# Physics 224
# The Interstellar Medium

Lecture #9: HII Regions and DUST!!!!

# Outline

- Part I: Nebular Diagnostics
- Part II: Heating & Cooling in HII Regions
- Part III: Dust

# Part I: Nebular Diagnostics

# Nebular Diagnostics

Collisionally excited lines from ionized gas that give us diagnostics for density, temperature, etc.

Two types:

1) temperature sensitive
2) density sensitive

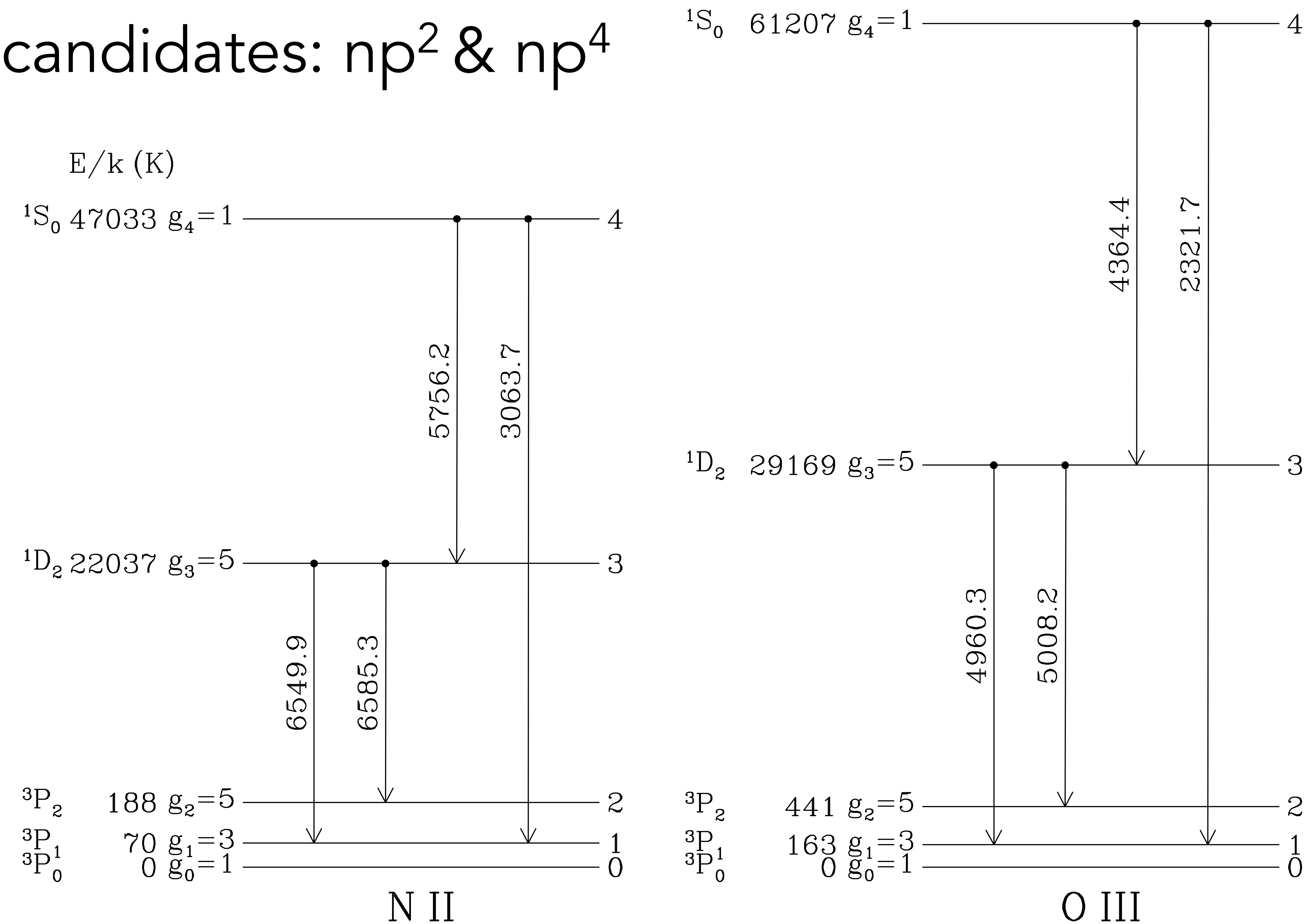
# Temperature Sensitive Line Ratios

What we want:
two levels that can both be collisionally excited at typical HII region temperatures (~$10^4$ K) but which have different enough energies that the ratio of populations depends on temperature of the gas

Requires two energy levels with $E/k < 70{,}000$ K

# Temperature Sensitive Line Ratios

best candidates: $np^2$ & $np^4$



# Temperature Sensitive Line Ratios

| Ground configuration | Terms (in order of increasing energy) | Examples |
|---|---|---|
| $...ns^1$ | $^2S_{1/2}$ | H I, He II, C IV, N V, O VI |
| $...ns^2$ | $^1S_0$ | He I, C III, N IV, O V |
| $...np^1$ | $^2P^o_{1/2,3/2}$ | C II, N III, O IV |
| $...np^2$ | $^3P_{0,1,2}$, $^1D_2$, $^1S_0$ | C I, N II, O III, Ne V, S III |
| $...np^3$ | $^4S^o_{3/2}$, $^2D^o_{3/2,5/2}$, $^2P^o_{1/2,3/2}$ | N I, O II, Ne IV, S II, Ar IV |
| $...np^4$ | $^3P_{2,1,0}$, $^1D_2$, $^1S_0$ | O I, Ne III, Mg V, Ar III |
| $...np^5$ | $^2P^o_{3/2,1/2}$ | Ne II, Na III, Mg IV, Ar IV |
| $...np^6$ | $^1S_0$ | Ne I, Na II, Mg III, Ar III |

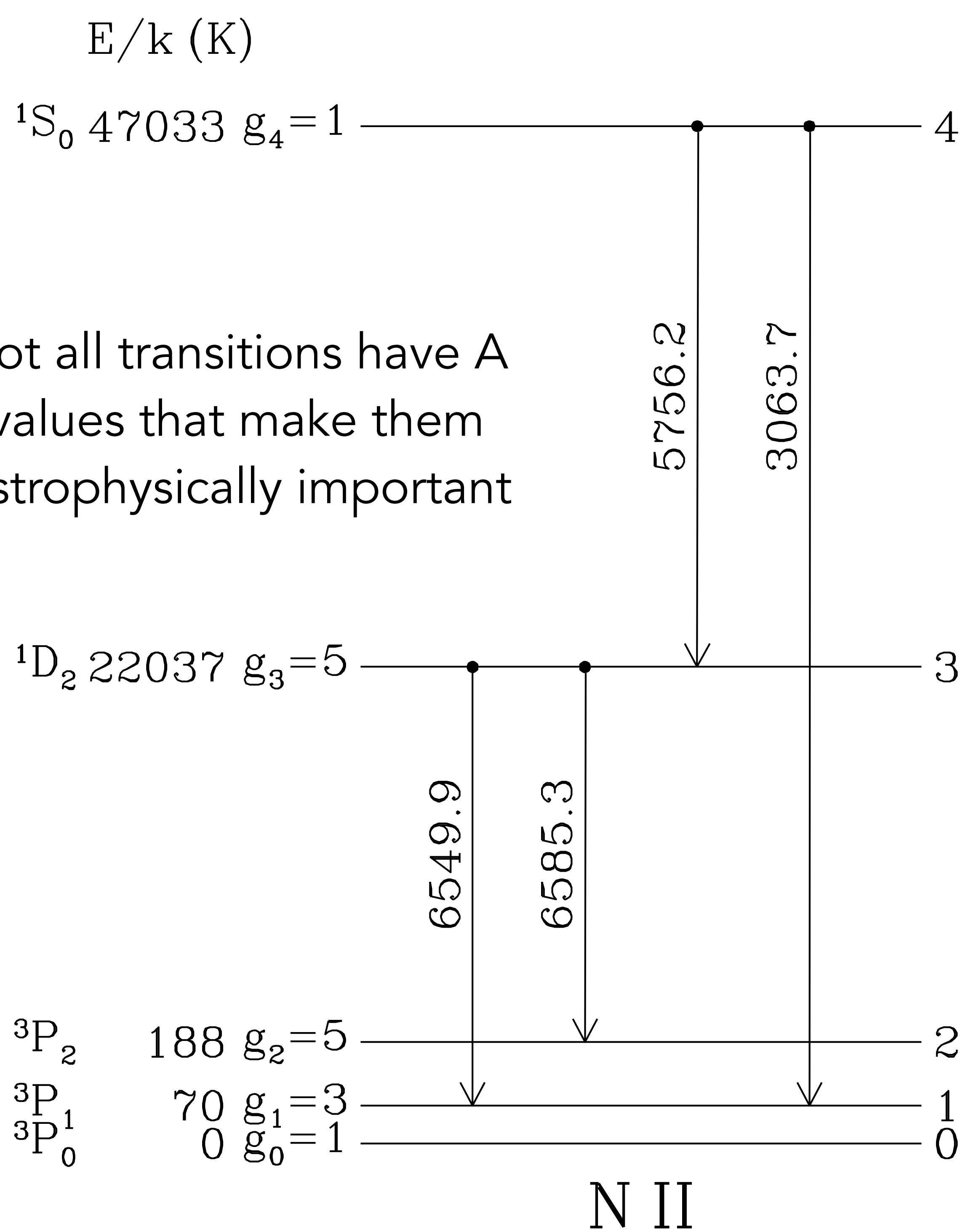
CI,OI don't exist in HII regions (carbon is ionized)

NeV, MgV is too highly ionized

NII, OIII and SIII are useful temperature diagnostics

(Ne III and Ar III useful as well, but req higher energy photons)

# Temperature Sensitive Line Ratios




**$n_{crit,4}$ ~ $10^7$ cm$^{-3}$**

**$n_{crit,3}$ ~ $7.7\times10^4$ cm$^{-3}$**

not all transitions have A values that make them astrophysically important

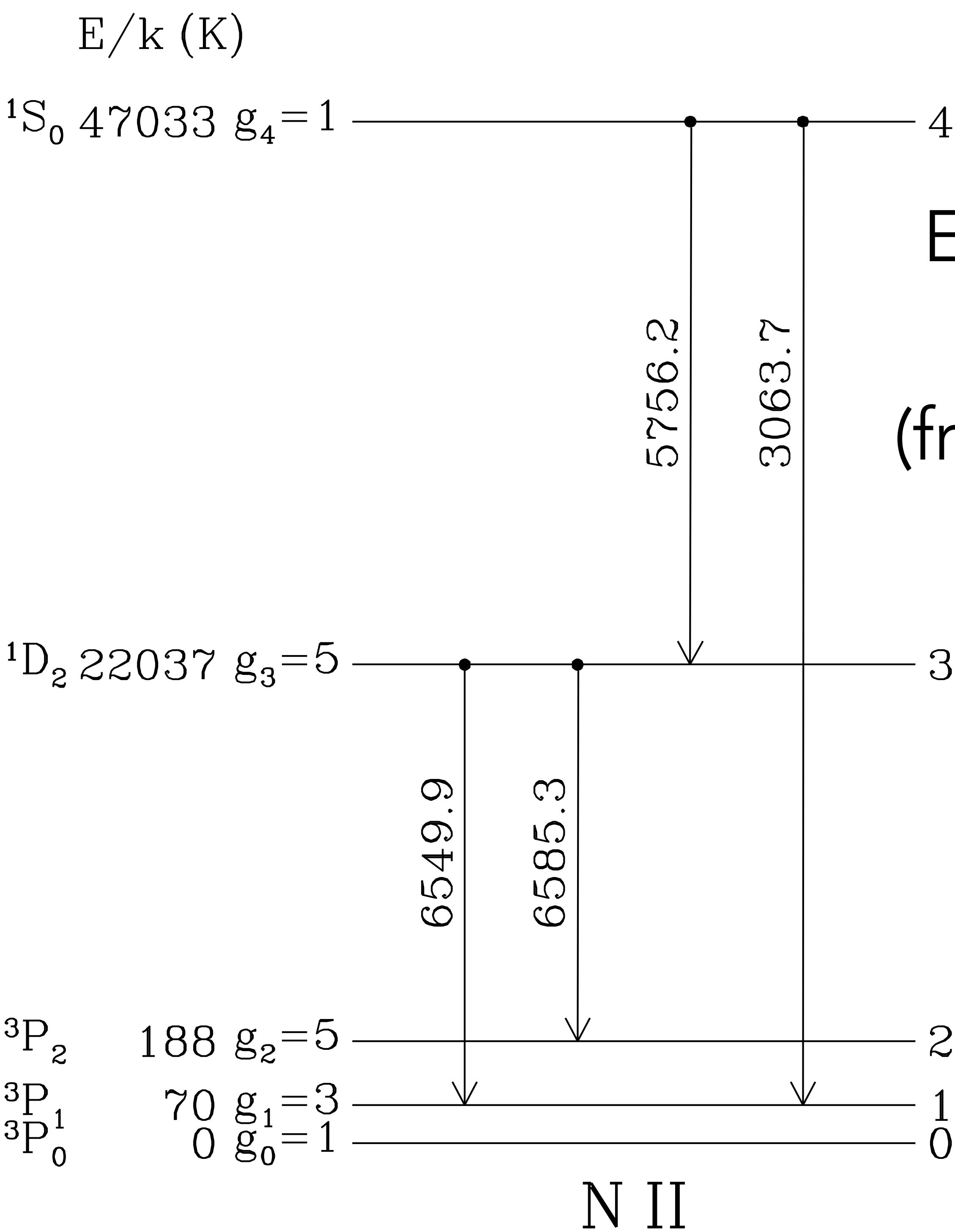
at typical HII region densities, NII transitions from $^1S_0$ and $^1D_2$ are below critical density

*means:*

*approximately every collision results in a radiative decay*

*(i.e. A wins over k)*

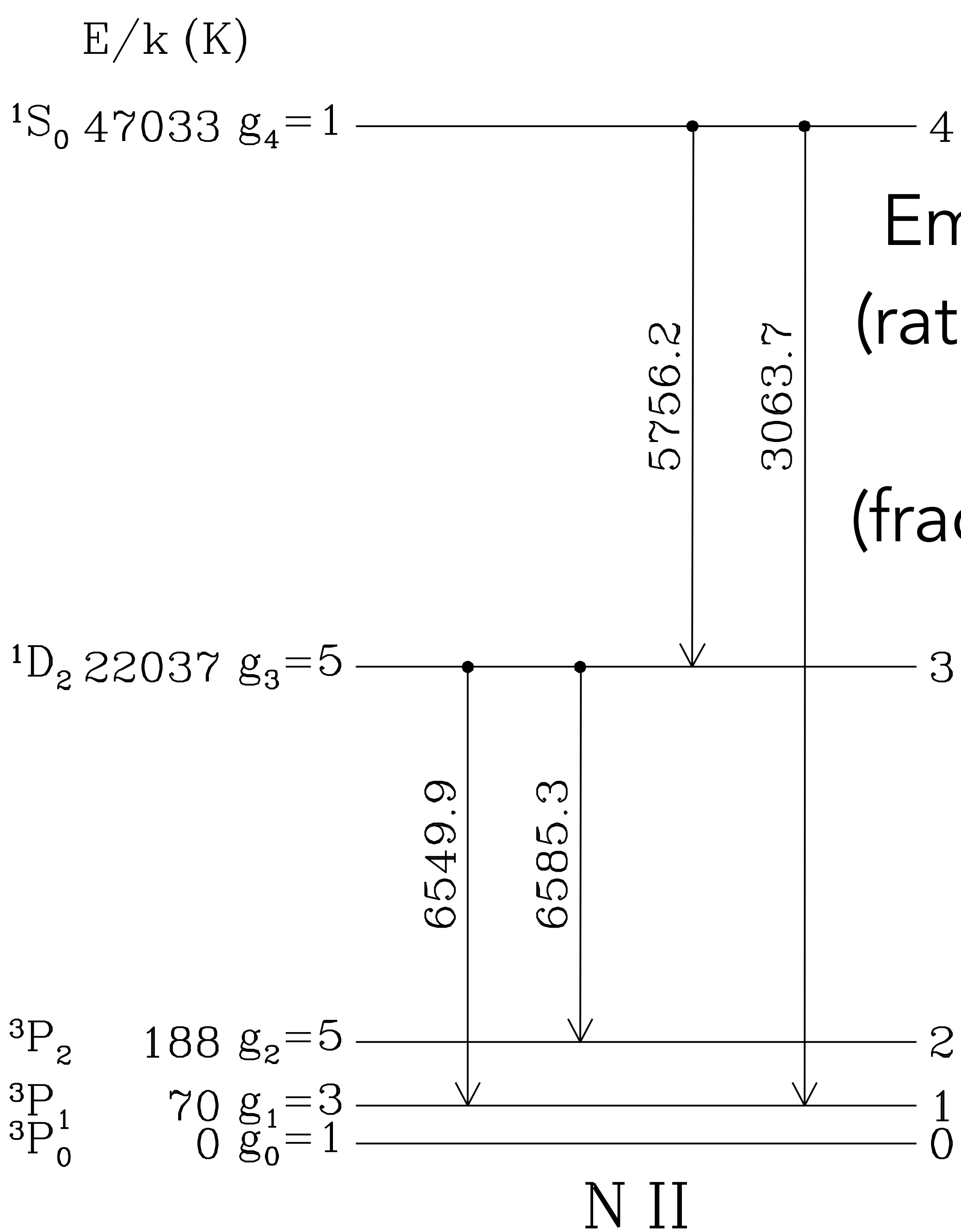
# Temperature Sensitive Line Ratios




Emission from 4-3 transition per NII =
(rate of collisions that populate 4) x
(fraction of radiative transitions in 4-3) x
(energy of 4-3 transition)

$P(4\rightarrow3)$ =
$n_e\, k_{04}$ x
$A_{43}/(A_{43}+A_{41})$ x
$E_{43}$

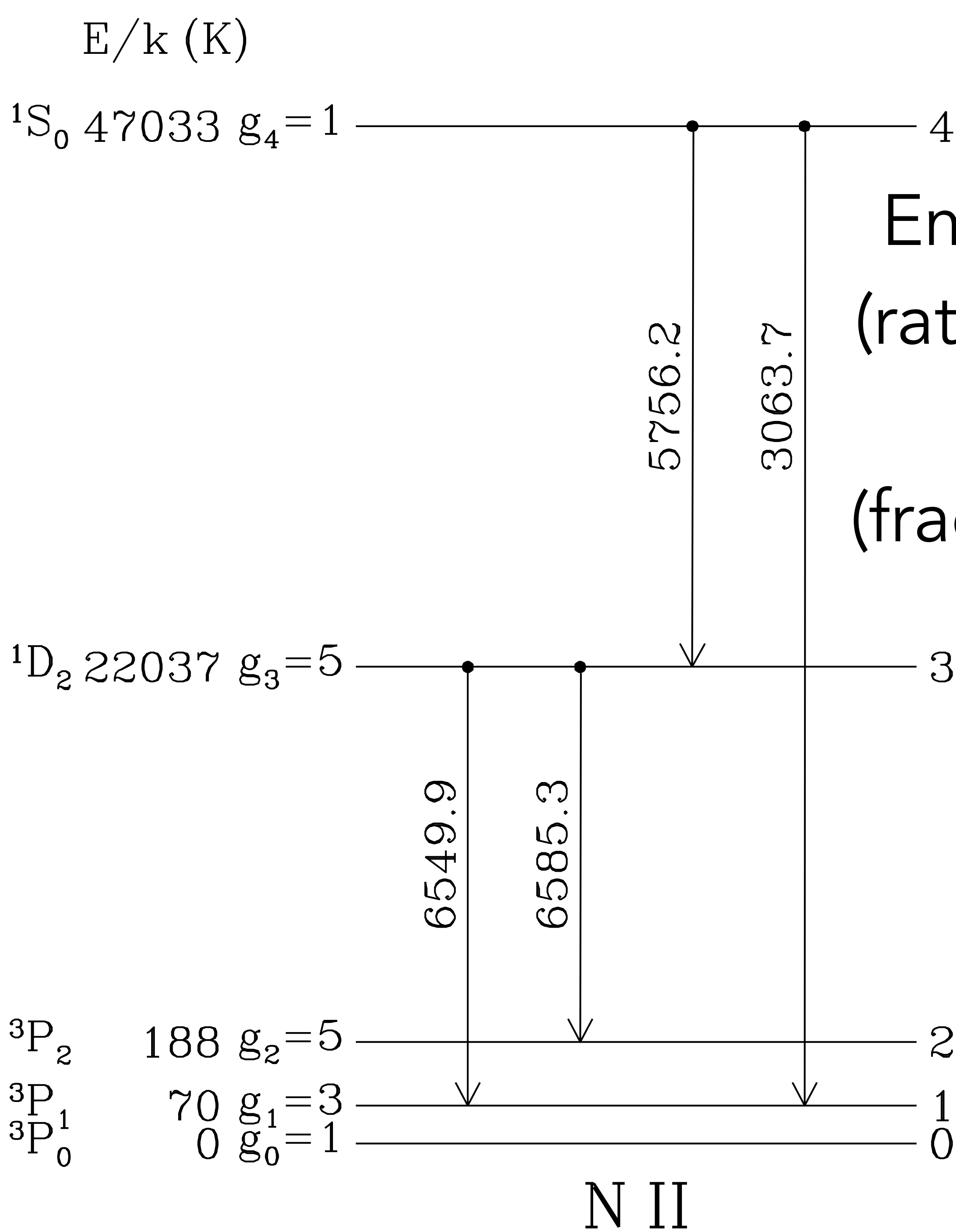
# Temperature Sensitive Line Ratios




Emission from 3-2 transition per NII = (rate of collisions & radiative transitions that populate 3) x (fraction of radiative transitions in 3-2) x (energy of 3-2 transition)

$$P(3 \rightarrow 2) = n_e\, (k_{03} + k_{04} A_{43}/(A_{43}+A_{41})) \times A_{32}/(A_{32}+A_{31}) \times E_{32}$$

# Temperature Sensitive Line Ratios

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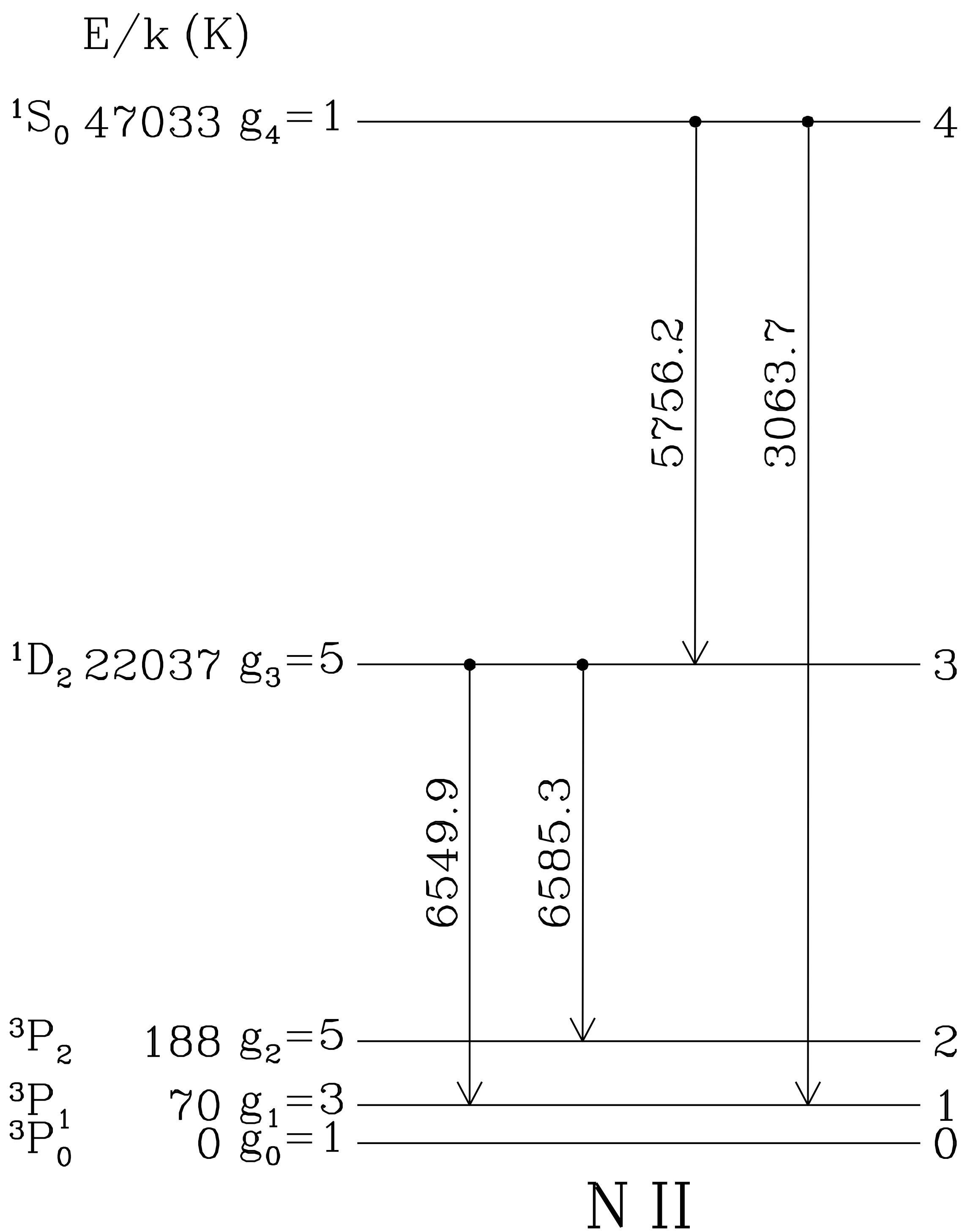
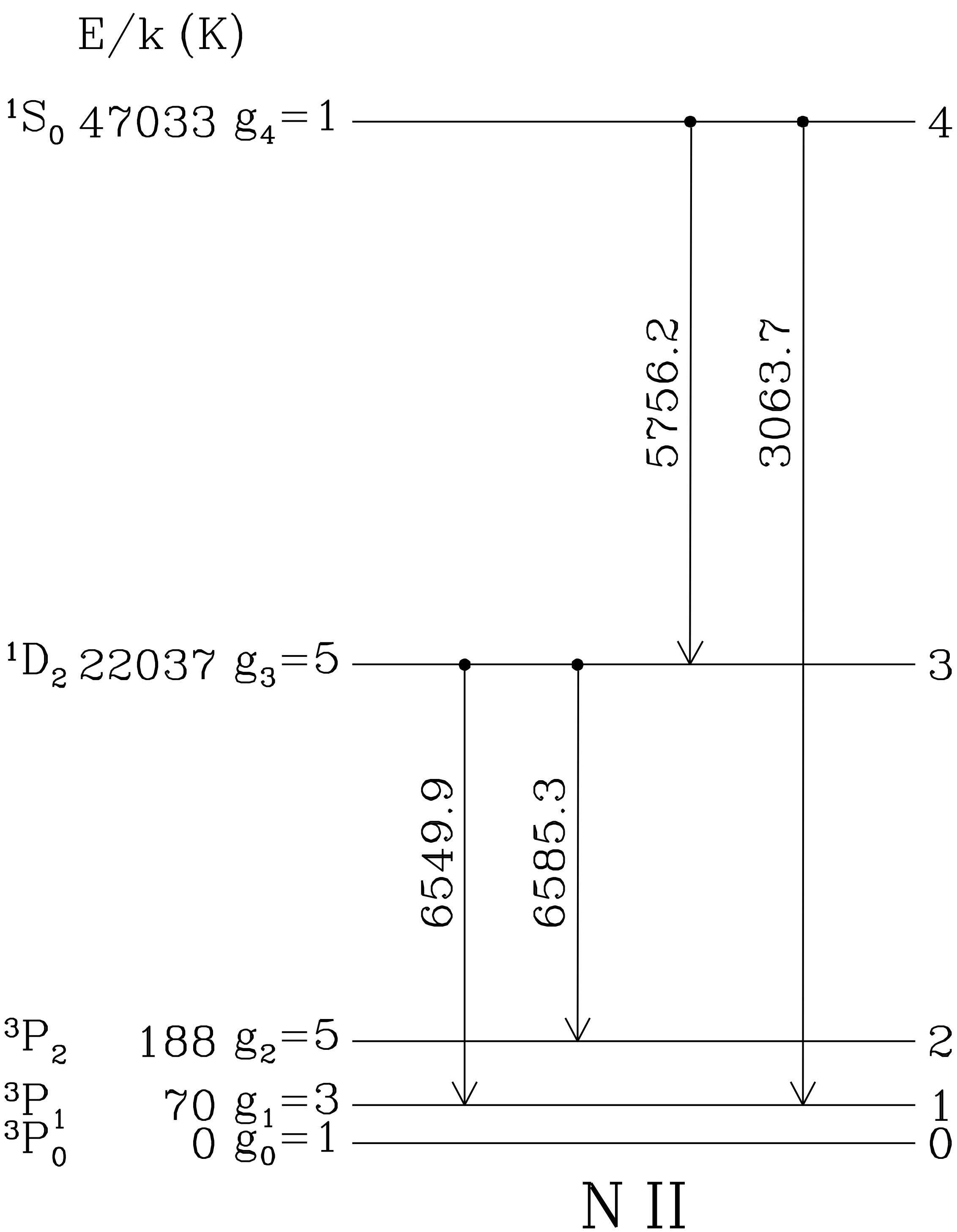



Line Ratio:

$$\frac{P(4 \to 3)}{P(3 \to 2)} = \frac{A_{43}E_{43}}{A_{32}E_{32}} \left[ \frac{k_{04}(A_{32} + A_{31})}{k_{03}(A_{43} + A_{41}) + k_{04}A_{43}} \right]$$

# Temperature Sensitive Line Ratios

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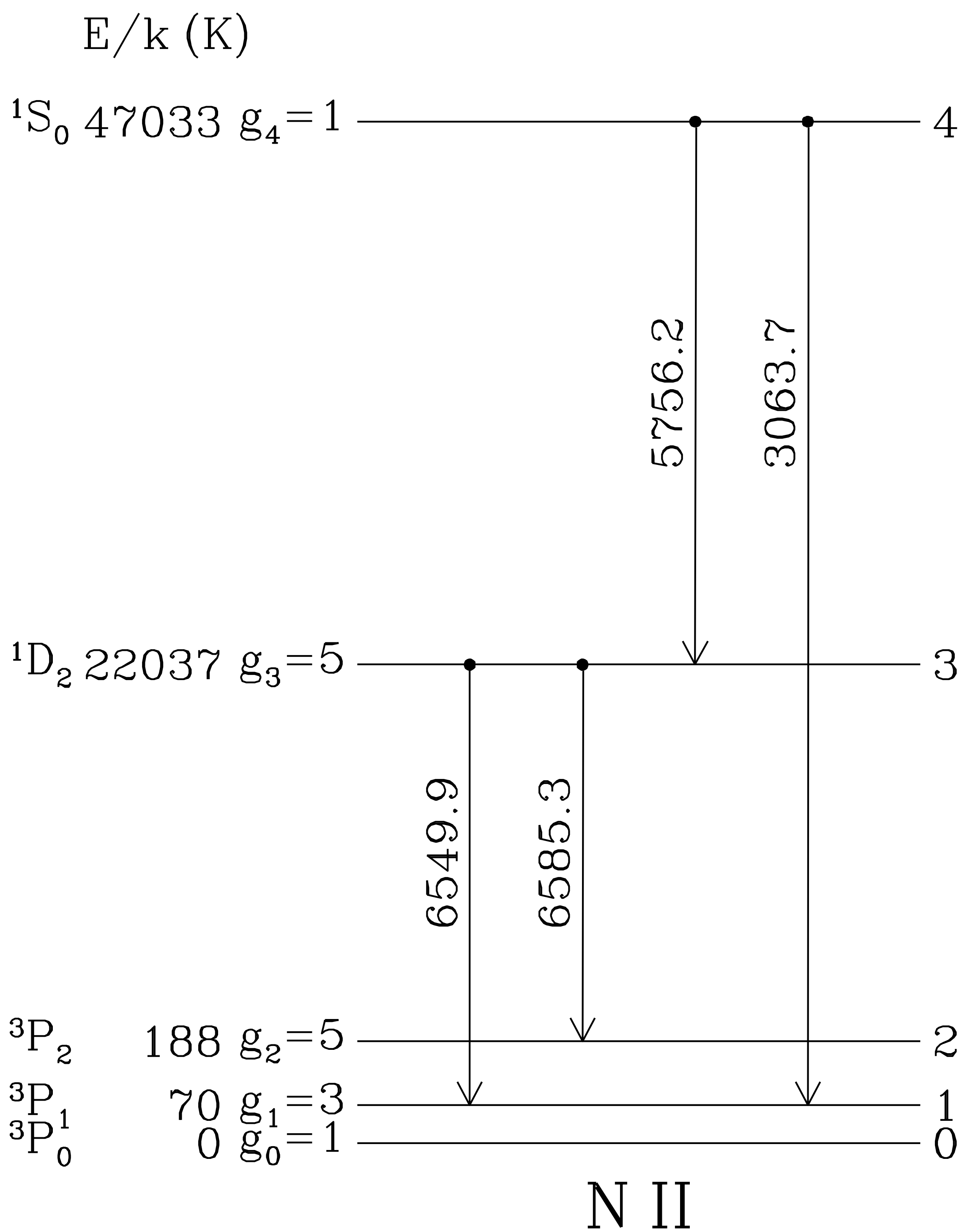
Define "collision strength" $\Omega_{ul}$

$$k_{u\ell} = \frac{h^2}{(2\pi m_e)^{3/2}}\frac{1}{(kT)^{3/2}}\frac{\Omega_{u\ell}}{g_u}$$

separates gas temperature from atomic properties

# Temperature Sensitive Line Ratios

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separates gas temperature from atomic properties

Detailed balance lets us get $k_{ul}$ from $k_{lu}$

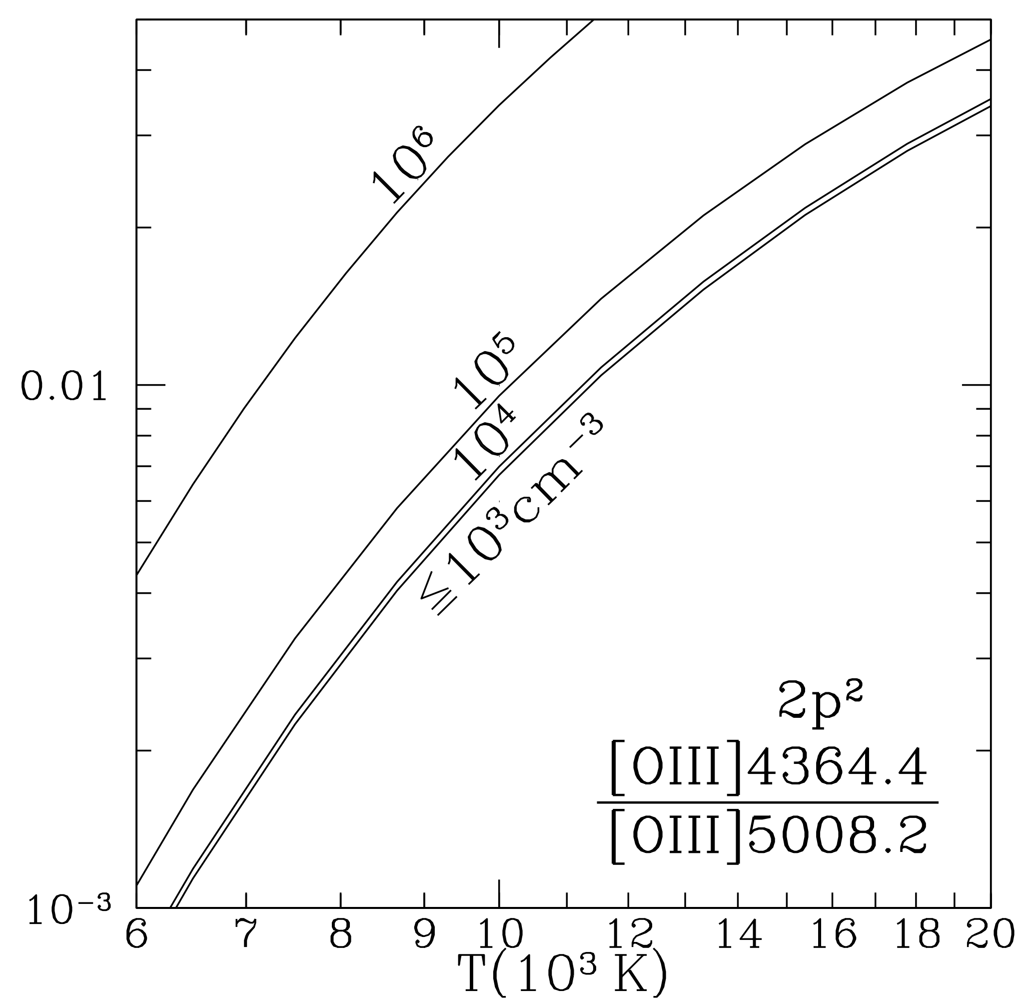
# Temperature Sensitive Line Ratios

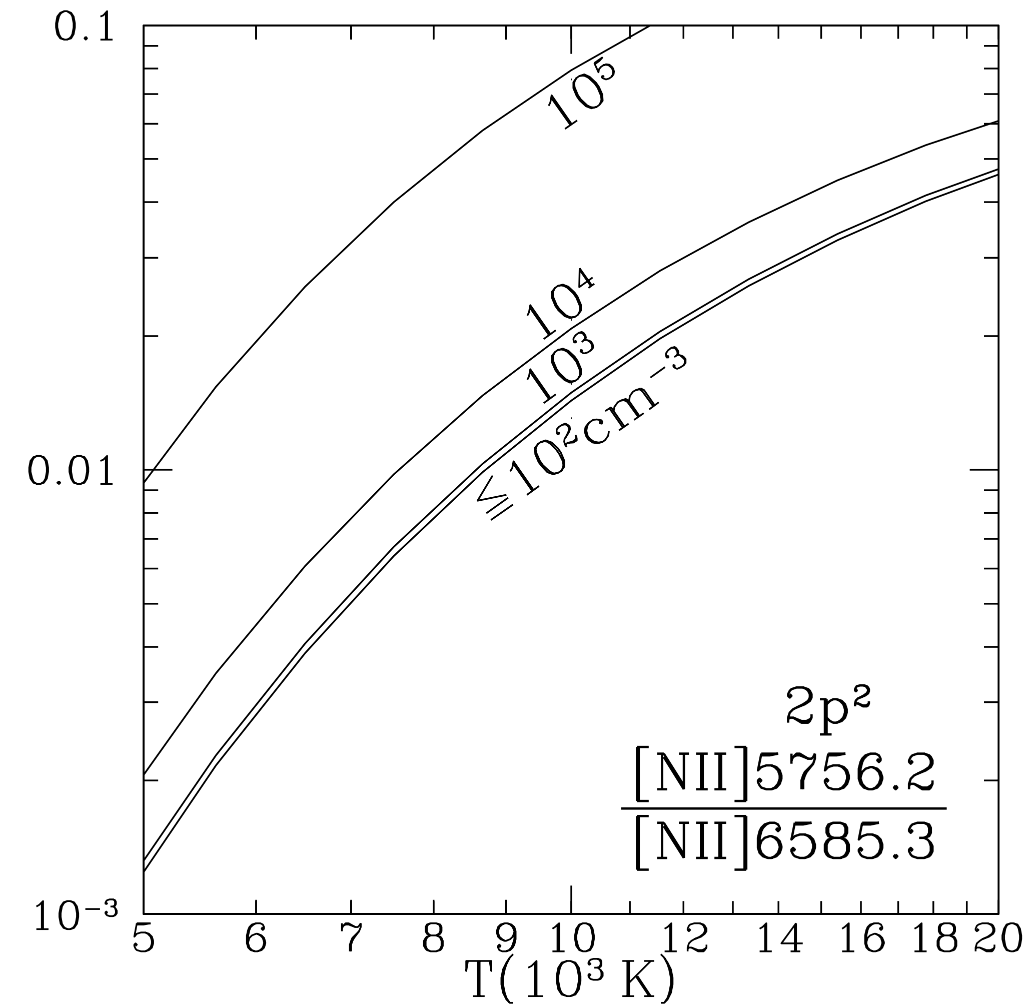
$$\frac{P(4 \to 3)}{P(3 \to 2)} = \frac{A_{43}E_{43}}{A_{32}E_{32}} \left[ \frac{\Omega_{40}(A_{32} + A_{31})}{\Omega_{30}(A_{43} + A_{41})e^{E_{43}/kT} + \Omega_{40}A_{43}} \right]$$

Line ratio doesn't depend on density, only on temperature.

Only density insensitive below the critical density.

# Temperature Sensitive Line Ratios



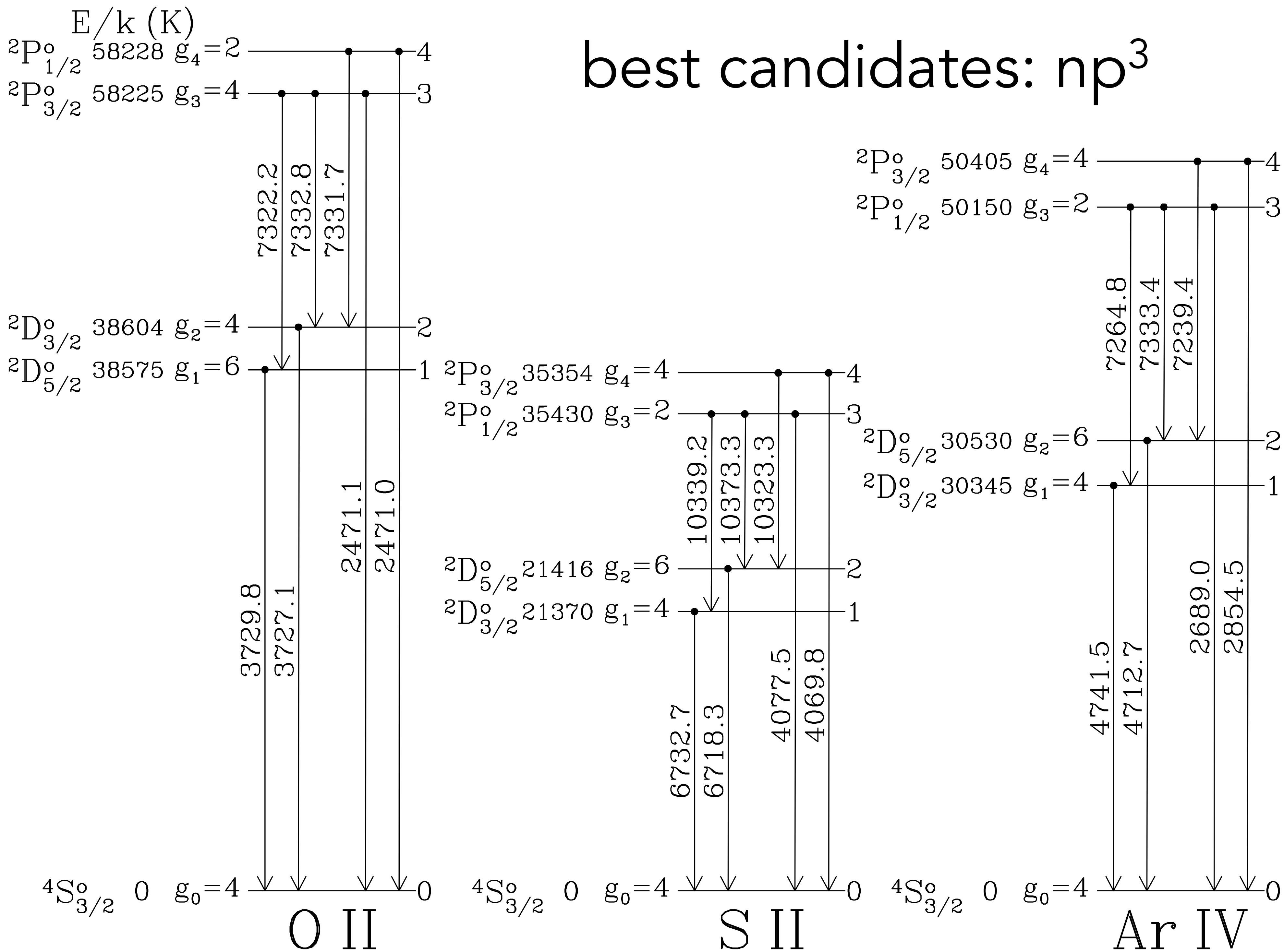



# Density Sensitive Line Ratios

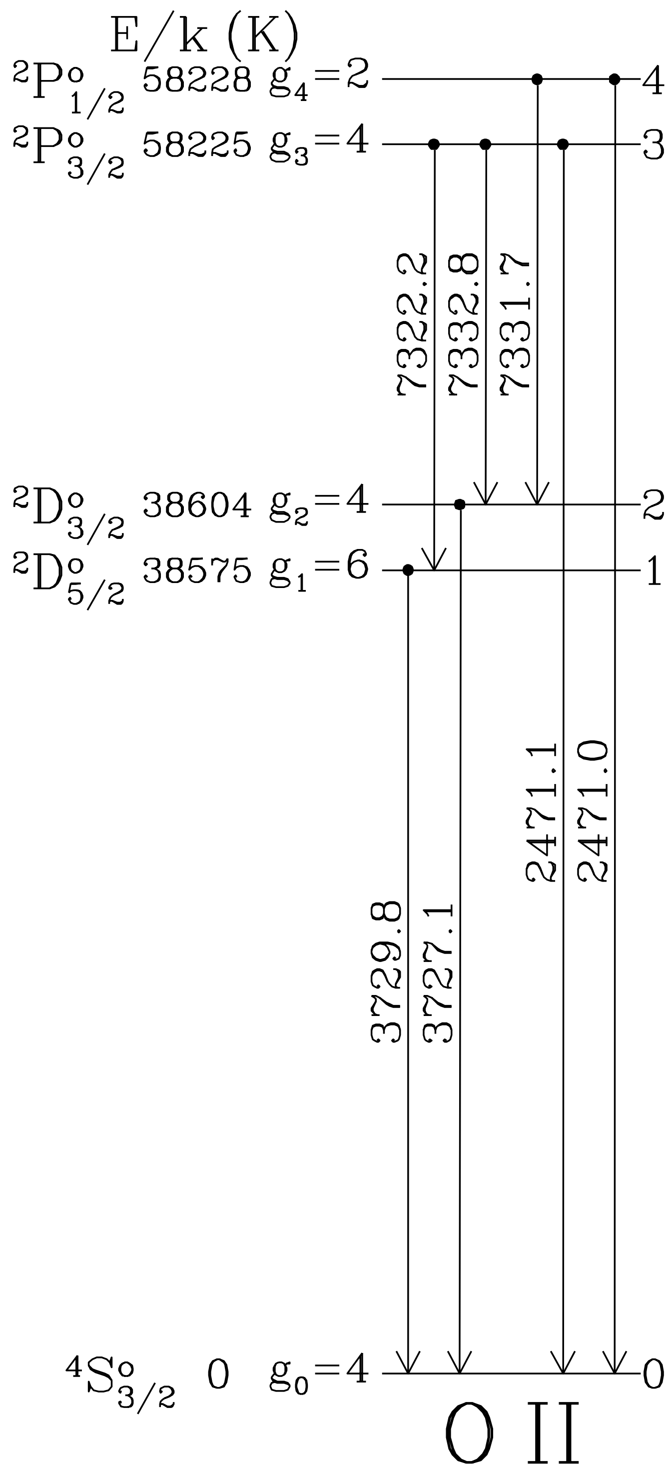
What we want:
two levels at approximately the same energy
that can be collisionally excited so that
line ratio doesn’t depend on temperature but
does depend on collisional excitation rate

# Density Sensitive Line Ratios

best candidates: $np^3$



# Density Sensitive Line Ratios




Lets look at 2→0 and 1→0 transitions

<u>Low Density Limit</u>

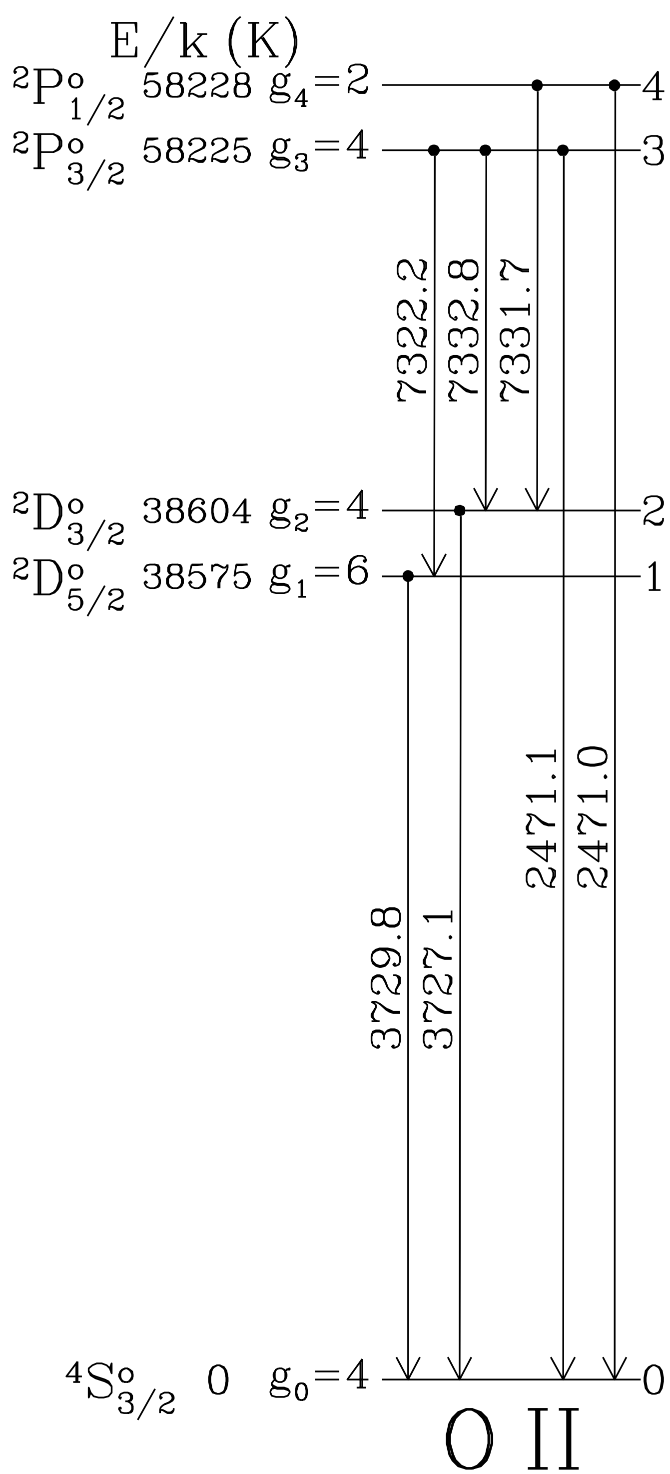
at low densities, every collisional excitation leads to a radiative transition

$P(2\rightarrow 0) = n_e\, k_{02}\, E_{20}$

$P(1\rightarrow 0) = n_e\, k_{01}\, E_{10}$

$$\frac{P(2\rightarrow 0)}{P(1\rightarrow 0)} = \frac{E_{20}k_{02}}{E_{10}k_{01}} = \frac{E_{20}}{E_{10}}\frac{\Omega_{20}}{\Omega_{10}}e^{-E_{21}/kT}$$

# Density Sensitive Line Ratios

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approximately equal

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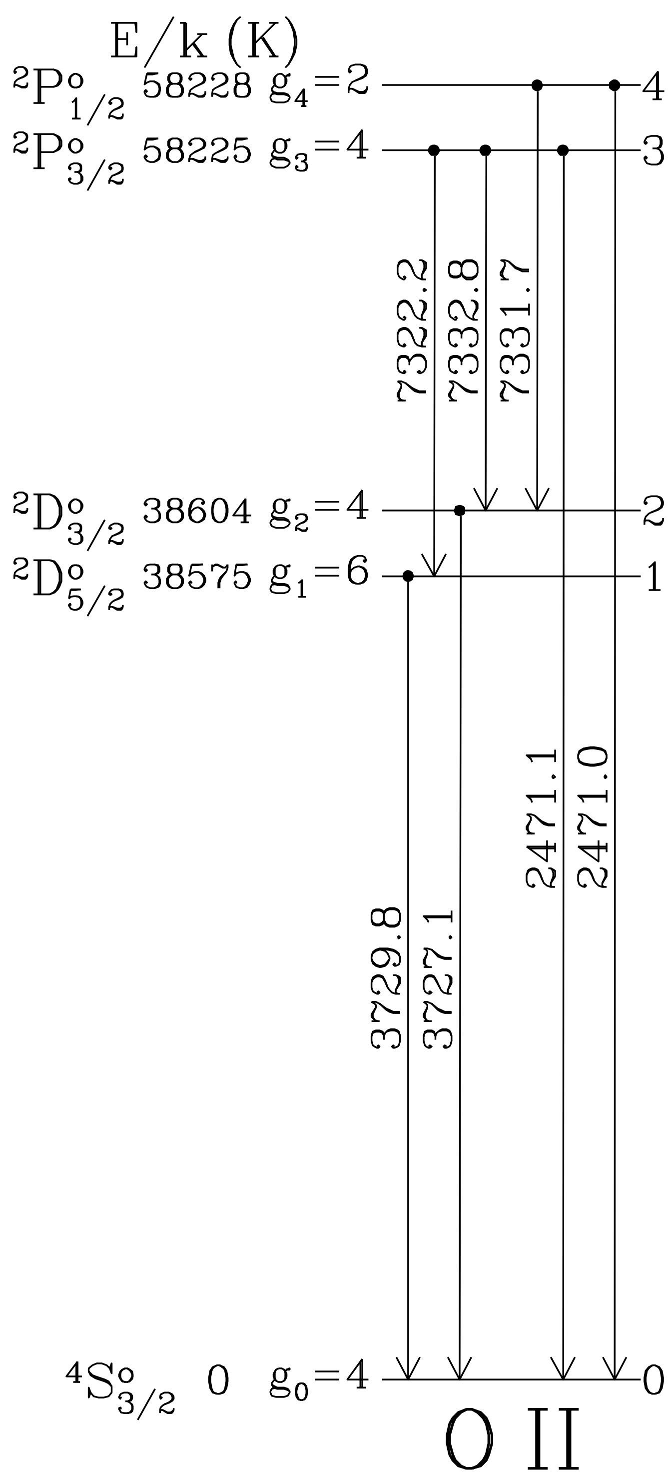


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approximately equal ~1

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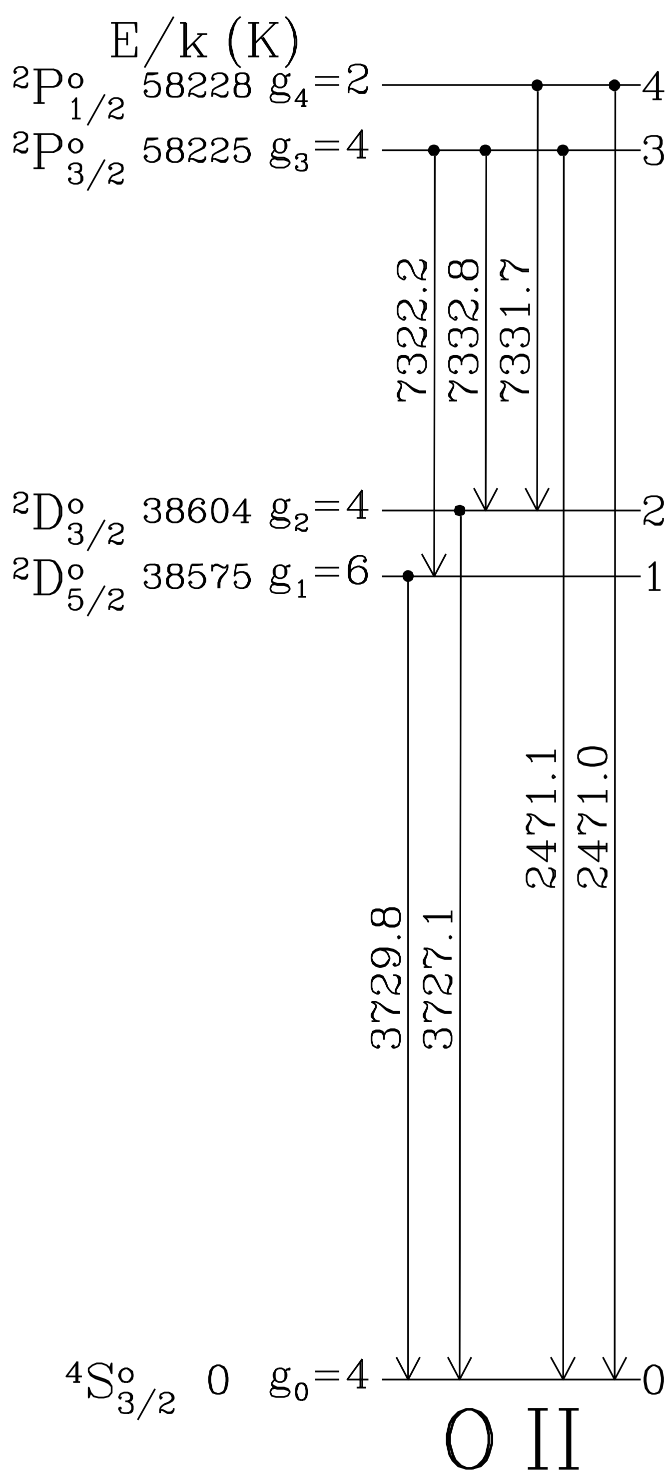


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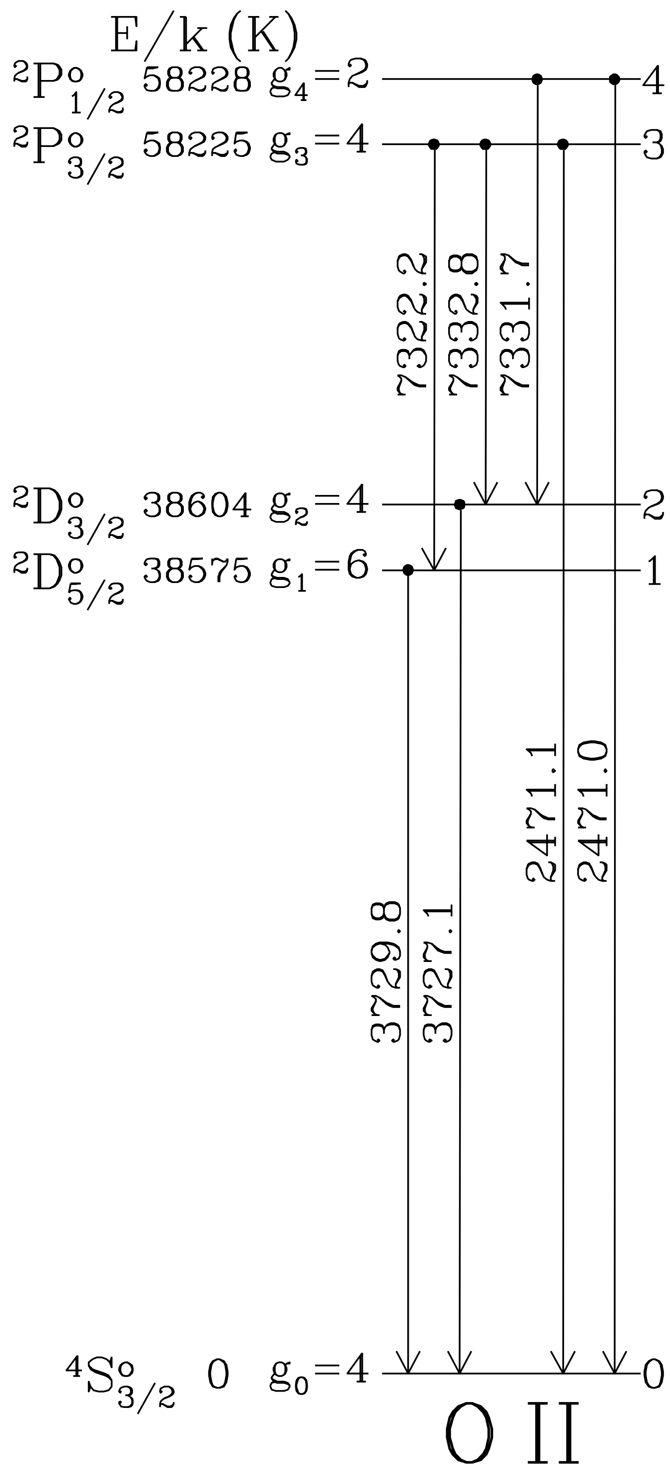
approximately equal ~1

# Density Sensitive Line Ratios



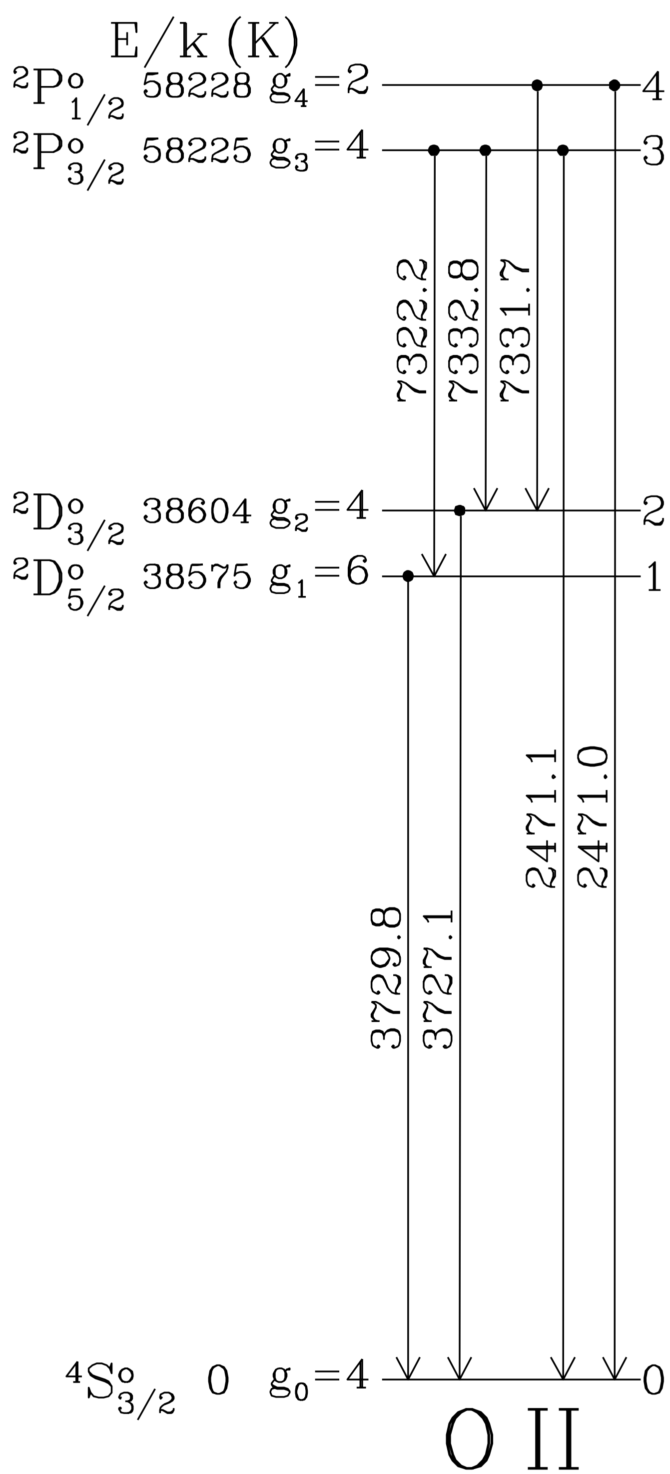

Lets look at 2→0 and 1→0 transitions

<u>High Density Limit</u>

Level populations set by collisions, radiative transitions occur but don't control the level populations

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

# Density Sensitive Line Ratios

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~1

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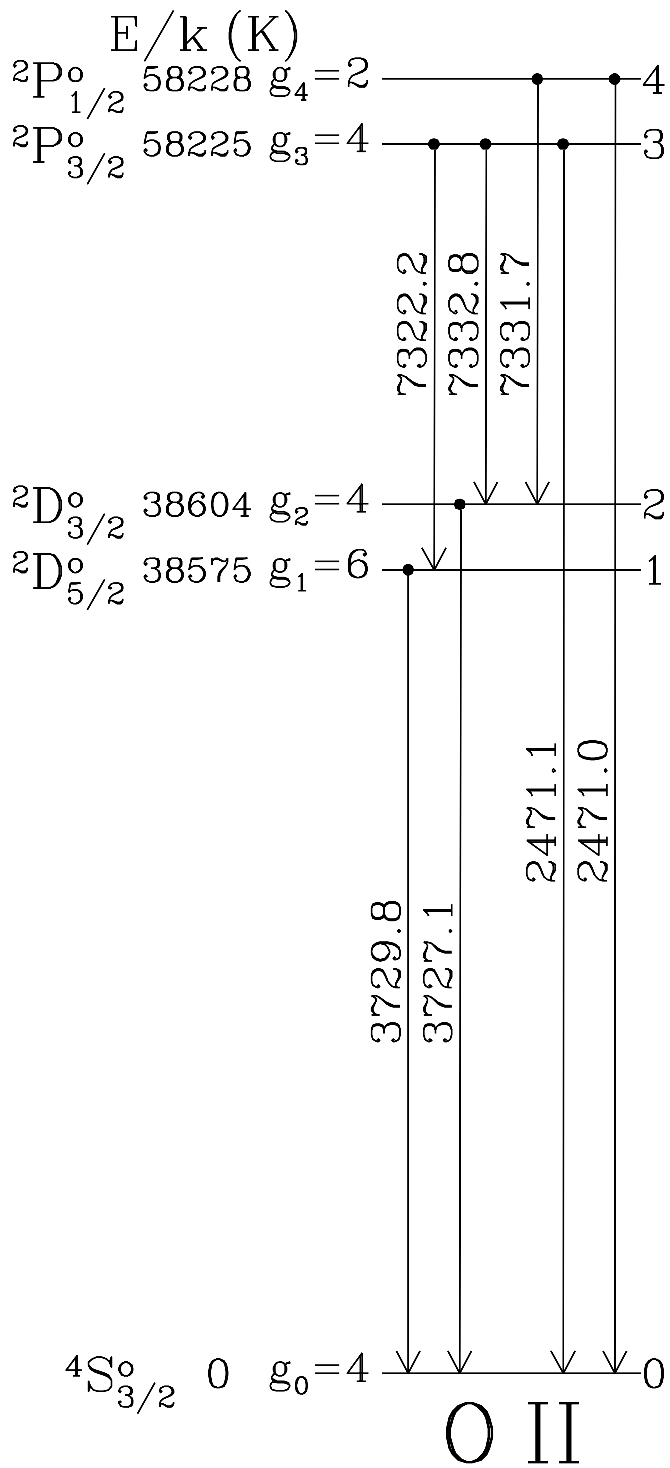


Lets look at 2→0 and 1→0 transitions

High Density Limit

Rate of spontaneous emission:

(2→0): $n_2 A_{20}$

(1→0): $n_1 A_{10}$

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

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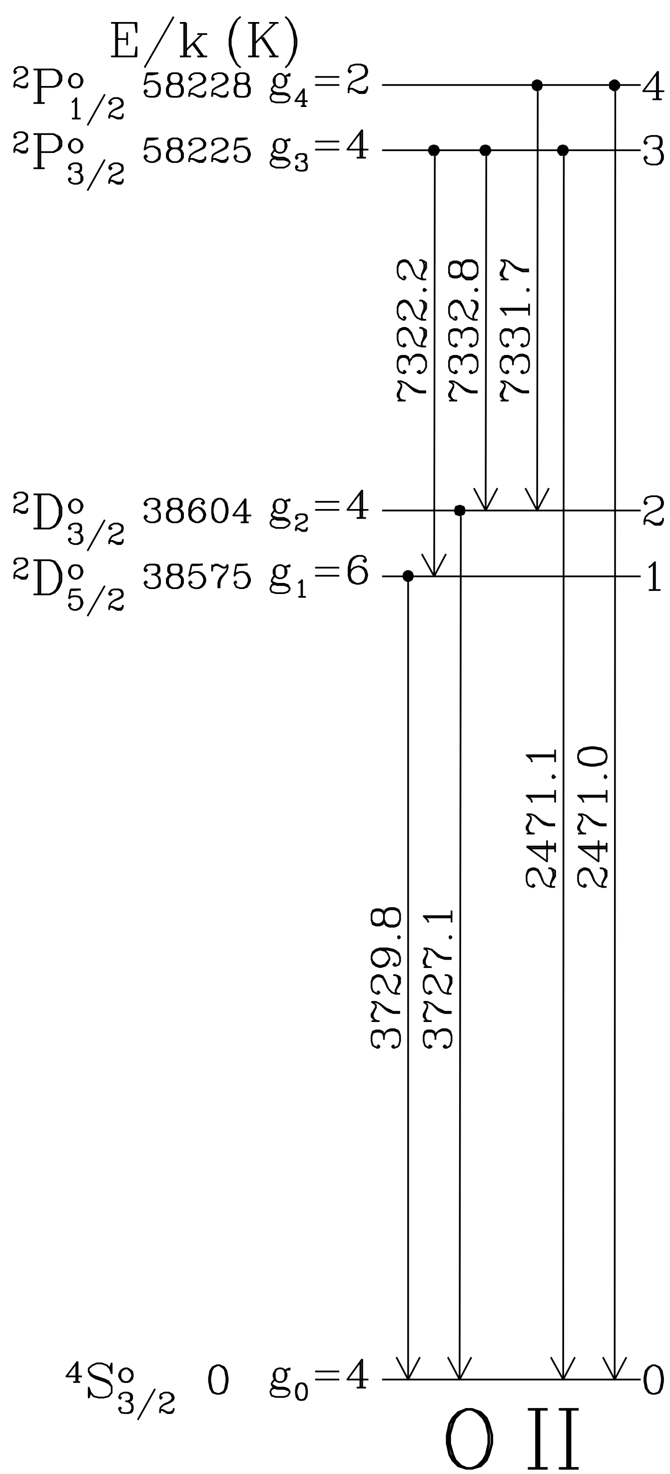


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approximately equal ~1

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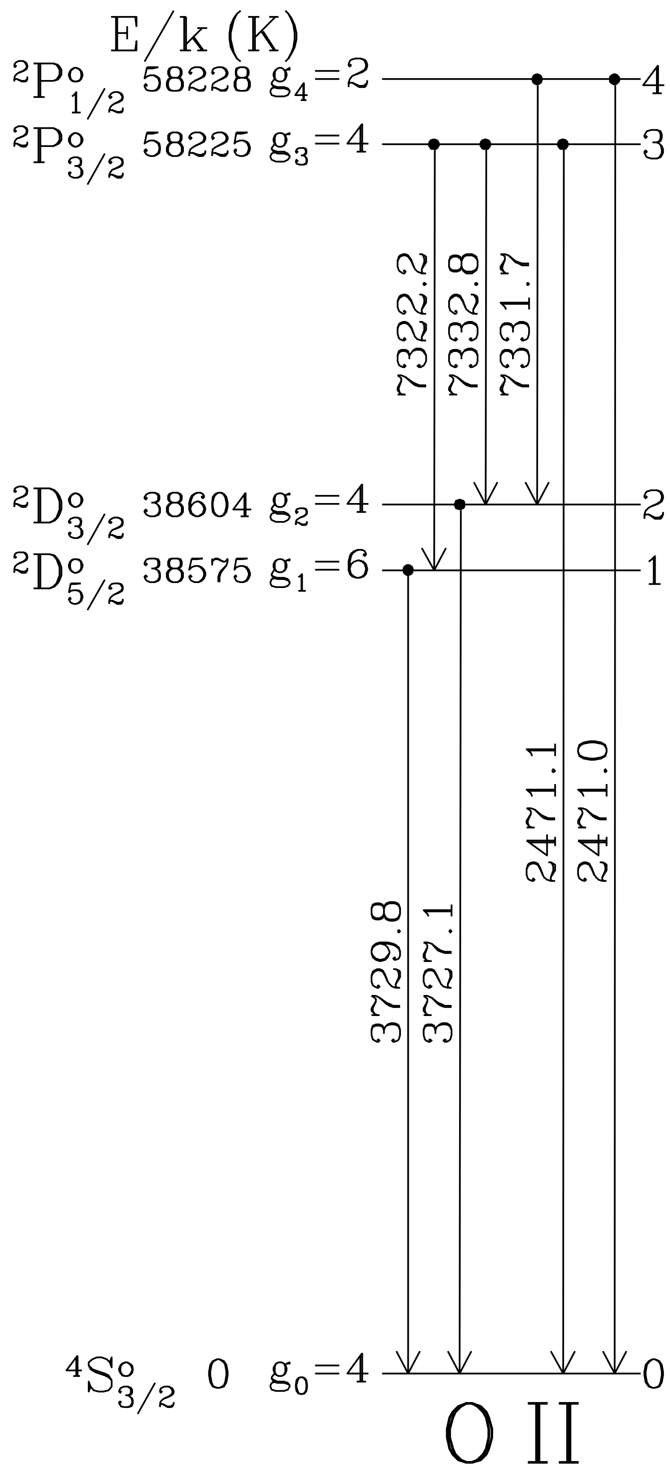


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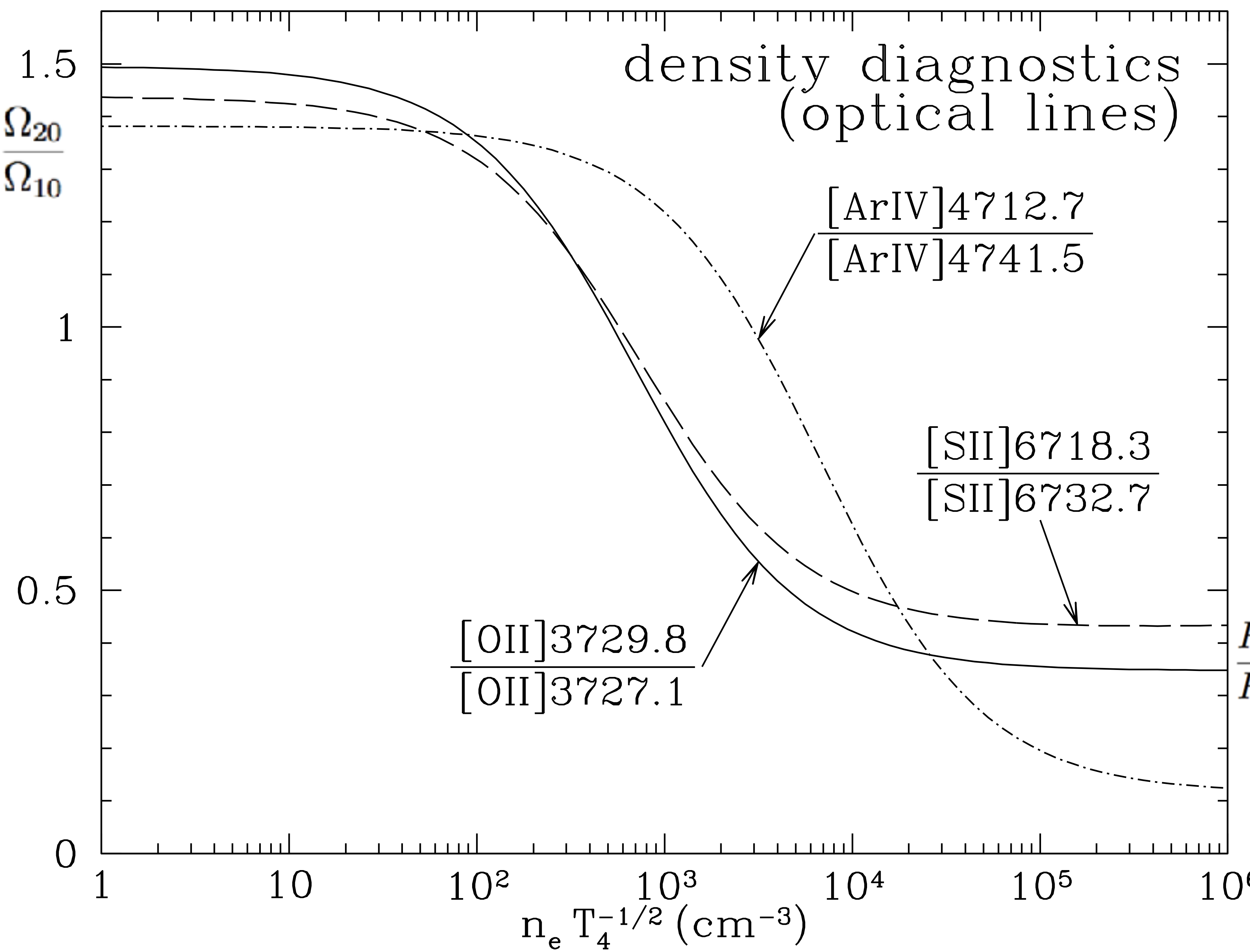
(2→0): $n_2 A_{20}$

(1→0): $n_1 A_{10}$

$$\frac{P(2 \to 0)}{P(1 \to 0)} \approx \frac{g_2 A_{20}}{g_1 A_{10}}$$

# Density Sensitive Line Ratios

$$\frac{P(2\rightarrow 0)}{P(1\rightarrow 0)} \approx \frac{\Omega_{20}}{\Omega_{10}}$$

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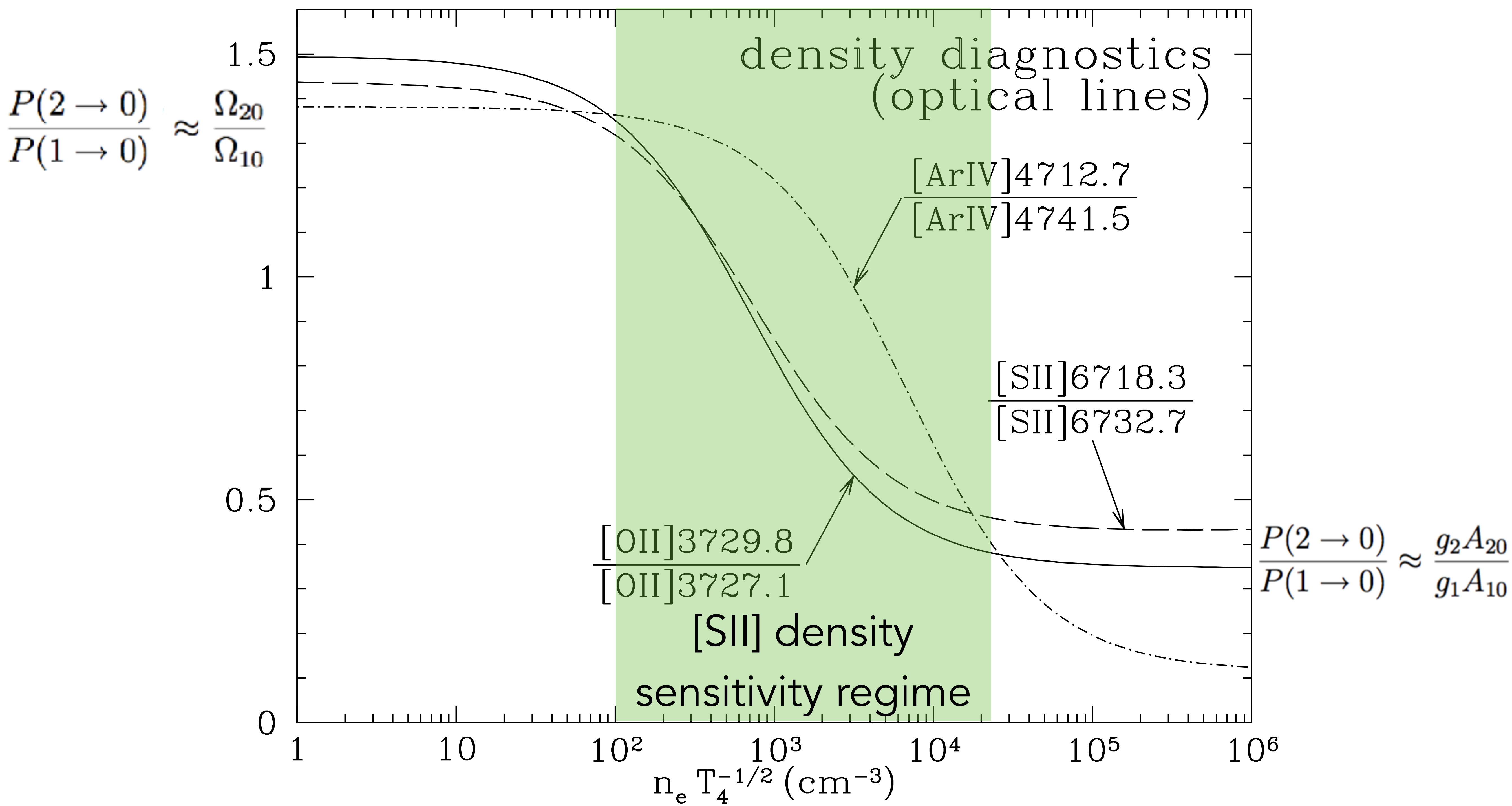

# MUSE Orion Nebula map of [SII] based $n_e$ from Weilbacher et al. 2015

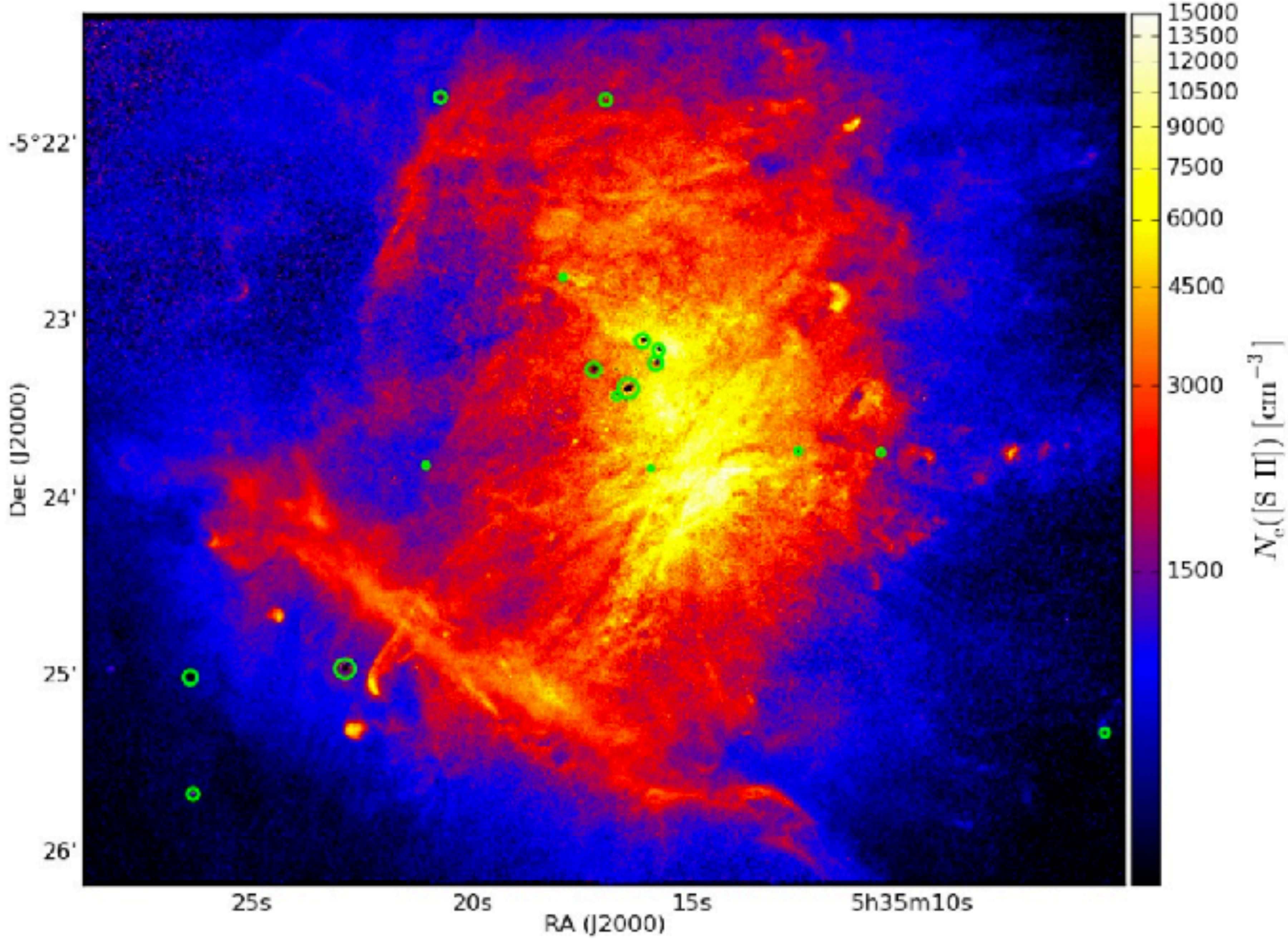


**Fig. 26.** [S II]-derived $N_e$-map of the central Orion Nebula, smoothed by a median filter of $3 \times 3$ pixels box width, displayed in asinh scaling.

# Part IV: Heating & Cooling in HII Regions

# Heating

- Photoionization heating
- Photoelectric Emission from dust
- Cosmic Rays
- Damping of magnetohydrodynamic waves

*Dominates in almost all circumstances*

# Heating

$$X^{+r} + h\nu \rightarrow X^{+r+1} + \boxed{e^- + KE}$$

Species *X*
in ionization state *r*

initial photon energy

Species *X*
in ionization state *r+1*

electron carries away
some kinetic energy

If $h\nu_0$ = ionization threshold energy
each photoionization injects an electron with $E_{kin} = (h\nu - h\nu_0)$

# Heating

$$\Gamma_{\rm pi} = n(X^{+r}) \int_{\nu_0}^{\infty} \sigma_{\rm pi}(\nu)\ c\ \left[\frac{u_\nu}{h\nu}\right]\ (h\nu - h\nu_0)\ d\nu$$

# Heating

heating rate
per unit volume

$$\boxed{\Gamma_{\rm pi}} = n(X^{+r}) \int_{\nu_0}^{\infty} \sigma_{\rm pi}(\nu)\; c\; \left[\frac{u_\nu}{h\nu}\right]\; (h\nu - h\nu_0)\; d\nu$$

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collision rate per unit volume
of atoms/ions in state *r* with photons

# Heating

heating rate
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collision rate per unit volume
of atoms/ions in state *r* with photons

kinetic energy
produced per
ionization

# Heating

To estimate heating rates we can define:

$$\psi \equiv \frac{E_{\rm pi}(X^{+r})}{kT_c}$$

$E_{\rm pi}(X^{+r})$ ← average photoelectron energy

$kT_c$ ← "color temperature" of star

"color temperature" means the temperature of
a blackbody spectrum that approximates the spectrum of the star

# Heating

Right near the star, before any of the stellar spectrum has been absorbed.

$$\psi_0 \equiv \frac{1}{kT_c} \frac{\int_{\nu_0}^{\infty} \sigma_{\rm pi}(\nu) \frac{B_\nu(T_c)}{h\nu} h(\nu - \nu_0)\, d\nu}{\int_{\nu_0}^{\infty} \sigma_{\rm pi}(\nu) \frac{B_\nu(T_c)}{h\nu}\, d\nu}$$

$\psi$ should be ~1

Because $T_{13.6\ \mathrm{eV}} >> T_c$ we are in the low freq part of the blackbody, where slope with $\nu$ is fixed.

# Heating

heating rate
per unit volume

$$\boxed{\Gamma_{\mathrm{pi}}} = n(X^{+r}) \int_{\nu_0}^{\infty} \sigma_{\mathrm{pi}}(\nu)\ c\ \left[\frac{u_\nu}{h\nu}\right]\ (h\nu - h\nu_0)\ d\nu$$

Depends on density of species being ionized.

# Heating

heating rate
per unit volume

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$$\alpha_B n_e n(X^{+r+1})$$

In ionization equilibrium
rate of ionization = rate of recombination

# Heating

heating rate
per unit volume

$$\boxed{\Gamma_{\rm pi}} = \boxed{n(X^{+r}) \int_{\nu_0}^{\infty} \sigma_{\rm pi}(\nu)\ c\ \left[\frac{u_\nu}{h\nu}\right]} \boxed{(h\nu - h\nu_0)}\, d\nu$$

$$\alpha_B n_e n(X^{+r+1}) \qquad\qquad \psi k T_c$$

In ionization equilibrium
rate of ionization = rate of recombination

# Cooling

- Recombination
- Free-free Emission
- Collisional excitation

*All can be important, collisional excitation is dominant.*

# Cooling

Recombination removes kinetic energy from the gas

$$\Lambda_{\rm rr} = \alpha_{A,B} n_e n_{\rm H^+} \langle E_{\rm rr} \rangle$$

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cooling rate
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Recombination removes kinetic energy from the gas

$$\boxed{\Lambda_{\rm rr}} = \alpha_{A,B} n_e n_{\rm H^+} \boxed{\langle E_{\rm rr} \rangle}$$

cooling rate
per unit volume

average energy of
recombining electron

# Cooling

Recombination removes kinetic energy from the gas

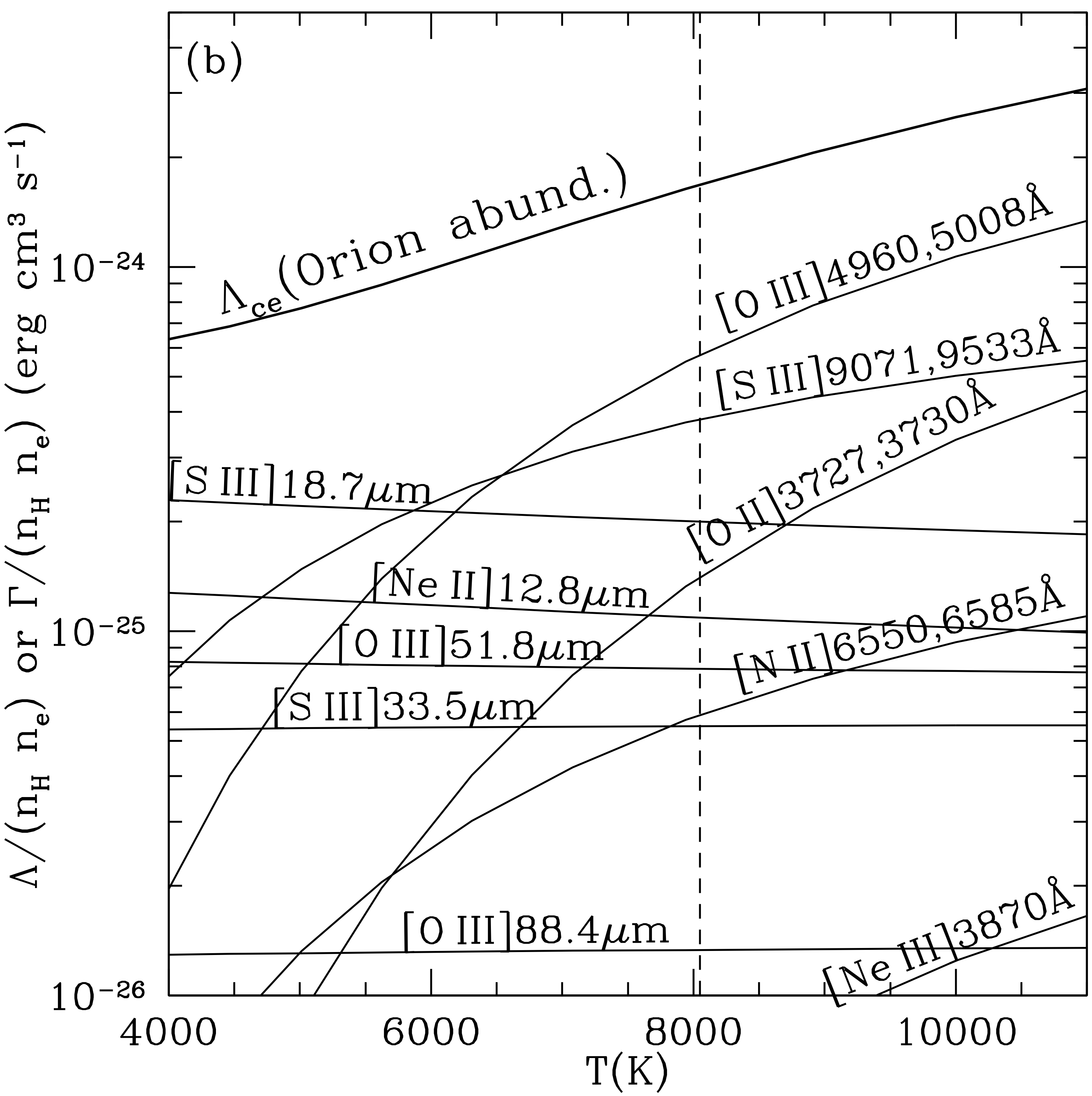
$$\boxed{\Lambda_{\rm rr}} = \alpha_{A,B} n_e n_{\rm H^+} \boxed{\langle E_{\rm rr} \rangle}$$

cooling rate per unit volume

average energy of recombining electron

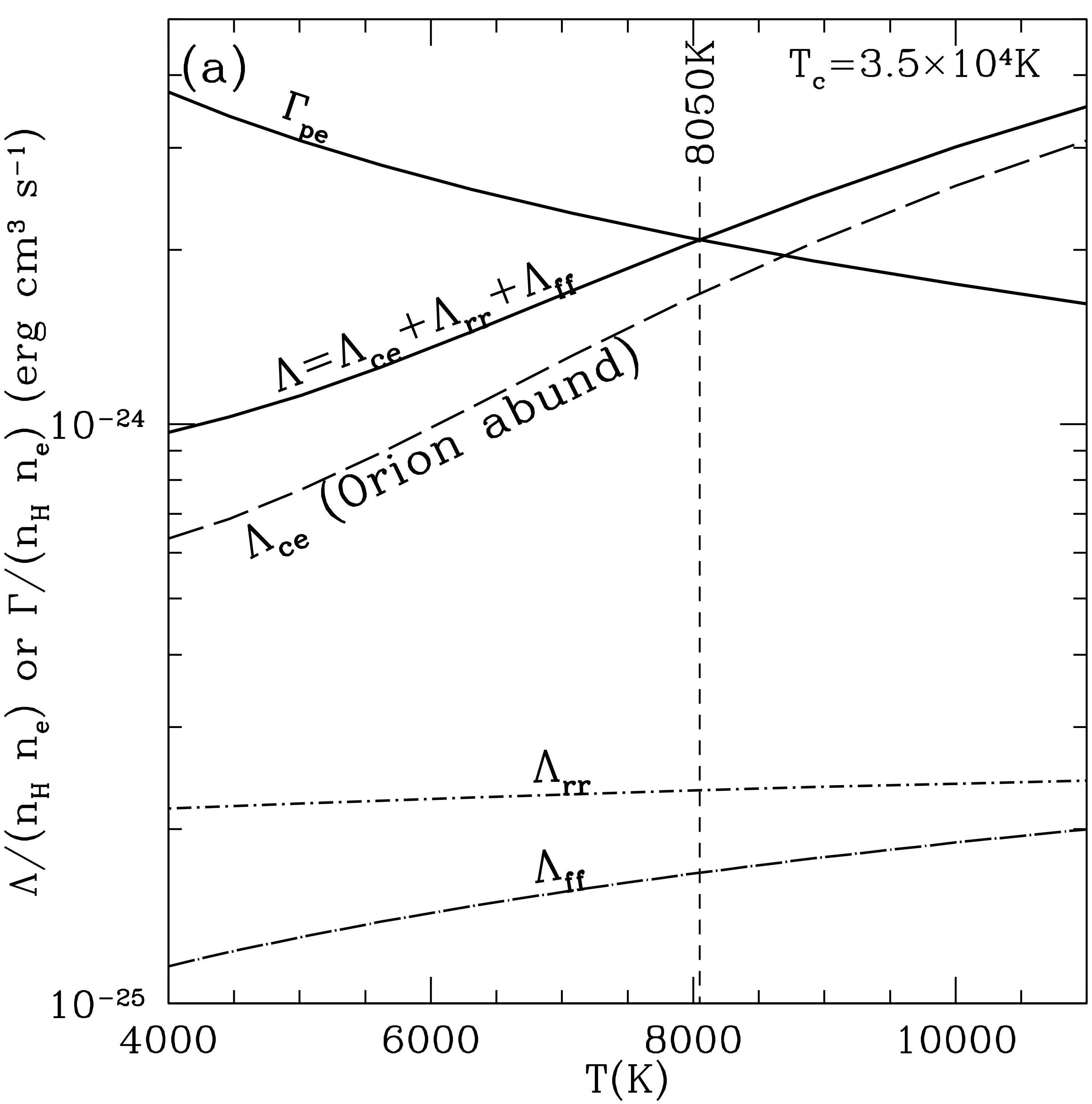
$\langle E_{rr} \rangle <$ mean electron kinetic energy of the gas because the recombination cross section is weighted towards low energy electrons!

# Cooling



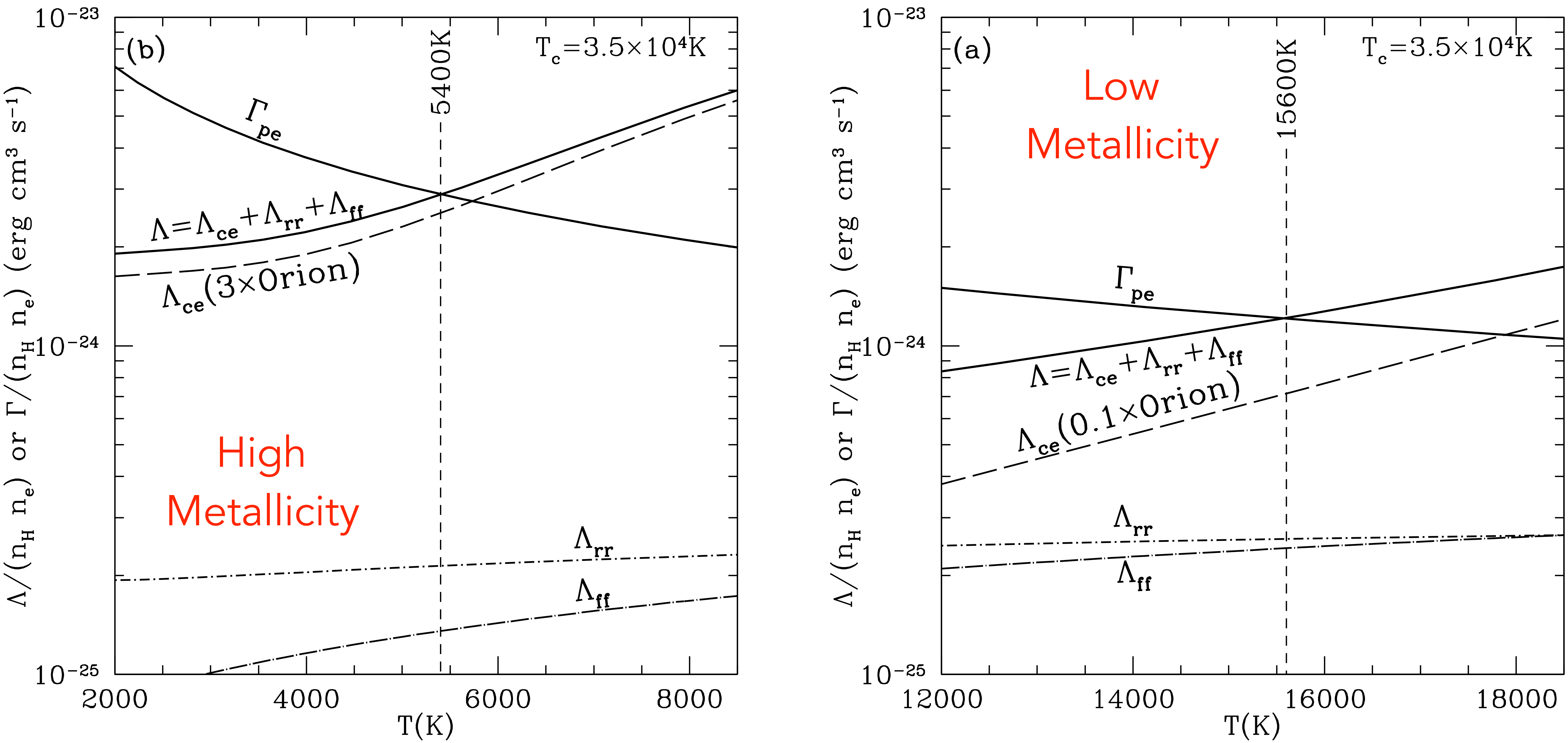

Cooling from collisionally excited emission lines is the most important coolant of HII regions.

# Thermal Balance



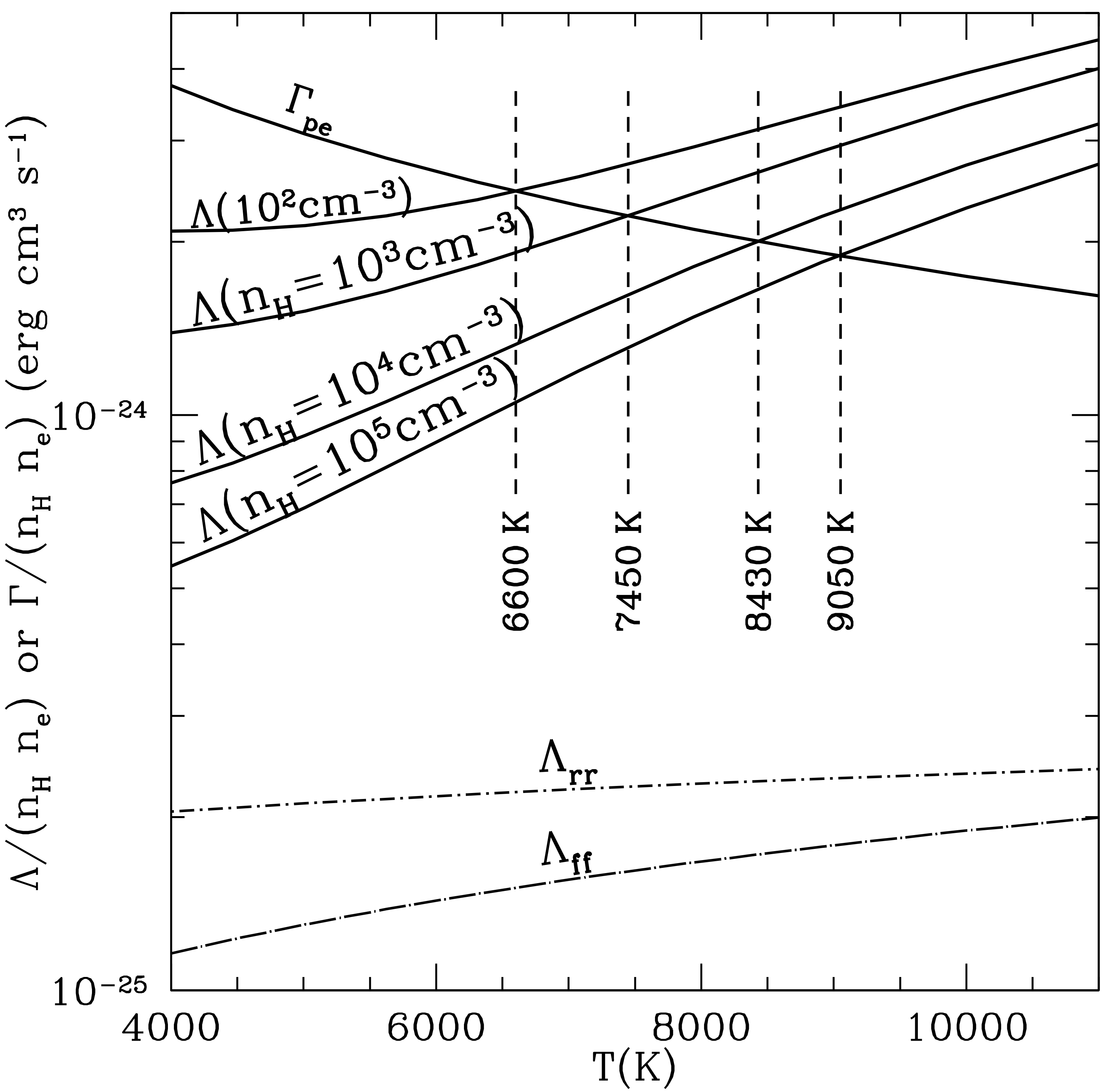

Balance between photoionization heating and collisional excitation cooling sets temperature of HII region.

# Thermal Balance




Abundance of heavy elements (e.g. coolants) greatly changes HII region temperature!!

# Thermal Balance




Density changes thermal balance.

At densities above the critical density of the coolants, cooling is less efficient (not every collision results in a photon).

Credit: NASA,ESA, M. Robberto (Space Telescope Science Institute/ESA)
and the Hubble Space Telescope Orion Treasury Project Team

# Part III: Dust

We have talked fairly extensively now about
the interaction of radiation with gas.

This occurs at specific frequencies (absorption by atoms, ions, molecules)
or at certain frequency ranges (ionizing radiation).

Now we move on to talking about dust -
which interacts with light at a wide range of wavelengths.

<u>Dust is key for coupling radiation with the gas.</u>

# How we learn about dust

- Extinction: wavelength dependence of how dust attenuates (absorbs & scatters) light
- Polarization: of starlight and dust emission
- Thermal emission from grains
- Microwave emission from spinning small grains
- Depletion of elements from the gas relative to expected abundance
- Presolar grains in meteorites or ISM grains from Stardust mission (7 grains!)

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Dust/Light Interaction

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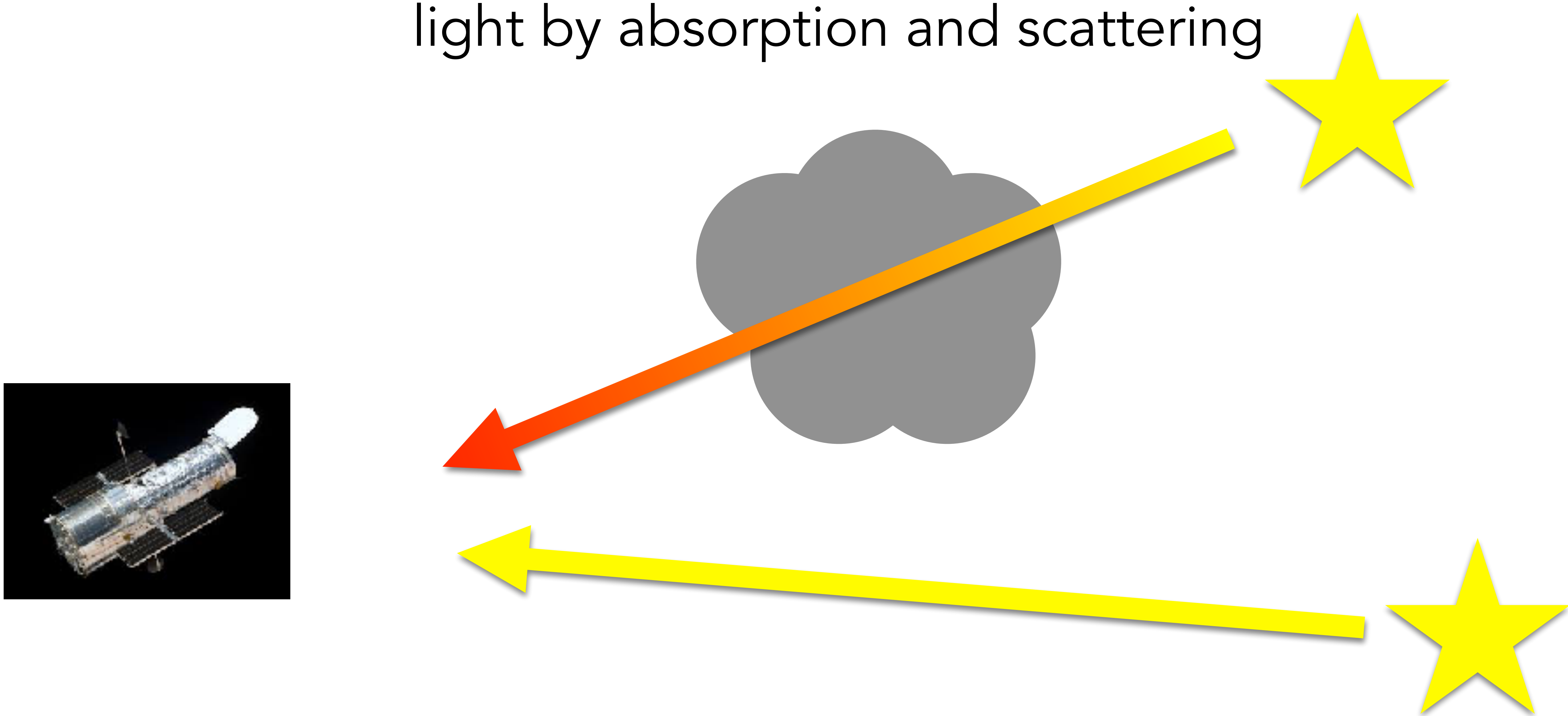
Dust/Light Interaction

First: definitions

Then: dust optical properties

# Extinction

wavelength dependent attenuation of light by absorption and scattering



Basic method for measuring extinction:
"pair method" - two stars of the same type behind differing amounts of dust

# Extinction

$$\frac{A_\lambda}{\text{mag}} = 2.5 \log_{10}[F^0_\lambda / F_\lambda]$$

Extinction at wavelength λ

expected flux w/o dust

observed flux

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note: $\tau_\lambda$ includes both absorption & scattering

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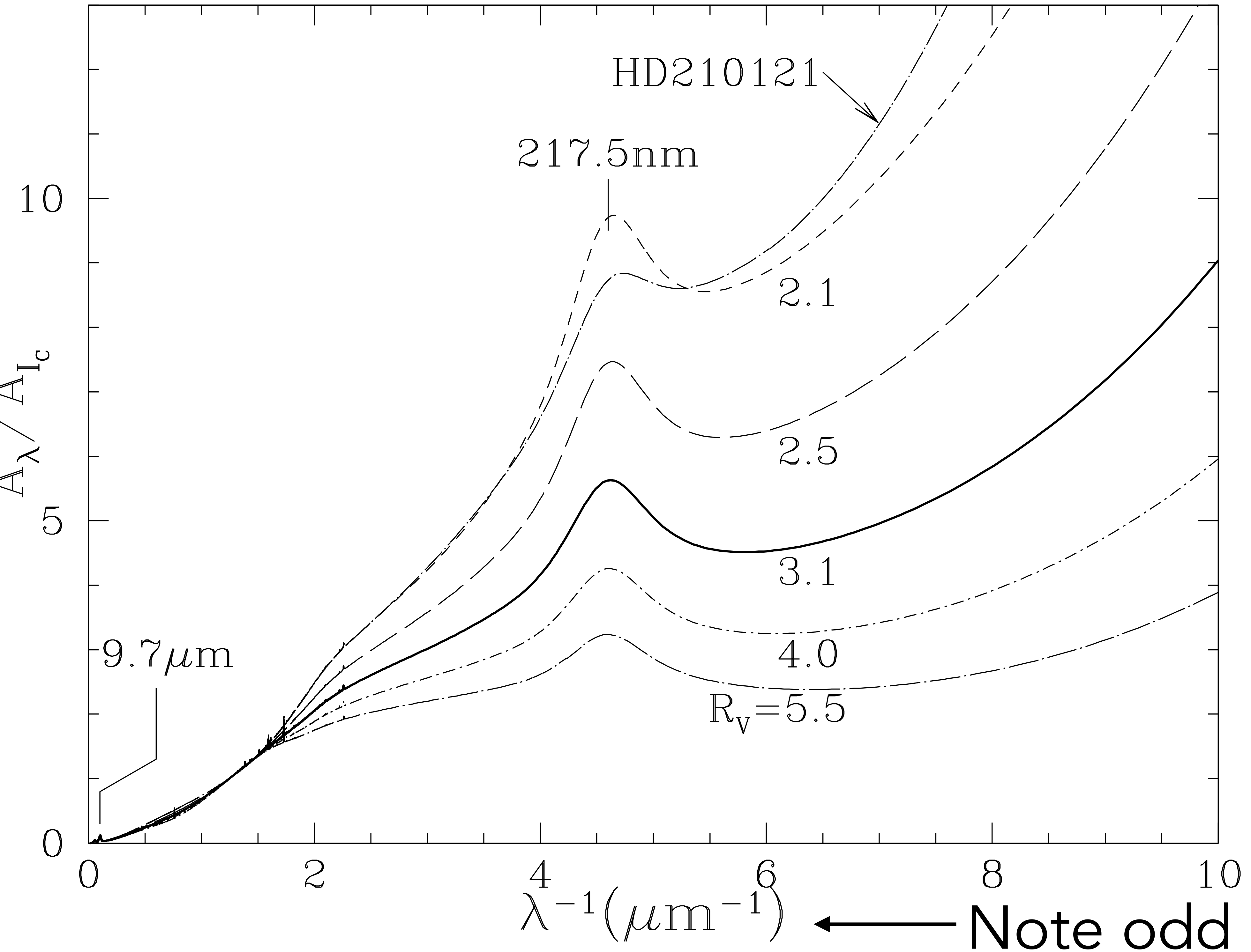
This can be tough to measure, because to know the expected flux we need to know both the stellar spectrum and the distance to the star.

# Milky Way Dust Extinction Curves

long wavelengths short wavelengths

$A_\lambda$ normalized to a long wavelength




Note odd units

# Reddening or "Color Excess"

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If we don't know the distance, we can still measure the change in the color of a star due to dust.

"color" = difference in magnitude at 2 wavelengths for example B band (4405 Å) and V band (5470 Å)

intrinsic $$(B-V)_0 = 2.5\log_{10}[F_B^0/F_V^0]$$

observed $$(B-V) = 2.5\log_{10}[F_B/F_V]$$

dependence on distance cancels, since it is the same at both wavelengths

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$$E(B-V) = (B-V)_0 - (B-V) = 2.5\log_{10}\left[\frac{F_B^0/F_V^0}{F_B/F_V}\right]$$

"color excess" or "reddening"

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rearrange this

$$E(B-V) = 2.5\log_{10}[F_B^0/F_B] - 2.5\log_e[F_V^0/F_V] = A_B - A_V$$