# Scaling **Gaussian Processes** and the search for **exoplanets**

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# I study astronomy.

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

this isn't what
my data look like →

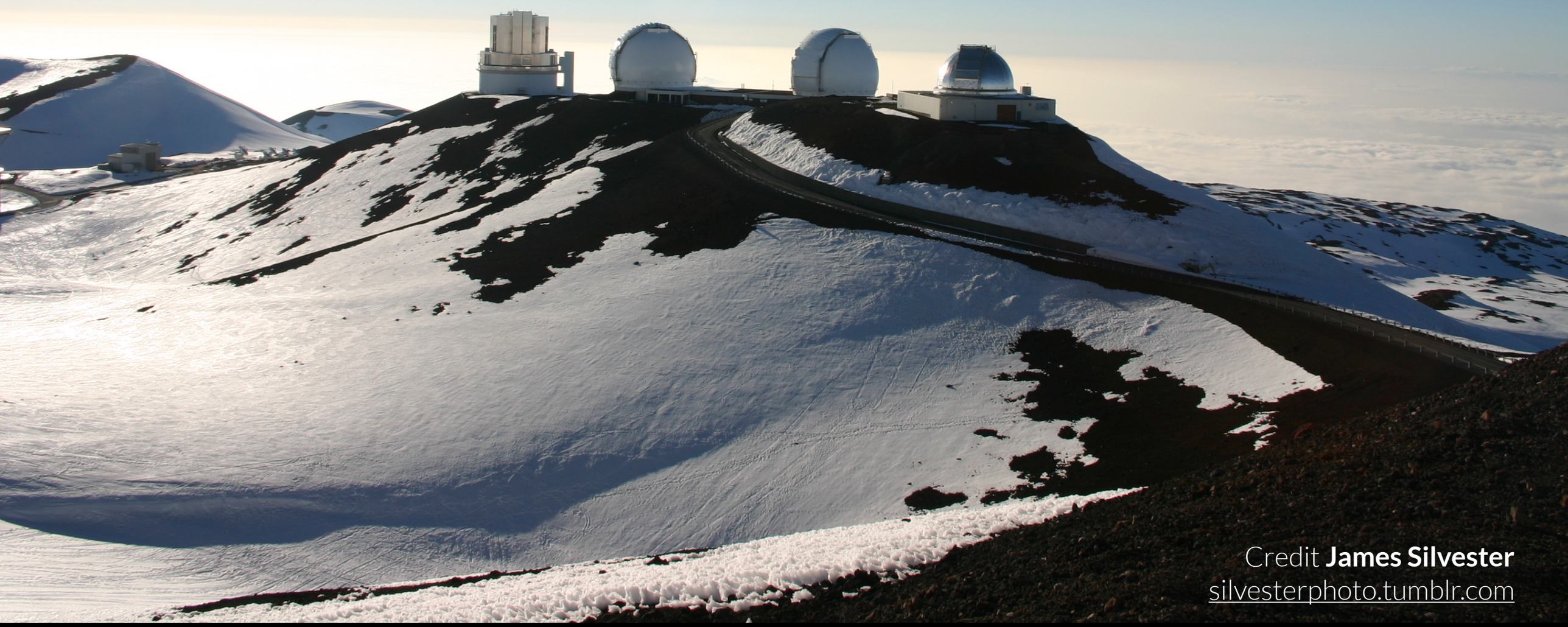
# I study astronomy.

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

*I do data science…*

*(don't we all?)*

*this is **not** what my data science looks like.*



Credit **James Silvester**
silvesterphoto.tumblr.com

*that's more like it...*

*this is what my data science looks like.*

*my*

# GOALS

*for today's talk*

*convince you that*

# exoplanets are cool

# GOALS

*for today's talk*

*convince you that*

# exoplanets are cool

*demonstrate some*

# sick Python code

*for today's talk*

# 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?*

1307 transit

644 radial velocity

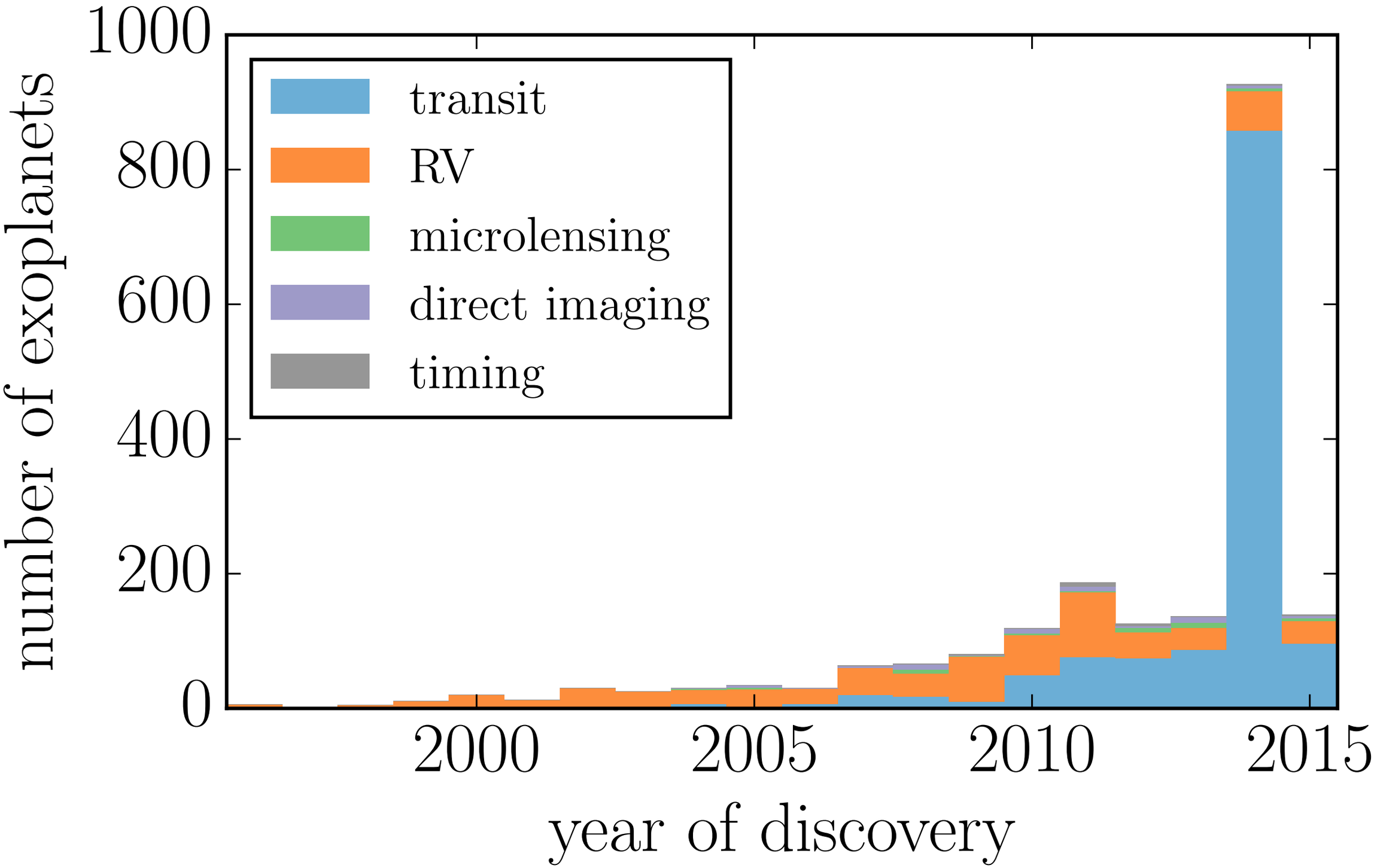
48 direct imaging

37 microlensing

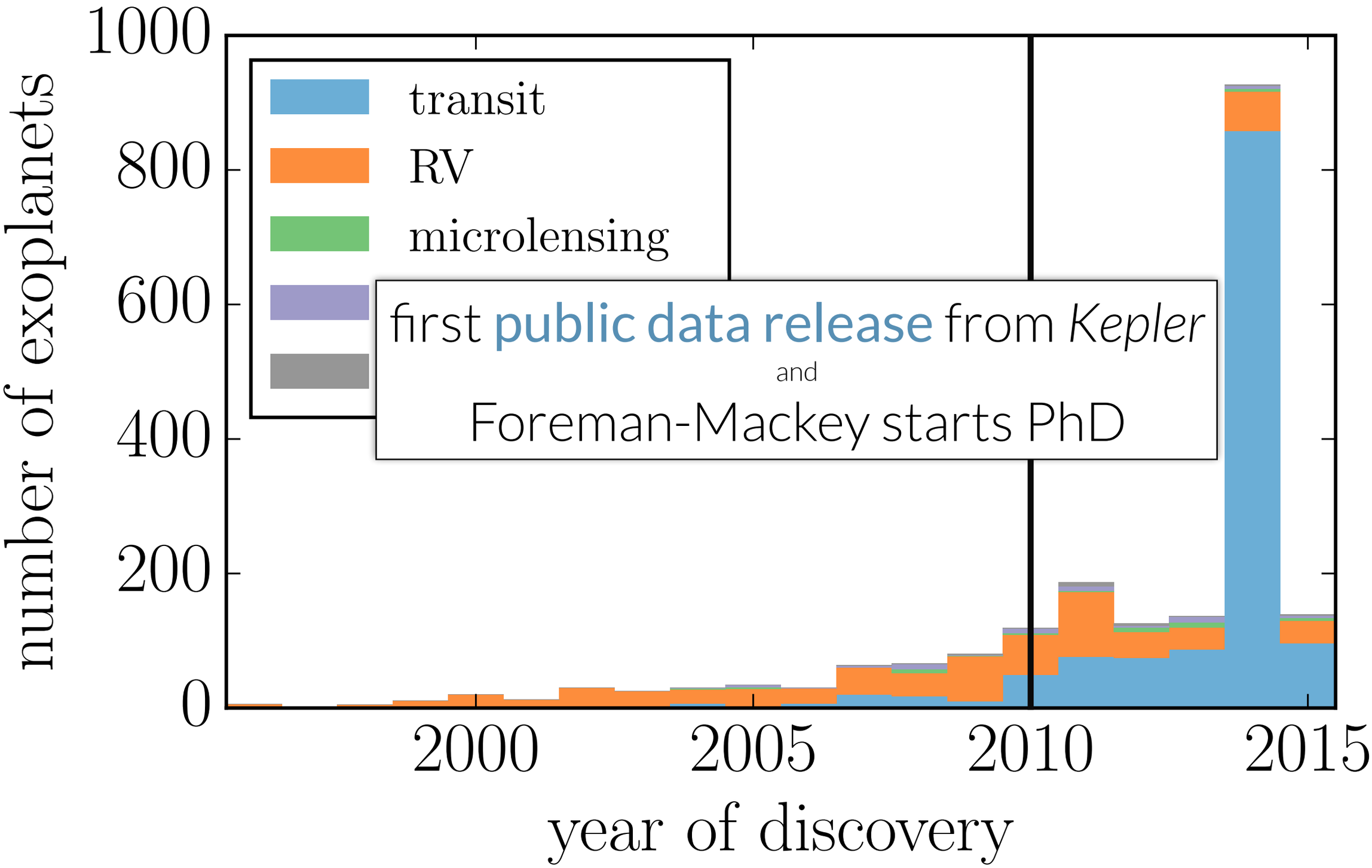
24 timing

0 astrometry

Data from **Open Exoplanet Catalogue** (2015-10-28)

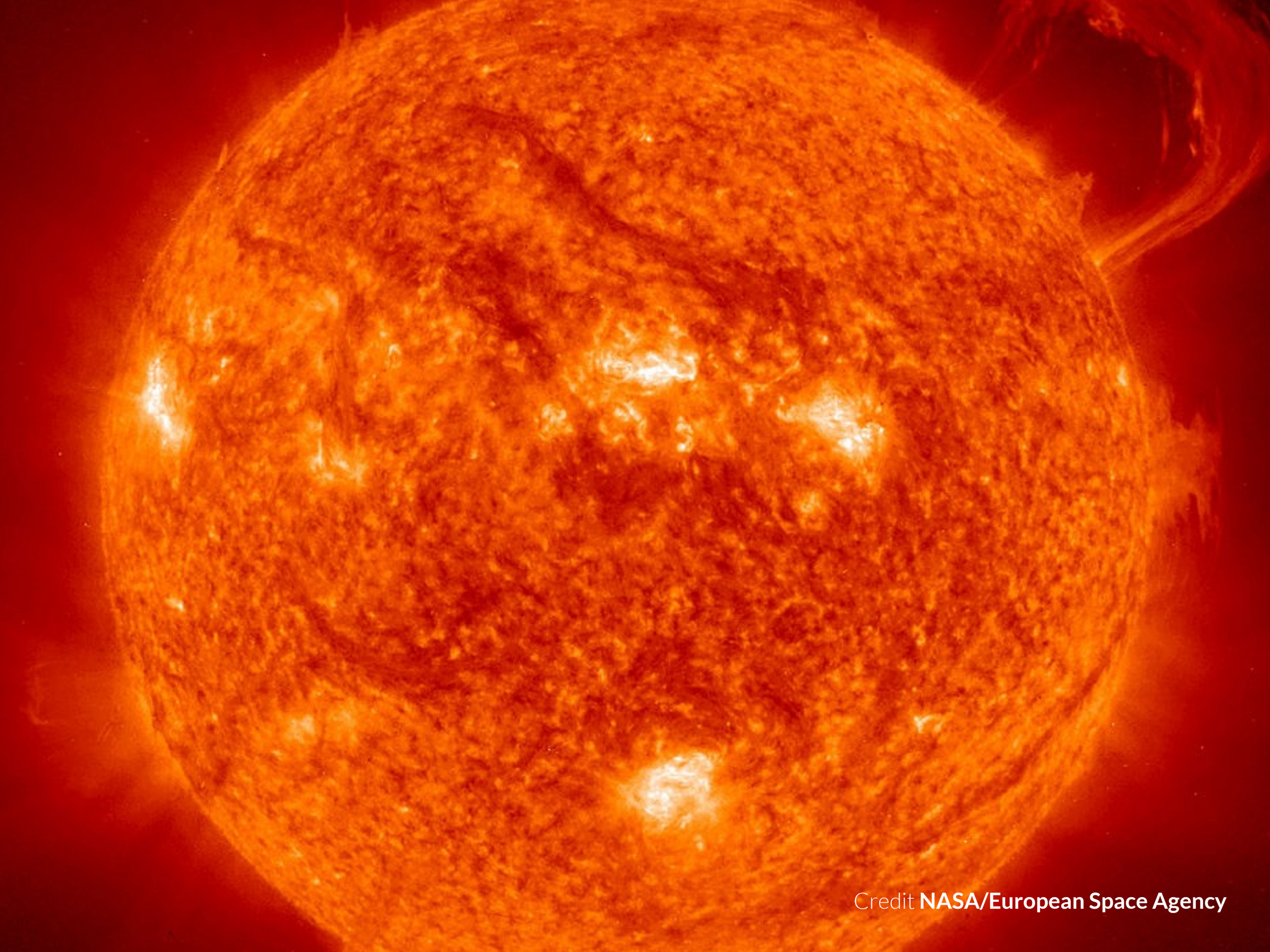



Data from **Open Exoplanet Catalogue** (2015-10-28)

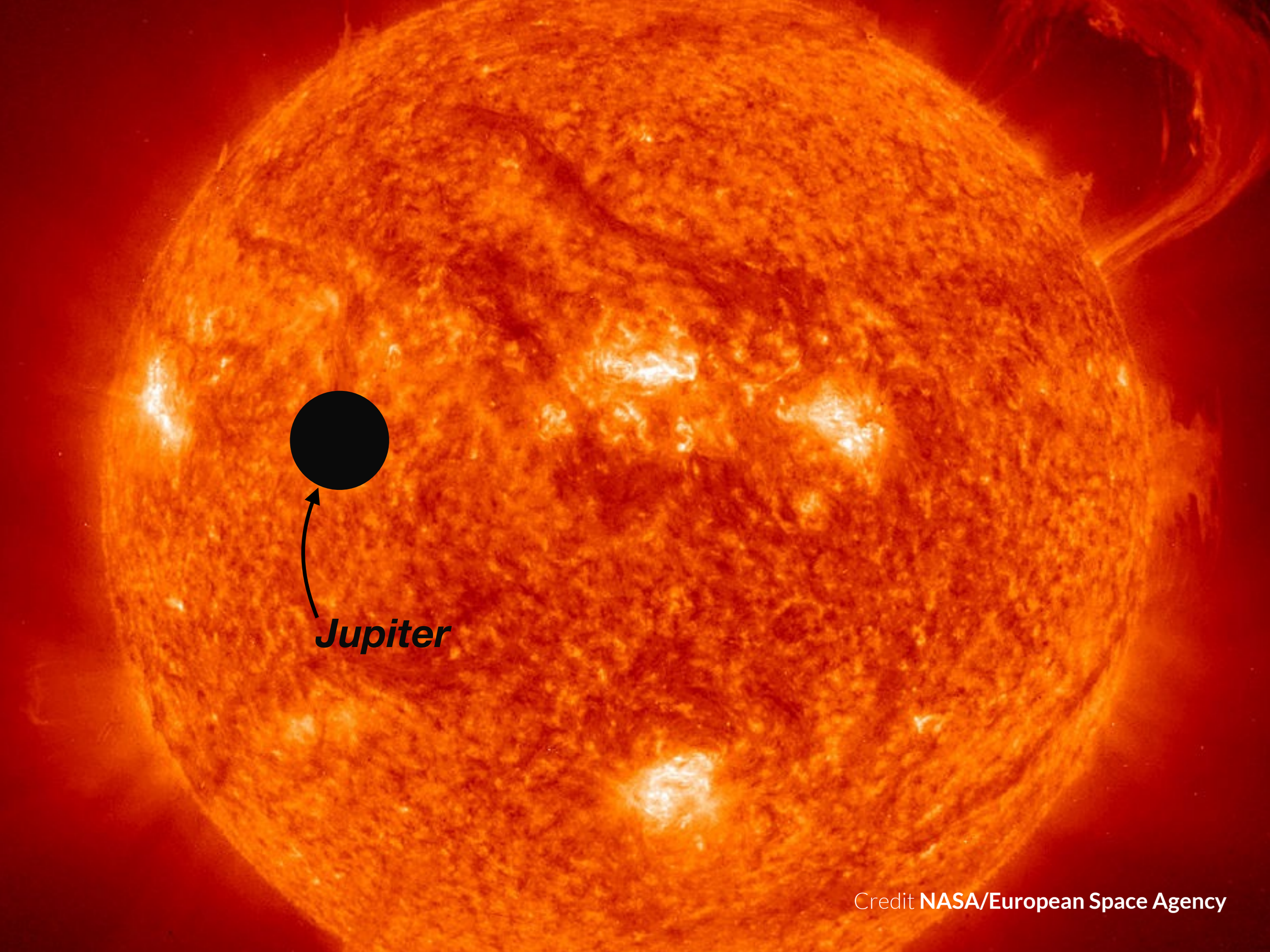



Data from **Open Exoplanet Catalogue** (2015-10-28)

*the **transit** method*



Credit **NASA/European Space Agency**

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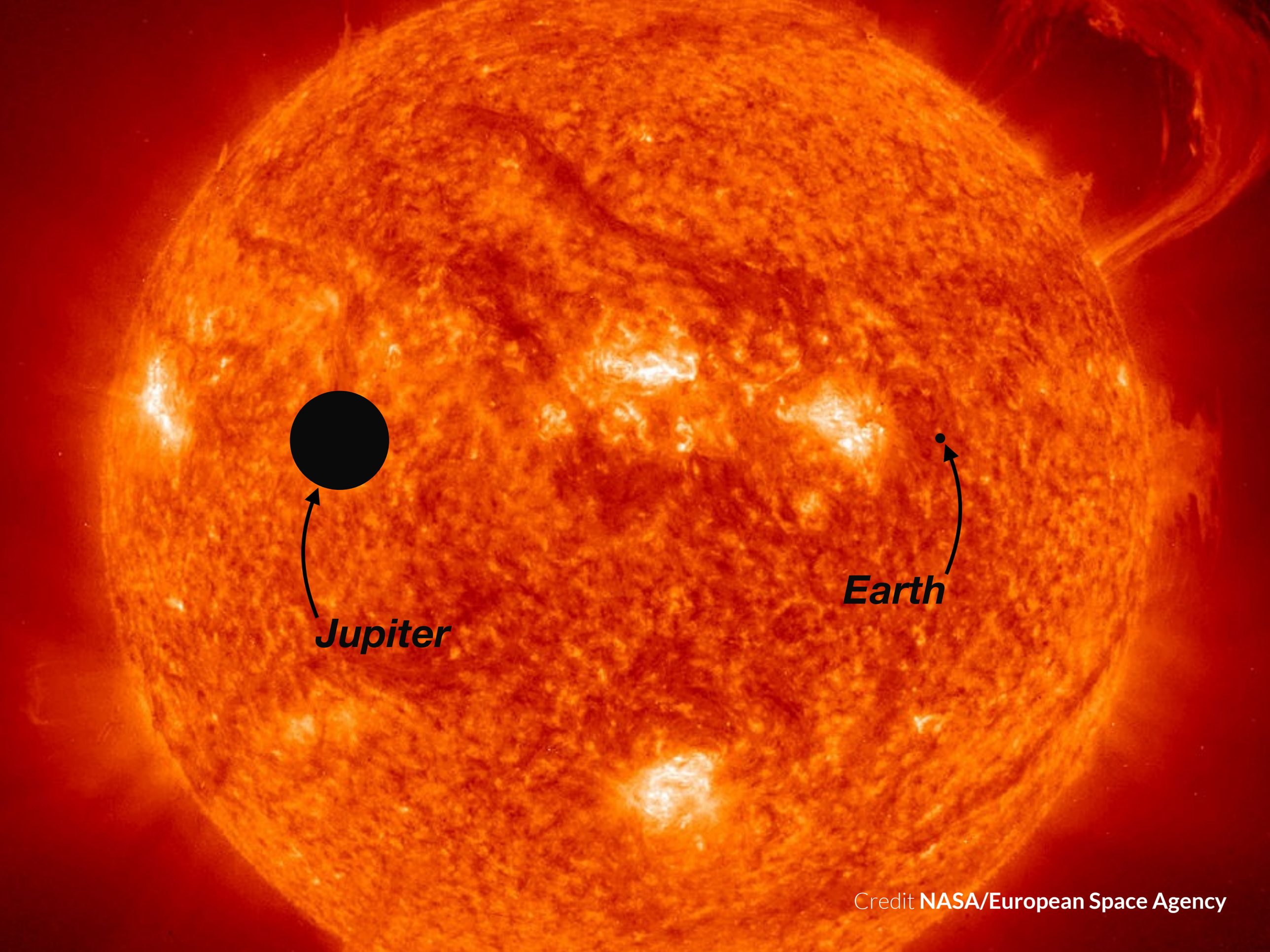
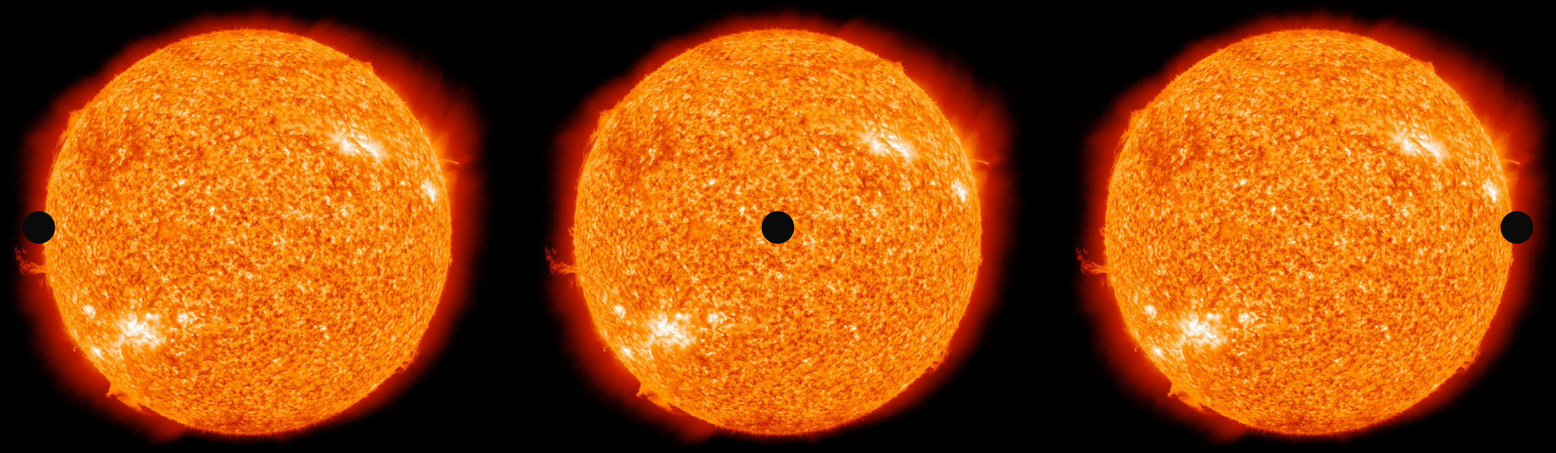
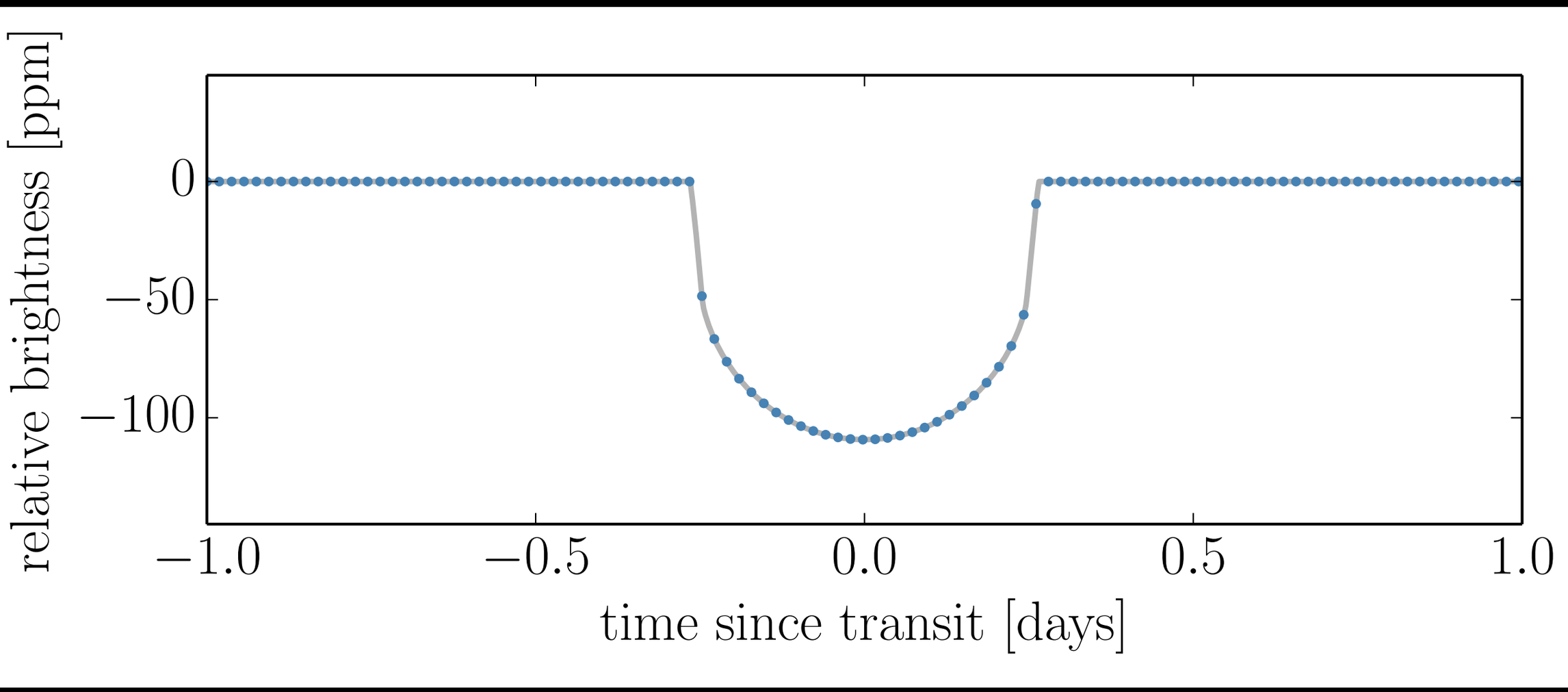



Credit **NASA/European Space Agency**

*that's not what most stars look like!*

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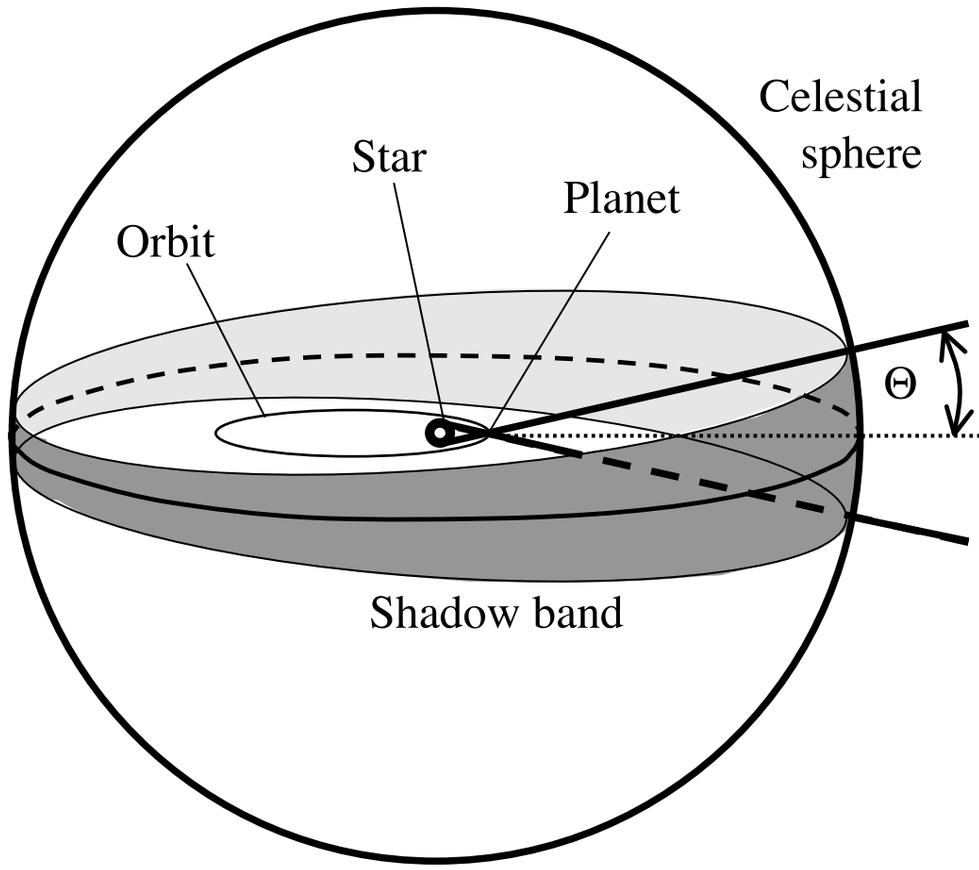
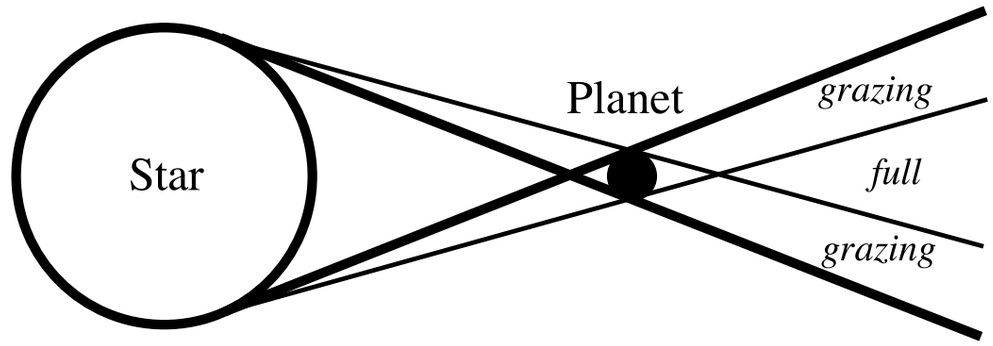
−100
−1.0
−0.5
0.0
0.5
1.0
time since transit [days]

*everything is against us!*




Close-up

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

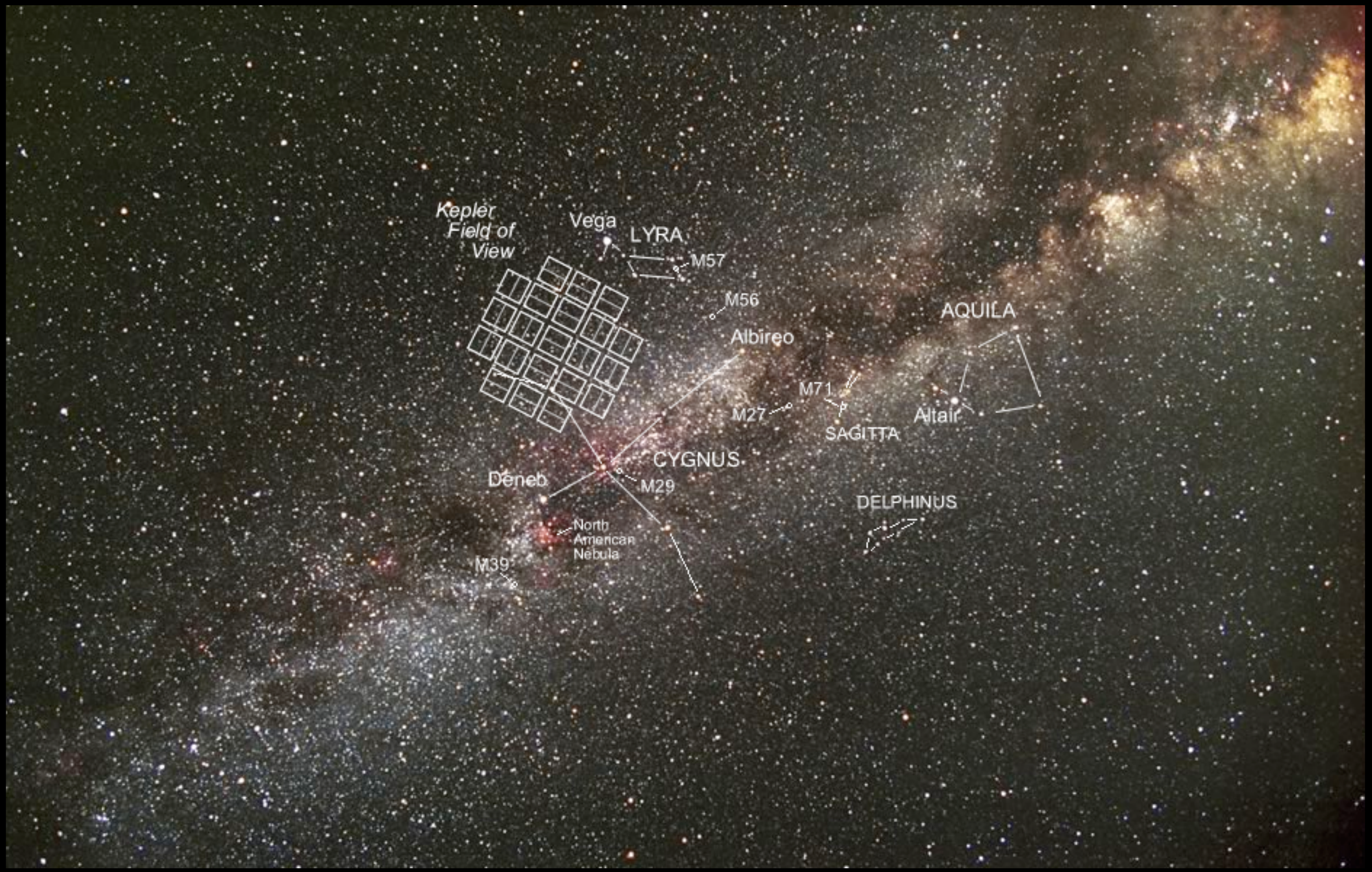
need to look at **the right place**
at **the right time**

and measure
***extremely precise***
photometry

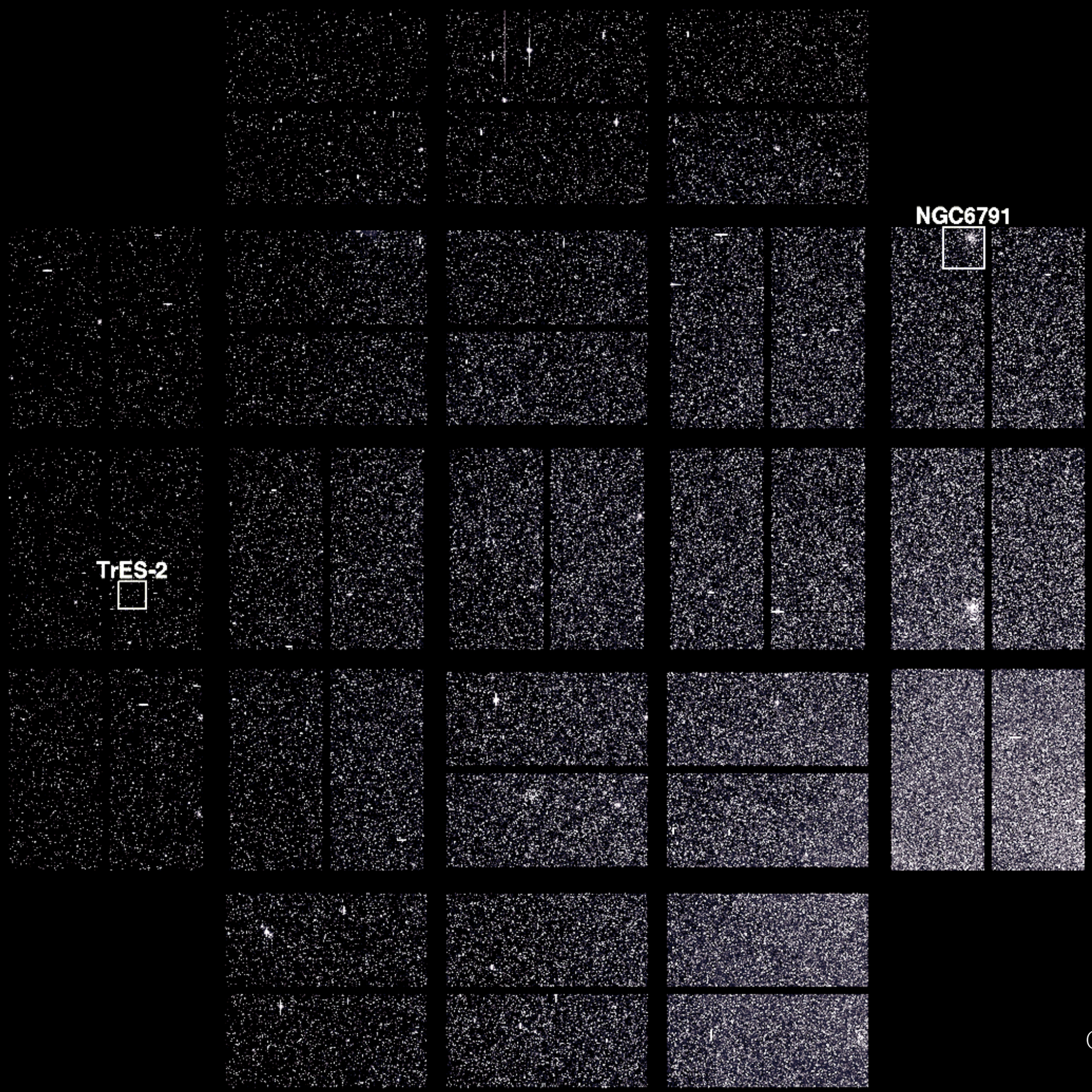
# *Kepler*

Credit **NASA**

Credit **NASA**



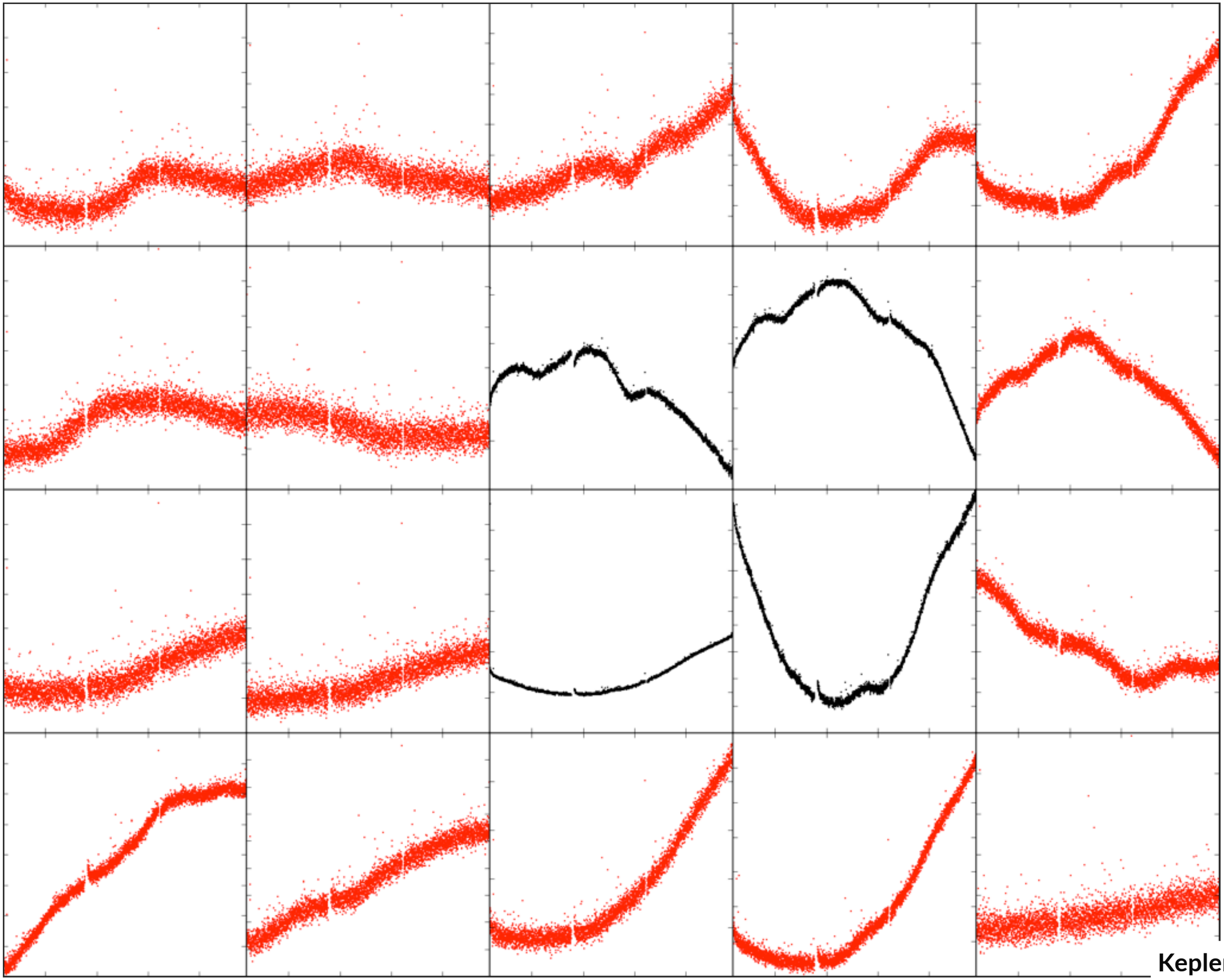

Credit **Carter Roberts**



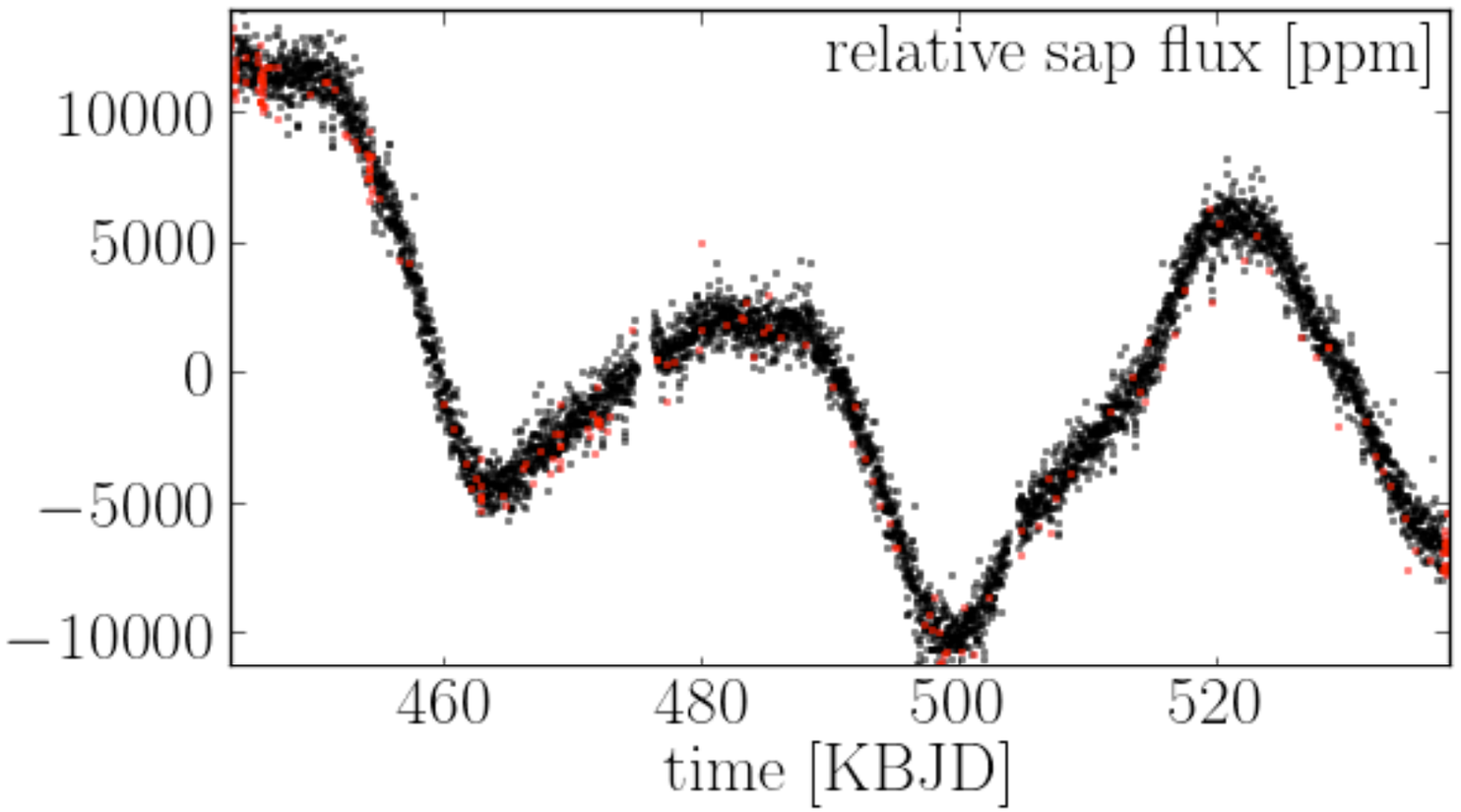

Credit **NASA**

Kepler-32

Kepler-32



Kepler-32


relative sap flux [ppm]
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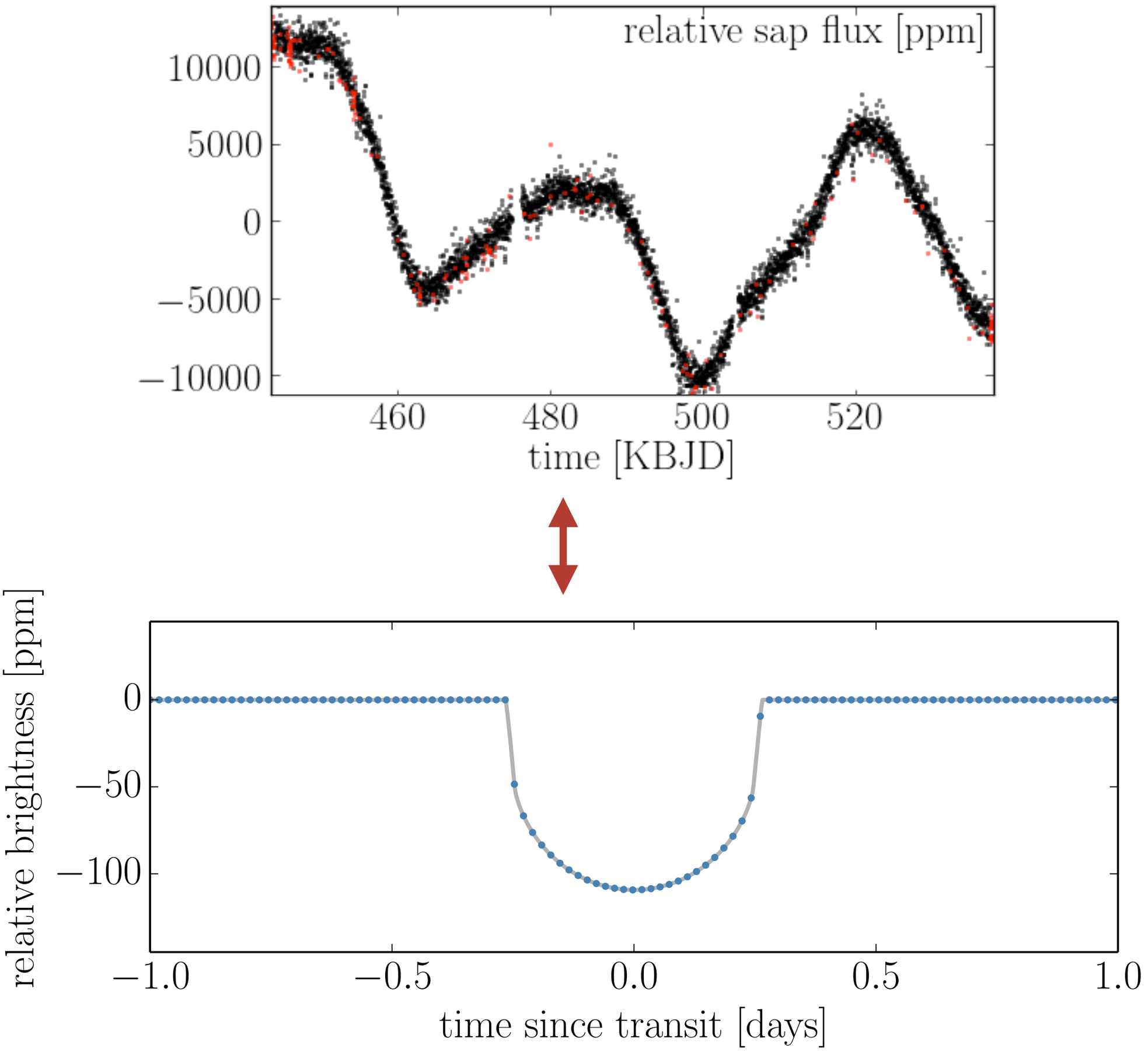
480
500
520
time [KBJD]


relative sap flux [ppm]
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time [KBJD]
relative brightness [ppm]
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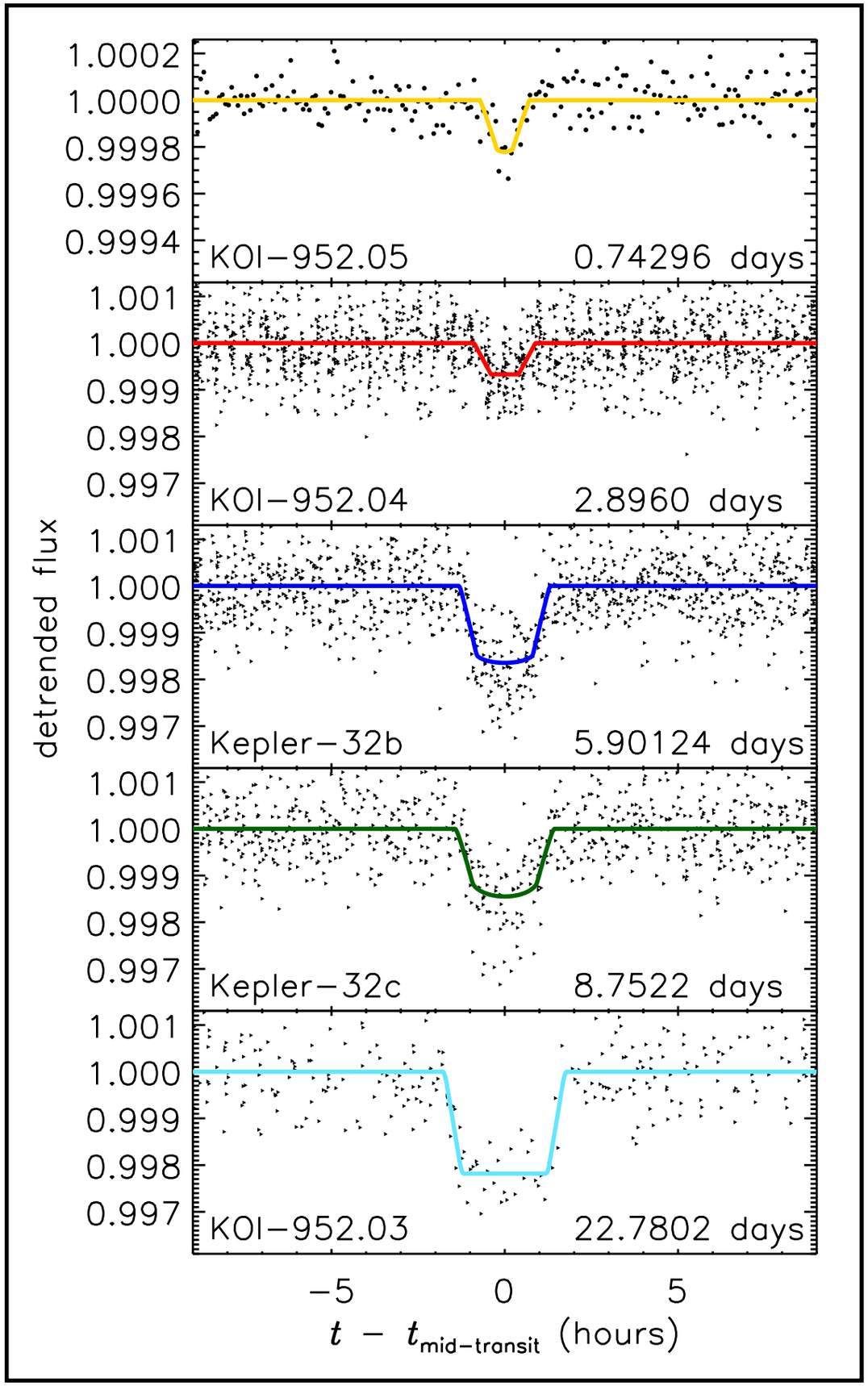
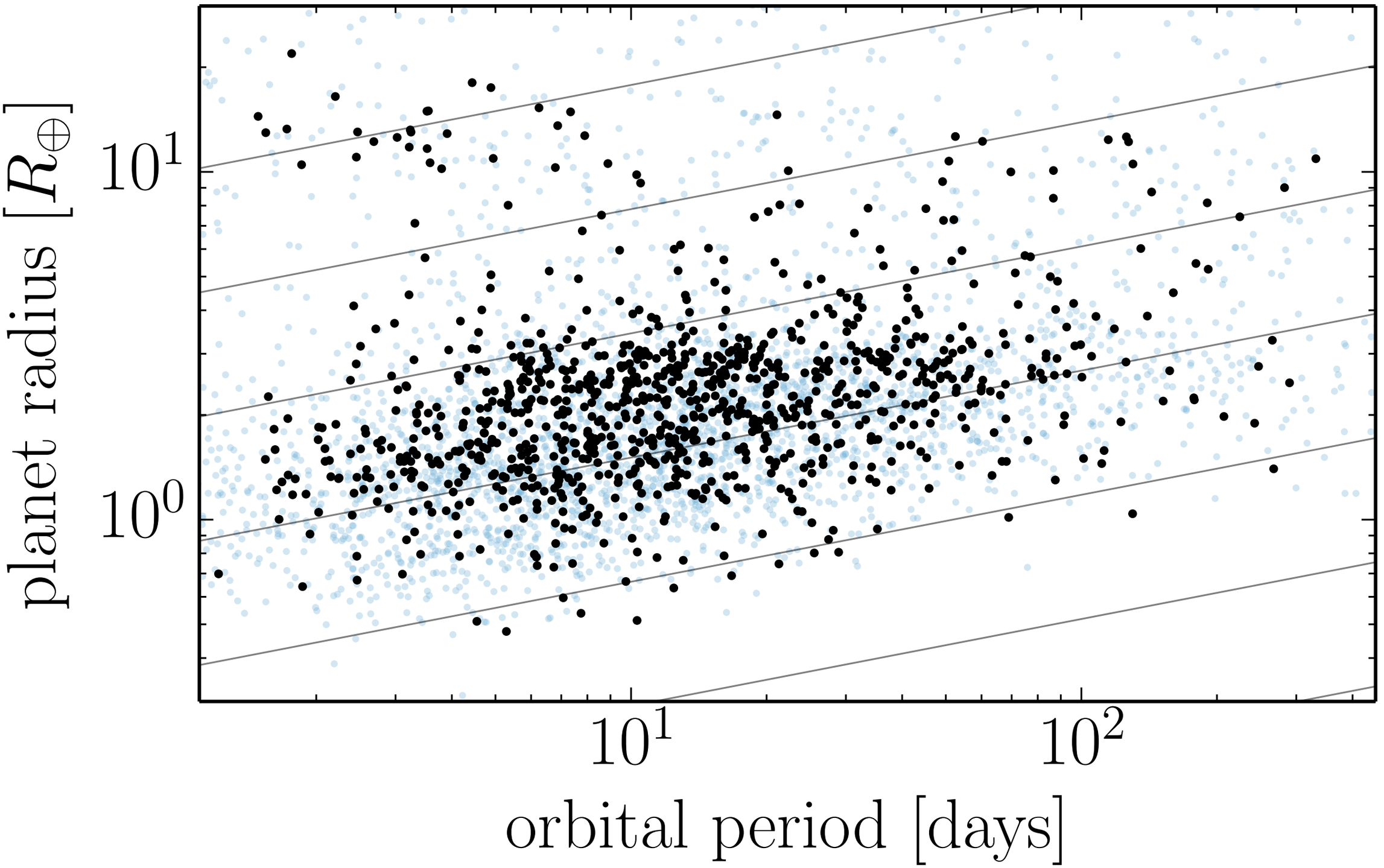
time since transit [days]

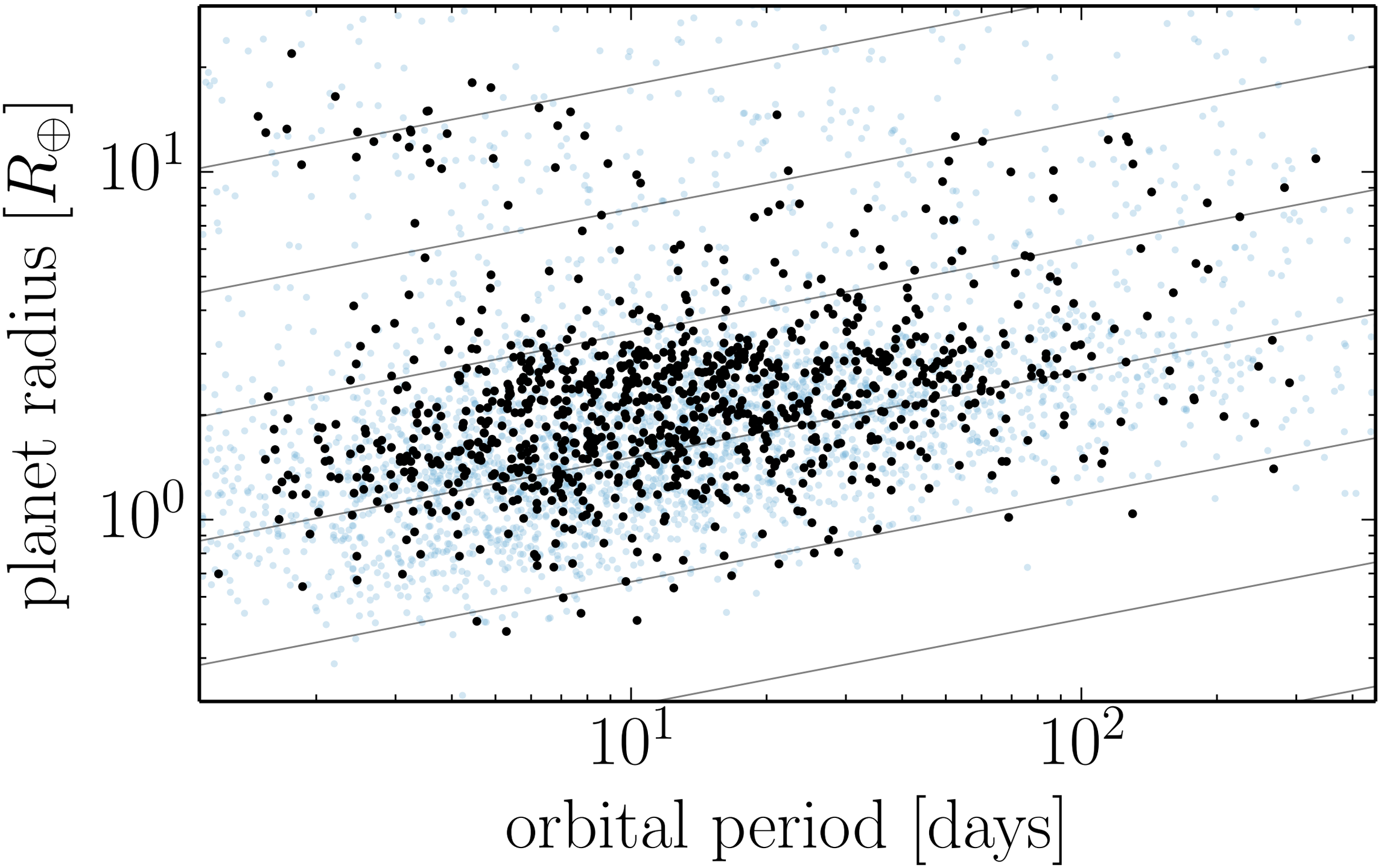



Credit **Fabrycky *et al.* (2012)**




Data from **NASA Exoplanet Archive**

*that looks pretty good…*

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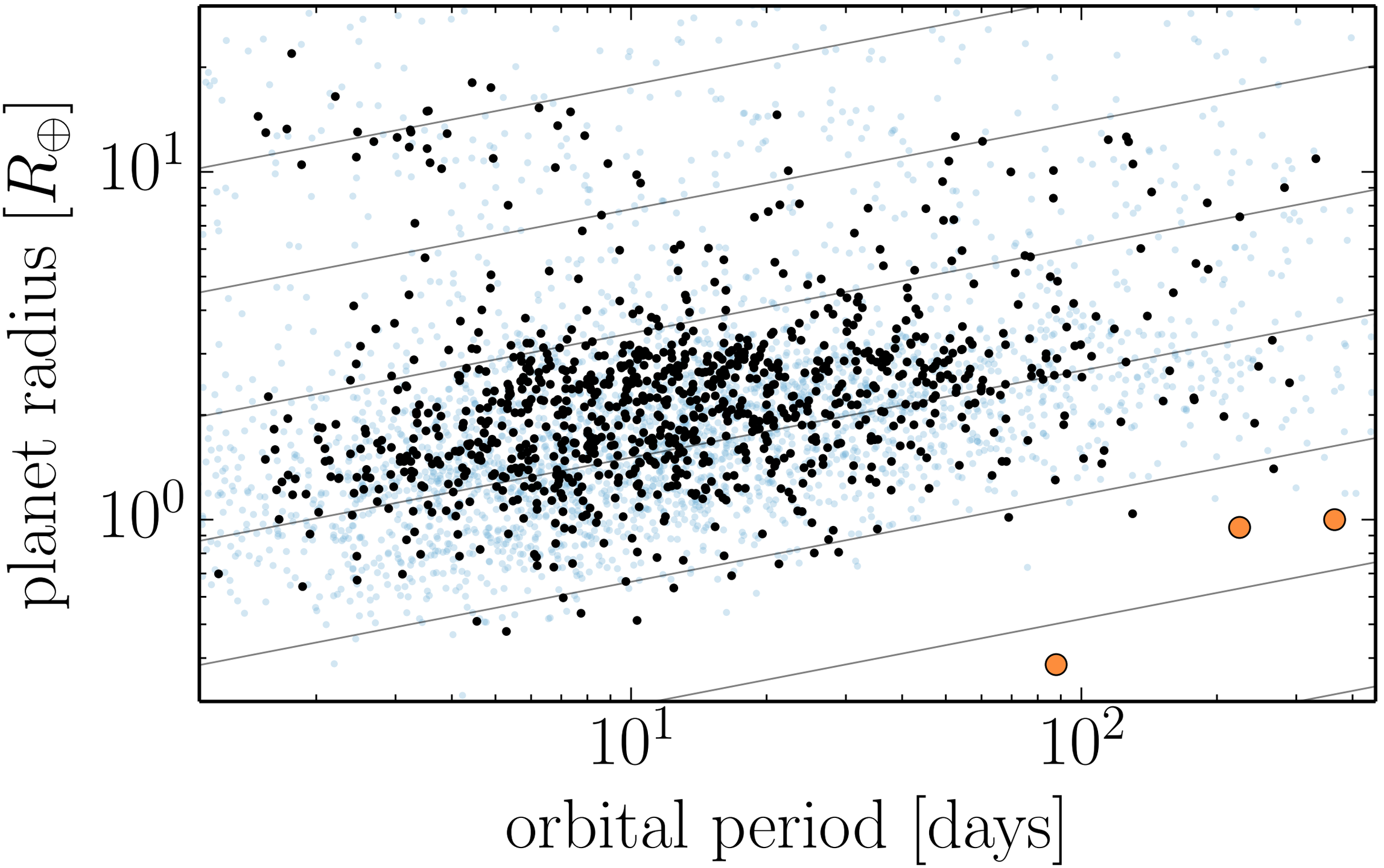


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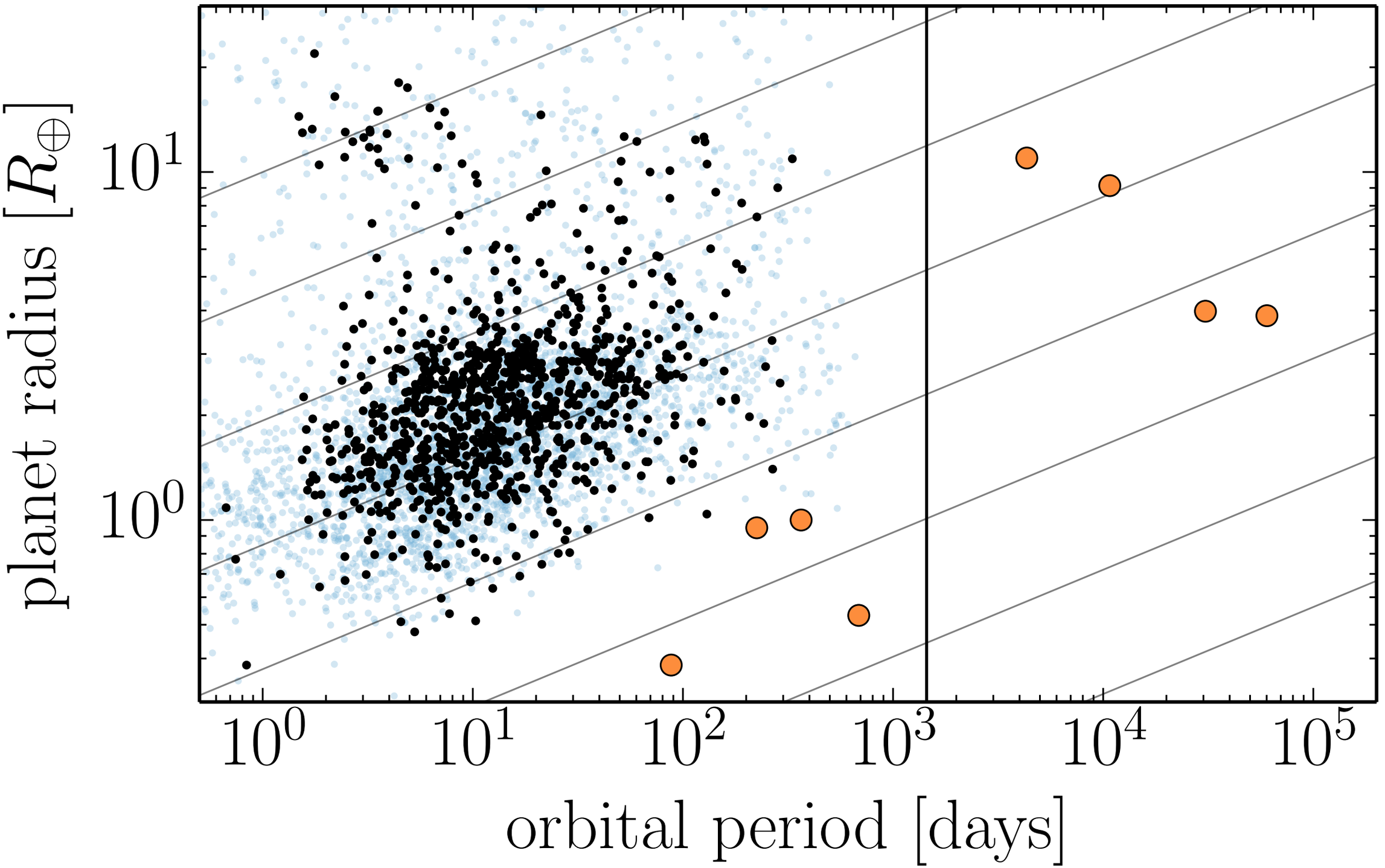


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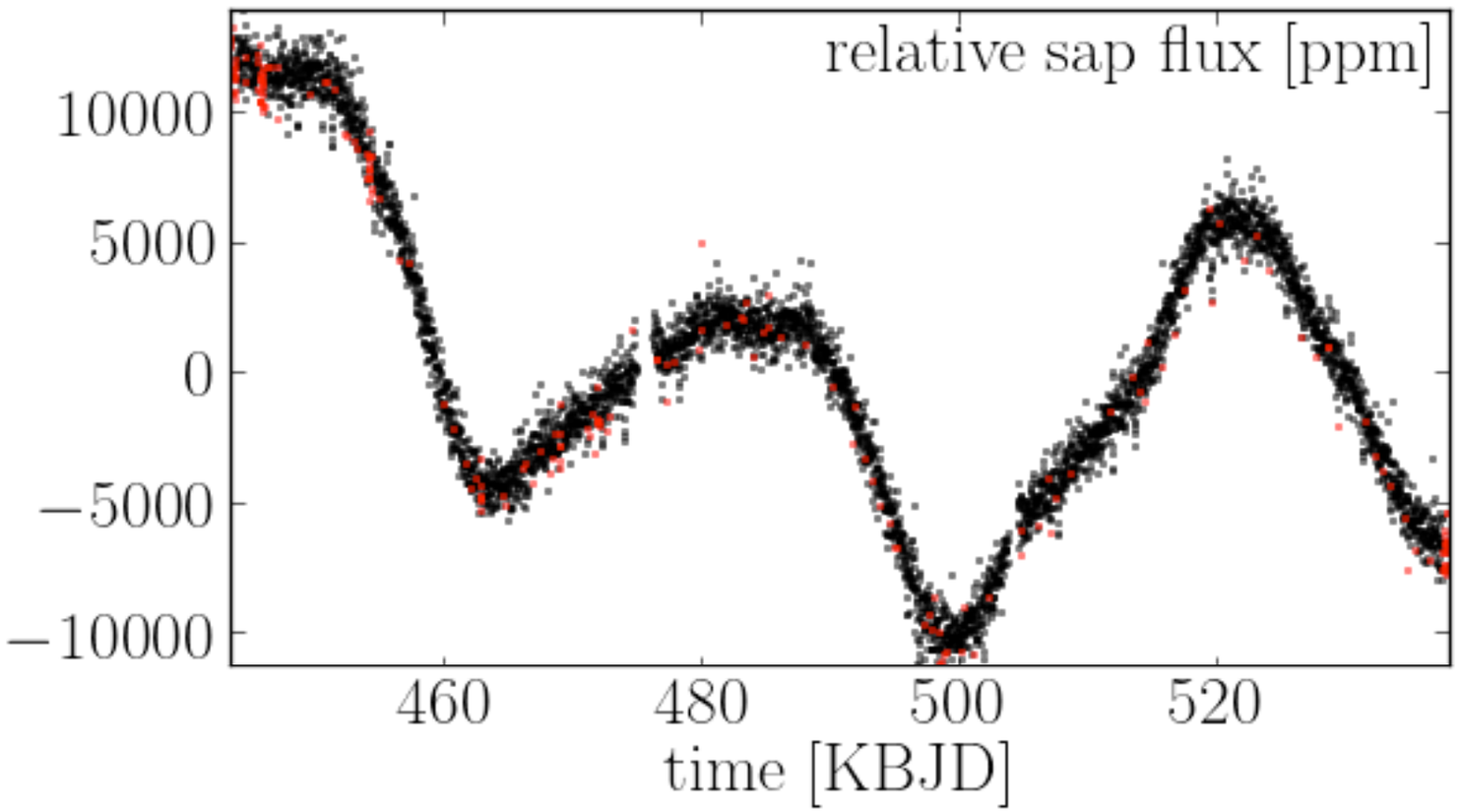
relative sap flux [ppm]
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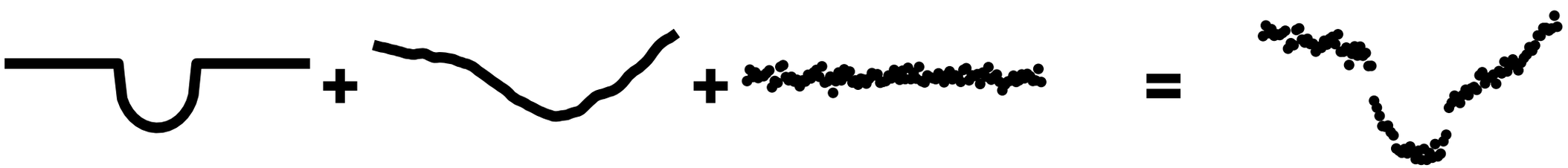
520
time [KBJD]

# The anatomy of a transit observation



signal variability noise data

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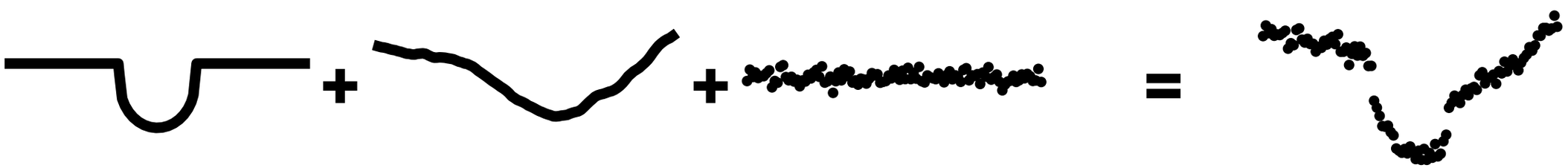

signal variability noise data

**astrophysics** and **spacecraft**

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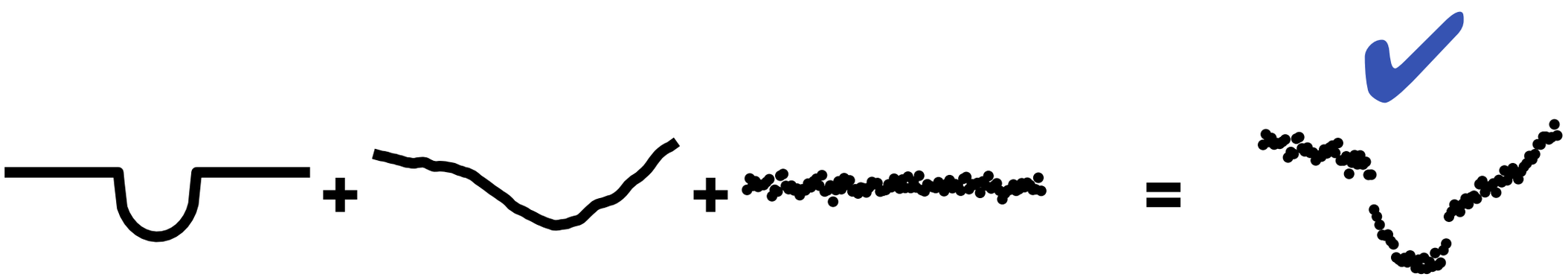
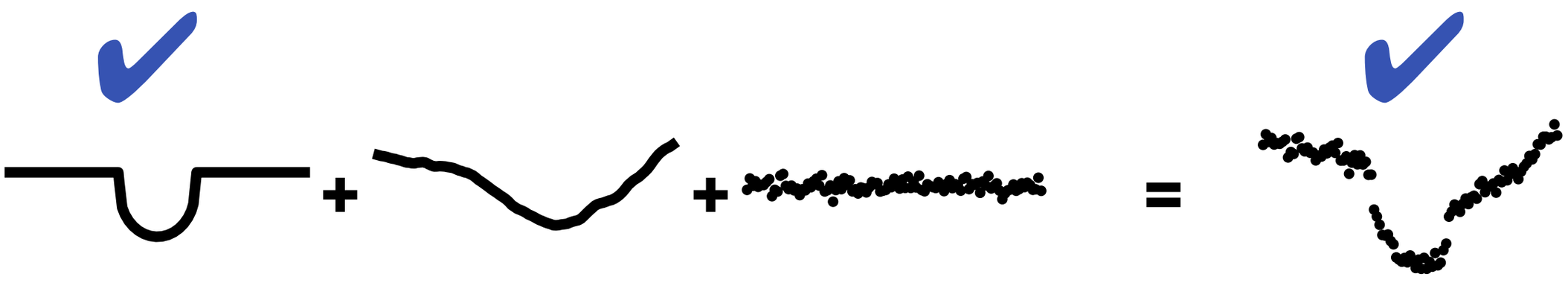


signal variability noise data

**astrophysics** and **spacecraft**

# The anatomy of a transit observation



signal variability noise data

**astrophysics** and **spacecraft**

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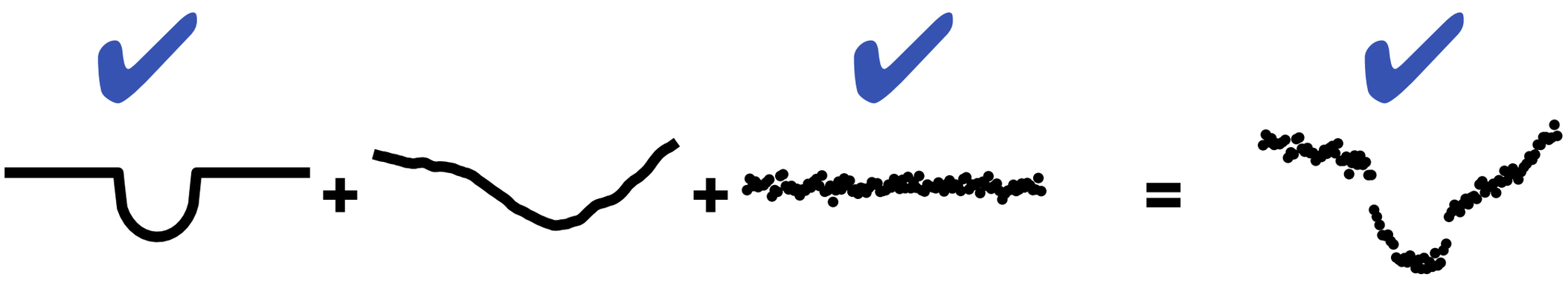

signal variability noise data

**astrophysics** and **spacecraft**

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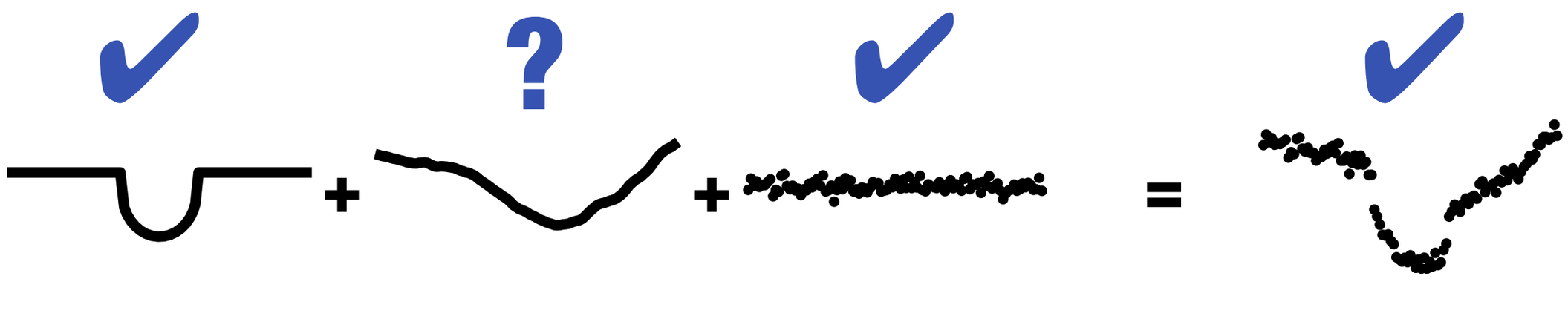
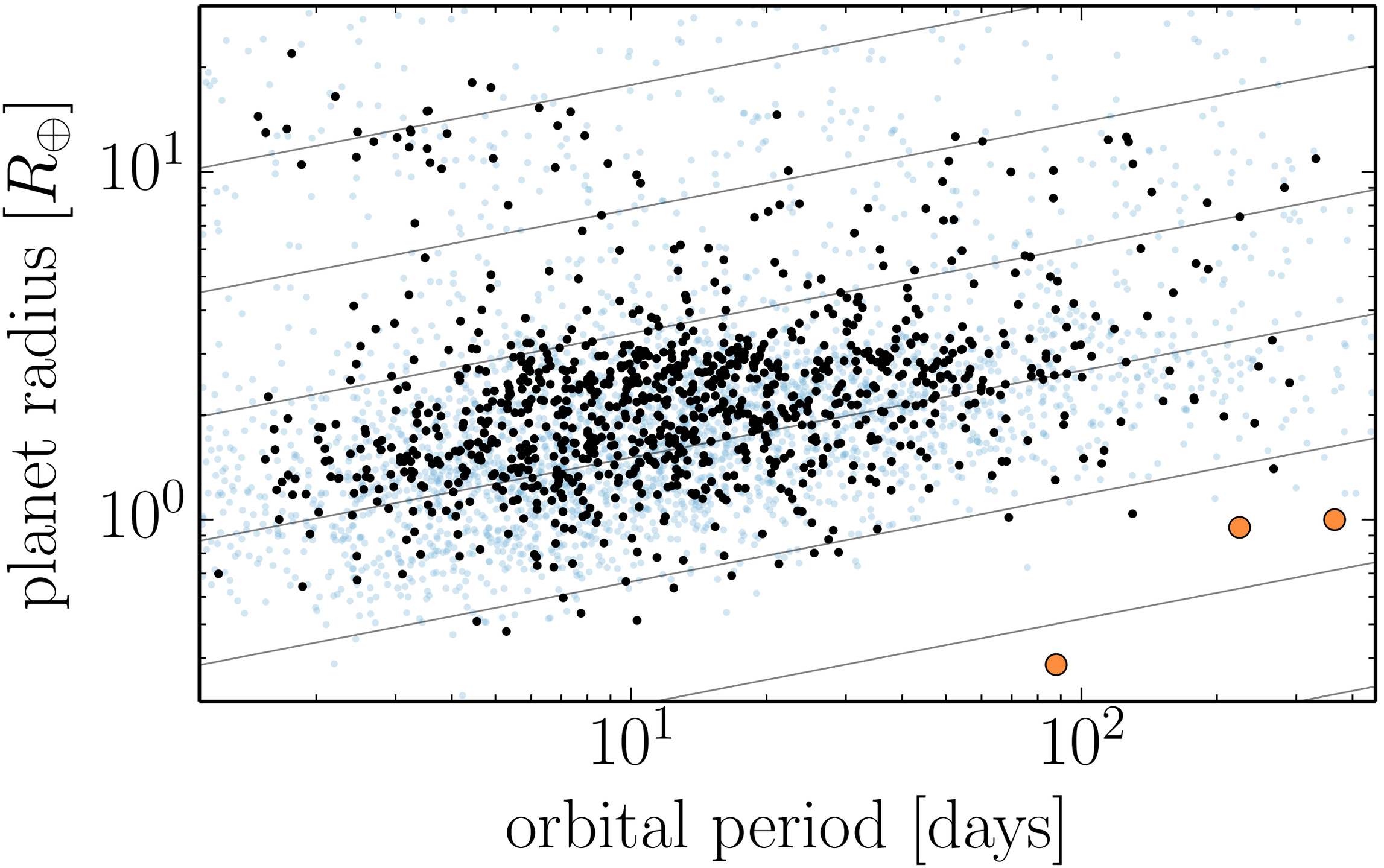


signal variability noise data

**astrophysics** and **spacecraft**

*how do we clean up this mess?*

# Standard practice: **Filtering**




Data from **NASA Exoplanet Archive**

# Exoplanets are **hard** to find

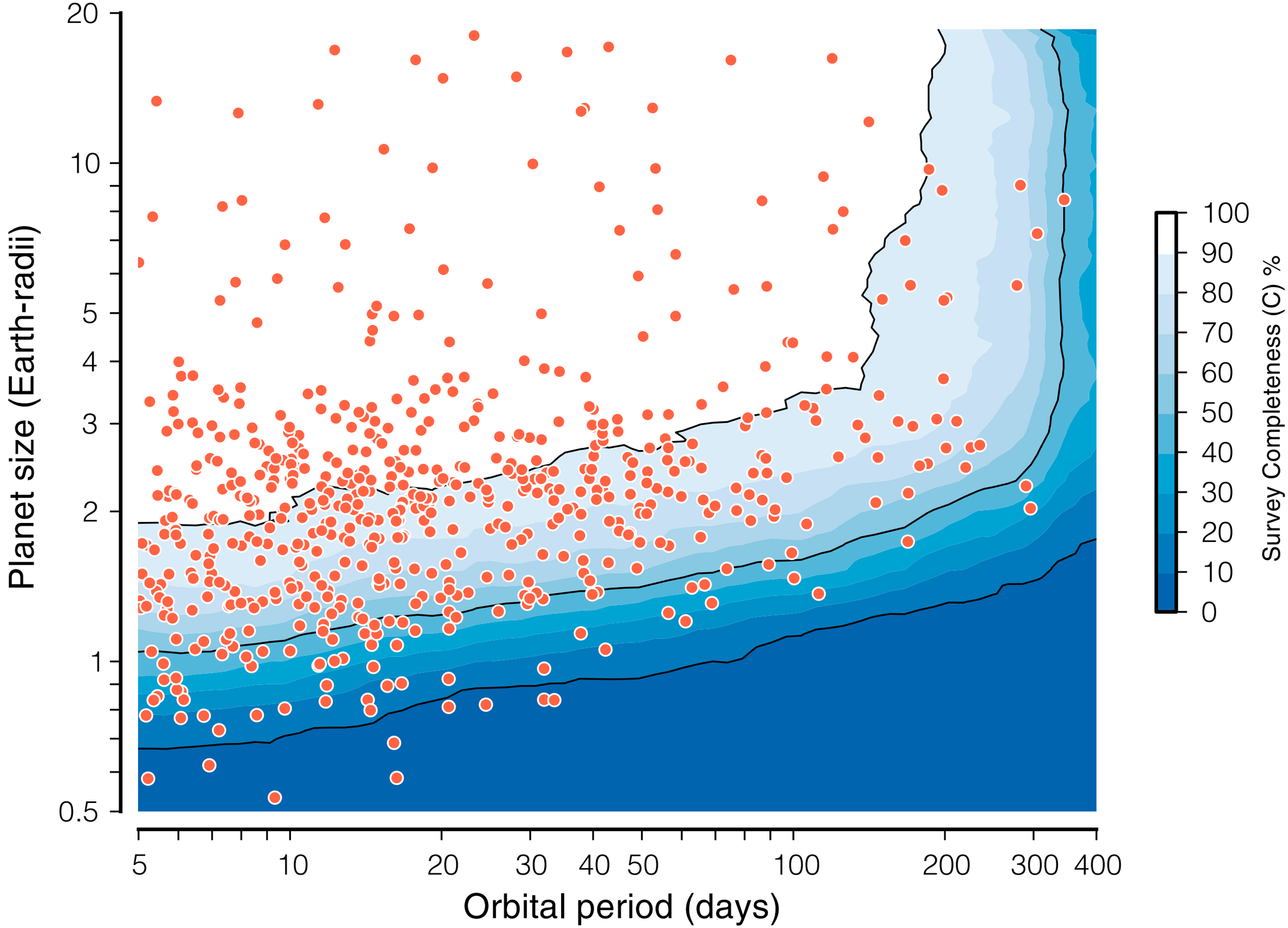


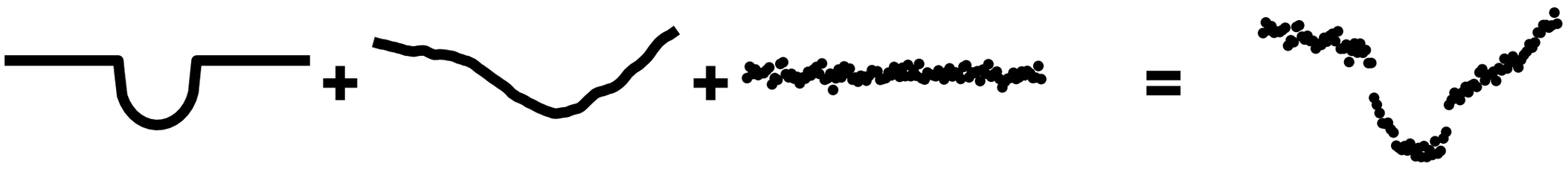

Figure credit: **Petigura, Howard & Marcy (2013)**

# What about Gaussian Processes?

gaussianprocess.org/gpml

Rasmussen & Williams

# Modeling a light curve using a **Gaussian Processes**



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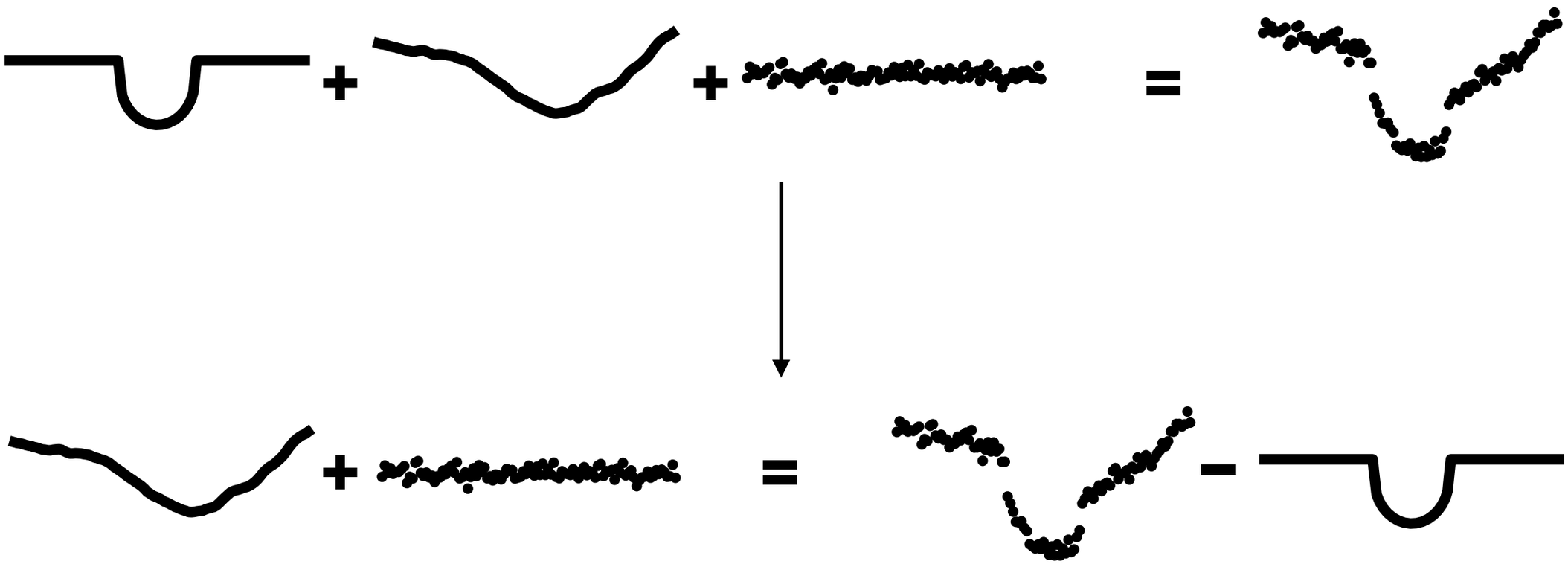

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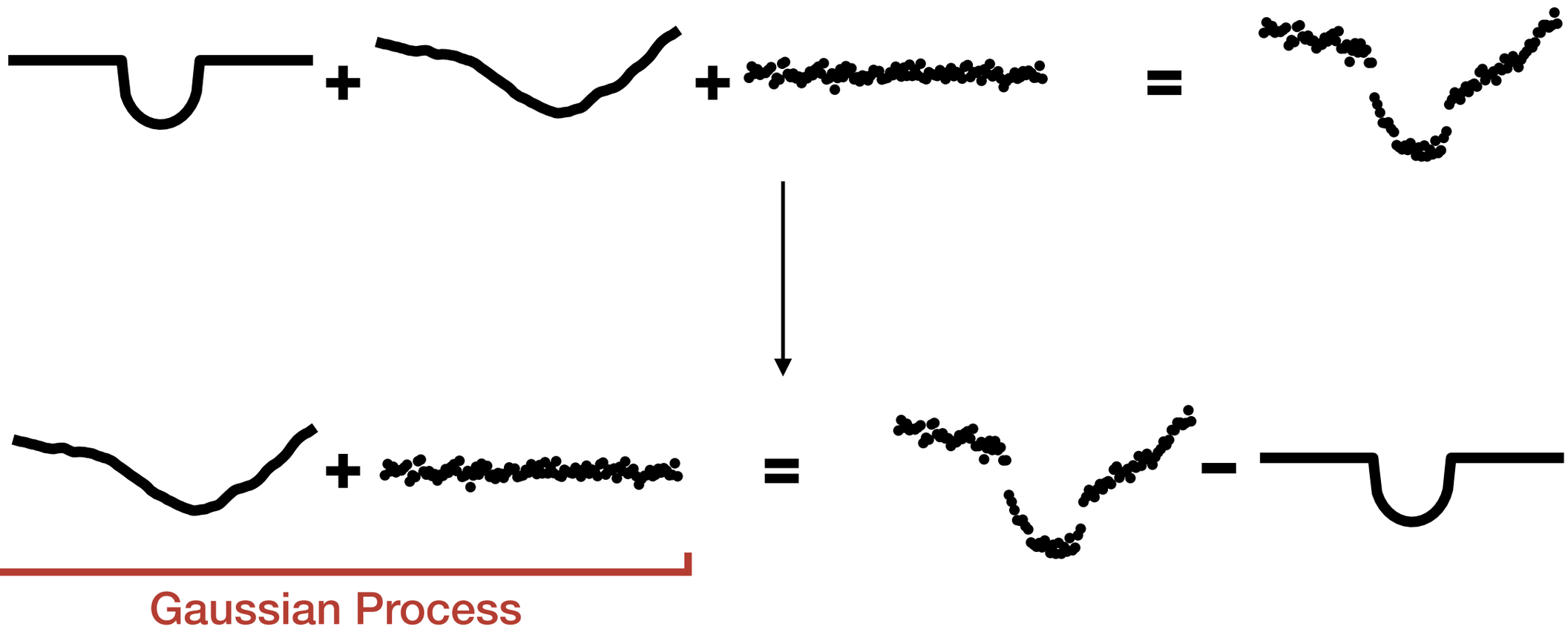
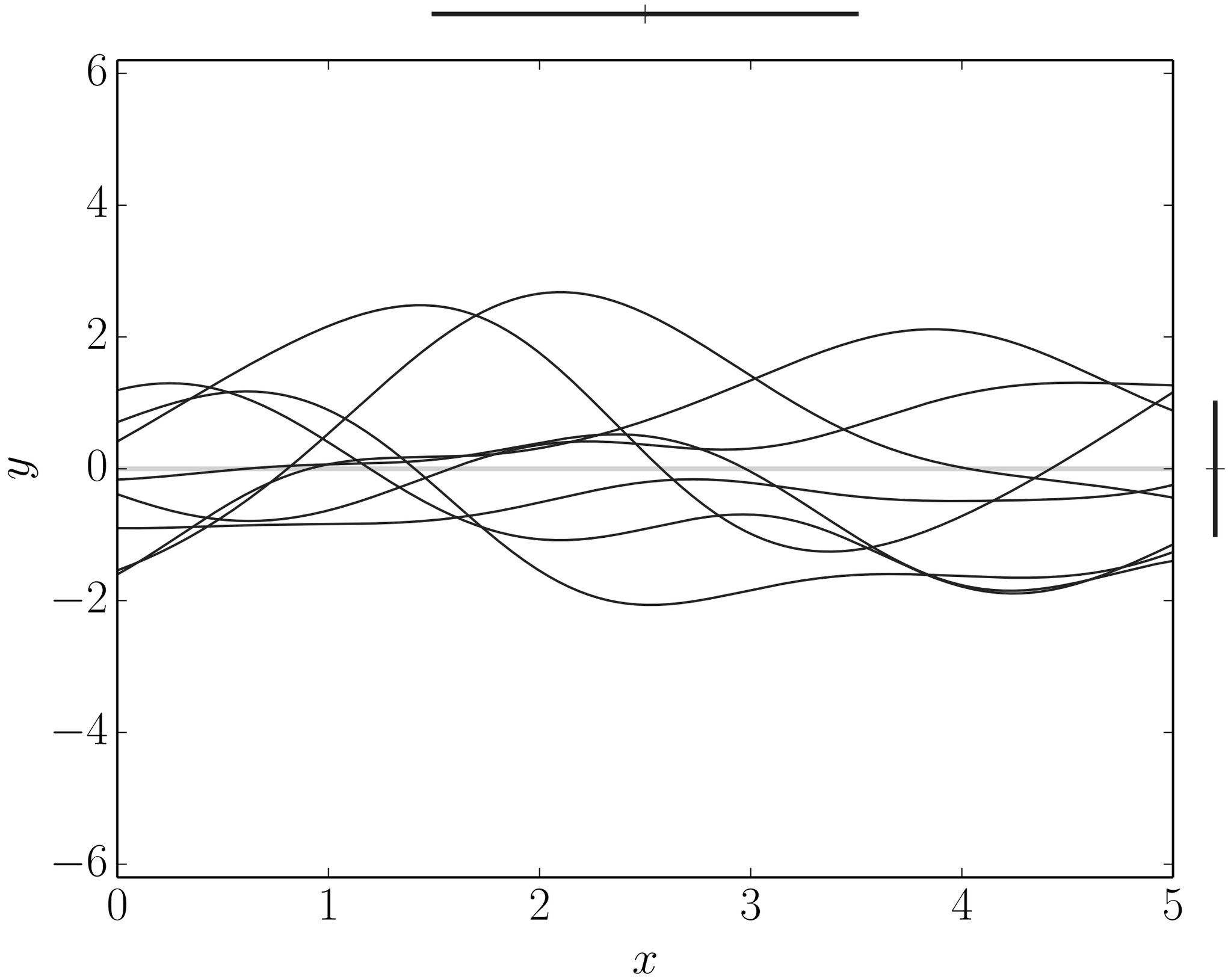


# What is a Gaussian Process?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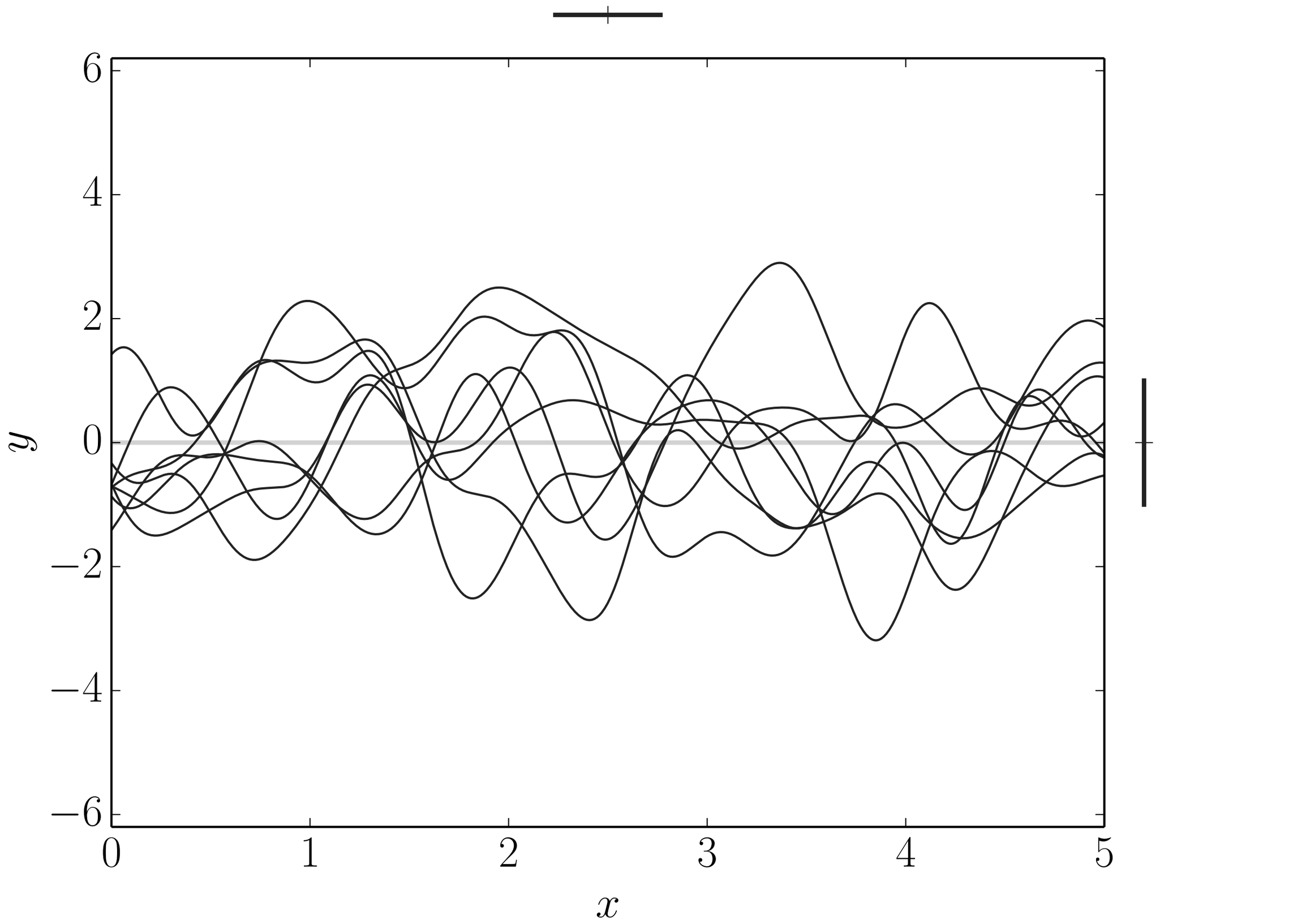
−4
−6
y
0
1
2
3
4
5
x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y
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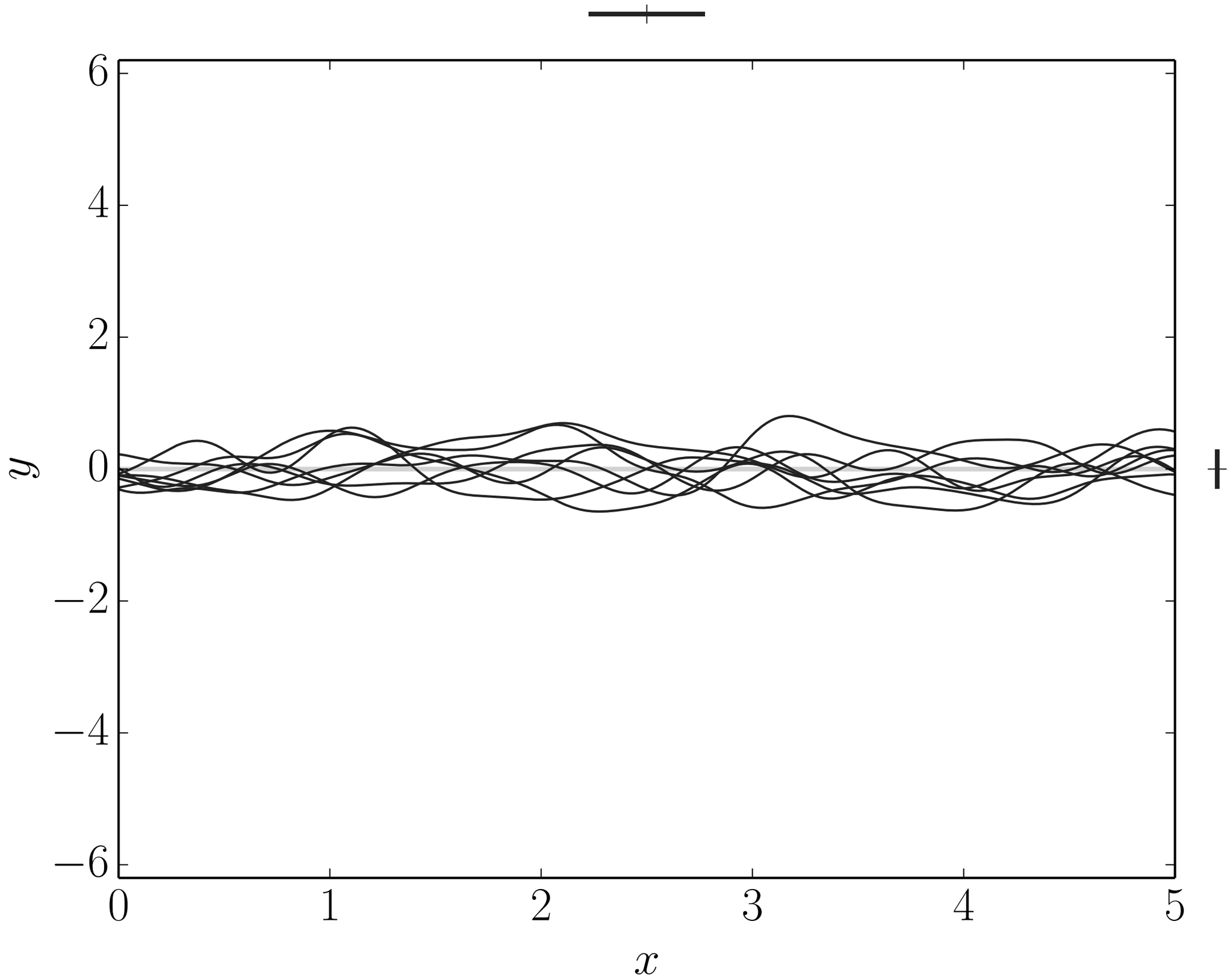
x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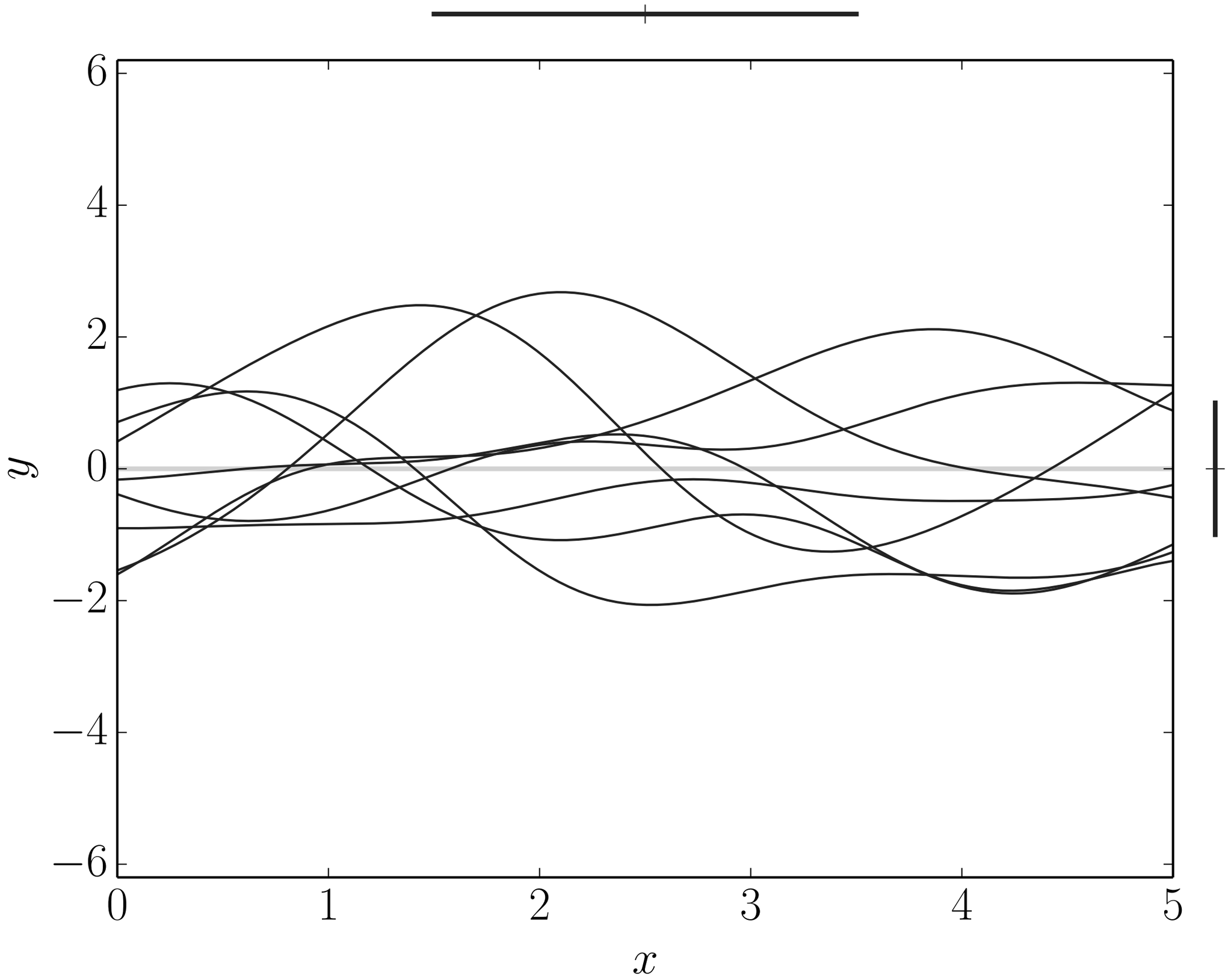
6
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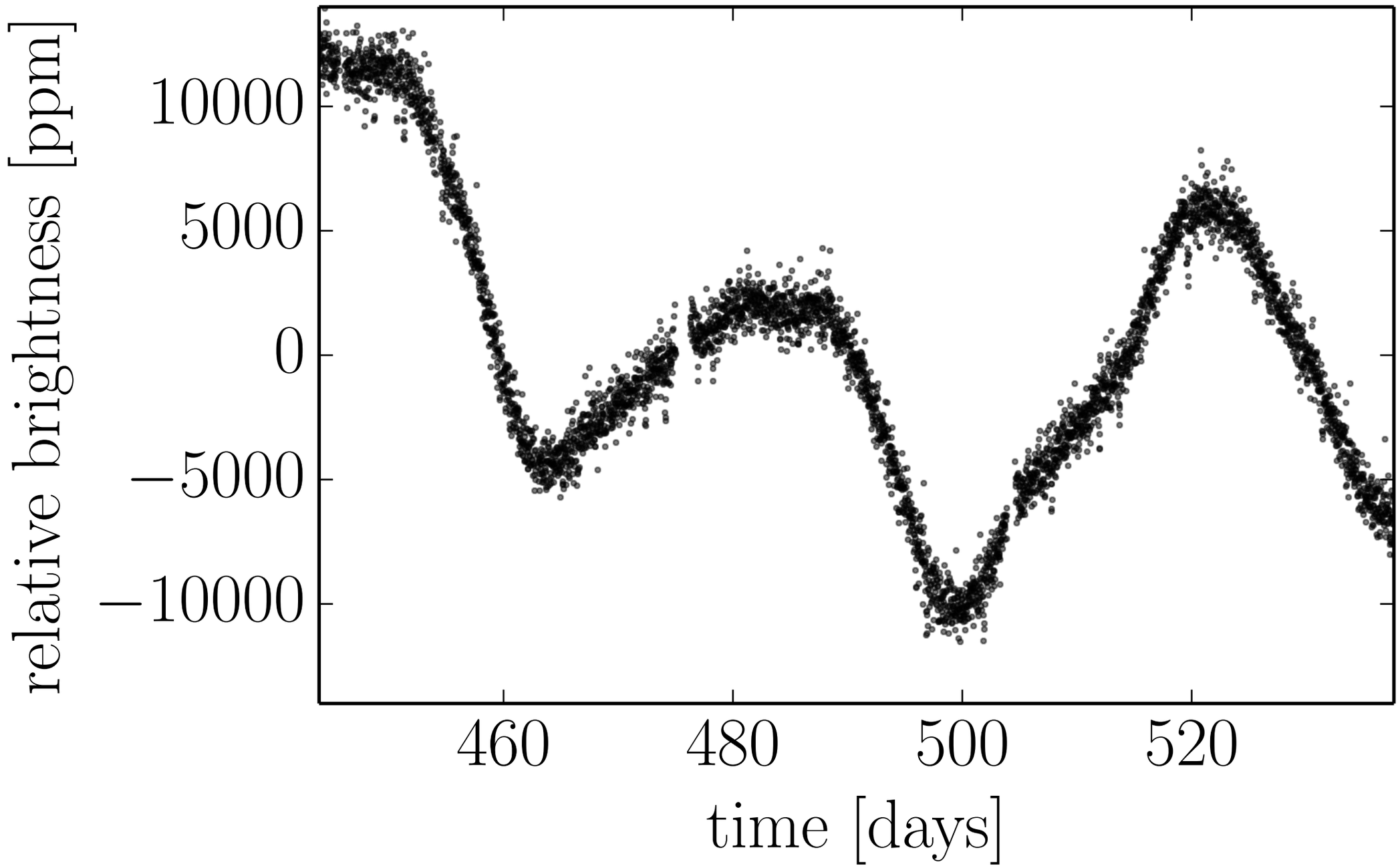
x


relative brightness [ppm]
10000
5000
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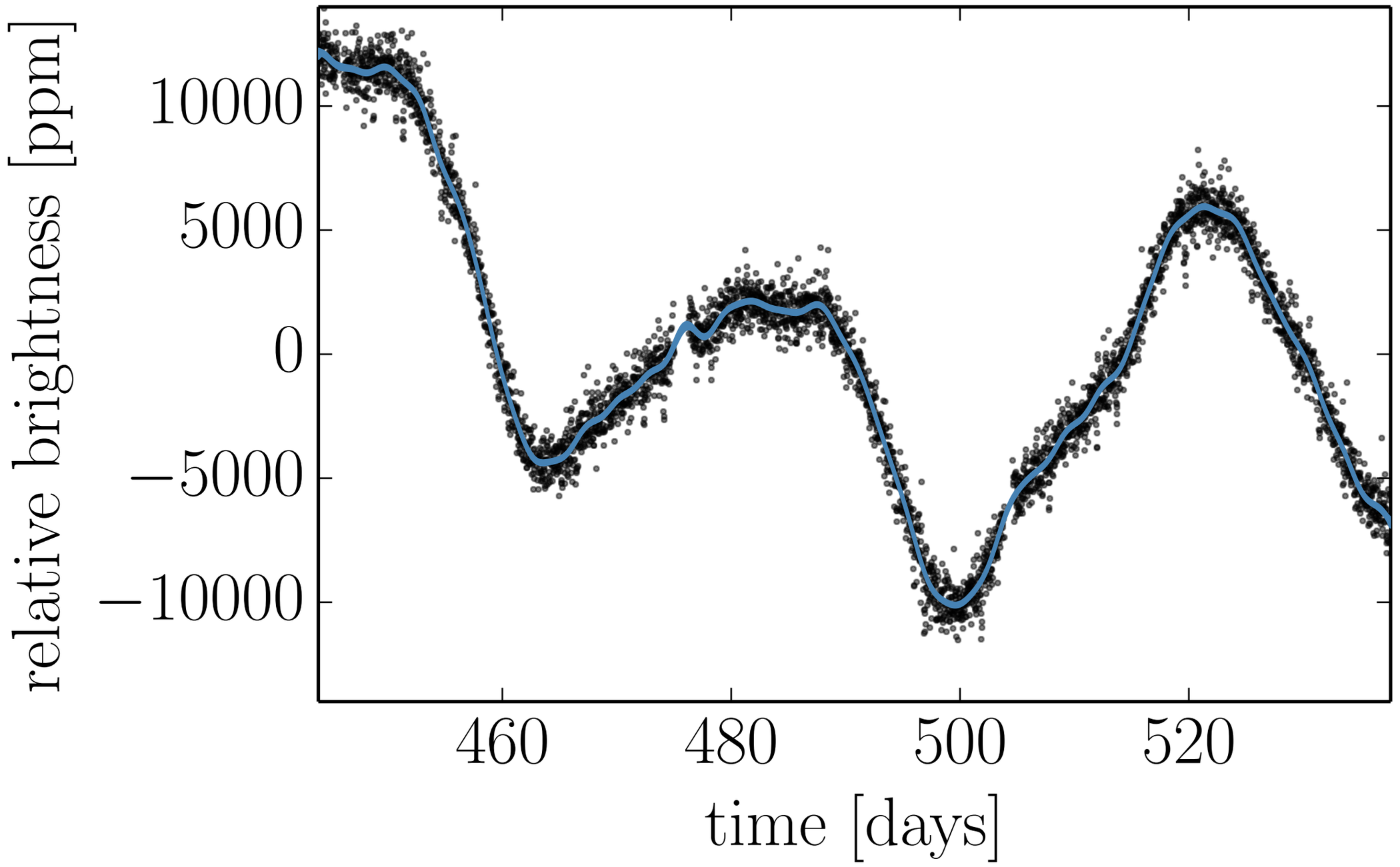
−10000
460
480
500
520
time [days]


relative brightness [ppm]
10000
5000
0
−5000
−10000
460
480
500
520
time [days]

the data are drawn from one

# HUGE*

# Gaussian

* the dimension is the number of data points.

# The mathematical model

$$\boldsymbol{y} \sim \mathcal{N}\left(\boldsymbol{f_\theta}(\boldsymbol{x}),\, K_{\boldsymbol{\alpha}}(\boldsymbol{x},\, \boldsymbol{\sigma})\right)$$

where

$$\left[K_{\boldsymbol{\alpha}}(\boldsymbol{x},\, \boldsymbol{\sigma})\right]_{ij} = {\sigma_i}^2\, \delta_{ij} + k_{\boldsymbol{\alpha}}(x_i,\, x_j)$$

# The mathematical model

$$\log p(\boldsymbol{y} \,|\, \boldsymbol{x},\, \boldsymbol{\sigma},\, \boldsymbol{\theta},\, \boldsymbol{\alpha}) = -\frac{1}{2}\,[\boldsymbol{y} - \boldsymbol{f}_{\boldsymbol{\theta}}(\boldsymbol{x})]^{\mathrm{T}}\, K_{\boldsymbol{\alpha}}(\boldsymbol{x},\, \boldsymbol{\sigma})^{-1}\,[\boldsymbol{y} - \boldsymbol{f}_{\boldsymbol{\theta}}(\boldsymbol{x})] - \frac{1}{2}\log\det K_{\boldsymbol{\alpha}}(\boldsymbol{x},\, \boldsymbol{\sigma}) - \frac{N}{2}\log 2\,\pi$$

where

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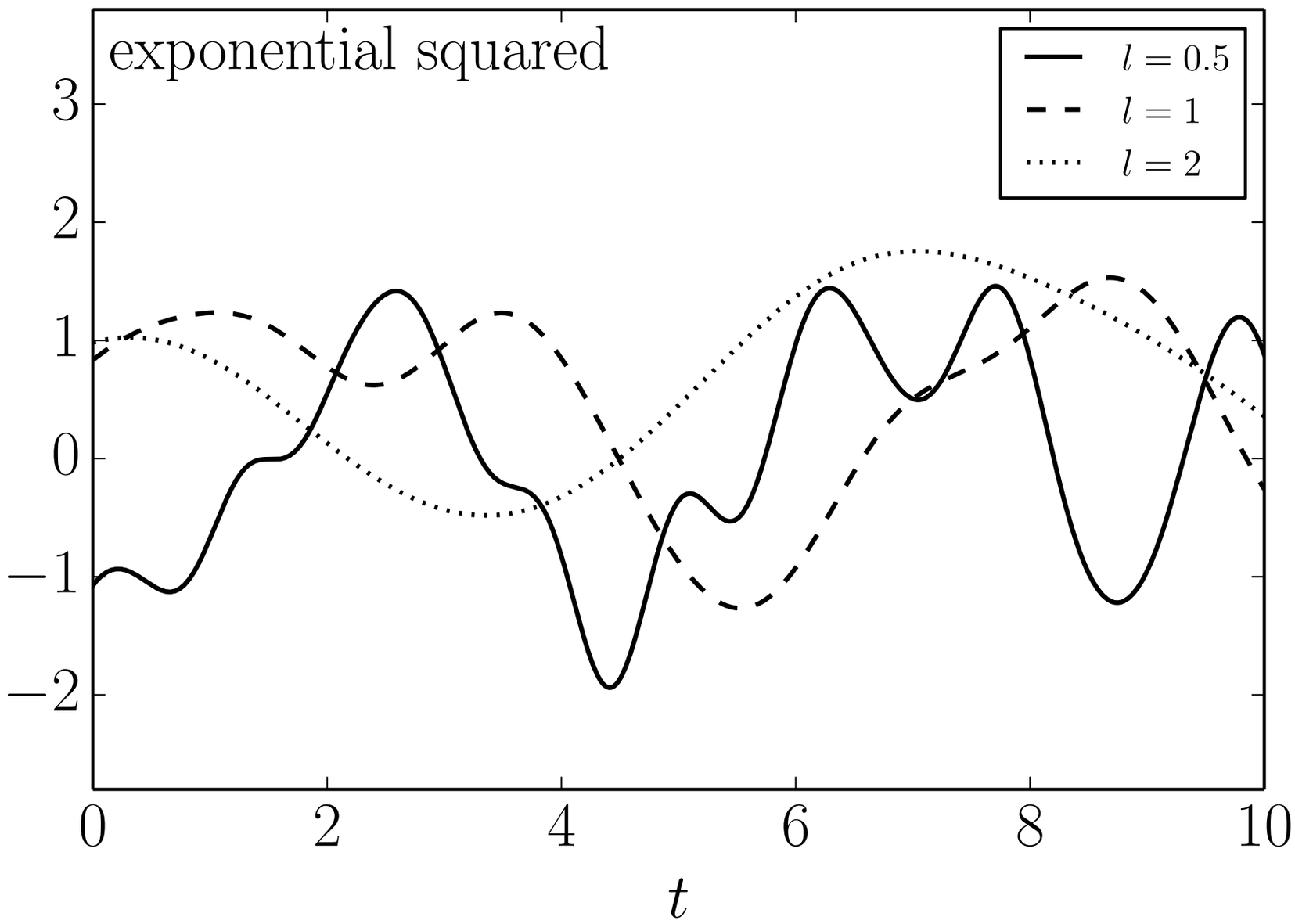
where

$$\left[K_{\boldsymbol{\alpha}}(\boldsymbol{x},\, \boldsymbol{\sigma})\right]_{ij} = {\sigma_i}^2\,\delta_{ij} + \underbrace{k_{\boldsymbol{\alpha}}(x_i,\, x_j)}_{\textbf{kernel function}}$$

*(where the magic happens)*

# The choice of kernel

$$k_{\boldsymbol{\alpha}}(x_i,\, x_j) = \exp\left(-\frac{[x_i - x_j]^2}{2\,\ell^2}\right)$$



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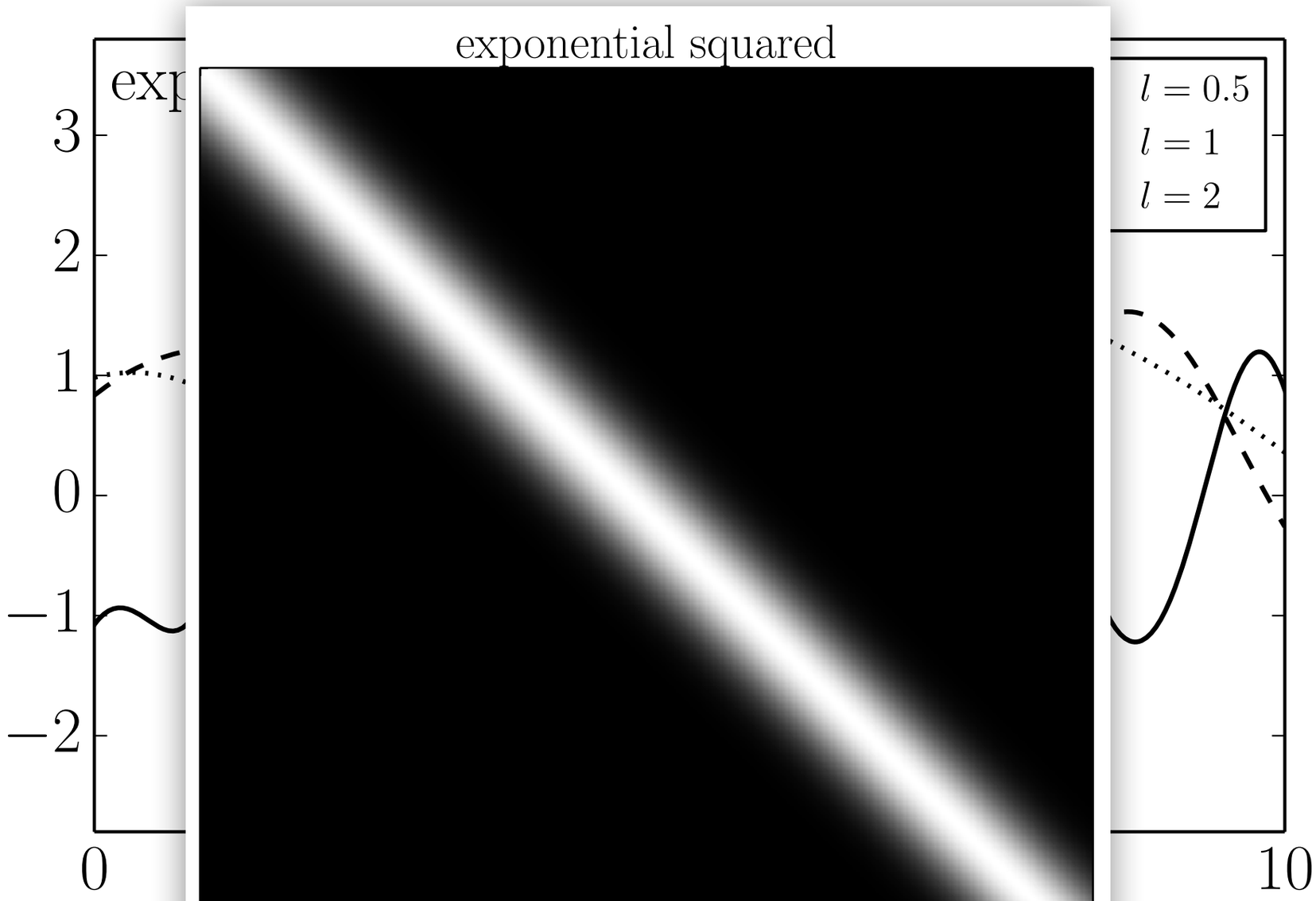
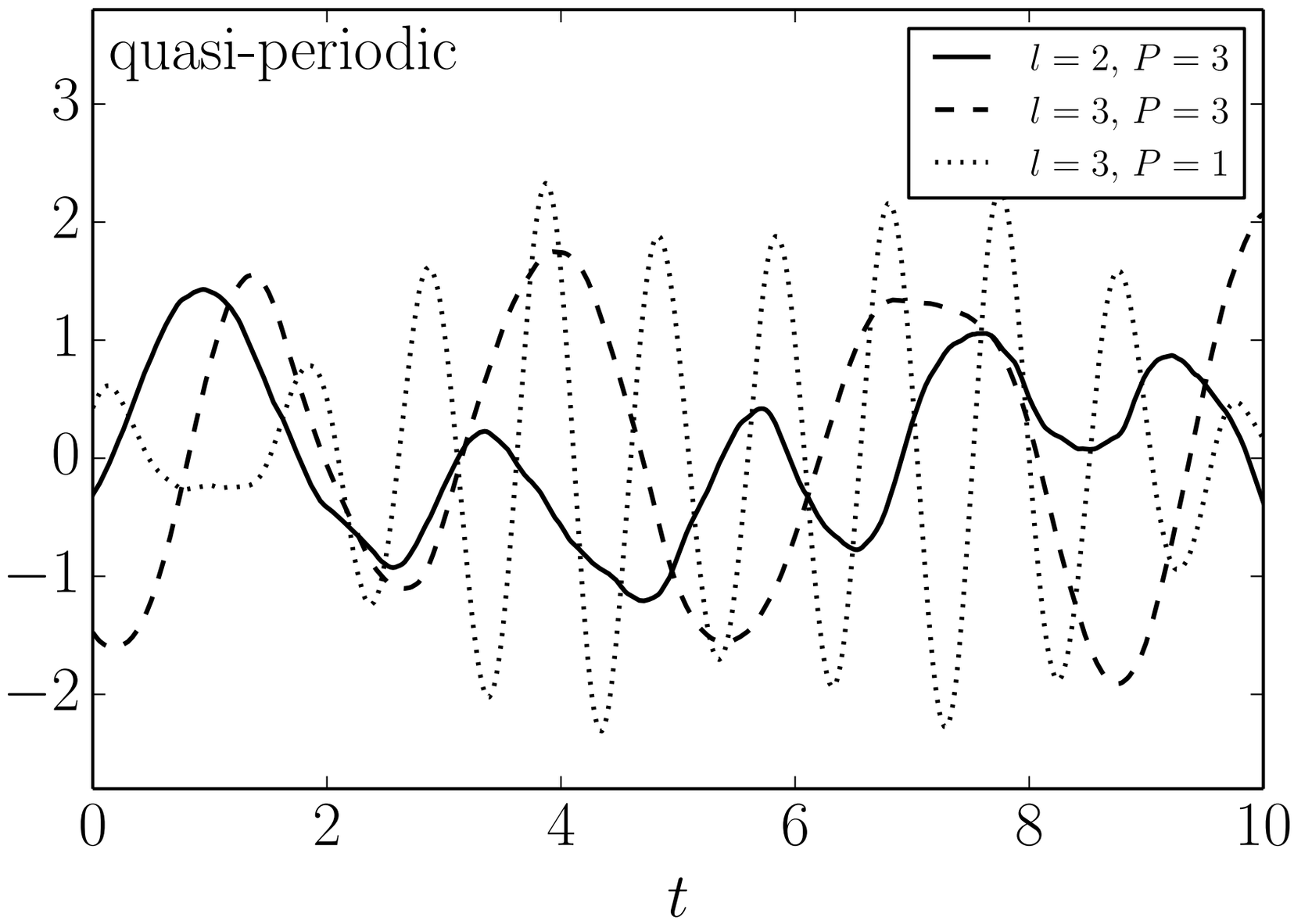


# The choice of kernel

$$k_{\boldsymbol{\alpha}}(x_i,\, x_j) = \left[1 + \frac{\sqrt{3}\,|x_i - x_j|}{\ell}\right] \exp\left(-\frac{|x_i - x_j|}{\ell}\right) \cos\left(\frac{2\,\pi\,|x_i - x_j|}{P}\right)$$



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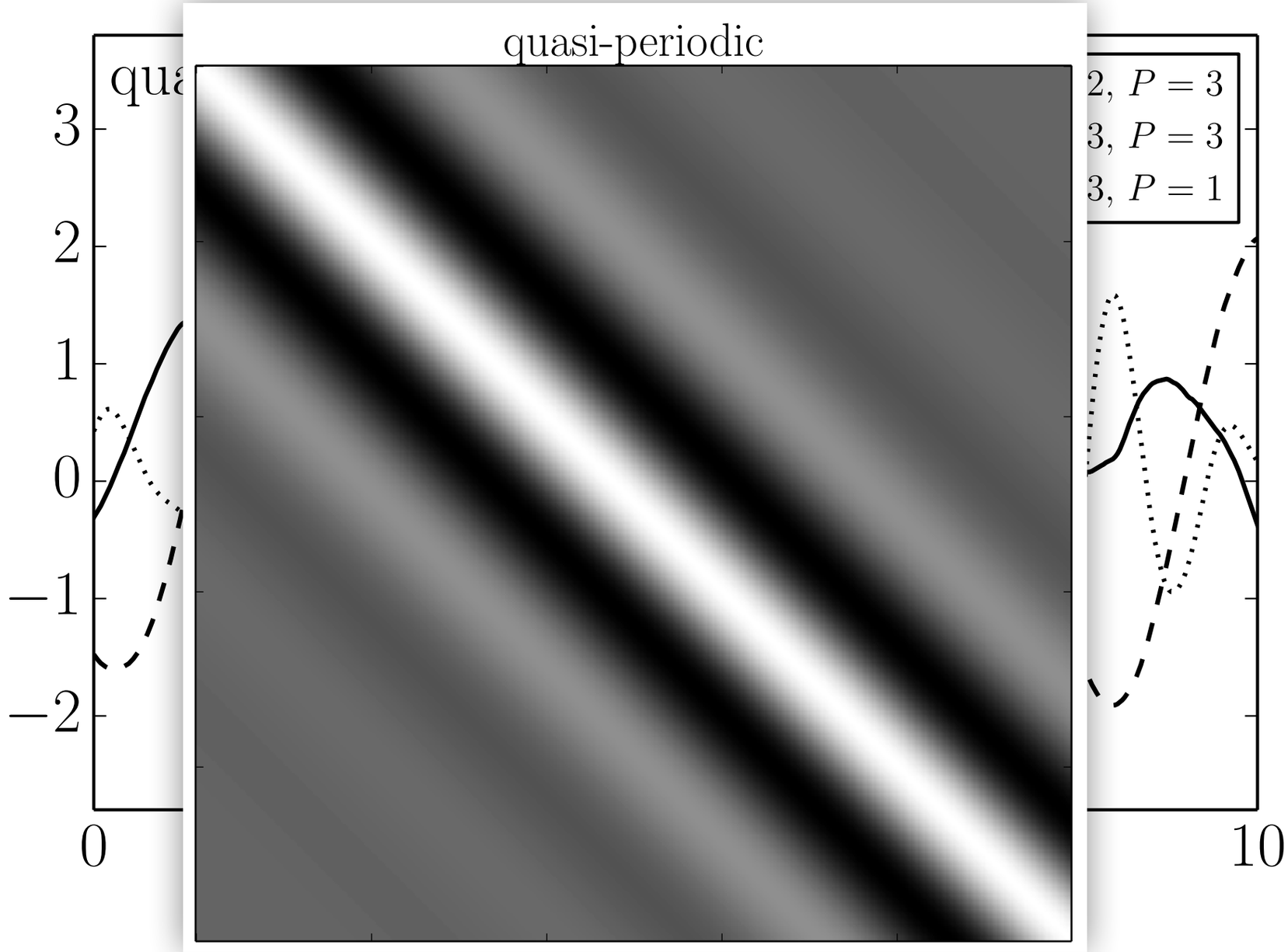

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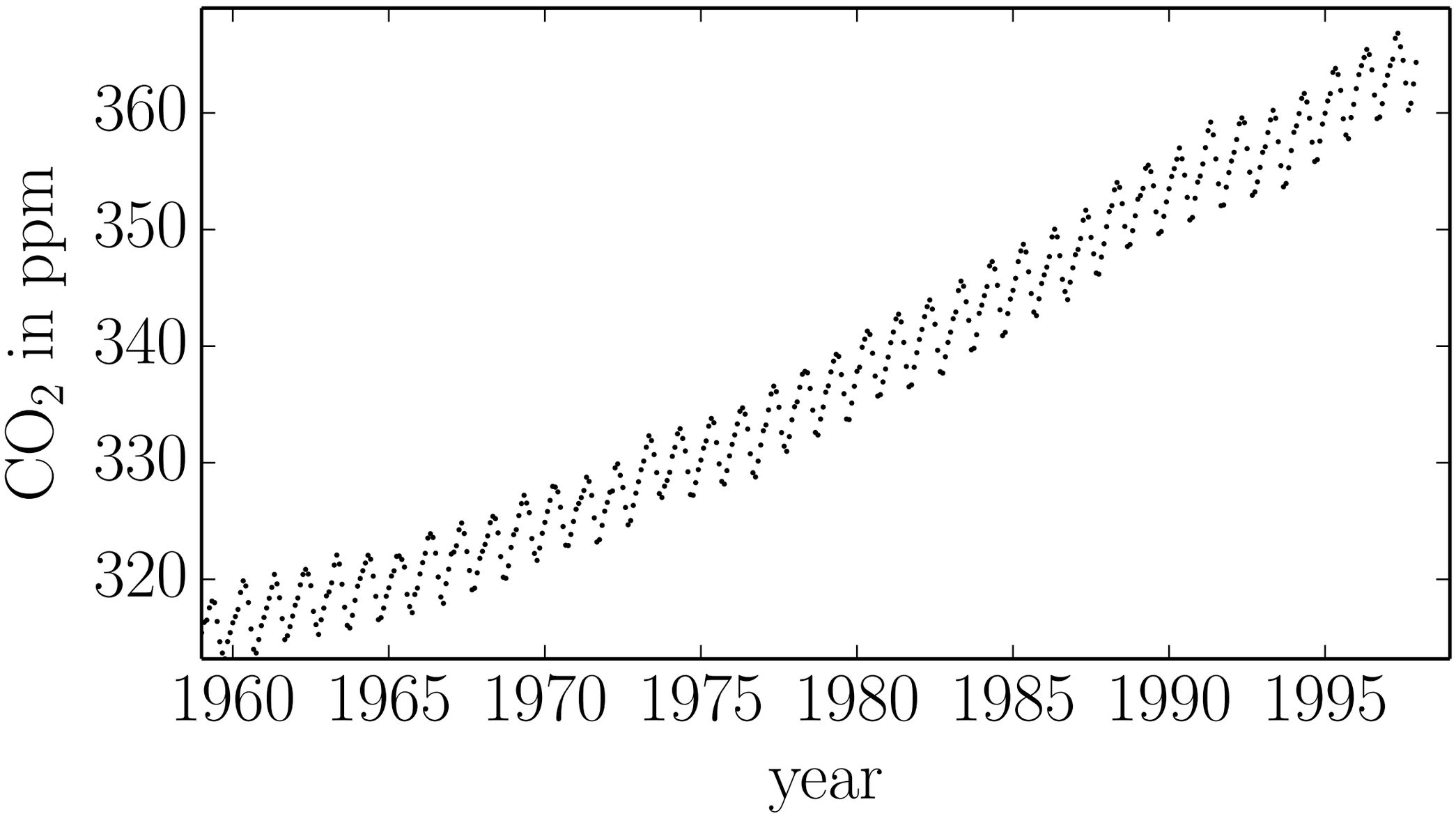


Full write-up at **dfm.io/george**

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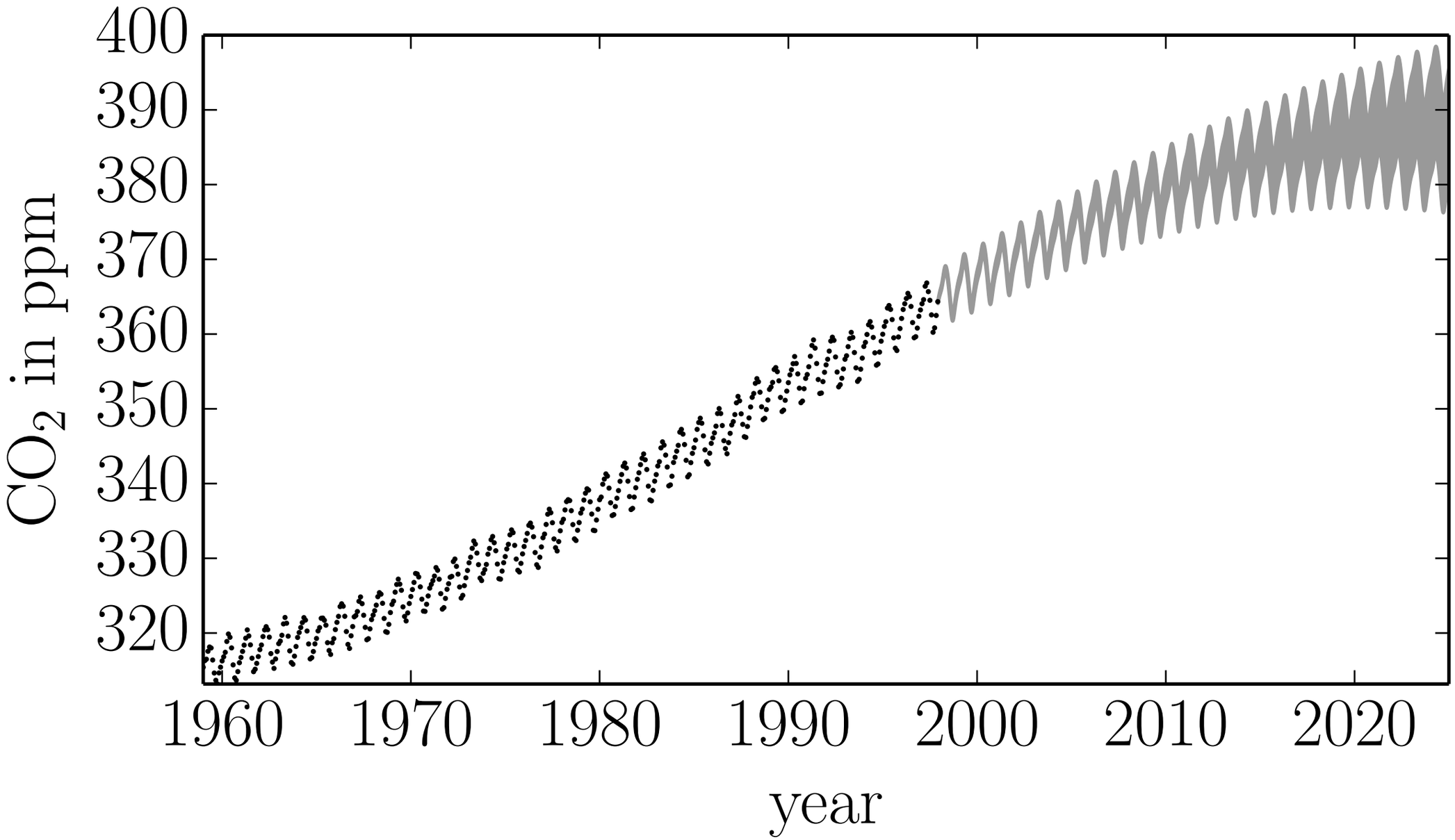
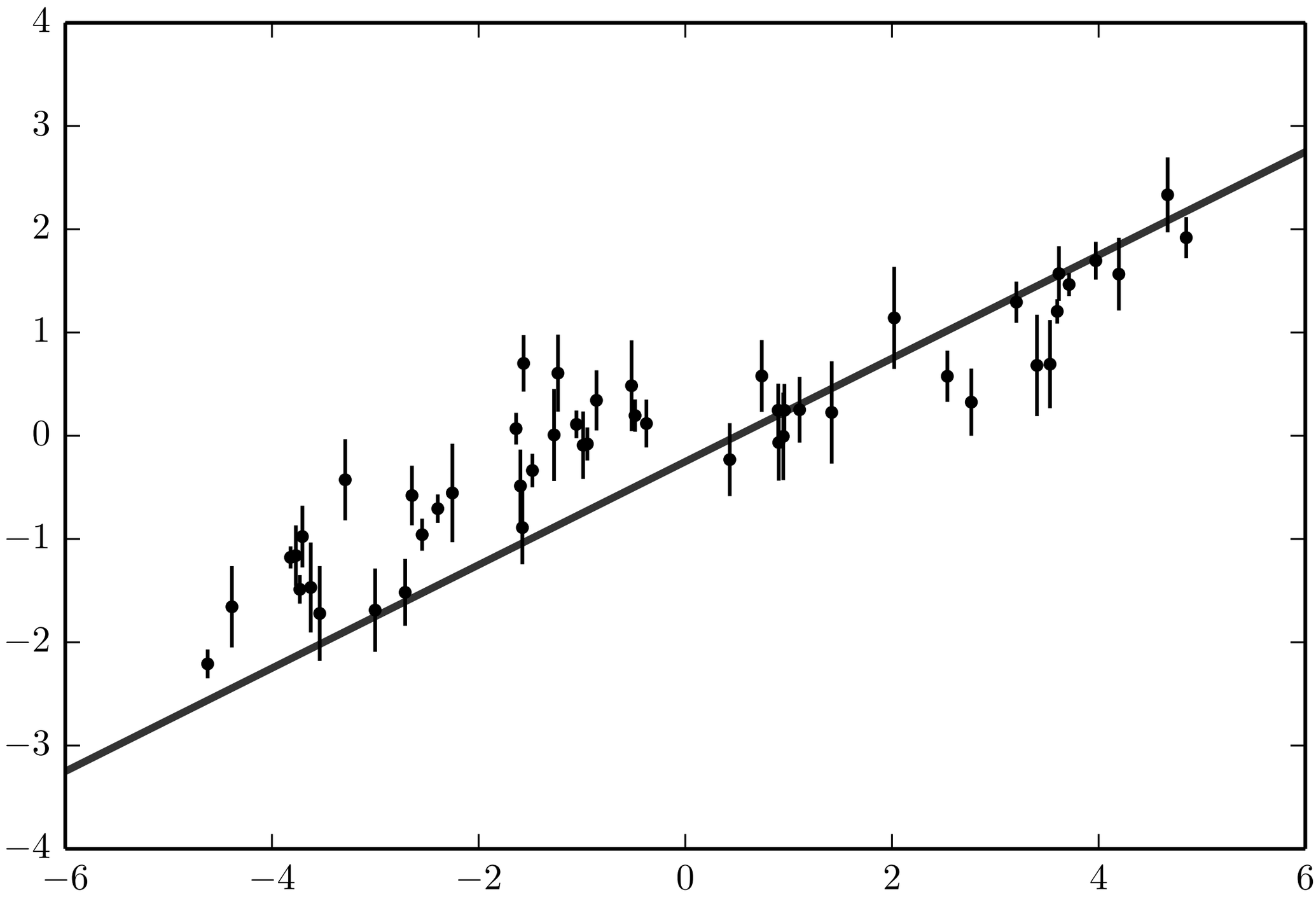



Full write-up at **dfm.io/george**

# Does this matter?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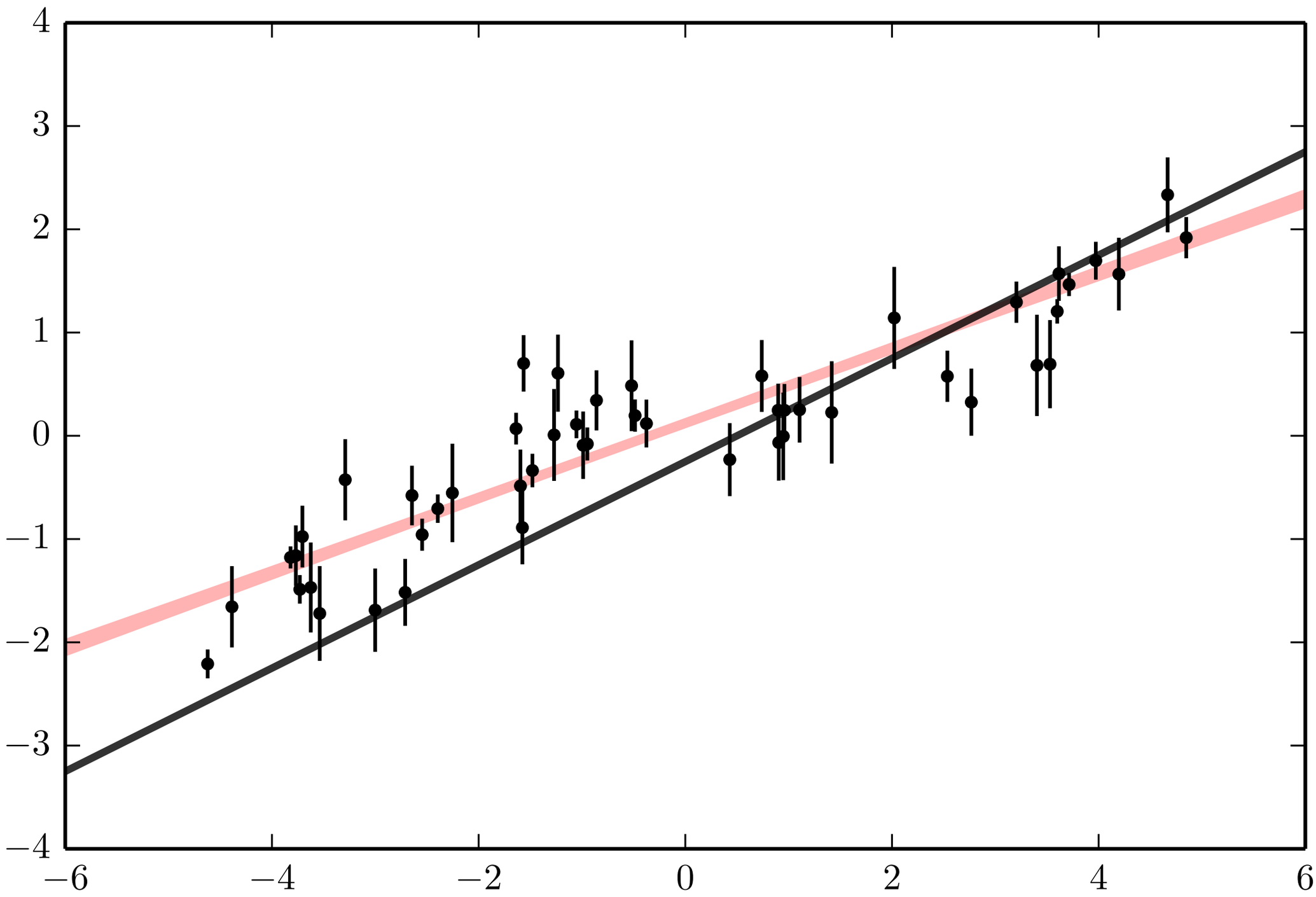
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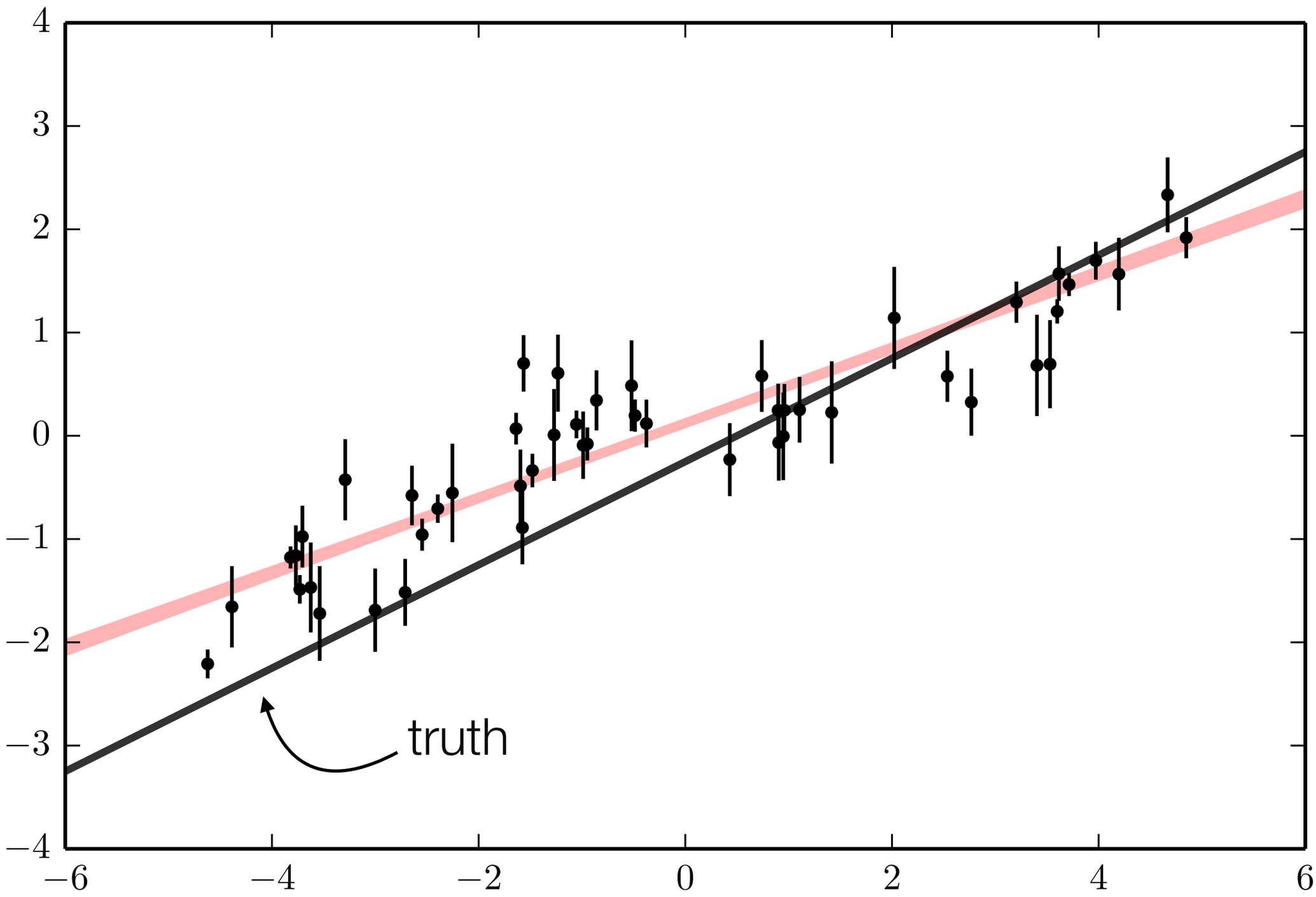
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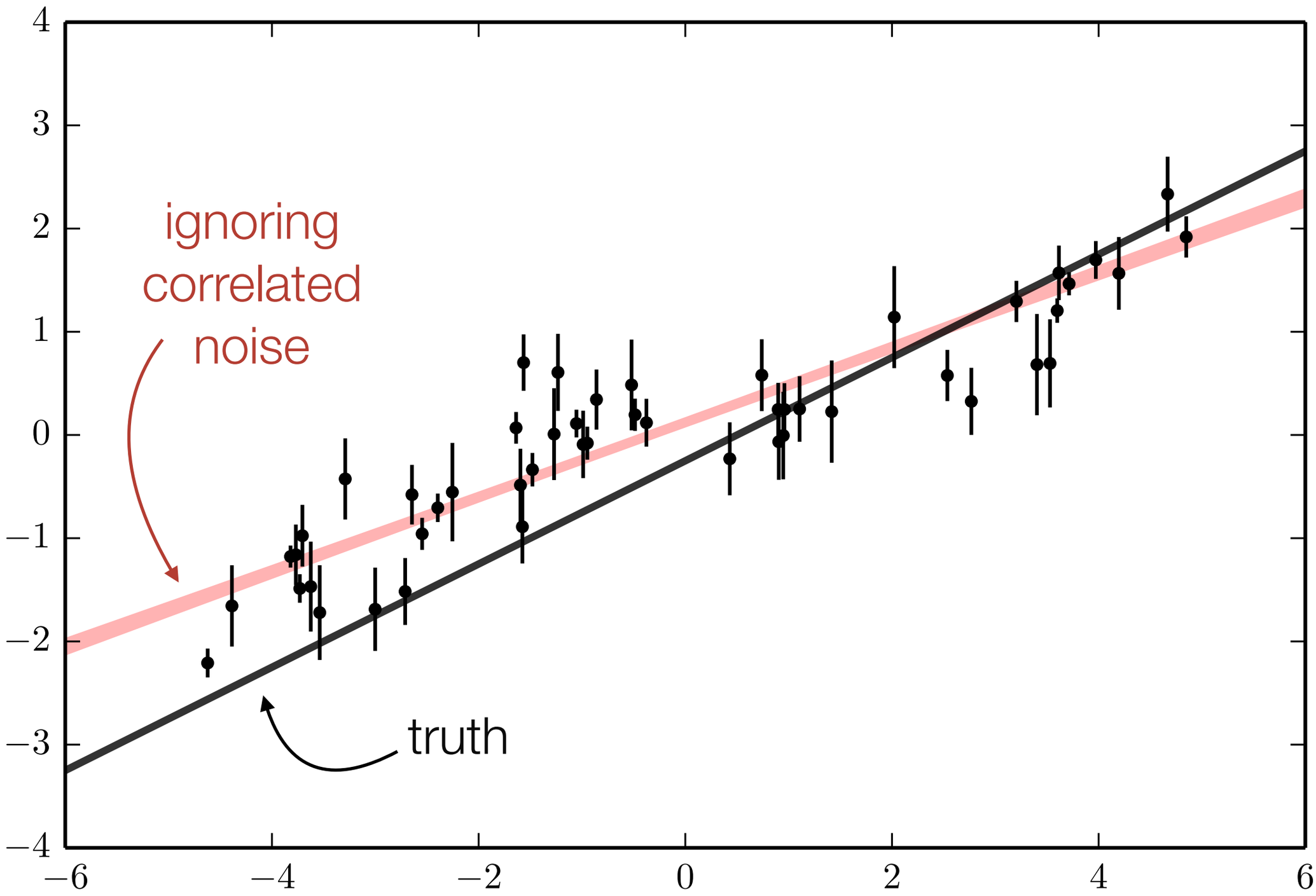
truth


ignoring
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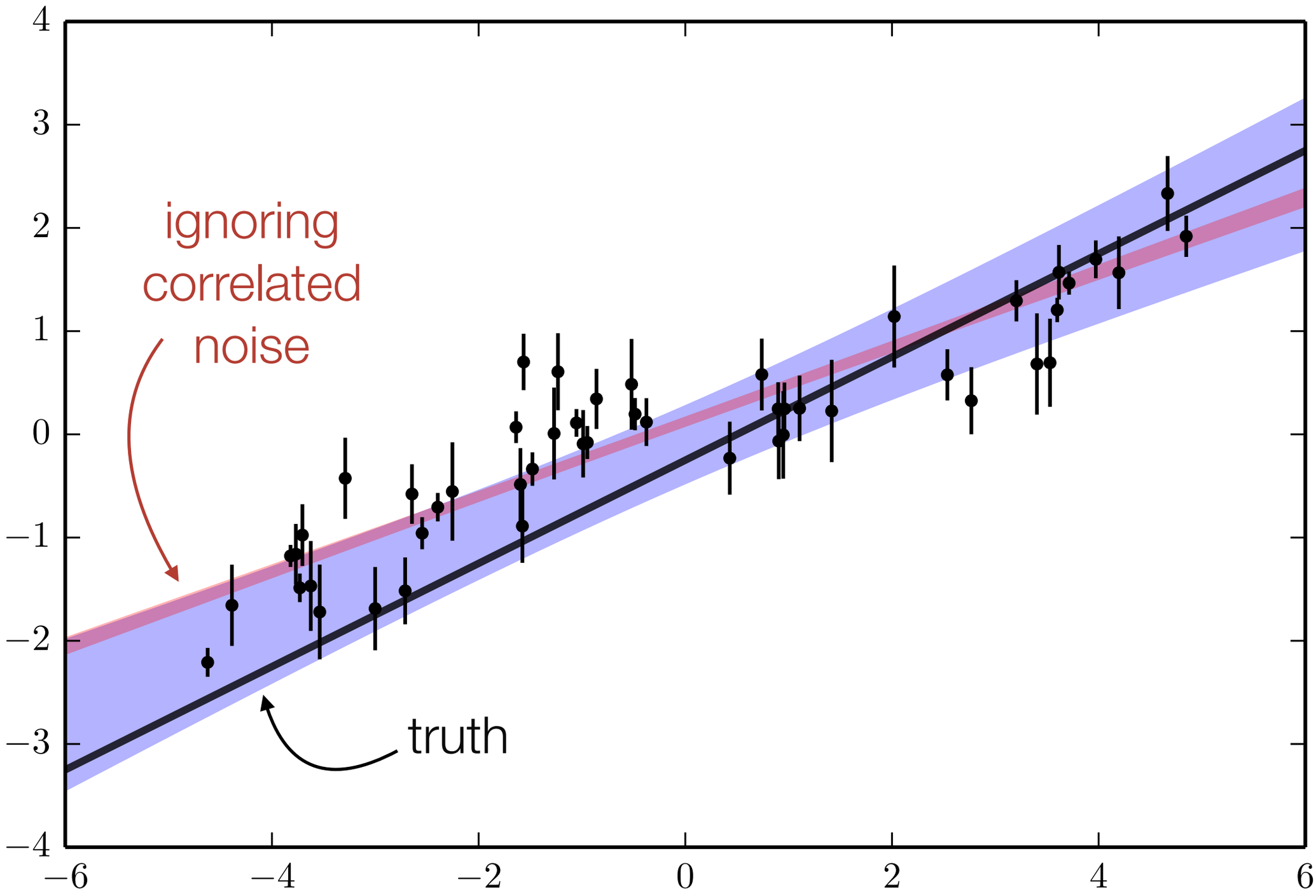
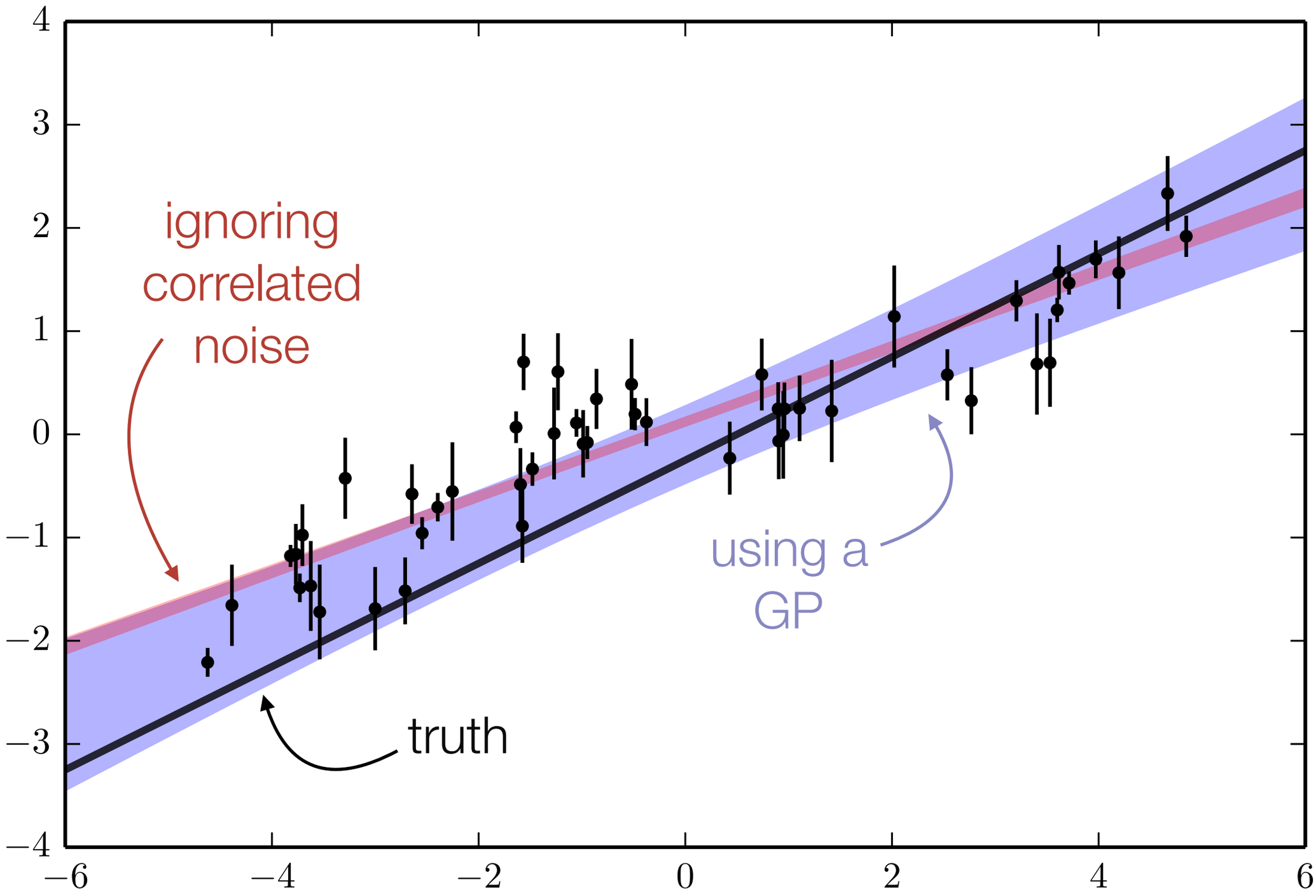
After.



After.


ignoring
correlated
noise
using a
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# How to use Gaussian Processes?

# The mathematical model

$$\log p(\boldsymbol{y} \,|\, \boldsymbol{x},\, \boldsymbol{\sigma},\, \boldsymbol{\theta},\, \boldsymbol{\alpha}) = -\frac{1}{2}\left[\boldsymbol{y} - \boldsymbol{f}_{\boldsymbol{\theta}}(\boldsymbol{x})\right]^{\mathrm{T}} K_{\boldsymbol{\alpha}}(\boldsymbol{x},\, \boldsymbol{\sigma})^{-1}\left[\boldsymbol{y} - \boldsymbol{f}_{\boldsymbol{\theta}}(\boldsymbol{x})\right] - \frac{1}{2}\log\det K_{\boldsymbol{\alpha}}(\boldsymbol{x},\, \boldsymbol{\sigma}) - \frac{N}{2}\log 2\,\pi$$

where

$$\left[K_{\boldsymbol{\alpha}}(\boldsymbol{x},\, \boldsymbol{\sigma})\right]_{ij} = {\sigma_i}^2\,\delta_{ij} + \underbrace{k_{\boldsymbol{\alpha}}(x_i,\, x_j)}_{\textbf{kernel function}}$$

*(where the magic happens)*

# A simple & efficient Python implementation

```python
import numpy as np
from scipy.linalg import cho_factor, cho_solve

def kernel(x1, x2):
    # ...

def gp_lnlike(x, y, yerr):
    C = kernel(x[:, None], x[None, :])
    C[np.diag_indicies_from(C)] += yerr ** 2
    factor, flag = cho_factor(C)
    logdet = 2*np.sum(np.log(np.diag(factor)))
    return -0.5 * (np.dot(y, cho_solve((factor, flag), y))
                   + logdet + len(x)*np.log(2*np.pi))
```

# Using George

```
import george
import numpy as np

# kernel = george.kernels...

def george_lnlike(x, y, yerr):
    gp = george.GP(kernel)
    gp.compute(x, yerr)
    return gp.lnlikelihood(y)
```

github.com/dfm/george

# What's the catch?

What's the catch?

# *My Problem*

# =

# *Big Data*

(by some definition)

*Note: I hate myself for this slide too…*

# Computational complexity.

$$\log p(\boldsymbol{y} \,|\, \boldsymbol{x},\, \boldsymbol{\sigma},\, \boldsymbol{\theta},\, \boldsymbol{\alpha}) = -\frac{1}{2}\,[\boldsymbol{y} - \boldsymbol{f}_{\boldsymbol{\theta}}(\boldsymbol{x})]^{\mathrm{T}}\, K_{\boldsymbol{\alpha}}(\boldsymbol{x},\, \boldsymbol{\sigma})^{-1}\,[\boldsymbol{y} - \boldsymbol{f}_{\boldsymbol{\theta}}(\boldsymbol{x})] - \frac{1}{2}\log\det K_{\boldsymbol{\alpha}}(\boldsymbol{x},\, \boldsymbol{\sigma}) - \frac{N}{2}\log 2\,\pi$$

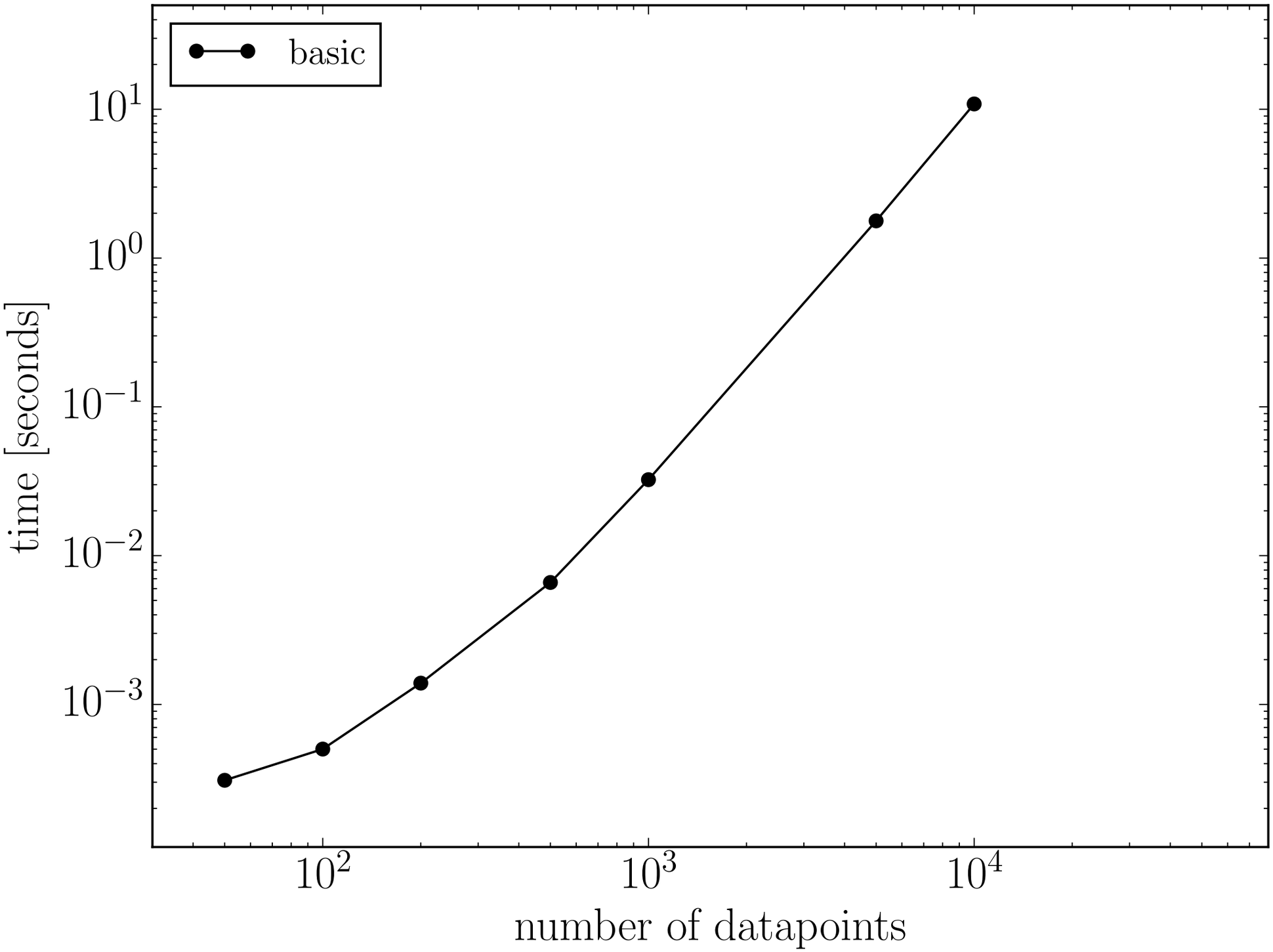
compute factorization // evaluate log-det // apply inverse

naïvely: $\mathcal{O}(N^3)$

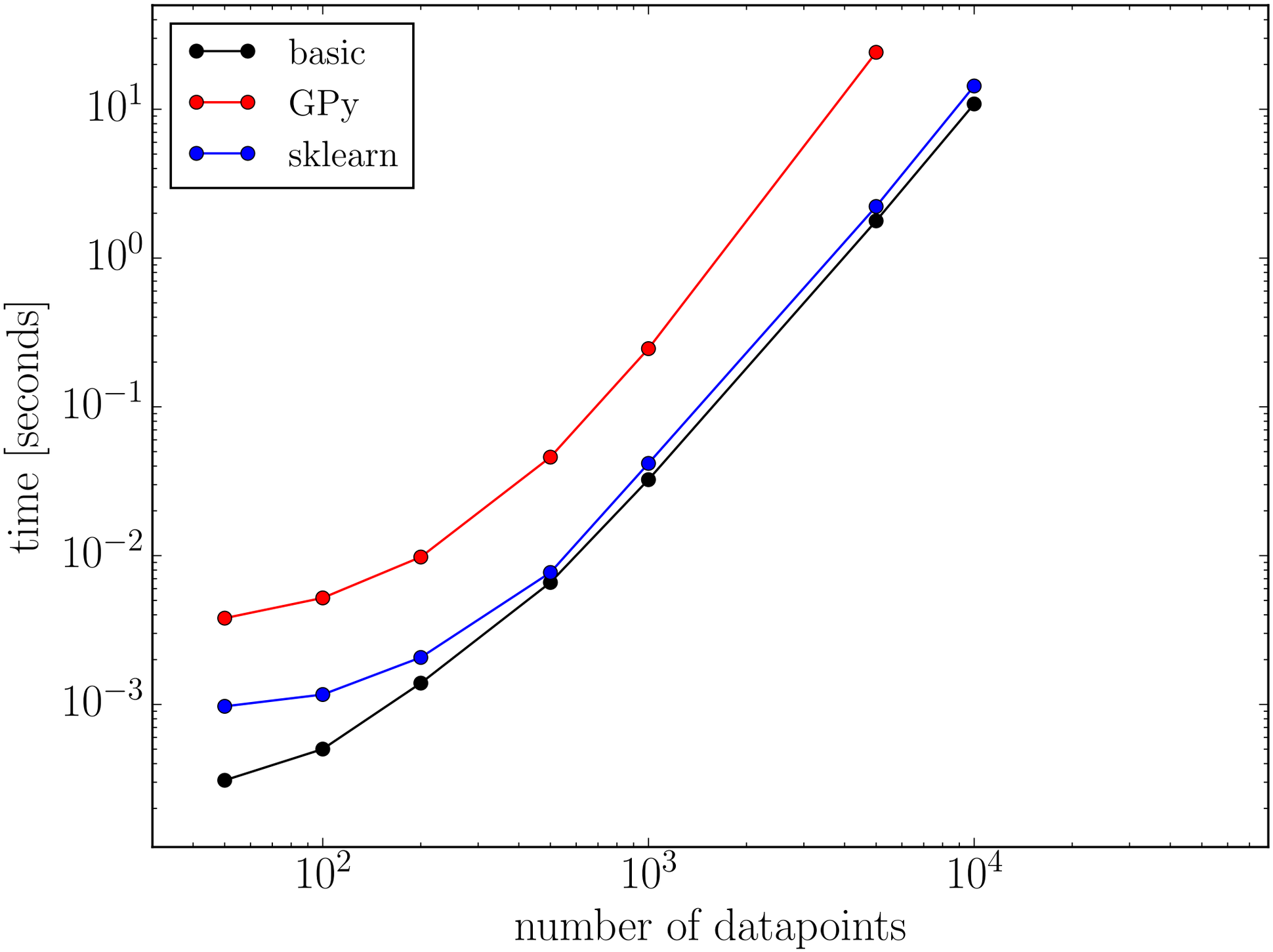
# Using George

```
import george
import numpy as np

# kernel = george.kernels...

def george_lnlike(x, y, yerr):
    gp = george.GP(kernel)
    gp.compute(x, yerr)
    return gp.lnlikelihood(y)
```

github.com/dfm/george




github.com/dfm/george




github.com/dfm/george

# How can we scale?

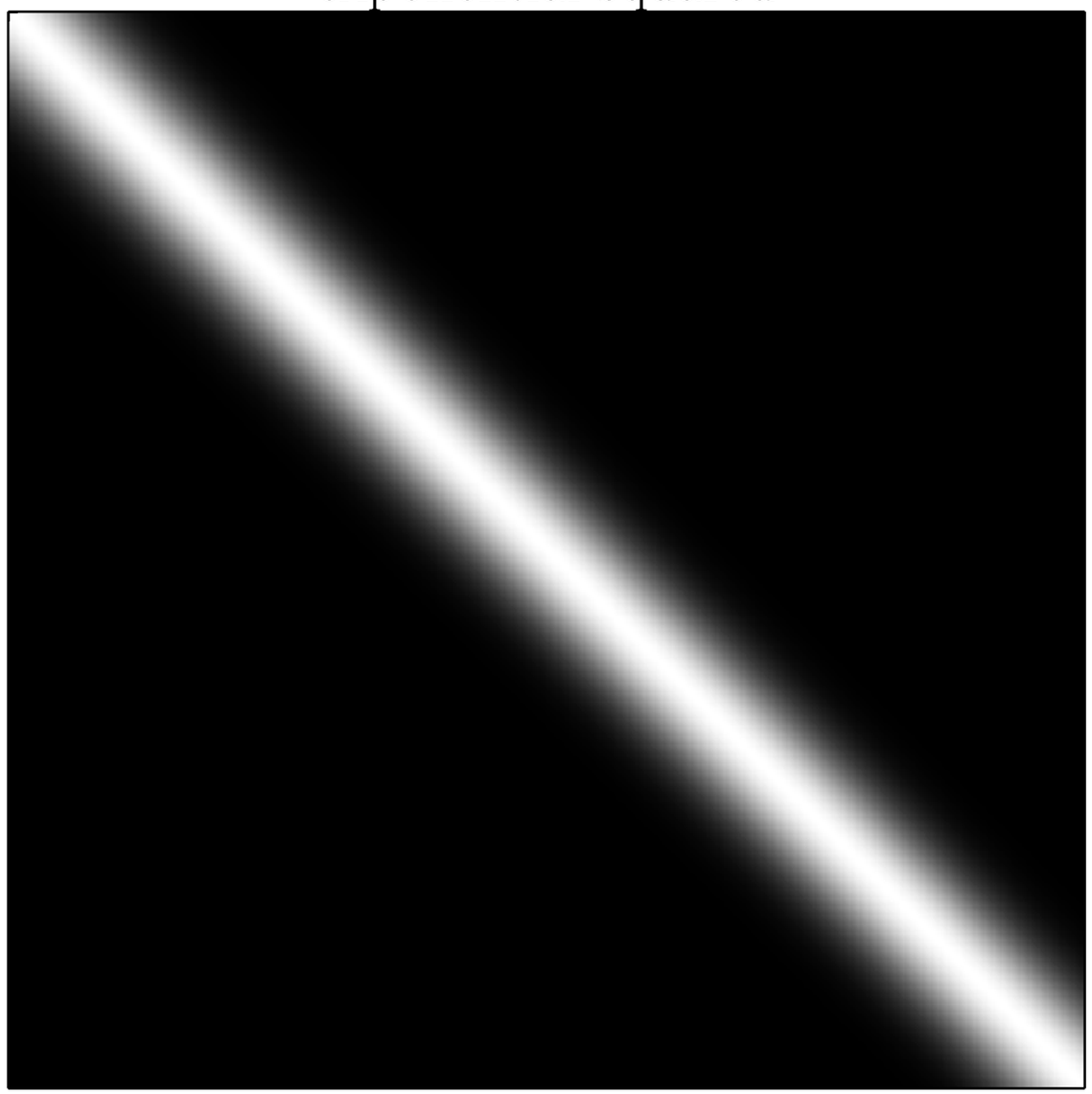
$$\log p(\boldsymbol{y} \,|\, \boldsymbol{x},\, \boldsymbol{\sigma},\, \boldsymbol{\theta},\, \boldsymbol{\alpha}) = -\,\frac{1}{2}\,[\boldsymbol{y} - \boldsymbol{f}_{\boldsymbol{\theta}}(\boldsymbol{x})]^{\mathrm{T}}\, K_{\boldsymbol{\alpha}}(\boldsymbol{x},\, \boldsymbol{\sigma})^{-1}\,[\boldsymbol{y} - \boldsymbol{f}_{\boldsymbol{\theta}}(\boldsymbol{x})]$$
$$-\,\frac{1}{2}\log\det K_{\boldsymbol{\alpha}}(\boldsymbol{x},\, \boldsymbol{\sigma}) - \frac{N}{2}\log 2\,\pi$$

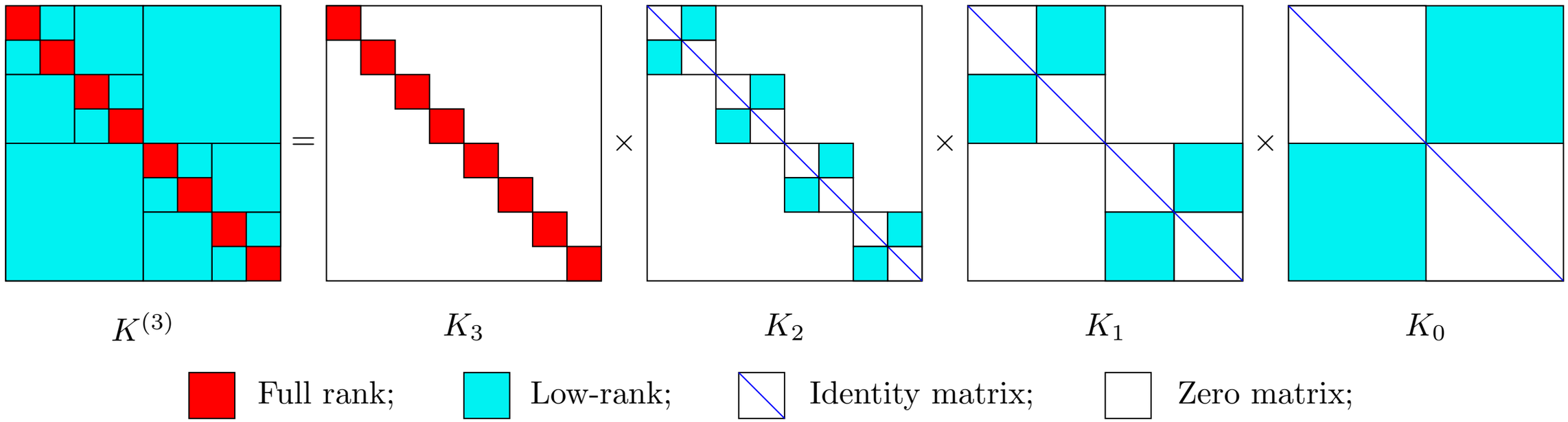
“

Aren’t kernel matrices Hierarchical Off-Diagonal Low-Rank?

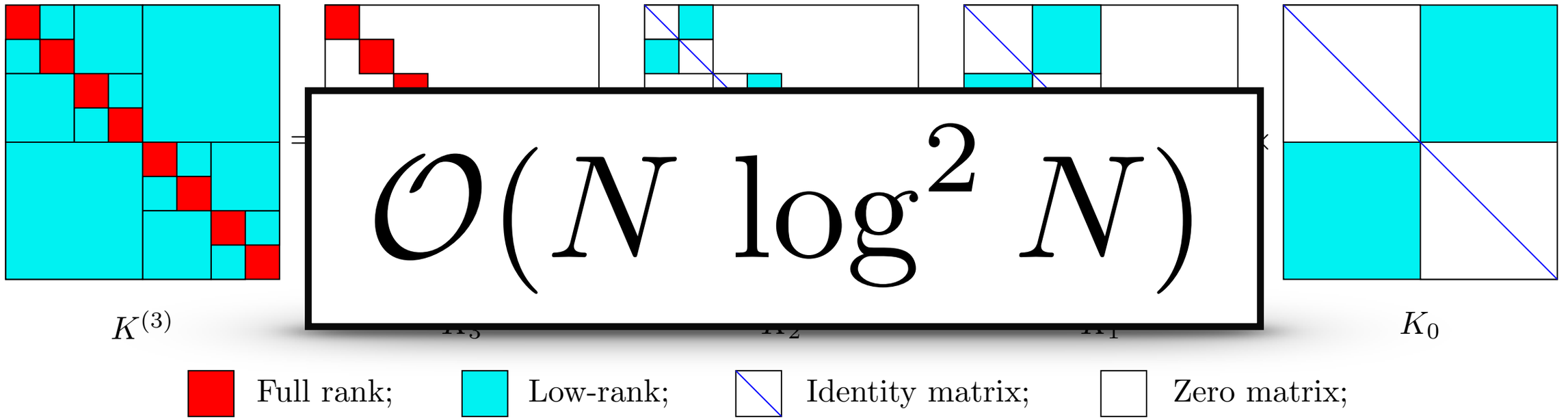
— not me

exponential squared



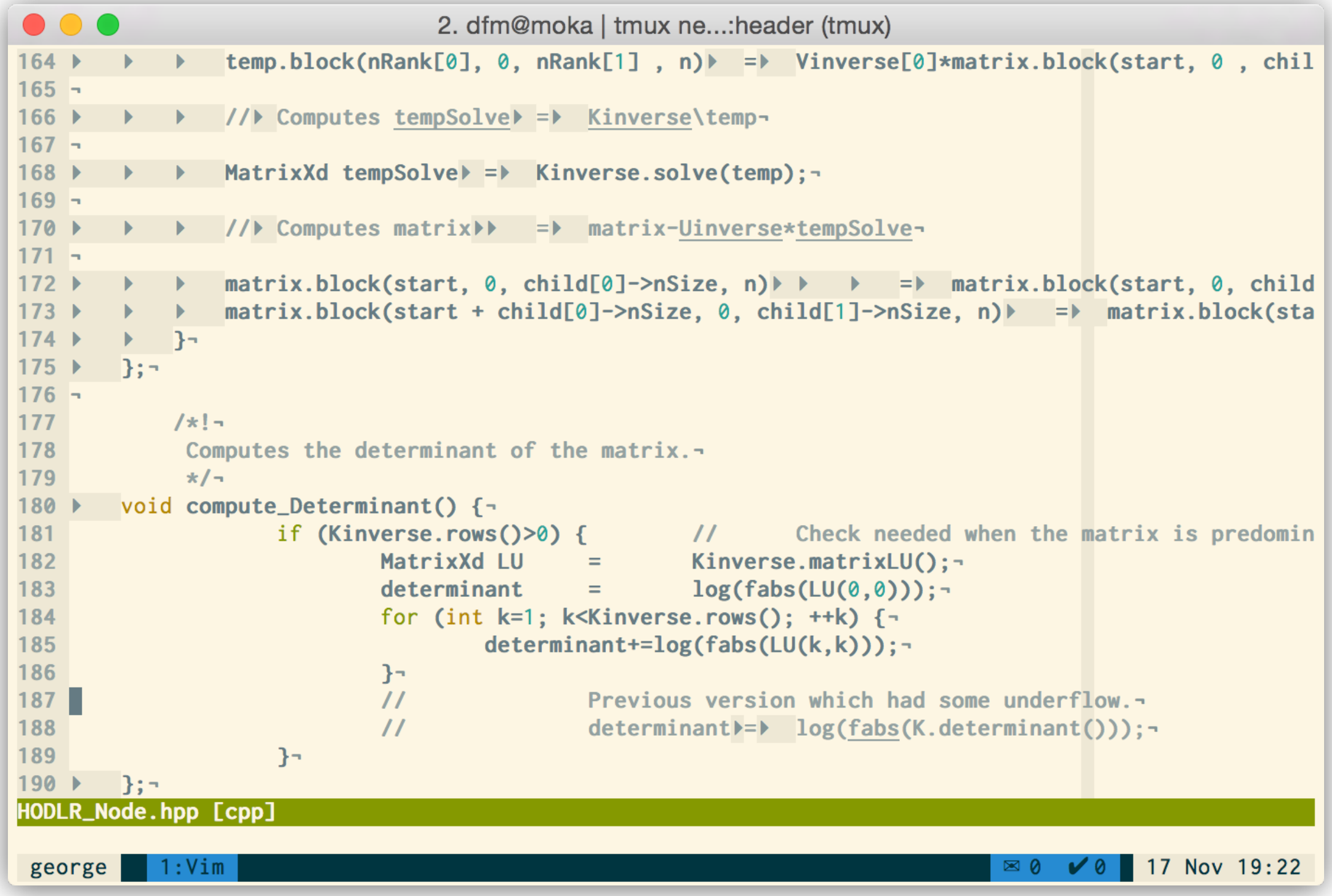



Ambikasaran, DFM, *et al.* (arXiv:1403.6015)




Ambikasaran, DFM, *et al.* (arXiv:1403.6015)

github.com/sivaramambikasaran/HODLR




github.com/sivaramambikasaran/HODLR

# The HODLR solver from George

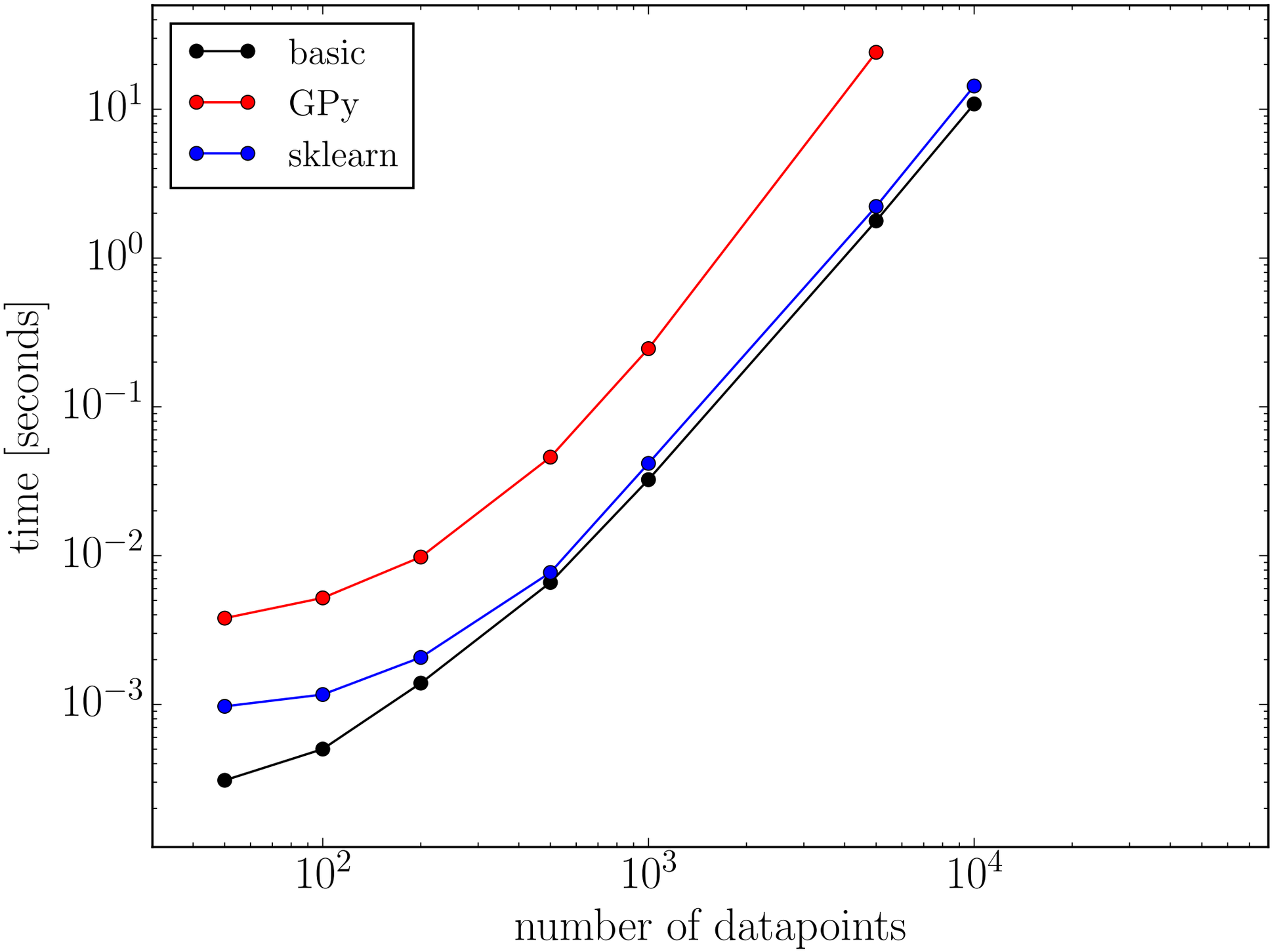
```python
import george
import numpy as np

# kernel = george.kernels...

def george_lnlike(x, y, yerr):
    gp = george.GP(kernel)
    gp.compute(x, yerr)
    return gp.lnlikelihood(y)
```

github.com/dfm/george

# The HODLR solver from George

```
import george
import numpy as np

# kernel = george.kernels...

def george_lnlike(x, y, yerr):
    gp = george.GP(kernel, solver=george.HODLRSolver)
    gp.compute(x, yerr)
    return gp.lnlikelihood(y)
```

github.com/dfm/george

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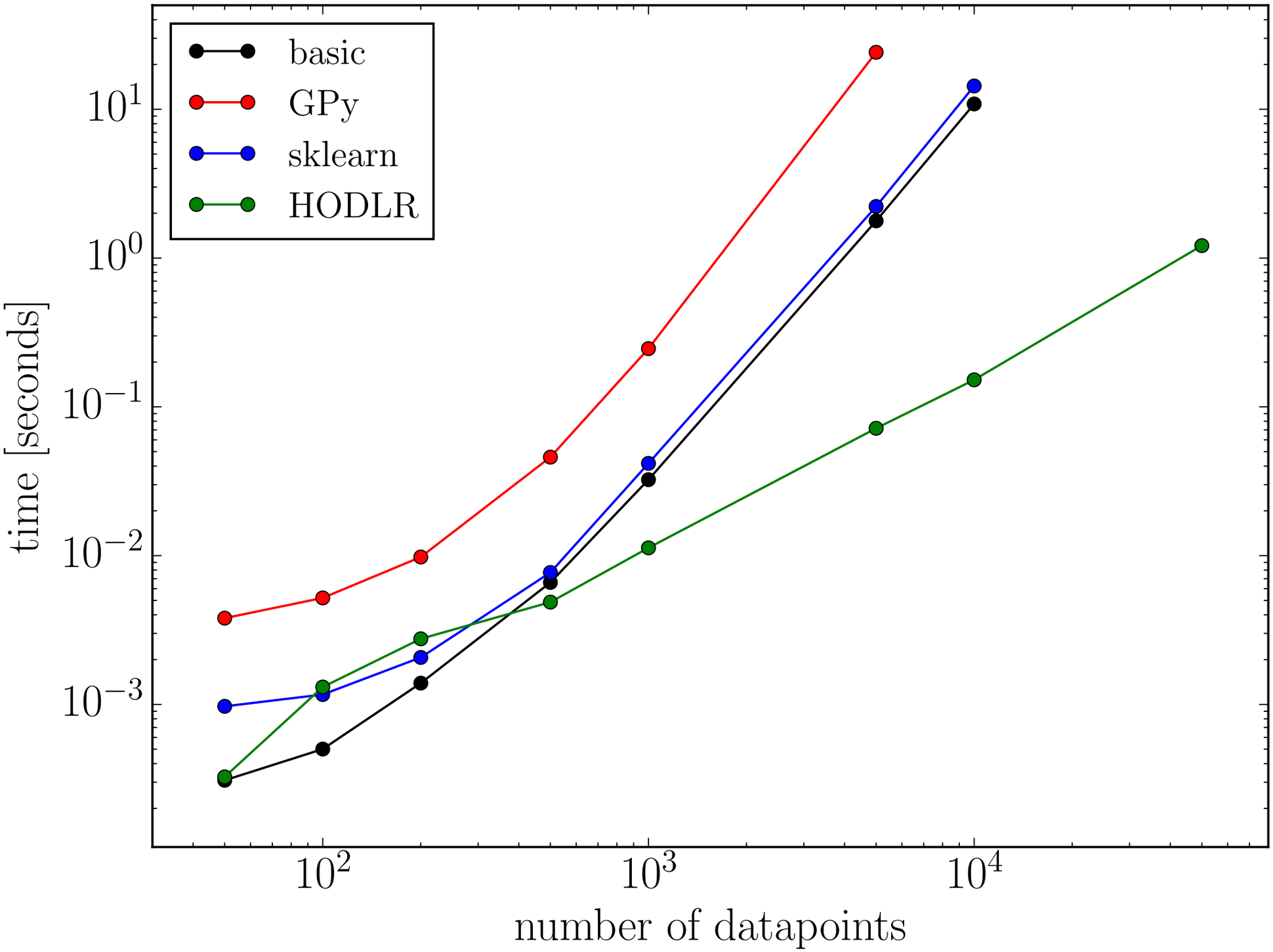



github.com/dfm/george

Does this **work**?

Yes.

## *K2* Campaign 1 exoplanet discoveries

21,703 stars

80 days of data

36 planet candidates

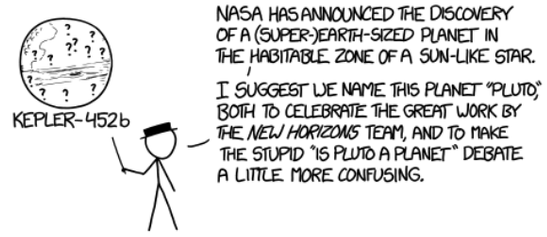
18 confirmed planets

*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)

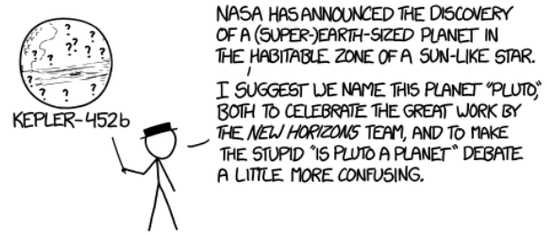



## WHILE WE WAIT TO HEAR FROM THE IAU, HERE'S A REVISED AND UPDATED LIST OF PLANET NAME SUGGESTIONS (SEE XKCD.COM/1253)

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

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| KEPLER-296 | b | KERBAL SPACE PLANET |
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| | f | SPRINGFIELD |
| HR 7722 | b | BETELGEUSE |
| | c | BEETLEJUICE |
| EPIC 201912552 | b | NETHERLANDS VI |
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| PI MENSAE | b | MOON HO |
| HD 189733 | b | |
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| 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

dfm/george at 1.0-dev

Dan

GitHub, Inc. [US] https://github.com/dfm/george/tree/1.0-dev

This repository Search

Pull requests Issues Gist

# dfm / george

Unwatch 14 Star 98 Fork 35

Fast Gaussian Processes for regression http://dan.iel.fm/george — Edit

430 commits 3 branches 1 release 5 contributors

Branch: 1.0-dev george / +

This branch is 79 commits ahead, 2 commits behind master. Pull request Compare

dfm fixing general metric bug and multi-d constant kernel scaling Latest commit 2e32ce3 19 days ago

| | | |
|---|---|---|
| docs | py3 xrange in kernels | 2 months ago |
| document | A few words for the paper | 10 months ago |
| george | fixing general metric bug and multi-d constant kernel scaling | 19 days ago |
| hodlr @ 2213b25 | updating hodlr for symmetric assembly | a year ago |
| kernels | building bounded kernels | 2 months ago |
| templates | fixing general metric bug and multi-d constant kernel scaling | 19 days ago |
| .gitignore | moving solvers | 2 months ago |
| .gitmodules | Starting C++ and HODLR version | 2 years ago |

Code

Issues 15

Pull requests 1

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https://github.c

You can clone with HTTPS, SSH, or Subversion.

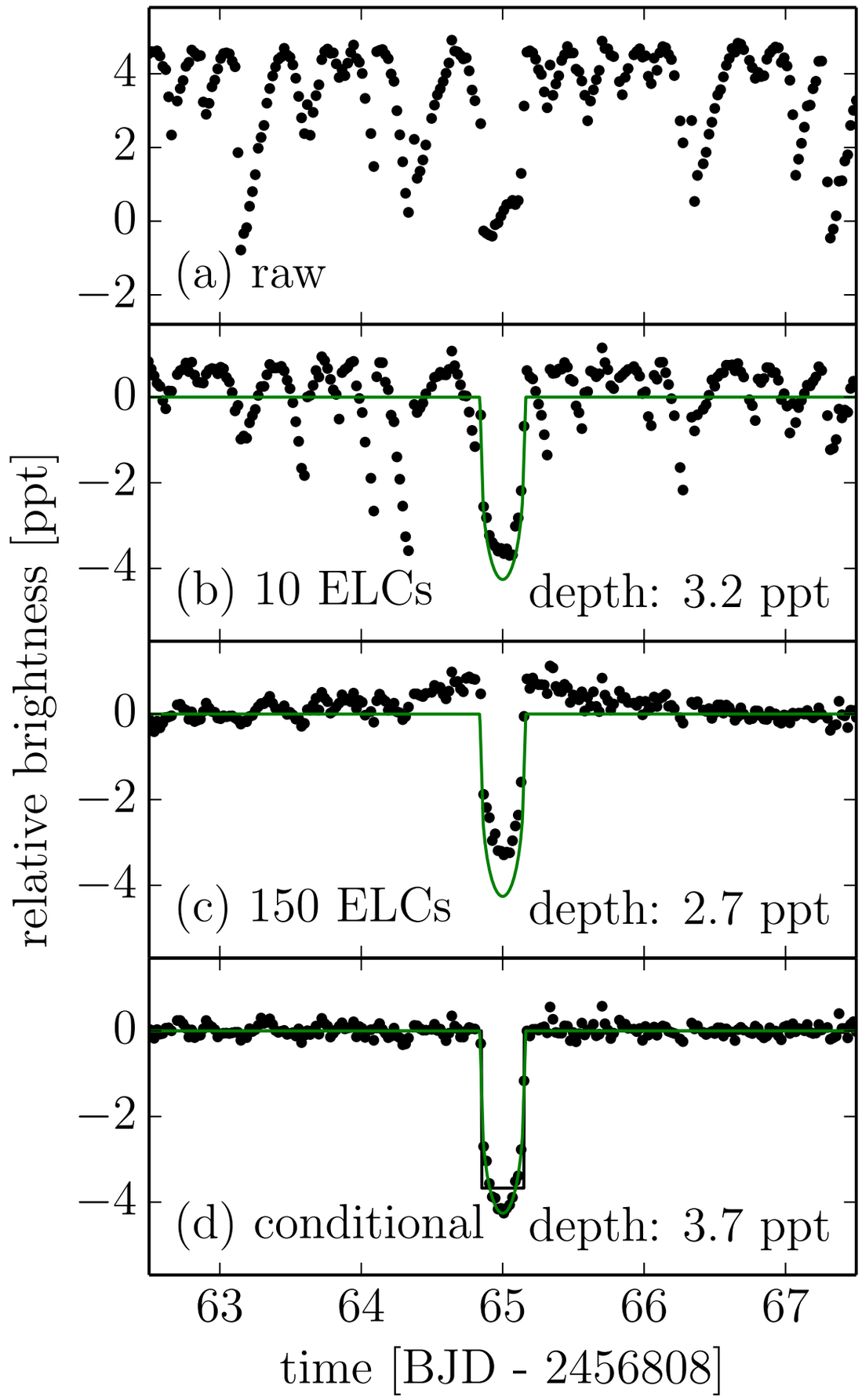
Clone in Desktop

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

gaussianprocess.org/**gpml**
github.com/**dfm/george**
dfm.io/**george**

**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)

extra


(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
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0
−2
−4
63
64
65
66
67