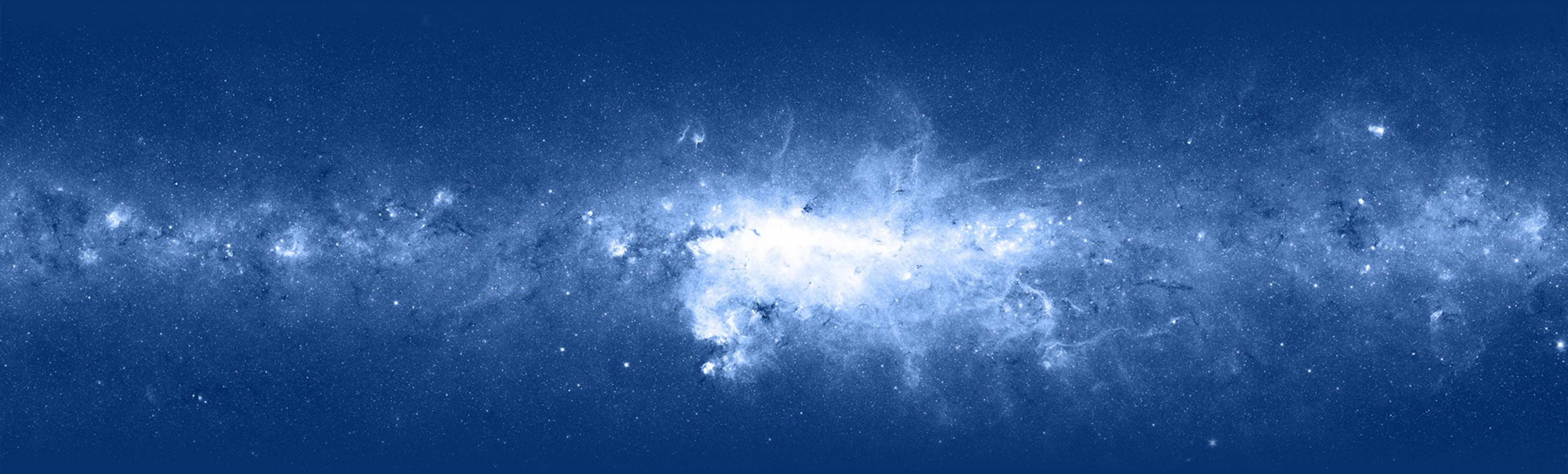
ASTR 670: Interstellar medium and gas dynamics

Prof. Benedikt Diemer



Chapter 6 • Photoionized gas and H II regions

§6.1 • Ionization equilibrium around a star

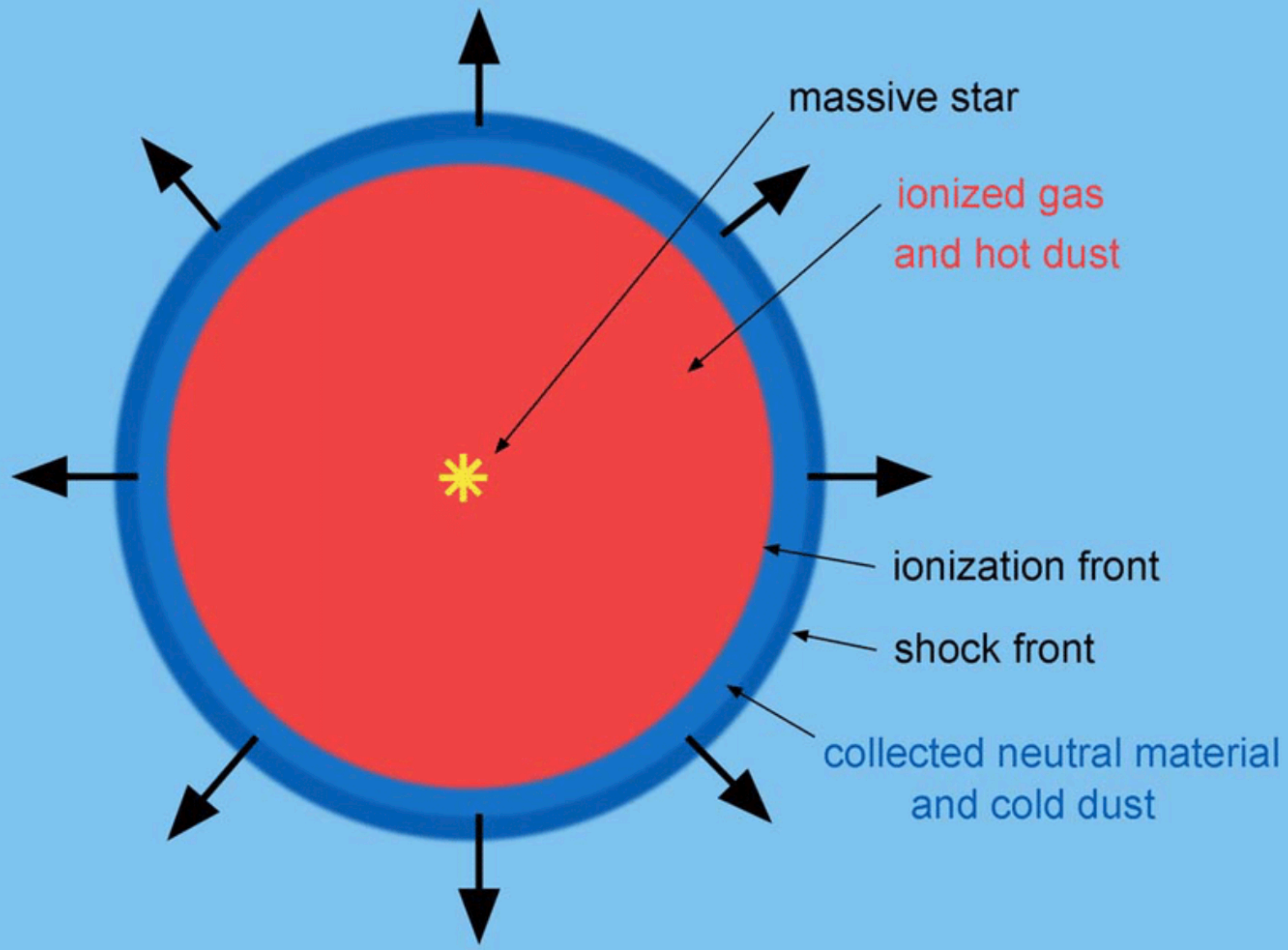
Star types

SpTp	$M/M_\odot$	$T_{\rm eff}$(K)	$\log_{10}(Q_0/{\rm s}^{-1})$ [b]	Q_1/Q_0 [c]	$\log_{10}(L/L_\odot)$ [d]
O3V	58.0	44850	49.64	0.251	5.84
O4V	46.9	42860	49.44	0.224	5.67
O5V	38.1	40860	49.22	0.209	5.49
O5.5V	34.4	39870	49.10	0.204	5.41
O6V	31.0	38870	48.99	0.186	5.32
O6.5V	38.0	37870	48.88	0.162	5.23
O7V	25.3	36870	48.75	0.135	5.14
O7.5V	22.9	35870	48.61	0.107	5.05
O8V	20.8	34880	48.44	0.072	4.96
O8.5V	18.8	33880	48.27	0.0347	4.86
O9V	17.1	32830	48.06	0.0145	4.77
O9.5V	15.6	31880	47.88	0.0083	4.68
O3III	56.0	44540	49.77	0.234	5.96
O4III	47.4	42420	49.64	0.204	5.85
O5III	40.4	40310	49.48	0.186	5.73
O5.5III	37.4	39250	49.40	0.170	5.67
O6III	34.5	38190	49.32	0.158	5.61
O6.5III	32.0	37130	49.23	0.141	5.54
O7III	29.6	36080	49.13	0.129	5.48
O7.5III	27.5	35020	49.01	0.105	5.42
O8III	25.5	33960	48.88	0.072	5.35
O8.5III	23.7	32900	48.75	0.0417	5.28
O9III	22.0	31850	48.65	0.0257	5.21
O9.5III	20.6	30790	48.42	0.0129	5.15
O3I	67.5	42230	49.78	0.204	5.99
O4I	58.5	40420	49.70	0.182	5.93
O5I	50.7	38610	49.62	0.158	5.87
O5.5I	47.3	37710	49.58	0.151	5.84
O6I	44.1	36800	49.52	0.141	5.81
O6.5I	41.2	35900	49.46	0.132	5.78
O7I	38.4	34990	49.41	0.115	5.75
O7.5I	36.0	34080	49.31	0.100	5.72
O8I	33.7	33180	49.25	0.079	5.68
O8.5I	31.5	32270	49.19	0.065	5.65
O9I	29.6	31370	49.11	0.0363	5.61
O9.5I	27.8	30460	49.00	0.0224	5.57

Draine §15.1

§6.2 • Strömgren spheres

Ionization balance



Deharveng et al. 2010

THE PHYSICAL STATE OF INTERSTELLAR HYDROGEN

BENGT STRÖMGREN

ABSTRACT

The discovery, by Struve and Elvey, of extended areas in the Milky Way in which the Balmer lines are observed in emission suggests that hydrogen exists, in the ionized state, in large regions of space. The problem of the ionization and excitation of hydrogen is first considered in a general way. An attempt is then made to arrive at a picture of the actual physical state of interstellar hydrogen. It is found that the Balmer-line emission should be limited to certain rather sharply bounded regions in space surrounding O-type stars or clusters of O-type stars. Such regions may have diameters of about 200 parsecs, which is in general agreement with the observations. Certain aspects of the problem of the ionization of other elements and of the problem of the relative abundance of the elements in interstellar space are briefly discussed. The interstellar density of hydrogen is of the order of $N = 3\ \mathrm{cm}^{-3}$. The extent of the emission regions at right angles to the galactic plane is discussed and is found to be small.

Strömgren 1939

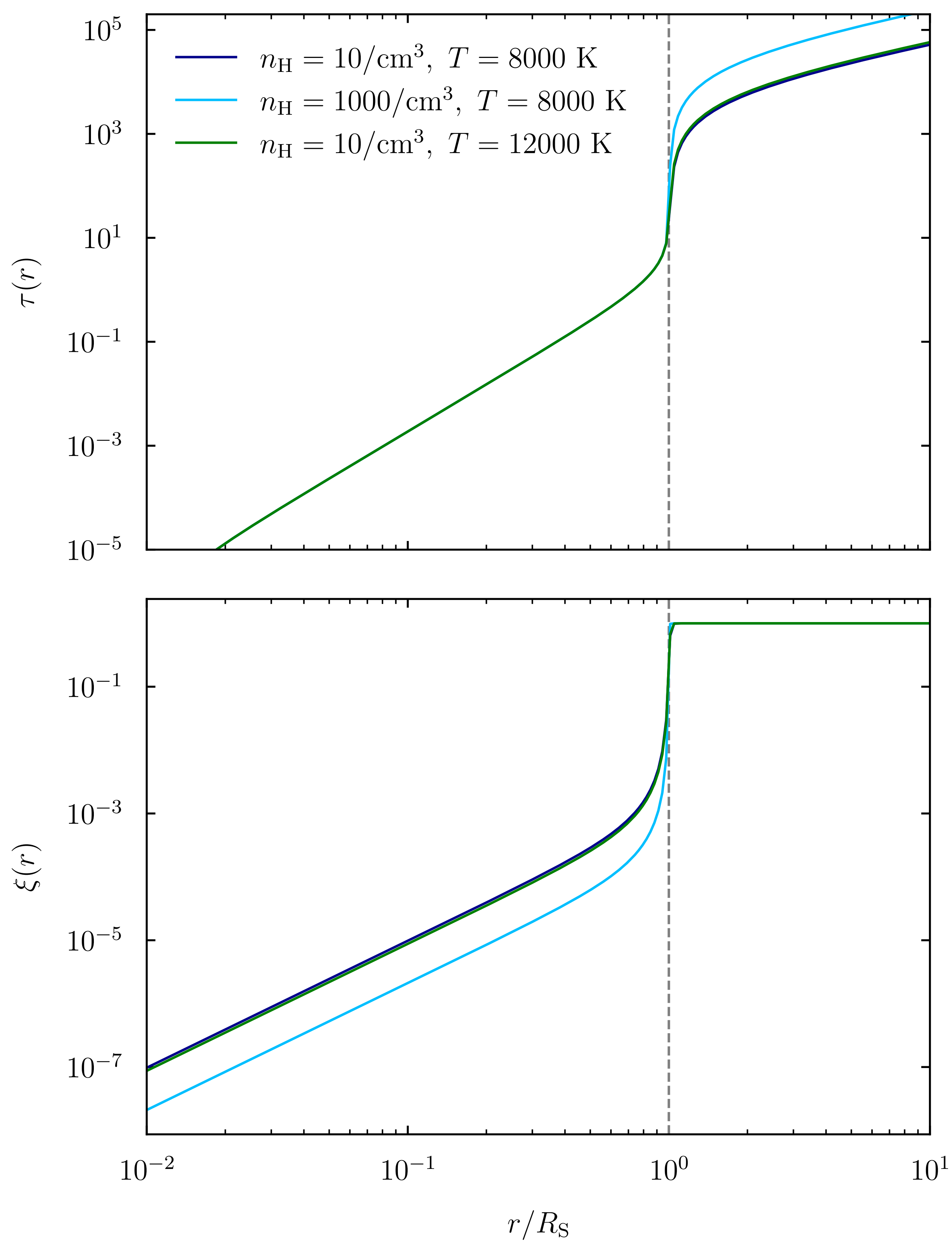
Strömgen radii

Spectral type	T_* (K)	M_V	log $Q(H^0)$ (photons/s)	log $n_e n_p r_1^3$ n in cm^{-3}; r_1 in pc	log $n_e n_p r_1^3$ n in cm^{-3}; r_1 in pc	r_1 (pc) $n_e = n_p = 1$ cm^{-3}
O3 V	51,200	−5.78	49.87	49.18	6.26	122
O4 V	48,700	−5.55	49.70	48.99	6.09	107
O4.5 V	47,400	−5.44	49.61	48.90	6.00	100
O5 V	46,100	−5.33	49.53	48.81	5.92	94
O5.5 V	44,800	−5.22	49.43	48.72	5.82	87
O6 V	43,600	−5.11	49.34	48.61	5.73	81
O6.5 V	42,300	−4.99	49.23	48.49	5.62	75
O7 V	41,000	−4.88	49.12	48.34	5.51	69
O7.5 V	39,700	−4.77	49.00	48.16	5.39	63
O8 V	38,400	−4.66	48.87	47.92	5.26	57
O8.5 V	37,200	−4.55	48.72	47.63	5.11	51
O9 V	35,900	−4.43	48.56	47.25	4.95	45
O9.5 V	34,600	−4.32	48.38	46.77	4.77	39
B0 V	33,300	−4.21	48.16	46.23	4.55	33
B0.5 V	32,000	−4.10	47.90	45.69	4.29	27
O3 III	50,960	−6.09	49.99	49.30	6.38	134
B0.5 III	30,200	−5.31	48.27	45.86	4.66	36
O3 Ia	50,700	−6.4	50.11	49.41	6.50	147
O9.5 Ia	31,200	−6.5	49.17	47.17	5.56	71

Osterbrock & Ferland §2.3

§6.3 • The radial evolution of ionization

Strömgen radii

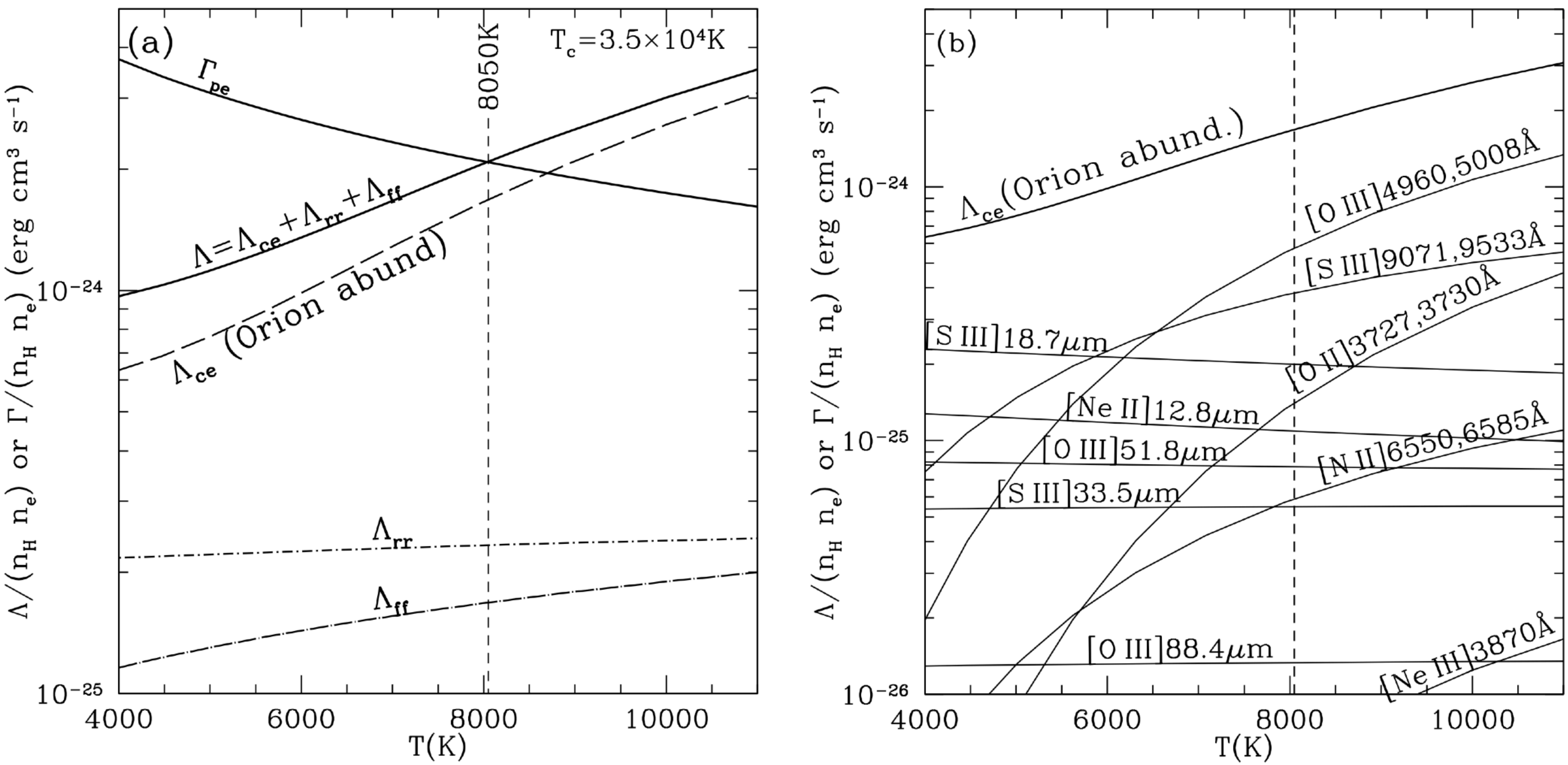


H II regions

- Additional complications:
  - Non-uniform density
  - Dust causes radiation pressure
  - Radially varying temperature
  - Helium and metals
  - Multiple stars at center
  - …

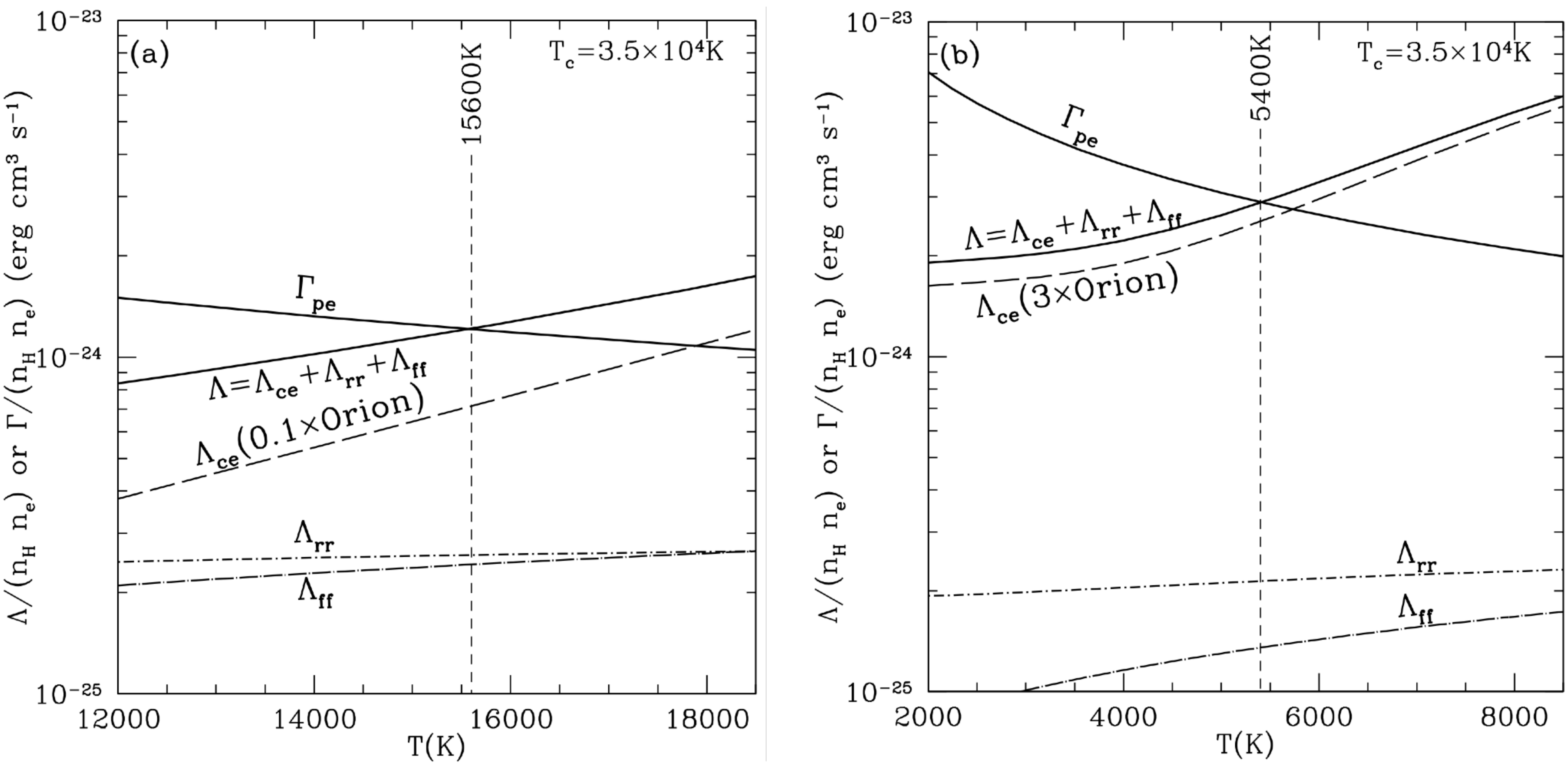
§6.4 • Thermal balance

Heating and cooling rates



Draine §27

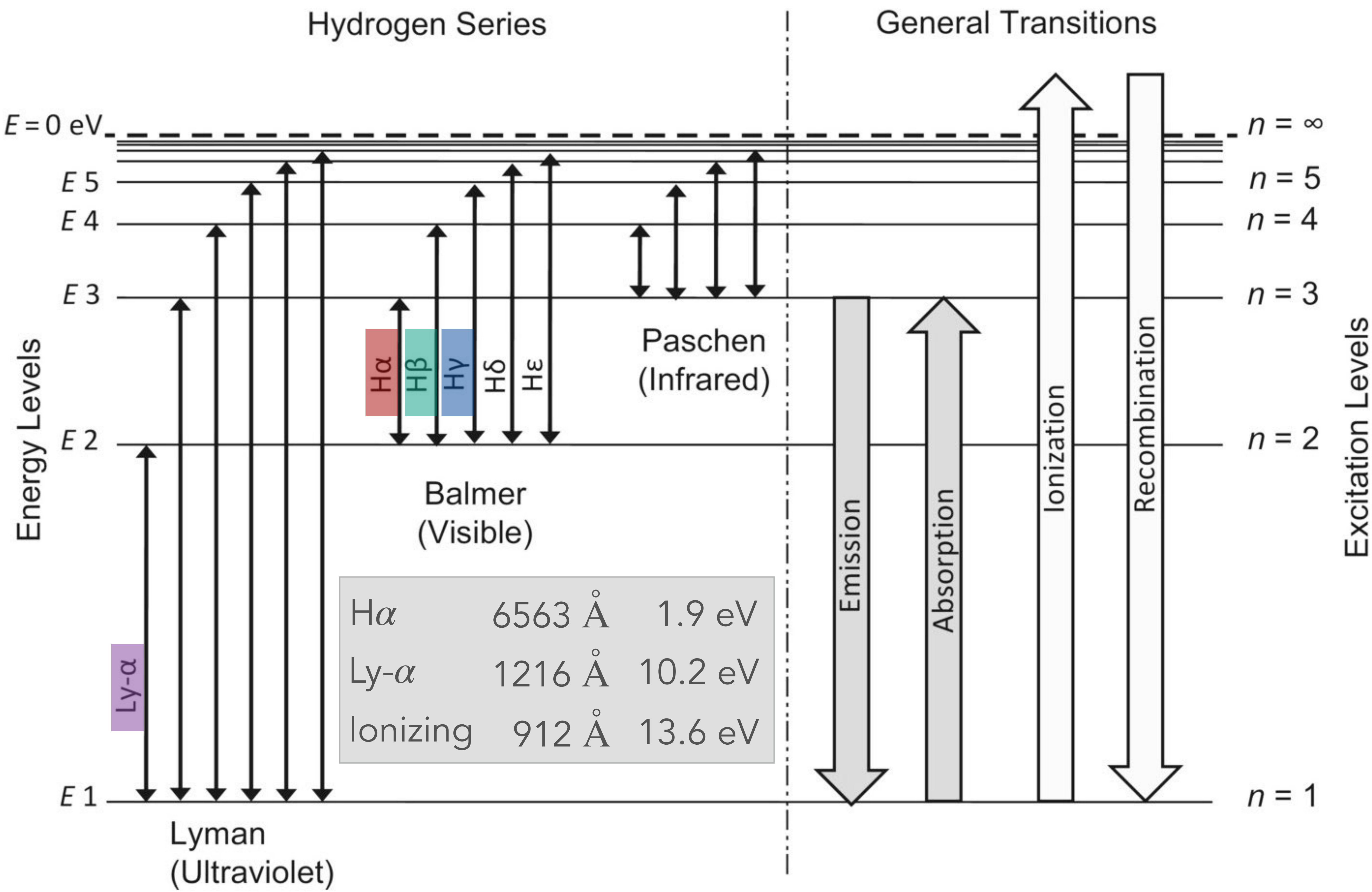
Heating and cooling rates



Draine §27

§6.5 • Observational diagnostics

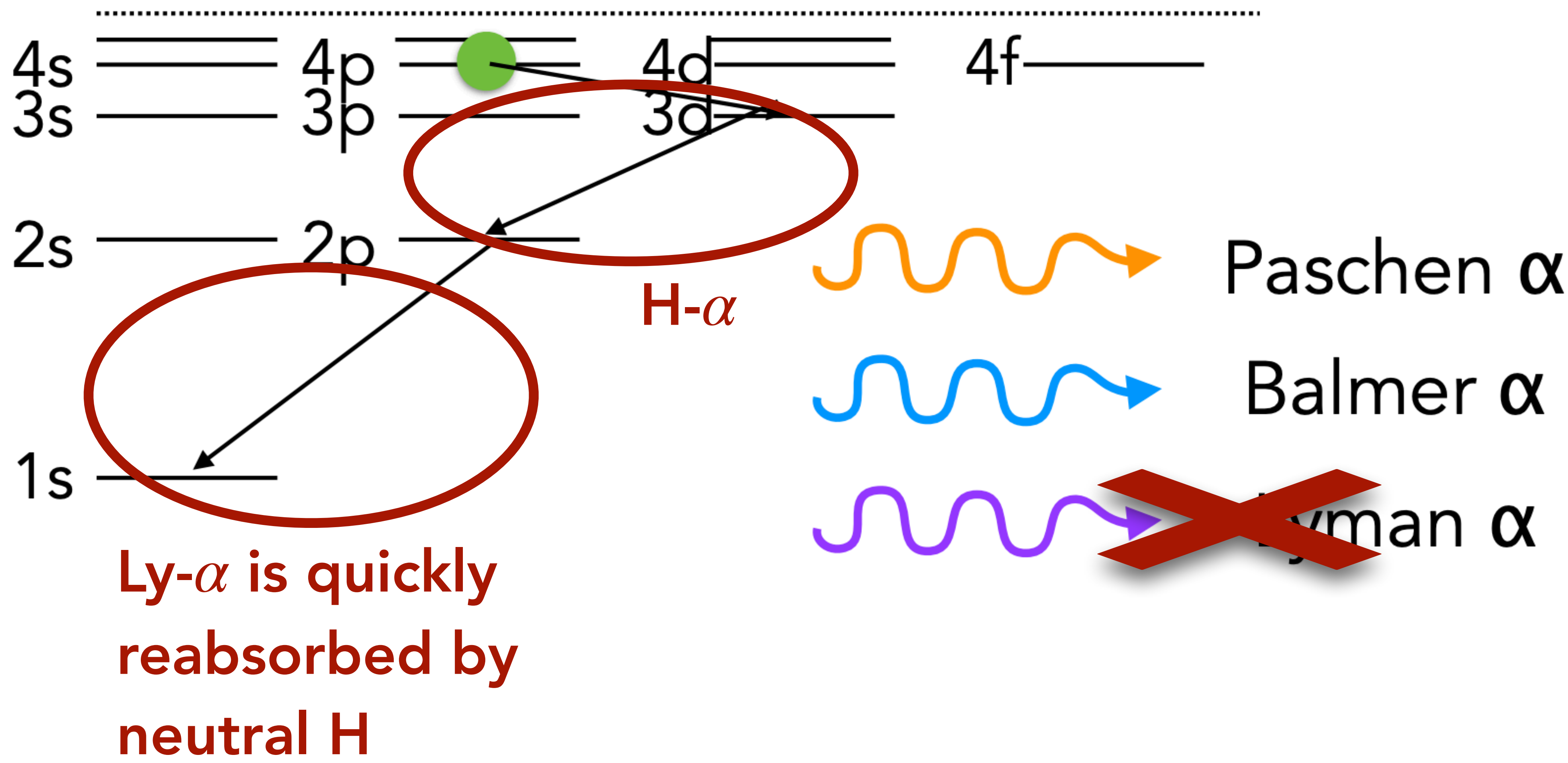
Energy level diagram of hydrogen



Hα	6563 Å	1.9 eV
Ly-α	1216 Å	10.2 eV
Ionizing	912 Å	13.6 eV

Trypsteen & Walker 2017

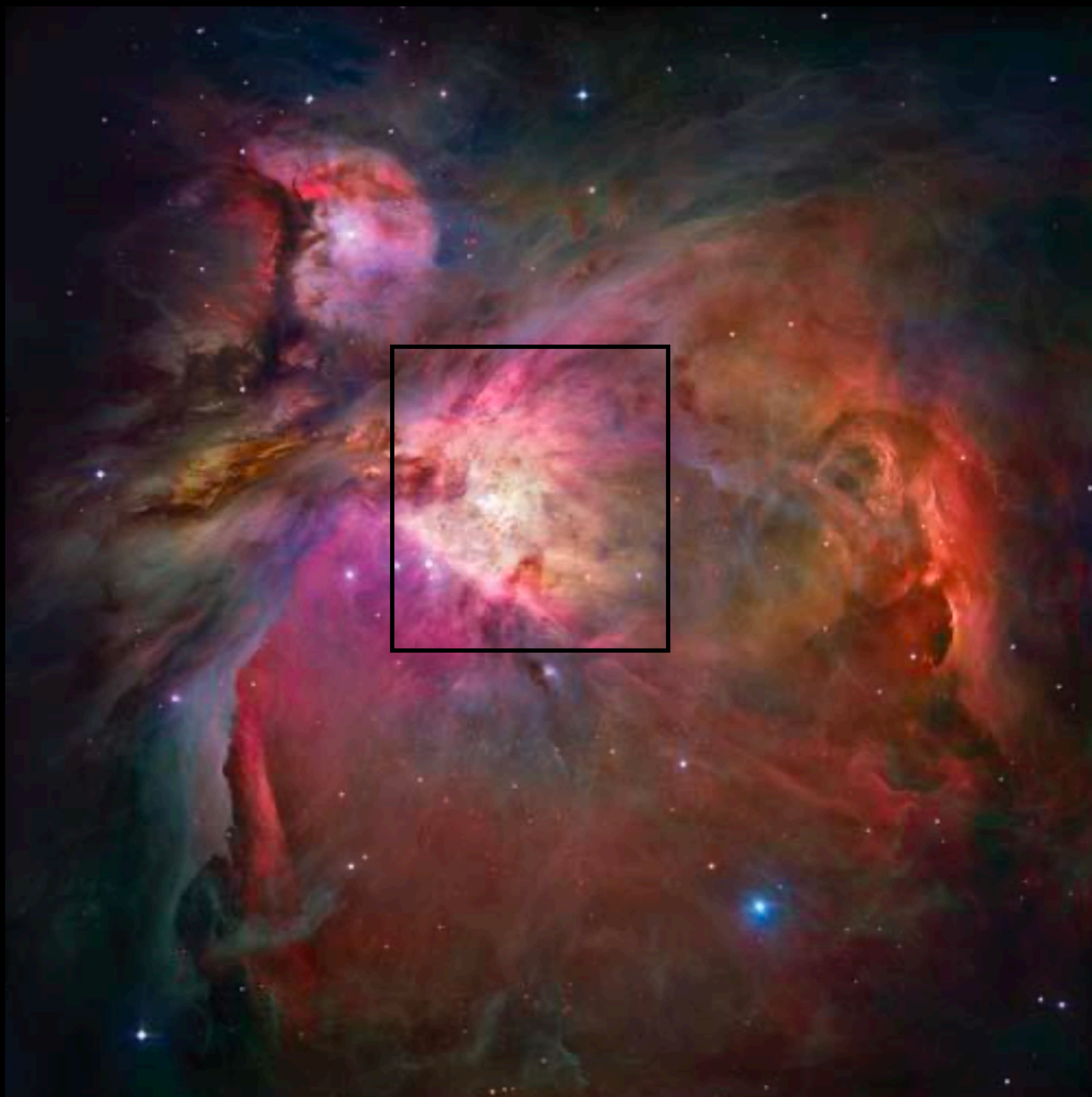
Emission from hydrogen

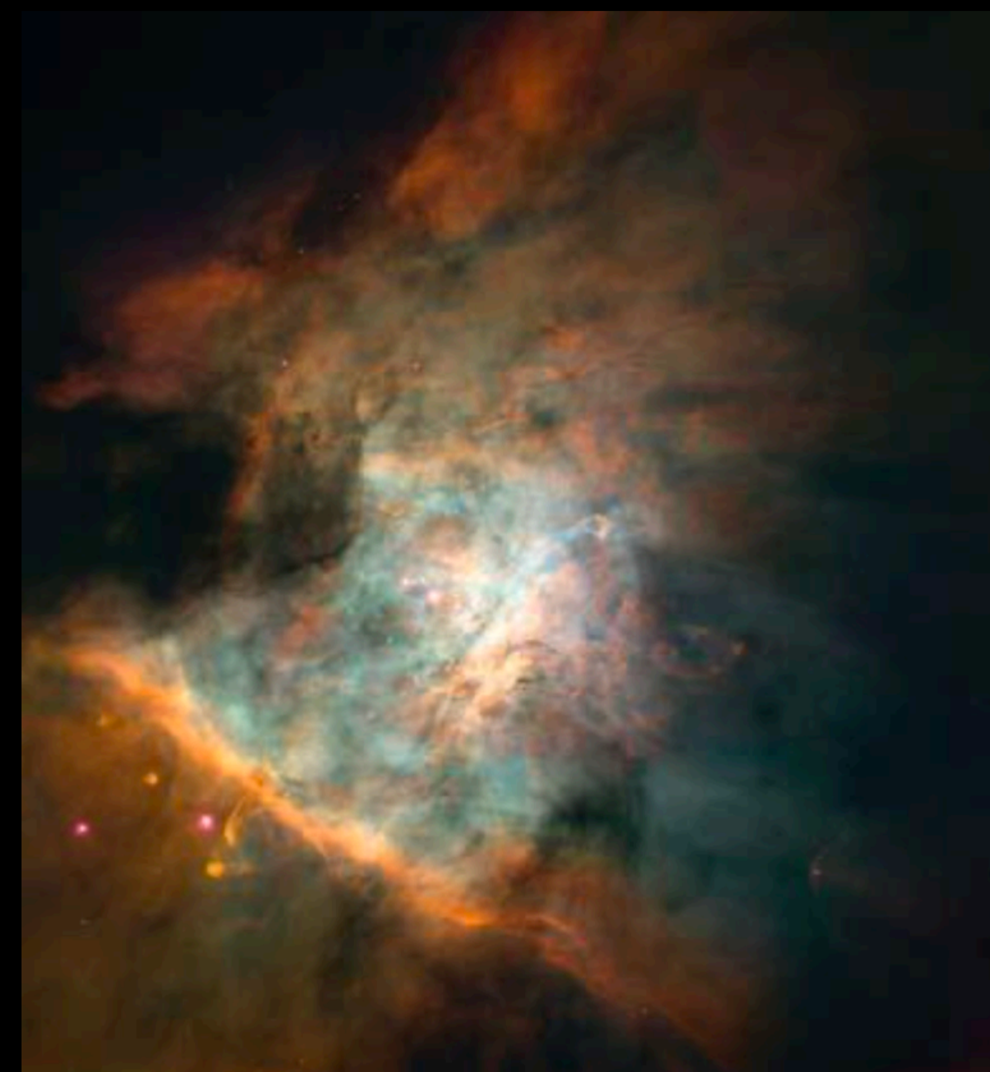


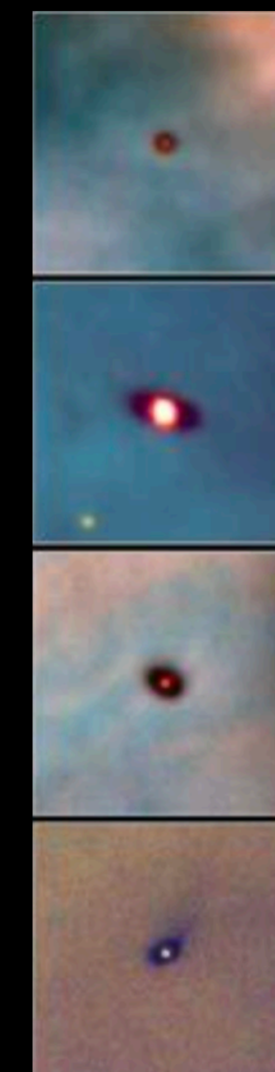
Hα is the dominant tracer of ionized hydrogen!

Image: Karen Sandstrom

Orion nebula







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Trifid nebula

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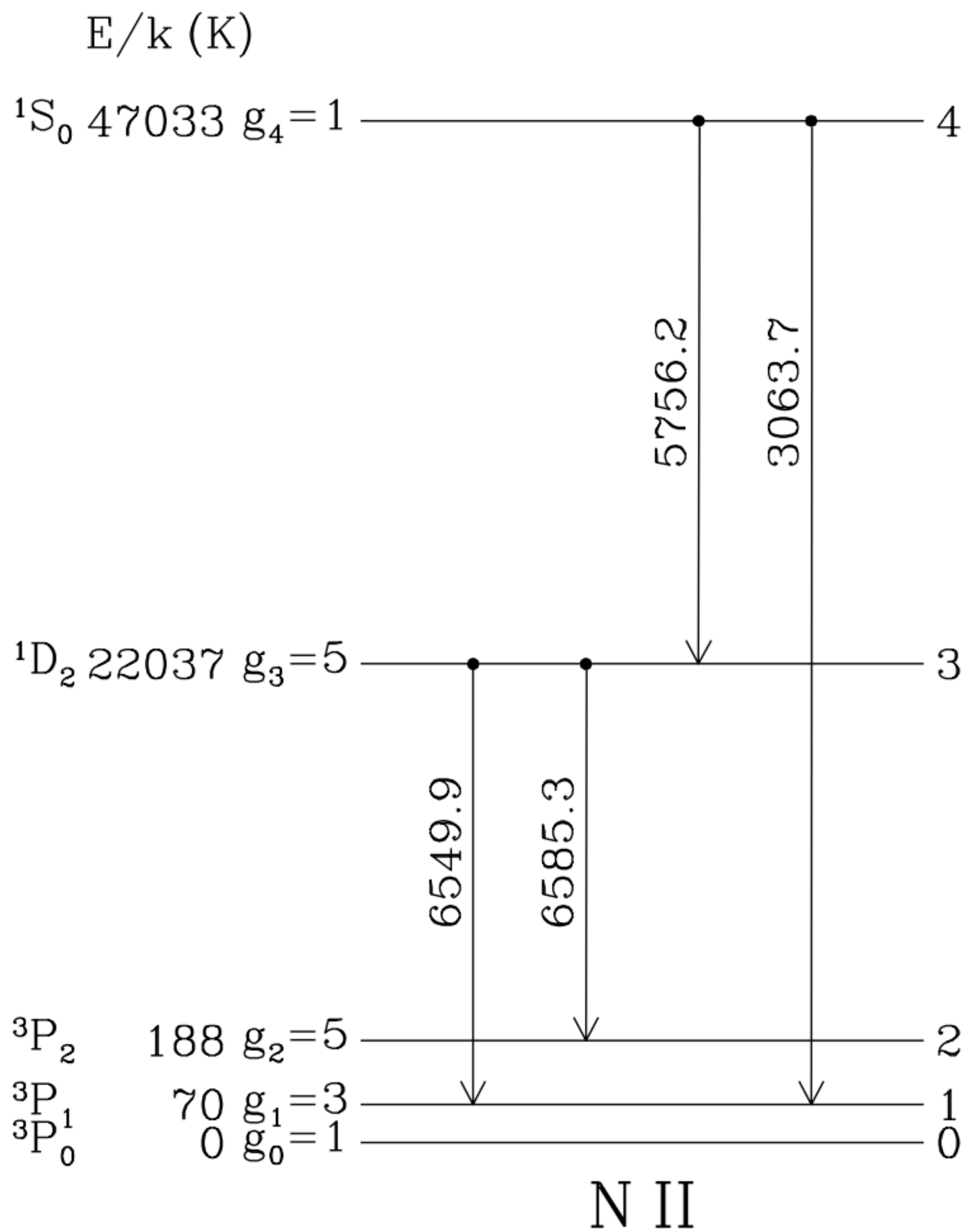
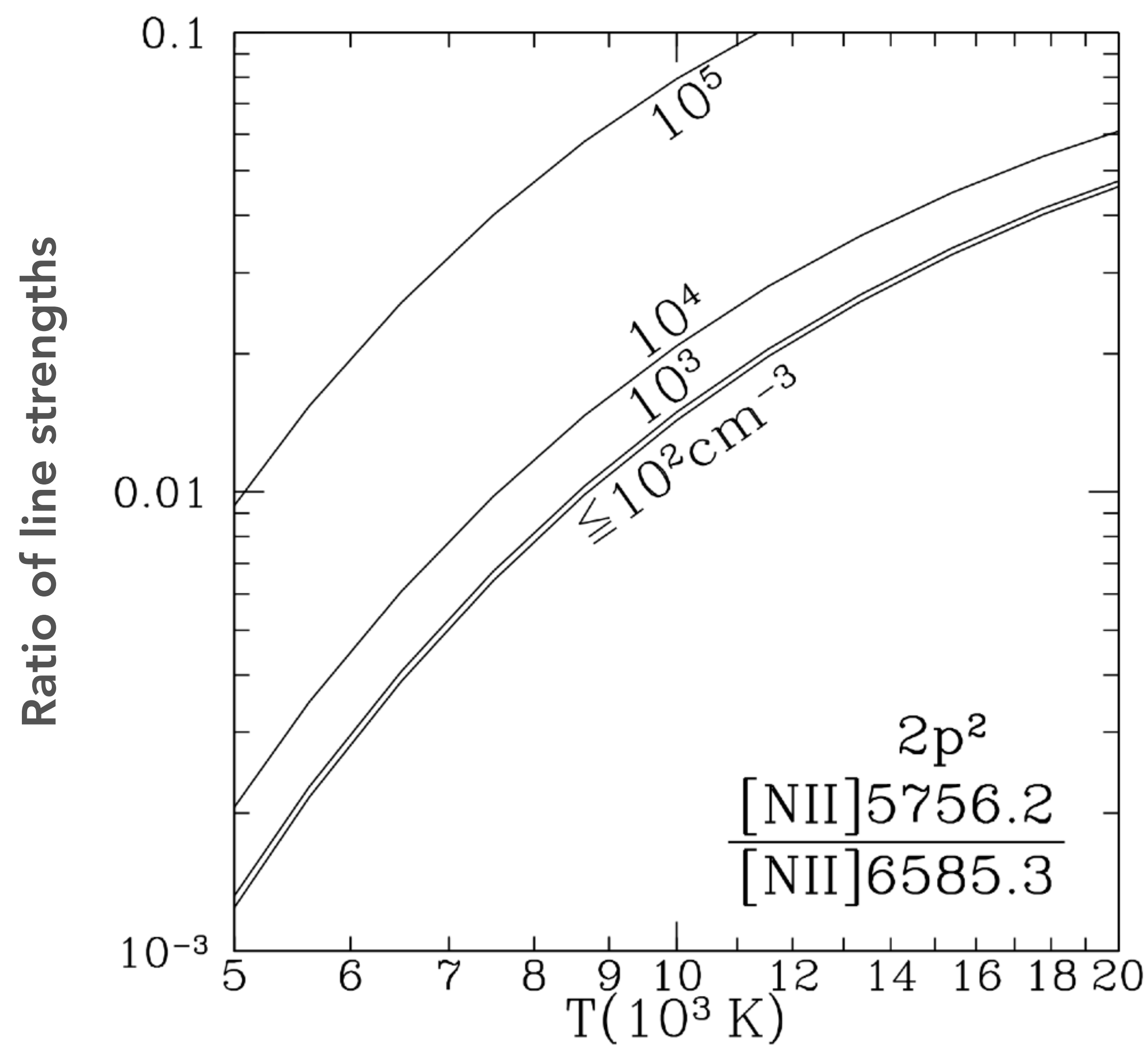
Temperature diagnostics

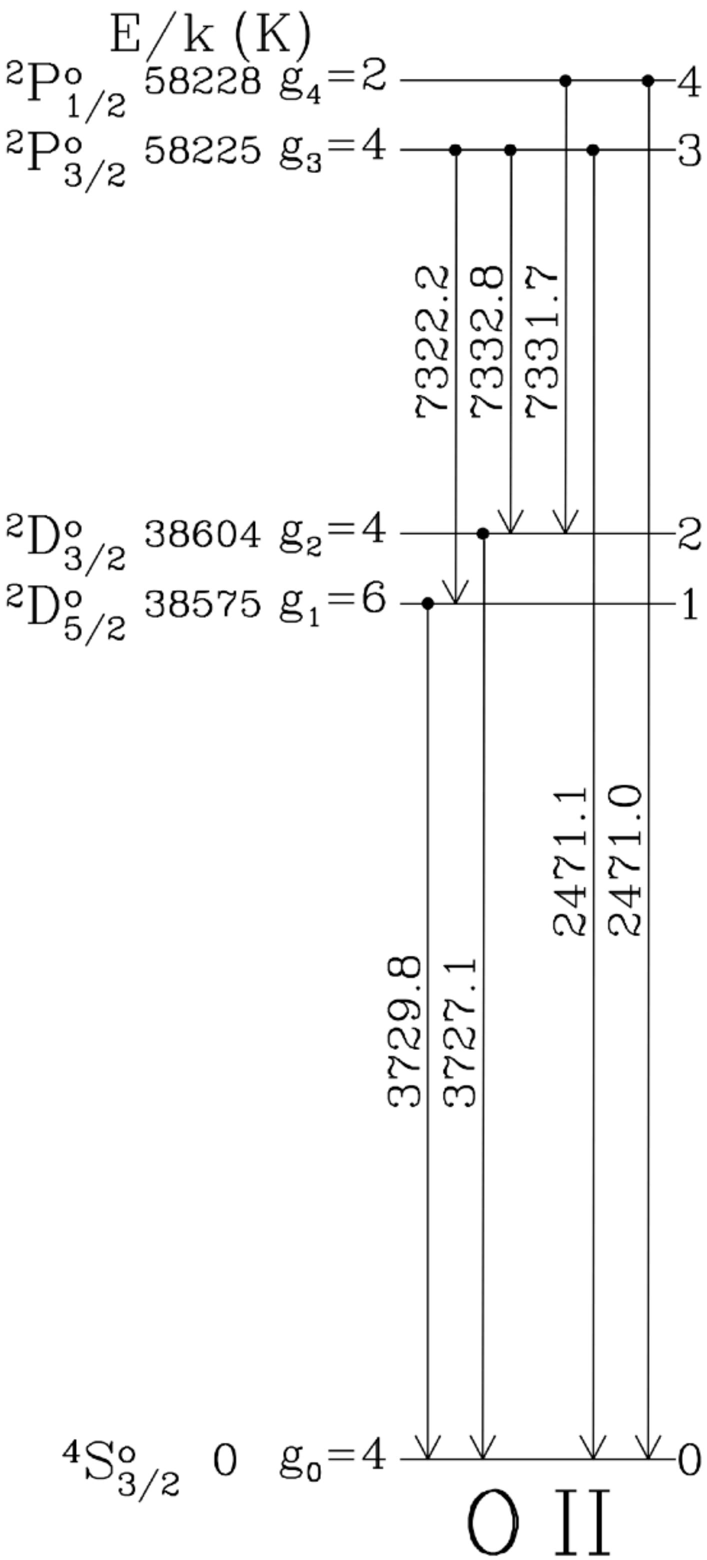




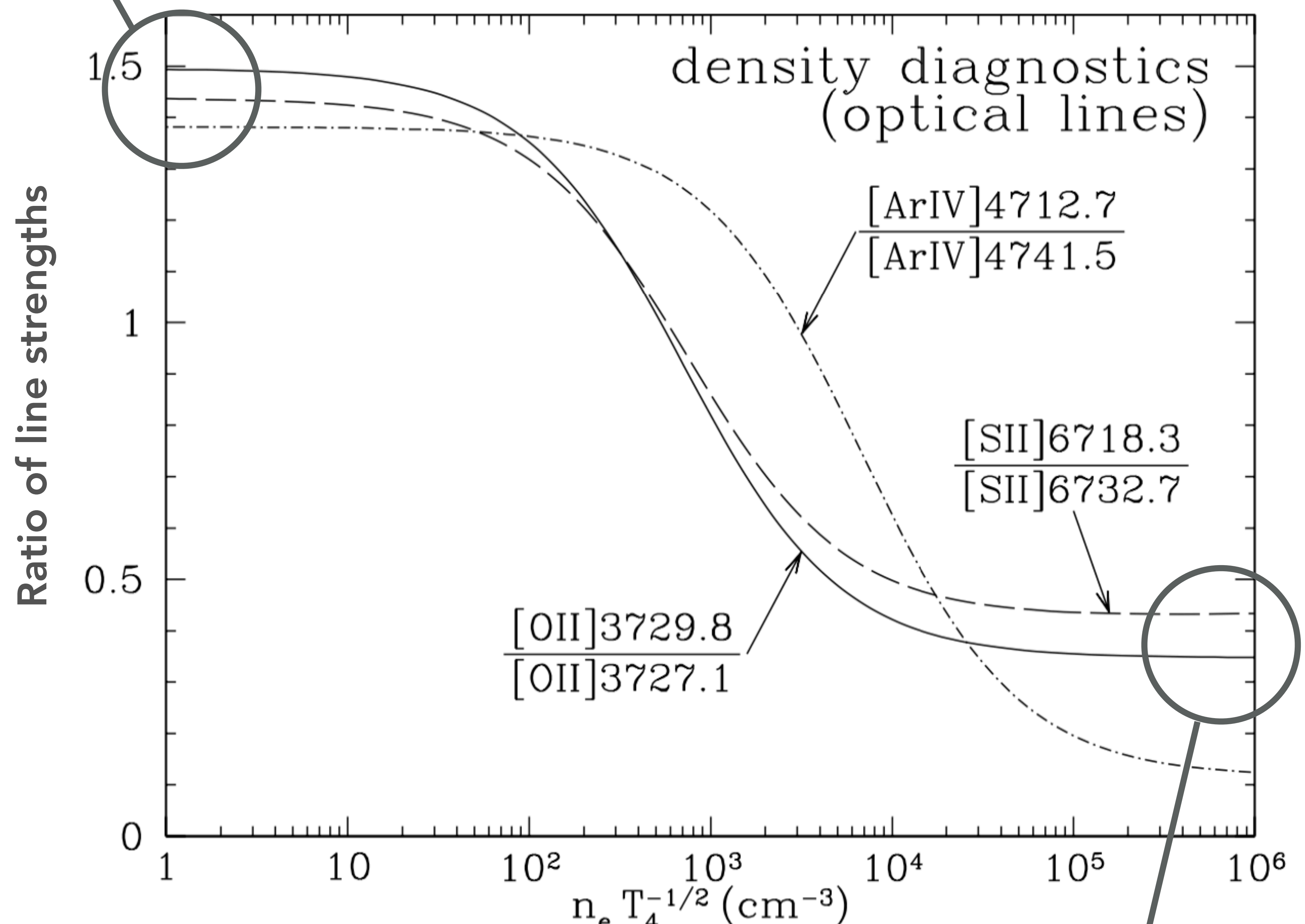
$$\frac{j(4 \to 3)}{j(3 \to 2)} = \frac{A_{43}E_{43}}{A_{32}E_{32}} \frac{(A_{32} + A_{31})\Omega_{04}\, \mathrm{e}^{-E_{43}/kT}}{\left[(A_{43} + A_{41})\Omega_{03} + A_{43}\Omega_{04}\, \mathrm{e}^{-E_{43}/kT}\right]}$$

Draine §18

Density diagnostics



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

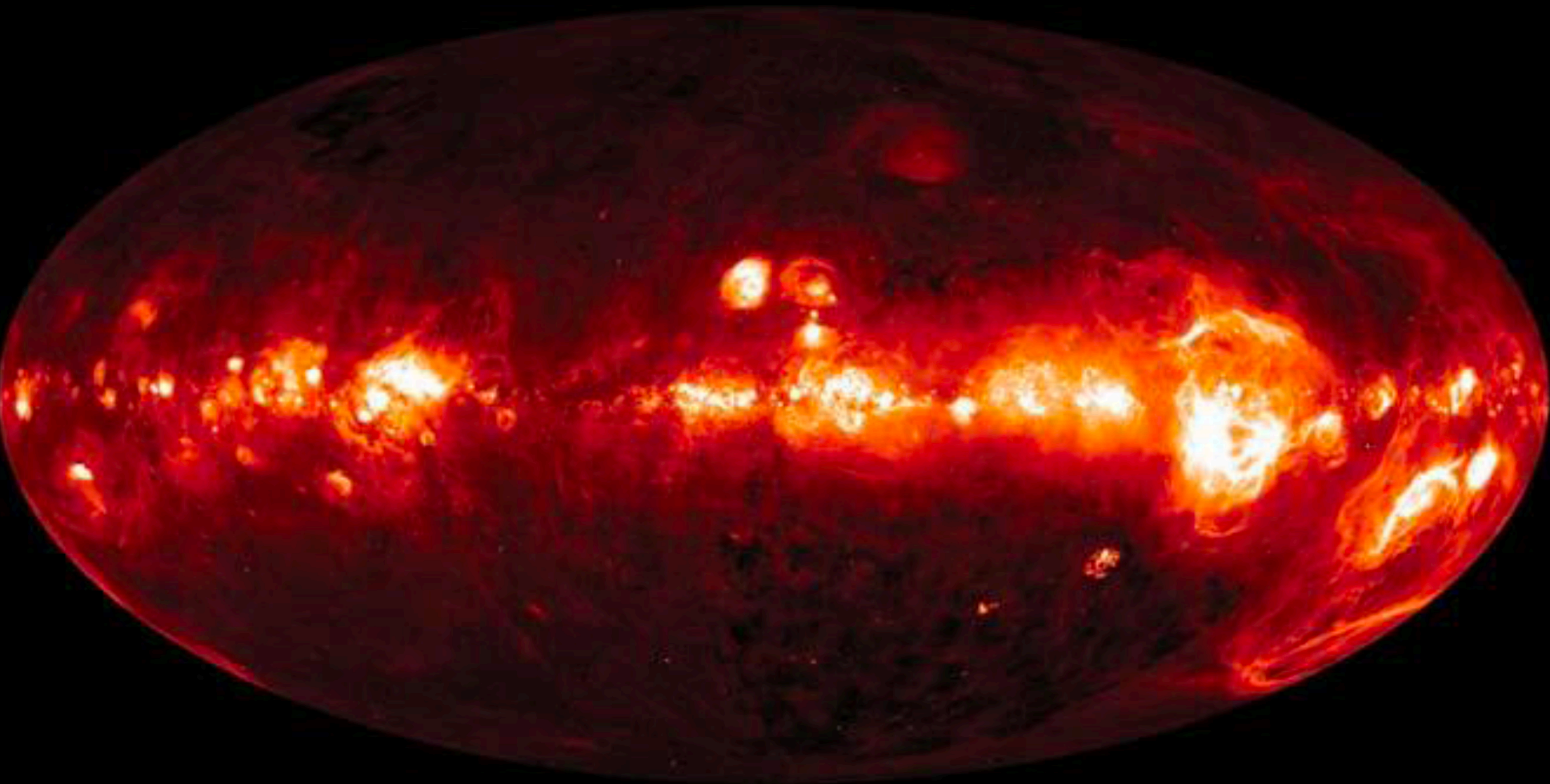


$$\frac{j(2\rightarrow 0)}{j(1\rightarrow 0)} = \frac{g_2}{g_1}e^{-E_{21}/kT}\frac{E_{20}A_{20}}{E_{10}A_{10}} \approx \frac{g_2 A_{20}}{g_1 A_{10}}$$

Draine §18

§6.6 • Diffuse ionized gas

Hα

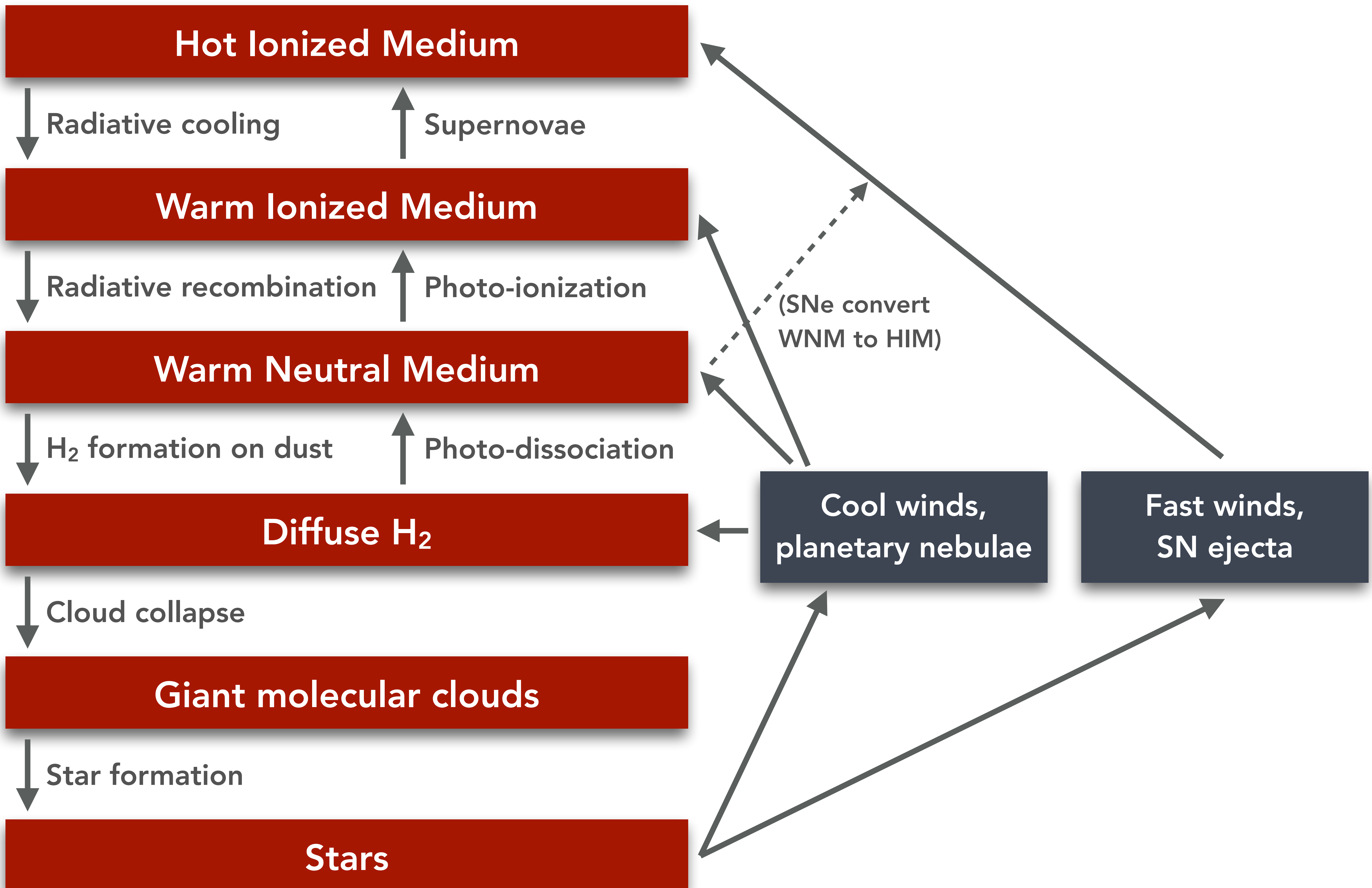


Draine

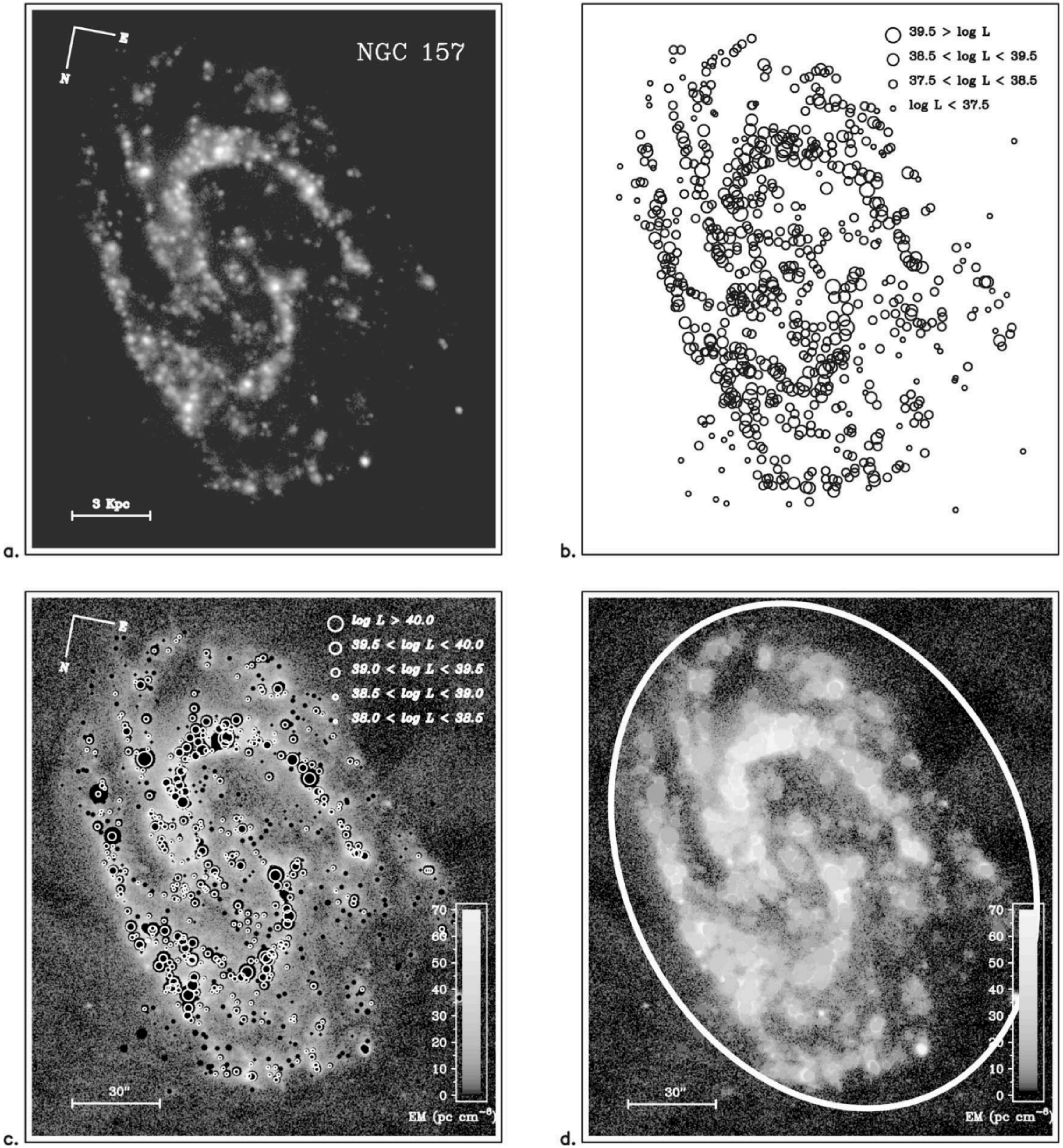
Gas phases (in the Milky Way)

Phase		T (K)	n_H (cm^{-3})	f_V -	P/k_B (K/cm^3)	Comments
H II 23%	**Hot ionized medium (HIM)**	$10^{5.7}$	0.004	0.5	4400	Collisionally ionized, shock-heated by supernovae and stellar winds
	H II regions	10000	$0.1\text{-}10^4$	0.01	varies	Photo-ionized nebulae around stars; density and pressure vary across these bubbles
	Warm ionized medium (WIM)	8000	0.2	0.1	4400	Diffuse photo-ionized gas, large scatter in temperature and density
H I 60%	**Warm neutral medium (WNM)**	8000	0.5	0.4	4400	About 60% of HI by mass; in pressure equilibrium witn CNM
	Cool neutral medium (CNM)	100	40	0.01	4400	Significant fraction of the mass despite small volume filling fraction
H_2 17%	**Diffuse molecular gas**	50	150	0.001	4400	Self-shielded against dissociation, but not dense enough to form stars
	Molecular clouds	10-50	$10^3\text{-}10^6$	0.0001	>10000	The site of star formation; more or less gravitationally bound

Transformation between phases



Diffuse ionized gas



a) Continuum-subtracted Hα image of NGC 157

b) H II region catalog

c) Diffuse Hα map after subtracting H II regions

d) Upper limit on diffuse ionized gas brightness

Zurita et al. 2000 • Haffner et al. 2009

Reading

Draine

- §15.1-3
- §18.1-2
- §27.4

O&F

- §2.3
- §3.1-3