

**Relatividade:  
de cones de luz às ondas  
gravitacionais  
*na velocidade da luz***

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IF-UFRJ**

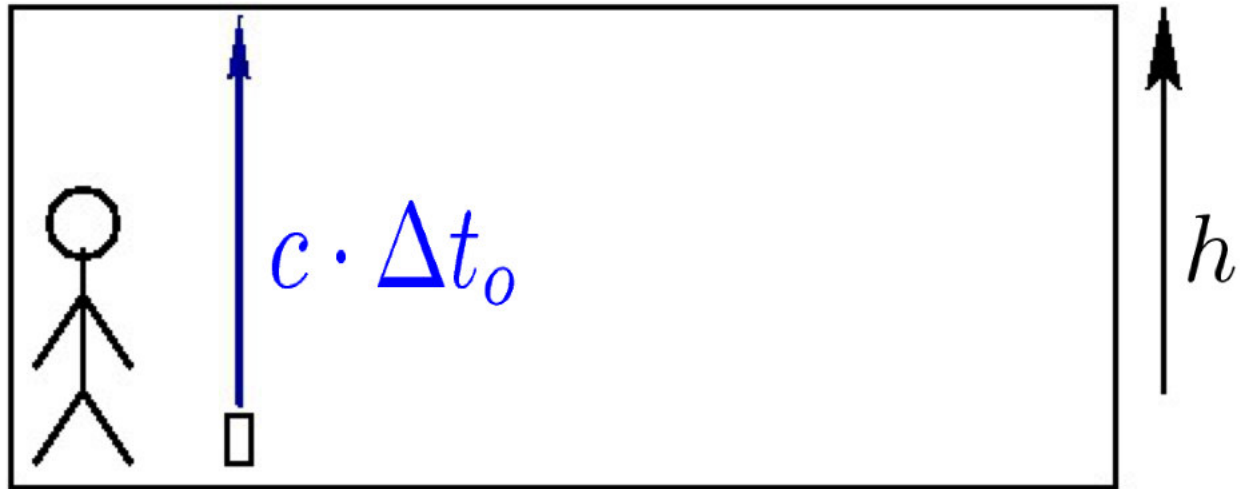
Mestrado Profissional em Ensino de Física  
IF-UFRJ  
março de 2016

# Método Científico

- **Suposição**
- **Previsão**
- **Teste Experimental**
- **Conclusão**

*c* = constante

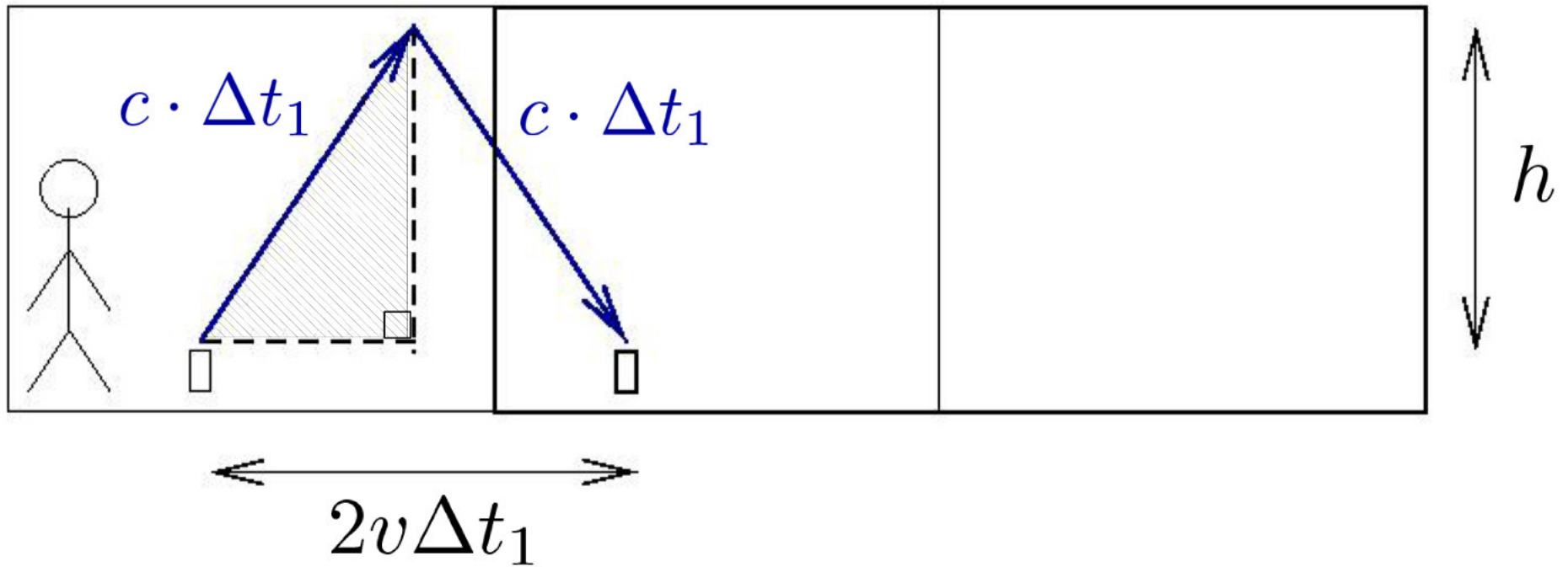
$$v = 0$$



IDA (OU VOLTA):

$$h = c \cdot \Delta t_0$$

$$v \neq 0$$



$$(c \cdot \Delta t_1)^2 = h^2 + (v \cdot \Delta t_1)^2$$

$$(\Delta t_1)^2 (c^2 - v^2) = h^2 = (c \cdot \Delta t_0)^2$$

$$\Delta t_1 = \frac{c}{\sqrt{c^2 - v^2}} \Delta t_0$$

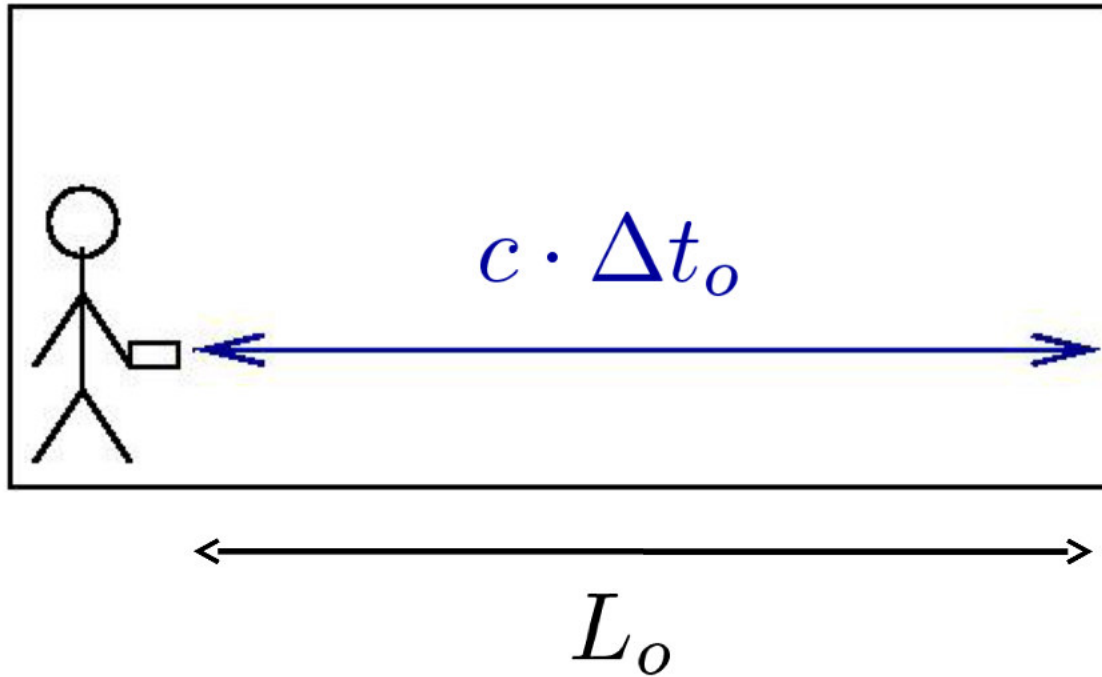
$$\Delta t_1 = \frac{1}{\sqrt{1 - v^2/c^2}} \Delta t_0$$

$$\gamma \equiv \frac{1}{\sqrt{1 - v^2/c^2}}$$

$$\gamma > 1$$

$$\Delta t_1 > \Delta t_0$$

$$v = 0$$

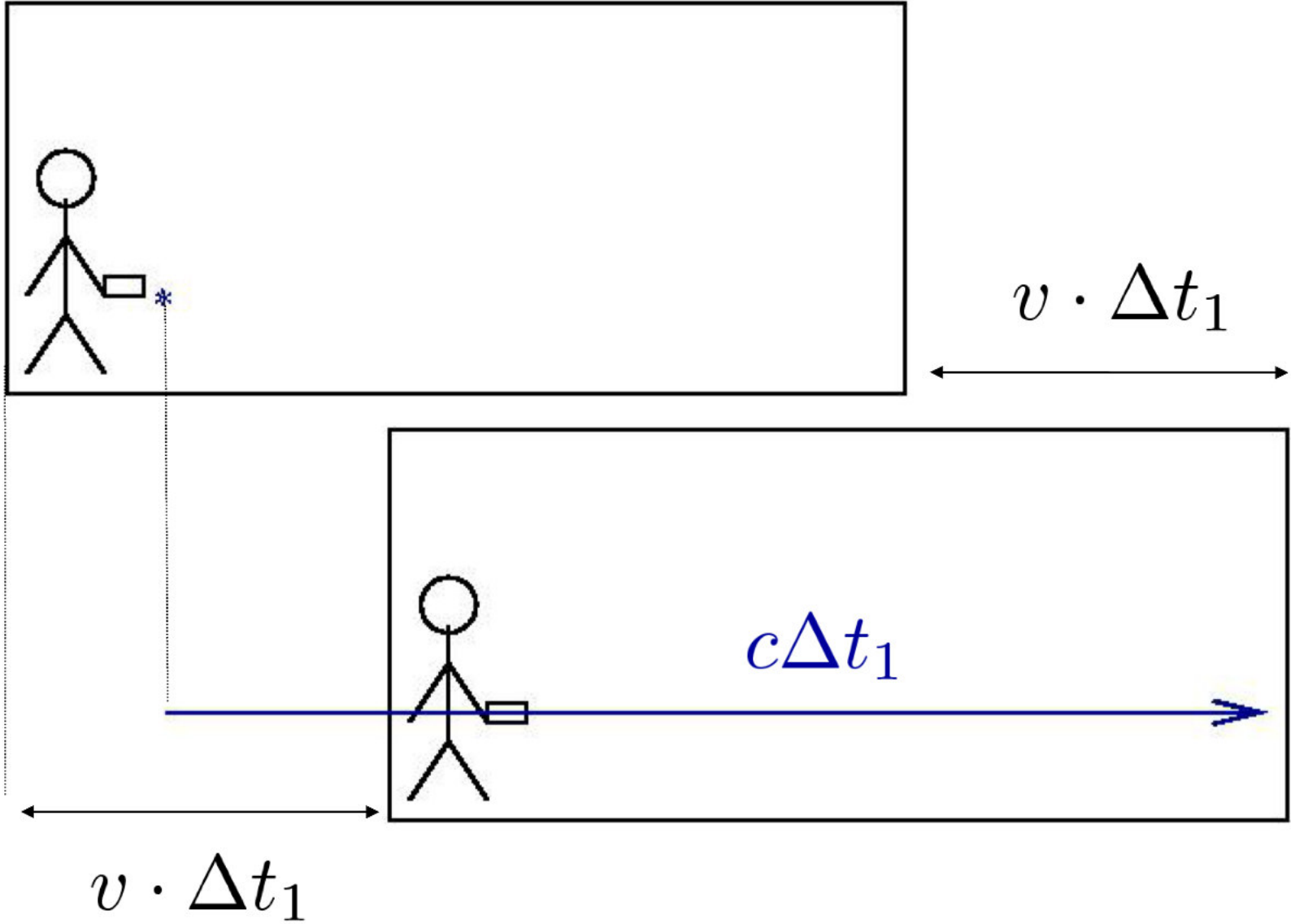


IDA + VOLTA:

$$2L_o = c \cdot \Delta t_o \quad \Rightarrow \quad \Delta t_o = \frac{2L_o}{c}$$

$L$ 

$$v \neq 0$$

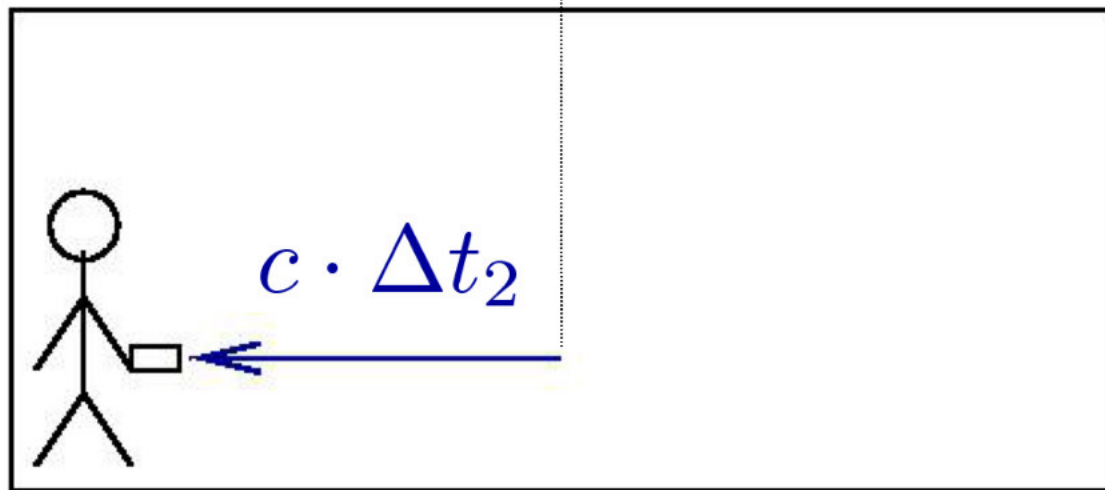
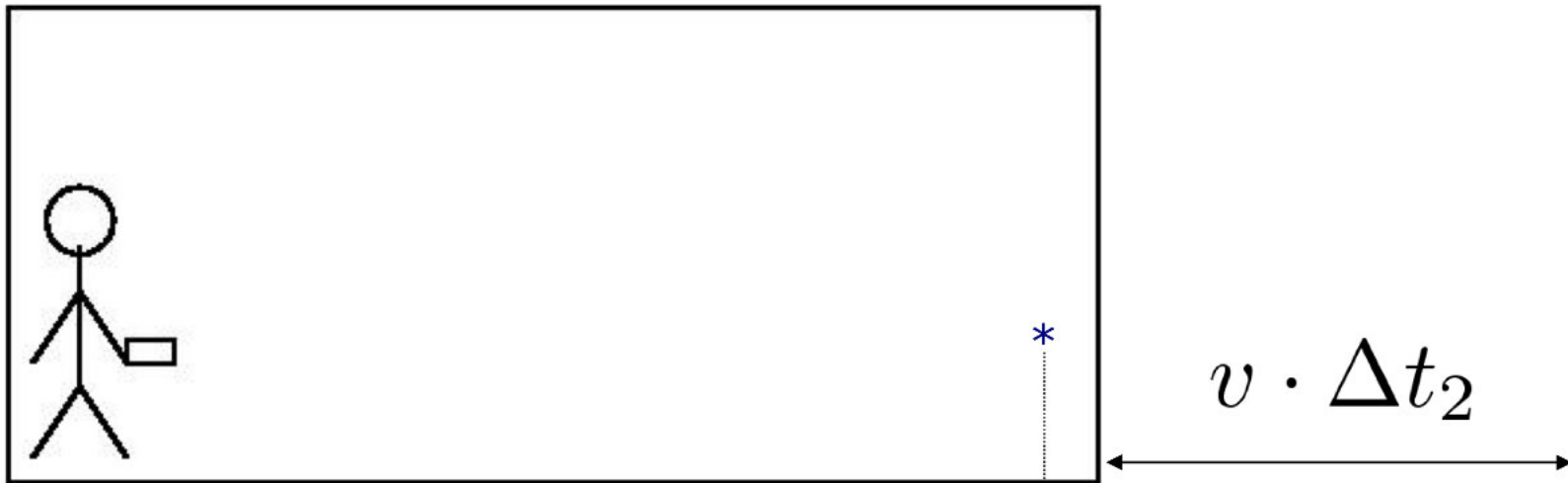




$$L + v \cdot \Delta t_1 = c \cdot \Delta t_1$$

$$L = (c - v)\Delta t_1$$

$$\Delta t_1 = \frac{L}{c - v}$$



$L$

$$L - v \cdot \Delta t_2 = c \cdot \Delta t_2$$

$$L = (c + v)\Delta t_2$$

$$\Delta t_2 = \frac{L}{c + v}$$

$$\Delta t_1 = \frac{L}{c - v}$$

$$\Delta t_{tot} = L \left( \frac{1}{c-v} + \frac{1}{c+v} \right)$$

$$\Delta t_{tot} = 2 \frac{Lc}{c^2 - v^2} = 2 \frac{L/c}{1 - v^2/c^2}$$

mas, do cálculo anterior:

$$\Delta t_{tot} = L \left( \frac{1}{c-v} + \frac{1}{c+v} \right)$$

$$\Delta t_{tot} = 2 \frac{Lc}{c^2 - v^2} = 2 \frac{L/c}{1 - v^2/c^2}$$

mas, do cálculo anterior:

$$\Delta t_{tot} = \frac{1}{\sqrt{1 - v^2/c^2}} \Delta t_o \quad \leftarrow \quad \Delta t_o = \frac{2L_o}{c}$$

$$\Delta t_{tot} = \frac{2L_o/c}{\sqrt{1 - v^2/c^2}}$$

então

$$2 \frac{L_o/c}{\sqrt{1 - v^2/c^2}} = 2 \frac{L/c}{1 - v^2/c^2}$$

$$L = L_o \sqrt{1 - v^2/c^2}$$

$$\gamma \equiv \frac{1}{\sqrt{1 - v^2/c^2}}$$

$$L = \frac{1}{\gamma} L_o$$

$$\gamma > 1$$


$$L < L_o$$

$$\Delta t_1 > \Delta t_0$$

$$L < L_0$$

# Dilatação Temporal

$$\Delta t_1 > \Delta t_0$$

$$L < L_0$$

# Contração Espacial



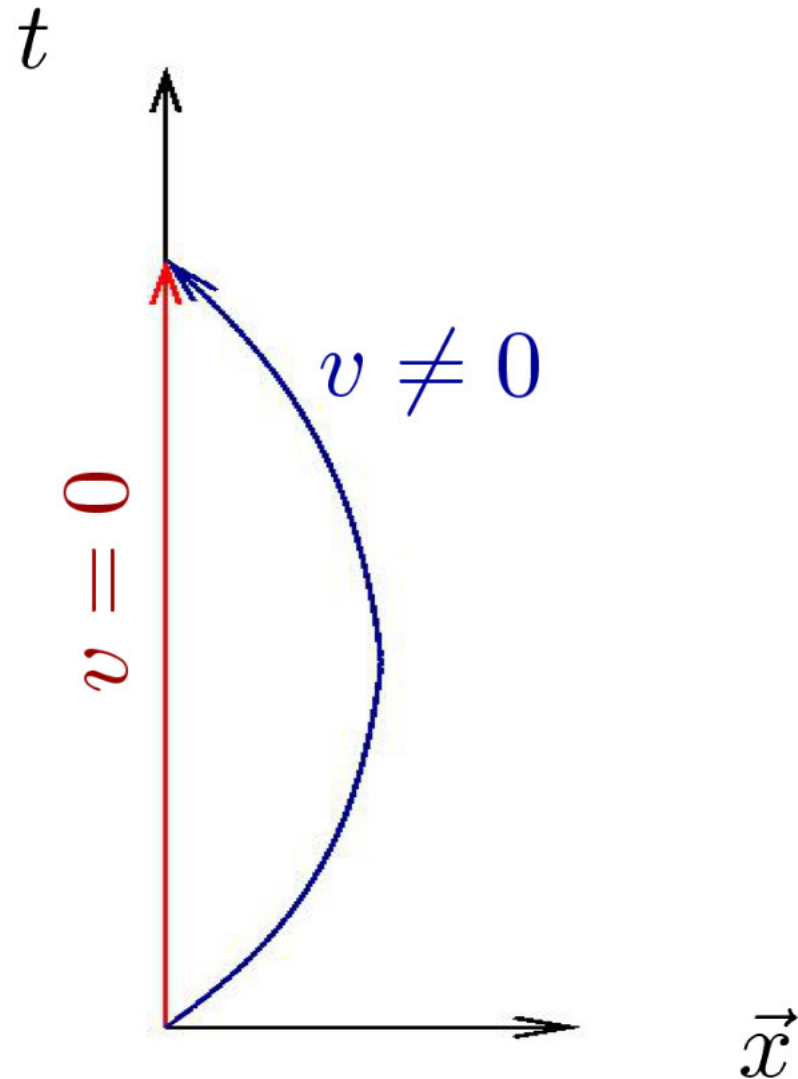
# Efeitos mensuráveis?

- **Aceleradores de partículas**
- **Raios cósmicos**
- **Sistema de posicionamento global (GPS)**

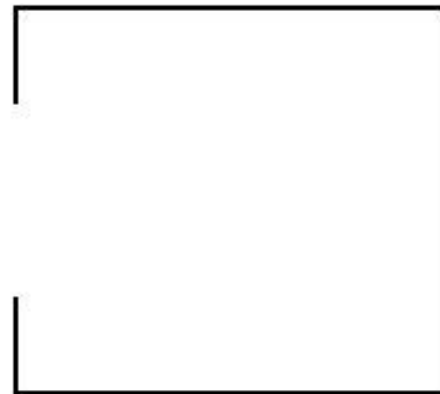
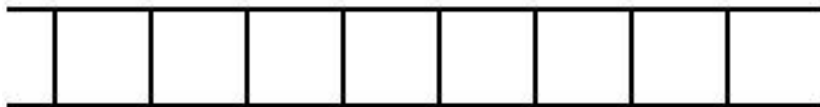
# Alguns paradoxos interessantes...

## Gêmeos

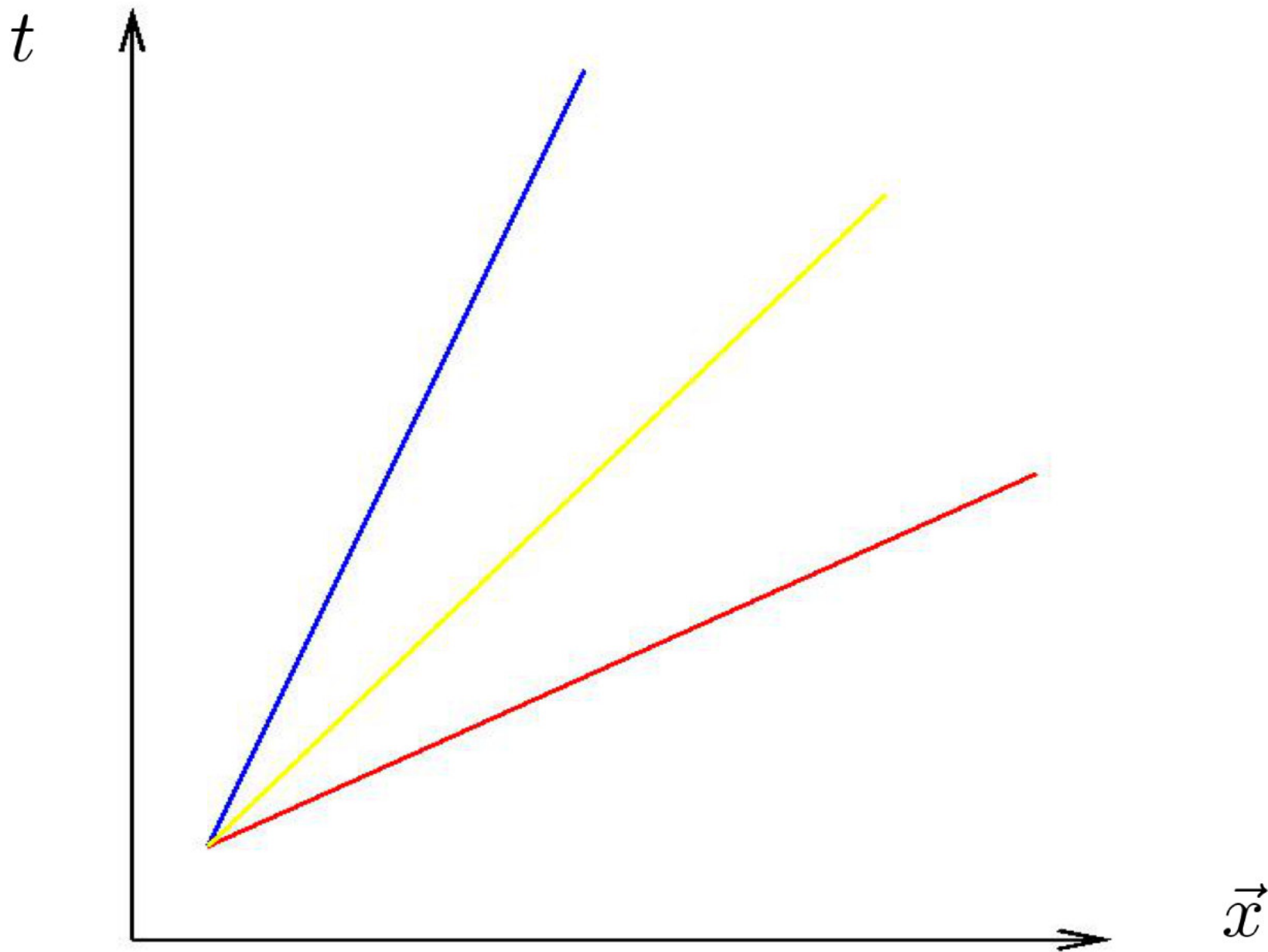
$$\Delta t_1 = \gamma \Delta t_0$$

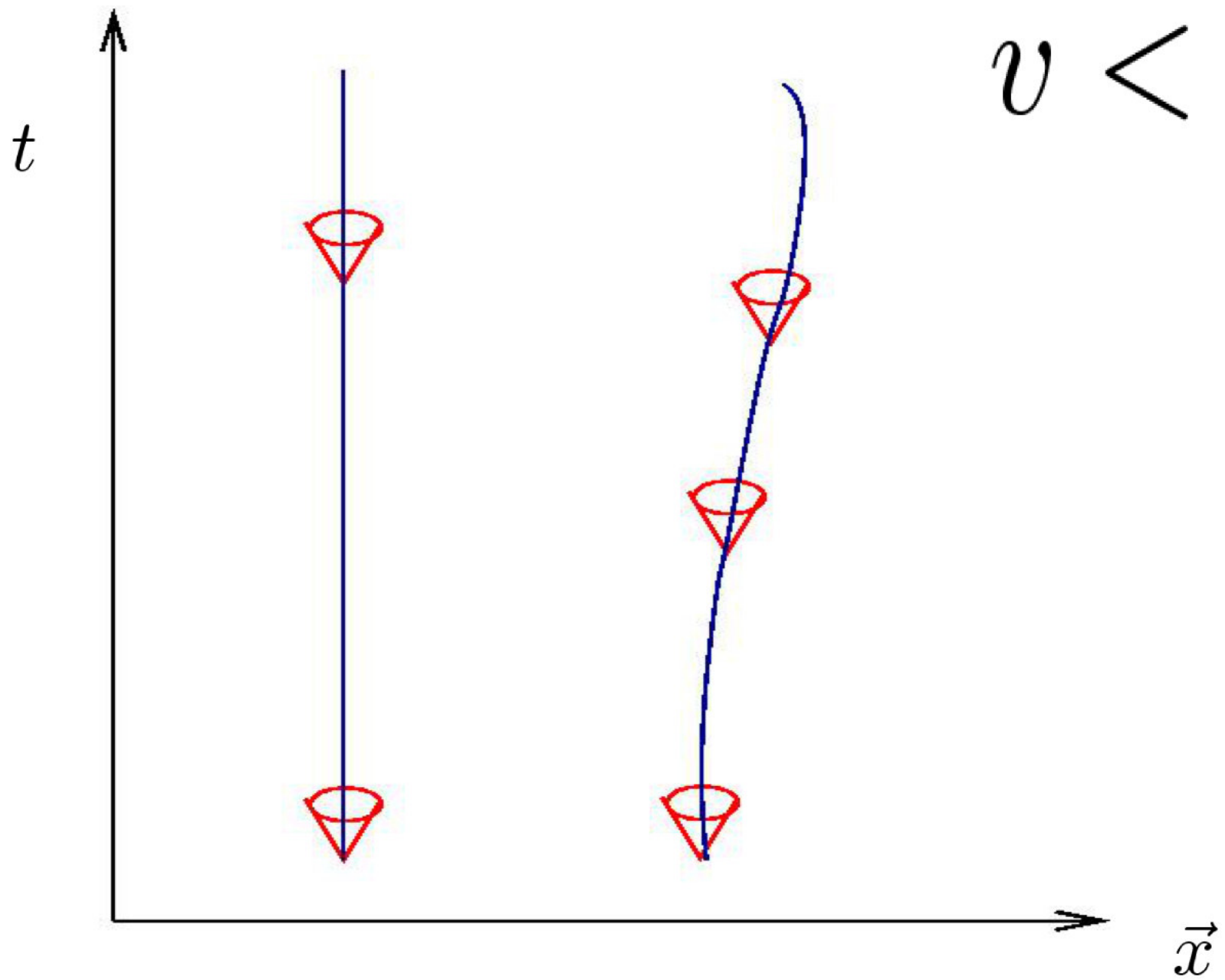


# Escada e o celeiro



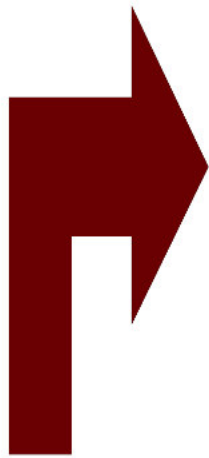
# Diagramas Espaço-tempo





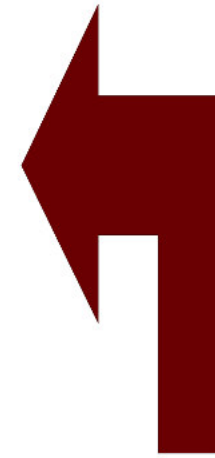
# Relatividade geral

O elevador de Einstein e o Princípio da equivalência



$$F = m_i \cdot a$$

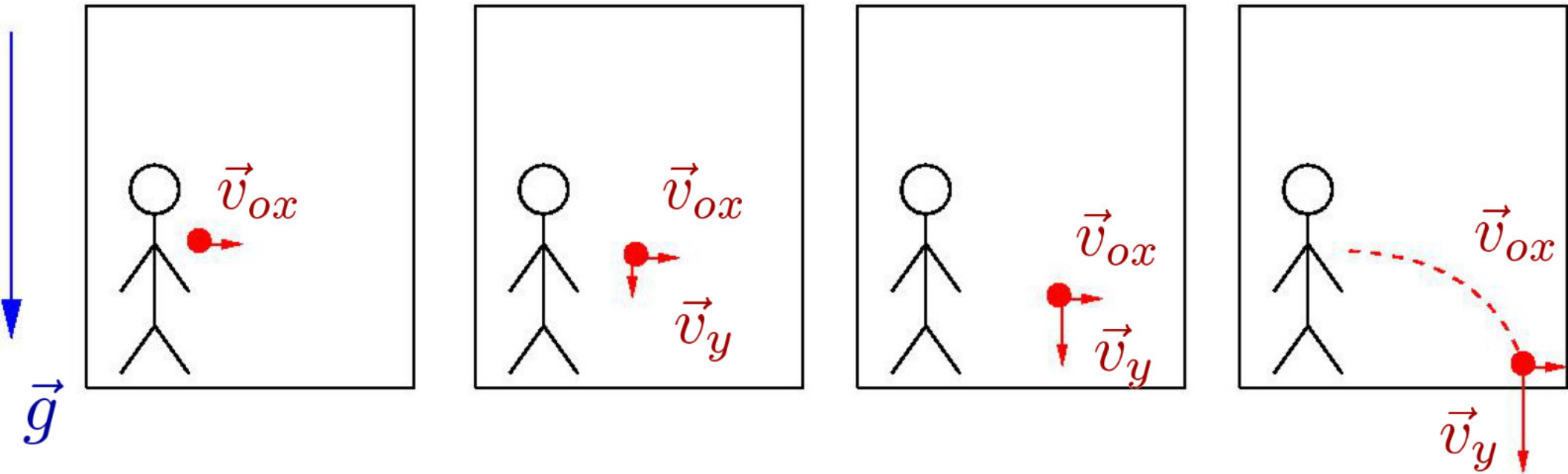
$$m_i = m_g$$



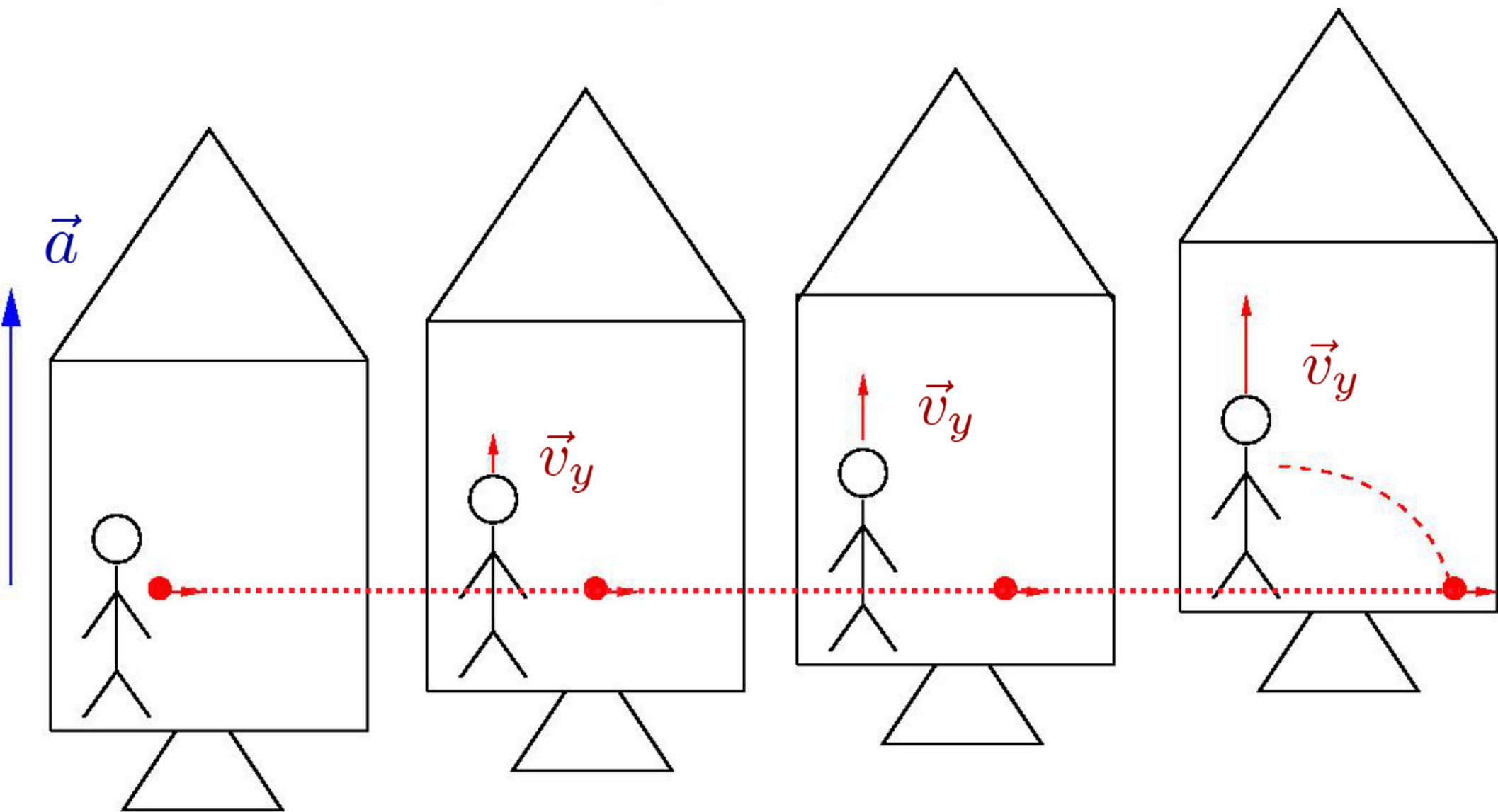
$$F_g = G \frac{m_{g1} \cdot m_{g2}}{r^2}$$

$$\left( F_E = k \frac{q_1 \cdot q_2}{r^2} \right)$$

$$\vec{v} = 0 \quad \vec{a} = 0$$

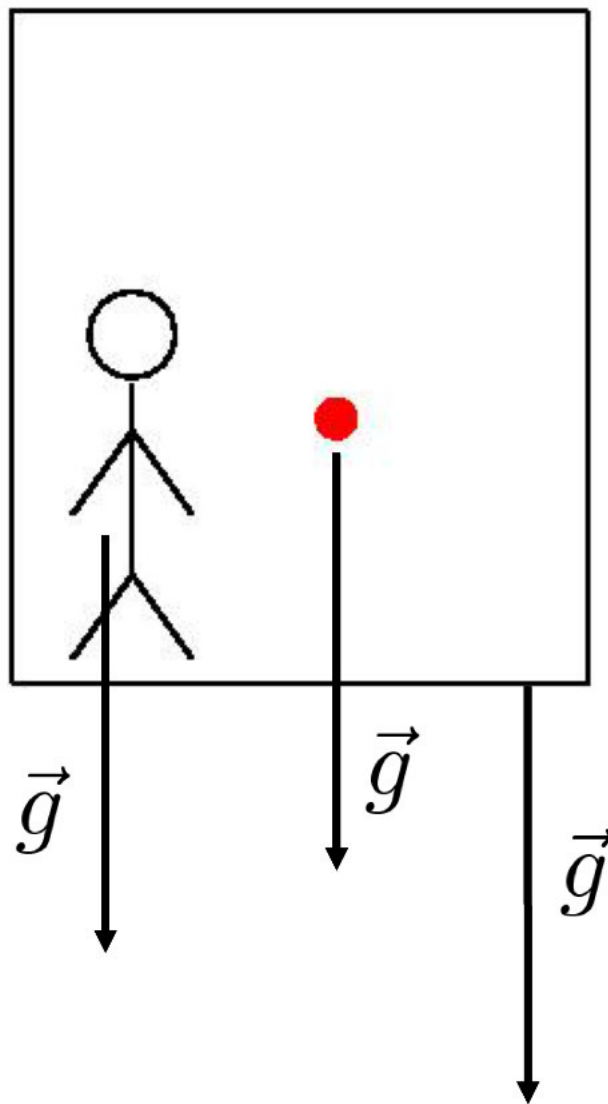


$$\vec{g} = 0$$

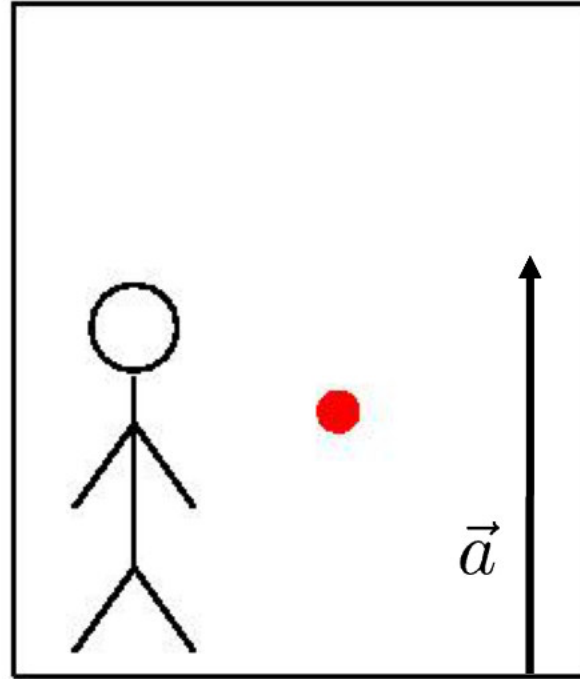




$$\vec{g} \neq 0 \quad \vec{a} = 0$$



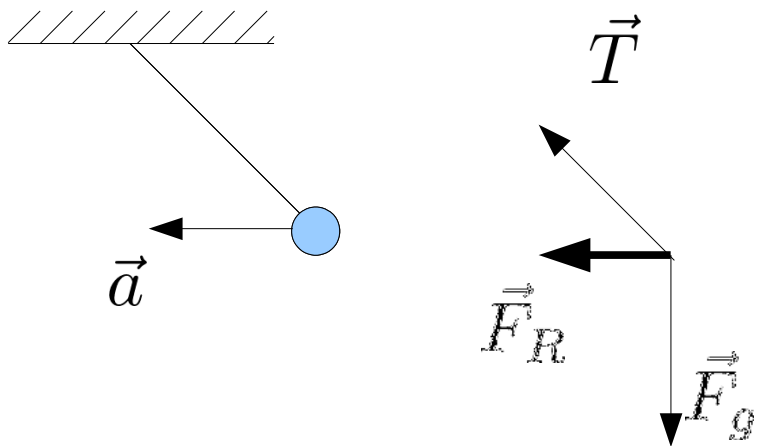
$$\vec{g} = 0 \quad \vec{a} \neq 0$$



$$m_i = m_g$$

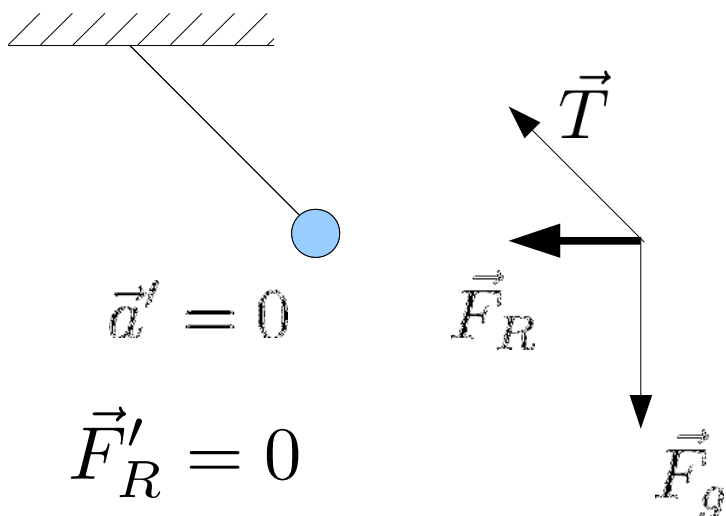
FORÇA DE INÉRCIA ?!

## REFERENCIAL INERCIAL

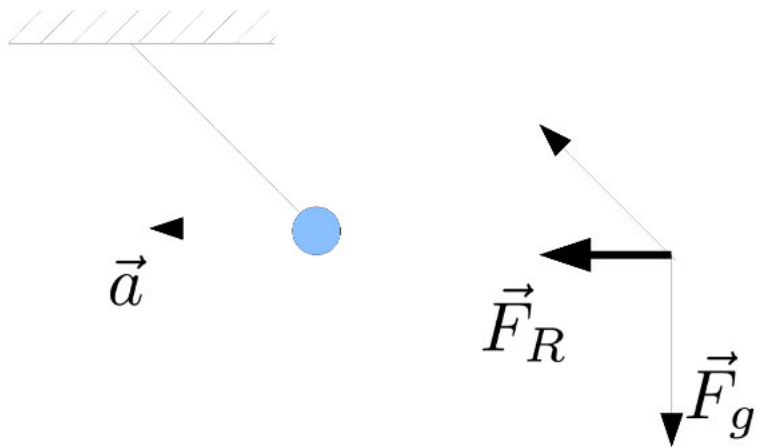


$$0 \neq m\vec{a} = \vec{F}_R$$

## REFERENCIAL NÃO-INERCIAL

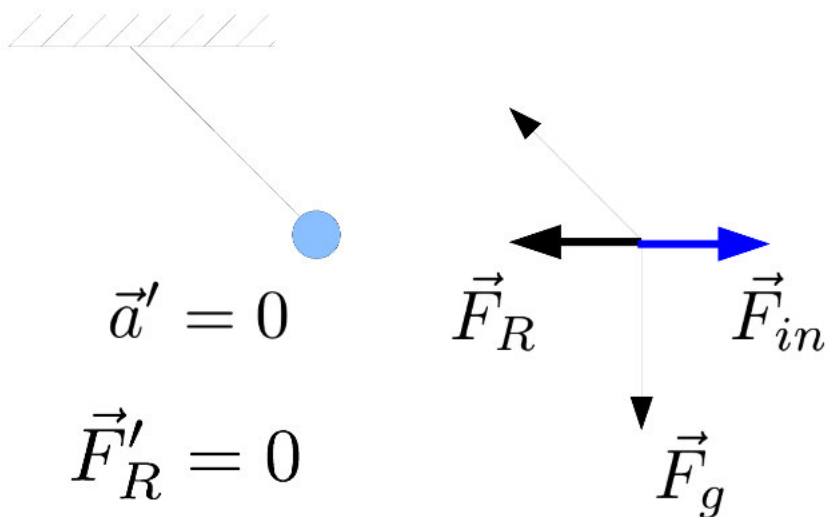


## REFERENCIAL INERCIAL



$$0 \neq m\vec{a} = \vec{F}_R$$

## REFERENCIAL NÃO-INERCIAL

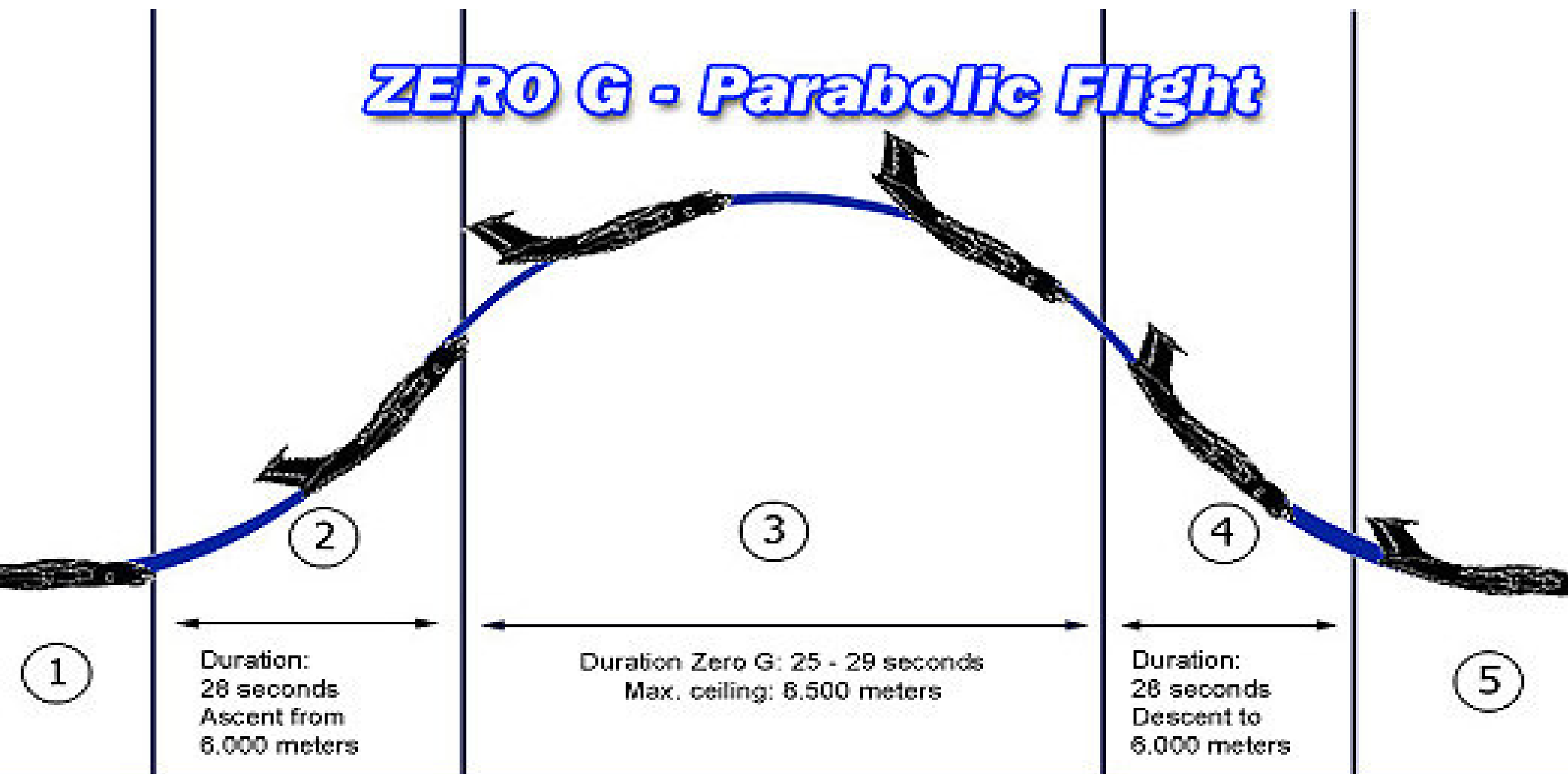


$$0 = m\vec{a}' = \vec{F}'_R$$

$$\vec{F}'_R \equiv \vec{F}_R + \vec{F}_{in} = 0$$

$$\Rightarrow \vec{F}_{in} = -\vec{F}_R = -m\vec{a}$$

# ZERO G - Parabolic Flight



## HOW DOES IT WORK?

1. Horizontal Flight: 1G

2. Pull up Phase: 2G

3. Zero G Injection Phase: 0G

4. Pull out Phase: 2G

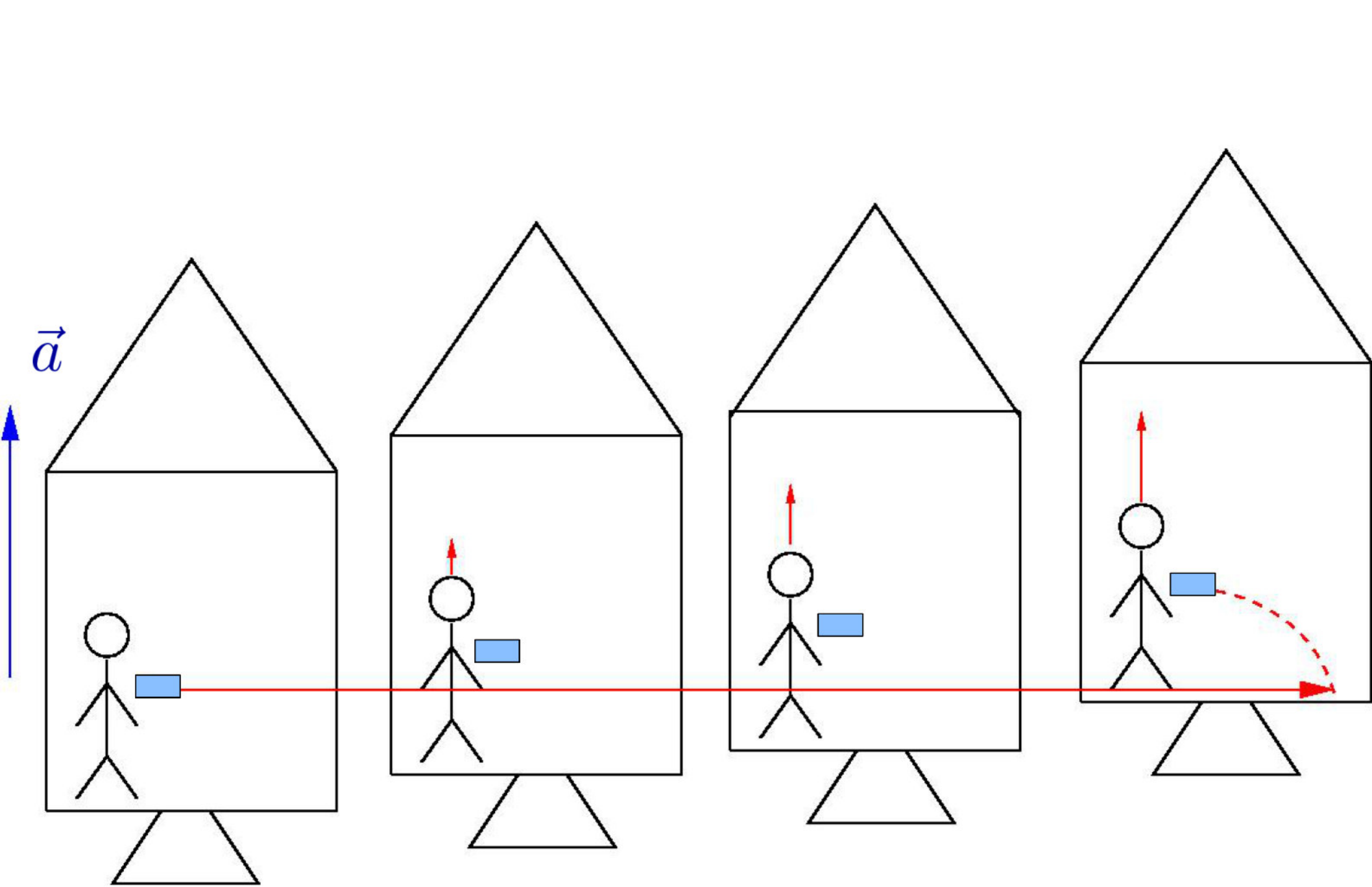
5. Normal Flight: 1G



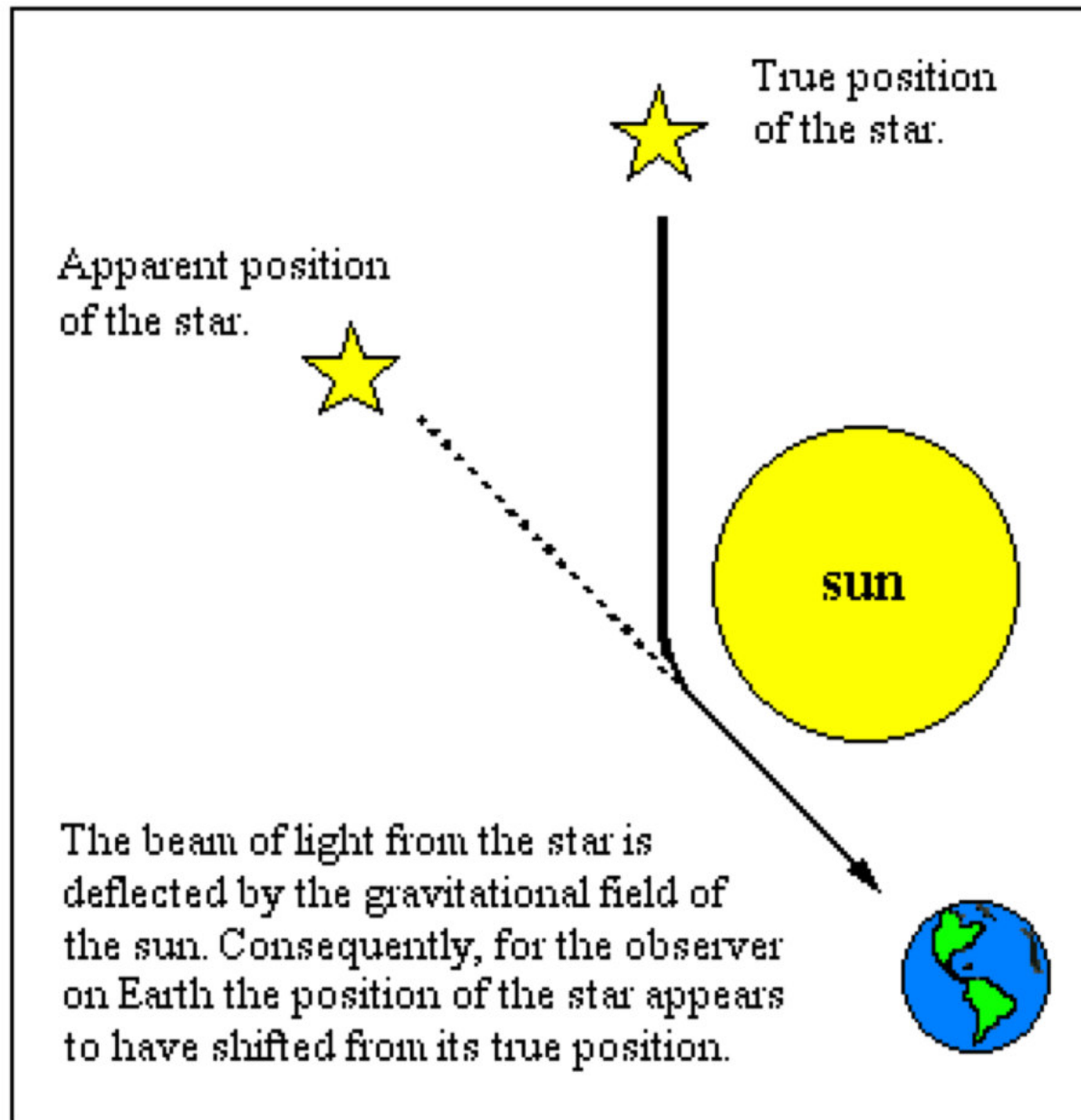
26 / abril / 2007

Se as descrições são  
mesmo completamente  
equivalentes,  
então....

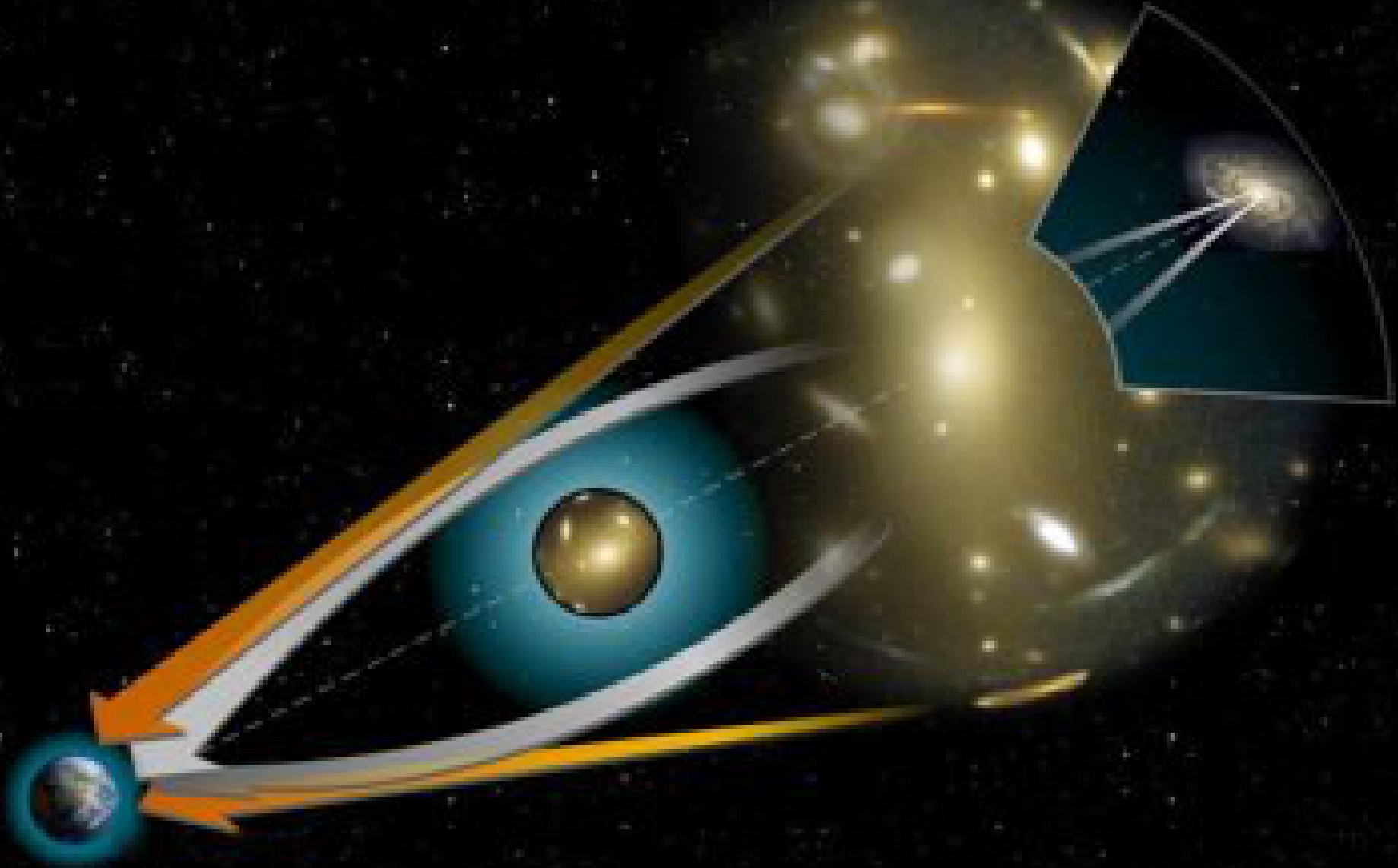


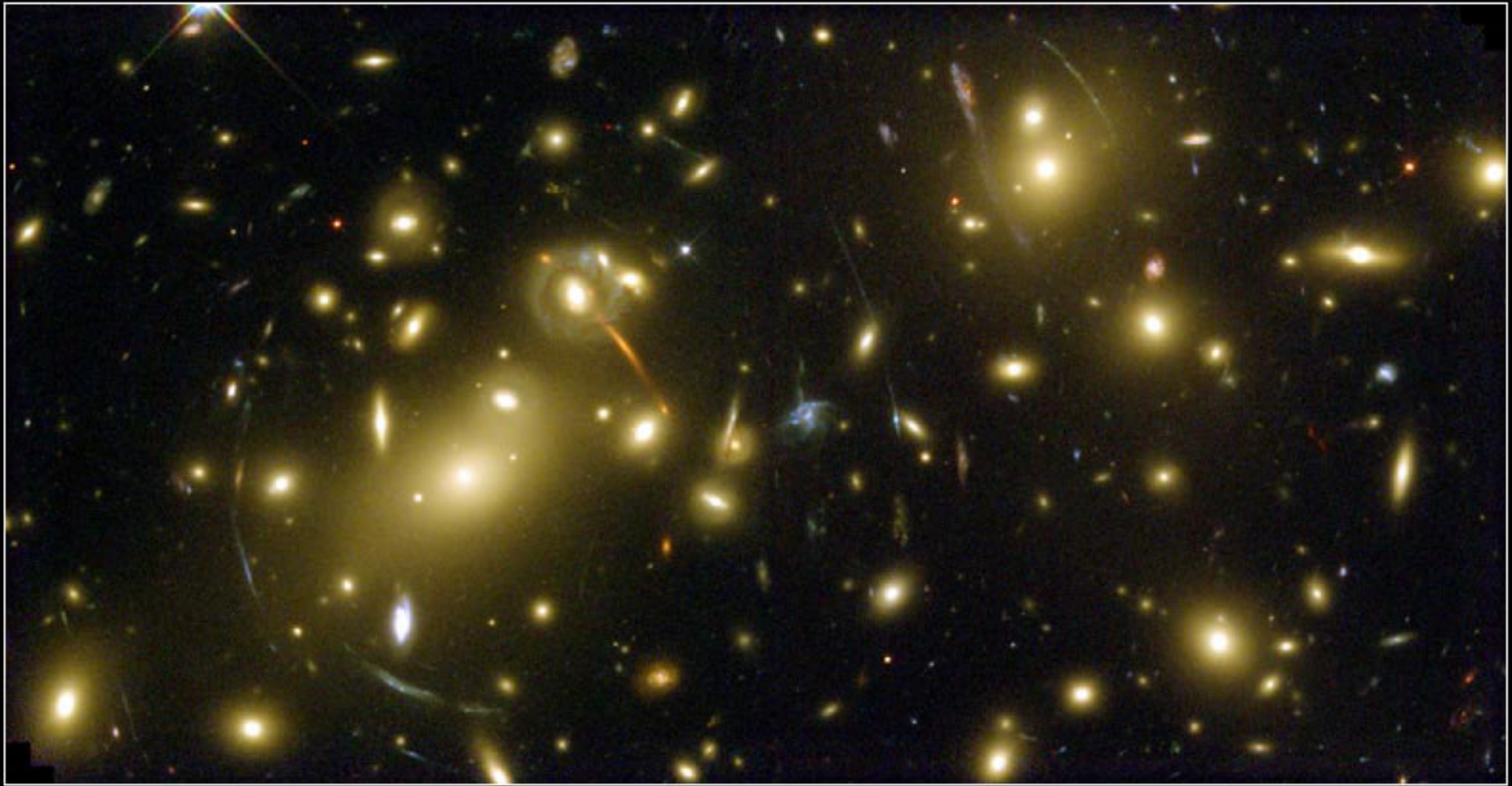


- Desvio da luz pelo Sol



# lentes gravitacionais





**Galaxy Cluster Abell 2218**

**HST • WFPC2**

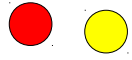
NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08



<http://ircamera.as.arizona.edu/NatSci102/NatSci102/lectures/galaxydist.htm>



Vamos ver como esta ideia  
pode ser útil em casos mais  
concretos...





















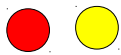








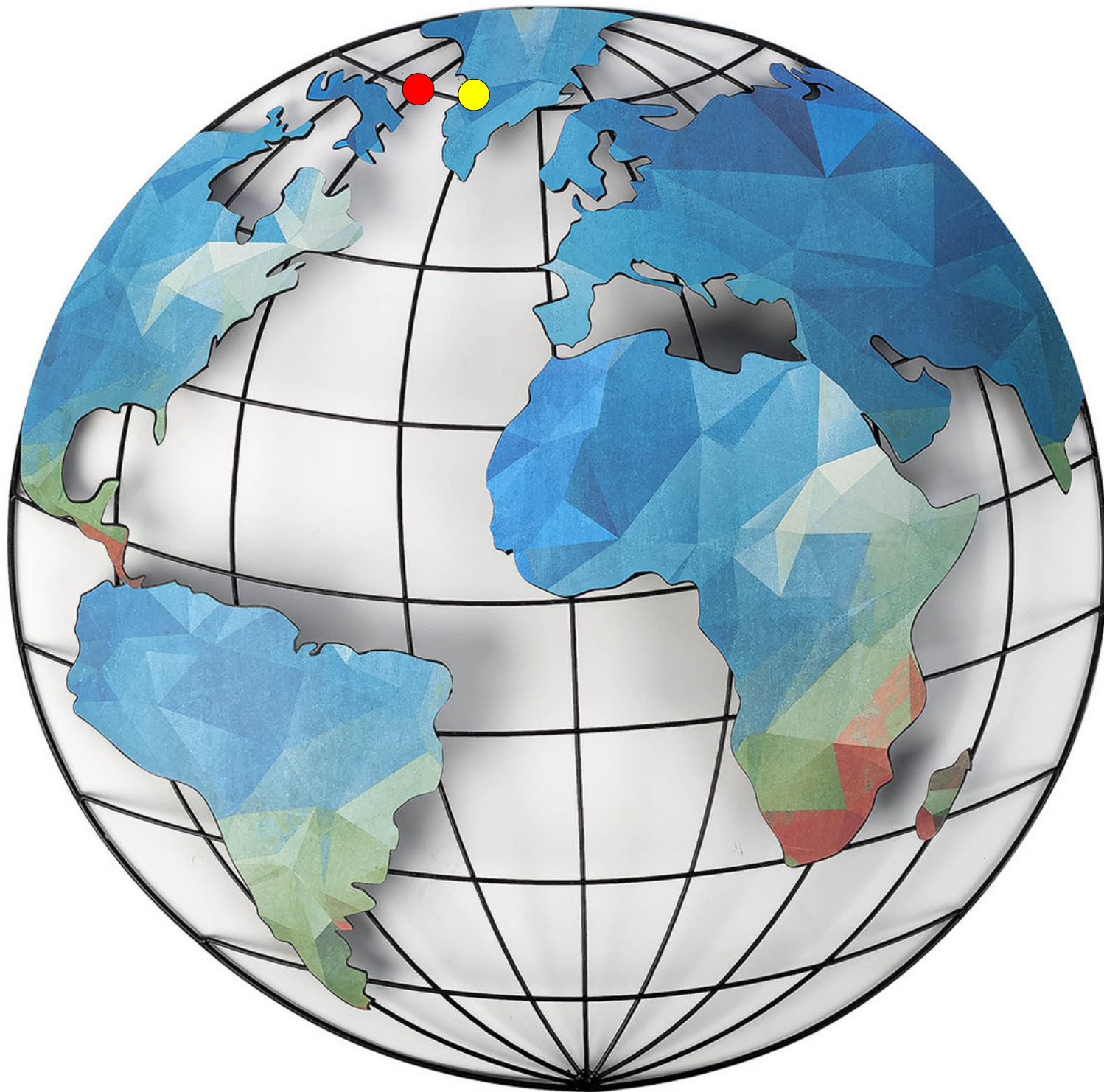




As partículas se afastam e  
depois se aproximam.

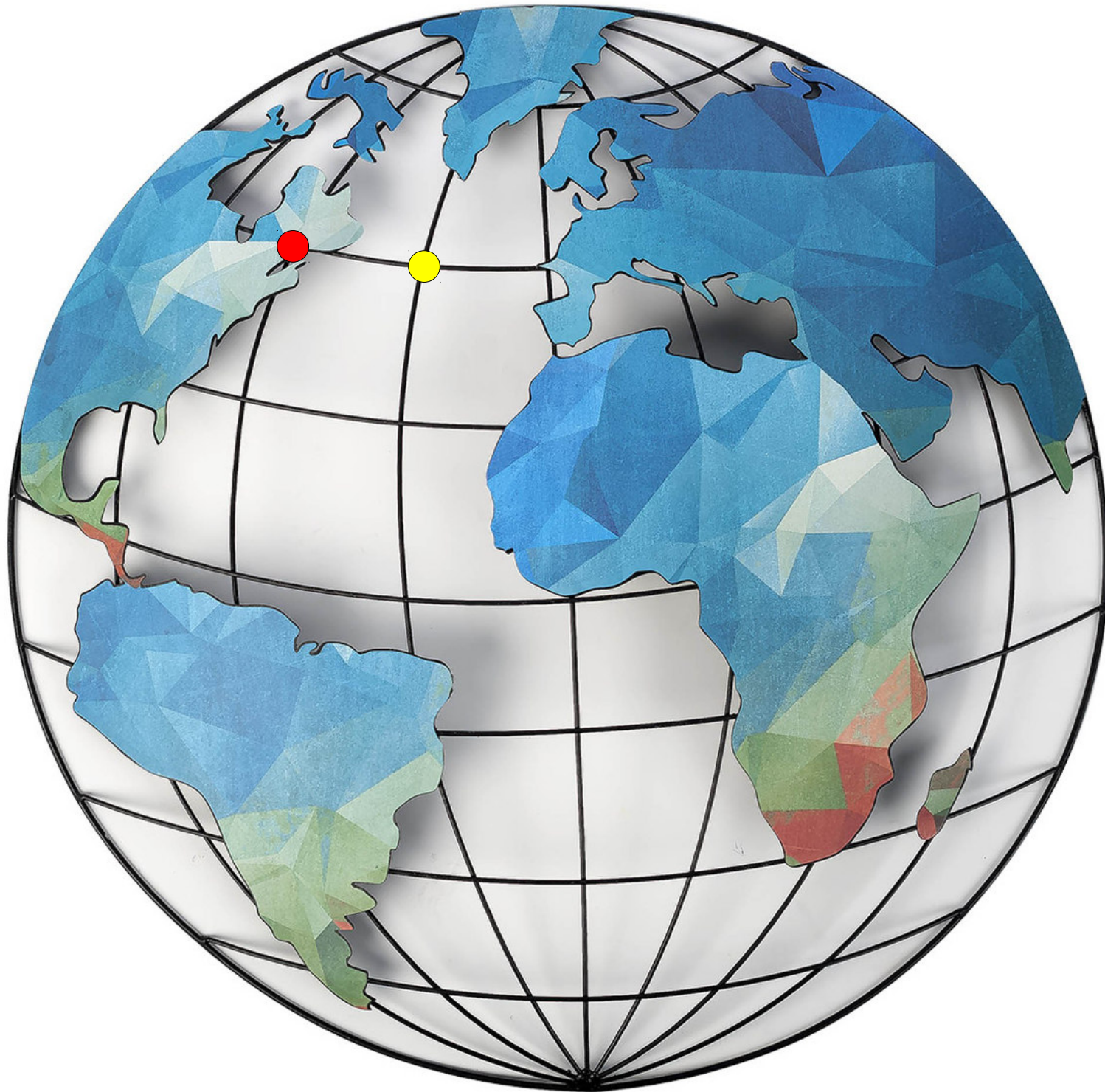
Deve, portanto, haver uma  
força de interação  
entre elas!

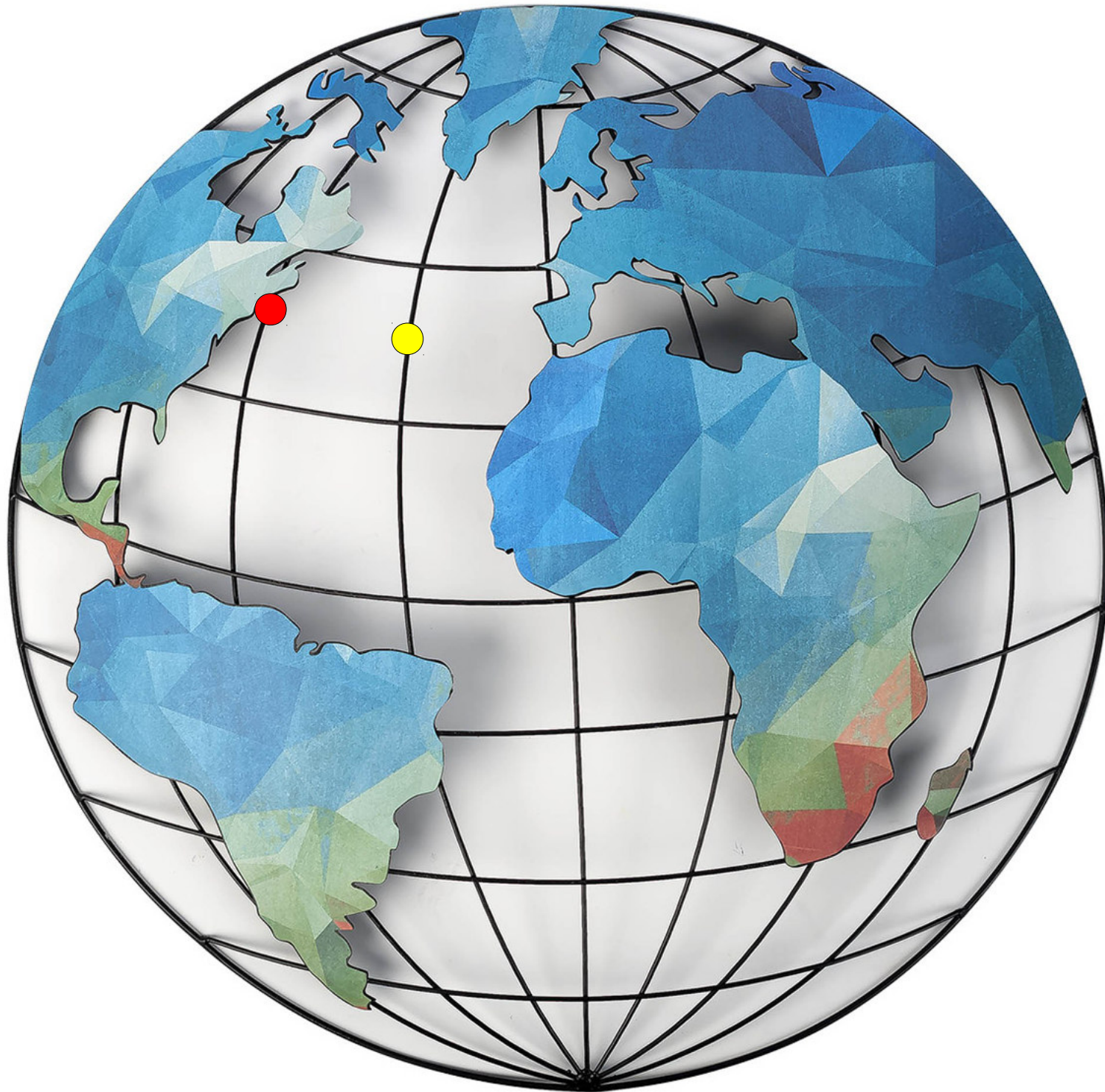
Mas existe uma maneira mais  
fácil de explicar estas  
deformações nas trajetórias,  
SEM falar de força gravitacional  
nem aceleração!

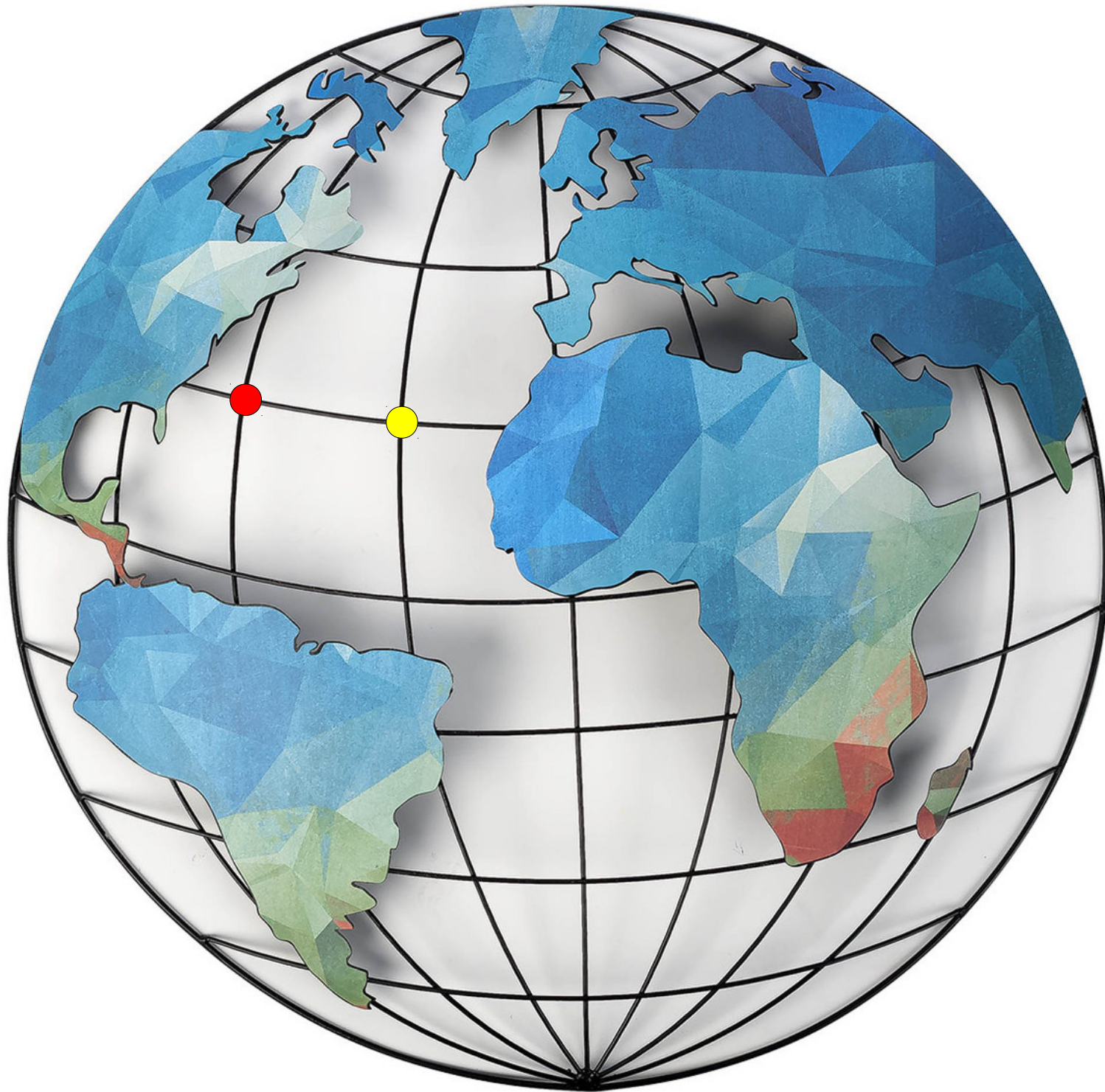


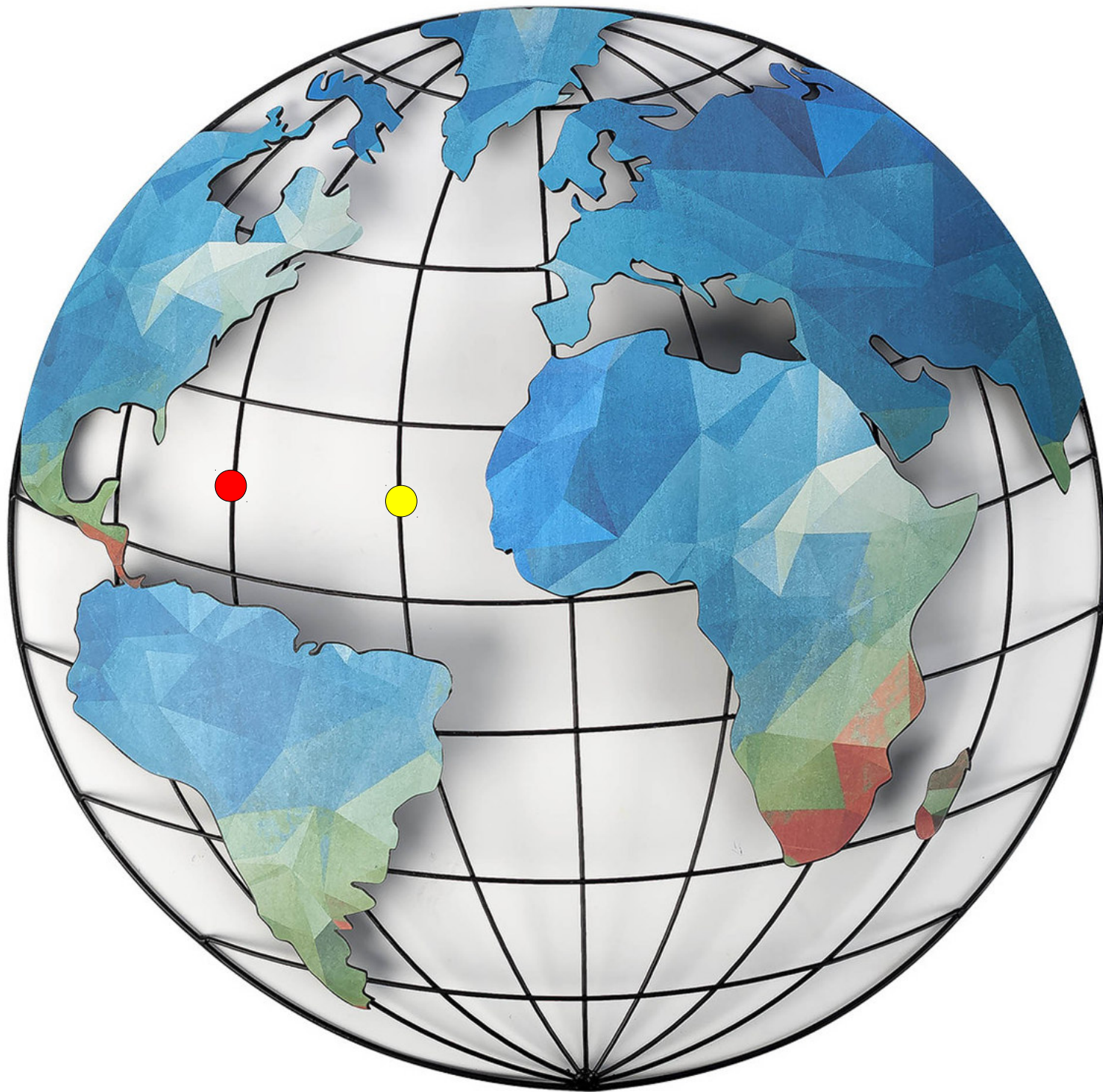


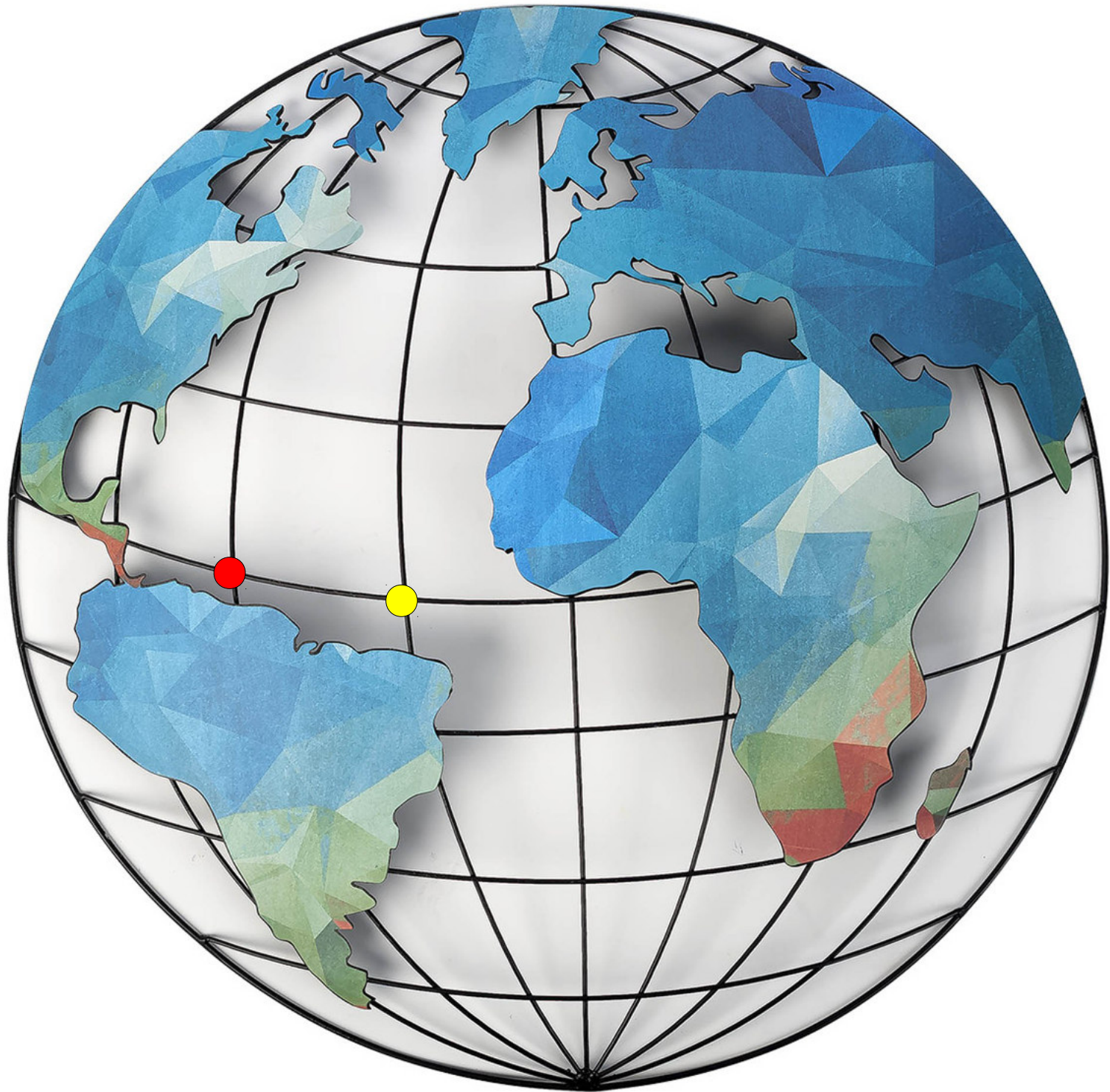


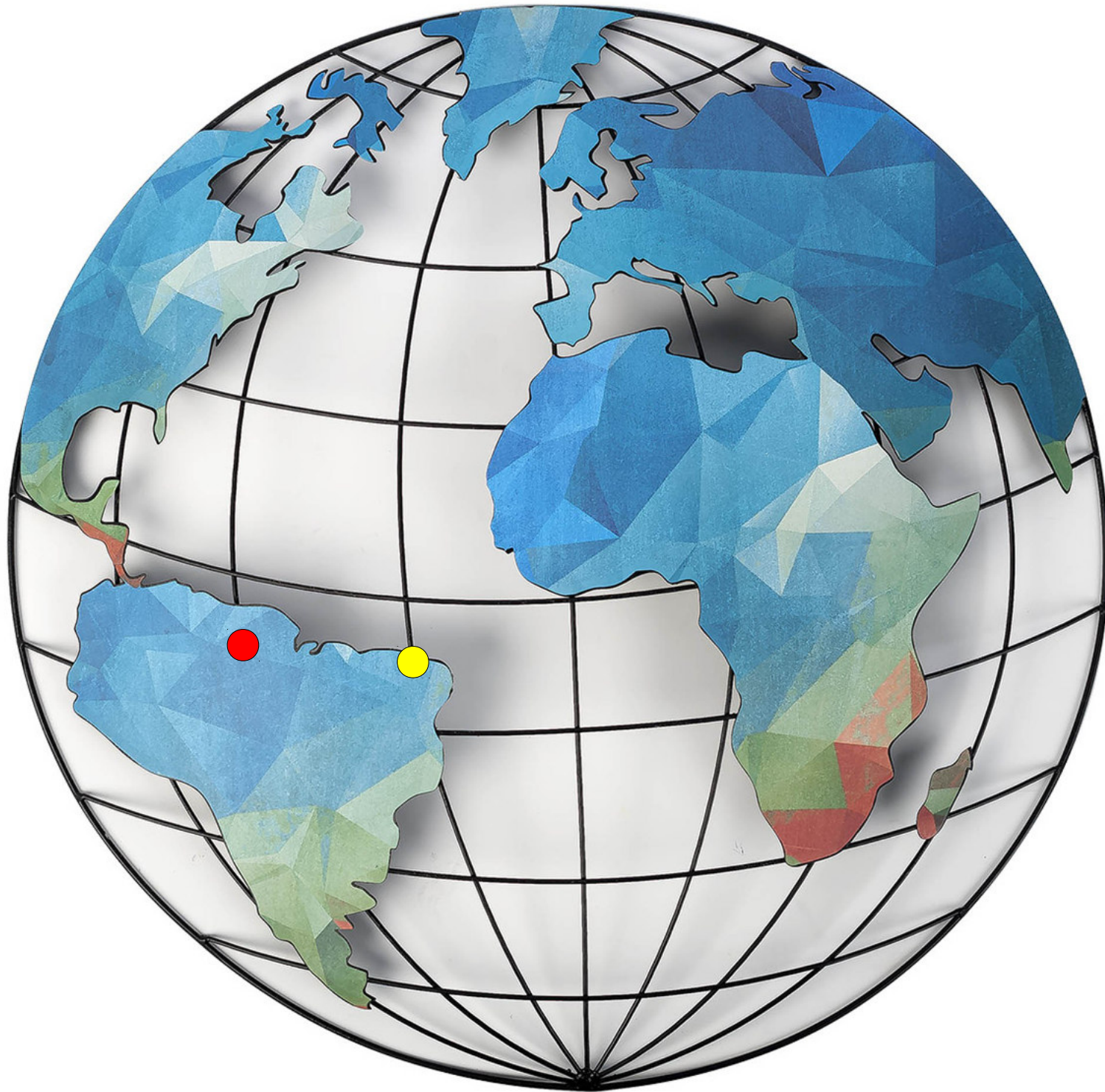


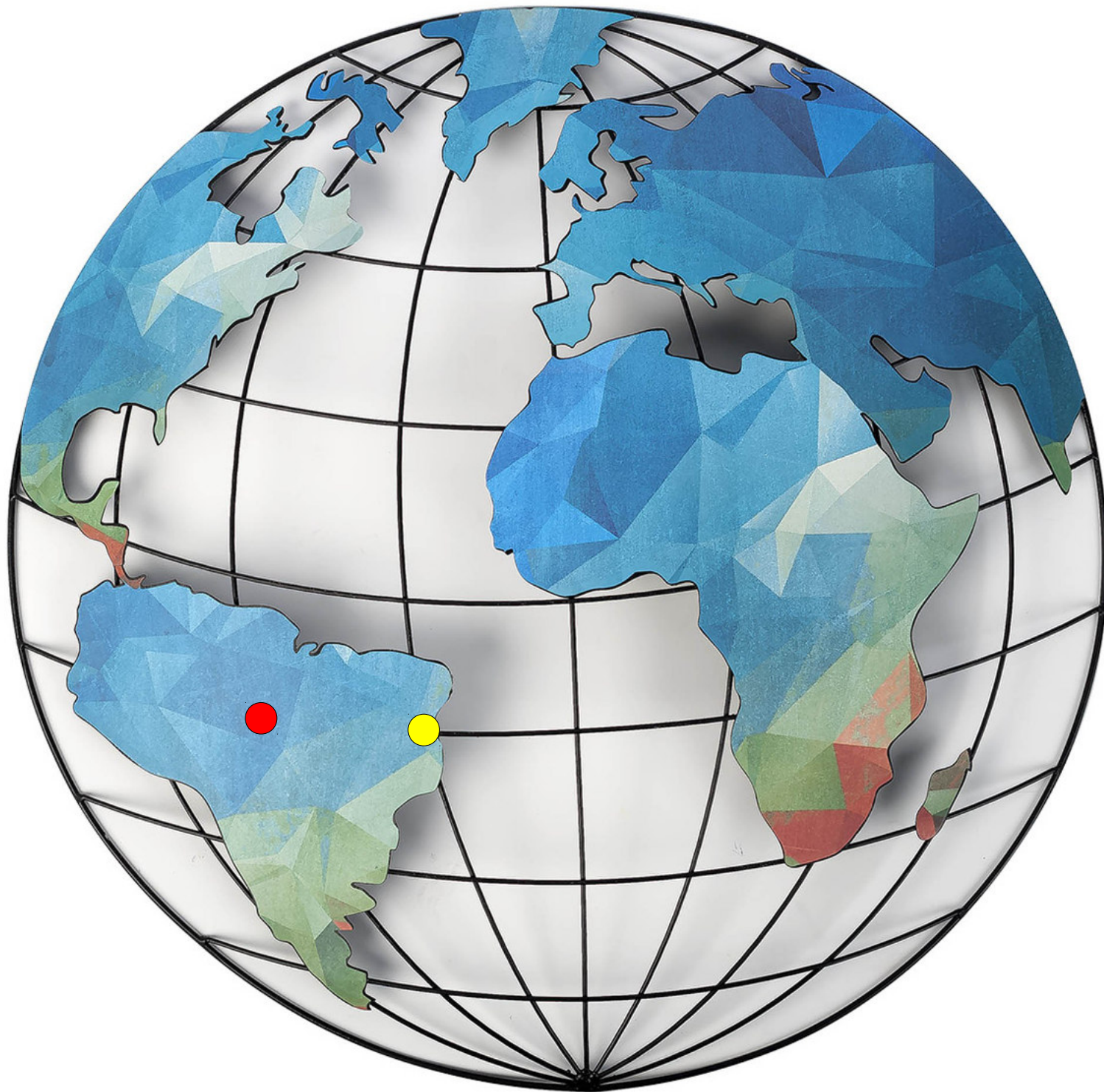








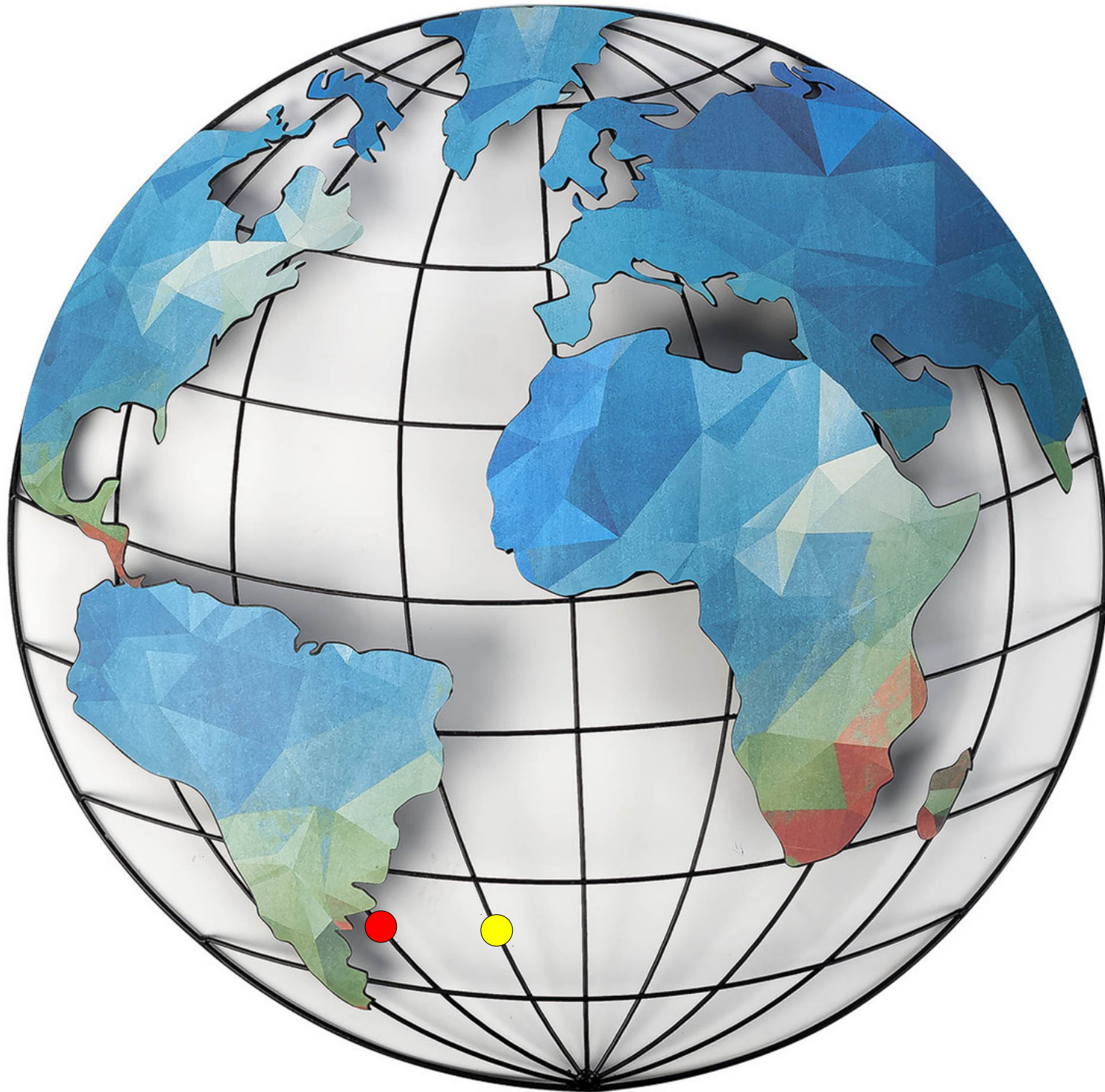


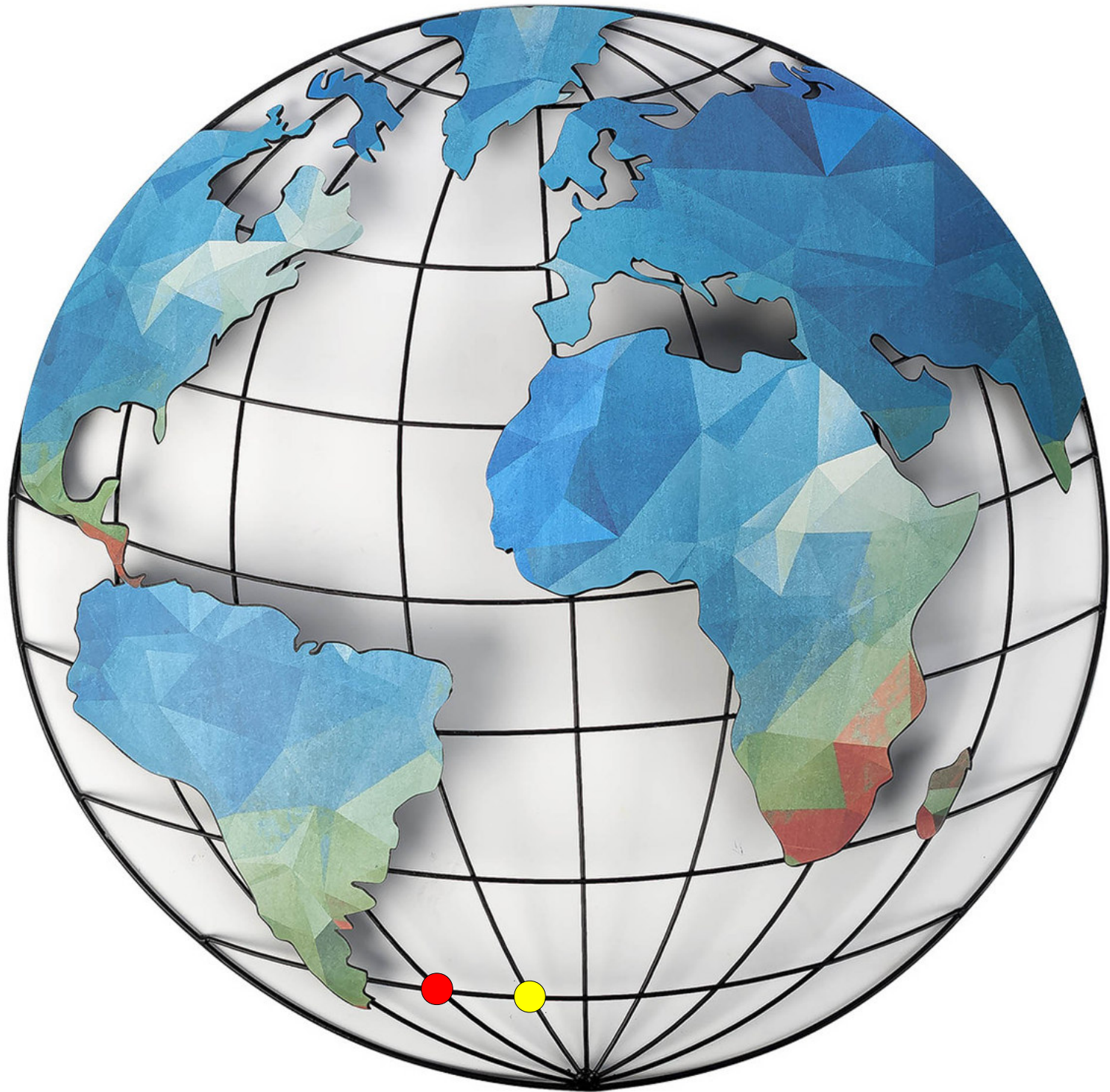


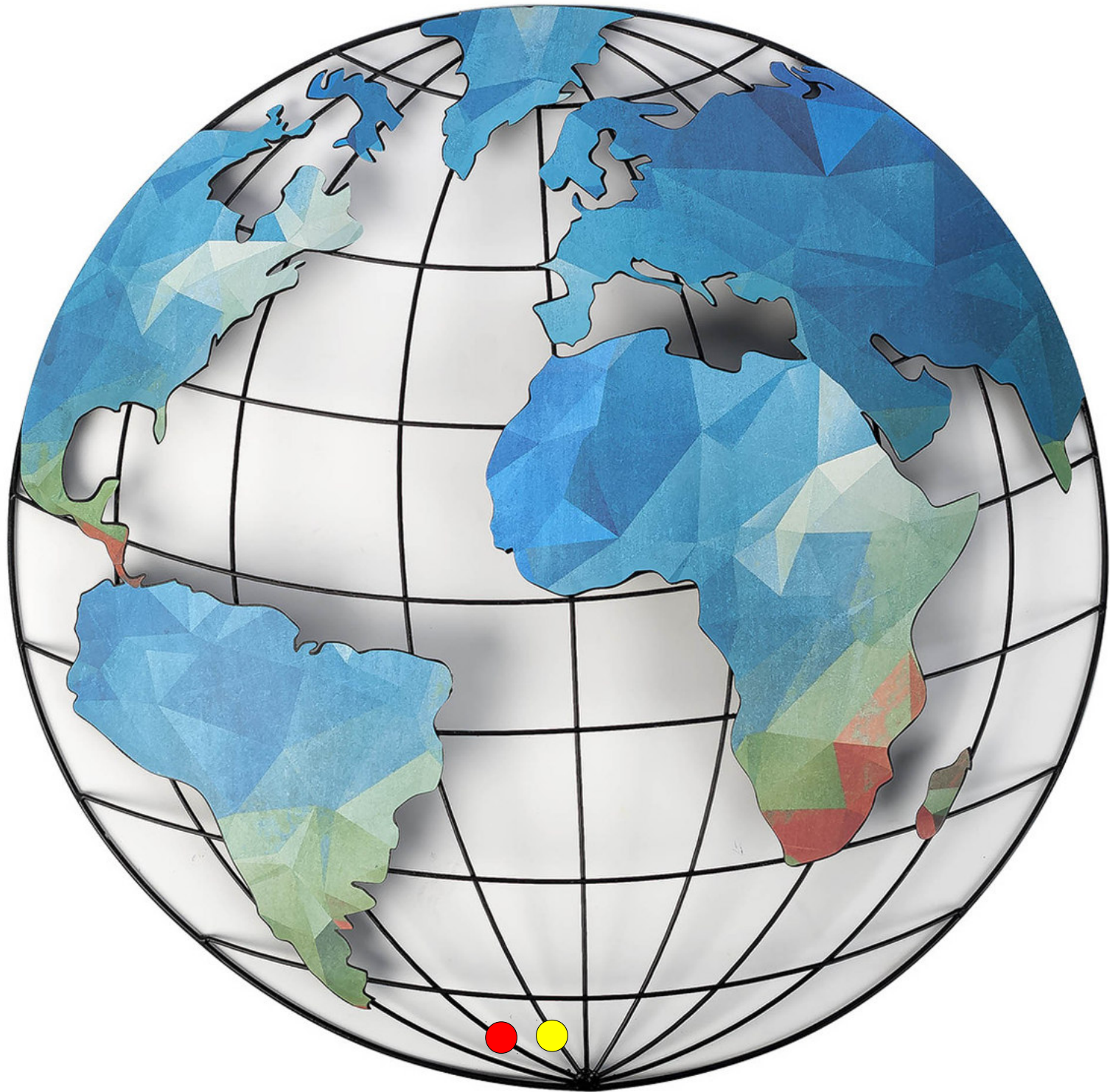




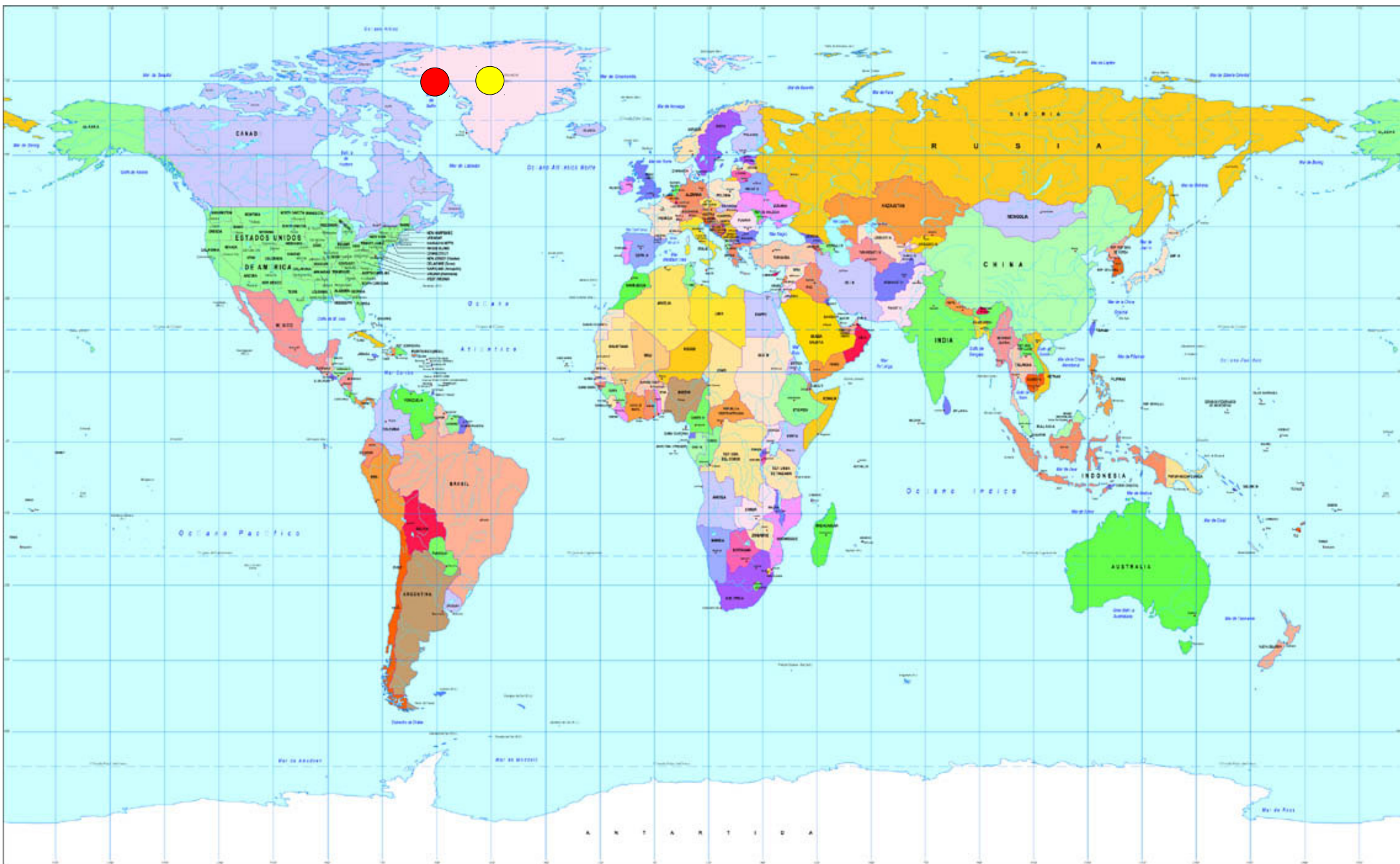


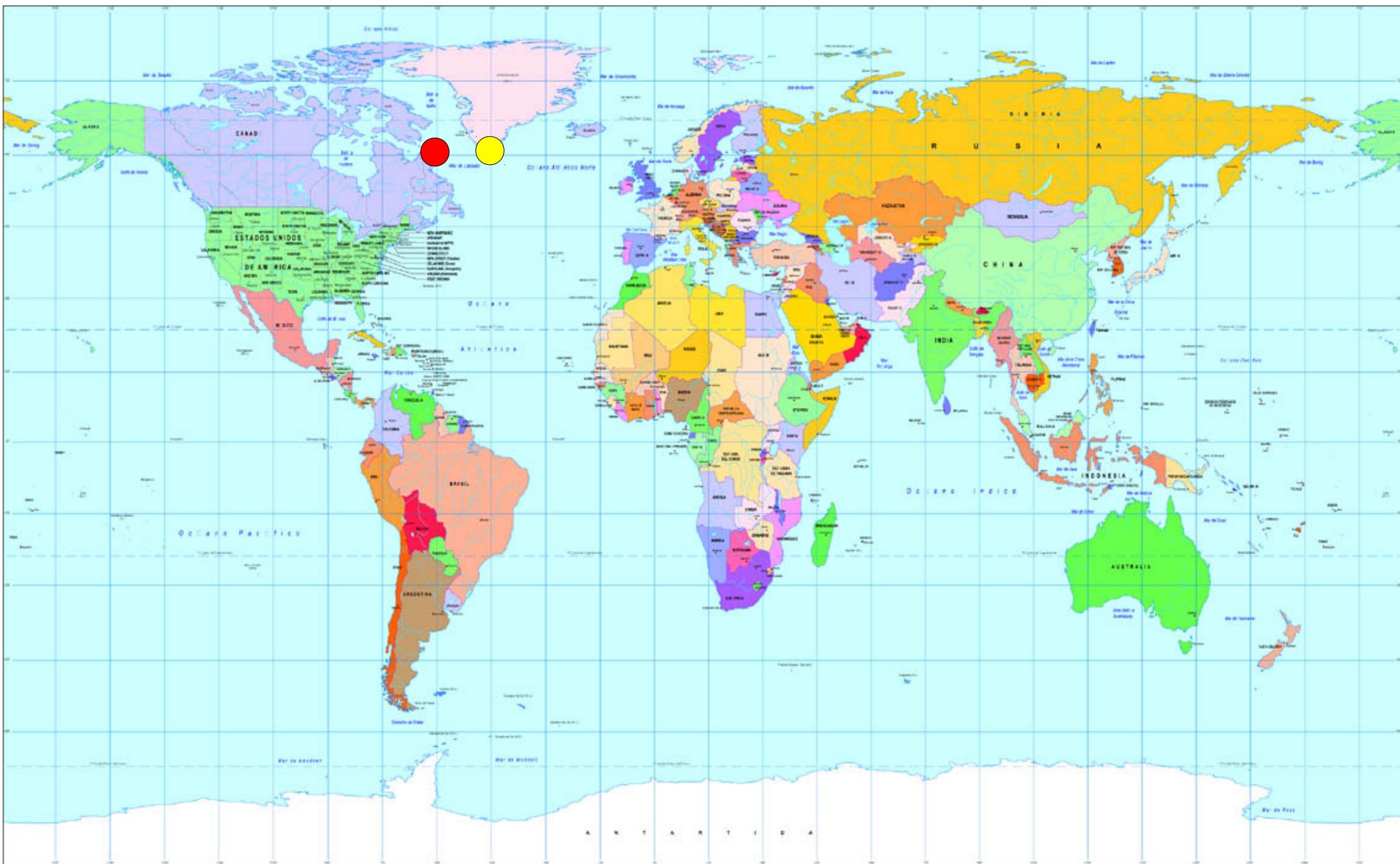




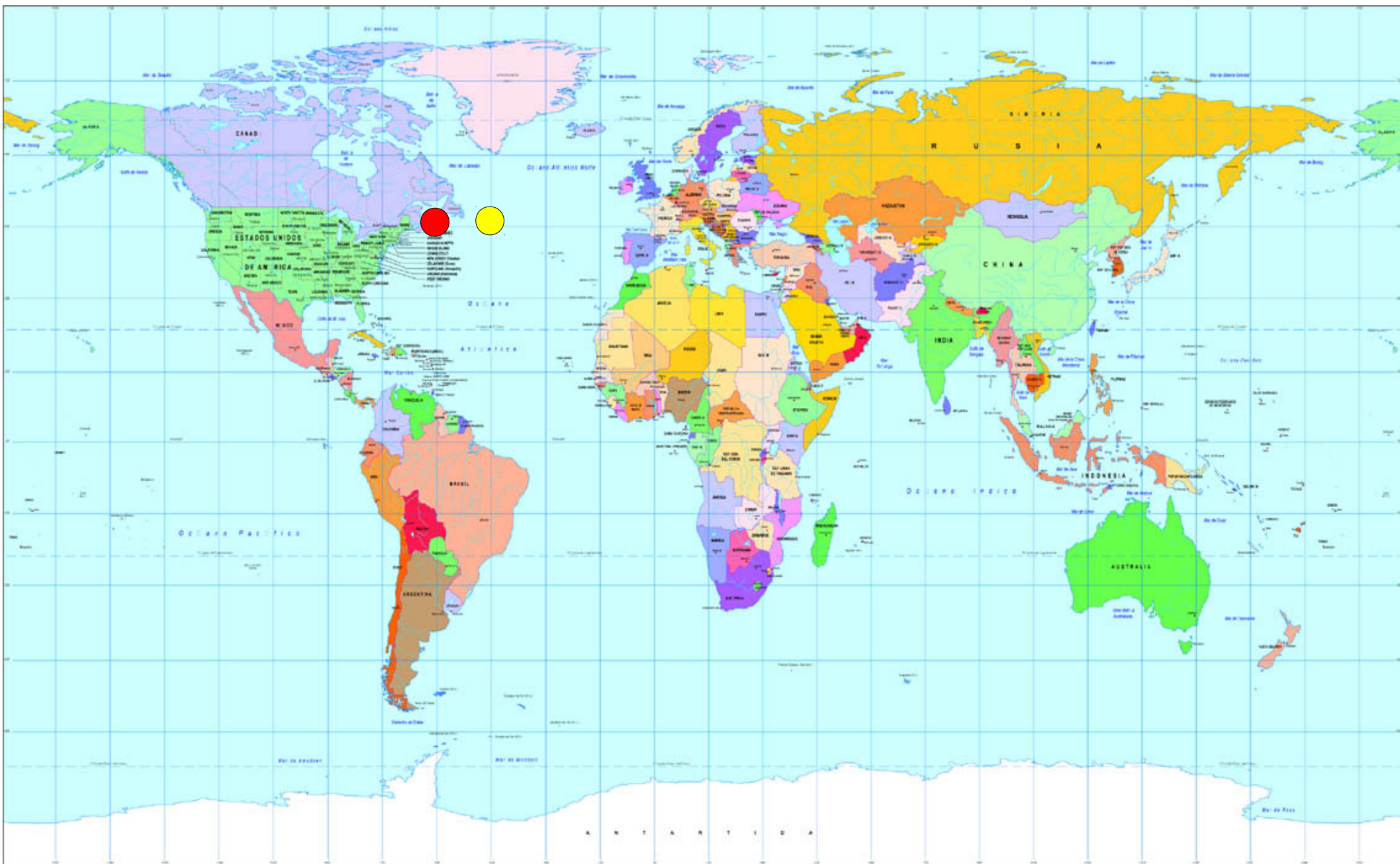


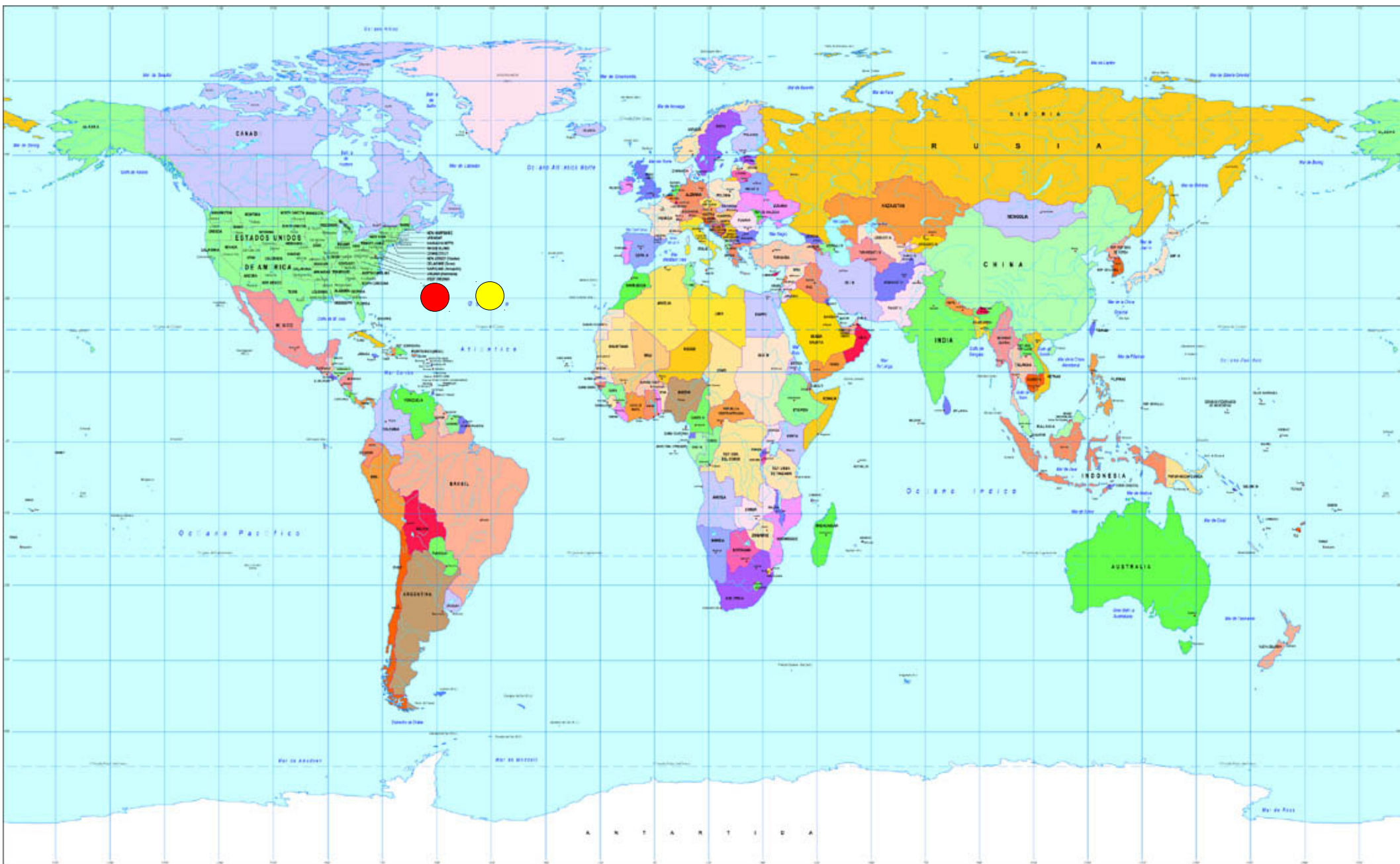
Uma outra opção  
é mudar a geometria,  
ou seja, nossa medida  
de distância !

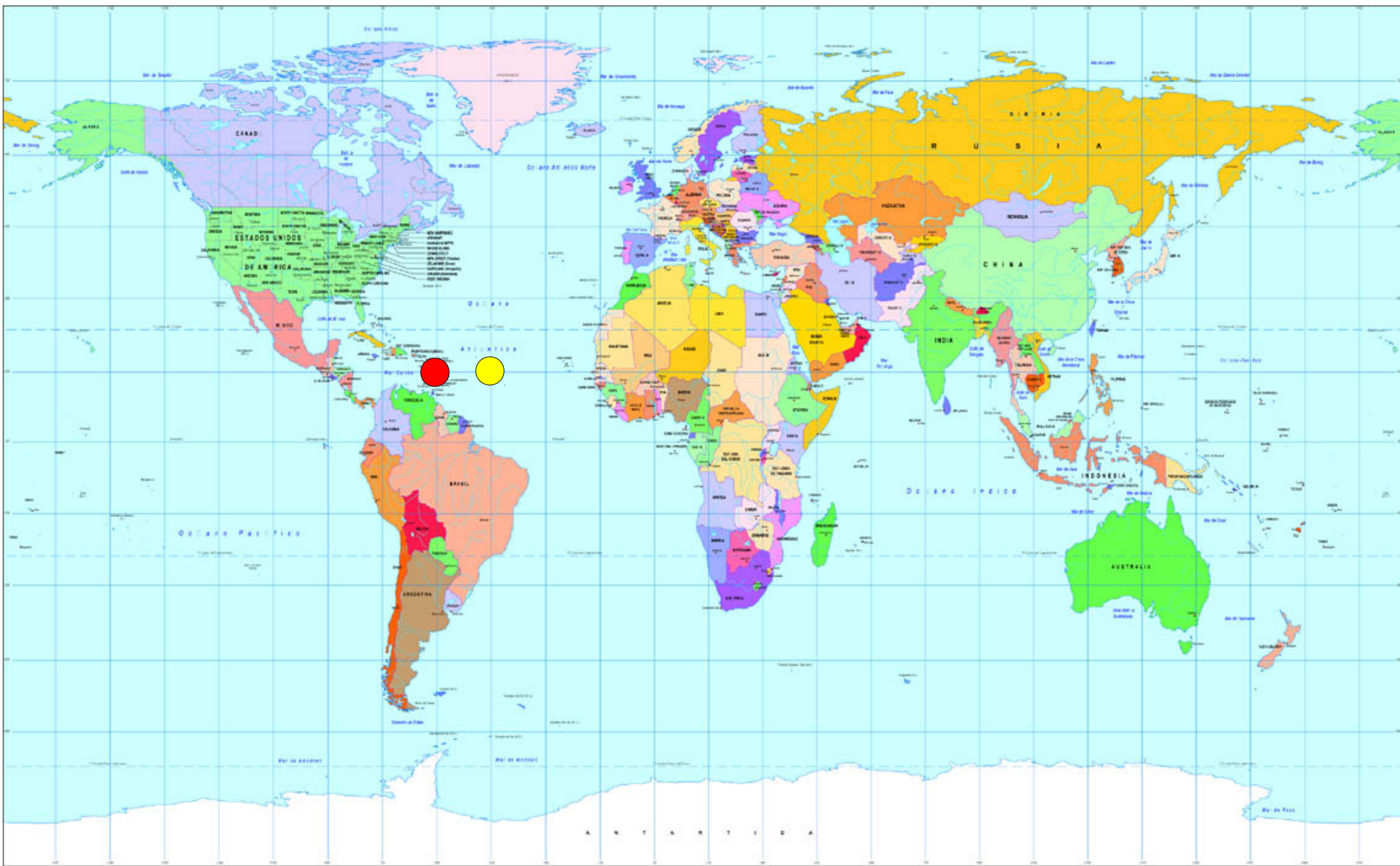


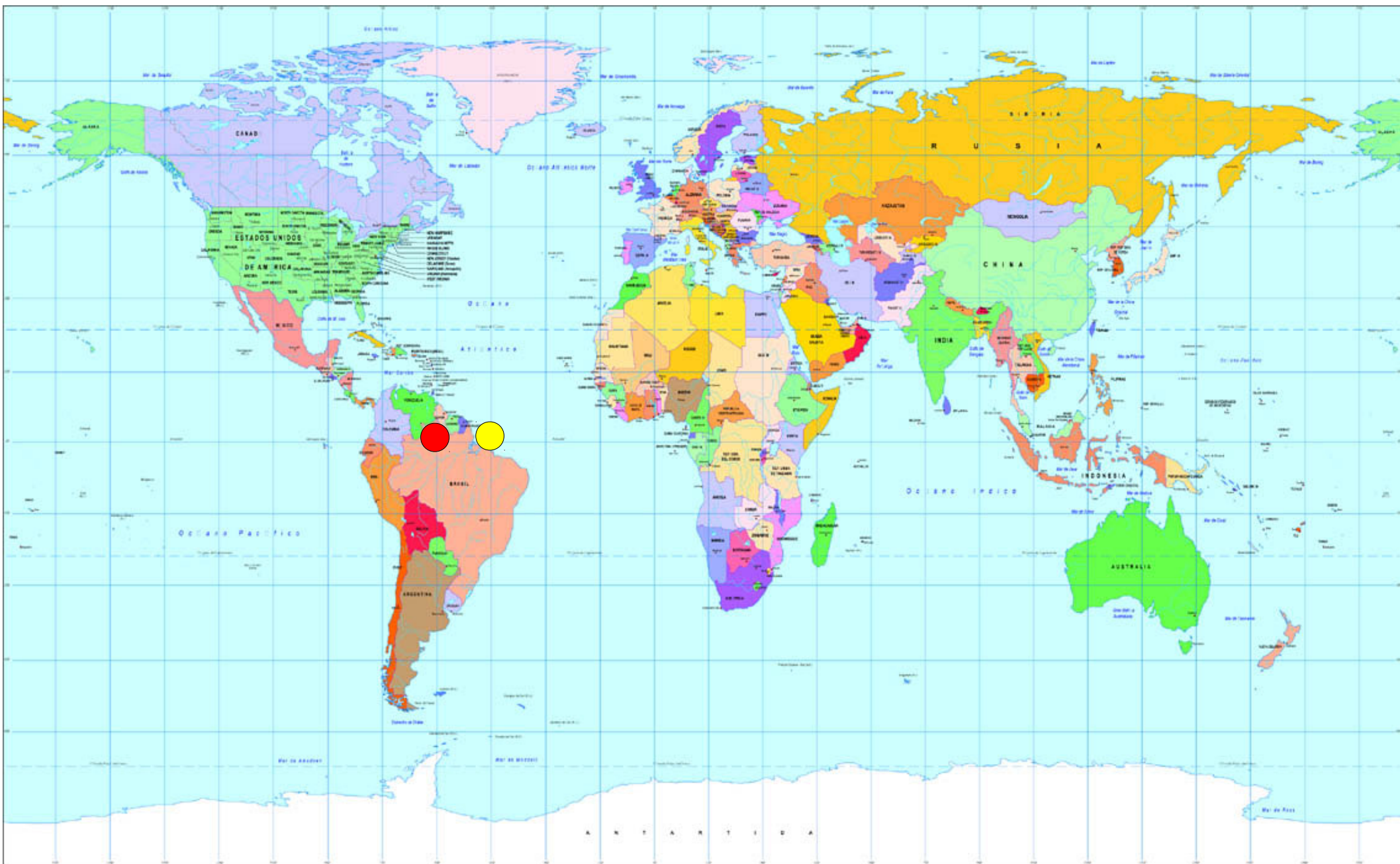


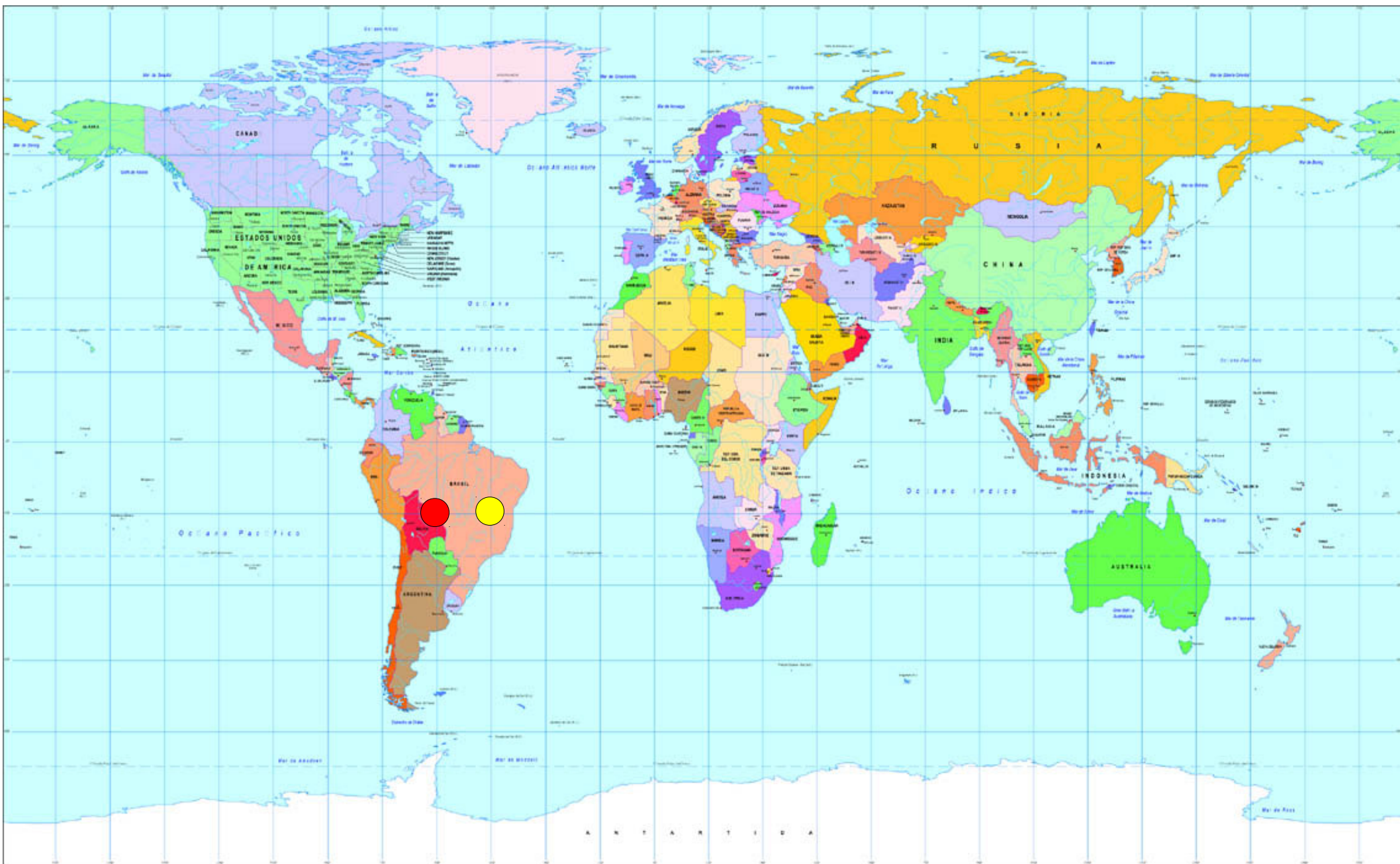






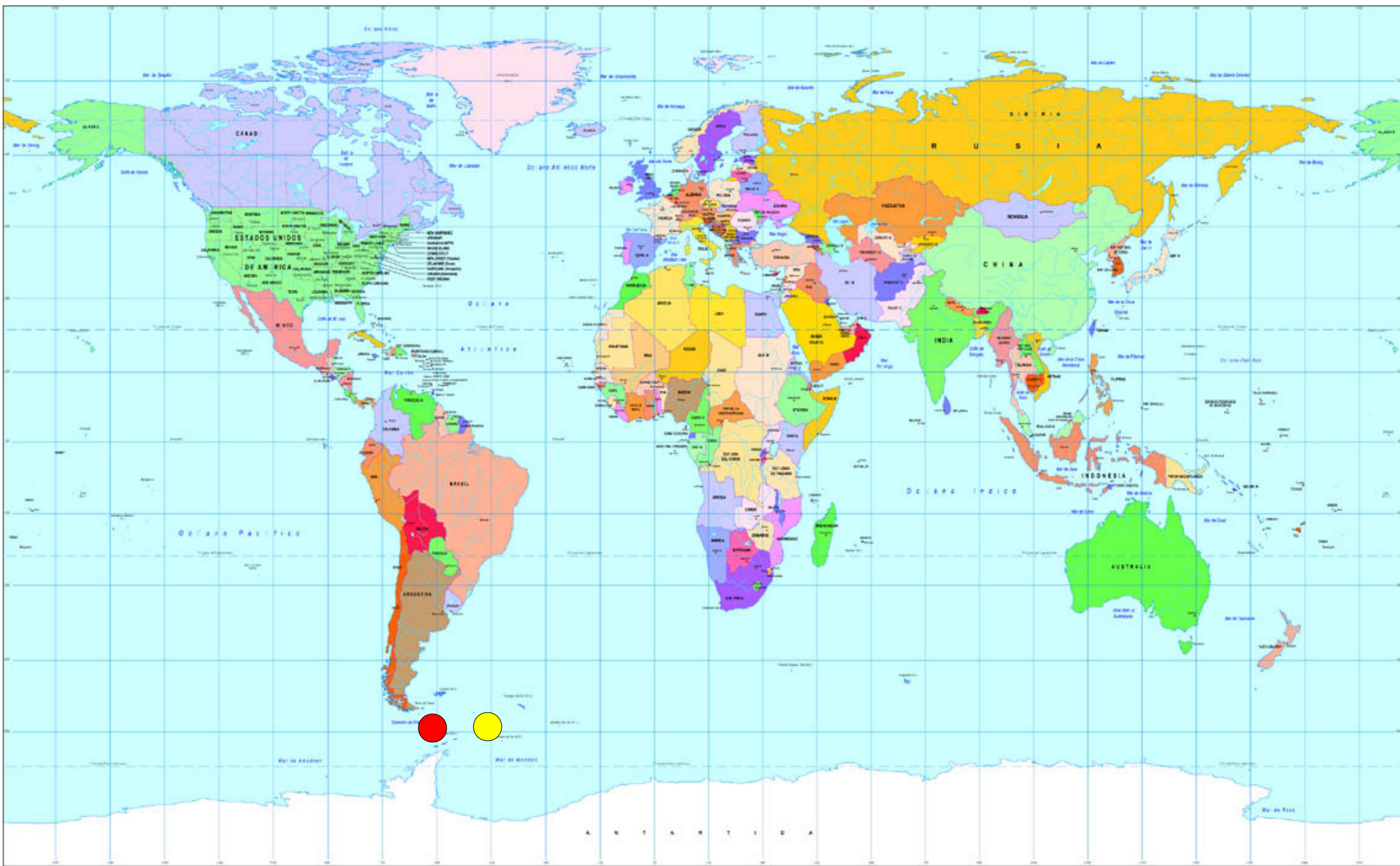




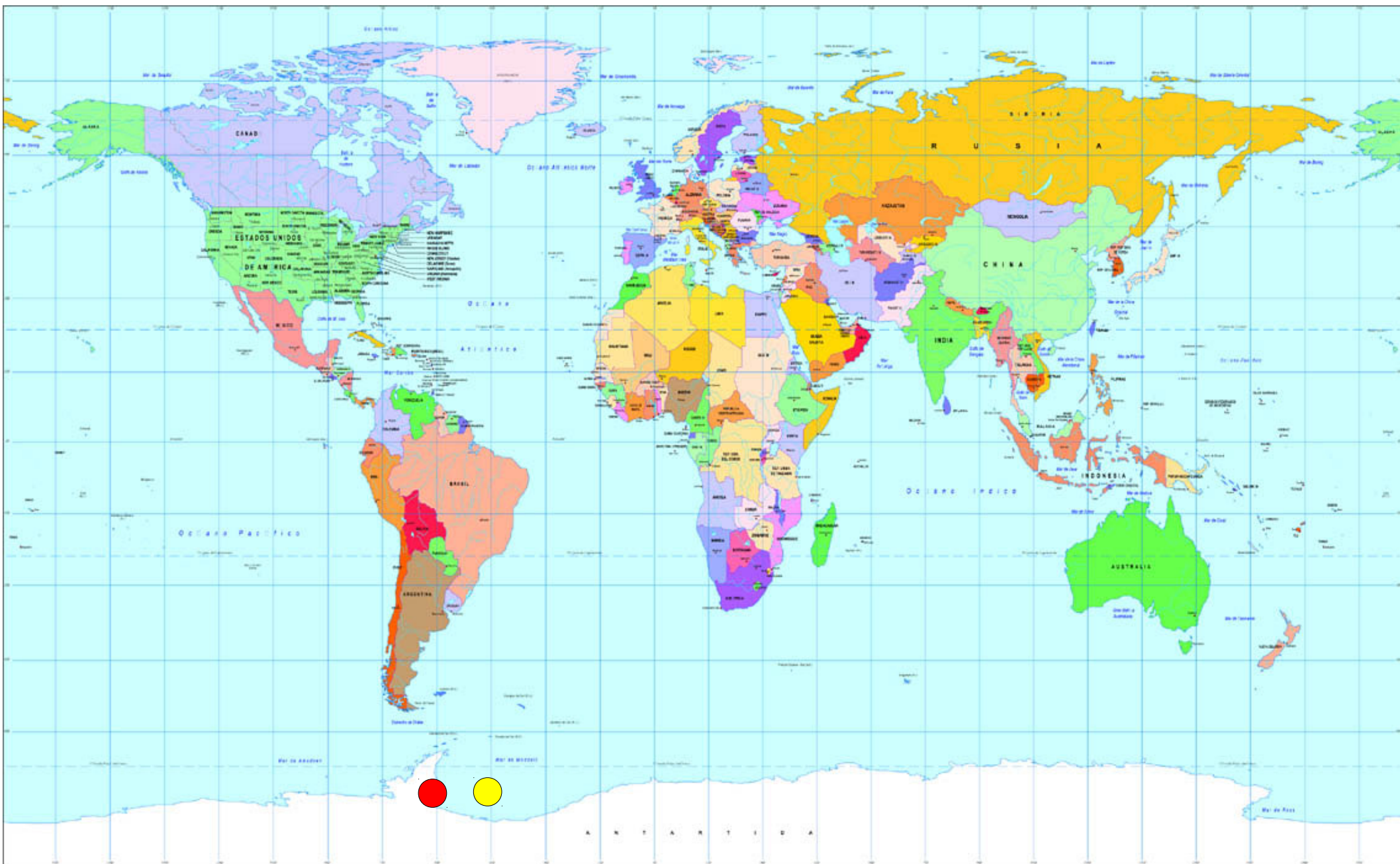












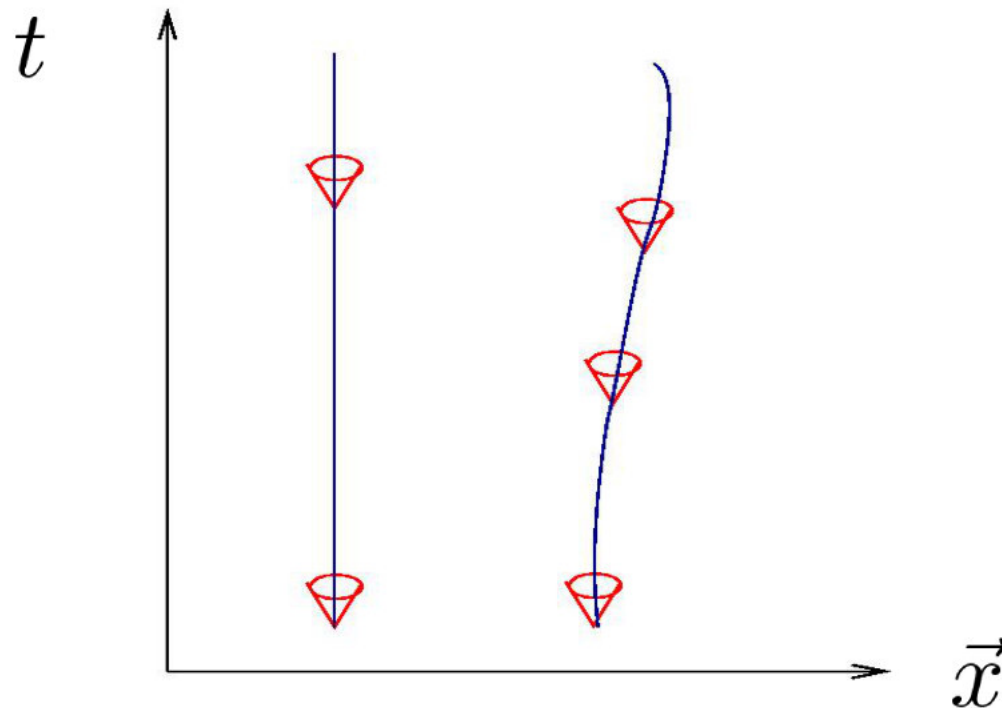
Nesta nova geometria,  
não há  
necessidade de introduzir  
uma força gravitacional!

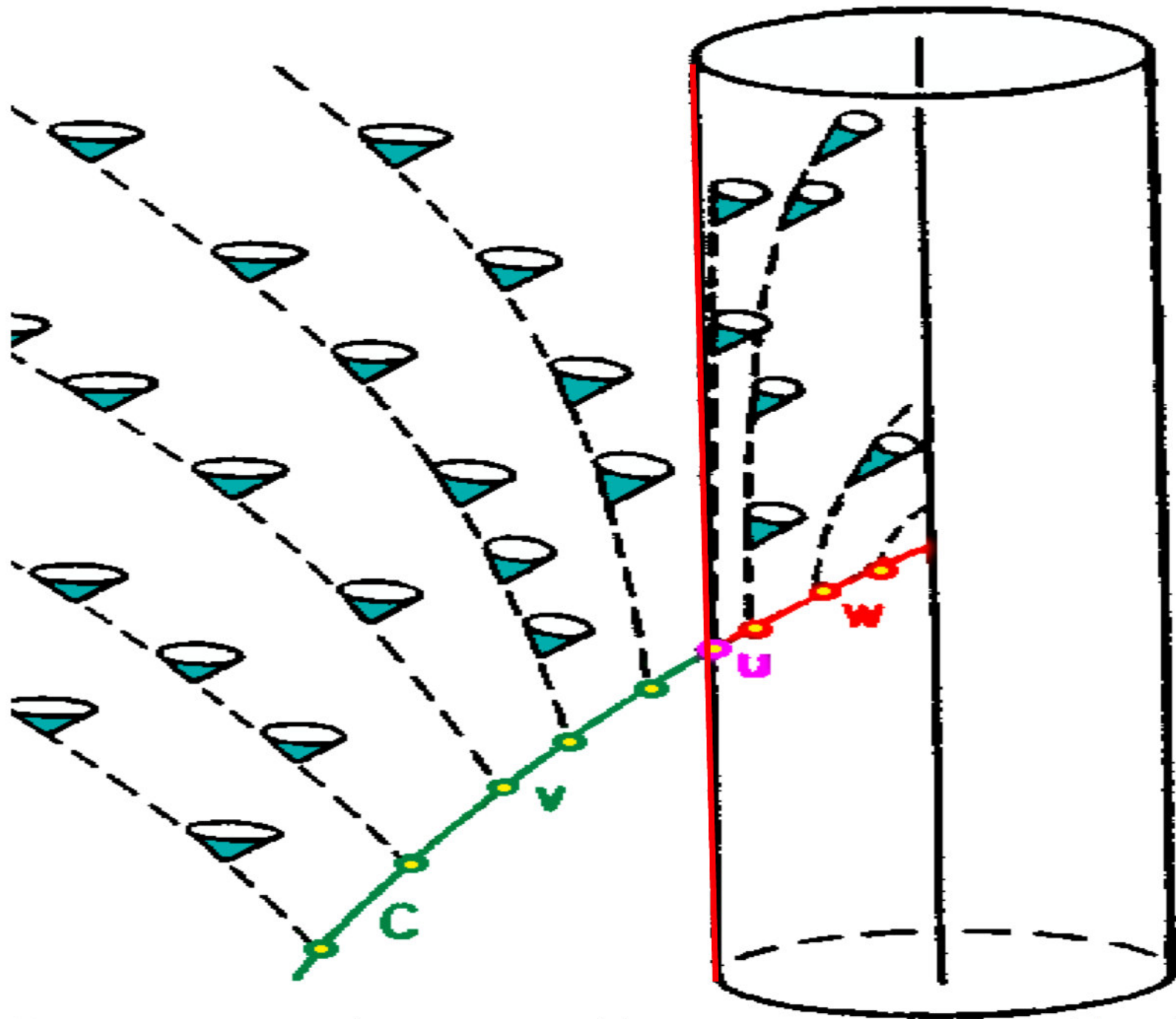




Estes efeitos são maiores  
próximos a grandes massas

- **Buracos negros**
  - **Clássicos**
  - **Relativísticos**
  - **Origem estelar ou cosmológica**



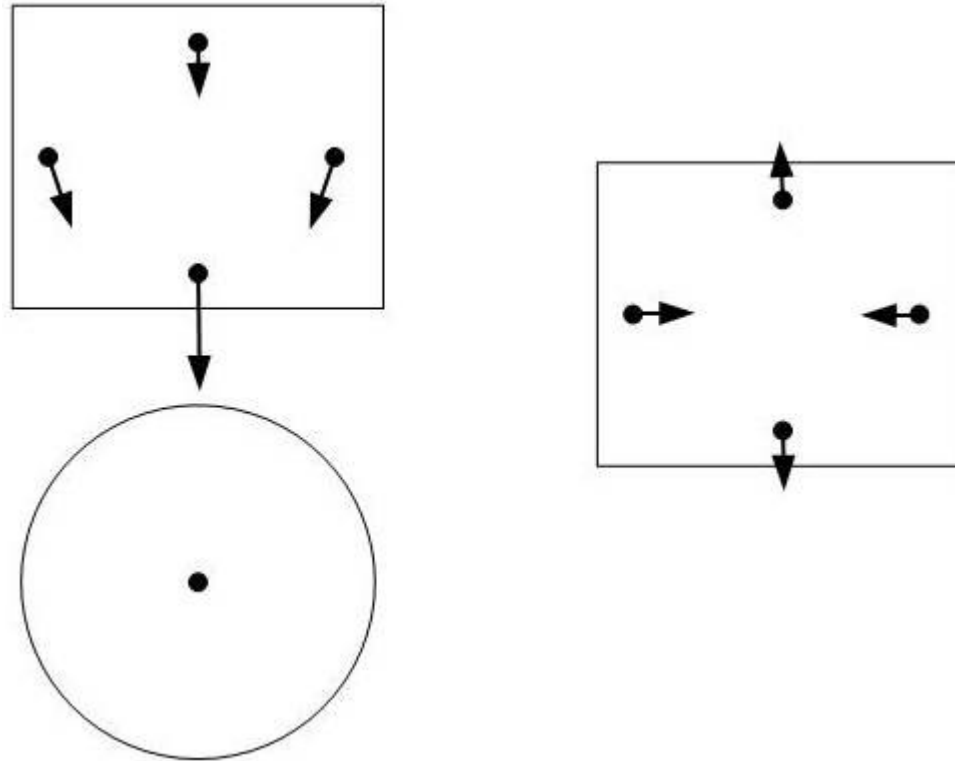


<http://www.phy.syr.edu/courses/modules/LIGHTCONE/schwarzschild.html>

**Horizonte de eventos  
não é uma barreira!**



- efeitos de maré

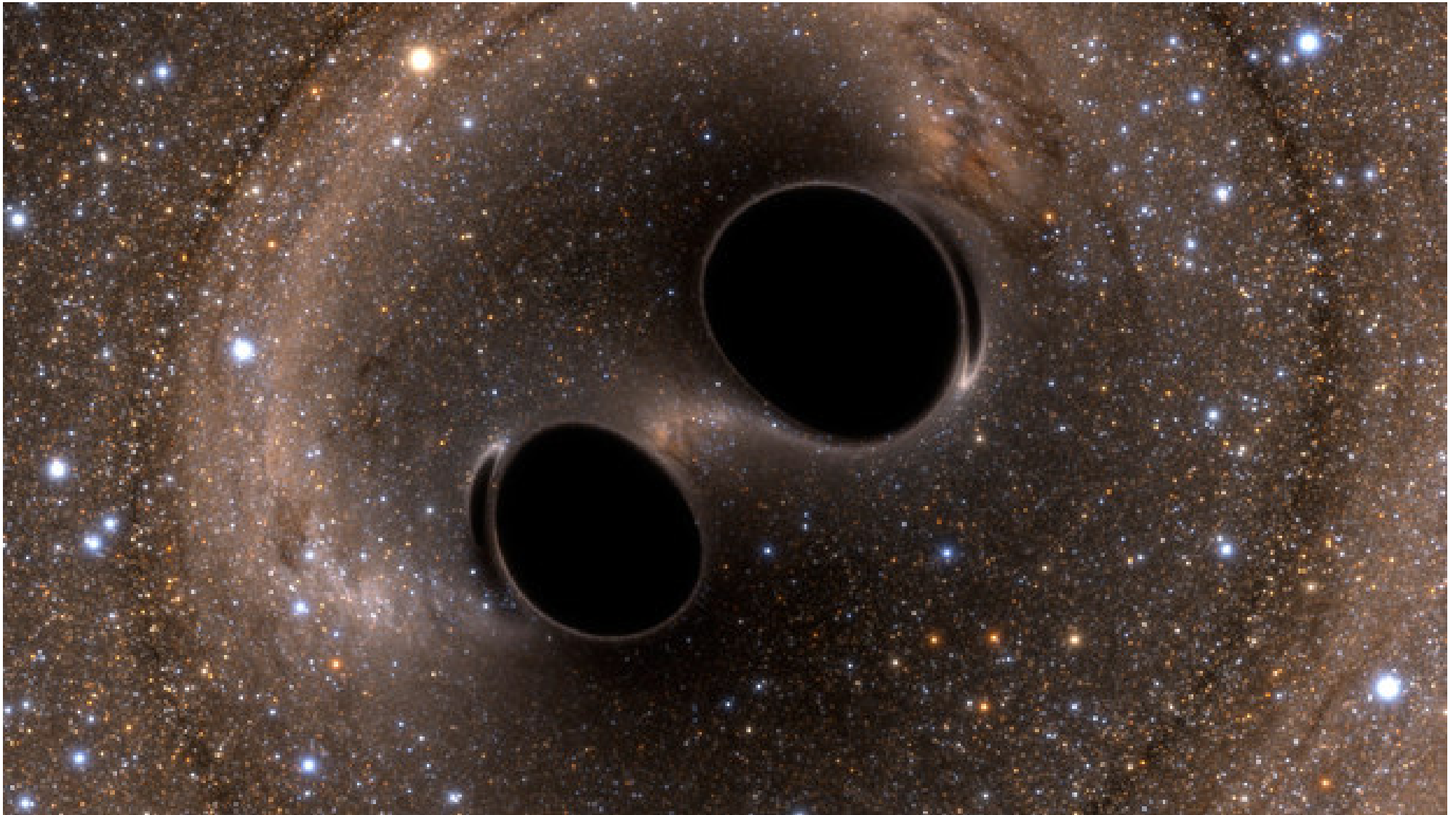


<http://quantumrelativity.calsci.com/Physics/SpaceAndTime2.html>

# Radiação Hawking

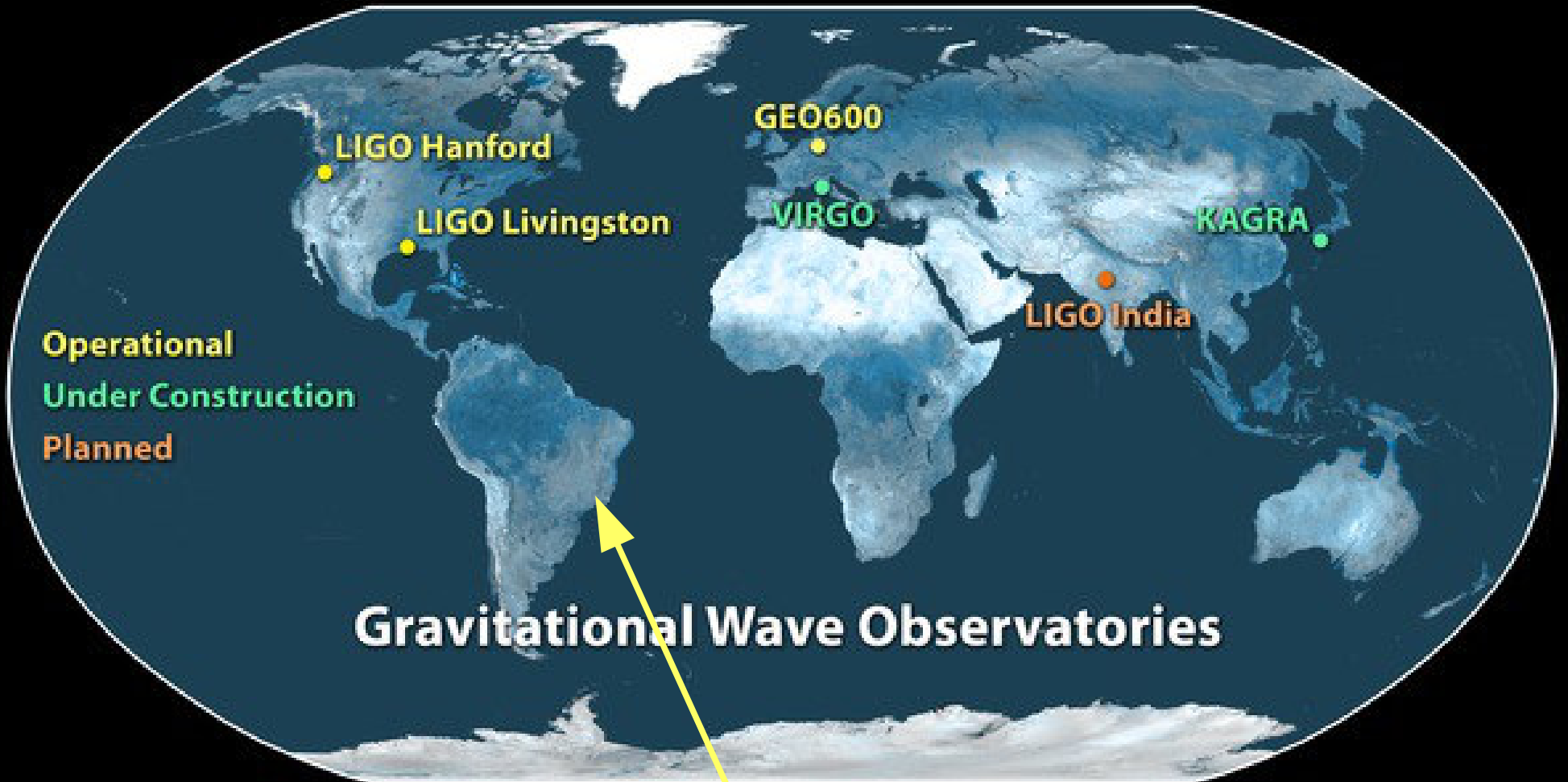
- criação de pares partícula-antipartícula
- taxa de criação  $\sim \frac{1}{M_{BN}}$
- final ( $M \rightarrow 0$ ): **?!?!?!**

# LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY



# Participação Brasileira

- Odylio Denys de Aguiar (Pesquisador Titular III, servidor do INPE)
- Marcos André Okada (Tecnico III, servidor do INPE)
- César Augusto Costa (Pos-doc, bolsista do CNPq)
- Márcio Constâncio Jr (aluno de doutorado do curso de pós-graduação em Astrofísica do INPE, bolsista da FAPESP)
- Elvis Camilo Ferreira (aluno de doutorado do curso de pós-graduação em Astrofísica do INPE, bolsista da CAPES)
- Allan Douglas dos Santos Silva (aluno de iniciação científica, bolsista da FAPESP)
- Riccardo Sturani (ICTP-SAI FR, no IFT-UNESP, bolsista "Jovem Pesquisador" da FAPESP)

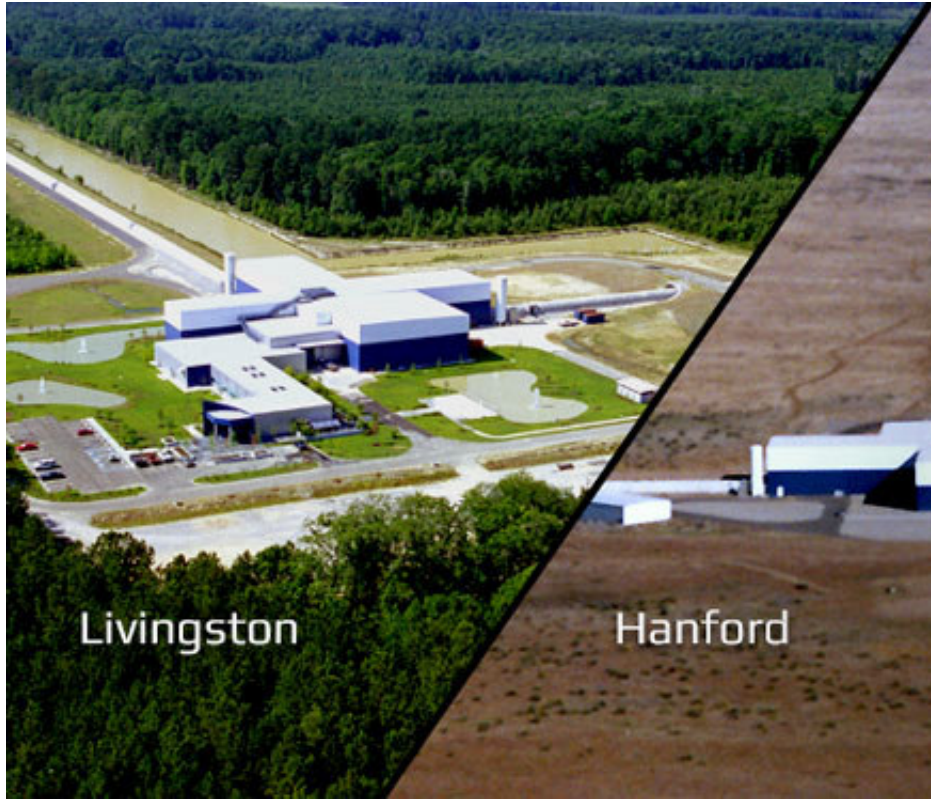


**Operational**  
**Under Construction**  
**Planned**

# Gravitational Wave Observatories

**Schenberg**

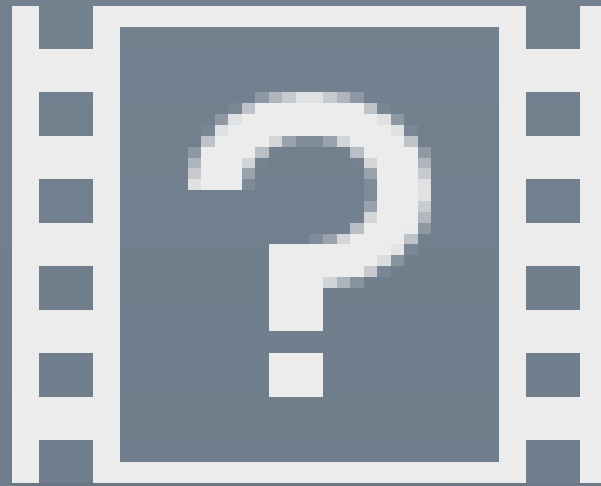




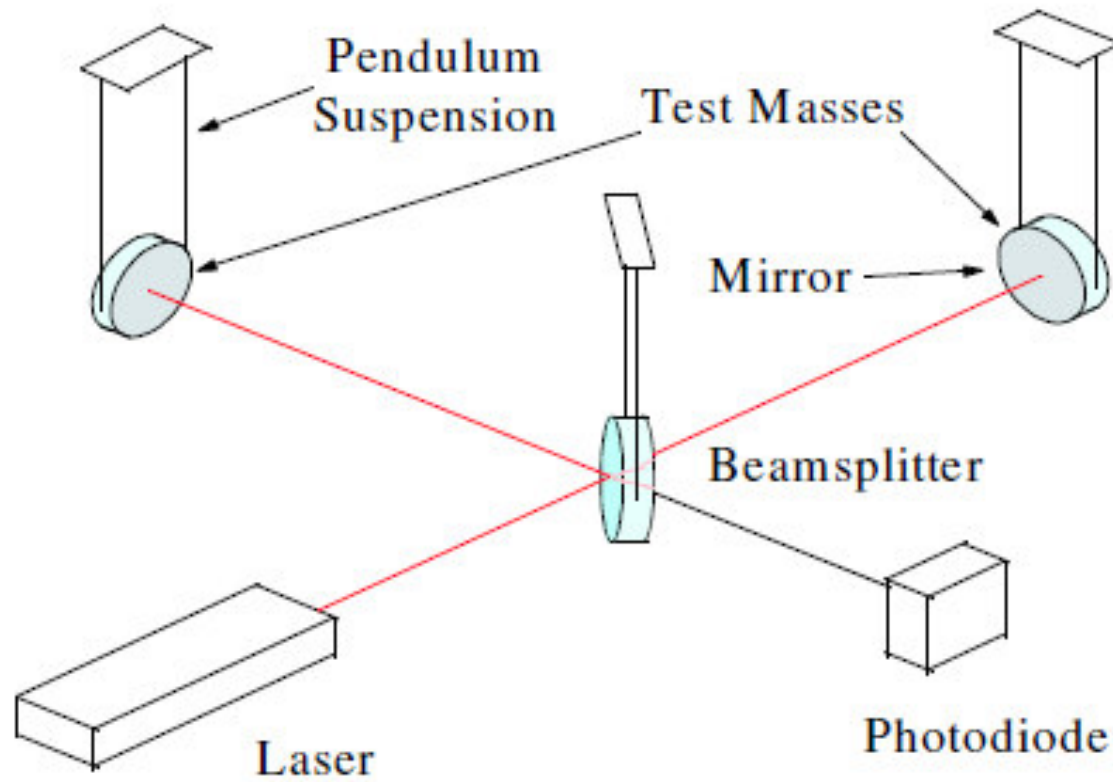
Livingston



Hanford

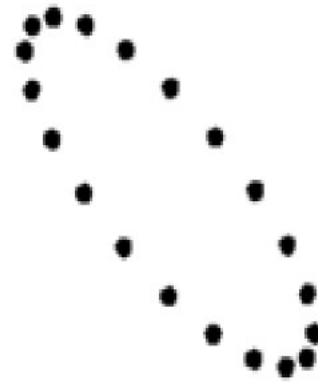
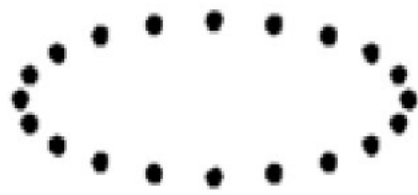


<https://youtu.be/FIDtXIBrAYE>



**Figure 3:** Schematic of gravitational-wave detector using laser interferometry.





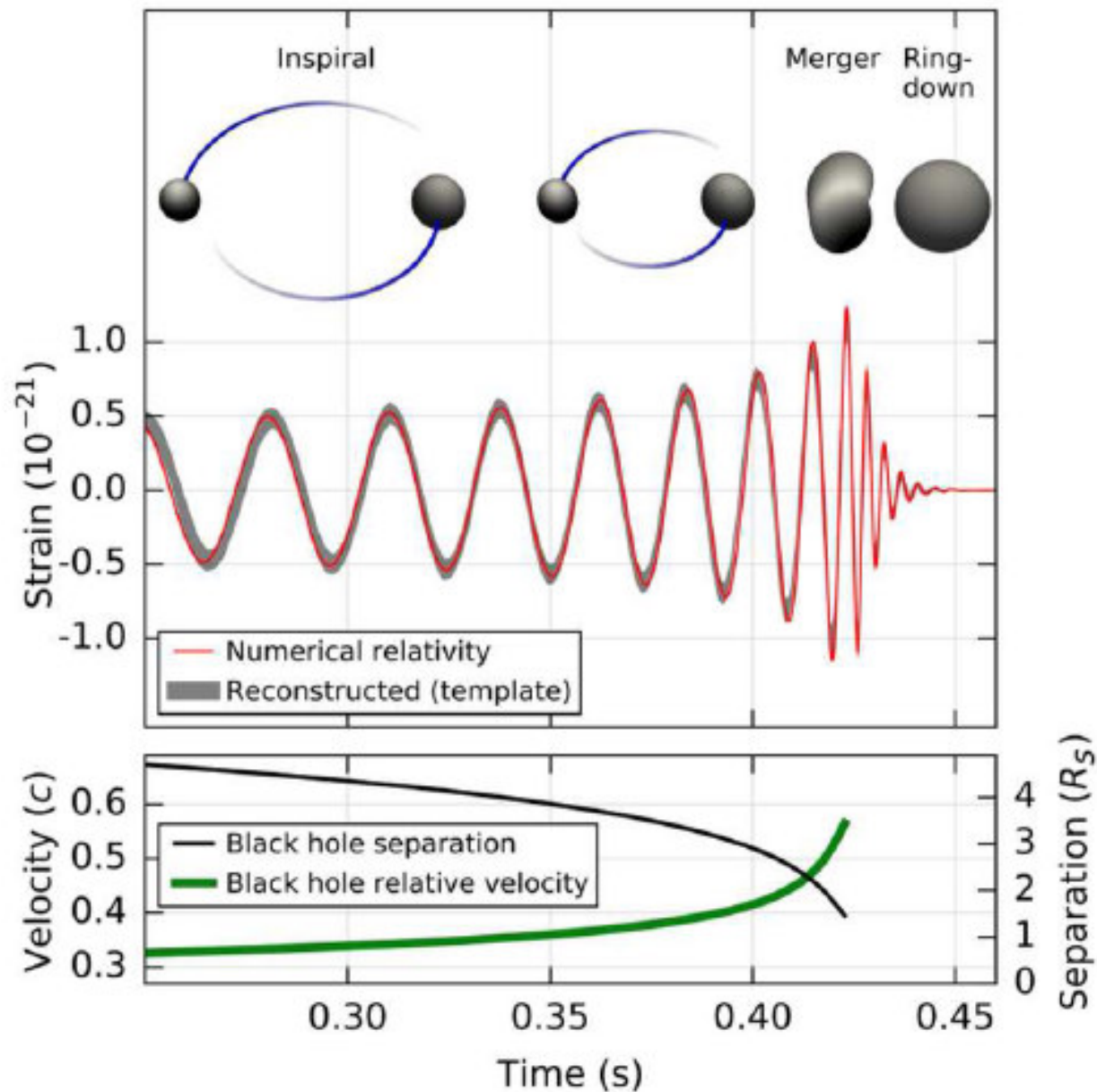
$$h = 2 \frac{\Delta L}{L}$$

$$h(t) = \int |\tilde{h}(f)|^2 df$$

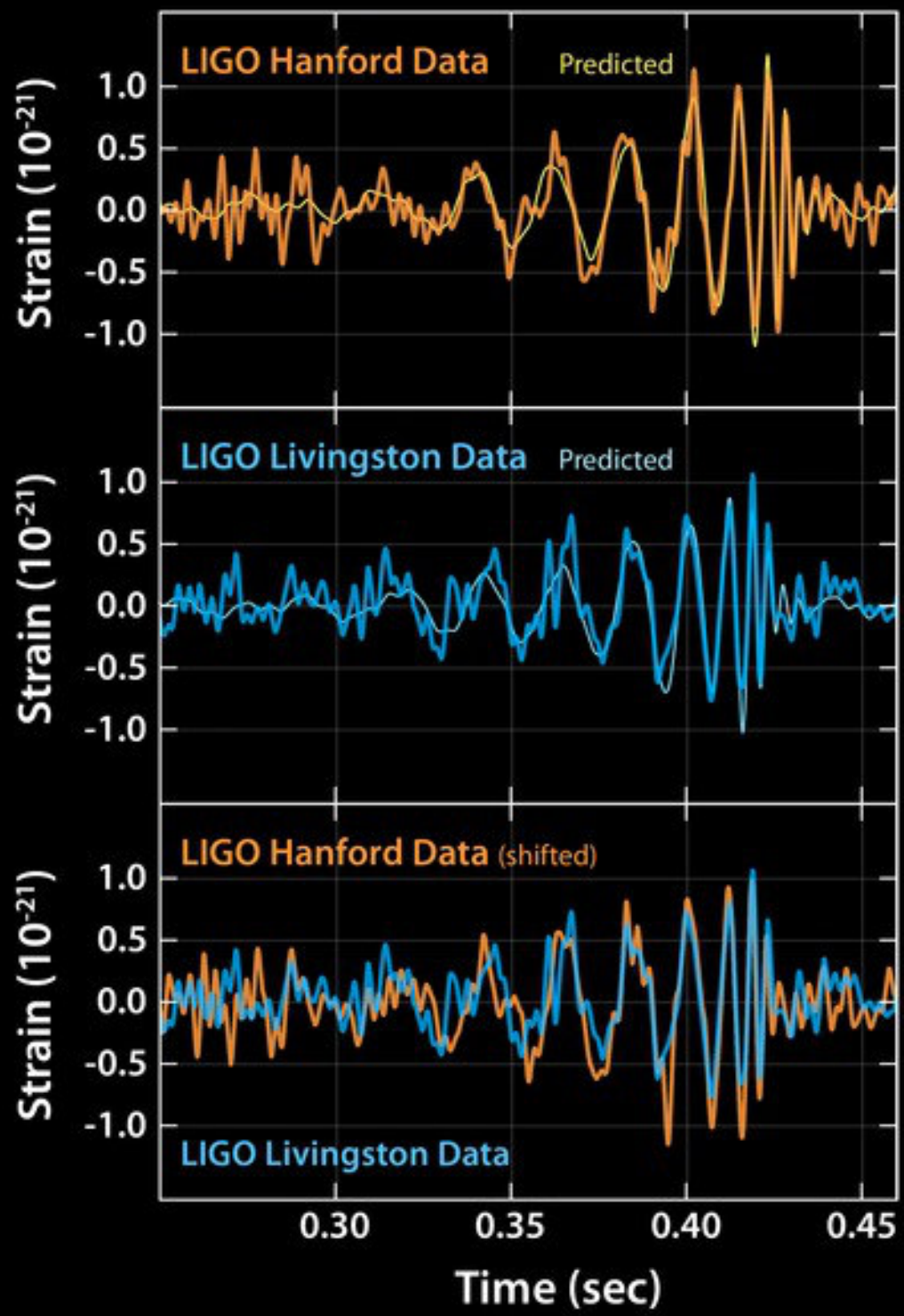
$$[\tilde{h}] = \text{Hz}^{-1/2}$$

$$h \approx 10^{-21} \iff \Delta L \approx 10^{-18} m$$





**Figure 3.** Some key results of our analysis of GW150914, comparing the reconstructed gravitational-wave strain (as seen by H1 at Hanford) with the predictions of the best-matching waveform computed from general relativity, over the three stages of the event: inspiral, merger and ringdown. Also shown are the separation and velocity of the black holes, and how they change as the merger event unfolds.



# FACT SHEET

<b>observed by</b>	<b>LIGO L1, H1</b>
<b>source type</b>	<b>black hole (BH) binary</b>
<b>date</b>	<b>14 Sept 2015</b>
<b>time</b>	<b>09:50:45 UTC</b>
<b>likely distance</b>	<b>0.75 to 1.9 Gly 230 to 570 Mpc</b>
<b>redshift</b>	<b>0.054 to 0.136</b>
<b>signal-to-noise ratio</b>	<b>24</b>
<b>false alarm prob.</b>	<b>&lt; 1 in 5 million</b>
<b>false alarm rate</b>	<b>&lt; 1 in 200,000 yr</b>
<b>signal arrival time delay</b>	<b>arrived in L1 7 ms before H1</b>
<b>likely sky position</b>	<b>Southern Hemisphere</b>

# FACT SHEET

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<b>false alarm prob.</b>	<b>&lt; 1 in 5 million</b>
<b>false alarm rate</b>	<b>&lt; 1 in 200,000 yr</b>
<b>signal arrival time delay</b>	<b>arrived in L1 7 ms before H1</b>
<b>likely sky position</b>	<b>Southern Hemisphere</b>

(Andrômeda: 2 Mly)

# FACT SHEET

Source Masses	$M_{\odot}$
total mass	60 to 70
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	58 to 67

duration from 30 Hz ~ 200 ms  
# cycles from 30 Hz ~10

peak displacement of interferometers arms  $\pm 0.002$  fm

peak GW luminosity  $3.6 \times 10^{56}$  erg  $s^{-1}$   
radiated GW energy 2.5-3.5  $M_{\odot}$



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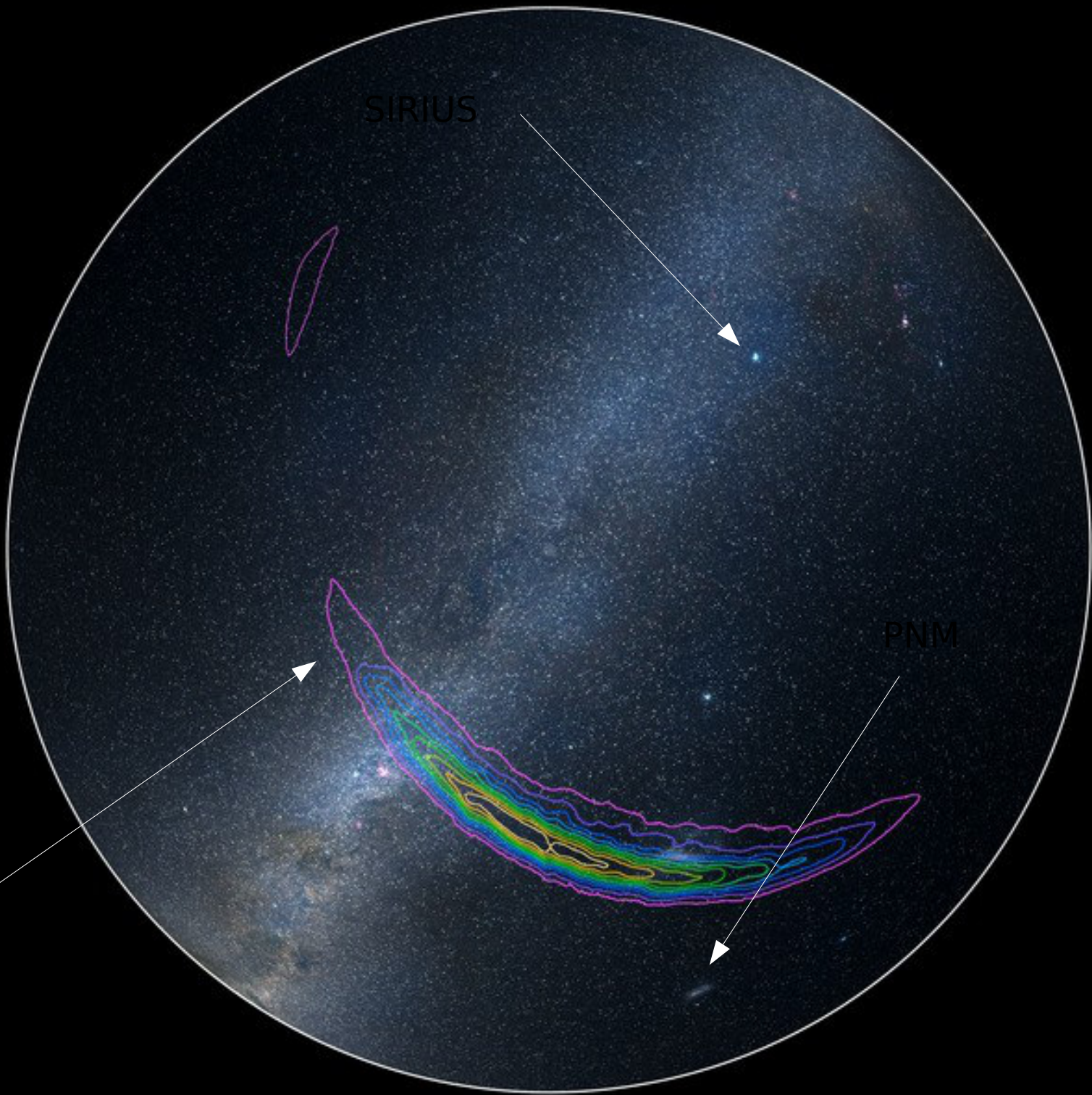
peak displacement of  
interferometers arms  $\pm 0.002$  fm

peak GW luminosity  $3.6 \times 10^{56} \text{ erg s}^{-1}$  ( $\sim 50$  x total energy of universe)  
radiated GW energy 2.5-3.5  $M_{\odot}$

# FACT SHEET

<b>consistent with general relativity? graviton mass bound</b>	<b>passes all tests performed &lt; <math>1.2 \times 10^{-22}</math> eV</b>
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<b>coalescence rate of binary black holes</b>	<b>2 to 400 <math>\text{Gpc}^{-3} \text{yr}^{-1}</math></b>
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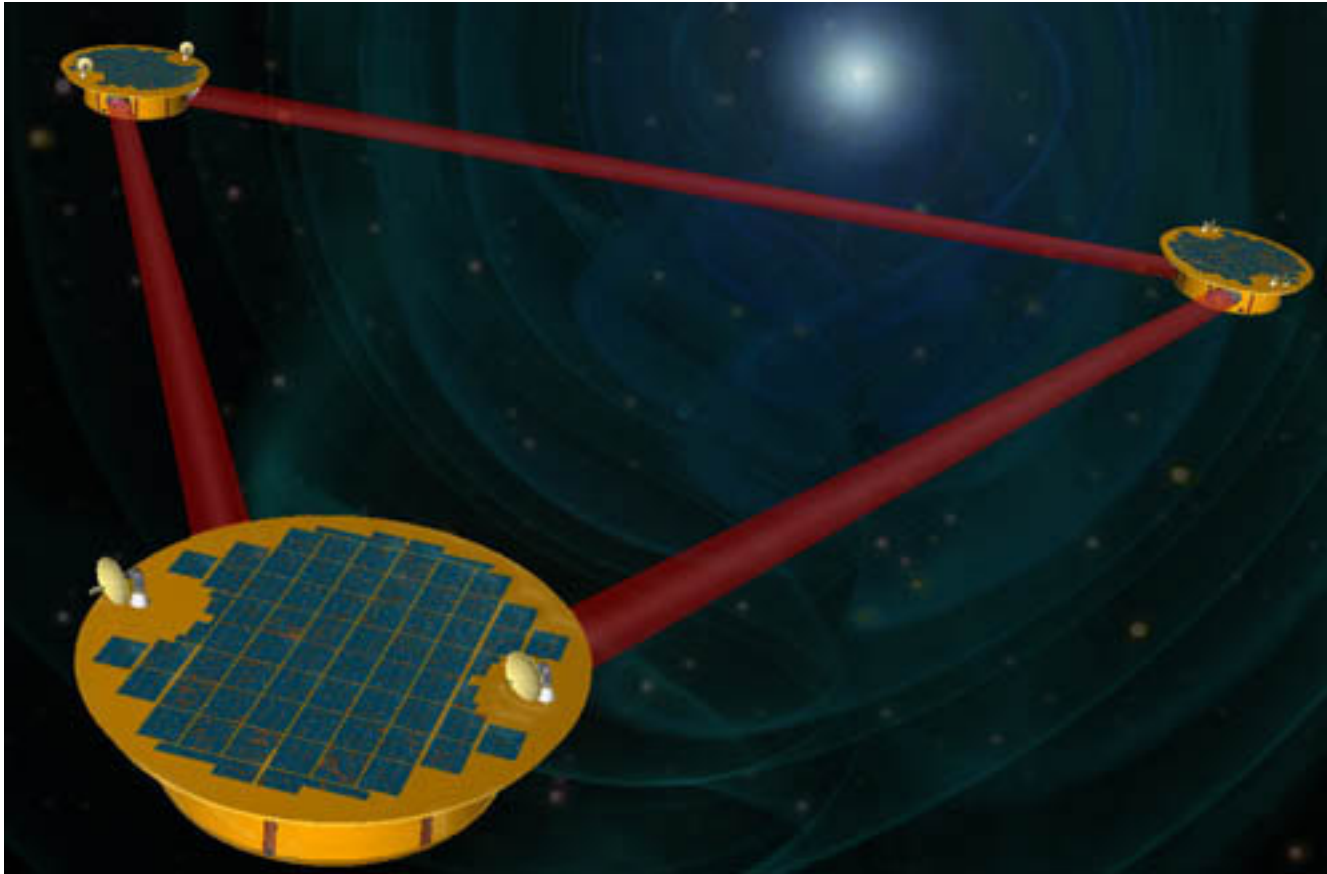
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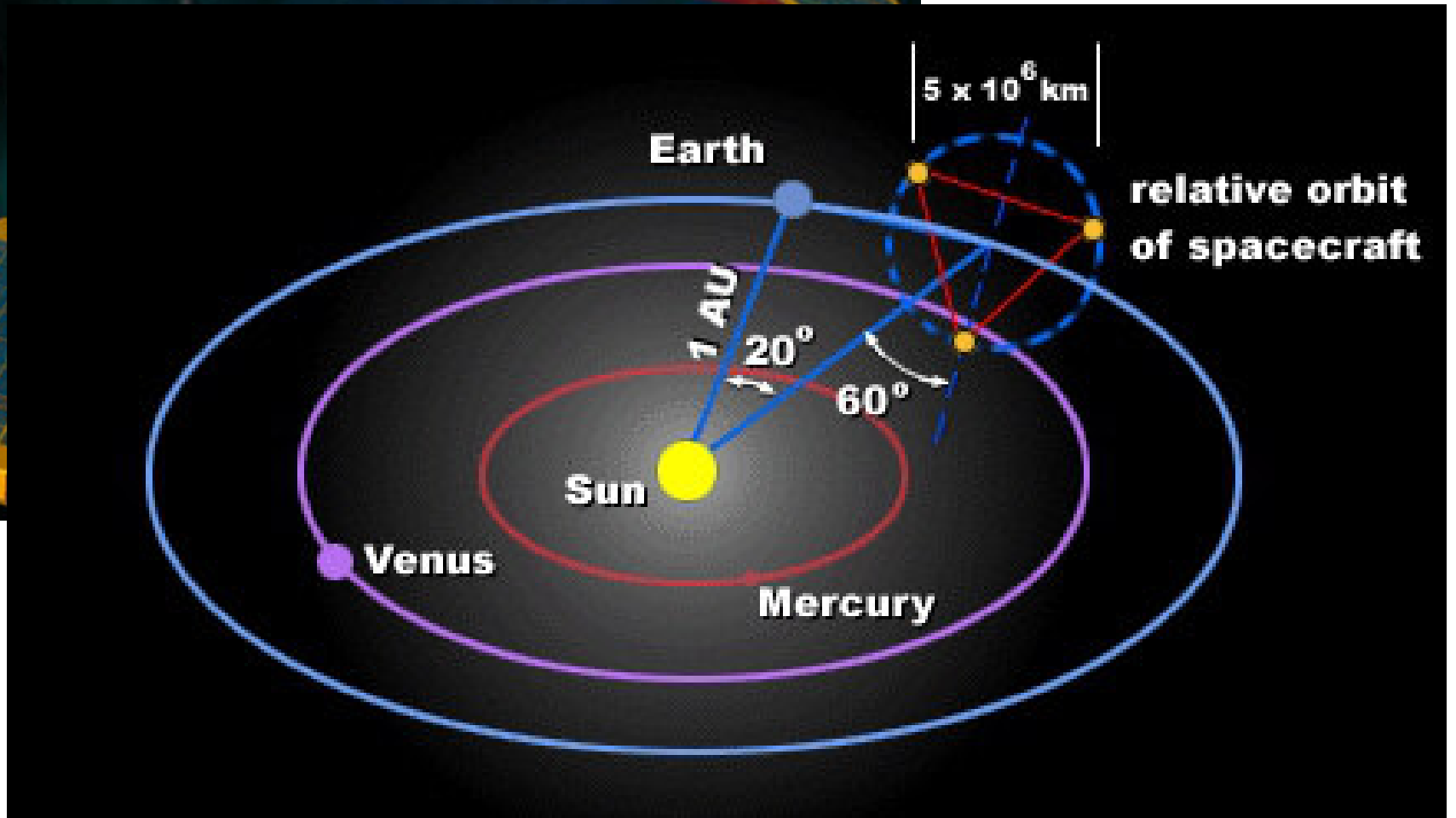
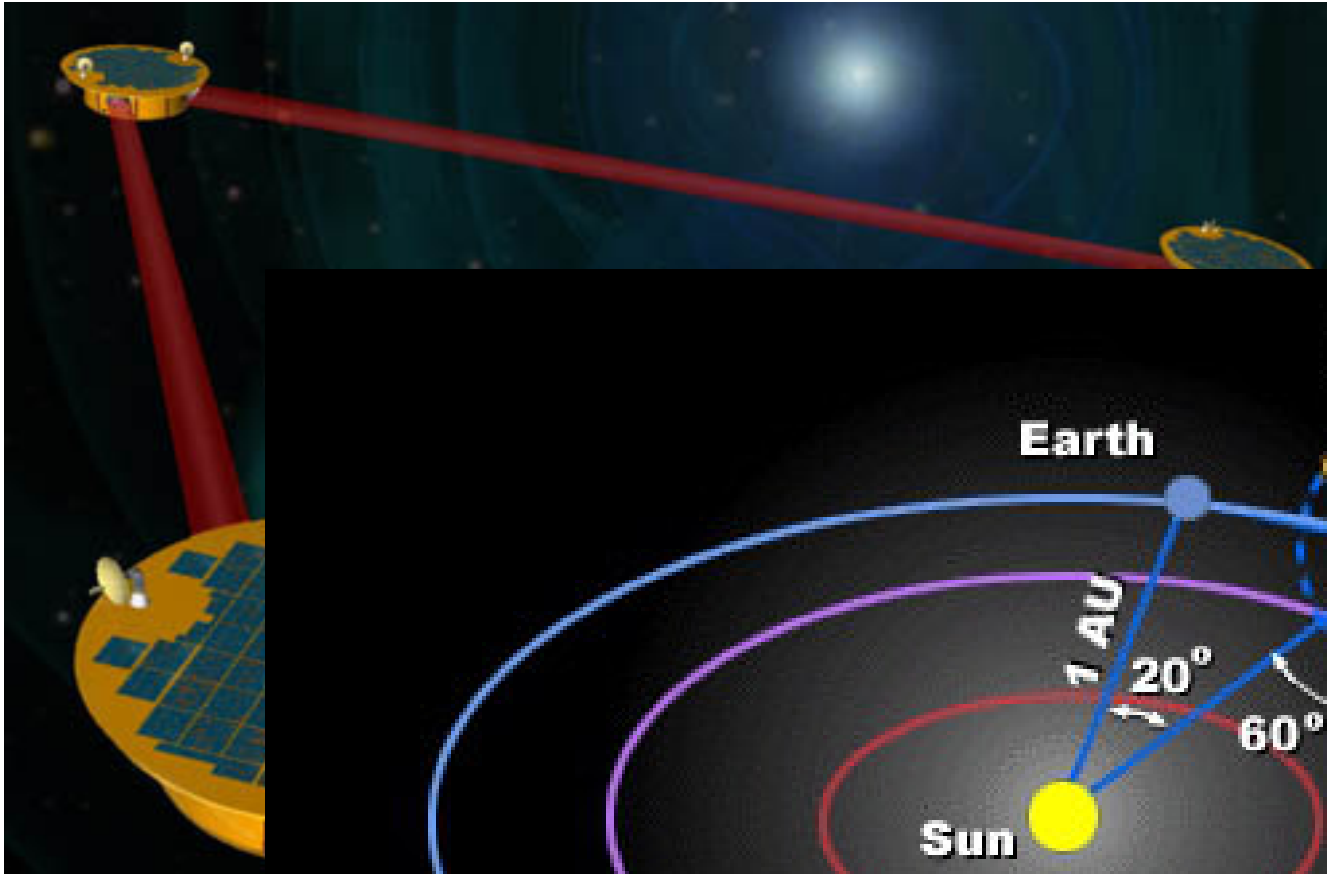
# Conclusões (até agora)

- $c = \text{cte}$ : muito forte, mas é real!
- A relatividade de Einstein ainda está sendo testada
- Ainda há muito o que fazer (vide problemas da **matéria e energia escuras**)!  
~ **96% do universo!**

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