

# Grand Tour of the Universe

A Brief Introduction to Cosmology

Discovery of Dark Energy

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# Menu

- Part 1: Space Time Travel
  - Travel in Time
  - Travel in Space
  - Current Understanding of the Universe
- Part 2 : Observing the Universe
- Discovery of Dark Energy
- Future Research

# Universe (宇宙)

- 宇 : Space
- 宙 : Present, Past, Future (Time)
- 往古來今宙謂、四方上下宇謂 (「淮南子」、齊俗訓)
- Space Time : 時空

# The Top 10 Biggest Events in the Universe

- 1. Big Bang
- 2. Big Bang Nucleosynthesis (Birth of Elements)
- 3. The Birth of the First Star
- 4. Galaxies Formation
- 5. Solar System forms
- 6. The oldest life-form appears on the Earth
- 7. The first animals appeared
- 8. Animals begin colonization of land
- 9. Extinction of Dinosaurs
- 10. Modern Human-being appears

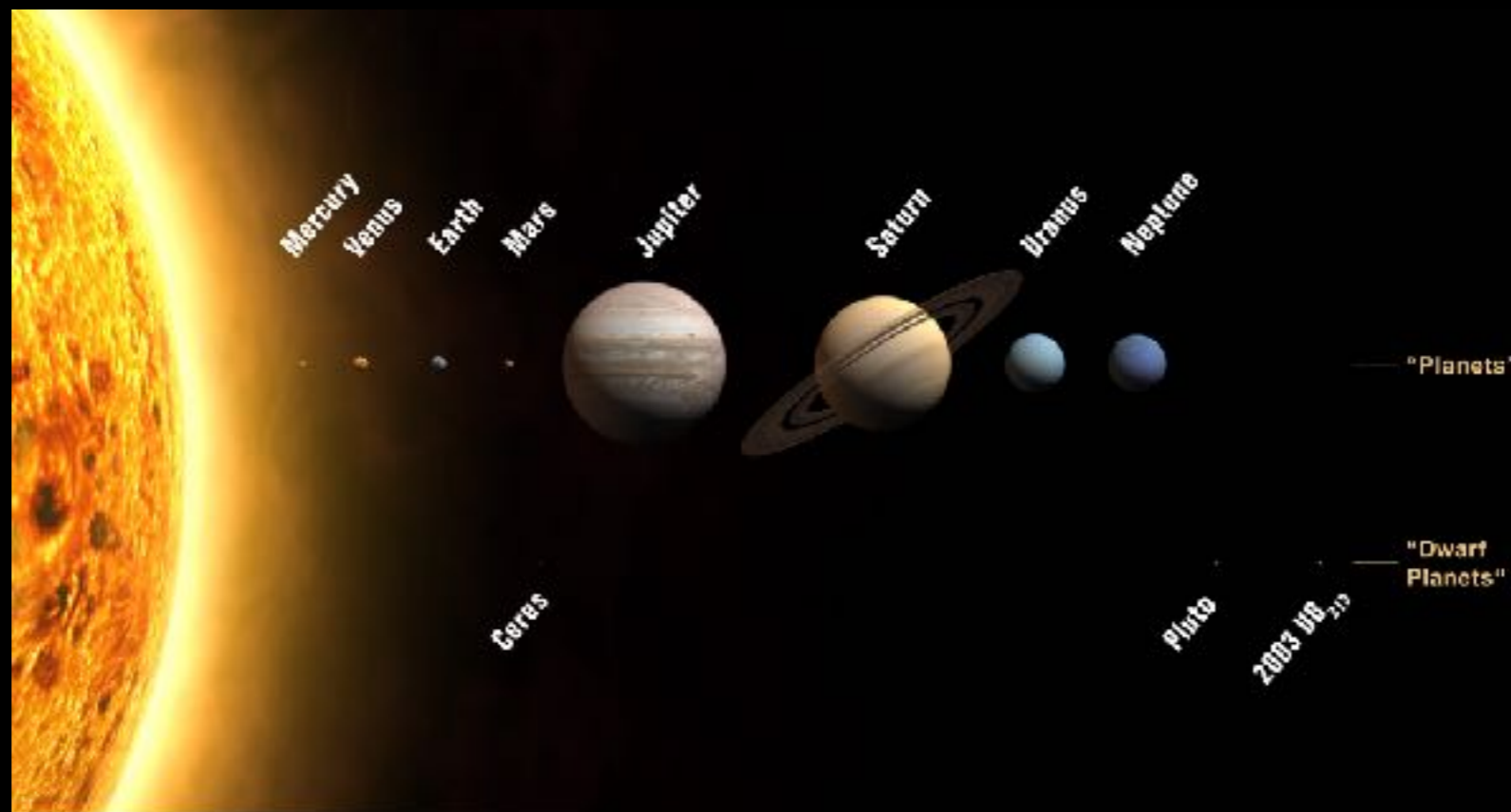
# Cosmic Calendar

## Universe (13.8Gyr) in One Year

- 1. Big Bang Jan 1st 0:00:00
- 2. Big Bang Nucleosynthesis Jan 1st 0:00:00.000000001
- 3. First Star Jan 1st 10:00:00
- 4. Galaxy Formation May 1st
- 5. Birth of the Solar System Aug 30th : 4.6 billion years ago
- 6. First Life Form Sep 28th
- 7. First Animal Dec 16th
- 8. Land Colonization Dec 20th
- 9. Extinction of Dinosaurs Dec 29th
- 10. Modern Human Dec 31st 23:59:36.9

# Travel in Space

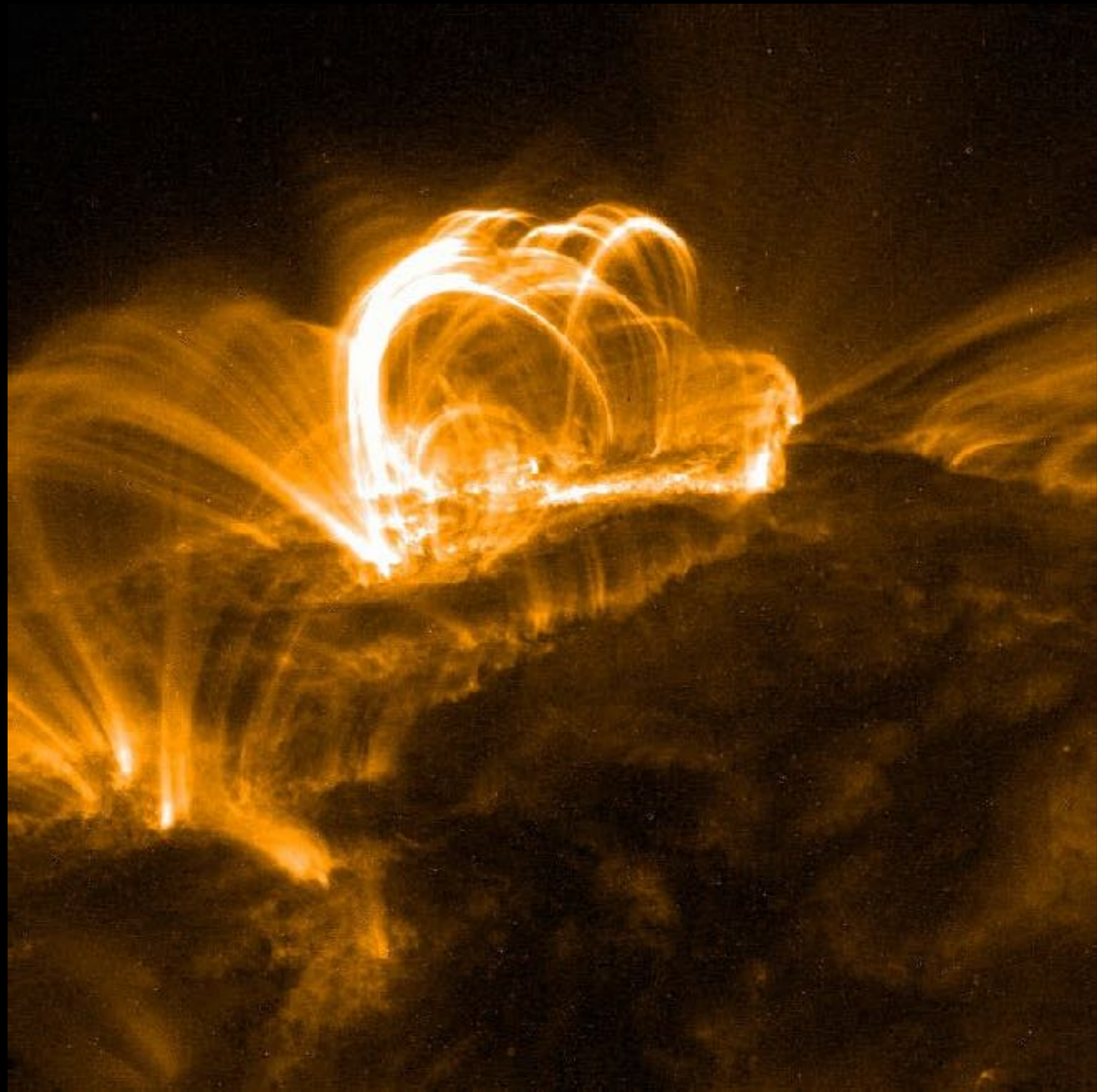
- Q. Suppose the Size of the Sun is a Quarter Coin, what are the distances to the planets?



# Sun



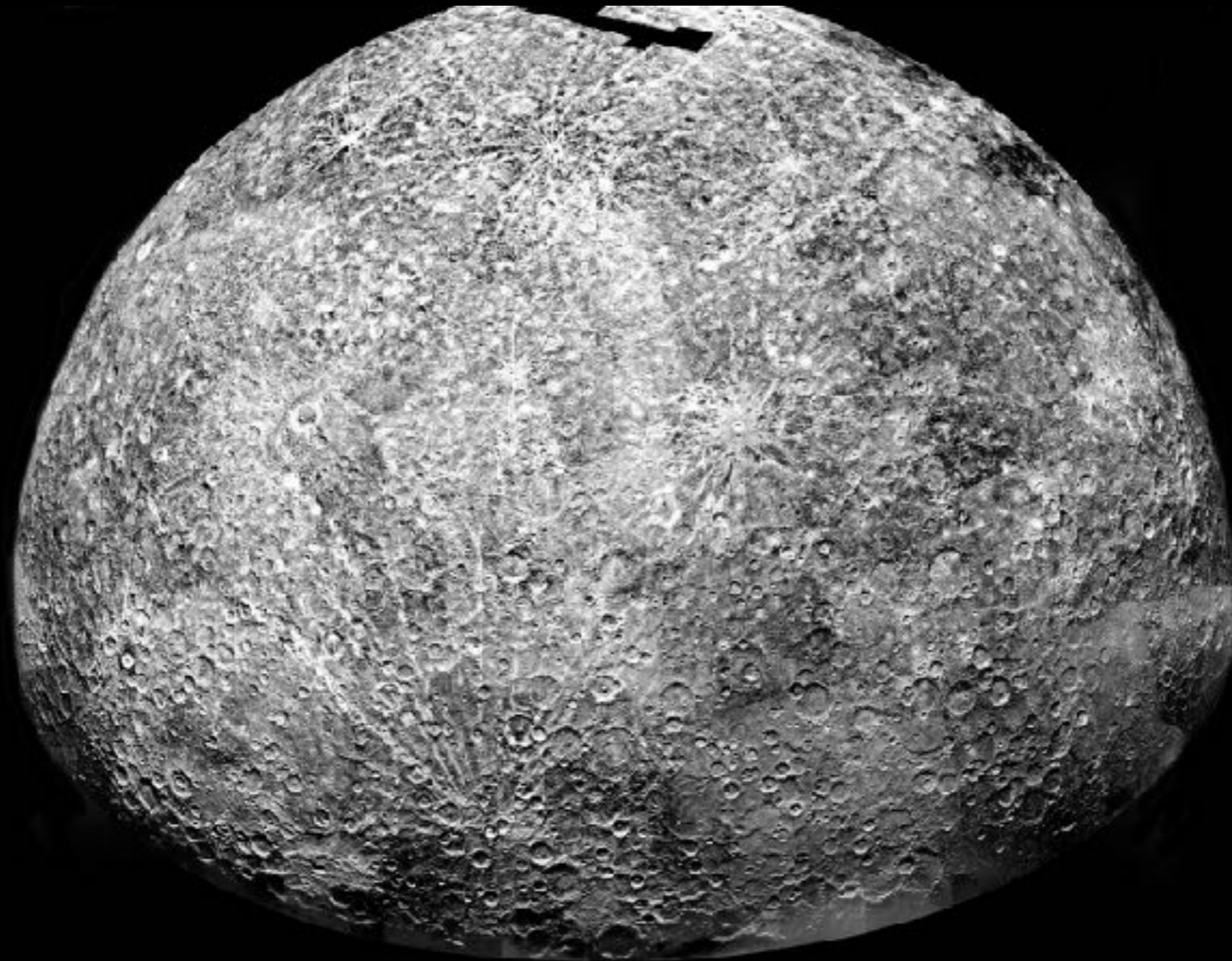




QuarkNet 2022

Mercury

$R=1.0 \text{ m (0.387AU)}$



Venus

$R=1.86 \text{ m (0.723 AU)}$



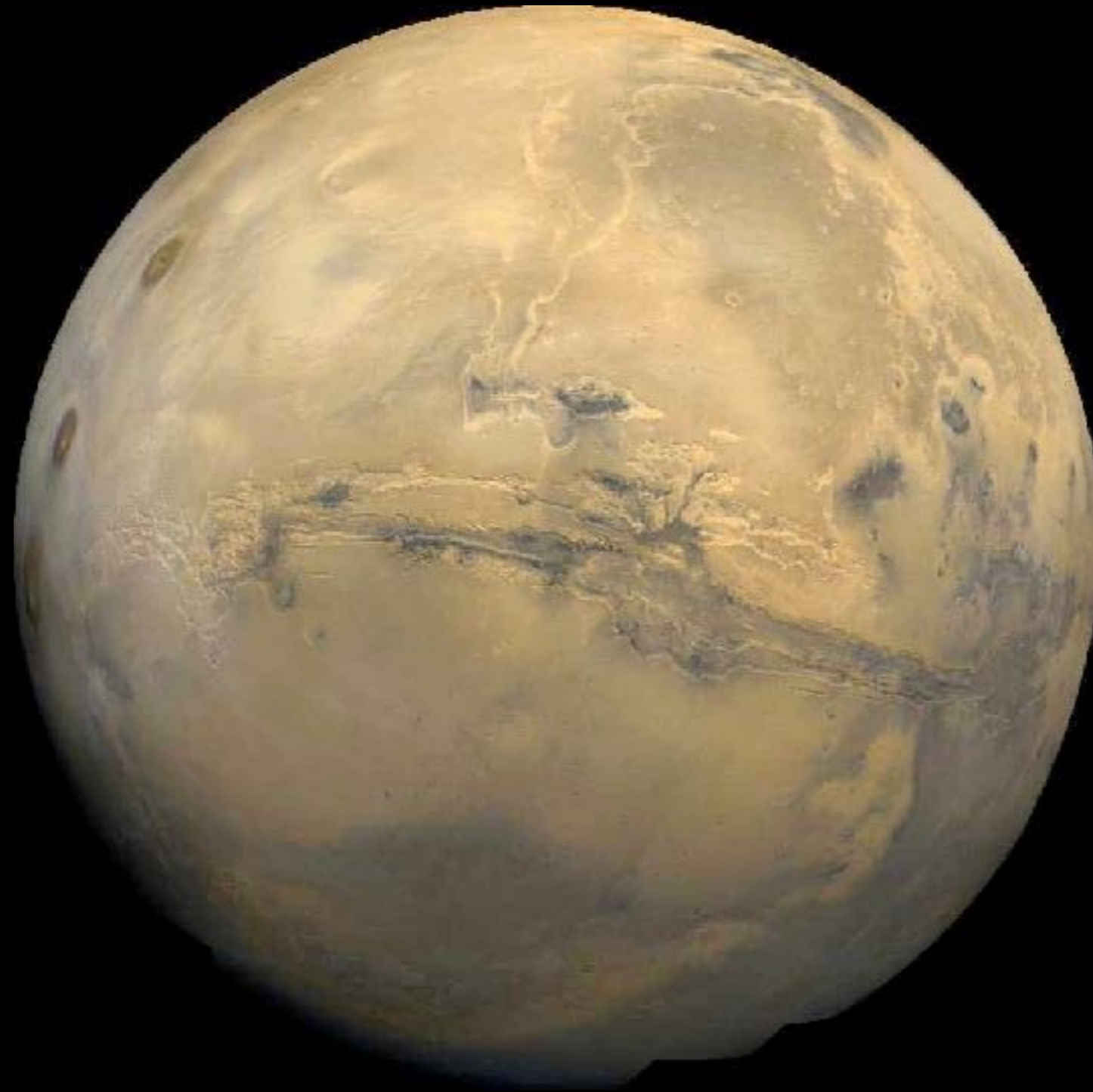
Earth

$R=2.58 \text{ m (1.00AU)}$



Mars

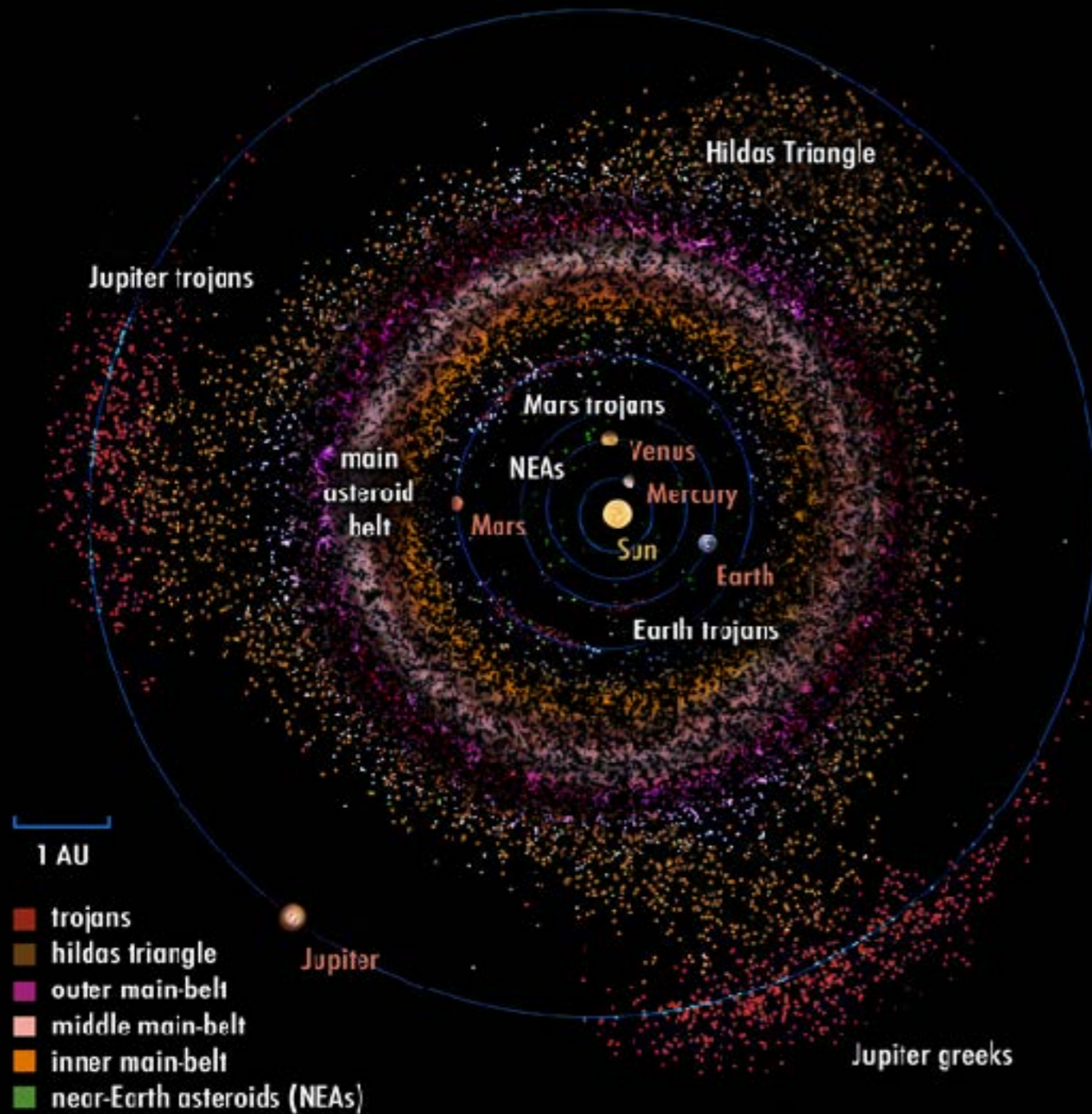
$R=3.97 \text{ m}$  (1.524AU)



# Mars Satellite Phobos



# Asteroids



Itokawa and Ryugu to scale (Ish)



25143 Itokawa  
0.5 × 0.3 × 0.2 km  
Hayabusa 2005



162173 Ryugu  
1.0 km  
Hayabusa2 2018

Images: NASA, University of Tokyo, JAXA, University of Guelph, Japan Space Agency, University of Technology, University of Arizona, University of Colorado Boulder, The Planetary Society. All rights reserved.

1921: 1,000

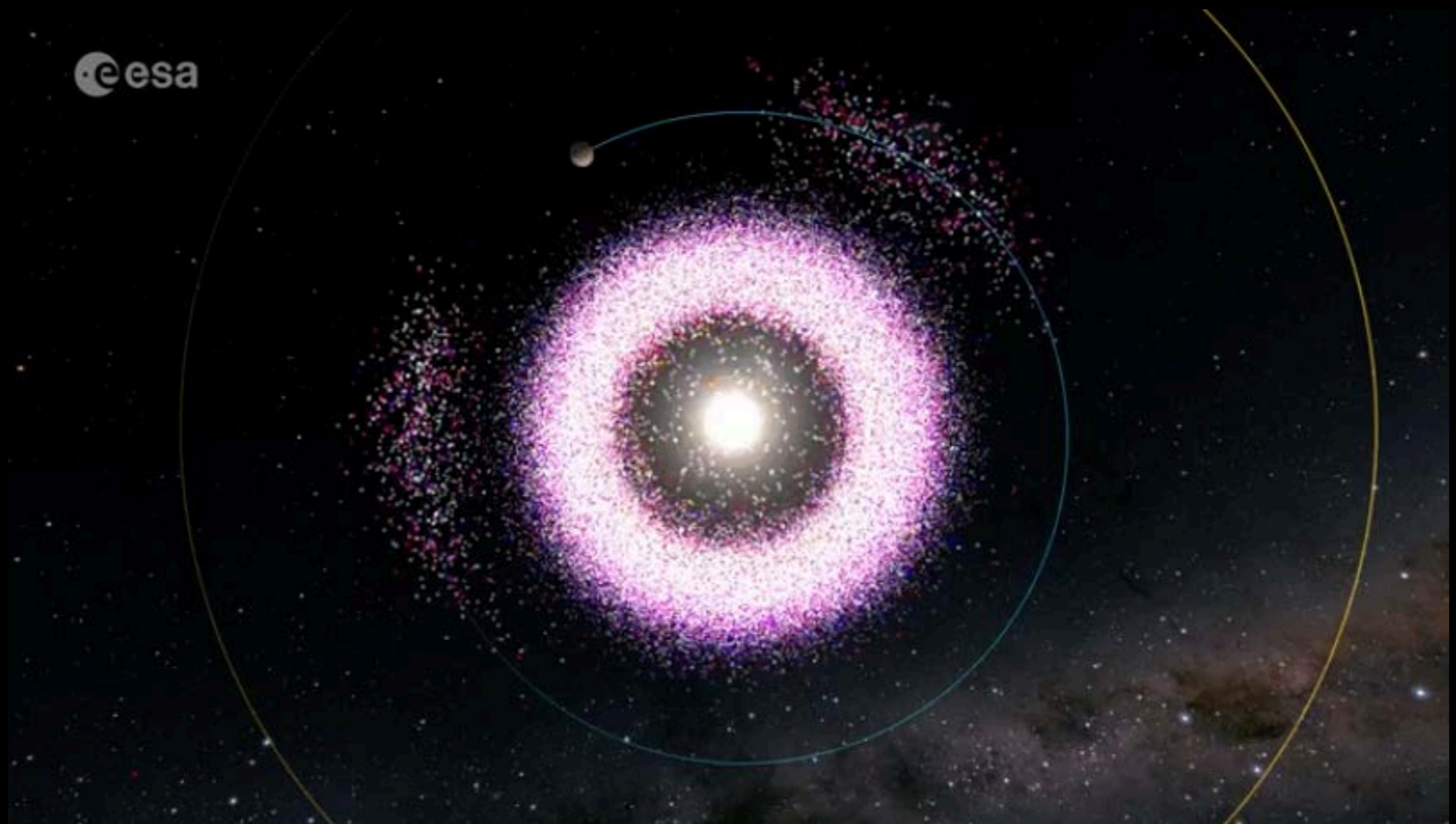
1981: 10,000

2000: 100,000

2022-06-12 GAIA DR3

154,721 Asteroids

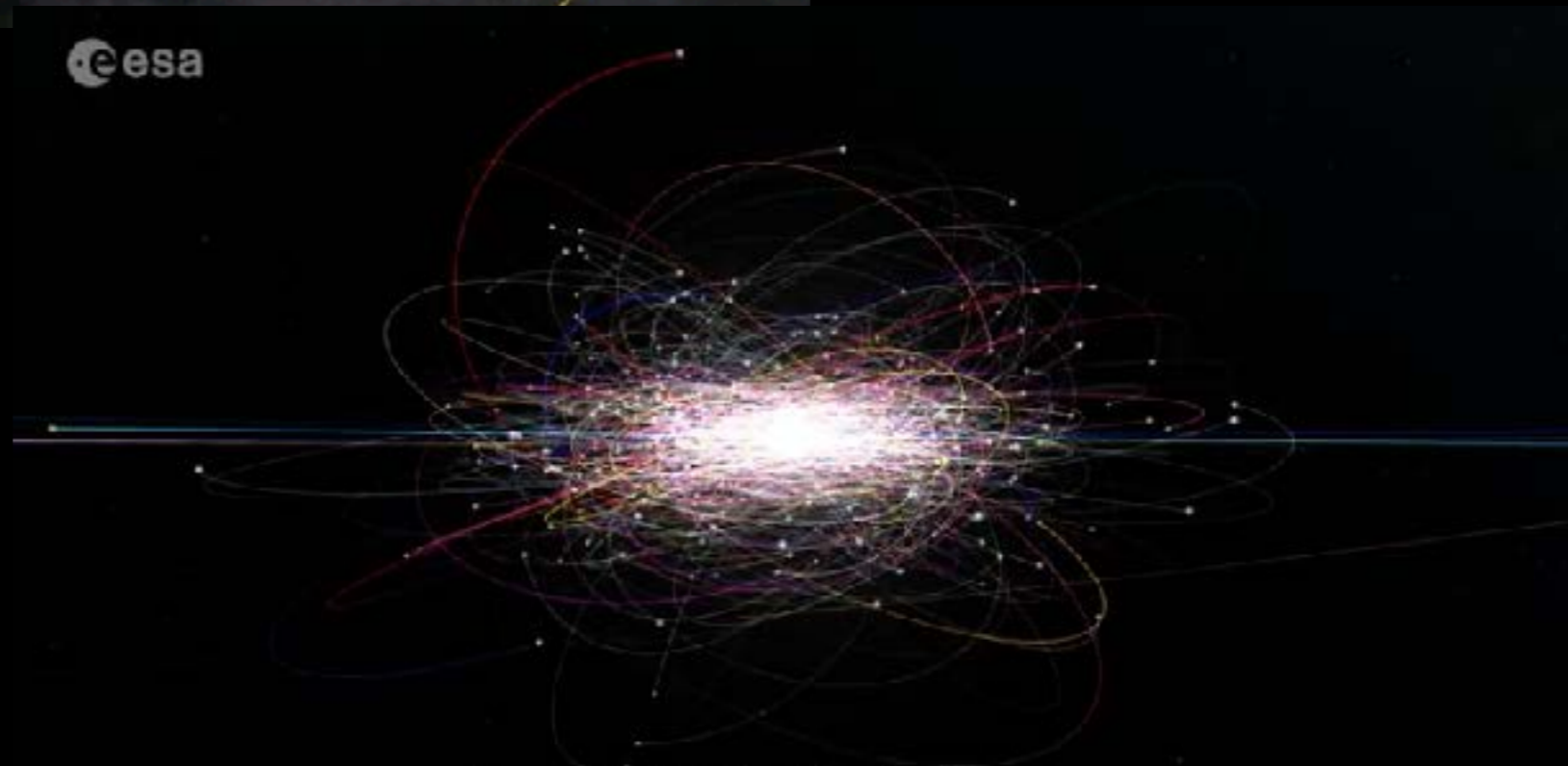
# 154,721 Asteroids







Back in the Inner Solar System, we find those objects that come close to the Earth and sometimes cross its orbit.



with respect to the Earth's orbit and can also come very close to the Sun where they experience strong heating.

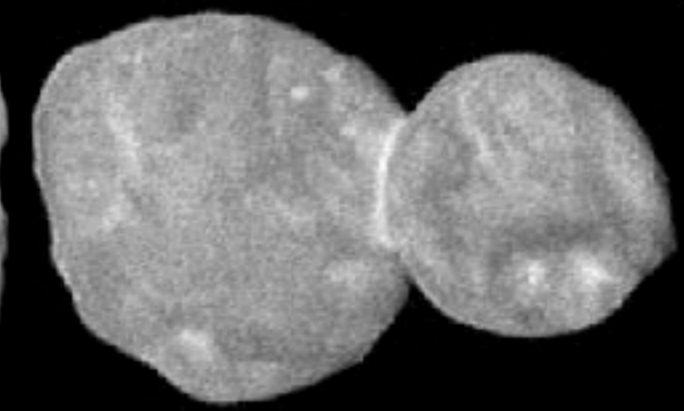
# 446 Near Earth Asteroids



We now move close to the Earth and observe this group of 446 Near Earth Asteroids (NEAs).



253 Mathilde - 66 × 48 × 44 km  
NEAR, 1997



103/P Hartley 2  
2.2 × 0.5 km  
Deep Impact/EPOXI 2010

2014 MU69  
33.5 × 19.5 × 19.5 km  
New Horizons, 2019



433 Eros - 33 × 13 km  
2000

5535 Annefrank  
6.6 × 5.0 × 3.4 km  
Stardust, 2002

2867 Steins  
5.9 × 4.0 km  
Rosetta, 2008



951 Gaspra  
18.2 × 10.5 × 8.9 km  
Galileo, 1991

25143 Itokawa  
0.5 × 0.3 × 0.2 km  
Hayabusa, 2005

9969 Braille  
2.1 × 1 × 1 km  
Deep Space 1, 1999



243 Ida - 58.8 × 25.4 × 18.6 km  
Galileo, 1993



67P/Churyumov-Gerasimenko  
4.1 × 3.2 × 2.5 km  
Rosetta, 2014



9P/Tempel 1  
7.6 × 4.9 km  
Deep Impact, 2005



Dactyl  
[(243) Ida I]  
1.6 × 1.2 km  
Galileo, 1993

1P/Halley - 16 × 8 × 8 km  
Vega 2, 1986



81P/Wild 2  
5.5 × 4.0 × 3.3 km  
Stardust, 2004



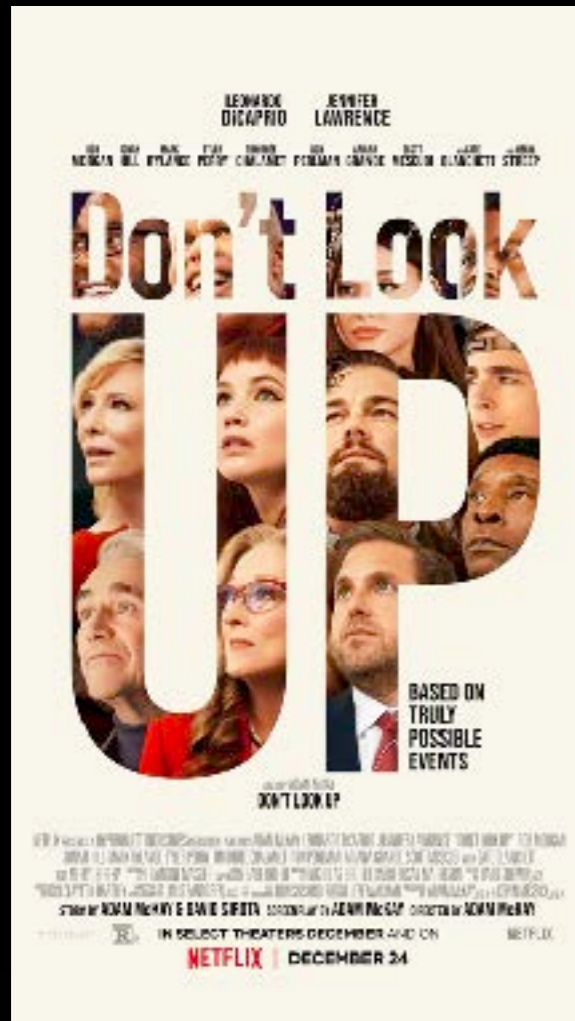
19P/Borrelly  
8 × 4 km  
Deep Space 1, 2001

4179 Toutatis  
4.6 × 2.3 × 1.9 km  
Chang'E 2, 2012

162173 Ryugu  
1.0 km  
Hayabusa 2, 2018

101955 Bennu  
0.5 km  
OSIRIS-REx, 2018

# Hunting for Supernova using Subaru Hyper-Suprime Cam



But they happen to find a killer asteroid-



Credit: Don't Look Up (2021); Netflix



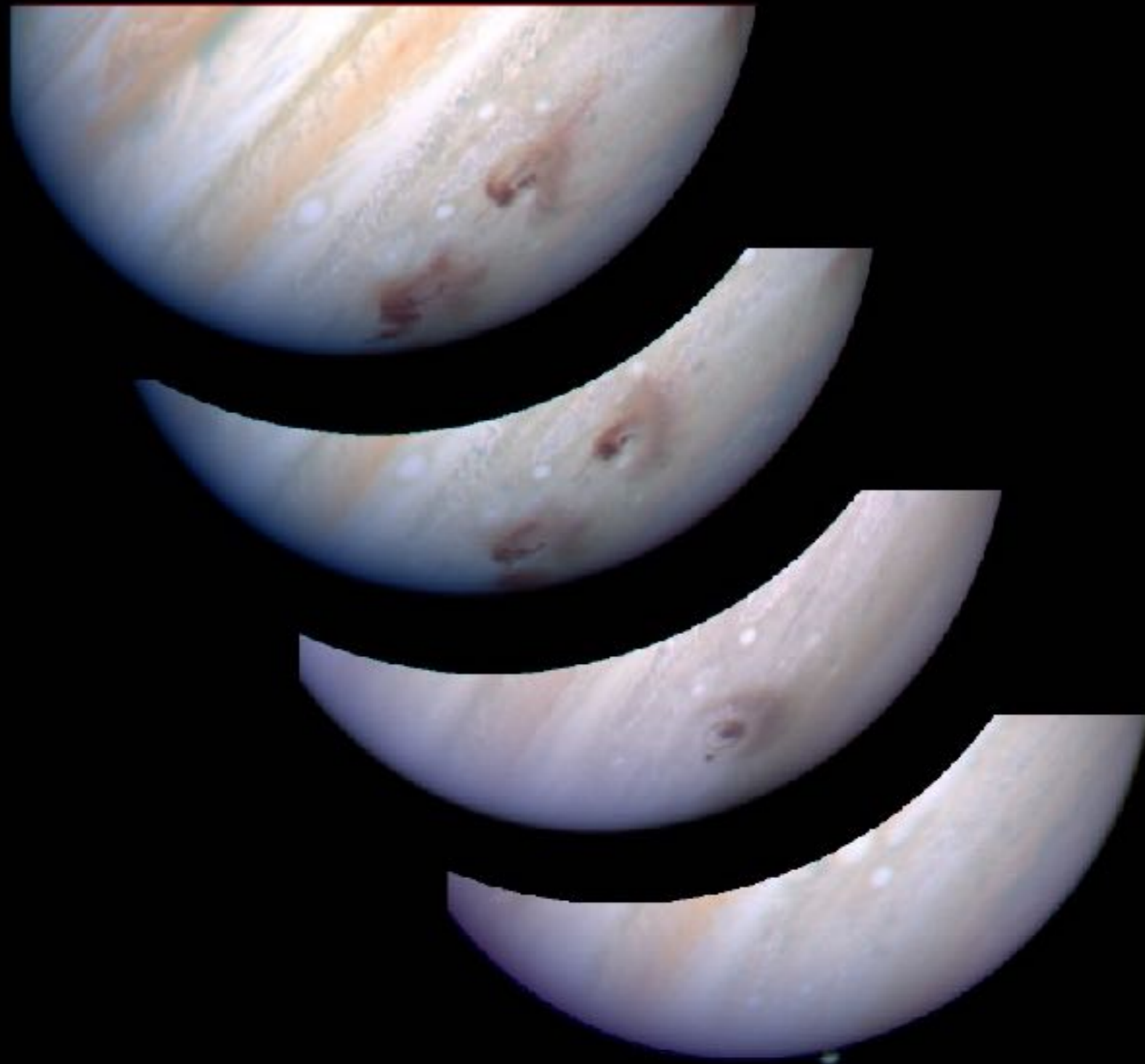
Credit: Don't Look Up (2021); Netflix

Jupiter

$R=13.4 \text{ m}$  (5.203 AU)



# Deep Impact in 1992





Juno Mission





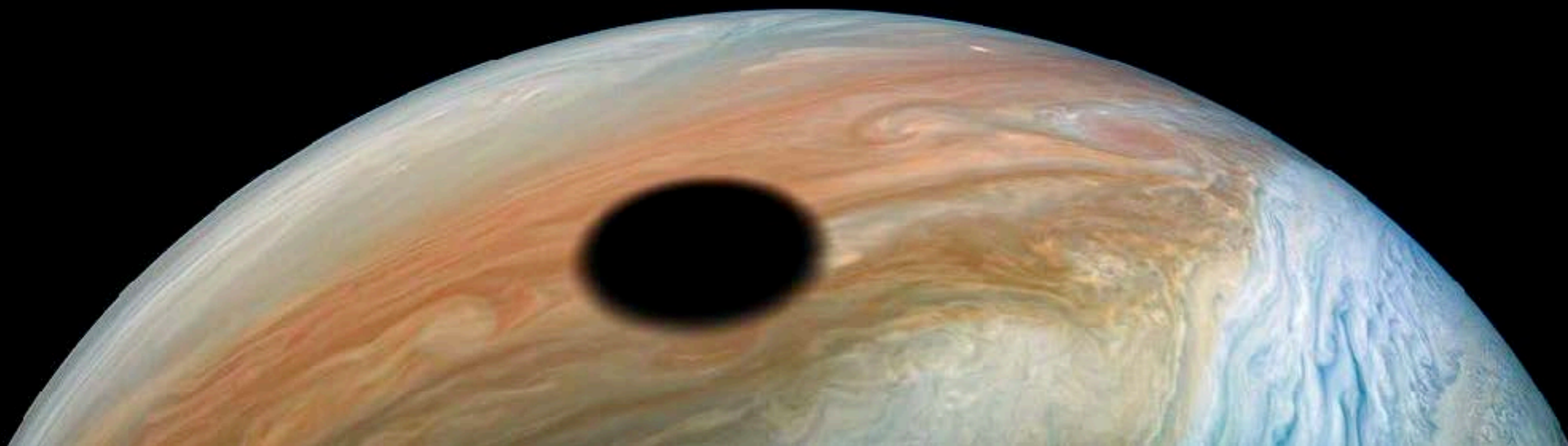
QuarkNet 2022



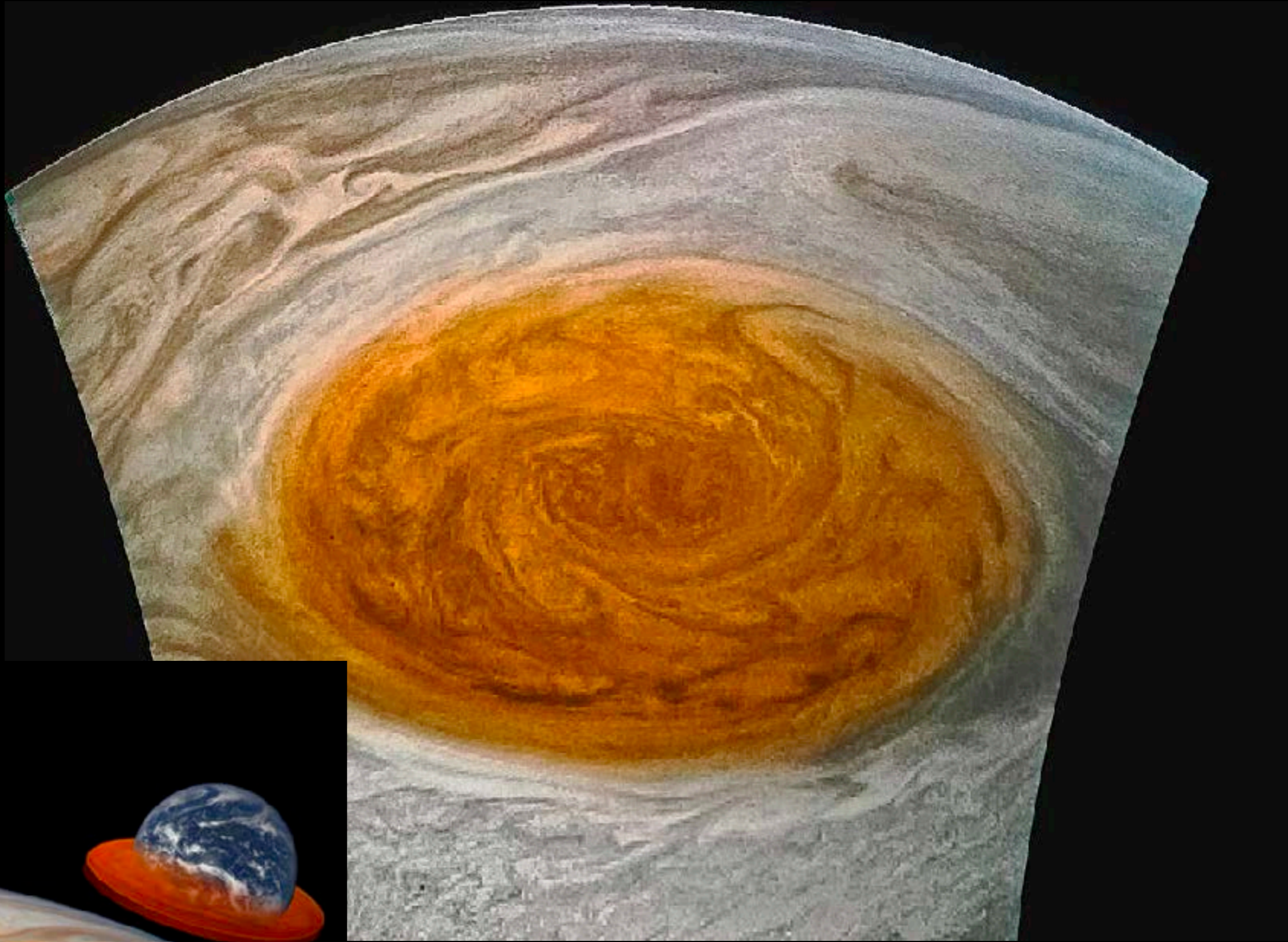


QuarkNet 2022

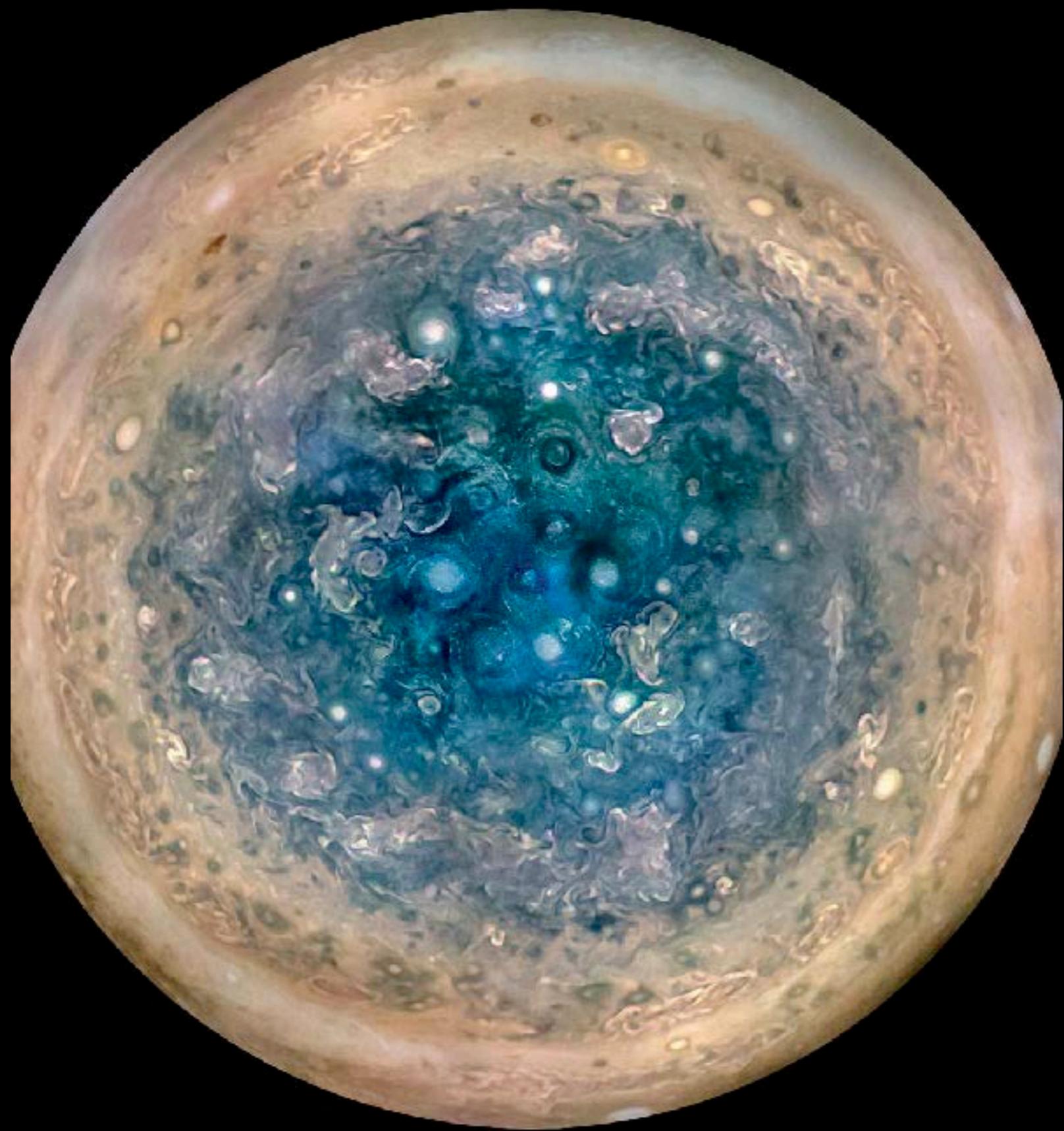




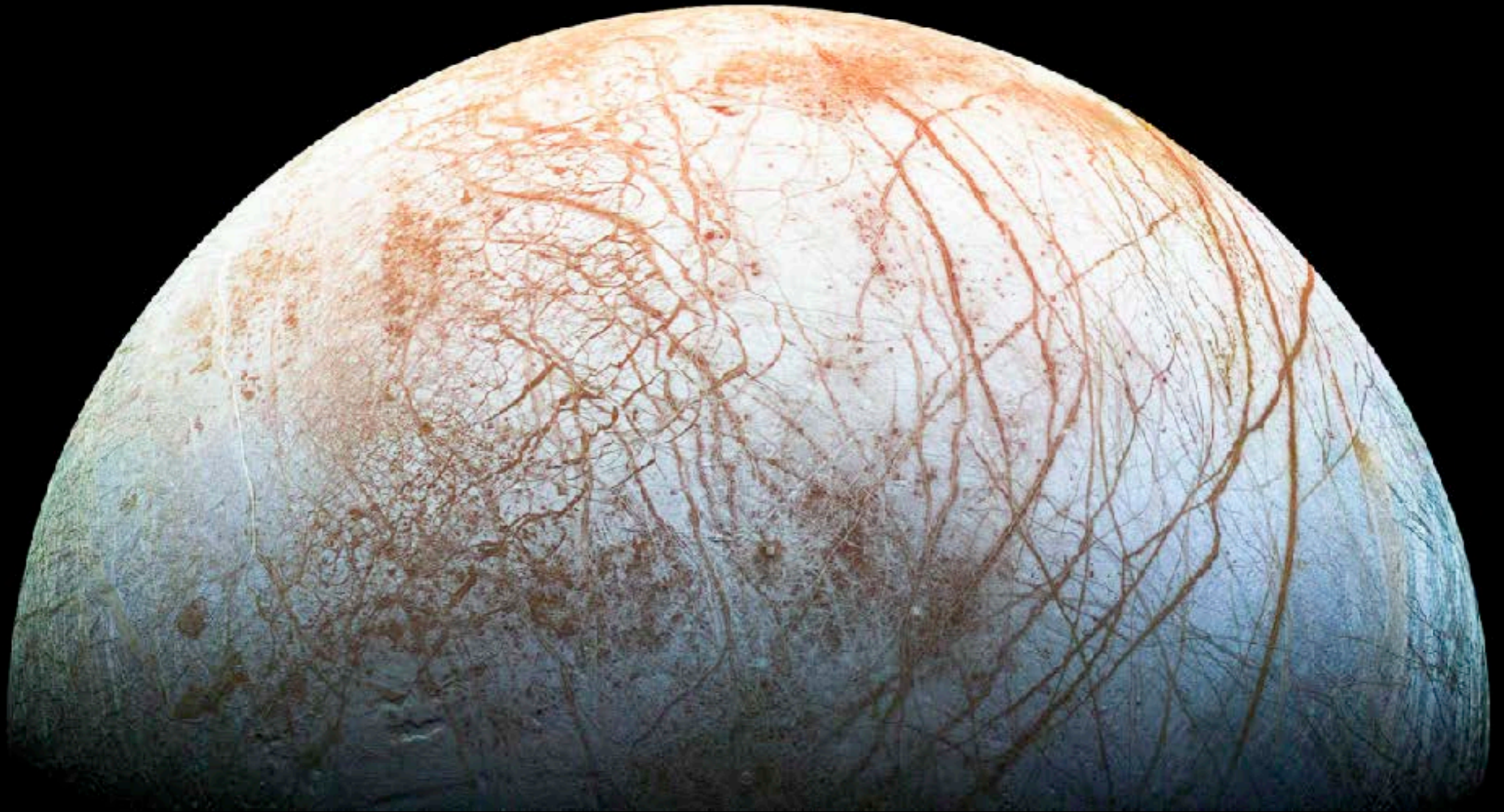
QuarkNet 2022



QuarkNet 2022



# Jupiter's Satellite Europa



Saturn

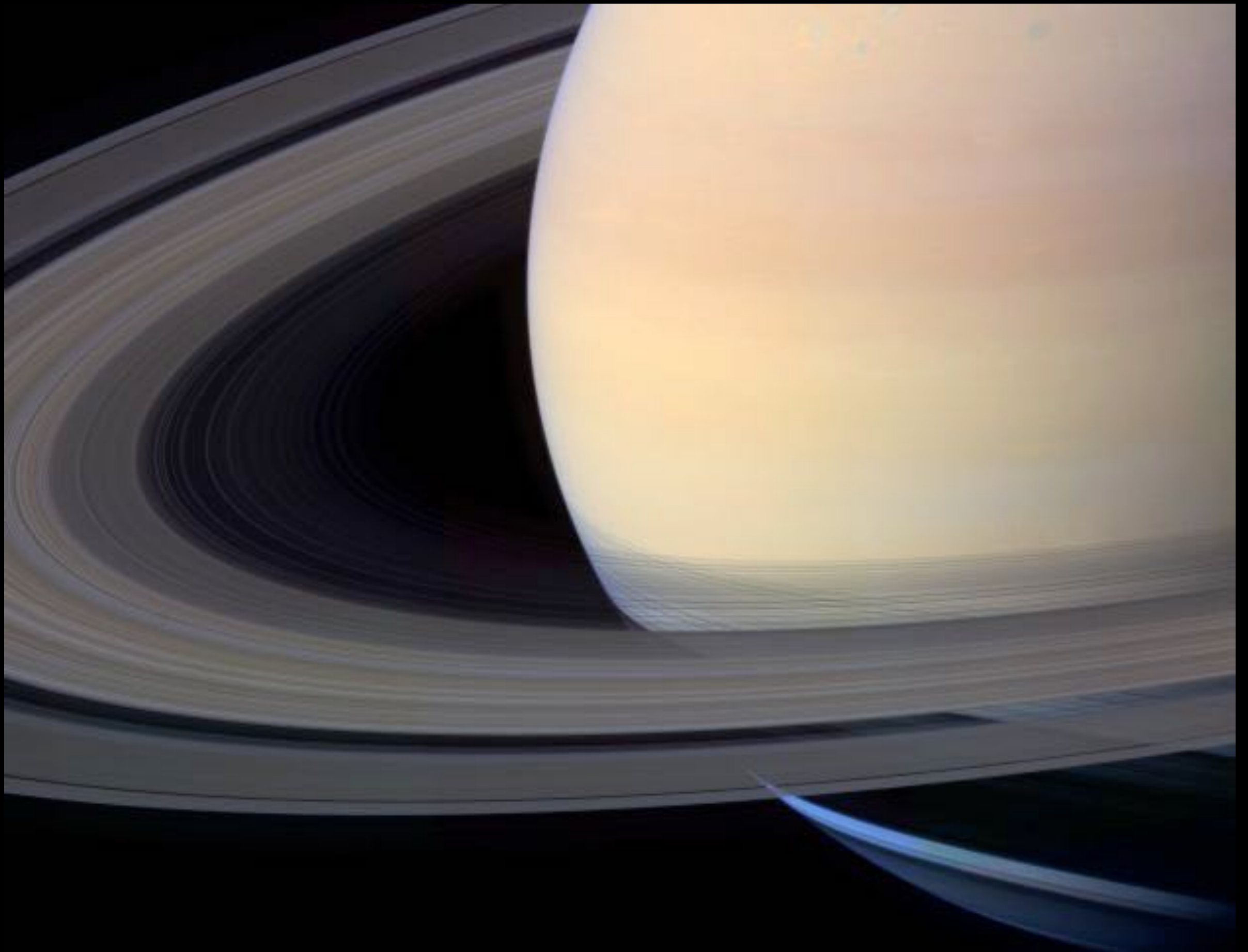
$R=24.6 \text{ m (9.54AU)}$





QuarkNet 2022



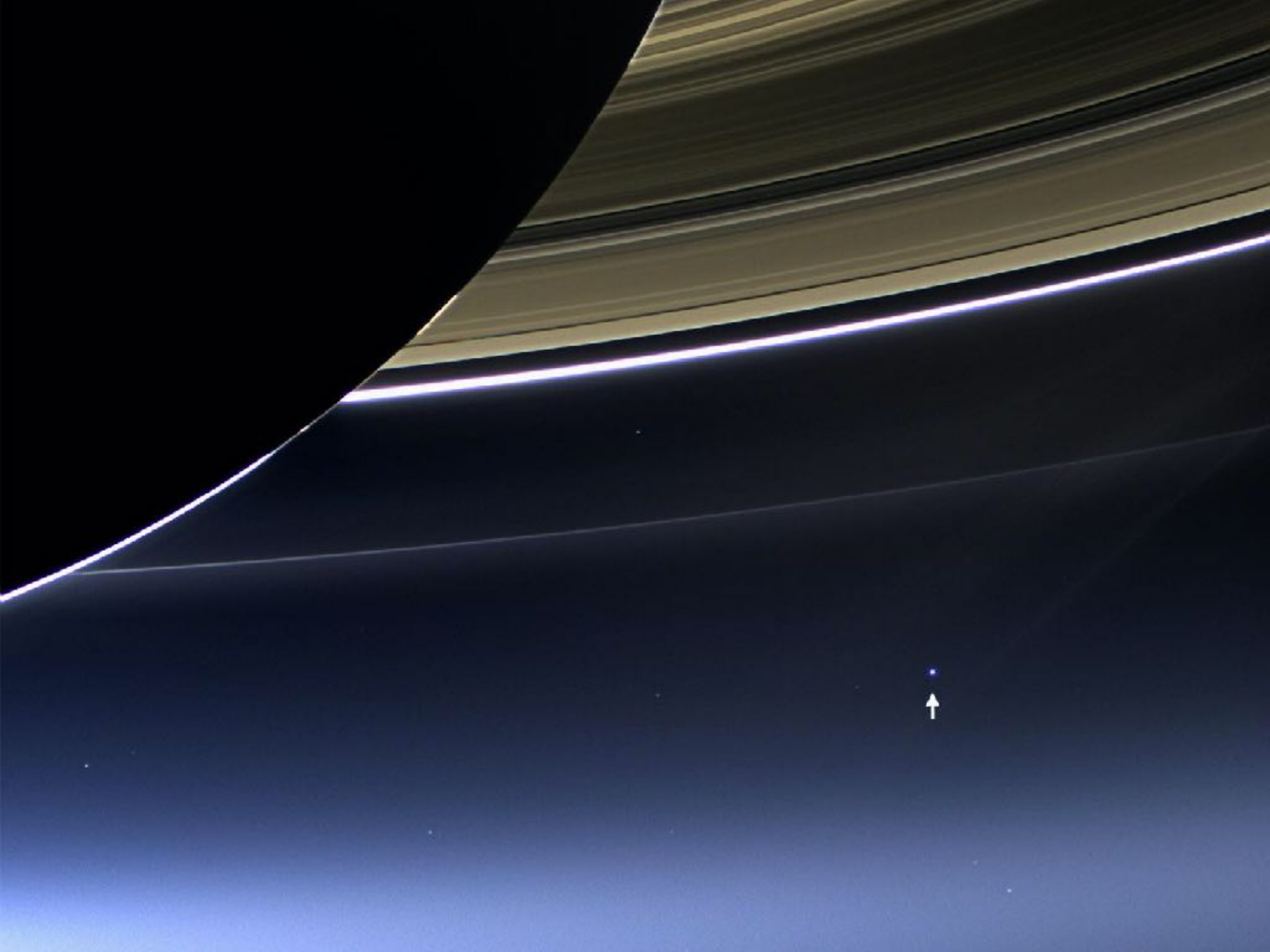


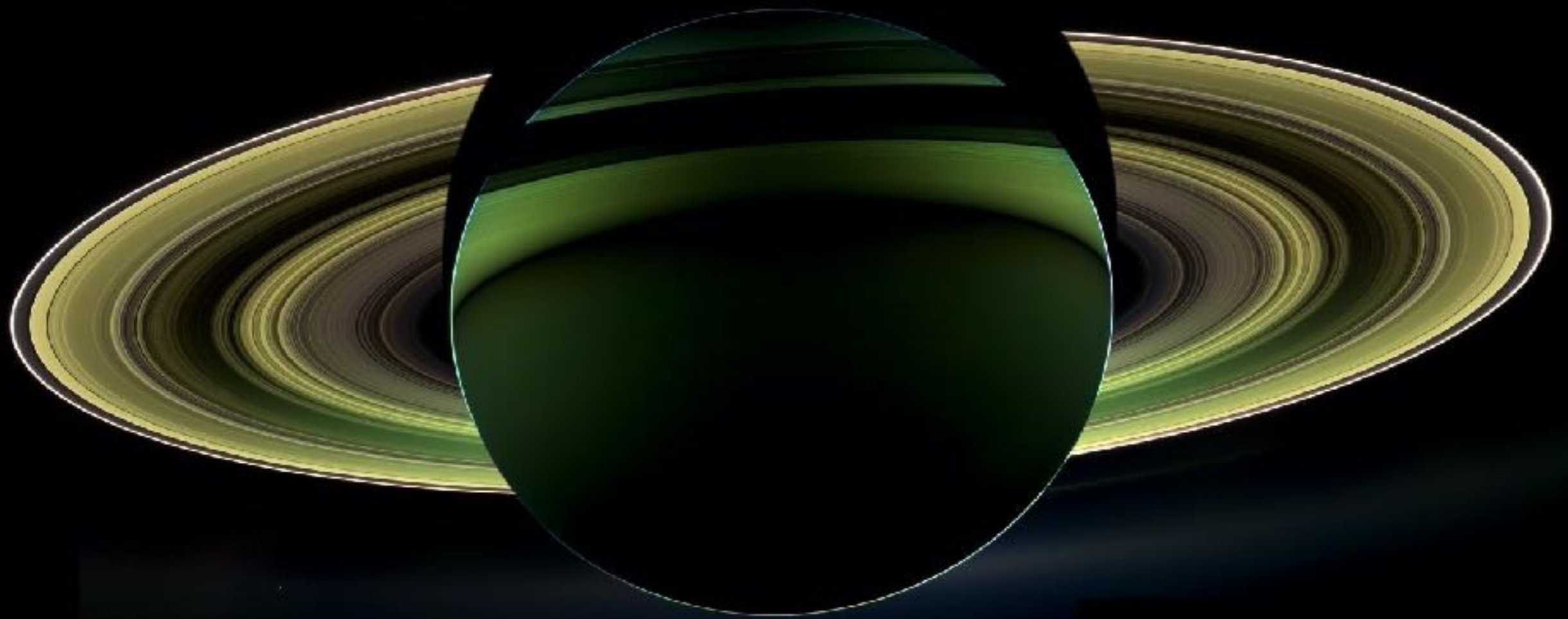


QuarkNet 2022



QuarkNet 2022

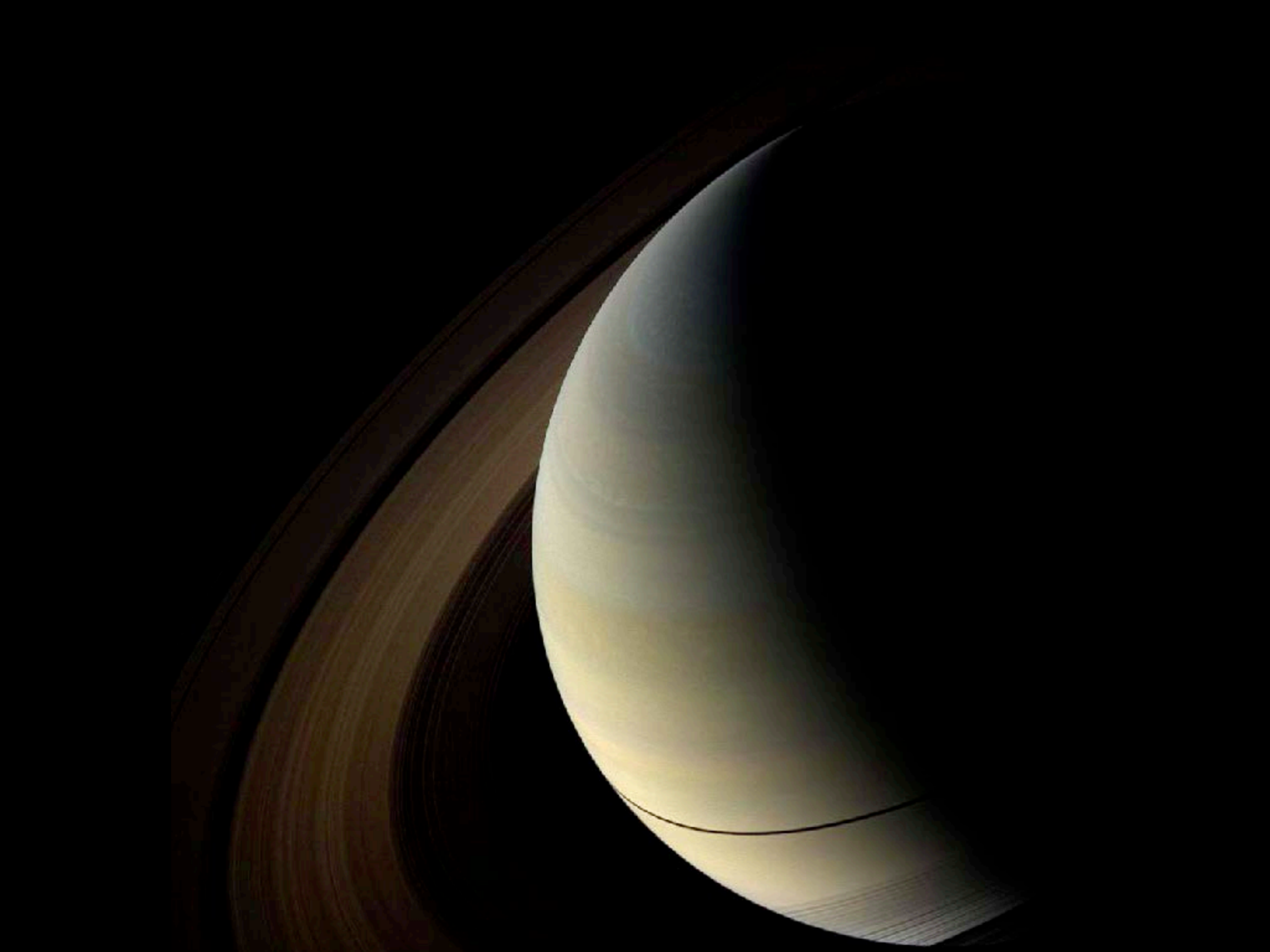


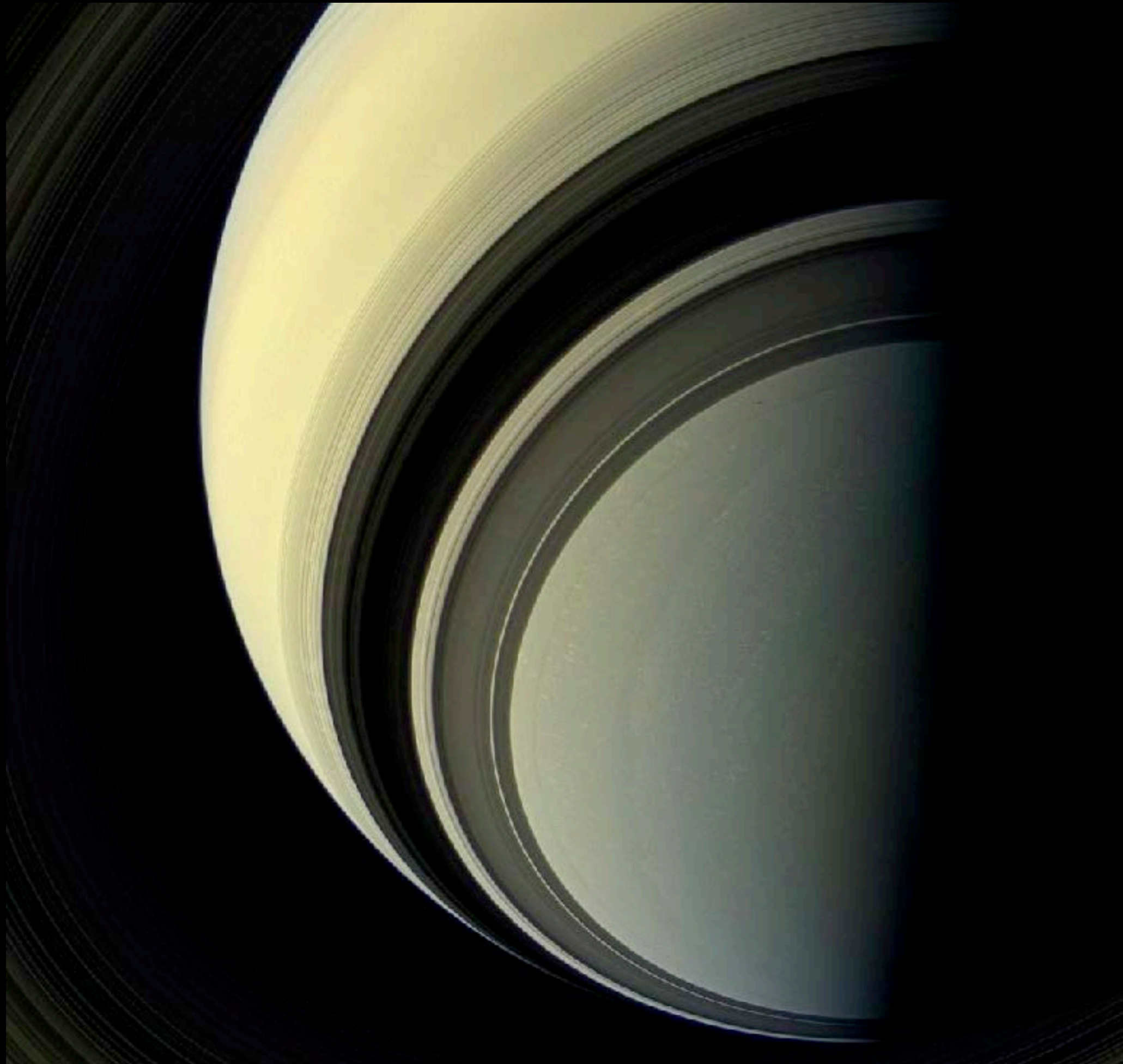


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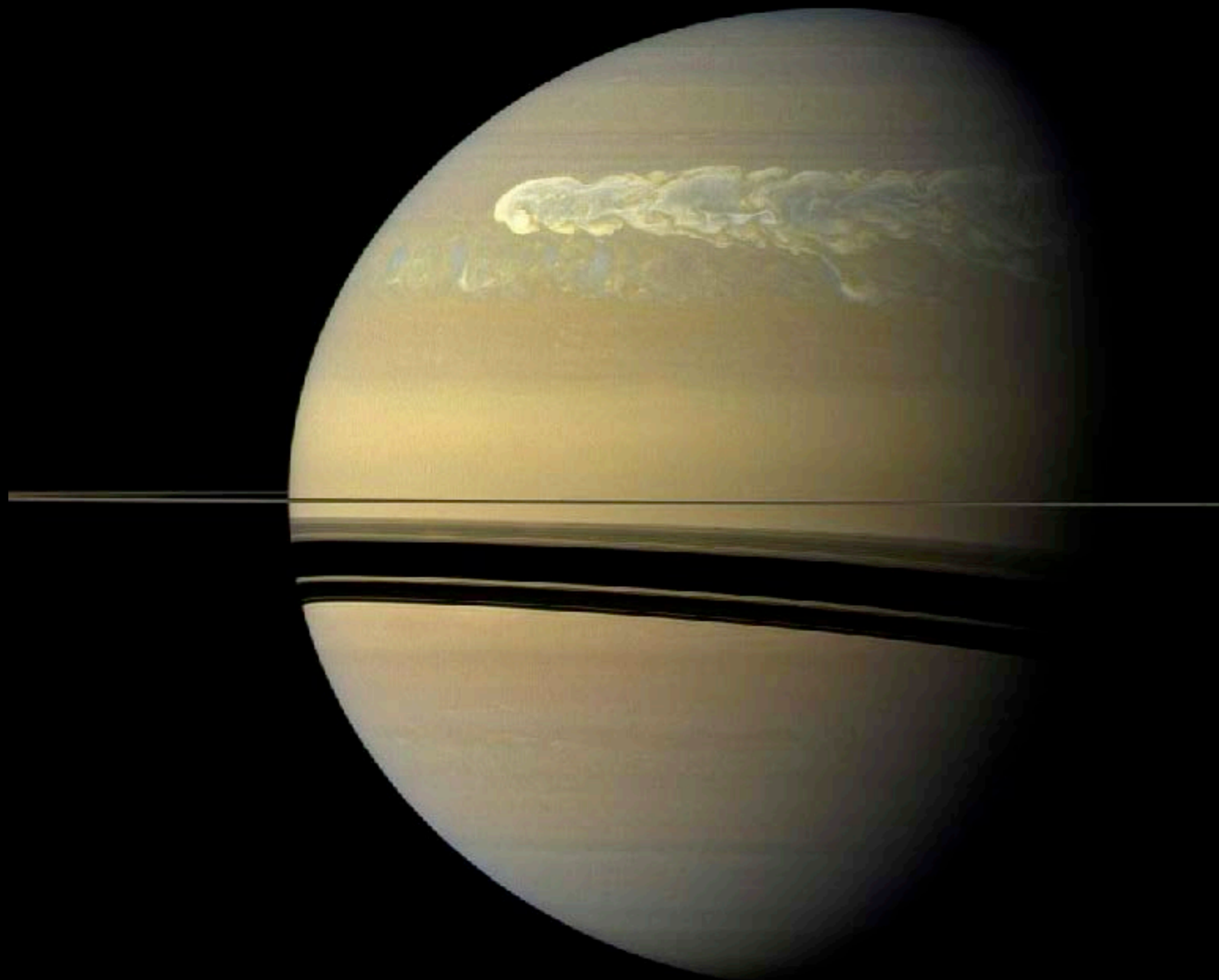


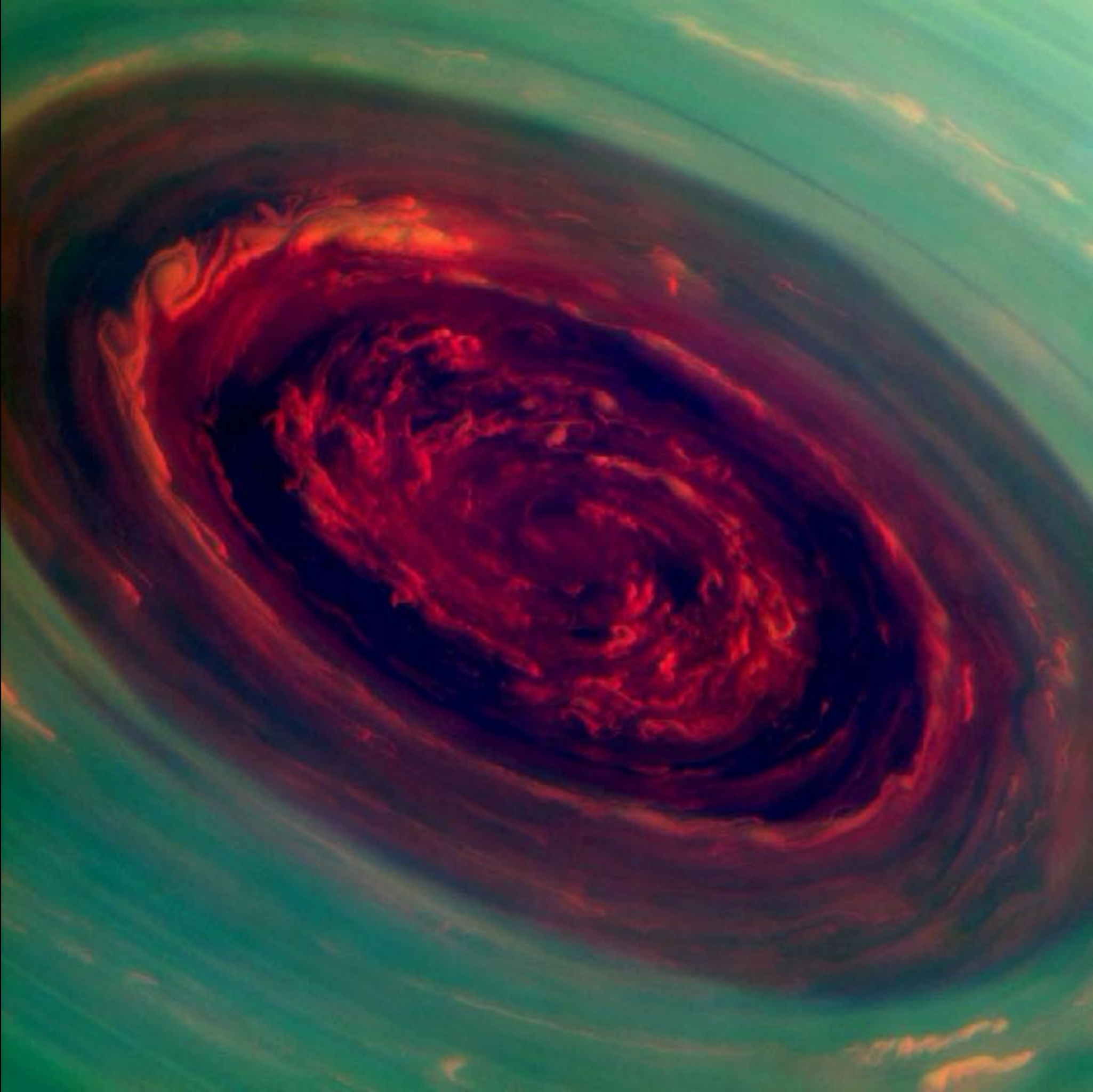
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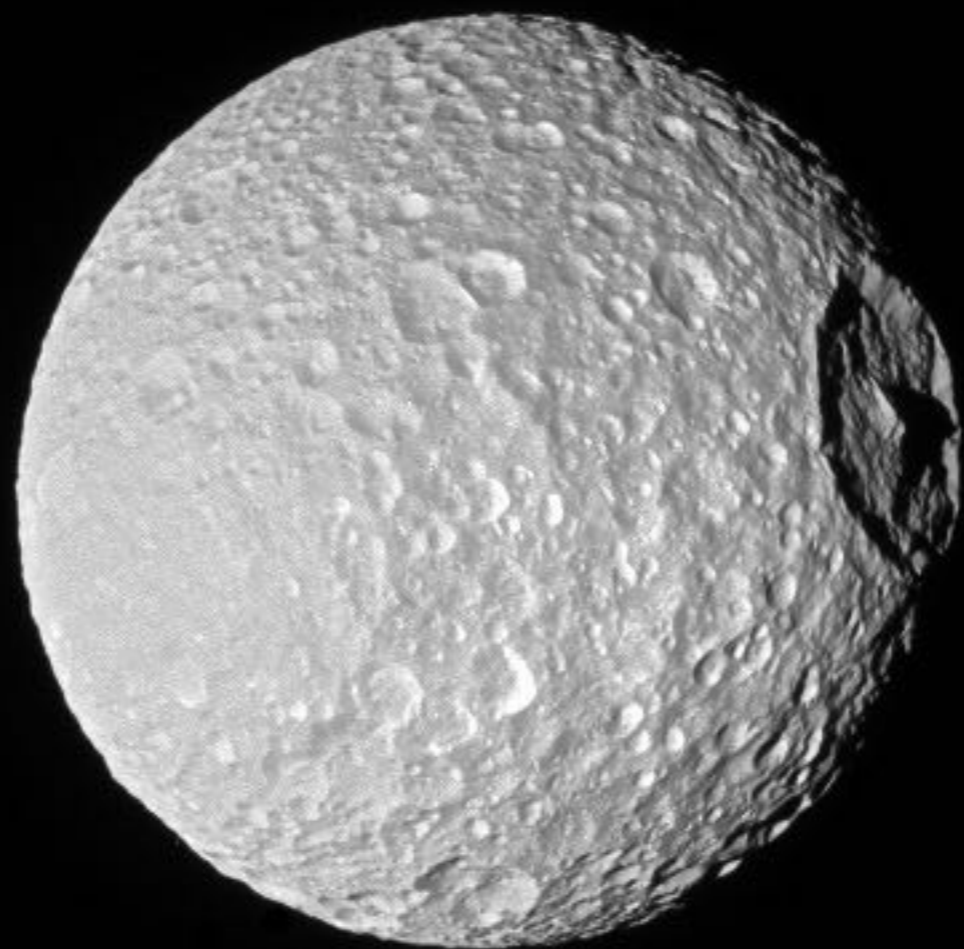






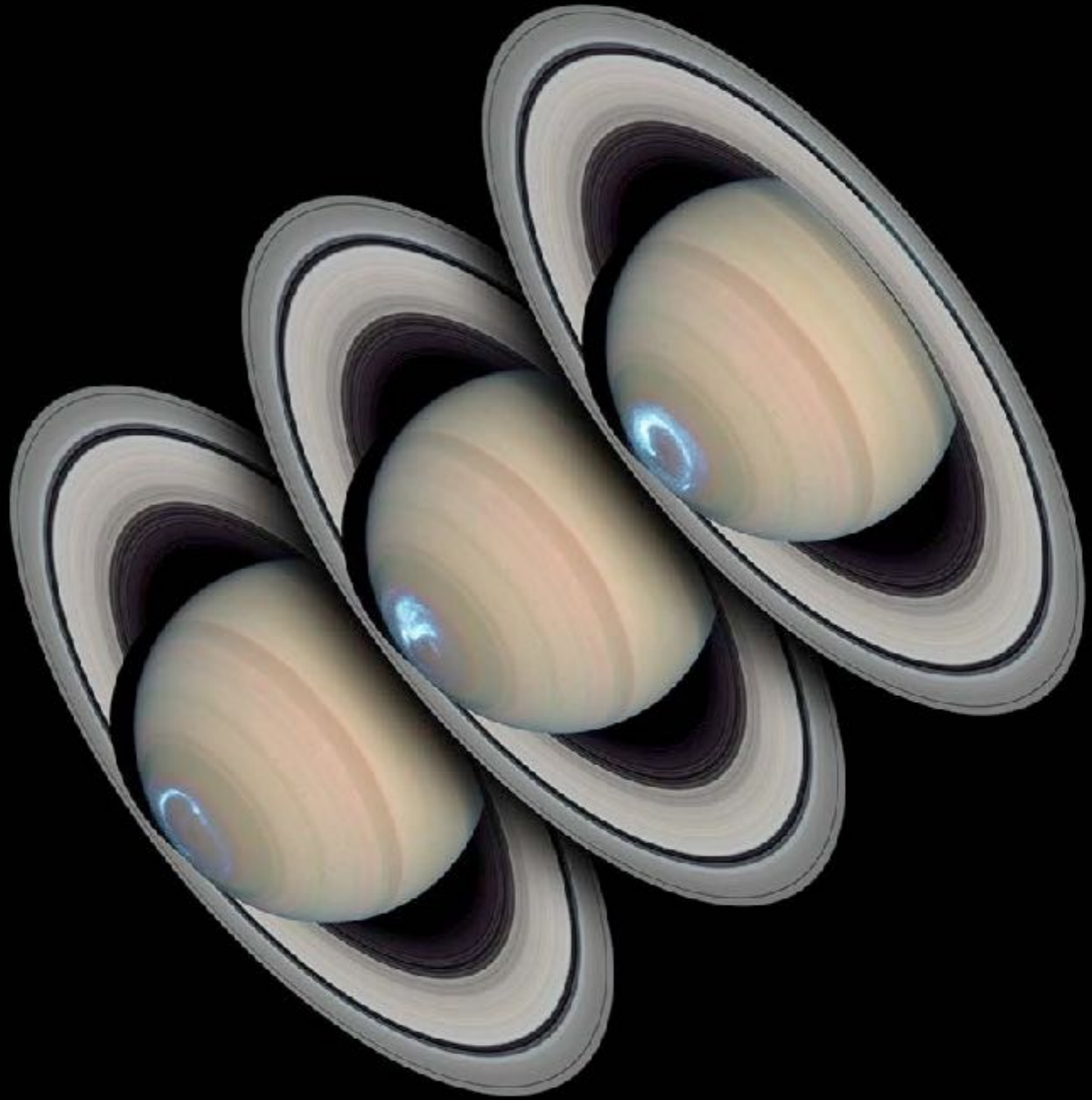






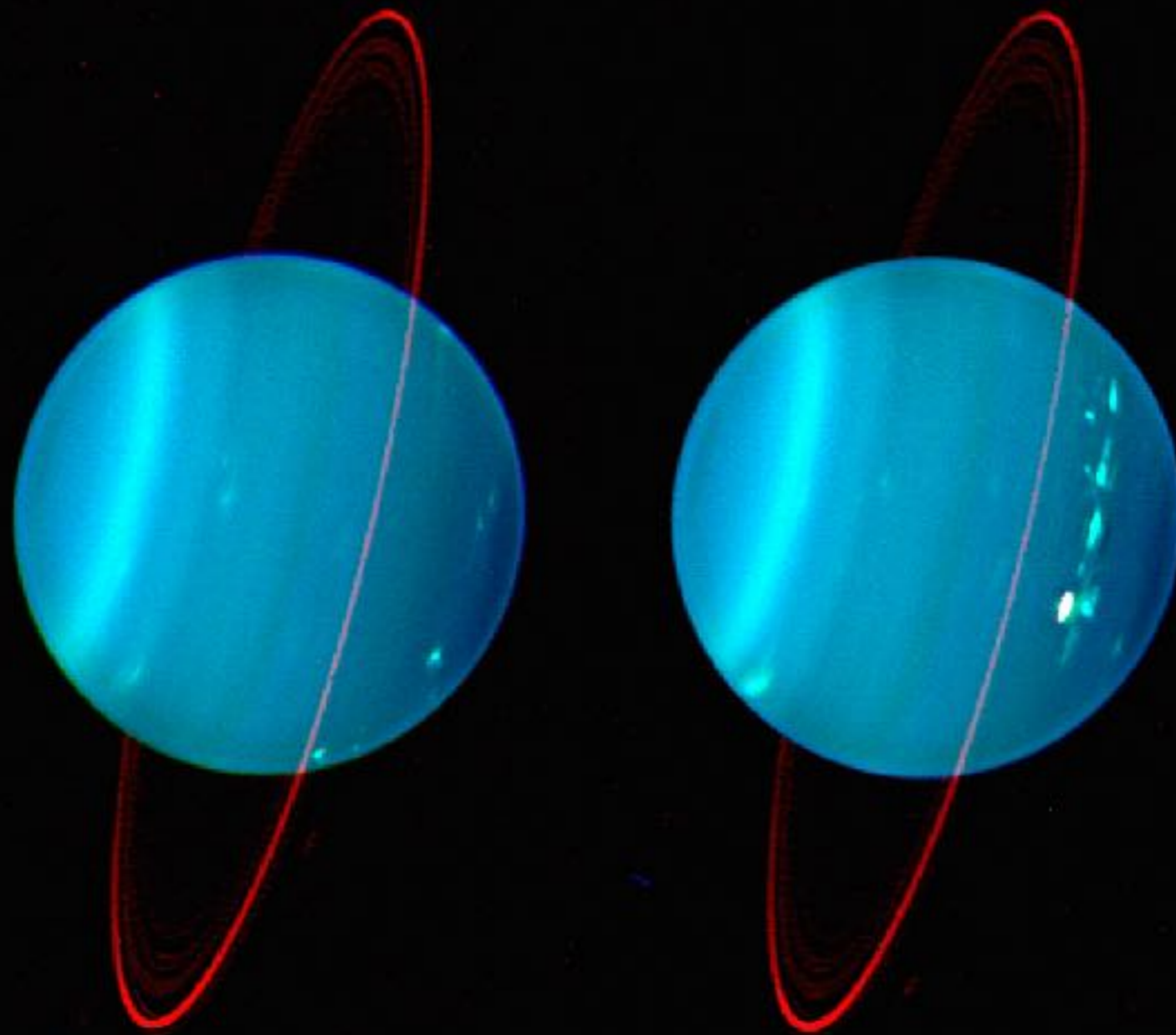


QuarkNet 2022



Uranus

$R=49.48 \text{ m (19.18AU)}$



# Neptune

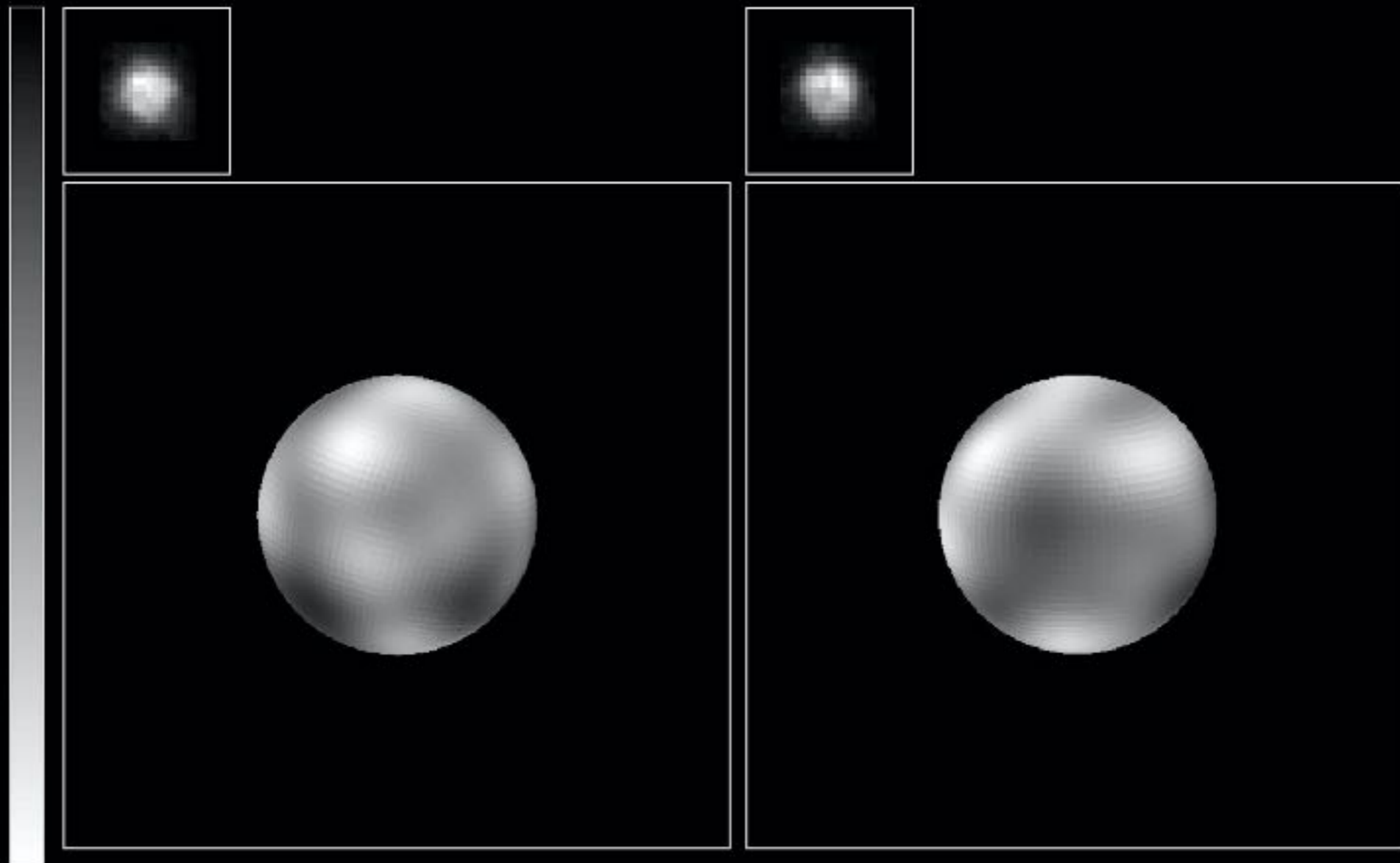
$R=77.55 \text{ m (30.06AU)}$



# Pluto

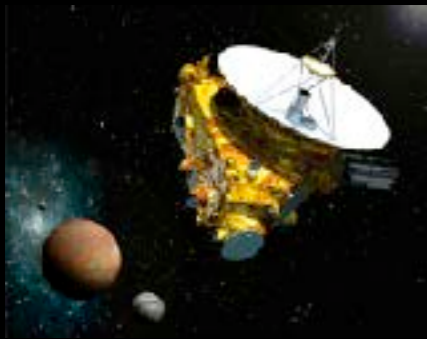
$R=101.7 \text{ m (39.44AU)}$

## Hubble Space Telescope Image





Pluto  $R=101.7 \text{ m (39.44AU)}$

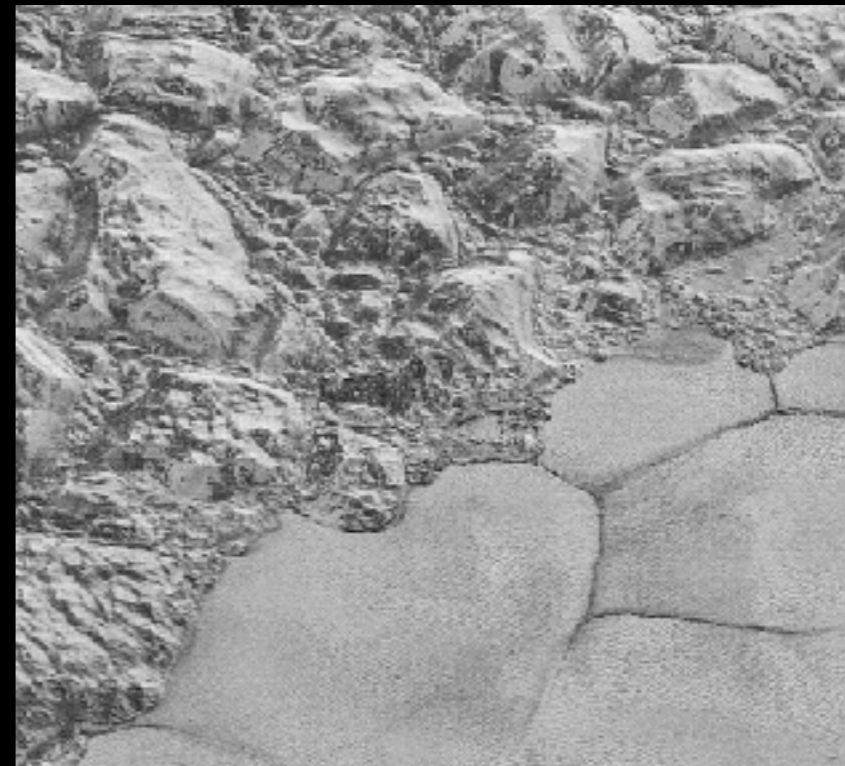
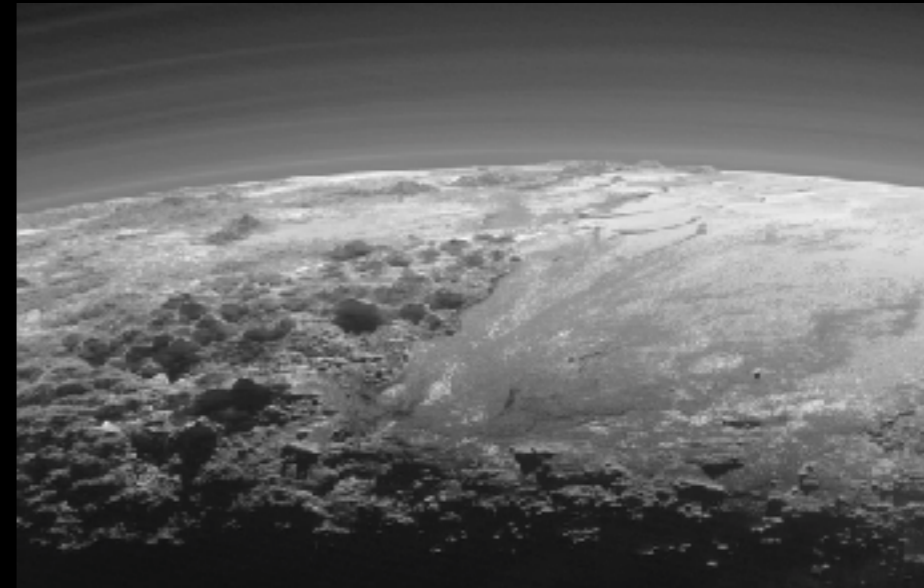
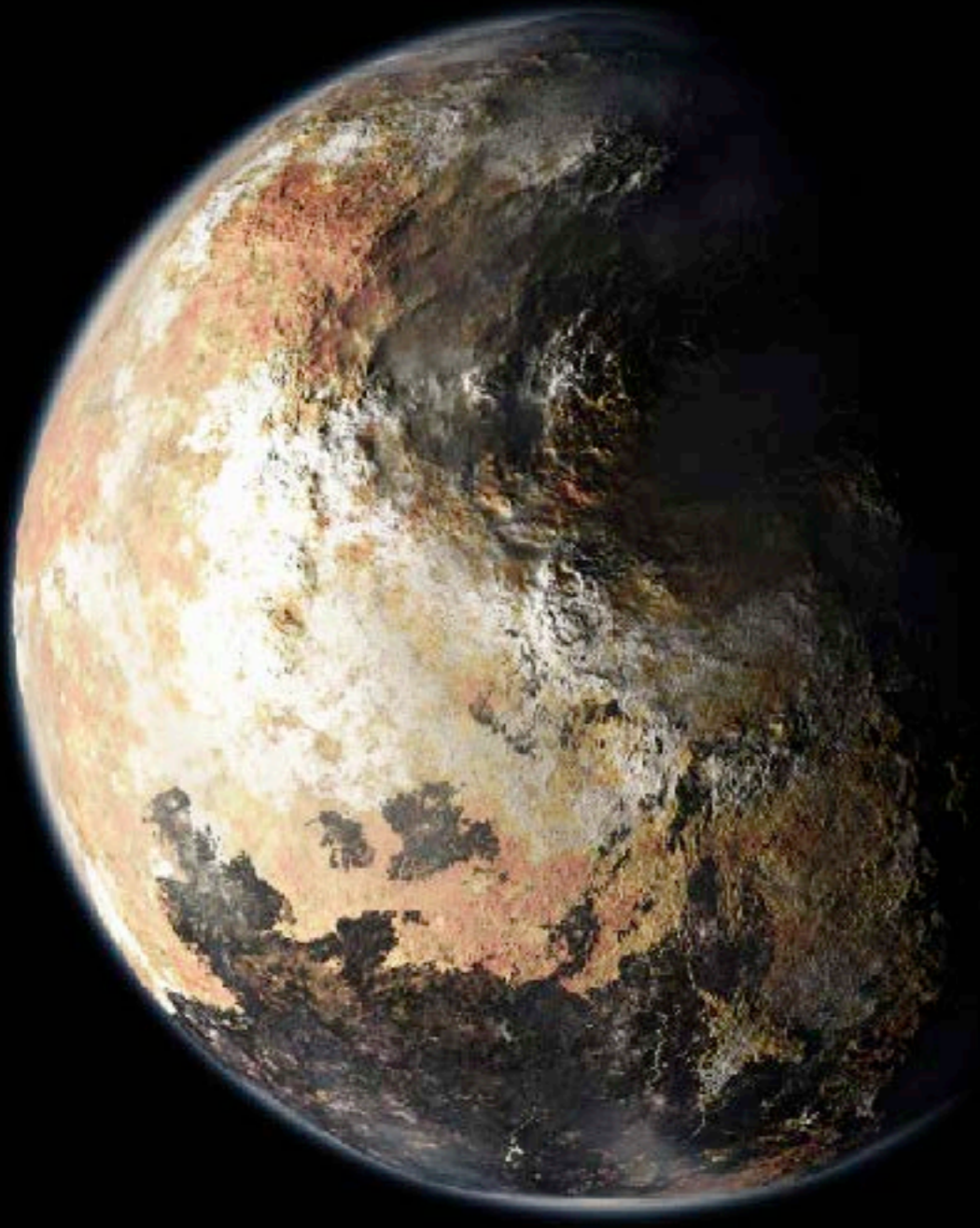


New Horizons

QuarkNet 2022

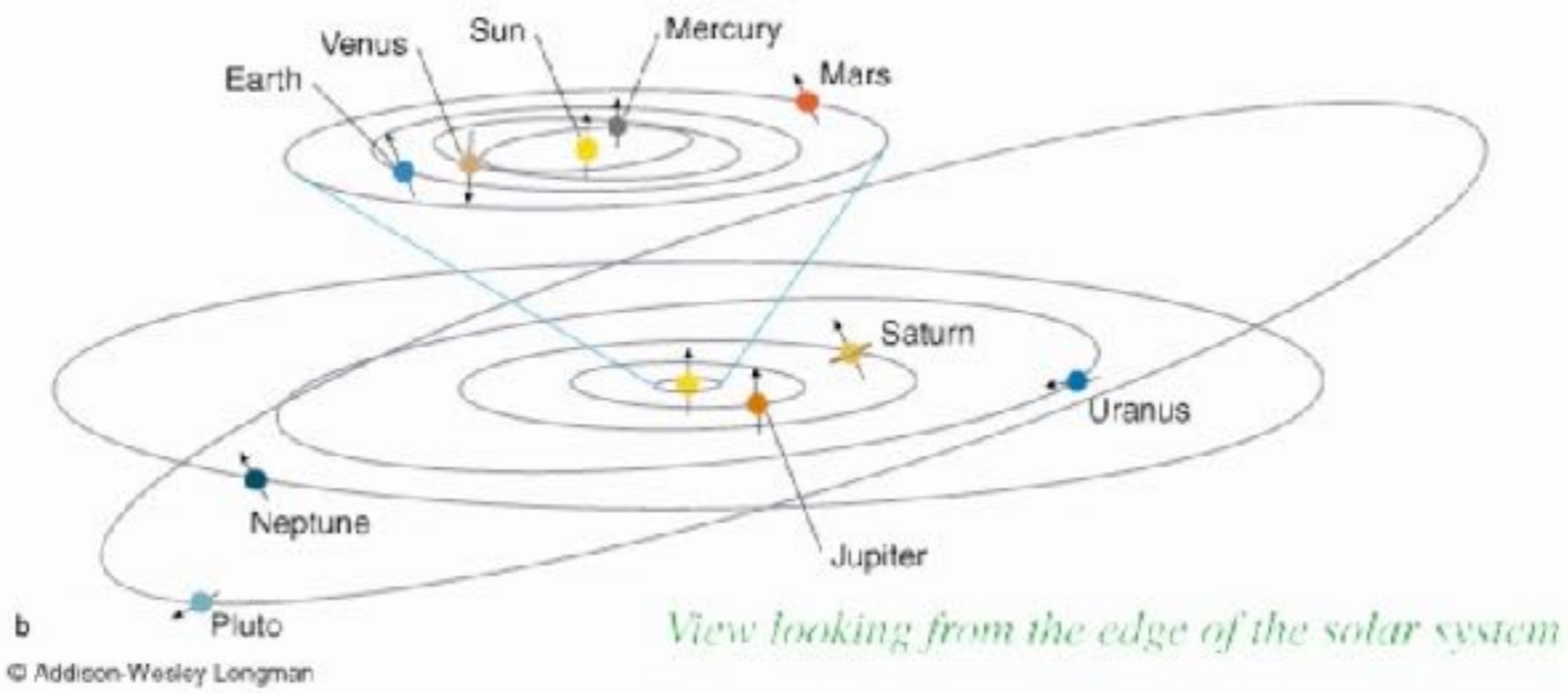
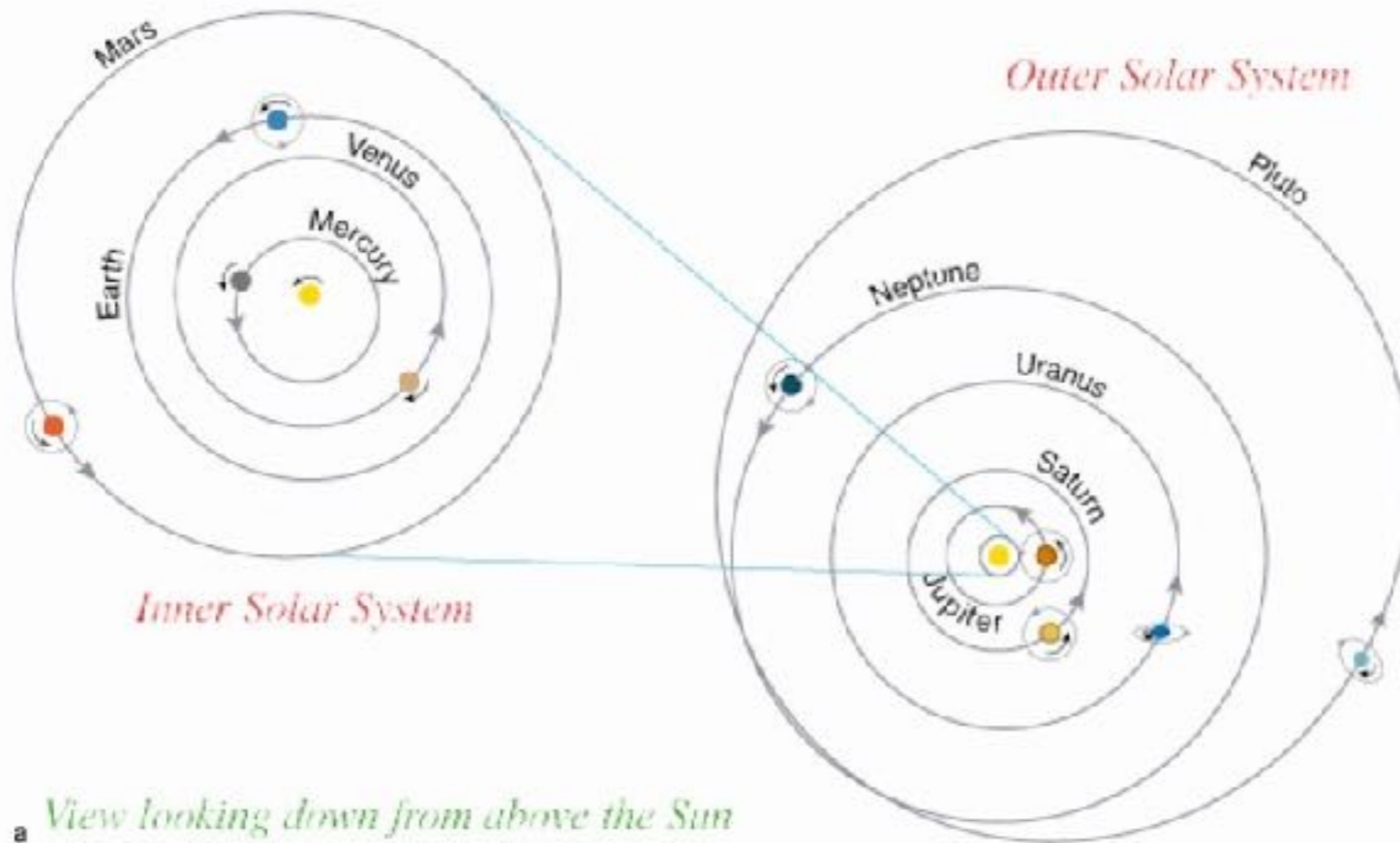
# Pluto

R=101.7 m (39.44AU)



# Dwarf Planets







QuarkNet 2022

# Beyond Solar System



# Nearest Star : Cen $\alpha$

- Q. If the size of the Sun is a quarter coin sitting at LBNL, where is Cen  $\alpha$ ?
- 1. : Cafeteria (1/4 mile)
- 2. : UC Berkeley Campus (1/2 mile)
- 3. : San Francisco Pier 39 (16 miles)
- 4. : San Jose Airport (50 miles)
- 5. : Los Angeles (380 miles)

# Cen $\alpha$ : 4.3 Light Years

- How long does it take to travel to Cen  $\alpha$  with the fastest airplane on the Earth?  
(X-15 Mach 6.3)
- 1. 5.5 yrs
- 2. 55 yrs
- 3. 550 yrs
- 4. 5,500 yrs
- 5. 550,000 yrs





# Milky Way Galaxy I

- How many stars do we have in our Galaxy?
- 1. : 2,000
- 2. : 20,000
- 3. : 200,000
- 4. : 200,000,000
- 5. : 200,000,000,000

Spiral Galaxy NGC 4414



Hubble  
Heritage

PRCS4-25 • Hubble Space Telescope WFC32 • Hubble Heritage Team (AURA/STScI/NASA)

# Our Galaxy II

- Suppose the size of a star is a grain of salt.  
200 billion grains of salt would fill up :
  - 1. a cup
  - 2. a bucket
  - 3. a car
  - 4. a truck
  - 5. an olympic size pool



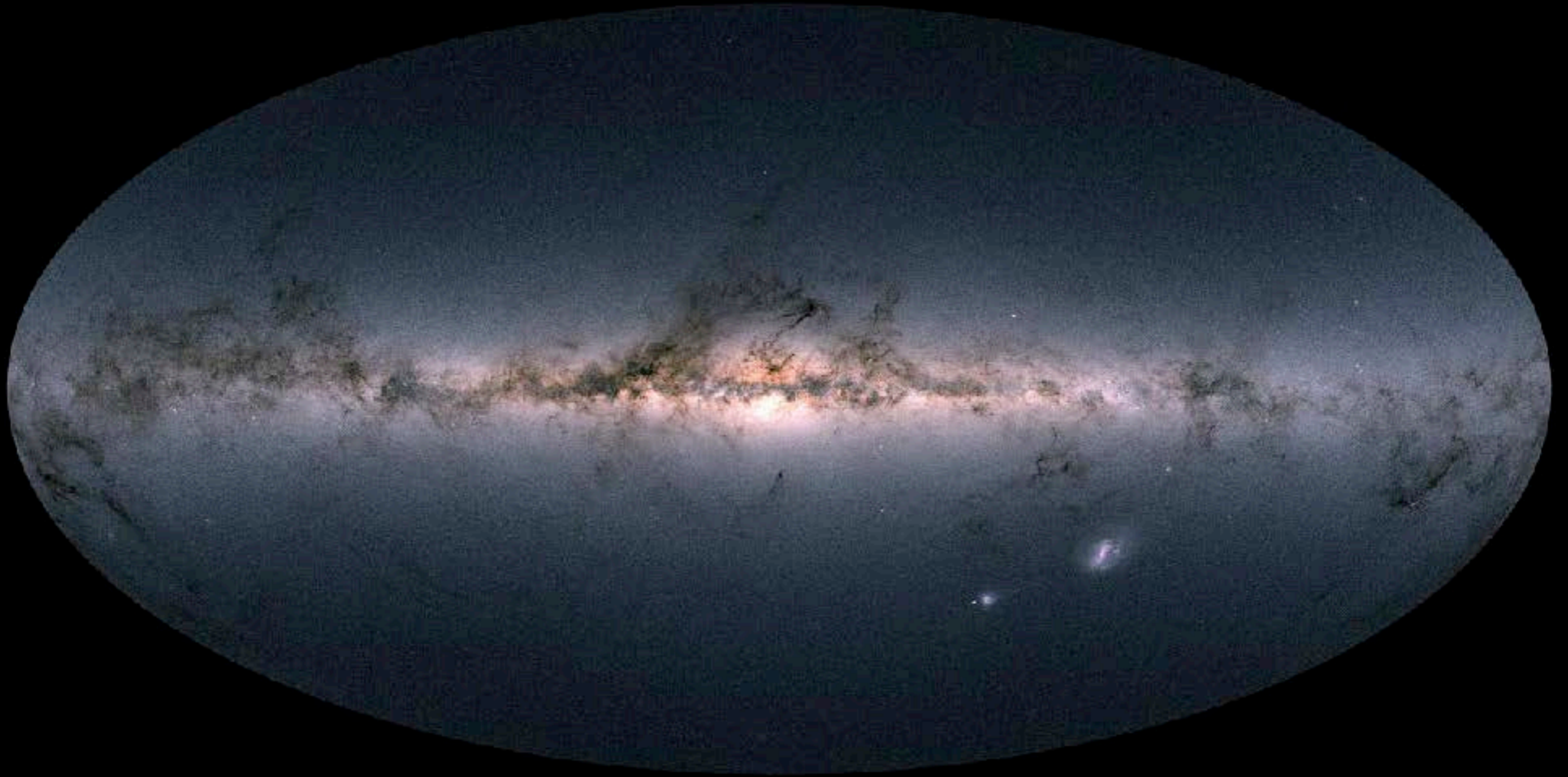
NASA, ESA, The Hubble Heritage Team (STScI/NASA), and the Rest (STScI)  
Hubble Space Telescope, COSMOS - STScI/NASA

# 1.8 billion Stars are observed

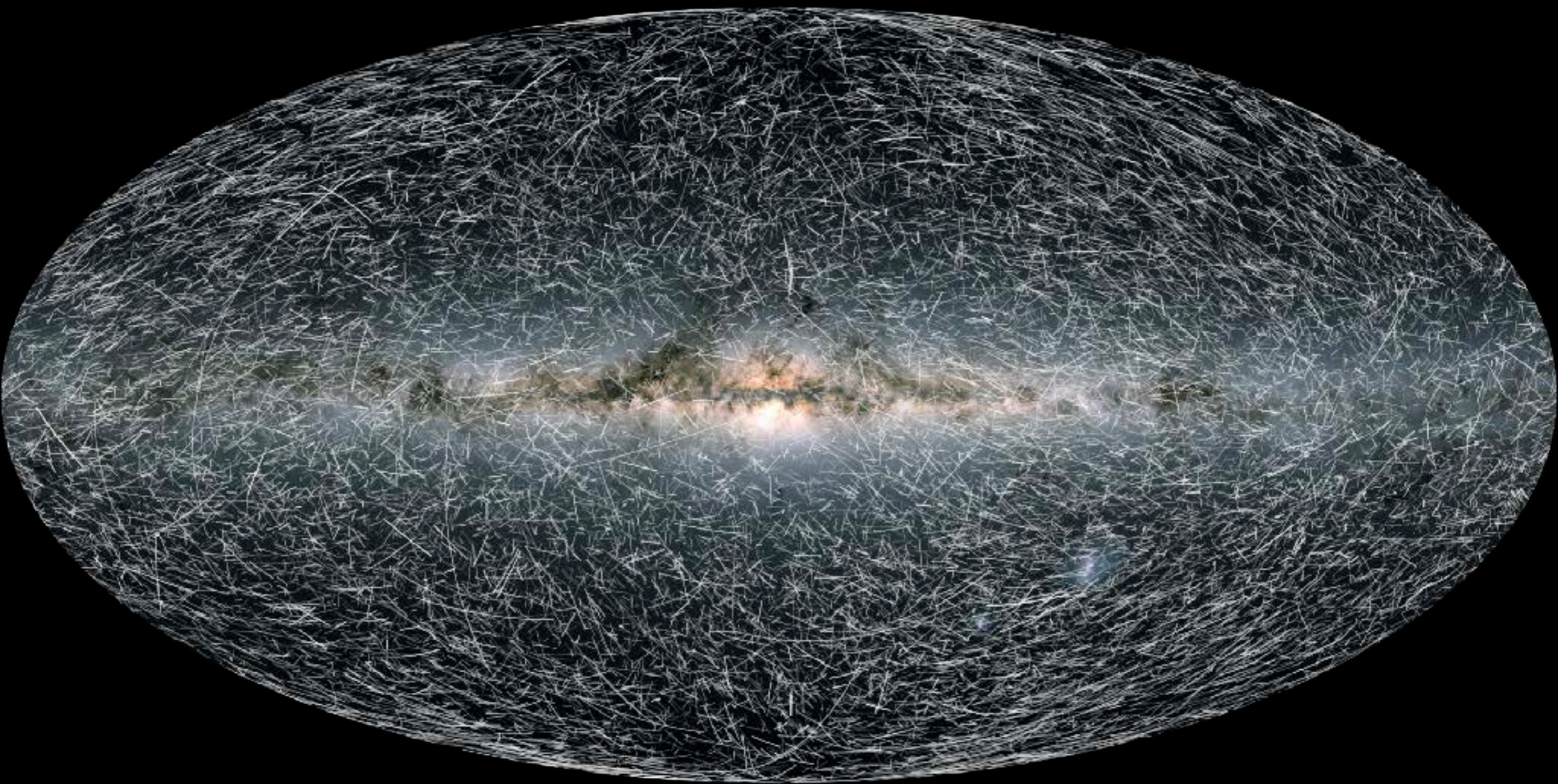
1,811,709,711 Stars  
June 13th 2022 Release



But it's only 1% of Milky Way Stars (200 Billion)



QuarkNet 2022

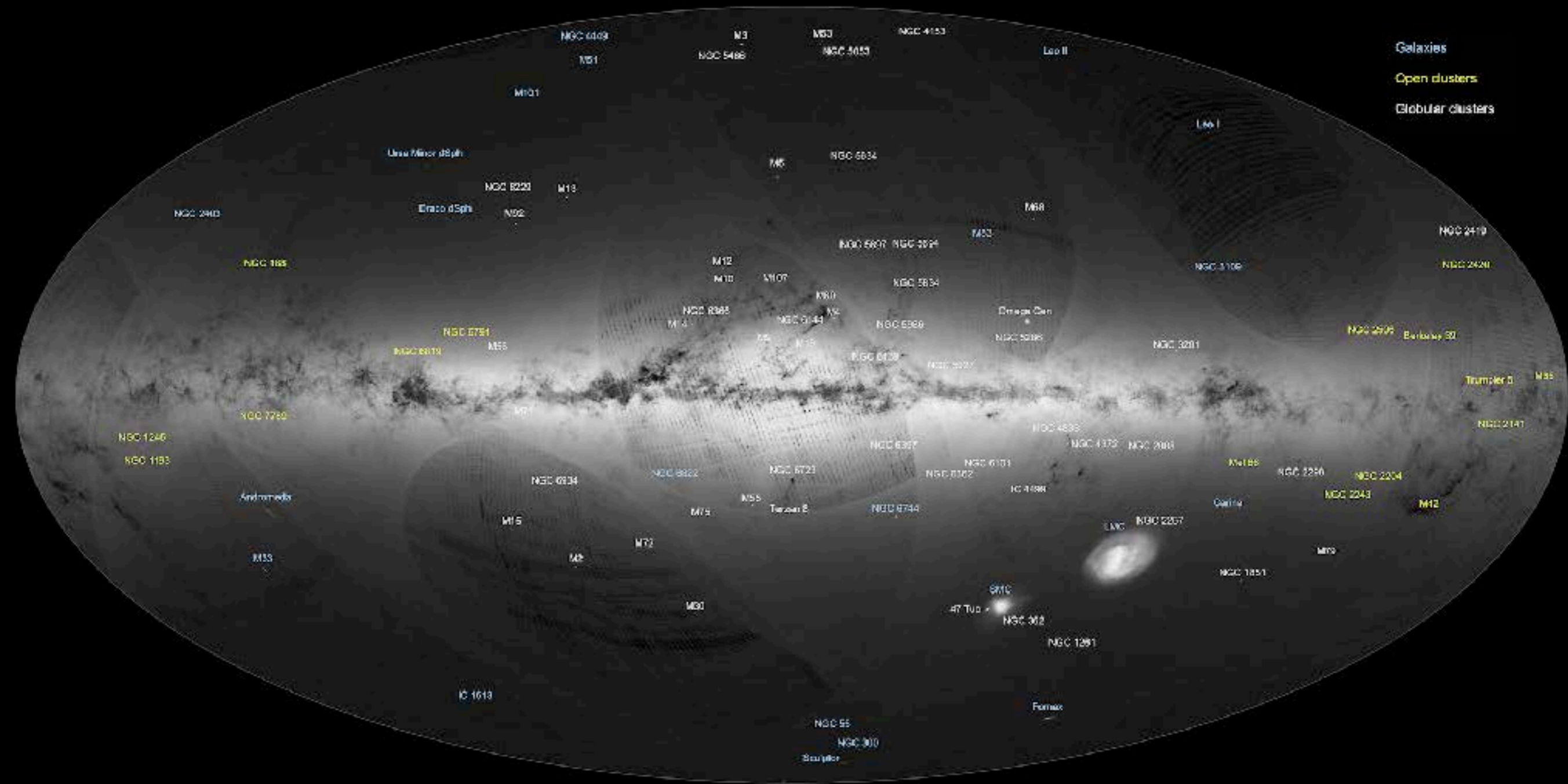


QuarkNet 2022

# → GAIA'S FIRST SKY MAP



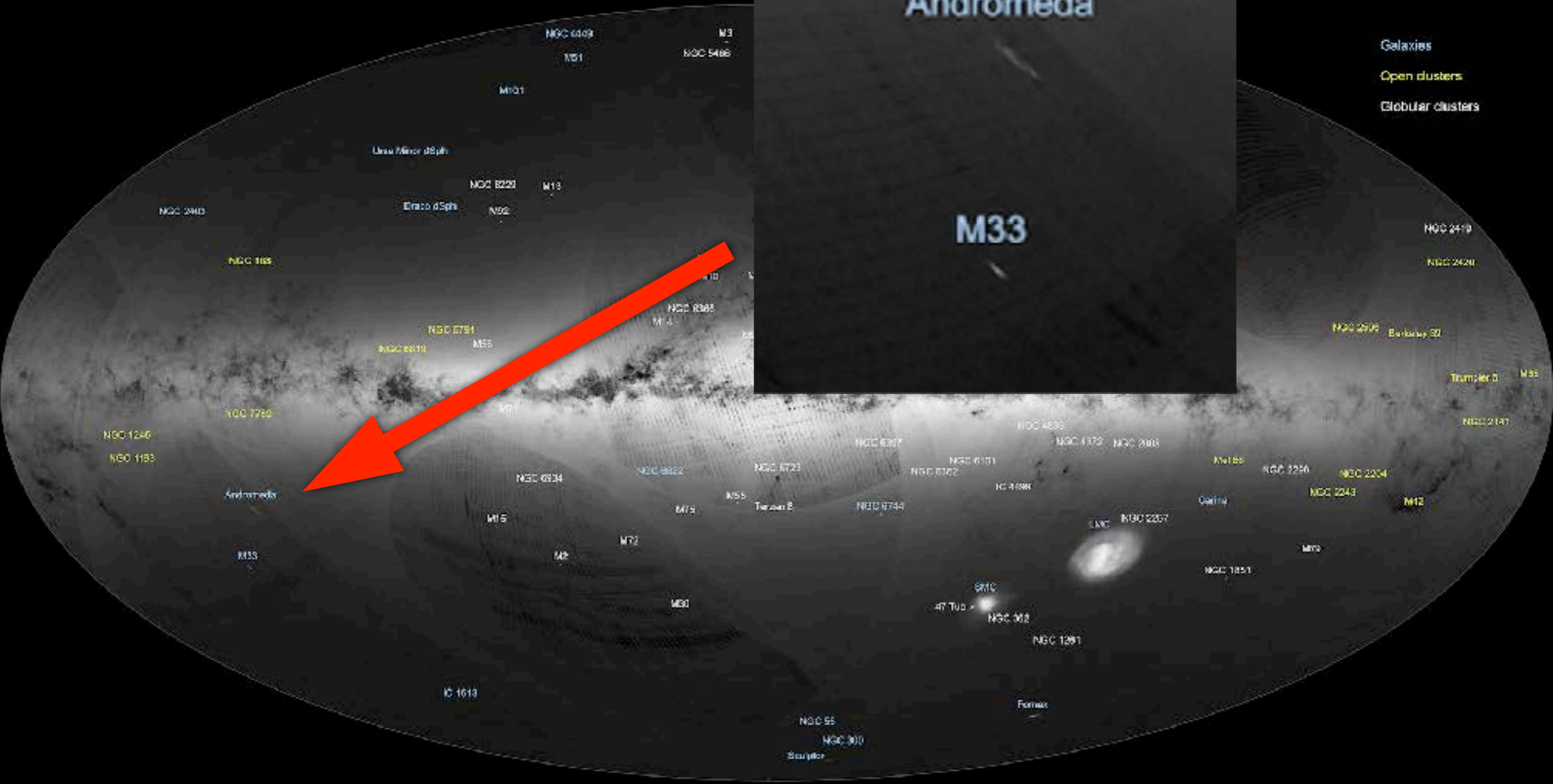
- Galaxies
- Open clusters
- Globular clusters

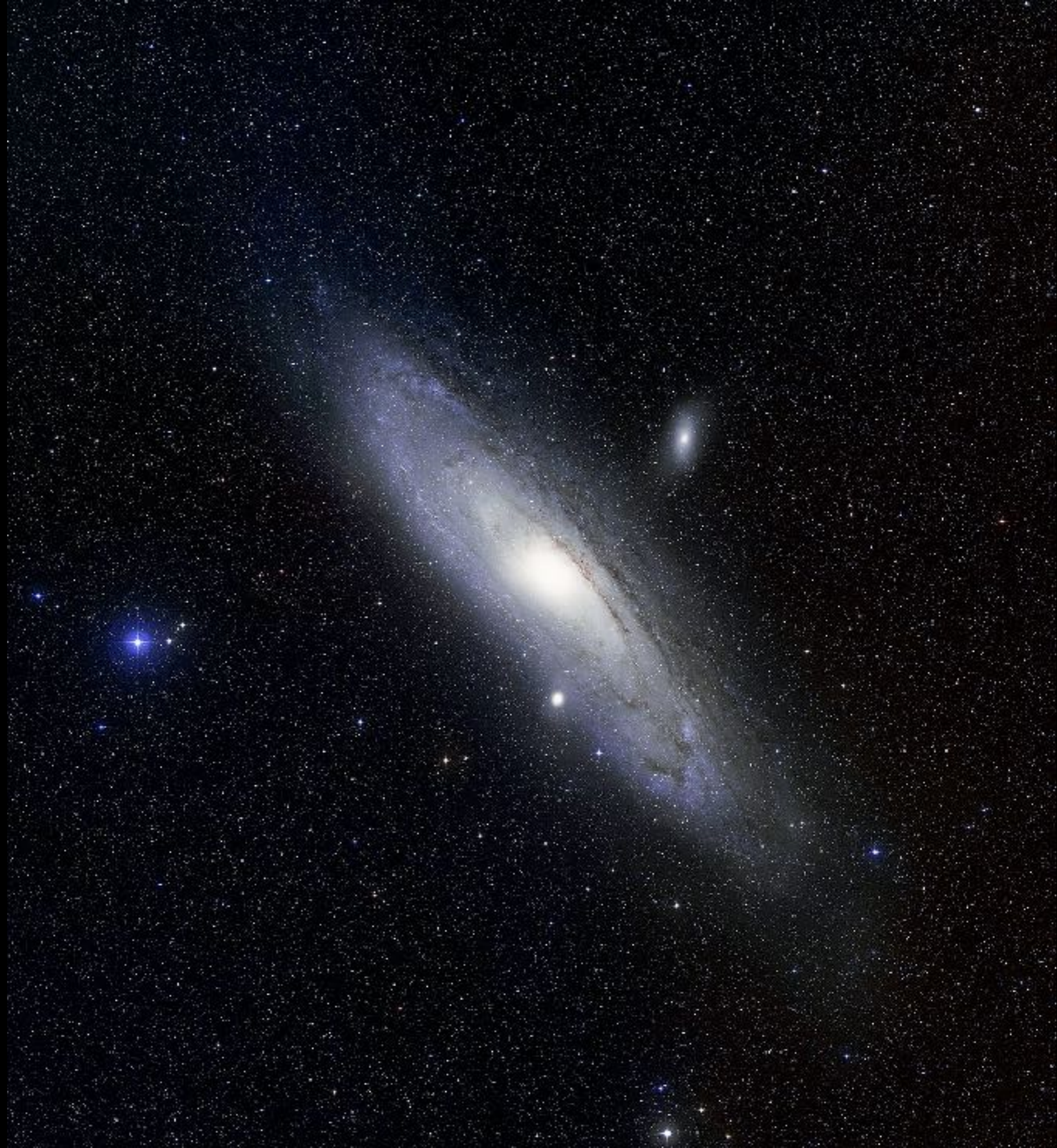


# → GAIA'S FIRST SKY MAP



- Galaxies
- Open clusters
- Globular clusters







# Nearest Galaxy : Andromeda

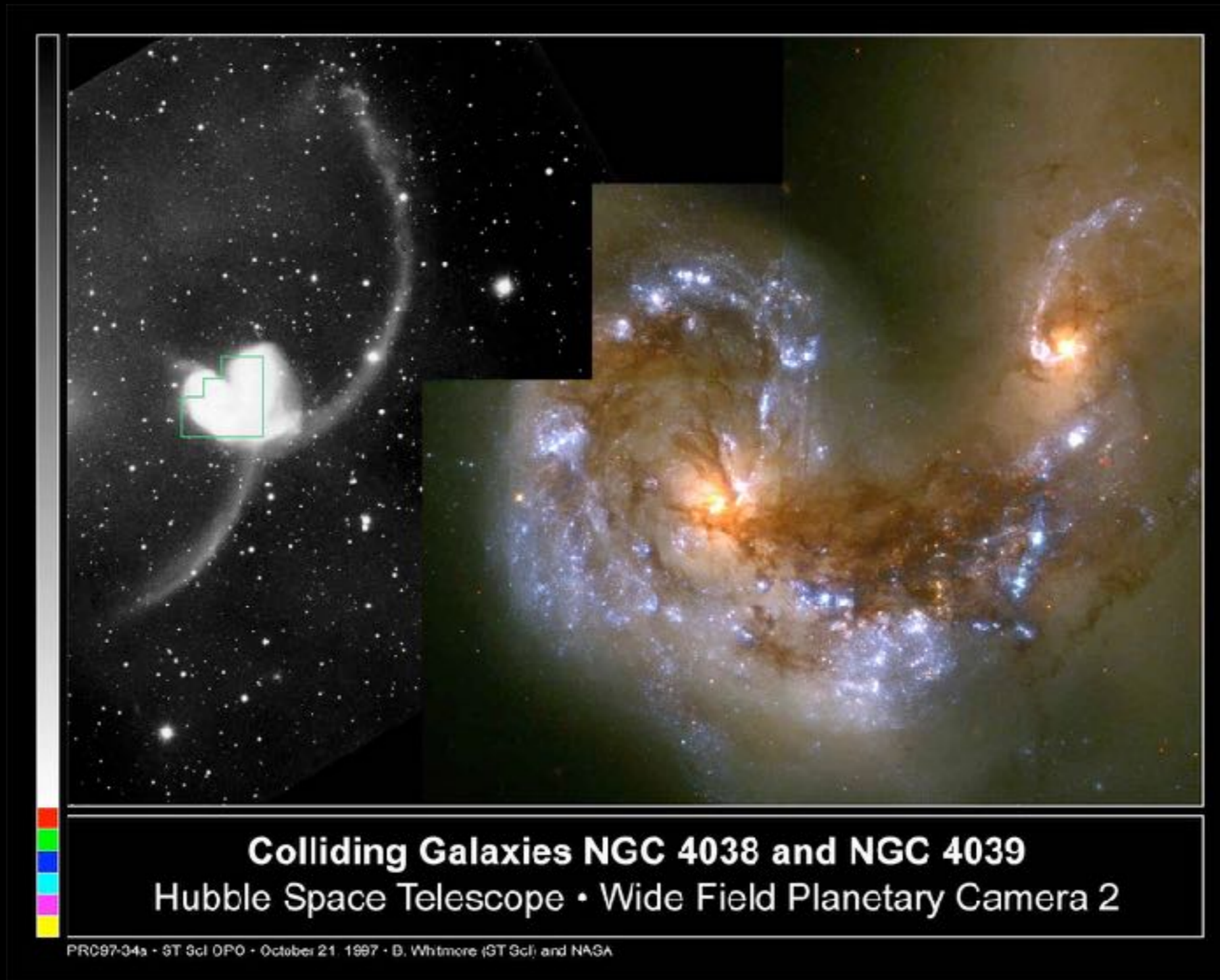
- Q. Suppose the size of our Milky Way Galaxy is a quarter coin. What is the distance to the Andromeda Galaxy?
- 1. 40 cm
- 2. 4 m
- 3. San Francisco
- 4. New York
- 5. Tokyo



# Colliding Galaxies



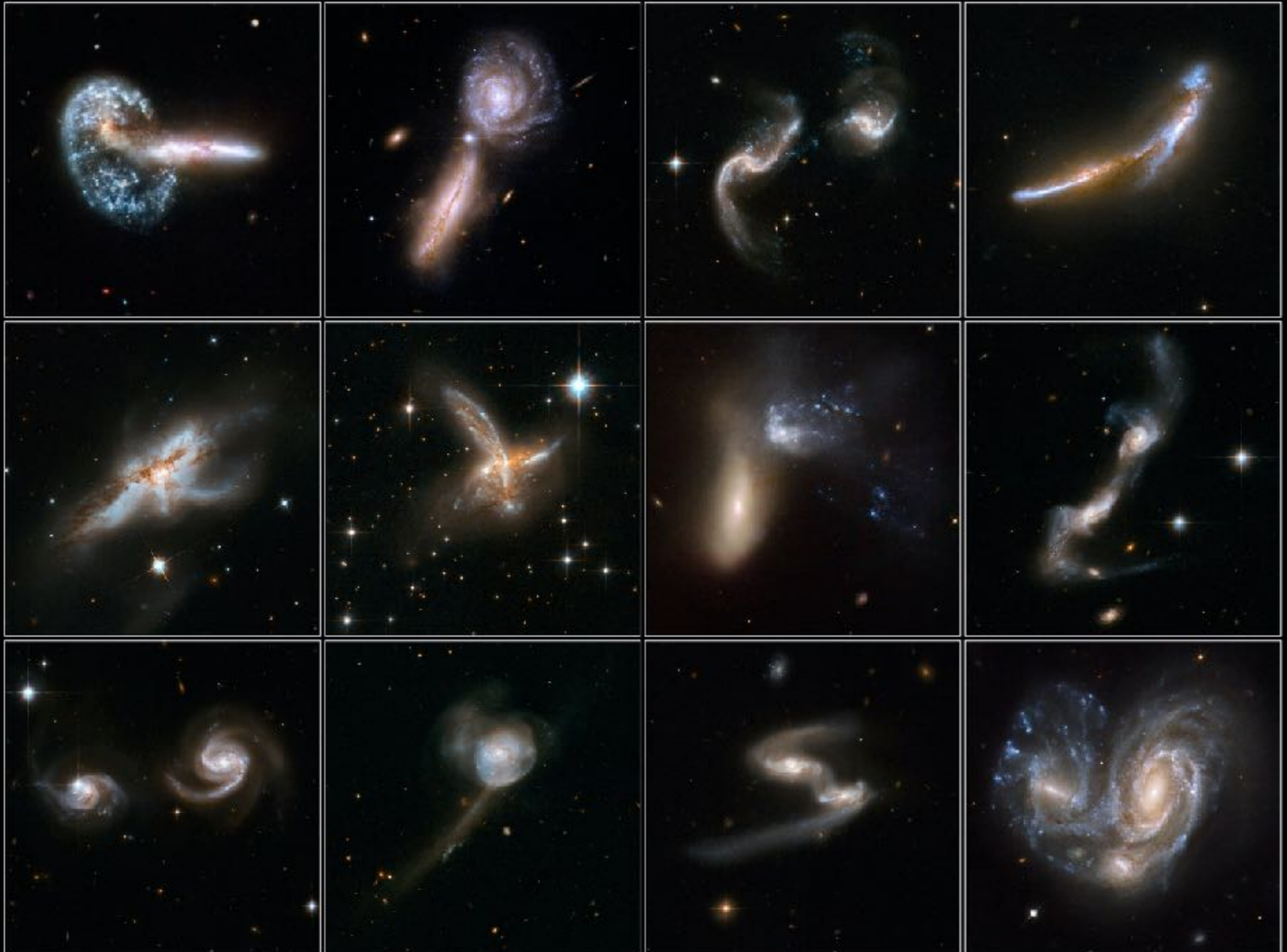
# Colliding Galaxies: Observation






# Interacting Galaxies

Hubble Space Telescope • ACS/WFC • WFPC2





In 3.75 billion years









QuarkNet 2022



QuarkNet 2022

# Blackhole Image in M87 by Event Horizon Telescope

## Perfecting Black Hole Imagery with space telescopes

Model, 690 GHz



M. Mościbrodzka

Model, 230 GHz



M. Mościbrodzka

Simulated EHI observation



F. Roelofs

Simulated EHT observation

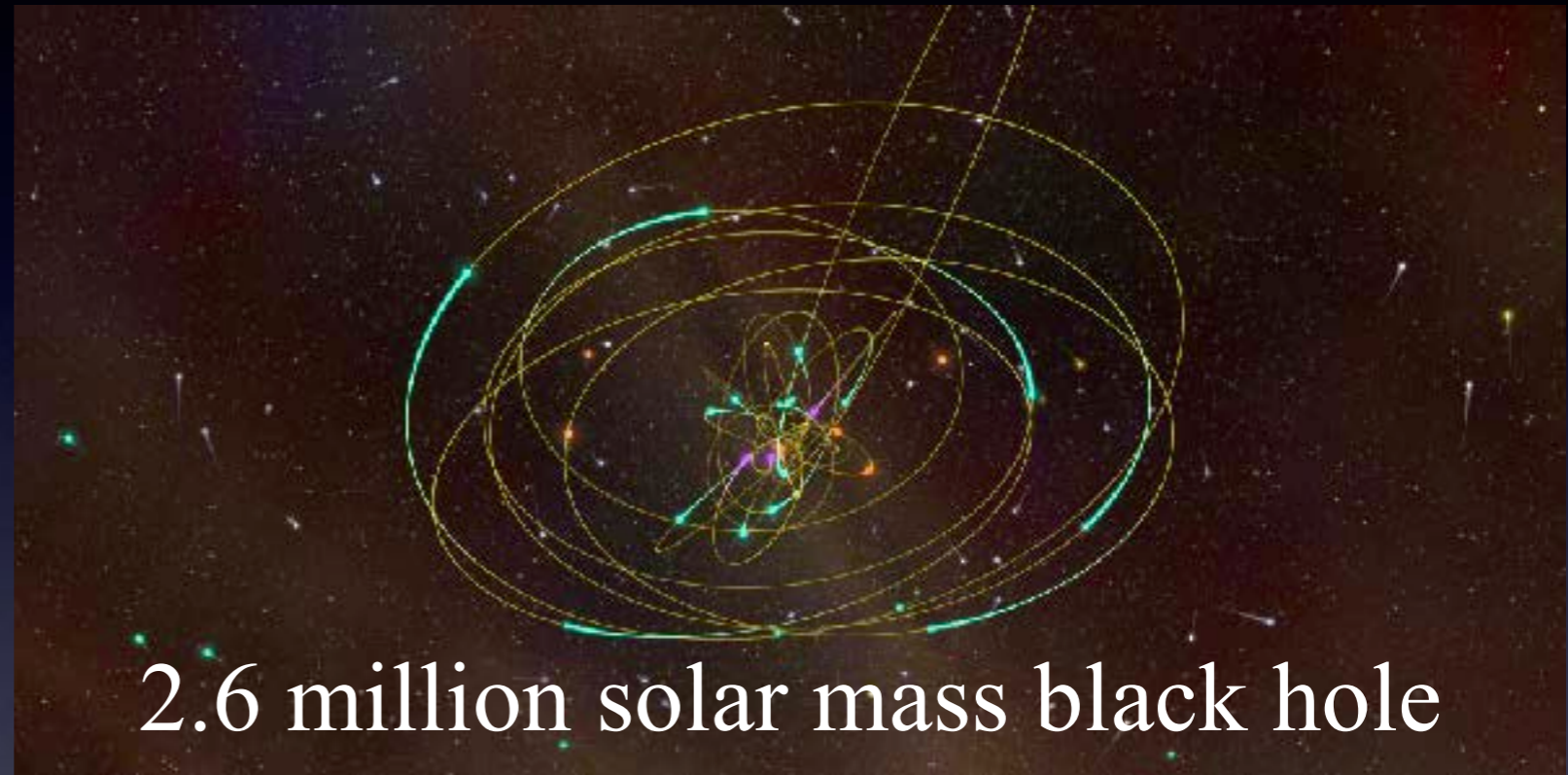
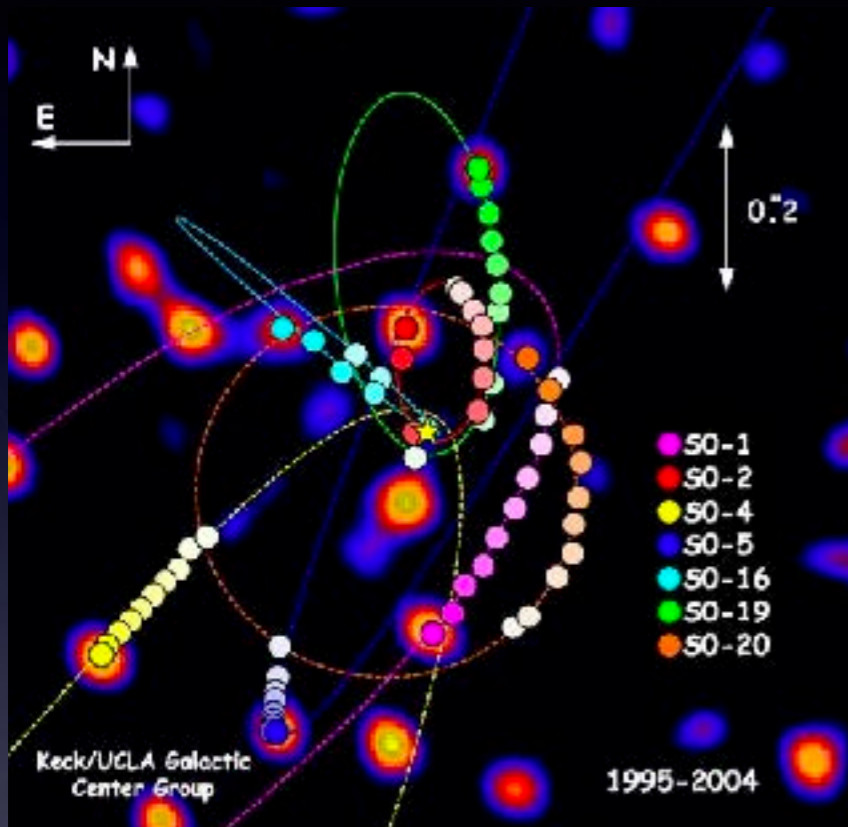


F. Roelofs

# Supermassive Black Hole At the Center of Milky Way



2020 Nobel Prize



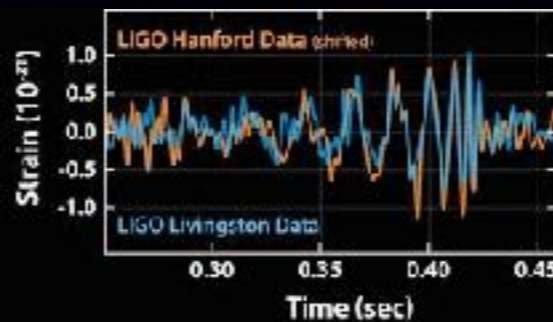
2.6 million solar mass black hole



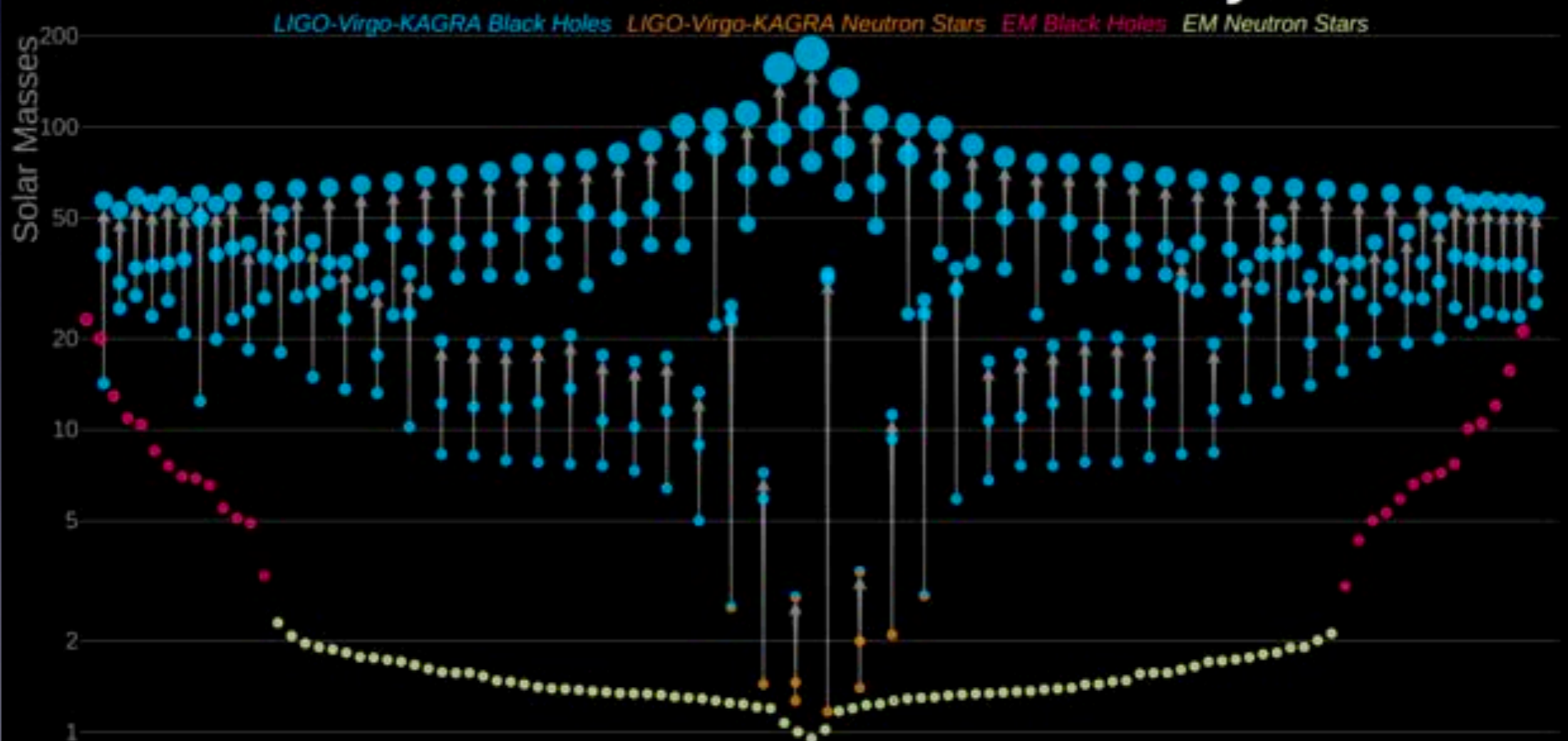
2022 May EHT Press Release

# Blackhole-Black Hole Merger by Gravitational Wave

2017 Nobel Prize

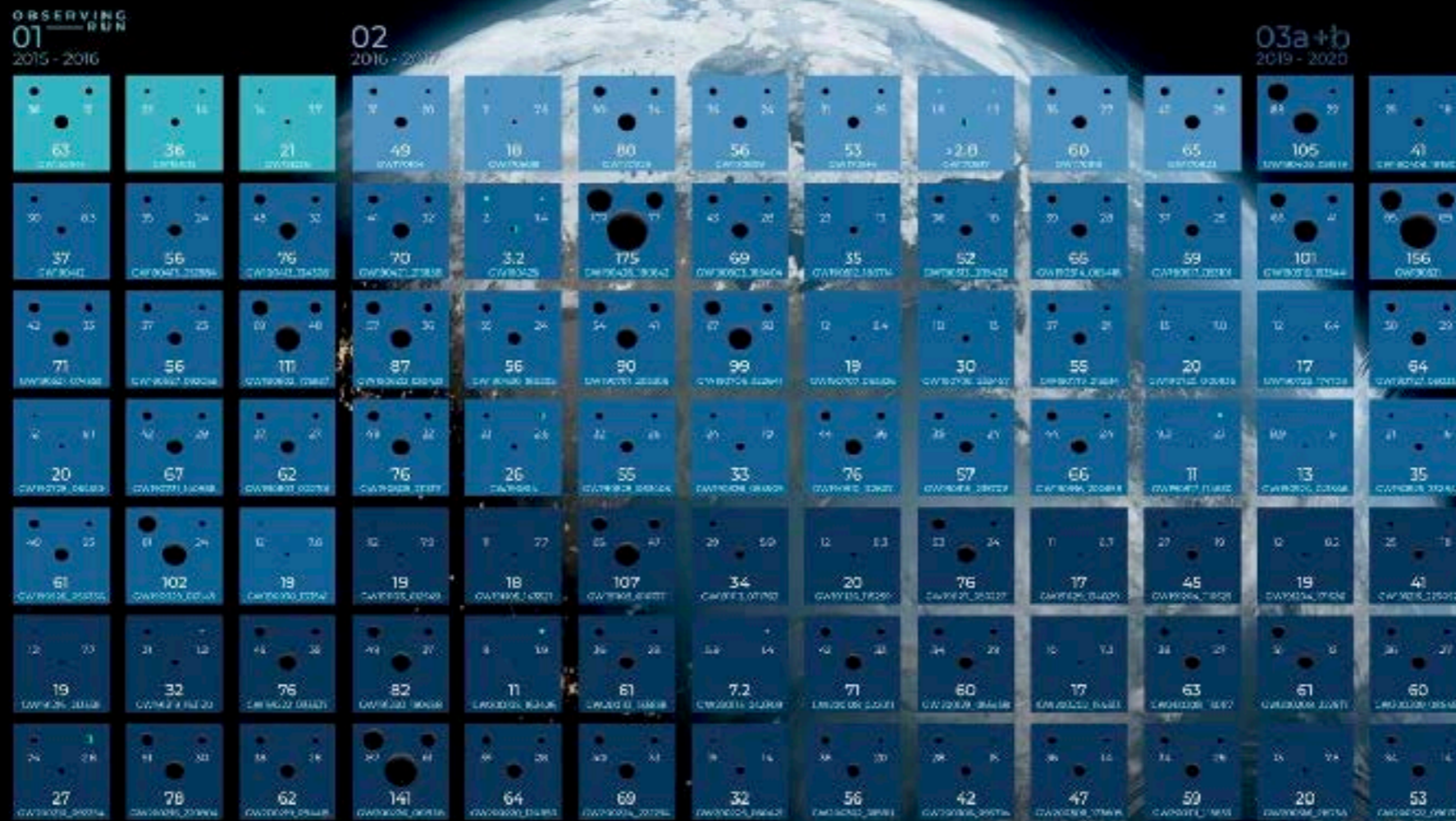


## Masses in the Stellar Graveyard



# Blackhole-Black Hole Merger by Gravitational Wave

## 90 Events are reported as of Today



**KEY**

- BLACK HOLE
- PRIMARY MASS
- FINAL MASS
- NEUTRON STAR
- BLACK HOLE
- BY PRODUCT MASS
- DATE (TIME)

UNITS ARE SOLAR MASSES  
LOOK AT MASS 17 AND 17P14

UNITS ARE SOLAR MASSES  
LOOK AT MASS 17 AND 17P14

GRAVITATIONAL WAVE  
**MERGER**  
DETECTIONS  
SINCE 2015

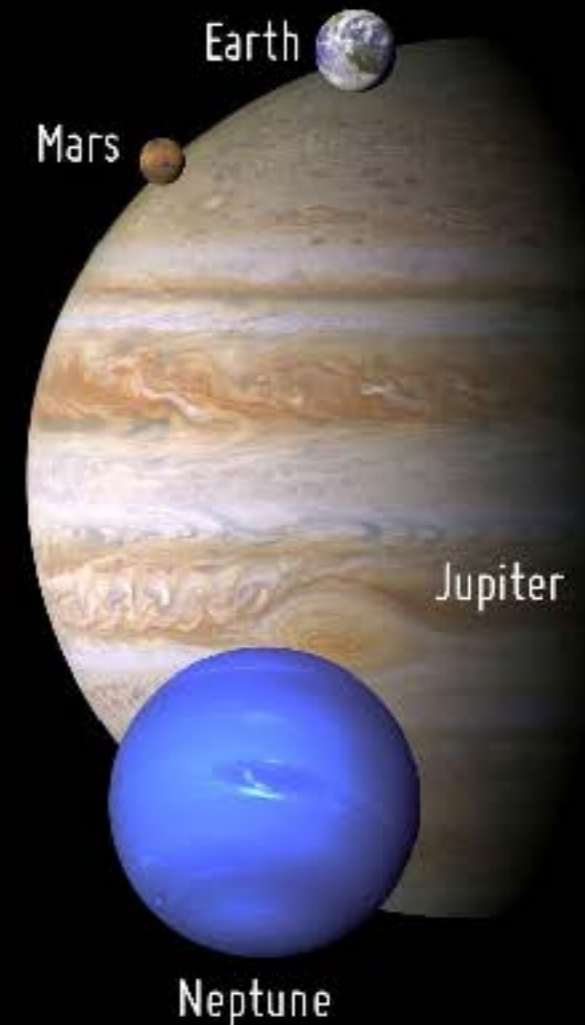


# Exoplanet Discoveries

## 4884 planets today

### Potentially Habitable Exoplanets

Ranked by Distance from Earth (light years)



# Biggest Discovery in Astrophysics in the last 30 years => Dark Energy

#	Bibcode Authors	Cites Title	Date	List of Links Access Control Help
1	<a href="#">1998AJ...116.1009R</a> Riess, Adam G.; Filippenko, Alexei V.; Challis, Peter; Clocchiatti, Alejandro; Diercks, Alan; Garnavich, Peter M.; Gilliland, Ron L.; Hogan, Craig J.; Jha, Saurabh; Kirshner, Robert P.; and 10 coauthors	11836.000 Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant	09/1998	<a href="#">A</a> <a href="#">EF</a> <a href="#">X</a> <a href="#">D</a> <a href="#">RC</a> <a href="#">SN</a> <a href="#">UH</a>
2	<a href="#">1999ApJ...517.565P</a> Perlmutter, S.; Aldering, G.; Goldhaber, G.; Knop, R. A.; Nugent, P.; Castro, P. G.; Deustua, S.; Fabbro, S.; Goobar, A.; Groom, D. E.; and 23 coauthors	11745.000 Measurements of $\Omega$ and $\Lambda$ from 42 High-Redshift Supernovae	06/1999	<a href="#">A</a> <a href="#">EF</a> <a href="#">X</a> <a href="#">D</a> <a href="#">RC</a> <a href="#">SN</a> <a href="#">UH</a>
3	<a href="#">1998ApJ...500.525S</a> Schlegel, David J.; Finkbeiner, Douglas P.; Davis, Marc	11266.000 Maps of Dust Infrared Emission for Use in Estimation of Reddening and Cosmic Microwave Background Radiation Foregrounds	06/1998	<a href="#">A</a> <a href="#">EF</a> <a href="#">X</a> <a href="#">RC</a> <a href="#">S</a> <a href="#">UH</a>
4	<a href="#">1981PhRvB..23.5048P</a> Perdew, J. P.; Zunger, Alex	11147.000 Self-interaction correction to density-functional approximations for many-electron systems	05/1981	<a href="#">E</a> <a href="#">RC</a> <a href="#">U</a>
5	<a href="#">1973A&amp;A...24.337S</a> Shakura, N. I.; Sunyaev, R. A.	9271.000 Black holes in binary systems. Observational appearance.	00/1973	<a href="#">EG</a> <a href="#">RC</a> <a href="#">S</a> <a href="#">QUH</a>
6	<a href="#">2003ApJS..148.175S</a> Spergel, D. N.; Verde, L.; Peiris, H. V.; Komatsu, E.; Nolta, M. R.; Bennett, C. L.; Halpern, M.; Hinshaw, G.; Jarosik, N.; Kogut, A.; and 7 coauthors	9000.000 First-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Determination of Cosmological Parameters	09/2003	<a href="#">A</a> <a href="#">EF</a> <a href="#">X</a> <a href="#">RC</a> <a href="#">SN</a> <a href="#">UH</a>
7	<a href="#">2005Natur.438..197N</a> Novoselov, K. S.; Geim, A. K.; Morozov, S. V.; Jiang, D.; Katsnelson, M. I.; Grigorieva, I. V.; Dubonos, S. V.; Firsov, A. A.	8735.000 Two-dimensional gas of massless Dirac fermions in graphene	11/2005	<a href="#">A</a> <a href="#">E</a> <a href="#">X</a> <a href="#">RC</a> <a href="#">U</a>

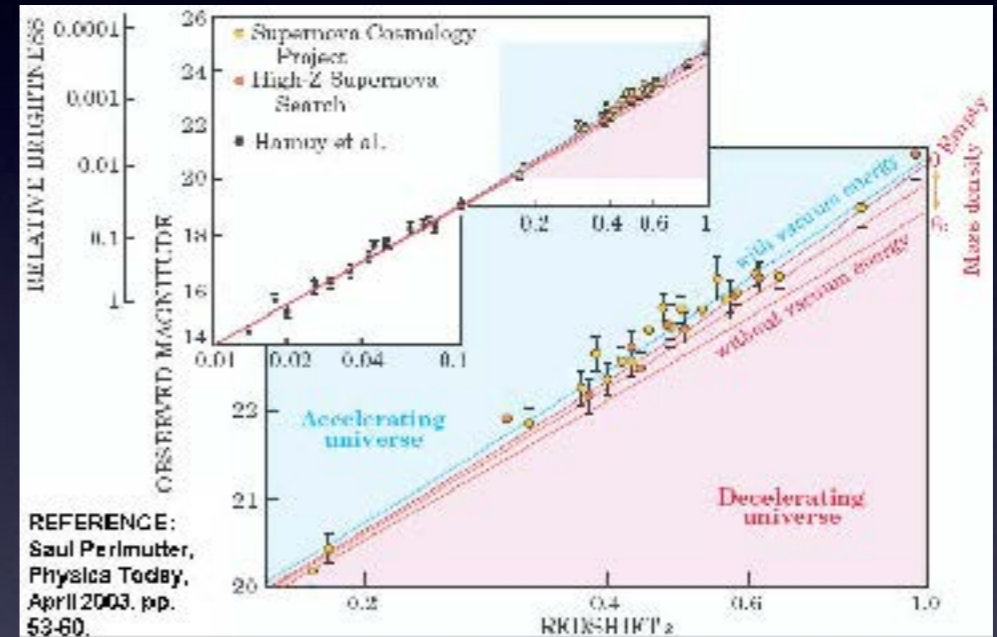
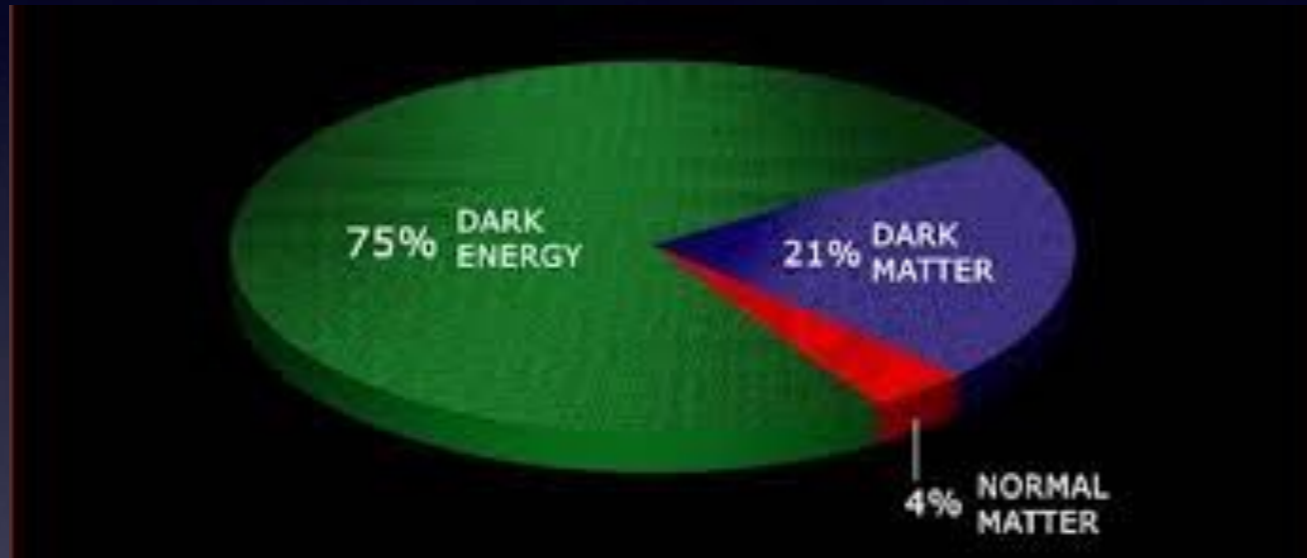




# Dark Energy

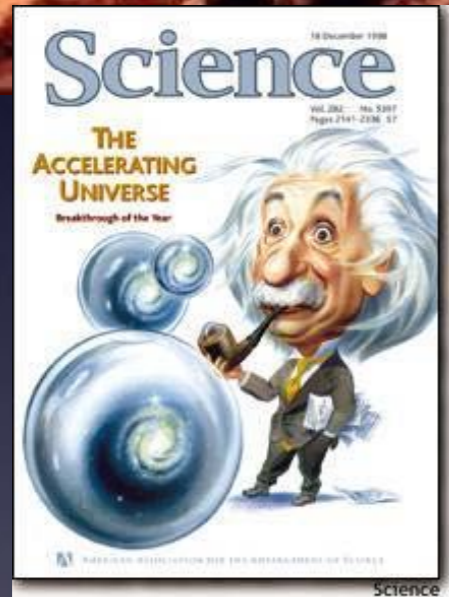
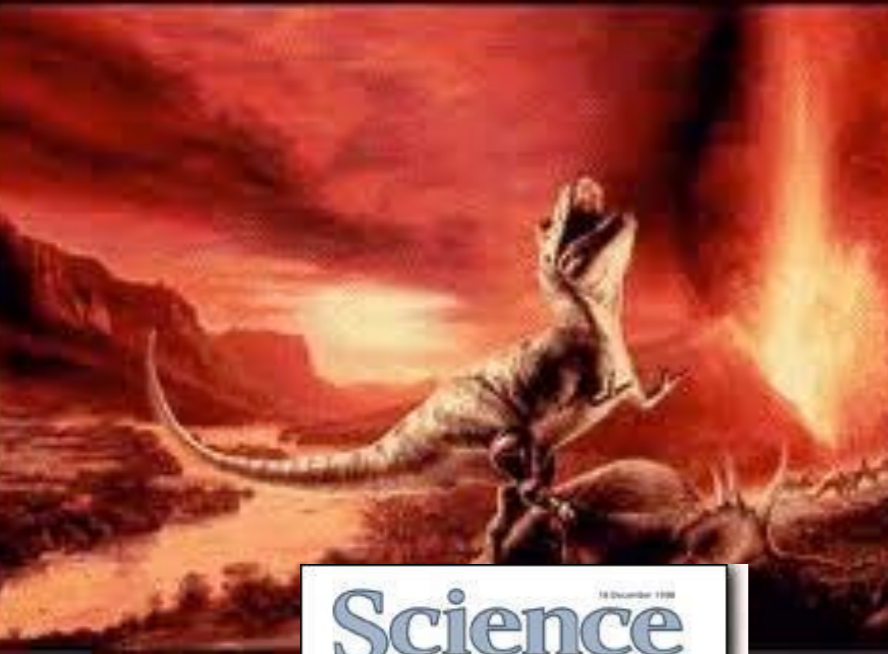


Discovery of Accelerating Universe  
Nobel Prize in Physics 2011



- 70% of Energy in the Universe today, is in the form of mysterious Dark Energy which is causing the acceleration of the expansion of the universe. We don't know what it is

# Adventure of Luis Alvarez (1911-88)



SCIENTIST. INVENTOR. ADVENTURER.

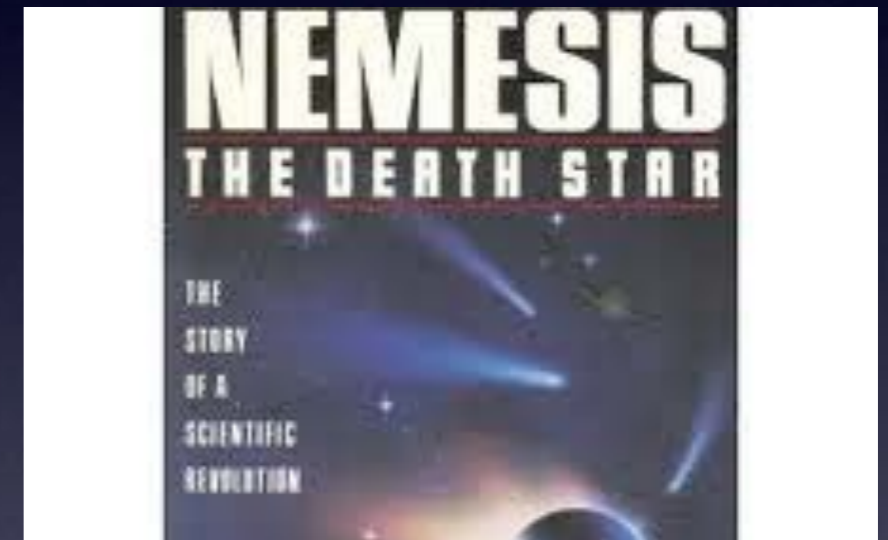
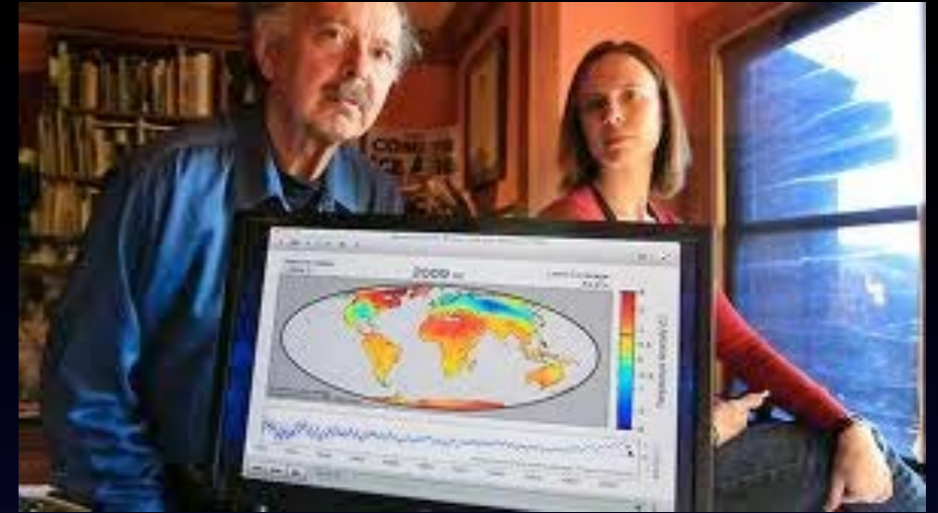
THE LUIS ALVAREZ 100TH ANNIVERSARY SYMPOSIUM  
NOV. 19-20, 2011, STANLEY HALL, UC BERKELEY

REGISTER: LUIS-ALVAREZ-SYMPOSIUM@LBL.GOV

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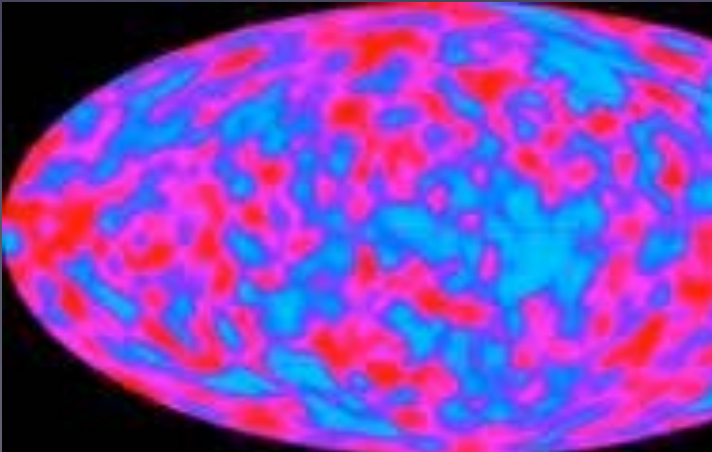
PROGRAM COORDINATOR: DANIEL JACOB, JACK LLOYD, CARL PENNAPPECKER, ANDREW ROSENBLUTH, CHARLES SMITH

U.S. DEPARTMENT OF ENERGY  
Office of Science



THE ASTROPHYSICAL JOURNAL, 217:183-185, 1980 May 1  
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THE LUMINOSITY OF TYPE I SUPERNOVAE

STERRING A. COLGATE  
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, and  
New Mexico Institute of Mining and Technology, Socorro, New Mexico

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New Mexico Institute of Mining and Technology, Socorro, New Mexico

AND

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University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico  
Received 1979 November 15; accepted 1980 February 1

**ABSTRACT**

We have recalculated the luminosity of type I supernovae by using (1) the diffusive release of  $\text{Ni}^{56}$  decay energy (Colgate and McKee), (2) the progressive gamma-ray transparency as calculated by a Monte Carlo gamma-ray simulation code, and (3) the fractional deposition of positrons ( $A_{\text{net}}$ ). If we take 100% optical fluorescence efficiency (Meyrout) and choose a nebula that is expanding uniformly and at constant velocity such that it is the  $\gamma$ -ray mean free path ( $3.5 \text{ g cm}^{-2}$ ) thick at 28 days, we obtain excellent agreement with observations. Three independent physical phenomena are involved. The first is the diffusive release of thermal radiation that with the 61 day  $\text{Ni}^{56}$  decay determines the height and width of the optical peak. The second is the initial fast decay of the optical peak by a factor of roughly 100 as determined by the progressive transparency to  $\gamma$ -rays. The third is the apparent 56 day half-life that results from the progressive escape of the positron fraction of the 77 day  $\text{Co}^{56}$  decay. To obtain agreement with observations, each of these three independent phenomena requires that the expanding nebula be described by a single relation  $M_e v_e = 0.22 \pm 0.05$ , where  $M_e$  is the ejected mass in solar masses and  $v_e$  is the expansion velocity in units of  $10^4 \text{ cm s}^{-1}$ . Total energy requirements exclude the possibility of the ejection of an envelope  $\geq 0.75 M_{\odot}$ , yet the optical luminosity requires that  $\sim 0.25 M_{\odot}$  of the ejected matter be  $\text{Ni}^{56}$ .

**Subject heading:** nuclear reactions — stars: supernovae

# Dinosaur Extinction

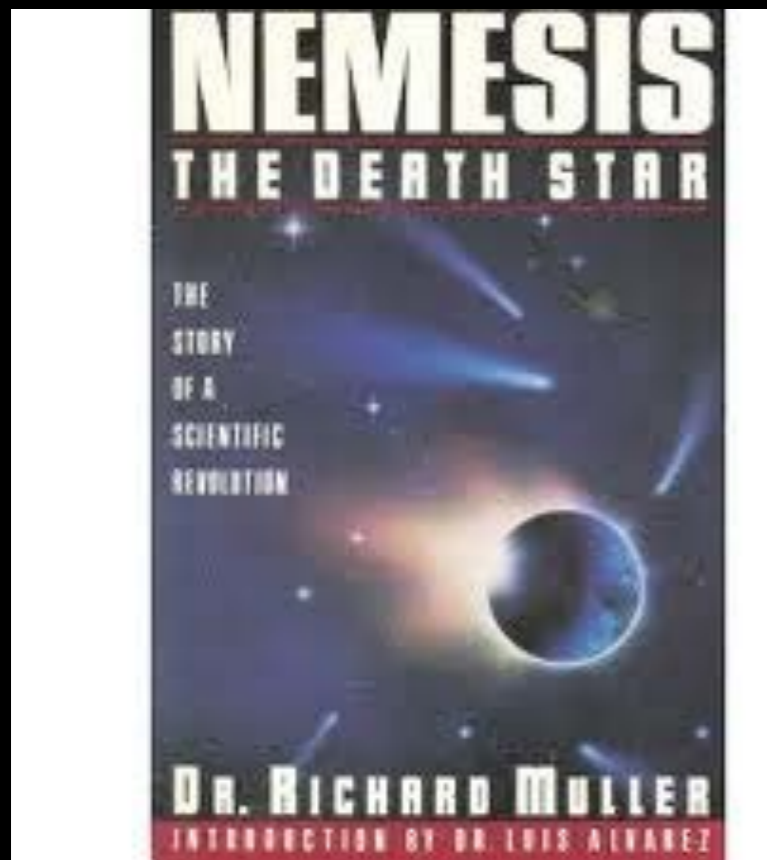
## Key Signature : Iridium

### with Walter Alvarez (Geology)



Thesis Advisor : Richard Muller  
Grad Student : Saul Perlmutter  
PhD Thesis

“An Astrometric Search for a Stellar  
Companion to the Sun” PhD 1986



Hunting for Killer Astroids but happened to find supenovae

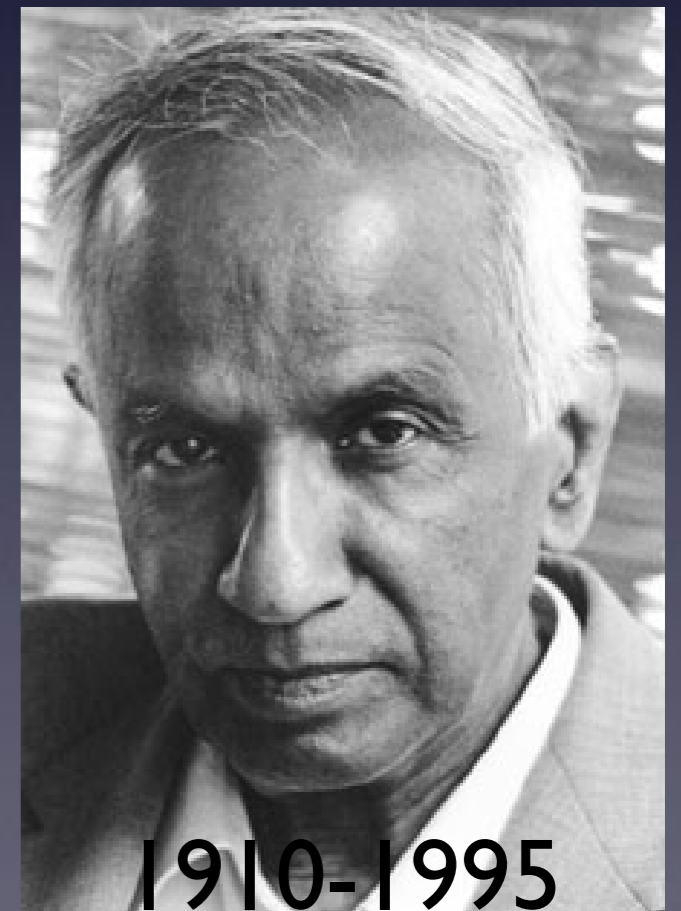
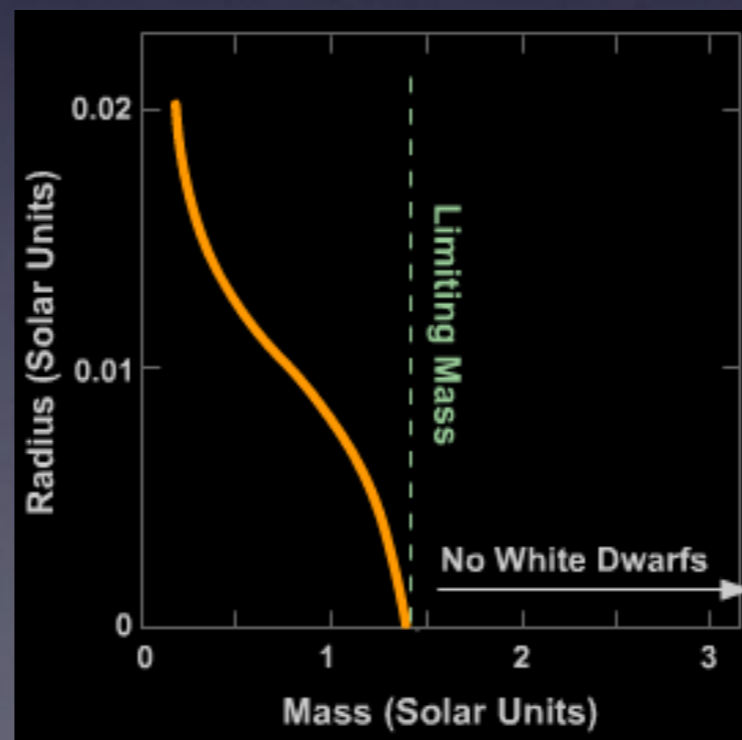
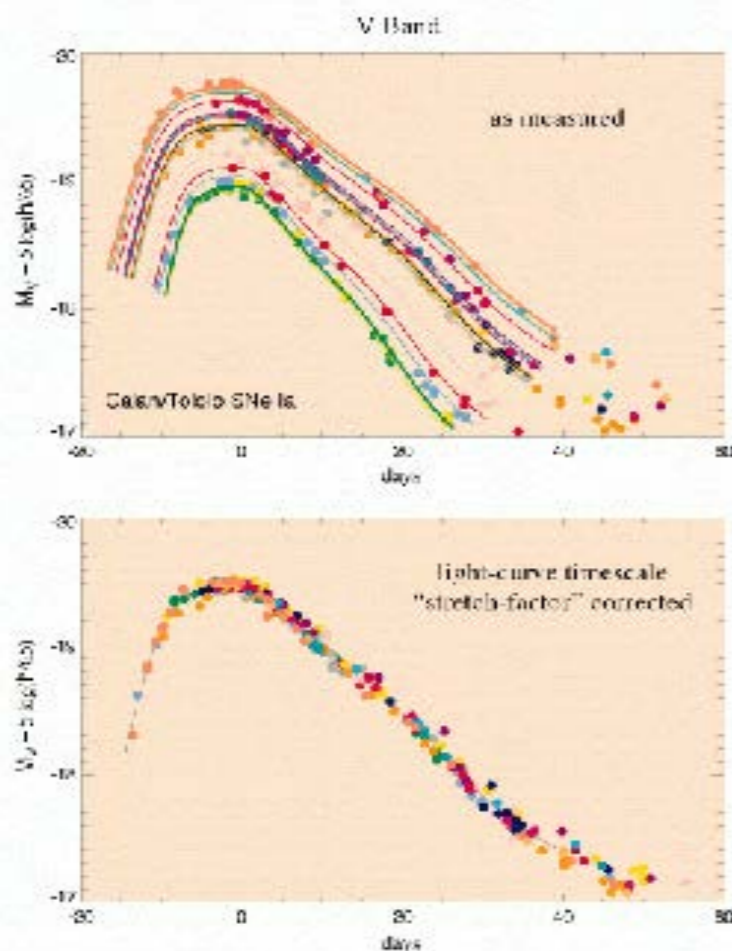
# Q: How fast the Universe is Expanding? Type Ia Supernova Cosmology

Phillips Relation (1993)  
Brightness is Constant

Chandrasekhar Mass Limit

Type Ia Supernova  
always explodes at  
1.4 Solar Mass

Low Redshift Type Ia  
Template Lightcurves

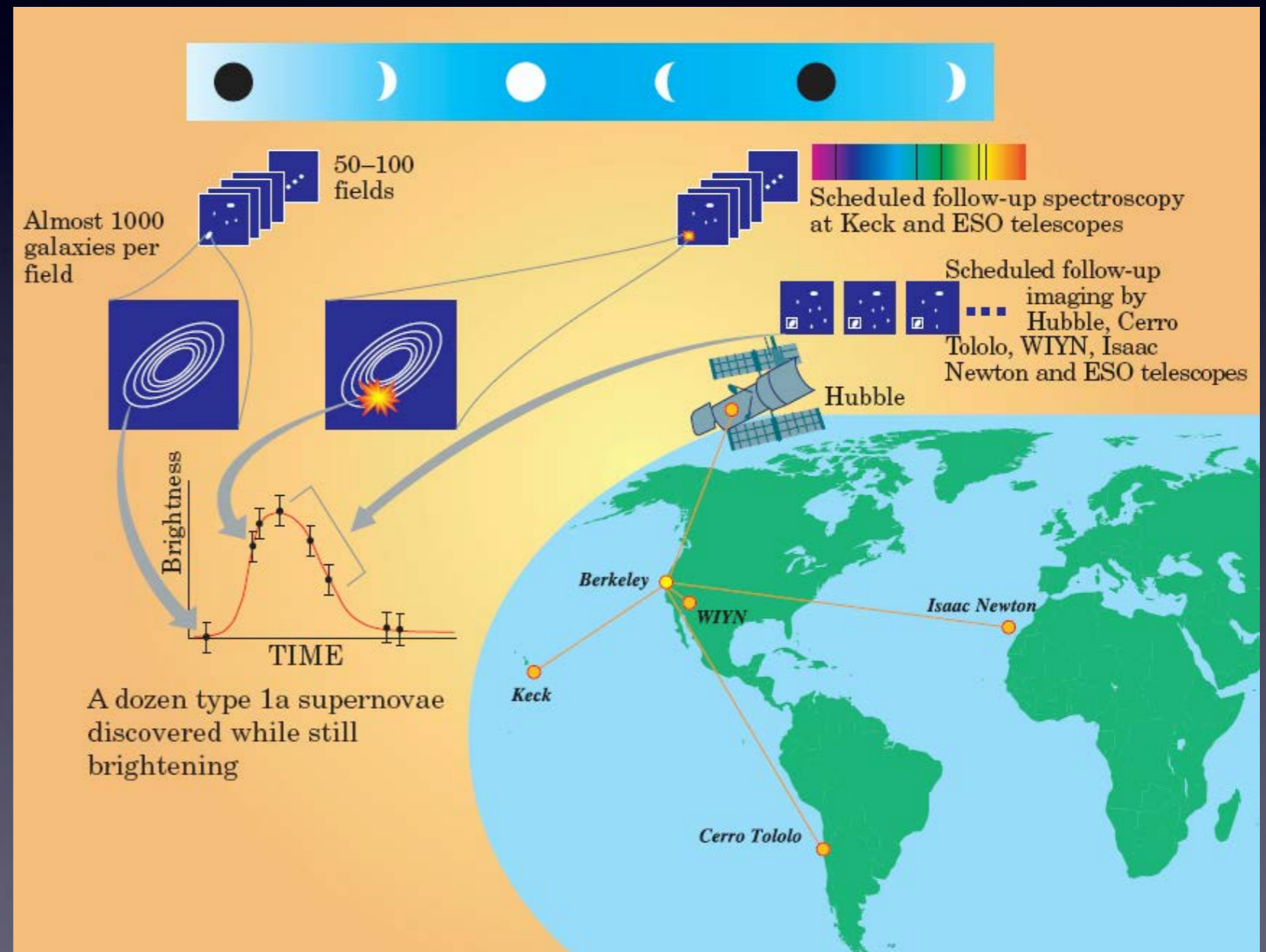


1910-1995

# Supernova Cosmology Project (SCP)

Phillips ('93), Hubble Space Telescope('90), 10m Keck Telescope ('92), VLT & Subaru ('98)

Saul Perlmutter



# Supernova Cosmology Project 1986-1992

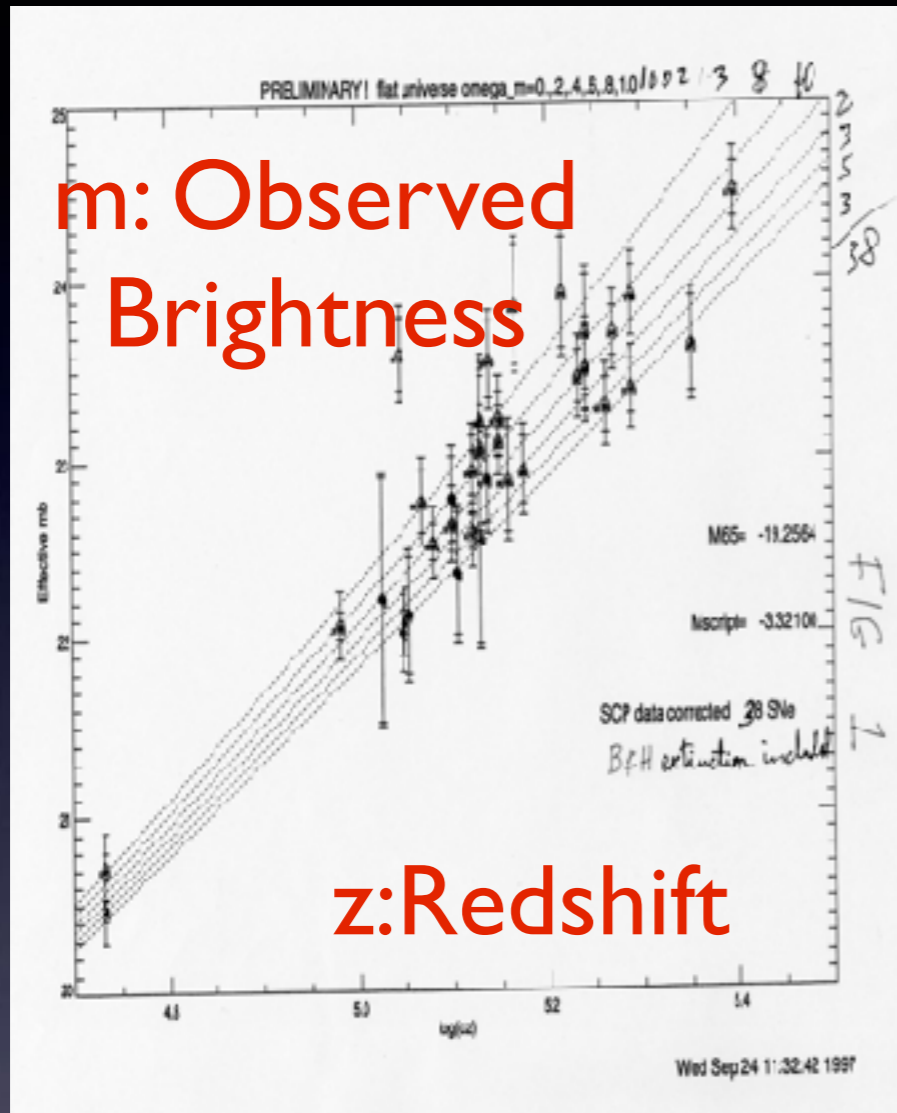


1991. Early days of the Supernova Search project, later to become the SCP.

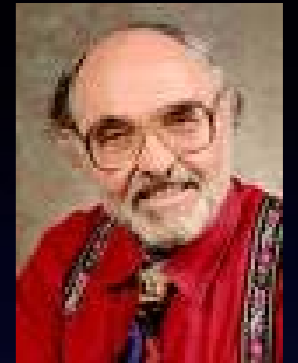
L. to r., Carl Pennypacker, Saul Perlmutter, Heidi Marvin, Gerson, Rich Muller, at LBL.

**FIGURE 1.** The SCP group at Berkeley in 1990-91. Carl Pennypacker, Saul Perlmutter, Heidi Marvin, Gerson Goldhaber, and Rich Muller l. to r.

# Discovery of Dark Energy (SCP 1997)



Gerson Goldhaber  
 $\Lambda$  is needed !



1997 Sep 24th

Einsteins Equation

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R - \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{Kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

$$M_V^0 - 5 \log H_0$$

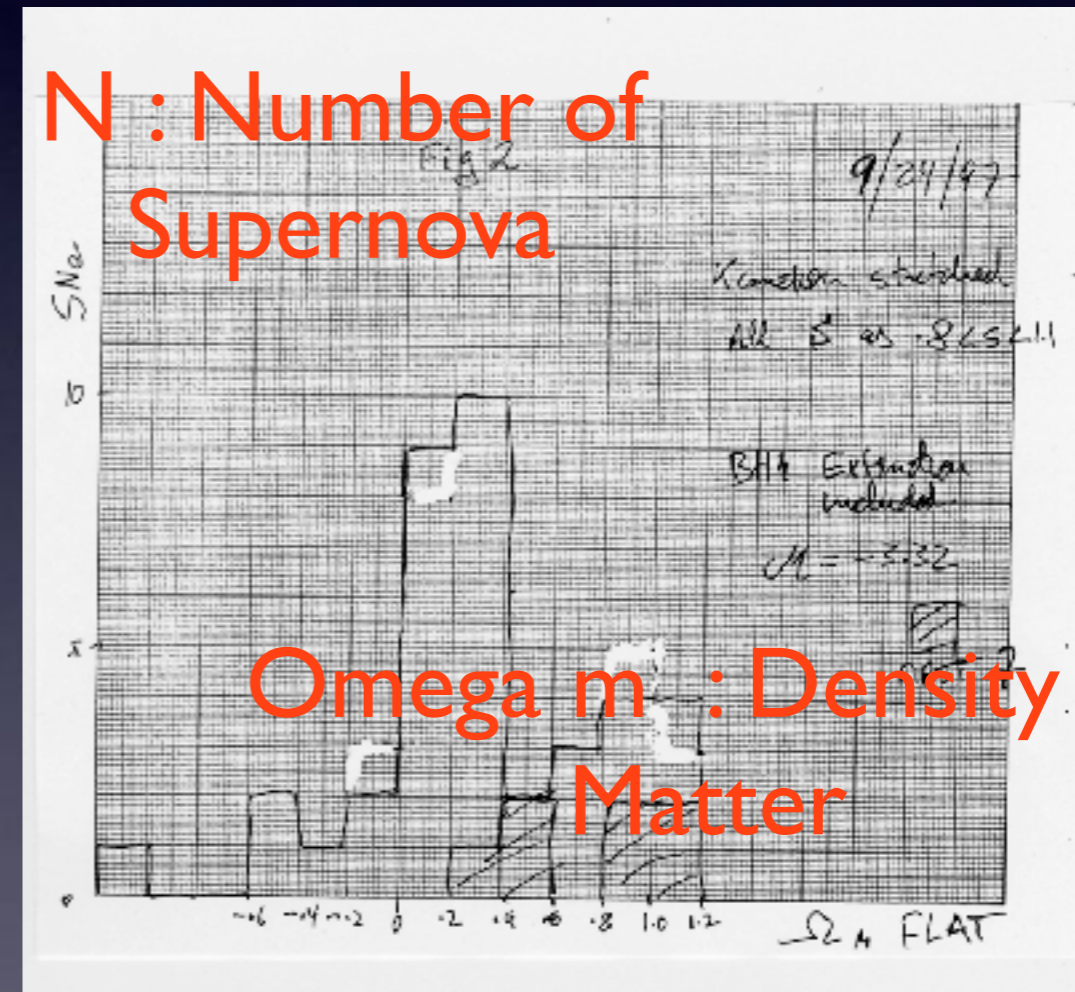
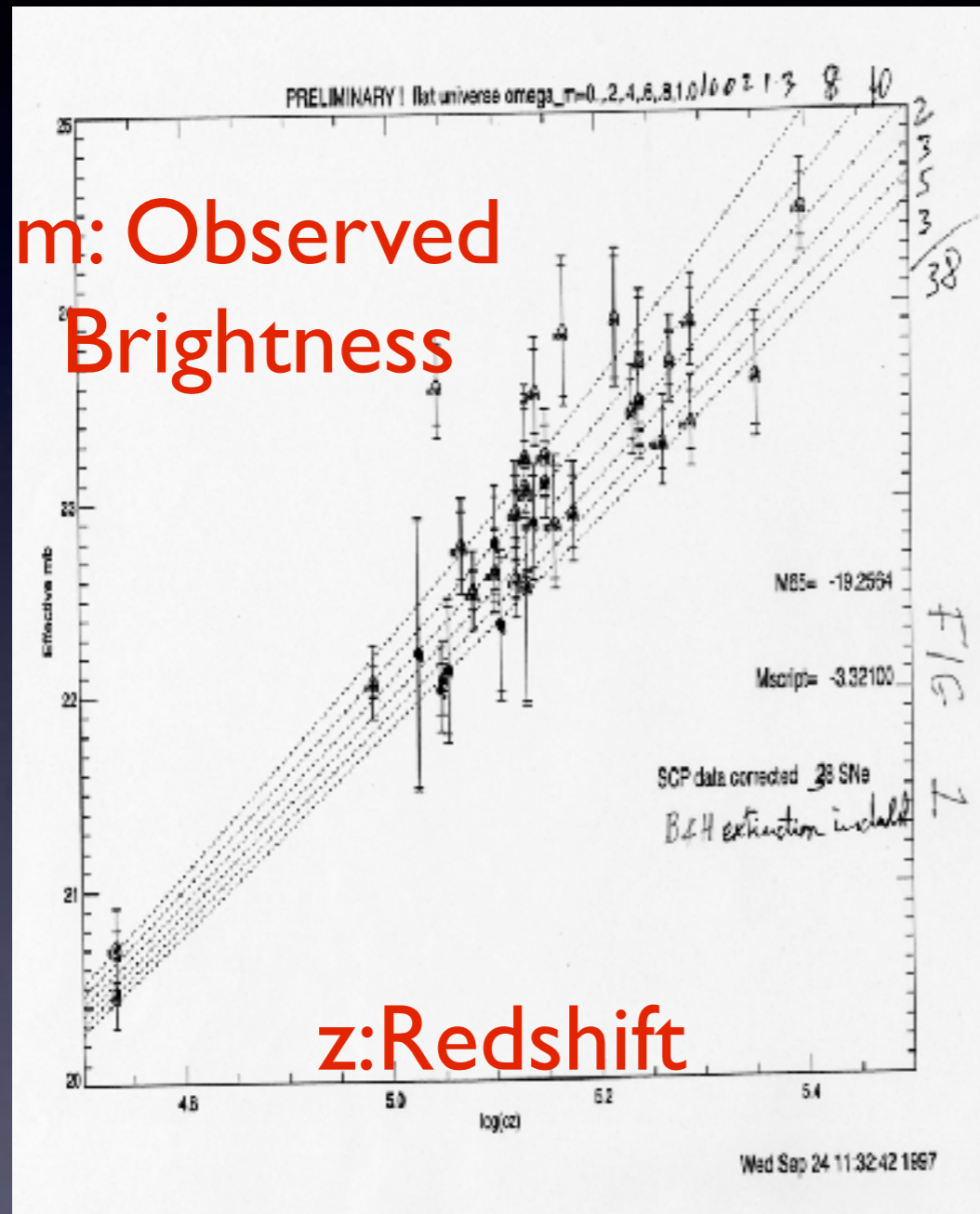
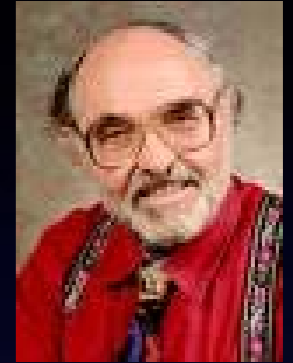
Observed magnitude (Brightness)  
 is a function of cosmological model

$$= m_V^0 - 25 - 5 \log \left( c(1+z) \int_0^z \left[ \Omega_M(1+z')^3 + \Omega_\Lambda \right]^{-1/2} dz' \right),$$



# Discovery of Dark Energy (SCP 1997)

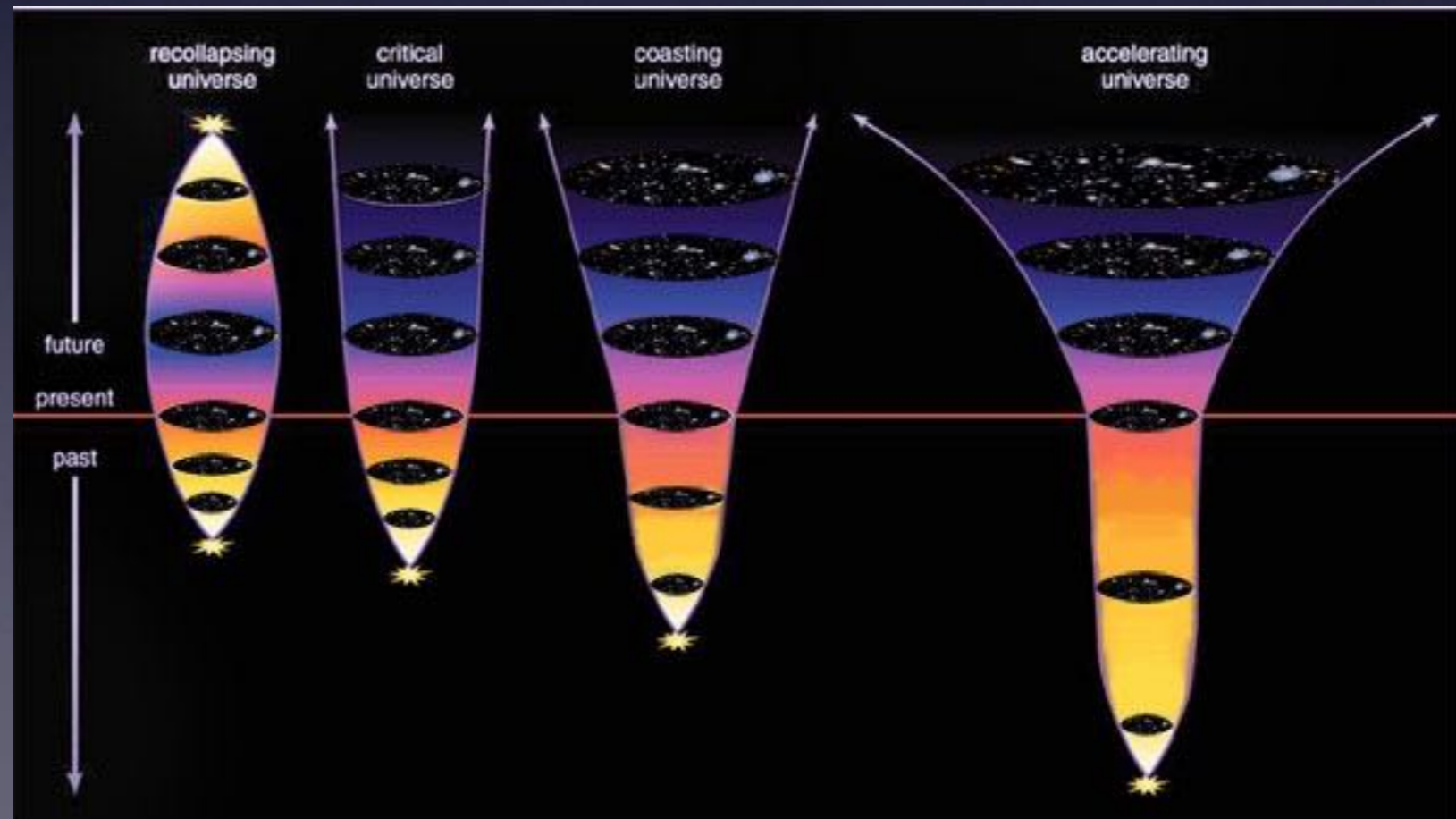
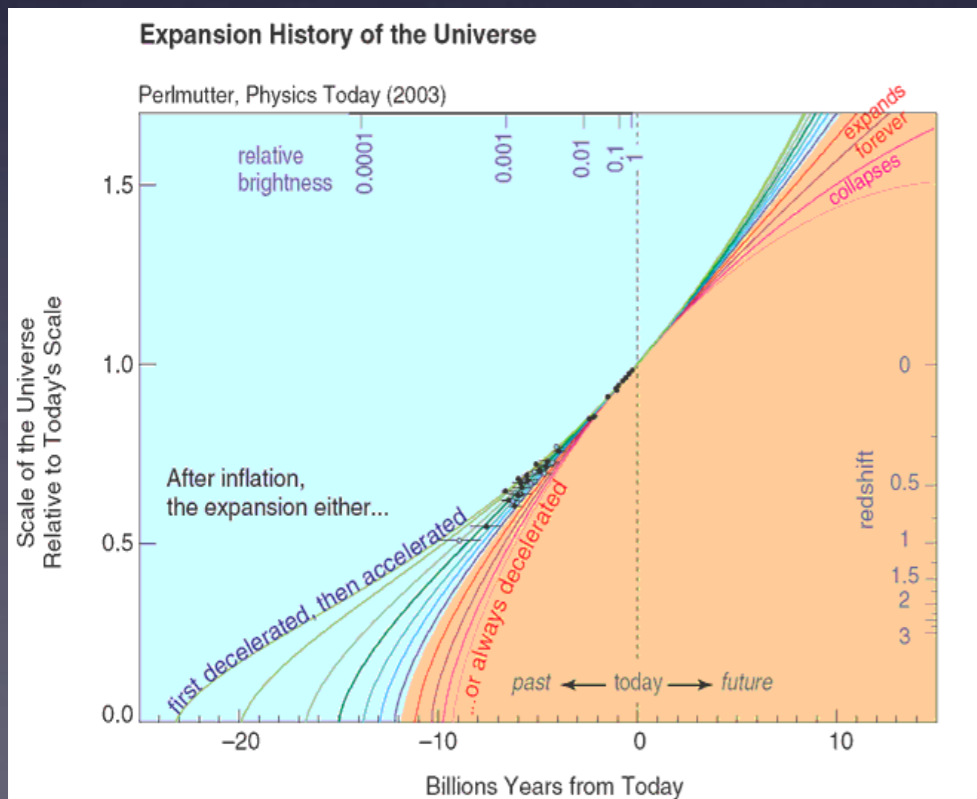
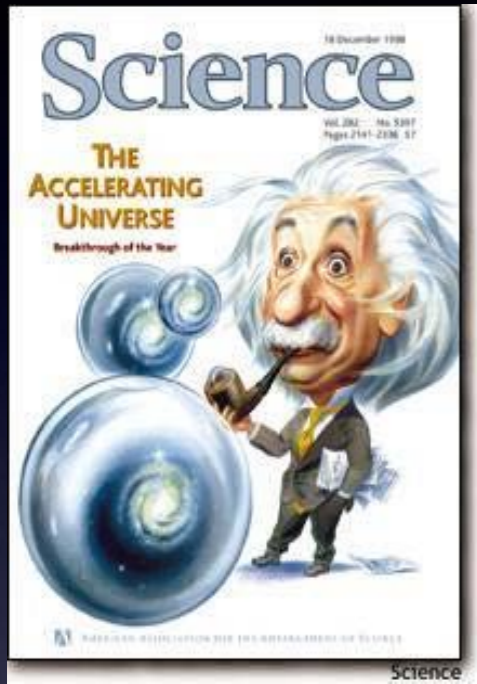
Gerson Goldhaber reported non-zero  $\Lambda$  on 24th in Sep '97



# Discovery of Accelerating Universe Breakthrough of the Year in 1998!

Our Universe expands forever!  
In fact, the expansion is accelerating now!

Science 1998



# HST Cluster SN Survey

Nao Suzuki & SCP  
 PI: Saul Perlmutter



HST



Keck



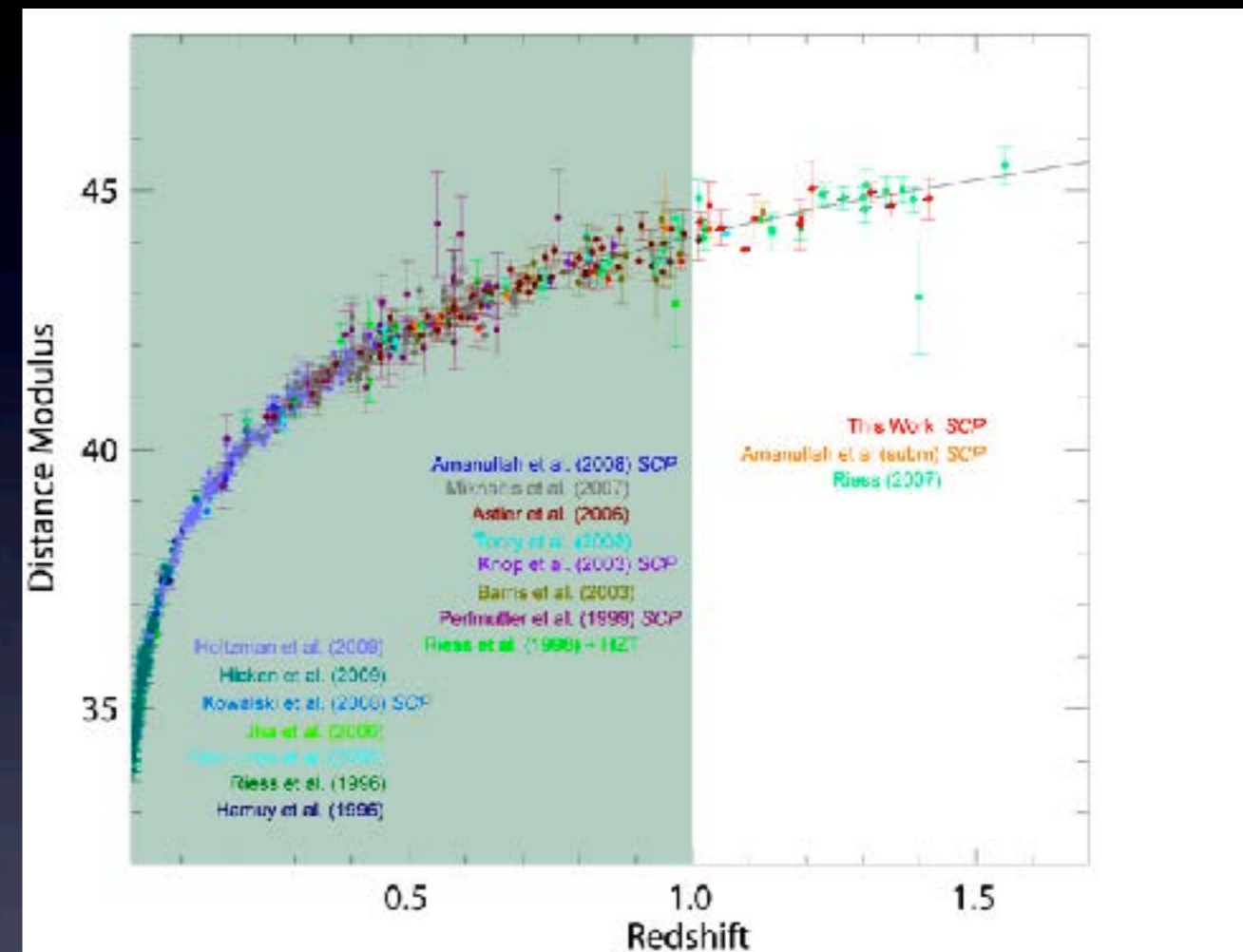
VLT



Subaru



SCP06K0 $z=1.415$	SCP06G4 $z=1.349$	SCP05D6 $z=1.315$	SCP06H5 $z=1.231$
SCP06R12 $z=1.212$	SCP06A4 $z=1.192$	SCP06N33 $z=1.188$	SCP06F12 $z=1.110$
SCP06C0 $z=1.092$	SCP06U4 $z=1.050$	SCP06E12 $z=1.030$	SCP05D0 $z=1.014$
SCP06C1 $z=0.980$	SCP06H3 $z=0.850$	SCP05P9 $z=0.821$	SCP06Z5 $z=0.623$



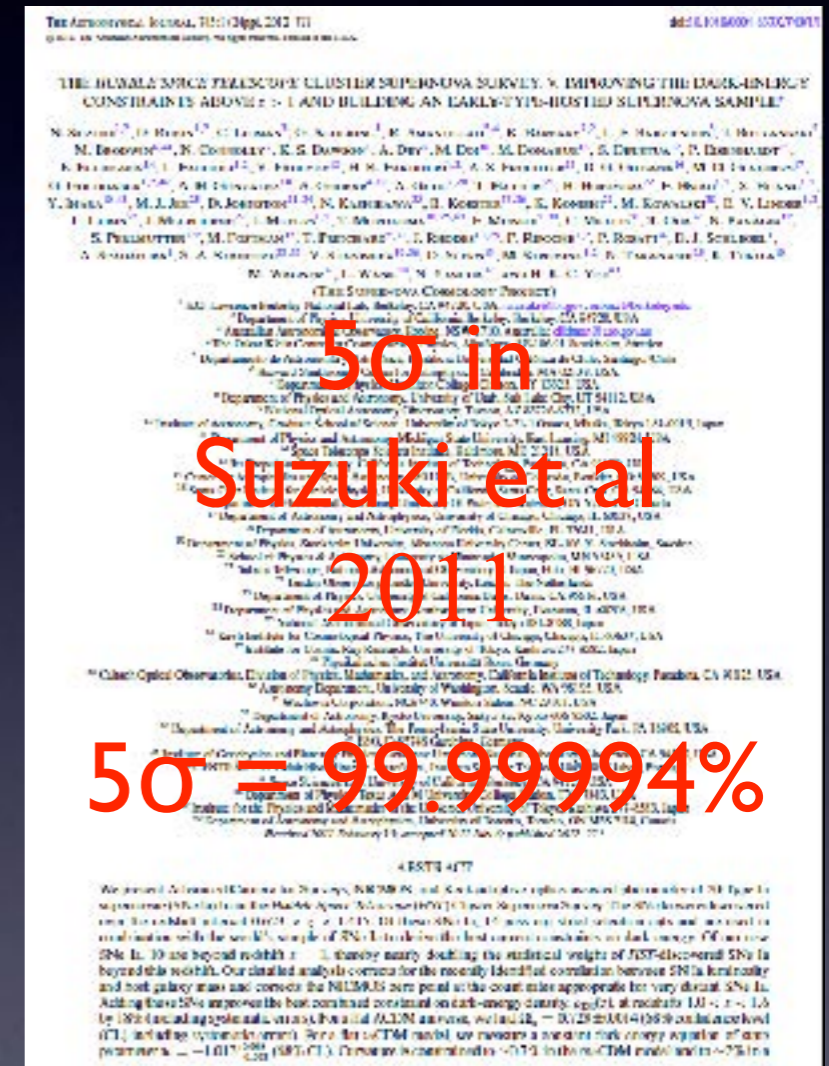
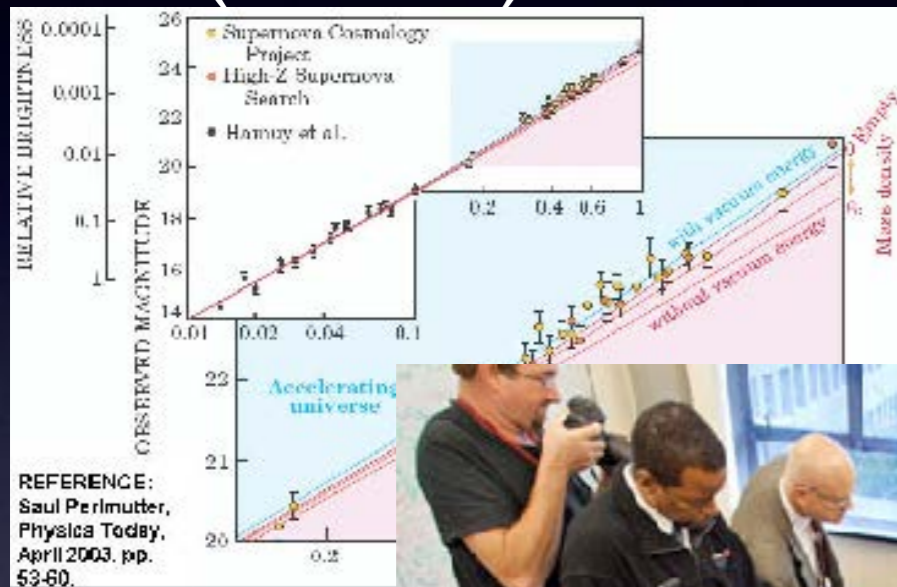


# Dark Energy

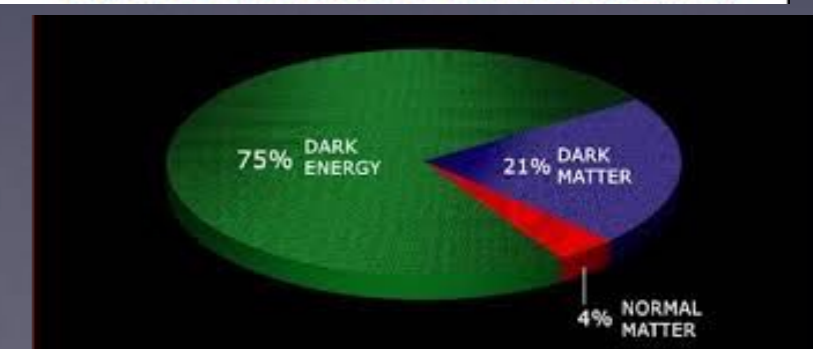


Discovery of Accelerating Universe  
Nobel Prize in Physics 2011

$2\sigma$  (95.4 %) in 1997



- 70% of Energy in the Universe is in the form of mysterious Dark Energy





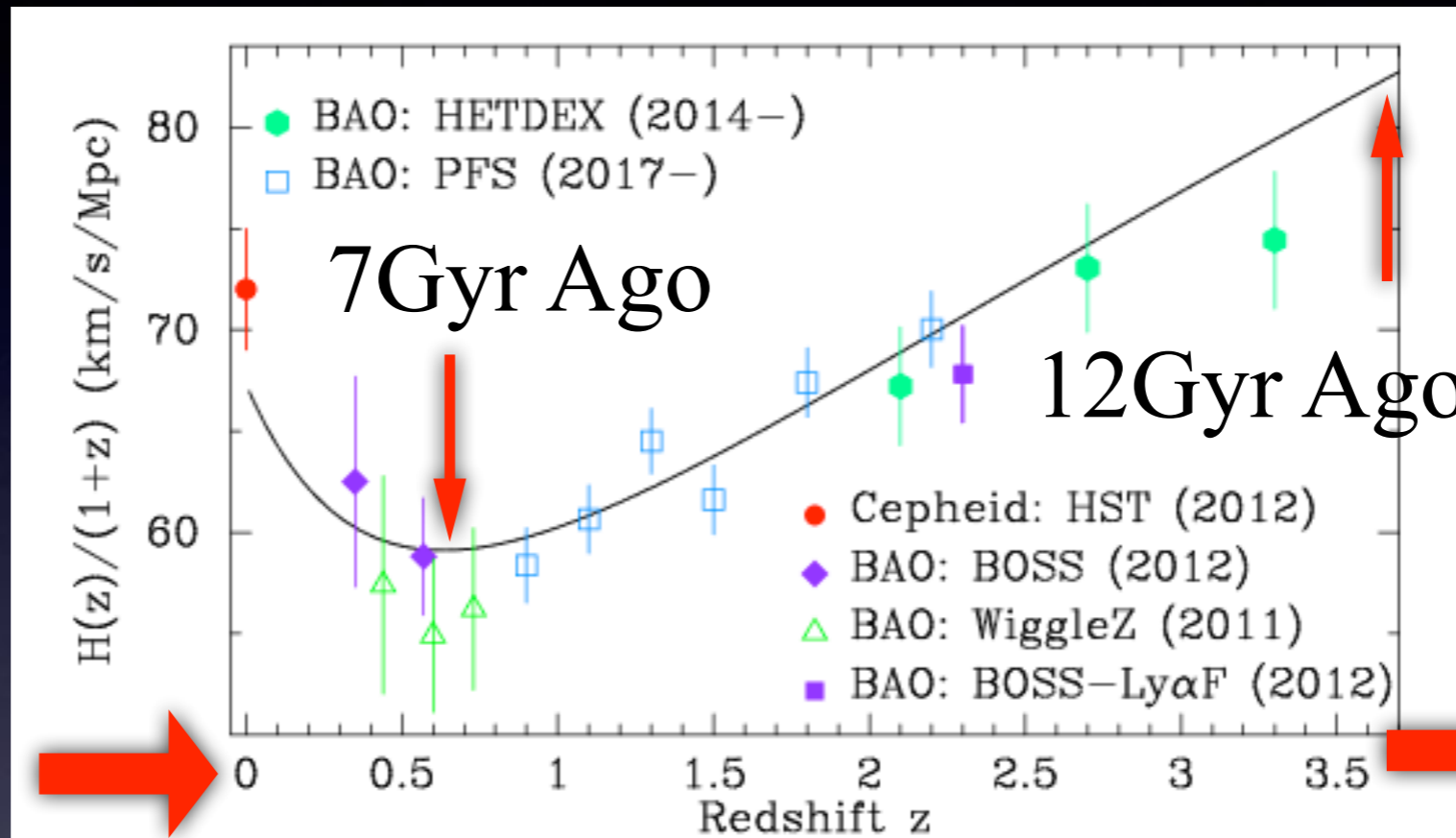


# Mysterious Expansion of the Universe

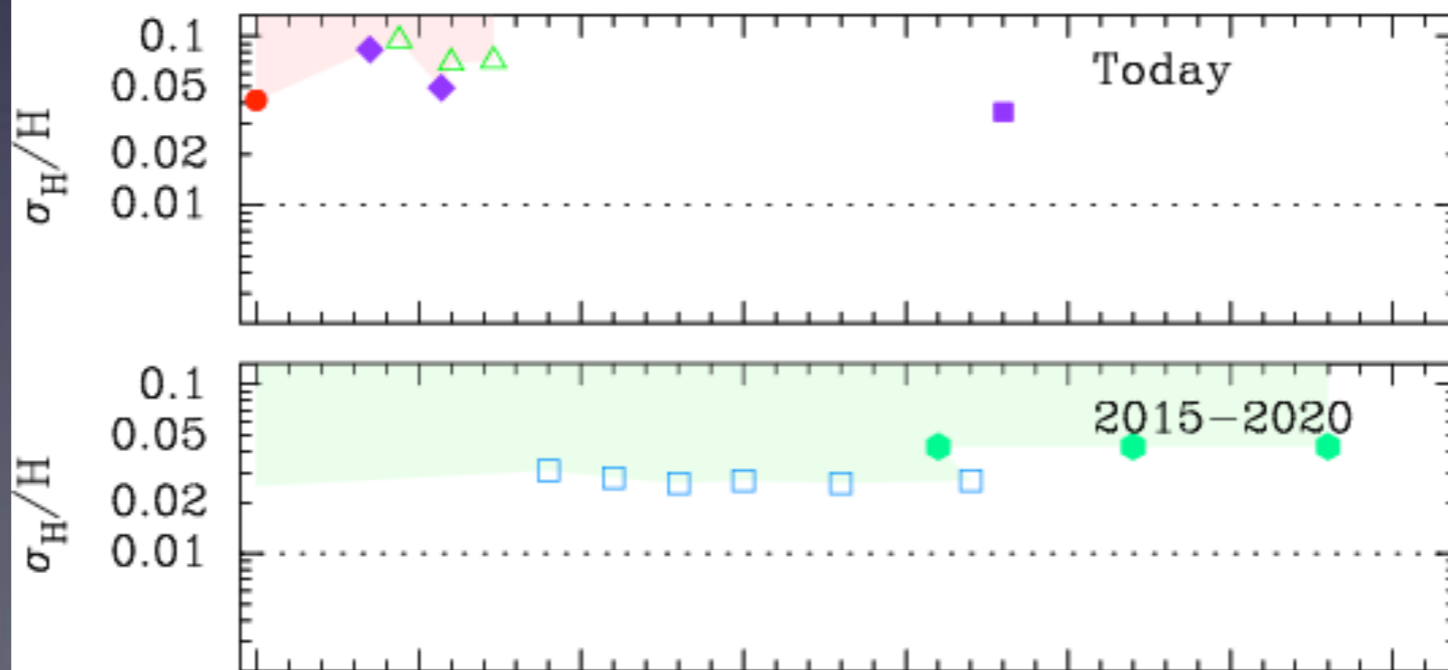
## Deceleration to Acceleration

### Dark Energy is not well understood...

Now Expansion Speed



Fractional Error



Not Well  
Constrained

# HSC SNIa Cosmology for Dark Energy

Subaru HSC Discovery

Hubble Space Telescope

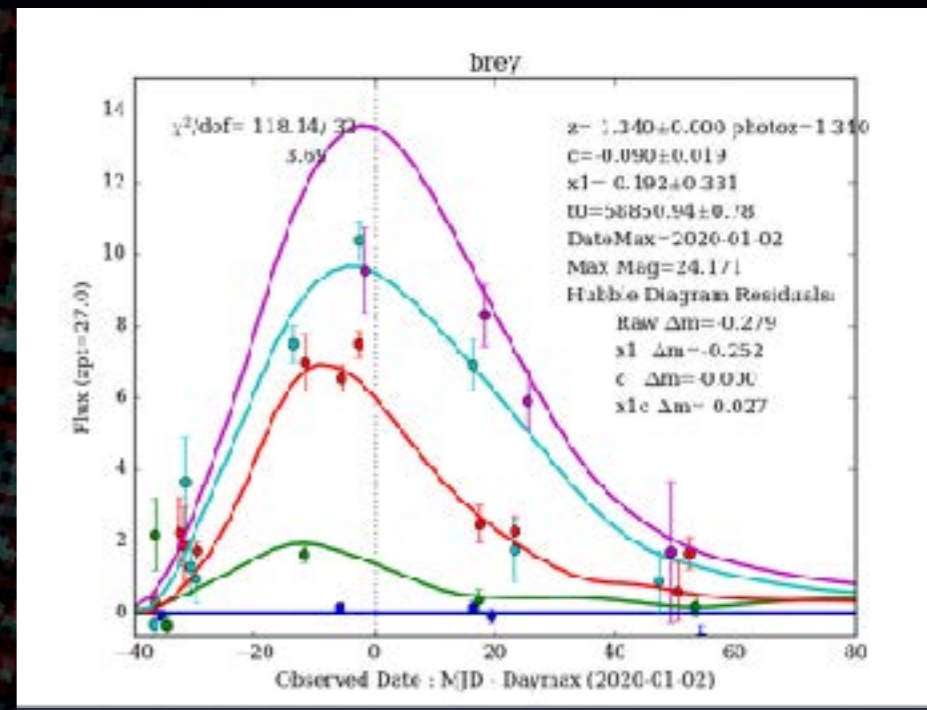
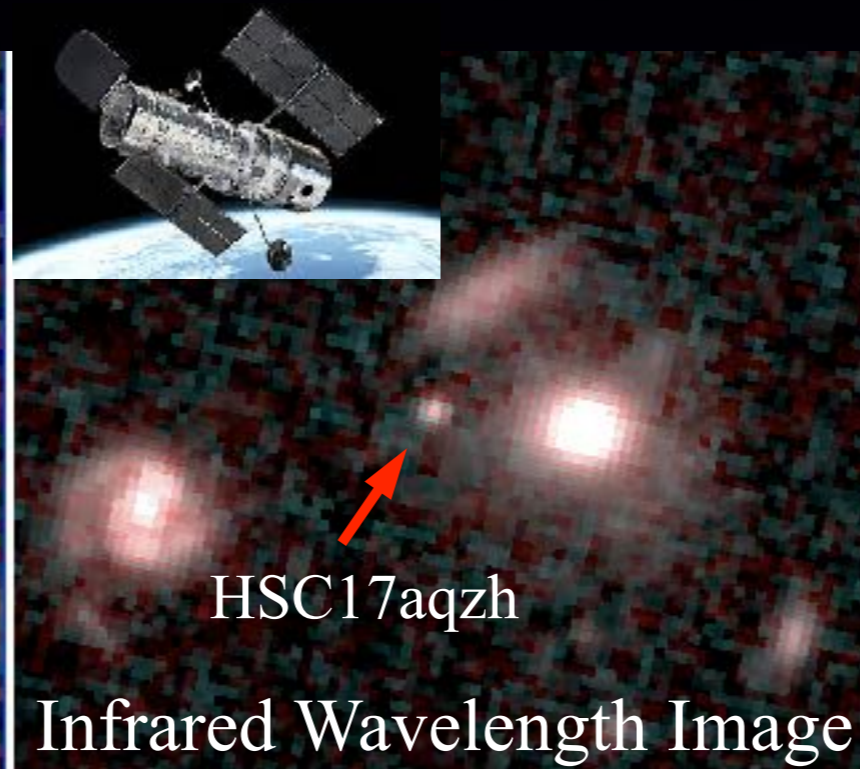
HSC SNIa Light Curve:  $z=1.34$

SN Classification & Trigger

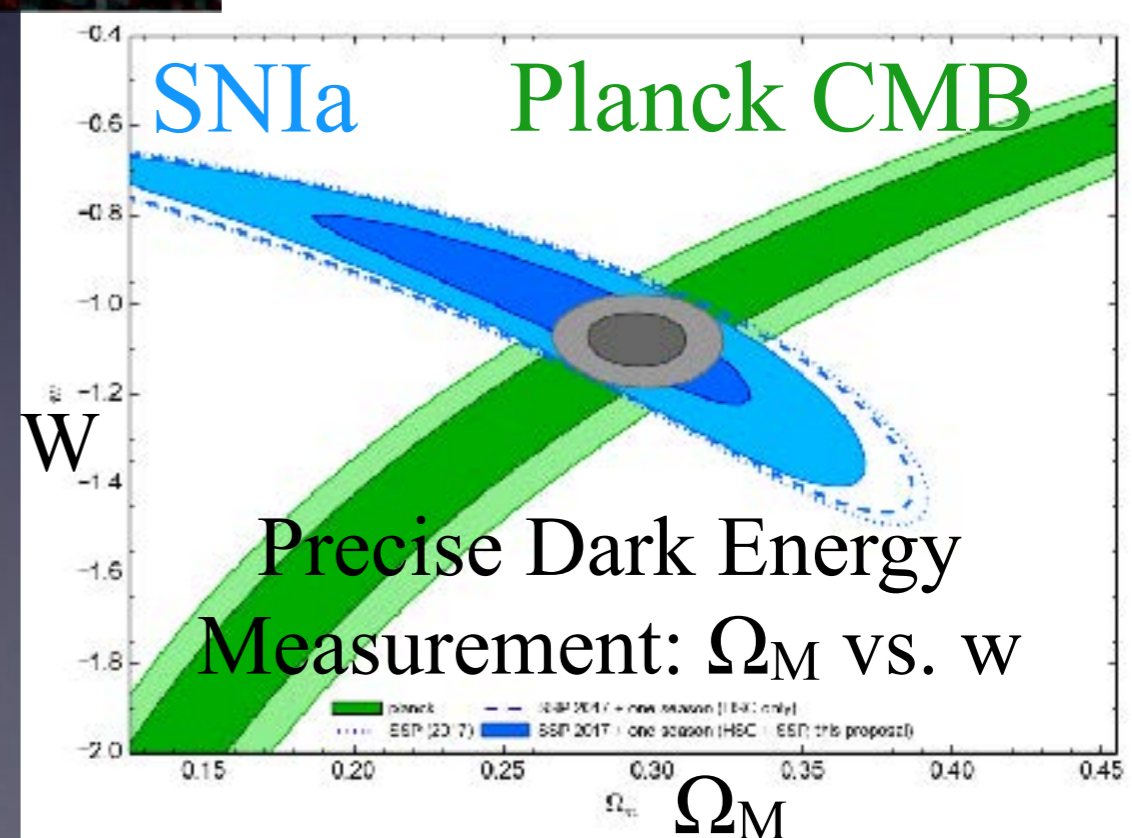
HSC Observation

HSC17aqzh

Visible Wavelength Image



Spectroscopic Follow-up by International Collaborators  
 Berkeley Lab (US), LPNHE (Paris), Barcelona (Spain),  
 Lancaster (UK), Australian National University







# Alvarez's Dream on Pyramids comes true in 2017



## Search for Hidden Chambers in the Pyramids

The structure of the Second Pyramid of Giza is determined by cosmic-ray absorption.

Luis W. Alvarez, Jared A. Anderson, F. El Bedwei, James Burkhard, Ahmed Fakhry, Adib Girgis, Amr Goneid, Fikhy Hassan, Dennis Iverson, Gerald Lynch, Zenab Miligy, Ali Hilmy Moussa, Mohammed-Sharkawi, Lauren Yazolino

Science, 167, 832 (Feb 1970)

## LETTER

doi:10.1038/nature24647

## Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons

Kunihiko Morishima<sup>1</sup>, Mitsuki Kuno<sup>1</sup>, Akira Nishio<sup>1</sup>, Nobuko Kitagawa<sup>1</sup>, Yuta Manabe<sup>1</sup>, Masaki Moto<sup>1</sup>, Fumihiko Takamaki<sup>2</sup>, Hirofumi Fujii<sup>2</sup>, Kotaro Sato<sup>2,3</sup>, Hidetoyo Kodama<sup>4</sup>, Kohei Hayashi<sup>5</sup>, Shigeru Odaka<sup>6</sup>, Sébastien Procureur<sup>7</sup>, David Assis<sup>8</sup>, Simon Houtelle<sup>9</sup>, Denis Calvet<sup>9</sup>, Christopher Alois<sup>10</sup>, Patrick Wagner<sup>10</sup>, Irakis Manjavvite<sup>11</sup>, Marc Kallio<sup>12</sup>, Benoit Marin<sup>13</sup>, Pierre Gable<sup>14</sup>, Yoshitaka Date<sup>15</sup>, Makiko Sugiyama<sup>16</sup>, Yasuhiro Ishiyama<sup>17</sup>, Tamer Elmaghrabi<sup>18</sup>, Mostapha Emry<sup>19</sup>, Emmanuel Guerrier<sup>20</sup>, Vincent Stetler<sup>21</sup>, Nicolas Serikoff<sup>22</sup>, Jean-Baptiste Moussé<sup>10,23,24</sup>, Bernard Charles<sup>25</sup>, Hany Helal<sup>26</sup> & Mehdi Tayoubi<sup>4,23</sup>

The Great Pyramid, or Khufu's Pyramid, was built on the Giza plateau in Egypt during the fourth dynasty by the pharaoh Khufu (Cheops)<sup>1</sup>, who reigned from 2599 to 2483 BC. Despite being one of the oldest and largest monuments on Earth, there is no consensus about how it was built<sup>2,3</sup>. To understand its internal structure better, we imaged the pyramid using muons, which are by-products of cosmic rays that are only partially absorbed by stone<sup>4-6</sup>. The resulting muon-ray image radiography allows us to visualize the known and any unknown voids in the pyramid in a non-invasive way. Here we report the discovery of a large void (with a cross-section similar to that of the Grand Gallery and a maximum length of 30 metres) situated above the Grand Gallery. This constitutes the first major inner structure found in the Great Pyramid since the nineteenth century<sup>7</sup>. The void, named ScarPyramid's Big Void, was first observed with nuclear emulsion films<sup>7-9</sup> installed in the Queen's

chamber, then confirmed with scintillator hodoscopes<sup>10,11</sup> set up in the same chamber and finally as confirmed with gas detectors<sup>12</sup> outside the pyramid. This large void has therefore been detected with high confidence by three different muon detection technologies and three independent analyses. These results constitute a breakthrough for the understanding of the internal structure of Khufu's Pyramid. Although there is currently no information about the intended purpose of this void, these findings show how modern particle physics can shed new light on the world's archaeological heritage. The pyramid of Khufu is 139 m high and 230 m wide<sup>1,13</sup>. There are three known chambers (Fig. 1), at different heights of the pyramid, which all lie in the north-south vertical plane<sup>14</sup>: the subterranean chamber, the Queen's chamber, and the King's chamber. These chambers are connected by several corridors; the most notable one being the Grand Gallery (8.6 m high × 46.7 m long × 2.1–1.0 m wide). The Queen's

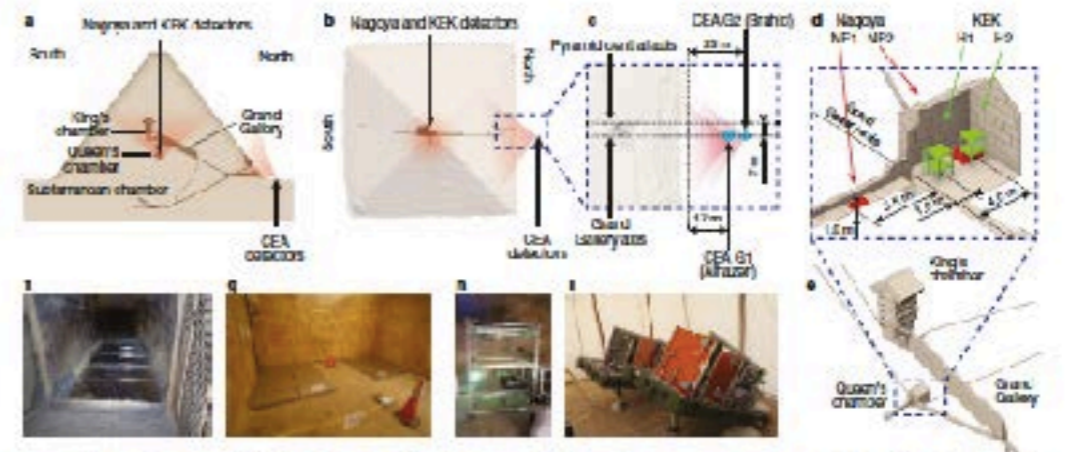


Figure 1 | Muon detectors installed for Khufu's Pyramid. a, Side view of the pyramid, with sensor positions and indicative field of view. b, Top view. c, Close view of the position of the gas detectors in the Queen's chamber (CEA). d, Orthographic view of Queen's chamber with nuclear emulsion films (Nagoya University red positions N11 and N12) and scintillator hodoscopes (KEK, green positions H1 and H2). e, Orthographic view of the main known internal structures. f, Nuclear emulsion plates in position N11 (Nagoya University). g, Nuclear emulsion plates in position N12 (Nagoya University). h, Scintillator hodoscope setup for position H1 (KEK). i, Gas detector (beam telescope, CFA).

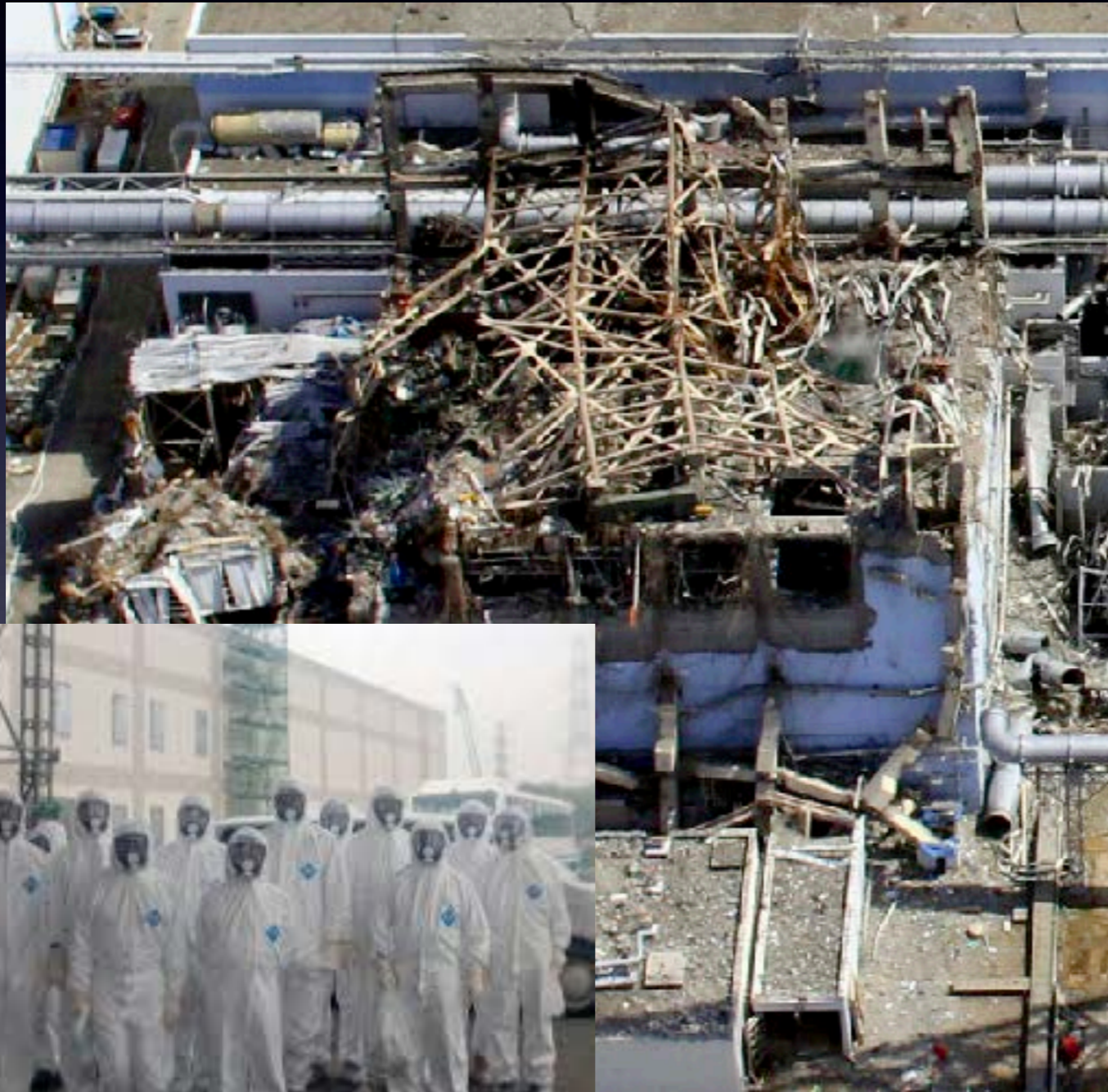
<sup>1</sup>Y. Ishi, Nagoya University, Gokiso Chikusa-ku, Nagoya, Aichi 464-8602, Japan; <sup>2</sup>High Energy Accelerator Research Organization (KEK), 1-1, Honcho, Tsukuba, Ibaraki 305-0801, Japan; <sup>3</sup>Unité de Recherche sur les Sites Préhistoriques de l'Unesco (URSP), Commissariat à l'Énergie Atomique et aux Énergies Alternatives (CEA), Université Paris-Saclay, 91191 Gif-sur-Yvette, France; <sup>4</sup>KEP Institute, 10 rue de l'Étoile, 92082 Paris, France; <sup>5</sup>Research Center for Cosmic Rays, 7-3 rue de Valenciennes, 75009 Paris, France; <sup>6</sup>RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0192, Japan; <sup>7</sup>Centre National de la Recherche Scientifique, 100 rue de la Vierge, 91191 Gif-sur-Yvette, France; <sup>8</sup>Universidade Federal do Rio de Janeiro, Caixa Postal 687, 21941-900 Rio de Janeiro, Brazil; <sup>9</sup>CEA Saclay, 91191 Gif-sur-Yvette, France; <sup>10</sup>CEA Saclay, 91191 Gif-sur-Yvette, France; <sup>11</sup>University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland; <sup>12</sup>University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland; <sup>13</sup>University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland; <sup>14</sup>University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland; <sup>15</sup>University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland; <sup>16</sup>University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland; <sup>17</sup>University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland; <sup>18</sup>University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland; <sup>19</sup>University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland; <sup>20</sup>University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland; <sup>21</sup>University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland; <sup>22</sup>University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland; <sup>23</sup>University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland; <sup>24</sup>University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland; <sup>25</sup>University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland; <sup>26</sup>University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland.



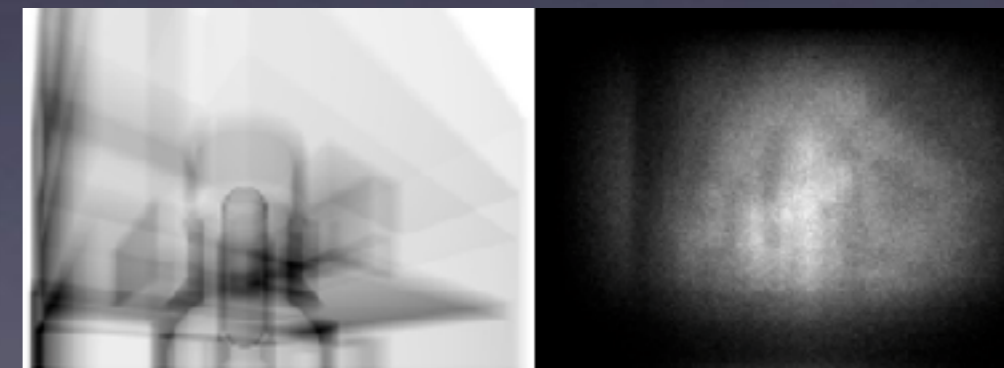
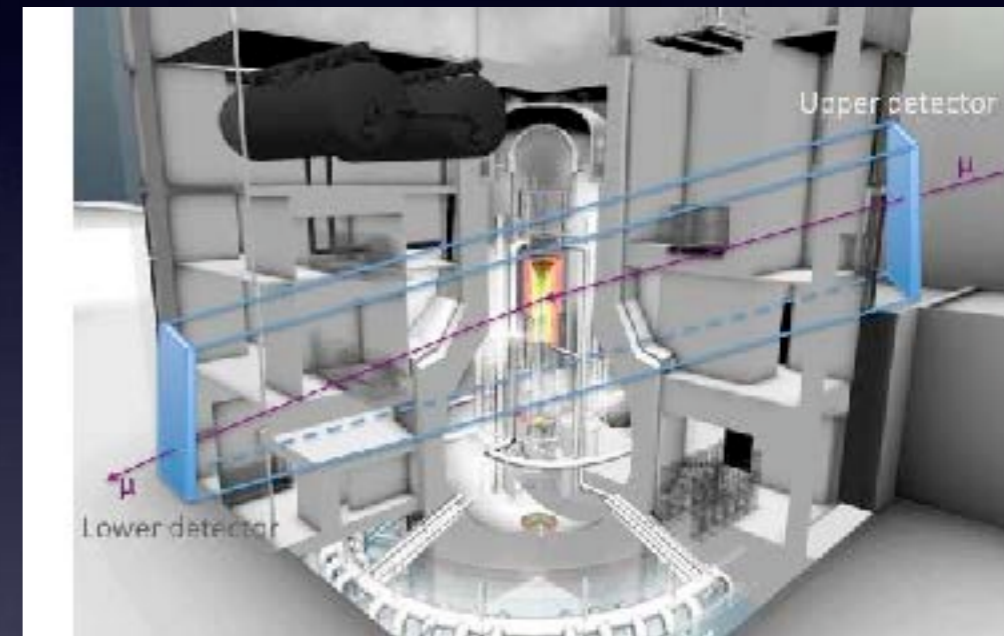
# Detected!!! Nature Nov 2017

# Alvarez's idea is applied to Fukushima Nuclear Power Plant Disaster (2011)

Probe the status of Nuclear Fuels inside the system



LBNL Team Members



Toshiba Press Release

# Future Prospects

## Big Data grows Bigger Quickly

TMT 30m



JWST Space Telescope  
2021



LSST

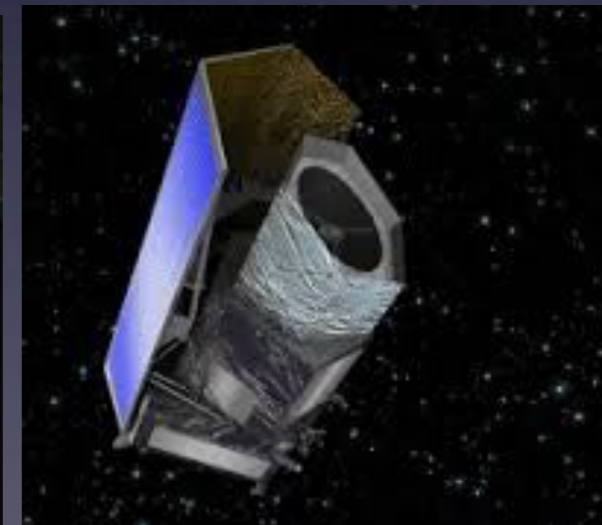


20TB/Day

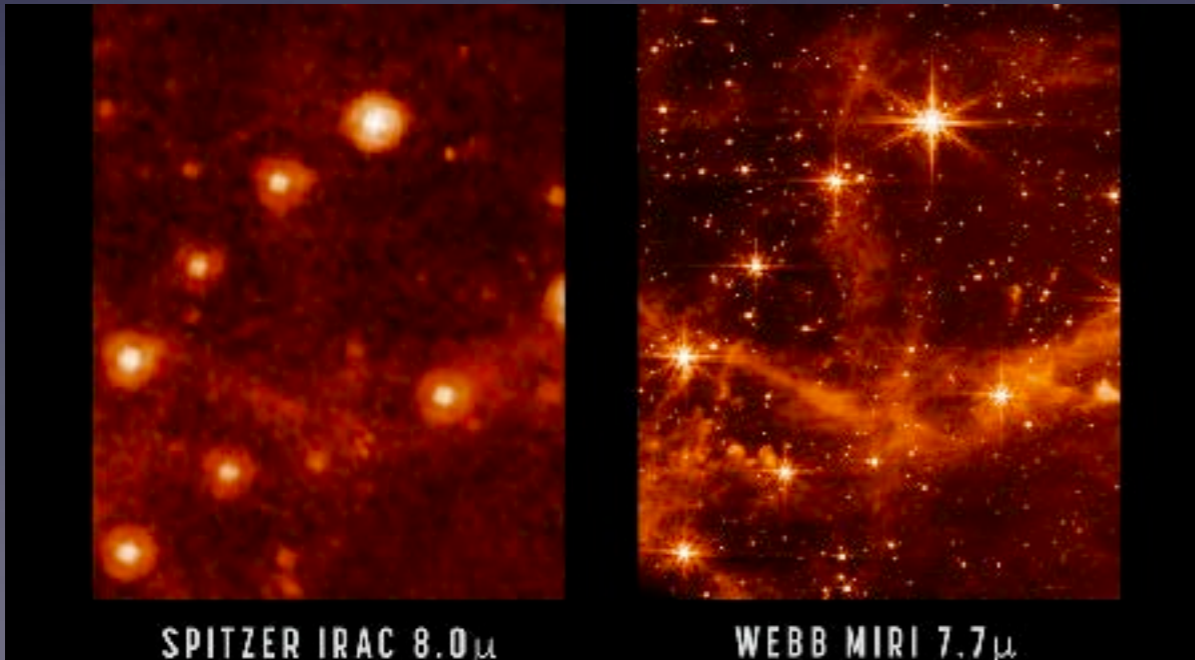
WFIRST/Roman 2027



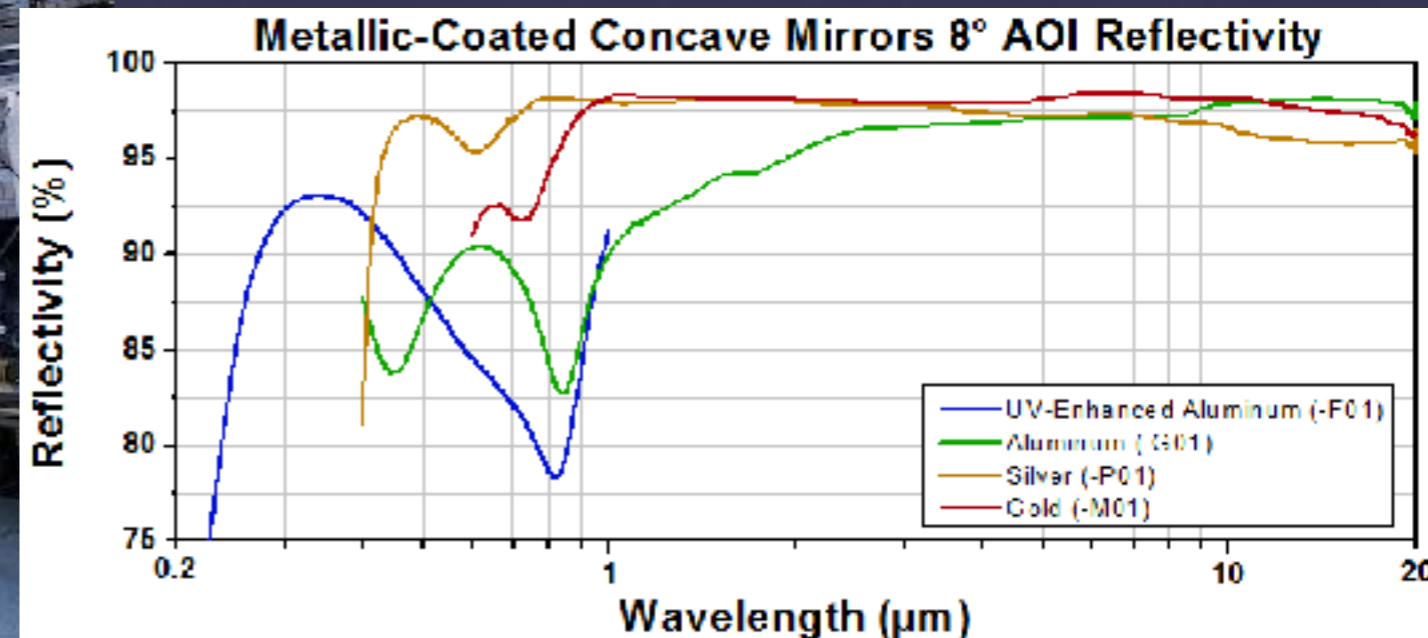
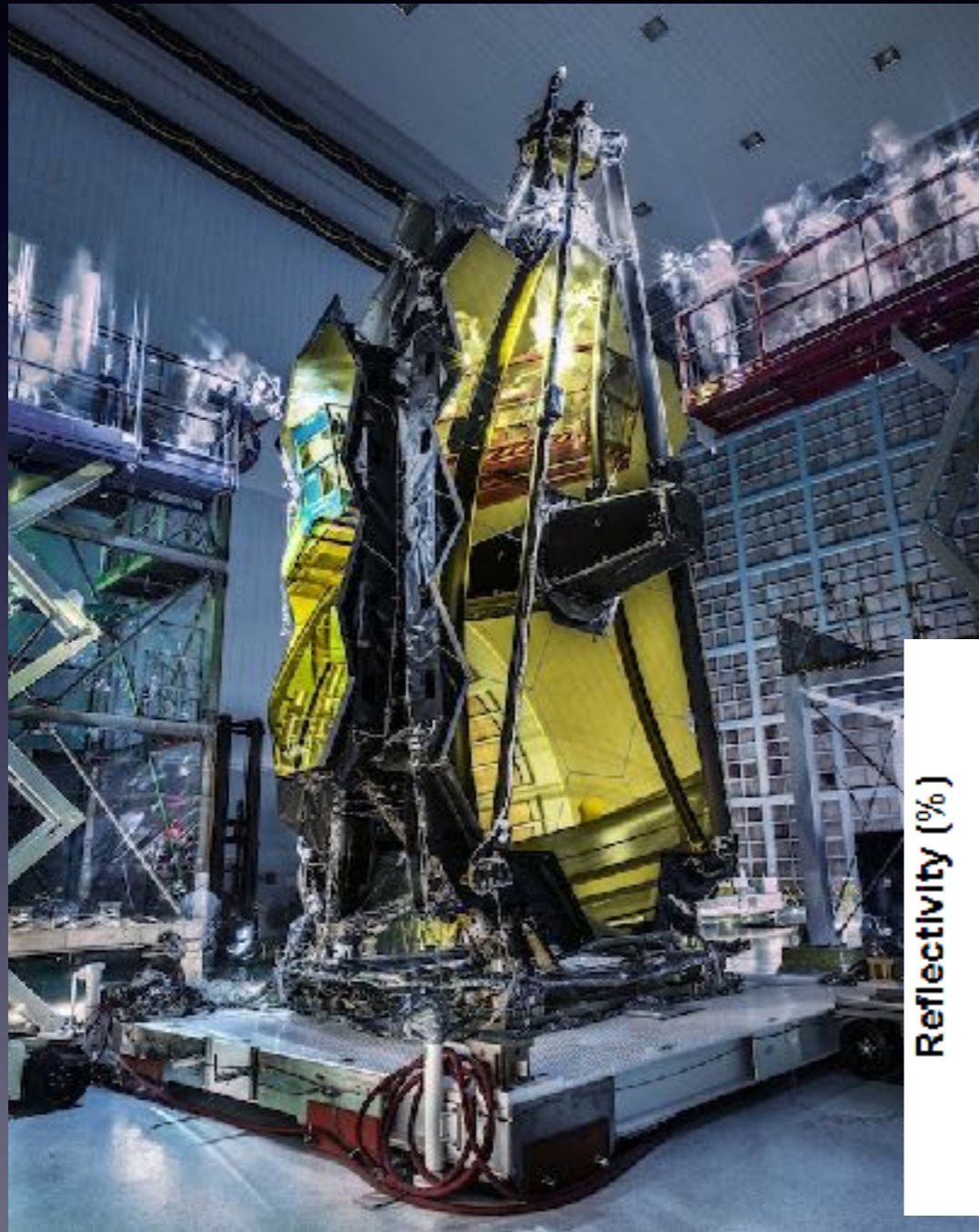
Euclid 2023



# JWST Press Release July 12th!



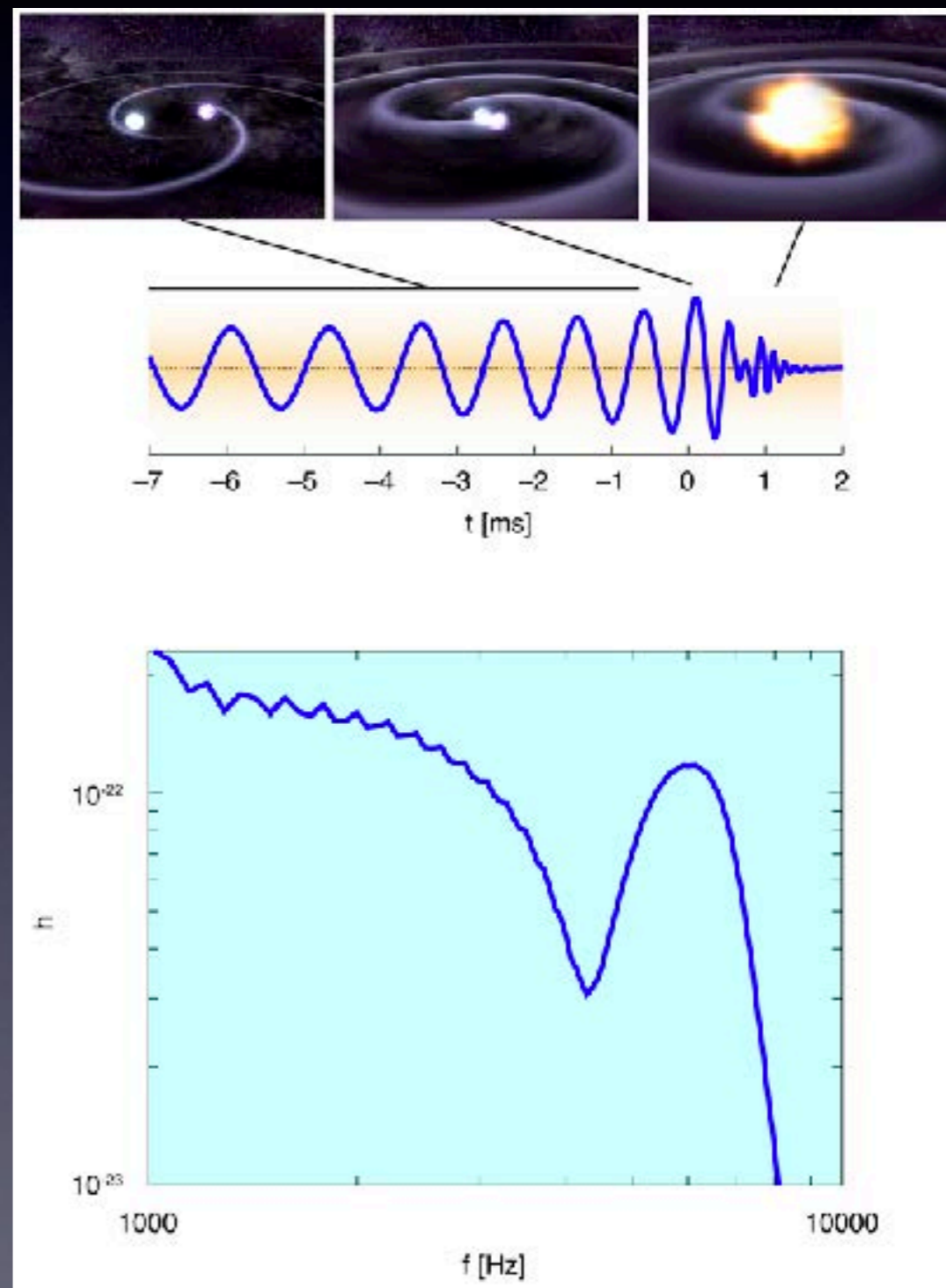
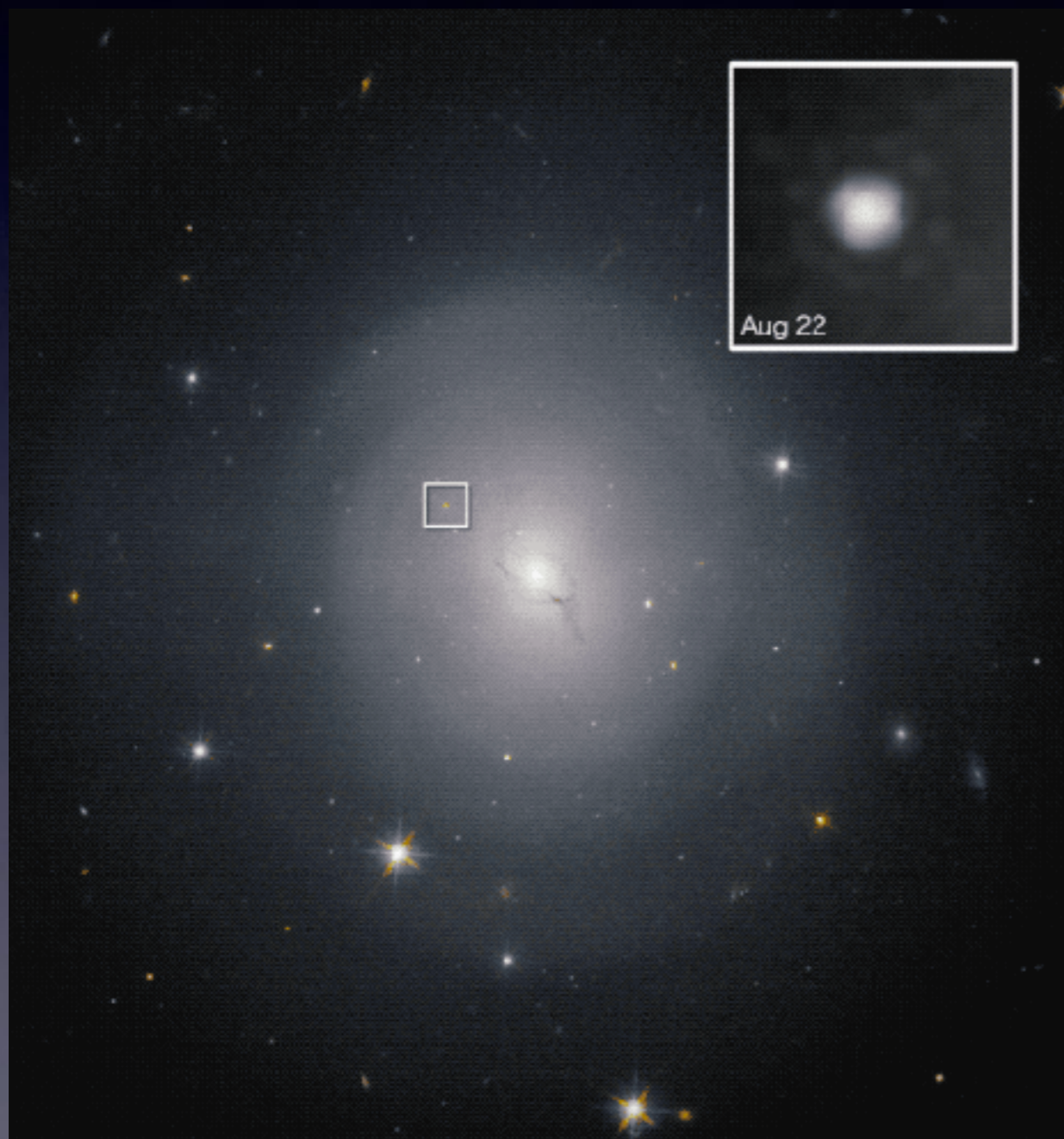
# Gold Primary Mirror

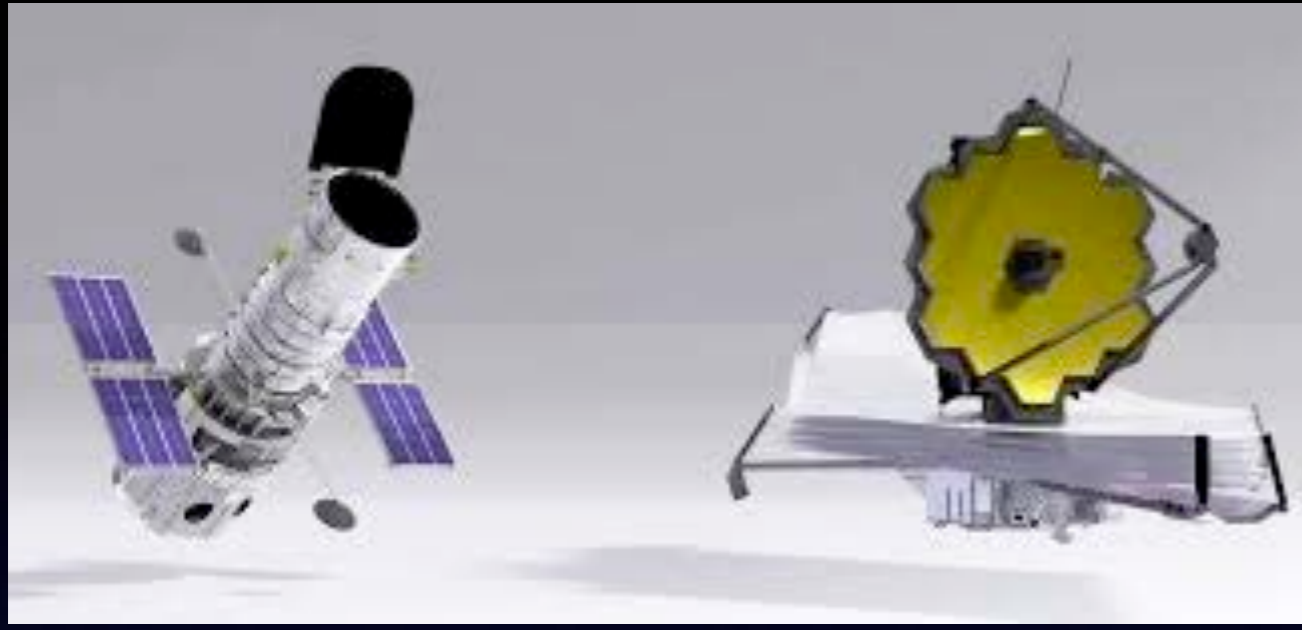


Gold : 48.25g, 1000 Angstrom thick



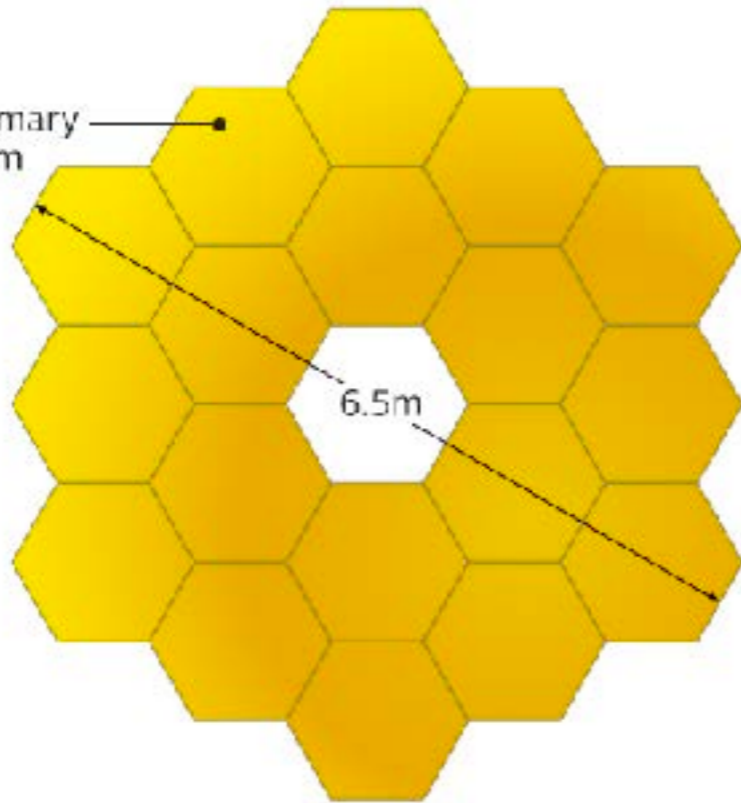
# Gold is made in “Neutron Star Merger” (GW170817) Gravitational Wave Detection





## James Webb Space Telescope primary mirror is 6.5 metres wide

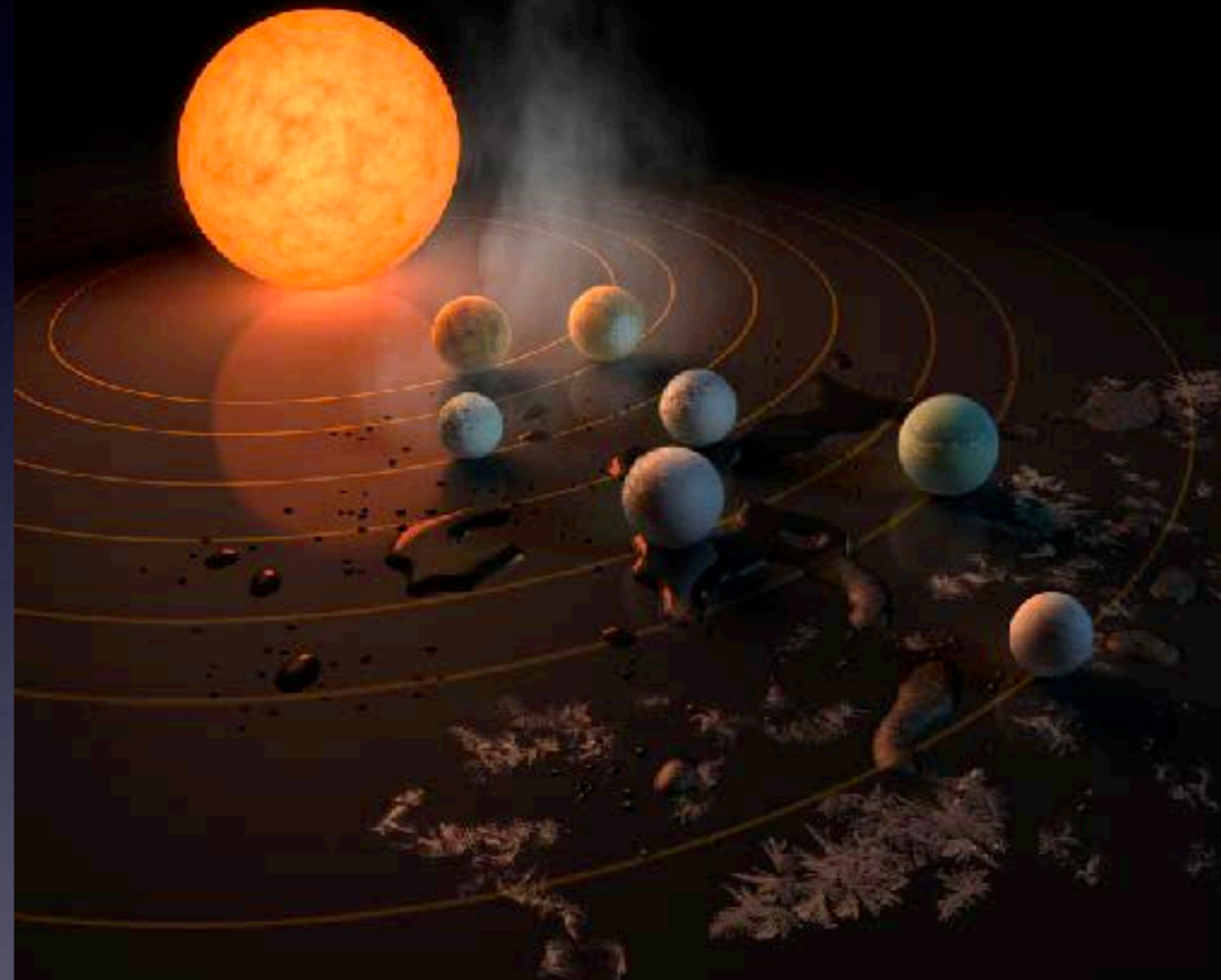
The mirrors making up the primary mirror are made from beryllium and coated with 48.25g gold



Hubble primary mirror

Source: Nasa

BBC



# Great Discoveries are waiting for you!



Primordial Blackhole

Habitable Planets



Galactic Supernova







In other words: We mortal, limited humans joining together in teams from around the world, and in time across civilizations, become *capable* – in our case, capable of just glimpsing one additional bit of how the universe works. It is exhilarating,

But it is in the doing, in the process of working together to explore the universe that we learn to truly appreciate each other, and to enjoy each other's company and ... spark, as all humans should be appreciated. – And that, too, is exhilarating.

