Exoplanets: Their Discovery, Characterization, and Formation

Group: Exoplanet Summer School 2023

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Jupiter, as seen from the JUNO mission

Some questions for this week

- How do we detect exoplanets?
- How do exoplanets form?
- Is our planetary system common?
- Can we detect life?

Group: Exoplanet Summer School 2023

Wechat group and lectures

Group: Exoplanet Summer School 2023

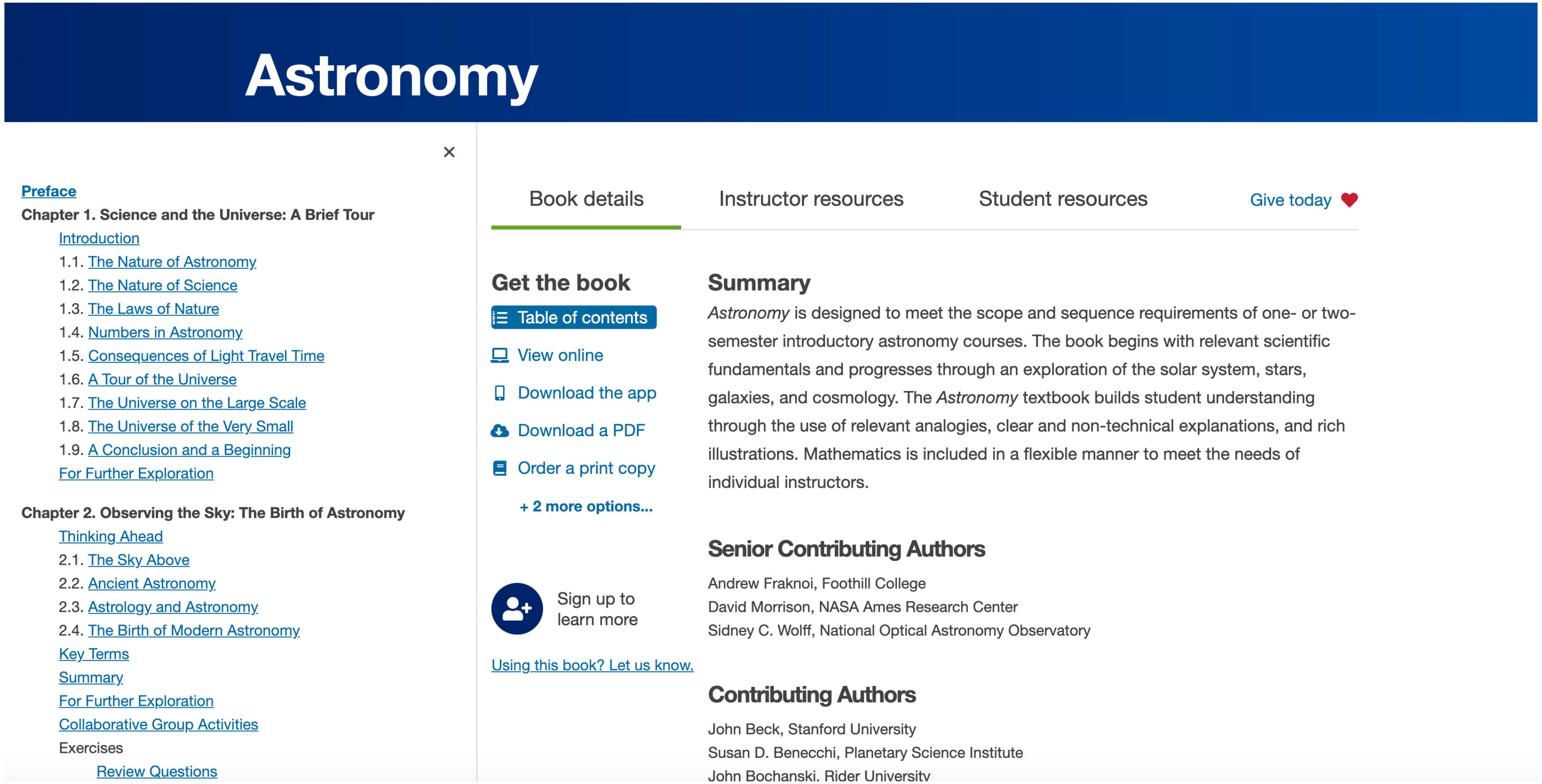
- Quiz on Saturday (format uncertain)
- “Homework” due at 6pm today
  - Send by email to gjh1@pku.edu.cn
  - Circulated by wechat at end of class
- Lectures circulated at github:

Scanning the left won’t work with wechat;
https://gherczeg.github.io/exoplanetssummercourse

Or just google my name, Gregory Herczeg, with github, or wait for webpage to be linked from our wechat group

openstax "textbook"

https://openstax.org/details/books/astronomy



Astronomy

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Summary

Astronomy is designed to meet the scope and sequence requirements of one- or two-semester introductory astronomy courses. The book begins with relevant scientific fundamentals and progresses through an exploration of the solar system, stars, galaxies, and cosmology. The *Astronomy* textbook builds student understanding through the use of relevant analogies, clear and non-technical explanations, and rich illustrations. Mathematics is included in a flexible manner to meet the needs of individual instructors.

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David Morrison, NASA Ames Research Center
Sidney C. Wolff, National Optical Astronomy Observatory

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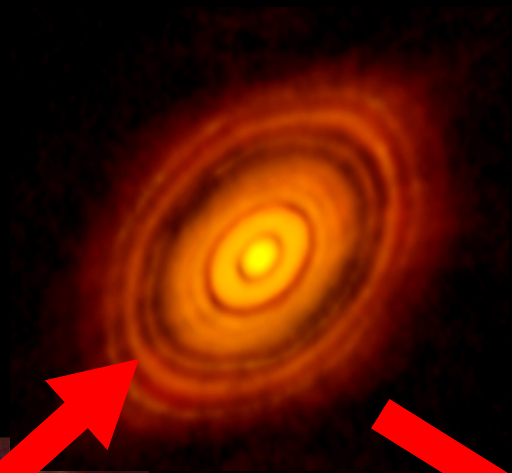
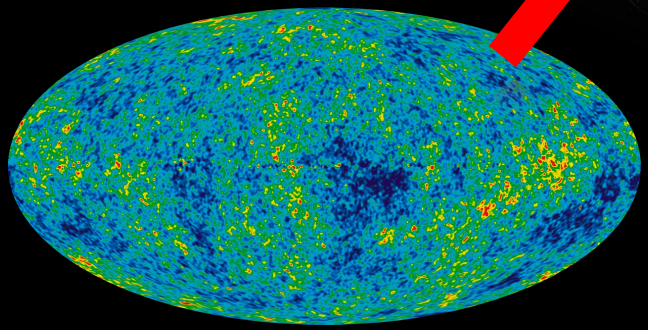
Susan D. Benecchi, Planetary Science Institute
John Bochanski, Rider University

Our astrophysical origins

Milky Way Galaxy
(if we could see it from "above")

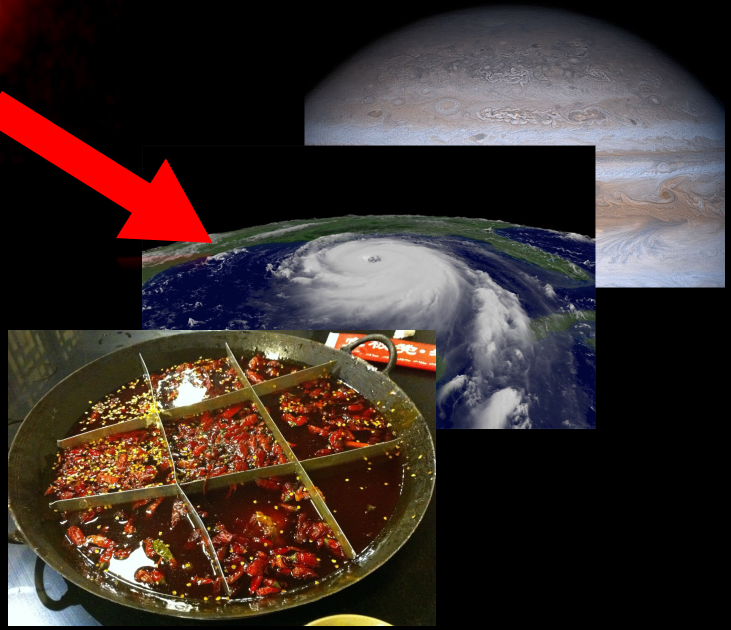


Protoplanetary disks



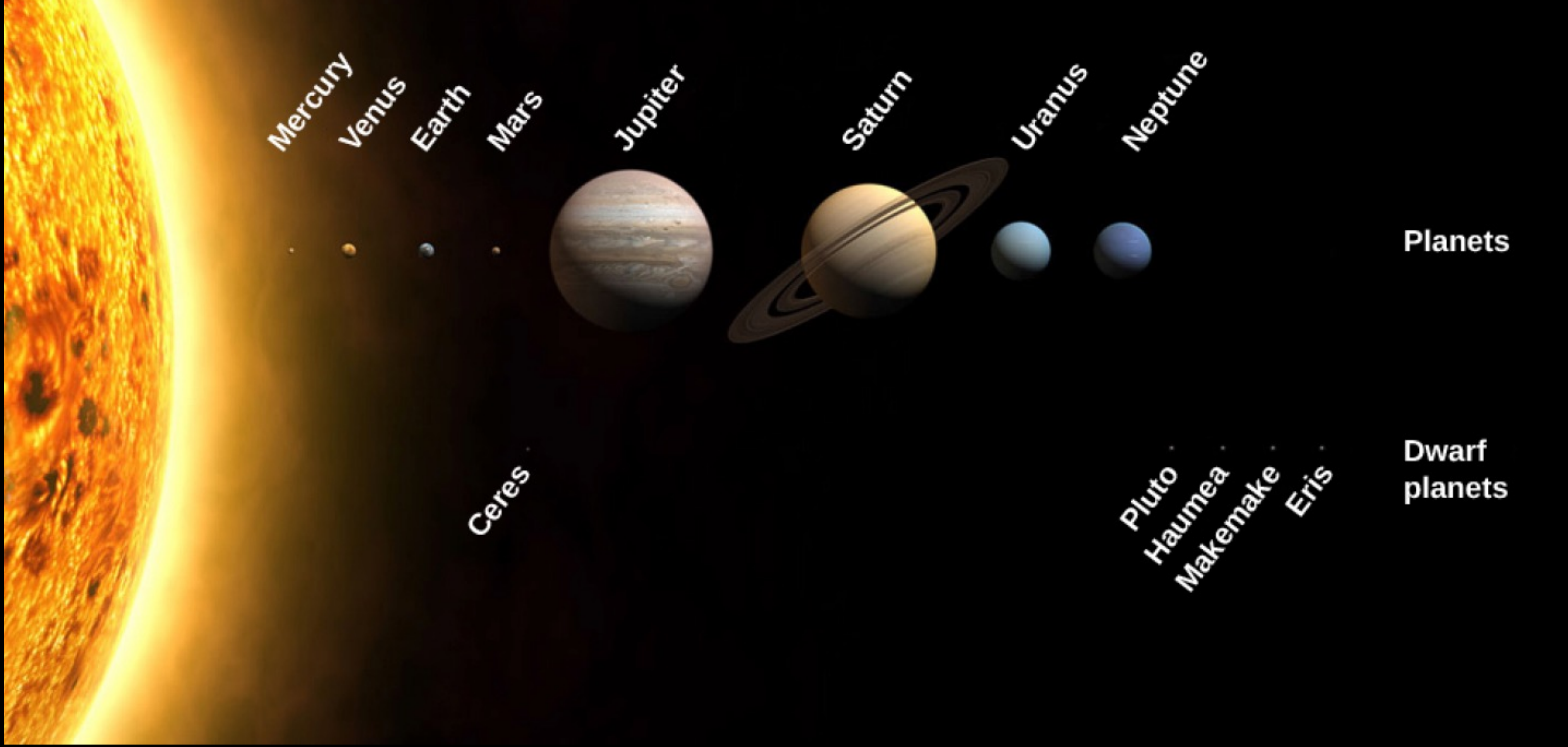
Cosmic Microwave Background (early universe)

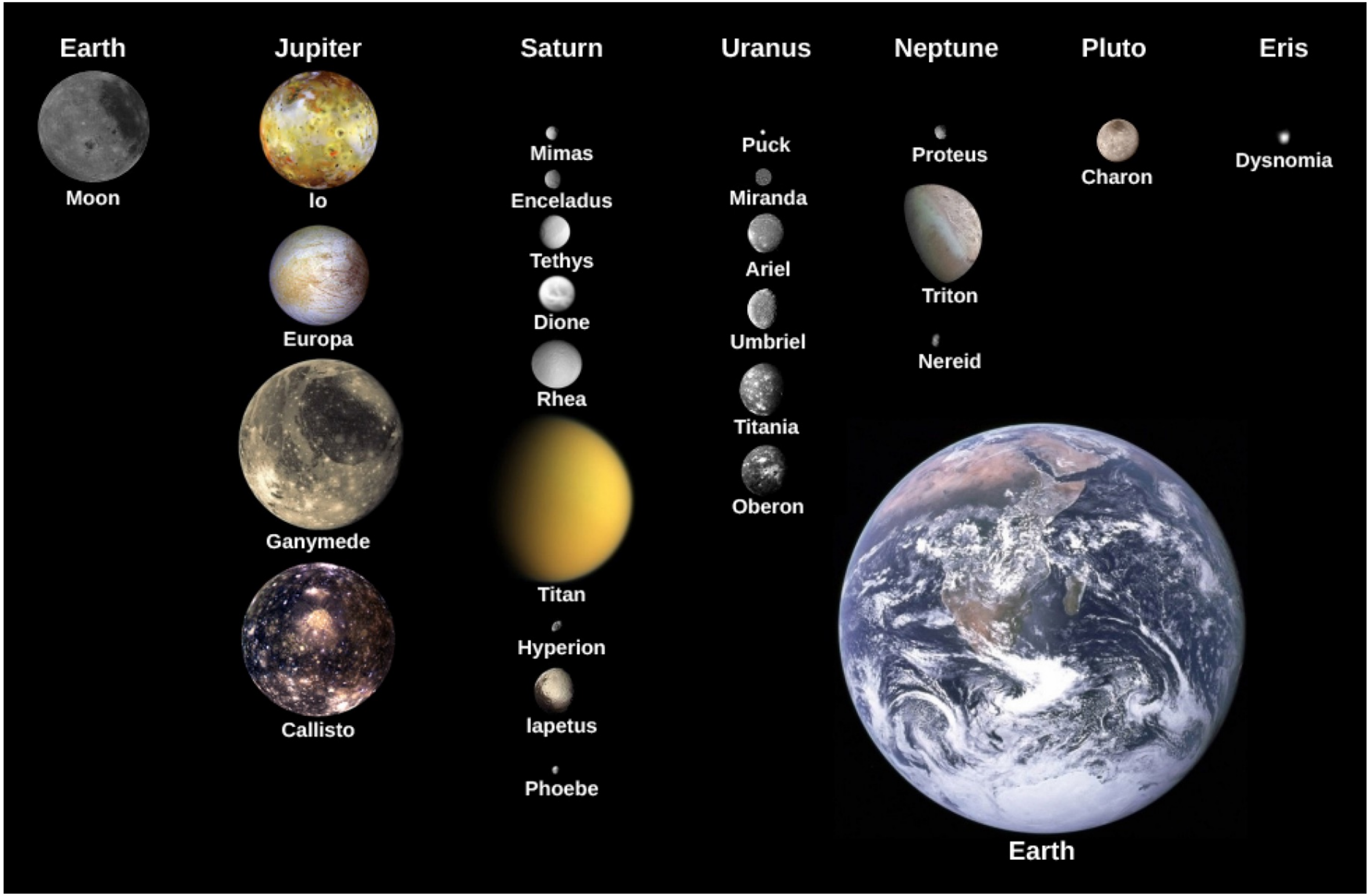
Molecular Clouds



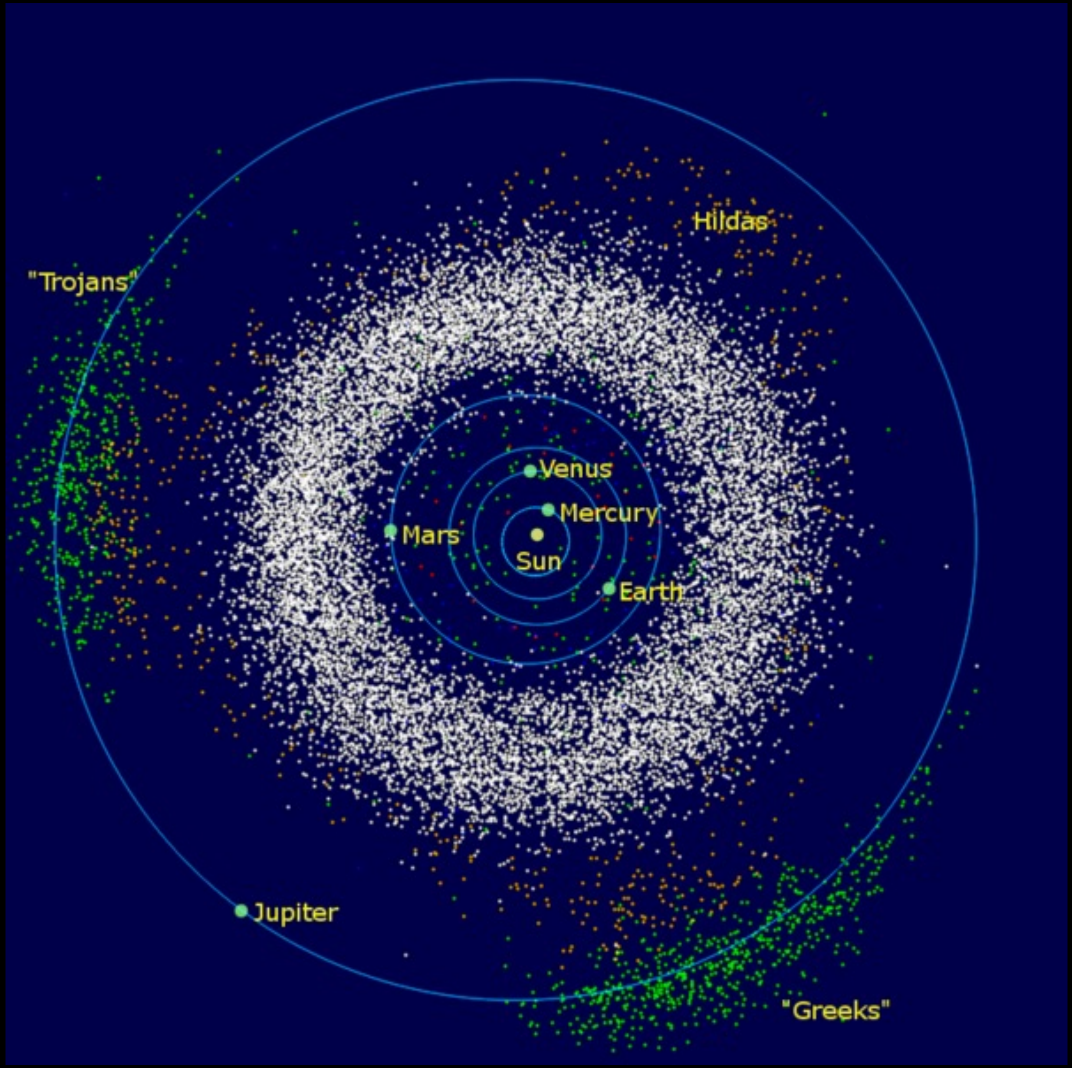
Planets, atmospheres, and life!

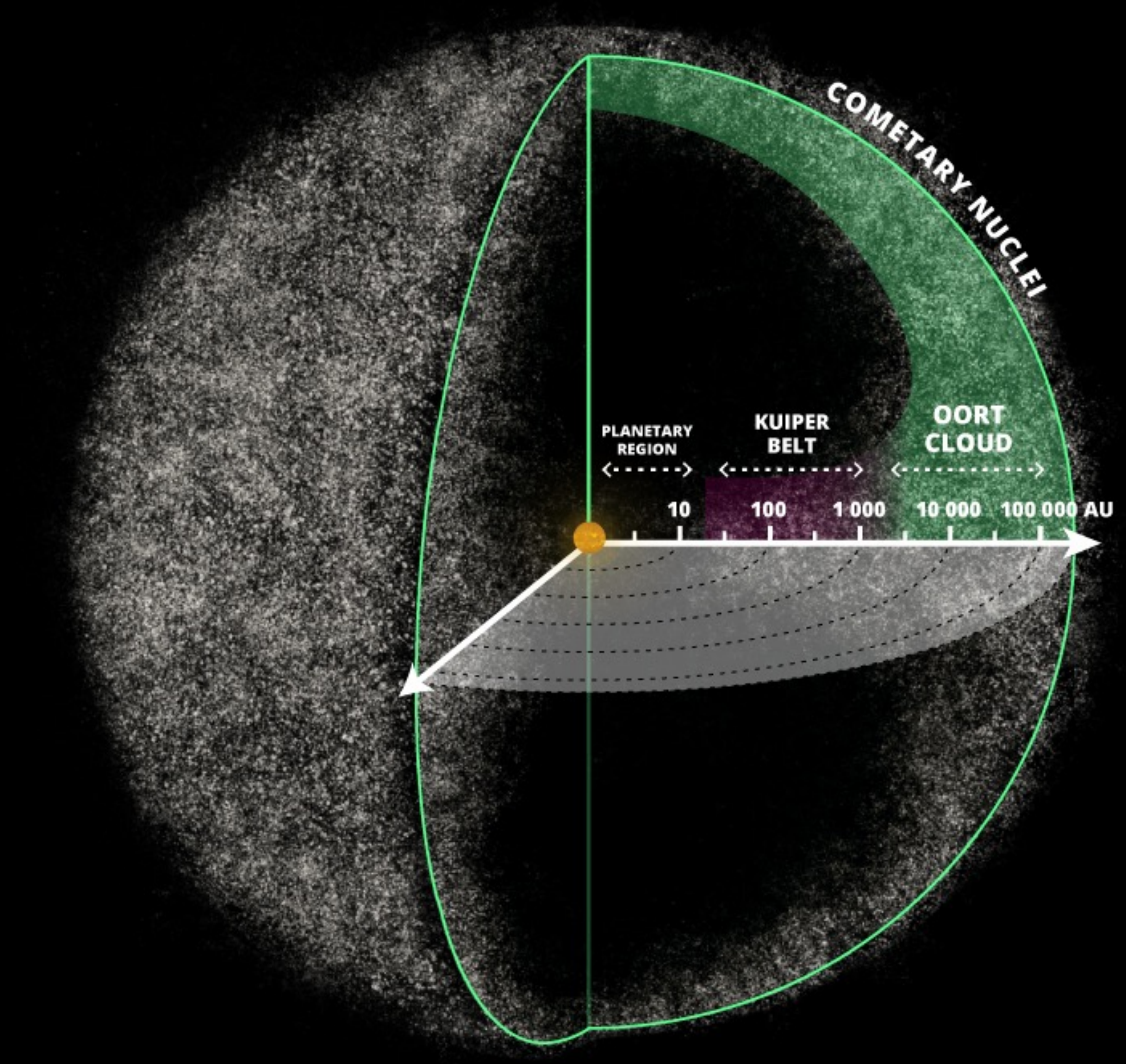
Our solar system




Earth
Jupiter
Saturn
Uranus
Neptune
Pluto
Eris
Moon
Io
Europa
Ganymede
Callisto
Mimas
Enceladus
Tethys
Dione
Rhea
Titan
Hyperion
Iapetus
Phoebe
Puck
Miranda
Ariel
Umbriel
Titania
Oberon
Proteus
Triton
Nereid
Charon
Dysnomia
Earth

Debris from the solar system:
asteroids, comets, Kuiper Belt Objects





Space Facts / Laurine Moreau

What are the general properties of the solar system?

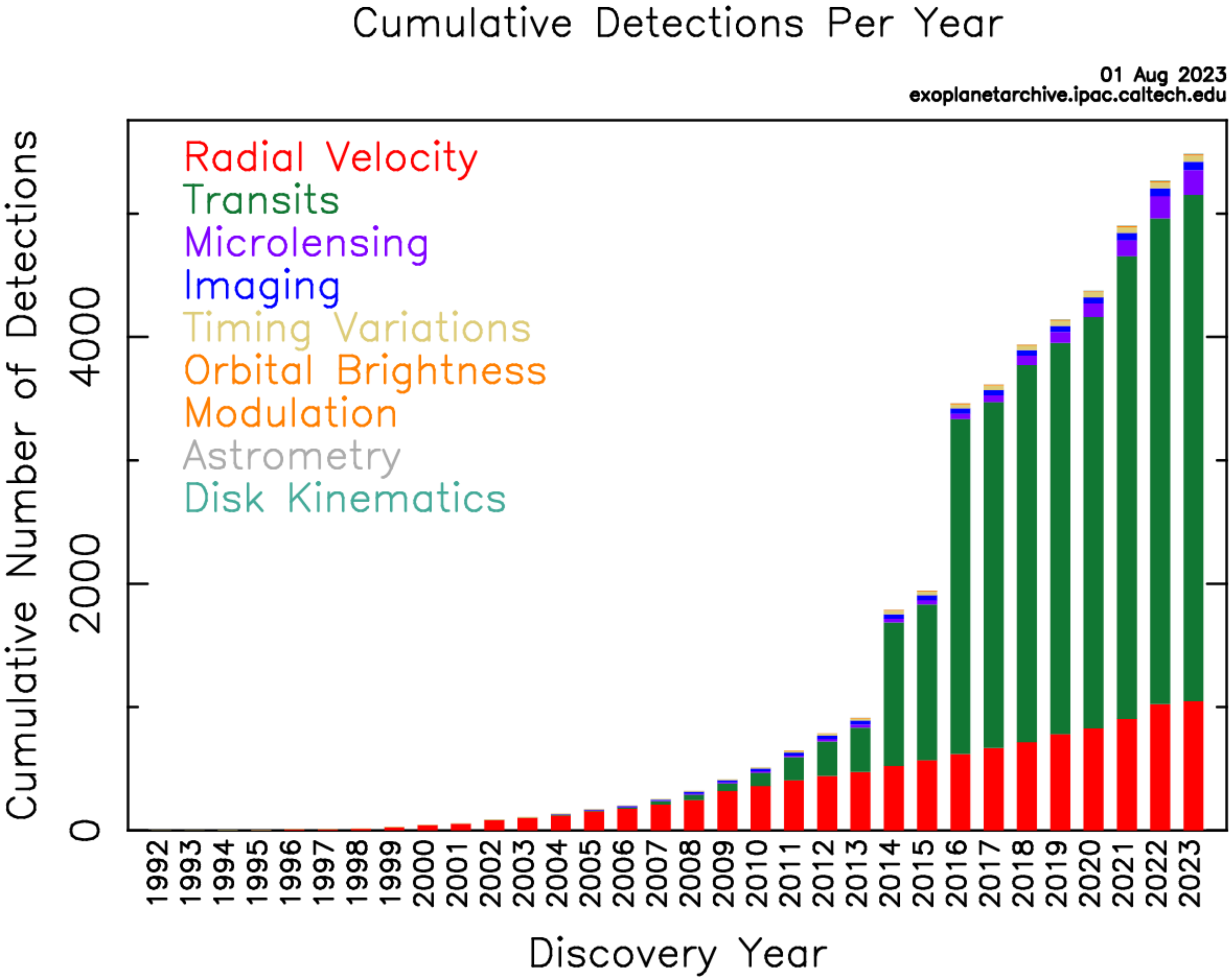
- Discuss properties

Kepler's Laws

1: Orbit of a planet is an ellipse with sun at the focus

2: A line segment joining a planet and the Sun sweeps out equal areas during equal intervals of time.

3: Period^2 = semi-major axis^3



Cumulative Detections Per Year
01 Aug 2023
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness
Modulation
Astrometry
Disk Kinematics
Cumulative Number of Detections
0
2000
4000
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
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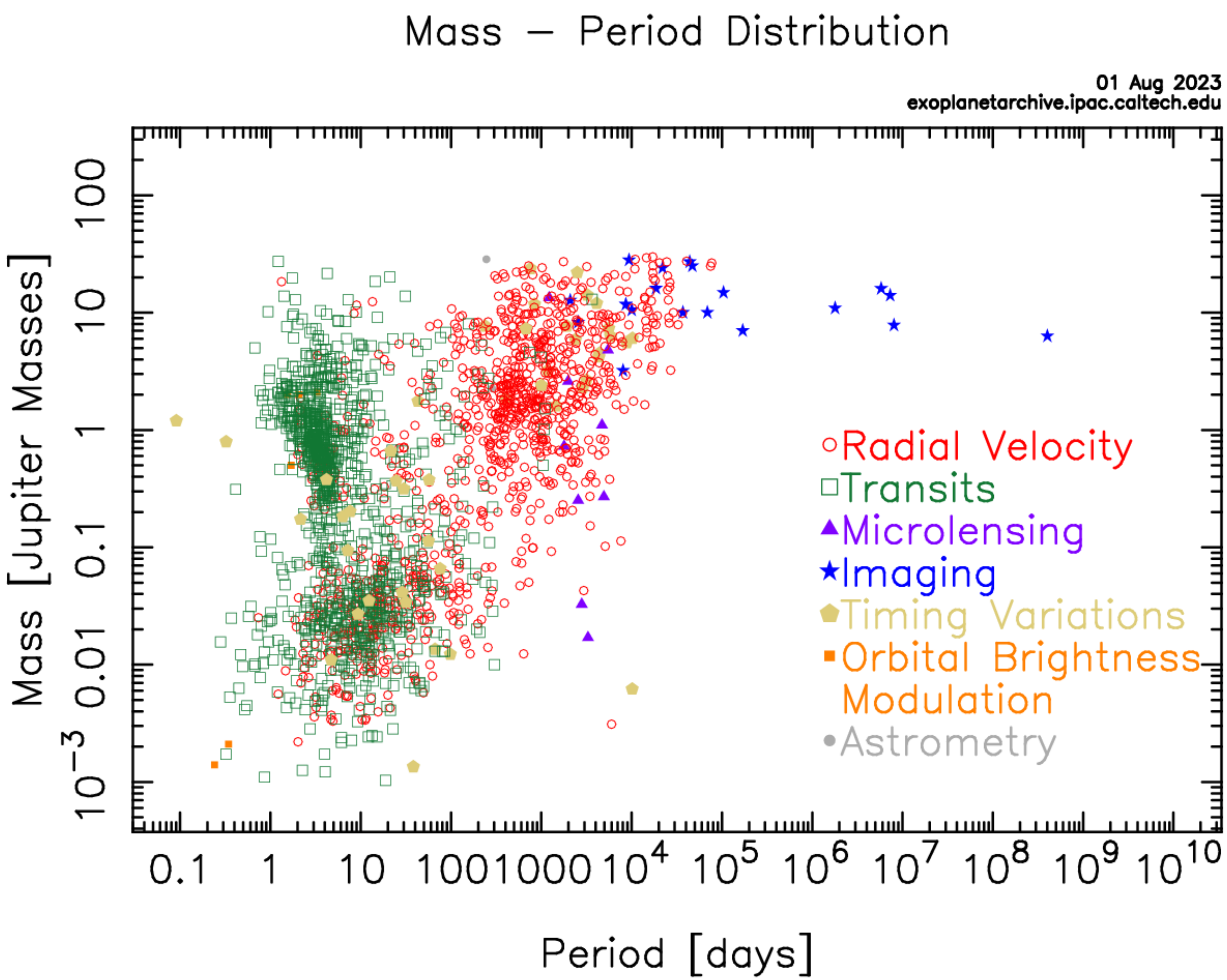
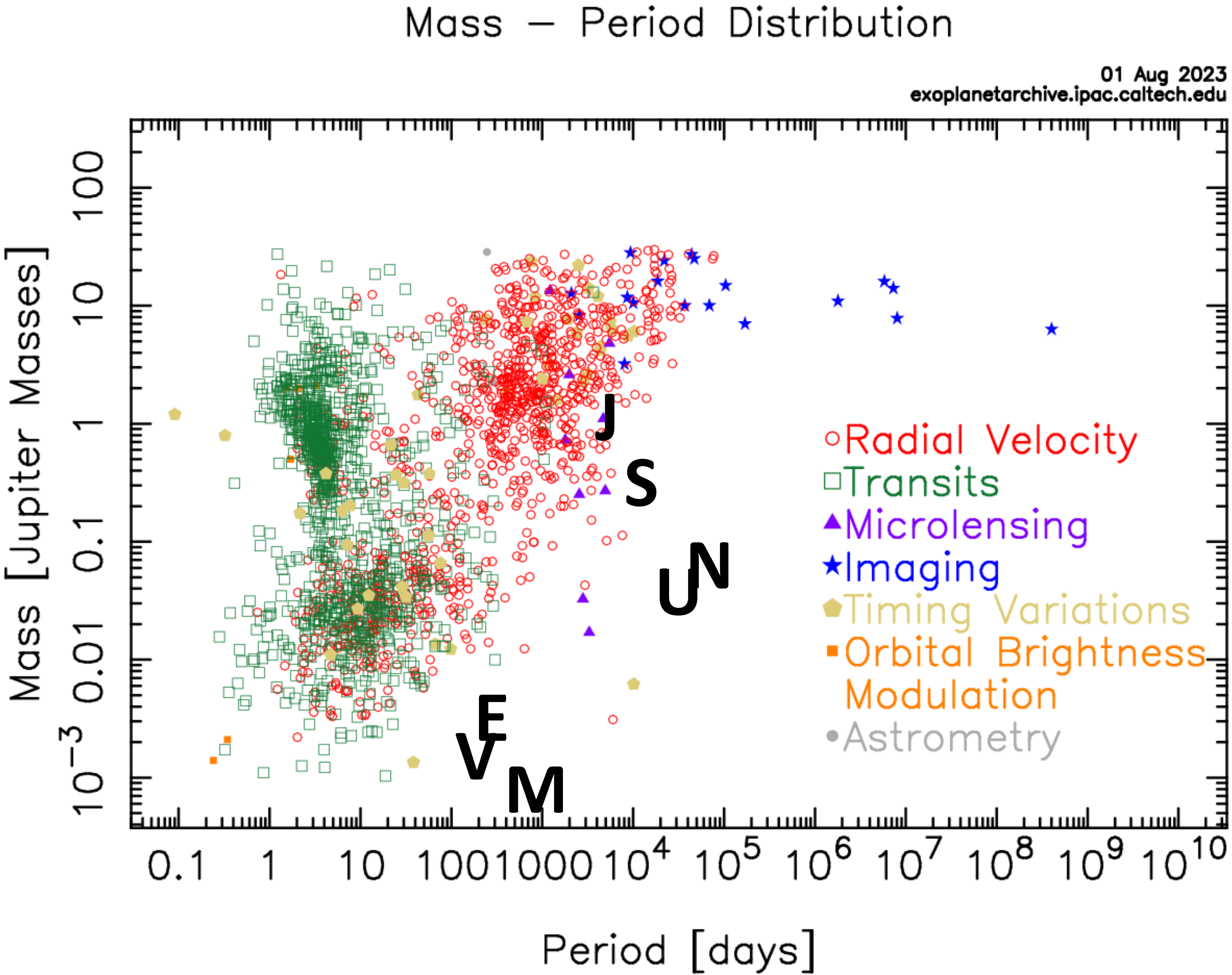
2016
2017
2018
2019
2020
2021
2022
2023
Discovery Year



Mass – Period Distribution
01 Aug 2023
exoplanetarchive.ipac.caltech.edu
Mass [Jupiter Masses]
100
10
1
0.1
0.01
10^{-3}
0.1
1
10
100
1000
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
Period [days]
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness Modulation
Astrometry



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1000
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10^5
10^6
10^7
10^8
10^9
10^{10}
J
S
U
N
E
V
M
Radial Velocity
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Microlensing
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Astrometry

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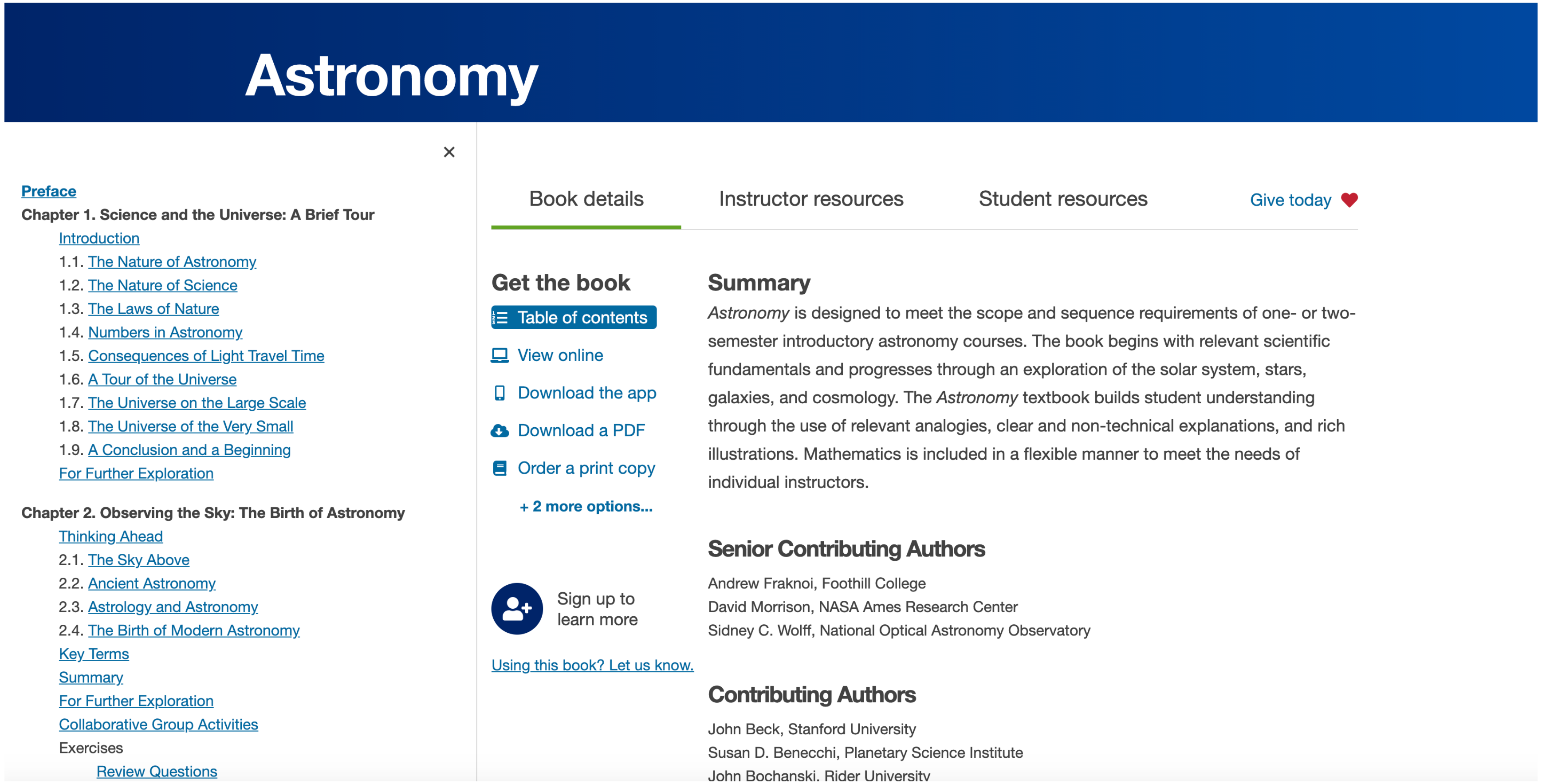
Let’s start at the very beginning

openstax "textbook"

https://openstax.org/details/books/astronomy



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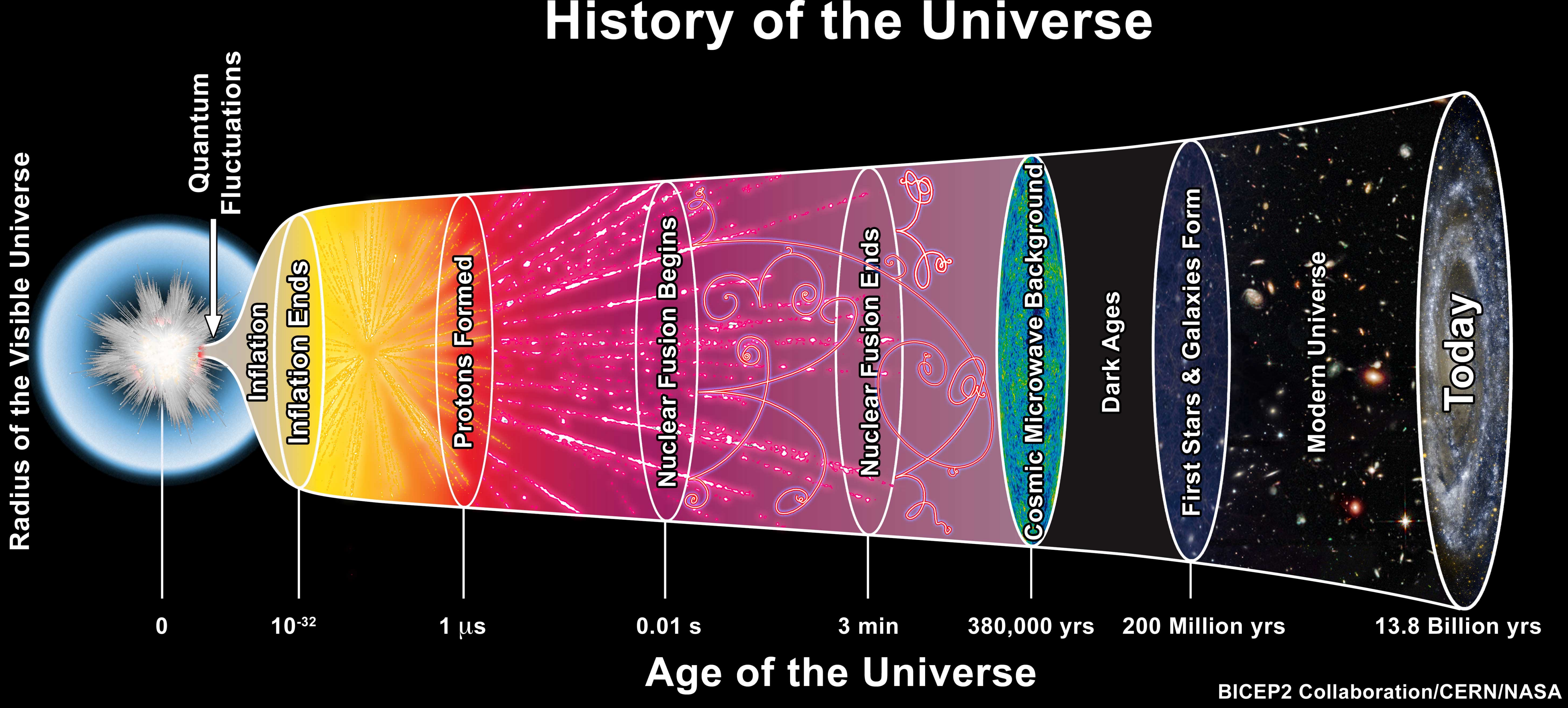
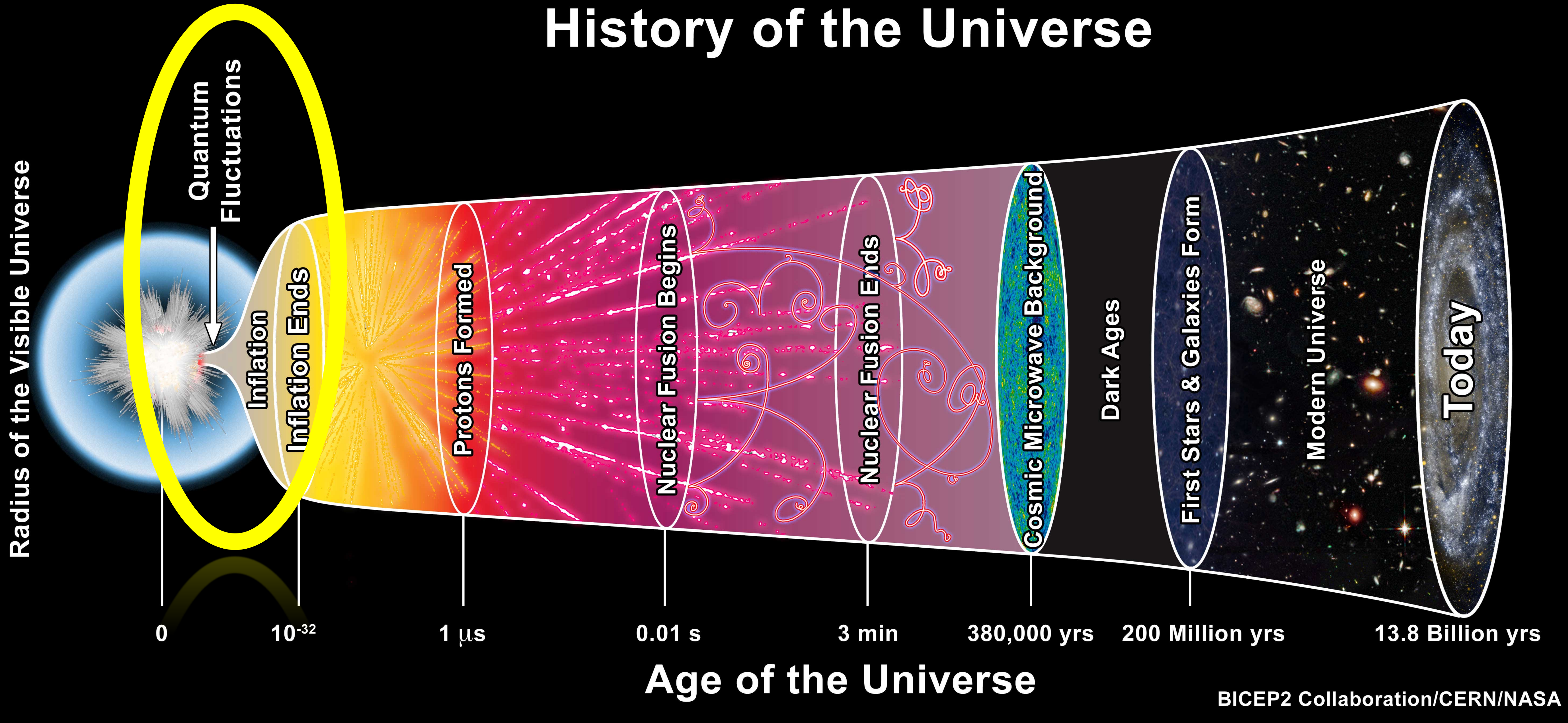
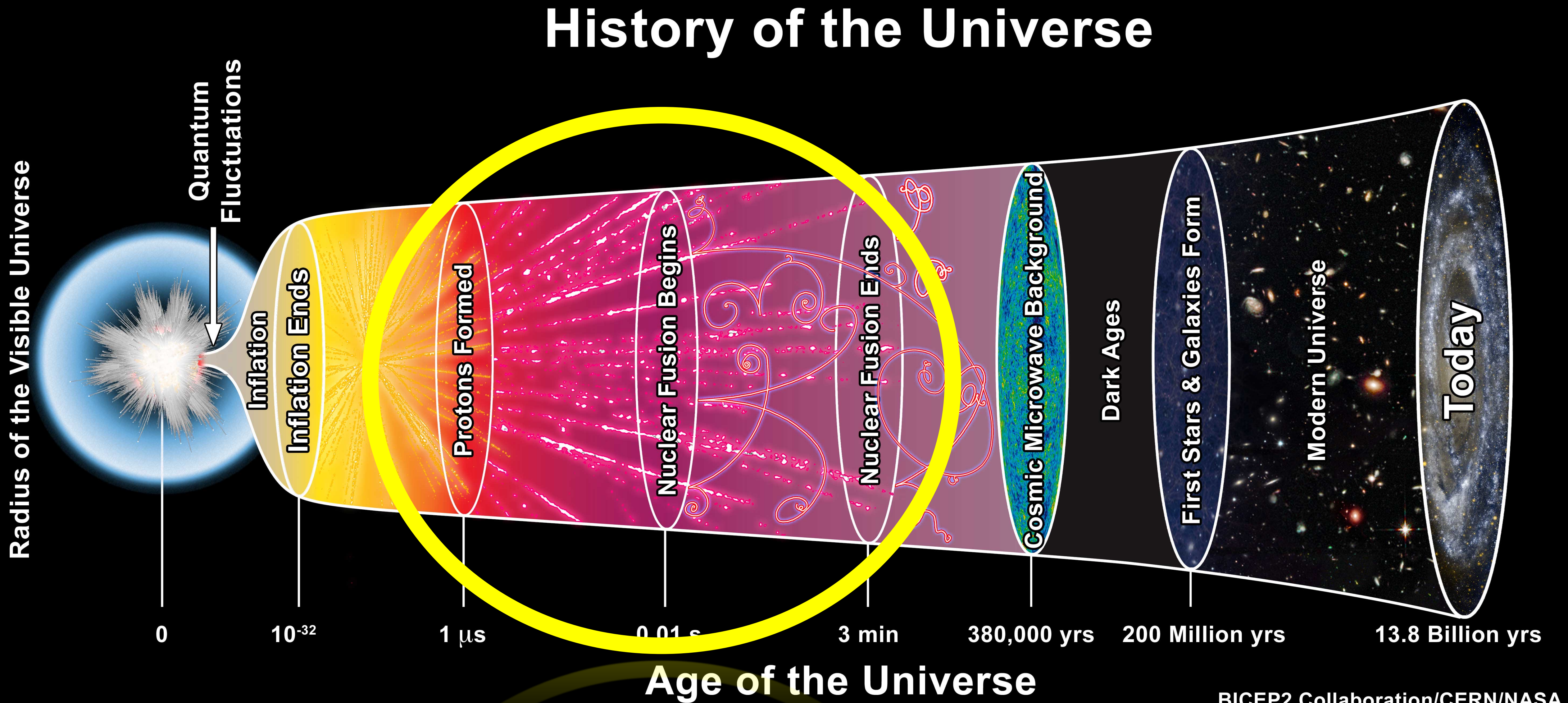

History of the Universe
Radius of the Visible Universe
Quantum Fluctuations
Inflation
Inflation Ends
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Dark Ages
First Stars & Galaxies Form
Modern Universe
Today
0
10-32
1 μs
0.01 s
3 min
380,000 yrs
200 Million yrs
13.8 Billion yrs
Age of the Universe
BICEP2 Collaboration/CERN/NASA

Inflation: from 10^{-36} to 10^{-32} seconds: universe expanded by a factor of 10^{26}! Smooths out everything except quantum fluctuations

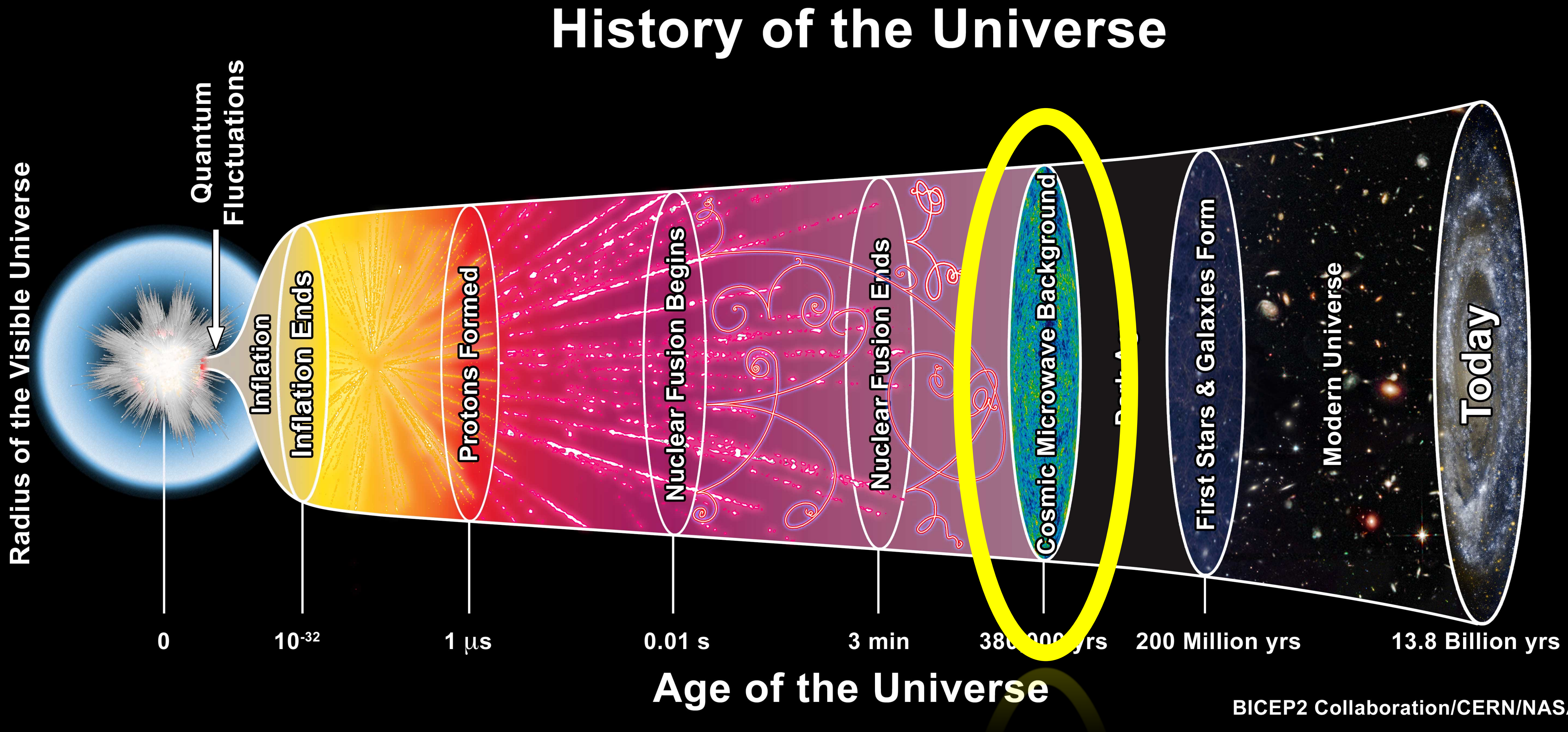


Quark soup to atoms: protons, deuterium, helium (and a little Lithium)



BICEP2 Collaboration/CERN/NASA

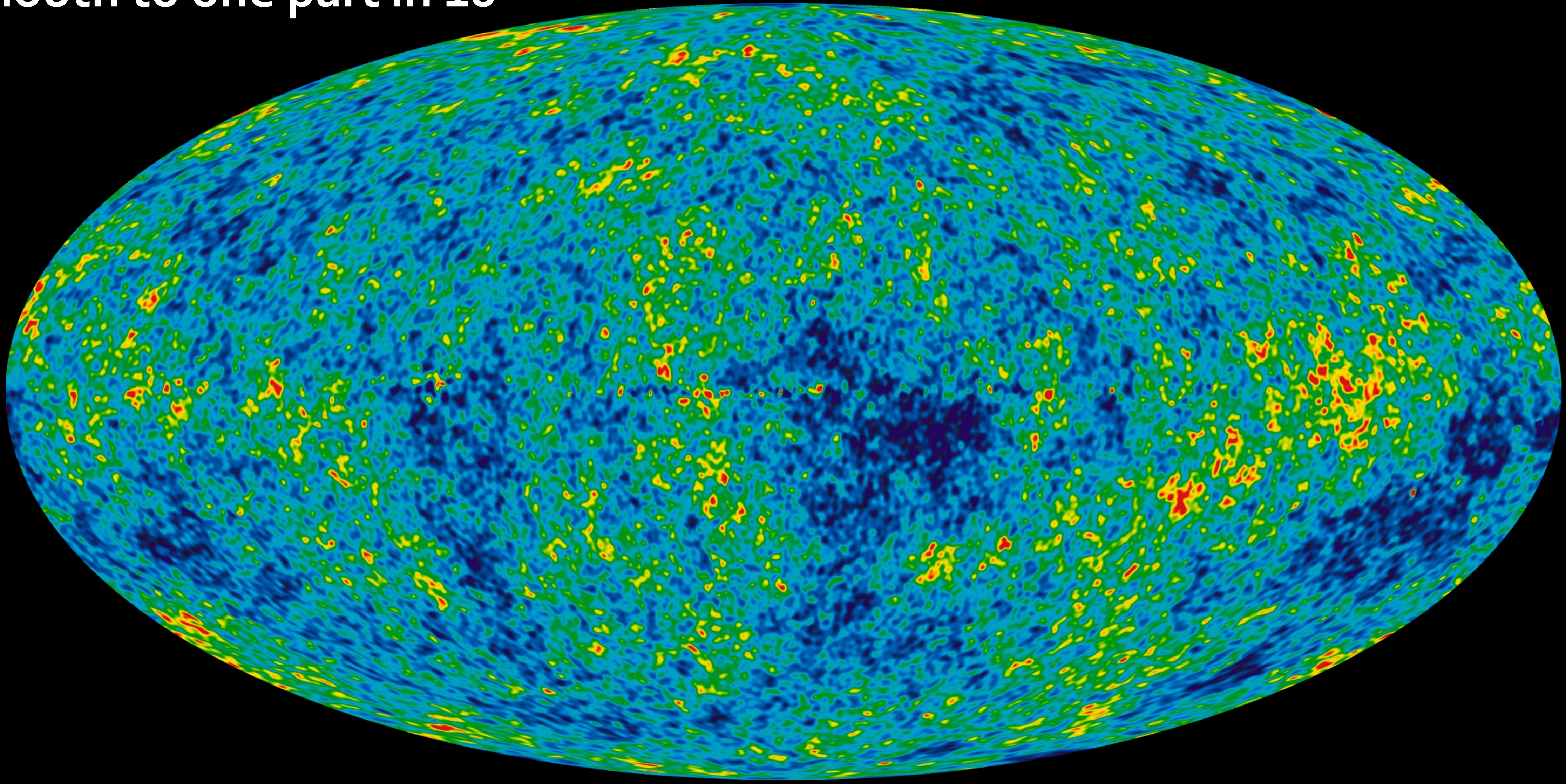
Cosmic Microwave Background: protons+electrons combine



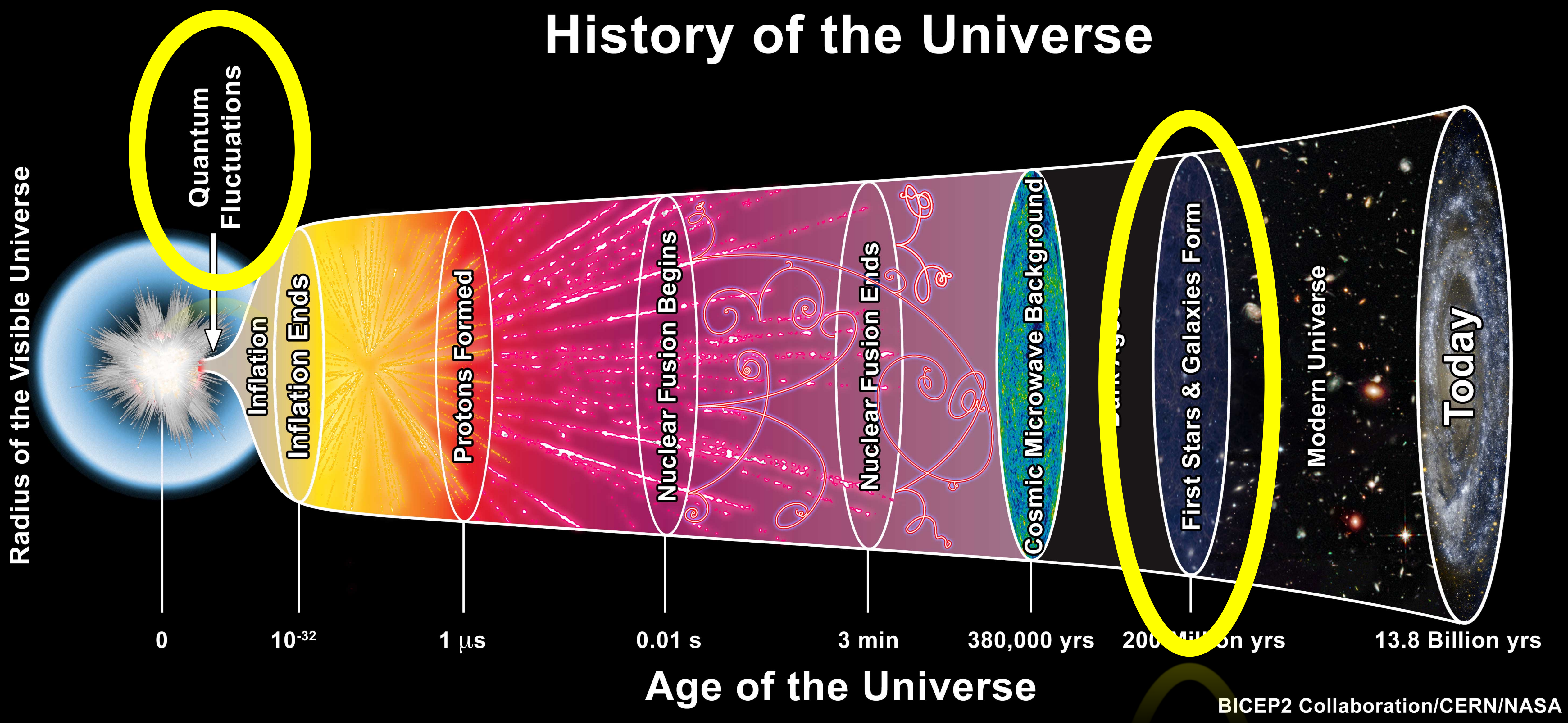
BICEP2 Collaboration/CERN/NASA

Cosmic Microwave Background (observed with Planck)

- 2.7 K (3000 K blackbody, redshifted)
- Smooth to one part in 10^4



Structure formation (quantum fluctuations => galaxy clusters)

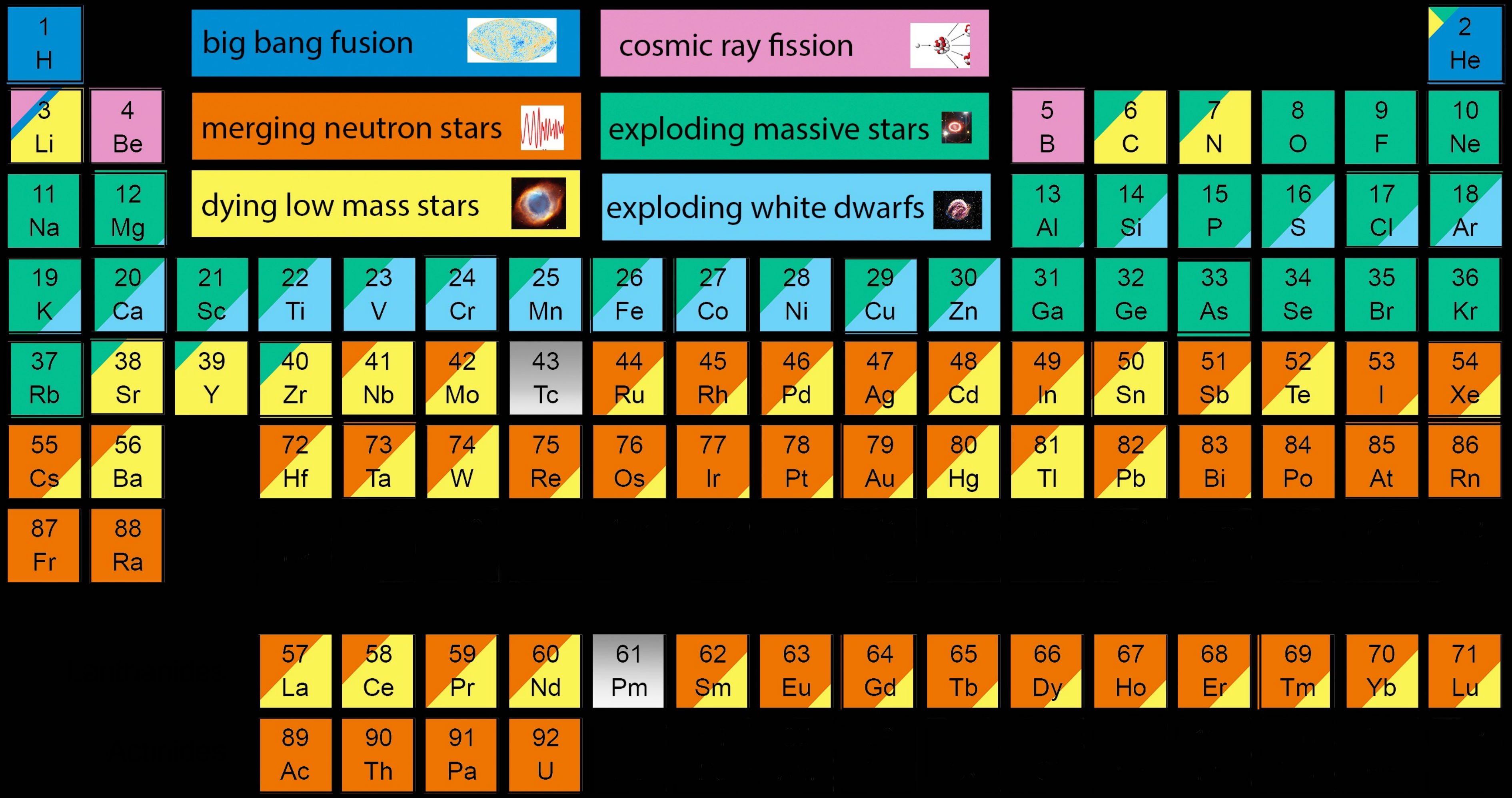


Simulations of Milky Way Formation

January	February	March	April	May	June	July	August	September	October	November
Big Bang occurs.				Milky Way Galaxy forms.				Our solar system forms. Life on Earth begins.	Earth's atmosphere becomes oxygenated.	First complex life forms appear.

December						
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	**19 Vertebrates appear.**	**20 Land plants appear.**	21
22	23	24	**25 Dinosaurs appear.**	**26 Mammals appear.**	27	28
29	**30 Dinosaurs become extinct.**	**31 Humans appear.**				

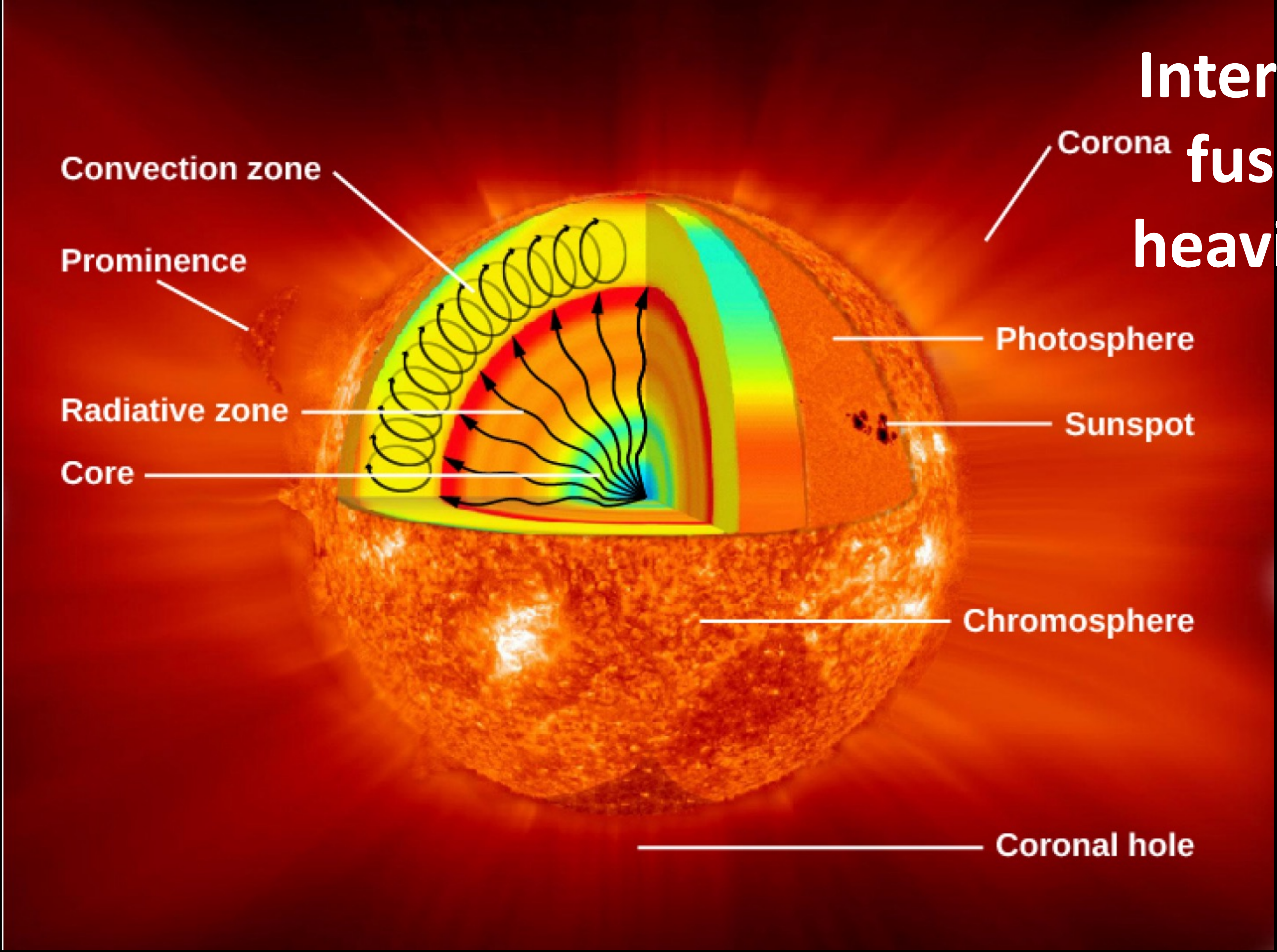
The Origin of the Solar System Elements



Graphic created by Jennifer Johnson

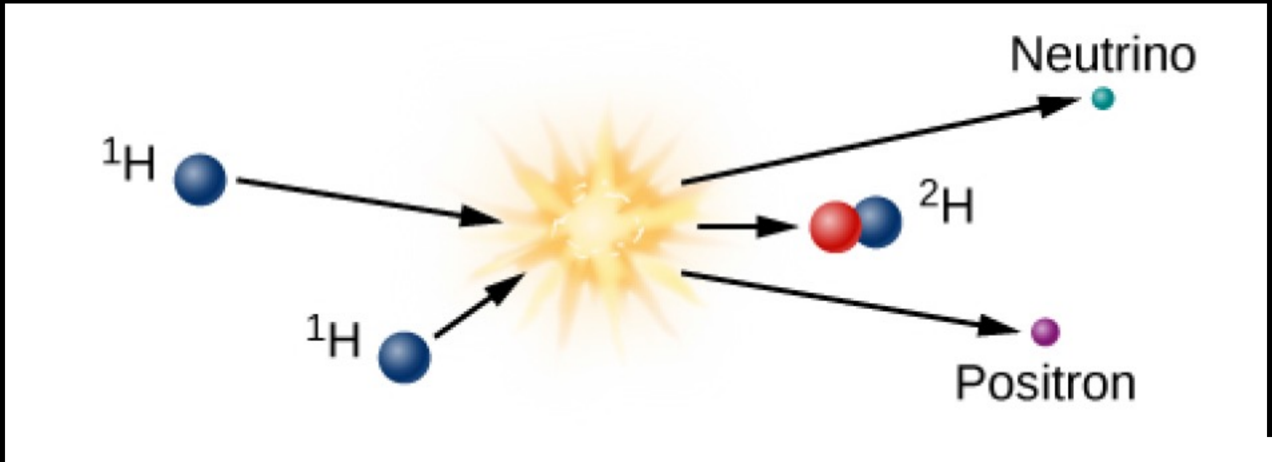
Astronomical Image Credits:
ESA/NASA/AASNova

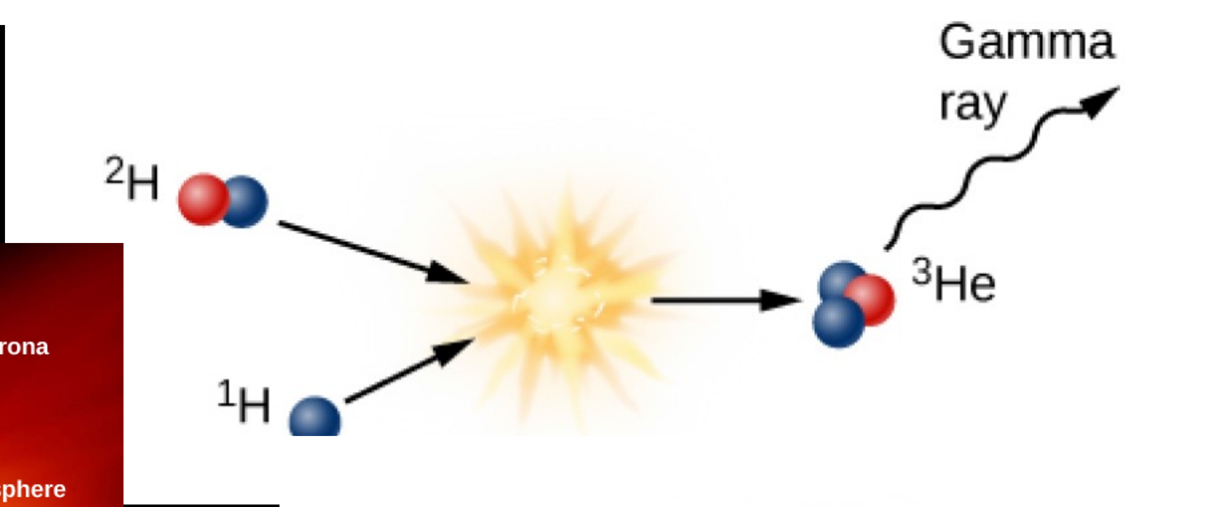
Interior of a star: fusion of H to heavier elements

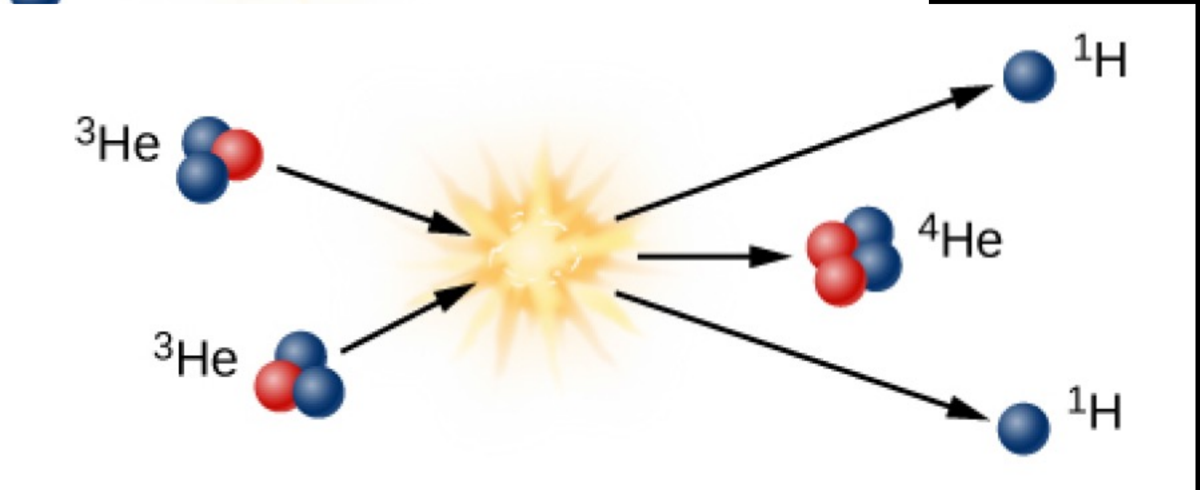


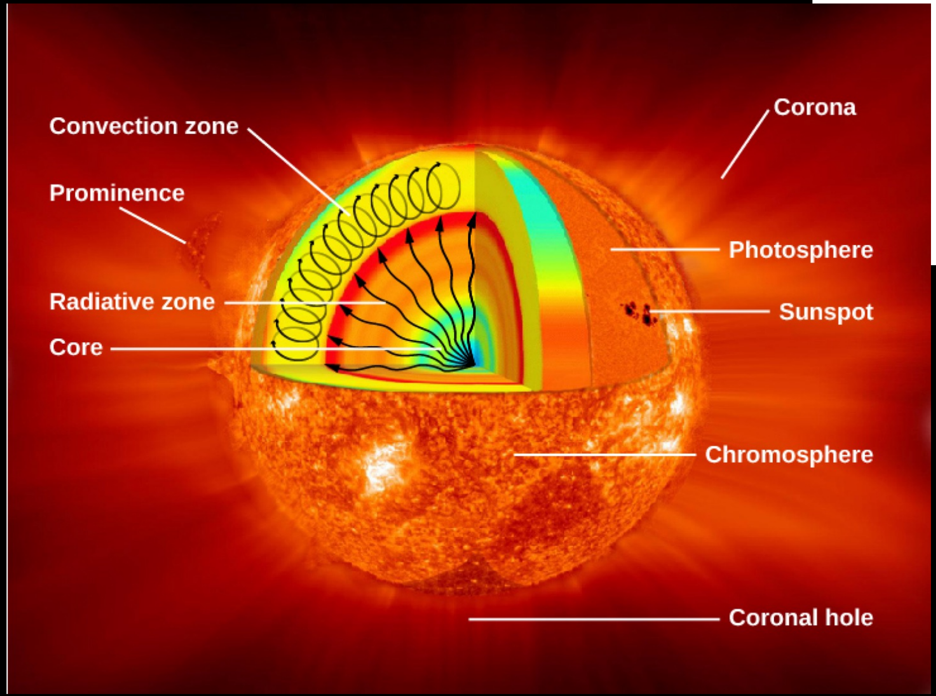
Fusion at core of "main sequence" star

4 Hydrogen atoms turns into 1 He atom

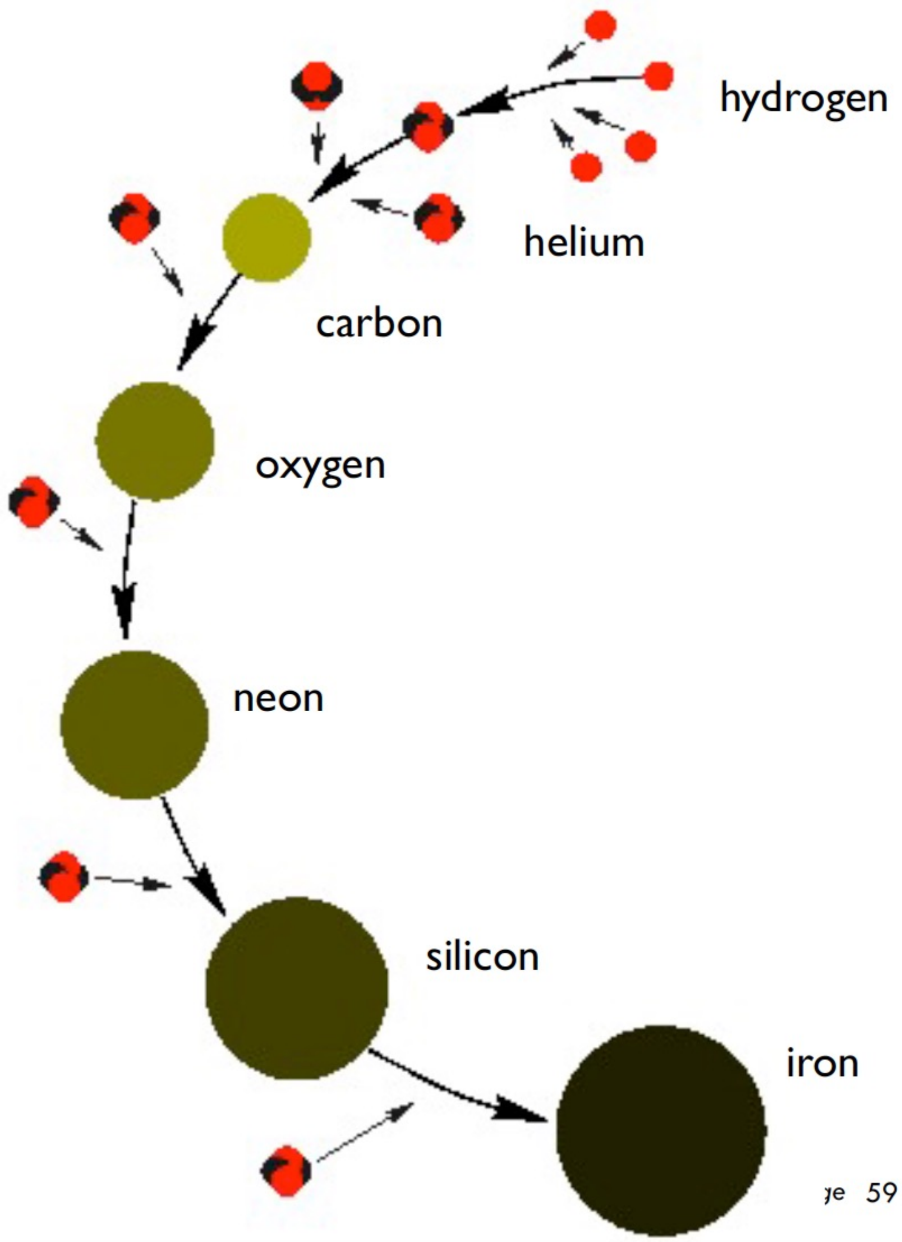


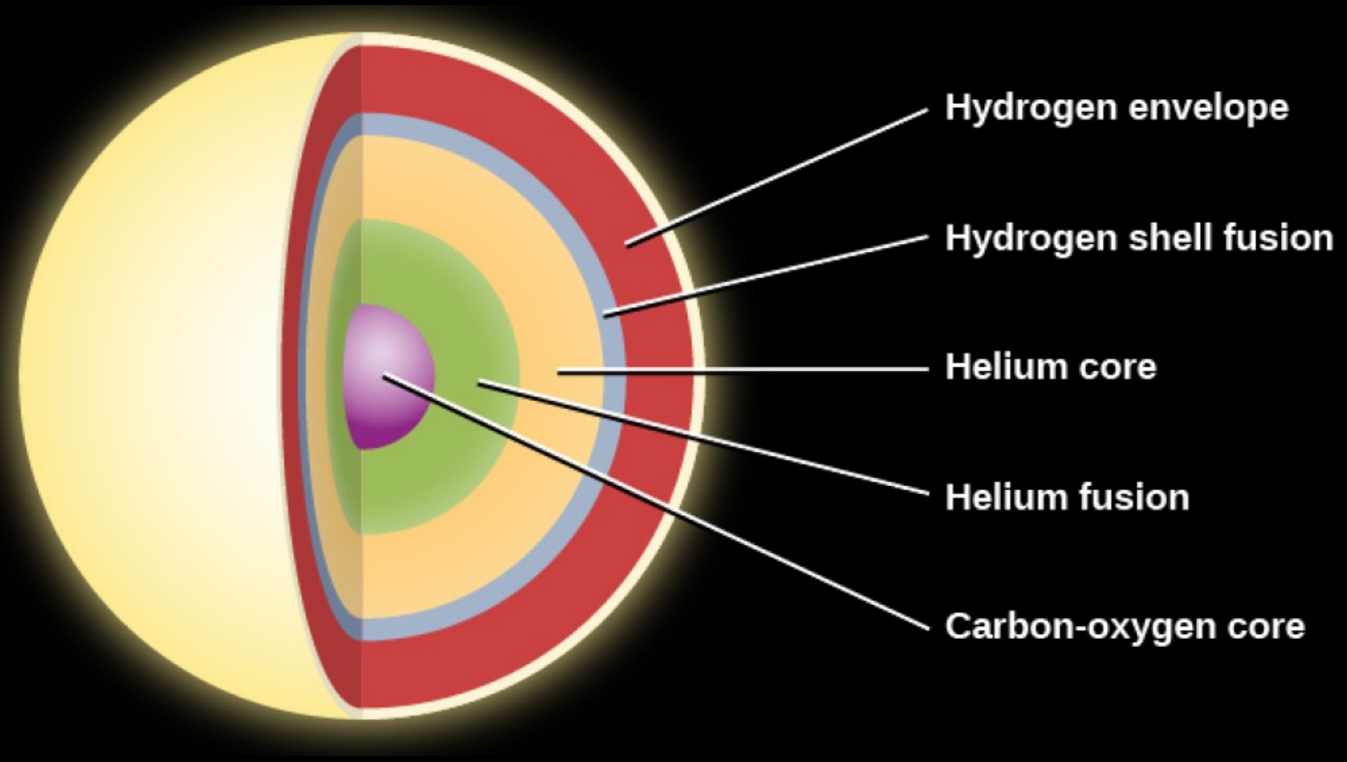




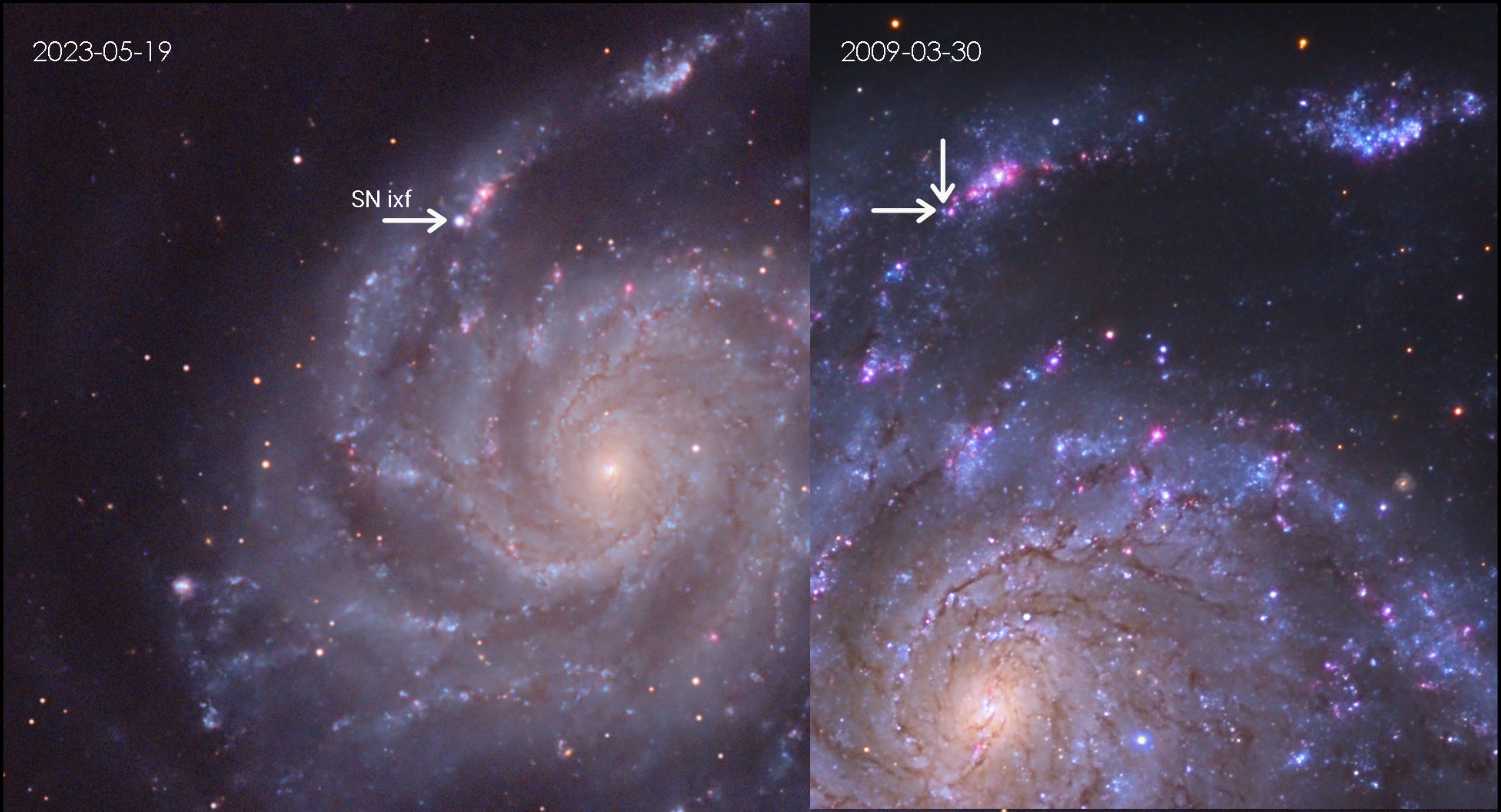


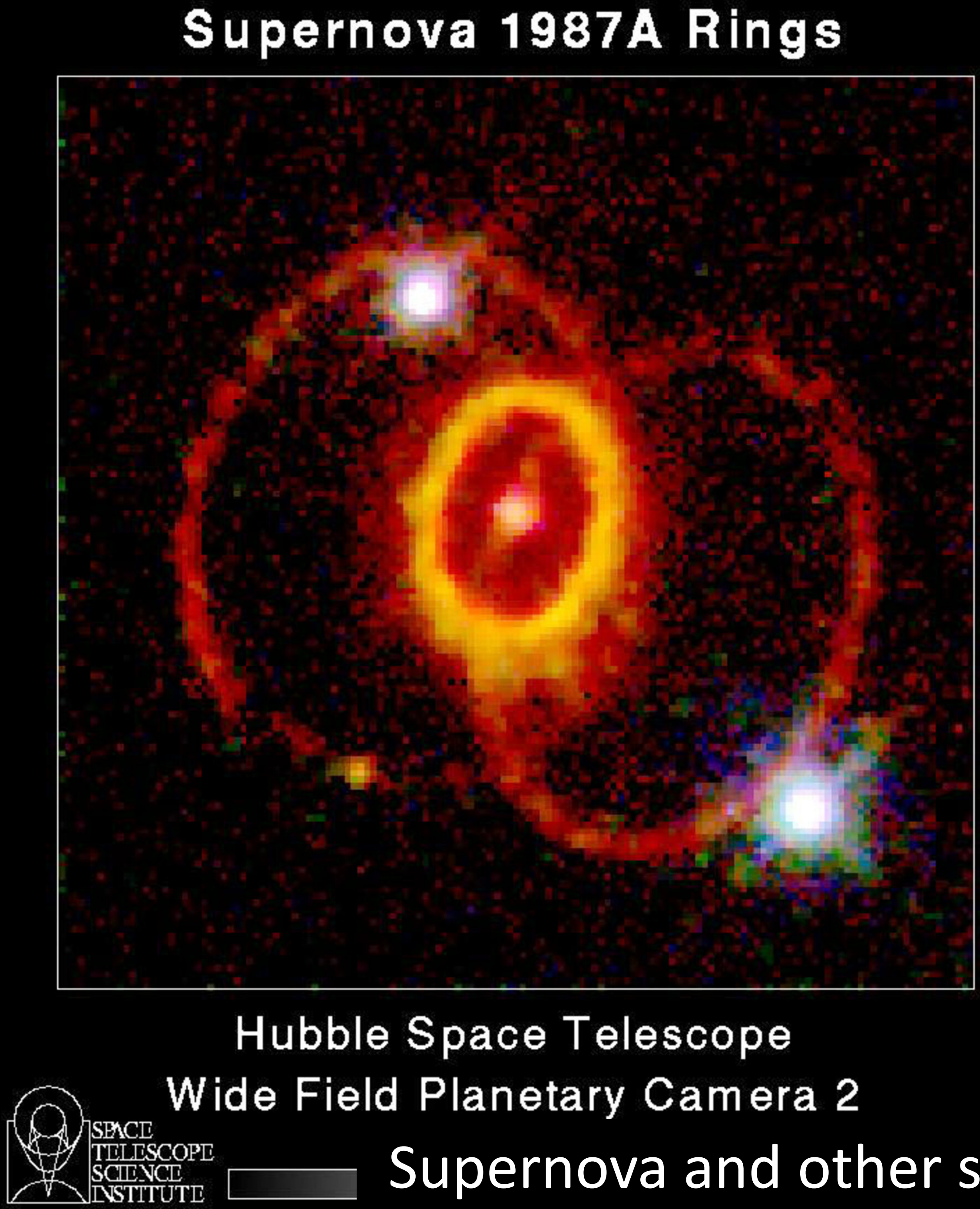
Interior structure of evolved (older) star; He burns to heavier elements, then CO, …



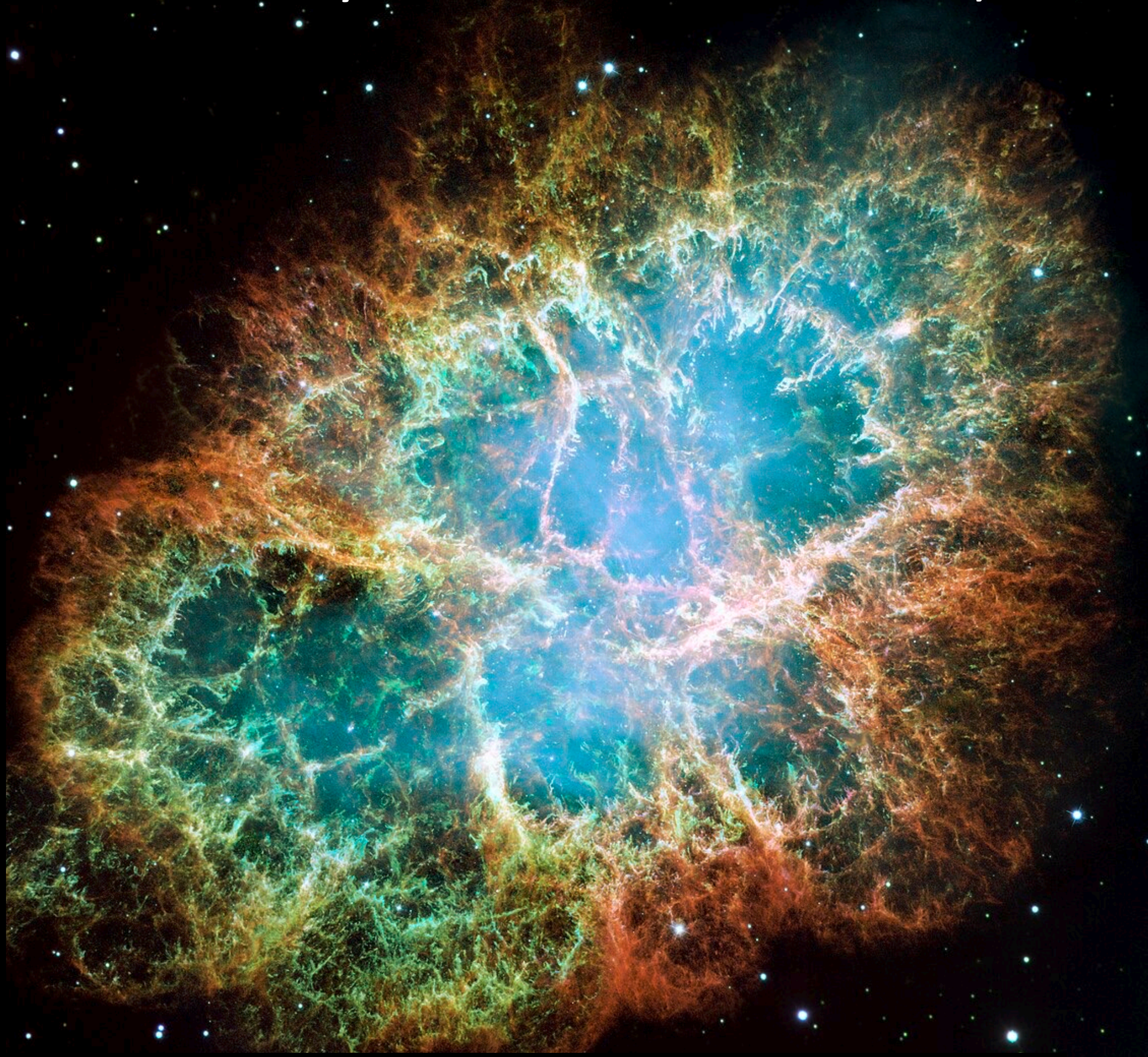


Supernova in nearby galaxy M101



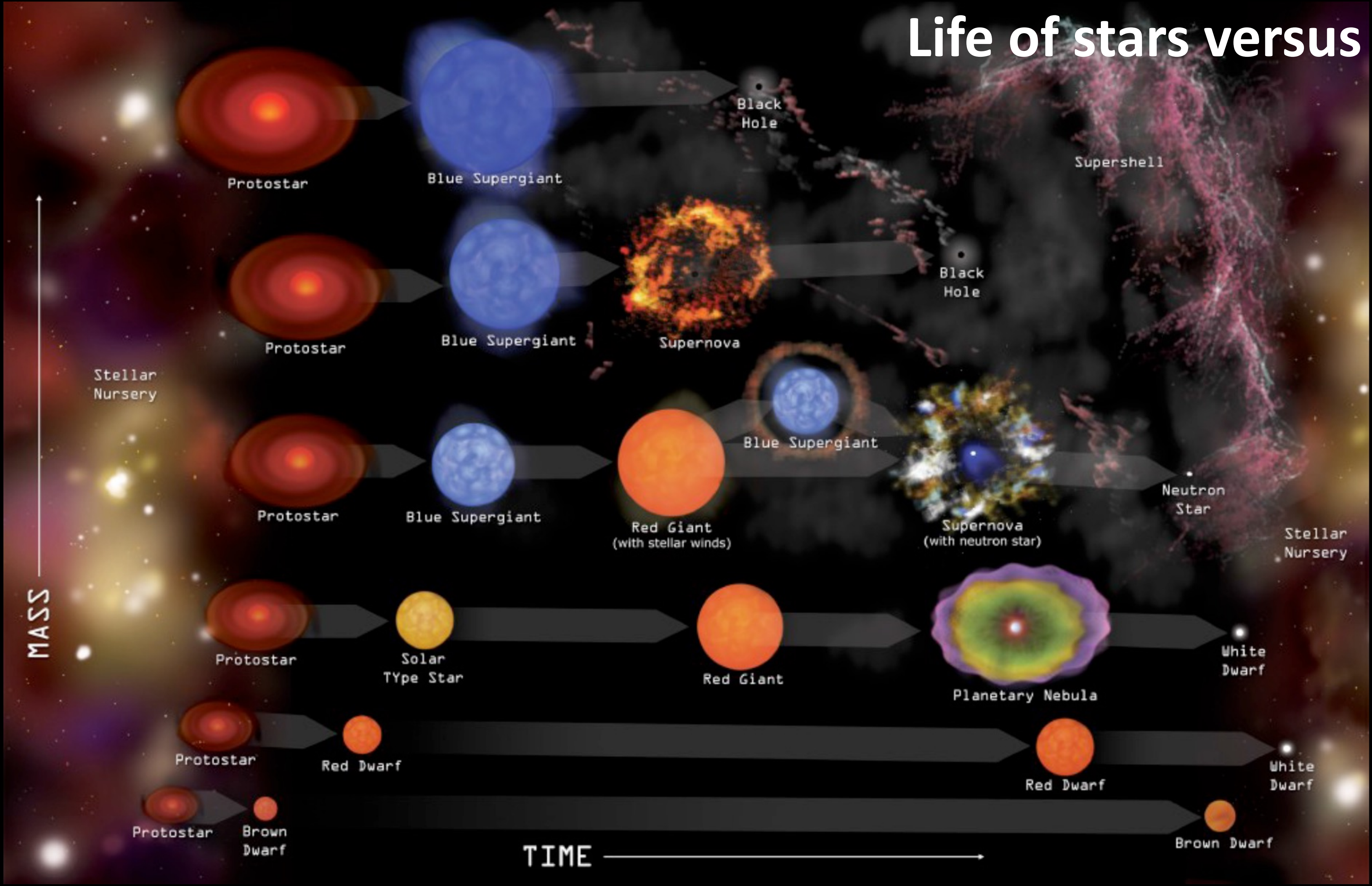


Crab Nebula (supernova in 1054, seen by Chinese astronomers)

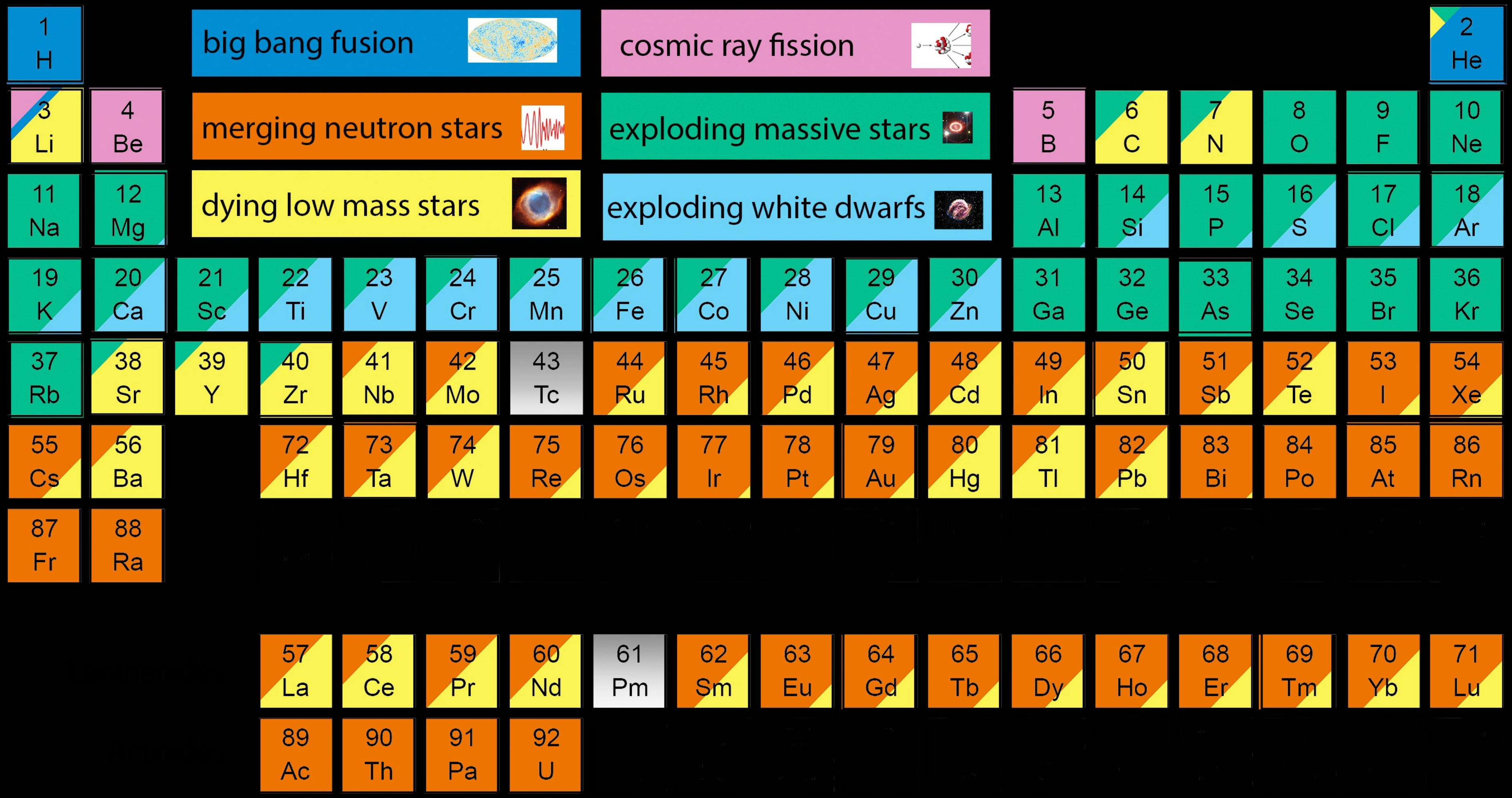


Supernova and other stellar explosions form heavy elements!

Life of stars versus mass



The Origin of the Solar System Elements



Graphic created by Jennifer Johnson

Astronomical Image Credits:
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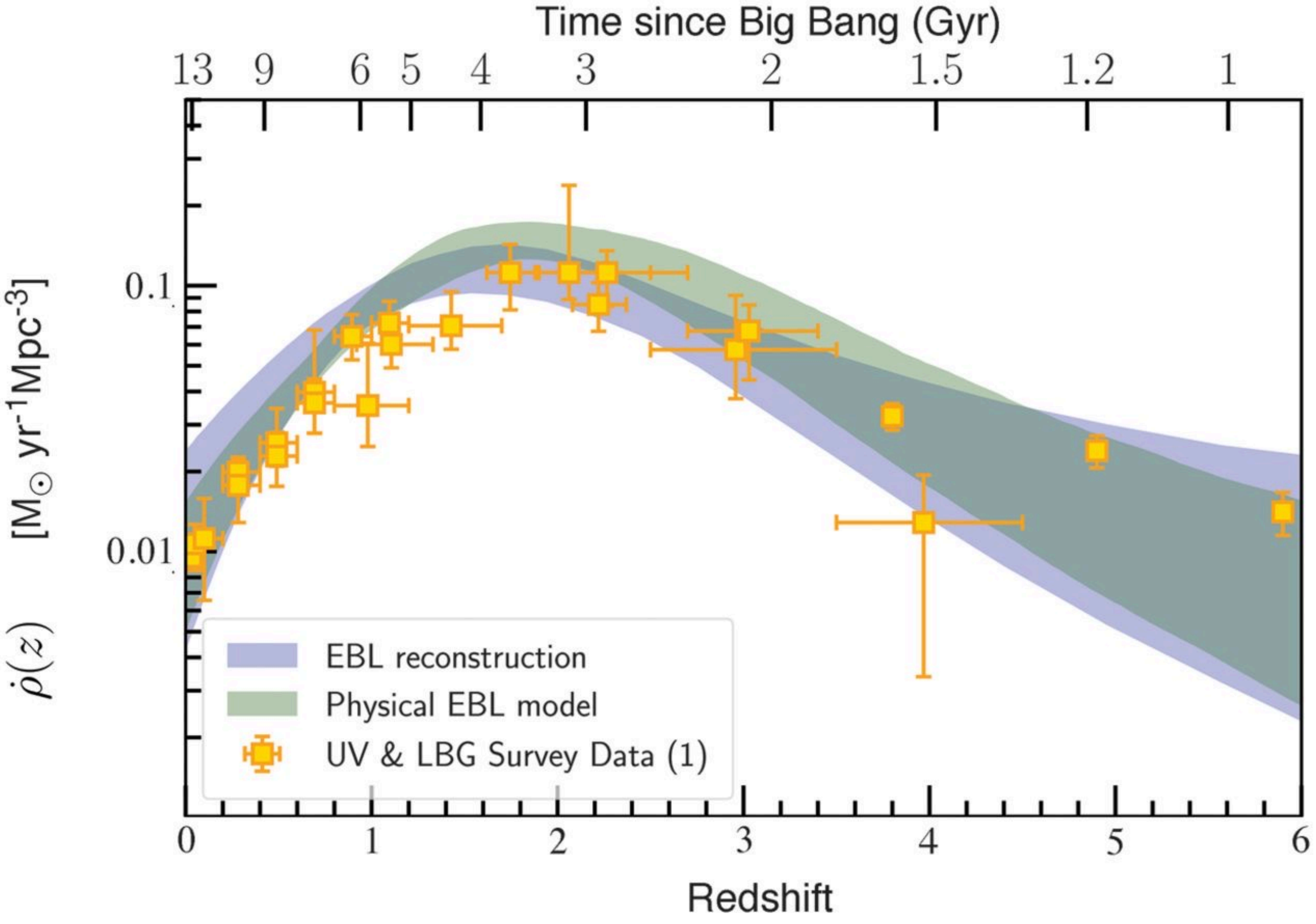
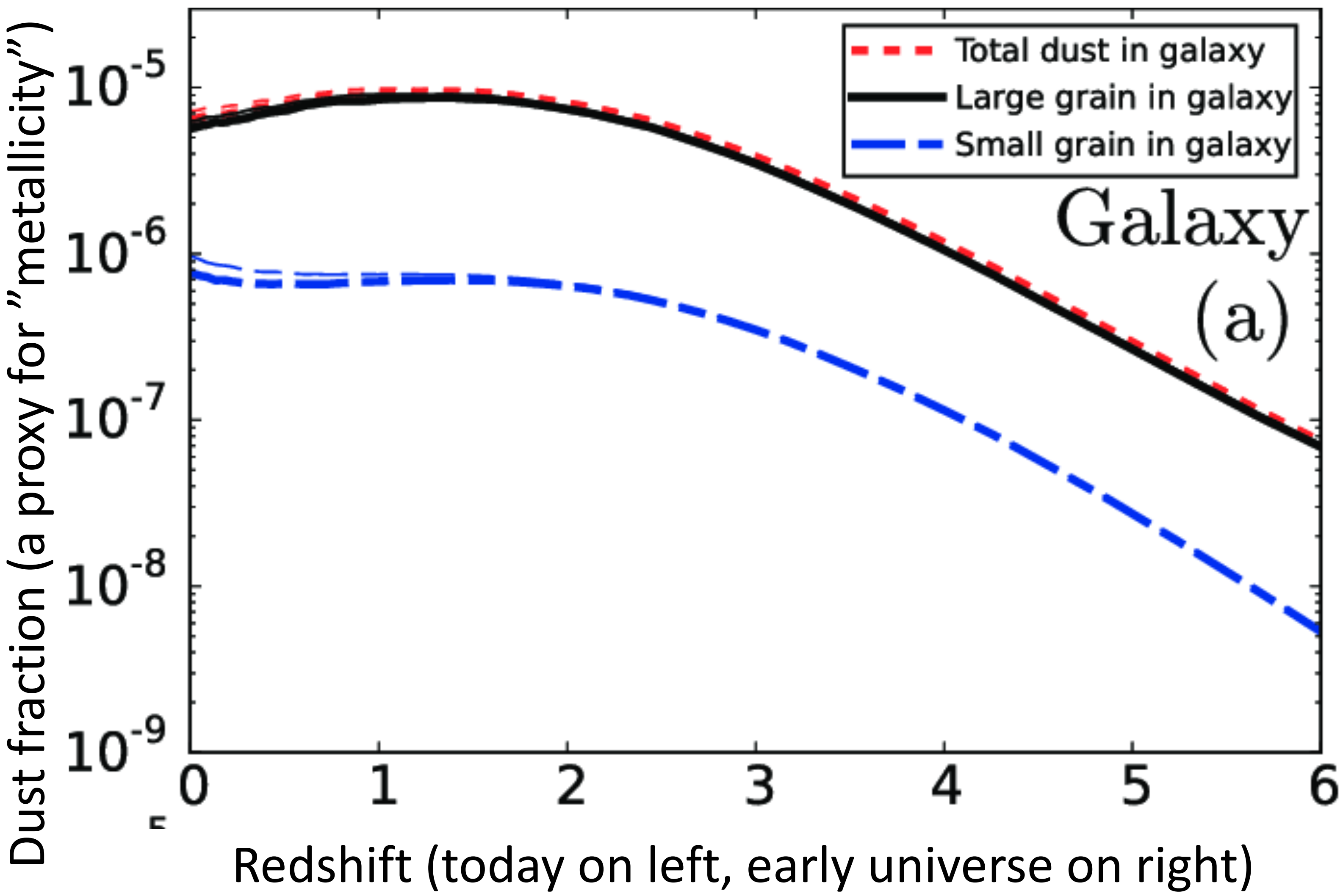
Star formation history of the universe



- Solar system formed at z=0.45

Enrichment of universe



- In astronomy, everything not H or He is called a "metal". Seriously.
- Enough metals to form planets early.

Planets: detection methods

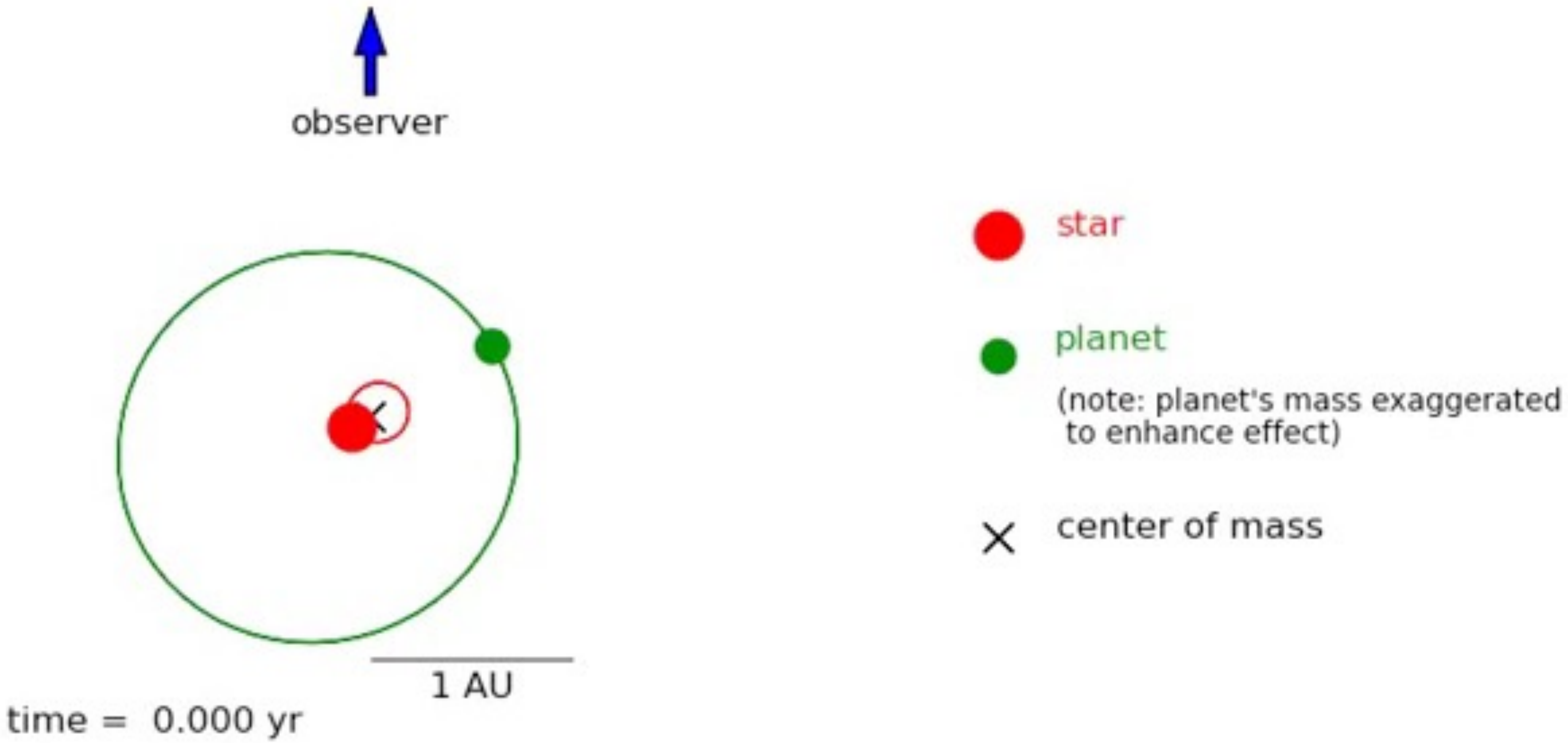
- How would you detect planets?

Planets: detection methods

- Radial velocity (motion of star in our line-of-sight)
- Transit photometry
- Direct imaging
- Astrometry (motion of star on sky)
- Microlensing
- Transit Timing Variation

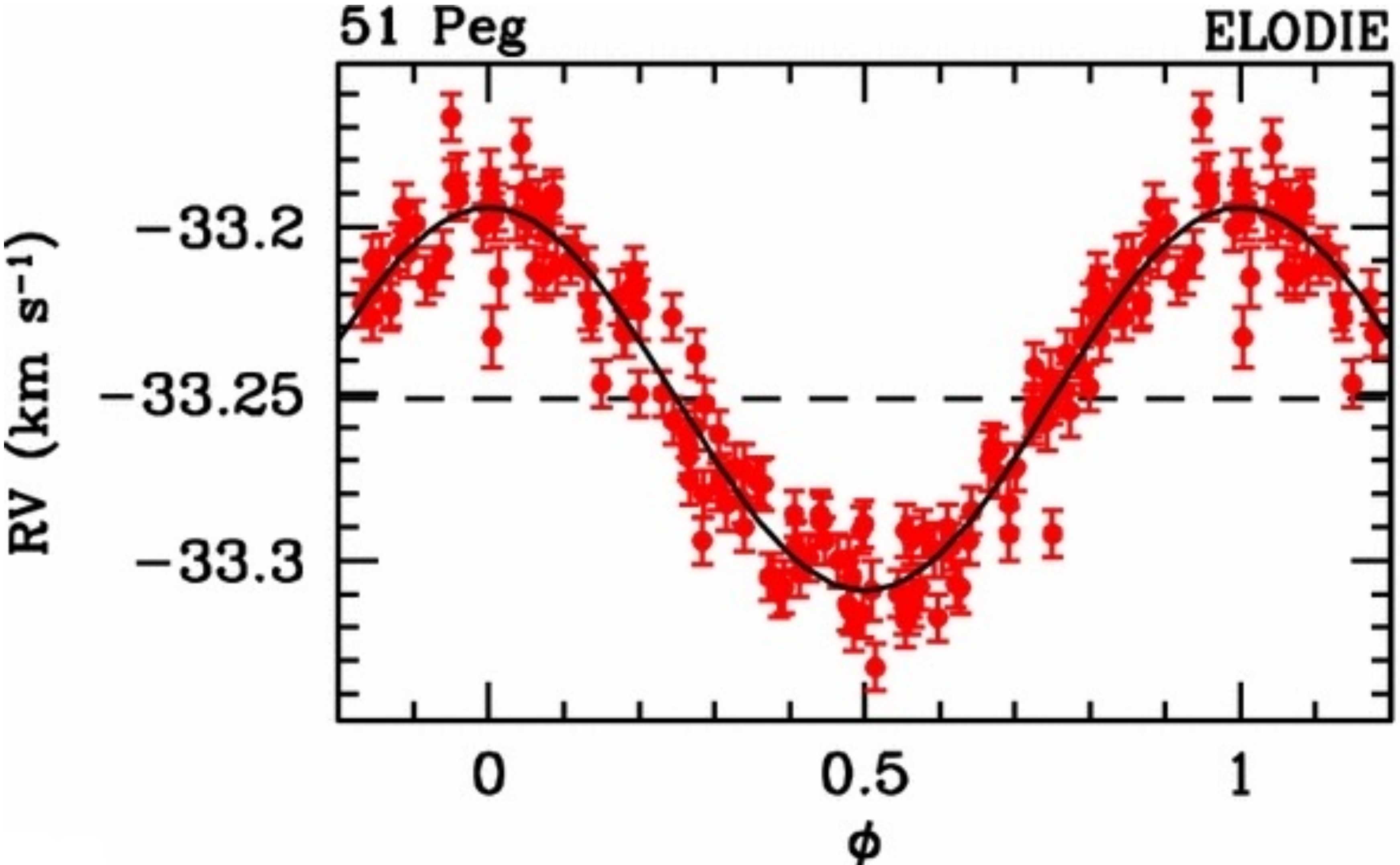
Radial velocity

- Planets go around a star (center of mass): gravity
- Planets also pull on the star
- Logic out the equation


observer
star
planet
(note: planet's mass exaggerated
to enhance effect)
center of mass
1 AU
time = 0.000 yr

First planet detected around a sun-like star

(Mayor & Queloz 1995; Nobel Prize winning discovery)



a "hot" Jupiter

Jupiter-mass planet on a 4-day orbit:

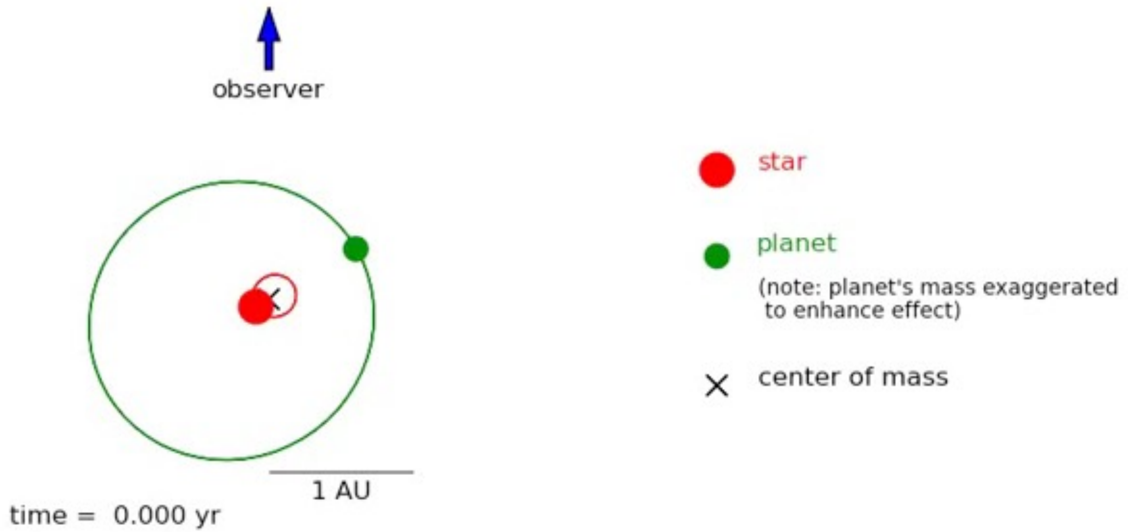
Radial velocity: limitations and biases

$$v_{\rm obs} = 28.4 \frac{M_P \sin i}{P_{\rm orb}^{1/3} M_*^{2/3}}$$

- M_P in Jupiter masses
- $P_{\rm orb}$ in years
- M_* in solar masses

Astrometry

- Planets go around a star (center of mass): gravity
- Planets also pull on the star
- Similar to radial velocity, but in plane of the sky
  - Centroiding of images is a different method



Techniques

Transit photometry

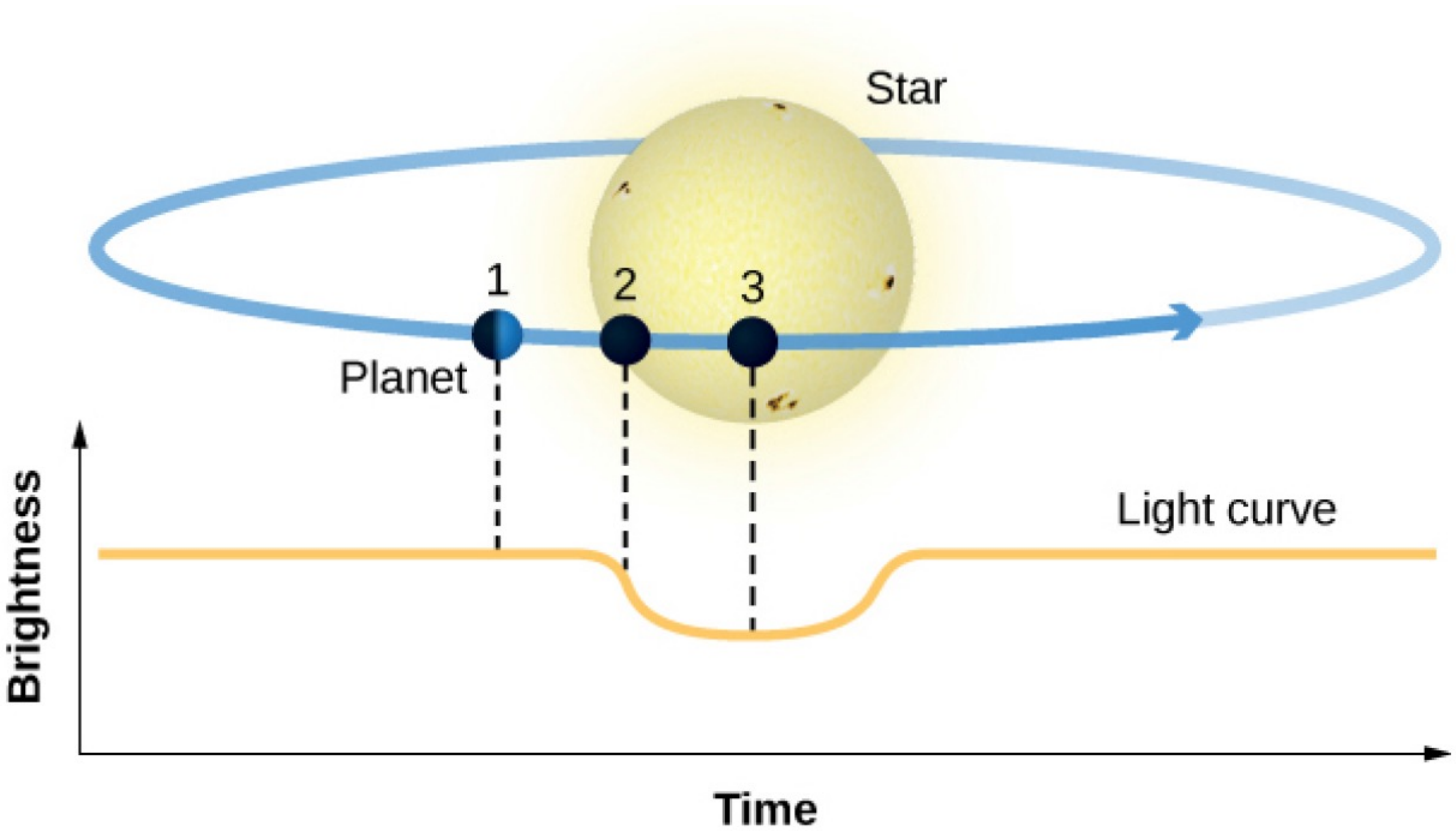
- Planet passes in front of the star
- What is the equation?

Transit photometry

- Planet passes in front of the star
- What is the equation?

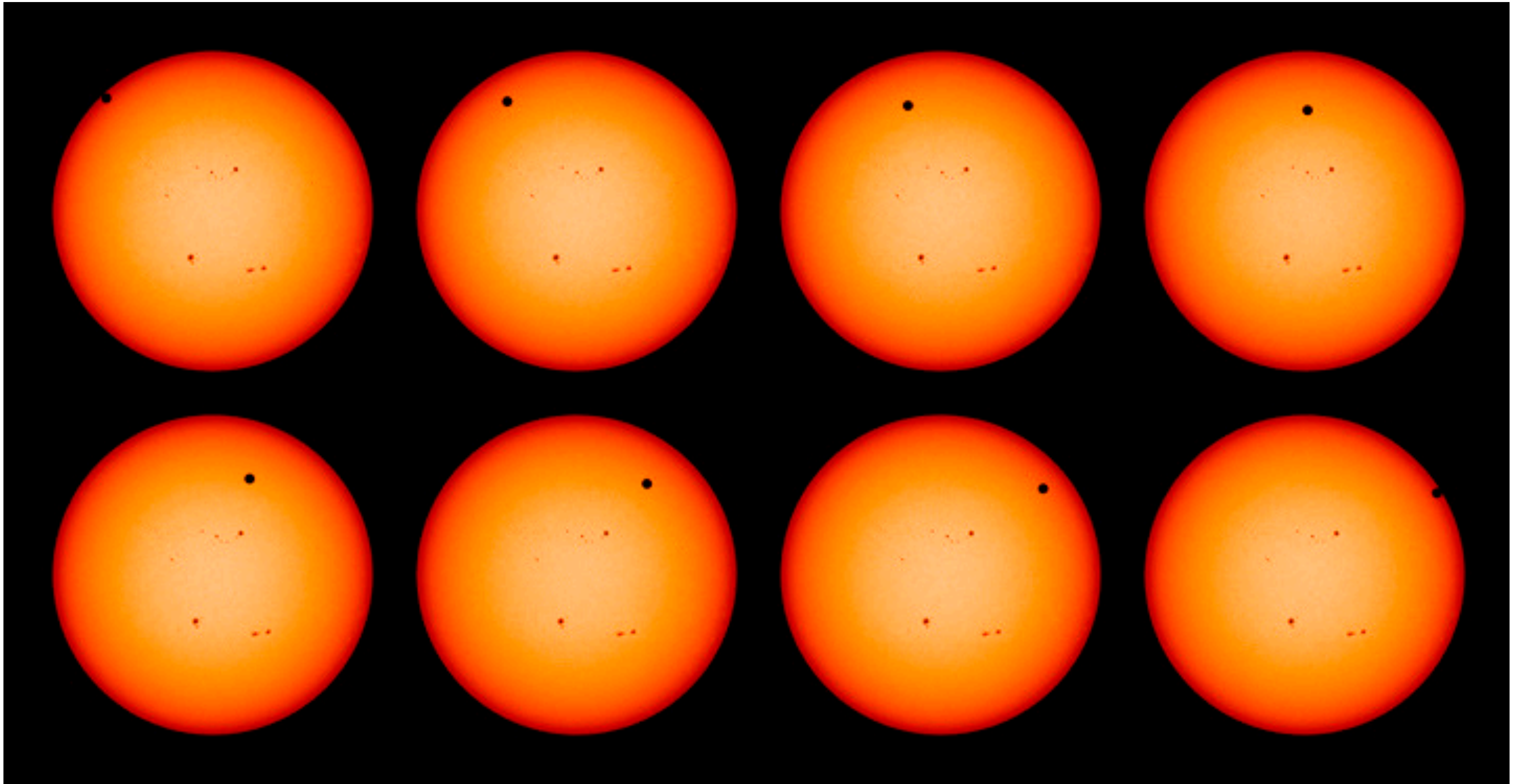
$$R_p = R_\star \sqrt{\text{Depth}}$$

Probability of transit:
R_{star}/star-planet distance


Star
1
2
3
Planet
Brightness
Light curve
Time

Venus transit

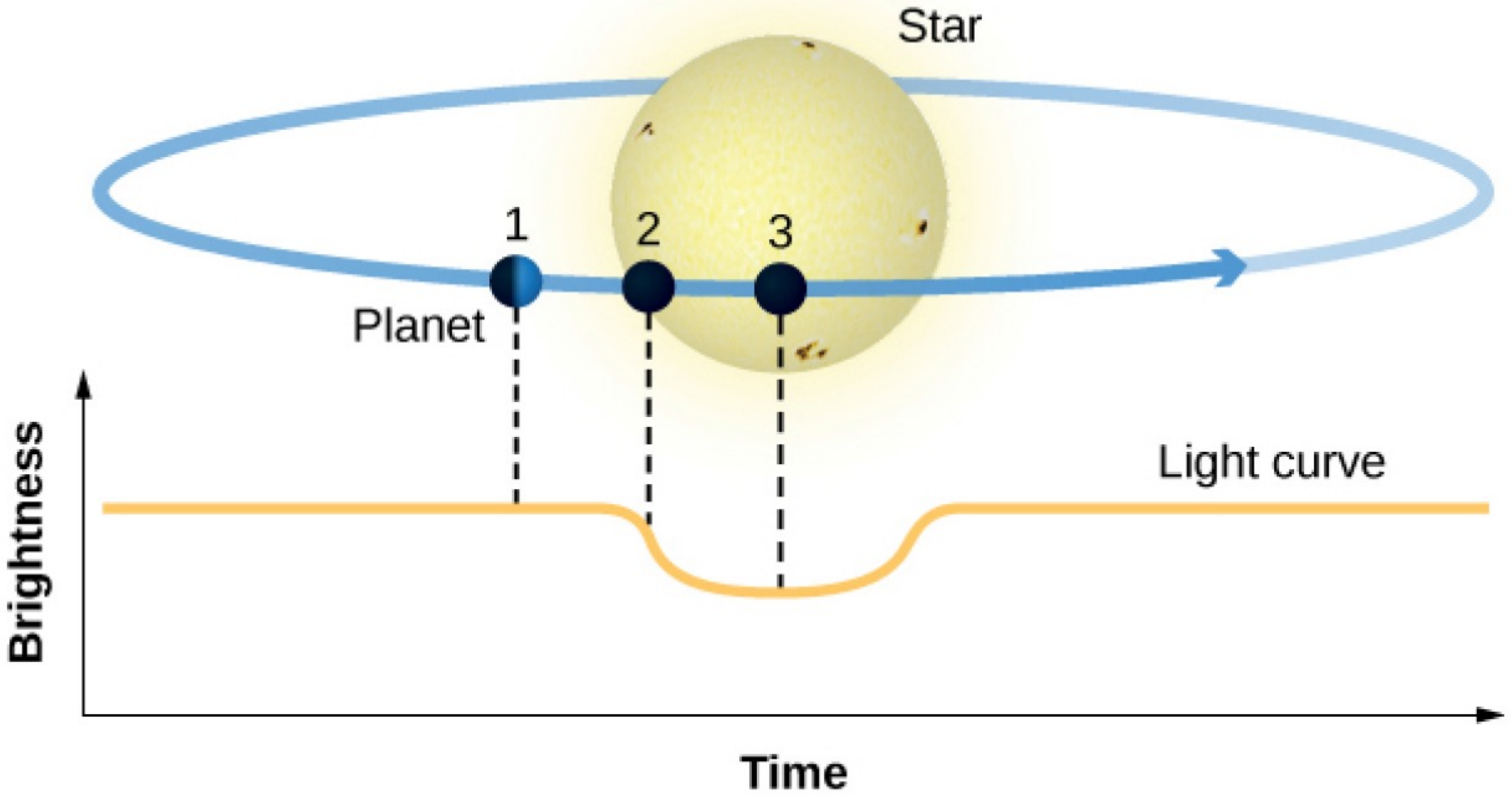
Every 112 years: (two times, separated by 8 years); most recently in 2004/2012



Venus transit

Guillaume Le Gentil: the unluckiest astronomer

1761/1769 transits from India?


Star
1
2
3
Planet
Light curve
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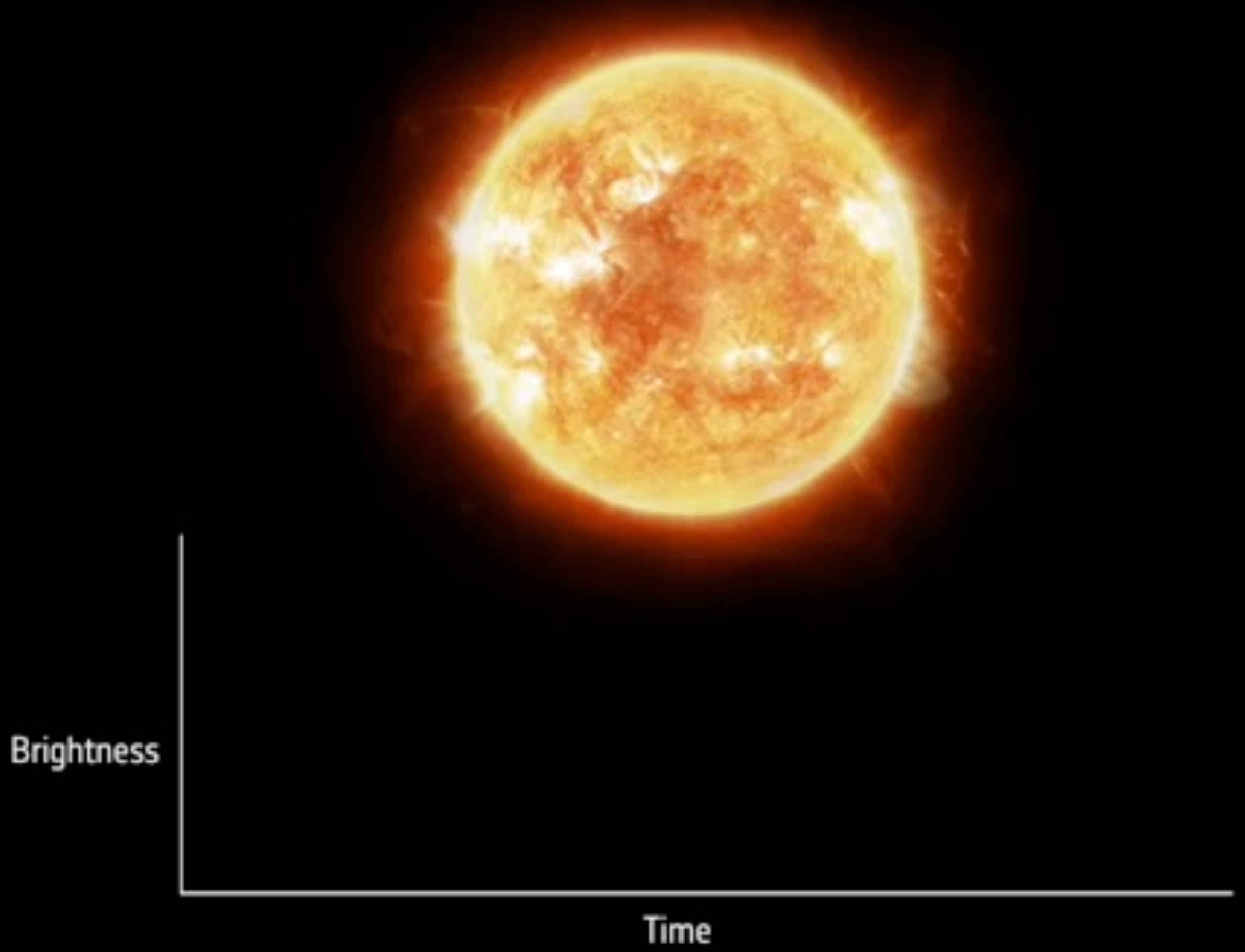
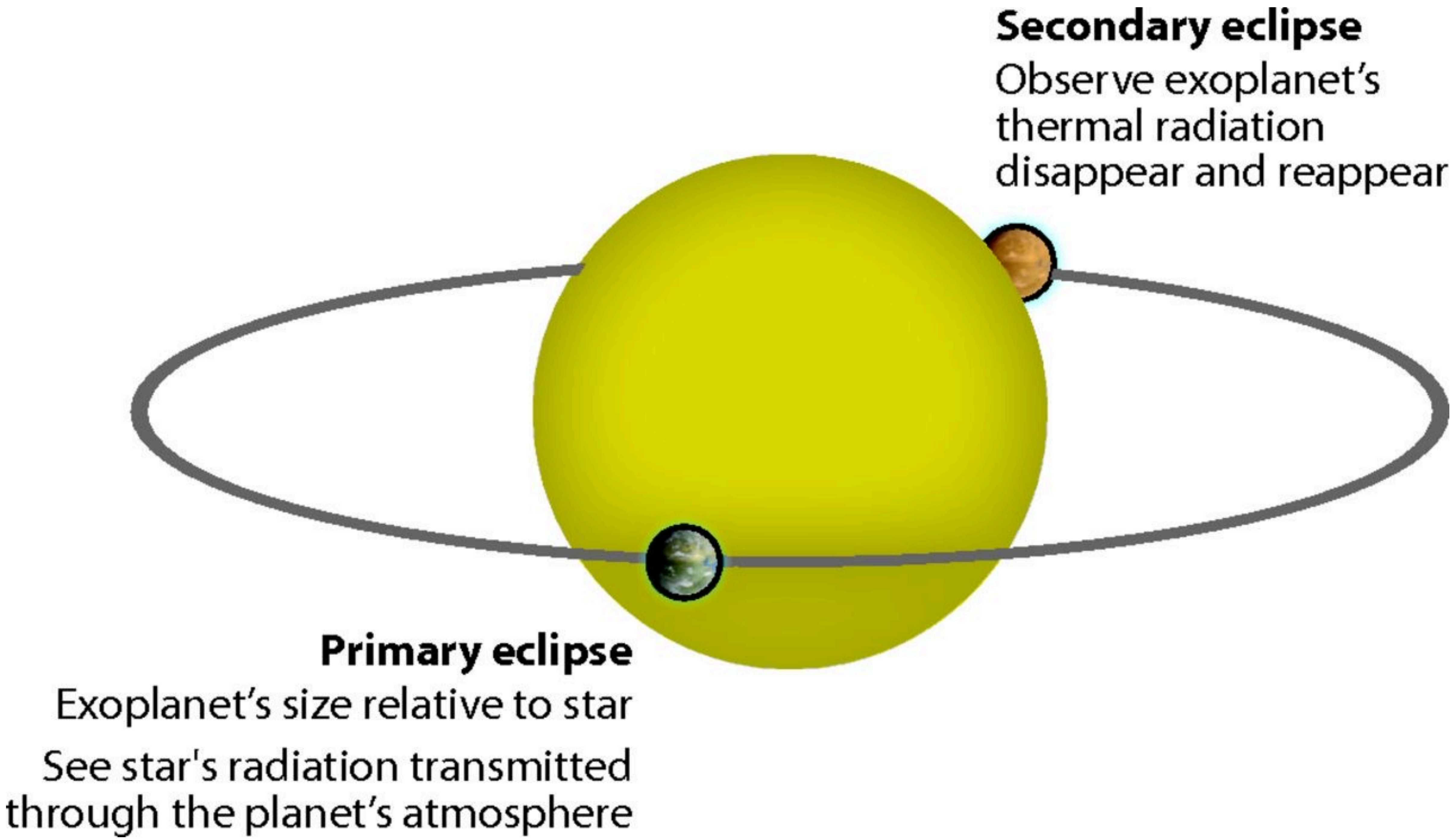
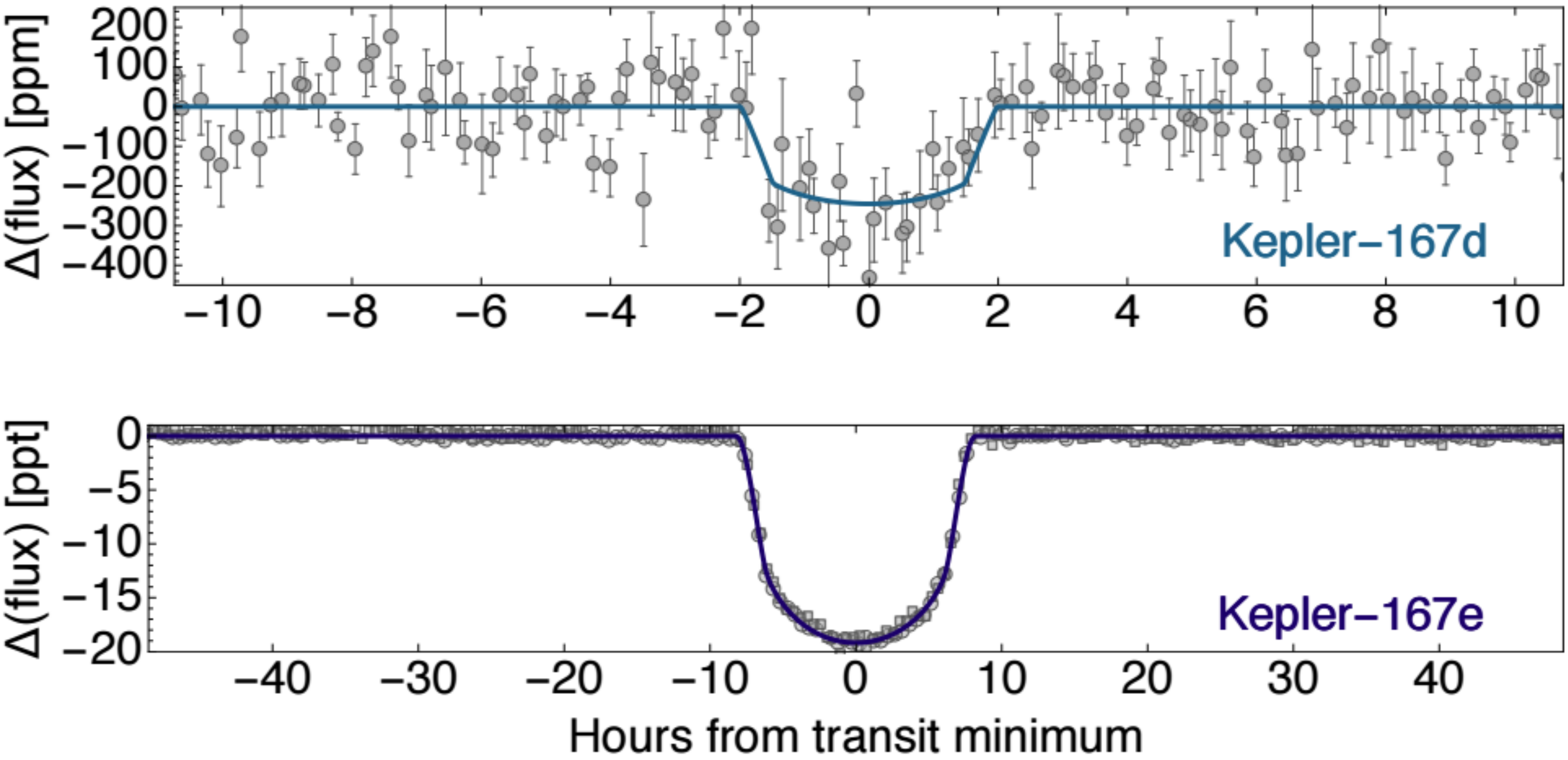

Brightness
Time


Secondary eclipse
Observe exoplanet's thermal radiation disappear and reappear
Primary eclipse
Exoplanet's size relative to star
See star's radiation transmitted through the planet's atmosphere


Δ(flux) [ppm]
200
100
0
−100
−200
−300
−400
Kepler−167d
−10
−8
−6
−4
−2
0
2
4
6
8
10
Δ(flux) [ppt]
0
−5
−10
−15
−20
Kepler−167e
−40
−30
−20
−10
0
10
20
30
40
Hours from transit minimum

Bias of transits

- What kinds of planets are easiest to detect?
  - Close to star
  - Large radius

$$R_p = R_\star \sqrt{\mathrm{Depth}}$$

Earth: 6.4e8 cm

Sun: 6.96e10 cm

Sun-Earth distance: 1.5e13 cm

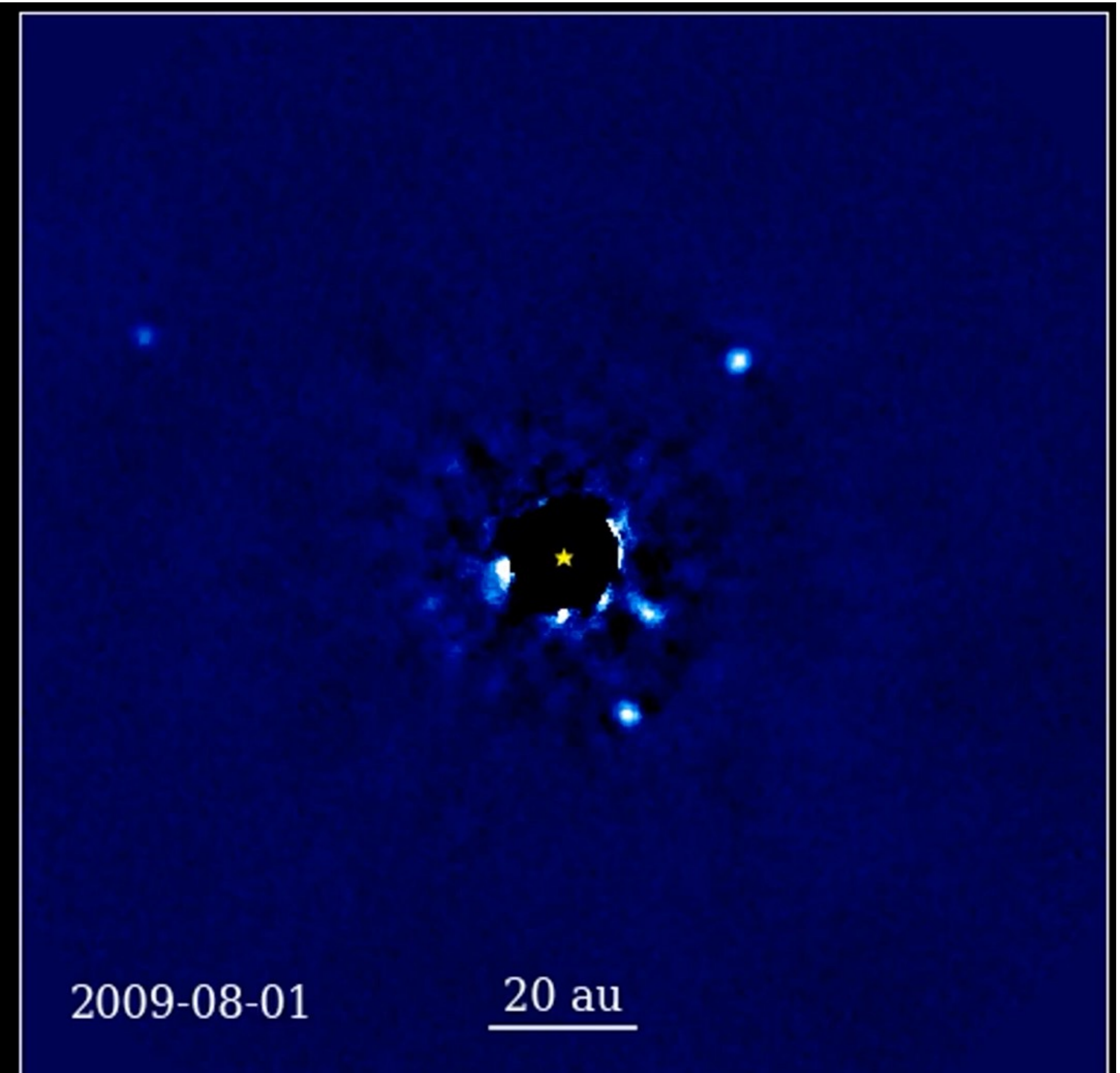
Probability of transit:
R_{star}/star-planet distance

(R_earth/Rsun)^2=10^{-4}

Kepler photometric precision: about 1e-5 (depends on brightness)

Likelihood of detecting Earth: 4e-5

Kepler: 150,000 stars, should detect 6 (but only a 3-year mission, many stars lower S/N)



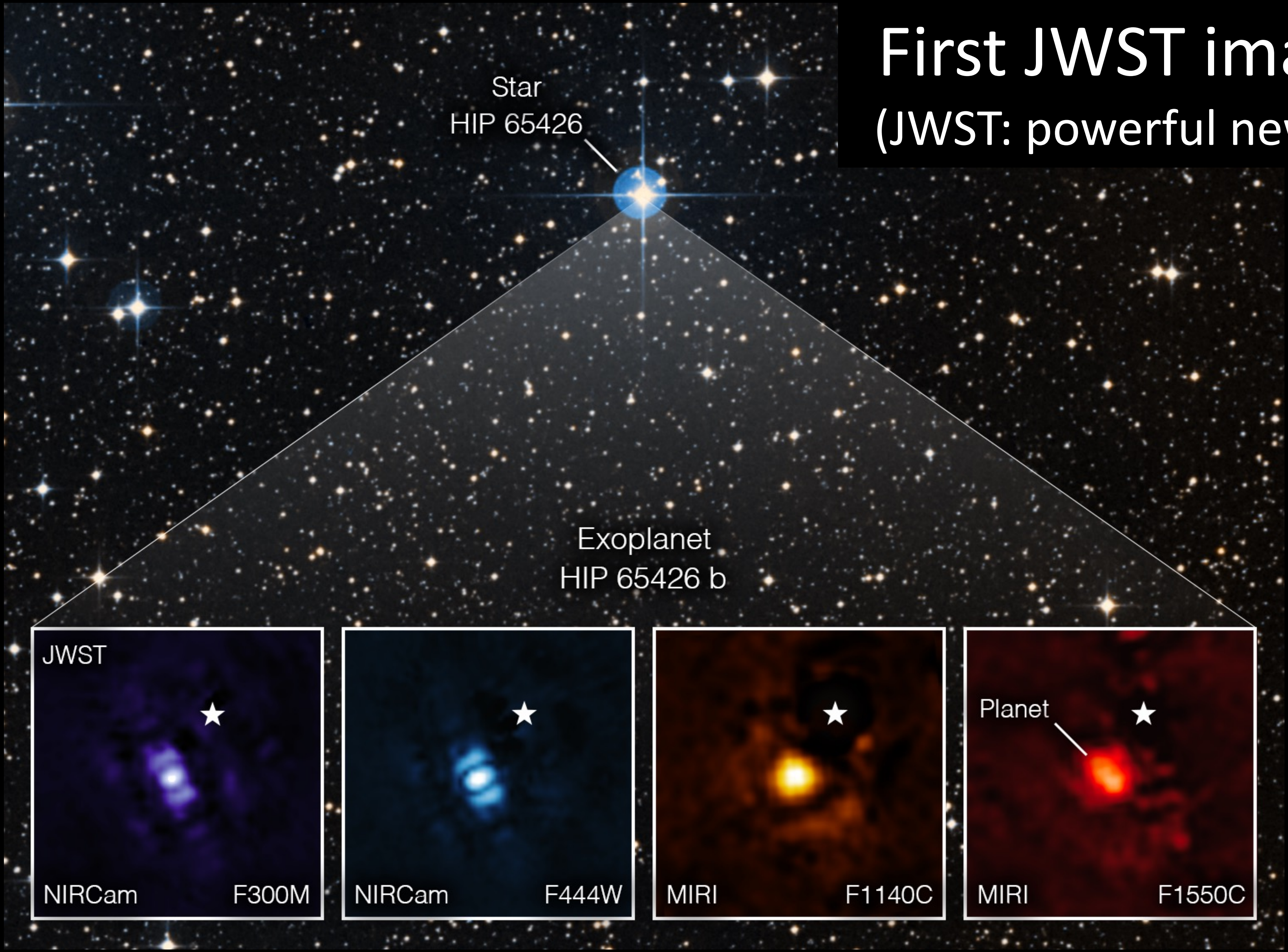
Direct Imaging:

requires coronagraph to block out a very bright star

- (similar to an eclipse)
- blocking bright starlight is not perfect

First JWST image of a planet

(JWST: powerful new infrared telescope)



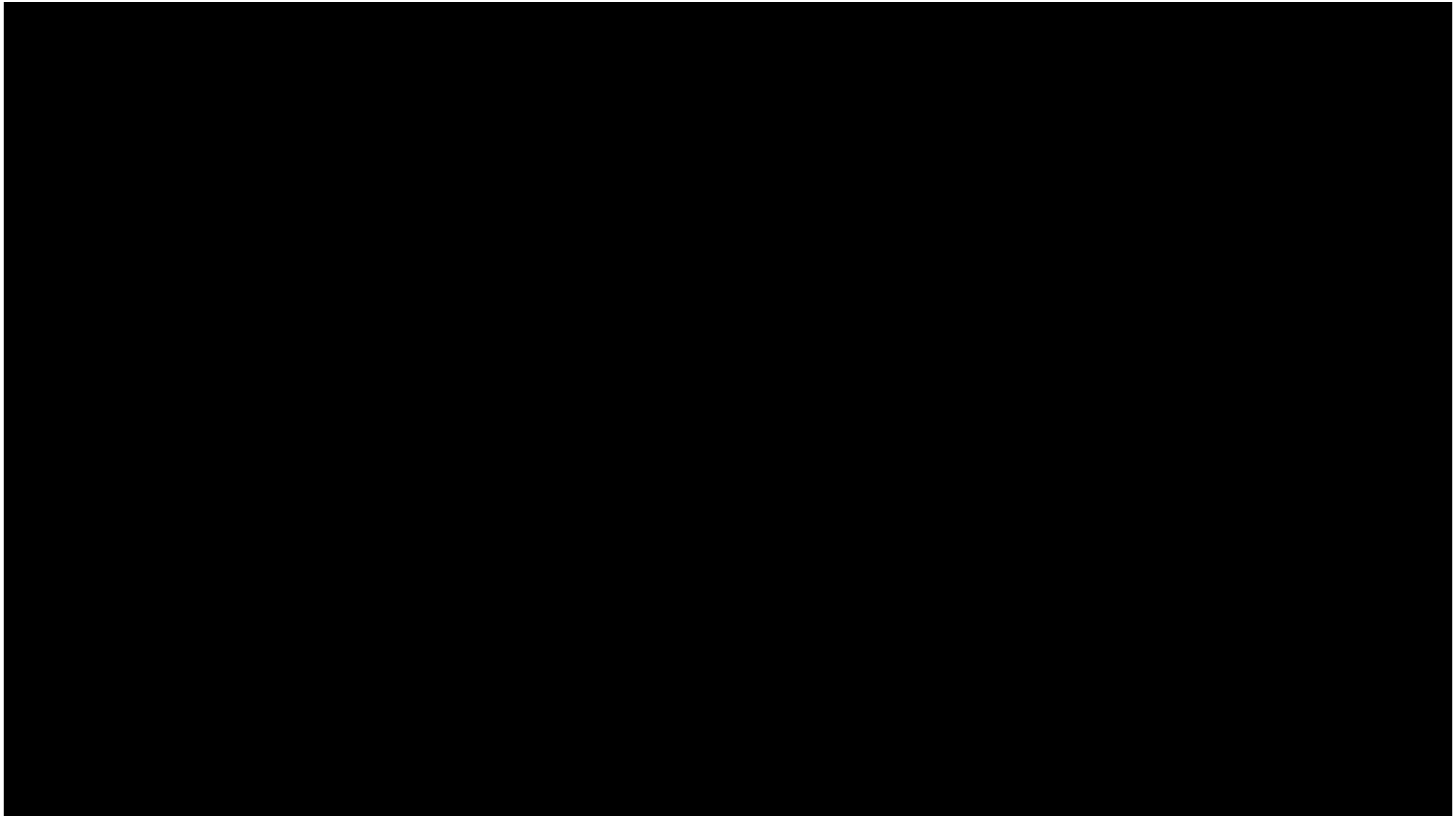
Biases of direct imaging

- What kinds of planets are easiest to detect?

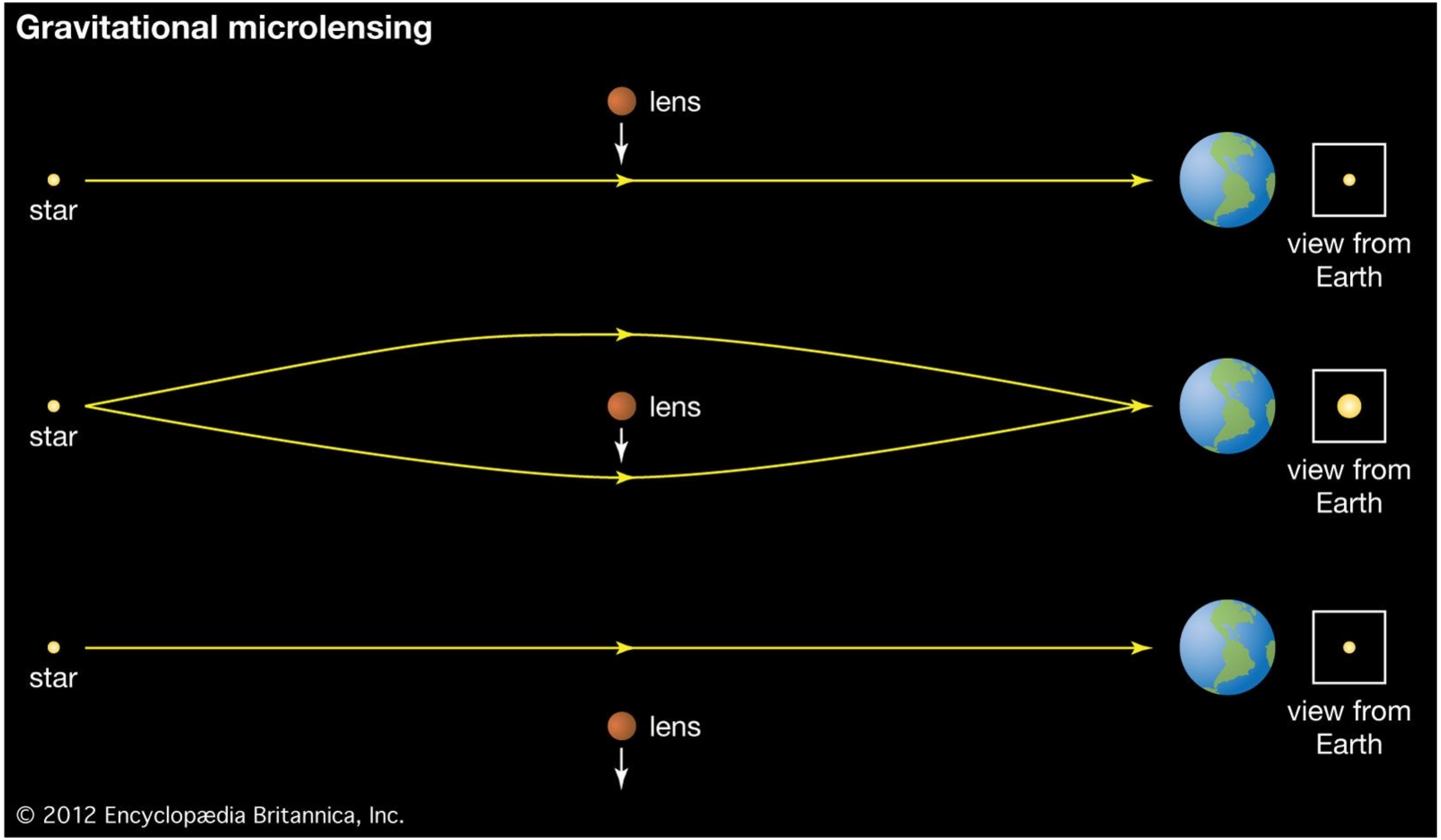
- Very bright (higher mass)
- Far from the star!

[also this is very hard]

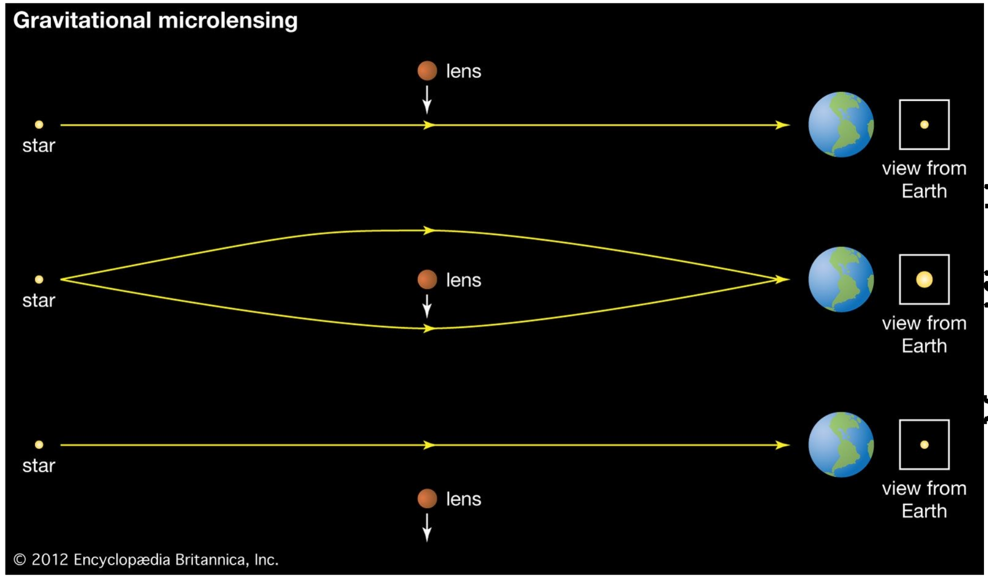
Transit Timing Variations (multi-planet systems)

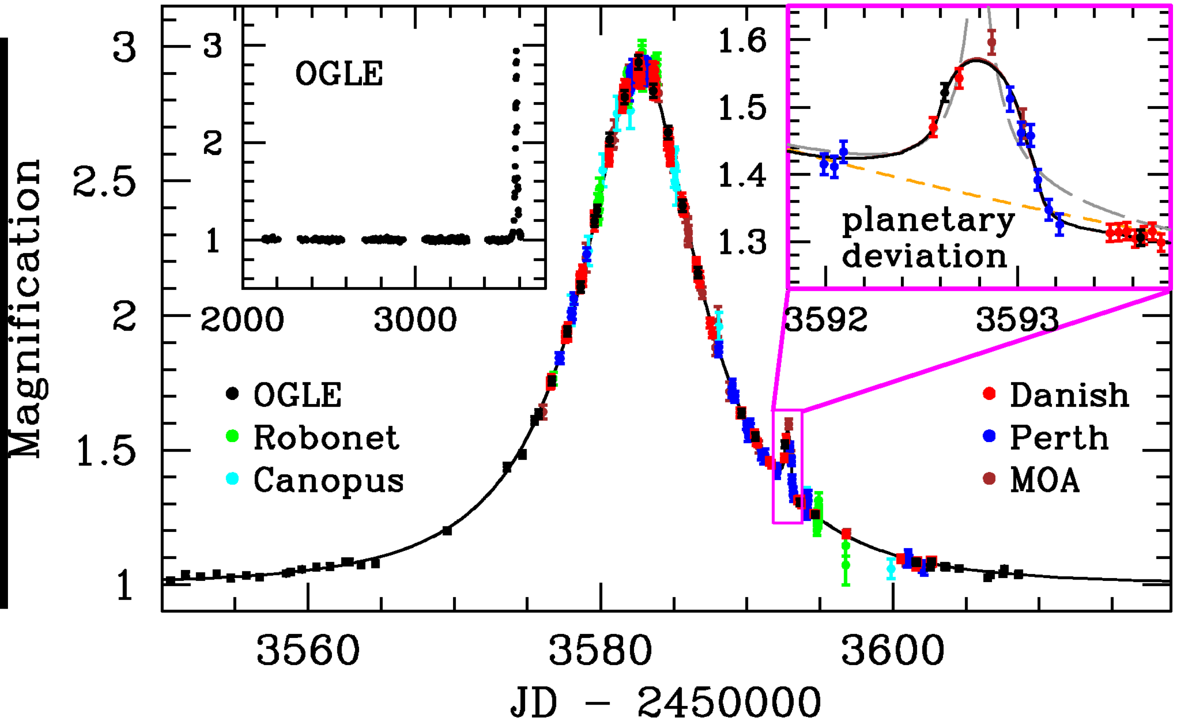


Microlensing discoveries of exoplanets



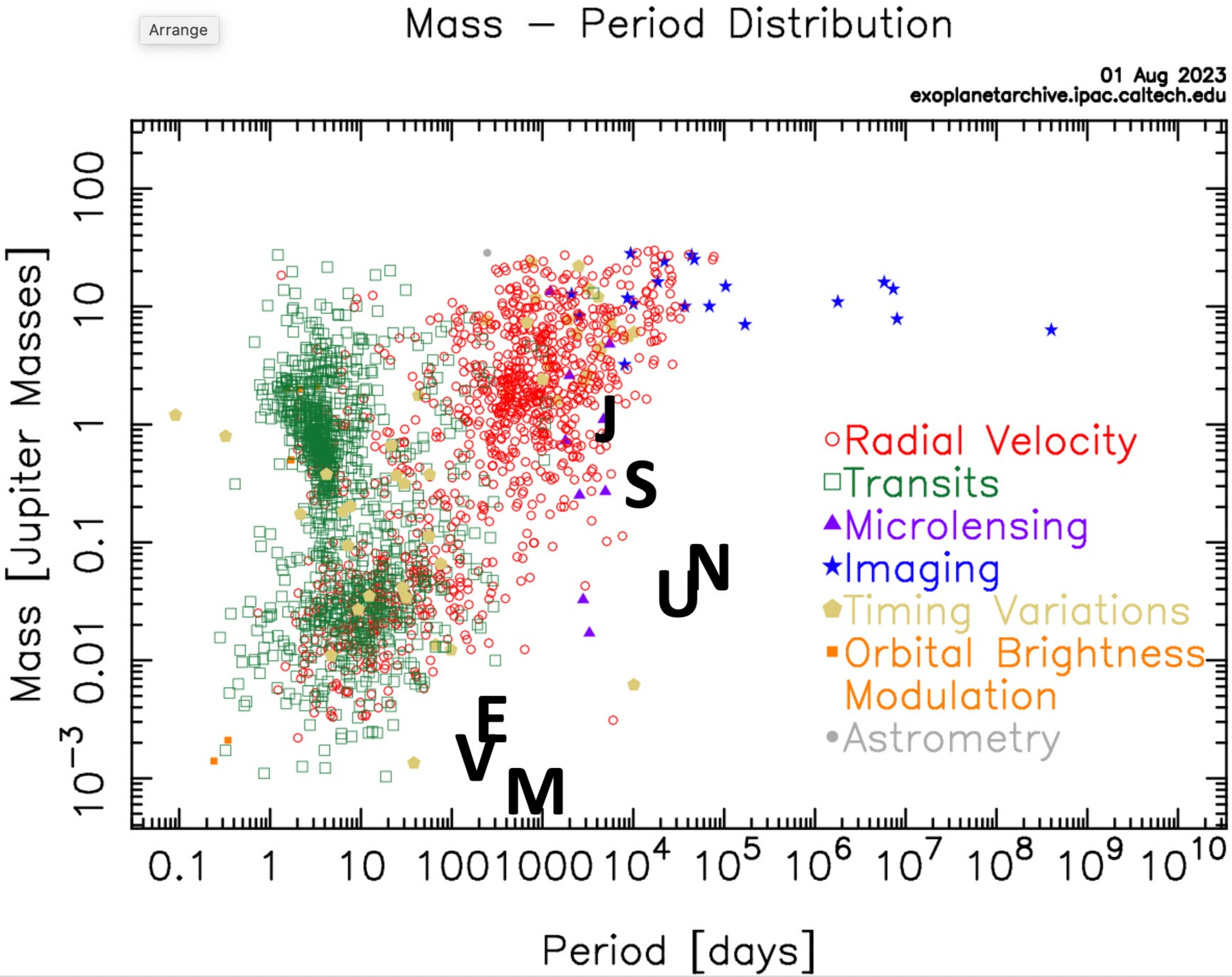
Microlensing discoveries of exoplanets





- Unusual geometry – need a lot of stars (stare at galactic center)
- Planet mass: equivalent to duration of deviation
- Limited follow-up
- Only current technique to measure frequency of true Earth analogs

Arrange



Group: Exoplanet
Summer School 2023