The Diffuse Ionized Gas resolved by HOLMES

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Summary

- What is the DIG?
- DIG is not an HII region, hotter?
- Heating the DIG, how?
- Grid of models for NGC891:
  - Absorbed OB stars… doesn’t work (fluorescence)
  - HOLMES at work, **solving the puzzle!**

Short historical

In 1963, Hoyle and Ellis: "*ionized layer along the Galactic plane [...] of 5 10^8 solar masses*".

The DIG (Diffuse ionized Gas) was clearly established by Reynolds in our Galaxy (1971, 1989).

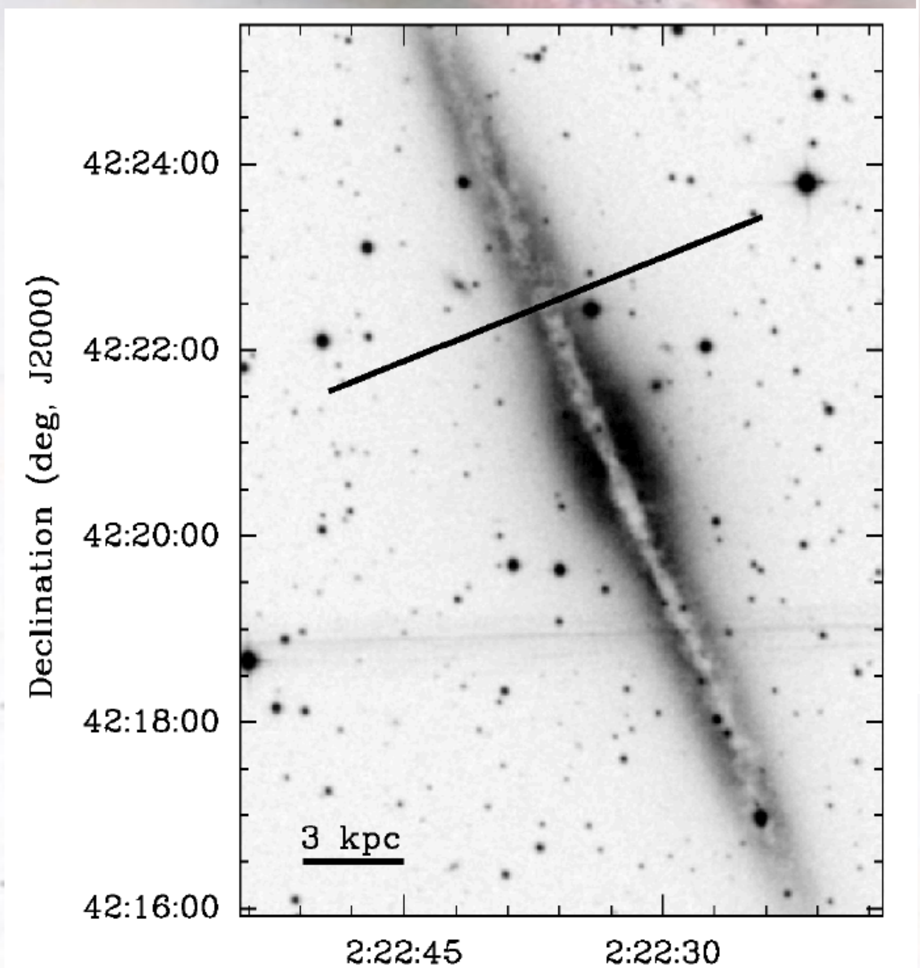
It appears to be a common **and major** component of the interstellar medium in galaxies.

What ionizes the DIG?

- The DIG is ionized at high altitudes (up to 4 kpc).
- OB stars from the disk? -> Porosity of the HII regions?
- Mathis (1983) :

We conclude that the DIG is ionized by the radiation from O stars. This radiation presumably escapes from H II regions surrounding the stars but which are not completely radiation bounded.

Observations of NGC891



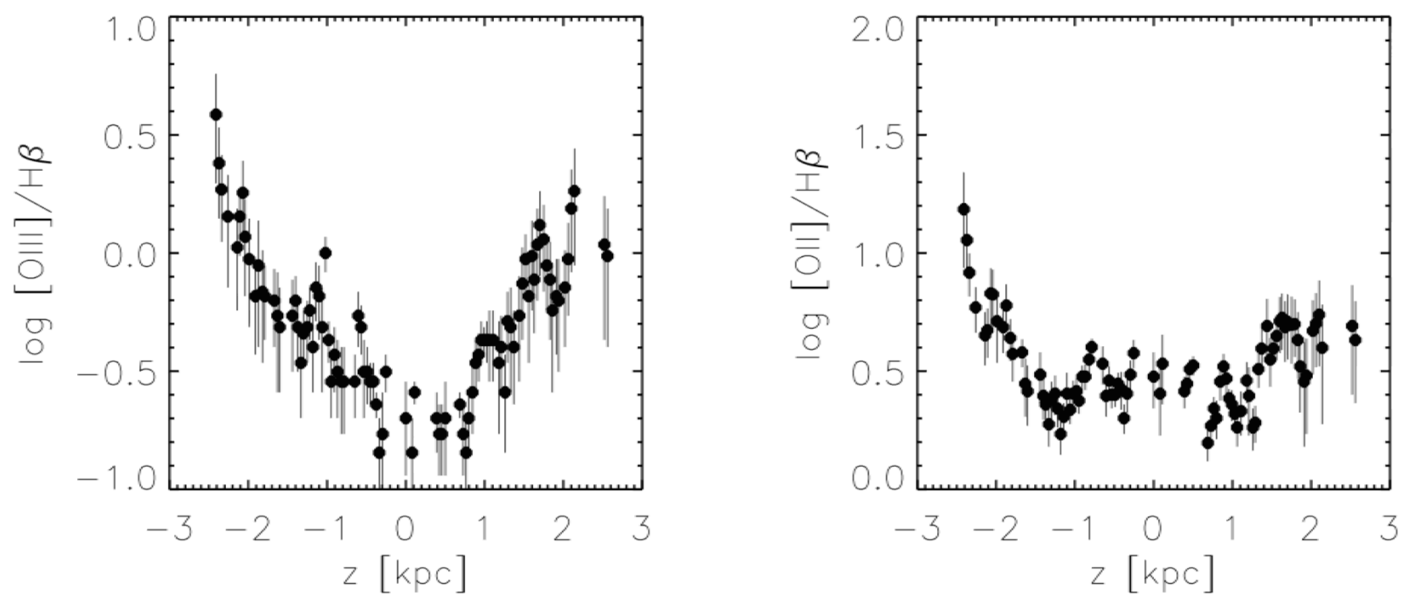
Rand (1990) and Otte (2001) observed the DIG of NGC891, an edge-on galaxy very similar to the Milky Way.

They put the slit perpendicular to the disk to study the variation of the line ratios vs. |z|.

What ionizes/heats the DIG?

- The DIG is ionized at high altitudes (up to 4 kpc).
- OB stars from the disk?
- BUT an increase of [OII], [NII] and [OIII] lines (over HI lines) with galactic height is observed.

Forbidden lines over HI lines increase with |z|



This is observed in various edge-on galaxies.

Here for NGC891, see **DIGEDA** (Flores-Fajardo 2010) for more data.

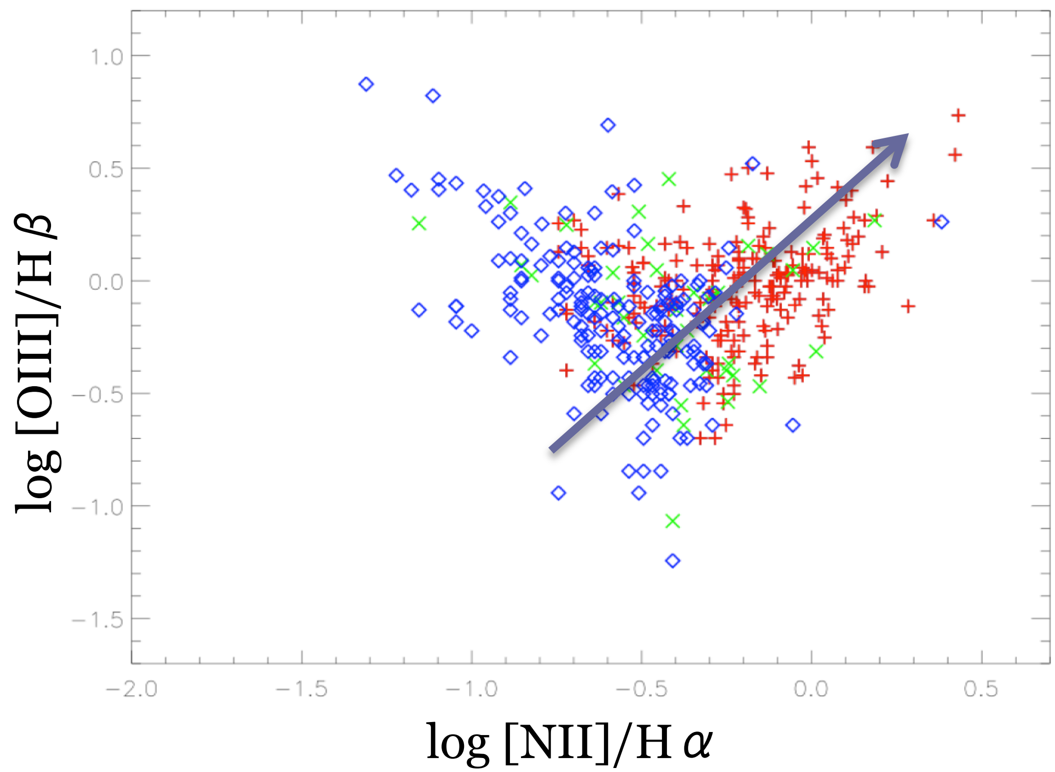
What ionizes/heats the DIG?

- Mathis (2000) :

An important modification to the simplest picture of photoionizing the WIM is that extra heating beyond that supplied by photoionization is required (Reynolds, Haffner, & Tufte 1999). The diagnostics of this requirement are the large [N II]/Hα ratio that is observed at large $|z|$ in both the Perseus arm and, especially, in NGC 891. Another feature is the observed constancy of [S II]/[N II] at $\sim$0.6. There are several possible sources of this extra heating. It must be relatively unimportant for low $|z|$.

NGC 891 at $|z| = 2$ kpc is very interesting in that it shows very strong [O III] and He$^+$ far above the plane. The combinations of models show that very hot stars ($T_* \sim$ 50,000 K) are needed, most plausibly at high $|z|$. If the exciting stars are found near the plane, their radiation must propagate through almost a vacuum up to the $|z| = 2$ kpc region.

Forbidden lines over HI lines increase with |z|



On the BPT diagram, the DIGs (red) are on the right side, while HII regions (blue) are on the left side.

Forbidden lines over HI lines increase with |z|

"Normal" photoionization models doesn't reproduce this behaviour.

Collisionally excited lines emissivity increases with the **electron temperature.**

Thus one need an extra heating (ionizing) process to reproduce this behavior:

- Shocks
- Turbulent Mixing Layers
- Magnetic reconnection
- Cosmic rays
- Photoelectric heating from small grains
- …

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Or perhaps just "anormal" photoionization models.

Heating the gas

The electron temperature in a **photoionized** region is the result of the equilibrium between heating and cooling, where:

- **Cooling**: by emission of photons, mainly in lines (recombination and forbidden): **SEEN**
- **Heating**: by thermalization of the photoelectron --> the mean energy of the electron (temperature) is related to the mean energy of the ionizing photons: **UNSEEN**

Harder ionizing spectrum

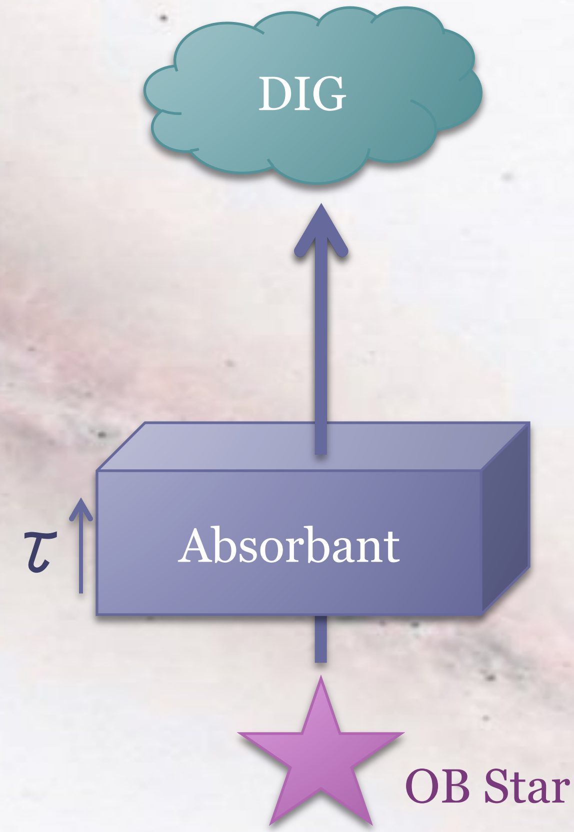
Heating:

$$G_{pi}(\mathrm{H}) = n \int_{\nu_{ion}}^{\infty} 4\pi J_\nu \left(\boxed{\frac{\nu - \nu_{ion}}{\nu}} \right) \sigma_{ion}(\nu)\,\mathrm{d}\nu$$

- To obtain a SED with a high mean energy of (ionizing) photons, we can:
  - Increase the amount of energetic photons
  - Decrease the amount of low energy photons

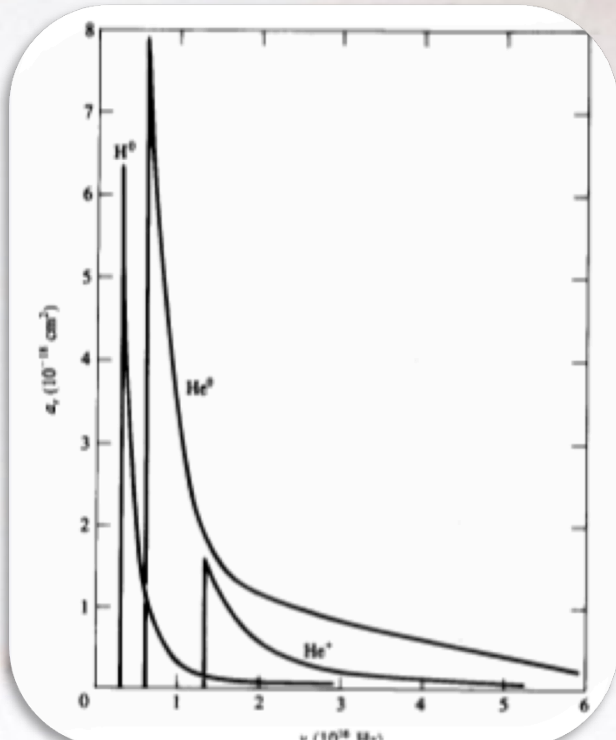
Absorbed OB stars

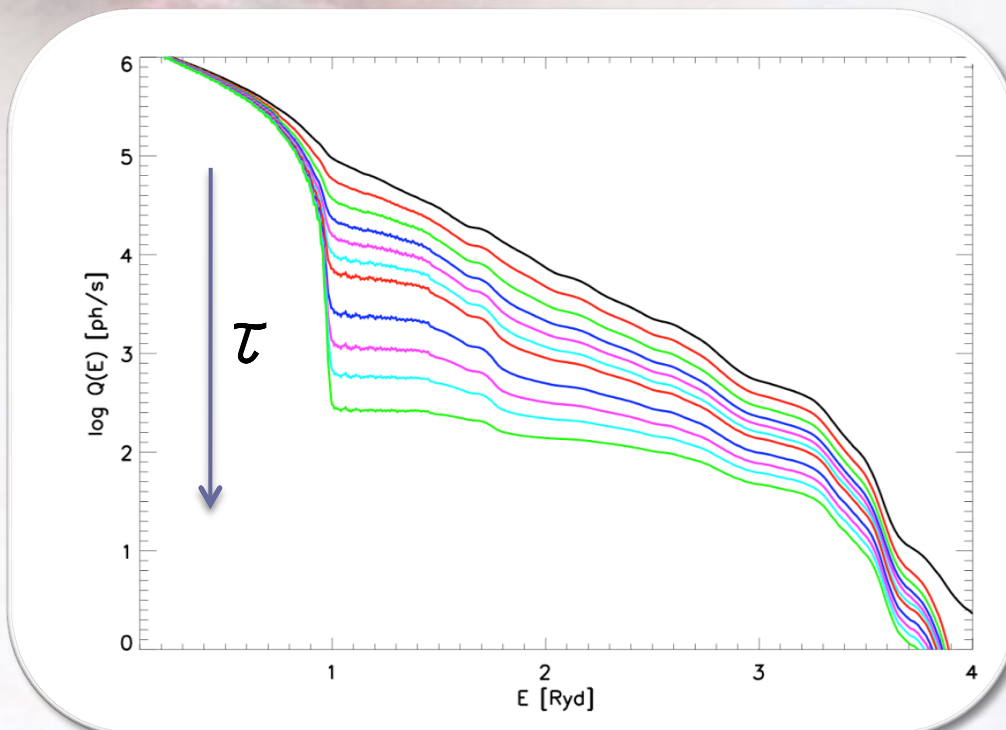
Sokolowski (1993) used absorbed OB stars to increase the mean energy of the ionizing photons.



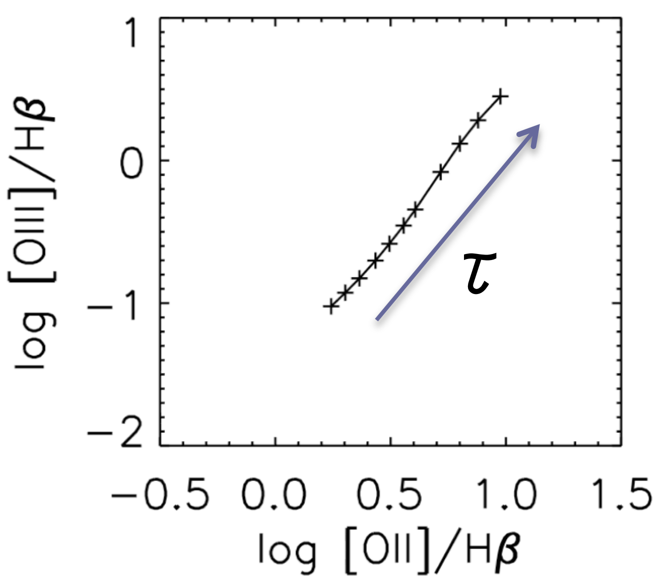
Absorbed OB stars

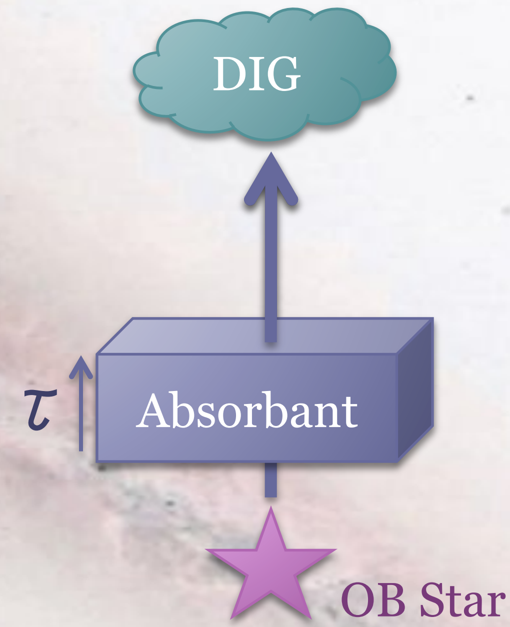
- Photoionization cross section decreases with energy -> lower energy photons are more absorbed.





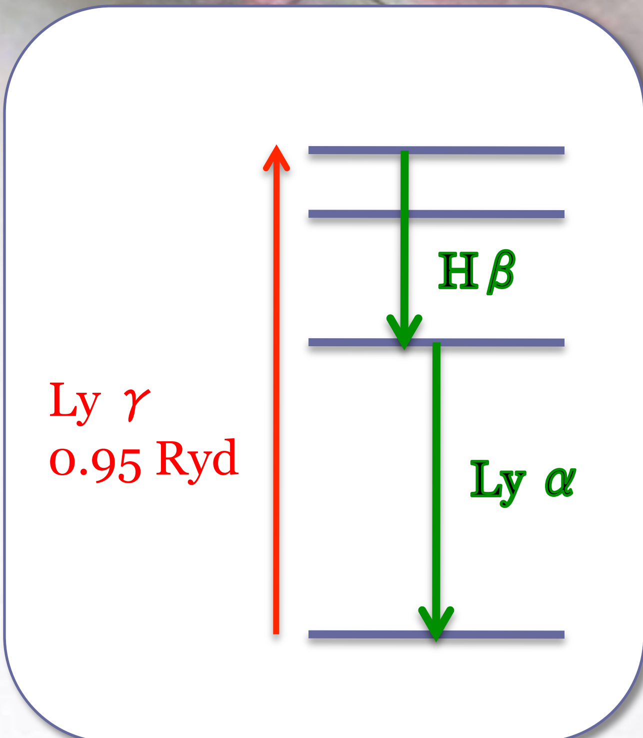
Absorbed OB stars… and fluorescence

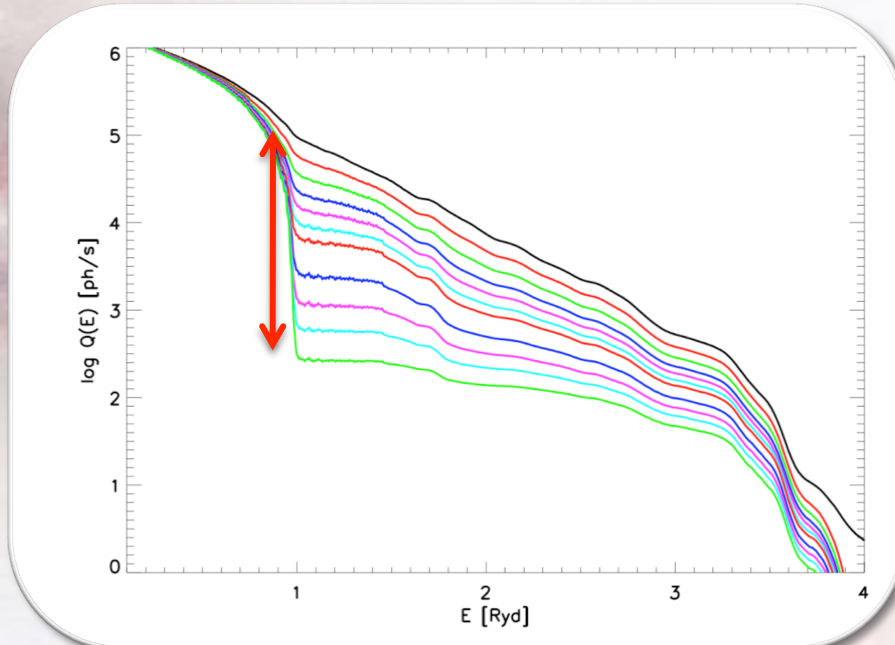




Increasing τ leads to an increase of the DIG temperature and it seems to be the solution. BUT…

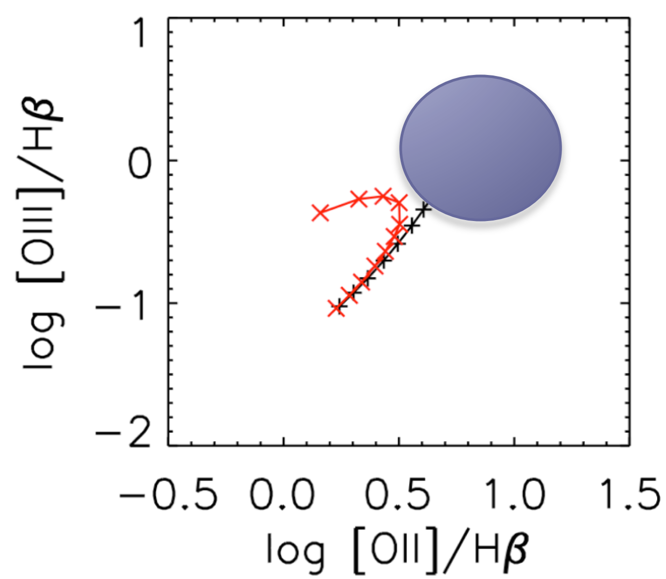
Absorbed OB stars… and fluorescence





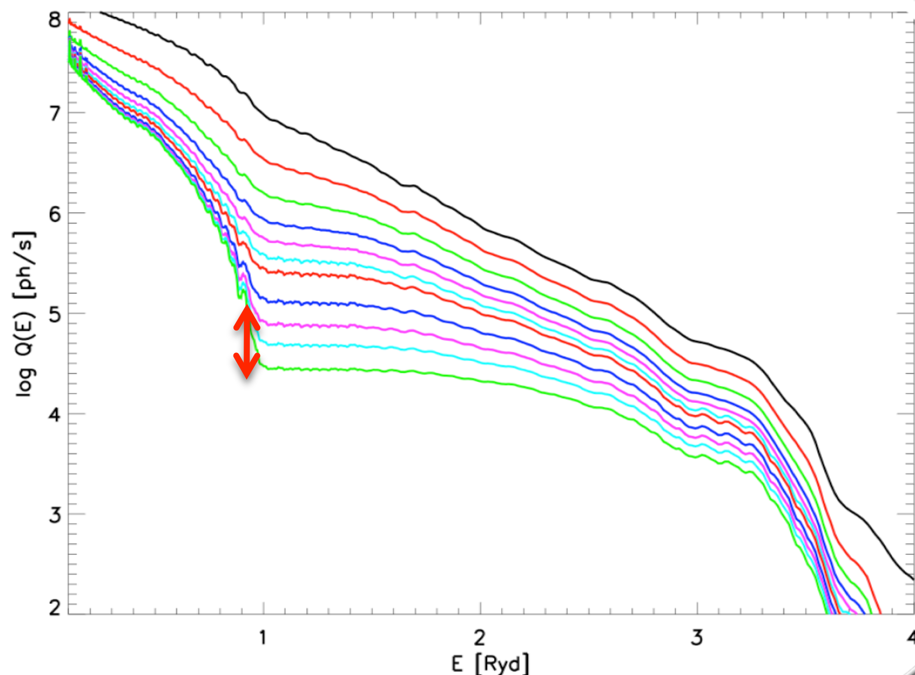
The Lyman β, γ, δ, ε, etc photons are not absorbed AND they are exciting H^0, leading to fluorescent emission of HI lines, killing [X]/HI.

Absorbed OB stars… and fluorescence



No way to reach the DIG region…

Absorbed OB stars, fluorescence and dust…

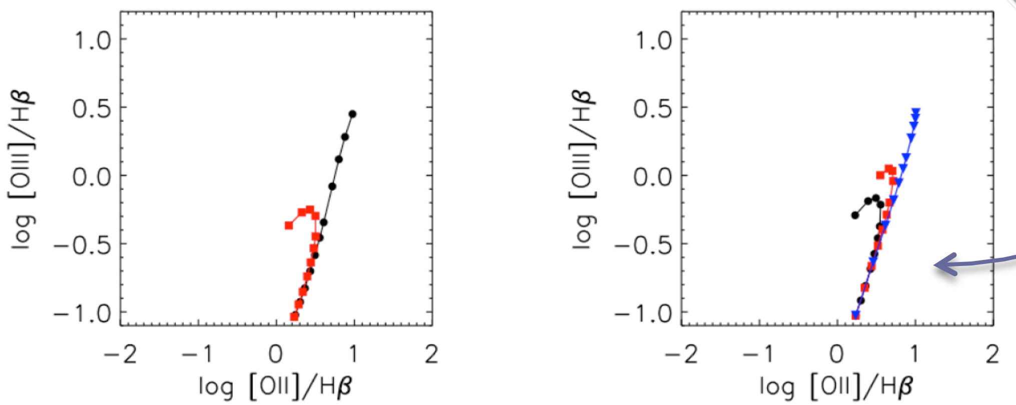


If dust is dominating the absorption, the fluorescence effect is strongly reduced.

This require a large ionization parameter, to reduce the absorption by photoionization.

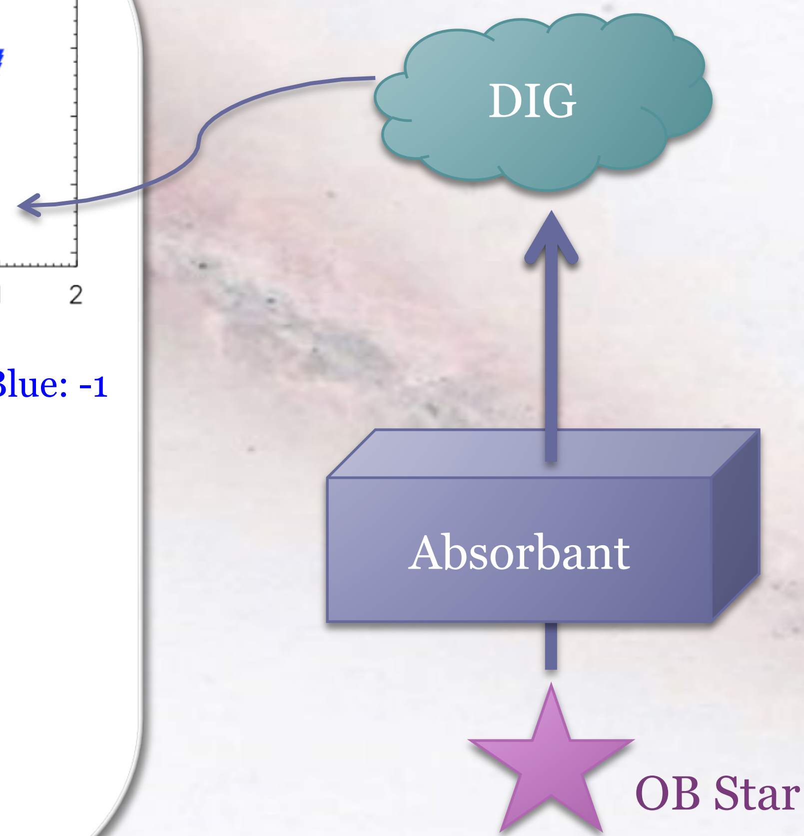
Absorbed OB stars, fluorescence and dust…

Dust-free absorber | Dusty absorber

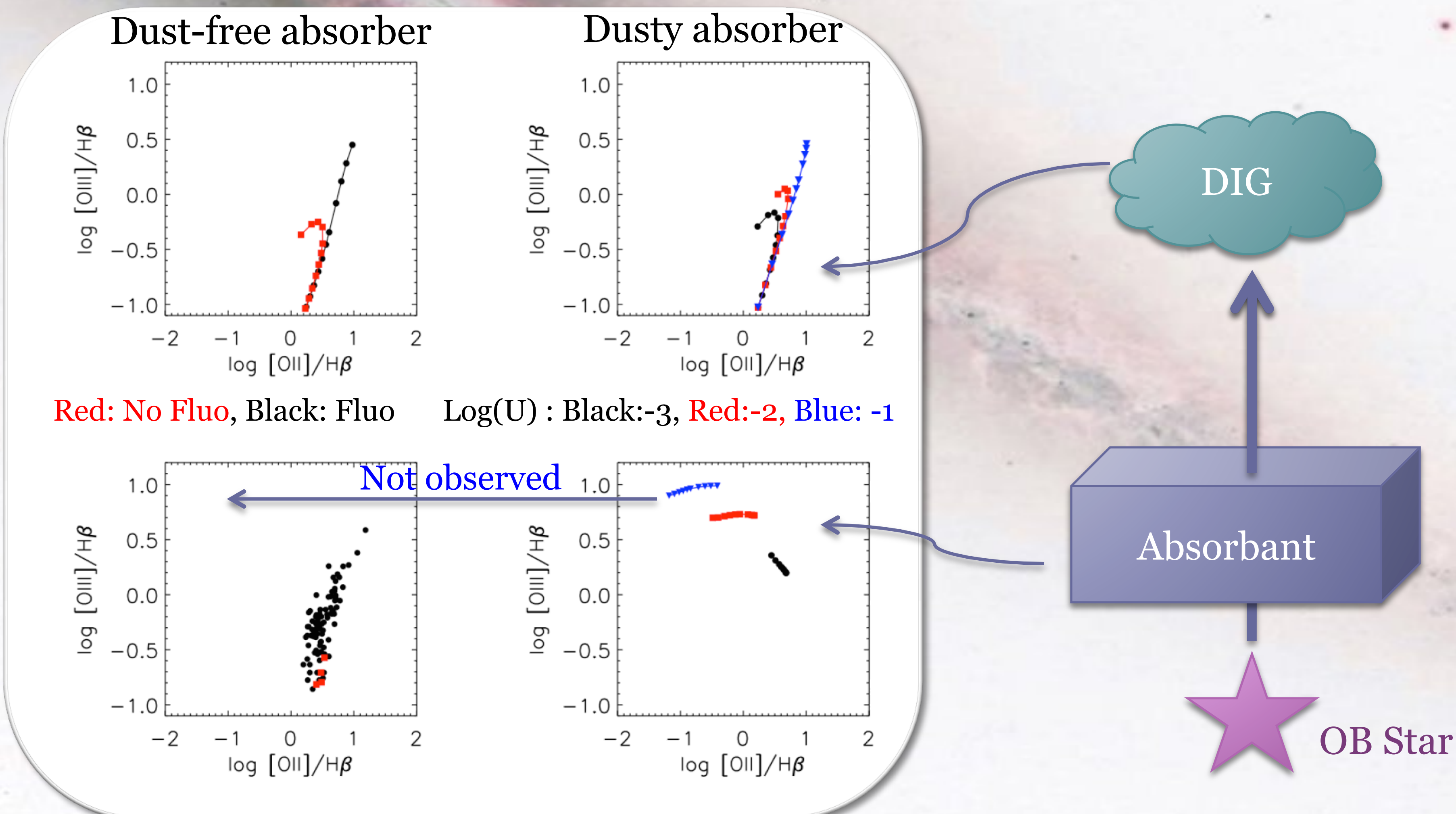


Black: No Fluo Red: Fluo

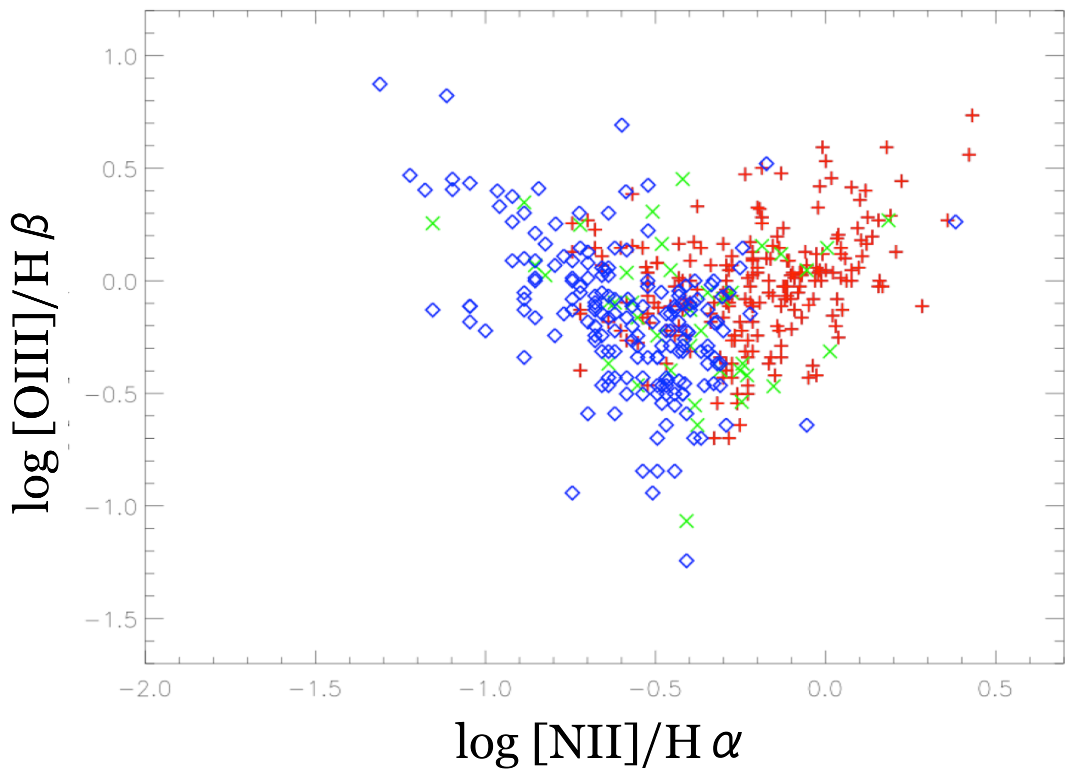
Log(U) : Black:-3, Red:-2, Blue: -1



Absorbed OB stars, fluorescence and dust…



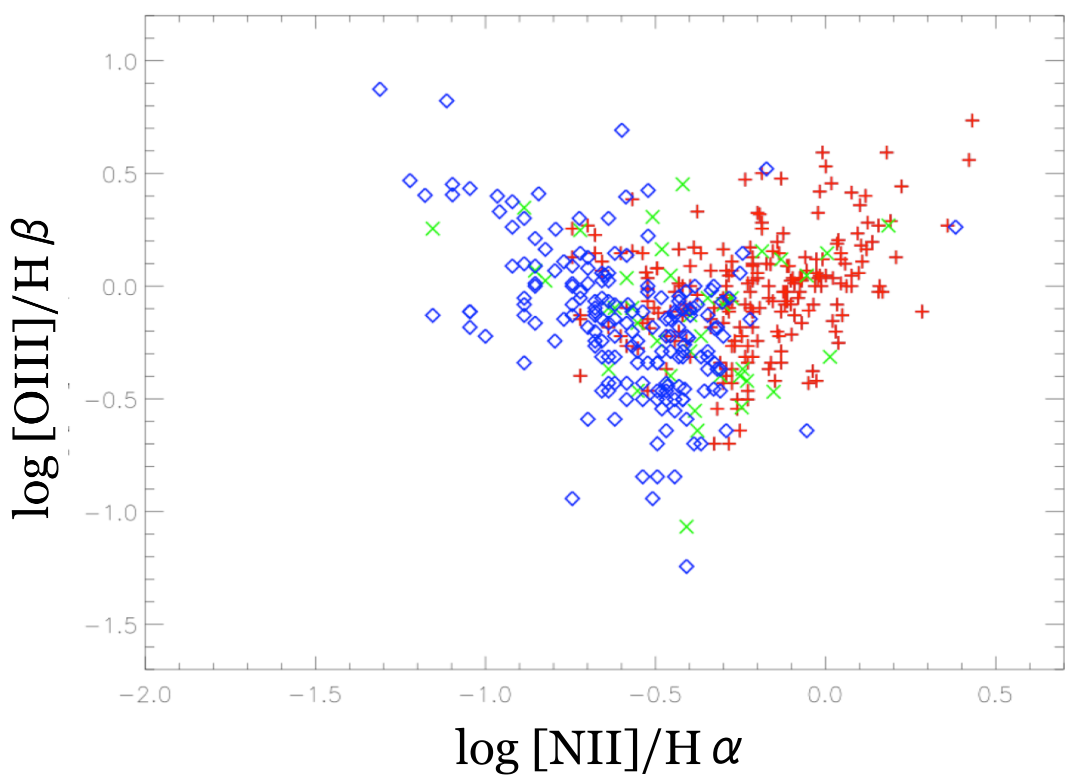
Adding high energy photons to the SED: HOLMES's coming



The position of the DIG in the BPT diagram correspond to the AGNs and the LINERS…

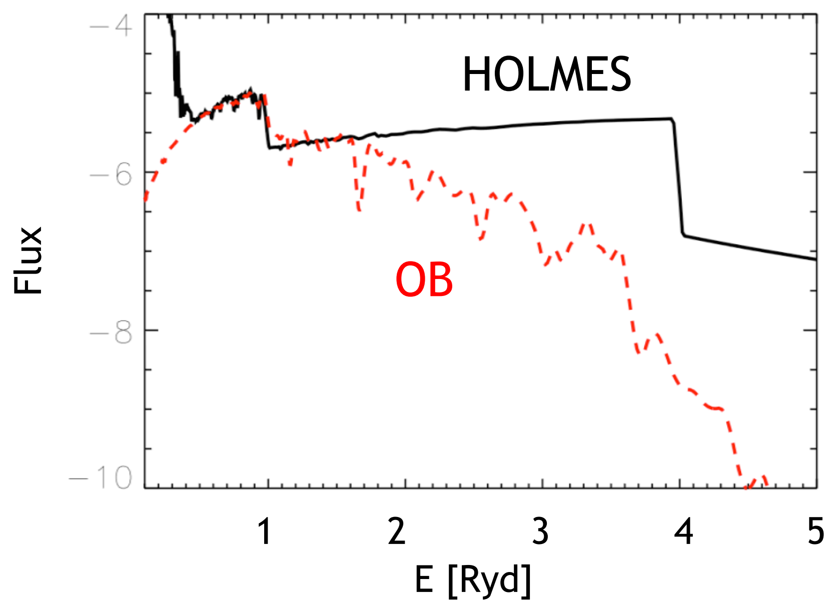
BUT

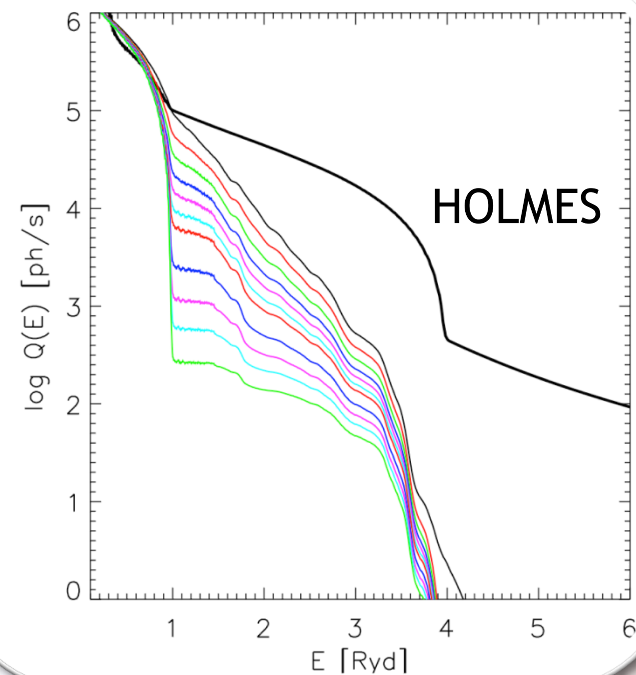
Adding high energy photons to the SED: HOLMES's coming



- The position of the DIG in the BPT diagram also reminds a work by Stasinska et al. on « retired » galaxies.
- **HOLMES : Hot Low Mass Evolved Stars** (WD, post AGB stars, naked PNCS) are quite numerous in the halo… and they provide high energy photons.

HOLMES SED

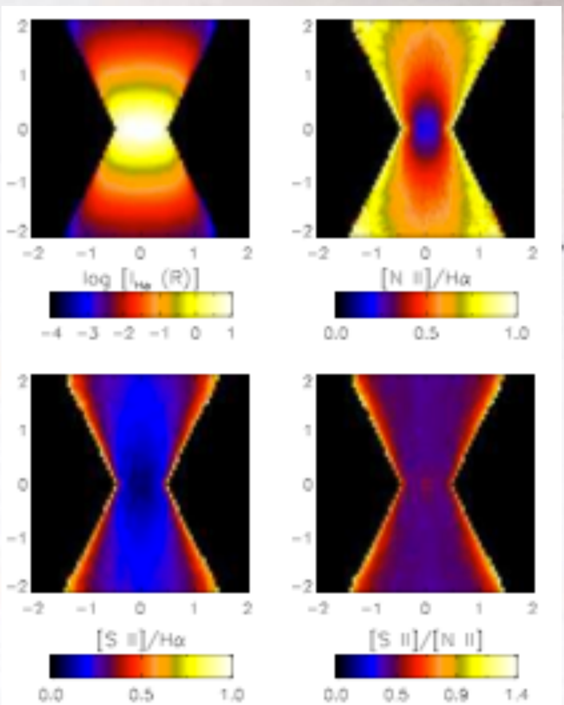


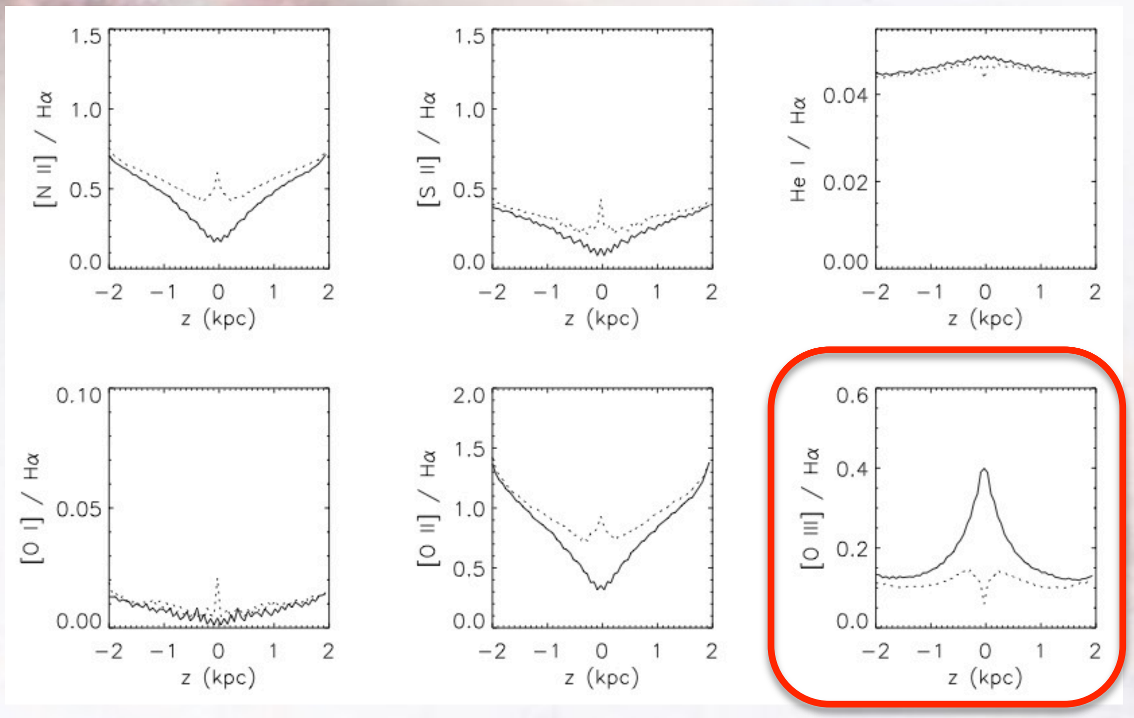


HOLMES' SED is really more energetic than OB stars.

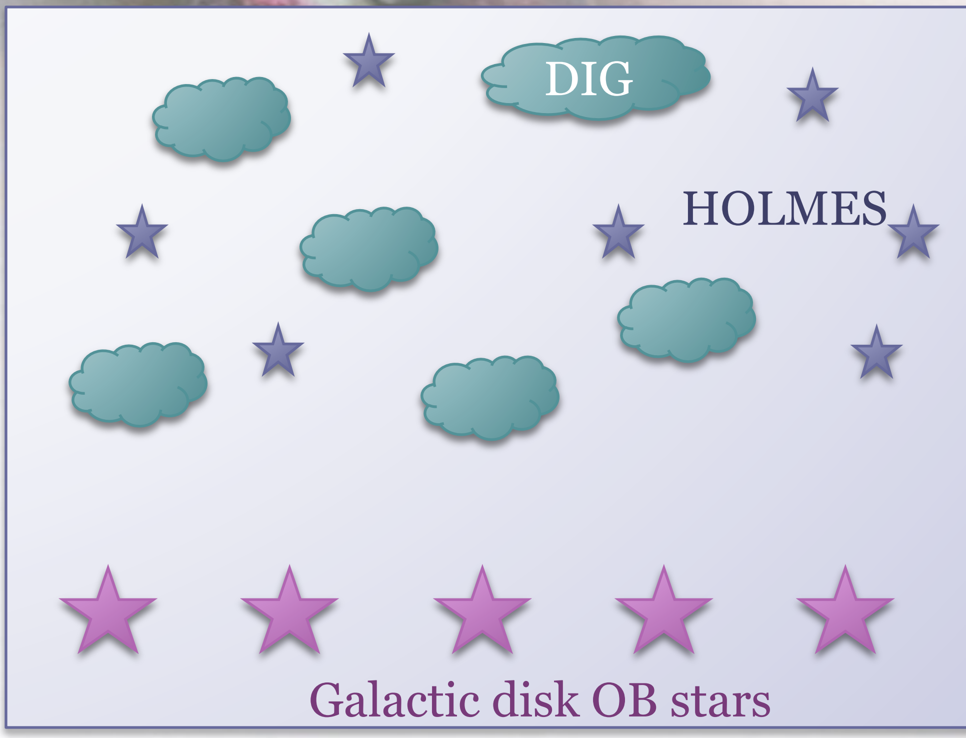
Morphology

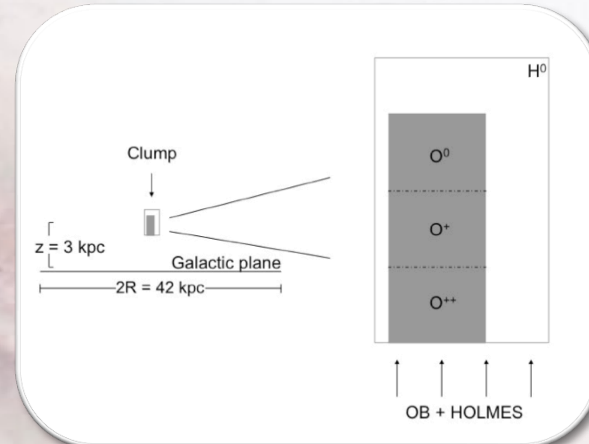
A continuous medium leads to an inescapable decrease of [OIII]/Hß (Wood and Mathis 2004).





Scenario for the models





- The extraplanar gas is ionized by OB stars from the galactic plane and HOLMES from the halo.
- When z increase, the relative contribution of the OB stars decreases.

Photoionization models combining OB stars and HOLMES

- We perform a grid of Cloudy models, setting as variable parameters:
  - The contribution of the OB stars Φ_{OB} / Φ_{TOTAL}
  - The ionizing parameter $U = \Phi_{TOTAL} / n_e.c$
  - O/H (and the other metals following O)
  - N/O

$(\Phi = Q_0/4\pi R^2)$

- A high resolution grid is obtain by interpolating within a medium resolution grid, leading to **54432** models.

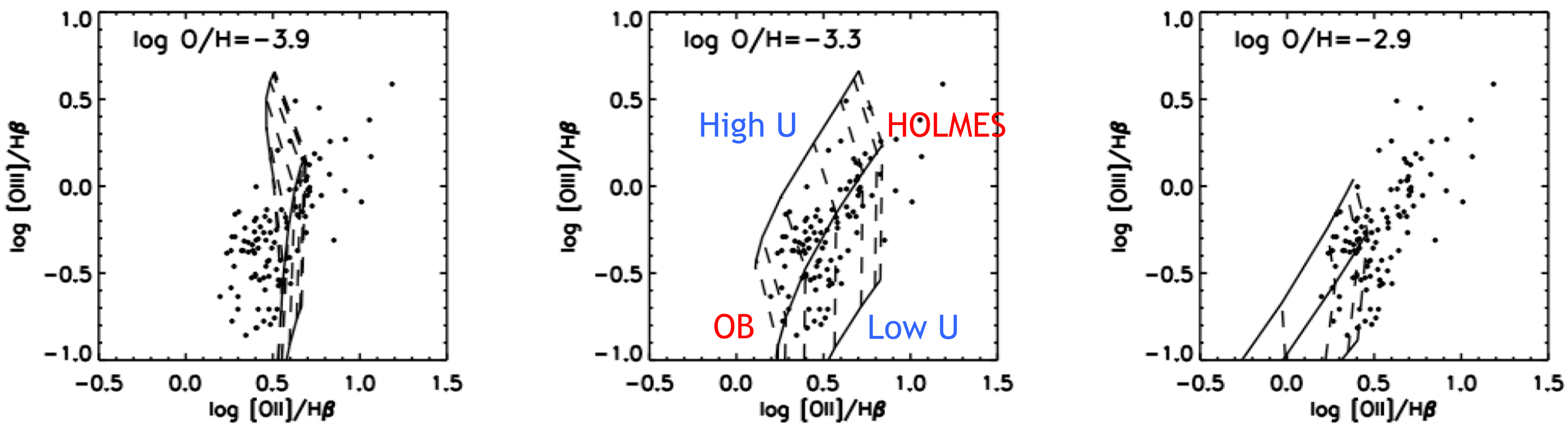
Counting the stars: OB

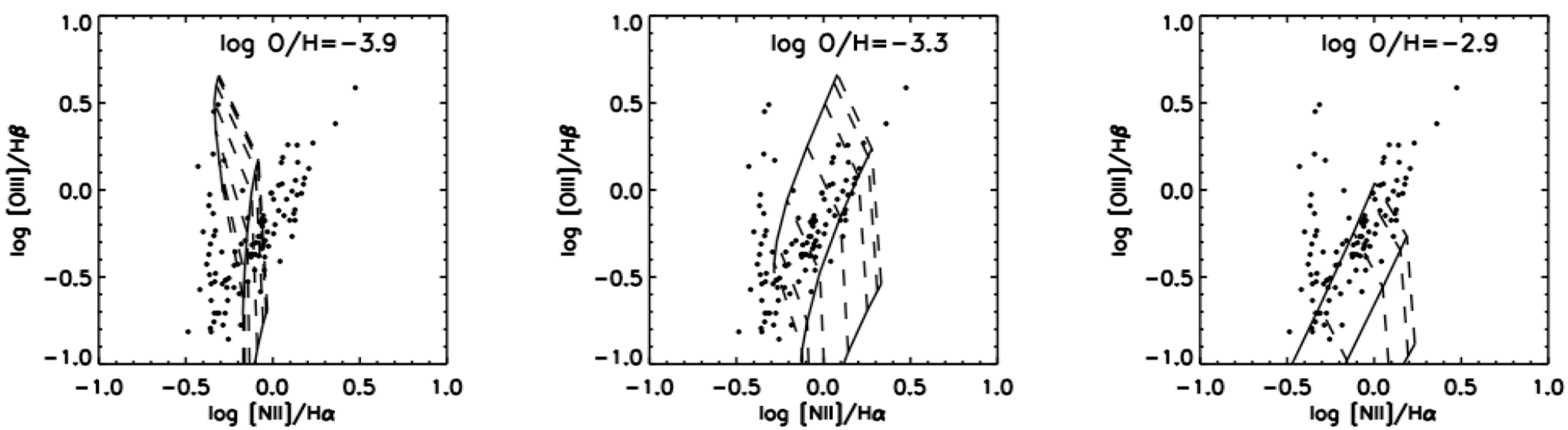
- The ionizing flux emitted by the OB stars is obtained using Starburst99, with a Kroupa IMF, for stellar masses ranging from 0.1 to 100 $M_{\odot}$.
- We use a continuous star formation of 10^7 yrs.
- The total IR luminosity of NGC891 is 2.6 10^{10} $L_{\odot}$
- The present-day star formation is 5.2 $M_{\odot}$/yr.
- Starburst99 give a total number of ionizing photons for 1 $M_{\odot}$/yr of $10^{53.2}$ ph/s.
- $Q(H^0)_{OB}$ = 7.8 10^{53} ph/s.
- **$\Phi_{OB} = Q(H^0)_{OB}/(2\pi R^2)$ = 3.1 10^7 ph/cm^2/s.**

Counting the stars: HOLMES

- The SED emittedby the HOLMES is computed by PEGASE (Fioc & Rocca-Volmerange 1997).
- Single burst of 10 Gyr (Solar, Kroupa).
- The number of ionizing photons is $7\ 10^{40}$ ph/s/$M_{\odot}$
- The mass of the old thick disk is $3\ 10^{10}\ M_{\odot}$
- The total ionizing photons emission rate is thus: $2.1\ 10^{51}$ ph/s, leading to:
- $\mathbf{\Phi_{HOLMES} = 8.4\ 10^{4}\ ph/cm^{2}/s.}$

Grid of models

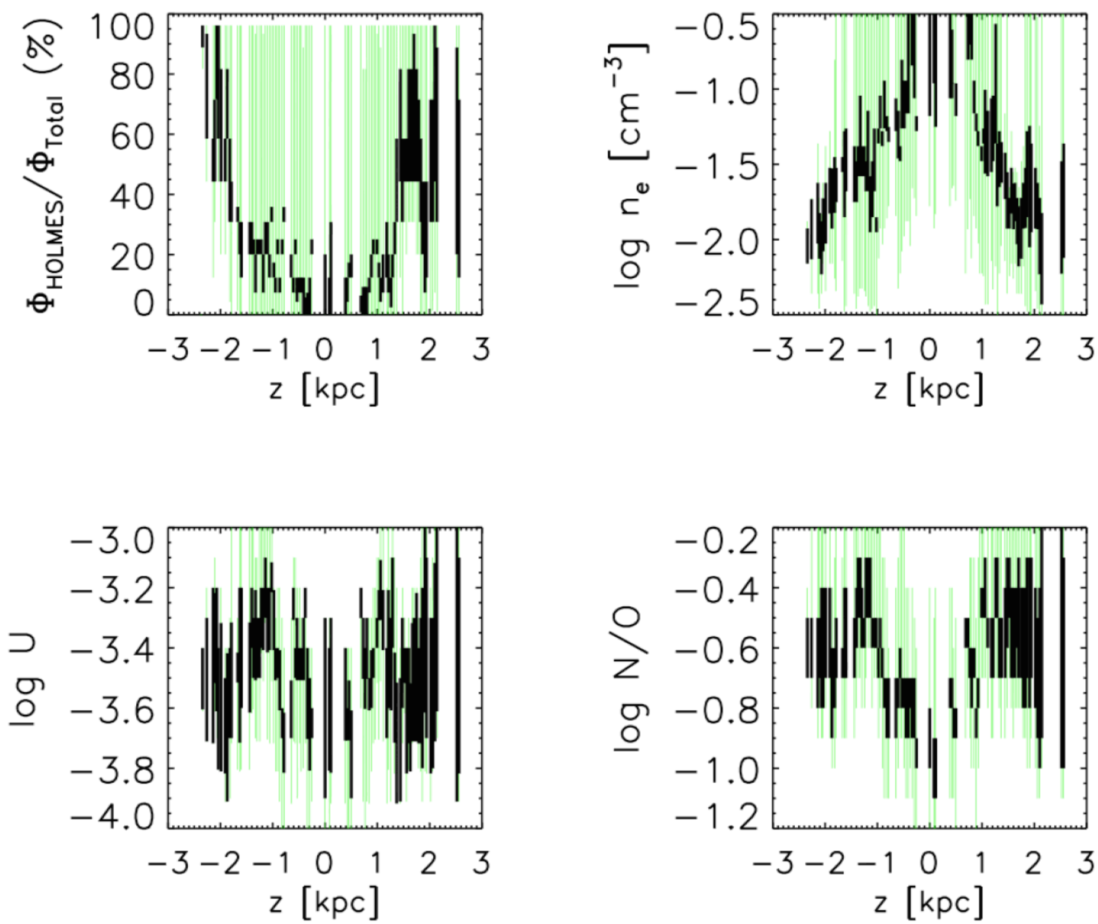




Results

- Each observed point is defined by :
  - Position z
  - Line ratios [NII]/Hα, [OII]/Hβ, and [OIII]/Hβ
- For each point, we look for ALL the models that **simultaneously** fit the 3 line ratios.
- This gives the range of validity for every free parameter (U, HOLMES proportion, Z, N/O) at every altitude z.

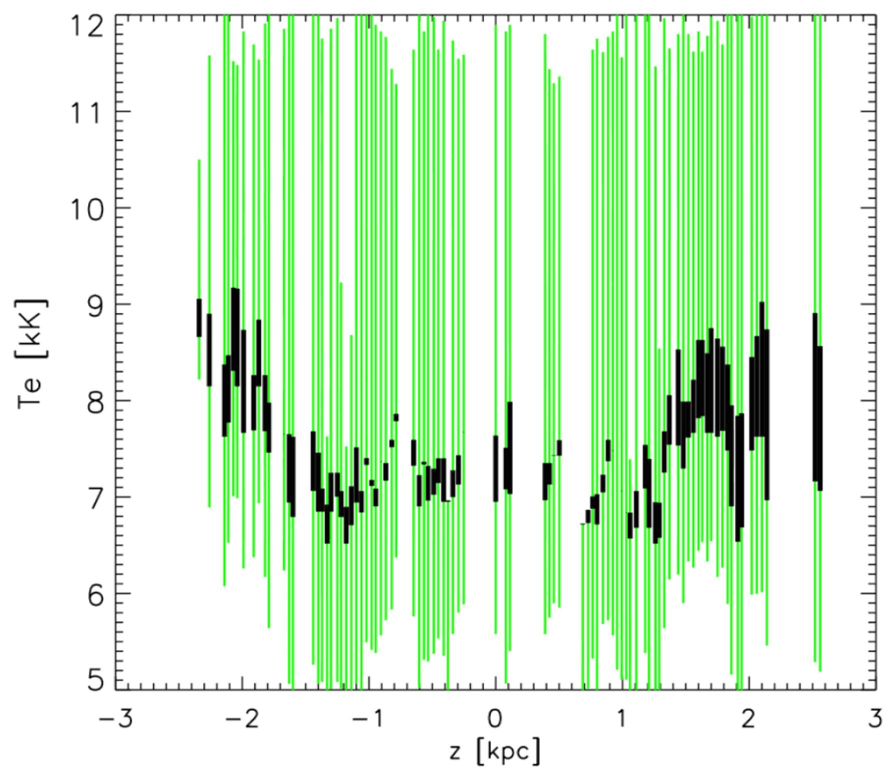
Results



- The contribution of the HOLMES increases with |z|.
- The density decreases.
- The ionization parameter U is relatively constant.
- N/O could be seen as increasing with |z|.

Green: free metallicity models. Black: solar metallicity solutions.

Results : Te(z)

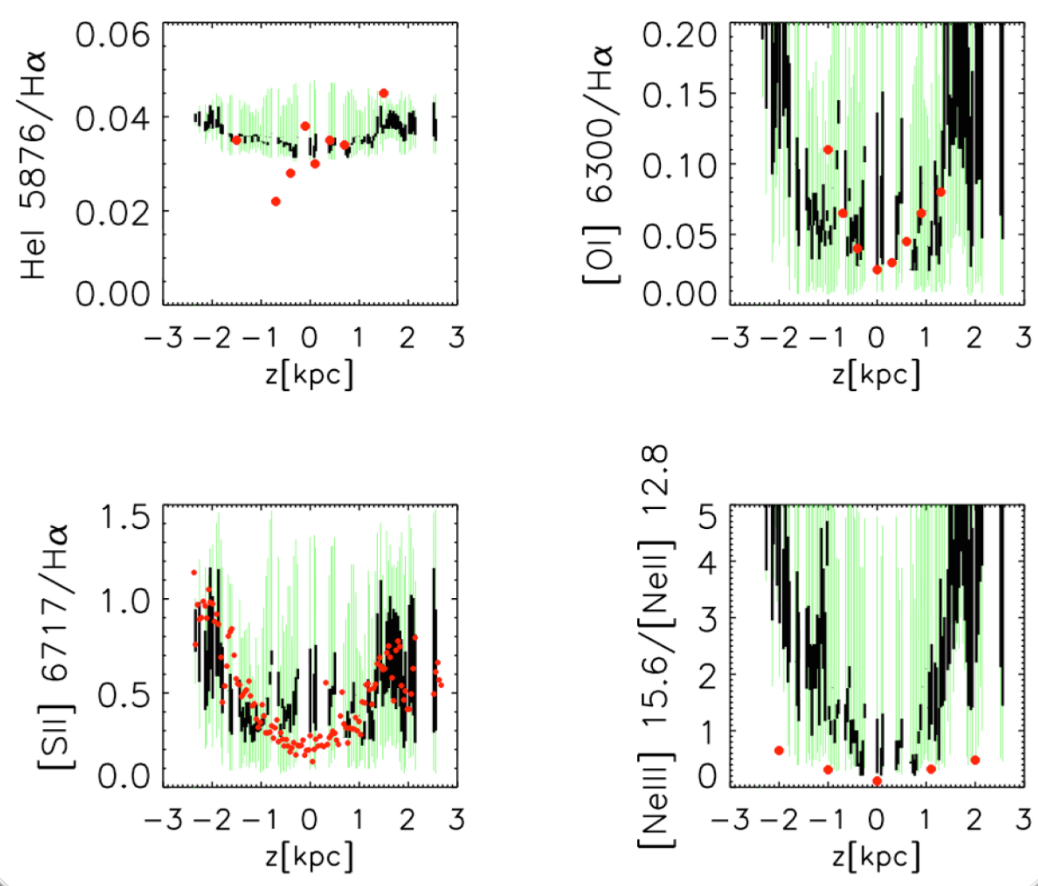


The electron temperature increases with the distance z to the galactic plane.

The main hypothesis is verified.

Green: free metallicity models. Black: solar metallicity solutions.

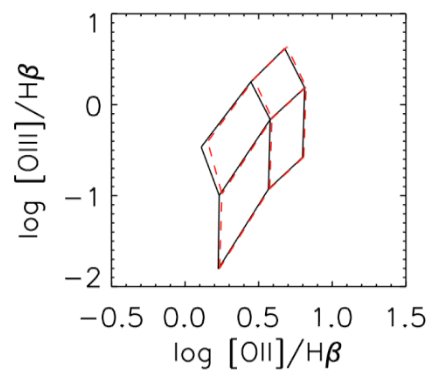
Results

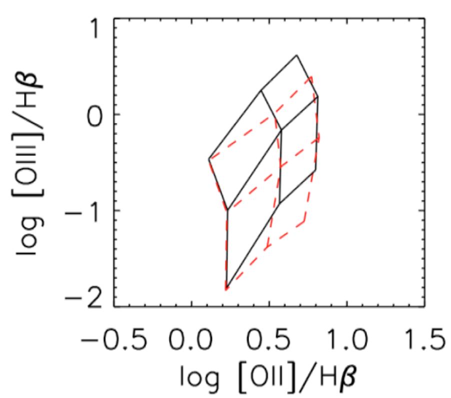


- The predictions of some lines (not used for the determination of the models) are satisfactory.
- [NeIII] strongly depends on the SED above 41eV, which may not be very accurate in the models used by PEGASE.

Green: free metallicity models. Black: solar metallicity solutions.

Some 2nd order effects





- Dust doesn't affect the line ratios.
- Geometry: We check that changing the morphology of the scenario is the same than changing the flux density, and that the same solutions (same U) can be found by only changing the gas density.

DIG in dwarf galaxies

The few observations of the DIG in dwarf galaxies place them on the extreme upper-left part of the BTP diagram.

Thus it seems that no HOLMES are needed in this part of the diagram.

This can be understood by the lack of these stars in such galaxies.

Stay tuned, work in progress…

Conclusions

- The DIG characteristics can be reproduced by pure photoionization models, without extra heating.
- The contribution of the HOLMES to the global SED is the dominant effect that leads to an increase of the temperature and of the line ratios at high $|z|$.
- The N/O ratio increases in the halo, where the nucleosynthesis is dominated by the low mass stars.