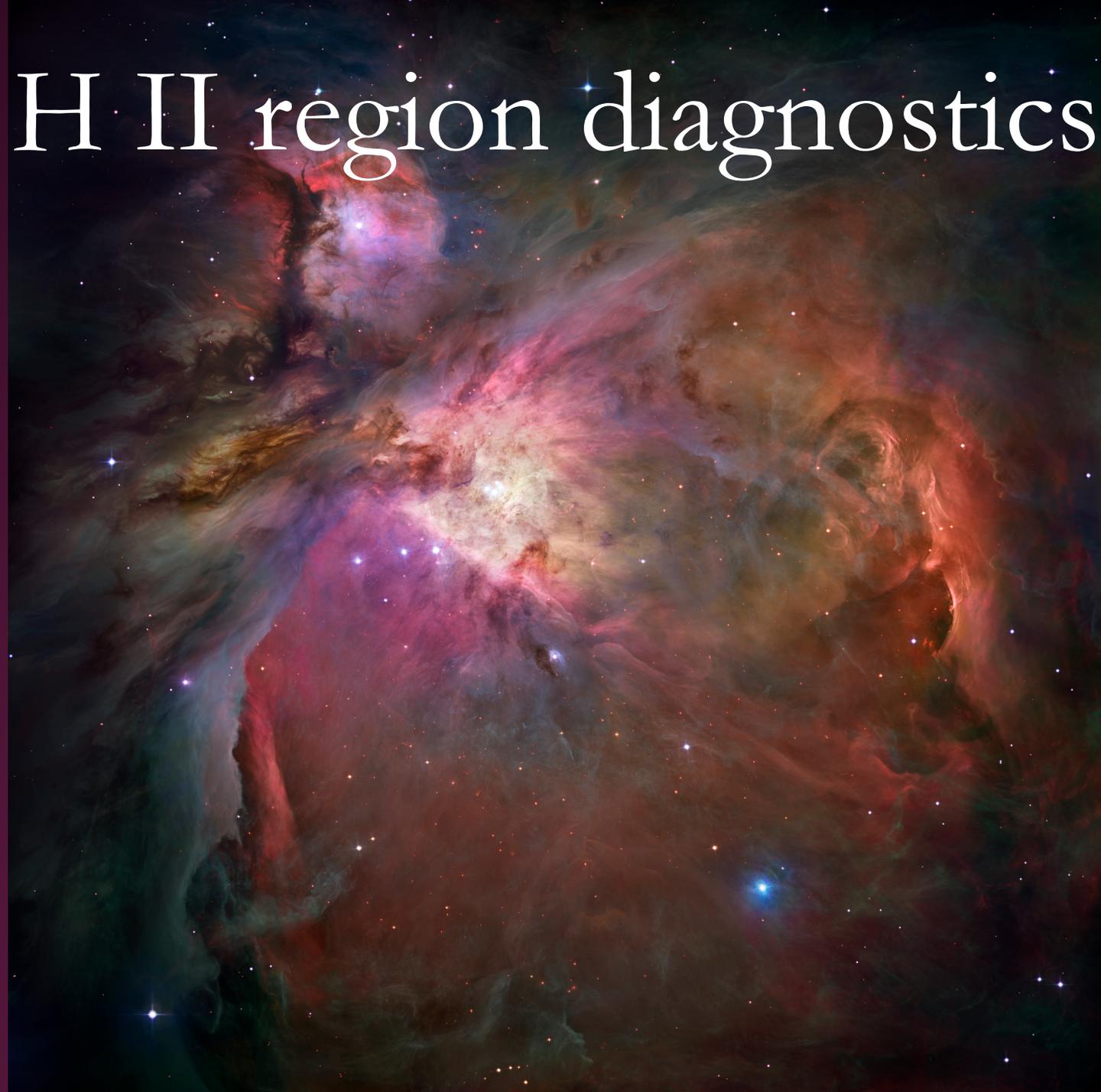


# H II region diagnostics



ASTR 605  
Joe Burchett  
9/20/2021

# Classes of diagnostics

- Temperature
  - Two excited energy levels well separated in energy ( $\Delta E \sim kT$ )
  - Emission lines reflect temperature-sensitive populations of energy levels
- Density
  - Two excited energy levels with nearly the same energy
  - Emission lines reflect populations of energy levels due to collisions
- Abundances
  - Determine relative density of some species relative to hydrogen
- Ionization source
  - Distinguish between emission lines from H II regions and active galactic nuclei

# Recap: Emission and level population

Emissivity due to spontaneous emission

- ‘radiative decay’ to lower energy level

$$j_\nu d\nu = \frac{n_u A_{ul} h\nu_{ul}}{4\pi}$$

Level populations (Boltzmann equation)

- Definition of excitation temperature

$$\frac{n_2}{n_1} = \frac{g_2}{g_1} e^{-E_{21}/kT}$$

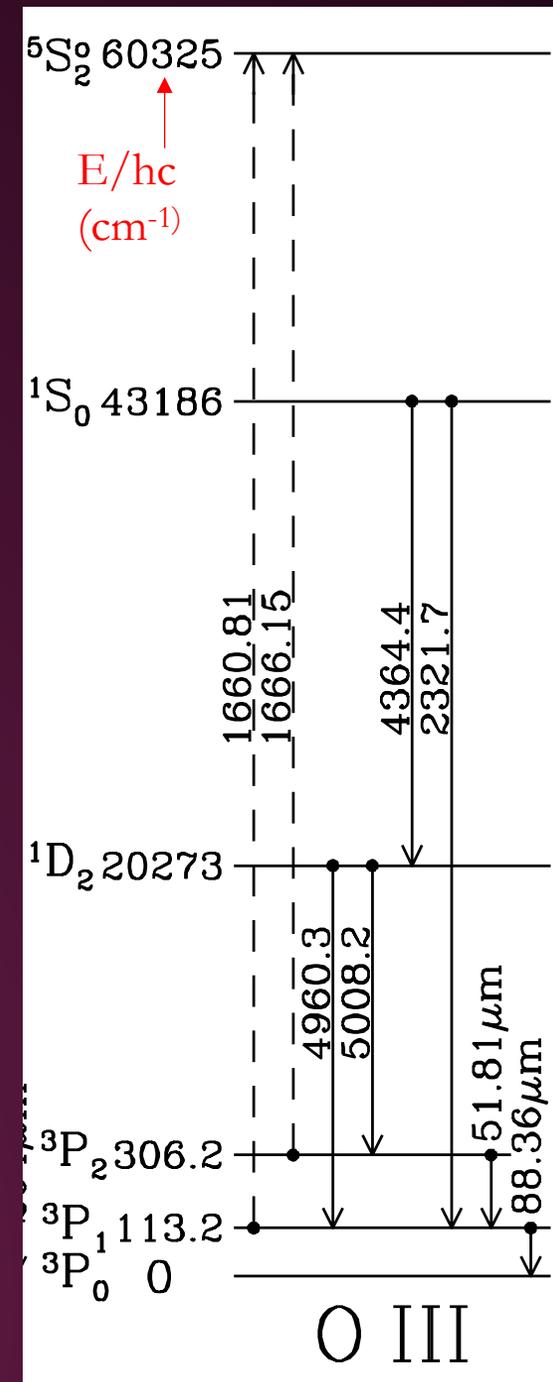
Rate of collisional deexcitation

- ‘Collision strength’  $\Omega_{ul}$  tabulated in Appendix F of Draine

$$k_{ul} = \frac{8.629 \times 10^{-8}}{\sqrt{T^4}} \frac{\Omega_{ul}}{g_u} \text{ cm}^3 \text{ s}^{-1}$$

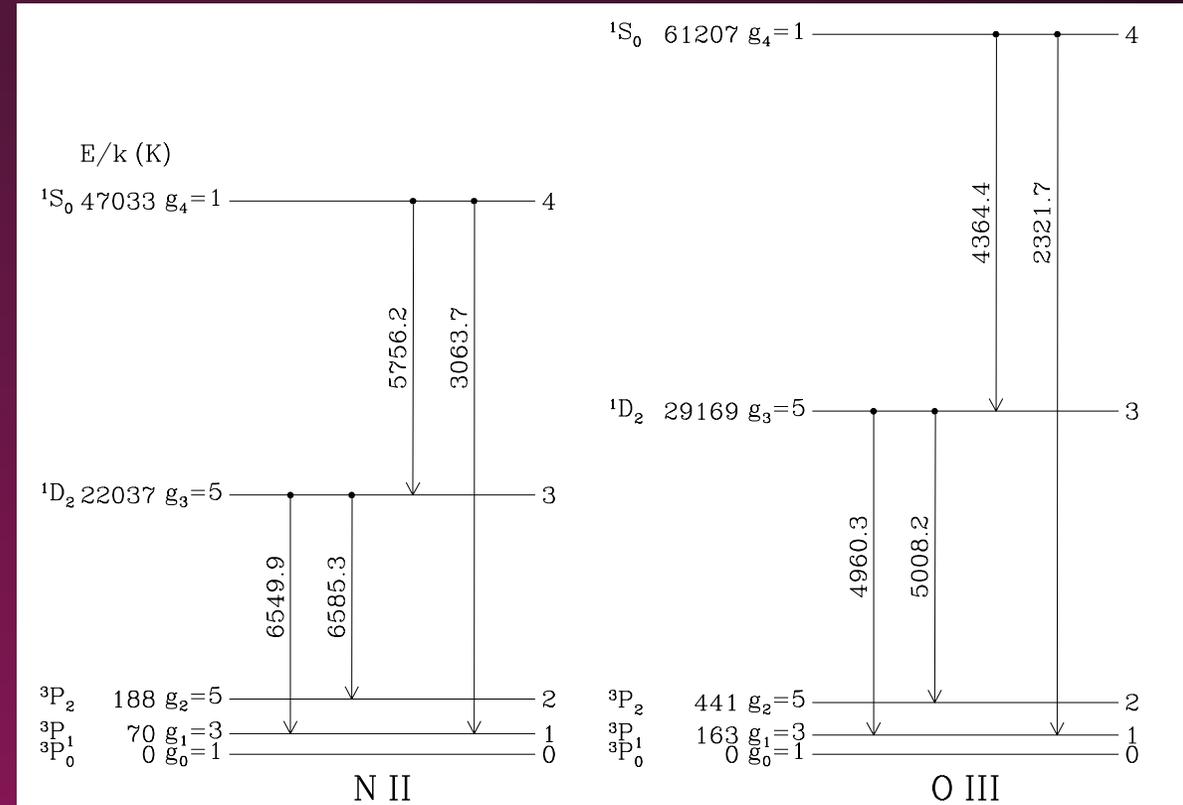
# Temperature diagnostic considerations

- Energy levels widely separated in energy ( $\Delta E \sim kT$ )
  - $k$  ( $10^4$  K)  $\sim 1$  eV
- Levels must be ‘energetically accessible’
  - Enough kinetic energy must present to collisional excite level
  - Example:  $^5S_2$  level of O III ( $E/k \sim 87,000$  K)
  - Guideline:  $E/k \lesssim 70,000$  K
- Ion should be abundant
  - O II  $\rightarrow$  O III ionization energy: 35 eV
  - O V  $\rightarrow$  O VI ionization energy: 114 eV



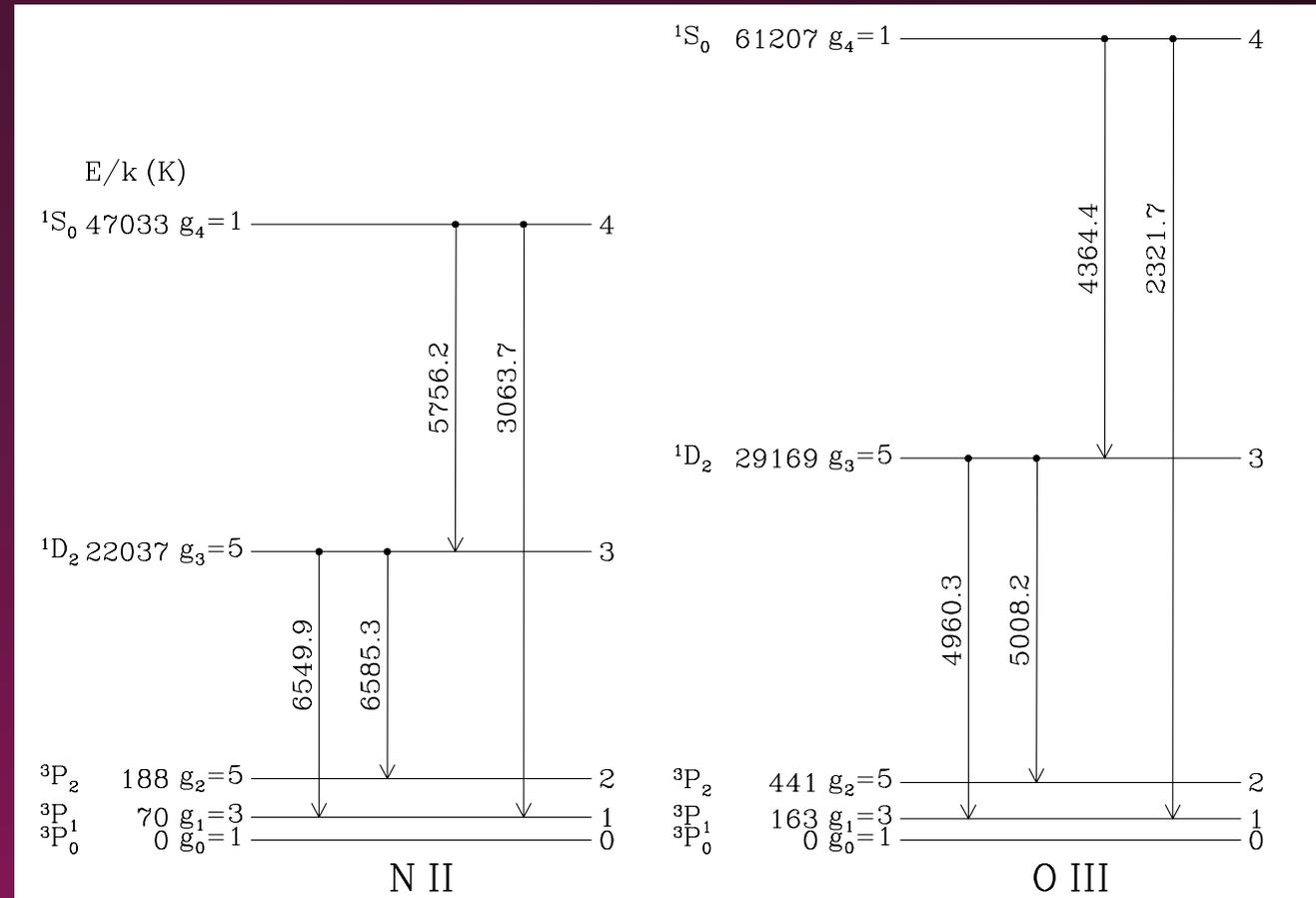
# Ions with $np^2$ and $np^4$ have terms $^3P$ (ground state) and $^1D$ and $^1S$

- We can get these configurations for species with 6 or 14 electrons ( $np^2$ ) or 8 or 16 electrons ( $np^4$ )
- Primary ions of interest in H II regions:
  - N II, O III, P II, and S III ( $np^2$ )
  - O I, F II, Ne III, Cl II, Ar III, and K IV ( $np^4$ )
- Transitions among terms (levels) can be described categorically (e.g.,  $^1D \rightarrow ^3P$ )
- Line ratios of  $^1D \rightarrow ^3P$  and  $^1S \rightarrow ^3P$  transitions related to temperature-dependent level populations



# ‘Low-density limit’ ( $n \ll n_{\text{crit}}$ )

- Recall,  $n_{\text{crit}}$  is defined *for each transition*
- Each excitation will be followed by an immediate radiative decay to ground state
- $j(u \rightarrow l) \propto P(u \rightarrow l)$
- Consider excited states of  $2p^2$  ion
  - Labeled 0, 1, 2, 3, 4 in energy diagram
- Possible transitions from  $^1S_0$  (3):
  - $4 \rightarrow 3$
  - ~~$4 \rightarrow 2$~~
  - $4 \rightarrow 1$
- $\Delta J = 2$  disfavored transition
  - Even ‘forbidden’ transitions subject to quantum mechanical transition probabilities!



# ‘Low-density limit’ ( $n \ll n_{\text{crit}}$ )

- Consider only transitions from state 4 to 3 and 2
  - $^1S_0 \rightarrow ^3P_2$  and  $^1S_0 \rightarrow ^3P_1$

$$P(4 \rightarrow 3) = E_{43} [n_0 C_{04}] \frac{A_{43}}{A_{43} + A_{41}}, \quad (18.1)$$

$$P(3 \rightarrow 2) = E_{32} \left[ n_0 C_{03} + n_0 C_{04} \frac{A_{43}}{A_{43} + A_{41}} \right] \frac{A_{32}}{A_{32} + A_{31}}, \quad (18.2)$$

$$C_{lu} = 8.629 \times 10^{-8} T_4^{-1/2} \frac{\Omega_{lu}}{g_l} e^{-E_{ul}/kT} n_e \text{ cm}^3 \text{ s}^{-1}. \quad (18.3)$$

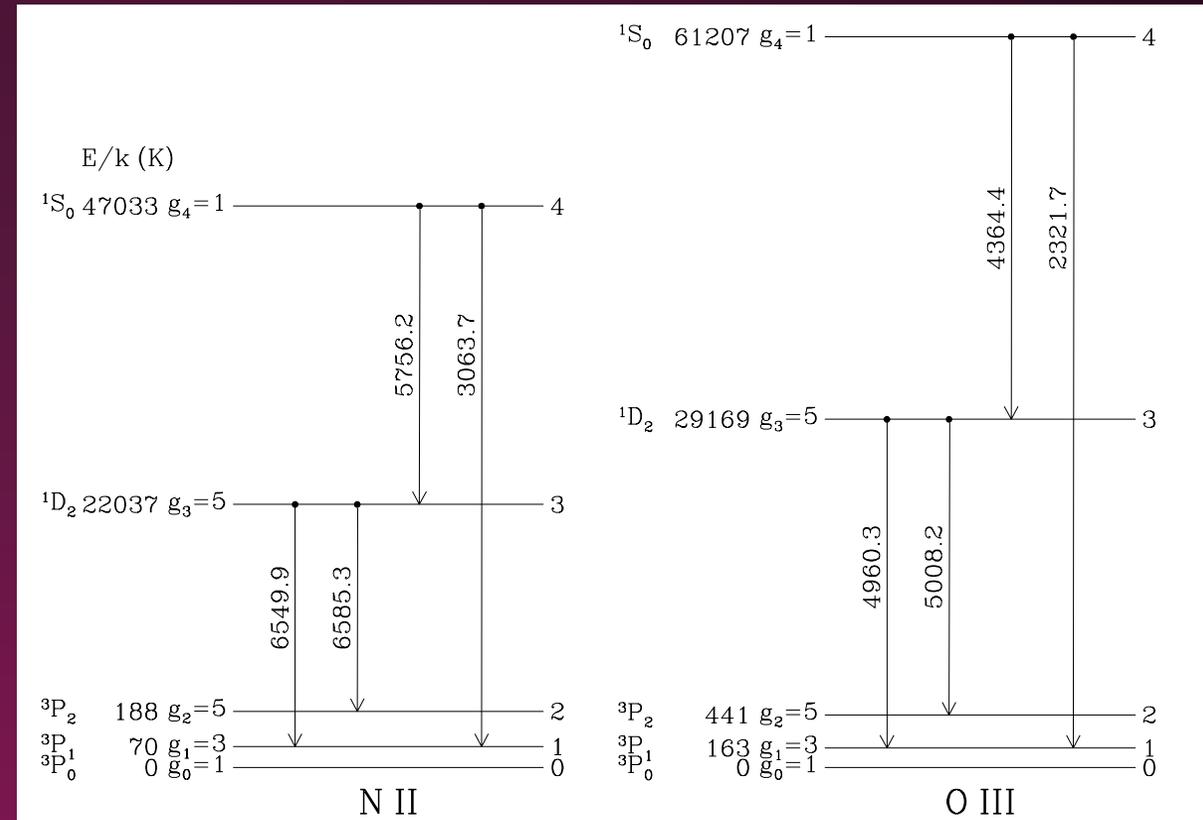
‘Collision strength’  $\Omega_{ul}$  tabulated for each transition

- Take  $n_e \rightarrow 0$ :

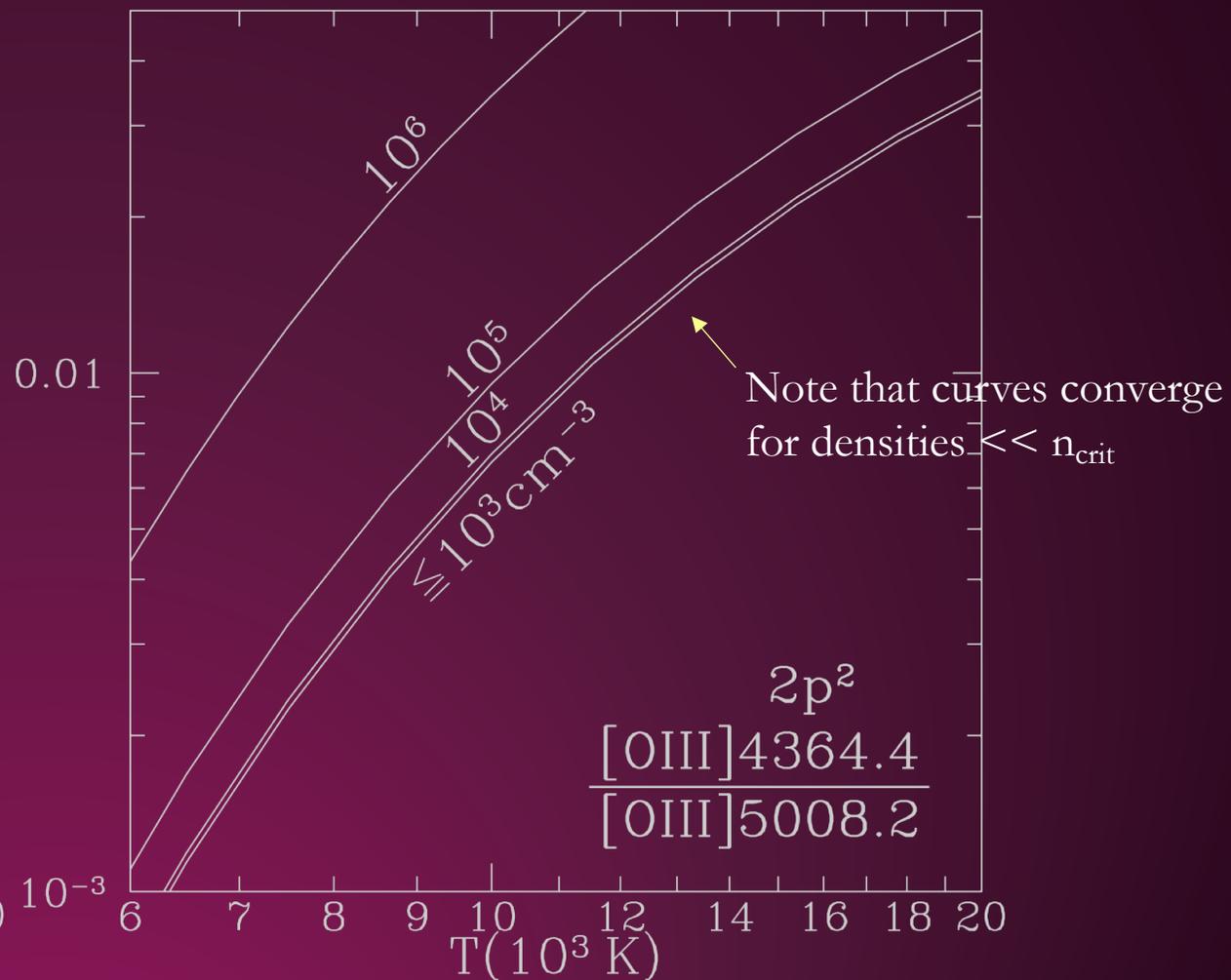
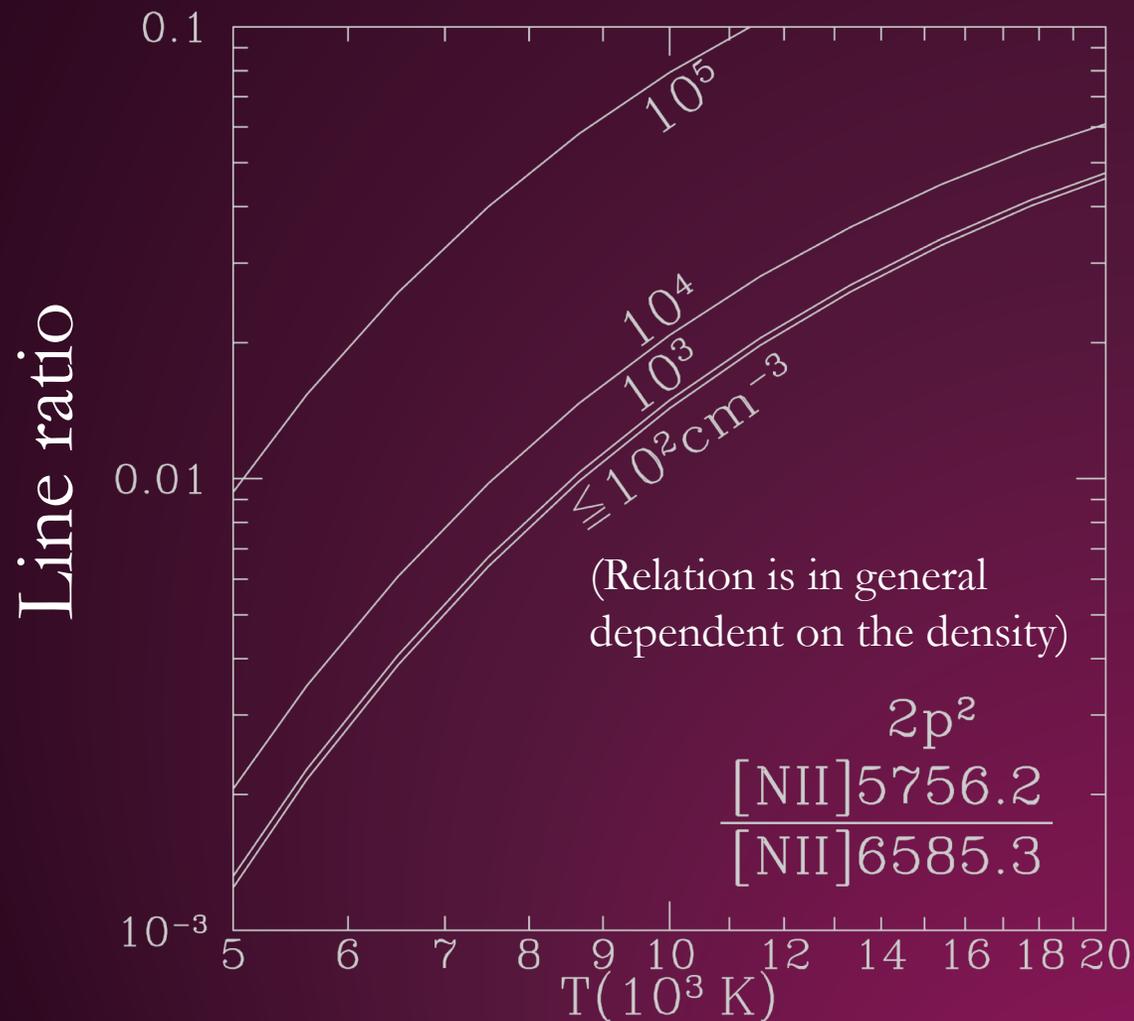
$$\frac{j(4 \rightarrow 3)}{j(3 \rightarrow 2)} = \frac{A_{43} E_{43}}{A_{32} E_{32}} \frac{(A_{32} + A_{31}) \Omega_{04} e^{-E_{43}/kT}}{[(A_{43} + A_{41}) \Omega_{03} + A_{43} \Omega_{04} e^{-E_{43}/kT}]}. \quad (18.4)$$

The variables here are just good ol’ fashion atomic physics!

- Emissivity ratio just reduces to flux ratio in practice
  - This we measure!



# Line ratios and derived temperatures



# ‘Low-density limit’ ( $n \ll n_{\text{crit}}$ )

- Consider only transitions from state 4 to 3 and 2
  - $^1S_0 \rightarrow ^3P_2$  and  $^1S_0 \rightarrow ^3P_1$

$$P(4 \rightarrow 3) = E_{43} [n_0 C_{04}] \frac{A_{43}}{A_{43} + A_{41}}, \quad (18.1)$$

$$P(3 \rightarrow 2) = E_{32} \left[ n_0 C_{03} + n_0 C_{04} \frac{A_{43}}{A_{43} + A_{41}} \right] \frac{A_{32}}{A_{32} + A_{31}}, \quad (18.2)$$

$$C_{lu} = 8.629 \times 10^{-8} T_4^{-1/2} \frac{\Omega_{lu}}{g_l} e^{-E_{ul}/kT} n_e \text{ cm}^3 \text{ s}^{-1}. \quad (18.3)$$

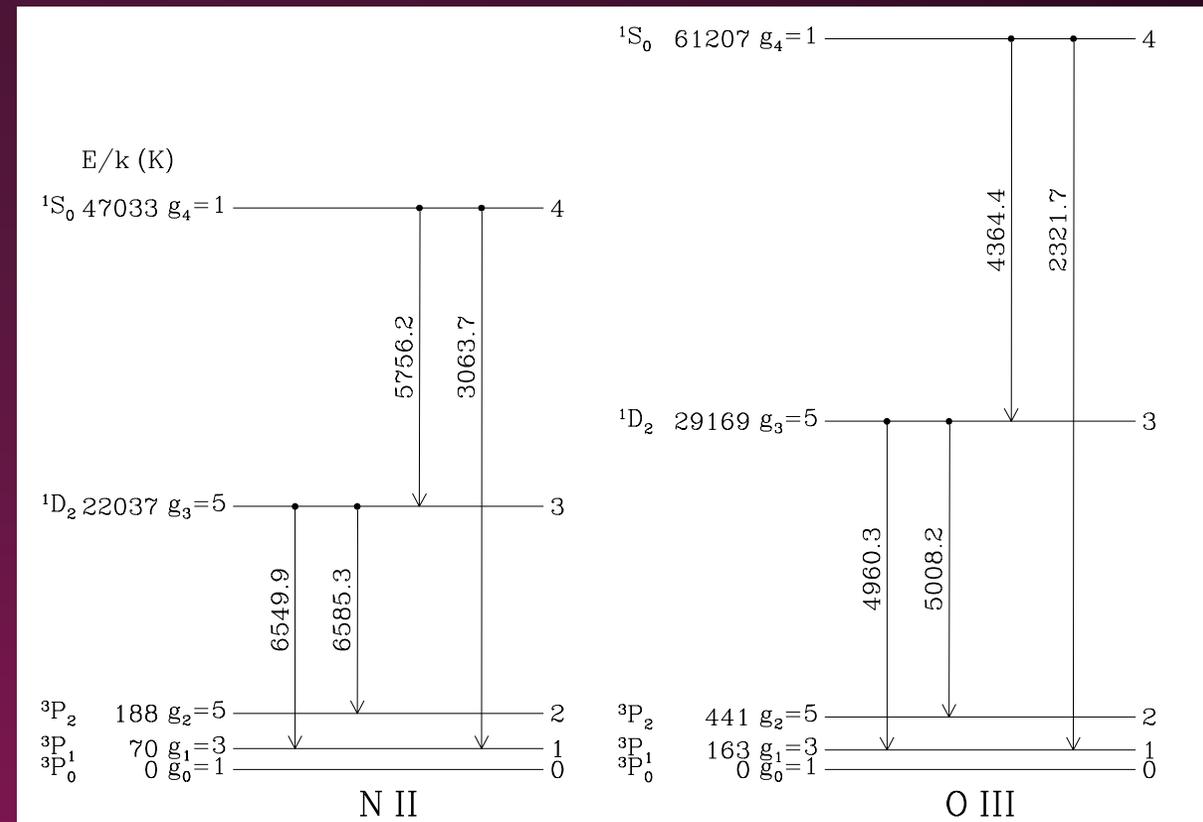
‘Collision strength’  $\Omega_{ul}$  tabulated for each transition

- Take  $n_e \rightarrow 0$ :

$$\frac{j(4 \rightarrow 3)}{j(3 \rightarrow 2)} = \frac{A_{43} E_{43}}{A_{32} E_{32}} \frac{(A_{32} + A_{31}) \Omega_{04} e^{-E_{43}/kT}}{[(A_{43} + A_{41}) \Omega_{03} + A_{43} \Omega_{04} e^{-E_{43}/kT}]}. \quad (18.4)$$

The variables here are just good ol’ fashion atomic physics!

- Emissivity ratio just reduces to flux ratio in practice
  - This we measure!

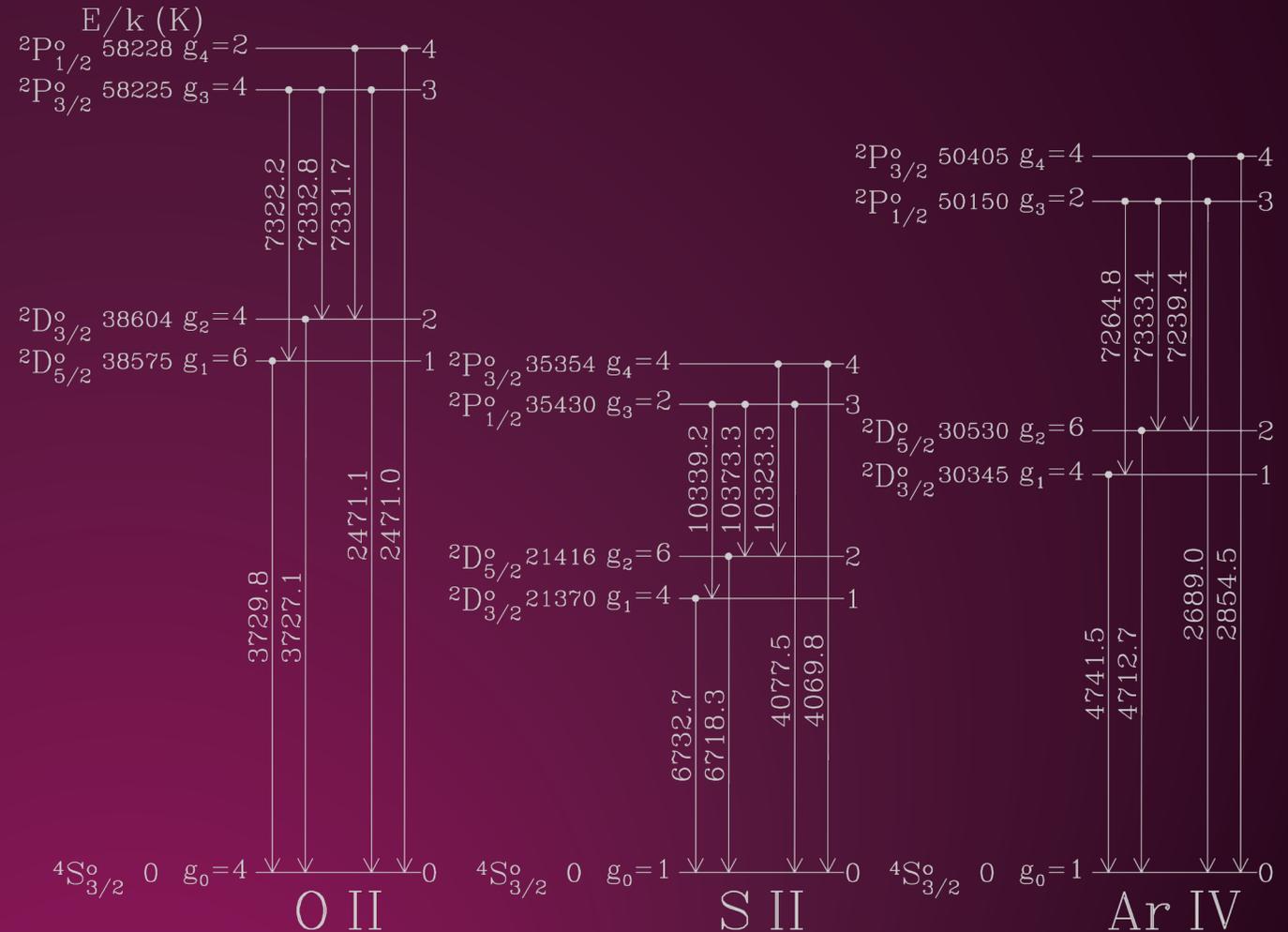


# Temperatures with $np^3$ ions

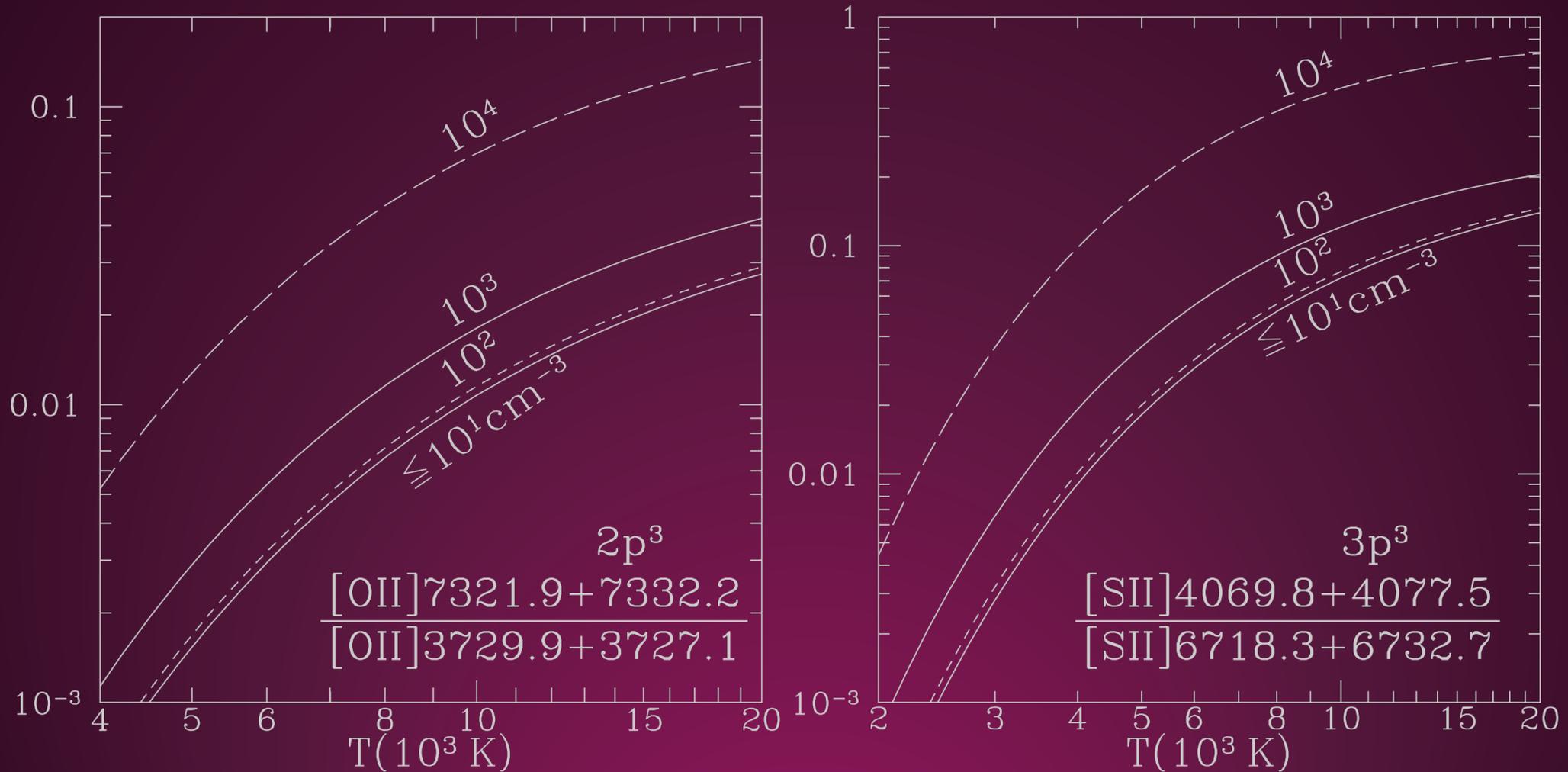
- Key ions
  - 7 electrons ( $2p^3$ ): O II, F III, Ne IV
  - 15 electrons ( $3p^3$ ): S II, Cl III, Ar IV
- However,  $n_{\text{crit}}$  lower than  $np^2$  and  $np^4$  ions
  - Need to know density through some other means if not  $n > 10^2 \text{ cm}^{-3}$

**Table 18.2** Critical Electron Density  $n_{\text{crit}}(e^-)$  ( $\text{cm}^{-3}$ ) for Selected  $np^3$  Ions, for  $T = 10^4 \text{ K}$

Configuration	Ion	$n_{\text{crit}}(e^-)$ at $T = 10^4 \text{ K}$			
		$^2D_{3/2}^o$	$^2D_{5/2}^o$	$^2P_{1/2}^o$	$^2P_{3/2}^o$
$1s^2 2s^2 2p^3$	NI	$2.18 \times 10^4$	$1.19 \times 10^4$	$7.11 \times 10^7$	$3.15 \times 10^7$
	OII	$4.49 \times 10^3$	$3.31 \times 10^3$	$5.30 \times 10^6$	$1.03 \times 10^7$
	Ne IV	$1.40 \times 10^6$	$4.66 \times 10^5$	$4.17 \times 10^8$	$2.79 \times 10^8$
$1s^2 2s^2 2p^6 3s^2 3p^3$	SII	$1.49 \times 10^4$	$1.57 \times 10^3$	$1.49 \times 10^6$	$1.91 \times 10^6$
	Ar IV	$1.35 \times 10^6$	$1.55 \times 10^4$	$1.06 \times 10^7$	$1.81 \times 10^7$



# Temperatures with $np^3$ ions



# Densities of H II regions

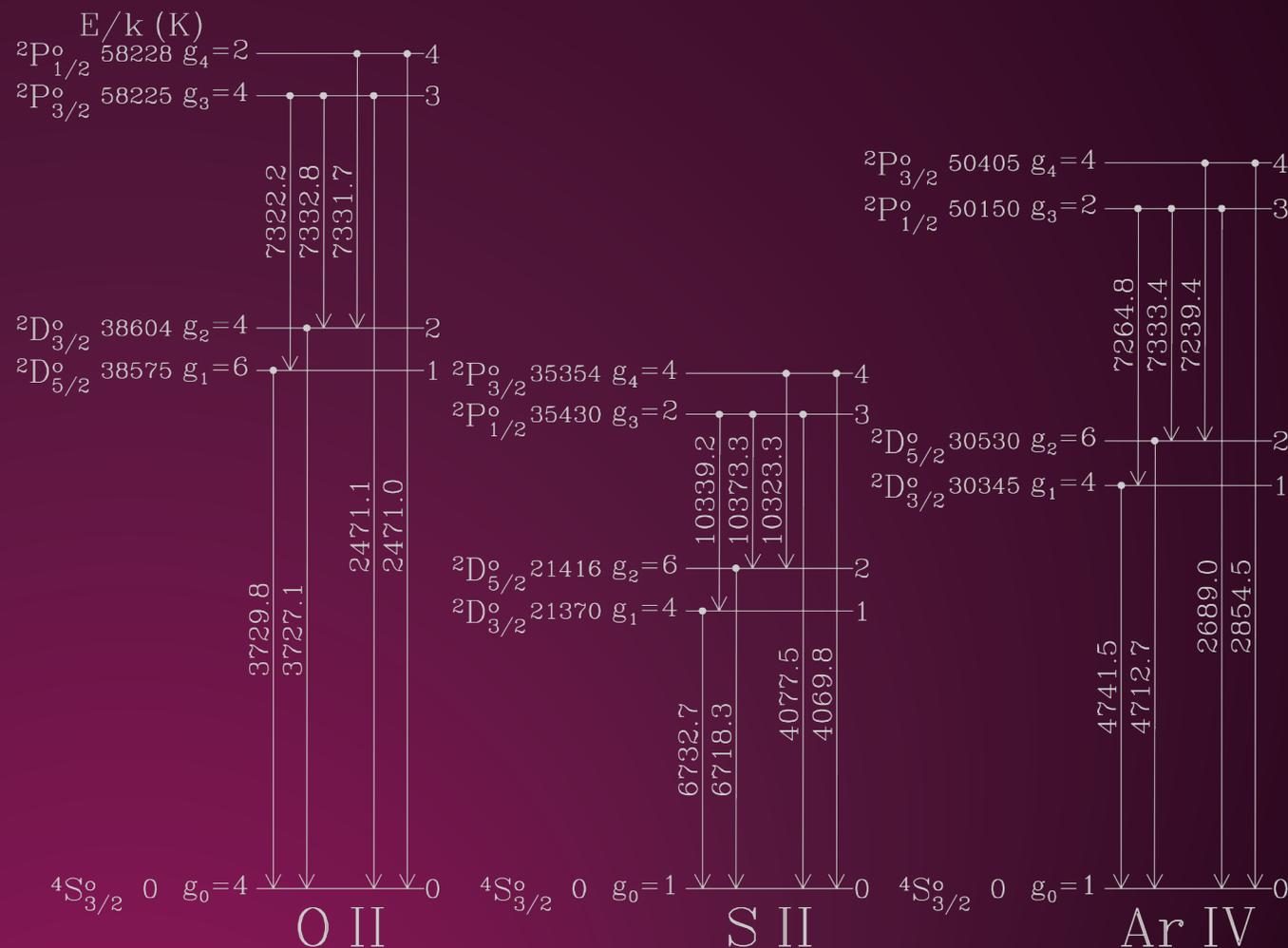
- $np^3$  useful here because of multiplicity in  $^2D$  terms
  - First and second excited states
  - $^2D_{3/2}$  and  $^2D_{1/2}$  terms
- Leverage fact that  $E_{21} \ll kT$  and  $E_{21} \ll E_{10}$

Low-density limit

$$\frac{j(2 \rightarrow 0)}{j(1 \rightarrow 0)} = \frac{\Omega_{20}}{\Omega_{10}} \frac{E_{20}}{E_{10}} e^{-E_{21}/kT} \approx \frac{\Omega_{20}}{\Omega_{10}}$$

High-density limit

$$\frac{j(2 \rightarrow 0)}{j(1 \rightarrow 0)} = \frac{g_2}{g_1} e^{-E_{21}/kT} \frac{E_{20} A_{20}}{E_{10} A_{10}} \approx \frac{g_2 A_{20}}{g_1 A_{10}}$$



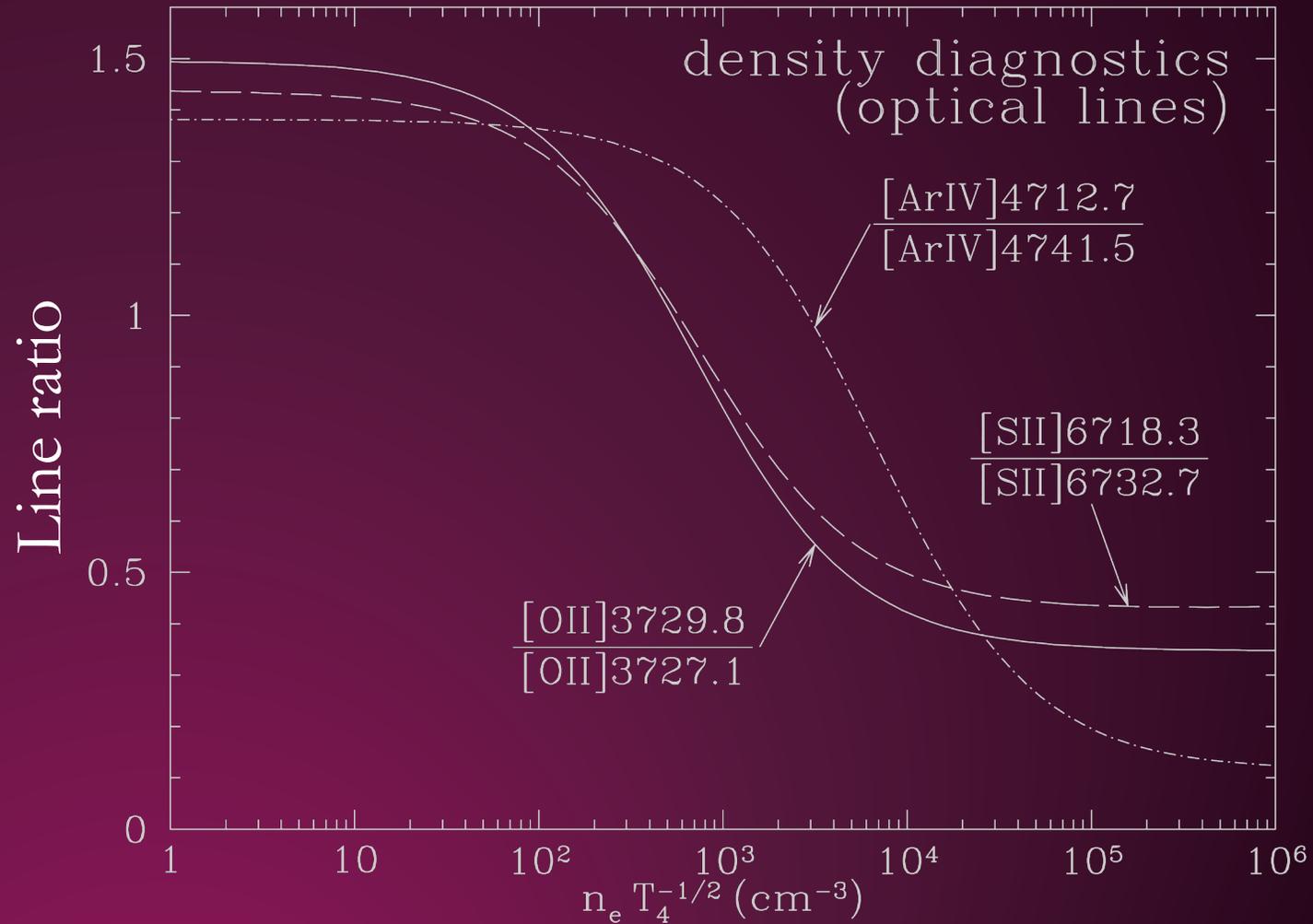
# Line ratios and density

Low-density limit

$$\frac{j(2 \rightarrow 0)}{j(1 \rightarrow 0)} = \frac{\Omega_{20}}{\Omega_{10}} \frac{E_{20}}{E_{10}} e^{-E_{21}/kT} \approx \frac{\Omega_{20}}{\Omega_{10}}$$

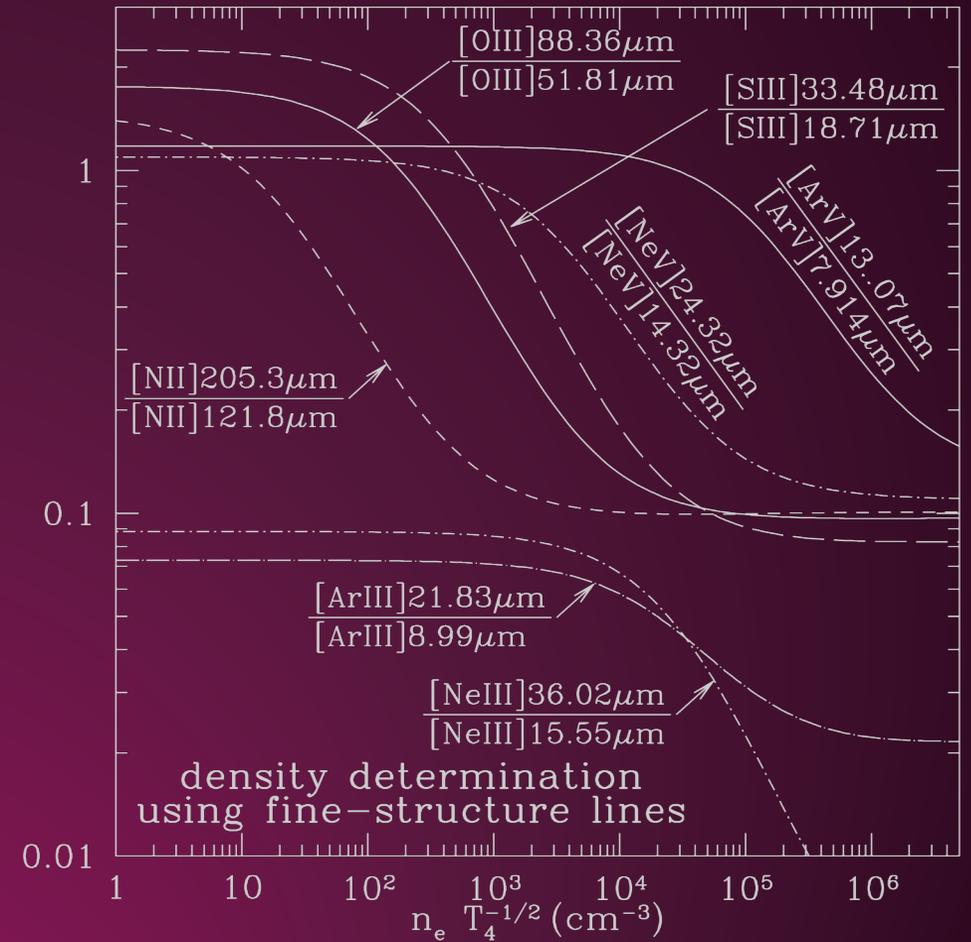
High-density limit

$$\frac{j(2 \rightarrow 0)}{j(1 \rightarrow 0)} = \frac{g_2}{g_1} e^{-E_{21}/kT} \frac{E_{20} A_{20}}{E_{10} A_{10}} \approx \frac{g_2 A_{20}}{g_1 A_{10}}$$



# Things to note – density diagnostics

- Other temperature diagnostics
  - Fine-structure lines in far-IR (Draine 18.3)
  - ‘Balmer jump’  $\sim 3645 \text{ \AA}$  (Draine 18.4.1)
  - Dielectronic recombination (Draine 18.4.2)
- Other density diagnostics
  - Fine-structure lines in far-IR (Draine 18.3)
  - ‘Balmer decrement’ (18.4.3)
    - Line ratios:  $H\alpha/H\beta$ ,  $H\beta/H\gamma$ , etc.
- **IMPORTANT:** All of these are subject to extinction from dust!



# H II region abundances

- Ratios of ‘metal’ lines to hydrogen lines can be used to determine abundances of species relative to hydrogen
  - Note: temperature-dependent!

Abundance of O<sup>2+</sup> relative H (low-density limit):

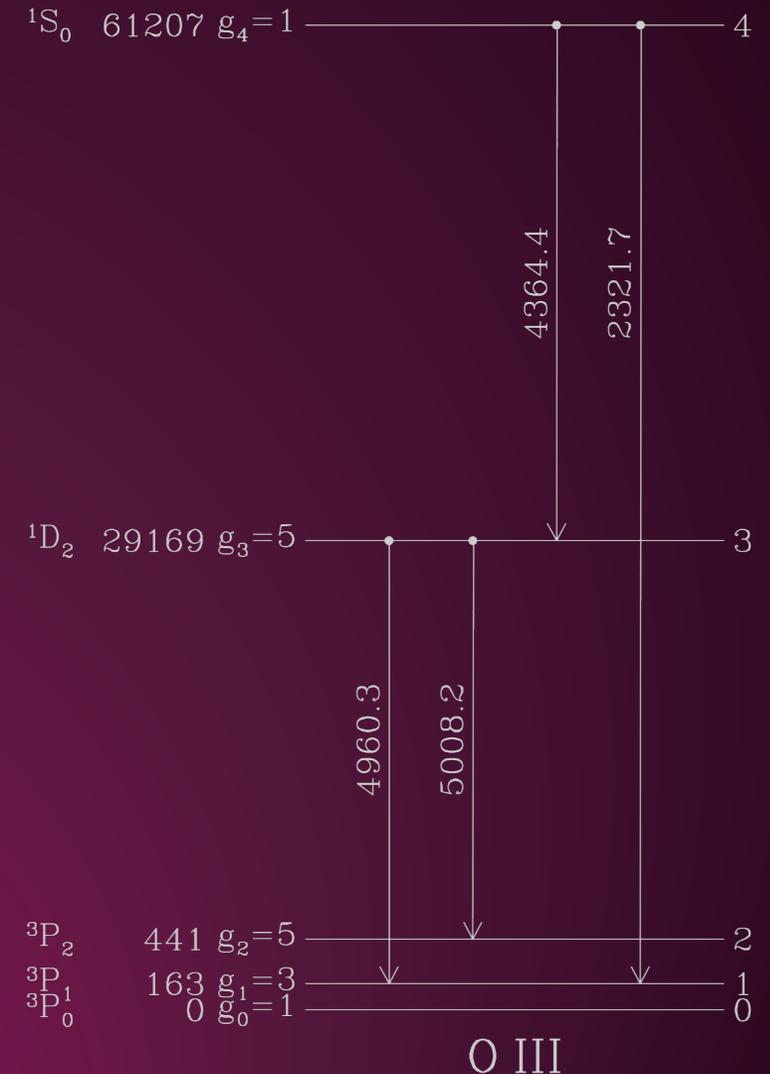
$$\frac{I([\text{O III}]5008)}{I(\text{H}\beta)} = \frac{n_e n(\text{O III}) k_{03} E_{32} A_{32} / (A_{31} + A_{32})}{n_e n(\text{H}^+) \alpha_{\text{eff}, \text{H}\beta} E_{\text{H}\beta}}$$

Collisional rate coefficient

$$k_{03} = 8.629 \times 10^{-8} T_4^{-1/2} \frac{\Omega_{03}}{g_0} e^{-E_{30}/kT} \text{ cm}^3 \text{ s}^{-1}$$

Employ  $\alpha \propto T_4^{-0.87}$  for  $T_4 \sim 1$  and assume  $\Omega_{03}$  indep. of T

$$\frac{n(\text{O III})}{n(\text{H}^+)} = C \frac{I([\text{O III}]5008)}{I(\text{H}\beta)} T_4^{-0.37} e^{2.917/T_4}$$



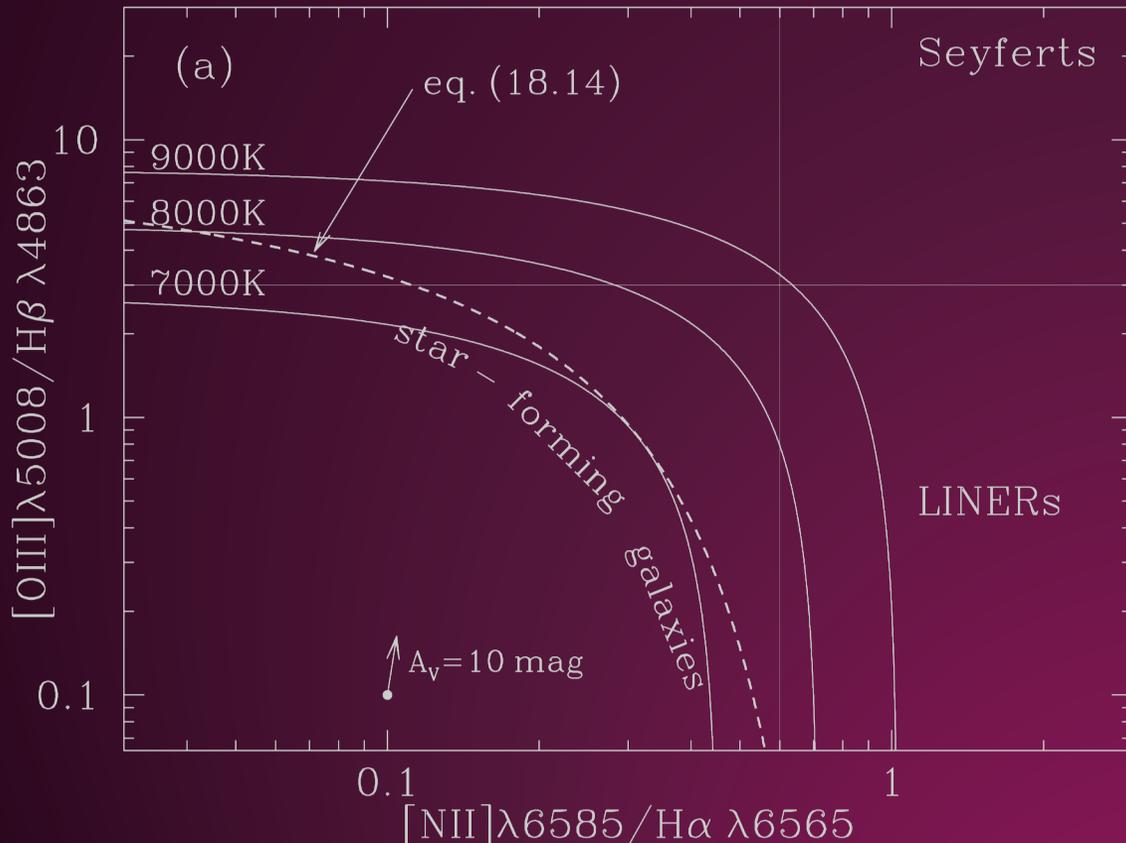
# Ionization and Excitation in H II regions

- Physics we have gone through above tell us how line ratios *should* behave in H II regions
  - Assumed typical radiation fields from O and B stars
  - Assumed temperatures  $\sim 10^4$  K
- Emission lines can also arrive from transitions excited by harder and higher intensity radiation from active galactic nuclei (AGN)
  - Not only UV photons but X-rays as well
- AGN spectra exhibit different features
  - Seyfert - strong emission from highly ionized species (e.g., C IV)
  - LINER – ‘low ionization nuclear emission region’



# Ionization and Excitation in H II regions

- Can use ratios of lines with similar kT to ‘diagnose’ contributions from AGN in ionization and excitation



‘BPT’ diagram  
(after Baldwin, Phillips, & Terlevich)

Theoretical tracks for H II region  
(vary  $\xi$  from 0 to 1):

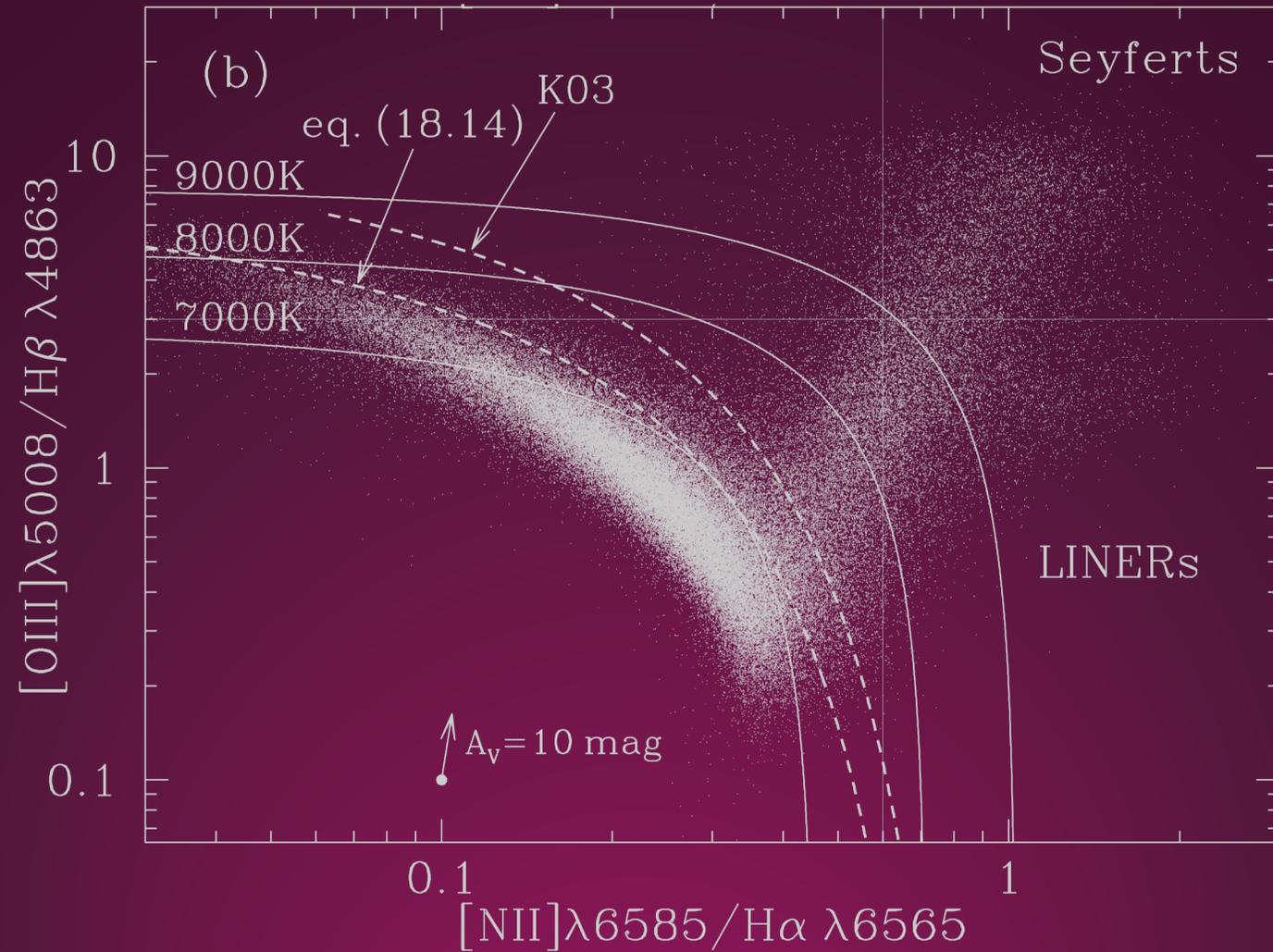
$$\frac{[\text{O III}]\lambda 5008}{\text{H}\beta} \approx 214 \xi T_4^{0.494+0.089 \ln T_4} e^{-2.917/T_4} \left( \frac{n_{\text{O}}/n_{\text{H}}}{0.8 \times 5.37 \times 10^{-4}} \right)$$

$$\frac{[\text{N II}]\lambda 6585}{\text{H}\alpha} \approx 12.4(1 - \xi) T_4^{0.495+0.040 \ln T_4} e^{-2.204/T_4} \left( \frac{n_{\text{N}}/n_{\text{H}}}{7.41 \times 10^{-5}} \right)$$

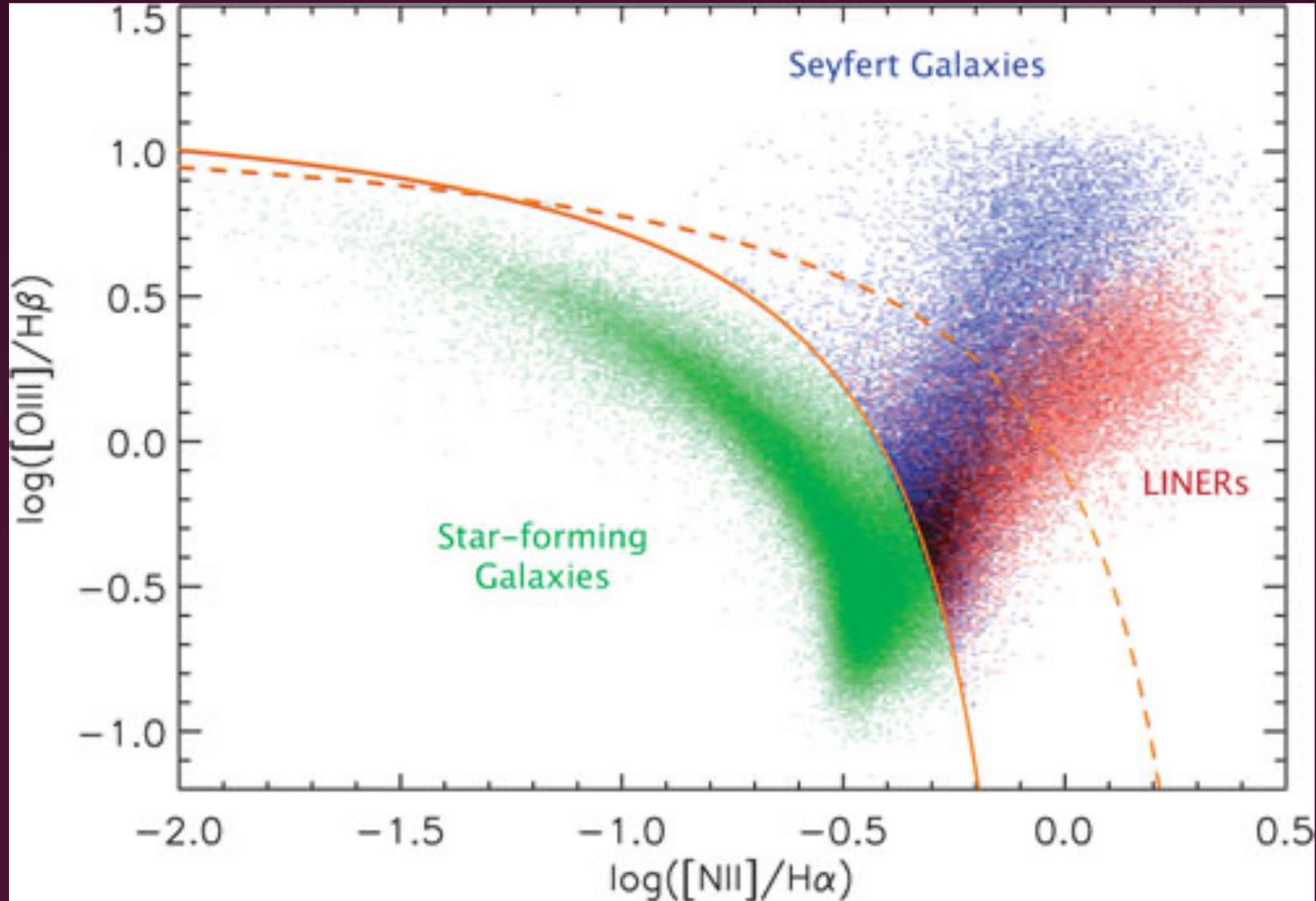
Equation 18.14:

$$\log_{10} ([\text{O III}]\lambda 5008 / \text{H}\beta) < 1.10 - \frac{0.60}{0.01 - \log_{10} ([\text{N II}]\lambda 6585 / \text{H}\beta)}$$

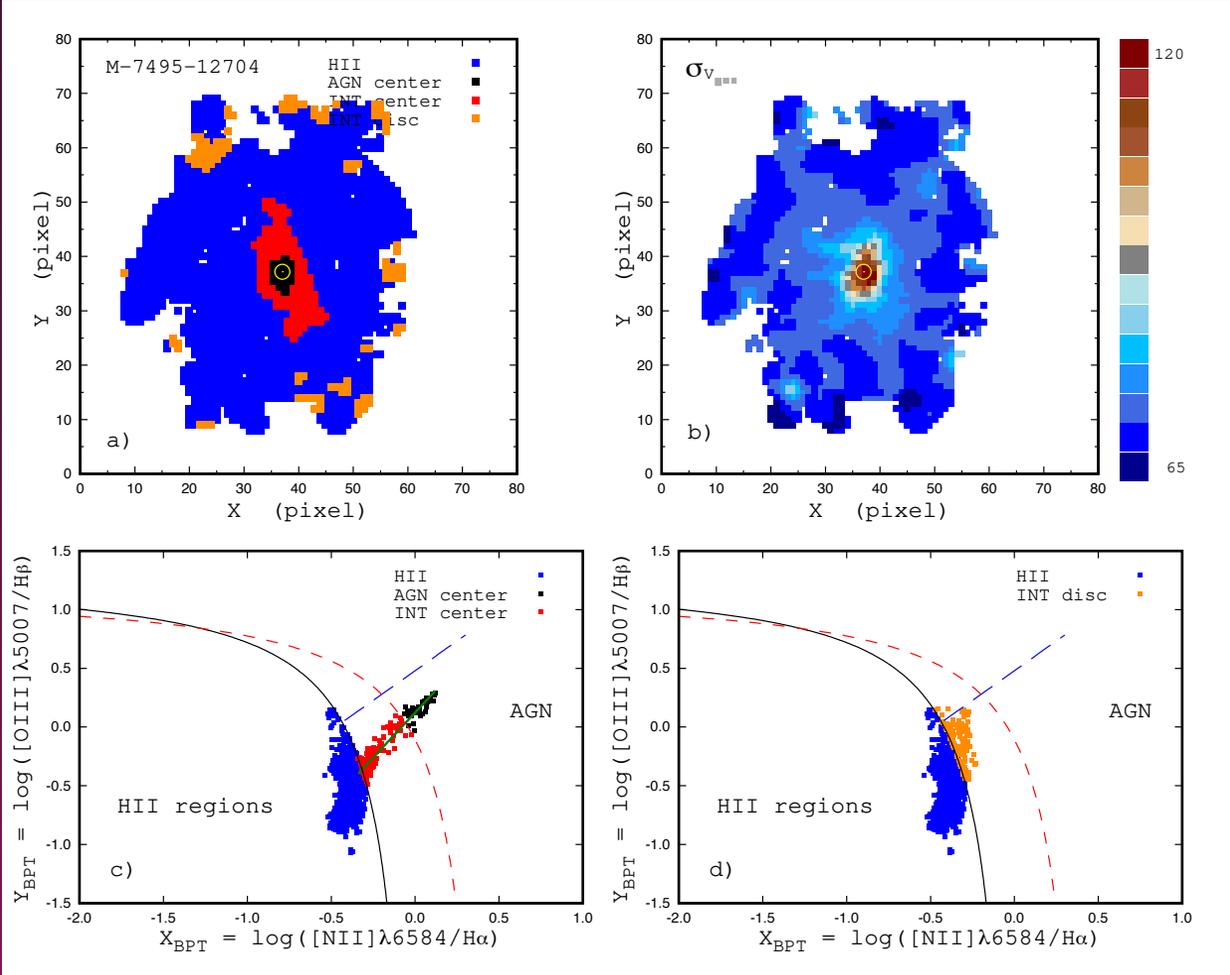
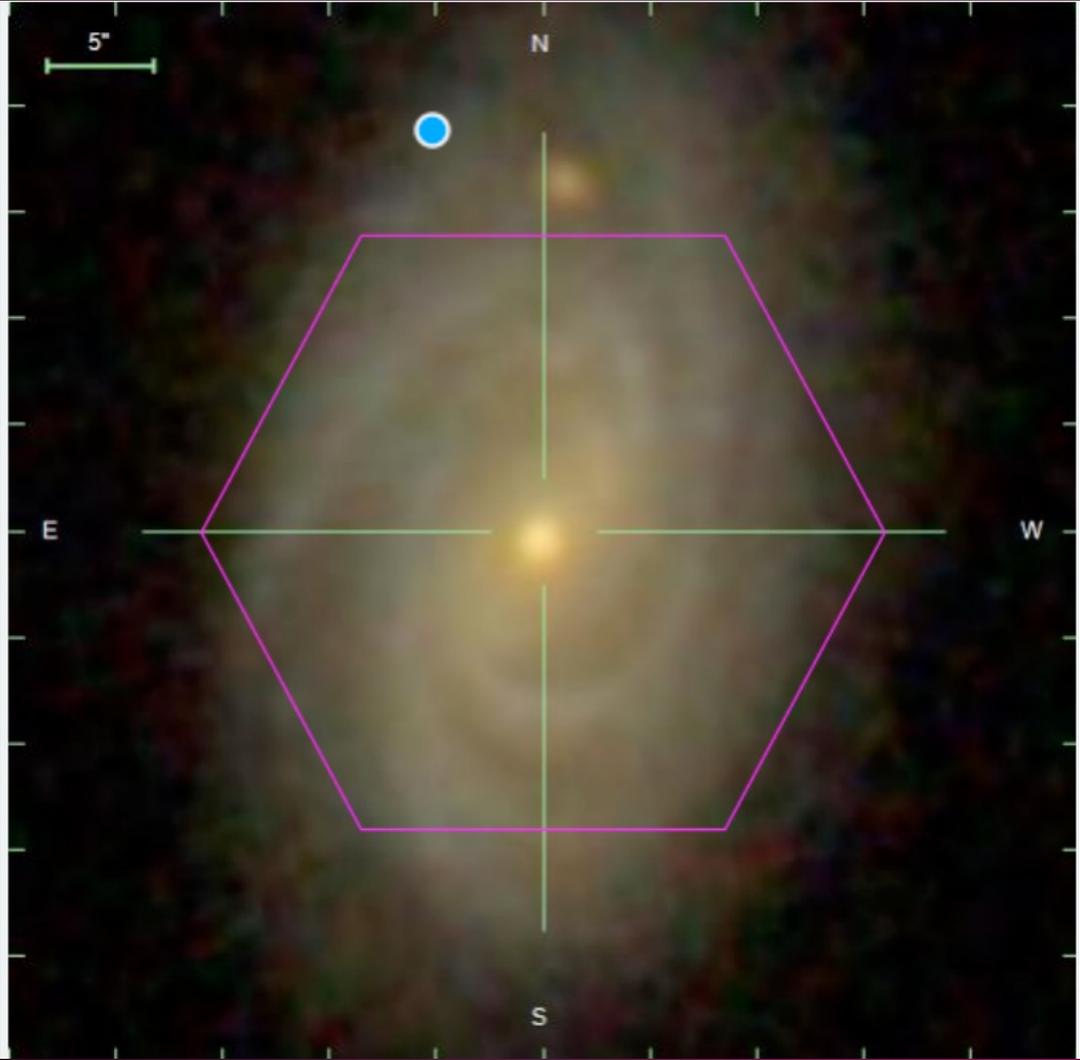
# Empirical data (galaxies from SDSS DR8)



# Empirical data (galaxies from SDSS DR8)



# BPT within single galaxy (from MaNGA)



# Exercise: Fun with Marvin!

- <http://www.sdss.org/dr15/manga/marvin>
- Galaxy: 7960-6102
- Let's calculate temperatures of H II regions
- Then, approximate the abundance of O III
- Then, identify AGN-like regions if any

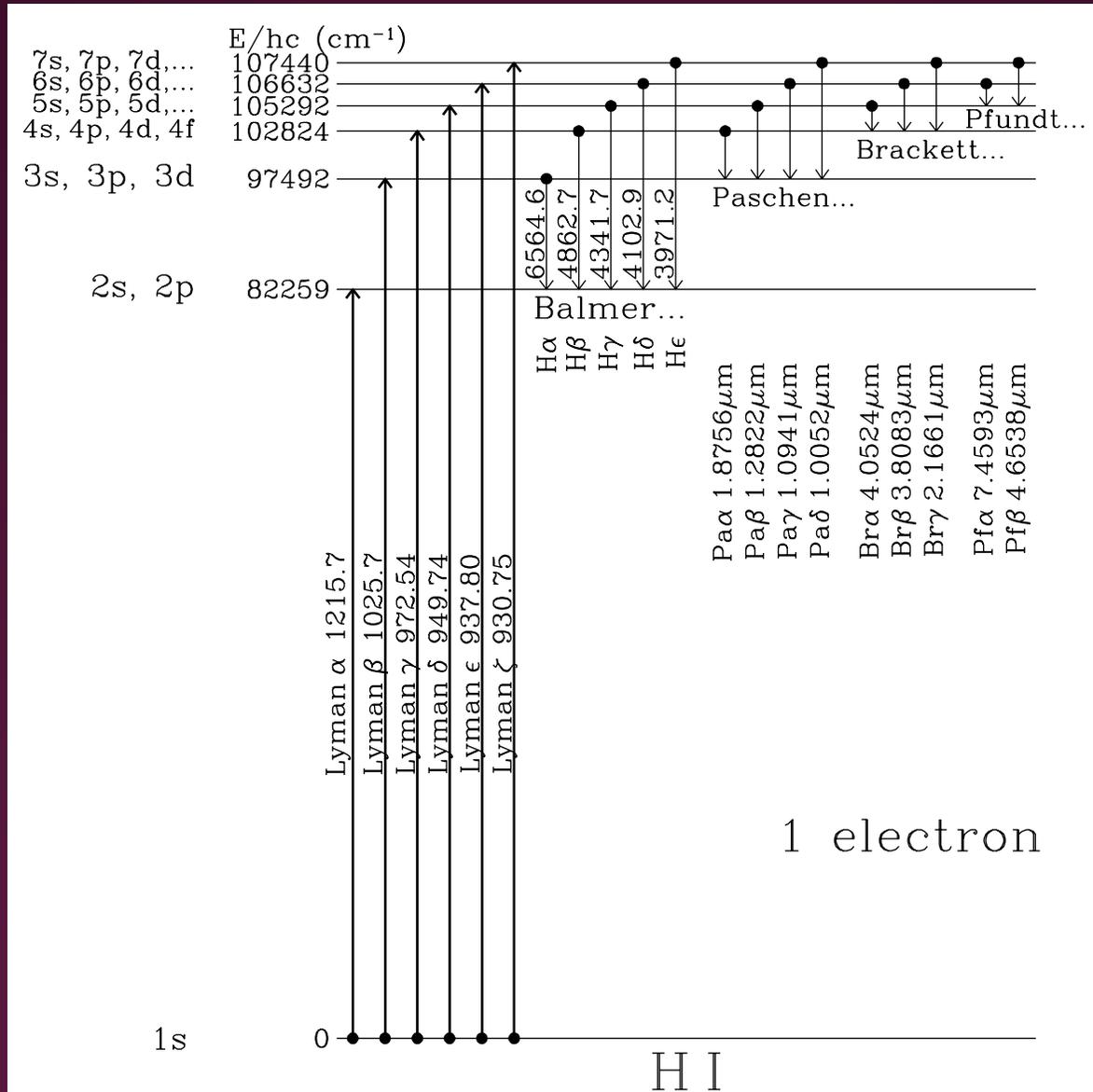
# Periodic table of the elements

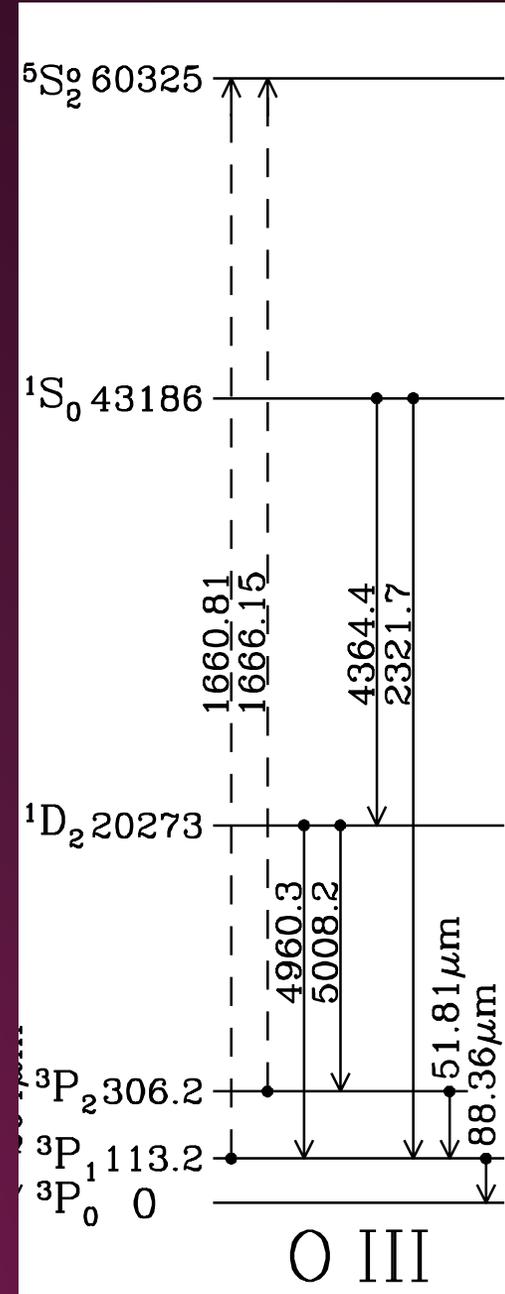
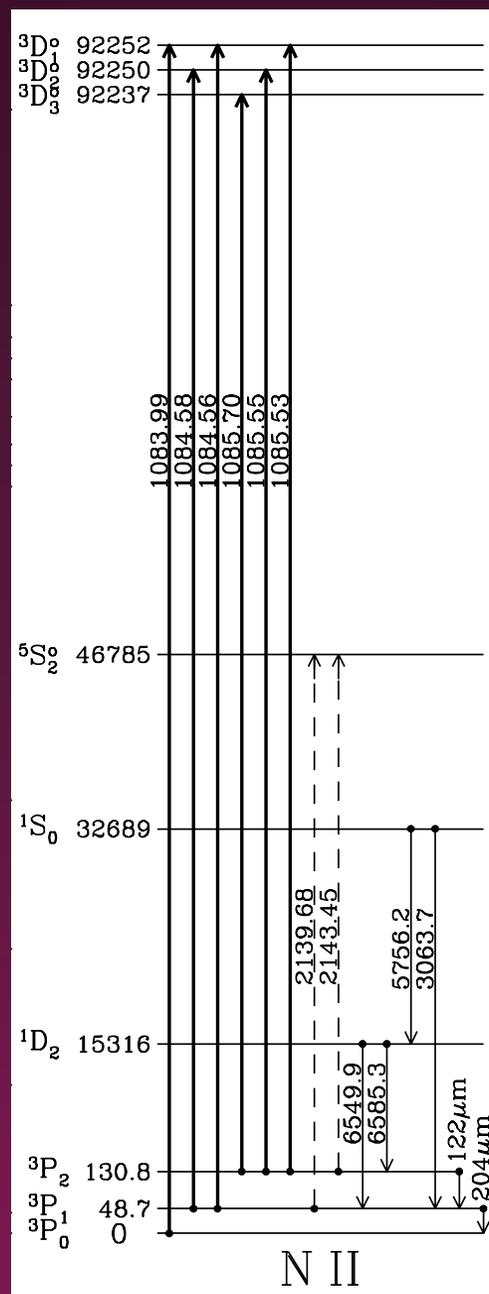
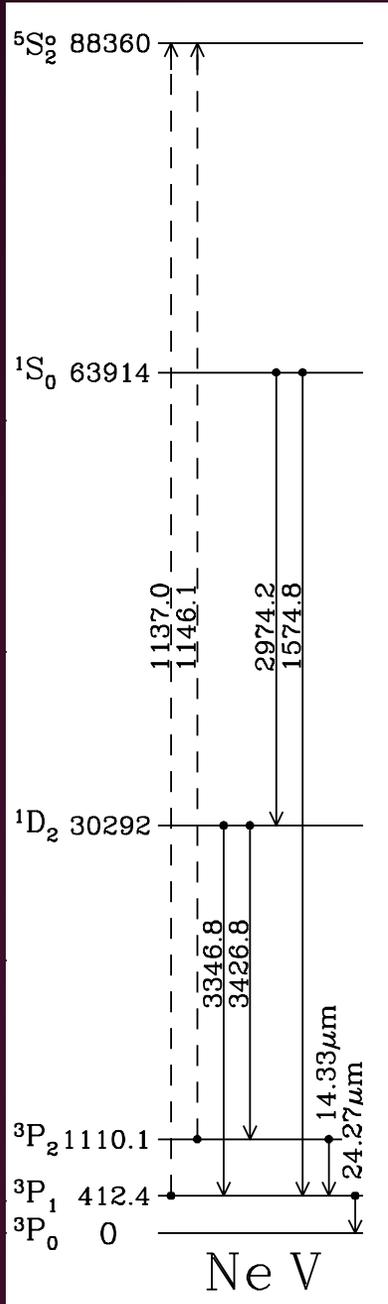
group																	18	
1*													13	14	15	16	17	18
1	<b>H</b>	2											5	6	7	8	9	10
2	<b>Li</b>	<b>Be</b>											<b>B</b>	<b>C</b>	<b>N</b>	<b>O</b>	<b>F</b>	<b>Ne</b>
3	<b>Na</b>	<b>Mg</b>	3	4	5	6	7	8	9	10	11	12	<b>Al</b>	<b>Si</b>	<b>P</b>	<b>S</b>	<b>Cl</b>	<b>Ar</b>
4	<b>K</b>	<b>Ca</b>	<b>Sc</b>	<b>Ti</b>	<b>V</b>	<b>Cr</b>	<b>Mn</b>	<b>Fe</b>	<b>Co</b>	<b>Ni</b>	<b>Cu</b>	<b>Zn</b>	<b>Ga</b>	<b>Ge</b>	<b>As</b>	<b>Se</b>	<b>Br</b>	<b>Kr</b>
5	<b>Rb</b>	<b>Sr</b>	<b>Y</b>	<b>Zr</b>	<b>Nb</b>	<b>Mo</b>	<b>Tc</b>	<b>Ru</b>	<b>Rh</b>	<b>Pd</b>	<b>Ag</b>	<b>Cd</b>	<b>In</b>	<b>Sn</b>	<b>Sb</b>	<b>Te</b>	<b>I</b>	<b>Xe</b>
6	<b>Cs</b>	<b>Ba</b>	<b>La</b>	<b>Hf</b>	<b>Ta</b>	<b>W</b>	<b>Re</b>	<b>Os</b>	<b>Ir</b>	<b>Pt</b>	<b>Au</b>	<b>Hg</b>	<b>Tl</b>	<b>Pb</b>	<b>Bi</b>	<b>Po</b>	<b>At</b>	<b>Rn</b>
7	<b>Fr</b>	<b>Ra</b>	<b>Ac</b>	<b>Rf</b>	<b>Db</b>	<b>Sg</b>	<b>Bh</b>	<b>Hs</b>	<b>Mt</b>	<b>Ds</b>	<b>Rg</b>	<b>Cn</b>	<b>Nh</b>	<b>Fl</b>	<b>Mc</b>	<b>Lv</b>	<b>Ts</b>	<b>Og</b>

lanthanoid series 6	<b>58</b>	<b>59</b>	<b>60</b>	<b>61</b>	<b>62</b>	<b>63</b>	<b>64</b>	<b>65</b>	<b>66</b>	<b>67</b>	<b>68</b>	<b>69</b>	<b>70</b>	<b>71</b>
	<b>Ce</b>	<b>Pr</b>	<b>Nd</b>	<b>Pm</b>	<b>Sm</b>	<b>Eu</b>	<b>Gd</b>	<b>Tb</b>	<b>Dy</b>	<b>Ho</b>	<b>Er</b>	<b>Tm</b>	<b>Yb</b>	<b>Lu</b>
actinoid series 7	<b>90</b>	<b>91</b>	<b>92</b>	<b>93</b>	<b>94</b>	<b>95</b>	<b>96</b>	<b>97</b>	<b>98</b>	<b>99</b>	<b>100</b>	<b>101</b>	<b>102</b>	<b>103</b>
	<b>Th</b>	<b>Pa</b>	<b>U</b>	<b>Np</b>	<b>Pu</b>	<b>Am</b>	<b>Cm</b>	<b>Bk</b>	<b>Cf</b>	<b>Es</b>	<b>Fm</b>	<b>Md</b>	<b>No</b>	<b>Lr</b>

\*Numbering system adopted by the International Union of Pure and Applied Chemistry (IUPAC). © Encyclopædia Britannica, Inc.

# Energy level diagram for hydrogen





# Nomenclature for lines

- “Allowed” transitions

- $A_{ul} \sim 10^8 \text{ s}^{-1}$



- “Semi-forbidden” transitions

- $A_{ul} \sim 10^2 \text{ s}^{-1}$



- “Forbidden transitions

- $A_{ul} \sim 20 \text{ min lifetime}$

