

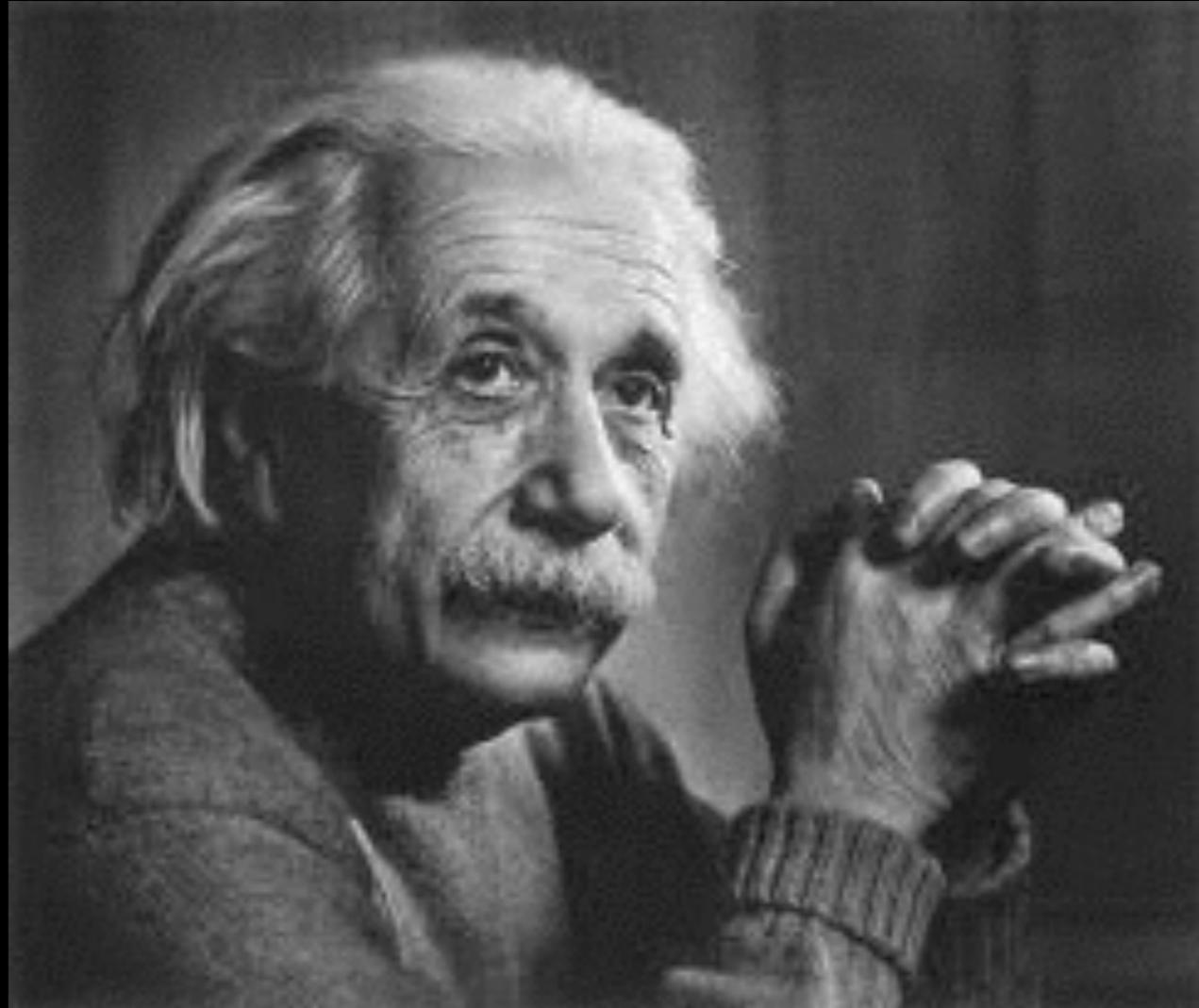
# ESPACIOTIEMPO

de los agujeros negros a la  
expansión del universo

J.L.F. Barbón



Instituto de  
Física  
Teórica



$\Phi$



RELATIVIDAD

CUANTICA

*espaciotiempo*

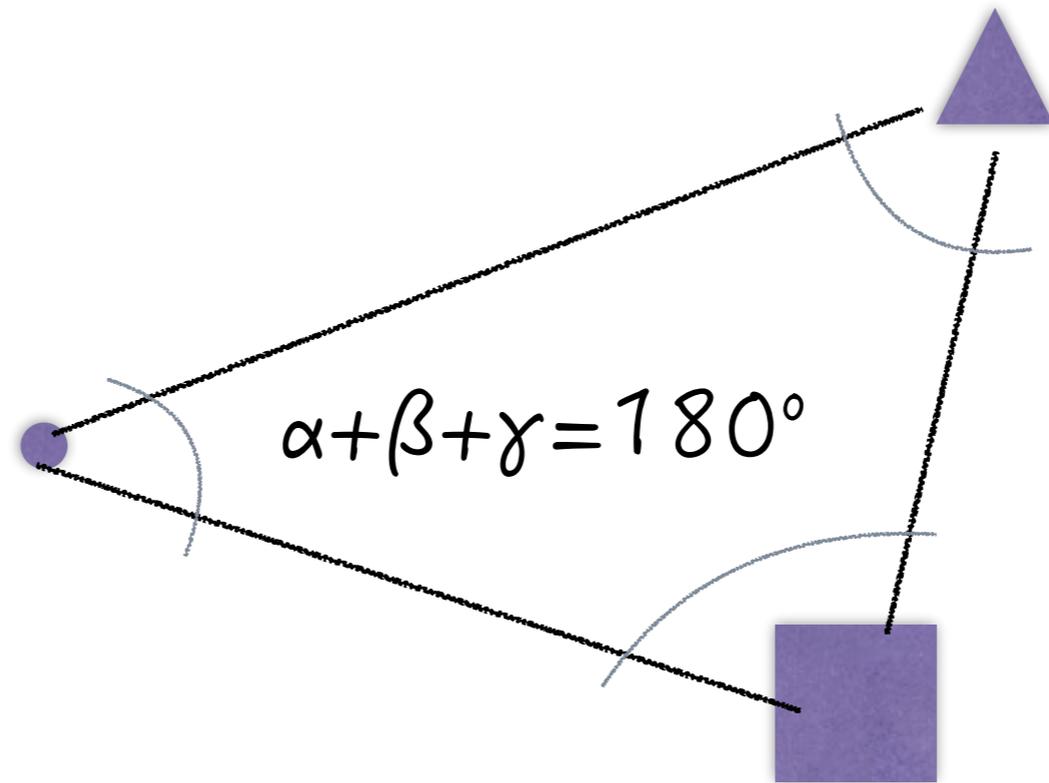
*particulas*

ESPACIO

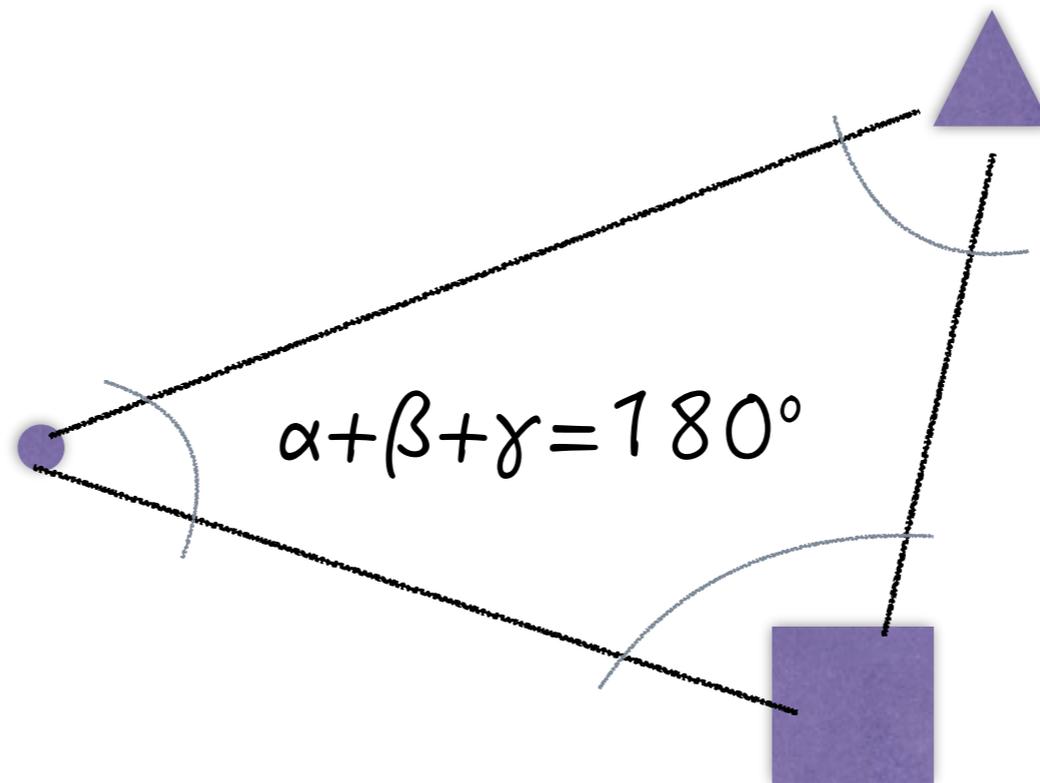
ESPACIO



# ESPACIO

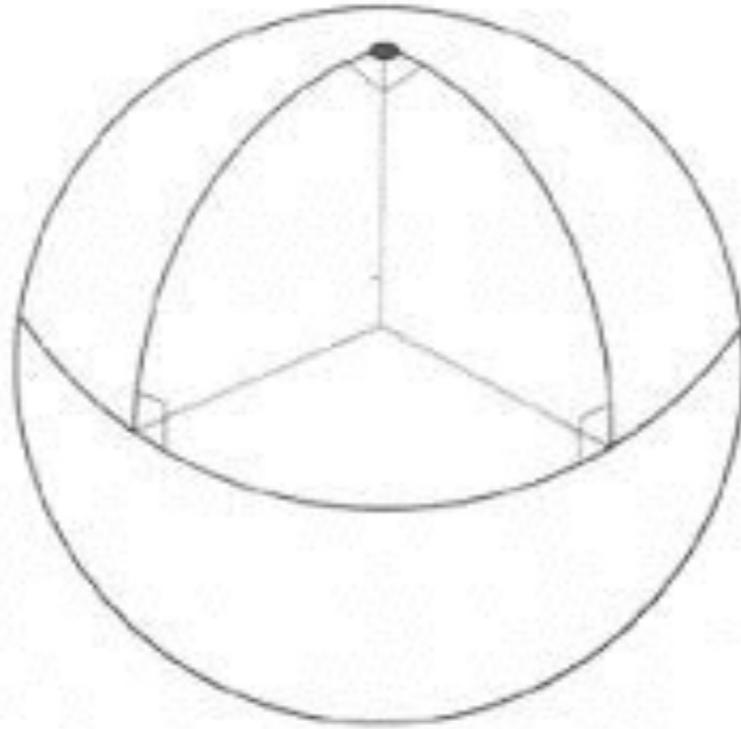


# ESPACIO



Estructura del espacio = GEOMETRIA

PERO ...



$$\alpha + \beta + \gamma > 180^\circ$$

La geometría del espacio físico  
es una cuestión experimental

TIEMPO

TIEMPO



TIEMPO

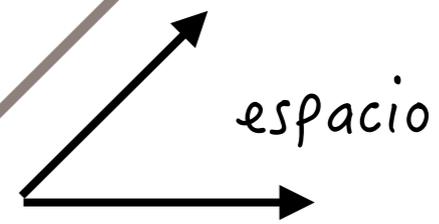
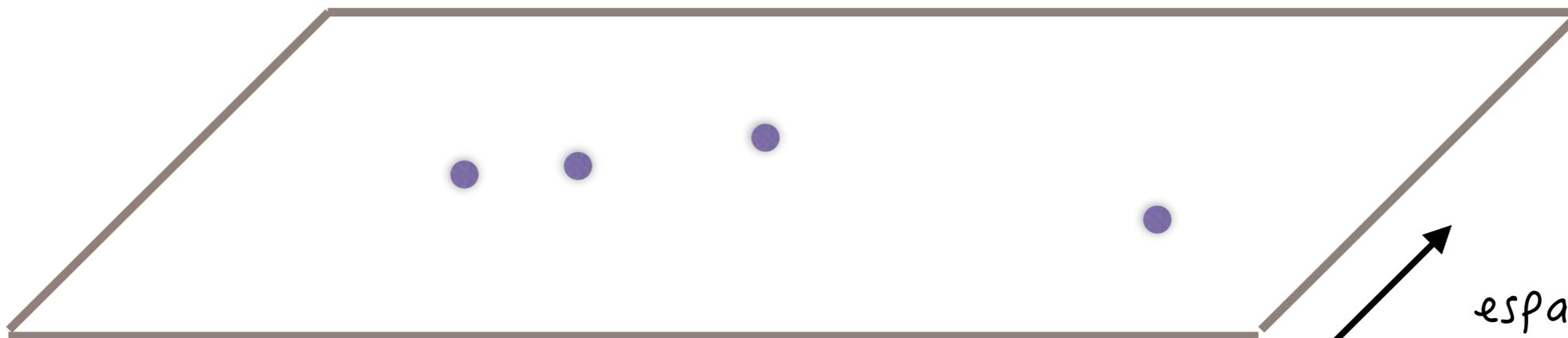


# TIEMPO



La estructura del tiempo es la DINAMICA

tiempo

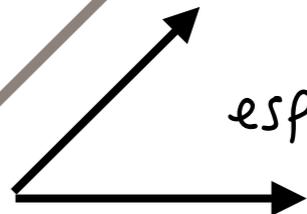
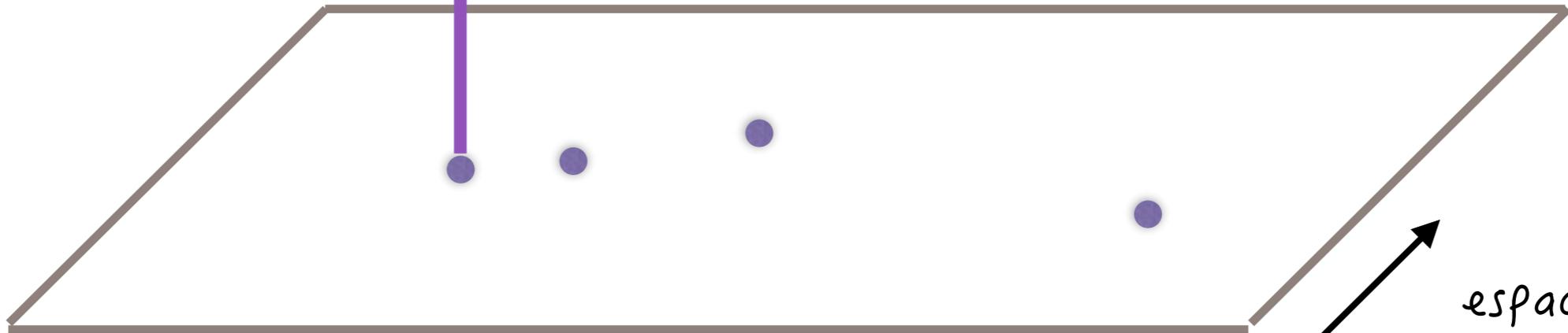


espacio

ESPACIO - TIEMPO

tiempo

parado



espacio

ESPACIO - TIEMPO

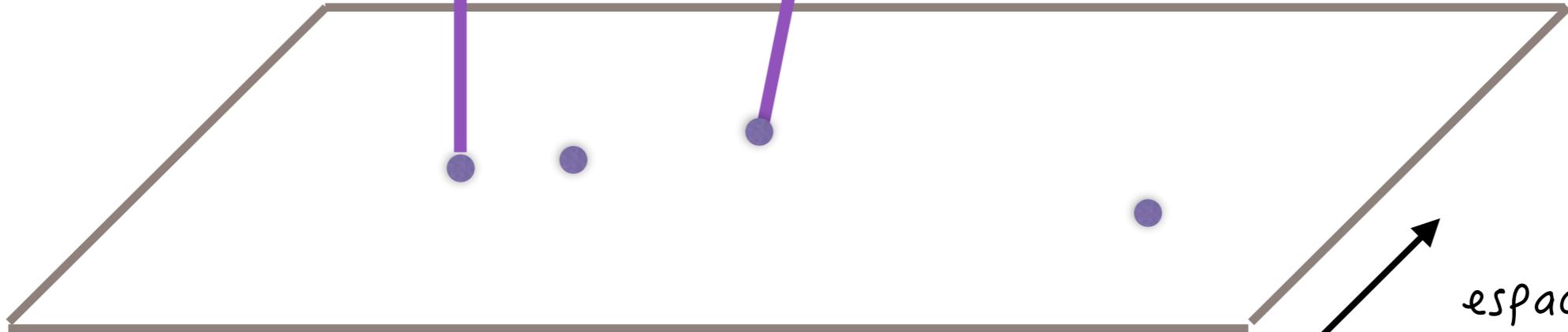
tiempo

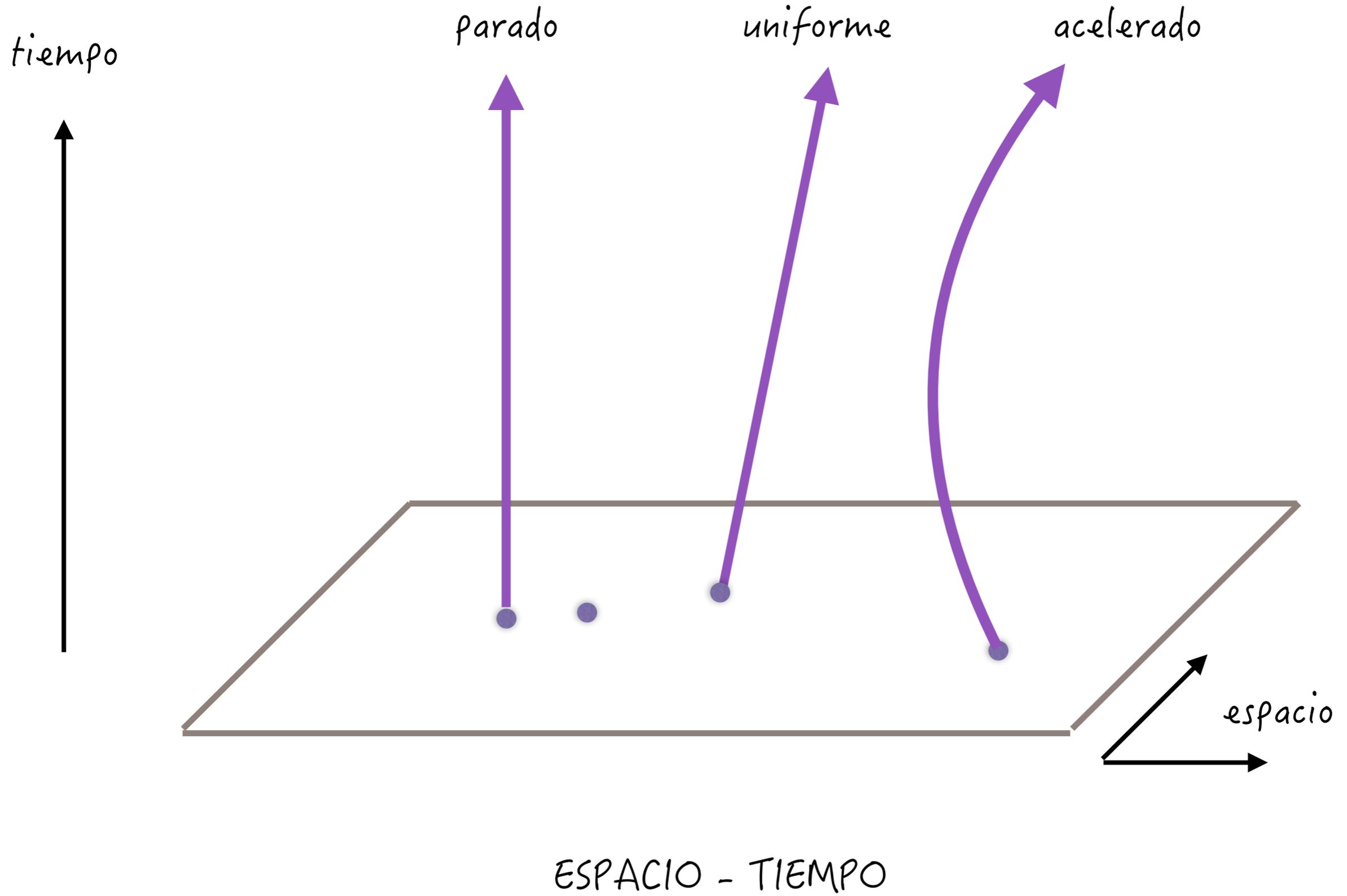
parado

uniforme

espacio

ESPACIO - TIEMPO



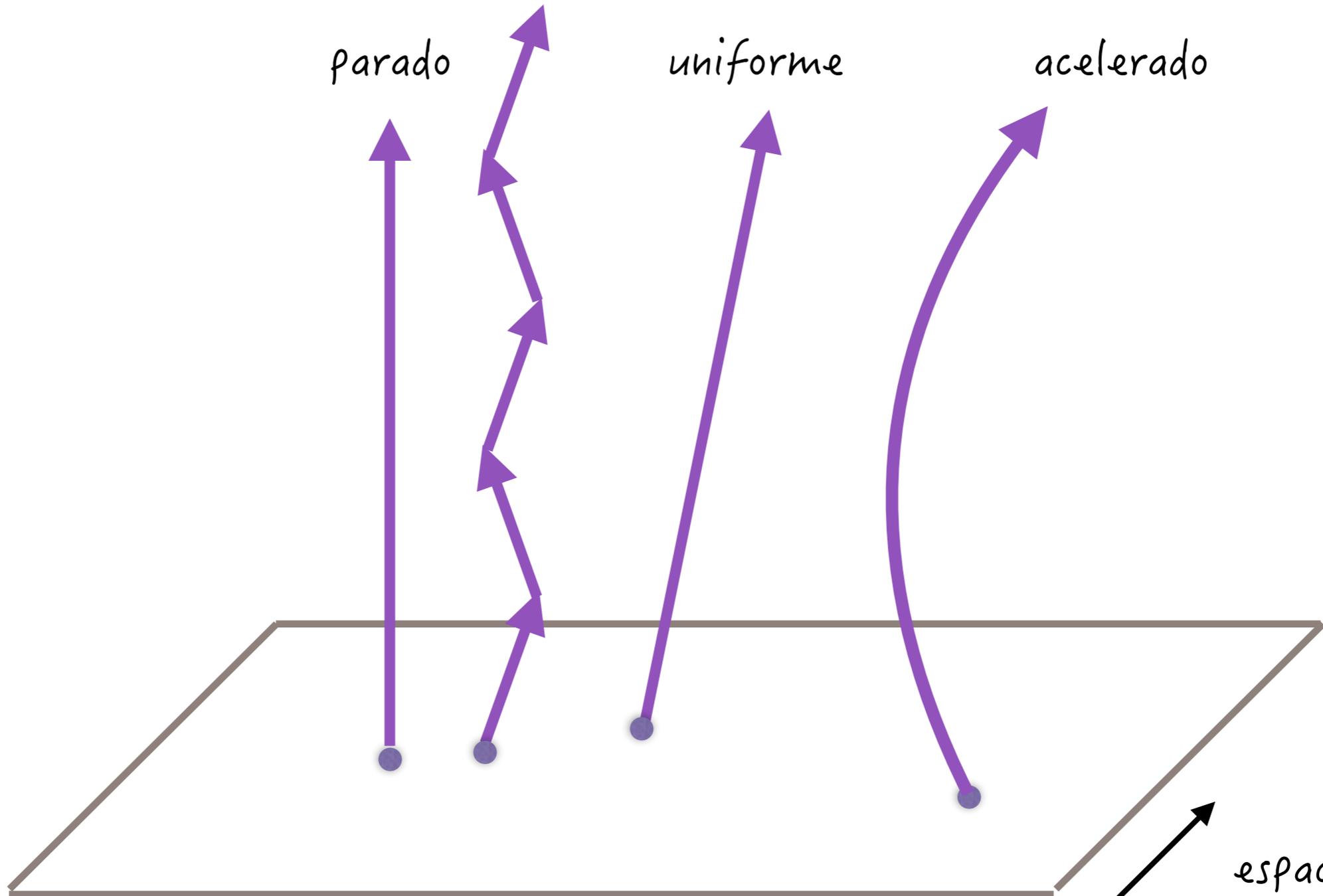
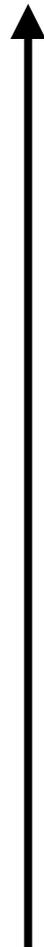


tiempo

parado

uniforme

acelerado



espacio

ESPACIO - TIEMPO

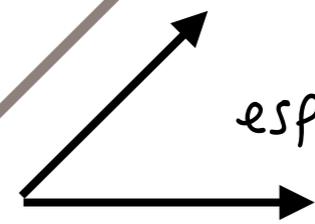
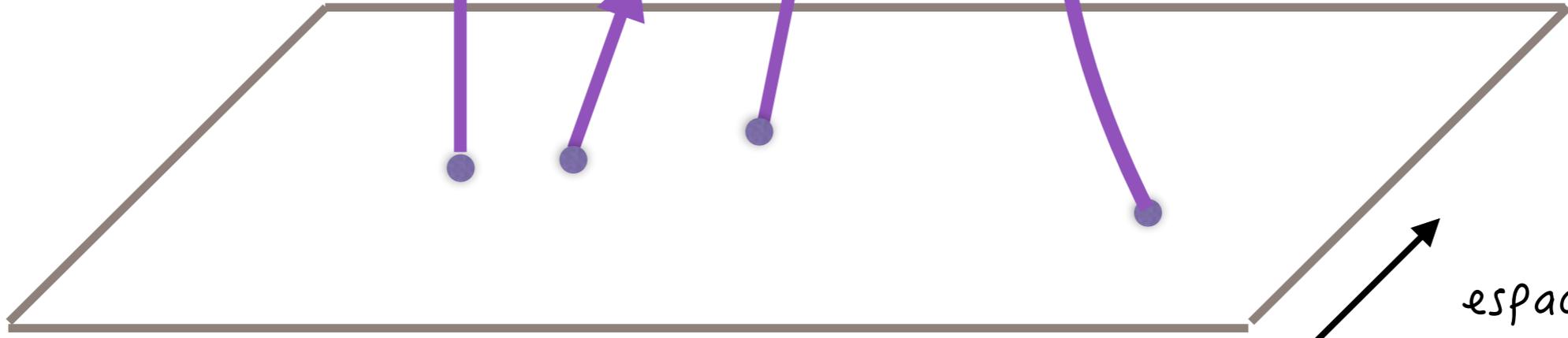
tiempo

¡reloj!

parado

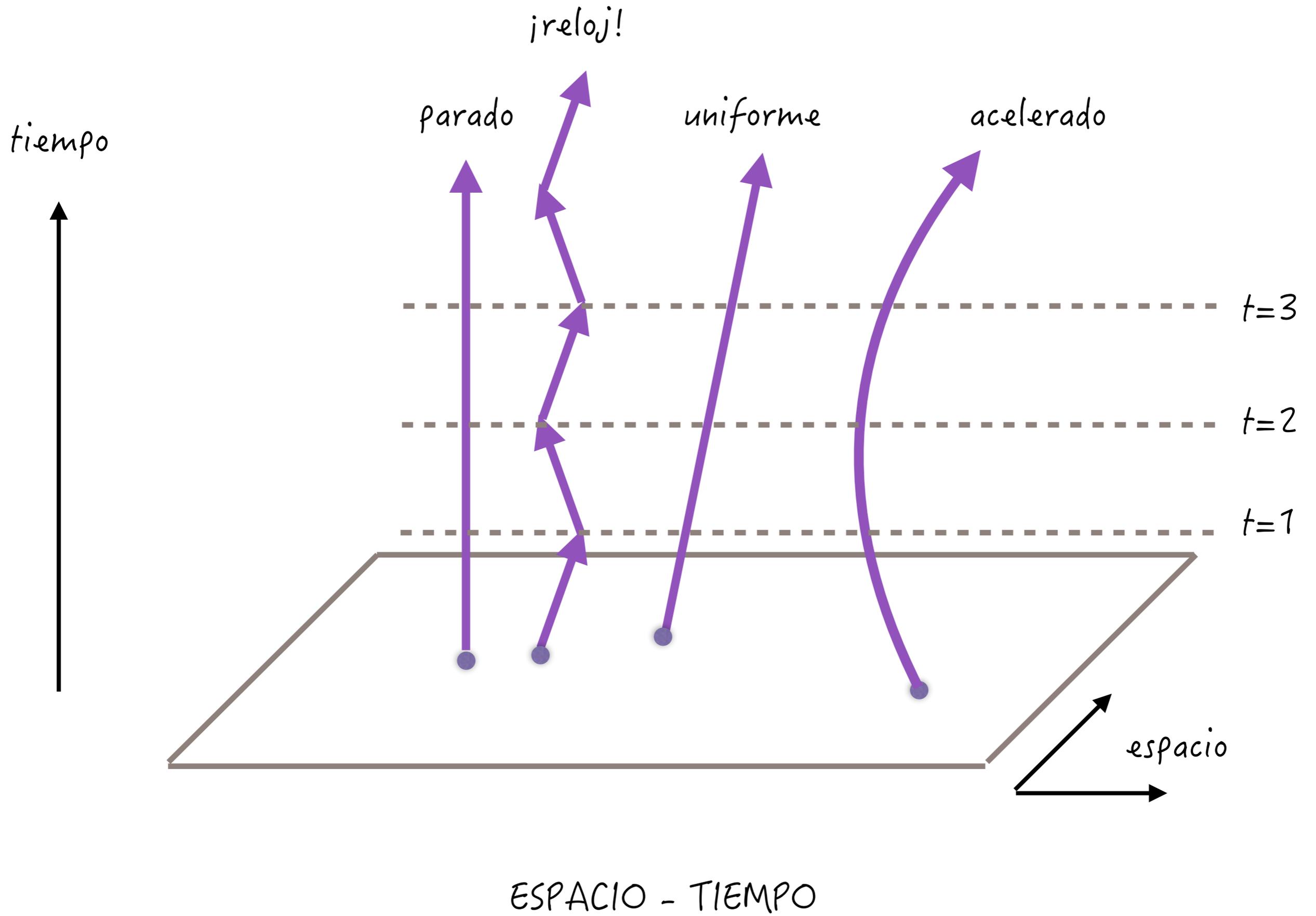
uniforme

acelerado



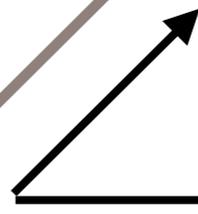
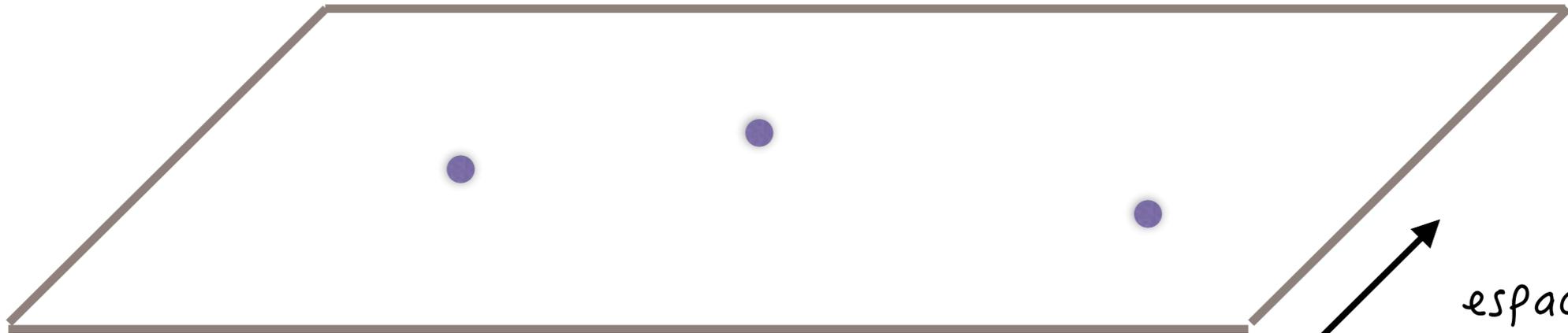
espacio

ESPACIO - TIEMPO



# ARISTOTELES

tiempo



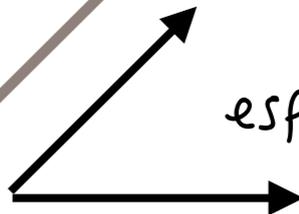
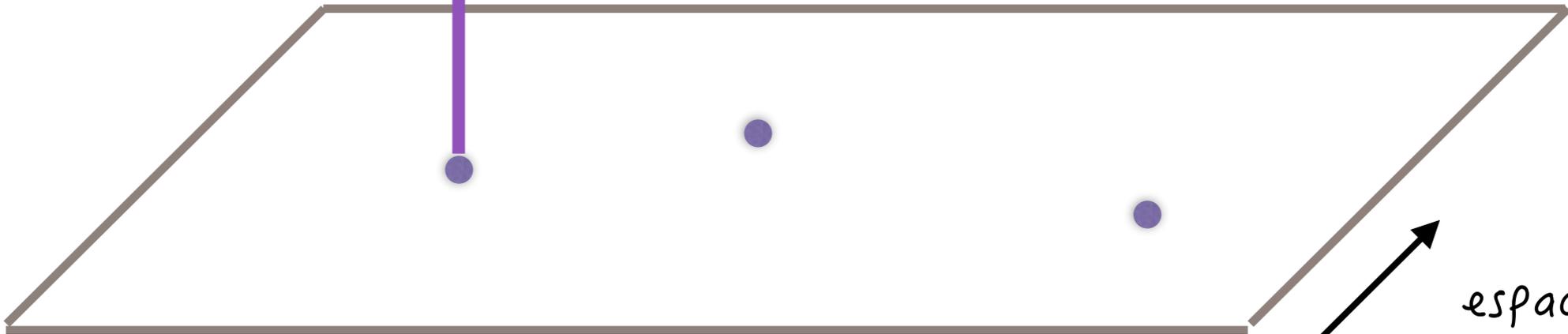
espacio

# ARISTOTELES

tiempo

parado

espacio

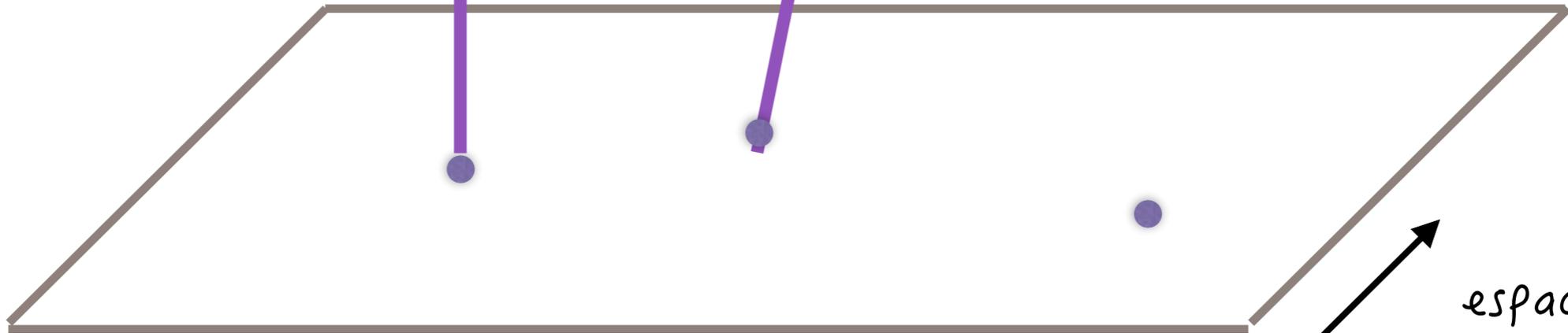


# ARISTOTELES

tiempo

parado

uniforme



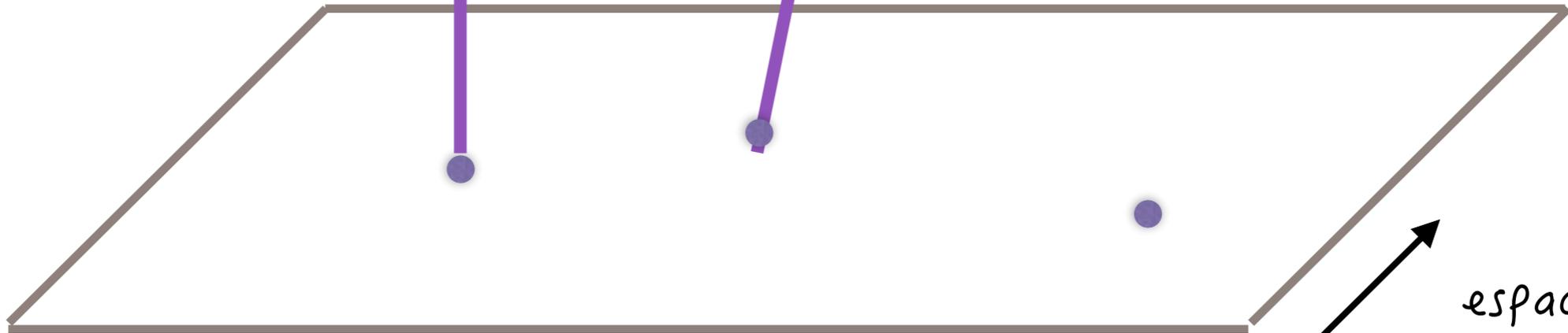
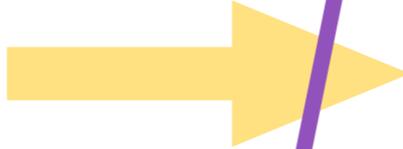
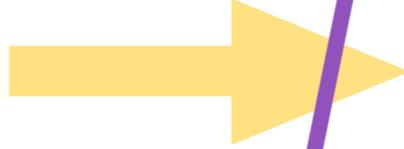
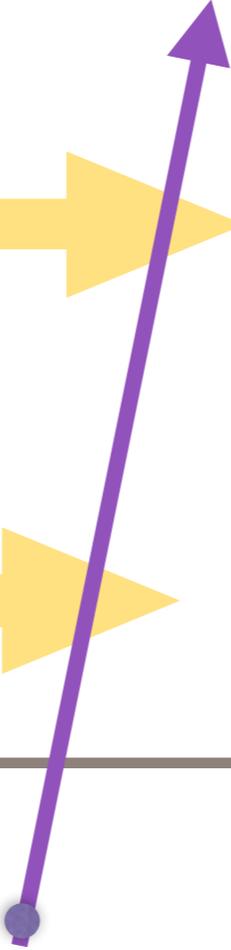
espacio

# ARISTOTELES

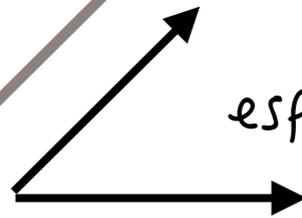
tiempo

parado

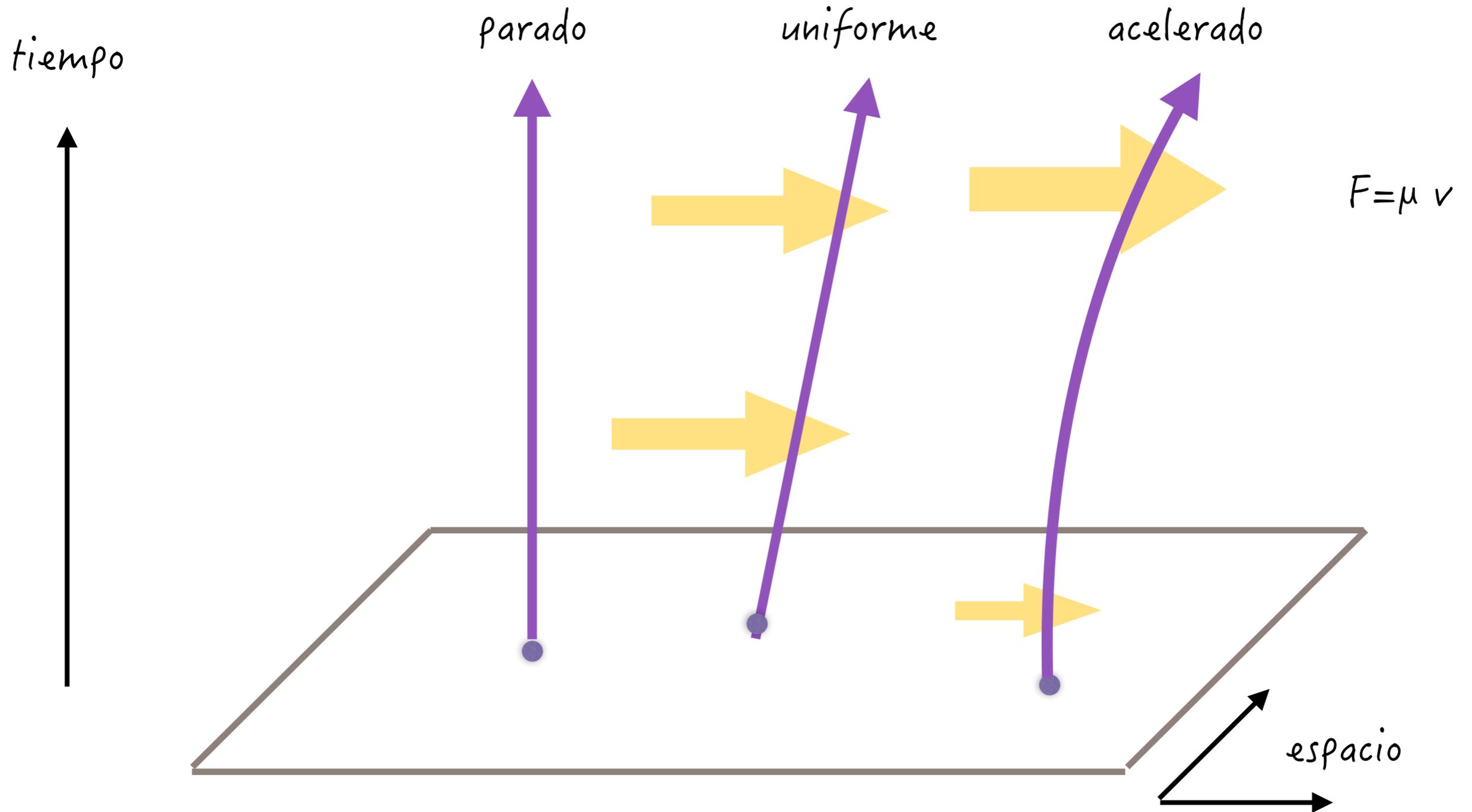
uniforme



espacio

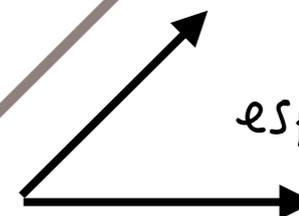
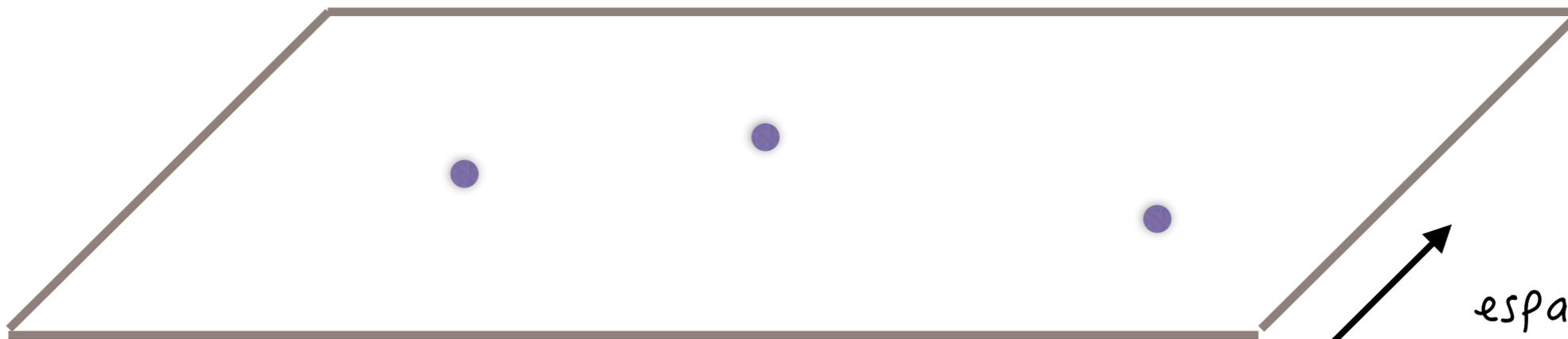


# ARISTOTELES



# GALILEO & NEWTON

tiempo

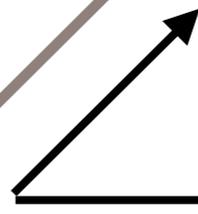
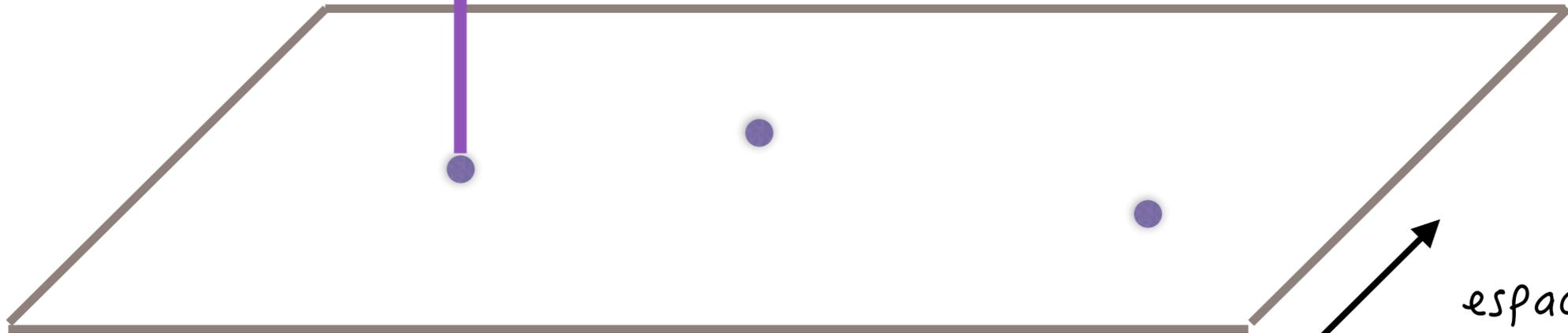


espacio

# GALILEO & NEWTON

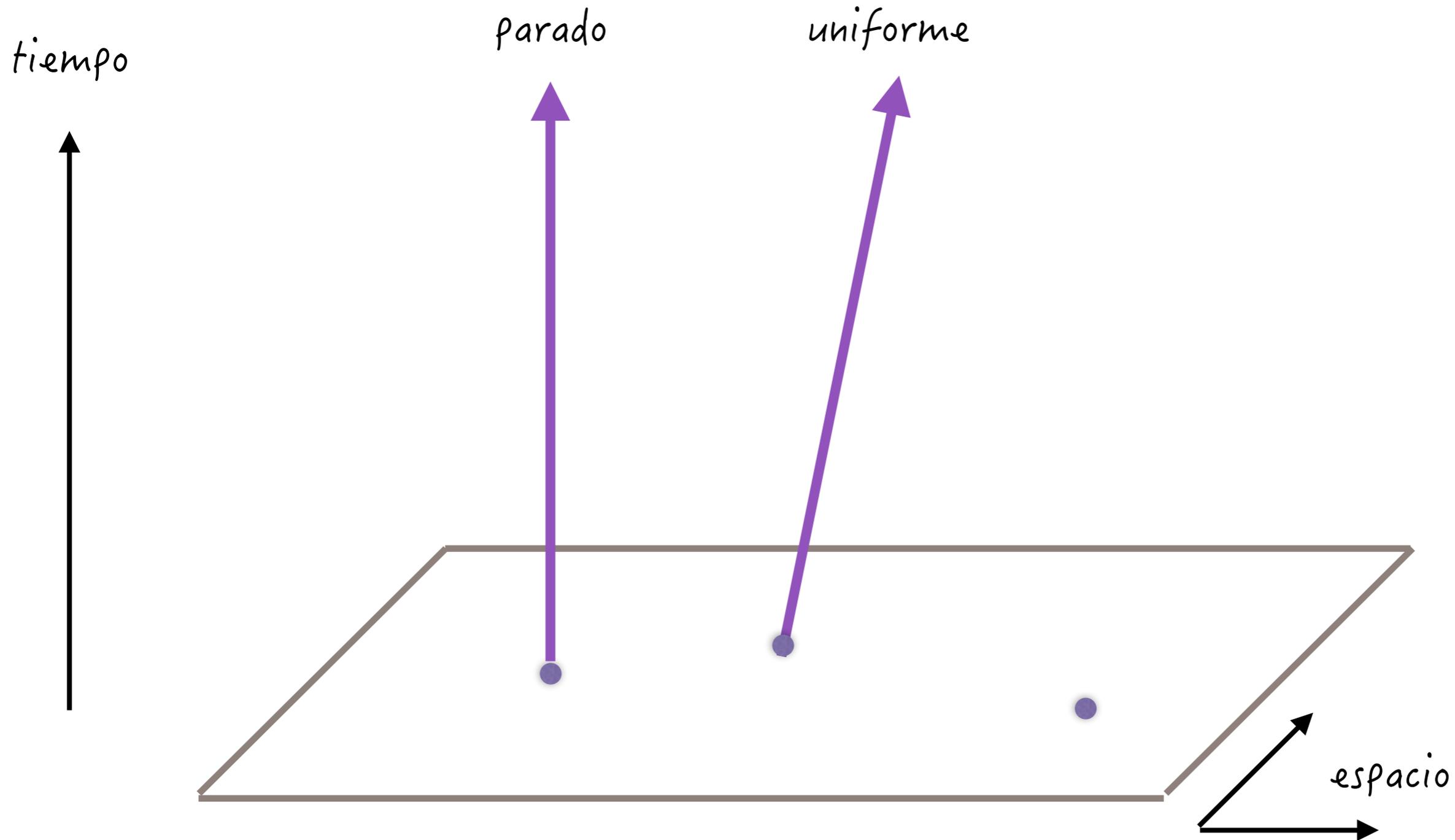
tiempo

parado

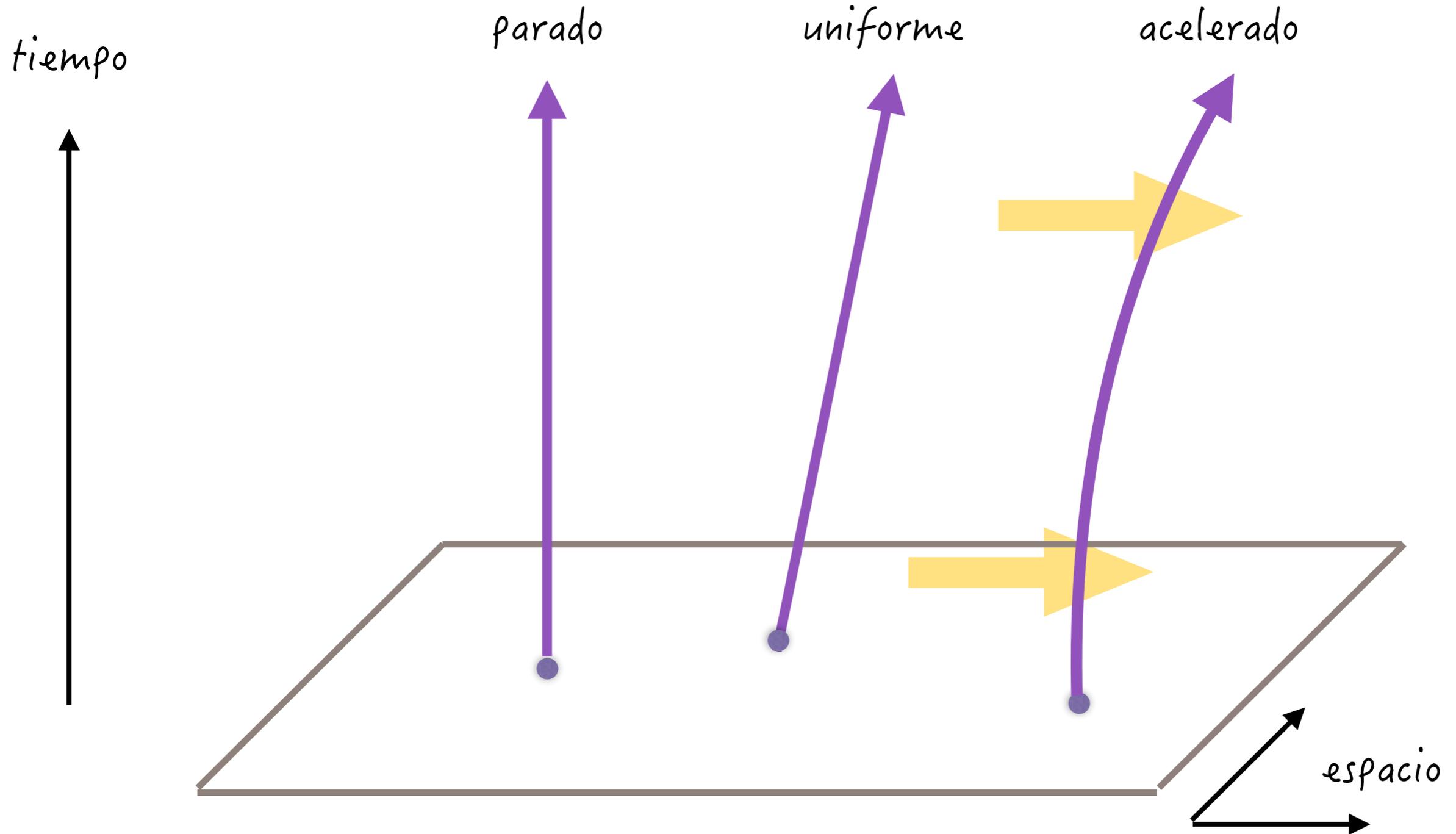


espacio

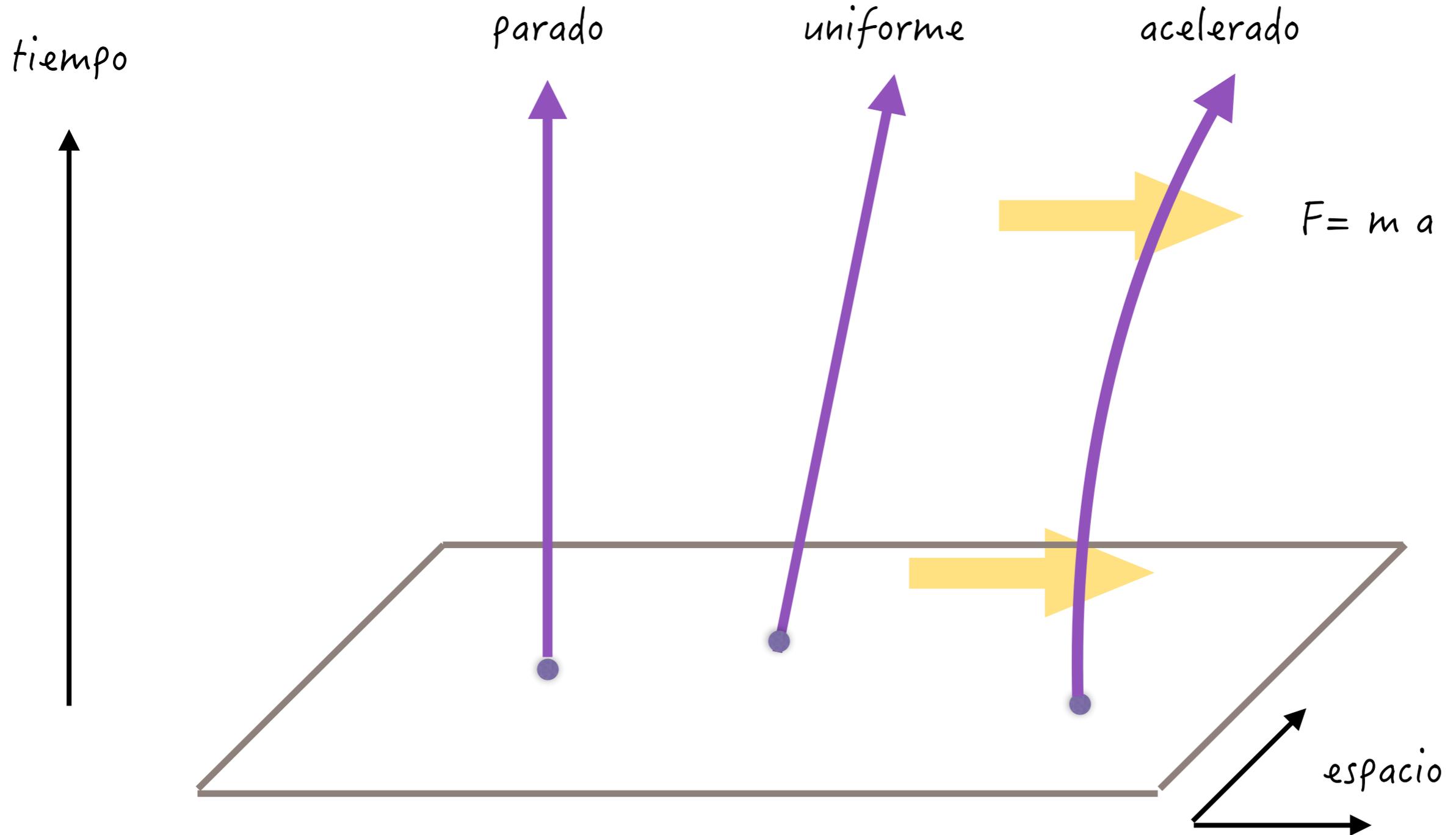
# GALILEO & NEWTON



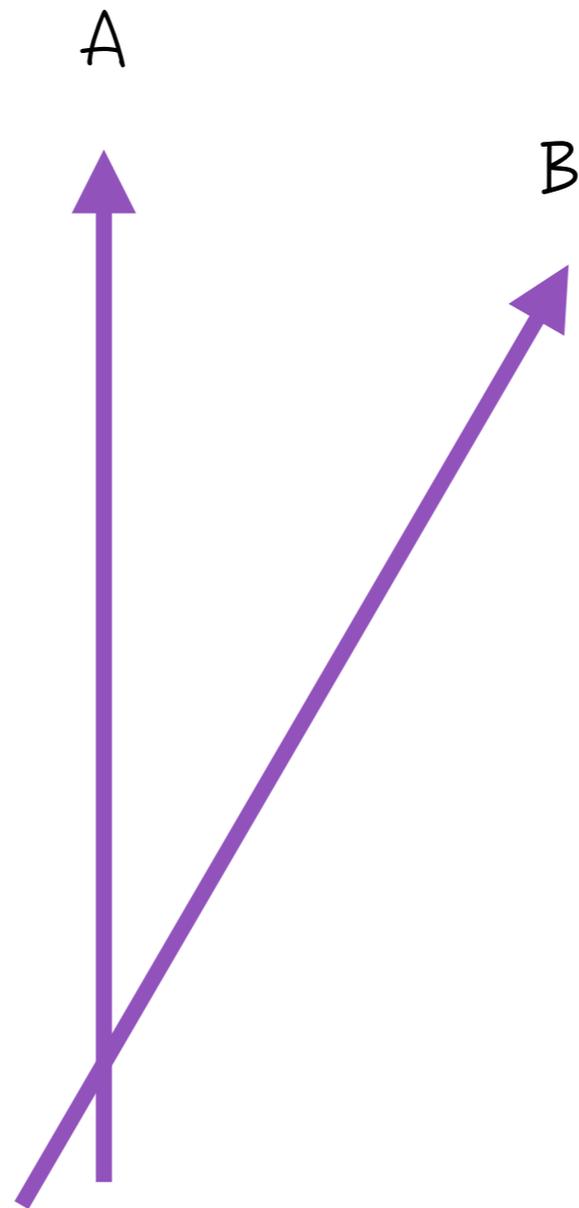
# GALILEO & NEWTON



# GALILEO & NEWTON

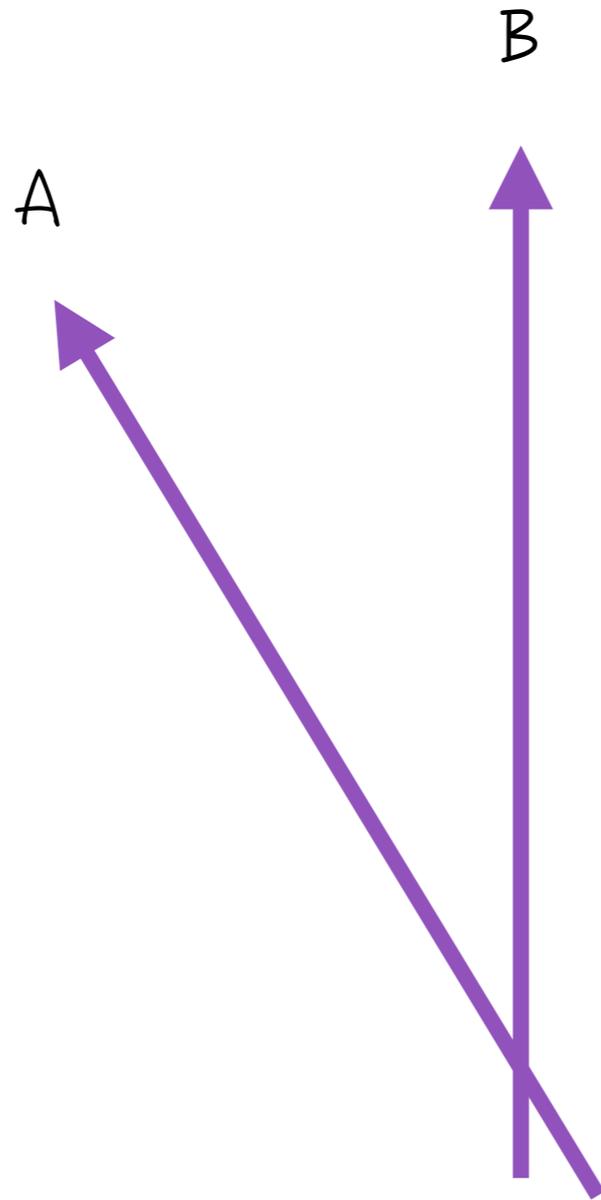


Según Alicia ...



Bernardo se mueve con velocidad  $V$

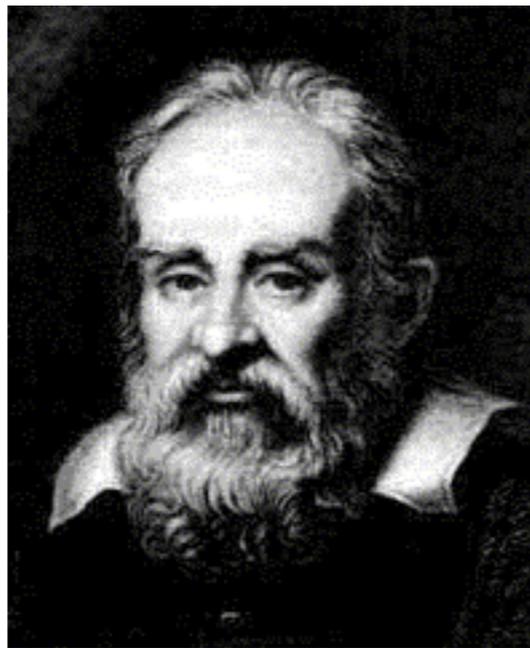
Según Bernardo ...



Alicia se mueve con velocidad  $-V$

# PRINCIPIO DE RELATIVIDAD

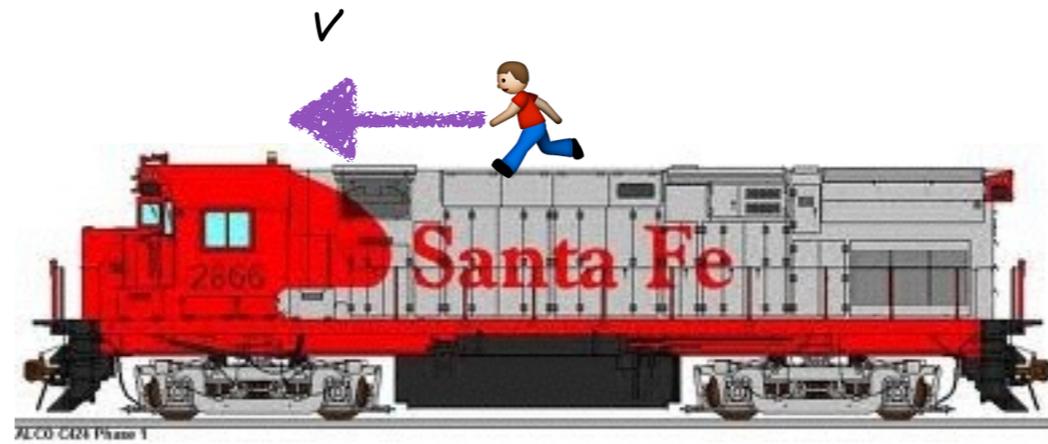
El movimiento uniforme no se puede detectar "desde dentro"



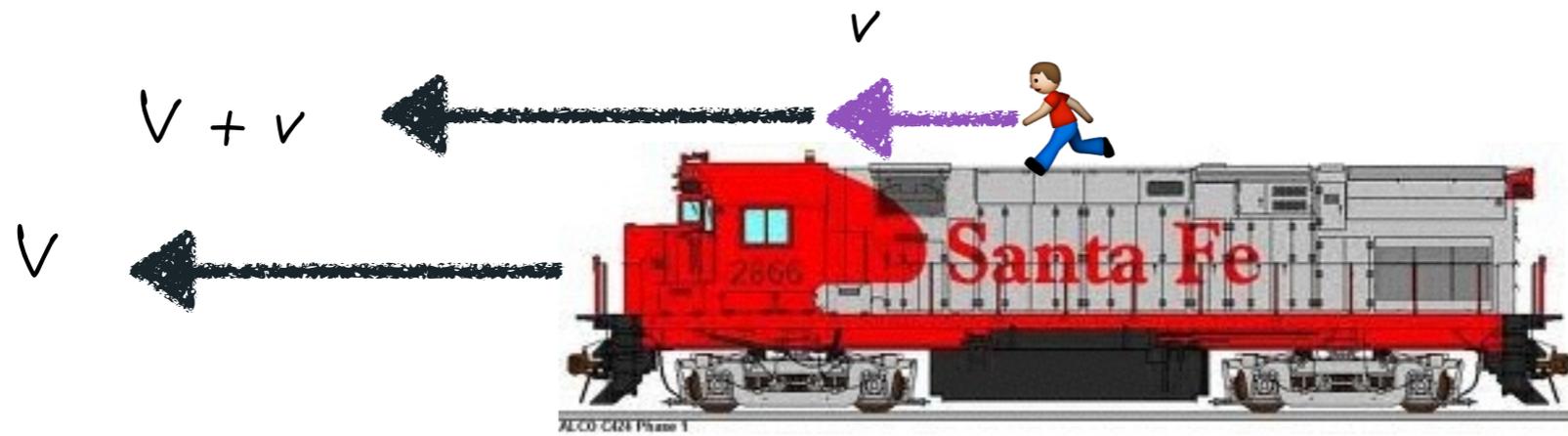
propiedad fundamental



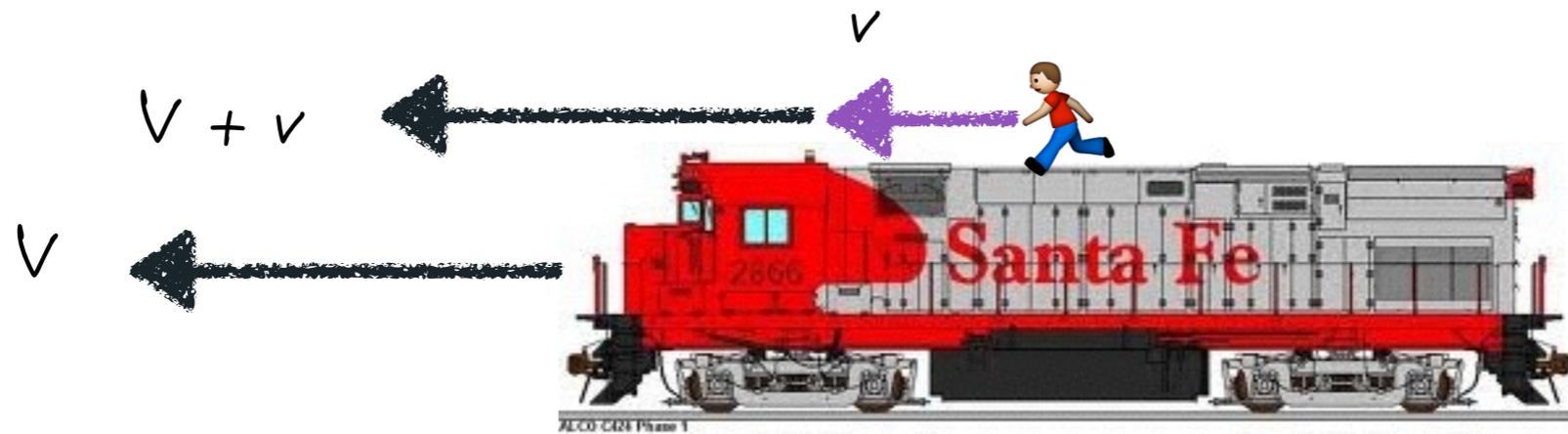
propiedad fundamental



# propiedad fundamental



# propiedad fundamental



Las velocidades relativas se suman

EN ESTE CASO...

NO PODRIA EXISTIR UNA VELOCIDAD LIMITE

No existiría una noción precisa de

**LOCALIDAD**

LOCALIDAD  $\longleftrightarrow$  VELOCIDAD LIMITE

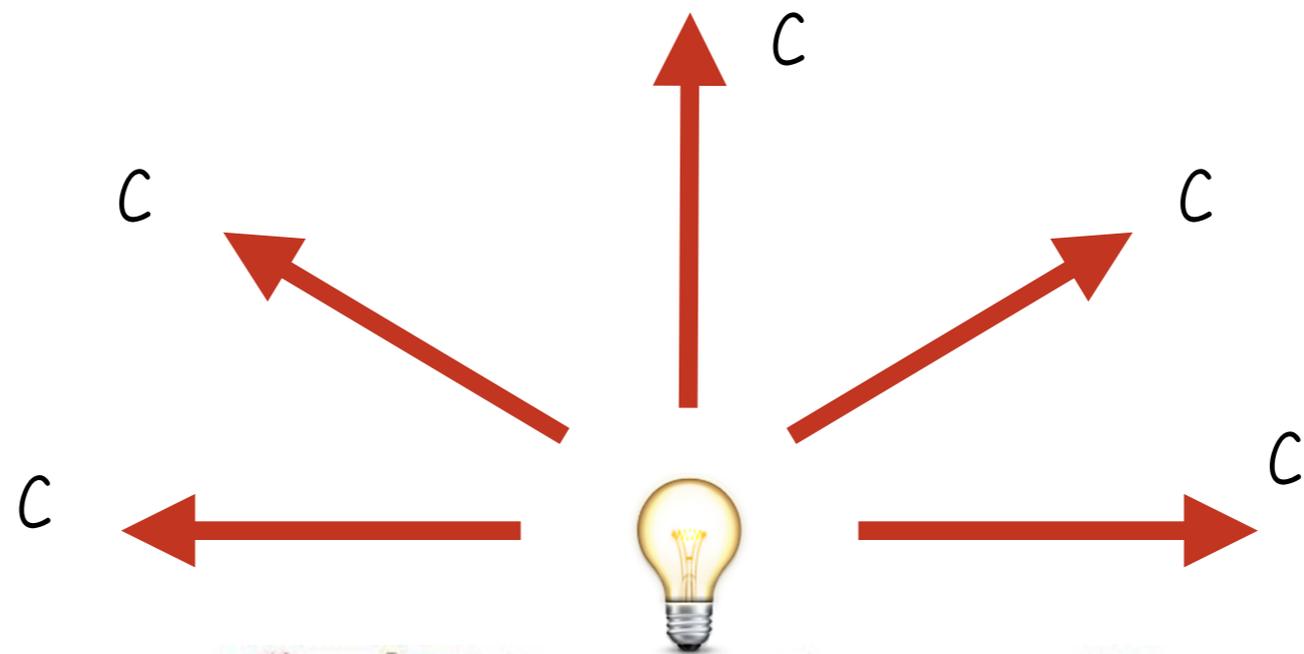
Si existe una velocidad máxima ...

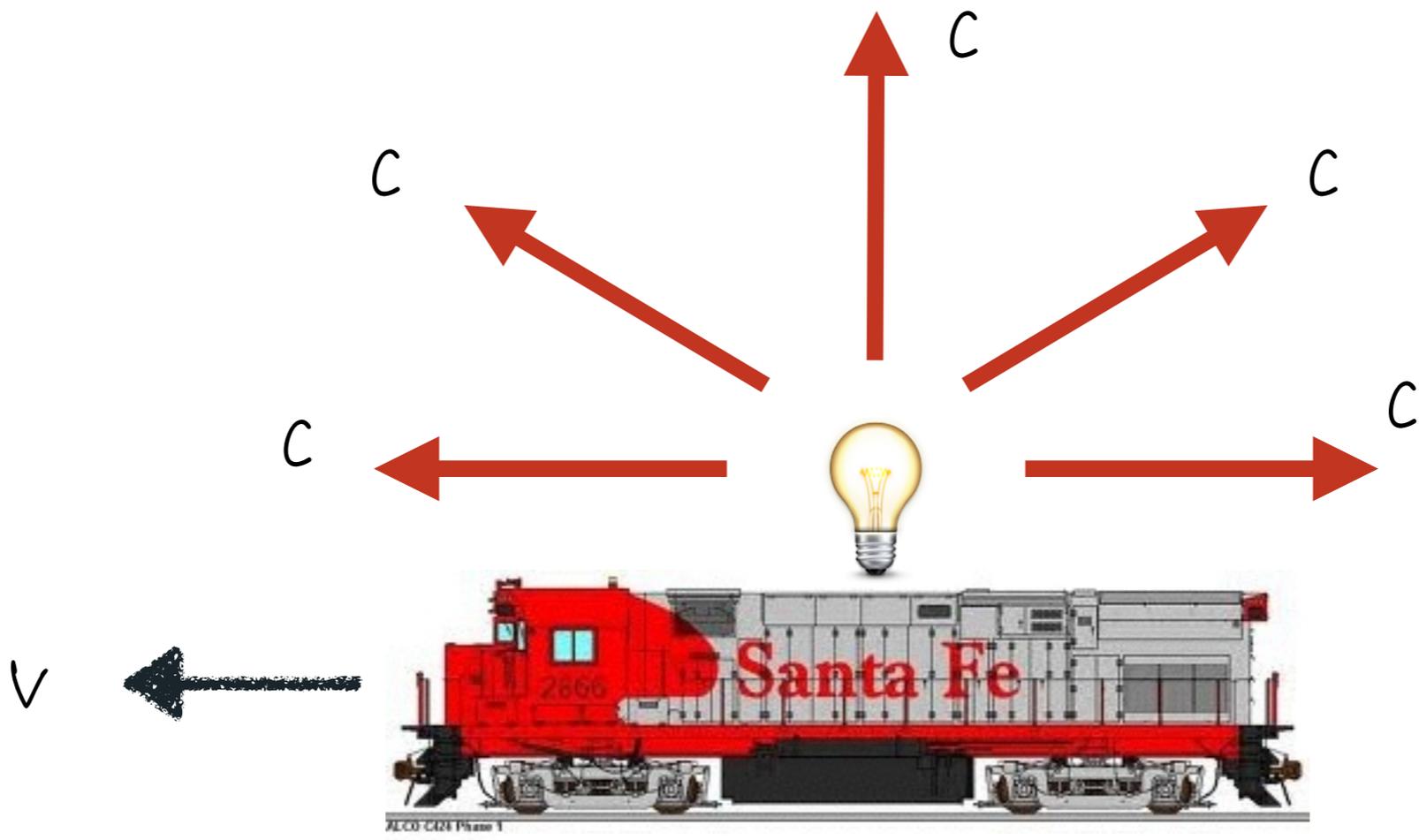
El principio de relatividad IMPLICA que

Necesariamente es una constante UNIVERSAL

# UNA VELOCIDAD MAXIMA ABSOLUTA VIOLARIA EL TEOREMA DE SUMA DE VELOCIDADES

Exactamente esto es lo que se descubrió durante el siglo XIX  
en el comportamiento de la luz





SI LA VELOCIDAD MAXIMA ES  
ABSOLUTA

EL TIEMPO ES NECESARIAMENTE  
RELATIVO

Según Alicia, L y R son simultáneos



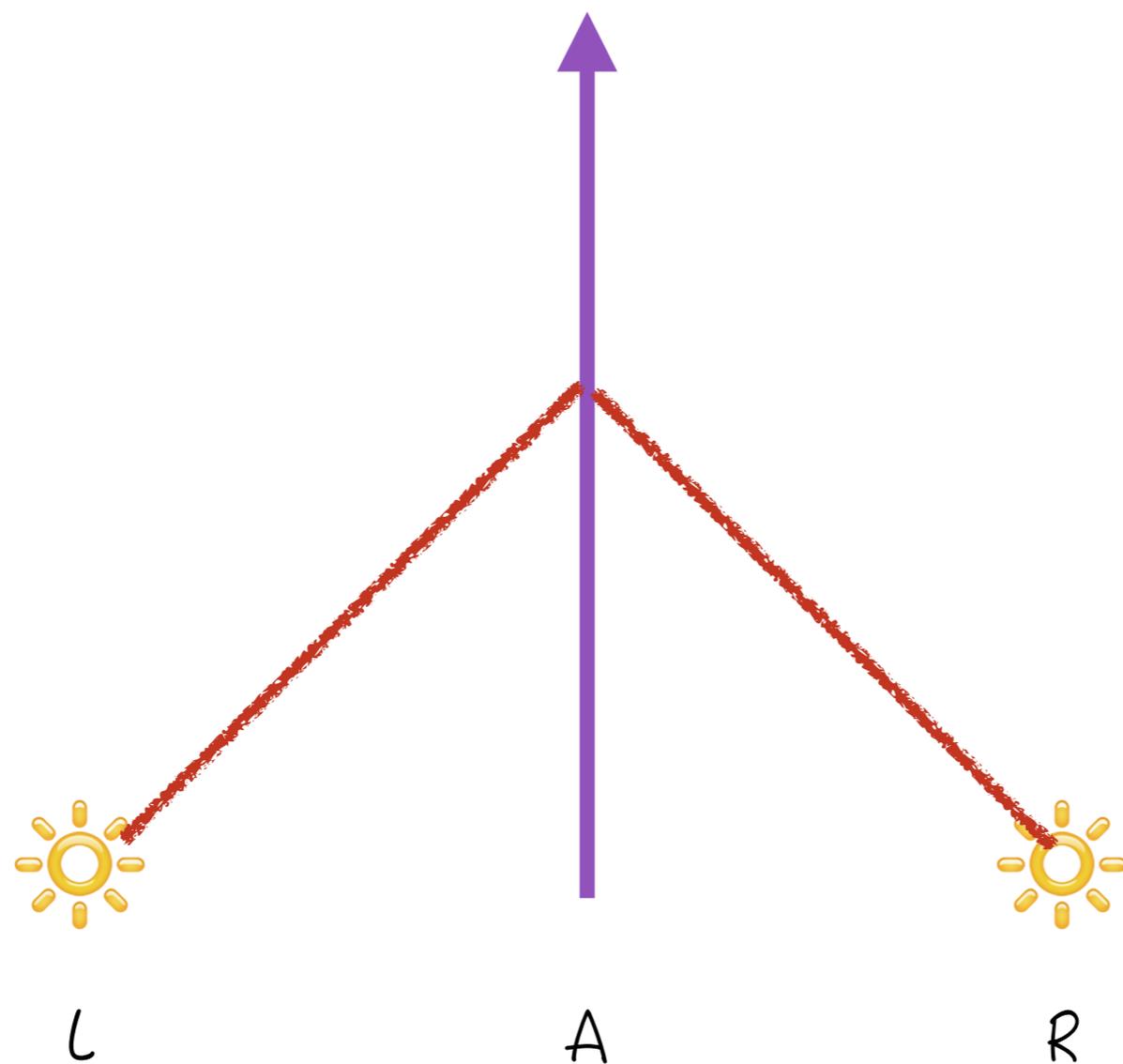
L

A

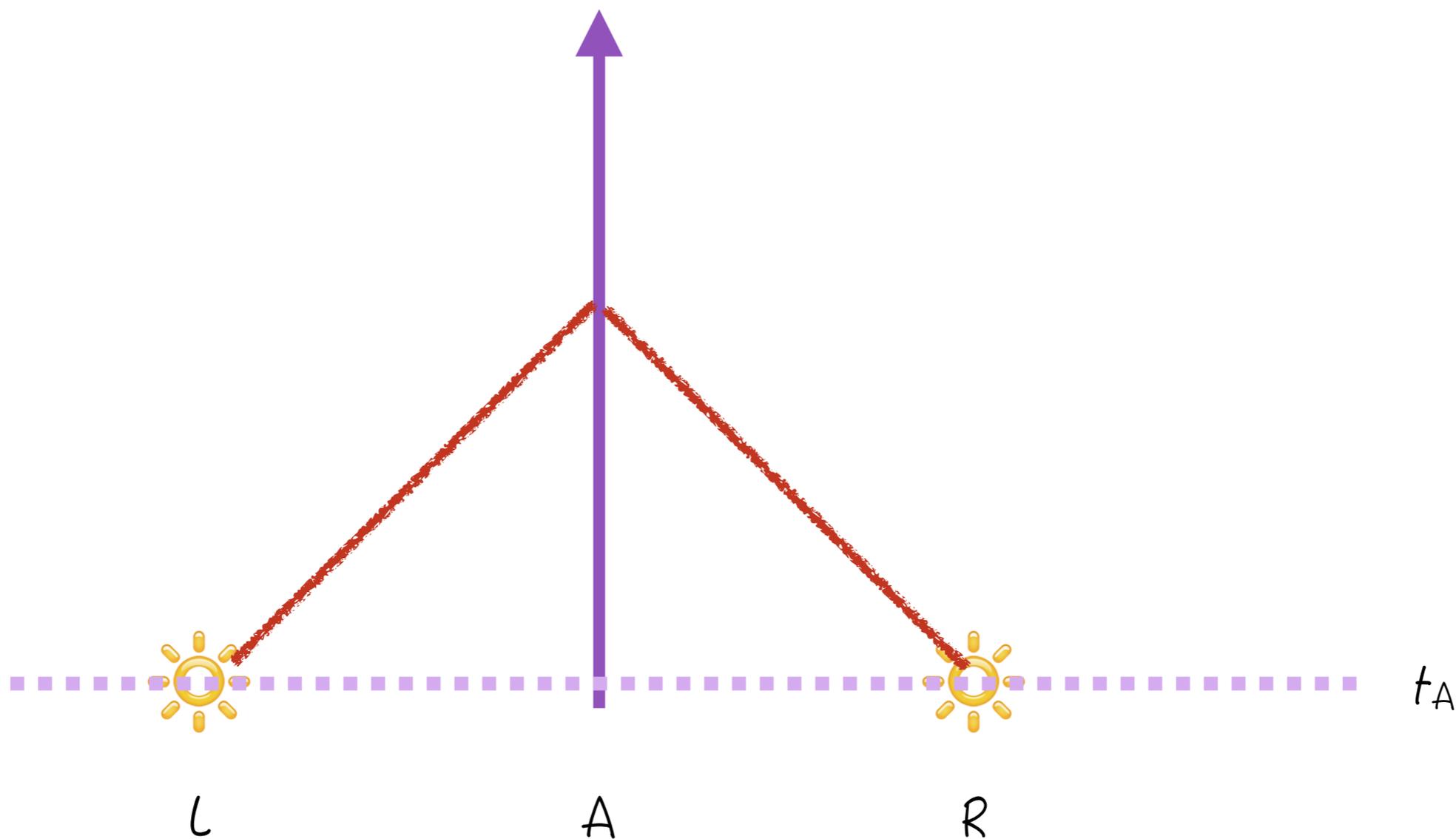


R

Según Alicia, L y R son simultáneos



Según Alicia, L y R son simultáneos



Según Bernardo, R ocurre antes que L



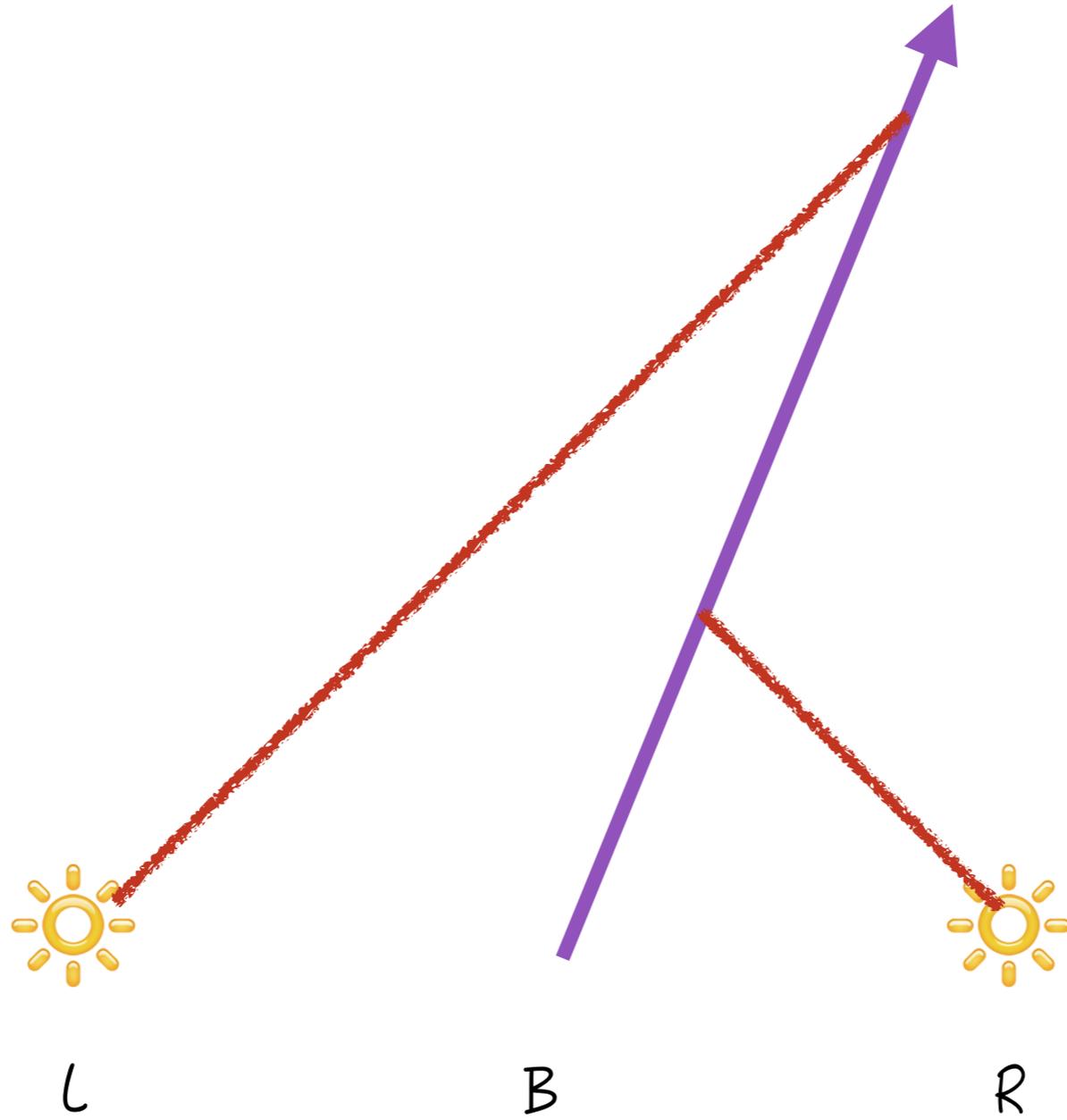
L

B

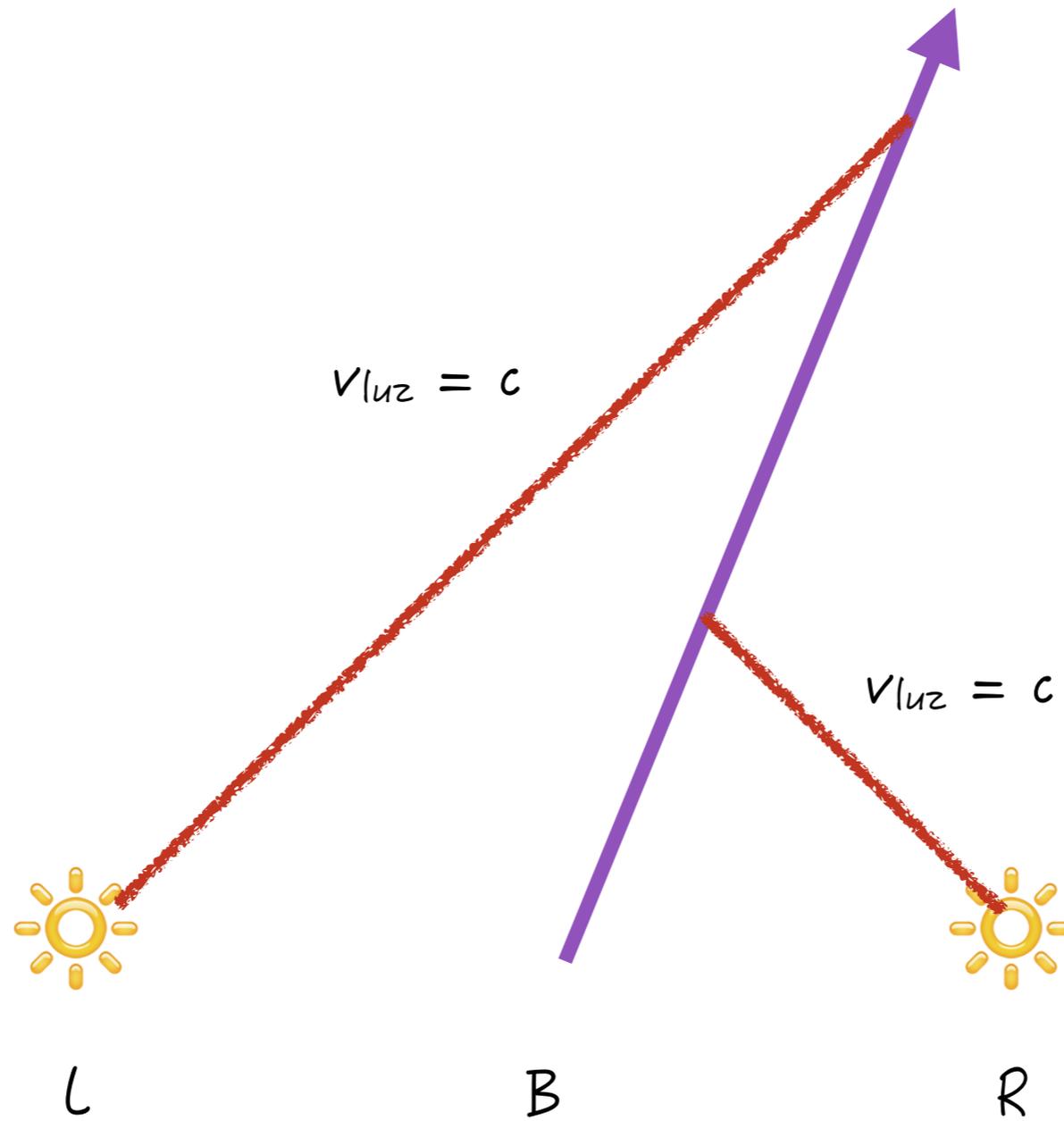


R

Según Bernardo, R ocurre antes que L



Según Bernardo, R ocurre antes que L



El punto de vista de Bernardo en la teoría no relativista

L ve más tarde porque la luz de L es más lenta



L

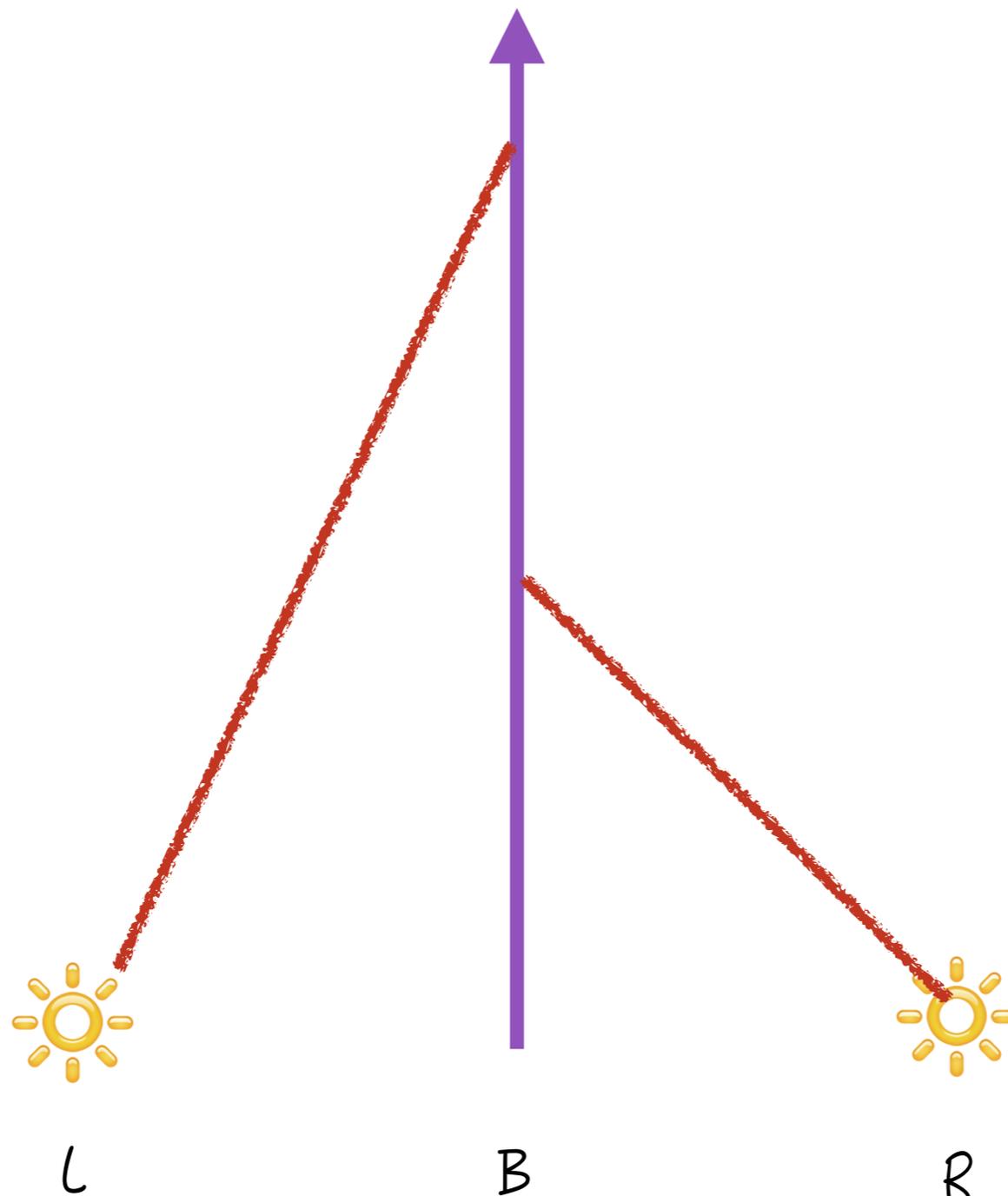
B



R

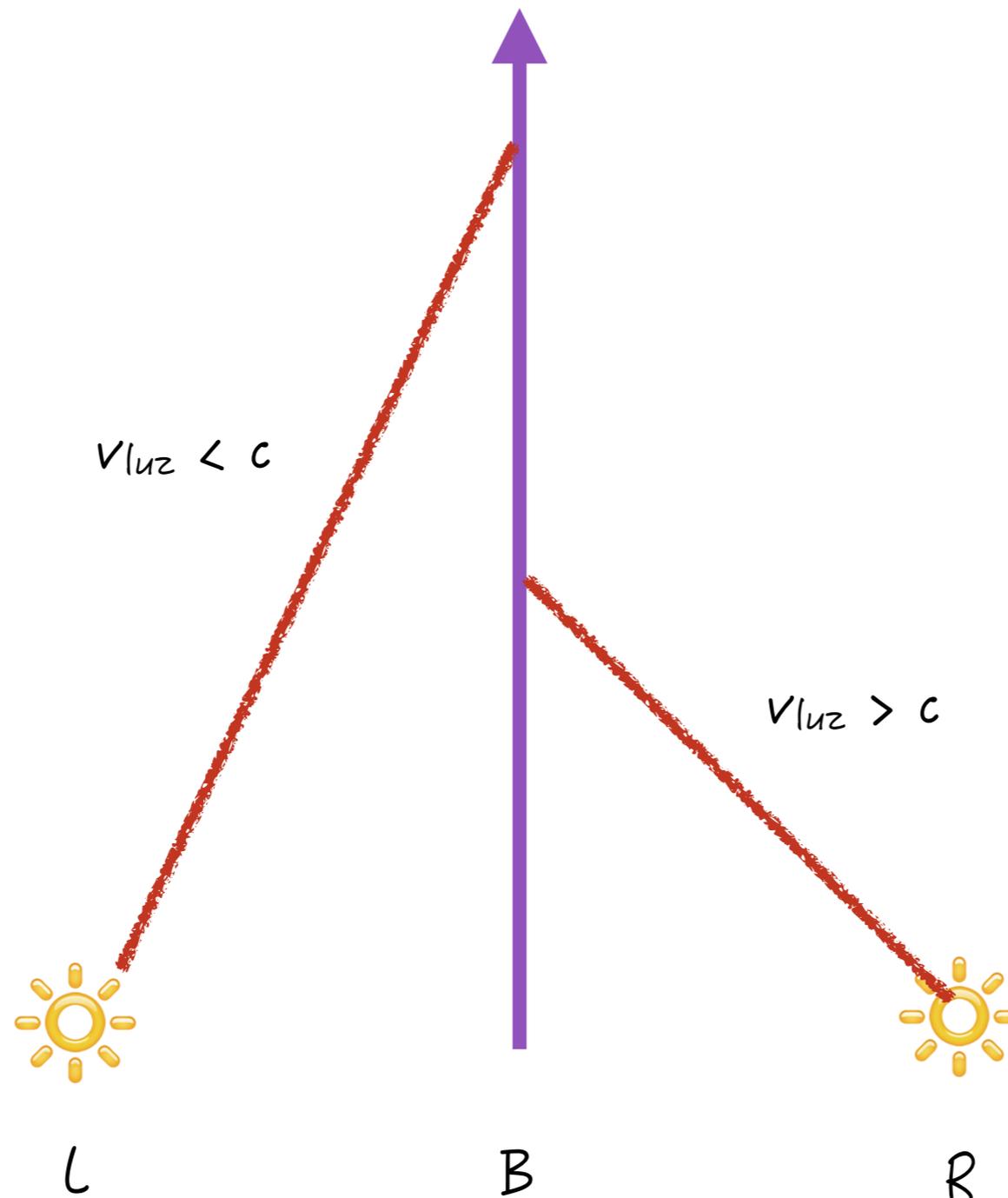
El punto de vista de Bernardo en la teoría no relativista

L ve más tarde porque la luz de L es más lenta



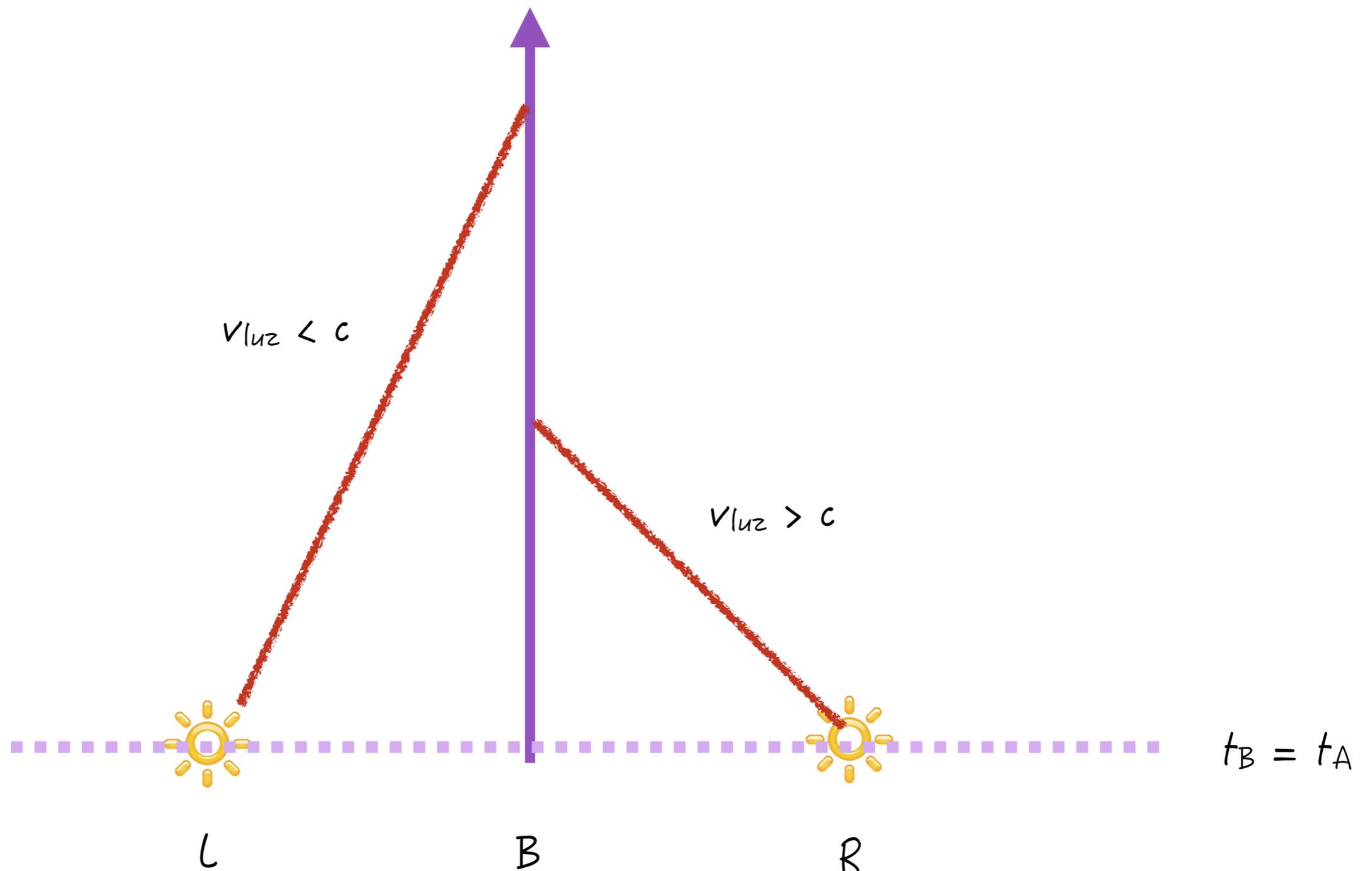
El punto de vista de Bernardo en la teoría no relativista

L ve más tarde porque la luz de L es más lenta



El punto de vista de Bernardo en la teoría no relativista

L ve más tarde porque la luz de L es más lenta



El punto de vista de Bernardo en la teoría relativista

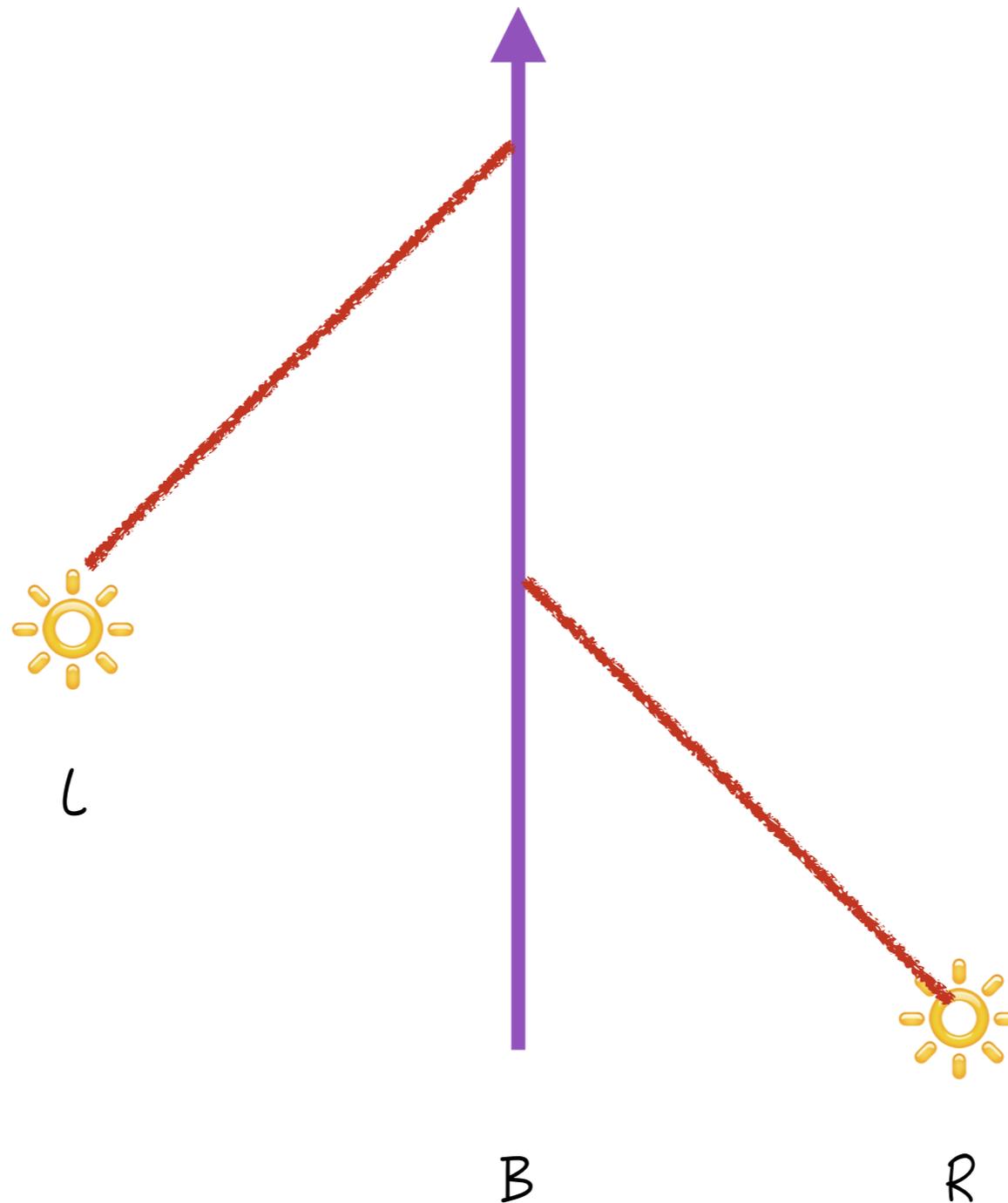


B

R

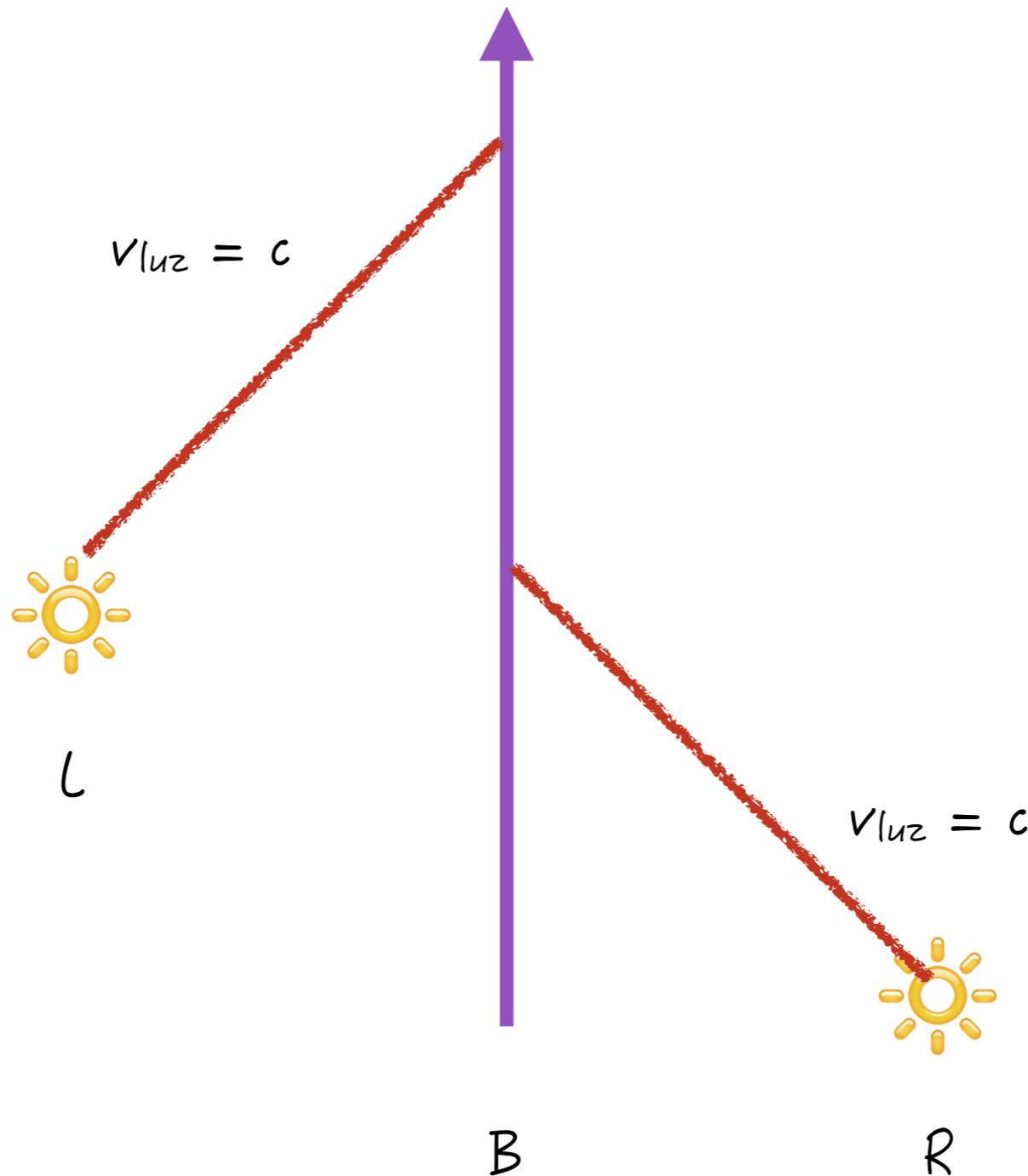
El punto de vista de Bernardo en la teoría relativista

L se ve después porque OCURRE más tarde que R



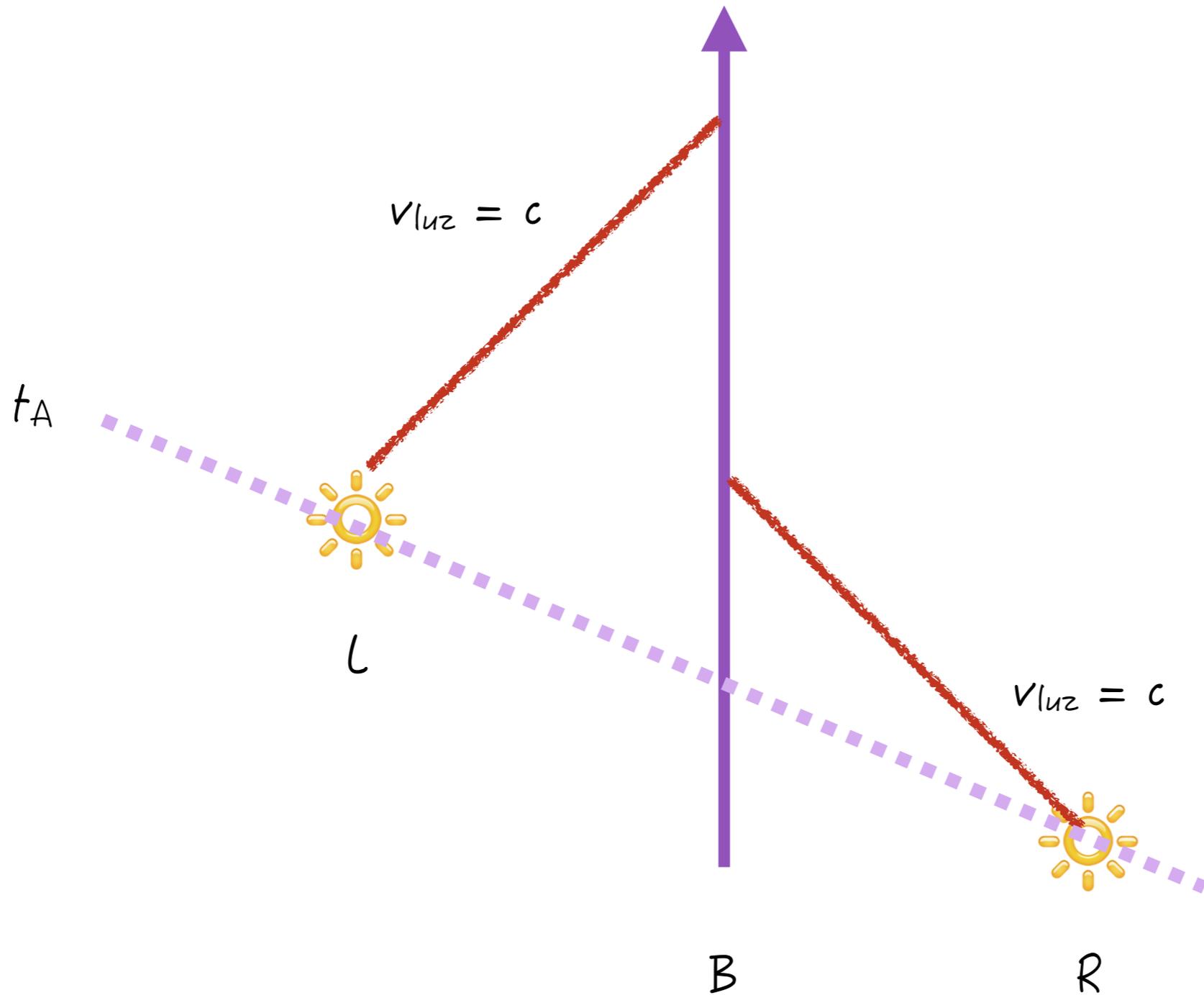
El punto de vista de Bernardo en la teoría relativista

L se ve después porque OCURRE más tarde que R



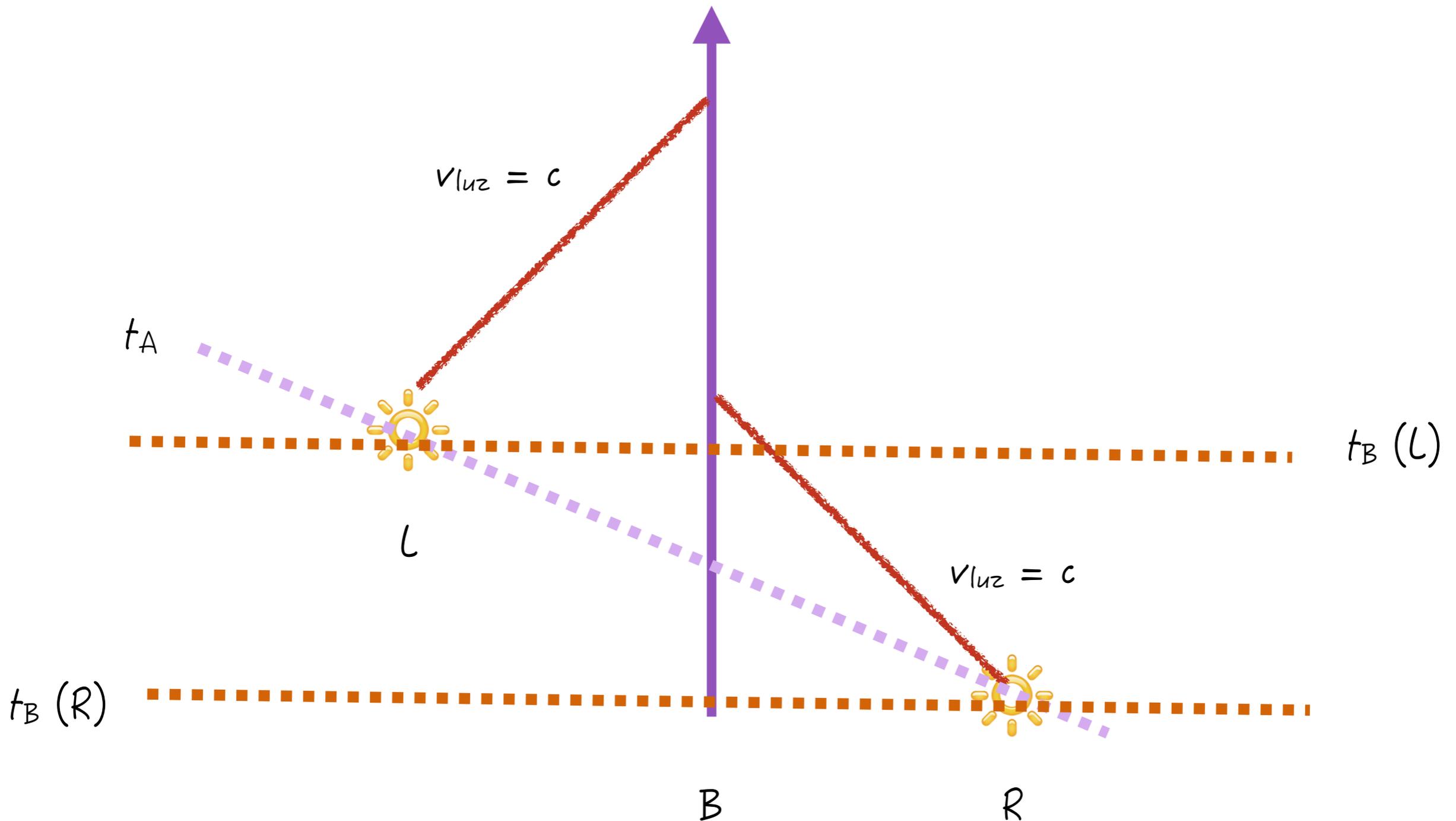
El punto de vista de Bernardo en la teoría relativista

L se ve después porque OCURRE más tarde que R



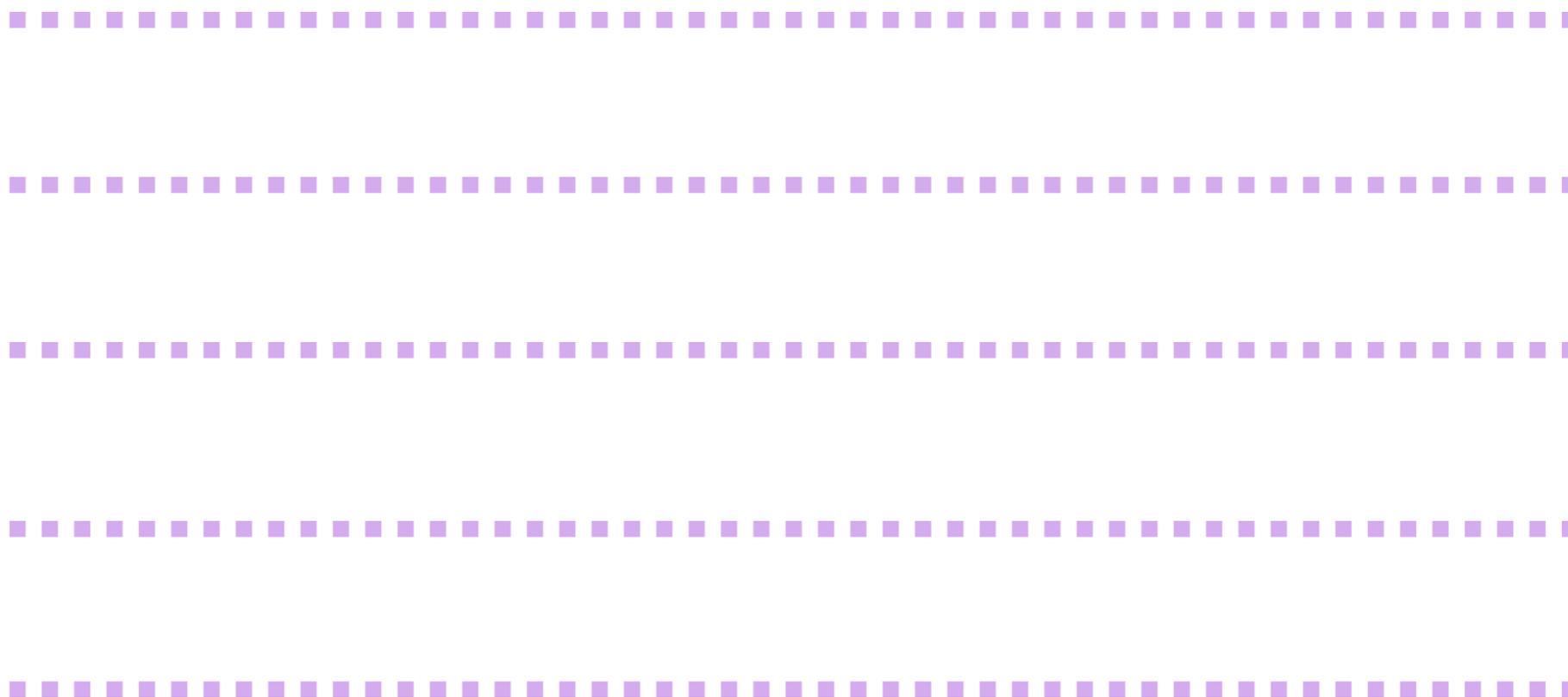
El punto de vista de Bernardo en la teoría relativista

L se ve después porque OCURRE más tarde que R



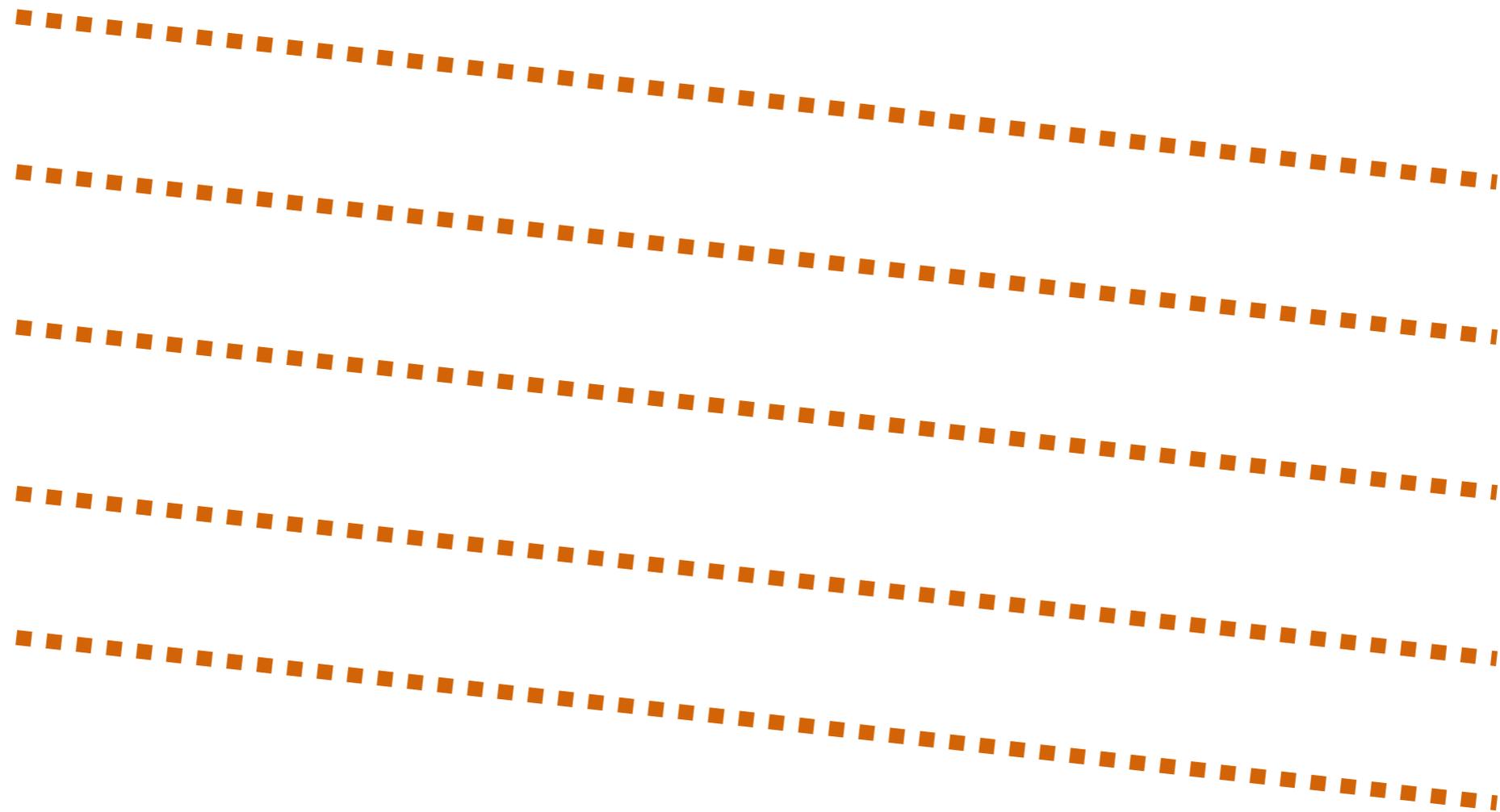
El movimiento relativo afecta a la partición entre  
espacio y tiempo

El movimiento relativo afecta a la partición entre  
espacio y tiempo



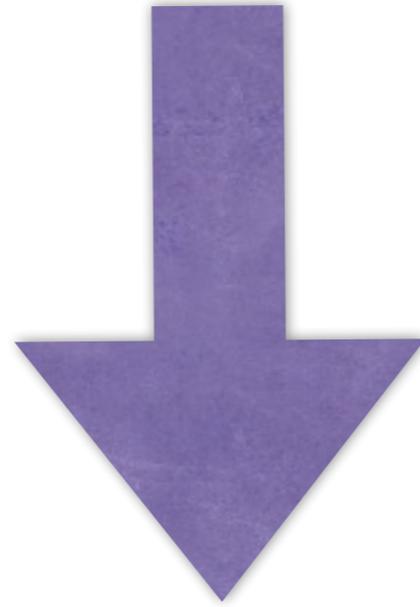
partición espacial de Alicia

El movimiento relativo afecta a la partición entre  
espacio y tiempo



partición espacial de Bernardo

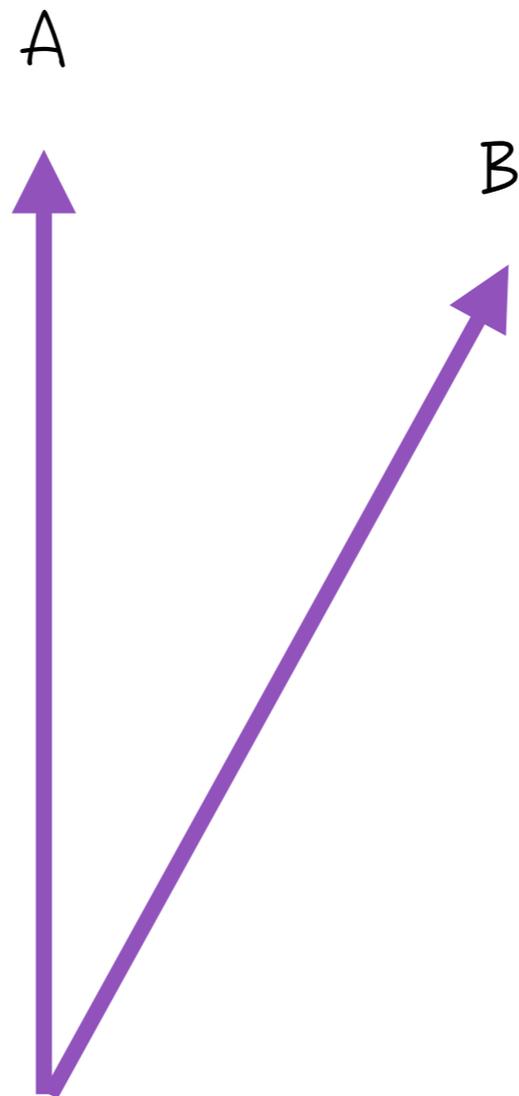
ESPACIO Y TIEMPO SE MEZCLAN EN



ESPACIOTIEMPO

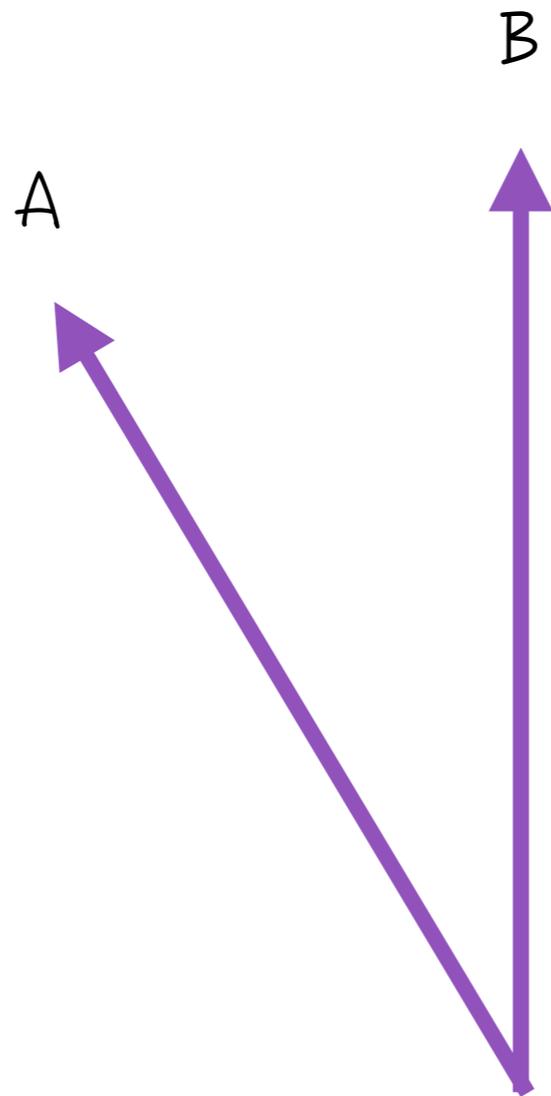
¿RELATIVIDAD GENERAL?

Según Alicia ...



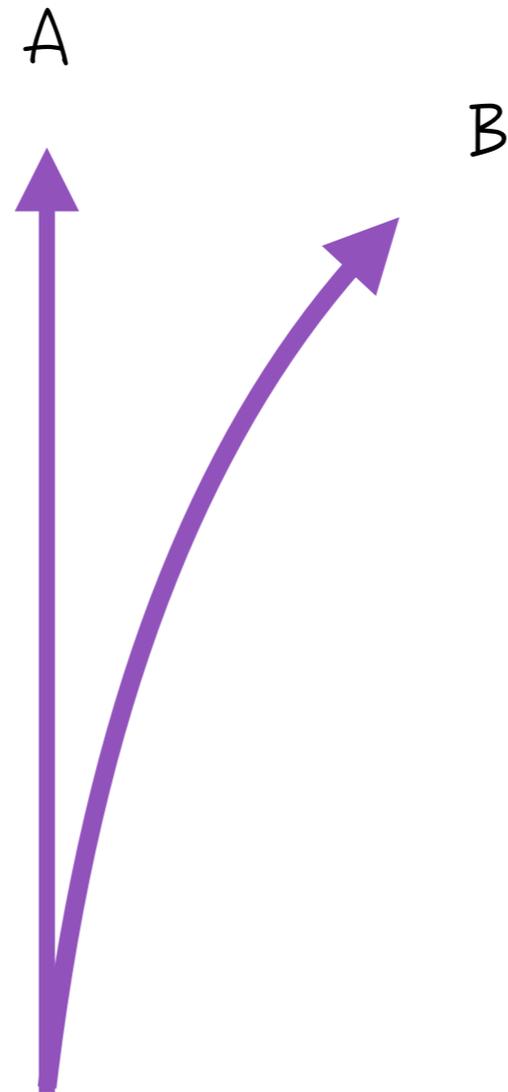
Bernardo se mueve con velocidad  $V$

Según Bernardo ...

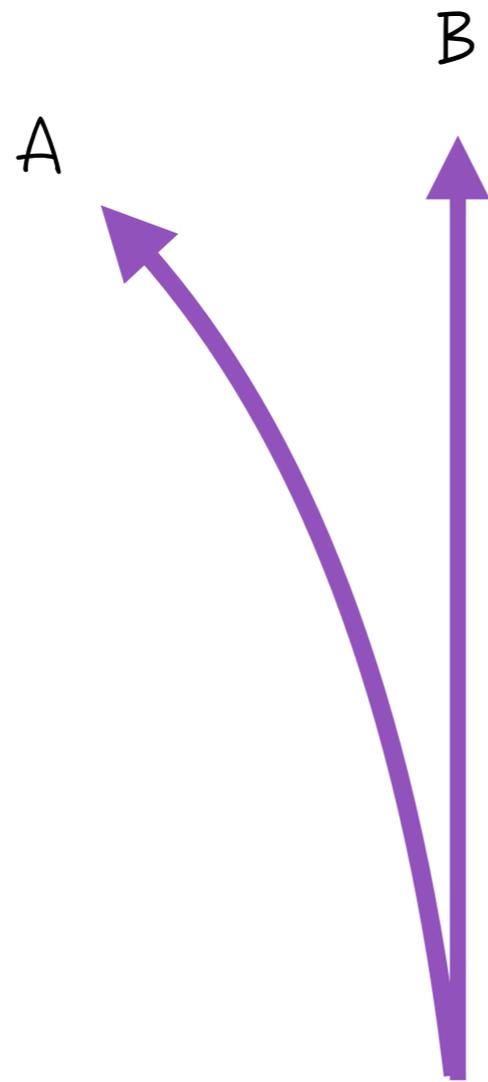


Alicia se mueve con velocidad  $-V$

¿Qué pasa si Bernardo acelera?

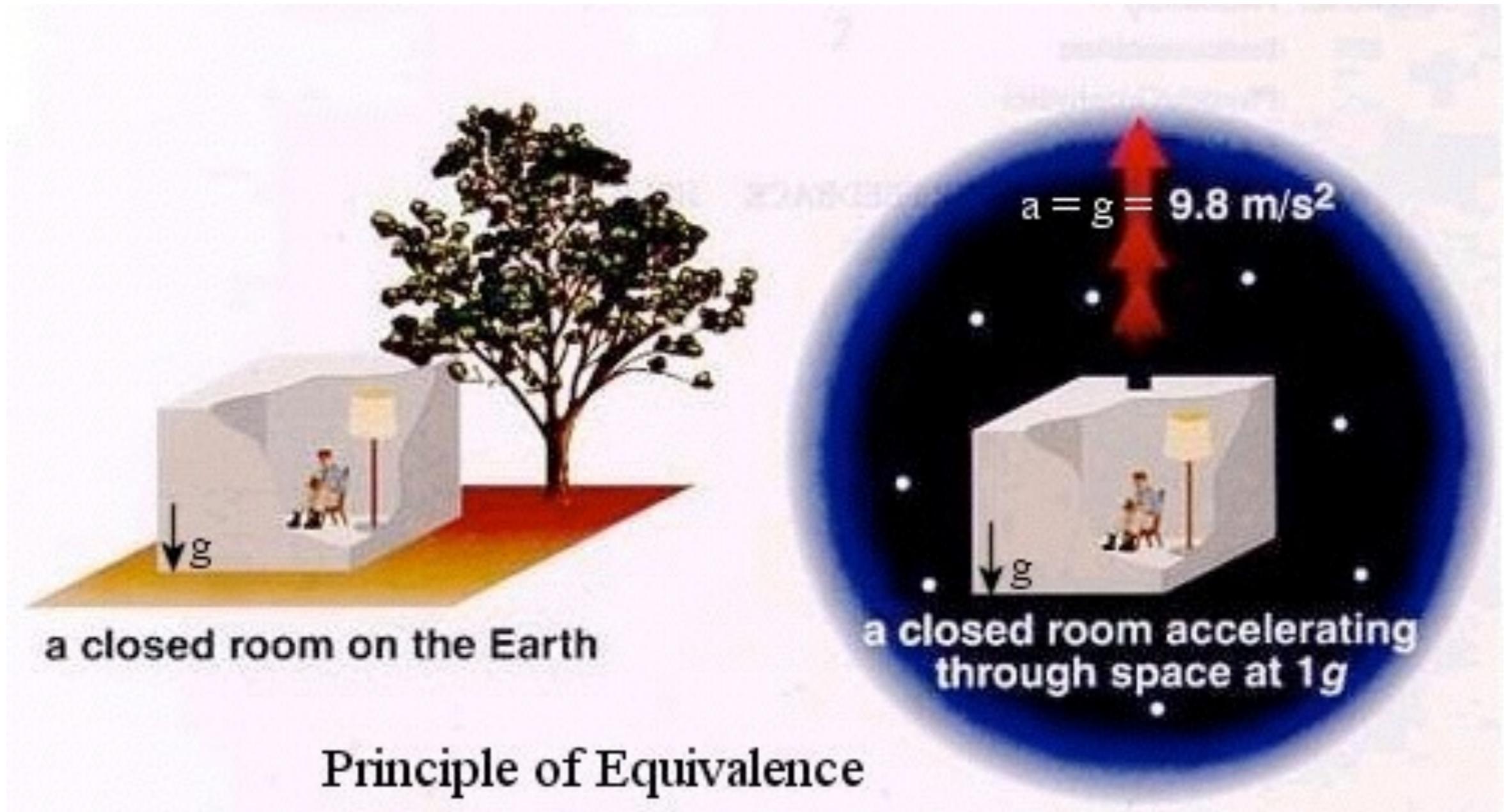


Aparentemente...



Pero Bernardo puede detectar su aceleración "desde dentro"

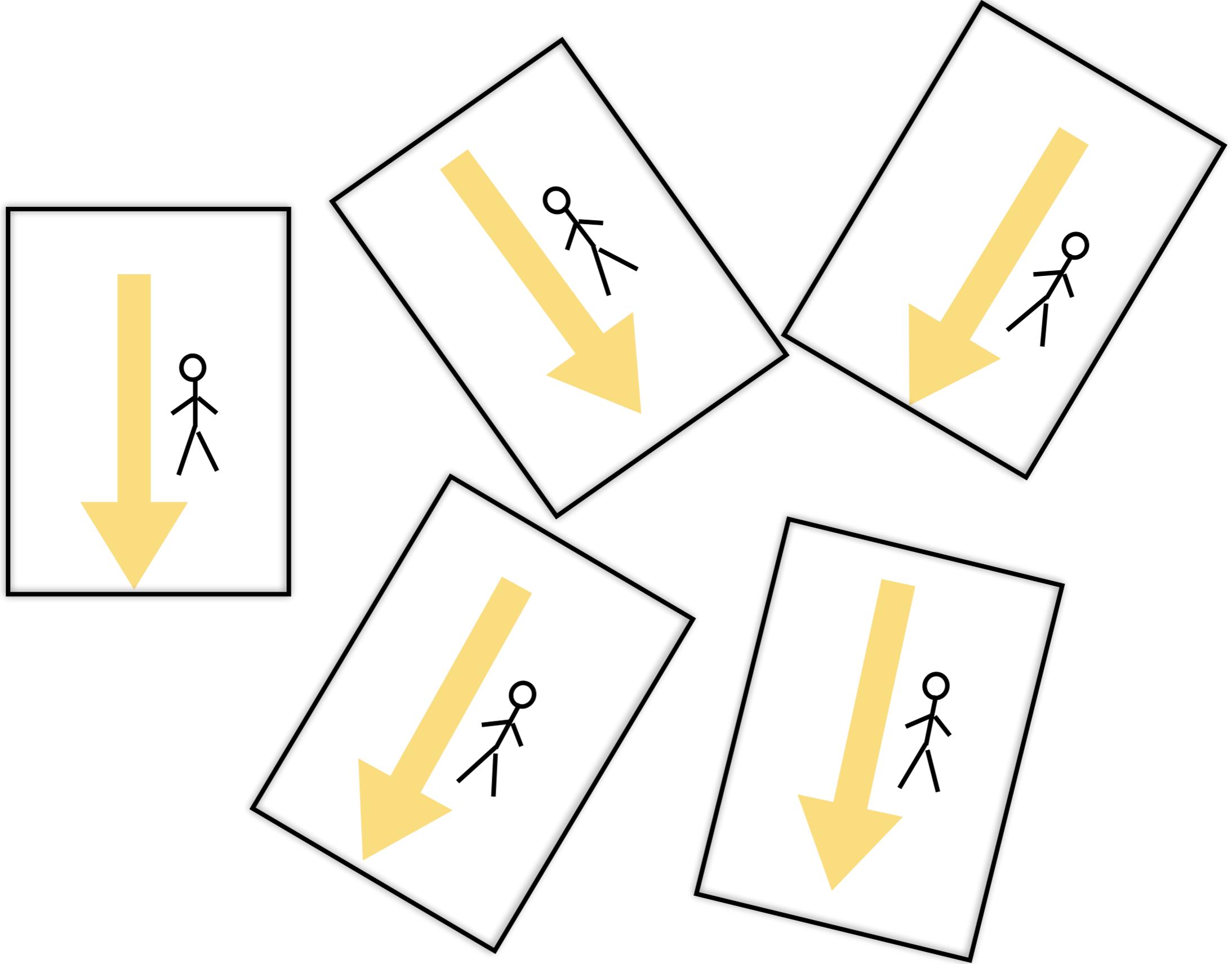
# PRINCIPIO DE EQUIVALENCIA



Einstein salva así el principio de relatividad

... lo convierte en el principio de relatividad general

... y construye una teoría de la gravitación sobre esta base

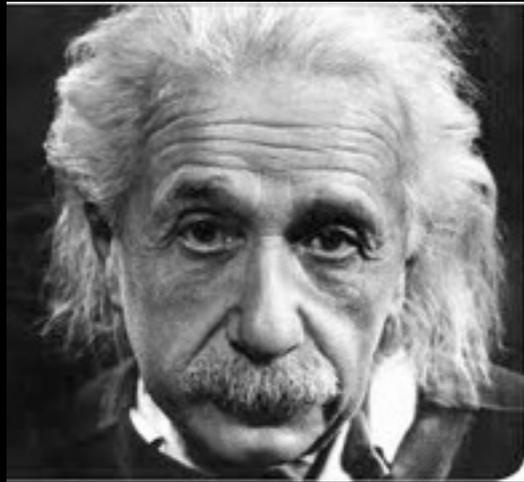


En cada caja, en caída libre, no se nota el campo gravitacional, que solo aparece al "pegar" las cajas.





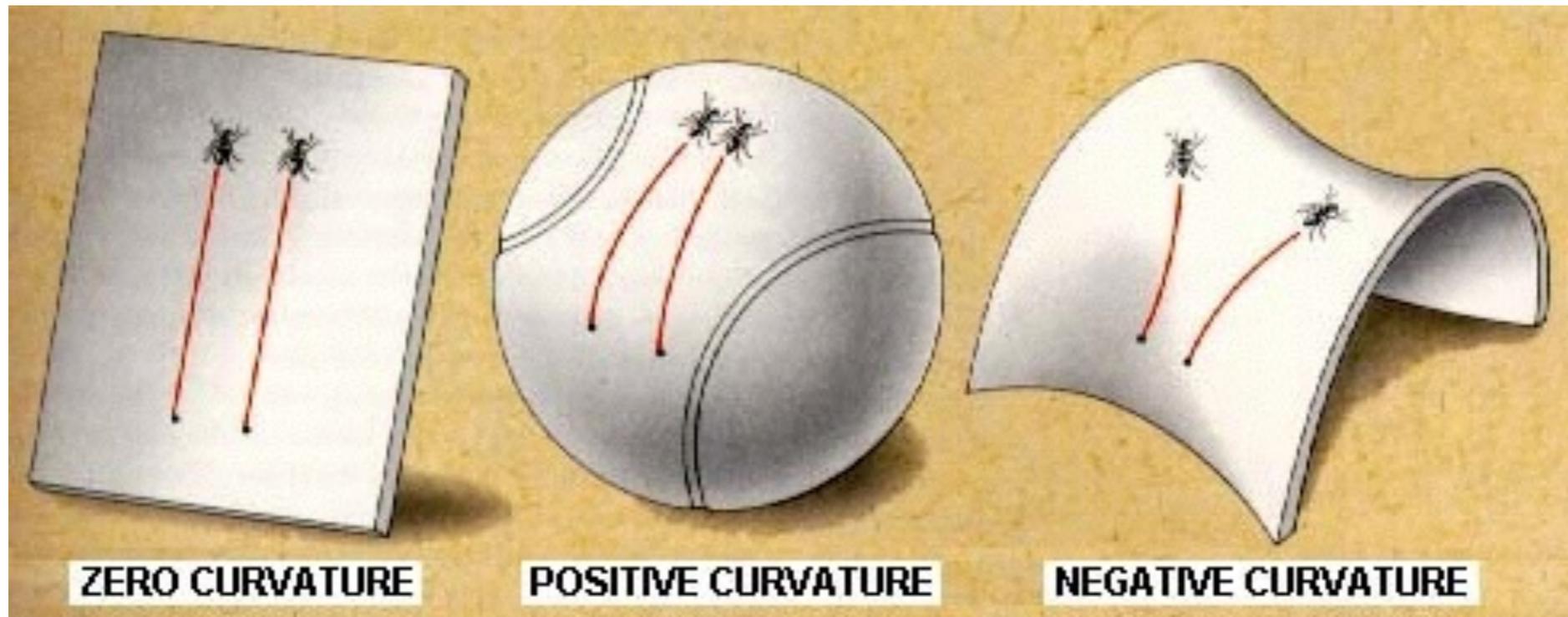
¡CURVATURA!



# ESLOGAN

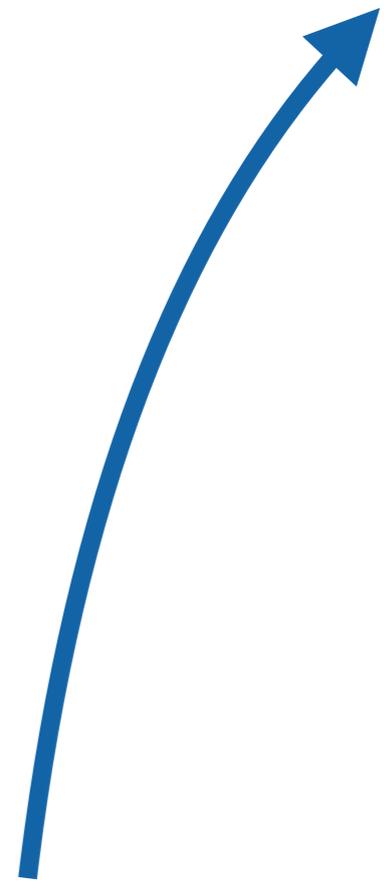
Gravitación  $\approx$  "curvatura" del espacio-tiempo

# LA CURVATURA ESPACIAL CAMBIA LA GEOMETRIA DEL ESPACIO

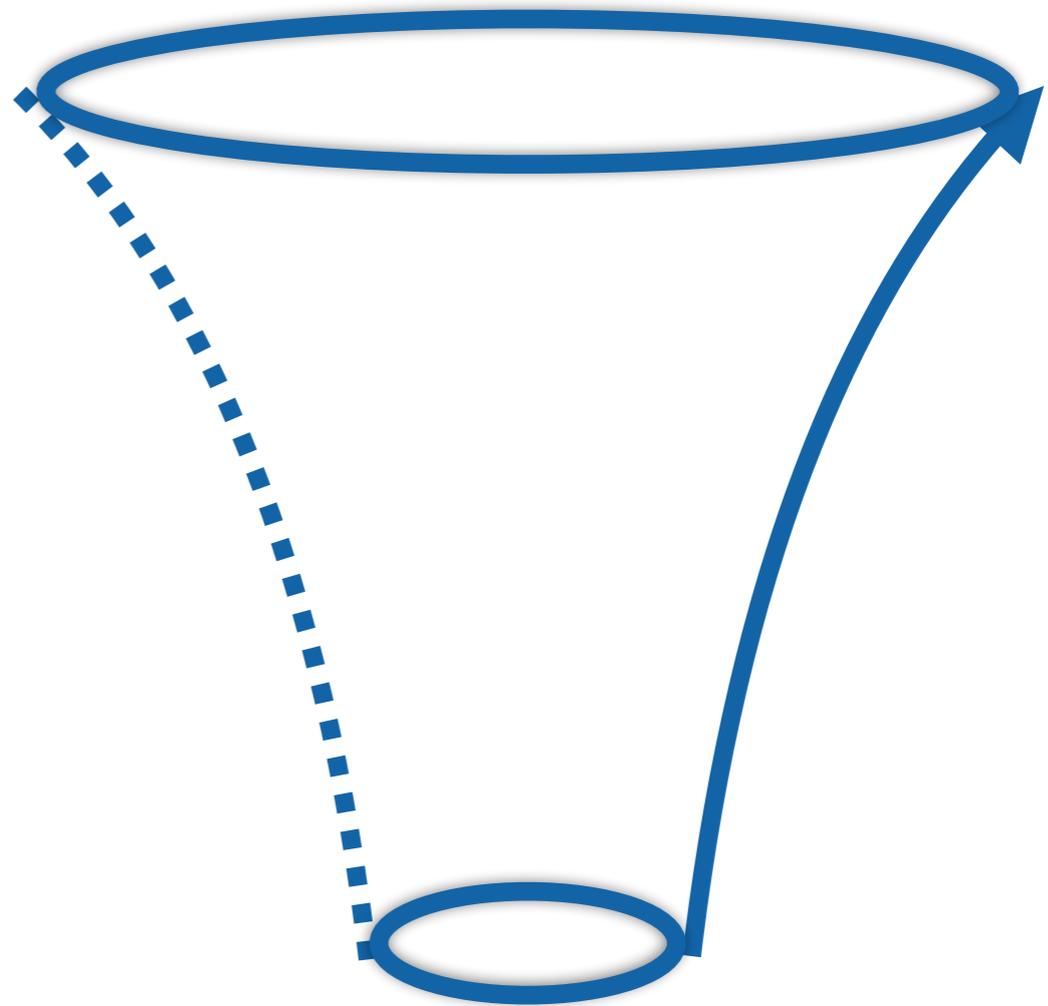


LA CURVATURA TEMPORAL CAMBIA LA VELOCIDAD DE EXPANSION DEL ESPACIO

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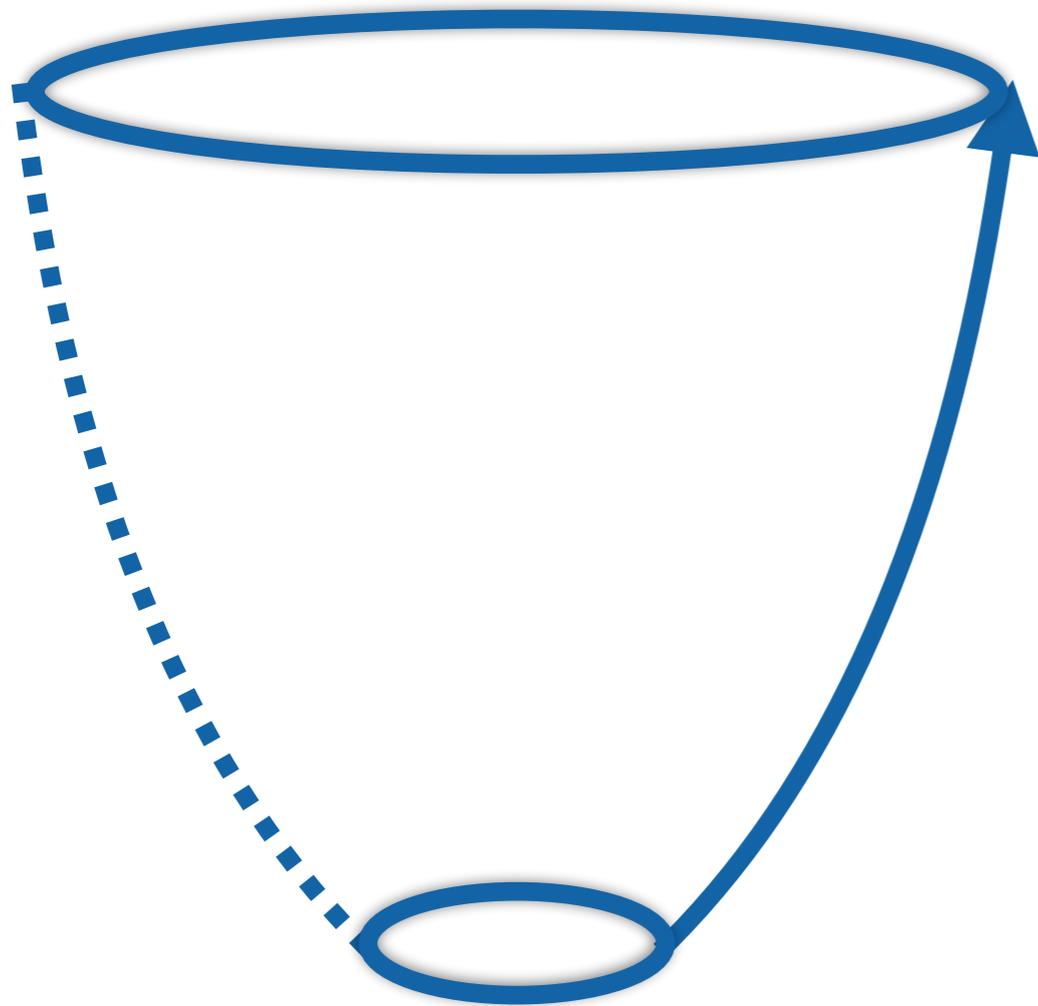


LA CURVATURA TEMPORAL CAMBIA LA VELOCIDAD DE EXPANSION DEL ESPACIO

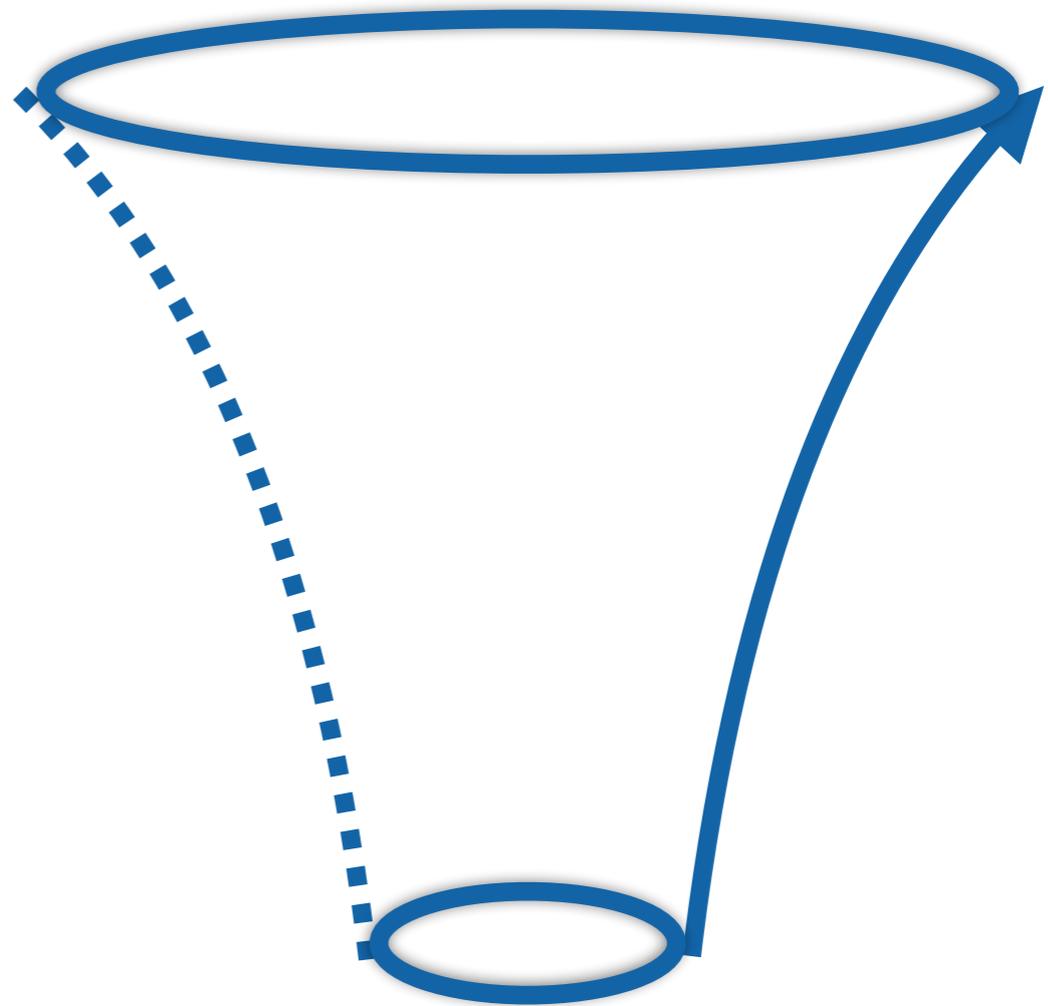


EXPANSION ACELERADA

LA CURVATURA TEMPORAL CAMBIA LA VELOCIDAD DE EXPANSION DEL ESPACIO



EXPANSION DECELERADA



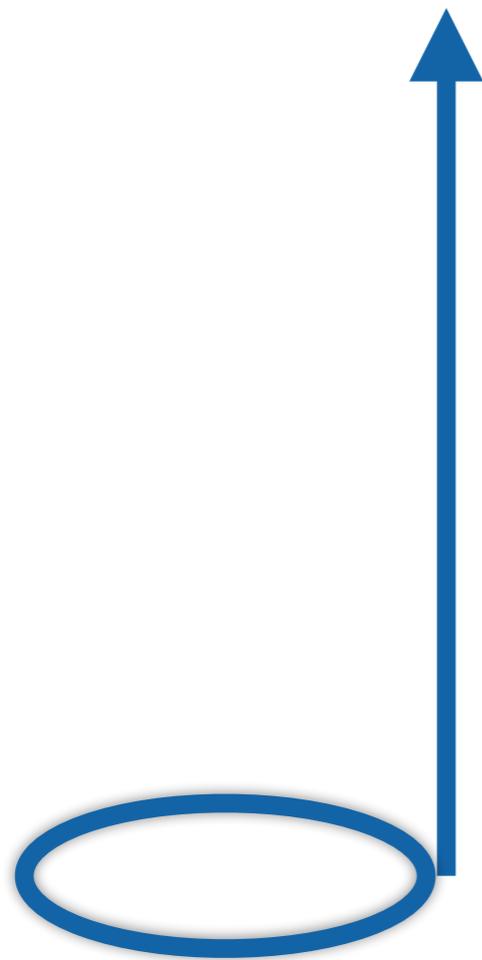
EXPANSION ACELERADA

SIN CURVATURA TEMPORAL

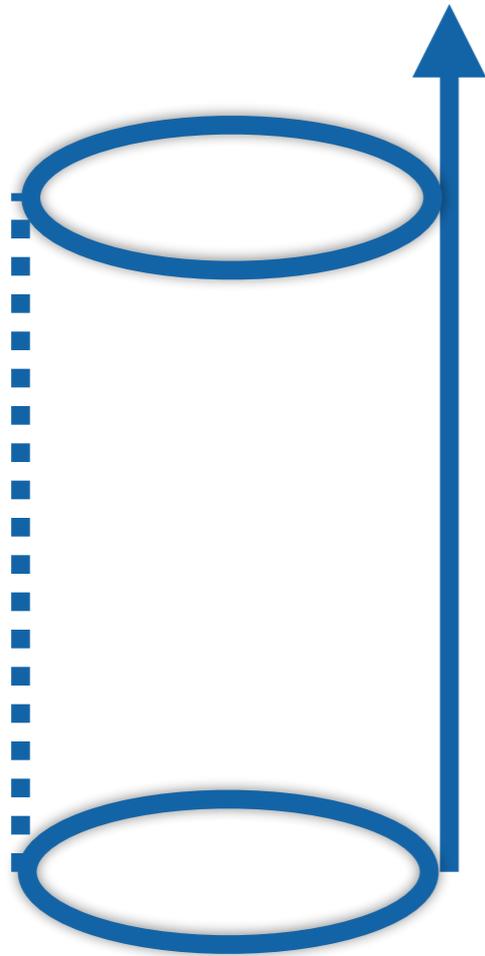
SIN CURVATURA TEMPORAL



SIN CURVATURA TEMPORAL

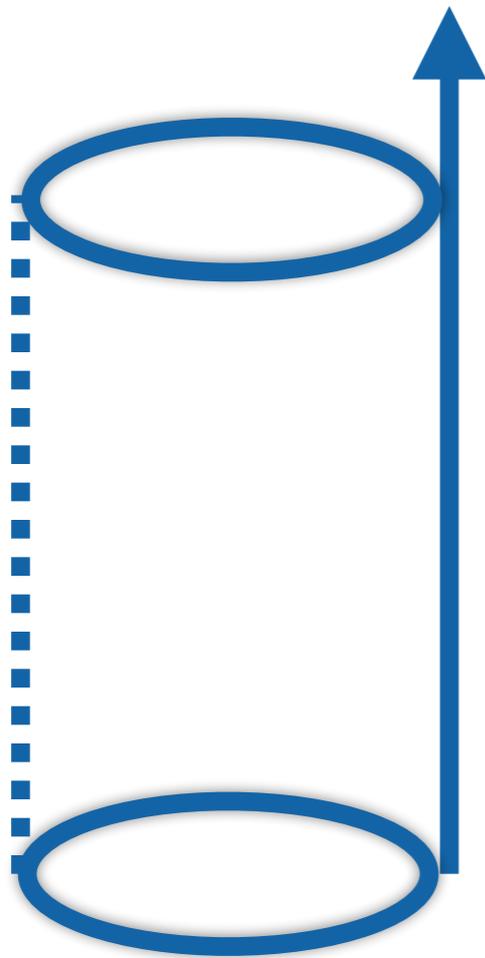


SIN CURVATURA TEMPORAL

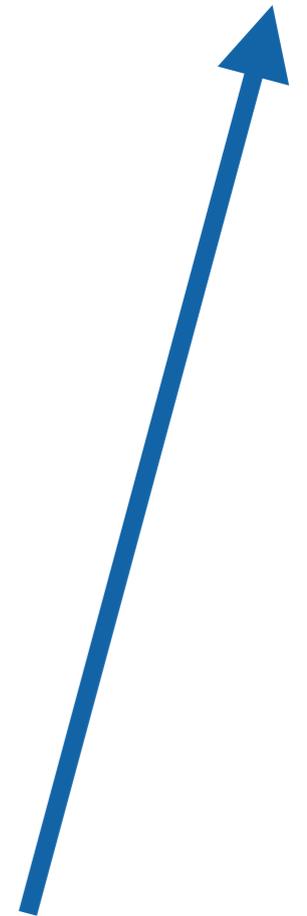


ESTATICO

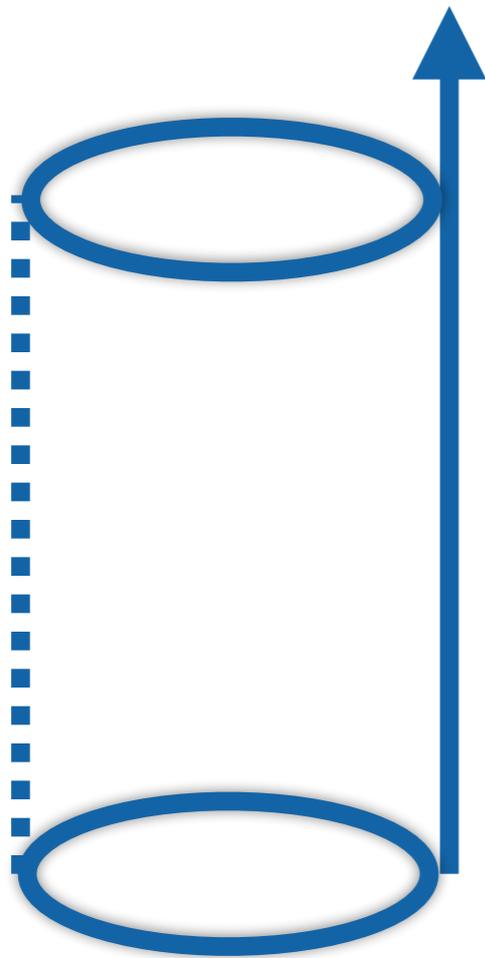
SIN CURVATURA TEMPORAL



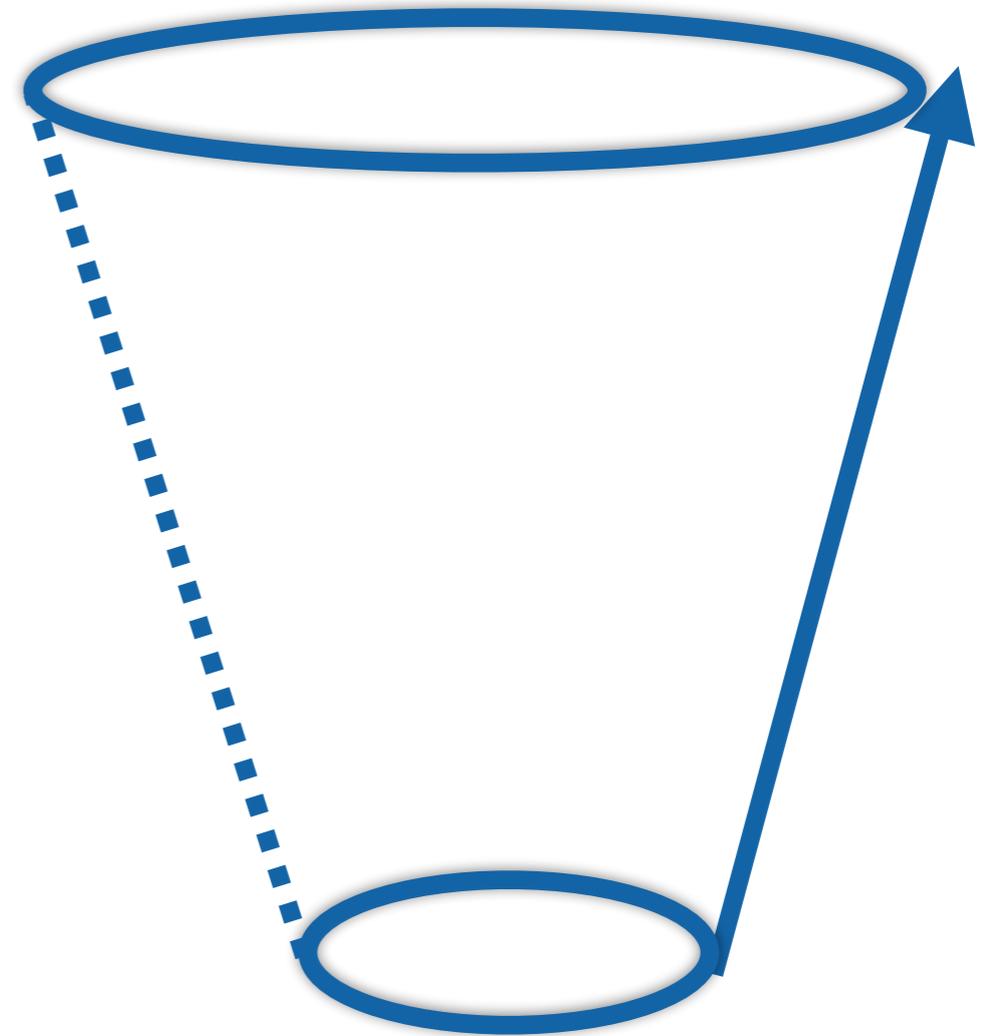
ESTATICO



SIN CURVATURA TEMPORAL



ESTATICO



EXPANSION UNIFORME

El efecto combinado es una CURVATURA del  
ESPACIOTIEMPO

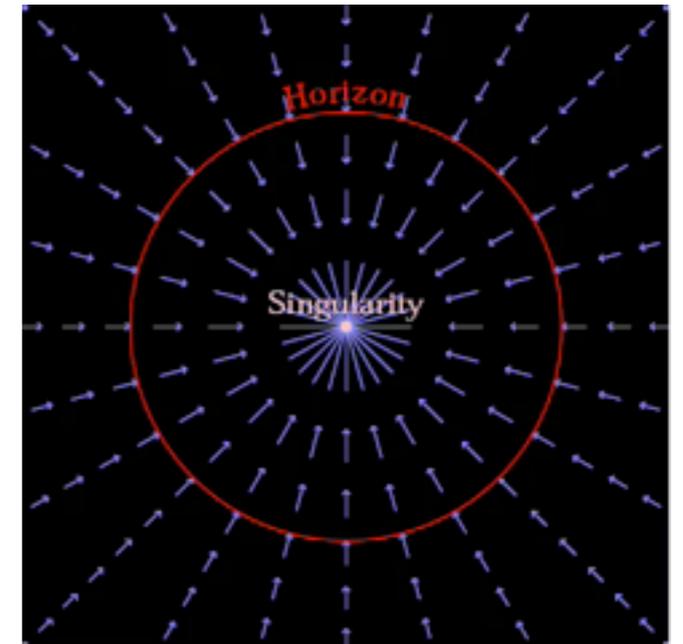
$$\text{CURVATURA}_{\text{espacio-tiempo}} = \text{CURVATURA}_{\text{espacio}} + (\text{ACELERACION}_{\text{espacio}})^2$$

## ECUACIONES DE EINSTEIN

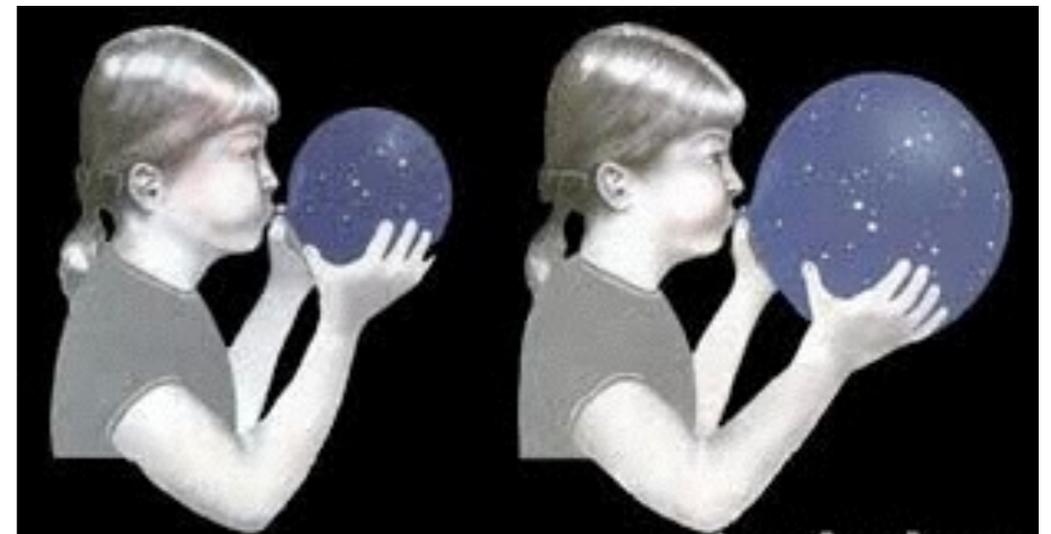
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$$\text{CURVATURA}_{\text{espacio-tiempo}} = G \text{ (DENSIDAD DE ENERGIA)}$$

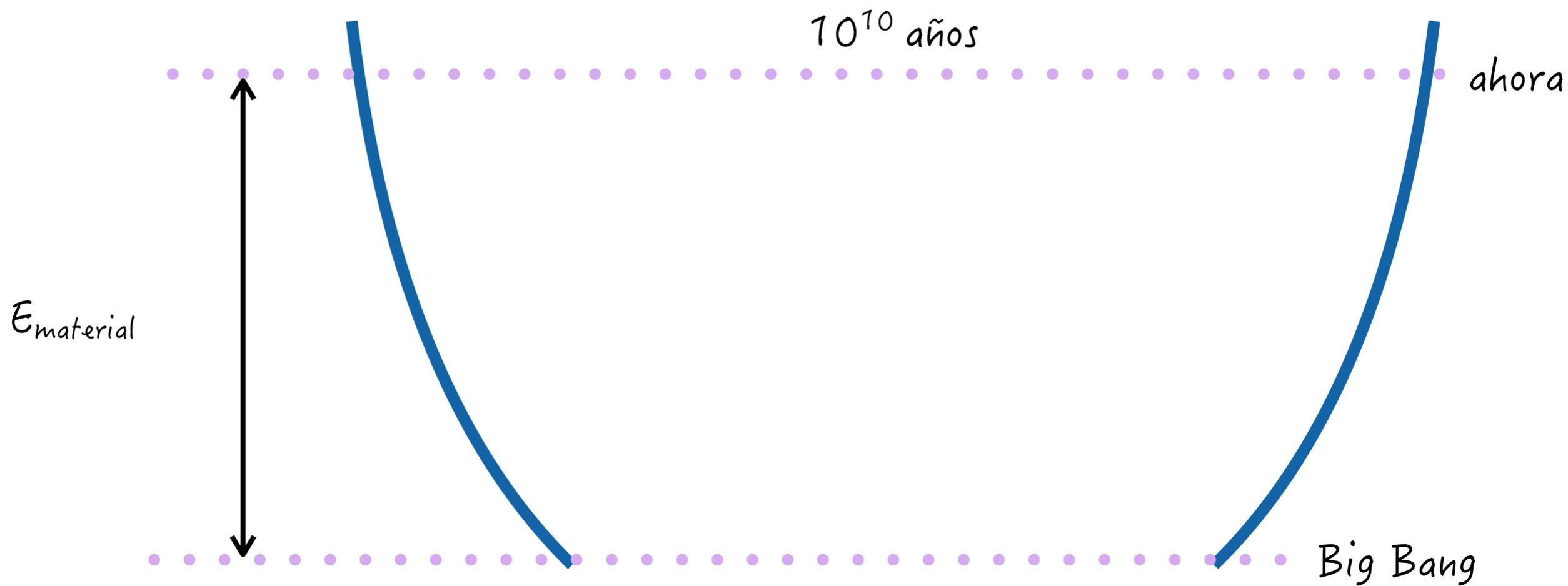
La energía "material" tiende a contraer el espacio

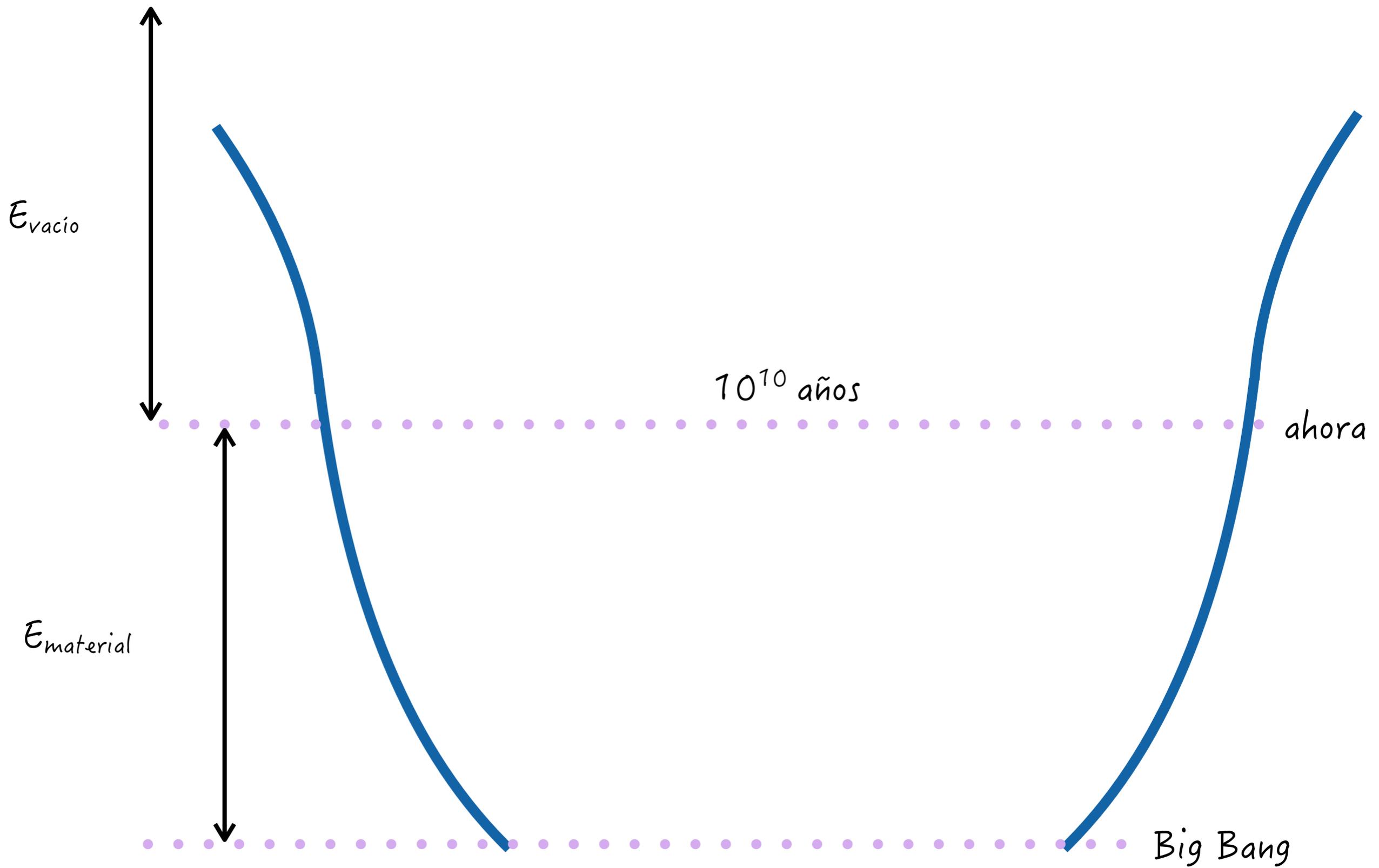


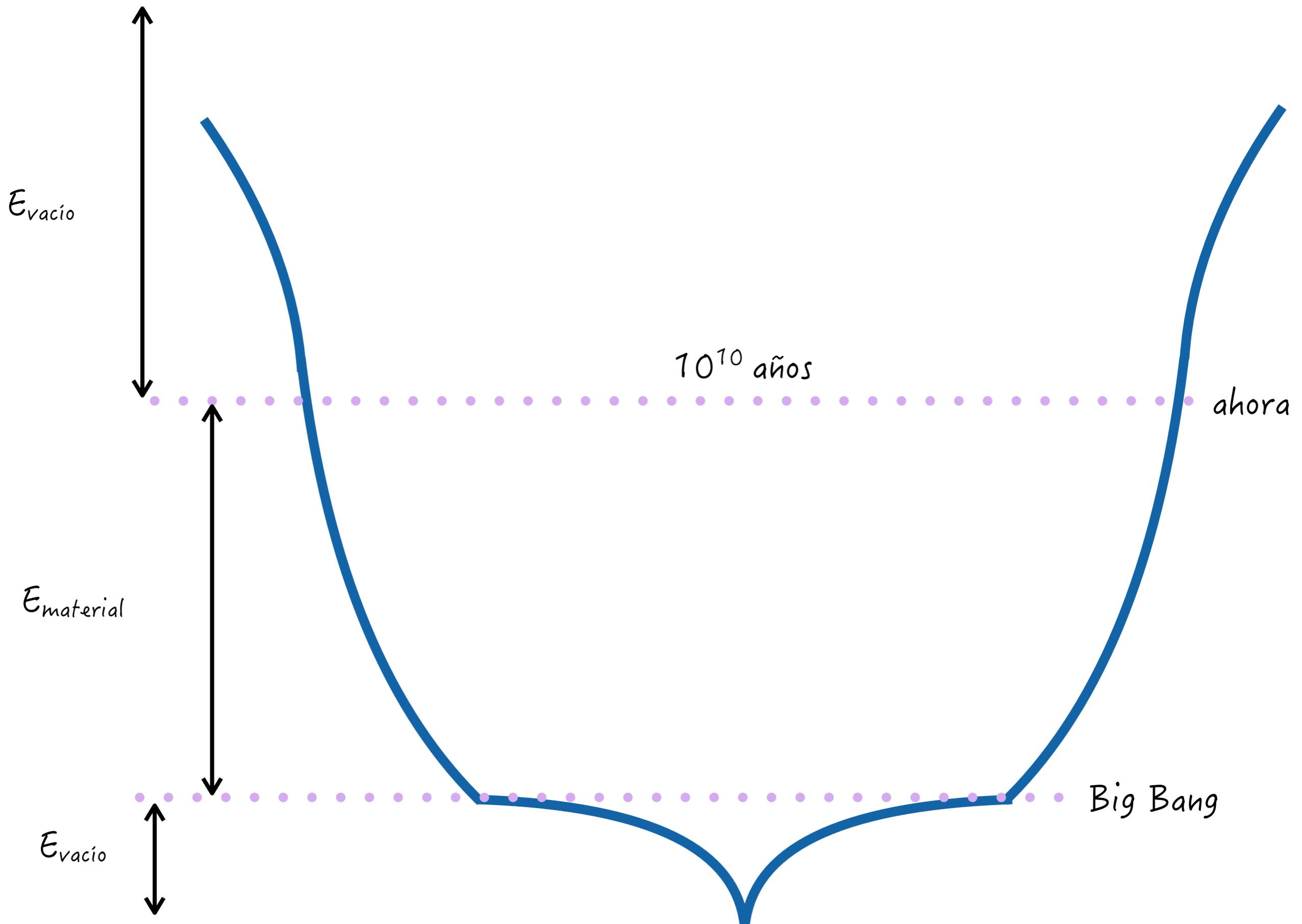
La energía de "vacío" tiende a estirar el espacio

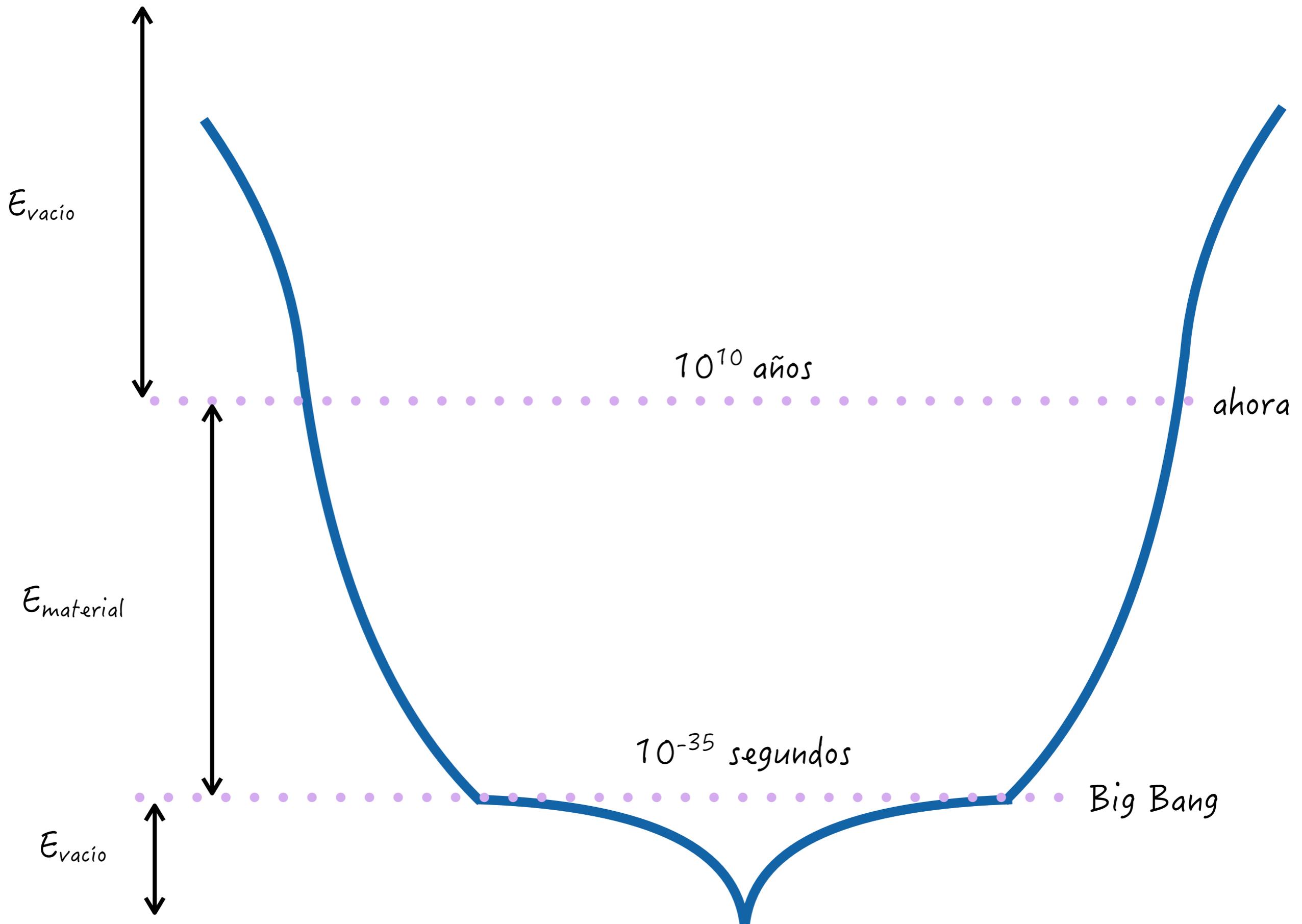












BANDE ORIGINALE DE LA MUSIQUE DU FILM  
ORIGINAL MOTION PICTURE SOUNDTRACK



VS-9603 F

# LE TROU NOIR

## THE BLACK HOLE

MUSIQUE DE  
**JOHN BARRY**



© 1979 Walt Disney Productions

BANDE ORIGINALE DE LA MUSIQUE DU FILM  
ORIGINAL MOTION PICTURE SOUNDTRACK

Disneyland  
RECORDED  
VS-9603 F

# LE TROU NOIR

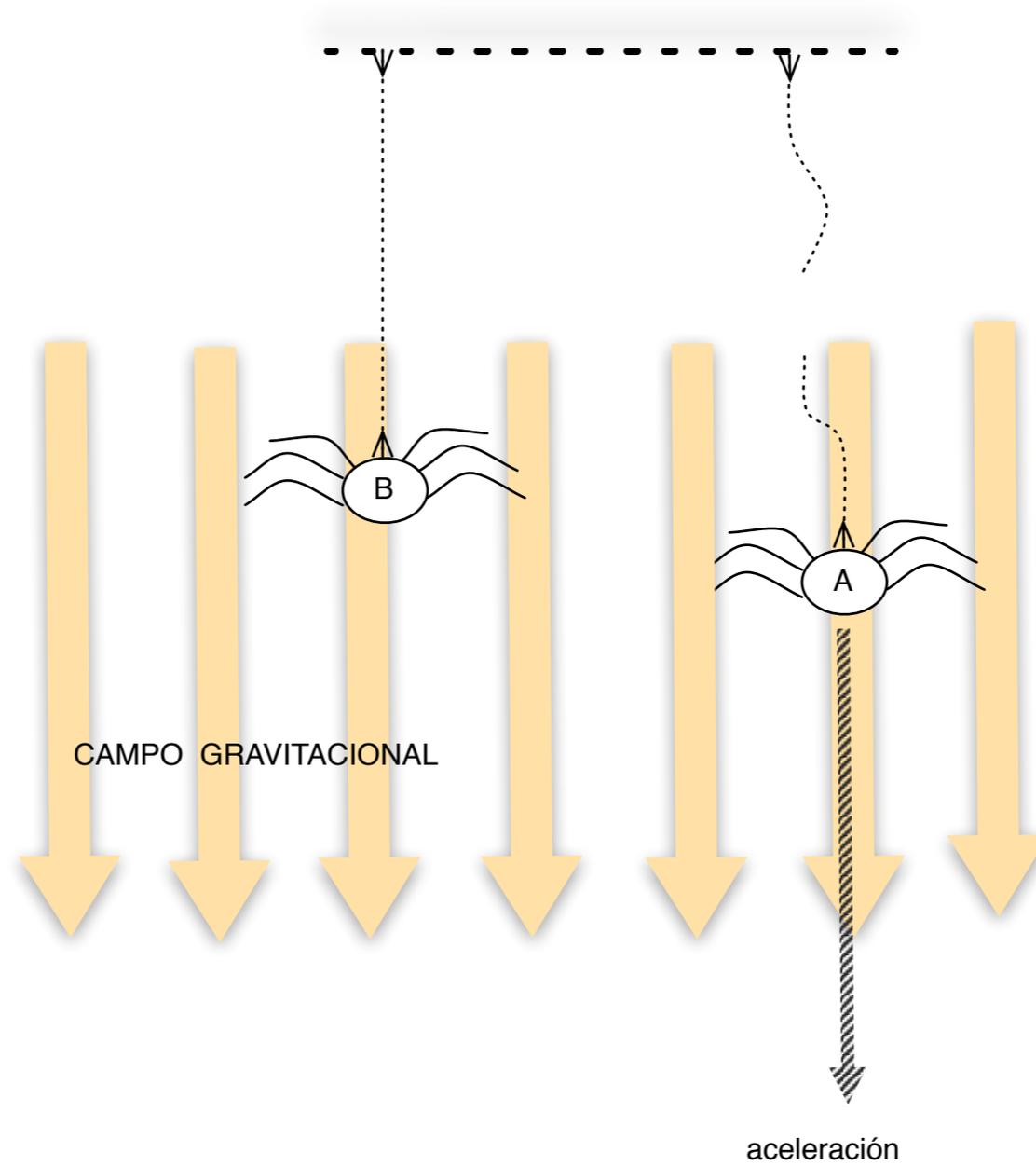
## THE BLACK HOLE

JOHN WILLIAMS

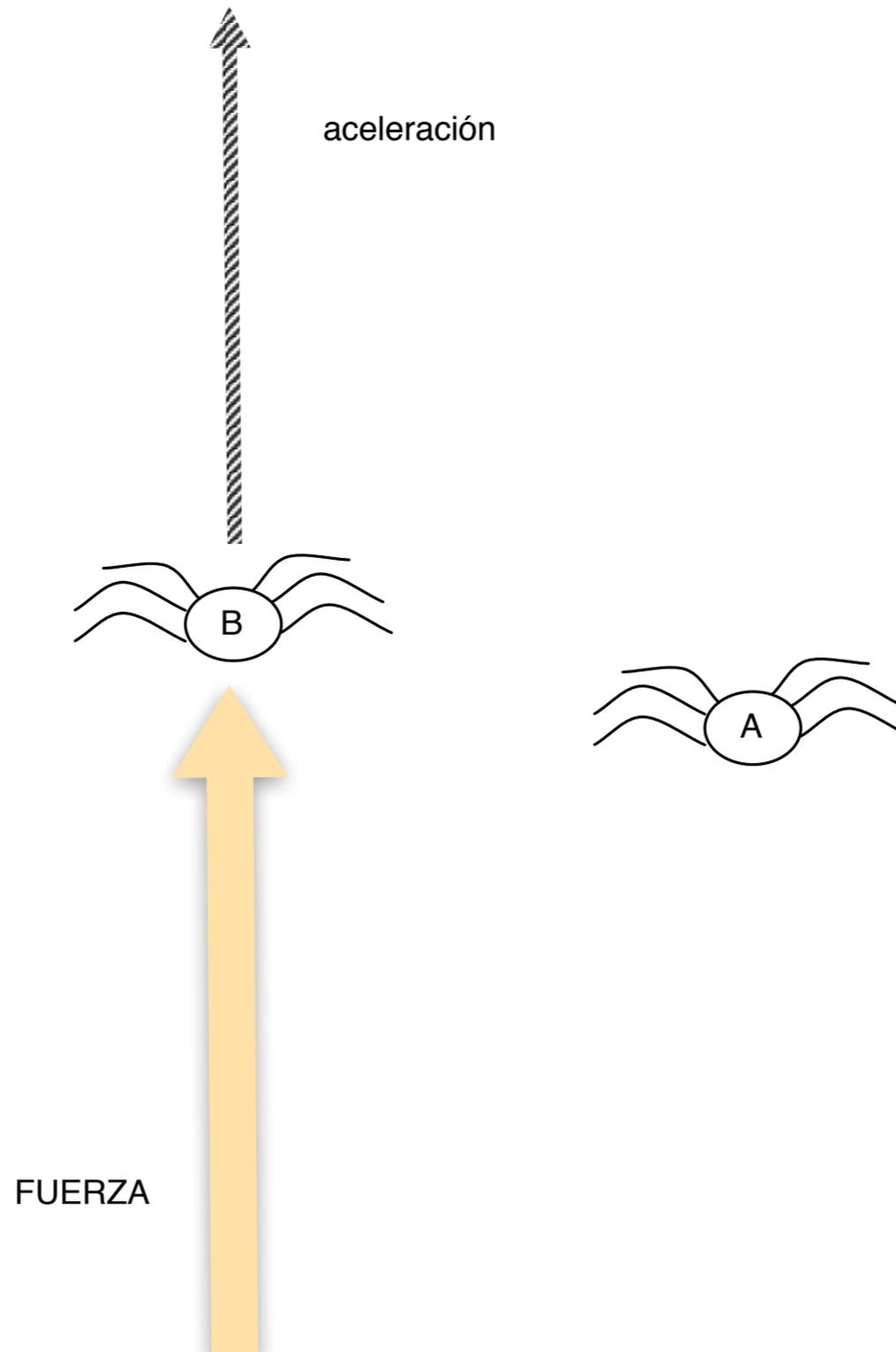
Adès



# El punto de vista de Bernardo



# El punto de vista de Alicia



# El punto de vista de Alicia

$t_A$



espacio A

# El punto de vista de Alicia

$t_A$

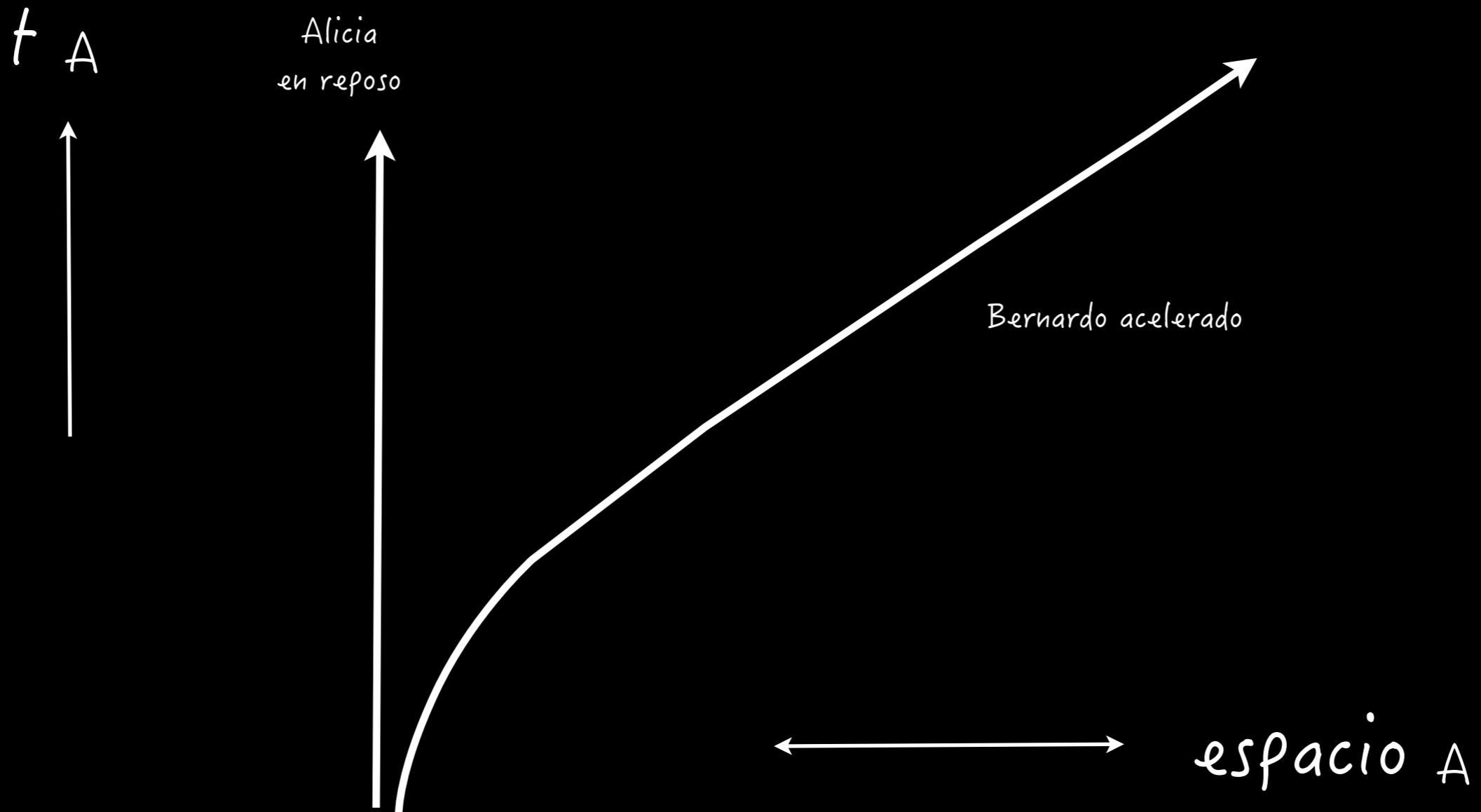


Alicia  
en reposo

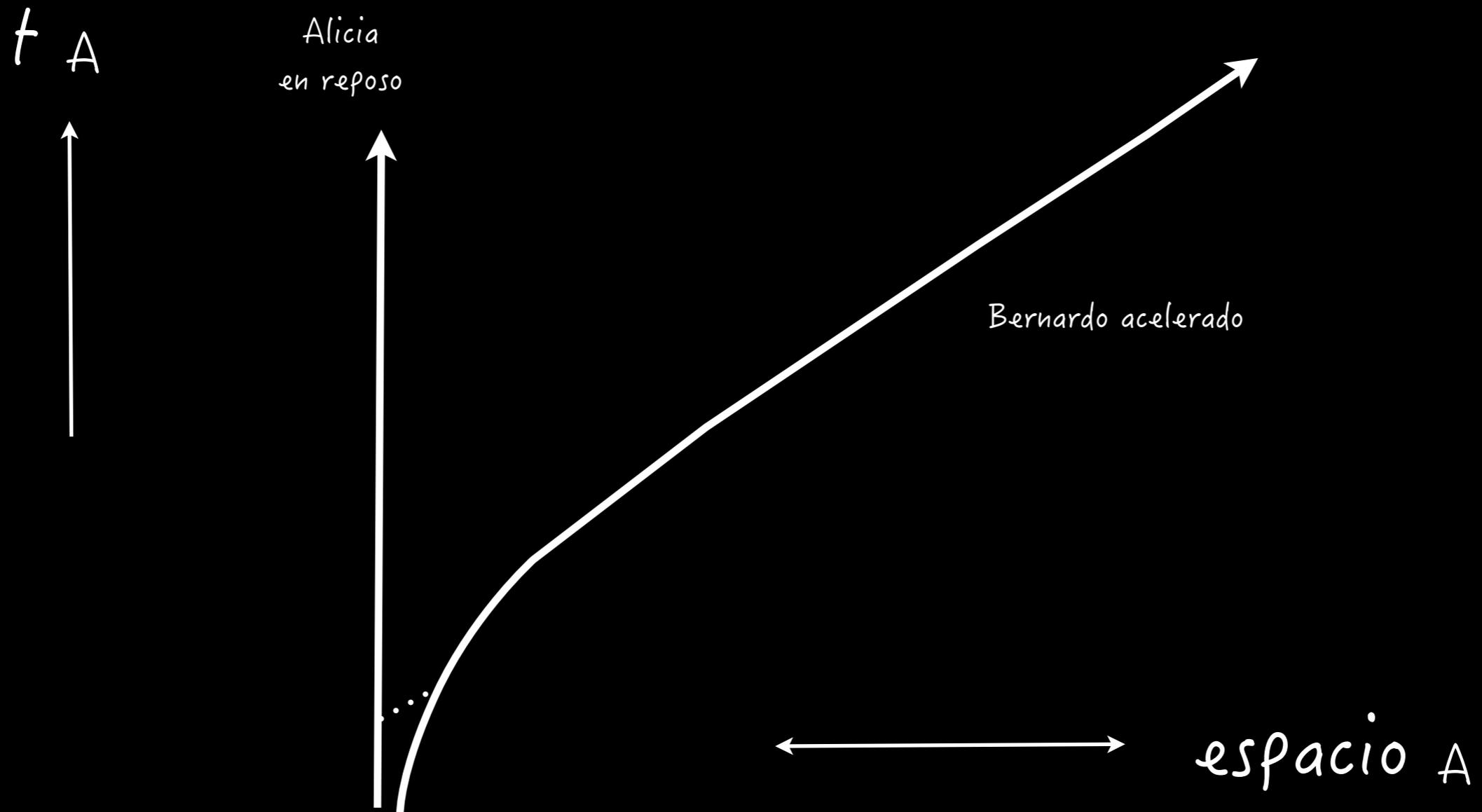


espacio A

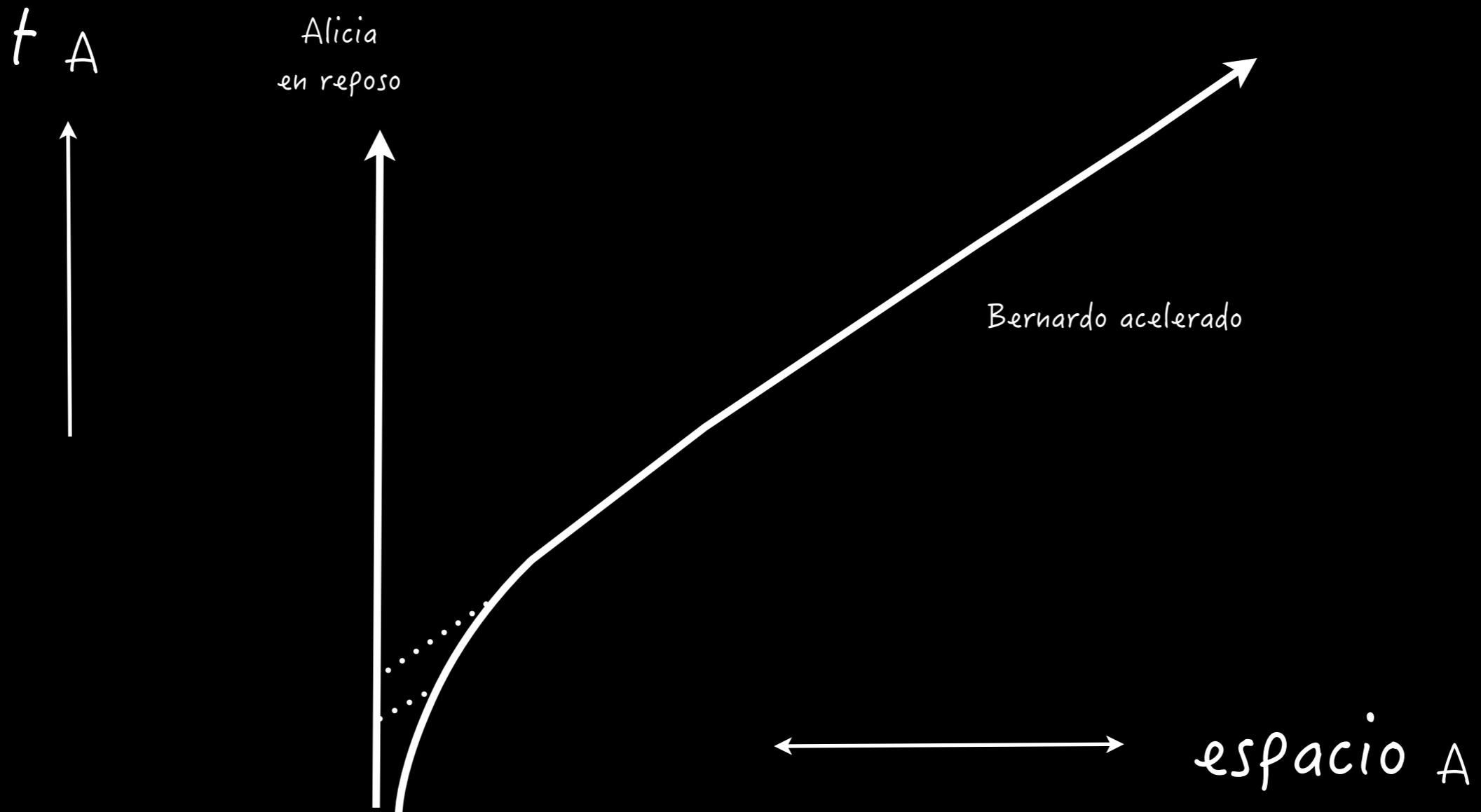
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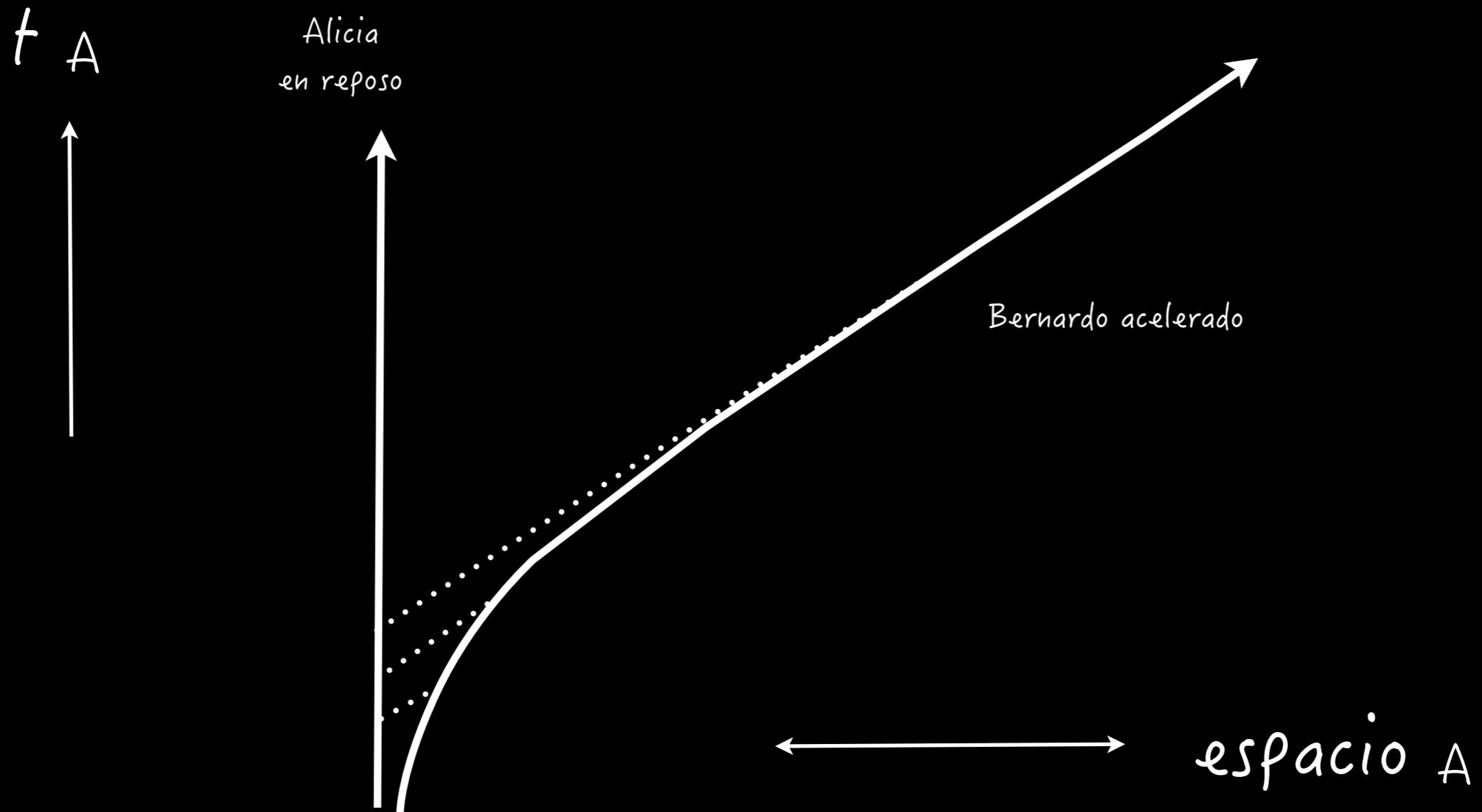
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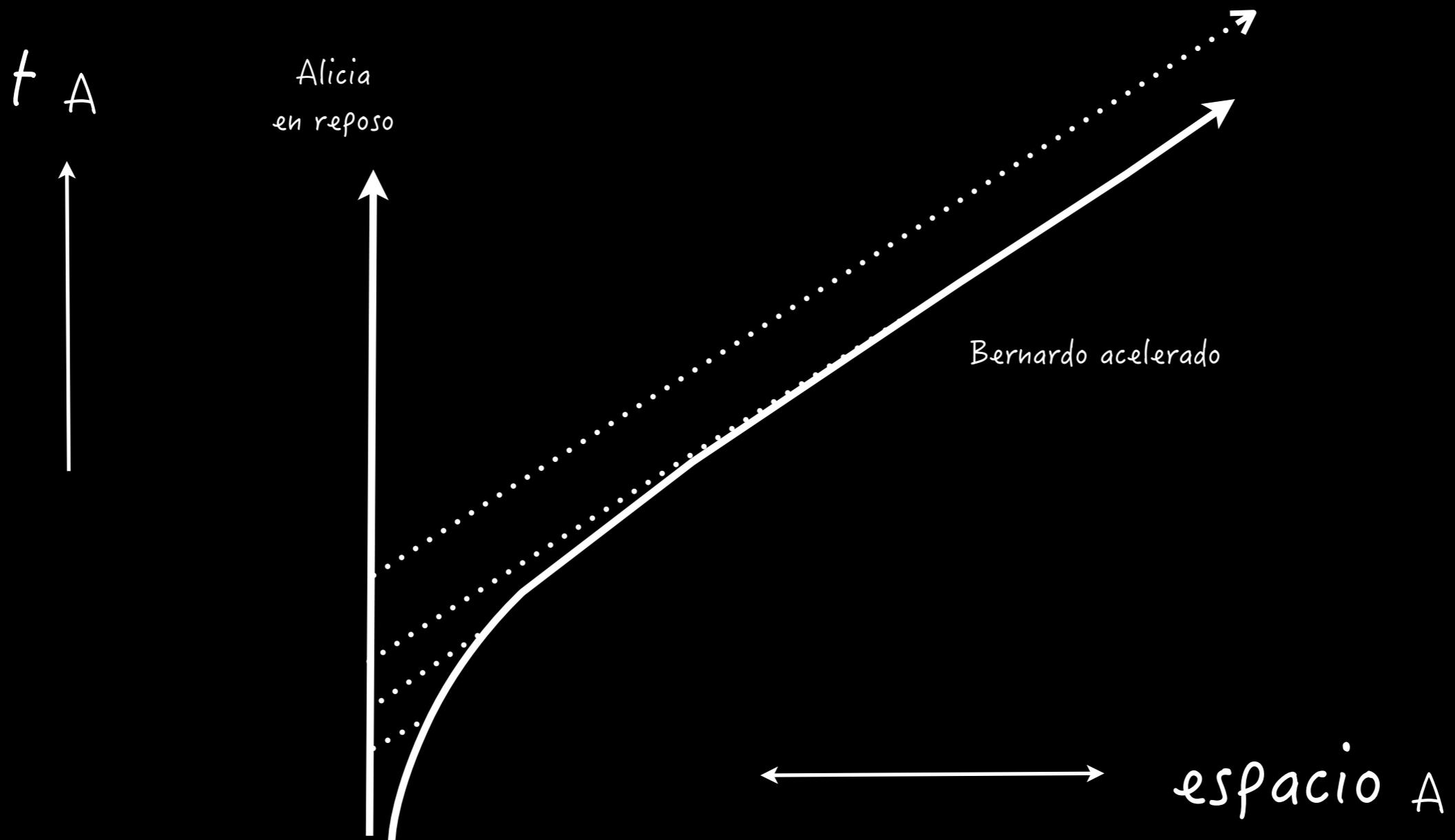
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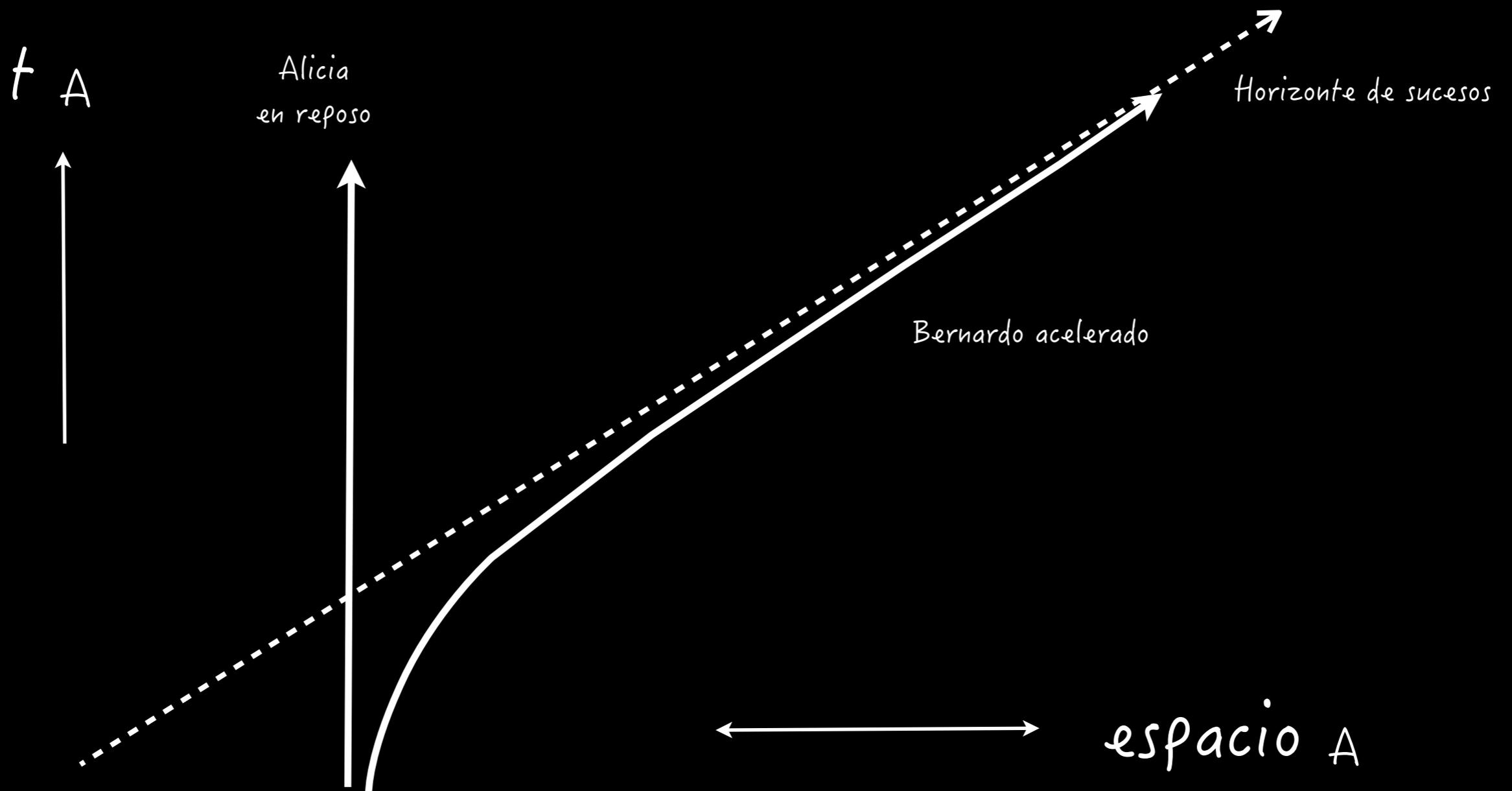
# El punto de vista de Alicia



# El punto de vista de Alicia



# El punto de vista de Alicia



# El punto de vista de Bernardo

$t_B$



espacio  $B$

# El punto de vista de Bernardo

$t_B$

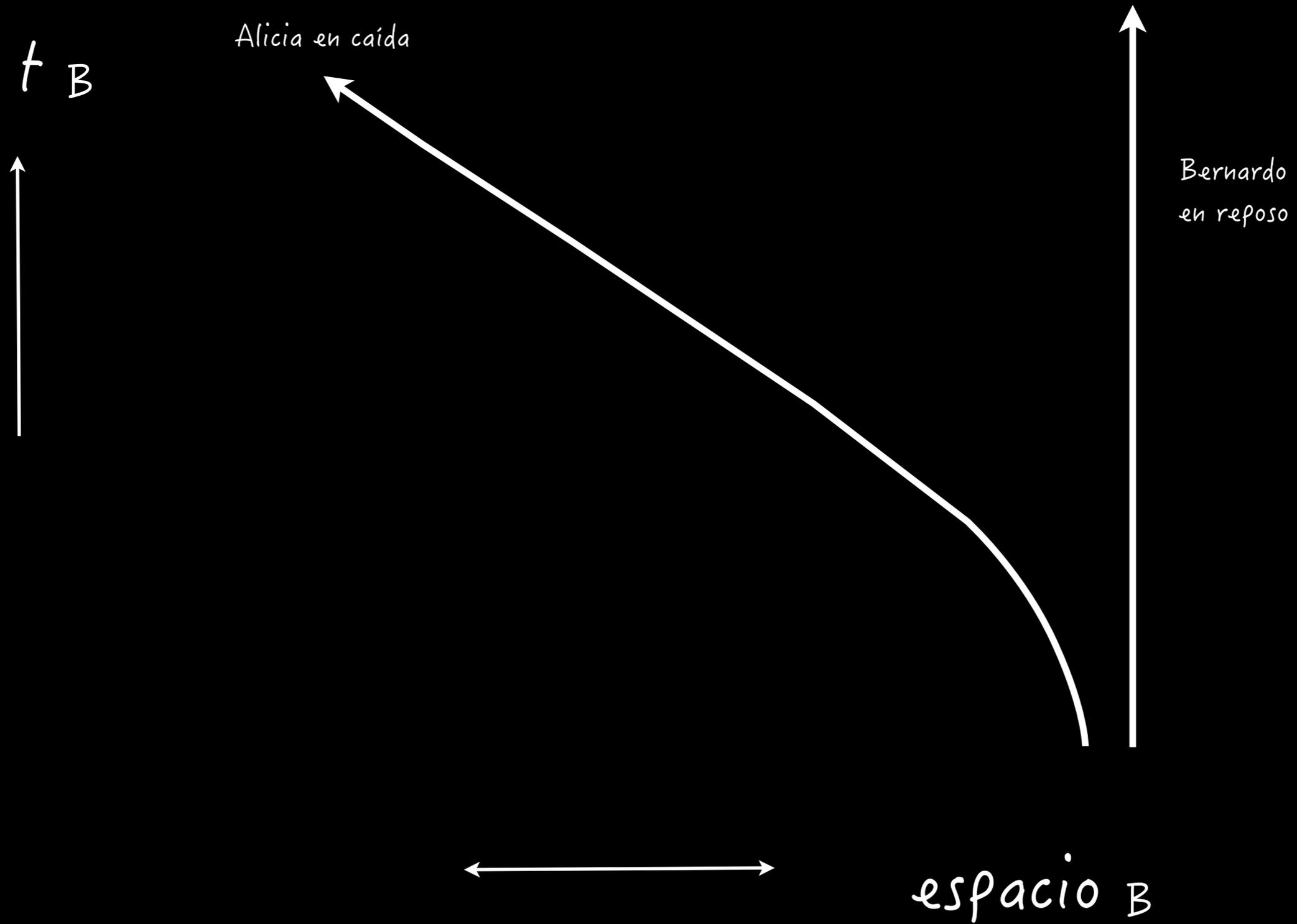


Bernardo  
en reposo

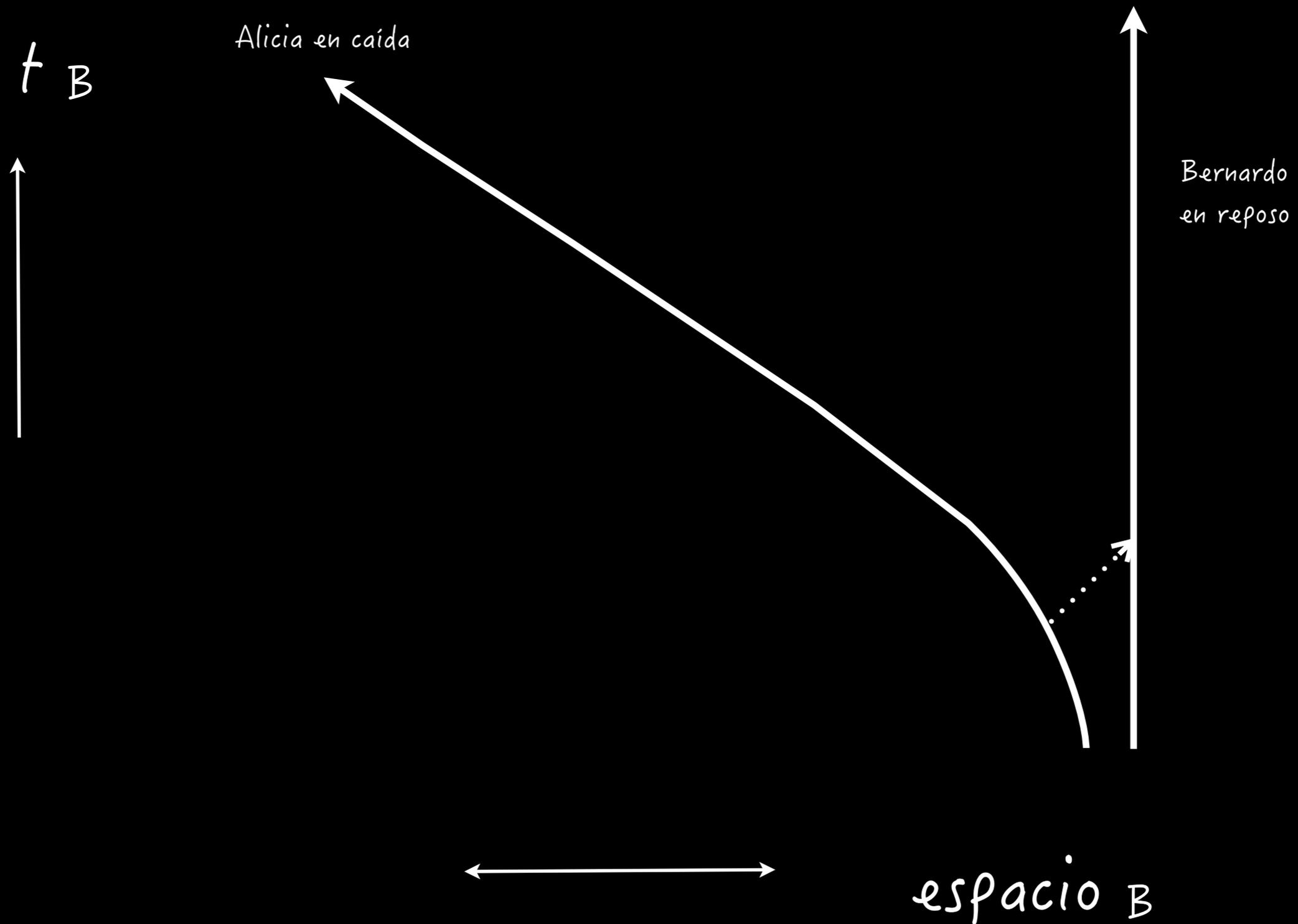


espacio B

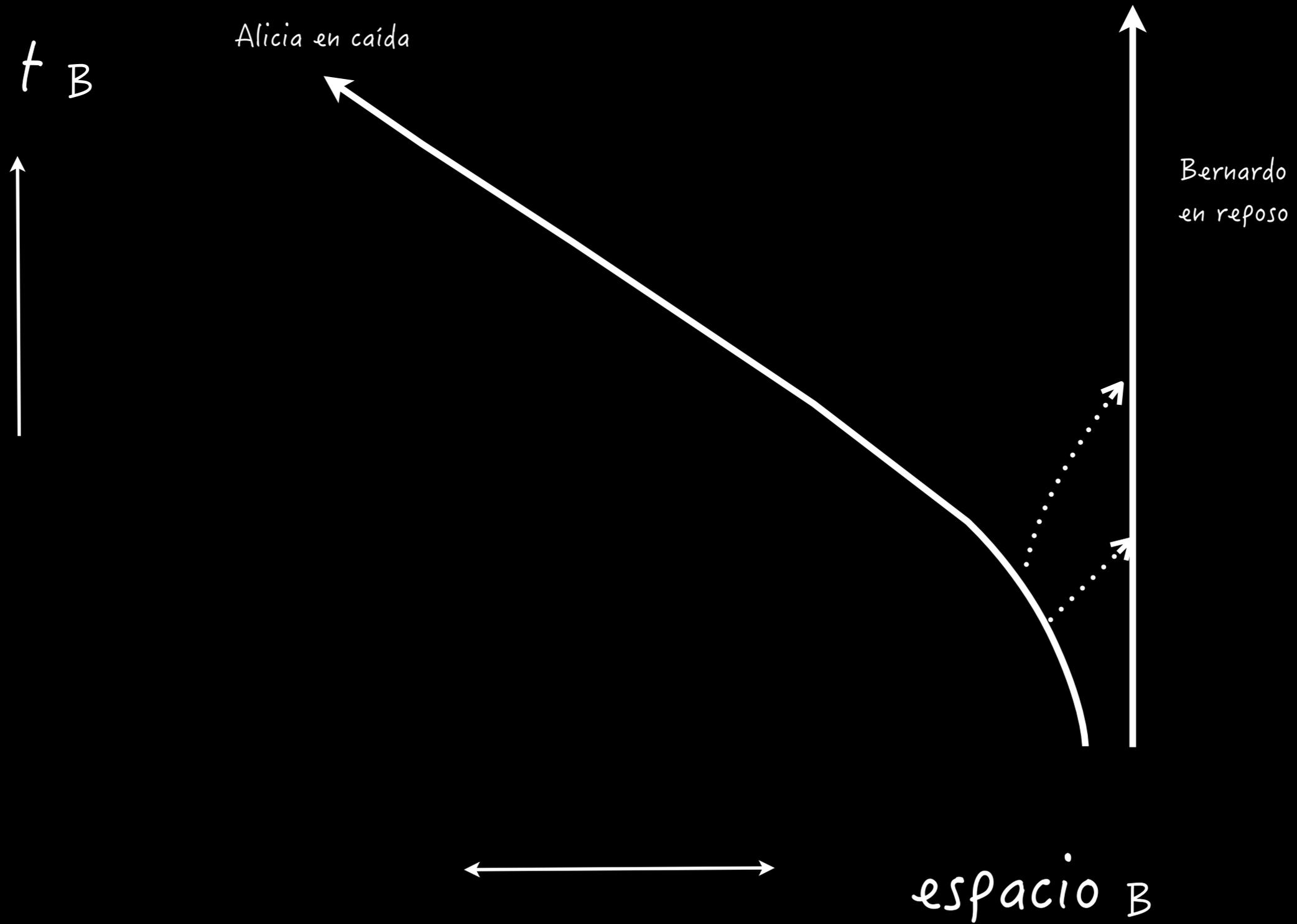
# El punto de vista de Bernardo



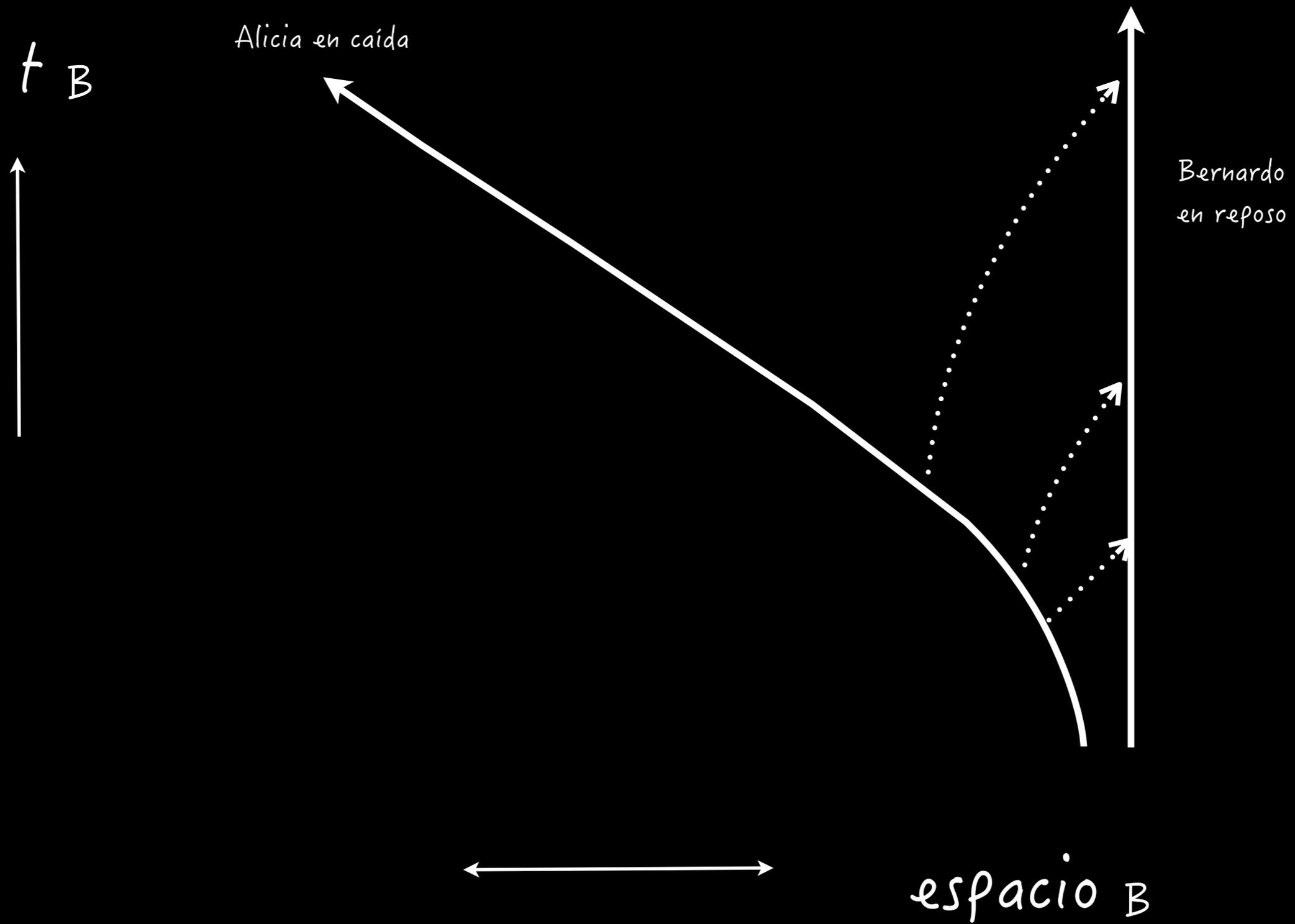
# El punto de vista de Bernardo



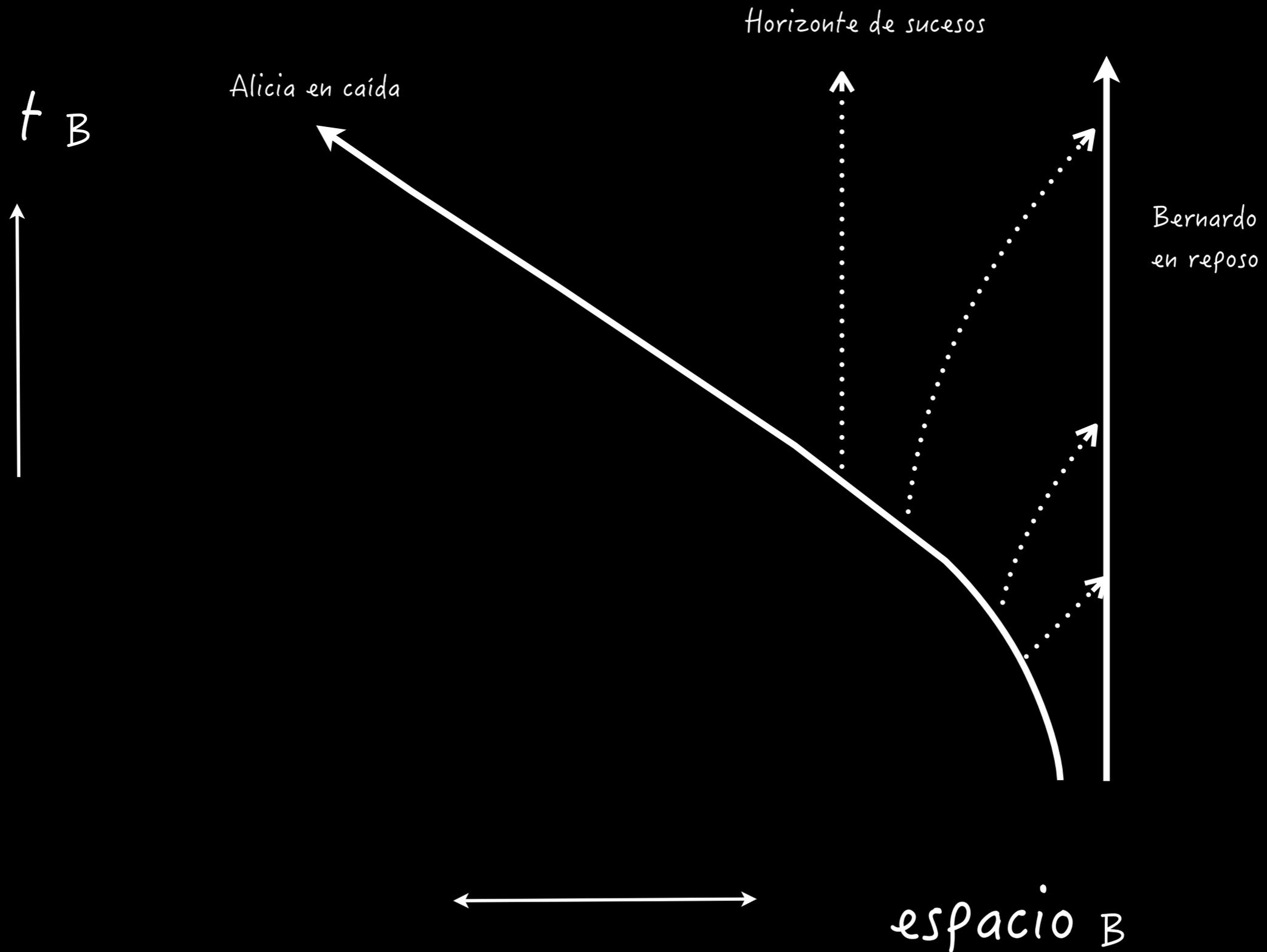
# El punto de vista de Bernardo



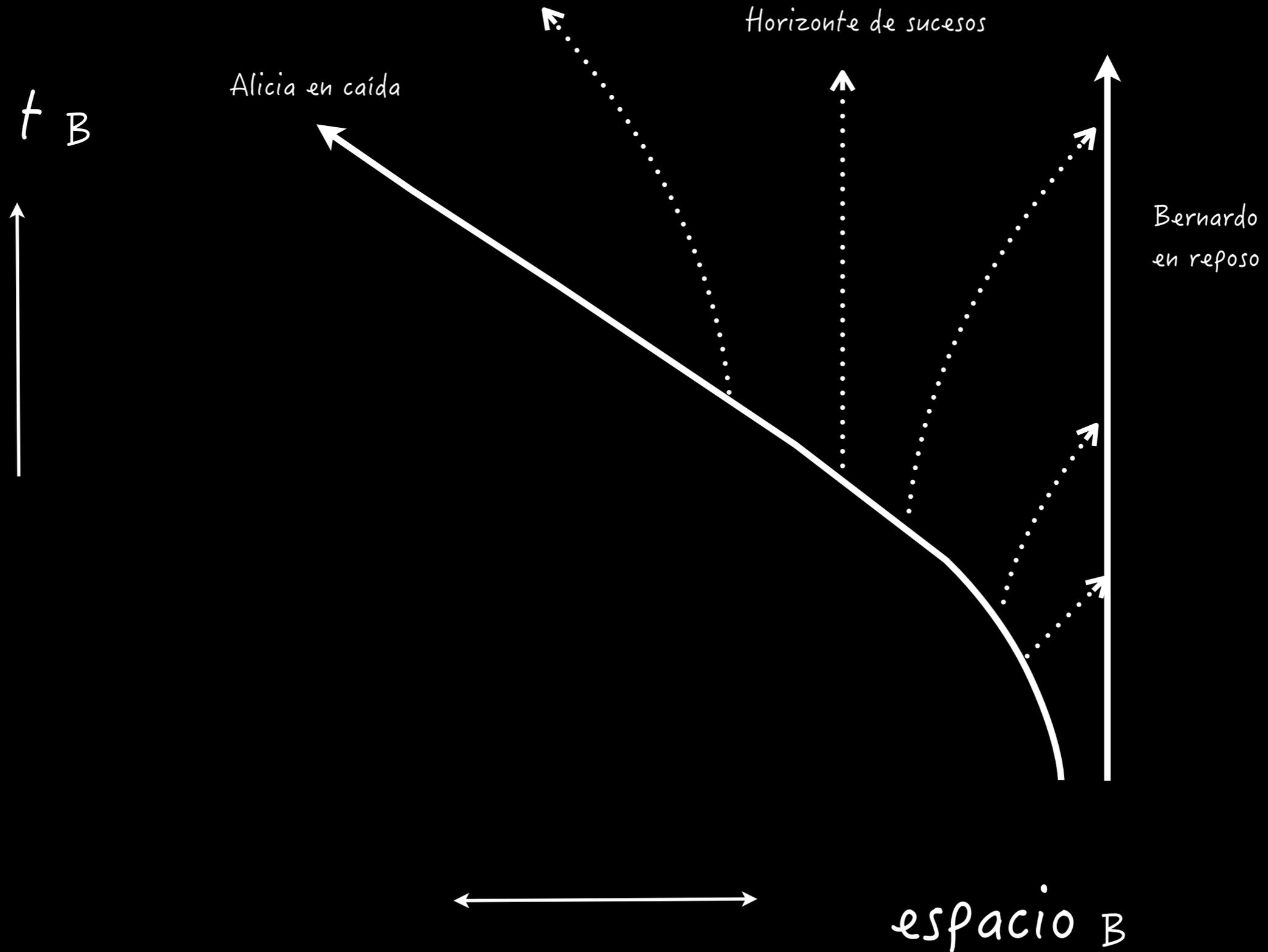
# El punto de vista de Bernardo



# El punto de vista de Bernardo



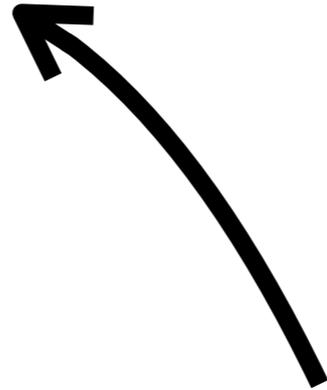
# El punto de vista de Bernardo





Bernardo  
en  
reposo

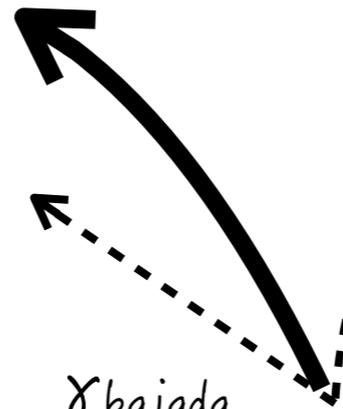
Alicia cae



Bernardo  
en  
reposo



Alicia cae

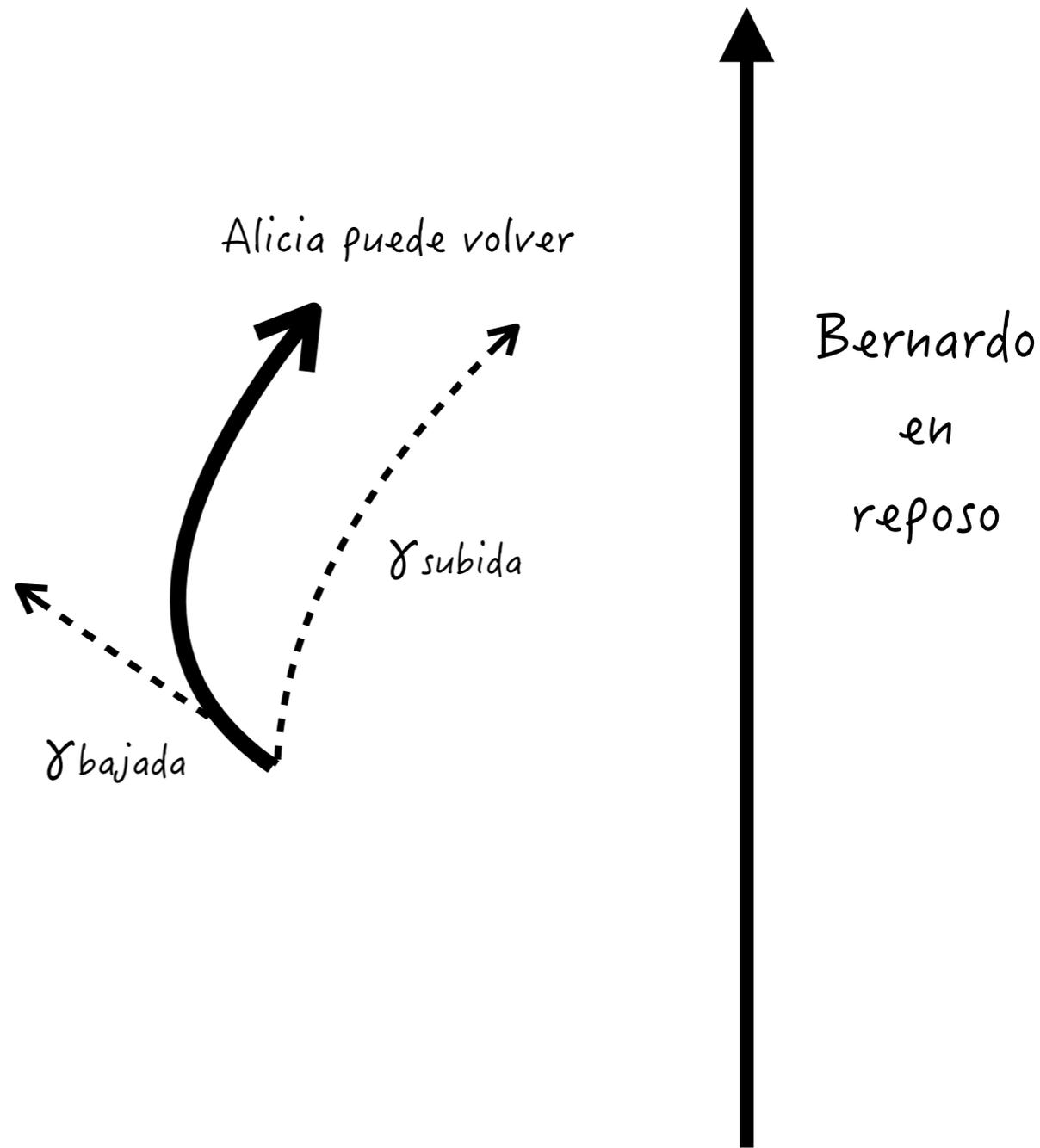


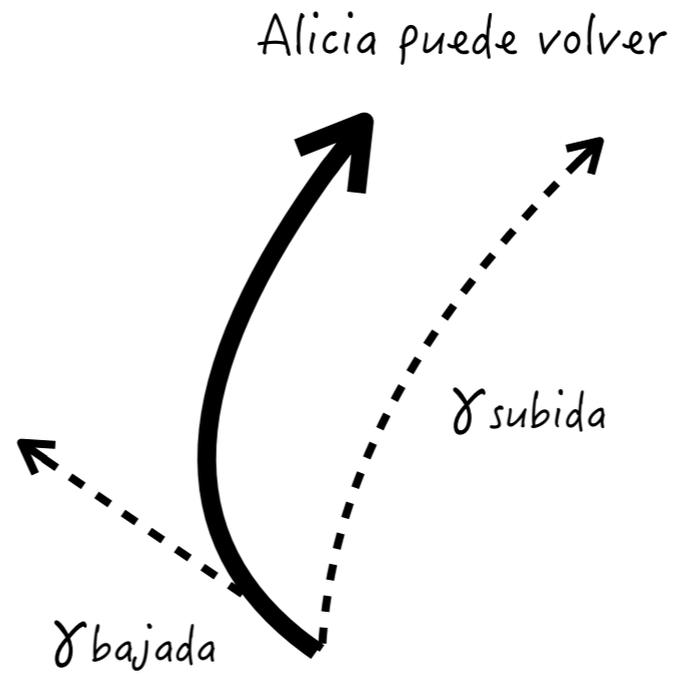
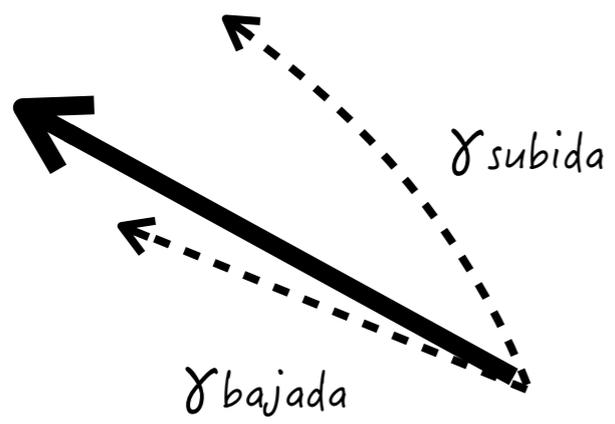
$\gamma$  subida

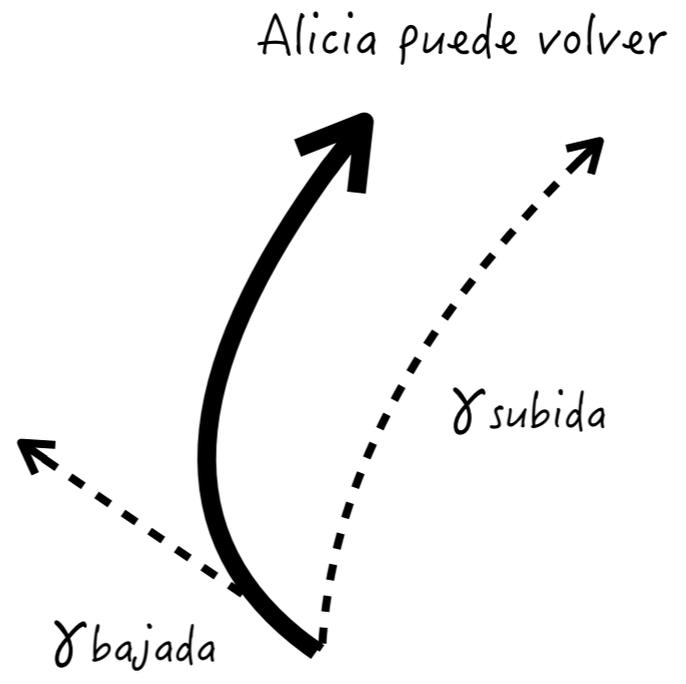
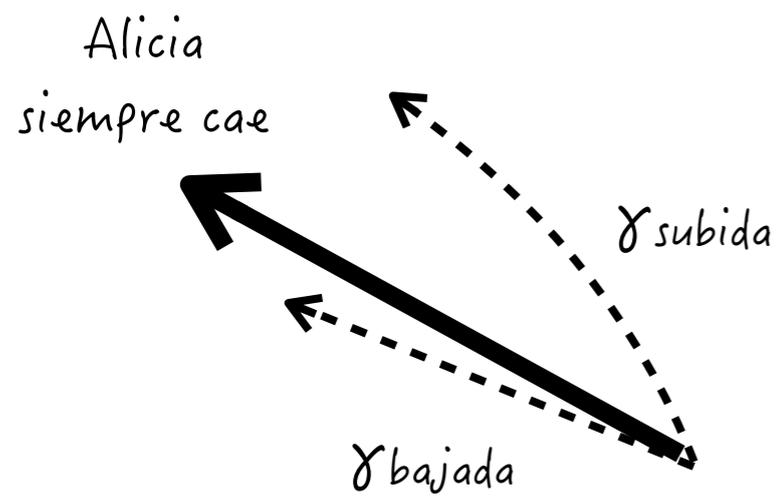
$\gamma$  bajada



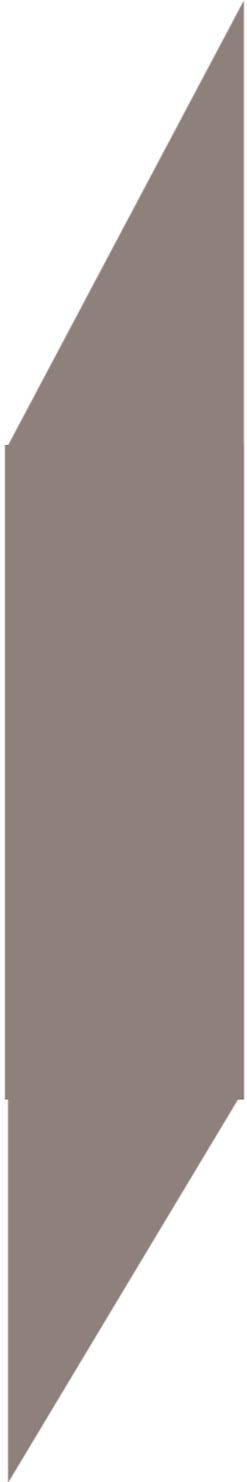
Bernardo  
en  
reposo



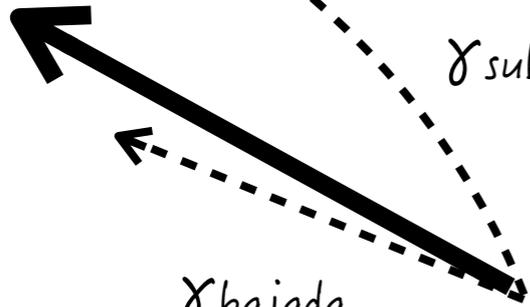




horizonte



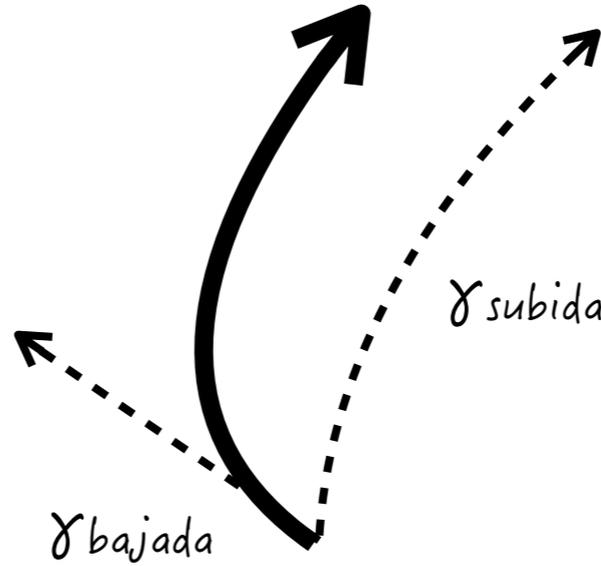
Alicia  
siempre cae



$\gamma_{subida}$

$\gamma_{bajada}$

Alicia puede volver

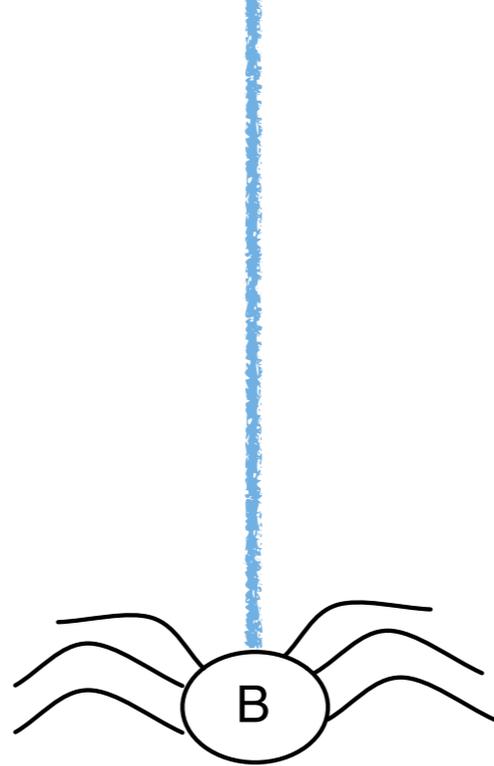


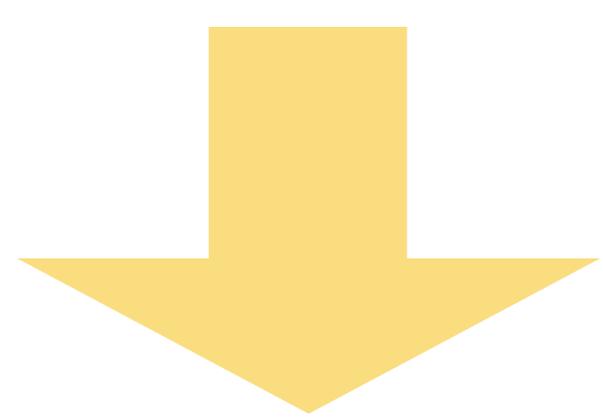
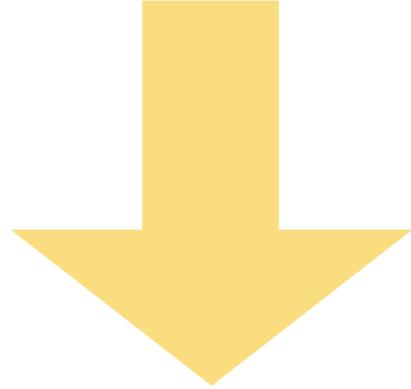
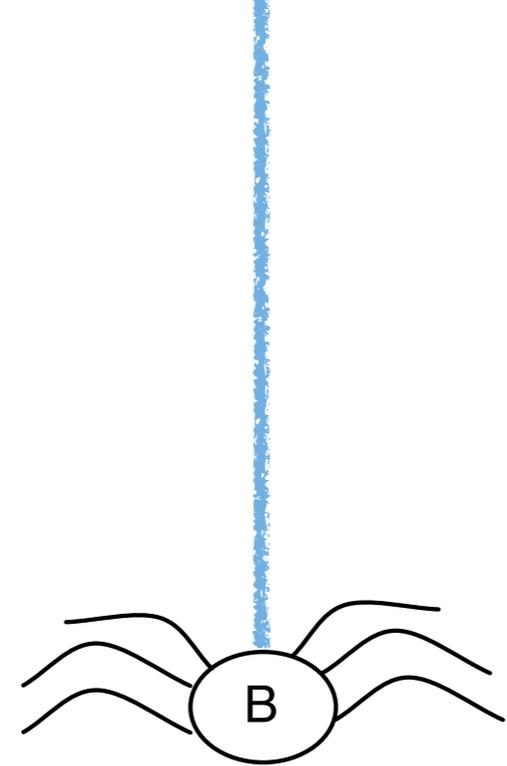
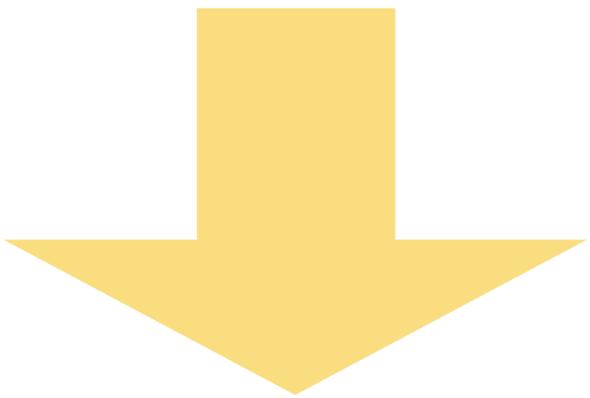
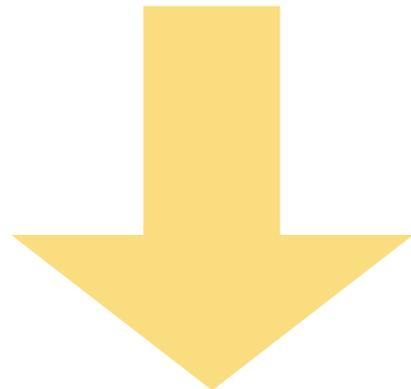
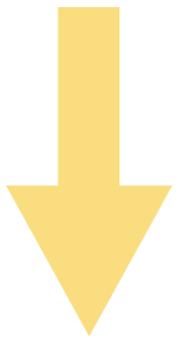
$\gamma_{subida}$

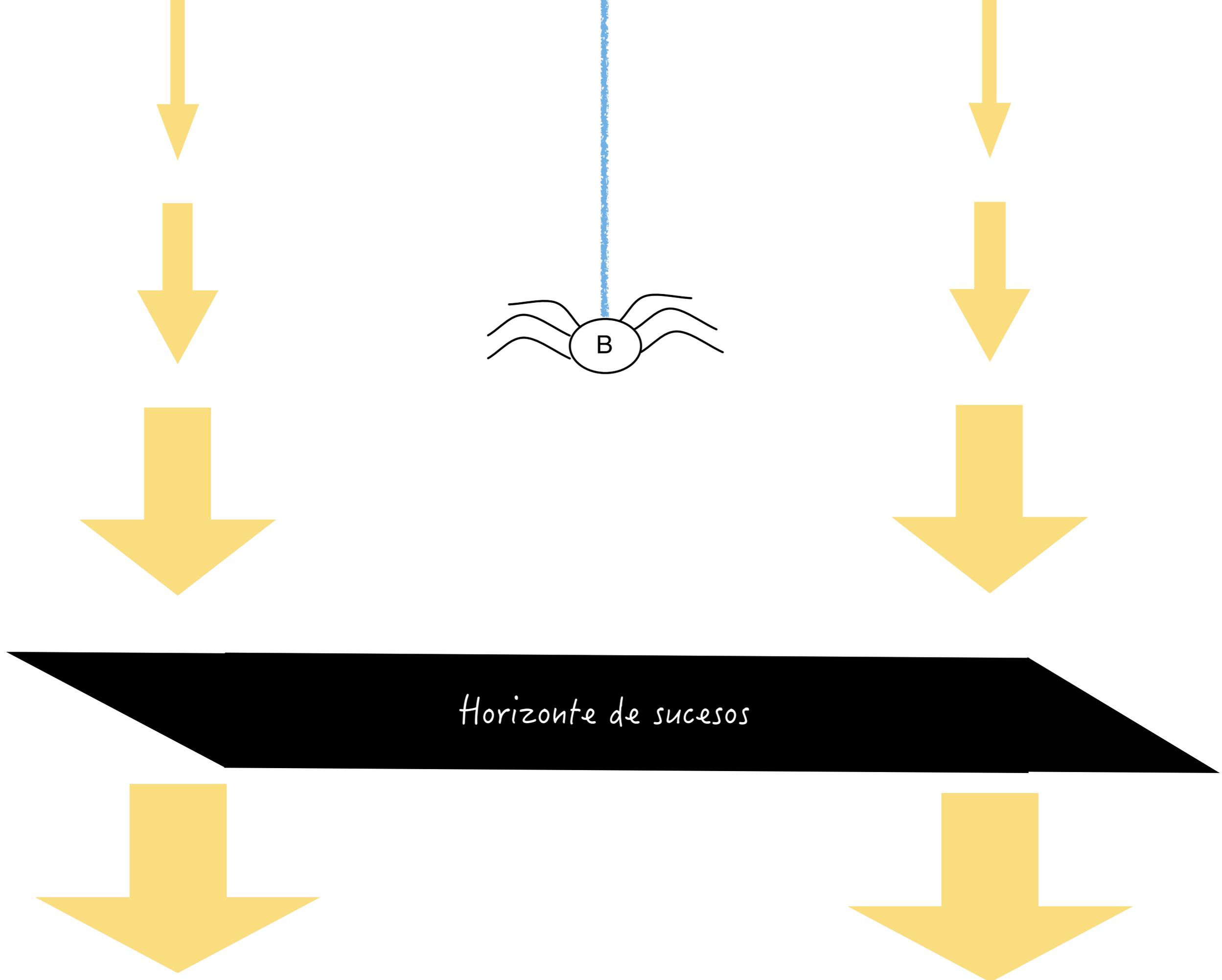
$\gamma_{bajada}$

Bernardo  
en  
reposo

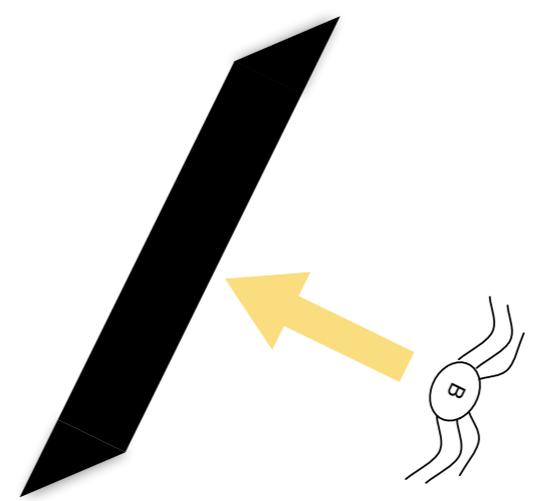
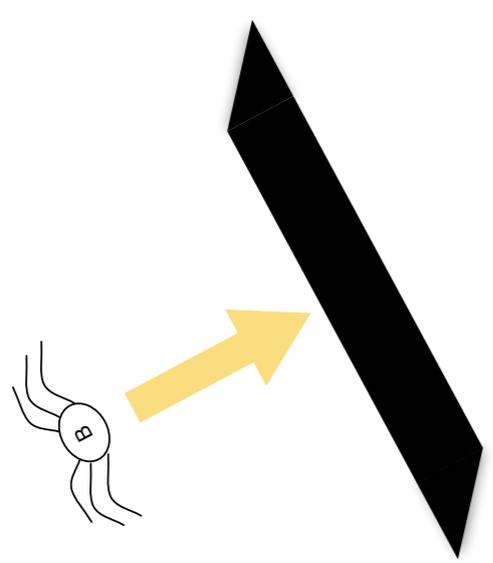
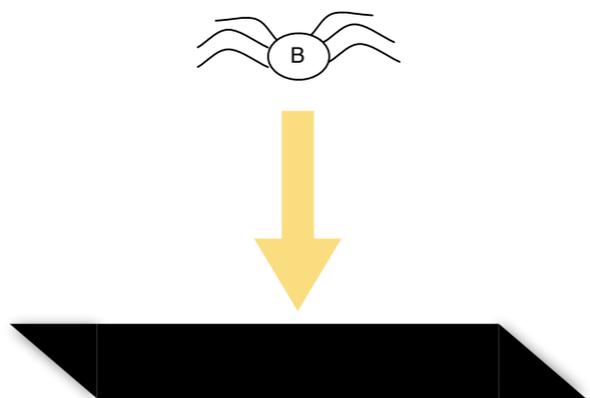


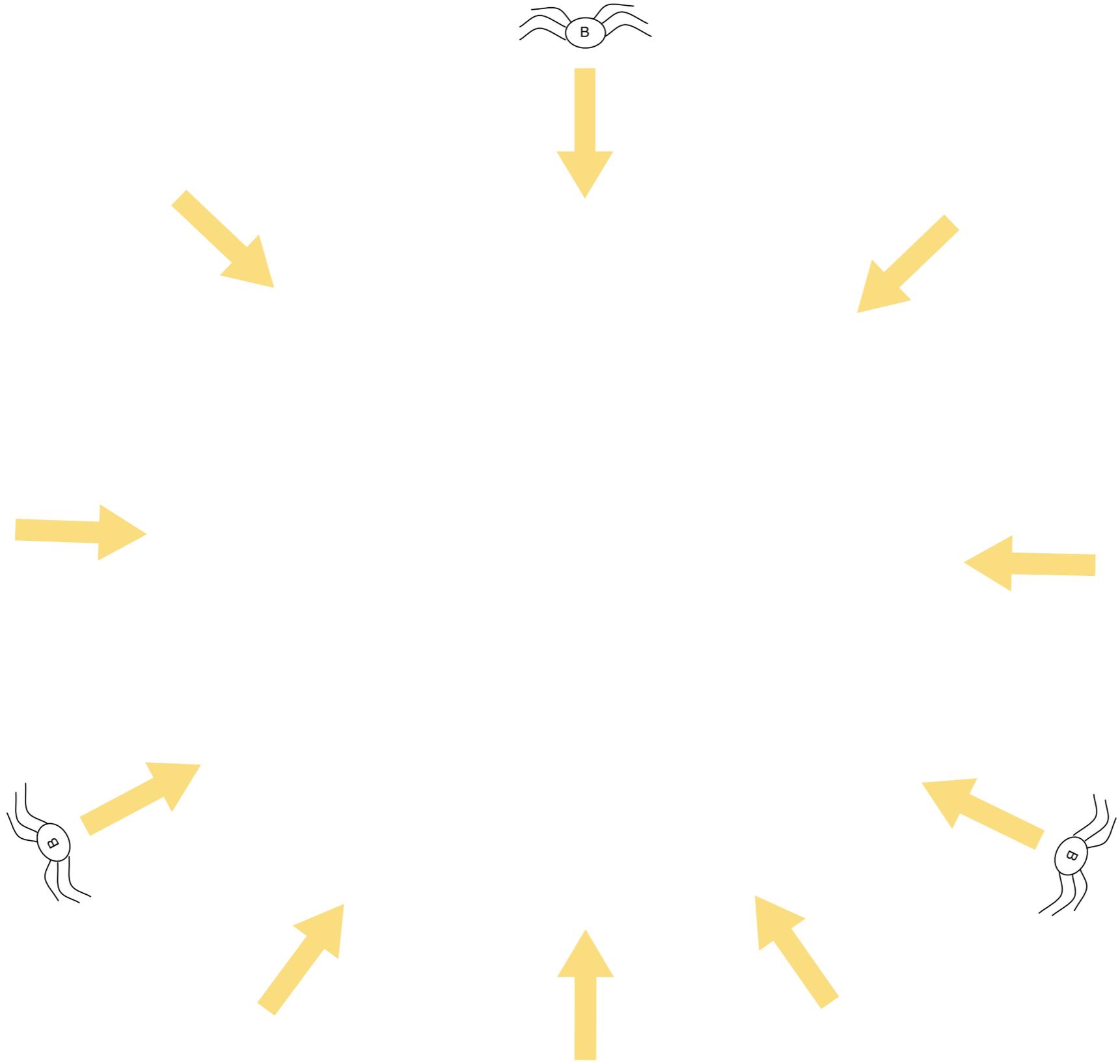


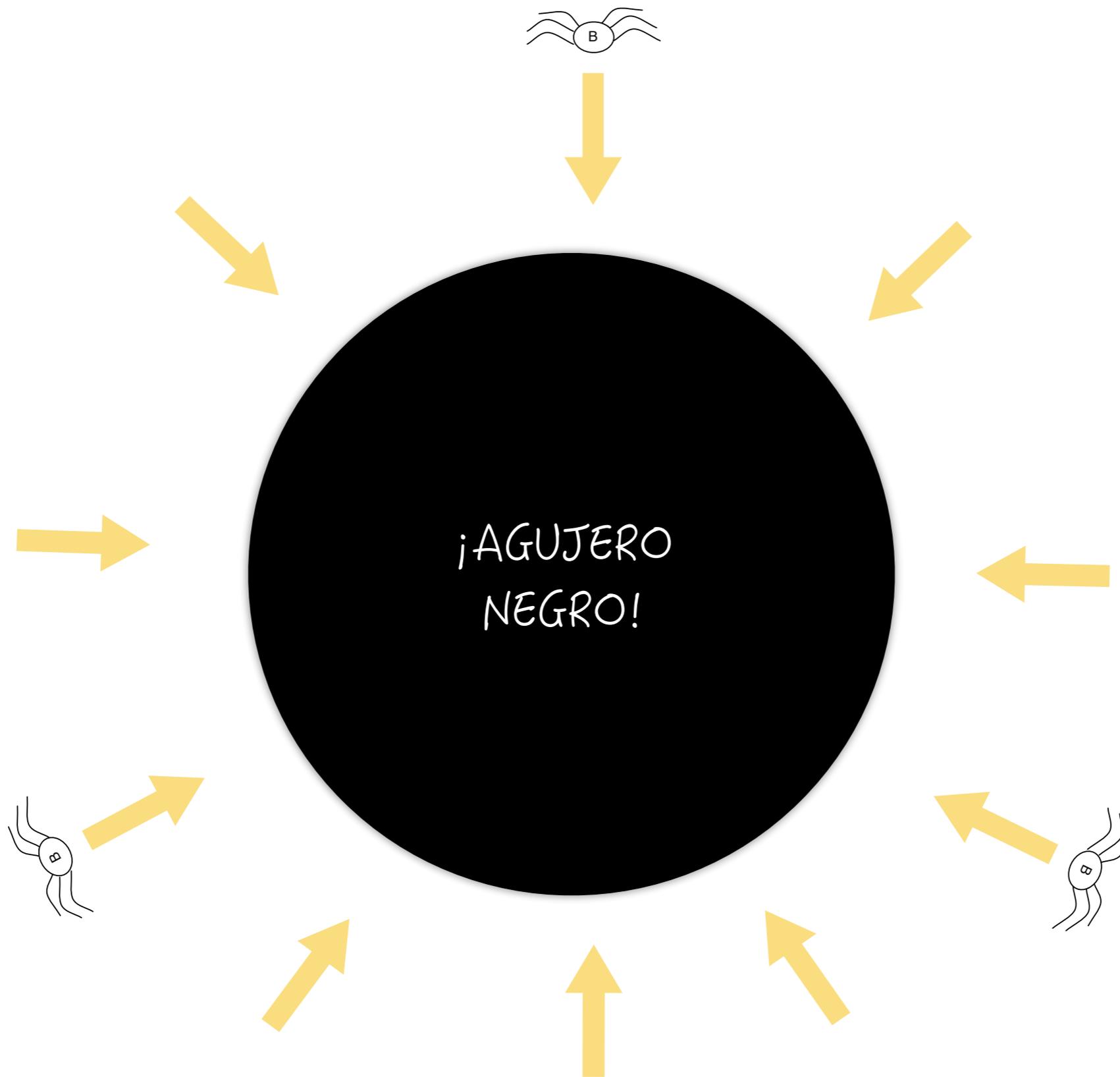




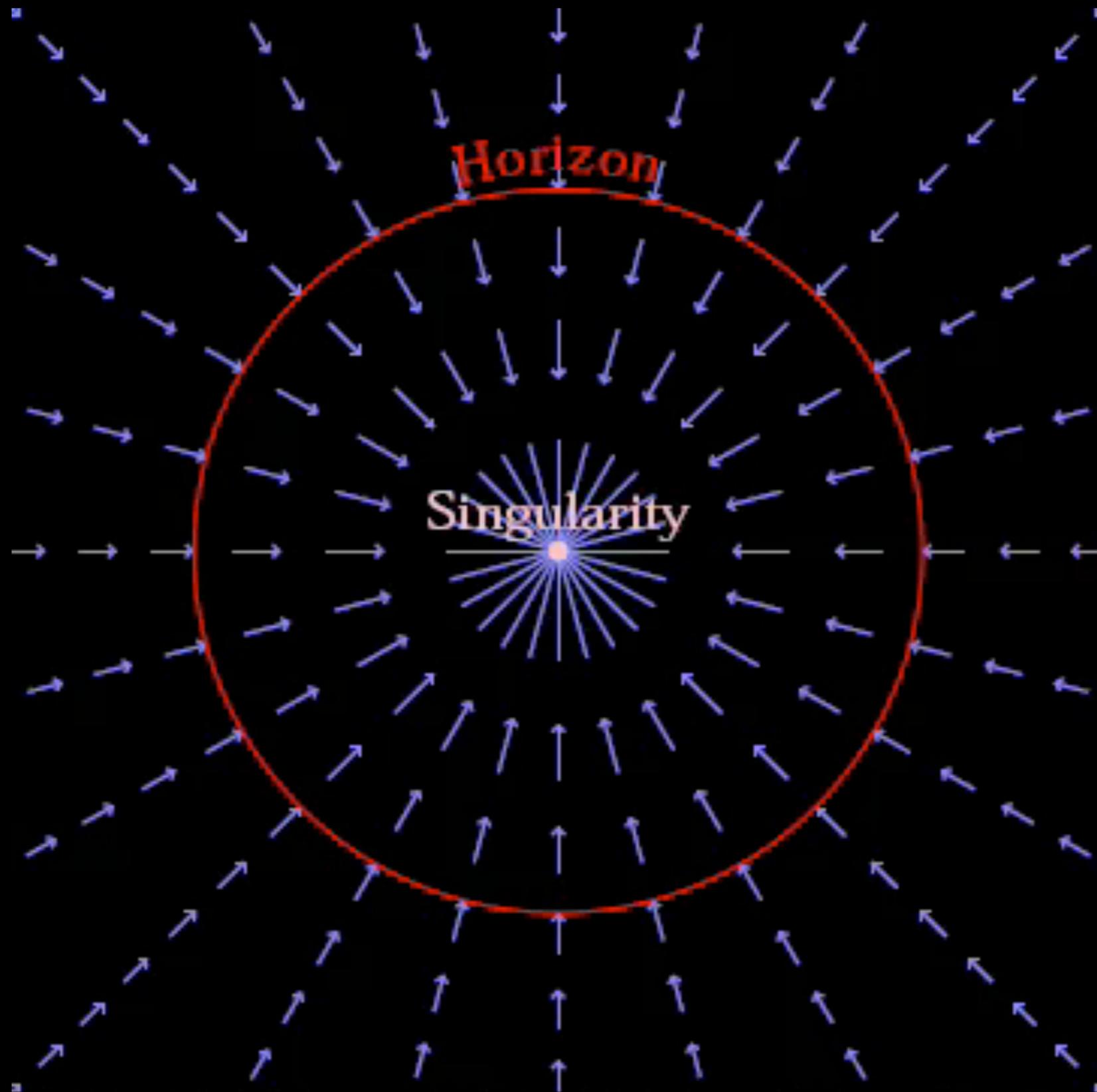
*Horizonte de sucesos*



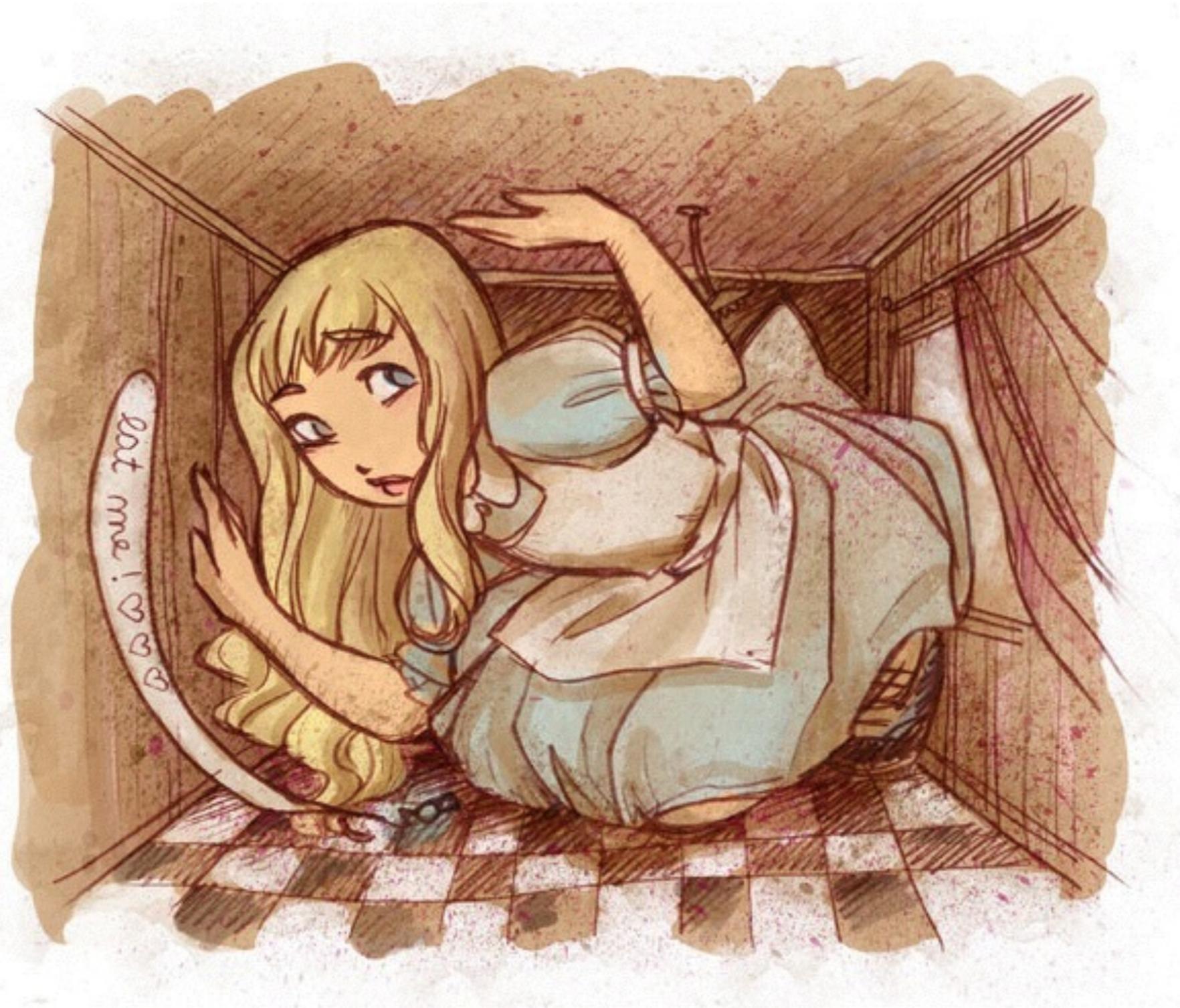




El espacio queda "aplastado" en la singularidad

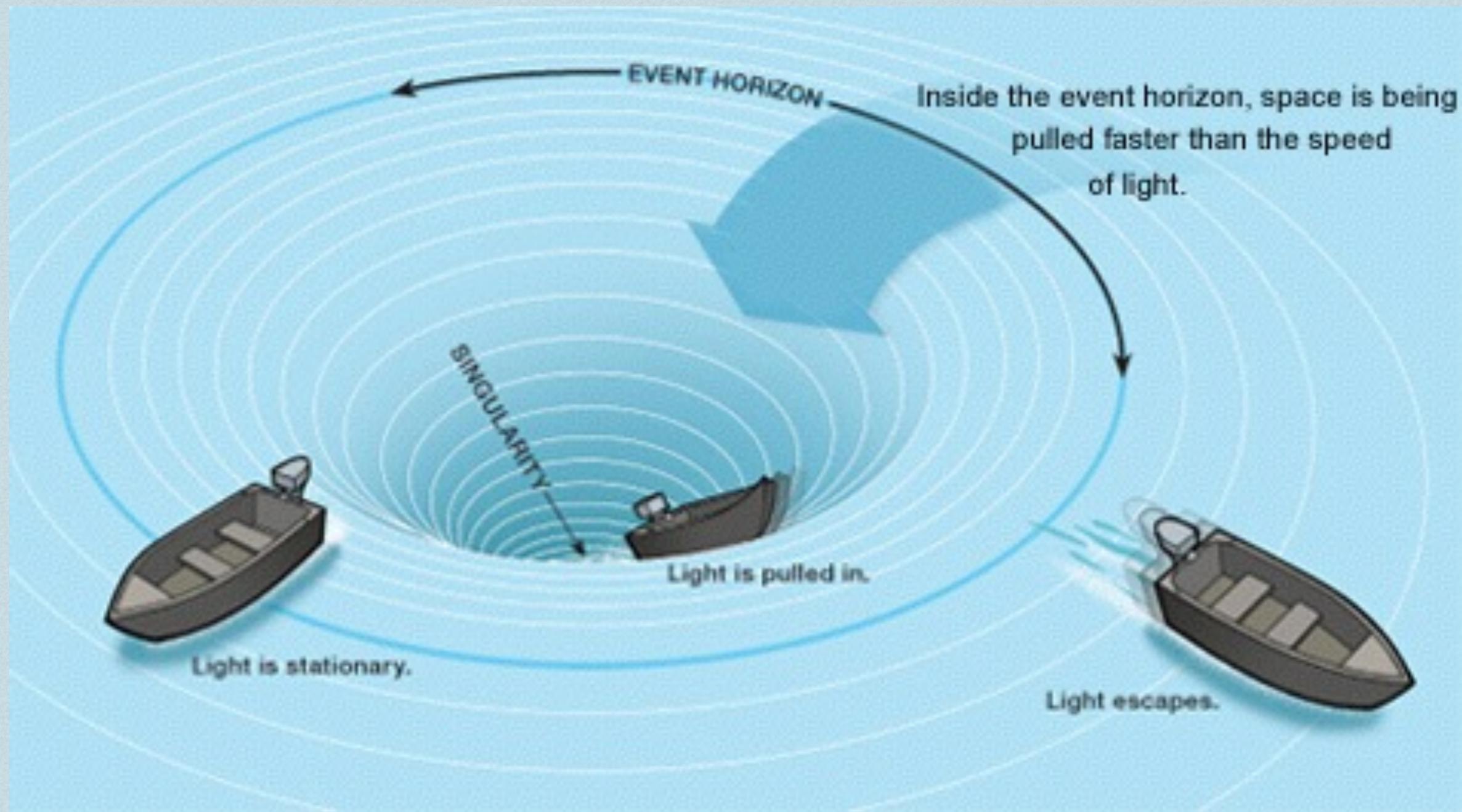


# VIDA INTERIOR



# VIDA INTERIOR

...es como un  
Big Bang  
al revés



EVENT HORIZON

Inside the event horizon, space is being pulled faster than the speed of light.

SINGULARITY

Light is stationary.

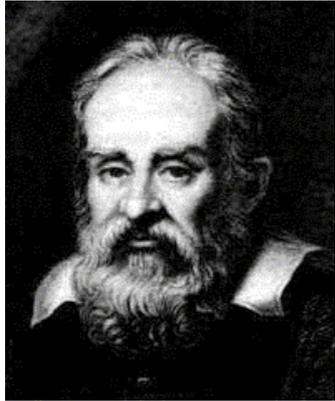
Light is pulled in.

Light escapes.



**Maelstrom!!!**

# Velocidad de escape



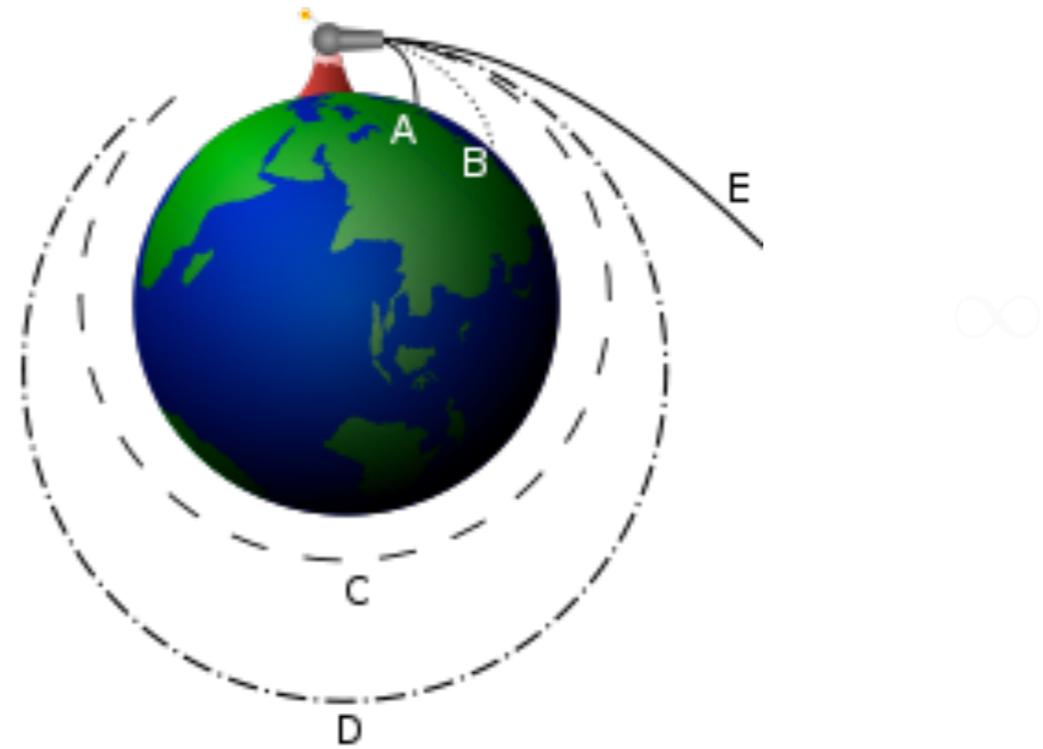
Galileo



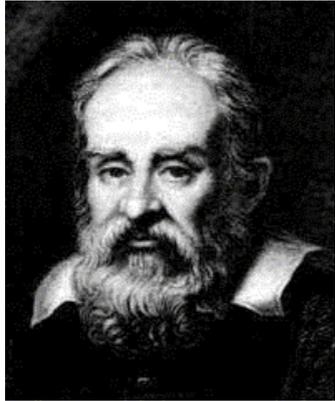
Kepler



Newton



# Velocidad de escape



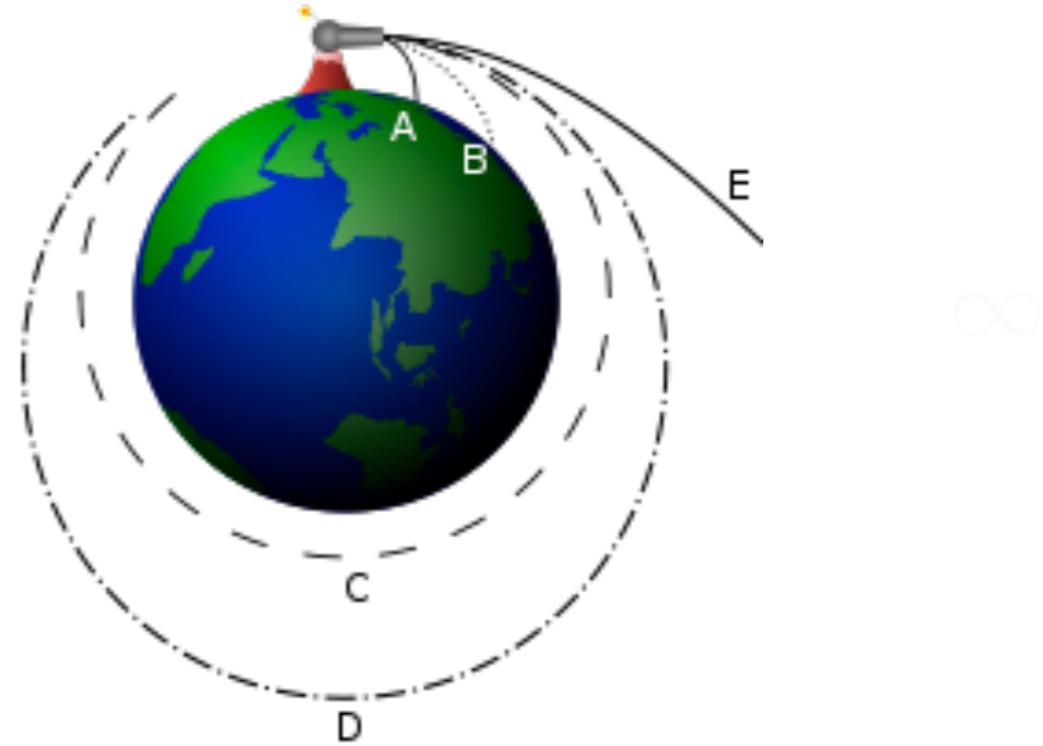
Galileo



Kepler

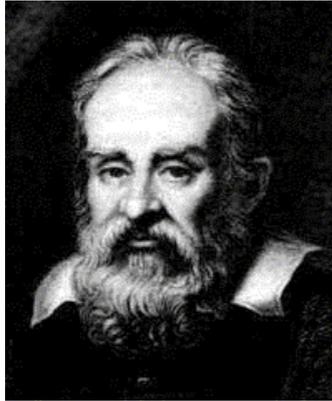


Newton



$$V_{\text{escape}} = \sqrt{\frac{2GM}{R}}$$

# Velocidad de escape



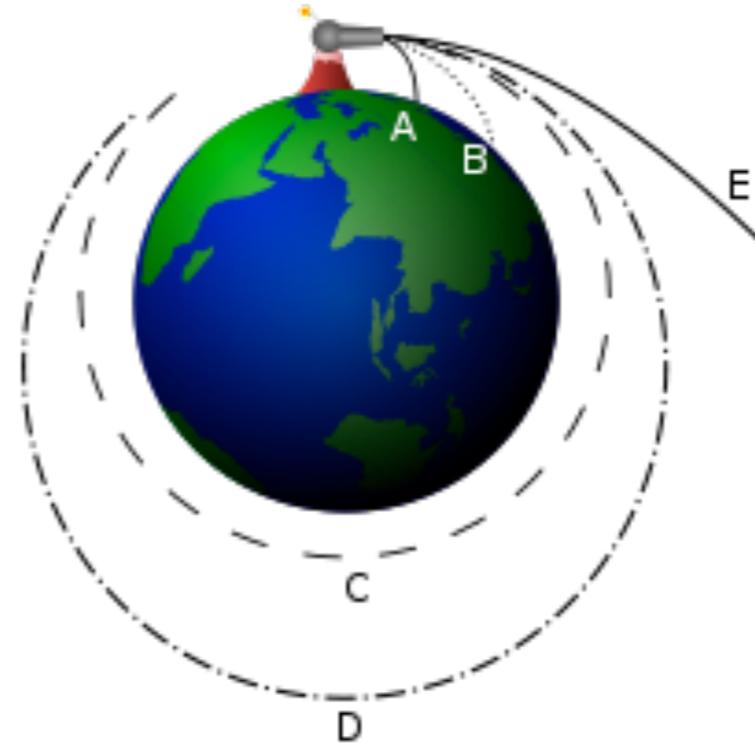
Galileo



Kepler



Newton



$$V_{\text{escape}} = \sqrt{\frac{2GM}{R}}$$

$$V_{\text{escape}} (\text{🌍}) \sim 11 \text{ Km/s}$$

¿Qué tamaño debería tener la Tierra para que su velocidad de escape fuera igual a la velocidad de la luz?

# RADIO DE SCHWARZSCHILD



velocidad de escape = velocidad de la luz

$$R_s = \frac{2GM}{c^2}$$

# RADIO DE SCHWARZSCHILD

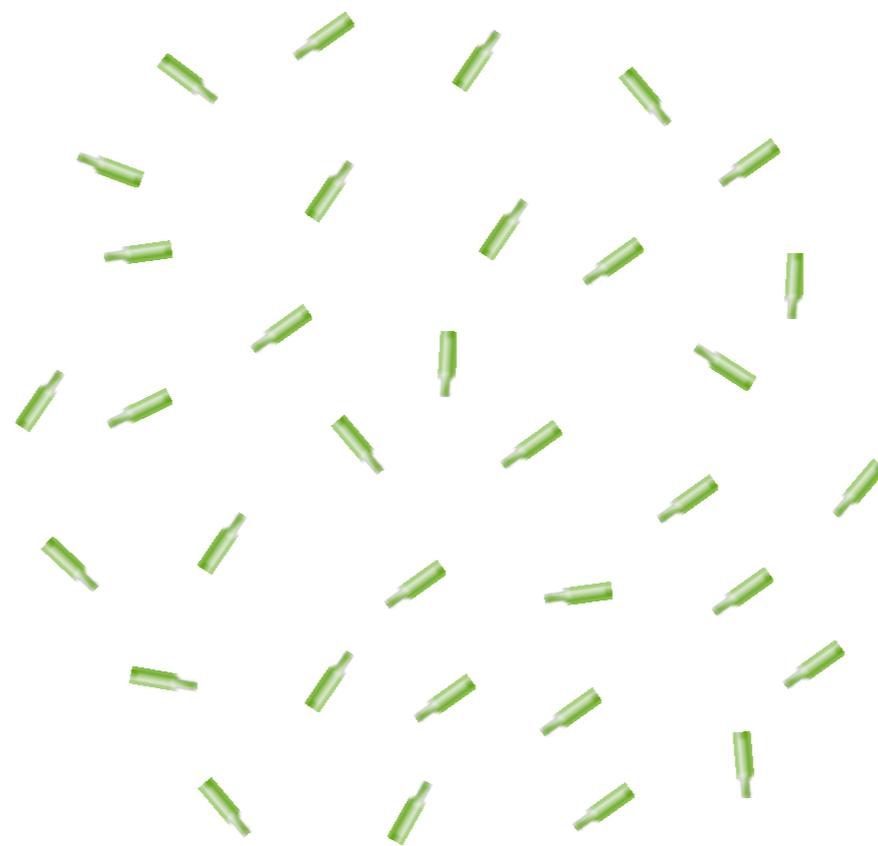


velocidad de escape = velocidad de la luz

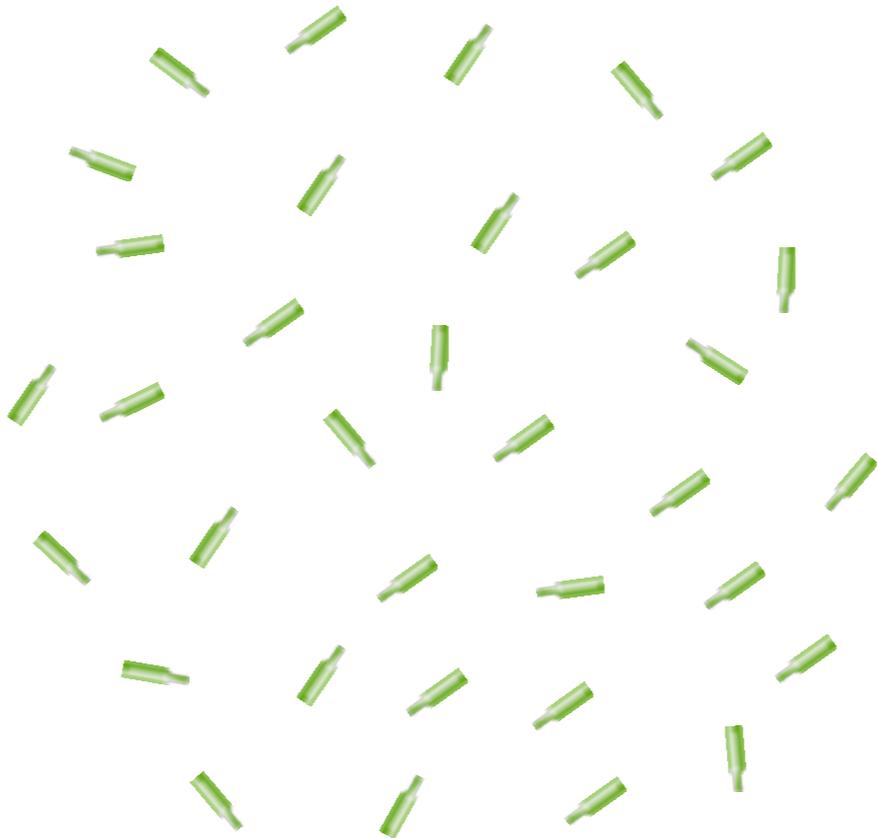
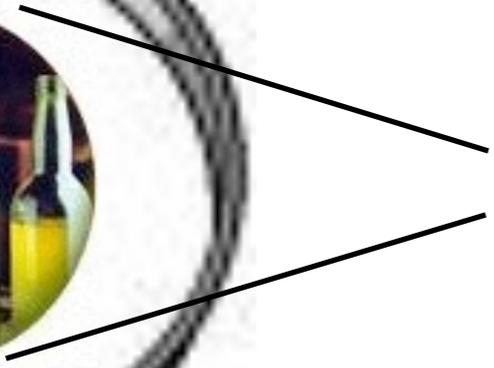
$$R_s = \frac{2GM}{c^2}$$

$$R_s(\text{🌍}) \sim 3 \text{ cm}$$

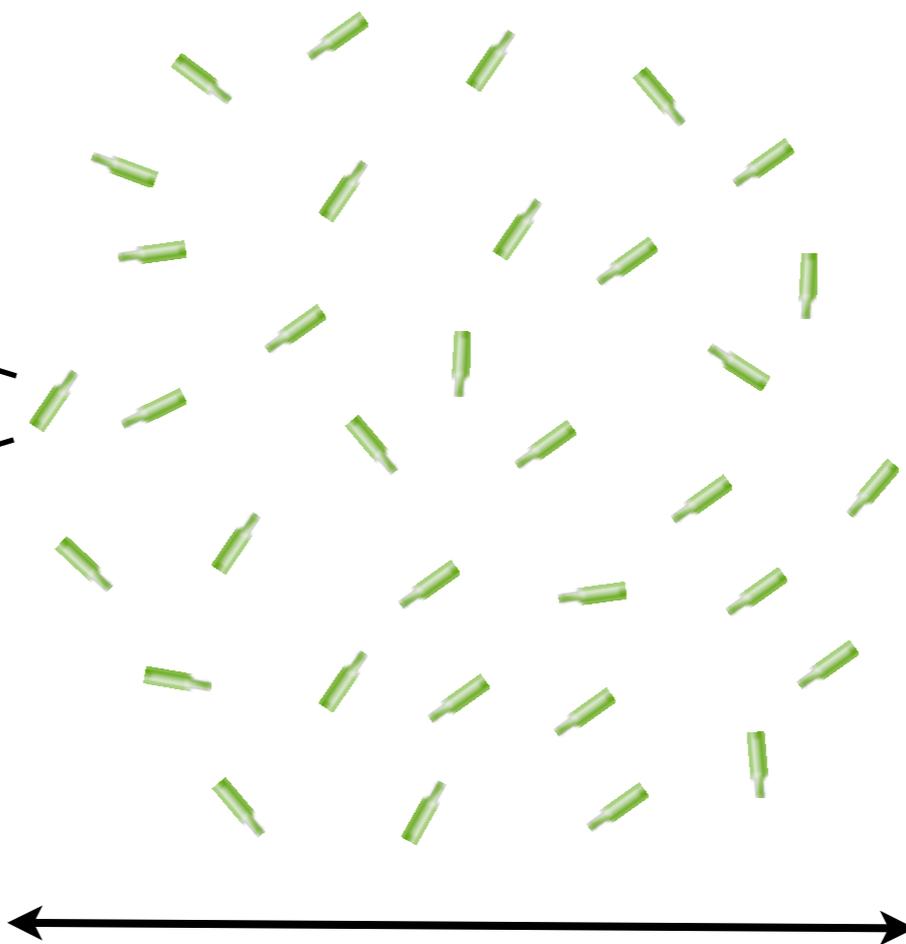
$$R_s(\text{☀️}) \sim 3 \text{ Km}$$



10 botellas/m<sup>3</sup>



10 botellas/m<sup>3</sup>



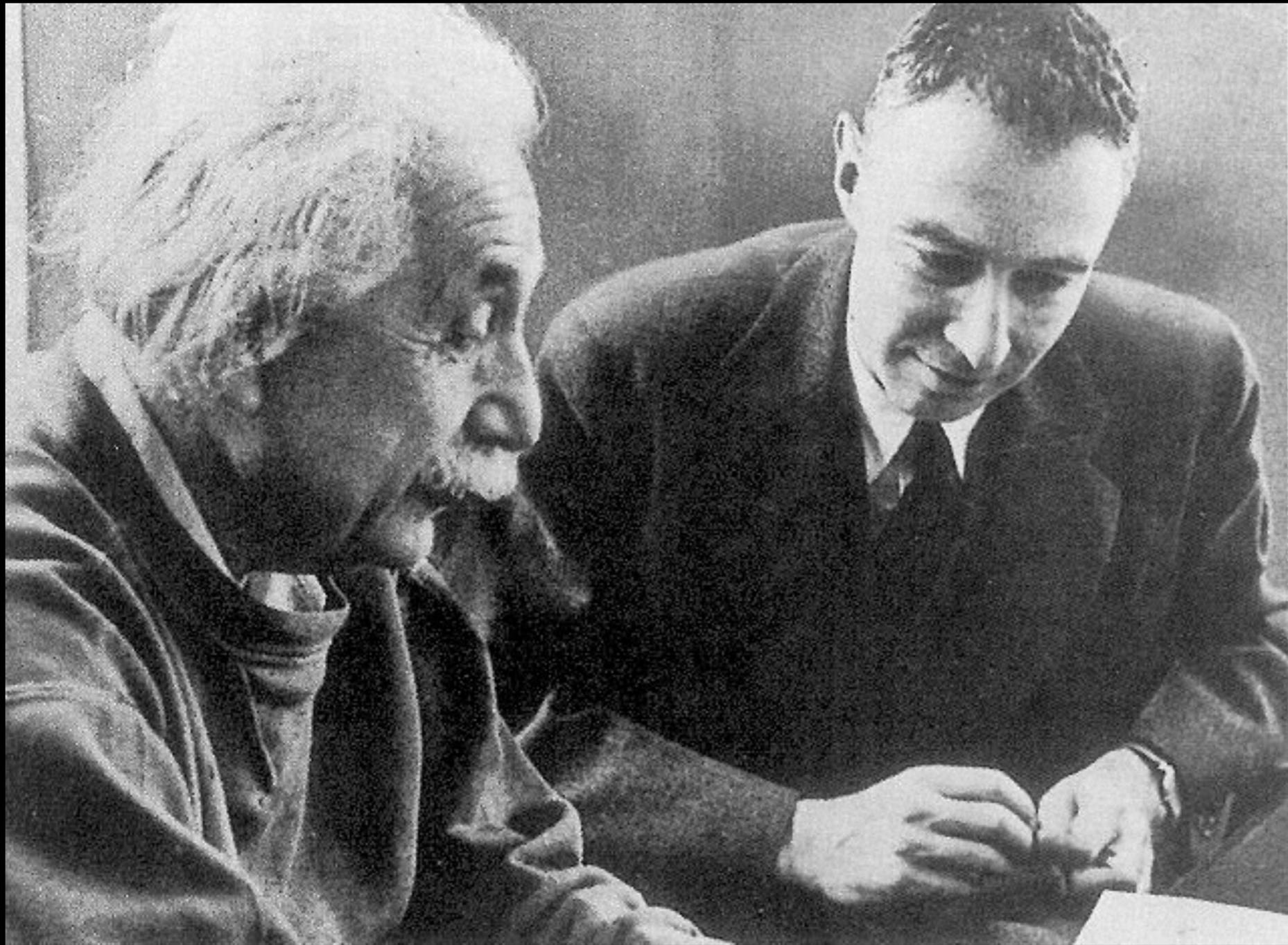
10 botellas/m<sup>3</sup>

órbita de Urano ~ 

$$M_{\text{botellas}} \sim 10^9 M_{\text{Sol}}$$



¡No se precisan situaciones extremas!





CLASSICAL

QUANTUM

$t$

$x$

A B

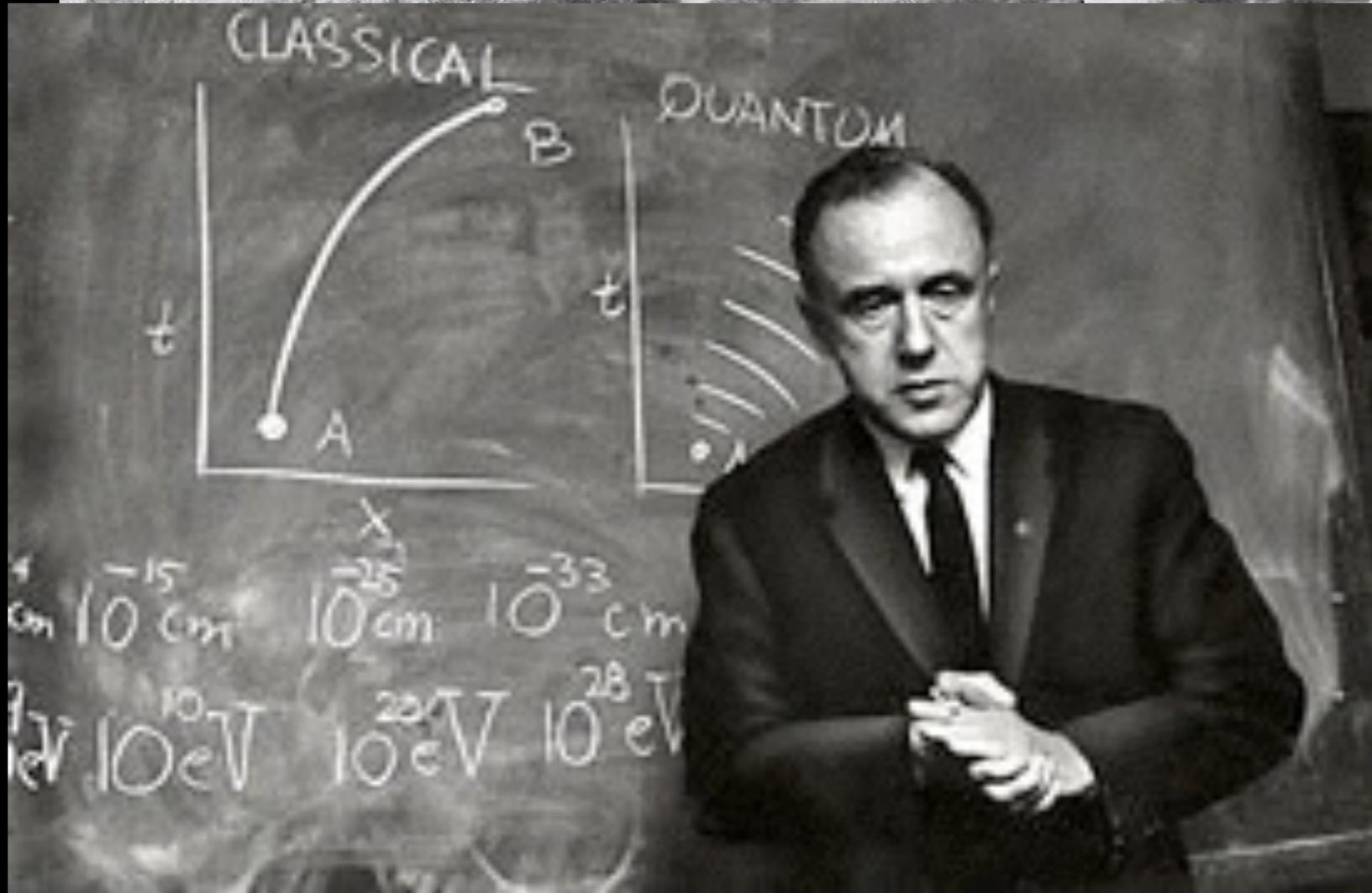
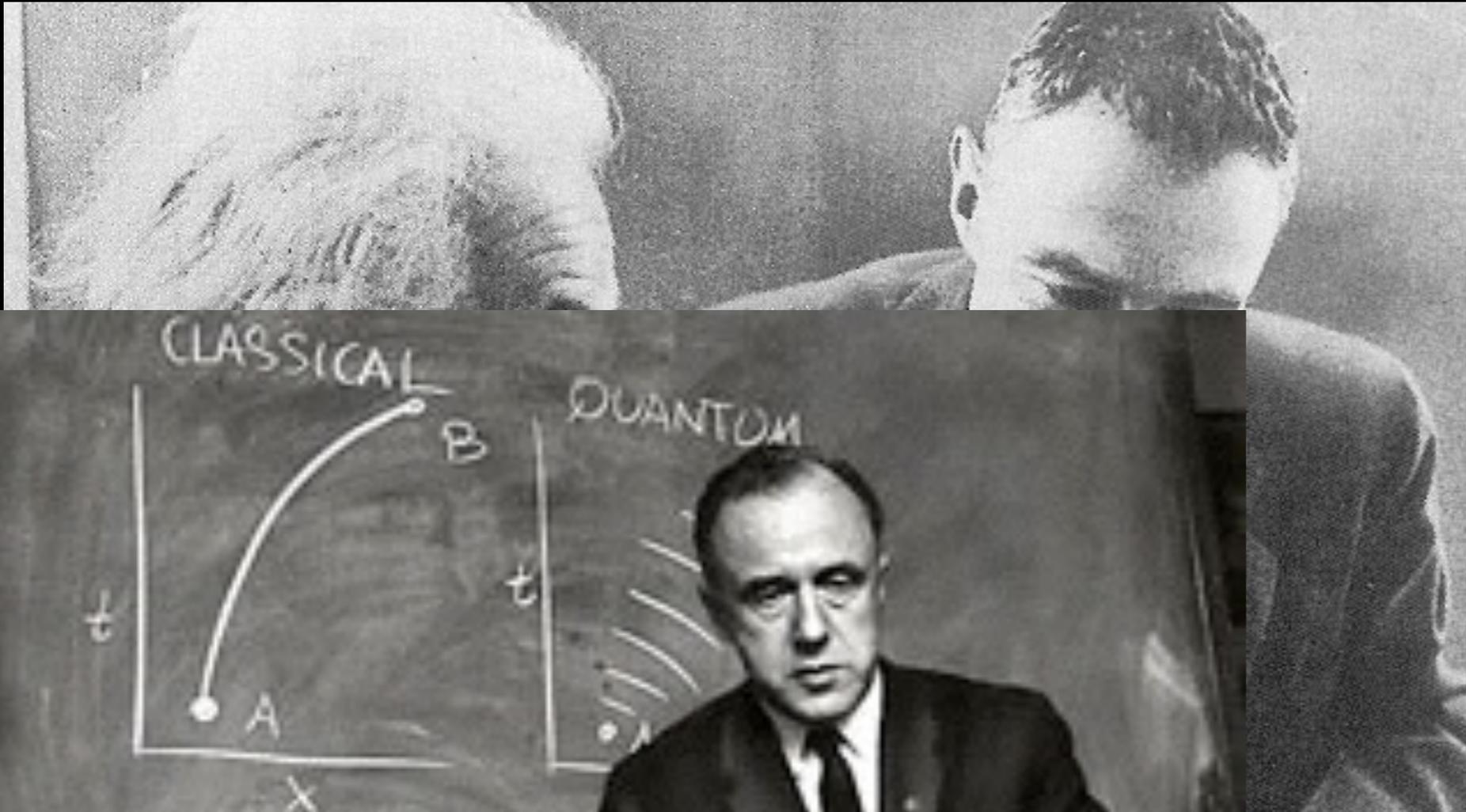
$10^{-15}$   $10^{-25}$   $10^{-33}$  cm

$10^{10}$   $10^{20}$   $10^{28}$  eV

10 eV 10 eV 10 eV

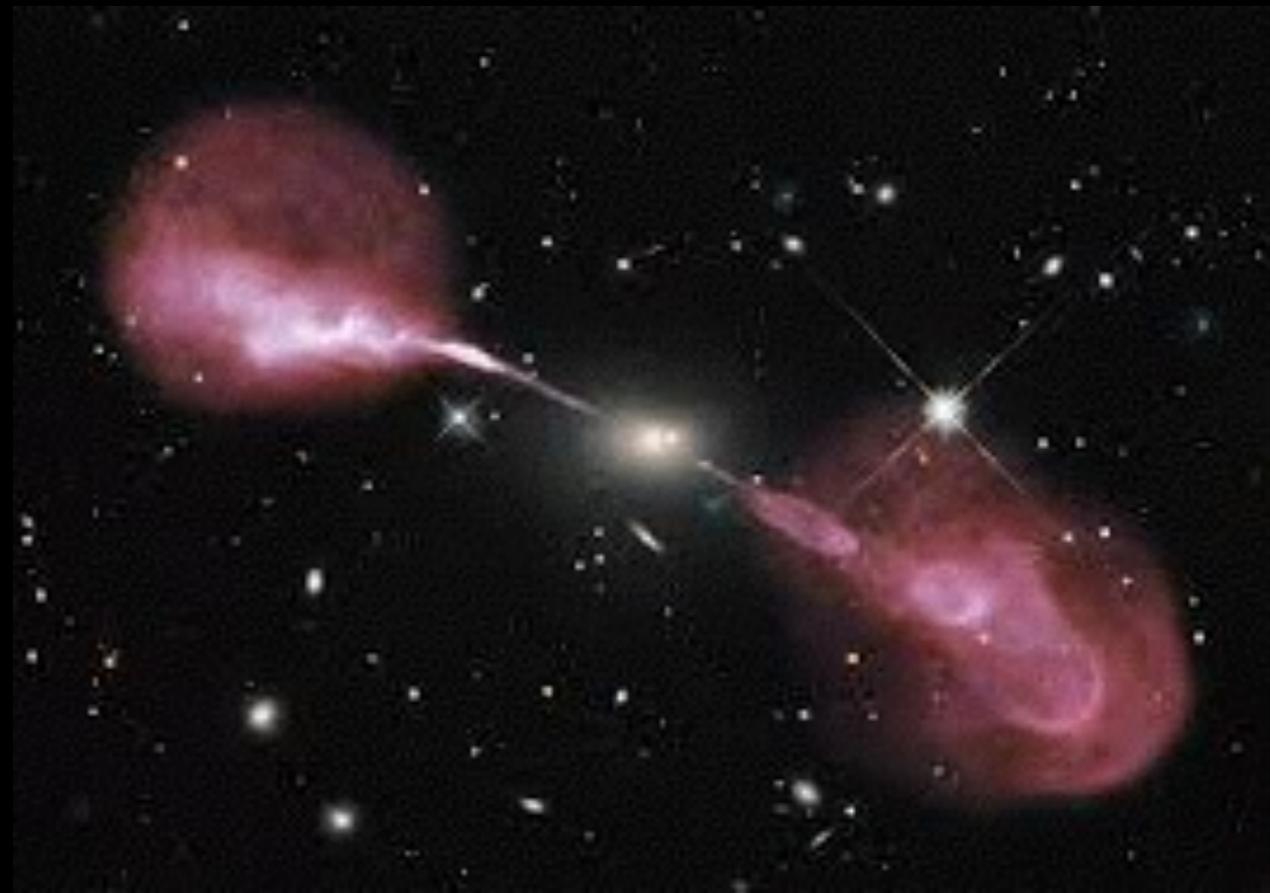
Albert Einstein

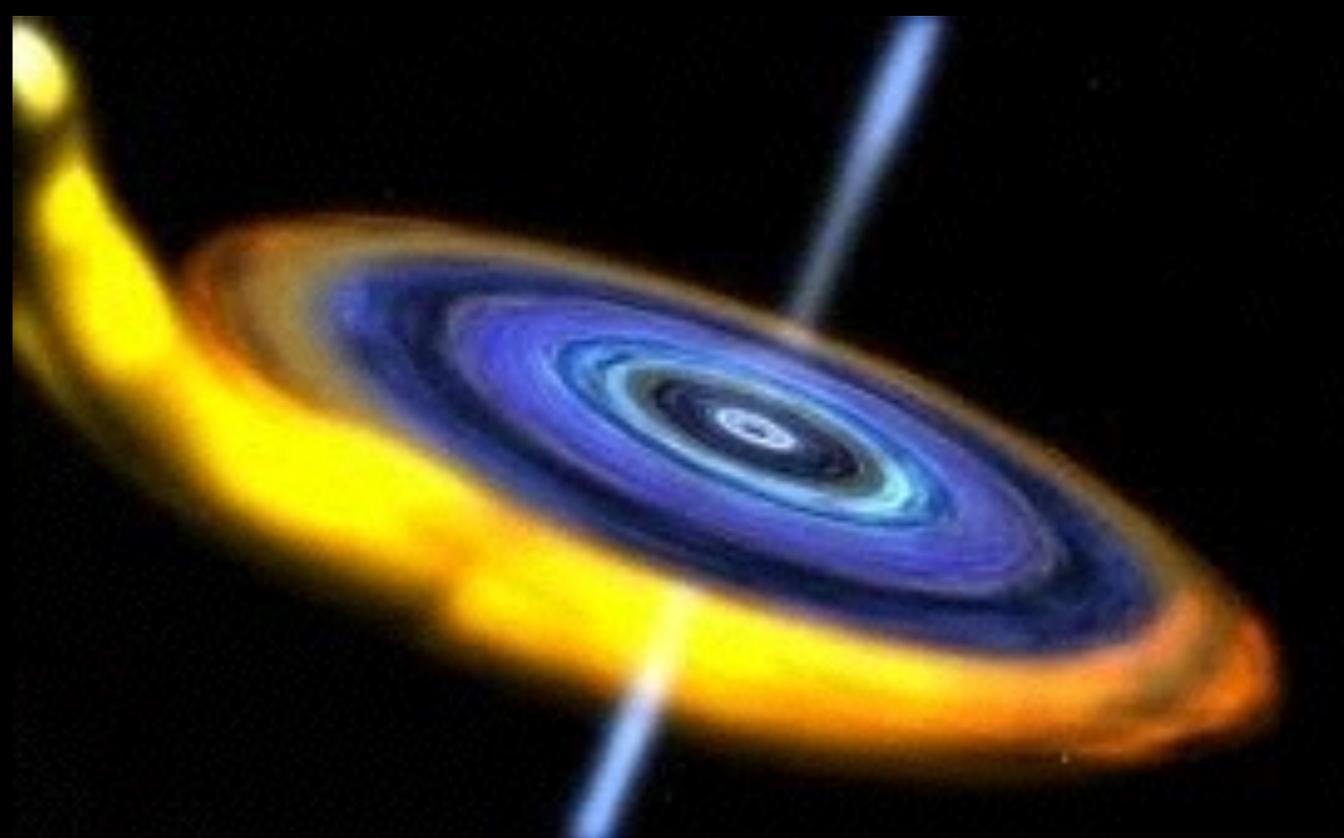
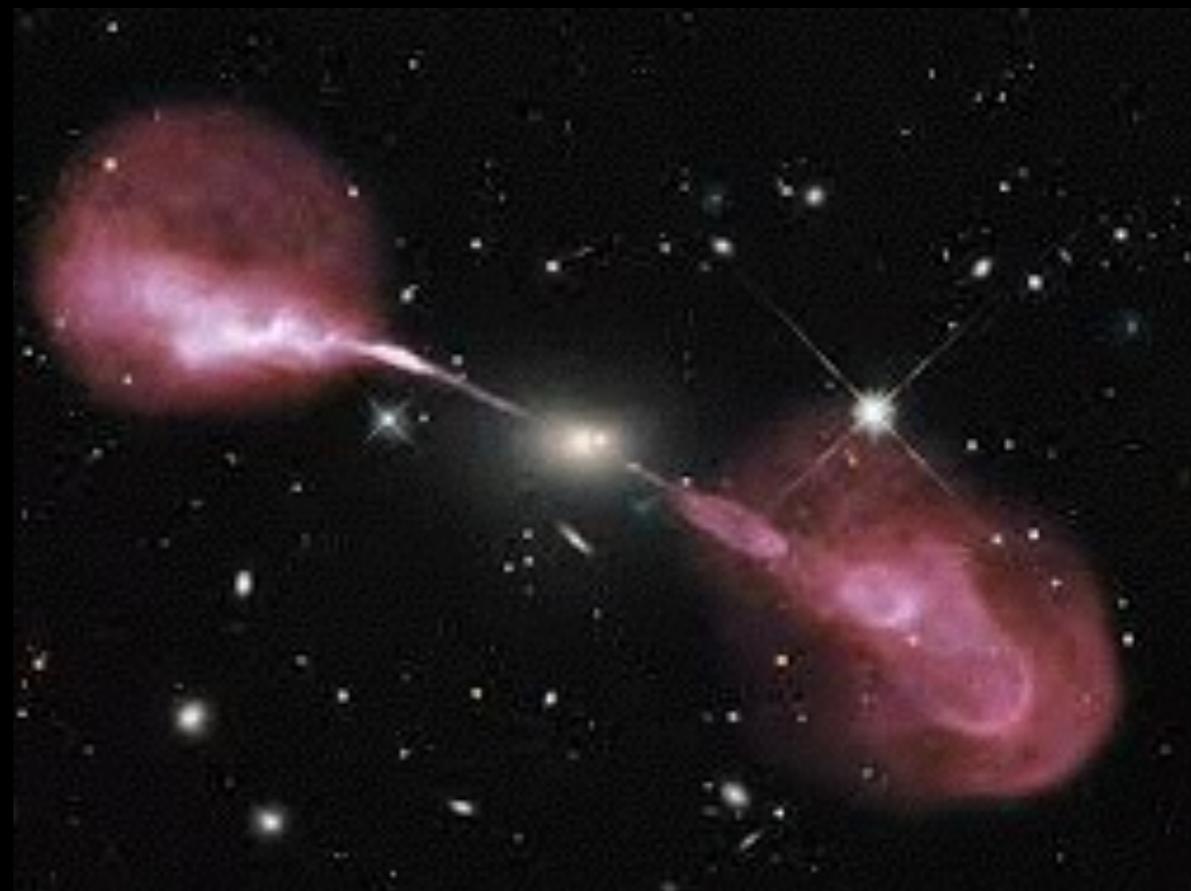
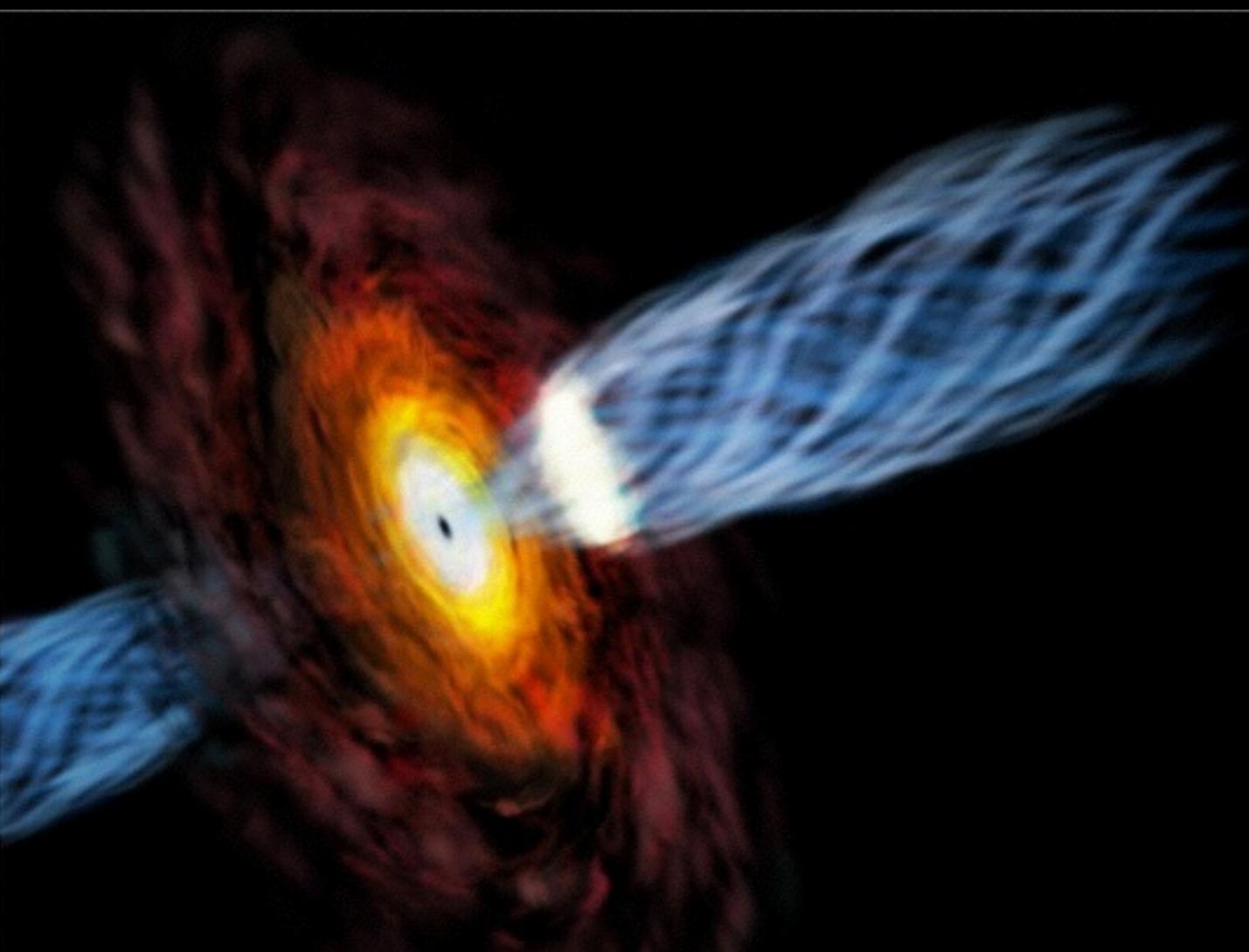


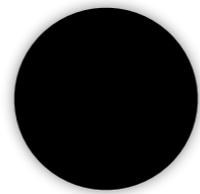


1967

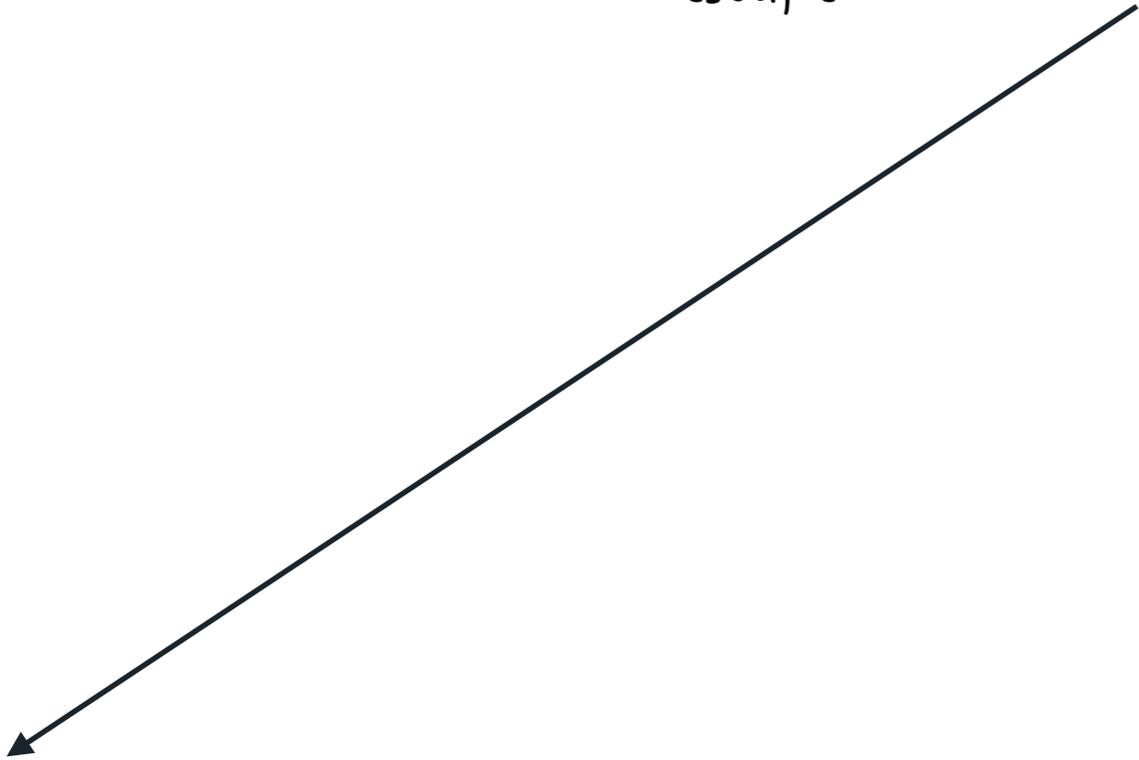
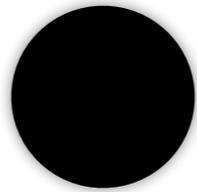


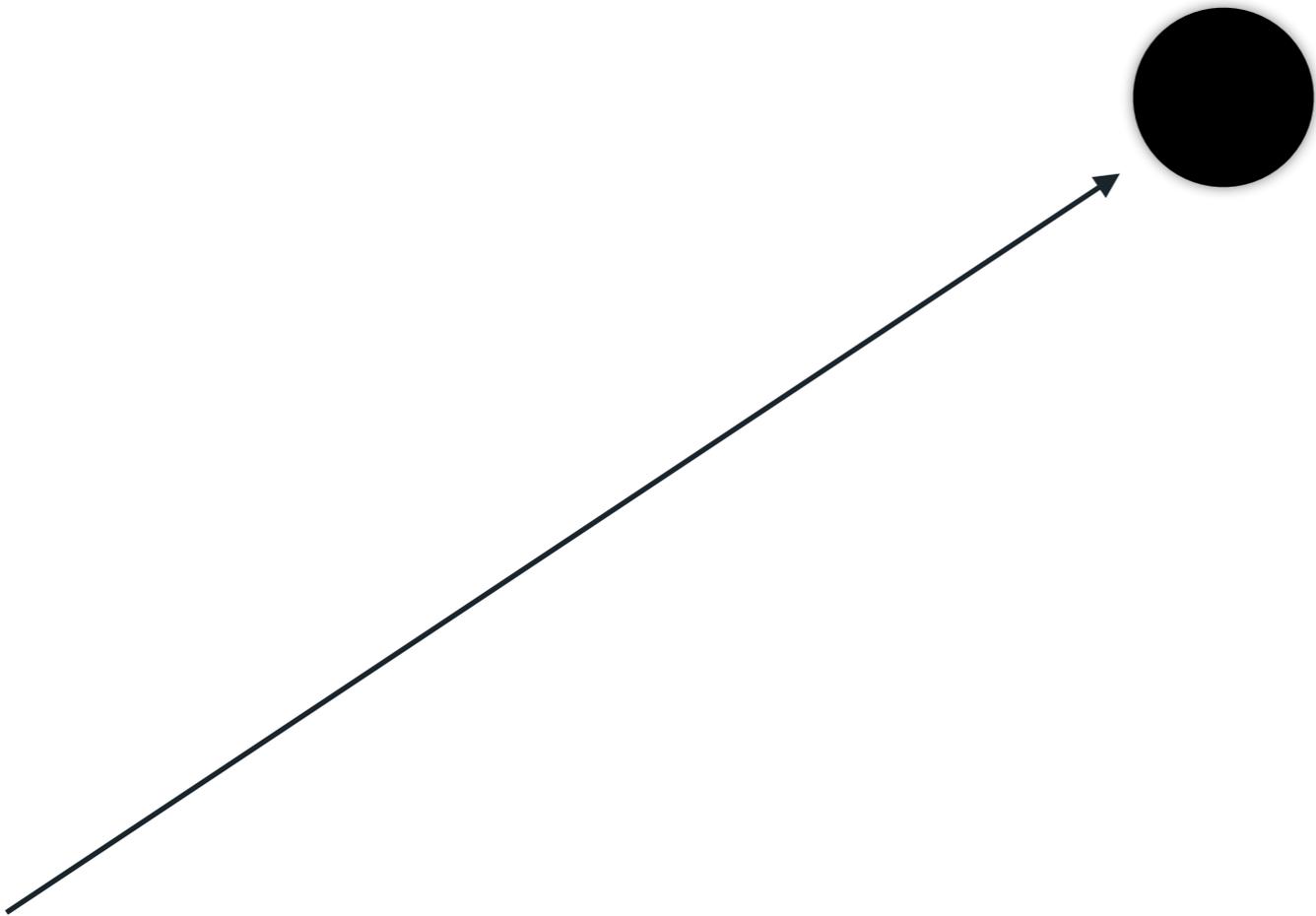




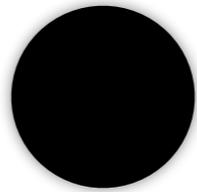


$v_{\text{escape}} \sim c$

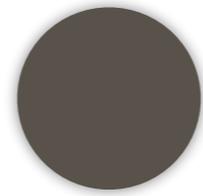




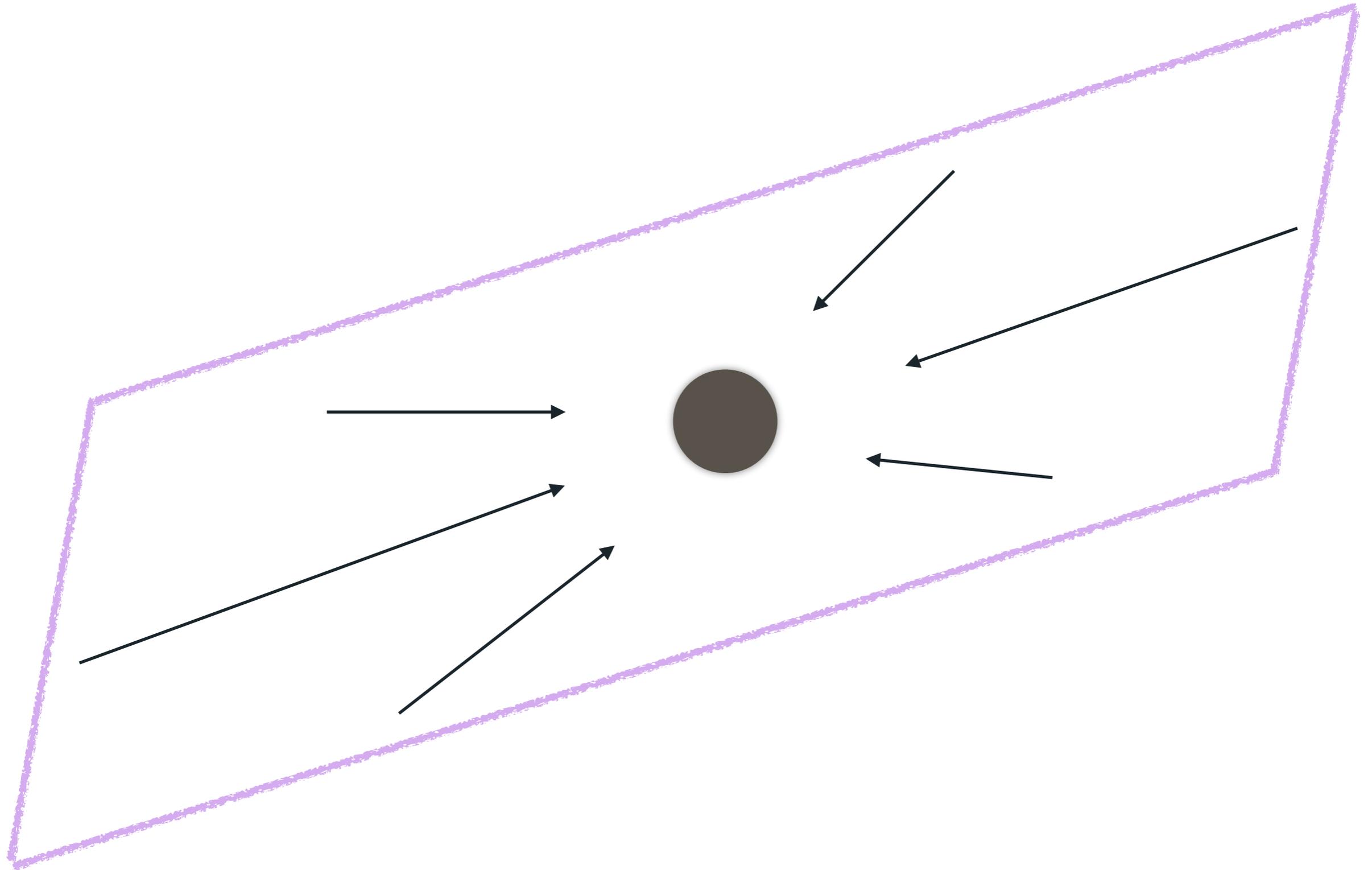
$V_{\text{impacto}} \sim c$



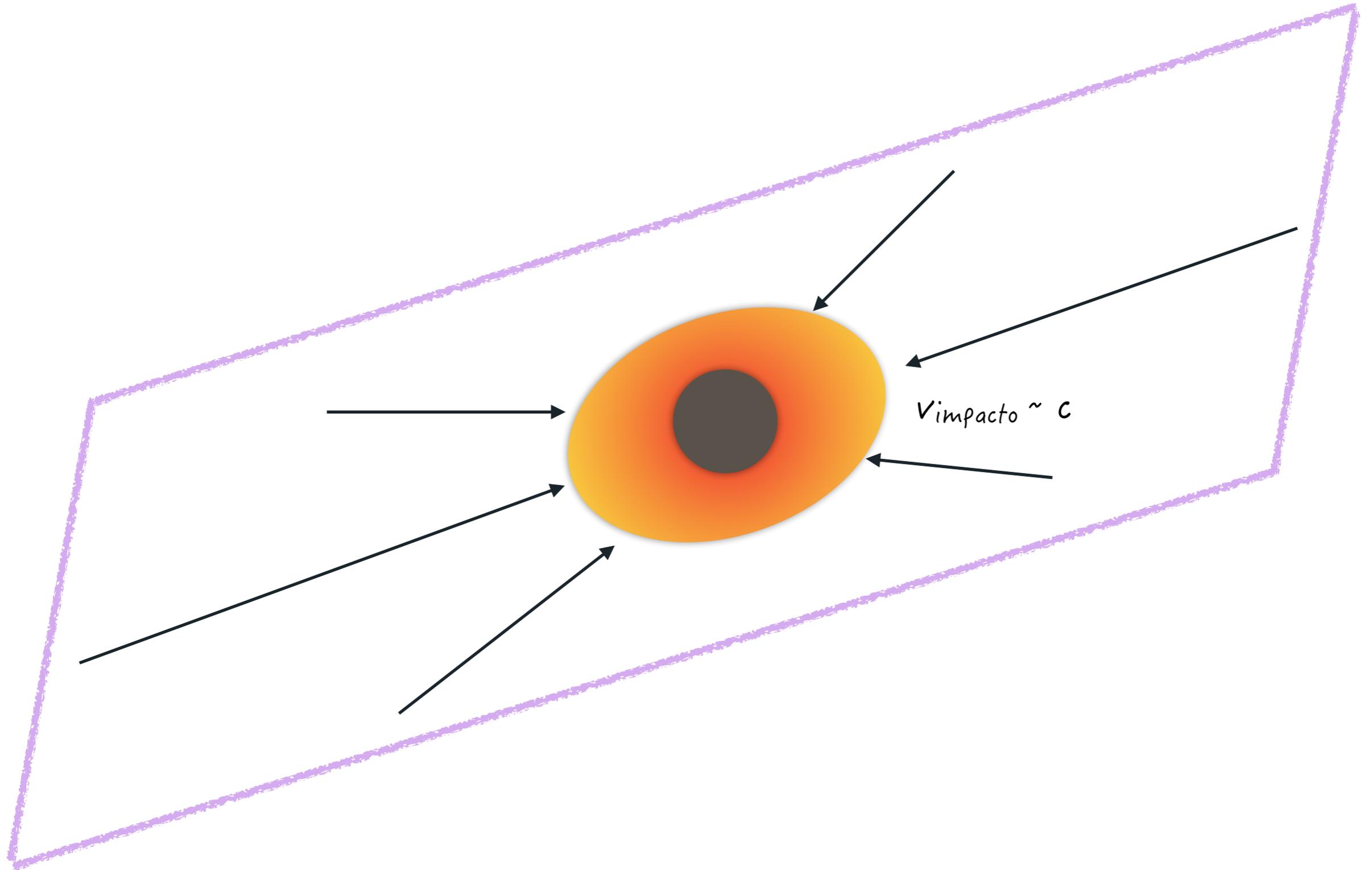
# MOTORES GRAVITACIONALES



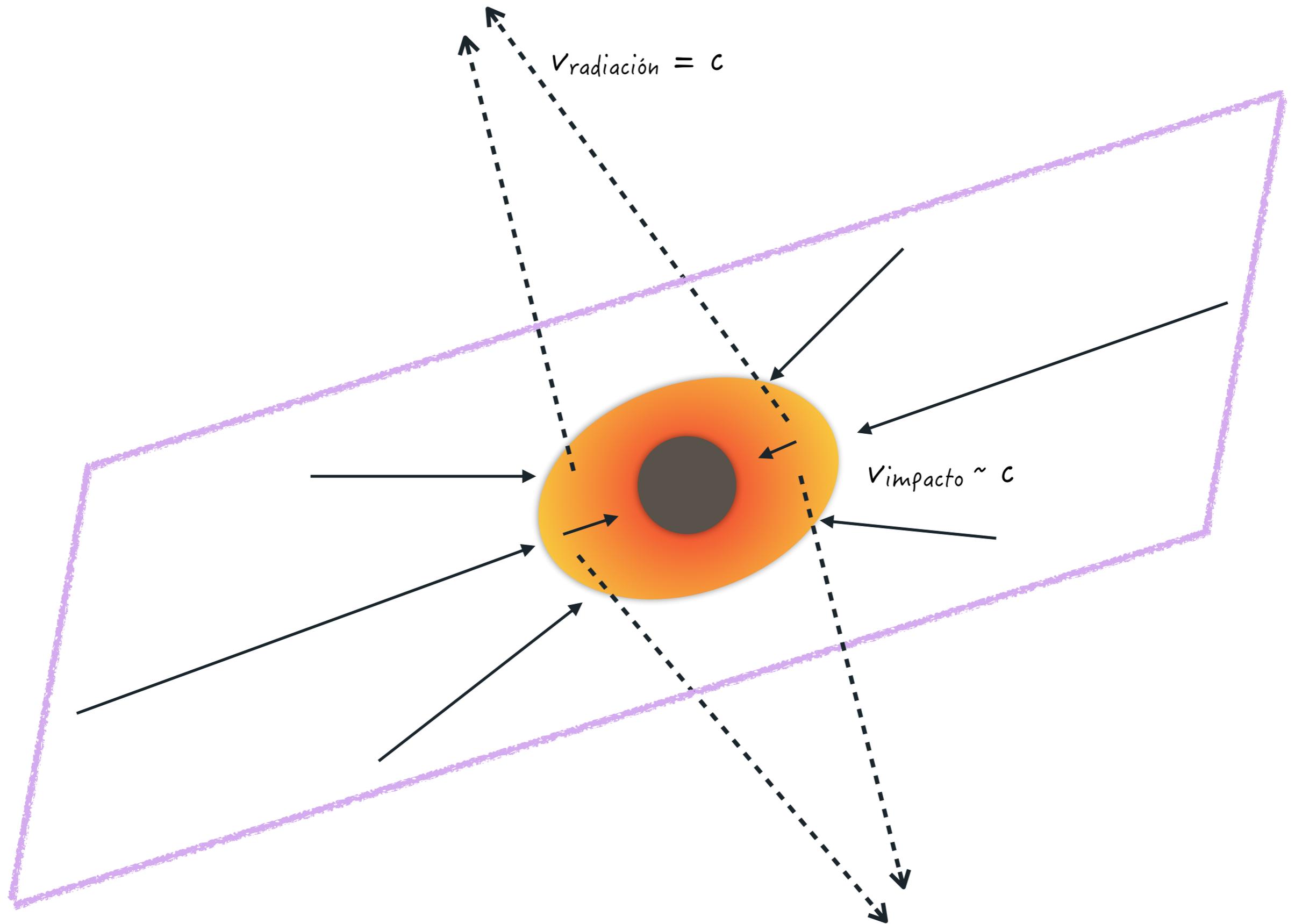
# MOTORES GRAVITACIONALES

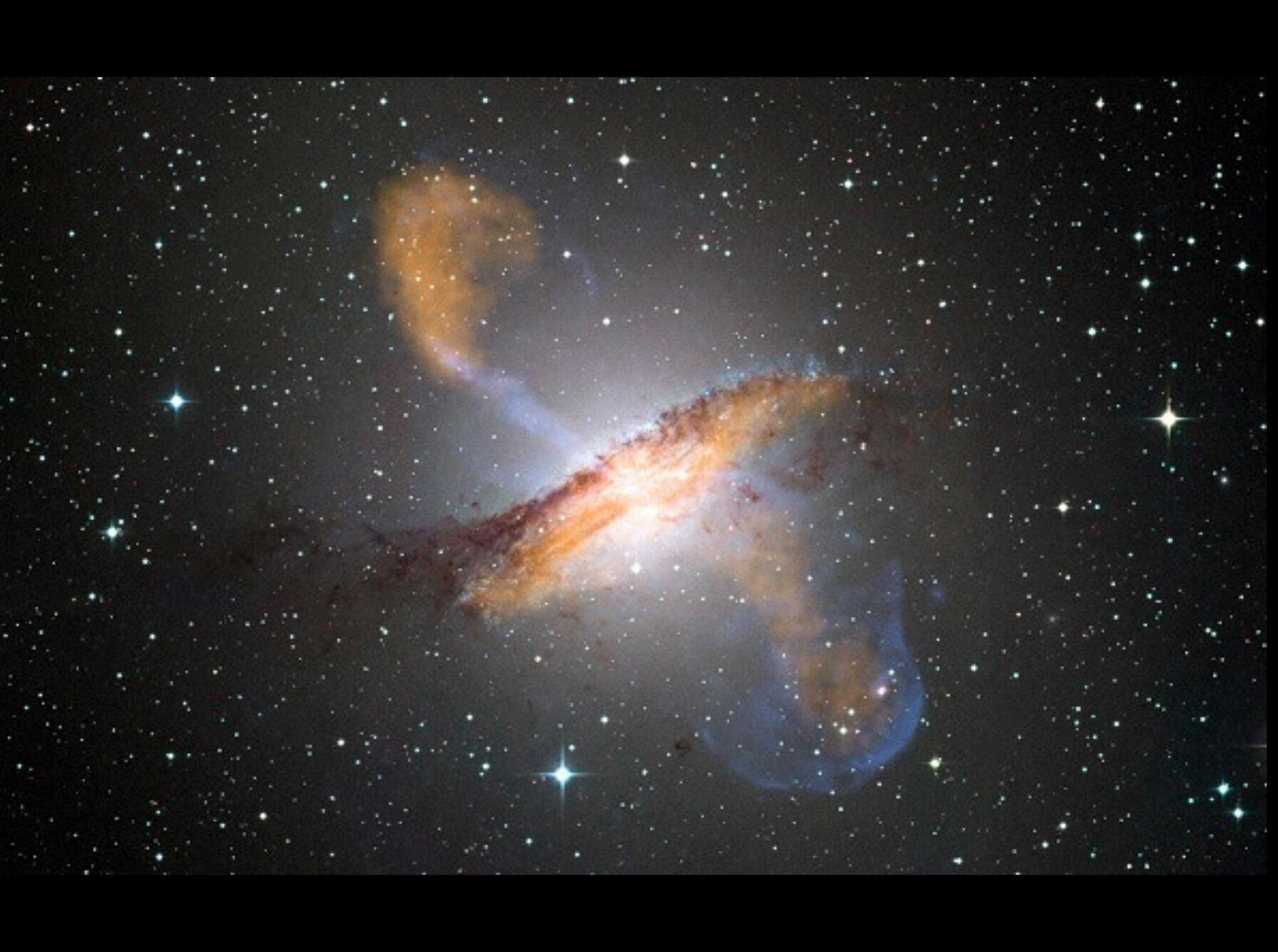


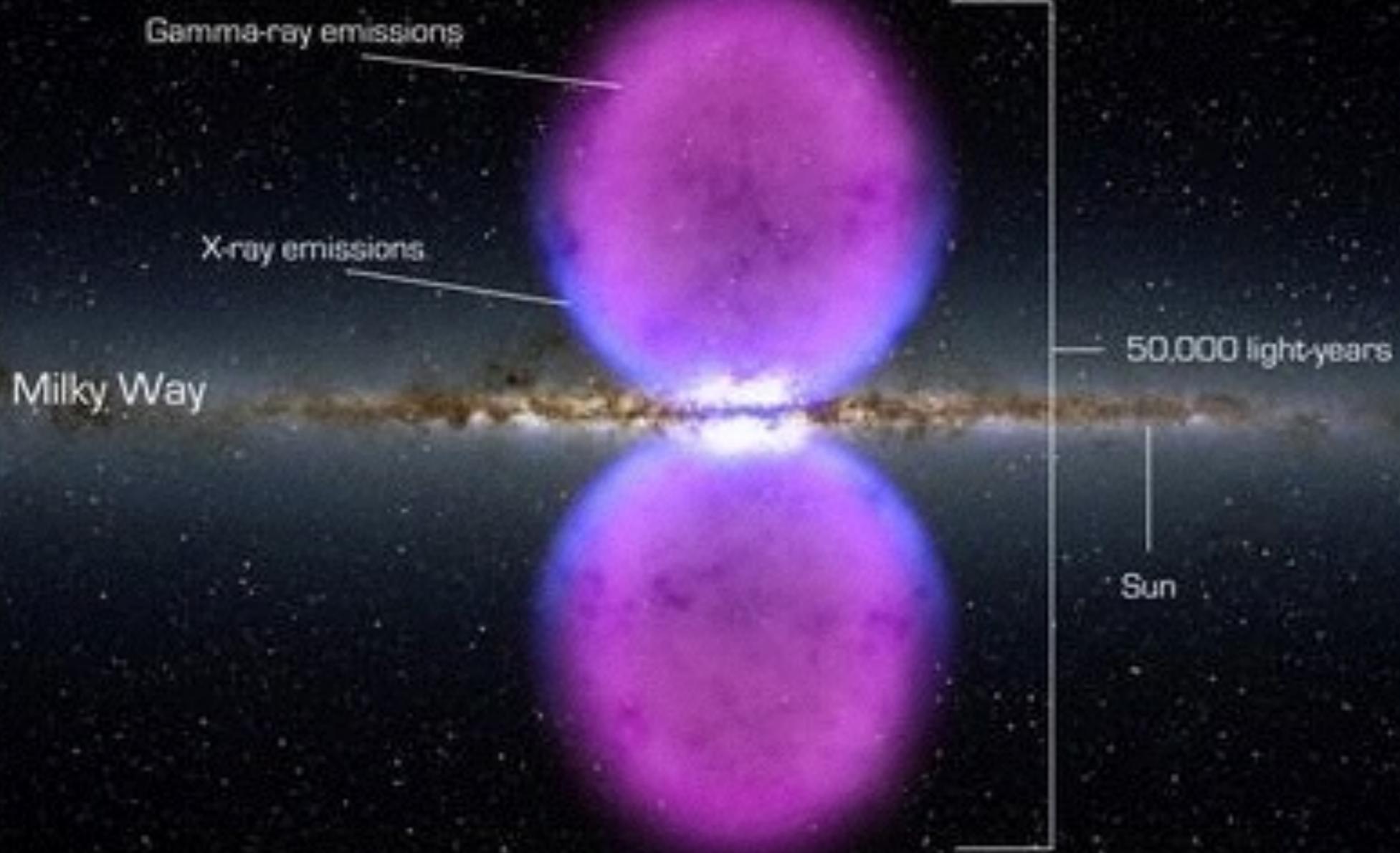
# MOTORES GRAVITACIONALES



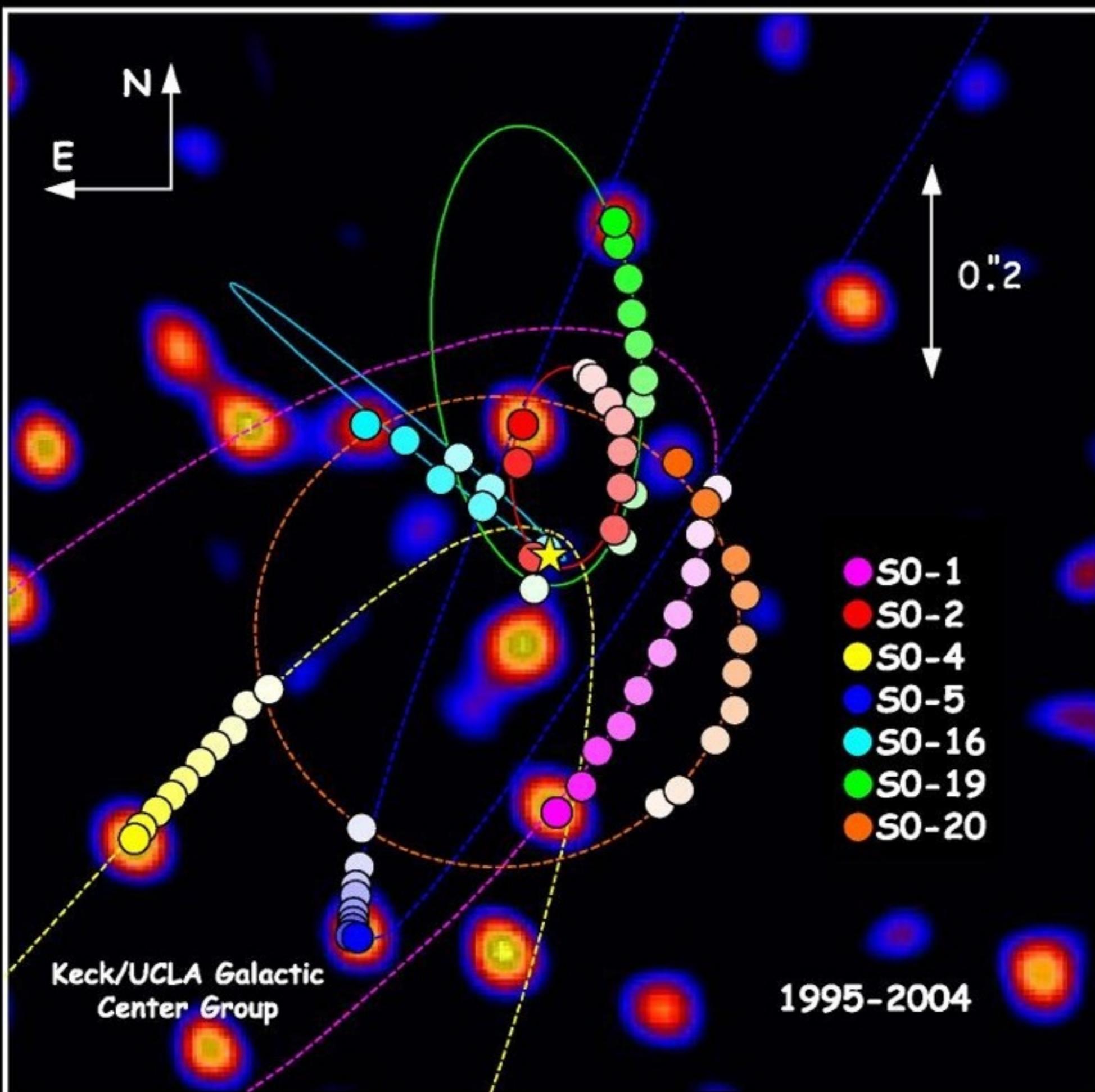
# MOTORES GRAVITACIONALES







$10^6 M_{\text{sol}}$





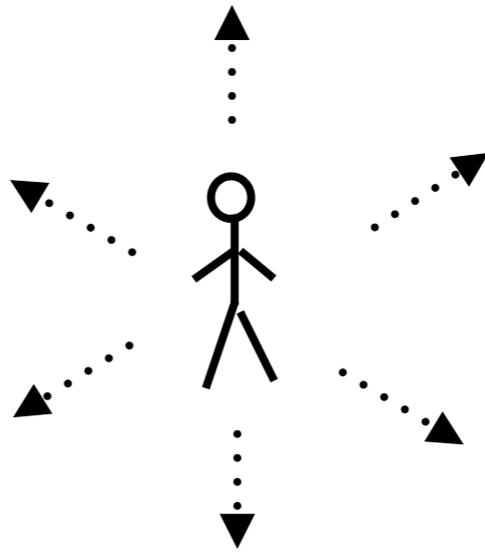
$10^9 M_{\text{sol}}$



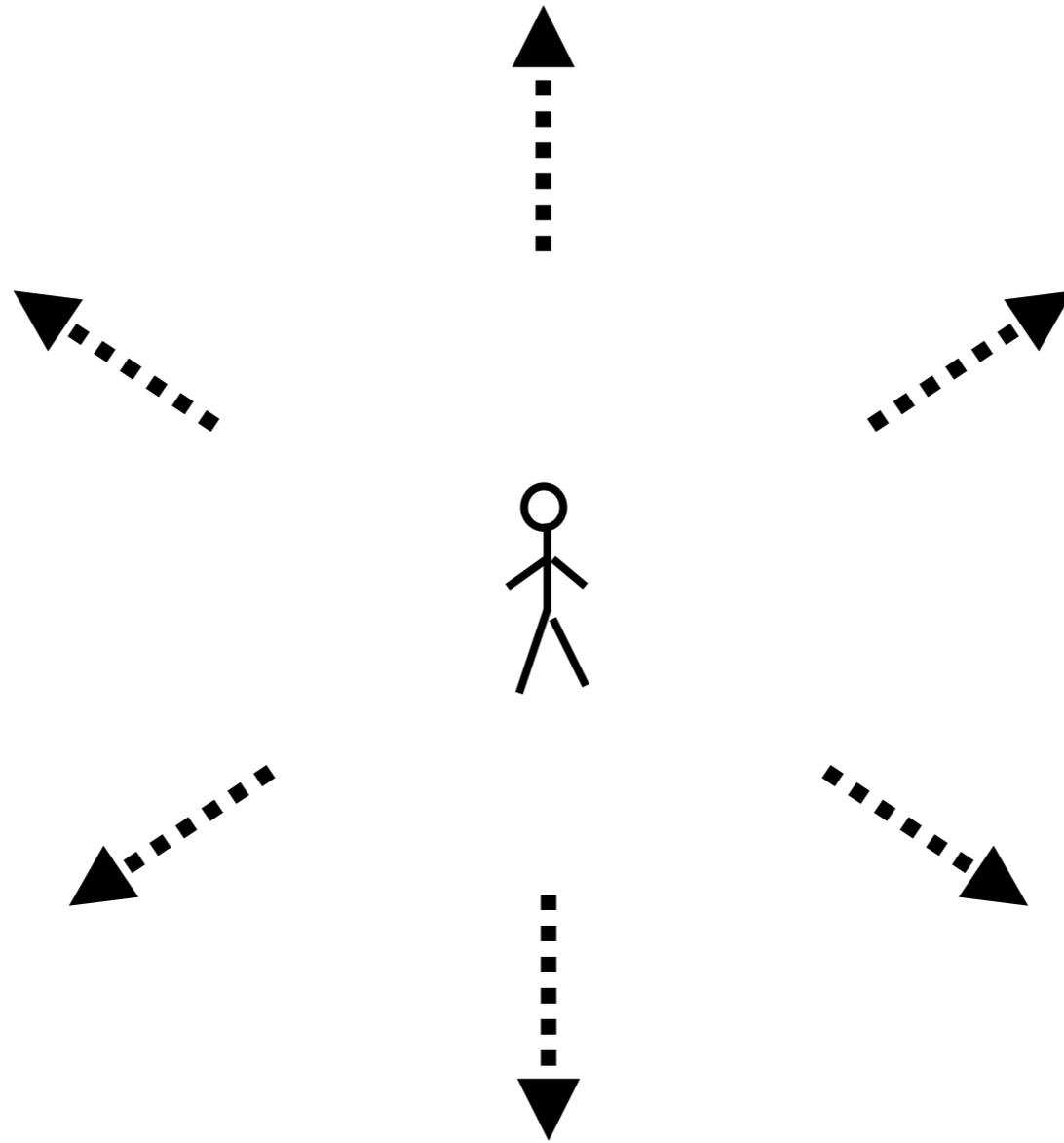
# EPILOGO

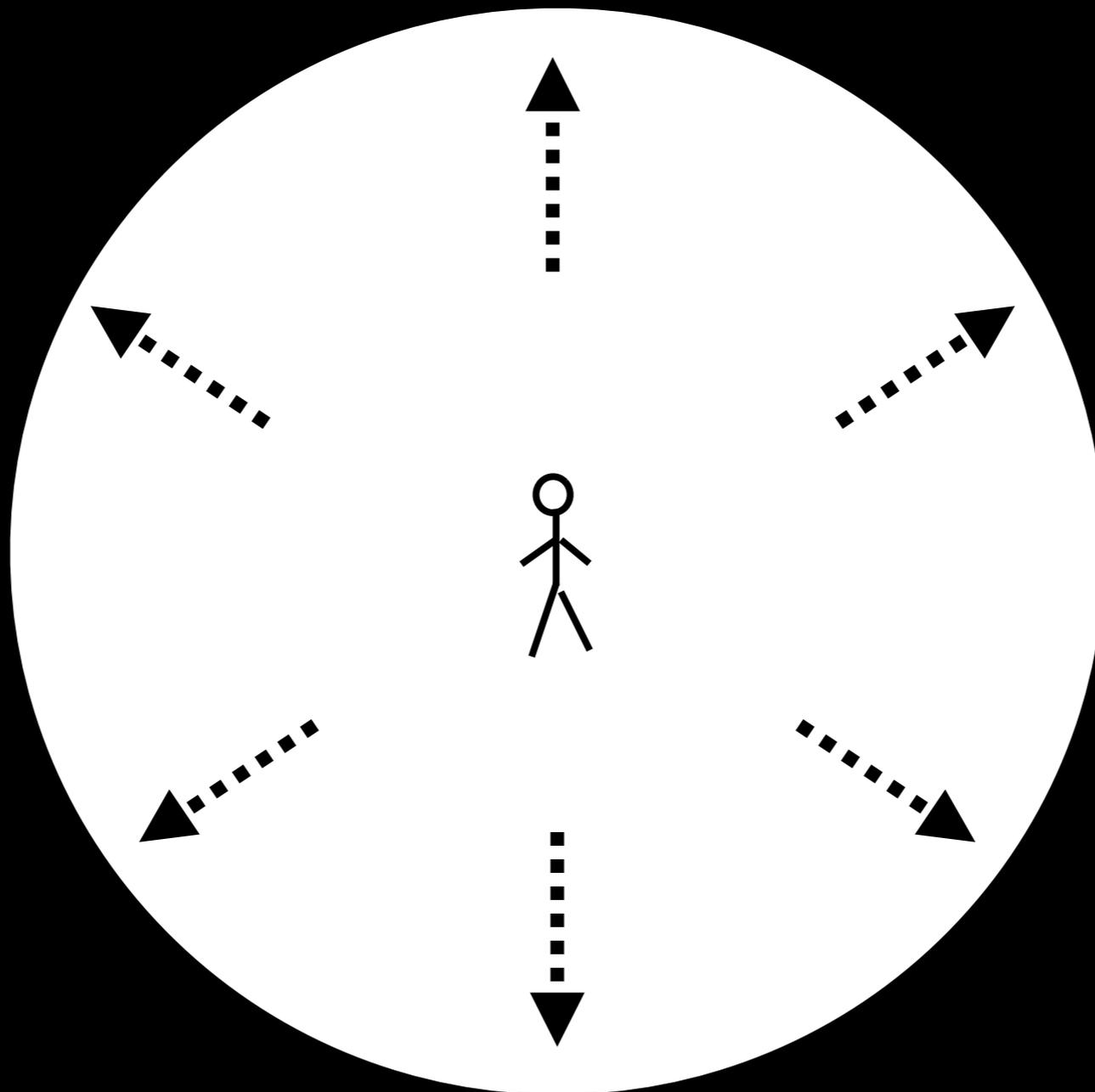


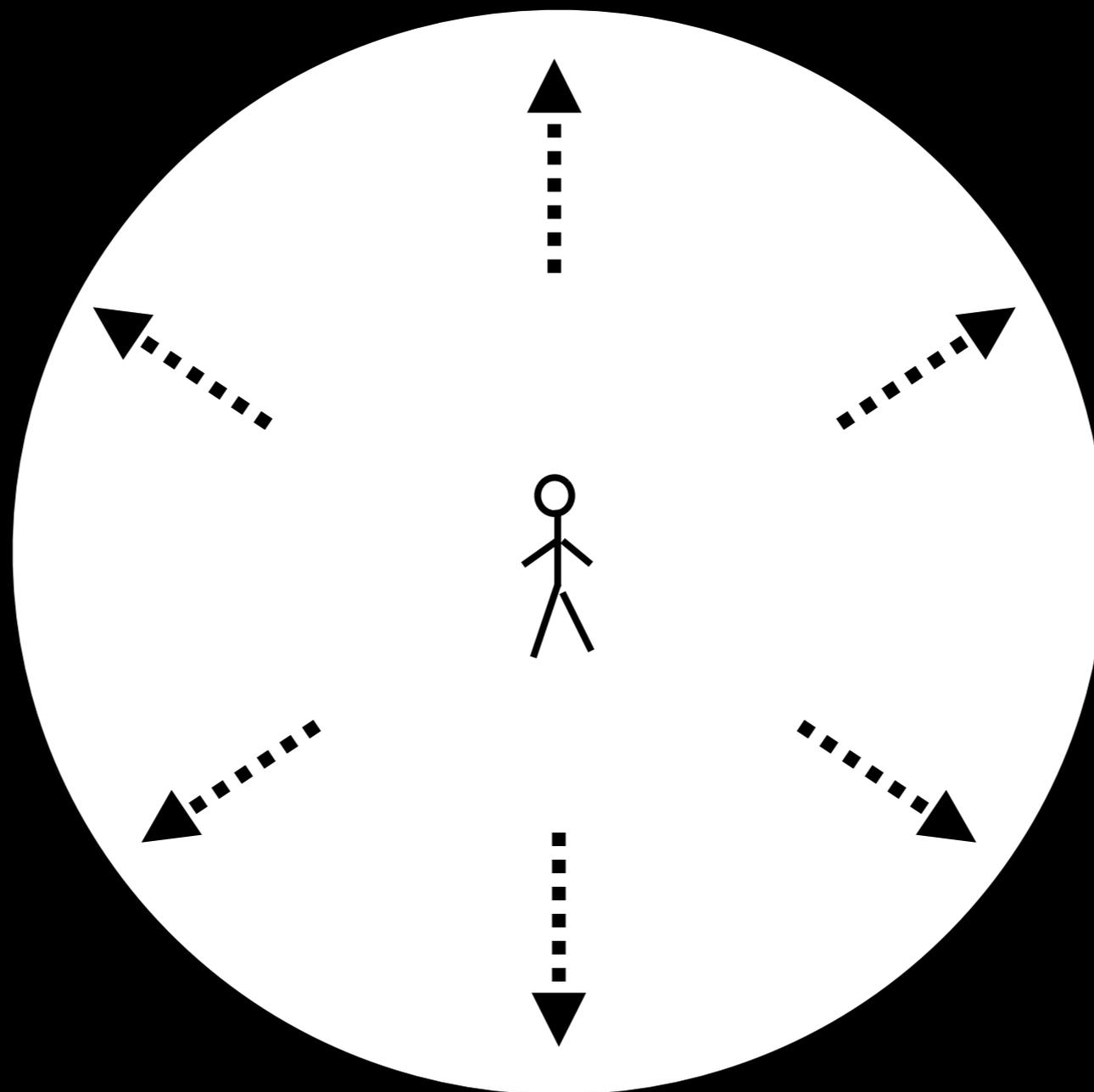
# EPILOGO



# EPILOGO







$10^{28}$  cm



¡GRACIAS!

