



Universidad Nacional de Río Negro

Int. Partículas, Astrofísica & Cosmología - 2016

- **Unidad** 01 – Relatividad
- **Clase** 0104 – 04/16
- **Fecha** 01 Sep 2016
- **Cont** Partículas 1
- **Cátedra** Asorey
- **Web** github.com/asoreyh/unrn-ipac
- **Youtube** www.youtube.com/watch?v=vdtZKNhPv1w
- **Archivo** a-2016-U01-C04-0901-particulas-1



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 billion times the size of a nuclear particle. Since then it has expanded—a lot—fighting gravity all the way.

Inflation
In less than a nanosecond a repulsive energy field inflates space exponentially until it's a soup of subatomic particles called quarks.

Age: 10^{-3} milliseconds
Size: Infinitesimal to golf ball

Early building blocks
Quarks clump into protons and neutrons, creating blocks of atomic nuclei. Perhaps dark matter forms.

Age: .01 milliseconds
Size: 0.1-million 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: .01 to 200 seconds
Size: 1-billionth present size

First atoms, first light
As electrons begin orbiting nuclei, creating atoms, the glow from their infalling orbits is unveiled. This light is as far back as our instruments can see.

Age: 380,000 years
Size: .0009 to 0.1 present size

The "dark ages"
For 300 million years this combination of density and light is the only light. Clumps of dark matter will eventually form galaxies and stars. Nuclear fusion lights up the stars.

Age: 300 million years
Size: 0.1 present size

Gravity wins: first stars
Dense gas clouds collapse under their own gravity and attract dark matter that will become galaxies and stars. Nuclear fusion lights up the stars.

Age: 300 years
Size: .77 present size

Antigravity wins
After being slowed for billions of years by gravity, cosmic expansion accelerates again. The culprit: dark energy. Its nature: unclear.

Age: 10 billion years
Size: 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



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 23 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 counters 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.



DO WE LIVE IN A MULTIVERSE?

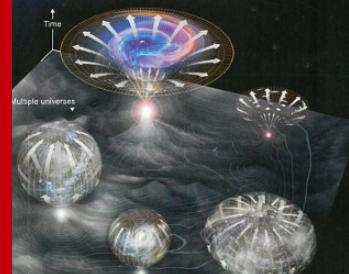
What came before the big bang? Maybe other big bangs. The uncertainty principle holds that even the vacuum of space has quantum energy fluctuations. Inflation theory suggests universes exploded from such a fluctuation—a random event that, odds are, had happened many times before. Our cosmos may be one 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.

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.



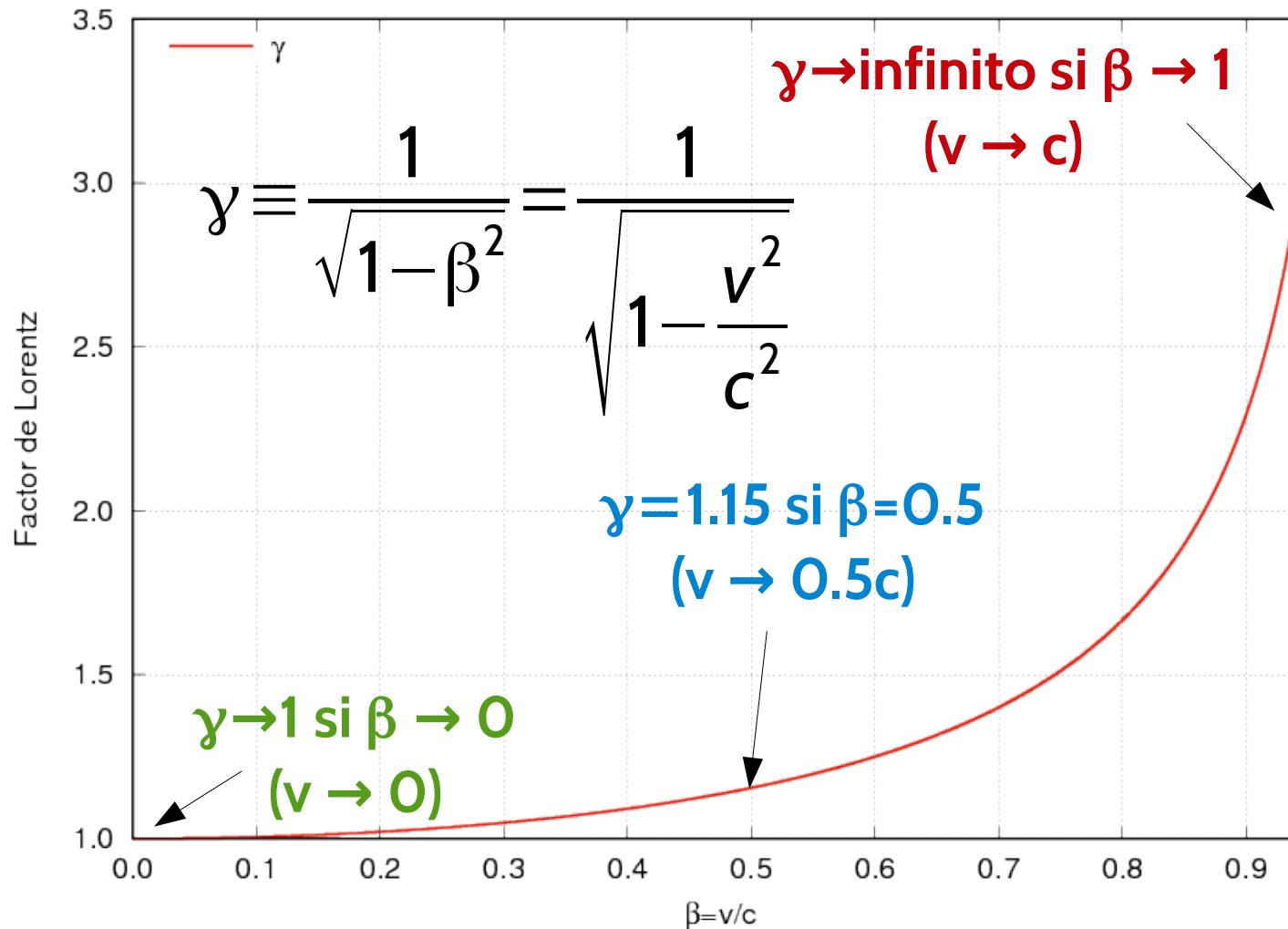
Unidad 1 Partículas 1 *todo es relativo*

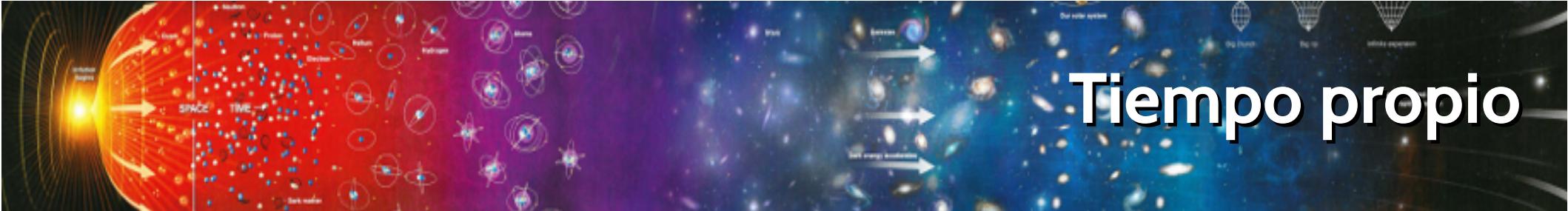


Fly through the universe on our digital edition.
LONDON PHOTOS: ANDREW STONE; FERNE GOLDBECK; ART: WOLFGANG DEGEN; SOURCES: CHARLES BENNETT, JOHN HESKETH, ANDREW LAMBERT, ANDREW LISTER, UNIVERSITY OF CHICAGO; COURTESY OF NATIONAL GEOGRAPHIC SOCIETY

Factor de Lorentz

- Estudiemos la función gamma, ecuación (10)





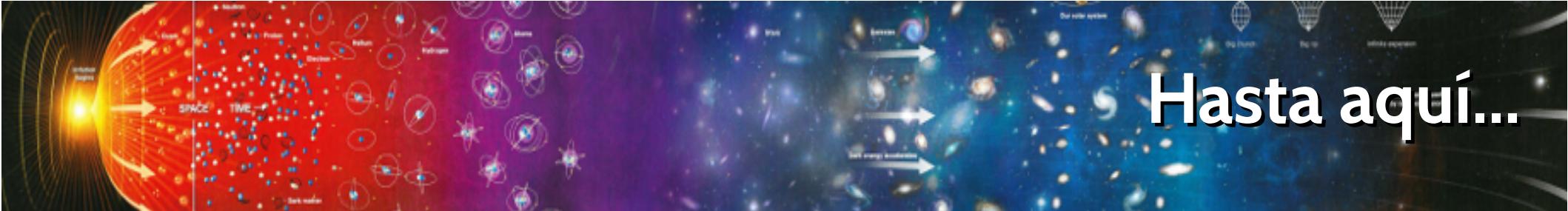
Tiempo propio

- Dado que cada marco de referencia tiene su propio tiempo, **podemos definir un marco de referencia adherido a un objeto en movimiento.**
- **El tiempo de ese marco es el tiempo que “percibe” un observador que se mueve junto con el objeto.**
Llamaremos a este marco “comovil”.
- El tiempo del marco comovil es el tiempo propio: es independiente de las coordenadas.

$$ds^2 = c^2 dt^2 - dr^2 = ds'^2 = c d\tau^2 \quad \text{Tiempo propio}$$

$$\Rightarrow c^2 dt^2 - dr^2 = c^2 d\tau^2$$

$$dt = \gamma d\tau$$



Hasta aquí...

- Los postulados de Einstein implican cambios profundos en la concepción de la Naturaleza.
 - Estos afectan nuestra percepción de distancia y lapso temporal, de espacio y tiempo.
- Las transformaciones de Lorentz indican como transforman las leyes de la física entre dos marcos de referencia inerciales.
 - Son las transformaciones válidas entre marcos de referencia.
- La mecánica Newtoniana es una aproximación válida para velocidades bajas respecto a la velocidad de la luz.
 - ¿Cómo puede ser generalizada?

La conservación de p es un principio básico

- Al igual que nos pasó con u , debemos recordar lo que dijo Alberto: al derivar, el tiempo depende del marco de referencia. Antes eso no nos preocupaba:

Clásico: $\vec{p} = \frac{d}{dt}(m\vec{r})$ y $\vec{p}' = \frac{d}{dt}(m\vec{r}')$

Correcto: $\vec{p} = \frac{d}{dt}(m\vec{r})$ y $\vec{p}' = \frac{d}{dt'}(m\vec{r}')$

- Y como todos los marcos son equivalentes, ¡podemos usar el marco comovil!

Cant. de movimiento relativista

$$\vec{p} = m \frac{d\vec{r}}{d\tau}$$



Una nueva magnitud conservada

- Hemos visto que al aplicar los principios relativistas y pedir conservación del impulso, una nueva magnitud conservada aparece naturalmente:

La energía se conserva

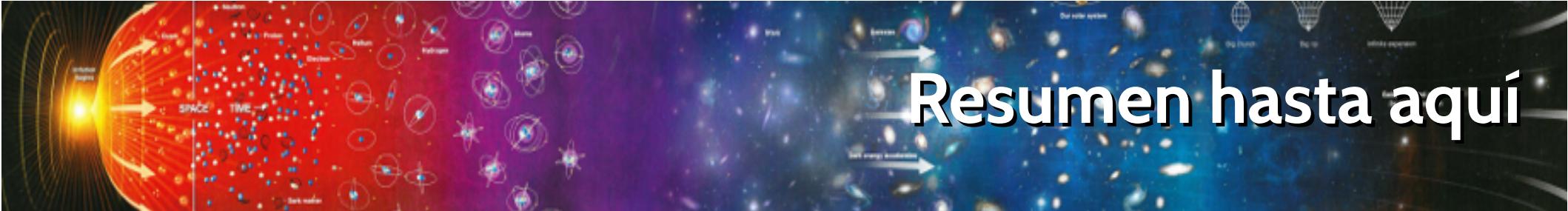
$$E = \gamma mc^2 \approx mc^2 + \frac{1}{2}mv^2$$

Energía cinética clásica

- Recordar que la energía de un cuerpo es $E = \gamma mc^2$
- $E = \frac{1}{2}mv^2$ es una aproximación válida si $v \ll c$.

$$E_K \equiv E - mc^2 = (\gamma - 1)mc^2$$

Energía cinética
(en ausencia de otras
interacciones)



Resumen hasta aquí

- Cantidad de movimiento relativista (correcto siempre):

$$\vec{p} = \gamma m \vec{v}$$

- Energía relativista (correcta siempre):

$$E = \gamma m c^2$$

- Un nuevo invariante relativista:

$$E^2 - (pc)^2 = (mc^2)^2$$

Invariante
relativista



¿y si no la partícula no tiene masa?

- ¡No importa, tiene energía y tiene cantidad de movimiento!

$$m=0 \rightarrow E^2 - (pc)^2 = (mc^2)^2 \Rightarrow E^2 - (pc)^2 = 0$$

**Cantidad de
movimiento de
partículas sin masa**

$$E = pc$$

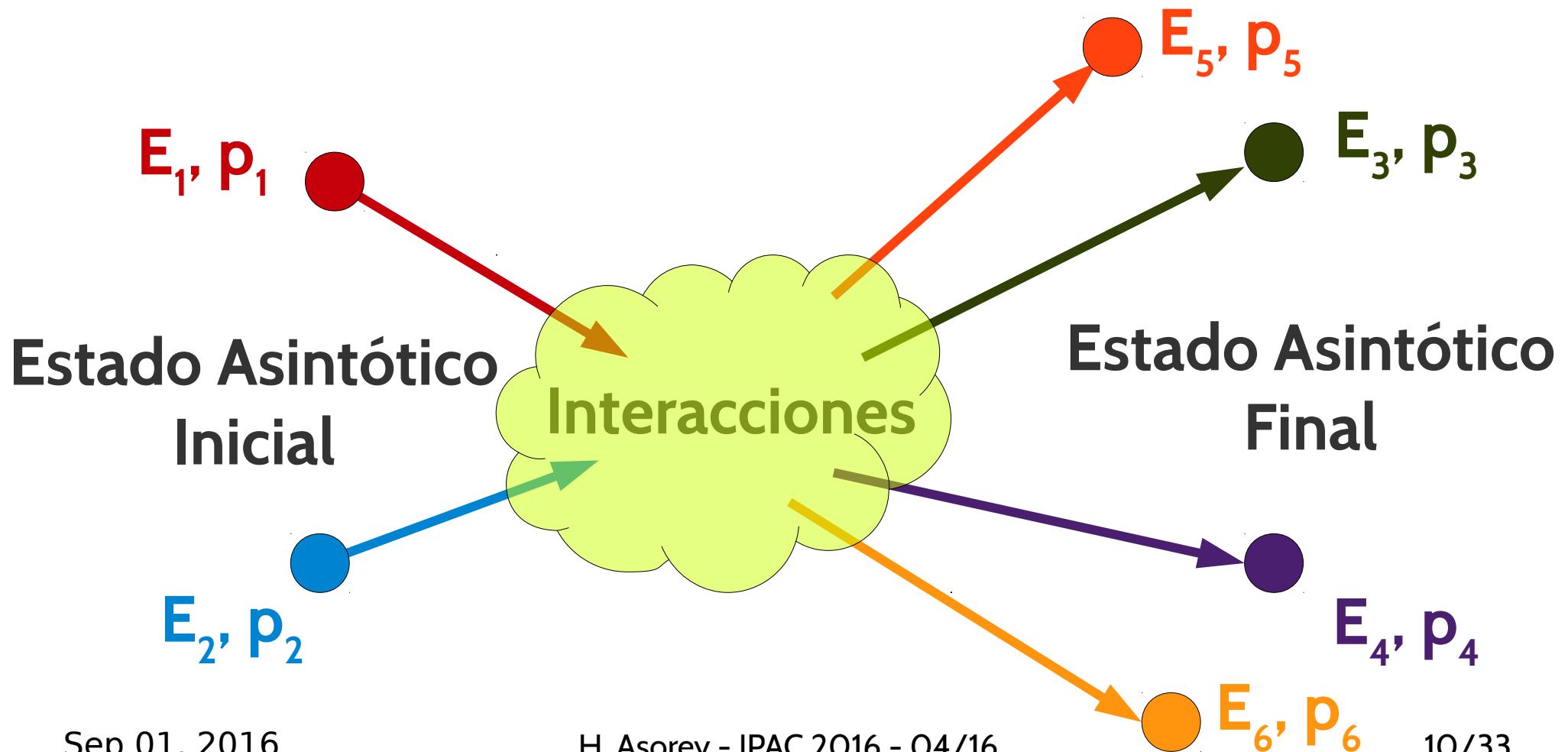
- Por ejemplo, un fotón violeta:

$$\lambda = 420 \text{ nm} \rightarrow E = hc/\lambda = 0.473 \text{ aJ} \text{ (attojoules, atto=}10^{-18})$$

$$\rightarrow p = 1.58 \times 10^{-27} \text{ kg m/s}$$

¿Cómo funciona la conservación?

- Y todo por pedir que c tiene que tener el mismo valor para todos los observadores inerciales.





Así funciona la Naturaleza

- La Energía total se conserva

$$\left. \begin{aligned} E^{\text{inicial}} &= \sum_j^{n^{\text{inicial}}} E_j^{\text{inicial}} = \sum_j m_j \gamma_j c^2 \\ E^{\text{final}} &= \sum_k^{n^{\text{final}}} E_k^{\text{final}} = \sum_k m_k \gamma_k c^2 \end{aligned} \right\} E^{\text{inicial}} = E^{\text{final}}$$

- La cantidad de movimiento total se conserva

$$\left. \begin{aligned} \vec{p}^{\text{inicial}} &= \sum_j^{n^{\text{inicial}}} \vec{p}_j^{\text{inicial}} = \sum_j m_j \gamma_j \vec{v}_j \\ \vec{p}^{\text{final}} &= \sum_k^{n^{\text{final}}} \vec{p}_k^{\text{final}} = \sum_k m_k \gamma_k \vec{v}_k \end{aligned} \right\} \vec{p}^{\text{inicial}} = \vec{p}^{\text{final}}$$



Una disgresión sobre cargas

Fuera eléctrica

Fuerza Gravedad

Una disgresión sobre cargas

Fuera eléctrica

$$F_E = \left(\frac{1}{4\pi\epsilon_0} \right) \frac{q_1 q_2}{r^2}$$

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

$$F_E = \left(k_e \frac{q_1}{r^2} \right) q_2 = m_2^i \frac{d^2 x}{dt^2}$$

$$F_E = \left(k_e \frac{q_1}{r^2} \right) \frac{q_2}{m_2^i} = \frac{d^2 x}{dt^2}$$

?

Fuerza Gravedad

$$F_G = G \frac{m_1^g m_2^g}{r^2}$$

$$F_e = G \frac{m_1^g}{r^2} m_2^g$$

$$F_e = \left(G \frac{m_1^g}{r^2} \right) m_2^g = m_2^i \frac{d^2 x}{dt^2}$$

$$F_e = \left(G \frac{m_1^g}{r^2} \right) \frac{m_2^g}{m_2^i} = \frac{d^2 x}{dt^2}$$

$$F_e = \left(G \frac{m_1^g}{r^2} \right) = \frac{d^2 x}{dt^2} = g$$



Richard Feynman dijo

- “For those who want to learn just enough about it so they can solve problems, that is all there is to the [special] theory of relativity - it just changes Newton’s laws by introducing a correction factor to the mass”

- Luego:

$$\vec{F} = \frac{d(m\vec{v})}{dt}$$

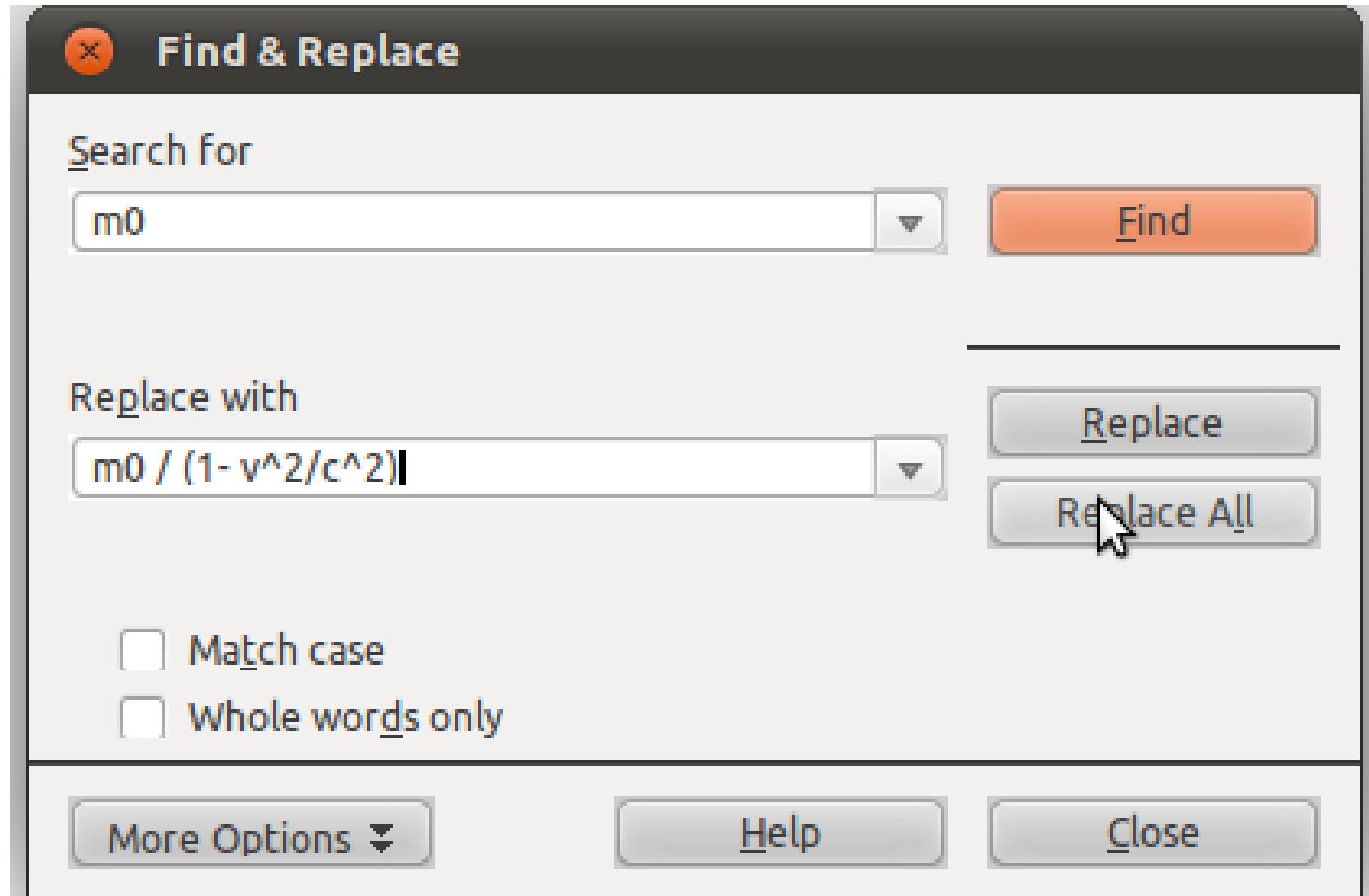
- donde

$$m \rightarrow m\gamma = \frac{m}{\sqrt{1-\beta^2}}$$



Aprendiendo relatividad en Windows

- Search & replace (CTRL+F)



Desarrollo en serie

- Desarrollemos para $v \rightarrow 0$:

$$m = \gamma m = m \left(1 - \frac{v^2}{c^2}\right)^{-1/2} = m \left(1 + \frac{1}{2} \frac{v^2}{c^2} + \frac{3}{8} \frac{v^4}{c^4} + \dots\right)$$

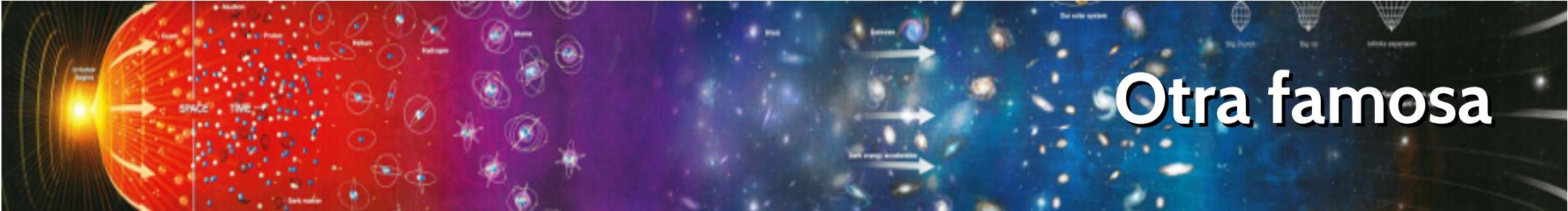
- Luego, la famosa fórmula

$$m \approx m + \frac{1}{2} m \frac{v^2}{c^2}$$

$$\rightarrow mc^2 \approx mc^2 + \frac{1}{2} mv^2$$

$$\rightarrow E=mc^2$$





Otra famosa

- Y ahora

$$p^2 c^2 = \frac{m^2 \beta^2 c^4}{1 - \beta^2} - \left(\frac{m^2 c^4}{1 - \beta^2} \right) + \left(\frac{m^2 c^4}{1 - \beta^2} \right)$$

$$p^2 c^2 = \frac{m^2 c^4 (\beta^2 - 1)}{1 - \beta^2} + m^2 \gamma^2 c^4$$

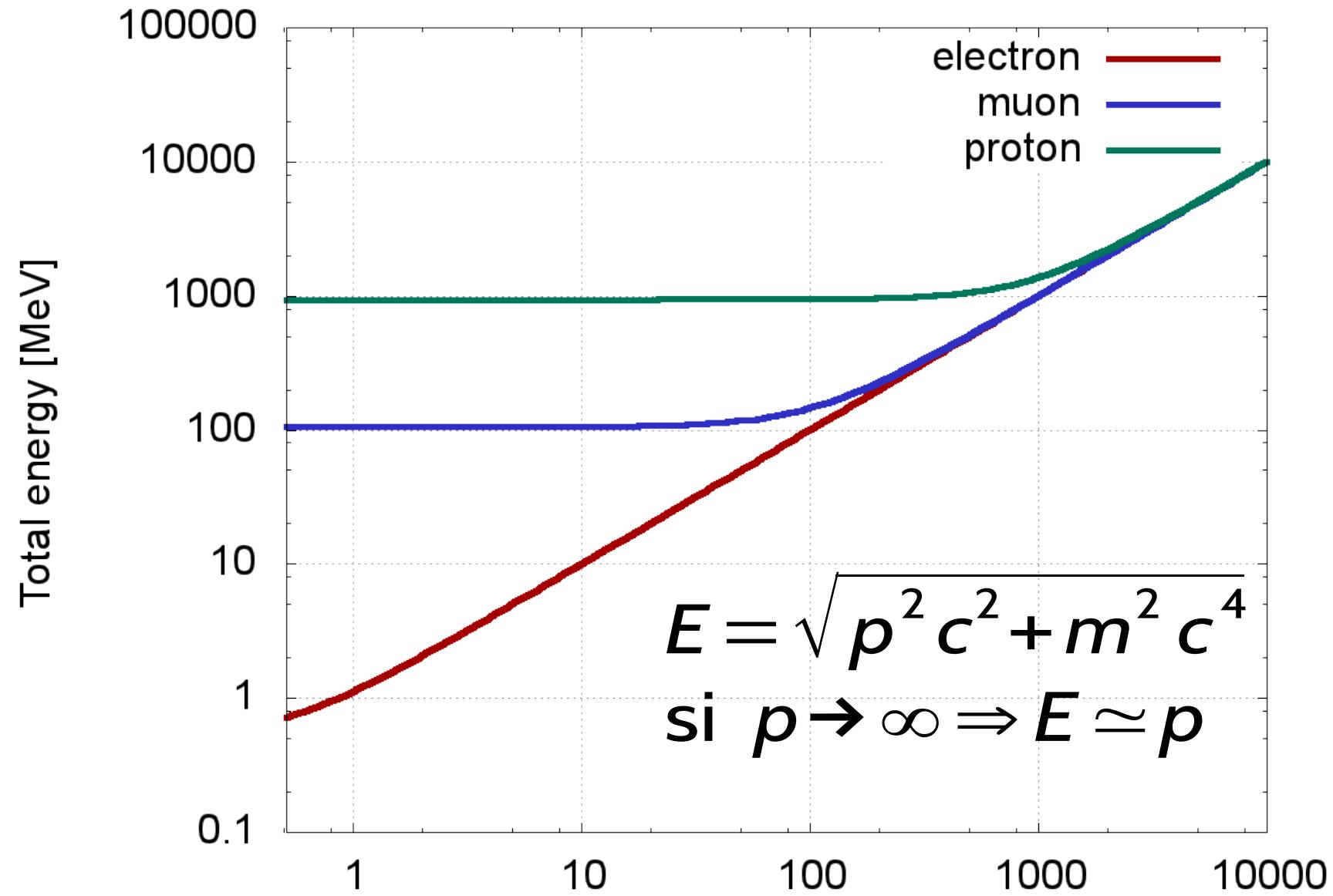
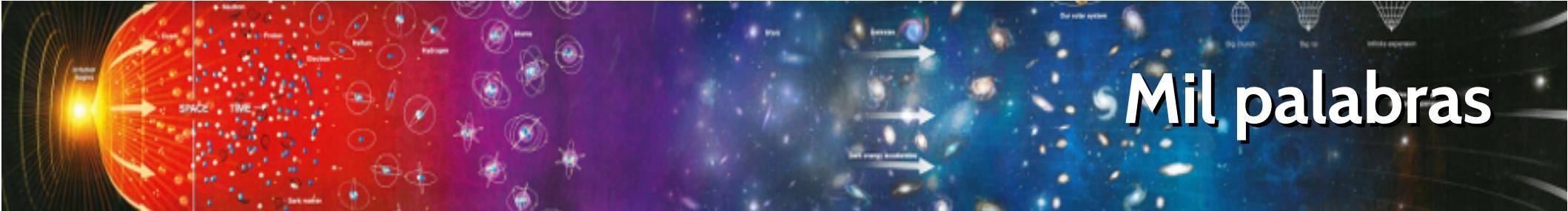
$$p^2 c^2 = -m^2 c^4 + m^2 \gamma^2 c^4$$

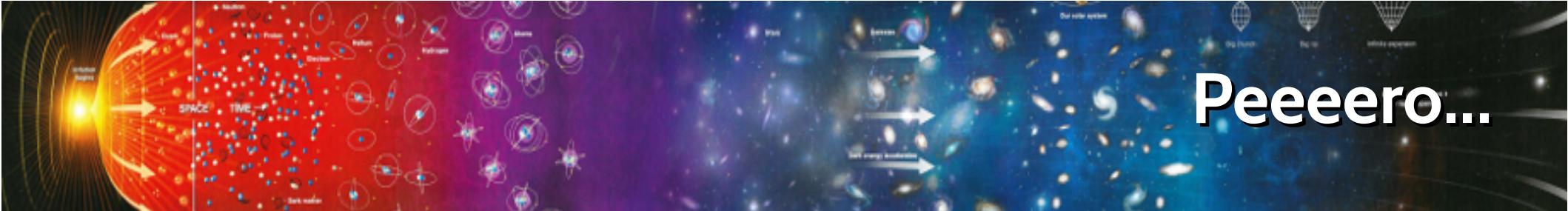
$$p^2 c^2 = -m^2 c^4 + E^2$$

- Entonces:

$$E^2 = p^2 c^2 + m^2 c^4 \rightarrow E = \pm \sqrt{p^2 c^2 + m^2 c^4}$$

Mil palabras





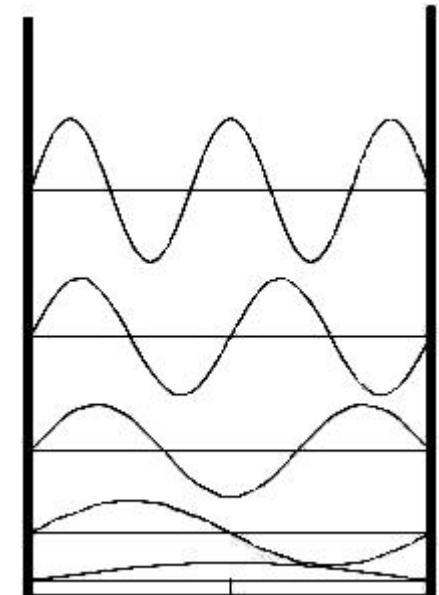
Peeeero...

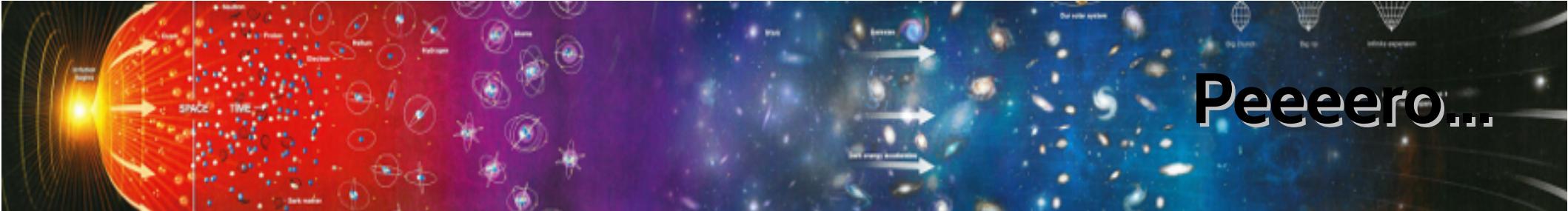
- También tenemos

$$E^2 = p^2 c^2 + m^2 c^4 \rightarrow E = -\sqrt{p^2 c^2 + m^2 c^4}$$

- La relatividad anticipa estados con energía total negativa... → **PROBLEMAS**
- Y encima son infinitos → **MÁS PROBLEMAS**
- Partícula en una caja

$$E_n = \left(\frac{\hbar^2}{8mL^2} \right) n^2$$



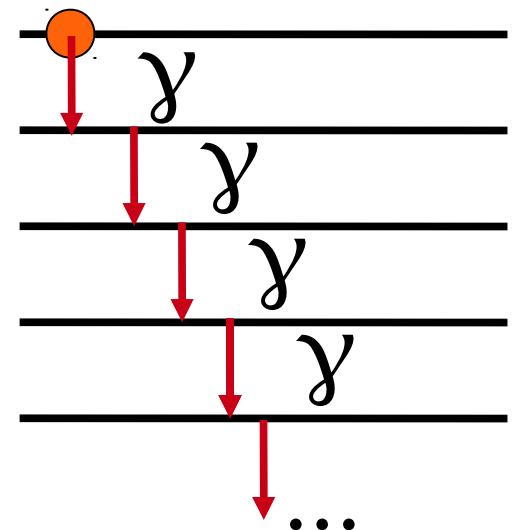


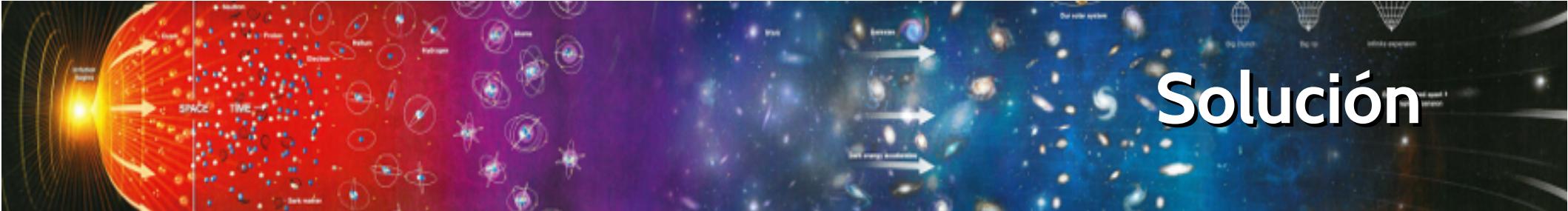
Peeeero...

- También tenemos

$$E^2 = p^2 c^2 + m^2 c^4 \rightarrow E = -\sqrt{p^2 c^2 + m^2 c^4}$$

- La relatividad anticipa estados con energía total negativa... → **PROBLEMAS**
- Y encima son infinitos → **MÁS PROBLEMAS**
- Aquí no tengo “estado fundamental”
- **COLAPSO**



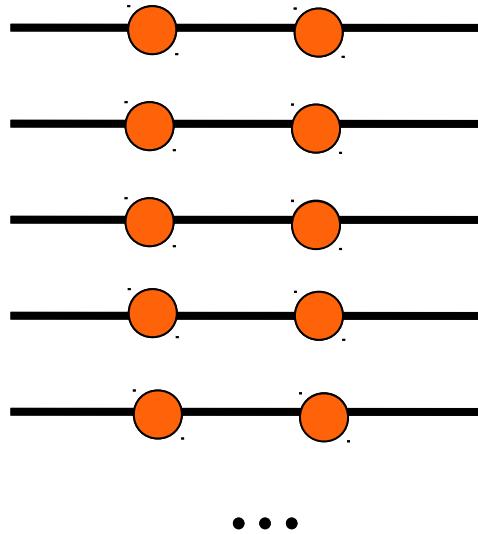
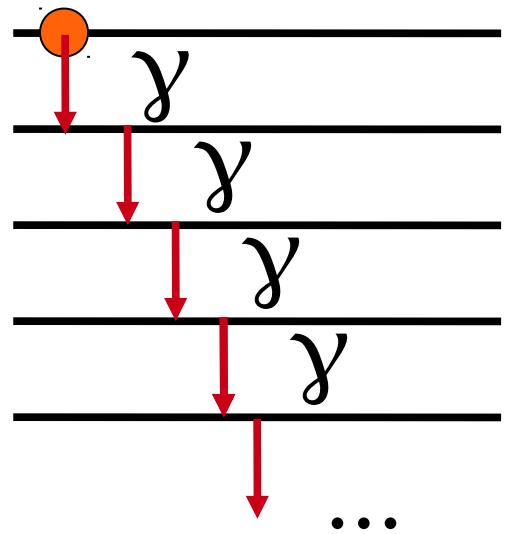


Solución

- Dirac (1928) obtiene la versión relativista de la ec. de Schrödinger y observa ese problema
- Propone que todos los estados de energía negativa están ocupados
- Los electrones obedecen el principio de exclusión de Pauli
- Solución: el “vacío” es el estado en el cual todos los estados de energía negativos están llenos

Felicidad

- No hay colapso porque no hay estados vacíos

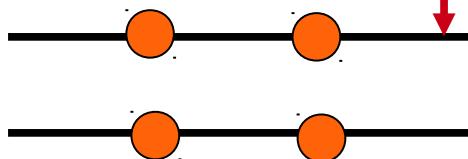


$E < 0$

$$E = 2mc^2 = 1.022 \text{ MeV}$$

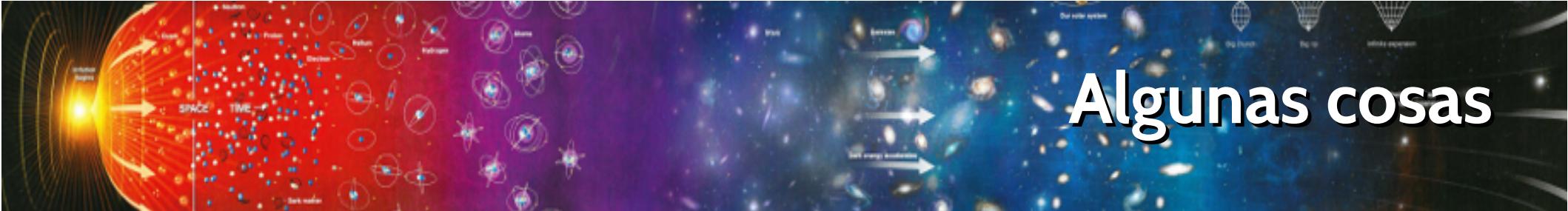


$E > 0$



$E < 0$

$$E = \pm mc^2$$



Algunas cosas

- El espacio está lleno con infinitas partículas
- Energía infinita
- Energía de punto 0 (como el oscilador armónico)

No olvidar que son Modelos

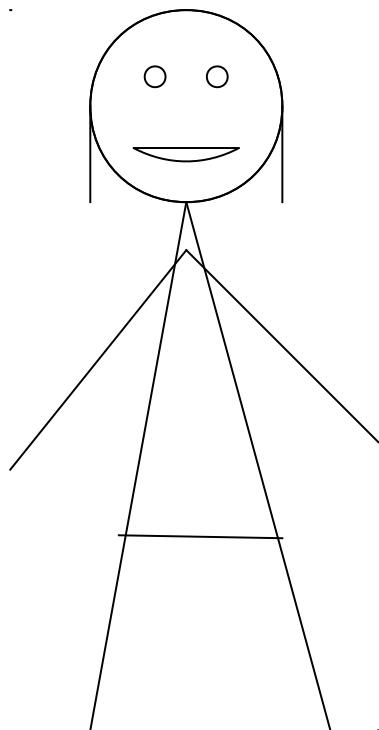


Un modelo representa a esto...



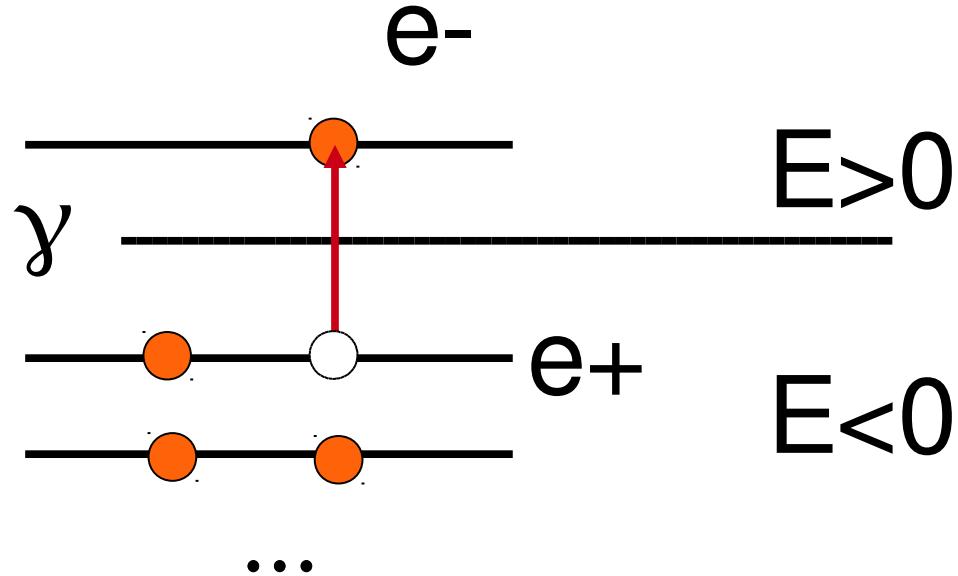


... con esto: “órdene cero”



Materia-Antimateria

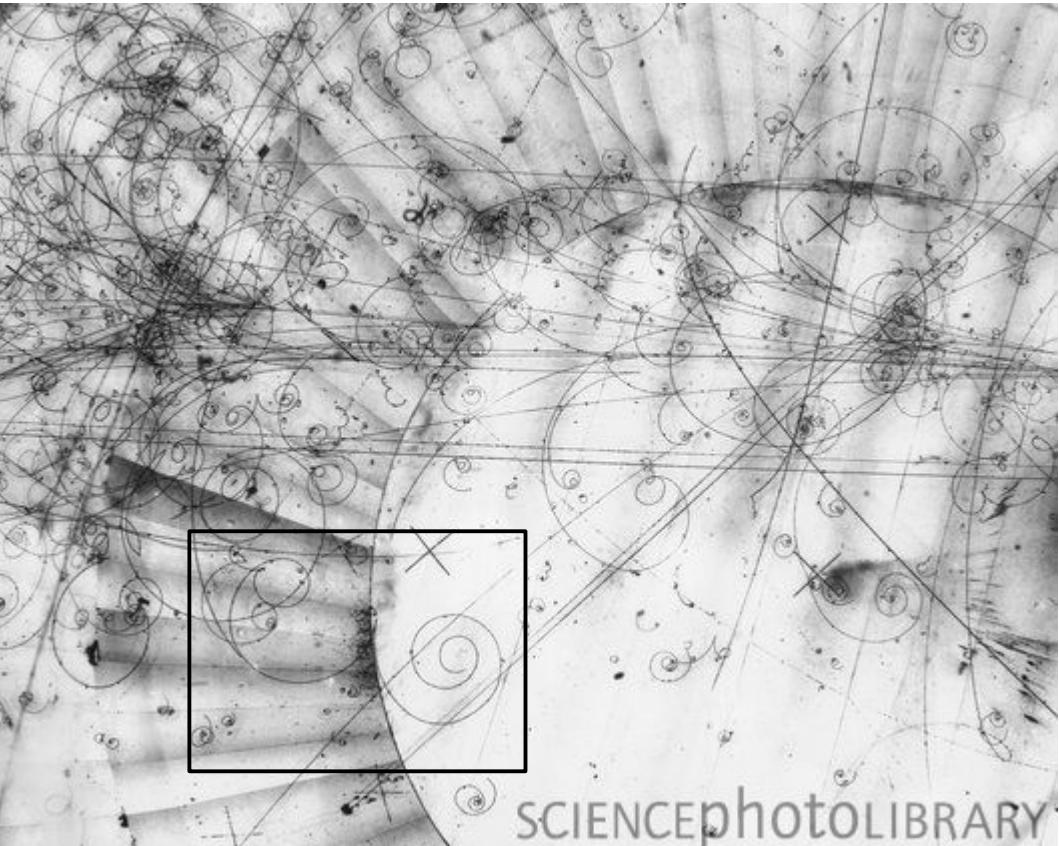
- En una interacción EM (scattering) es posible sacar un electrón del mar
- El “hueco” se ve como un electrón positivo

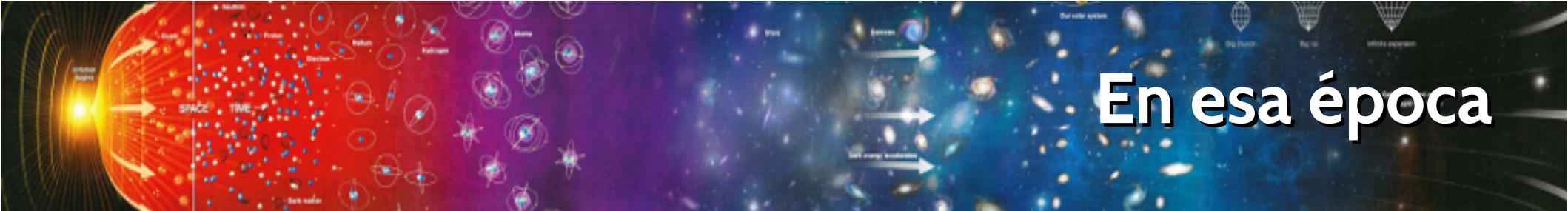


$$E_\gamma \geq 1.022 \text{ MeV}$$

Sep 01, 2016

H. Asorey - IPAC





En esa época

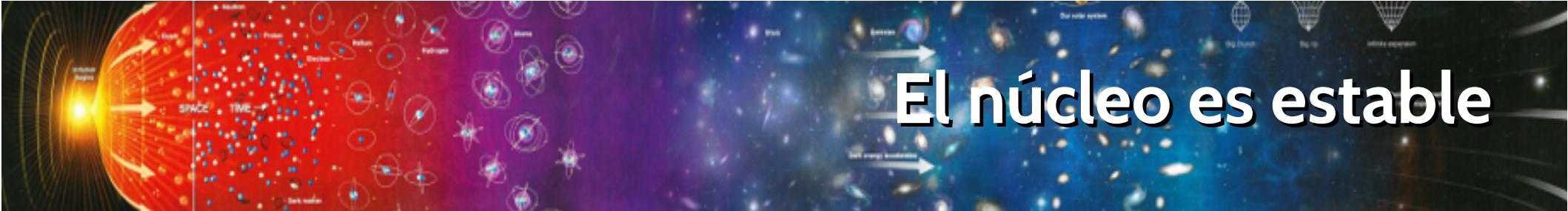
- Se conocían cuatro partículas:
 - Protón (+)
 - Electrón (-)
 - Fotón (0) ← interacciones cargadas
 - Neutrón (0)
- Si existía el antielectrón, ¿por qué no un antiproton?
- La idea del antineutrón es más compleja (sin carga)



El modelo atómico

- Un simple modelo atómico
- Radio atómico: $a_0 \sim 53 \text{ pm} = 53000 \text{ fm}$
- Radio núcleo: $f_0 \sim 1.2 \text{ fm}$
- Relación: ~ 44200
- Núcleo 4 mm → electrones 177 m
- La naturaleza es escencialmente vacío





El núcleo es estable

- Tiene que haber una fuerza más fuerte que la fuerza eléctrica

$$F_E = \left(\frac{1}{4\pi\epsilon_0} \right) \frac{e^2}{r^2}$$

$$F_E = 160 N$$

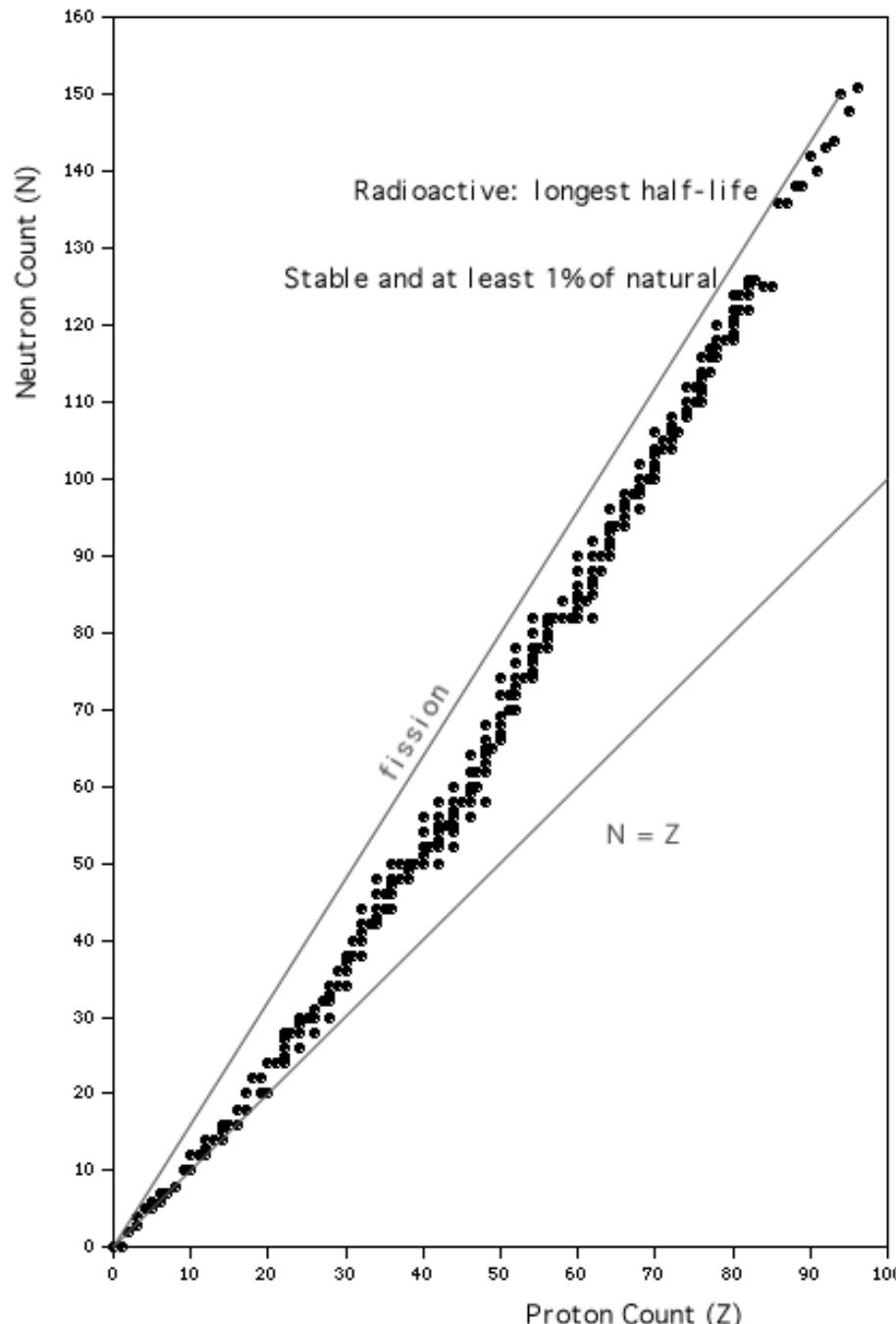
$$F_E = 1.2 \times 10^{36} F_G$$

Ayuda: En general el núcleo tiene más neutrones que protones

$$A = Z + N$$

$$N \geq Z$$

Tabla de nucléidos

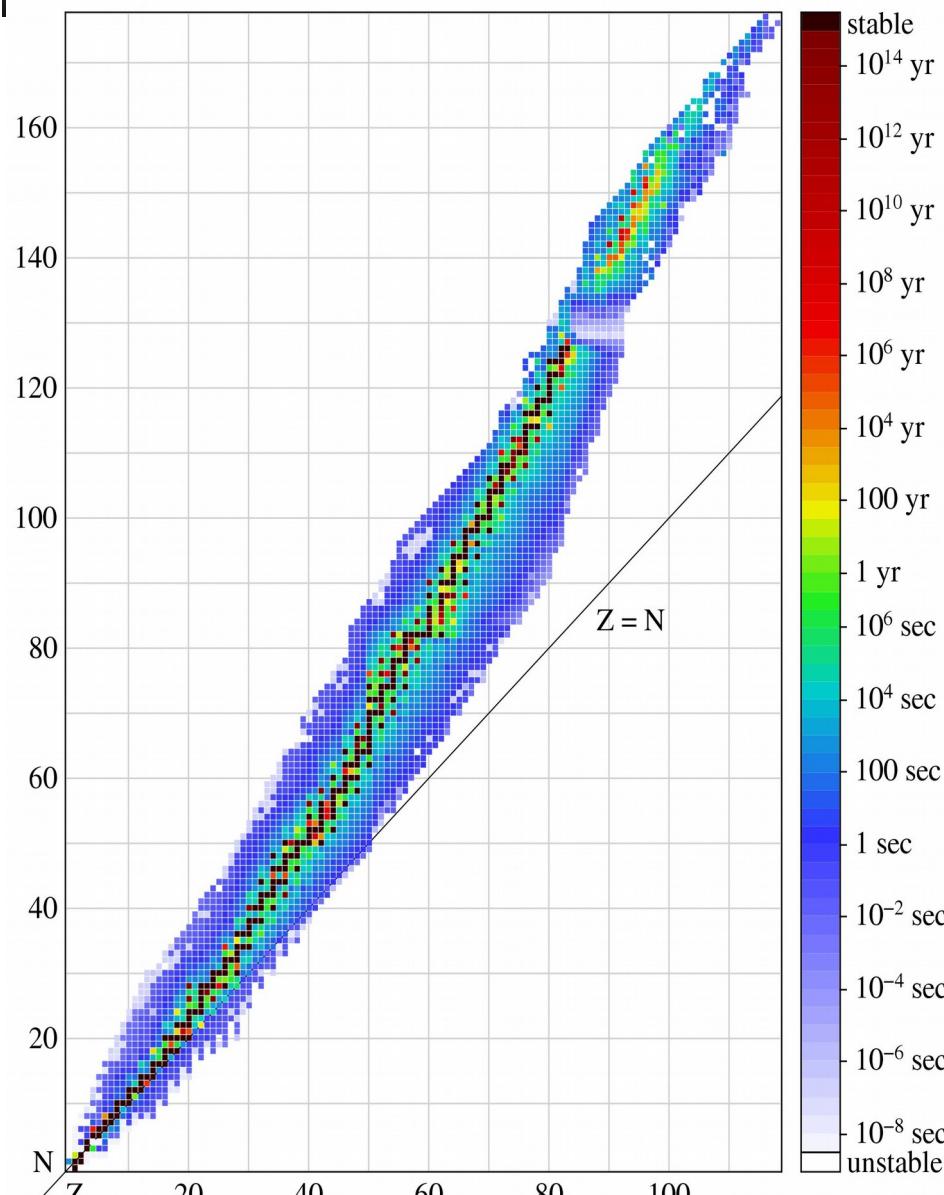


- $F_E \sim Z^2$
- Neutrones sin carga
- 1H_1 4He_2 ${}^{238}U_{92}$

Los neutrones ayudan a la cohesión

Fuerza Fuerte
Matrimonio

Emisión radioactiva de electrones



Sep 01, 2016

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- Reacción nuclear

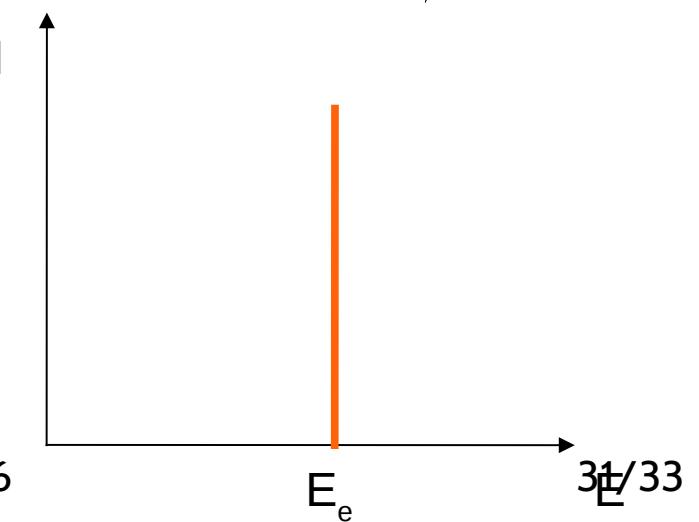


P. ej:



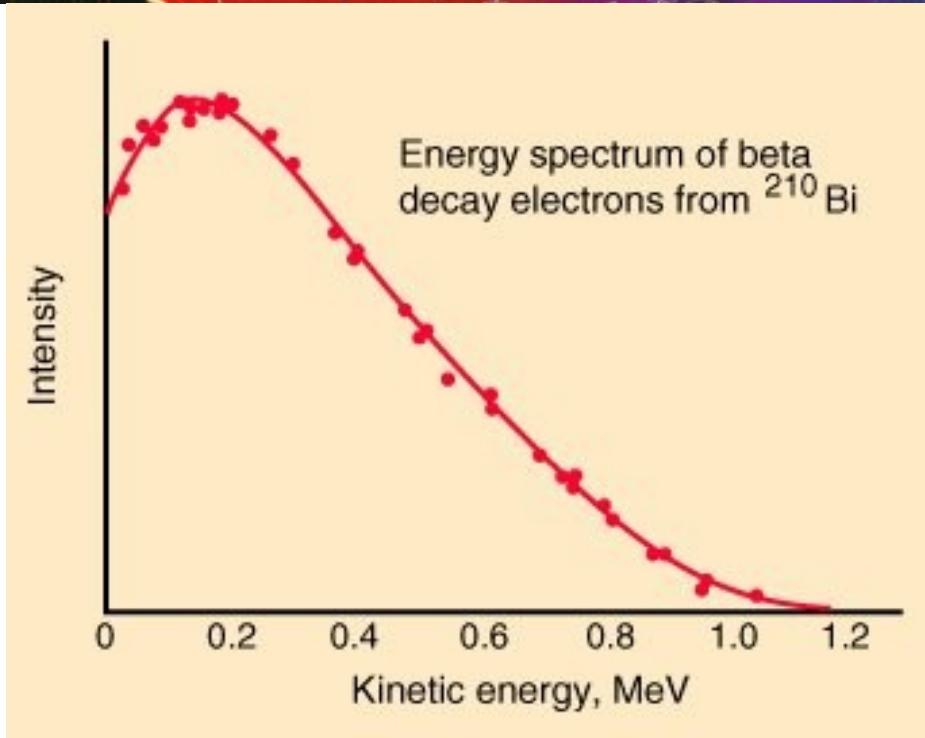
$$m_{\text{Bi}} c^2 = m_{\text{Po}} c^2 + m_e c^2 + Q$$

$$Q = (m_{\text{Bi}} - m_{\text{Po}} - m_e) c^2 \approx E_e$$

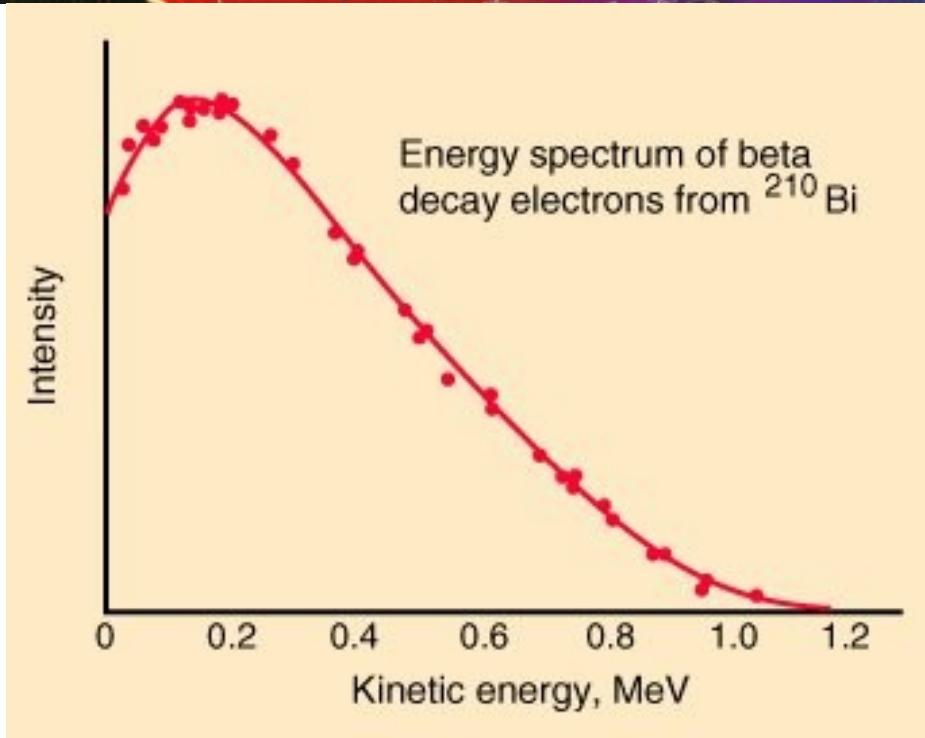


${}^{31}\text{E}_{e/33}$

La medición



La medición



$$n \rightarrow p^+ + e^- + \nu + Q$$



$$Q = (m_{Bi} - m_{Po} - m_e - m_\nu) c^2$$

$$Q \approx E_e + E_\nu$$