Evolution of Galaxies:
Abundances from the gas

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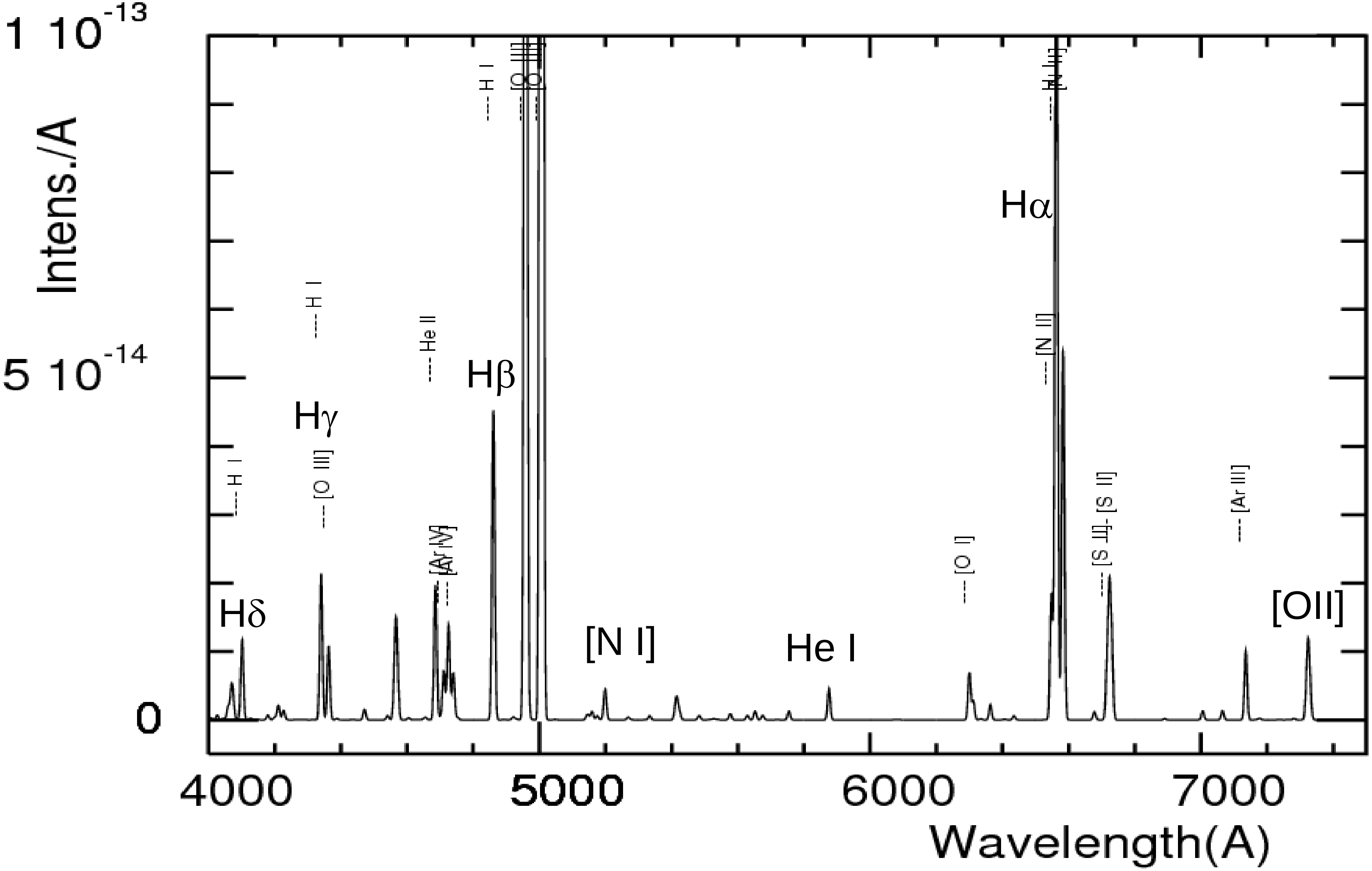
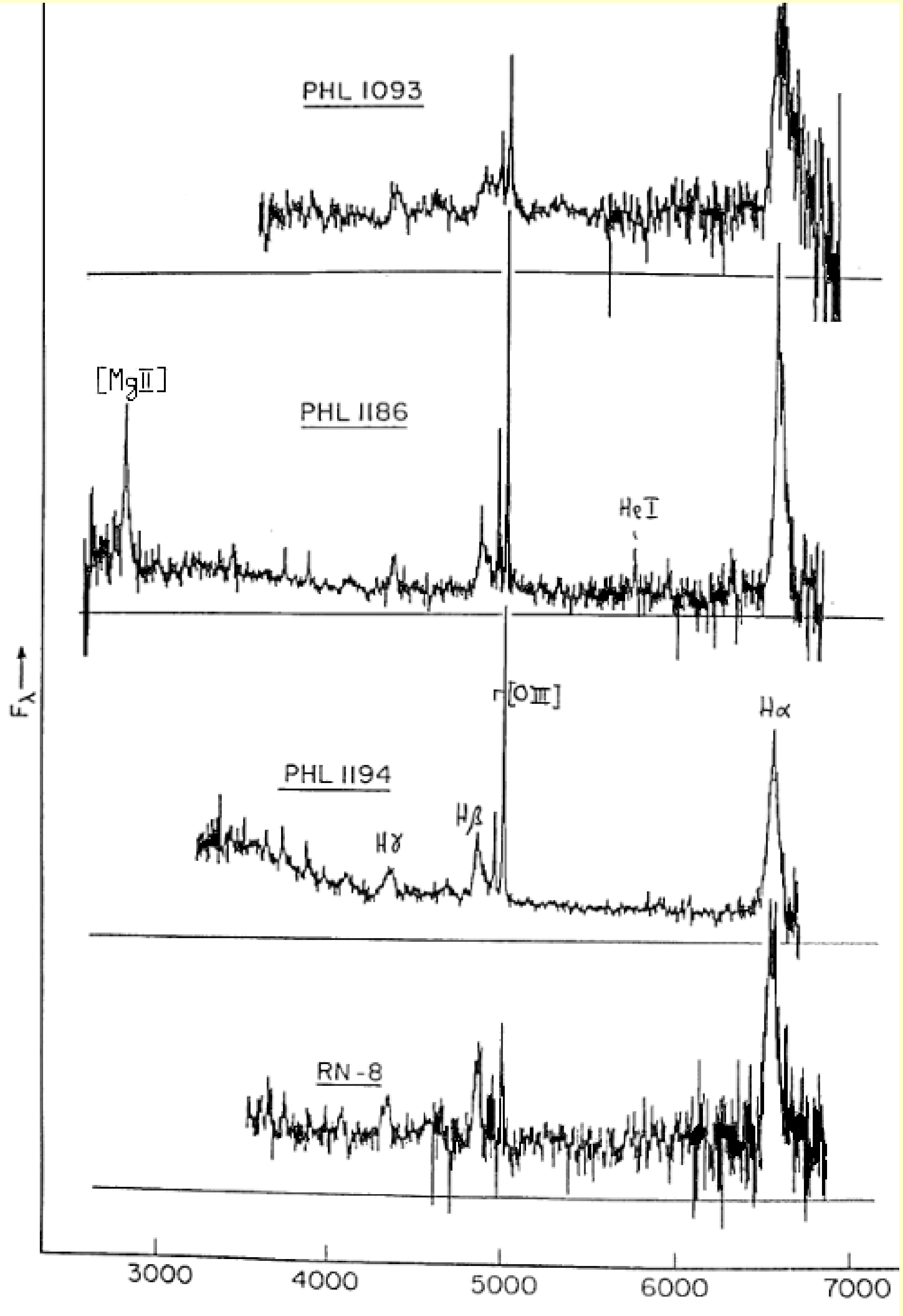
http://astro.u-strasbg.fr/~koppen/JKHome.html

Gas observed in emission lines

- Optical (IR, UV) lines = atomic transitions (E ~ eV)
  - – Hα 6563, [O II] 3727, [O III] 5007, CIV 1550, [O III] 88 µm
  - – Indicates warm, ionized gas (10^4 K)
  - – HII regions, PN, SNR, AGN

Theoretical PN spectrum





Spectra of quasars

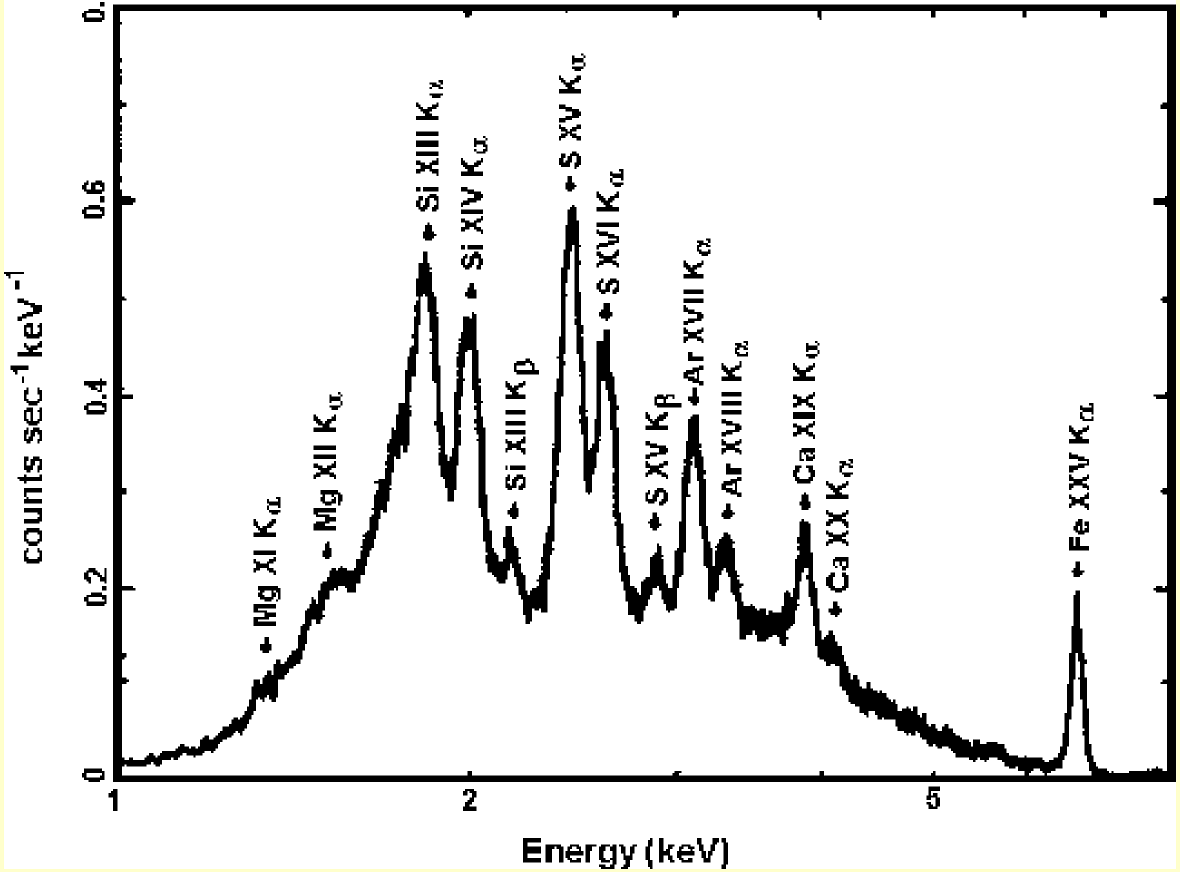
at different redshifts
(de-redshifted)

Gas observed in emission lines

- Radio lines = atomic fine structure, molecule rotation (E ~ meV)
  - Warm ionized gas: HII, HeII, CII … recombination
  - Neutral gas: HI 21 cm
  - Molecular gas: ^{12}CO 2.6mm, ^{13}CO, NH_3, H_2CO, H_2O, ...

Gas observed in emission lines

- X-ray lines = inner shell atomic (E ~ keV)
  - – Hot gas: Fe XXV Kα, SiXIII Kαβ, ...



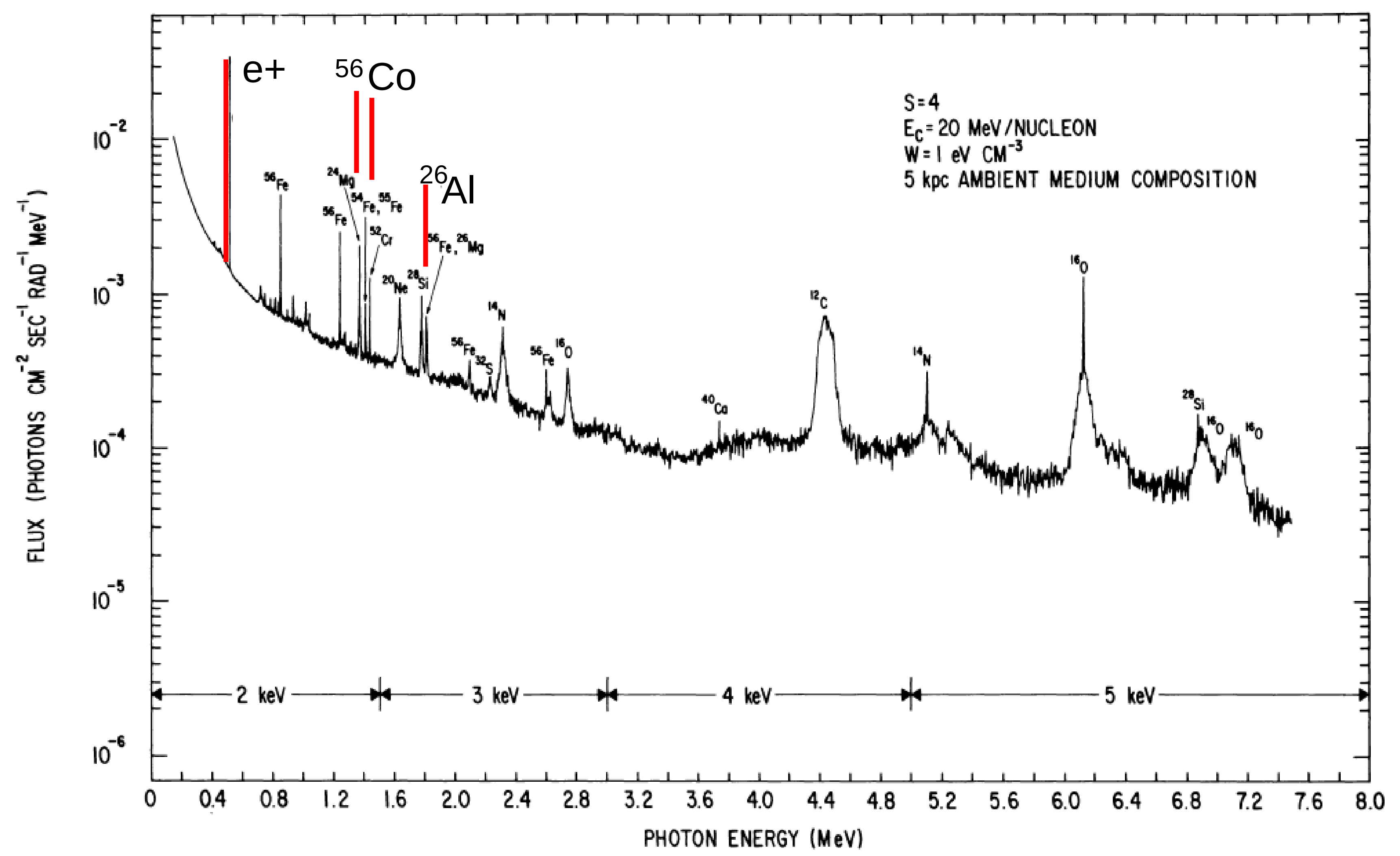
SNR W49B

ASCA 1995 NASA

Gas observed in emission lines

- γ-ray lines = nuclear transitions (E ~ MeV)
  - (hot) gas: ^{12}C,^{14}N,^{16}O,^{56}Fe, …

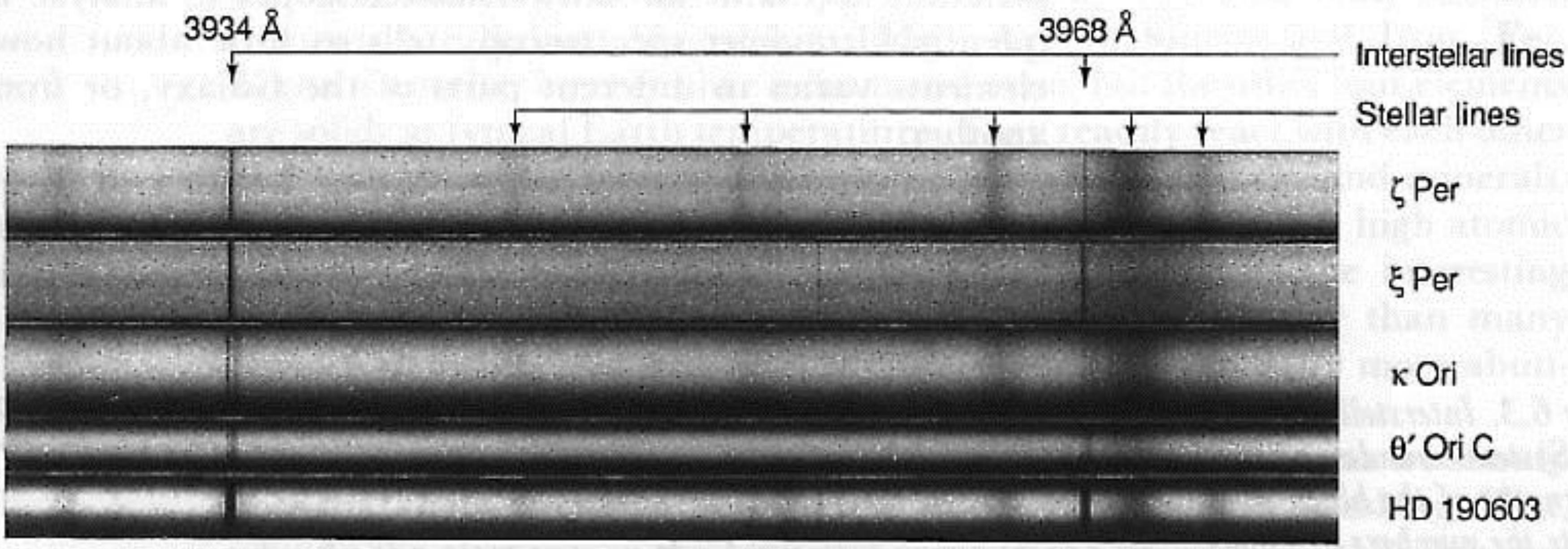
γ-spectrum expected from Galactic Centre



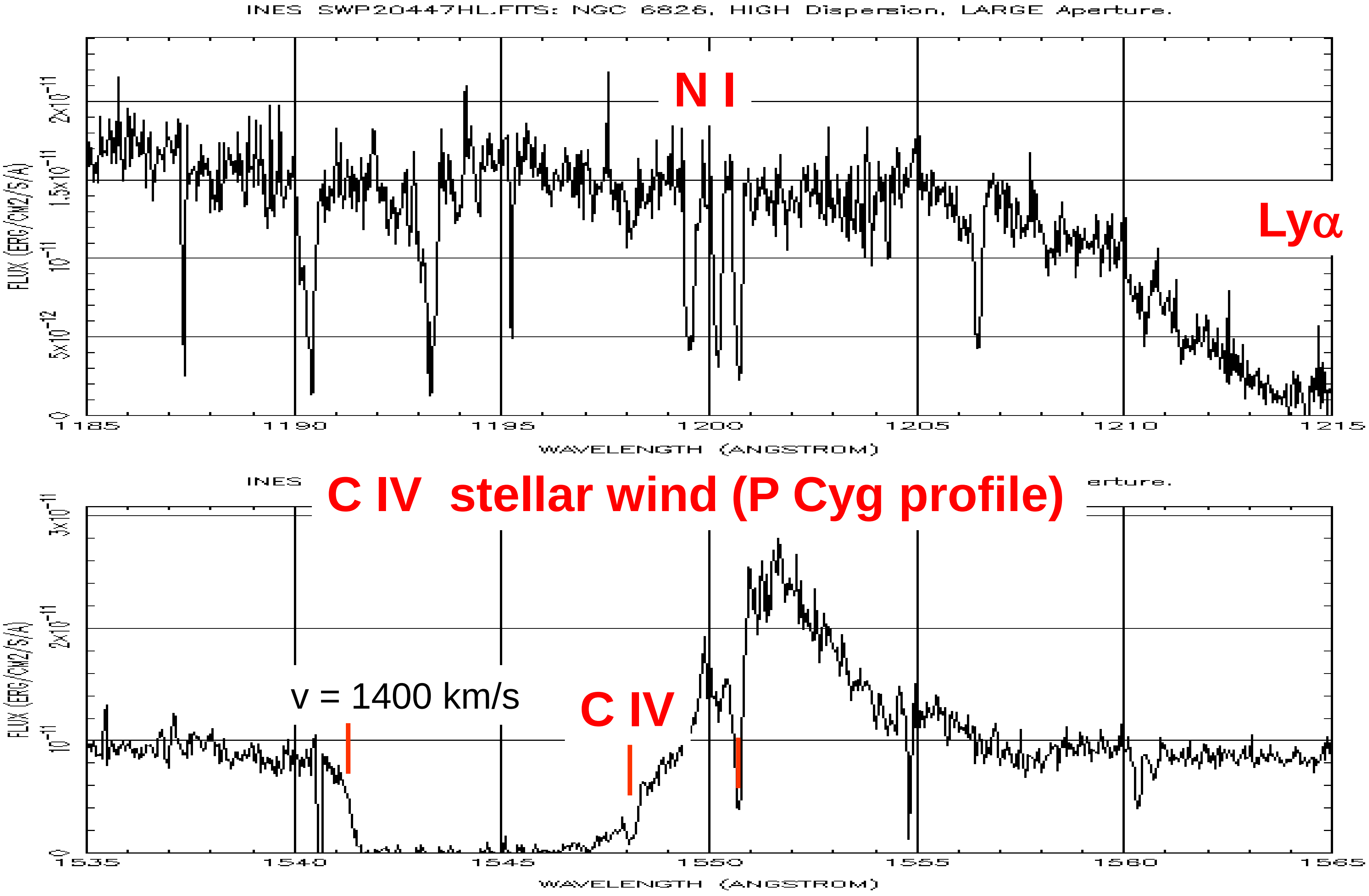
Ramaty Lingenfelter 1979

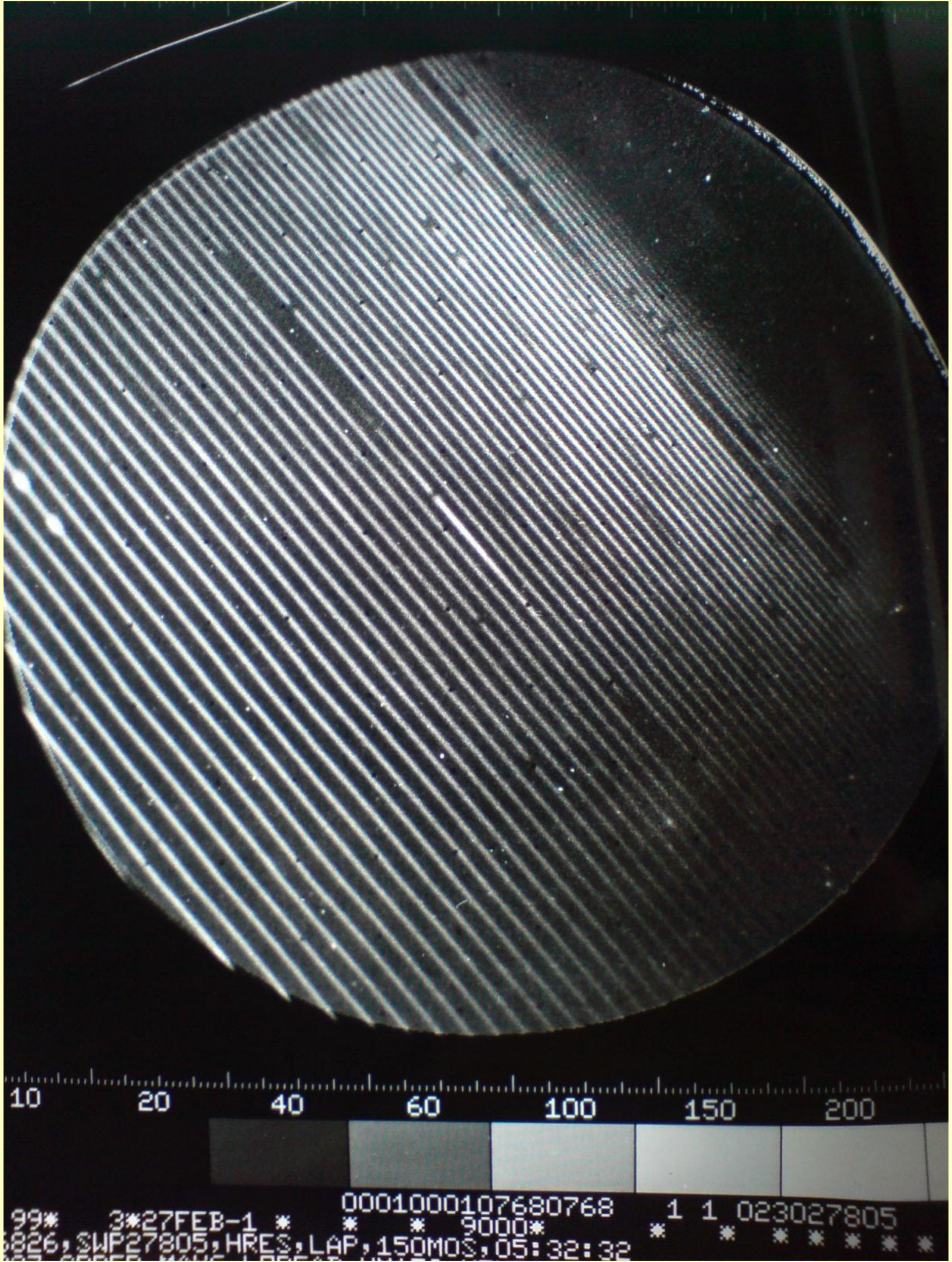
Absorption lines

- Optical (IR, UV) absorption lines
  - – Cool … hot gas: NI, CII, CIV, SiIV, OVI …
  - – ISM, IGM (quasar abs.lines)



IS abs.lines: PN NGC 6826



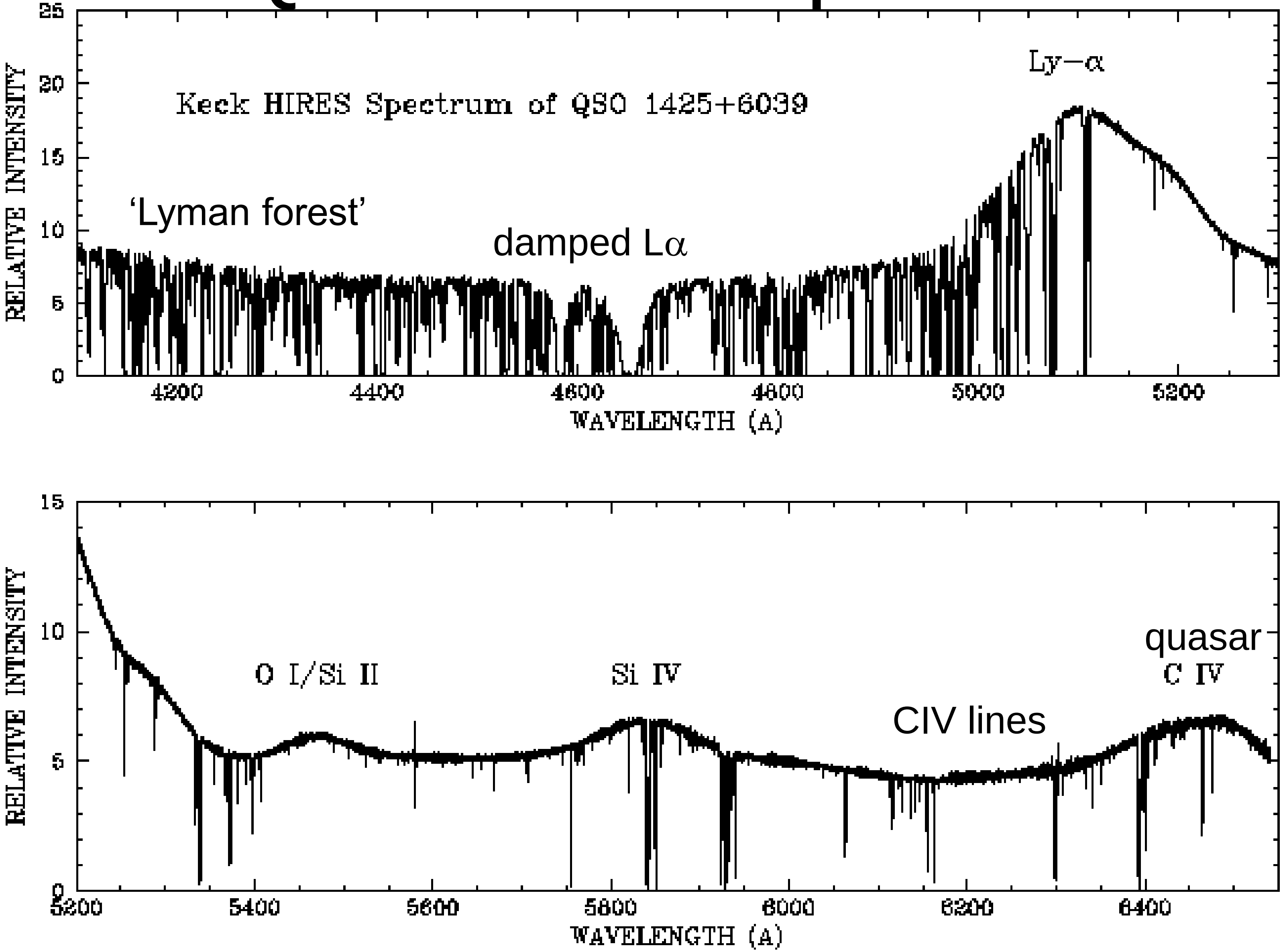


PN NGC 6826 UV echelle spectrum (IUE)

HI Ly α (Geocorona, ISM abs)
NI (ISM abs)
CIV (PCyg + ISM abs)
[CIII (nebular emission)

CR hits (bright single pixels)

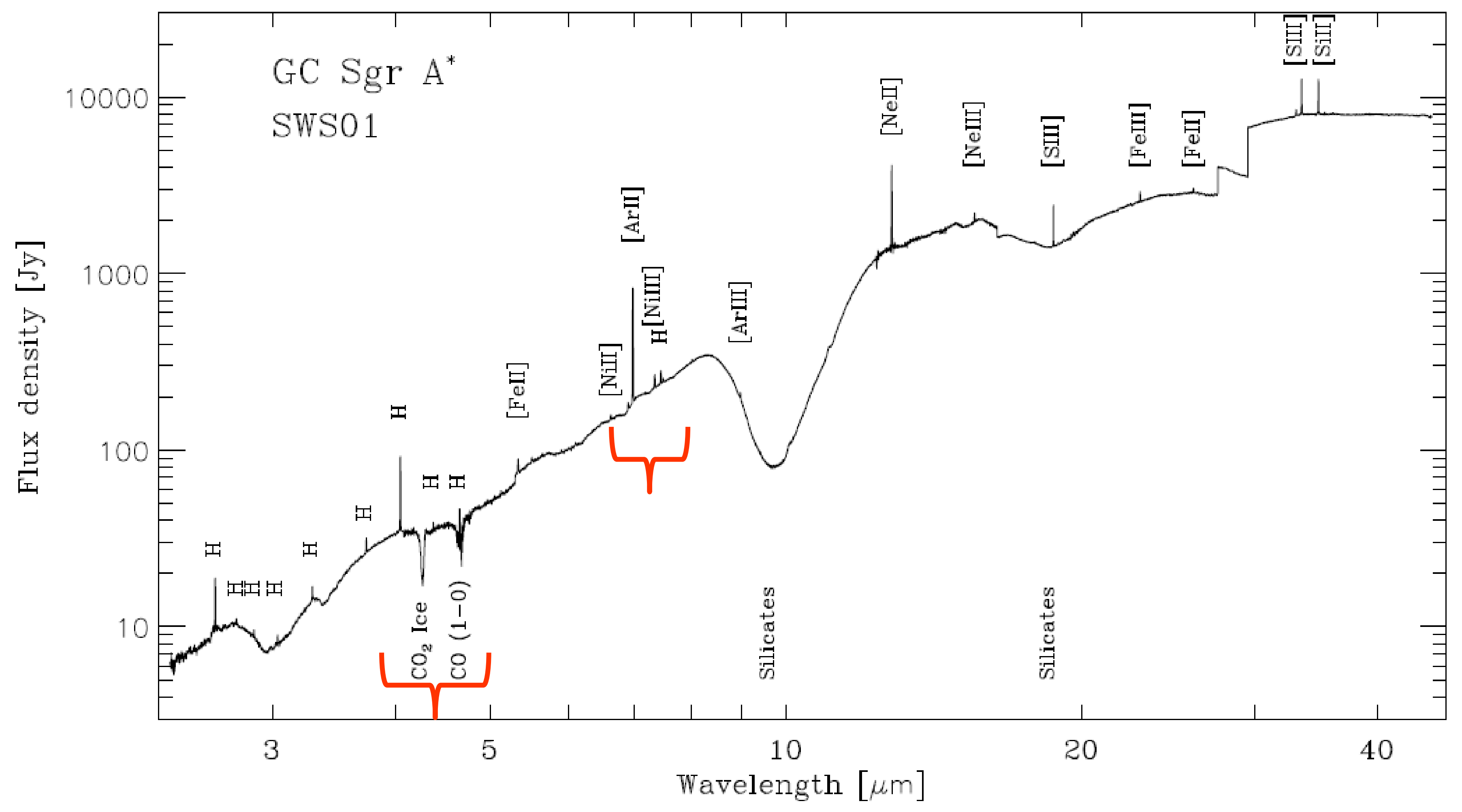
Quasar absorption lines



Dust features

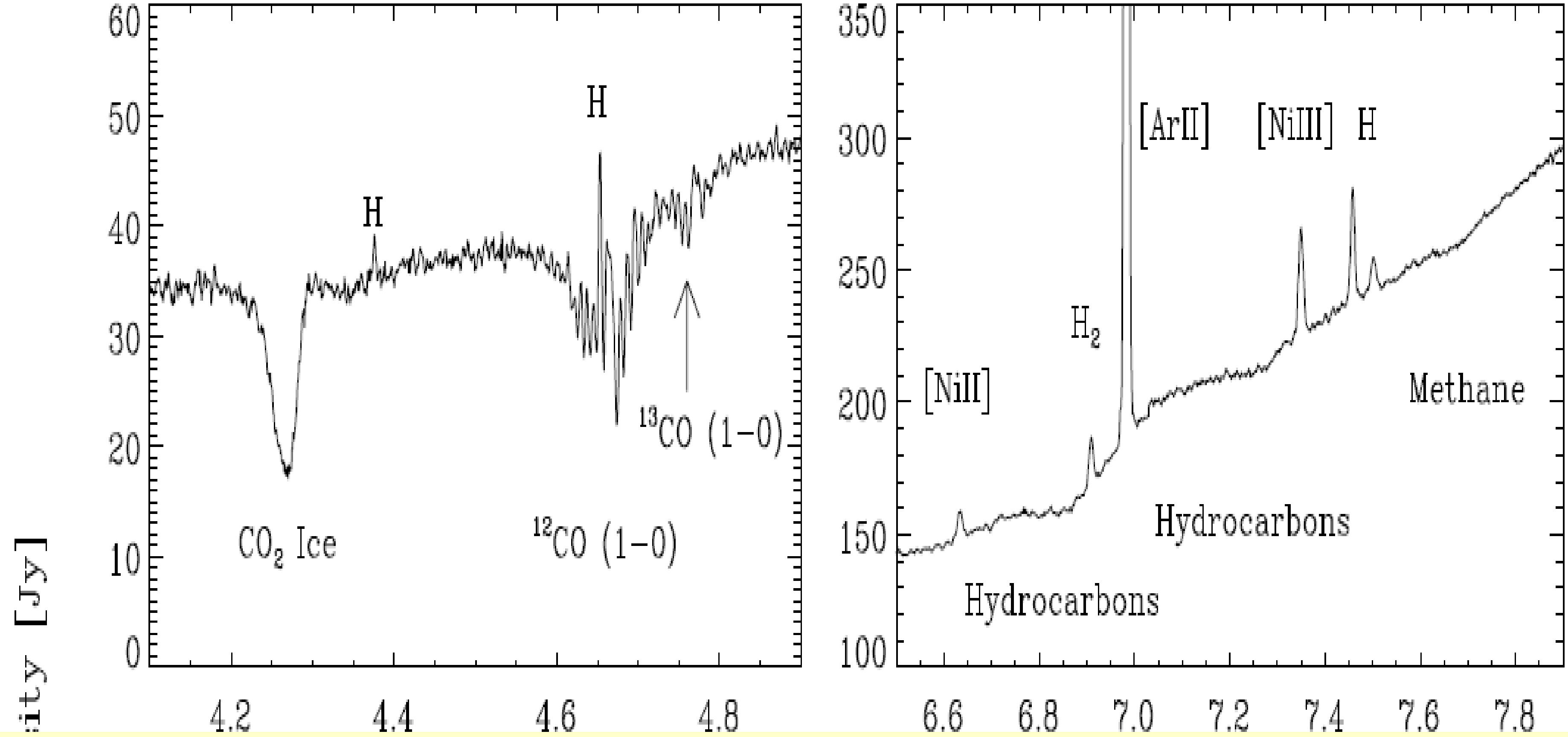
- – Emission/absorption
- – Warm clouds + circumstellar shells
- – Silicates, PolyAromaticHydrocarbons(=C-rich) …
- – Features depend on grain size+structure ➔ only rough estimates of composition

IR spectrum (Gal.centre)



Lutz 1996

IR spectrum (Gal.centre)



Lutz 1996

Abundances: notation

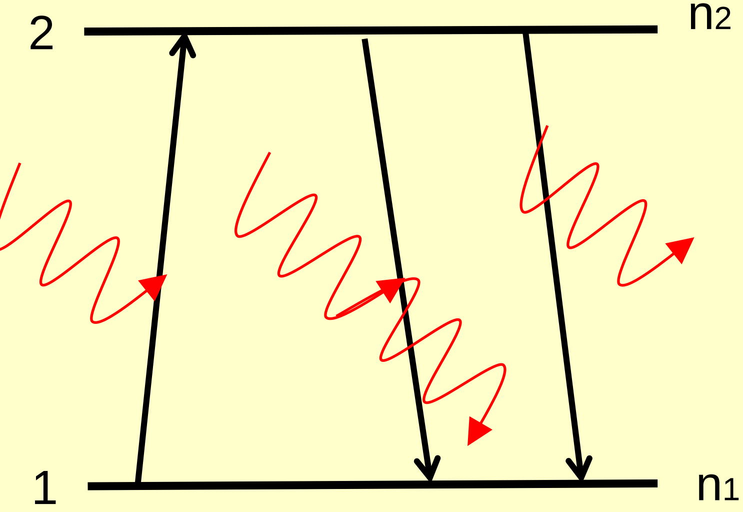
- Spectroscopy: by number density
  - $A(O) = O/H = 12 + \log(O/H) = 12 + \log(n(O)/n(H))$
  - Arbitrary normalization: $A(H) = 12$
  - $[O/H] = \log(O/H) - \log(O/H)_{sun}$

- Stellar & galactic evolution: mass fraction
  - $X + Y + Z = 1$ means: H + He + 'metals'

Solar composition (Asplund 2009)

	by number (old)		**by mass (old)**	
H	12.00		0.737	(0.706)
He	10.93	(11.00)	0.251	(0.275)
C	8.39	(8.76)	0.0022	
N	7.78	(8.10)	0.00062	
O	8.66	(8.91)	0.0054	
Fe	7.45		0.0116	
Z = metals	---		0.012	(0.02)

Lines and the 2-level atom



n_2 number density of atoms in state 2 [cm $^{-3}$]

Spontaneous emission	rate= n_2 $\mathbf{A}_{21}$
Absorption	n_1 $\mathbf{B}_{12}$ J_{12}
Stimulated Emission	n_2 $\mathbf{B}_{21}$ J_{12}
	[s $^{-1}$ cm $^{-3}$]

Relation between Einstein coefficients:

$g_2\,\mathbf{B}_{21} = g_1\,\mathbf{B}_{12}$ g = statistical weight of level; H : $g_n = 2\,n^2$

$2\,h\,\nu^3/c^2 * \mathbf{B}_{21} = \mathbf{A}_{21}$

$$\mathbf{A}_{21} = 1/(\text{lifetime of excited state}) \sim \begin{cases} 10^8 \quad 1/\text{s} & \text{dipole-permitted line} \\ 1 \quad 1/\text{s} & \text{‘forbidden’ line} \end{cases}$$

Line optical depth?

- Optical depth at line centre

$$\tau = L \underbrace{\frac{h\nu_{12}}{4\pi}\,\varphi_\nu(\nu_{12})\,(n_1 B_{12} - n_2\,B_{21})}_{\text{abs.coeff.= density*cross section}}$$

  - L = path length
  - φ = line profile $\int \varphi\, d\nu = 1$
  - NB. Oscillator strength f:

$$\frac{\pi\, e^2}{mc} f = \frac{h\nu_{12}}{4\pi}\, B_{12}$$

Line optical depth?

- Line width b: $\varphi_v(v_{12}) \approx \frac{1}{b}$
- ISM (low density, far from radiation sources): $n_2 \ll n_1$; neglect stim.emission
- ground state number density

$$n_1 = \frac{n_1}{n_{ion}} \times \frac{n_{ion}}{n_{elem}} \times \frac{n_{elem}}{n_H} \times n_H$$

excitation=1 ionization? abundance ε

Line optical depth?

observe dominant ion of the element (N_H = n_H*L = hydrogen column density):

$$\tau_{12} = N_H \times \varepsilon \times \frac{\lambda^3}{8\pi b} \times \frac{g_2}{g_1} \times A_{21}$$

➔For ISM gas in clouds and nebulae:

- H I Ly α (permitted, ground state) THICK
- H I Hα, Pα… (permitted, excited state) **THIN**
- Metals (forbidden lines, ground state) **THIN**

  (some exceptions HeI 3888, CIV 1550 …)

Advantages of optically thin lines

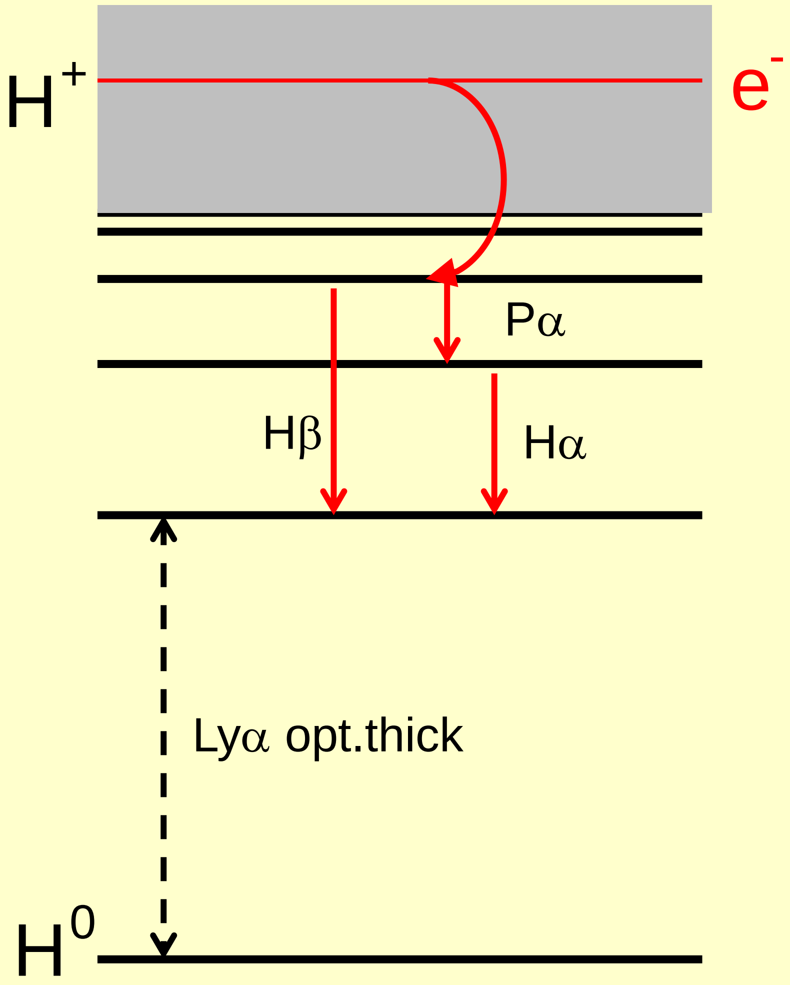
- Measured flux is sum of all contributions from emitting volume: $f_{obs} = \frac{1}{4\pi\, d^2} \int 4\pi j \, dV$
- emissivity integrated over entire line:

$$j = n_2 A_{21} \int \frac{h\nu}{4\pi} \varphi_\nu(\nu) d\nu = \frac{h\nu}{4\pi} n_2 A_{21}$$

➔ $f_{obs} \quad \propto \quad jV \quad \propto \quad n_2 V \quad \propto \quad \varepsilon\, n_H V$

- Linear dependence on abundance
- Independent of line shape
- Independent of exact source geometry

Recombination lines (H, He,



cascade of lines after recombination to higher level: optical (Hα) … radio (H109α)

solution of cascade: emissivity

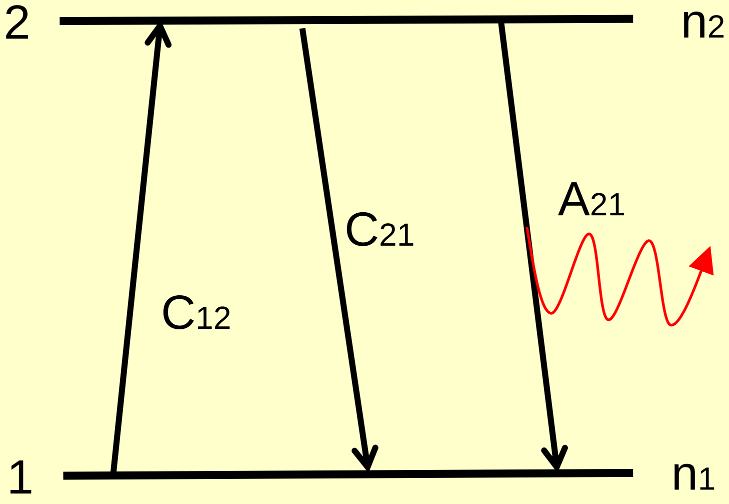
$$j = \frac{h\nu}{4\pi} n_+ n_e \, \alpha_{eff}$$

effective recomb.coefficient

$$\alpha_{eff} \propto T_e^{-0.6} \sim 10^{-13} \, cm^3/s$$

recomb.lines of metals are very weak (< 0.001) due to their low abundance

Collisionally excited lines



Collisions with thermal electrons

Excitation:

$$C_{12} = C_{21}\,\frac{g_2}{g_1}\,\exp\left(-\frac{E_{12}}{kT}\right)$$

De-excitation:

$$C_{21} \propto \frac{n_e}{\sqrt{T_e}}$$

Steady state $n_1 C_{12} = n_2 (C_{21} + A_{21})$

Low density limit $C_{21} \ll A_{21}$ gives

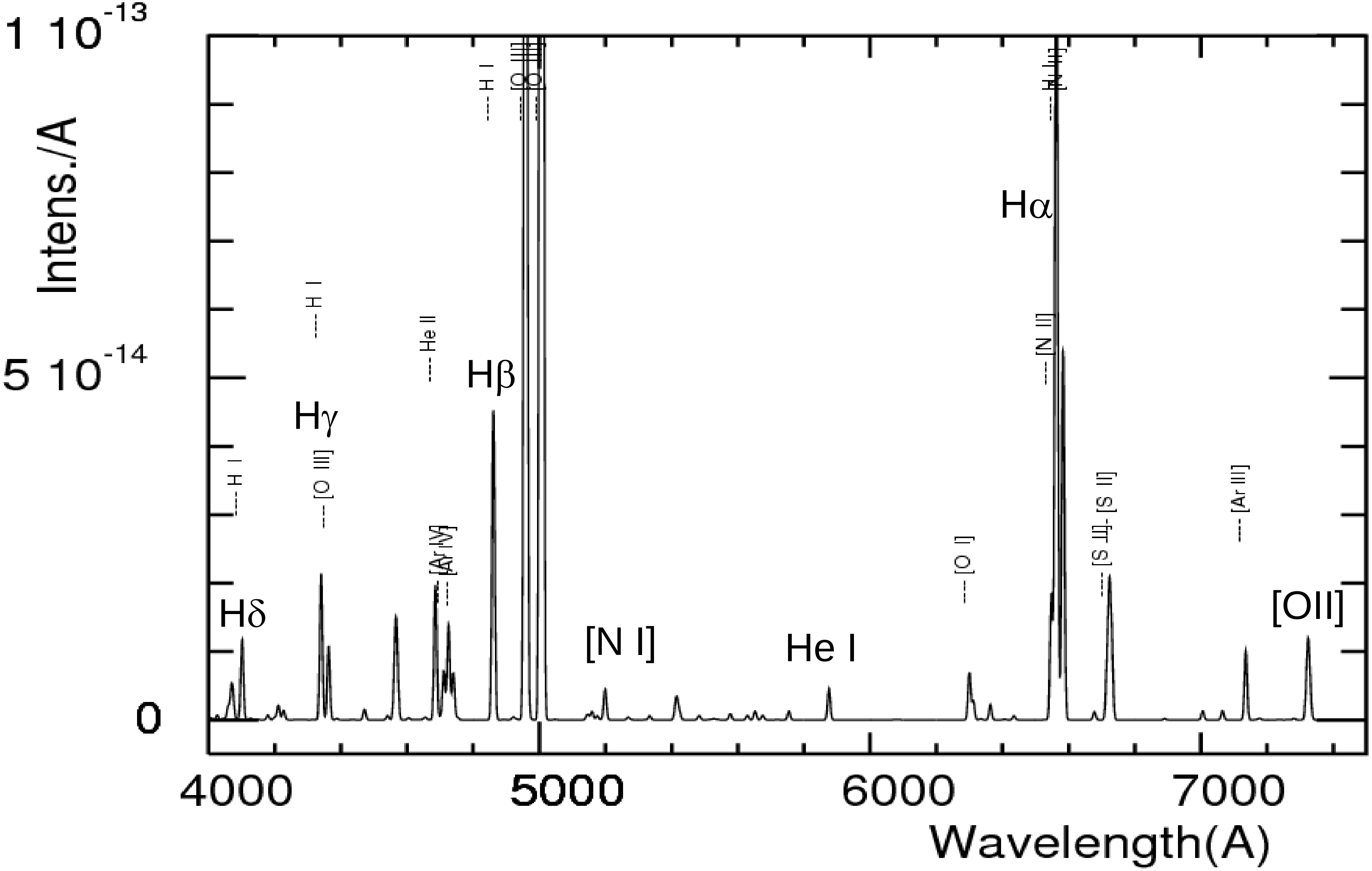
$$j \propto n_2 A_{21} = n_1 C_{21} \propto \frac{n_1 n_e}{\sqrt{T_e}}\,\exp\left(-\frac{E_{12}}{kT}\right)$$

Sensitive to electron temperature

Most lines are ‘forbidden’: [OII] 3727, [OIII] 5007, [ArIII] 7135 …

Also permitted resonance lines CIV 1550, NV 1240, …

Theoretical PN spectrum



Analysis: Plasma diagnostics

- Assume: nebula is isothermal & homogeneous
- Electron temperature from diagnostic line ratios:

  [OIII] 5007/4363, [NII] 6583/5755, … ratio ~300 !!!
- Electron density from line ratios:

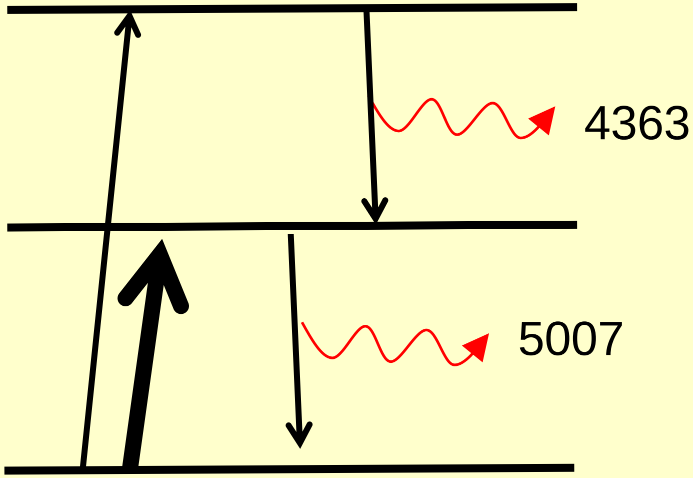
  [SII] 6731/6717, … lines are weak and closeby
- Compute line emissivities, get ionic abundances

  [OIII]/Hβ → O^+/H^+
- Ionization correction (empirical factors ICF):

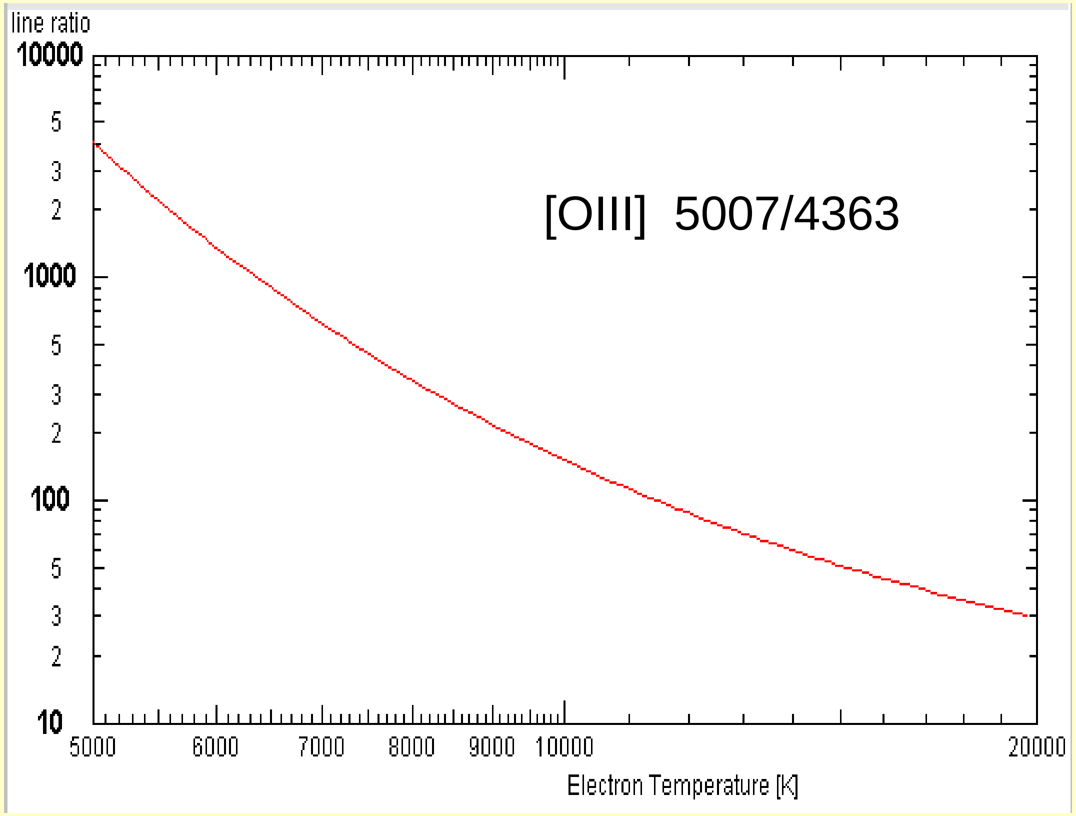
  $O/H = (O^+/H^+ + O^{++}/H^+) * (He/He^+)$

  $N/H = (O/H) (N^+/O^+)$

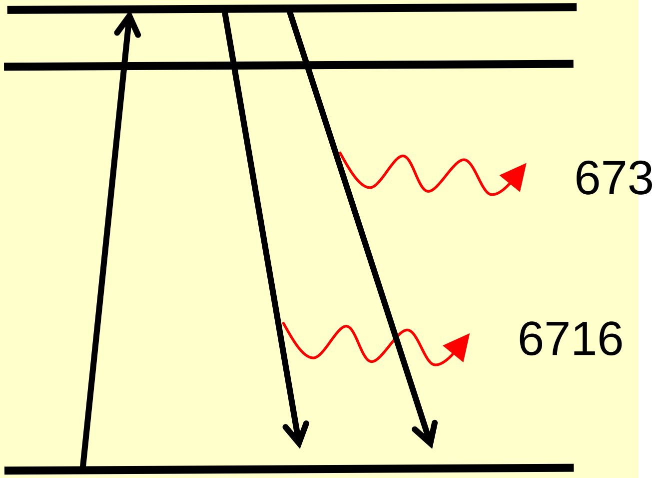
Electron temperature diagnostic

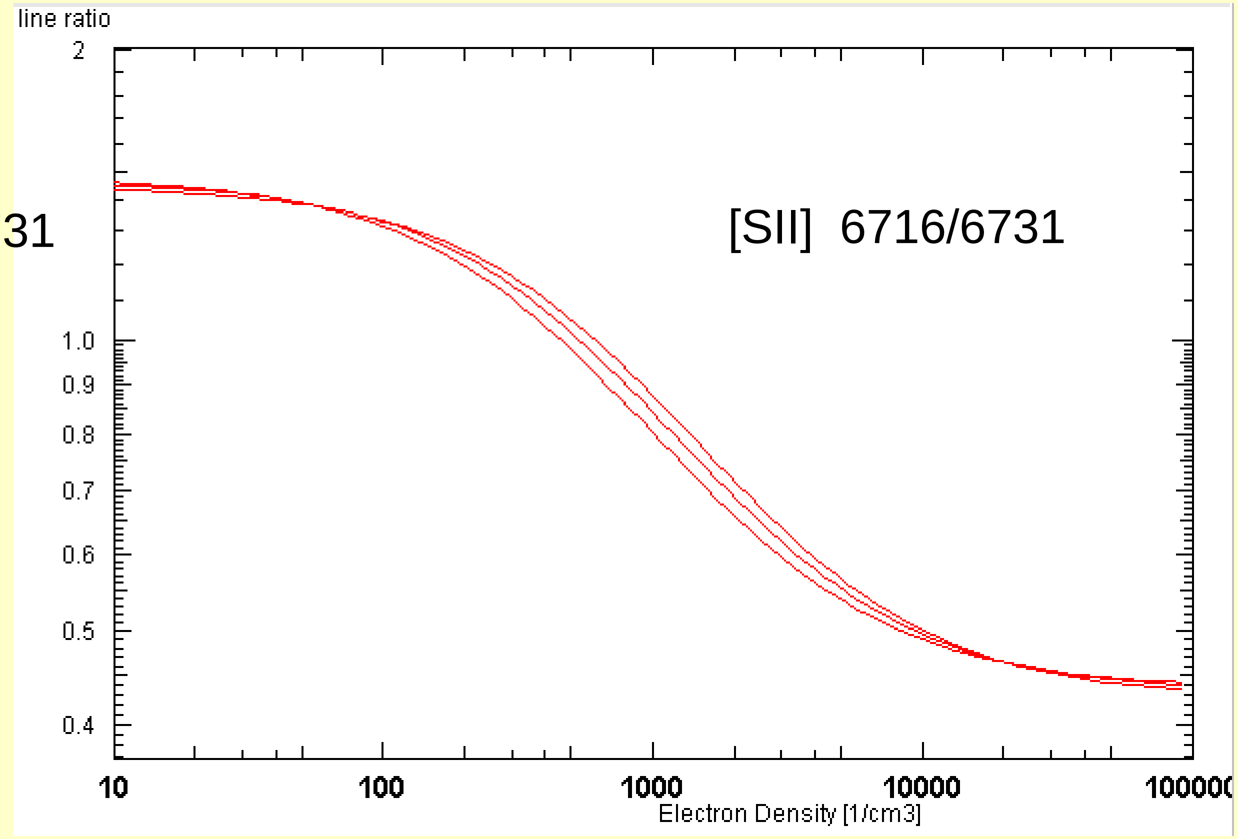


$$C_{12} \propto \exp(-\frac{E_{12}}{kT})$$



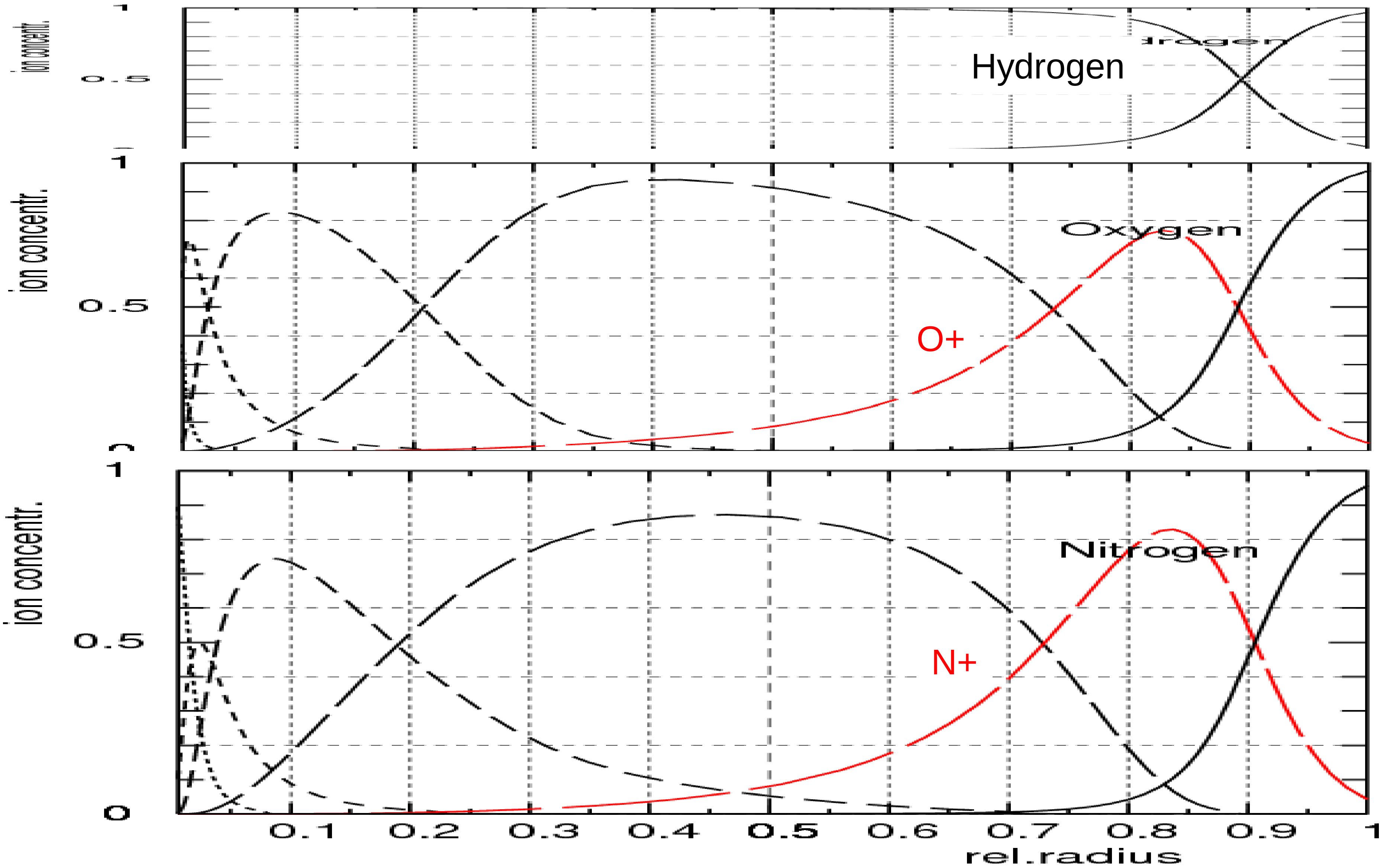
Electron density diagnostic



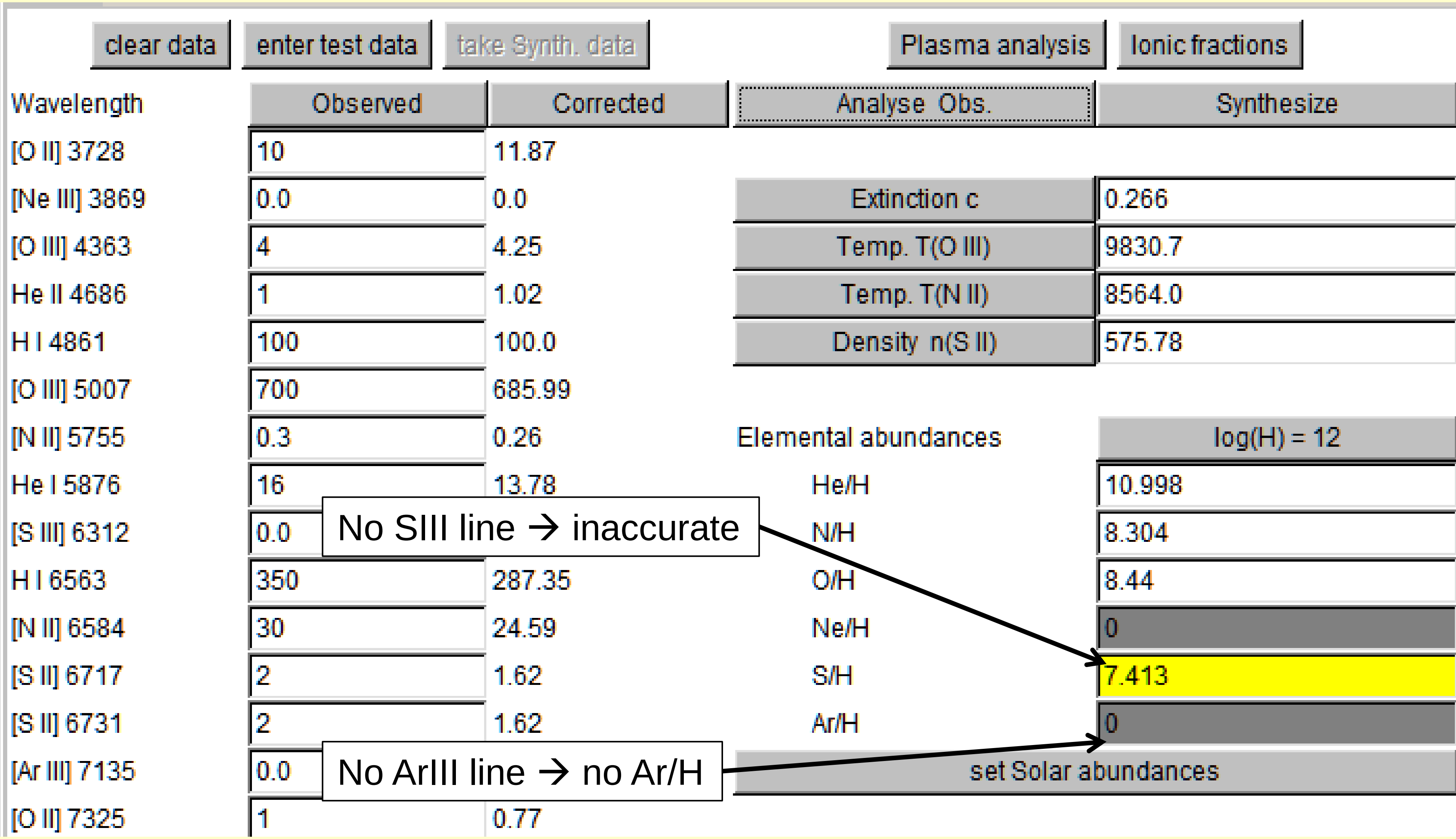


$$A_{21} \leftrightarrow C_{21} \propto n_e$$

N/O ionization correction



http://astro.u-strasbg.fr/~koppen/Plasma.html



Wavelength	Observed	Corrected
[O II] 3728	10	11.87
[Ne III] 3869	0.0	0.0
[O III] 4363	4	4.25
He II 4686	1	1.02
H I 4861	100	100.0
[O III] 5007	700	685.99
[N II] 5755	0.3	0.26
He I 5876	16	13.78
[S III] 6312	0.0	
H I 6563	350	287.35
[N II] 6584	30	24.59
[S II] 6717	2	1.62
[S II] 6731	2	1.62
[Ar III] 7135	0.0	
[O II] 7325	1	0.77

Extinction c	0.266
Temp. T(O III)	9830.7
Temp. T(N II)	8564.0
Density n(S II)	575.78

Elemental abundances	log(H) = 12
He/H	10.998
N/H	8.304
O/H	8.44
Ne/H	0
S/H	7.413
Ar/H	0

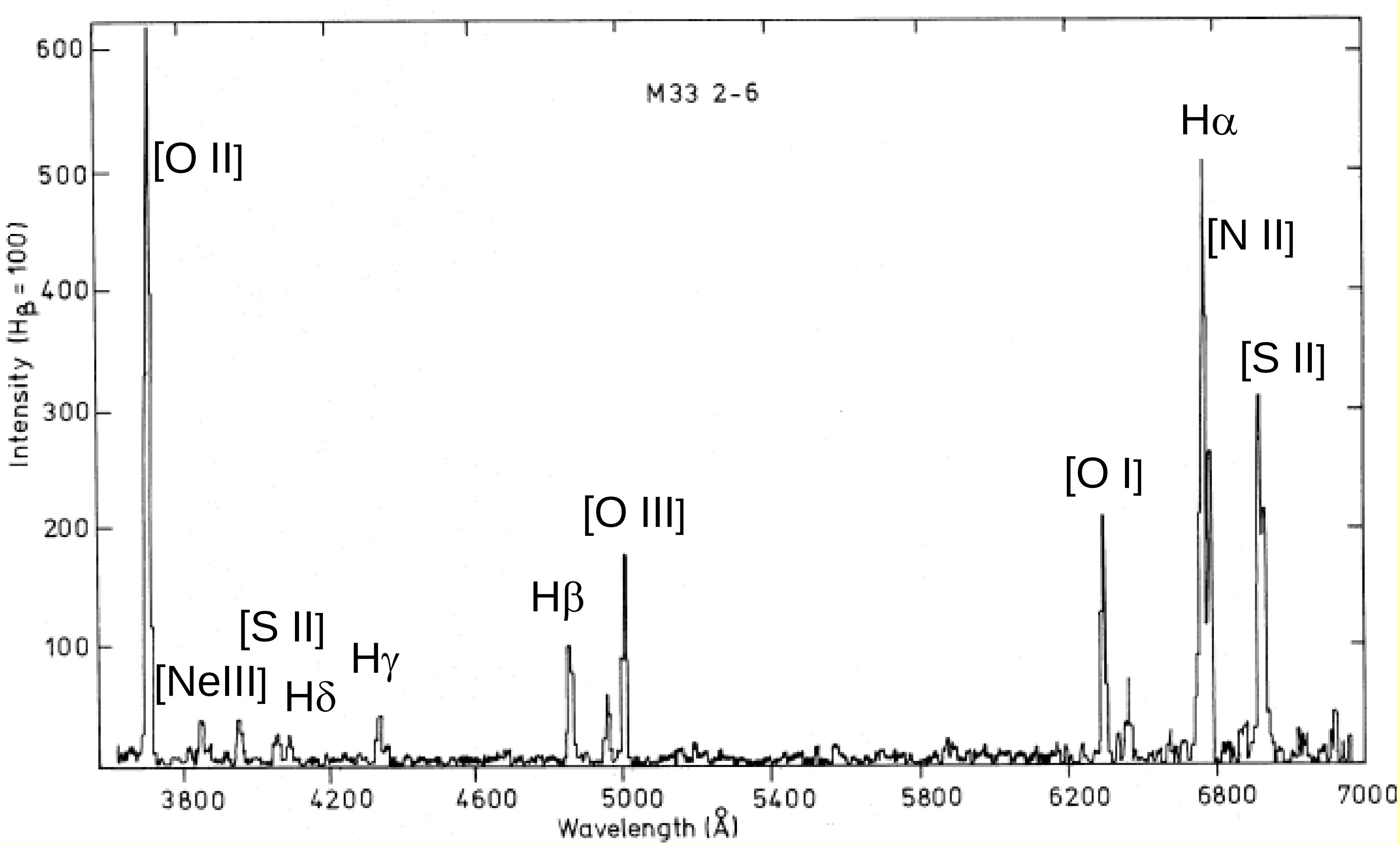
No SIII line → inaccurate

No ArIII line → no Ar/H

Analysis methods (II)

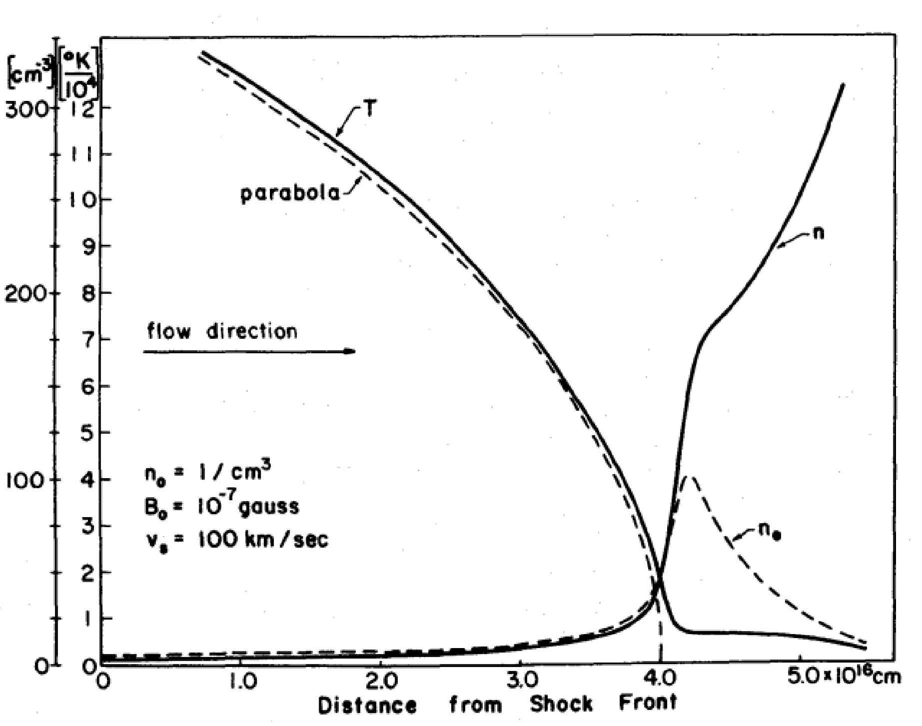
- Model fitting: compute ionization and excitation due to all known processes:
  - HII, PN: photoionization
  - SNR: collisional ionization (shock)
- ‘Strong Line Methods’: diagnostic relations obtained from model grids (Pagel, …)
- Lines not optically thin: radiative transfer, depends on source geometry, velocity field → derive correction terms for opt.thin case

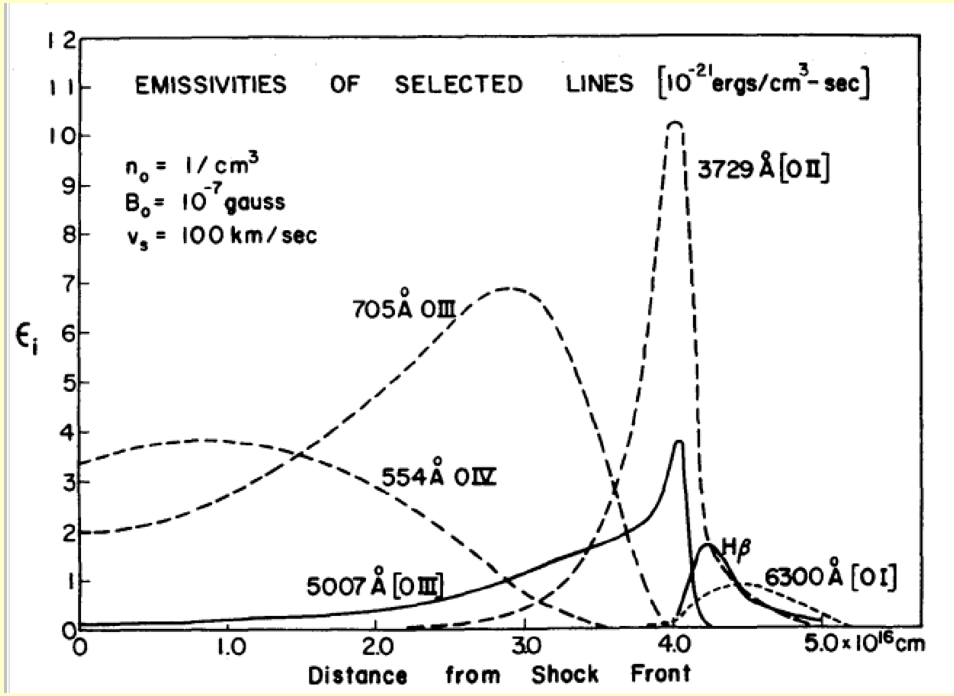
SNR spectrum



Dopita et al. 1980

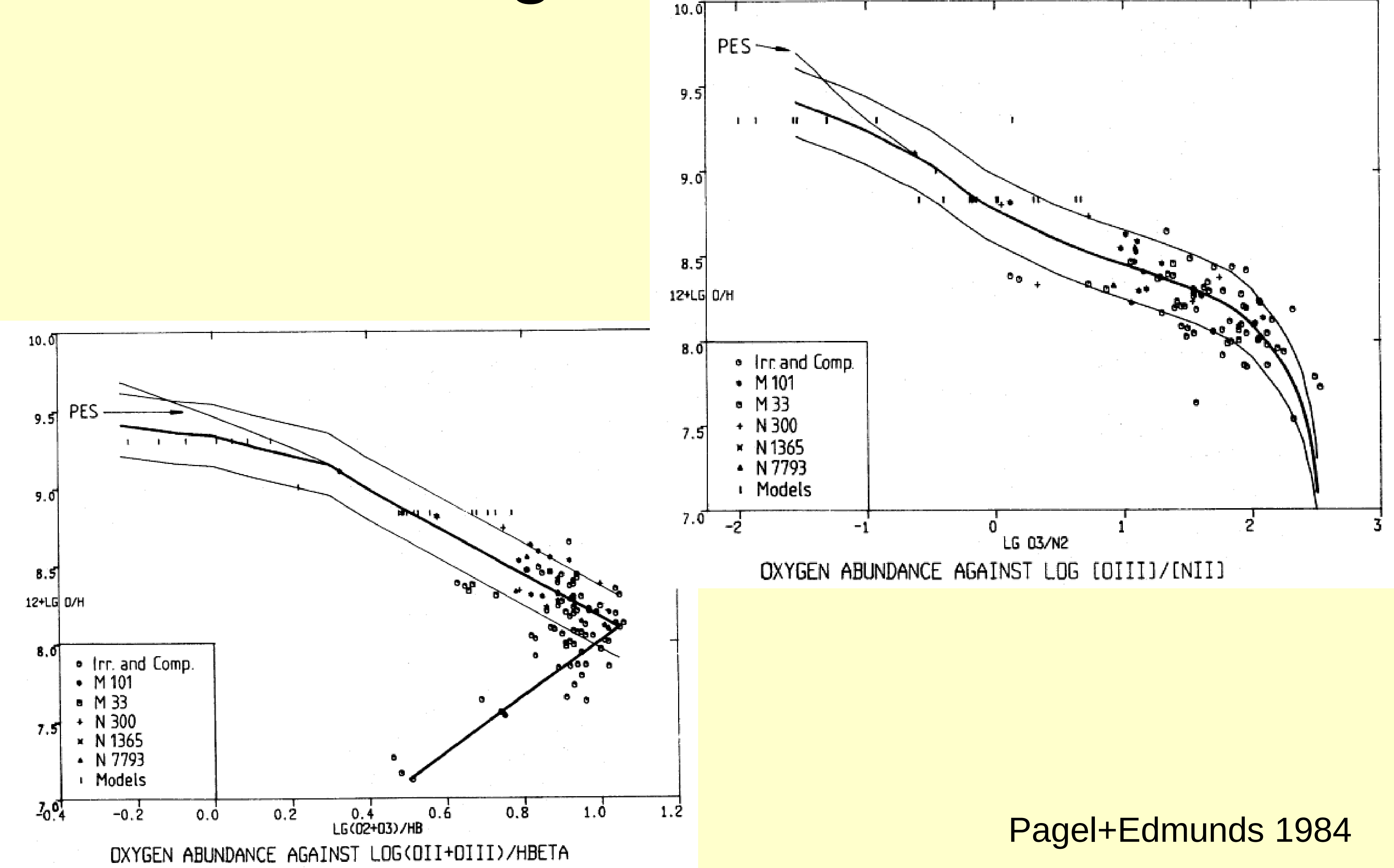
Model of a shock





Cox 1972

Strong Line Methods



OXYGEN ABUNDANCE AGAINST LOG [OIII]/[NII]

OXYGEN ABUNDANCE AGAINST LOG(OII+OIII)/HBETA

Pagel+Edmunds 1984

Summary: emission lines

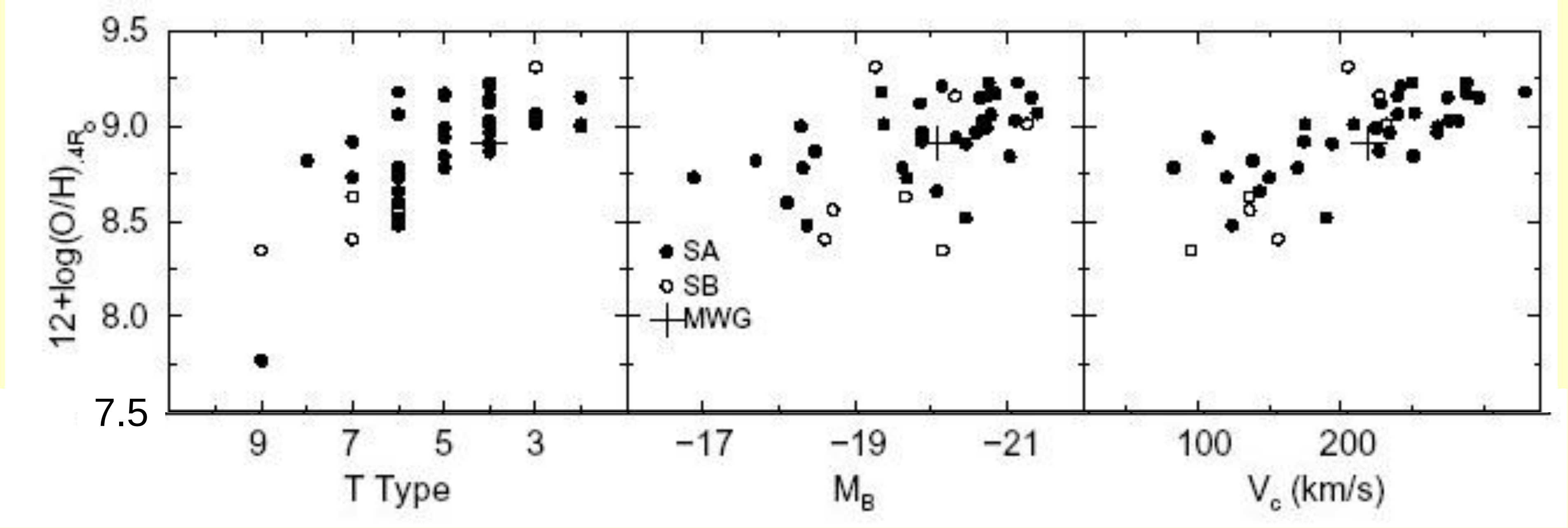
- Problems:
  - Diagnostic lines are faint
  - No good ICF
  - Temperature fluctuations ➔ overestimate average T ➔ underestimate abundance by 0.1 dex
- Accuracy
  - Atomic data: ±5…10 %
  - Single object, very good spectrum (plasma/model)
    - He/H ±0.02 dex = 5%
    - O/H ±0.1 dex
    - Other elements: ±0.3 .. 0.5 dex
  - External galactic HII region: O/H ~< ±0.2 dex

Abundances (from HII regions)

- MWG@8.5 kpc O/H = 8.68±0.05
  Sun: 8.66 (old: 8.91)
- Spirals: characteristic O/H increases with mass and morphological type
- SB = S
- LSBs 1/3 Zsun
- Cluster gals: perhaps higher Z
- Bulge PN (MWG, M31): O/H lower than expected from stellar [Fe/H] $O_B=O_D$

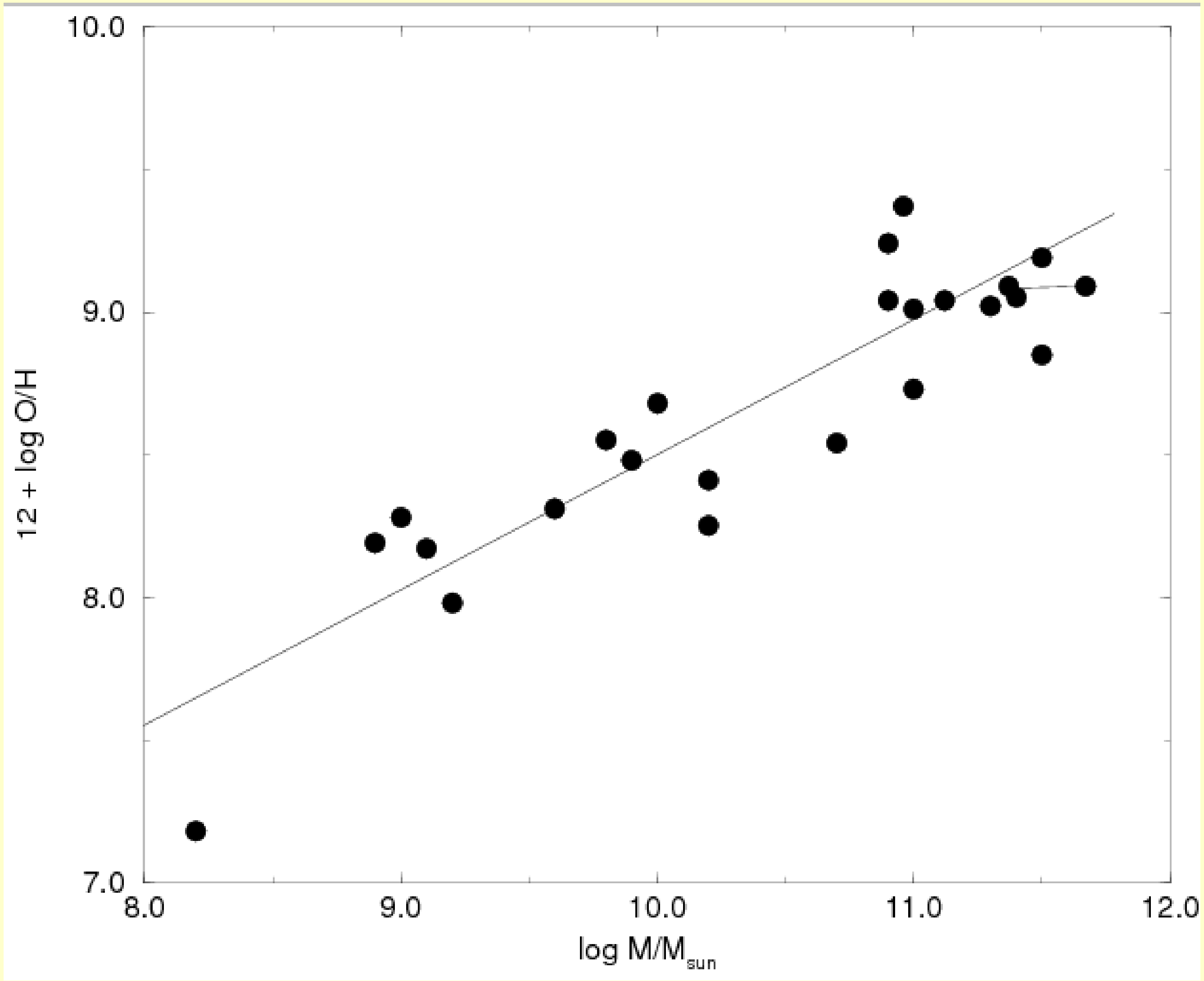
Abundance and Gal.parameter

Sc Sb



Henry+Worthey 1999

O-abundance at effective radius in spirals

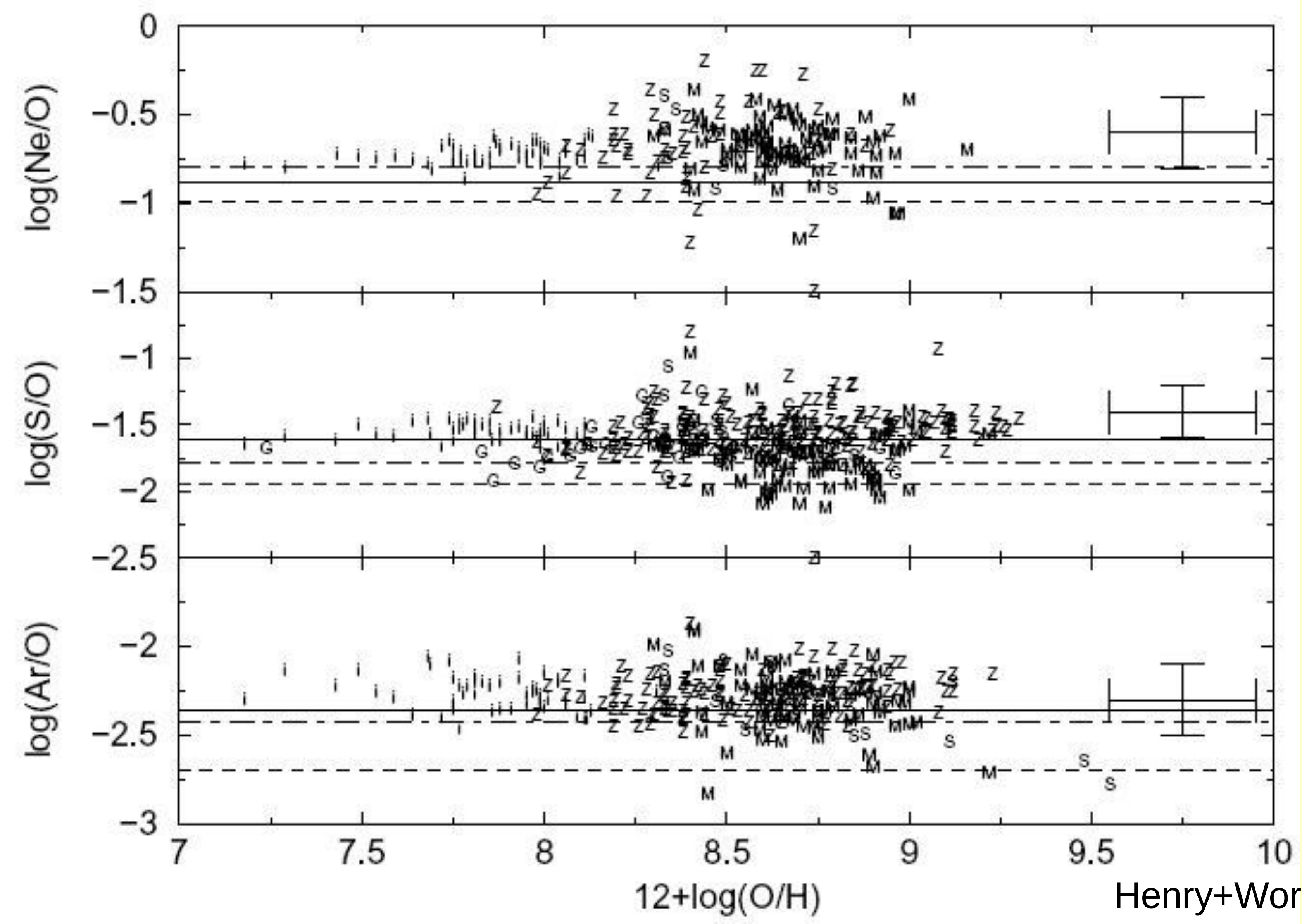


Henry+Worthey 1999

Abundance ratios

- O – Ne – S – Ar : go in lockstep, as expected from their synthesis in massive stars
- C/O and N/O cf. chemical evolution (later)

O-Ne-S-Ar go in lockstep

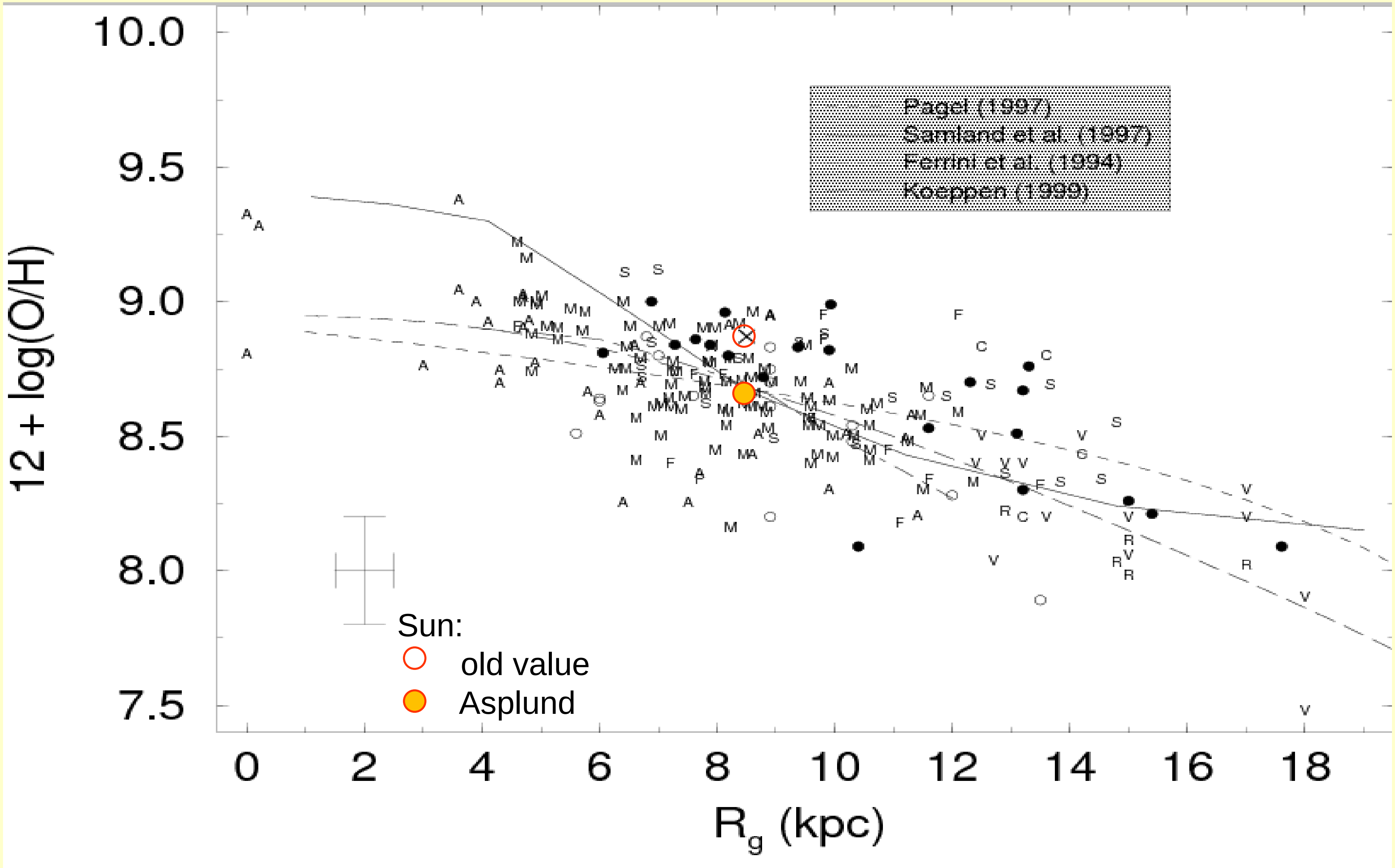


Henry+Worthey 1999

Abundance profiles

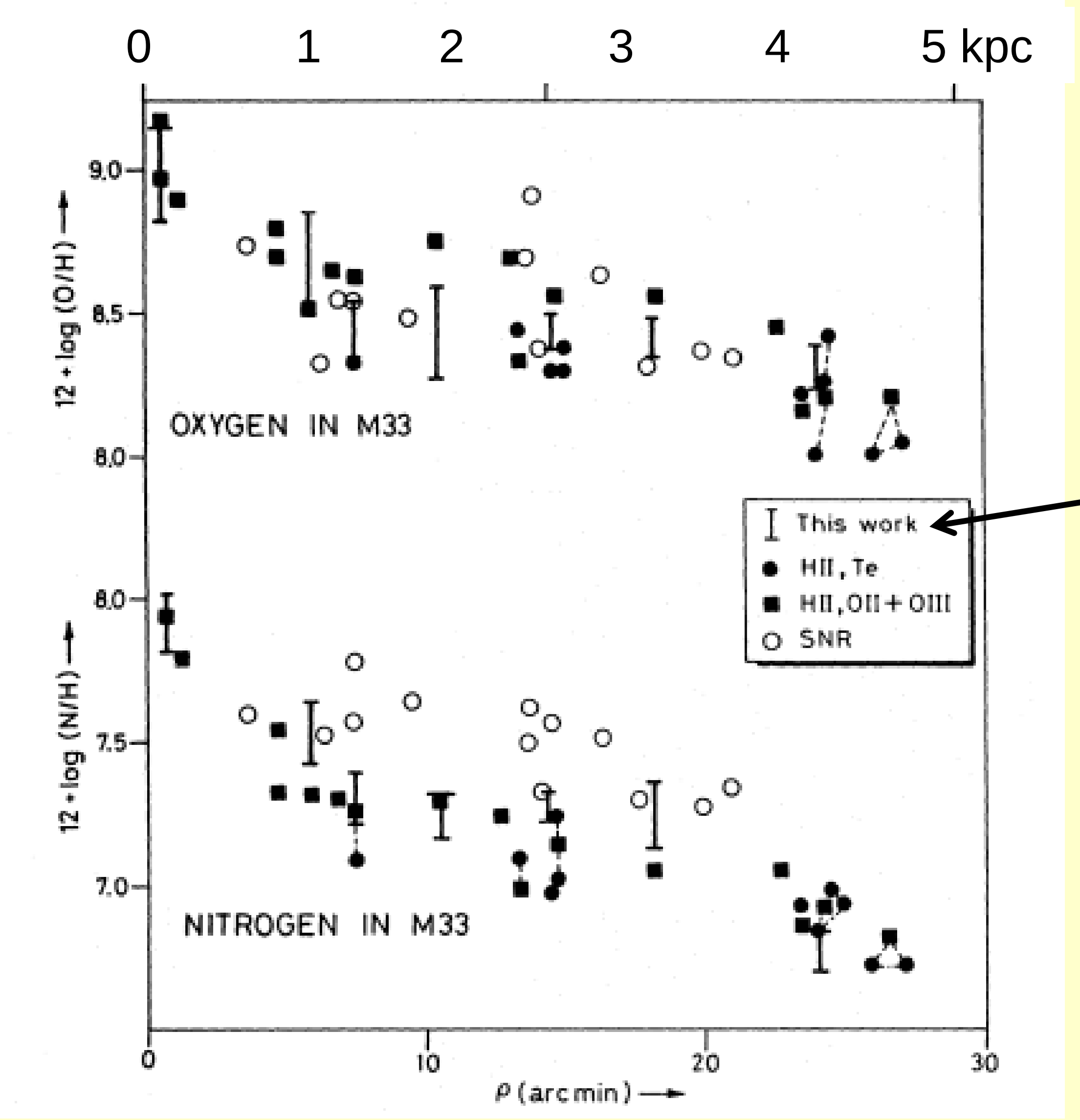
- MWG: gradient O/H -0.06 ± 0.01 dex/kpc
  - no genuine scatter (± 0.2 dex noise)
  - flattens beyond 10 kpc (HII, PN) …
- Other spirals: M31, M33, M81, M83, M101 … http://ned.ipac.caltech.edu/level5/Ewald/Abundances/frames.html
- SB: no gradient (strong bar ➔ radial mixing)
- LSB: no gradient
- Shape of profile: expon., power, flattening …
- Vertical 'gradient': MWG as expected from stellar σ-age relation

Abundance gradient MWG: HII



Henry+Worthey 1999

HII and SNR give same gradient

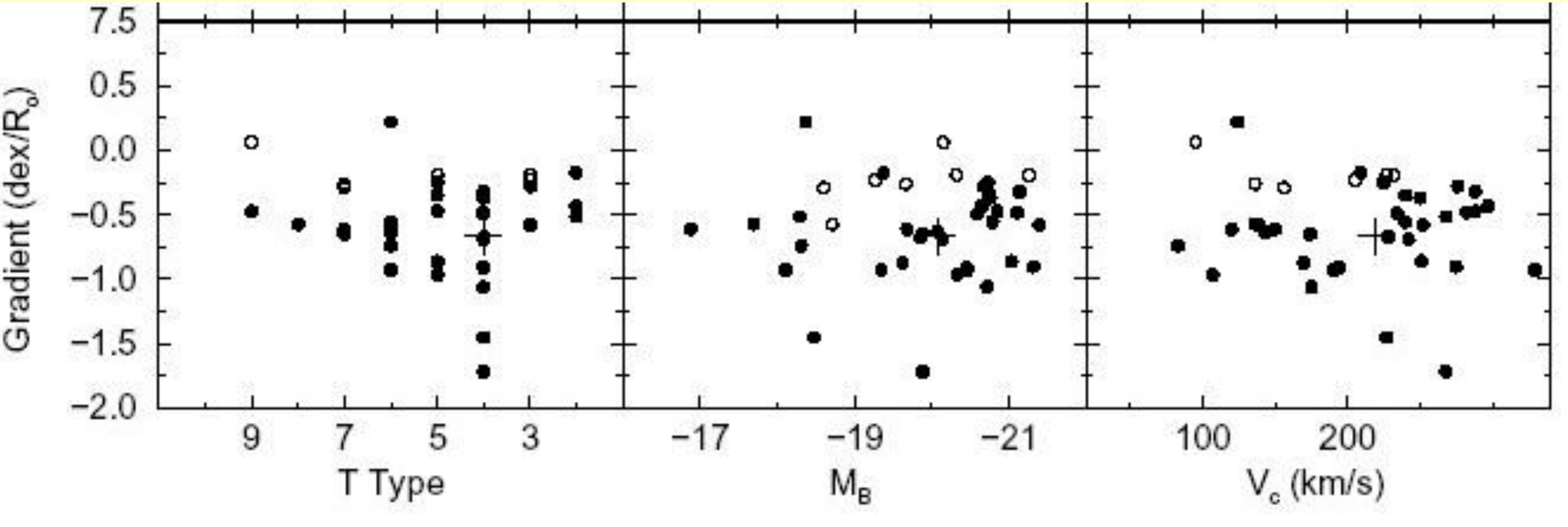


Vilchez et al. 1988

With Te from 5007/4363

Gradient vs. Gal.parameter ?

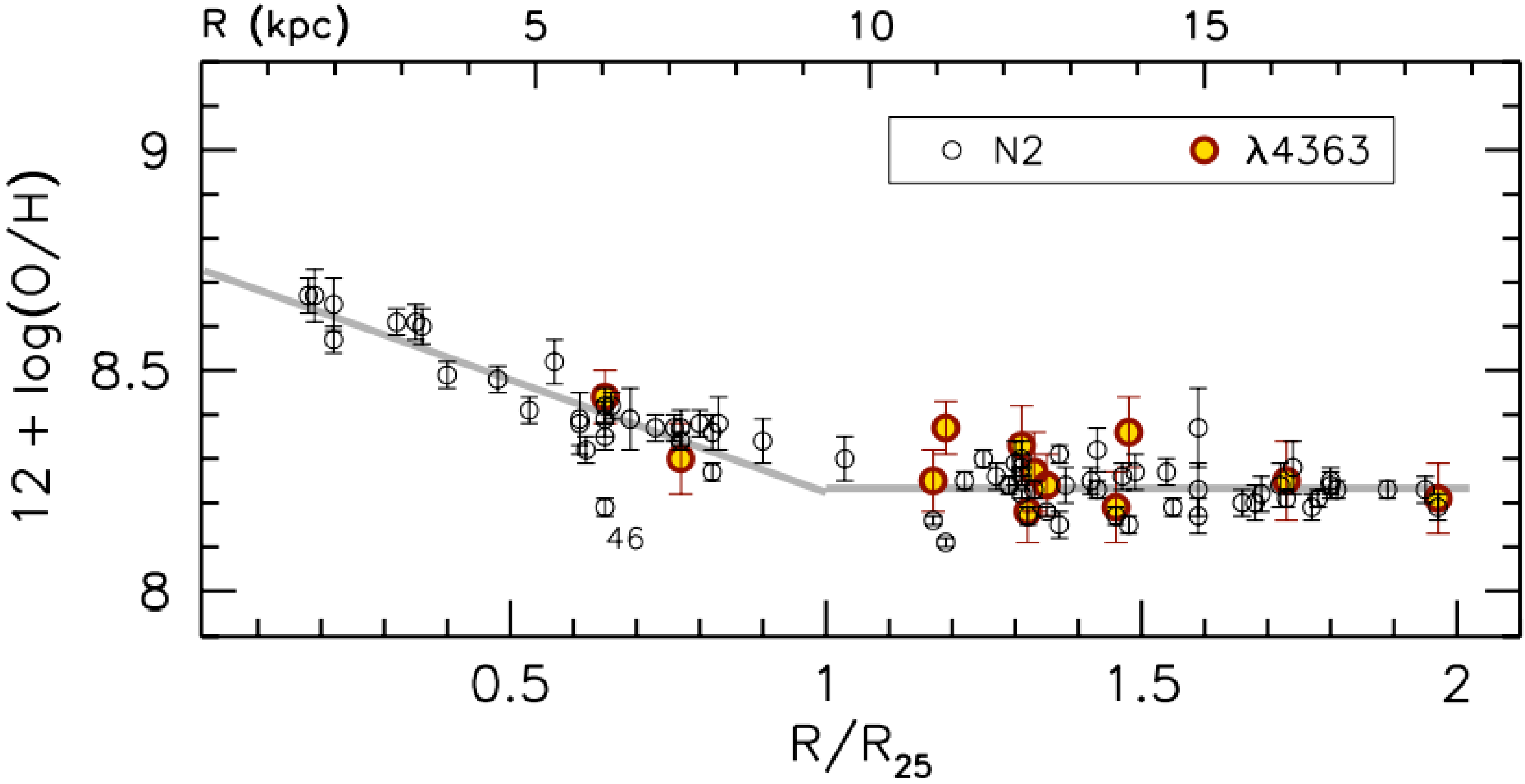
Sc Sb



Nothing!

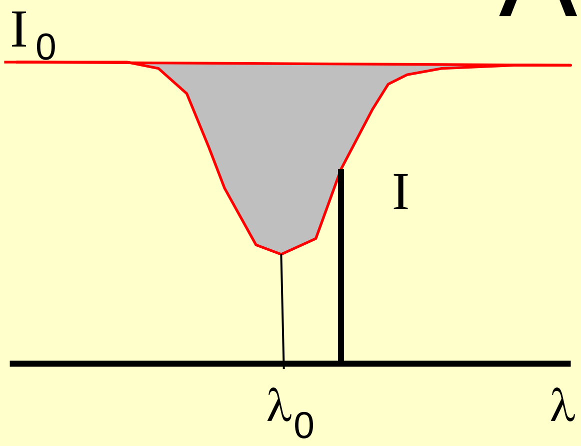
Henry+Worthey 1999

Gradient flattening



Bresolin 2012

Absorption lines

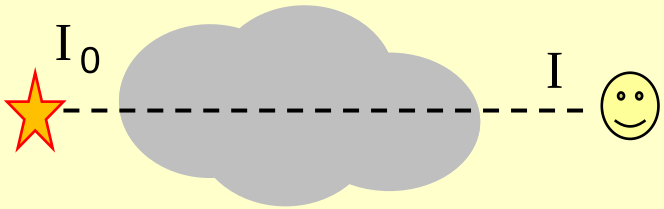


Equivalent width

$$W_\lambda = 2\int \frac{I_0 - I(\Delta\ \ )}{I_0}\, d\Delta\lambda$$

Compute *I(Δλ)* from absorbing column

$$I(\Delta\lambda) = I_0 \exp(-\tau(\Delta\lambda))$$



Monochromatic optical depth

$$\tau(\Delta\lambda) = \int \kappa(\Delta\lambda) dl$$

Absorption coefficient

$$\kappa(\Delta\lambda) = \frac{hv}{4\pi}\, \varphi(\Delta\lambda)\, (n_1 B_{12} - n_2 B_{21})$$

Uniform cloud ($\tau_0 \propto n_1\, l = N_1$ column density)

$$\tau(\Delta\lambda) = \tau_0 b \quad \varphi(\Delta\lambda)$$

Absorption lines

All together

$$W_\lambda = 2\int_0^\infty (1 - \exp(-\tau(\Delta\lambda))\ d\Delta\lambda$$

With a Gaussian line profile (broadening by thermal and/or microscale motions) of width $b = \frac{\lambda_0}{c}\sqrt{\frac{RT}{\mu} + \xi^2}$

$$\varphi(\Delta\lambda) = \frac{1}{b\sqrt{2\pi}}\ \exp(-\frac{1}{2}(\Delta\lambda/b)^2)$$

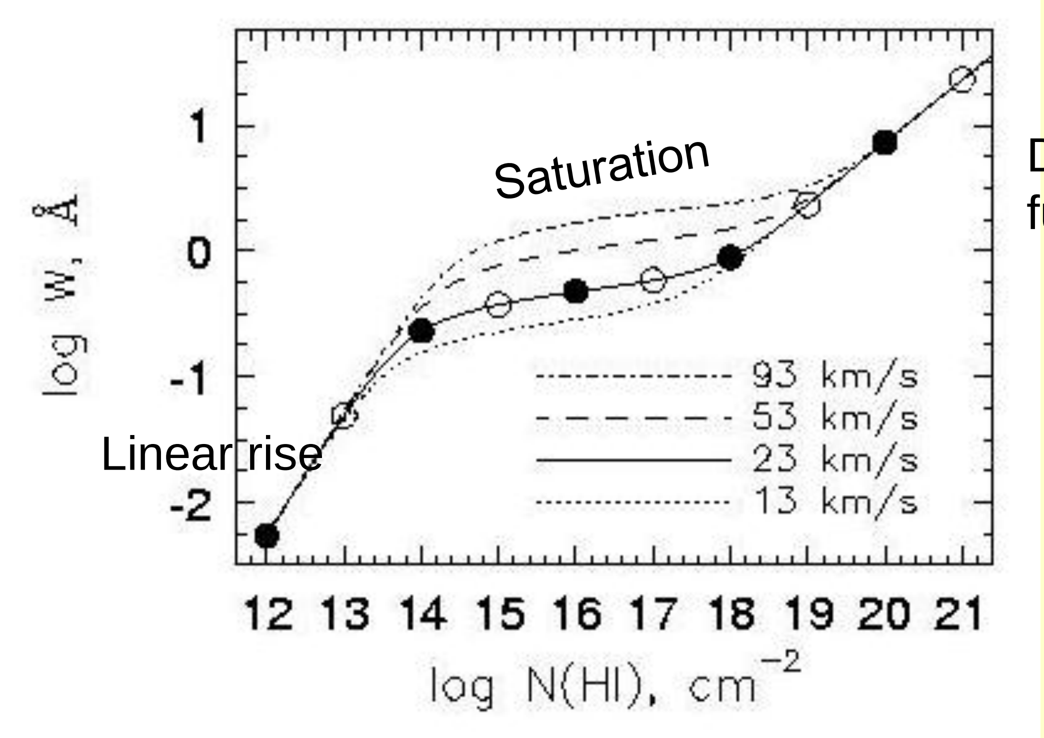
One gets

$$W_\lambda = 2b\ \int_0^\infty (1 - \exp(-\frac{\tau_0}{\sqrt{2\pi}}\ \exp(-\frac{1}{2}(\Delta\lambda/b)^2)\,))\ d(\Delta\lambda/b)$$

Note that optical depth at line centre $\tau_0 \propto f\ N_1\ /b$ depends on line strength, lower state column density and line width.

W_λ as function of τ_0 is the **Curve of Growth** or **Saturation Curve**

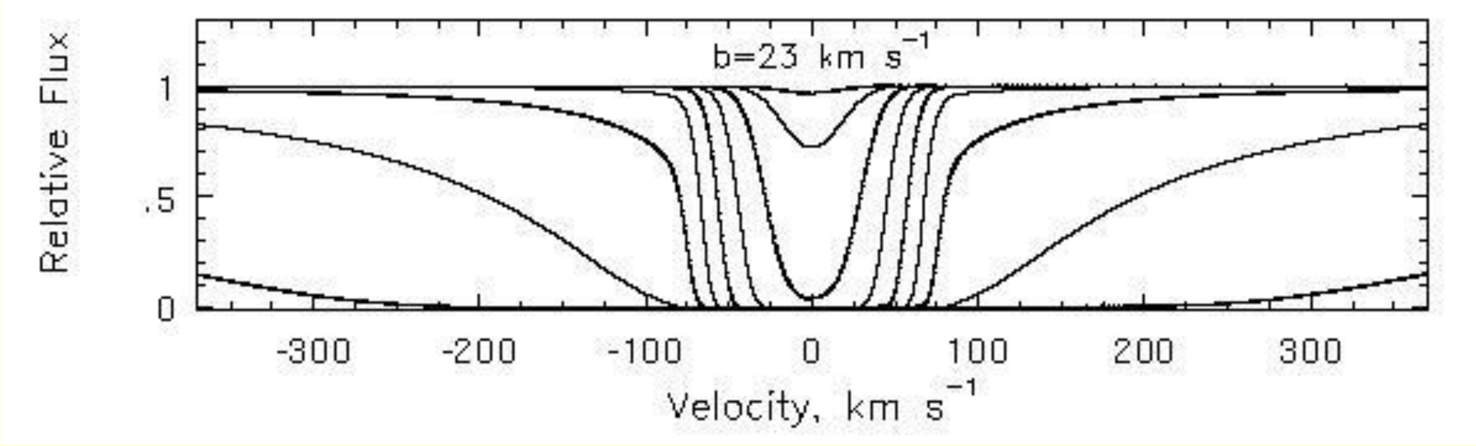
Curve of growth



Saturation

Linear rise

Damping wings give further slow rise



JPL/IPAC

COG: limiting cases

- Weak lines: linear part

optically thin: $1 - \exp(-\tau) \approx \tau$ gives

$$W_\lambda \approx \frac{2\tau_0}{\sqrt{2\pi}} \int_0^\infty e^{-\frac{x^2}{2}}\, dx = \tau_0$$

- Saturation $W_\lambda \propto b\sqrt{\ln(fN/b)}$
- Damping wings $\varphi(\Delta\lambda) \rightarrow \frac{1}{\gamma^2 + \Delta\lambda^2}$ (Lorentz-profile)

composite profile Voigt function H(a,v) = Gauss*Lorentz

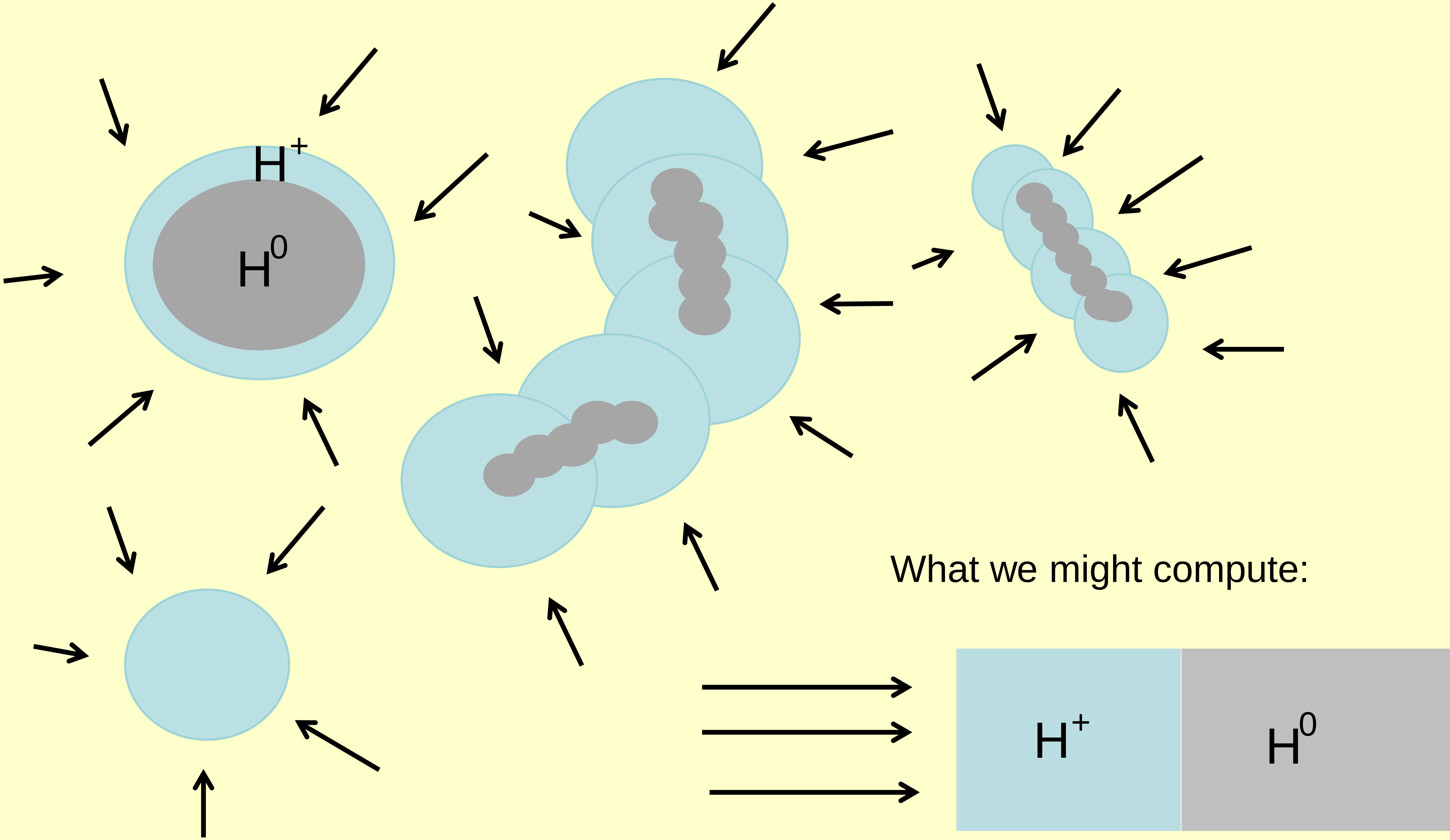
gives: $W_\lambda \rightarrow b\sqrt{\tau_0 \frac{\gamma}{b}}$

Absorption line analysis

- Get ***b*** from hi-res.profiles of weak lines
- Get **ionic column densities** via COG
- **Ionization correction**
  - Sum up all ions
  - Assume that visible ion is dominant one
  - Models

- Problems:
  - Ionization correction
  - Saturation of strong lines
- Accuracy: <0.3 dex … 1 dex …

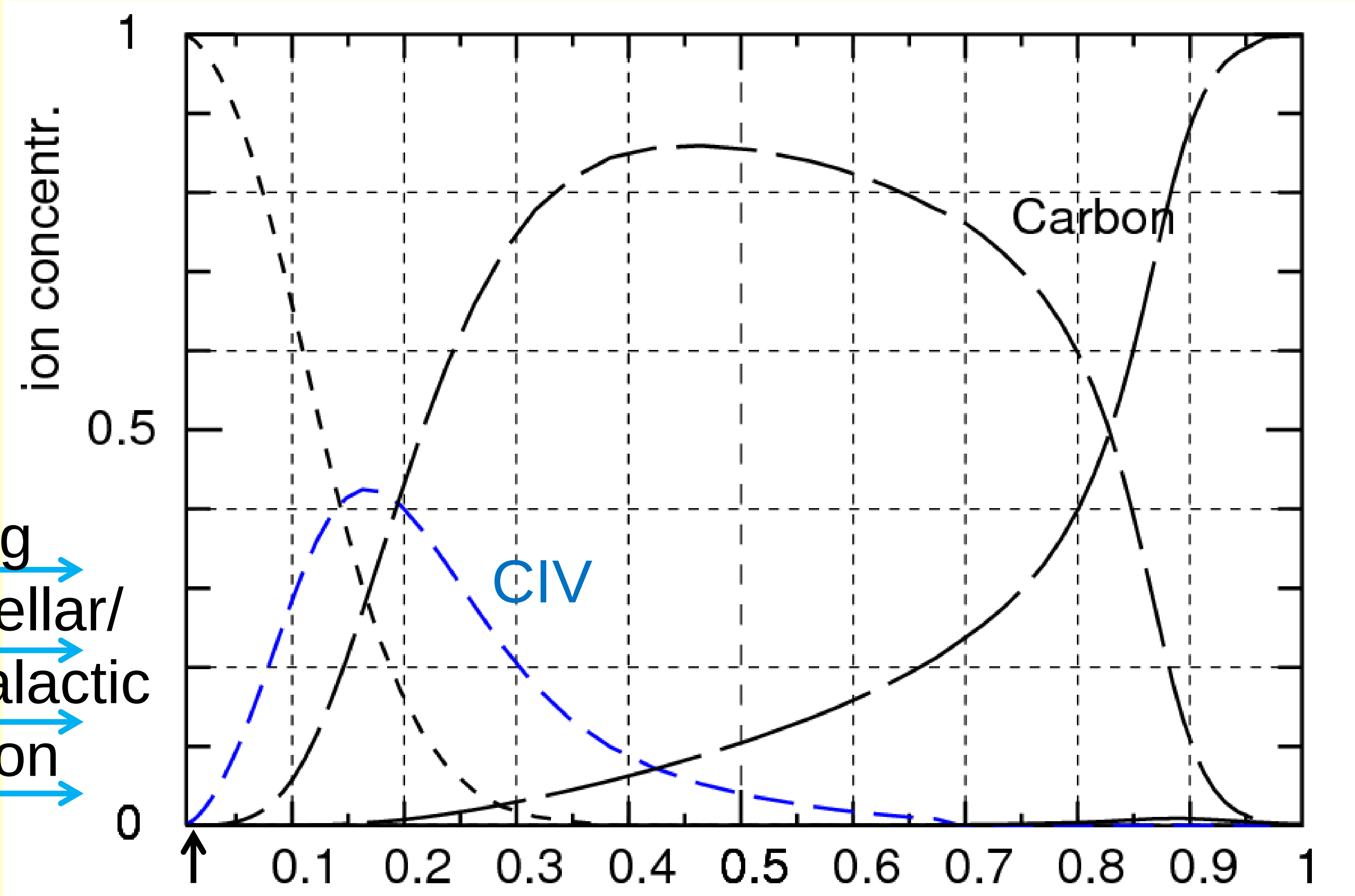
How clouds might look like



What we might compute:

Model: ionization stratification

ionizing
interstellar/
intergalactic
radiation



↑
surface

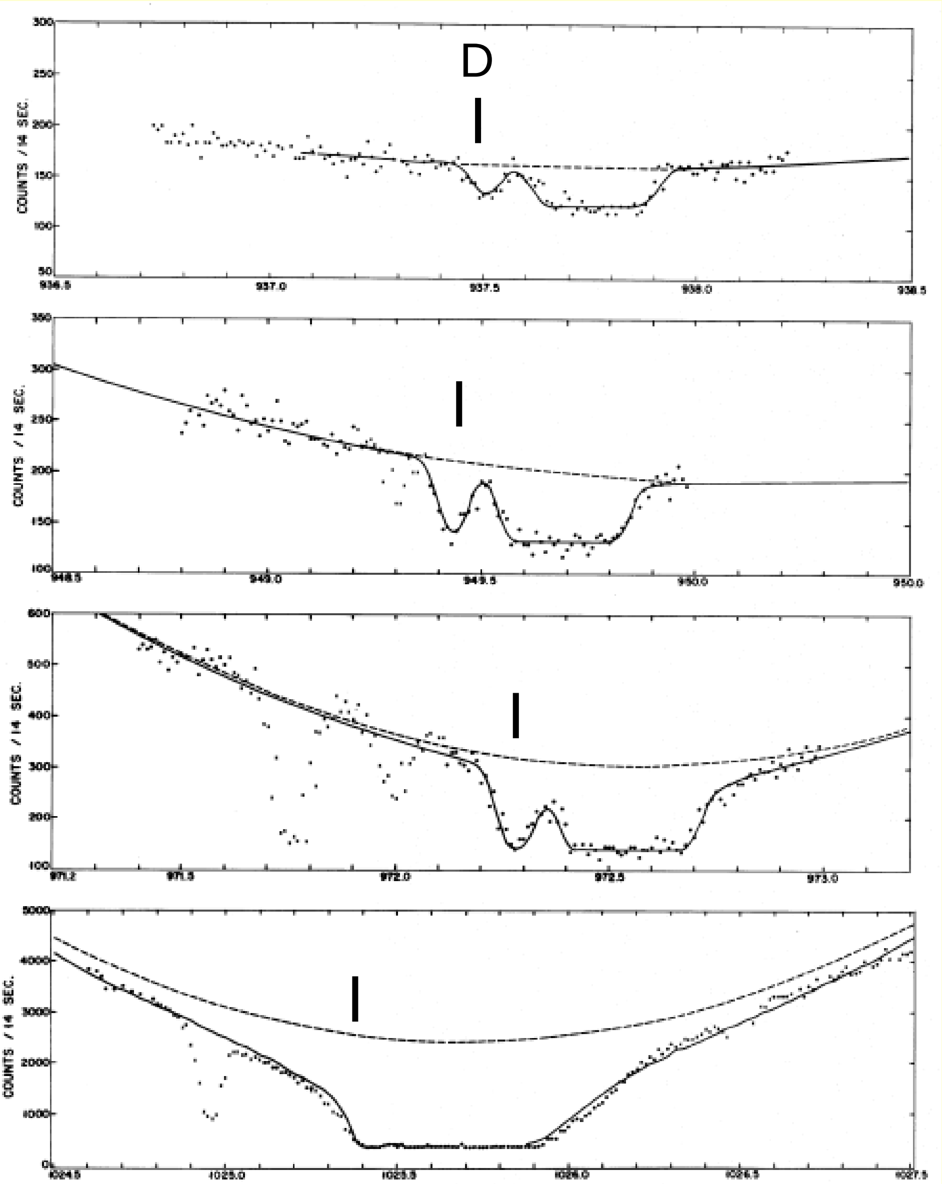
Depth from surface

Absorption lines: results

- MWG: ISM of thin disk
  - Same metallicity as HII regions = present gas
  - But depletion onto dust grains (Si, Fe, …)
  - Ionization: neutral NI … Si IV, CIV, **OVI**

    ➔ neutral clouds embedded in hot (10^6 K) low density 'coronal' gas
- MWG halo:
  - Low and high I.P.; metallicity~disk; brought up by galactic fountains (← SN ← SF)

Lyman lines of H and D



Ly ε

Ly δ

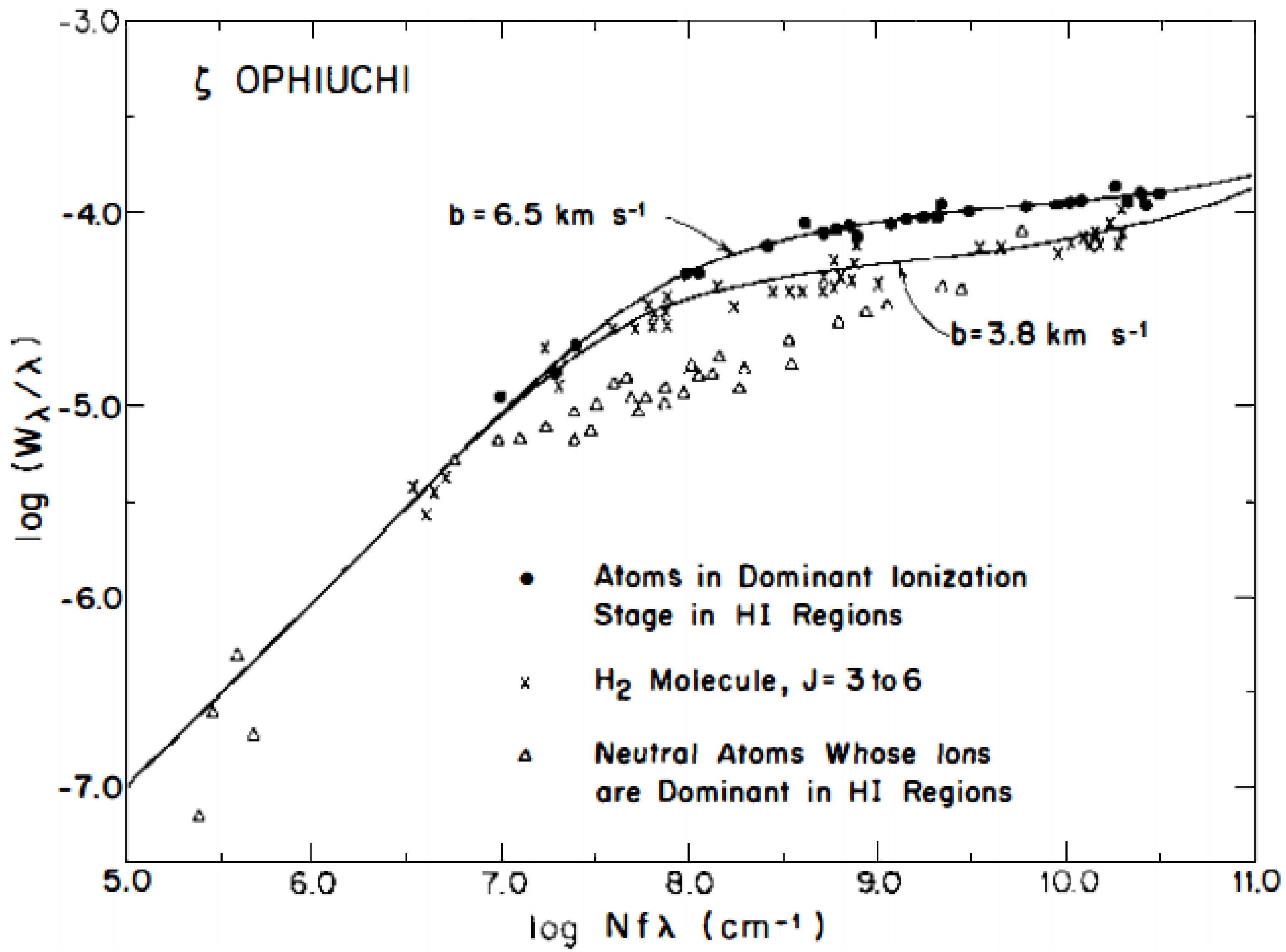
seen towards γCas

Ly γ

Ly β

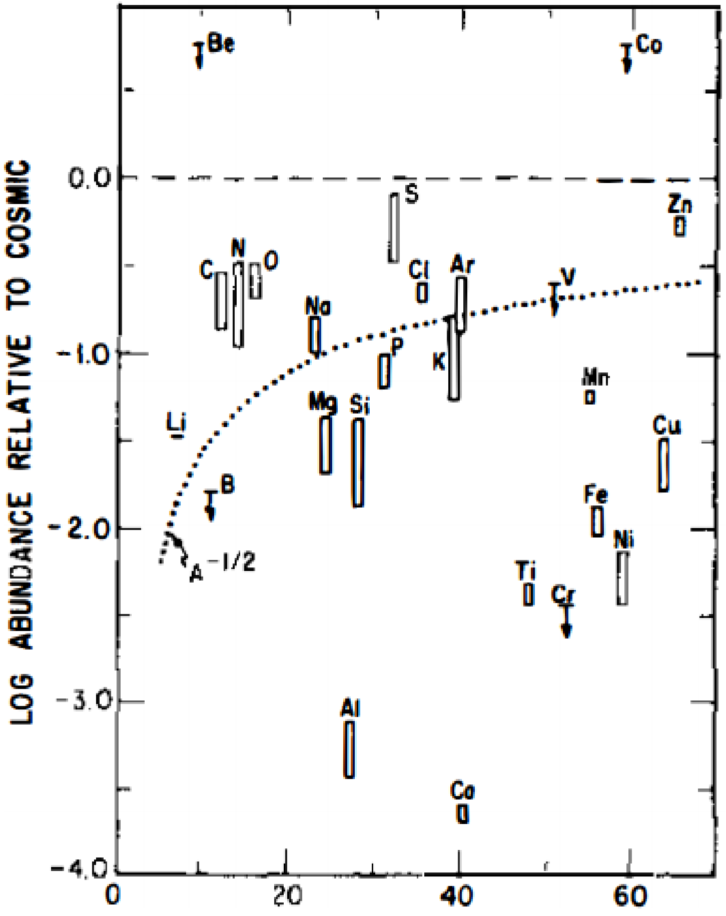
Vidal-Majar 1977

COG of interstellar lines

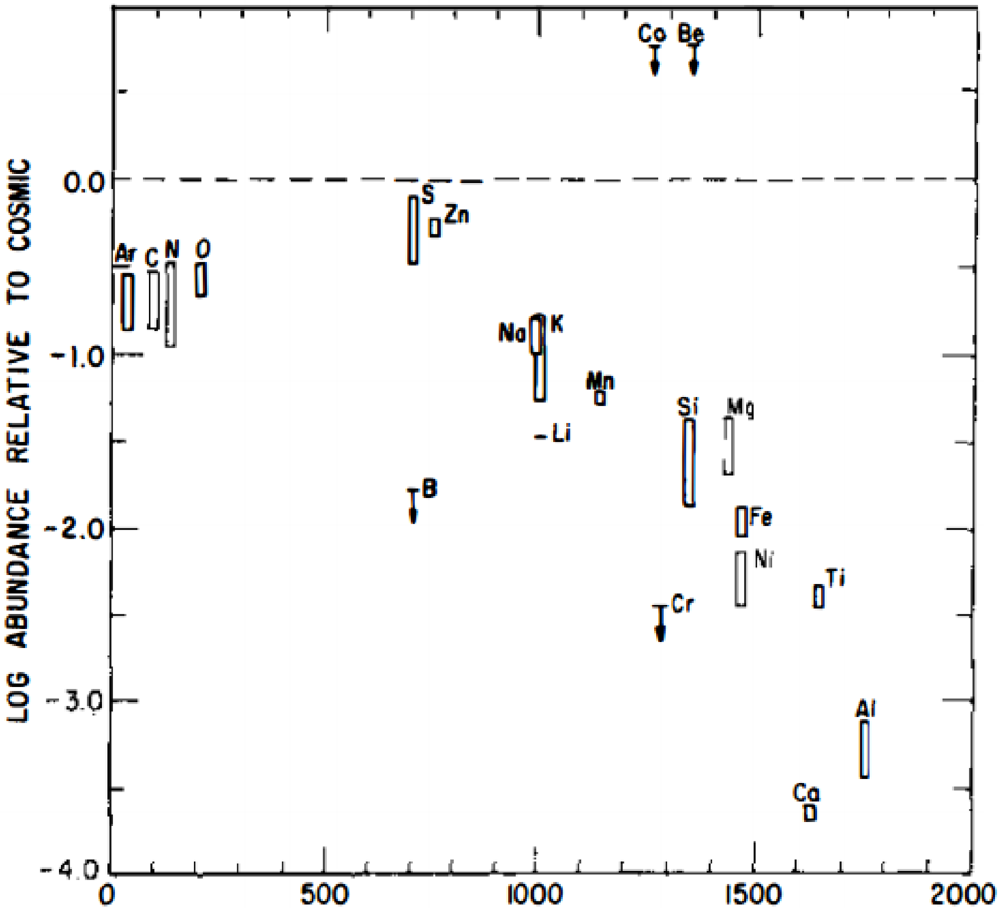


Spitzer 1975

ISM: depletion of gas phase



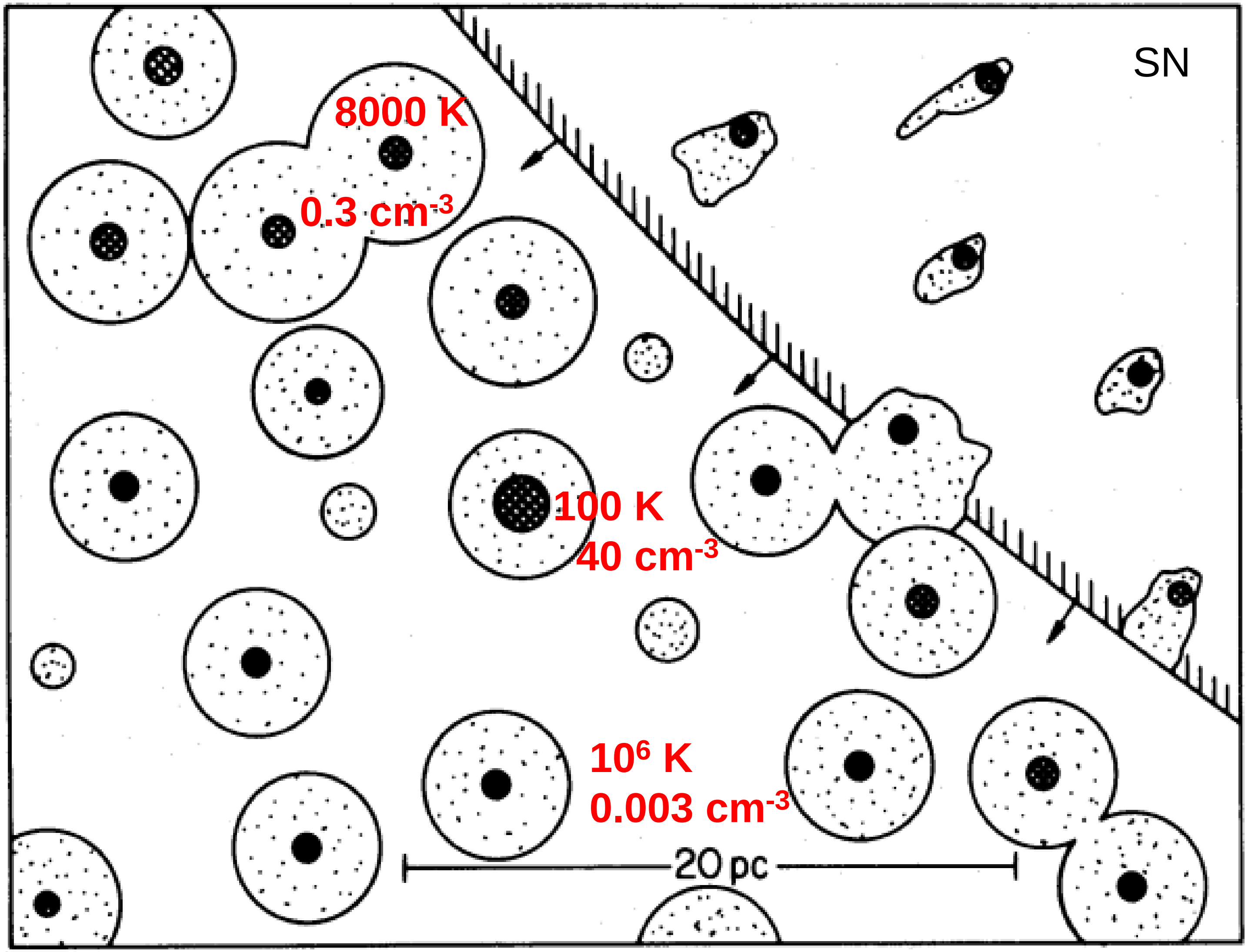
Atomic mass number



Condensation temperature

Spitzer 1975

Multi-phase ISM



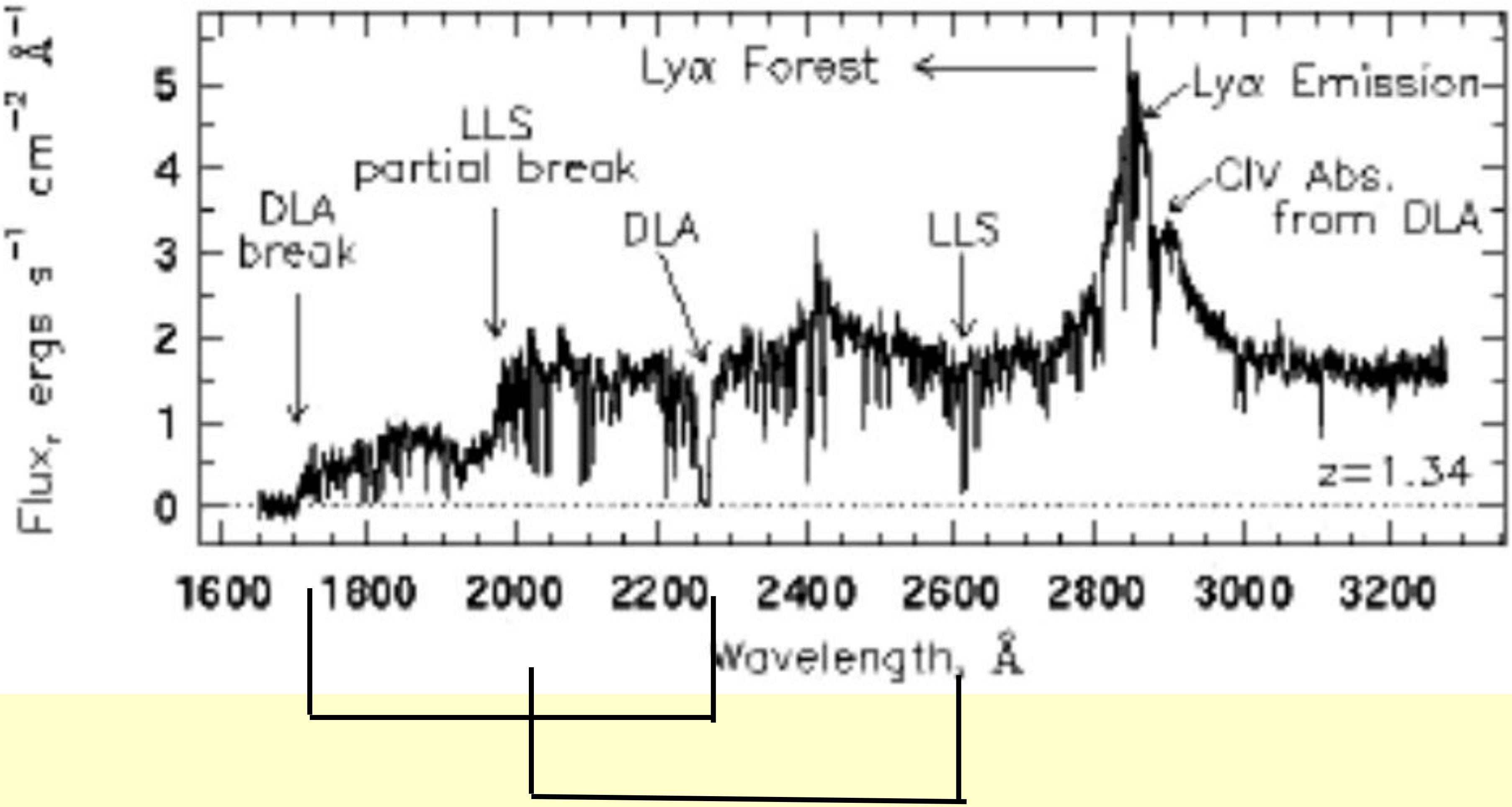
McKee+Ostriker 1977

Absorption lines: results

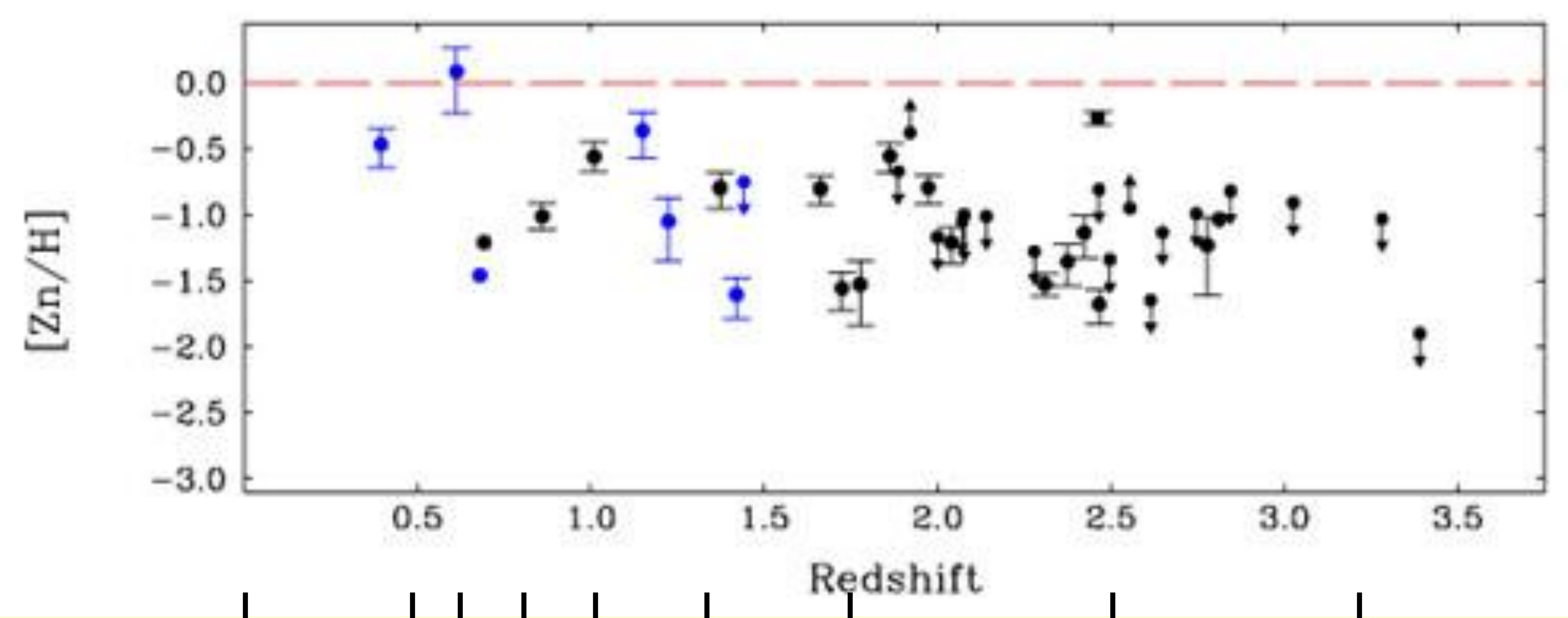
- LMC+SMC: also coronal gas Si IV, CIV
- Quasar absorption lines = gas between redshifted quasar and us:
  - Lyman forest
  - Damped Ly-α system (DLA) = galactic disks?
  - Lyman Limit Systems = Lyman edge 911Å
  - Metallicity 0.01 … 1 Zsun

  still uncertain, but nothing outrageously different

Quasar absorption lines



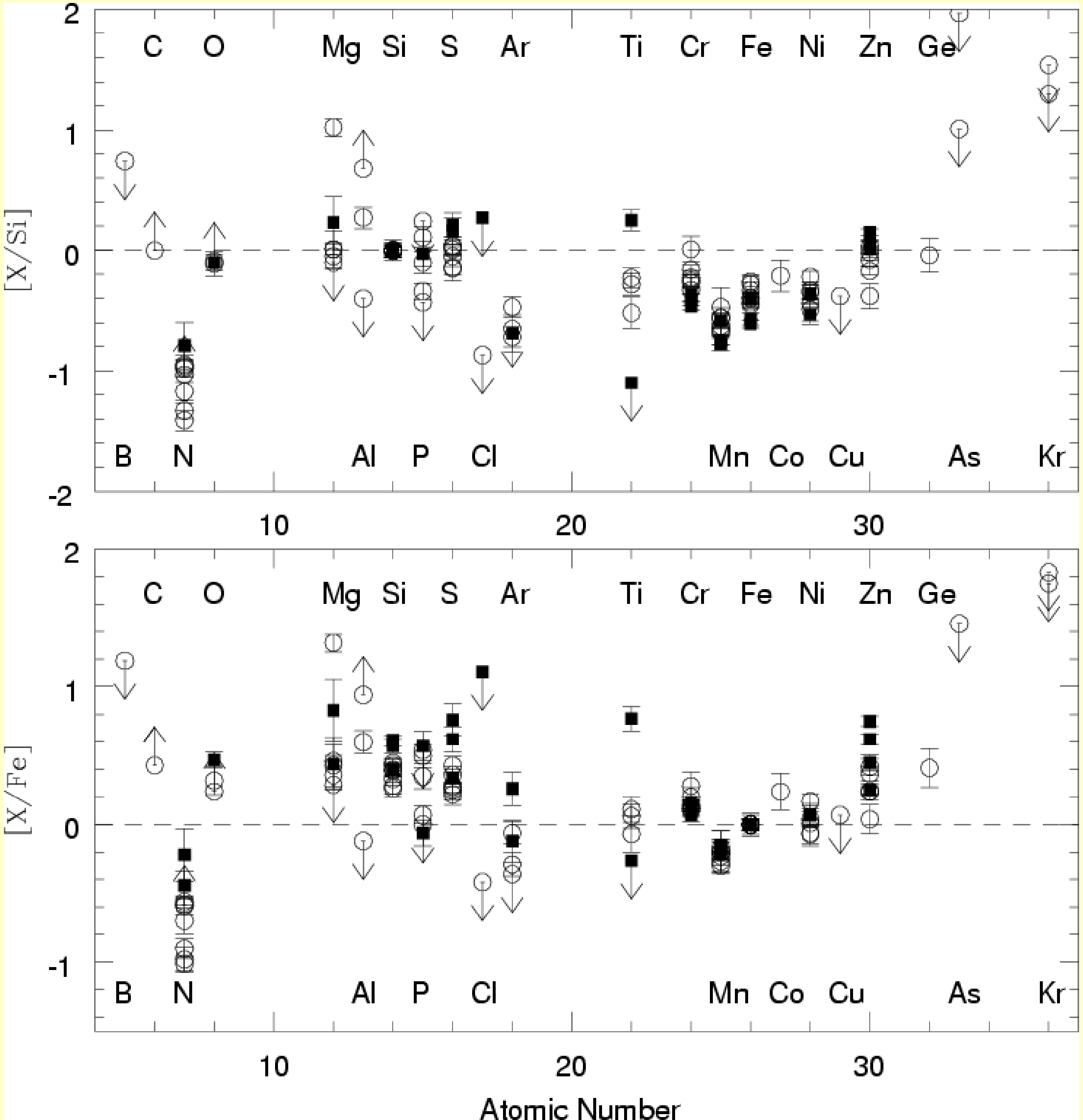
Metallicity-Redshift evolution?



Age 0 5 6 7 8 9 10 11 11.5 Gyr

Pettini 1999

DLA: Abundance pattern



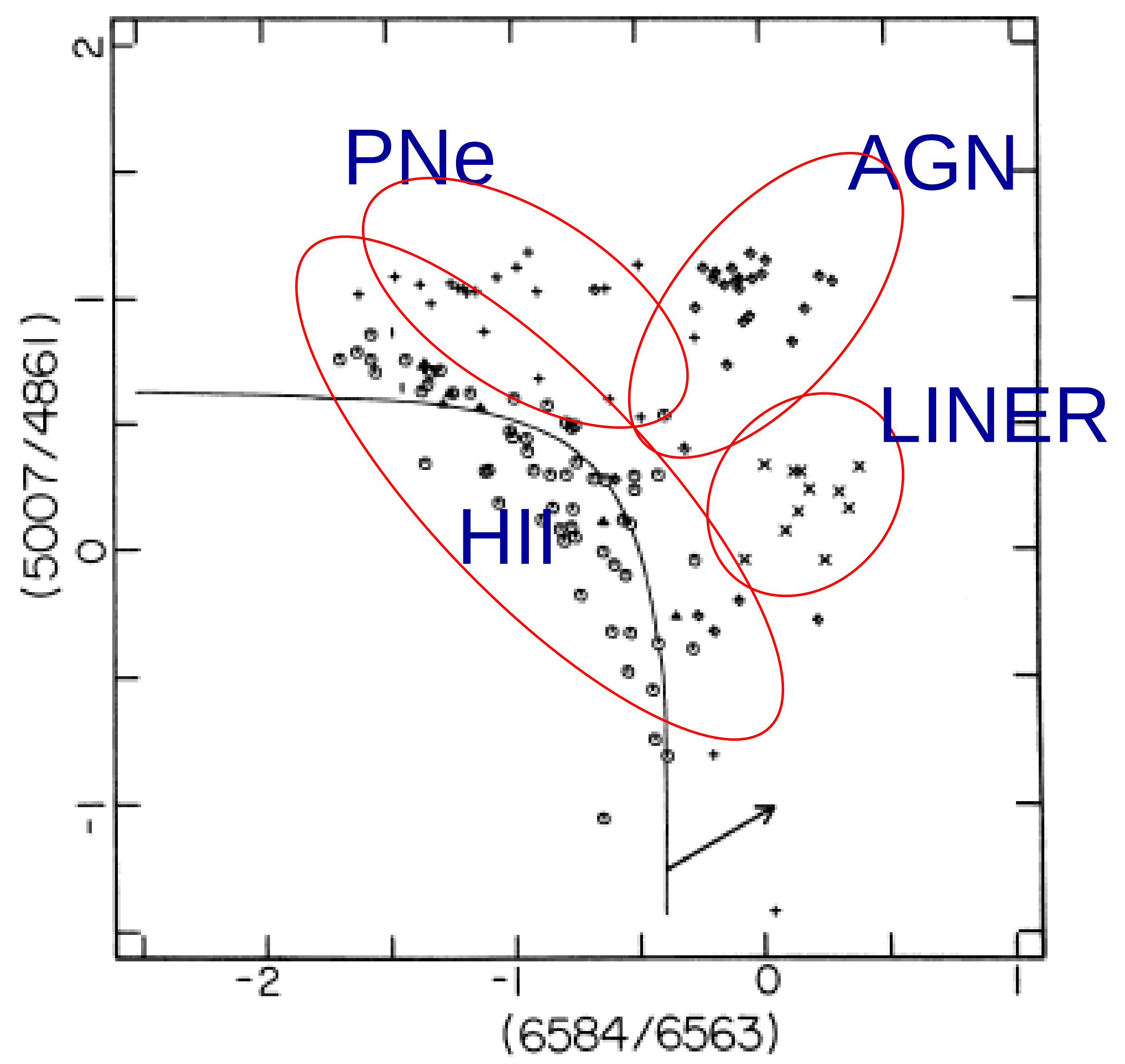
11 DLAs
quite uniform

dust depletion effects
Ionization differences

Dessauges-Zavadsky 2006

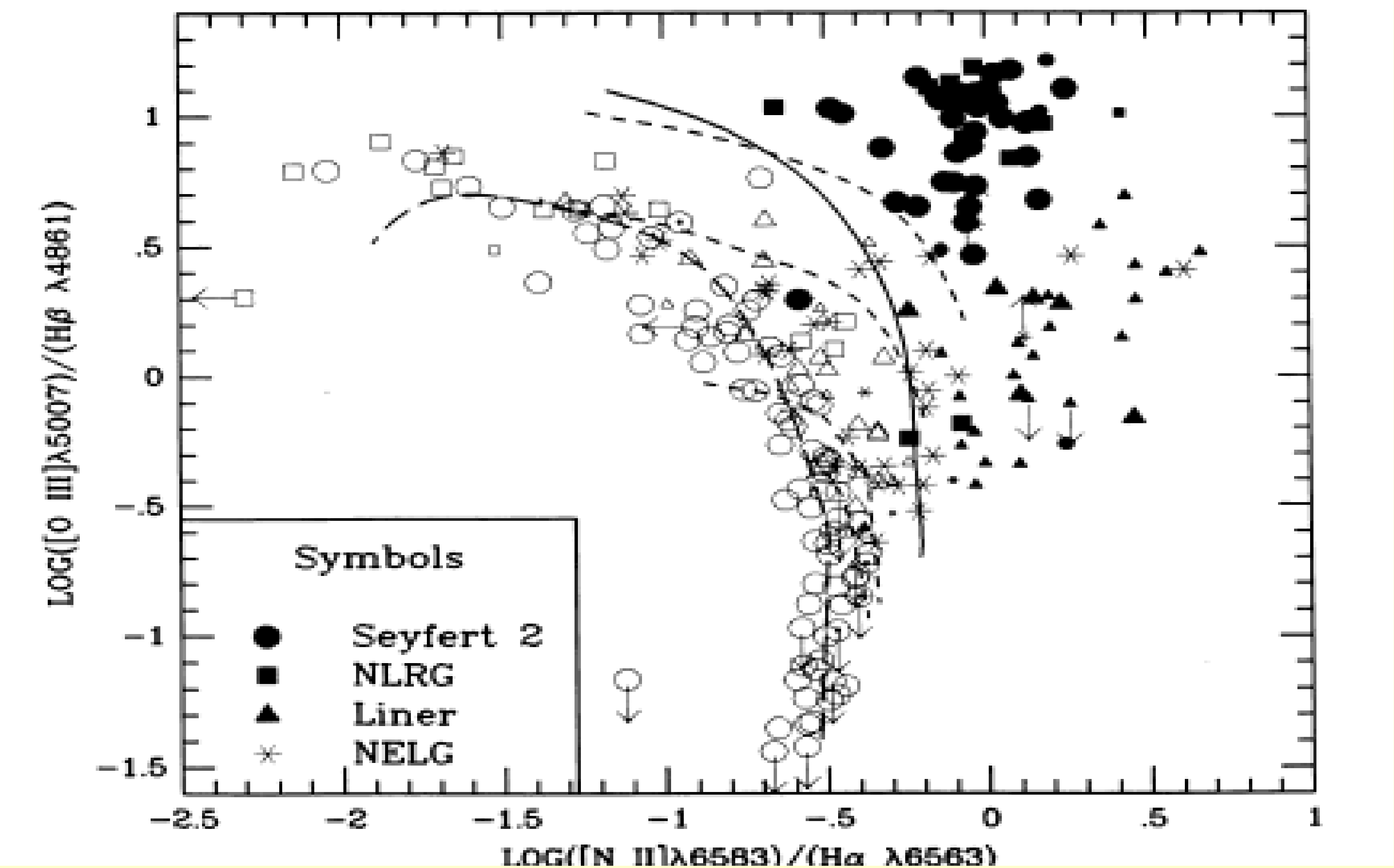
back to Emission Lines

‘BPT Diagrams’: e.g. [OIII]/Hβ vs. [NII]/Hα

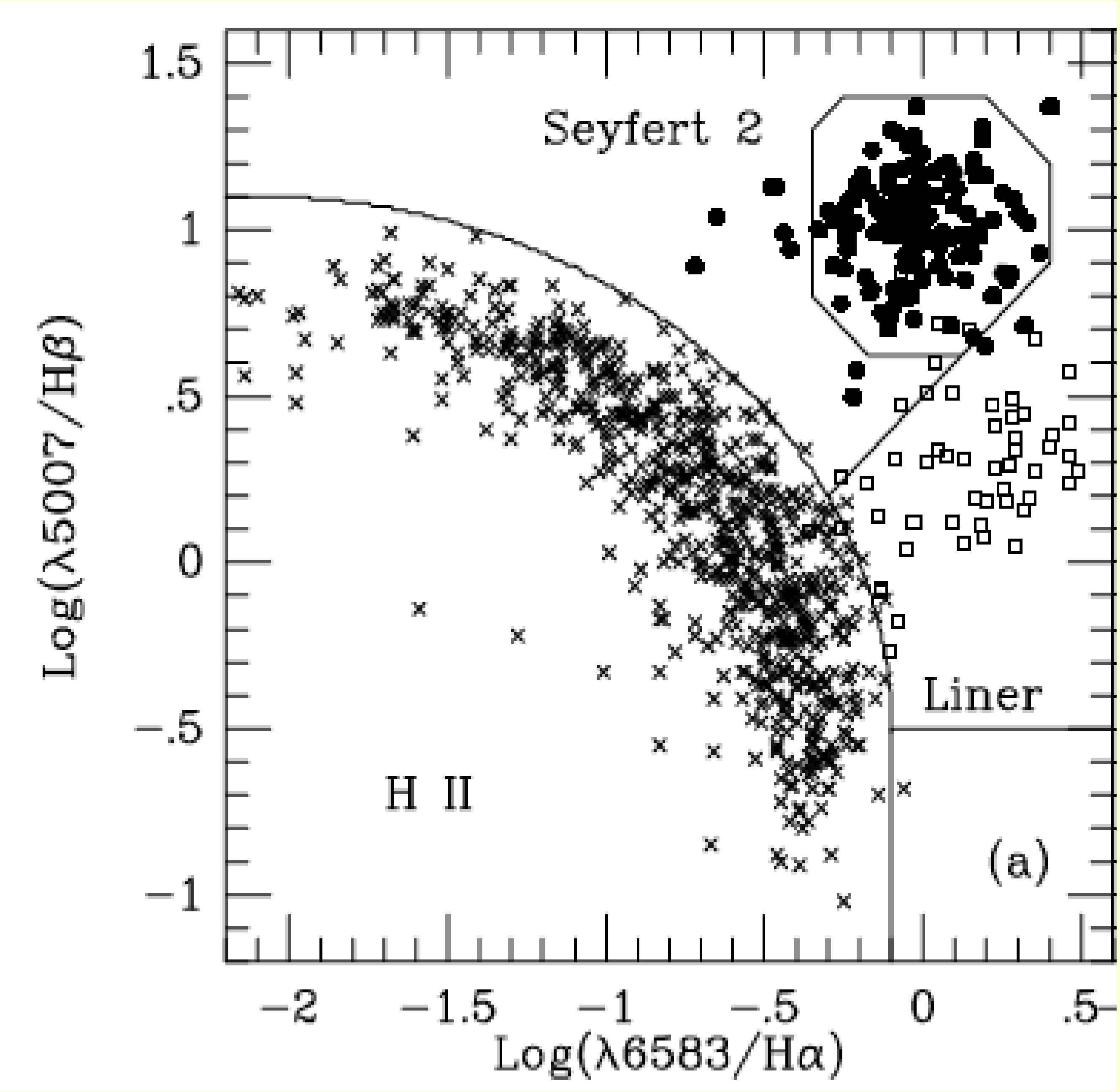


Baldwin, Phillips & Terlevich 1981

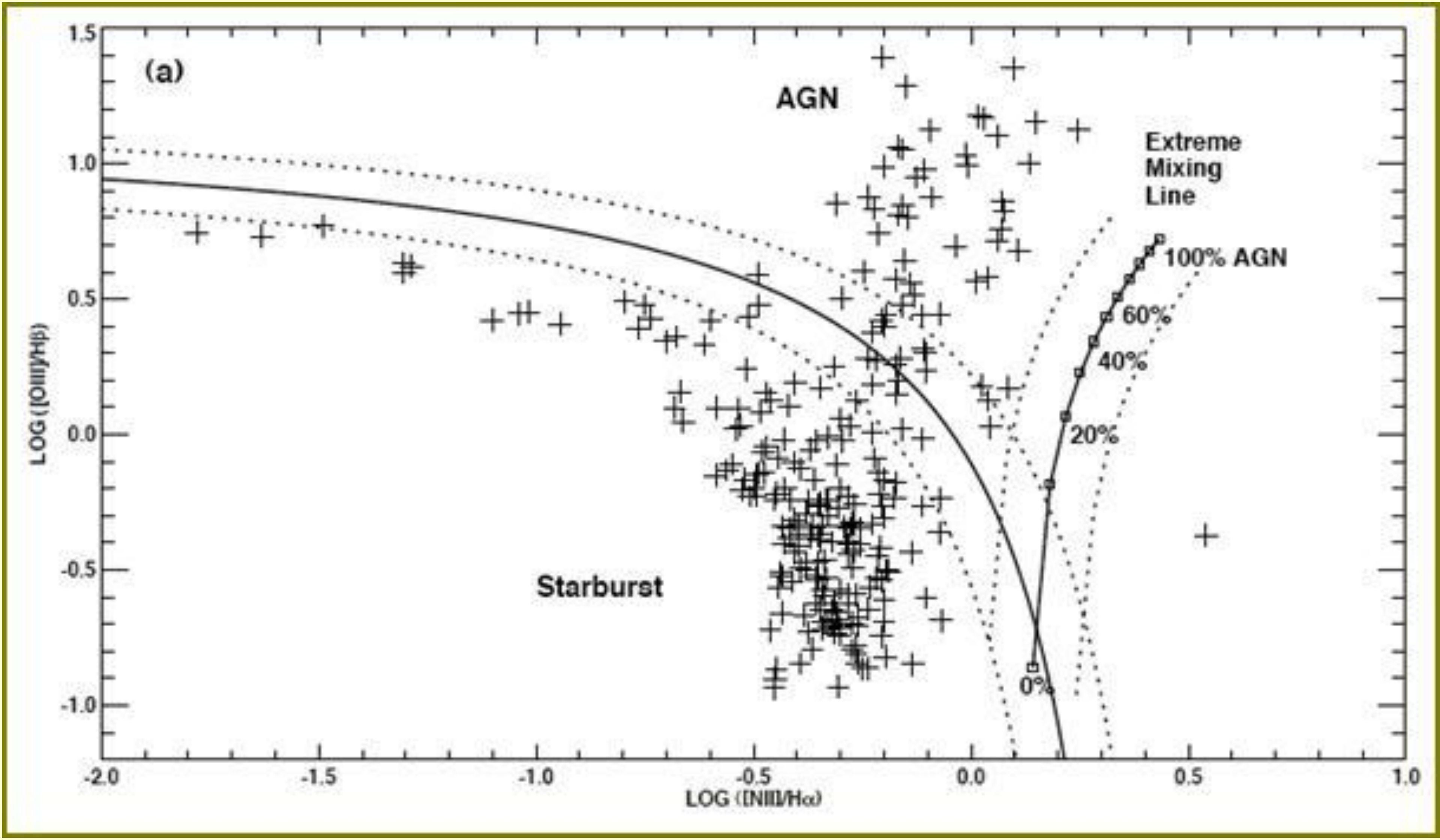
Following slides adapted from R.Cid-Fernandez



Veilleux &
Osterbrock 1987



Veron-Cetty & Veron 2000

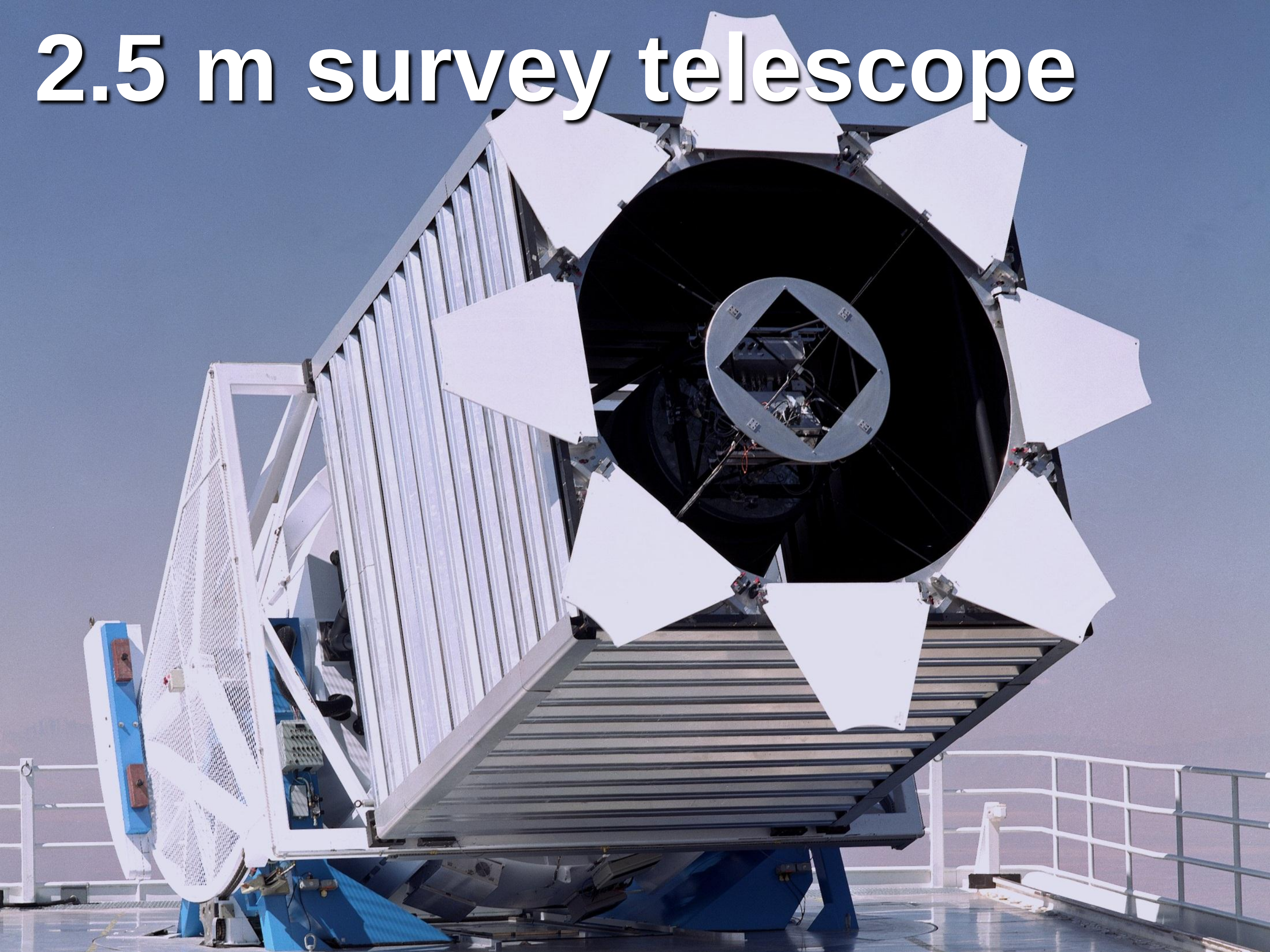


Kewley et al. 2001

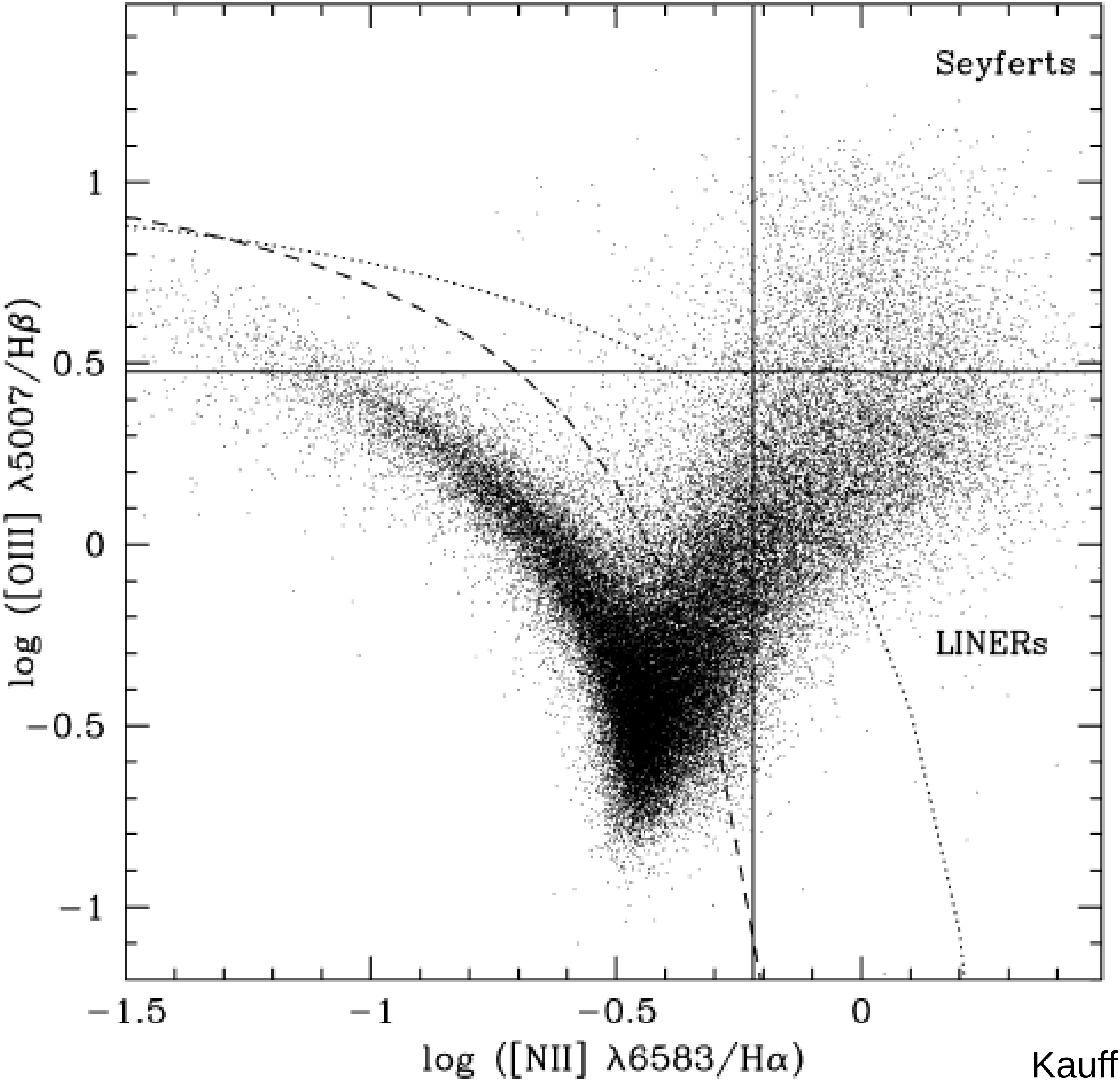
Apache Point Observatory

Where in the world is the Apache Point Observatory???

2.5 m survey telescope

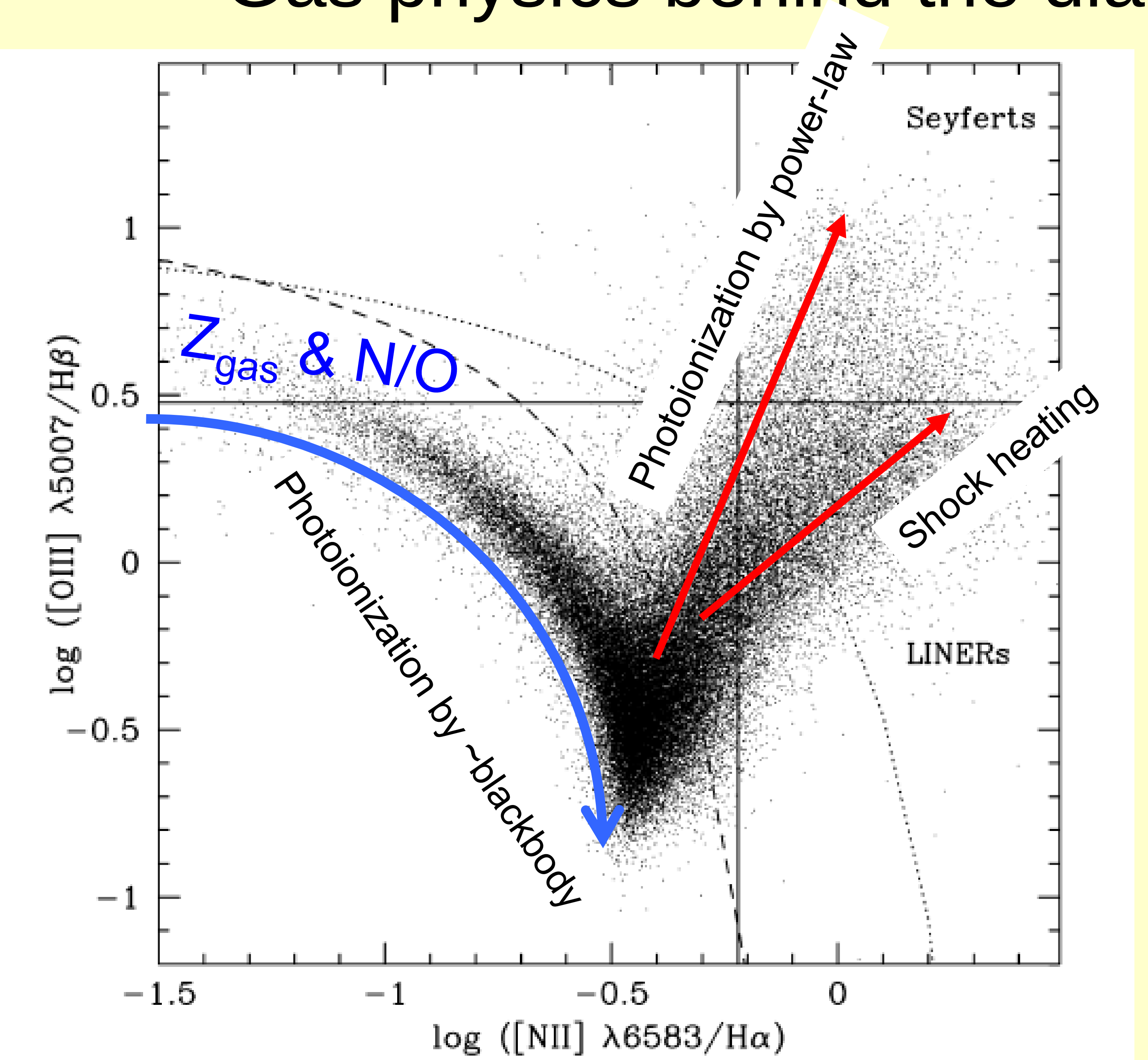


SDSS

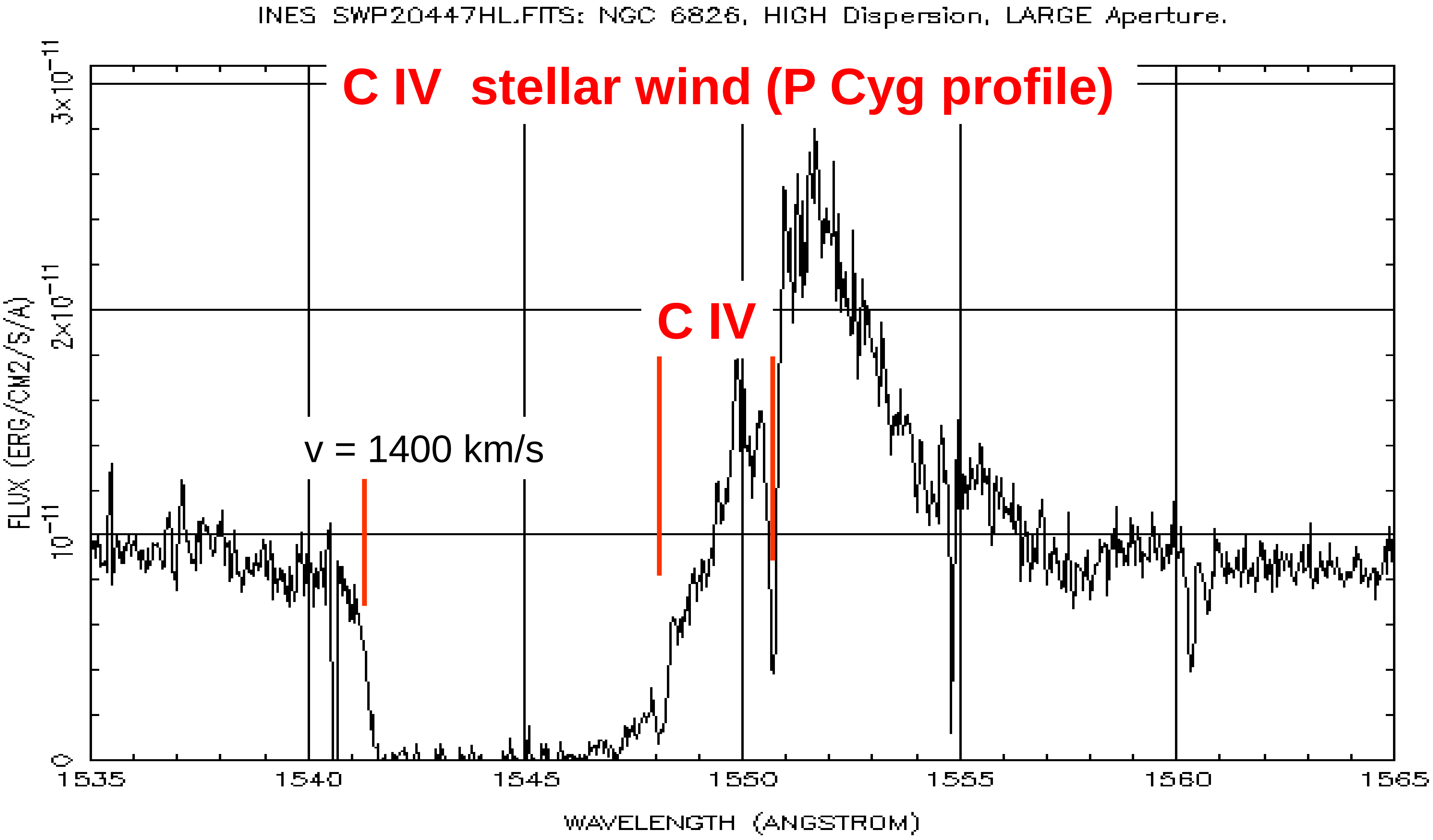


Kauffmann et al. 2003

Gas physics behind the diagram



NGC 6826 CIV


INES SWP20447HL.FITS: NGC 6826, HIGH Dispersion, LARGE Aperture.
C IV stellar wind (P Cyg profile)
C IV
v = 1400 km/s
FLUX (ERG/CM2/S/A)
0
10^{-11}
2×10^{-11}
3×10^{-11}
1535
1540
1545
1550
1555
1560
1565
WAVELENGTH (ANGSTROM)

P Cyg line profile