

# TESTING GRAVITY WITH GRAVITATIONAL WAVES

SERGI SIRERA LAHOZ  
WITH JOHANNES NOLLER

BRIT GRAV 23 - SOUTHAMPTON

[2301.10272]



sergisl/ringdown-calculations

Public

WHAT?

WHY?

How?

WHEN?

# TESTING GRAVITY WITH GRAVITATIONAL WAVES

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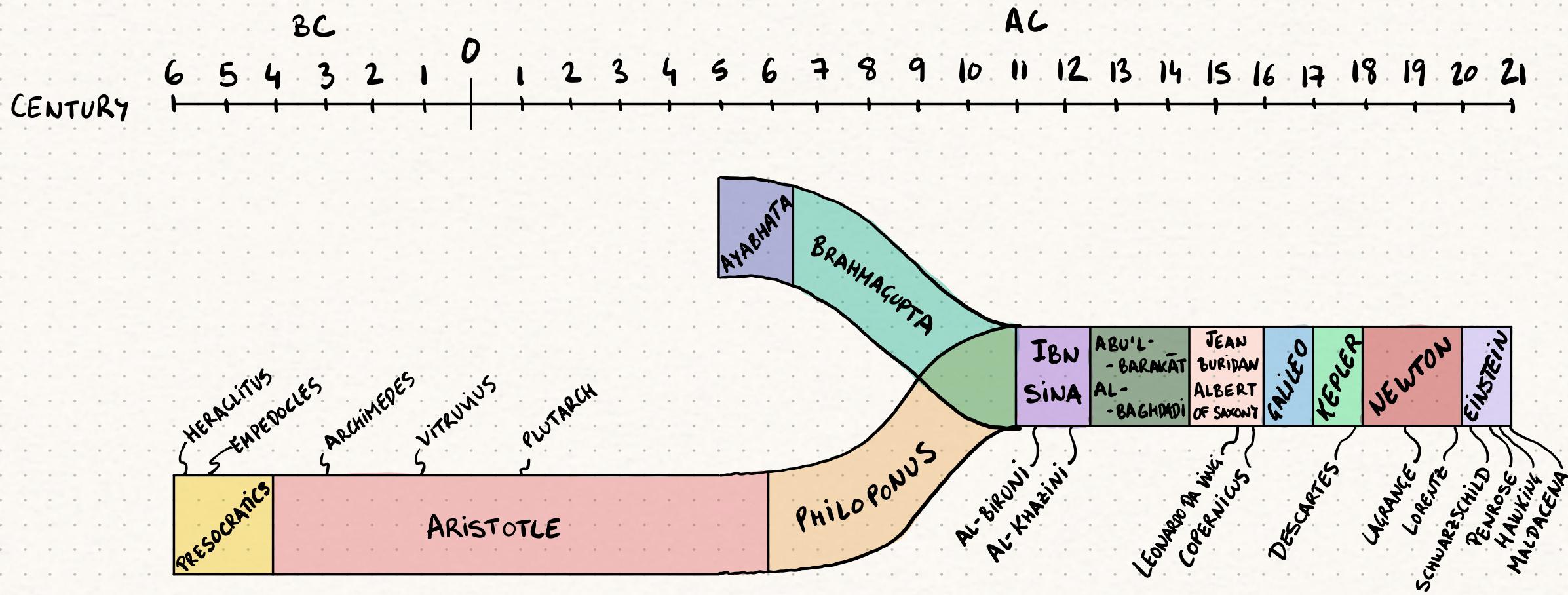


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Public

# TESTING GRAVITY

## - HISTORY OF GRAVITY:



# TESTING GRAVITY

- SO WHY SHOULD WE TEST GR ?

- DARK ENERGY
- SINGULARITIES
- NOT QUANTIZABLE
- WHY NOT?

# TESTING GRAVITY

$$\left. \begin{array}{l} 4D \\ g_{\mu\nu} \\ \text{LOCAL} \\ 2^{\text{nd}} \text{order EOM} \end{array} \right\} \text{GR} \quad \rightarrow \quad S = \int d^4x \sqrt{-g} R[g_{\mu\nu}]$$

(LOVELOCK'S THEOREM)

# TESTING GRAVITY

$$\left. \begin{array}{l} 4D \\ g_{\mu\nu} \\ \text{LOCAL} \\ \text{2}^{\text{nd}} \text{order EOM} \end{array} \right\} \text{GR} \rightarrow S = \int d^4x \sqrt{-g} R[g_{\mu\nu}]$$

(LOVELOCK'S THEOREM)

$$\left. \begin{array}{l} 4D \\ g_{\mu\nu} + \phi \\ \text{LOCAL} \\ \text{2}^{\text{nd}} \text{order EOM} \end{array} \right\} \text{HORNDESKI} \rightarrow S = \int d^4x \sqrt{-g} H[g_{\mu\nu}, \phi]$$

# TESTING GRAVITY

THEORY  
↓  
OBSERVABLE

$S = \int d^4x \sqrt{-g} R$   
↓  
 $\alpha = 0$

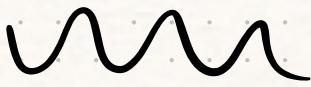
$S = \int d^4x \sqrt{-g} H$   
↓  
 $\alpha \neq 0$

"SMOKING  
GUN SIGNAL"

# GRAVITATIONAL WAVES

GR

$$S = \int d^4x \sqrt{-g} R \longrightarrow G_{\mu\nu} = T_{\mu\nu} \xrightarrow[\text{WEAK FIELD}]{g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}} \square h_{\mu\nu} = T_{\mu\nu}$$

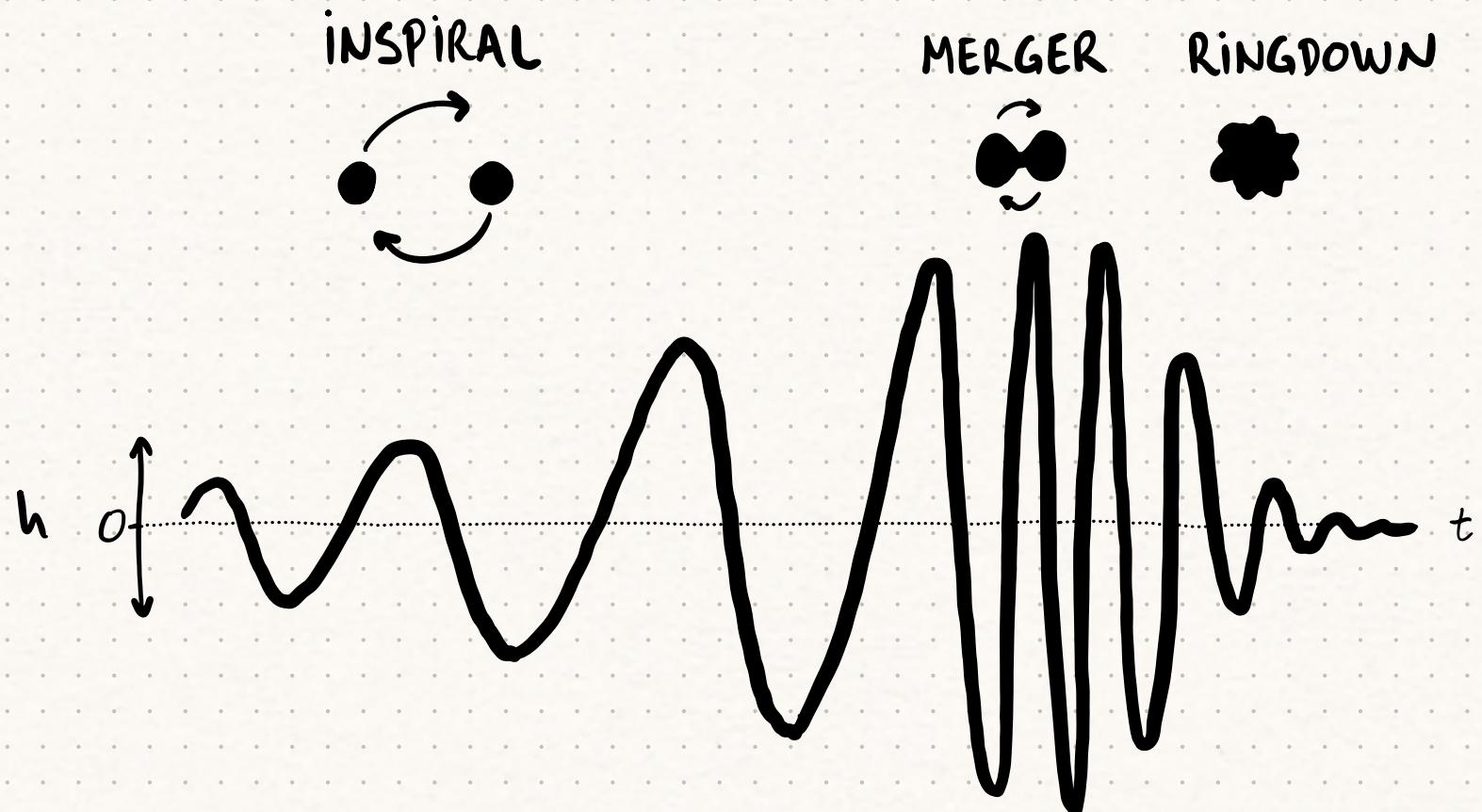


# GRAVITATIONAL WAVES

GR

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ASTROPHYSICAL SOURCES : MERGERS ( BLACK HOLES / NEUTRON STARS )



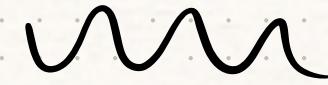
# GRAVITATIONAL WAVES

GR

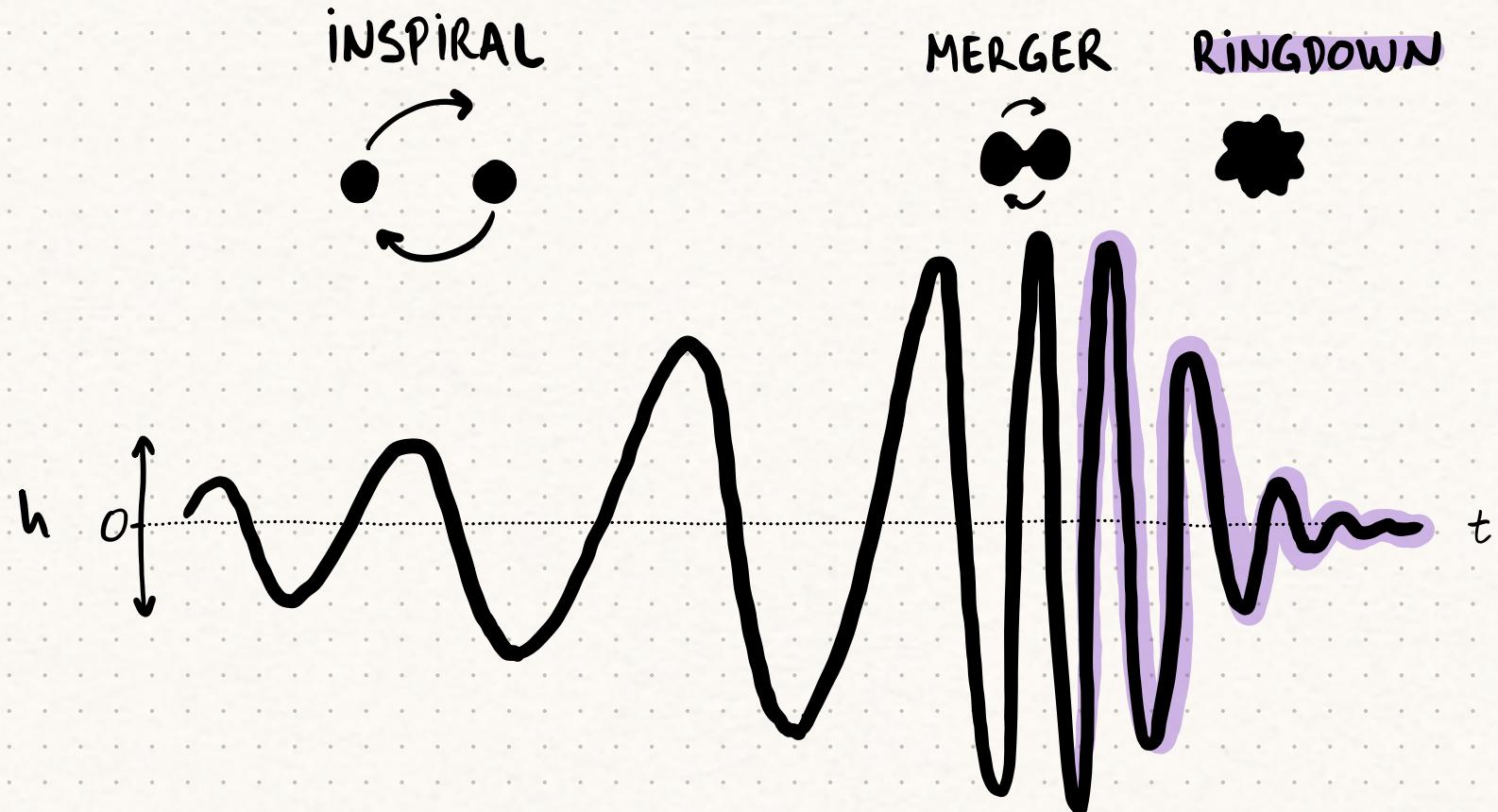
$$S = \int d^4x \sqrt{g} R \longrightarrow G_{\mu\nu} = T_{\mu\nu}$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \xrightarrow{\text{WEAK FIELD}}$$

$$\square h_{\mu\nu} = T_{\mu\nu}$$



ASTROPHYSICAL SOURCES : MERGERS ( BLACK HOLES / NEUTRON STARS )

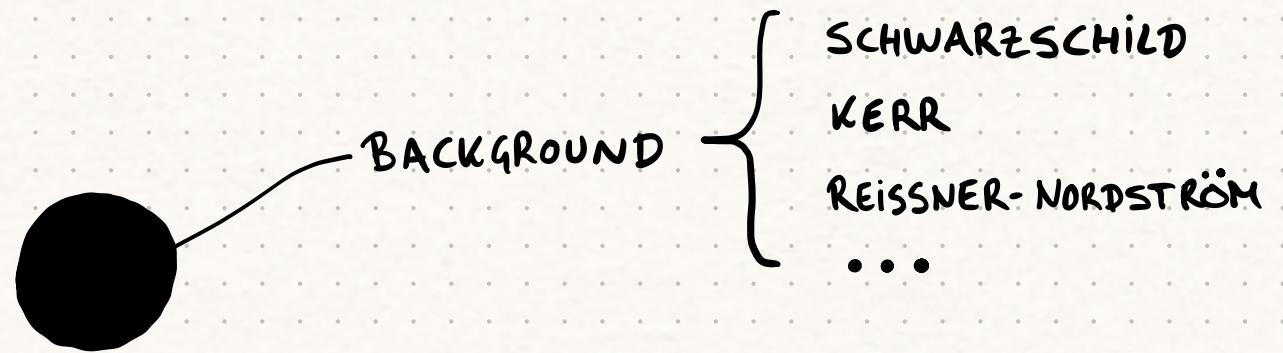


# GRAVITATIONAL WAVES

GR

RINGDOWN : BLACK HOLE PERTURBATION THEORY

$$g_{\mu\nu} = \bar{g}_{\mu\nu}$$

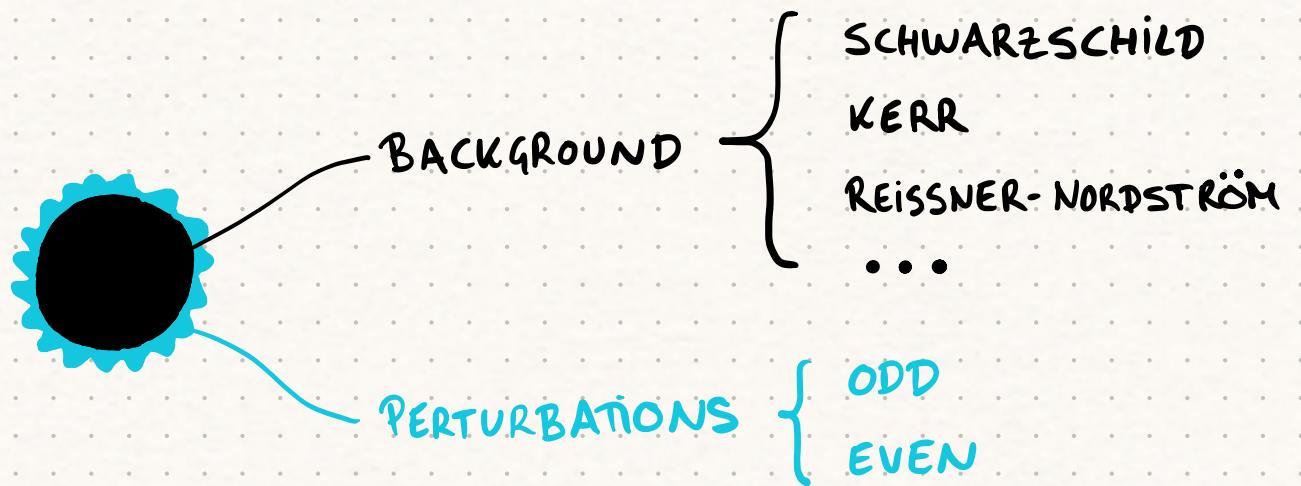


# GRAVITATIONAL WAVES

GR

RINGDOWN : BLACK HOLE PERTURBATION THEORY

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$$



# GRAVITATIONAL WAVES

GR

RINGDOWN : BLACK HOLE PERTURBATION THEORY

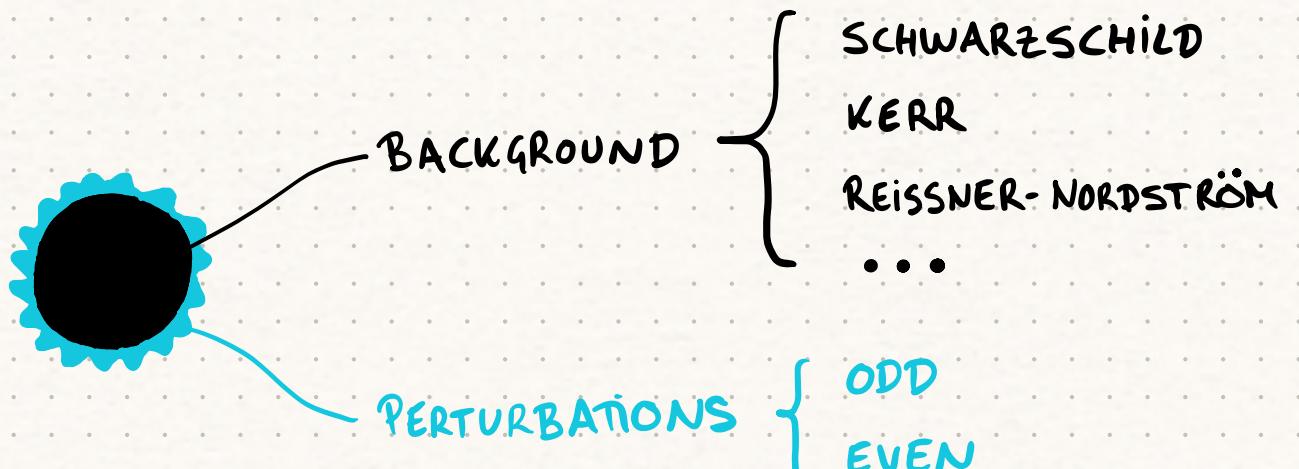
$$g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$$



$$G_{\mu\nu} = 0$$



$$\frac{d^2 h}{dr_*^2} + [\omega^2 - V] h = 0$$



# GRAVITATIONAL WAVES

GR

RINGDOWN : BLACK HOLE PERTURBATION THEORY

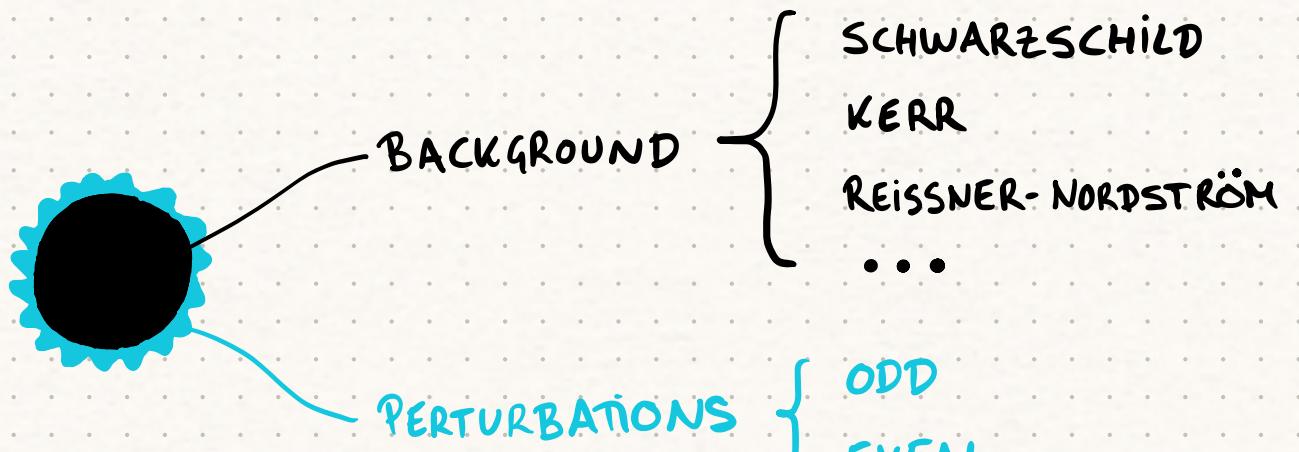
$$g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$$



$$G_{\mu\nu} = 0$$



$$\frac{d^2 h}{dr_*^2} + [\omega^2 - V] h = 0$$



QUASINORMAL MODES :  $\omega(M, a)$

(NO HAIR THEOREM)

# GRAVITATIONAL WAVES

## BLACK HOLE SPECTROSCOPY

$\omega(M, a)$  • 1st QNM sets  $M$

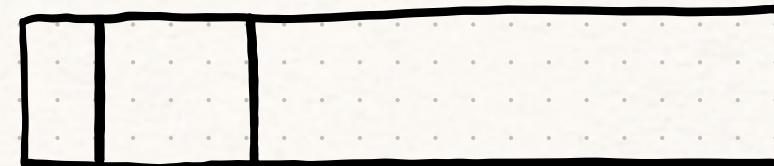
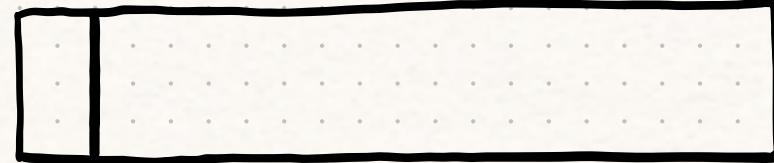


# GRAVITATIONAL WAVES

## BLACK HOLE SPECTROSCOPY

$\omega(M, a)$

- 1st QNM sets  $M$
- 2nd QNM sets  $a$

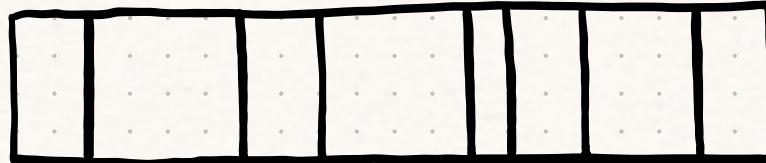


# GRAVITATIONAL WAVES

## BLACK HOLE SPECTROSCOPY

$\omega(M, a)$

- 1st QNM sets  $M$
- 2nd QNM sets  $a$
- All other QNMs are fixed in GR

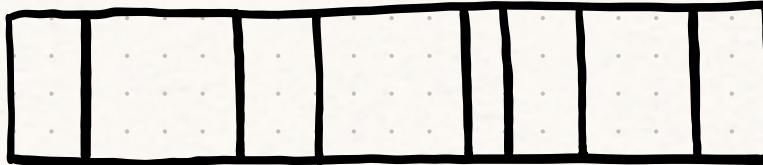
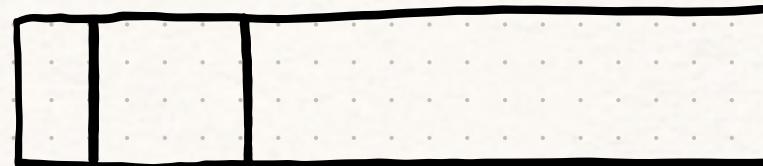


# GRAVITATIONAL WAVES

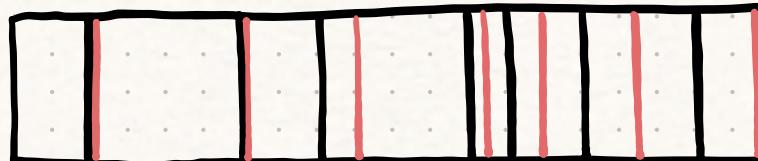
## BLACK HOLE SPECTROSCOPY

$\omega(M, a)$

- 1st QNM sets  $M$
- 2nd QNM sets  $a$
- All other QNMs are fixed in GR



MEASURING QNMs PROVIDES CLEAN TESTS OF  
BACKGROUND GEOMETRY AND UNDERLYING THEORY



GR       $\omega(M, a)$   
MG       $\omega(M, a, \alpha)$

# TESTING GRAVITY WITH GRAVITATIONAL WAVES

GR

$$S = \int d^4x \sqrt{-g} R(g_{\mu\nu})$$



$$\frac{d^2 h}{dr_*^2} + [w^2 + V] h = 0$$



$$\omega(M, a)$$

$$\alpha_T = 0$$

HORNDESKI

$$S = \int d^4x \sqrt{-g} H(g_{\mu\nu}, \phi)$$



$$\frac{d^2 h}{dr_*^2} + [w^2(1 + \alpha_T) + V + \alpha_T \delta V] h = 0$$



$$\omega(M, a, \alpha_T)$$

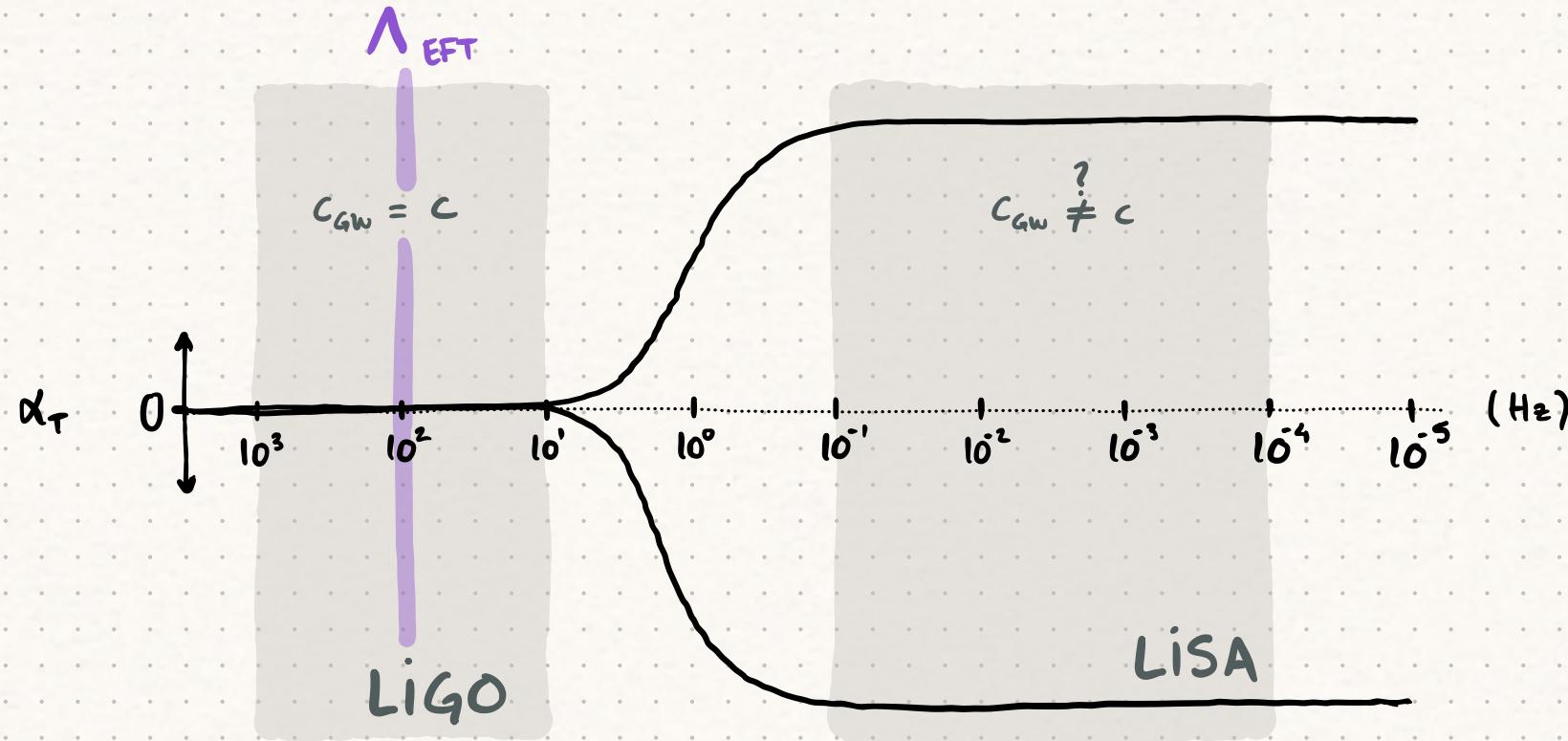
$$\alpha_T = \frac{c_{GW} - c}{c} \neq 0$$

GRAVITATIONAL WAVE SPEED EXCESS

# TESTING GRAVITY WITH GRAVITATIONAL WAVES

WHAT DO WE KNOW ABOUT  $\alpha_T$ ?

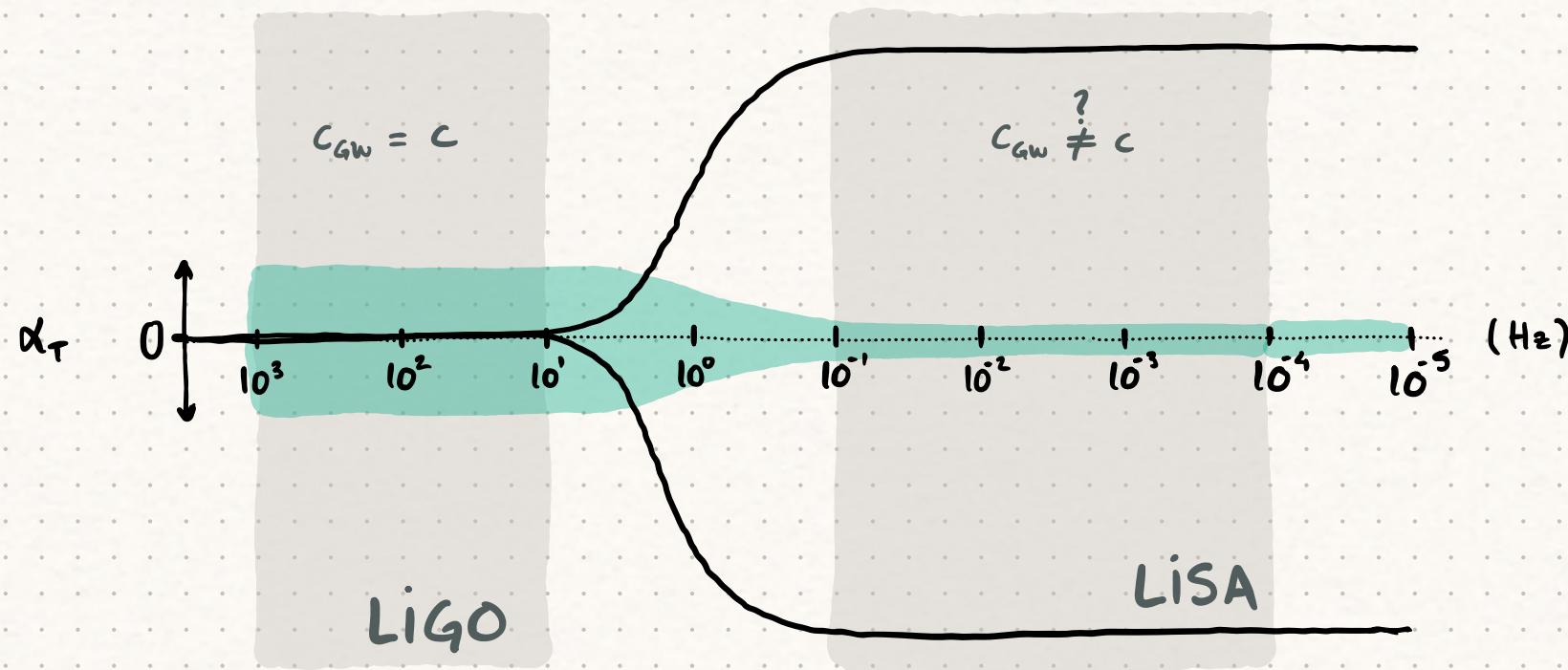
- LIGO :  $\alpha_T \lesssim 10^{-15}$  (GW170817)
- DARK ENERGY EFTs : CUTOFF AT  $\sim 10^2$  Hz



# TESTING GRAVITY WITH GRAVITATIONAL WAVES

WHAT DO WE KNOW ABOUT  $\alpha_T$ ?

- LIGO :  $\alpha_T \lesssim 10^{-15}$  (GW170817)
- DARK ENERGY EFTs : CUTOFF AT  $\sim 10^2$  Hz



## FISCHER FORECASTS:

FOR 1 LOUD MERGER :

- LISA :  $\alpha_T \lesssim 10^{-4}$
- LIGO/ET  $\alpha_T \lesssim 10^{-1}$

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# FUTURE DIRECTIONS

- RINGDOWN OF BHs IN EXPANDING UNIVERSE
- INCLUDE SOME UV PHYSICS TO MODEL  $\alpha_T(f)$  (FREQUENCY DEPENDENCE)
- IMPLEMENT SOME MODIFIED GRAVITY PARAMETERS IN LIGO ANALYSIS PIPELINE

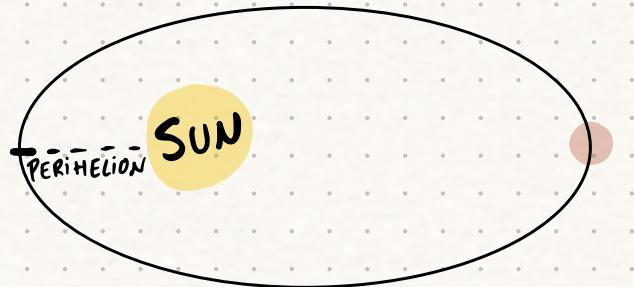
THANKS!

# TESTING GRAVITY

## - HISTORY OF GRAVITY:

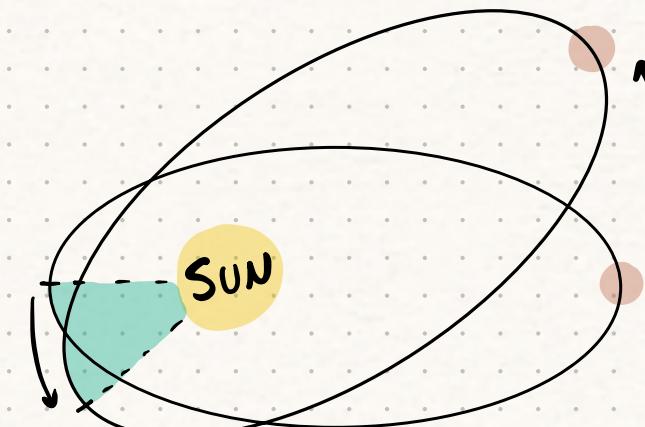
NEWTONIAN  $\xrightarrow{\text{MERCURY}}$  GENERAL RELATIVITY

PREDICTION



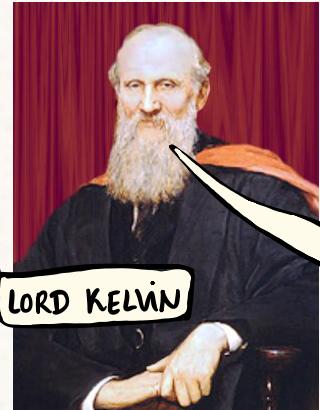
VS

OBSERVATION



$$\delta = 0$$

$$\delta \neq 0$$



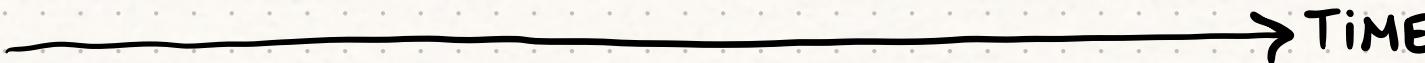
LORD KELVIN

THERE IS NOTHING NEW TO BE  
DISCOVERED IN PHYSICS NOW.  
ALL THAT REMAINS IS MORE  
AND MORE PRECISE MEASUREMENT.

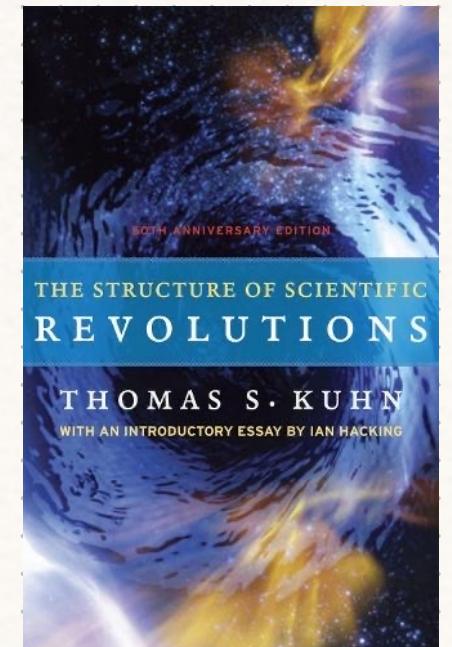
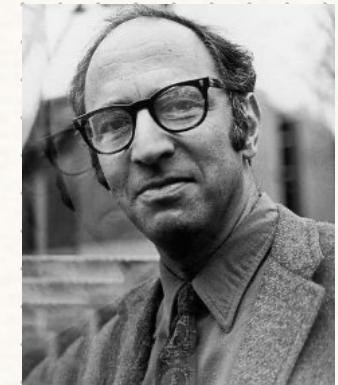
# TESTING GRAVITY

- How DOES SCIENCE WORK ?

THOMAS KUHN (1962) :



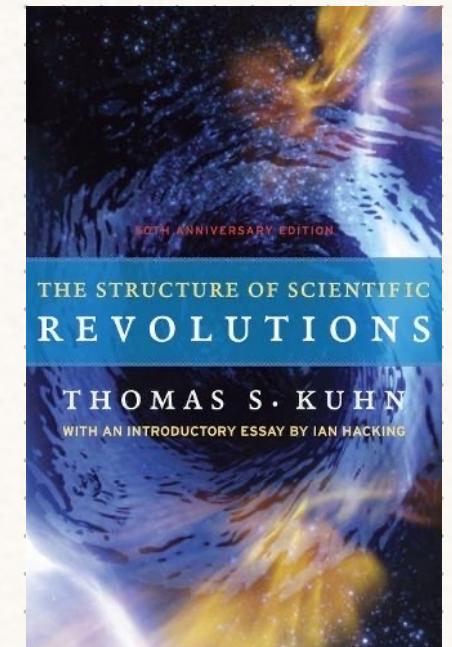
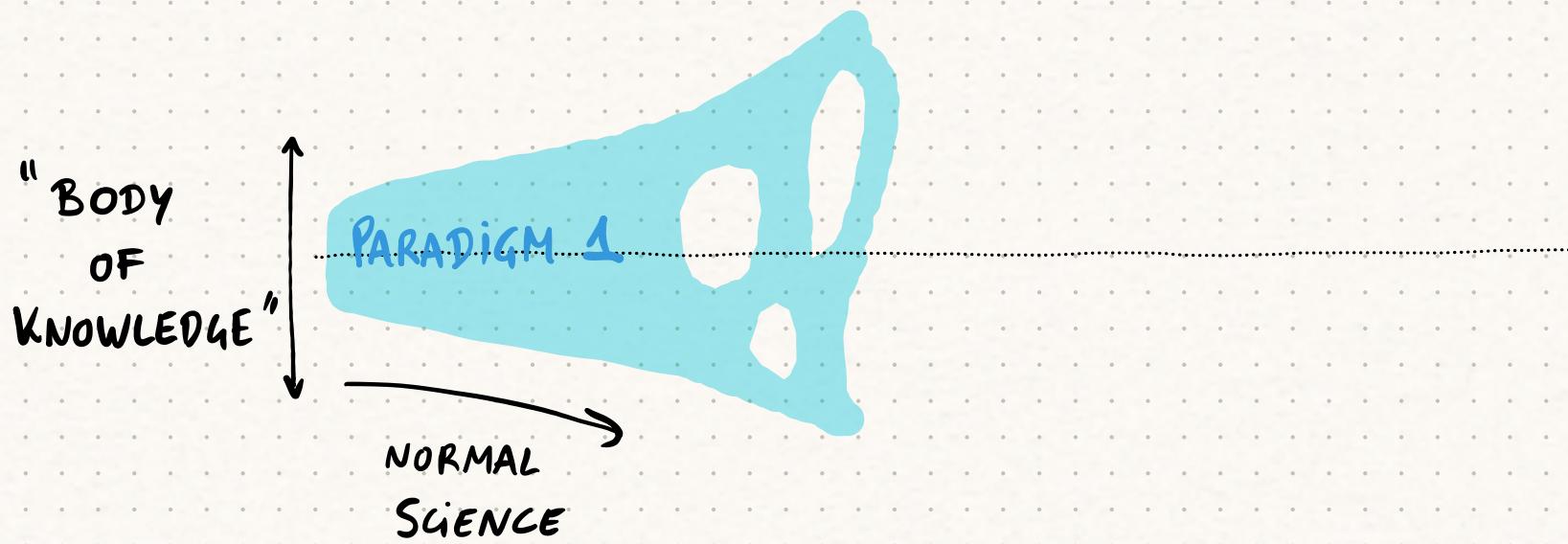
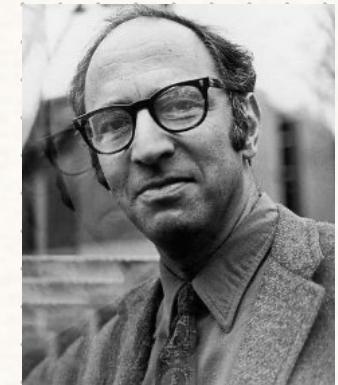
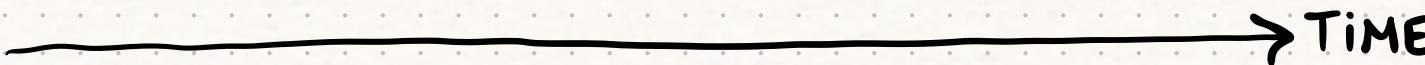
"BODY  
OF  
KNOWLEDGE"



# TESTING GRAVITY

- How DOES SCIENCE WORK ?

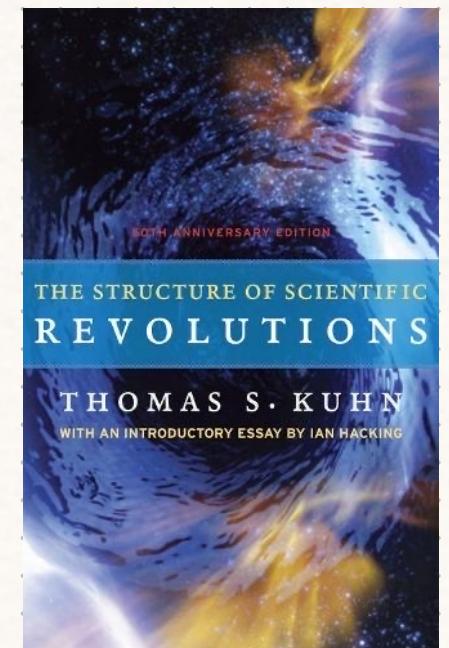
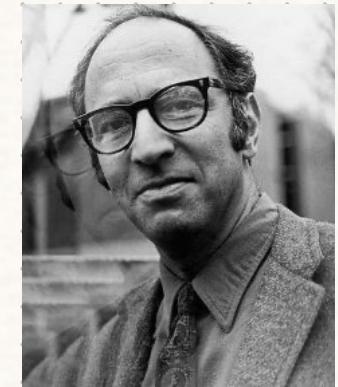
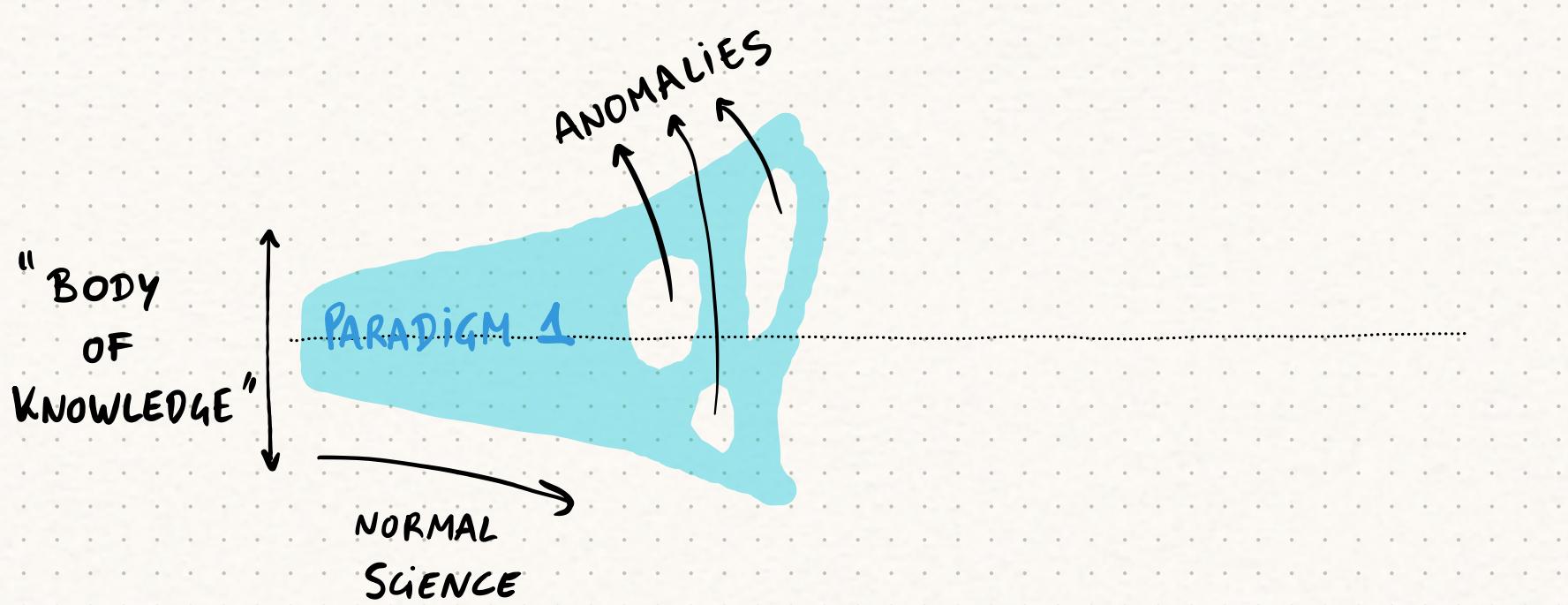
THOMAS KUHN (1962) :



# TESTING GRAVITY

- How DOES SCIENCE WORK ?

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