The Evolution of Star-Forming Galaxies Traced by their Nebular emission

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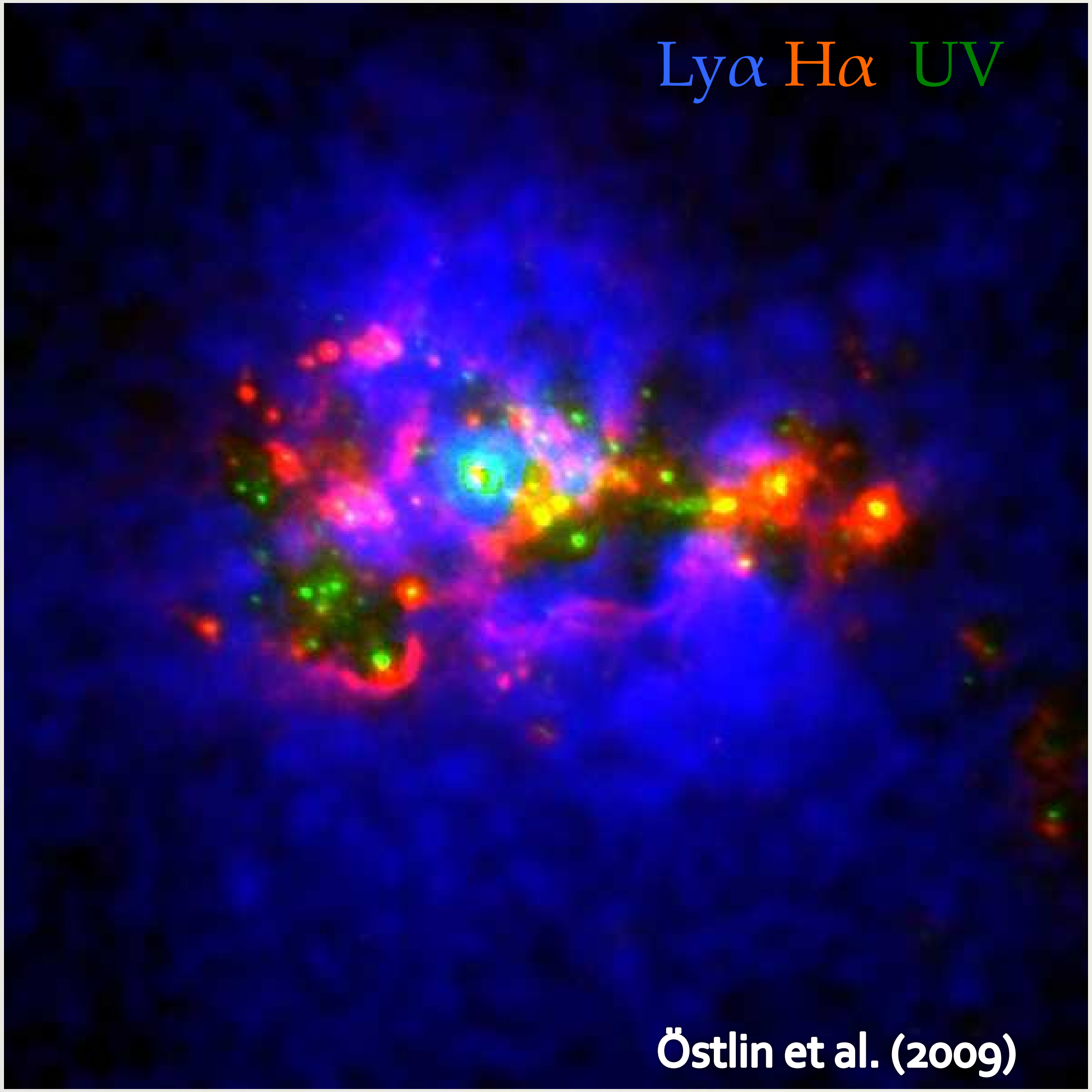
Multi-wavelength view of a local starburst

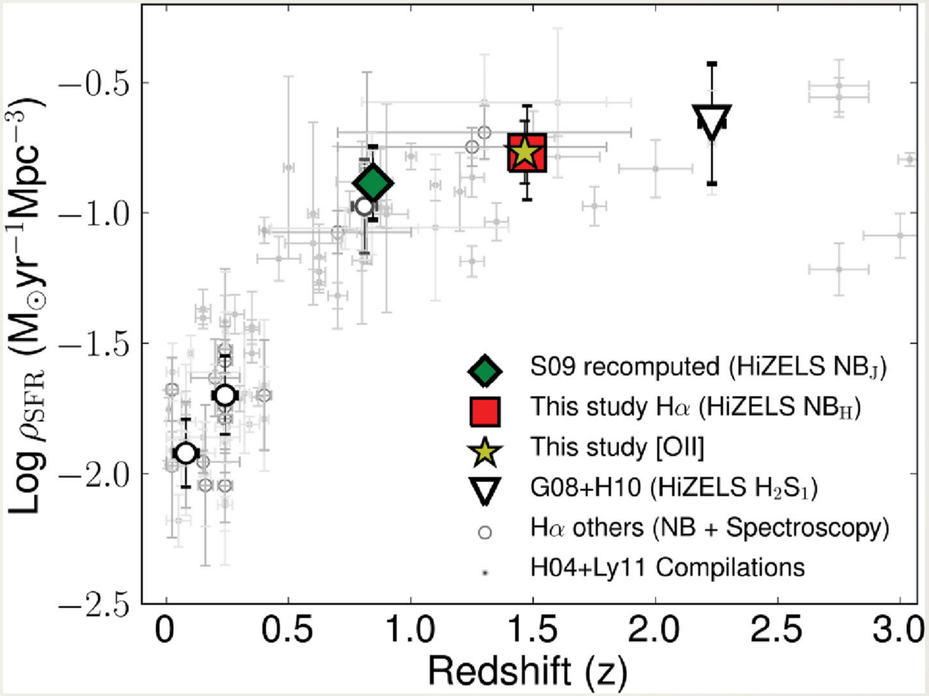


- ESO 338-IG04
- Hα traces instantaneous star formation (~10 Myrs.)
  - ∝ Number rate of ionizing photons
- UV luminosity has a longer timescale (~100 Myrs.)
- Lyα is produced like Hα, but is observed in a diffuse, extended component
  - Outflows
  - Resonant scattering

Nebular emission lines as astrophysical tools

Tipically,

- Star-formation rate indicators (mostly Hα)
- Metallicity Diagnostic (R_{23}, O3N2,...)
- Discriminate between star-forming galaxies and AGNs (BPT diagram)
- Very high redshift galaxies (LAEs)



Sobral et al. (2012)

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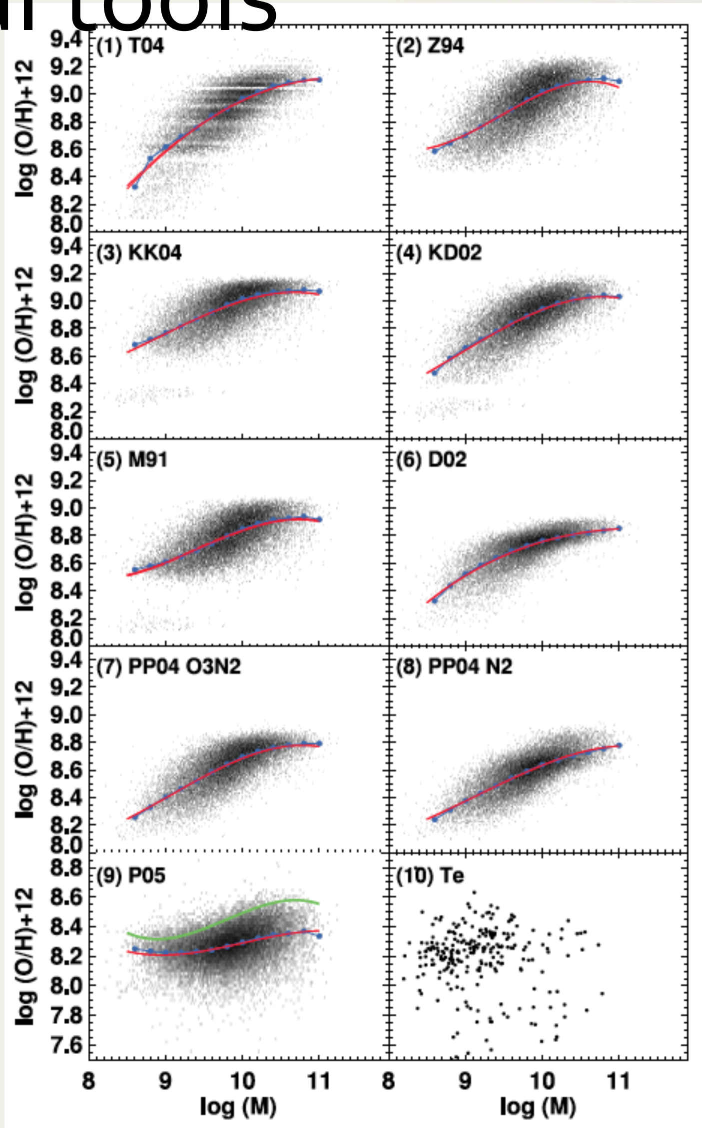

Kewley &Ellison (2008)

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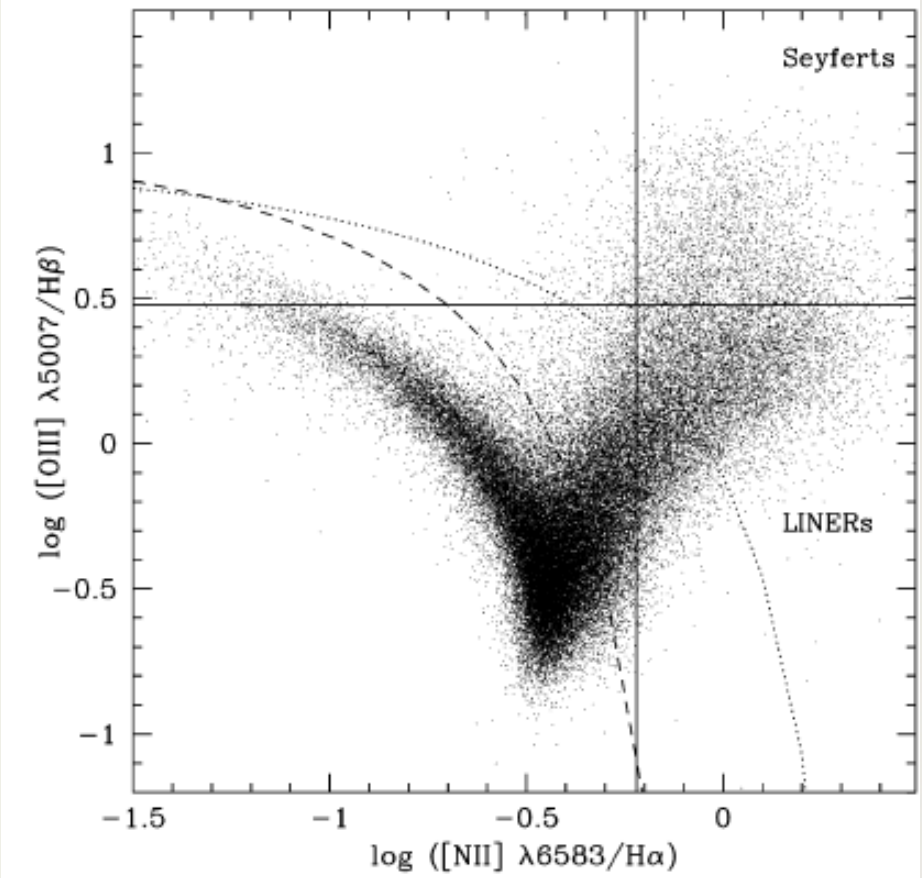

Kauffmann et al. (2003)

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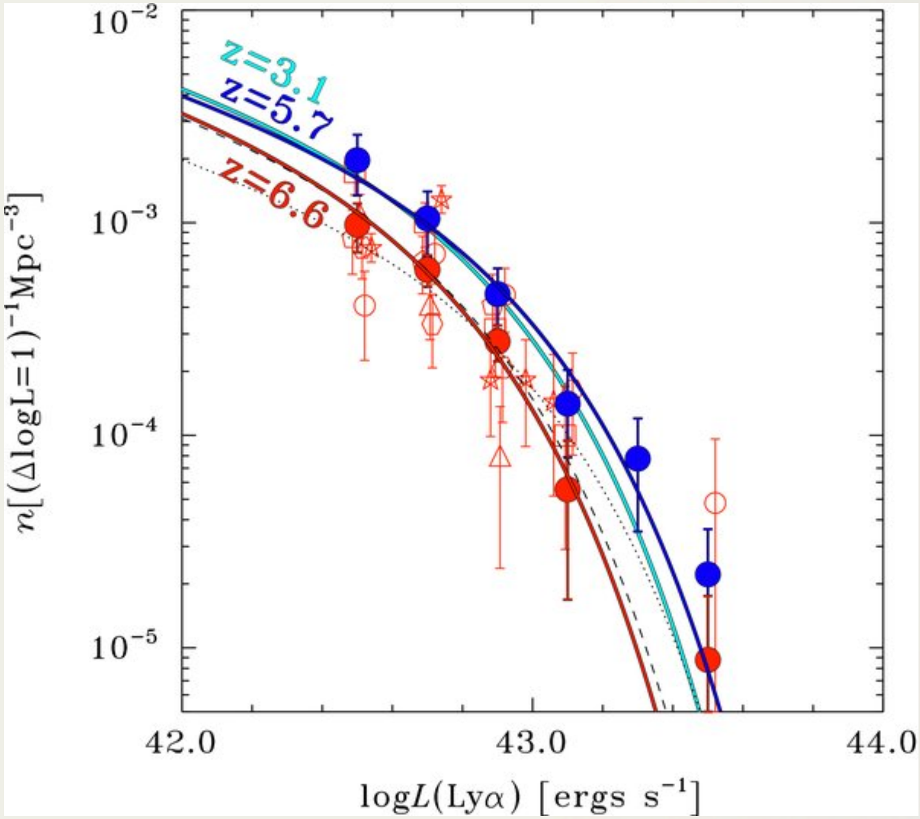

Ouchi et al. (2010)

Nebular lines define a galaxy population

Tipically,

- Star-formation rate indicators (mostly Hα)
- Metallicity Diagnostics

  (R_{23}, O3N2,...)
- Discriminate between star-forming galaxies and AGNs (BPT diagram)
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Other properties

- Alternative SFR indicators?
  - [O II] λ 3727
  - [O III] λ5007
  - [C II] λ 158 μm
  - [N II] λ 205 μm
- Typical stellar masses, ages, halo masses?
- Tracers of massive structures?
- Large scale structure?
- Lyα line profile properties?

Emission line production in galaxies

- Hot, massive stars ionize their environment

$$Q(H^0) = \int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} \mathrm{d}\nu$$

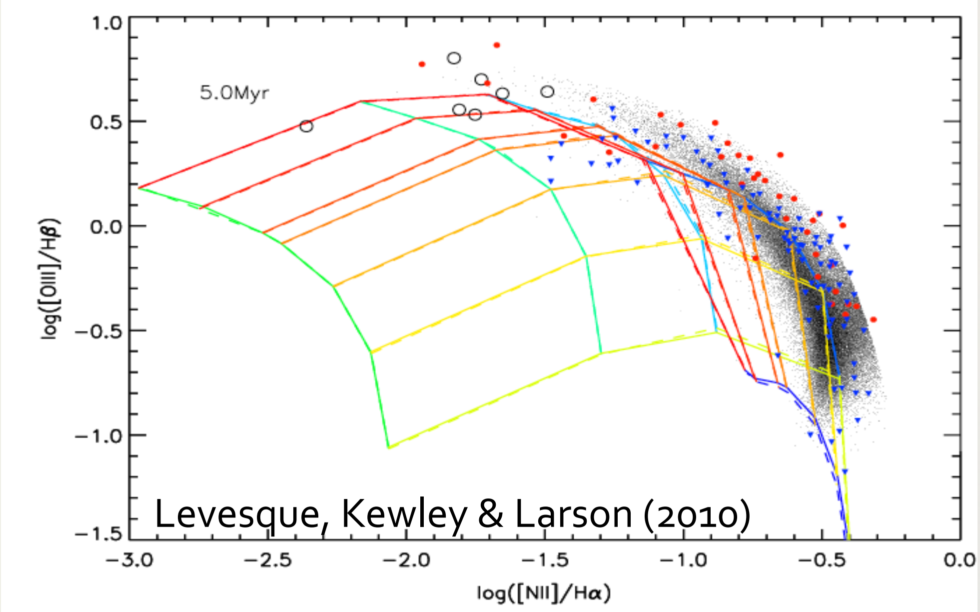
- Recombination and collisional excitation radiation triggered by photoionization

- Hydrogen recombination lines directly related to $Q(H^0)$:

$$L(H\alpha) = \frac{\alpha_{H\alpha}^{\mathrm{eff}}}{\alpha_B} h\nu_{H\alpha} Q(H^0)$$

- MAPPINGS-III code computes photoionization that leads to the production of emission lines

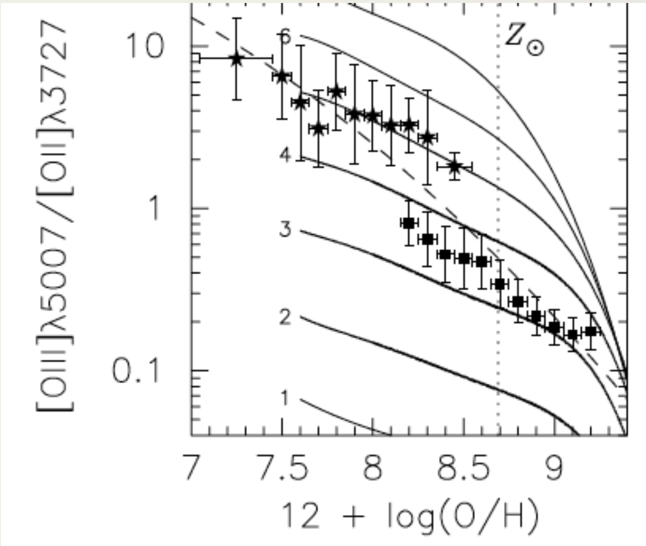
- Emission line properties are characterized by 2 parameters:
  - Ionization parameter $q = \frac{S_{H0}}{n}$ $[\mathrm{s}^{-1}\ \mathrm{cm}]$
  - Metallicity Z



Levesque, Kewley & Larson (2010)

The ionization parameter

Nagao, Maiolino & Marconi (2006)



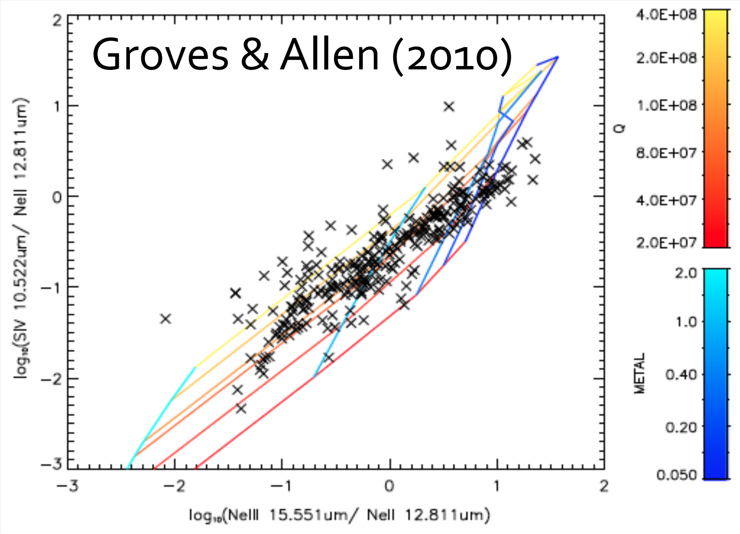
- There is evidence that a constant q cannot reproduce the relation found between line ratios and metallicity)

- Stellar winds and atmospheres are more opaque to ionizing photons when metal abundances high (Dopita et al., 2006)

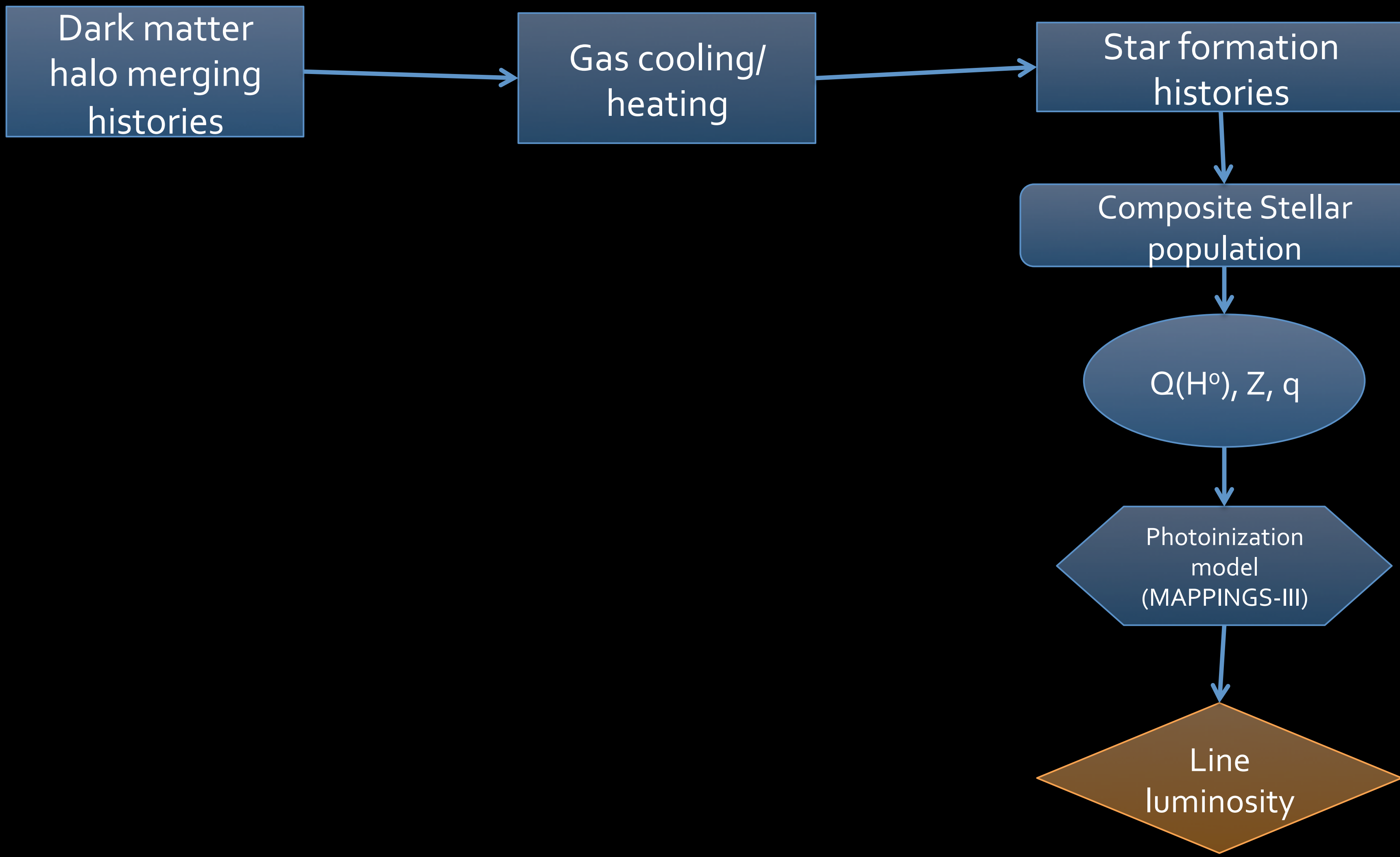
- Nagao et al. (2006):
- Ionization parameter increases as metallicity decreases by 0.7 dex

- We choose to relate both quantities by making

$$q(Z) = K\left(\frac{Z_{\rm cold}}{Z^*}\right)^{\gamma}$$



Semi-analytical models of Galaxy formation



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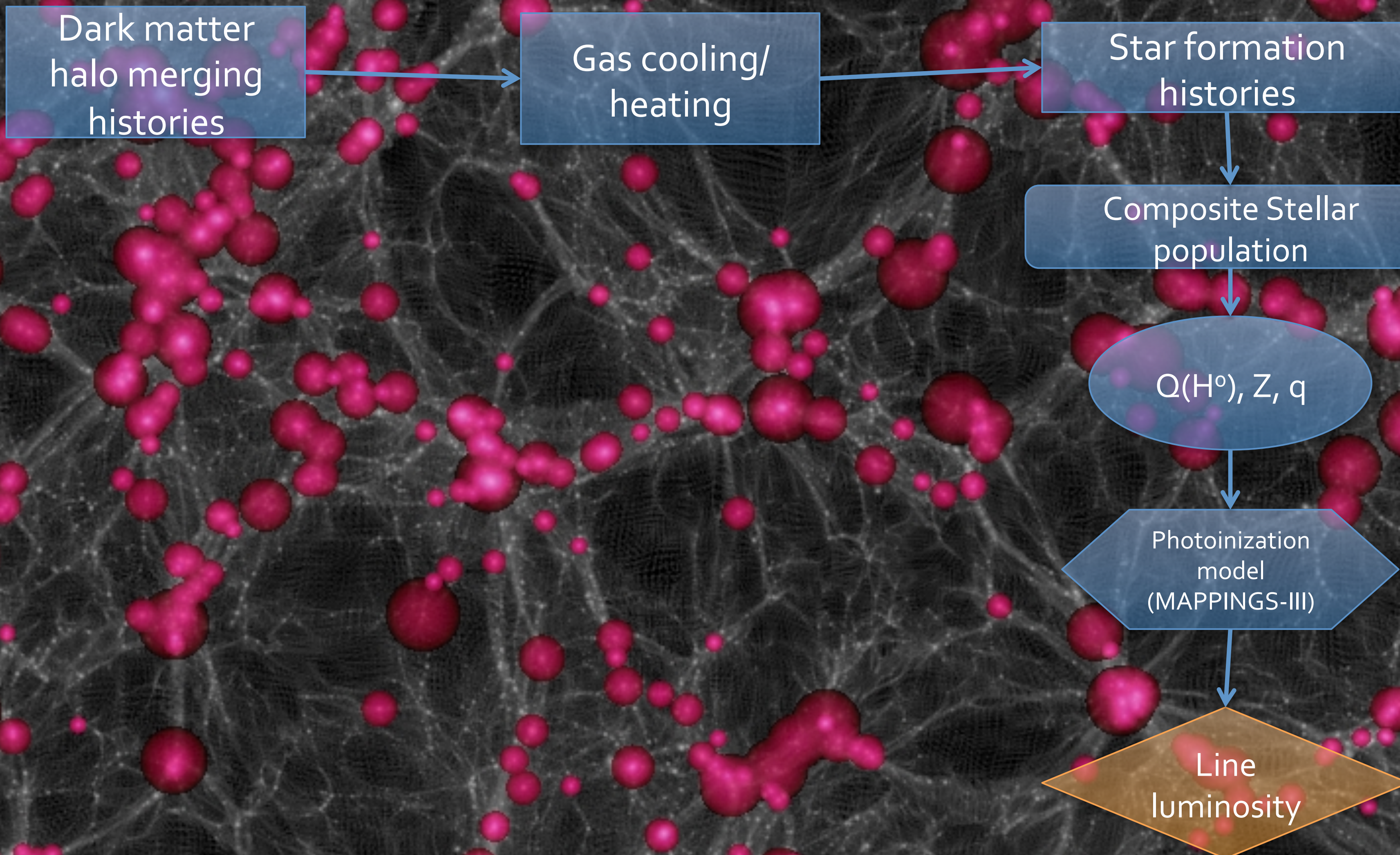
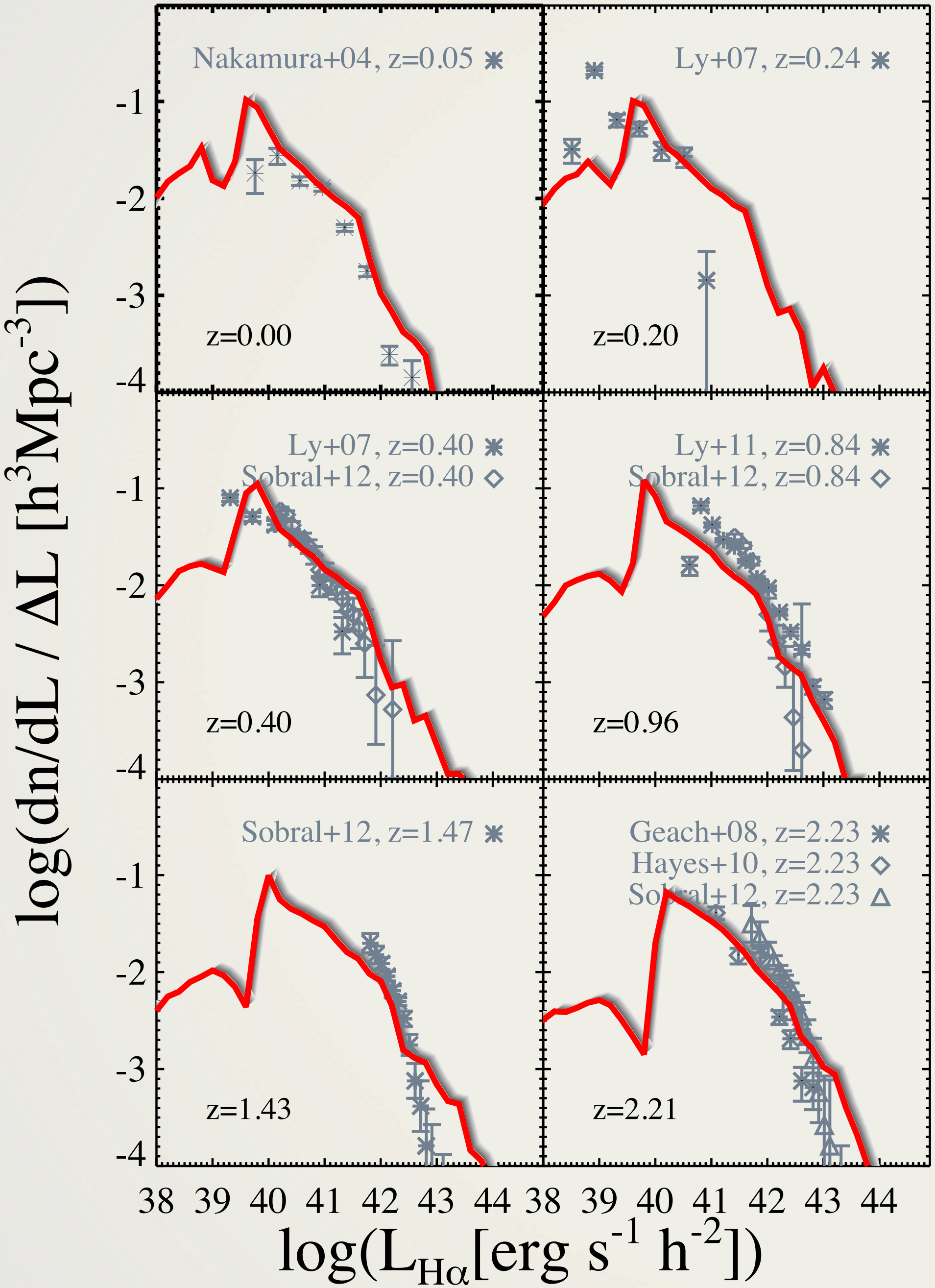
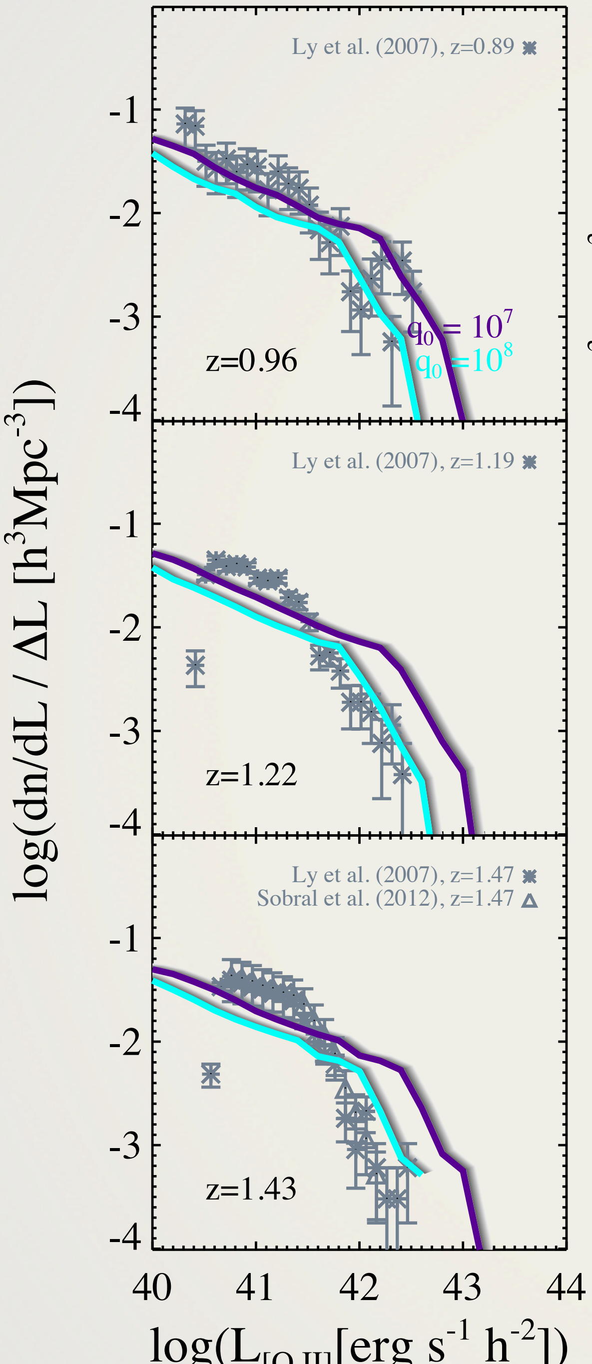


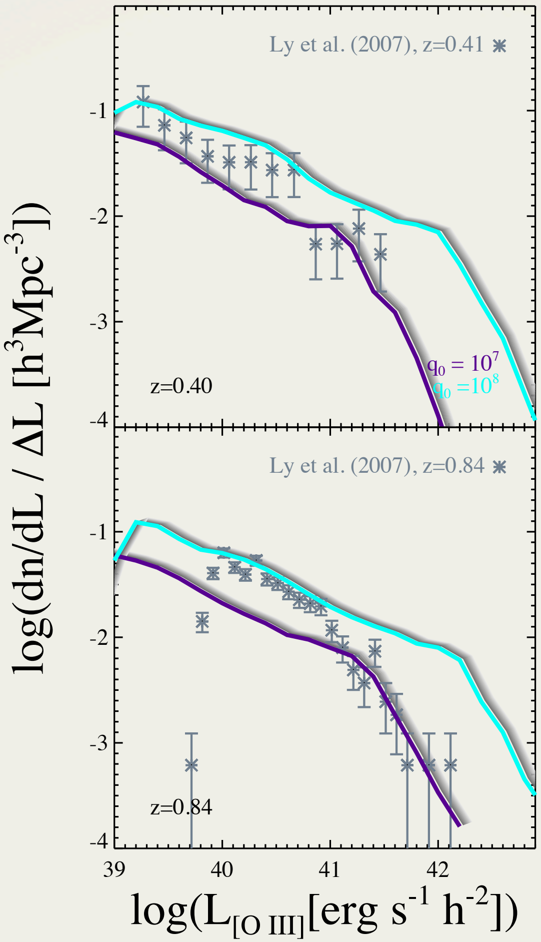
[O II] λ 3727 line luminosity in SAG galaxies

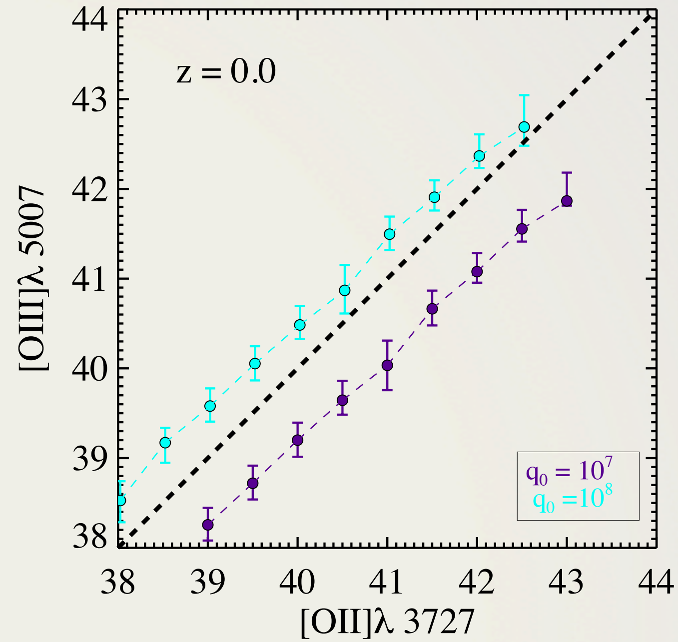


The Hα luminosity function at 0<z<2.2

- All different model variants predict the same Hα luminosity
- Model consistent with obs.
- Hα clean tracer of SFR
  - Model predicts correct star formation histories

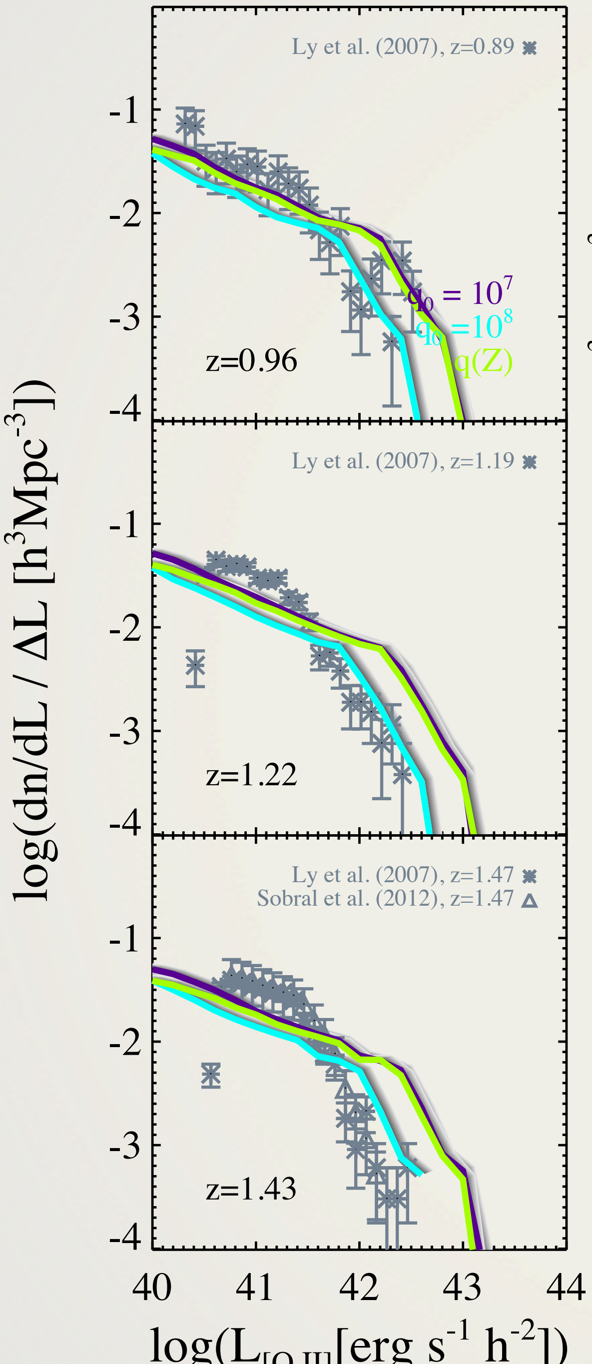


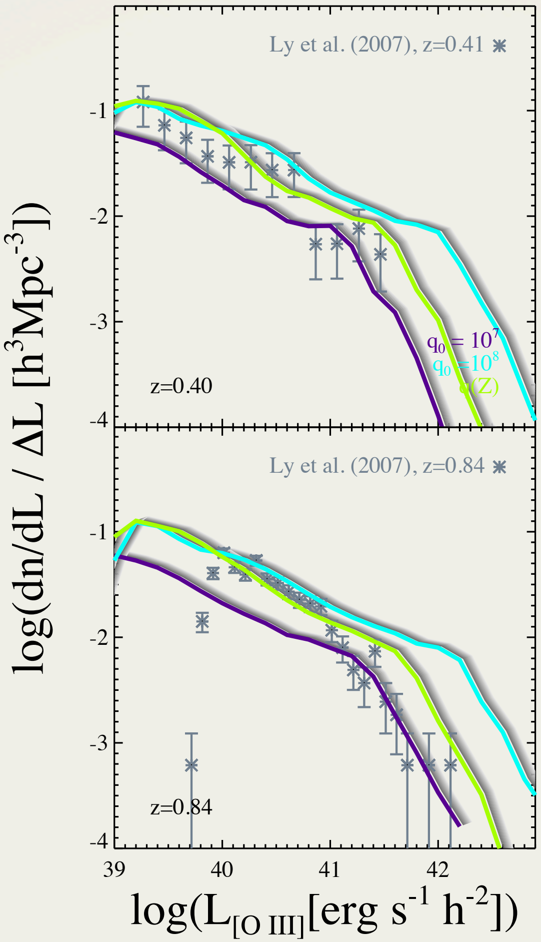


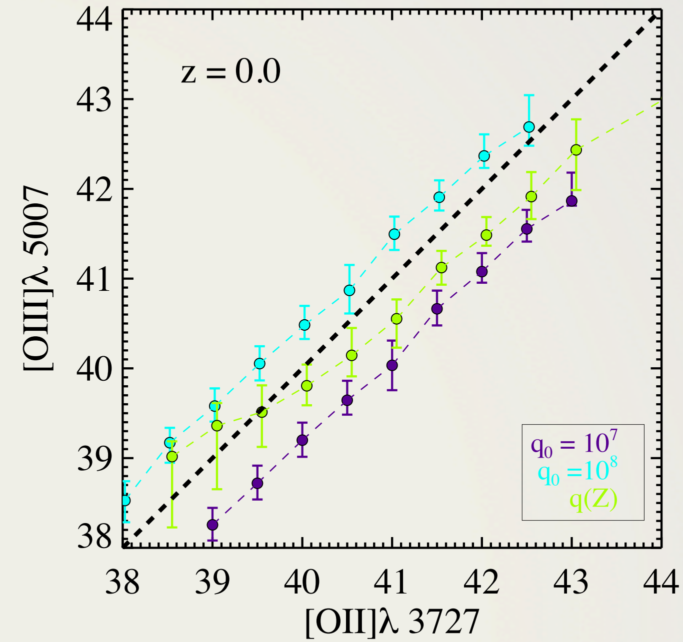


Constant ionization parameter fails to reproduce the [O II] and [O III] Luminosity functions

High and low ionization parameter
result in opposite trends.







Constant ionization parameter fails to reproduce the [O II] and [O III] Luminosity functions

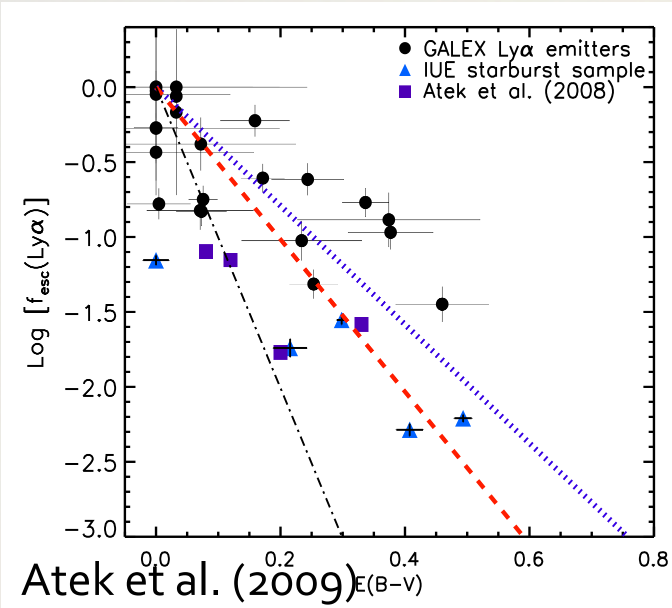
High and low ionization parameter result in opposite trends.

Variable ionization parameter interpolates between both values

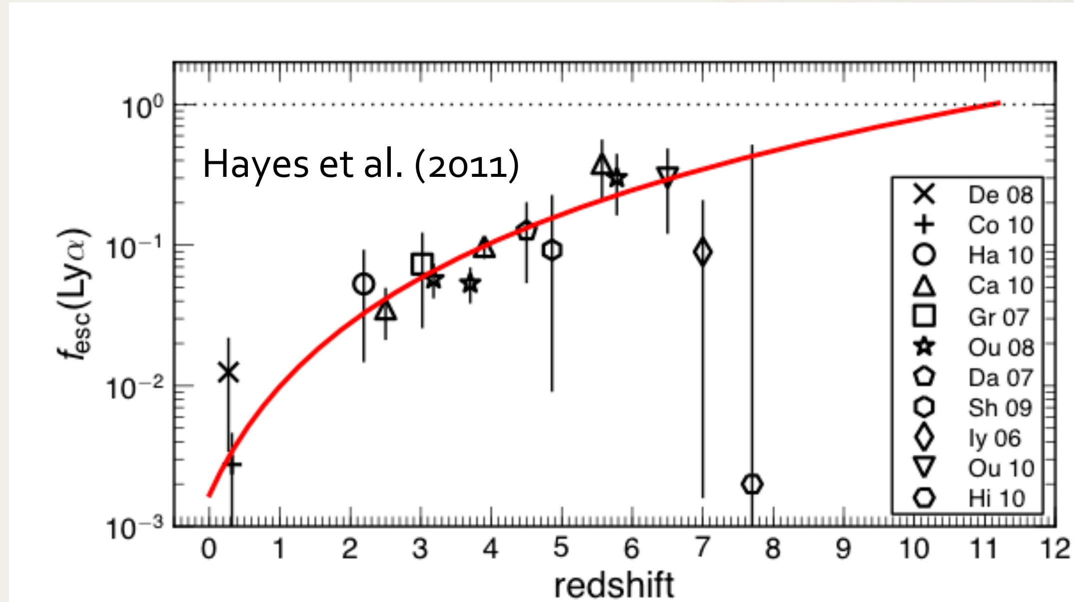
Better agreement with obs. [OIII] LF

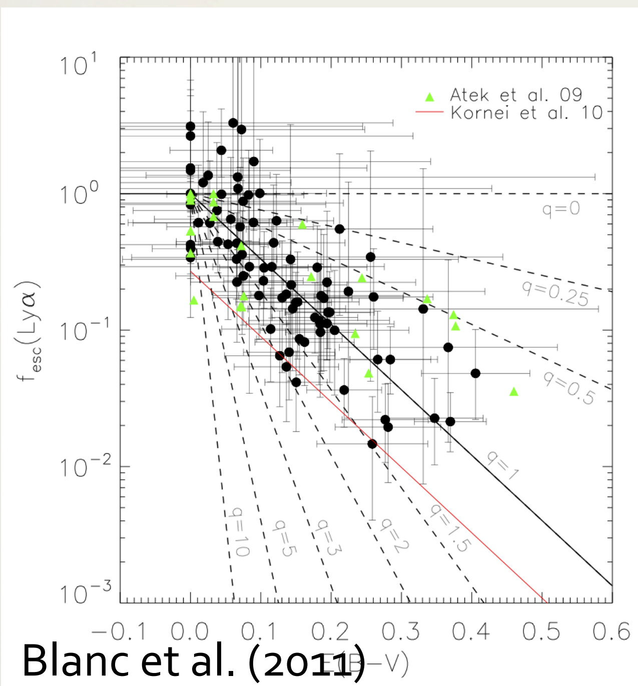
Fails with obs. [OII] LF.

The problem with LAEs: f_{esc}



Atek et al. (2009)





Blanc et al. (2011)

f_{esc}(Lyα) decreases with higher dust content?

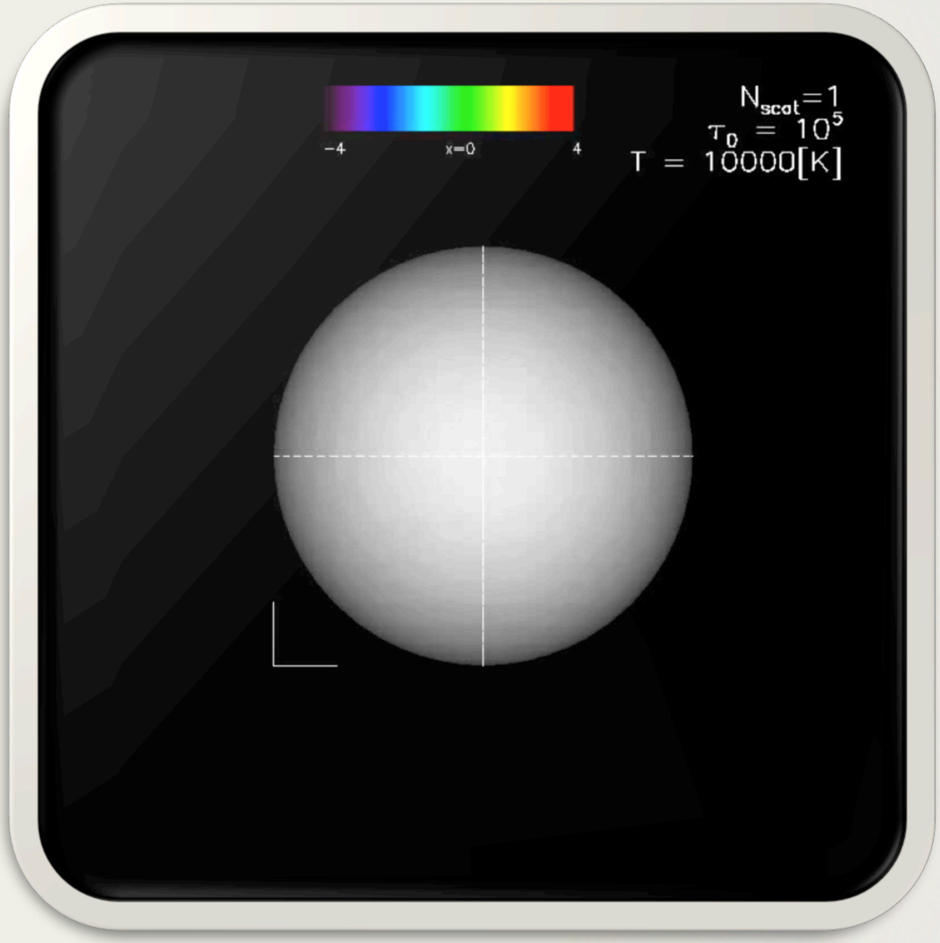
f_{esc}(Lyα) increases with redshift?

The Lyα escape fraction can vary significantly!

Monte Carlo Lyα radiative transfer

Problem

- Resonant scattering makes escape fraction of Lyα photons difficult to predict



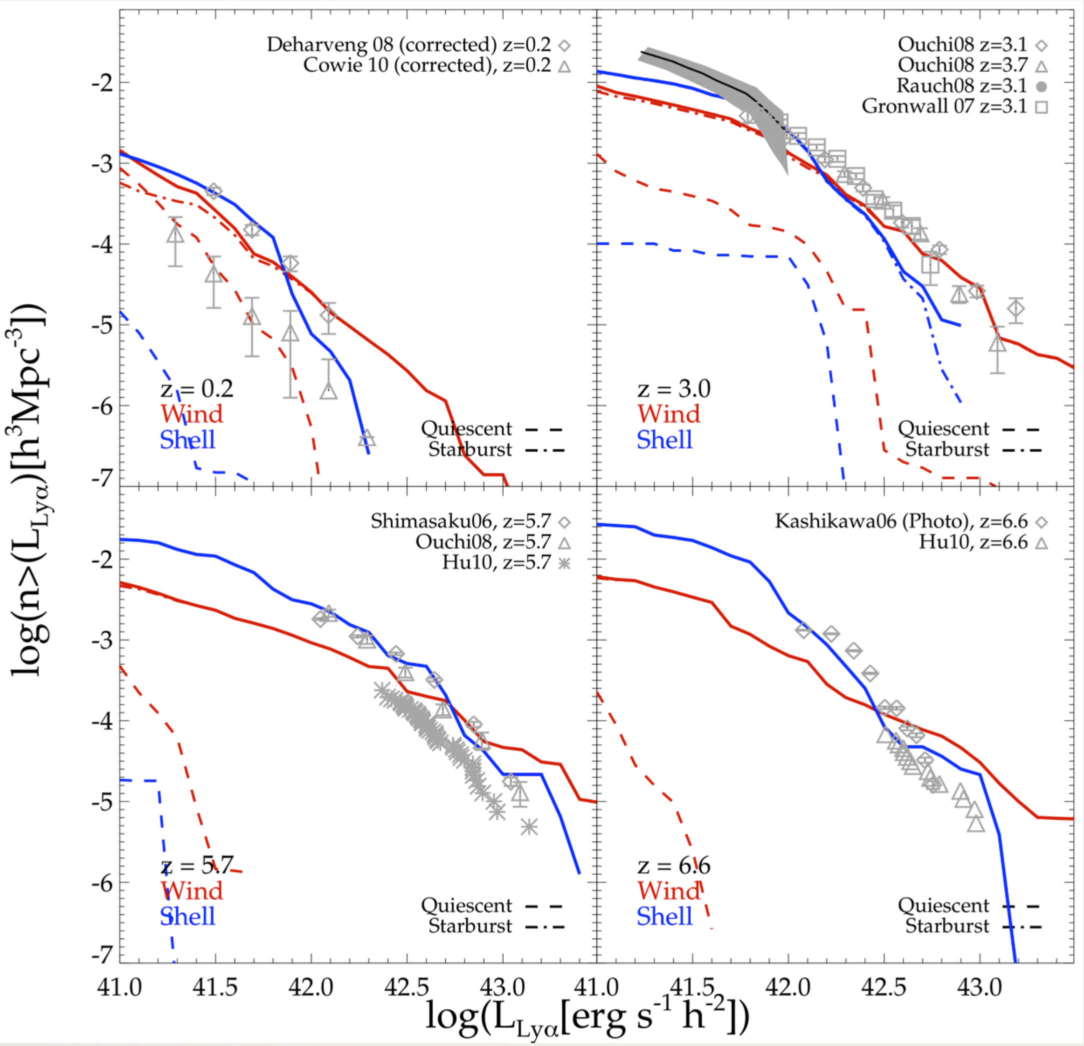
MC Lyα RT

- Follows the path of single photons as they scatter through an HI cloud
  - Count how many photons escape
  - Obtain frequency distribution
  - Get f_{esc}

Semianalytical model + Lyα RT

➔ f_{esc}(SFR, M_{gas}, R_{disk}, V_{circ}, Z_{cold}, etc...)

The Lyα Cumulative Luminosity Function

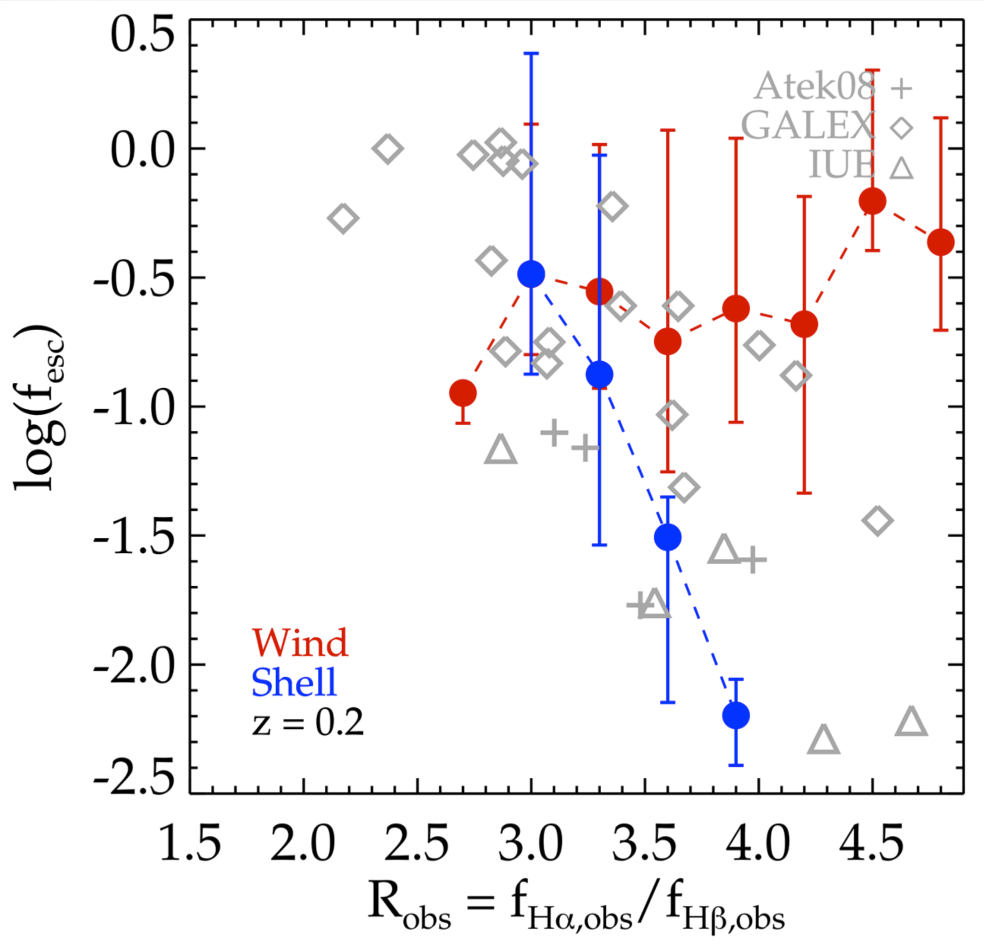


We try two outflow geometries: a Thin shell, and a Galactic wind. Both can reproduce the Lyα luminosity functions.

As a consequence, starbursts dominate the abundance of Lyα emitters at high redshifts

Orsi et al (2012)

Lya escape fractions

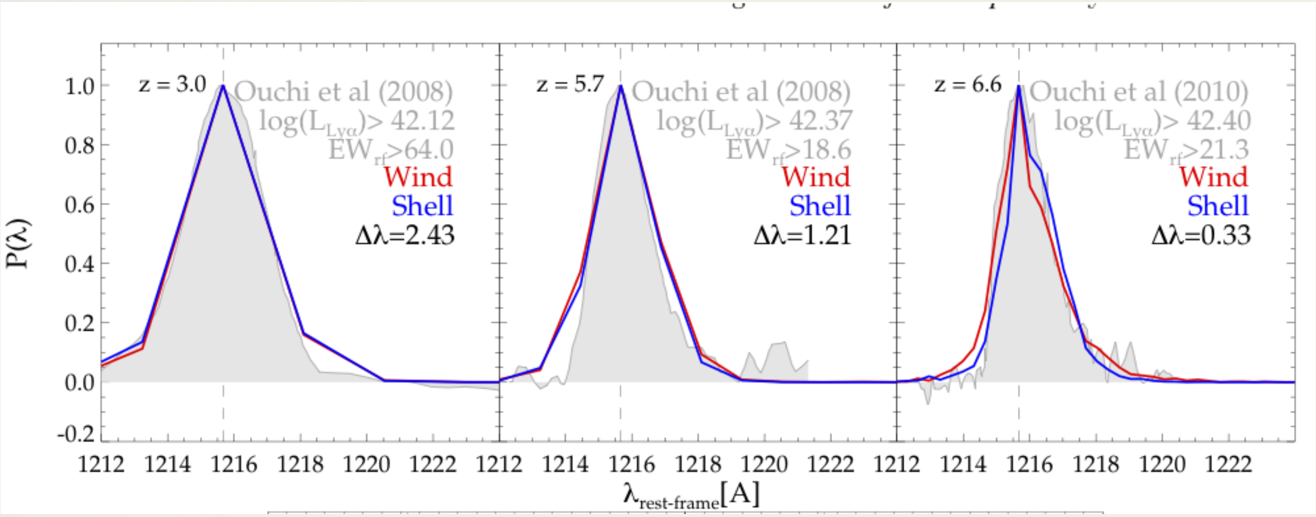


Outflow geometries are consistent with observed f_{esc}

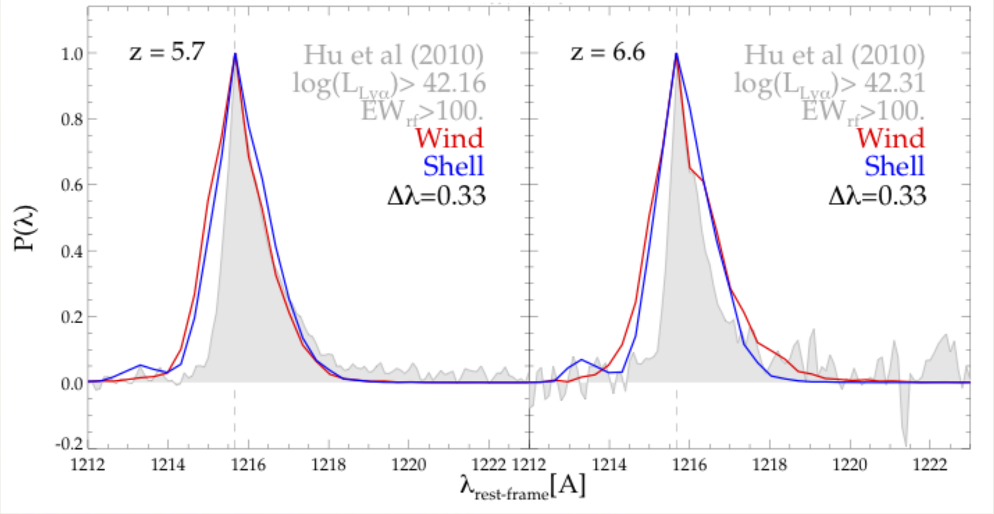
Thin shell geometry reproduces the observed steep decline of f_{esc}

Orsi et al (2012)

Composite Lyα line profiles



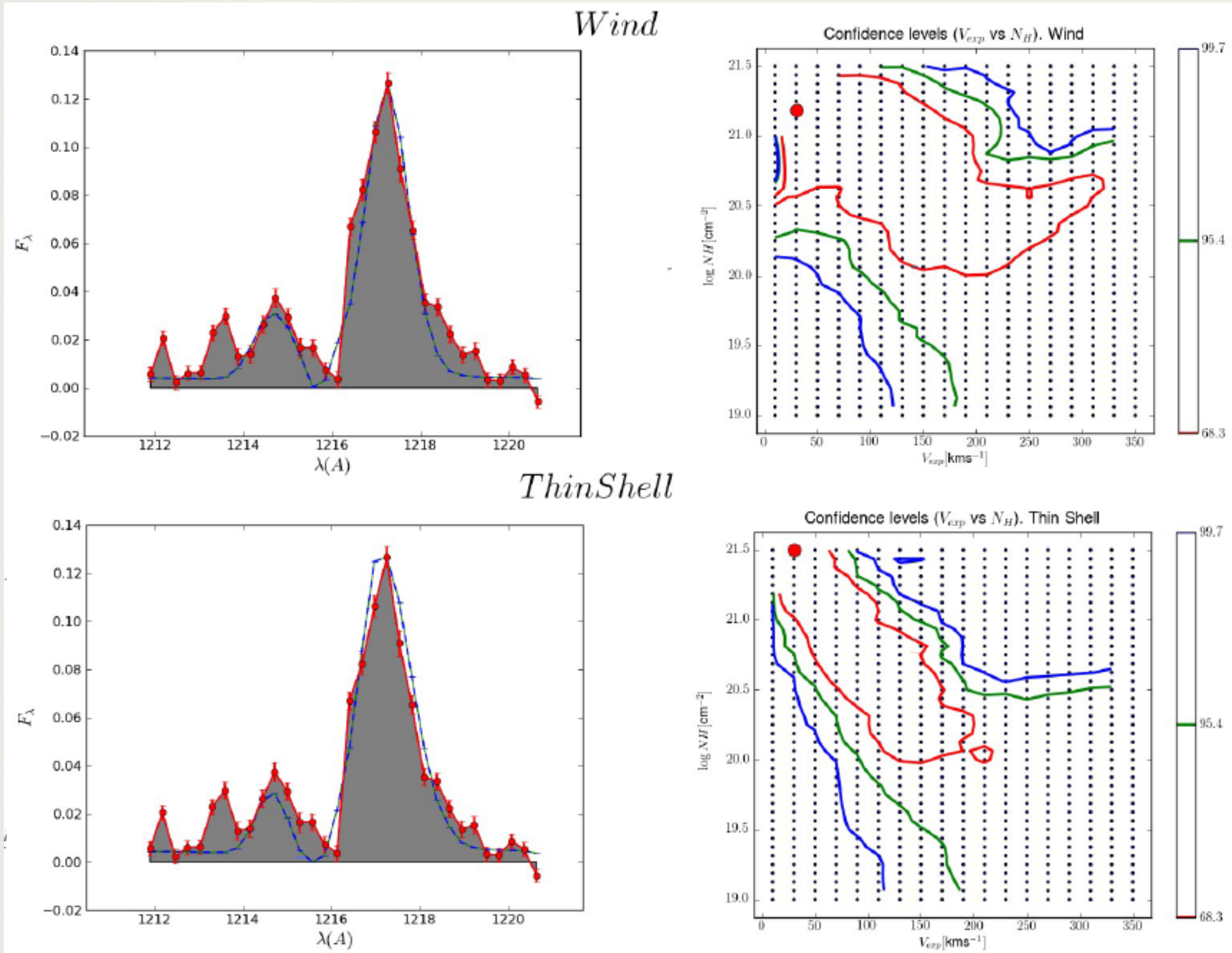
Our model can reproduce the observed composite spectra of Ouchi et al. (2008,2010)



Excess of blue photons when reproducing Hu et al. (2010) composite spectra

Orsi et al (2012)

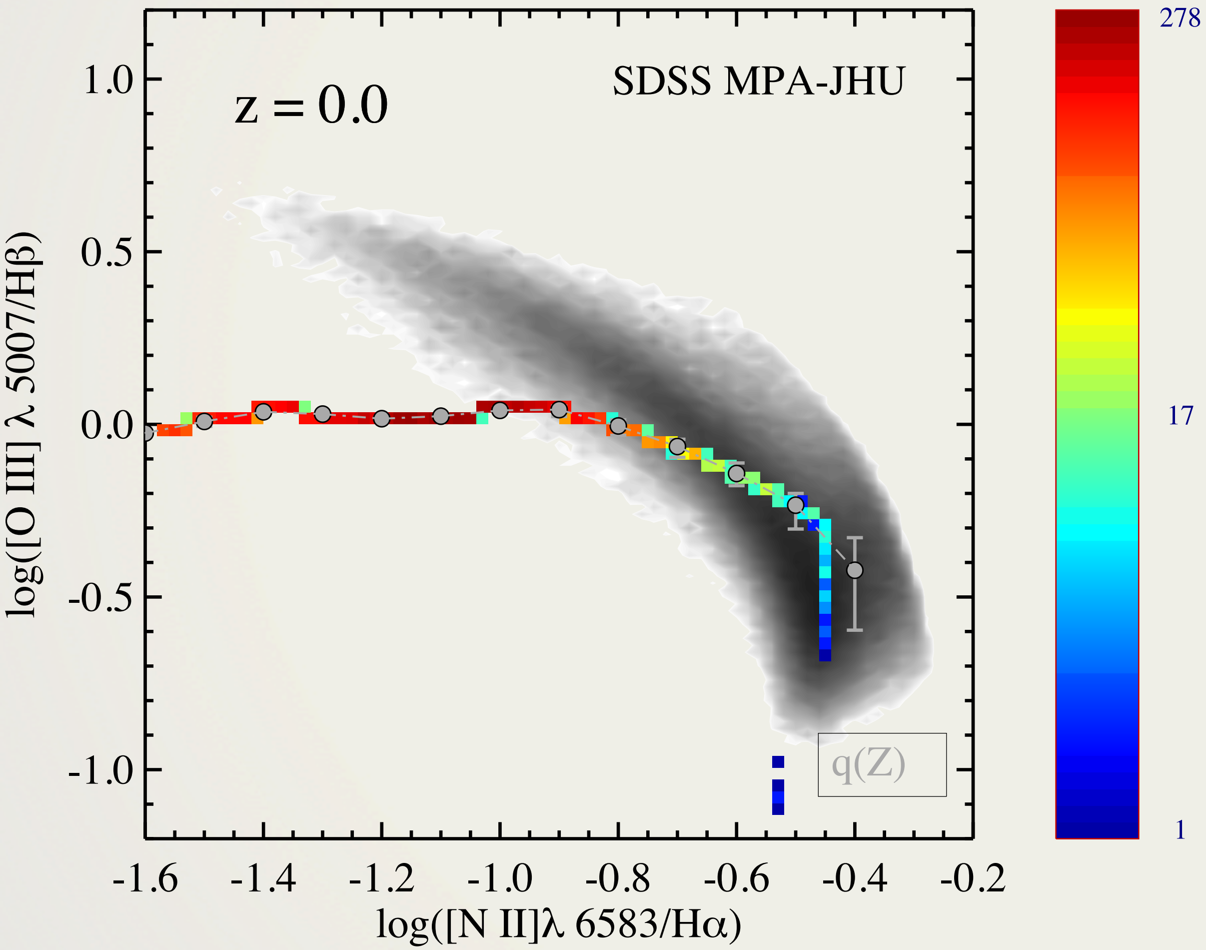
Lyα line profile fitting



- Line profiles have the potential to constrain physical parameters of the ISM of LAEs:
  - Kinematics
  - Gas column densities
  - Outflow propreties
- Combination with extended Lyα surface brightness profiles

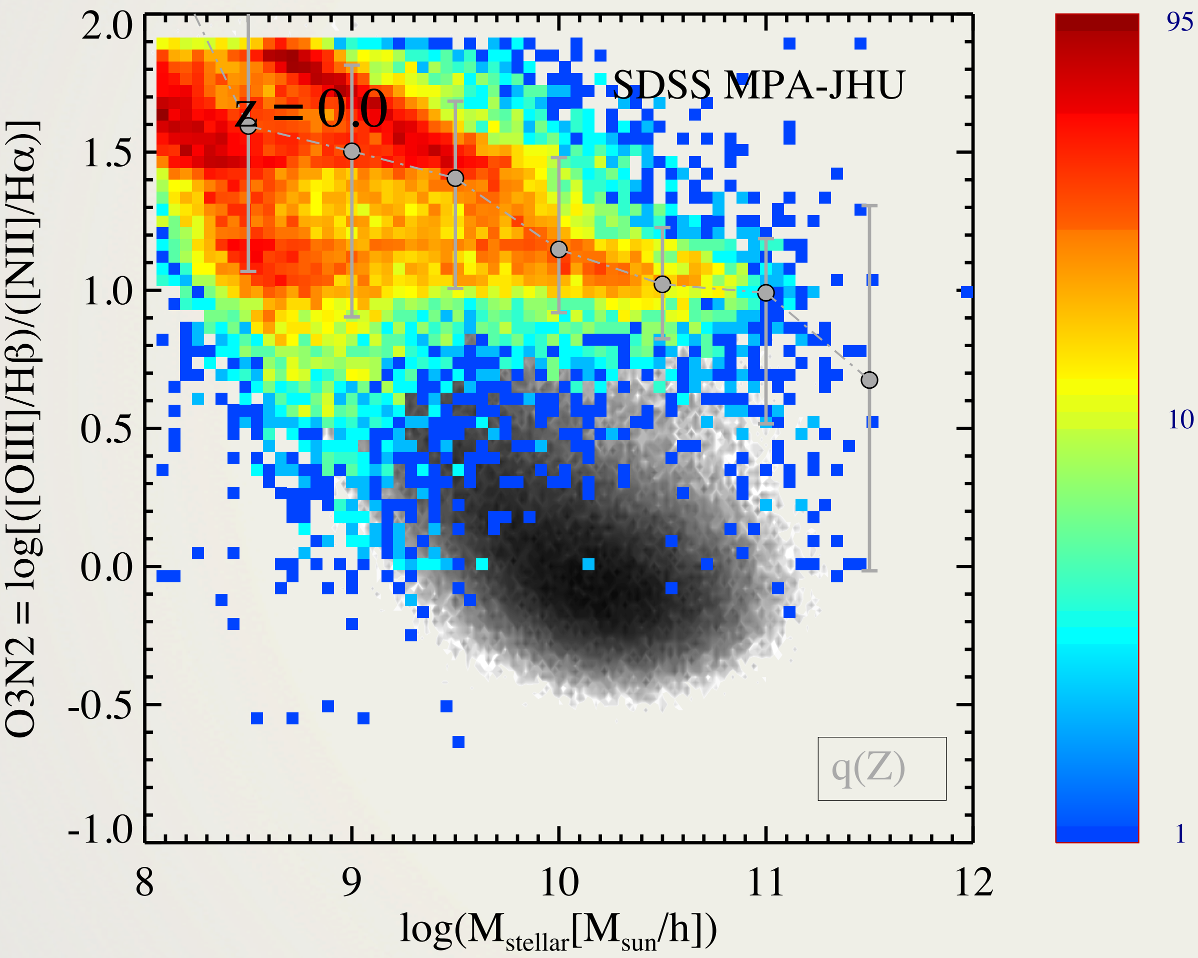
Mejía et al. (2013), in prep.

Emission Line ratios



Predicted line ratios are consistent with
the star-forming sequence shown obs.
in the BPT diagram

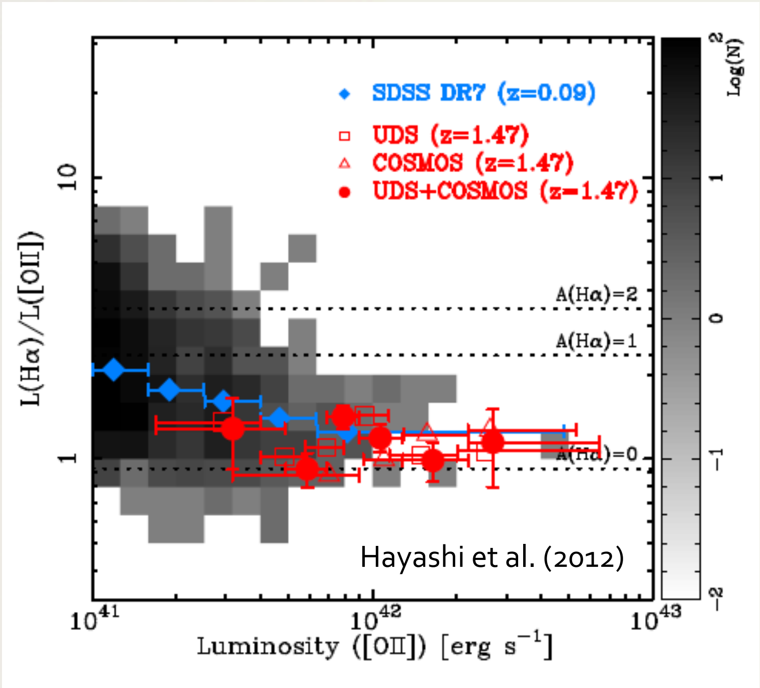
Emission Line ratios

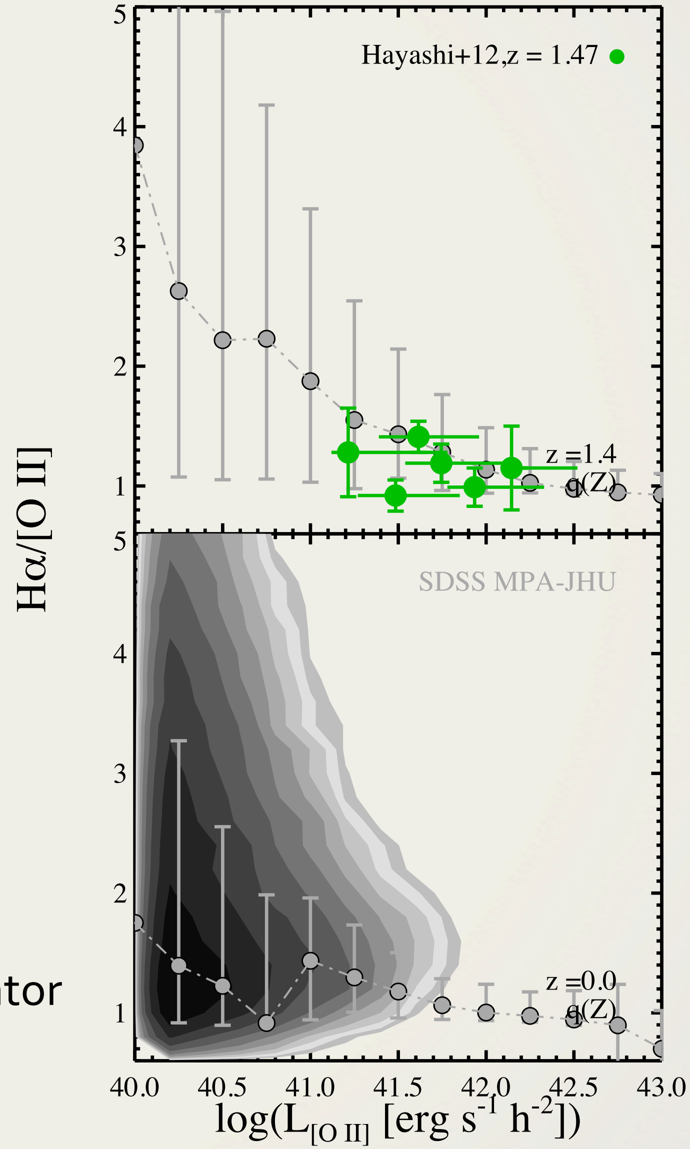


O3N2 values are higher than those measured from SDSS MPA-JHU.

[NII]/Hα smaller than observed in local sample

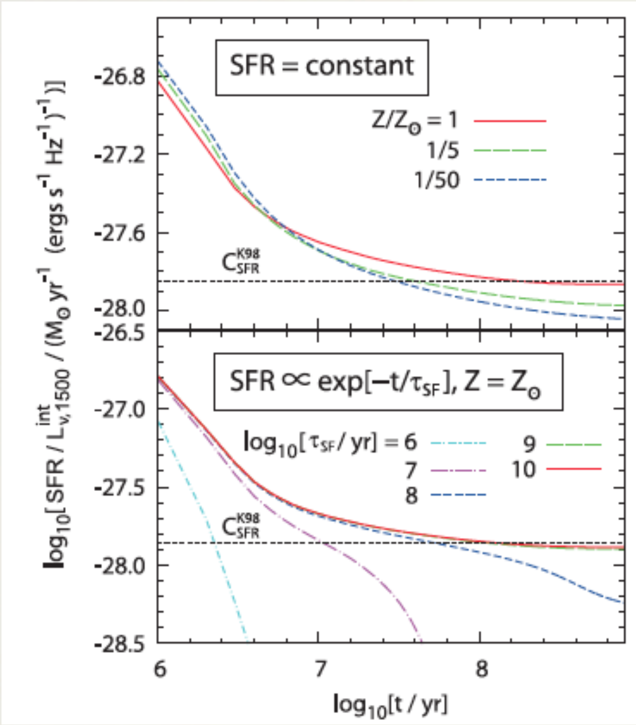
Emission Line ratios



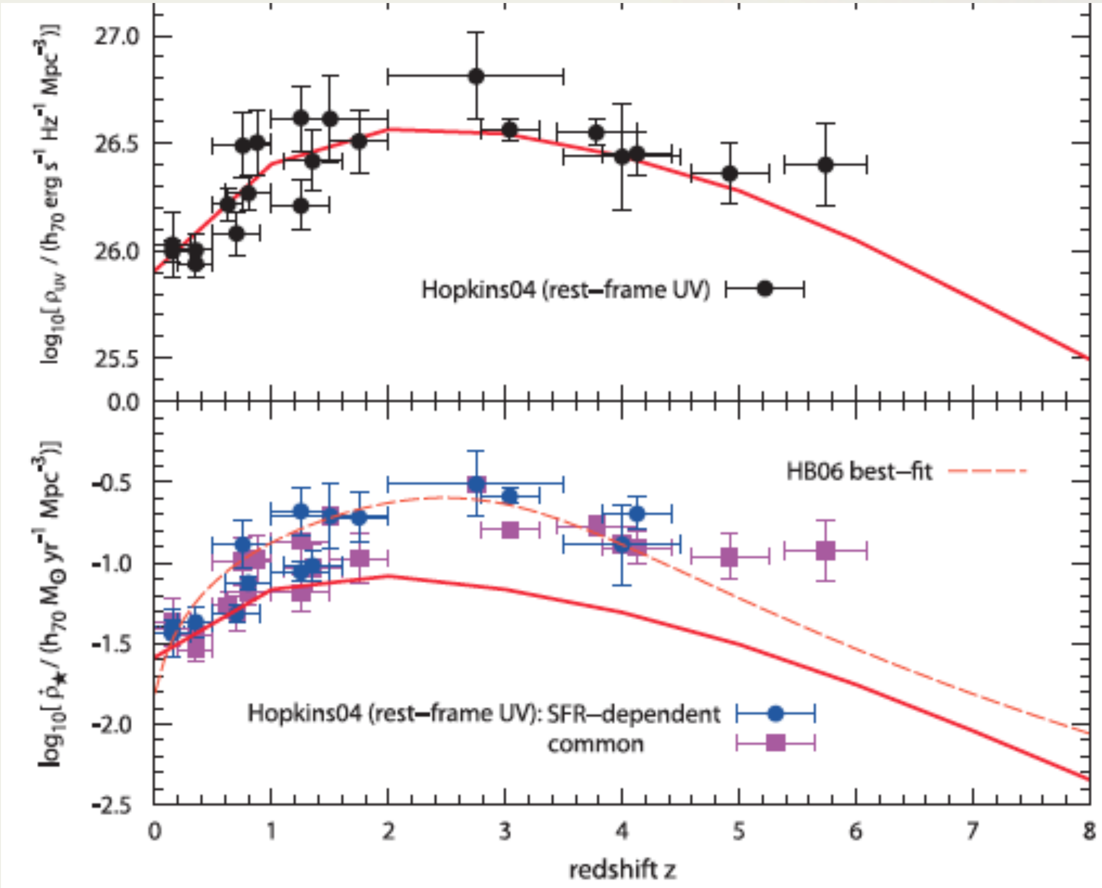


- Hα/[OII] ratio predicted agrees very well with observed values at 0<z<1.5
- Calibration of [OII] to be used as SFR indicator

Emission lines as star formation rate indicators

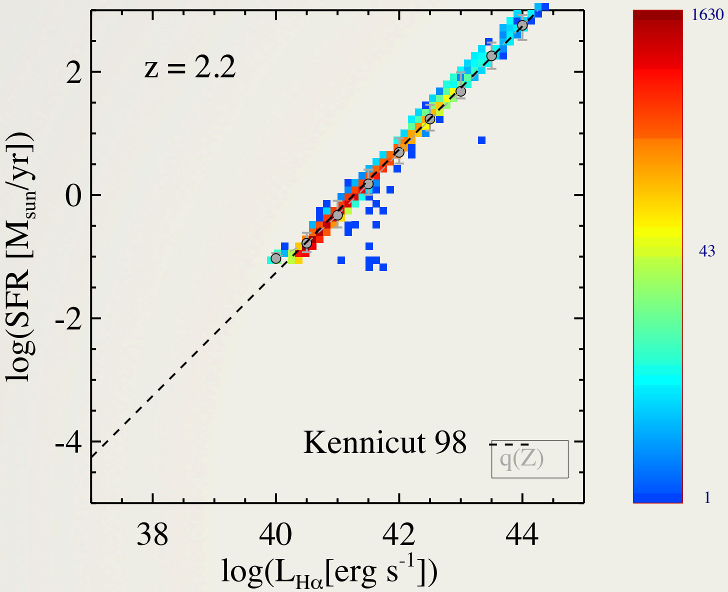


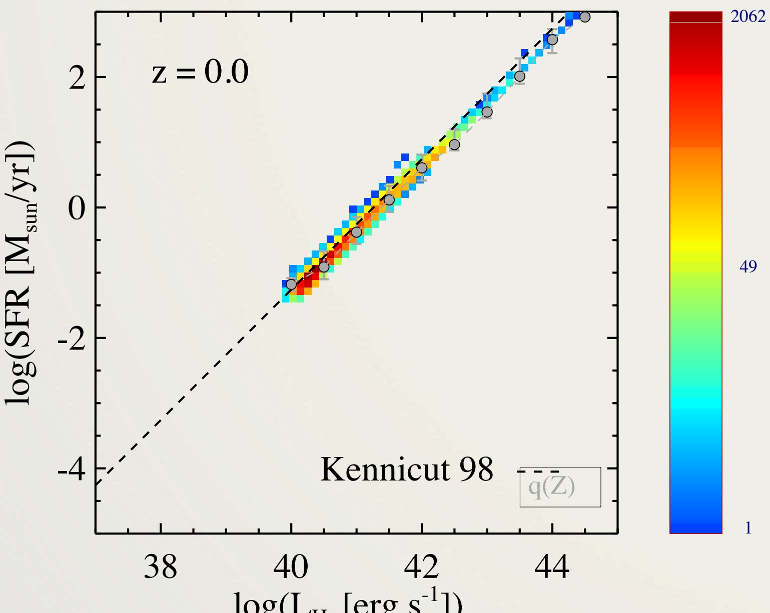
Kobayashi et al. (2013)



- The conversion between continuum UV luminosity and SFR is complicated and can lead to an overestimation of the true ρ_{SFR}
  - Dust obscuration
  - SFR conversion

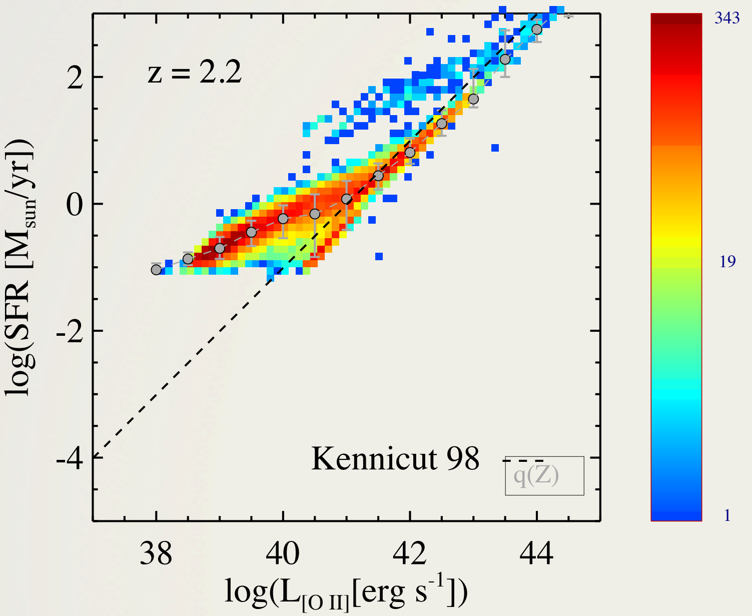
Emission lines as star formation rate indicators

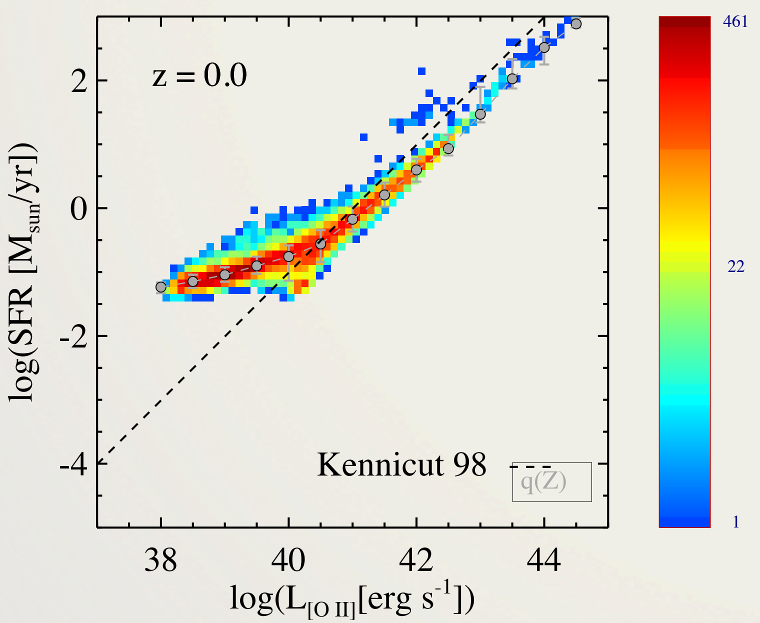




- H-alpha

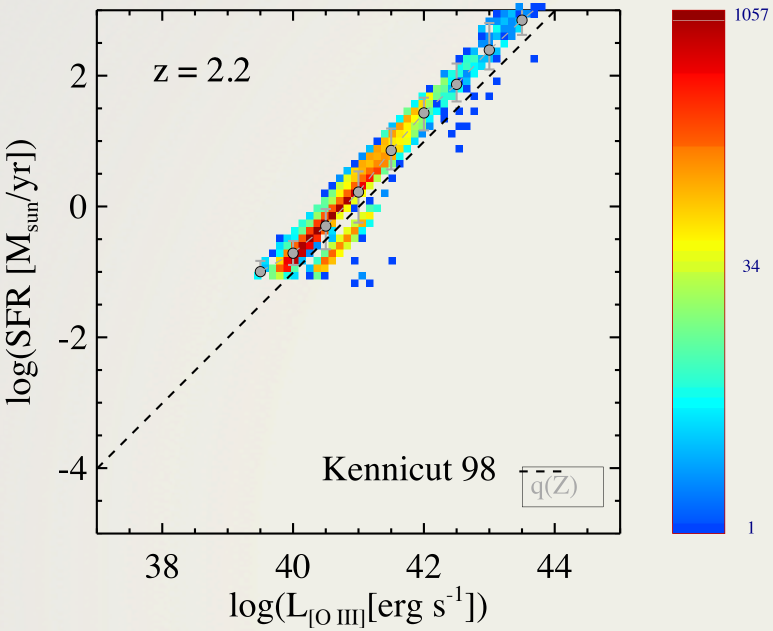
Emission lines as star formation rate indicators

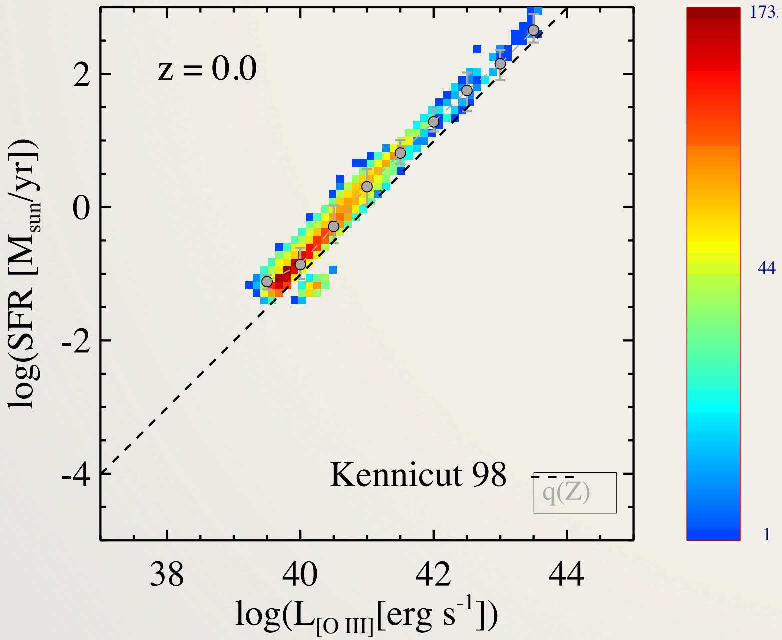




- Model shows that simple scaling does not take into account large scattering of the [OII]-SFR relation

Emission lines as star formation rate indicators





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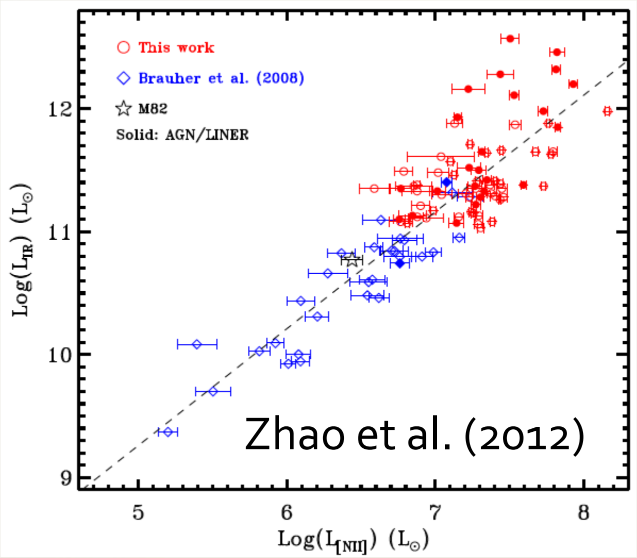
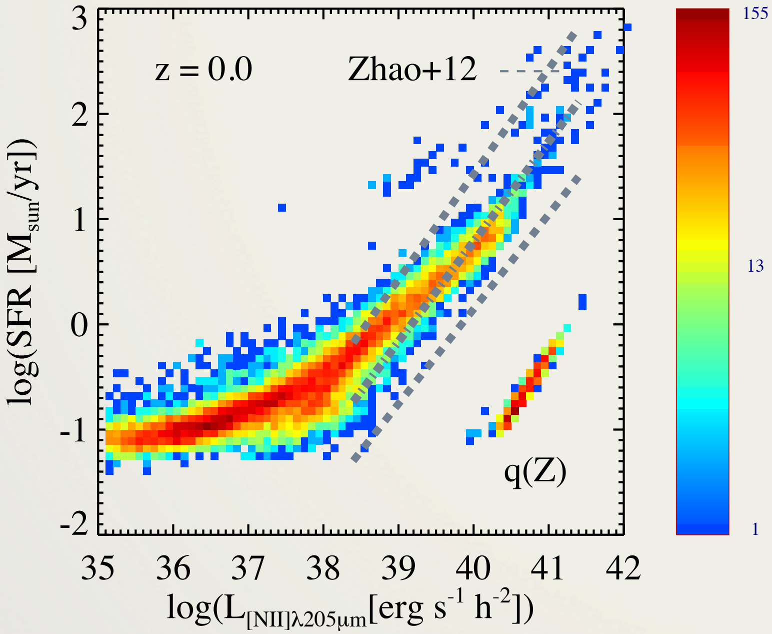
- The [OIII]-SFR relation is predicted to be linear, although with a large scattering

Emission lines as star formation rate indicators





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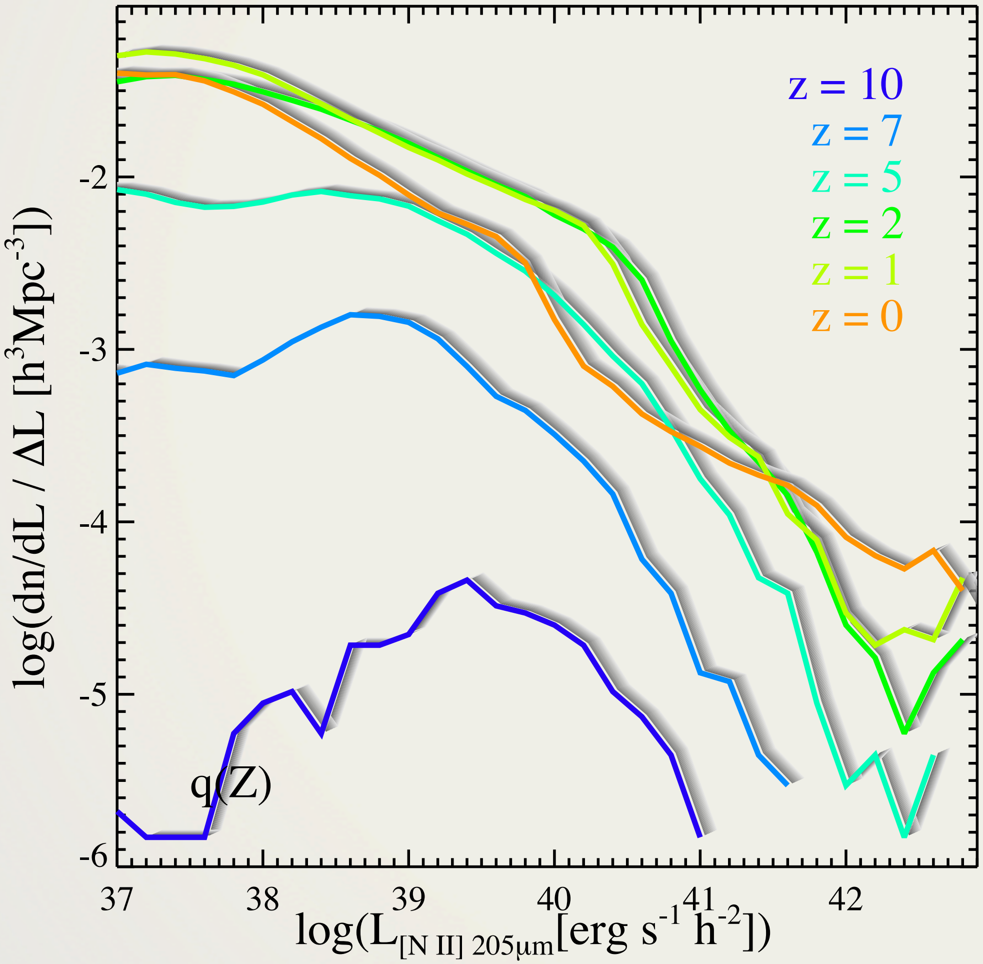
- [NII] 205μm line shows a large scattering at low luminosities, and a tight relation for high luminosities
  - Consistent with the Zhao+12 derived relation

Emission line galaxies at very high redshifts: The [N II] λ 205μm Luminosity function



The [NII] 205μm Luminosity function in the range 0<z<10

ALMA could detect these galaxies up to z~16

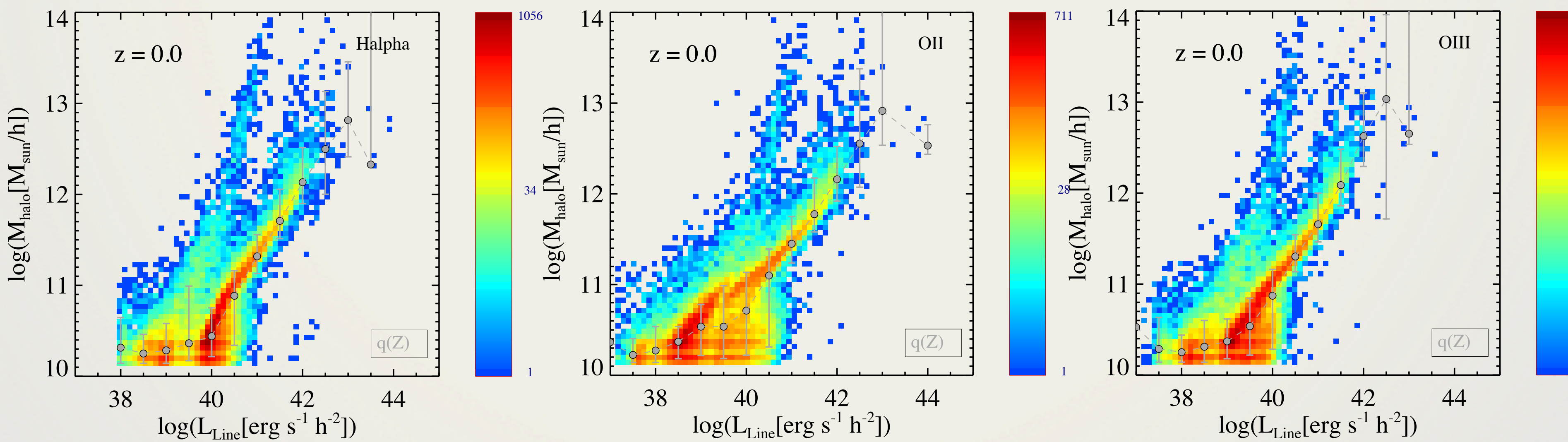
- Cosmic Star formation rate density at z>10 !

- Model predictions key to assess likelihood of detections

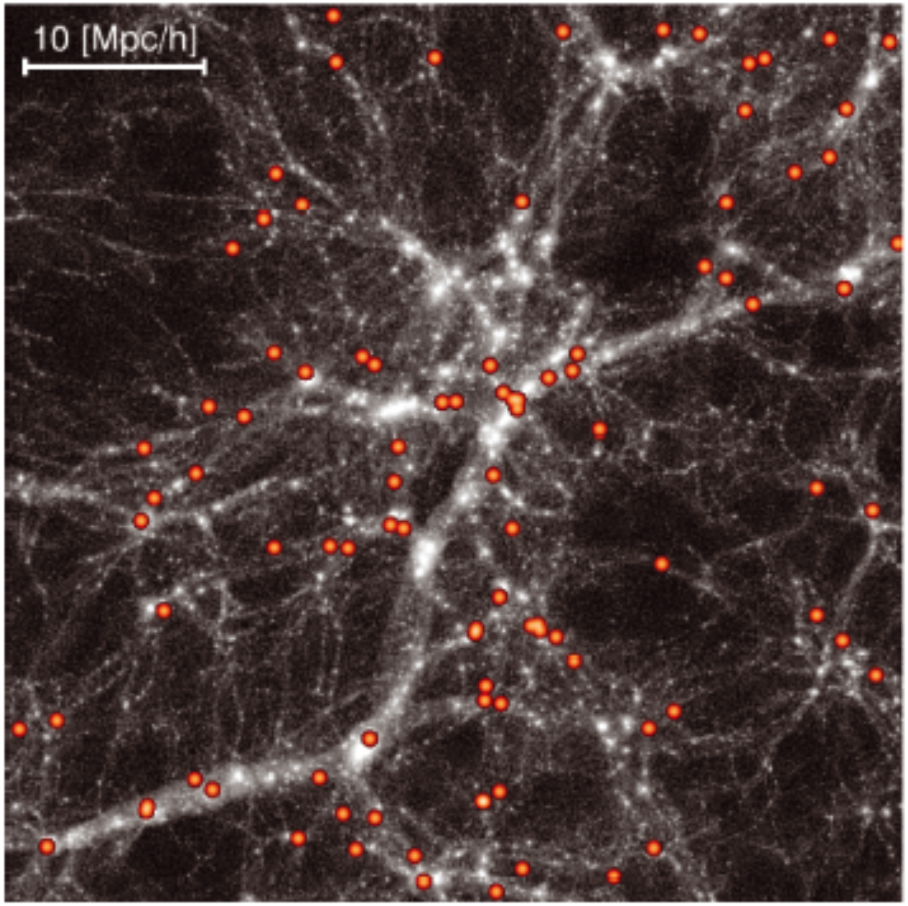
Correlations with other galaxy properties

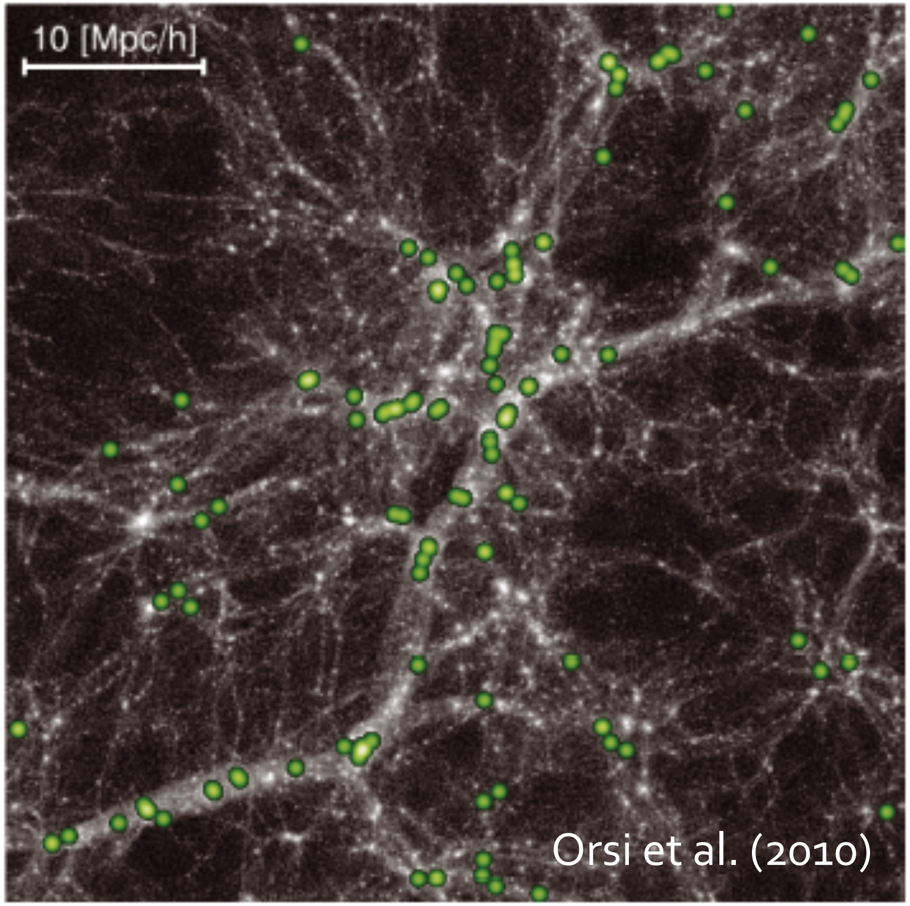
The dark matter haloes of emission line galaxies

- The luminosity of ELGs correlates with their halo mass
- Their typical halo masses are ~10^{12} M_{sun}/h



Emission line galaxies avoid the peaks of the DM density

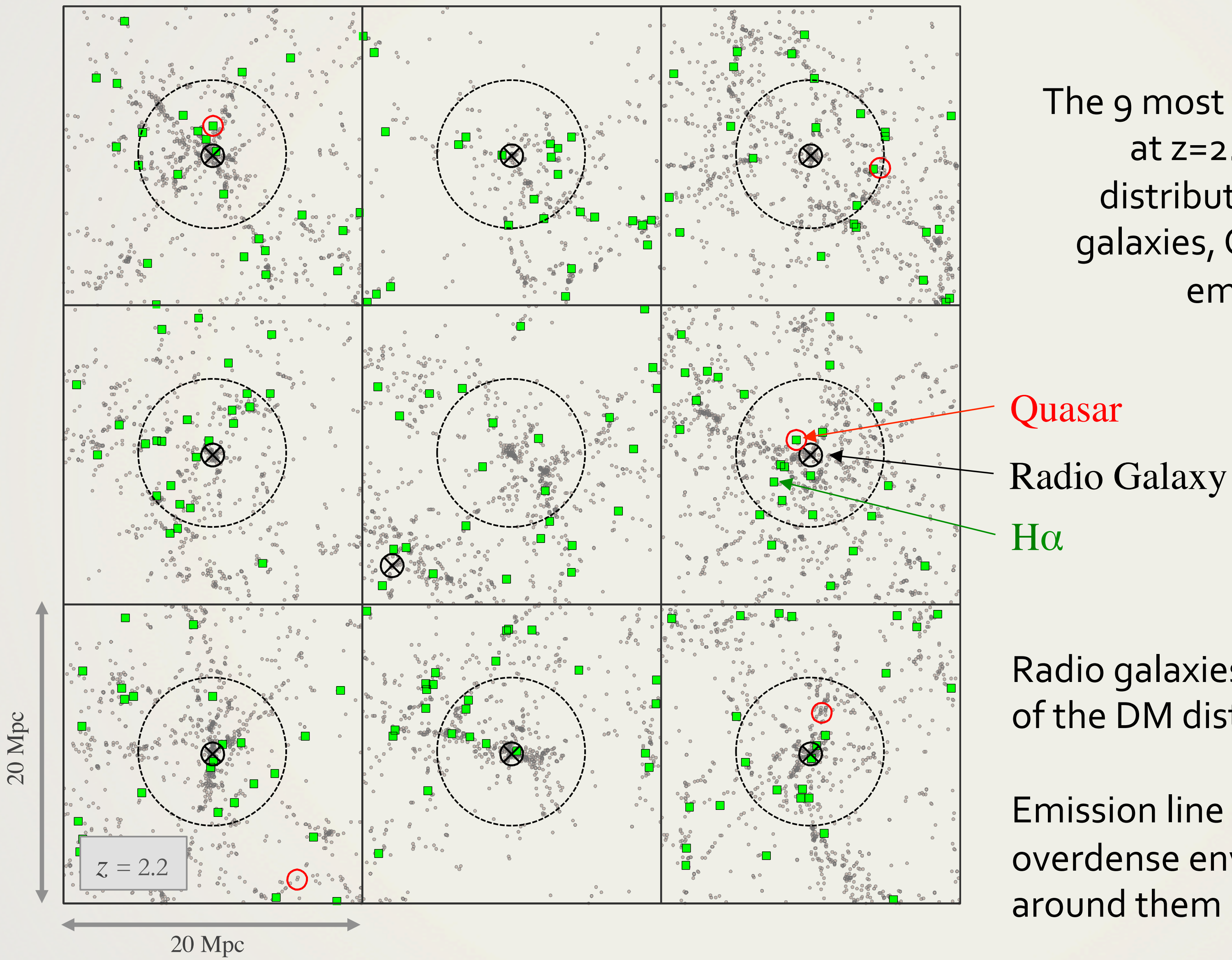




Hα emitters

H-band magnitude limited sample

Tracing massive structures

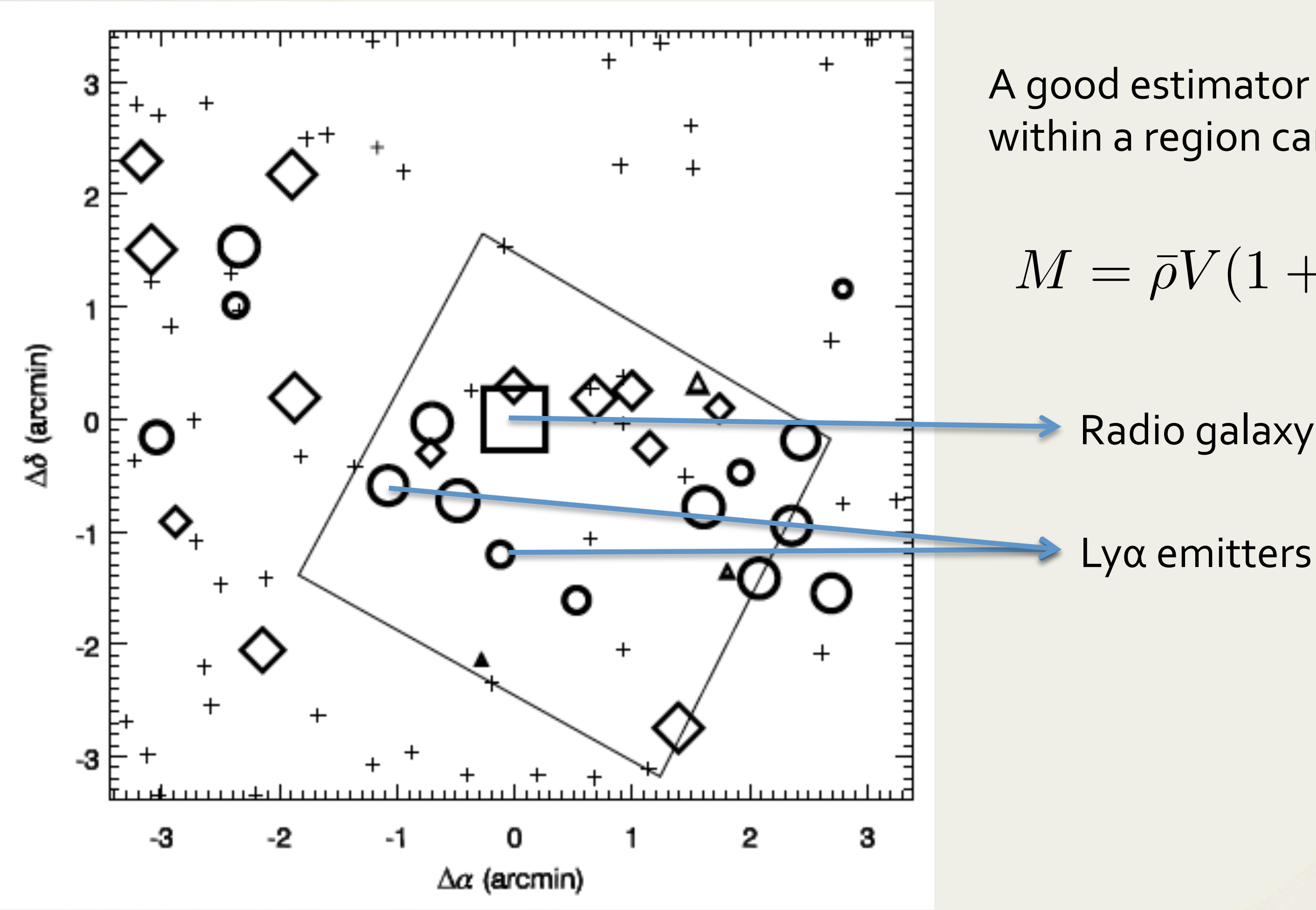


The 9 most massive haloes at z=2.2 and the distribution of radio galaxies, QSOs and Hα emitters.

Radio galaxies trace the peaks of the DM distribution

Emission line galaxies trace overdense environments around them

Tracing massive structures around radio-galaxies

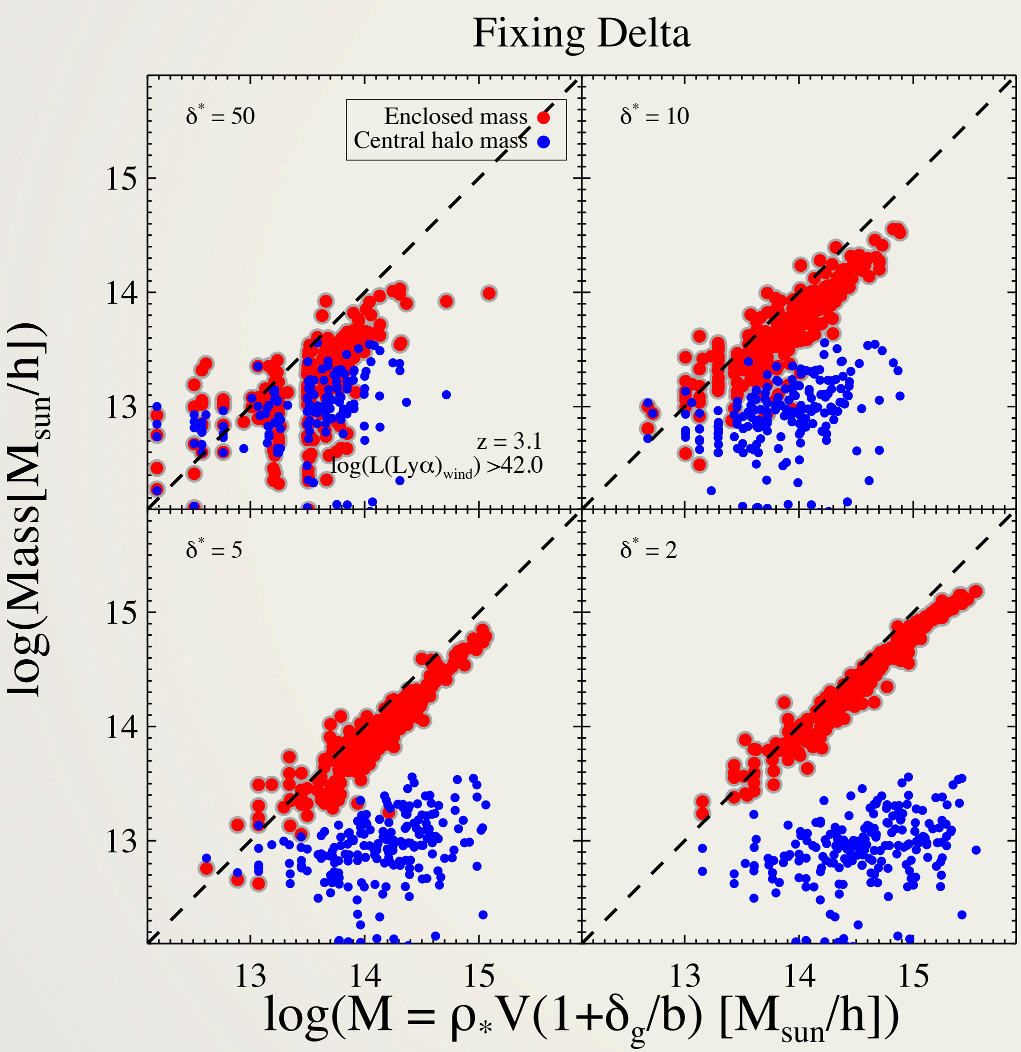


A good estimator of the mass within a region can be calculated by using

$$M = \bar{\rho} V (1 + \delta_g / b)$$

Venemans et al. (2005)

Tracing massive structures around radio-galaxies



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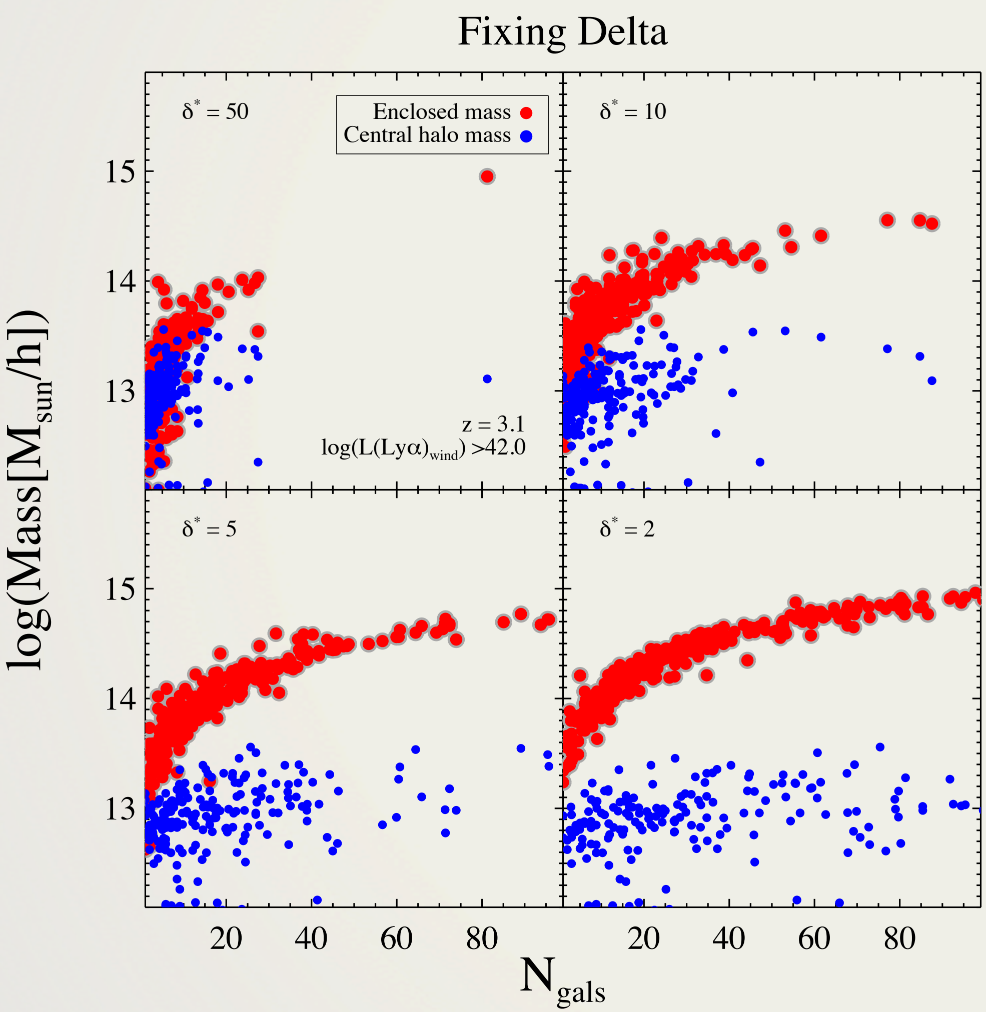

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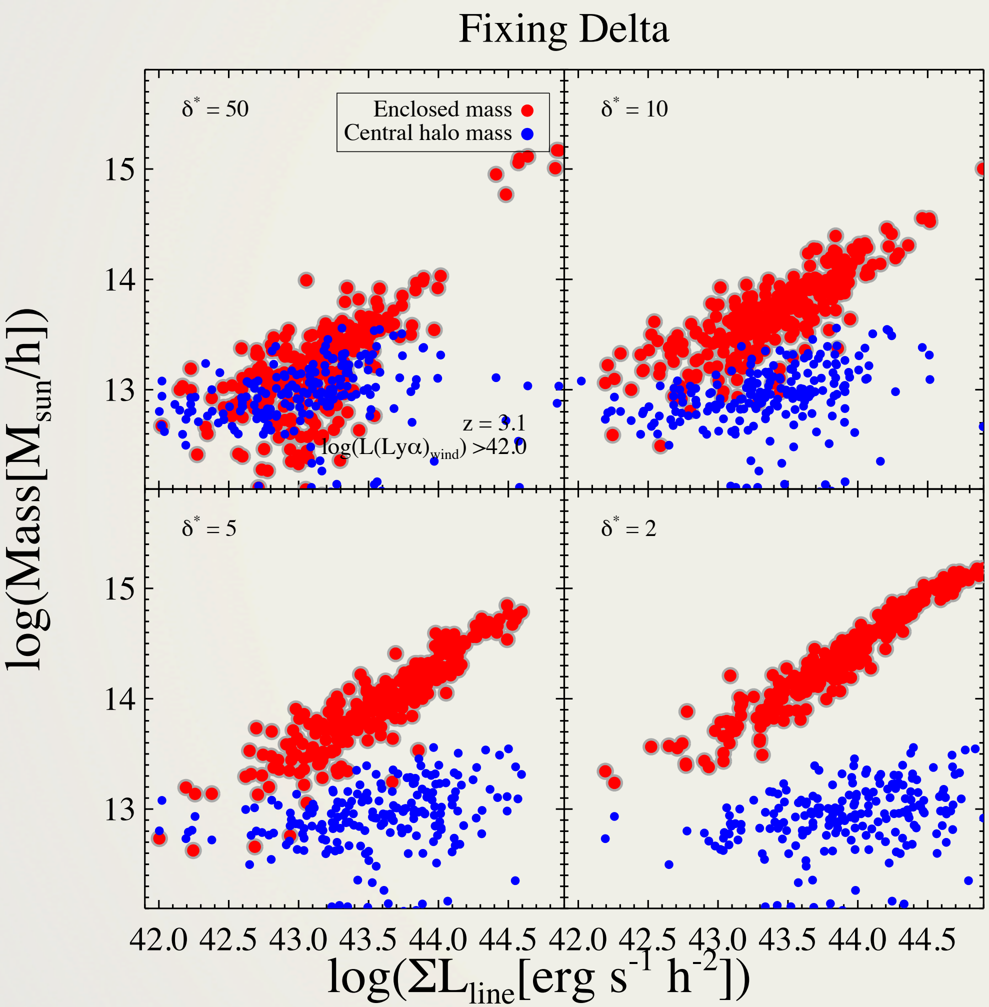
The number of Lyα emitters could also be used as an estimator

Tracing massive structures around radio-galaxies



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The number of Lyα emitters could also be used as an estimator

The sum of the luminosity also correlates with the enclosed mass

Conclusions

- Simple model relating the ionization parameter with the metallicity can reproduce many properties of ELGs
  - [OII] LF suggests q(Z) model is incomplete.
- Resonant scattering of Lyα makes modeling difficult, but also offers an insight into the physical conditions of the ISM of high redshift galaxies
- Next generation of observational facilities will shed light into the high redshift universe
  - Crucial to understand the ELG population from a galaxy formation perspective