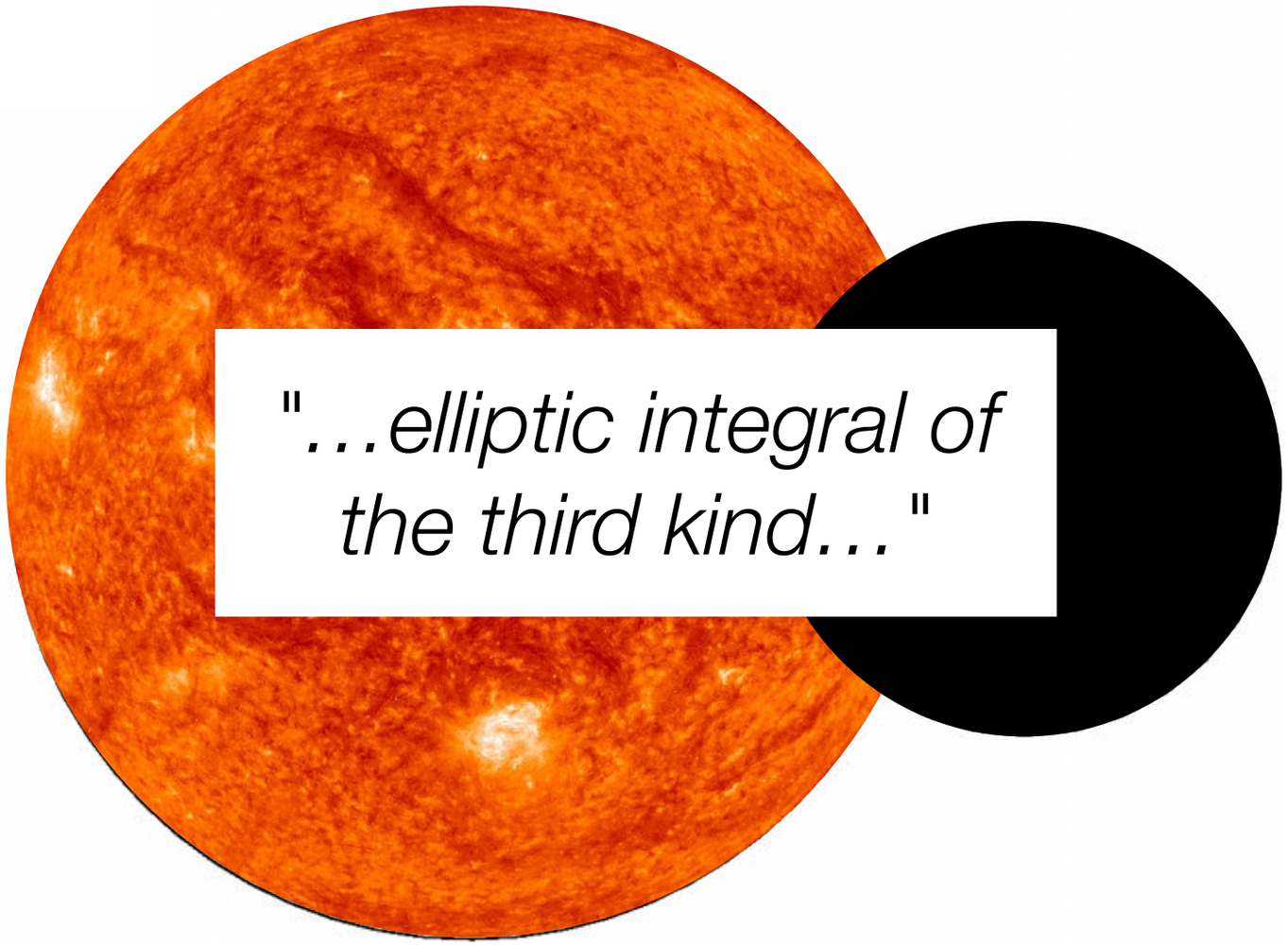
Reference Mandel & Agol (2002); arXiv:astro-ph/0210099

The planet transit model



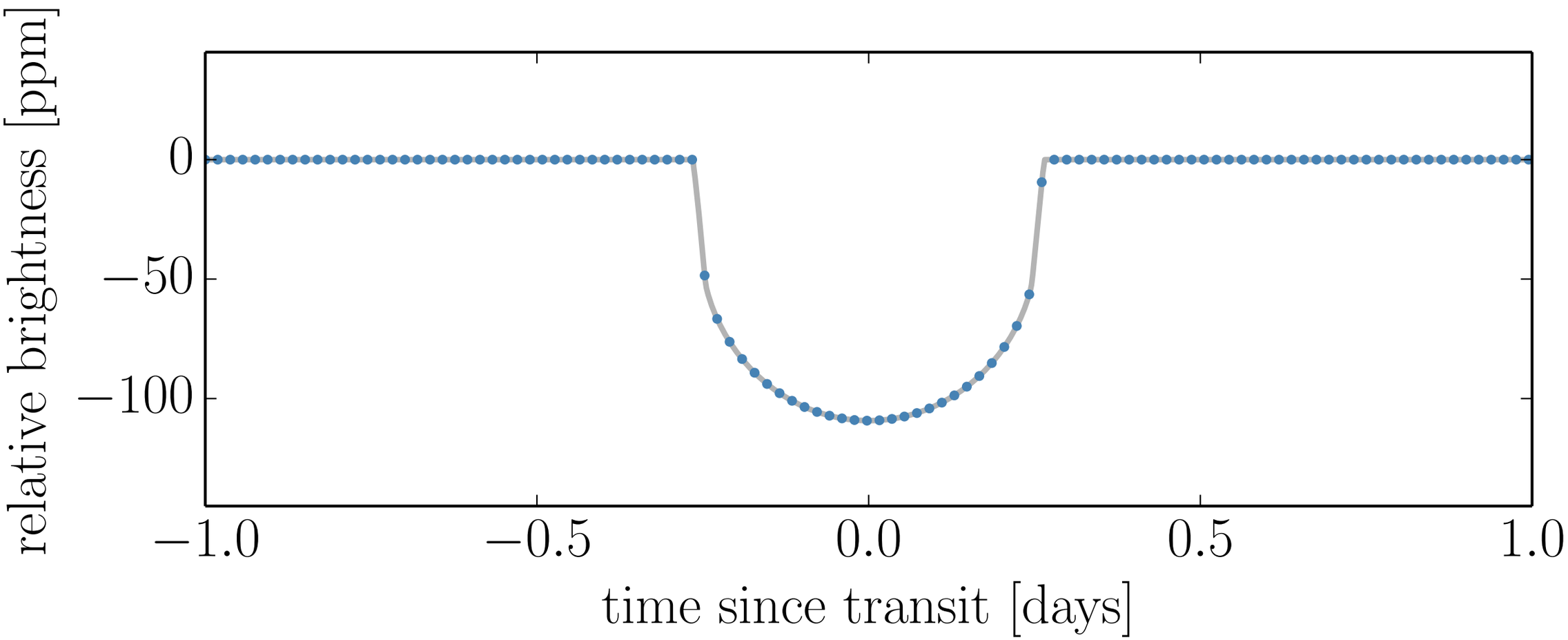
Reference Mandel & Agol (2002); arXiv:astro-ph/0210099

The planet transit model



Reference Mandel & Agol (2002); arXiv:astro-ph/0210099

The planet transit model



Reference Mandel & Agol (2002); arXiv:astro-ph/0210099

Designing the probabilistic model

representation:

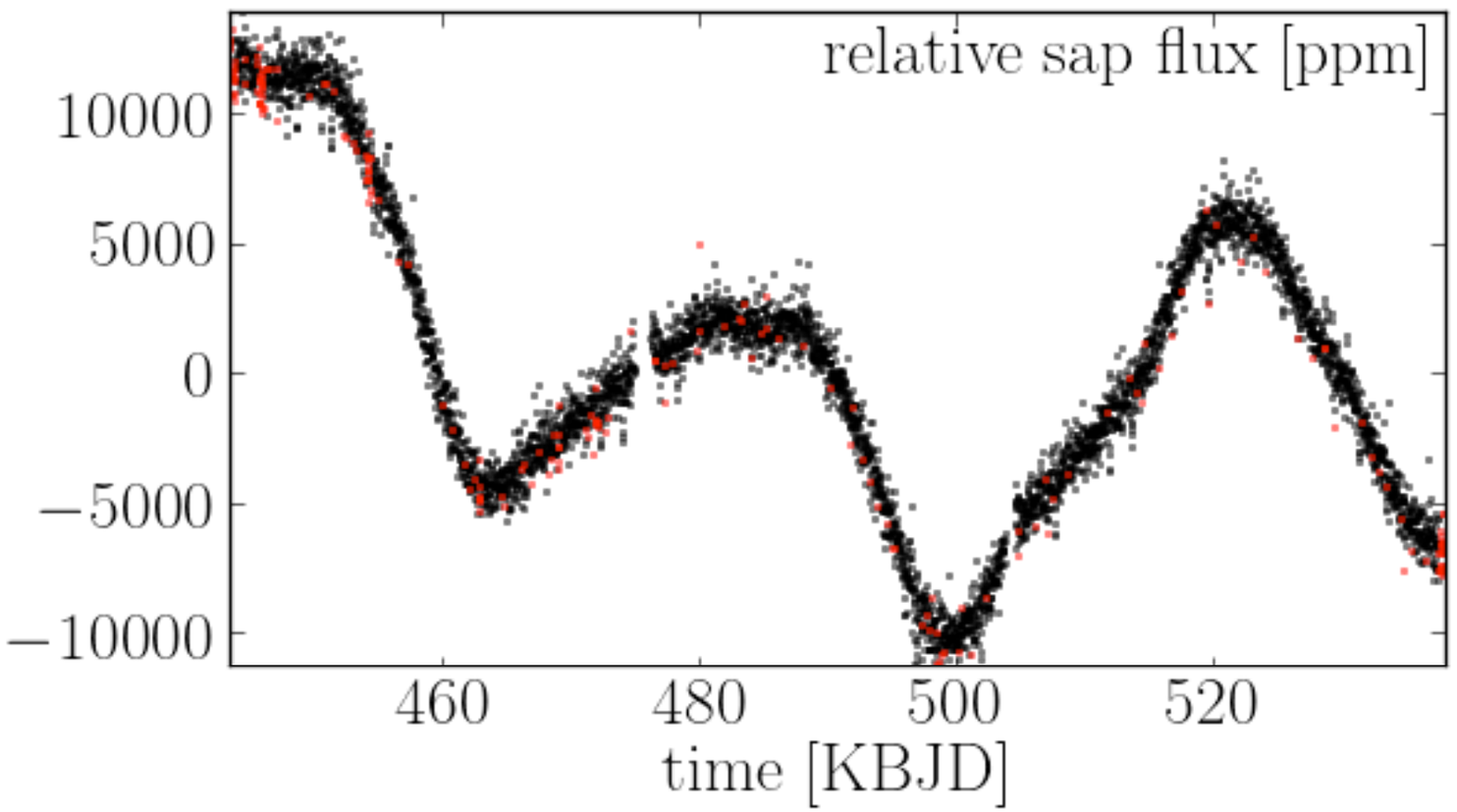
planet: physics and geometry

star: continuous in time → GP

noise: CCD, photon noise → Poisson

space craft: ??

The stellar variability model



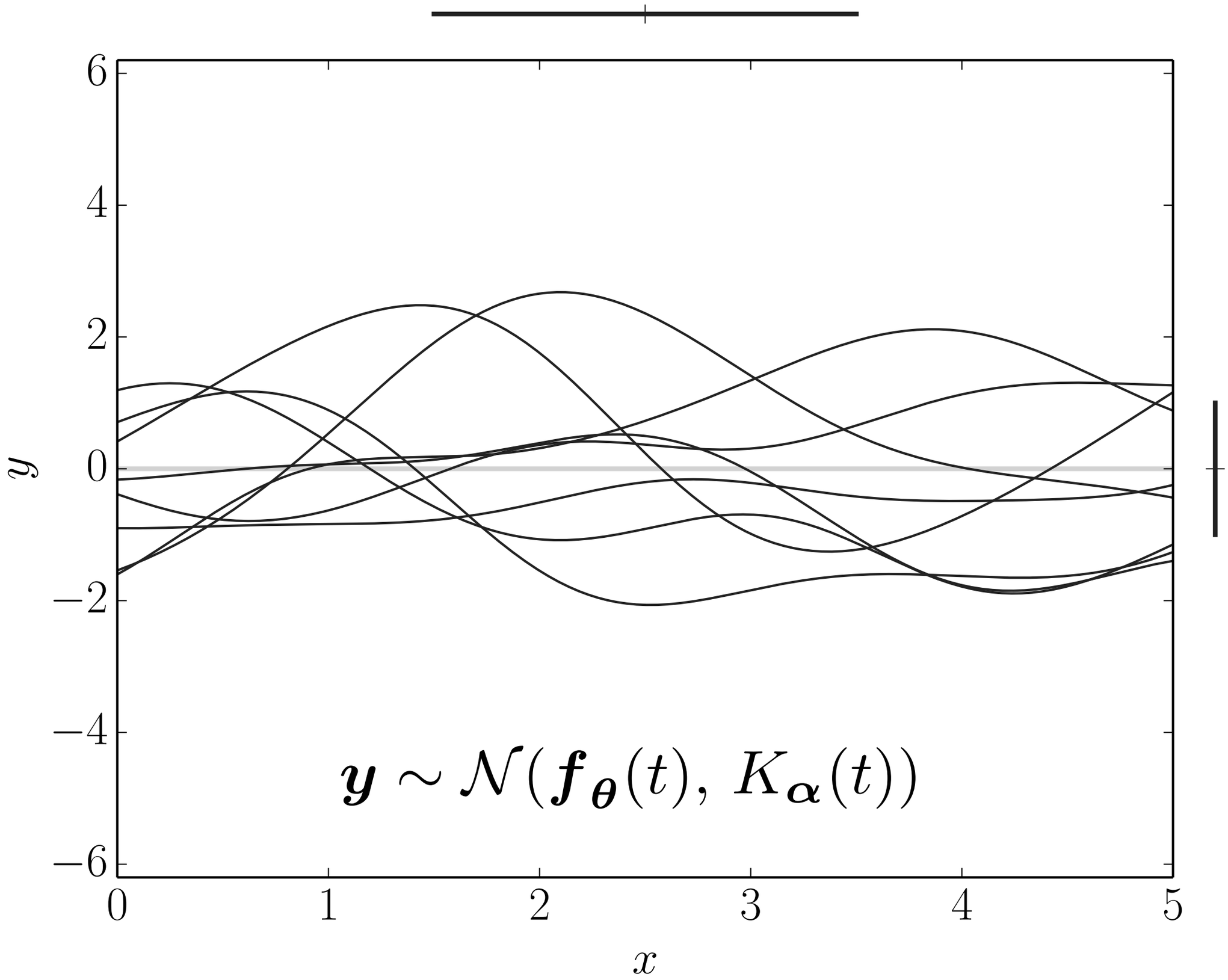
The stellar variability model

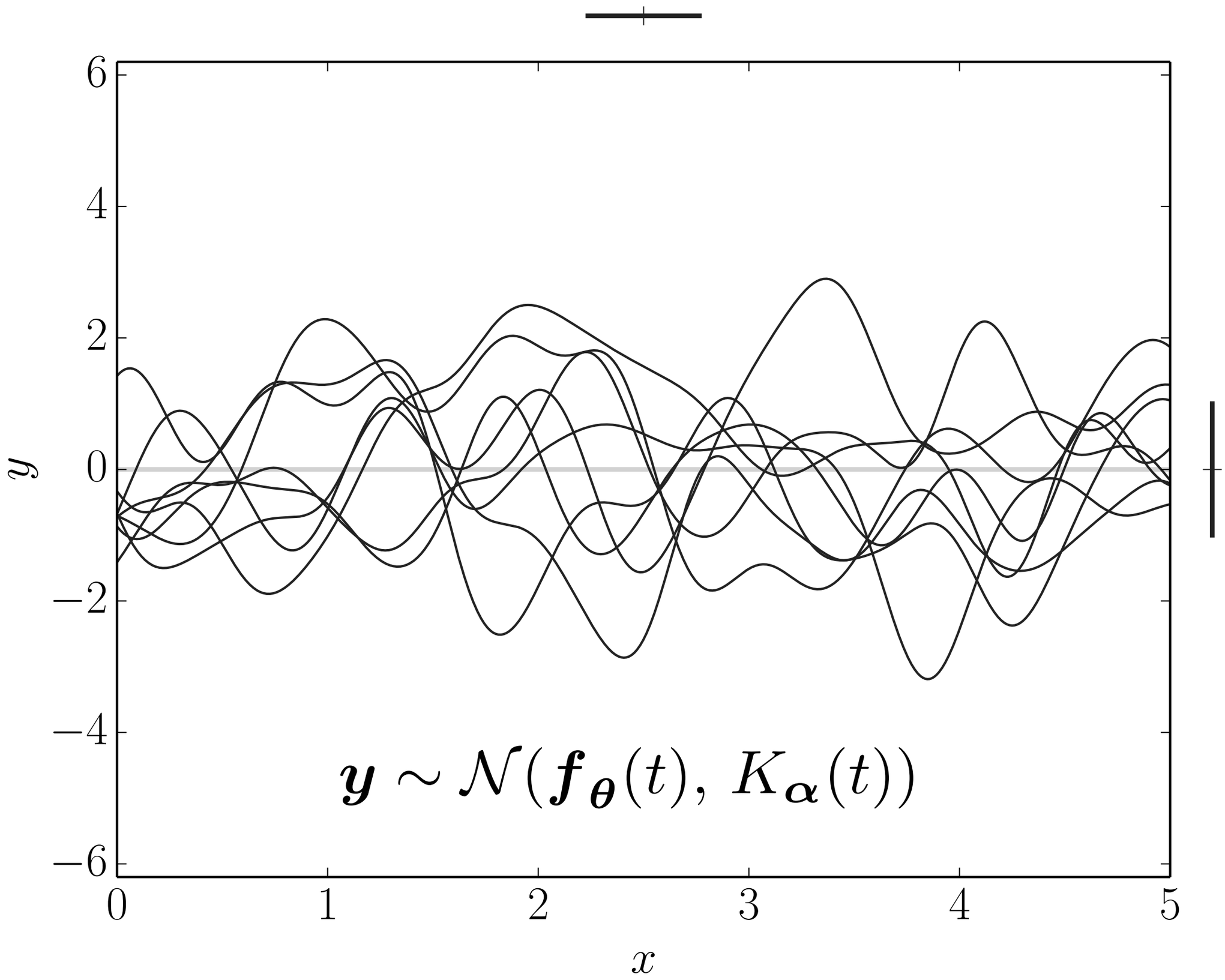
Gaussian

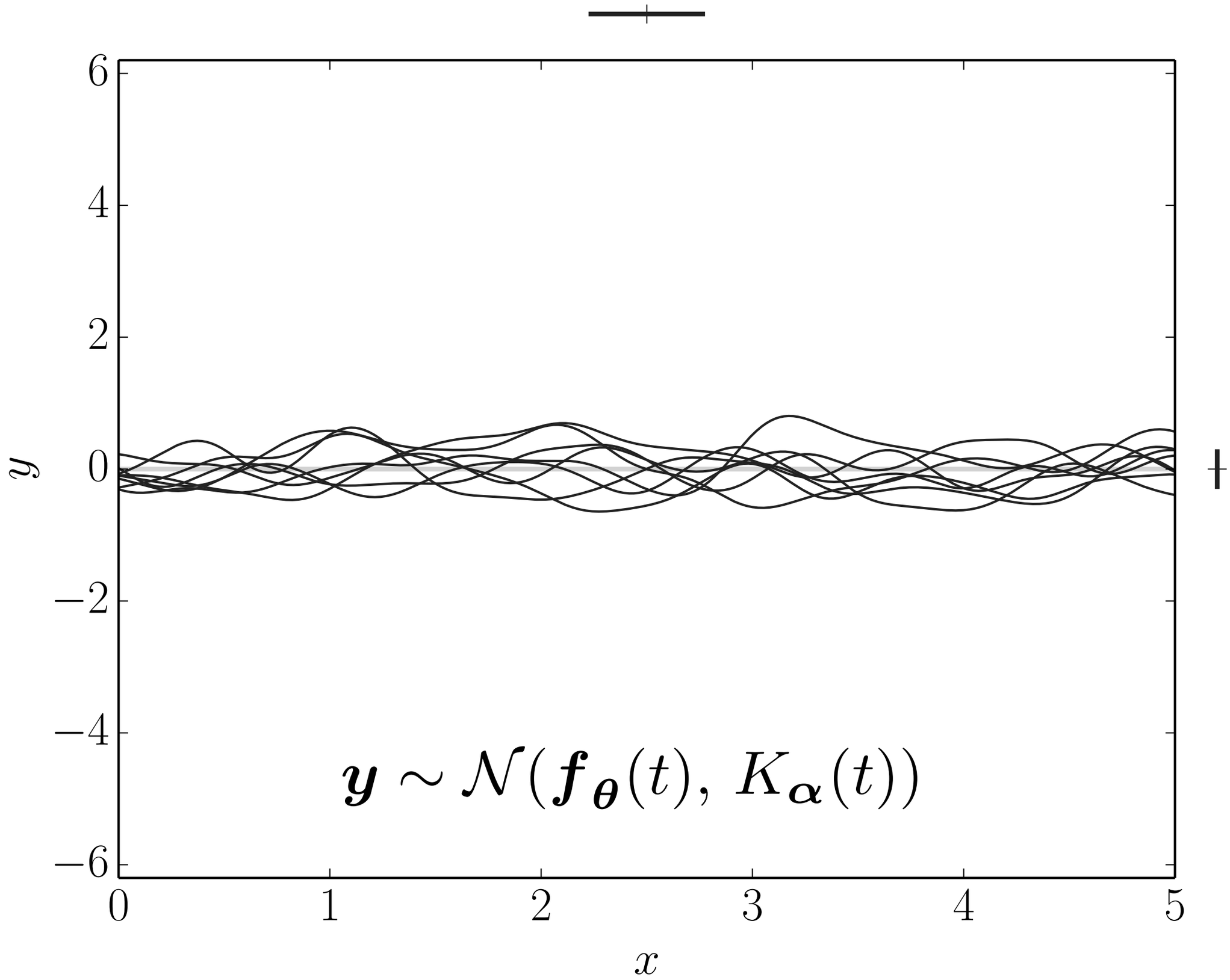
Covariance

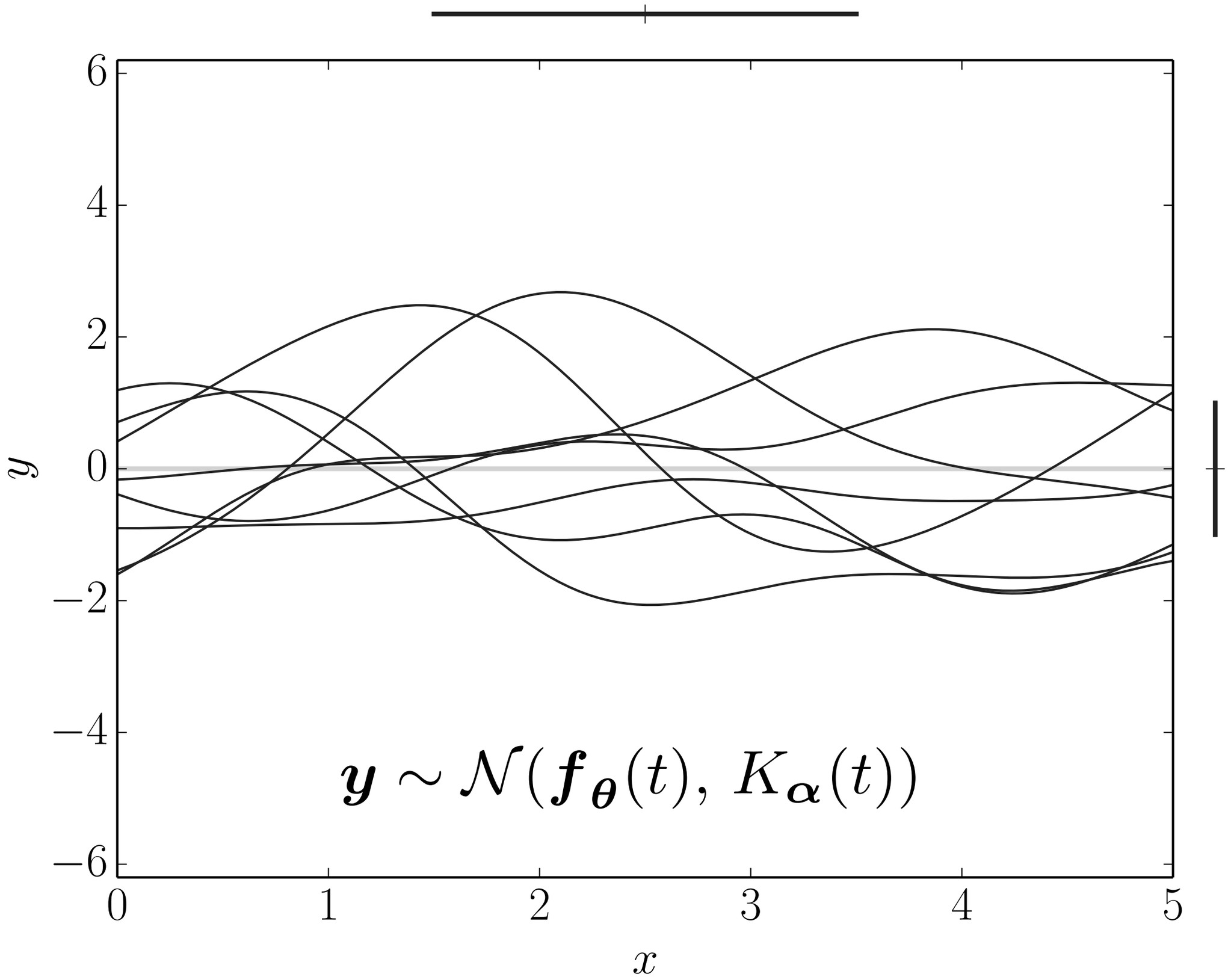
$$\boldsymbol{y} \sim \mathcal{N}(\boldsymbol{f_\theta}(t),\, K_{\boldsymbol{\alpha}}(t))$$

Mean

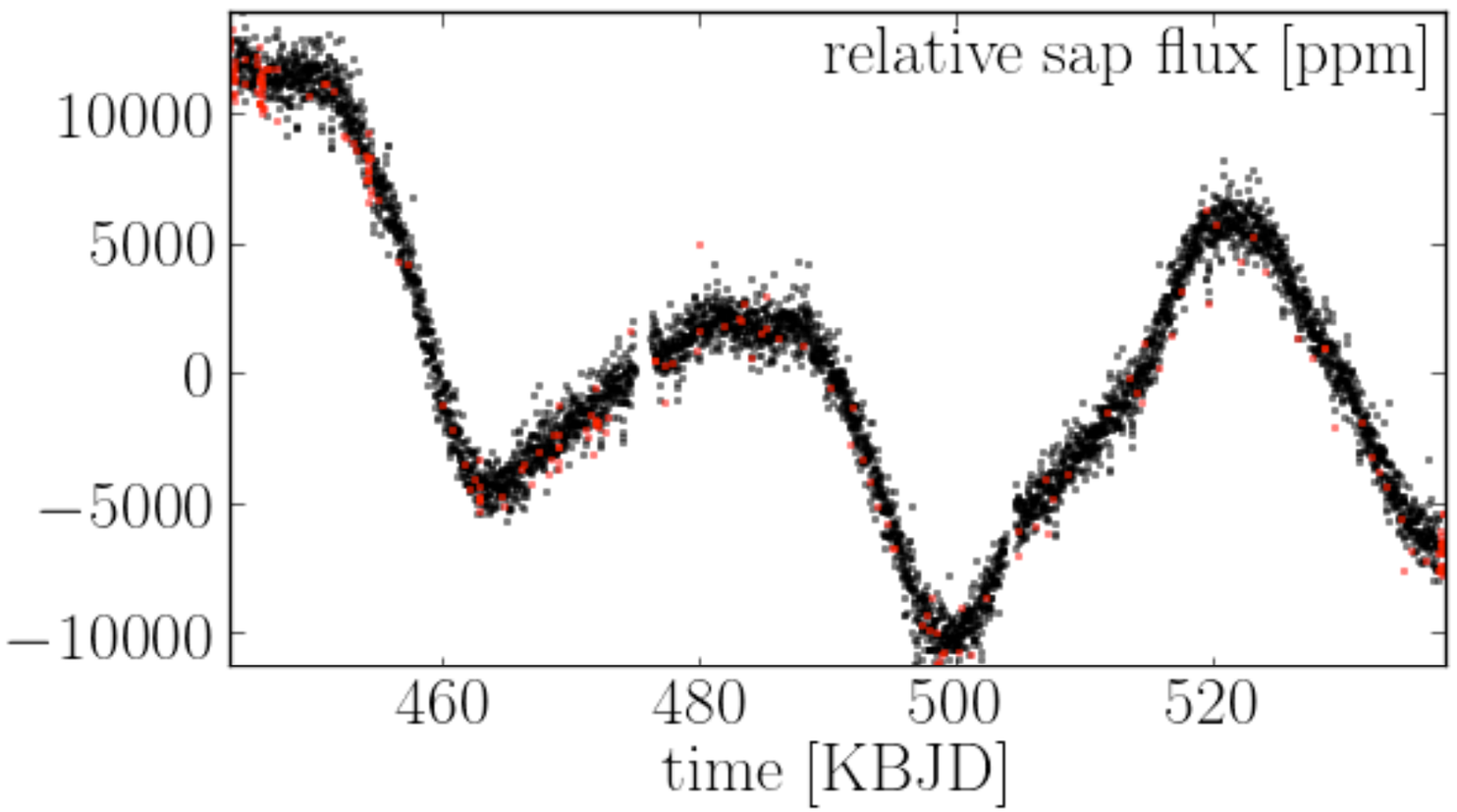

6
4
2
0
−2
−4
−6
y
0
1
2
3
4
5
x
$\boldsymbol{y} \sim \mathcal{N}(\boldsymbol{f}_{\boldsymbol{\theta}}(t),\, K_{\boldsymbol{\alpha}}(t))$


6
4
2
0
−2
−4
−6
y
0
1
2
3
4
5
x
$\boldsymbol{y} \sim \mathcal{N}(\boldsymbol{f}_{\boldsymbol{\theta}}(t),\, K_{\boldsymbol{\alpha}}(t))$


6
4
2
0
−2
−4
−6
0
1
2
3
4
5
x
y
$\boldsymbol{y} \sim \mathcal{N}(\boldsymbol{f}_{\boldsymbol{\theta}}(t),\, K_{\boldsymbol{\alpha}}(t))$


6
4
2
0
−2
−4
−6
y
0
1
2
3
4
5
x
$\boldsymbol{y} \sim \mathcal{N}(\boldsymbol{f}_{\boldsymbol{\theta}}(t),\, K_{\boldsymbol{\alpha}}(t))$

The stellar variability model



Designing the probabilistic model

representation:

planet: physics and geometry

star: continuous in time → GP

noise: CCD, photon noise → Poisson

space craft: ??

The **noise** model

Credit **NASA**

Designing the probabilistic model

representation:

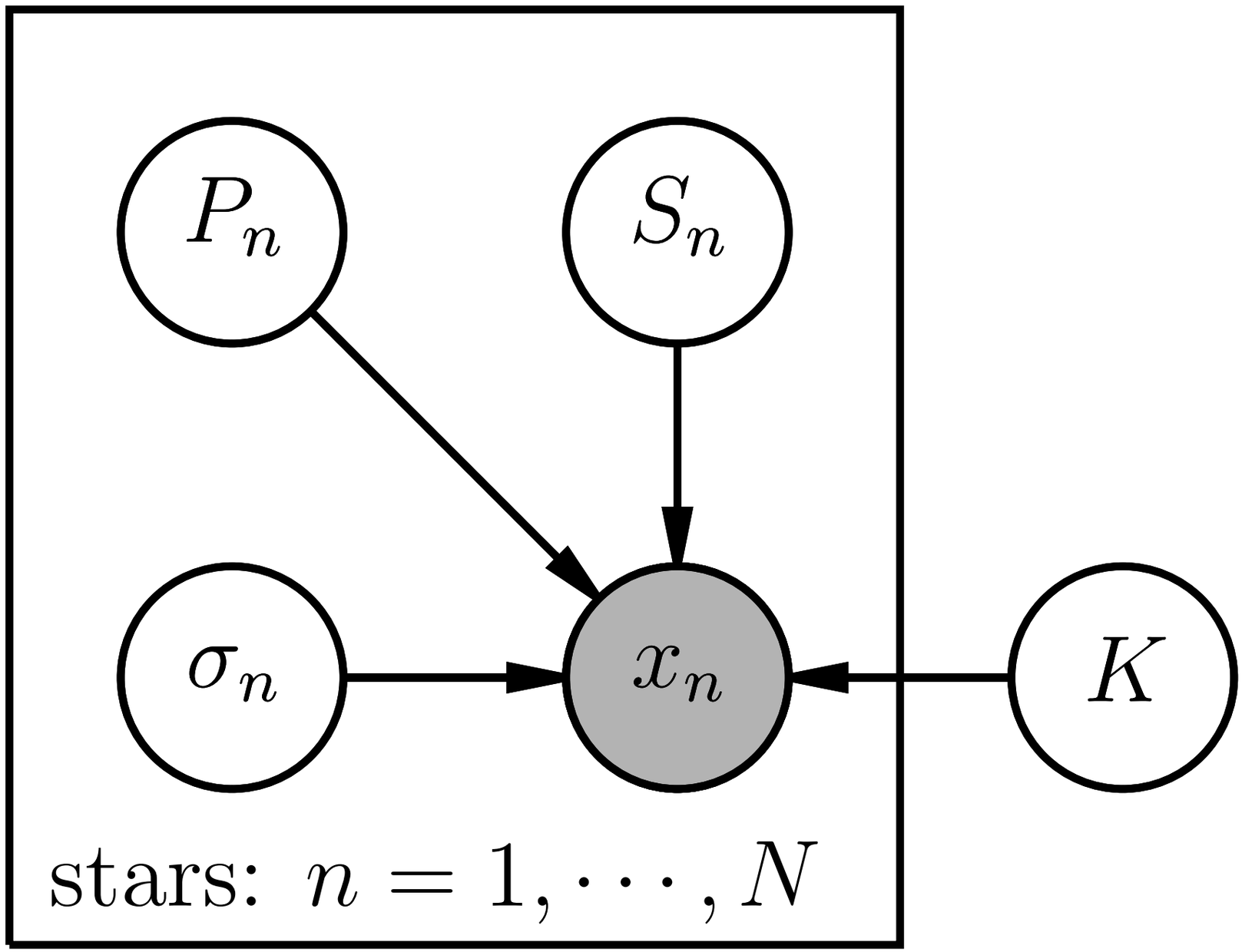
planet: physics and geometry

star: continuous in time → GP

noise: CCD, photon noise → Poisson

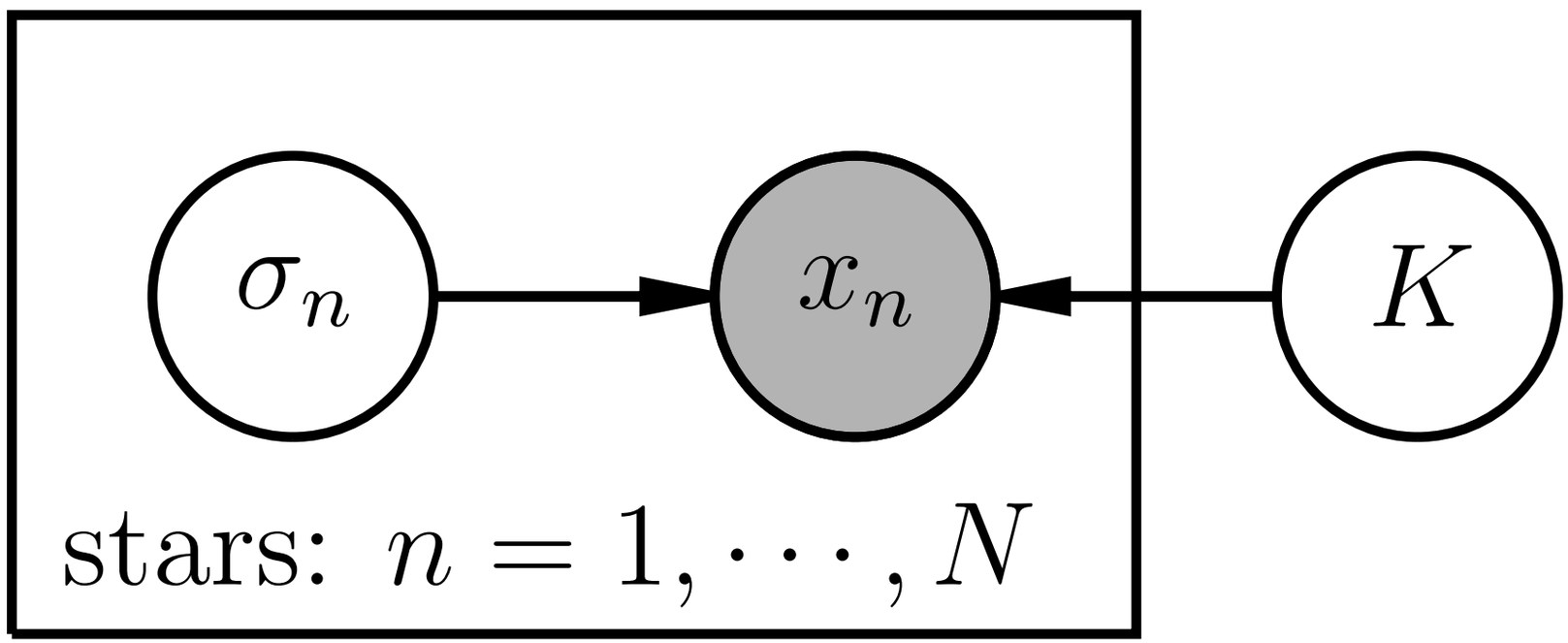
space craft: ??

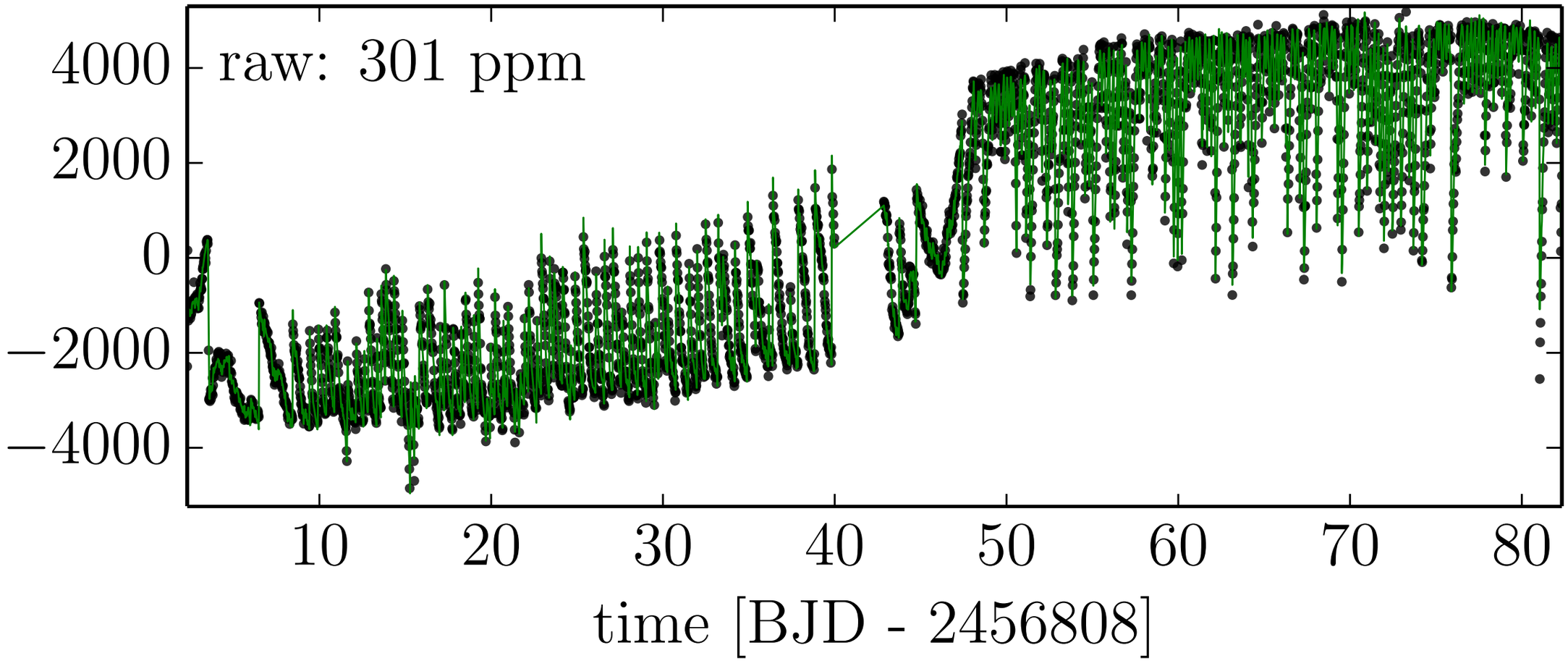
Designing the probabilistic model

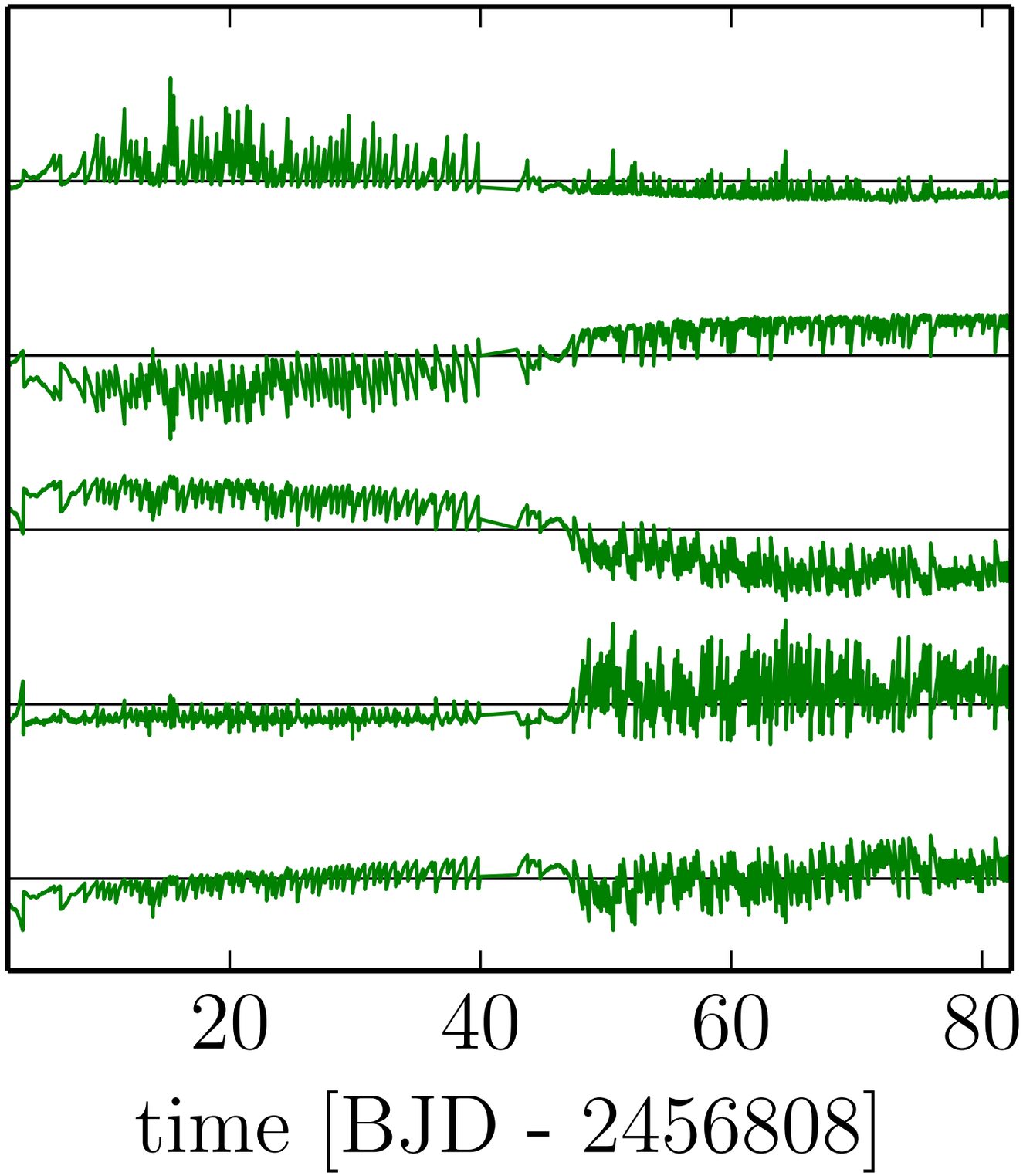


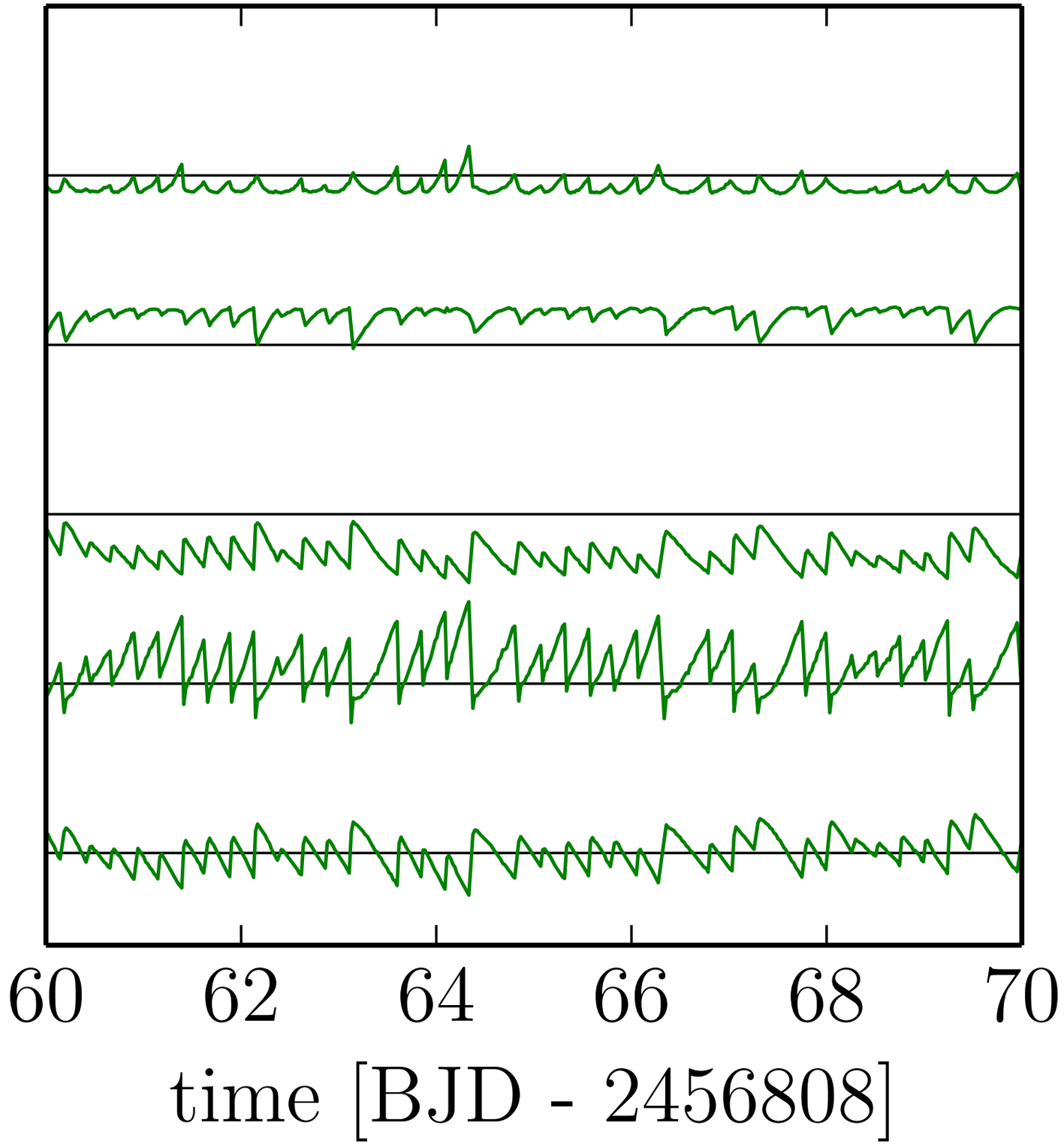
Designing the probabilistic model

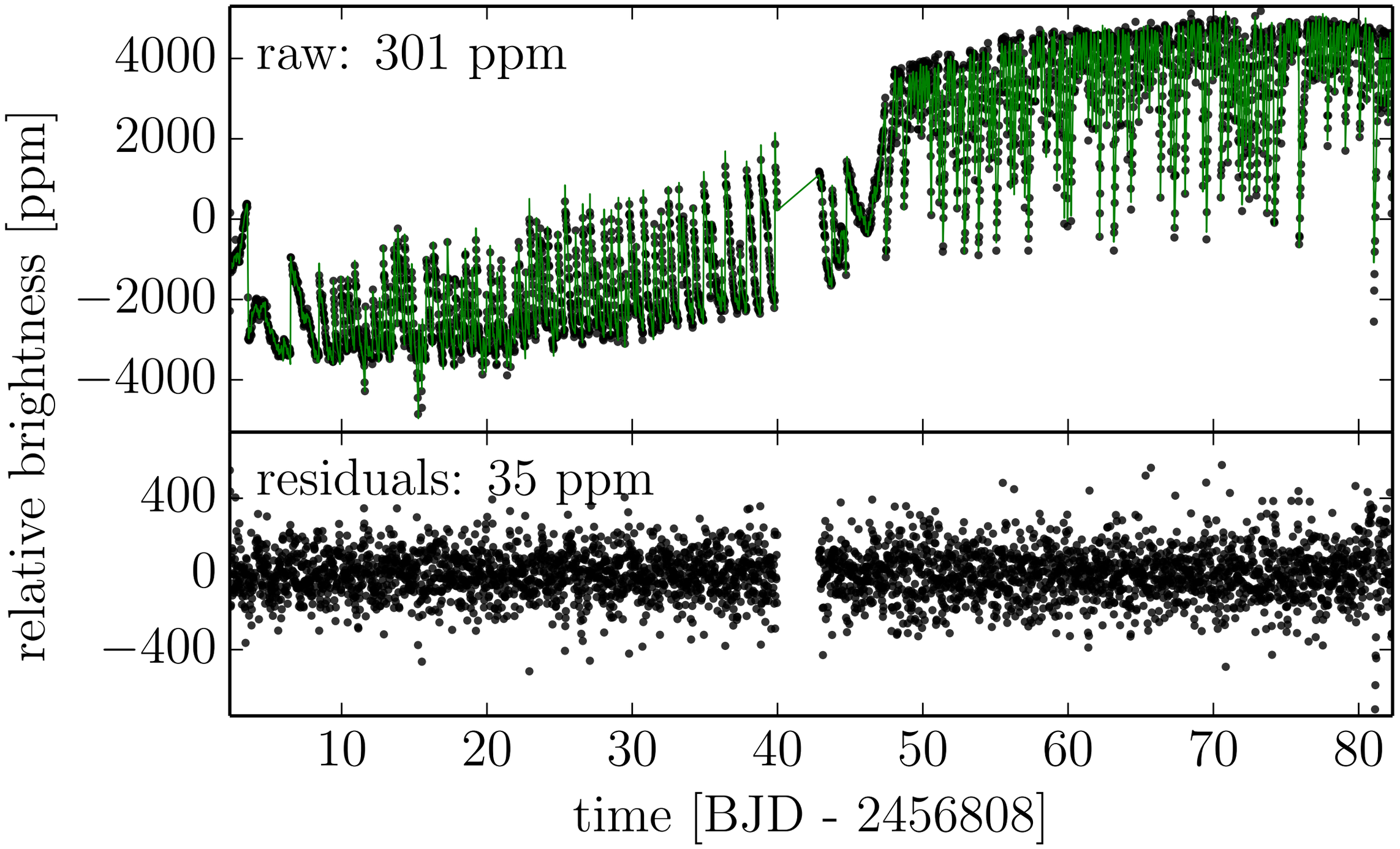
simple space craft assumption:




raw: 301 ppm
4000
2000
0
−2000
−4000
10
20
30
40
50
60
70
80
time [BJD - 2456808]


20
40
60
80
time [BJD - 2456808]


60
62
64
66
68
70
time [BJD - 2456808]

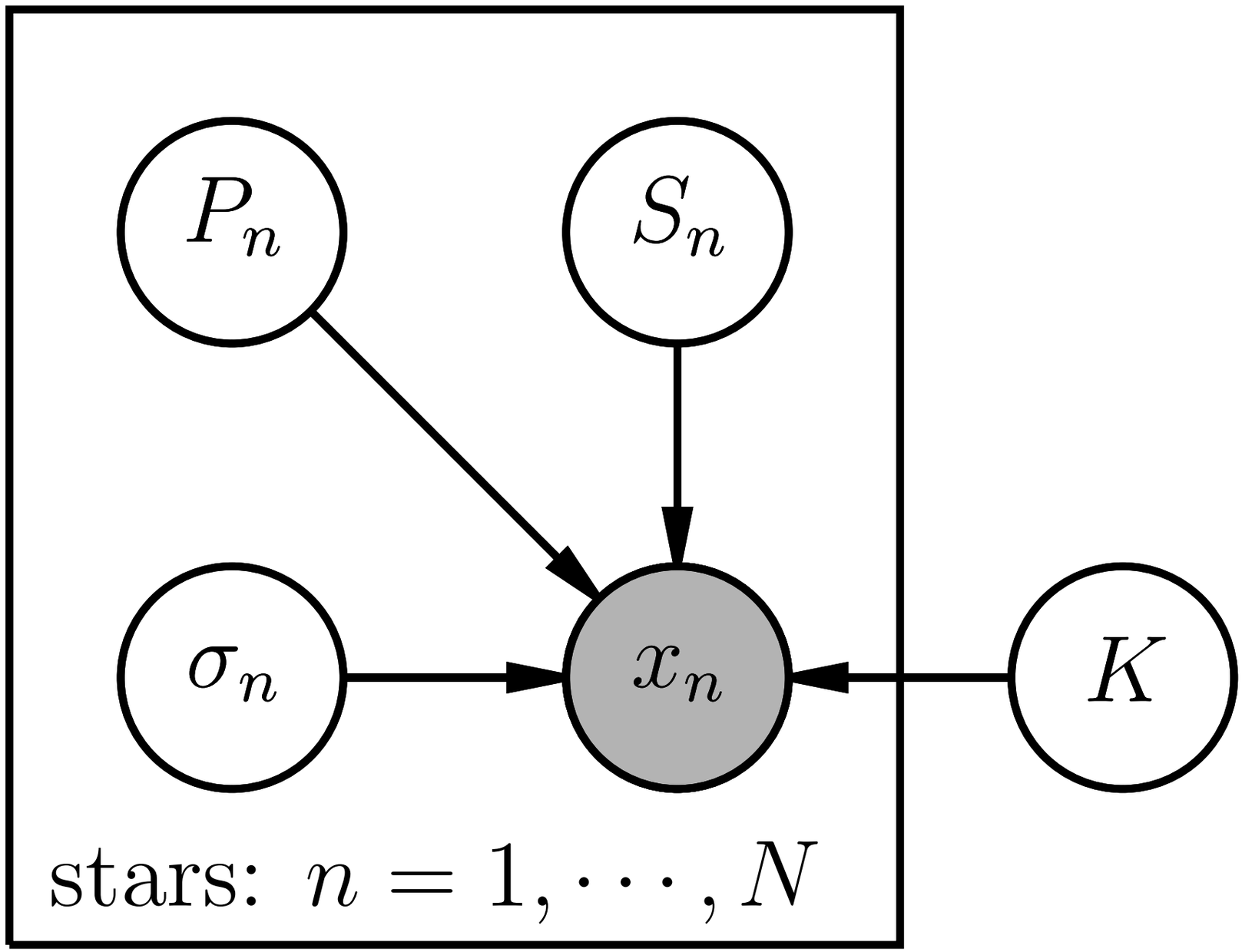

raw: 301 ppm
residuals: 35 ppm
relative brightness [ppm]
4000
2000
0
−2000
−4000
400
0
−400
10
20
30
40
50
60
70
80
time [BJD - 2456808]

Designing the probabilistic model

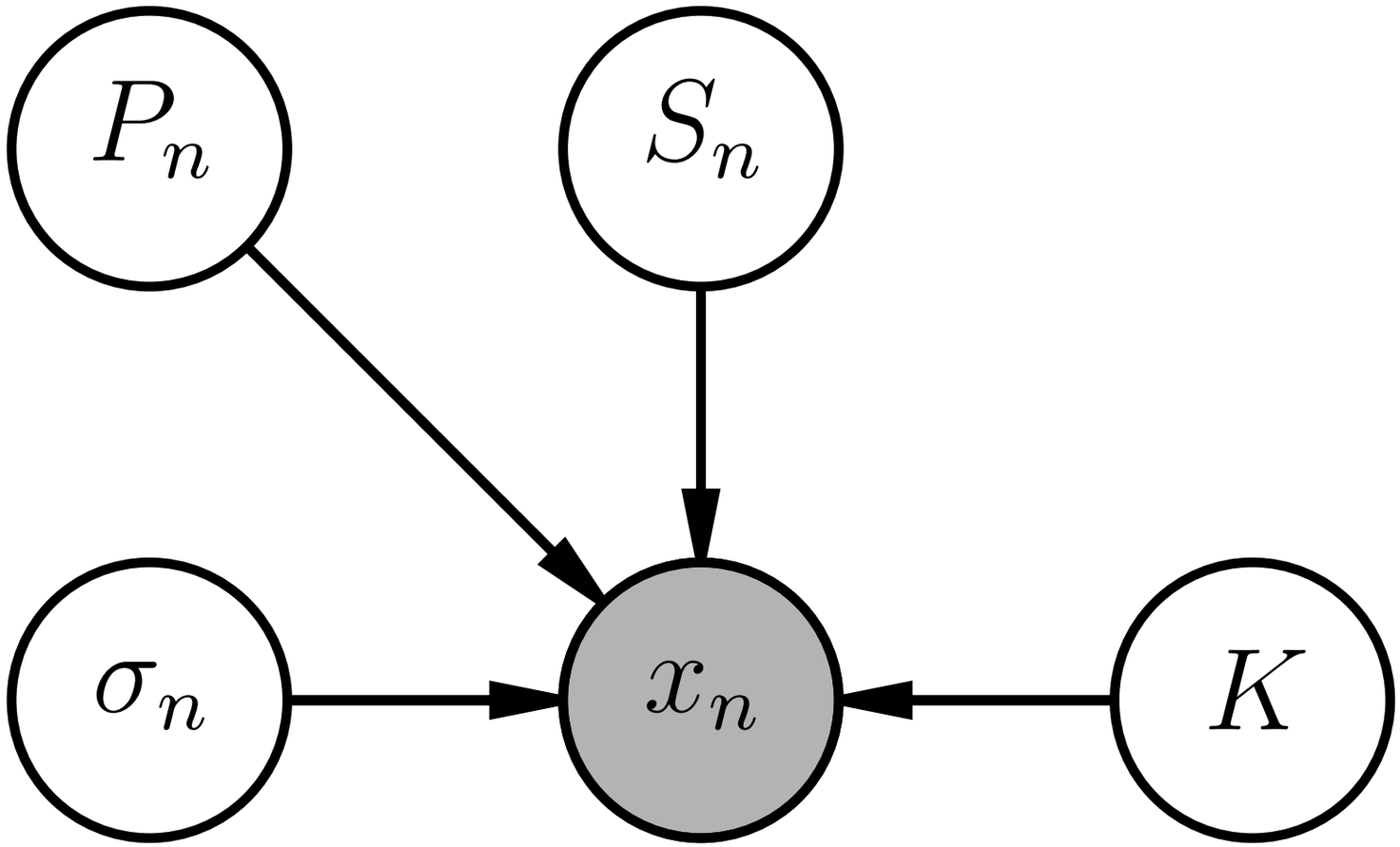
representation:

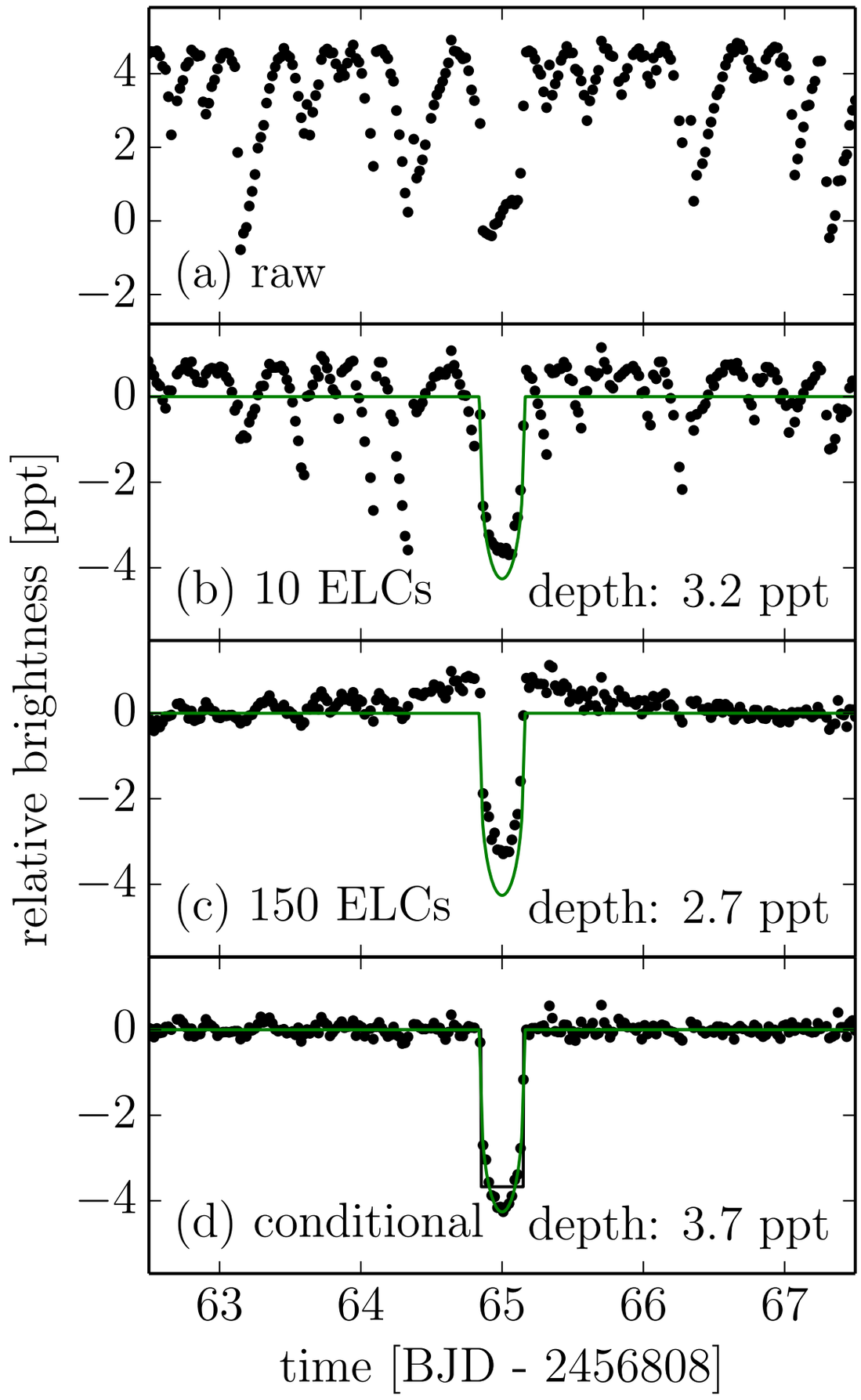
planet:	physics and geometry
star:	continuous in time → GP
noise:	CCD, photon noise → Poisson
space craft:	data-driven linear model

Designing the probabilistic model



Designing the probabilistic model




(a) raw
(b) 10 ELCs
depth: 3.2 ppt
(c) 150 ELCs
depth: 2.7 ppt
(d) conditional
depth: 3.7 ppt
relative brightness [ppt]
time [BJD - 2456808]
4
2
0
−2
−4
63
64
65
66
67

Can we find planets using ***K2***?

Yes.

K2 Campaign 1 exoplanet discoveries

21,703 stars

80 days of data

36 planet candidates

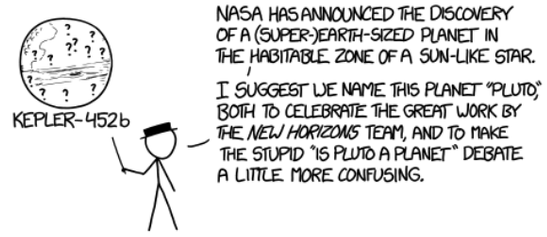
18 confirmed planets

Published:

Foreman-Mackey, Montet, Hogg, *et al.* (arXiv:1502.04715)

Montet, Morton, **Foreman-Mackey**, *et al.* (arXiv:1503.07866)

Schölkopf, Hogg, Wang, **Foreman-Mackey**, *et al.* (arXiv:1505.03036)

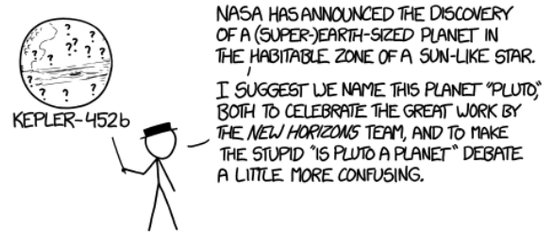


WHILE WE WAIT TO HEAR FROM THE IAU, HERE'S A REVISED AND UPDATED LIST OF PLANET NAME SUGGESTIONS (SEE XKCD.COM/1253)

NEW OR UPDATED ENTRIES IN RED

STAR	PLANET	SUGGESTED NAME
GUESE 667C	b	SPACE PLANET
	c	PILF
	d	A STAR
	e	e'); DROP TABLE PLANETS;--
	f	BLOGOSPHERE
	g	BLOGODROME
	h	EARTH
TAU CETI	b	SID MEIER'S TAU CETI B
	c	GIANT DOG PLANET
	d	TINY DOG PLANET
	e	PHIL PLAINET
	f	UNICODE SNOWMAN
GLIESE 832	b	ASSHOLE JUPITER
	c	*WATERWORLD* STARRING KEVIN COSTNER
GLIESE 581	b	WAIST-DEEP CATS
	c	PLANET #14
	d	BALLDERAAN
	e	ETERNIA PRIME
	f	TAUPE MARS
	g	JELLY-FILLED PLANET
EPSILON ERIDANI	b	SKYDOT
	c	LASER NOISES
GLIESE 176	b	PANDORA
	c	PANTERA
KEPLER-61	b	GOLDENPALACE.COM
GROOMBRIDGE 34A	b	HOT MESS
KEPLER-442	b	SEAS OF TOOTHPASTE
GLIESE-422	b	THIS ONE WEIRD PLANET
EPIC-201367065	b	SULAWESI
	c	HUGE SOCCER BALL
	d	GEODUDE
KEPLER-296	b	KERBAL SPACE PLANET
	c	A$APLANET
	d	JURASSIC WORLD
	e	THIS LAND
	f	SPRINGFIELD
HR 7722	b	BETELGEUSE
	c	BEETLEJUICE
EPIC 201912552	b	NETHERLANDS VI
GLIESE 3293	b	ANTISPIT
	c	GOOGLE EARTH
	d	PLANET OF THE APES (DISAMBIGUATION)
KEPLER-283	b	ˈjʊərənəs
	c	jʊˈreɪnəs
UPSILON ANDROMEDAE	b	FOURTHMEAL
	c	STAMPY
	d	MOONCHILD
	e	HAM SPHERE
HD 20794	b	COSMIC SANDS
	c	LEGOLAND
	d	PLANET WITH ARMS
HD 85512	b	LAX MORALITY
HD 40307	b	GOOD PLANET
	c	PROBLEMLAND
	d	SLICKLE
	e	SPARE PARTS
	f	NEW JERSEY VI
	g	HOW DO I JOIN THE IAU
GLIESE 163	b	NEIL TYSON'S MUSTACHE
	c	HELP@GMAIL.COM
	d	HAIR-COVERED PLANET
PI MENSAE	b	MOON HOLDER
HD 189733	b	PERMADEATH
KEPLER-22	b	BLUE IVY
KOI-2474	b	STORE-BRAND EARTH
KEPLER-437	b	UNICORN THRESHER
KOI-2418	b	SPHERICAL DISCWORLD
KEPLER-438	b	EMERGENCY BACKUP EARTH
KOI-3010	b	FEEEOOOOOOOOP
KEPLER-442	b	LIZ
82 ERIDANI	b	HORSEMEAT SURFACE
	c	THE MOON
	d	CONSTANT SAXOPHONES
HD 102365	b	LITTLE BIG PLANET
GLIESE 180	b	DUNE
	c	ARRAKIS
FOMALHAUT	b	SWARM OF BEES
KEPLER-62	b	SPORTY
	c	BABY
	d	SCARY
	e	GINGER
	f	POSH
HD 69830	b	PLANET.XXX
	c	NOVELLA
	d	SEXOPLANET
GLIESE 682	b	VERDANT HELLSCAPE
	c	UNSUBSCRIBE
KEPLER-452	b	PLUTO

XKCD/1555



WHILE WE WAIT TO HEAR FROM THE IAU, HERE'S A REVISED AND UPDATED LIST OF PLANET NAME SUGGESTIONS (SEE XKCD.COM/1253)

NEW OR UPDATED ENTRIES IN RED

STAR	PLANET	SUGGESTED NAME
GUESE 667C	b	SPACE PLANET
	c	PILF
	d	A STAR
	e	e'); DROP TABLE PLANETS;--
	f	BLOGOSPHERE
	g	BLOGODROME
	h	EARTH
TAU CETI	b	SID MEIER'S TAU CETI B
	c	GIANT DOG PLANET
	d	TINY DOG PLANET
	e	PHIL PLAINET
	f	UNICODE SNOWMAN
GLIESE 832	b	ASSHOLE JUPITER
	c	WATERWORLD STARRING KEVIN COSTNER
GLIESE 581	b	WAIST-DEEP CATS
	c	PLANET #14
	d	BALLDERAAN
	e	ETERNIA PRIME
	f	TAUPE MARS
	g	JELLY-FILLED PLANET
EPSILON ERIDANI	b	SKYDOT
	c	LASER NOISES
GLIESE 176	b	PANDORA
	c	PANTERA
KEPLER-61	b	GOLDENPALACE.COM
GROOMBRIDGE 34A	b	HOT MESS
KEPLER-442	b	SEAS OF TOOTHPASTE
GLIESE-422	b	THIS ONE WEIRD PLANET
EPIC-201367065	b	SULAWESI
	c	HUGE SOCCER BALL
	d	GEODUDE
KEPLER-296	b	KERBAL SPACE PLANET
	c	A$APLANET
	d	JURASSIC WORLD
	e	THIS LAND
	f	SPRINGFIELD
HR 7722	b	BETELGEUSE
	c	BEETLEJUICE
EPIC 201912552	b	NETHERLANDS VI
GLIESE 3293	b	ANTISPIT
	c	GOOGLE EARTH
	d	PLANET OF THE APES (DISAMBIGUATION)
KEPLER-283	b	ˈjʊərənəs
	c	juˈreɪnəs
UPSILON ANDROMEDAE	b	FOURTHMEAL
	c	STAMPY
	d	MOONCHILD
	e	HAM SPHERE
HD 20794	b	COSMIC SANDS
	c	LEGOLAND
	d	PLANET WITH ARMS
HD 85512	b	LAX MORALITY
HD 40307	b	GOOD PLANET
	c	PROBLEMLAND
	d	SLICKLE
	e	SPARE PARTS
	f	NEW JERSEY VI
	g	HOW DO I JOIN THE IAU
GLIESE 163	b	NEIL TYSON'S MUSTACHE
	c	HELP@GMAIL.COM
	d	HAIR-COVERED PLANET
PI MENSAE	b	MOON HO
HD 189733	b	
KEPLER-22		
KOI-2474		
KEPLER-43		
KOI-2418		
KEPLER-438		
KOI-3010	b	
KEPLER-442	b	LIZ
82 ERIDANI	b	HORSEME SURFA
	c	THE M N
	d	CONSTANT SAXOPHONES
HD 102365	b	LITTLE BIG PLANET
GLIESE 1	b	DUNE
	c	ARRAKIS
FOMALHAUT	b	SWARM OF BEES
KEPLER-62	b	SPORTY
	c	BABY
	d	SCARY
	e	GINGER
	f	POSH
HD 69830	b	PLANET.XXX
	c	NOVELLA
	d	SEXOPLANET
GLIESE 682	b	VERDANT HELLSCAPE
	c	UNSUBSCRIBE
KEPLER-452	b	PLUTO

HR 7722 b BETELGEUSE
c BEETLEJUICE
EPIC 201912552 b NETHERLANDS VI
GLIESE 3293 b ANTISPIT
c GOOGLE EARTH

XKCD/1555

Probabilistic modeling—combining physical and data-driven models—enables the discovery of new planets using open data and open source software

Foreman-Mackey, Montet, Hogg, *et al.* (arXiv:1502.04715)
Montet, Morton, **Foreman-Mackey**, *et al.* (arXiv:1503.07866)
Schölkopf, Hogg, Wang, **Foreman-Mackey**, *et al.* (arXiv:1505.03036)