Physics 224
The Interstellar Medium

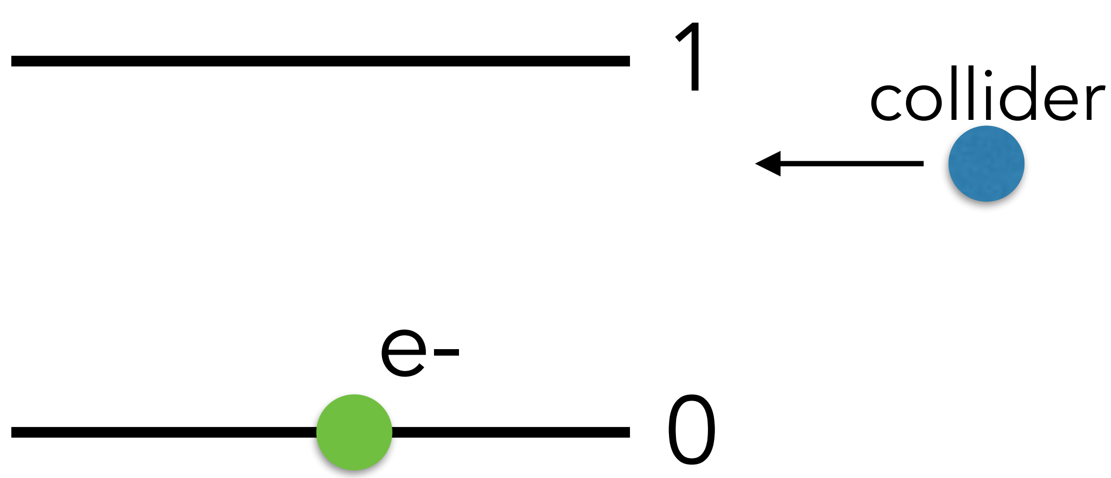
Lecture #10

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


HII Region:
Photoionized gas surrounding
young, hot stars
Credit: NASA,ESA, M. Robberto (Space Telescope Science Institute/ESA)
and the Hubble Space Telescope Orion Treasury Project Team

Collisional Excitation

Two Level Atom



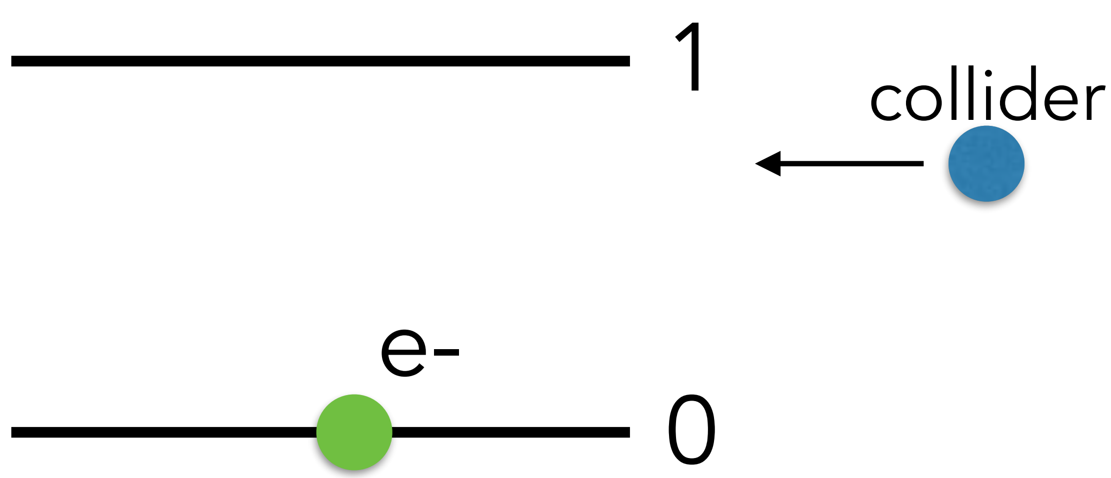
Assume no background radiation field
(i.e. ignore stimulated emission)

dn_1/dt = (rate of collisions from 0 to 1) -
(rate of collisions from 1 to 0) -
(spontaneous emission from 1 to 0)

*per volume

Collisional Excitation

Two Level Atom



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(i.e. ignore stimulated emission)

dn_1/dt = (rate of collisions from 0 to 1) -
(rate of collisions from 1 to 0) -
(spontaneous emission from 1 to 0)

$dn_1/dt = n_c\, n_0\, k_{01} -$
$n_c\, n_1\, k_{10} -$
$n_1\, A_{10}$

*per volume

Collisional Excitation

$$\frac{n_1}{n_0} = \left(\frac{1}{1 + A_{10}/(n_c k_{10})} \right) \frac{g_1}{g_0} e^{-E_{10}/kT_{\rm gas}}$$

Collisional Excitation

$$\frac{n_1}{n_0} = \left(\frac{1}{1 + A_{10}/(n_c k_{10})}\right) \frac{g_1}{g_0} e^{-E_{10}/kT_{\rm gas}}$$

define "critical density"

ratio of collisional to spontaneous rates
that depopulate level 1

$$n_{\rm crit} = \frac{A_{10}}{k_{10}}$$

Collisional Excitation

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$$n_{\rm crit} = \frac{A_{10}}{k_{10}}$$

$$\frac{n_1}{n_0} = \left(\frac{1}{1 + n_{\rm crit}/n_c}\right) \frac{g_1}{g_0} e^{-E_{10}/kT_{\rm gas}}$$

Critical Density

Multi-level atom & including radiation field:

$$n_{\mathrm{crit},u}(c) \equiv \frac{\sum_{l<u}[1 + \langle n_\gamma \rangle_{ul}]A_{ul}}{\sum_{l<u} k_{ul}(c)}$$

ratio of total radiative and collisional depopulation rates to lower levels

note: only good in cases where gas is optically thin to radiation from u->l transition

Nebular Diagnostics

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

Two types:

1) temperature sensitive
2) density sensitive

Nebular Diagnostics

Element	H II and He I zone[b] Ion	$h\nu$ (eV)[d]	H II and He II zone[c] Ion	$h\nu$ (eV)[d]
H	H II	13.60	H II	13.60
He	He I	0	He II	24.59
C	C II	11.26	C III[e]	24.38
			C IV	47.88
N	N II	14.53	N III	29.60
			N IV	47.45
O	O II	13.62	O III	35.12
Ne	Ne II	21.56	Ne III	40.96
Na	(Na II)[f]	5.14	(Na II)[f]	5.14
			Na III	47.29
Mg	Mg II	7.65	(Mg III)[f]	15.04
	(Mg III)[f]	15.04		
Al	Al III	18.83	(Al IV)[f]	28.45
Si	Si III	16.35	Si IV	33.49
			(Si V)[f]	45.14
S	S II	10.36	S III	23.33
	S III	23.33	S IV	34.83
Ar	Ar II	15.76	Ar III	27.63
			Ar IV	40.74
Ca	Ca III	11.87	Ca IV	50.91
Fe	Fe III	16.16	Fe IV	30.65
Ni	Ni III	18.17	Ni IV	35.17

First note which atoms and ions will be abundant in HII regions.

pick elements where $N_X/N_H > 10^{-6}$

[a] Limited to elements X with $N_X/N_H > 10^{-6}$.
[b] Ions that can be created by radiation with $13.60 < h\nu < 24.59$ eV.
[c] Ions that can be created by radiation with $24.59 < h\nu < 54.42$ eV.
[d] Photon energy required to create ion.
[e] Ionization potential is just below 24.59 eV.
[f] Closed shell, with no excited states below 13.6 eV.

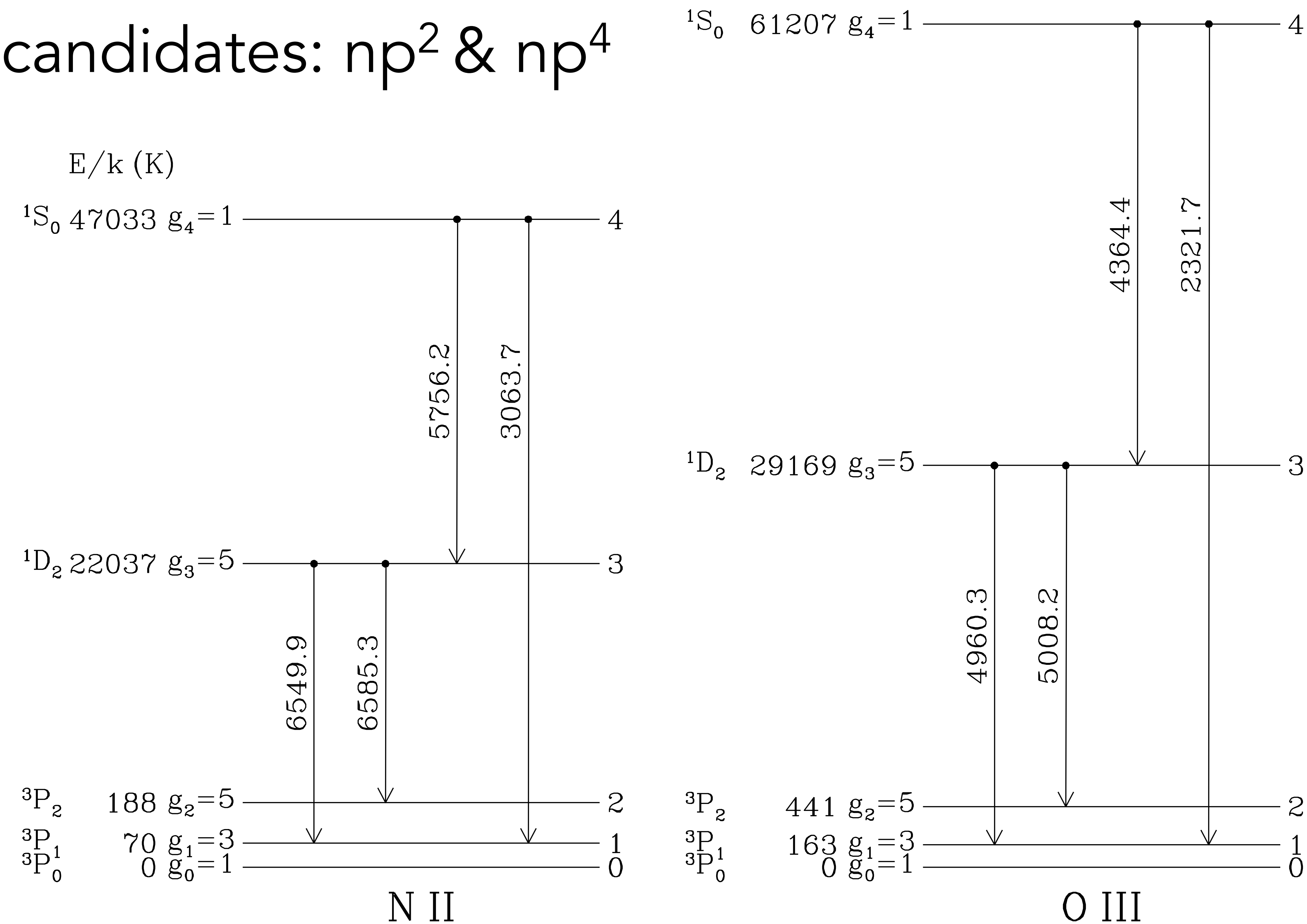
Temperature Sensitive Line Ratios

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

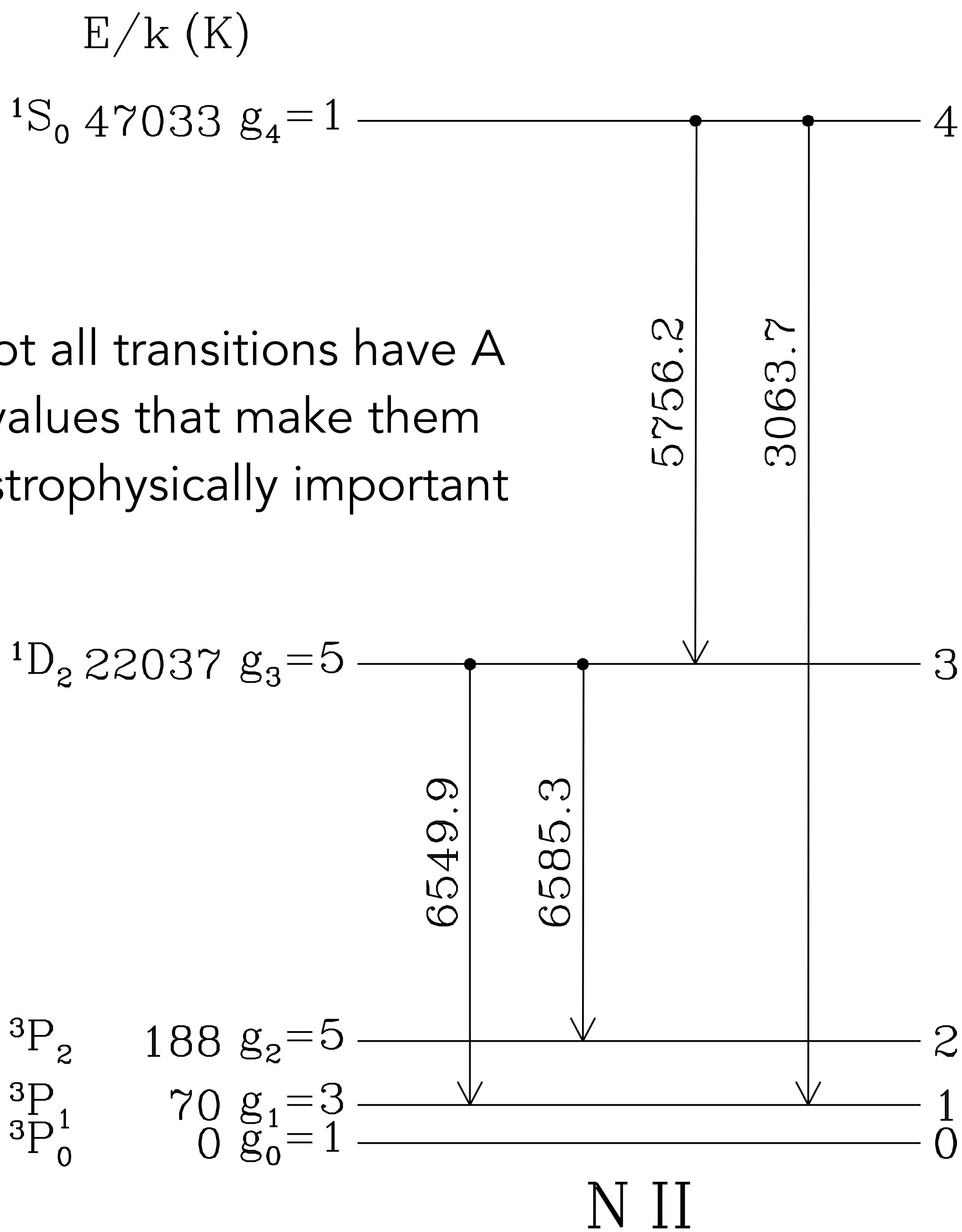
CI,OI don't exist in HII regions (carbon is ionized)

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



$n_{crit,4} \sim 10^7$ cm^{-3}

$n_{crit,3} \sim 7.7\text{x}10^4$ cm^{-3}

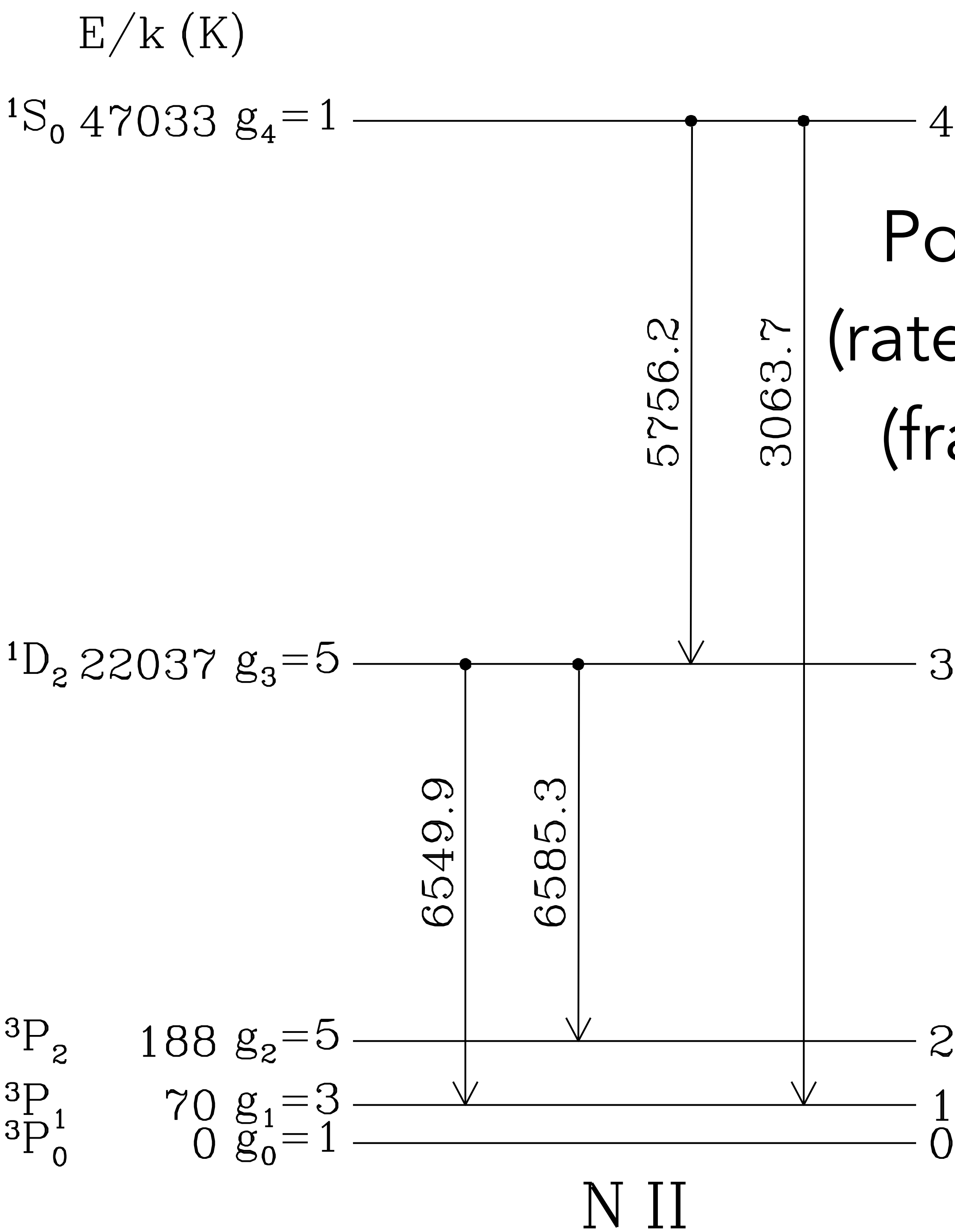
not all transitions have A values that make them astrophysically important

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

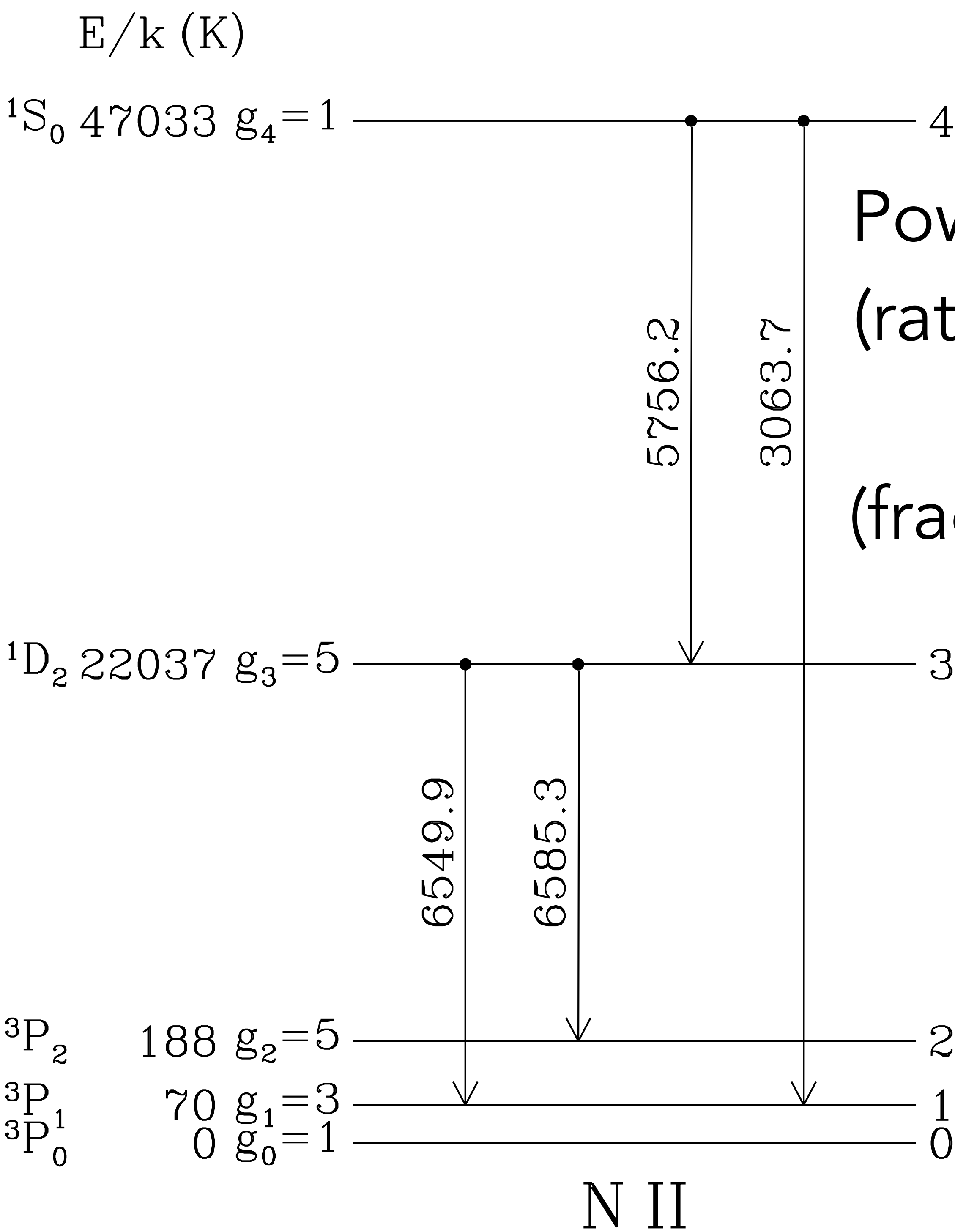


Power from 4-3 transition per volume =
(rate of collisions per vol that populate 4) x
(fraction of radiative transitions in 4-3) x
(energy of 4-3 transition)

$P(4 \rightarrow 3) =$
$n_0 \, n_e \, k_{04}$ x
$A_{43}/(A_{43}+A_{41})$ x
E_{43}

*note: collision rate from 0,1,2 are all ~equal and energy difference is negligible so treat all in 0

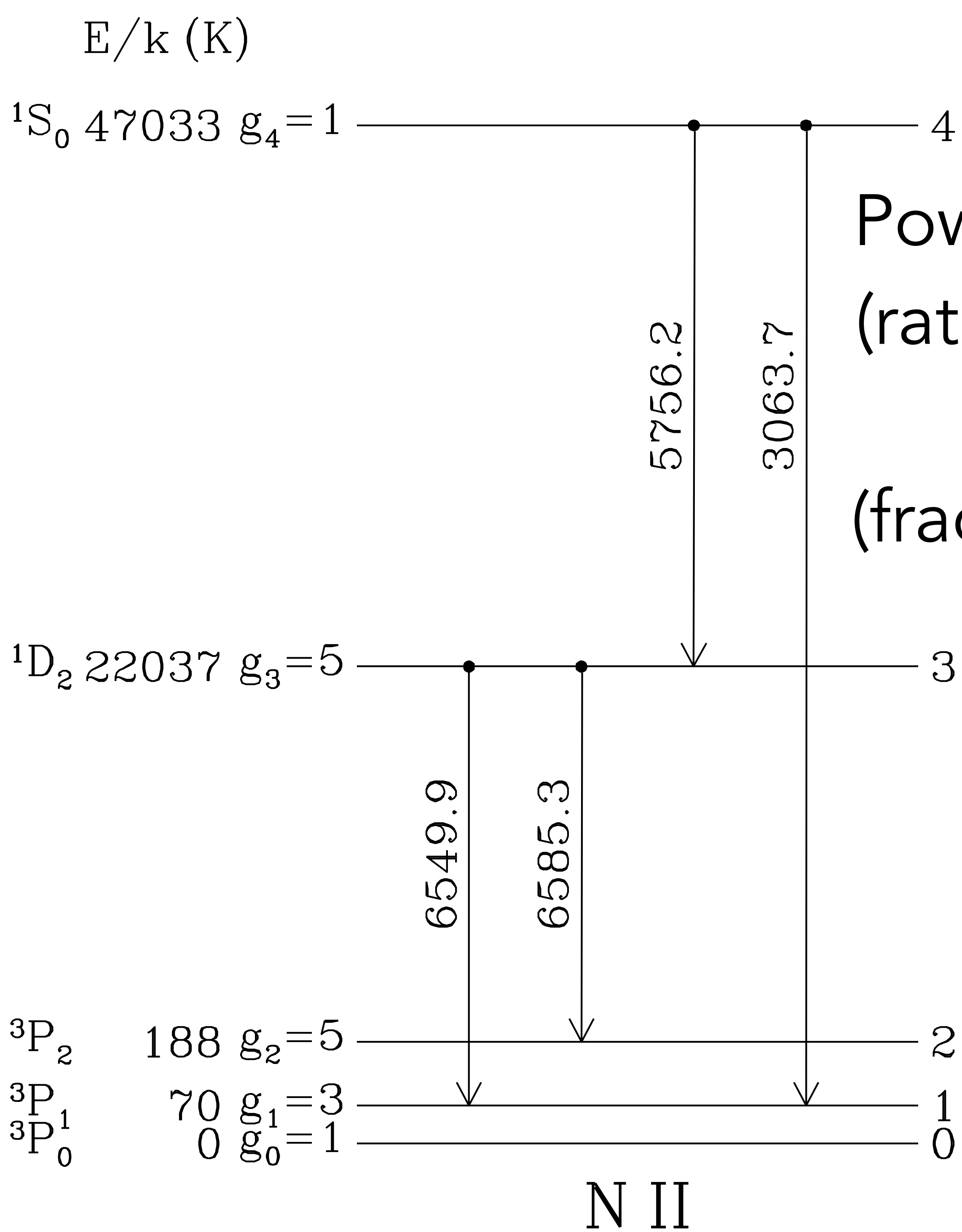
Temperature Sensitive Line Ratios



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

$$P(3 \rightarrow 2) = n_0 n_e (k_{03} + k_{04} A_{43}/(A_{43}+A_{41})) \times A_{32}/(A_{32}+A_{31}) \times E_{32}$$

Temperature Sensitive Line Ratios



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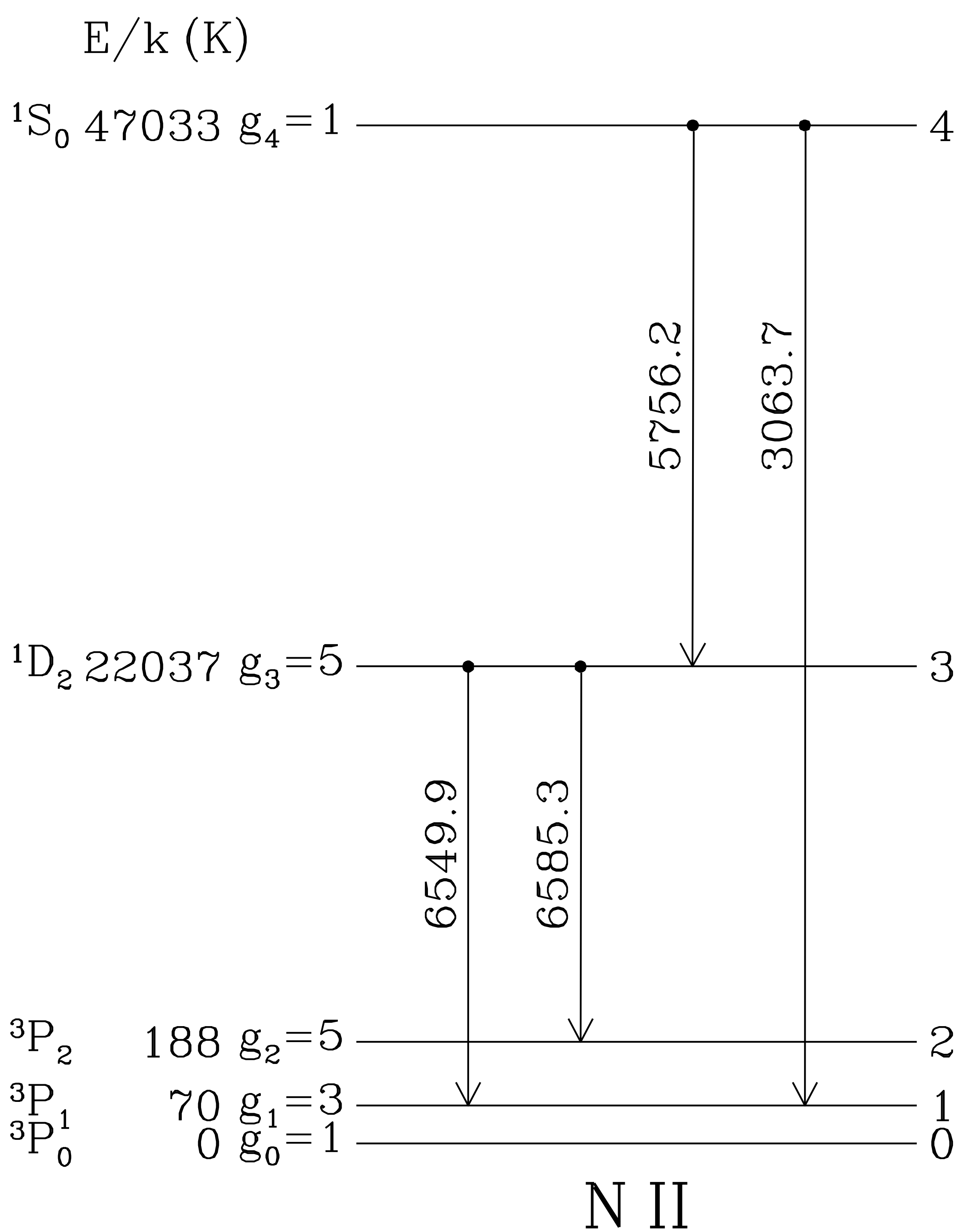
$n_0 \, n_e \, (k_{03} + k_{04} A_{43}/(A_{43}+A_{41})) \times$

$A_{32}/(A_{32}+A_{31}) \times$

E_{32}

Temperature Sensitive Line Ratios



Line Ratio:

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

Temperature Sensitive Line Ratios

Collisional rate coefficient for exctiation/de-excitation:

$$k_{ul} = \langle \sigma v \rangle_{u \to l} \equiv \frac{h^2}{(2\pi m_e)^{3/2}} \frac{1}{(kT)^{1/2}} \frac{\Omega_{ul}(T)}{g_u}$$

Define “collision strength” Ω_{ul}

separates gas temperature from atomic properties

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

Temperature Sensitive Line Ratios

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

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

Only density insensitive below the critical density.

Temperature Sensitive Line Ratios

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quantum mechanics

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Temperature Sensitive Line Ratios

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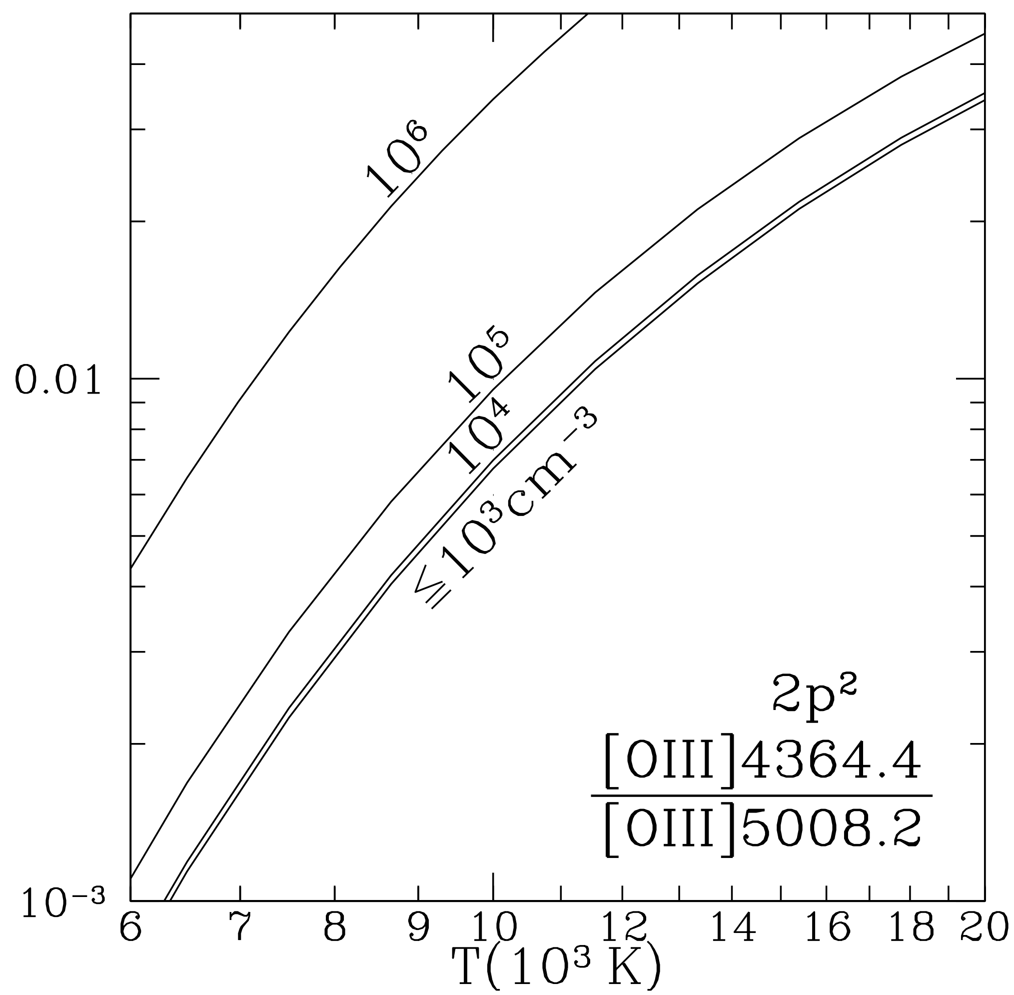
quantum mechanics

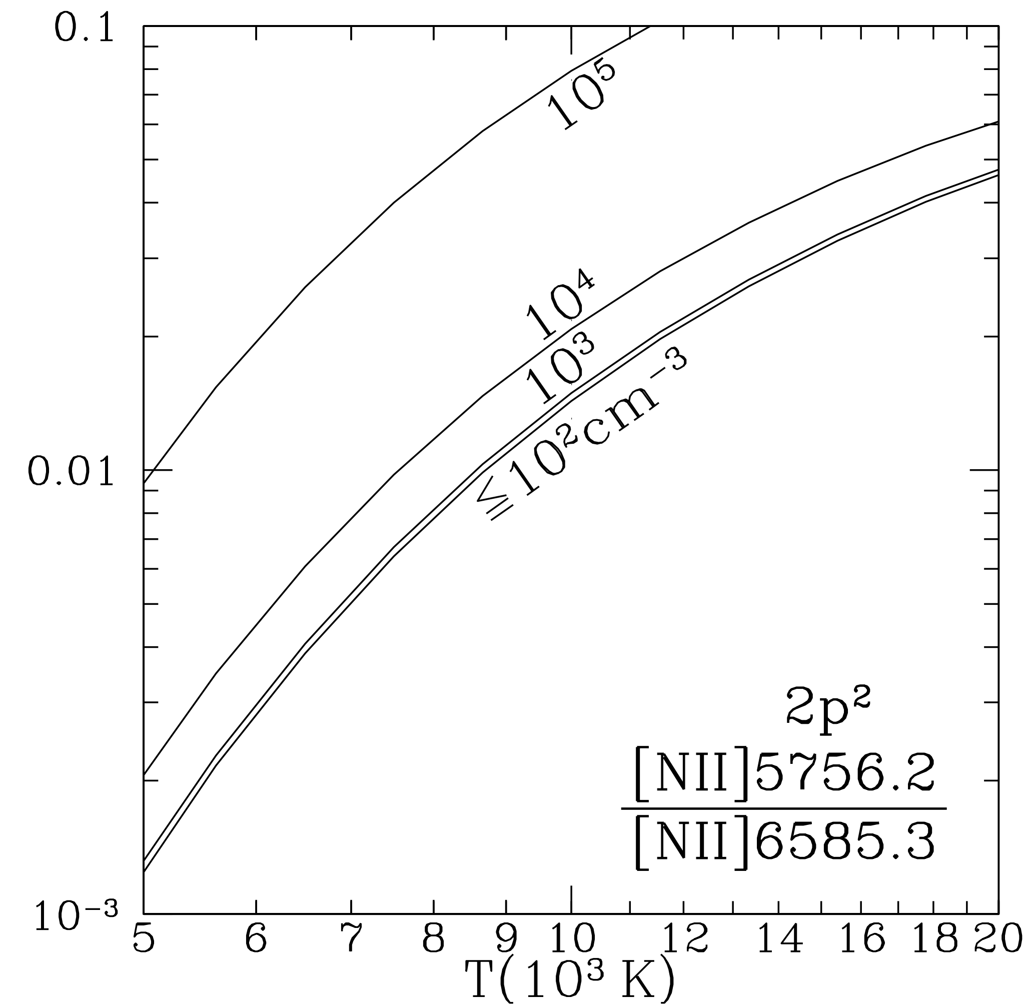
gas temperature

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

Only density insensitive below the critical density.

Temperature Sensitive Line Ratios





Why this behavior at high n?

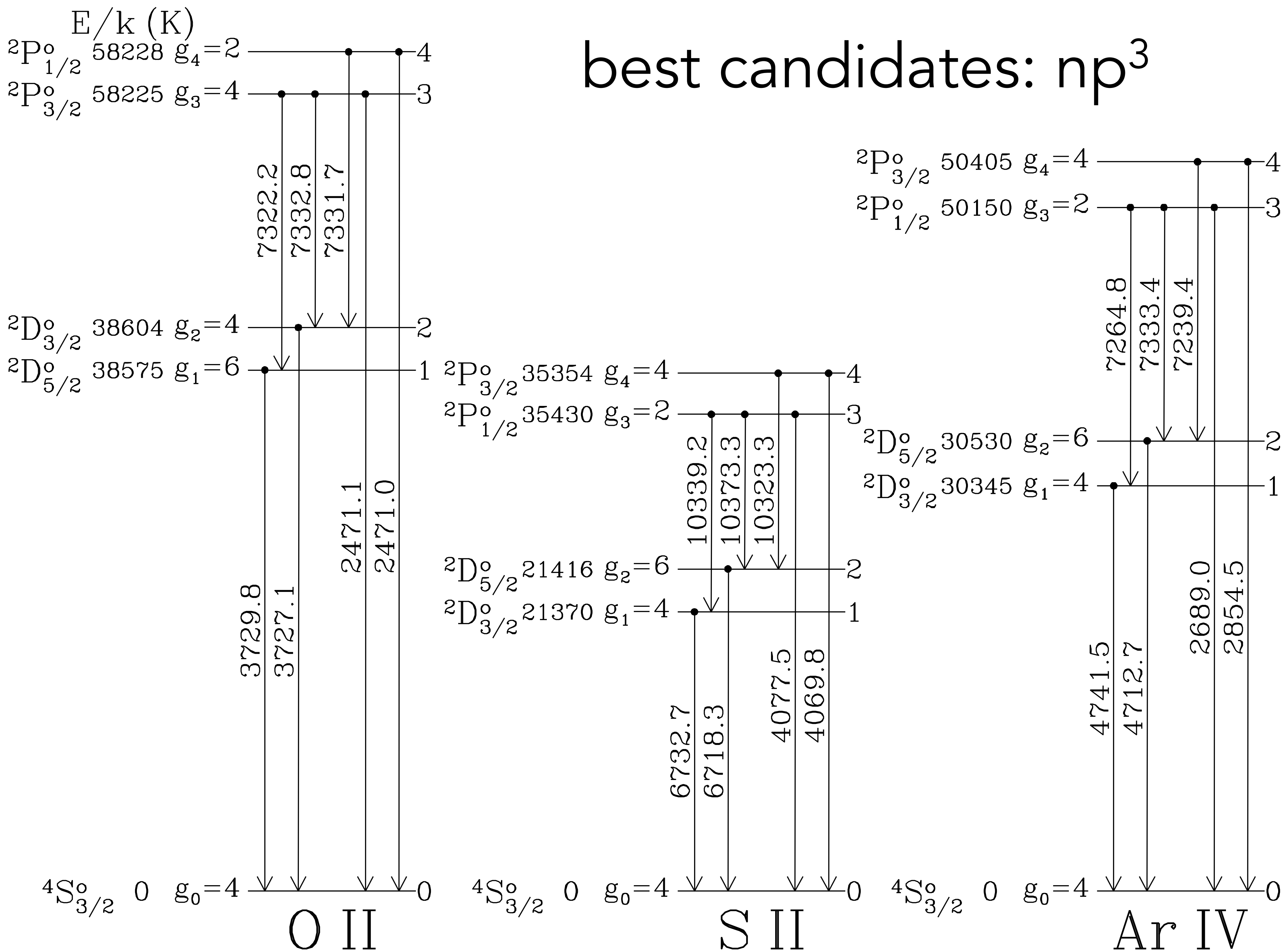
for [NII]: $n_{crit,5756.2}$ ~ 10^7 cm^{-3} and $n_{crit,6585.3}$ ~ 7.7×10^4 cm^{-3}

Density Sensitive Line Ratios

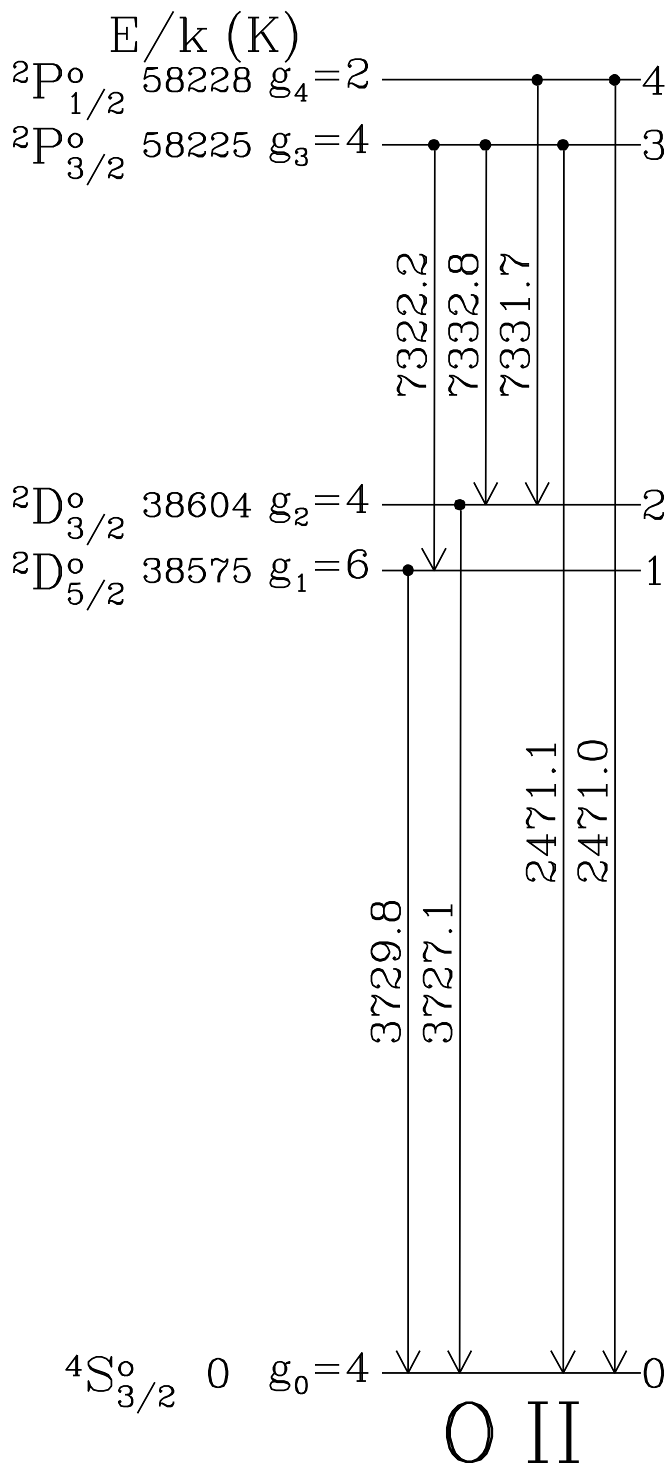
What we want:
two levels at approximately the same energy
that can be collisionally excited so that
line ratio doesn't depend on temperature but
does depend on collisional excitation rate

Density Sensitive Line Ratios

best candidates: np^3



Density Sensitive Line Ratios



Lets look at 2→0 and 1→0 transitions

Low Density Limit

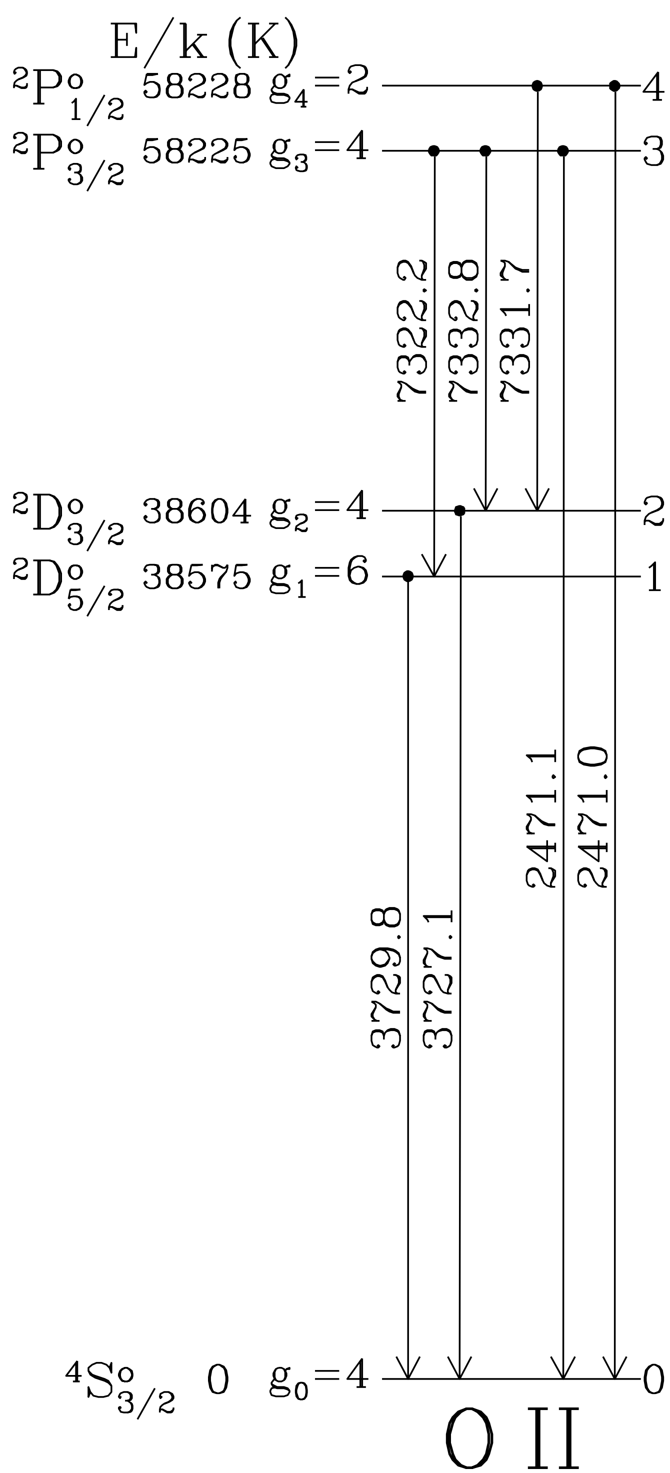
at low densities, every collisional excitation leads to a radiative transition

$P(2 \rightarrow 0) = n_0\, n_e\, k_{02}\, E_{20}$

$P(1 \rightarrow 0) = n_0\, n_e\, k_{01}\, E_{10}$

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

Density Sensitive Line Ratios



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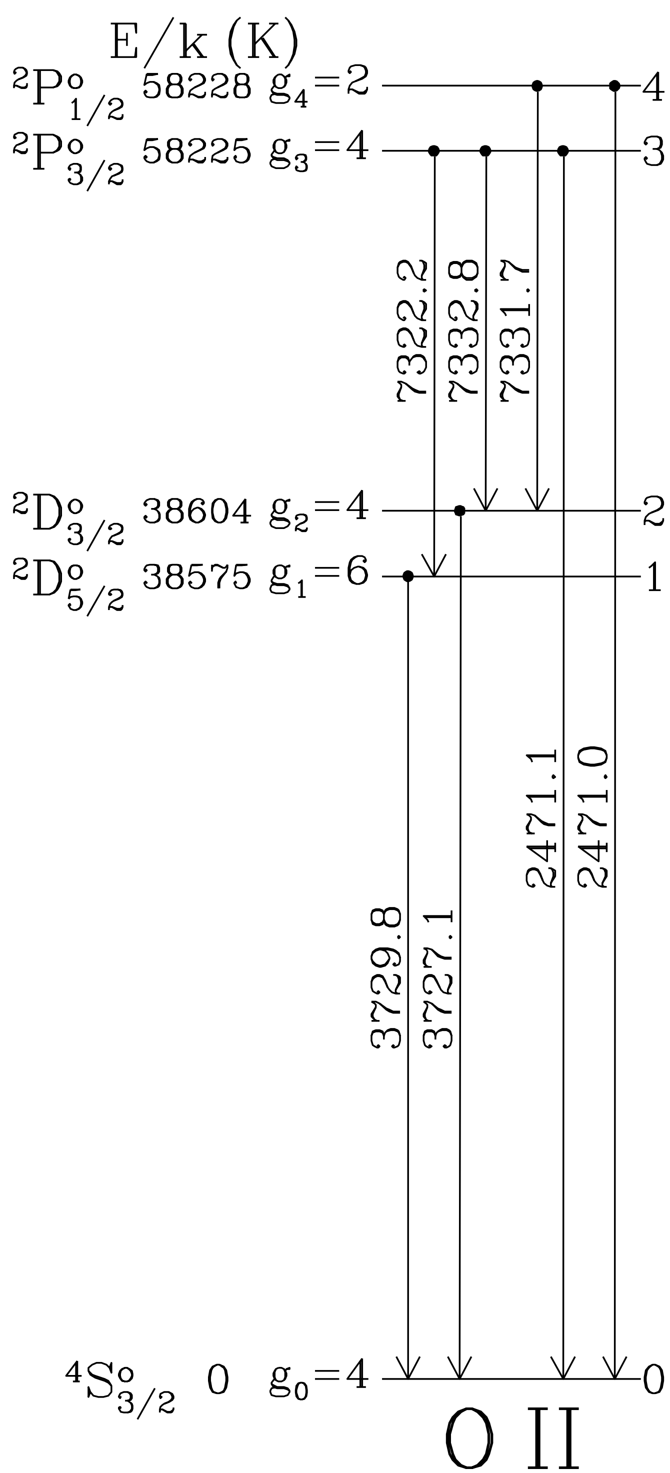
approximately equal

Density Sensitive Line Ratios



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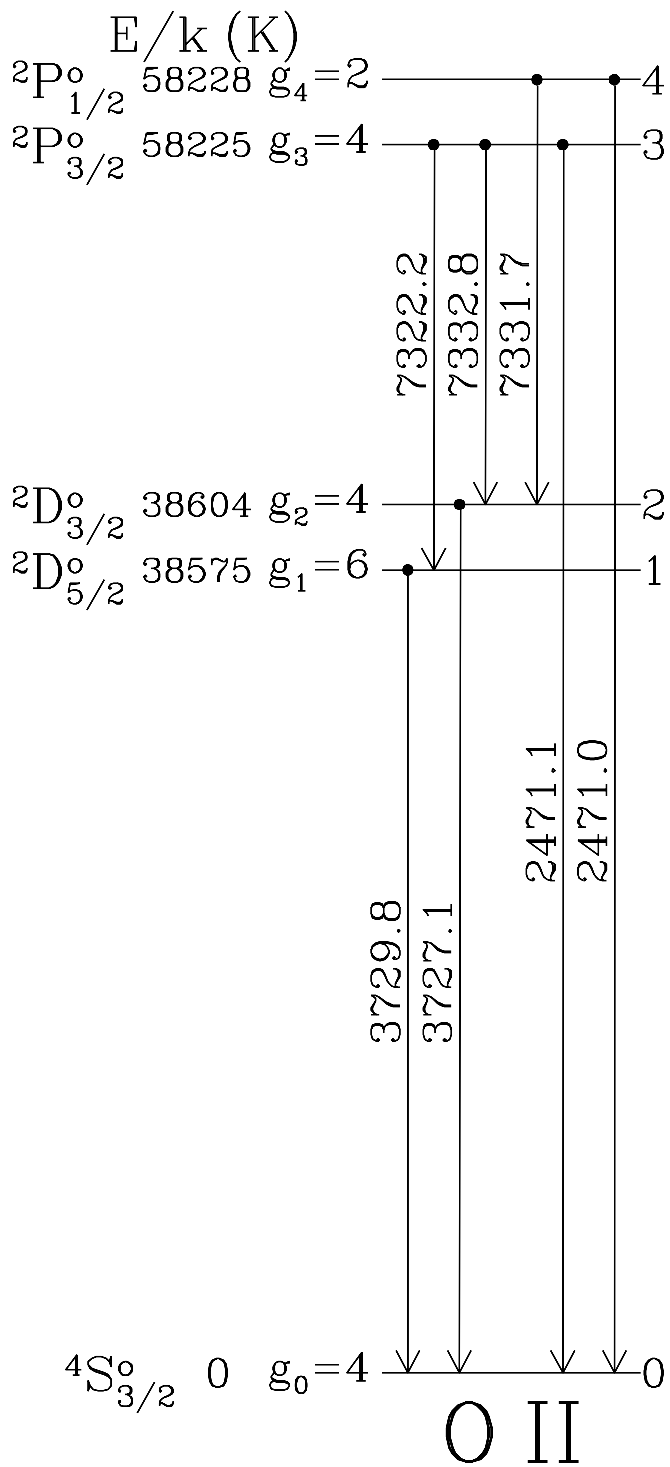
approximately equal ~1

Density Sensitive Line Ratios



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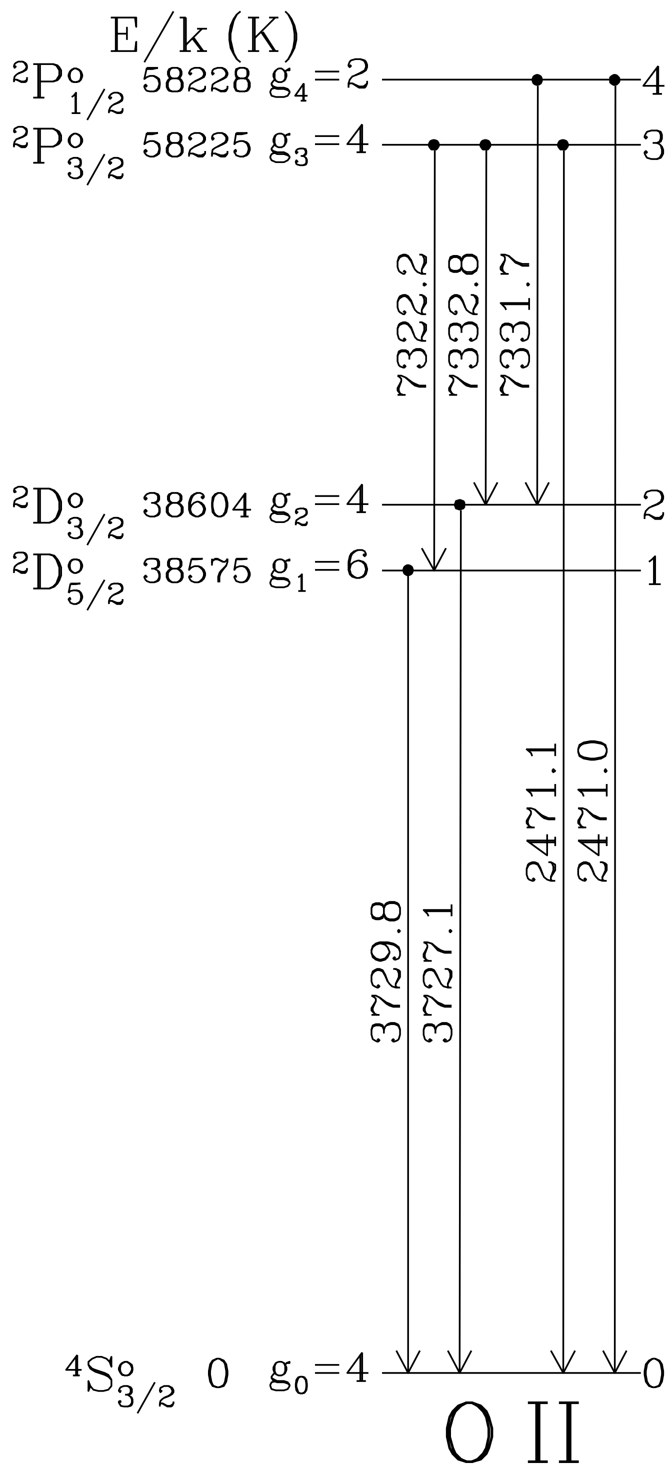
approximately equal ~1

Density Sensitive Line Ratios



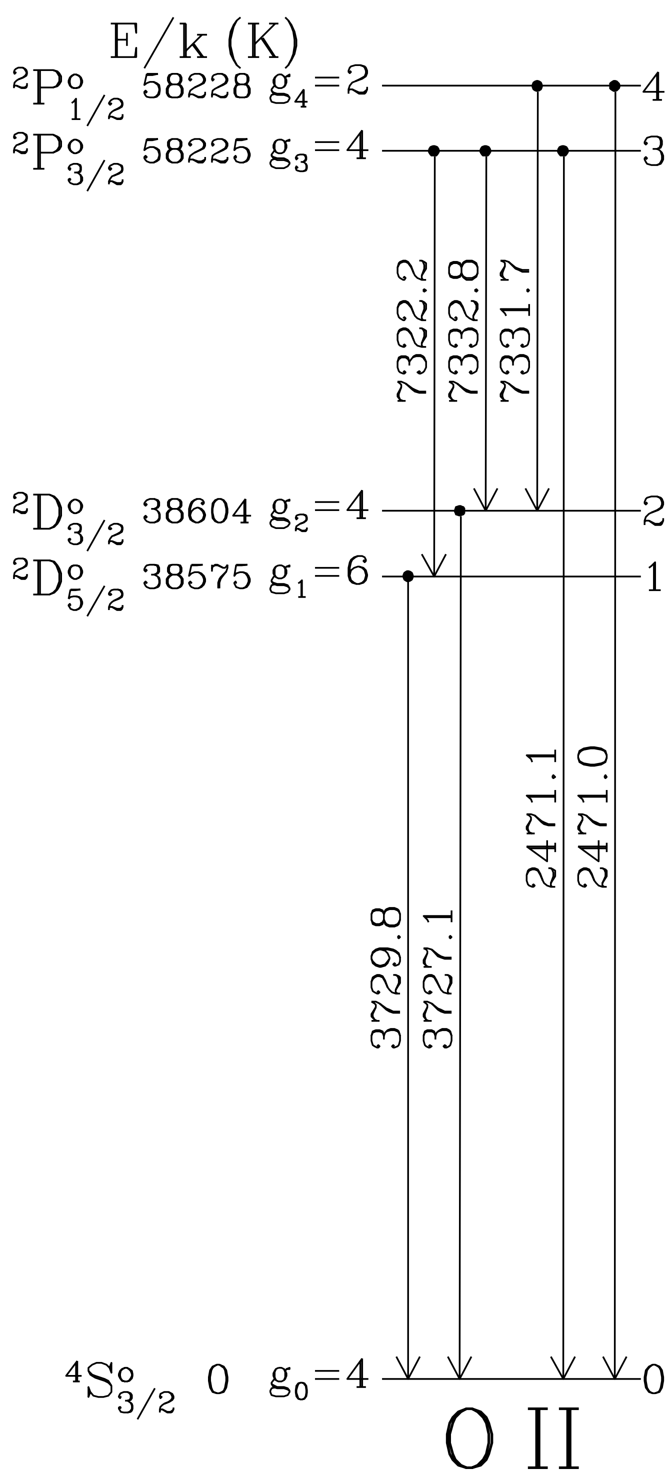
Lets look at 2→0 and 1→0 transitions

<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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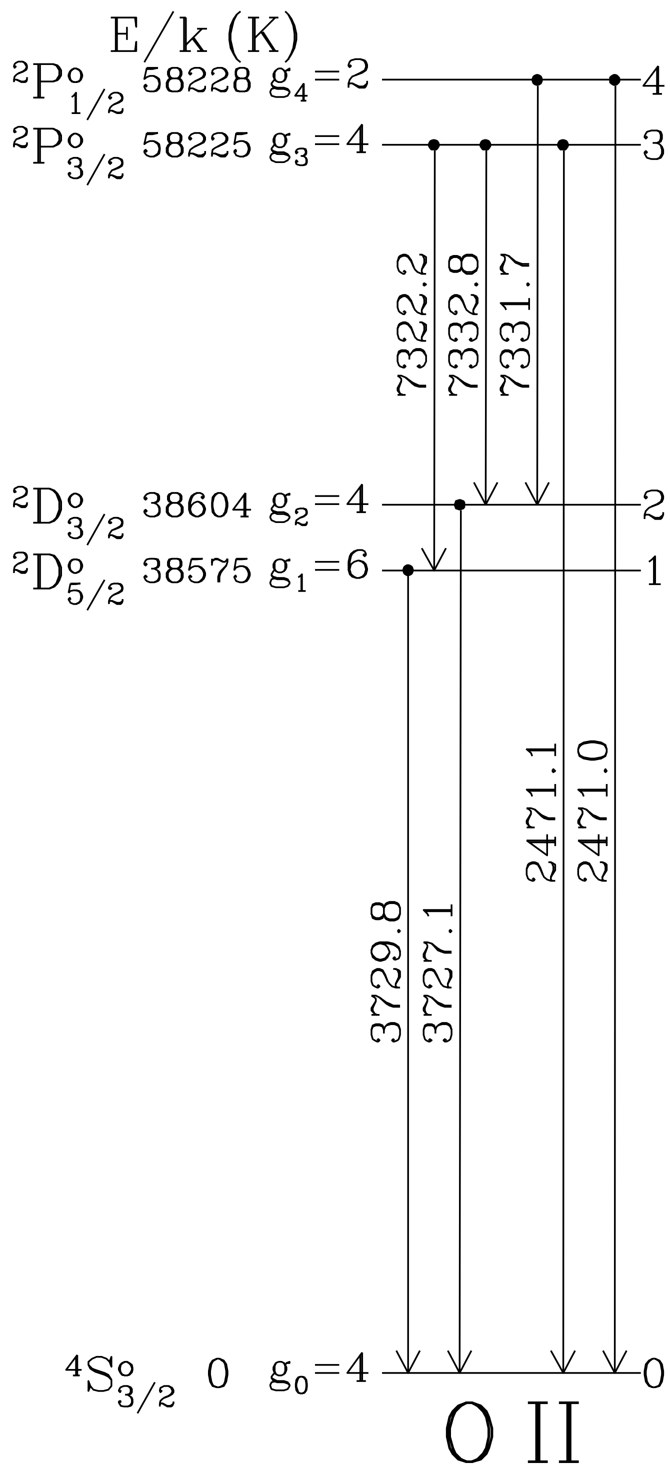
~1

Density Sensitive Line Ratios



Lets look at 2→0 and 1→0 transitions

<u>High Density Limit</u>

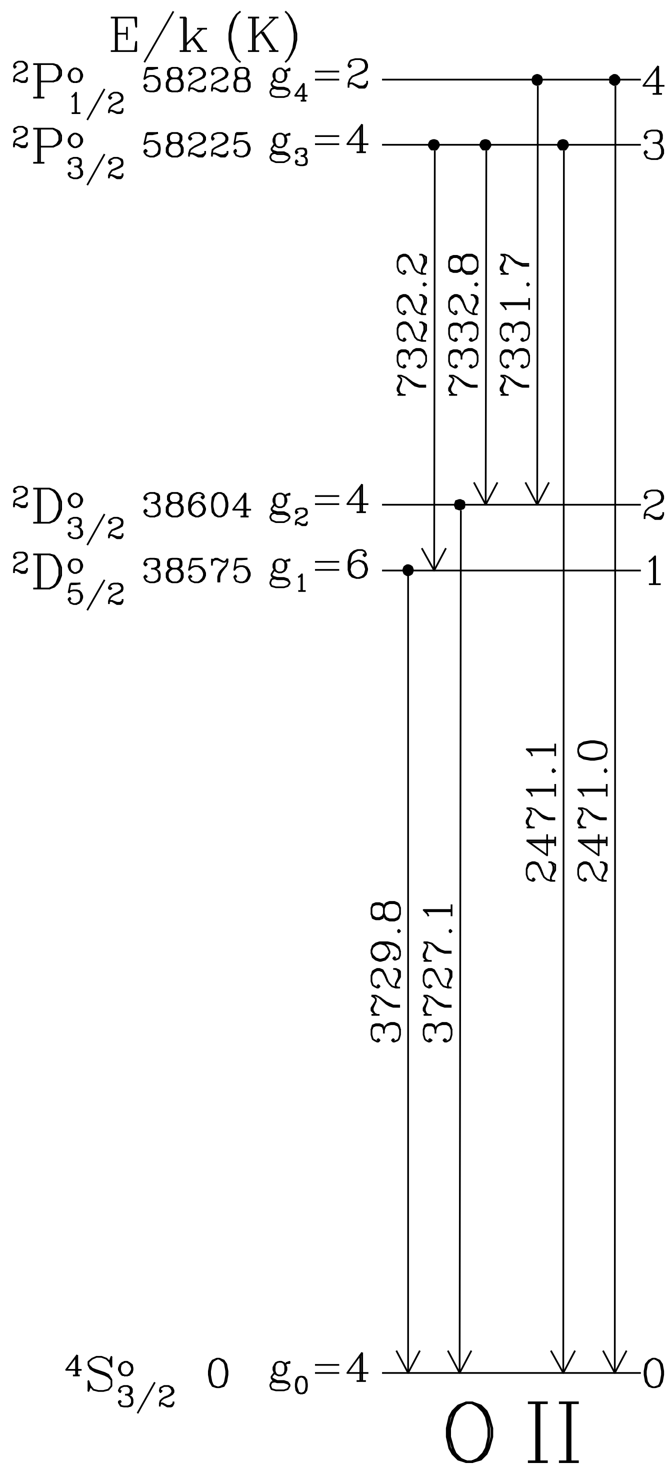
Rate of spontaneous emission:

(2→0): $n_2 A_{20}$

(1→0): $n_1 A_{10}$

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

Density Sensitive Line Ratios



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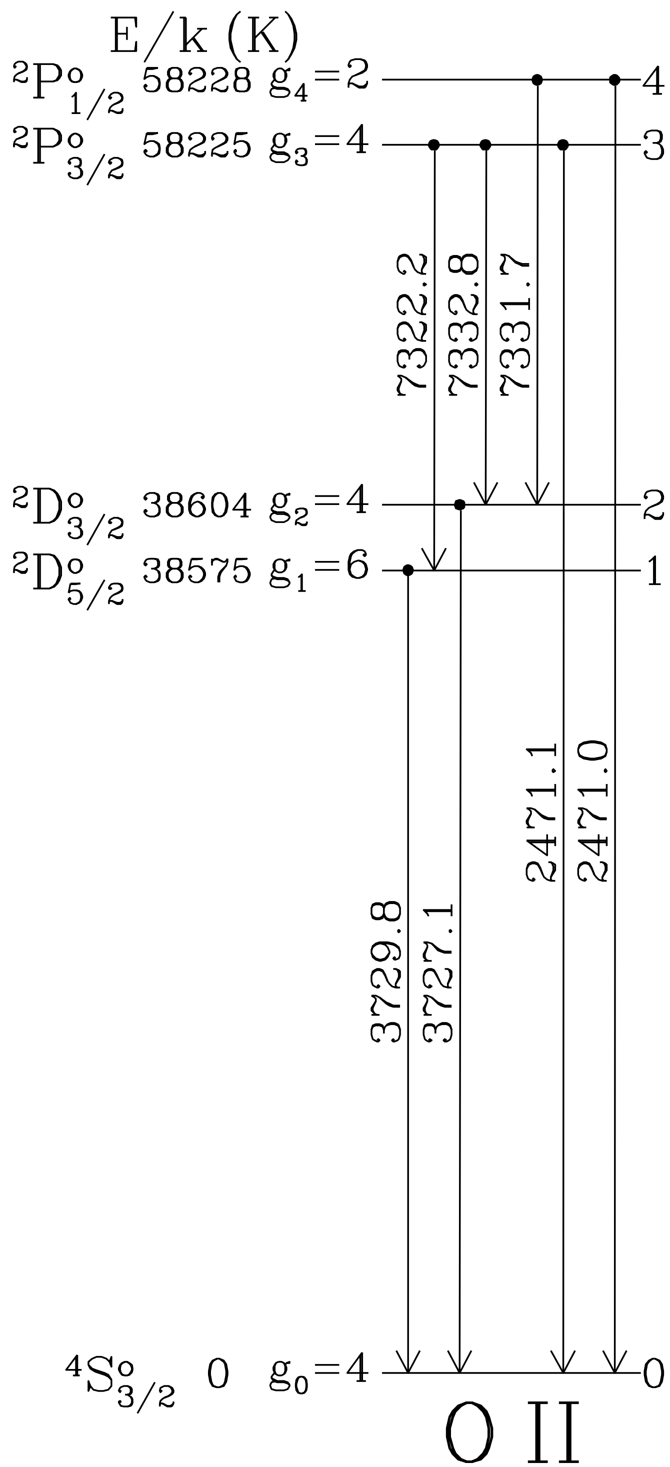
Density Sensitive Line Ratios



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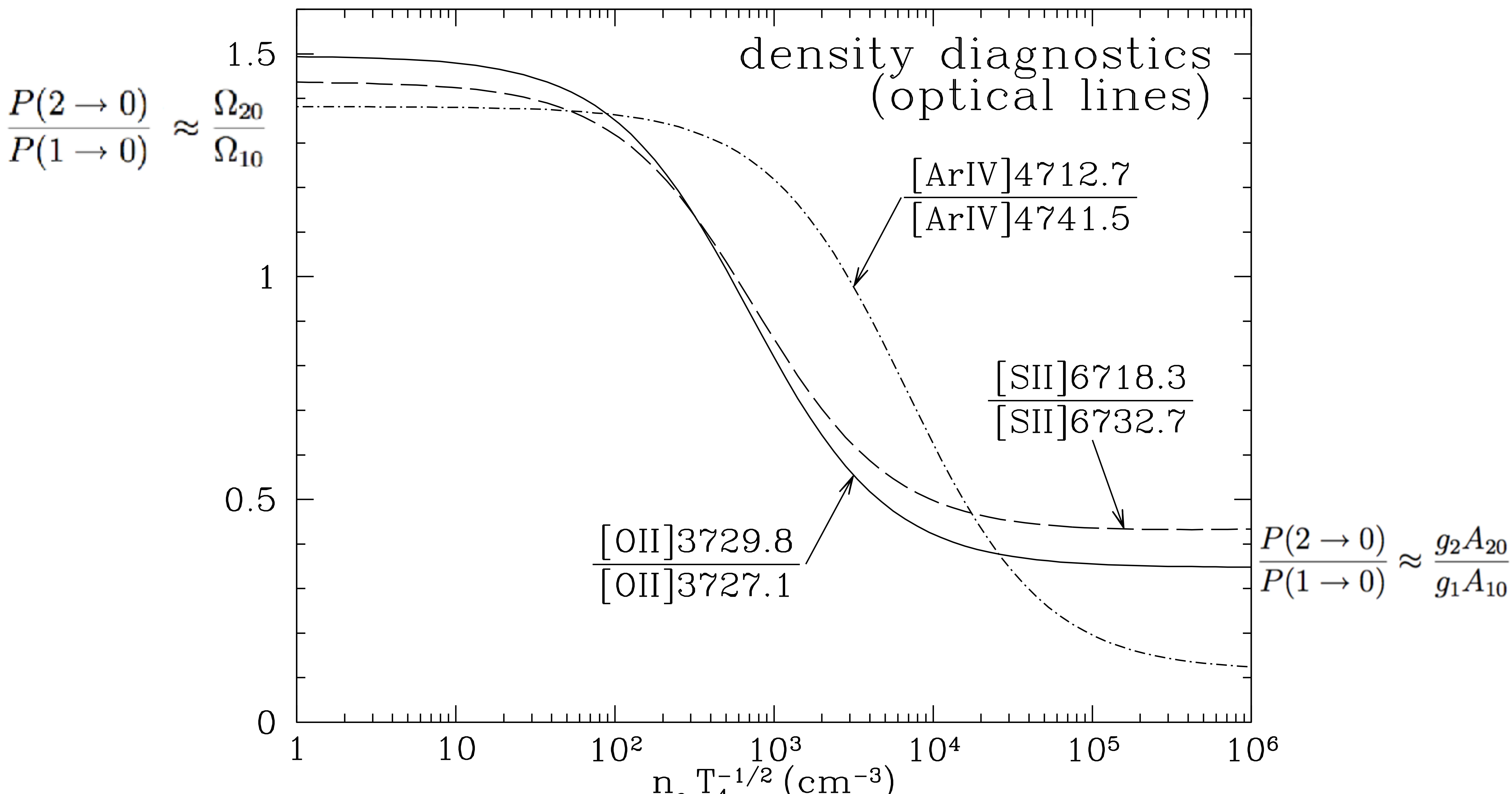
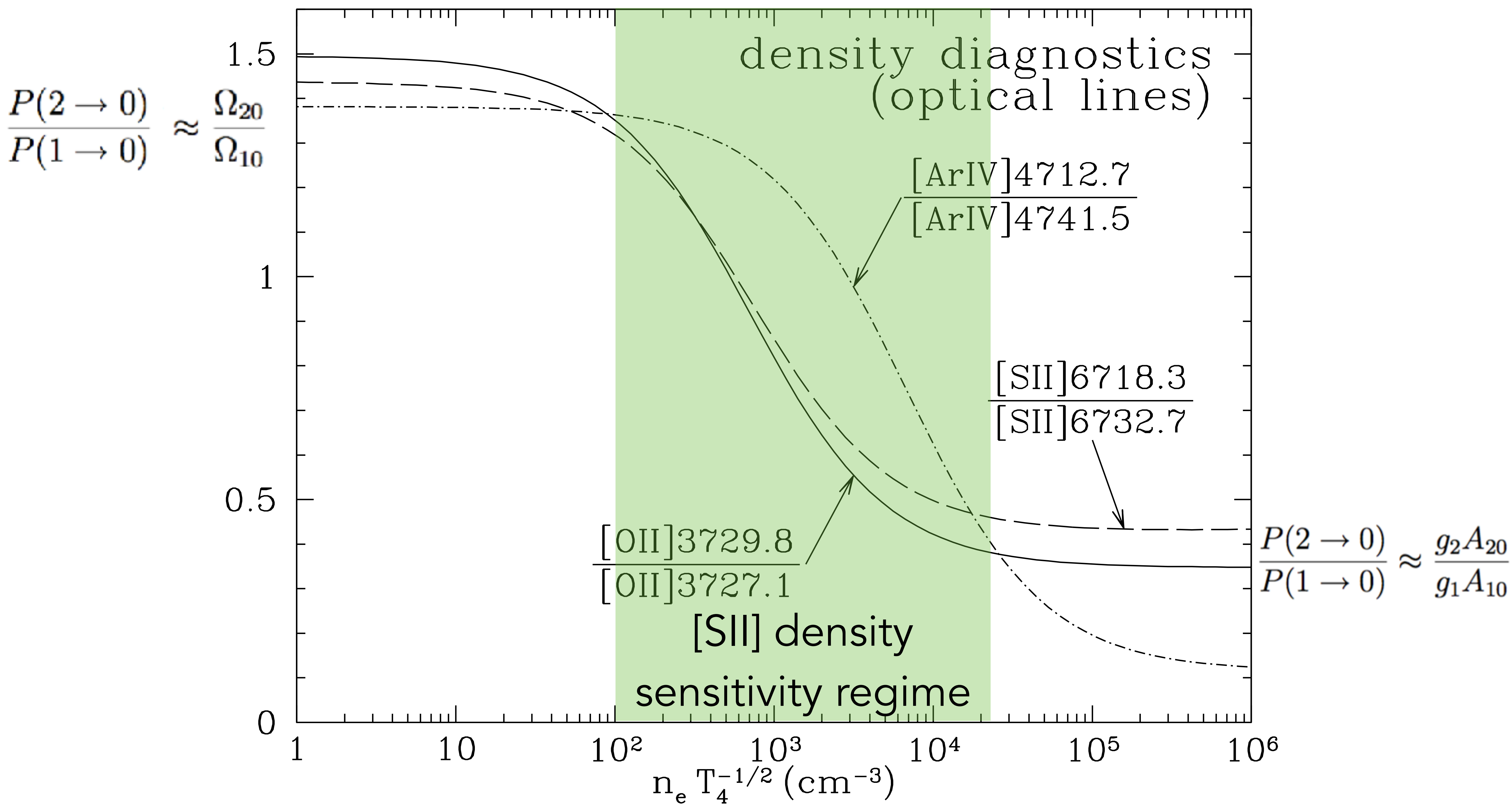
Density Sensitive Line Ratios



Density Sensitive Line Ratios



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

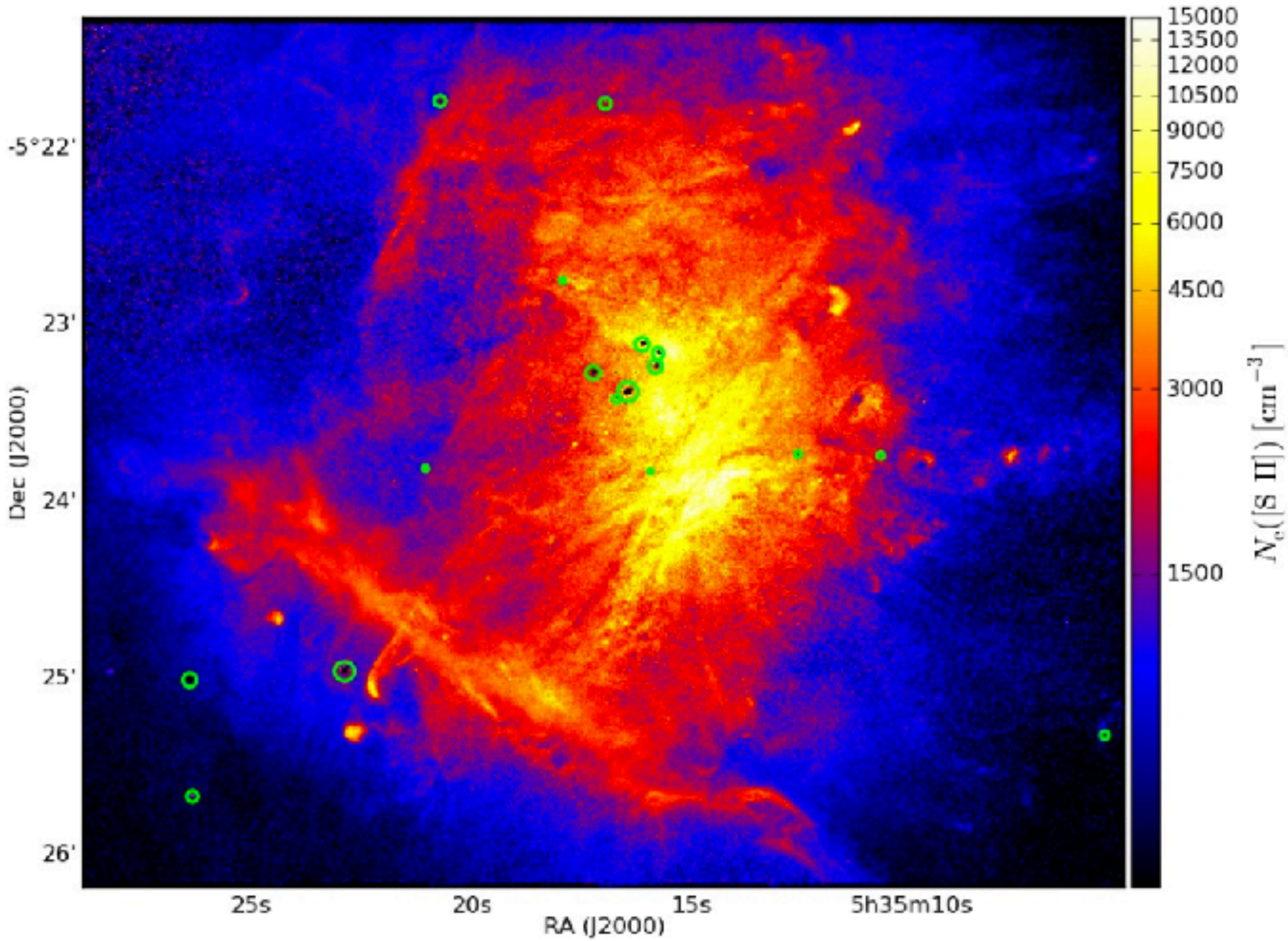


Fig. 26. [S II]-derived N_e-map of the central Orion Nebula, smoothed by a median filter of 3×3 pixels box width, displayed in asinh scaling.

Part II: 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
per unit volume

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

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.

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

ψ ~1 across a wide range of T_c

because most photons are emitted near kT_c

Heating

heating rate
per unit volume

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

Depends on density of species being ionized.

Heating

heating rate
per unit volume

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

Heating

heating rate
per unit volume

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

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

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

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

Cooling

Recombination removes kinetic energy from the gas

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

cooling rate
per unit volume

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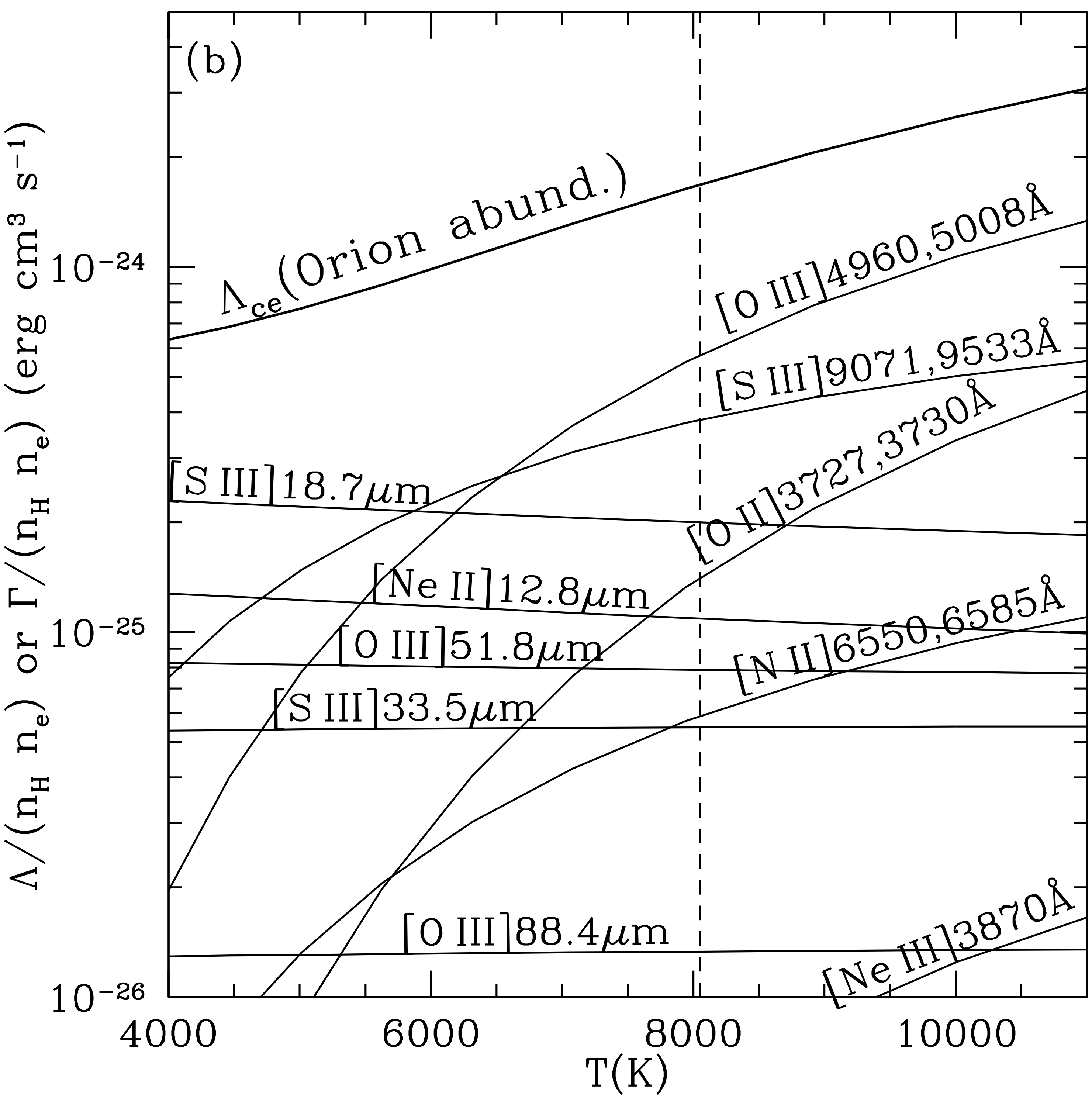
average energy of recombining electron

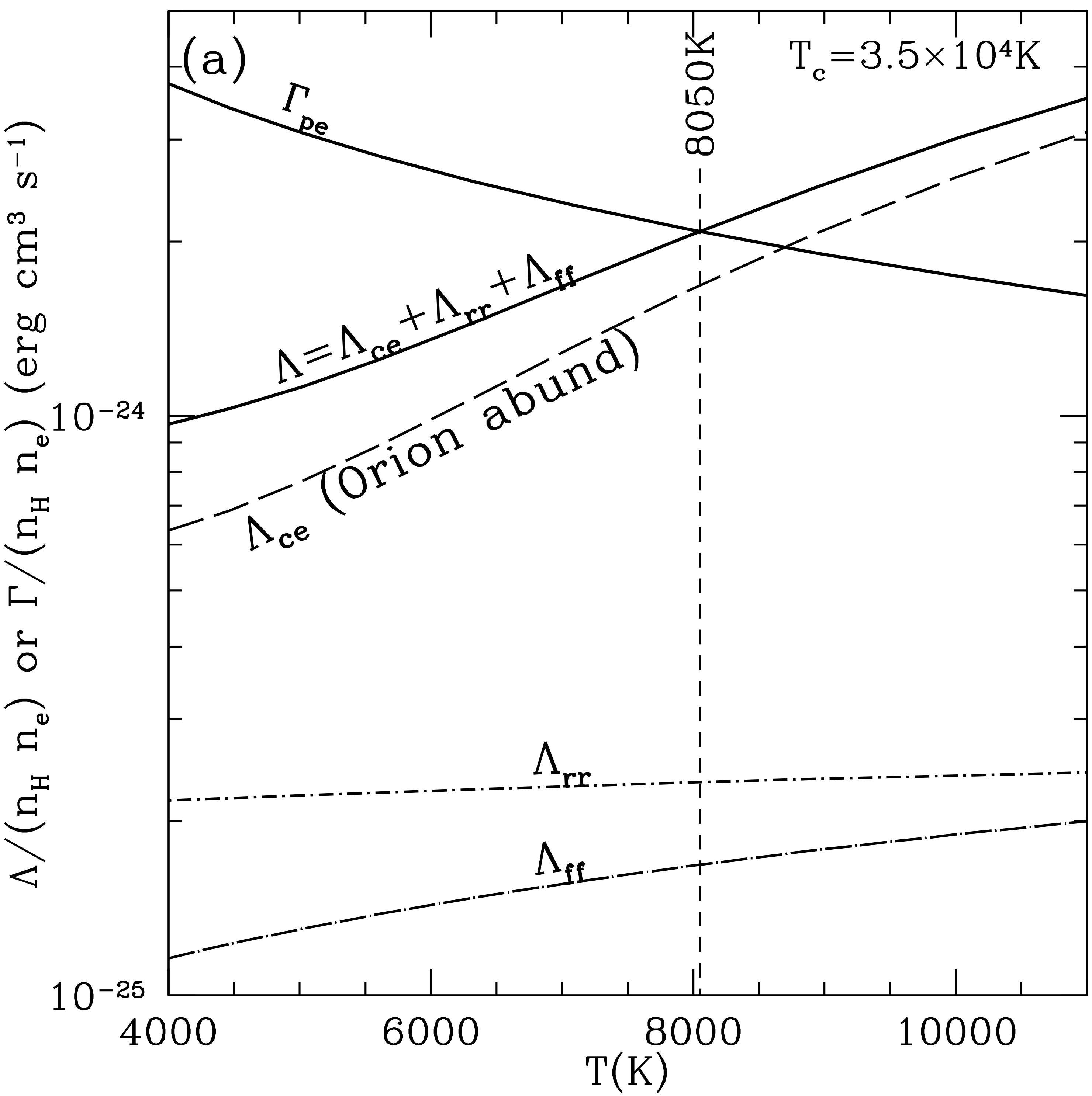
$\langle E_{rr} \rangle$ < mean electron kinetic energy of the gas because the recombination cross section is weighted towards low energy electrons!

Cooling



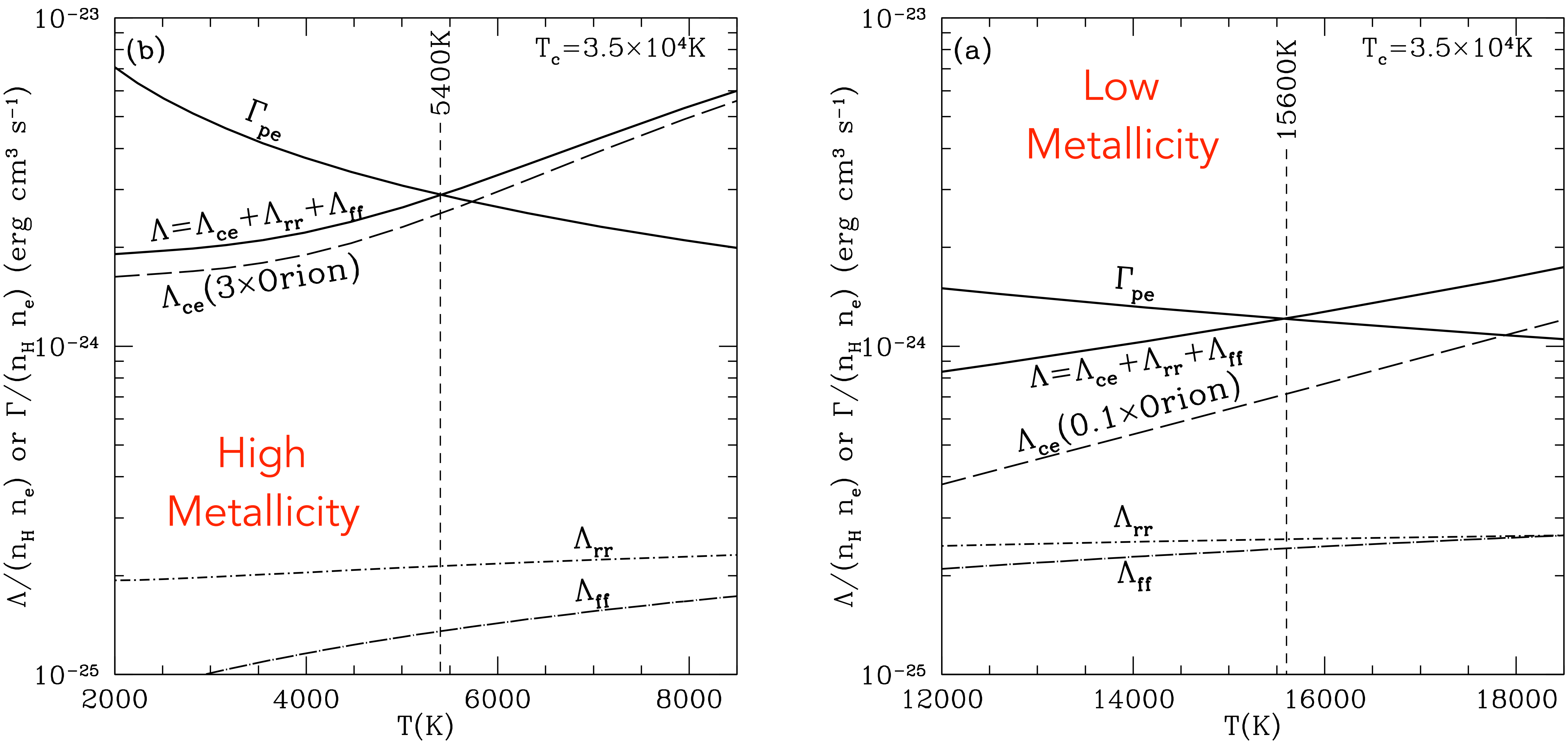
Cooling from collisionally excited emission lines is the most important coolant of HII regions.

Thermal Balance



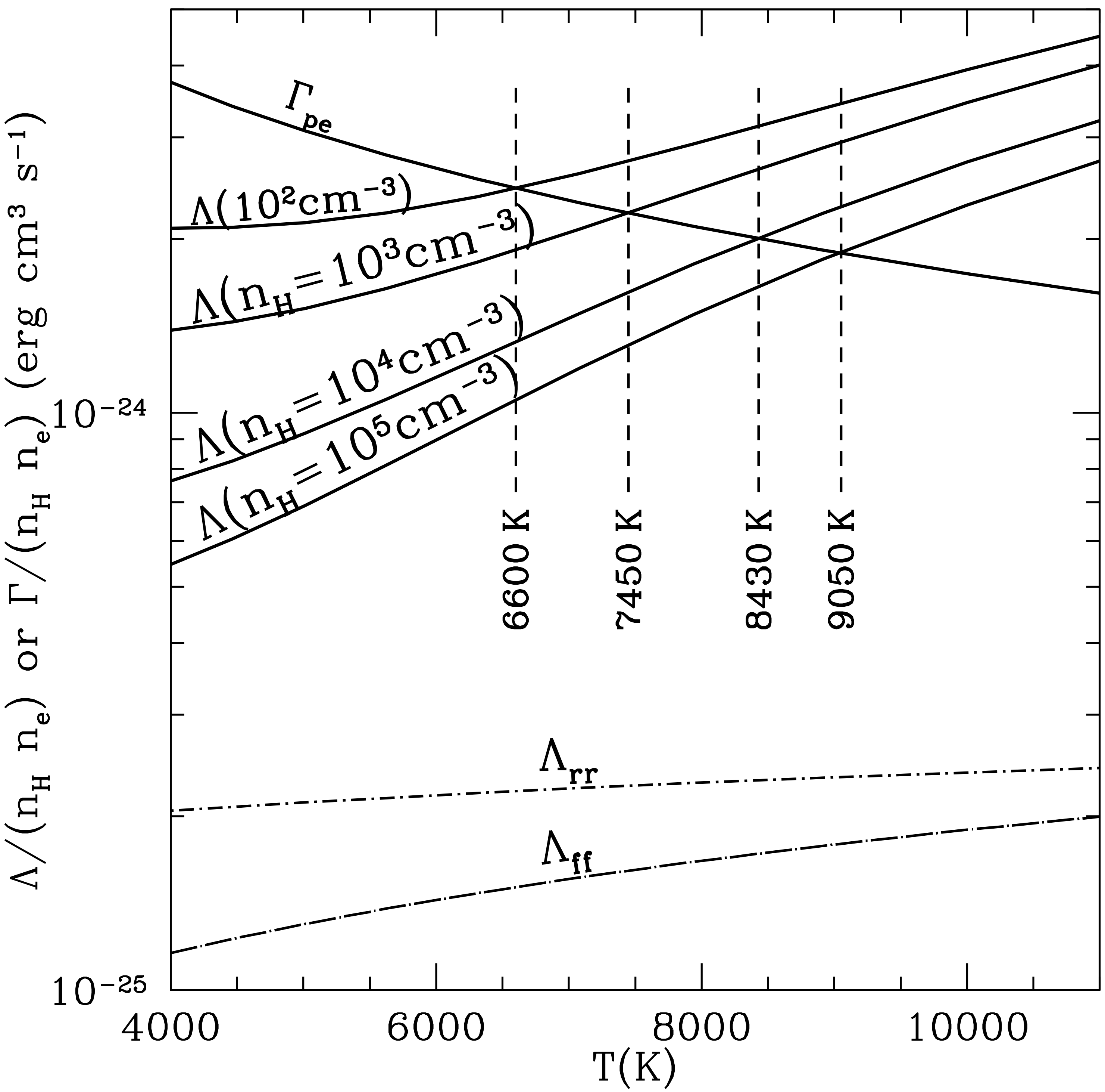
Balance between photoionization heating and collisional excitation cooling sets temperature of HII region.

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