

artist's concept

# OM-NOM-NOM-NOM IT'S A STAR-EAT-PLANET WORLD WASP-12b

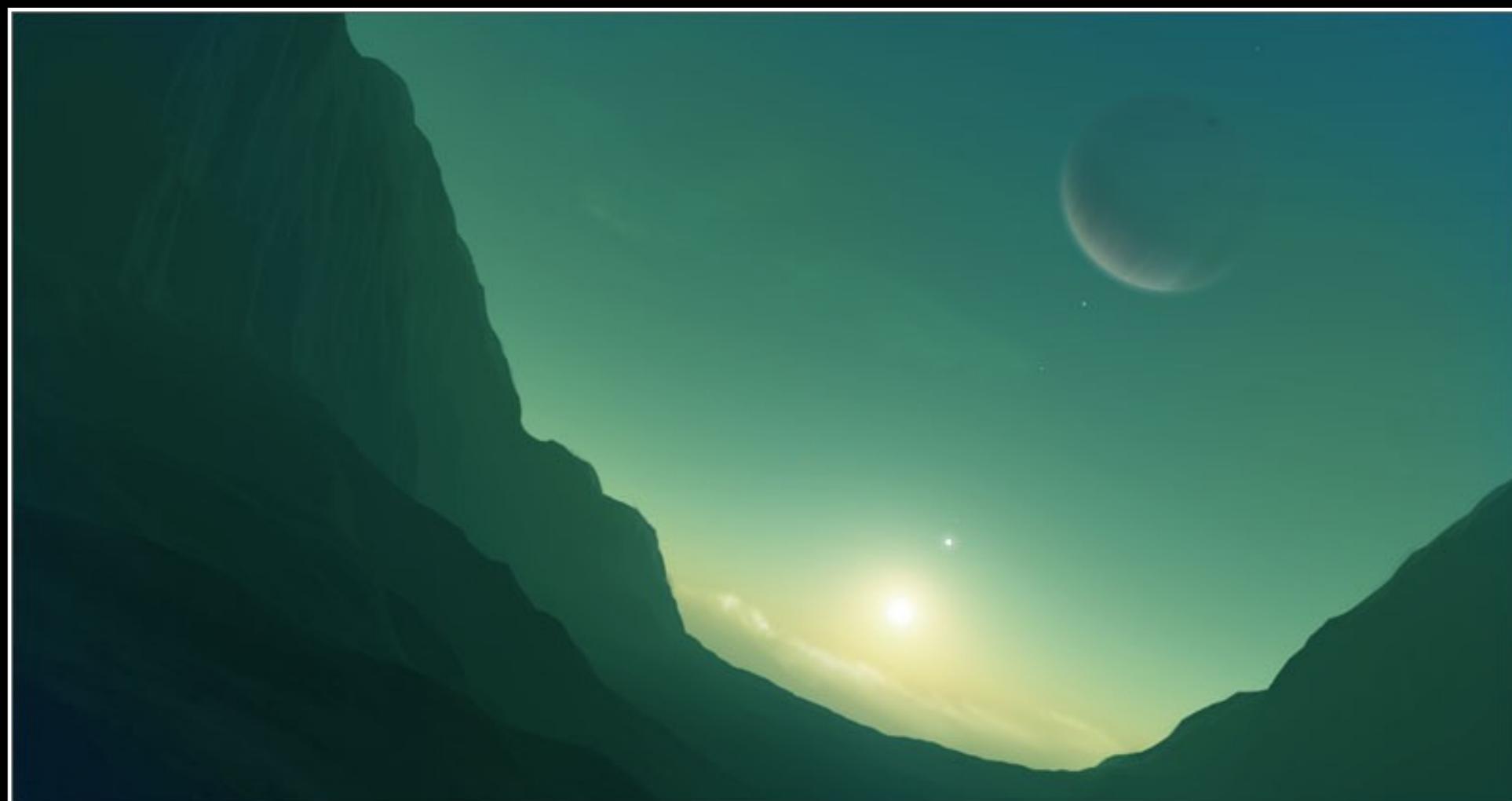


WE'RE OUT THERE

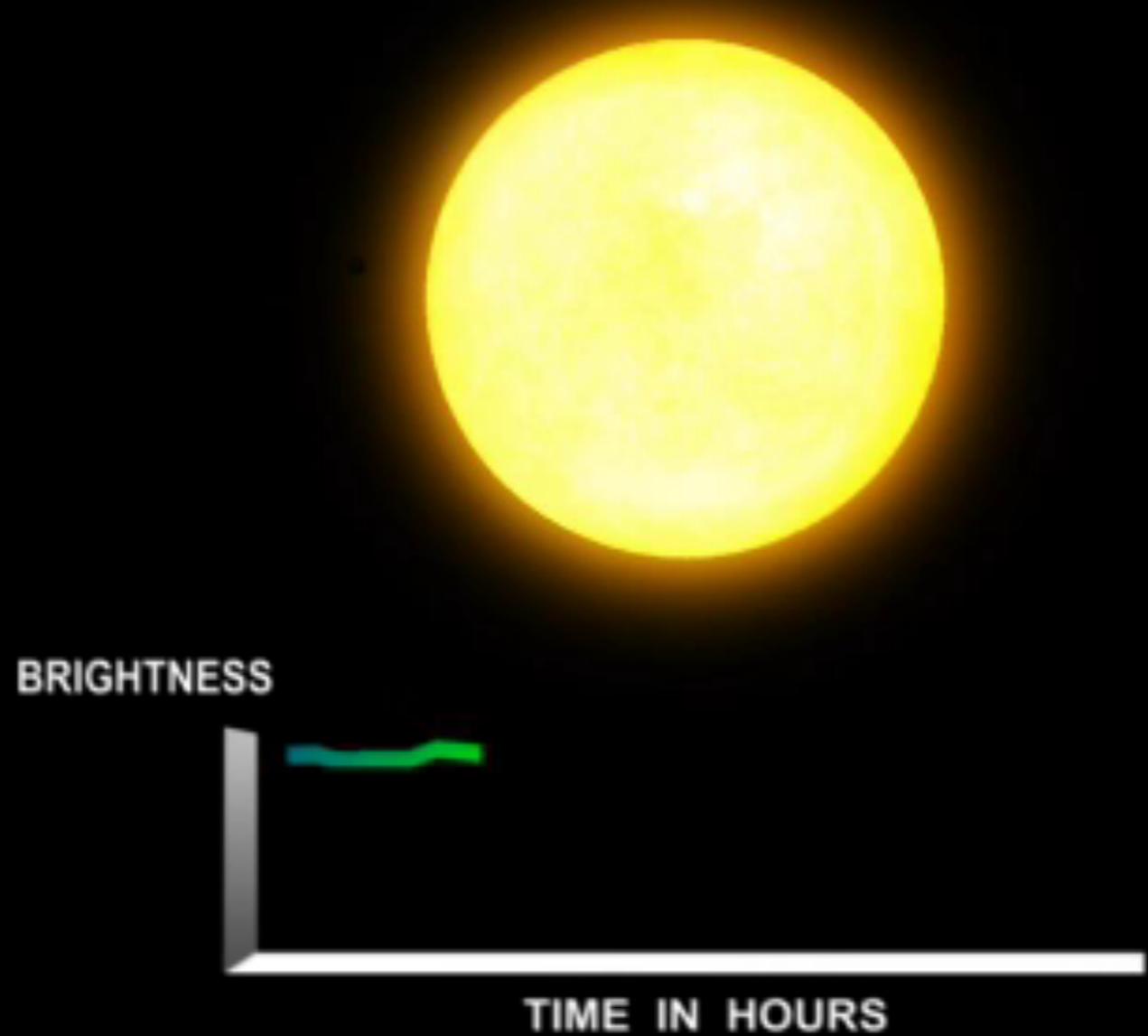
YEARS OF  
**20**  
EXOPLANETS

A planet orbiting another star is called an **extrasolar planet** (or exoplanet).

Since 1993, we have over FOUR THOUSAND CONFIRMED extrasolar planetary systems with more coming in every day



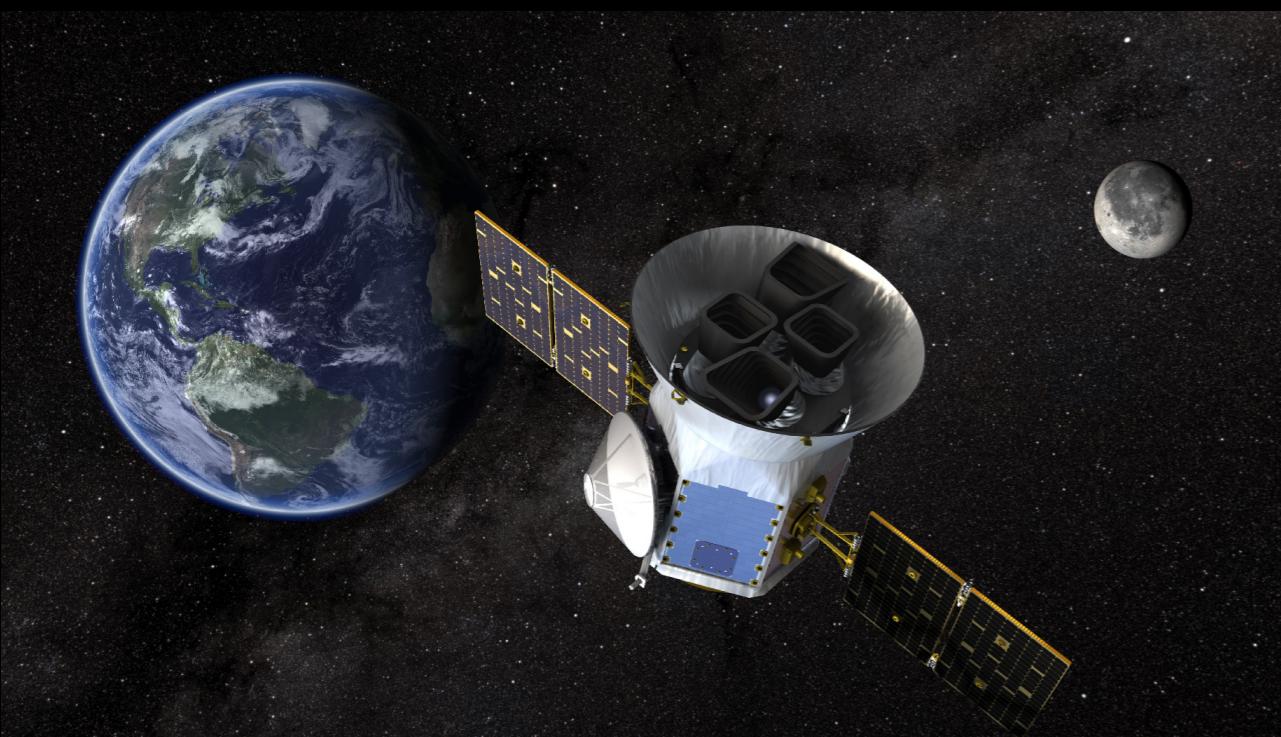
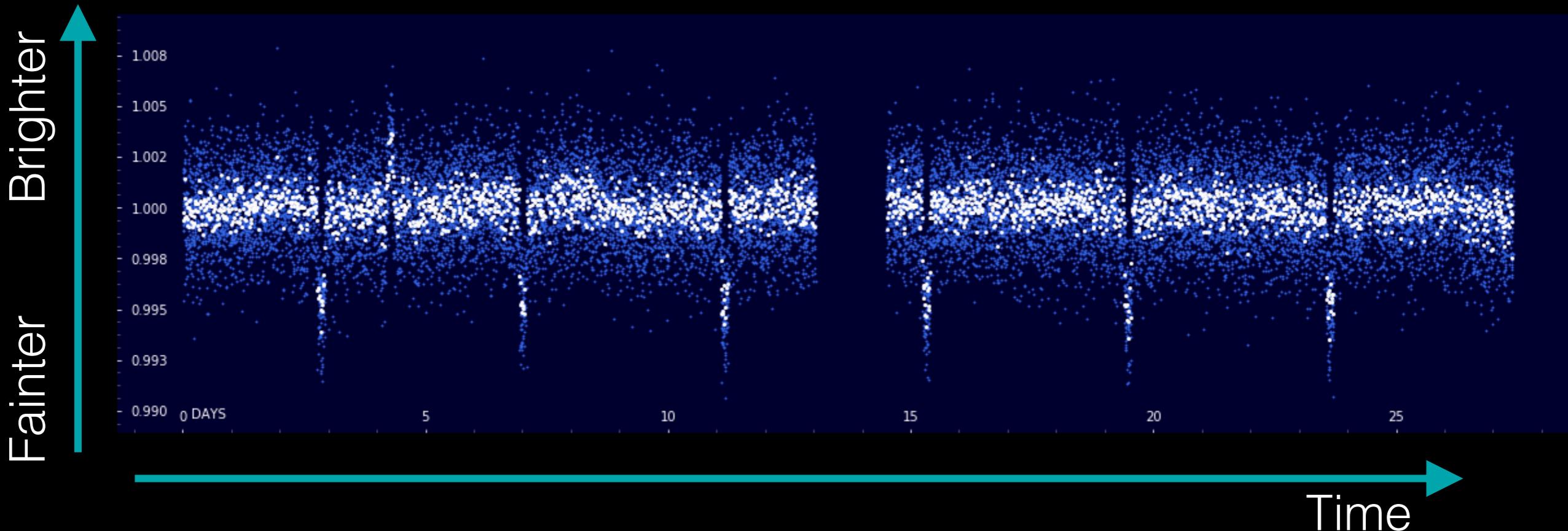
# Method planets found via the transit method





© Toshio

# Kepler is no longer operating, but now NASA's TESS Mission is making new discoveries...



# How do we find exoplanets??

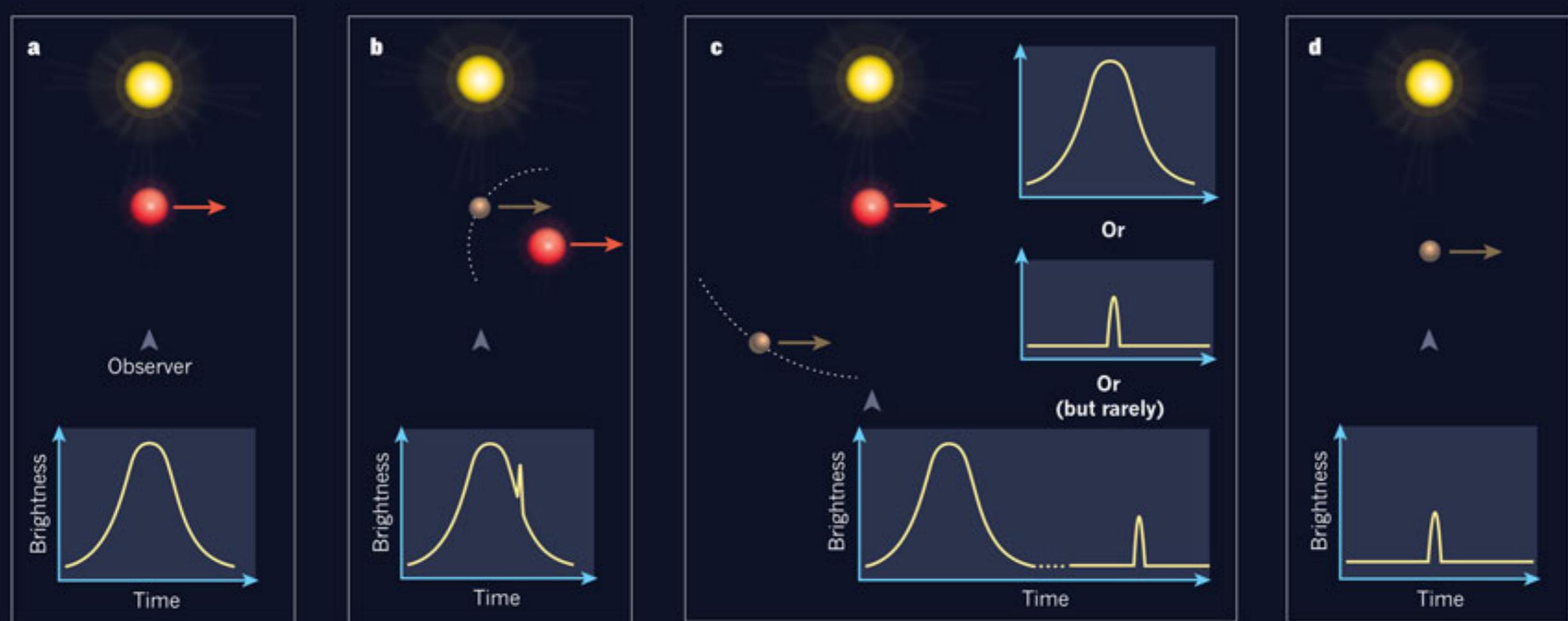
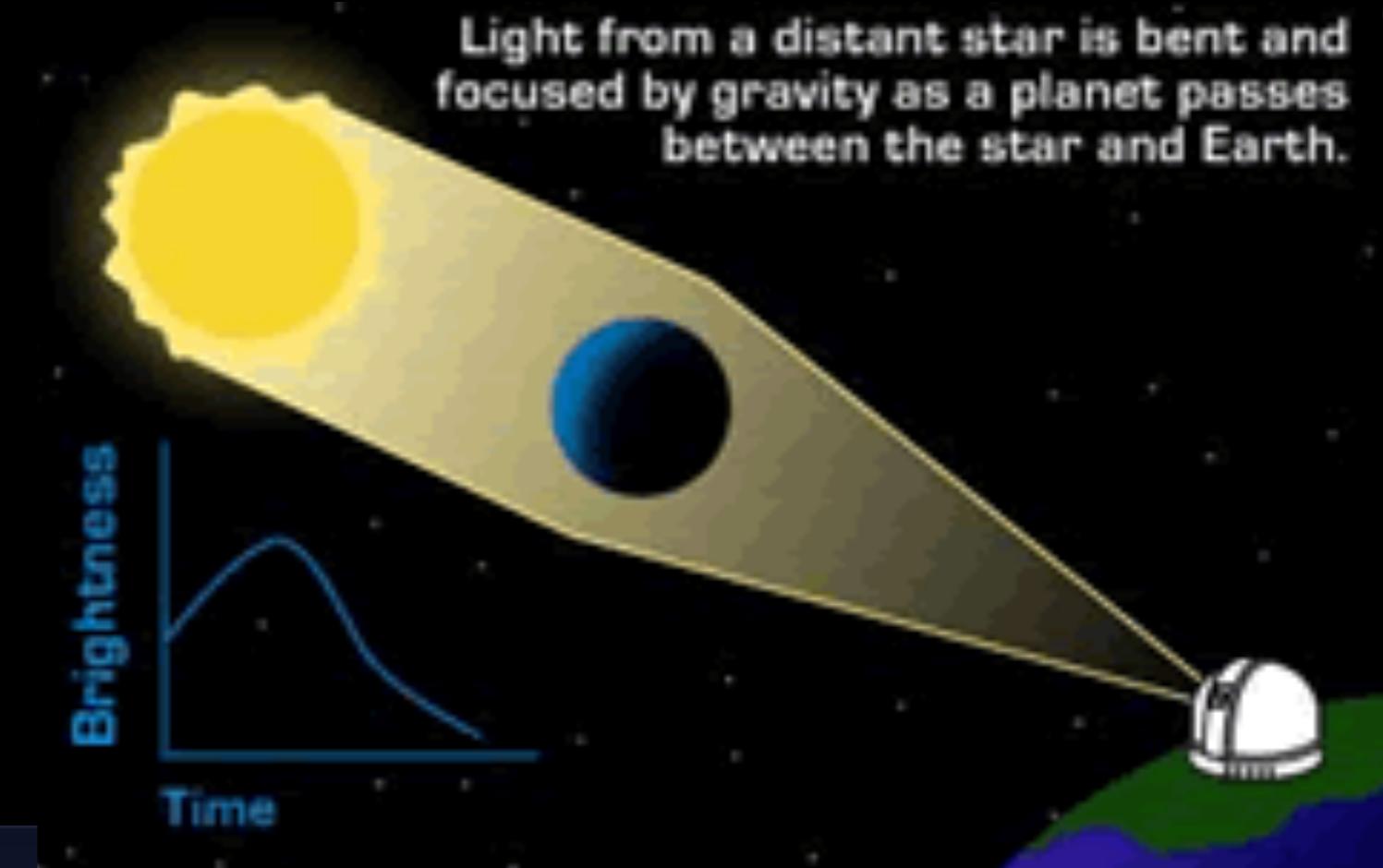
- Monitoring the brightness of stars to find transits
- Monitoring the radial velocity of stars to detect the “doppler wobble”
- ... and a few other methods that we’ll go over next.

# How else do we find exoplanets?

- Monitor the brightness of stars

# Gravitational Microlensing

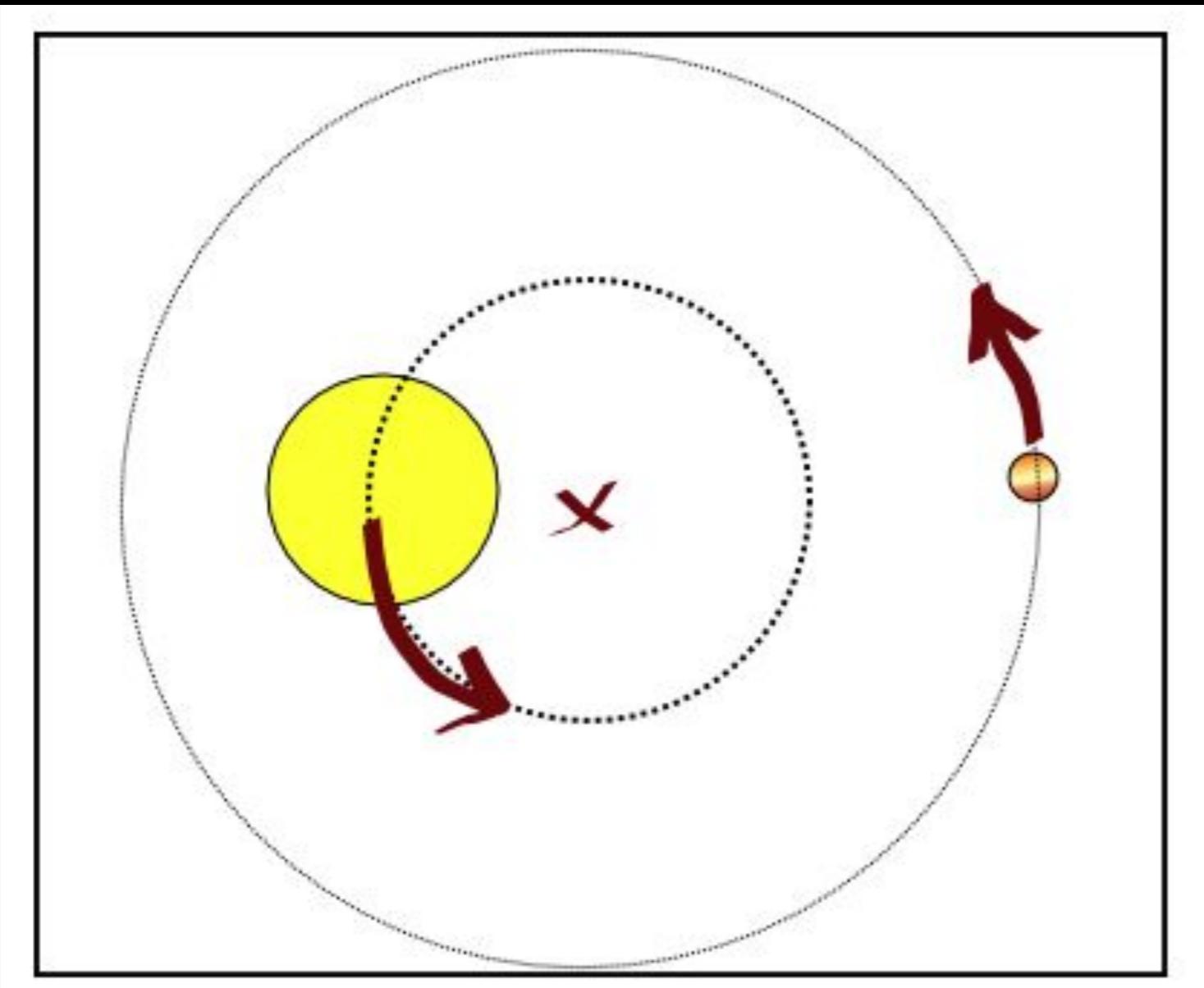
Light from a distant star is bent and focused by gravity as a planet passes between the star and Earth.



# How else do we find exoplanets?

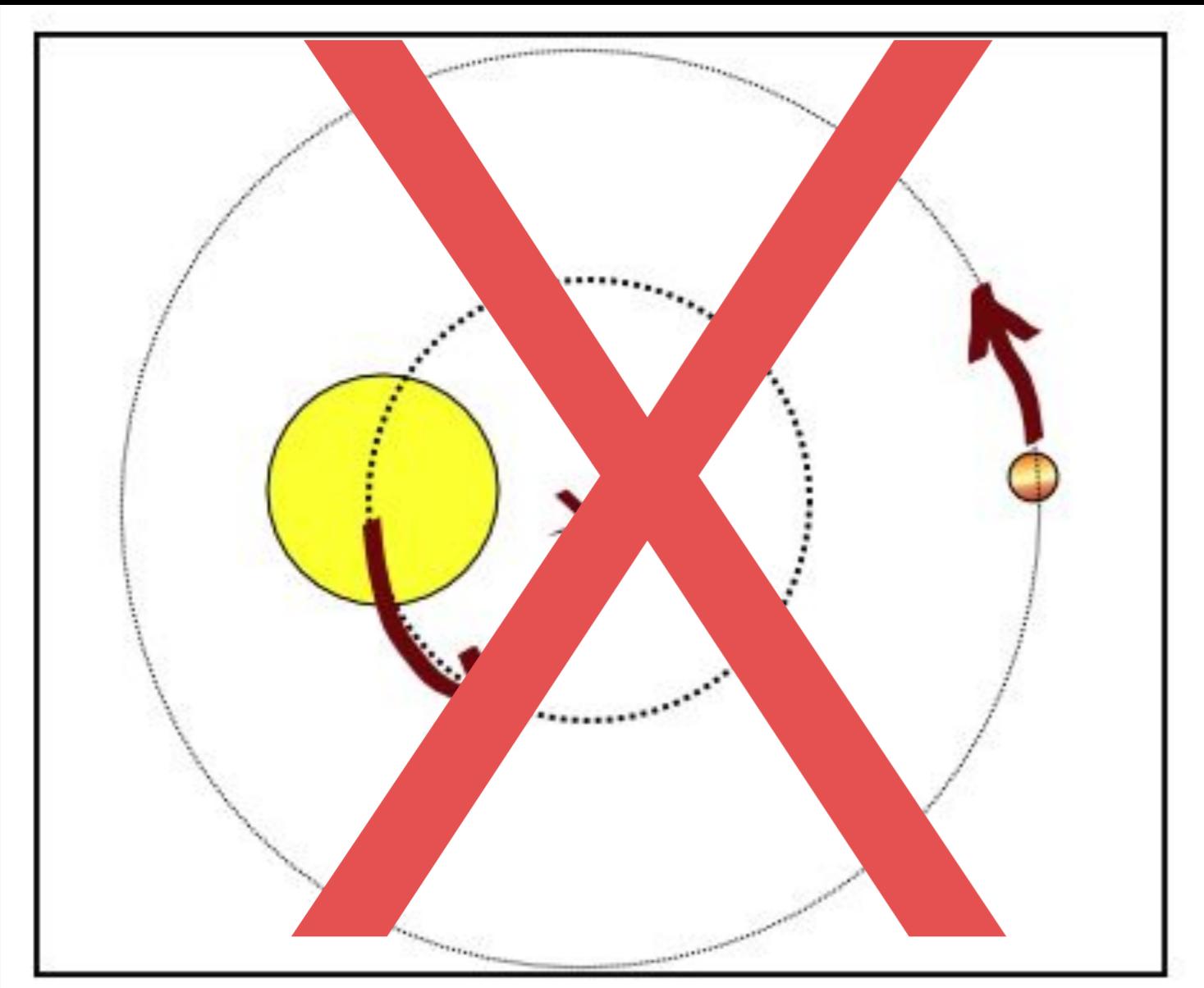
- Monitor the positions of stars

# Astrometric Technique



- We can detect planets by measuring the change in a star's position on sky.
- However, these tiny motions are very difficult to measure ( $\sim 10^{-7}$  degrees).

# Astrometric Technique



- We can detect planets by measuring the change in a star's position on sky.
- However, these tiny motions are very difficult to measure ( $\sim 10^{-7}$  degrees).

But we want to take a picture!



# How else do we find exoplanets?

- Direct imaging

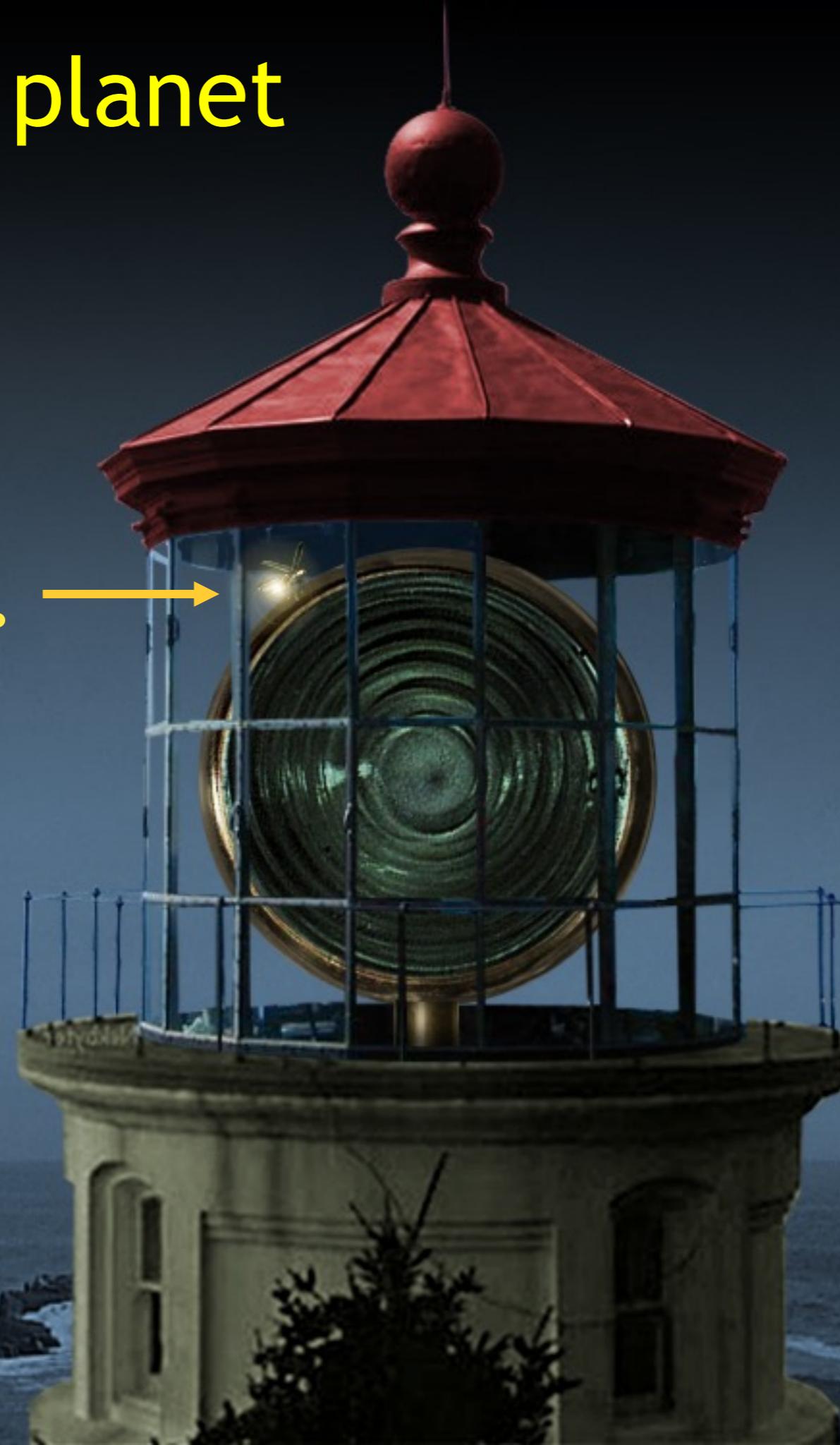
Stars are a billion

times brighter...



...than the planet

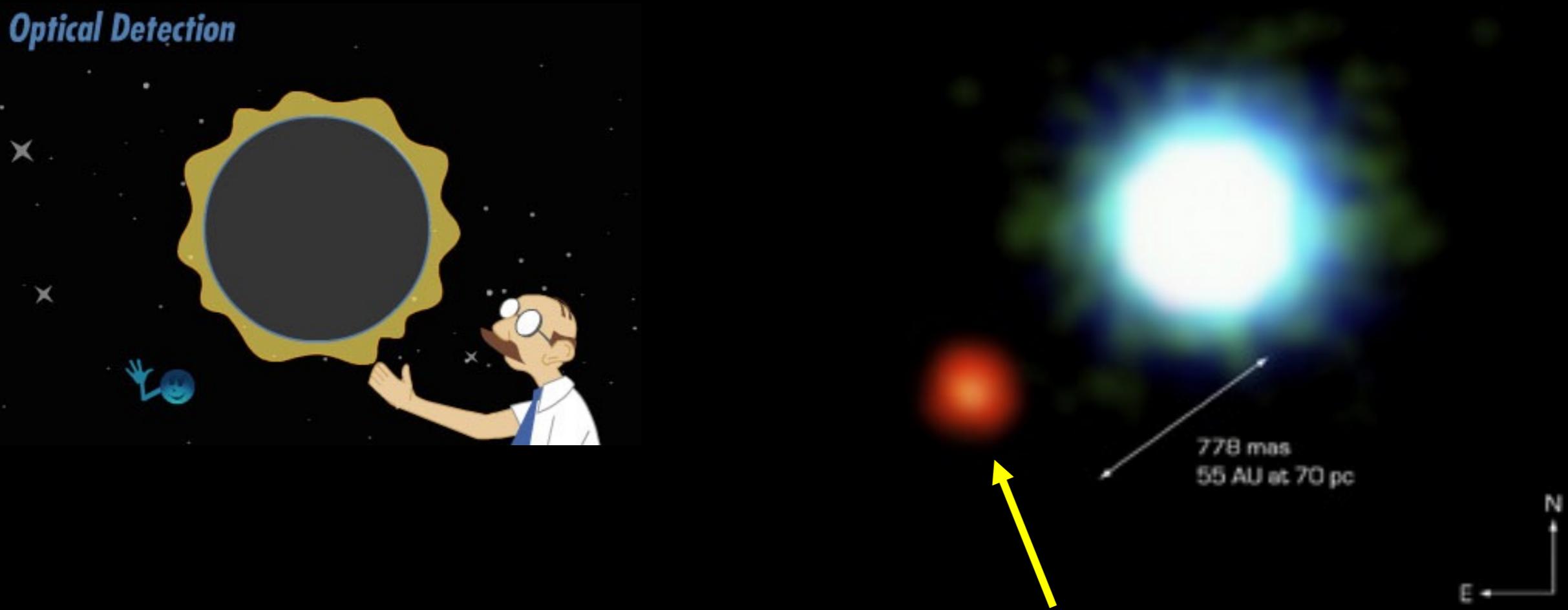
*...hidden  
in the glare.* —→



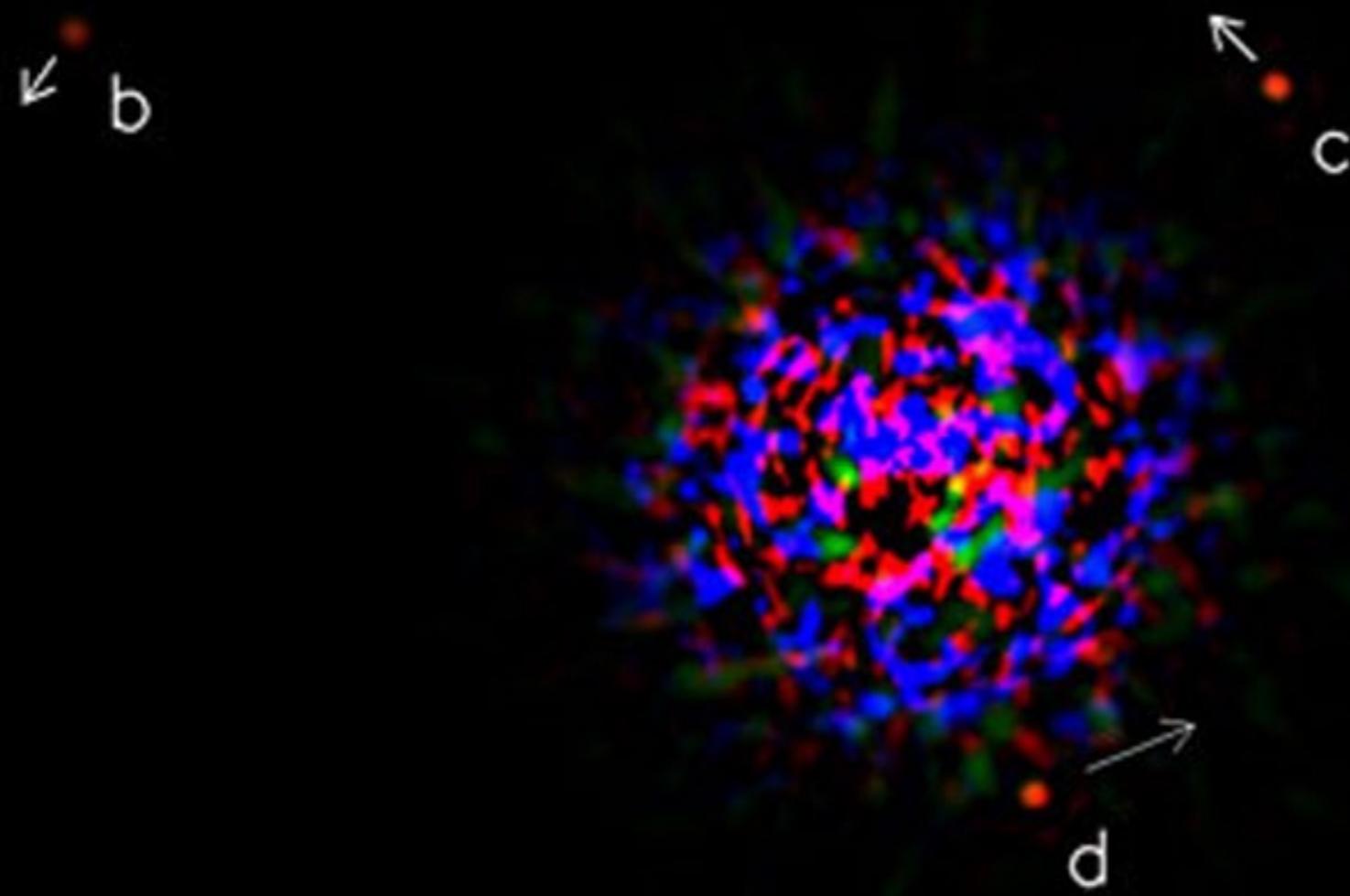
# For direct detection, we block out the bright light from the star

2MASSWJ1207334-393254

## *Optical Detection*



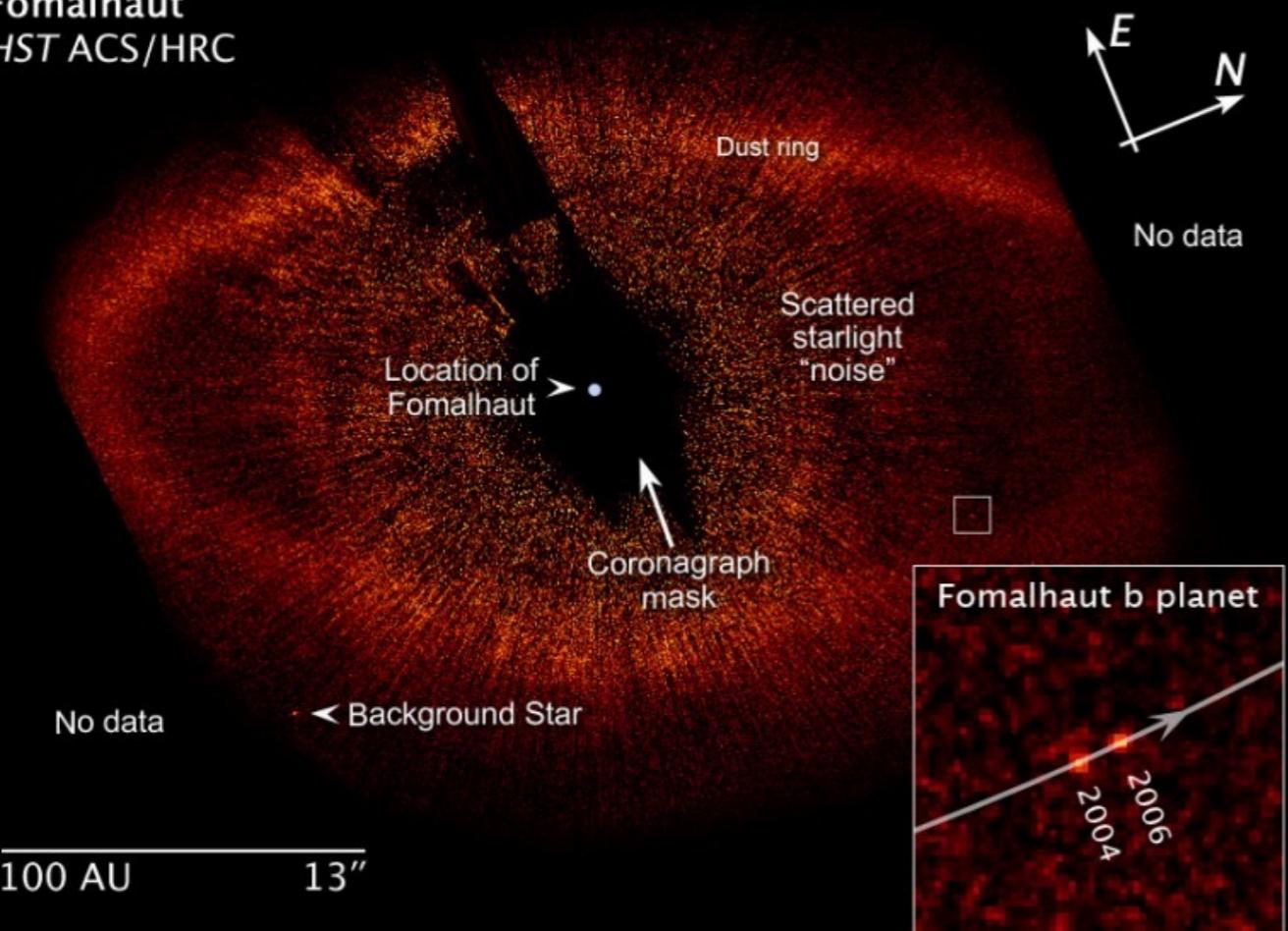
In 2009, we took a picture of another solar system!



HR 8799

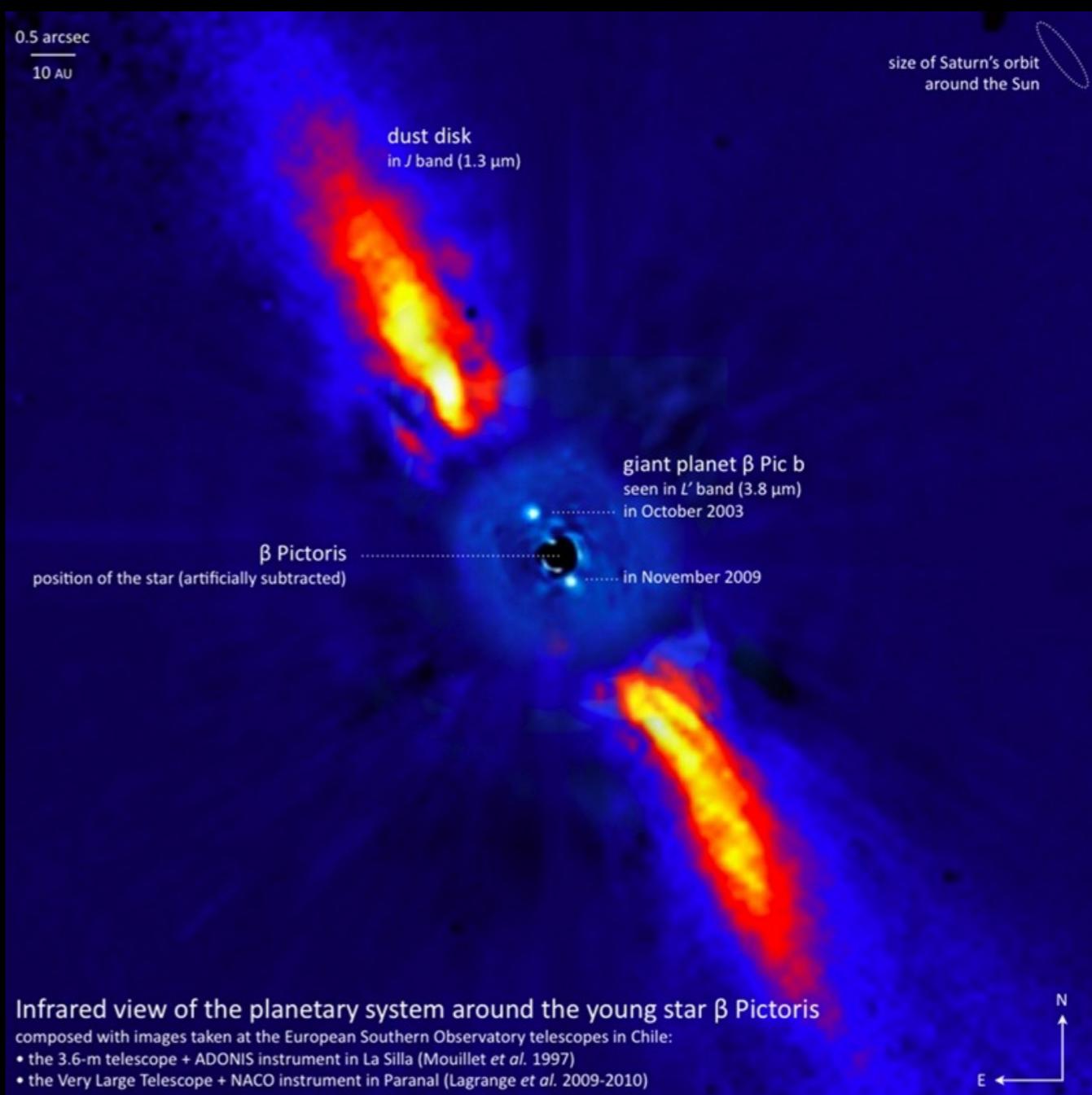
# There were more to follow ...

Fomalhaut  
HST ACS/HRC

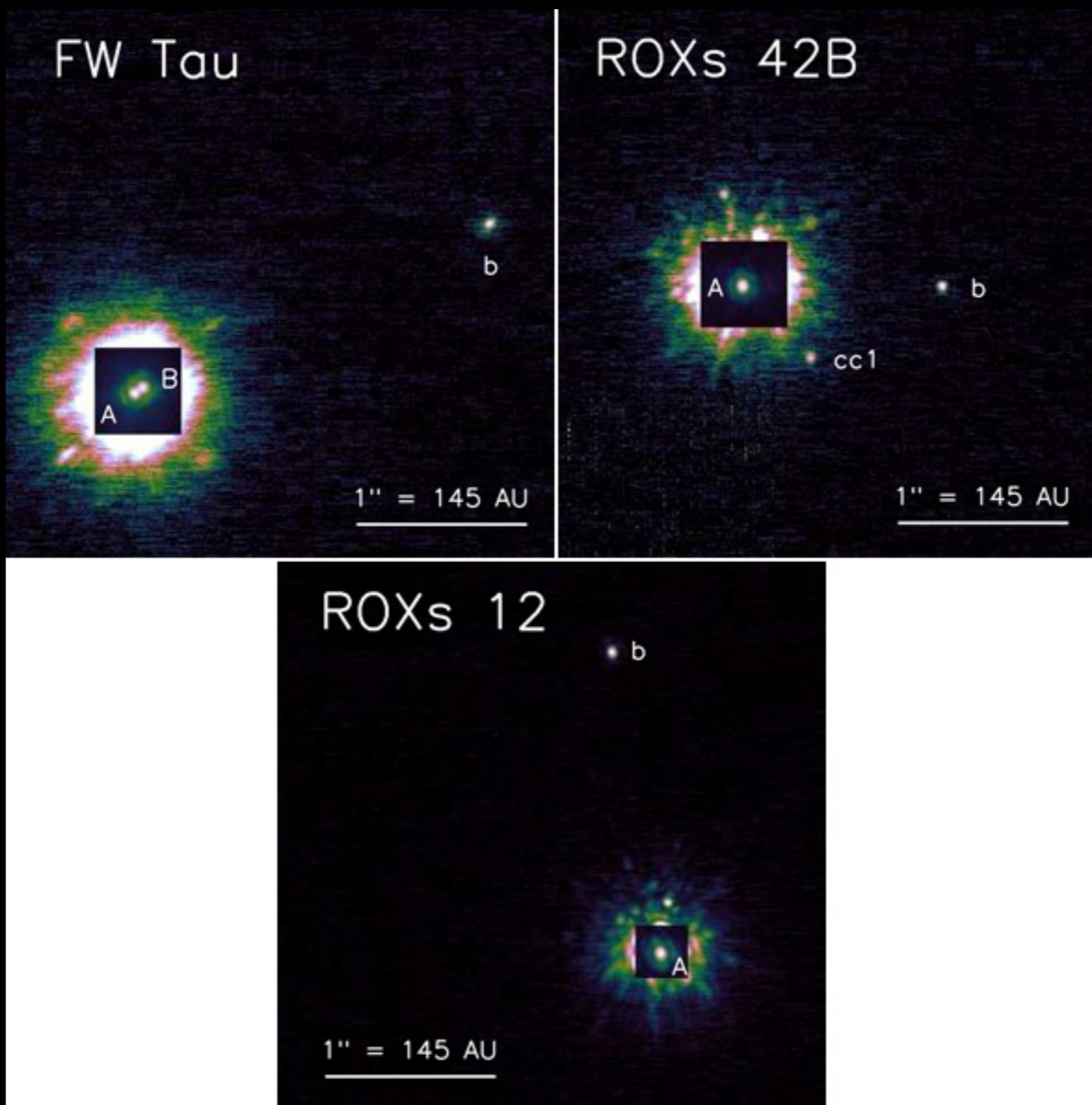


## Fomalhaut

## Beta Pic



# It's easier to image planets around young stars



Q: What method of extrasolar planet detection has thus far discovered the most planets?

- A) Doppler method
- B) Direct imaging
- C) Transit detection
- D) Astrometry
- E) Gravitational microlensing

Q: What method of extrasolar planet detection has thus far discovered the most planets?

- A) Doppler method
- B) Direct imaging
- C) **Transit detection**
- D) Astrometry
- E) Gravitational microlensing

# 5 Ways to Find a Planet

## RADIAL VELOCITY

Watching for Wobble

796 planets discovered

## TRANSIT

Searching for Shadows

3150 planets discovered

## DIRECT IMAGING

Taking Pictures

49 planets discovered

## GRAVITATIONAL MICROLENSING

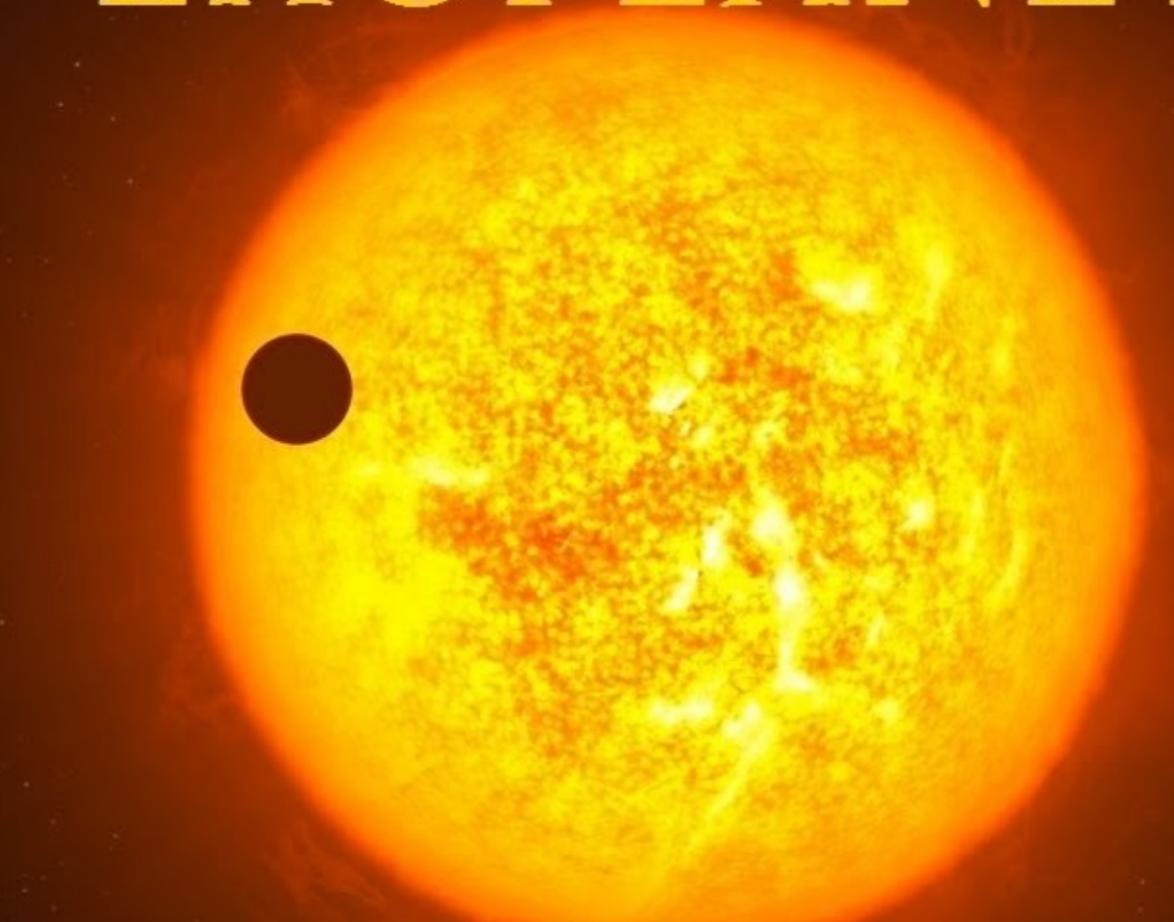
Light in a Gravity Lens

86 planets discovered

## ASTROMETRY

Minuscule Movements

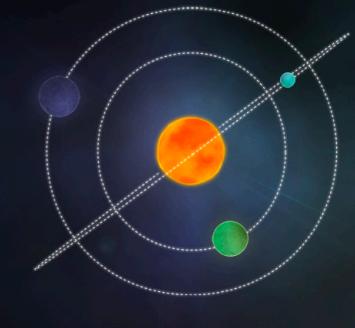
1 planet discovered



# HOW YOU FIND EXOPLANETS FROM HOME

Credit: ESO

# Try out Planet Hunters!



The screenshot shows the Planet Hunters.org interface. On the left, there's a large image of Earth from space and a smaller image of a sunset over a landscape. The main area features a light curve plot with a prominent dip at day 31, indicating a planetary transit. To the right of the plot is a circular decision interface asking, "Does the star have any transit features?". It has two options: "YES" (green) and "NO" (orange). Below this are details about the star: Type of star: Dwarf, Apparent visual magnitude: 13.9, Temperature: 6015 (K), and Radius: 0.8x Sol. At the bottom right is a "MARK AS FAVORITE" button.

planethunters.org

join the search for exoplanets using the latest Kepler data

a partnership with  
PLANETQUEST

HELP RESTART

Does the star have any transit features?

YES NO

Type of star: Dwarf

Apparent visual magnitude: 13.9

Temperature: 6015 (K)

Radius: 0.8x Sol

★ MARK AS FAVORITE

1.0015

1.0010

1.0005

1.0000

0.9995

0.9990

0.9985

0.9980

0.9975

0.9970

0.9965

0.9960

0.9955

0.9950

0.9945

0.9940

0.9935

0.9930

0.9925

0.9920

0.9915

0.9910

0.9905

0.9900

0.9895

0.9890

0.9885

0.9880

0.9875

0.9870

0.9865

0.9860

0.9855

0.9850

0.9845

0.9840

0.9835

0.9830

0.9825

0.9820

0.9815

0.9810

0.9805

0.9800

0.9795

0.9790

0.9785

0.9780

0.9775

0.9770

0.9765

0.9760

0.9755

0.9750

0.9745

0.9740

0.9735

0.9730

0.9725

0.9720

0.9715

0.9710

0.9705

0.9700

0.9695

0.9690

0.9685

0.9680

0.9675

0.9670

0.9665

0.9660

0.9655

0.9650

0.9645

0.9640

0.9635

0.9630

0.9625

0.9620

0.9615

0.9610

0.9605

0.9600

0.9595

0.9590

0.9585

0.9580

0.9575

0.9570

0.9565

0.9560

0.9555

0.9550

0.9545

0.9540

0.9535

0.9530

0.9525

0.9520

0.9515

0.9510

0.9505

0.9500

0.9495

0.9490

0.9485

0.9480

0.9475

0.9470

0.9465

0.9460

0.9455

0.9450

0.9445

0.9440

0.9435

0.9430

0.9425

0.9420

0.9415

0.9410

0.9405

0.9400

0.9395

0.9390

0.9385

0.9380

0.9375

0.9370

0.9365

0.9360

0.9355

0.9350

0.9345

0.9340

0.9335

0.9330

0.9325

0.9320

0.9315

0.9310

0.9305

0.9300

0.9295

0.9290

0.9285

0.9280

0.9275

0.9270

0.9265

0.9260

0.9255

0.9250

0.9245

0.9240

0.9235

0.9230

0.9225

0.9220

0.9215

0.9210

0.9205

0.9200

0.9195

0.9190

0.9185

0.9180

0.9175

0.9170

0.9165

0.9160

0.9155

0.9150

0.9145

0.9140

0.9135

0.9130

0.9125

0.9120

0.9115

0.9110

0.9105

0.9100

0.9095

0.9090

0.9085

0.9080

0.9075

0.9070

0.9065

0.9060

0.9055

0.9050

0.9045

0.9040

0.9035

0.9030

0.9025

0.9020

0.9015

0.9010

0.9005

0.9000

0.8995

0.8990

0.8985

0.8980

0.8975

0.8970

0.8965

0.8960

0.8955

0.8950

0.8945

0.8940

0.8935

0.8930

0.8925

0.8920

0.8915

0.8910

0.8905

0.8900

0.8895

0.8890

0.8885

0.8880

0.8875

0.8870

0.8865

0.8860

0.8855

0.8850

0.8845

0.8840

0.8835

0.8830

0.8825

0.8820

0.8815

0.8810

0.8805

0.8800

0.8795

0.8790

0.8785

0.8780

0.8775

0.8770

0.8765

0.8760

0.8755

0.8750

0.8745

0.8740

0.8735

0.8730

0.8725

0.8720

0.8715

0.8710

0.8705

0.8700

0.8695

0.8690

0.8685

0.8680

0.8675

0.8670

0.8665

0.8660

0.8655

0.8650

0.8645

0.8640

0.8635

0.8630

0.8625

0.8620

0.8615

0.8610

0.8605

0.8600

0.8595

0.8590

0.8585

0.8580

0.8575

0.8570

0.8565

0.8560

0.8555

0.8550

0.8545

0.8540

0.8535

0.8530

0.8525

0.8520

0.8515

0.8510

0.8505

0.8500

0.8495

0.8490

0.8485

0.8480

0.8475

0.8470

0.8465

0.8460

0.8455

0.8450

0.8445

0.8440

0.8435

0.8430

0.8425

0.8420

0.8415

0.8410

0.8405

0.8400

0.8395

0.8390

0.8385

0.8380

0.8375

0.8370

0.8365

0.8360

0.8355

0.8350

0.8345

0.8340

0.8335

0.8330

0.8325

0.8320

0.8315

0.8310

0.8305

0.8300

0.8295

0.8290

0.8285

0.8280

0.8275

0.8270

0.8265

0.8260

0.8255

0.8250

0.8245

0.8240

0.8235

0.8230

0.8225

0.8220

0.8215

0.8210

0.8205

0.8200

0.8195

0.8190

0.8185

0.8180

0.8175

0.8170

0.8165

0.8160

0.8155

0.8150

0.8145

0.8140

0.8135

0.8130

0.8125

0.8120

0.8115

0.8110

0.8105

0.8100

0.8095

0.8090

0.8085

0.8080

0.8075

0.8070

0.8065

0.8060

0.8055

0.8050

0.8045

0.8040

0.8035

0.8030

0.8025

0.8020

0.8015

0.8010

0.8005

0.8000

0.7995

0.7990

0.7985

0.7980

0.7975

0.7970

0.7965

0.7960

0.7955

0.7950

0.7945

0.7940

0.7935

0.7930

0.7925

0.7920

0.7915

0.7910

0.7905

0.7900

0.7895

0.7890

0.7885

0.7880

0.7875

0.7870

0.7865

0.7860

0.7855

0.7850

0.7845

0.7840

0.7835

0.7830

0.7825

0.7820

0.7815

0.7810

0.7805

0.7800

0.7795

0.7790

0.7785

0.7780

0.7775

0.7770

0.7765

0.7760

0.7755

0.7750

0.7745

0.7740

0.7735

0.7730

0.7725

0.7720

0.7715

0.7710

0.7705

0.7700

0.7695

0.7690

0.7685

0.7680

0.7675

0.7670

0.7665

0.7660

0.7655

0.7650

0.7645

0.7640

0.7635

0.7630

0.7625

0.7620

0.7615

0.7610

0.7605

0.7600

0.7595

0.7590

0.7585

0.7580

0.7575

0.7570

0.7565

0.7560

0.7555

0.7550

0.7545

0.7540

0.7535

0.7530

0.7525

0.7520

0.7515

0.7510

0.7505

0.7500

0.7495

0.7490

0.7485

0.7480

0.7475

0.7470

0.7465

0.7460

0.7455

0.7450

0.7445

0.7440

0.7435

0.7430

0.7425

0.7420

0.7415

0.7410

0.7405

0.7400

0.7395

0.7390

0.7385

0.7380

0.7375

0.7370

0.7365

0.7360

0.7355

0.7350

0.7345

0.7340

0.7335

0.7330

0.7325

0.7320

0.7315

0.7310

0.7305

0.7300

0.7295

0.7290

0.7285

0.7280

0.7275

0.7270

0.7265

0.7260

0.7255

0.7250

0.7245

0.7240

0.7235

0.7230

0.7225

0.7220

0.7215

0.7210

0.7205

0.7200

0.7195

0.7190

0.7185

0.7180

0.7175

0.7170

0.7165

0.7160

0.7155

0.7150

0.7145

0.7140

0.7135

0.7130

0.7125

0.7120

0.7115

0.7110

0.7105

0.7100

0.7095

0.7090

0.7085

0.7080

0.7075

0.7070

0.7065

0.7060

0.7055

0.7050

0.7045

0.7040

0.7035

0.7030

0.7025

0.7020

0.7015

0.7010

0.7005

0.7000

0.6995

0.6990

0.6985

0.6980

0.6975

0.6970

0.6965

0.6960

0.6955

0.6950

0.6945

0.6940

0.6935

0.6930

0.6925

0.6920

0.6915

0.6910

0.6905

0.6900

0.6895

0.6890

0.6885

0.6880

0.6875

0.6870

0.6865

0.6860

0.6855

0.6850

0.6845

0.6840

0.6835

0.6830

0.6825

0.6820

0.6815

0.6810

0.6805

0.6800

0.6795

0.6790

0.6785

0.6780

0.6775

0.6770

0.6765

0.6760

0.6755

0.6750

0.6745

0.6740

0.6735

0.6730

0.6725

0.6720

0.6715

0.6710

0.6705

0.6700

0.6695

0.6690

0.6685

0.6680

0.6675

0.6670

0.6665

0.6660

0.6655

0.6650

0.6645

0.6640

0.6635

0.6630

0.6625

0.6620

0.6615

0.6610

0.6605

0.6600

0.6595

0.6590

0.6585

0.6580

0.6575

0.6570

0.6565

0.6560

0.6555

0.6550

0.6545

0.6540

0.6535

0.6530

0.6525

0.6520

0.6515

0.6510

0.6505

0.6500

0.6495

0.6490

0.6485

0.6480

0.6475

0.6470

0.6465

0.6460

0.6455

0.6450

0.6445

0.6440

0.6435

0.6430

0.6425

0.6420

0.6415

0.6410

0.6405

0.6400

0.6395

0.6390

0.6385

0.6380

0.6375

0.6370

0.6365

0.6360

0.6355

0.6350

0.6345

0.6340

0.6335

0.6330

0.6325

<p

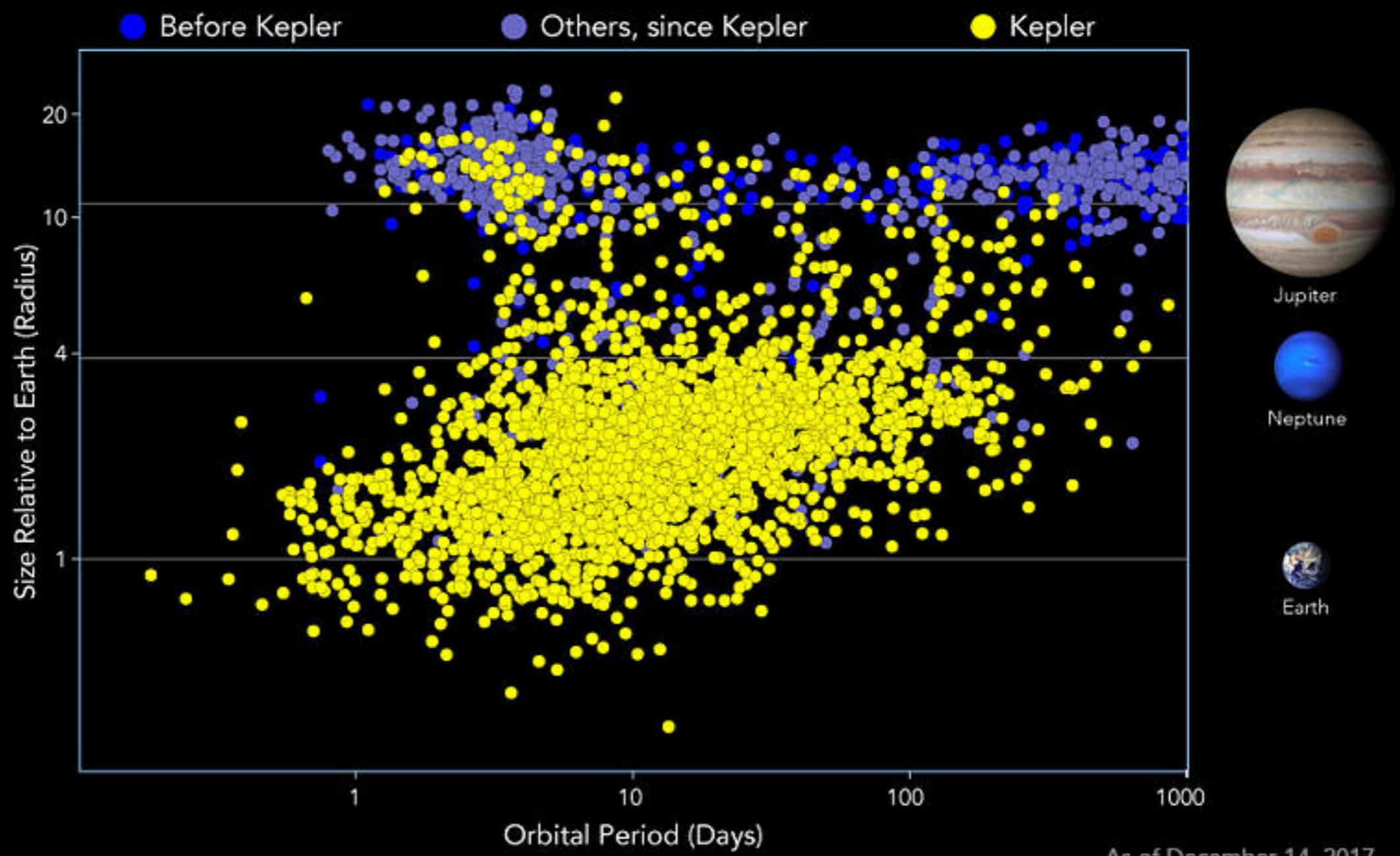
# What have we discovered out there?



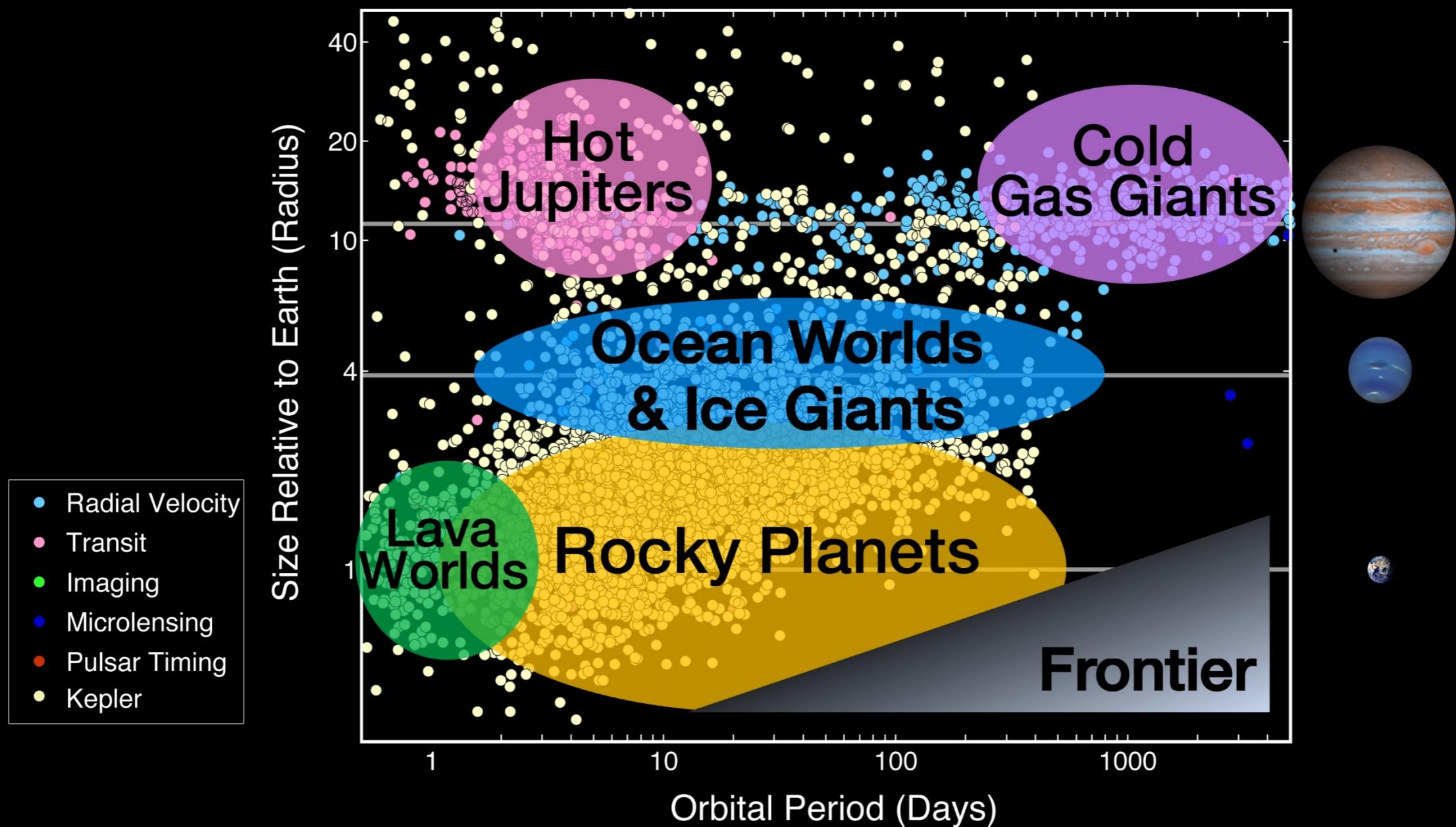
# Exoplanet Discoveries

Total confirmed exoplanets  
= 4,135

Total Kepler  
= 2,357



# Exoplanet Populations

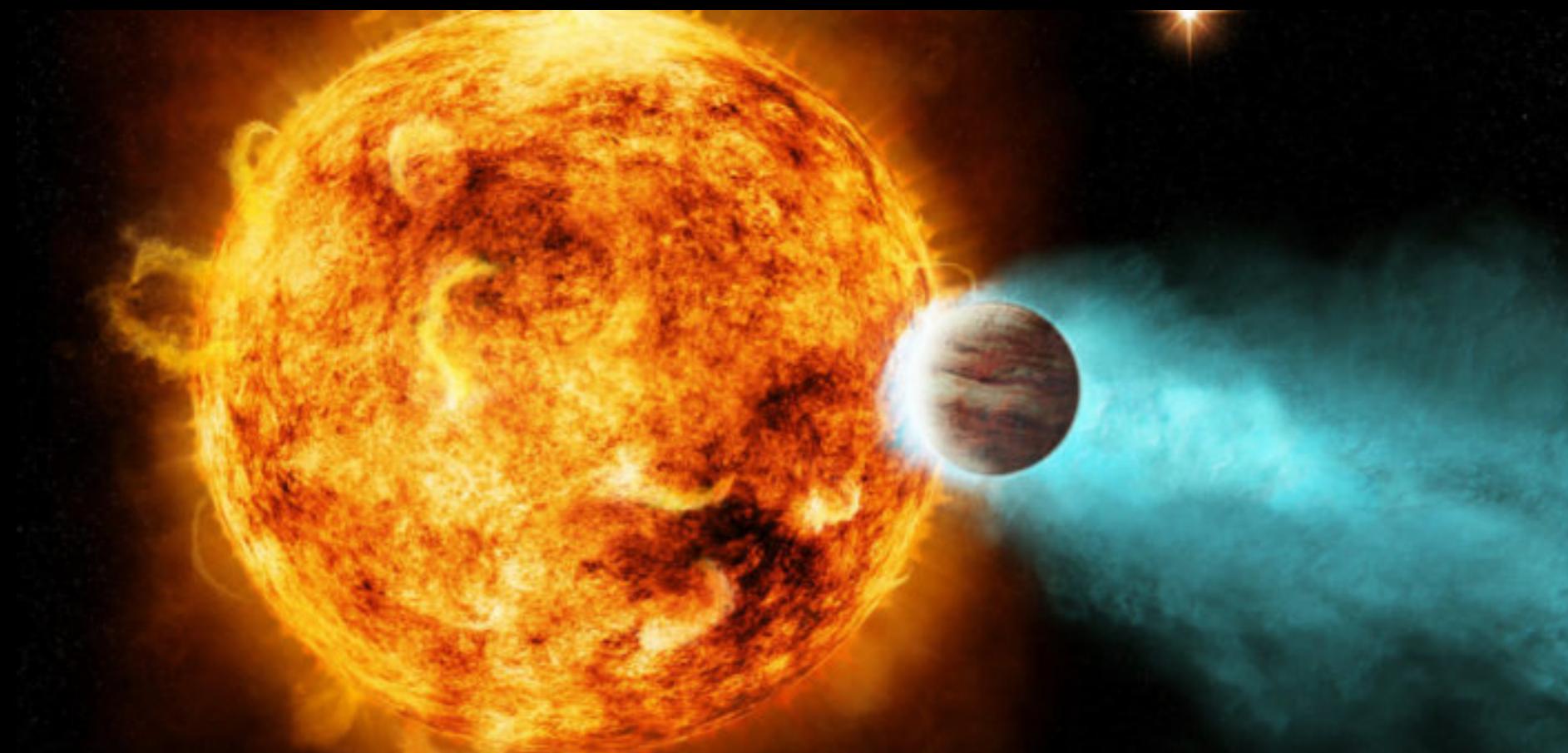


Hot Jupiters were a big surprise...



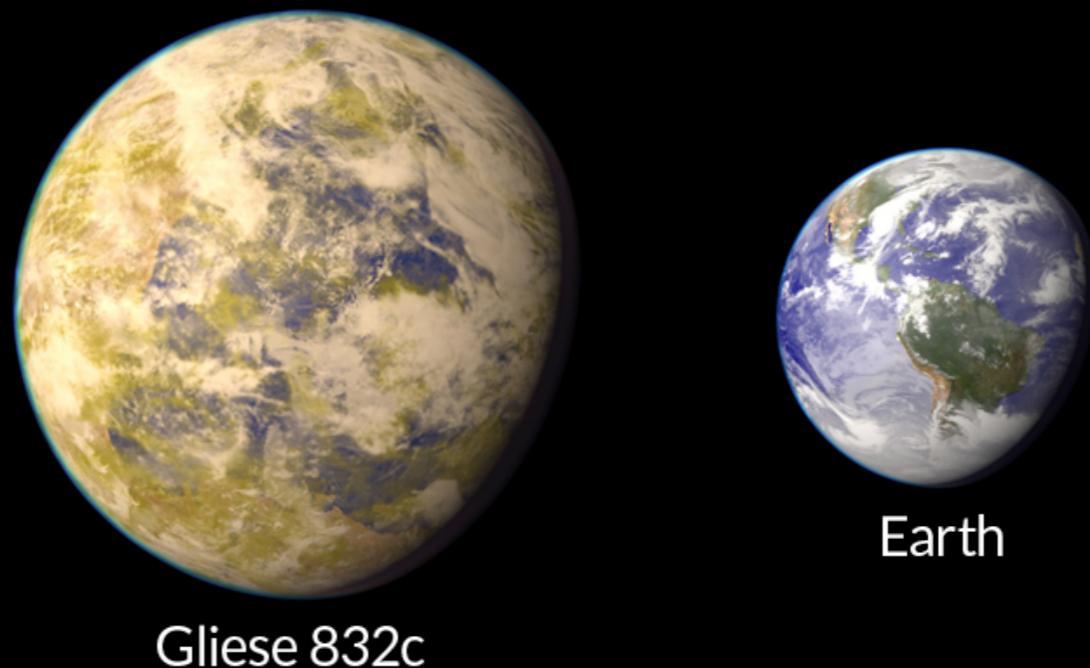
# Hot Jupiters were a big surprise...

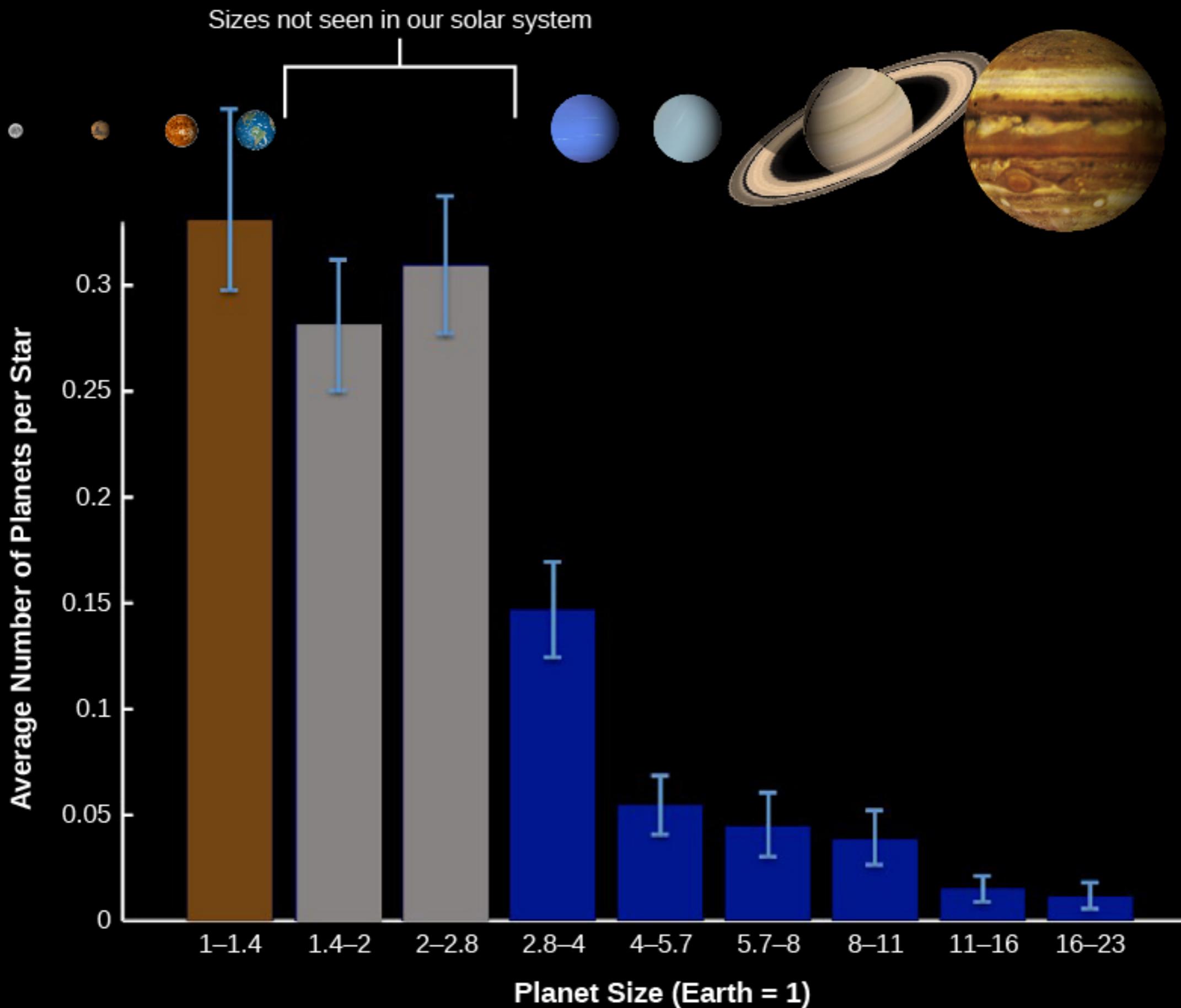
- Temperatures can be >2000 degrees!
- So hot that some are even evaporating like comets
- Orbital period of just a few days
- They orbit about 1% of stars
- → not that common, but easy to detect.



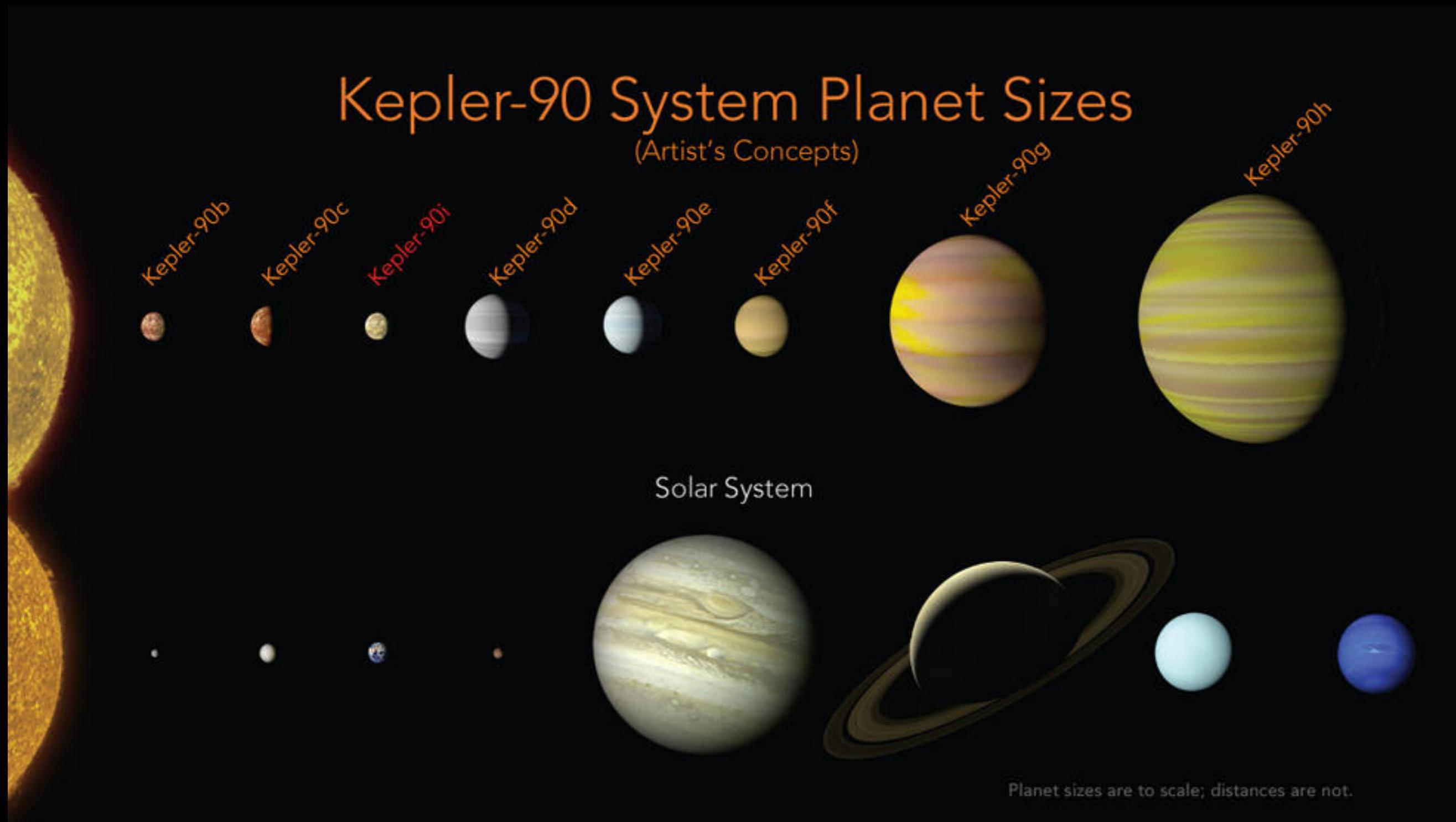
# Super-Earths and Mini-Neptunes were also a bit of a surprise...

- Super-Earth: 1.4-2.8 times the size of Earth
- Mini-Neptune: 2.8-4 times the size of Earth
- Kepler found many of these!
- We don't have anything of this size in our own Solar System.

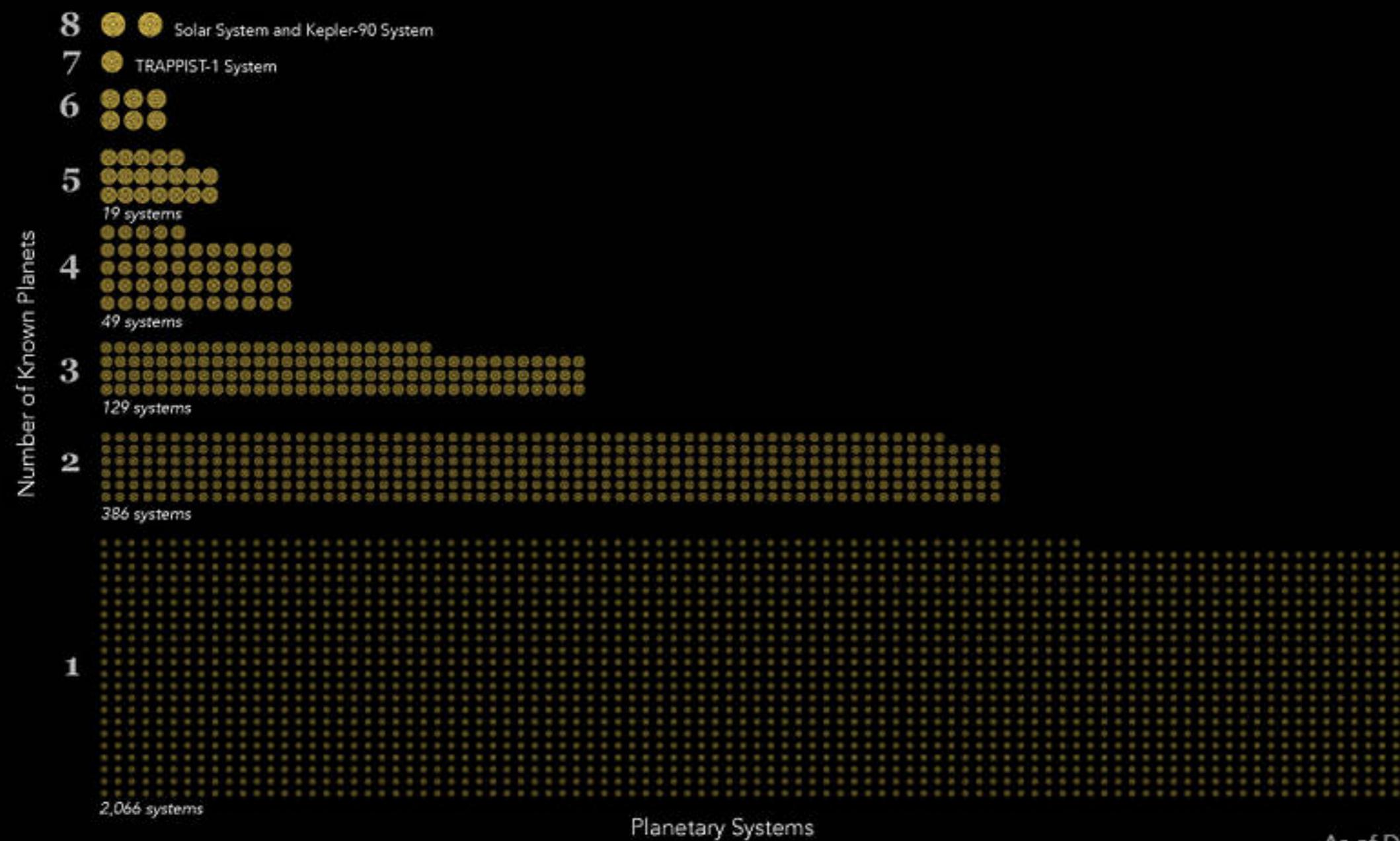




# Kepler found multi-planet systems!

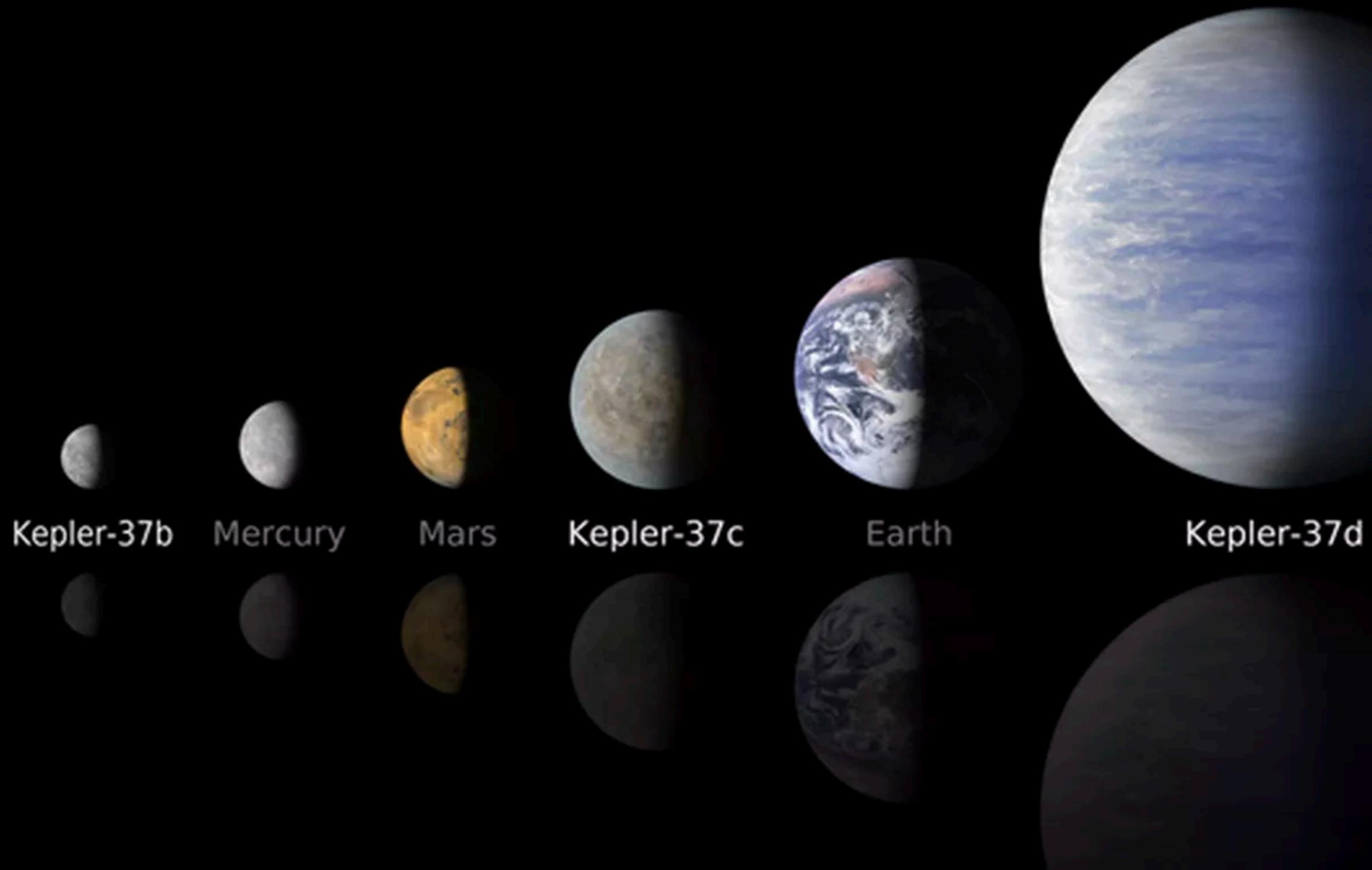


# Planetary Systems by Number of Known Planets



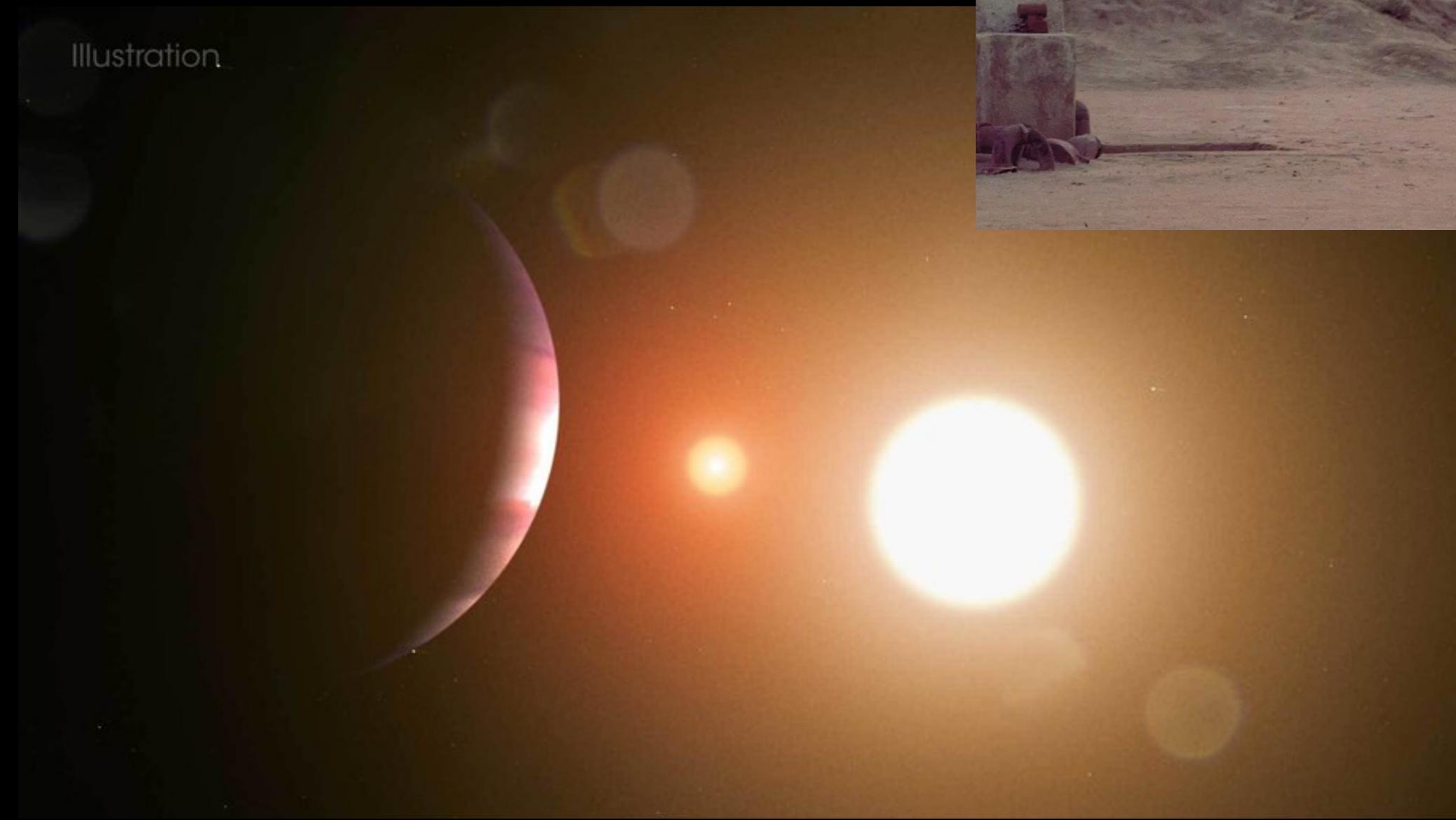
As of December 14, 2017

# Kepler-37b: the smallest planet found

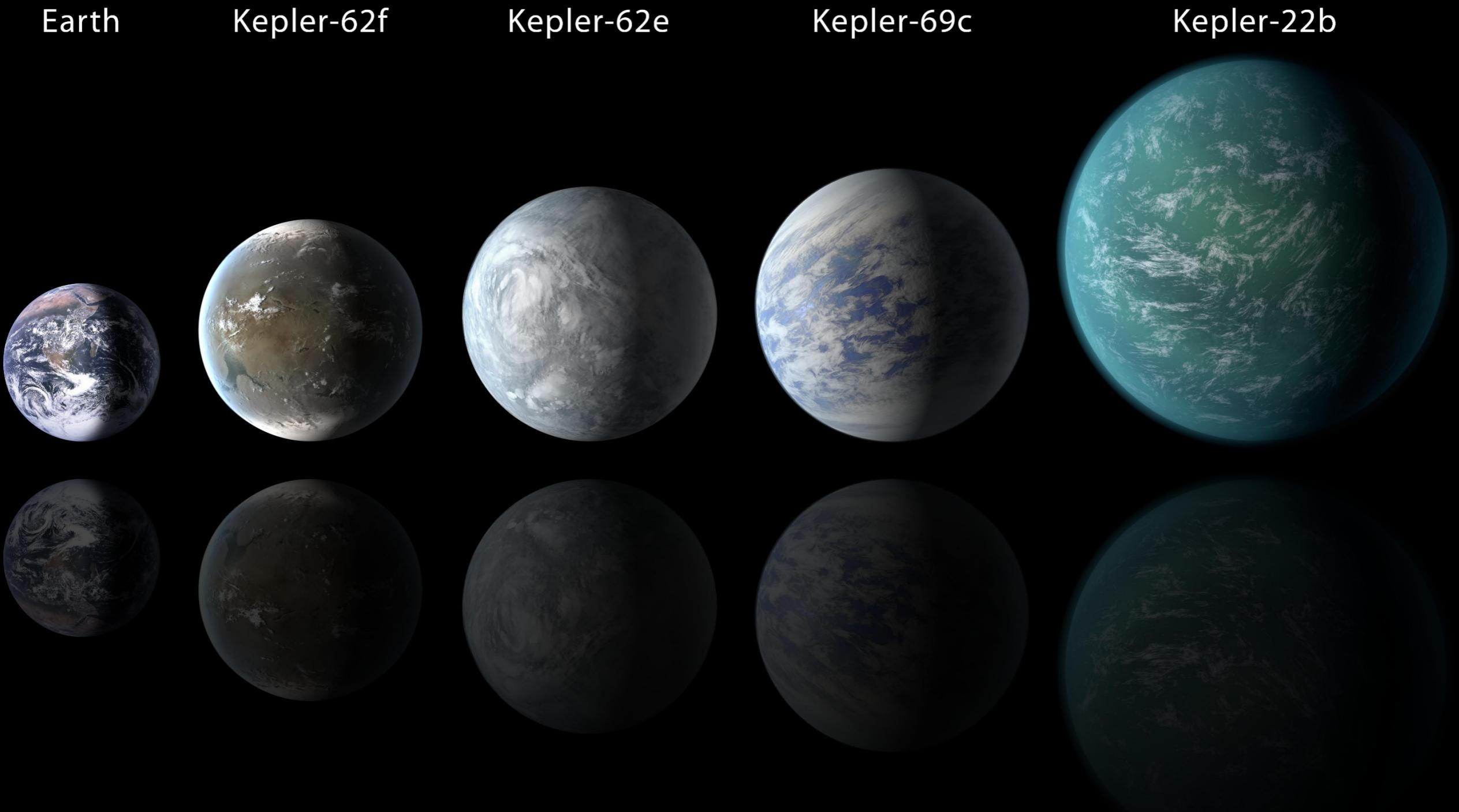


# Planets with multiple “suns”

Illustration



# Habitable Zone Planets



Q: What does it mean to be a  
“habitable” planet??