

Universidad Nacional de Río Negro

Int. Partículas, Astrofísica & Cosmología - 2016

- **Unidad** 01 – Relatividad
- **Clase** U01 C01
- **Fecha** 16 Ago 2018
- **Cont** Presentación, introducción, relatividad
- **Cátedra** Asorey
- **Web** <https://asoreyh.github.io/unrn-ipac/>
- **Youtube** <https://goo.gl/UZJzLk>





The image is a horizontal banner illustrating the evolution of the universe. It starts on the left with a bright yellow and orange glow representing the Big Bang, with labels for 'inflationary period', 'quark-hadron transition', and 'lepton-hadron transition'. This transitions into a red and purple field of particles labeled 'quarks', 'gluons', 'leptons', and 'photons'. Next is a section with atomic models labeled 'Hydrogen', 'Helium', and 'Lithium'. This is followed by a blue and purple space filled with galaxies, with labels for 'dark matter' and 'dark energy acceleration'. The right side of the banner shows a dark blue space with galaxies and labels for 'dark energy acceleration' and 'cosmic expansion'. The word 'Presentación' is written in large white letters on the right side of the banner.

Presentación



Colegas contando algunas experiencias

- Hernán Asorey

<hasorey@unrn.edu.ar> <asoreyh@gmail.com>

- Centro Atómico Bariloche e Instituto Balseiro:
líneas: Aplicaciones de Detectores de Partículas: Meteorología Espacial, Muongafía de Volcanes, Física Médica
- UNRN
Profesor Asociado, Física Moderna A; **Introducción a la Física de Partículas, Astrofísica y Cosmología (IPAC)**

A horizontal banner image depicting the evolution of the universe from the Big Bang to the present. It starts with a bright yellow-orange sphere on the left, representing the initial state, and transitions through various stages of expansion and cooling, including the formation of atoms and galaxies, to a dark blue space filled with distant galaxies on the right. Labels like 'SPACE', 'TIME', 'Dark matter', and 'Dark energy' are visible.

Charla abierta



Objetivos y metodología

- **Objetivos**
 - Adquirir una perspectiva del estado actual de la Física de Partículas, la Astrofísica y la Cosmología, a un nivel introductorio y que produzca las herramientas para su implementación en el aula de escuelas medias.
- **Metodología (orientada al trabajo grupal)**
 - Clases interactivas, virtuales y presenciales
 - Prácticas en clase y en casa

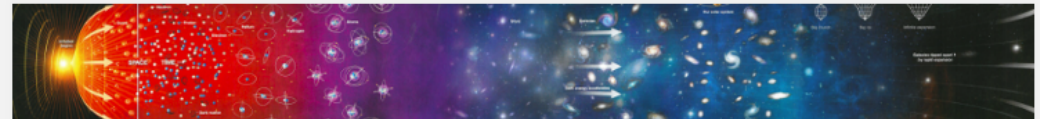
Puntos de contacto

- **Las clases:**
 - Jueves 20 a 23
 - Una hora a definir
- **La Bibliografía:**
 - Depende de la unidad
 - Apuntes de clase
 - Wikipedia

unrn-ipac

El curso de Astrofísica y Cosmología de la UNRN

[View on GitHub](#)



Introducción a Partículas, Astrofísica y Cosmología - Segundo semestre de 2018

Asignatura del cuarto año de la carrera de Profesorado en Física [Universidad Nacional de Río Negro](#)

Las clases fueron realizados en [LibreOffice Impress](#), la herramienta de presentaciones de [LibreOffice](#). Para poder visualizar correctamente las clases, por favor descarguelo siguiendo el este enlace: [Descargue LibreOffice](#). En Windows, puede ser necesario descargar también la fuente [Cabin](#). Para facilitar la difusión, se incluyen también versiones de las clases en formato pdf. Para visualizarlo, podría necesitar descargar [Acrobat Reader](#).

Clases

[Guías de ejercicios](#)



<https://asoreyh.github.io/unrn-ipac/>



IPAC2018



Formas de Aprobación...

- **Evaluación continua (60%)**
 - Participación en clases y laboratorios
 - Entrega de prácticos
 - Charla presentando un tema a elección
- **Final integrador (40%)**
- **Promoción, cumpliendo todas estas condiciones:**
 - Entrega del 100% de los prácticos en tiempo y forma, cumpliendo con las fechas pactadas
 - Entrega del 100% de los informes en tiempo y forma, cumpliendo con las fechas pactadas
 - Nota Evaluación Continua > 7.9
 - Dispone de un (y sólo un) “comodín” para las entregas



Contenidos mínimos

- **Los contenidos mínimos según su plan:**
Estrellas y galaxias. Evolución de las estrellas nacimiento y muerte de las estrellas. Relatividad general: gravedad y la curvatura del espacio. El universo en expansión. El Big-Bang y el fondo cósmico de microondas. El modelo estándar cosmológico. Los primeros tiempos del universo

Contenidos: un viaje en el tiempo

HOW DID OUR UNIVERSE BEGIN?

Some 13.8 billion years ago our entire visible universe was contained in an unimaginably hot, dense point a billionth the size of a nuclear particle. Since then it has expanded—a lot—fighting gravity all the way.

Inflation
In far less than a nanosecond, a repulsive energy field inflates space to visible size and fills it with a soup of subatomic particles called quarks.
Age: 10^{-32} milliseconds
Size: Infinitesimal to golf ball

Early building blocks
The universe expands, cools. Quarks clump into protons and neutrons, the building blocks of atomic nuclei. Perhaps dark matter forms.
Age: 0.1 milliseconds
Size: 0.1-trillionth present size

First nuclei
As the universe continues to cool, the lightest nuclei, of hydrogen and helium, arise. A thick fog of particles blocks all light.
Age: 0.01 to 200 seconds
Size: 1-billionth present size

First atoms, first light
As electrons begin orbiting nuclei, creating atoms, the glow from our infant universe is unveiled. This light is as far back as our instruments can see.
Age: 380,000 years
Size: .0009 present size

The "dark ages"
For 300 million years this cosmic background radiation is the only light. Clumps of matter that will become galaxies glow brightly.
Age: 380,000 to 300 million years
Size: .0009 to 0.1 present size

Gravity wins: first stars
Dense gas clouds collapse under their own gravity—and that of dark matter—to eventually form galaxies and stars. Nuclear fusion lights up the stars.
Age: 300 million years
Size: 0.1 present size

Antigravity wins
After being slowed for billions of years by gravity, cosmic expansion accelerates again. The output: dark energy, its nature: unclear.
Age: 10 billion years
Size: .77 present size

Today
The universe continues to expand, becoming ever less dense. As a result, fewer new stars and galaxies are forming.
Age: 13.8 billion years
Size: Present size

HOW WILL IT END?

Which will win in the end, gravity or antigravity? Is the density of matter enough for gravity to halt or even reverse cosmic expansion, leading to a big crunch? It seems unlikely—especially given the power of dark energy, a kind of antigravity. Perhaps the acceleration in expansion caused by dark energy will trigger a big rip that shreds everything, from galaxies to atoms. If not, the universe may expand for hundreds of billions of years, long after all stars have died.



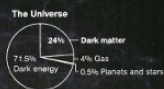
Galaxies ripped apart by rapid expansion

COSMIC QUESTIONS

In the 20th century the universe became a story—a scientific one. It had always been seen as static and eternal. Then astronomers observed other galaxies flying away from ours, and Einstein's general relativity theory implied space itself was expanding—which meant the universe had once been denser. What had seemed eternal now had a beginning and an end. But what beginning? What end? Those questions are still open.

WHAT IS OUR UNIVERSE MADE OF?

Stars, dust, and gas—the stuff we can discern—make up less than 5 percent of the universe. Their gravity can't account for how galaxies hold together. Scientists figure about 24 percent of the universe is a mysterious dark matter—perhaps exotic particles formed right after inflation. The rest is dark energy, an unknown energy field or property of space that counteracts gravity, providing an explanation for observations that the expansion of space is accelerating.



WHAT IS THE SHAPE OF OUR UNIVERSE?

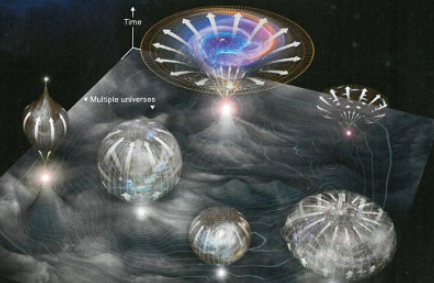
Einstein discovered that a star's gravity curves space around it. But is the whole universe curved? Might space close up on itself like a sphere or curve the other way, opening out like a saddle? By studying cosmic background radiation, scientists have found that the universe is poised between the two: just dense enough with just enough gravity to be almost perfectly flat, at least the part we can see. What lies beyond we can't know.

Observable Universe
The universe began 13.8 billion years ago. Because it has been expanding ever since, the farthest observable edge is now 47 billion light-years away.



DO WE LIVE IN A MULTIVERSE?

What came before the big bang? Maybe other big bangs. The uncertainty principle holds that even the vacuum of space has quantum energy fluctuations. Inflation theory says our universe exploded from such a fluctuation—a random event that, odds are, had happened many times before. Our cosmos may be one in a sea of others just like ours—or nothing like ours. These other cosmos will very likely remain forever inaccessible to observation, their possibilities limited only by our imagination.



Fly through the universe on our digital edition.
LAWSON PARKER, HOW STAFF, IANNA GRIFFITHS AND MICHAEL MATTIOTT
SOURCES: CHARLES BRANETT, JAMES HODGES, UNIVERSITY OF CHICAGO
COPYRIGHT © JUNE 2014 NATIONAL GEOGRAPHIC SOCIETY

Contenidos: un viaje en el tiempo

HOW DID OUR UNIVERSE BEGIN?

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Inflation

In less than a nanosecond, a repulsive energy field inflates space to visible size and fills it with a soup of subatomic particles called quarks.

Age: 10^{-32} milliseconds
Size: Infinitesimal to golf ball

Early building blocks

The universe expands, cools. Quarks clump into protons and neutrons, the building blocks of atomic nuclei. Perhaps dark matter forms.

Age: 0.1 milliseconds
Size: 0.1-trillionth present size

First nuclei

As the universe cools, the protons and neutrons fuse into the first nuclei of hydrogen and helium.

Age: 0.01 to 200 milliseconds
Size: 1-billionth present size

First atoms, first light

As electrons begin orbiting nuclei, creating atoms, the glow from our infant universe is unobscured. This light is as far back as our instruments can see.

Age: 380,000 years
Size: 0.0009 present size

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For 300 million years this cosmic background radiation is the only light. Clumps of matter that will become galaxies glow brightly.

Age: 380,000 to 300 million years
Size: 0.0009 to 0.1 present size

Gravity wins: first stars

Dense gas clouds come under their own gravity of dark matter to event form galaxies and stars. Fusion lights up the stars.

Age: 300 million years
Size: 0.1 present size

Antigravity wins

After being slowed for billions of years by gravity, cosmic expansion accelerates again. The output of dark energy, its nature: unclear.

Age: 10 billion years
Size: 0.77 present size

Today

The universe continues to expand, becoming ever less dense. As a result, fewer new stars and galaxies are forming.

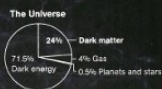
Age: 13.8 billion years
Size: Present size

Unidad 4 El Big Bang Allá lejos y hace tiempo

In the 20th century the universe became a story—a scientific one. It had always been seen as static and eternal. Then astronomers observed other galaxies flying away from ours, and Einstein's general relativity theory implied space itself was expanding—which meant the universe had once been denser. What had seemed eternal now had a beginning and an end. But what beginning? What end? Those questions are still open.

WHAT IS OUR UNIVERSE MADE OF?

Matter, dust, and gas—the stuff we can discern—make up less than 5 percent of the universe. Their gravity can't account for how galaxies hold together. Scientists figure about 24 percent of the universe is a mysterious dark matter—perhaps exotic particles formed right after inflation. The rest is dark energy, an unknown energy field or property of space that counteracts gravity, providing an explanation for observations that the expansion of space is accelerating.



Unidad 3 Cosmología No es lo que se ve Sino lo que se palpa

Observable Universe

The universe began 13.8 billion years ago. Because it has been expanding ever since, the farthest observable edge is now 47 billion light-years away.

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The Unknown Edge

What we can't see possible shapes



Unidad 2 Astrofísica Cálido y frío

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HOW WILL IT END?

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Unidad 1 Partículas 1 todo es relativo



Fly through the universe on our digital edition.

LAWRENCE P. KRAUSS, HOW STAFF, KIMBLE, GREGORY, AND MICHAEL B. STOKES, SOURCES: CHARLES BRANNETT, JAMES HOPKINS, UNIVERSITY OF CHICAGO, UNIVERSITY OF CHICAGO, UNIVERSITY OF CHICAGO, UNIVERSITY OF CHICAGO

U1: Todo es relativo

4 encuentros: del 08/Ago al 30/Ago

Relatividad Especial

- Introducción
- Cinemática y Dinámica Relativista
- Física de Partículas, 1ª parte
- Radiactividad
- Planck, Bosones y Fermiones
- Interacciones fundamentales

$E_k = \frac{1}{2} m v^2$ $\tan \vartheta_B = \frac{v_2}{v_1} = \frac{v_{21}}{v_1}$ $\rho V = n R T$ $\vec{\psi} = \iint \vec{D} d\vec{S} = A D$ $H_\lambda = \frac{\Delta M_e}{\Delta \lambda}$

$-\frac{\hbar^2}{2m} \frac{d^2 \psi}{dx^2} + V \psi = E \psi$ $\psi_e = \frac{L}{4\pi r^2}$ $\int \frac{\Delta \varphi}{2\pi} = \frac{\Delta x}{\lambda} = \frac{x_2 - x_1}{\lambda}$ $V = c/\lambda$ $\Phi = NBS$

$U_{ef} = \frac{1}{2} m v^2$ $E = k \frac{q_1 q_2}{r^2}$ $U = \frac{W_{AB}}{q} = \frac{|E_{PA} - E_{PB}|}{q}$ $X_L = \frac{U_m}{I_m} = \omega L = 2\pi f L$ $F_g = \frac{m_1 m_2}{r^2}$

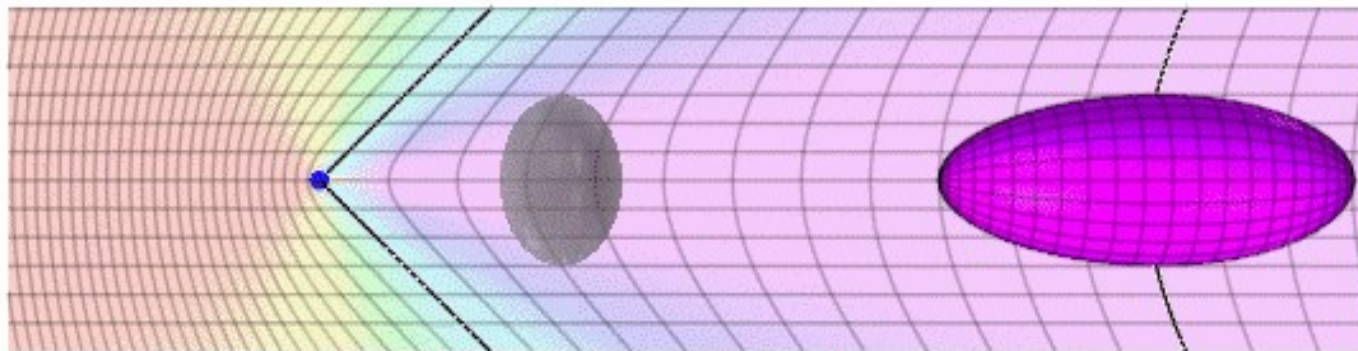
$\vec{B} = \mu_0 \frac{NI}{2\pi r}$ $K = \frac{p^2}{2m}$ $m_0 = \frac{M_m}{N_A} = \frac{M_r \cdot 10^{-3}}{N_A}$ $E = \frac{E_c}{a} \int_{-a/L}^{+a/L} \sin(\omega t + \phi) dy$ $\omega = 2\pi f$

$\lambda = \frac{h}{p}$ $f_0 = \frac{1}{2\pi} \sqrt{\frac{e}{m}}$ $\phi = \frac{2\pi \sin \vartheta}{\lambda}$ $\beta = \frac{\Delta I_c}{\Delta I_B}$ $\phi_e = \frac{\Delta E}{\Delta t} \frac{m_1}{x} + \frac{m_2}{x'} = \frac{m_2 - m_1}{v}$

$E = mc^2$ $\vec{E} \times \vec{B}$ $E_k = \frac{h^2}{8mL^2}$ $\iint \vec{D} d\vec{S} = Q^*$

$\lambda = \frac{h c}{E}$ $F_h = Shp g$ $\left(\frac{E_t}{E_0}\right)_{||} = \frac{2 \cos \vartheta_1 \cos \vartheta_2}{\cos(\vartheta_1 - \vartheta_2) \sin(\vartheta_1 + \vartheta_2)}$ $E_y = E_0 \sin(k_x - \omega t)$ $R = R_0 \sqrt[3]{A}$ $S = \frac{1}{A} \frac{dW}{dt}$

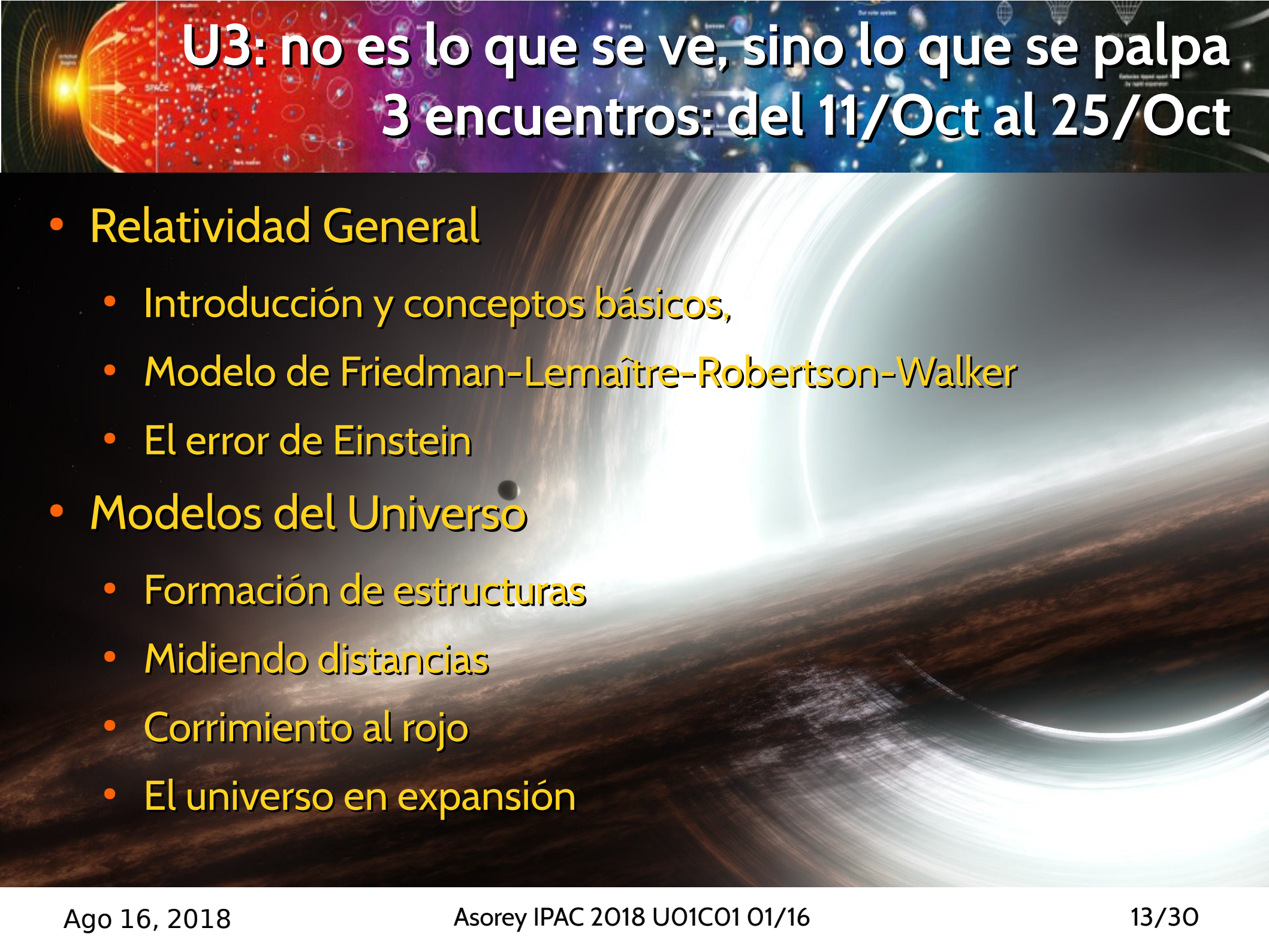
Ago 16, 2018



U2: Cálido y Frío

5 encuentros: del 06/Sep al 04/Oct

- Estrellas
 - Astronomía Observacional: sistemas de coordenadas y mapas estelares
 - Radiación de Cuerpo Negro
 - Ley de Eddington, Clasificación estelar, Diagrama H-R
 - Objetos Compactos y evolución estelar
- Planetas
 - Planetas y Exoplanetas
 - Vida en el Universo: Astrobiología
- Galaxias
 - Modelos y formación
 - Ejemplos: La Vía Láctea, Otras Galaxias, GalaxyZoo(*)



U3: no es lo que se ve, sino lo que se palpa

3 encuentros: del 11/Oct al 25/Oct

- Relatividad General
 - Introducción y conceptos básicos,
 - Modelo de Friedman-Lemaître-Robertson-Walker
 - El error de Einstein
- Modelos del Universo
 - Formación de estructuras
 - Midiendo distancias
 - Corrimiento al rojo
 - El universo en expansión



U4: Allá lejos y hace tiempo

4 encuentros: del 01/Nov al 22/Nov

- El modelo cosmológico estándar
 - Modelo de Alpher, Bethe & Gamow
 - El fondo de microondas
 - Modelo Λ CDM
- Historia térmica del universo
 - El Big Bang
 - Primeros segundos del universo
 - Épocas térmicas de tiempo, inflación, recombinación
 - Evolución futura del universo
 - ¿El fin?

Contenidos: un viaje en el tiempo

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0.1-trillionth present size

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380,000 years
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13.8 billion years
Present size

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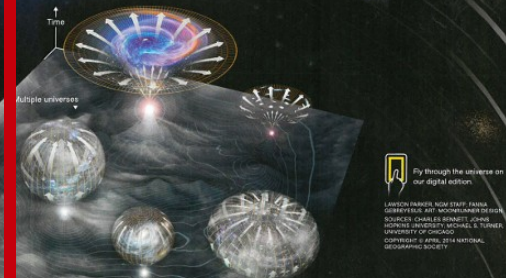


Galaxies ripped apart ▶

Unidad 1

Partículas 1

todo es relativo

 Fly through the universe on our digital edition

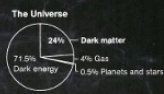
LAWSON PARKER, NOM STAFF; FANNA
GEBREYESLUS, ART; MOONRUNNER DESIGN
SOURCES: CHARLES BENNETT, JOHN
HOPKINS UNIVERSITY; MICHAEL S. TURNER,
UNIVERSITY OF CHICAGO
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GEOGRAPHIC SOCIETY

COSMIC QUESTIONS

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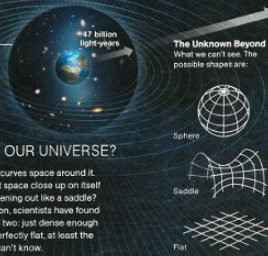
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A cosmic background image featuring a red and orange nebula on the left, transitioning into a deep blue space filled with distant galaxies and stars on the right. Overlaid on this image is the title text in a large, bold, white font with a black outline.

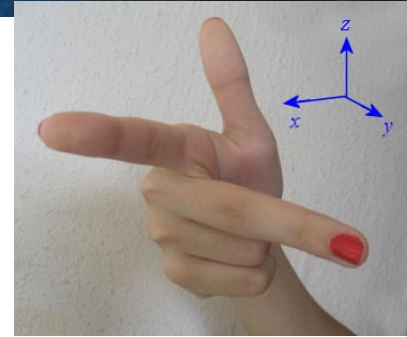
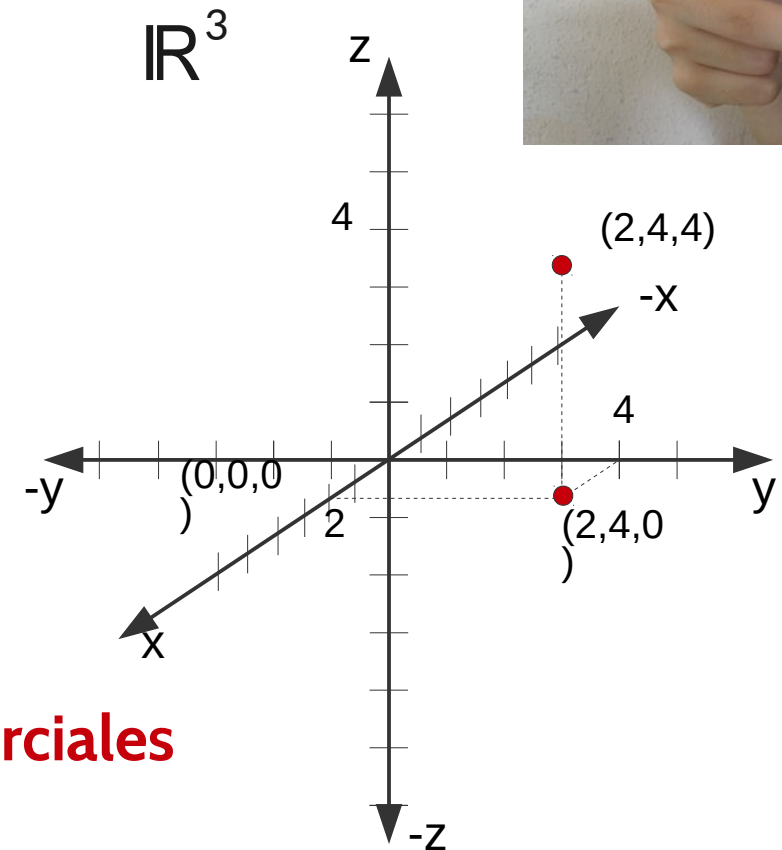
U1: Todo es relativo (08/Ago - 30/Ago)

- ¿Marco de referencia?
-
-
- ¿Marco de referencia inercial?
-
-
-

Marco de referencia

- **Marco de referencia**

- Sistema de coordenadas que fija la posición de objetos físicos de manera unívoca (localización y orientación)
- Existe un conjunto de medidas estandarizadas (una regla)
- Distintos tipos:
 - Fijos al cuerpo, fijos al espacio, **inerciales** y no inerciales

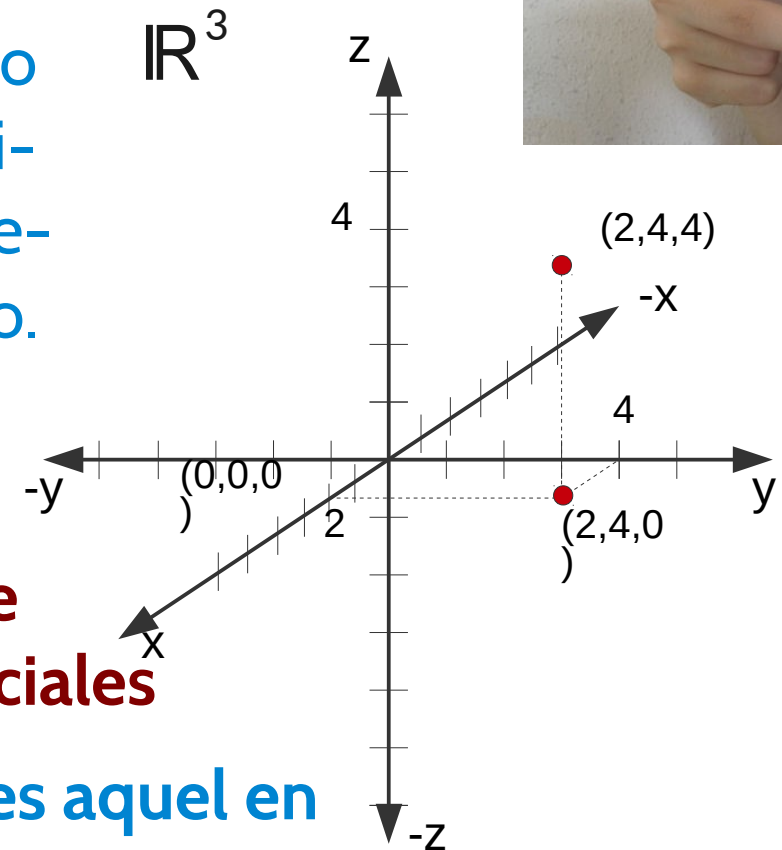


3-tupla: (x,y,z)

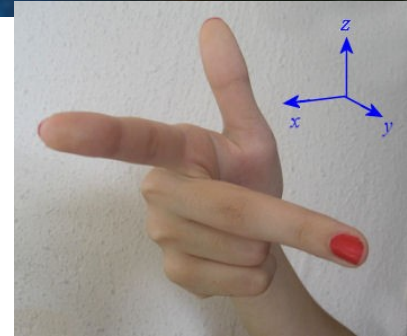
Marco de referencia **inercial**

- **Marco de referencia inercial**

- Describe el espacio homogénea (no hay lugares privilegiados) e isotrópicamente (no hay direcciones privilegiadas) e independiente del tiempo.
- Las leyes físicas tienen la “misma forma” en todo sistema inercial. Decimos que la física es **covariante frente a cambios de sistemas inerciales**
- Un sistema de referencia inercial es aquel en el que la primera ley de Newton es válida.



3-tupla: (x,y,z)





U1: Todo es relativo

- ¿Qué es la relatividad?

-

-

- ¿Quién la descubrió?

-

-

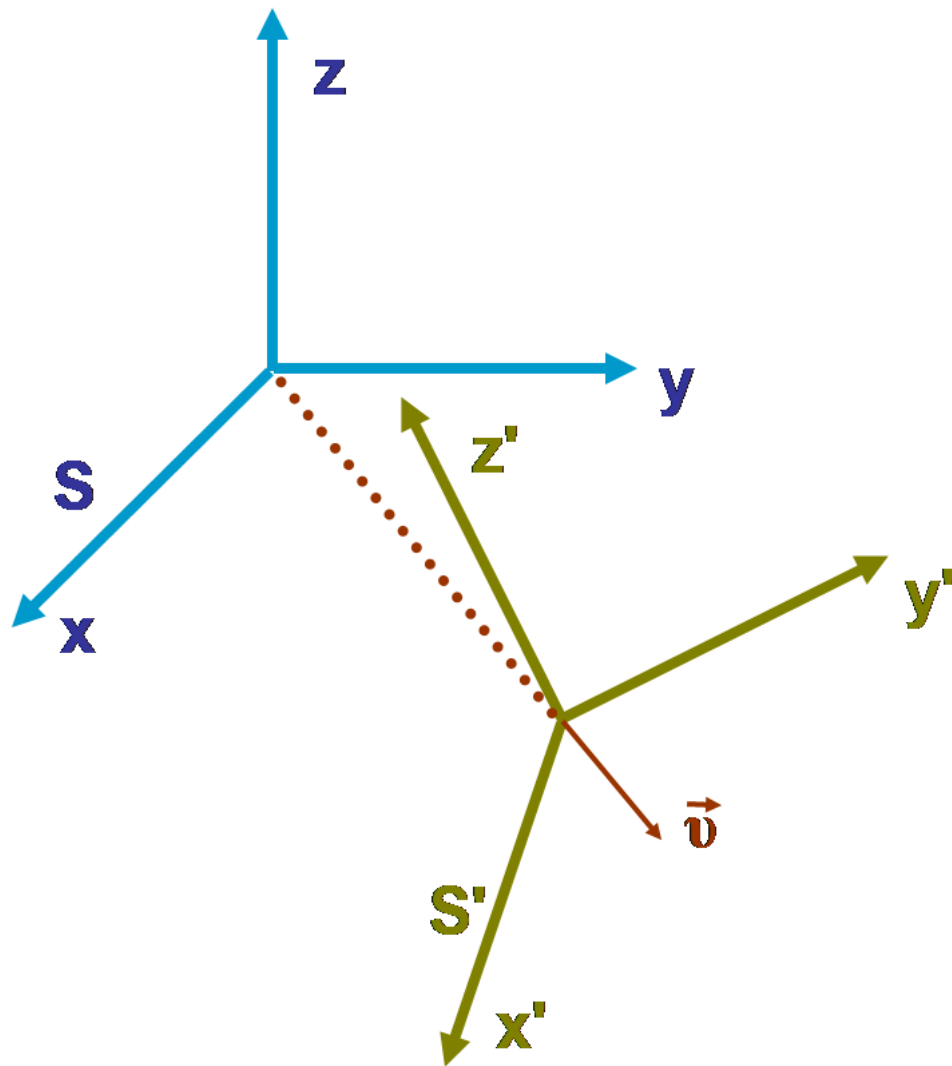
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Relatividad de Galileo

- Si la ley de la inercia es válida, las aceleraciones son provocadas sólo por fuerzas internas, no externas (p. ej. un sistema rotante)
- No hay forma de “saber” si estamos en movimiento
 - Propongan un ejemplo ahora
- **El tiempo y el espacio están claramente desacoplados** (¡vida diaria!)
- **Las leyes de la mecánica son invariantes en el tiempo**
 - → **El espacio es absoluto**
 - → **Todos los sistemas inerciales comparten el mismo tiempo**

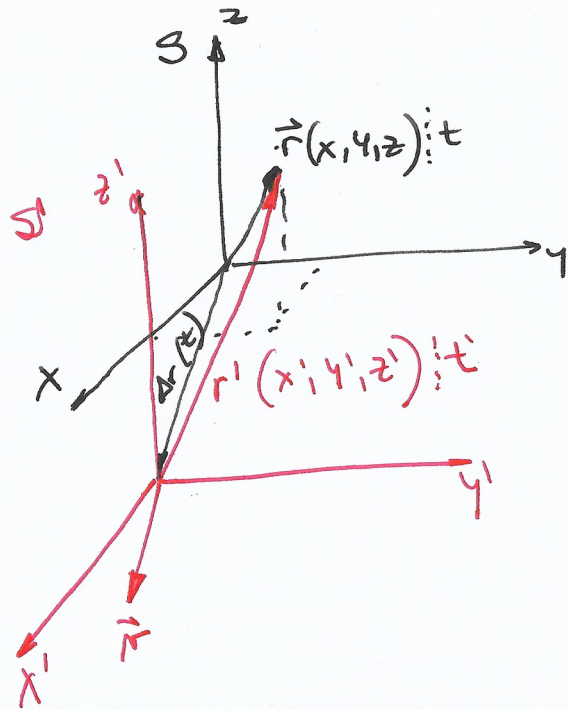
Relatividad de Galileo



- Sea un sistema S' que se mueve con velocidad constante v respecto a otro sistema S .
- Luego, un objeto en r , a tiempo t en S , tendrá posición $r'(t)$ dada por:

$$\vec{r}'(t) = \vec{r}(t) - \vec{v}t$$

Derivación



Ahora bien, por (2^a) postulado

$$t = t'$$

y por (1) en algún momento t_0

$$\vec{O}(t_0) = \vec{O}'(t_0) \Rightarrow \vec{r}(t_0) = \vec{r}'(t_0)$$

Eso ocurrió hace un tiempo $(t - t_0)$

\Rightarrow En ese tiempo, S' se desplazó $\Delta \vec{r} = \vec{v} \cdot (t - t_0)$

luego a tiempo t , y visto desde S

$$\vec{r}(t) - \vec{r}'(t) = \Delta \vec{r}(t)$$


$$\Rightarrow \vec{r}'(t) = \vec{r}(t) - \Delta \vec{r}(t)$$

$$\Rightarrow \vec{r}'(t) = \vec{r}(t) - \vec{v}(t - t_0)$$

Haciendo $t_0 = 0 \Rightarrow$

$$\vec{r}'(t) = \vec{r}(t) - \vec{v}t$$

$$\boxed{\vec{r}'(t) = \vec{r}(t) - \vec{v}t}$$



Y luego

Entonces.

Si el objeto en $r(t)$ se está moviendo, en S' será:

$$\vec{u}'(t) = \frac{d}{dt} r'(t) = \frac{d}{dt} (\vec{r}(t) - \vec{v}t) = \frac{d\vec{r}(t)}{dt} - \vec{v}$$

Recordar
 $\vec{v} = \text{cte}$

$$\Rightarrow u'(t) = \vec{u}(t) - \vec{v} \Rightarrow \boxed{u'(t) = \vec{u}(t) - \vec{v}}$$

Regla de
velocidades

$$\vec{u}'(t) = \vec{u}(t) - \vec{v}$$

Si el objeto se acelera \Rightarrow Su aceleración $\vec{a}(t)$ vista desde S' será:
 $= \vec{a}(t)$

$$\vec{a}'(t) = \frac{d}{dt} \vec{u}'(t) = \frac{d}{dt} (\vec{u}(t) - \vec{v}) = \frac{d\vec{u}(t)}{dt} - \frac{d\vec{v}}{dt}$$

$$\vec{a}'(t) = \vec{a}(t) \Rightarrow \boxed{\vec{a}'(t) = \vec{a}(t)}$$

Aceleración igual !!



Pero entonces... Invariancia de Galileo

- Este último resultado es crucial, ya que si

$$\vec{a}'(t) = \vec{a}(t)$$

- Y suponemos que la masa m es un invariante, $m = m'$

$$m \vec{a}'(t) = m \vec{a}(t) \Rightarrow \vec{F}'(t) = \vec{F}(t)$$

- ¡La segunda ley de Newton no cambia frente a cambios entre sistemas de referencias inerciales! (la primera ya valía)
- **Si las leyes de la mecánica valen en un marco inercial, valen en todos**

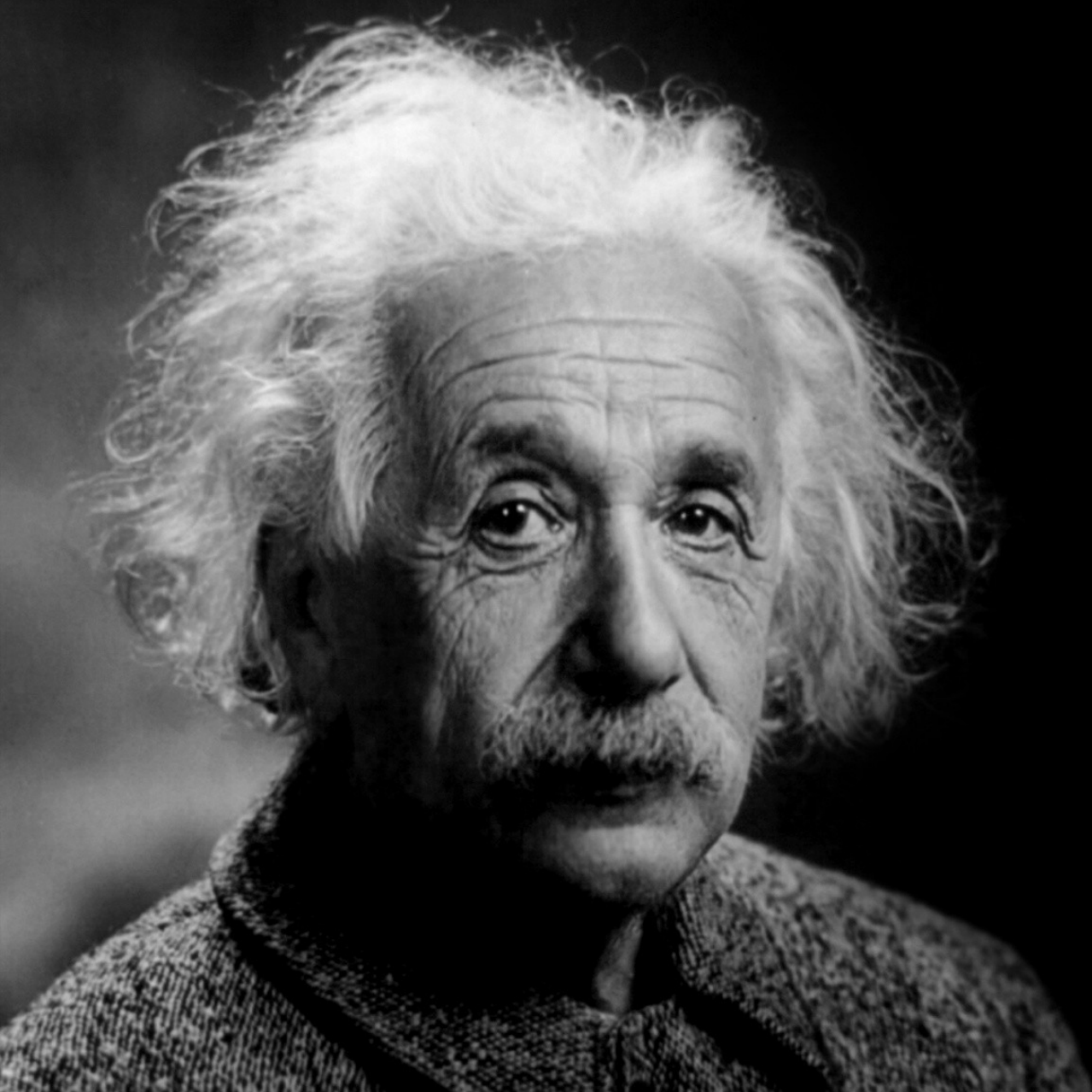
- Para llegar a este importante resultado, dimos por sentado algo que no es trivial:

**En todos los casos, derivamos respecto a t ,
ya que en Galileo,
 $t=t' \rightarrow dt = dt'$**

- Esto parece obvio, pero ¡no lo es!
- Y además, sólo vale para las leyes de Newton, en el electromagnetismo, esto no vale (\rightarrow F-4B)
 \rightarrow Transformaciones de Lorentz (ya vienen)



El genial Albert Einstein



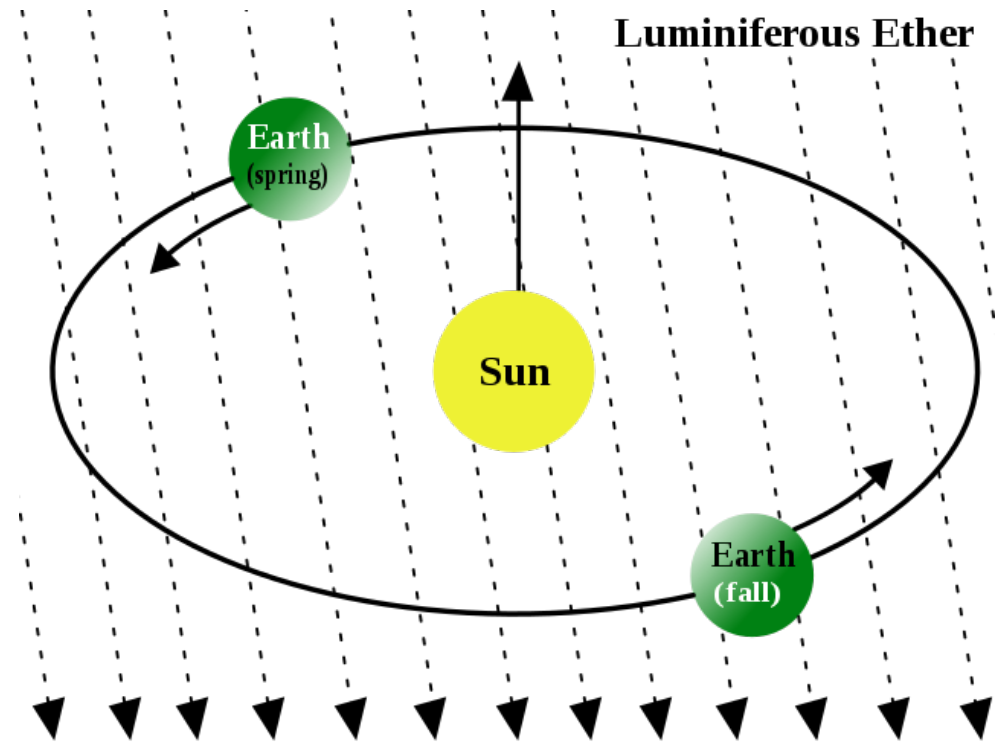
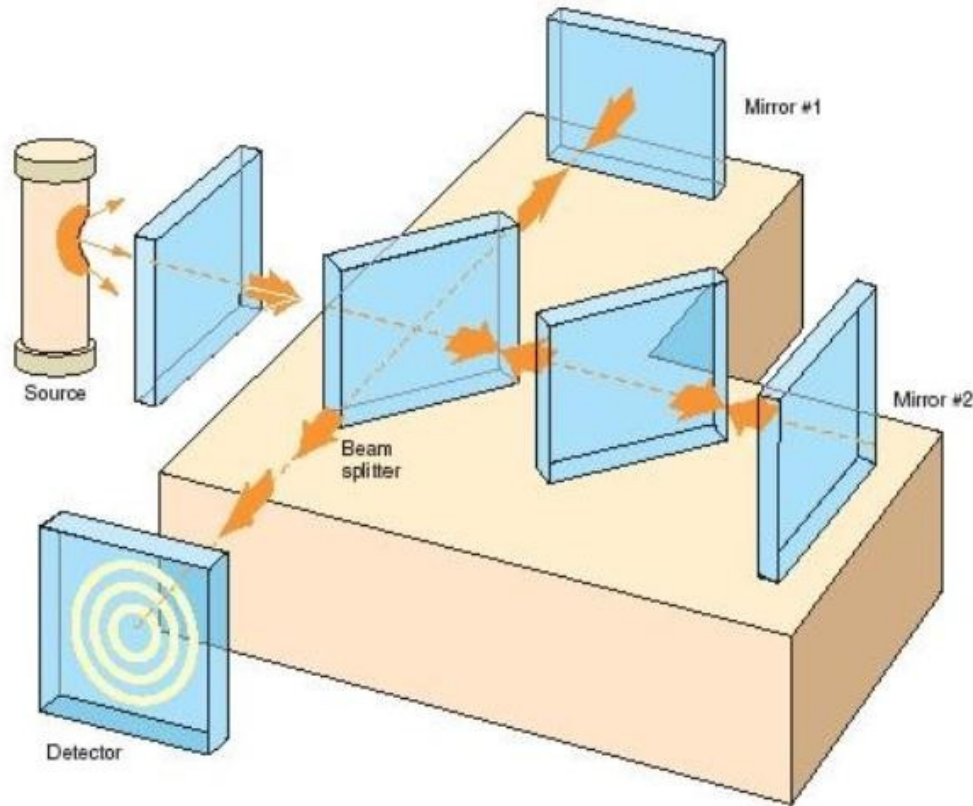
Albert Einstein



¿Qué pasa si....

- Ondas mecánicas necesitan un medio
→ Ondas electromagnéticas también → Éter
- Hay una fuerte inconsistencia entre las leyes de Newton y las leyes de Maxwell
- Michelson & Morley (1887) querían medir la velocidad del “viento del éter” (la Tierra se mueve a una velocidad de $30\text{km/s} \sim 0.0001 c$)...

El experimento de Michelson & Morley



En diferentes momentos del año, la velocidad de la luz medida en los brazos del interferómetro sería diferente, teniendo en cuenta la velocidad de propagación de la Tierra respecto al eter (viento del eter), que era donde se suponía se desplazaba la luz.



¿Qué pasa si....

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- Michelson & Morley (1887) querían medir la velocidad del “viento del éter” (la Tierra se mueve a una velocidad de $30\text{km/s} \sim 0.0001\text{ c}$) → **fallan estrepitosamente...**
- ... y esto es un **éxito rotundo**: demuestran que no hay necesidad de plantear la existencia del éter
- **Pero además, vieron que la velocidad de la luz era la misma en cualquier dirección!!!**



Einstein postula

- **El principio de la relatividad:**

Las leyes que gobiernan los cambios en los estados de los sistemas físicos son iguales para todos los observadores inerciales

- **El principio de la invarianza de la velocidad de la luz**

La luz se propaga en el vacío siempre con la misma velocidad, sin importar la velocidad de la fuente emisora de luz

... y paso a la historia



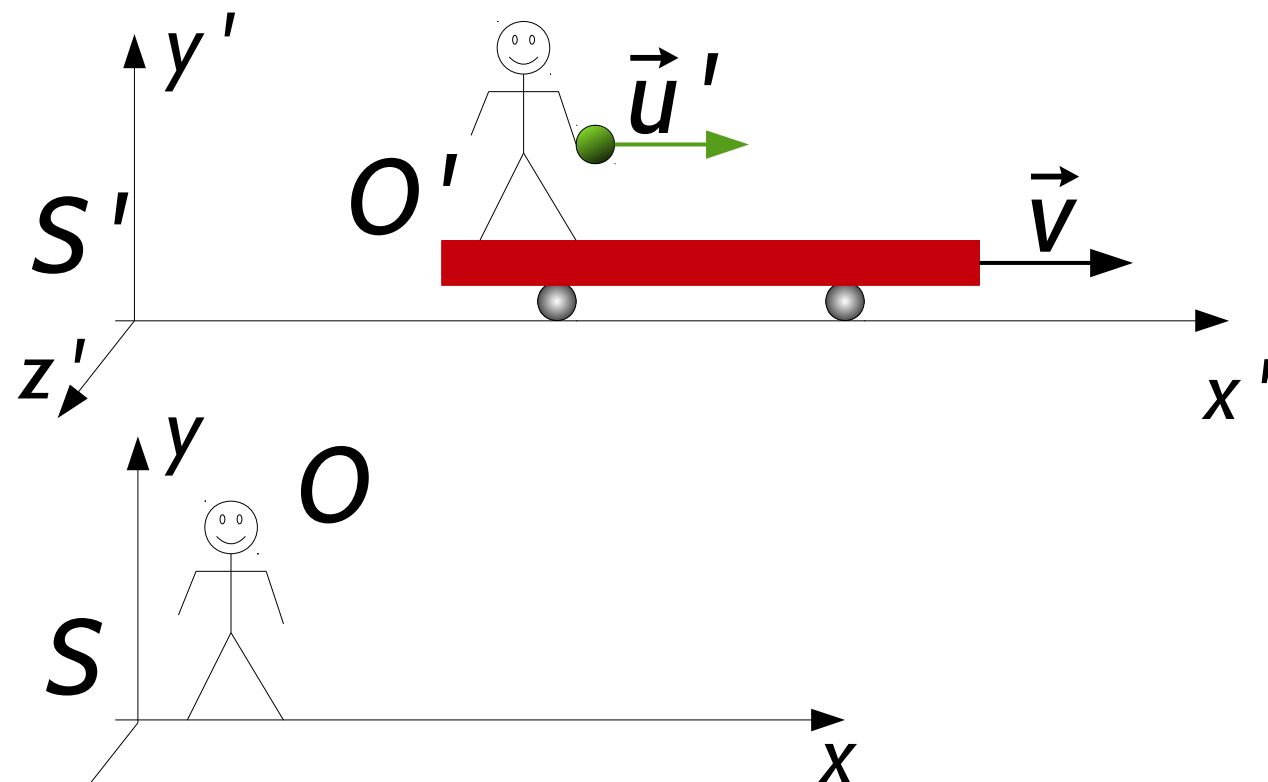
Cambio de paradigma 1

- **El primer postulado modifica la definición de sistema inercial: ya no importa la inercia**

“La debilidad del principio de inercia se encuentra en el hecho de que el mismo implica un argumento circular: una masa se mueve sin aceleración si está suficientemente lejos de otros cuerpos; y sabemos que la masa está suficientemente lejos de otros cuerpos sólo por el hecho de que se mueve sin aceleración” Albert Einstein, El significado de la relatividad

Entonces hagamos una prueba

- El primer postulado es claro, es lo que venimos haciendo con Galileo sobre la invariancia.



Por Galileo:

$$\vec{u}'(t) = \vec{u}(t) - \vec{v}$$

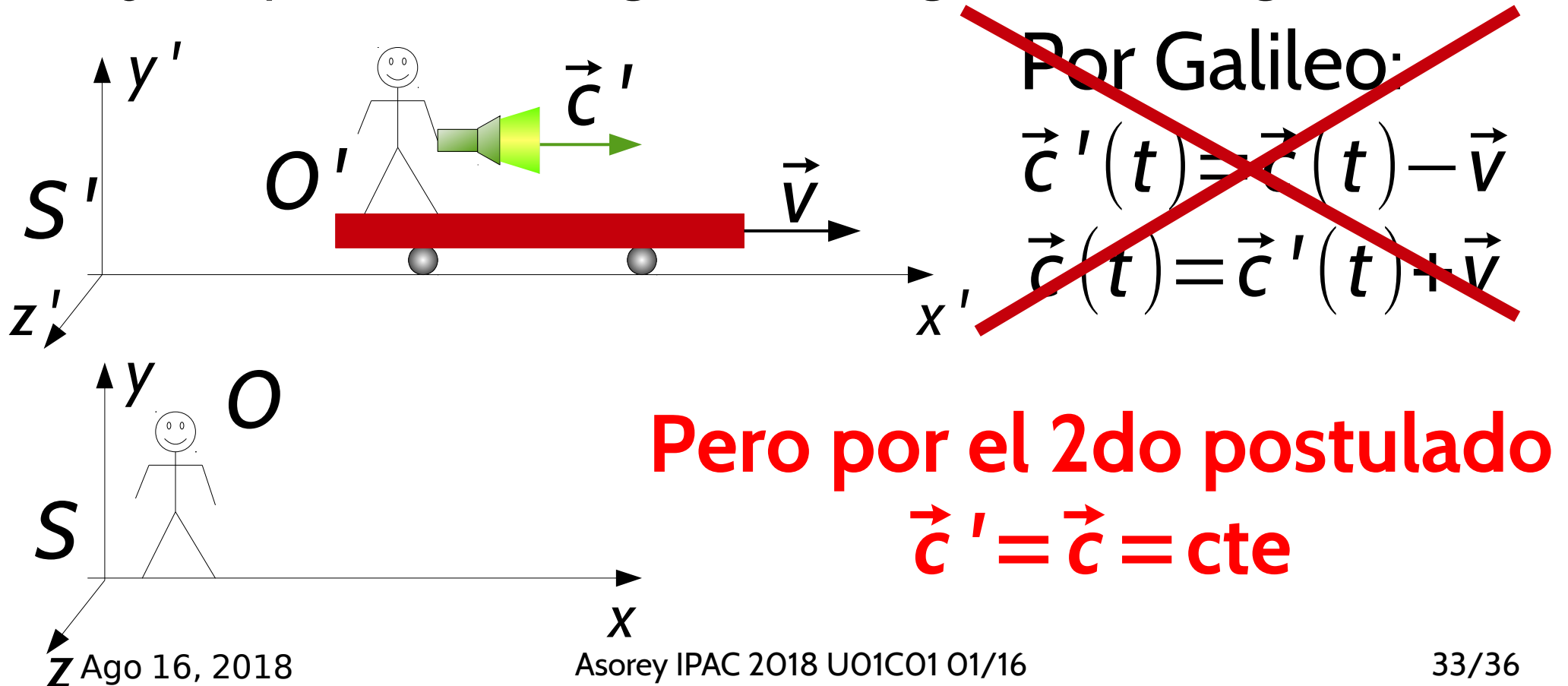
$$\vec{u}(t) = \vec{u}'(t) + \vec{v}$$

Claramente

$$\vec{u}'(t) \neq \vec{u}(t)$$

Cambio pelota por linterna verde...

- El primer postulado es claro, es lo que venimos haciendo con Galileo sobre la invariancia.
- ¿Qué pasa con el segundo? Imaginemos lo siguiente:





Cambio de paradigma 2

- Dado que la velocidad de la luz debe ser igual en ambos sistemas inerciales
- Y dado que uno se mueve respecto al otro, se anticipan problemas con la visión usual (de Galileo) de las cosas:

$$\vec{u} = \frac{\Delta \vec{r}}{\Delta t} \quad \text{y} \quad \vec{u}' = \frac{\Delta \vec{r}'}{\Delta t} \Rightarrow \vec{u}' \neq \vec{u} \rightarrow \frac{\Delta \vec{r}}{\Delta t} \neq \frac{\Delta \vec{r}'}{\Delta t}$$

- Esto no puede valer para la velocidad de la luz:

$$\vec{c} = \vec{c}'$$

en todos los sistemas inerciales



Cambio de paradigma 2

- La luz también se mueve en el espacio, entonces:

$$\vec{c} = \frac{\Delta \vec{r}}{\Delta t} \quad \text{y} \quad \vec{c}' = \frac{\Delta \vec{r}'}{\Delta t}$$

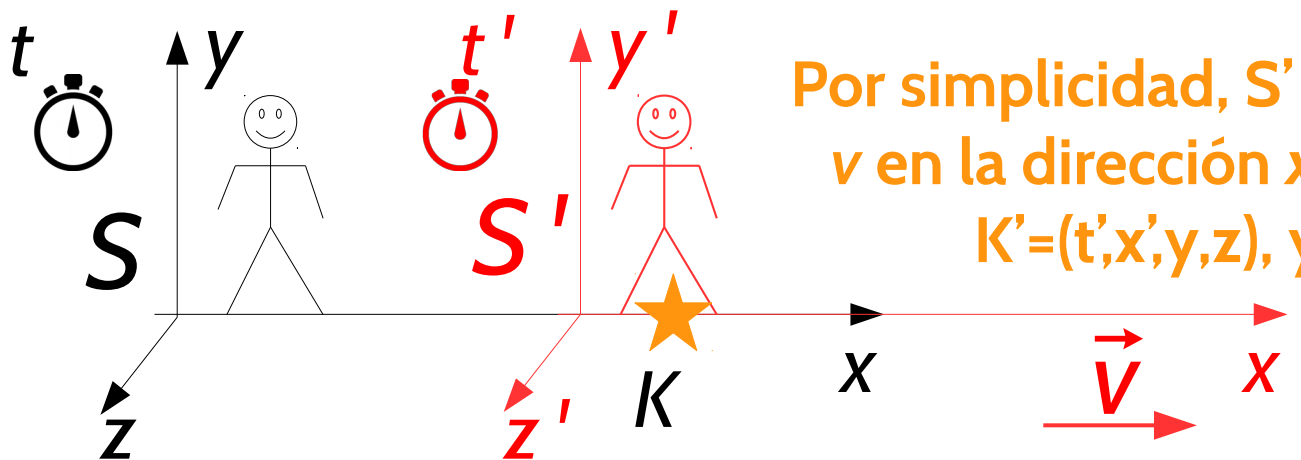
- Pero por el segundo postulado

$$\vec{c} = \vec{c}' \rightarrow \frac{\Delta \vec{r}}{\Delta t} = \frac{\Delta \vec{r}'}{\Delta t}$$

- Pero los desplazamientos “no deberían” ser iguales, ya que un sistema se mueve respecto al otro...
- ... o los intervalos temporales... (!!!)

Marco de Referencia

- **Marco de Referencia**
sistema de referencia inercial donde existe la habilidad de medir intervalos temporales mediante un reloj
- Espacio (3D) y tiempo → **espaciotiempo**
- **Evento**
es un punto en el espaciotiempo $K=(t,x,y,z)$



Por simplicidad, S' se mueve con velocidad v en la dirección x , entonces $K=(t,x,y,z)$ y $K'=(t',x',y,z)$, ya que $z'=z$ e $y'=y$