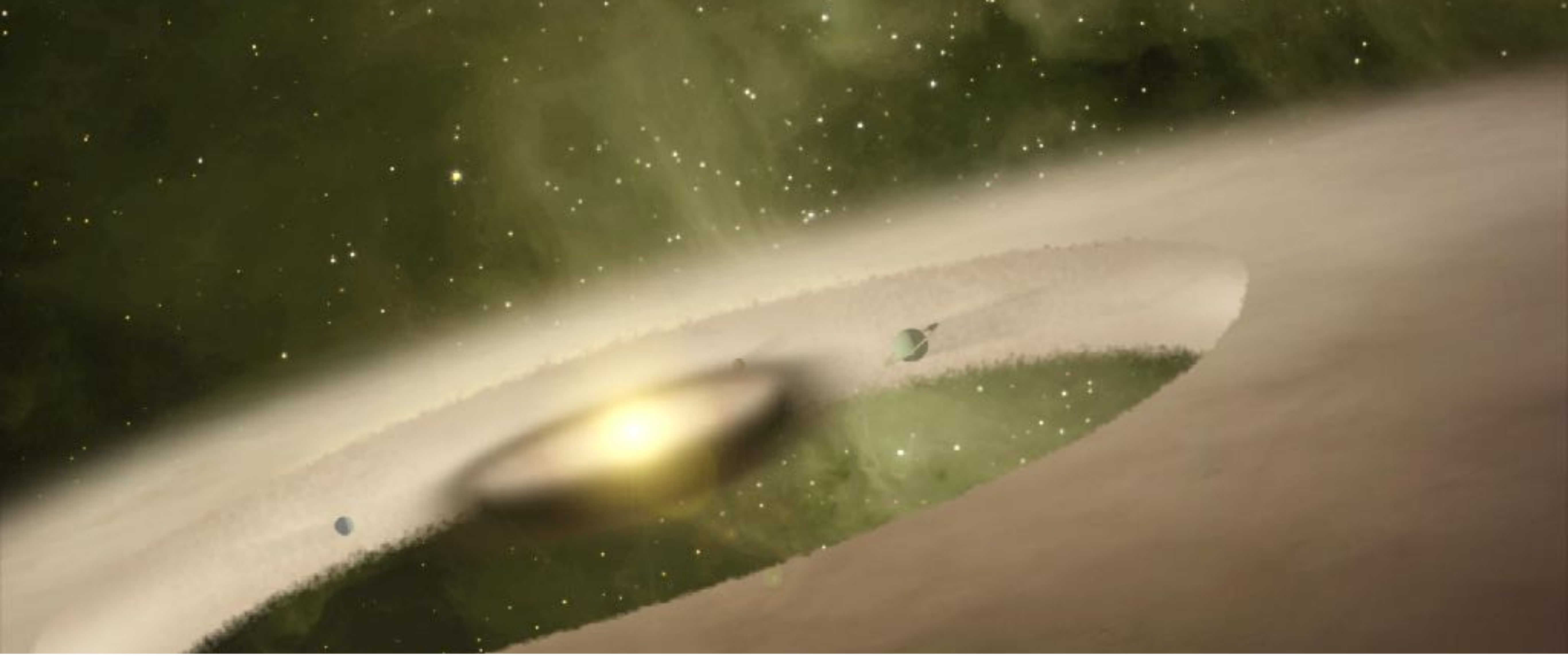


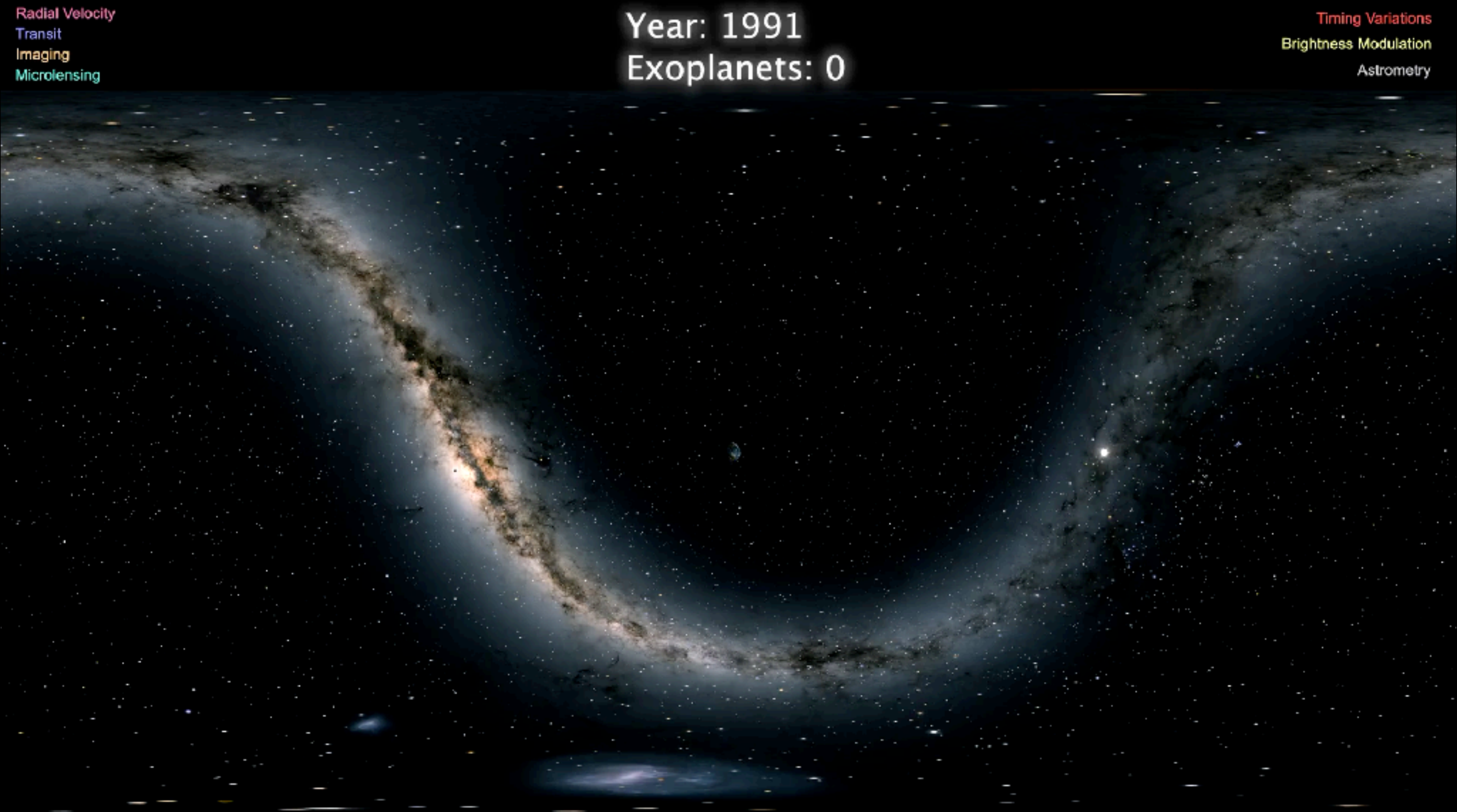
PLANETS BEYOND OUR SOLAR SYSTEM

CCE lecture series 2019 - Quarks to the Cosmos

Dr. Barnaby Norris, University of Sydney

Image: NASA/JPL-Caltech

Exoplanets – a ‘recent’ discovery



http://www.system-sounds.com/exoplanets4k/

Exoplanet.eu

Home | All Catalogs | Diagrams | Bibliography | Research | Meetings | Other Sites | VO

VO CONNECTION OFF ON

Catalog

Download VOTable | CSV | DAT

Status | Detection | Filter

Showing 4118 planets / 3063 planetary systems / 669 multiple planet systems

All fields

Show 100 entries

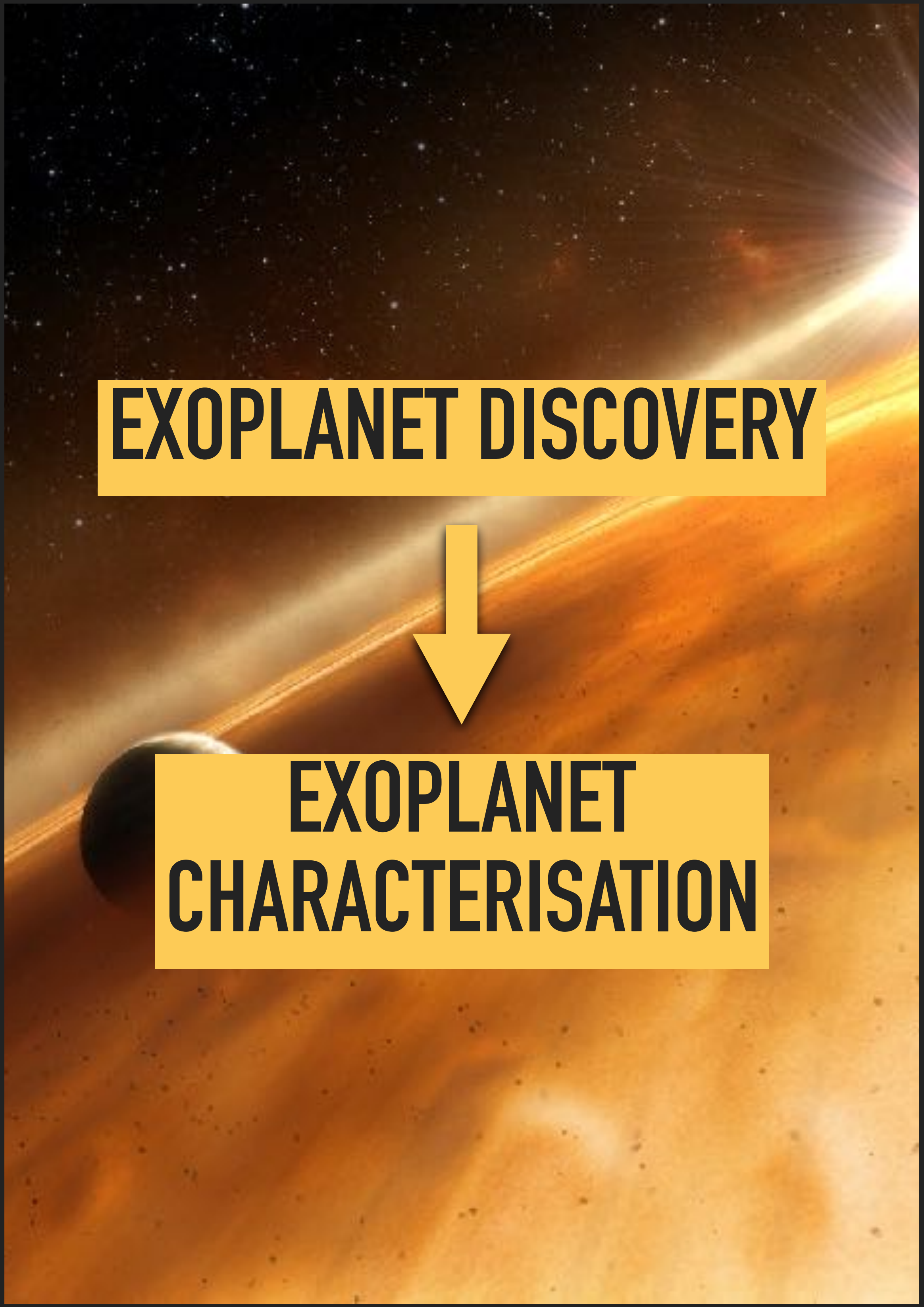
Planet Search

Show / hide columns

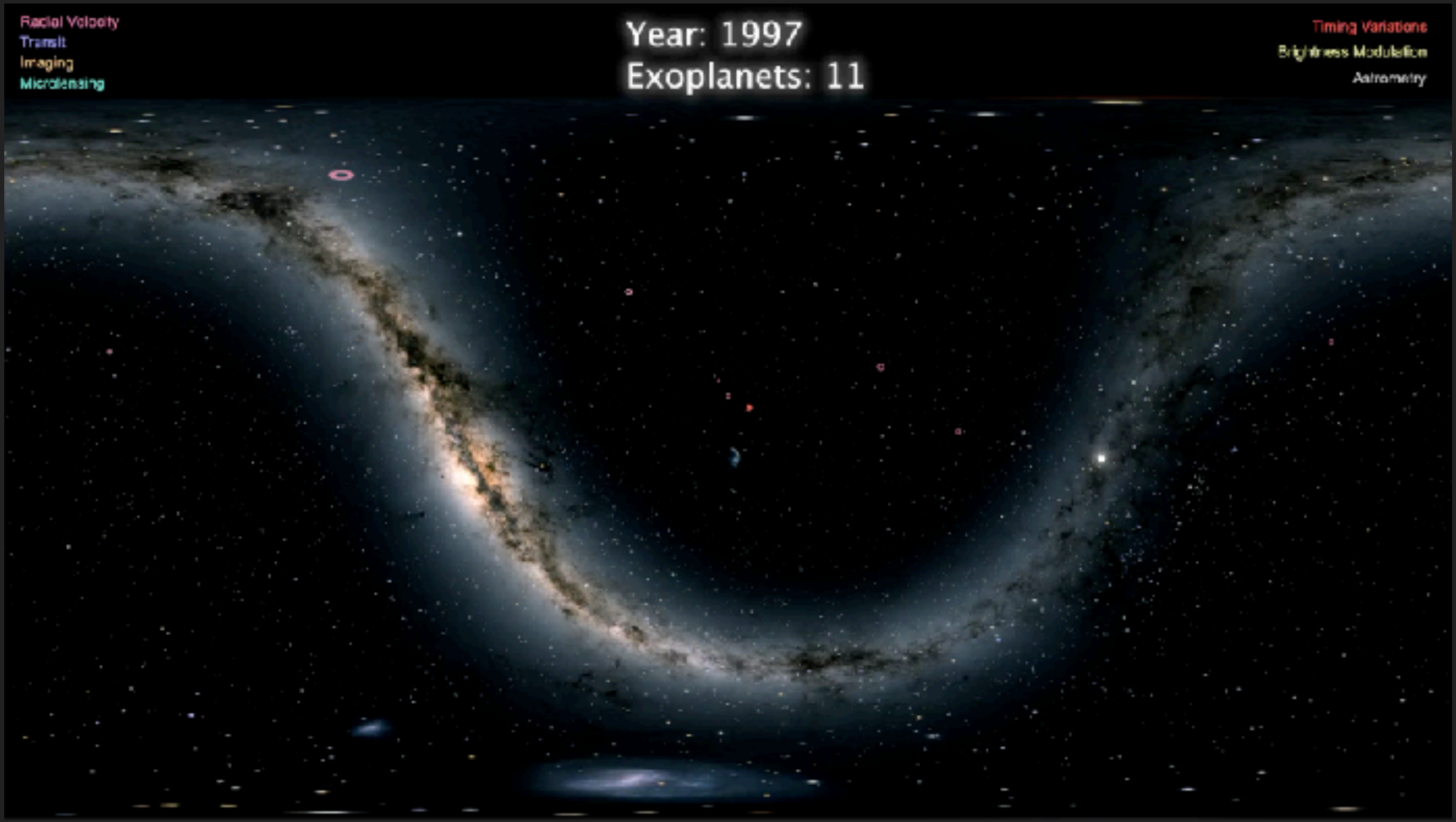
Planet	Mass (M_{Jup})	Radius (R_{Jup})	Period (day)	*a* (AU)	*e*	*i* (deg)	Ang. dist. (arcsec)	Discovery	Update
NGTS-10 b	2.162	1.205	0.7668944	0.0143	0	79	—	—	2019-09-30
OGLE-2017-BLG-1434L b	0.014	—	—	1.18	—	—	—	—	2019-01-22
WASP-143 b	0.725	1.234	3.778873	0.049	0.0007	89	—	—	2018-12-26
2I/Borisov	—	—	—	—	3.155	—	—	2019	2019-10-09
KELT-23A b	0.938	1.323	2.255251	0.03302	—	85.37	—	2019	2019-10-05
GJ 3512 b	—	—	203.59	0.338	0.4356	—	—	2019	2019-09-27
TOI-813 b	—	0.5986	83.8911	0.423	0.05	89.64	—	2019	2019-09-20
TOI-503 b	53.6	1.29	3.6775	—	0	82.65	—	2019	2019-09-19
TOI-163 b	1.22	1.489	4.231306	0.058	0	87.24	—	2019	2019-09-18
TOI-150 b	2.51	1.255	5.857487	0.0643	0.262	88.09	—	2019	2019-09-18
OGLE-2018-BLG-1700L b	4.4	—	—	2.8	—	—	—	2019	2019-09-12
Kepler-88 d	—	—	1431	2.464	0.432	—	—	2019	2019-09-06
WISE J0458+6434 A	57	—	15500	1	0.18	76.5	—	2019	2019-09-05
MASCARA-3 b	5.18	1.272	5.5514926	0.06971	0.085	89.16	—	2019	2019-09-05
GJ 357 b	0.006566	0.10411	3.93086	0.033	0.047	88.496	—	2019	2019-09-04
GJ 357 d	—	—	55.698	0.204	0.033	—	—	2019	2019-09-04

LECTURE OVERVIEW

- How to find an exoplanet
    - Various techniques, big results!
- Direct imaging - the next step
    - Why is it so hard?
    - Why do it?
- Why you want to do direct imaging…
    - Planet formation
    - Exoplanets
- The nitty gritty of direct imaging
    - How to beat the odds!



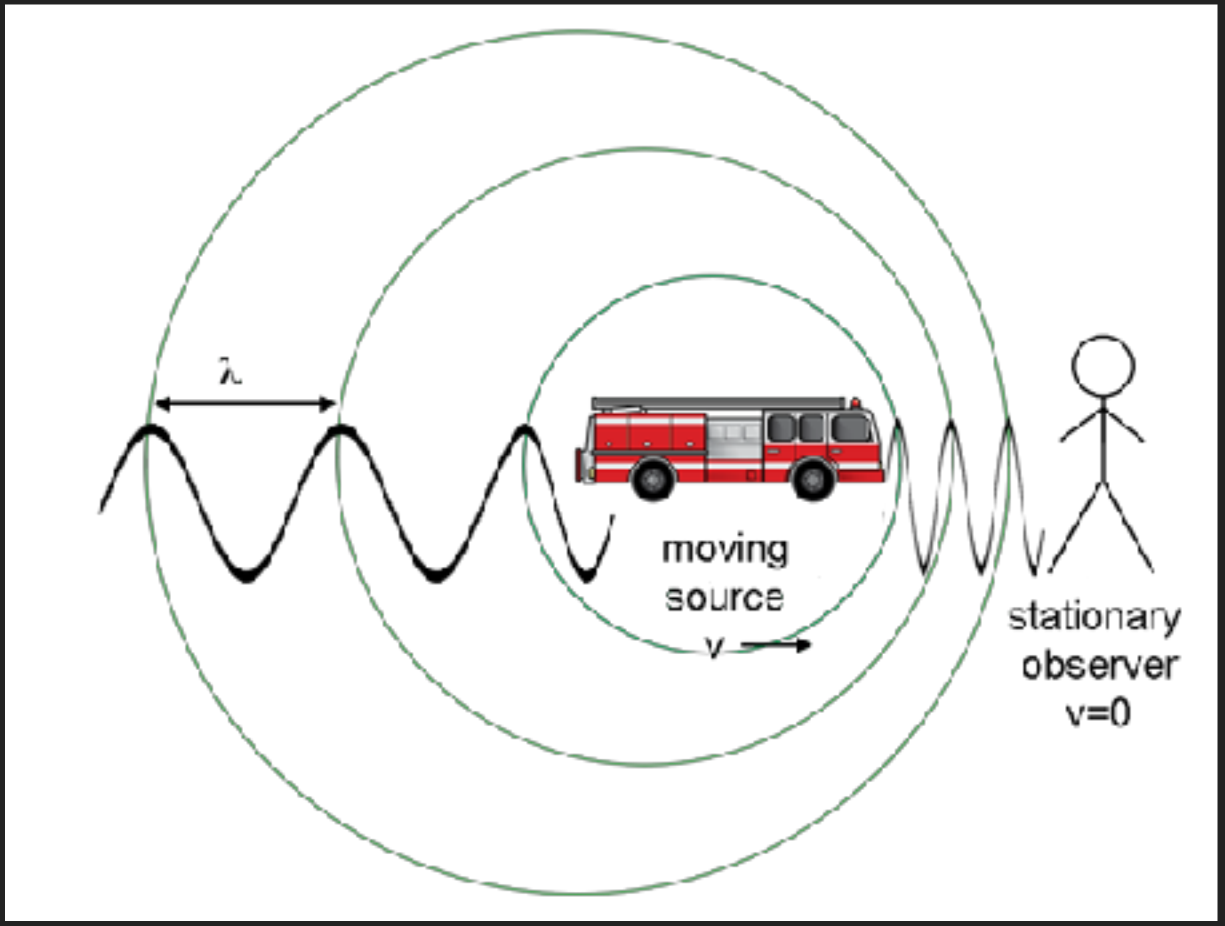
DETECTION METHODS



- Radial velocity
- Transit
- Astrometry
- Direct Imaging

RADIAL VELOCITY

- Doppler shift - shift frequency as object moves towards or away from you



https://imagine.gsfc.nasa.gov/features/yba/M31_velocity/spectrum/doppler_more.html

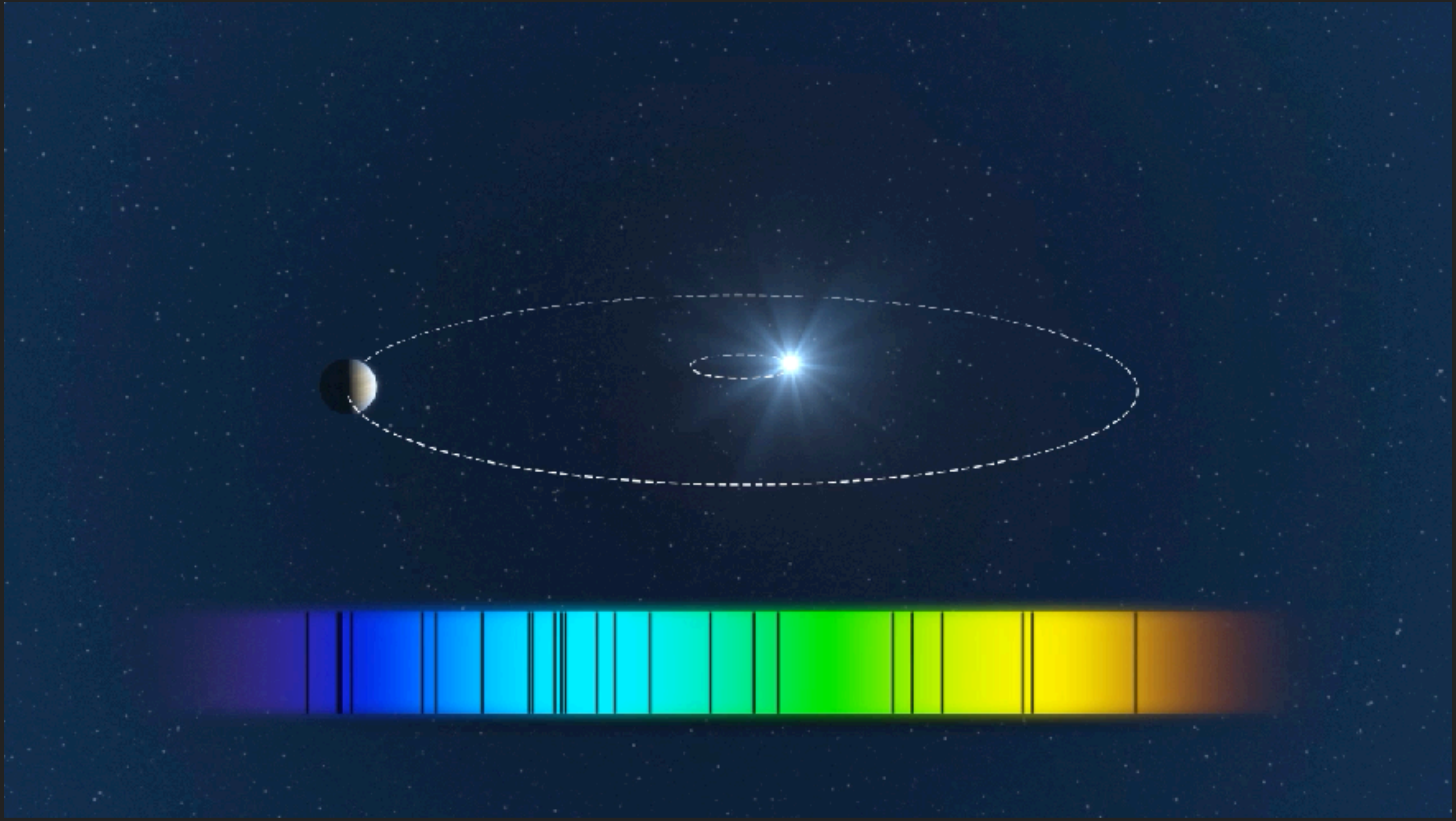
RADIAL VELOCITY

- Doppler shift in the star's spectrum as it's tugged by an orbiting planet

exoplanets.nasa.gov/alien-worlds/ways-to-find-a-planet/

RADIAL VELOCITY

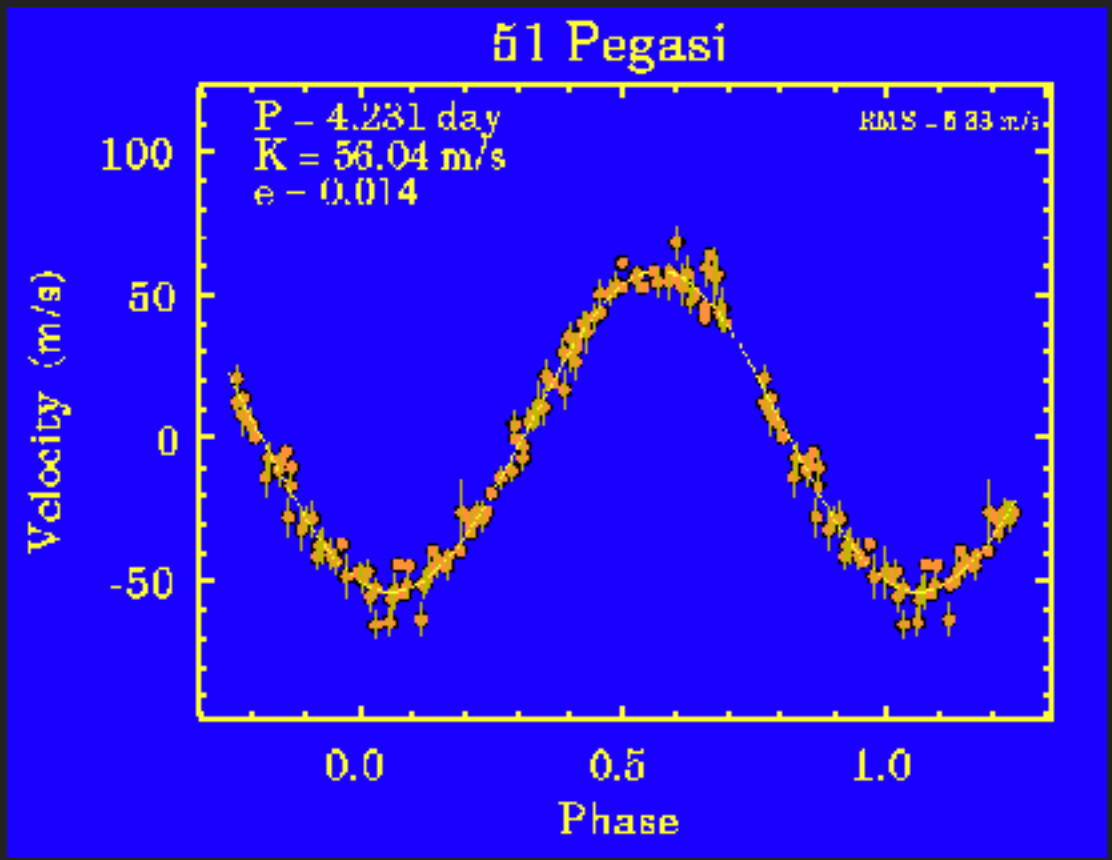
- Doppler shift in the star's spectrum as it's tugged by an orbiting planet



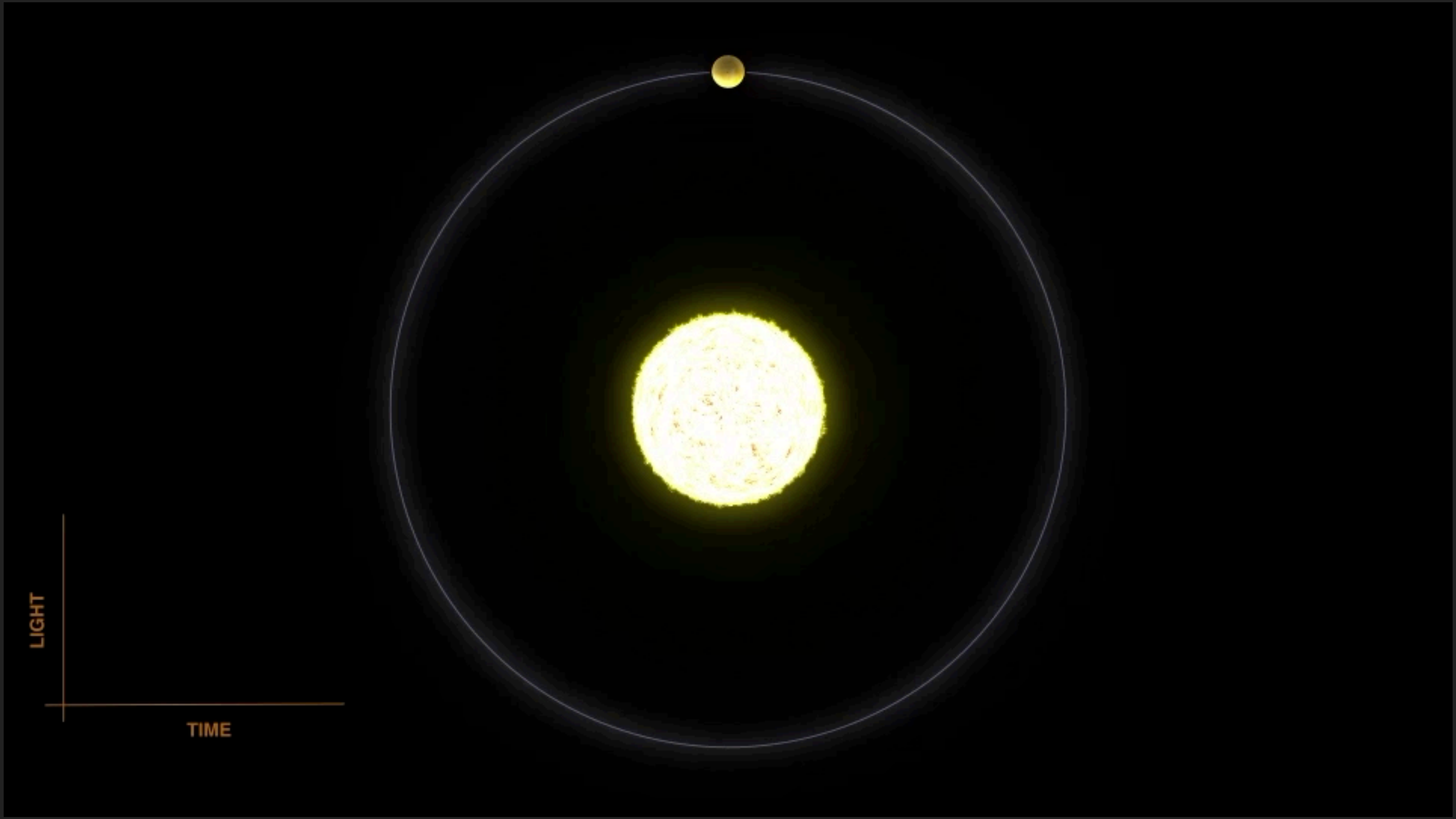
www.eso.org

RADIAL VELOCITY

- Doppler shift in the star's spectrum as it's tugged by an orbiting planet
- **Pros**:
  - The first and best method of detection from Earth. (Robust against seeing…)
  - Over half of exoplanets discovered this way (best way pre-Kepler)
- **Cons**:
  - Can't determine planet mass due to "sin(i)" problem - unknown orbital inclination
  - Biased to uninhabitable "hot Jupiters" - close to star (short periods), massive (big wiggles)



TRANSIT PHOTOMETRY



exoplanets.nasa.gov/alien-worlds/ways-to-find-a-planet/

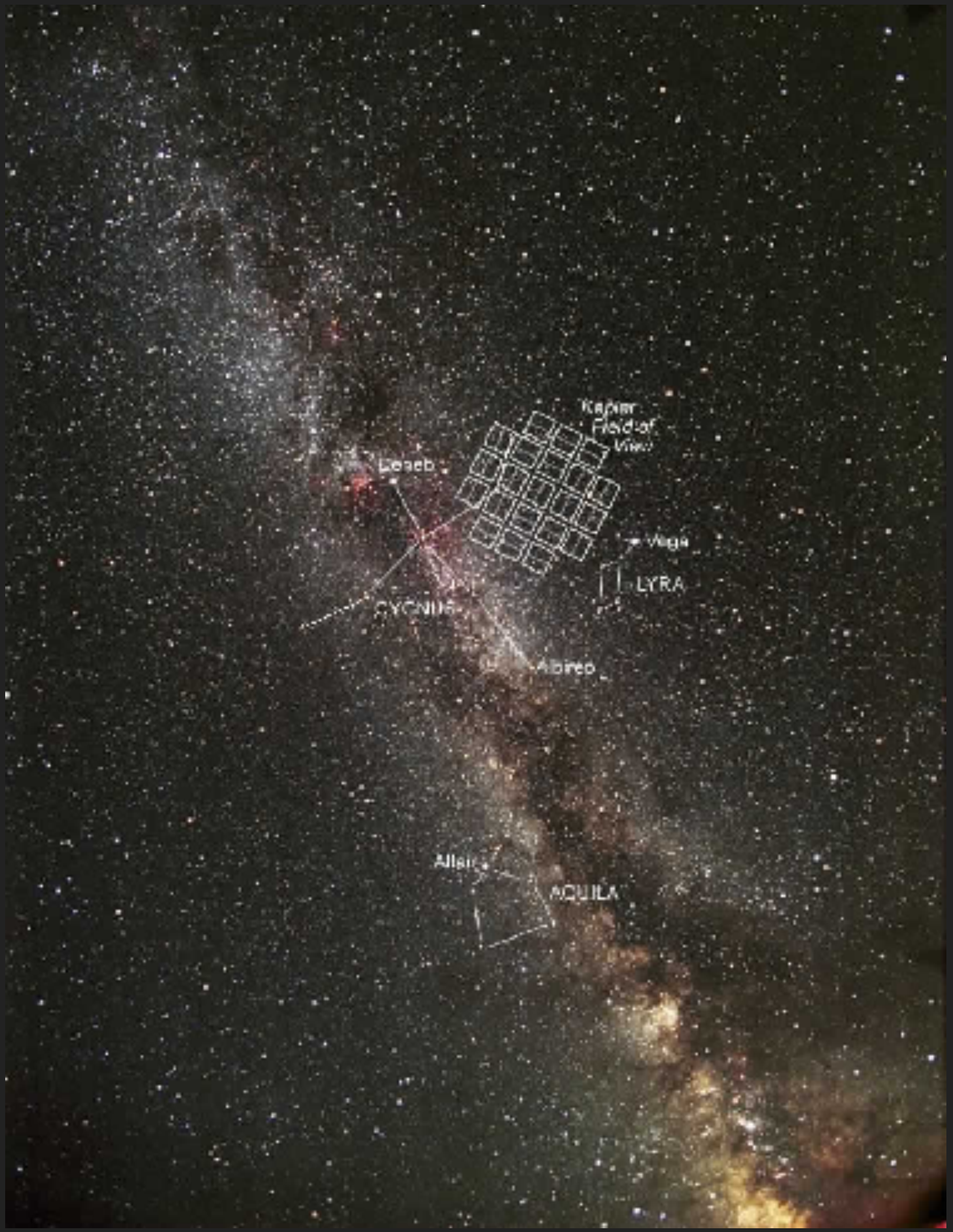
TRANSIT PHOTOMETRY

exoplanets.nasa.gov/alien-worlds/ways-to-find-a-planet/

TRANSIT PHOTOMETRY - KEPLER

- Stared at one patch of sky (in main mission)
- 9.6 years, observed 530,506 stars
- Discovered 2,662 planets (confirmed)
- Photometric precision ~20 ppm (0.002%)
- Retired - now we have TESS

NASA/JPL-Caltech/Wendy Stenzel

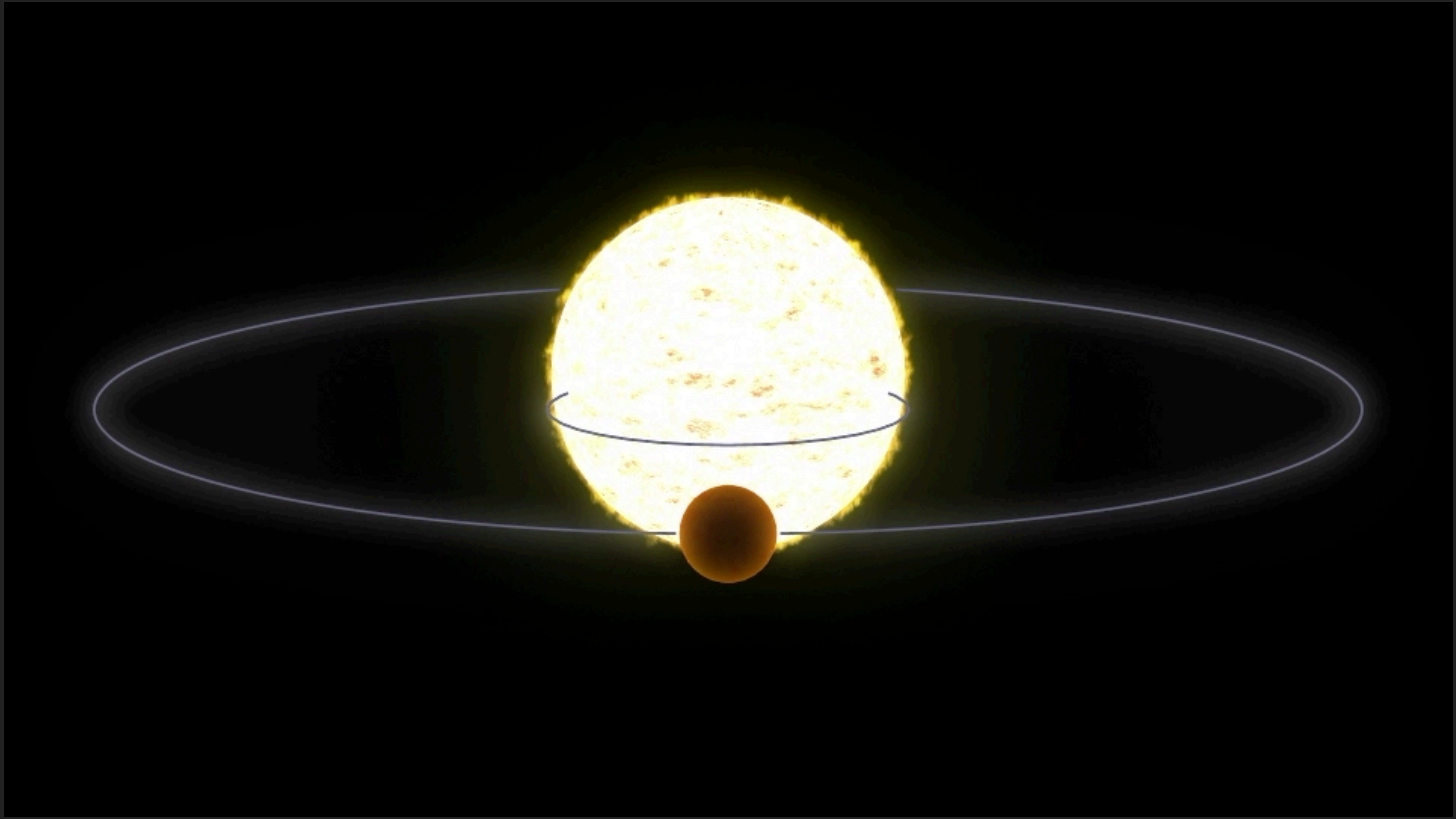


kepler.nasa.gov

TRANSIT PHOTOMETRY

- Starlight dims as planet passes in front of it
- **Pros**:
  - Most successful (thanks to Kepler)
  - The ‘dip’ in the light curve directly proportional to size of planet!
  - Combined with RV, get mass (since orbit is edge-on)
  - Can get rough planet spectrum
- **Cons**:
  - Chance of transiting system very small - need edge on orbit (lots of luck!)
  - Transit lasts small fraction of orbital period, so chance of catching one is low - needs continuous monitoring.
  - Need to detect multiple orbits - biased to close-in planets

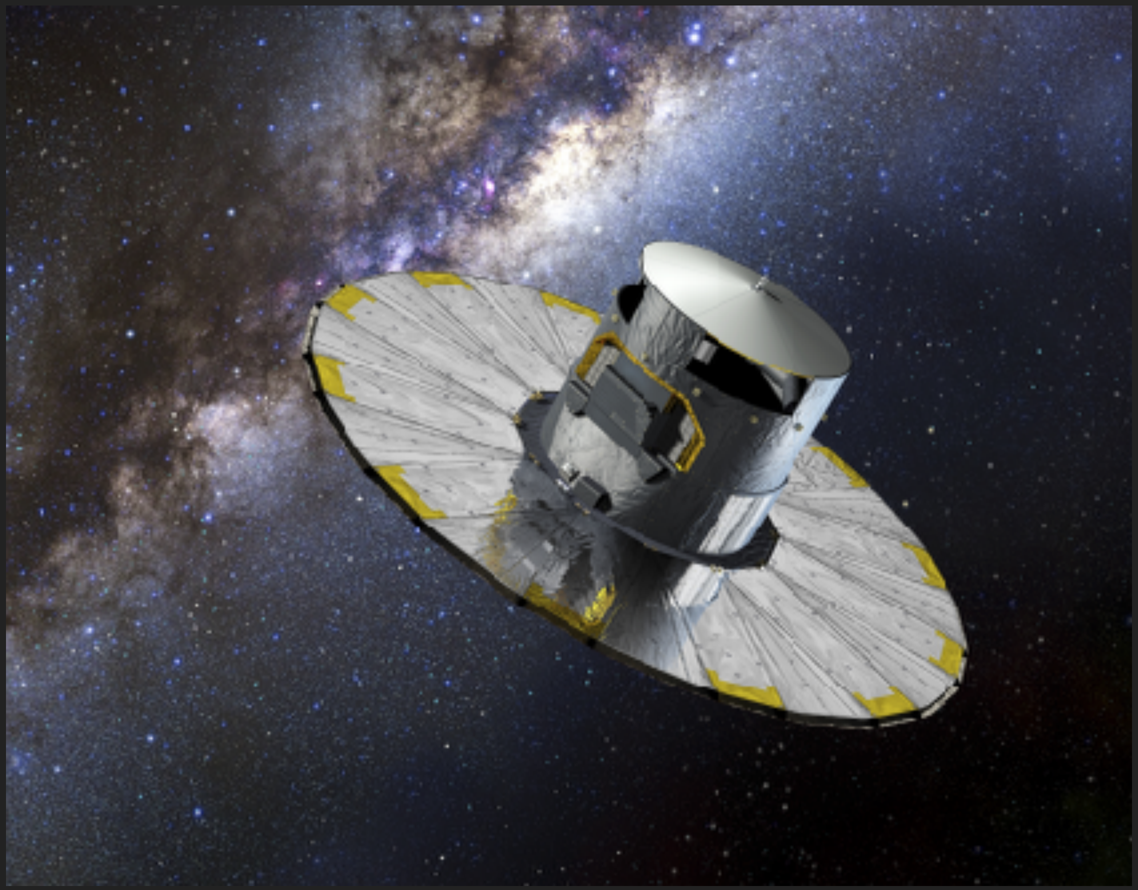
ASTROMETRY



exoplanets.nasa.gov/alien-worlds/ways-to-find-a-planet/

ASTROMETRY

- Observe tiny wiggle across the sky of star tugged by orbiting planet.
- **Pros**:
  - Doesn't rely on chance alignment like transits
  - Potentially very sensitive - measuring absolute movement rather than speed of star (like in RV)
- **Cons**:
  - Needs micro–arcsecond precision… golfball on the moon!
  - Really needs to be done in space, since Earth's atmosphere (seeing) has a huge effect…
    - … GAIA mission to provide astrometric detections! (10,000s of Jupiter-sized planets)

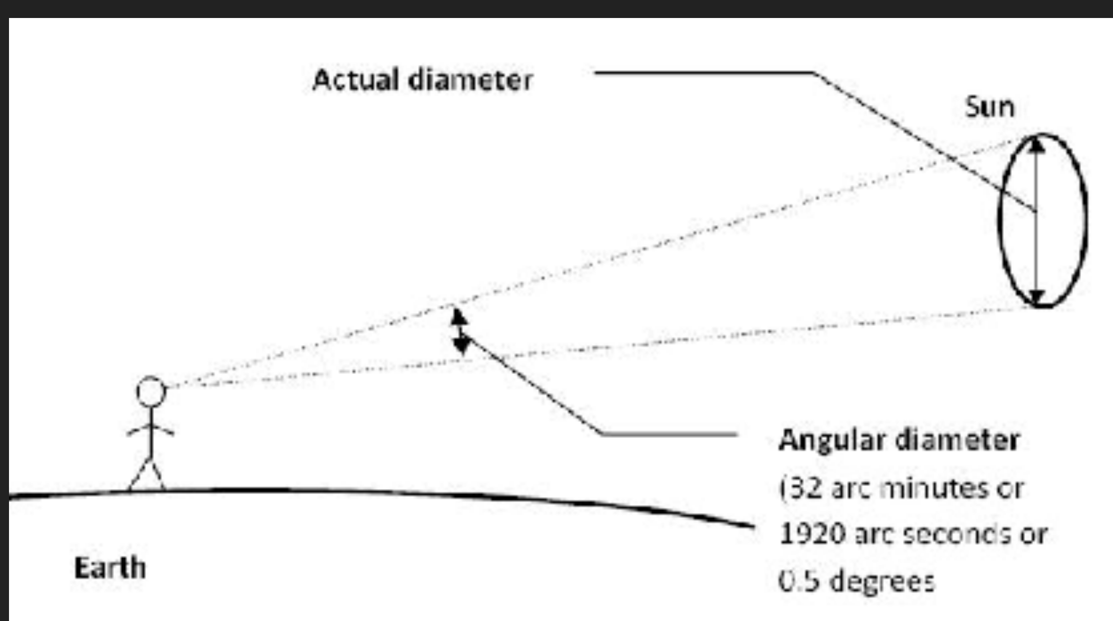


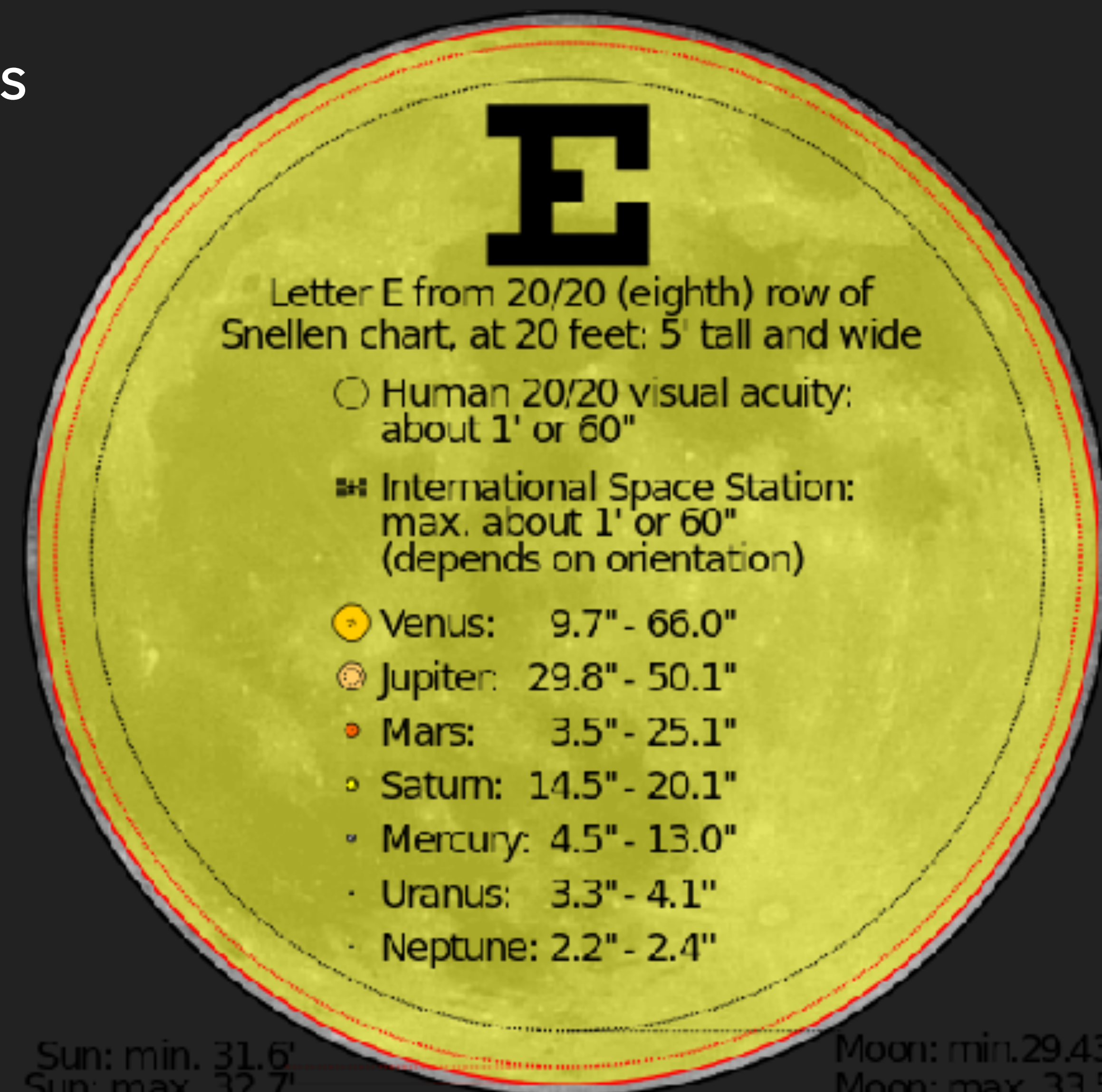
DIRECT IMAGING

- Just take a picture of the planet! How hard could it be?
- **Pros**:
  - Complete, unambiguous measurement of position and (with multiple images) orbits of planets
  - Brightness and even spectra of individual planets!
  - Probes planet sizes and orbits that other methods bias against
  - Complex structure, much more than just bare planets (planet formation)
- **Cons**:
  - … it's really really hard!!

1ST CHALLENGE – TINY SIZE

- Angular size is very small
- 1 AU at 100 parsecs is 0.000003 degrees
  = 10 milli-arcseconds
- This is a 20 cent coin in Sydney, seen from Melbourne!

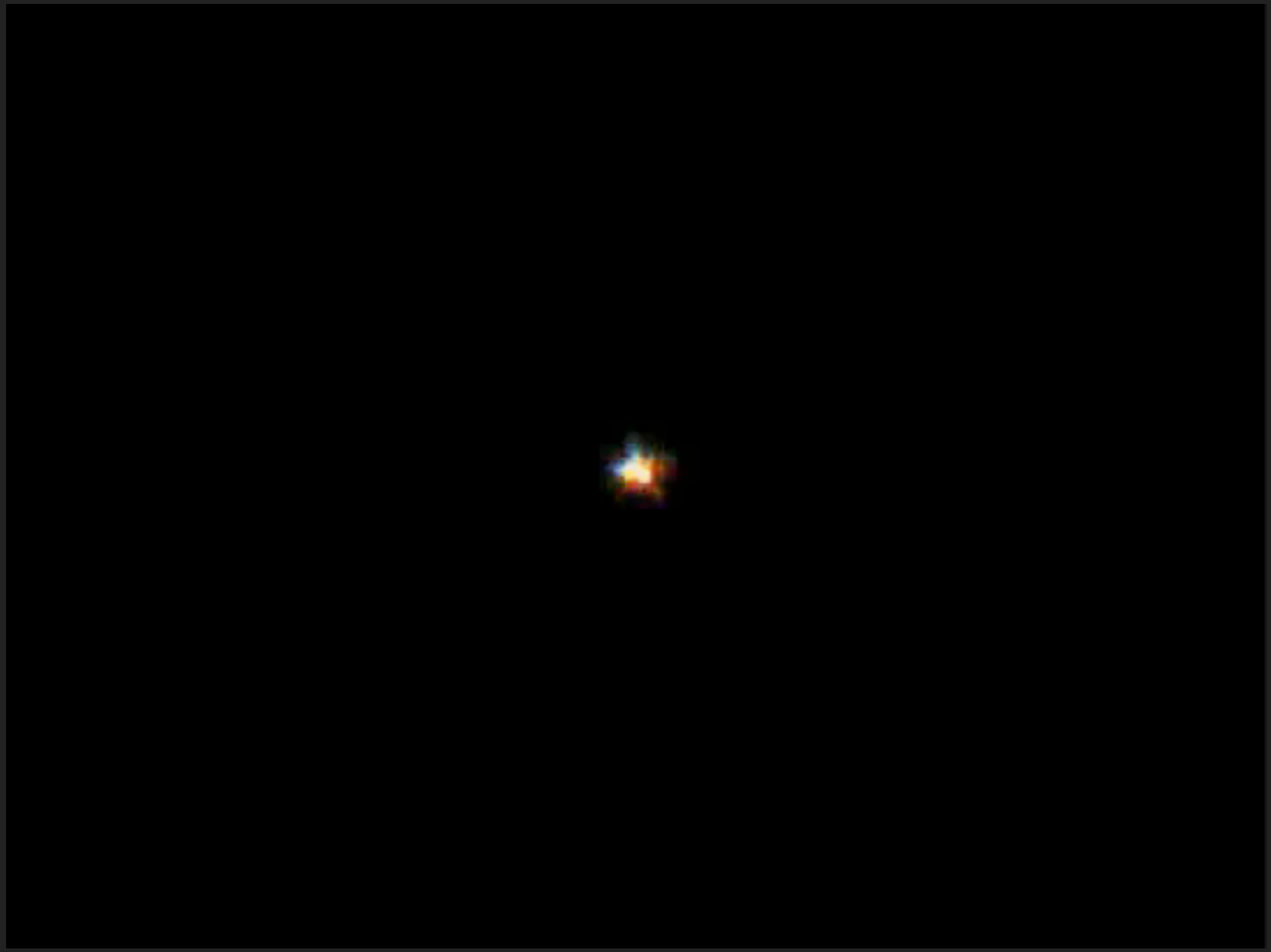




https://en.wikipedia.org/wiki/Angular_diameter

SEEING

- A big problem due to SEEING - effect of Earth's turbulent atmosphere
- 8 m telescope: diffraction limit ~ 10 milli-arcsec.
  Seeing ~ 1000 milli-arcsec



DIFFRACTION LIMIT

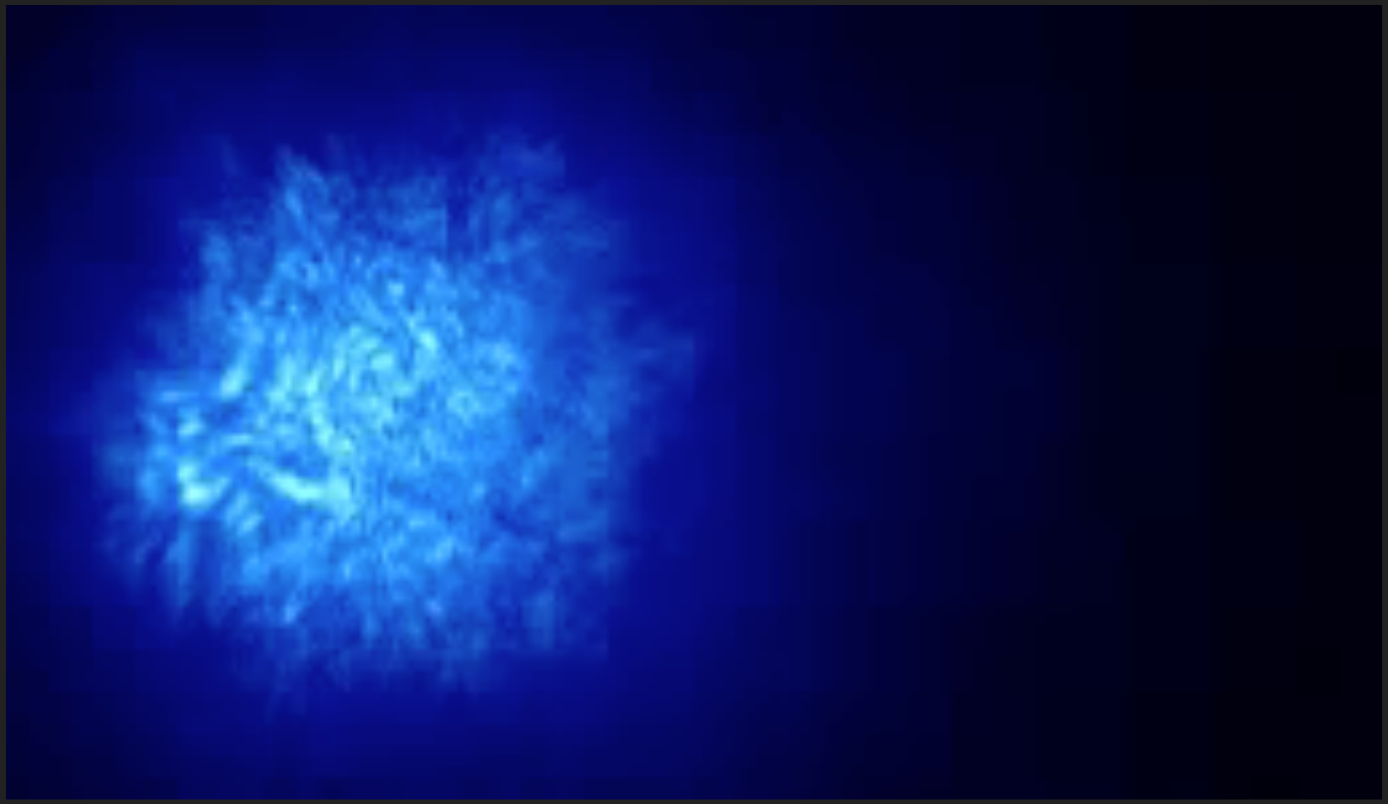
For wavelength λ, maximum achievable angular resolution θ depends on aperture size D

$$\theta = \lambda/D$$

SEEING

- A big problem due to SEEING - effect of Earth's turbulent atmosphere
- 8 m telescope: diffraction limit ~ 10 milli-arcsec.
  Seeing ~ 1000 milli-arcsec

Zoom in!



Typical seeing ~1"

1 AU (100 pc) ~ 0.01"

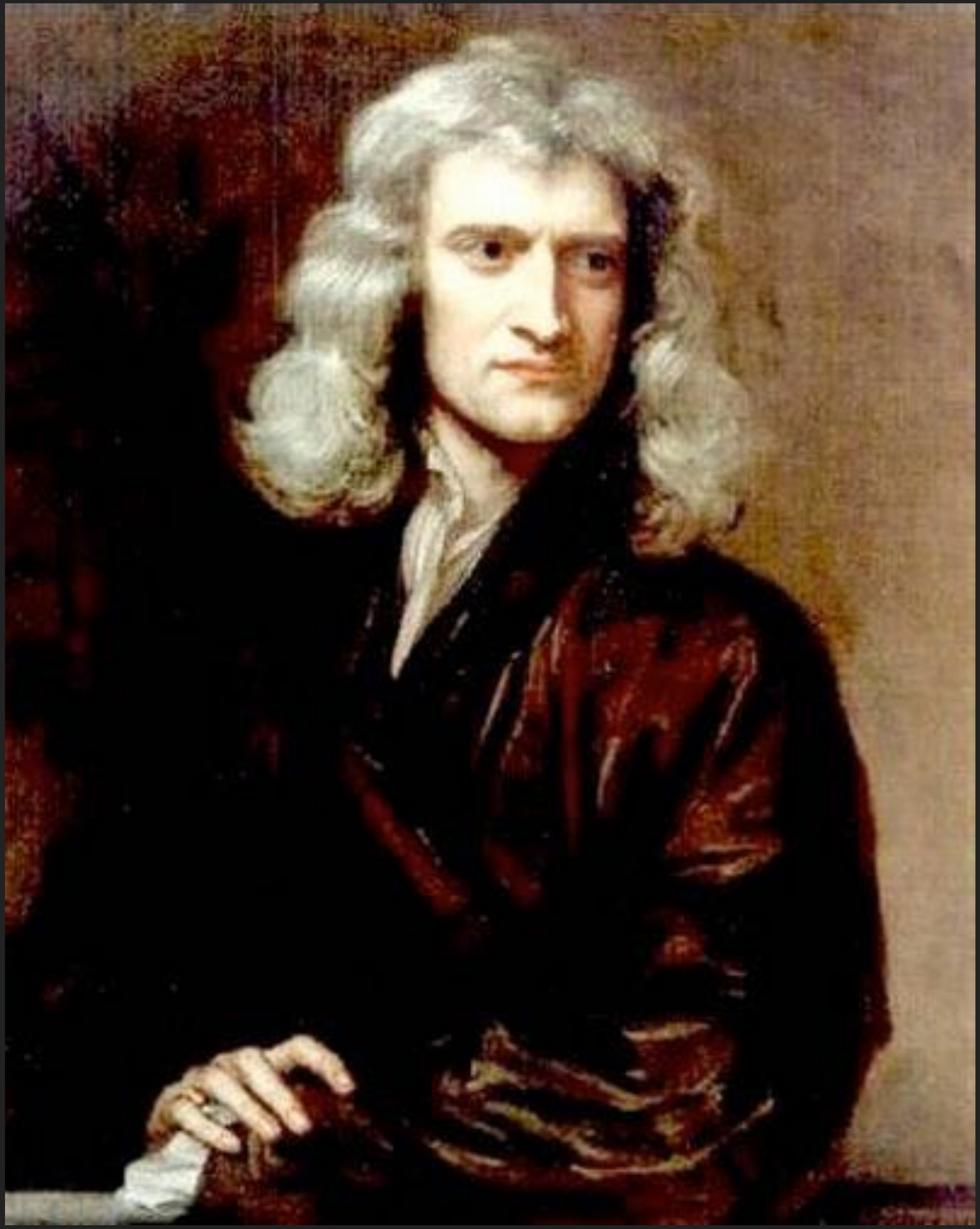
https://www.youtube.com/watch?v=ph9HUiY6_6E

DIFFRACTION LIMIT

For wavelength λ, maximum achievable angular resolution θ depends on aperture size D

$$\theta = \lambda/D$$

NEWTON DESCRIBES THE SEEING PROBLEM

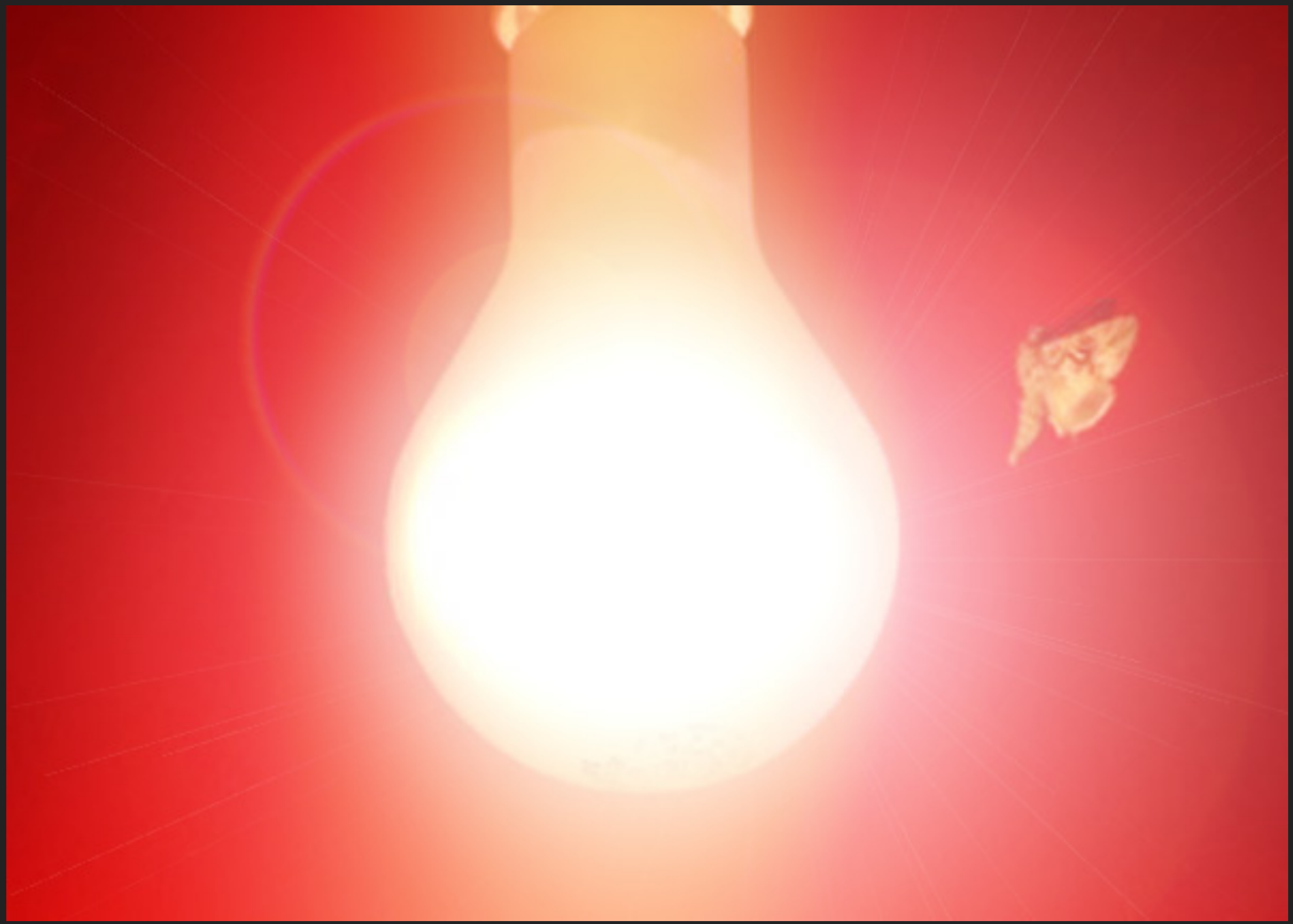


"If the theory of telescopes could at length be fully brought into practice, yet there would be bounds beyond which telescopes could not perform. For the Air through which we look upon the stars, is in perpetual Tremor, as may be seen by the tremulous motion of shadows cast from high towers, and by the twinkling of the fix'd Stars … those many trembling points, confusedly and insensibly mixed with one another … thereby cause the star to appear broader than it is … Long telescopes may cause objects to appear brighter and larger than short ones do, but they cannot be so formed as to take away that confusion of the Rays which arises from the Tremors of the Atmosphere. The only remedy is a most serene and quiet air, such as may be found on the tops of the highest mountains above the grosser clouds"

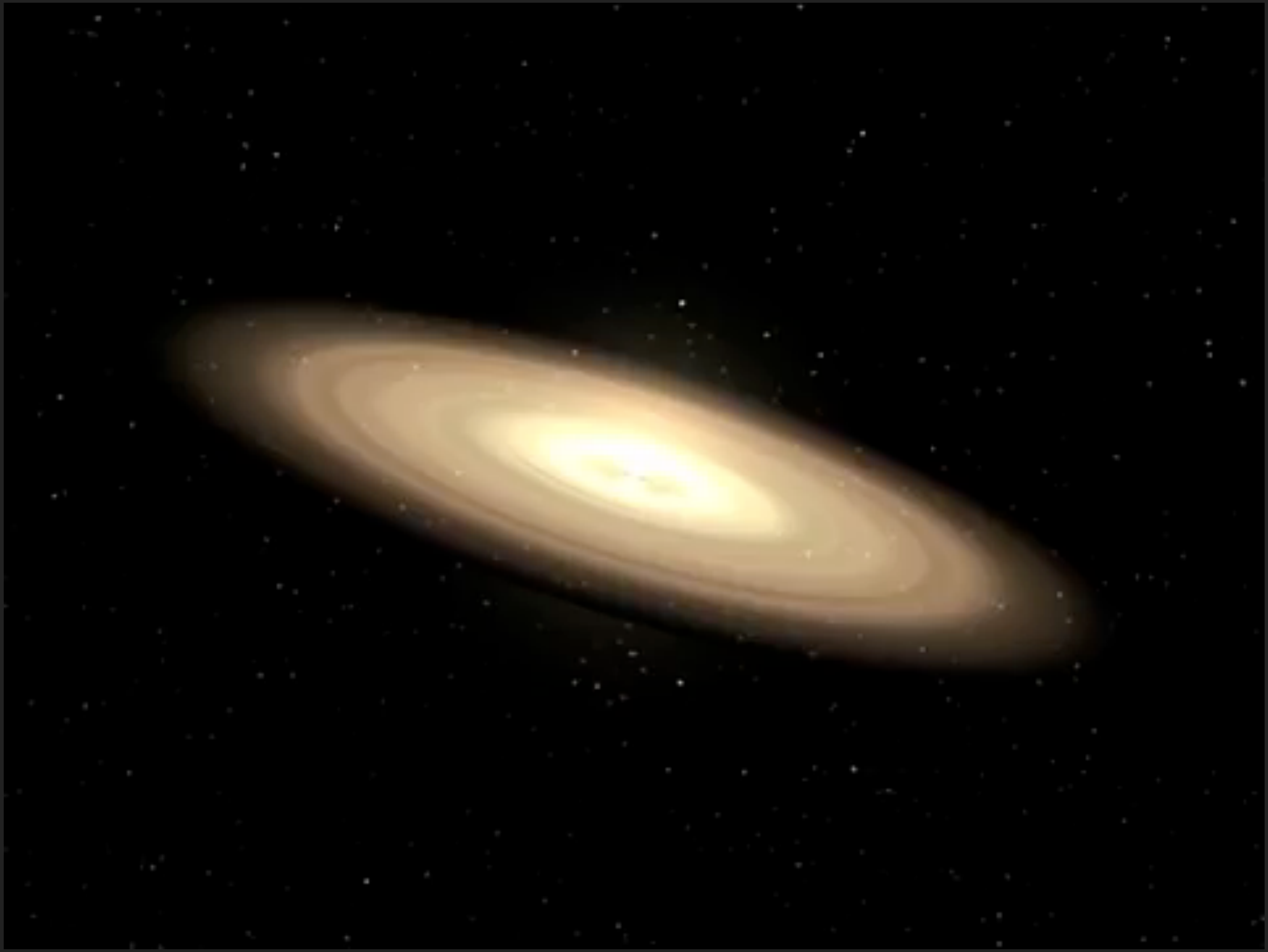
Isaac Newton, Opticks, 1704

2ND CHALLENGE – HIGH CONTRAST

- Star out-shines planet by up to 1 000 000 000 times
- Glare from star completely overwhelms faint planet

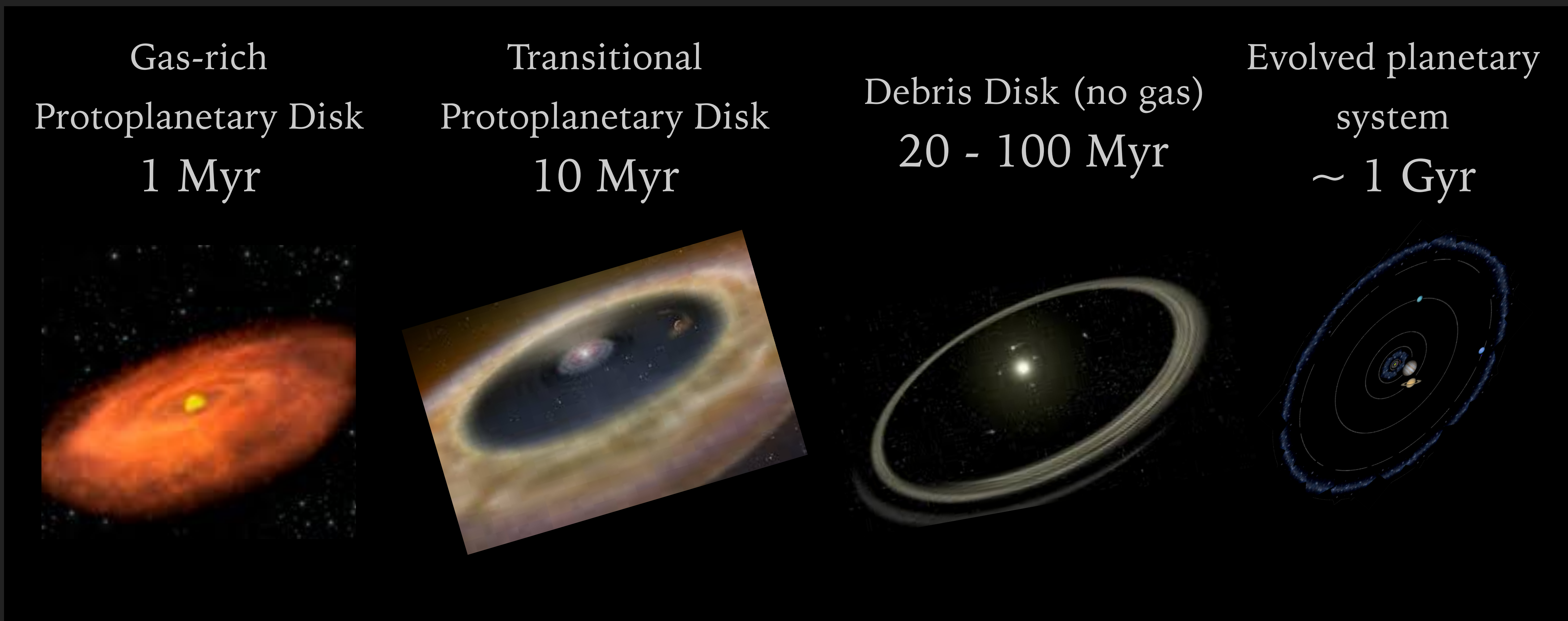


HOW ARE SOLAR SYSTEMS FORMED?



NASA / JPL

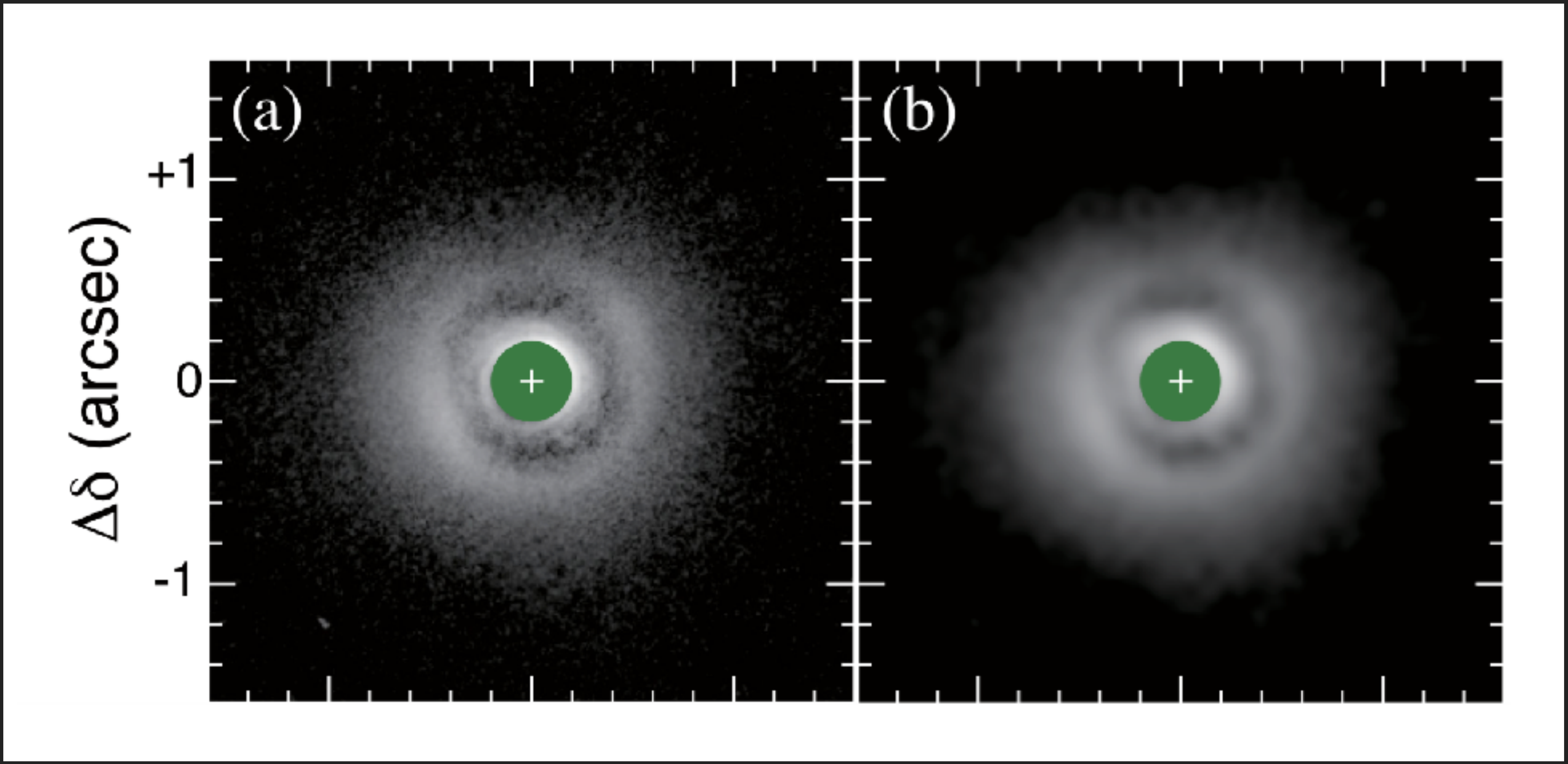
PROTOPLANETARY DISKS



Direct imaging - see the process of the planet formation happening!

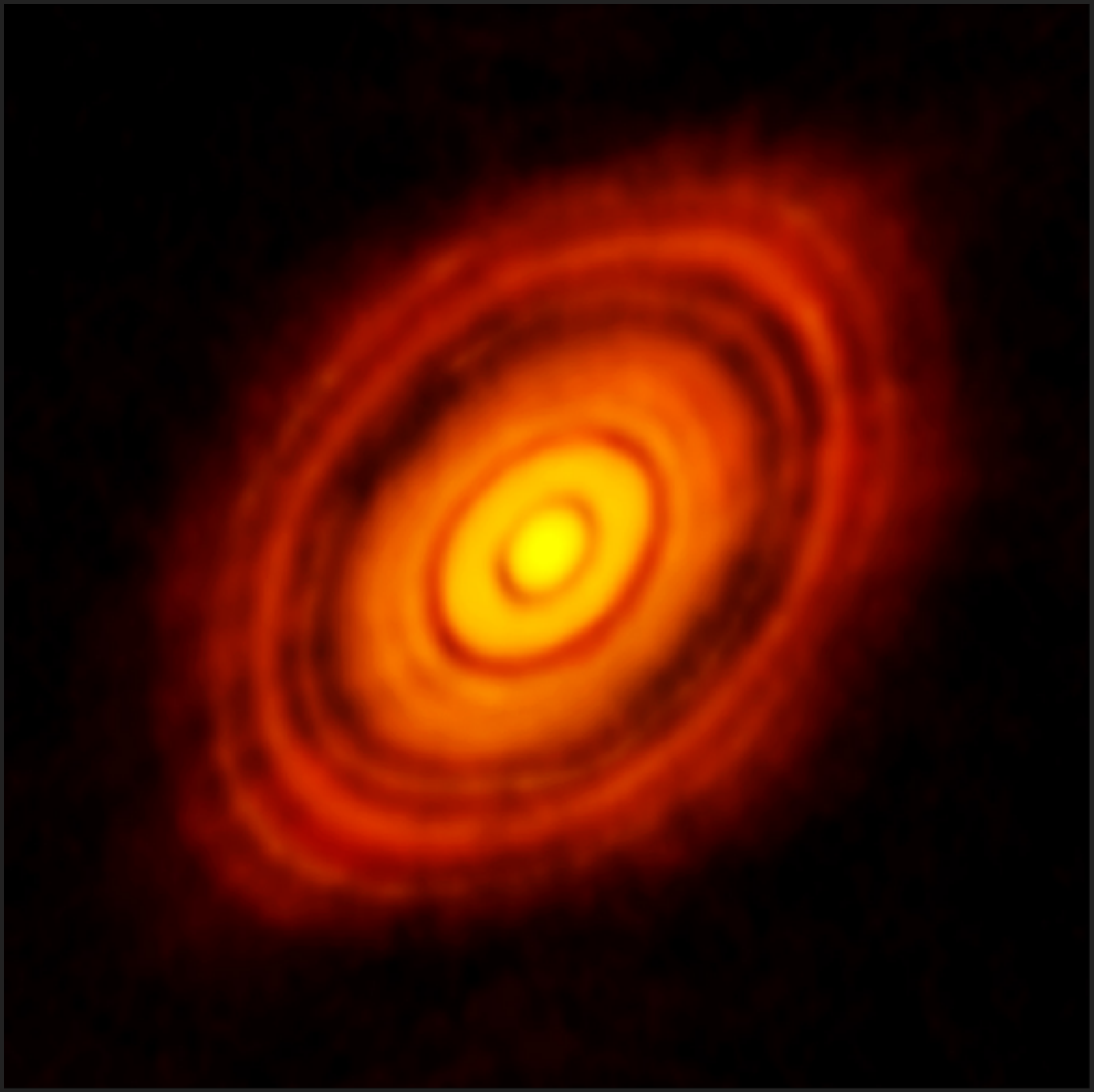
Formation of gaps betrays presence of forming planets - transitional disks

TRANSITIONAL DISK OBSERVED VIA DIRECT IMAGING



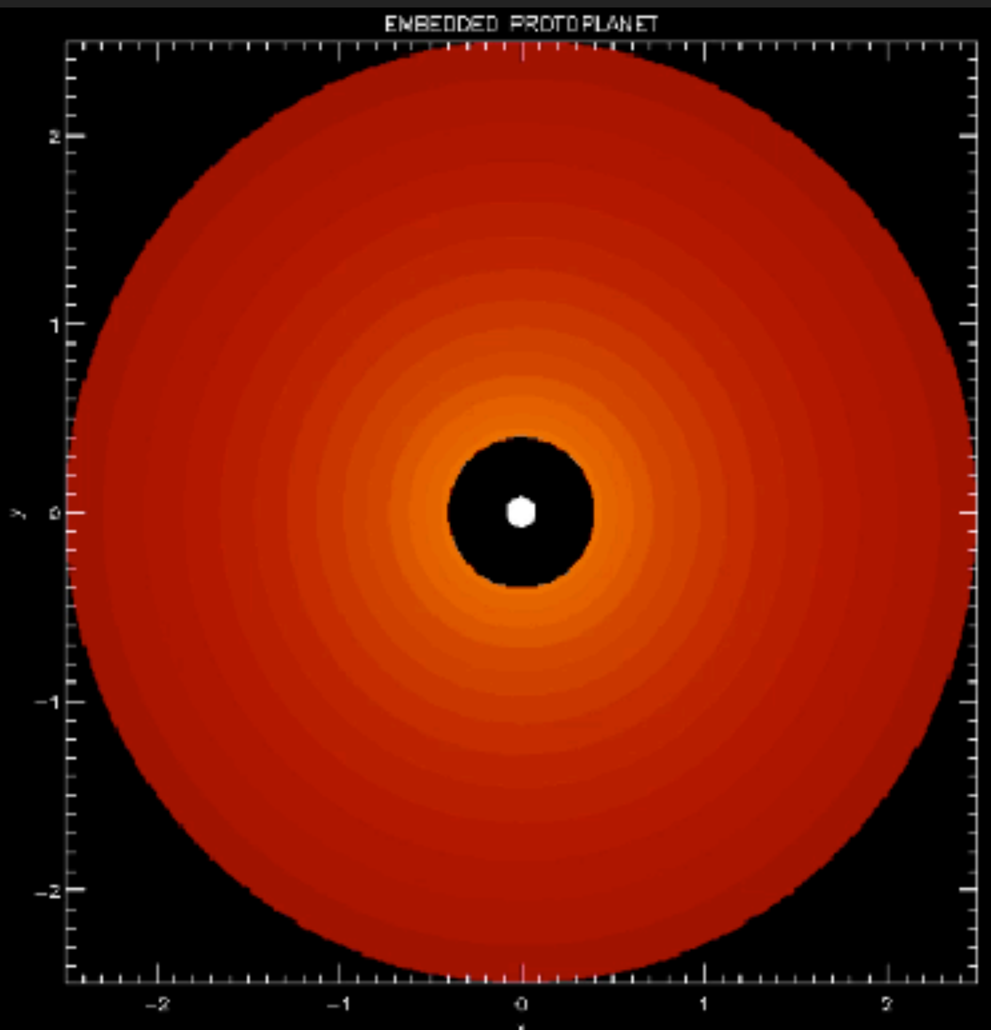
HD 169142 - Coronagraph NIR image, Subaru, HICIAO (MOMOSE et al. 2016)

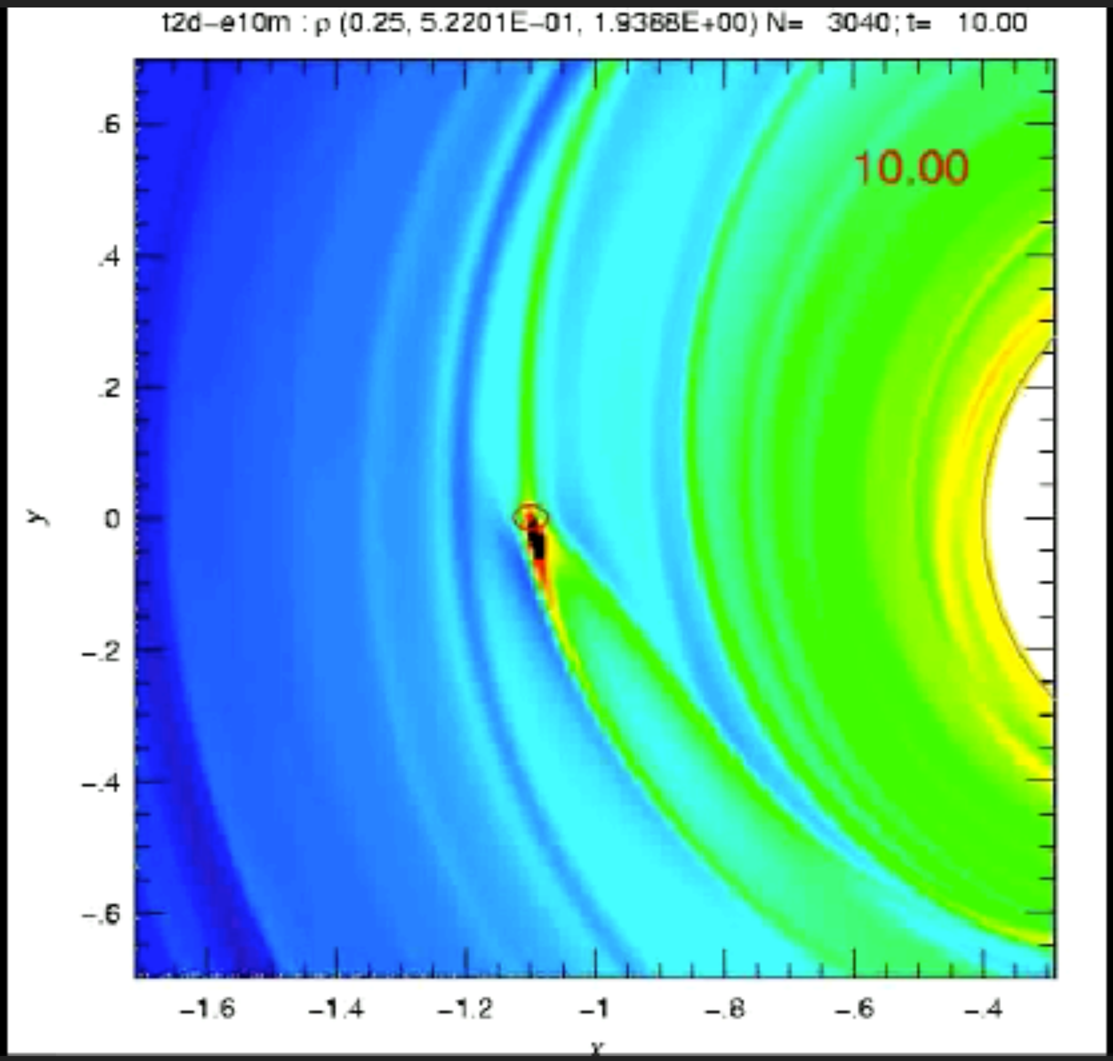
TRANSITIONAL DISK OBSERVED VIA DIRECT IMAGING



HL Tau (ALMA sub-mm image)

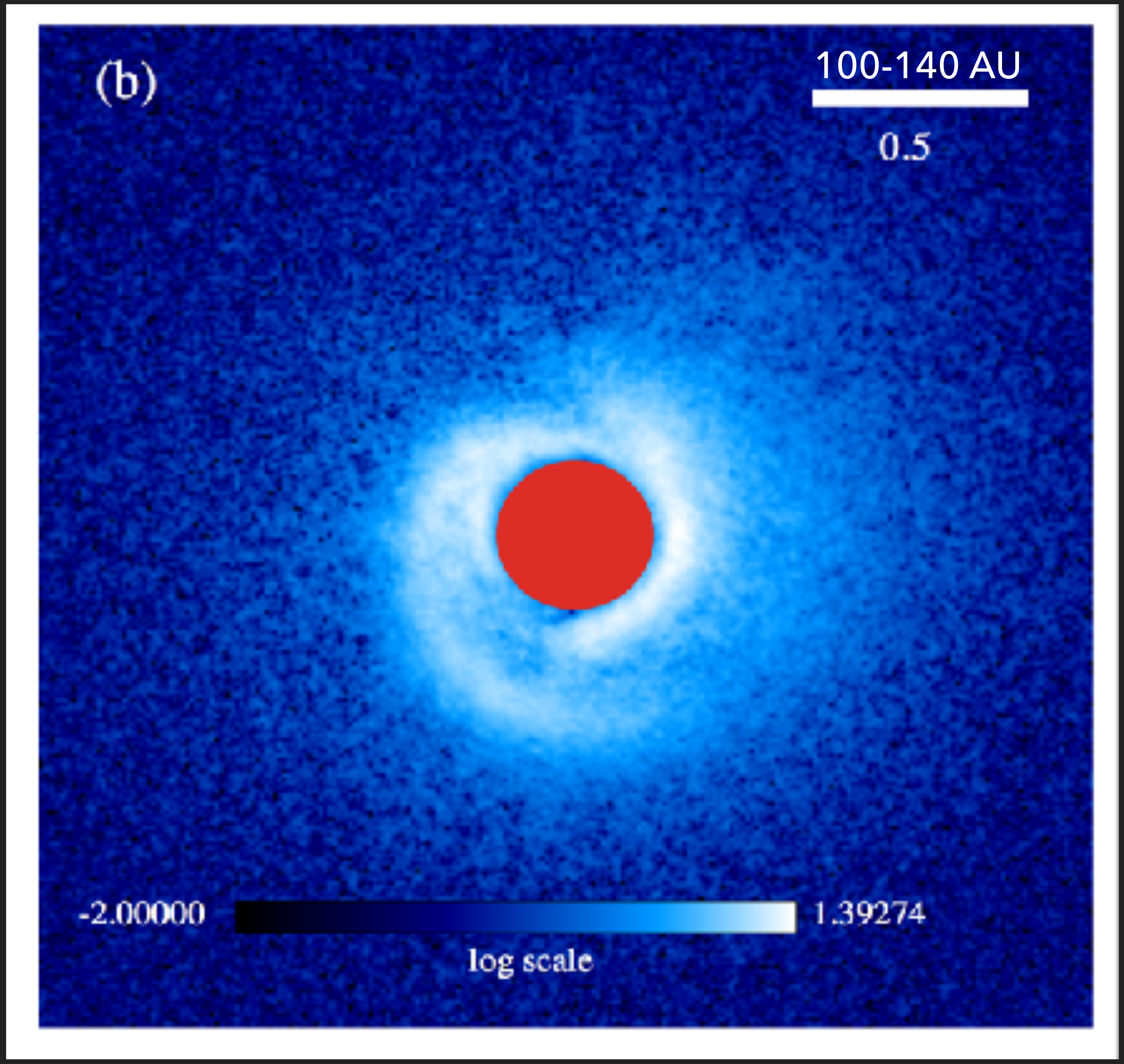
NOT JUST GAPS…



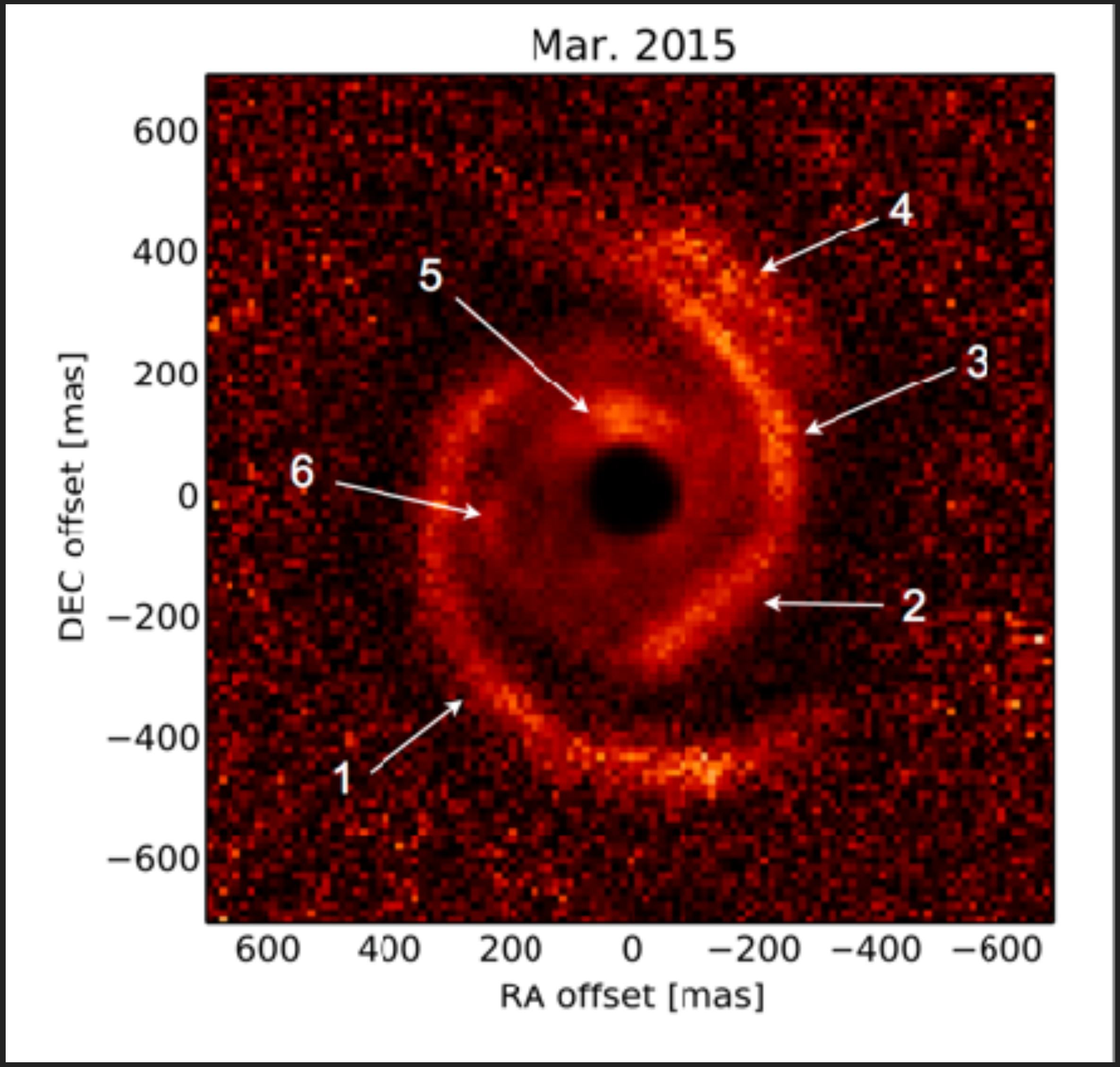


Models from Kley and Nelson, ARA&A 2012

NOT JUST GAPS…



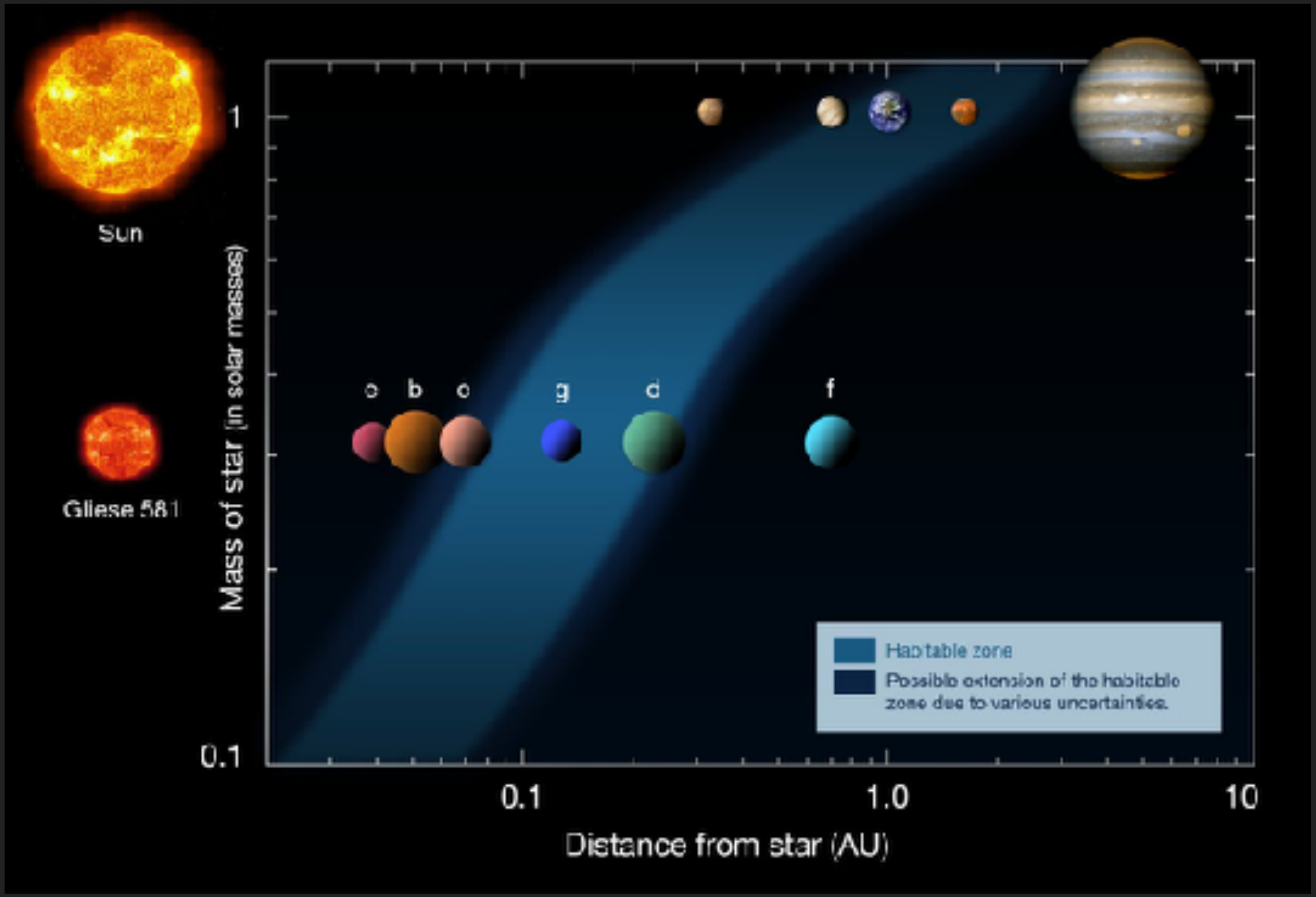
MWC758 - Subaru/HICIAO, Grady et al, 2013



MWC758 - VLT/SPHERE Coronagraphic image, ESO

TOWARDS THE HABITABLE ZONE

- Area of key interest - where we can find habitable planets, and… LIFE!
    - Area (range of orbits) where a planet surface can have liquid water
    - Hard to image - close to the star (resolution / contrast problem)
    - Depends on distance, stellar luminosity



1 AU at 100 PC is 10 mas!

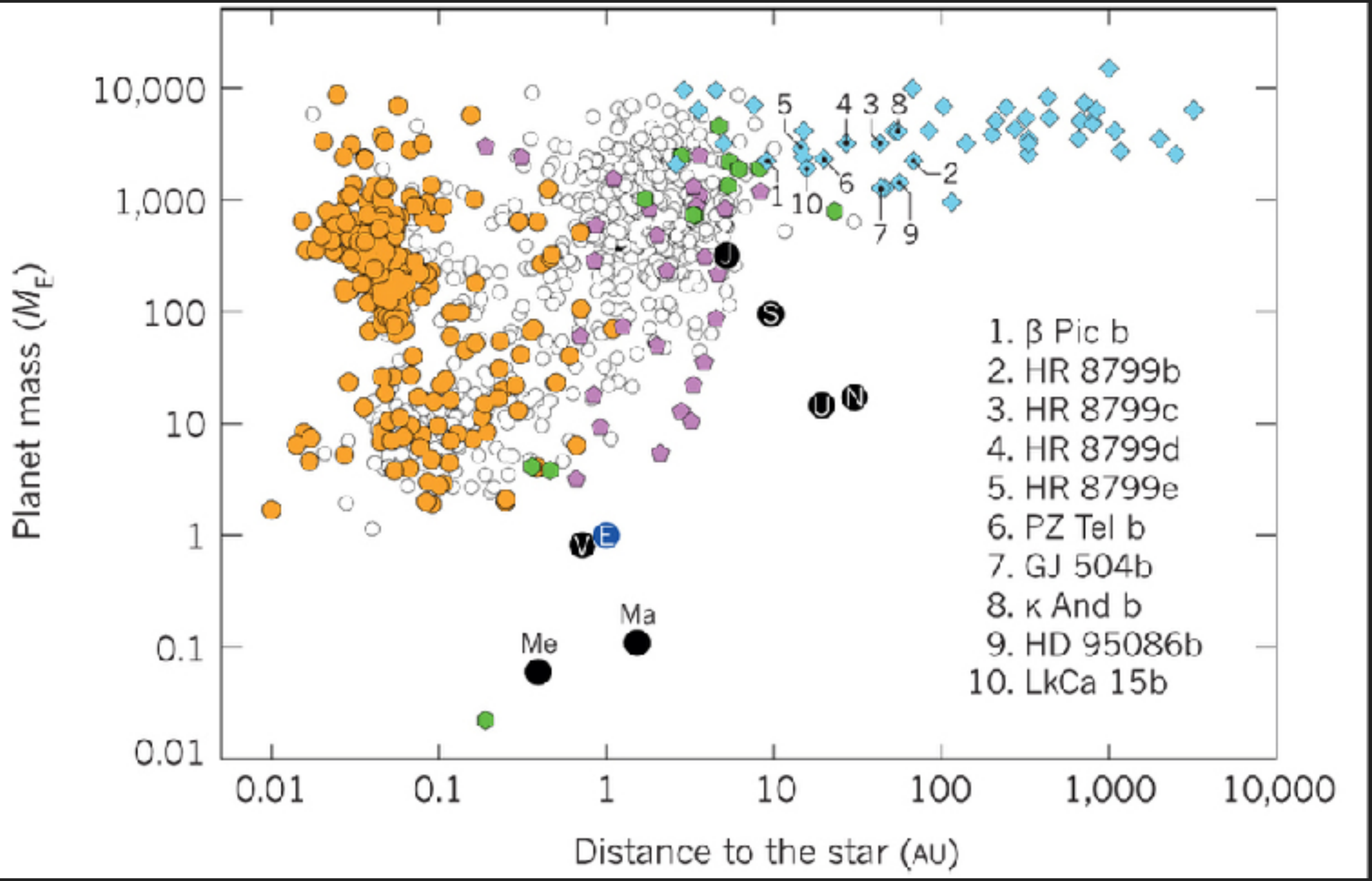
HD 106906AB - VLT/SPHERE

DIRECT IMAGING OF 'FINISHED' EXOPLANETS – STORY SO FAR...

(Marois et al. 2008, 2010; Kalas et al. 2008; Lagrange et al. 2010; Kraus & Ireland 2012; Carson et al. 2013; Rameau et al. 2013; Kuzuhara et al. 2013; Currie et al. 2014a; Quanz et al. 2013/Currie et al. 2014b; Currie et al. 2015b)

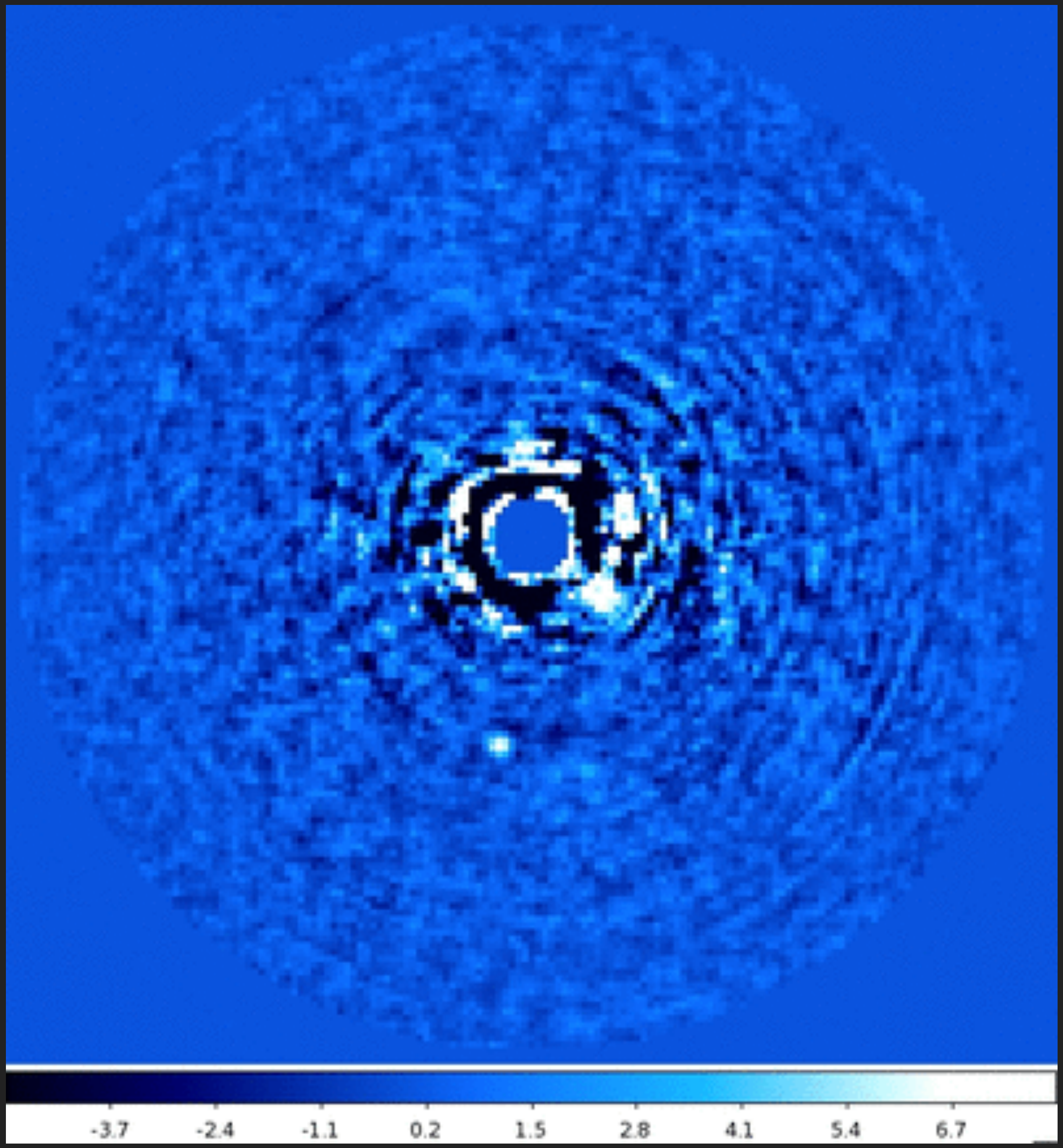
WHY DIRECTLY IMAGE EXOPLANETS?

- New region of 'parameter space' (meh)

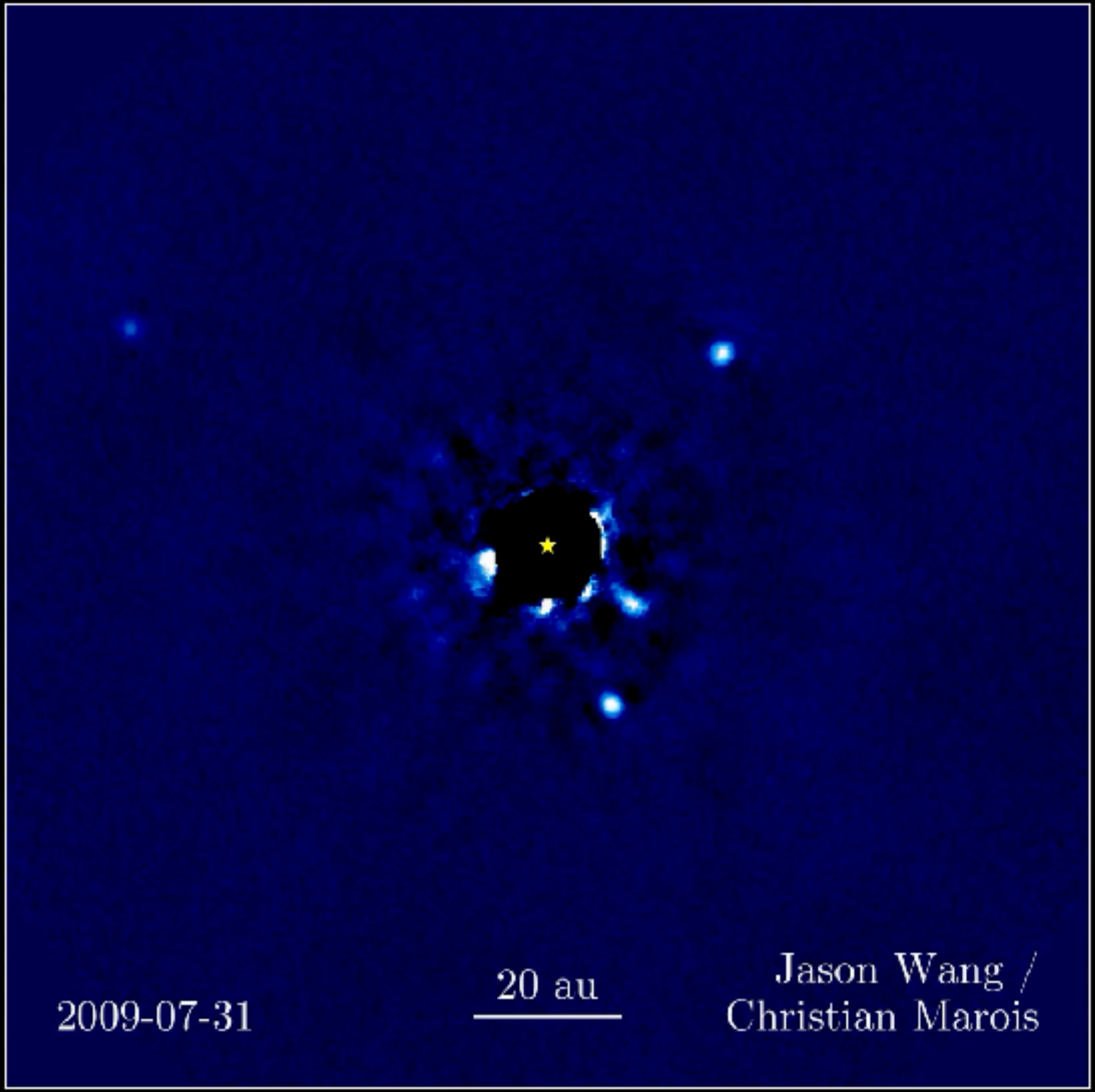


WHY DIRECTLY IMAGE EXOPLANETS?

- Doesn't depend on other biases, e.g. transit probability
- Unambiguously measure orbital parameters –> Mass
- Characterise exoplanets themselves!

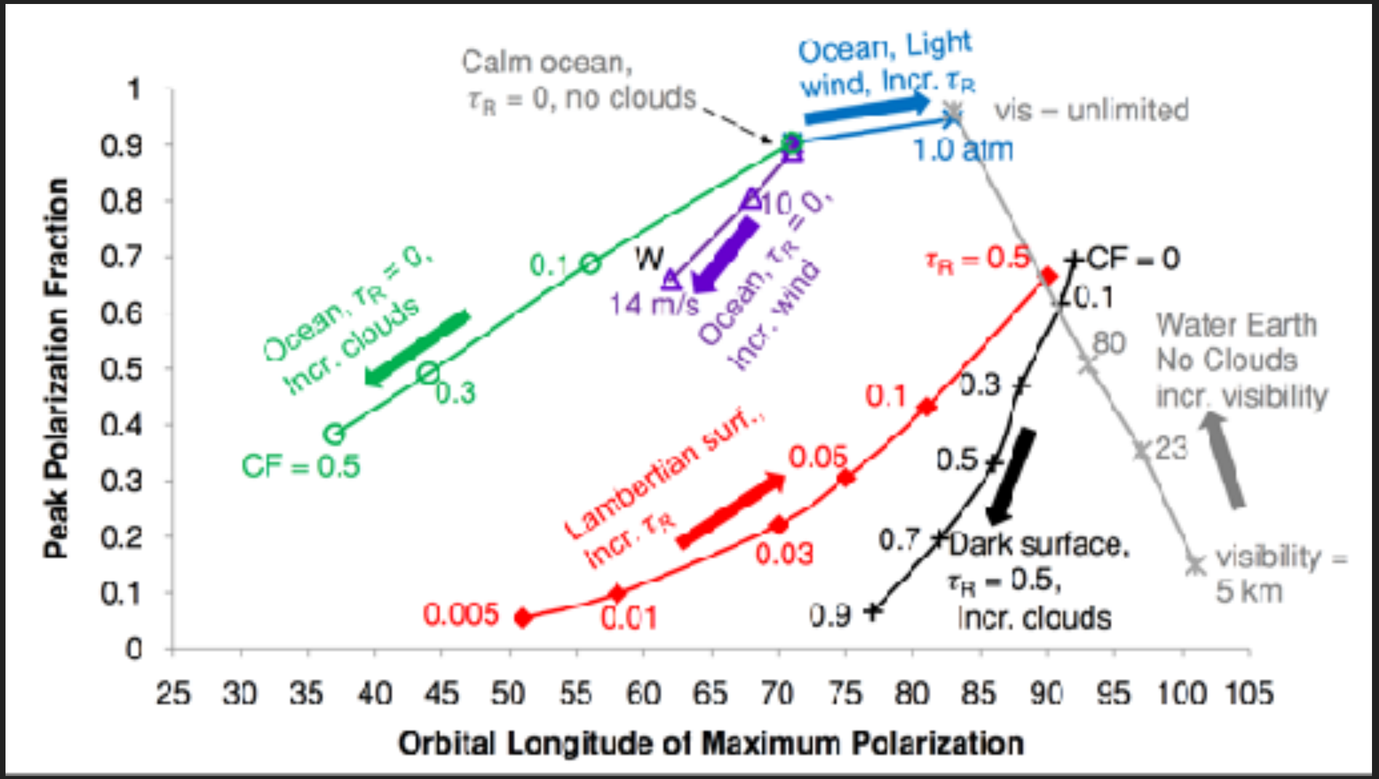


WHY DIRECTLY IMAGE EXOPLANETS?



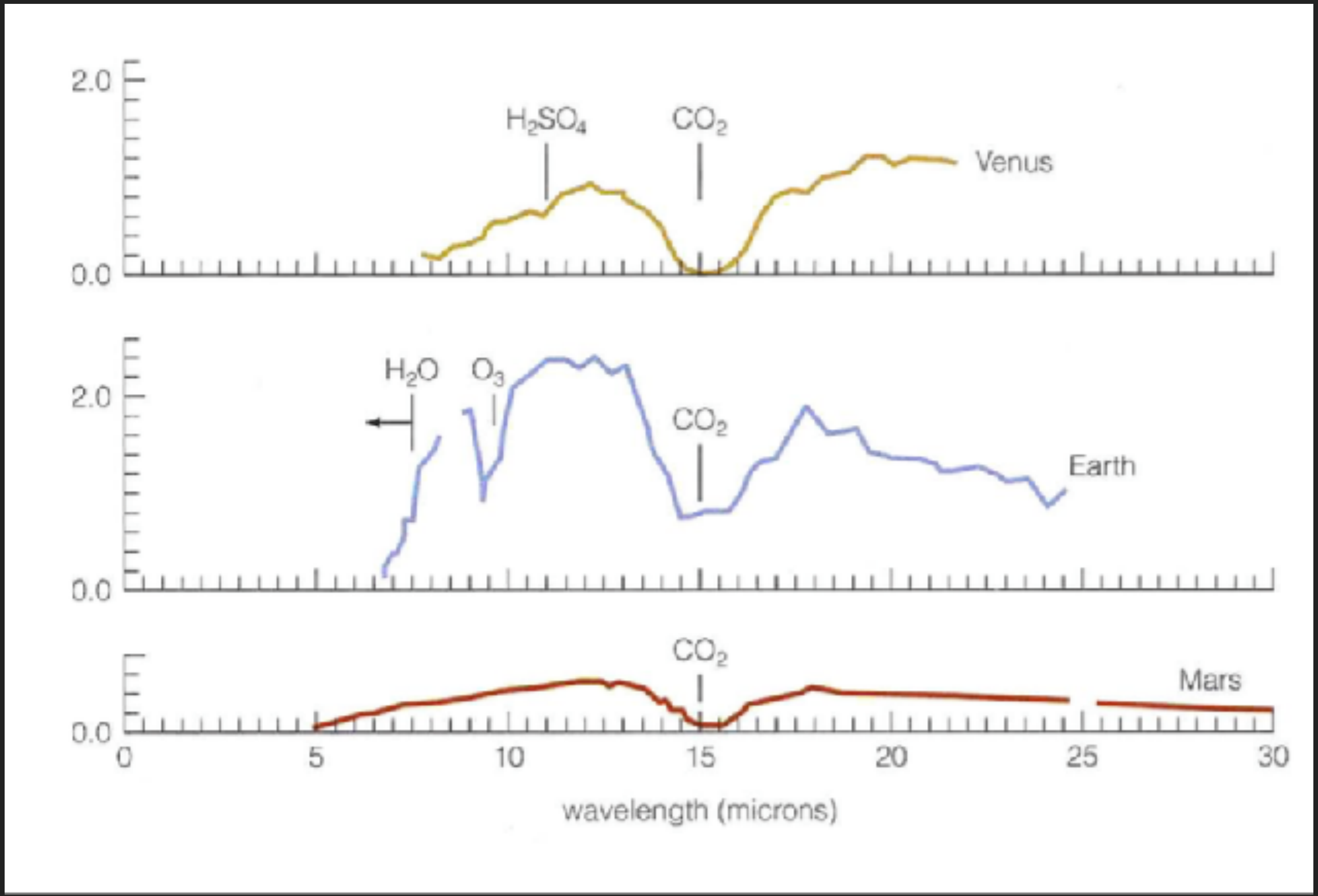
EXOPLANET CHARACTERISATION

- Spectra of reflected / scattered starlight
  - Atmospheric composition
  - Weather (storms? clouds?)
  - Surface material (rock? ice?) water?
- Polarisation of reflected starlight
  - Surface features
  - …vegetation…?



BIOSIGNATURES ON EXOPLANETS

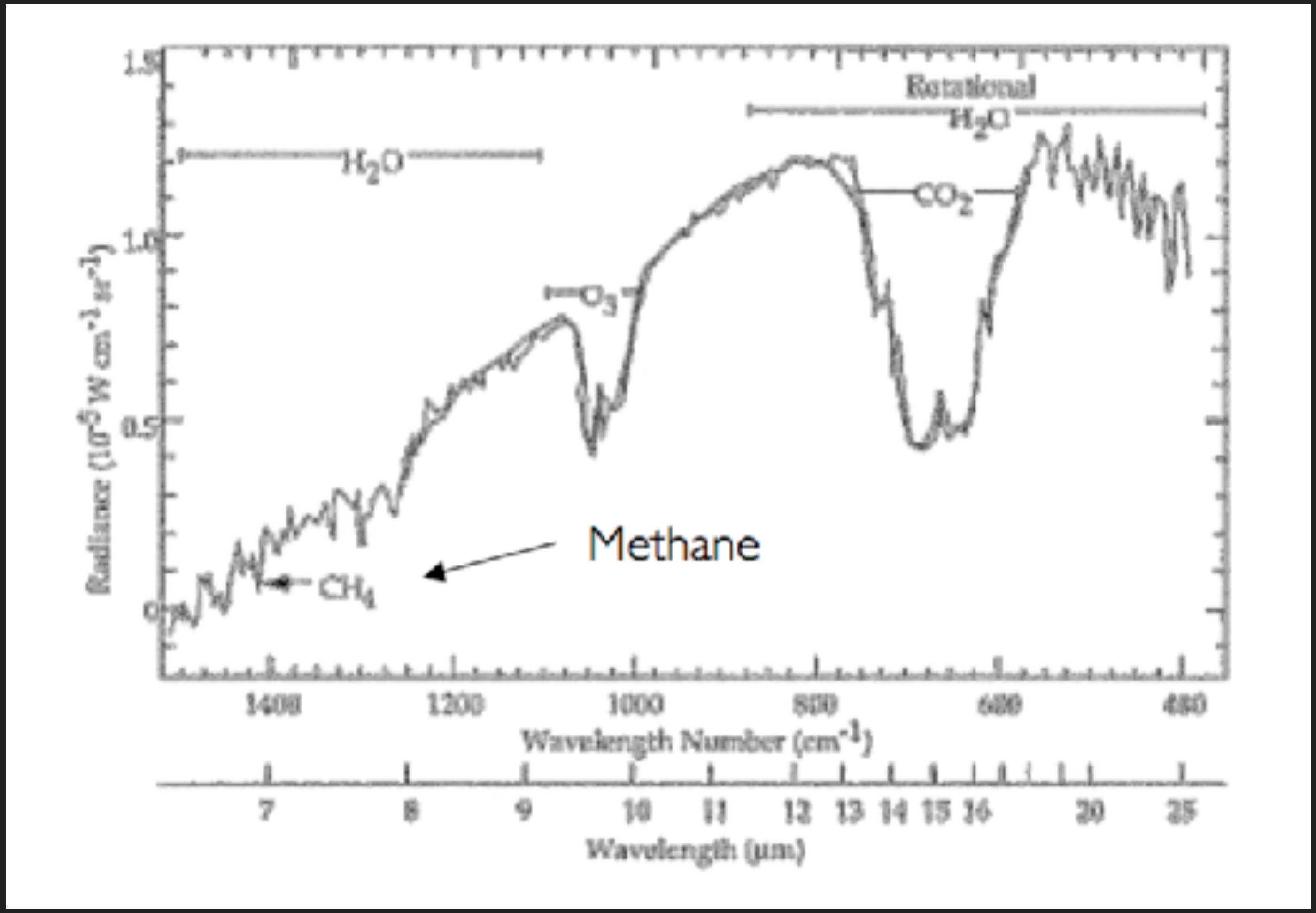
- Detection of life!
  - Atmospheric spectra



from Bennet & Shostak, 2012

BIOSIGNATURES ON EXOPLANETS

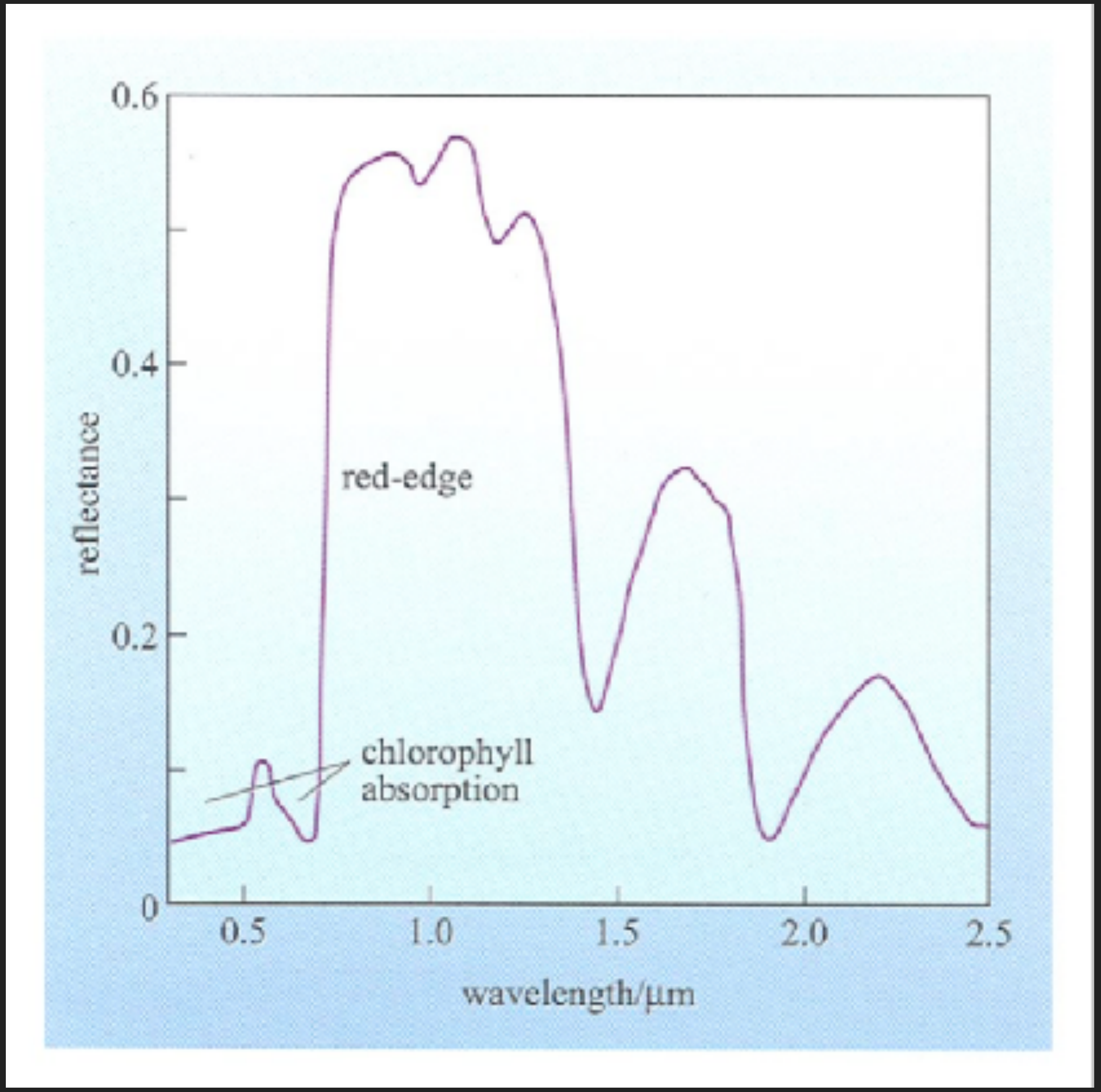
- Detection of life!
  - Atmospheric spectra
  - Look for signs the system is far from chemical equilibrium -> needs life to keep it there



http://www.as.utexas.edu/astronomy/education/fall08/scalo/secure/309l_sep25_plandet.pdf

BIOSIGNATURES ON EXOPLANETS

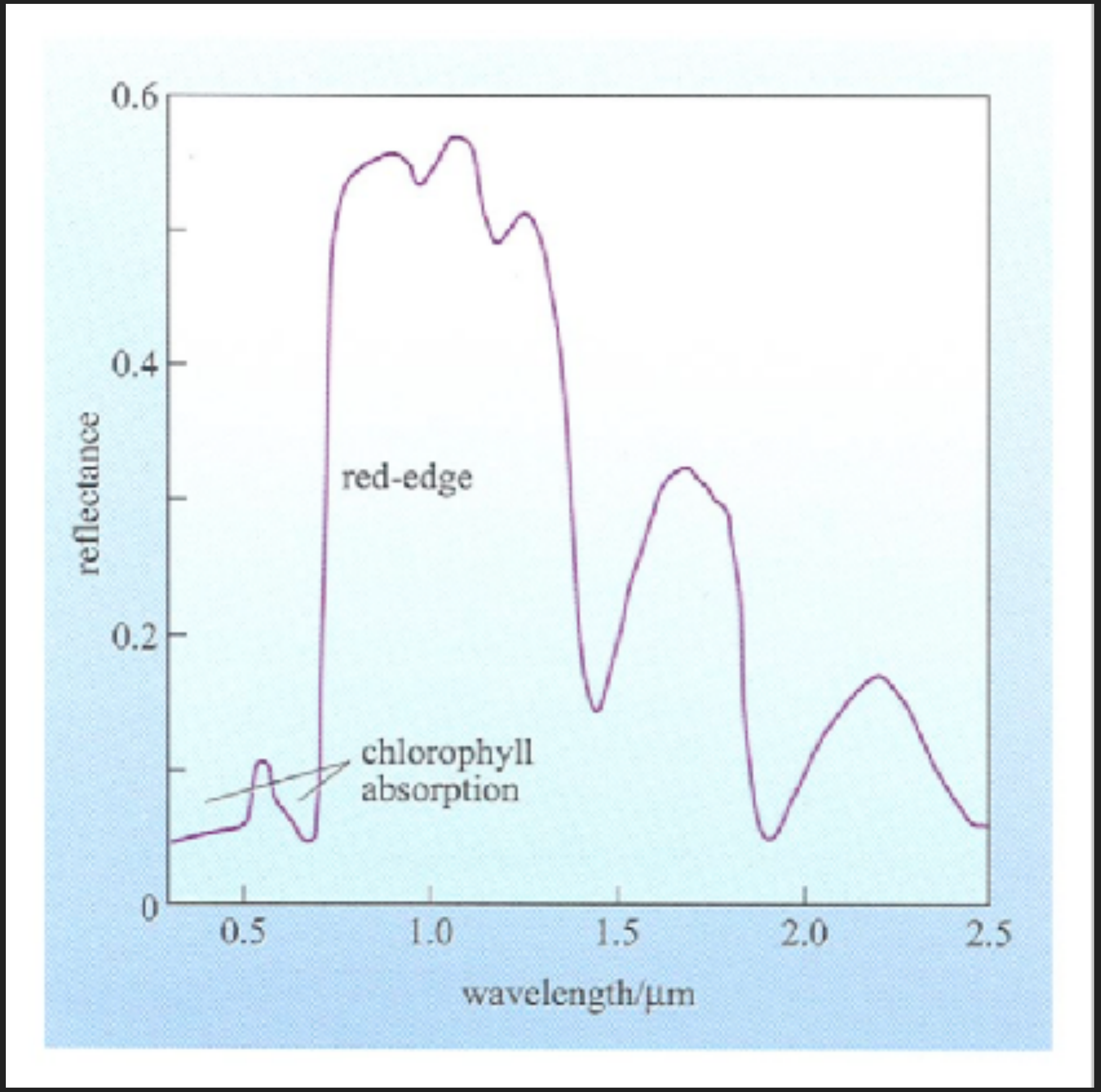
- Detection of life!
  - Atmospheric spectra
  - Look for signs the system is far from chemical equilibrium -> needs life to keep it there
  - Surface spectra - e.g. 'red edge' from vegetation



from Bennet & Shostak, 2012

BIOSIGNATURES ON EXOPLANETS

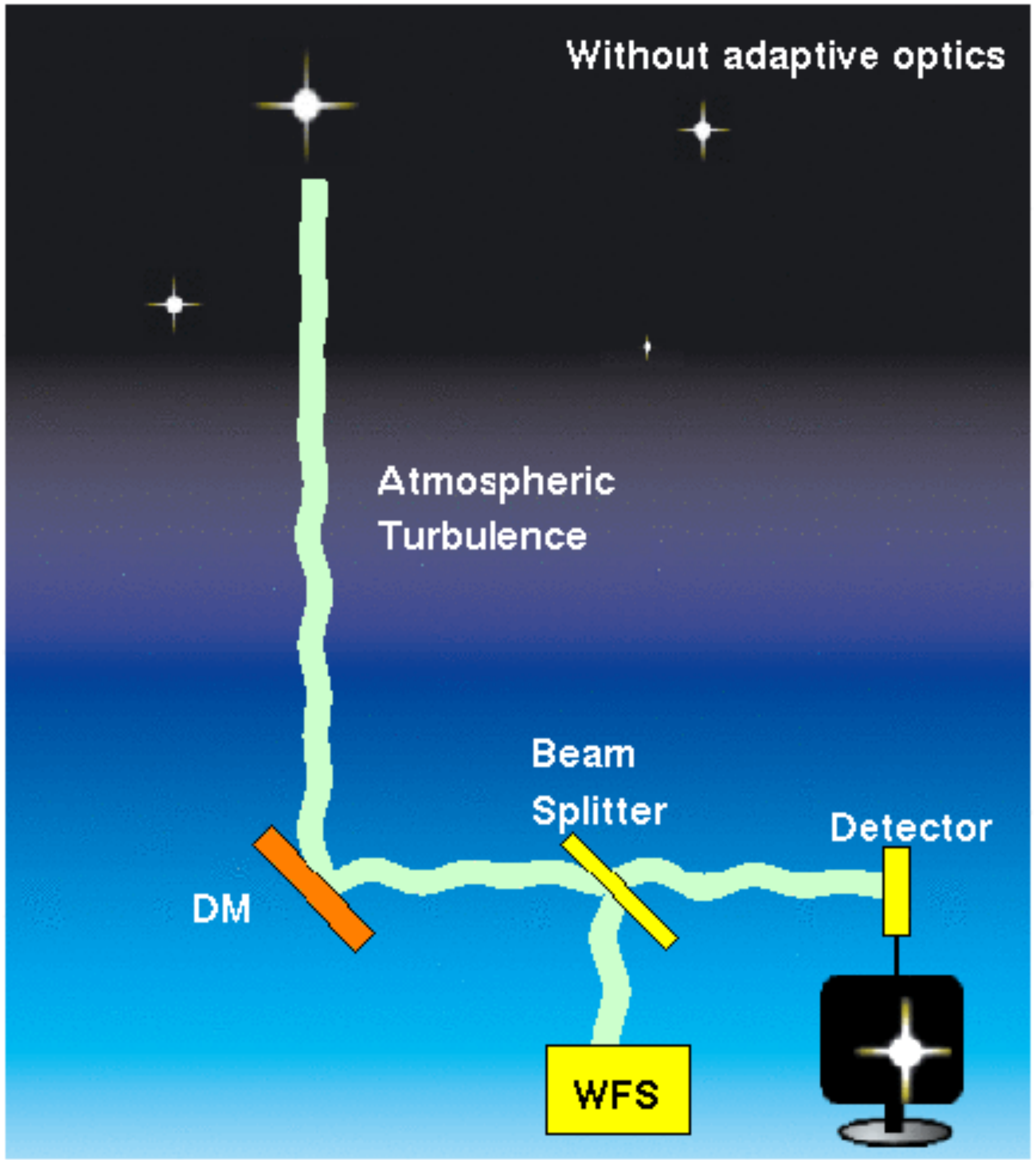
- Detection of life!
  - Atmospheric spectra
  - Look for signs the system is far from chemical equilibrium -> needs life to keep it there
  - Surface spectra - e.g. 'red edge' from vegetation
  - Reflected light polarisation and intensity curves



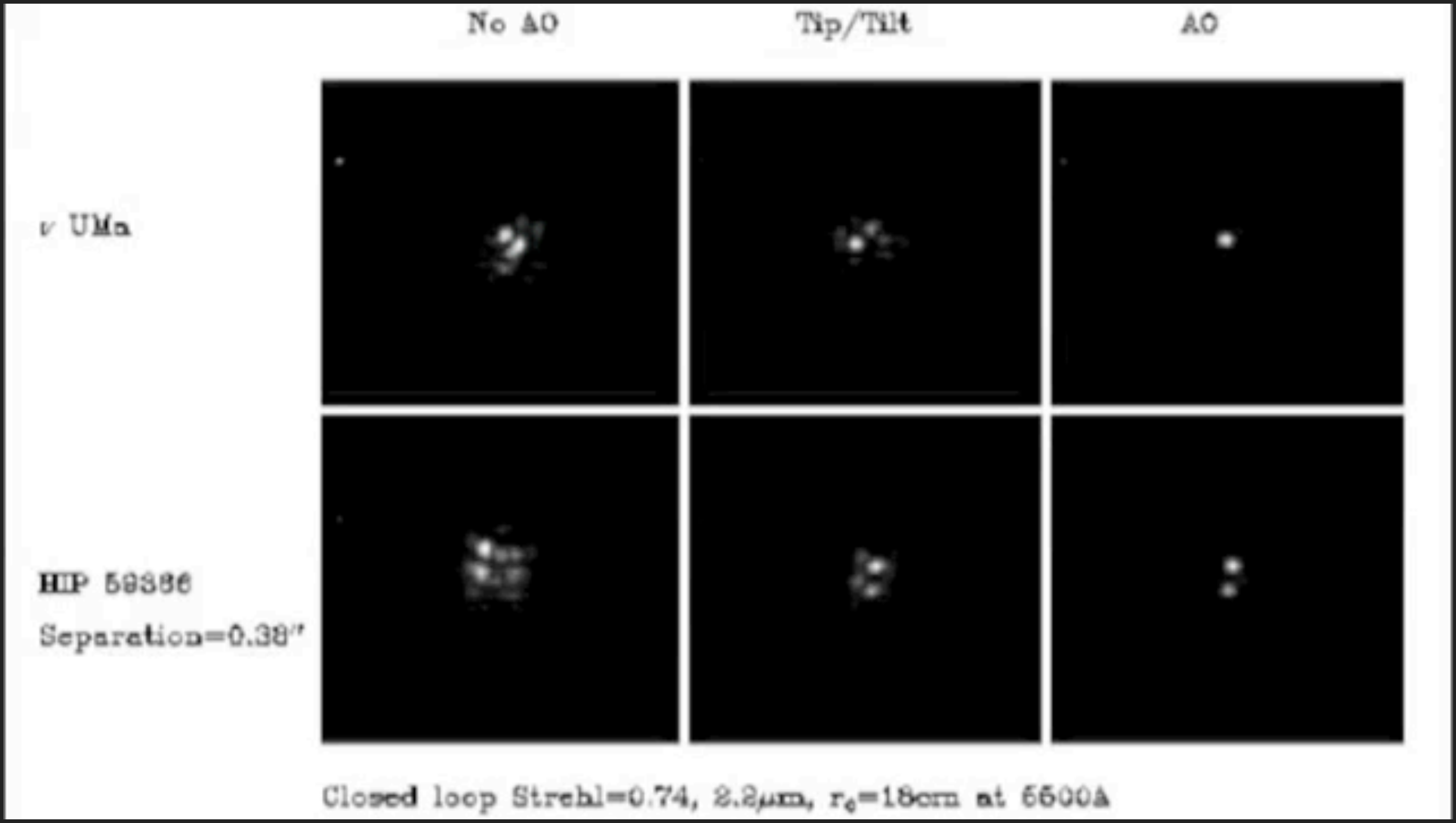
from Bennet & Shostak, 2012

SO HOW DO YOU DO IT?

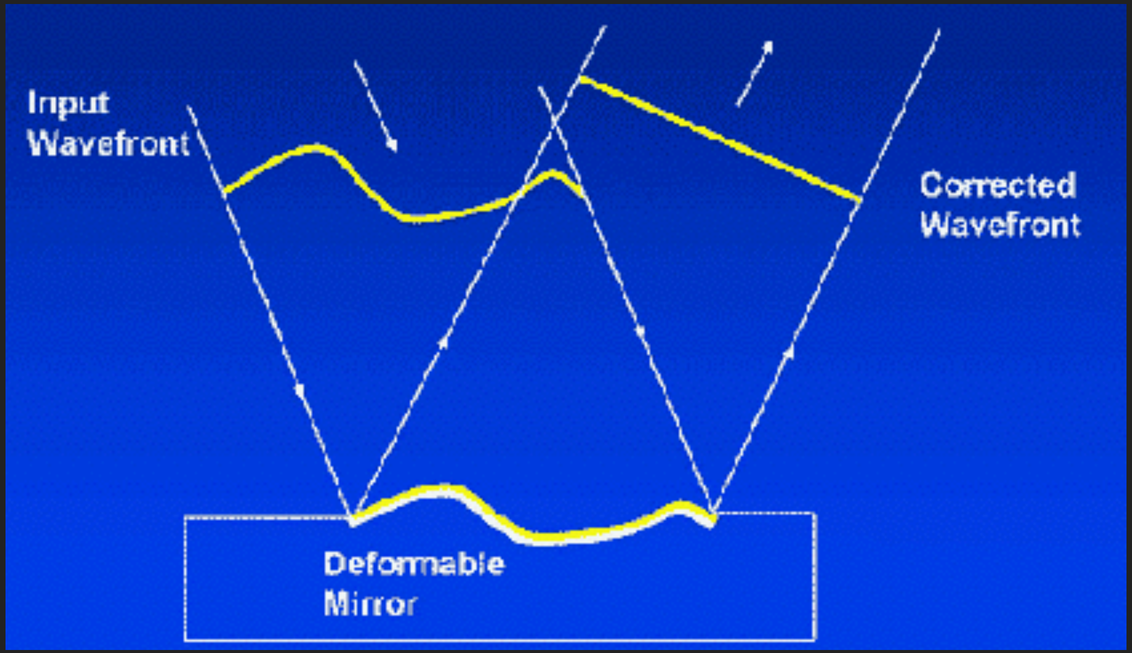
- 1) Adaptive optics
  - Try and fix the seeing!
  - Measure the changing distortions done to the light, and quickly un-do them
  - Very computationally and financially expensive…
  - Needs to measure wavefront, calculate correction and move mirror at ~1000 times /sec

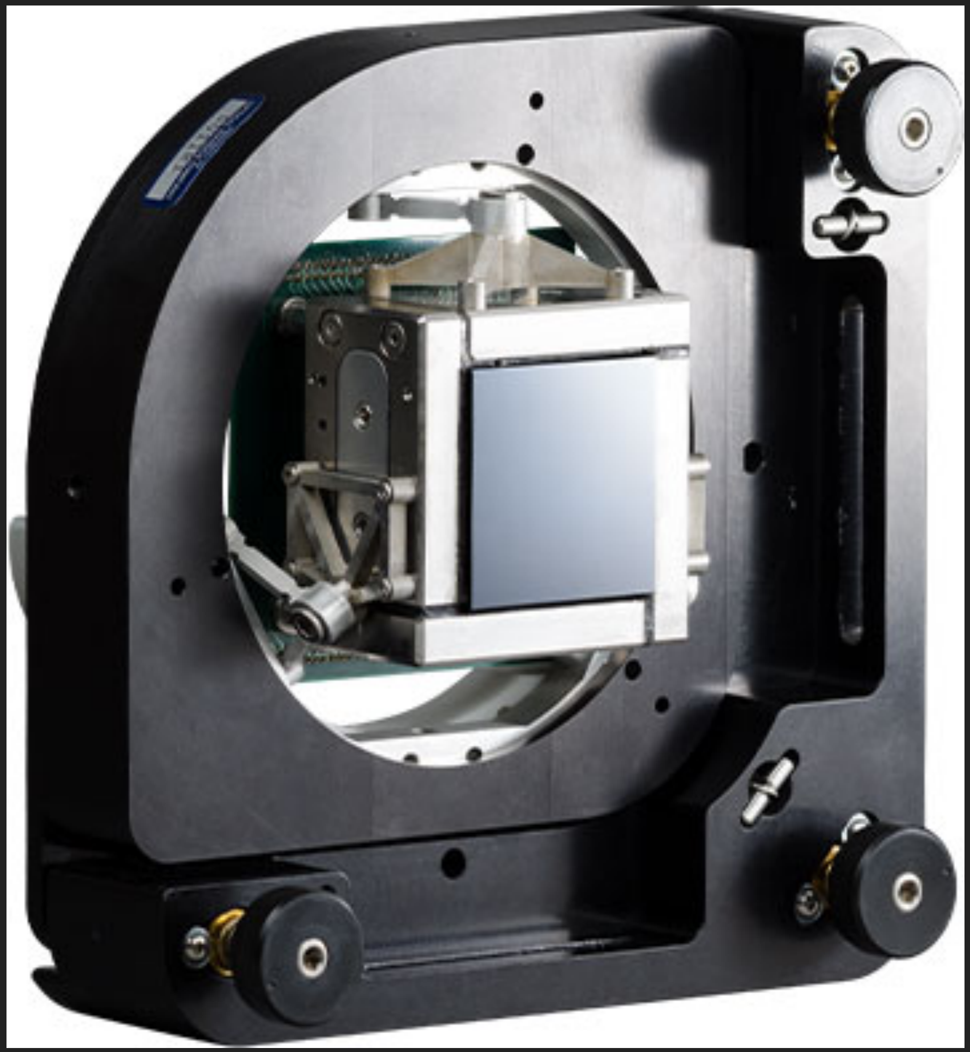


ADAPTIVE OPTICS

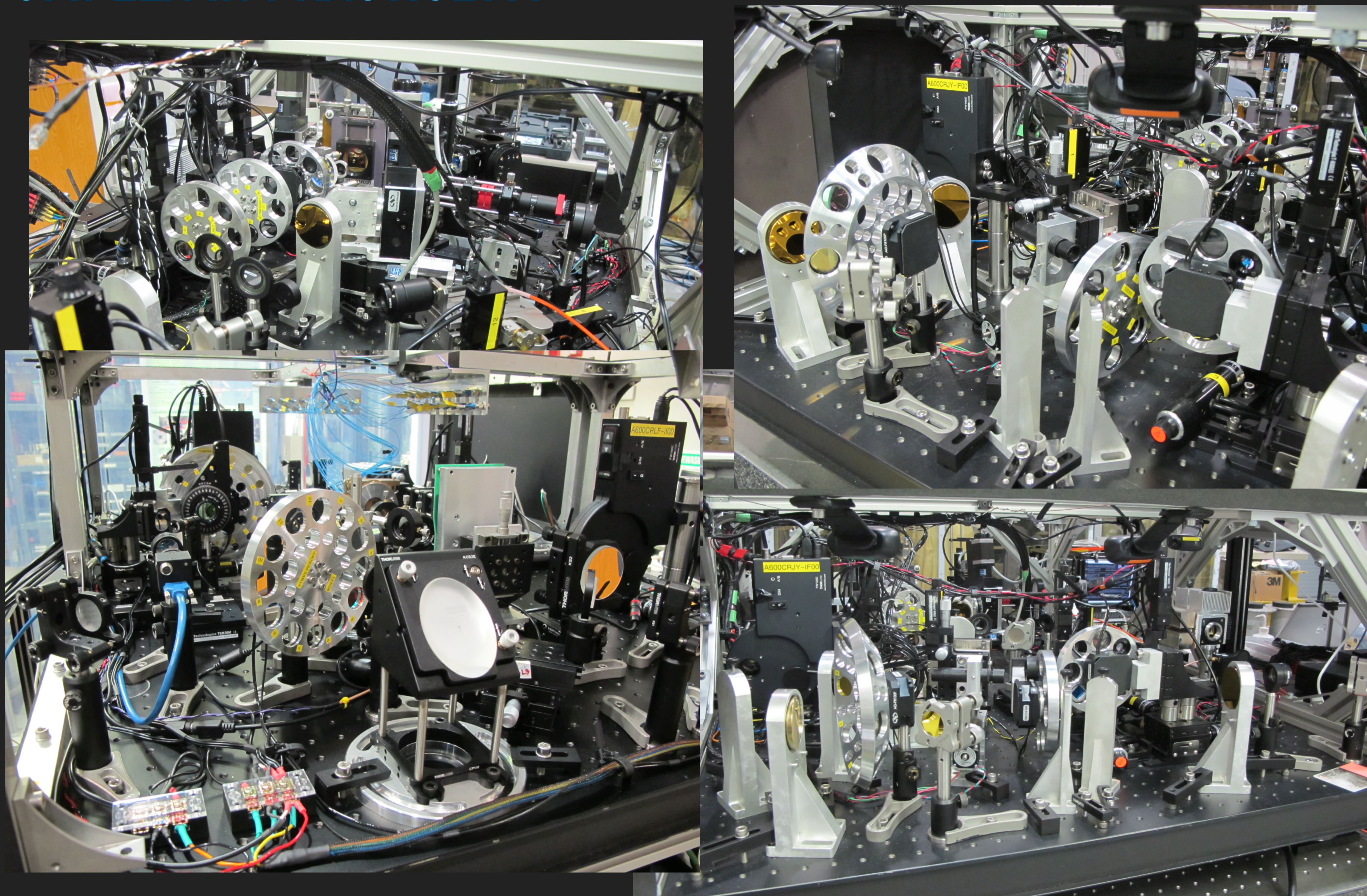


ADAPTIVE OPTICS –DEFORMABLE MIRROR



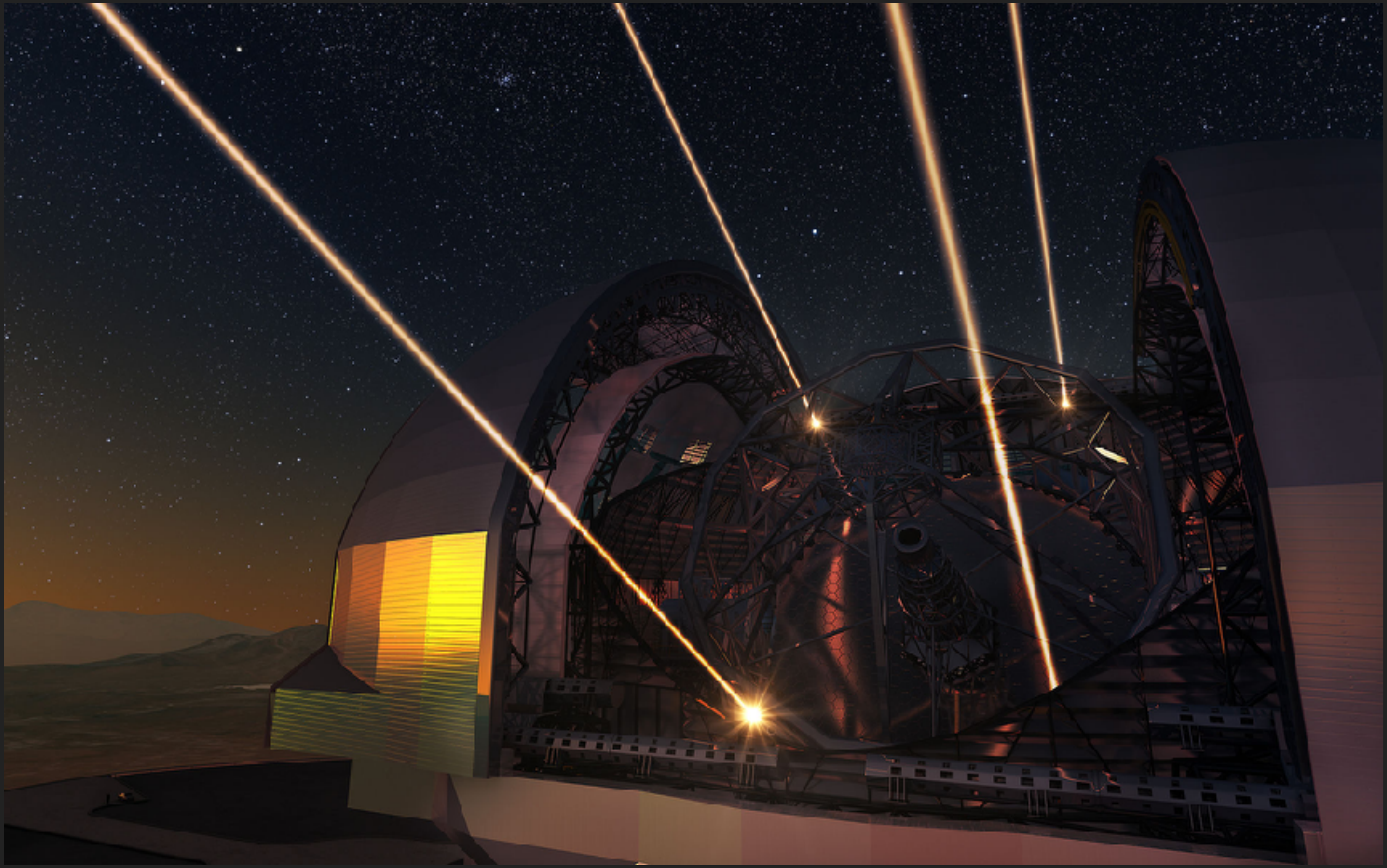


COMPLEX IN PRACTICE…



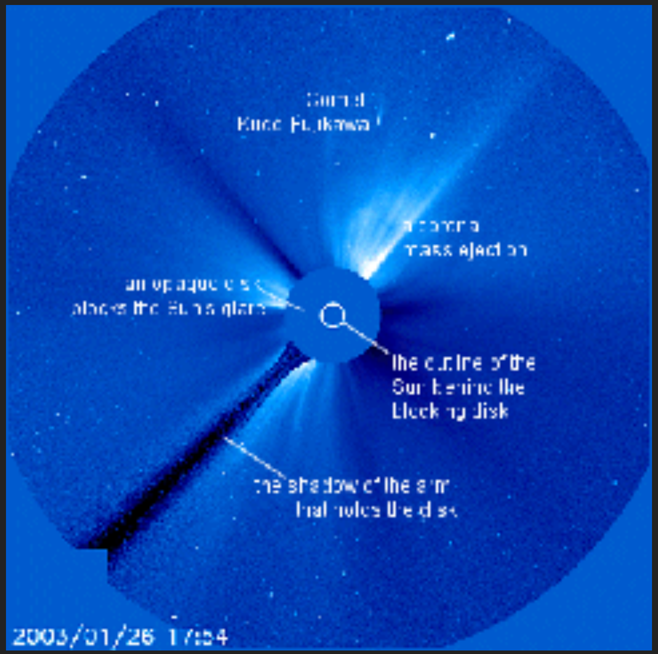
ADAPTIVE OPTICS - LASER GUIDE STAR

ADAPTIVE OPTICS - LASER GUIDE STAR

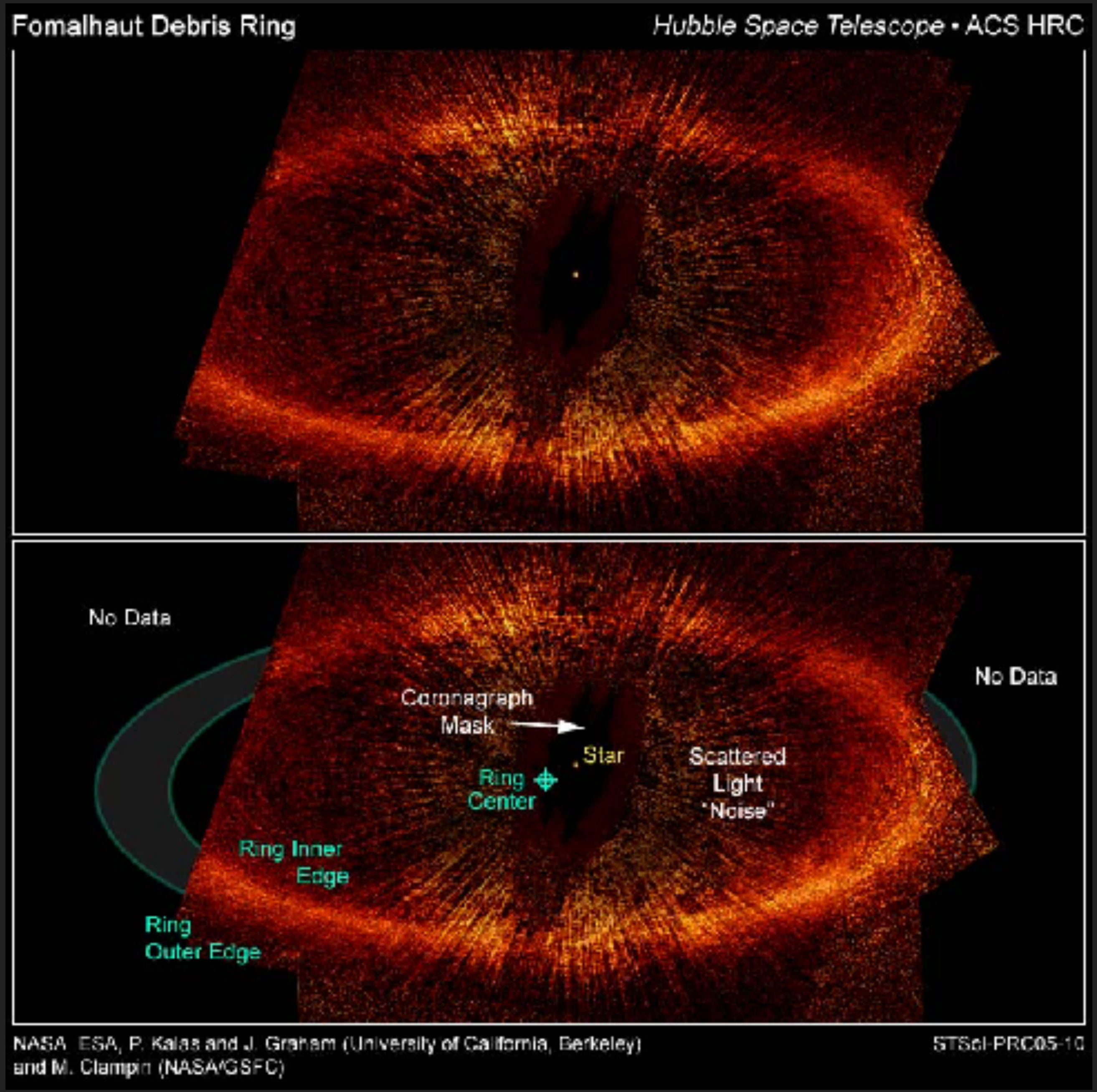


SO HOW DO YOU DO IT?

- 2) Coronagraphs
  - Try and fix the contrast problem!
  - Simple idea - block the star
  - Place opaque dot at image plane of telescope

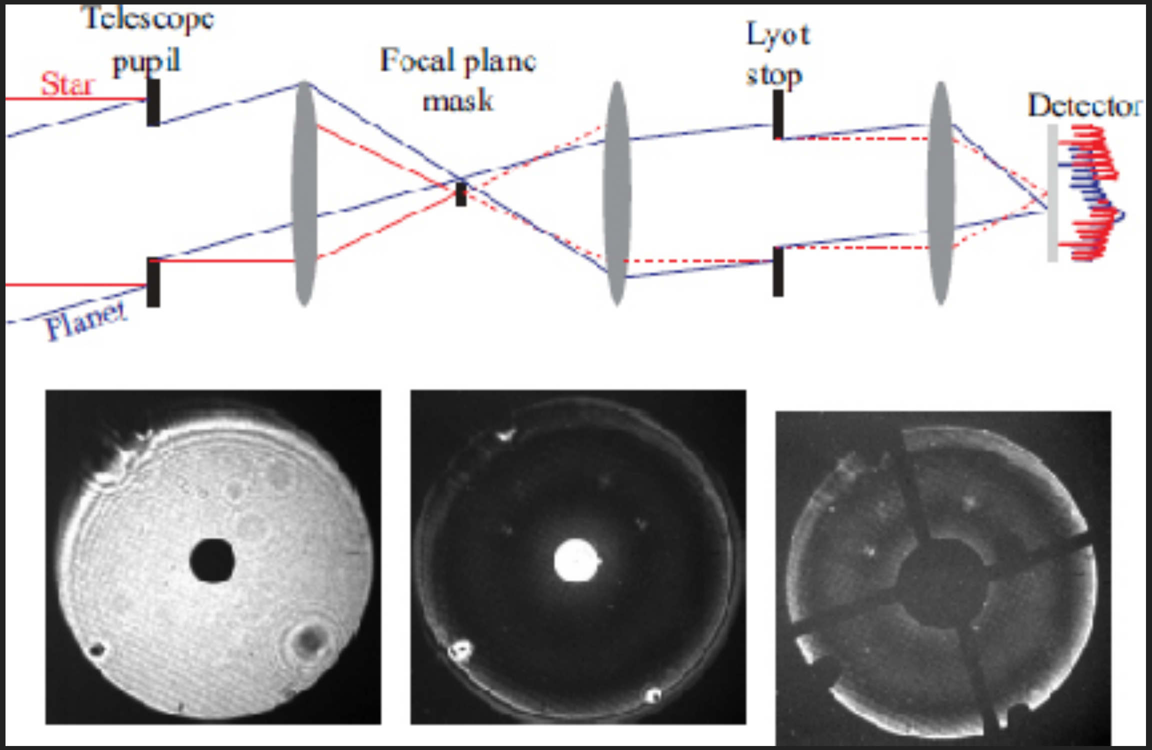


Originally used to study Sun's corona

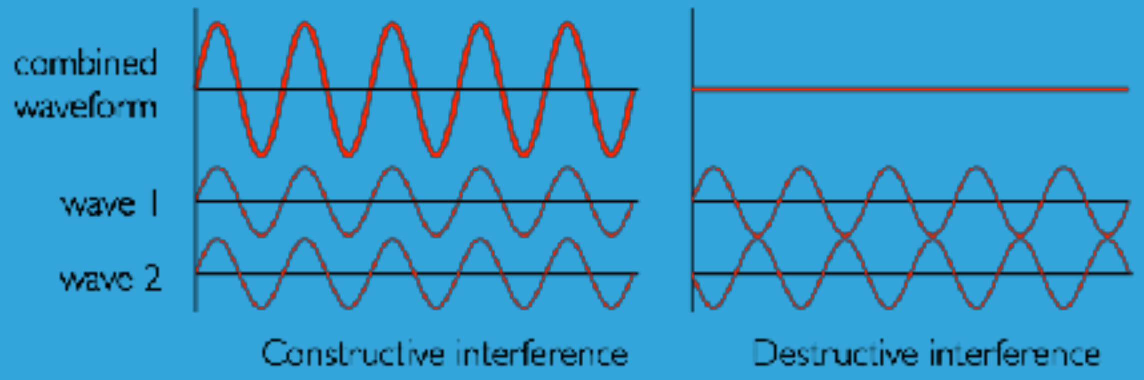


CORONAGRAPHS

- Tricky in practice
  - Performance characterised by Inner Working Angle (IWA)
  - Good NIR coronagraphs get to >100 mas from star
  - Used with AO to address the following challenges
- Challenges:
  - Star must be perfectly, stably positioned behind opaque spot, despite seeing
  - DIFFRACTION- An opaque spot won't actually stop light, rather it 'sprays' it out around the image
  - SPECKLE - Starlight isn't just where the star is - it is spread all over the image (seeing and diffraction in telescope)



http://www.nap.edu/read/21825/chapter/11

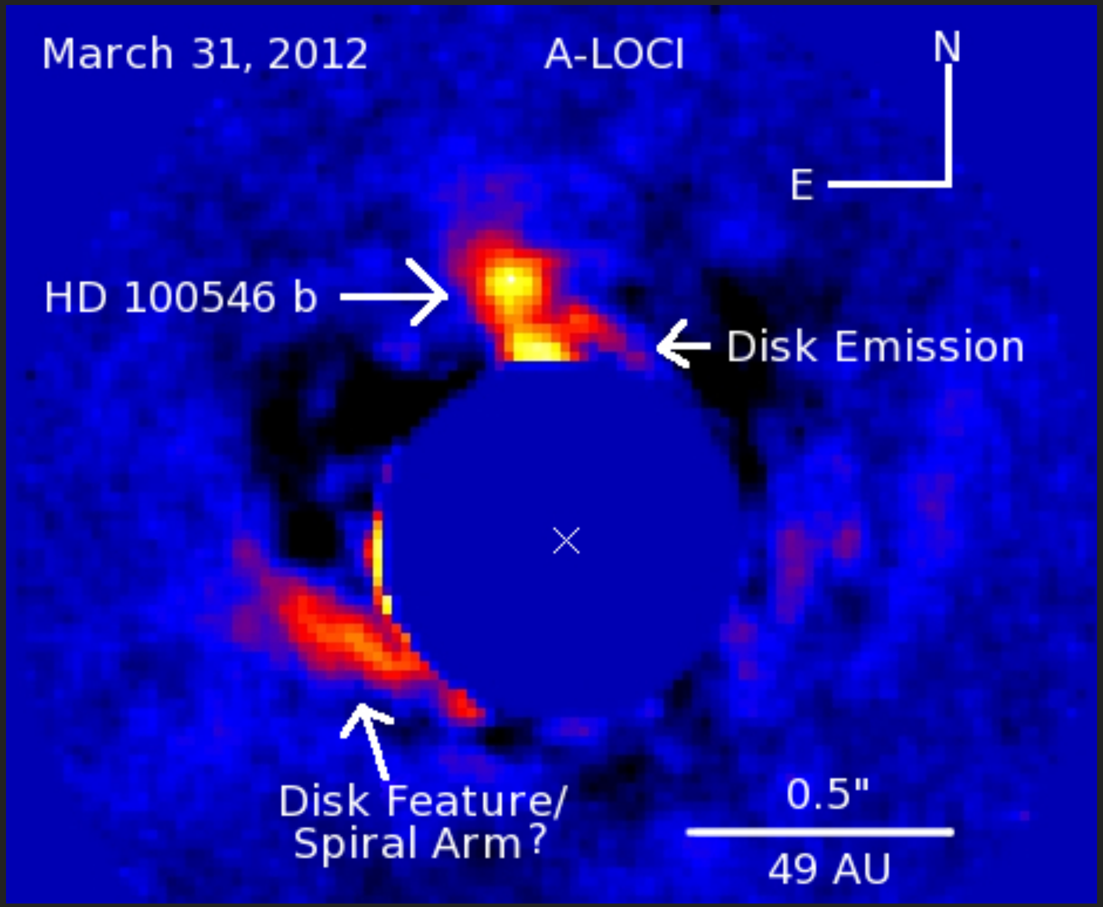


Either case (or a mix of both) can occur at different places in the image

SPECKLE:

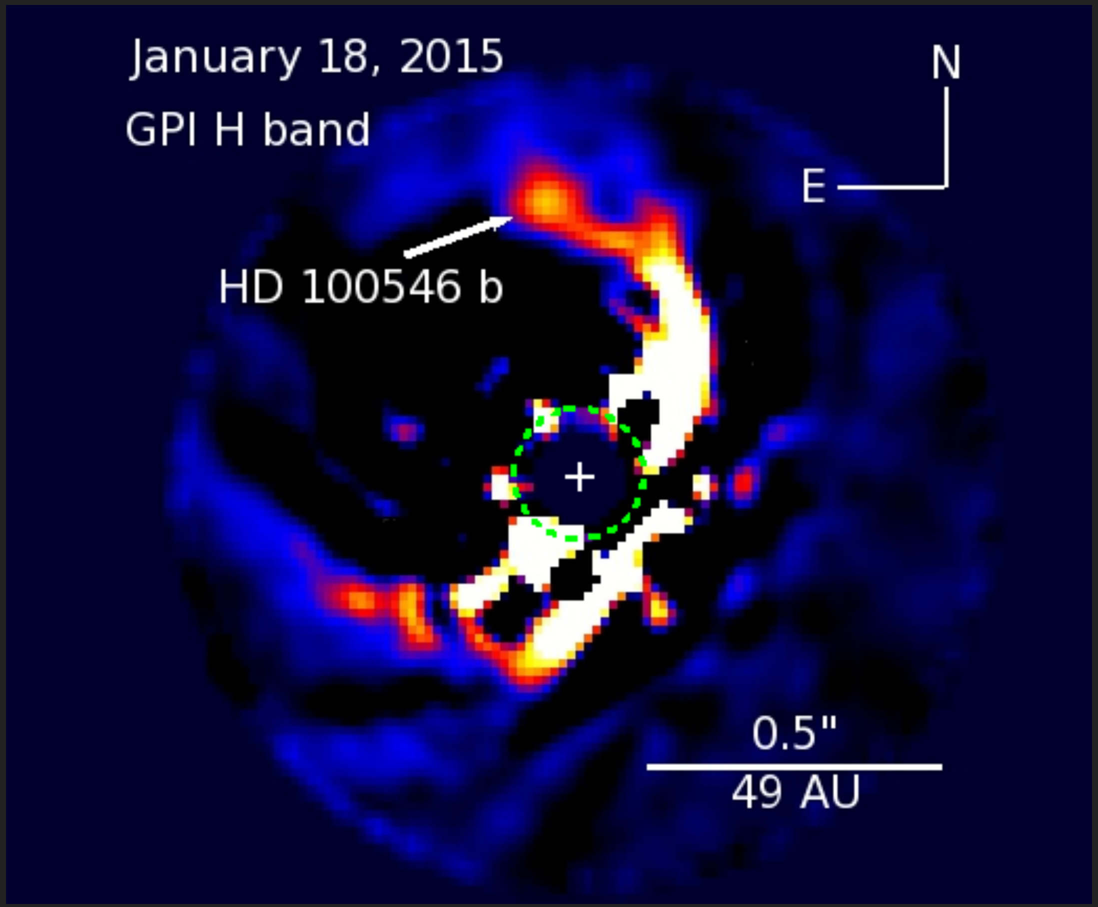
CORONAGRAPHS

HD 100546



Candidate protoplanet at ~ 47 AU with VLT/NaCo & Gemini/NICI

(Grady et al. 2005; Quanz et al. 2013; Currie et al. 2014; Quanz et al. 2015)



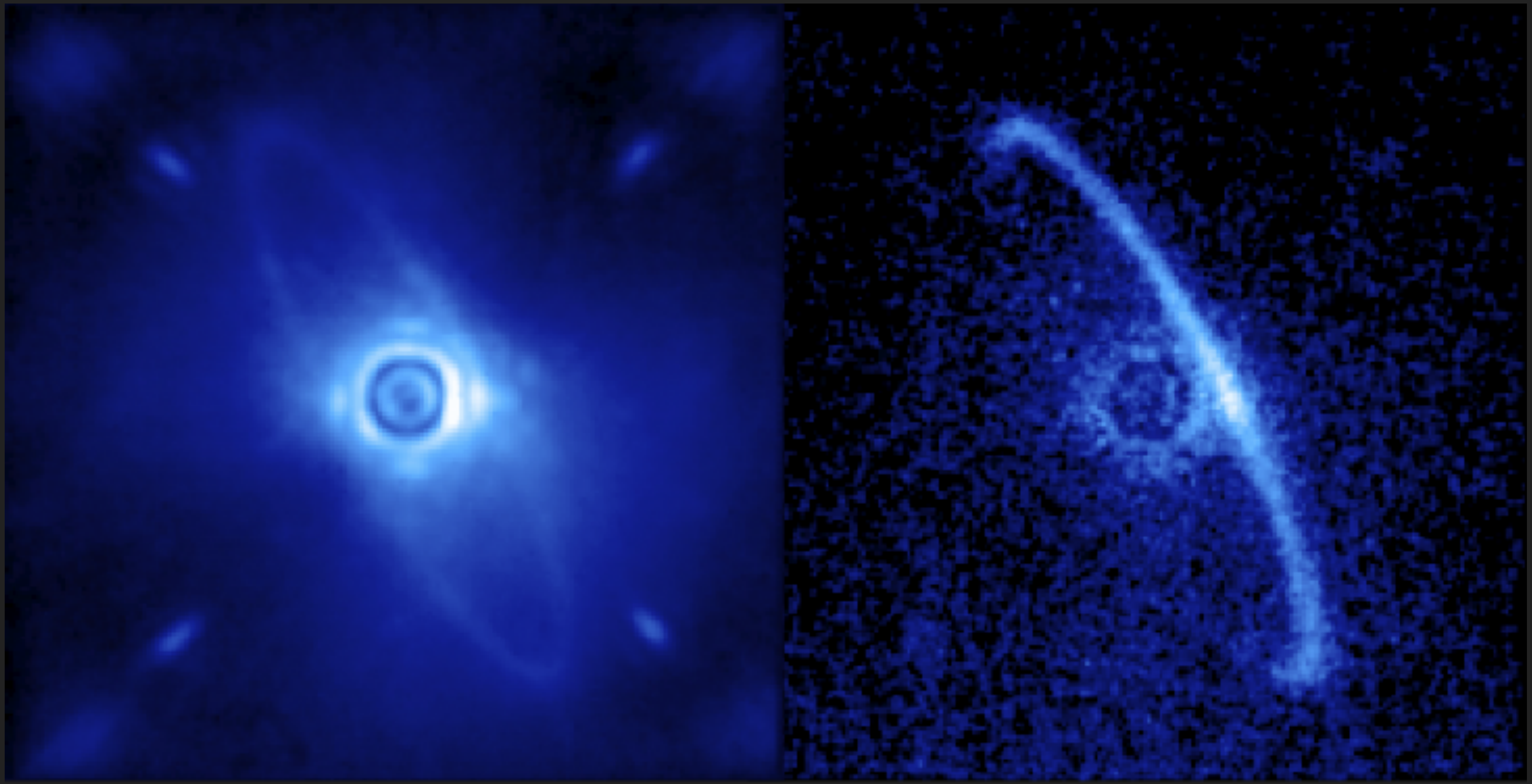
GPI - Spiral arm and point source

But very red - planet (likely) has its own circumplanetary disk!

(Currie et al, 2015)

CORONAGRAPHS + POLARISATION

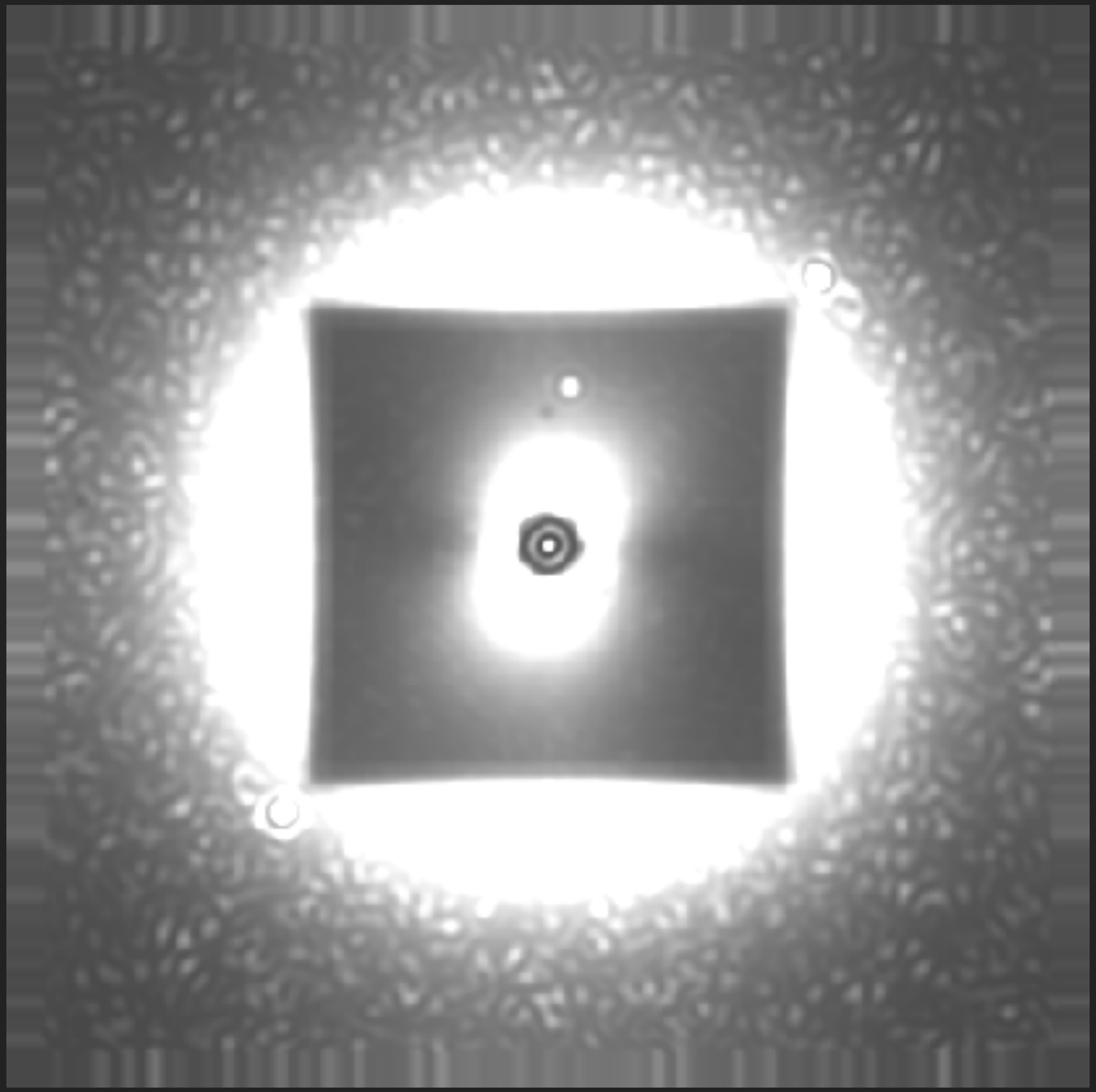
- Polarisation differential imaging
  - Star + speckles has no polarisation, scattered light from dust does



HR4796A (I, P) - Gemini/GPI

CORONAGRAPHS + COLOURS

- Spectral differential imaging
  - Speckles move with wavelength, planet stationary but changes brightness

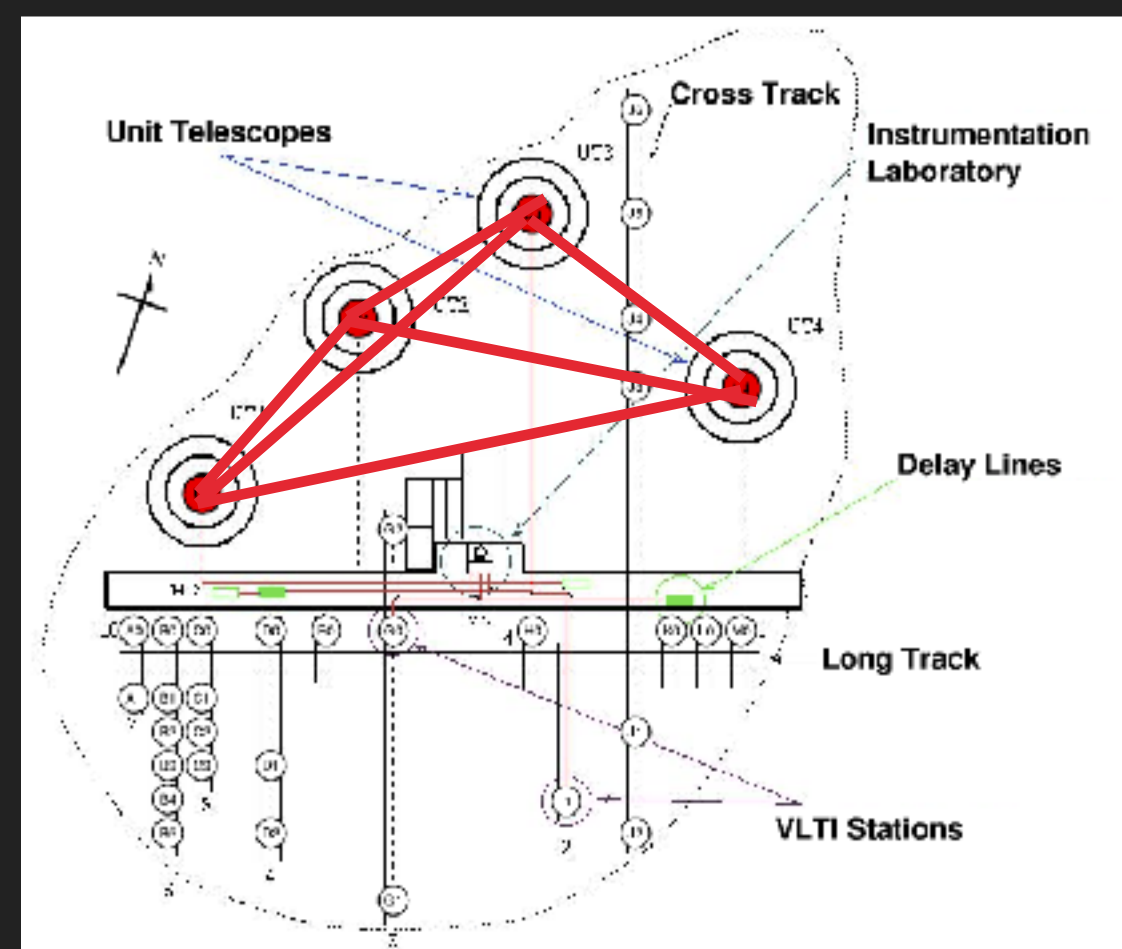


SO HOW DO YOU DO IT?

- 3) Interferometry
  - Recall absolute limiting resolution depends on telescope aperture size D…
  - Well, you can cheat.
  - Join 1 or more telescopes - D becomes their separation! (Baseline)
  - Better than 1 mas resolution (but not good at faint targets)

INTERFEROMETRY

- Combine multiple telescopes to get multiple baselines
  - Long baselines -> measure fine structure (high resolution detail)
  - Short baselines -> measure coarse structure (low resolution detail)
  - Angle of baseline -> angle of structure measured



VLTI in Chile (ESO)

SUMMARY

- How to find an exoplanet
  - RV, transit, astrometry, …
  - Each have pros and cons
- Direct imaging - the next step
  - Complex structure - e.g. planet formation in protoplanetary disks
  - Directly measure orbital parameters -> mass
  - Measure light reflected off planet - characterise atmosphere, surface material… look for life!
- Difficult
  - Small angular size, high contrast
  - Seeing limits achievable telescope resolution
- Several techniques, including:
  - Adaptive Optics
  - Coronagraphs
  - Interferometry
- Next breakthrough - high resolution reflected light spectrum of exoplanet… life!