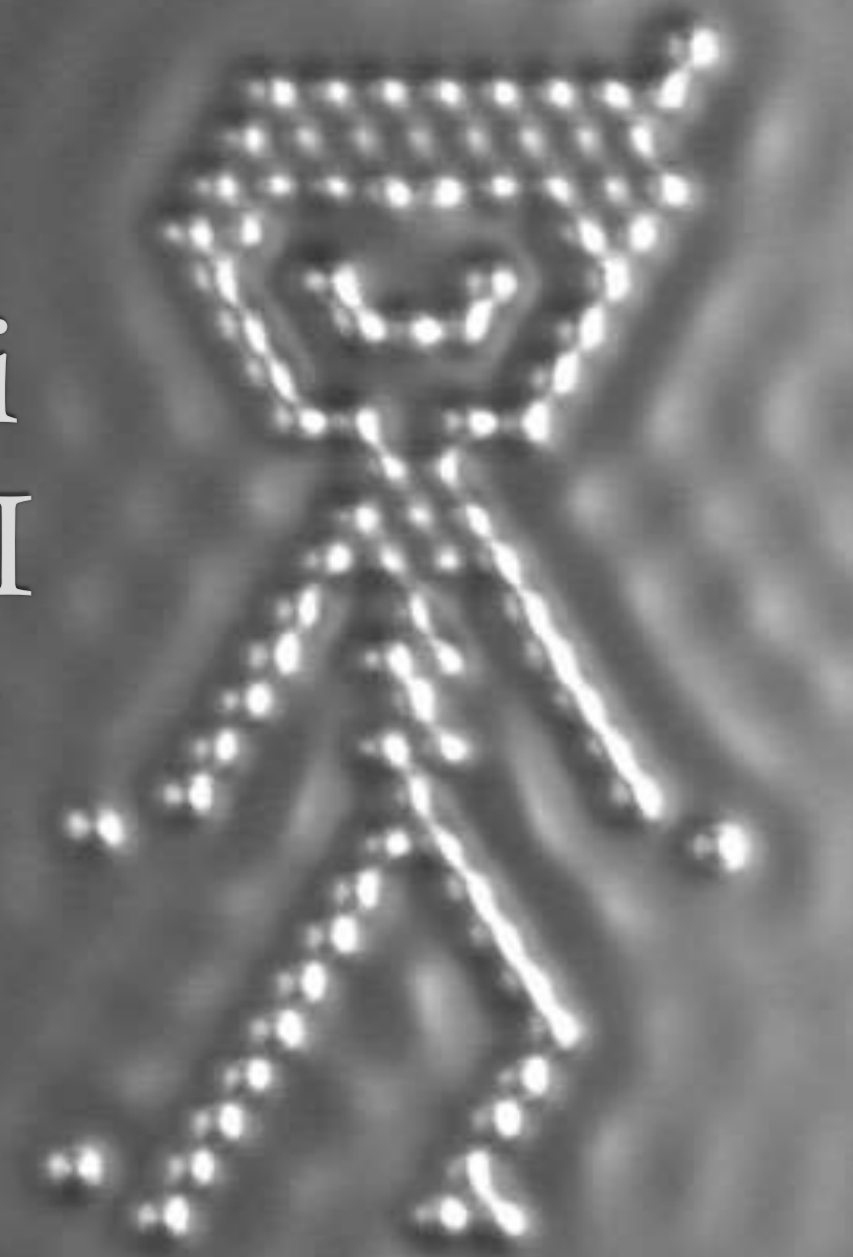


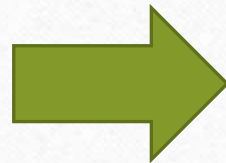
# Applicazioni Astrofisiche I

Dal corpo nero alla spettroscopia



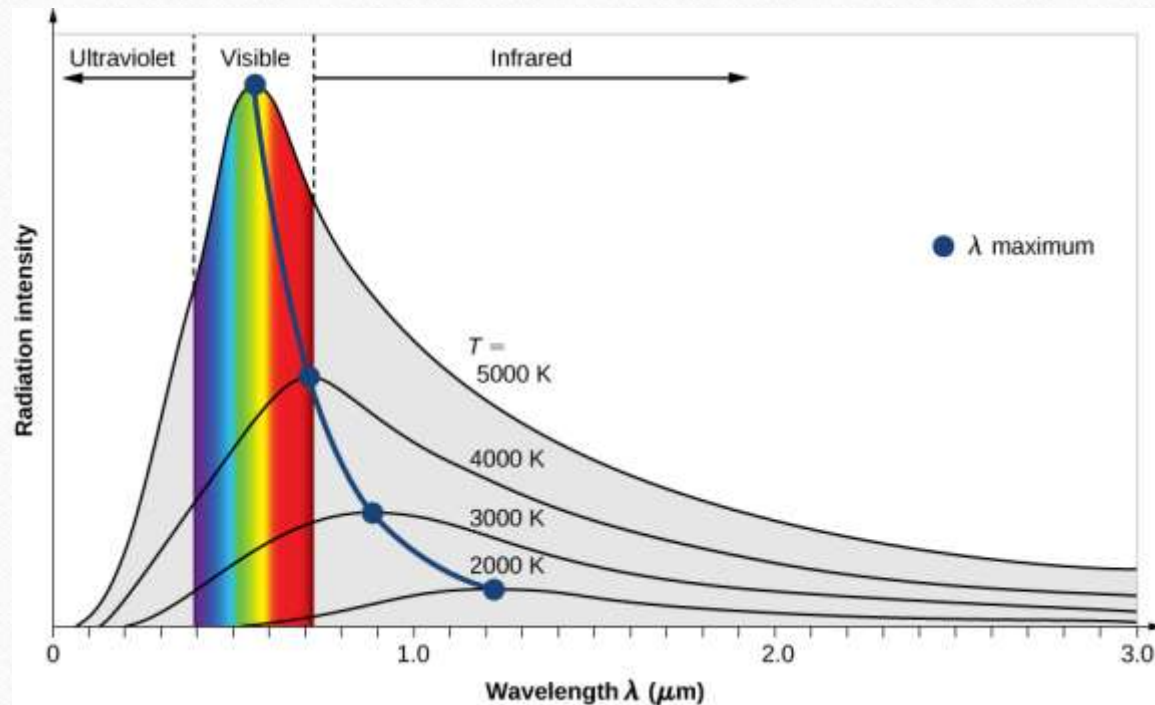
# Cosa vedremo stasera?

- Corpo nero in *Astronomia*
- Emissioni in riga
- Righe di assorbimento



- Radiazione cosmica a microonde
- Disco di accrescimento
- Polvere e gas
- Stelle
- Regioni H II

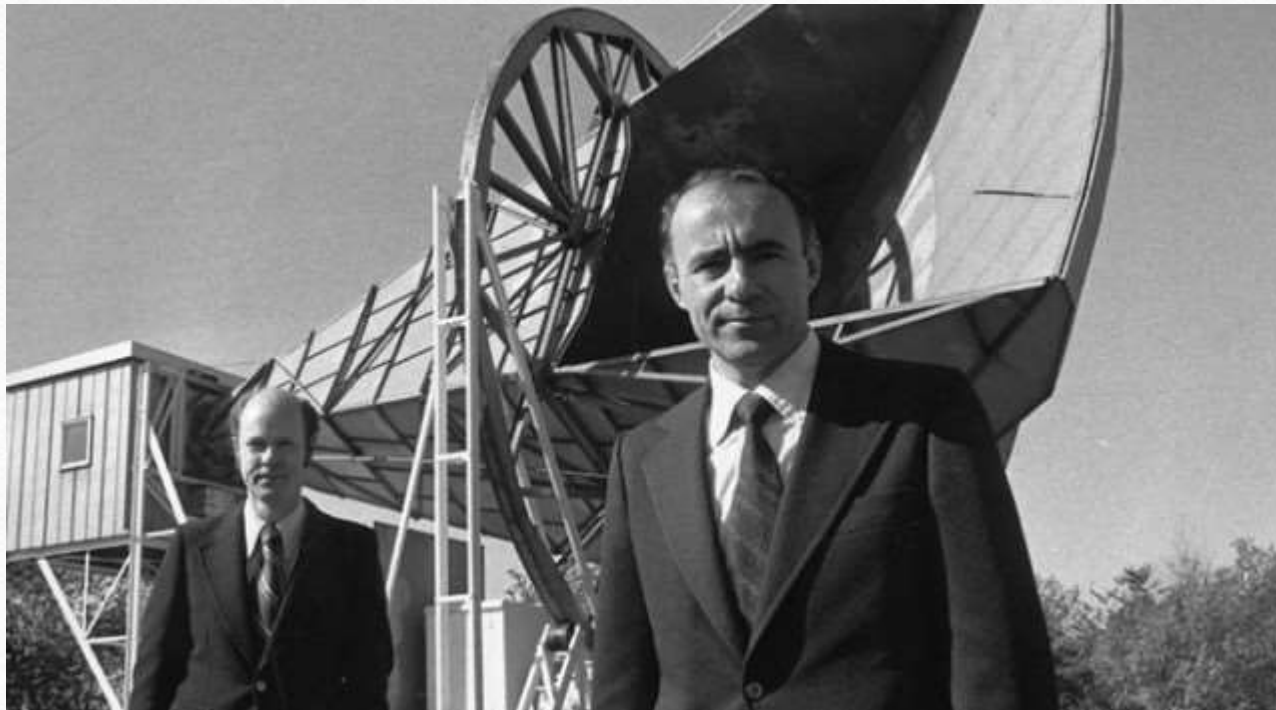
# Proprietà principali di un corpo nero



- $L_* = 4\pi R_*^2 \sigma T_*^4$  per Stefan-Boltzmann di una sfera
- $\lambda_{MAX} = \frac{\text{costante}}{T_*}$  per Wien
- $P_{RAD} = \frac{4\sigma}{3c} T_*^4$  è pressione di radiazione: importante per polvere, vento e sonde



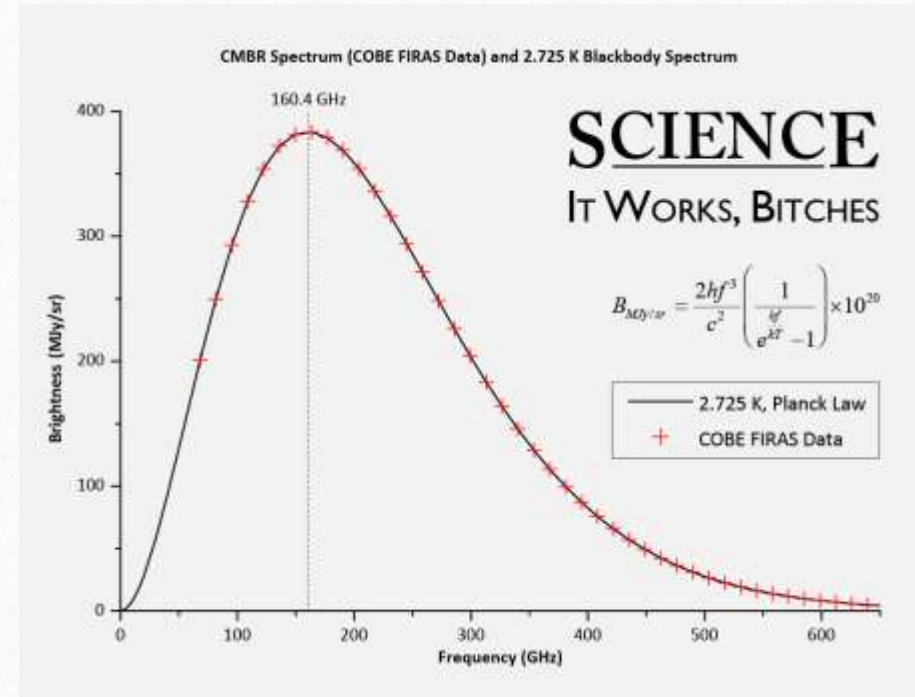
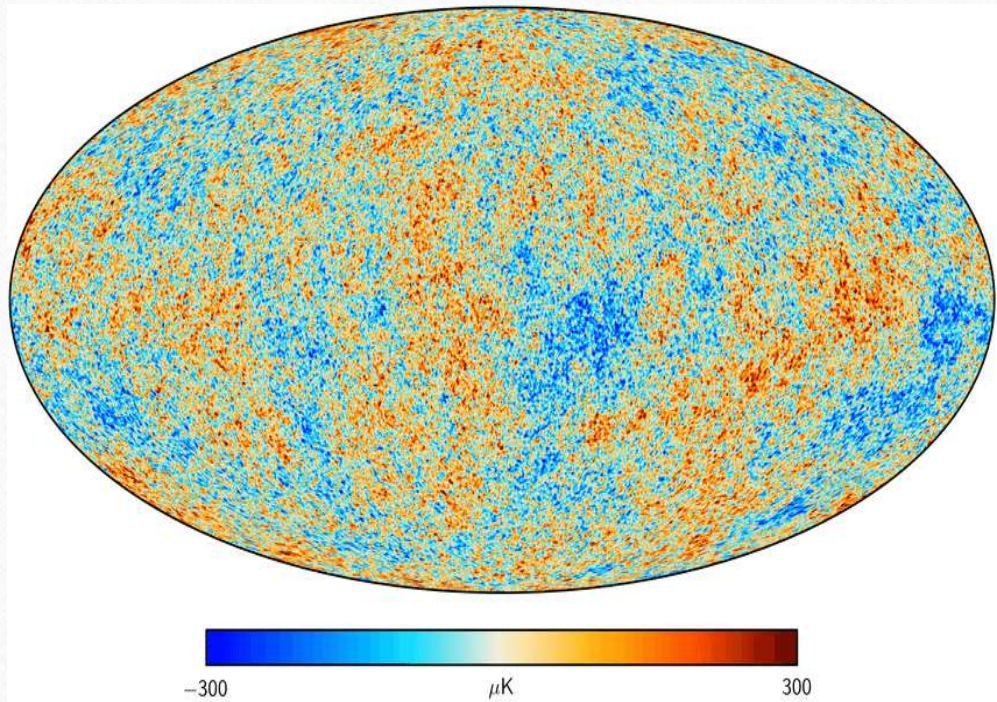
# Radiazione cosmica a microonde o semplici nidi di piccioni?



- Scoperta da Penzias e Wilson nel 1964 con un'antenna Horn da 6m.
- Vinceranno il Nobel per la Fisica nel 1978.
- Ipotizzata da Gamow nel 1948: prova della teoria del Big Bang.

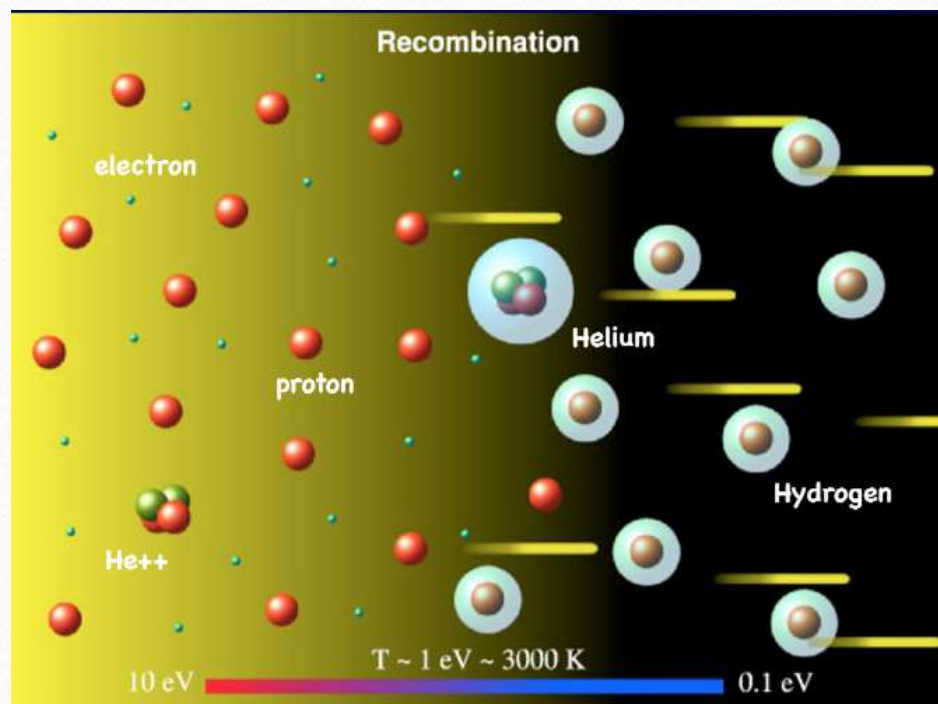
# Corpo nero a cosa serve?

## Radiazione cosmica di fondo





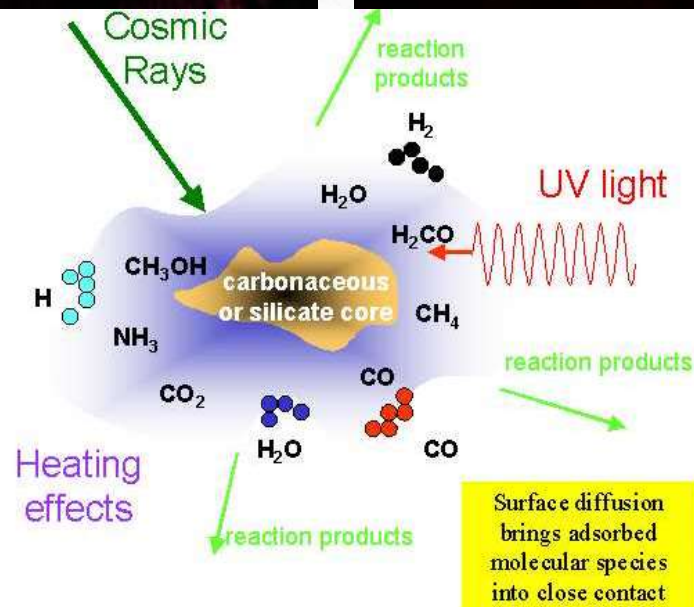
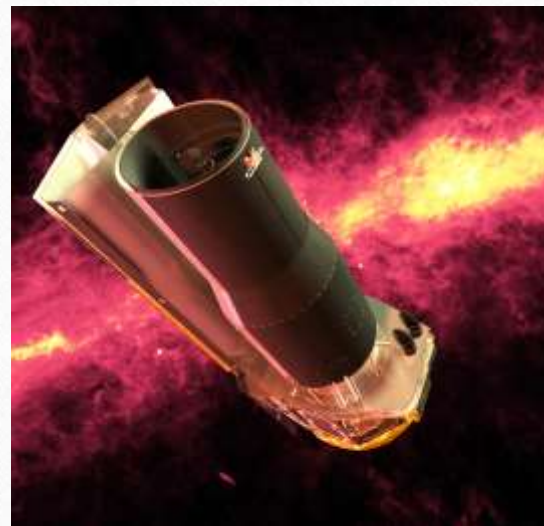
# Radiazione cosmica a microonde: perché la osserviamo?



- $\text{Li}^{3+} + e^{-} \rightarrow \text{Li}^{2+}$
- $\text{Li}^{2+} + e^{-} \rightarrow \text{Li}^{+}$
- $\text{He}^{2+} + e^{-} \rightarrow \text{He}^{+}$
- $\text{He}^{+} + e^{-} \rightarrow \text{He}$
- $\text{H}^{+} + e^{-} \rightarrow \text{H}$  circa 350 mila anni dopo il Big Bang

# Corpo nero a cosa serve? Polvere interstellare

- Presente nelle nubi molecolari giganti (aiuta formazione di  $H_2$  e nuove stelle)
- Diffonde e assorbe luce: nebulose oscure
- Composta da silicati e ghiaccio (dimensioni di pochi micron)
- Assorbe UV di stelle giovani e calde
- Emissione termica nel lontano infrarosso ( $T \approx 100$  K)
- Indica la formazione stellare delle galassie



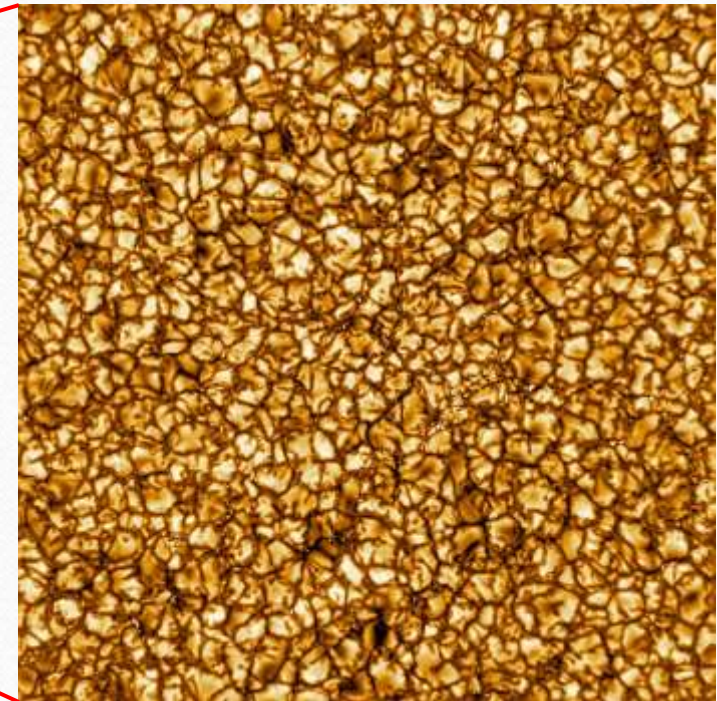
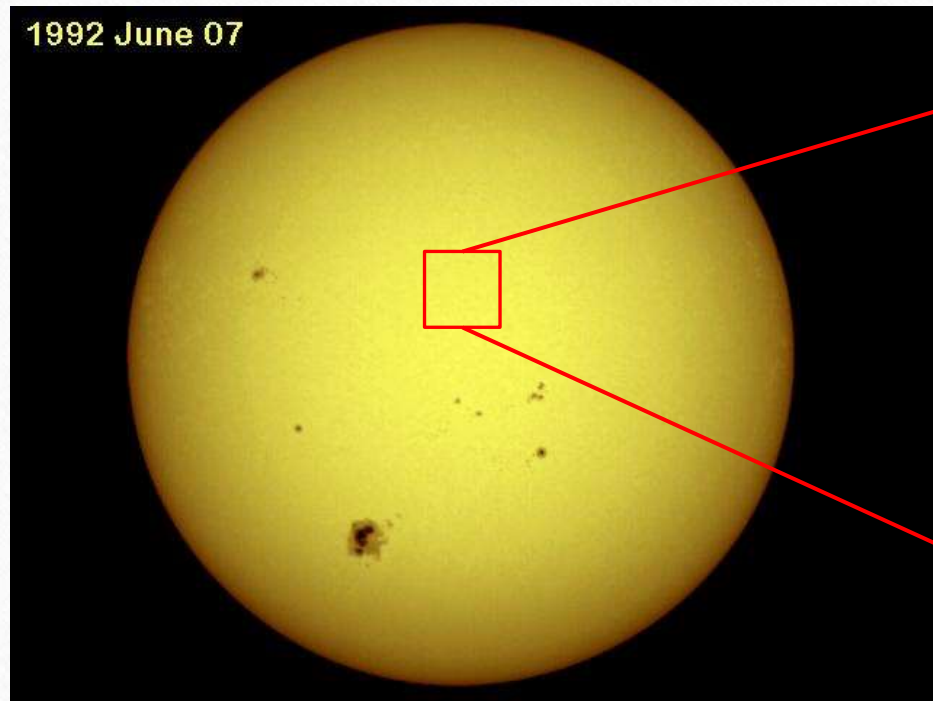


# Corpo nero a cosa serve? Disco di accrescimento

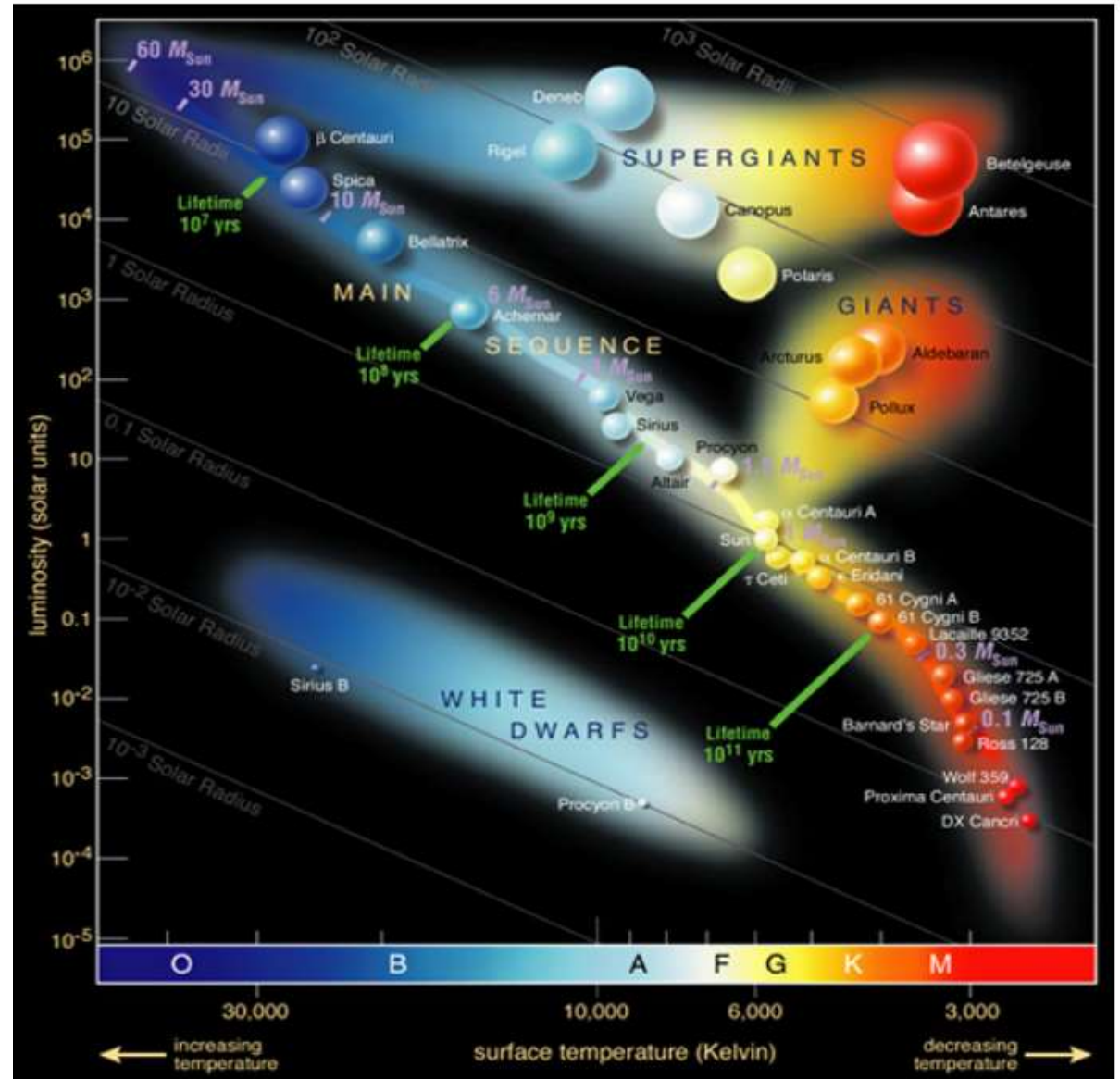




# Corpo nero a cosa serve? Stelle



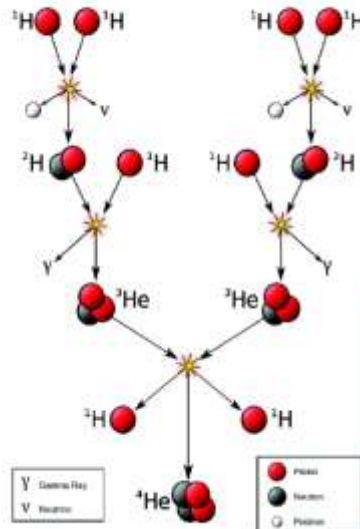
# Diagramma di Hertzsprung-Russell



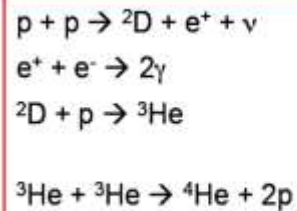


# Reazioni di fusione nucleare nelle stelle di sequenza principale

## Proton-Proton Chain

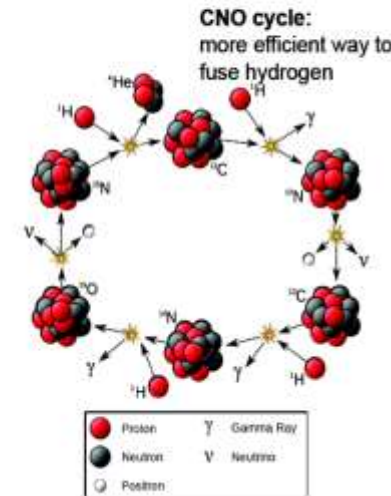


- Main nuclear reaction mechanism in the Sun
- Requires  $T > 10^7$  K
  - implies minimum stellar mass
  - requirement:  $M_{\text{star}} > 0.08 M_{\odot}$
  - star with  $M < 0.08 M_{\odot}$  is called?

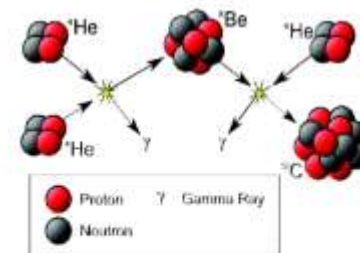


## More nuclear reactions

- More massive stars are hotter  $\rightarrow$  other reactions possible



**Triple Alpha Process:**  
build elements heavier than helium

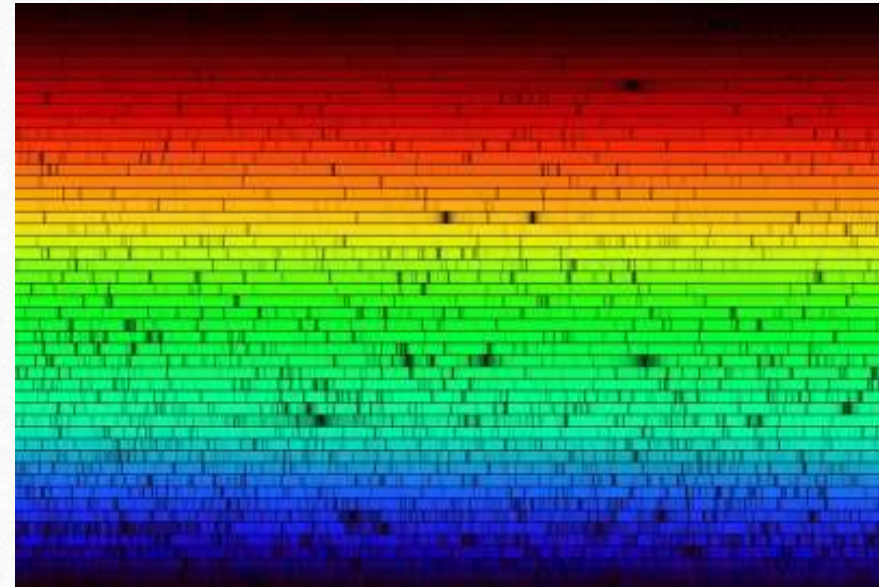
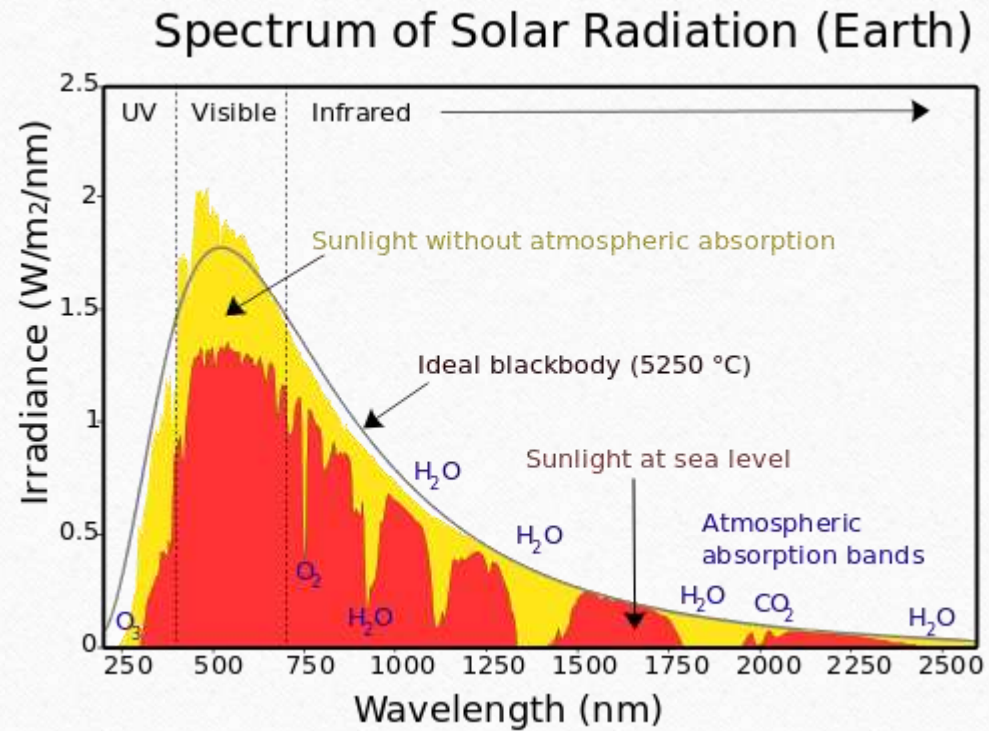


Non  
facciamo  
diventare  
sferiche le  
mucche!

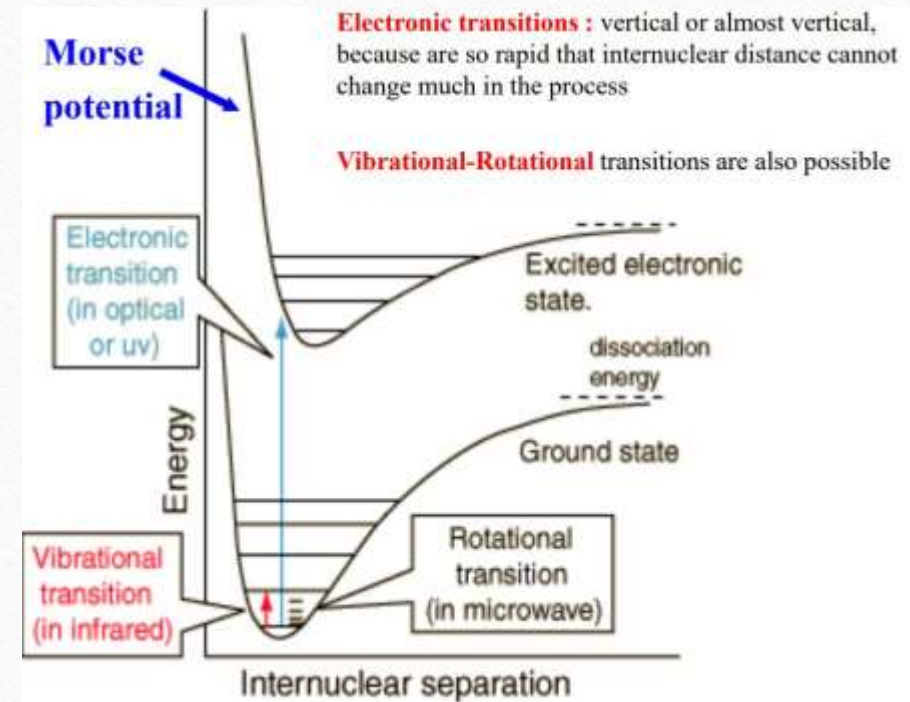
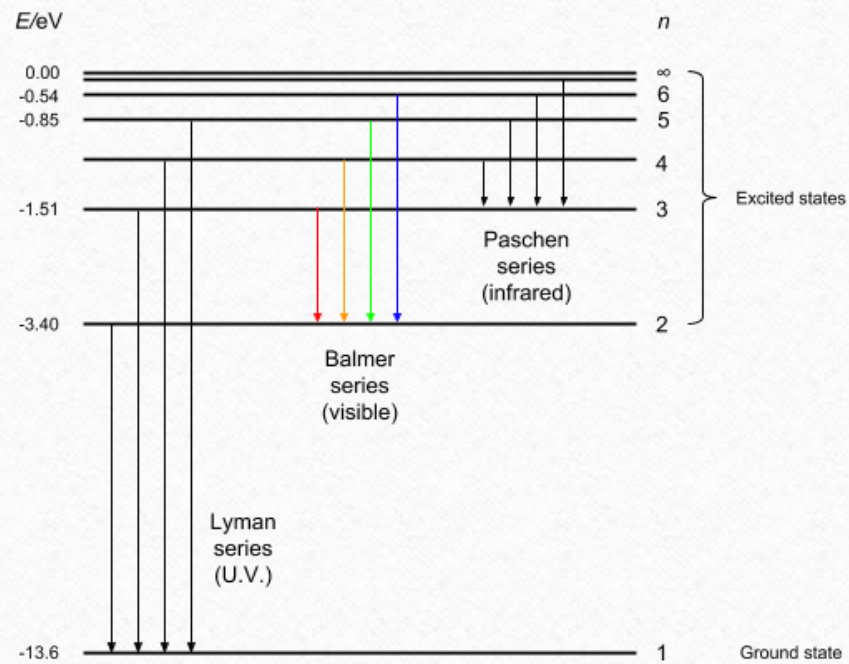




# Spettro del Sole

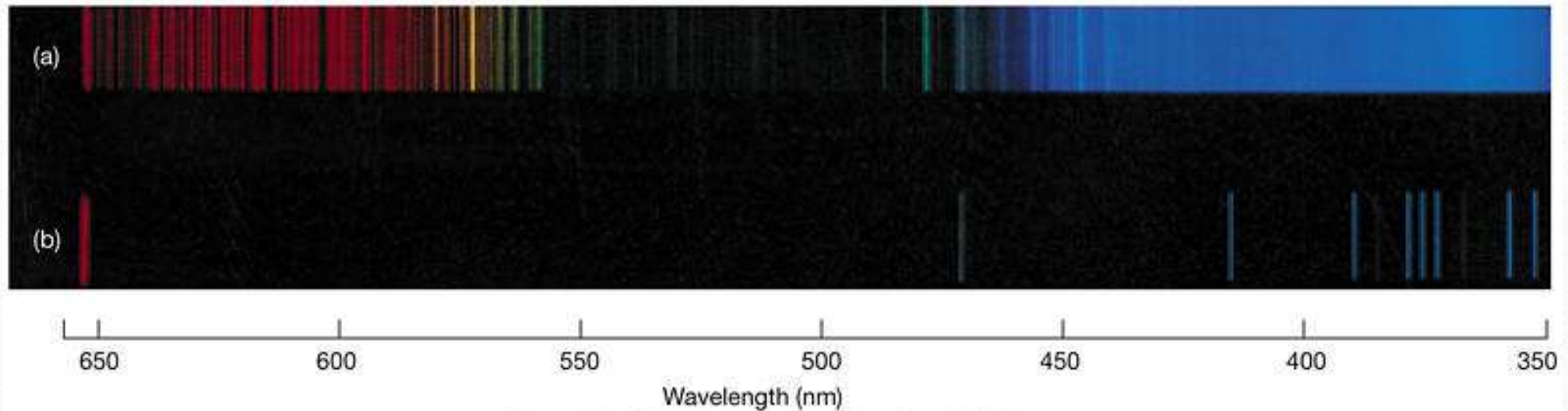


# Spettroscopia atomi e molecole: differenze



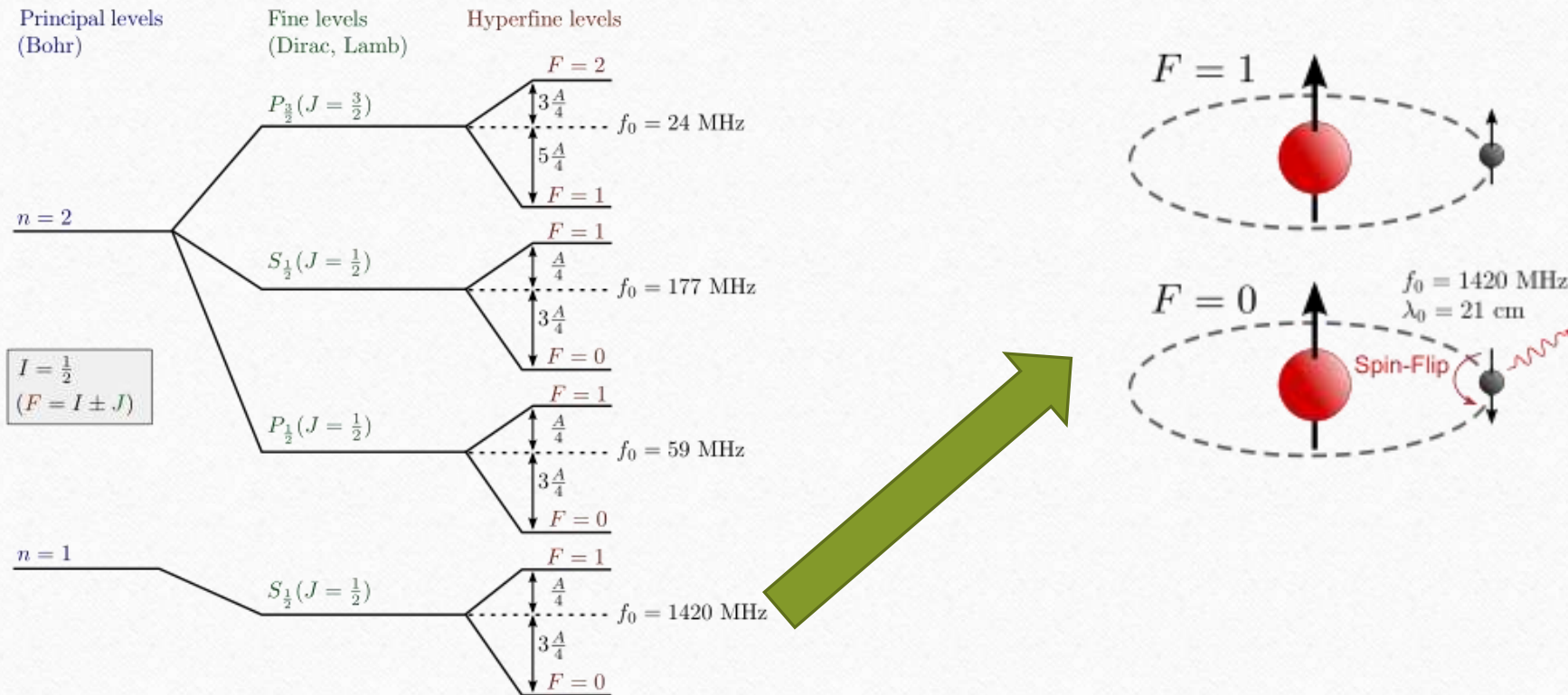


# Spettroscopia atomi e molecole: differenze



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# Struttura iperfine dell'idrogeno: riga «proibita» a 21 cm

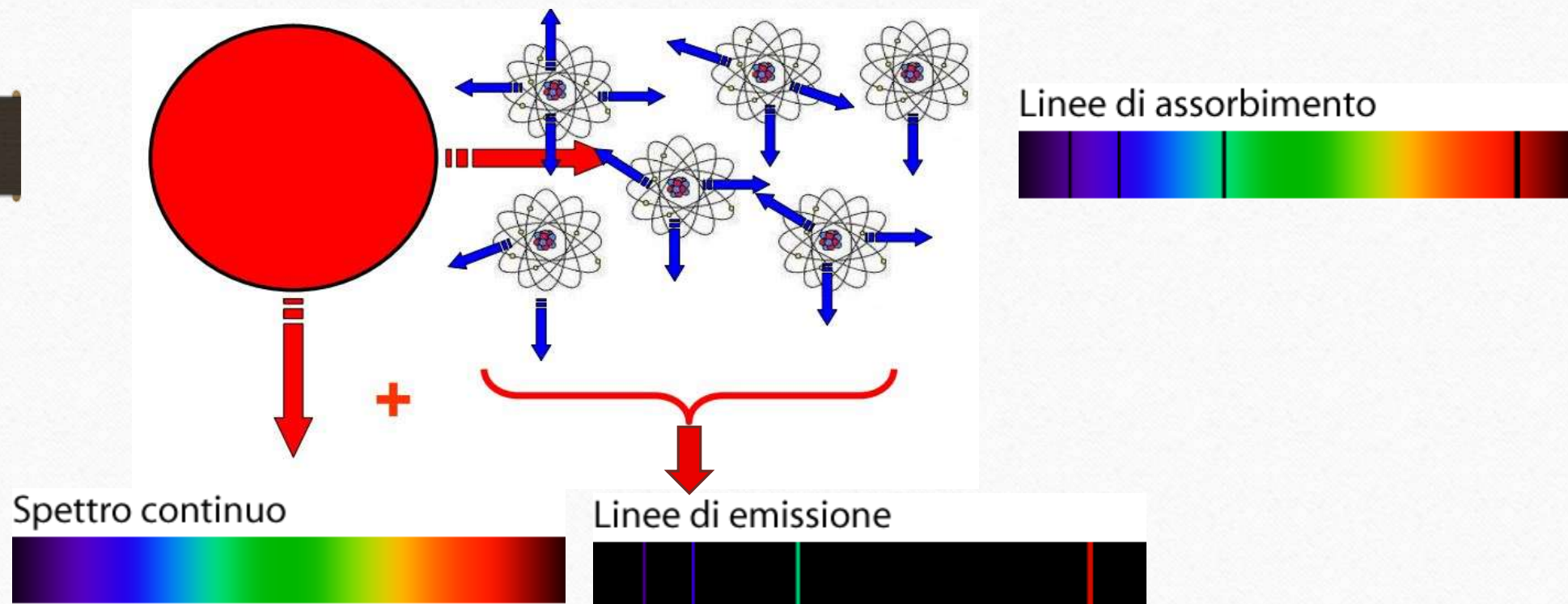




# Riga a 21 cm in Astrofisica: idrogeno neutro



# Assorbimento ed emissione in riga





# Profondità e allargamento delle righe

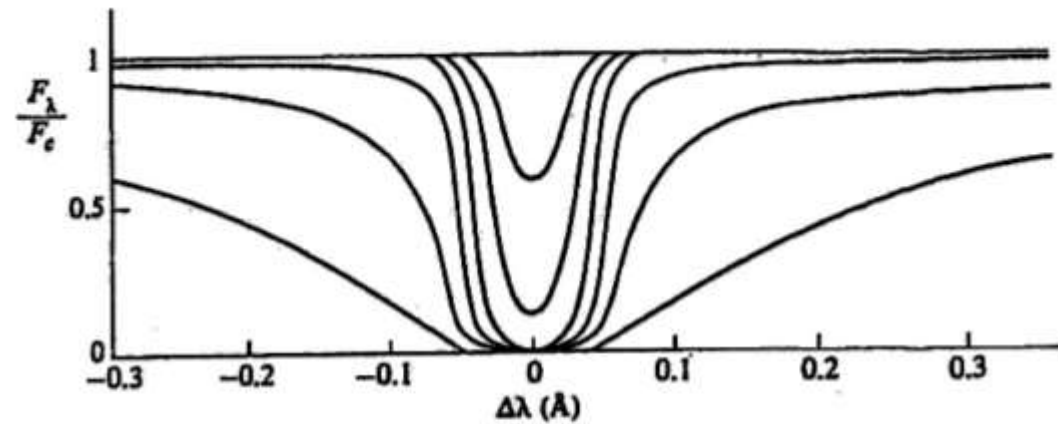
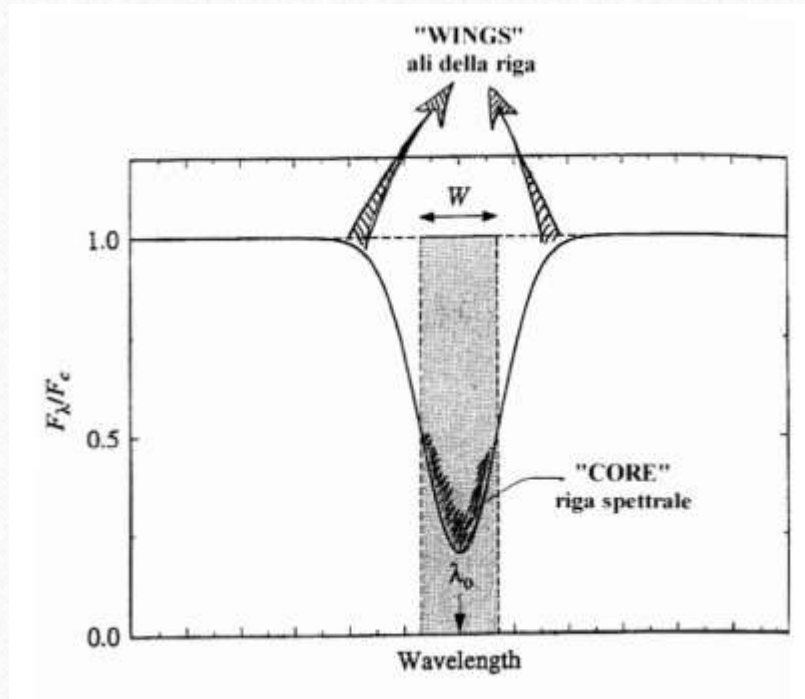
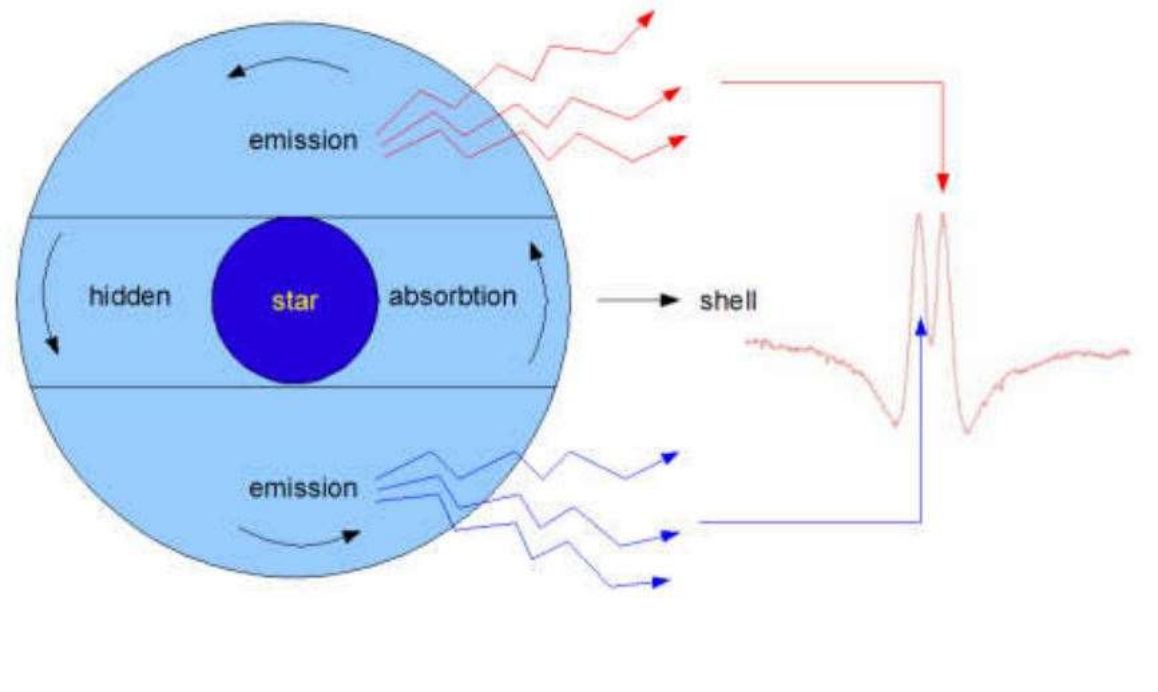
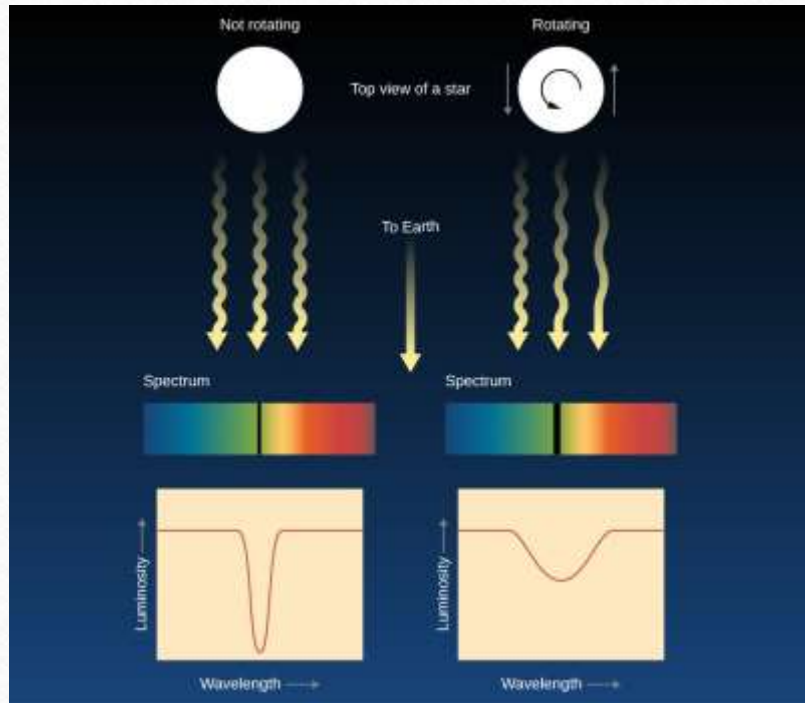


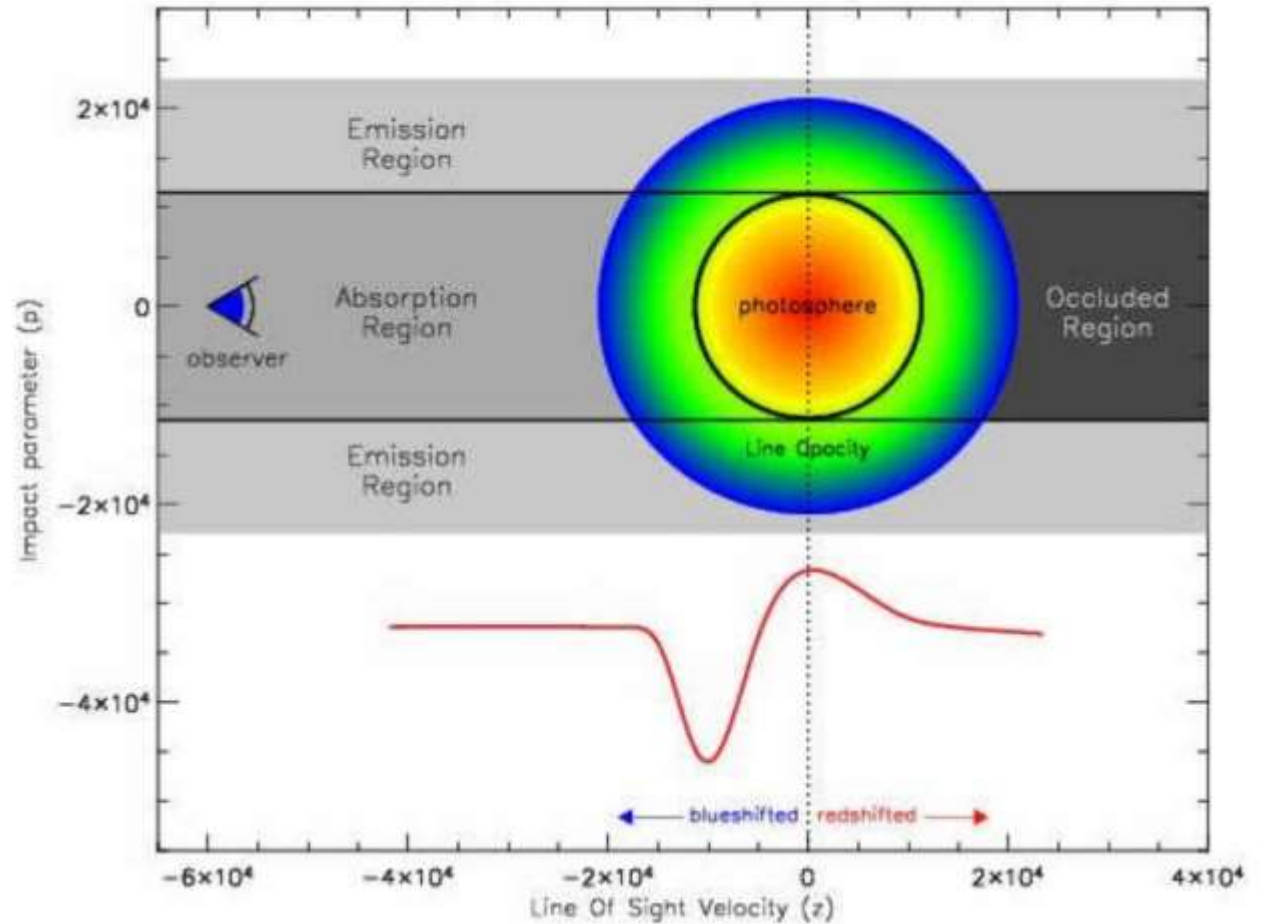
Figure 9.20 Voigt profiles of the K line of Ca II. The shallowest line is produced by  $N_a = 3.4 \times 10^{11}$  ions  $\text{cm}^{-2}$ , and the ions are ten times more abundant for each successively broader line. (Adapted from Novotny, *Introduction to Stellar Atmospheres and Interiors*, Oxford University Press, New York, 1973.)

# Effetti della rotazione di una stella e di un disco

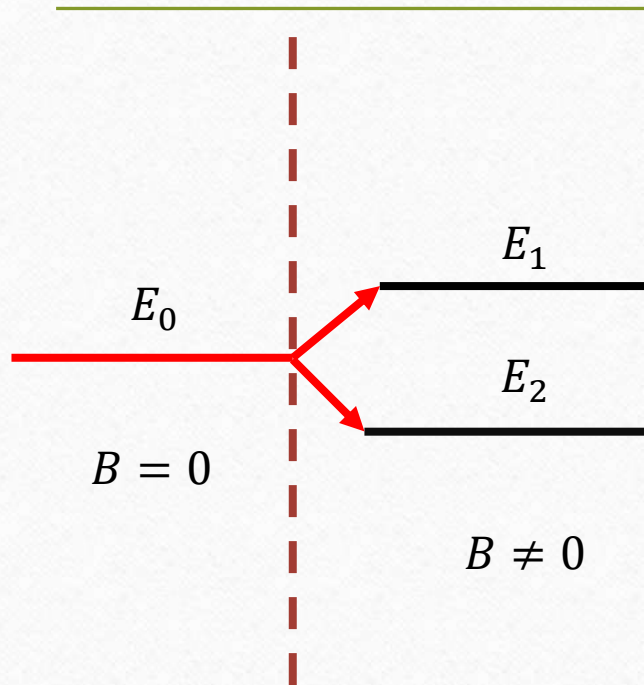




# Effetto P Cygni: gas espulso



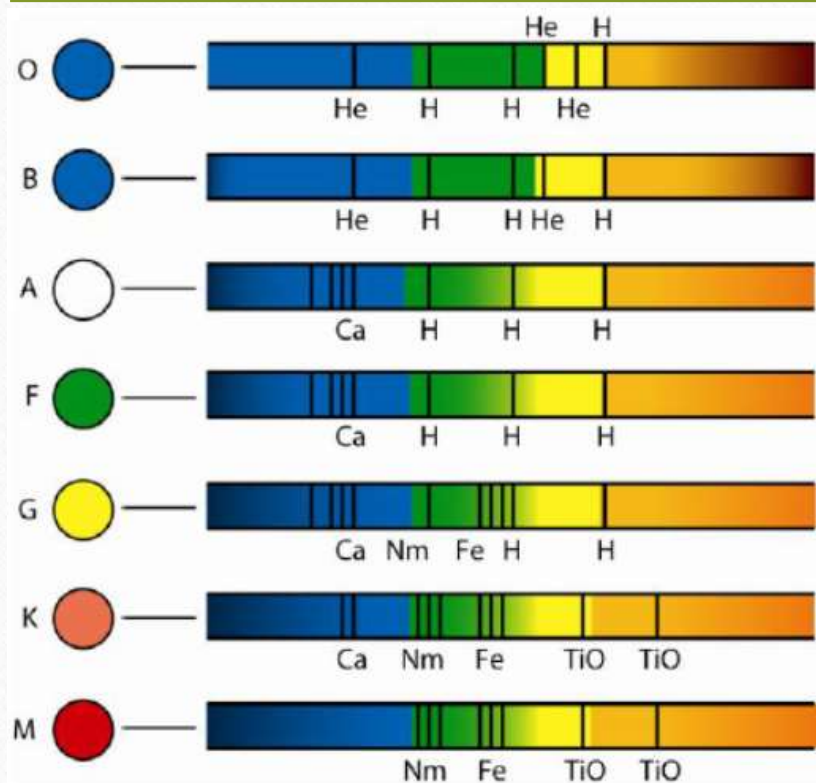
# Effetto Zeeman



[www.eso.org](http://www.eso.org)



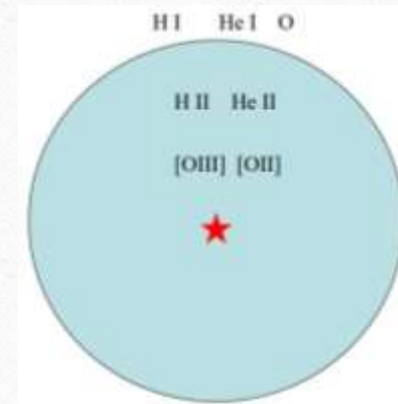
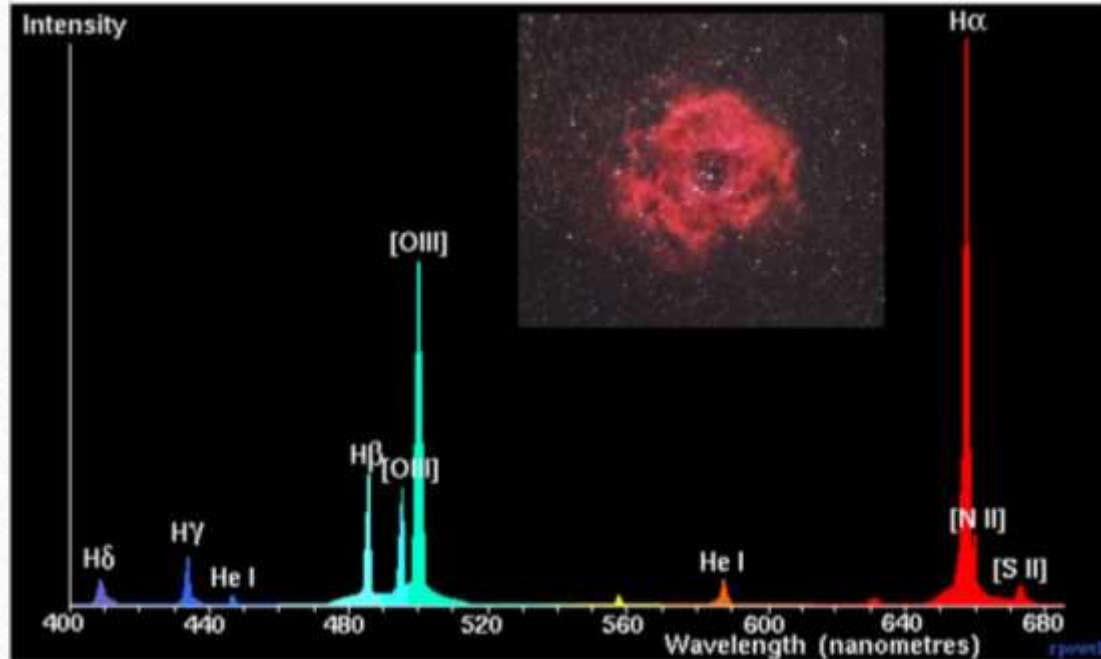
# Classificazione spettrale di Harvard



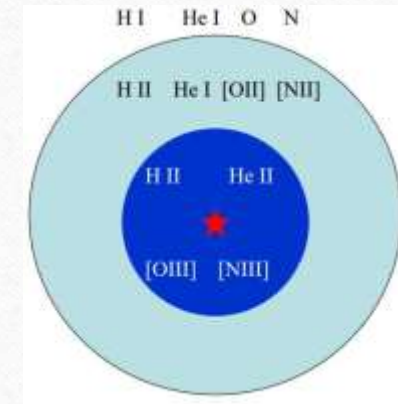
class	$T_{\text{eff}}$ (K)	colour	mass ( $M_{\odot}$ )	H lines	other lines	Fraction MS stars
O	>33,000	blue	>16	weak	multiple ionised atoms	~0.0003 %
B	10,000-33,000	blue/ white	2.1-16	medium	no ionised He, neutral He instead	~0.1%
A	7500-10,000	white/ blue	1.4-2.1	strong	ionised Ca lines visible, no He, neutral metals	~0.6%
F	6000-7500	white	1.0-1.4	medium	ionised Ca stronger, metals	~3%
G	5200-6000	yellow	0.8-1.0	weak	strong metal lines	~7.5%
K	3700-5200	yellow/ orange	0.45-0.8	very weak	neutral Ca, TiO	~12%
M	<3700	orange/ red	<0.45	very weak	strong Ca, TiO, neutral metals	~76%

*Oh Be A Fine Girl Kiss Me*

# Righe Proibite oppure Nebulium?



$T_* > 40000$  K



$T_* < 40000$  K



# Densità critica e raffreddanti principali

- Equilibrio tra emissione spontanea, stimolata ed eccitazione collisionale
- $L_{\text{riga}} = \text{costante} \cdot n_e^2$  per  $n_e \ll n_{\text{crit}}$
- $L_{\text{riga}} = \text{costante} \cdot n_e$  per  $n_e \gg n_{\text{crit}}$

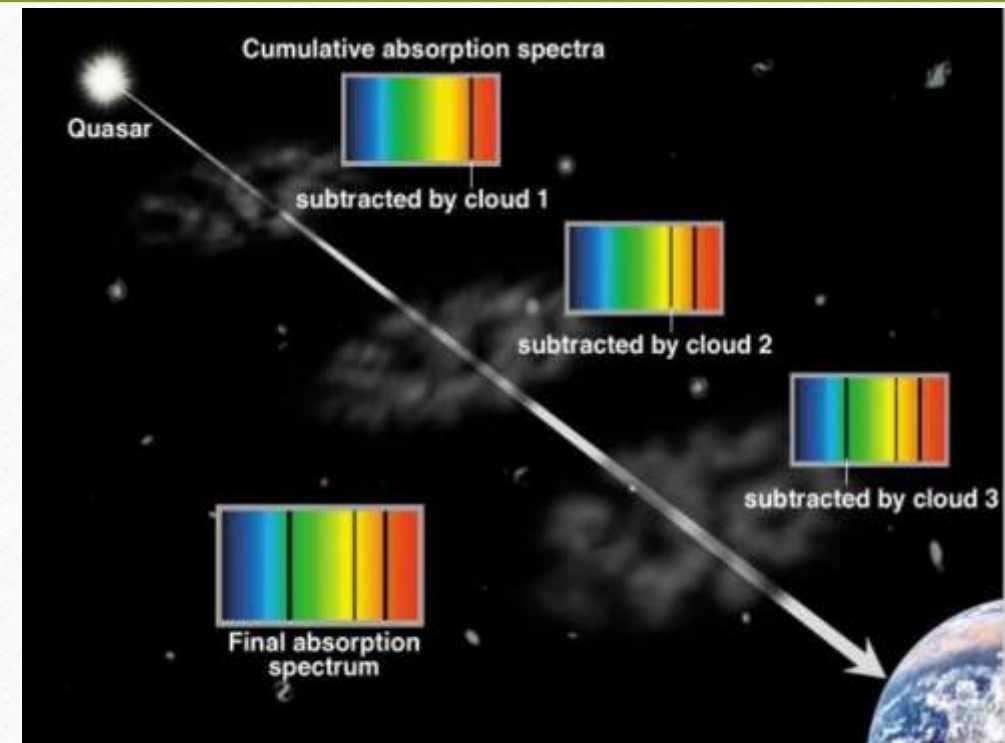
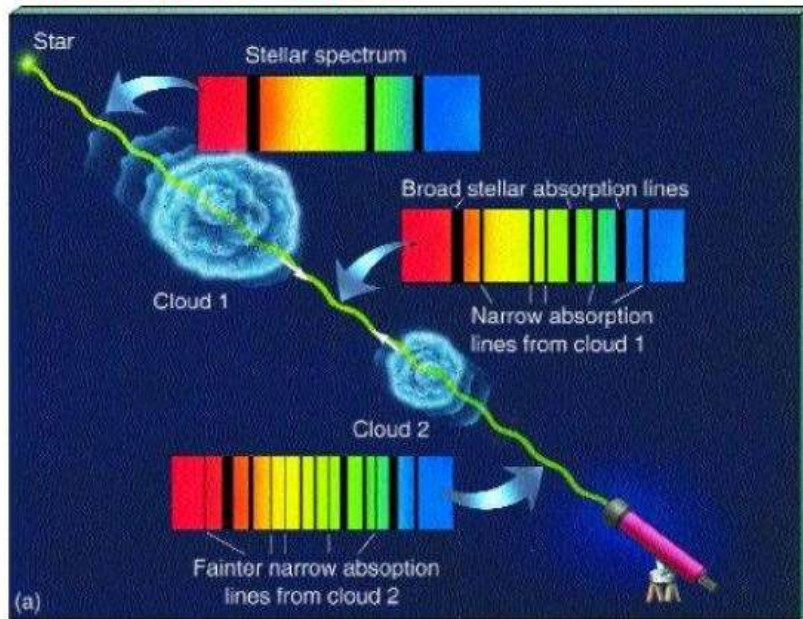
## Some critical densities

Line	Wavelength (Å)	$\log n_{\text{crit}} (\text{cm}^{-3})$	Line	Wavelength (Å)	$\log n_{\text{crit}} (\text{cm}^{-3})$
[C III]	1909	9.0	[Fe VII]	5721.1	7.6
[O II]	3726.1	3.5	[N II]	5754.6	7.5
[O II]	3728.8	2.8	[Fe VII]	6086.9	7.6
[Fe VII]	3760.3	7.6	[O I]	6300.3	6.3
[Ne III]	3868.8	7.0	[S III]	6312.1	7.2
[Ne III]	3967.5	7.0	[Fe X]	6374.6	9.7
[S II]	4068.6	6.4	[N II]	6583.4	4.9
[O III]	4363.2	7.5	[S II]	6716.4	3.2
[Ar IV]	4711.3	4.4	[S II]	6730.8	3.6
[Ar IV]	4740.0	5.6	[Ar III]	7135.4	6.7
[O III]	5006.9	5.8	[O II]	7319.9	6.8
[Fe VIII]	5159.0	6.5	[O II]	7330.2	6.8
[Fe VI]	5176.4	7.6	[N I]	5197.9	3.3

Temperature	Main coolant	Cooling rate [J m <sup>-3</sup> s <sup>-1</sup> ]
10 K	CO (rotational)	10 <sup>-45</sup> n <sup>2</sup>
100 K	H <sub>2</sub> , [C II]	10 <sup>-40</sup> n <sup>2</sup>
1000 K	Ions (Si <sup>+</sup> , Fe <sup>+</sup> , ...)	10 <sup>-38</sup> n <sup>2</sup>
10000 K	H, H II + e, [OII] ...	10 <sup>-35</sup> n <sup>2</sup>
≥ 10000 K	free – free continuum emission	

# Mezzo interstellare e intergalattico

## Absorption Lines – Interstellar Gas





# Idrogeno molecolare e Self-Shielding

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- La molecola più diffusa
- Difficile da detettare: visibili solo i livelli rotazionali
- Gli strati esterni proteggono le zone centrali dalla radiazione: Self-Shielding
- In ambienti densi diventa virtualmente invisibile
- Diventa più facile da osservare in ambienti caldi

# CO e conversione H<sub>2</sub>/CO

---

- Si crea a partire da CH e O
- Ha una forte energia di legame
- Forti transizioni rotazionali: ben visibile in radio
- Emette anche in presenza di gas freddo
- Per ogni molecola di CO vi sono 10 mila molecole di H<sub>2</sub>



# Indicatori formazione stellare

- ❑ **L(recombination lines)** (e.g.  $H\alpha$ ) (**primary**)
- ❑ **L(forbidden lines)** (e.g. [OII]3727) (empirical)
- ❑ **L(UV continuum)** from OB stars (1500-2800 Å)
- ❑ **L(IR)** (10-1000 $\mu$ m) (SEDs) (dust heated by OB stars) (accurate, but needs full SED and physical calibration)
- ❑ **L(radio)** (1.4 GHz) (SEDs) (free-free from H II regions + SNRs)
- ❑ **L(X)** (2-10 keV) (SEDs)
- ❑ **Caveat:** AGN “contamination”, dust extinction in UV-optical

# Bibliografia e letture

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- <https://ui.adsabs.harvard.edu/abs/1965ApJ...142..419P/abstract>  
(Articolo originale di Penzias e Wilson)
- <https://www.youtube.com/watch?v=oSCX78-8-q0>  
(Video atomo IBM)
- Per utenti consapevoli: «Astrofisica stellare» - Castellani  
(disponibile qui: <http://astrofisica.altervista.org/doku.php>)
- Livello avanzato: «Introduction to Galaxy Formation and Evolution: From Primordial Gas to Present-Day Galaxies » - Cimatti, Fraternali e Nipoti



Grazie!  
Alla prossima!

