# Deconstructing the diffuse ionised gas

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# Outline

- The diffuse ionised gas : observations
- Photoionisation blues
- Steps towards a deconstruction

with

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# MODA

## Actualidad

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## David Valls, la deconstrucción como leitmotif




**Colección completa de David Valls**

El creador catalán ha presentado una colección basada en el punto. Para los hombres, gruesos jerséis con ochos, y aplicaciones en chaquetas y pantalones, proporcionando un look muy rústico y confortable. Para la mujer, las mil variedades que ofrece el género de punto se trasladan a todas las prendas de una colección cuyo leitmotif parece ser la deconstrucción.

# The Era of Precision Cosmology

*In a few years, all the great physical constants will have been approximately estimated and [...] the only occupation which will then be left to the men of science will be to carry these measurements to another place of decimals.*

J.C. Maxwell (1871)

# I. The diffuse ionised gas

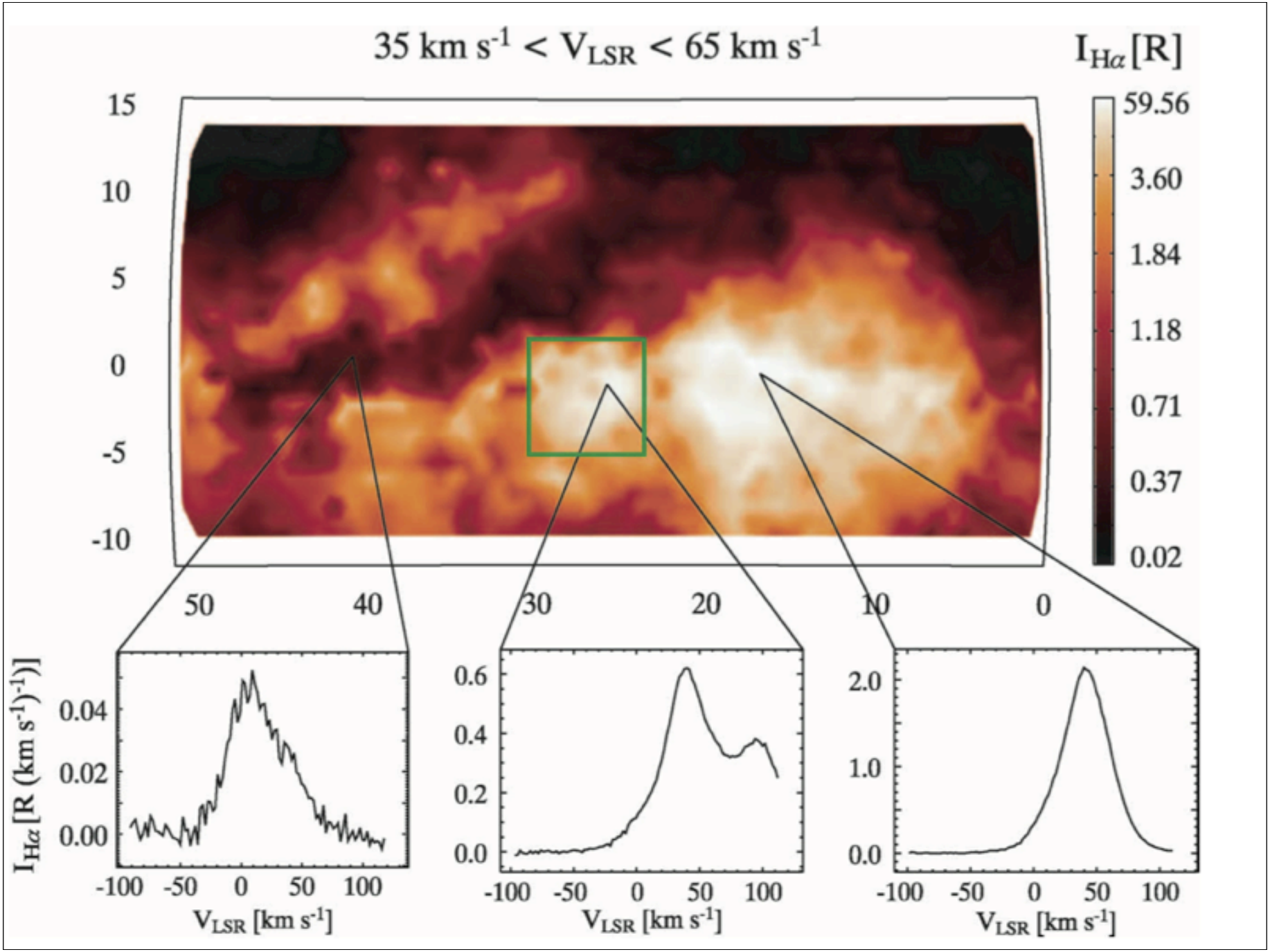
Diffuse, warm ionised gas in our Galaxy,
away from ionisation sources (Struve & Elvey 1938)

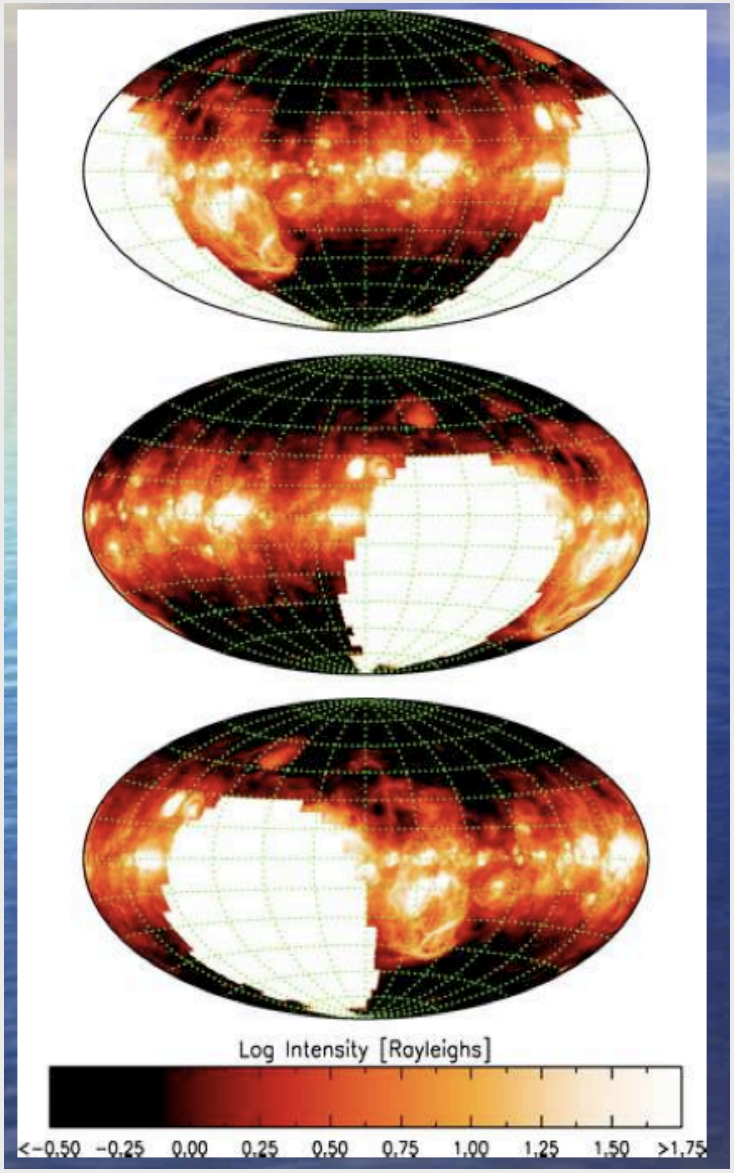
One of the major components of the ISM,
yet the least understood

Ubiquitous :

WHAM observations in the Galaxy (Reynolds et al. 1999)

Present at large |z| in irregular and spiral galaxies


35 km s-1 < VLSR < 65 km s-1
IHα [R]
59.56
3.60
1.84
1.18
0.71
0.37
0.02
15
10
5
0
-5
-10
50
40
30
20
10
0
IHα [R (km s-1)-1)]
0.04
0.02
0.00
0.6
0.4
0.2
0.0
2.0
1.0
0.0
-100 -50 0 50 100
VLSR [km s-1]




Haffner et al. (2003)

Electron densities $\sim 0.03$ cm$^{-3}$

Electronic temperatures $\sim$10,000 K

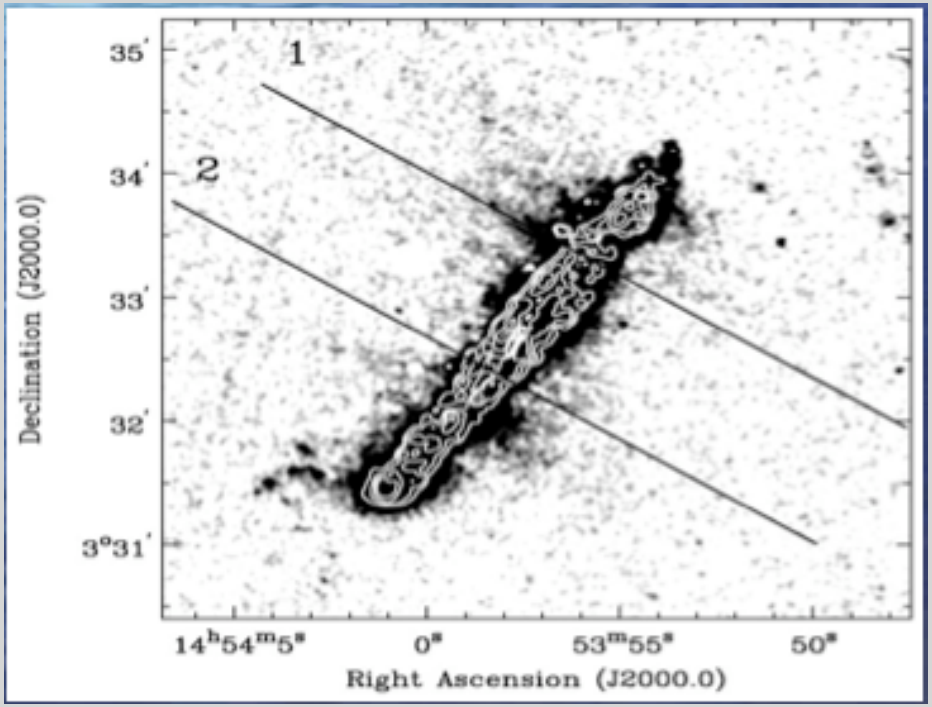
25% of total H content

Few local ionising sources

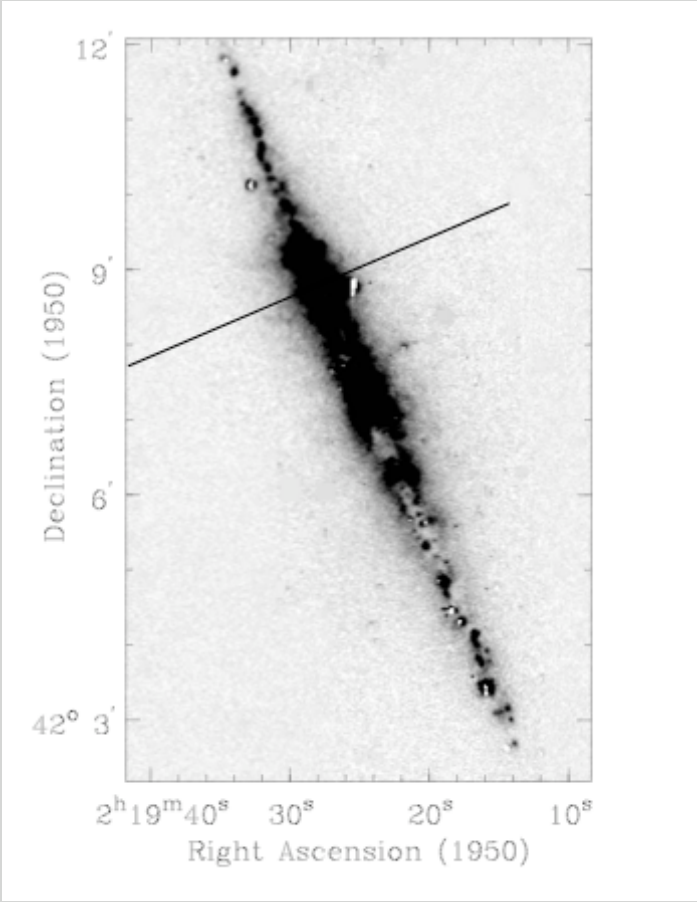
Power input : $\sim 10^{-4}$ erg cm$^{-2}$ s$^{-1}$

OB stars may provide just enough ionising power if their photons escape from the disc.

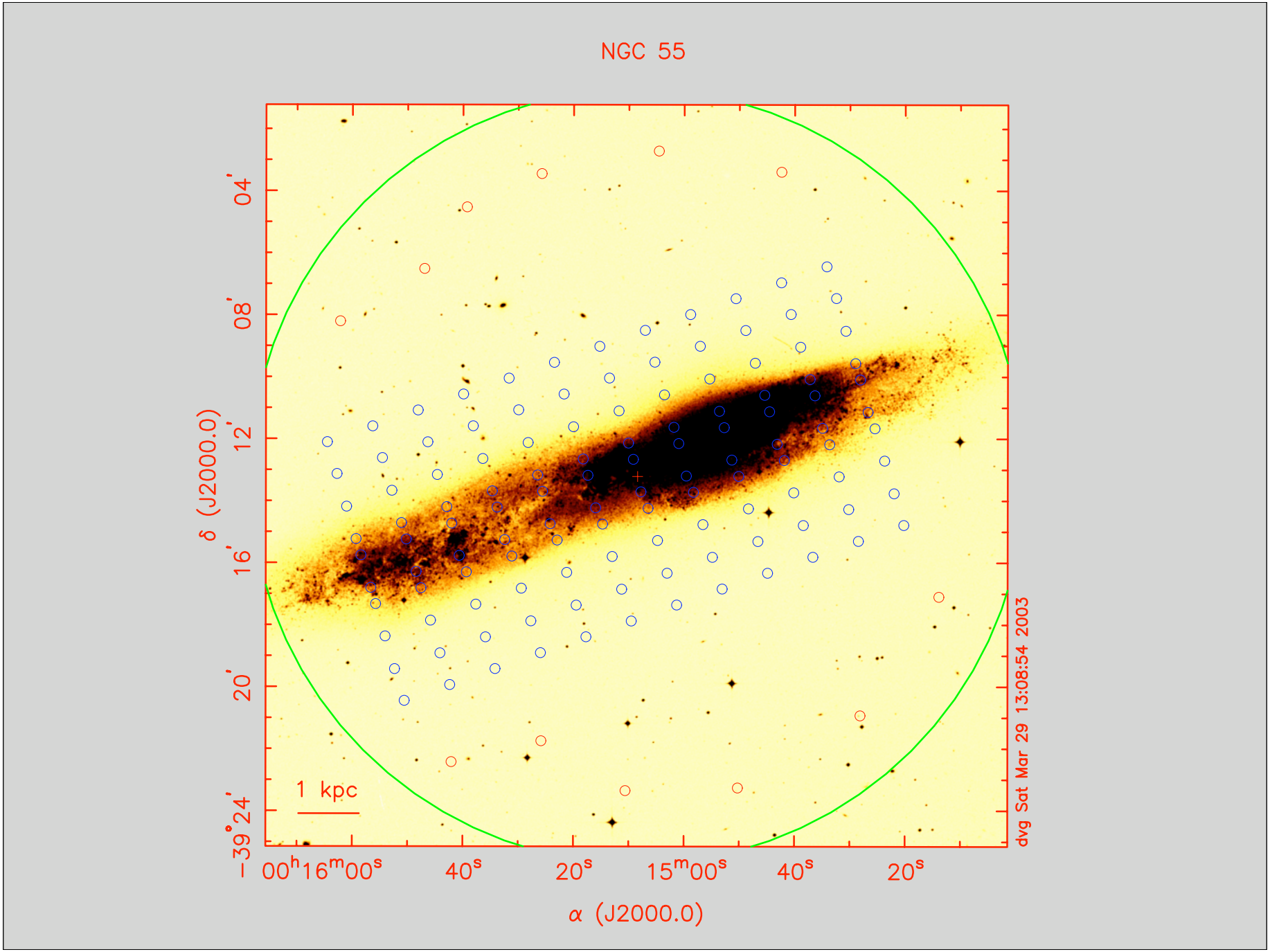
# Observed trends in (edge on) discs and irregular galaxies

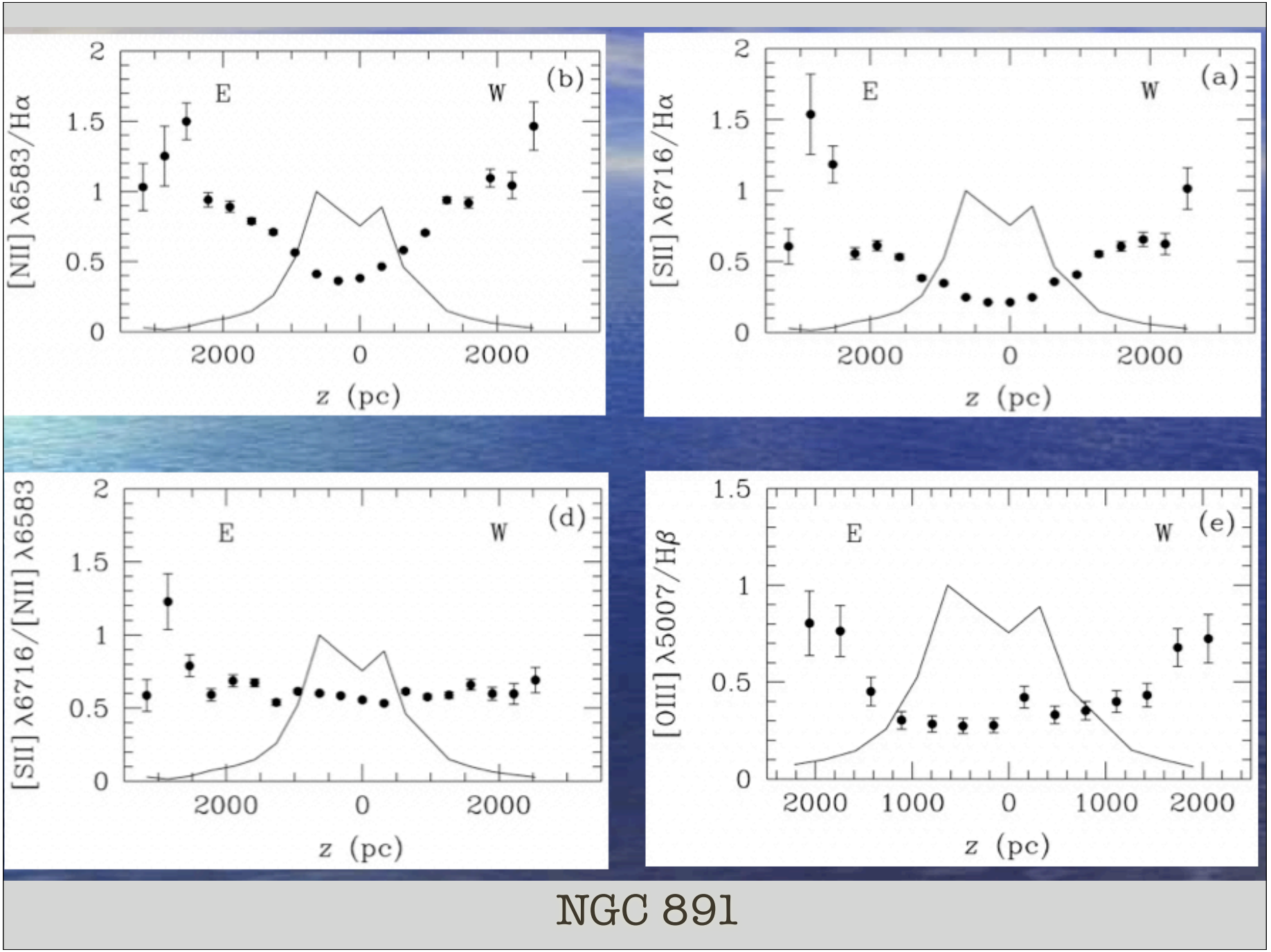



NGC 5775

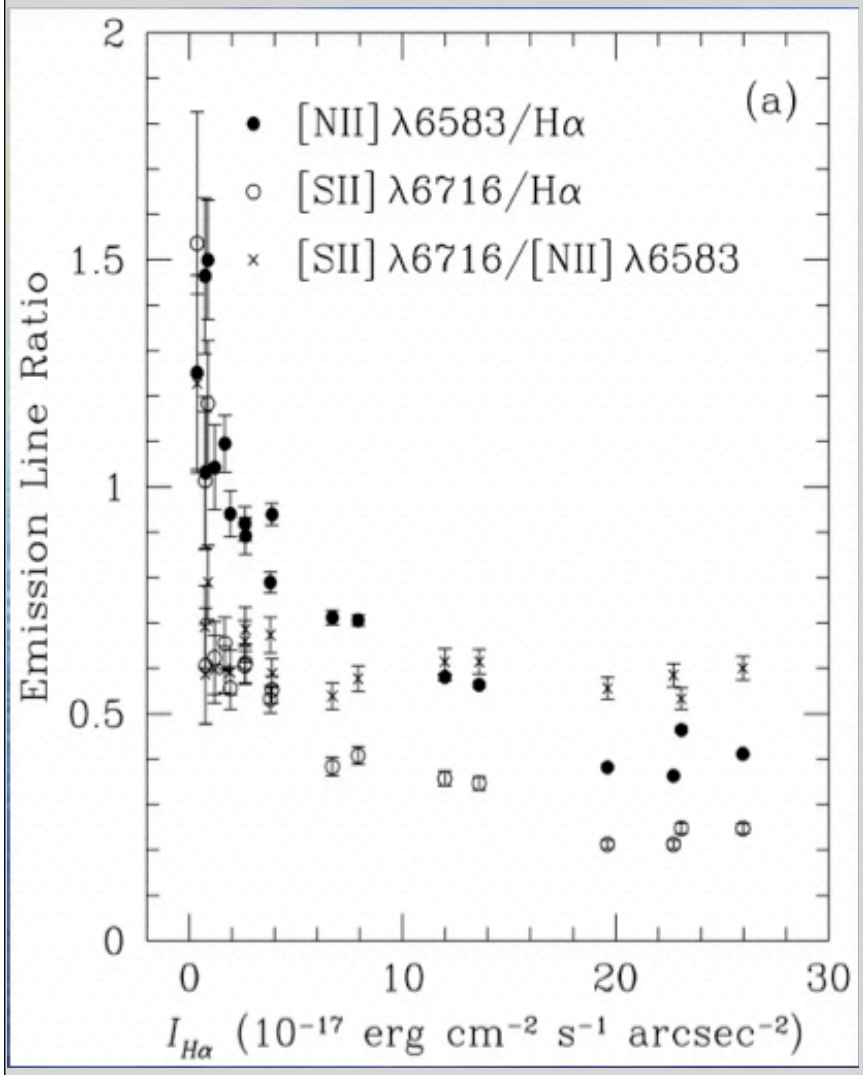


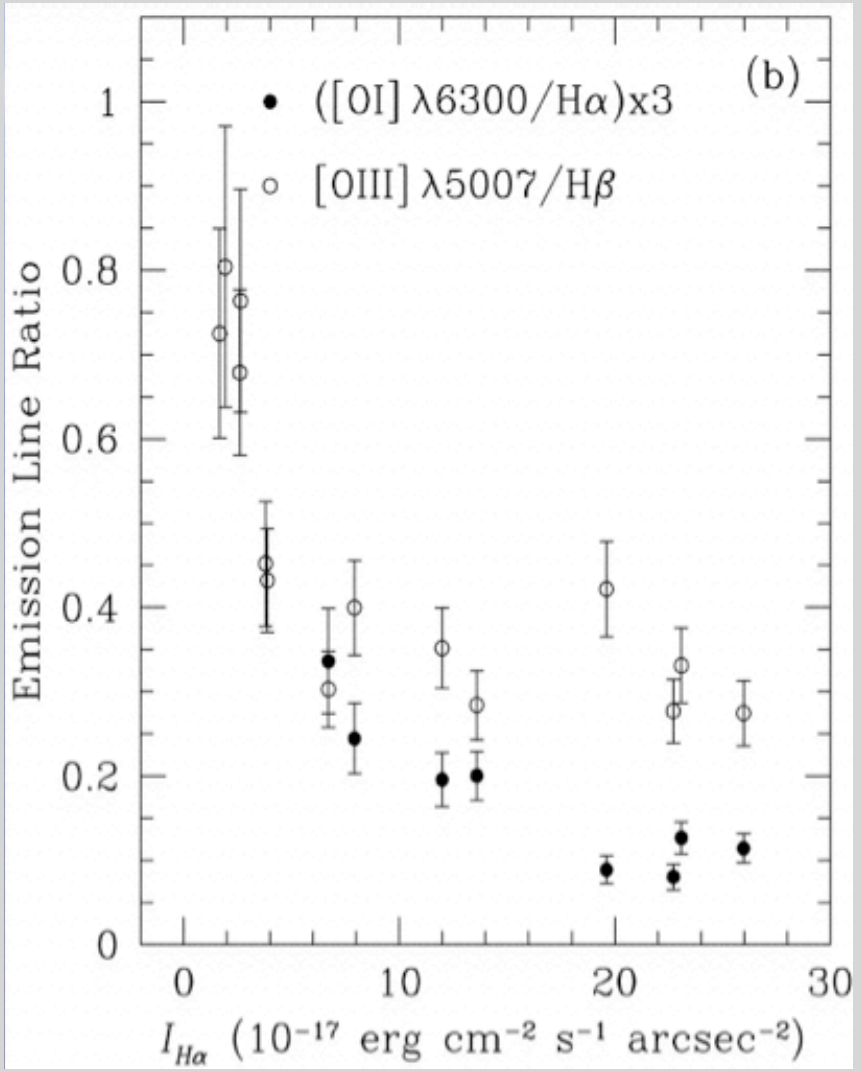

NGC 891


NGC 55
δ (J2000.0)
04'
08'
12'
16'
20'
−39°24'
1 kpc
00h16m00s
40s
20s
15m00s
40s
20s
α (J2000.0)
dvg Sat Mar 29 13:08:54 2003


[NII] λ6583/Hα
E
W
(b)
z (pc)
[SII] λ6716/Hα
(a)
[SII] λ6716/[NII] λ6583
(d)
[OIII] λ5007/Hβ
(e)

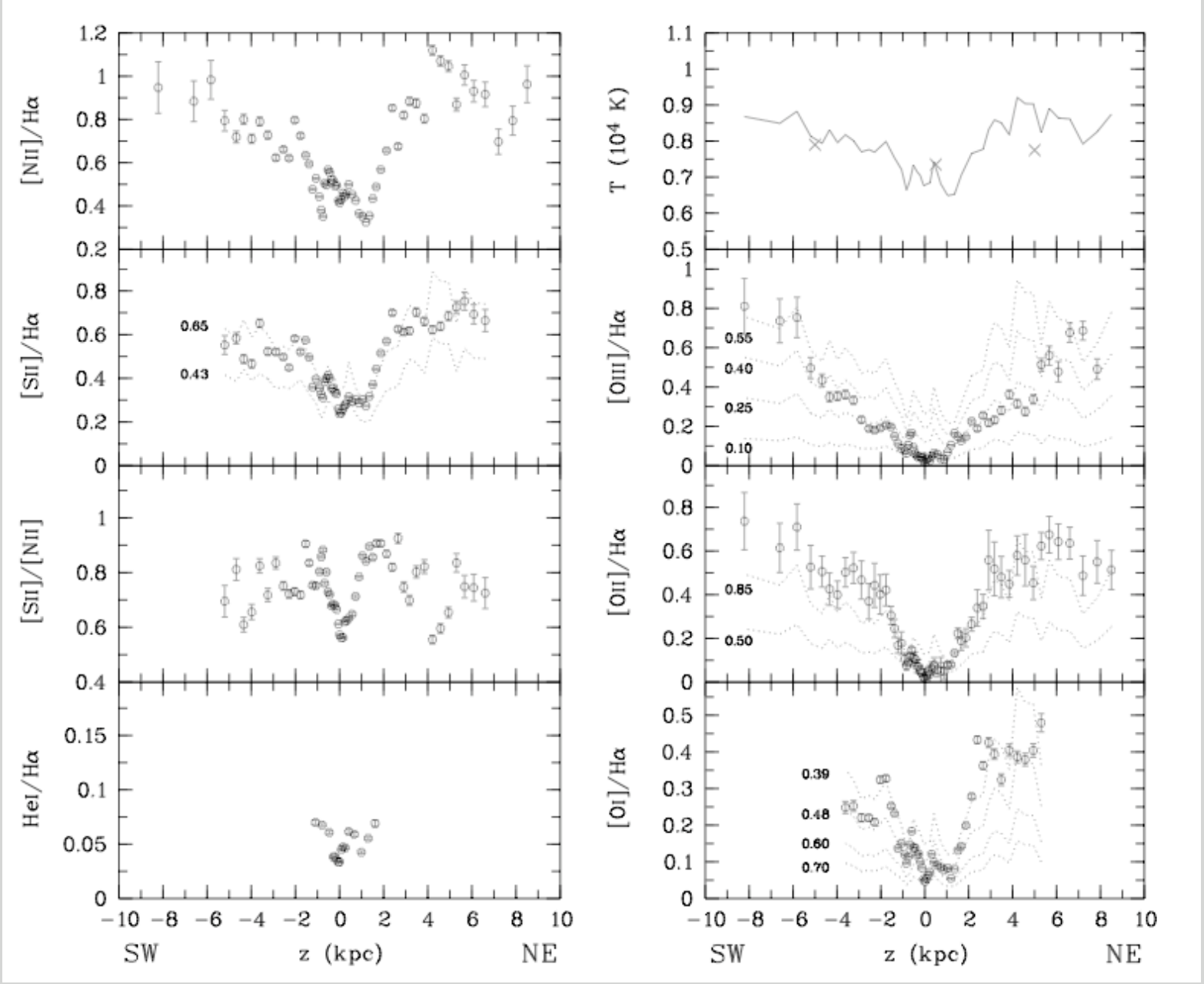
NGC 891


(a)
[NII] λ6583/Hα
[SII] λ6716/Hα
[SII] λ6716/[NII] λ6583
Emission Line Ratio
$I_{H\alpha}$ ($10^{-17}$ erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$)


(b)
([OI] λ6300/Hα)x3
[OIII] λ5007/Hβ
Emission Line Ratio
$I_{H\alpha}$ ($10^{-17}$ erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$)

NGC 891

# NGC 5775


[NII]/Hα
[SII]/Hα
0.65
0.43
[SII]/[NII]
HeI/Hα
0.15
0.1
0.05
SW
z (kpc)
NE
T (10⁴ K)
[OIII]/Hα
0.55
0.40
0.25
0.10
[OII]/Hα
0.85
0.50
[OI]/Hα
0.39
0.48
0.60
0.70

## II. Failure of photoionisation models

**Pure photoionisation**:

conflicting [SII]/[NII] vs [OIII]

**Shocks**:

rising [OIII] OK .... but [NII] fails

**Extra heating mechanism** seems required
but it must not ionise (since [SII]/[NII] is constant).

# III. Steps towards a solution

[1] Projection effects :

2D surface brightness vs 3D emissivity

$$\Sigma(R) = \int_{-\infty}^{+\infty} dz\, j(r) = 2 \int_{R}^{\infty} \phi(r)\, r \left(r^2 - R^2\right)^{-1/2} dr$$

Inverse:

$$j(r) = -\frac{1}{\pi} \int_{r}^{\infty} \frac{d\Sigma}{dR} \cdot \frac{dR}{\sqrt{R^2 - r^2}}$$

Usual assumption of local equilibrium :

$$\frac{I_f}{I_r} = \frac{j_f}{j_r} \propto \frac{n_i n_e \exp\left(-\alpha/kT\right)\ T^{-0.5}}{n_p n_e T^{-m}}$$

but densities and temperature vary along the l.o.s. !

Integration along the line of sight (l.o.s.)
in one-dimensional (CLOUDY) models :

$$\left(\frac{I_f}{I_r}\right)_{z_k} = \sum_{i=k}^{n-1} \left( \int_{s_i}^{s_{i+1}} j(f)_i \, ds \right) \Big/ \sum_{i=k}^{n-1} \left( \int_{s_i}^{s_{i+1}} j(r)_i \, ds \right)$$

**[2] Theorem** : Uniform models cannot possibly account for ANY rising [OIII]/Hα ratio

**Proof** : Consider the (local) ionisation balance equation for two succesive ionisation stages :

$$\left(\frac{n(X^{i+1})}{n(X^i)}\right) = \frac{\eta\, Q(H)\ < a(X^i) >}{4\pi\ \alpha(X^i, T)} \cdot \left(\frac{1}{r^2\ n_e(r)}\right)$$

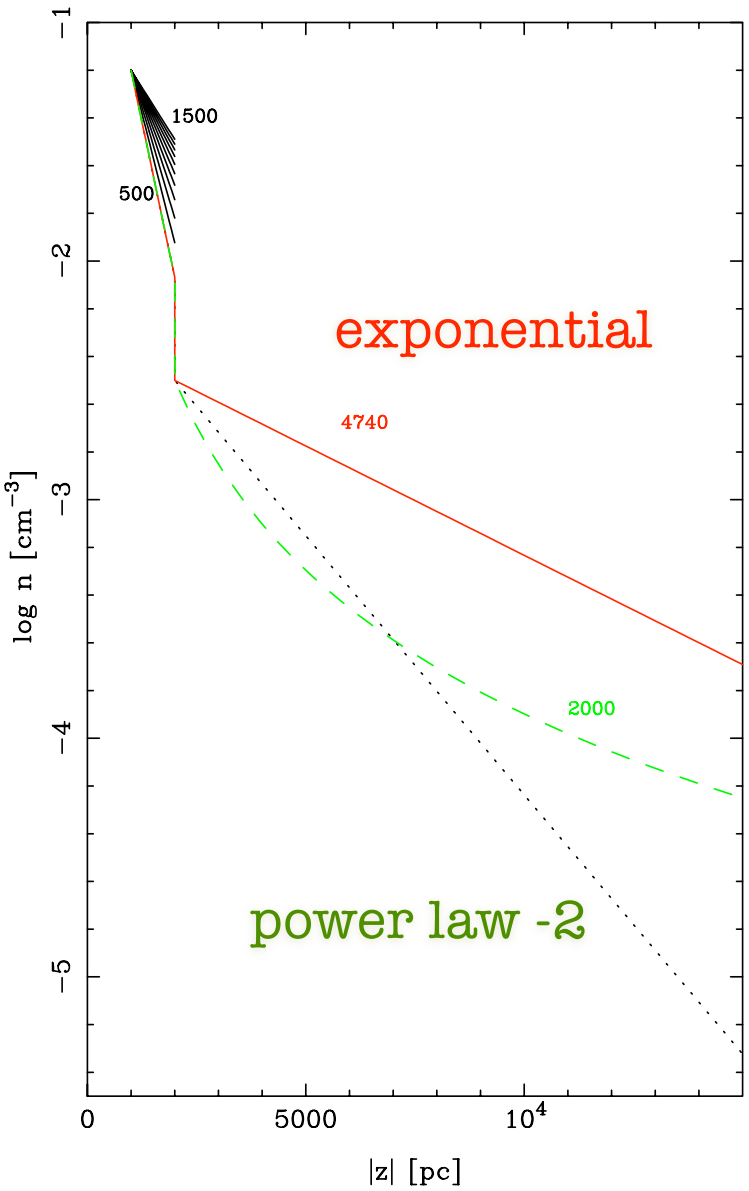
i.e. the dependence of the electron density with distance determines the ratio

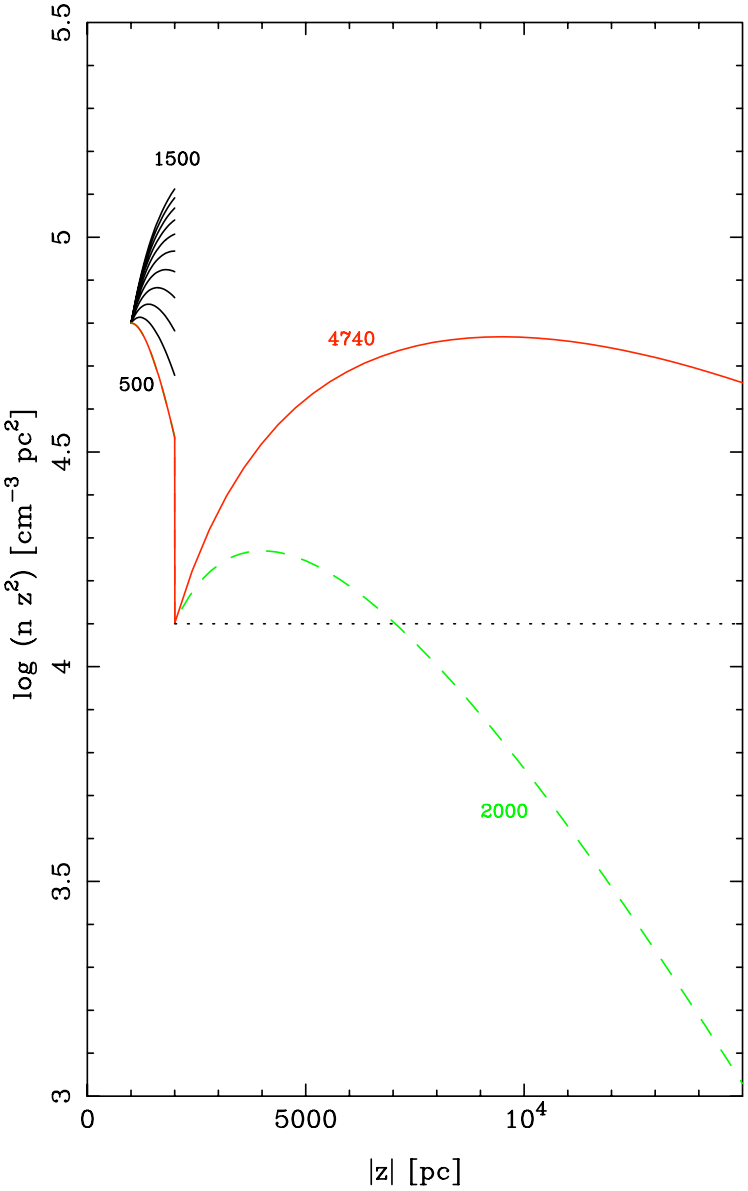
## The case of oxygen

For usual abundances, cooling dominated by [OIII]5007+4959, so neglecting the hardening of the radition field with distance :

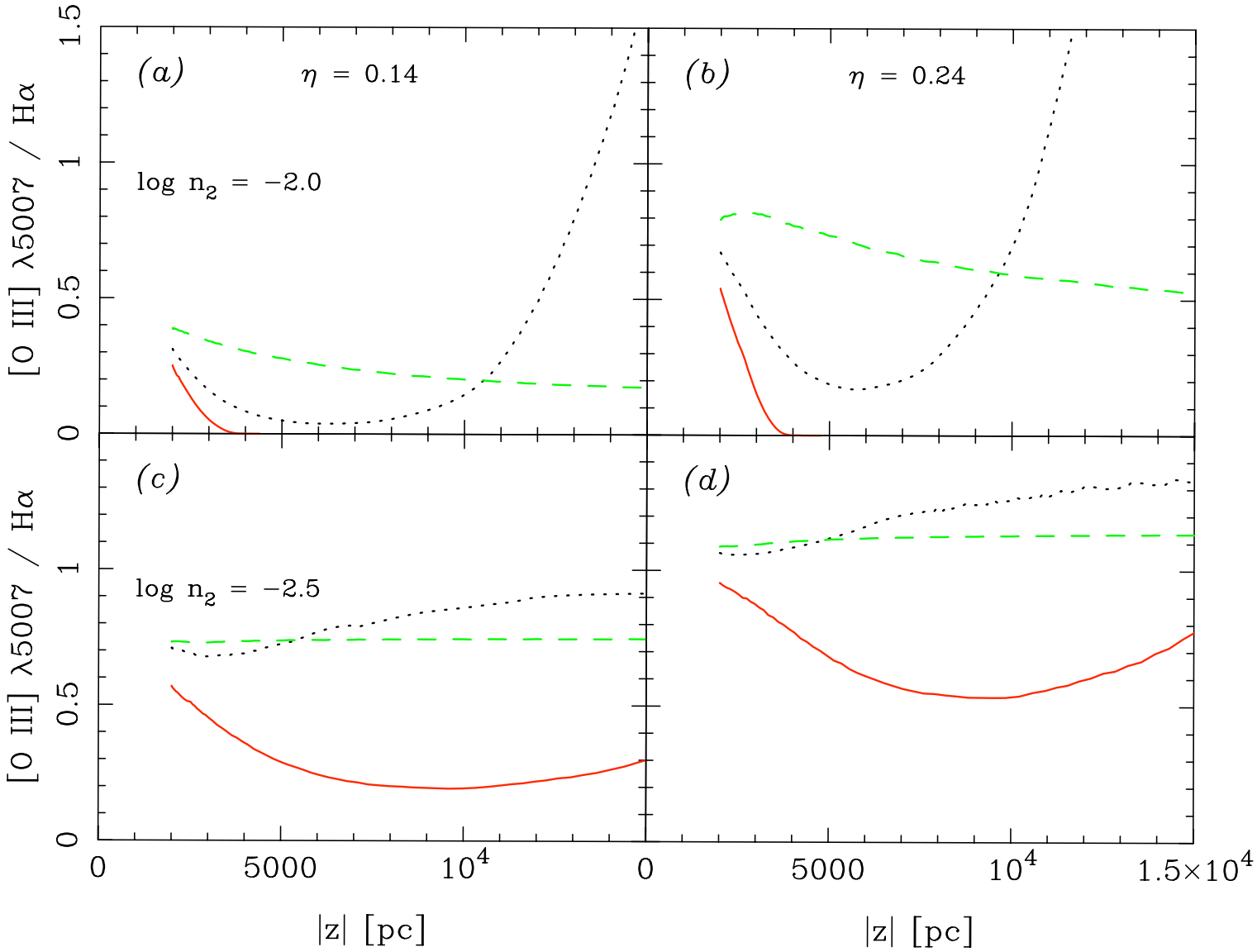
$$\left(\frac{O^{++}}{H^{+}}\right) = \left(\frac{O}{H}\right)\left(1+\frac{4\pi r^{2} n_{e}(r)\,\alpha(X^{+i},T)}{<a(X^{+i})>\;Q(H)\,\eta}\right)^{-1}$$

Expect 3 different regimes depending upon the functional dependence of n(r)


exponential
power law -2
1500
500
4740
2000
log n [cm$^{-3}$]
|z| [pc]
−1
−2
−3
−4
−5
0
5000
$10^4$


1500
500
4740
2000
log (n z$^2$) [cm$^{-3}$ pc$^2$]
|z| [pc]
5.5
5
4.5
4
3.5
3
0
5000
$10^4$

exponential large H power law -2 exponential small H



$$\left(\frac{O^{++}}{H^{+}}\right) = \left(\frac{O}{H}\right)\left(1+\frac{4\pi r^2 n_e(r)\alpha(X^{+i},T)}{<a(X^{+i})>\ Q(H)\eta}\right)^{-1}$$

(i) for n(r) decreasing more slowly than $r^{-2}$: ionisation front is trapped. Classic uniform, ionisation-bounded : the ionic ratio always decreases with z.

(ii) critical dependence: ratio roughly constant, the ionisation front extends to infinity : (critical) matter-bounded region.

(iii) exponentially decreasing densities: ionisation increases with distance : matter-bounded region. Ionising photons escape.

## [3] The problem of sulphur

Dielectronic recombination could be as important as radiative recombination at low densities.

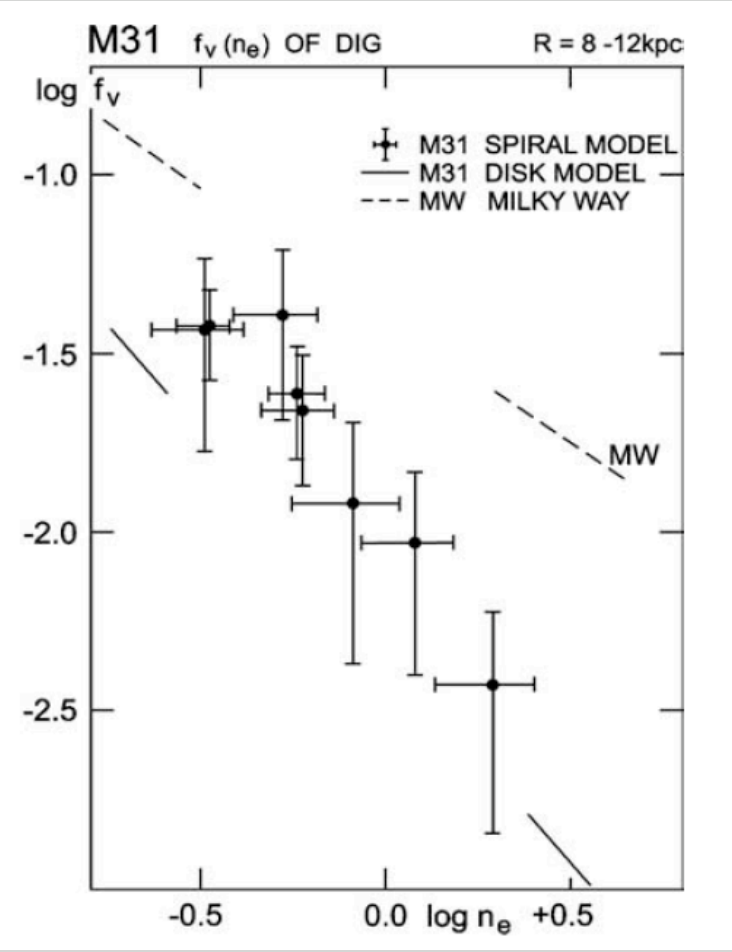
**Problem**: coefficients are barely known !

$$\alpha(X0) = (3\pm2)\ 10^{-13}$$
$$\alpha(X1) = (3\pm2)\ 10^{-12}$$
$$\alpha(X2) = (1.5\pm0.5)\ 10^{-11}$$
$$\alpha(X3) = (2.5\pm1.4)\ 10^{-11}$$

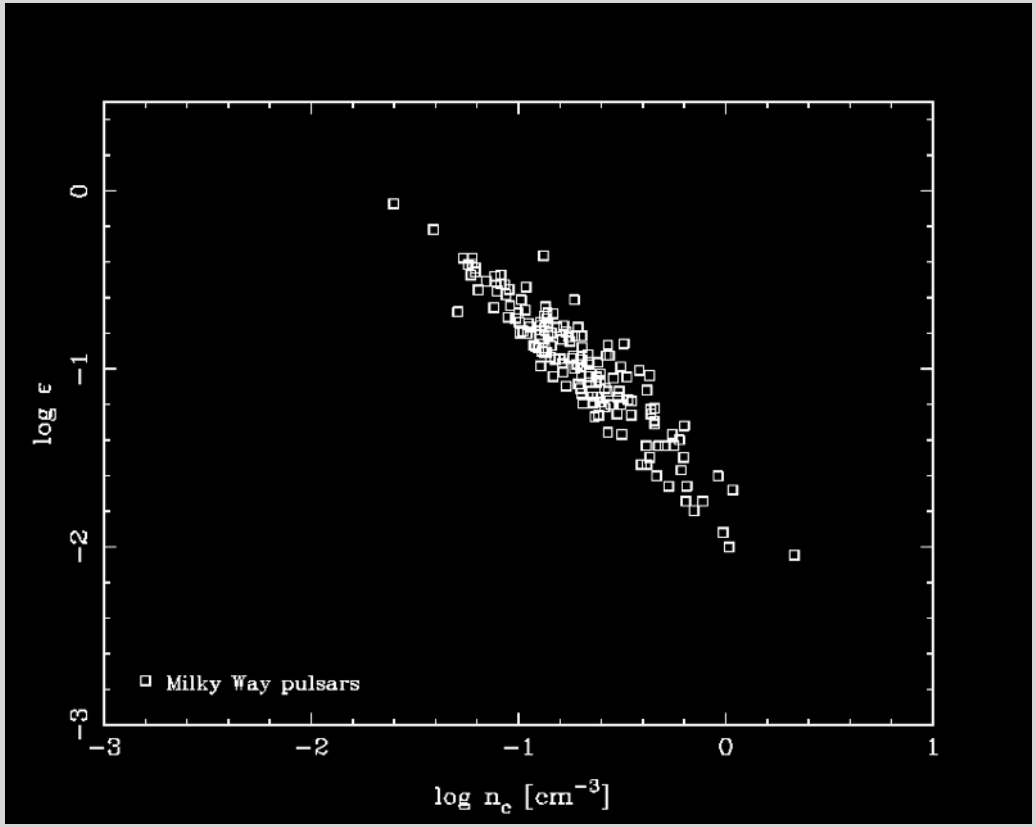
**Solution**: run Monte Carlo simulations with random values within the $3\sigma$ ranges.

# [4] Filling factor : galactic haloes are inhomogeneous

The filling factor of the ionised gas in the halo increases with height above the plane :

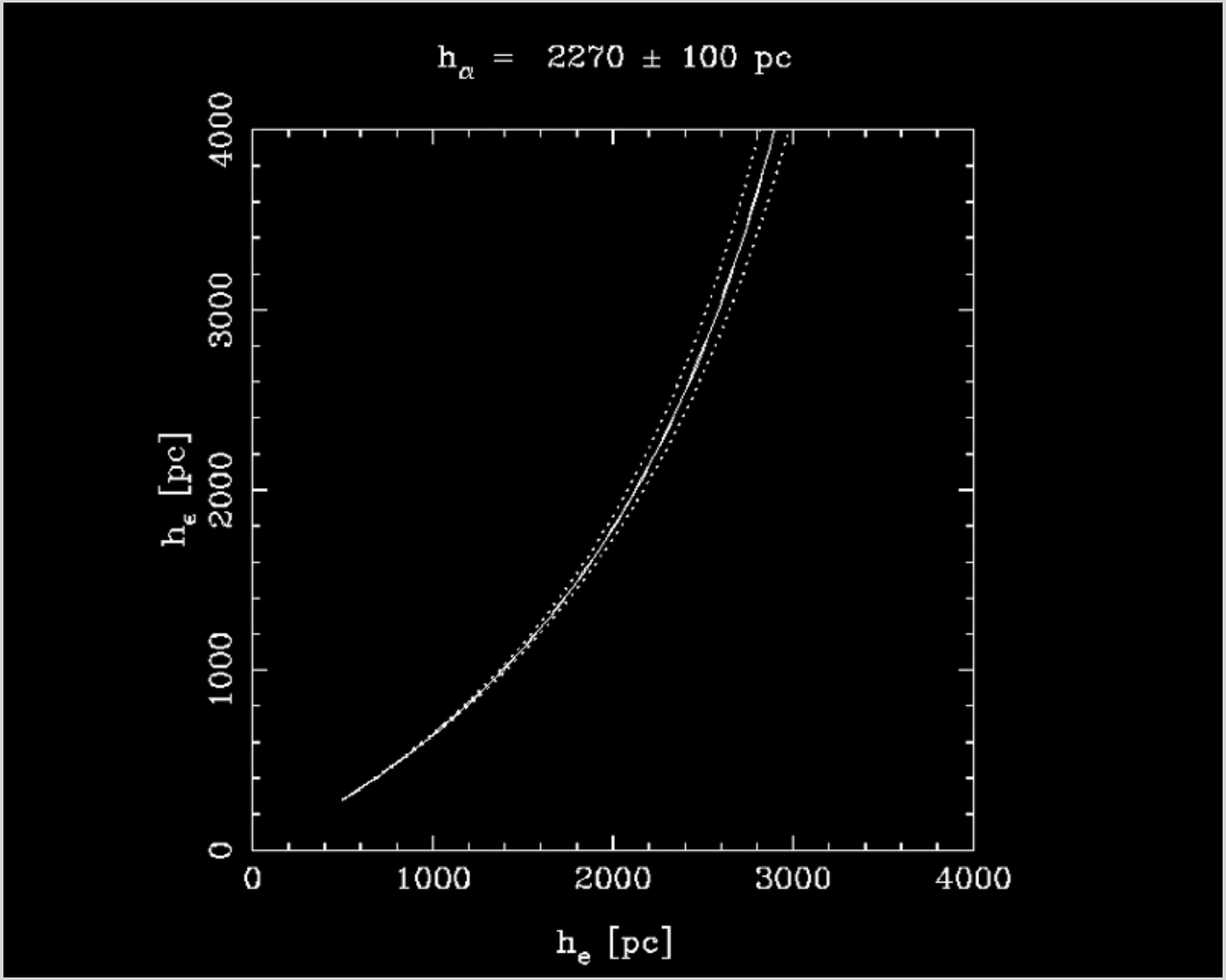



Berkhuijsen (1999)

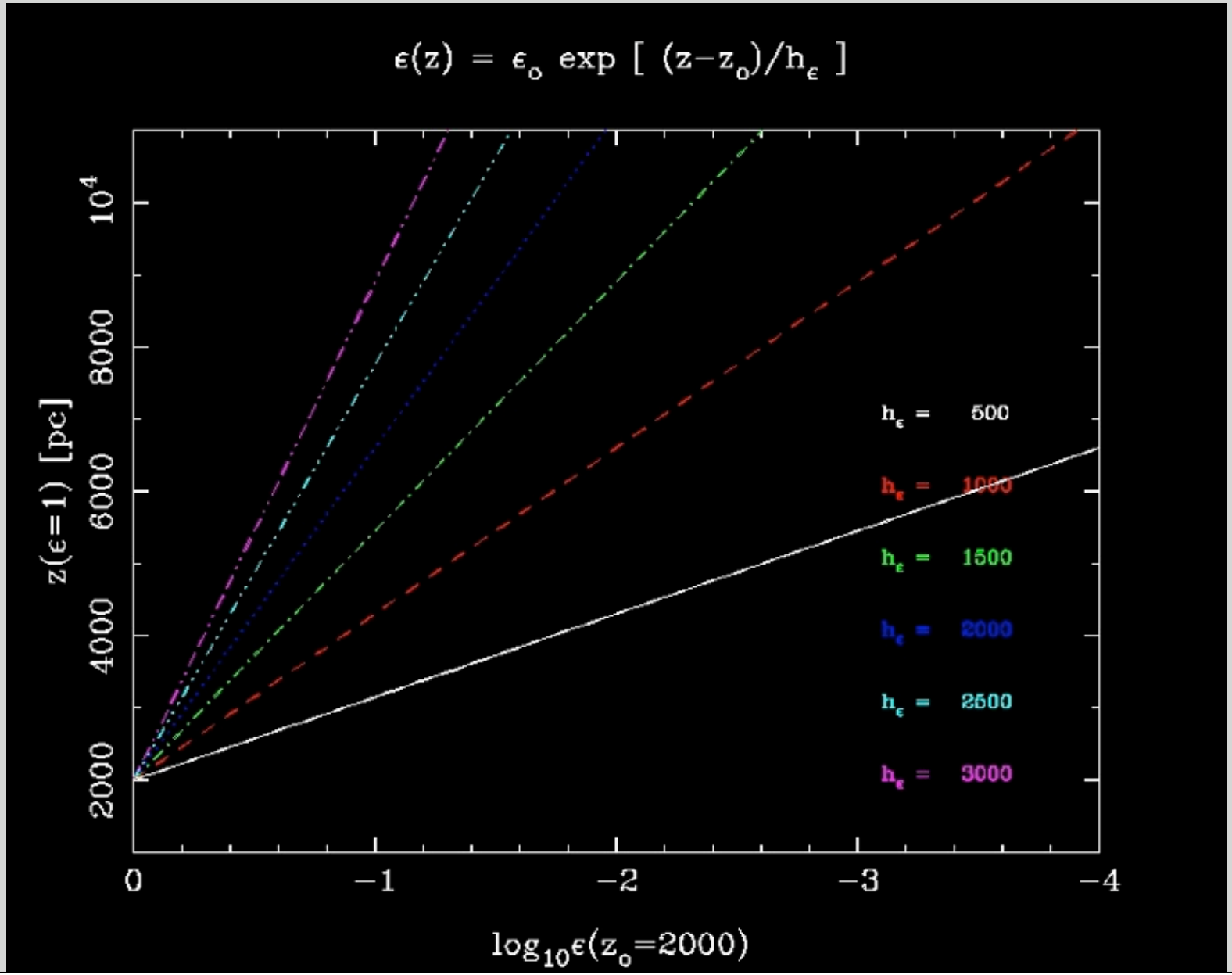



Data from Mitra et al. (2006)

# For a given observed exponential scale height



# For a given observed exponential scale height



**To recap :**

[1] Compute projected emissivities
along the line of sight. Do not use local values.

[2] Use exponential distributions
for the electron density, as inferred from
the observed surface brightness distribution

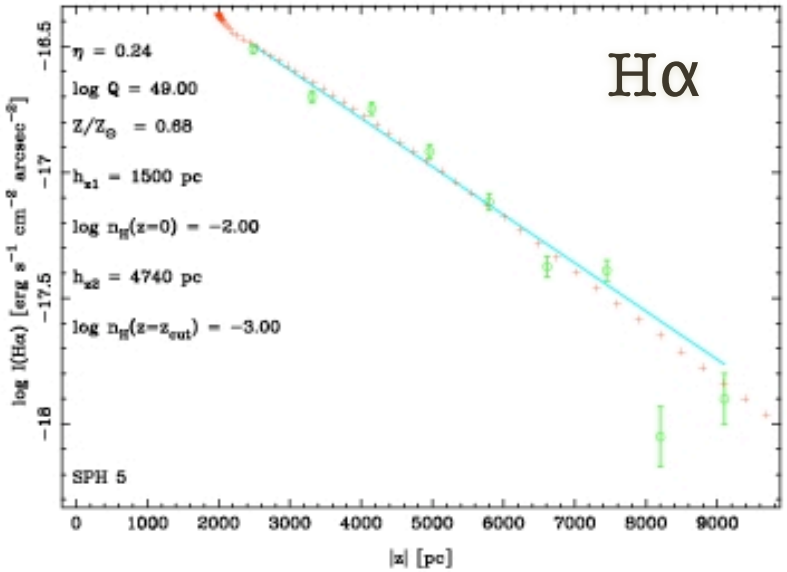
[3] Run Monte Carlo simulations
changing the dielectronic recombination coeffs.

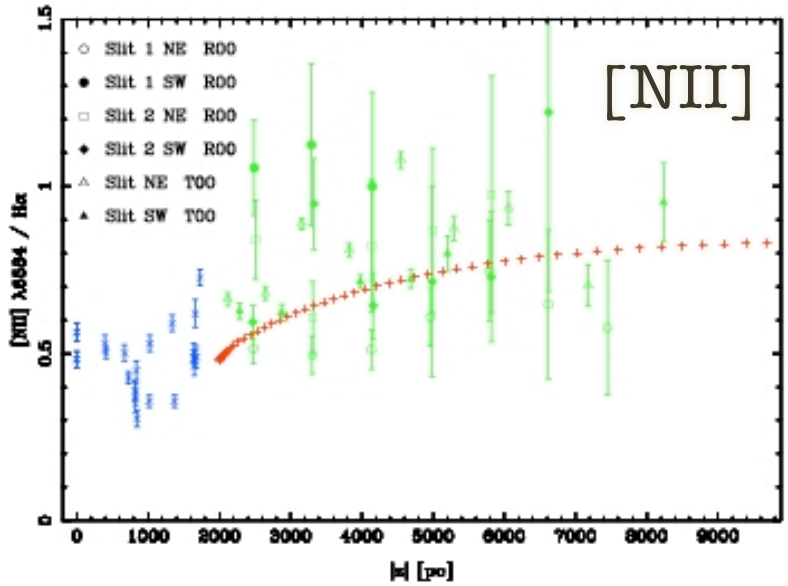
[4] Use filling factors which increase with height |z|

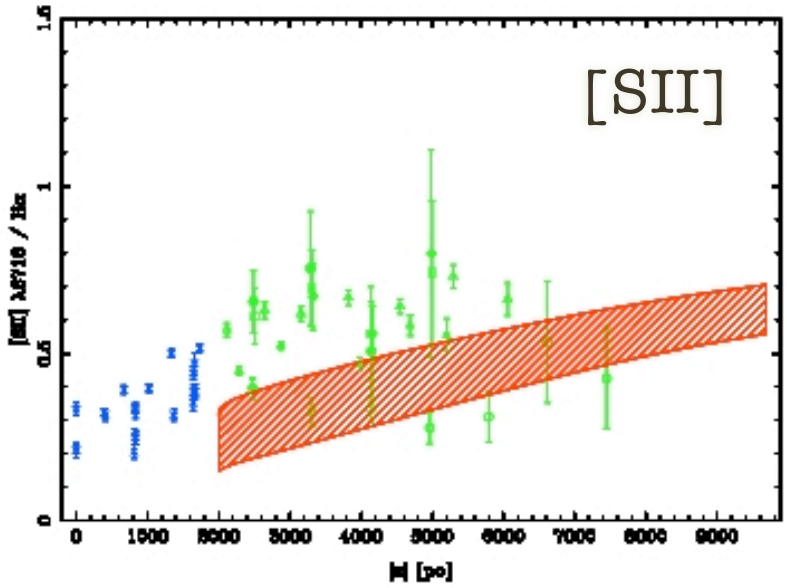
=> change CLOUDY accordingly

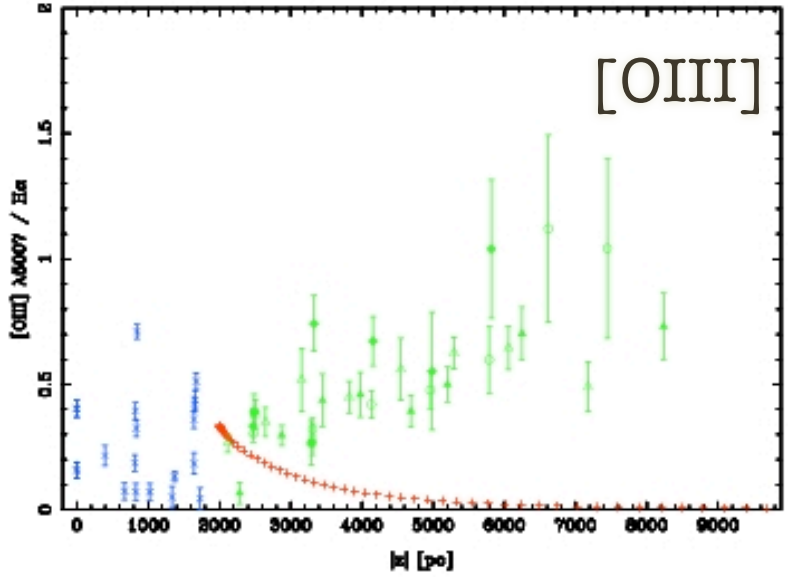
NGC 5775

# Classic ionisation-bounded models



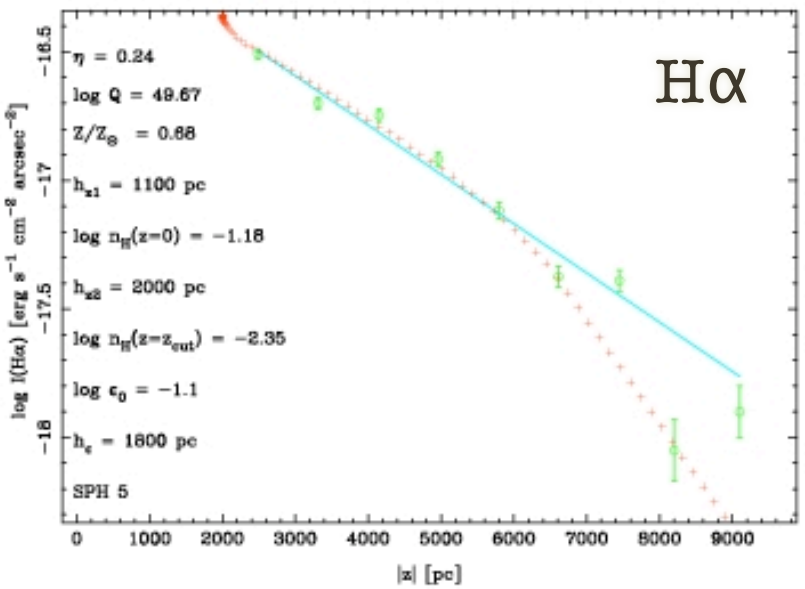



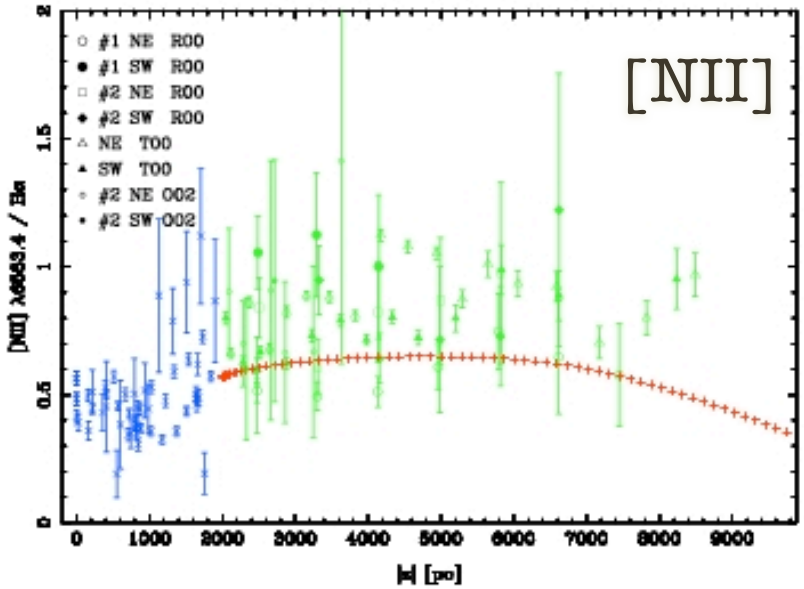



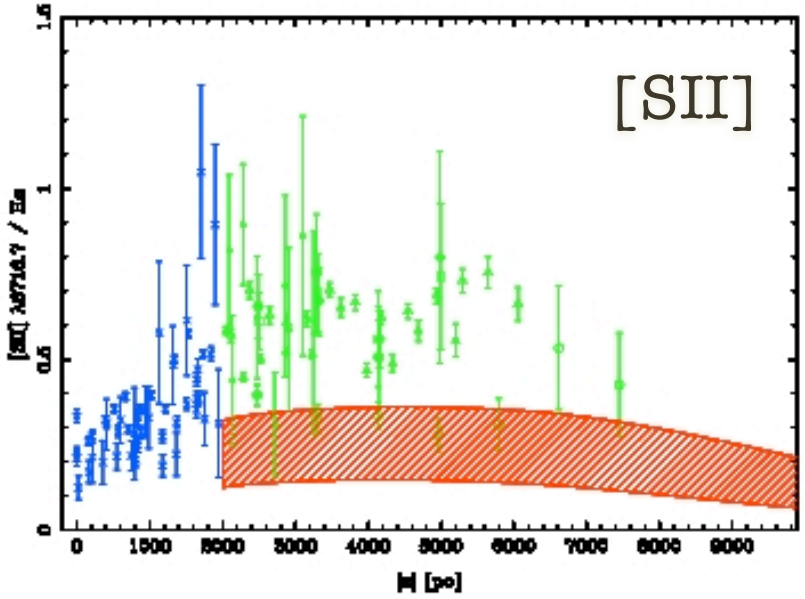



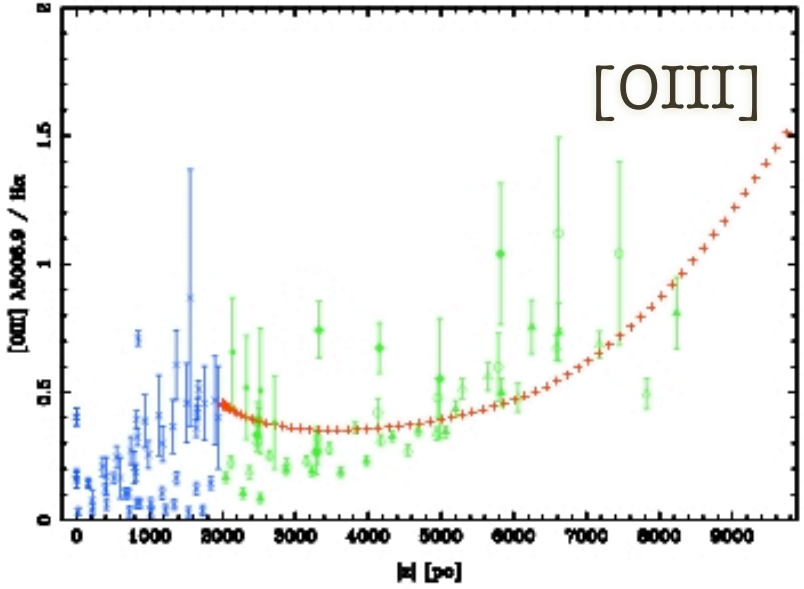
# NGC 5775

## New matter-bounded models

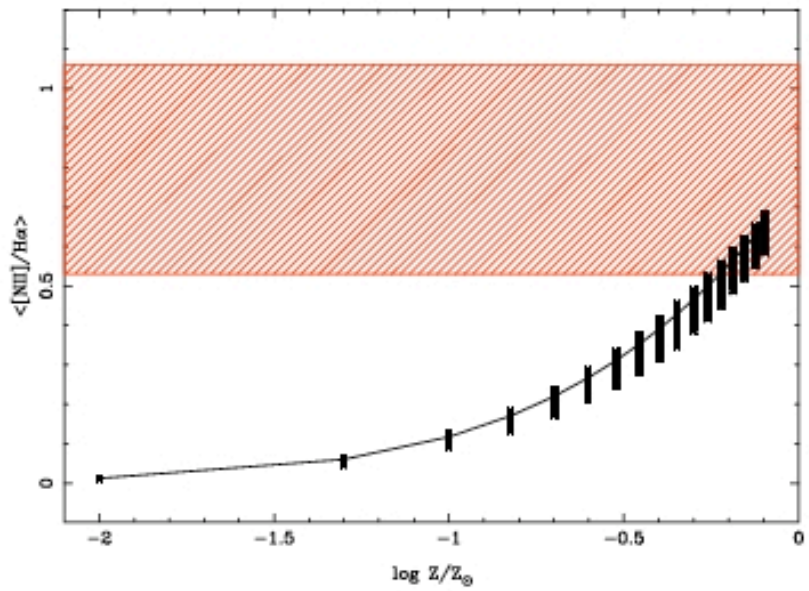


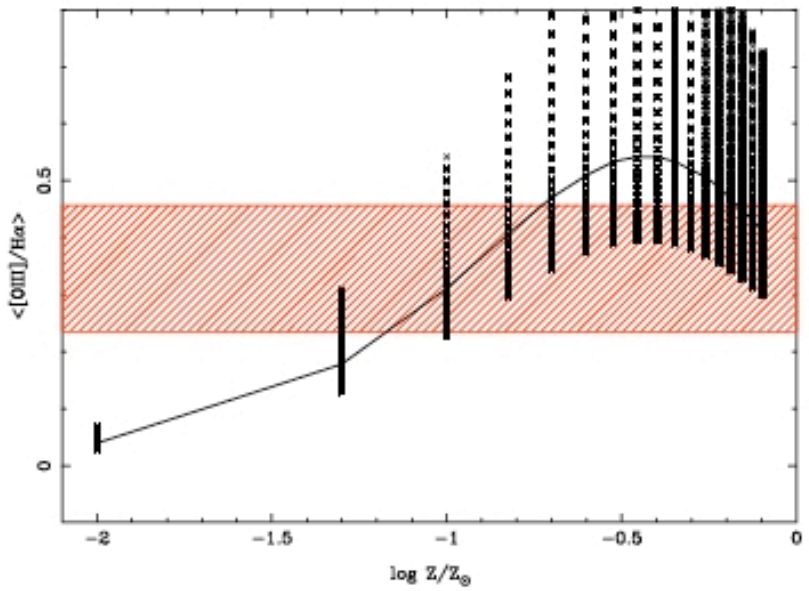



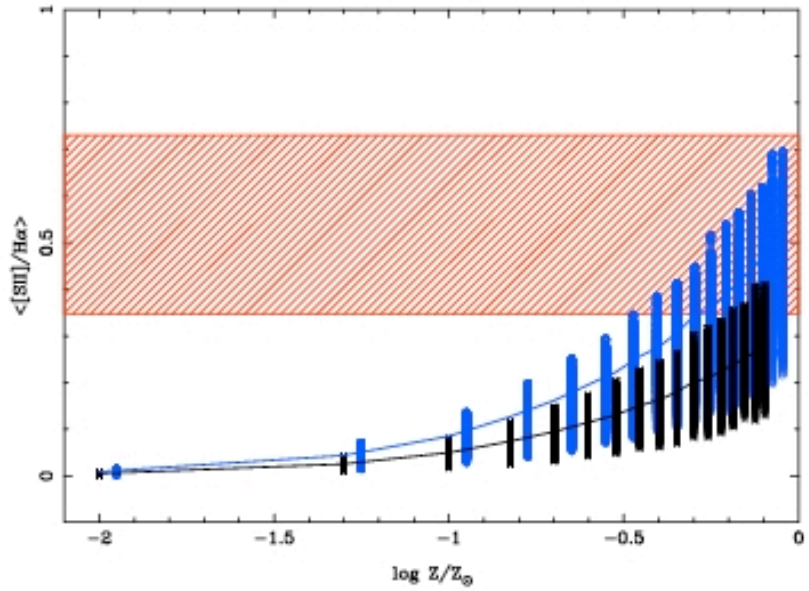



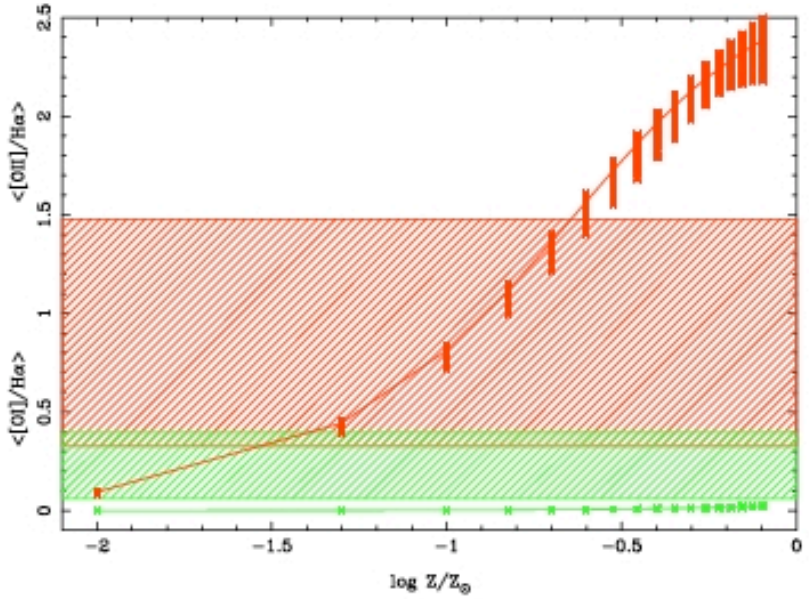



# Problem : relatively large metallicities

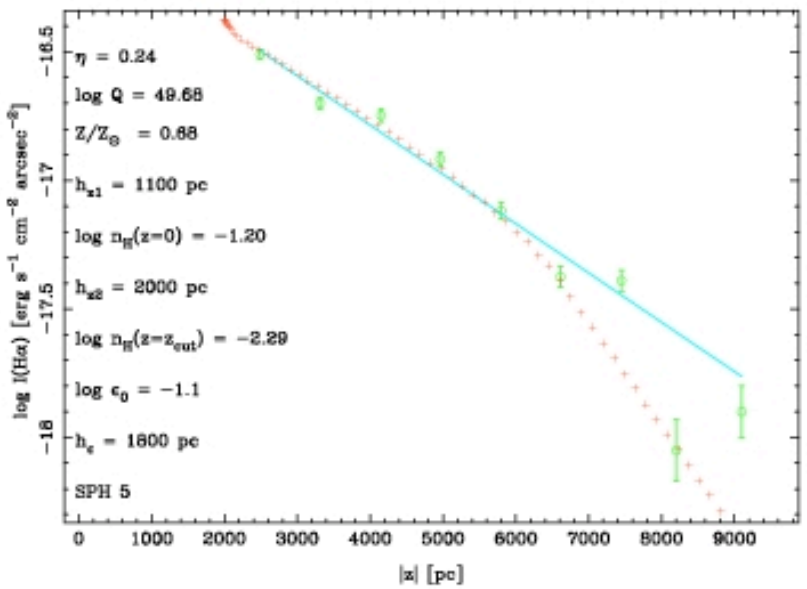


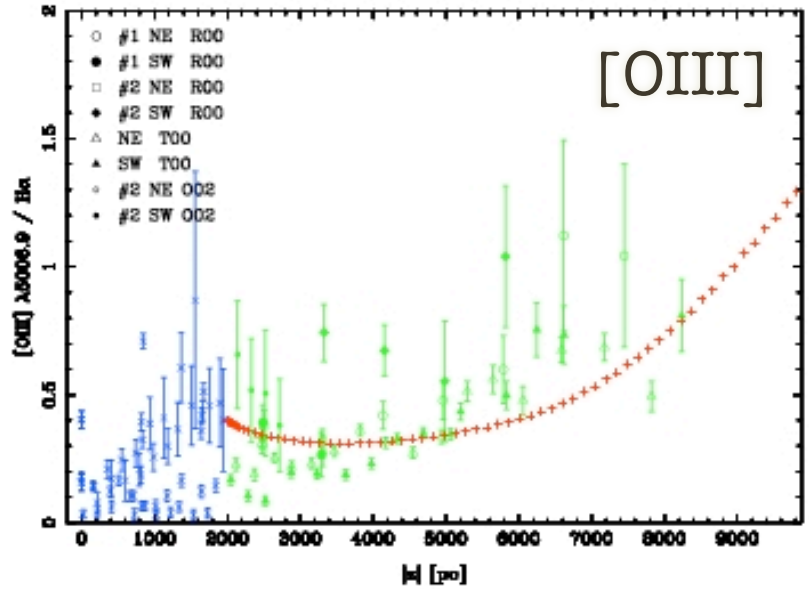



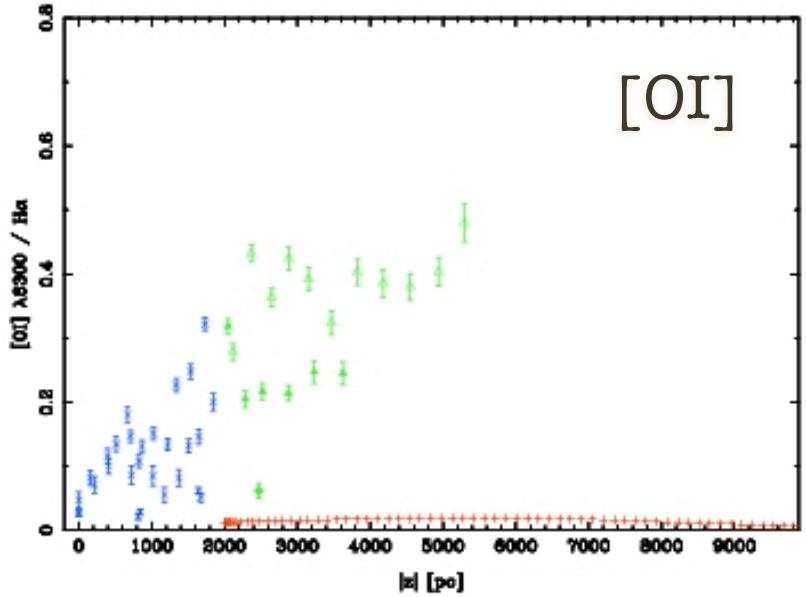



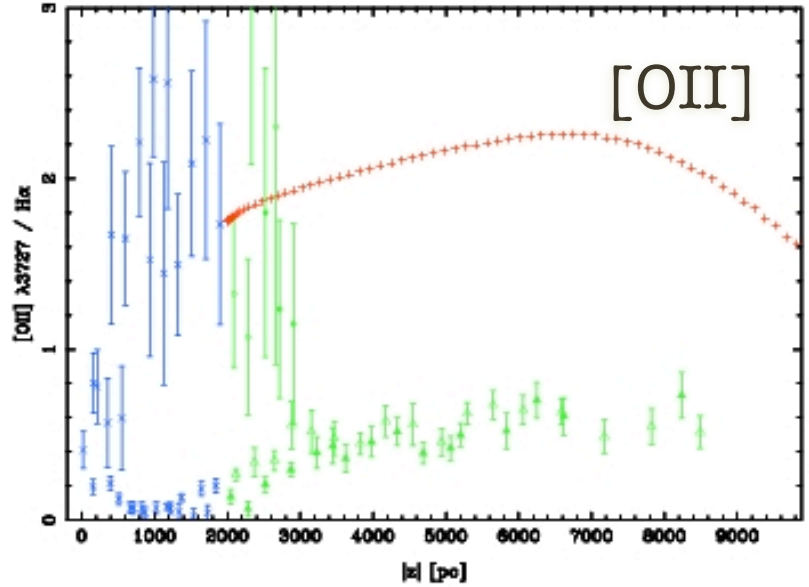



# Problem : ionisation stages of oxygen (again)



# Summary

☑ Understanding the failures of previous attempts at fitting the observed properties of the DIG.

☑ No need for proper 3-dimensional modelling nor unplausible non-ionising heating mechanism.

☑ A physical model which accounts for the observed trends in [NII] [SII] and [OIII].

📌 TBD : Ionisation balance of oxygen ions / metallicities / pressure equilibrium