



# Universidad Nacional de Río Negro

## Int. Partículas, Astrofísica & Cosmología - 2016

- **Unidad** 02 – Astrofísica
- **Clase** 0203 – 08/16
- **Fecha** 29 Sep 2016
- **Cont** Estrellas 3
- **Cátedra** Asorey
- **Web** [github.com/asoreyh/unrn-ipac](https://github.com/asoreyh/unrn-ipac)
- **Youtube** próximamente
- **Archivo** a-2016-U02-C03-0929-estrellas-3



# 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. Isolated of dark matter, they eventually form galaxies and stars. Galaxies glow brightest.

**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 dented. What had seemed eternal now had a beginning and an end. But what beginning? What end? Those questions are still open.

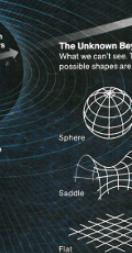
## WHAT IS OUR UNIVERSE MADE OF?

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.



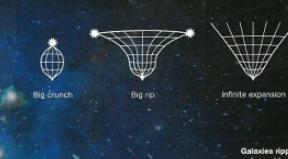
## Unidad 2 Astrofísica Cálido y frío

### 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



By through the universe on  
our digital edition

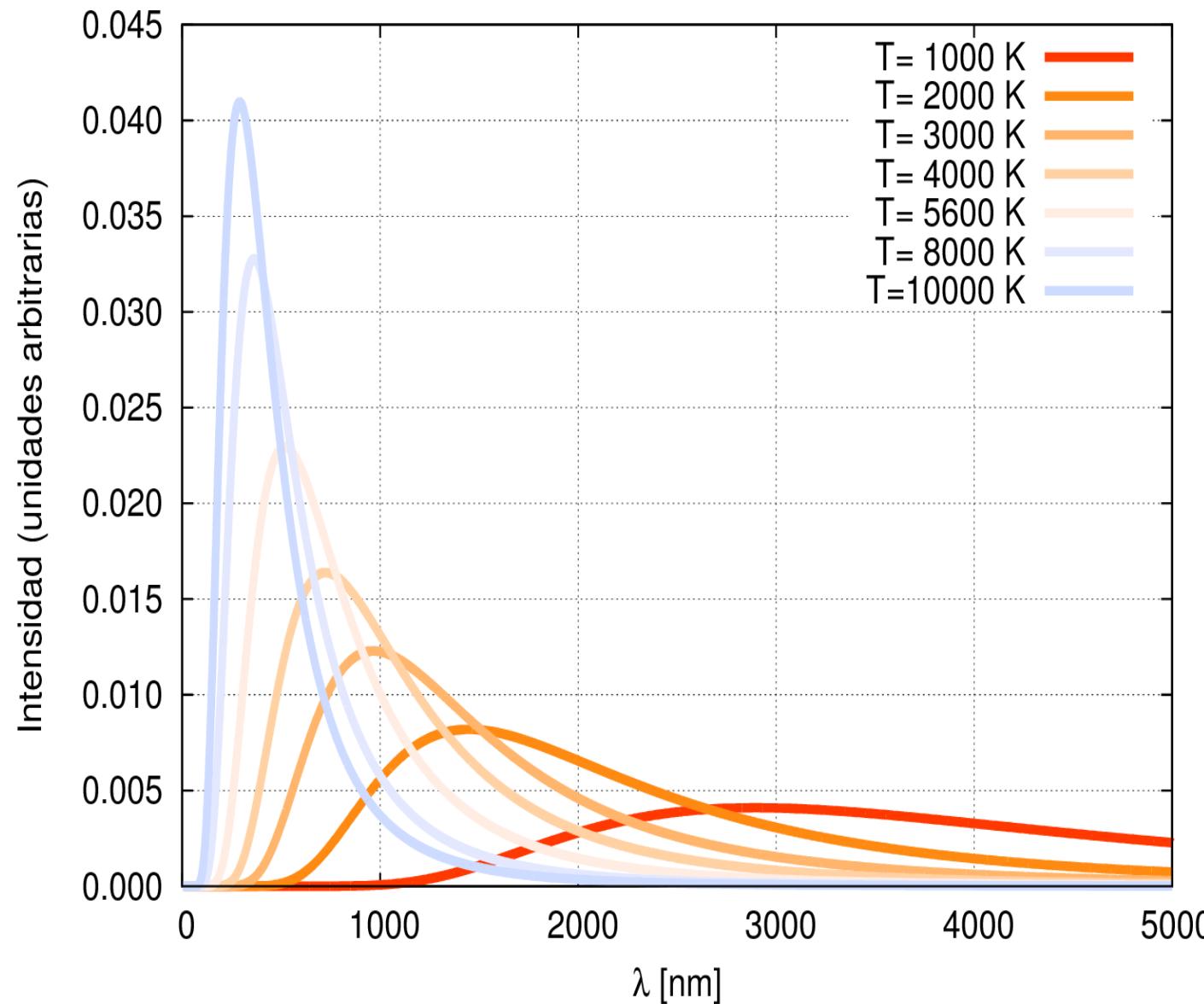
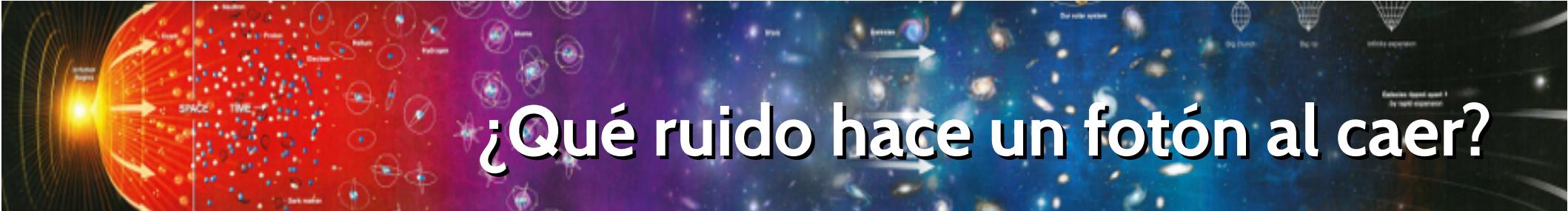
ILLUSTRATION: RICHARD HARRIS; DESIGN: JEFFREY L. FRIEDMAN; INFORMATION: NICK STONE; IMAGE: GREGORY PITTMAN; ART: MICHAEL HANNAH; DESIGN: JEFFREY L. FRIEDMAN; SOURCES: CHARLES BENNETT, JOHN C. MELTZER, ANDREW COOPER, ANDREW LINSLEY, UNIVERSITY OF CHICAGO; CHRISTOPHER ROM, NATIONAL GEOGRAPHIC SOCIETY

# Mismo objeto: Infrarrojo y visible

<http://crispme.com/50-amazing-examples-of-infrared-photography/>



# ¿Qué ruido hace un fotón al caer?



- Ley de Wien
  - Posición de  $\lambda_{\max}$

$$\lambda_{\max} = \frac{b}{T}$$

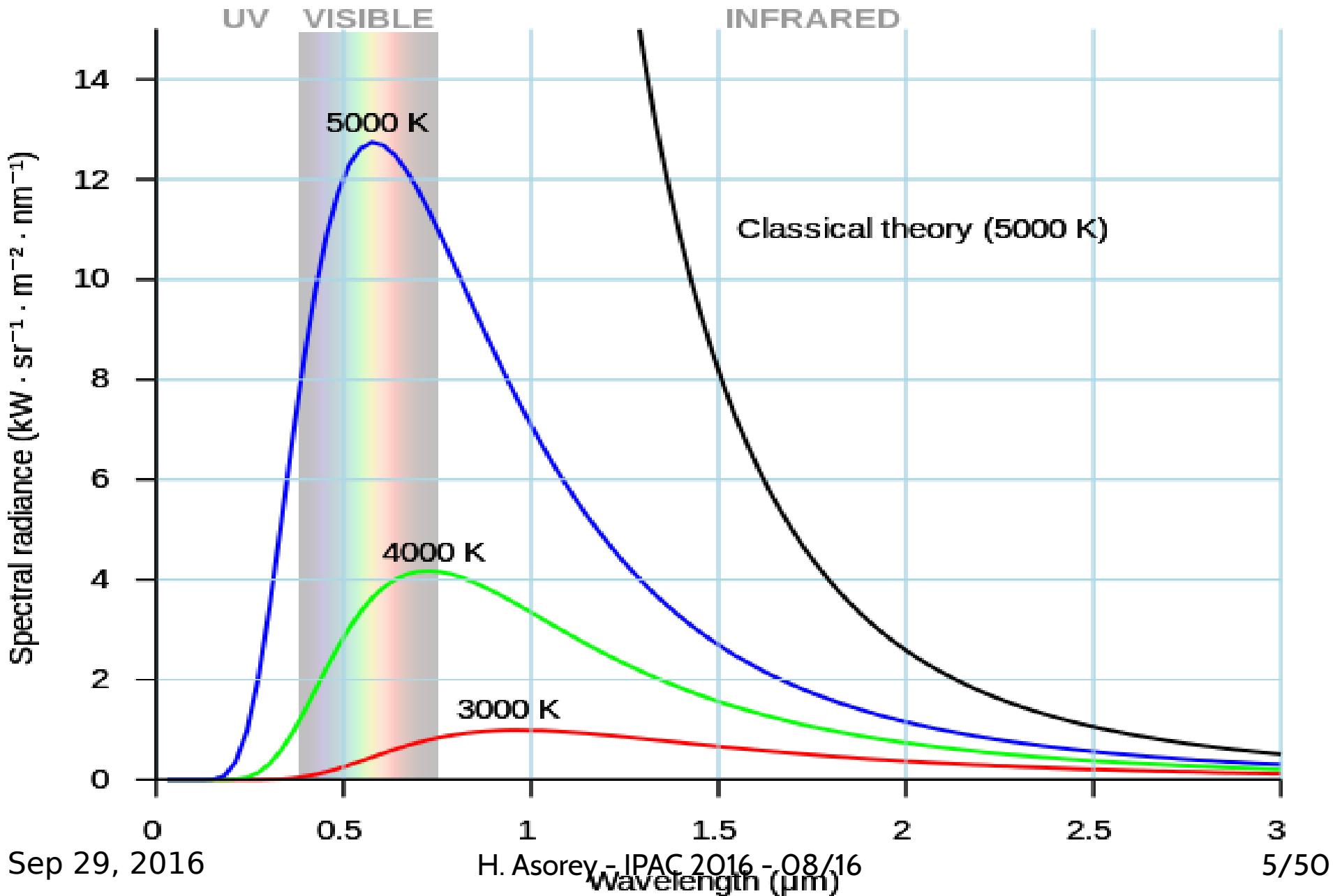
$$b = 2.9 \text{ mm K}$$

- Ley de Stefan-Boltzmann

$$L \equiv \frac{\Delta E}{\Delta t} = \sigma A T^4$$

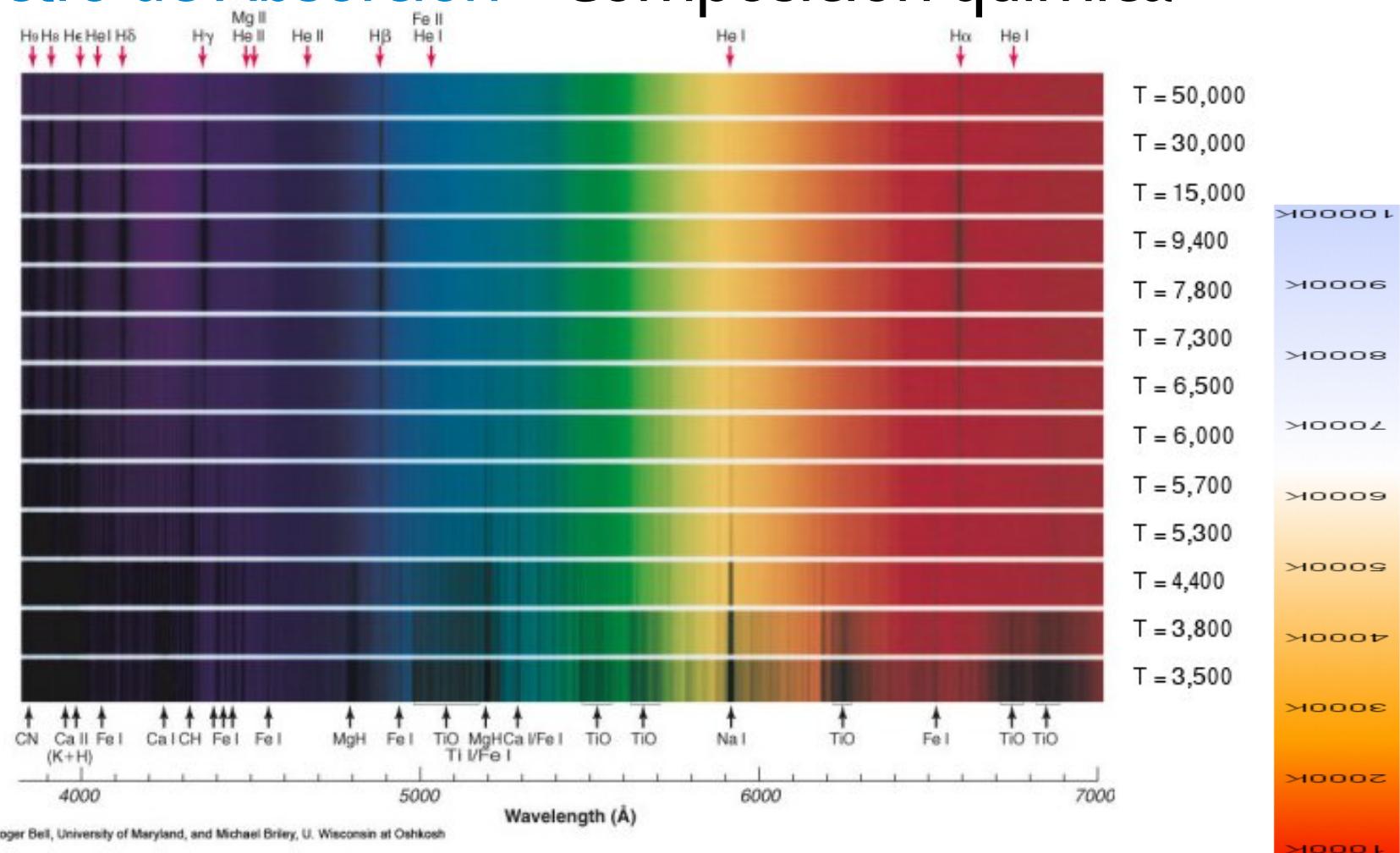
$$\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$$

# El color dependerá de la emisión integrada en la región visible del espectro

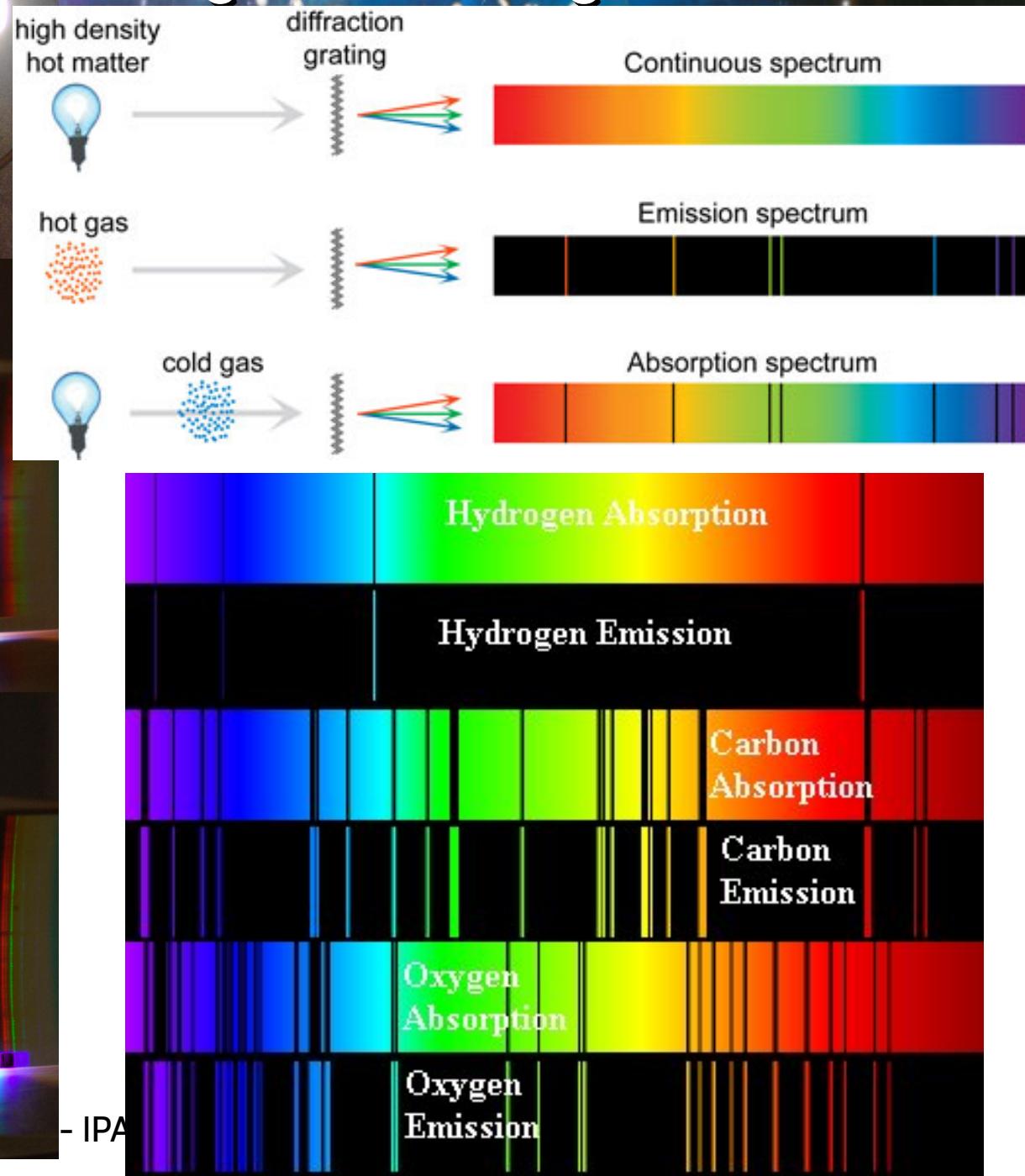
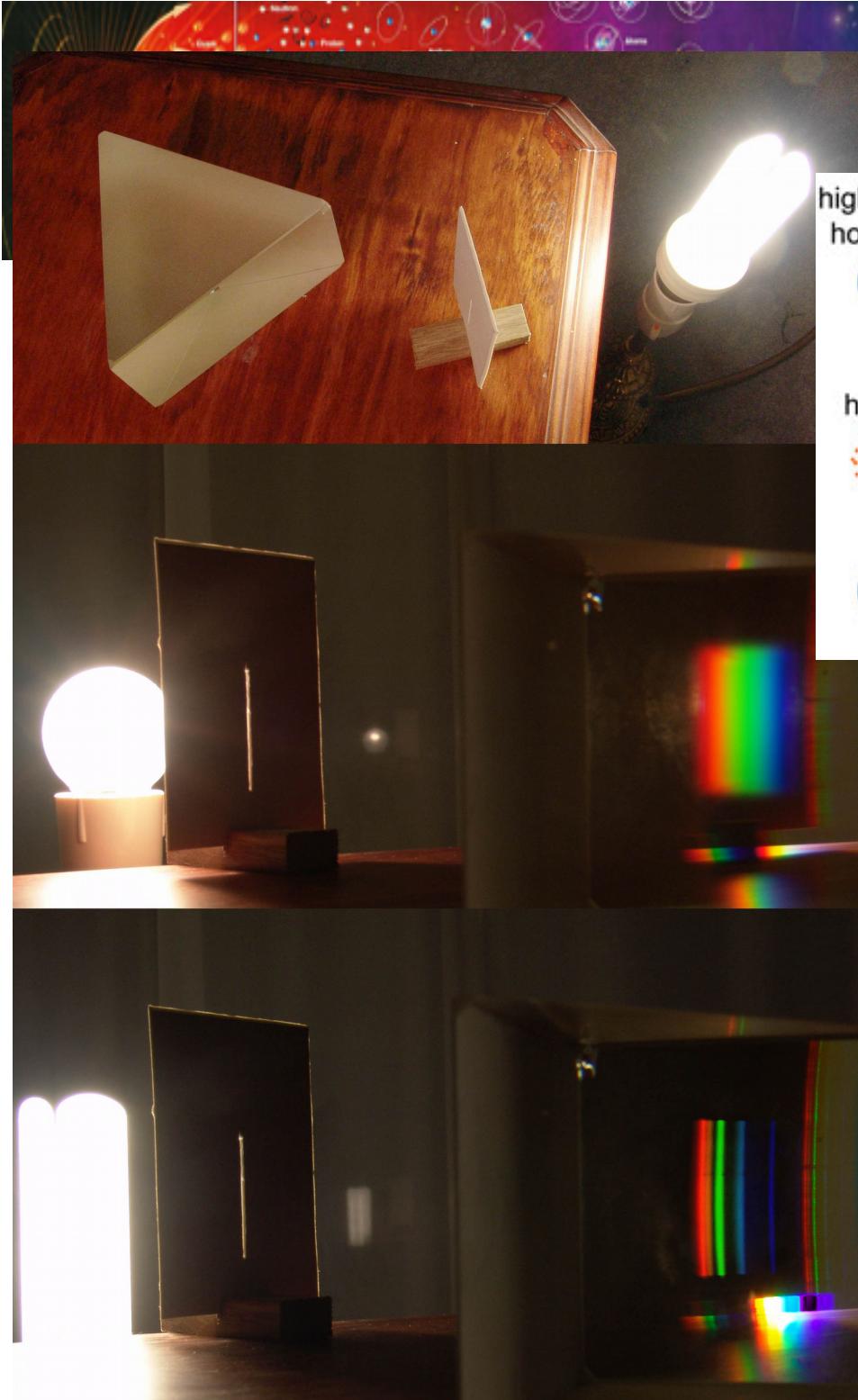


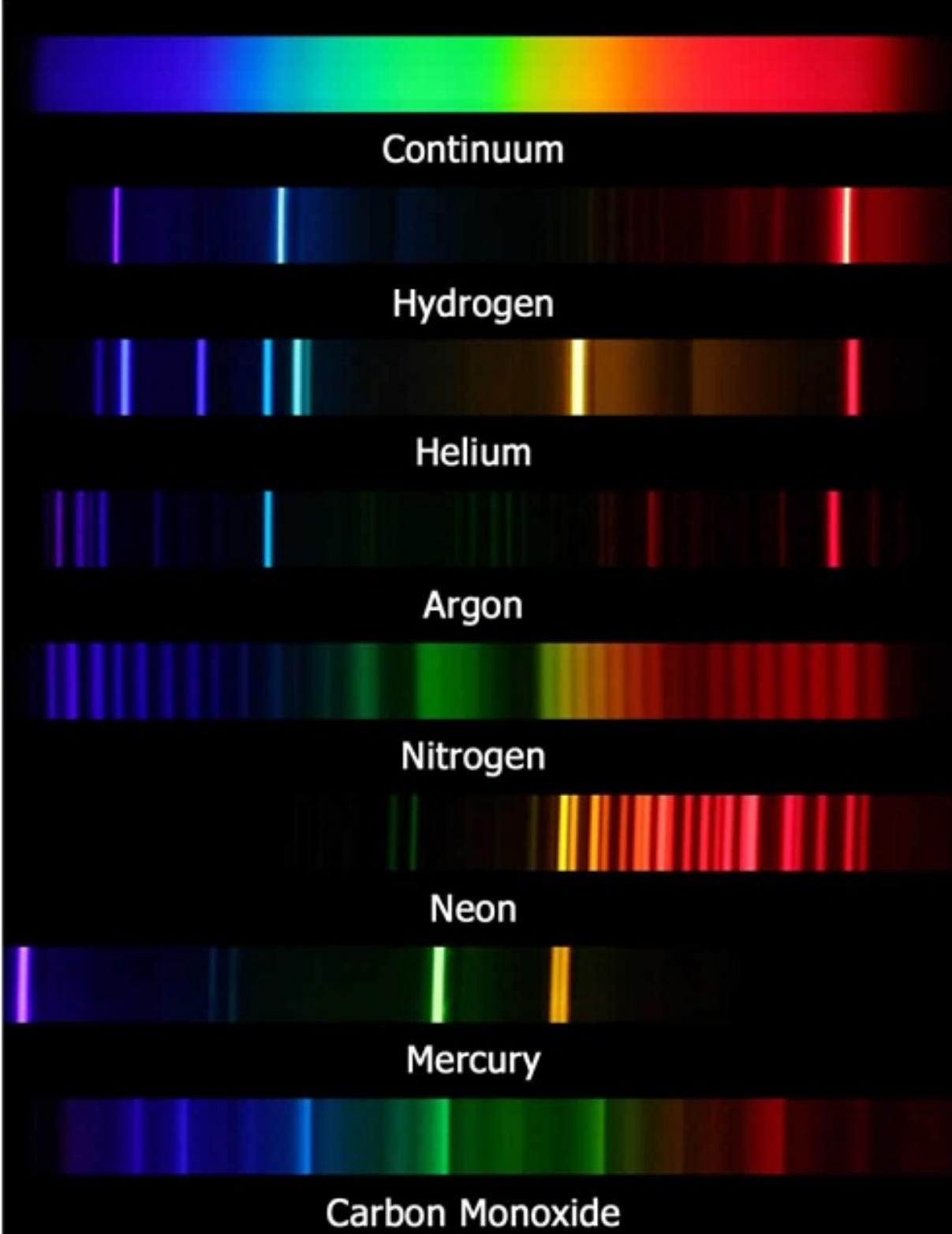
# Espectros estelares

- Emisión continua → Cuerpo Negro → Color → Temp.
- Espectro de Absorción → Composición química



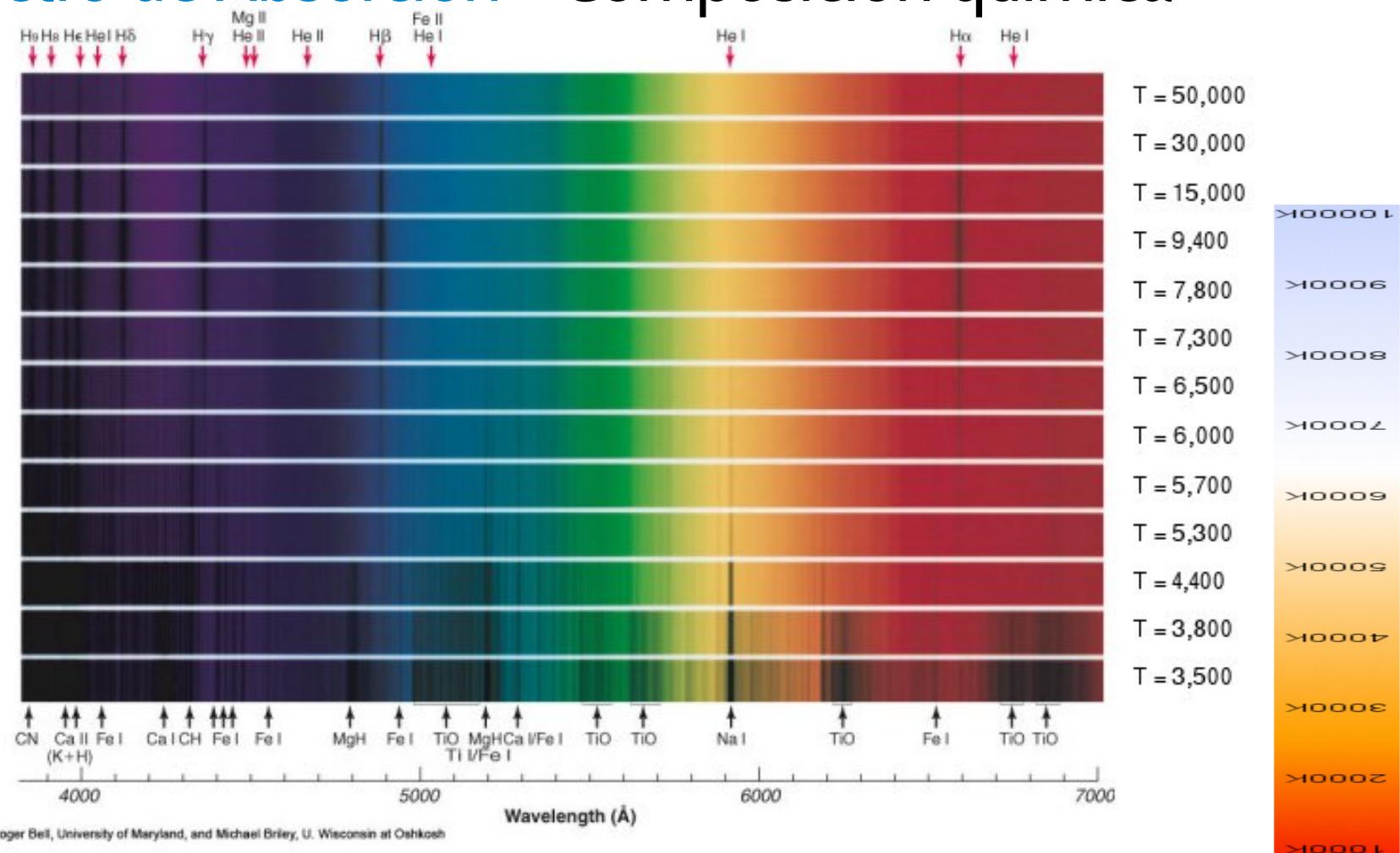
# ¿Emisión? ¿Absorción?





# Espectros estelares

- Emisión continua → Cuerpo Negro → Color → Temp.
- Espectro de Absorción → Composición química



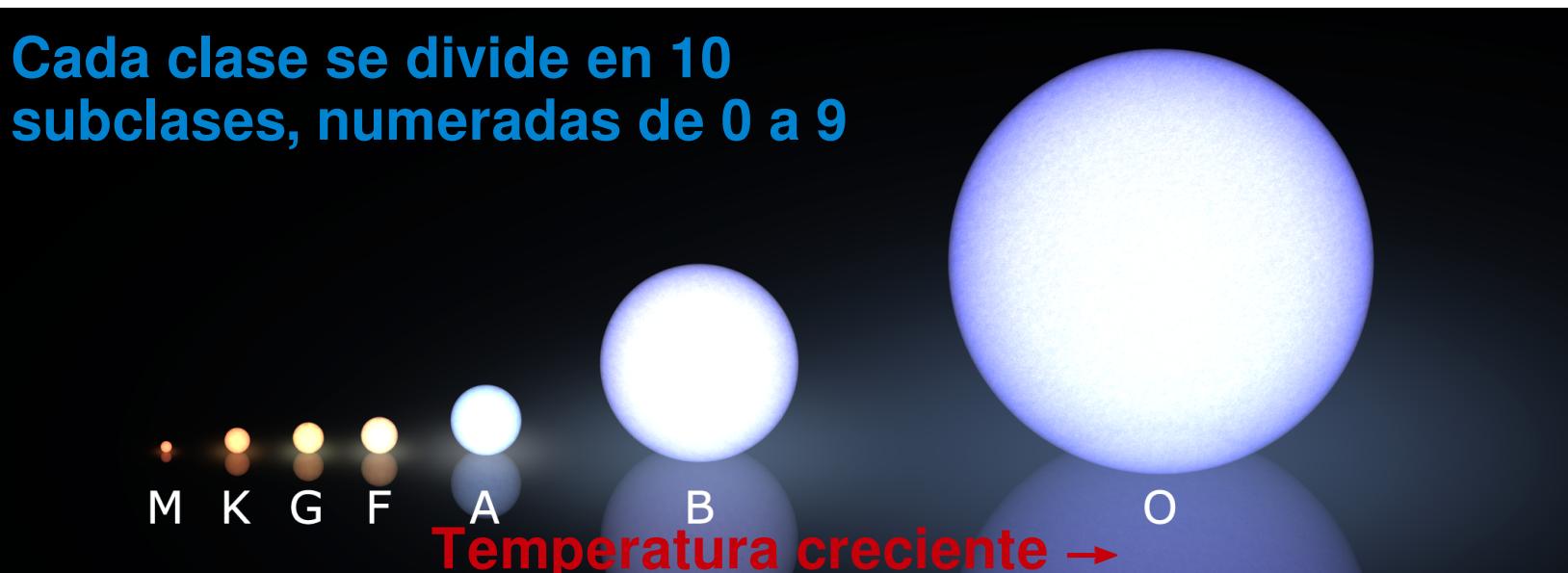
# ¡Podemos clasificarlas!

- A B C... por temperatura superficial

O B A F G K M R N S

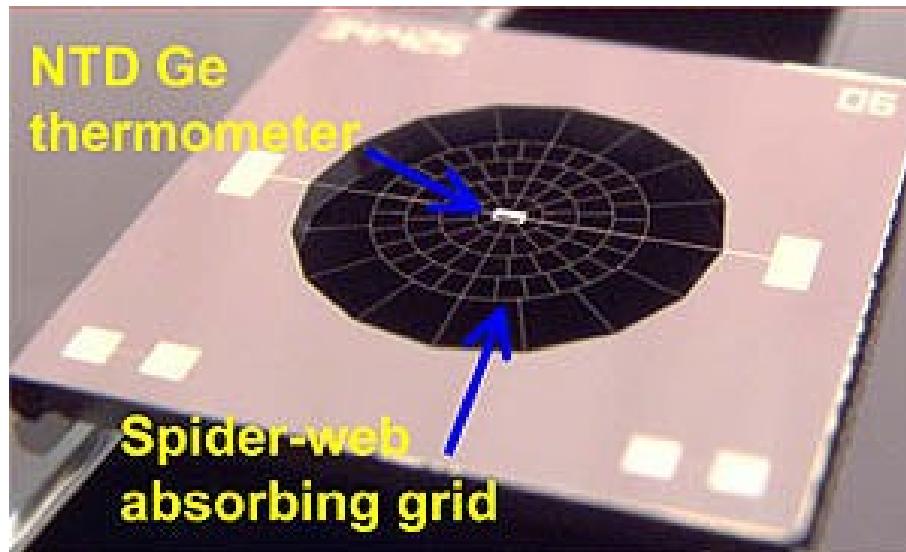
- Oh Be A Fine Girl and Kiss Me Right Now Sweet
- Oh Besame Amor, Fasinadora Gitana, Kilómetros Median Rompiendo Nuestros Sueños

Cada clase se divide en 10 subclases, numeradas de 0 a 9



# ¿Cómo se mide la luminosidad?

- **Bolómetro: instrumento para medir el flujo de radiación electromagnética en distintas bandas (IR,V,UV...)**



- Uso la definición del flujo sobre la superficie esfera:

$$F = \frac{L}{4\pi d^2}$$

- Conociendo la distancia  $d$  (próxima unidad), puedo calcular la luminosidad:

$$L = 4\pi d^2 F$$

- Ó, conociendo  $L$ , calculo  $d$

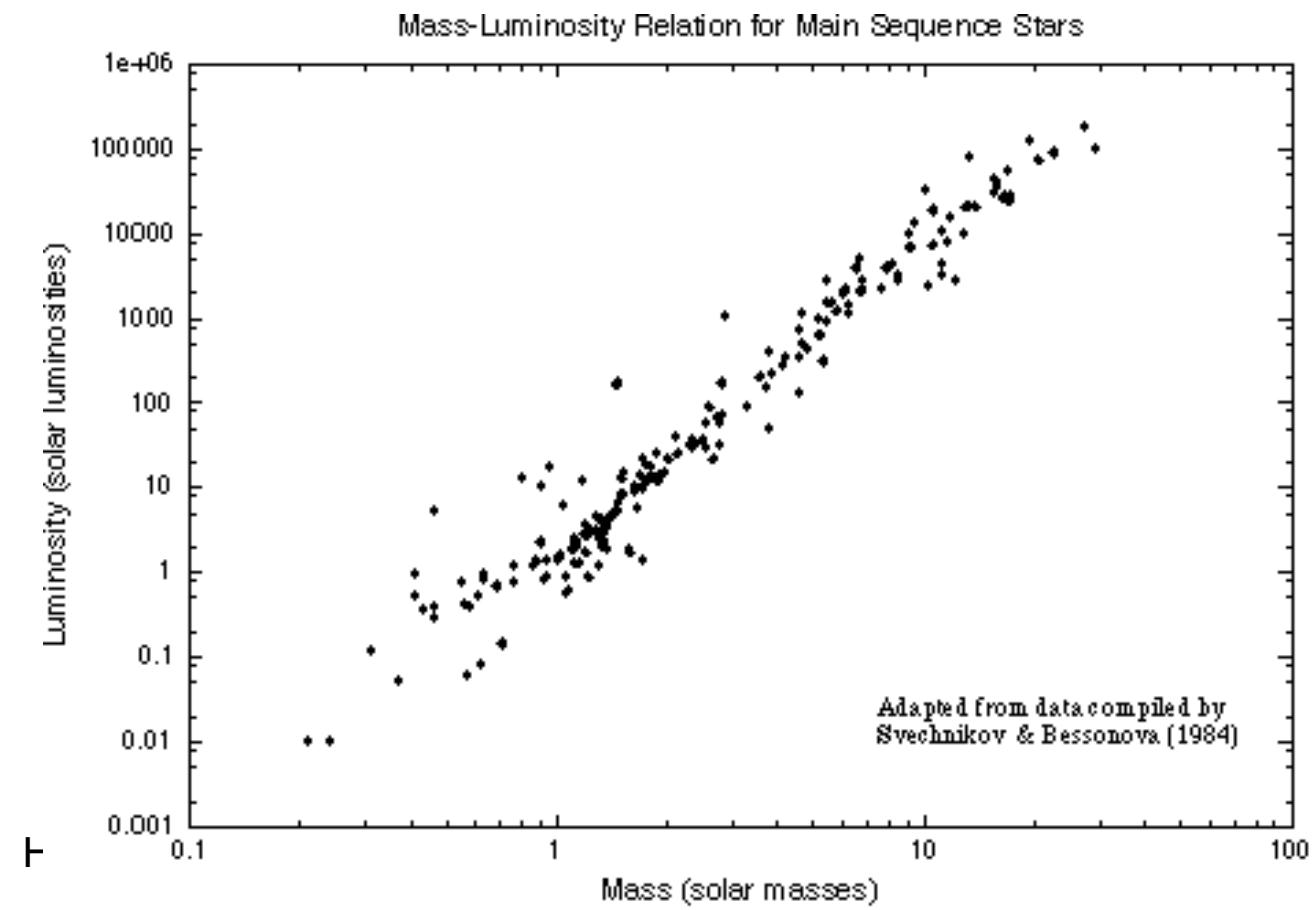
$$d = \sqrt{\frac{L}{4\pi F}}$$

# 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)

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

Sep 29, 2016

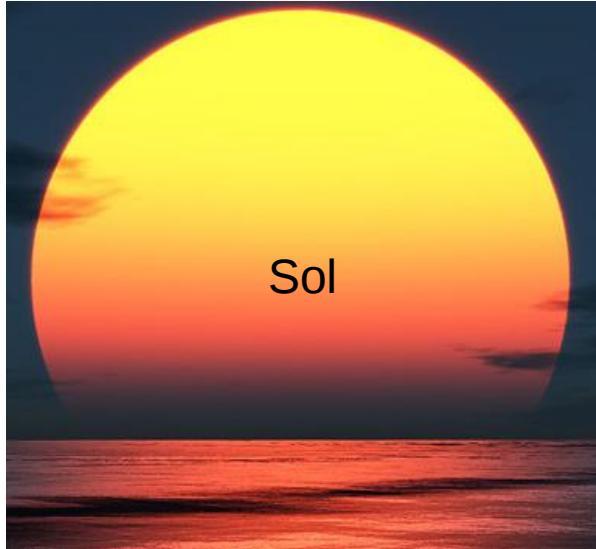




# Luminosidad → Masa

- Ejemplo

# $Y: (\text{Luminosidad, Temperatura}) \rightarrow \text{Radio}$



- $T = 5700 \text{ K}$  (Amarilla)
- $L = L_S$
- $T = 3400 \text{ K}$  (Roja)
- $L = 135000 L_S$

# Y: (Luminosidad, Temperatura) → Radio



- $T = 5700 \text{ K}$  (Amarilla)
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**Menor temperatura,  
menos emisión  
Pero, la emisión es  
mucho mayor**

# Y: (Luminosidad, Temperatura) → Radio

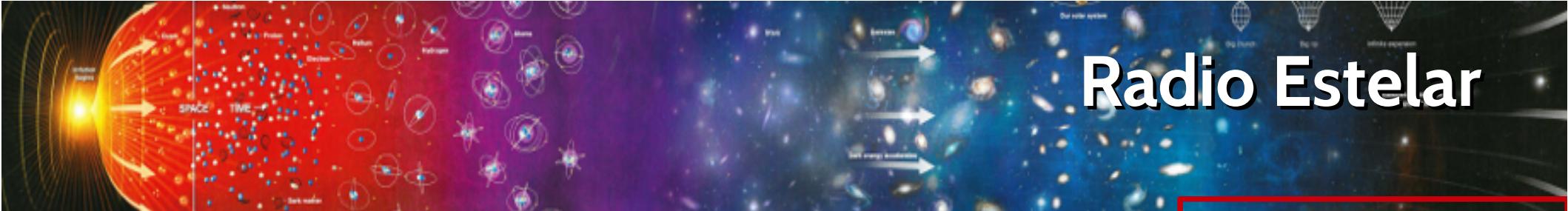


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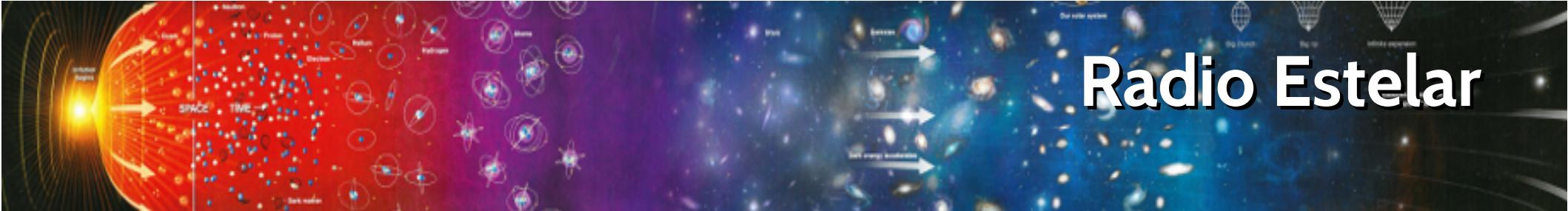
**Betelgeuse debe  
ser mucho más  
grande que el  
Sol**



# Radio Estelar

- Comparando las temperaturas
- ¡Pero también depende del radio!

$$L = 4\pi\sigma R^2 T^4$$



# Radio Estelar

- Veamos....  $(T_B/T_S)^4$ 
  - $(3400 / 5700)^4 \sim = 1/7.8$
  - Si dependiera sólo de T, el Sol sería 7.8 veces más luminoso que Betelguese
- Pero...

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

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

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

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

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

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

**Betelgeuse es una supergigante roja**

mas luminoso que Betelgeuse

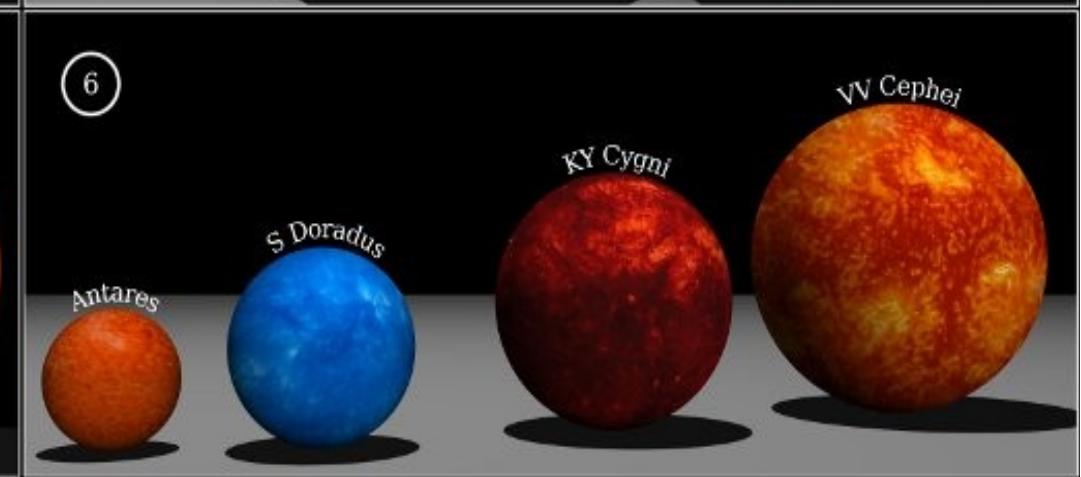
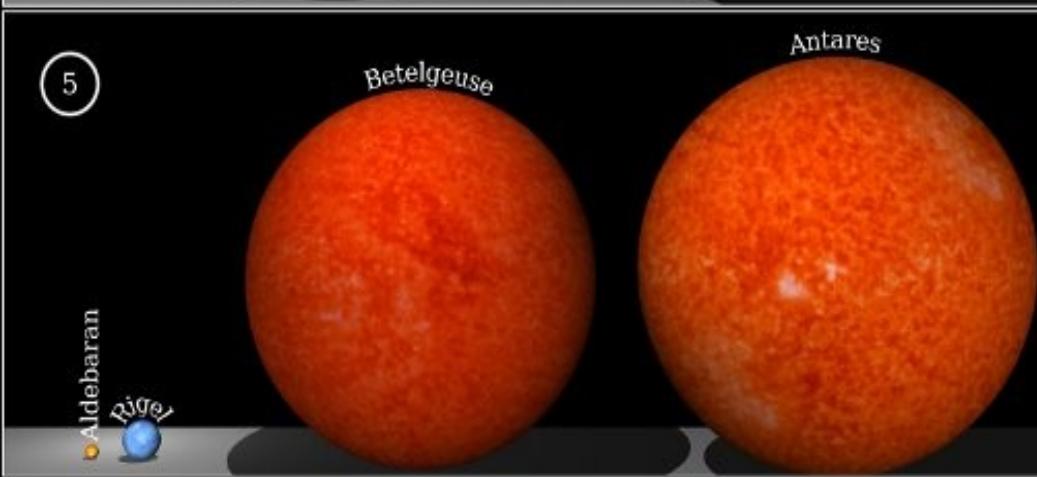
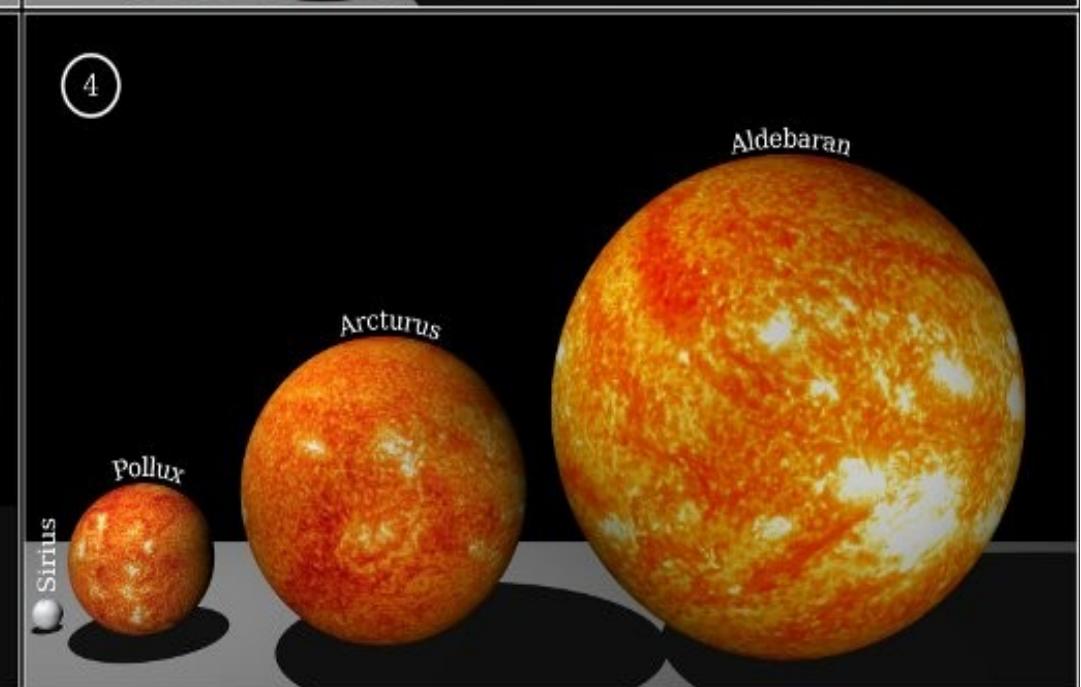
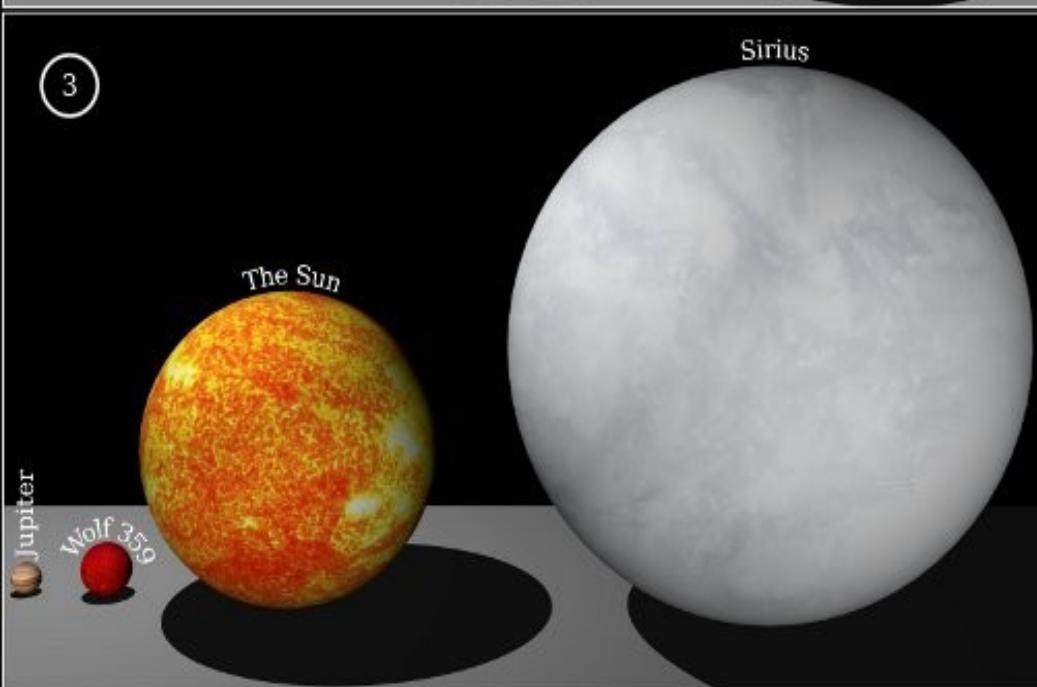
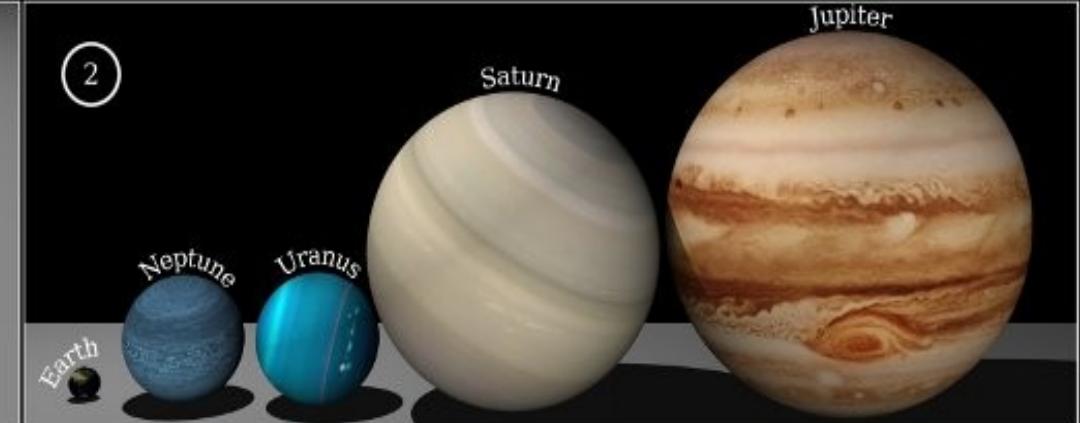
- Pero...

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

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





# 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:

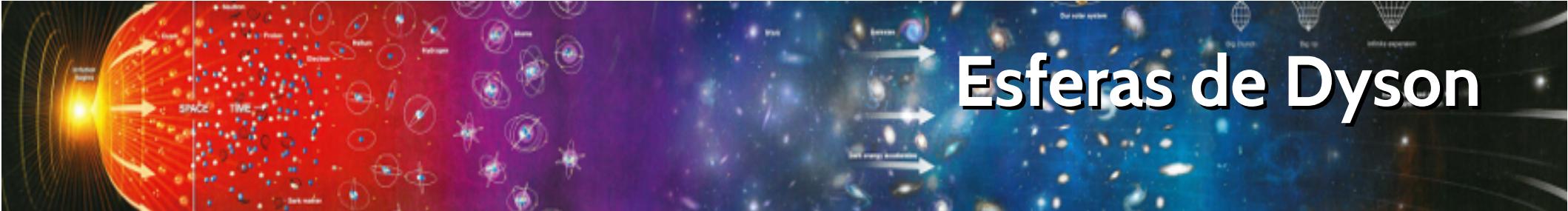
$$R_{\text{Sol}} = 6.96 \times 10^8 \text{ m} = 696000 \text{ km}$$

- 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)**

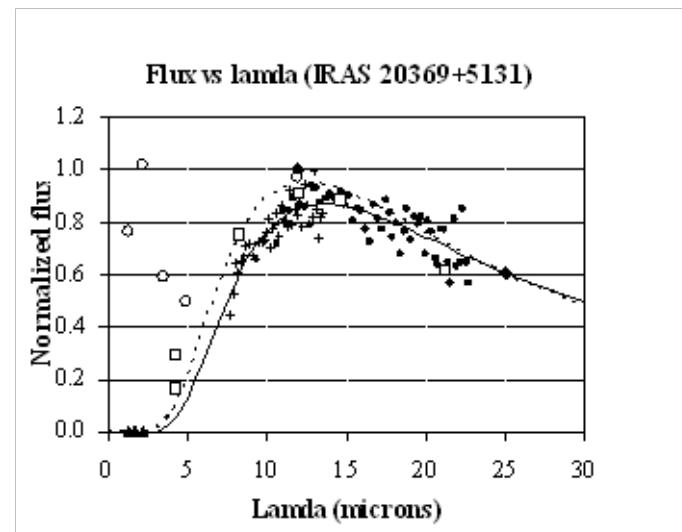
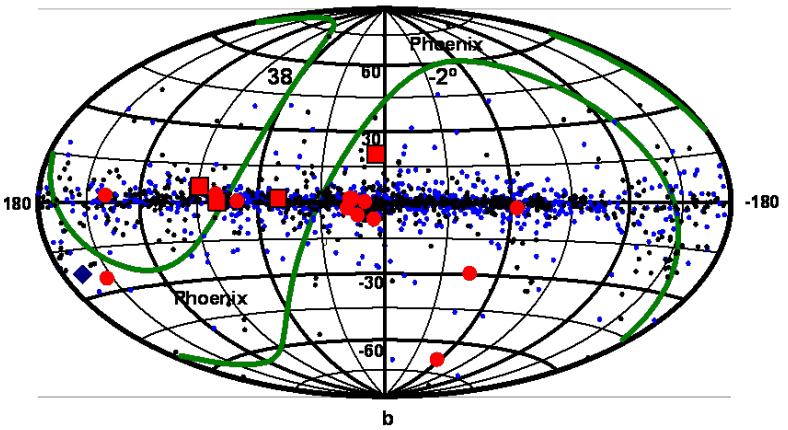


# Esferas de Dyson

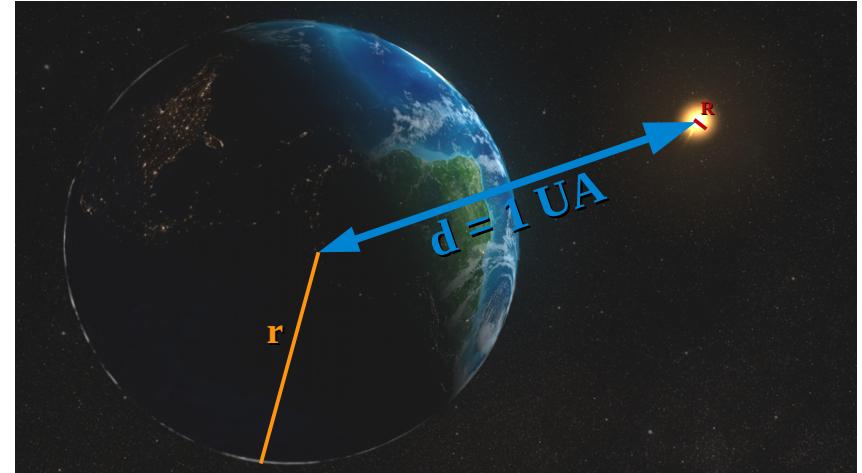


# IRAS (InfraRed Astronomical Satellite)

[http://home.fnal.gov/~carrigan/infrared\\_astronomy/Fermilab\\_search.htm](http://home.fnal.gov/~carrigan/infrared_astronomy/Fermilab_search.htm)



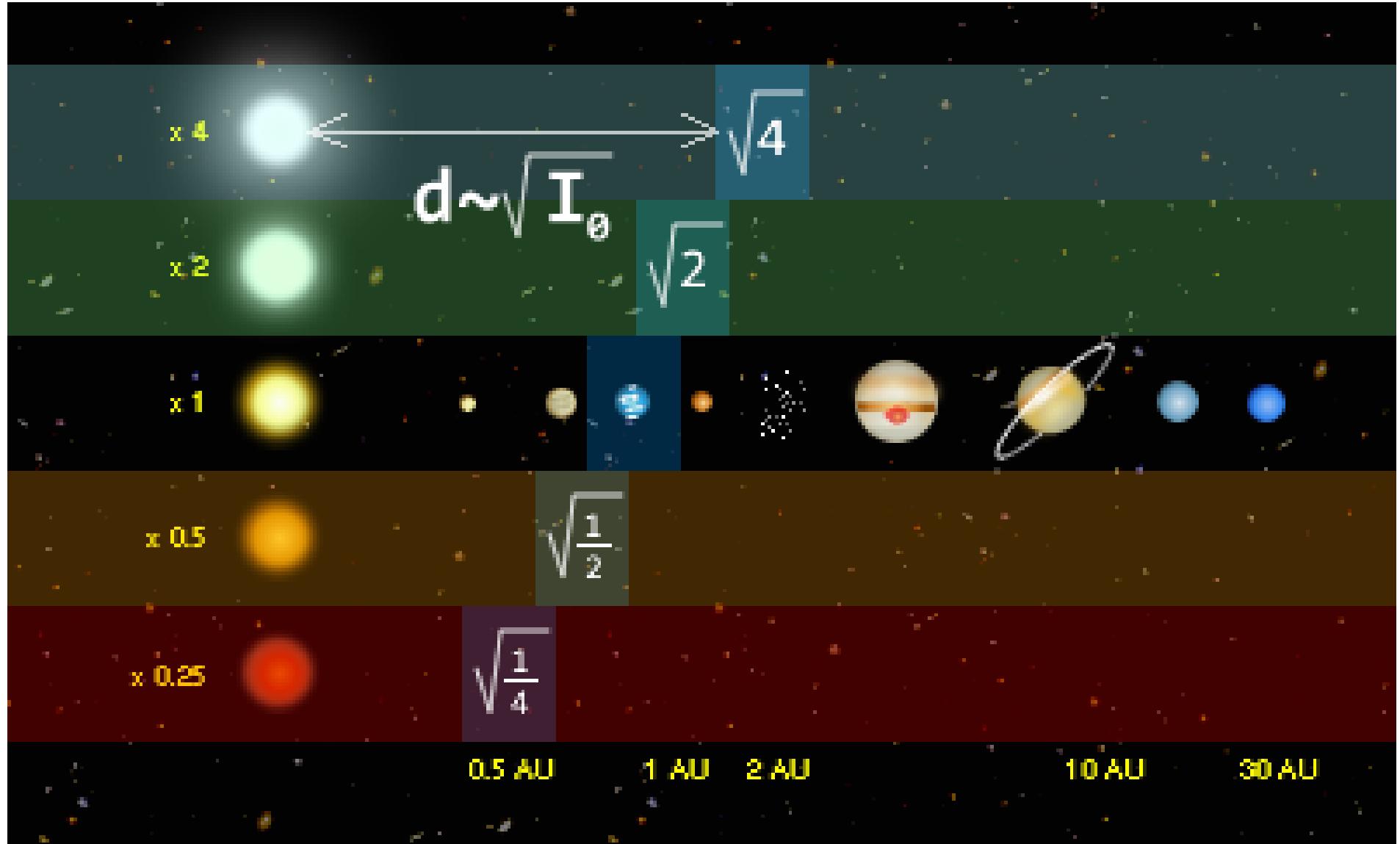
# ¿Y si fuera un planeta?



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

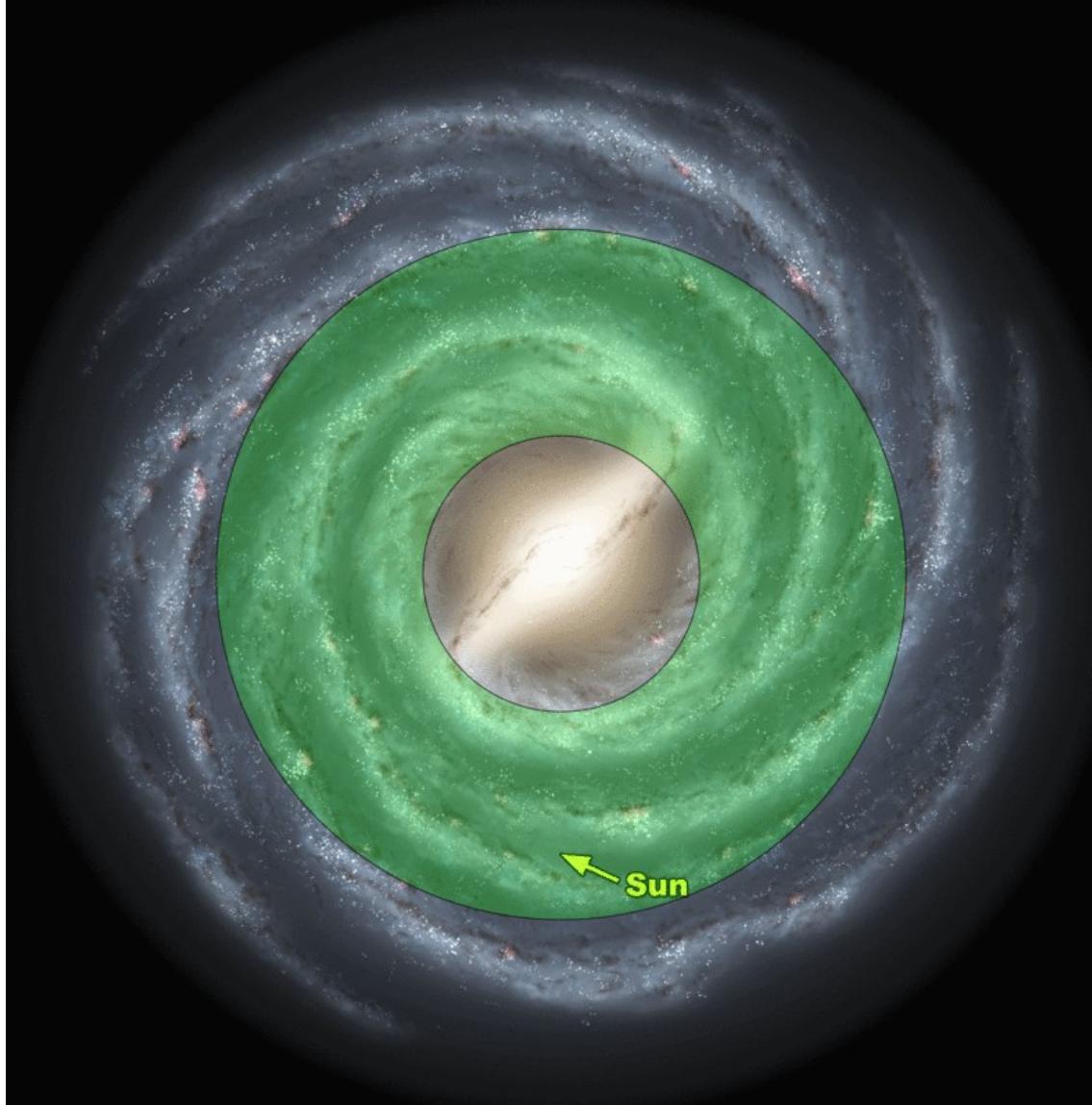
$$T_{\oplus} = \sqrt[4]{\frac{L_{\odot}}{16\pi\sigma d^2}}$$
$$T_{\oplus} = \sqrt{\frac{R_{\odot}}{2d}} T_{\odot}$$
$$d = \frac{1}{2} \left( \frac{T_{\odot}}{T_{\oplus}} \right)^2 R_{\odot}$$

# Zona habitable: Agua líquida (volveremos...)

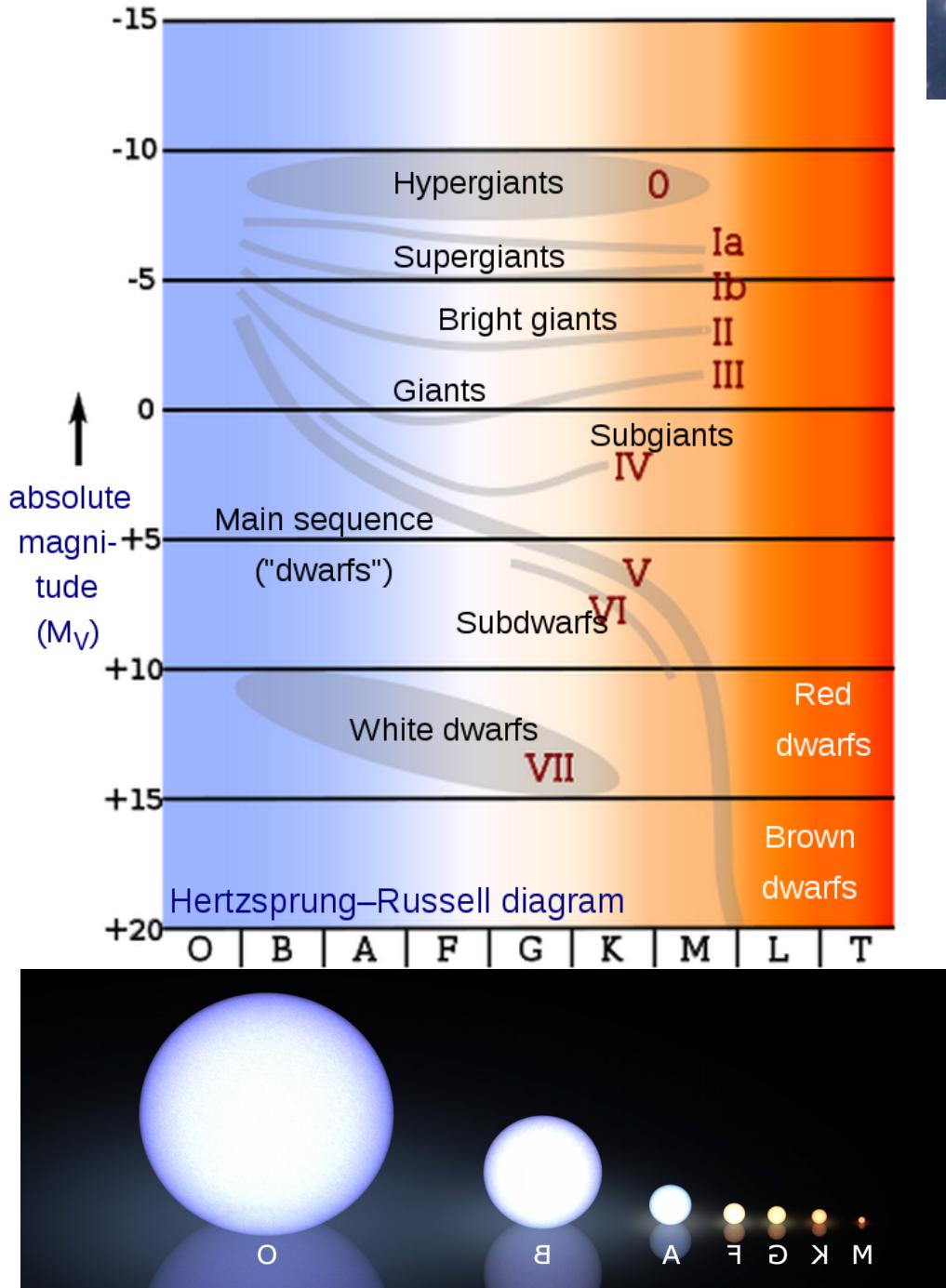




zona habitable... galáctica



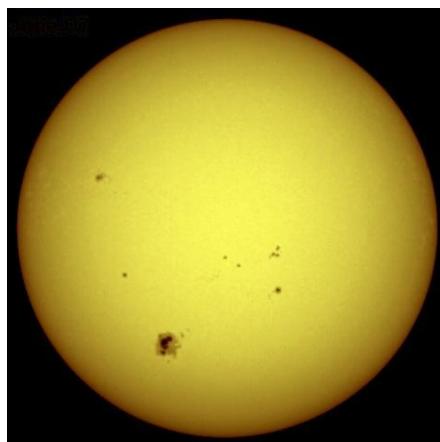
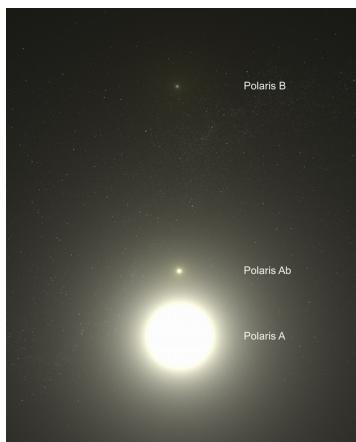
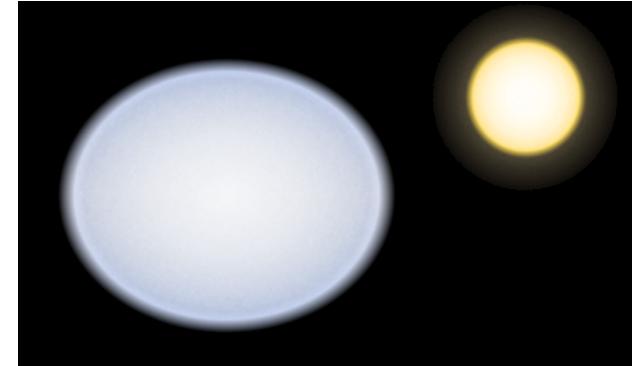
# Dijimos que la masa define todo



Surface temperature ranges for different stellar classes<sup>[134]</sup>

Class	Temperature	Sample star
O	33,000 K or more	Zeta Ophiuchi
B	10,500–30,000 K	Rigel
A	7,500–10,000 K	Altair
F	6,000–7,200 K	Procyon A
G	5,500–6,000 K	Sun
K	4,000–5,250 K	Epsilon Indi
M	2,600–3,850 K	Proxima Centauri

# Secuencia principal → OBAFGKM





**SPECTRAL CLASS O**

Dark Blue  
28,000 - 50,000 K  
Ionized Atoms, especially helium  
Example: Mintaka (O1-3III)



**SPECTRAL CLASS B**

Blue  
10,000 - 28,000 K  
Neutral helium, some hydrogen  
Alpha Eridani A (B3V-IV)



**SPECTRAL CLASS A**

Light Blue  
7,500 - 10,000 K  
Strong hydrogen, some ionized metals  
Sirius A (A0-1V)



**SPECTRAL CLASS F**

White  
6,000 - 7,500 K  
Hydrogen and ionized metals,  
calcium and iron  
Procyon A (F5V-IV)

Yellow  
5,000 - 6,000 K  
Ionized calcium, both neutral and  
ionized metals  
Example: Sol (G2V)

**SPECTRAL CLASS G**



Orange  
3,500 - 5,000 K  
Neutral Metals  
Alpha Centauri B (K0-3V)

**SPECTRAL CLASS K**



Red  
2,500 - 3,500 K  
Ionized atoms, especially helium  
Wolf 359 (M5-8V)

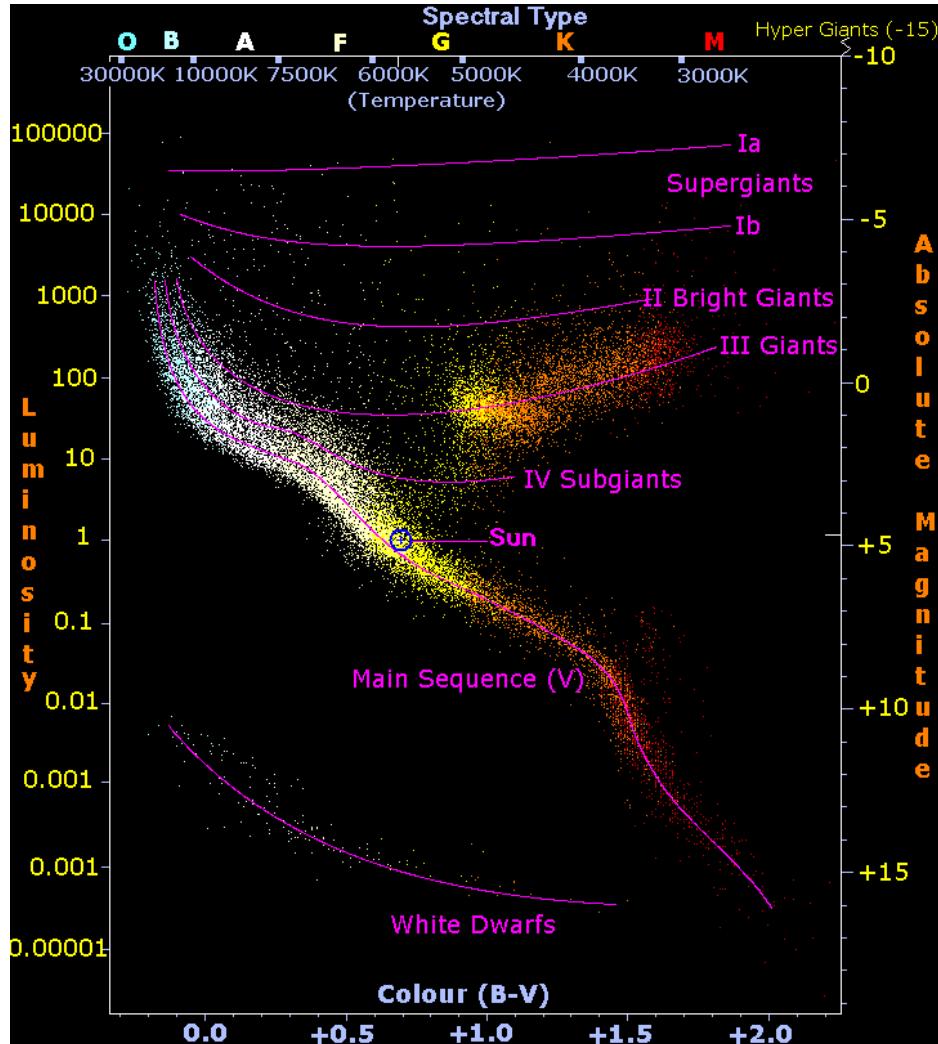
**SPECTRAL CLASS M**



**Non-Main Sequence Types**

Class W: Wolf-Rayet Star  
Up to 70,000 K  
Carbon, nitrogen, or oxygen  
Gamma Velorum A (WC)  
Class L: Dwarf Star  
J,300 - 2,000 K  
Metal hydrides and alkali metals  
VW Hyi  
Class T: Methane Dwarf  
700 - 1,000 K  
Methane  
Epsilon Indi Ba  
Class Y: Ammonia Dwarf  
<700 K  
Ammonia  
Not yet observed  
Class C: Carbon  
Class S: Zirconium Oxide  
Classes MS and SC  
Class D: Dwarf

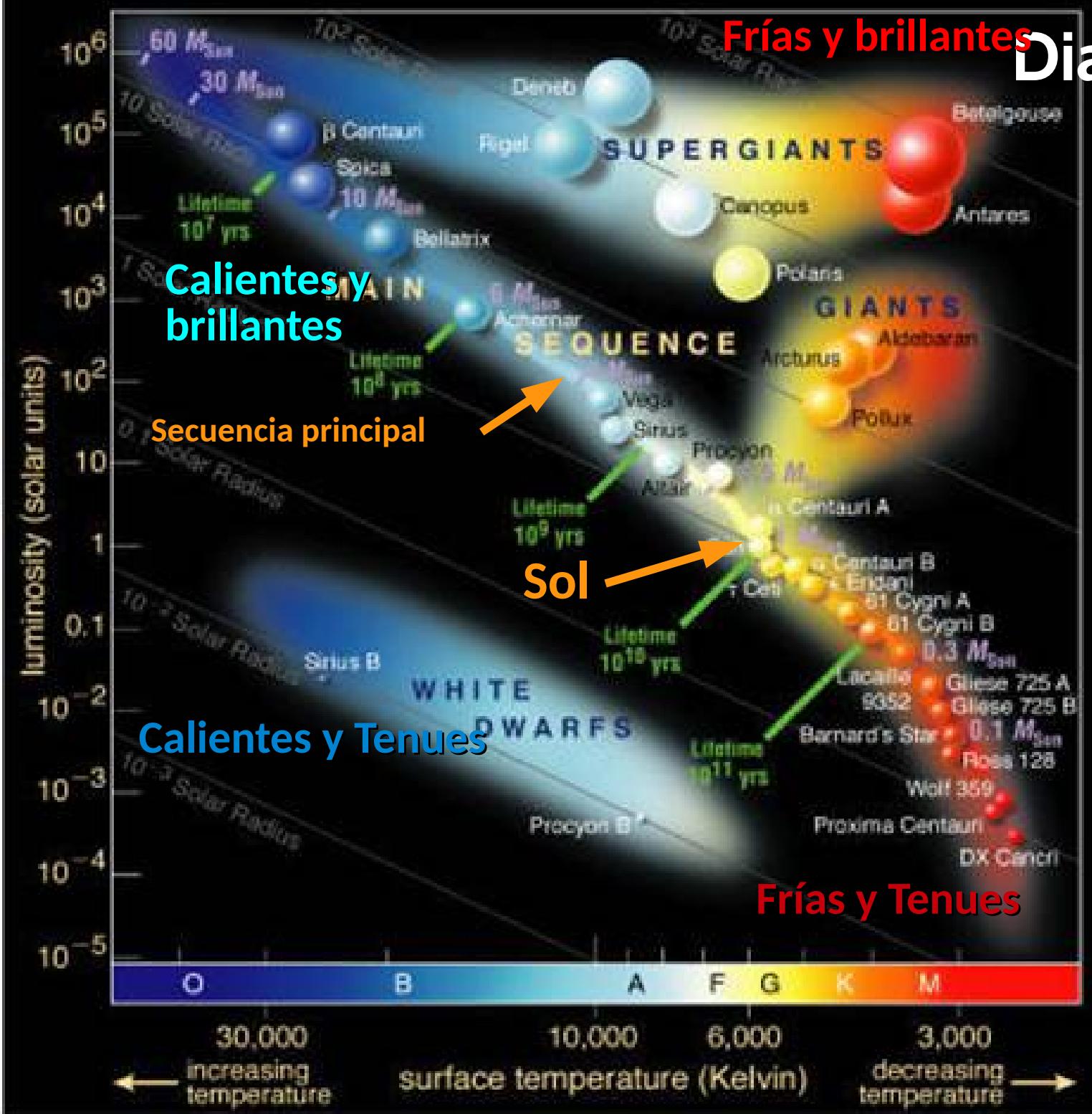
# Secuencia principal



- Estrellas que están en su fase normal de quema de combustible:  
 $H \rightarrow He$
- 90% del tiempo de vida las estrellas permanecen en este estadio
- **Metalicidad: contenido de elementos más masivos que el Helio**

Frías y brillantes

# Diagrama H-R

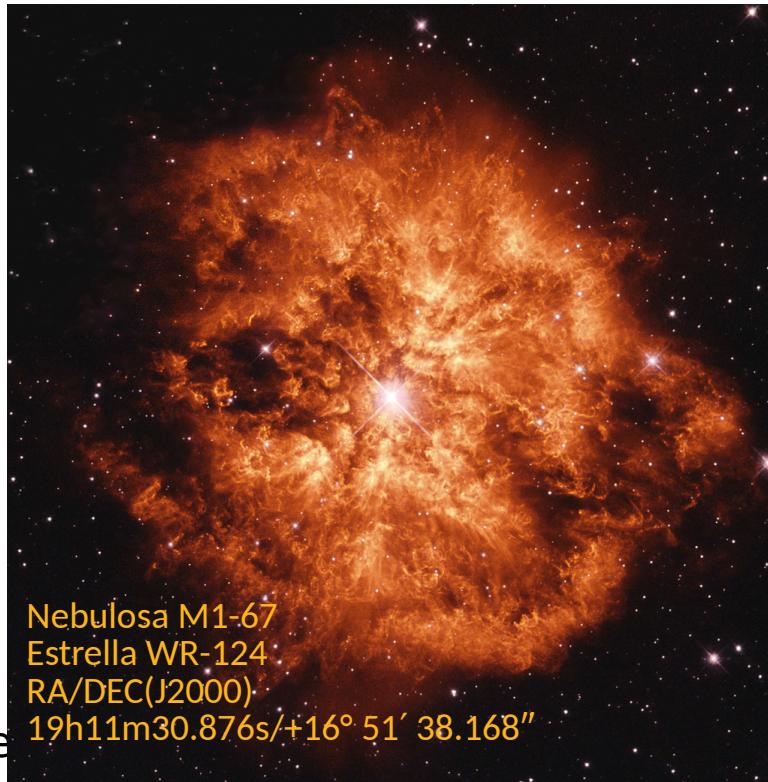


$$L \propto R^2 T^4$$

# 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  $10 < M/M_{Júp} < 90$**

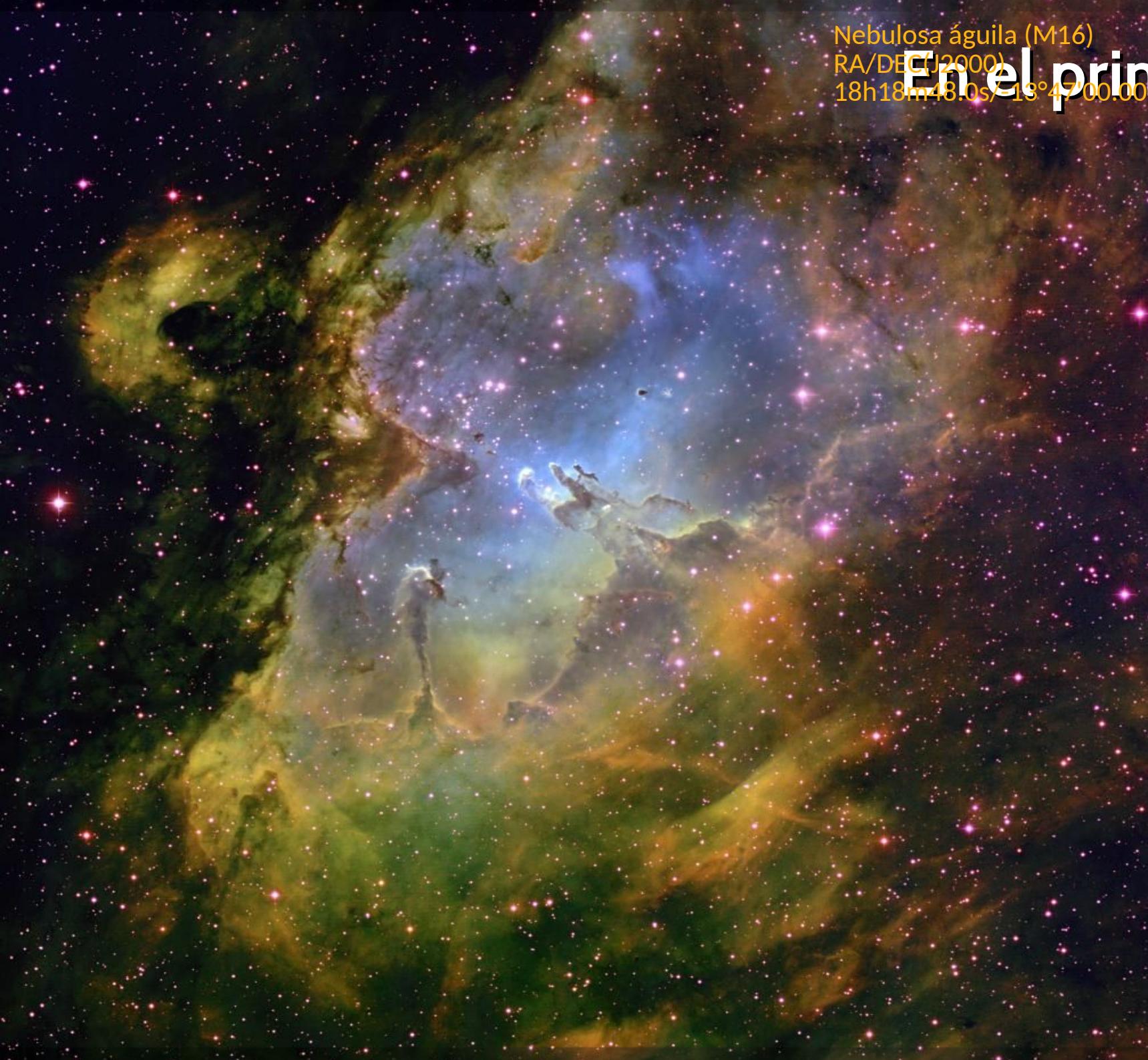


Nebulosa águila (M16)

RA/DEC (J2000)

18h18m48.0s / 13°47'00.00"

En el principio...



# En el principio...

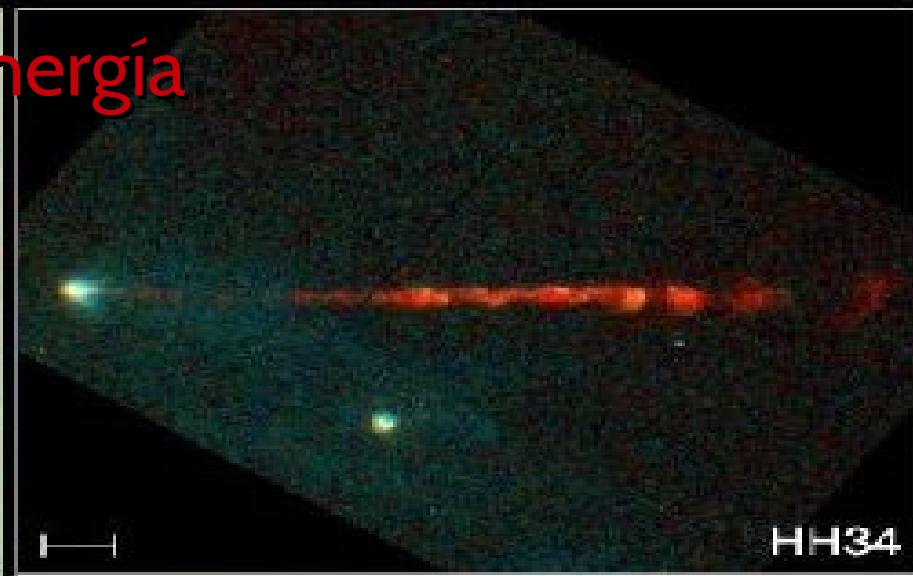
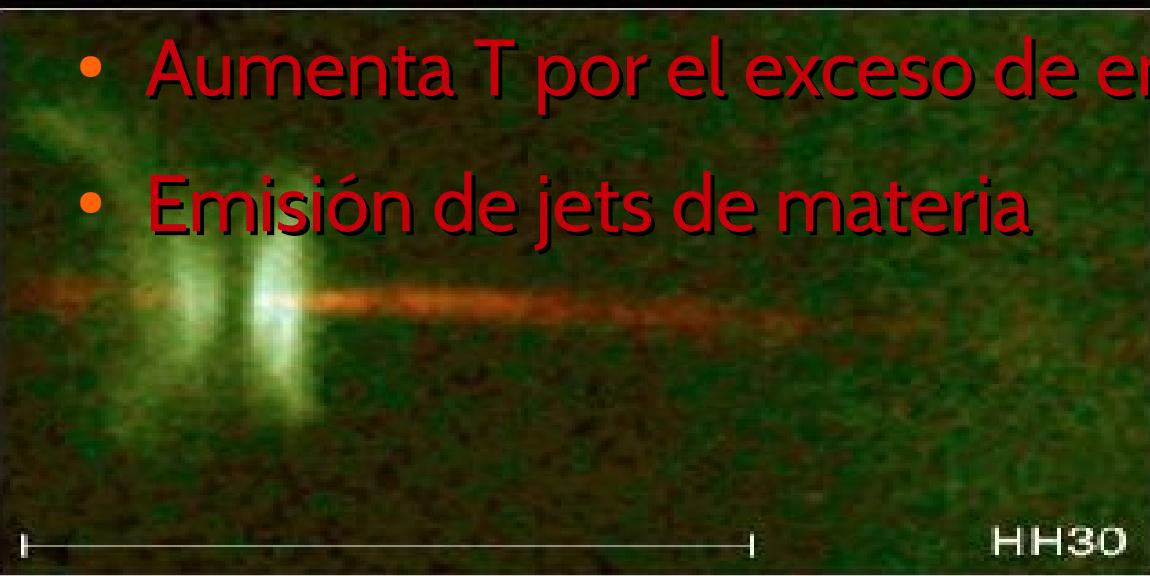
- Nubes de gas gigantes
- $6 \times 10^6 M_{\odot}$  y  $R \sim 15$  pc
- Colapso gravitacional
- Aumenta temperatura
- T es pequeña pero R es muy grande  
    *¡L es grande!*
- → Gigantes Rojas

- 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



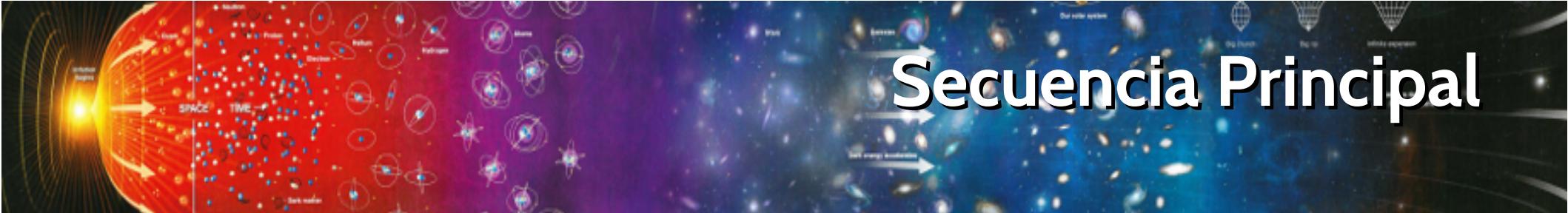
### Jets from Young Stars

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

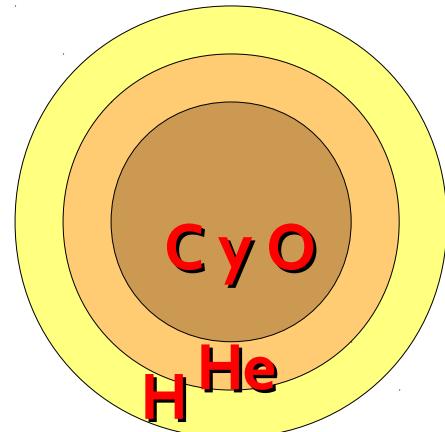
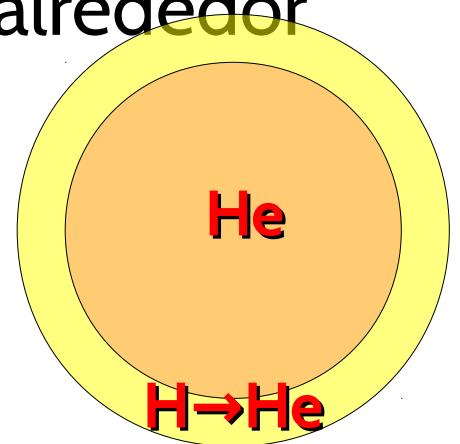


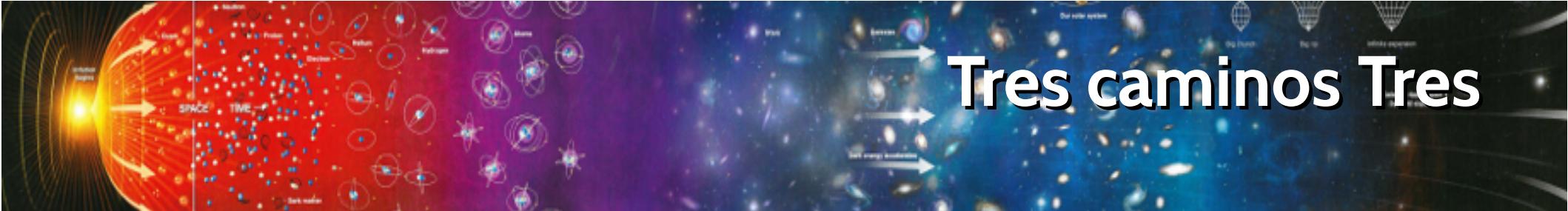
- Conversión  $H \rightarrow He$  es muy eficiente
- $10^{10}$  años para  $M = 1 M_{\text{Sol}}$ 
  - La energía radiada,  $L \sim R^2 T^4$  proviene del interior
  - Velocidad de reacciones en el centro:  $\sim T_c^4$
  - $R^3 \sim M T_c / P$  ( $\leftarrow$  Viene de  $PV=nRT$ )
- Si  $T_c \rightarrow 2 T_c \Rightarrow R \rightarrow 8 R$
- 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  $\rightarrow$  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:  $H \rightarrow He \rightarrow C \rightarrow O \rightarrow Si \rightarrow Fe$





# 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

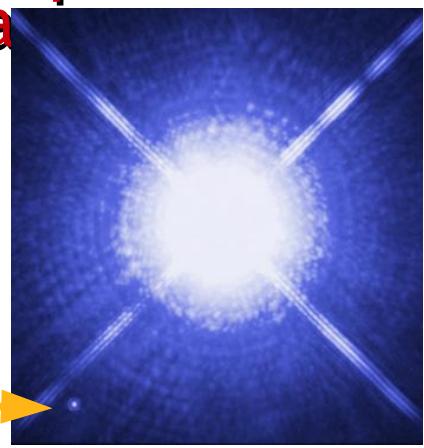
# Enana blanca

NGC2440 + HD62166  
(en Pupis)

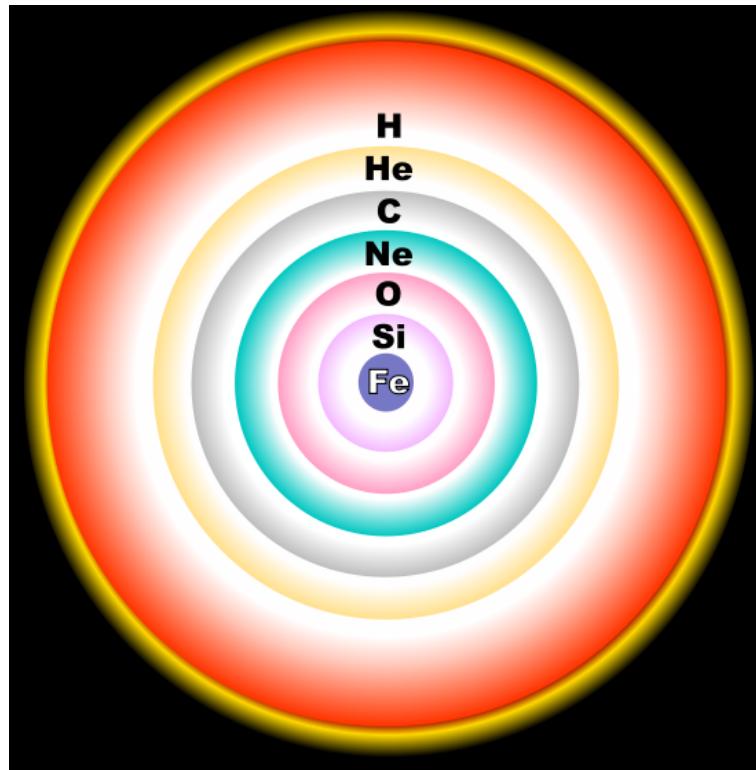
- No hay más **producción de energía**
- La gravedad **domina**
- El colapso comienza pero se detiene → **Pauli!**
- $R \sim R_{Tierra} \leftarrow$  Calcular  $p$  y  $v_e$
- La estrella se **enfria por radiación al espacio**  
→ Enana negra

:(

Sirio B



# Si la masa es mayor...

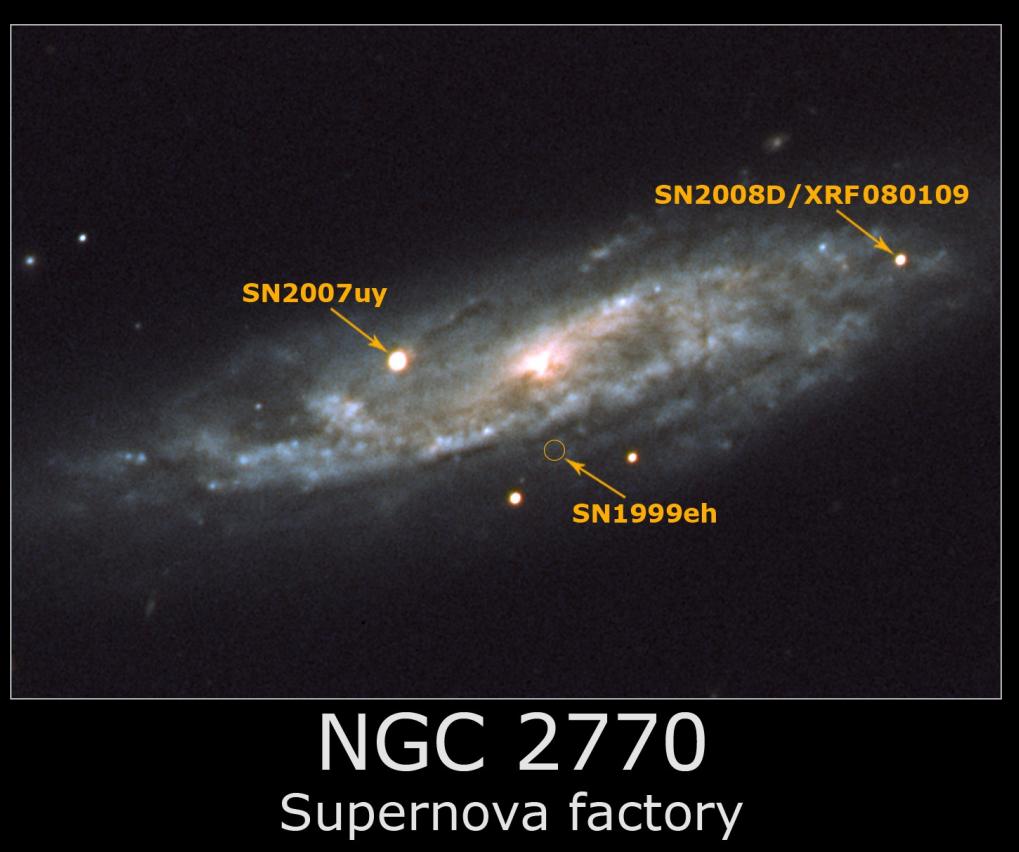


- El proceso en el núcleo continúa gracias a la compresión
- $\text{He} \rightarrow \text{C}/\text{O}$ ,  $\text{C} \rightarrow \text{Ne}$ ,  $\text{Ne} \rightarrow \text{O}, \text{O} \rightarrow \text{Si}$ ,  $\text{Si} \rightarrow \text{Fe}$
- Pero Fe es el más estable: no gano energía uniendo Fe
-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

**¡El núcleo colapsa!**

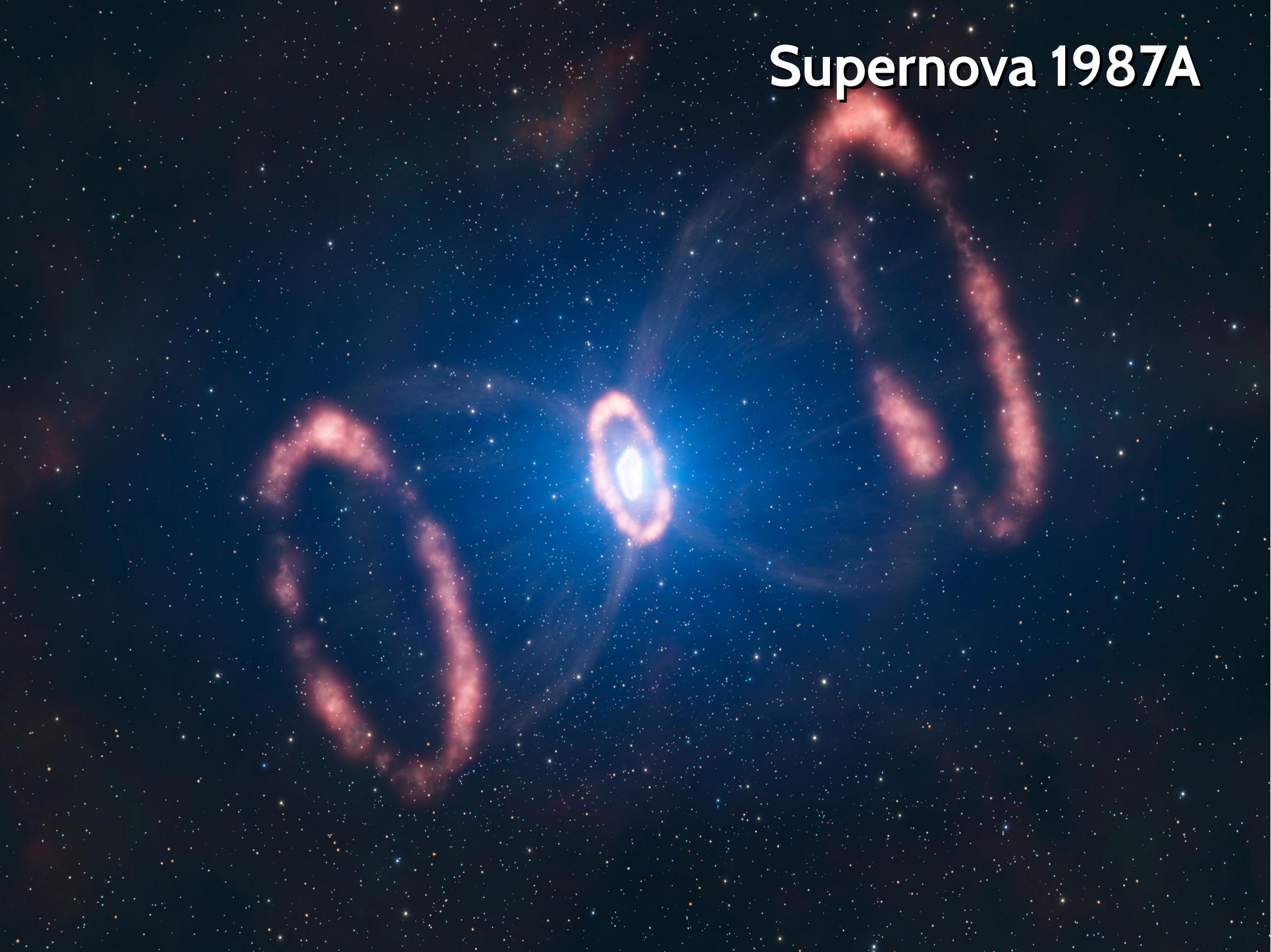
H. Asorey - IPAC 2016 - 08/16

# Supernovas



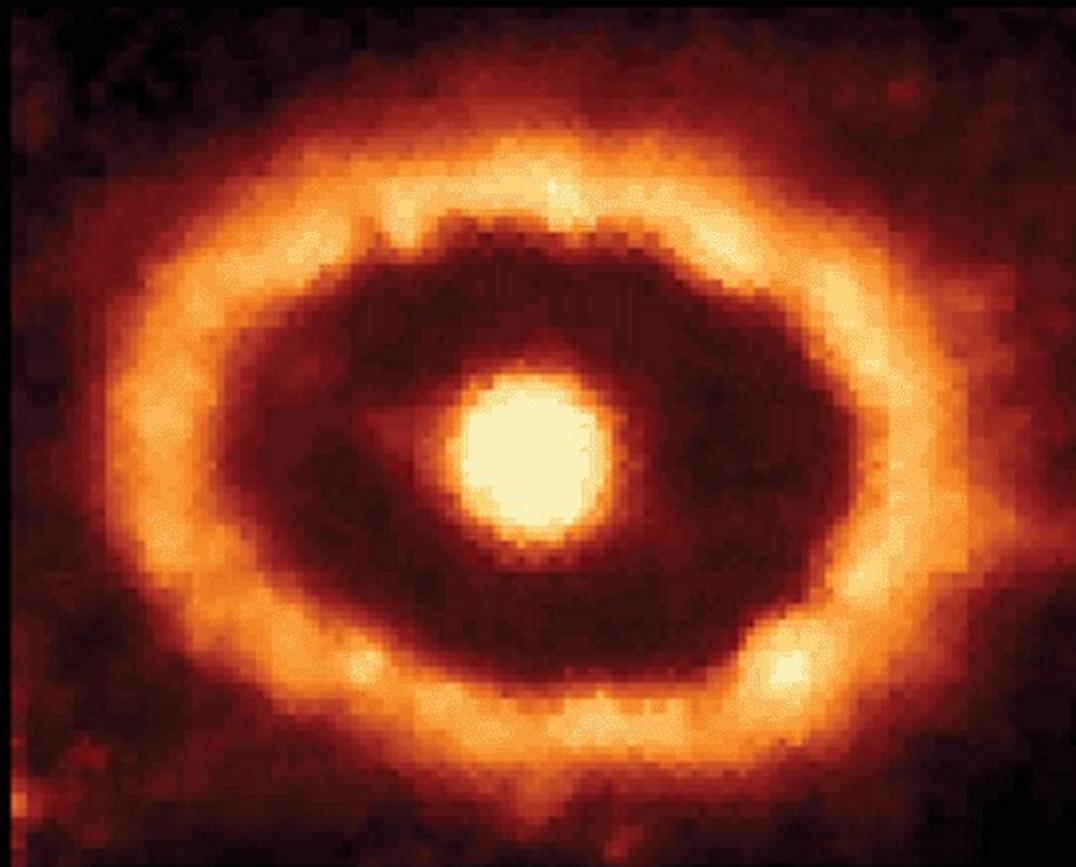
- Dos tipos de SN: I y II
- Estás son las tipo II
- En el núcleo:  
 $p^+ + e^- \rightarrow n + \nu_e$
- Estrella de neutrones
- $M \sim 2 M_{\text{Sol}}, R \sim 20 \text{ km}$
- ¡Calcular  $\rho$  y  $v_e$ !
- Pulsars (LGM)
- **$M$  grandes → Agujeros Negros**

# 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)



# Estrellas supermasivas

NGC3372 – Nebulosa Carina (Carina)

# Estrellas supermasivas



NGC3372 – Nebulosa Carina (Carina)

# $\eta$ Carinae: Una binaria a punto caramelito



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