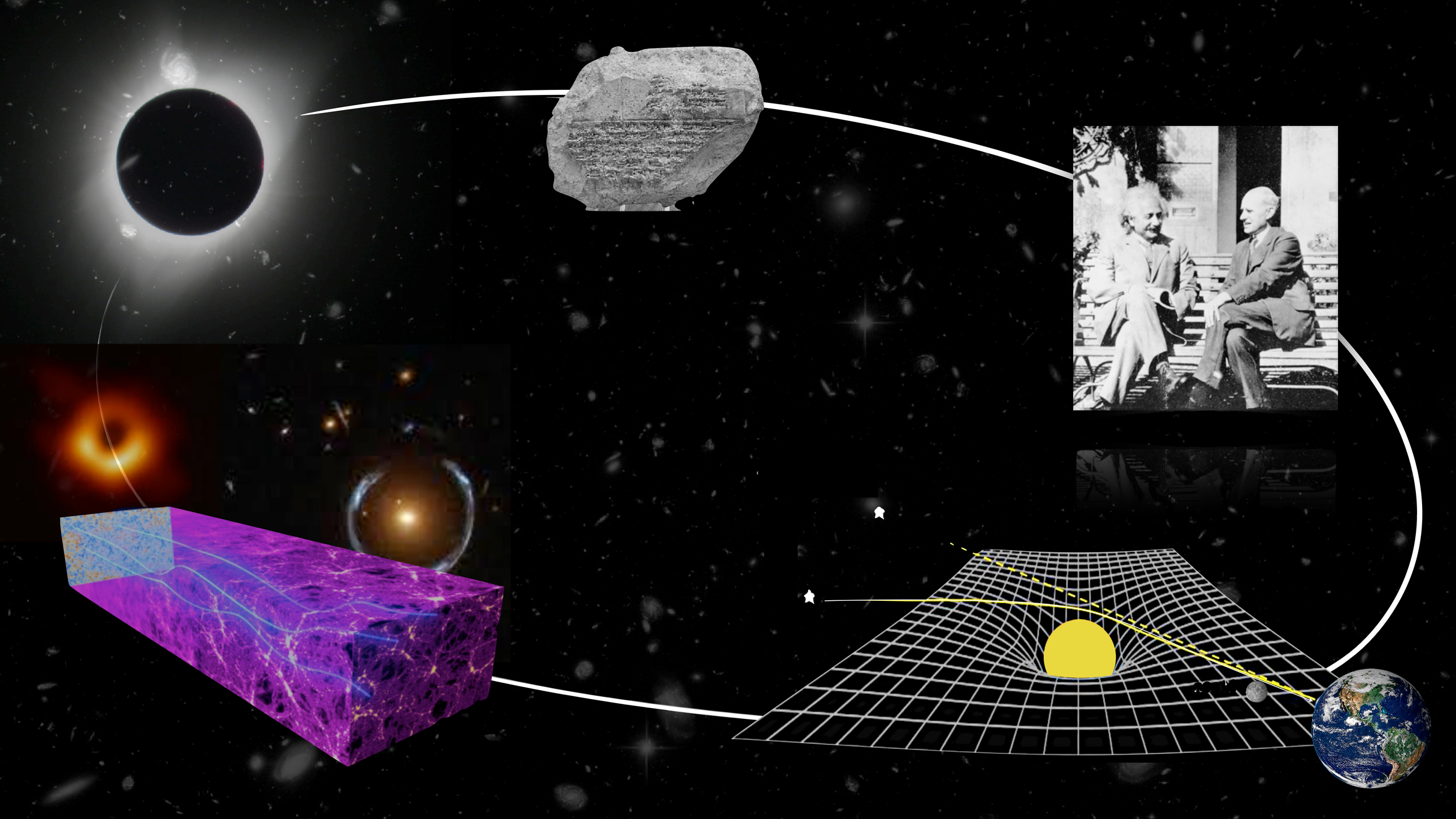
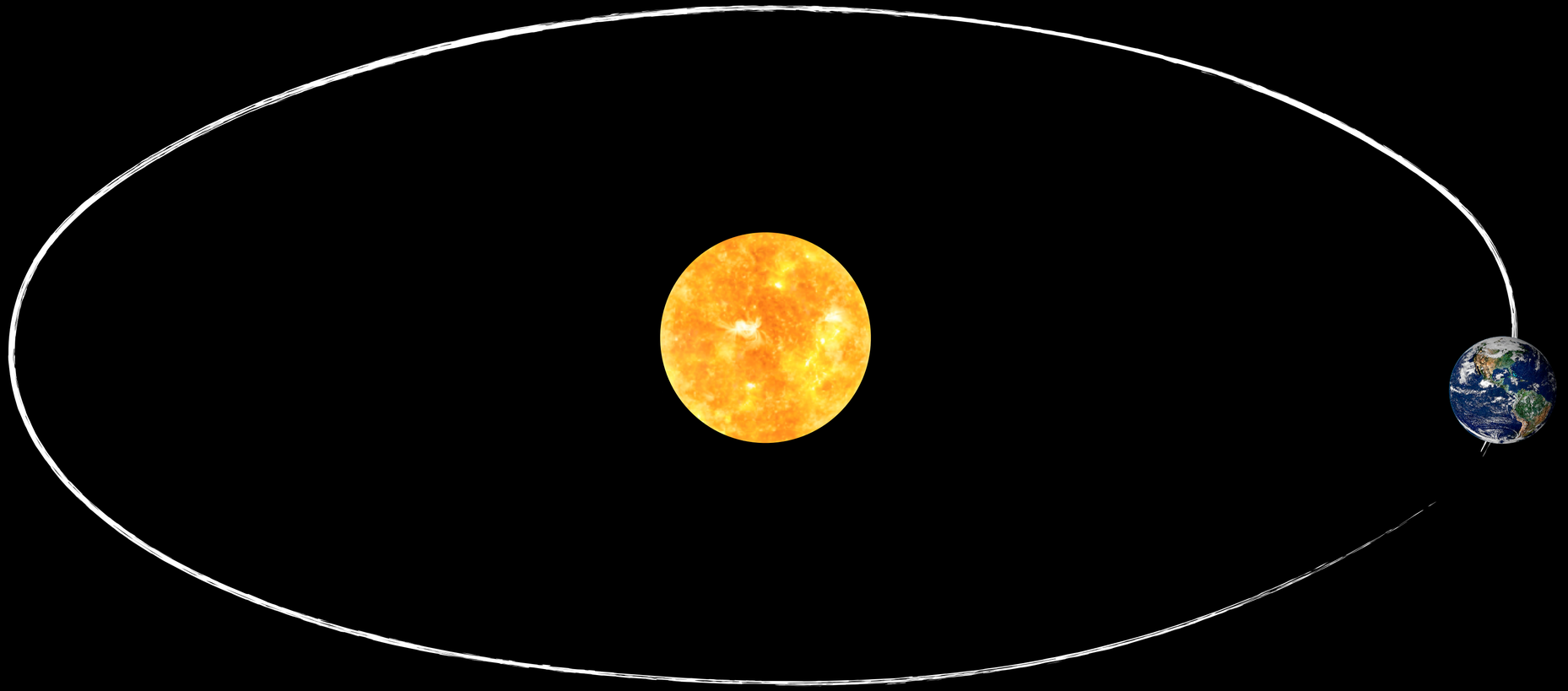
Light's "Straight" Path

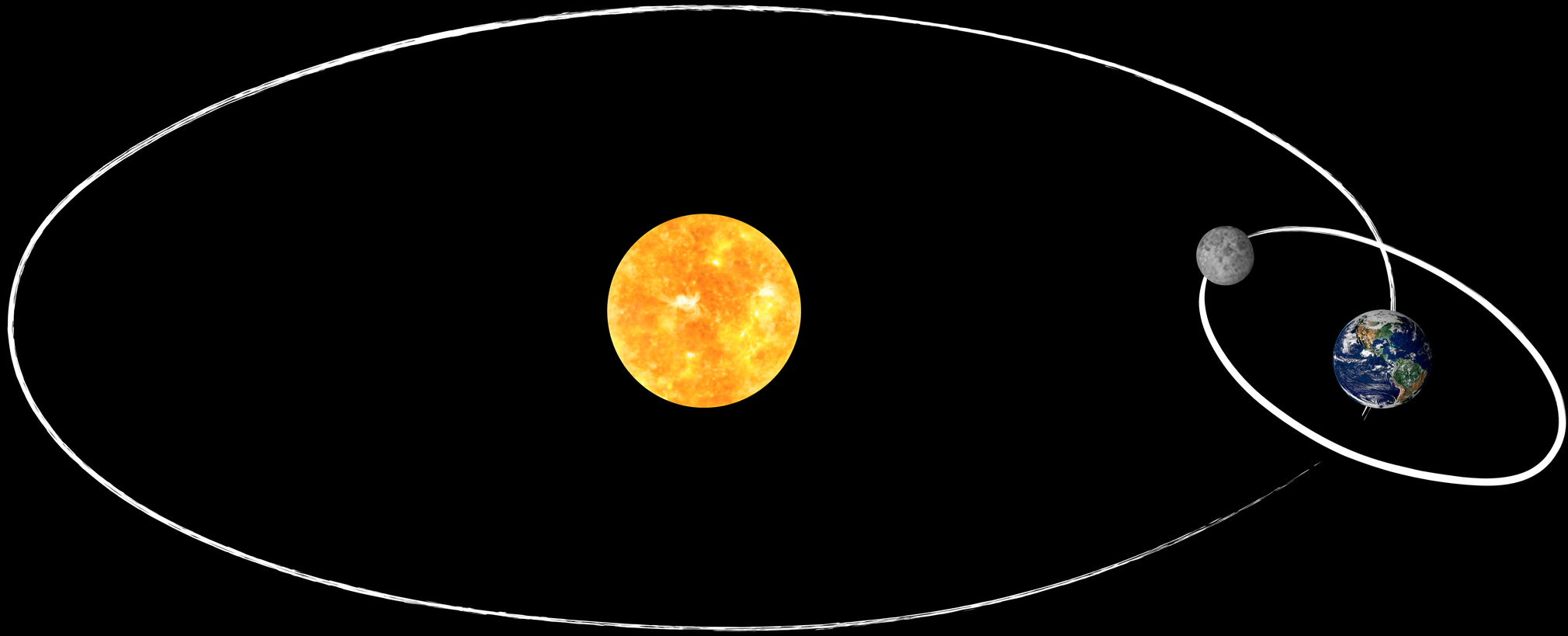
Mustafa A. Amin

Image credit: Finney



what is a solar eclipse ?





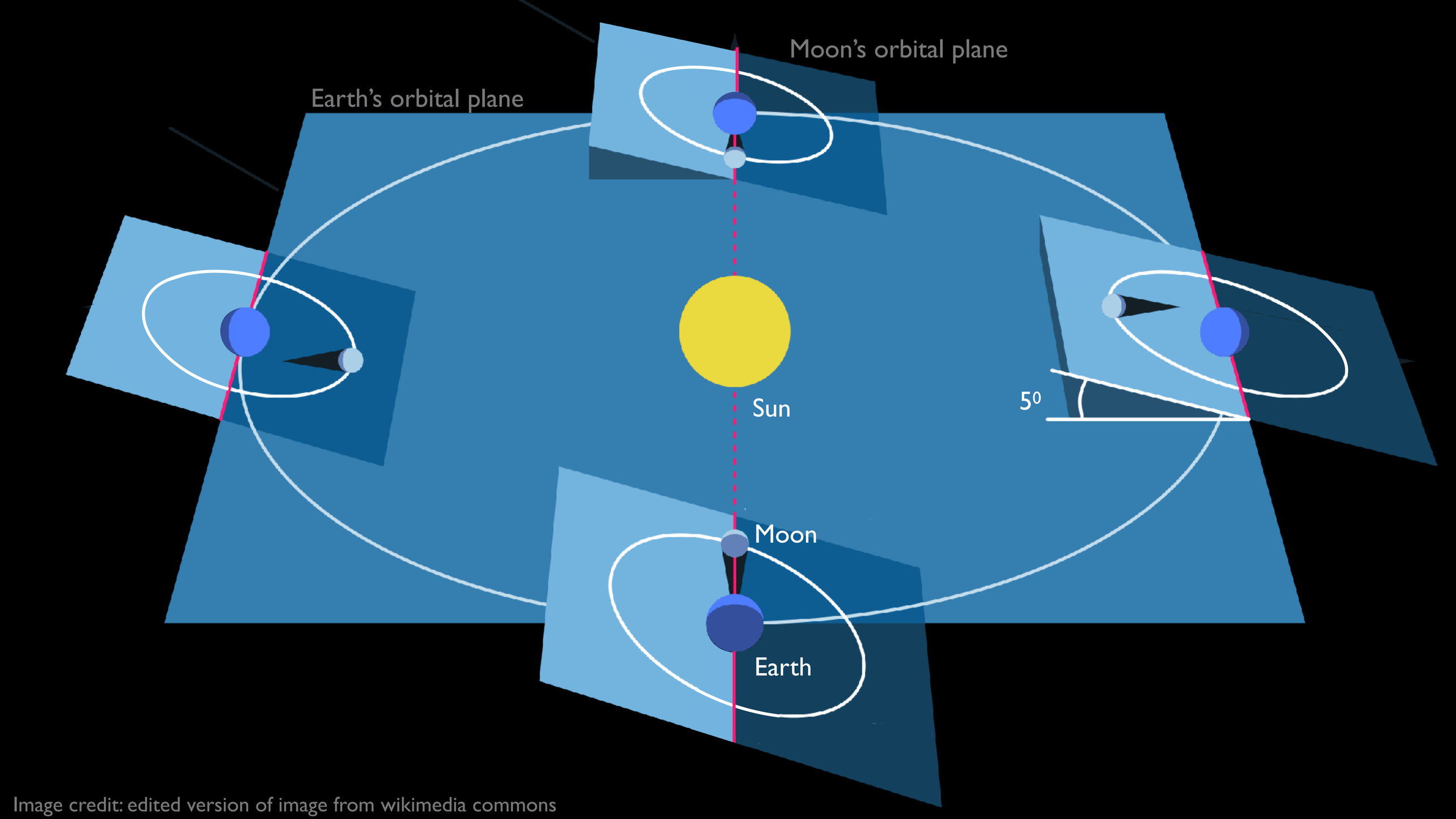
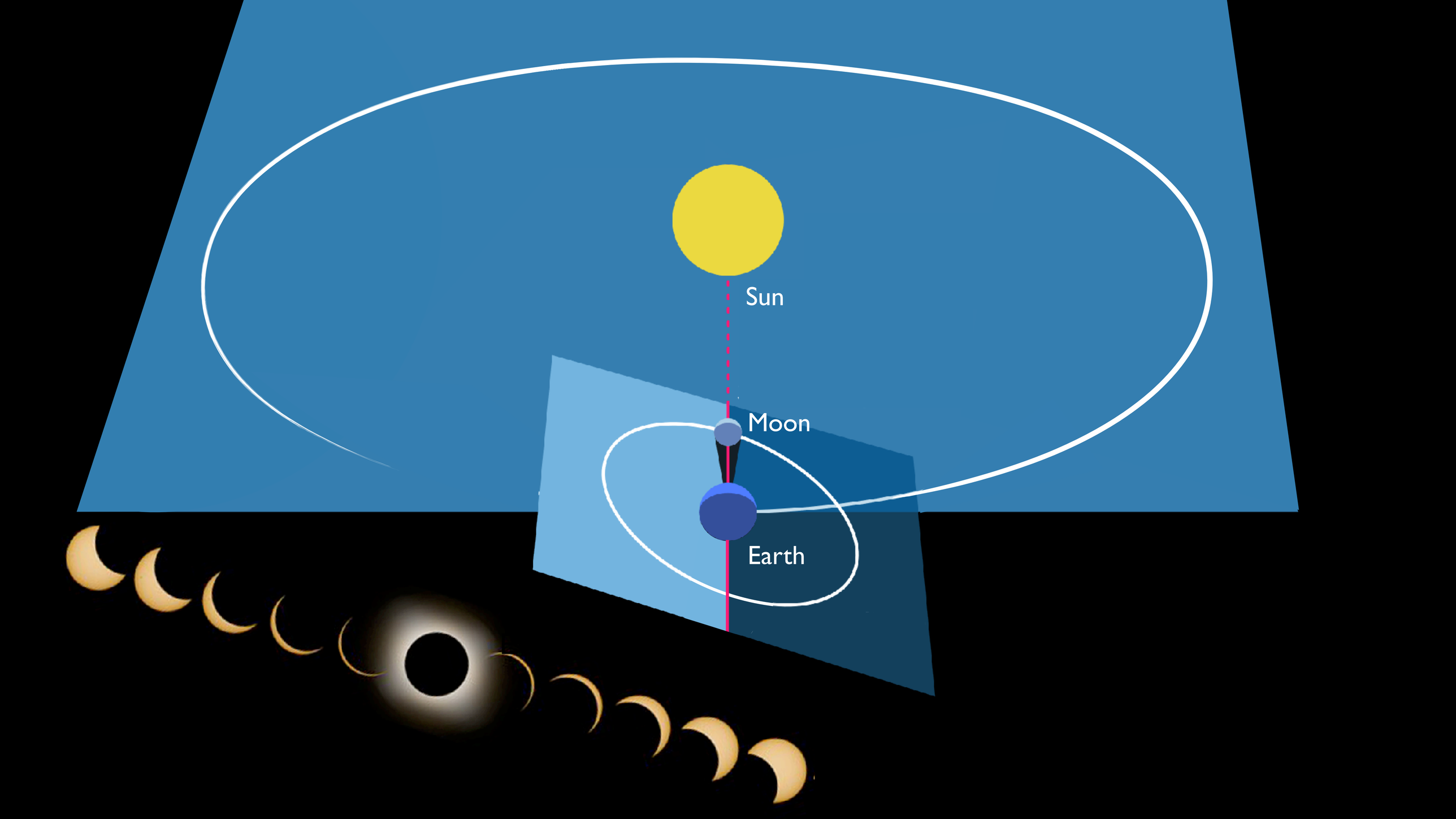
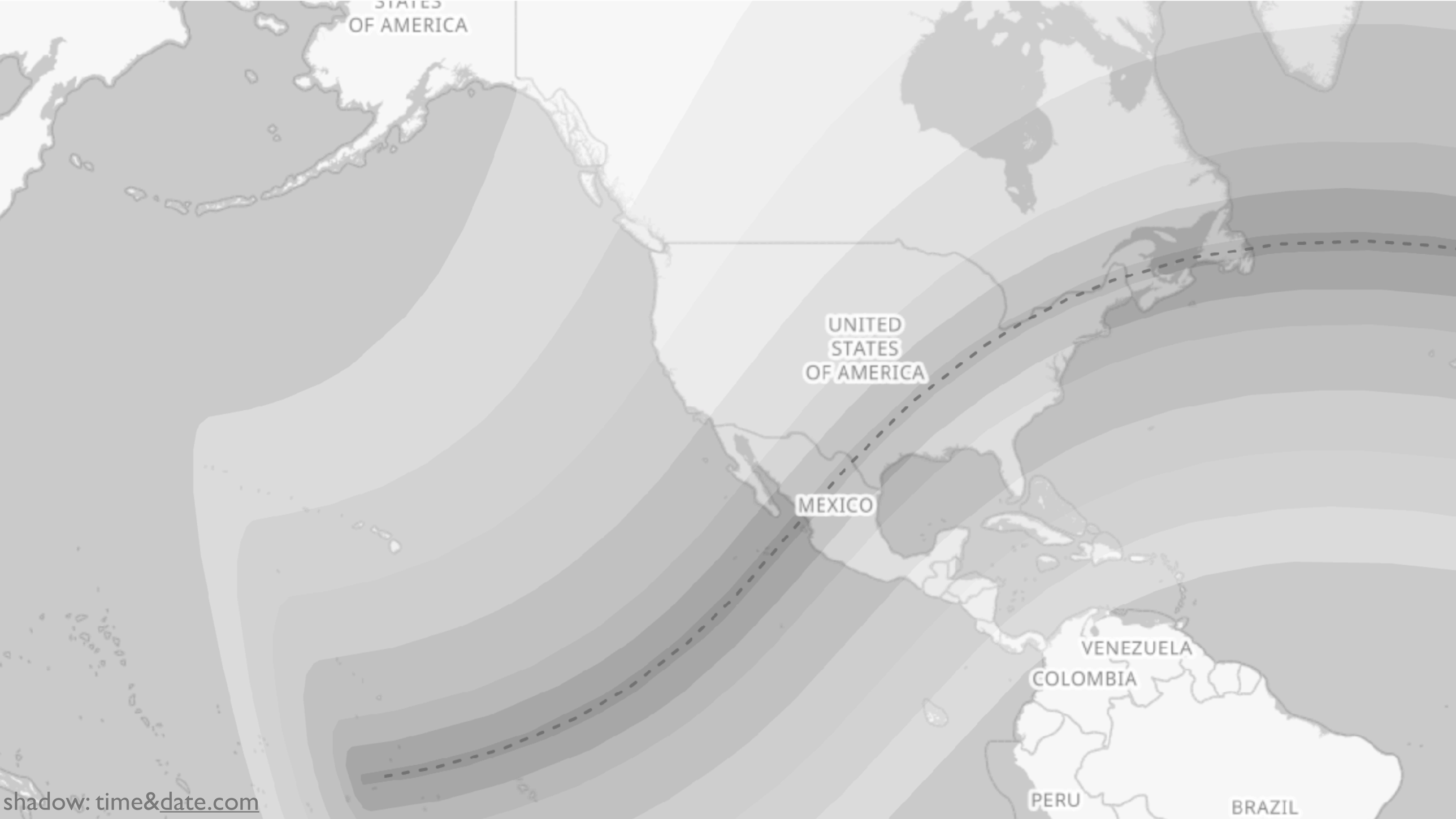


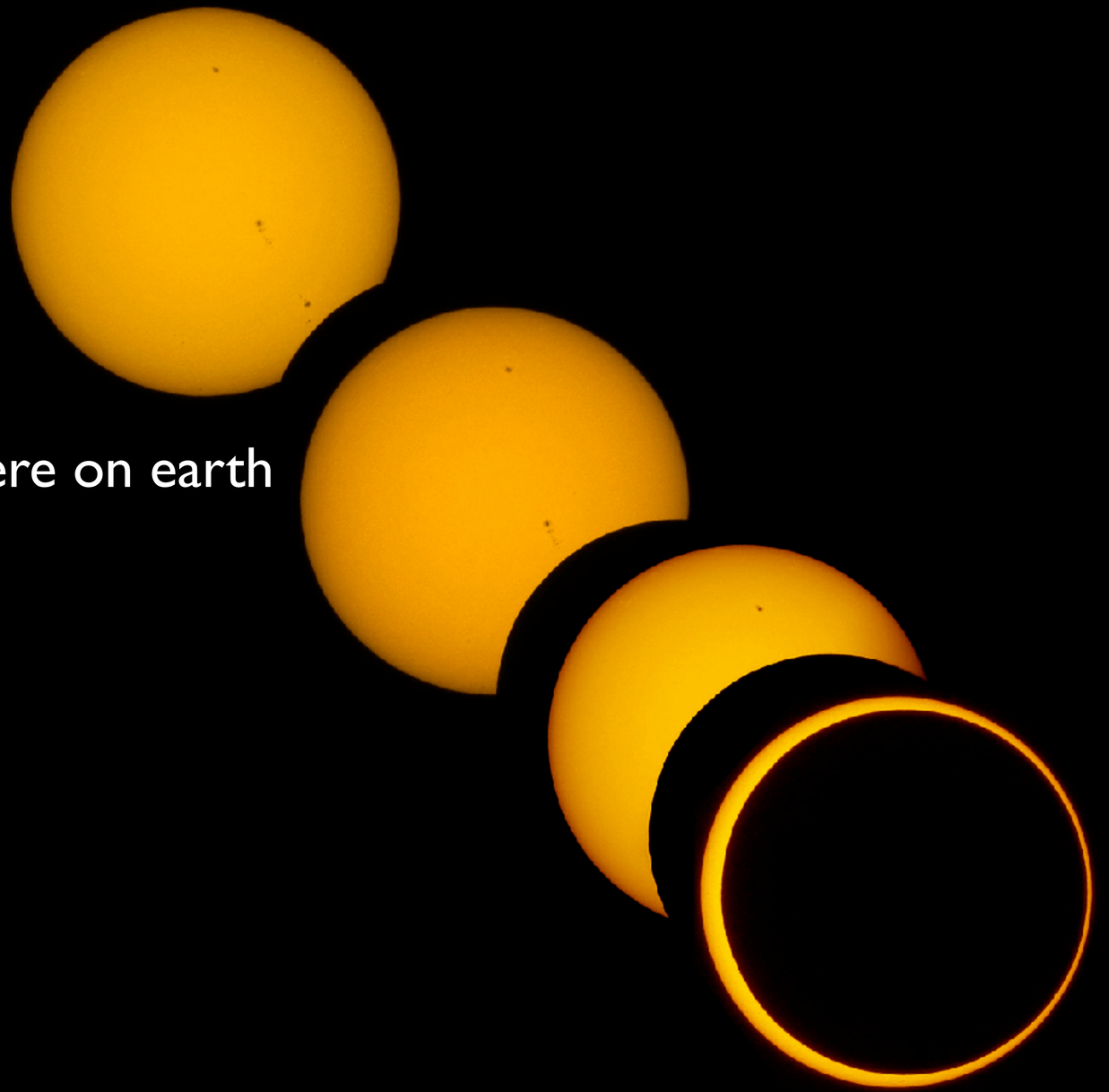
Image credit: edited version of image from wikimedia commons


Sun
Moon
Earth


April 8, 2024


STATES
OF AMERICA
UNITED
STATES
OF AMERICA
MEXICO
VENEZUELA
COLOMBIA
PERU
BRAZIL
shadow: time&date.com

common and rare



- partial + total : ~ few months, somewhere on earth
- total: ~18 months, somewhere on earth
- total: ~ 400 years at a any given location

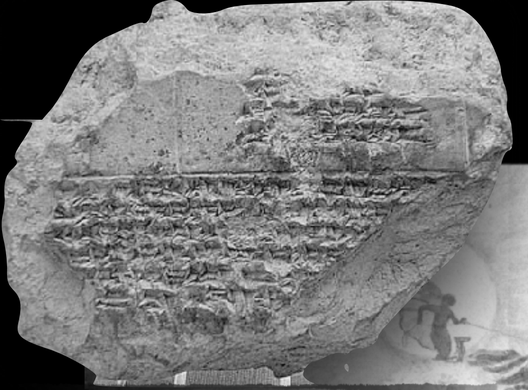
Image credit: from wikimedia commons

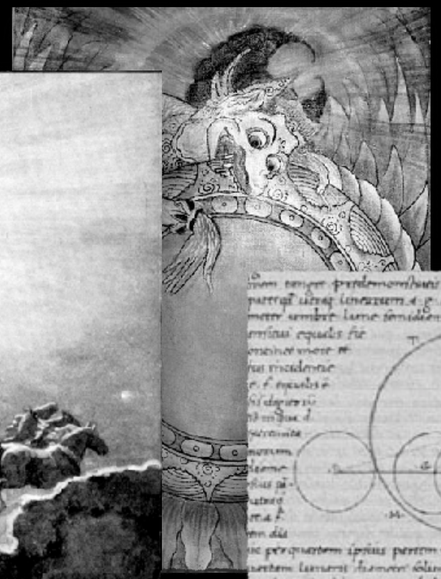
5th March, 1223 BCE

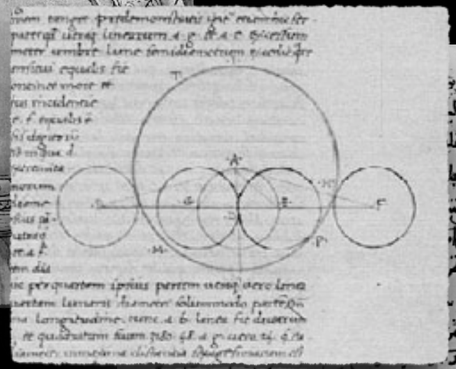
May 29, 1919 CE

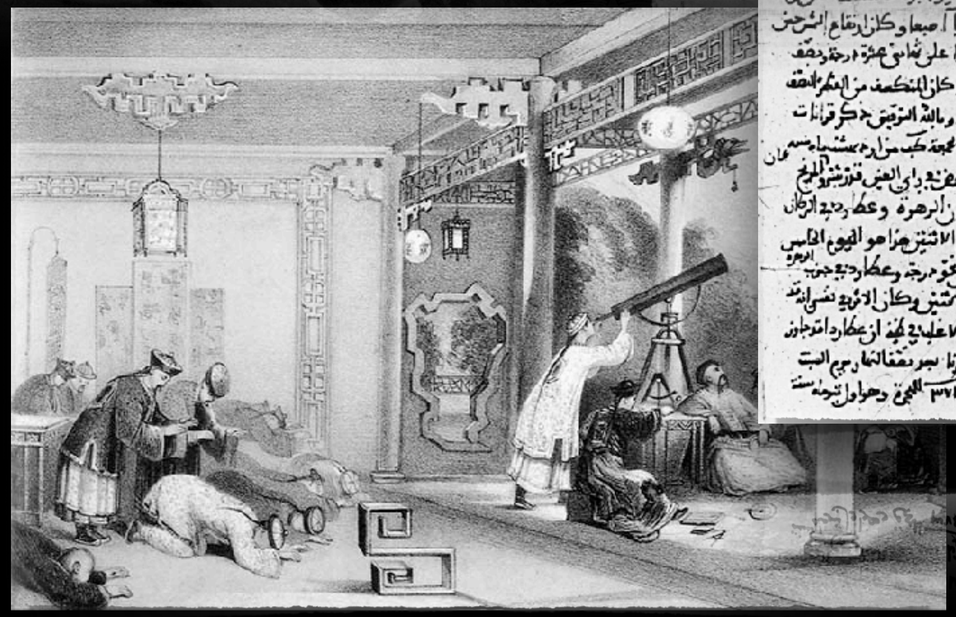
April 8, 2024 CE

Image Sources: Wikimedia Commons









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-
-

May 29, 1919 CE

-
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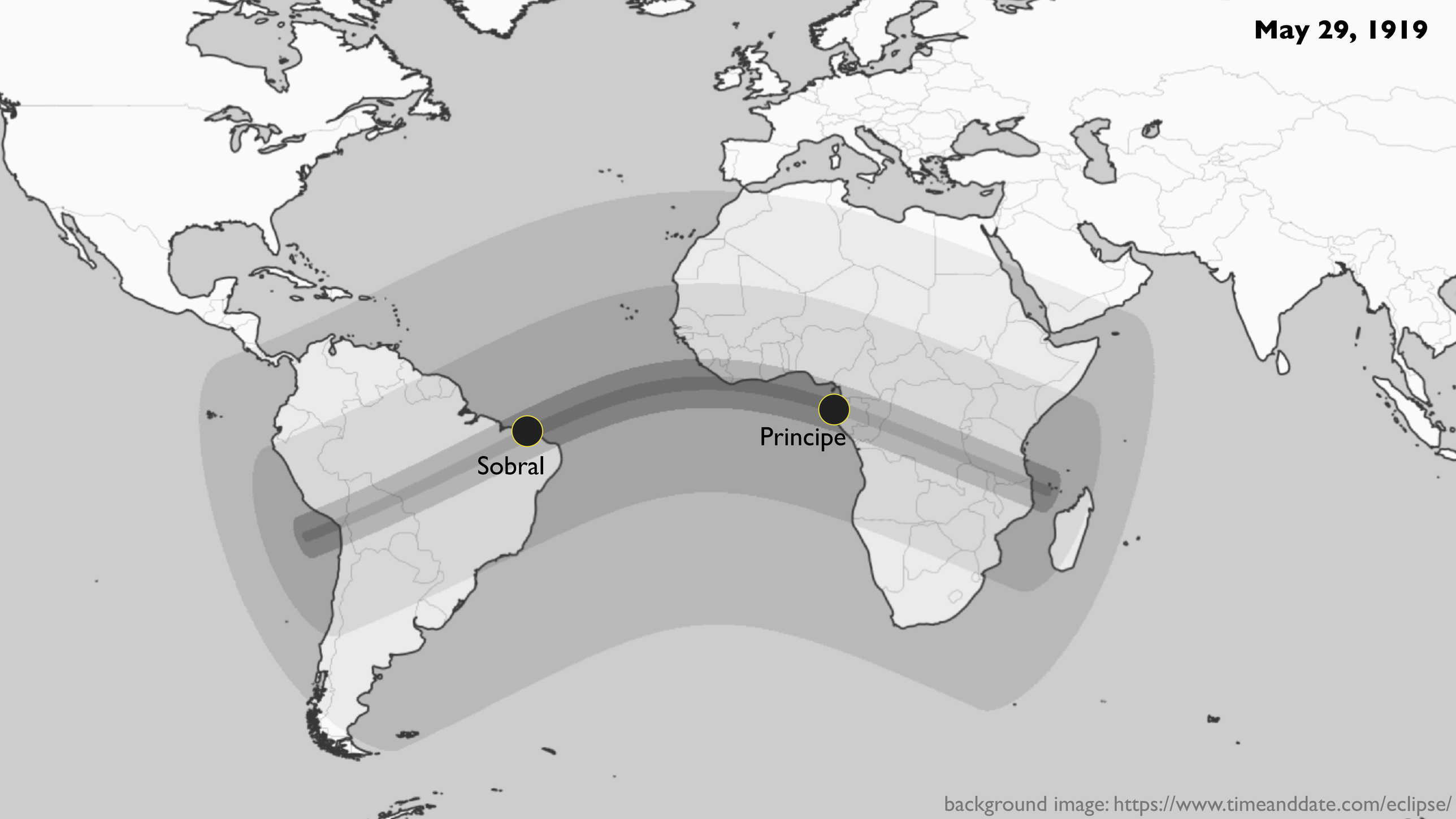
-
-

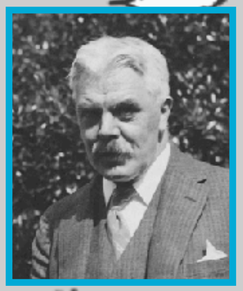
1919 eclipse



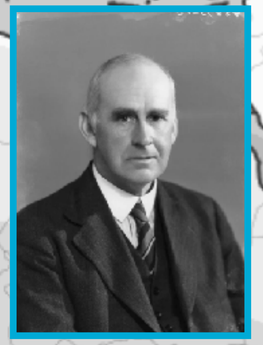
background image: https://www.timeanddate.com/eclipse/

May 29, 1919

World War I ended Nov 11, 1918



Dyson

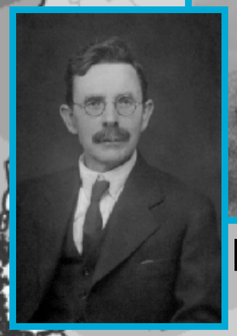


Eddington

Principe

Sobral

Davidson



Crommelin

LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

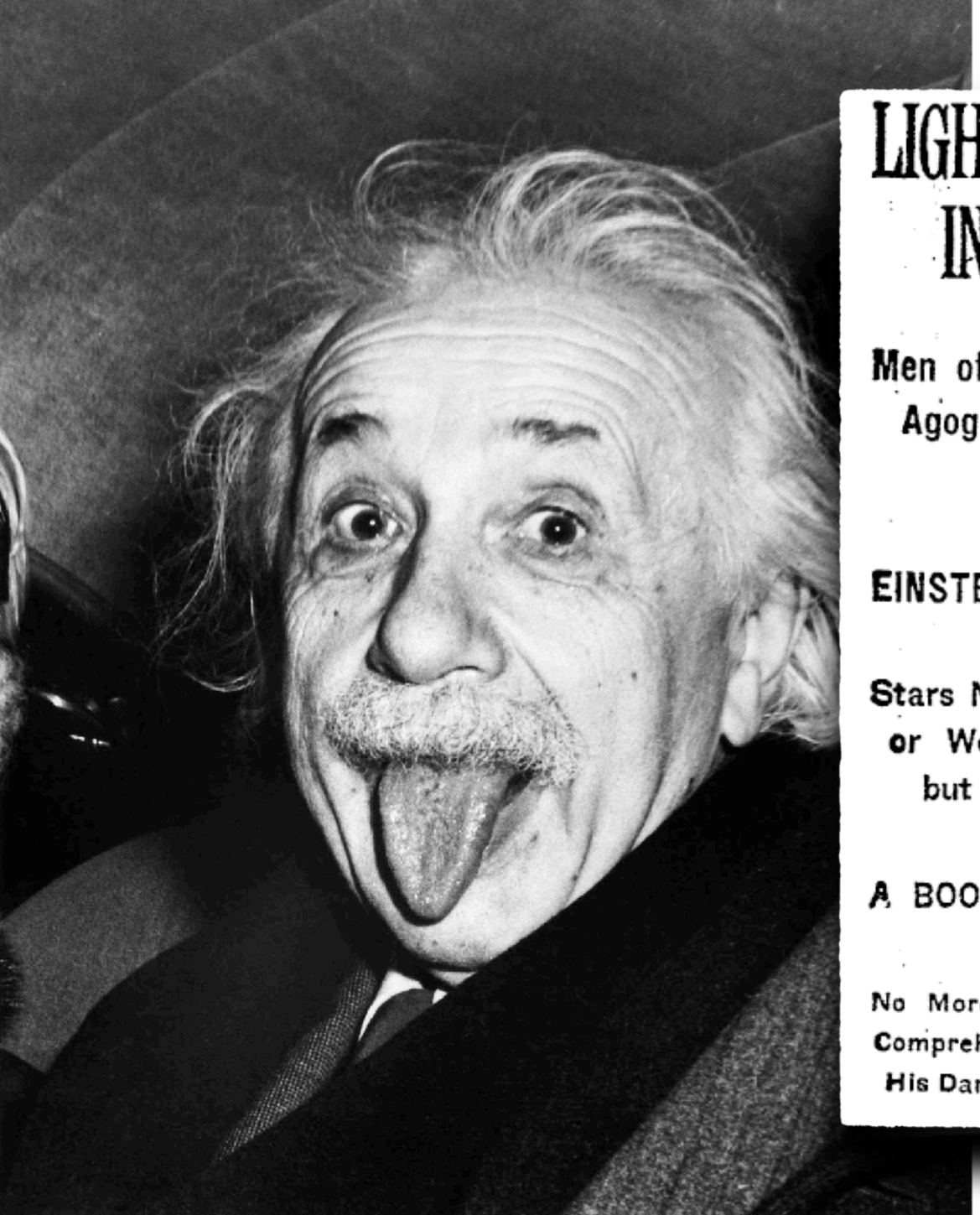


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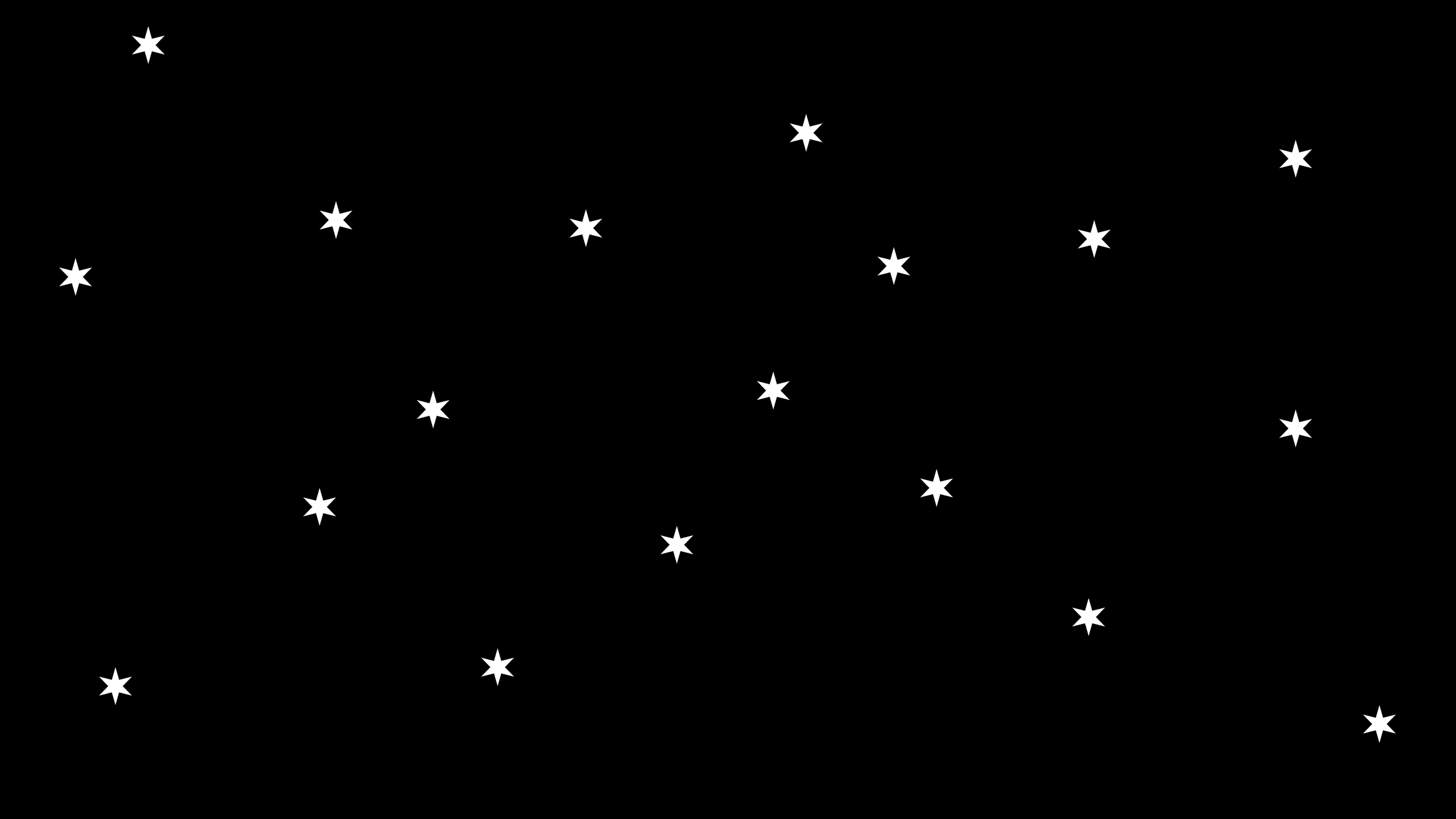
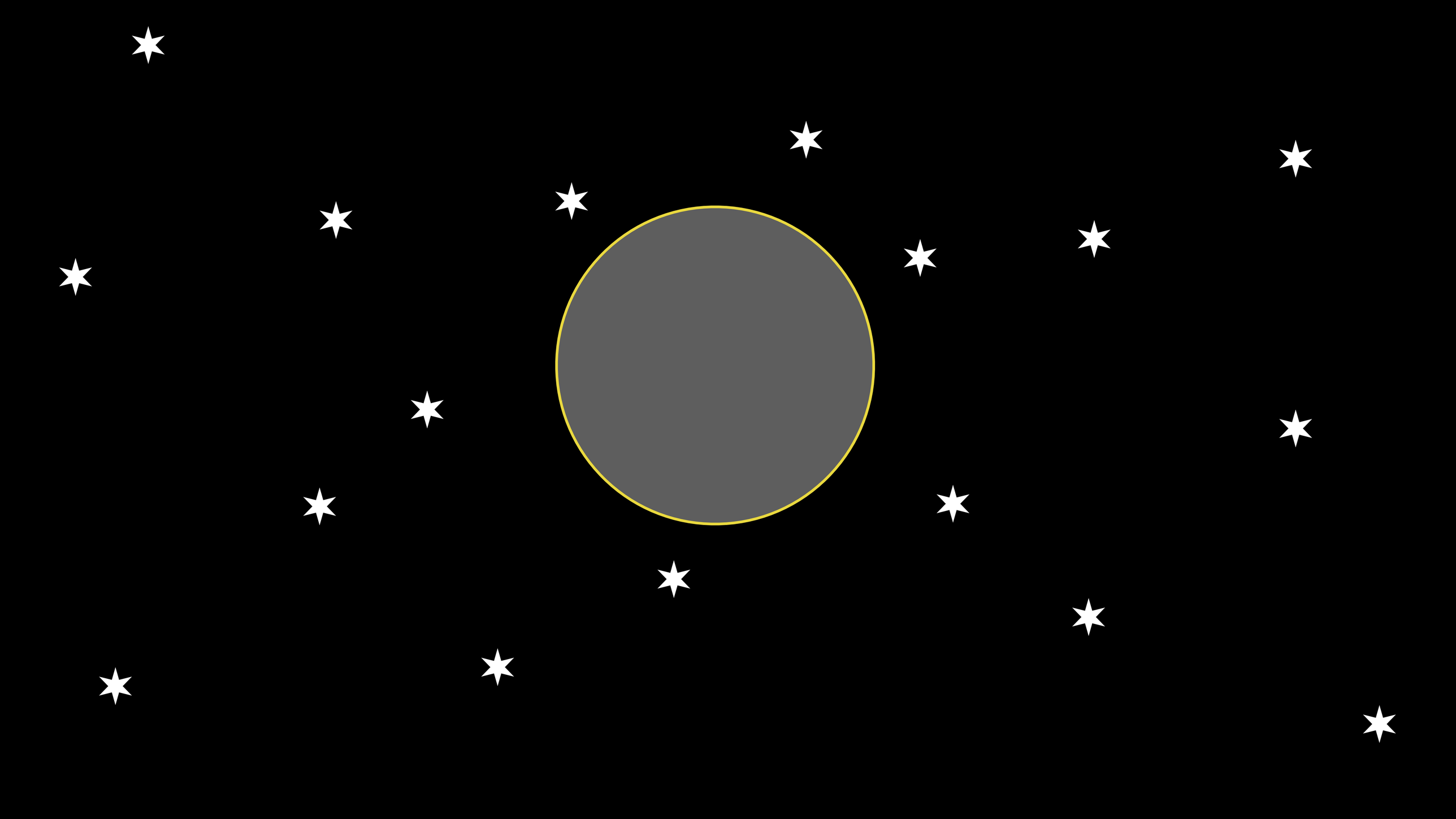
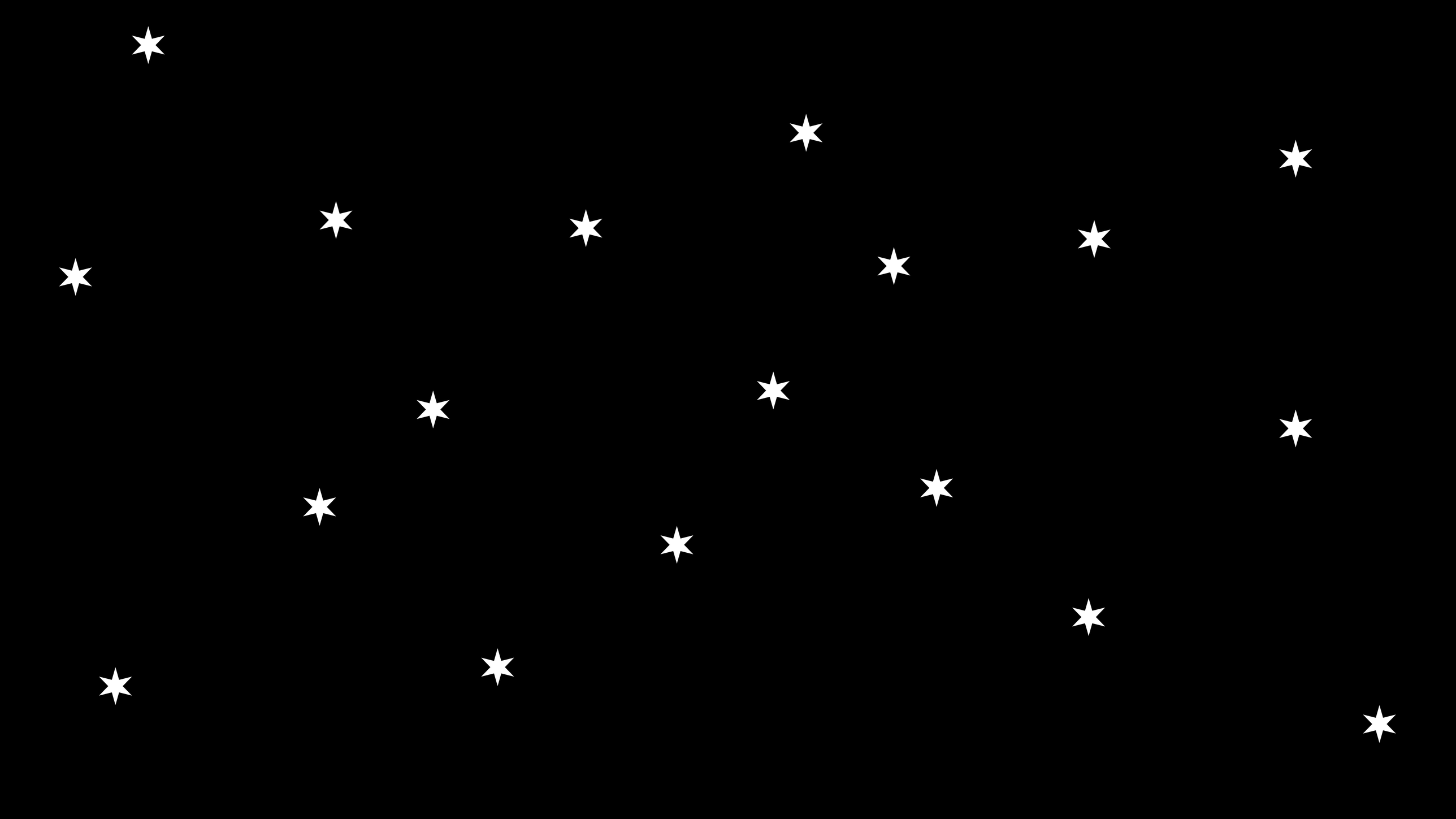
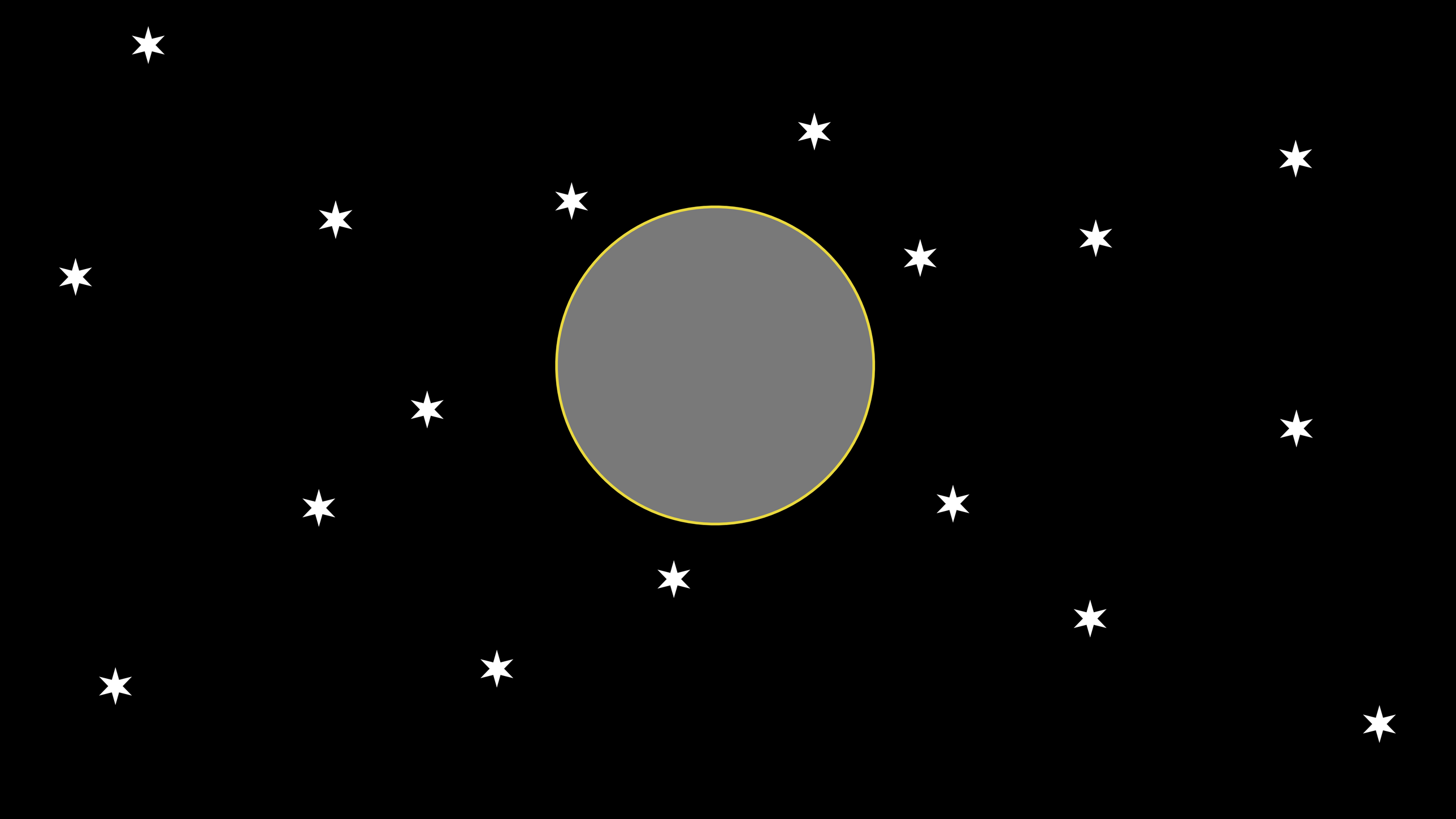
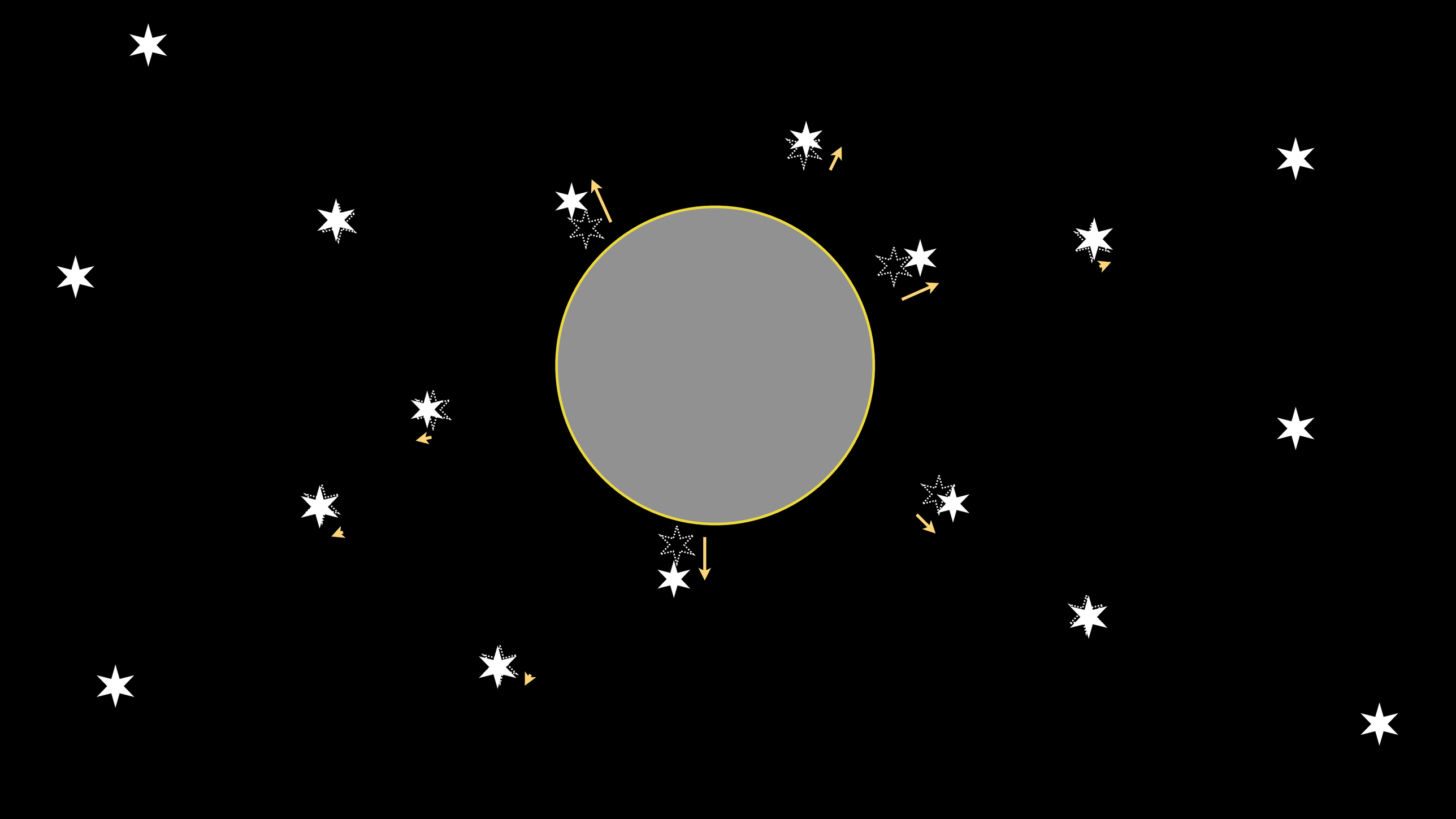
Image Credit: Caters/Mirror



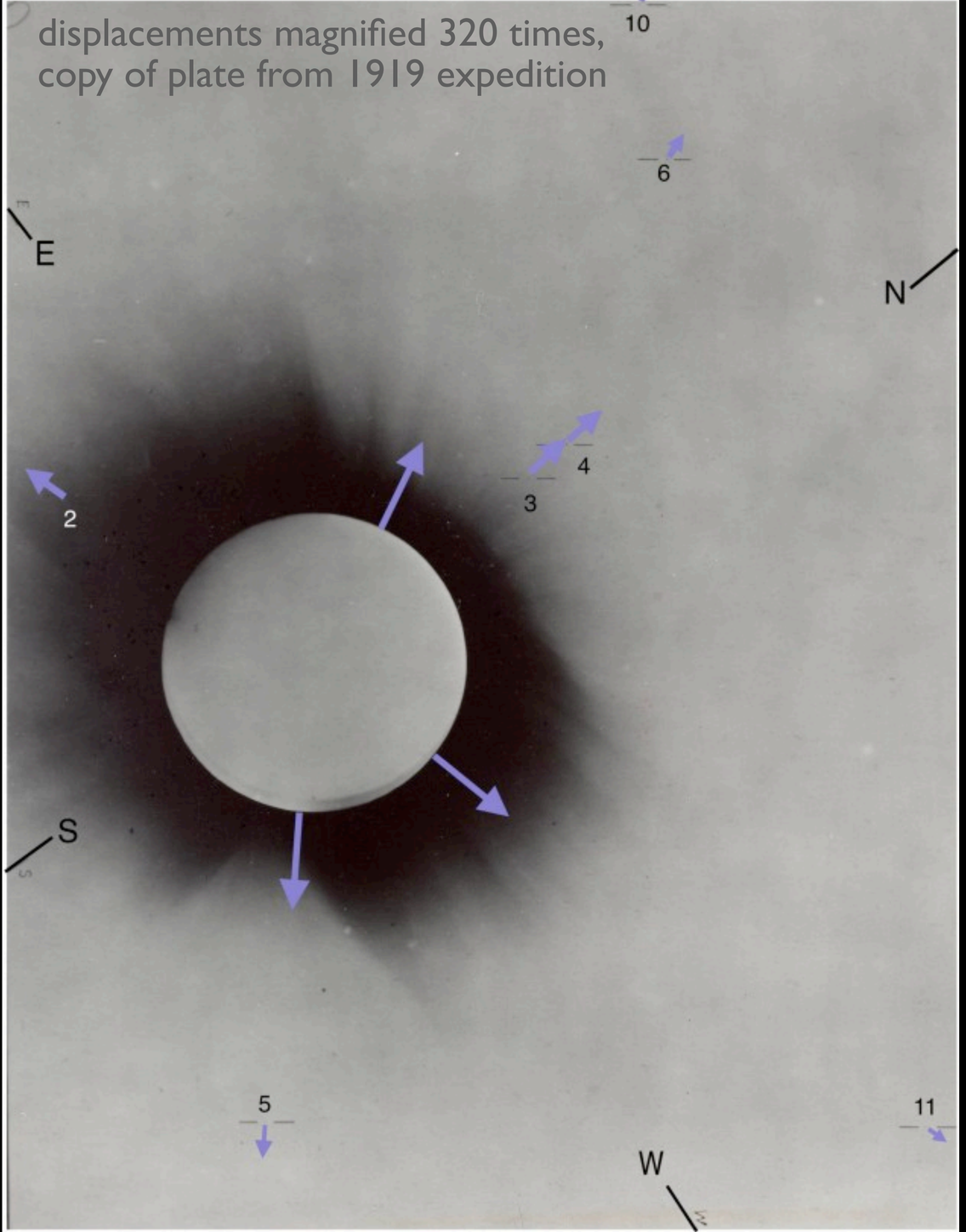


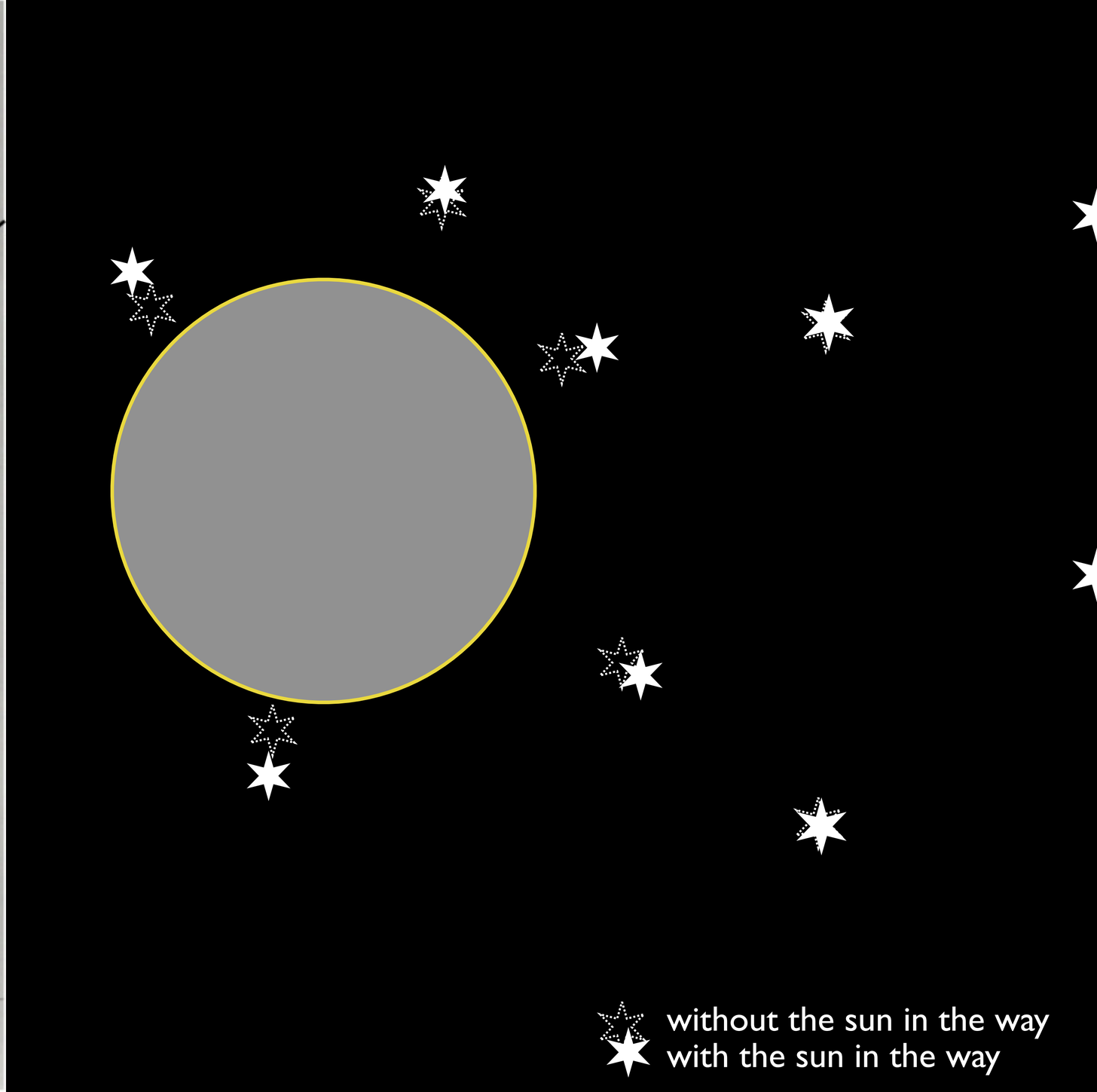




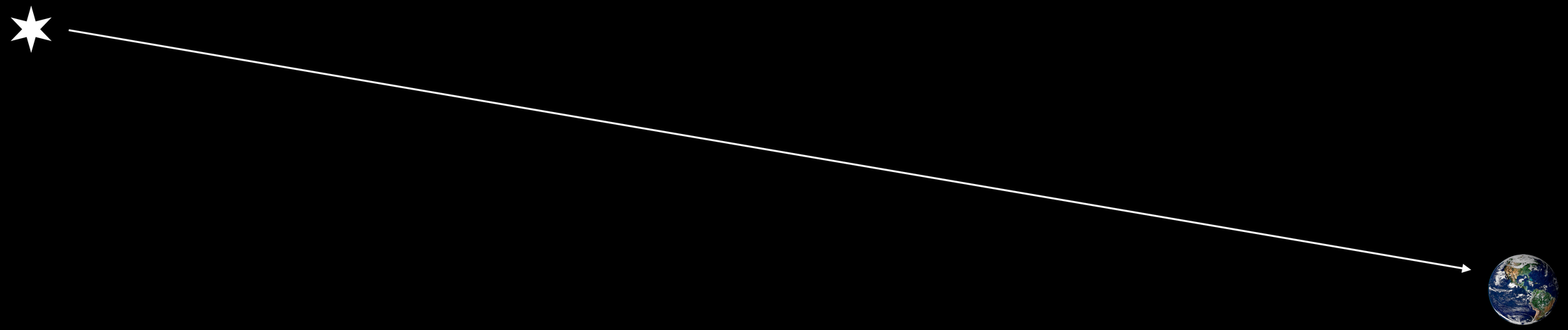


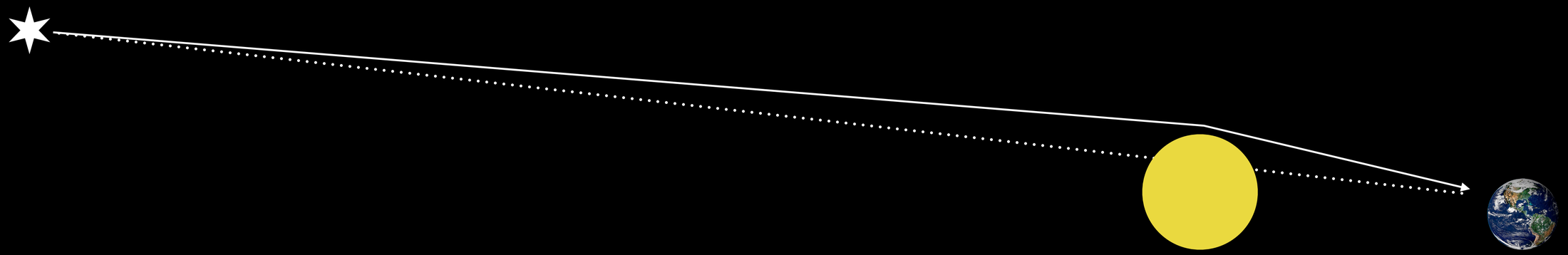
displacements magnified 320 times,
copy of plate from 1919 expedition

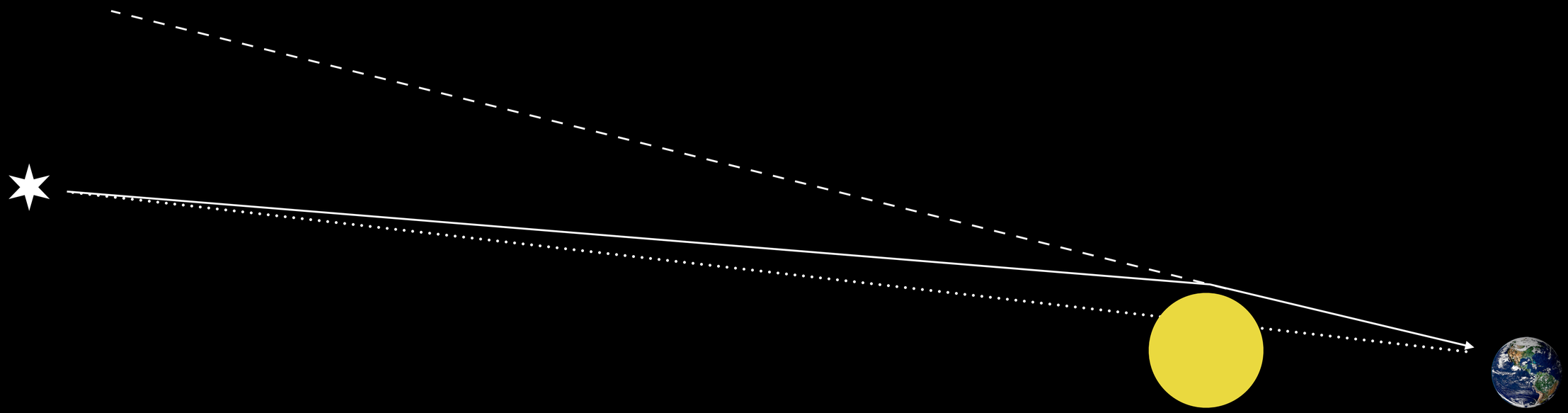


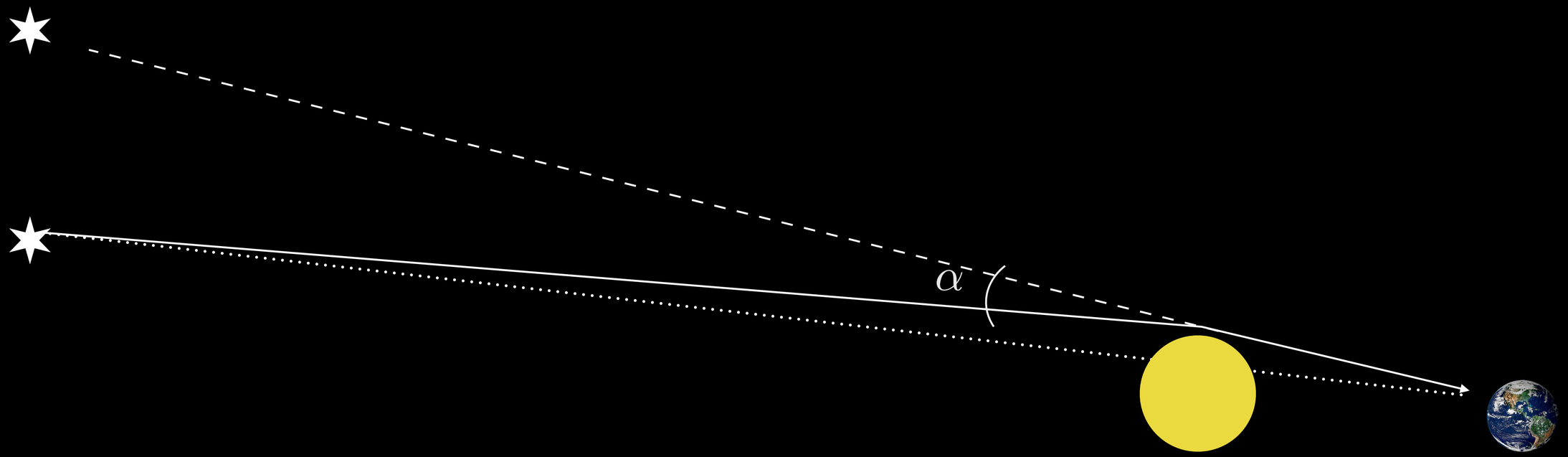


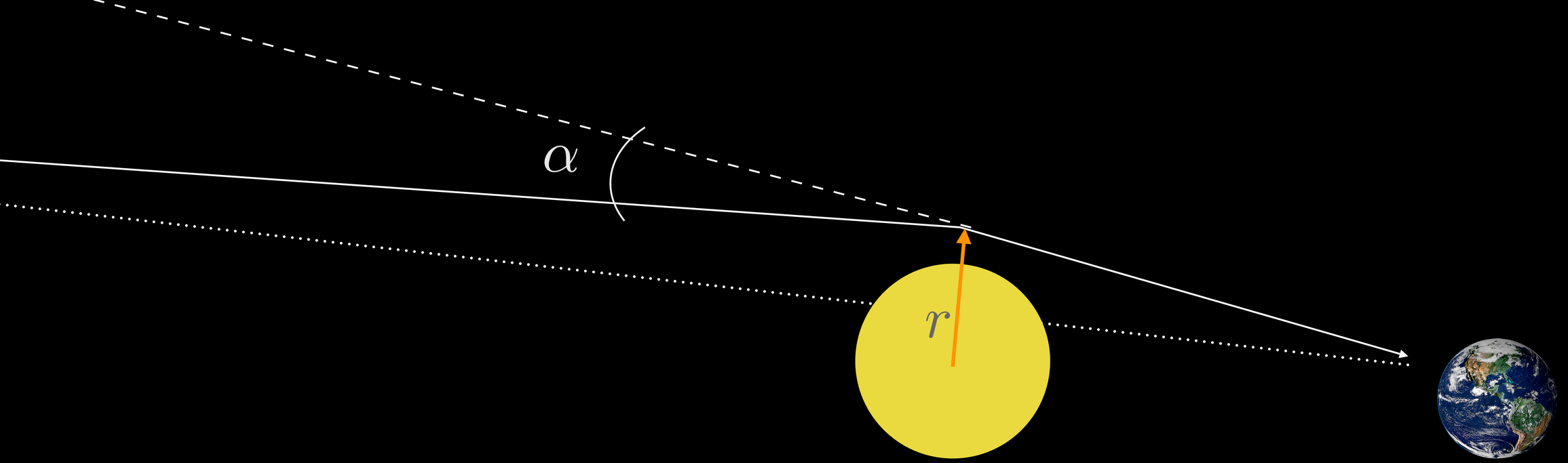
without the sun in the way
with the sun in the way



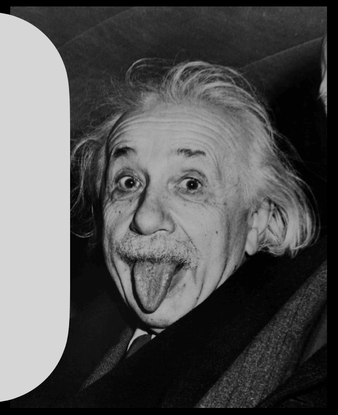





α



$$\alpha \approx \frac{4GM_\odot}{rc^2}$$

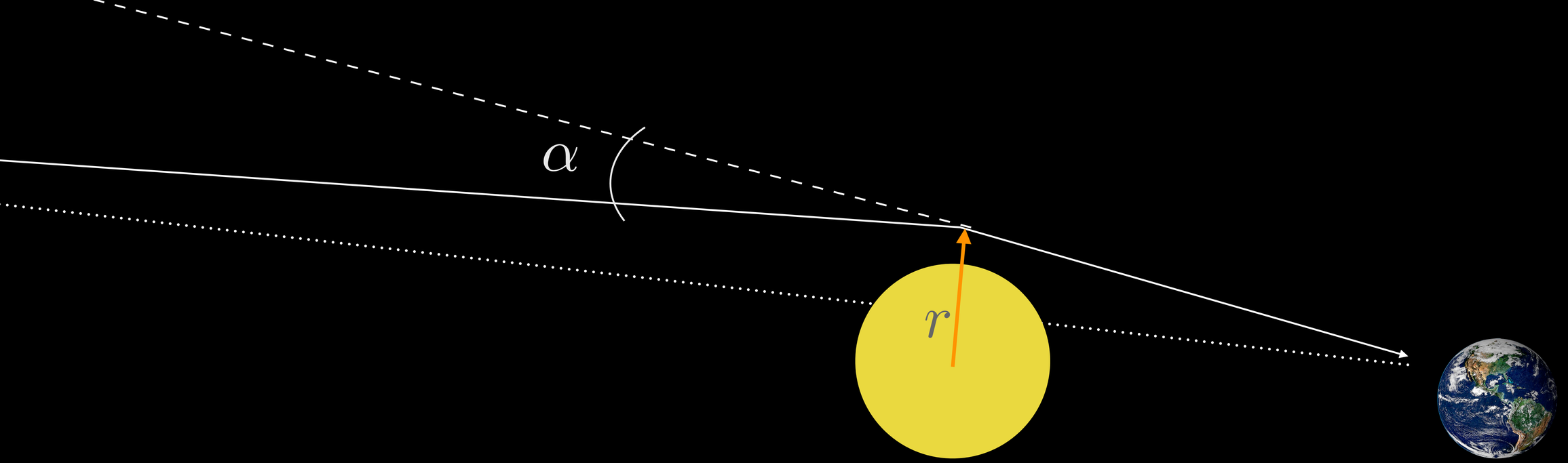


$M_\odot$ mass of sun

G gravitational constant

r distance of closest approach to sun

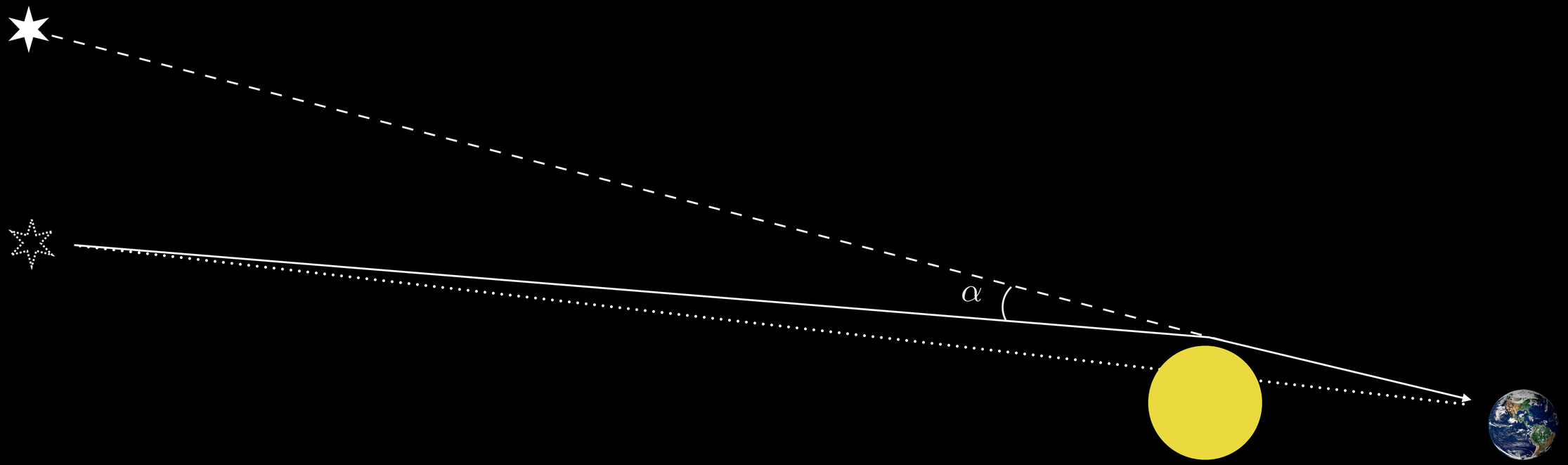
c speed of light



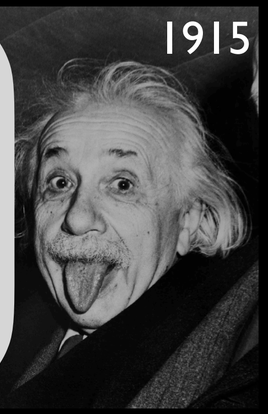
$$\alpha \approx \frac{4GM_\odot}{rc^2} \approx 1.75''$$

$r = R_\odot$

angular extend of the width of human hair held at a distance of ~10 meters!



$$\alpha \approx \frac{4GM_\odot}{rc^2}$$



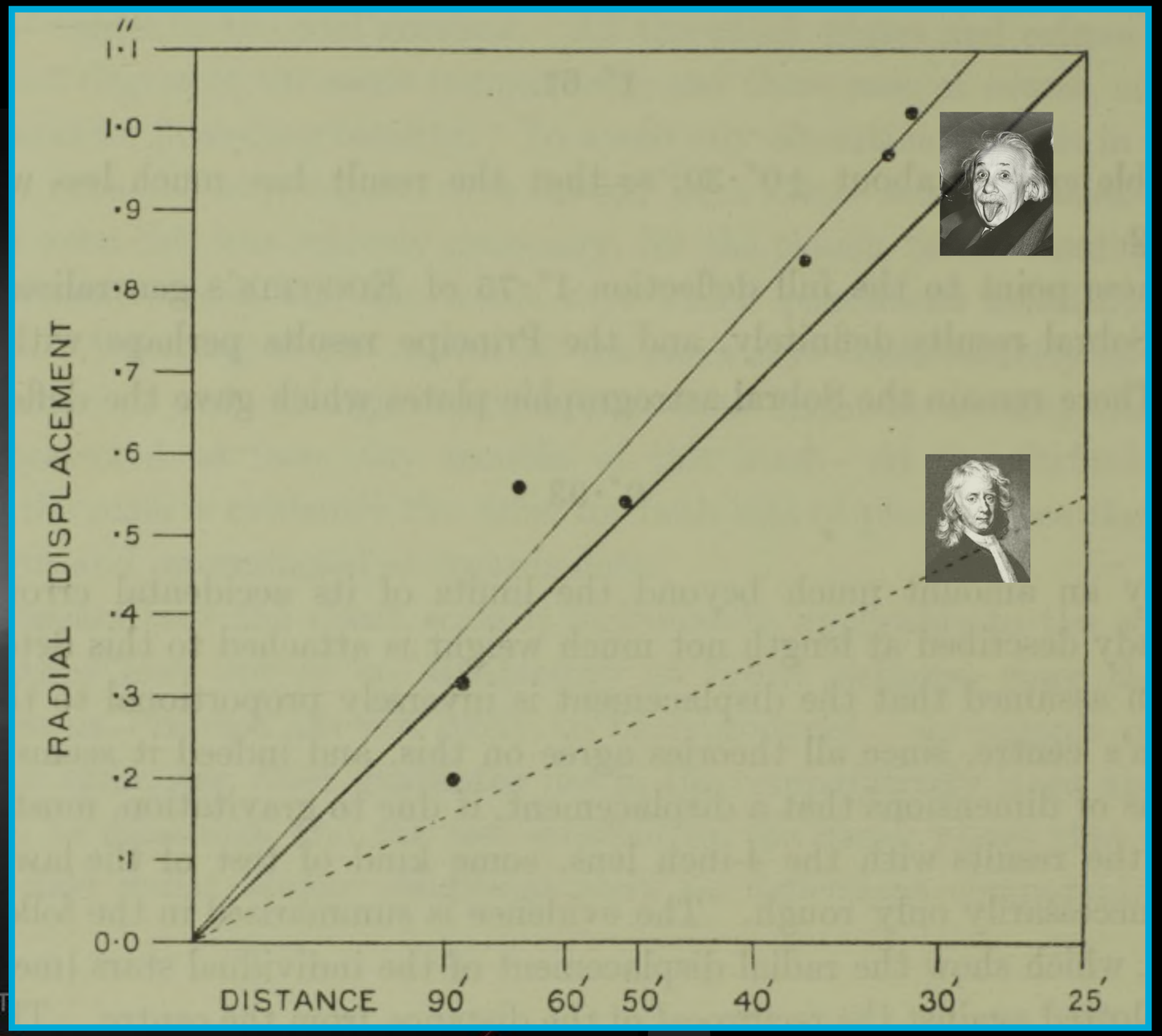
$$\alpha \approx \frac{2GM_\odot}{rc^2}$$

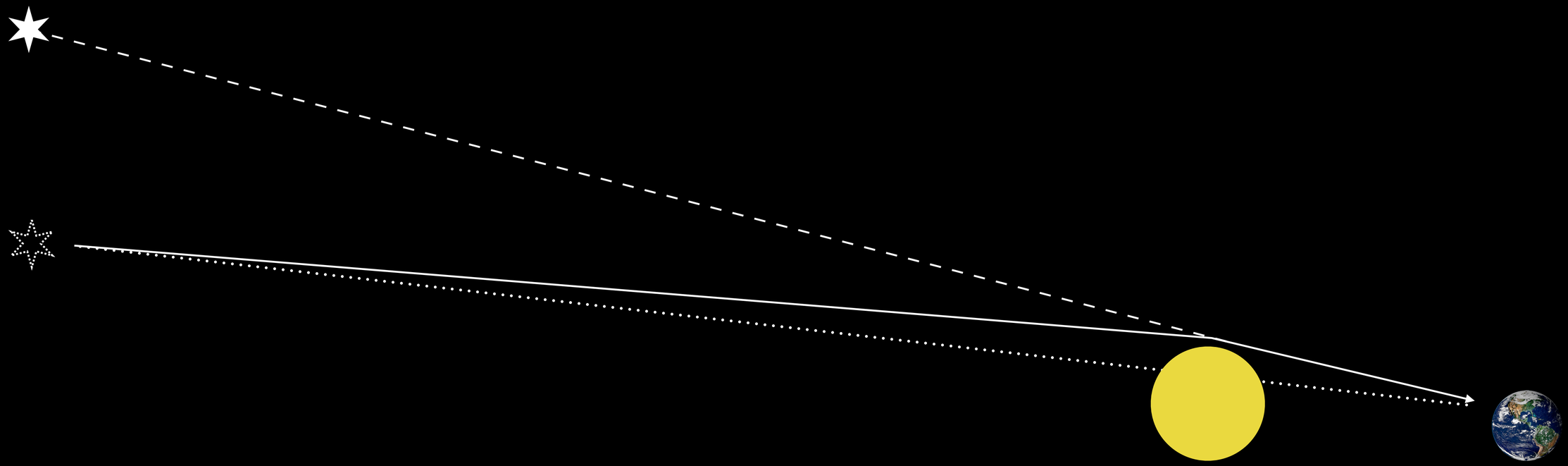
IX. *A Determination of the Deflection of Light by the Sun's Gravitational Field, from Observations made at the Total Eclipse of May 29, 1919.*

By Sir F. W. Dyson, *F.R.S., Astronomer Royal, Prof.* A. S. Eddington, *F.R.S., and Mr.* C. Davidson.

(*Communicated by the Joint Permanent Eclipse Committee.*)

Received October 30,—Read November 6, 1919.

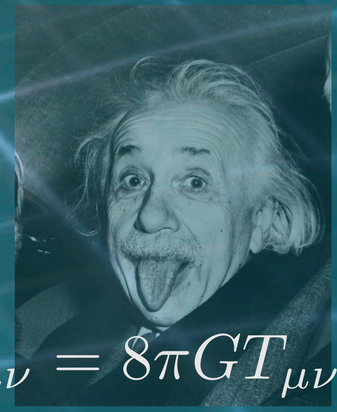




- why does the path of light "bend" ?
- why did my title mention "straight" path ?
- why was Einstein's 1915 prediction twice Newton's/ younger Einstein's ?

light's "straight" path

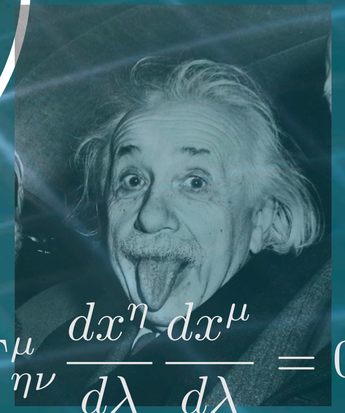
massive objects curve **spacetime** around them



1915, Einstein's General Theory of Relativity $G_{\mu\nu} = 8\pi G T_{\mu\nu}$

“particles” move on the “straightest” path in this curved spacetime

which straight path depends on initial speed and position

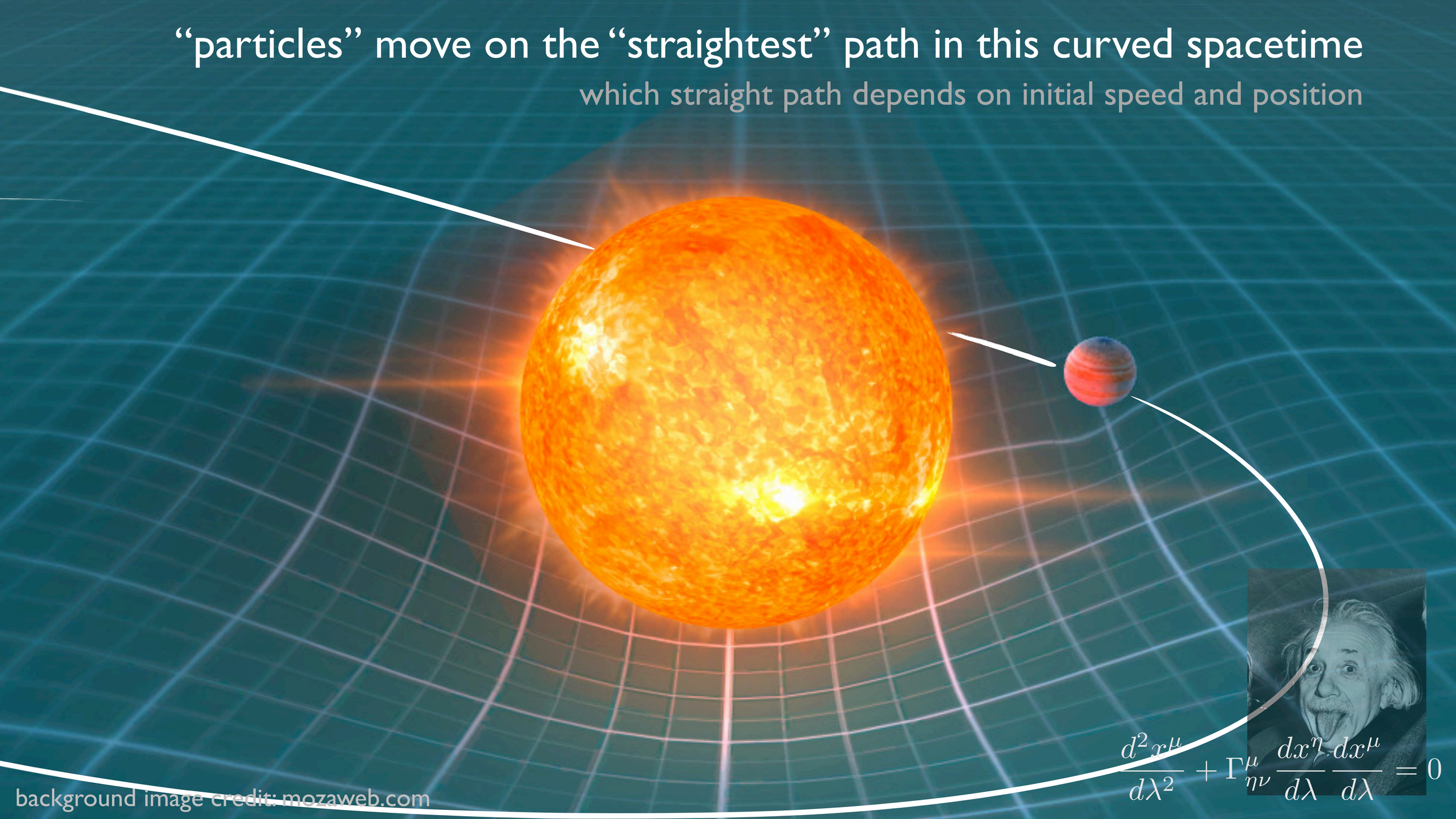


$$\frac{d^2x^\mu}{d\lambda^2} + \Gamma^\mu_{\eta\nu}\frac{dx^\eta}{d\lambda}\frac{dx^\mu}{d\lambda} = 0$$

curvature of spacetime, not just space and not just time.

“particles” move on the “straightest” path in this curved spacetime

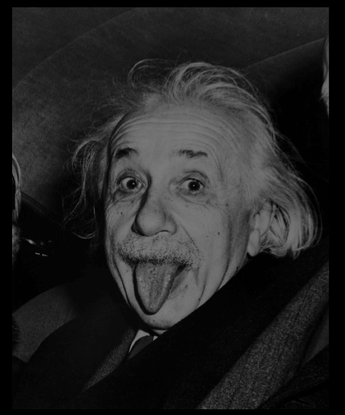
which straight path depends on initial speed and position



$$\frac{d^2x^\mu}{d\lambda^2} + \Gamma^\mu_{\eta\nu}\frac{dx^\eta}{d\lambda}\frac{dx^\mu}{d\lambda} = 0$$

background image credit: mozaweb.com

light move on the “straightest” path in this curved spacetime



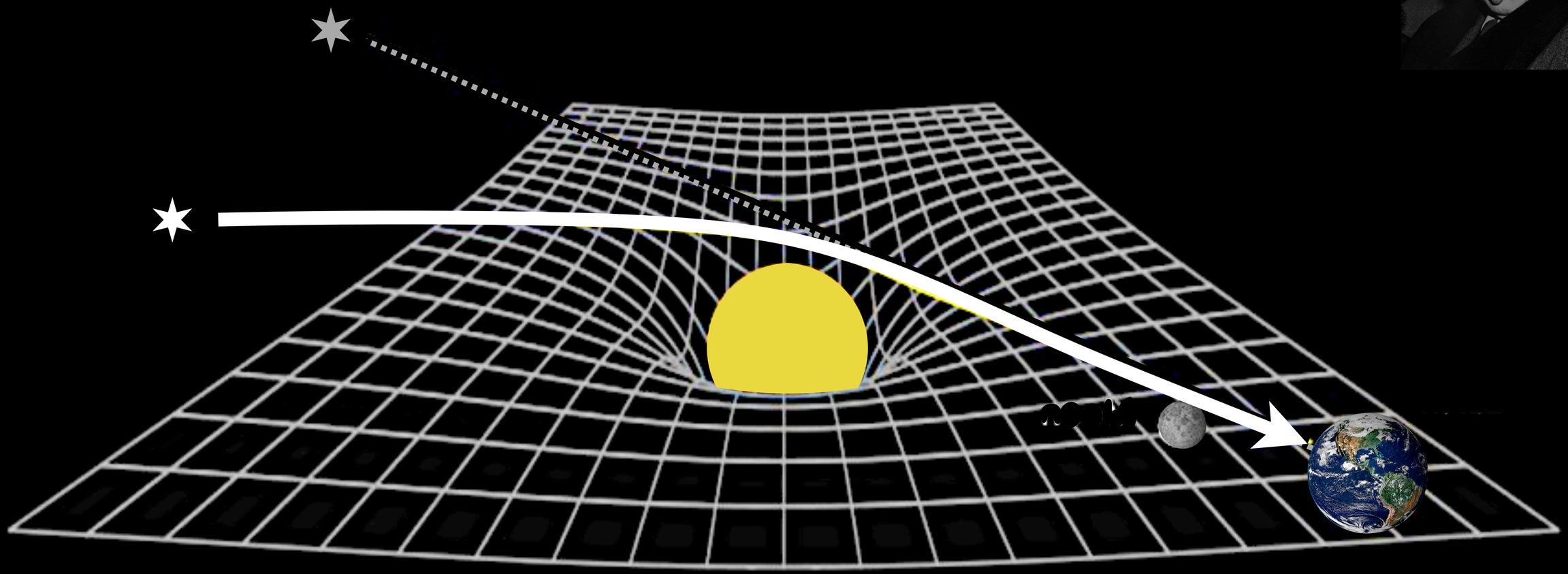


Image credit: Paolozzi et. al (2015) [edited]

spacetime is absolute

massive objects create a “gravitational field”

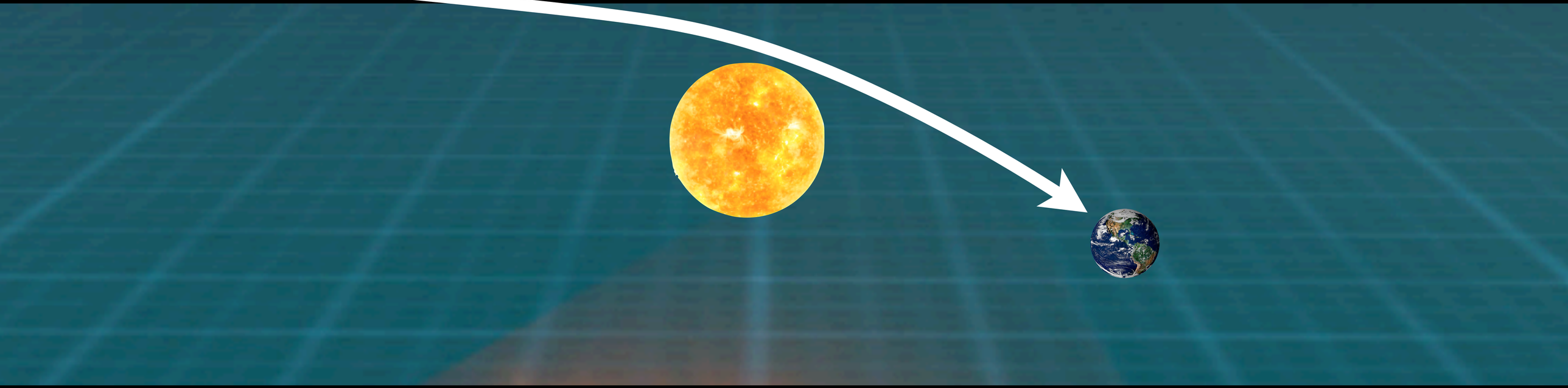
test particles move according to Newton’s 2nd law

results for planets almost identical to Einstein —- (but Mercury!)

"light particles" move according to Newton's 2nd law

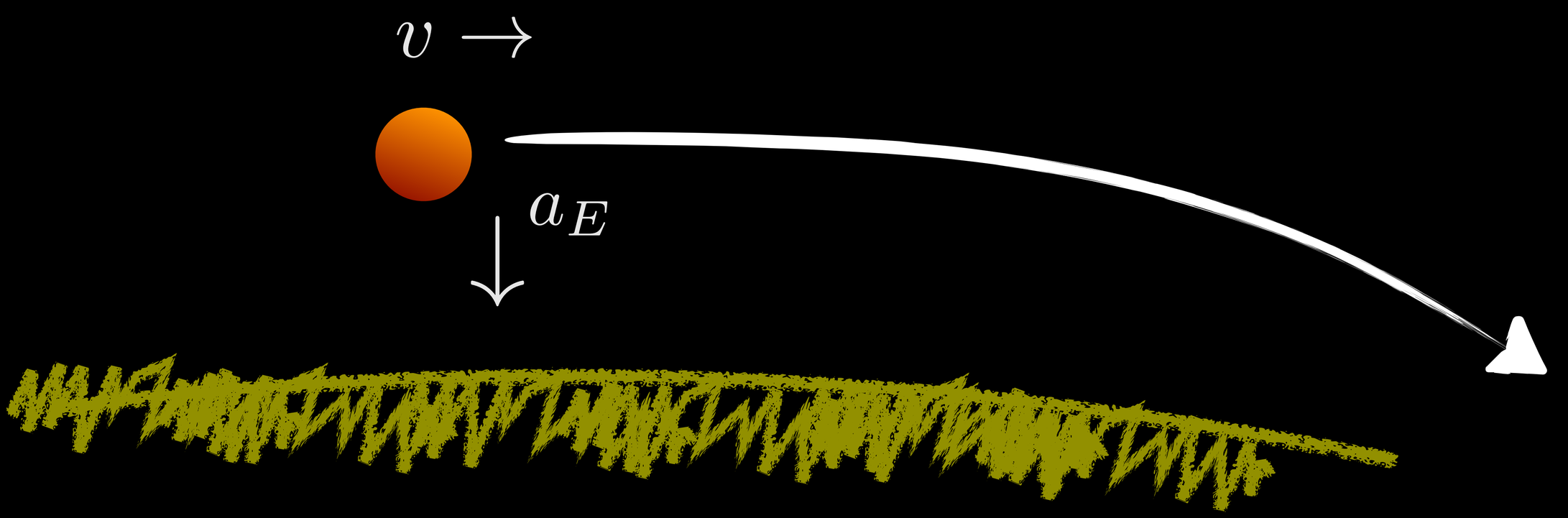
— yields **1/2** of Einstein's answer

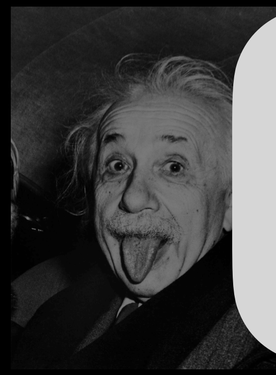
Calculated first by Cavendish (1784)



* needs some mumbling about light have "mass" — energy

* not everyone was convinced back then that light has "weight" — especially if we think about it as a wave

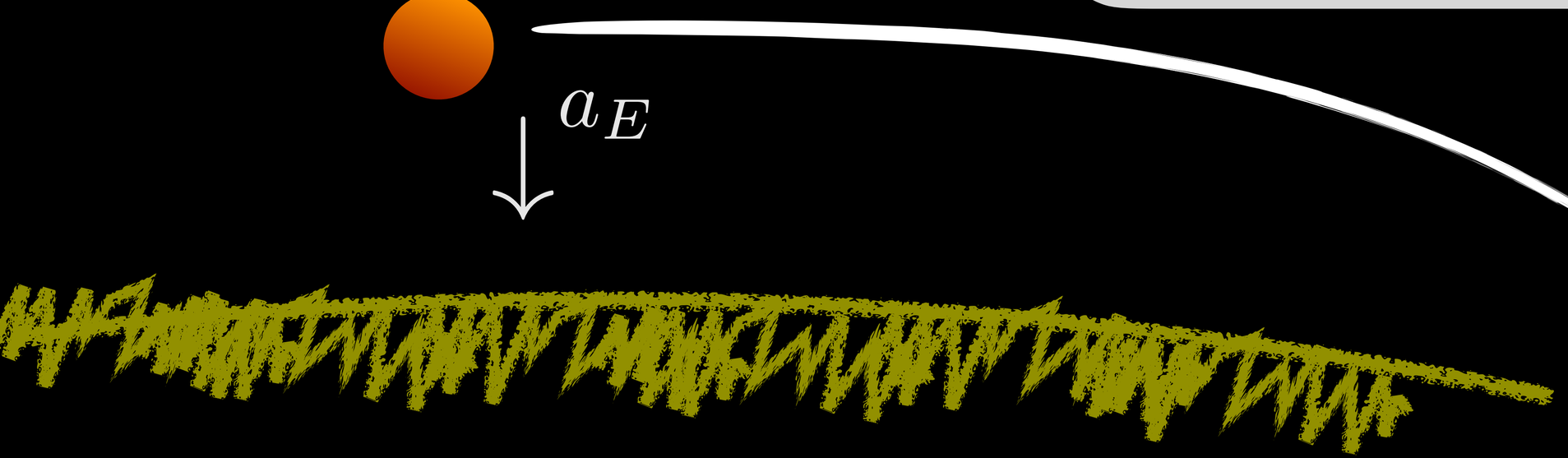


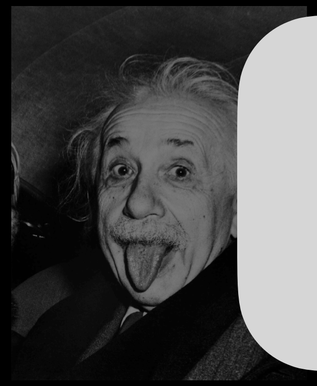


$$a_E \approx \left(1 + \frac{v^2}{c^2}\right) a_N$$

* I extremized the relativistic point particle action in weak field gravity in isotropic co-ordinates. Valid at launch time with co-ordinate velocity v.

The factor of 2 when $v = c$!





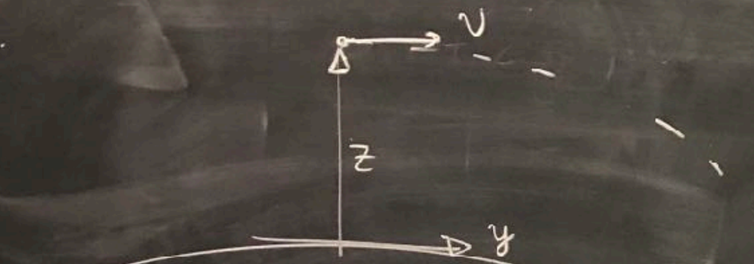
$$a_E \approx \left(1 + \frac{v^2}{c^2}\right) a_N$$

* I used the geodesic equation with weak field gravity in isotropic co-ordinates. Valid at launch time with co-ordinate velocity v.

$M_\oplus$

$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$

$\partial^2 g \ldots$



$$ds^2 = -\left(1+2\frac{\Phi}{c^2}\right)c^2dt^2 + \left(1-2\frac{\Psi}{c^2}\right)d\vec{x}^2$$

$$\left|\frac{\Phi}{c^2}\right| \simeq \left|\frac{\Psi}{c^2}\right| \ll 1$$

$$\frac{\Phi}{c^2} \simeq \frac{GM_\oplus}{rc^2}$$

$$r = \sqrt{y^2+z^2}$$

$$\tau = \int\sqrt{-ds^2}$$

$$\delta\tau = 0 \Rightarrow$$

$$\left.\frac{d^2z}{dt^2}\right|_{\dot z=0,\ \dot y=v} = -\left(\partial_z\Phi + \frac{v^2}{c^2}\partial_z\Psi\right)$$

spatial

$$\left.\frac{d^2y}{dt^2}\right|_{\dot z=0,\ \dot y=v} = \left(-1+2\frac{v^2}{c^2}\right)\partial_z\Phi + \frac{v^2}{c^2}\partial_z\Psi$$

spatial

$$\Rightarrow \boxed{a_z \simeq -\left(1+\frac{v^2}{c^2}\right)\partial_z\Phi}$$

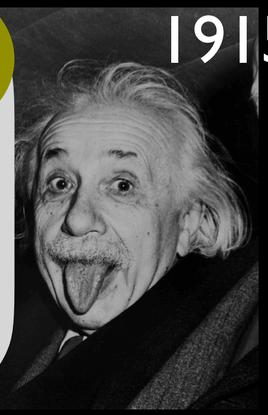
Erwin Finlay-Freundlich

Ask me !

$(\alpha$

$$\alpha \approx \frac{4GM_\odot}{rc^2}$$

1915



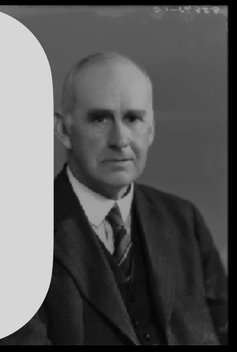
1911

$$\alpha \approx \frac{2GM_\odot}{rc^2}$$

Falling elevators

replace curved spacetime by flat spacetime + a refractive index

$$n(x) \approx \left[1 - 2\frac{\Phi_N(x)}{c^2}\right]$$



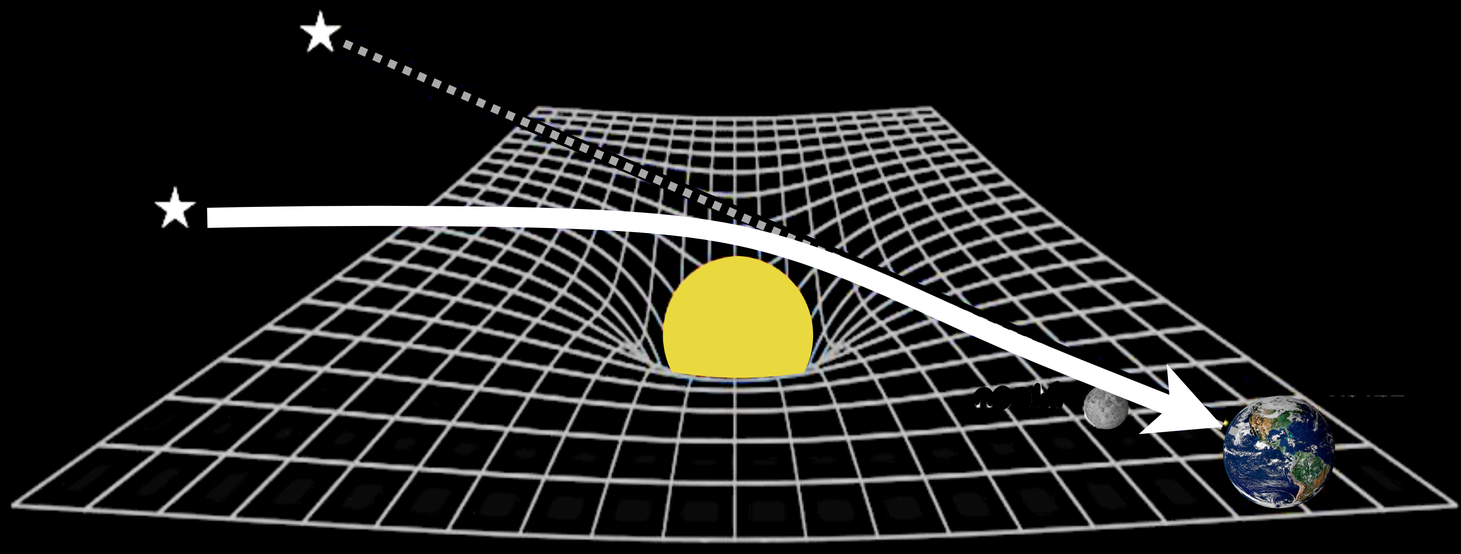
$$\Phi_N(r) = -GM_\odot/r$$

*works for slowly varying weak field gravity

gravitational lensing

replace curved spacetime by flat spacetime + a refractive index

$$n(x) \approx \left[1 - 2\frac{\Phi_N(x)}{c^2}\right]$$



images of galaxies distorted by intervening mass (that curves spacetime)

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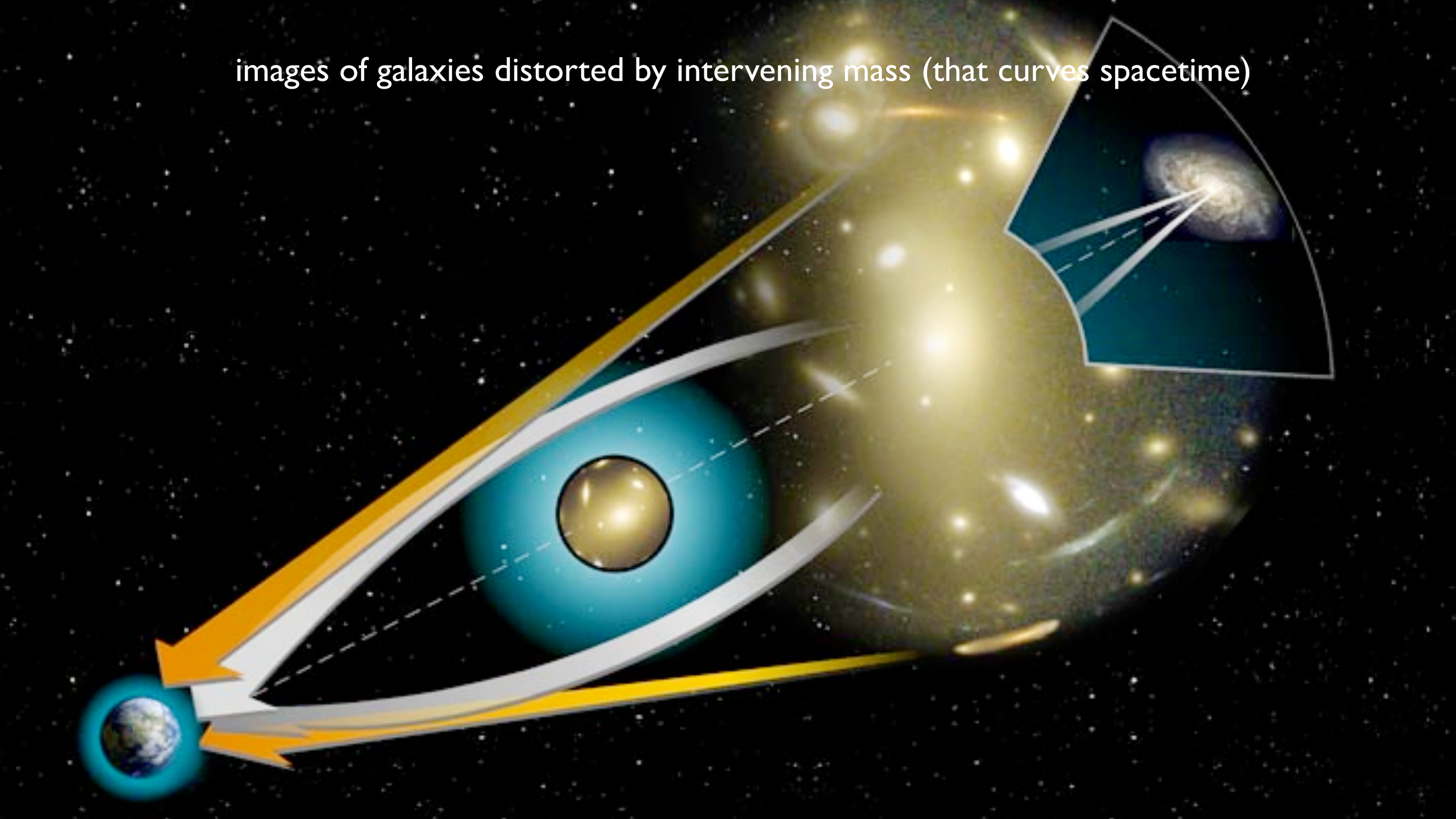
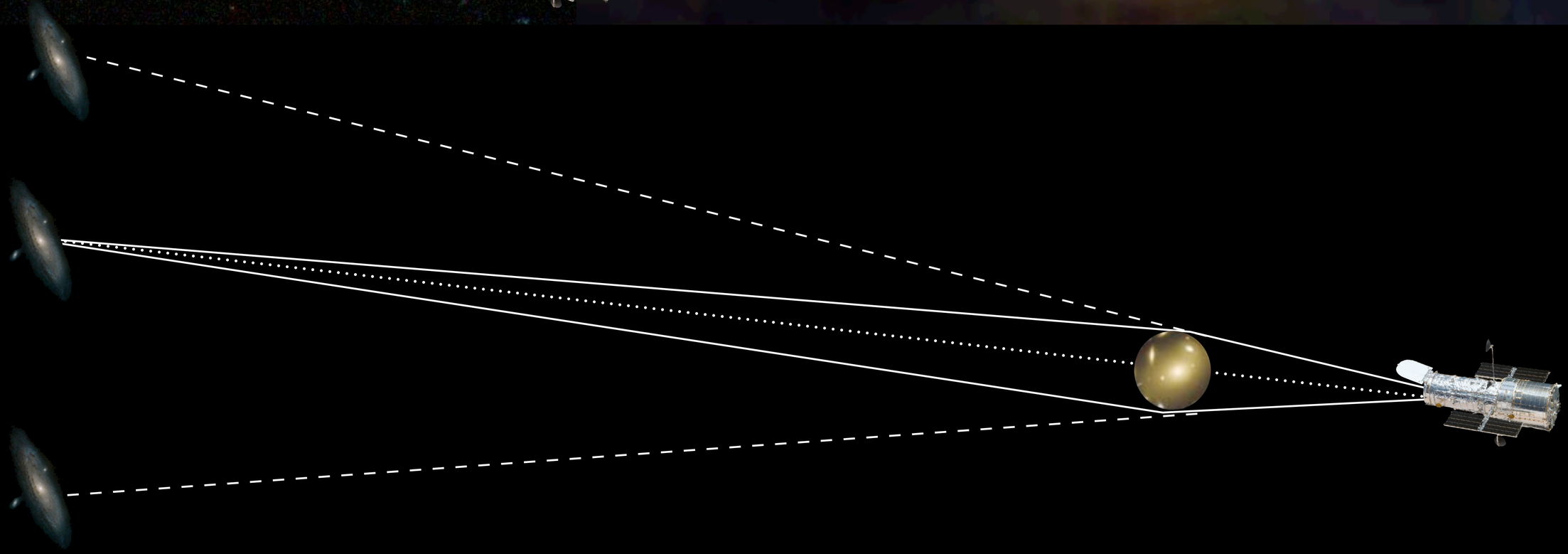
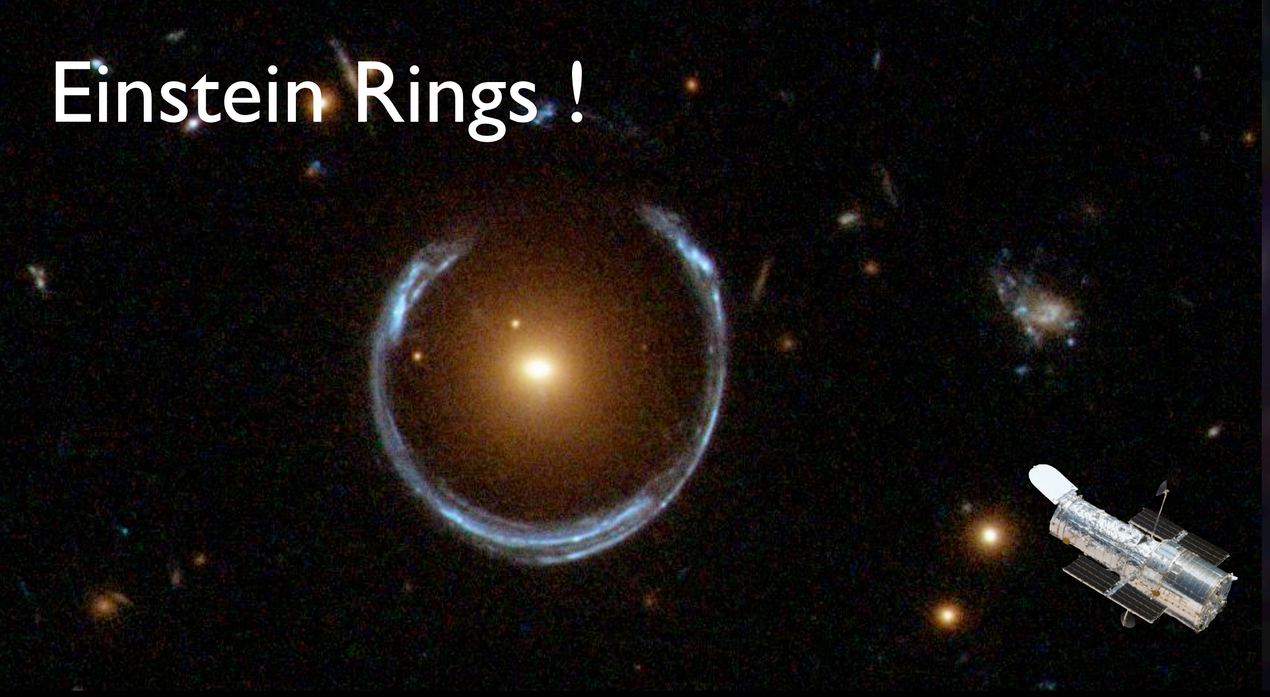


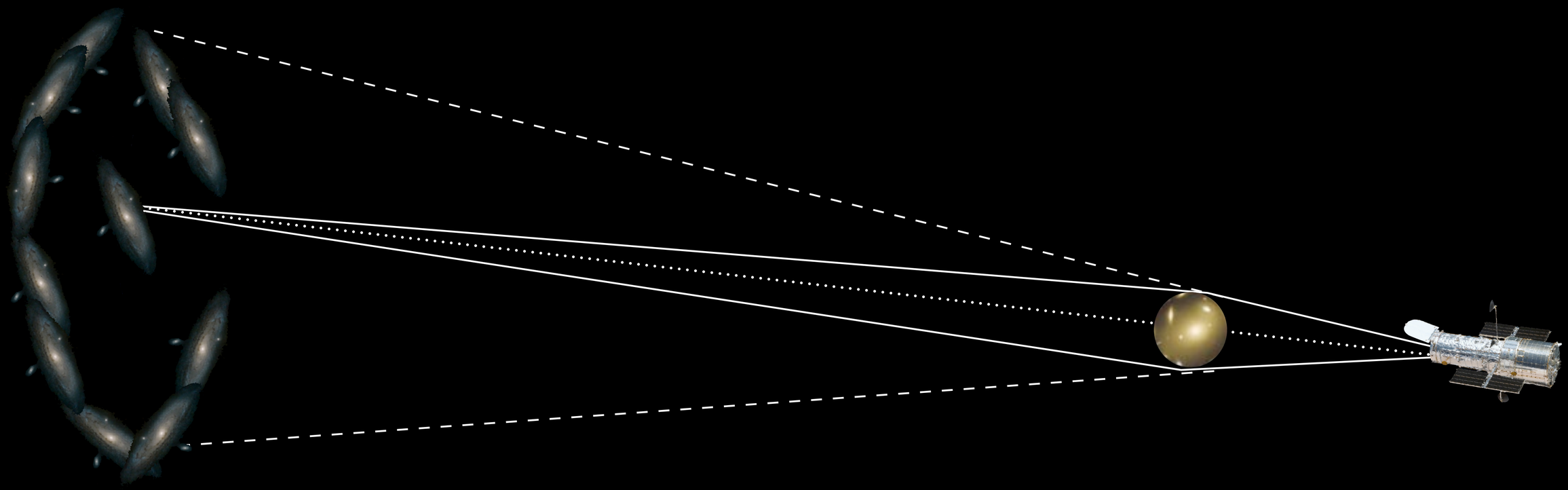

SDSS J1038+4849
NASA/ESA/Acknowledgement: Judy Schmidt

Einstein Rings !



Einstein Rings !



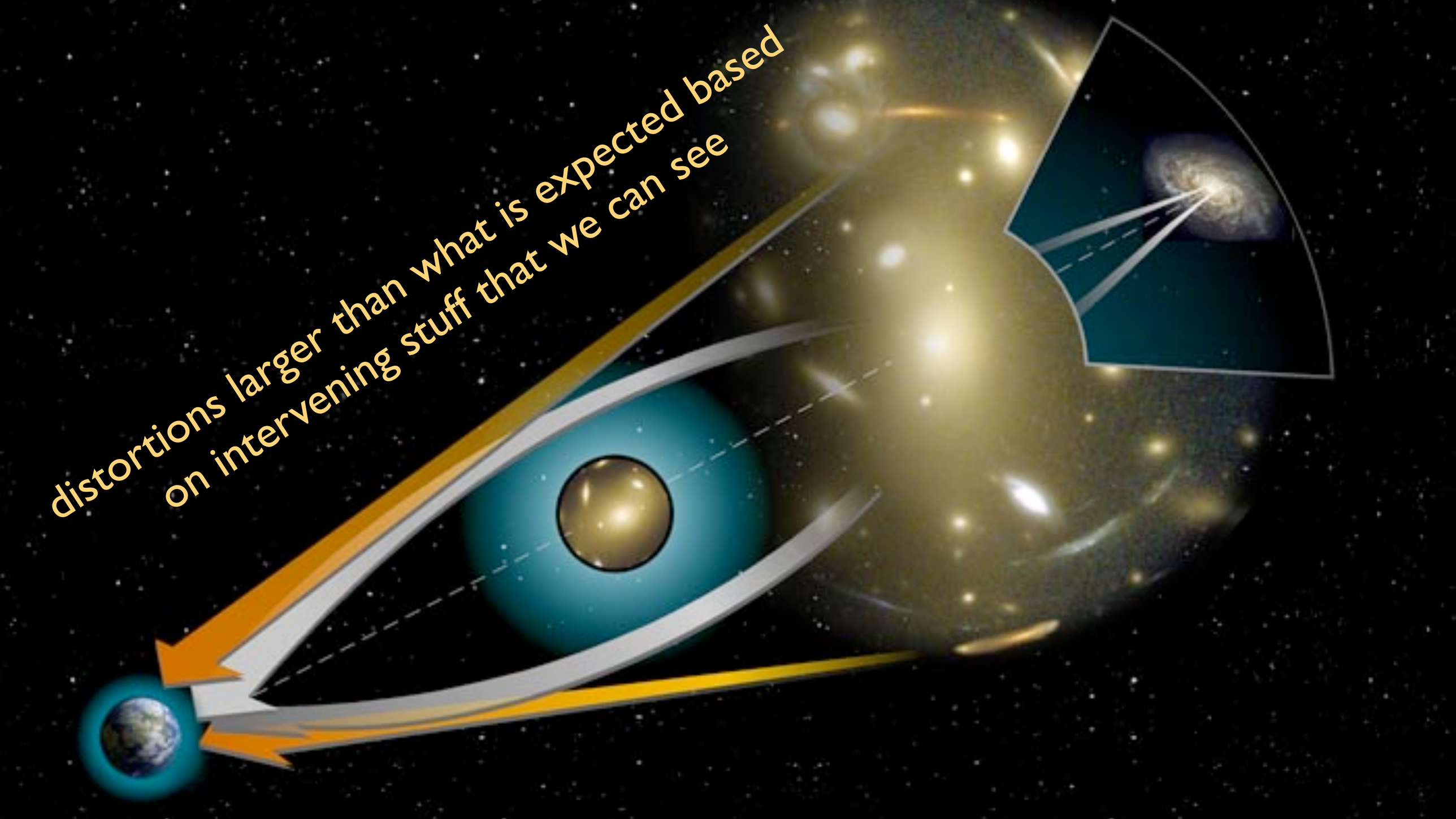


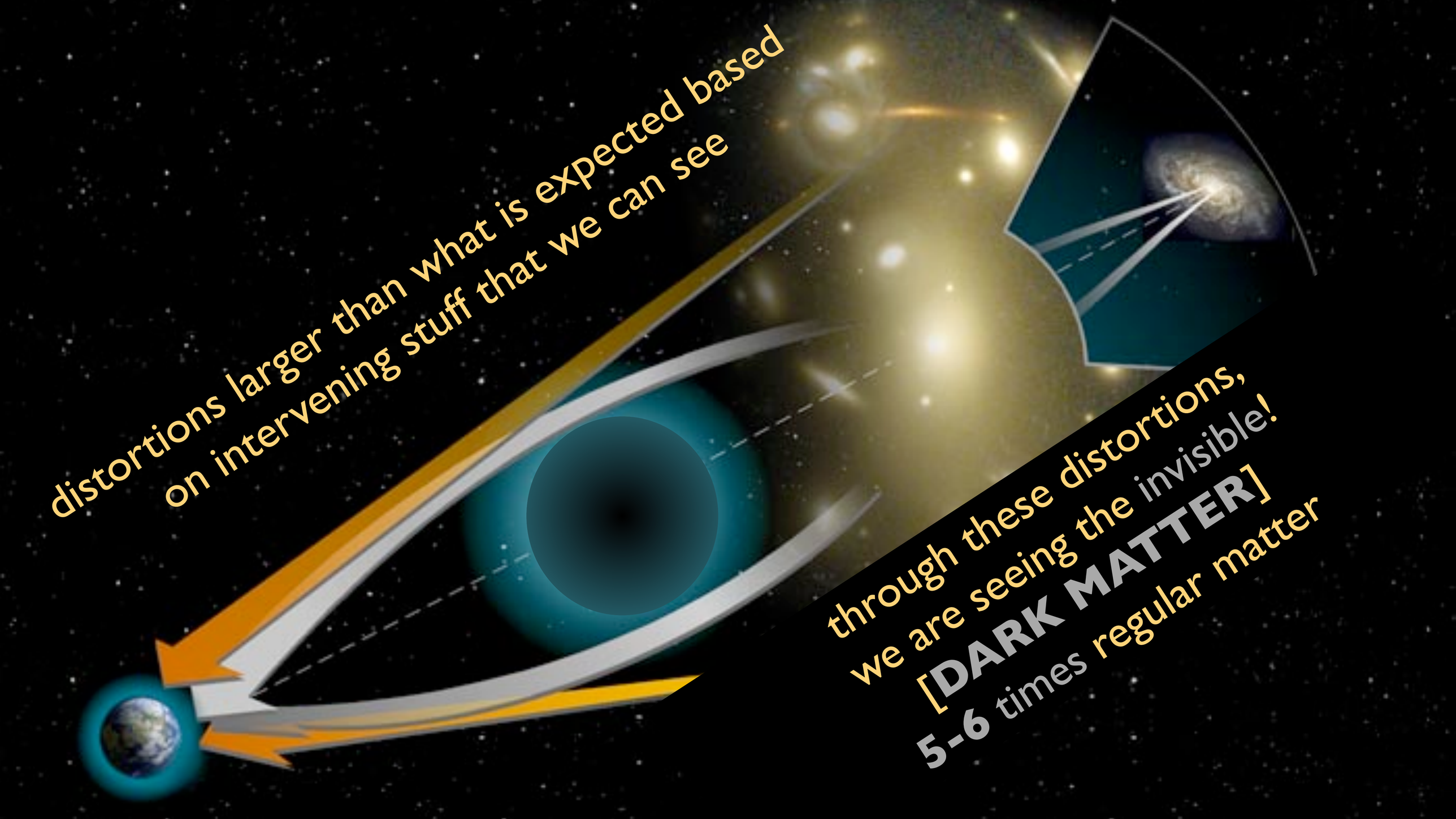

2002

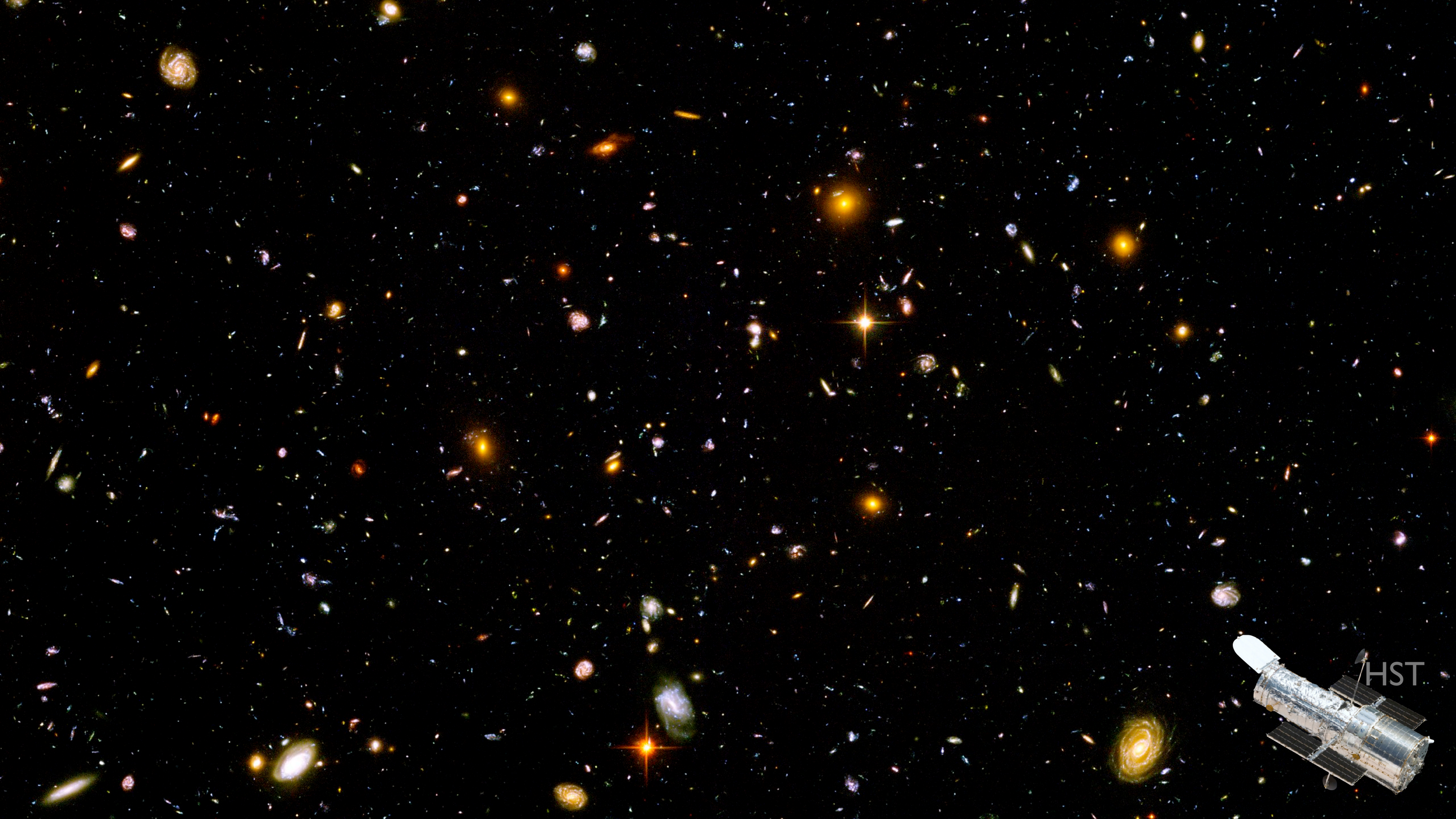
TM
DISHWASHER SAFE
2002
BPA FREE
CHINA

DISHWASHER SAFE
2002
BPA FREE
CHINA

gravitational lensing and dark matter


distortions larger than what is expected based
on intervening stuff that we can see

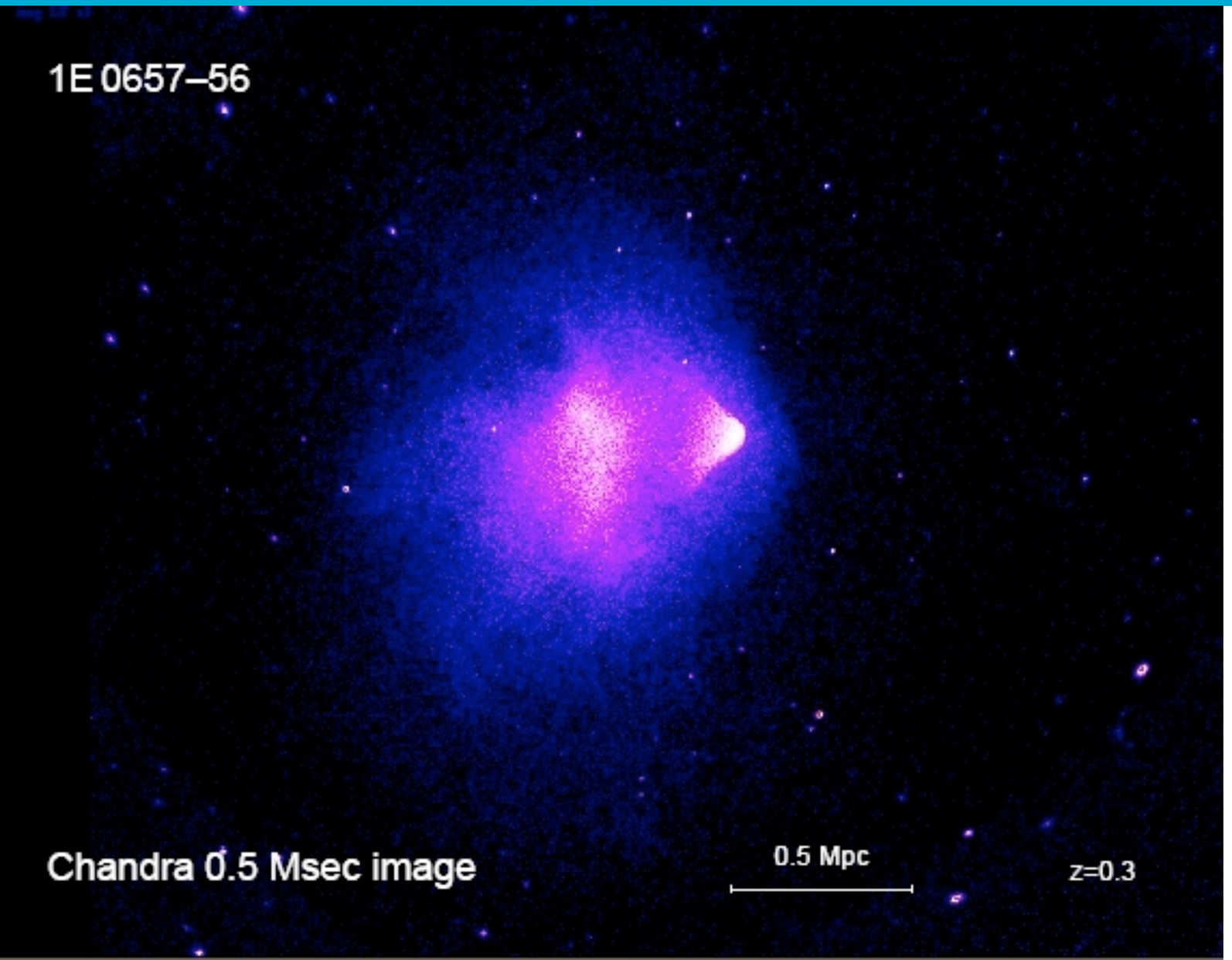

distortions larger than what is expected based on intervening stuff that we can see
through these distortions, we are seeing the invisible! [DARK MATTER] 5-6 times regular matter


HST


galaxy
~ 100,000,000,000 stars
Observable Universe
~ 100,000,000,000 galaxies
HST


$< 20\,\%$
HST

bullet cluster

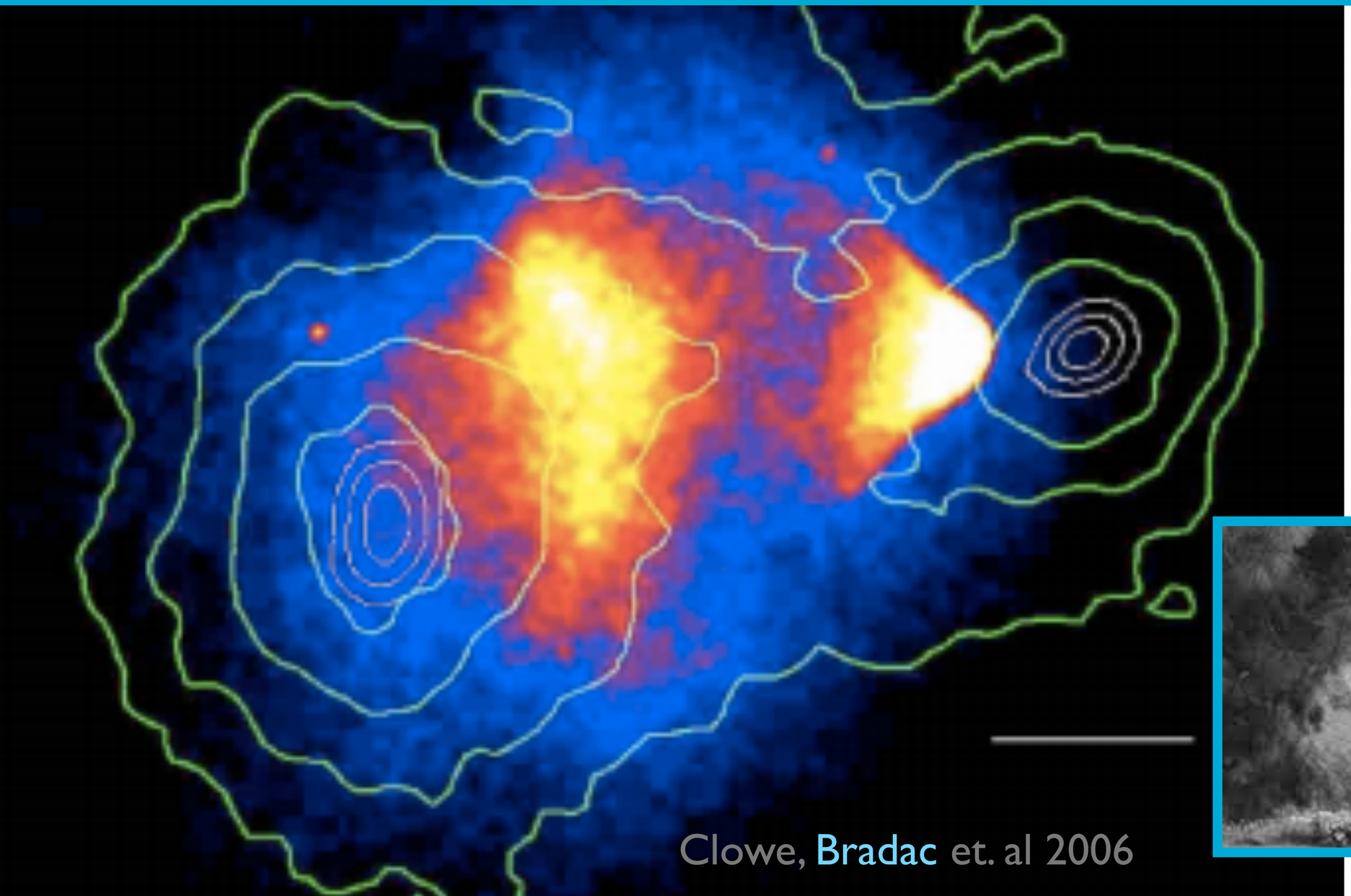


collision of two clusters of galaxies

“shocked” intergalactic gas slowed downs

most visible mass supposed to be in gas

bullet cluster

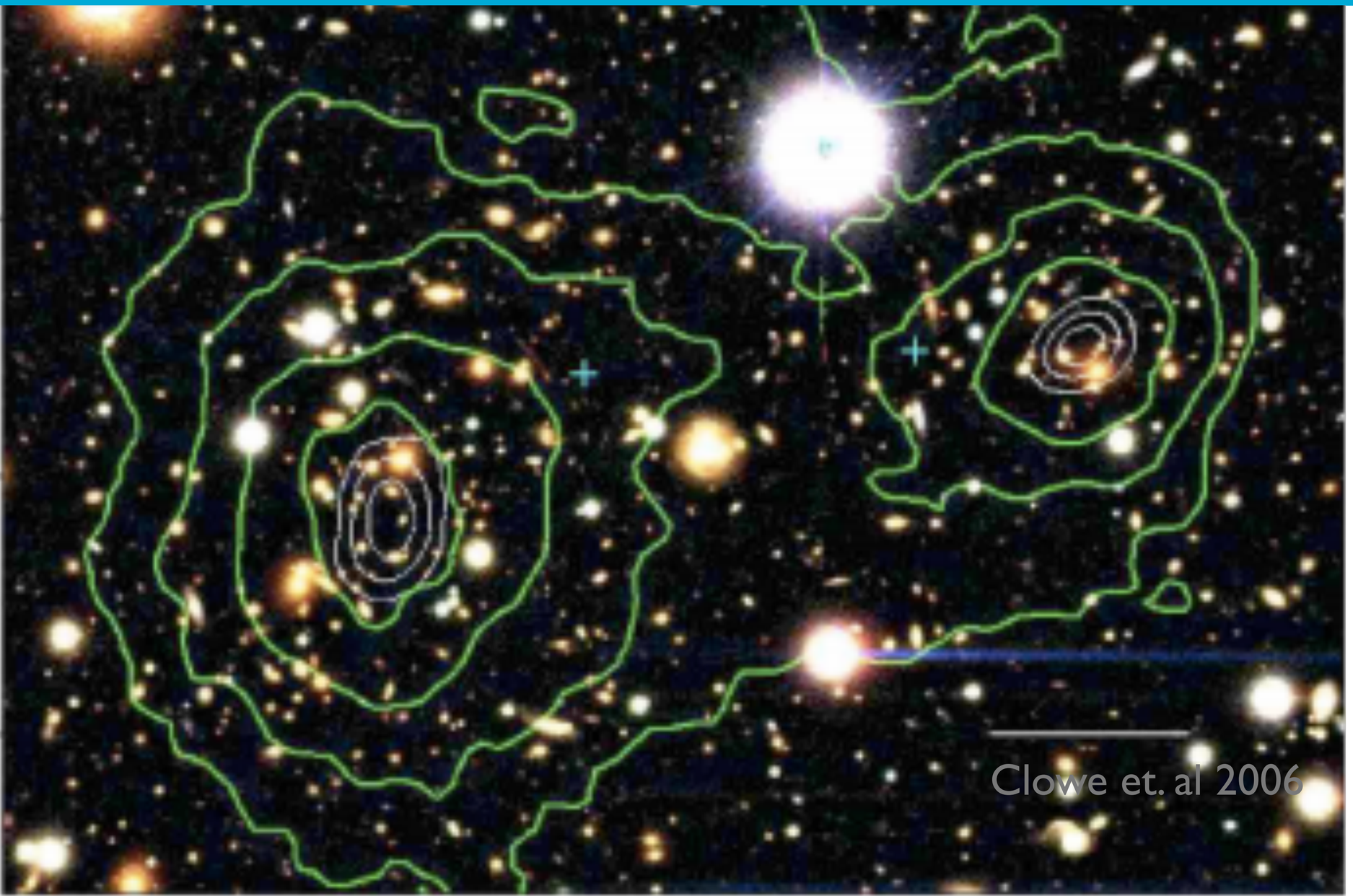


Clowe, Bradac et. al 2006

contours of where the mass is:

from gravitational lensing

bullet cluster

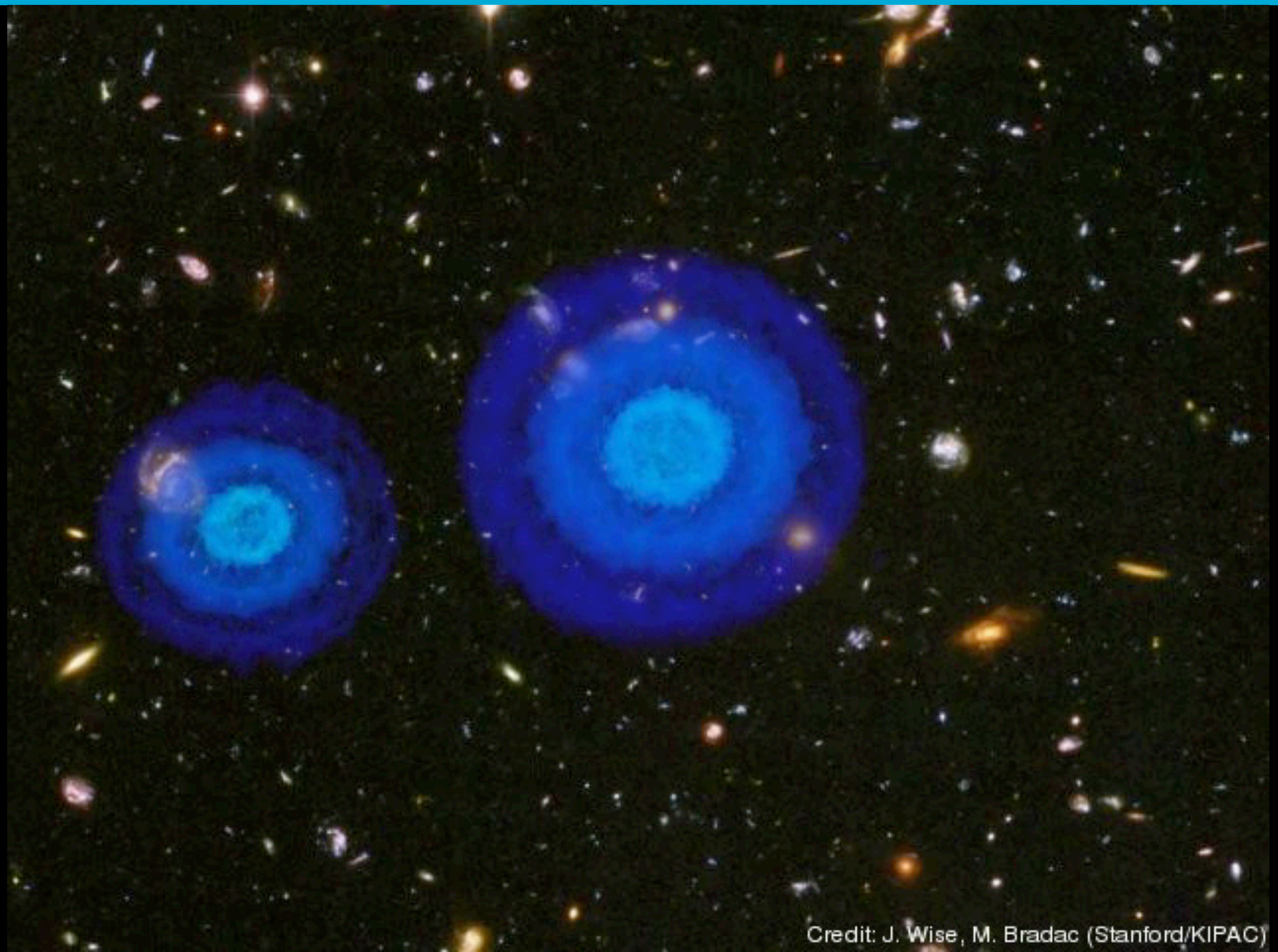


"collisonless" galaxies not slowed down

but mass from lensing much bigger than that from galaxies

—> Dark Matter

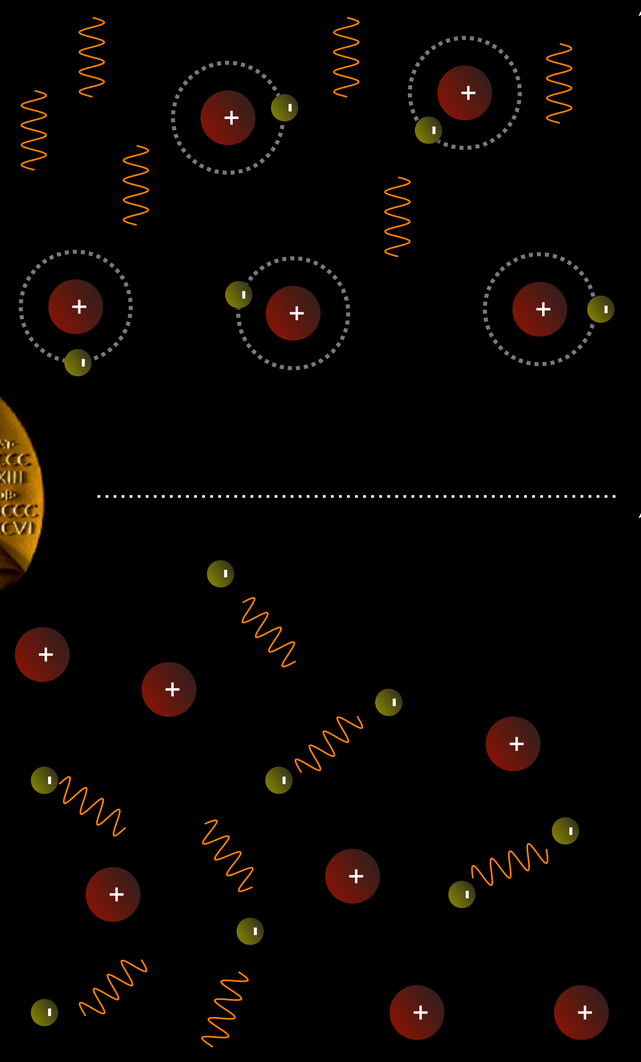
bullet cluster



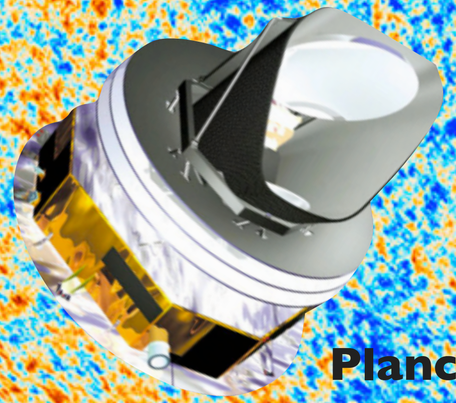
Penzias and **Wilson** (1965)

RICE

Credit: Roger Ressmeyer



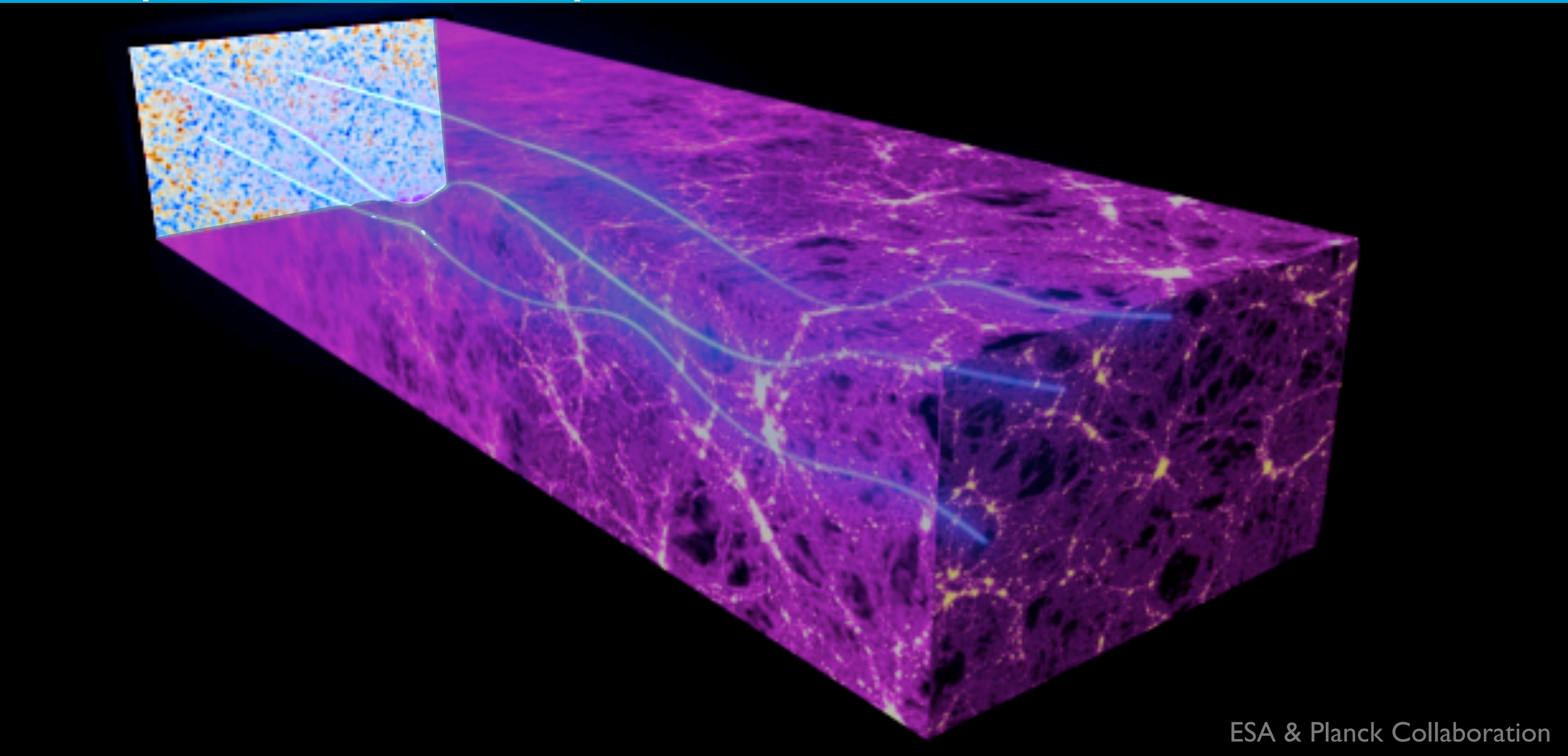
patterns in temperature of light from the first atoms



Planck 2018

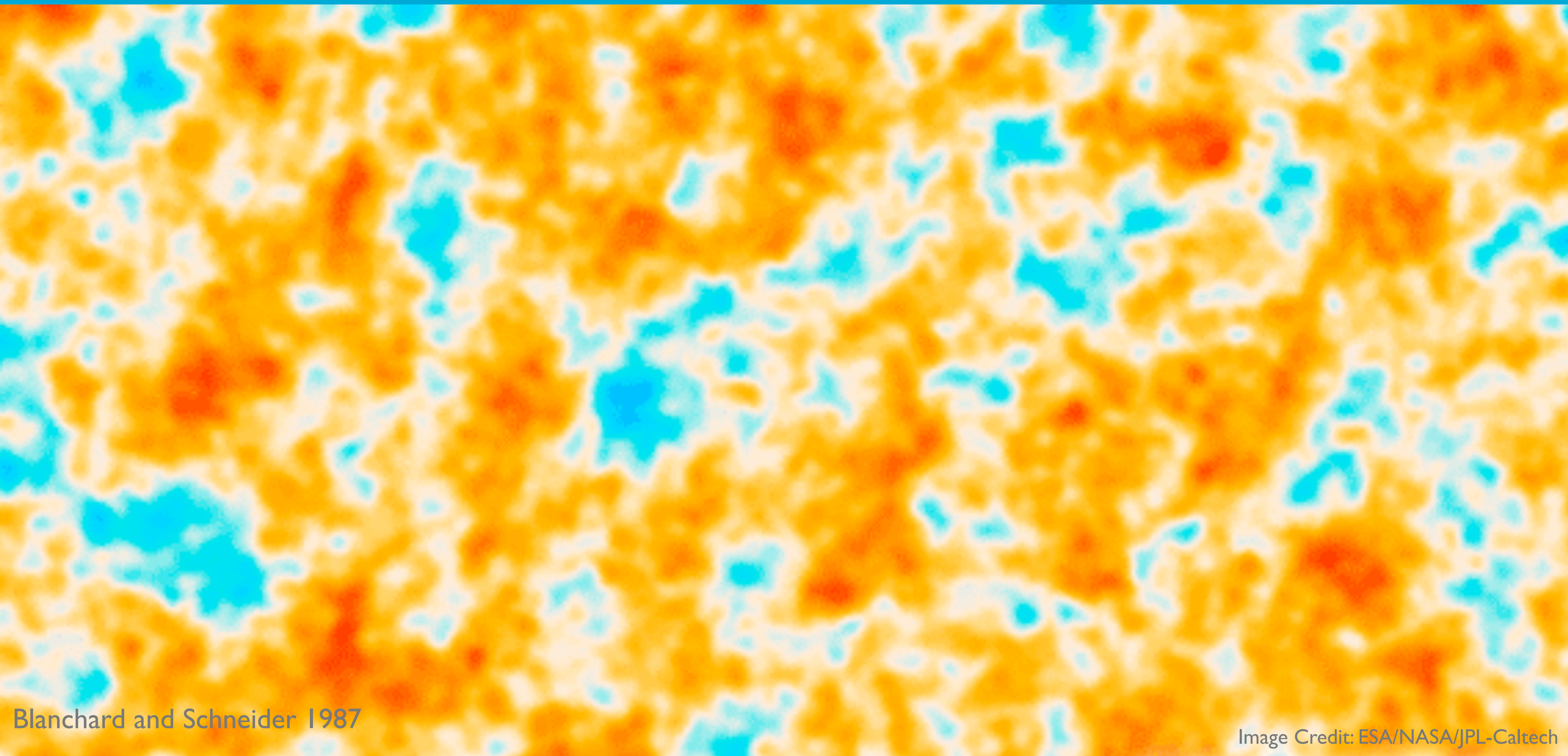
1°

light from first atoms passes through the (mildly) distorted spacetime on its way to us



ESA & Planck Collaboration

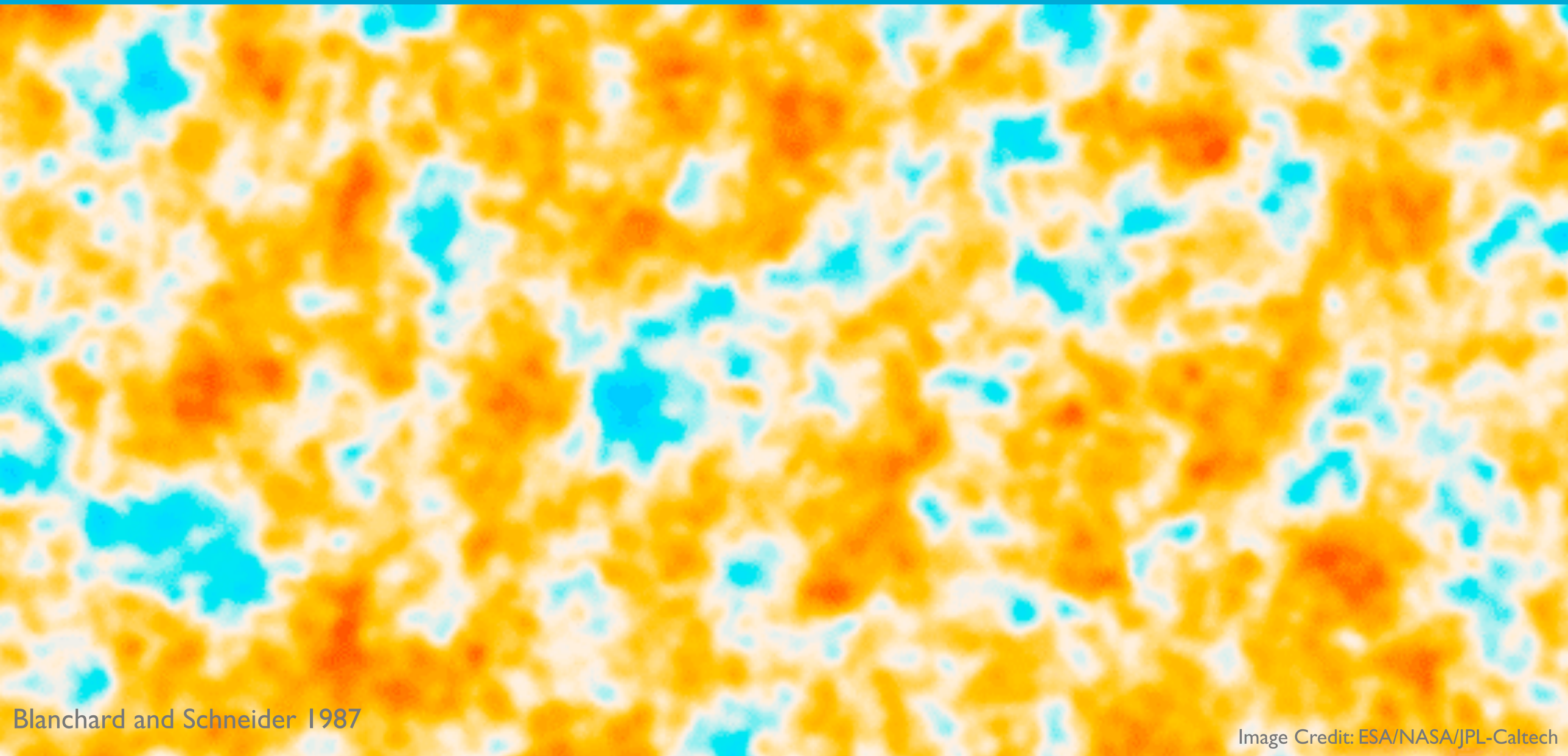
patterns in temperature of light from the first atoms



Blanchard and Schneider 1987

Image Credit: ESA/NASA/JPL-Caltech

patterns in temperature of light from the first atoms



Blanchard and Schneider 1987

Image Credit: ESA/NASA/JPL-Caltech

patterns in temperature of light from the first atoms

revealing information about (invisible) dark matter distribution!

dark matter makes up 85% of matter in the cosmos!

Background image credit: Abel, Emmart, Hahn & Kaehler

gravitational lensing and supermassive black holes


MATTHEW McCONAUGHEY
ANNE HATHAWAY
JESSICA CHASTAIN
MICHAEL CAINE
THE END OF EARTH WILL NOT BE THE END OF US.
INTERSTELLAR
IN 70MM IMAX, 70MM FILM AND 35MM FILM
ON NOVEMBER 5
EVERYWHERE
NOVEMBER 7

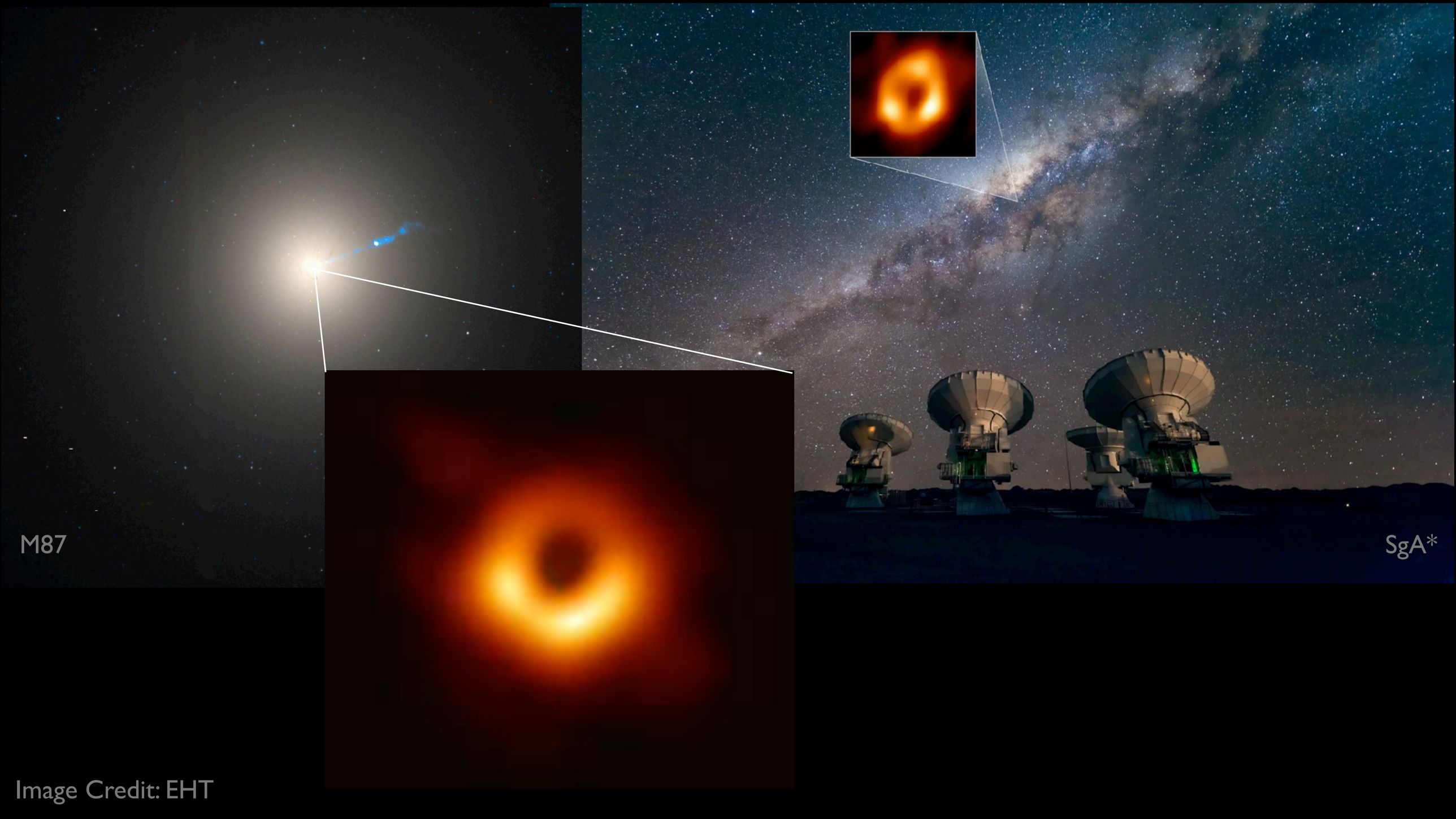
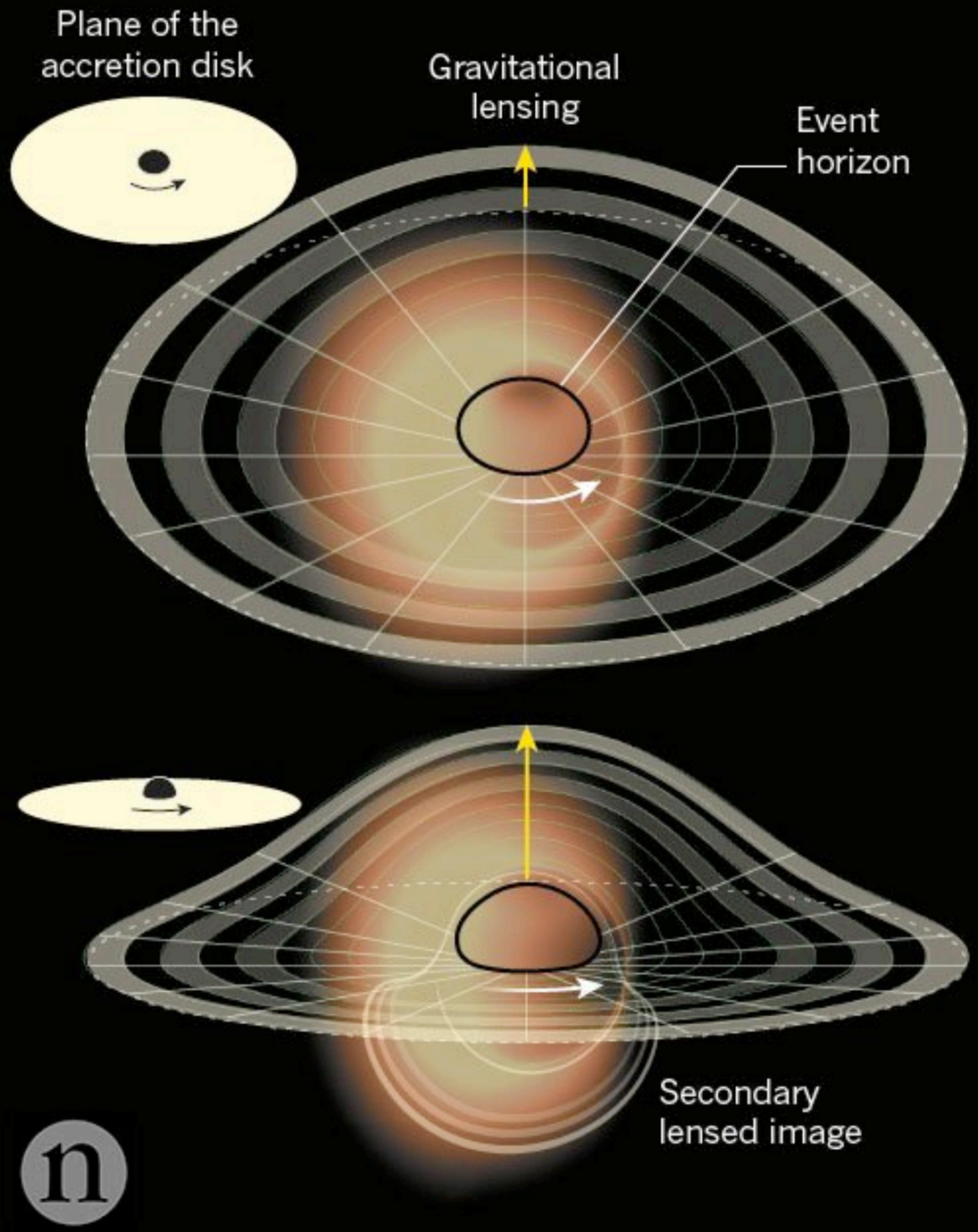
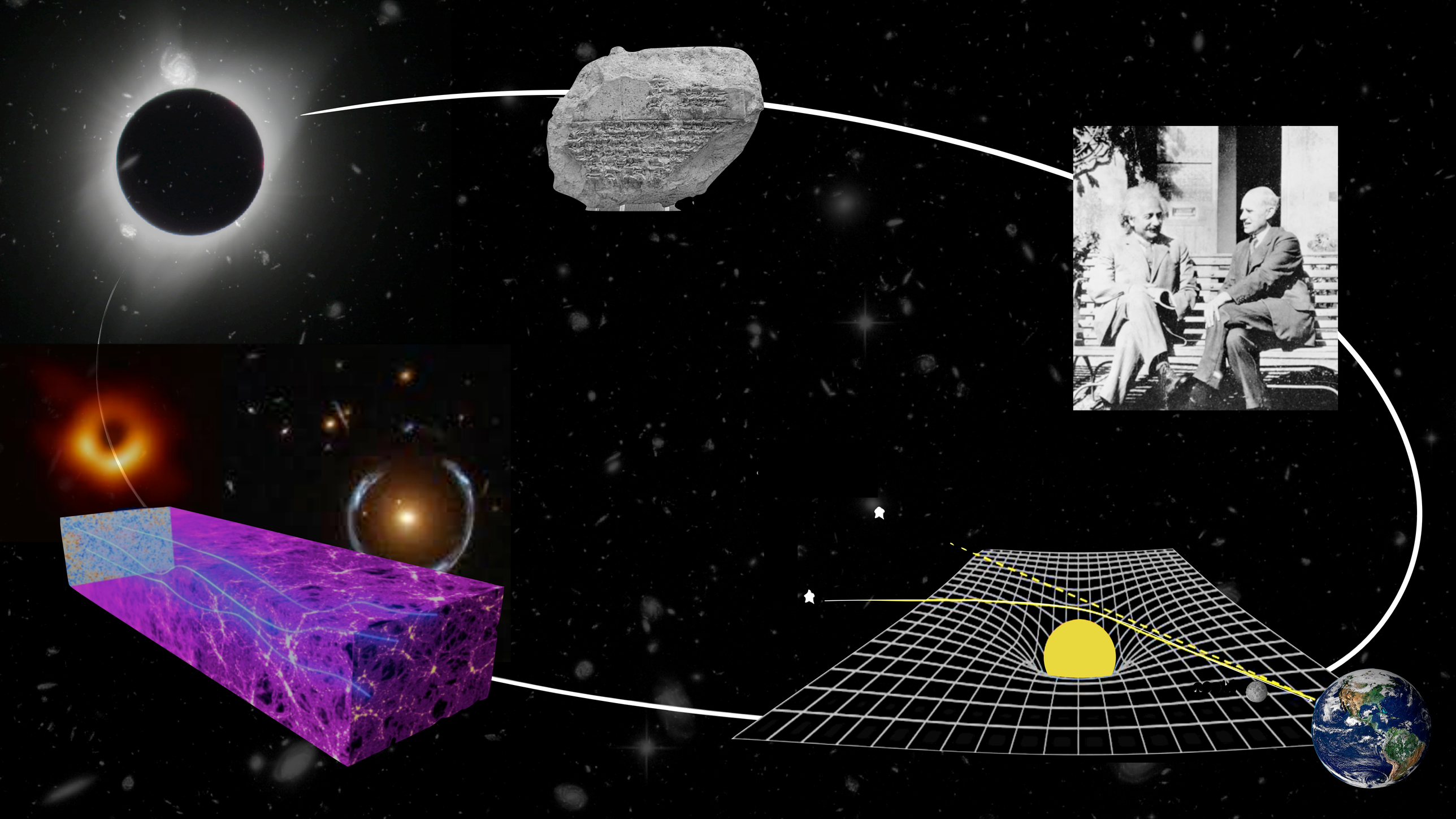


Image Credit: EHT


Plane of the accretion disk
Gravitational lensing
Event horizon
Secondary lensed image



same watertank on top of Hadiqat-e-Burhani, Surat, India, rest is a fanciful recreation


April 8, 2024