

GRAVITATIONAL WAVES

SERGIO SIRERA

ICG - UNIVERSITY OF PORTSMOUTH

THINK SPACE LECTURE 23/02/24

GRAVITATIONAL
WAVES

WHAT IS GRAVITY?

HOW HAVE WE UNDERSTOOD
IT THROUGHOUT HISTORY?

AND TODAY?

WHAT PREDICTIONS
CAN WE MAKE?

GRAVITATIONAL WAVES

WHAT IS GRAVITY?

HOW HAVE WE UNDERSTOOD
IT THROUGHOUT HISTORY?

AND TODAY?

WHAT PREDICTIONS
CAN WE MAKE?

GRAVITATIONAL

WAVES

WHAT IS A WAVE?

WHAT ARE SOME
PHYSICAL EXAMPLES?

WHAT ARE THEY ?

HOW ARE
THEY GENERATED?

WHEN WERE THEY
DISCOVERED ?

HOW DO WE
DETECT
THEM ?

HOW MANY HAVE
WE SEEN ?

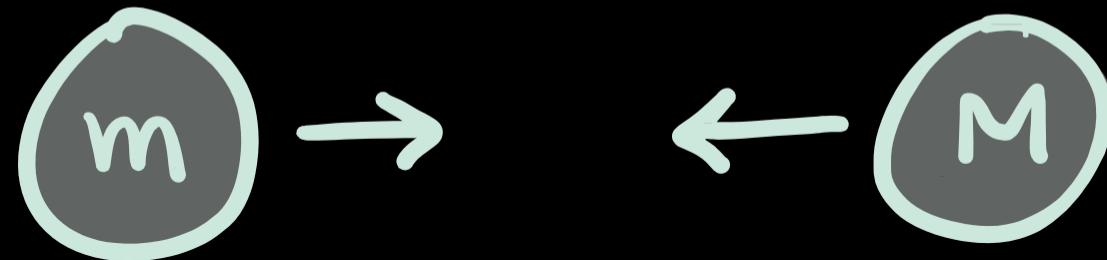
WHY ARE THEY
SO EXCITING ?

WHAT SCIENCE
CAN WE DO
WITH THEM ?

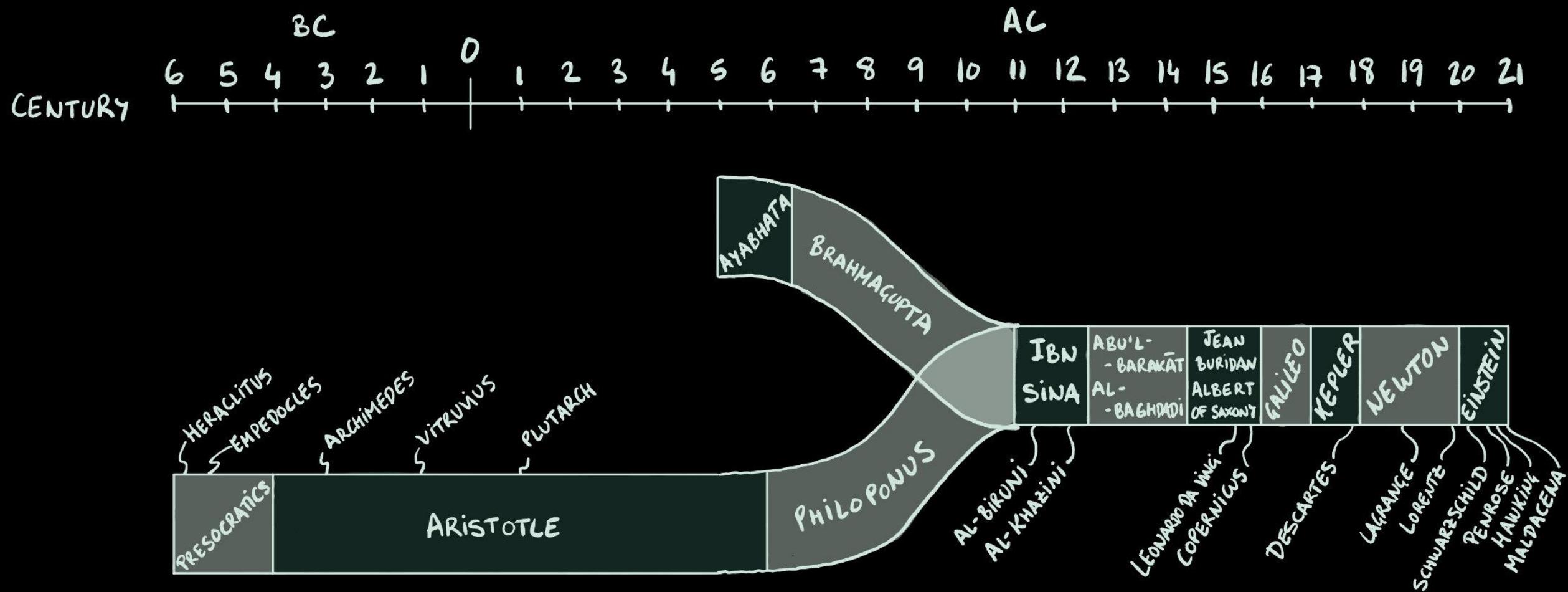
HOW DOES
THE FUTURE
LOOK LIKE ?

GRAVITATIONAL WAVES

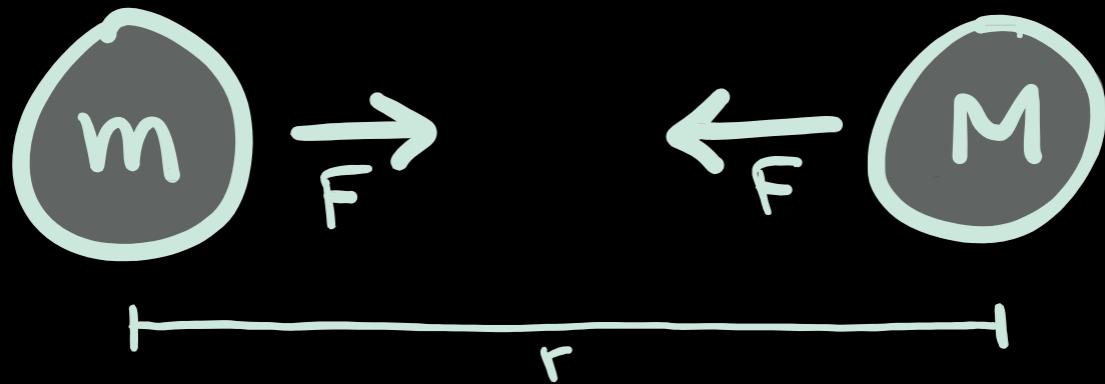
GRAVITY



HISTORY OF GRAVITY

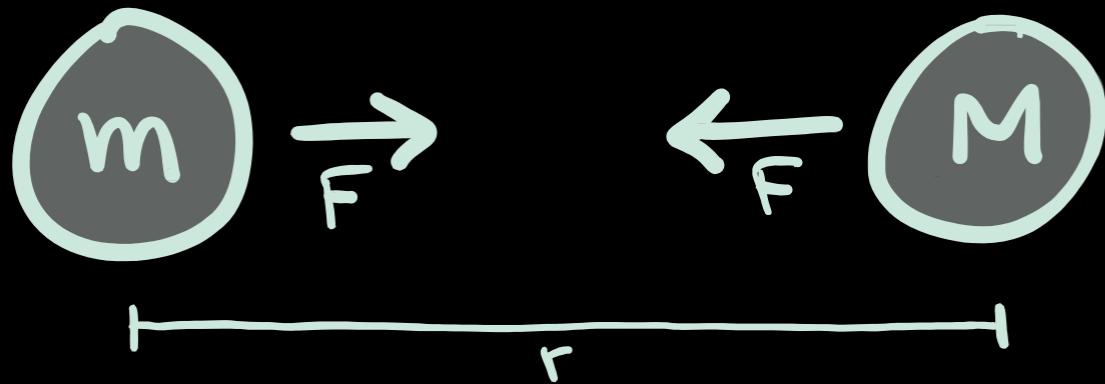


NEWTONIAN GRAVITY



$$F = \frac{GmM}{r^2}$$

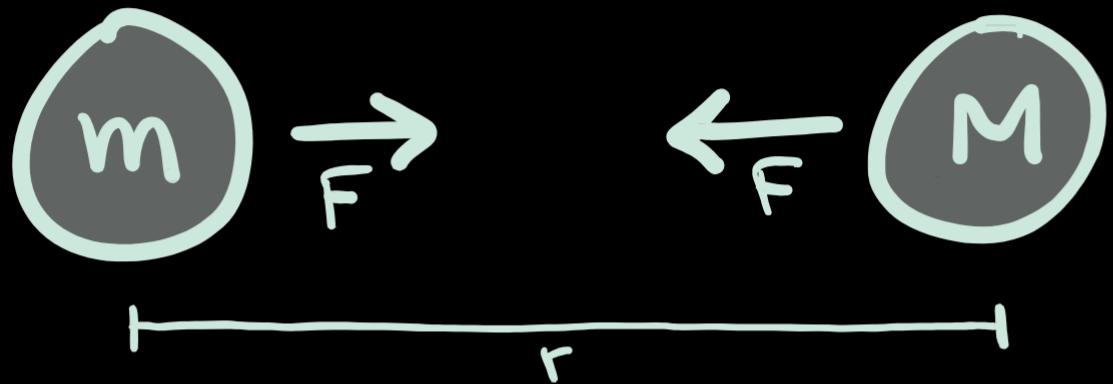
NEWTONIAN GRAVITY



$$F = \frac{G m M}{r^2}$$

2 MASSES

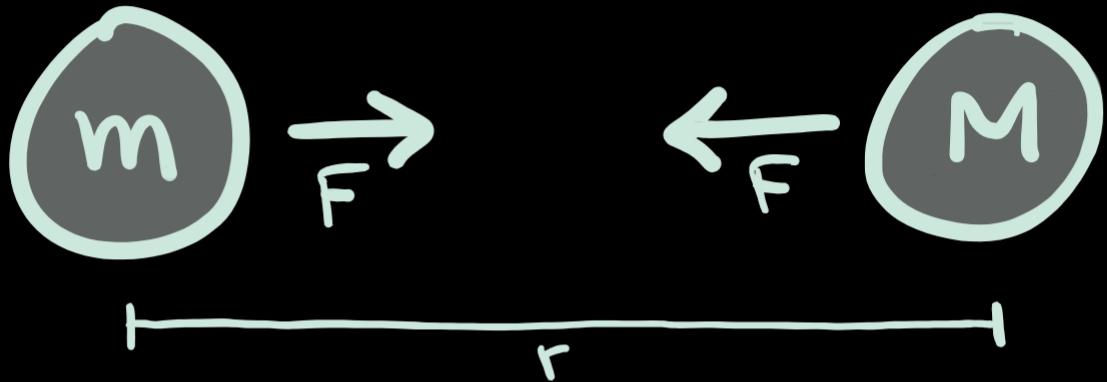
NEWTONIAN GRAVITY



$$F = \frac{GmM}{r^2}$$

2 MASSES
DISTANCE

NEWTONIAN GRAVITY

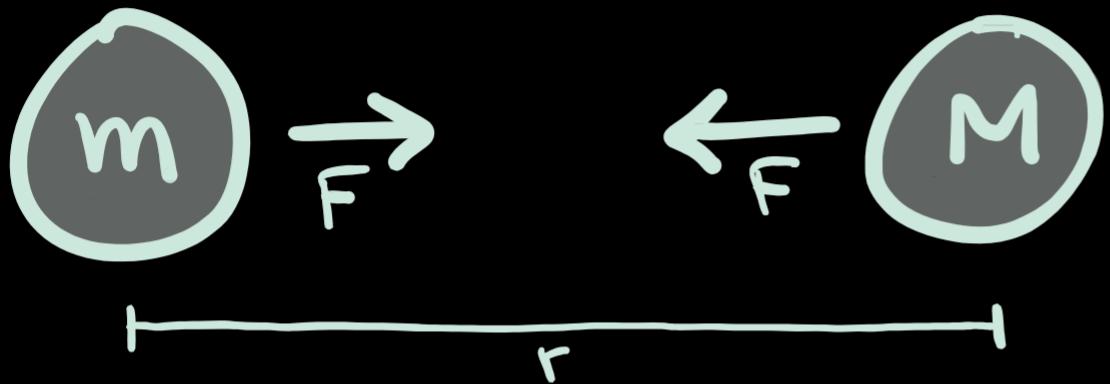


$$F = \frac{GmM}{r^2}$$

NEWTON'S GRAVITATIONAL CONSTANT
2 MASSES
DISTANCE

The equation $F = \frac{GmM}{r^2}$ is written in white chalk. Three arrows point from the text labels to the corresponding parts of the equation: one arrow points from 'NEWTON'S GRAVITATIONAL CONSTANT' to the constant 'G', another points from '2 MASSES' to the product 'mM', and a third points from 'DISTANCE' to the variable 'r' in the denominator.

NEWTONIAN GRAVITY



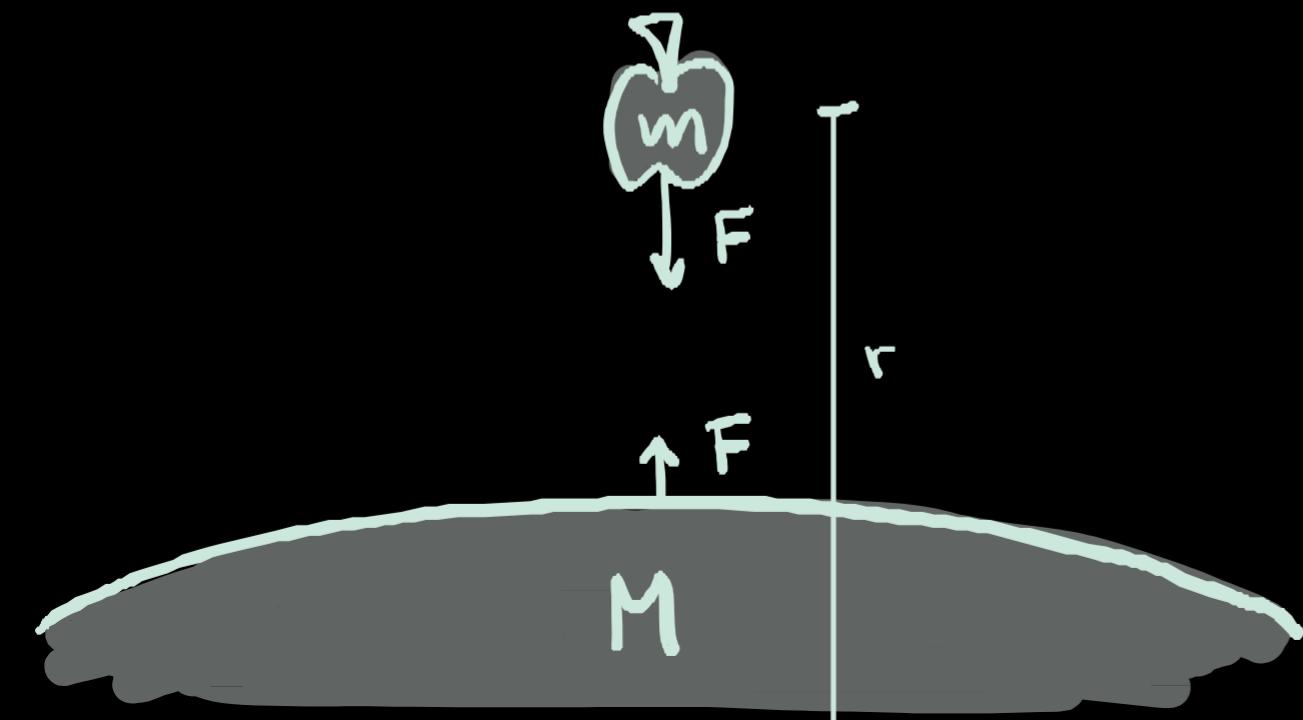
$$F = \frac{GmM}{r^2}$$

NEWTON'S GRAVITATIONAL CONSTANT
2 MASSES
FORCE
DISTANCE

The equation for gravitational force is $F = \frac{GmM}{r^2}$. Arrows point from the labels "FORCE" and "DISTANCE" to the corresponding terms in the equation. An arrow also points from the label "2 MASSES" to the product of the two masses (mM) in the numerator.

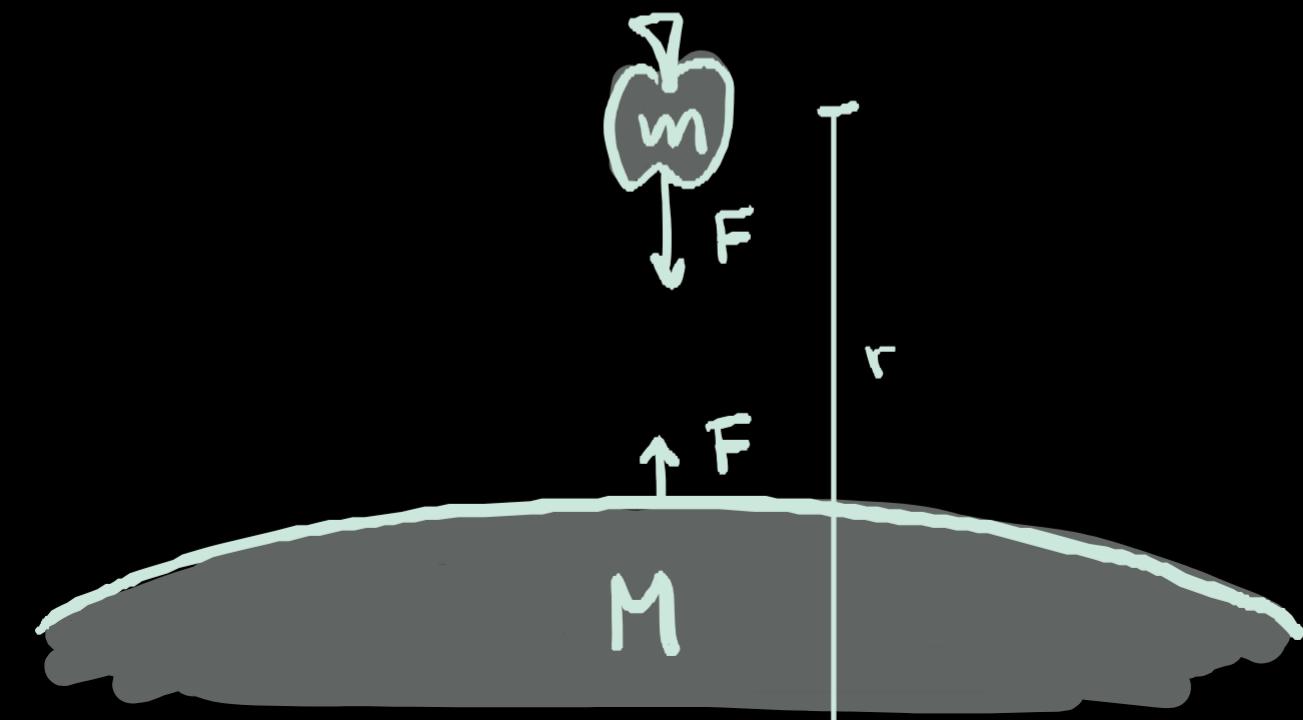
NEWTONIAN GRAVITY

HOW LONG WILL AN APPLE TAKE
TO FALL TO THE GROUND?

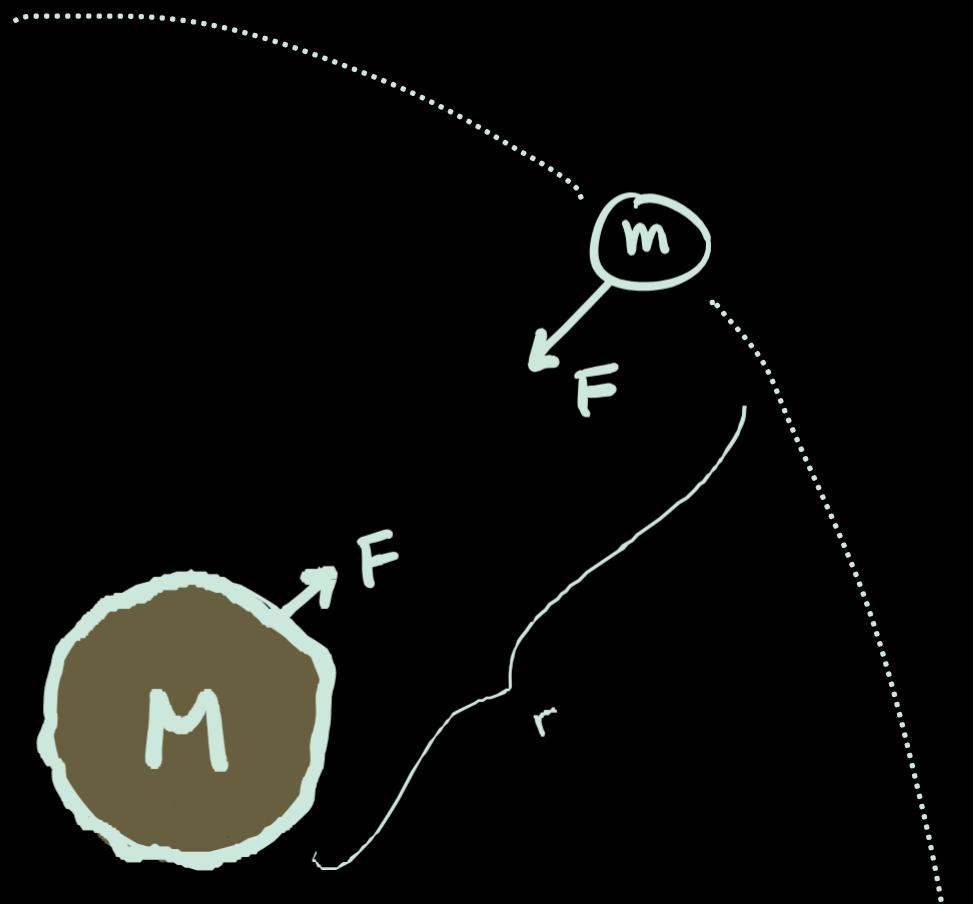


NEWTONIAN GRAVITY

HOW LONG WILL AN APPLE TAKE
TO FALL TO THE GROUND?



WHAT IS THE DISTANCE FROM
THE EARTH TO THE SUN?



PHYSICS AT LATE 1800s

NEWTONIAN MECHANICS

+

ELECTROMAGNETISM

+

THERMODYNAMICS

= PHYSICS IS COMPLETE

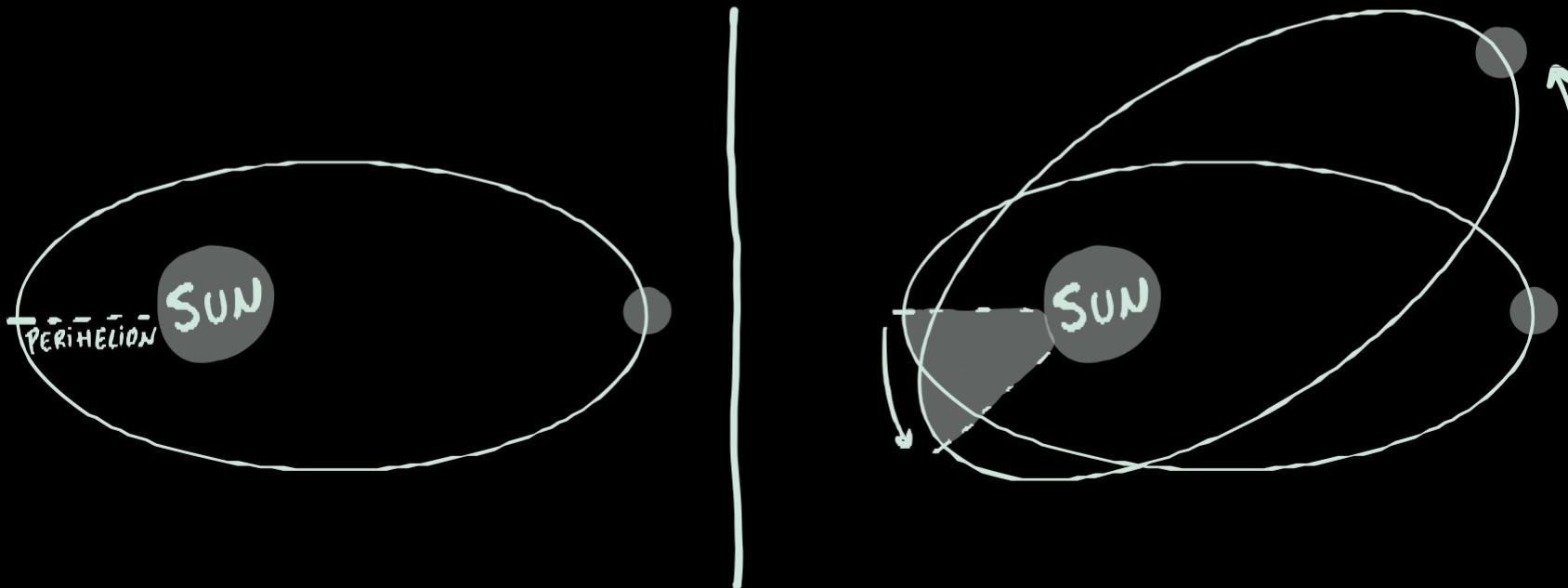
NEWTONIAN GRAVITY PROBLEMS!

MERCURY'S ORBIT

PREDICTION

vs

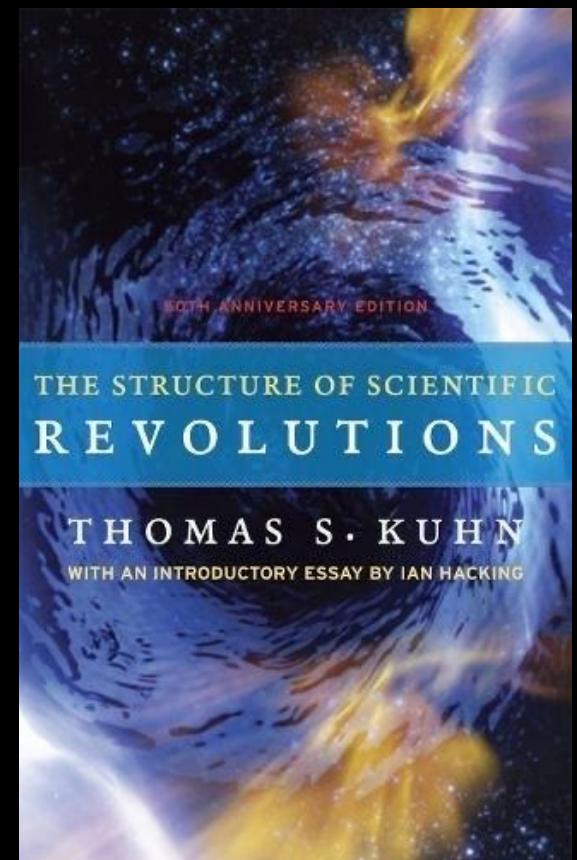
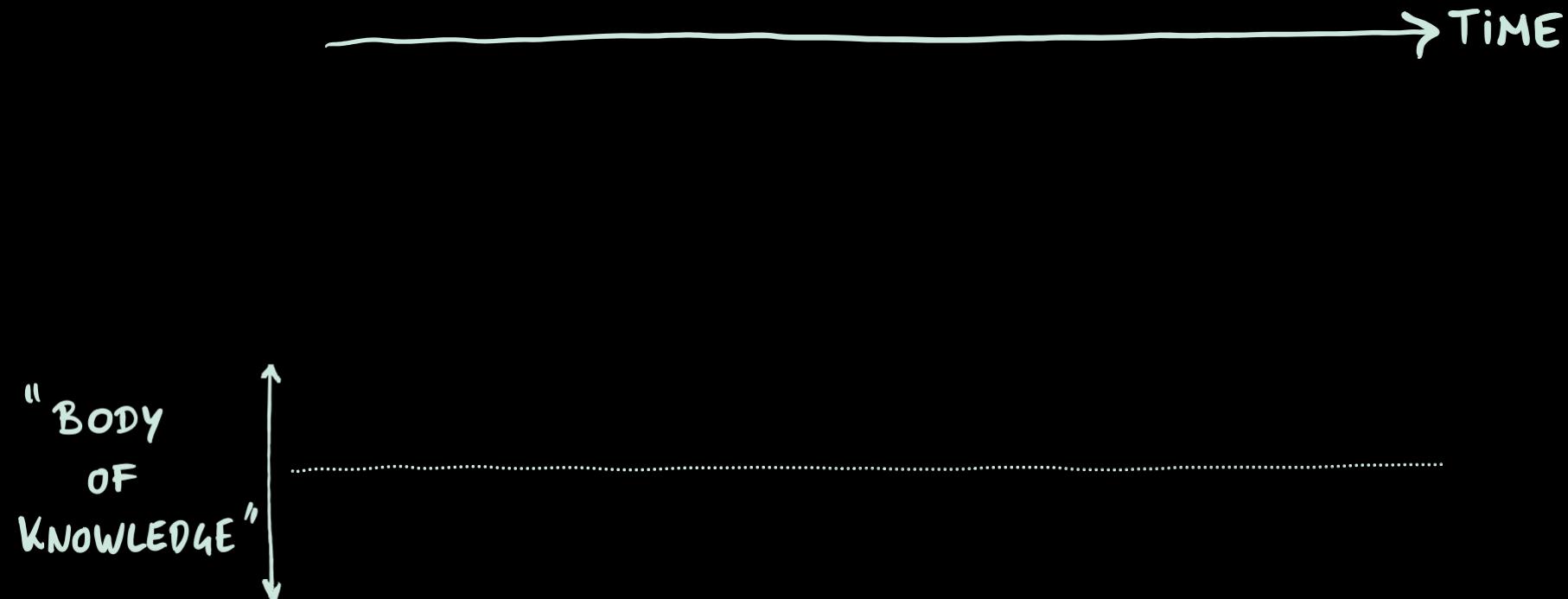
OBSERVATION



HOW DOES SCIENCE WORK?

(PHILOSOPHICAL TANGENT)

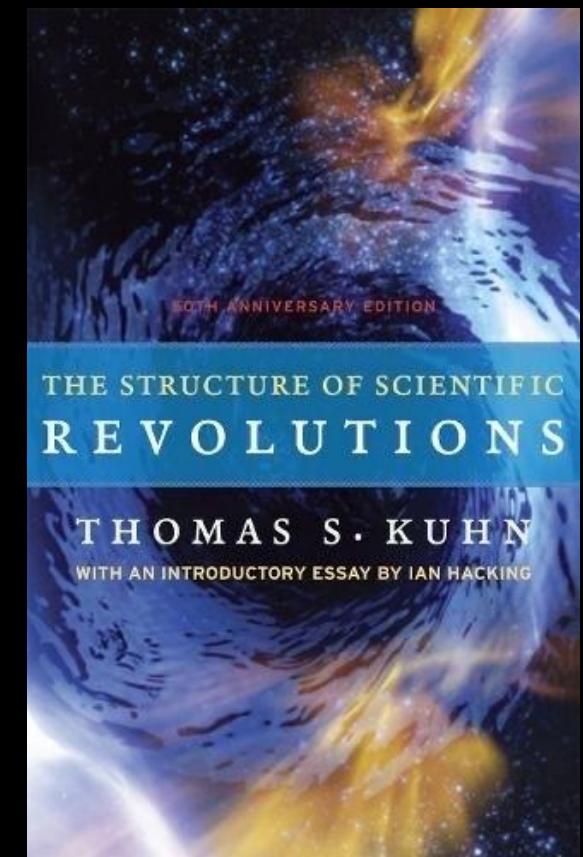
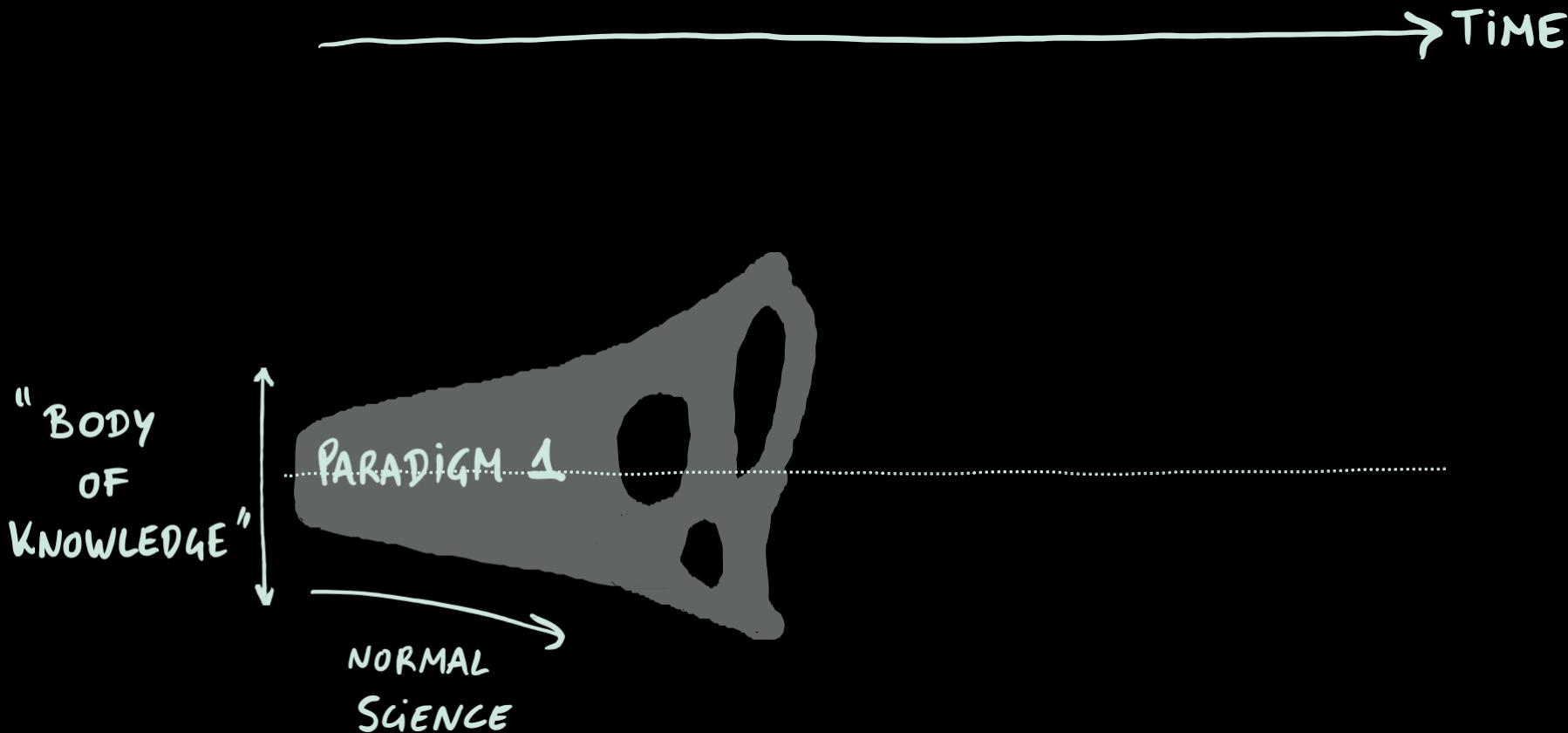
- THOMAS KUHN (1962)



HOW DOES SCIENCE WORK?

(PHILOSOPHICAL TANGENT)

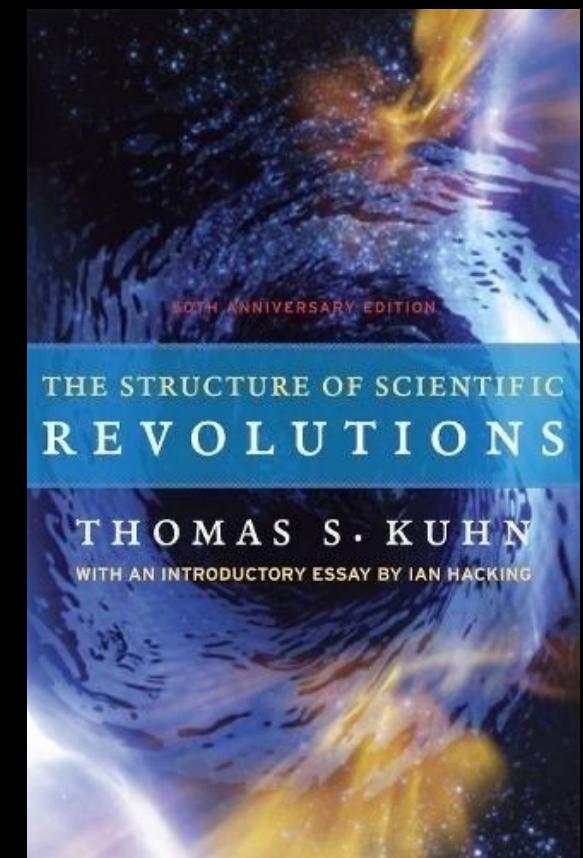
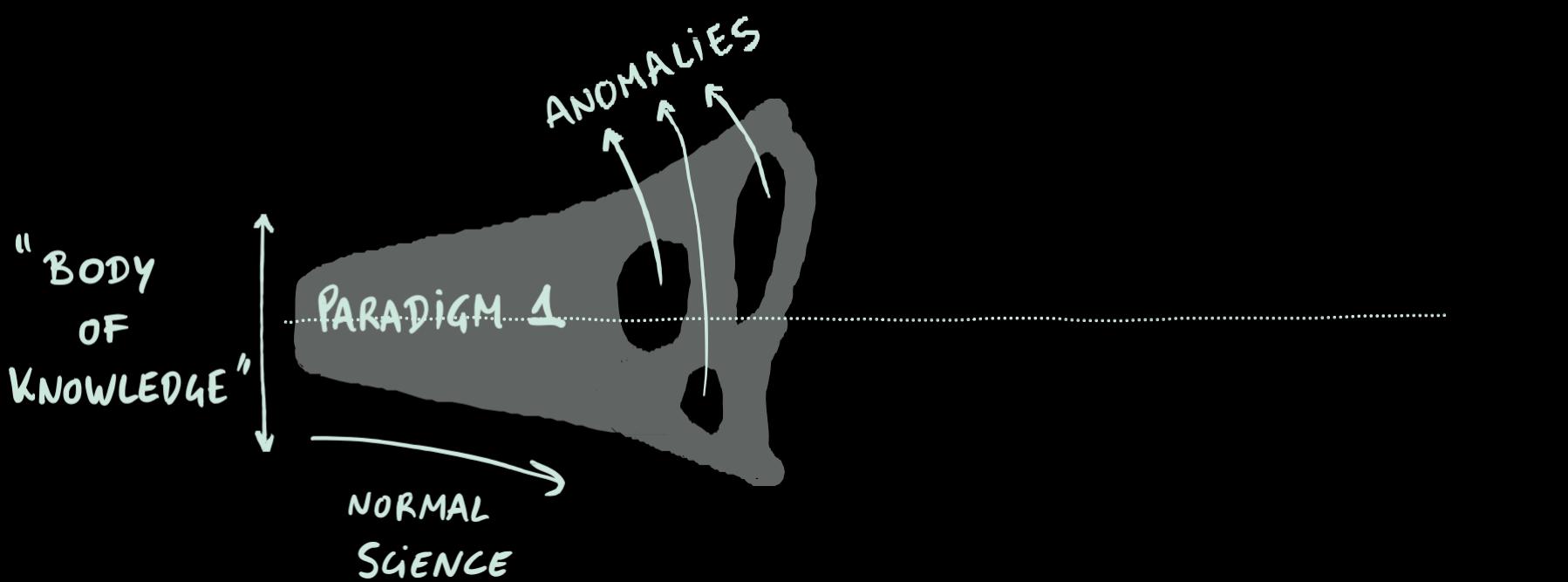
- THOMAS KUHN (1962)



HOW DOES SCIENCE WORK?

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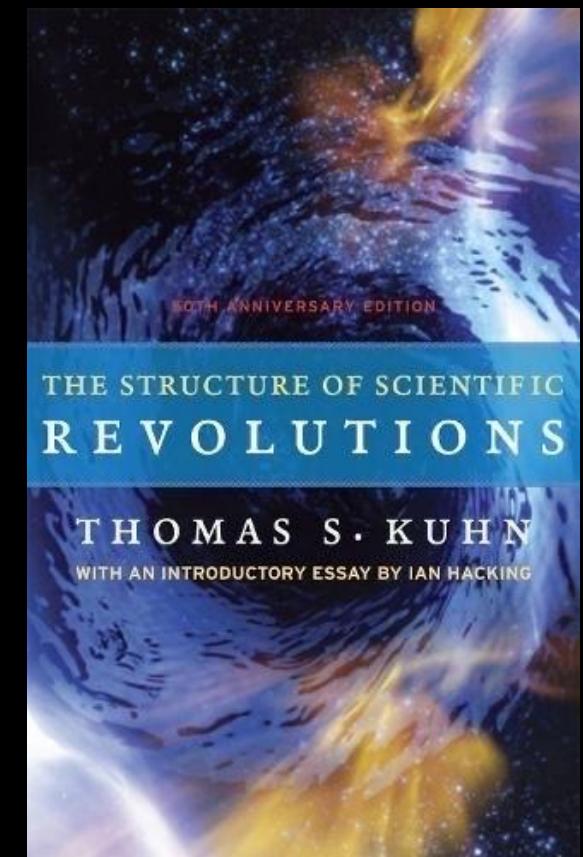
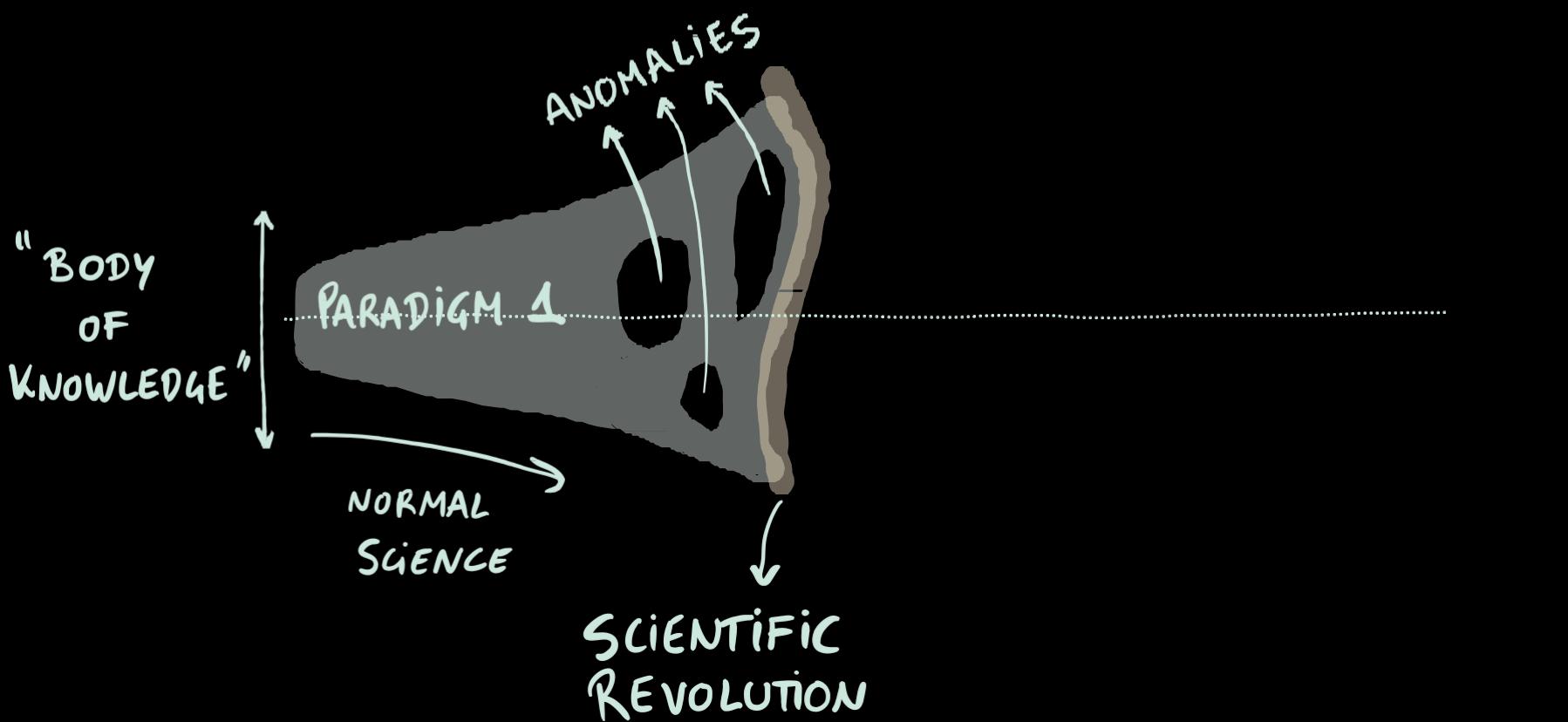
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HOW DOES SCIENCE WORK?

(PHILOSOPHICAL TANGENT)

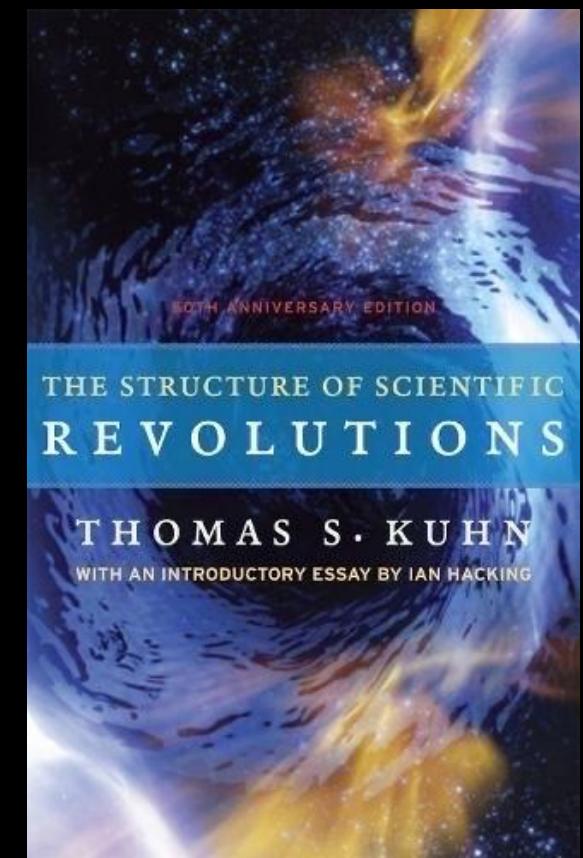
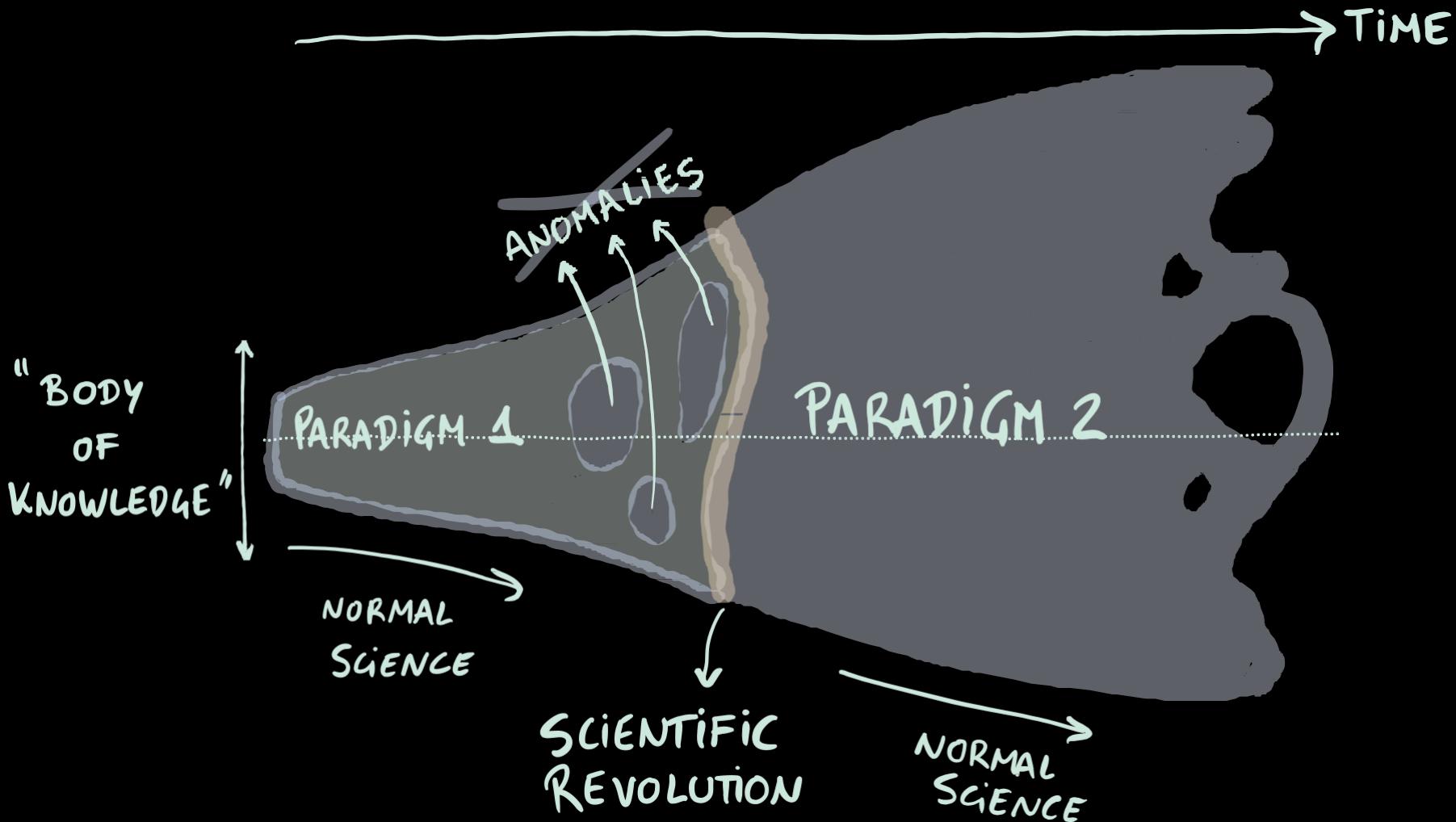
- THOMAS KUHN (1962)



HOW DOES SCIENCE WORK?

(PHILOSOPHICAL TANGENT)

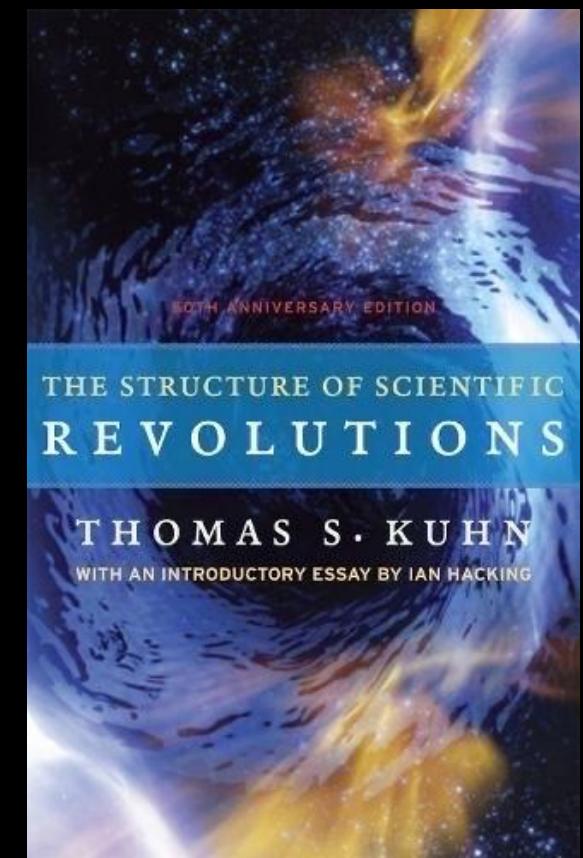
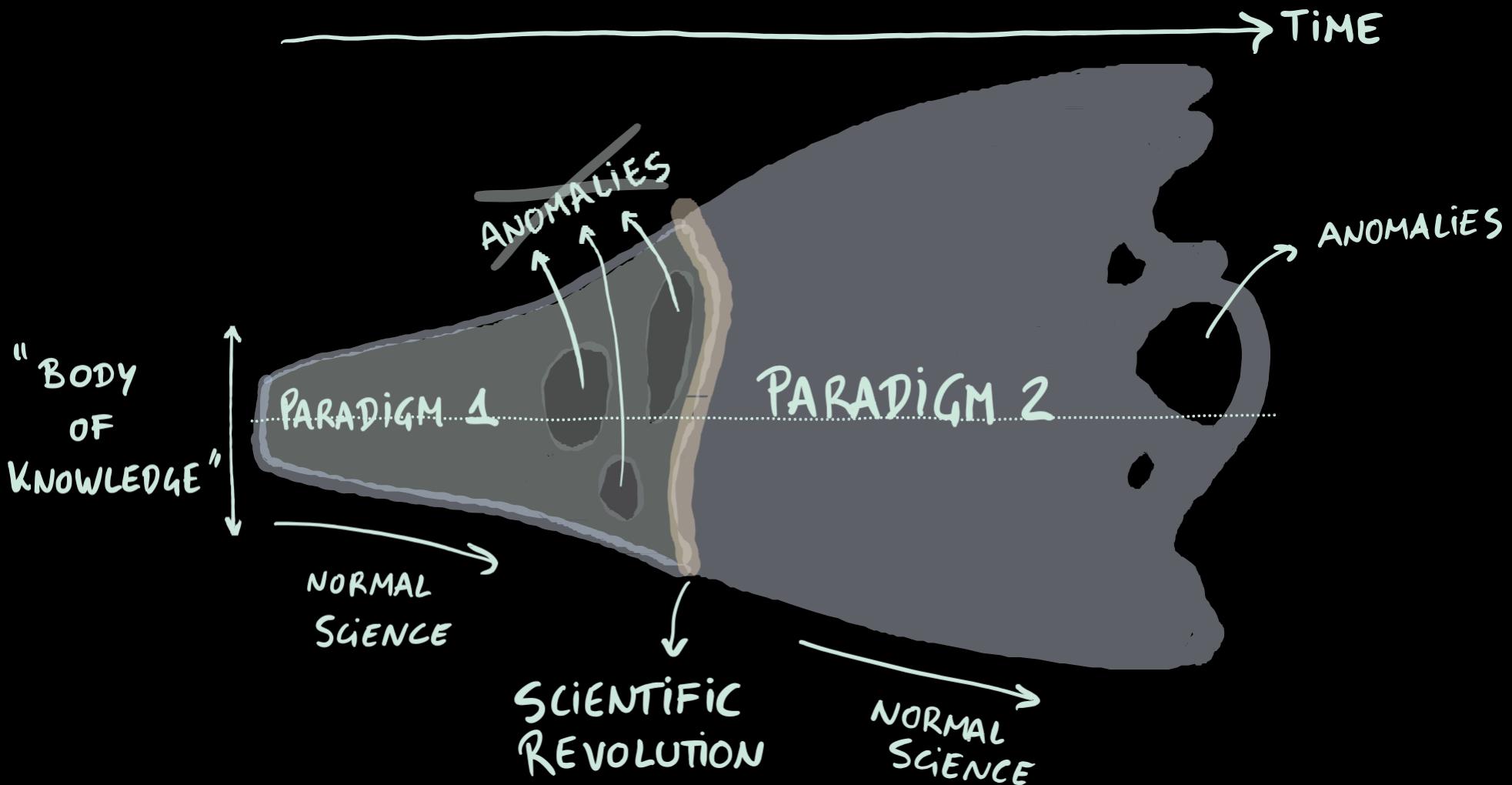
- THOMAS KUHN (1962)



HOW DOES SCIENCE WORK?

(PHILOSOPHICAL TANGENT)

- THOMAS KUHN (1962)

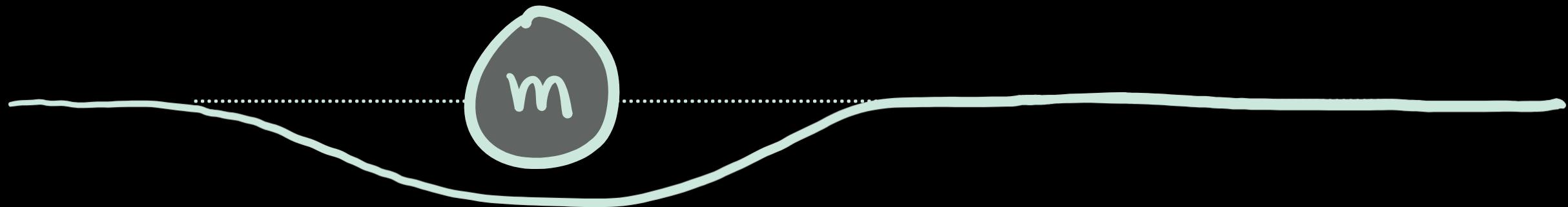


EINSTEIN'S GENERAL RELATIVITY

GRAVITY IS THE GEOMETRY OF SPACE + TIME

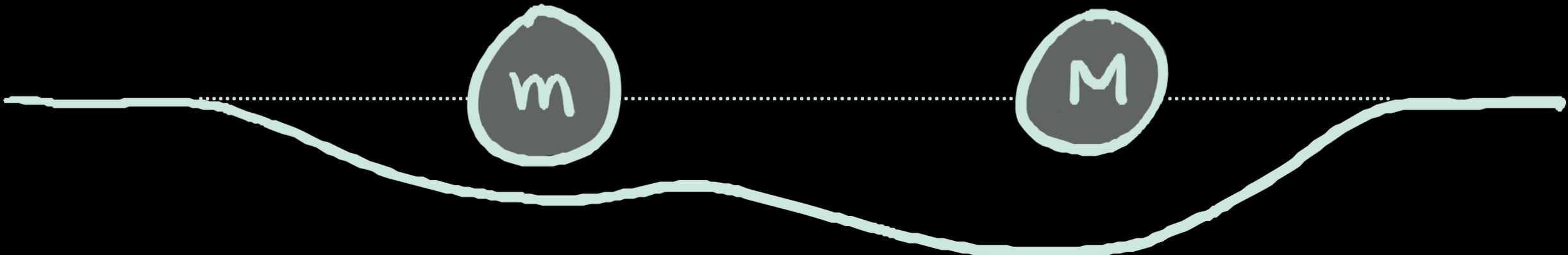
EINSTEIN'S GENERAL RELATIVITY

GRAVITY IS THE GEOMETRY OF SPACE + TIME



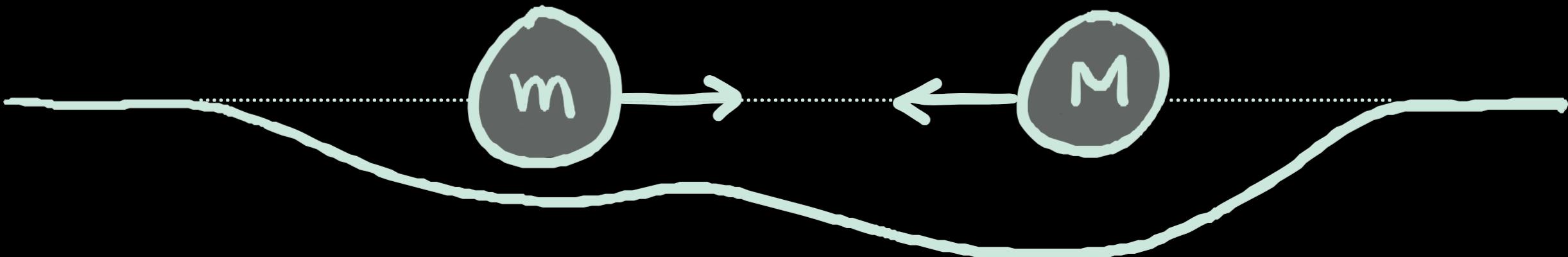
EINSTEIN'S GENERAL RELATIVITY

GRAVITY IS THE GEOMETRY OF SPACE + TIME



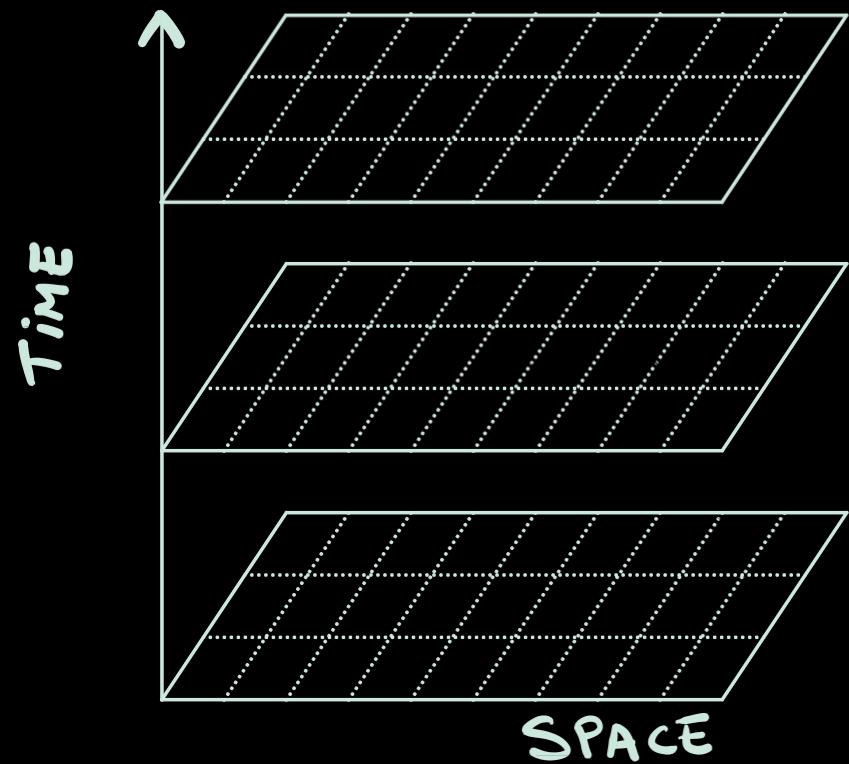
EINSTEIN'S GENERAL RELATIVITY

GRAVITY IS THE GEOMETRY OF SPACE + TIME

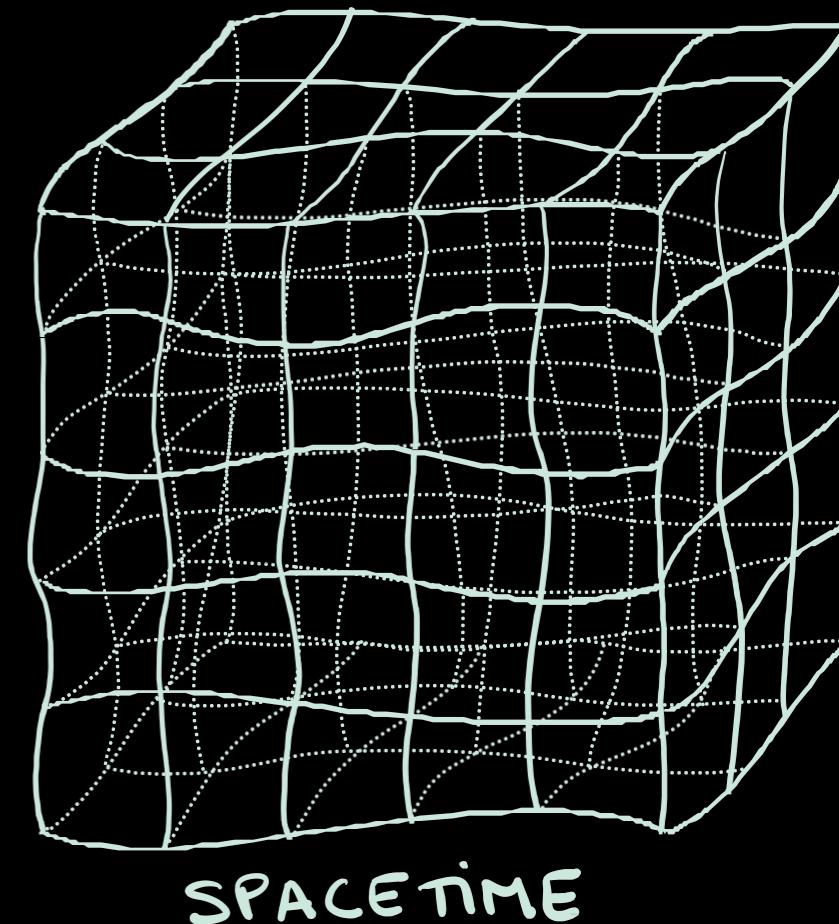


WHAT IS SPACETIME ?

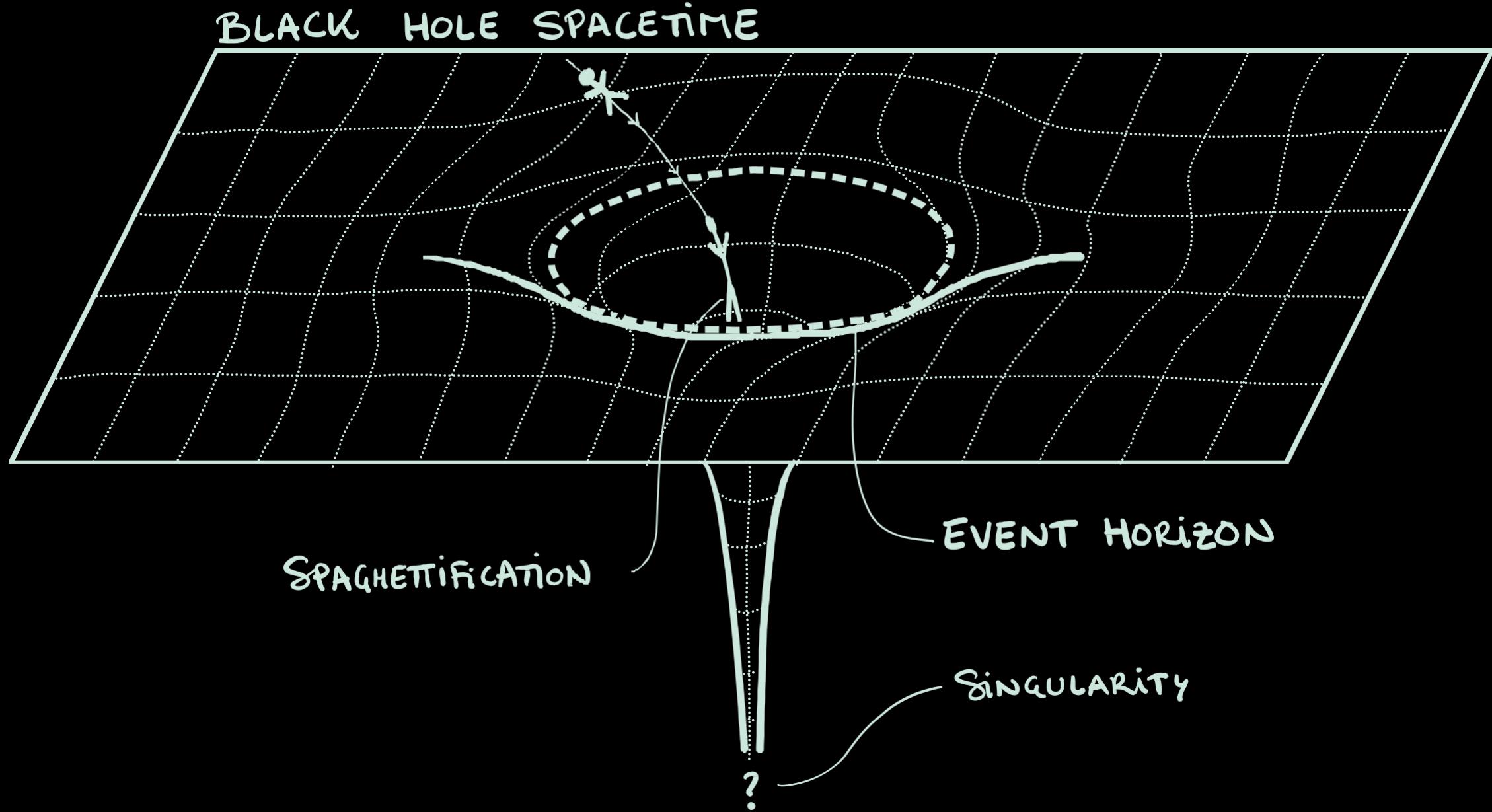
NEWTONIAN GRAVITY



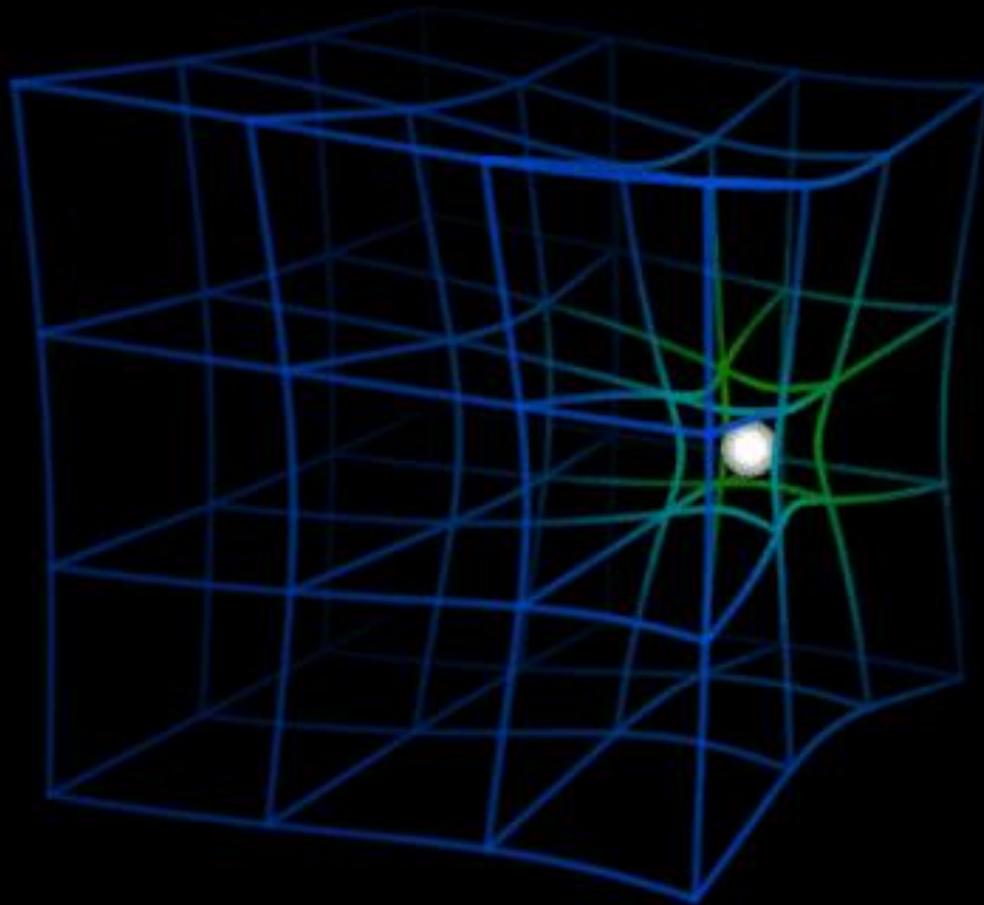
GENERAL RELATIVITY



WHAT IS SPACETIME ?



WHAT IS SPACETIME ?



EINSTEIN'S GENERAL RELATIVITY

GRAVITY IS THE GEOMETRY OF SPACE + TIME

EINSTEIN'S GENERAL RELATIVITY

GRAVITY IS THE GEOMETRY OF SPACE + TIME

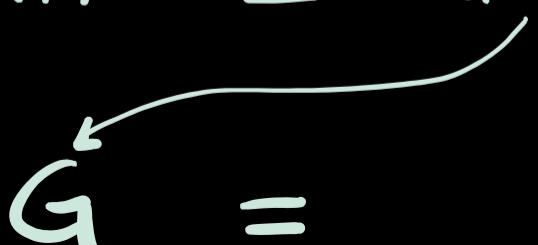
GRAVITY \equiv GEOMETRY OF SPACETIME

EINSTEIN'S GENERAL RELATIVITY

GRAVITY IS THE GEOMETRY OF SPACE + TIME

GRAVITY = GEOMETRY OF SPACETIME

$G =$



EINSTEIN'S GENERAL RELATIVITY

GRAVITY IS THE GEOMETRY OF SPACE + TIME

$$\text{GRAVITY} = \text{GEOMETRY OF SPACETIME}$$
$$G = T$$

The diagram consists of two equations. Above, 'GRAVITY' is equated to 'GEOMETRY OF SPACETIME'. Below, 'G' is equated to 'T'. Two curved arrows originate from the word 'GRAVITY' and point to the first equals sign in each equation. Another curved arrow originates from the phrase 'GEOMETRY OF SPACETIME' and points to the second equals sign. A final curved arrow originates from the letter 'G' and points to the first equals sign.

EINSTEIN'S GENERAL RELATIVITY

GRAVITY IS THE GEOMETRY OF SPACE + TIME

$$\text{GRAVITY} = \text{GEOMETRY OF SPACETIME}$$
$$G = T$$

EINSTEIN FIELD EQUATIONS

EINSTEIN FIELD EQUATIONS

$$G = T$$

$$G_{\mu\nu} = \kappa T_{\mu\nu}$$

EINSTEIN FIELD EQUATIONS

$$G = T$$

$$G_{\mu\nu} = \frac{\text{GRAVITATIONAL CONSTANT}}{\kappa} T_{\mu\nu}$$

EINSTEIN FIELD EQUATIONS

$$G = T$$

$$G_{\mu\nu} = \frac{1}{K} T_{\mu\nu}$$

GRAVITATIONAL CONSTANT
ENERGY-MOMENTUM TENSOR

EINSTEIN FIELD EQUATIONS

$$G = T$$

$$G_{\mu\nu} = \frac{1}{K} T_{\mu\nu}$$

GRAVITATIONAL CONSTANT
↑
EINSTEIN TENSOR ENERGY-MOMENTUM TENSOR

SCALAR: $a = a_0$

VECTOR: $a_\mu = (a_0, a_1, a_2, a_3)$

2-TENSOR: $a_{\mu\nu} = \begin{pmatrix} a_{00} & a_{01} & a_{02} & a_{03} \\ a_{10} & a_{11} & a_{12} & a_{13} \\ a_{20} & a_{21} & a_{22} & a_{23} \\ a_{30} & a_{31} & a_{32} & a_{33} \end{pmatrix}$

EINSTEIN FIELD EQUATIONS

$$G_{\mu\nu} = \kappa T_{\mu\nu}$$

EINSTEIN FIELD EQUATIONS

MATTER TELLS SPACETIME
HOW TO CURVE

$$G_{\mu\nu} = \kappa T_{\mu\nu}$$

EINSTEIN FIELD EQUATIONS

MATTER TELLS SPACETIME
HOW TO CURVE

$$G_{\mu\nu} = \kappa T_{\mu\nu}$$

CURVATURE TELLS
MATTER HOW TO MOVE

EINSTEIN FIELD EQUATIONS

$$G_{\mu\nu} = \kappa T_{\mu\nu}$$
$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R$$

EINSTEIN FIELD EQUATIONS

$$G_{\mu\nu} = \kappa T_{\mu\nu}$$



$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R$$

$$= \Gamma_{\delta\rho}^\sigma \Gamma_{\mu\nu}^\rho - \Gamma_{\mu\sigma}^\rho \Gamma_{\rho\nu}^\delta - \frac{1}{2} g_{\mu\nu} g^{\sigma\rho} (\Gamma_{\lambda\gamma}^\lambda \Gamma_{\sigma\mu}^\gamma - \Gamma_{\sigma\delta}^\lambda \Gamma_{\lambda\rho}^\gamma - \partial_\delta \Gamma_{\lambda\rho}^\lambda + \partial_\lambda \Gamma_{\delta\rho}^\lambda) - \partial_\mu \Gamma_{\delta\delta}^\sigma + \partial_\sigma \Gamma_{\mu\delta}^\delta$$

EINSTEIN FIELD EQUATIONS

$$G_{\mu\nu} = \kappa T_{\mu\nu}$$

$G_{\mu\nu} =$

$$\begin{aligned} & -\frac{1}{2} g_{cb} \left(\frac{1}{4} g^{df} g^{ei} (\partial_d g_{ef} + \partial_e g_{df} - \partial_f g_{de}) (\partial_b g_{ci} + \partial_c g_{bi} - \partial_i g_{bc}) - \frac{1}{4} g^{dj} g^{ek} (\partial_b g_{ej} + \partial_e g_{bj} - \partial_j g_{be}) (\partial_c g_{dk} + \partial_d g_{ck} - \partial_k g_{dc}) + \right. \\ & \quad \frac{1}{2} (-g^{dk1} (\partial_b \partial_c g_{dk1} + \partial_b \partial_d g_{ck1} - \partial_b \partial_k g_{dc}) + g^{dk2} g^{k1k3} \partial_b g_{k2k3} (\partial_c g_{dk1} + \partial_d g_{ck1} - \partial_k g_{dc})) + \\ & \quad \left. \frac{1}{2} (g^{dk4} (\partial_d \partial_b g_{ck4} + \partial_d \partial_c g_{bk4} - \partial_d \partial_k g_{bc}) - g^{dk5} g^{k4k6} \partial_d g_{k5k6} (\partial_b g_{ck4} + \partial_c g_{bk4} - \partial_k g_{bc})) \right) + \\ & \quad \frac{1}{2} (g^{de} (\partial_d \partial_b g_{ce} + \partial_d \partial_c g_{be} - \partial_d \partial_e g_{bc}) - g^{df} g^{ei} \partial_d g_{fi} (\partial_b g_{ce} + \partial_c g_{be} - \partial_e g_{bc})) + \\ & \quad \frac{1}{2} (-g^{de} (\partial_b \partial_c g_{de} + \partial_b \partial_d g_{ce} - \partial_b \partial_e g_{dc}) + g^{df} g^{ei} \partial_b g_{fi} (\partial_c g_{de} + \partial_d g_{ce} - \partial_e g_{dc})) + \\ & \quad \frac{1}{4} g^{df} g^{ei} (\partial_d g_{ef} + \partial_e g_{df} - \partial_f g_{de}) (\partial_b g_{ci} + \partial_c g_{bi} - \partial_i g_{bc}) - \\ & \quad \frac{1}{4} g^{df} g^{ei} (\partial_b g_{ef} + \partial_e g_{bf} - \partial_f g_{be}) (\partial_c g_{di} + \partial_d g_{ci} - \partial_i g_{dc}) \end{aligned}$$

EINSTEIN FIELD EQUATIONS

$$G_{\mu\nu} = \kappa T_{\mu\nu}$$

$$G_{\mu\nu} =$$

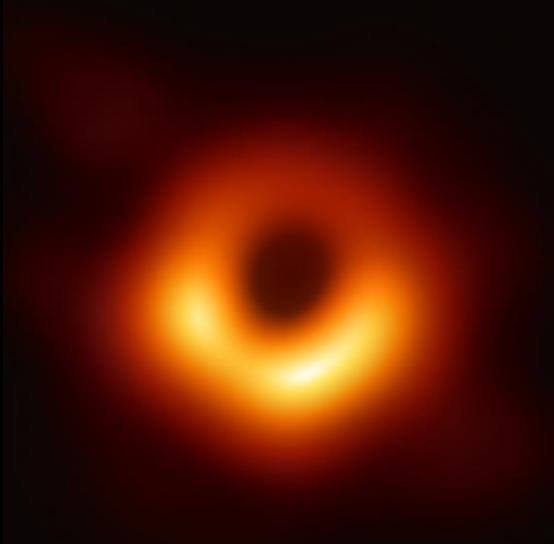
EINSTEIN FIELD EQUATIONS

$$G_{\mu\nu} = \kappa T_{\mu\nu}$$

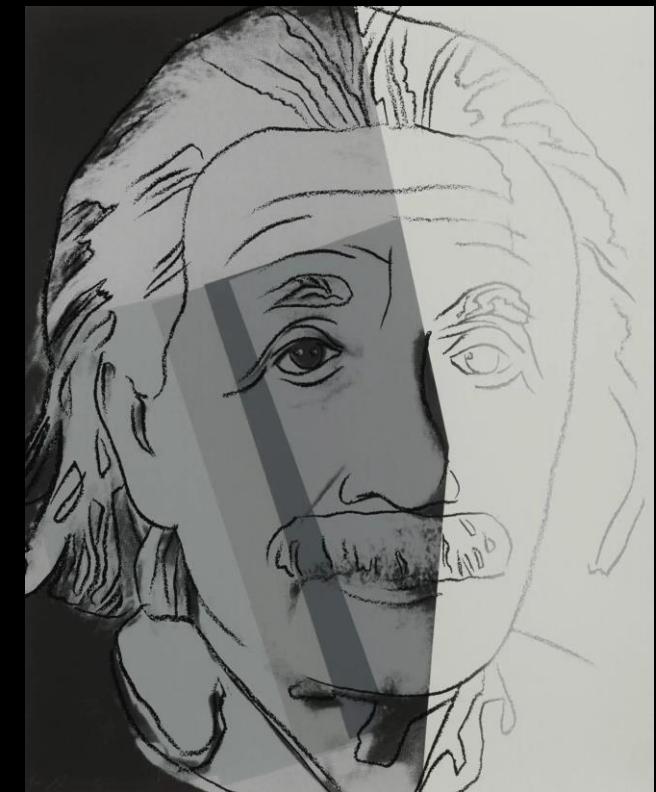
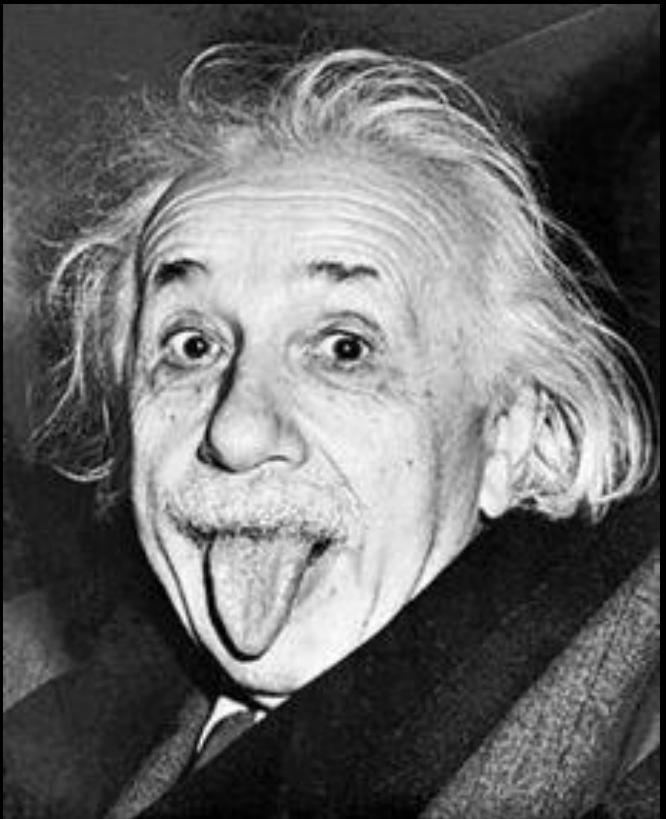
$$G_{\mu\nu} = \left\{ \left[\begin{array}{l} \dots 244 \dots + \frac{1}{2} \Gamma[\mathcal{D}]^d_{ce} g_{tt} g_{bd} g^b \dots 49 \dots g^{ef} g^{ij} \partial_j g_{fi} - \frac{1}{2} \Gamma[\mathcal{D}]^c_{ed} g_{tt} g_{bc} g^{bd} g^{ef} g^{ij} \partial_j g_{fi}, \\ \dots 290 \dots + \dots 1 \dots - \frac{1}{2} \Gamma[\mathcal{D}] \dots 49 \dots \dots 49 \dots \dots 49 \dots g_t \dots 49 \dots g \dots 49 \dots \dots 49 \dots g \dots 49 \dots \dots 49 \dots g \dots 1 \dots g^i \dots 49 \dots \partial_j g_f \dots 49 \dots, \dots 1 \dots, \dots 1 \dots \end{array} \right] \right\}$$

PREDICTIONS OF GENERAL RELATIVITY

- MERCURY'S ORBIT
- LIGHT DEFLECTED BY GRAVITY
- BLACK HOLES
- EXPANSION OF THE UNIVERSE
- GRAVITATIONAL WAVES !
- ...

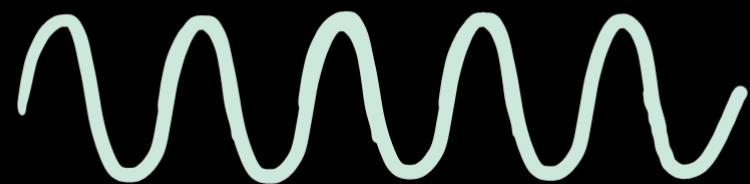


EINSTEIN IN POP CULTURE



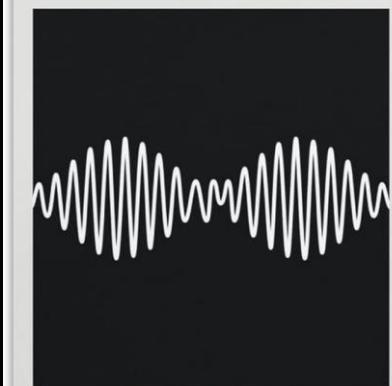
ANDY WARHOL

WAVES



PROPAGATING DISTURBANCE IN A MEDIUM

SOUND WAVES

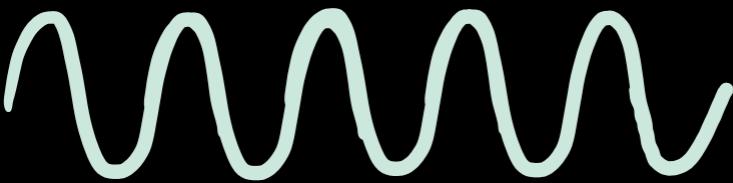


1 I WANNA KNOW
2 U
3 ONE FOR THE ROAD
4 ARABELLA
5 I WANT IT ALL
6 NO.1 PARTY ANTHEM
7 MID SOUNDS
8 REBEL
9 WHY'D YOU ONLY CALL ME
WHEN YOU'RE HIGH?
10 SNAP OUT OF IT
11 KNEE SOCKS
12 I WANNA BE YOURS

OUT NOW / SEPTEMBER 9, 2013
RELEASED BY DOMINO RECORDING COMPANY
THE FIFTH STUDIO ALBUM
4142 / 2013-2013
RELEASED BY DOMINO RECORDING COMPANY

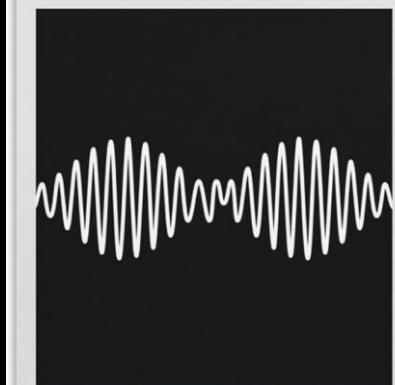
AiR

WAVES



PROPAGATING DISTURBANCE IN A MEDIUM

SOUND WAVES



1 I WANNA KNOW
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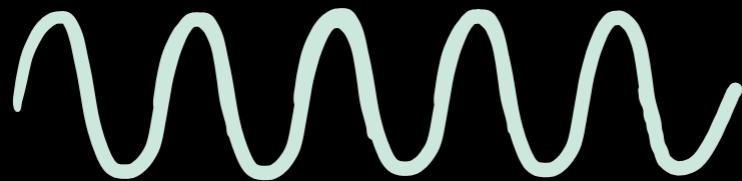
ARTIC MONKEYS
AM

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AIR

WAVES



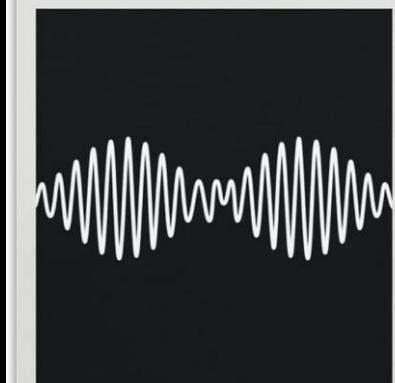
PROPAGATING DISTURBANCE IN A MEDIUM

SURFACE



WATER

SOUND WAVES



1 I WANNA KNOW
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Air

WAVES



PROPAGATING DISTURBANCE IN A MEDIUM

LIGHT WAVES



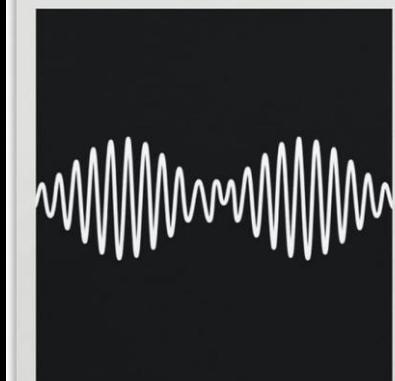
ELECTROMAGNETIC
FIELD

SURFACE



WATER

SOUND WAVES

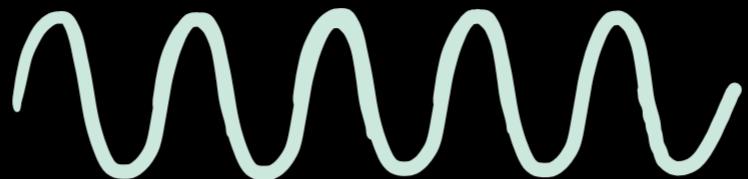


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Air

WAVES



PROPAGATING DISTURBANCE IN A MEDIUM

LIGHT WAVES



ELECTROMAGNETIC FIELD

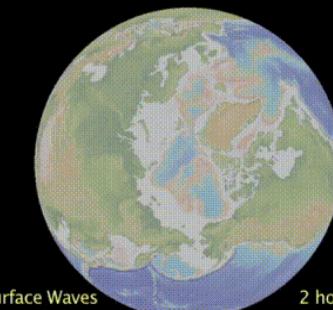
SURFACE



WATER

SEISMIC WAVES

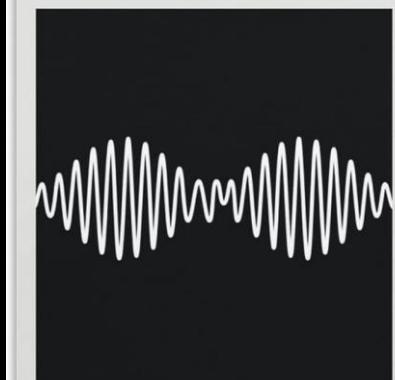
2011 Tohoku, Japan Earthquake



Surface Waves 2 hours

EARTH

SOUND WAVES



1 I WANNA KNOW
2 U
3 ONE FOR THE ROAD
4 ARABELLA
5 I WANT IT ALL
6 NO.1 PARTY ANTHEM
7 MID SOUNDS
8 REBEL
9 WHY'D YOU ONLY CALL ME
WHEN YOU'RE HIGH?
10 SNAP OUT OF IT
11 KNEE SOCKS
12 I WANNA BE YOURS

OUT NOW / SEPTEMBER 9, 2013
RELEASED BY DOMINO RECORDING COMPANY
THE FIFTH STUDIO ALBUM
4142 / 2013-2013
RELEASED BY DOMINO RECORDING COMPANY

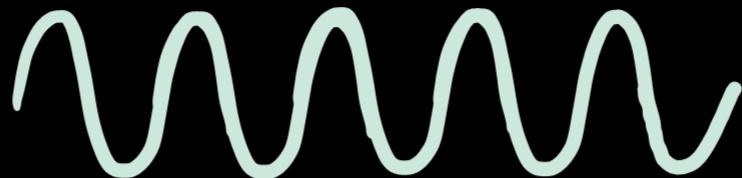
Air

SURFACE



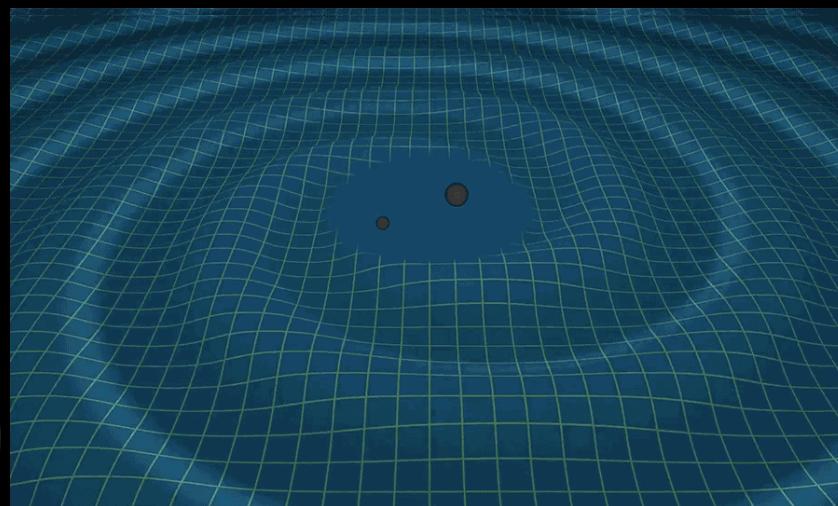
WATER

WAVES



PROPAGATING DISTURBANCE IN A MEDIUM

GRAVITATIONAL WAVES



SPACETIME

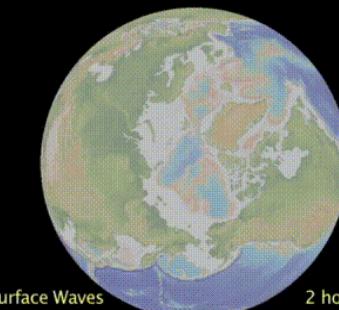
LIGHT WAVES



ELECTROMAGNETIC FIELD

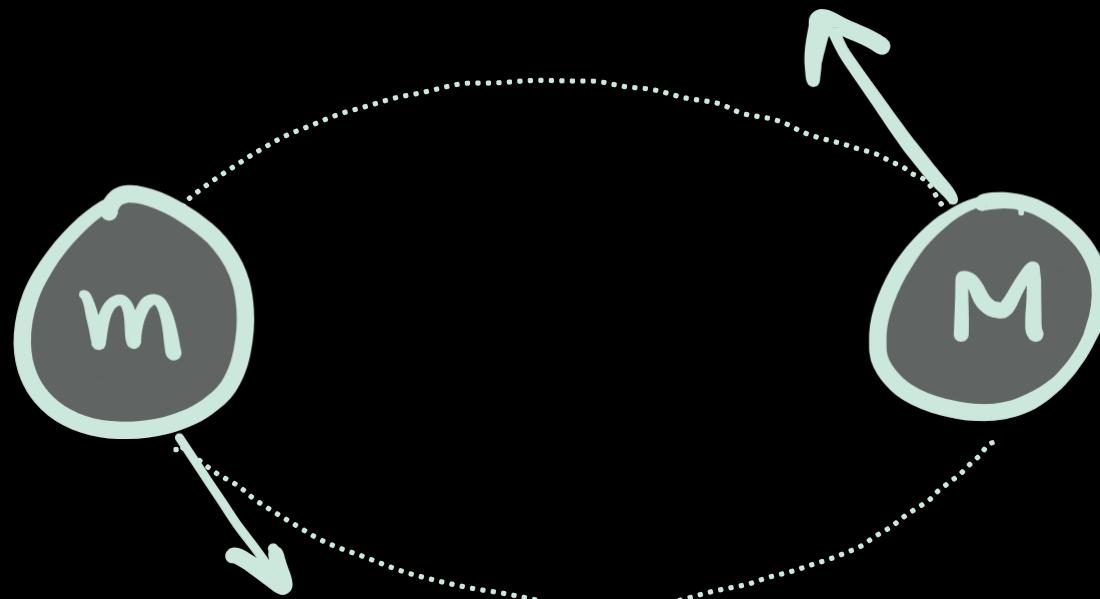
SEISMIC WAVES

2011 Tohoku, Japan Earthquake

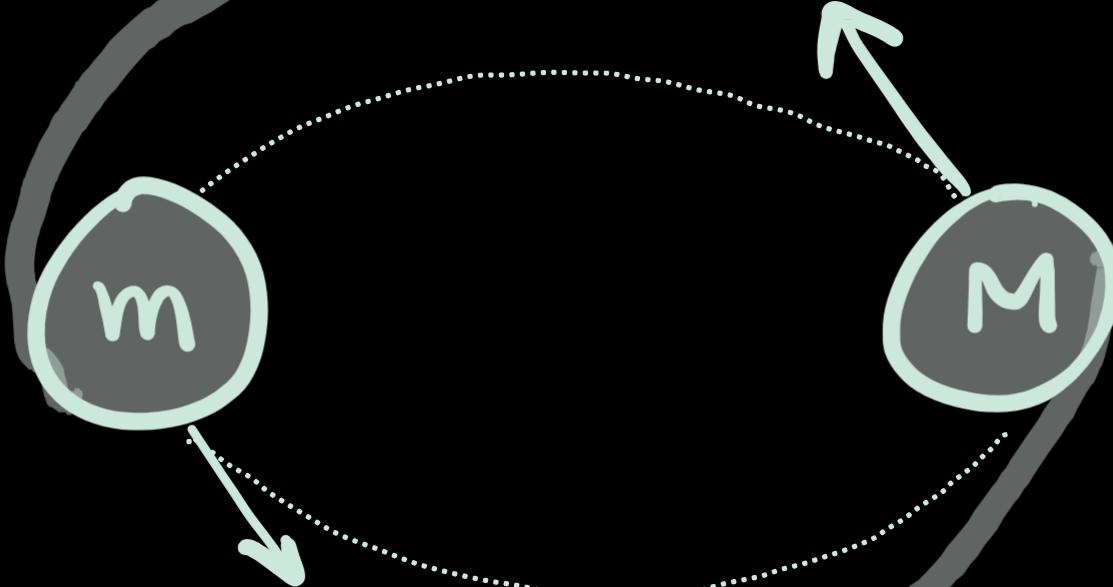


EARTH

GRAVITATIONAL WAVES

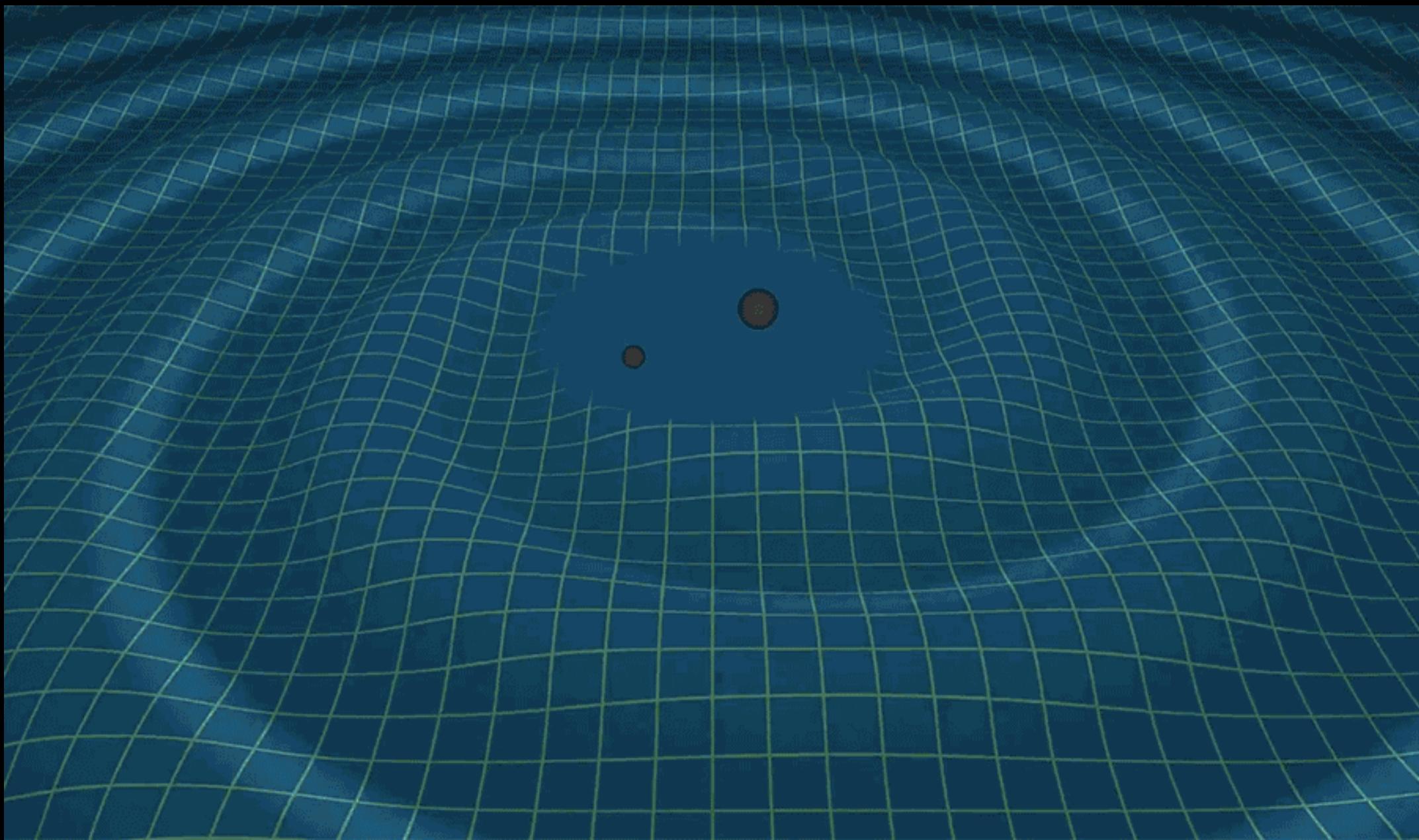


GRAVITATIONAL WAVES

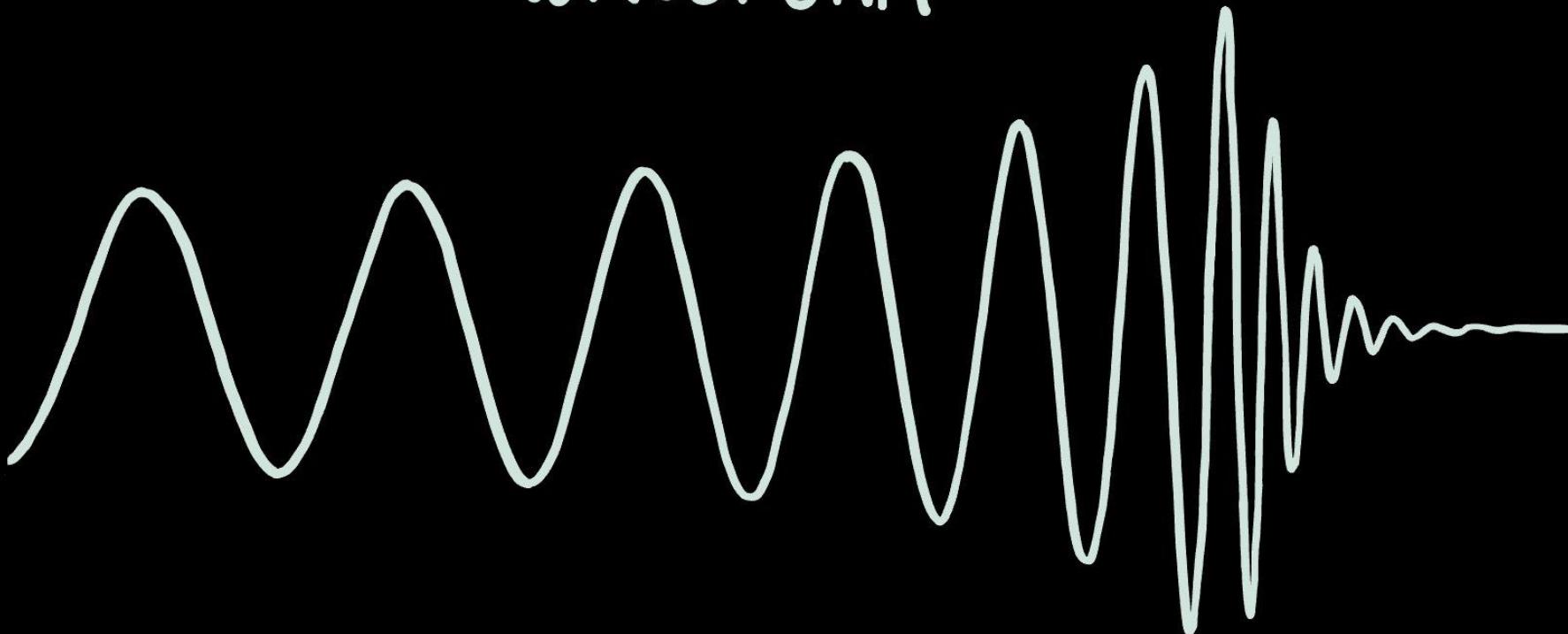


RIPPLES IN SPACETIME

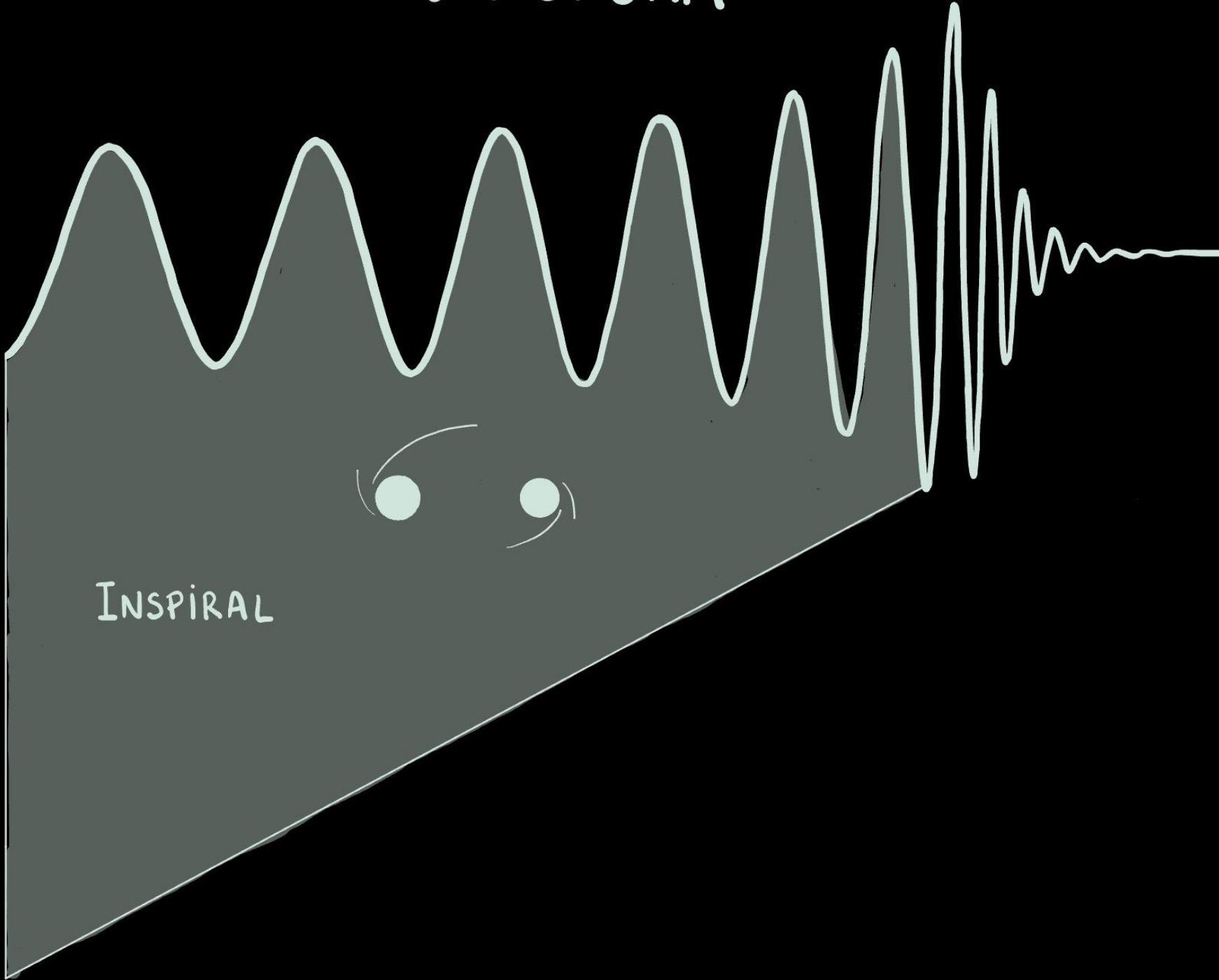
RIPPLES IN SPACETIME



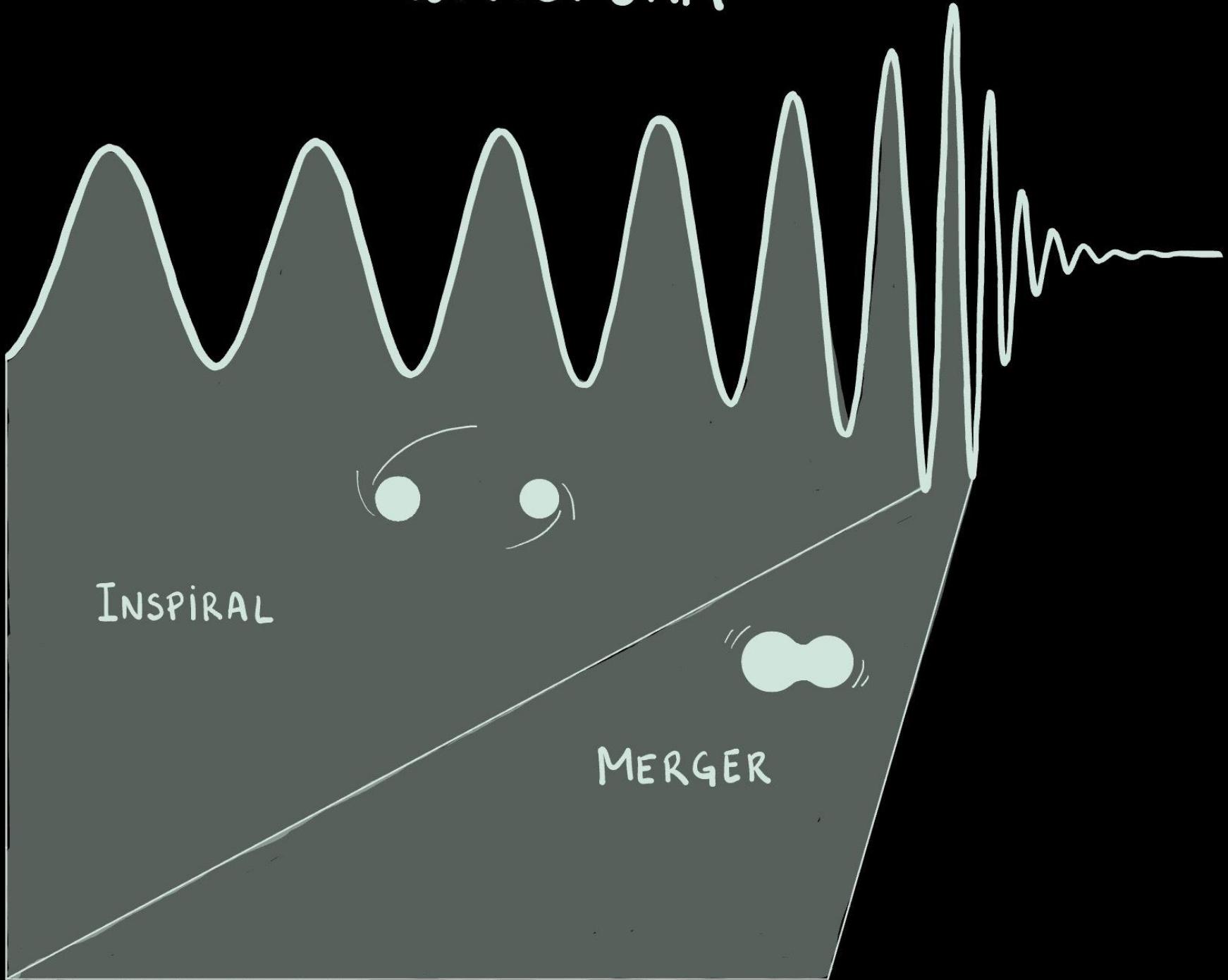
WAVEFORM



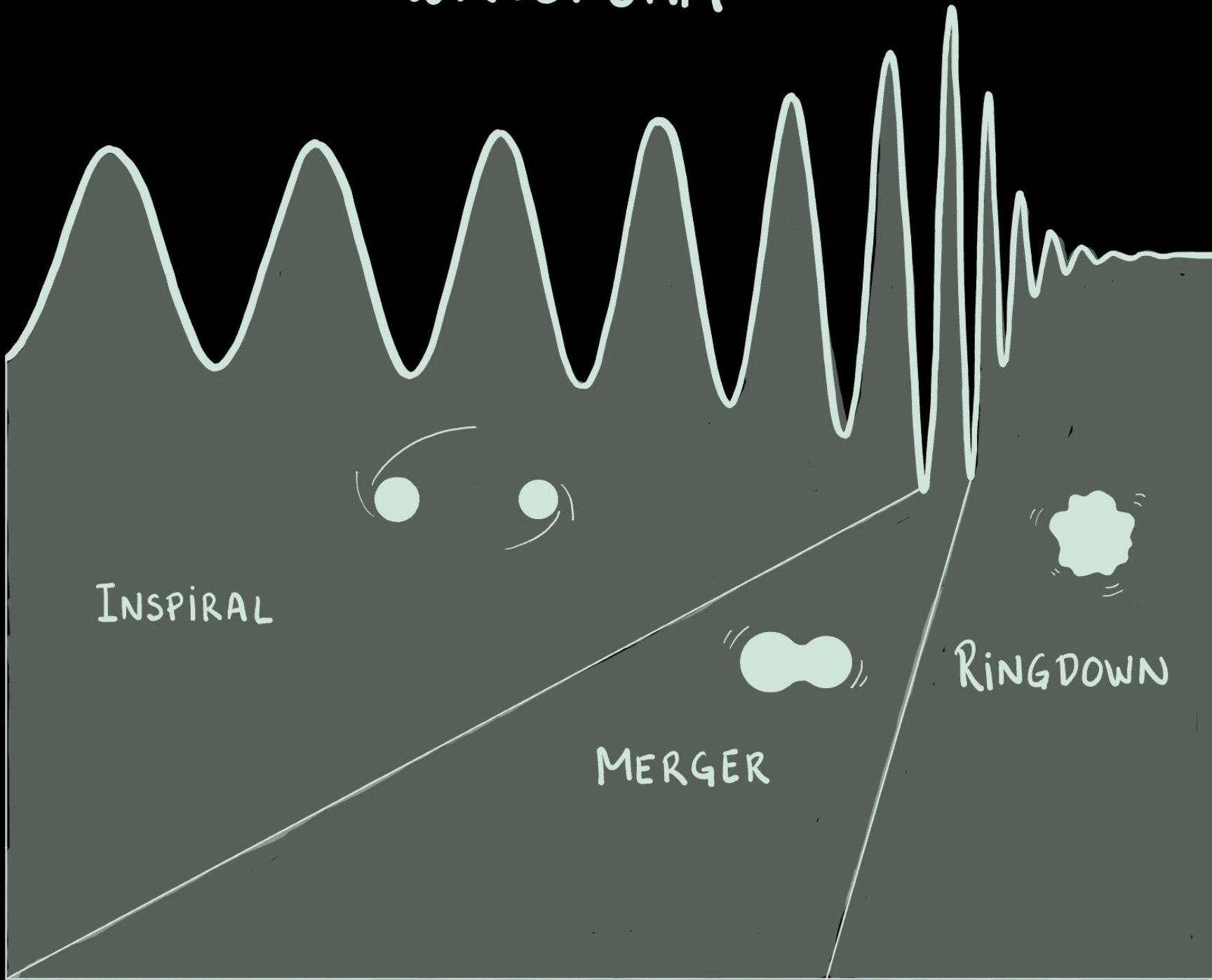
WAVEFORM



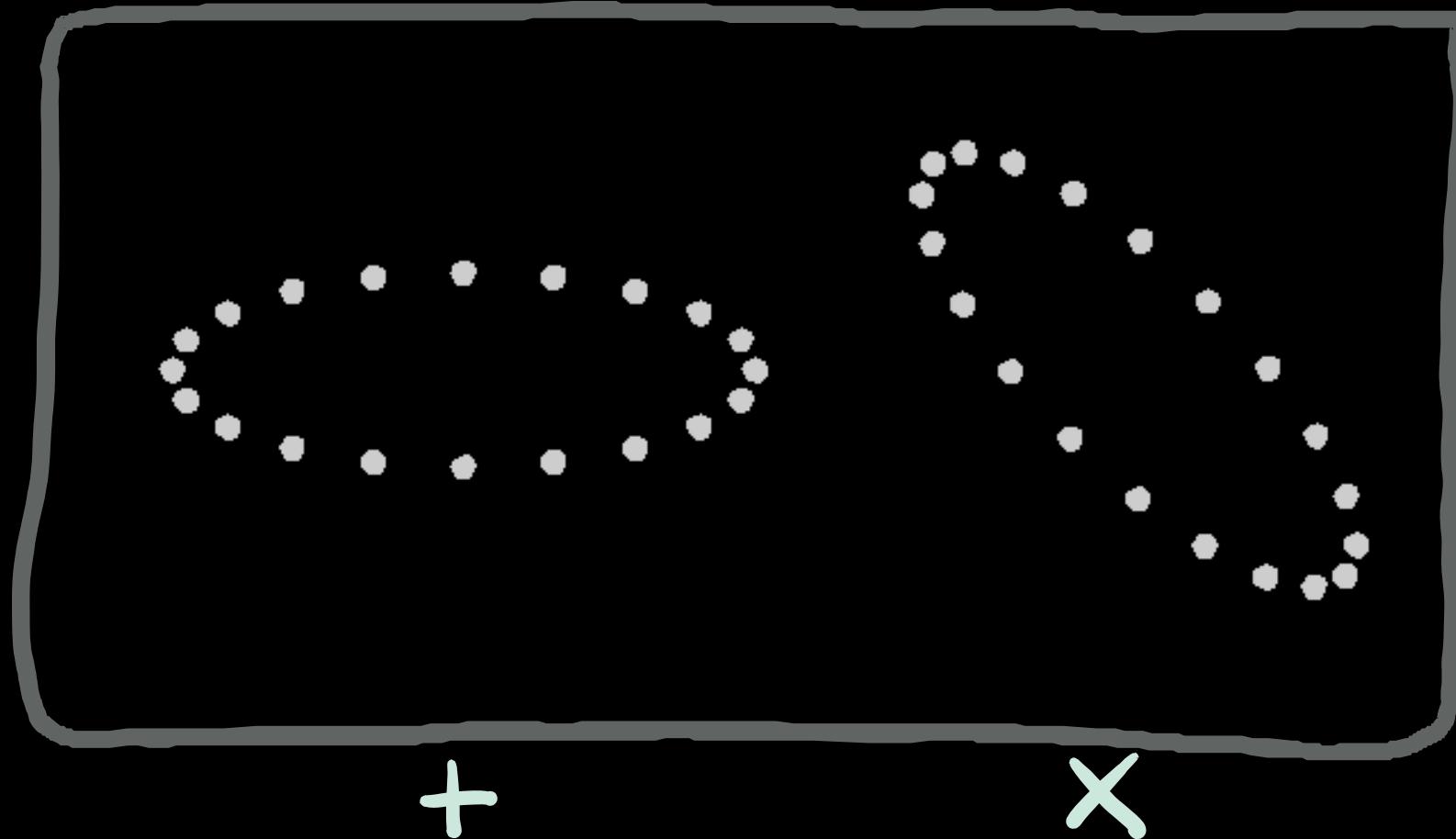
WAVEFORM



WAVEFORM



EFFECT ON MASSES

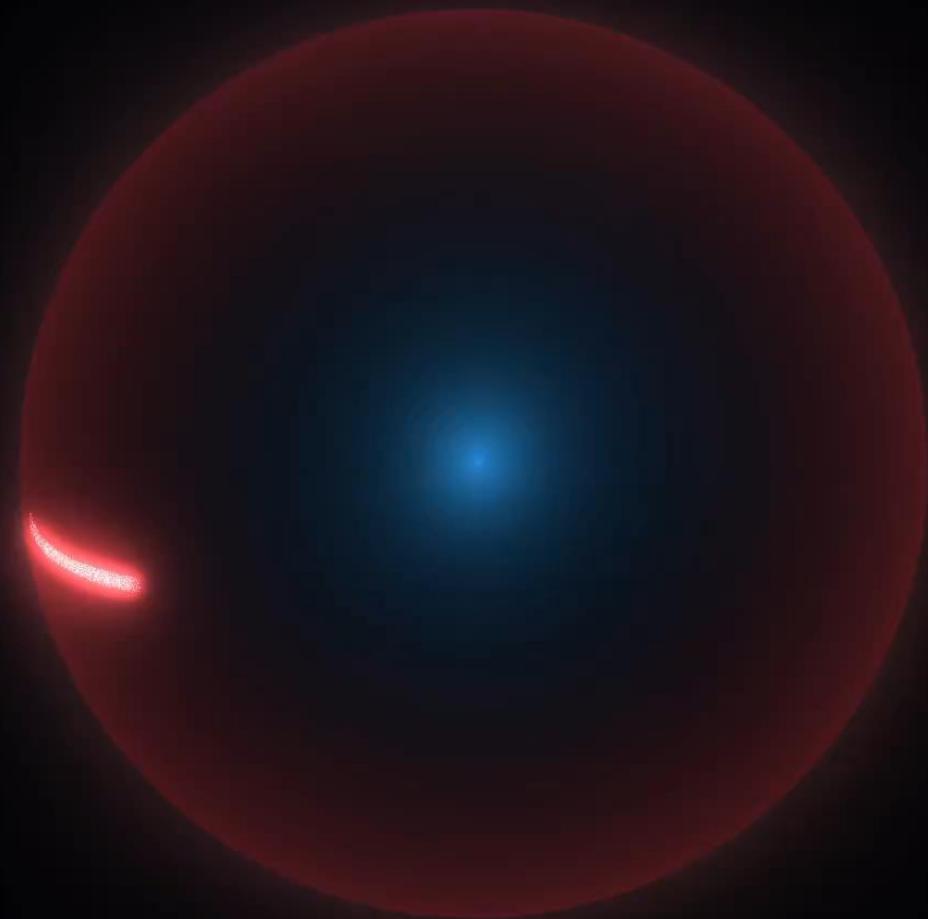


EFFECT ON MASSES

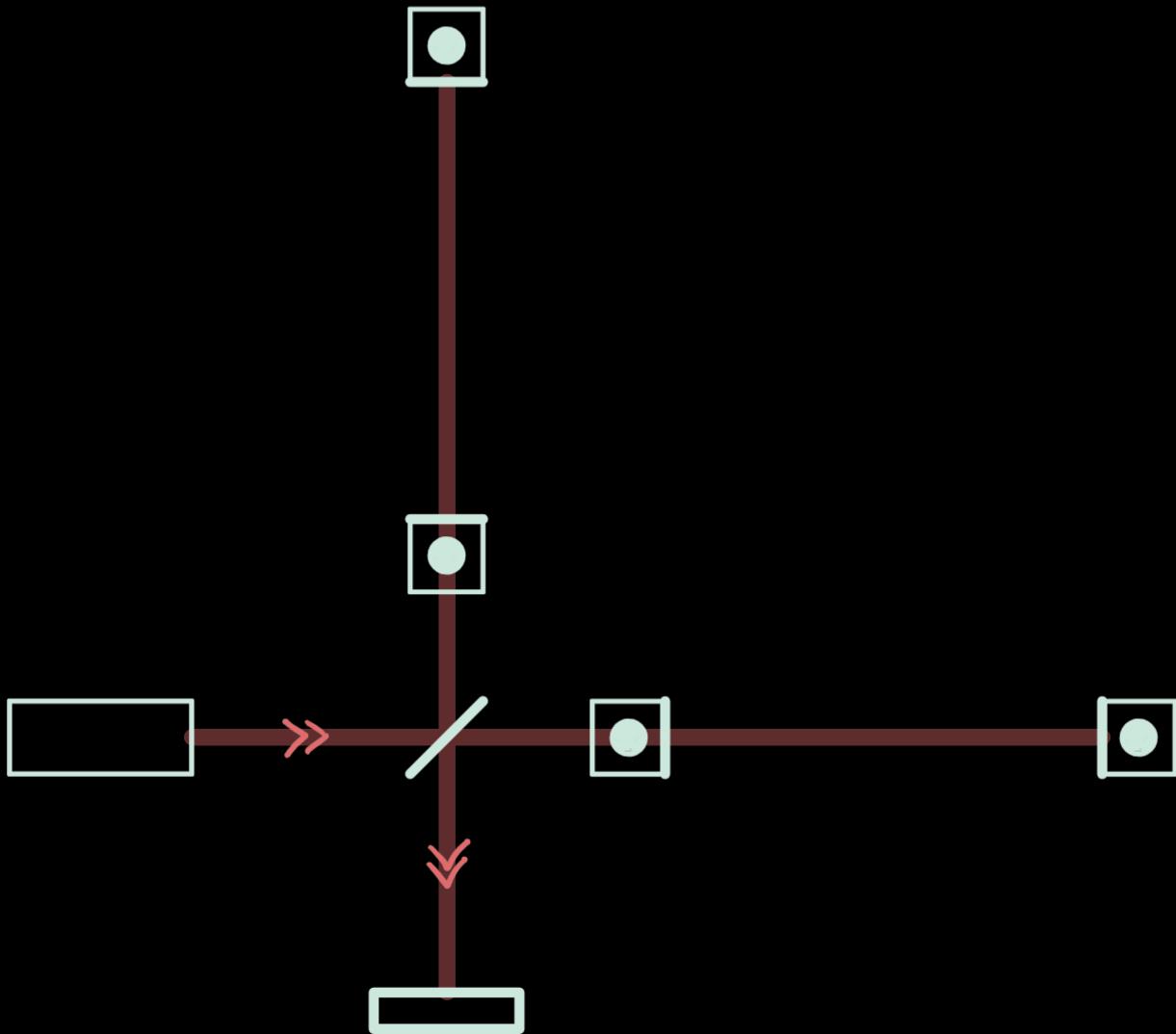


Scale of Effect Vastly Exaggerated

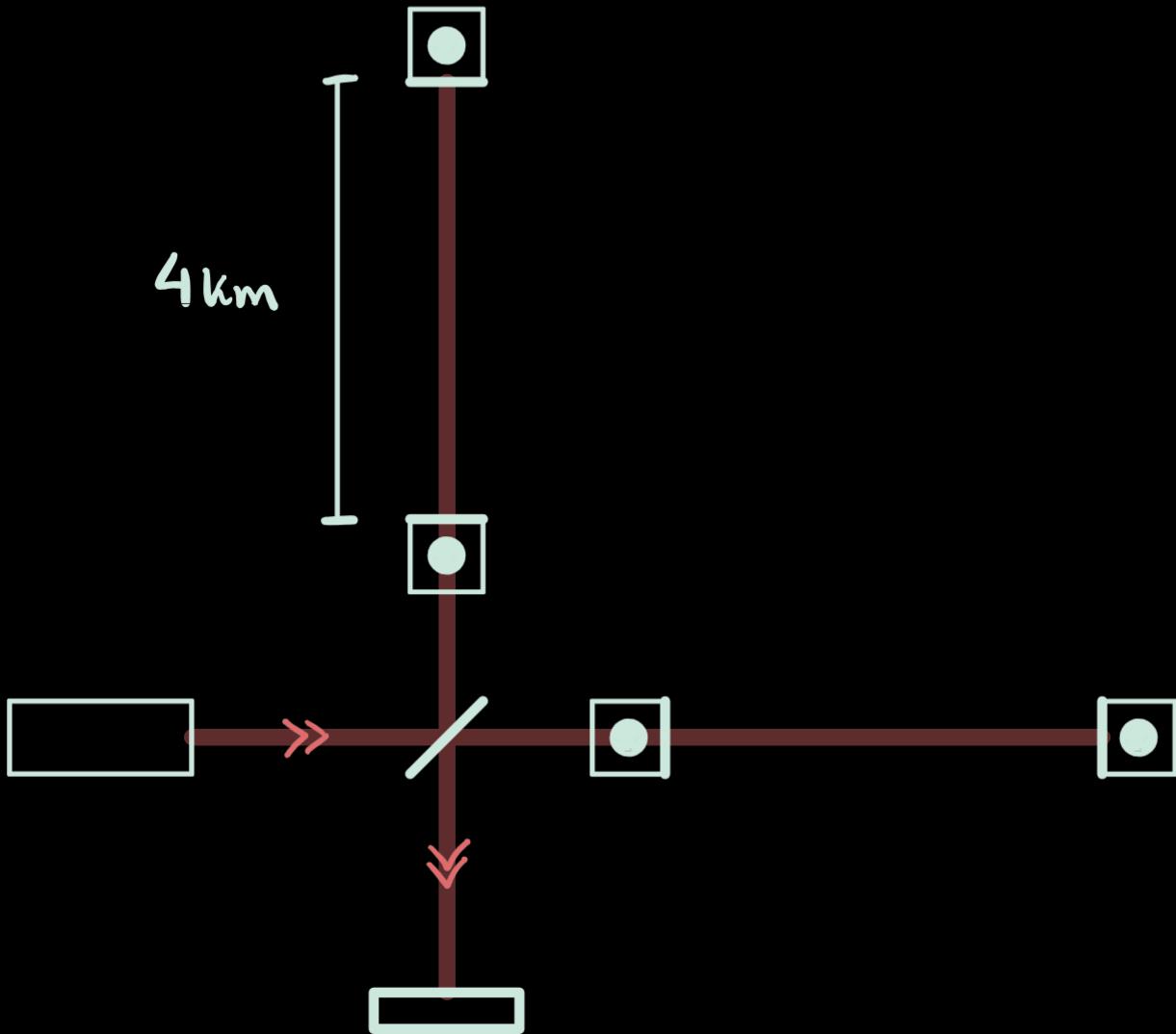
EFFECT ON MASSES



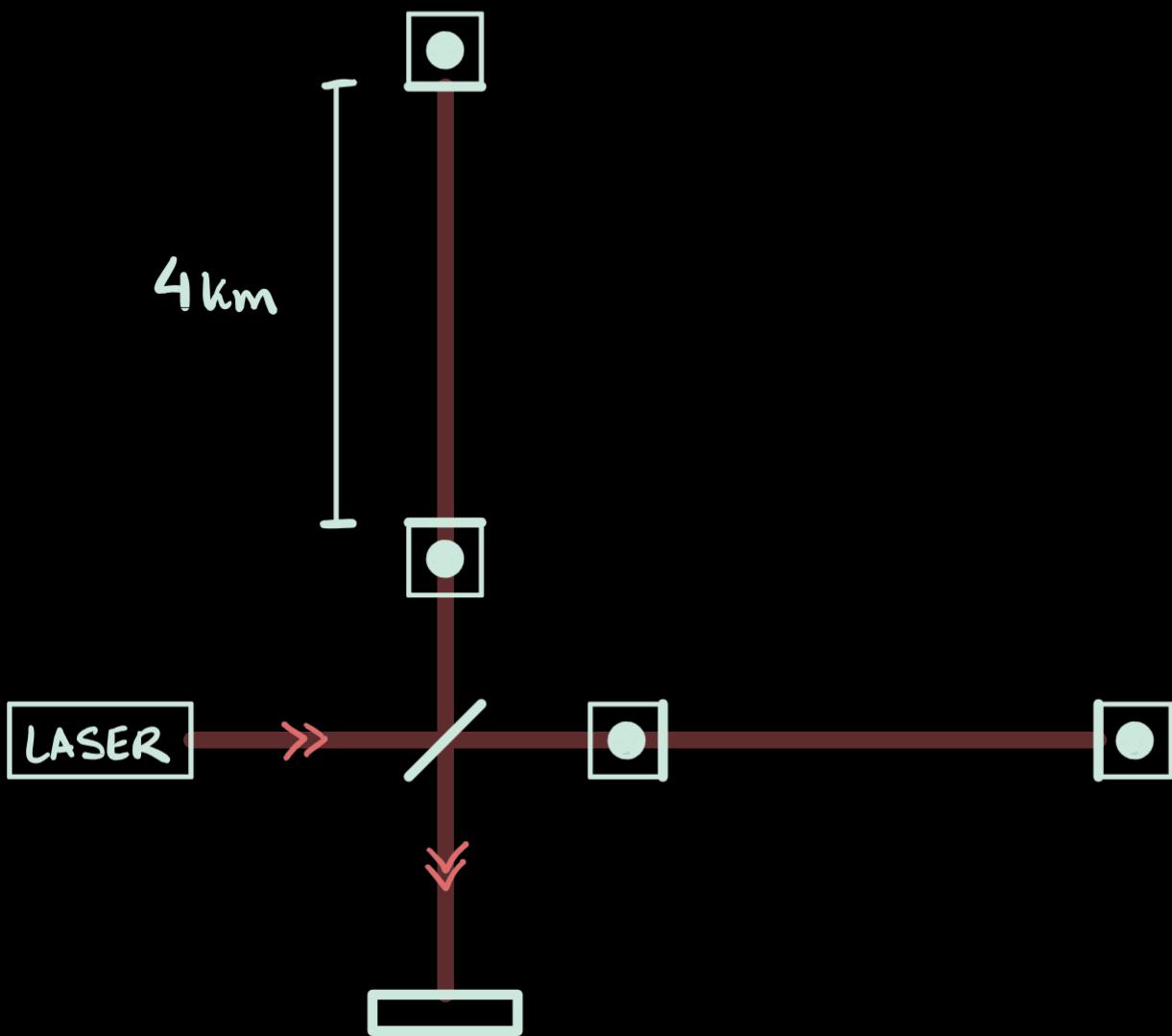
GRAVITATIONAL WAVE DETECTORS



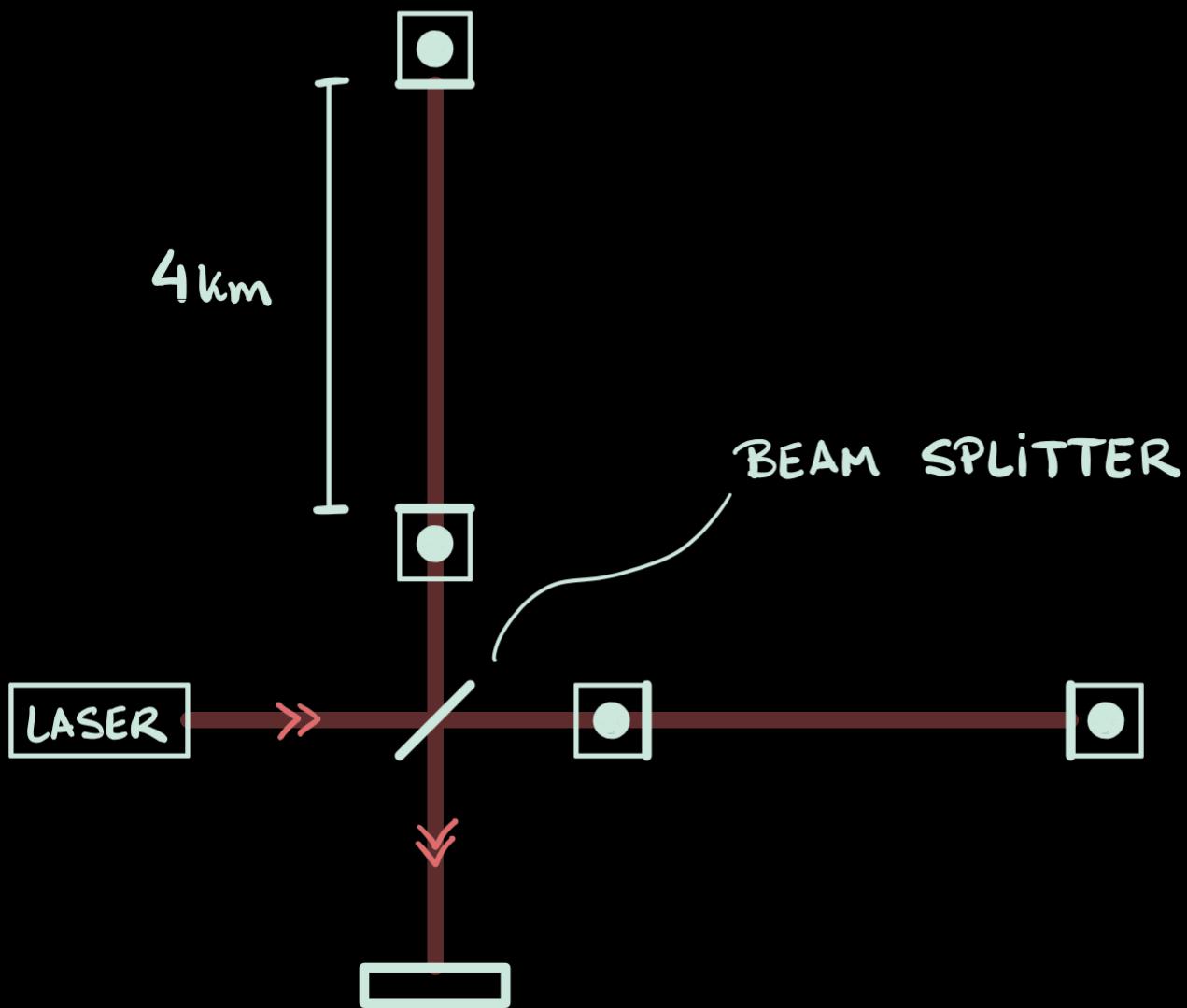
GRAVITATIONAL WAVE DETECTORS



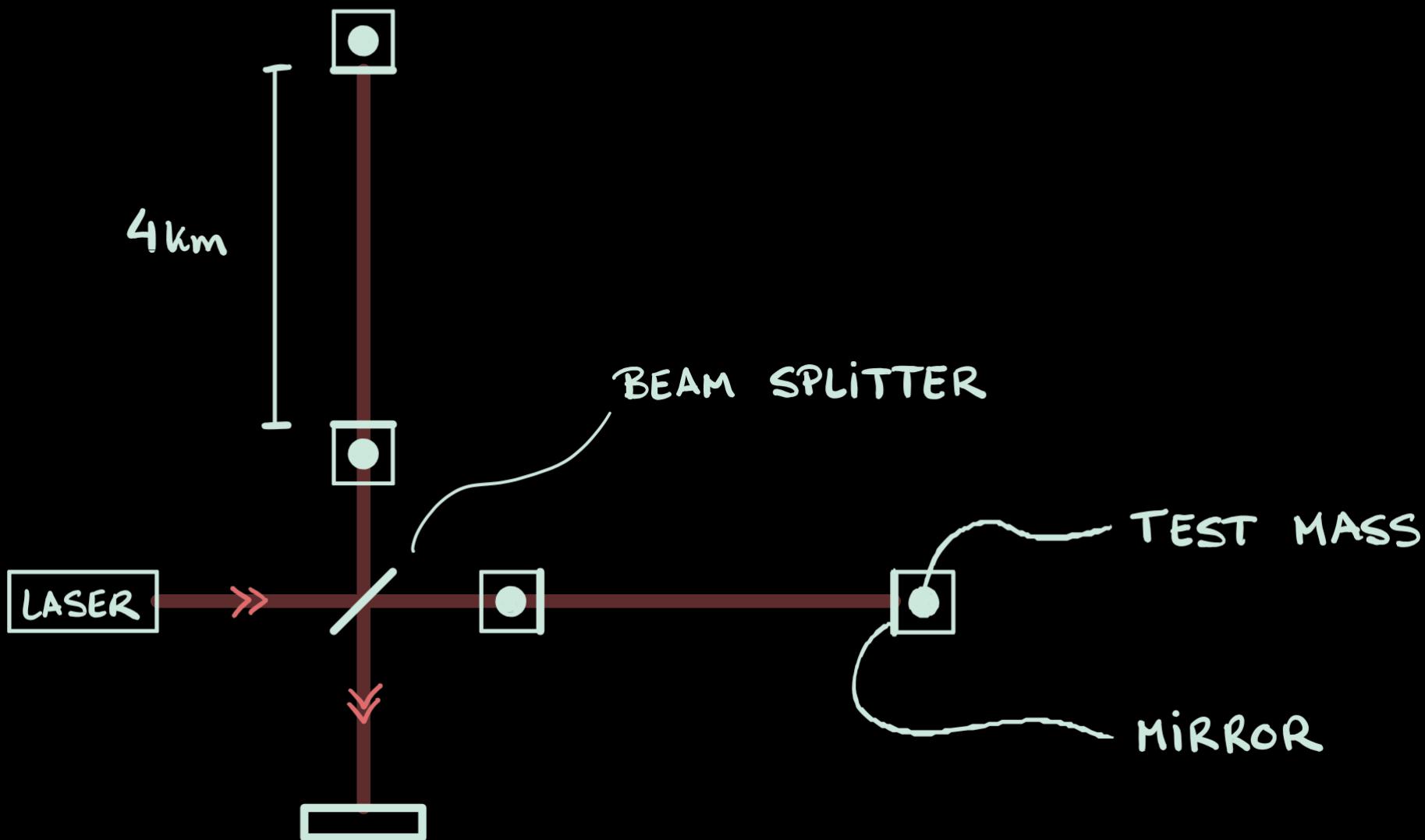
GRAVITATIONAL WAVE DETECTORS



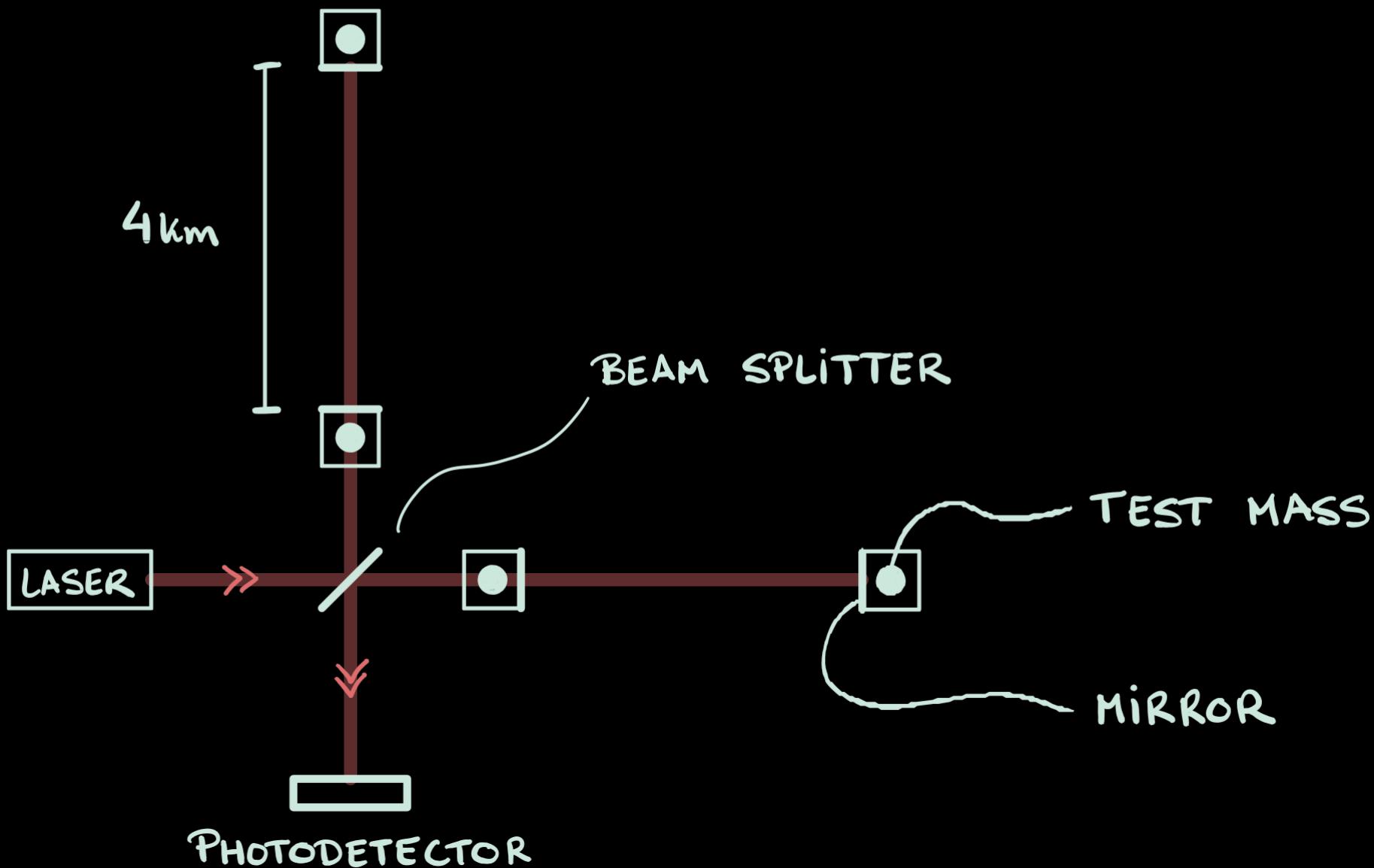
GRAVITATIONAL WAVE DETECTORS



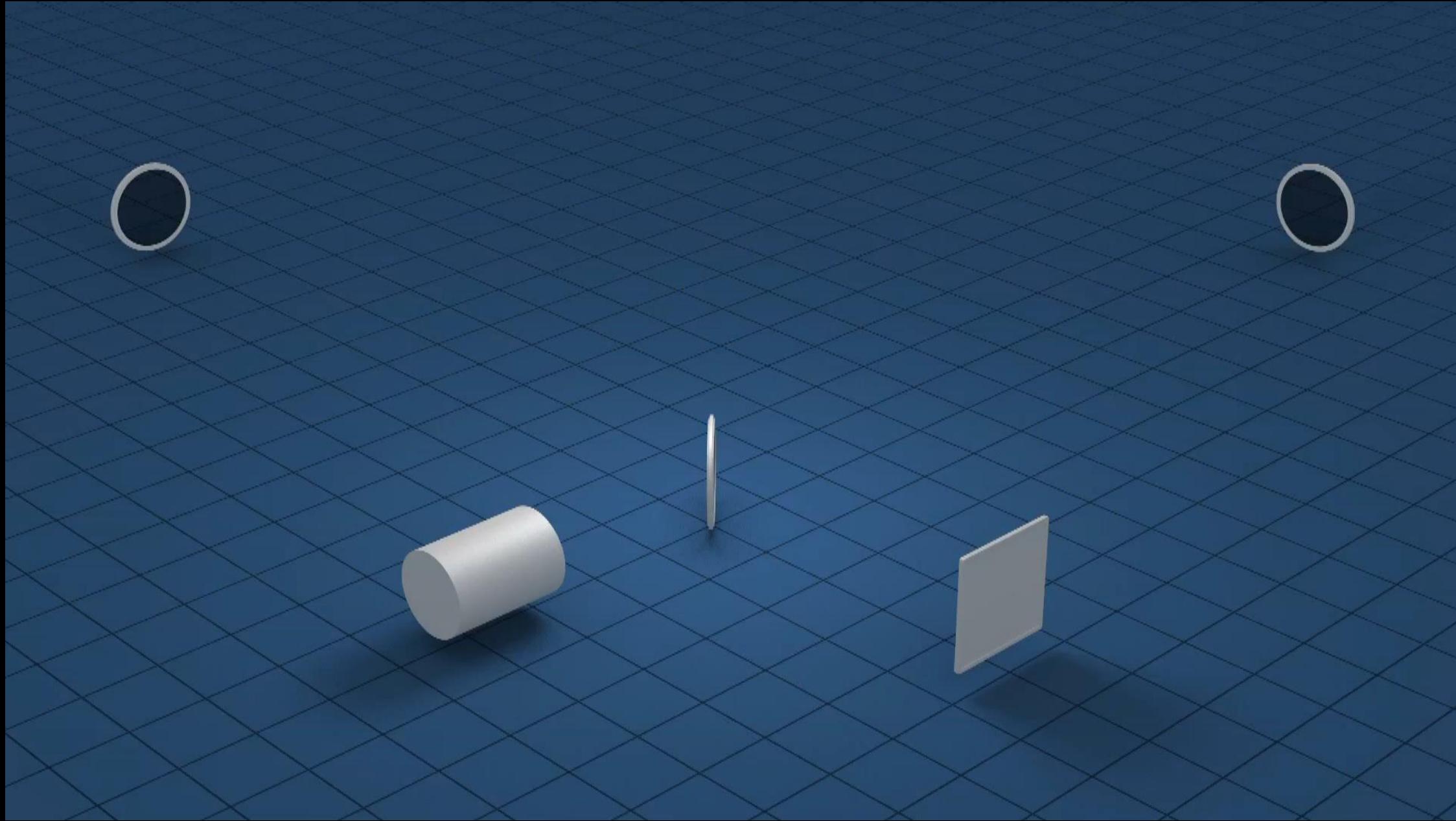
GRAVITATIONAL WAVE DETECTORS



GRAVITATIONAL WAVE DETECTORS



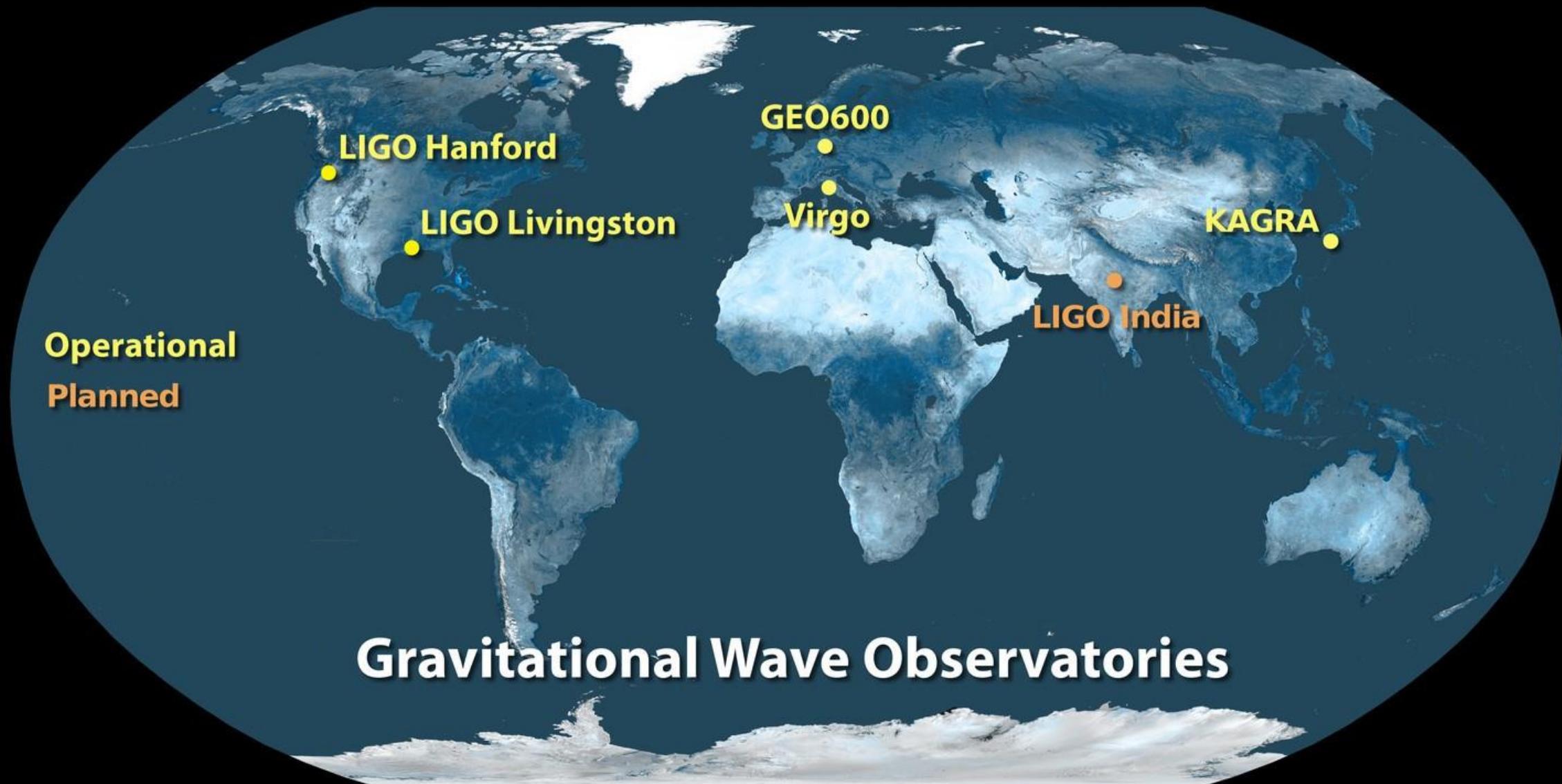
GRAVITATIONAL WAVE DETECTORS



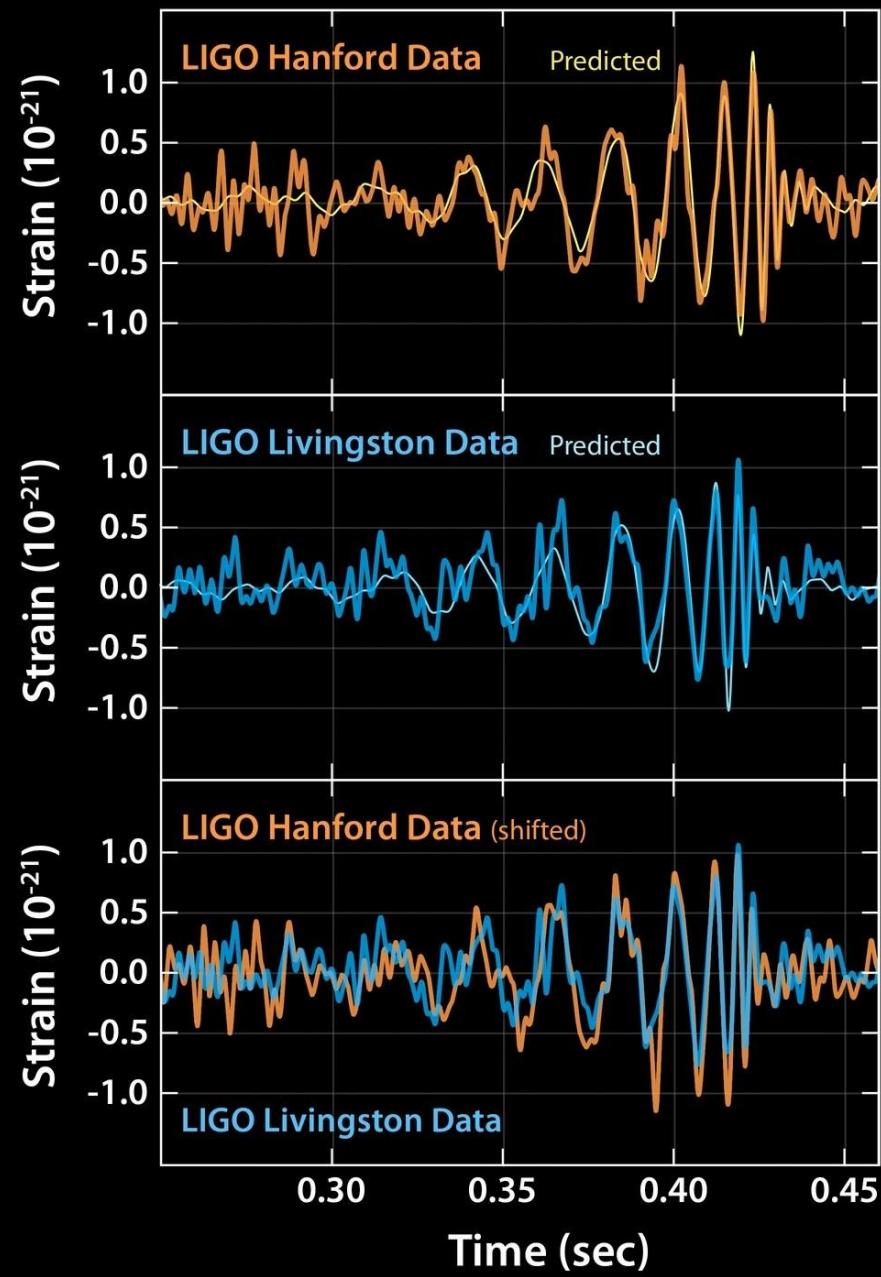
GRAVITATIONAL WAVE DETECTORS



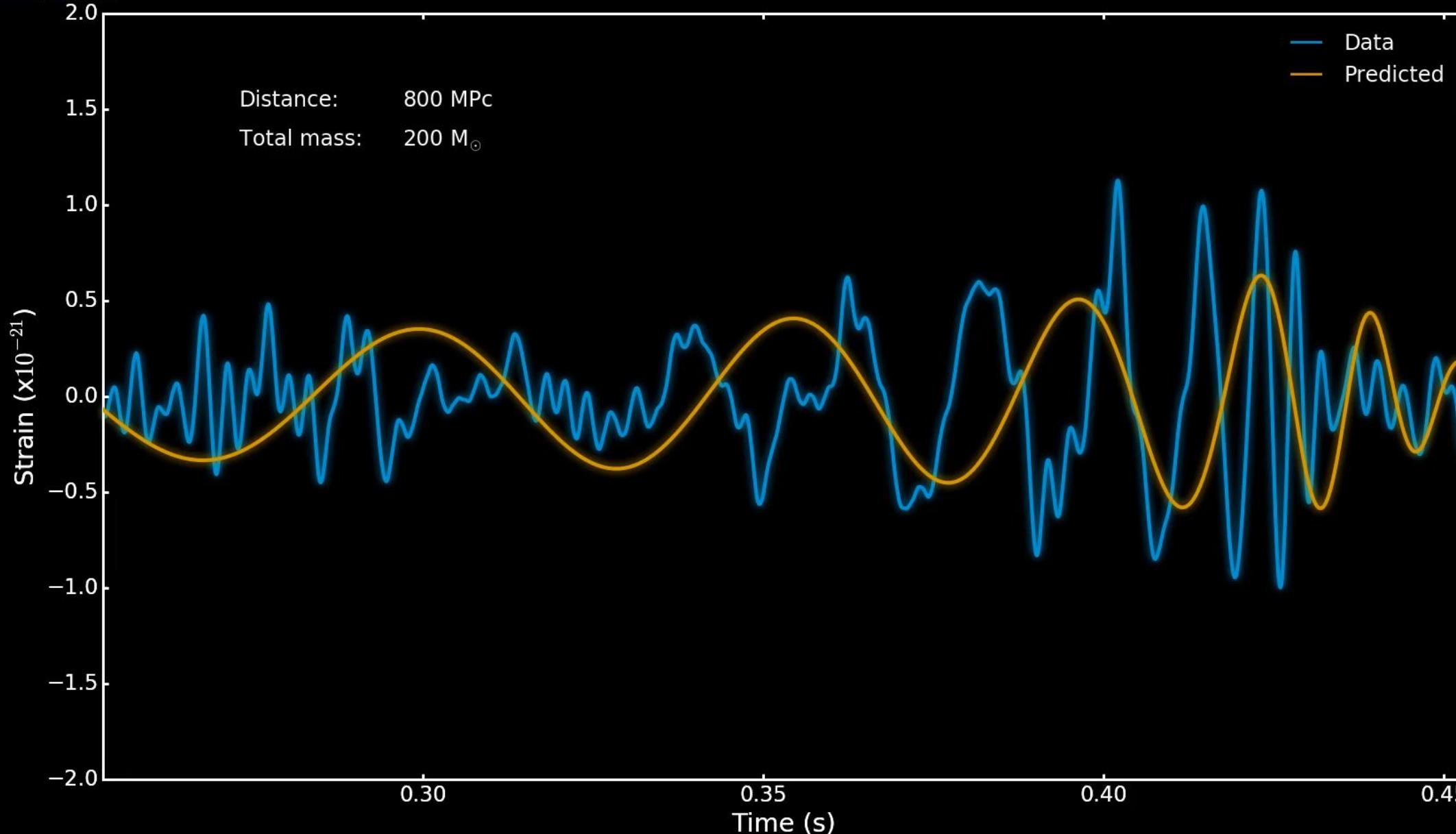
GRAVITATIONAL WAVE DETECTORS



GW150914



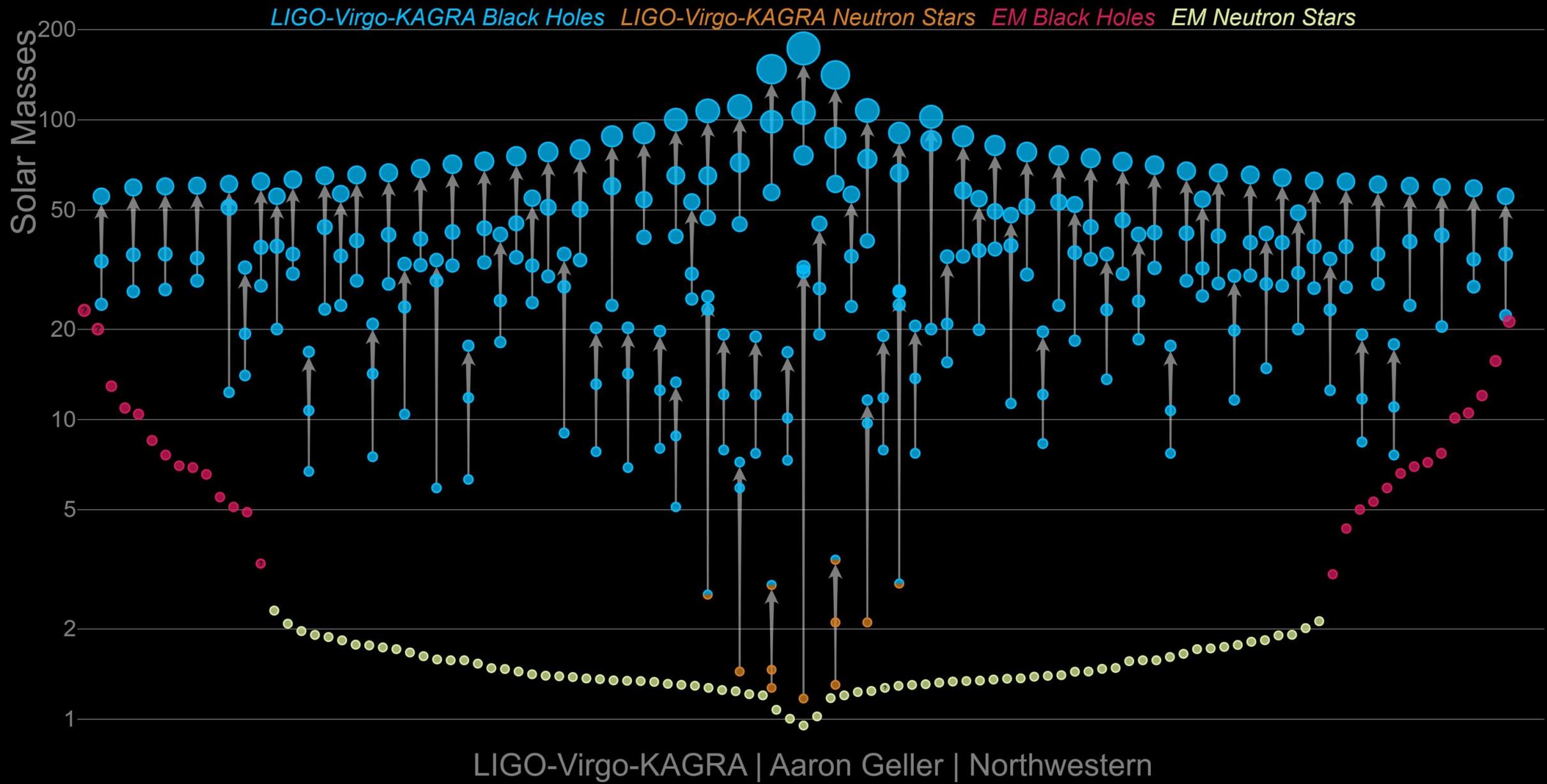
MATCHED FILTERING



GRAVITATIONAL WAVES IN THE NEWS

The image is a composite of two photographs. The left side shows the front page of The Independent newspaper, featuring a large headline about gravitational waves and a black hole image. The right side shows a black hole with a bright ring of light around it, set against a dark, star-filled background.

Masses in the Stellar Graveyard



THE SPECTRUM OF GRAVITATIONAL WAVES



Observatories & experiments

Ground-based experiment



Space-based observatory



Pulsar timing array



Cosmic microwave background polarisation



Timescales

milliseconds

seconds

hours

years

Frequency (Hz)

100

1

10^{-2}

10^{-4}

10^{-6}

10^{-8}

10^{-16}

Cosmic fluctuations in the early Universe

Cosmic sources



Supernova



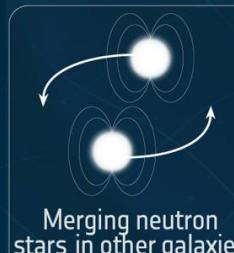
Pulsar



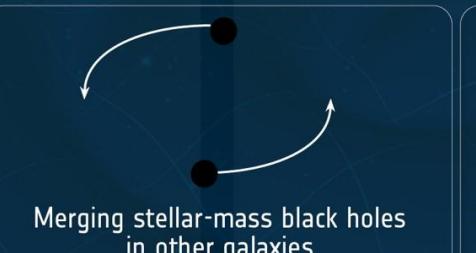
Compact object falling onto a supermassive black hole



Merging supermassive black holes



Merging neutron stars in other galaxies



Merging stellar-mass black holes in other galaxies



Merging white dwarfs in our Galaxy

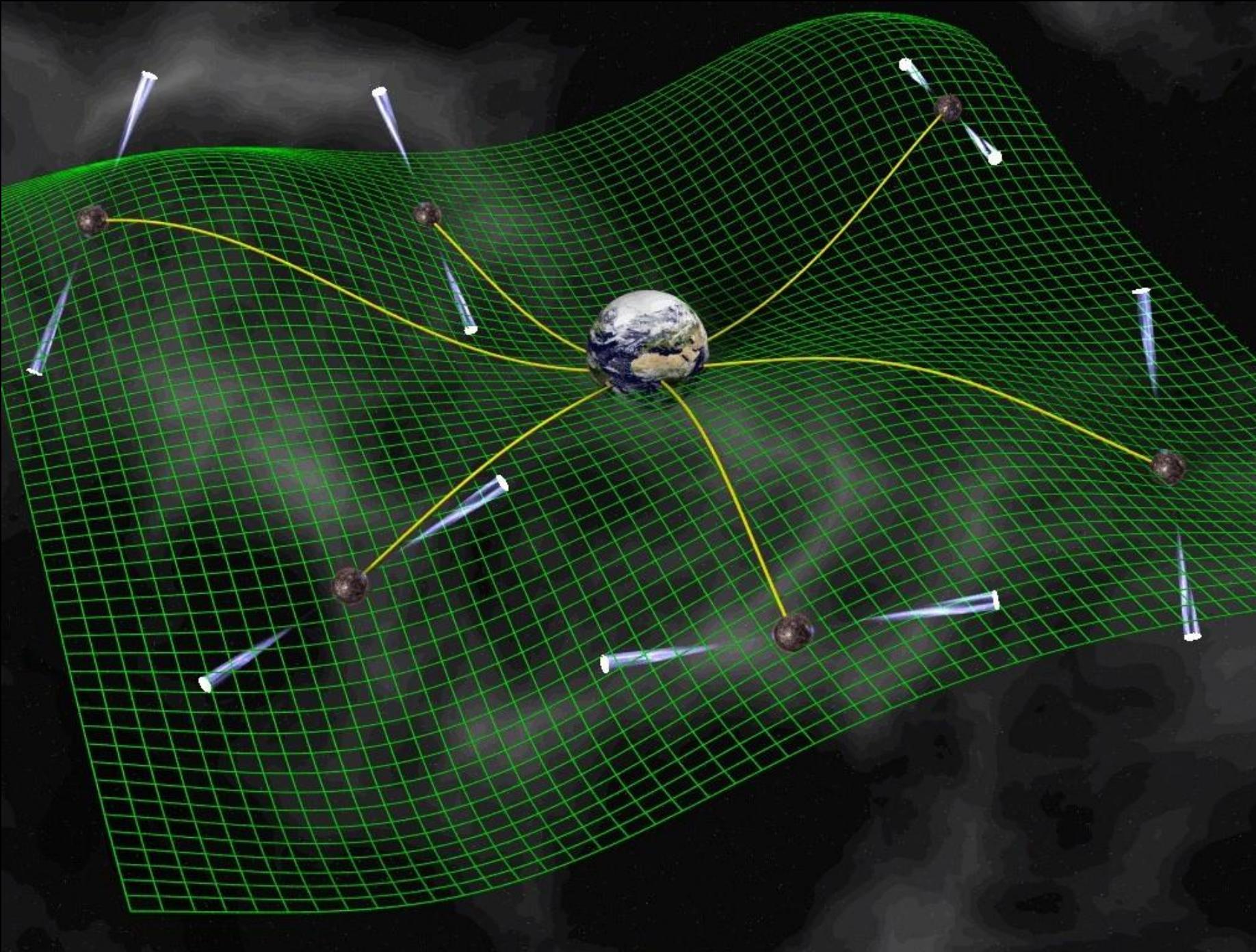
#lisa



LISA

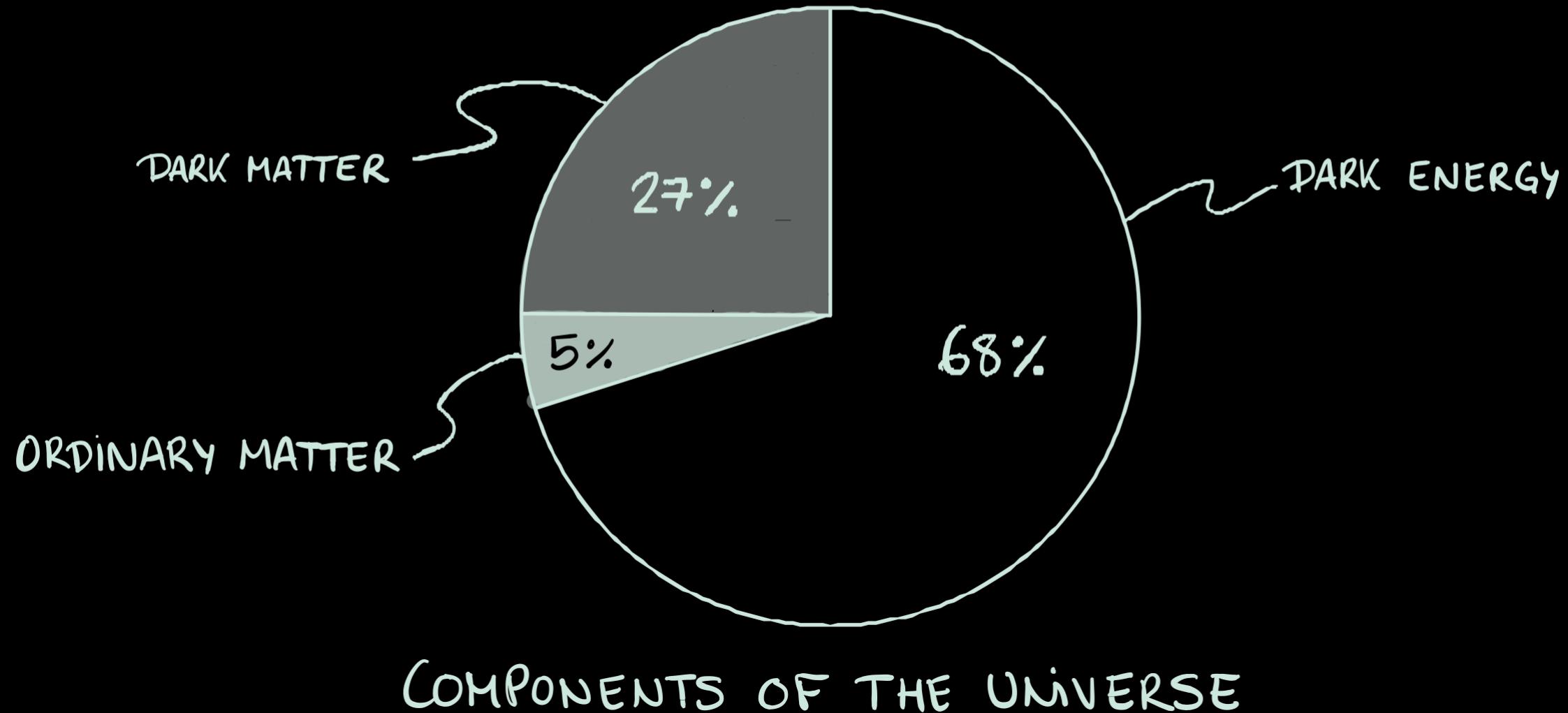


PULSAR TIMING ARRAYS



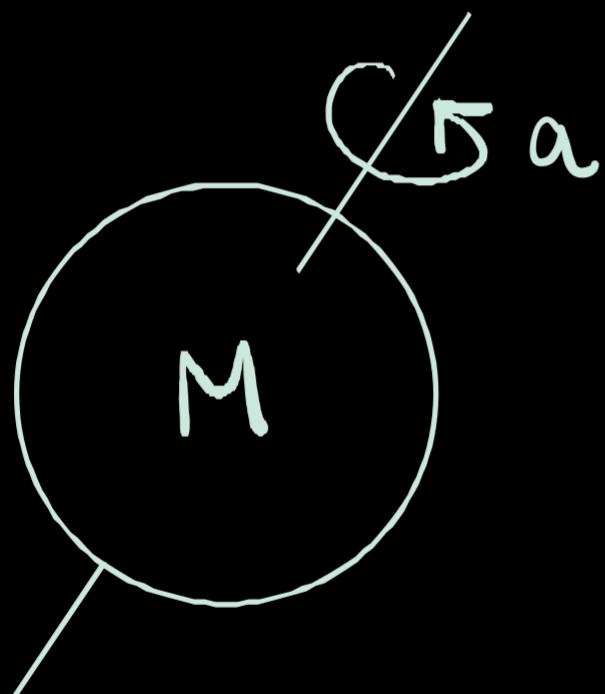
NEW SCIENCE WITH GWs

- INVESTIGATE THE NATURE OF DARK MATTER AND DARK ENERGY

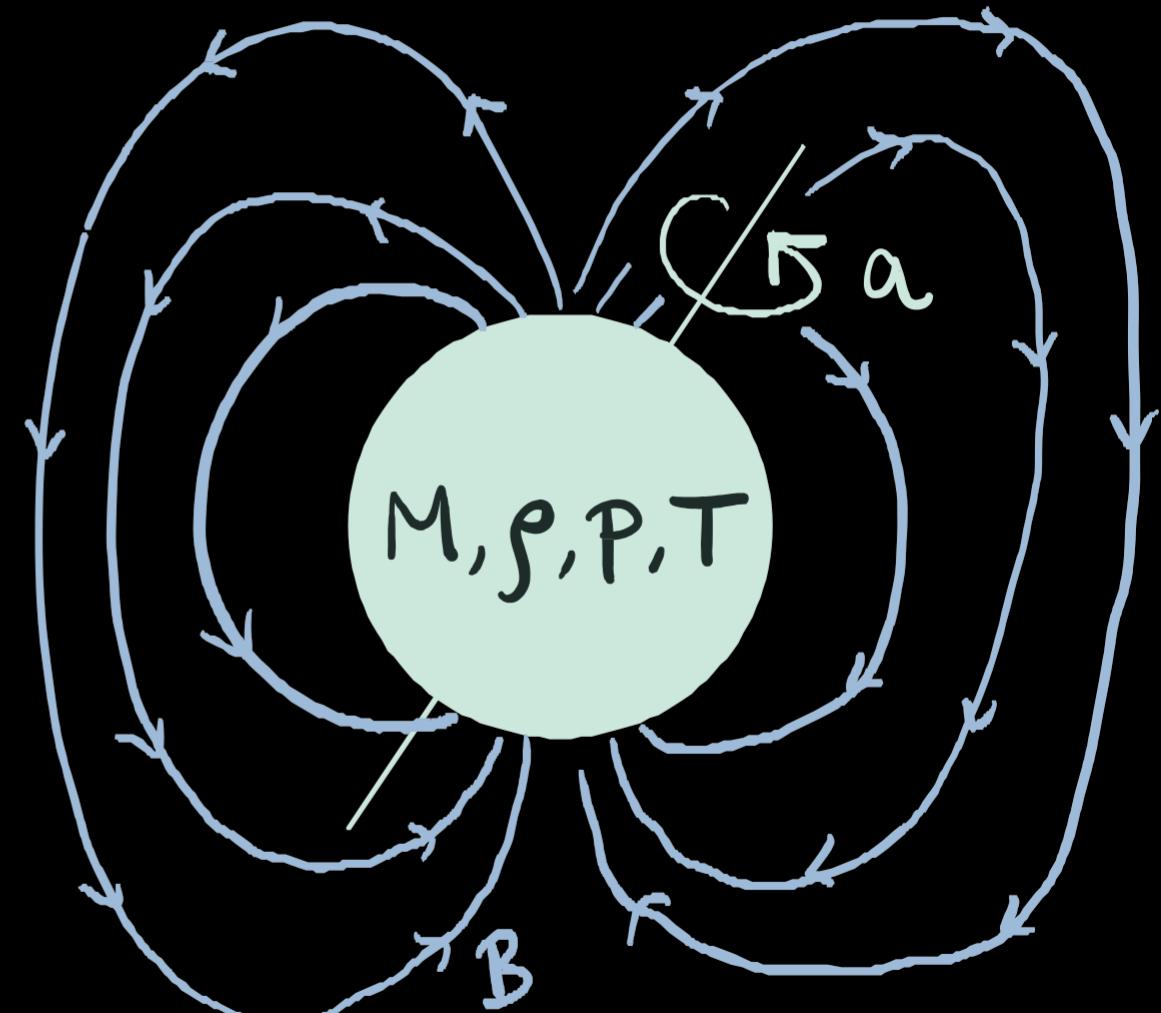


NEW SCIENCE WITH GWs

- LEARN ABOUT PROPERTIES OF BLACK HOLES AND NEUTRON STARS



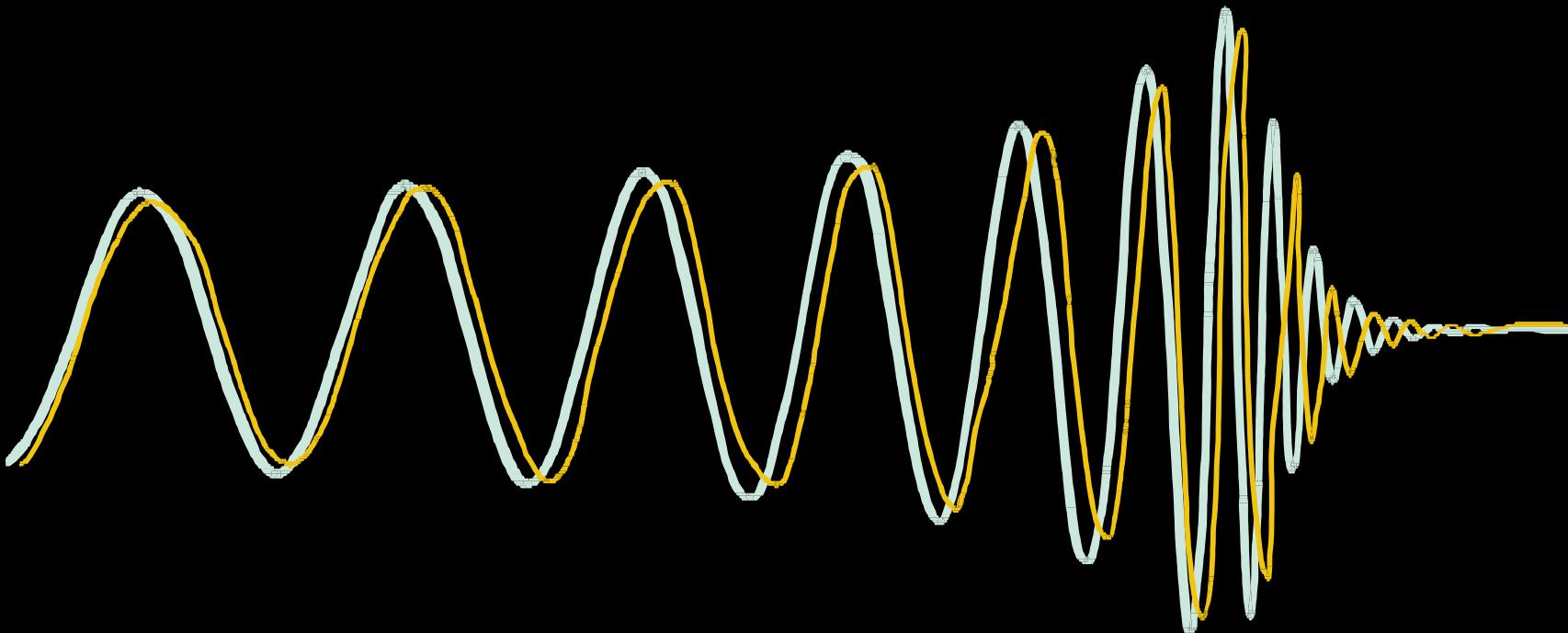
BLACK HOLES



NEUTRON STARS

NEW SCIENCE WITH GWs

- TEST NEW THEORIES OF GRAVITY

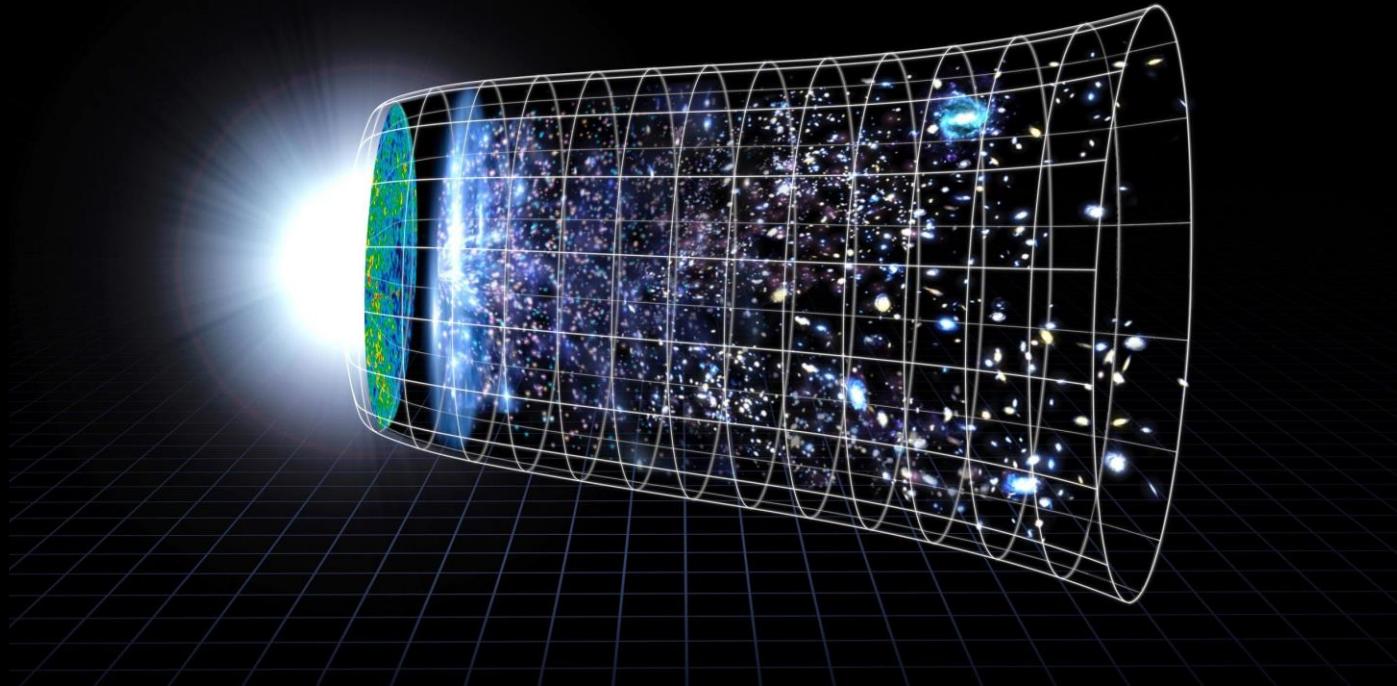


GENERAL RELATIVITY

MODIFIED GRAVIT

NEW SCIENCE WITH GWs

- MEASURE THE EXPANSION OF THE UNIVERSE
- LEARN ABOUT THE EARLY UNIVERSE



- AND MANY MORE !

THANKS

✗ @Sergisirera