



Universidad Nacional de Río Negro

Int. Partículas, Astrofísica & Cosmología - 2017

- **Unidad** 02 – Astrofísica
- **Clase** UO2C05 – 11
- **Fecha** 24 Oct 2017
- **Cont** Estrellas 3
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github.com/asoreyh/unrn-ipac
www.facebook.com/fisicareconocida/



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
The universe expands, cools a repulsive energy field inflates space faster than light fills it with 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-millionth 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 collection of gas and dust is the only light. Clumps of matter that will become galaxies glow brightest.

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. Puffs of dark matter eventually form galaxies and stars. Star fusion lights up the stars.

Age: 300 million years
Size: 0.1 present size

Antigravity wins
After being slowed for billions of years, gravity, cosmic expansion accelerates again. The culprit: 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

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.

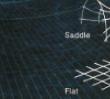
WHAT IS OUR UNIVERSE MADE OF?

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.



Unidad 2 Astrofísica Cálido y frío

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



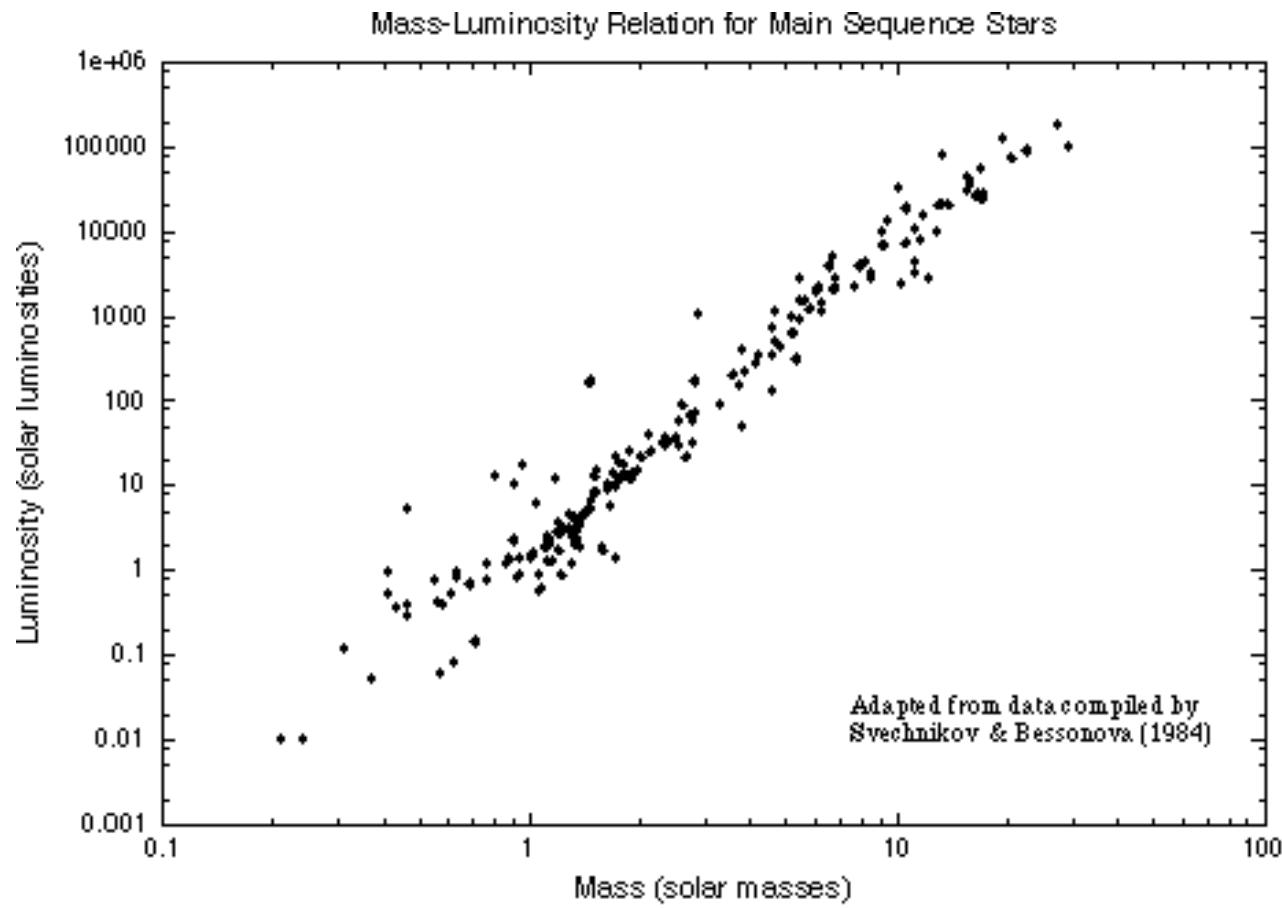
Fly through the universe on our digital edition.
LONDON PHOTOS: ANDREW STONE; FERNE GOLDBECK; ART: WOZNIAK/INTERACT DESIGN SOURCE: CHARLES BENNETT, JOHN HESKETH, AND JEFFREY KATZ, JET PROPULSION LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY, AND NATIONAL GEOGRAPHIC SOCIETY

Luminosidad → Masa

- Si: $(0.1 < \text{Masa Estelar} < 50)$ masas solares:
L es proporcional a la M^4
- Nota: En general, M^a , con a entre 3 y 4 (~ masa)

$$\left(\frac{L_{\text{Estrella}}}{L_{\text{Sol}}} \right) = \left(\frac{M_{\text{Estrella}}}{M_{\text{Sol}}} \right)^4$$

Oct 24, 2017



- Veamos.... $(T_B/T_S)^4$

$$R_B = 1026 R_{\text{Sol}}$$

Betelgeuse es una supergigante roja

mas luminoso que Betelgeuse

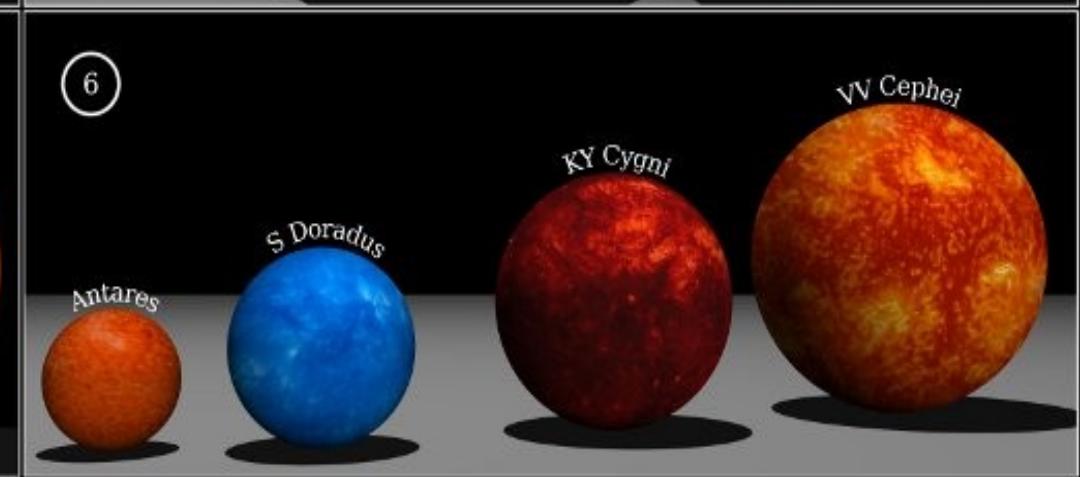
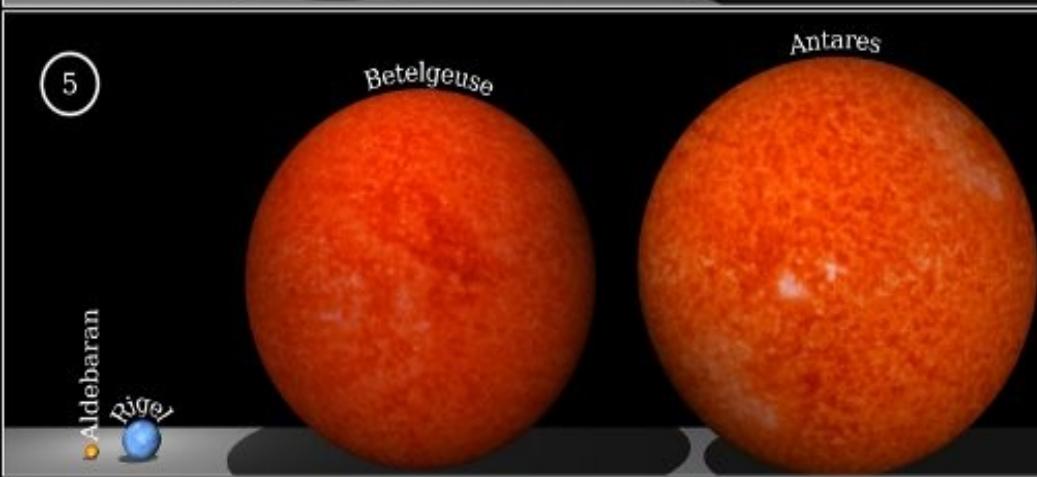
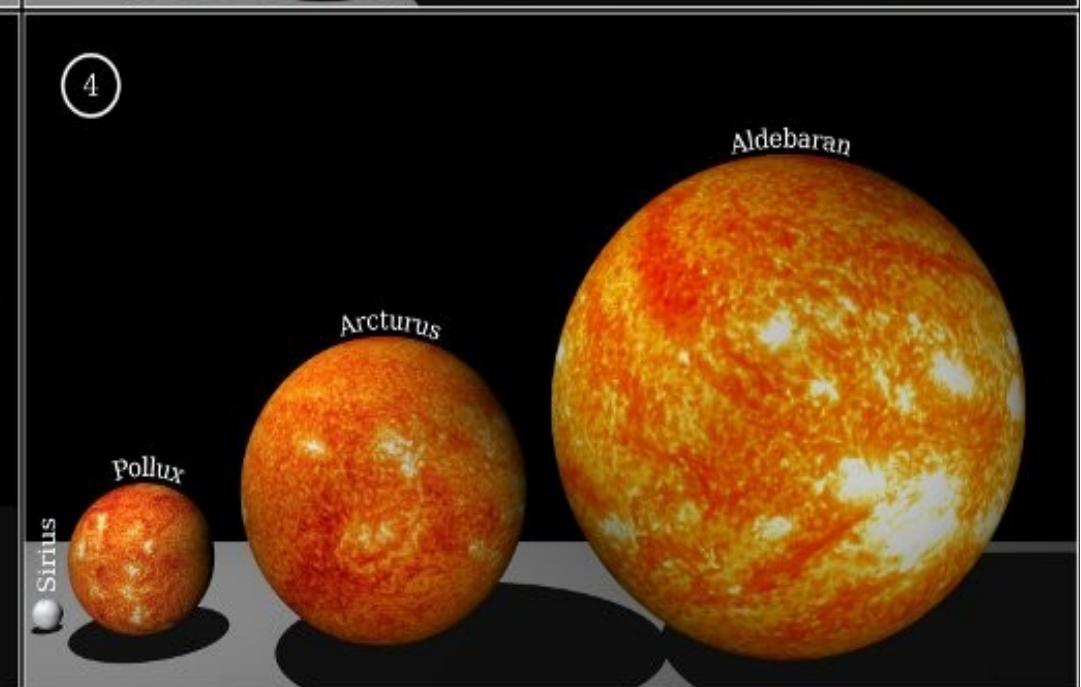
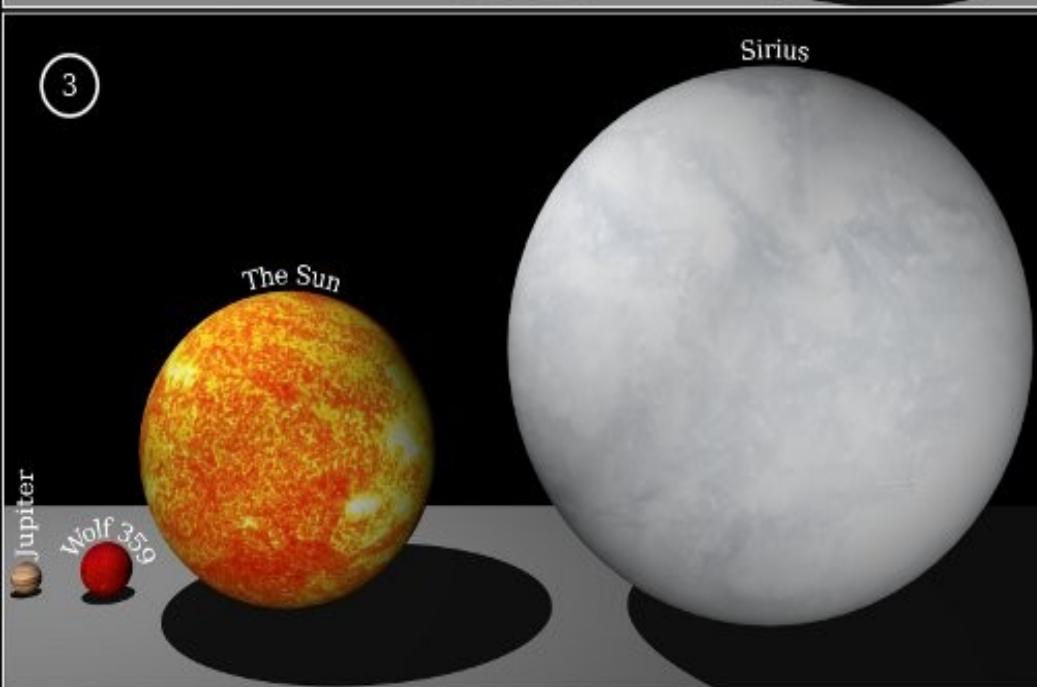
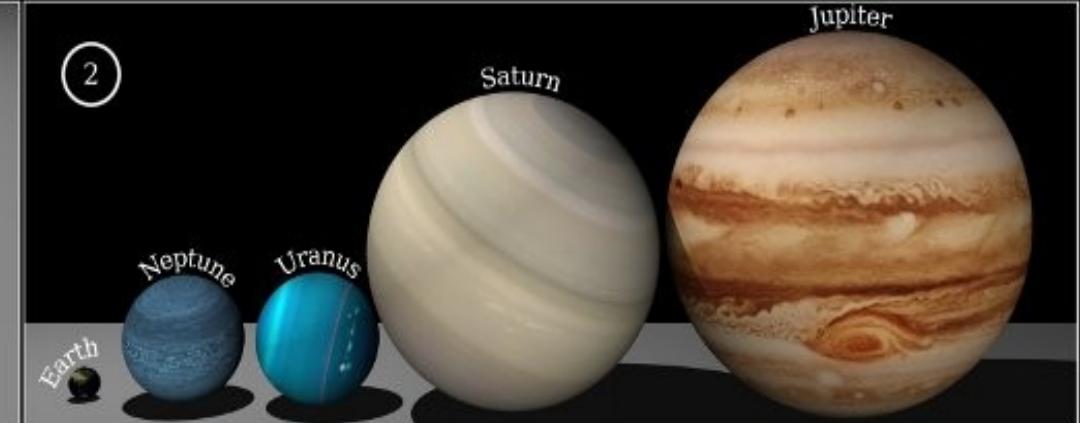
- Pero...

$$L_B / L_S = [(4\pi R_B^2) \sigma T_B^4] / [(4\pi R_S^2) \sigma T_S^4]$$

$$135000 = (R_B/R_S)^2 (T_B/T_S)^4$$

$$135000 = (R_B/R_S)^2 / 7.8$$

$$1.053 \times 10^6 = (R_B/R_S)^2$$





Es cómodo medir las cosas en términos solares

- Masa Solar:

$$M_{\text{Sol}} = 1.989 \times 10^{30} \text{ kg} \simeq 1000 M_{\text{Júpiter}} \simeq 333000 M_{\text{Tierra}}$$

- Radio Solar:

$$R_{\text{Sol}} = 6.96 \times 10^8 \text{ m} = 696000 \text{ km}$$

- Luminosidad Solar:

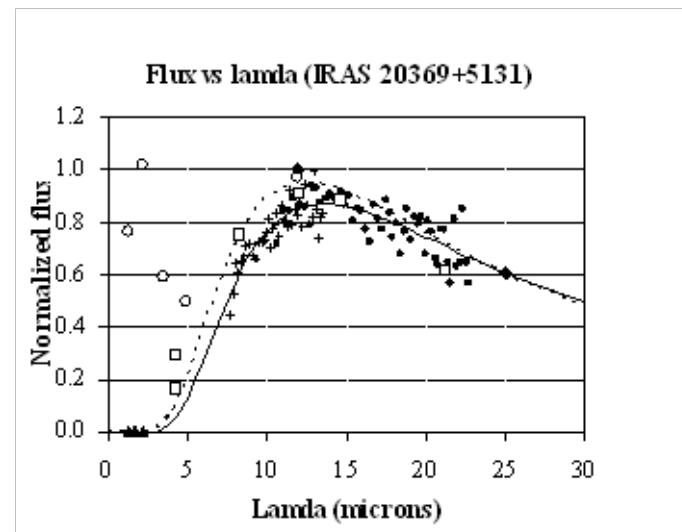
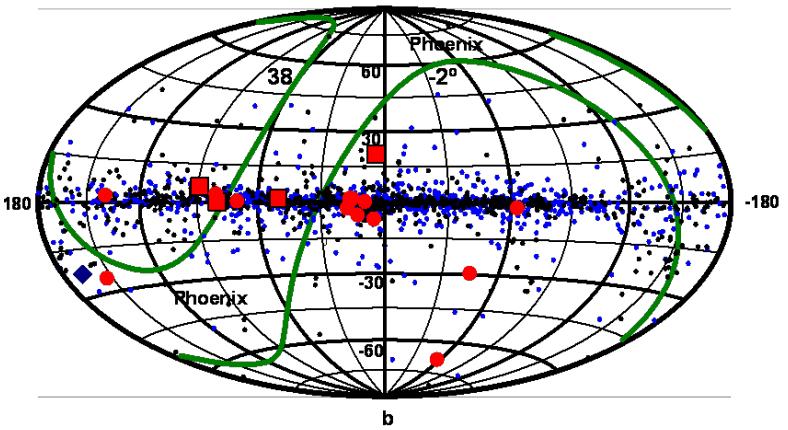
$$L_{\text{Sol}} = 3.83 \times 10^{26} \text{ W}$$

- Alto:

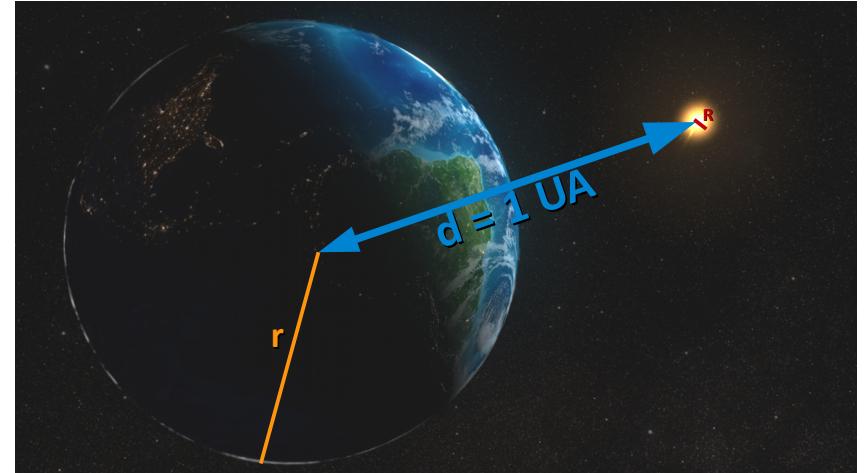
**1 segundo de energía liberada en el Sol
equivale a 800000 años de consumo humano (2013)**

IRAS (InfraRed Astronomical Satellite)

http://home.fnal.gov/~carrigan/infrared_astronomy/Fermilab_search.htm



¿Y si fuera un planeta?

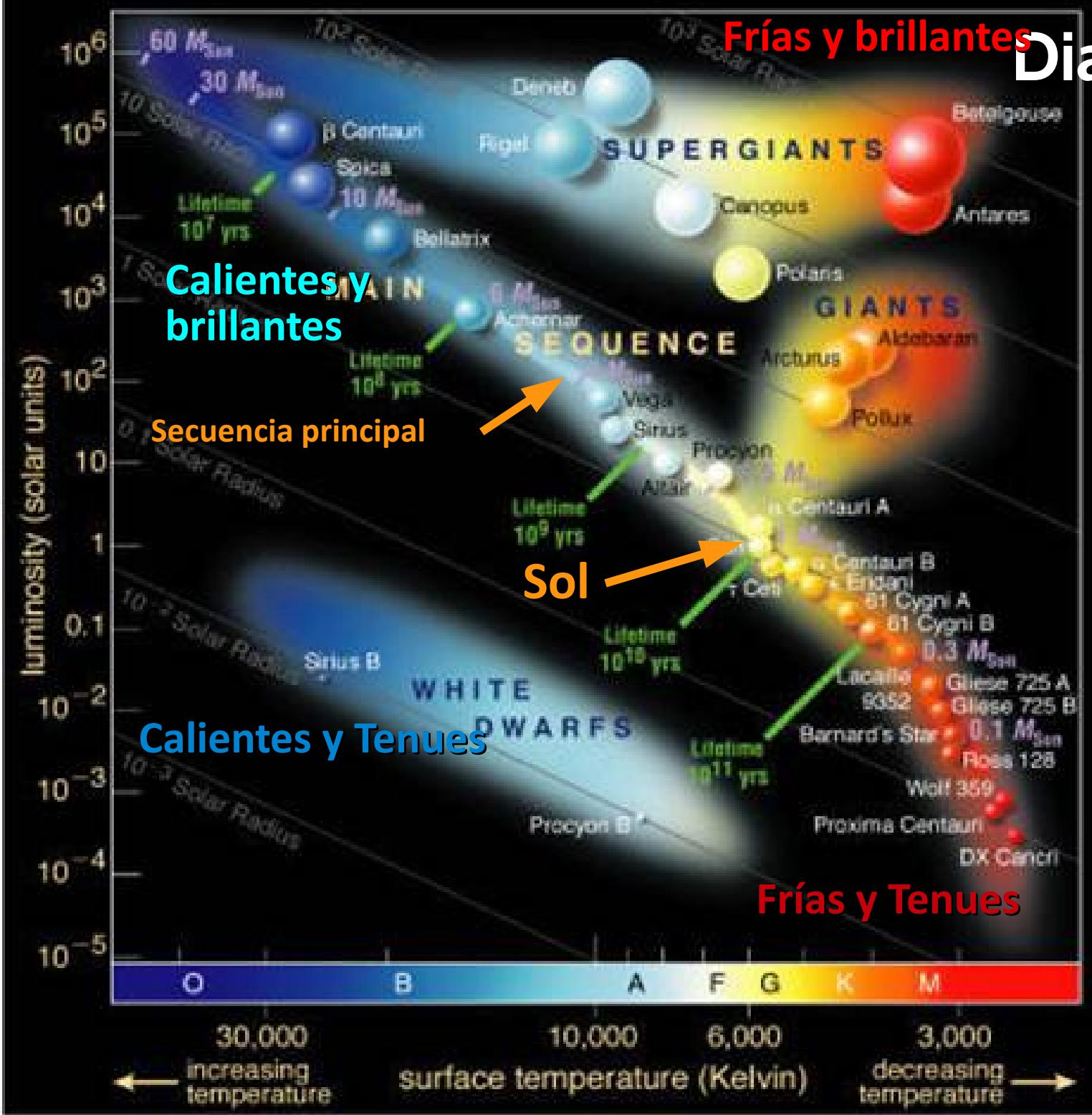


- ¿Qué fracción de la energía captura un planeta de radio r ?

$$T_{\oplus} = \sqrt[4]{\frac{L_{\odot}}{16\pi\sigma d^2}}$$
$$T_{\oplus} = \sqrt{\frac{R_{\odot}}{2d}} T_{\odot}$$
$$d = \frac{1}{2} \left(\frac{T_{\odot}}{T_{\oplus}} \right)^2 R_{\odot}$$

Frías y brillantes

Diagrama H-R

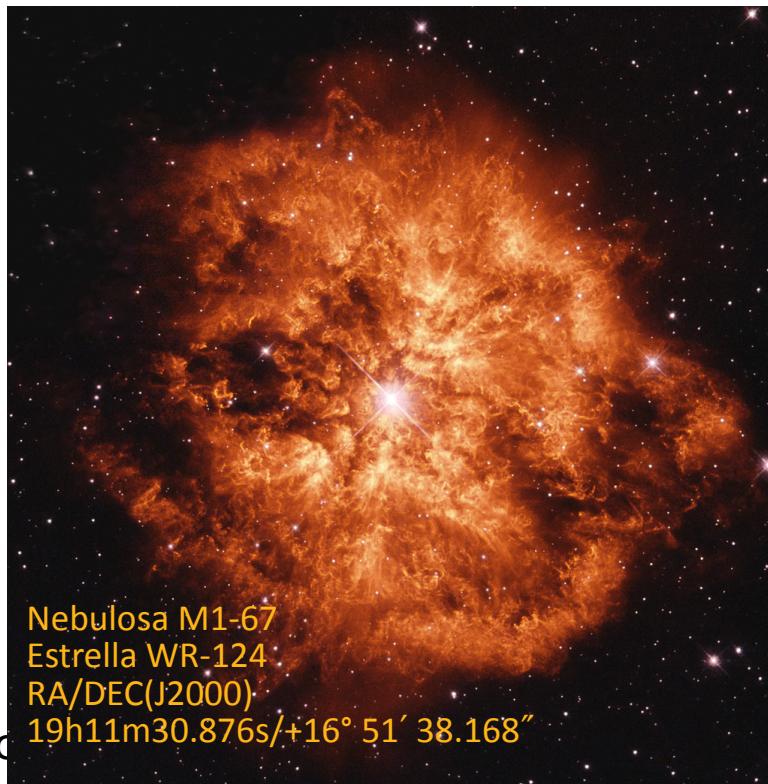


$$L \propto R^2 T^4$$

Otros tipos de estrellas

- W: Wolf-Rayet

- Estrellas masivas ($>20M_s$)
- Excesivamente calientes



- Los nuevos: L, T, Y

- L: Enanas frías o subestrellas, temperaturas $1300K < T < 2400K$
- T: Enanas marrones (subestrellas, sin fusión H) con prominencia de metano y $500K < T < 1300K$
- Y: enanas marrones ultra frías (superplanetas?) c/amoníaco y $T < 600K$, y $10 < M/M_{Júp} < 90$

Estrellas supermasivas

NGC3372 – Nebulosa Carina (Carina)

Estrellas supermasivas



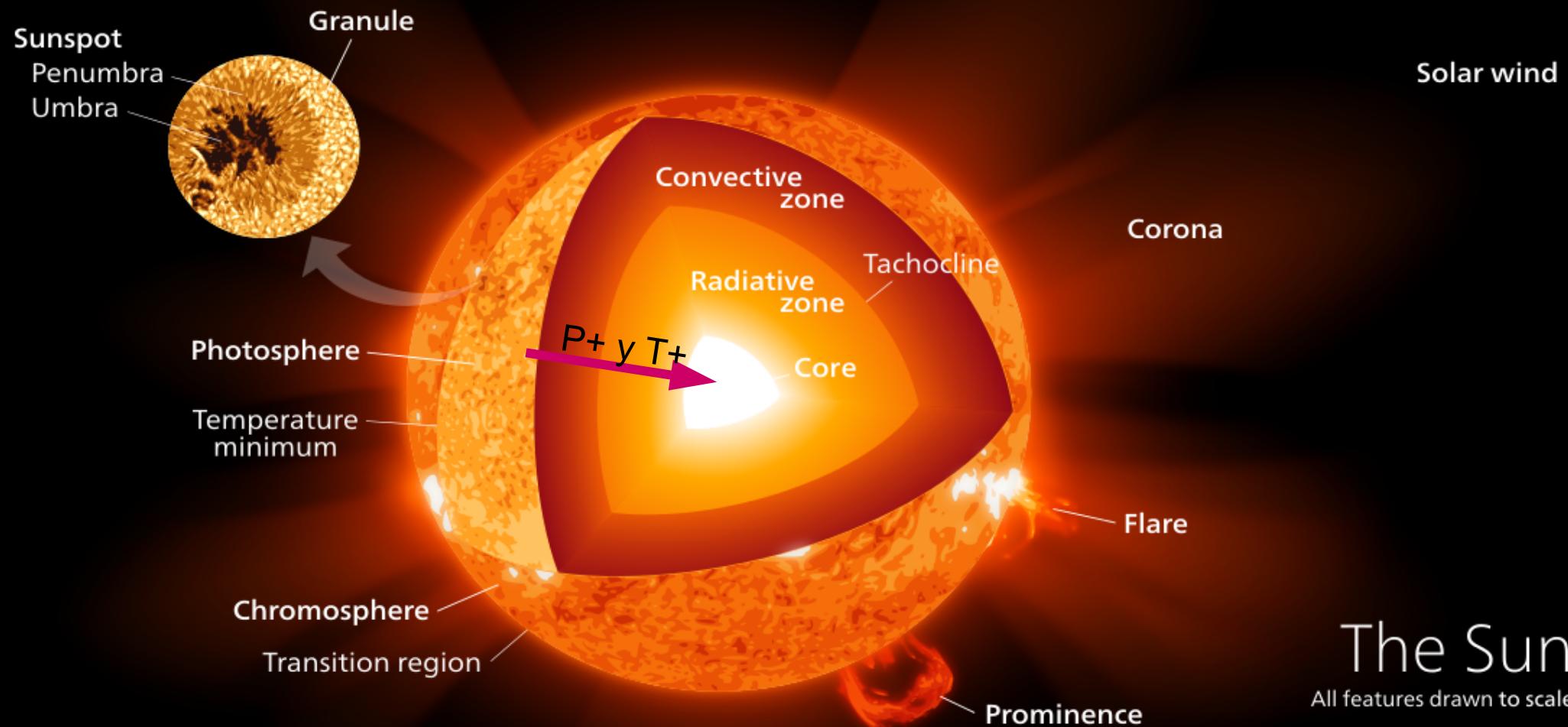
NGC3372 – Nebulosa Carina (Carina)

η Carinae: Una binaria a punto caramelito



Nebulosa Homúnculo en la Nebulosa Eta Carina (en la Nebulosa Carina)

Estructura de una estrella típica (Sol)



The Sun

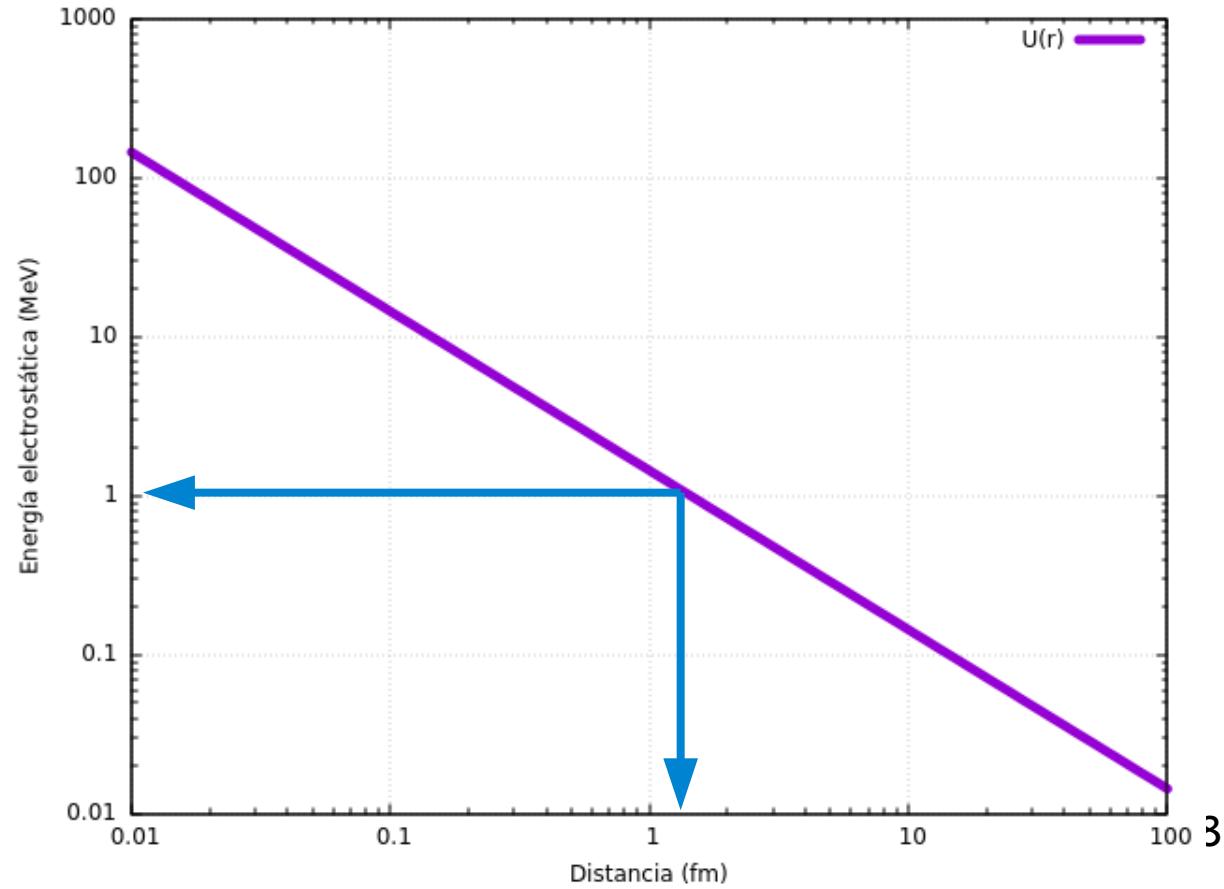
All features drawn to scale

Barrera Coulombiana

- Recordar, para dos cargas eléctricas puntuales,

$$U(r) = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r} \rightarrow U_{pp}(r) = \frac{1}{4\pi\epsilon_0} \frac{e^2}{r}$$

- Poniendo valores:
 $r \sim 1.2 \text{ fm}$
 $U_{pp}(r) \sim 1 \text{ MeV}$
- $E \sim 3/2 k T \rightarrow$
¡¡¡ $T \sim 2 \times 10^{10} \text{ K}$!!!



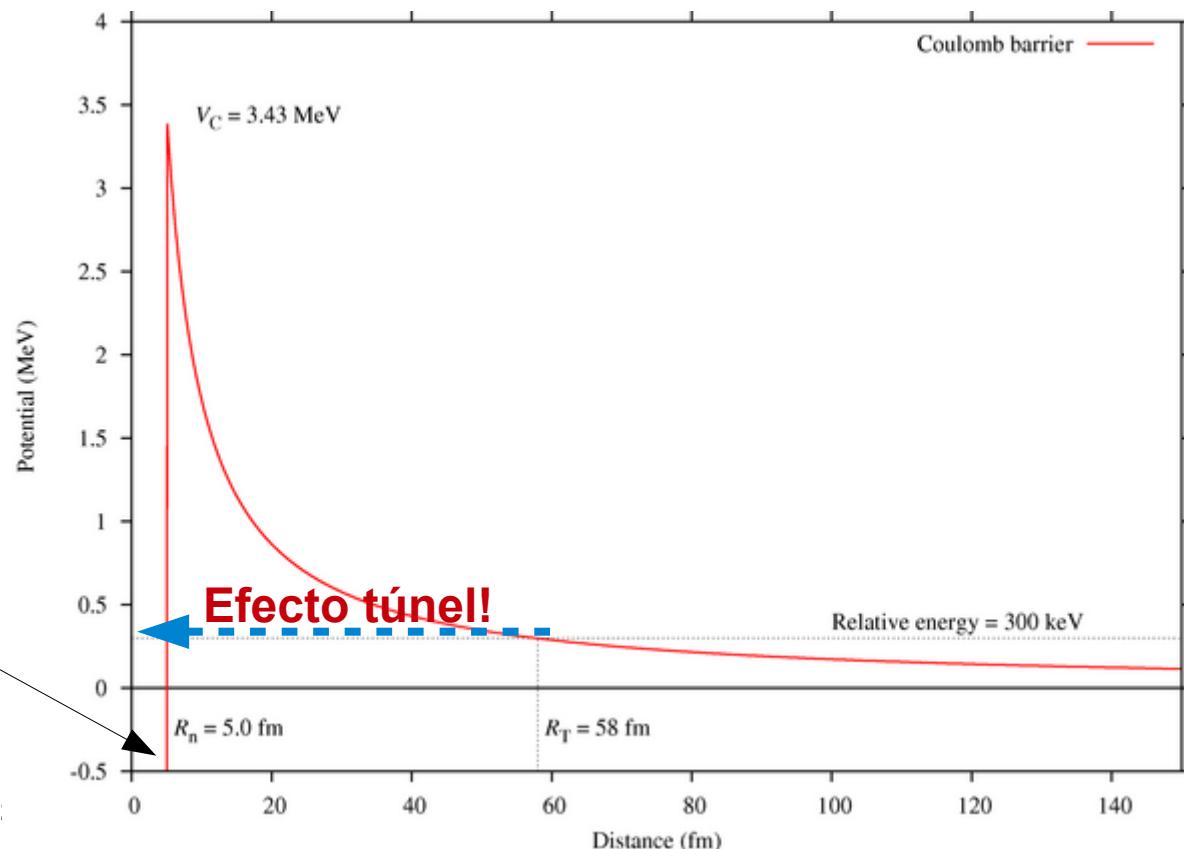
Sistemas compuestos y potencial nuclear

- En general, para dos núcleos ${}^A X_Z$ y ${}^B Y_Z$, entonces

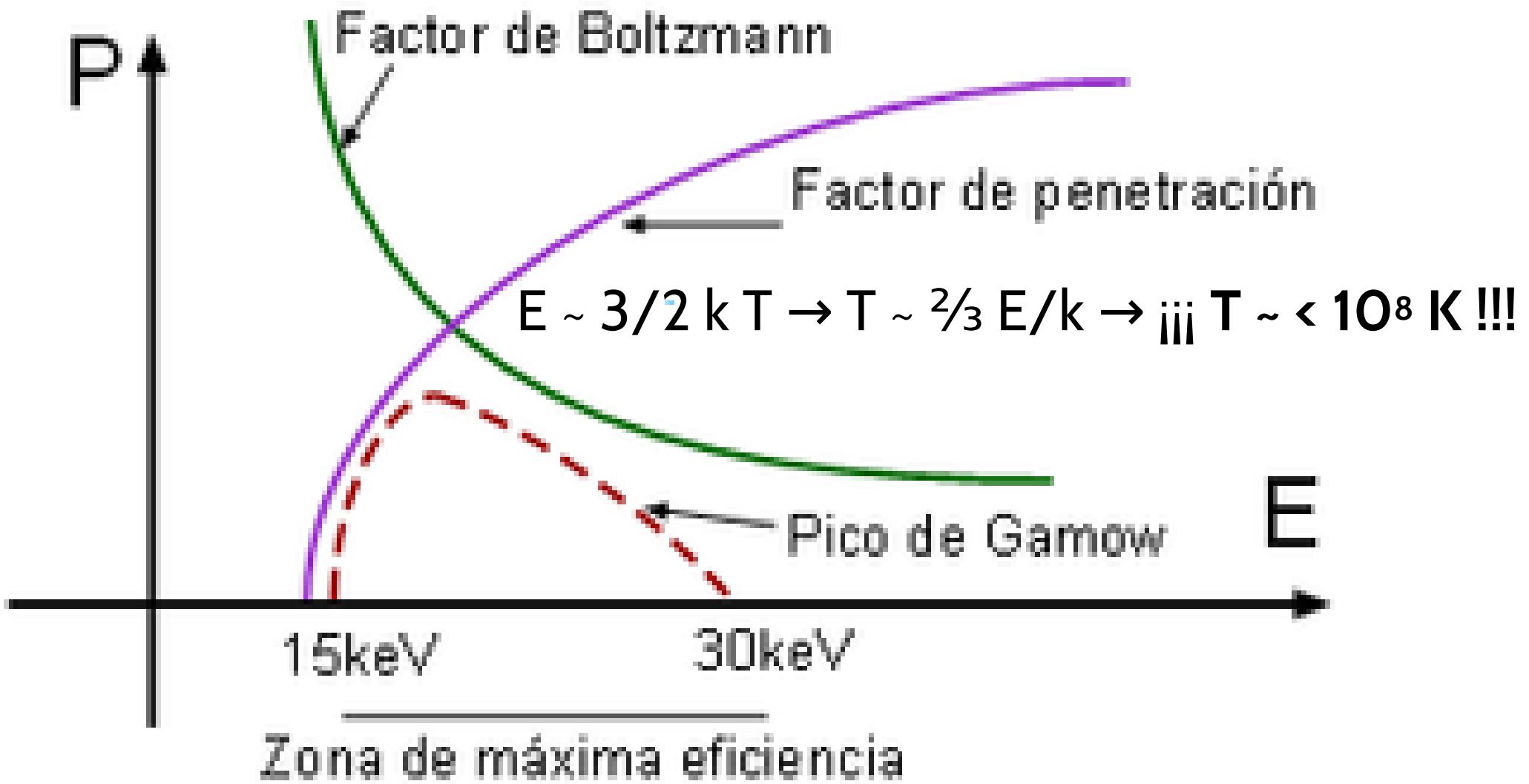
$$U_{XY}(r) = \left(\frac{e^2}{4\pi\epsilon_0} \right) \left(\frac{Z_X Z_Y}{A_X^{1/3} + A_Y^{1/3}} \right) \frac{1}{r} \rightarrow U_{XY}(r) \approx 1.44 \left(\frac{Z_X Z_Y}{A_X^{1/3} + A_Y^{1/3}} \right) \frac{1}{r} \text{ MeV}$$

- Barrera de Coulomb.
Por ej., ${}^{12}\text{C} + {}^4\text{He}$:

A distancias cortas,
el potencial nuclear es atractivo!



Efecto túnel → Pico de Gamow (1928)

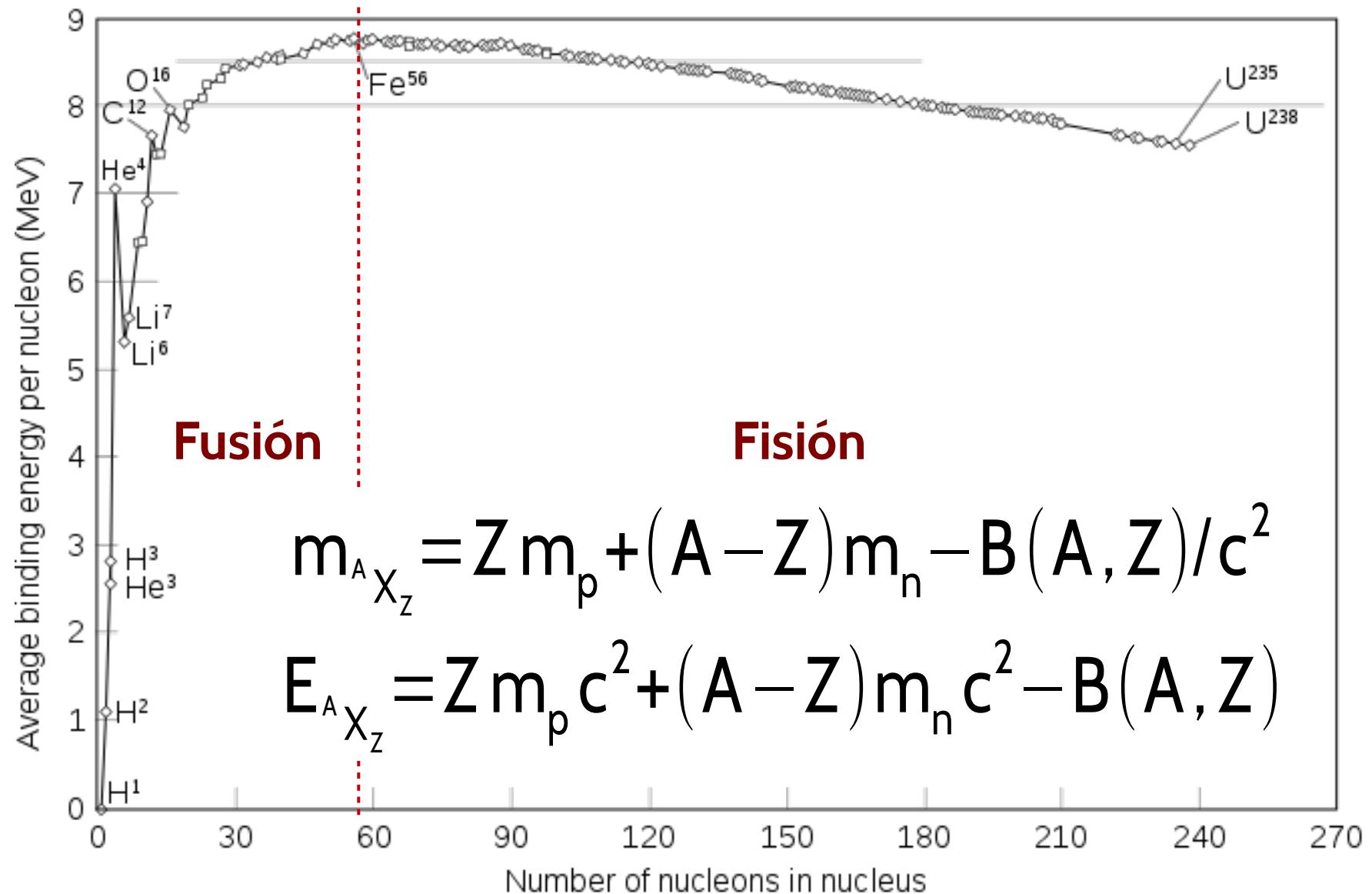


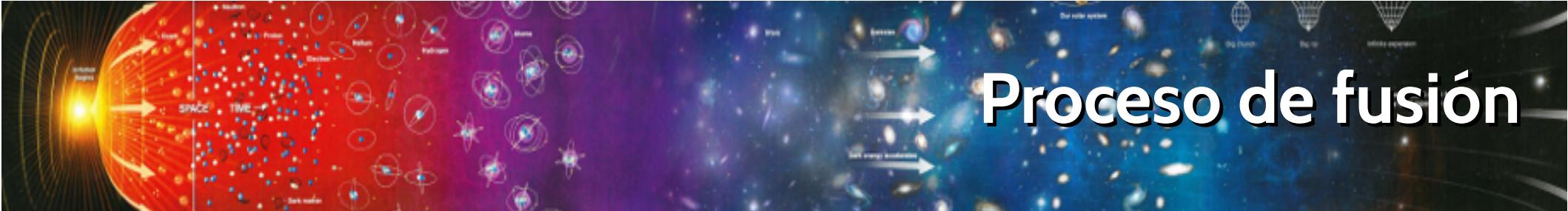


En estrellas como el Sol

- La temperatura central es $10 \text{ MK} < T < 20 \text{ MK}$
- El tiempo de reacción es $\sim 10^9$ años!!
- Hay tanto hidrógeno que el ritmo de reacción es sostenible (volveremos....)

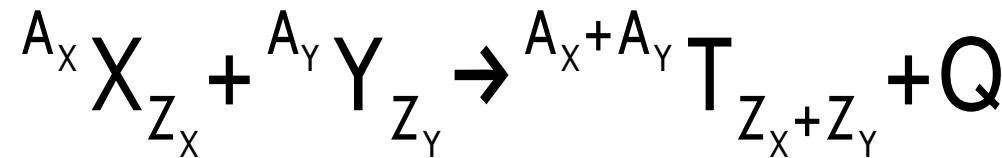
Energías de ligaduras



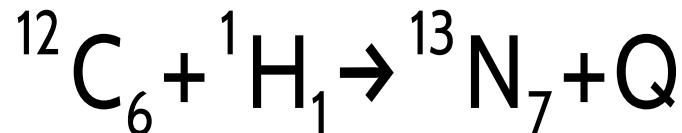
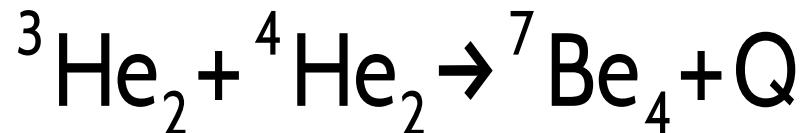


Proceso de fusión

- Dos núcleos se fusionan liberando energía:



- Por ejemplo:



- Y entonces, la energía liberada será

$$Q = (m_{\text{reactivos}} - m_{\text{productos}}) c^2$$

Energía liberada en un proceso de fusión



$$m_{{}^3\text{He}} = 2m_p + (3-2)m_n - B(3,2) = 2m_p + m_n - B(3,2)$$

$$m_{{}^4\text{He}} = 2m_p + (4-2)m_n - B(4,2) = 2m_p + 2m_n - B(4,2)$$

$$m_{{}^7\text{Be}} = 4m_p + (7-4)m_n - B(7,4) = 4m_p + 3m_n - B(7,4)$$

$$\Rightarrow Q = m_{{}^3\text{He}} + m_{{}^4\text{He}} - m_{{}^7\text{Be}}$$

$$\Rightarrow Q = 2m_p + m_n - B(3,2) + 2m_p + 2m_n - B(4,2) - 4m_p - 3m_n + B(7,4)$$

$$\Rightarrow Q = B(7,4) - B(3,2) - B(4,2) \quad \text{Usando los totales (ojo, es } B/A \text{ entables)} \Rightarrow$$

$$Q = 5,37 \text{ MeV} \cdot 7 - 2,572 \text{ MeV} \cdot 3 - 7,07 \text{ MeV} \cdot 4 = 1,594 \text{ MeV}$$

$$\Rightarrow Q = 1,594 \text{ MeV} > 0.$$

En general

$$Q = B_{\text{producto}} - \sum B_{\text{reacciones}}$$

Si $Q > 0$ la fusión es un proceso de liberación de energía



Energía liberada en un proceso de fusión

- Entonces:

$$Q = B_{\text{productos}} - \sum B_{\text{reactivos}}$$

- Los valores de $B(A,Z)$ pueden obtenerse de tablas
- Ver por ejemplo:

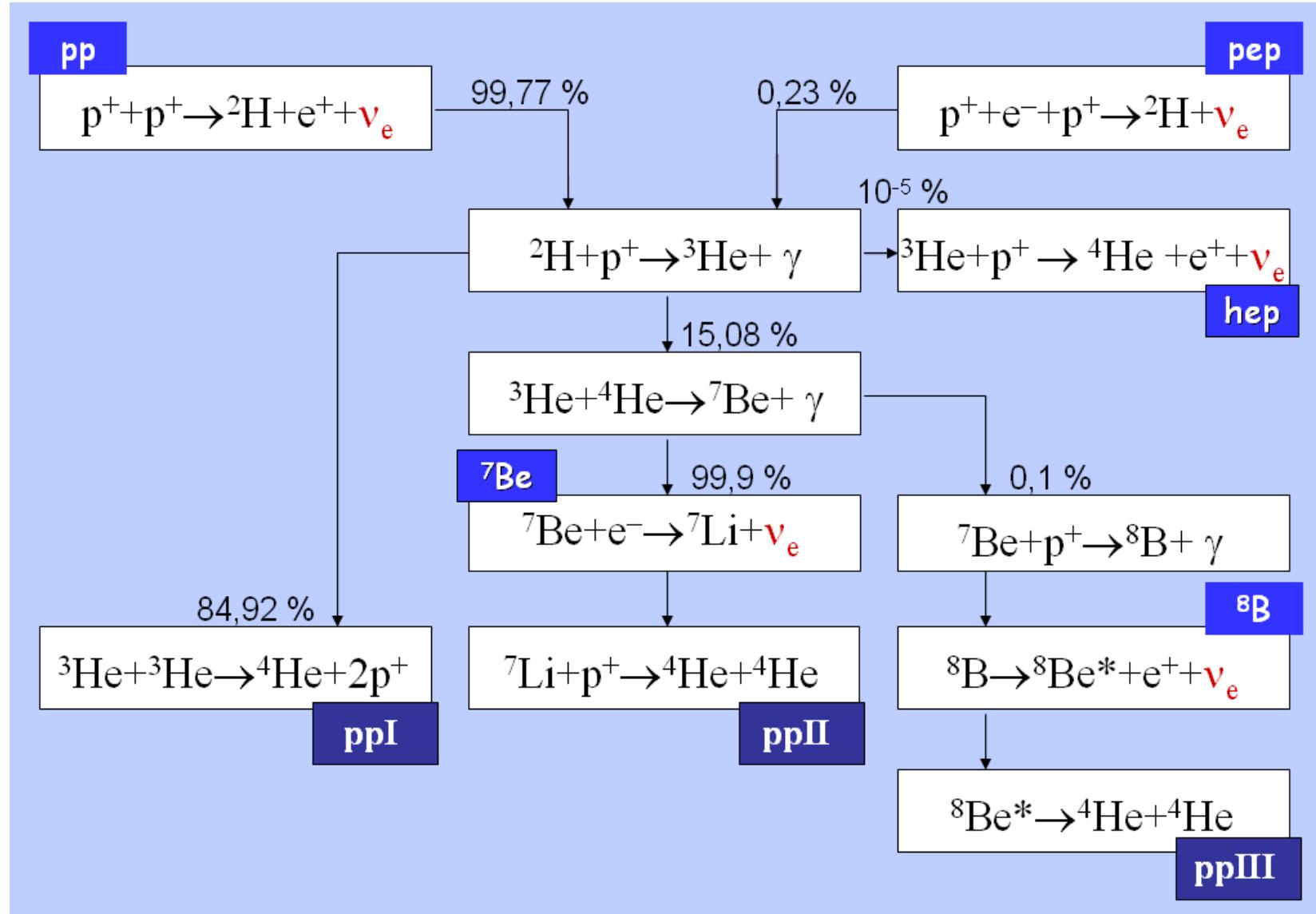
<https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html>

también en Google play!:

<https://play.google.com/store/apps/details?id=iaea.nds.nuclides>

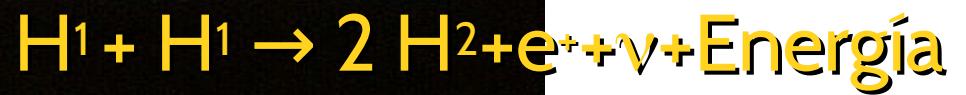
- Tener en cuenta que en la mayoría de las tablas se reporta la energía de ligadura por nucleón, es decir, B/A

La cadena protón protón (pp chain)



Fusión: Paso 1

STEP 1



NASA/NSSTC/Hathaway

Fusión: Paso 2

STEP 2

D^2

+

H^1



γ

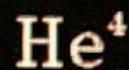
+

He^3

NASA/NSSTC/Hathaway

Fusión: Paso 3

STEP 3



NASA/NSSTC/Hathaway



Fusión: Producción neta



Masa inicial: $1.003 \times 10^{-26} \text{ kg}$

Masa final: $0.991 \times 10^{-26} \text{ kg}$

$$E=mc^2$$

~ 26,7 MeV por reacción



La conservación de energía implica

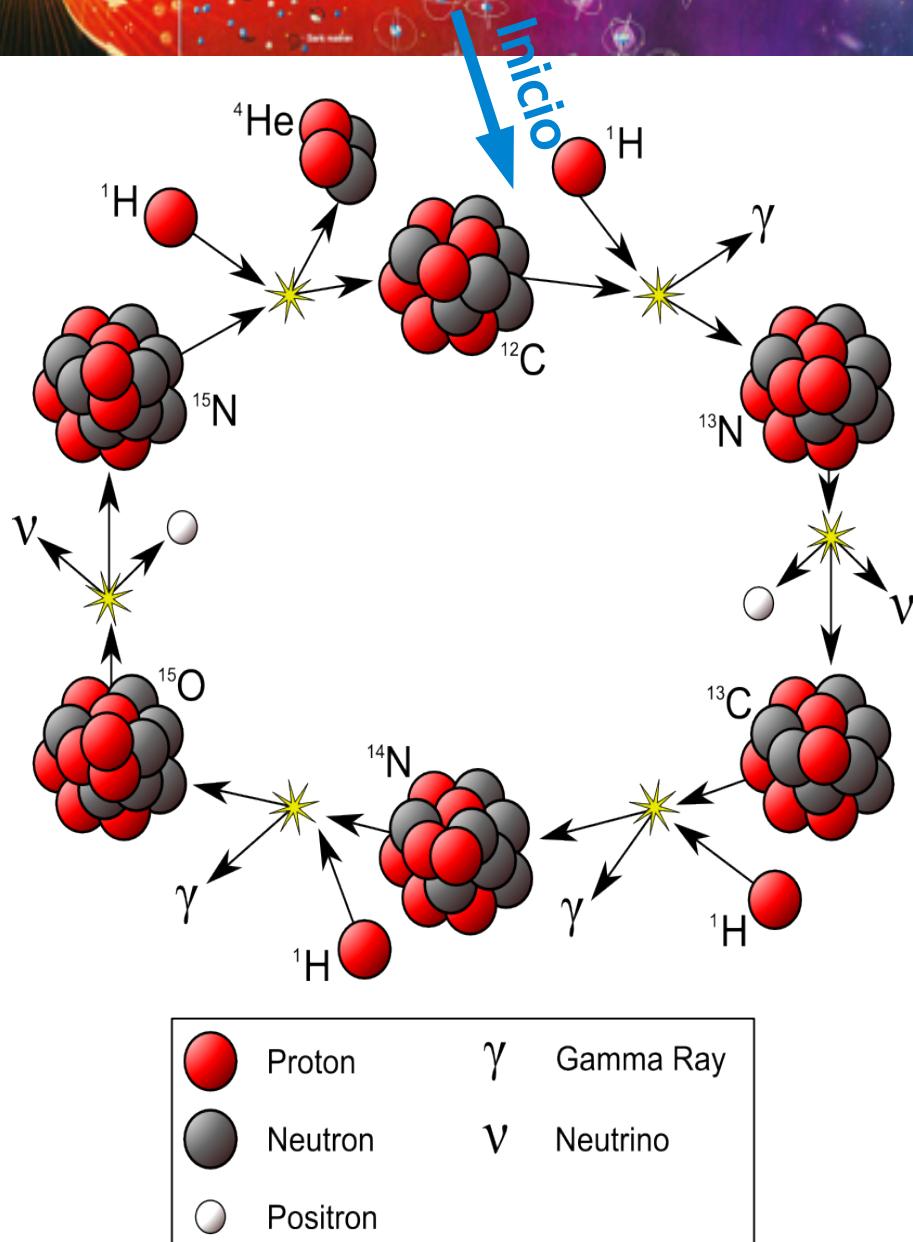
- Para el Sol:

$$L = 3.846 \times 10^{26} \text{ J/s} \text{ y sabiendo que } E_1 = 26.73 \text{ MeV}$$

$$L = nE_1 \rightarrow n = \frac{L}{E_1} \simeq 9 \times 10^{37} \text{ reacciones/s}$$

**Conversión de masa en energía:
4.000.000 toneladas/seg**

En estrellas más masivas, además... ciclo CNO



- Ciclo CNO (Carbono, Nitrógeno, Oxígeno)
- Usa el CNO como “catalizador”
- La reacción neta convierte $4 \text{ p} \rightarrow \text{He} + \text{neutrinos} + Q$, al igual que la cadena pp
- Libera la misma cantidad de energía neta por reacción (26.73 MeV)

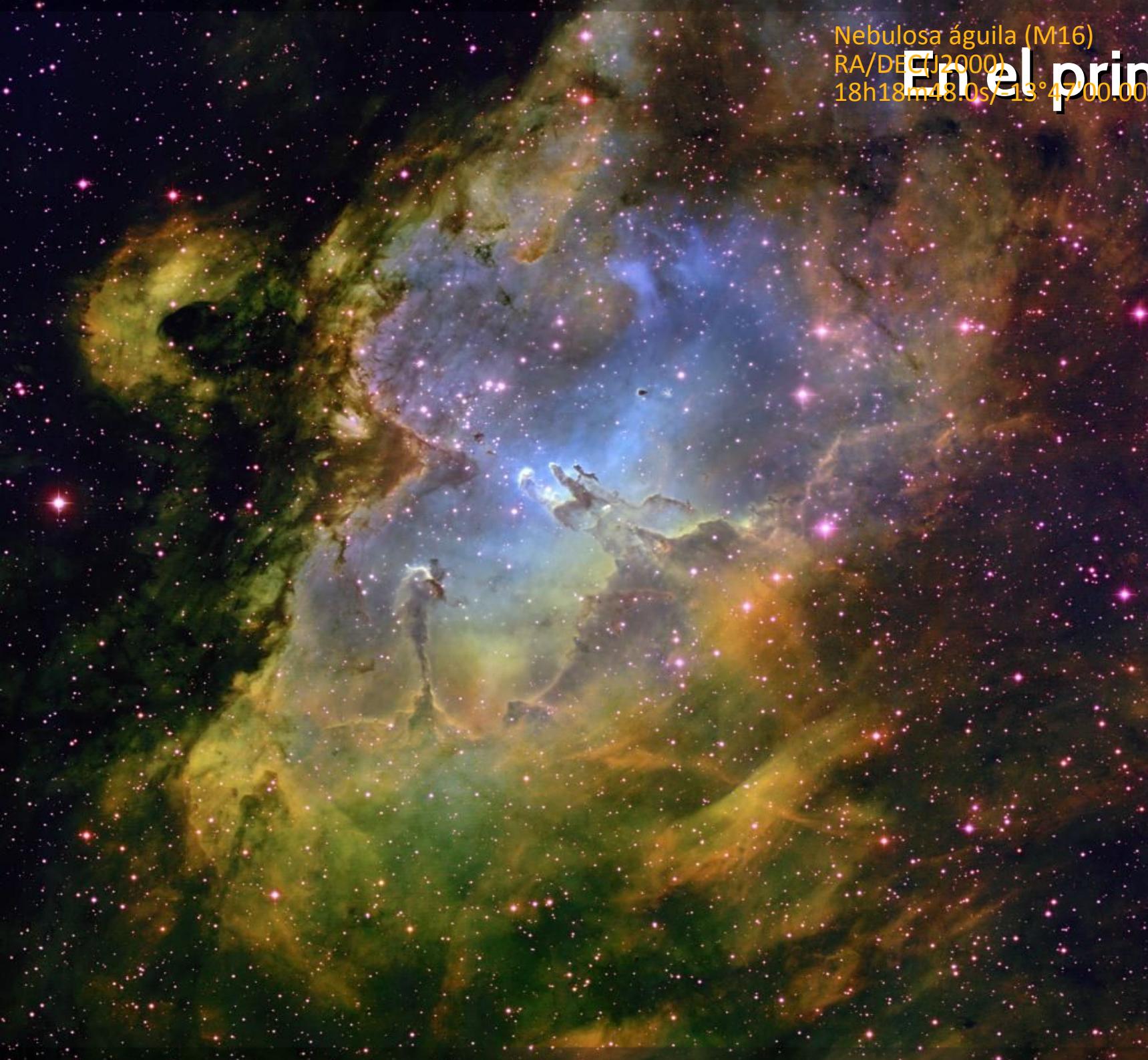


Nebulosa águila (M16)

RA/DEC(J2000)

18h18m48.0s / 13°47'00.00"

En el principio...



En el principio...

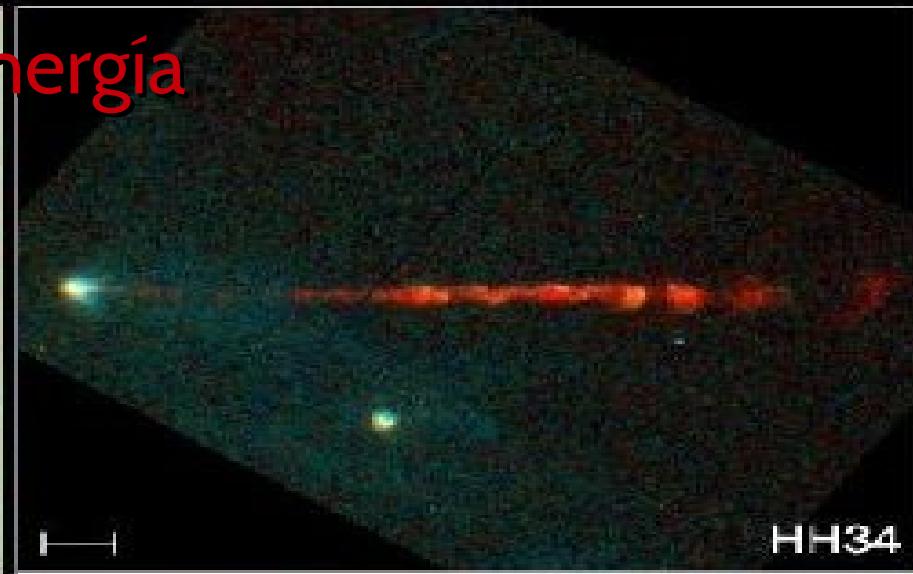
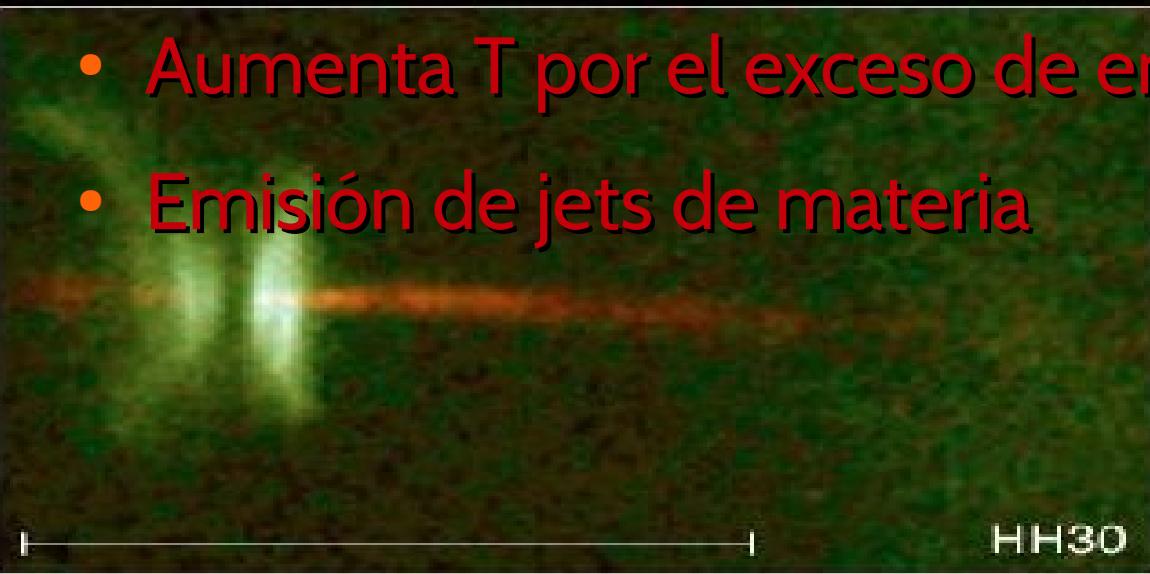
- Nubes de gas gigantes
- $6 \times 10^6 M_{\odot}$ y $R \sim 15$ pc
- Colapso gravitacional
- Aumenta temperatura
- T es pequeña pero R es muy grande
 ¡L es grande!
- → Gigantes Rojas

- La contracción se frena
- Continúa radiando

Pre-Secuencia

- $T_c \sim 10^7 \text{ K} \rightarrow \text{Fusión!}$

- Aumenta T por el exceso de energía
- Emisión de jets de materia



Jets from Young Stars

HST · WFPC2

PRC95-24a · ST Scl OPO · June 6, 1995

C. Burrows (ST Scl), J. Hester (AZ State U.), J. Morse (ST Scl), NASA

Secuencia Principal

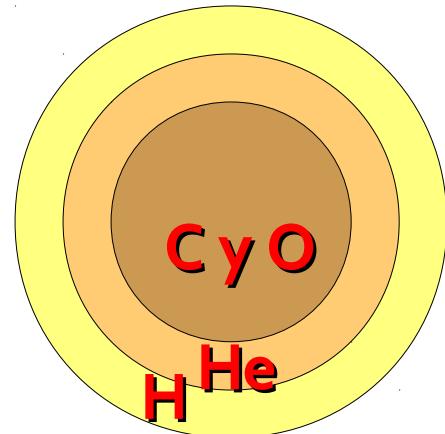
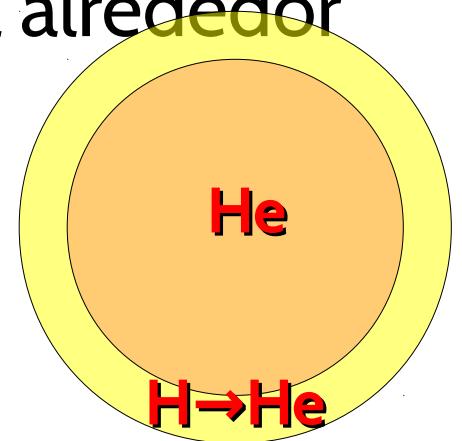


- Conversión $H \rightarrow He$ es muy eficiente
- 10^{10} años para $M = 1 M_{\text{Sol}}$
 - La energía radiada, $L \sim R^2 T^4$ proviene del interior
 - Velocidad de reacciones en el centro: $\sim T_c^4$
 - $R^3 \sim M T_c / P$ (\leftarrow Viene de $PV=nRT$)
- Si $T_c \rightarrow 2 T_c \Rightarrow R \rightarrow 8 R$
- Si $R \rightarrow 8R \Rightarrow L \rightarrow 64 L$
- ¡Mayor energía radiada!
- Moraleja: “**Vive rápido y morirás jóven**”

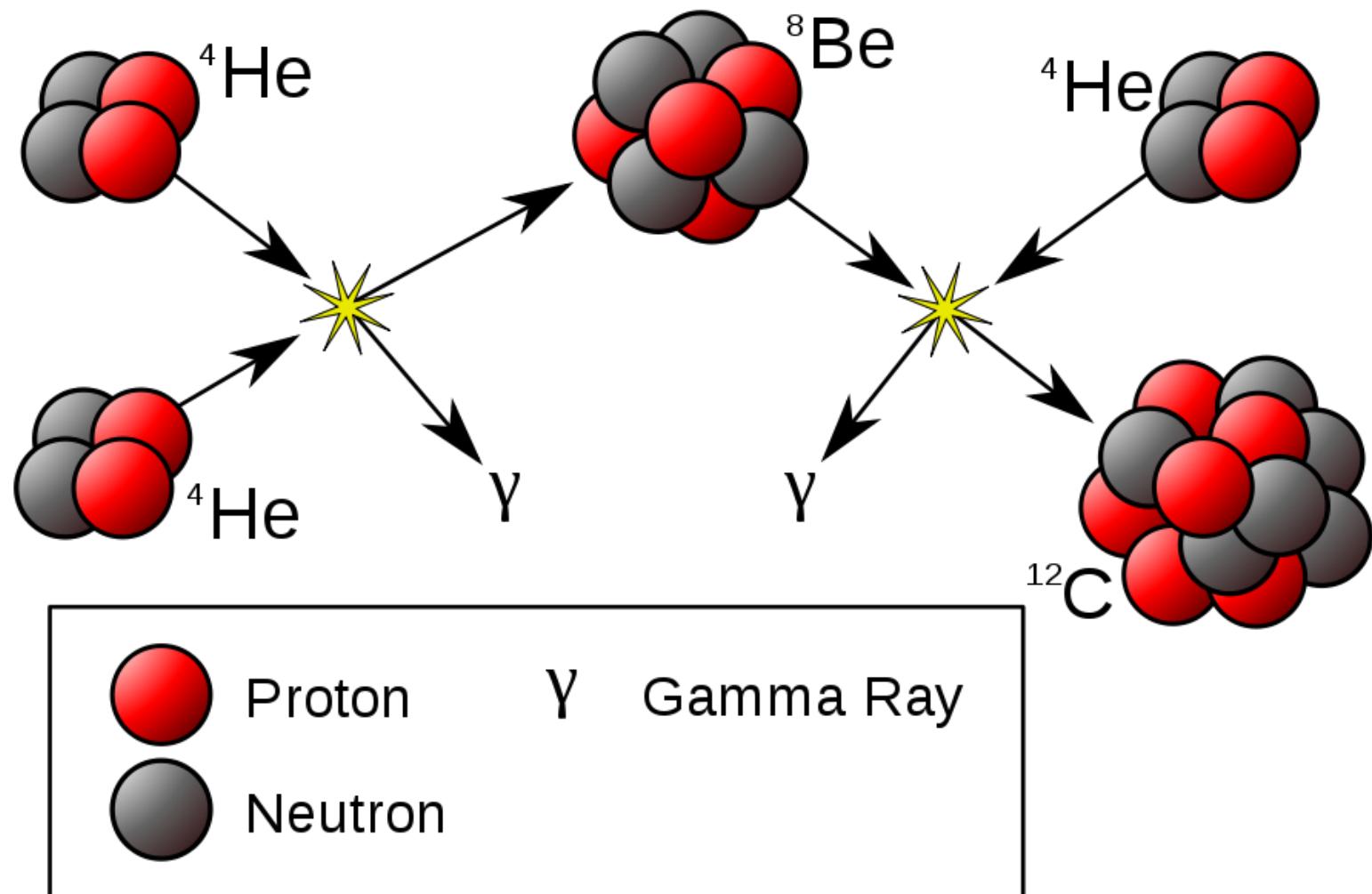
Vejez



- Se acabó el H en el núcleo, ¿y ahora?
- Conversión $H \rightarrow He$, sólo en una corona alrededor del centro
- No alcanza la energía → Contracción
- Aumenta $T_c \rightarrow$ Mayor producción de E
- Si $T_c = 10^8$ K, $He \rightarrow C$ (“Flash de Helio”)
- $R_{\text{Sol}} \rightarrow 220$ veces!!!
- Pero $220 (7 \times 10^5) \text{ km} \sim 1.5 \times 10^8 \text{ km}$



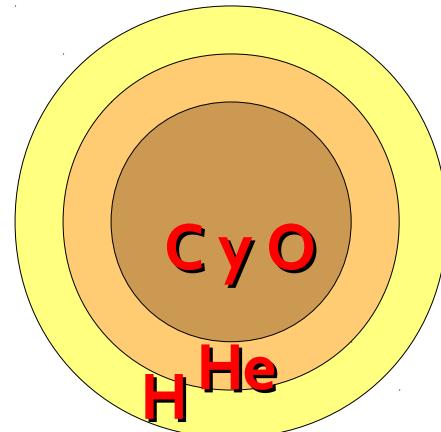
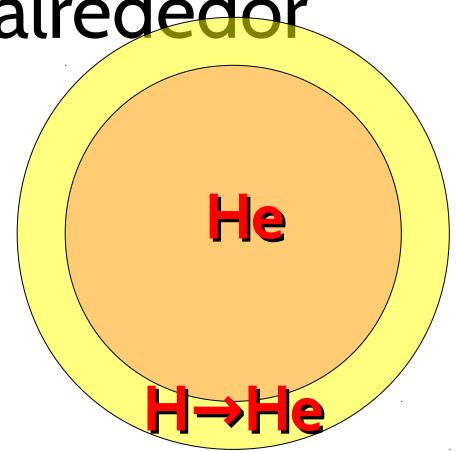
A mayor temperatura, es posible fusionar núcleos más pesados \Rightarrow Proceso Triple Alfa



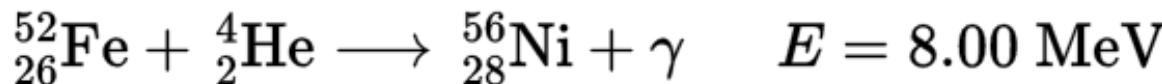
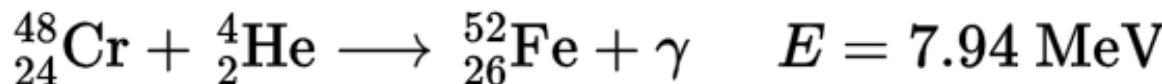
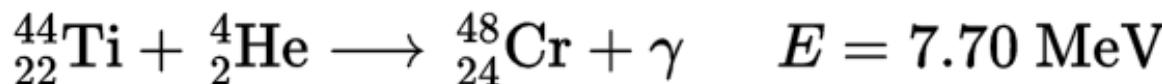
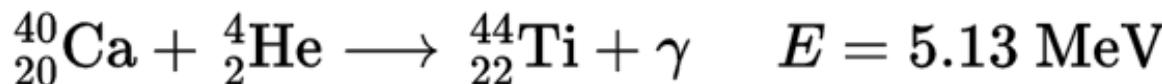
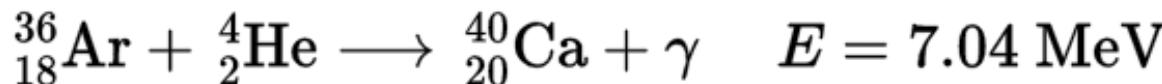
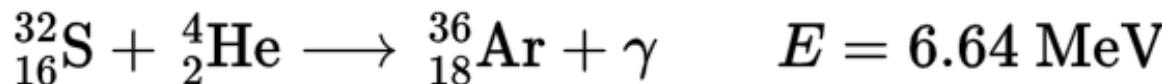
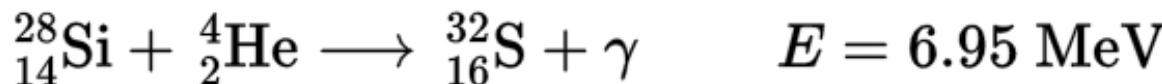
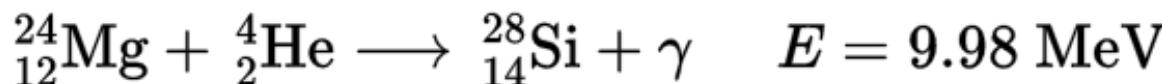
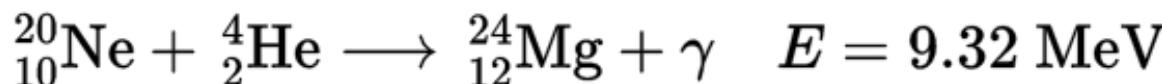
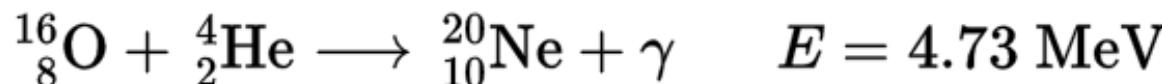
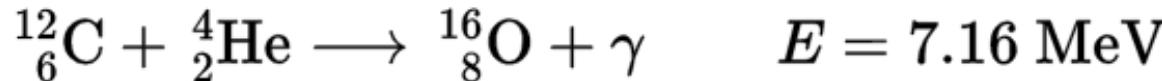
Vejez

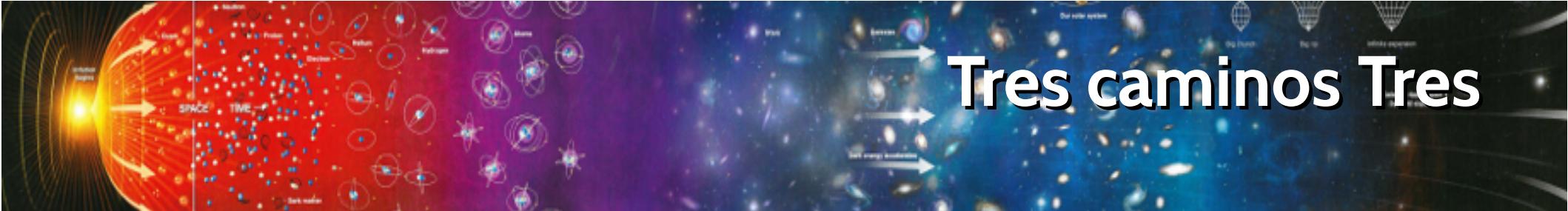


- Se acabó el H en el núcleo, ¿y ahora?
- Conversión $H \rightarrow He$, sólo en una corona alrededor del centro
- No alcanza la energía \rightarrow Contracción
- Aumenta $T_c \rightarrow$ Mayor producción de E
- Si $T_c = 10^8$ K, $He \rightarrow C$ (“Flash de Helio”)
- $R_{\text{Sol}} \rightarrow 220$ veces!!!
- Pero $220 (7 \times 10^5) \text{ km} \sim 1.5 \times 10^8 \text{ km}$
- Núcleo cebolla: $H \rightarrow He \rightarrow C \rightarrow O \rightarrow Si \rightarrow Fe$



Y después → más masa → más temperatura →
sigo subiendo la escalera nuclear (procesos alfa)





Tres caminos Tres

- La masa estelar en este punto (la masa final) determina el destino final
 - $M_f < 1.44 M_S \rightarrow$ Enana blanca
 - $1.44 M_S < M_f < 3 M_S \rightarrow$ Estrella de neutrones
 - $M_f > 3 M_S \rightarrow$ Agujero negro



Nebulosa planetaria

- Las capas exteriores son expulsadas por el intenso viento estelar
- La estrella continúa consumiendo el combustible en el interior
- $\sim 10^8$ años

Hubble
Heritage

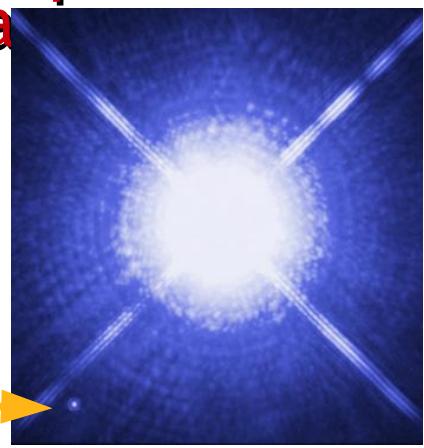
Enana blanca

NGC2440 + HD62166
(en Pupis)

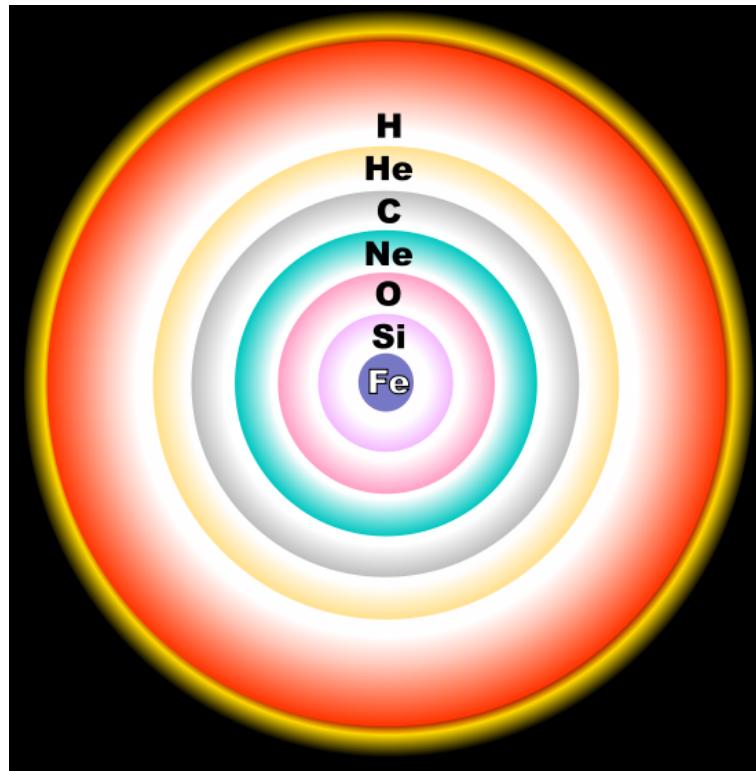
- No hay más **producción de energía**
- La gravedad **domina**
- El colapso comienza pero se detiene → **Pauli!**
- $R \sim R_{Tierra} \leftarrow$ Calcular p y v_e
- La estrella se **enfria por radiación al espacio**
→ Enana negra

:(

Sirio B



Si la masa es mayor...

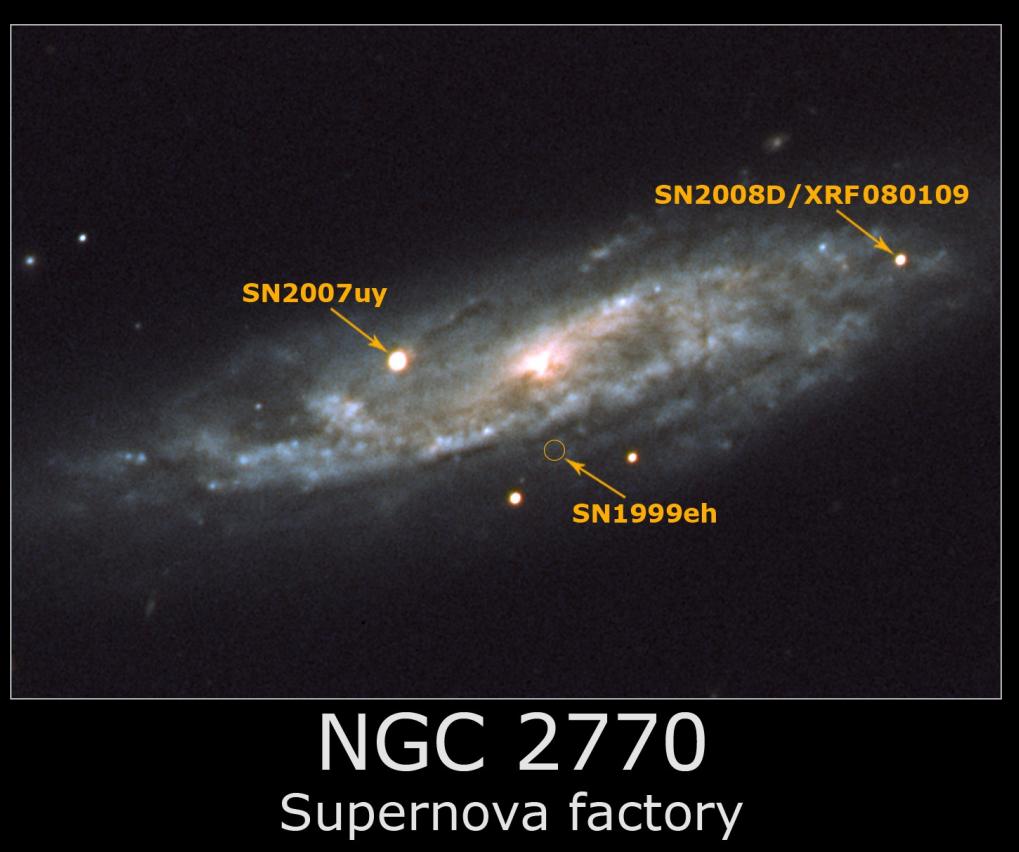


- El proceso en el núcleo continúa gracias a la compresión
- $\text{He} \rightarrow \text{C}/\text{O}$, $\text{C} \rightarrow \text{Ne}$, $\text{Ne} \rightarrow \text{O}, \text{O} \rightarrow \text{Si}$, $\text{Si} \rightarrow \text{Fe}$
- Pero Fe es el más estable: no gano energía uniendo Fe
- Sin fusión, desaparece la presión por radiación

¡El núcleo colapsa!

H. Asorey - IPAC 2017 - 11

Supernovas

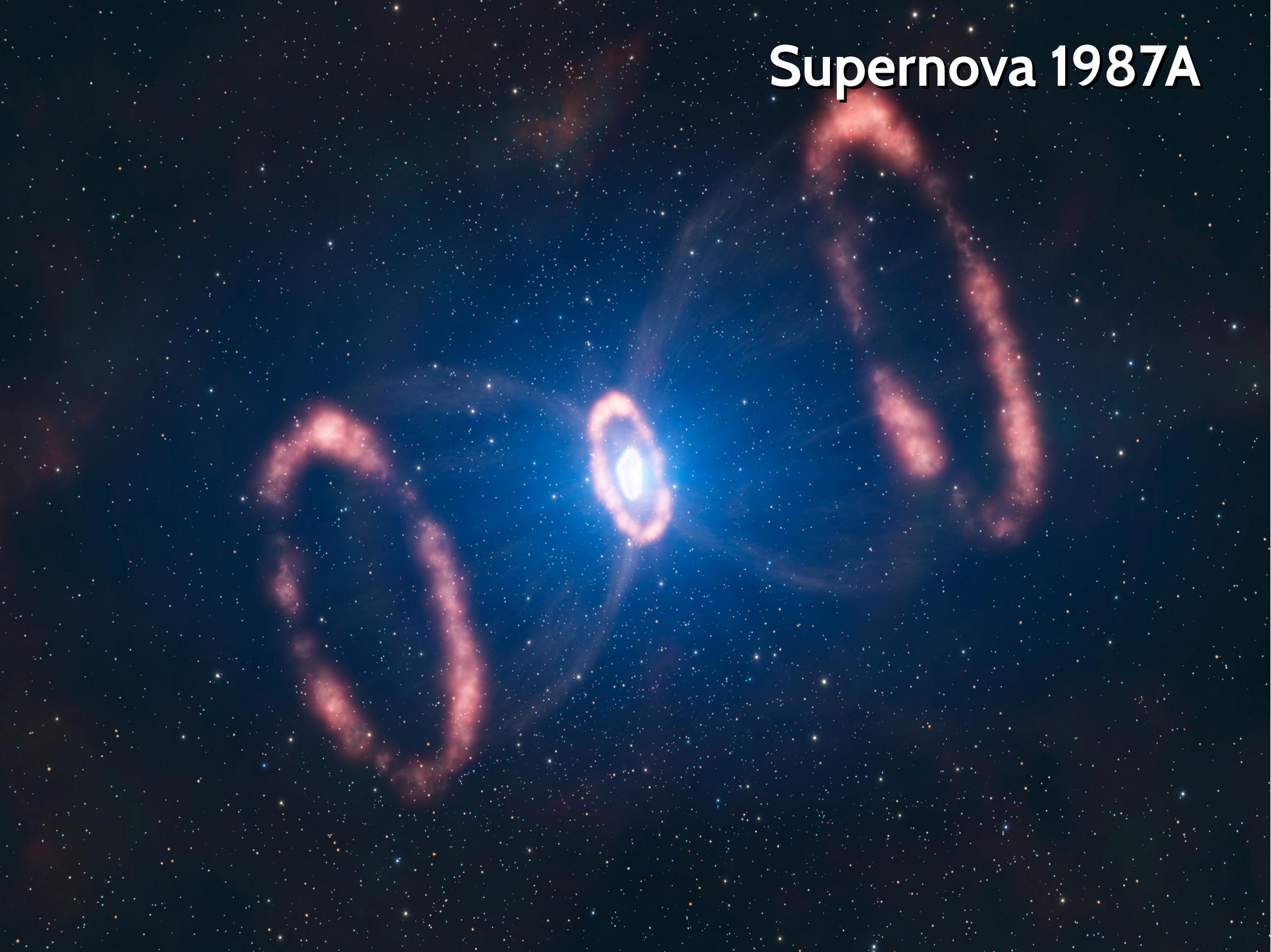


NGC 2770
Supernova factory

© Anglo-Australian Observatory

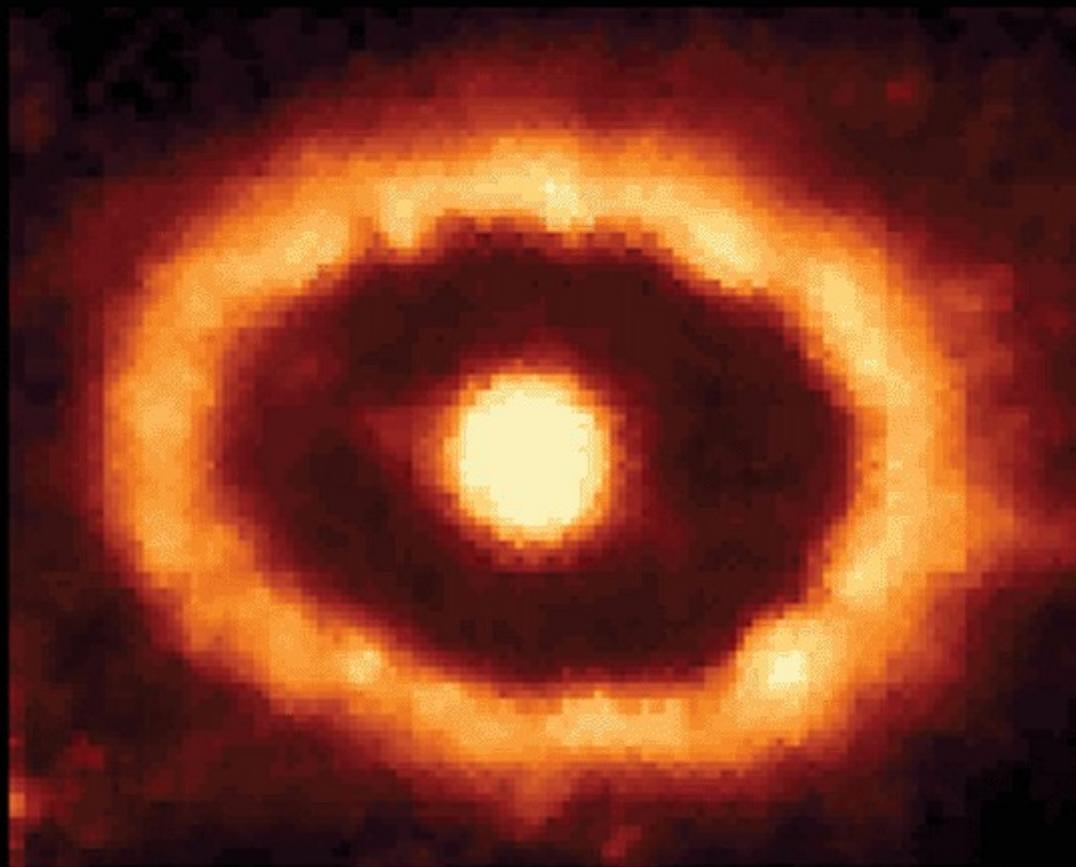
- Dos tipos de SN: I y II
- Estás son las tipo II
- En el núcleo:
 $p^+ + e^- \rightarrow n + \nu_e$
- Estrella de neutrones
- $M \sim 2 M_{\text{Sol}}, R \sim 20 \text{ km}$
- ¡Calcular ρ y v_e !
- Pulsars (LGM)
- **M grandes → Agujeros Negros**

Supernova 1987A



Supernova 1987A

(u03-c04-sn1987ashock.gif)



09/1994

Remanente de Supernovas



NGC2264 – Nebulosa Cono (Monoceros)

Agujeros negros

- Región del espacio tiempo donde nada, ni siquiera la luz, puede escapar
- Se lo observa por su interacción con materia
- Binaria de contacto Cygnus X1
- Horizonte de eventos
 - Radio de Schwarzschild

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

Gargantúa (Interstellar)



Nucleosíntesis

