

UNVEILING THE UNIVERSE WITH GRAVITATIONAL-WAVE OBSERVATIONS

Department of Physics, IIT Madras Chennai, March 9, 2022

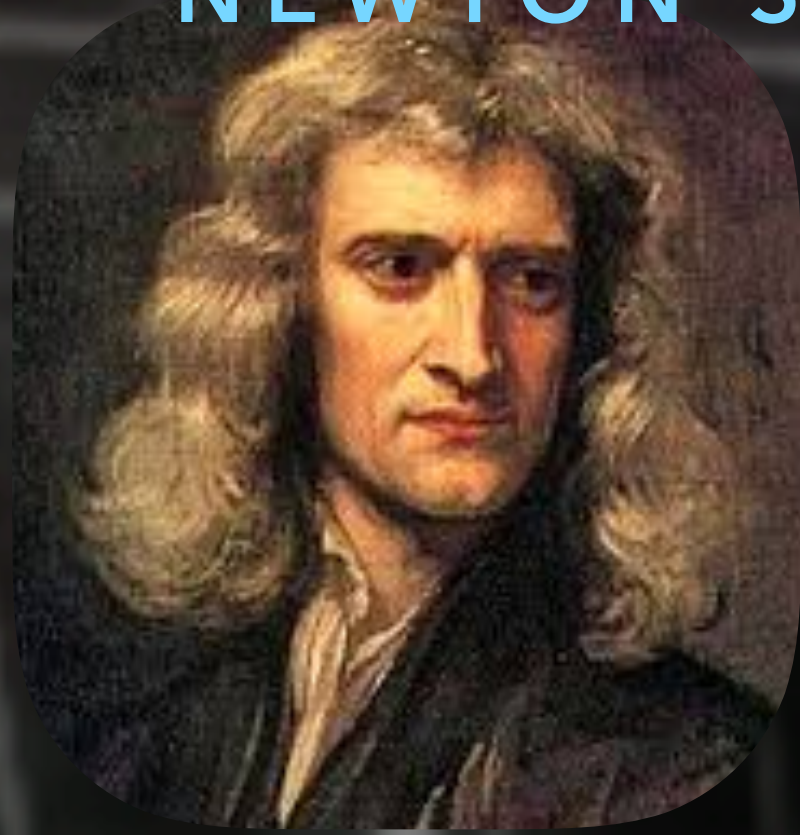
B.S. SATHYAPRAKASH

Penn State University, USA and Cardiff University, UK



NEWTON'S IDEAS OF SPACE AND TIME

... Sir Issac Newton, *Principia*



Absolute space, in its own nature, without relation to anything external

Absolute ... time, in and of itself and of its own nature, without reference to anything external, flows uniformly



3

NEWTON THOUGHT MATTER DOES NOT AFFECT THE GEOMETRY OF
SPACE OR FLOW OF TIME





EINSTEIN'S SPECIAL RELATIVITY

speed of light is same for all in relative motion

Consequences

- $E = mc^2$
- twin-paradox
- nothing can travel faster than light





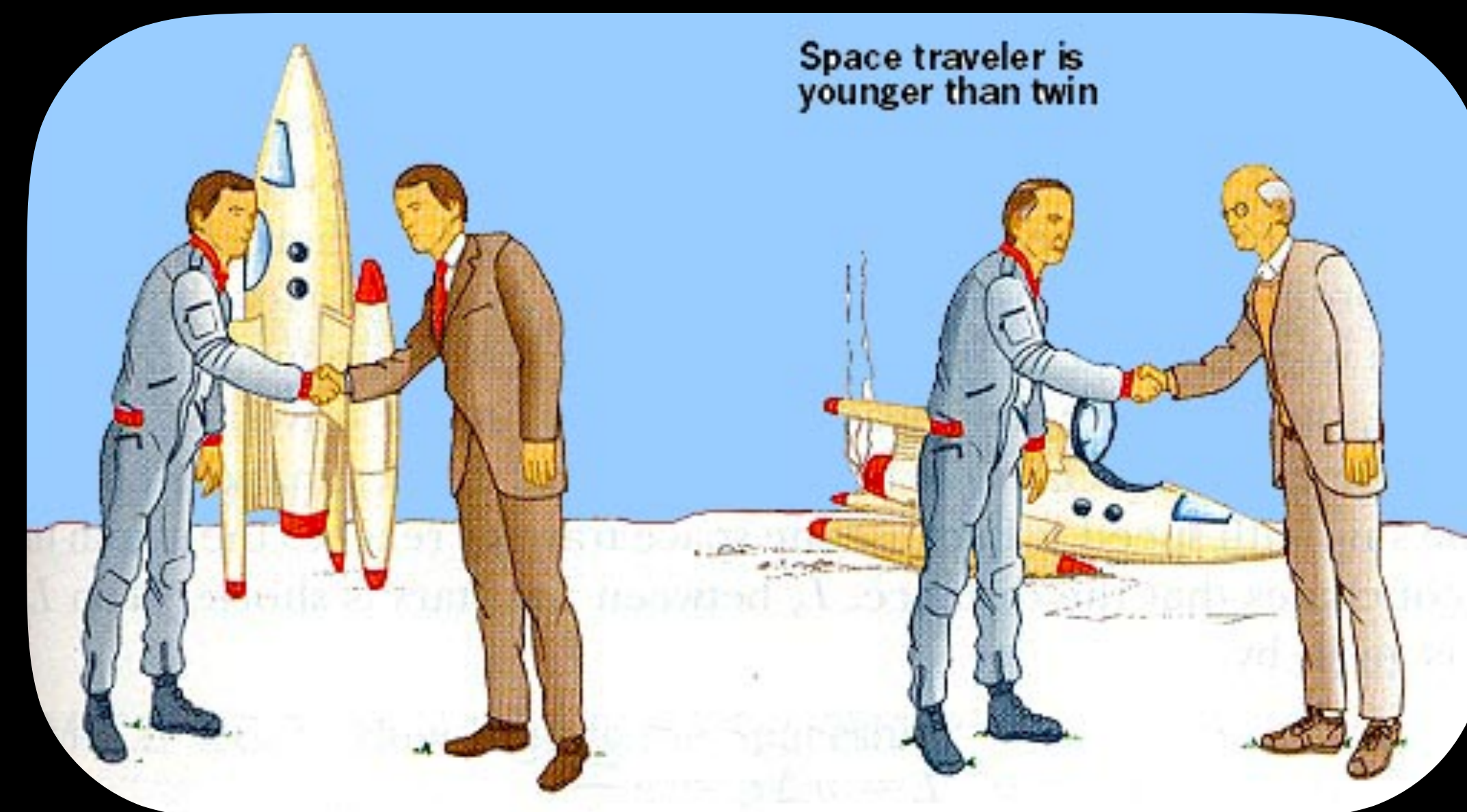
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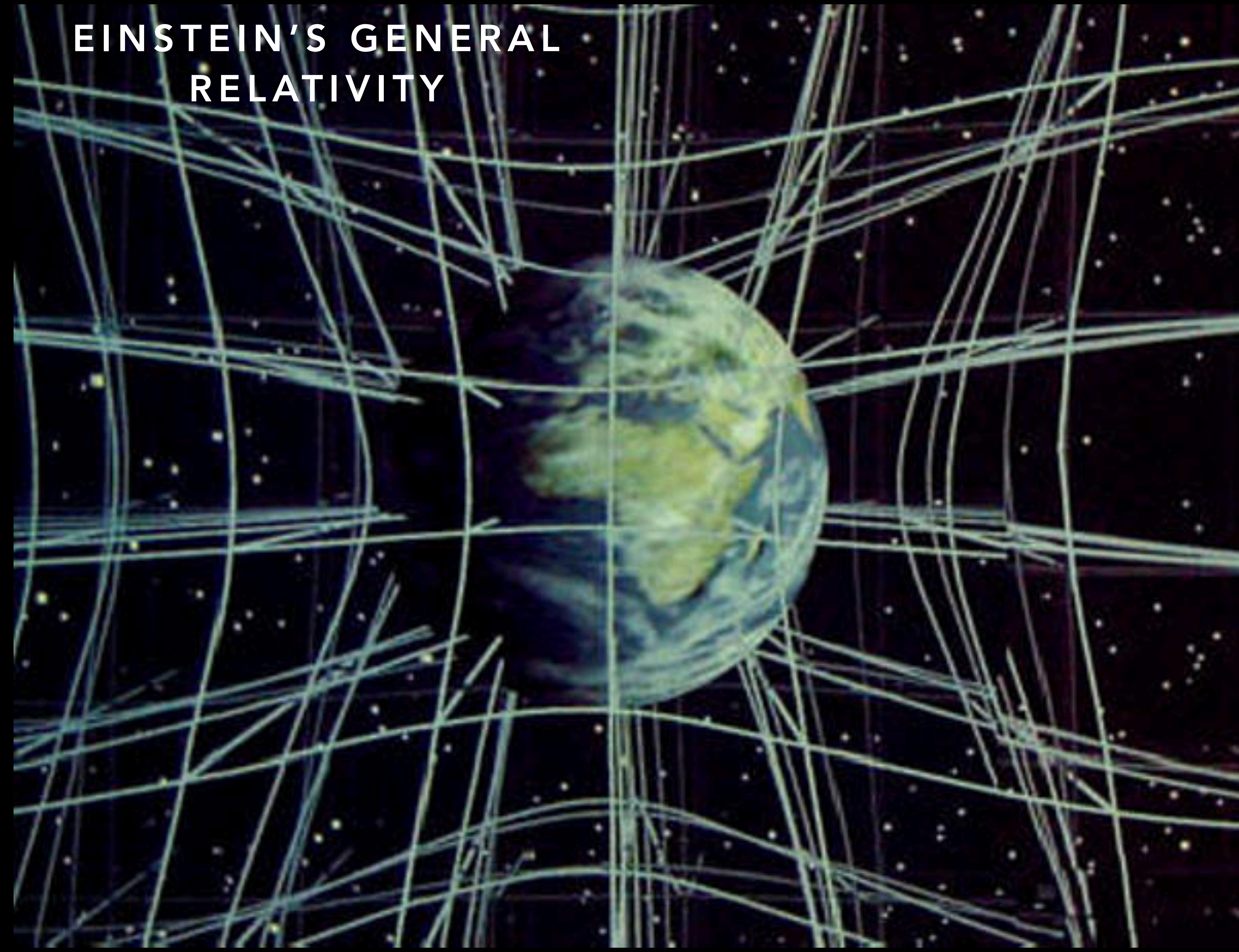
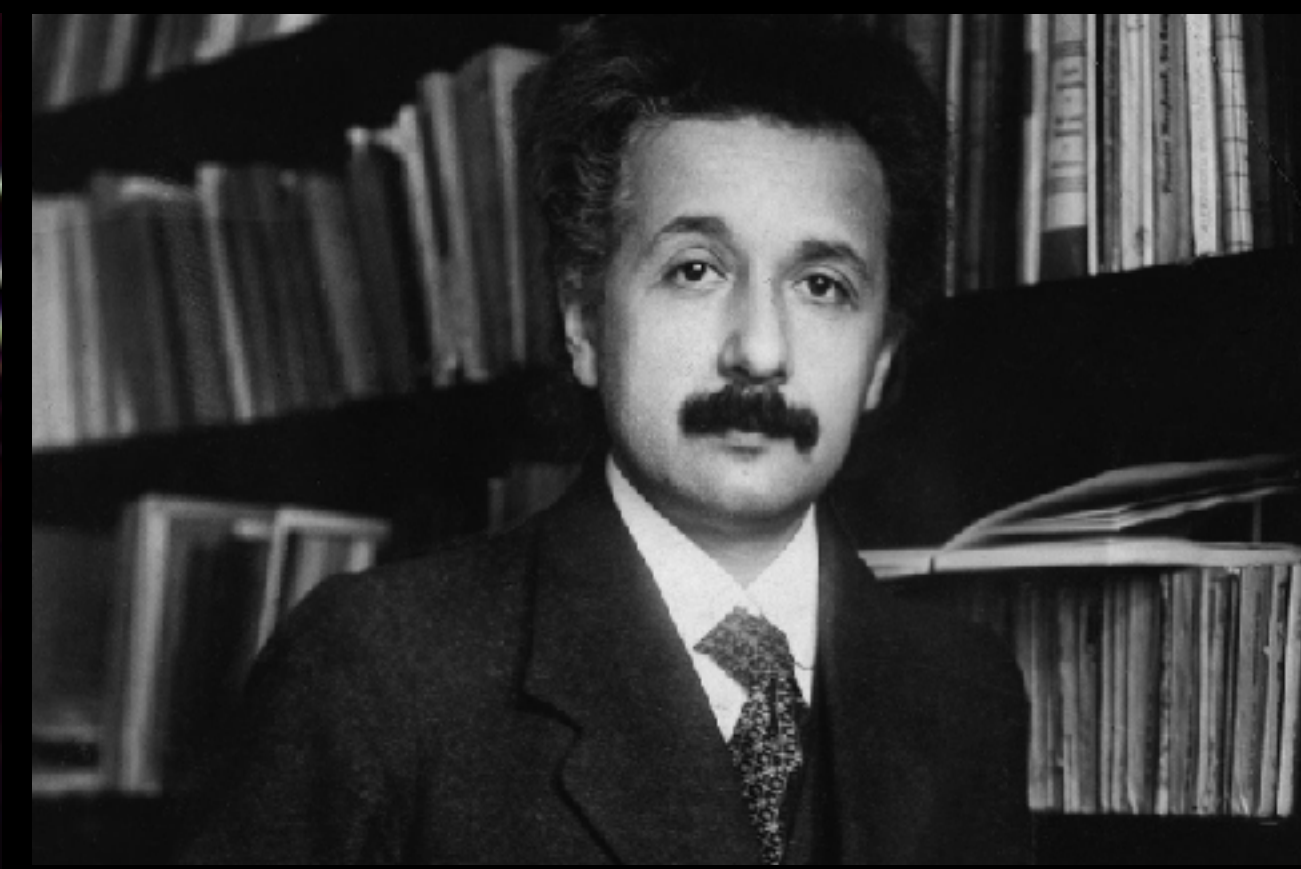
PRECESSION OF PERIHELION OF MERCURY

- Mercury's perihelion shifts forward with each pass:
- Newtonian gravity predicted 532 arc-sec/century
- observed 575 arc-sec/century, a discrepancy of 43 arc-sec/century

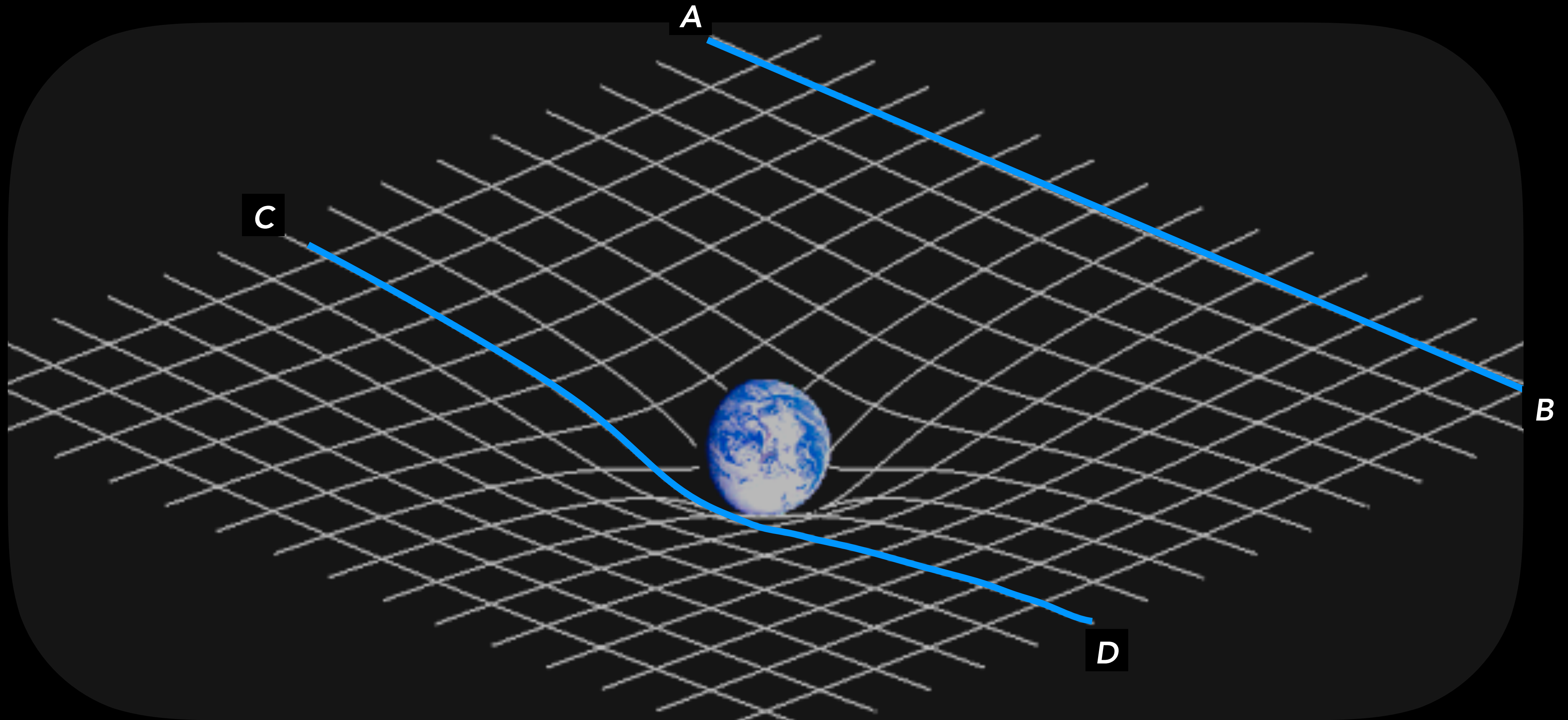
(1 arc-sec = $1/3600$ degree).



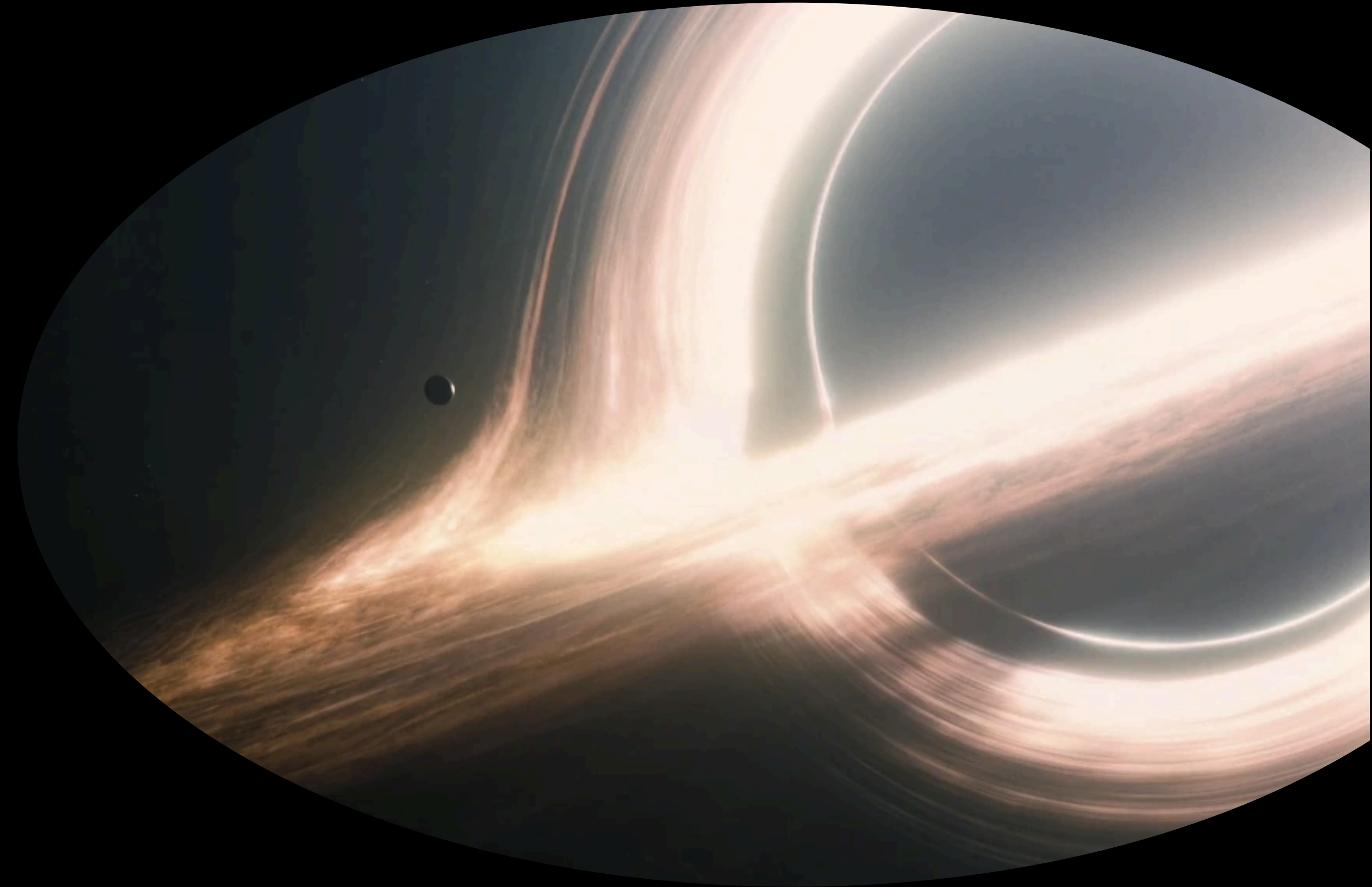
EINSTEIN'S GENERAL RELATIVITY



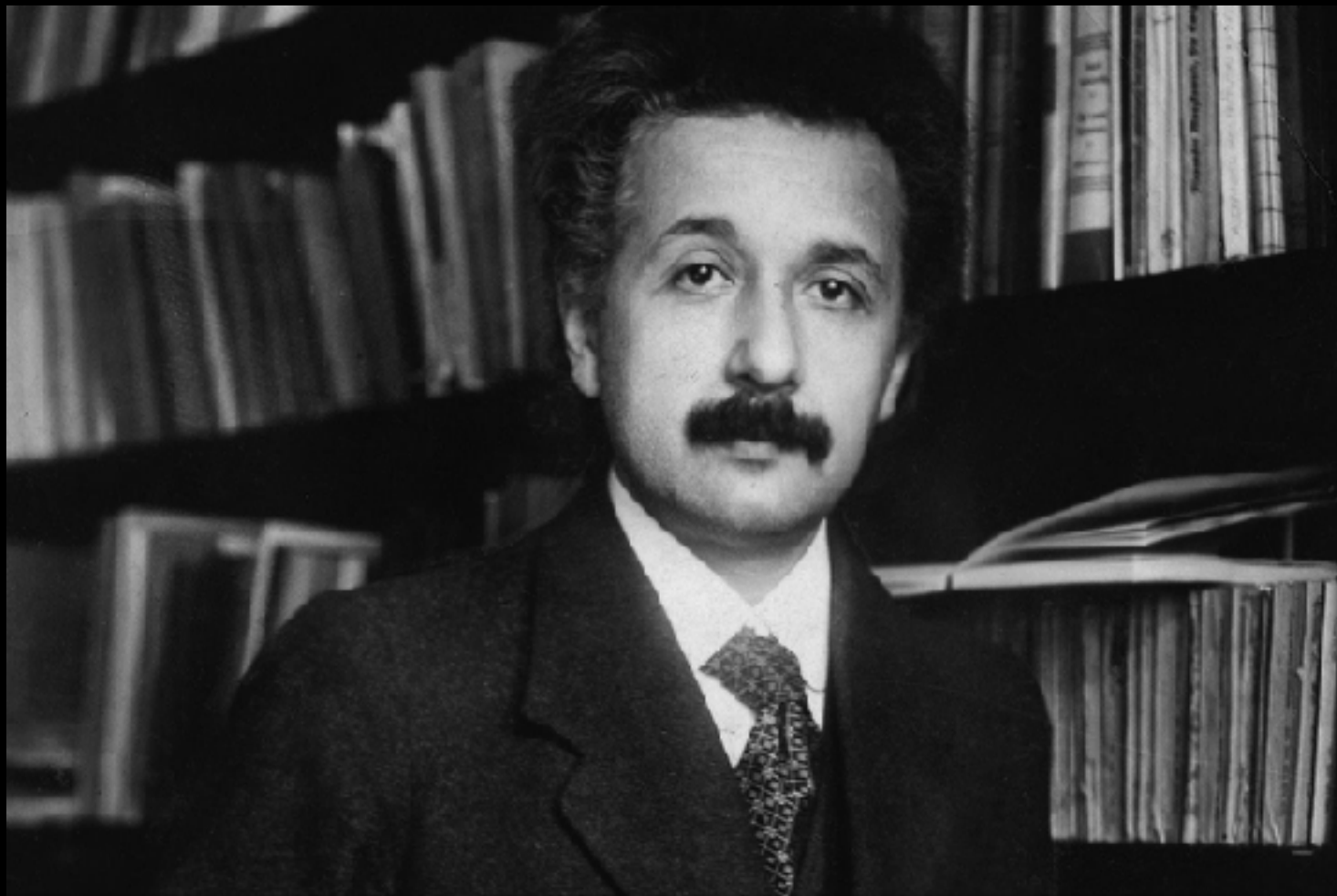
ACCORDING TO EINSTEIN, GRAVITY CURVES SPACE AND ...



... SLOWS TIME

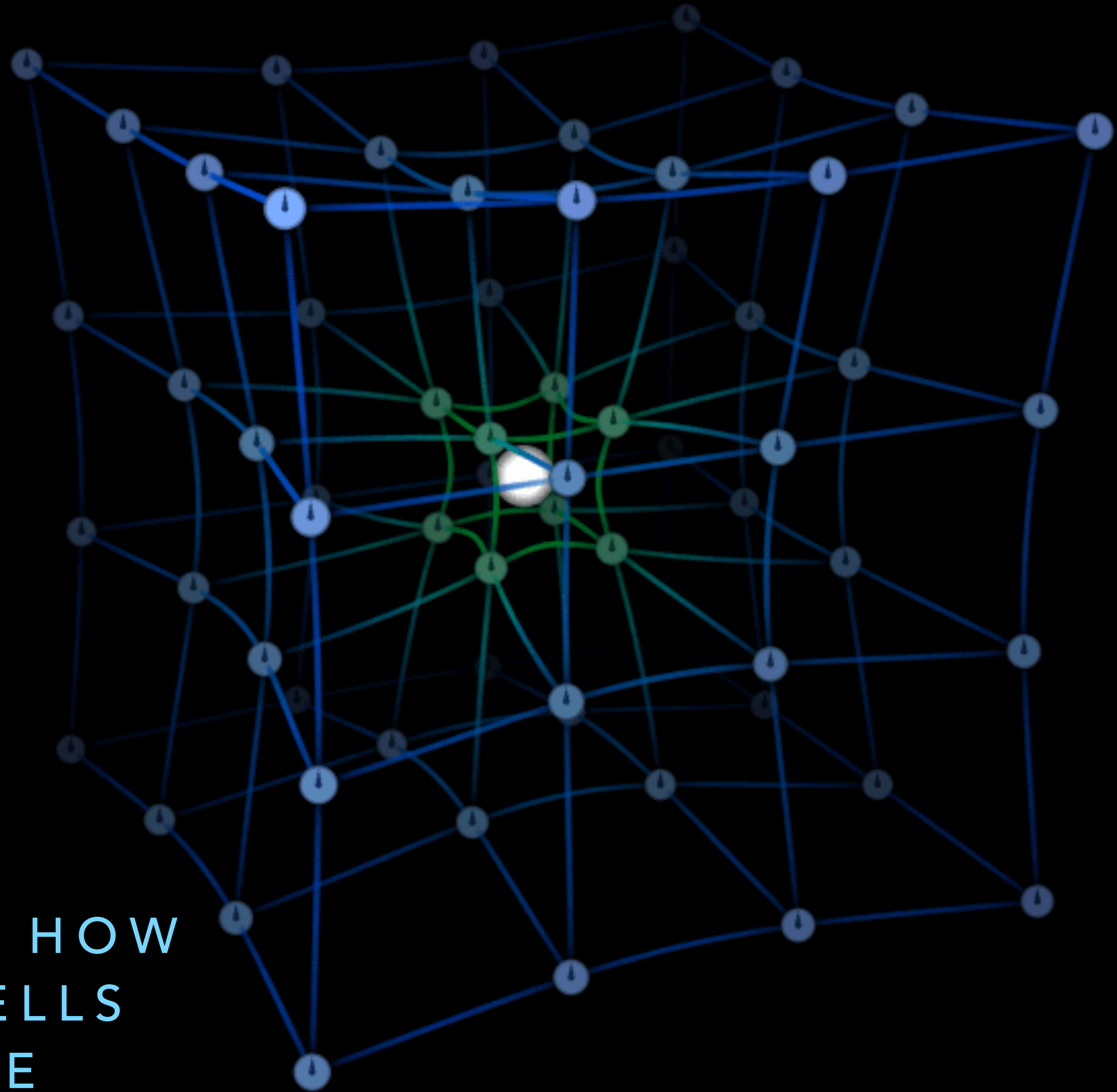


$$G_{\alpha\beta} = \frac{8\pi G}{c^4} T_{\alpha\beta}$$

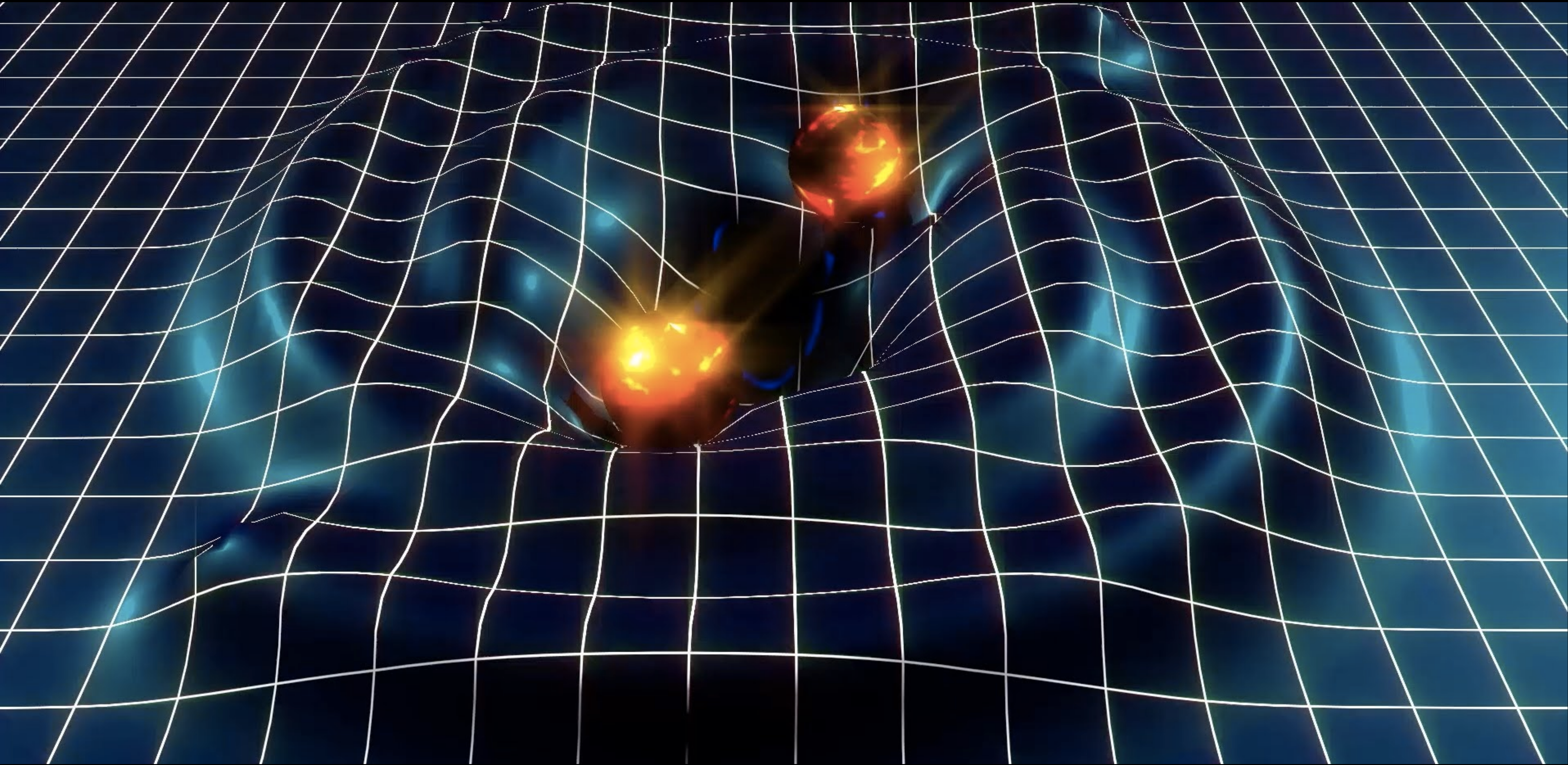


MATTER TELLS SPACETIME HOW
TO CURVE SPACETIME TELLS
MATTER HOW TO MOVE

John Wheeler



IN EINSTEIN'S GRAVITY SPACETIME CAN BEND, VIBRATE;
RIPPLES TRAVEL OUT AT THE SPEED OF LIGHT



SO, WHAT CAN BEND SPACETIME?

- ❖ In Einstein equations

$$G_{\alpha\beta} = \frac{8\pi G}{c^4} T_{\alpha\beta}$$

- ❖ the coupling constant has dimensions of force

$$G_F = c^4/G \sim 10^{44} \text{ N}$$

- ❖ Under what circumstance can such a force be felt?
Consider force on an orbiting body:

$$F = \frac{mv^2}{r} \quad \frac{m}{r} = \frac{v^2}{G} \quad F = \frac{v^4}{G} = \frac{c^4}{G} \left(\frac{v}{c}\right)^4$$

- ❖ Black holes in a binary can experience G_F

SO, HOW STIFF IS SPACETIME?

- a plane gravitational wave is given by:

$$h_{ij} \propto A_{ij} \exp(i\omega t) \Rightarrow \ddot{h}_{ij} \sim \omega^2 h_{ij}$$

- now, Einstein equations $G_{ij} = \frac{8\pi G}{c^4} T_{ij}$ for gravitational waves become:

$$G_{ij} \sim \ddot{h}_{ij} \sim \omega^2 h_{ij} = \frac{8\pi G}{c^4} T_{ij} \quad \frac{\text{Stress}}{\text{Strain}} \sim \frac{|T_{ij}|}{|h_{ij}|} = \frac{c^4 \omega^2}{8\pi G}$$

- for 1 kHz waves the Young's modulus of spacetime is 10^{24} Gpa

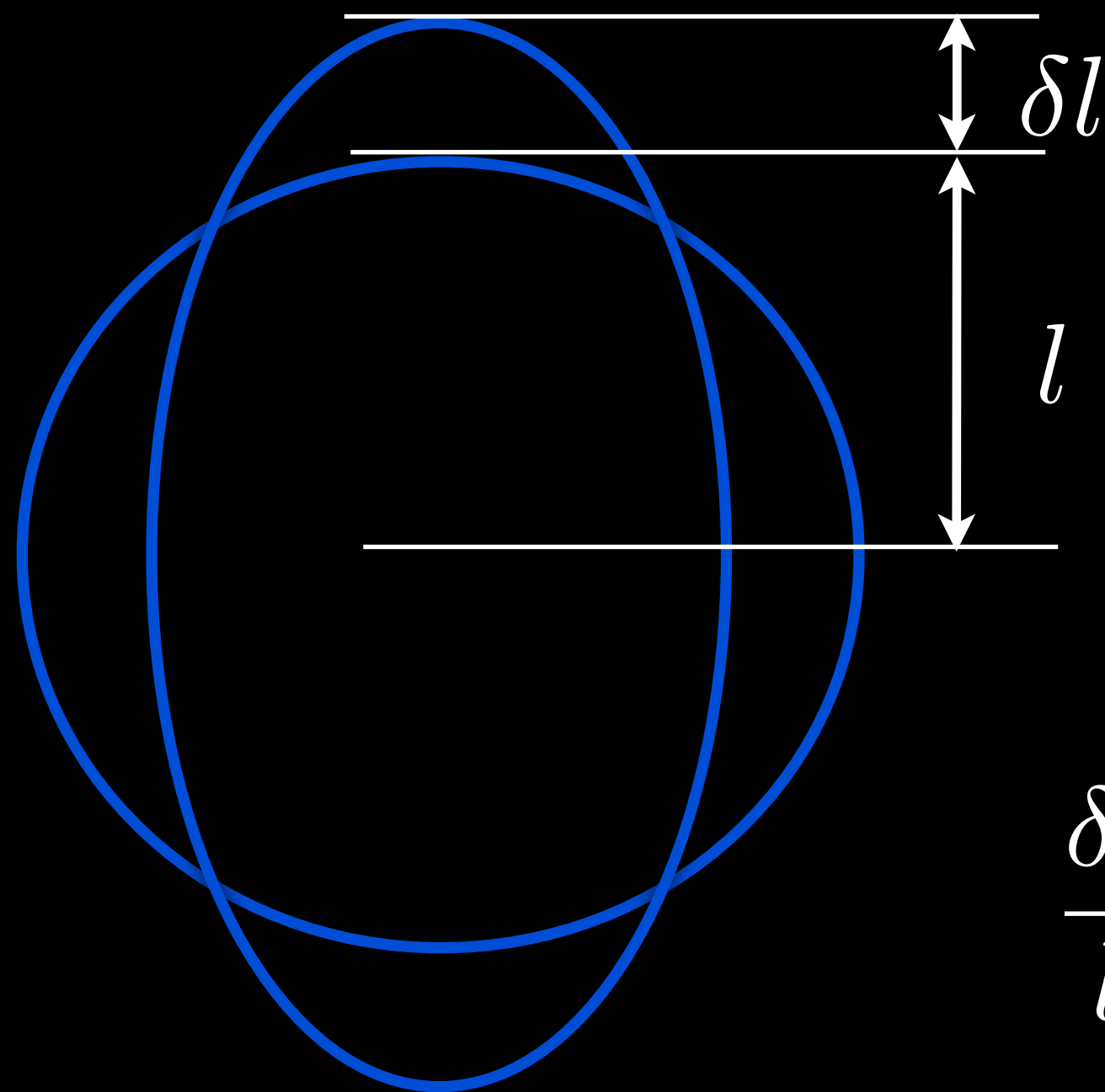
SPACETIME IS VERY RIGID

Wave Medium	Elastic Modulus (Gpa)
Rubber	0.1
Wood	10
Steel	200
Diamond	1200
Spacetime	10^{24}

Only catastrophic astronomical events can cause spacetime ripples of detectable magnitude

GRAVITATIONAL WAVE AMPLITUDE

- ❖ gravitational waves cause strain in space as they pass
- ❖ measurement of the strain gives the amplitude of gravitational waves



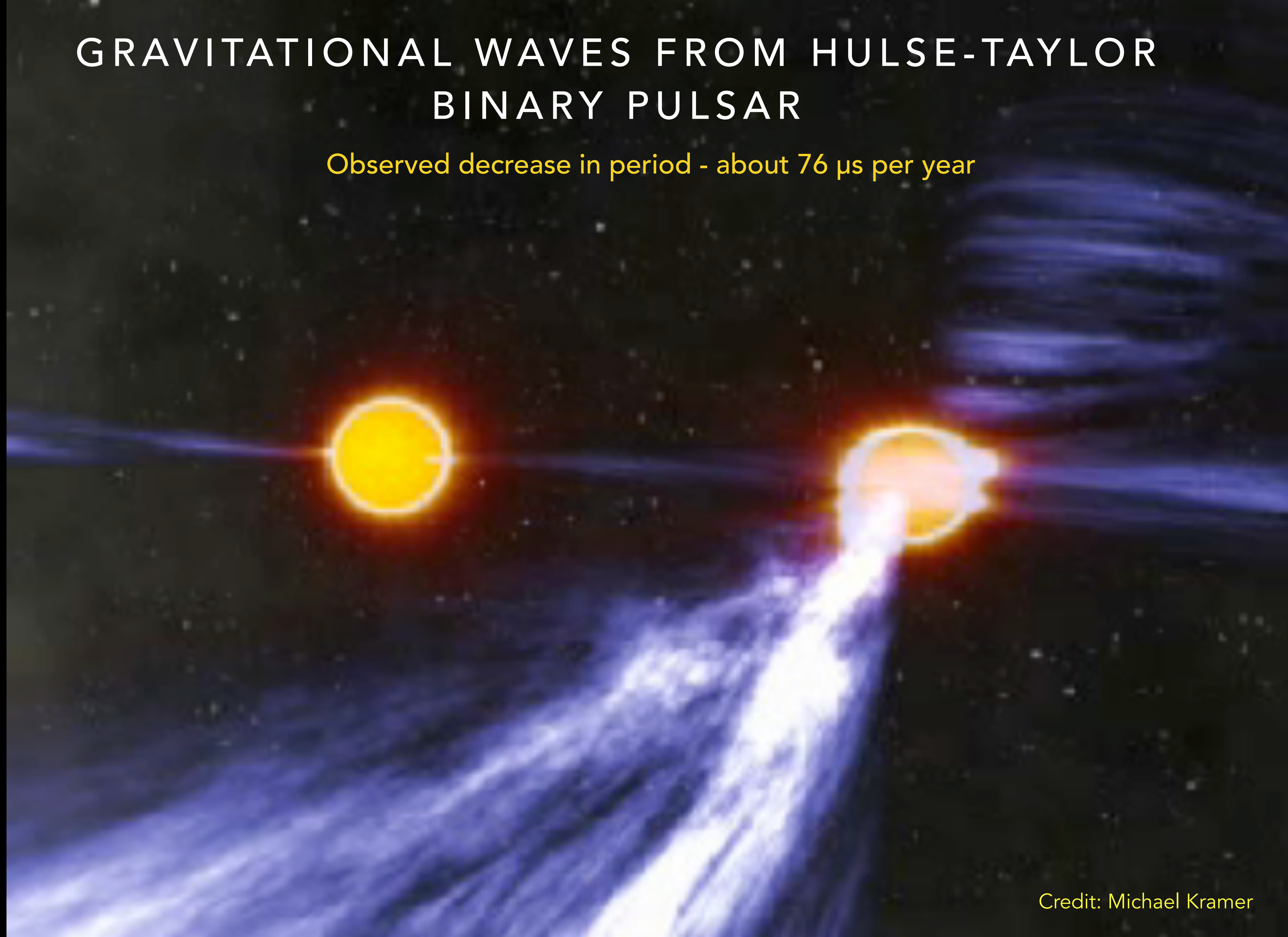
- ❖ amplitude of a pair of colliding black holes at 1.3 billion light years

$$\frac{\delta l}{l} = h \sim 10^{-21}; \quad \delta l \sim 10^{-18} \left(\frac{l}{\text{km}} \right)$$



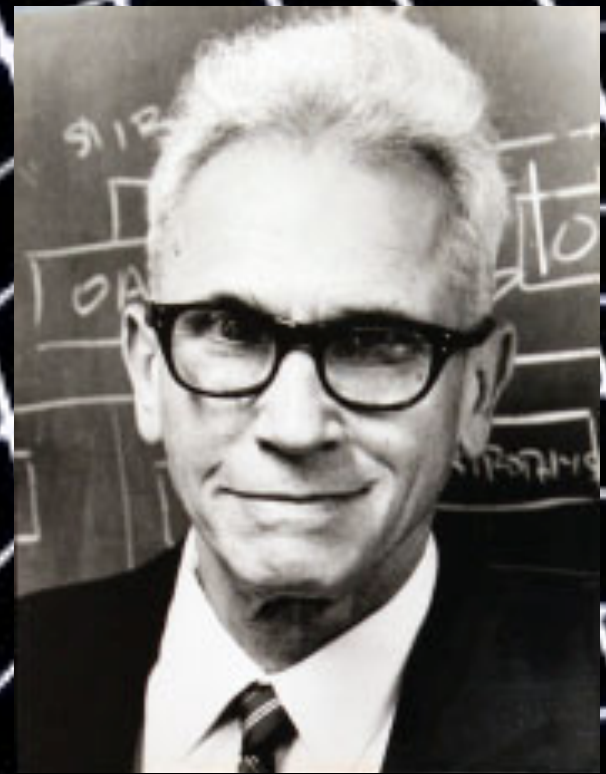
GRAVITATIONAL WAVES FROM HULSE-TAYLOR BINARY PULSAR

Observed decrease in period - about $76 \mu\text{s}$ per year



Credit: Michael Kramer

GRAVITATIONAL WAVES STRETCH AND
SQUEEZE SPACETIME; THEY ALTER
THE RATE AT WHICH CLOCKS TICK



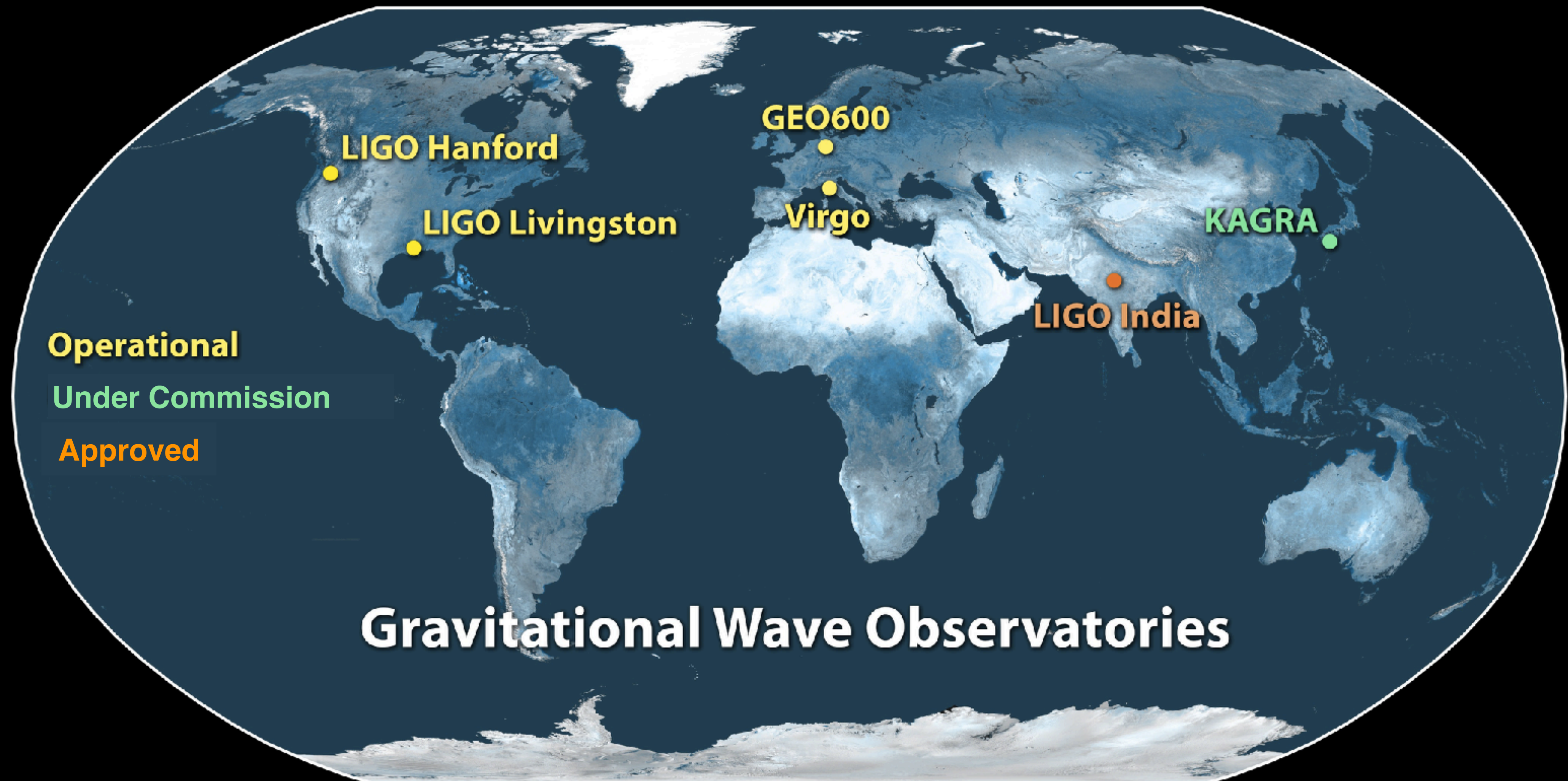
Jo Weber

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LASER INTERFEROMETER GRAVITATIONAL WAVE DETECTORS



LIGO-LIVINGSTON OBSERVATORY



Credit: LIGO Livingston

LIGO-HANFORD OBSERVATORY

Credit: LIGO Hanford



VIRGO AT CASCINA, ITALY

Credit: Virgo



KAGRA - KAMIOKA OBSERVATORY



LIGO INDIA



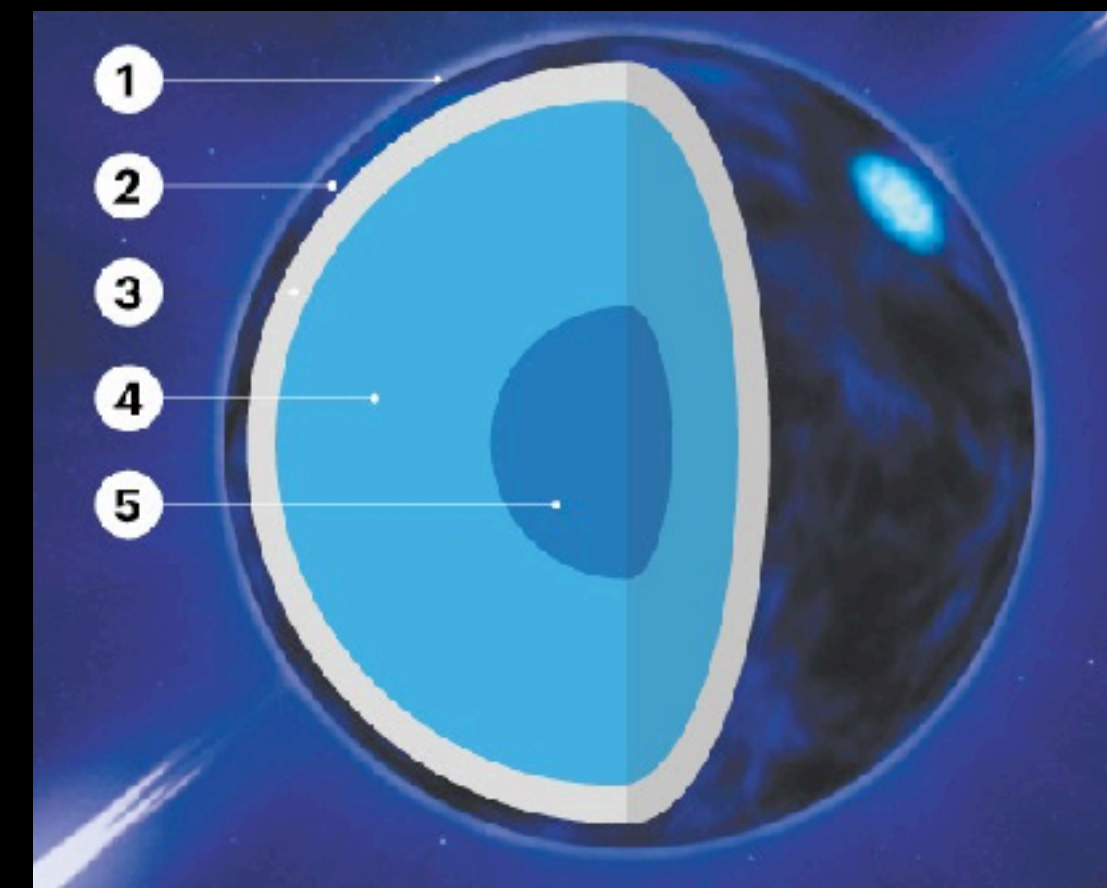
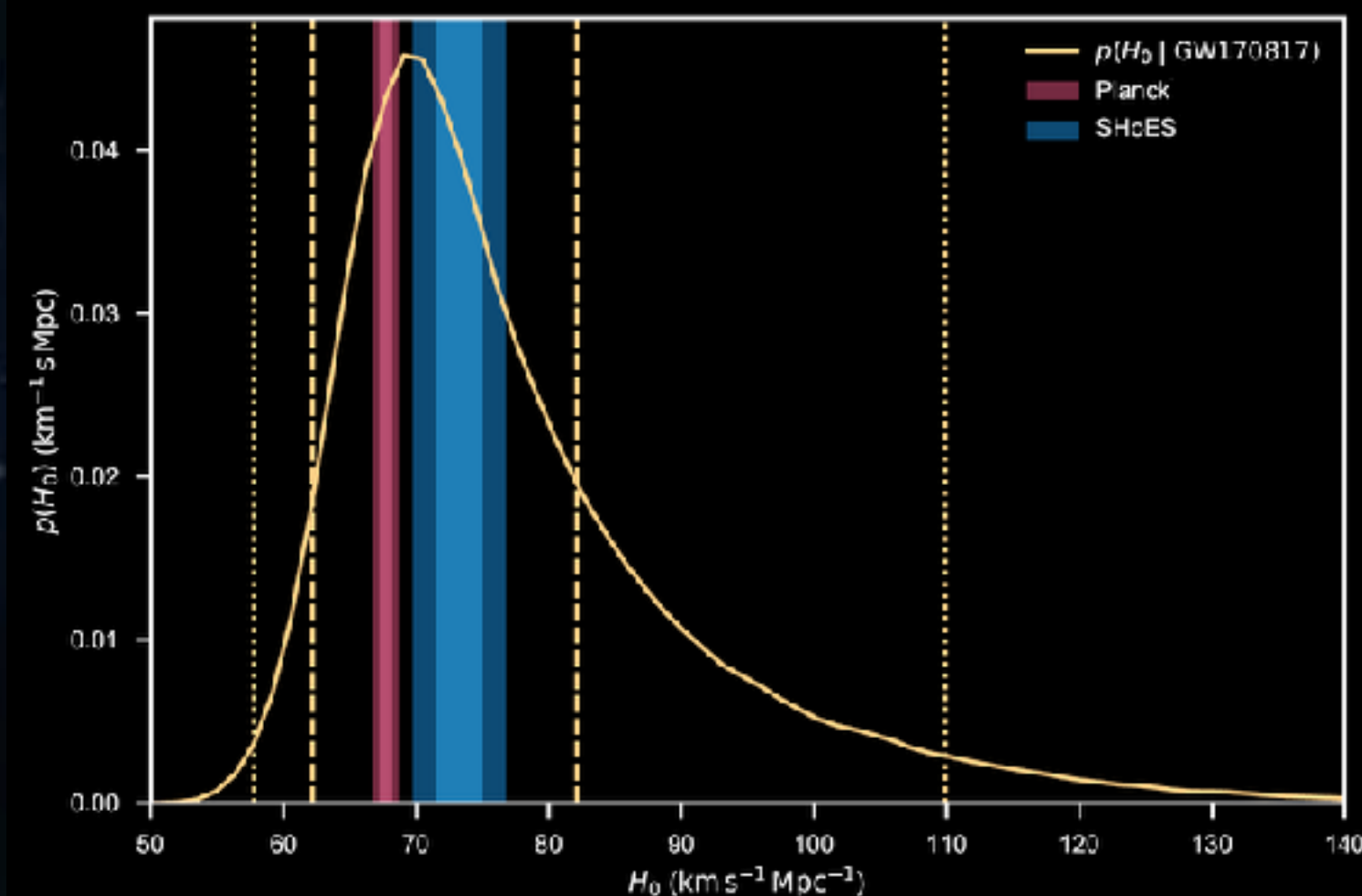
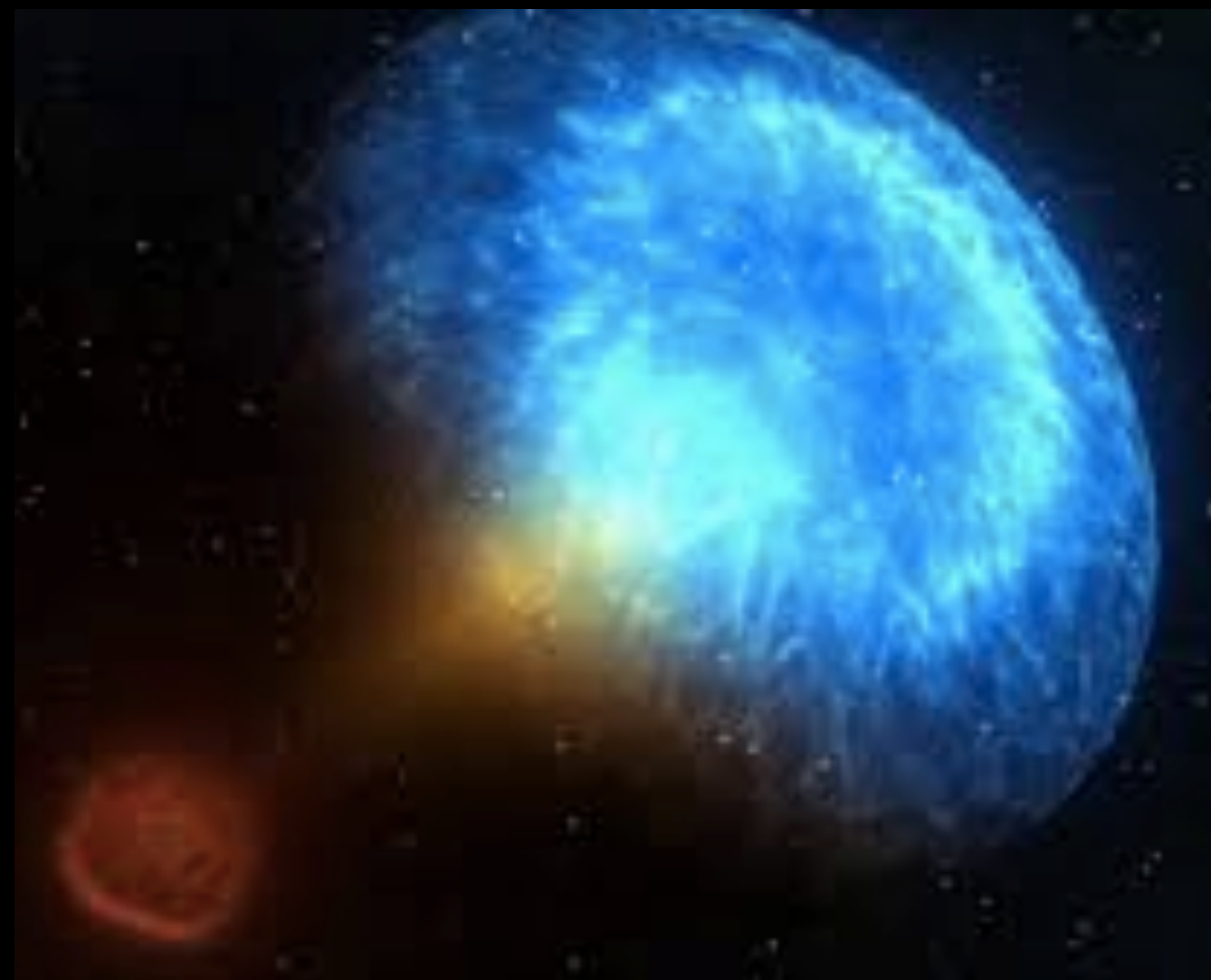
HIGHLIGHTS FROM FIRST DISCOVERIES

● GW150914:

- first detection of black hole binaries, first direct evidence for a black hole
- masses far larger than expected – challenge to astrophysics, challenge to astrophysical models, generated interest in primordial black holes
- O1 and O2 saw 10 binary black holes in total – a population unlike what we know in astronomy

● GW170817:

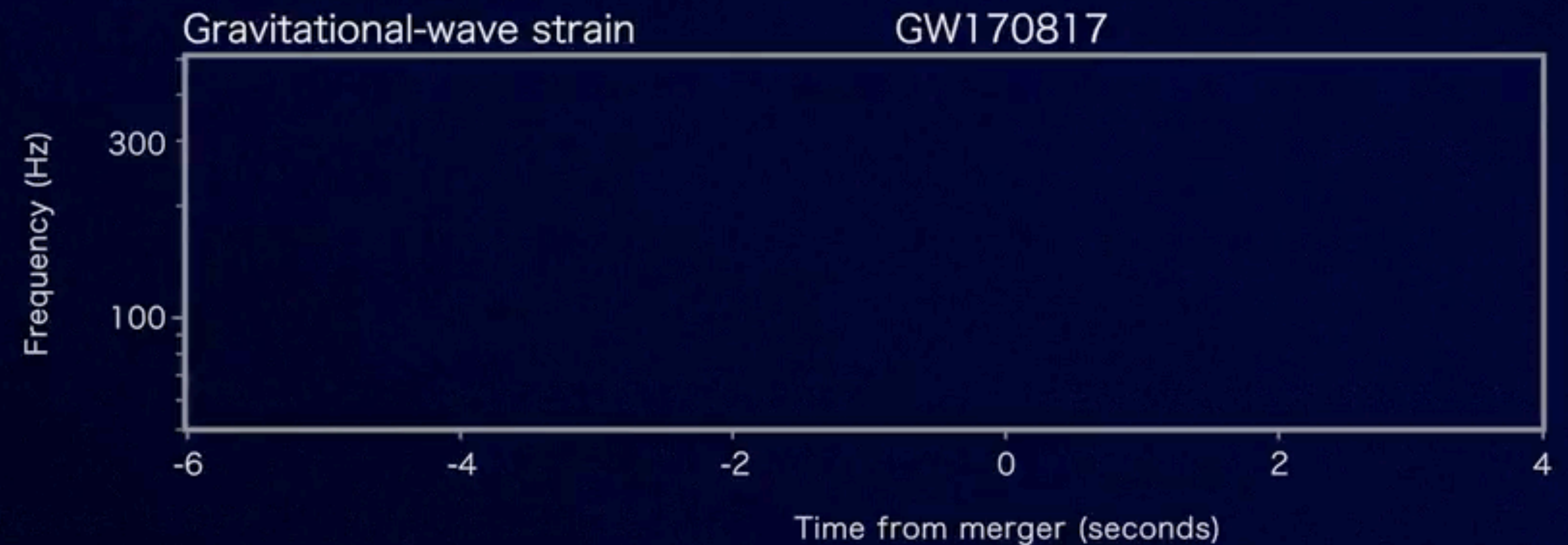
- first detection of a binary neutron star merger – a new era in multimessenger astronomy
- confirmed that the speed of GWs is essentially the same EM: ruled out many cosmological models invoked to explain dark energy
- prodigious sites of the formation of heavy elements (gold, platinum, lanthanides ...)
- a new tool for accurately measuring distances – a novel approach to cosmology
- equation of state of ultra-dense nuclear matter

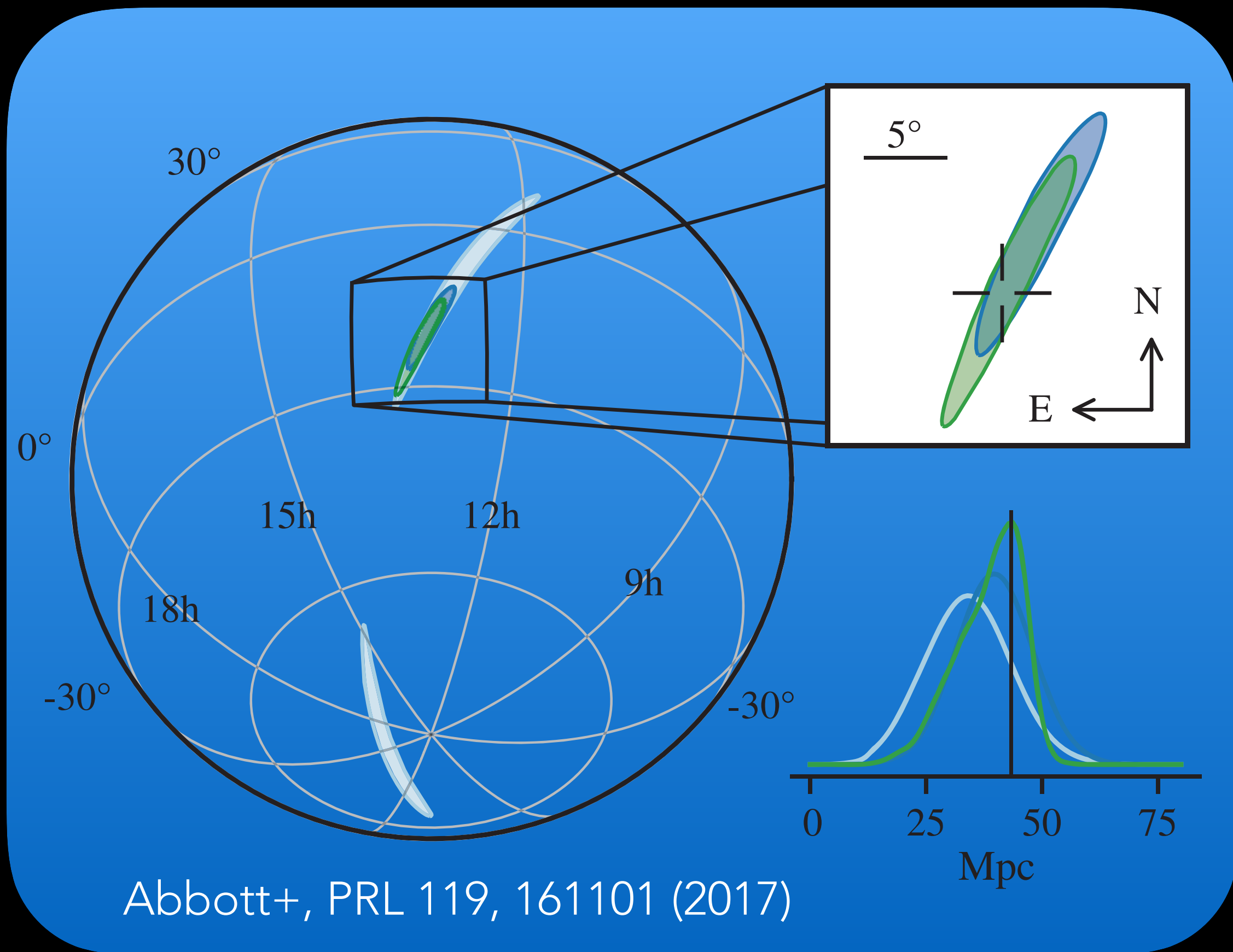


GW170817: DISCOVERY OF INSPIRALLING BINARY NEUTRON STARS

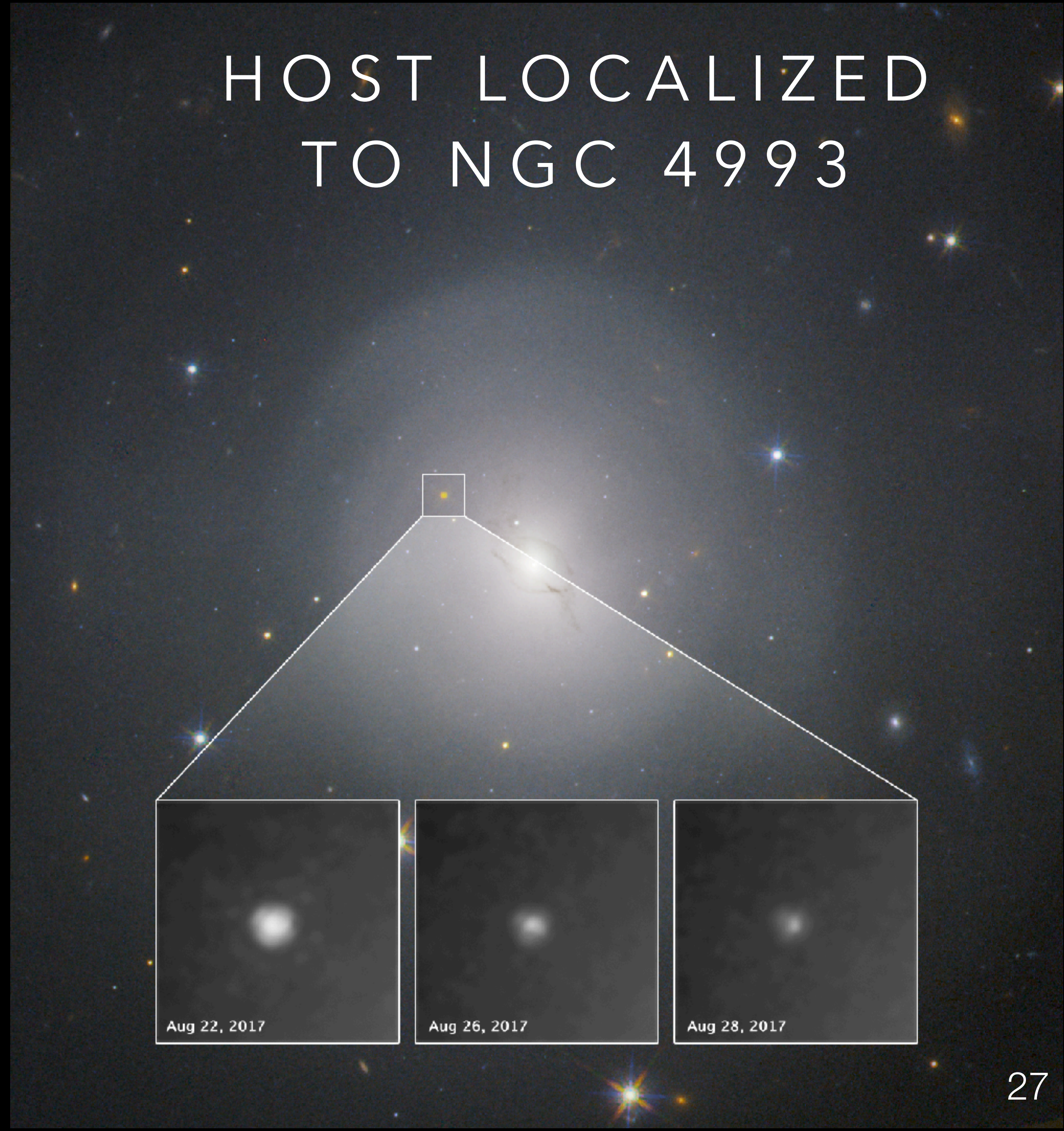


LIGO





- resolved the source to within 28 sq. degrees, final localization ~16 sq. degrees
- estimated distance of about 38 Mpc



SPEED OF GRAVITATIONAL WAVES = C?

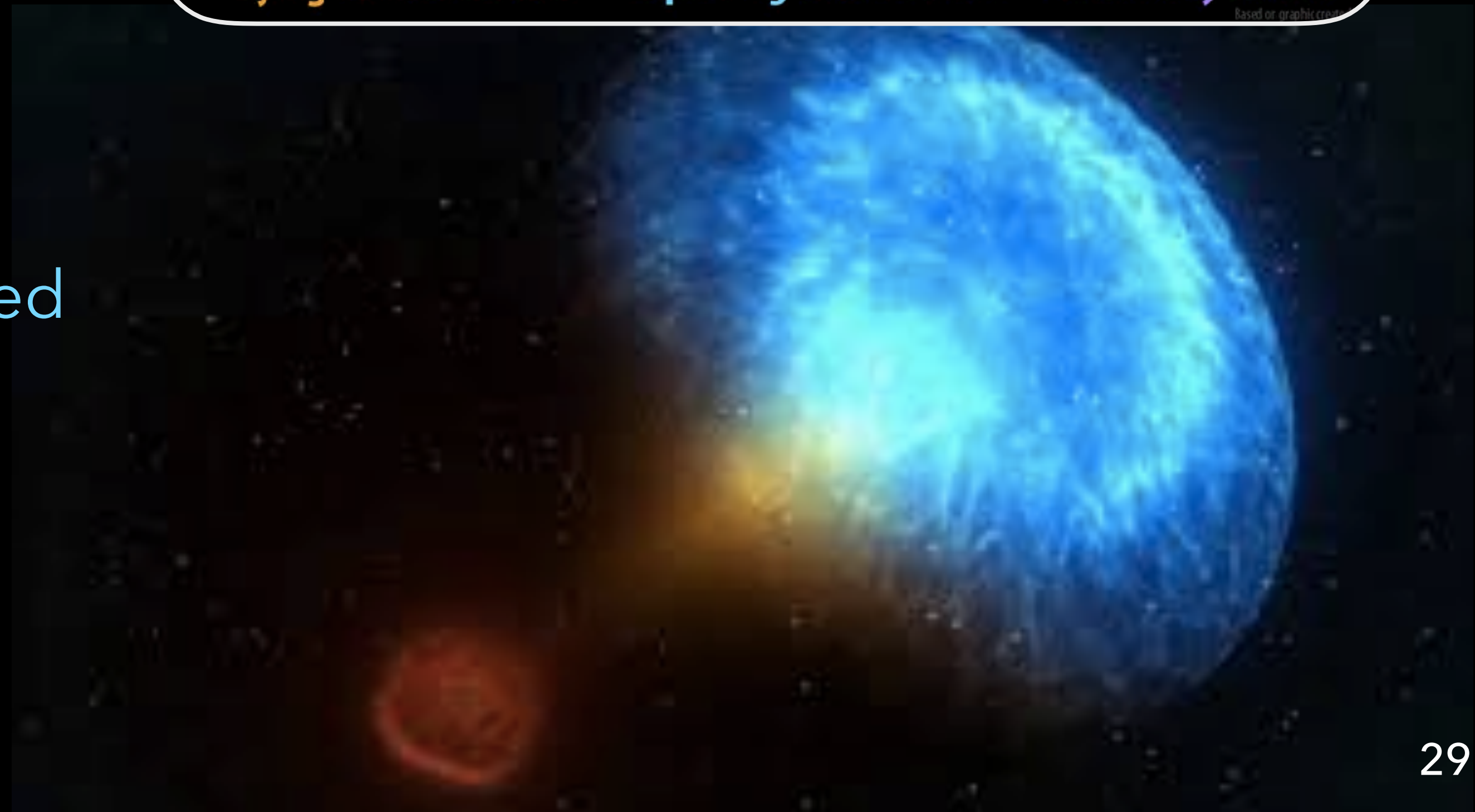
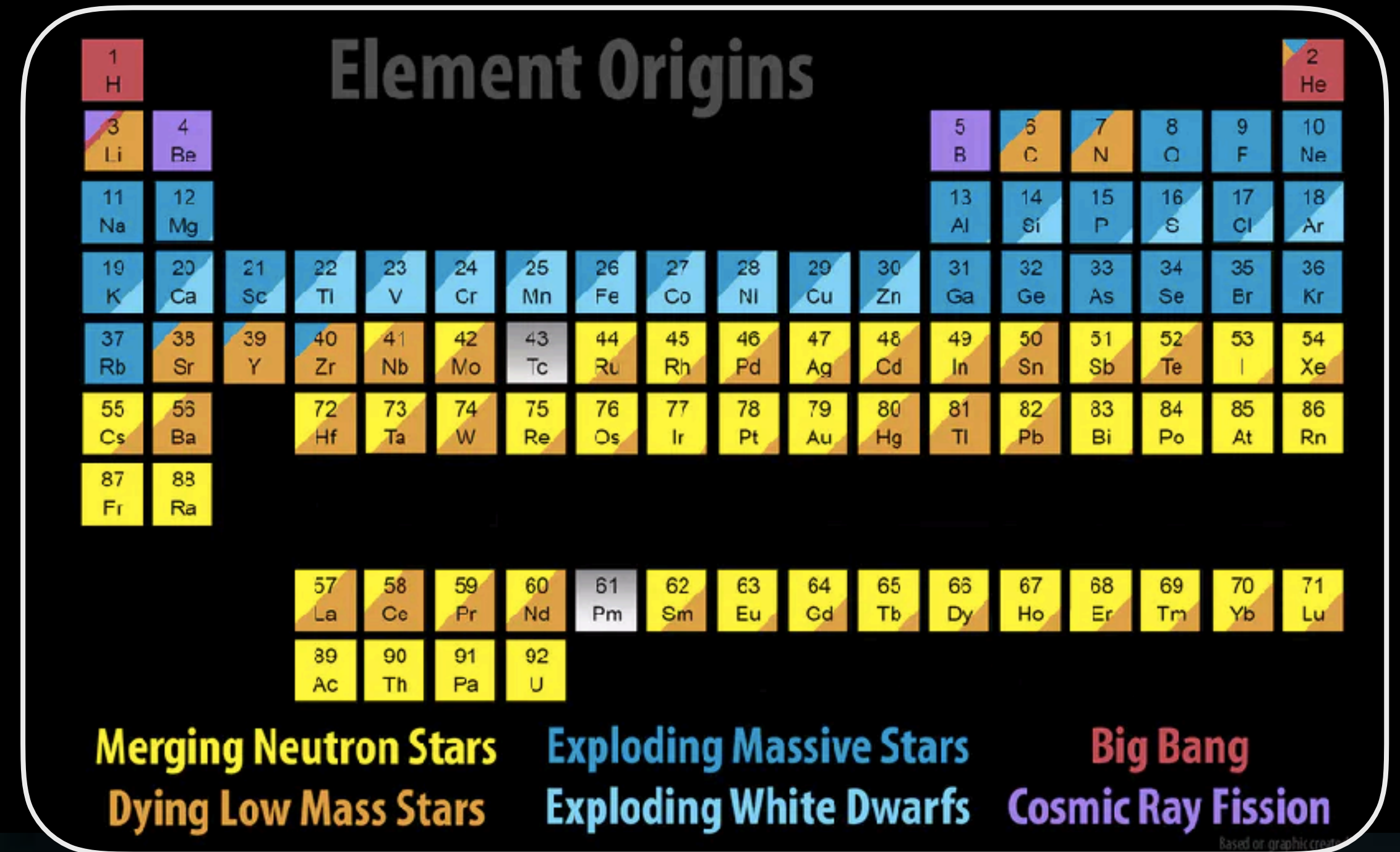
$$\frac{1.7 \text{ s}}{40 \text{ Mpc}/c} \sim 4 \times 10^{-16} \quad -3 \times 10^{-15} \leq \frac{v_{\text{GW}} - v_{\text{EM}}}{v_{\text{EM}}} \leq 7 \times 10^{-16}$$

THE ASTROPHYSICAL JOURNAL LETTERS, 848:L13 (27pp), 2017

this has ruled out many alternative theories of gravity proposed to explain dark energy

PRODUCTION OF HEAVY ELEMENTS

- in the aftermath of merger heavy elements are produced by r-process
- many of these heavy elements are unstable and radioactively decay
- the process produces a fireball called kilonova



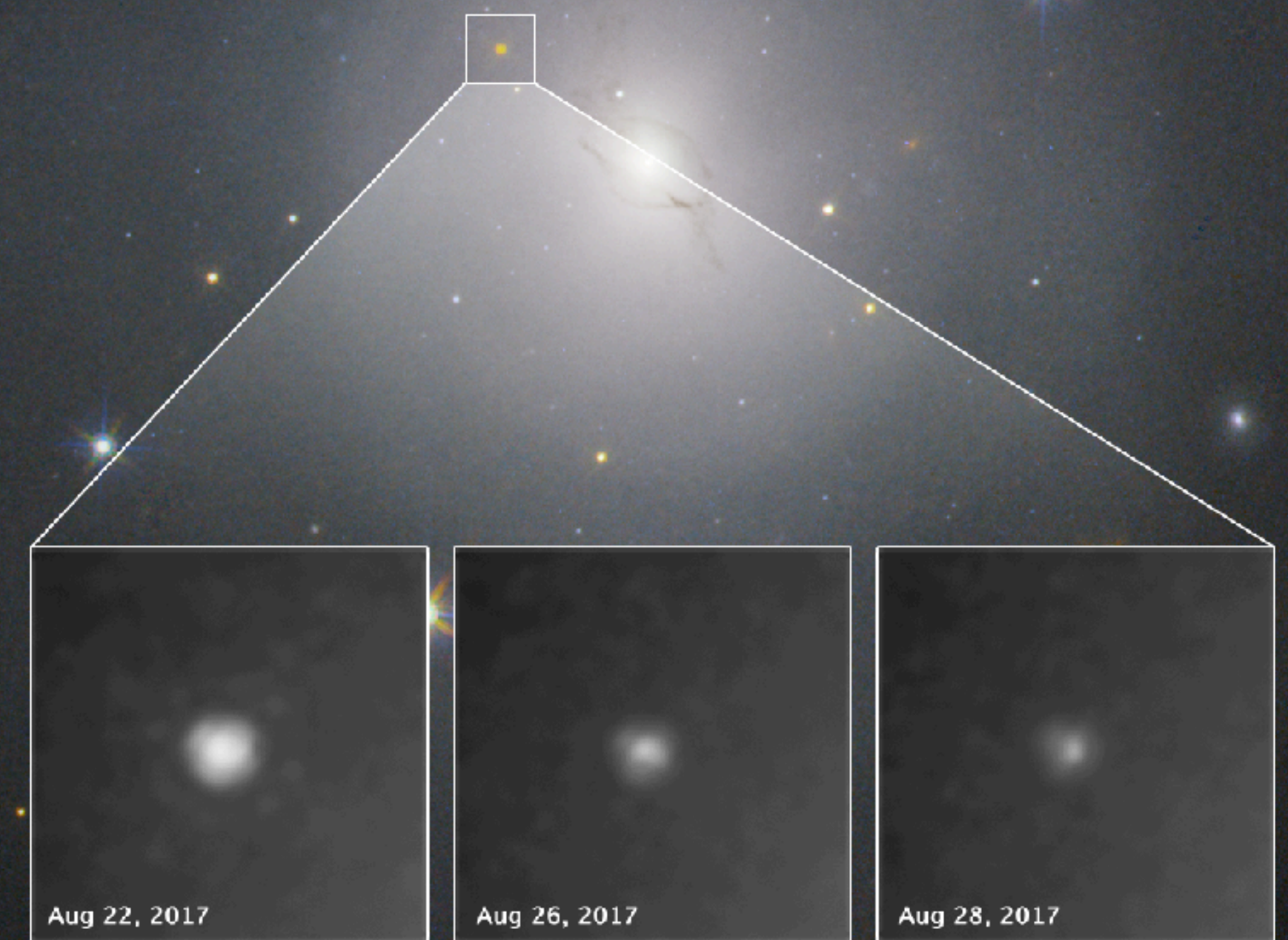
STANDARD SIREN COSMOLOGY

$$I \propto 1/r^2$$



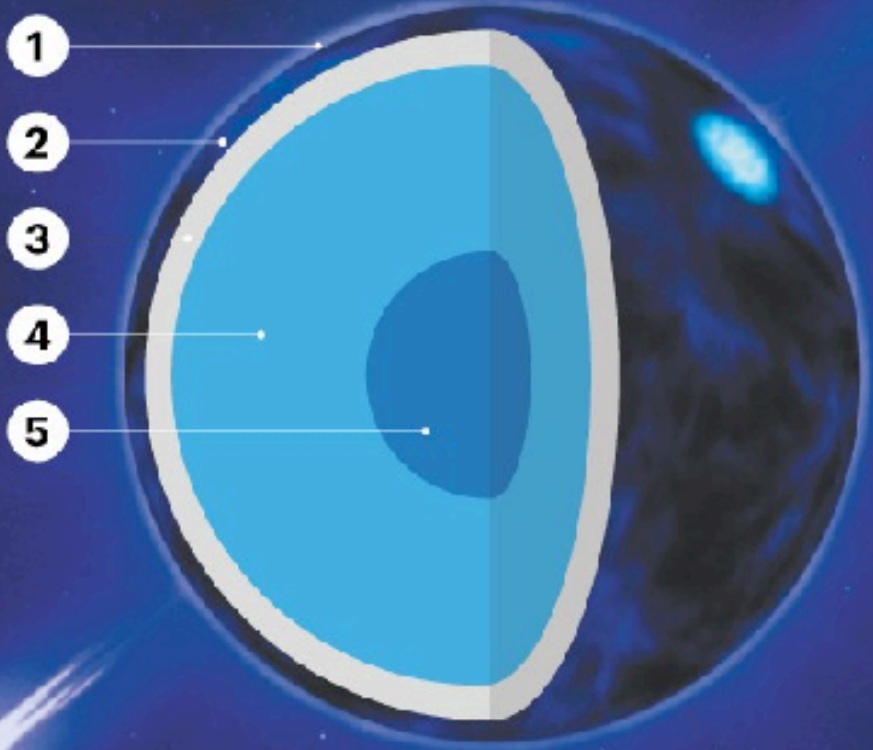
- gravitational wave observations can determine the luminosity distance to the source, but not its redshift
- combined with electromagnetic observations we can measure the expansion rate of the Universe
- GW170817 was used in this way to measure the Hubble constant

HOST LOCALIZED TO NGC 4993



DENSE MATTER

Neutron stars get denser with depth. Although researchers have a good sense of the composition of the outer layers, the ultra-dense inner core remains a mystery.



- 1. Atmosphere Mostly hydrogen and helium
- 2. Outer crust Atomic nuclei and free electrons
- 3. Inner crust Free neutrons and electrons, heavier atomic nuclei
- 4. Outer core Neutron-rich quantum liquid
- 5. Inner core Unknown, ultra-dense matter

Core scenarios
A number of possibilities have been suggested for the inner core, including these three options.

- u Up quark
- d Down quark
- s Strange quark
- anti-d Anti-down quark



Quarks
The constituents of protons and neutrons — up and down quarks — roam freely.

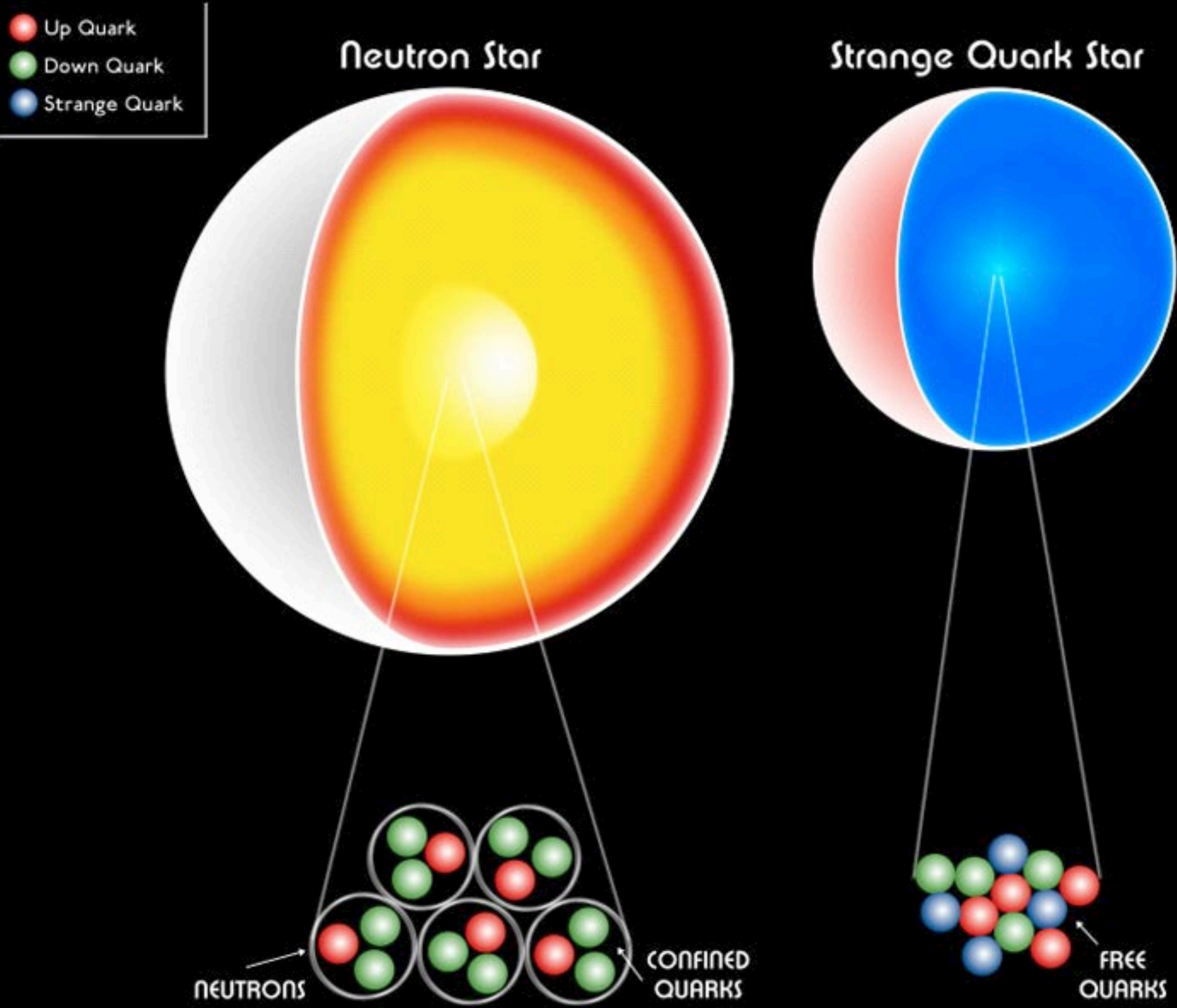


Bose-Einstein condensate
Particles such as pions containing an up quark and an anti-down quark combine to form a single quantum-mechanical entity.



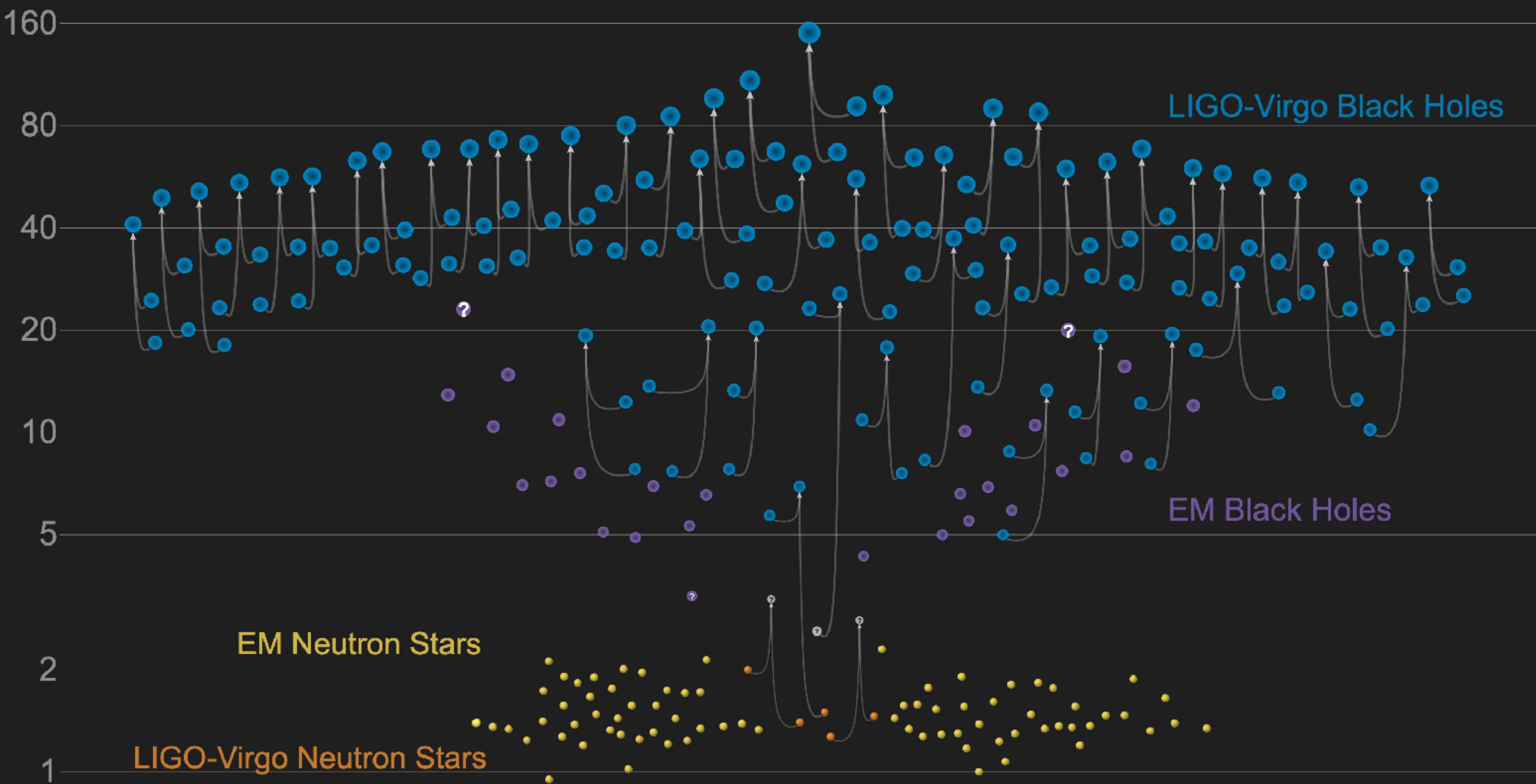
Hyperons
Particles called hyperons form. Like protons and neutrons, they contain three quarks but include 'strange' quarks.

UNDERSTANDING DENSE NUCLEAR MATTER



LIGO-VIRGO DISCOVERIES IN THE THIRD OBSERVING RUN

GWTC-2: 2ND GRAVITATIONAL-WAVE TRANSIENT CATALOG

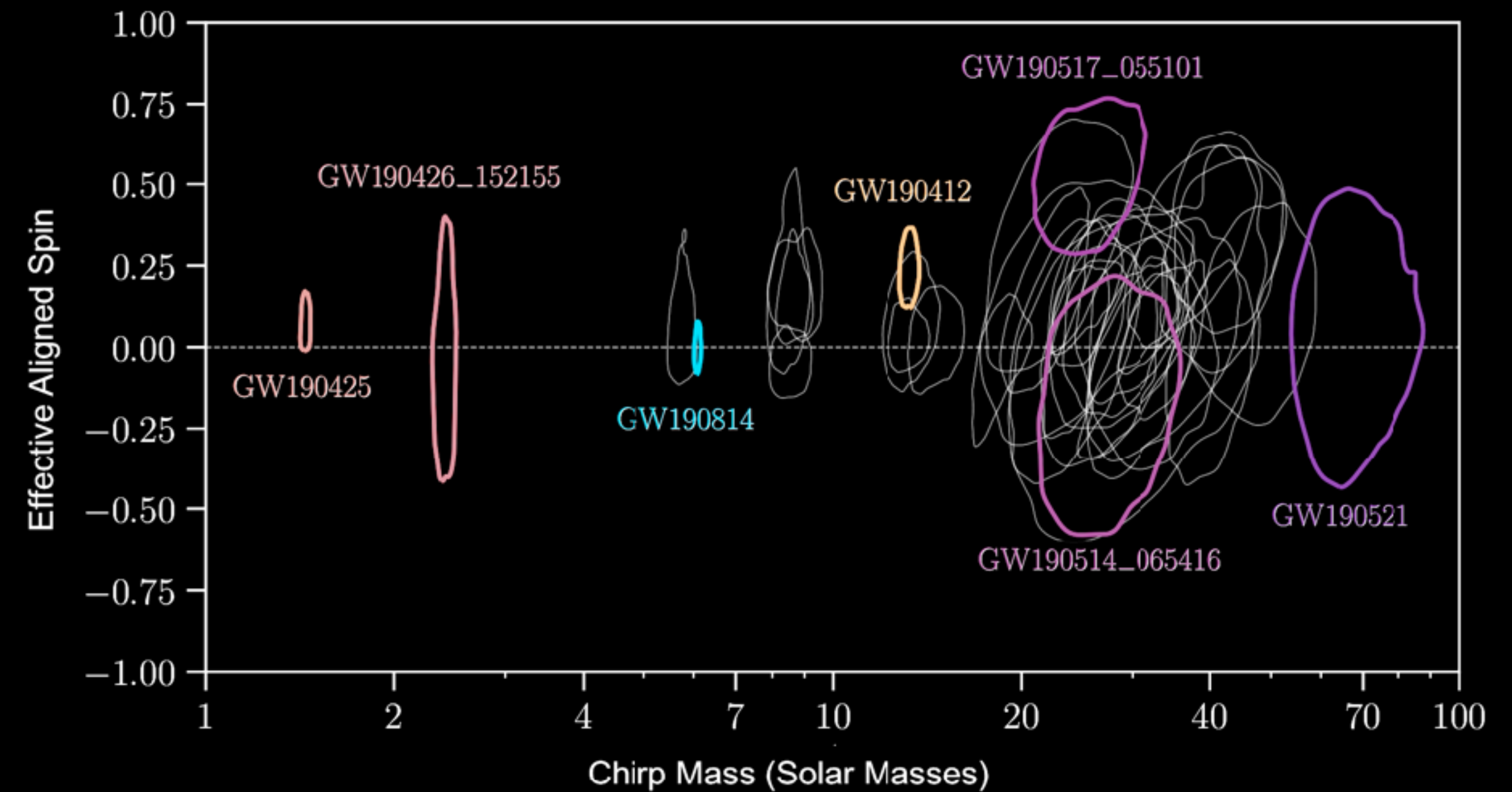
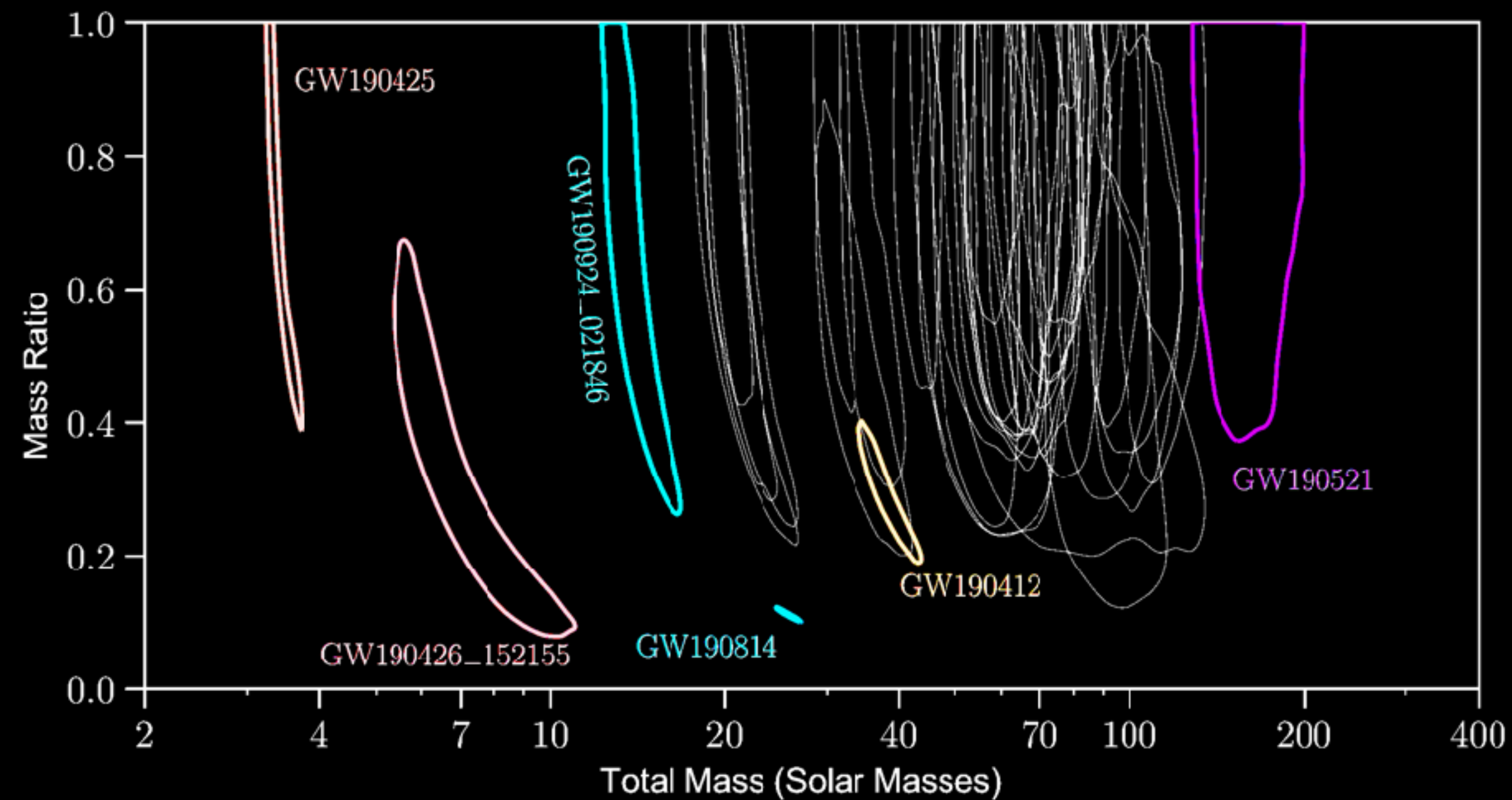


GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

POPULATION PROPERTIES

- what does the catalog contain:
 - 2 binary neutron star events
 - 44 confident binary black hole events
 - 1 neutron-star black hole candidate (which may be a binary black hole)
- rate at of mergers:
 - binary black holes merge at the rate of $\sim 25 \text{ yr}^{-1} \text{ Gpc}^{-3}$ (still a factor of 2 uncertain)
 - binary neutron stars merge at the rate of : $320 \text{ yr}^{-1} \text{ Gpc}^{-3}$
- 12% to 44% of systems have spins tilted by more than 90 degrees with the orbital angular momentum
- mass spectrum is broken power-law with a break around 40 solar masses:
 - global peak of the lower end of the mass spectrum has a peak around 8 solar masses
 - a lower mass gap between 2.4 solar mass and 6 solar mass

WHAT DOES THE POPULATION TELL US?



- most of our new detections are plain vanilla systems
- some stand out: GW190412, GW190425, GW190814, GW190521, GW190924, GW190426

GW190412

The first gravitational wave observation from the merger of two black holes with different masses

Discovery

12 April 2019

Distance

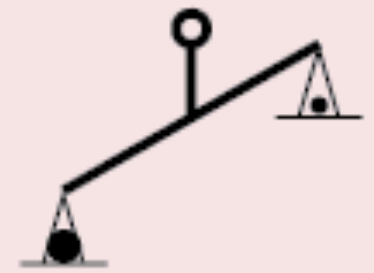
2.4 billion
light years away

3 Detectors

Three detectors made the observation: the two LIGO detectors in the USA and Virgo in Italy.



Binary Black Hole



Unequal Masses

This is the first BBH detection where the two black holes had very different masses



Higher Harmonics



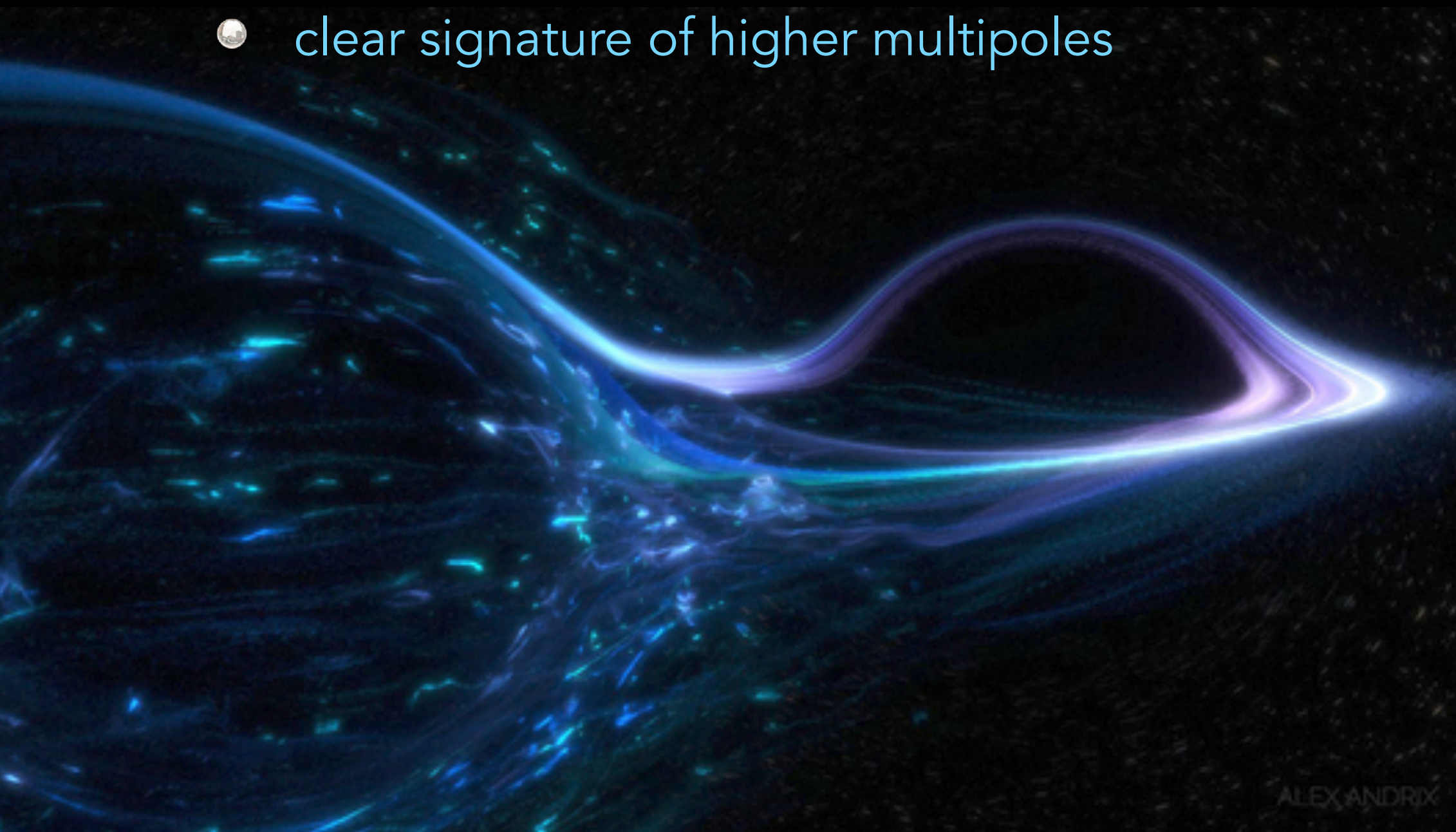
This event allowed the hum of higher harmonics to be measured in the signal. These allow new tests of General Relativity. Everything continues to be consistent with Einstein's theory following these tests.

GW190425

- second binary neutron star after GW170817
- heaviest binary neutron star ever, galactic neutron stars are far lighter
 - origin of such systems is a challenge to astrophysics
- must have produced a black hole in the lower mass-gap

THE LIGHTER COMPANION IN GW190814 IS A MYSTERY OBJECT BLACK HOLE OR A NEUTRON STAR?

- masses: $2.6 M_{\odot}$ and $23.2 M_{\odot}$
 - lighter companion is a mystery object
- GW190814 represents a new class of compact binaries
 - GW190814-like events should occur at the rate of $1\text{-}23 \text{ Gpc}^{-3} \text{ yr}^{-1}$
- most precisely localized source
 - 18.5 deg^2 and $241^{+41}_{-45} \text{ Mpc}$
- clear signature of higher multipoles



GW190814

The coalescence of a black-hole and a compact, unknown companion object

Discovery

14 August 2019

Distance

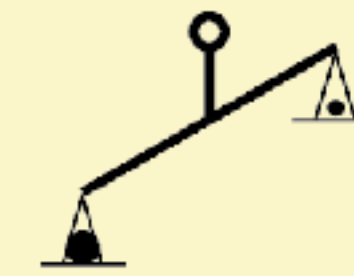
800 million
light years away

3 Detectors

Three detectors made the observation: the two LIGO detectors in the USA and Virgo in Italy.

Binary Black Hole Merger (Probably)

We can't be sure what the lighter object is - it's either the lightest black hole we've ever observed, or possibly the heaviest neutron star.



Unequal Masses

There is an almost nine-fold difference between the two objects' masses.

● ? BBH?



23.2
suns

2.6
suns

Premerger

0.2
suns

radiated as
GW energy

Merger

25.6
suns

Remnant

GW190814

Higher Harmonics



This event allowed the hum of higher harmonics to be measured in the signal.

These are even stronger in this signal than for GW190412, thanks to the greater asymmetry between the objects' masses.

These allow new tests of General Relativity.

Everything continues to be consistent with Einstein's theory following these tests.

GW190521

The most massive black hole collision observed so far

Discovery

21 May 2019

Distance

17 billion
light years away

3 Detectors

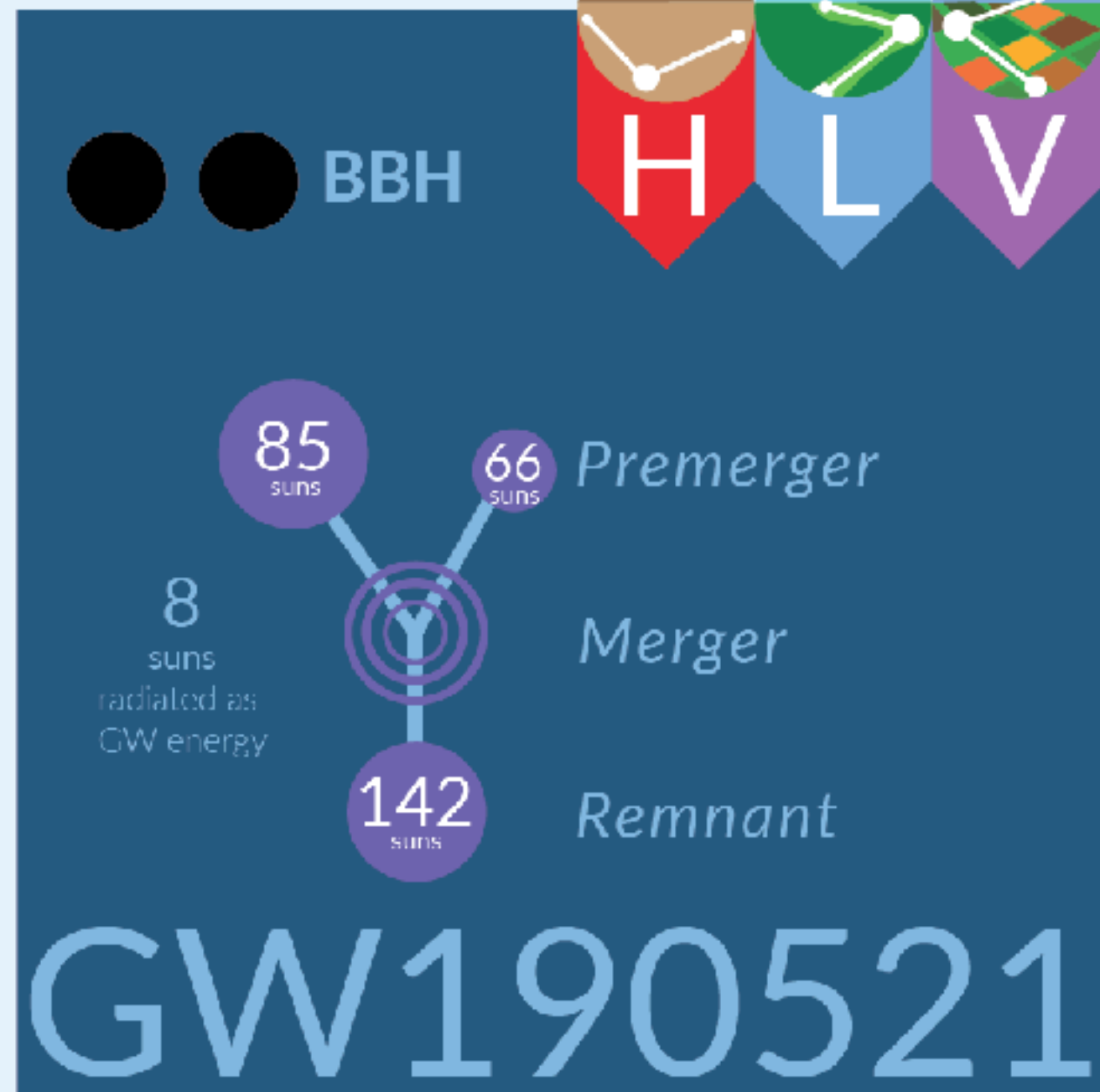
Three detectors made the observation: the two LIGO detectors in the USA and Virgo in Italy.

Binary Black
Hole Merger



High
Masses

This is the heaviest
pair of black holes
which have ever
been observed
colliding.



Origin Story

The black holes which collided to make GW190521 are so massive that we're not sure how they were formed. One possibility is that they are both the result of previous black hole collisions.

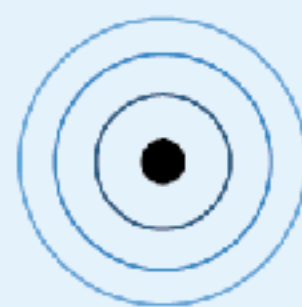


Ringdown

The black hole formed in the collision continues to vibrate after the merger, and "rings" like a bell for a while. This lets us test our theories.



Once again Einstein's
General Relativity passed
this test.



GW190521

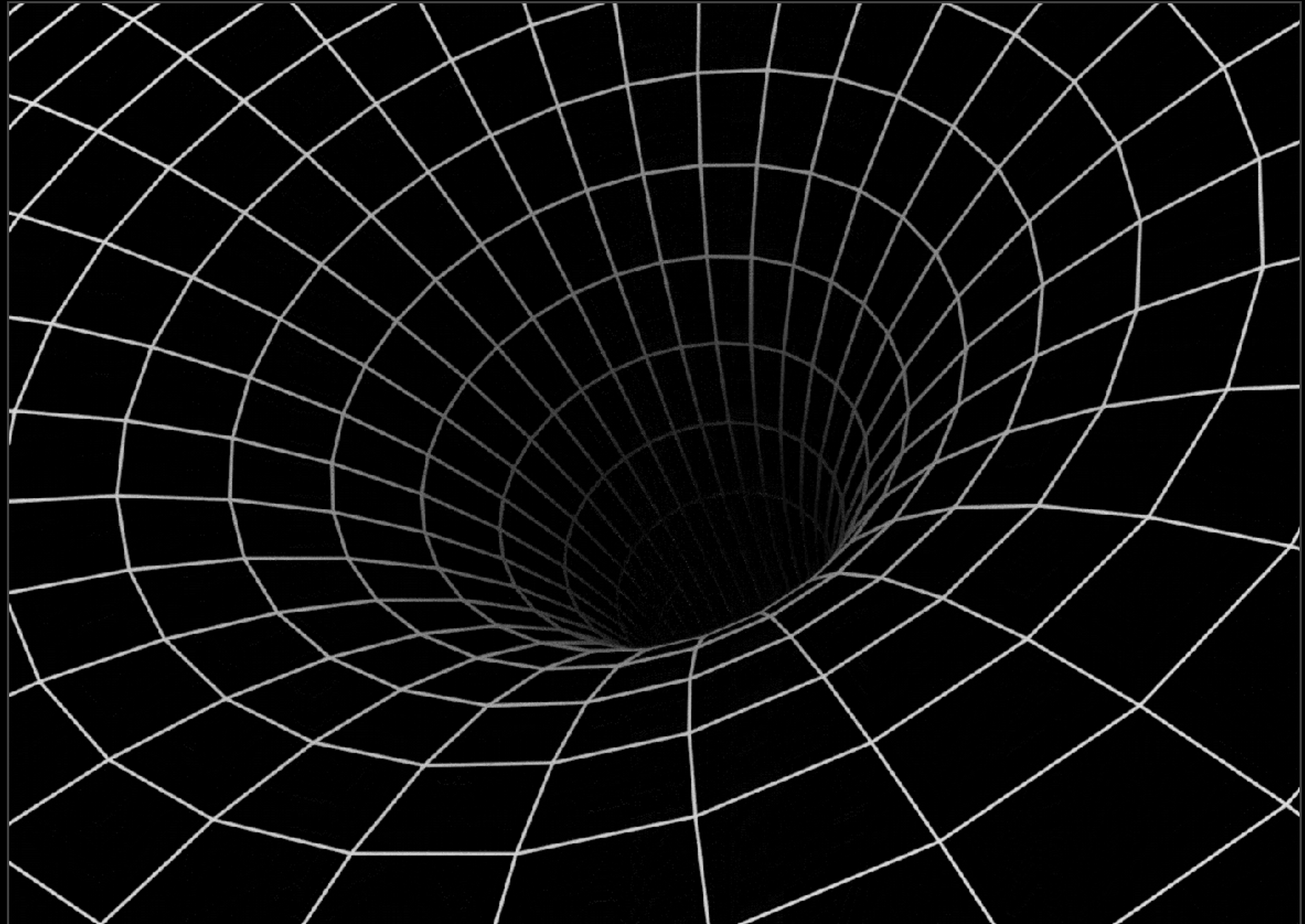


- with a total mass of $151 M_{\odot}$ this is the most massive black hole binary
- $9 M_{\odot}$ converted to pure radiation in a matter of a few milliseconds
- the primary companion (probably also the secondary) is in the pair instability supernova gap
- could not have formed by stellar evolution
- first observation of an intermediate mass black hole
- the most distant binary black hole so far $z=0.82$
- remnant might have produced an EM counterpart!

CRISIS IN PHYSICS

Credit: James Zanoni/Quanta Magazine

- ◆ black hole singularity
- ◆ lack of a viable theory of quantum gravity
- ◆ accelerated expansion of the Universe
- ◆ nature of dark energy
- ◆ origin of dark matter
- ◆ Hubble tension
- ◆ origin of supermassive black holes



CRISIS IN PHYSICS

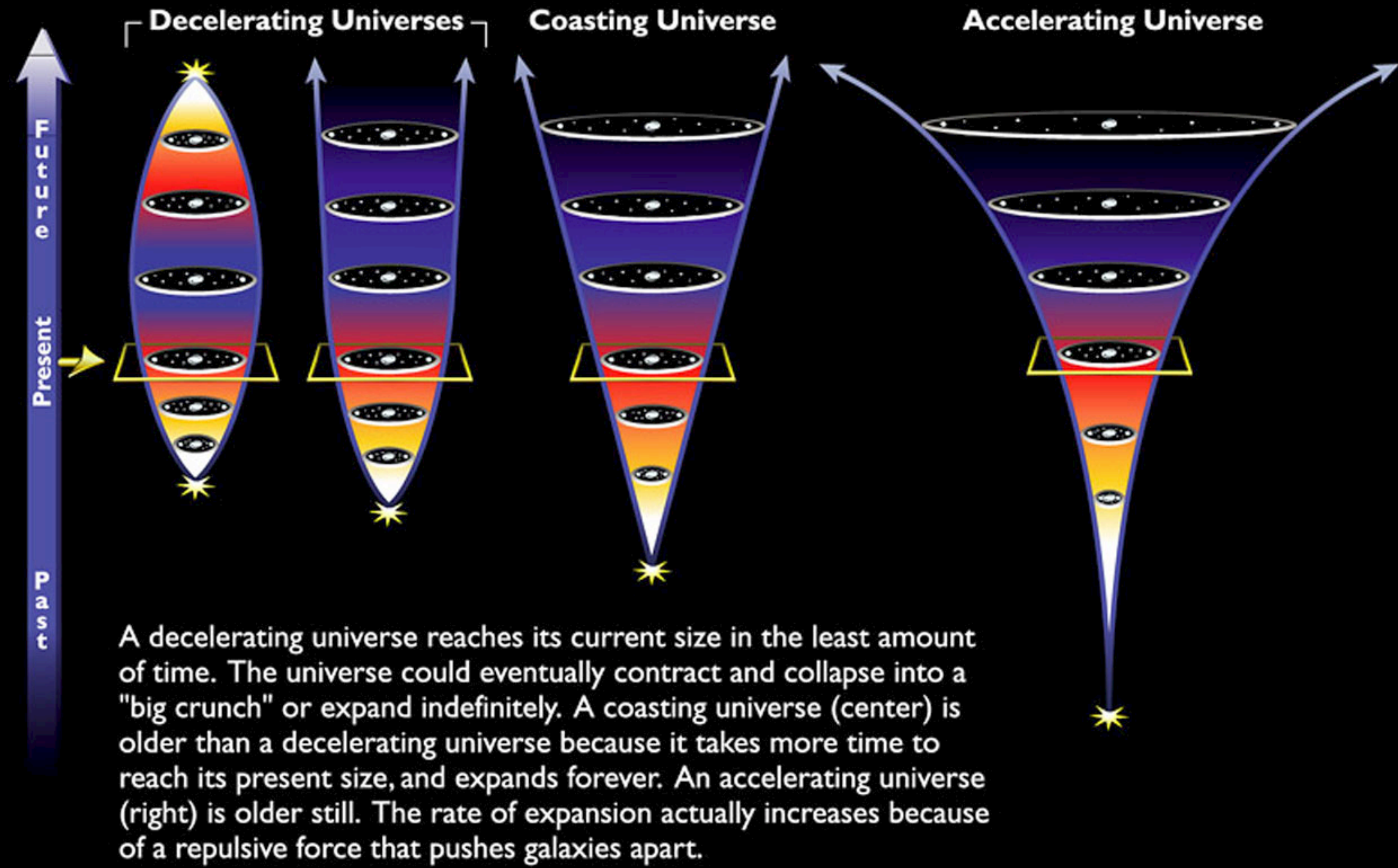
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Credit: T. Thiemann (FAU Erlangen), Albert Einstein Institute, Milde Marketing Wissenschaftskommunikation, exozet effects

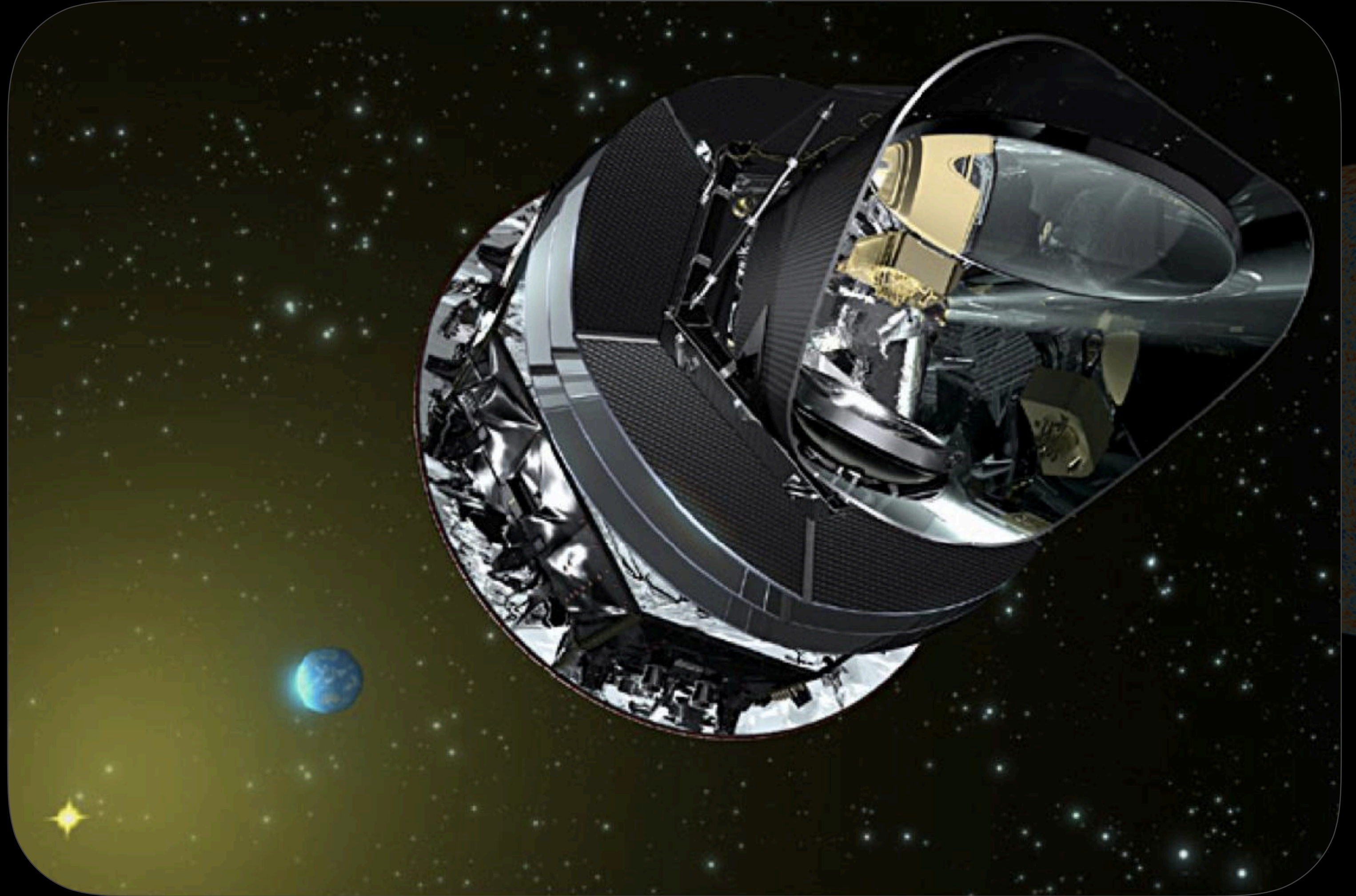
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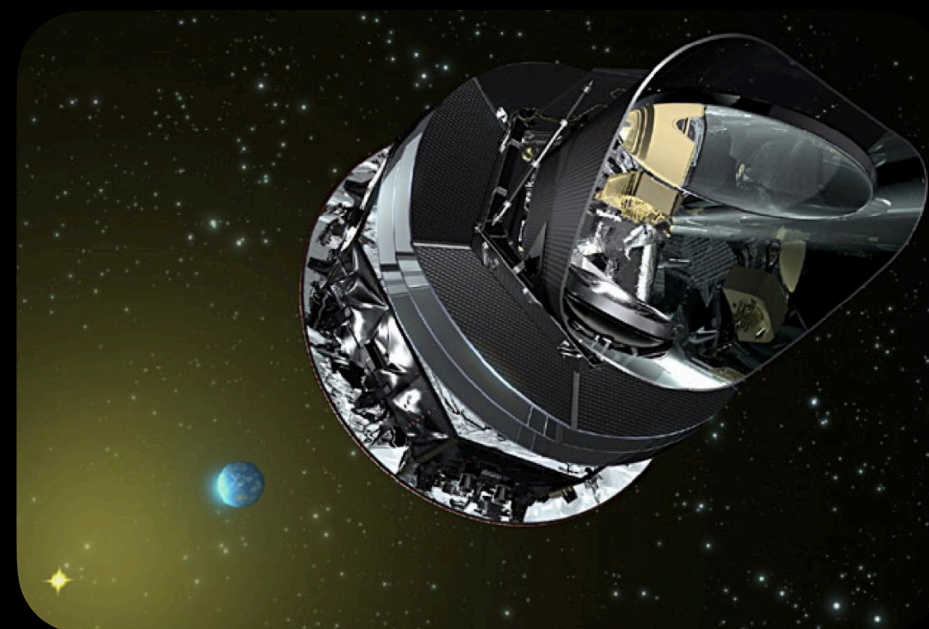
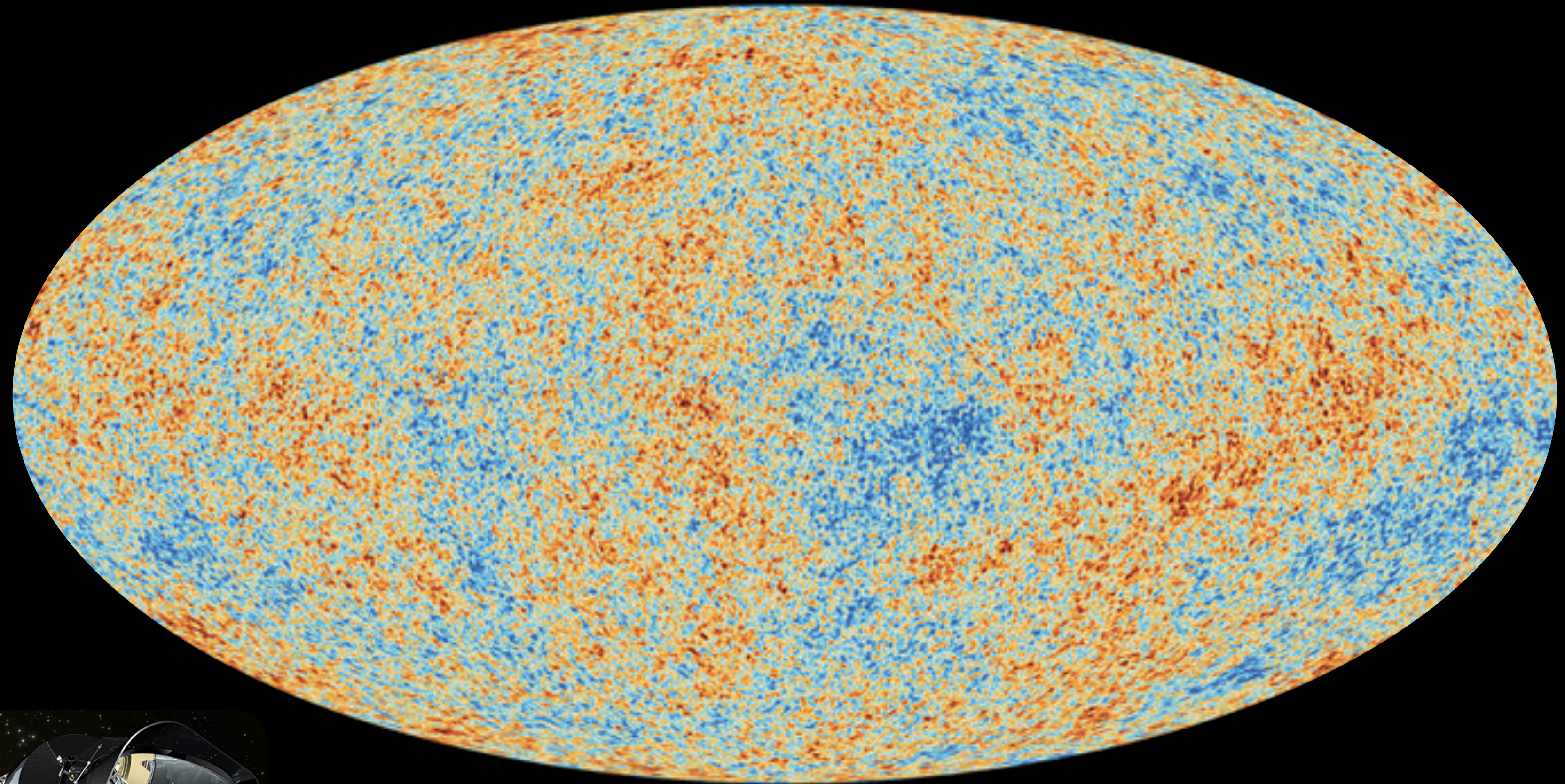
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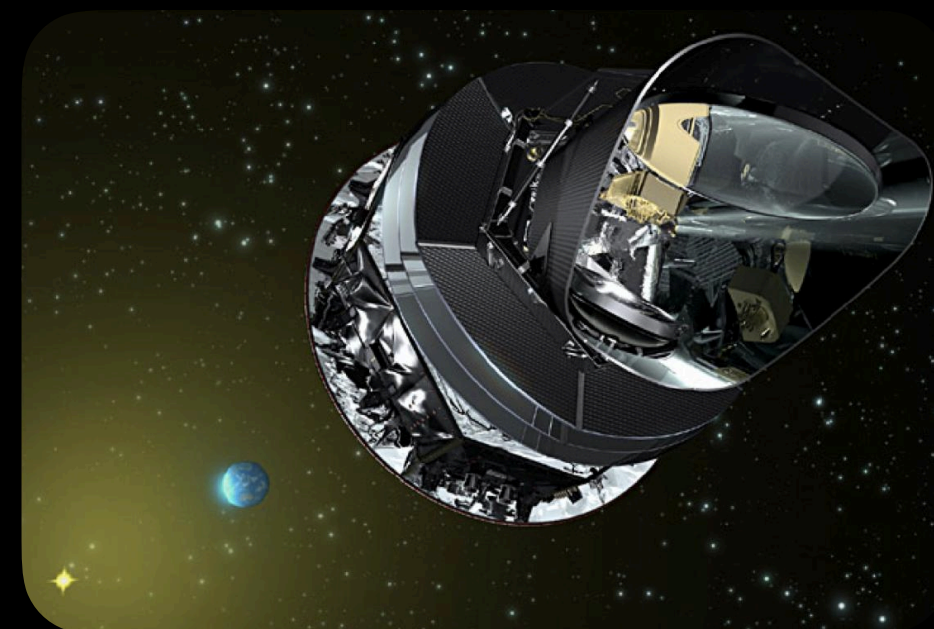
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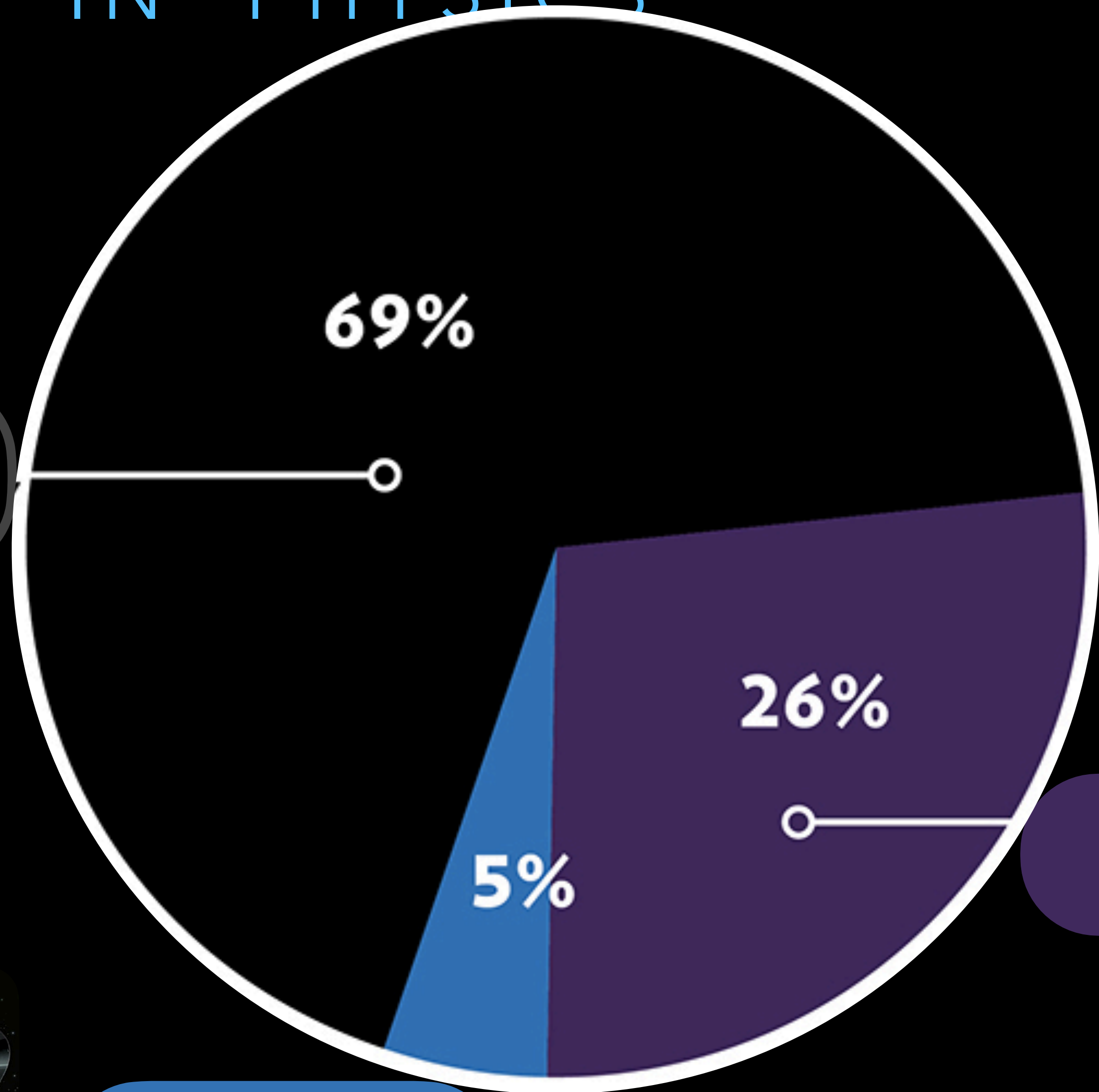


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Dark Energy

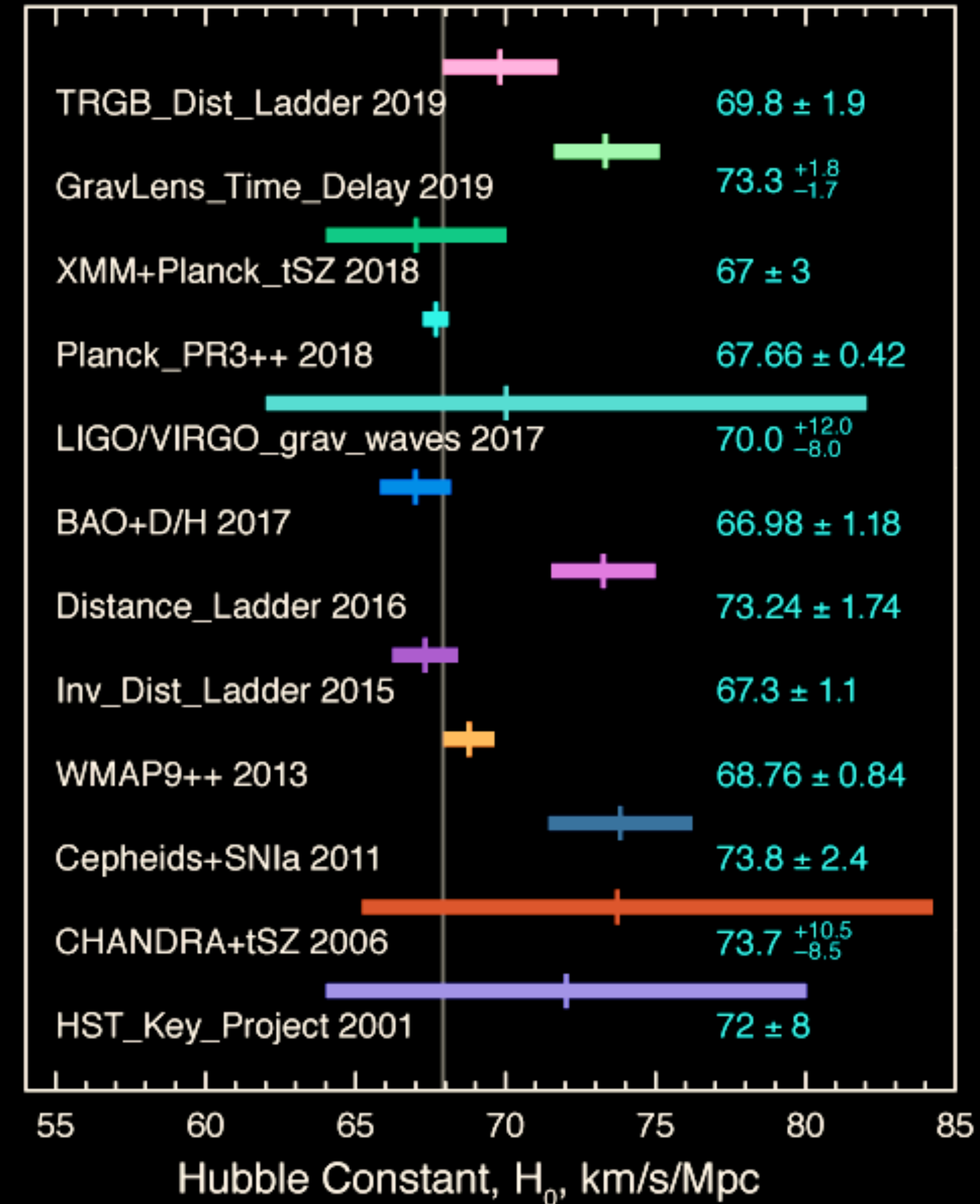
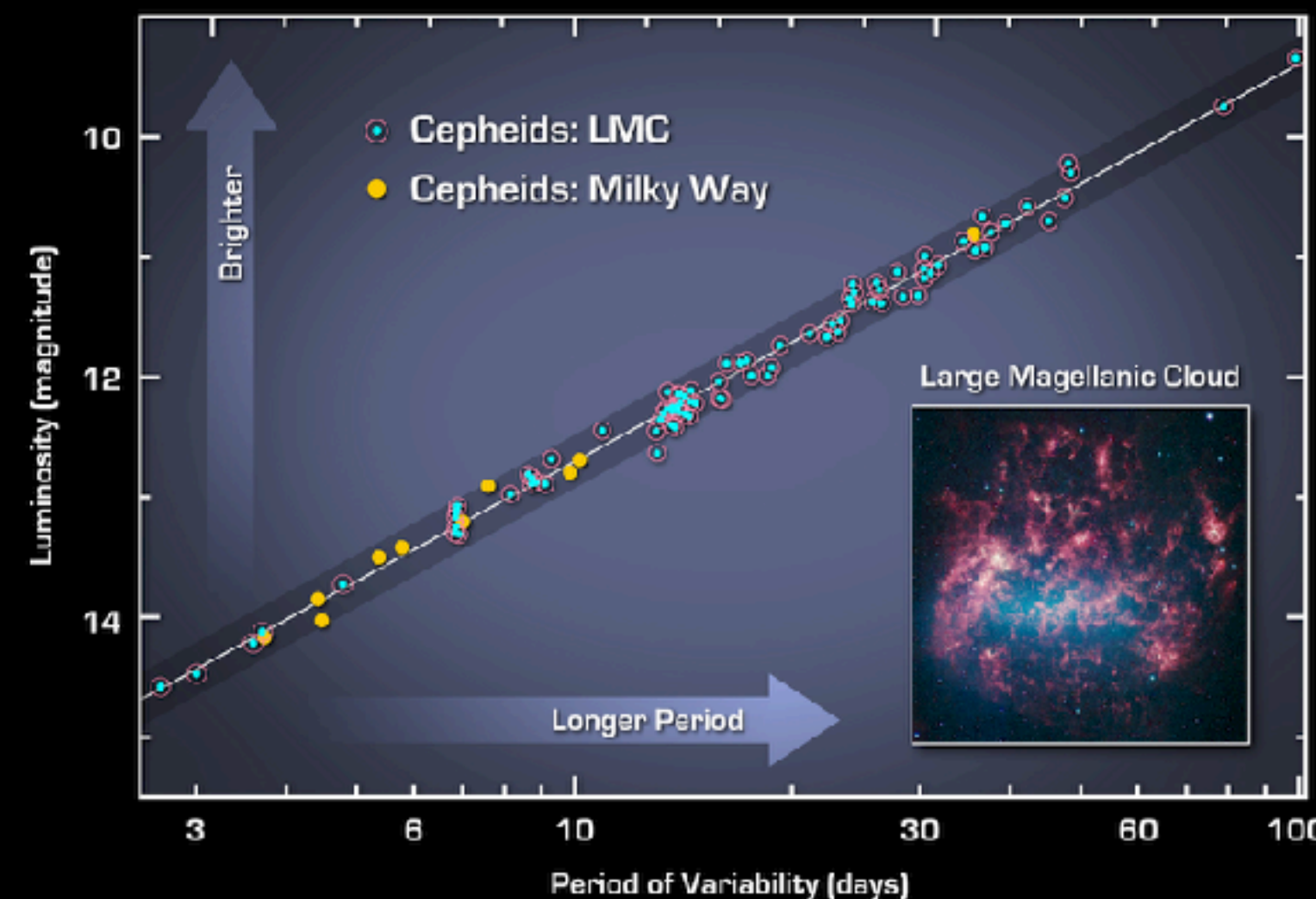
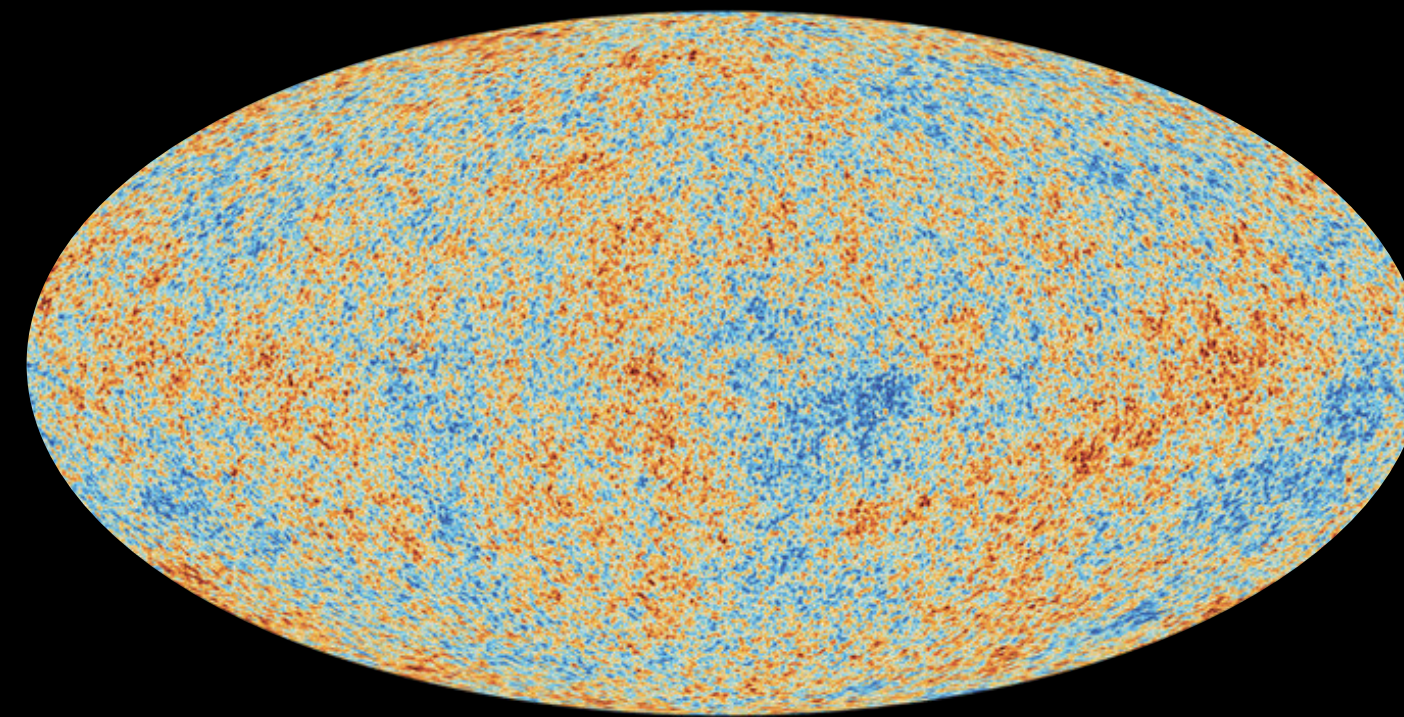


Normal Matter

Dark Matter

CRISIS IN PHYSICS

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- ✦ **Hubble tension**
- ✦ origin of supermassive black holes



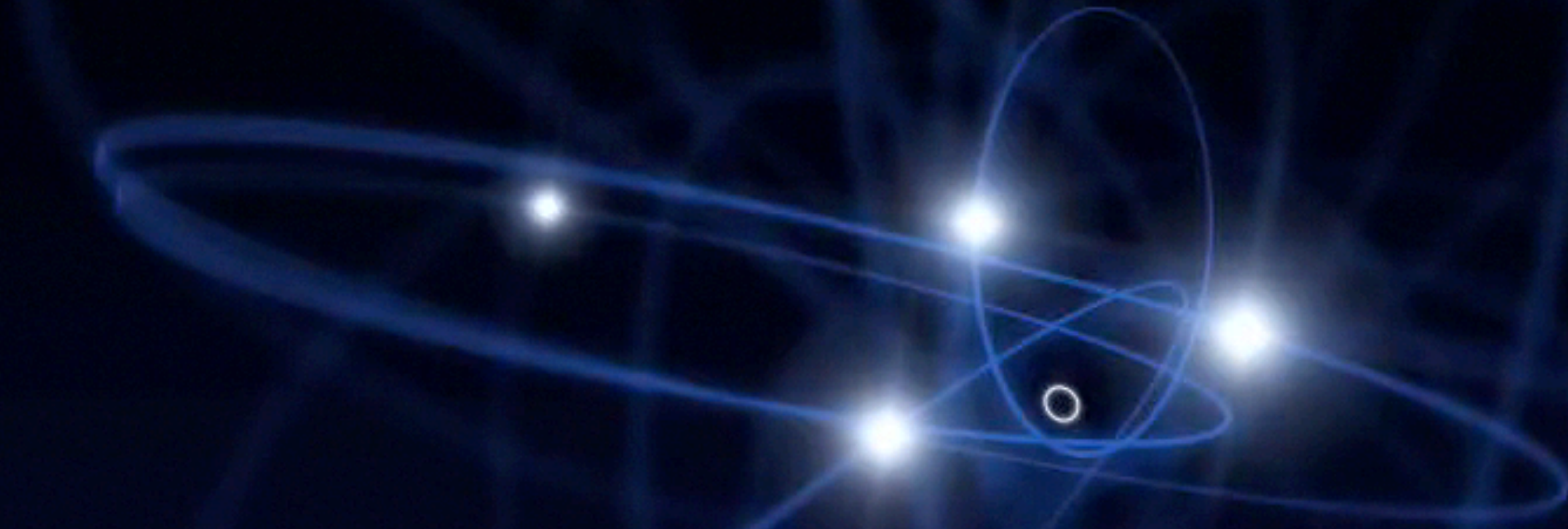
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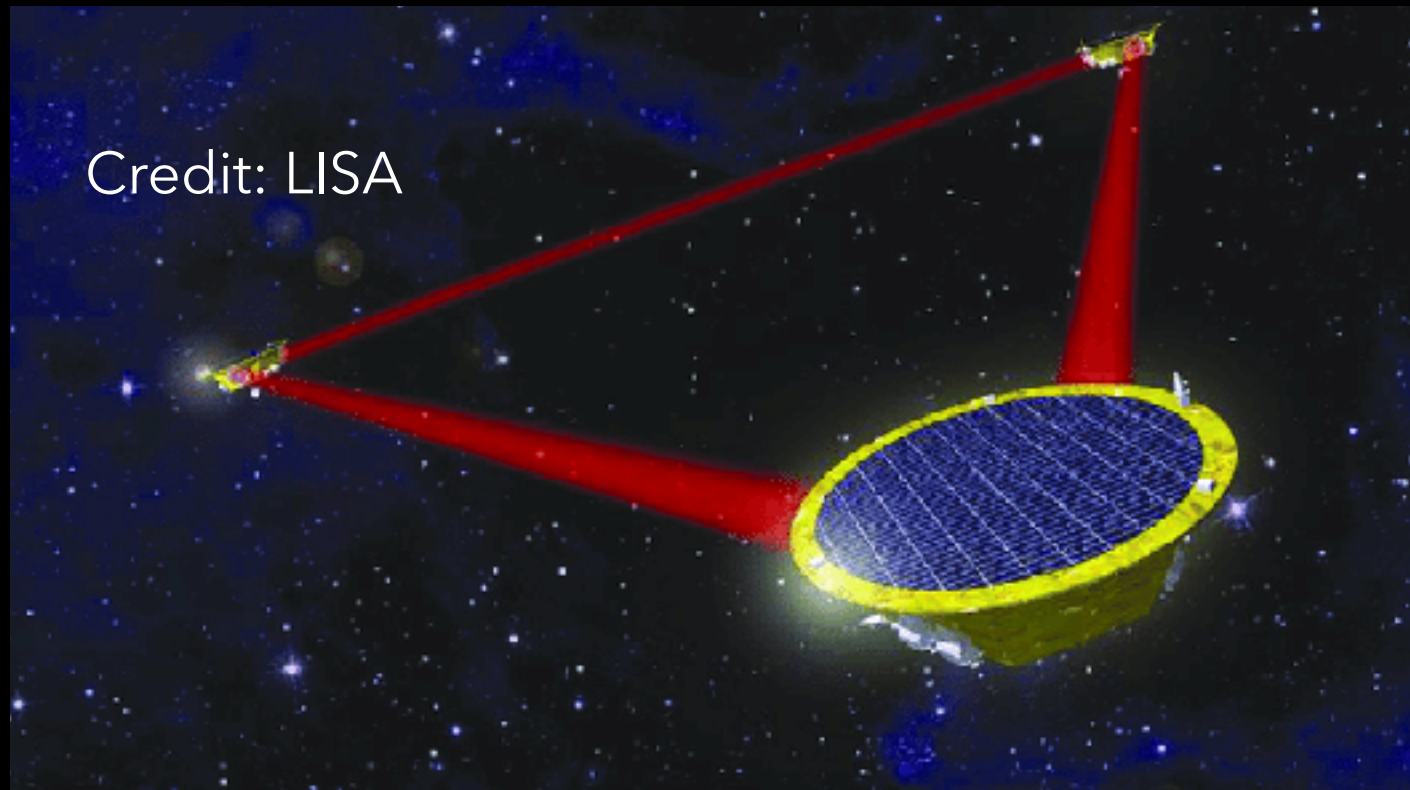


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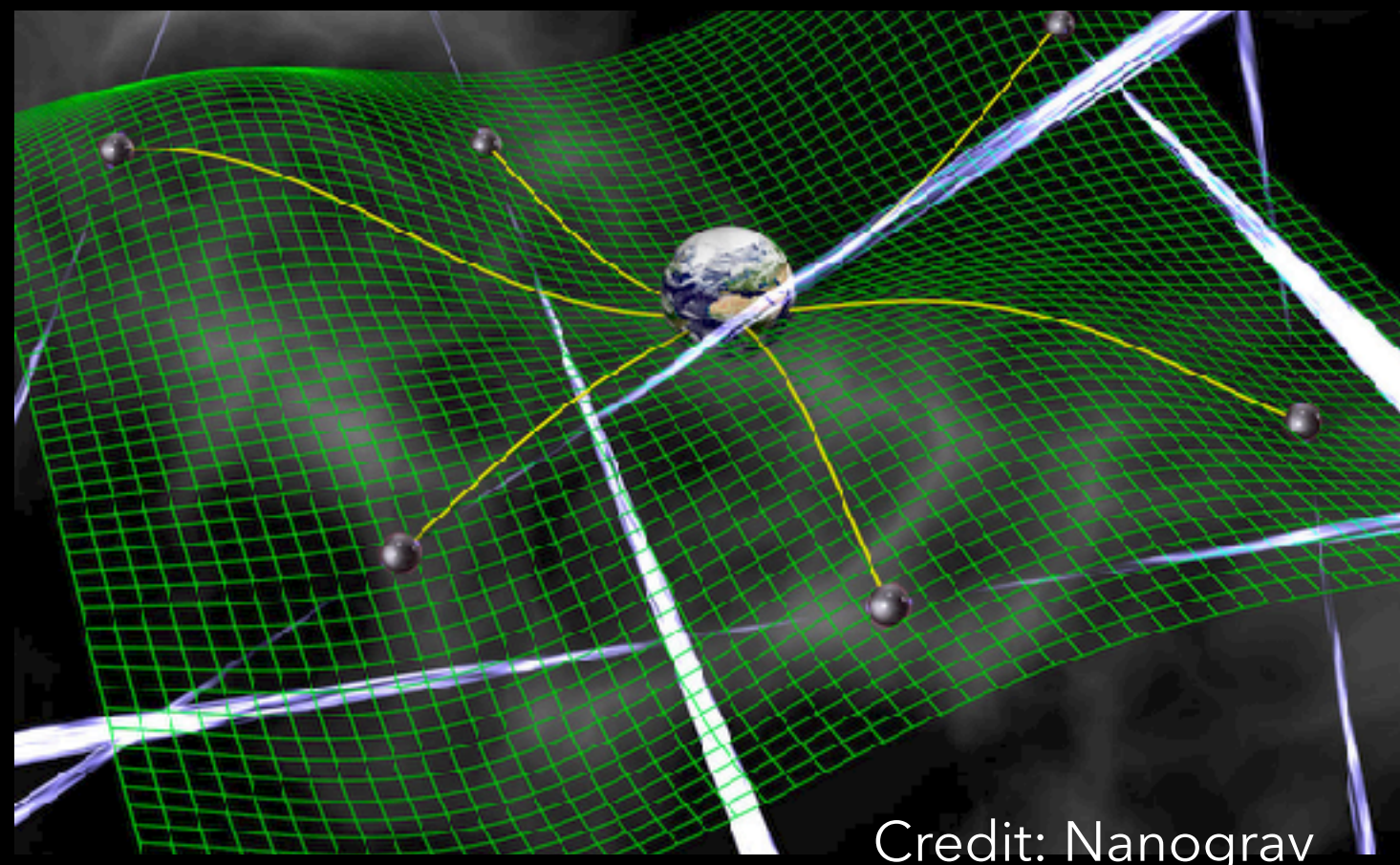
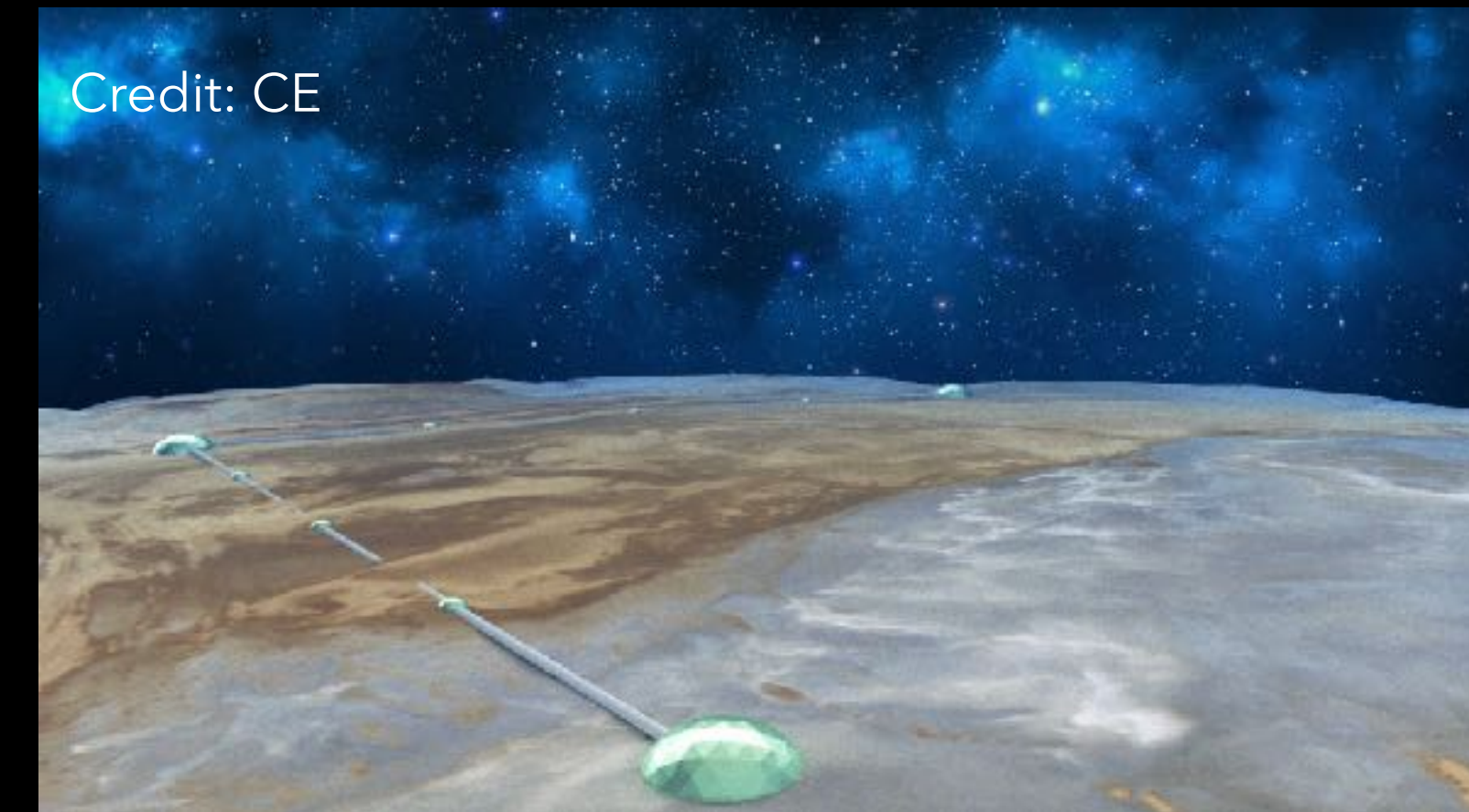
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- ✦ origin of supermassive black holes



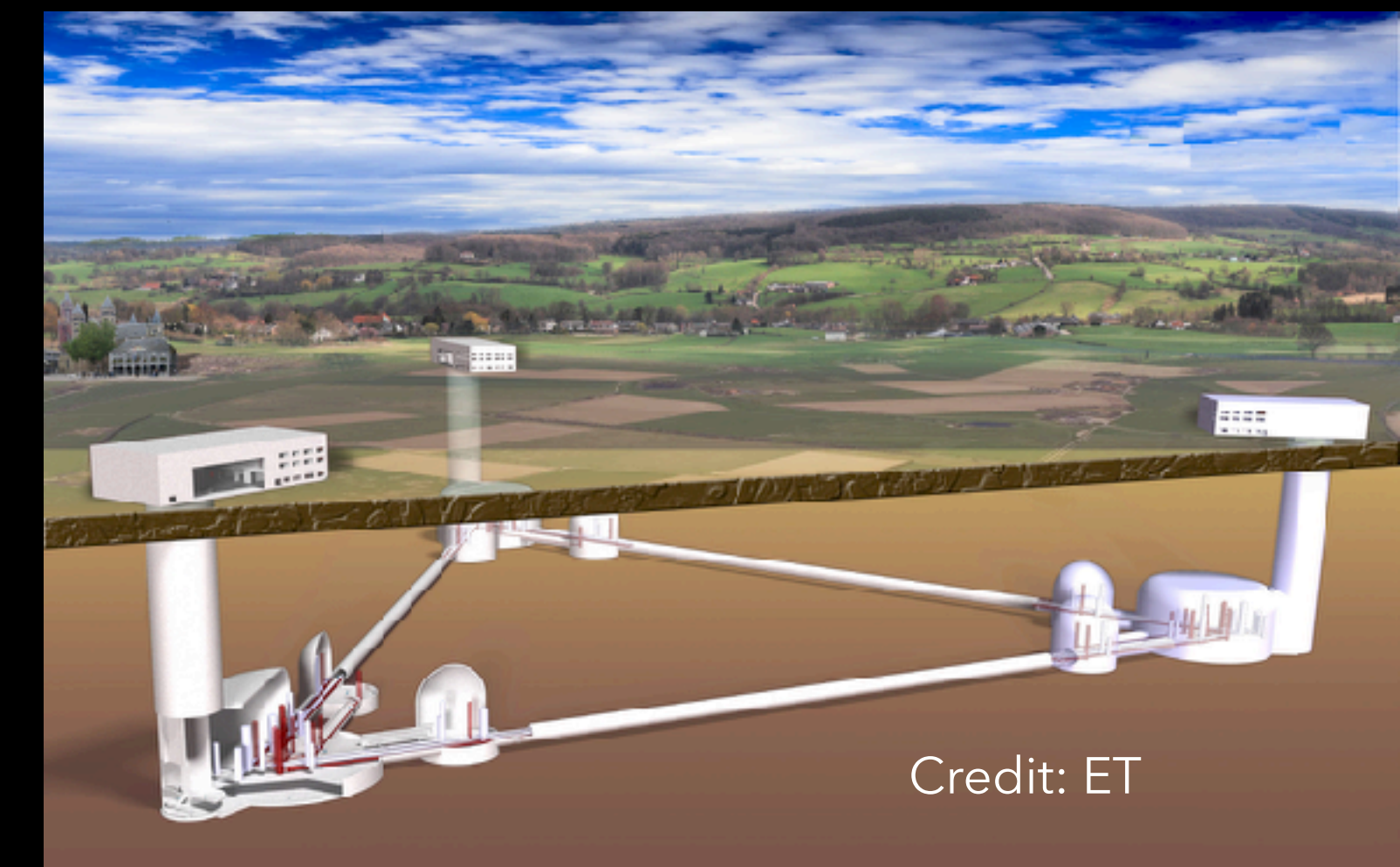
FUTURE GRAVITATIONAL-WAVE OBSERVATORIES



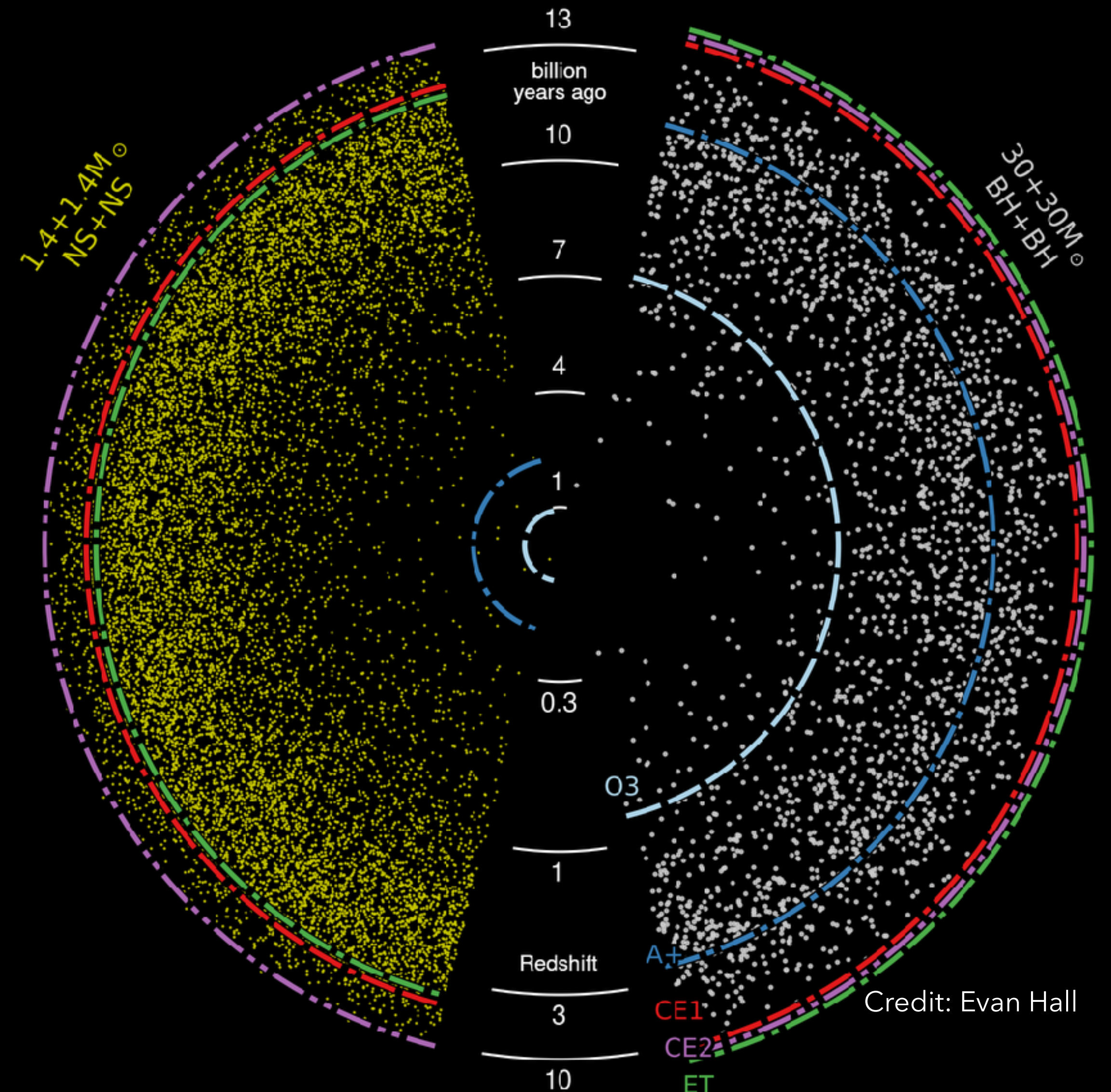
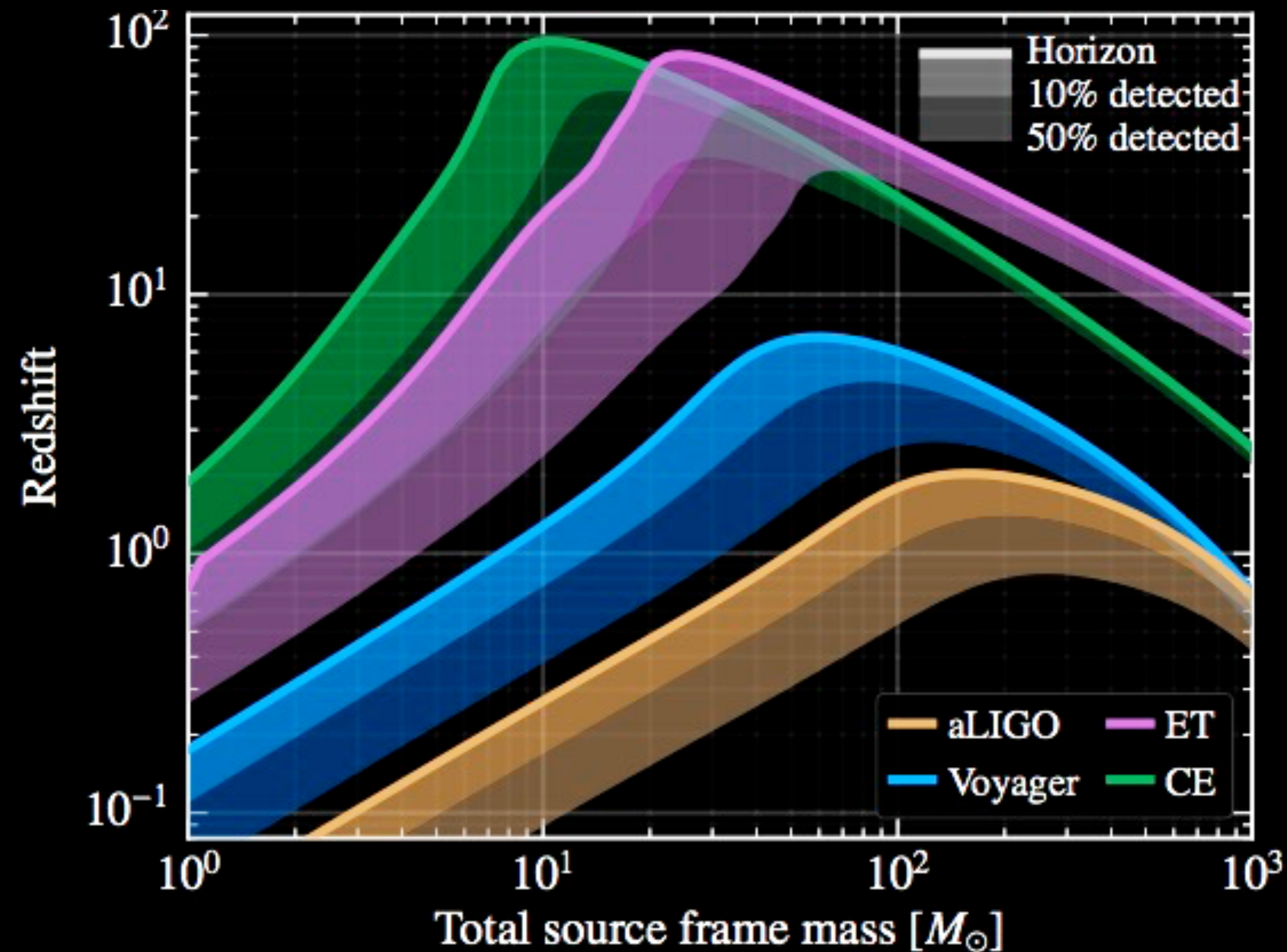
- LIGO/Virgo: black holes and neutron stars are fundamental physics laboratories
- upgrades: A+, KAGRA, LIGO-India (2025+), Voyager
- Future Observatories



- **High-f:** NEMO, Einstein Telescope, Cosmic Explorer (2030+)
- **Mid-f:** MAGIS, AION, AEDGE, DECIGO
- **Low-f:** LISA, Tianqin (mid-2030s)
- **Ultra-low-f:** Pulsar Timing Arrays, Nanograv, PPTA, EPTA, SKA (on going)



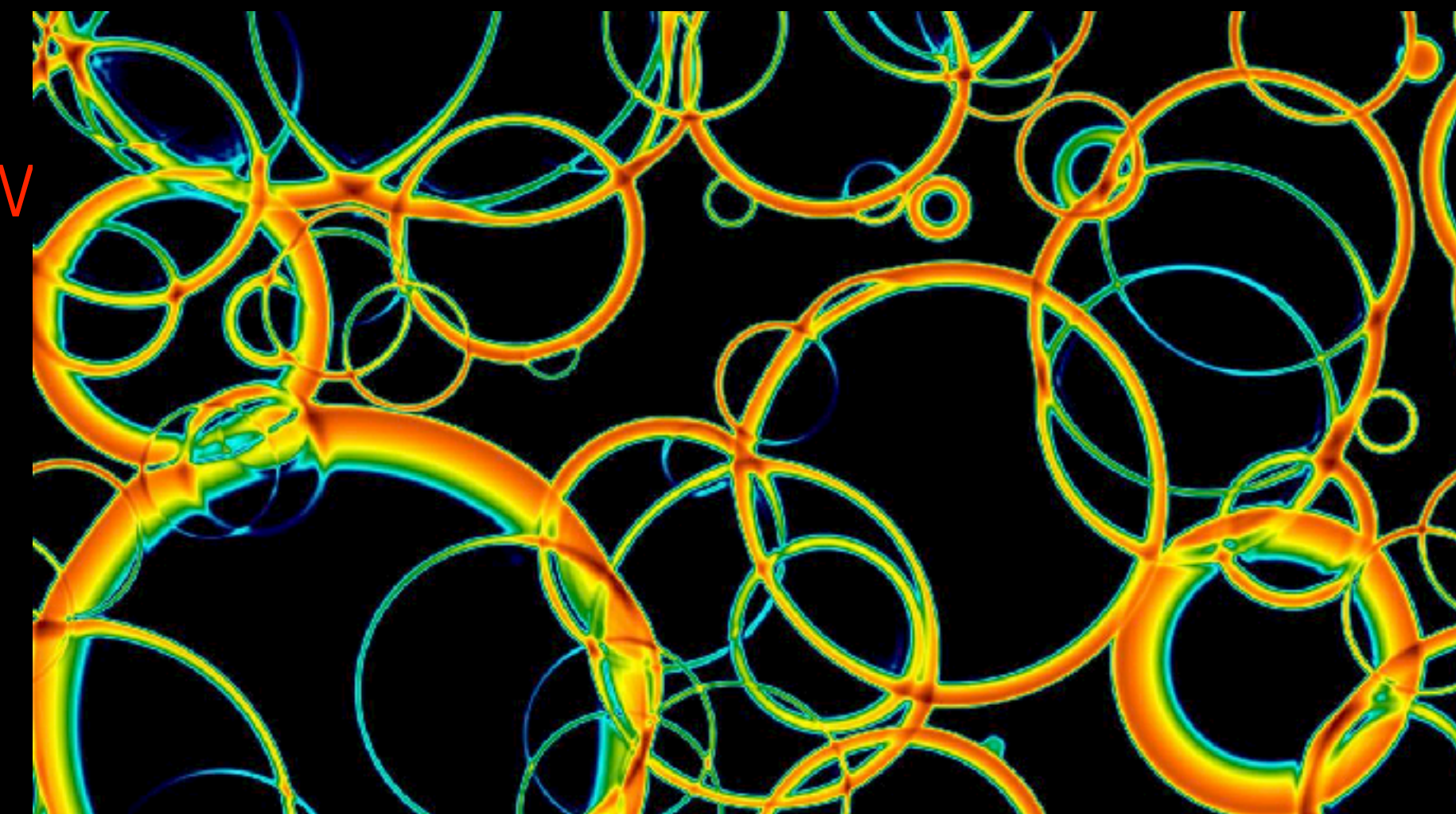
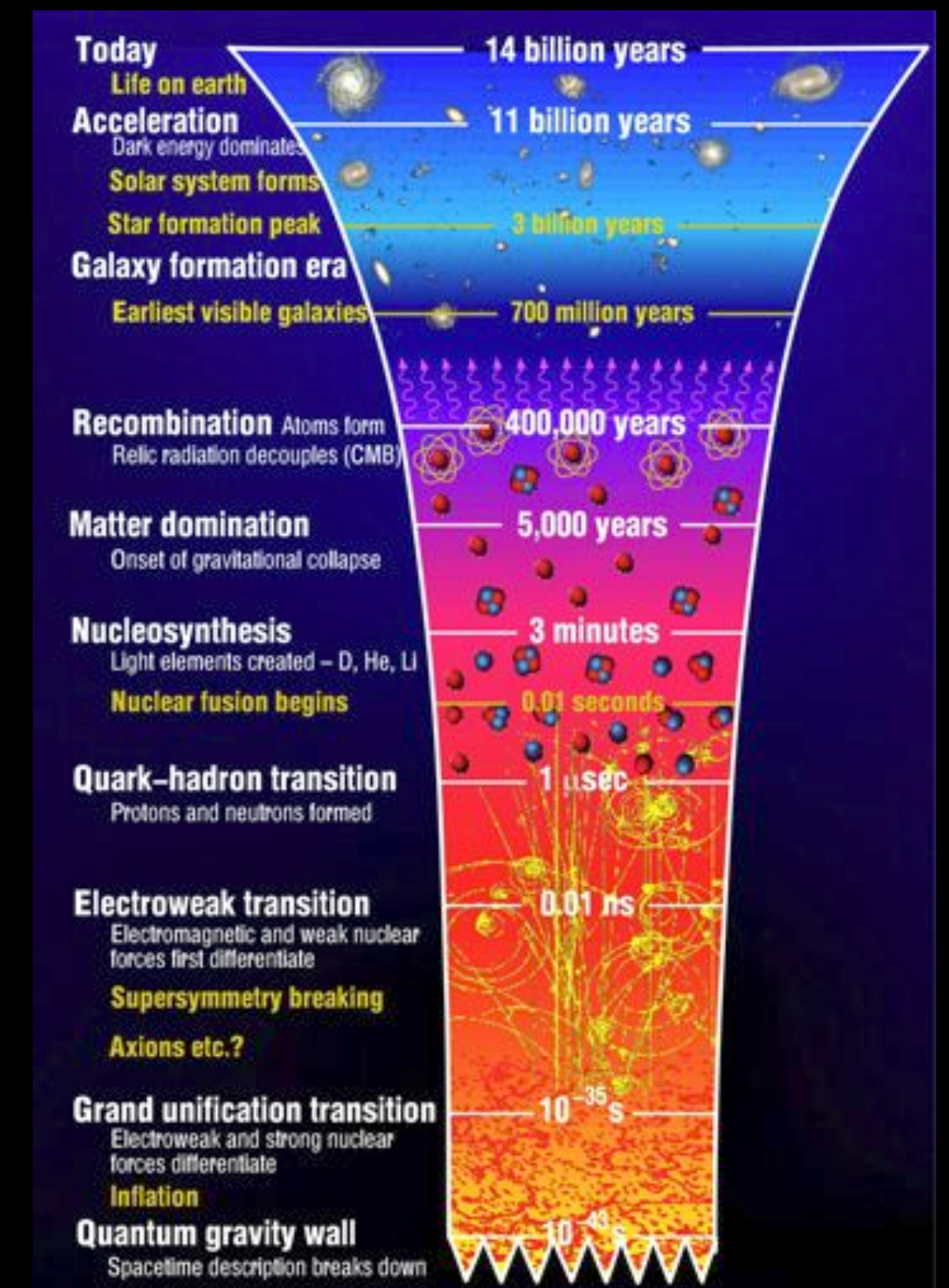
SENSITIVITY AND DISTANCE REACH OF FUTURE GROUND-BASED OBSERVATORIES



Credit: Evan Hall

EARLY UNIVERSE PHASE TRANSITIONS

- bubble collisions during phase transitions could produce observable gravitational waves
- energy scale determines the frequency at which they might appear
- beyond standard model physics
 - mass-gap between BSM particles and EW scale
 - e.g. SUSY phase transitions
 - is the Universe natural?
 - what order is the EW phase transition?
 - first order phase transitions in the Higgs condensate
 - presence of new physics could alter the thermal history of the EW symmetry breaking
 - to what extent do future GW observatories probe EW phase transitions?
- slow roll inflation produces primordial stochastic background
 - observable in CMB B-modes



Credit: D. Weir, University of Helsinki.

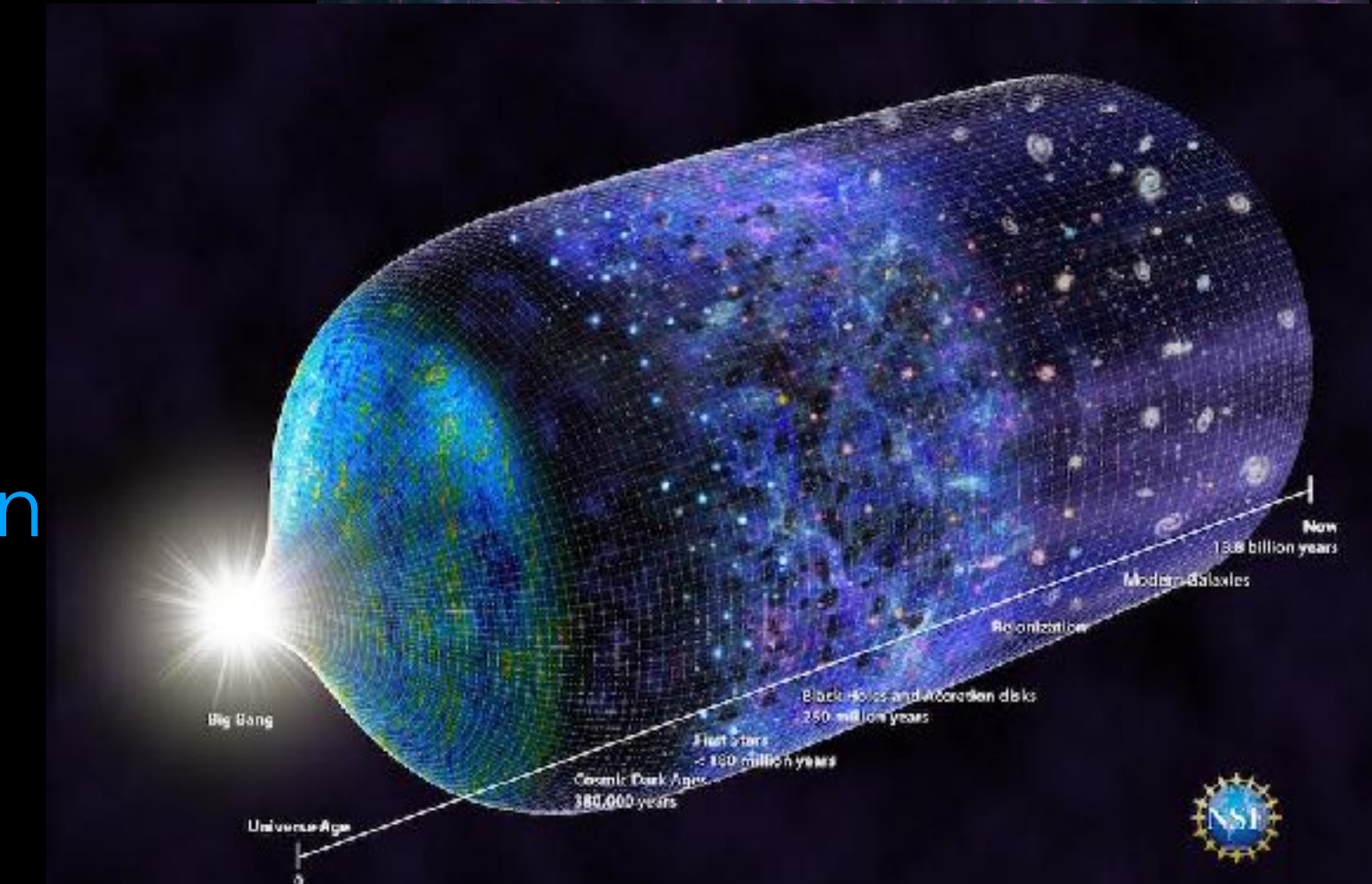
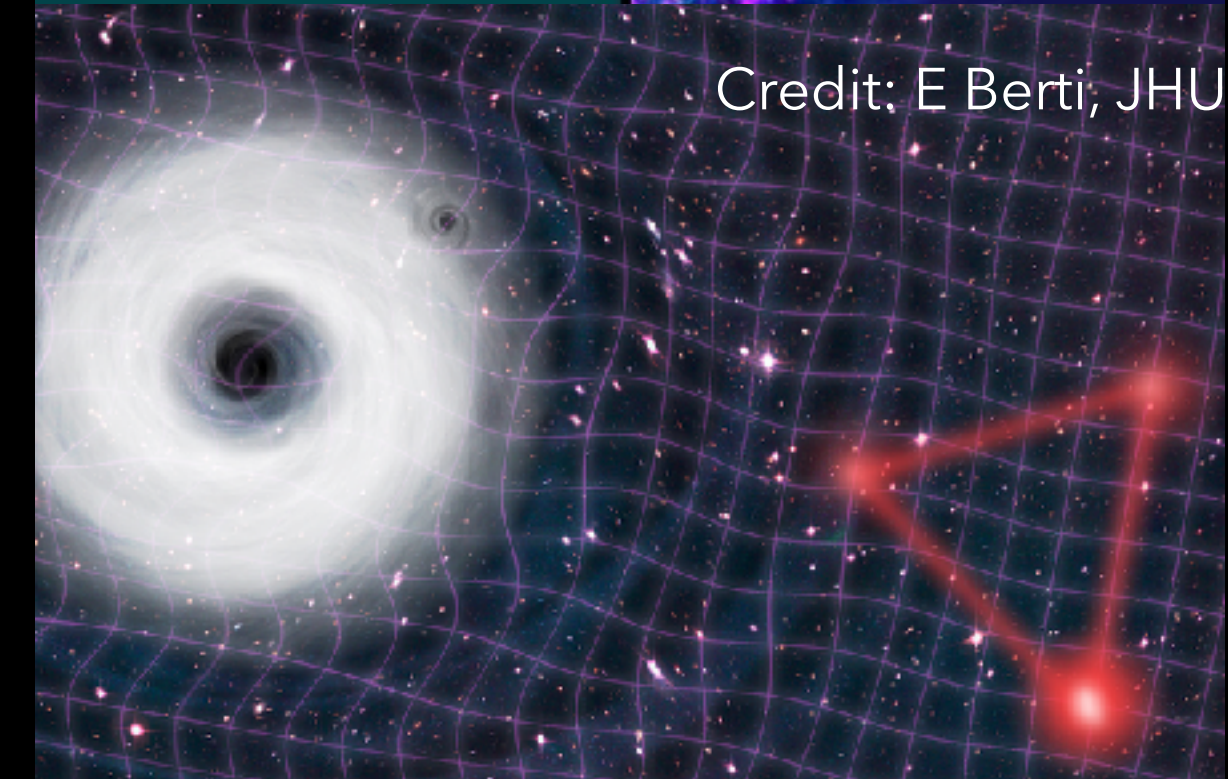
PRIMORDIAL BLACK HOLES

- masses of companion black holes in the first GW discovery was far greater than what **most** astrophysical models predicted
 - however, some models with low metallicity do accommodate the existence of such 'heavy' black holes
- recent discoveries are challenging stellar formation scenarios
 - light companion of GW190814, primary companion of GW190521
 - some of LIGO-Virgo black holes might well be primordial in origin
- how can we ascertain that black holes are not of stellar origin or merger products?
 - detection of sub-solar mass black holes
 - black holes spins that are essentially zero



FUNDAMENTAL PHYSICS

- Black hole horizons, quantum gravity, information paradox
 - black hole spectroscopy, multipolar structure, quantum modifications at horizon scales?
- Corrections to general relativity
 - additional fields, modifications of inspiral radiation
 - black hole uniqueness theorems violated: exotic compact objects?
- Probing dark matter
 - primordial black holes?, mini-charged dark matter, ultralight boson clouds, bosonovas, EM signatures?
- Gravitational-wave propagation and graviton mass
 - GW170817: constraints on Lorentz violation in the gravitational sector, Dispersion: graviton mass, extra dimensions, parity violation



FUTURE OF GRAVITATIONAL-WAVE ASTRONOMY

