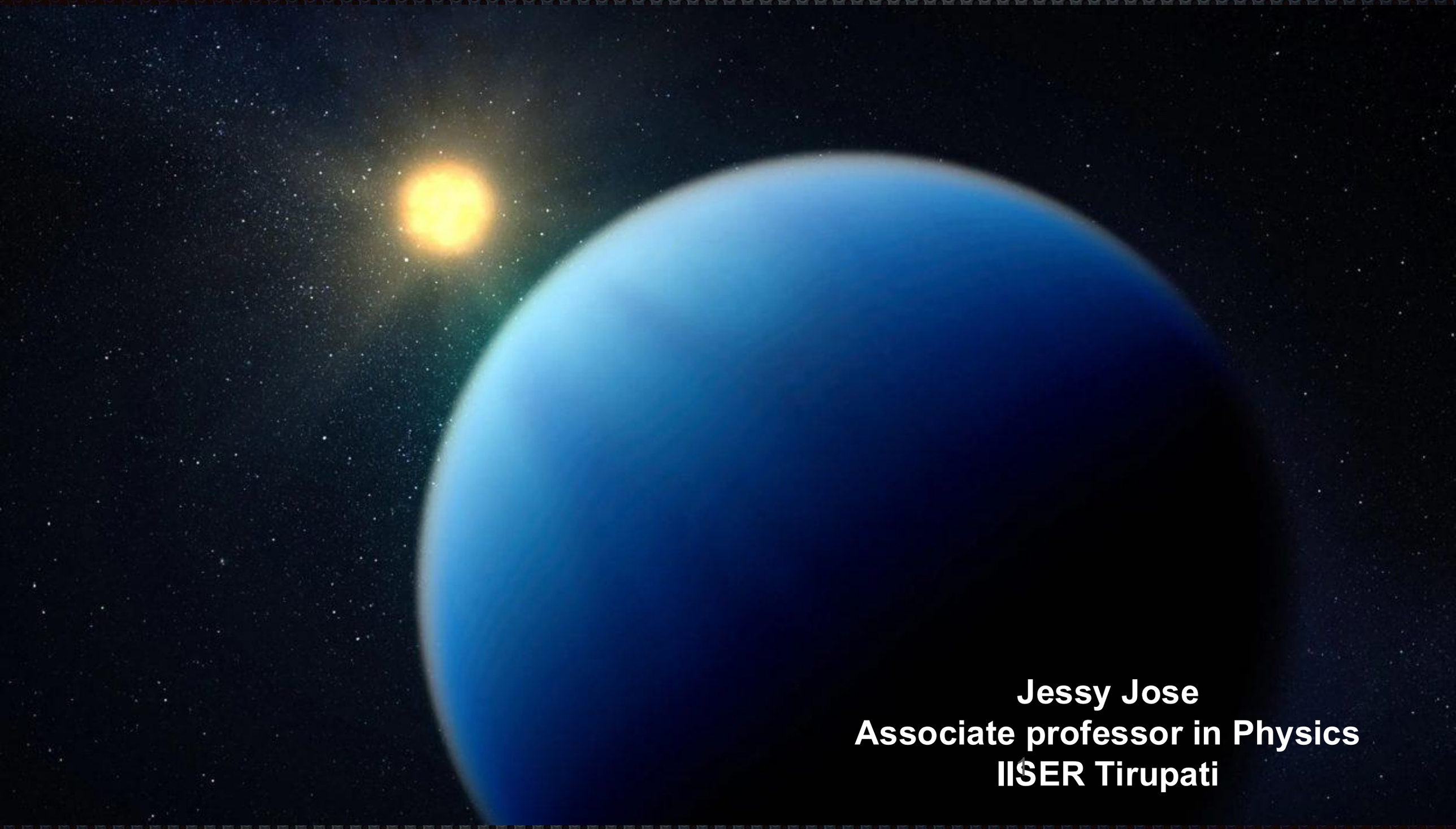
Exoplanets and Multi-messenger Astronomy



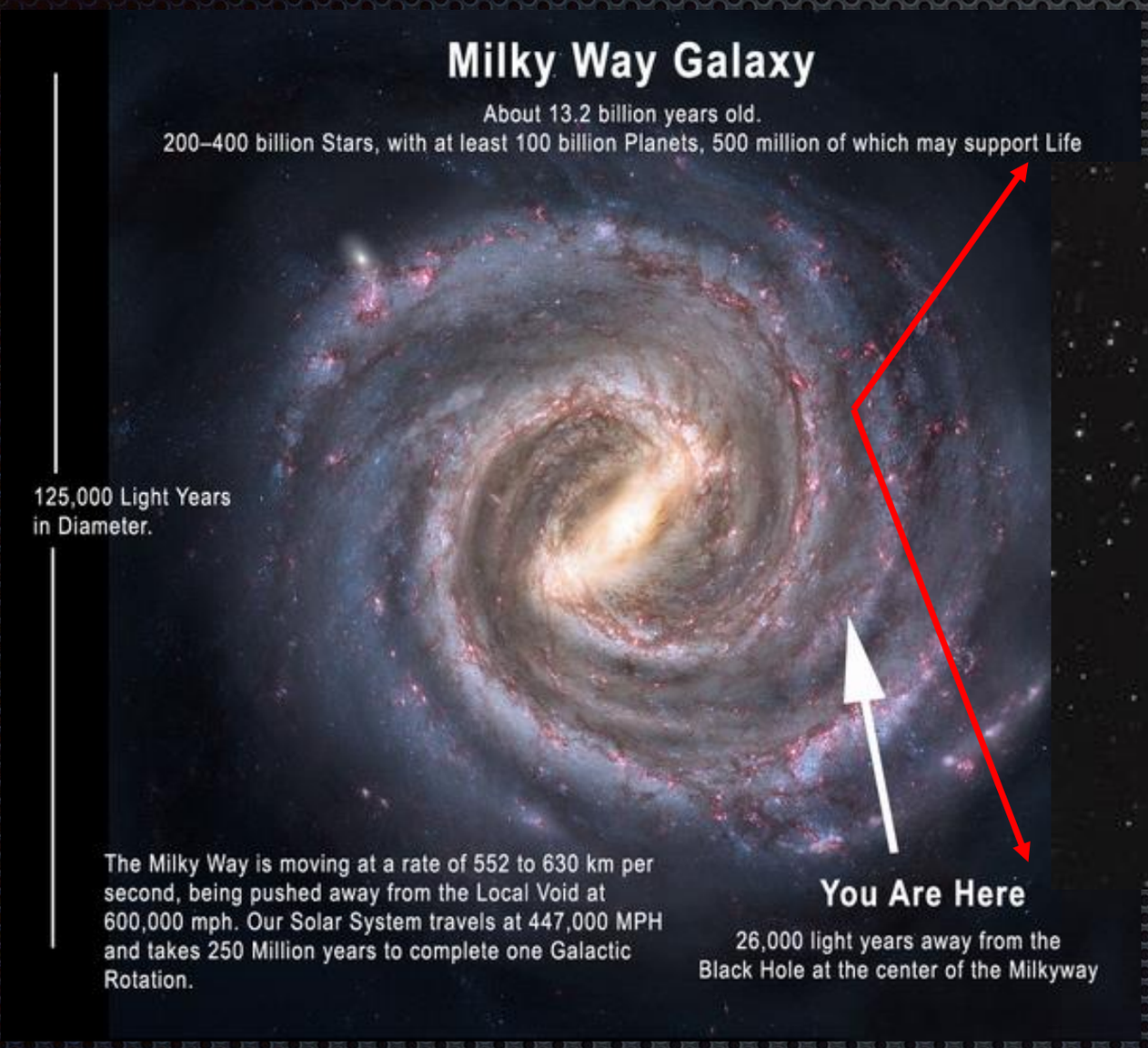
Jessy Jose
Associate professor in Physics
IISER Tirupati

Introduction to Astronomy & Astrophysics workshop @IIT Tirupati 24-25 Jan 2026

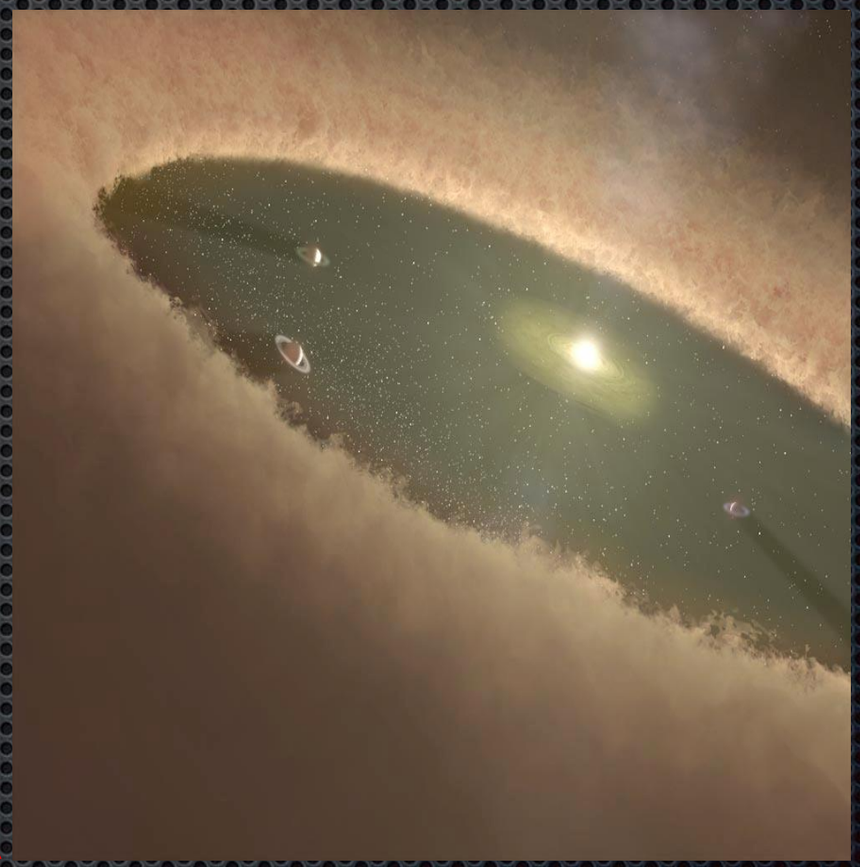
Twinkle Twinkle Little Star….

Milky Way : Our Galaxy

Milky Way : Our Galaxy contains ~ 200 billion stars



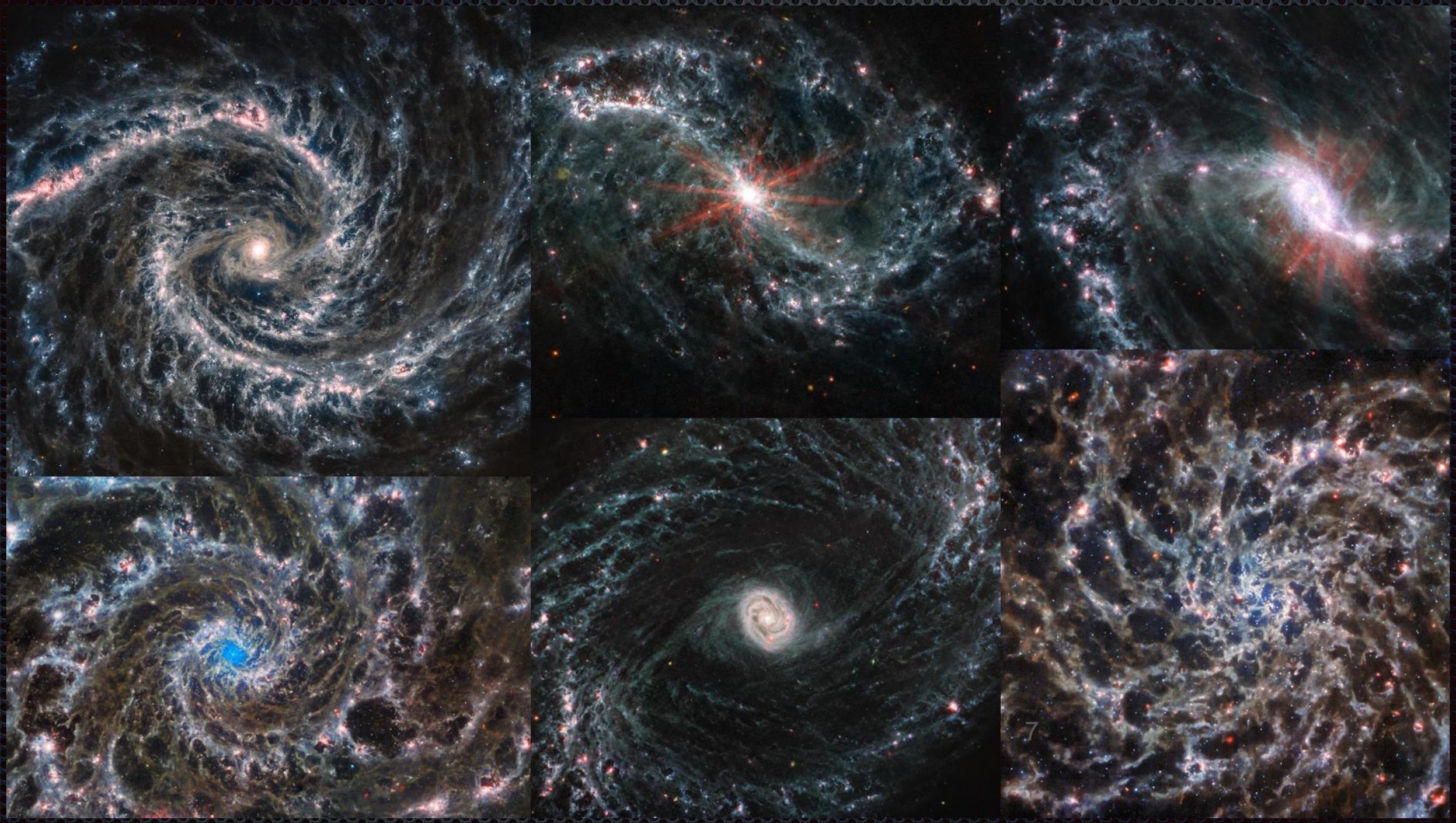
How many planets in the Universe?

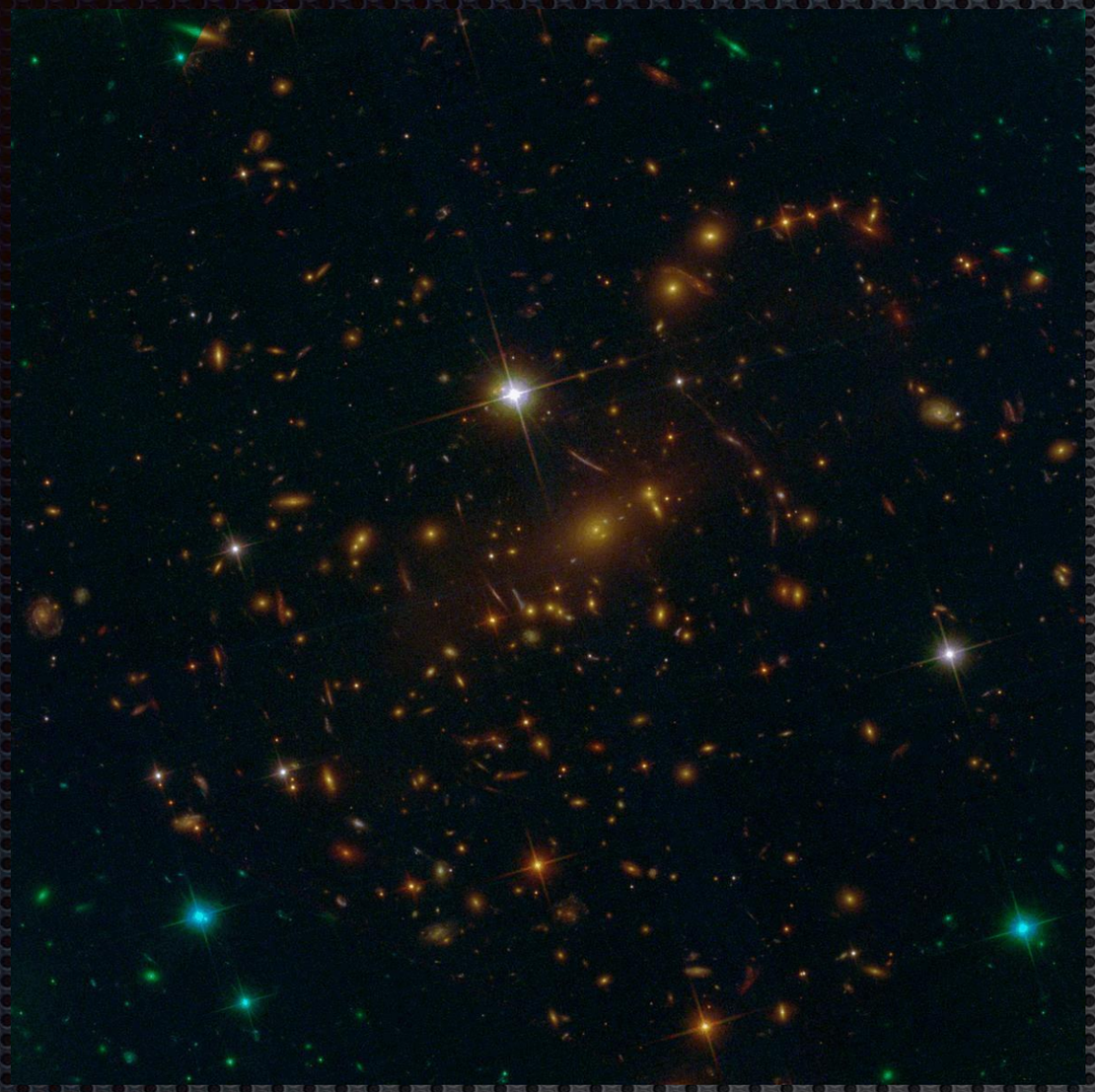


Every other star has at least one planet around them

How many galaxies Universe?

How many galaxies?



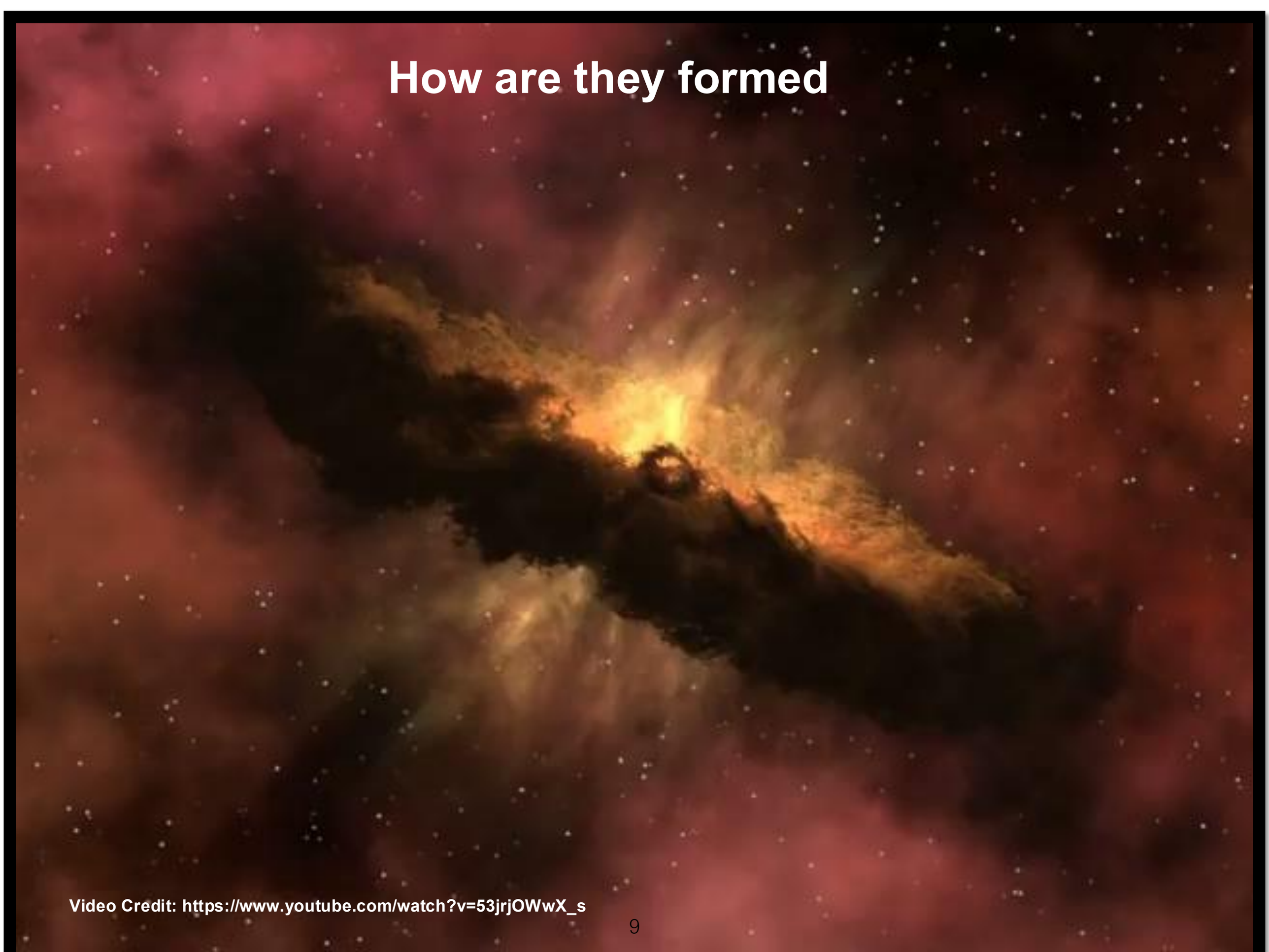


Hubble Space Telescope vs JWST

- 100 billion galaxies each with ~100 billion stars
- ~ 10^{22} stars in the Universe
- Every other star has at least one planet around them

How many planets ?

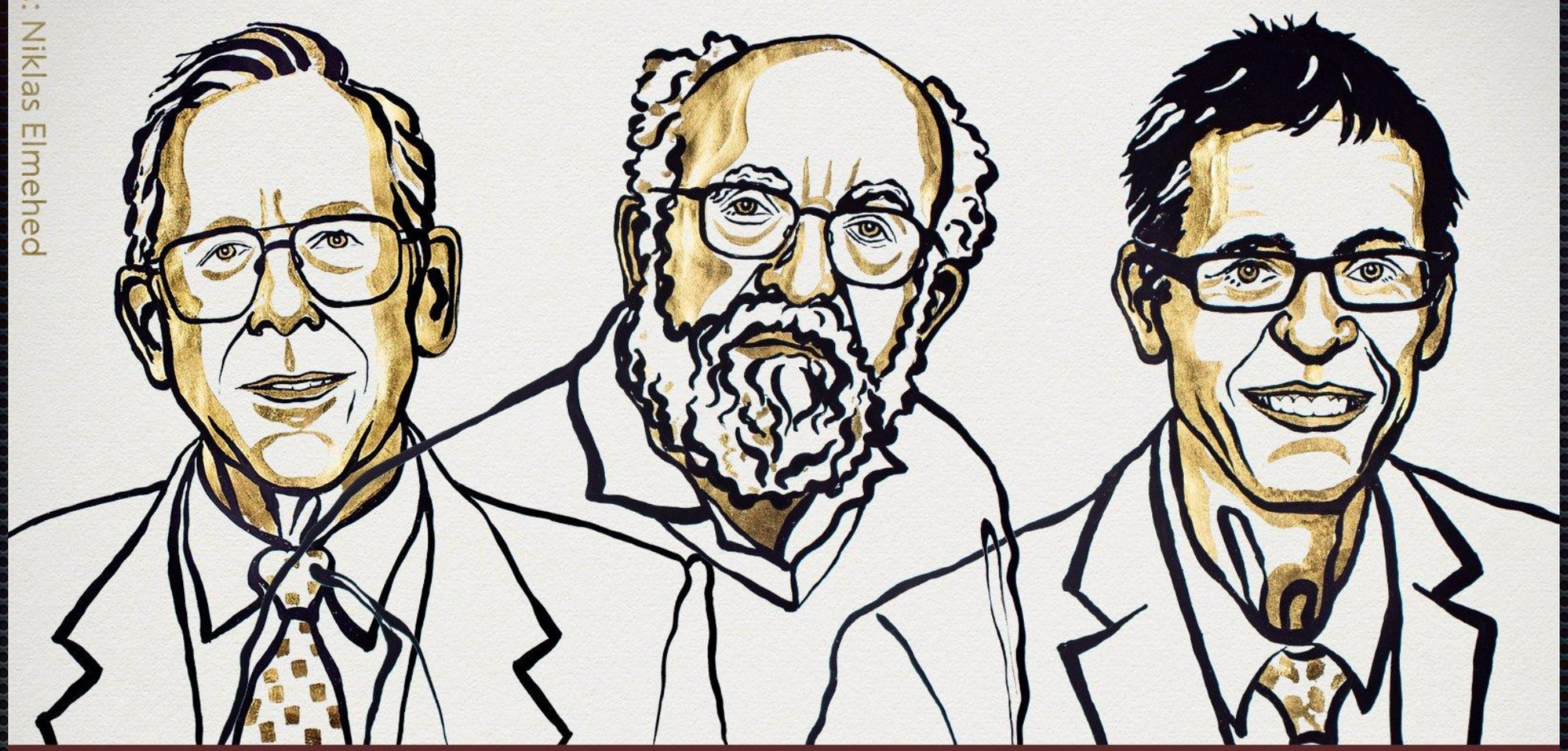
How are they formed



Video Credit: https://www.youtube.com/watch?v=53jrjOWwX_s

How to detect / characterize planets around stars ?

THE NOBEL PRIZE IN PHYSICS 2019



Illustrations: Niklas Elmehed

James Peebles

"for theoretical discoveries in physical cosmology"

Michel Mayor

Didier Queloz

"for the discovery of an exoplanet orbiting a solar-type star"

THE ROYAL SWEDISH ACADEMY OF SCIENCES

THE **FIRST PLANET** DISCOVERED AROUND A **SUN-LIKE** STAR

51 Pegasi b

Discovered October 6, 1995

This year we celebrate the discovery of 51 Pegasi b in October, 1995. This giant planet is about half the size of Jupiter and orbits its star in about 4 days. '51 Peg' helped launch a whole new field of exploration.

TEMPERATURE
51 Pegasi b has a temperature of **1000C°/1800F°**.

ORBITAL PERIOD
51 Pegasi b orbits its host star **every 4 days**.

DISTANCE FROM EARTH
51 Pegasi b is **50 light-years** from Earth.

PLANET COMPARISON

51 Pegasi b

Jupiter

51 Pegasi b is **47% less massive**, but **50% larger** than Jupiter.

STAR COMPARISON

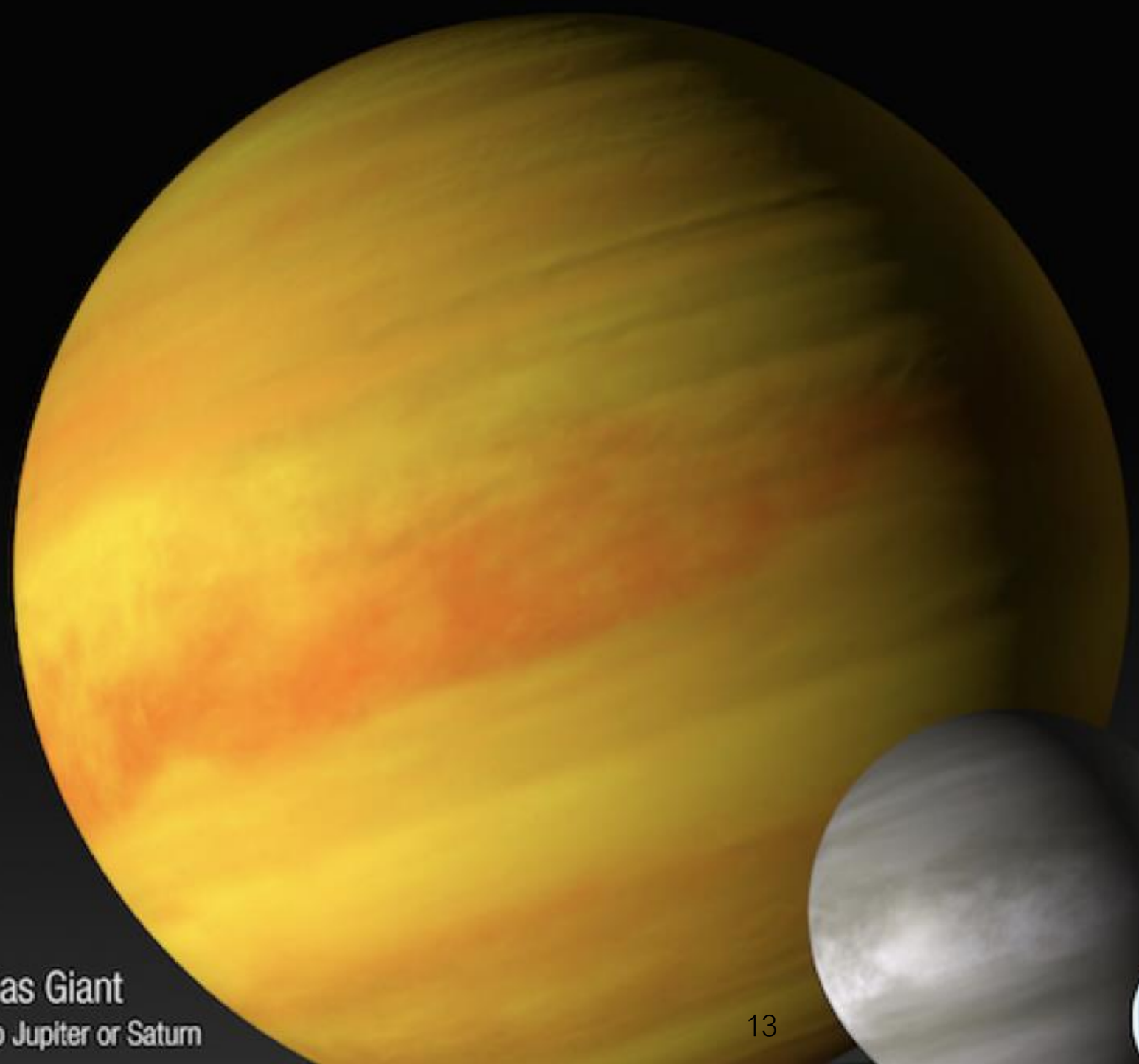
51 Pegasi

Our sun

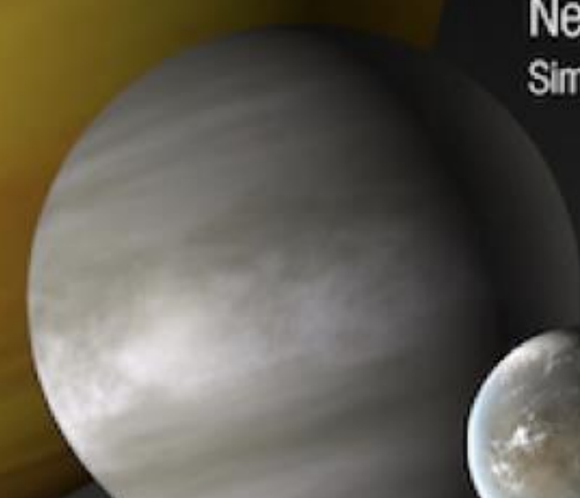
51 Pegasi is **11% more massive** and **23% larger** than our sun.

National Aeronautics and
Space Administration

What's Out There? Exoplanet Types



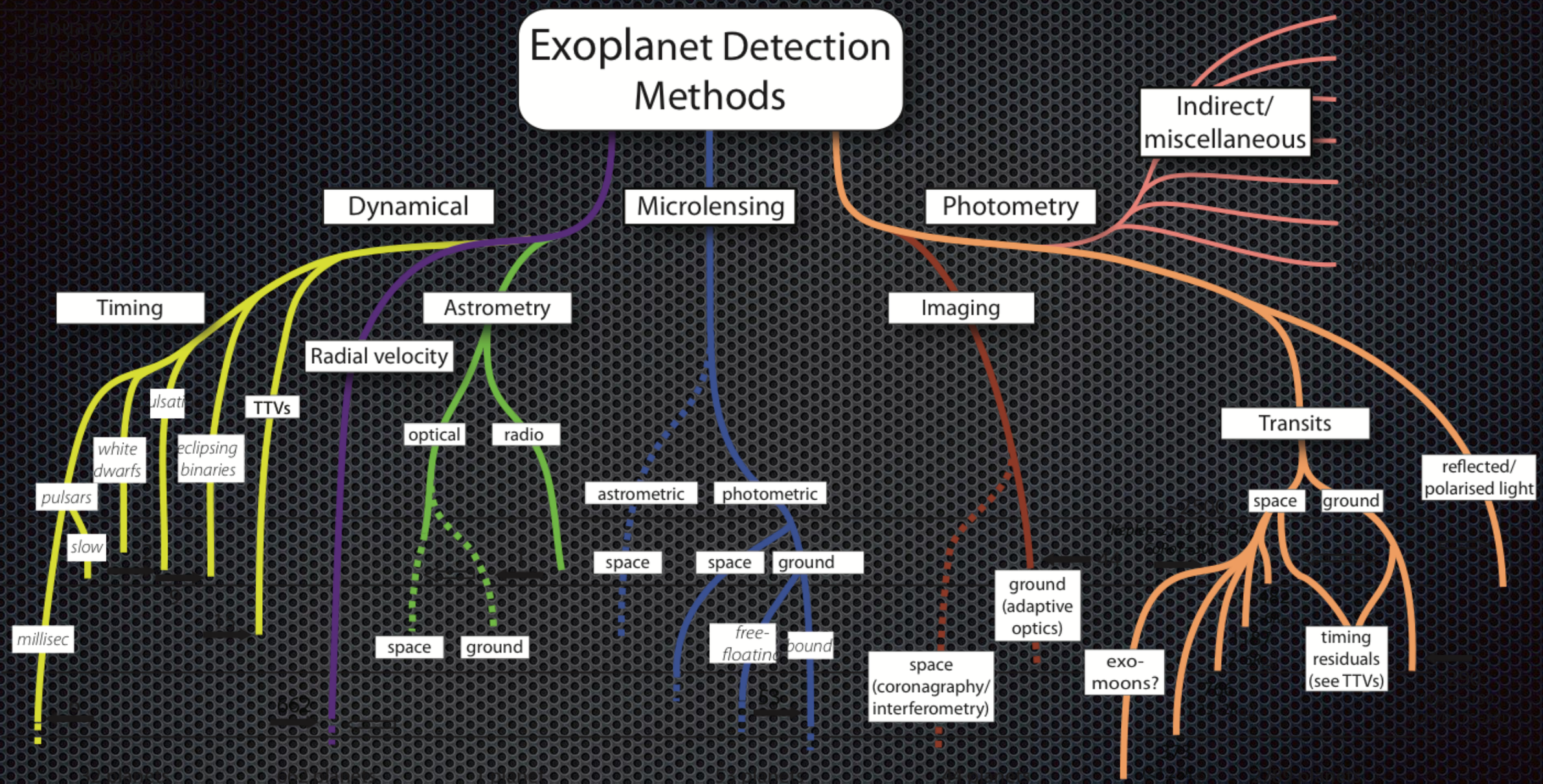
Gas Giant
Similar to Jupiter or Saturn



Neptune-Like
Similar to Uranus or Neptune

Super Earth
More massive than Earth, lighter than Neptune

Terrestrial
Rocky, in Earth's


Exoplanet Detection Methods
Dynamical
Microlensing
Photometry
Indirect/ miscellaneous
Timing
Astrometry
Imaging
Radial velocity
TTVs
pulsars
white dwarfs
eclipsing binaries
slow
millisec
optical
radio
space
ground
astrometric
photometric
space
space
ground
free-floating
bound
ground (adaptive optics)
space (coronagraphy/ interferometry)
Transits
reflected/ polarised light
space
ground
exo-moons?
timing residuals (see TTVs)

Major methods used now a days other than direct imaging –

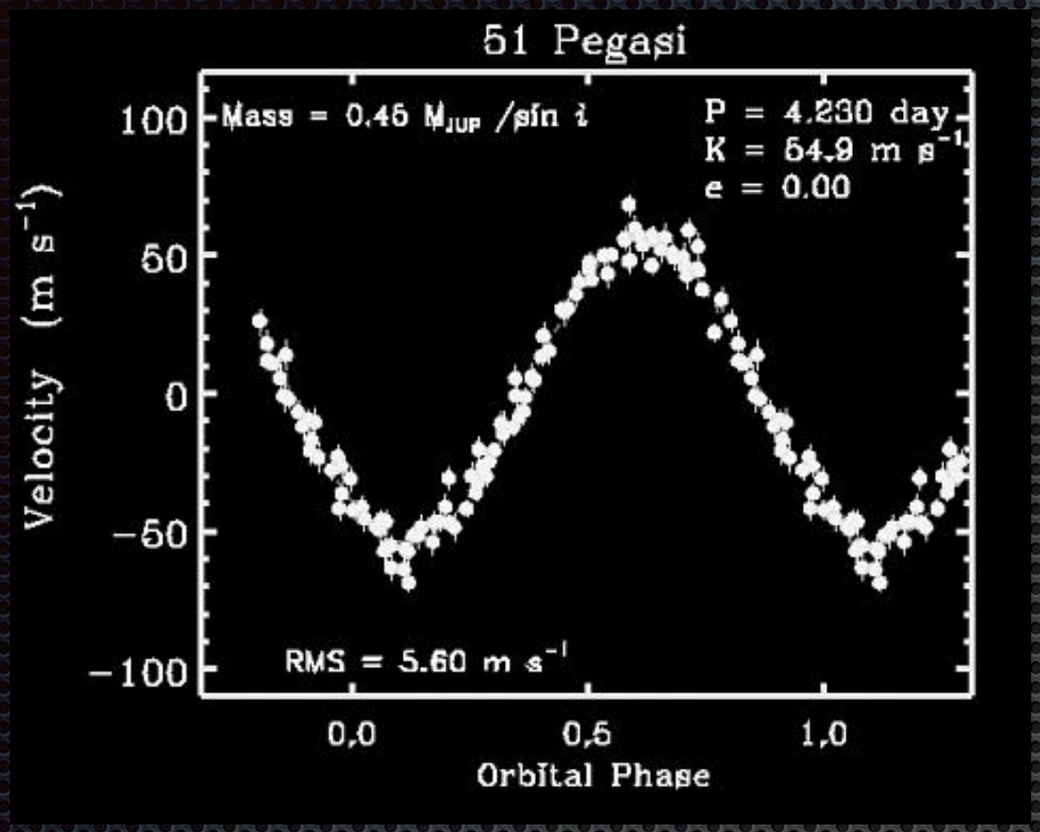
1)Radial velocity
2)Transit
3)Astrometry
4)Gravitational microlensing

- **Watching for wobble.**
- **Tug of war between star and planet.**
- **About 20% of all exoplanets discovered till today using this method**

Video credits: https://exoplanets.nasa.gov/alien-worlds/ways-to-find-a-planet/#/1

Observables and Key Parameters

$$K = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{M_p \sin i}{(M_\star + M_p)^{2/3}} \frac{1}{\sqrt{1-e^2}}$$



Velocity curve for 51 Pegasus
Mayor & Queloz, 1996

- Orbital period (P) – from the periodicity of the signal
- Radial velocity semi-amplitude (K) – depends on planet mass and orbit
- Orbital eccentricity (e)
- Minimum planet mass $M_p \sin i$

Observational Requirements

High-resolution spectroscopy ($R \gtrsim 50{,}000$–$100{,}000$)

Extreme wavelength stability (precision of ~1 m/s or better)

Long-term monitoring over months to years

Major methods used now a days other than direct imaging –

1)Radial velocity
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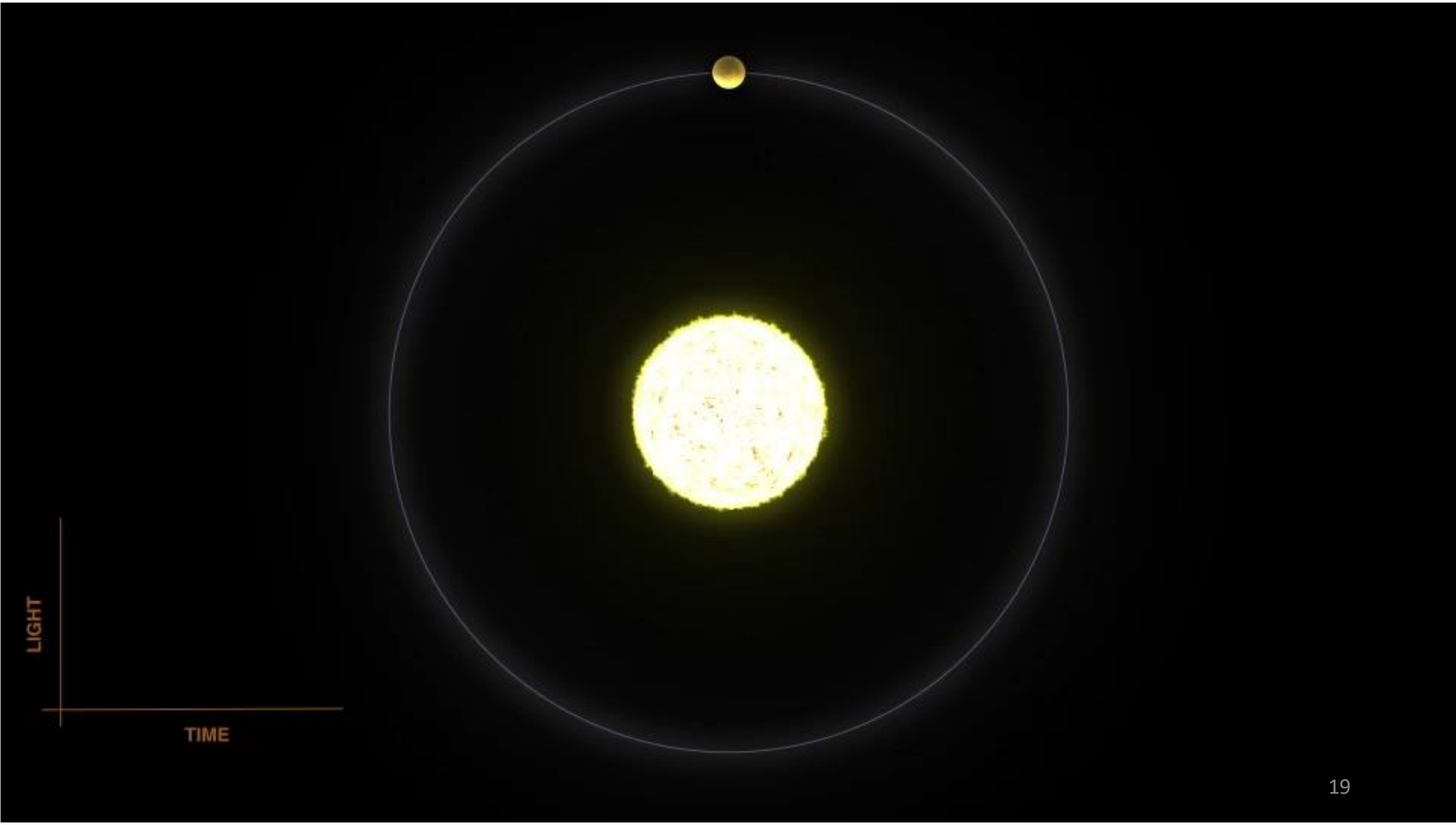

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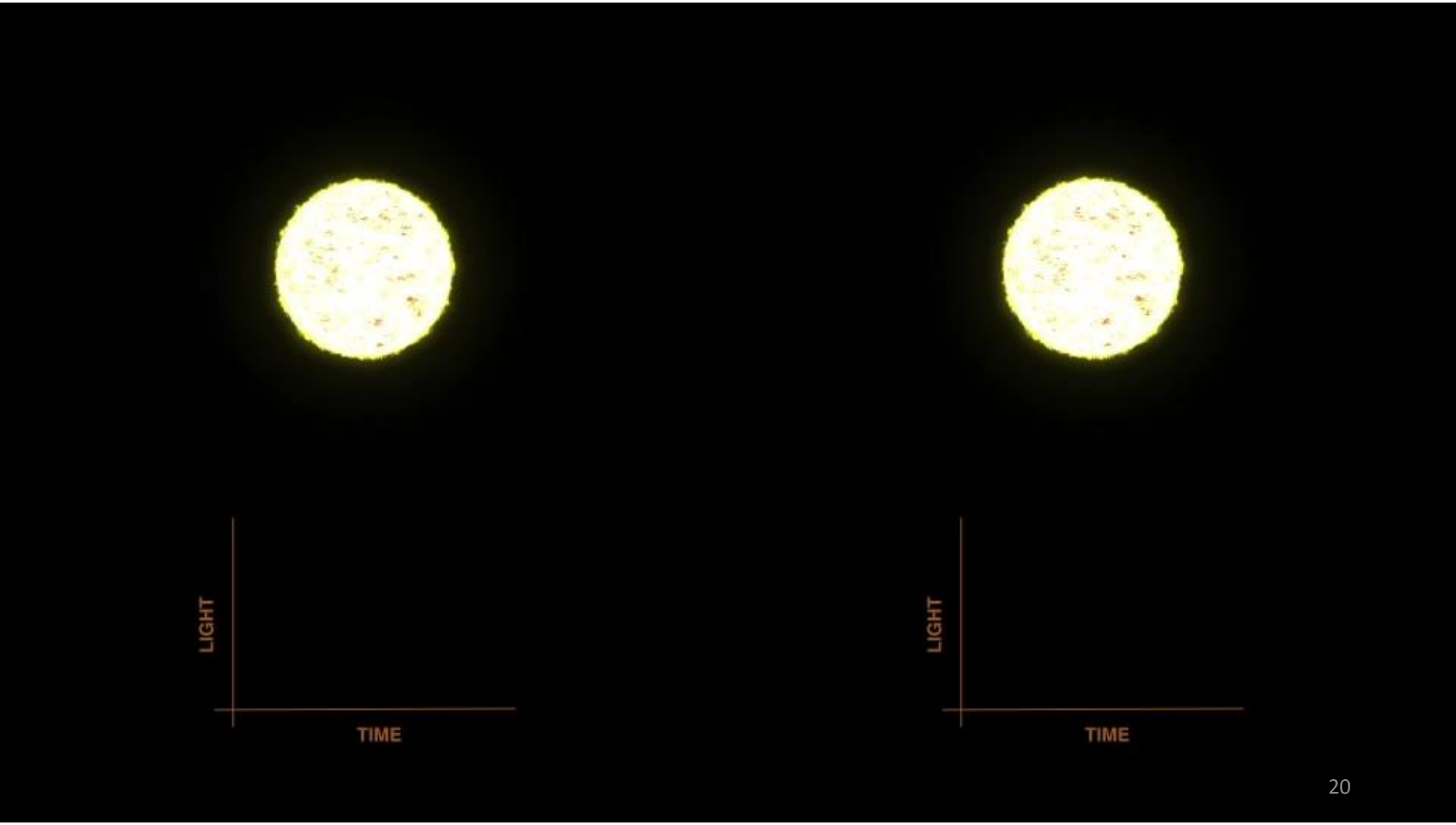


Video credits: ***https://exoplanets.nasa.gov/alien-worlds/ways-to-find-a-planet/#/1***

Key Observables from a Transit Light Curve

Transit depth (ΔF) : fractional loss of light and gives the planetary radius:

$$\frac{\Delta F}{F} \approx \left(\frac{R_p}{R_\star}\right)^2$$

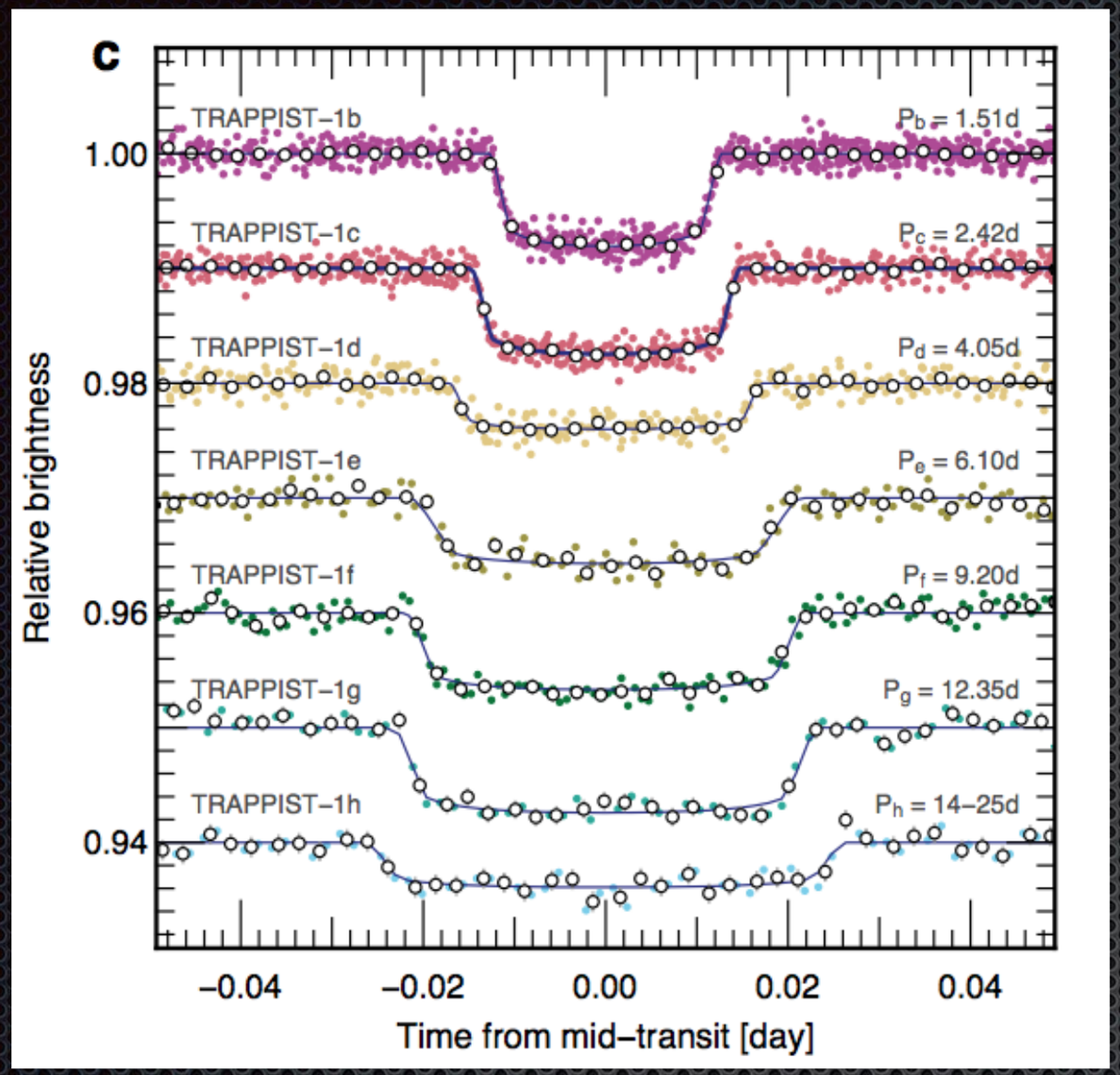
Orbital period (P): from the time interval between successive transits.

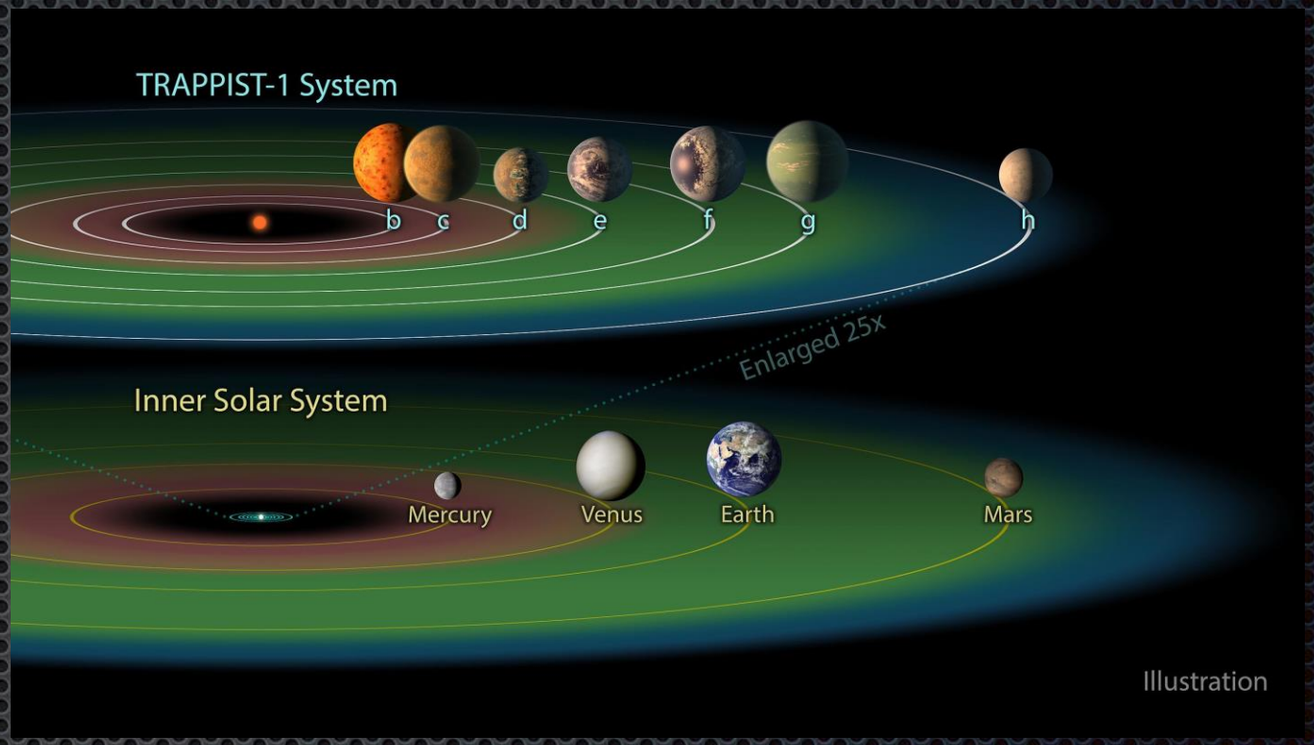
Transit duration and shape Provide information on: Orbital inclination (i), Scaled semi-major axis ($a/R_\star$)

Orbital radius (semi-major axis, a) Derived indirectly from P, using Kepler's third law, once the stellar mass is known.

Video credits: https://exoplanets.nasa.gov/alien-worlds/ways-to-find-a-planet/#/1

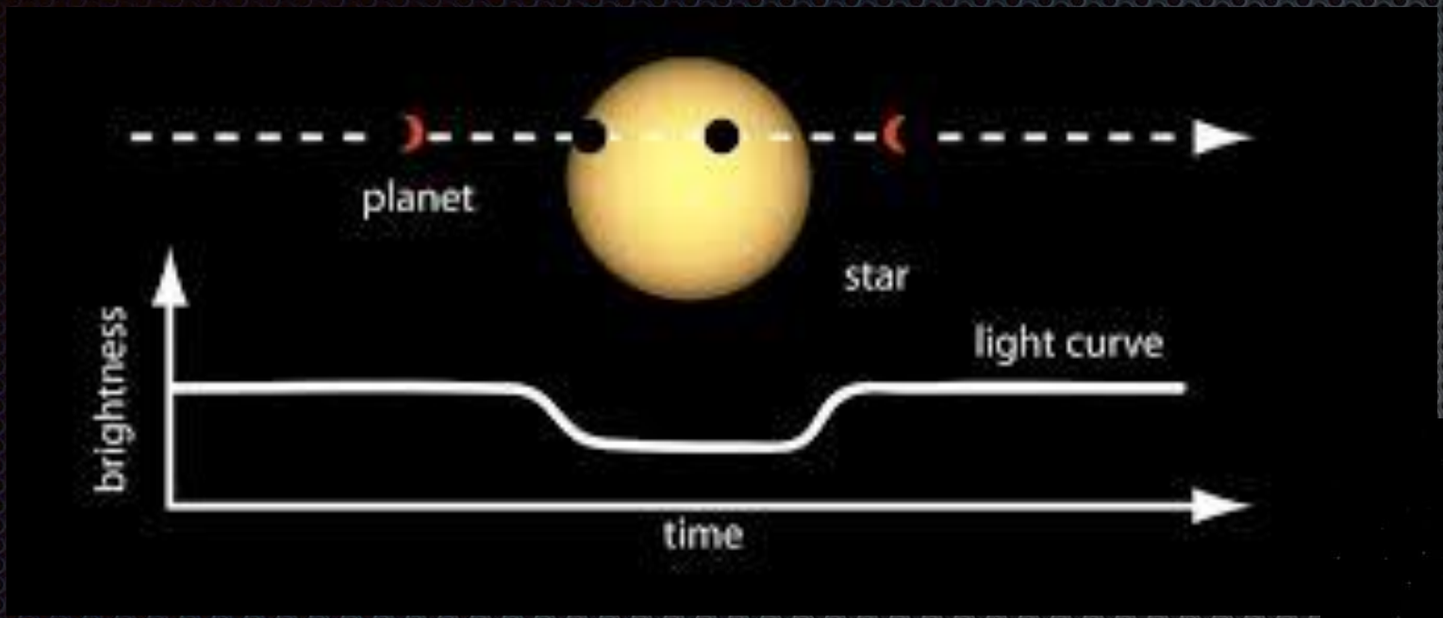
The Trappist-1 system

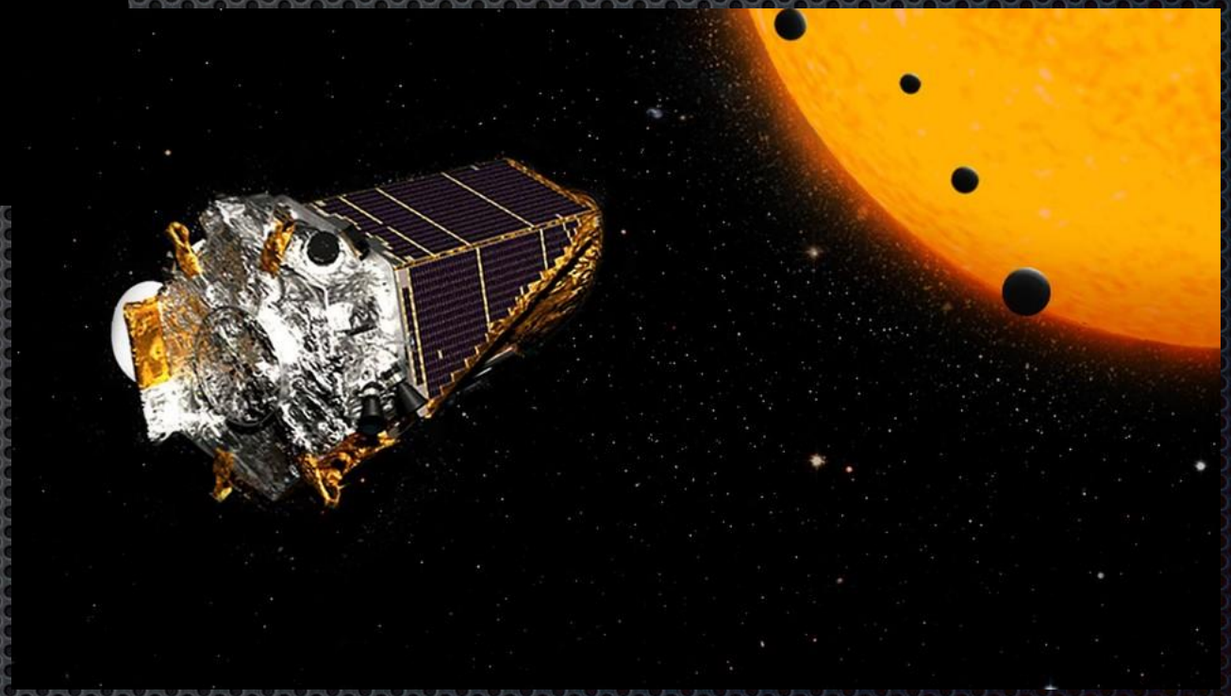




Gillon et al. 2017

Transit method

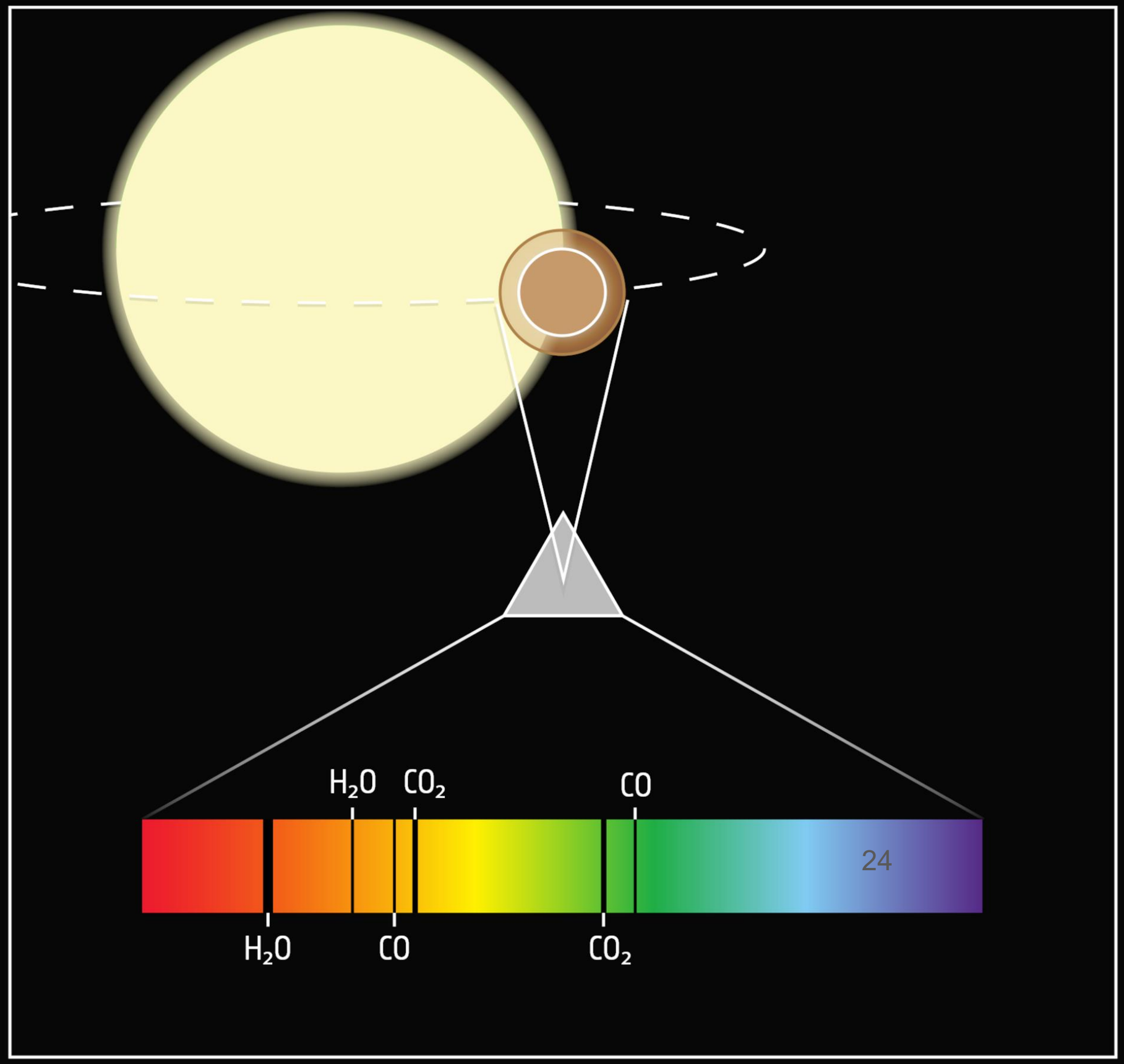




Kepler - NASA

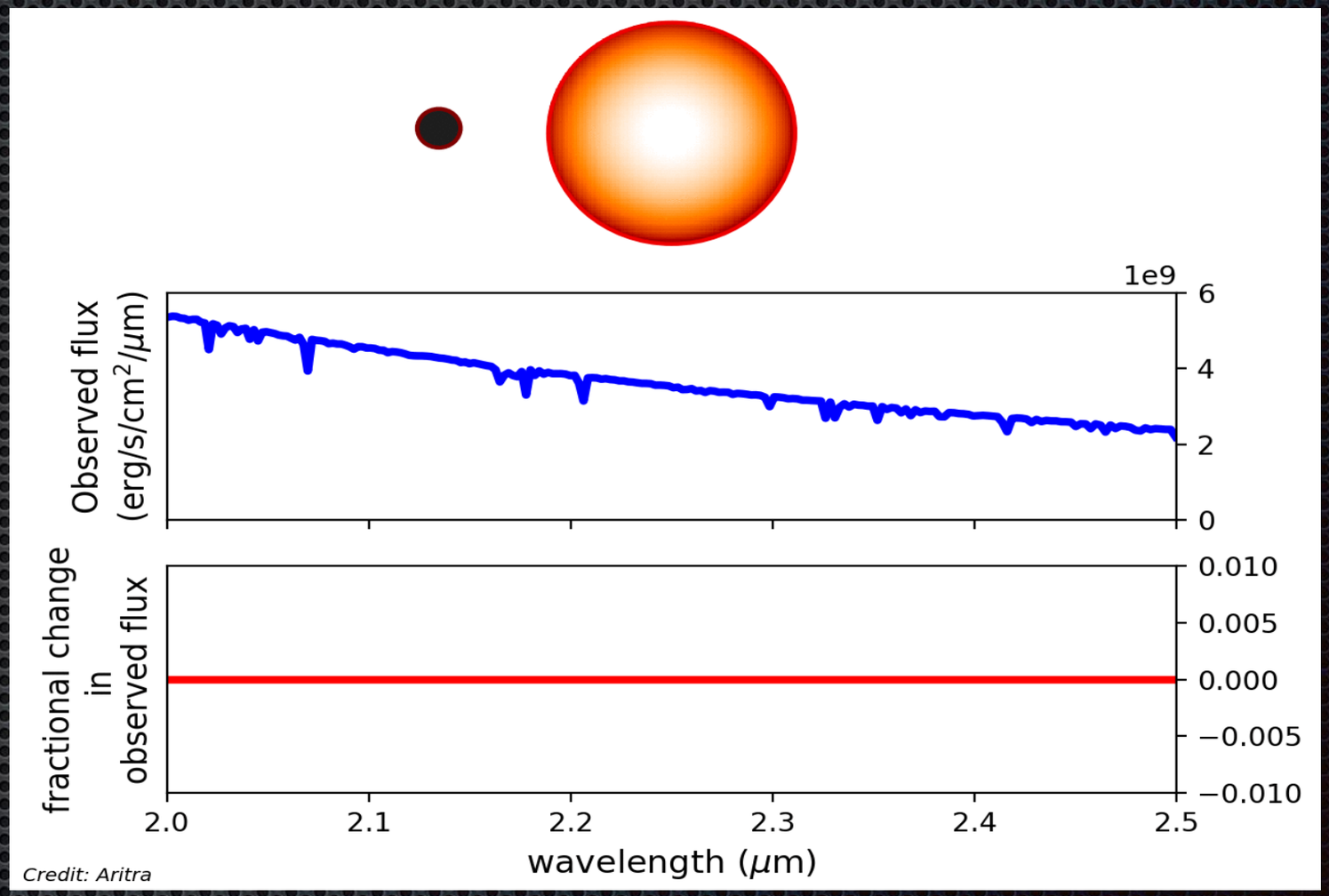
- Searching for shadows
- ~76% of all exoplanets discovered using this method.
- This technique is best for close-in, large planets.
- Also gives information about planets atmosphere – Transmission spectroscopy

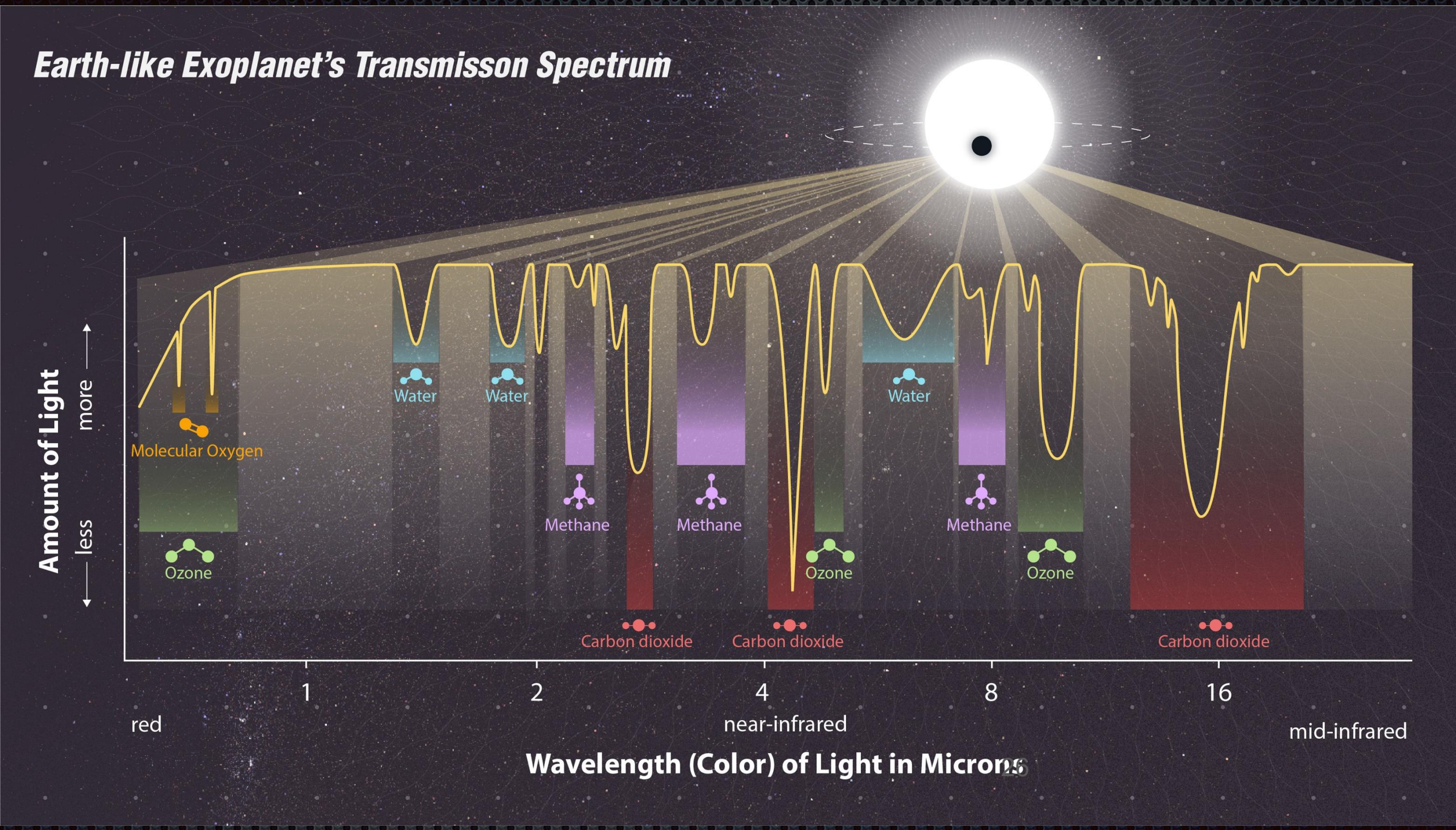
Transmission spectroscopy



Planet atmosphere: Transit spectroscopy

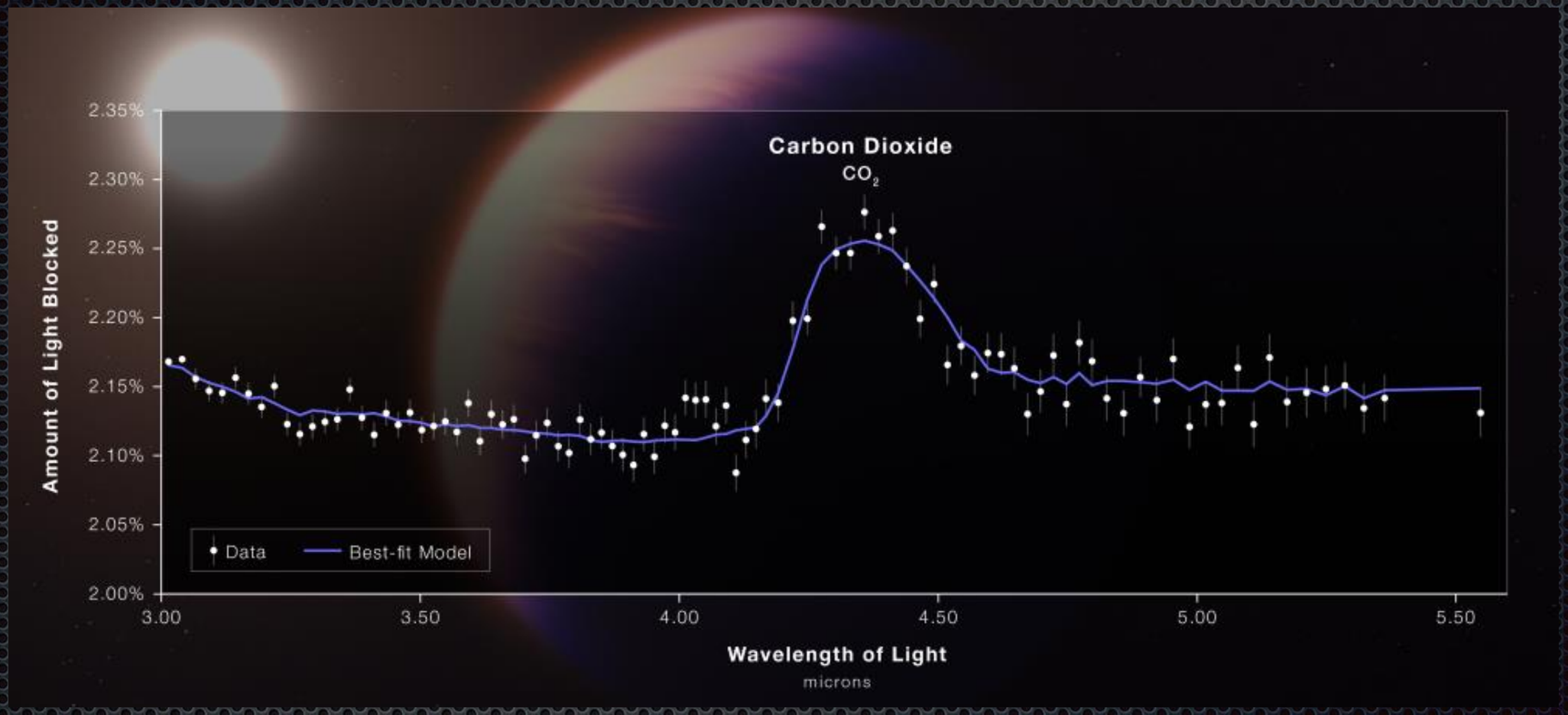
- Spectrum of star taken during transit
- Planet's atmosphere affects star spectrum
- We learn about planet's atmosphere!





•CREDIT: NASA, ESA, CSA, STScI, Joseph Olmsted (STScI)

First detection of CO_2 in a planet outside solar system by JWST



Credit: JWST/NASA

Major methods used now a days other than direct imaging –

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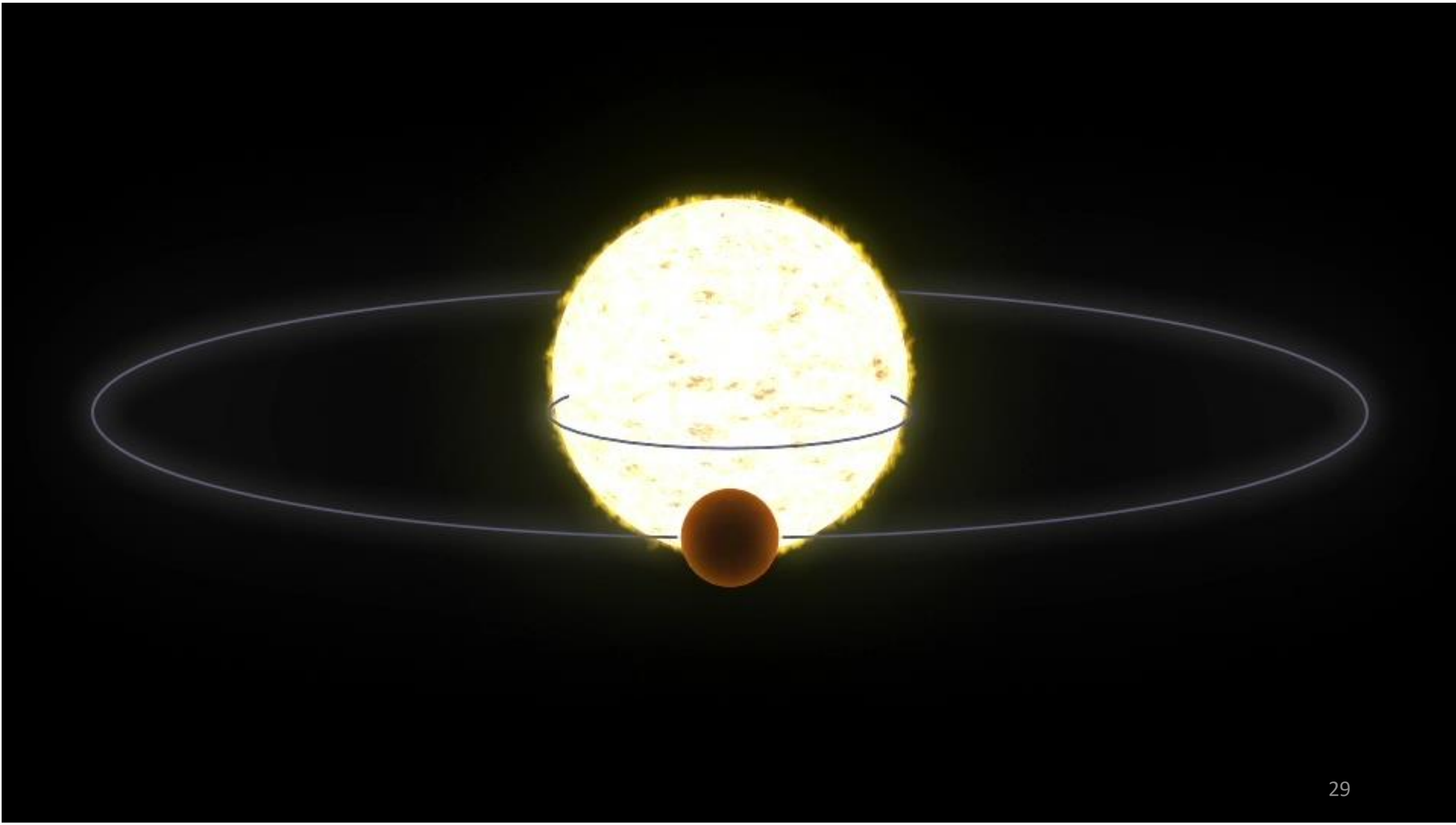
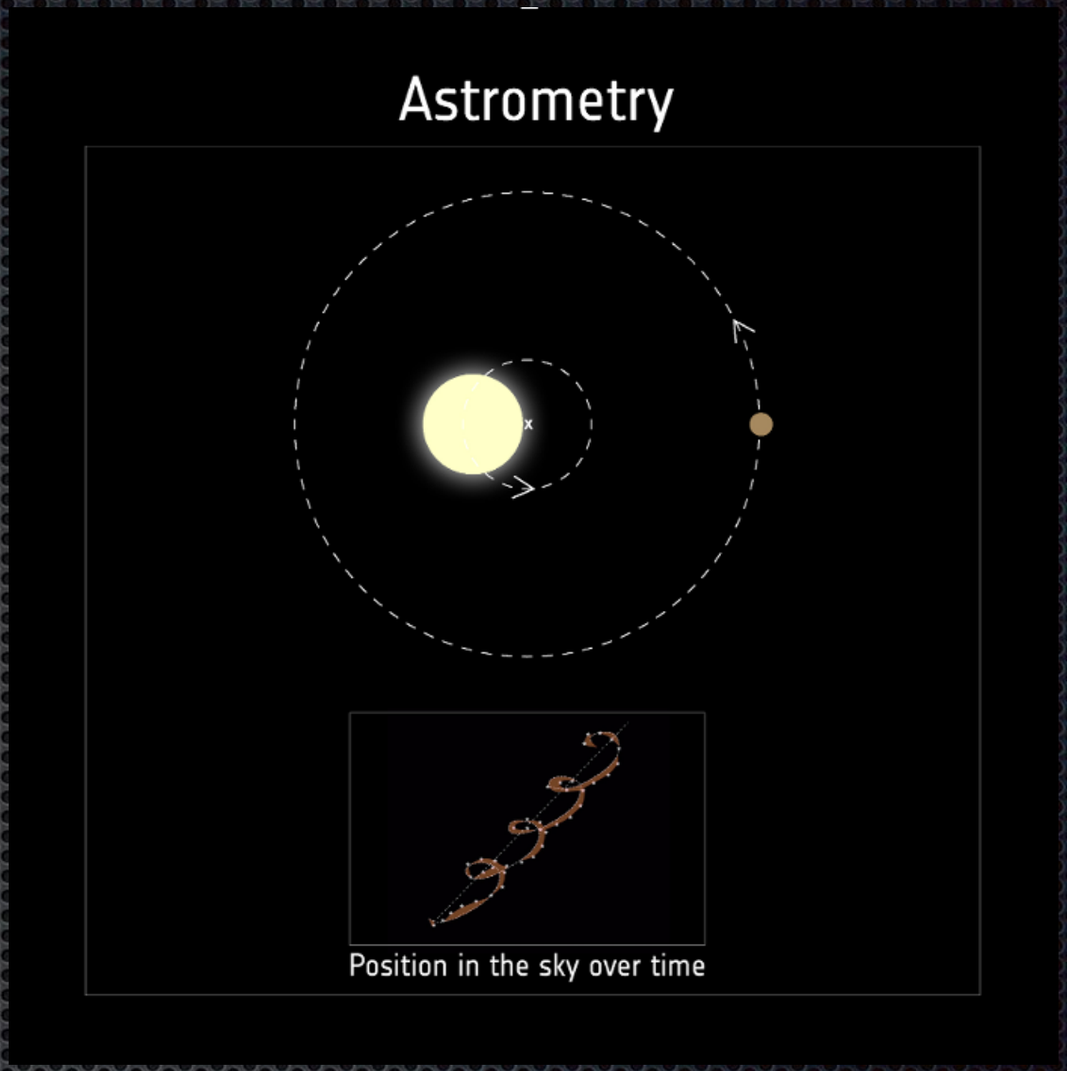


Precise positional motion of a star in the plane of the sky

Video credits: https://exoplanets.nasa.gov/alien-worlds/ways-to-find-a-planet/#/1

- Watching for minuscule movements of the host star.
- Same as that of radial velocity method.
- Instead of Doppler's shift, observe the changes in star’s apparent position with respect to fixed background.
- Very hard method to detect exoplanets.
- 0.02% of all exoplanets discovered using this method.
- Very hard to do from earth’s surface as the atmosphere will distort and bend the light.



Major methods used now a days other than direct imaging –

1)Radial velocity
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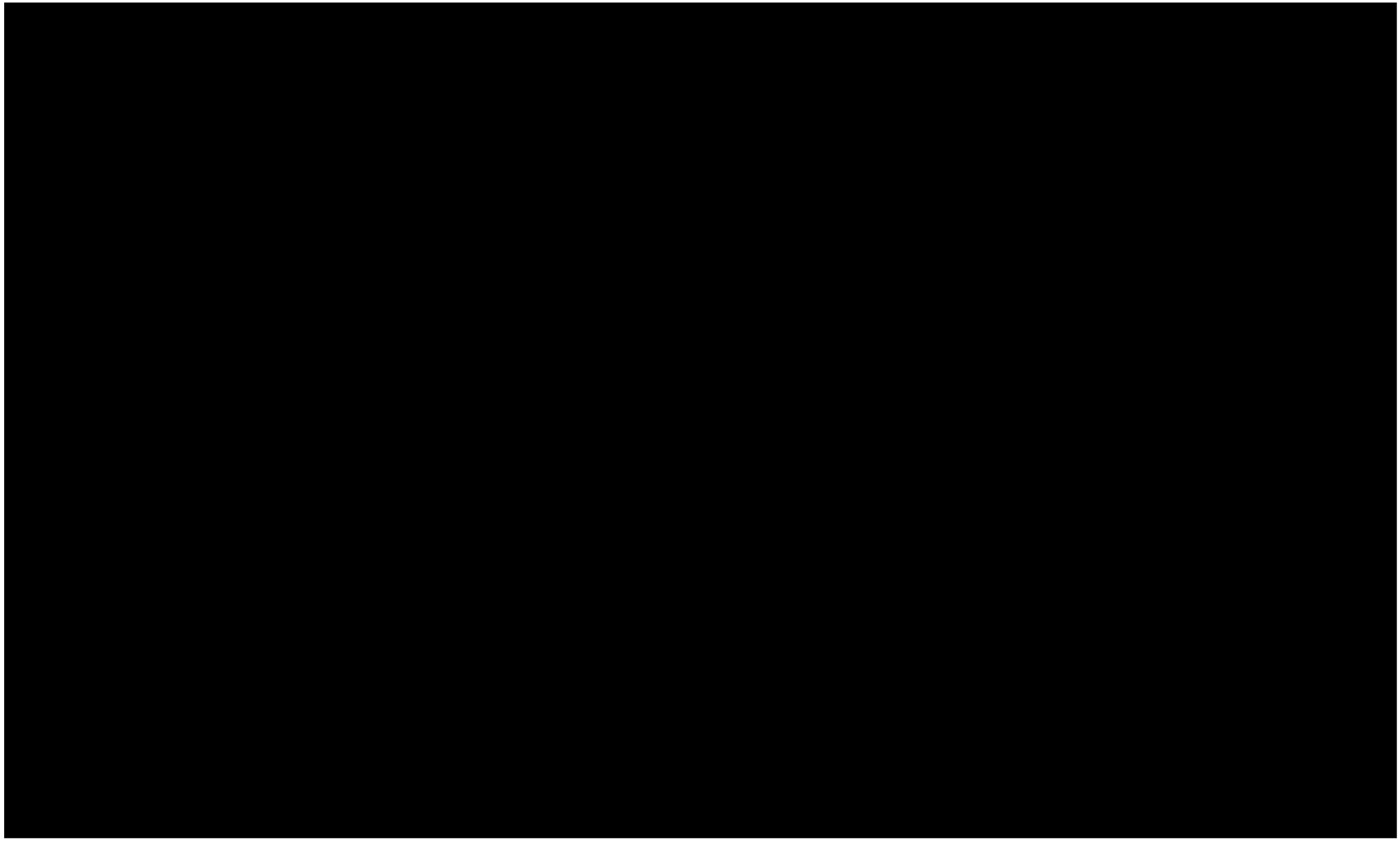
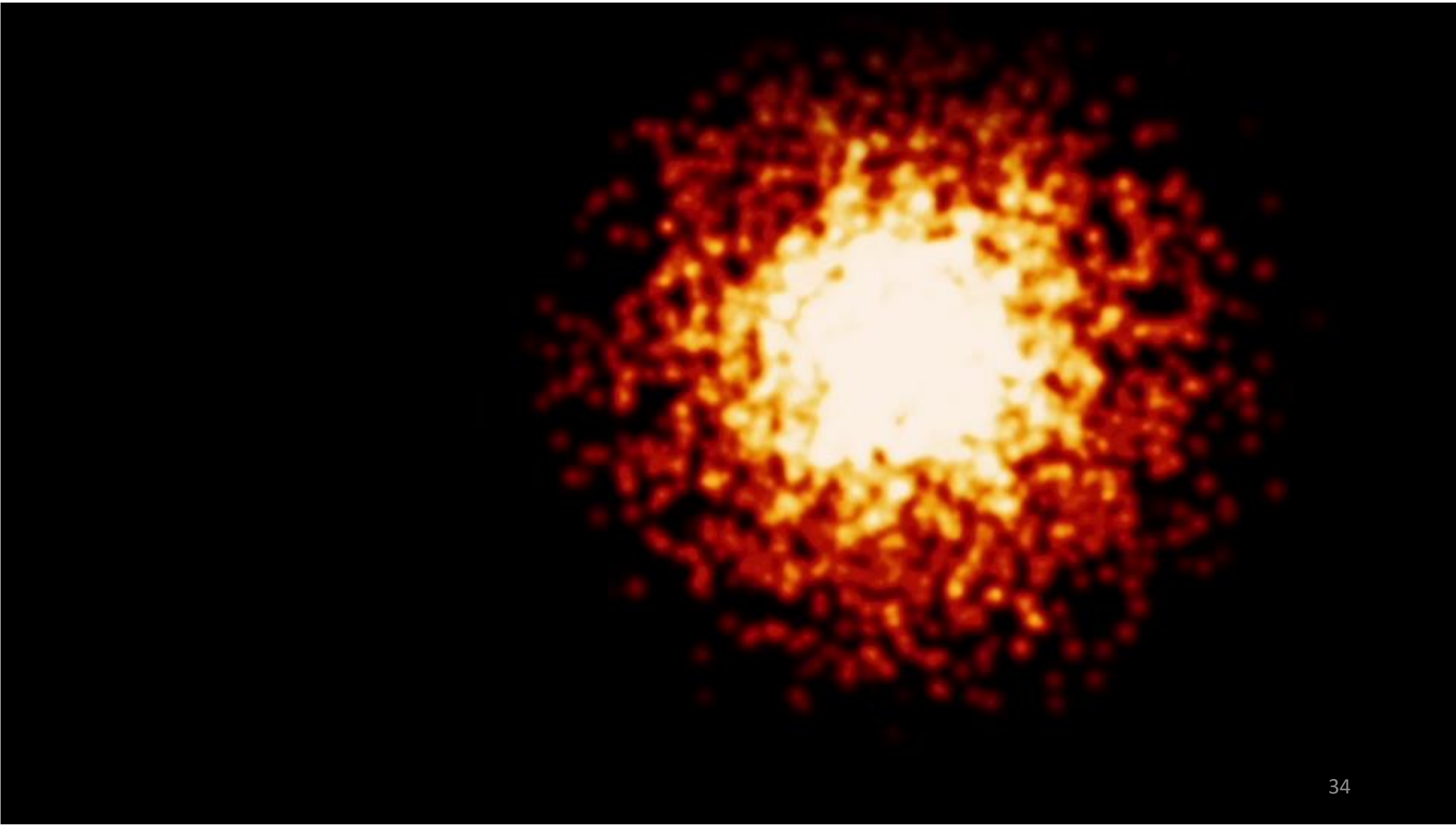


- **Light in a gravity lens**
- **Uses Einstein's definition of gravity in space–time.**
- **About 2% of all planets discovered using this method**

Video credits: https://exoplanets.nasa.gov/alien-worlds/ways-to-find-a-planet/#/1

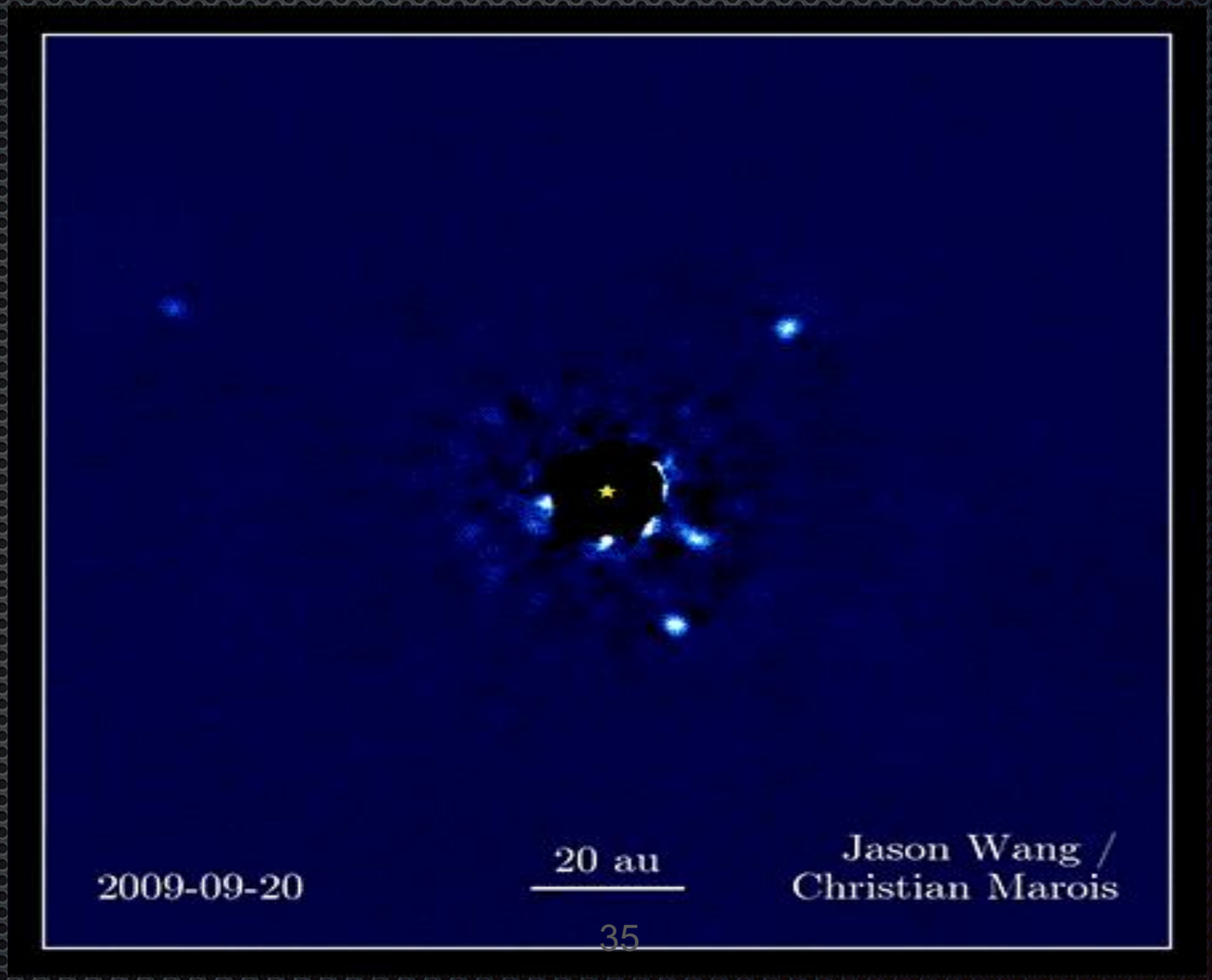
Direct Imaging Method



Video credits: ***https://exoplanets.nasa.gov/alien-worlds/ways-to-find-a-planet/#/1***

Directly Imaged Planetary Companions

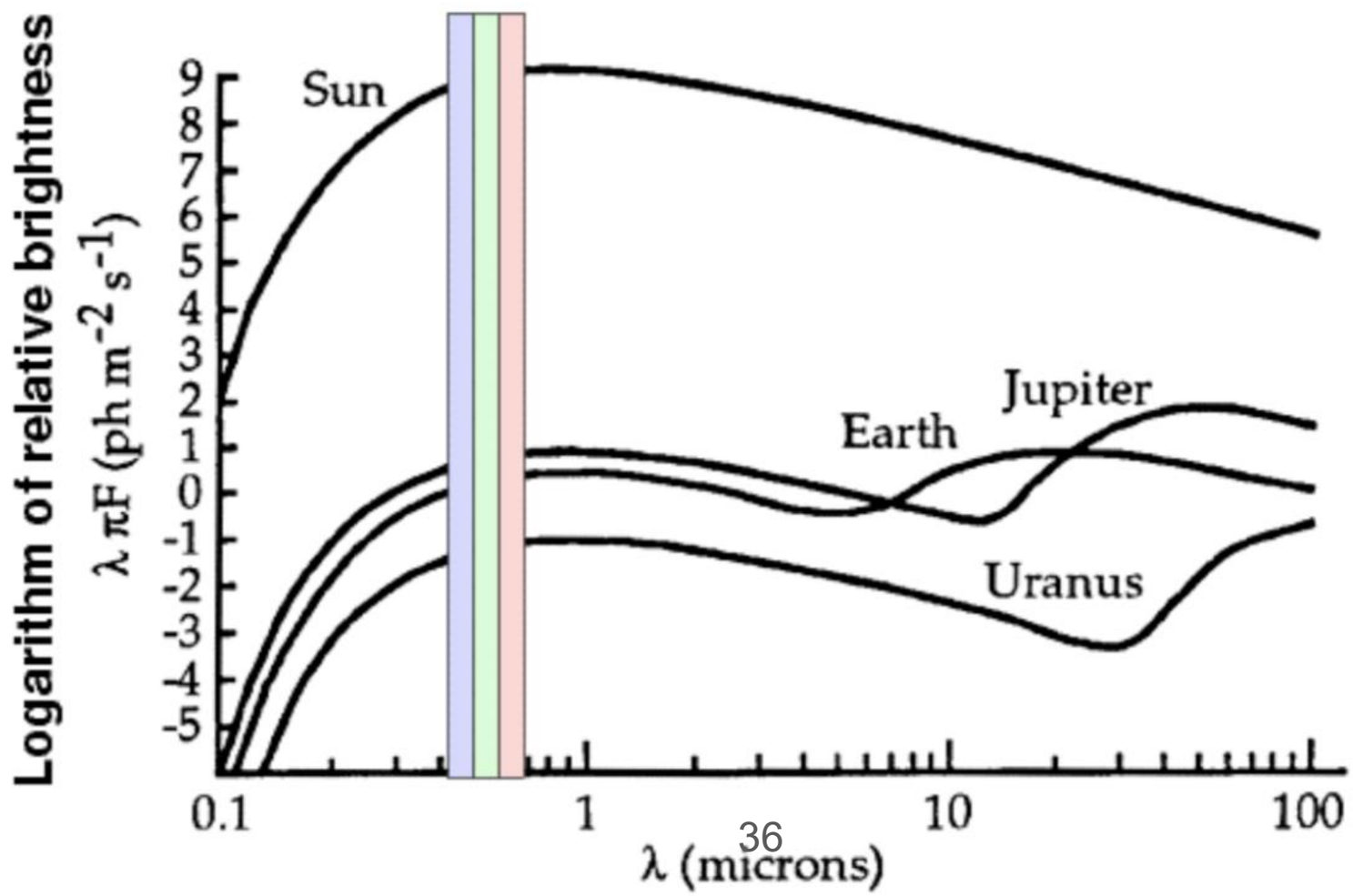
- Image in IR, planet emission or reflection
- Distant planets : 9-2000 AU
- Young planets : 1-100 Myr (Earth age: 4.5 Byr)

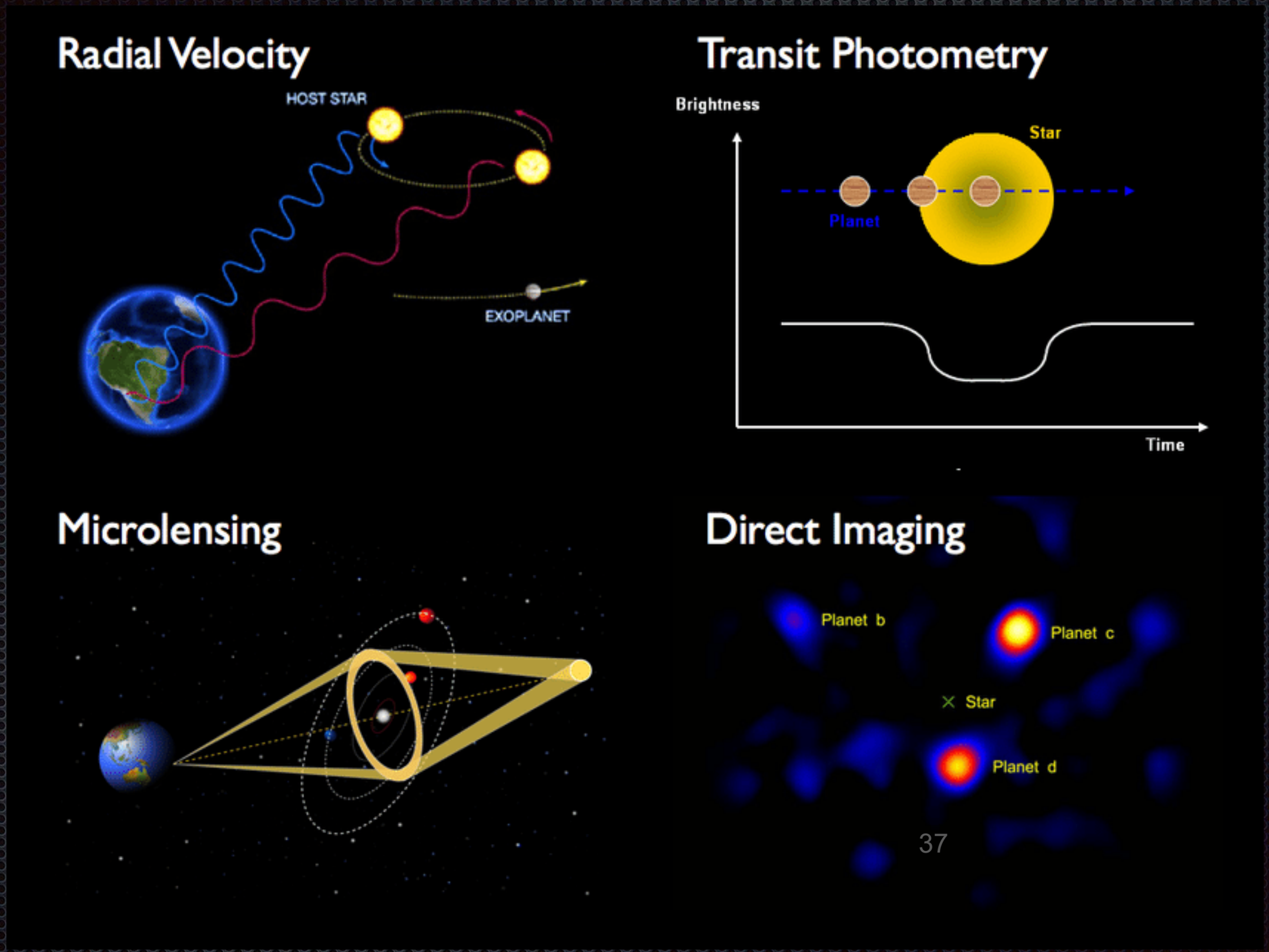


Planets around HR 8799 star

Challenge of Direct Imaging: Star-Planet Contrast

- In the visible–near-IR
  - $F_{Sun} / F_{Earth} \sim 10^9$
  - $F_{Sun} / F_{Jup} \sim 10^8$
  - challenging wavefront control
  - small PSF
  - can observe from the ground
- In mid-IR
  - $F_{Sun} / F_{Earth} \sim 10^6$
  - $F_{Sun} / F_{Jup} \sim 10^4$
  - easier wavefront control
  - >10 × larger PSF
  - need to observe from space





Credit: NASA /N. Batalha (NASA Ames)

So Far…

6080 confirmed exoplanets

https://exoplanets.nasa.gov

Big Question - Are We Alone?

Are there Earth-like planets?

Are they common?

Do they harbour life?

Multimessenger (MM) Astronomy

What is Multimessenger (MM) Astronomy?

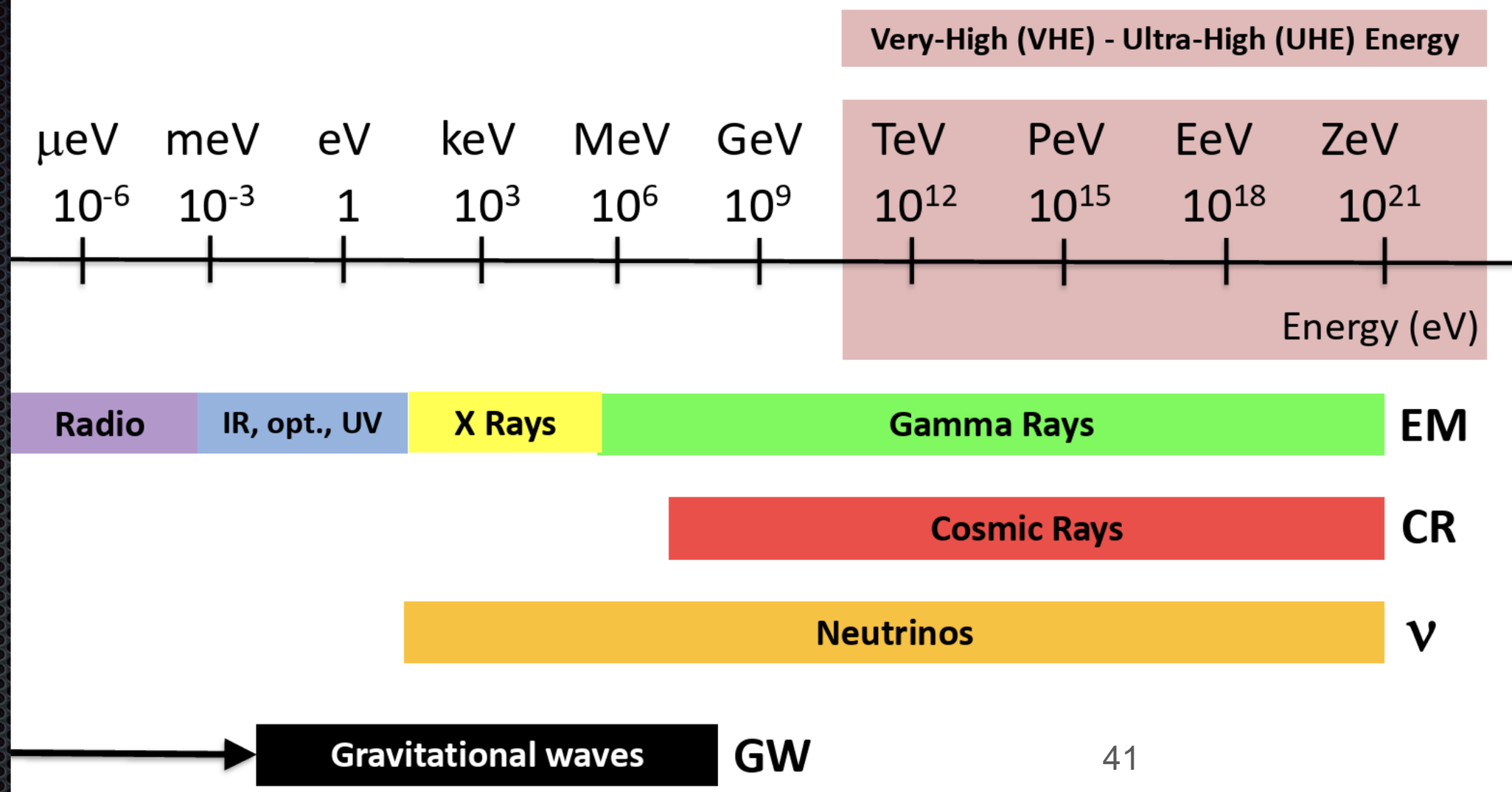
- **Exploration of Universe through the combination of information from multitude of cosmic messengers: –**

a) **Electromagnetic radiation**
b) **Gravitational Waves**
c) **Neutrinos**
d) **Cosmic-Rays**

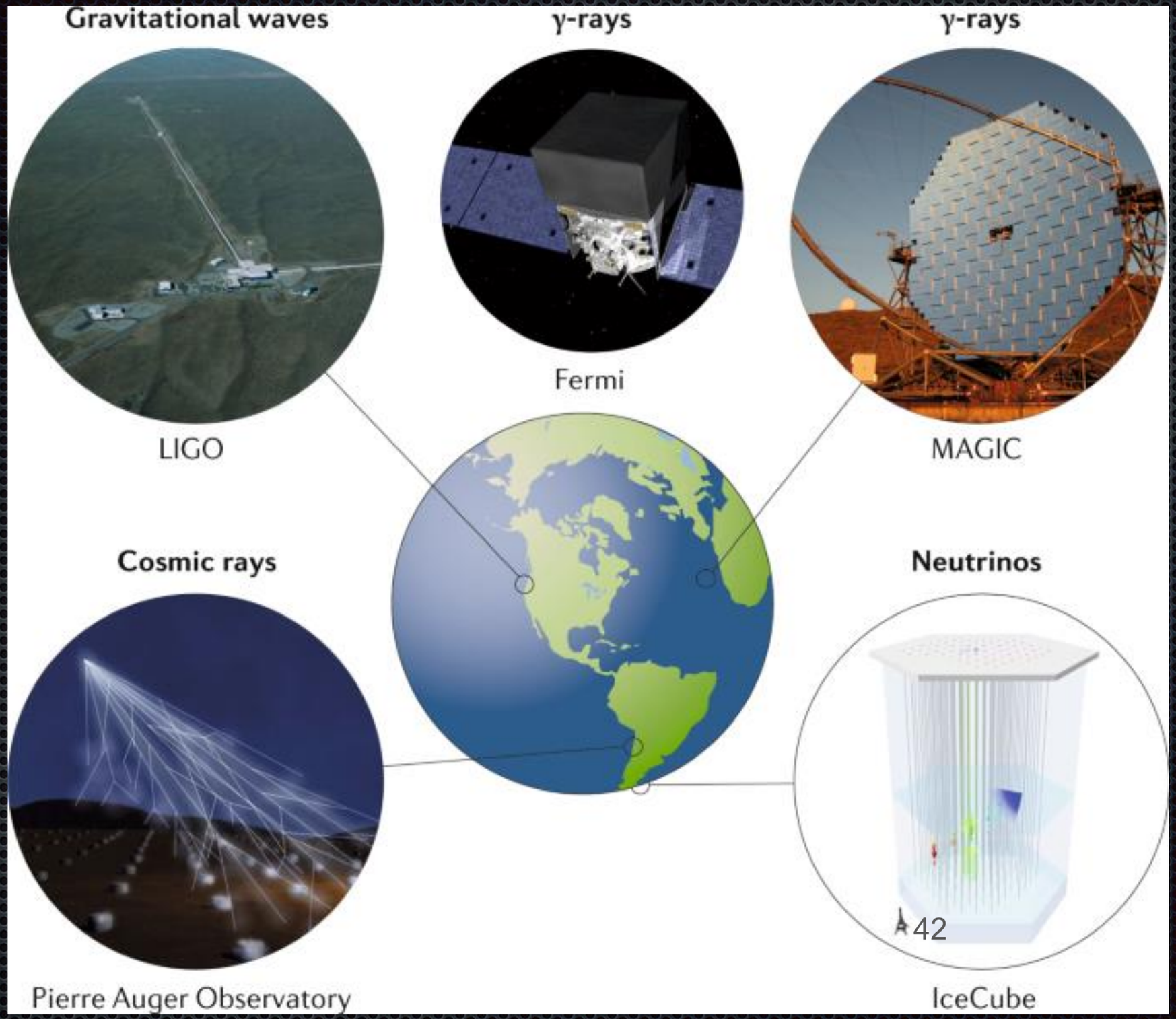
- **These messengers are created by different astrophysical processes, and thus reveal different & complementary information about their sources.**

- **MM Astronomy is the natural extension of the multi-wavelength astronomy.**

Energy range of messengers

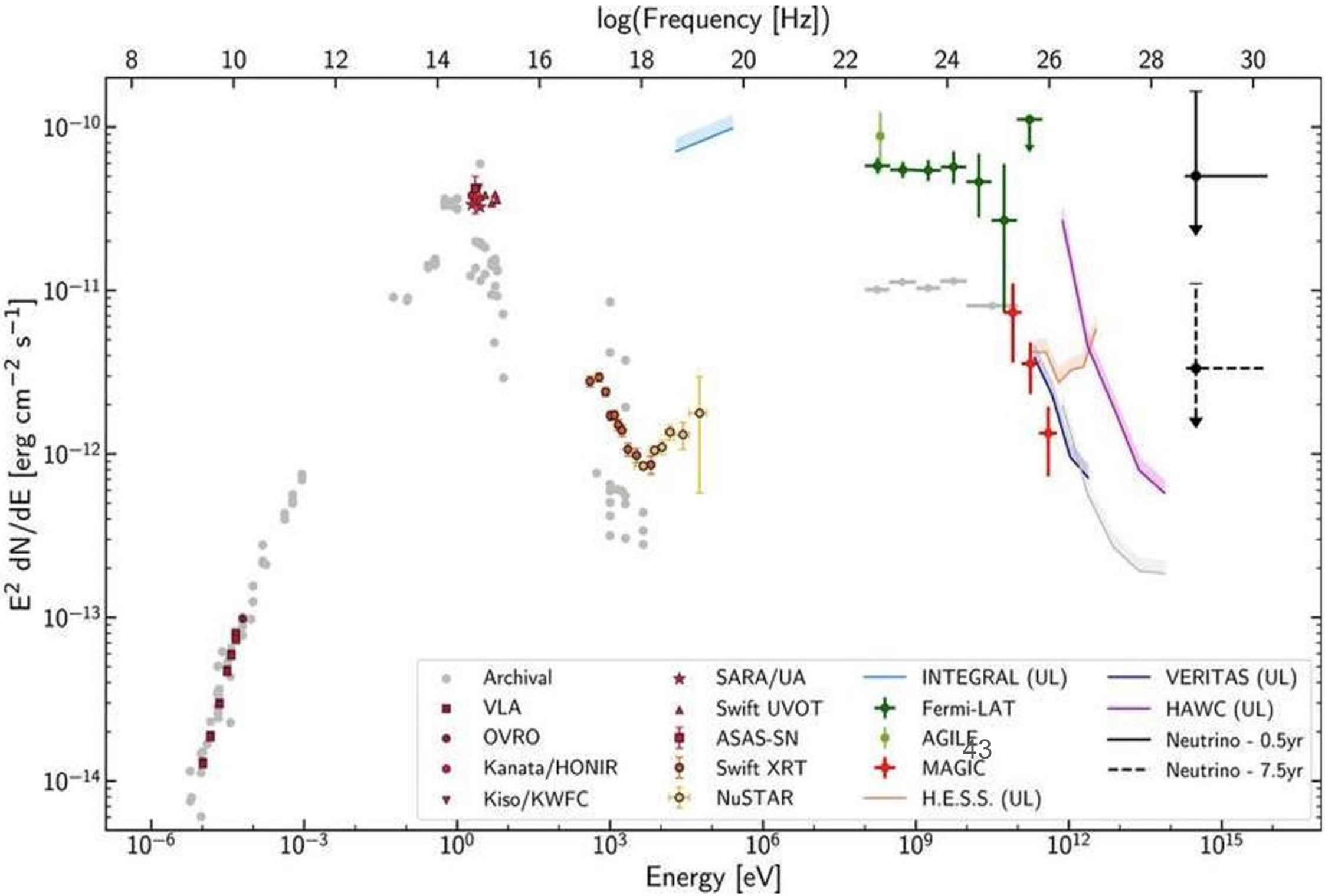


Multimessenger (MM) Astronomy



Electrom. & ν spectrum of TXS 0506+056

1st association of High-E ν & γ-ray source



Science 361 (2018) no.6398, eaat1378

Multimessenger Astronomy allows access to physics across multiple aspects/fields:

Messenger	What it Probes
Electromagnetic radiation	Temperature, composition, magnetic fields, chemistry
Gravitational waves	Compact objects, spacetime, masses, orbital dynamics
Neutrinos	Dense cores, nuclear reactions, hadronic jets
Cosmic rays	Particle acceleration, extreme energies

Indian Institute of Science Education and Research (IISER)

Location of the 7 IISERs offering admission

Indian Institute of Science Education and Research (IISER) Tirupati

Major Programs

1) 5 year Integrated BSMS (after plus two)
   Admission through IISER Aptitude Test
   (https://www.iiseradmission.in/)
   Fellowships for INSPIRE scholars

2) 2 year Master's by Research (MS-R)
   (Physics, Chemistry, Biology)
   Eligibility : 60% marks, B.Sc./B.Tech/B.E. or any equivalent degree
   (Final year students are also eligible to apply).
   JAM / JEST

3) PhD
   (MSc/B.E./BTech/M.E./MTech, BSMS or any equivalent degree)
   JEST, GATE, CSIR-UGC (JRF/NET-LS), INSPIRE scholars
   followed by interview (Twice in a year)

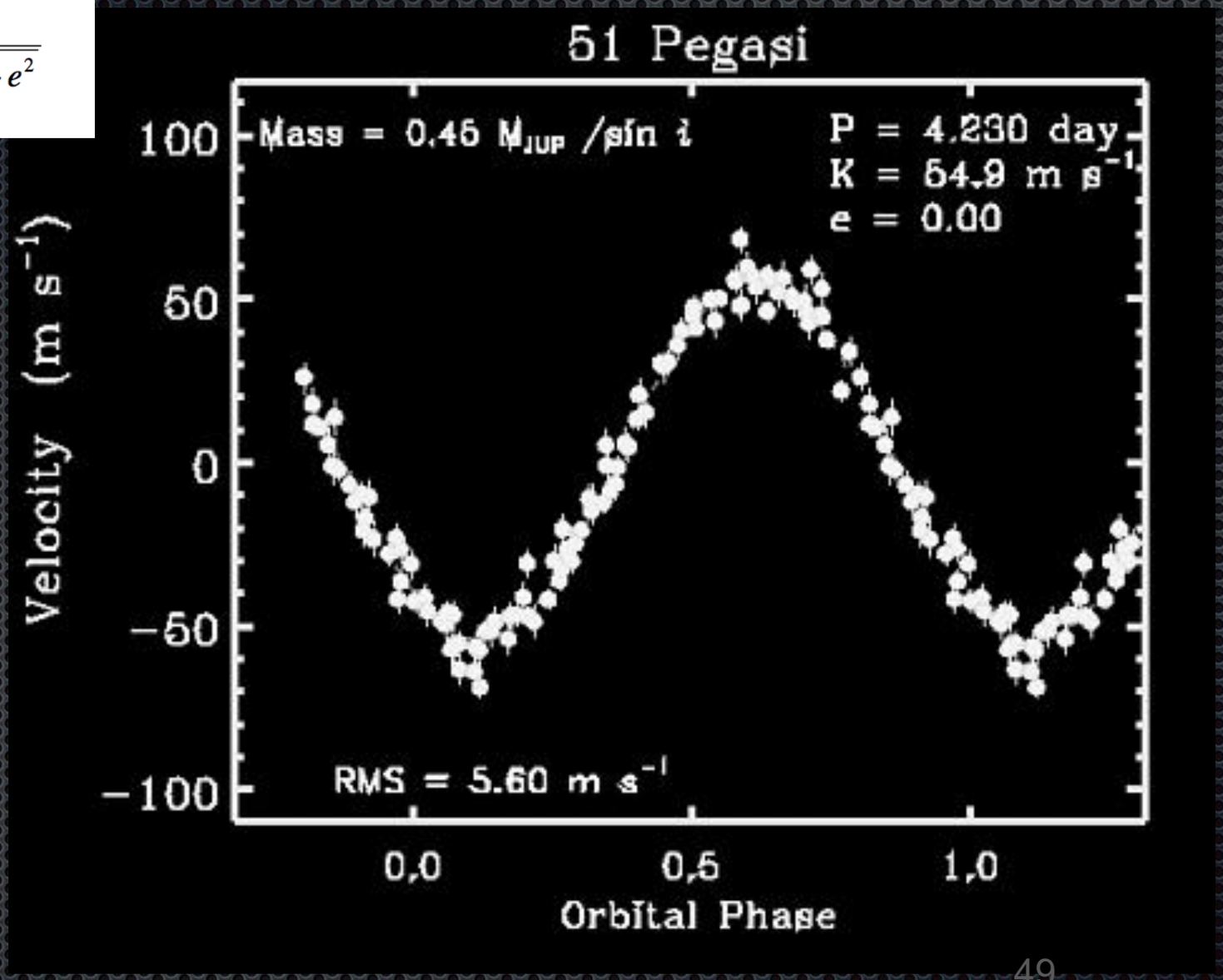
4) Post-doctoral programs

Check the website : http://www.iisertirupati.ac.in/admissions/

- **TeV (Tera-electron-volt, 10^{12} eV):** Used to measure energies in particle accelerators like the LHC and to detect gamma-ray sources.
- **PeV (Peta-electron-volt, 10^{15} eV):** Associated with high-energy cosmic rays, often detected by neutrino telescopes like IceCube.
- **EeV (Exa-electron-volt, 10^{18} eV):** Represents ultra-high-energy cosmic rays, often originating from extragalactic sources.
- **ZeV (Zetta-electron-volt, 10^{21} eV):** Used to define extreme, theoretical particle energies and to constrain, for example, the maximum possible energy of cosmic particles.

Velocity curve for 51 Pegasus (Mayor & Queloz, 1996)

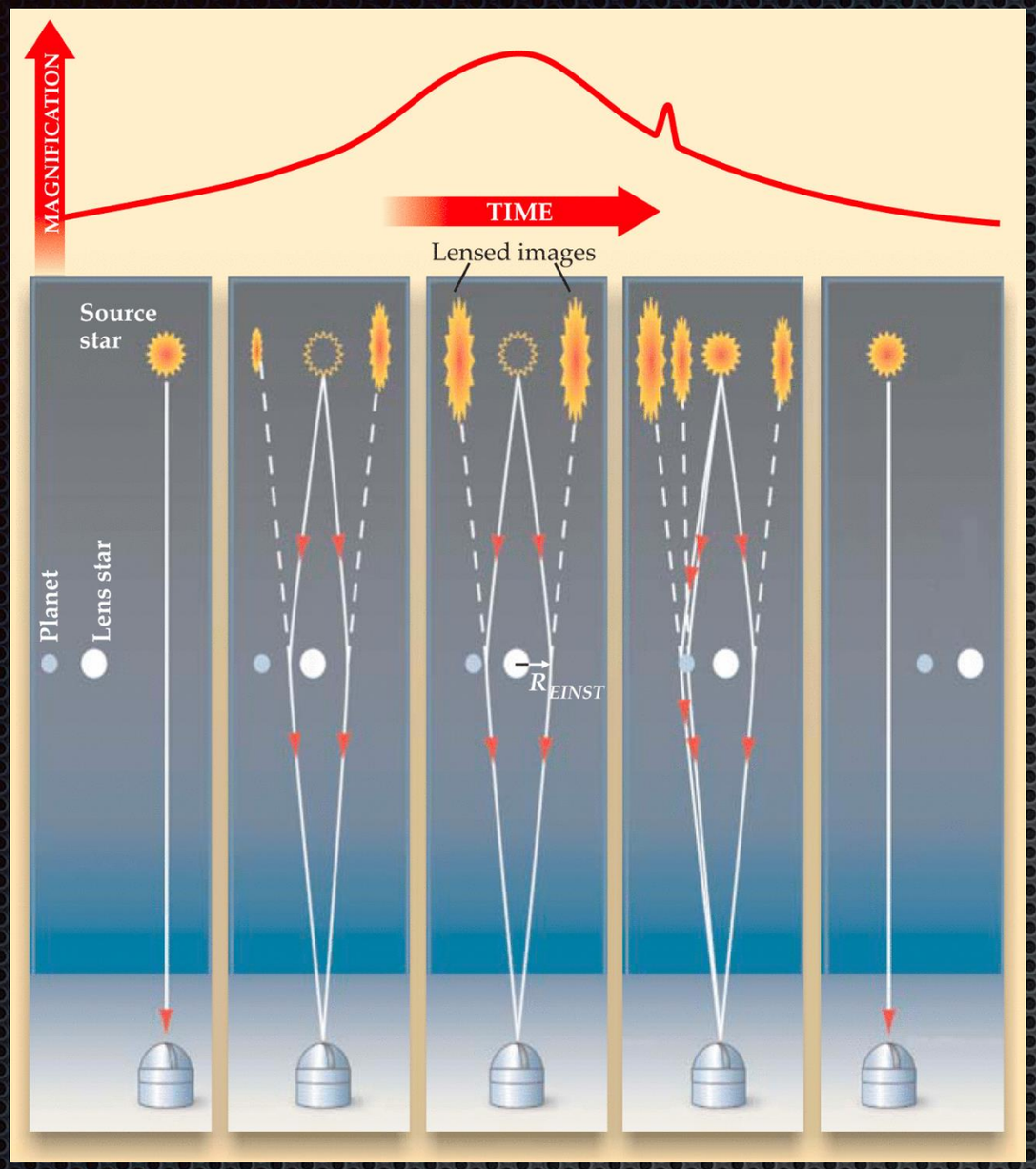
$$K_1 = \left(\frac{2\pi G}{P}\right)^{\frac{1}{3}} \frac{m_2 \sin i}{m_1^{2/3}} \frac{1}{\sqrt{1-e^2}}$$

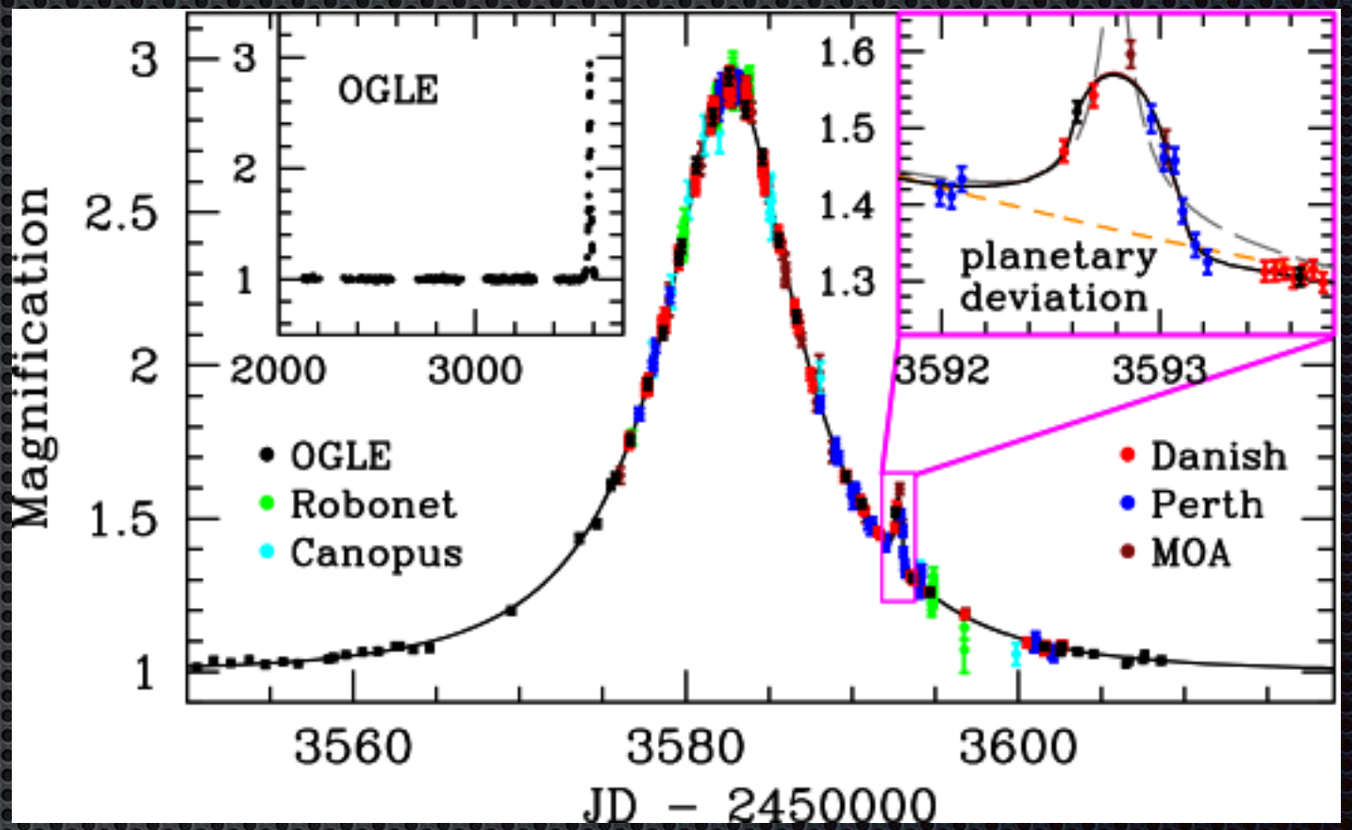


- Mass of the planet is only a lower limit because the plane of the planet's orbit is uncertain (Msin I = 0.47 M_J in this case)

http://obswww.unige.ch/~udry/planet/51peg.html

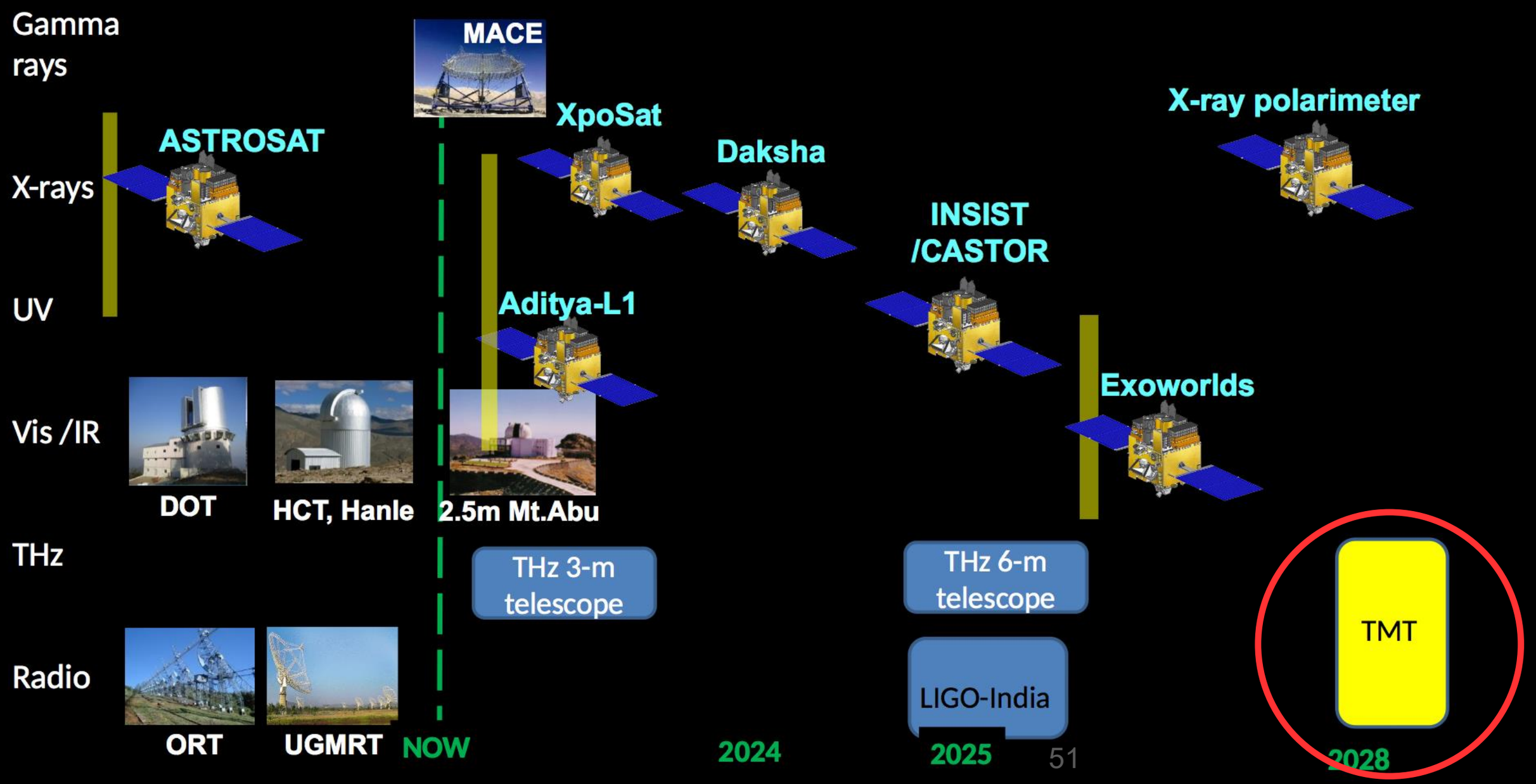
Planet Detection: Gravitational Microlensing





Microlensing can reveal exoplanets. By gravitational bending of light, a foreground lensing star passing near the sightline to a much brighter background source star displaces, distorts, and often duplicates the latter's image. If the Einstein radius *R* Einst, the characteristic size parameter of the lensing event, subtends an angle too small for a telescope to resolve, the observer does not see multiple images of the source star but only an ephemeral brightening of its light curve (red curve, top) as the lens star passes by. A planet accompanying the lens star at a distance comparable to *R* Einst can reveal itself as a bump on the light curve. =(Adapted from David Bennett's website: http://www.nd.edu/~bennett/moa53-ogle235.)

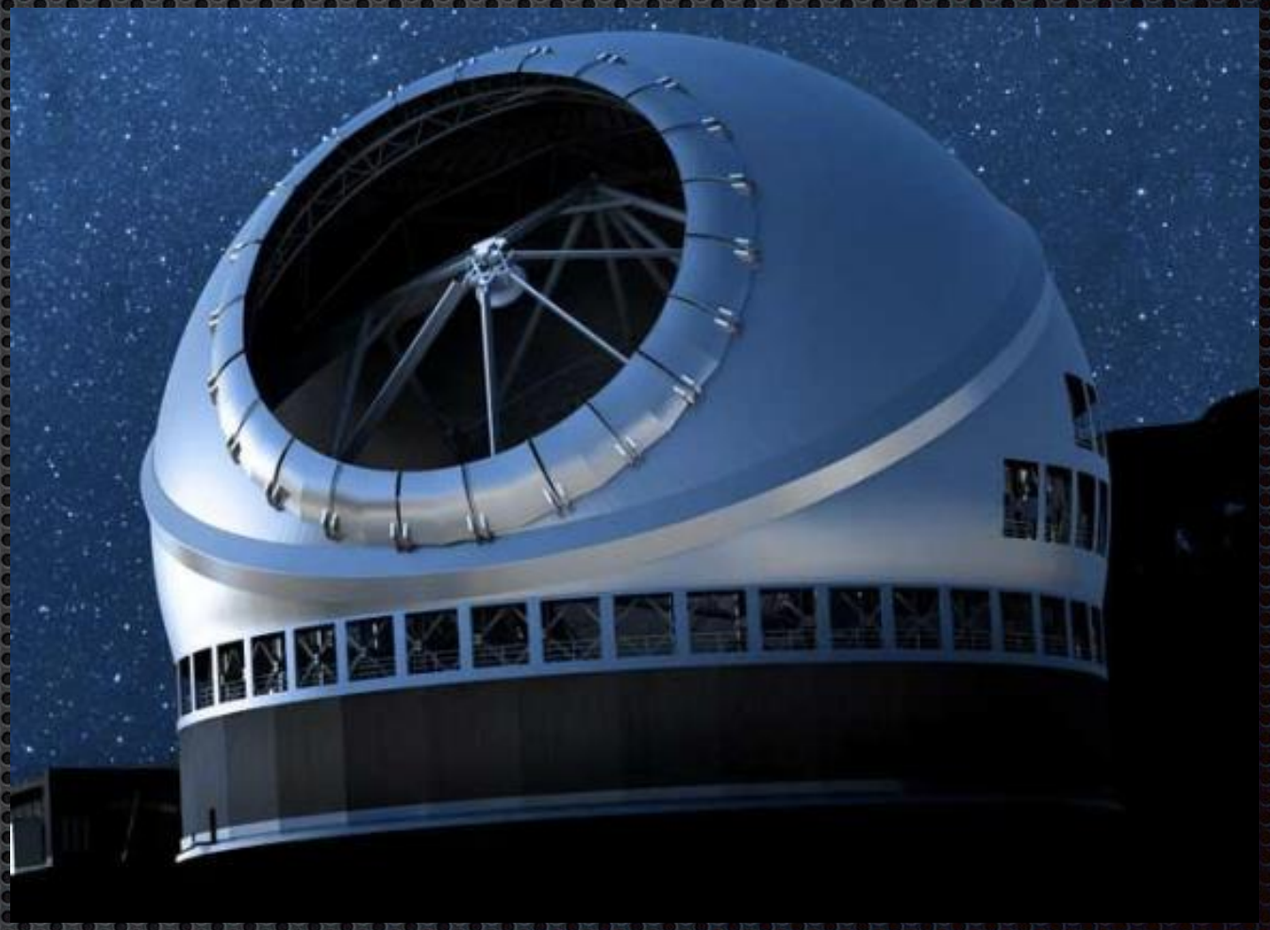
Indian astronomy– a snapshot of future facilities



Future facilities

- Radial velocity: Current achievement ~ 0.5 - 1 m/s
- TMT: very high resolution spectroscopy → 0.1 m/s (Earth-Sun)
- TMT will detect Earth-mass planets around Sun-like stars
- Look for biomarkers: H_2O, CO_2, CH_4, O_2, NH_3, N_2 etc.

Thirty meter telescope (TMT)



How to obtain mass of the Planet

Conservation of momentum

$$m_{Star} v_{Star} = m_{Planet} v_{Planet}$$

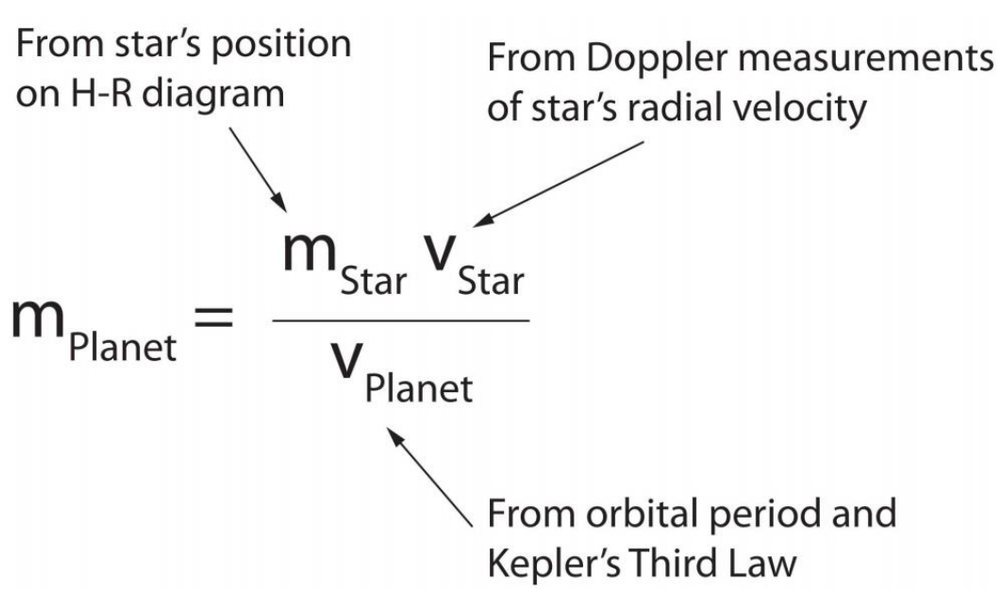
$$m_{Planet} = \frac{m_{Star} v_{Star}}{v_{Planet}} \qquad (1.1)$$

Kepler's Third Law as modified by Newton:

$$P^2 = \frac{a^3}{M} \qquad (1.2)$$

$$v_{Planet} = \frac{2\pi a}{P} \qquad (1.3)$$

$$v_{Planet} = \frac{2\pi \sqrt[3]{MP^2}}{P} = 2\pi \left(\frac{M}{P}\right)^{\frac{1}{3}} \qquad (1.4)$$



- **Planet's orbital period (P) is the same as the star's and you can get the star's mass (M) from its position on the H-R diagram, you can use Kerpler's Third Law to determine the semi-major axis (a) of the planet's orbit.**
- **a is the semi-major axis of the planet's orbit, and M is the mass of the star the planet is orbiting**

$$K_1 = \left(\frac{2\pi G}{P}\right)^{\frac{1}{3}} \frac{m_2 \sin i}{m_1^{2/3}} \frac{1}{\sqrt{1-e^2}}$$

Radial Velocity Signal Amplitude

$$K = \left(\frac{2\pi G}{P_{\rm orb}}\right)^{\frac{1}{3}} \frac{M_P \sin i}{(M_* + M_P)^{\frac{2}{3}}} \frac{1}{\sqrt{1-e^2}}$$

- Observe: period, velocity amplitude and shape
- Stellar mass unknown, but good estimate from stellar spectrum
- Jupiter: 12.4 m/s maximum velocity
- Saturn: 2.8 m/s
- Earth: 9 cm/s
- Heavier stars reduce the signal
- Lighter stars increase the signal