Semi-analytical modelling of LAE evolution

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Collaborators

- Carlton Baugh
- Morgan LeDelliou
- Alvaro Orsi
- Simon Morris

Publications

- LeDelliou et al 2005, MN 357, L11
- Le Delliou et al 2006, MN 365, 712
- Orsi et al 2008, MN 391, 1589

Outline

- Physical processes
- Choice of model
- Comparison to non-LAE obs
- Predictions for LAE LF evoln
- Other LAE properties
- Conclusions

- See talk tomorrow by Alvaro Orsi for LAE clustering predictions

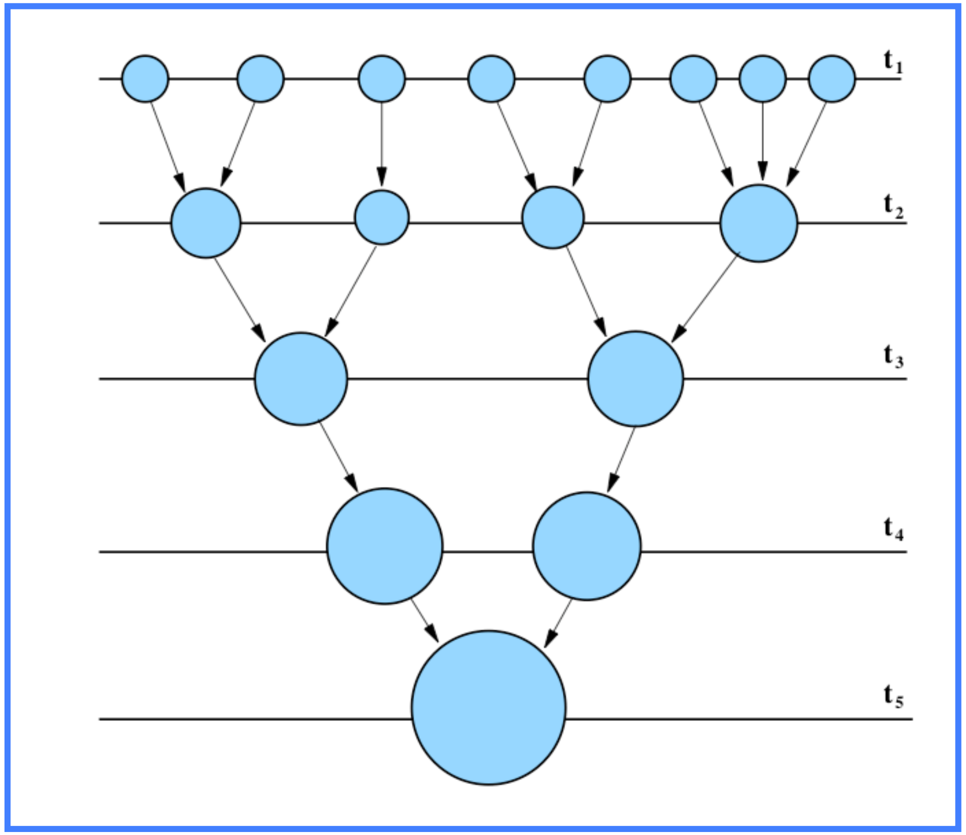
Semi-analytical models of galaxy formation: WHAT & WHY

- Problem with numerical simulations is limited dynamic range: cannot directly simulate all important processes from structure formation (>10 Mpc) down to star formation & feedback (<1 pc)
- Semi-analytical models: instead use simplified analytical prescriptions for main physical processes
- Allows to simulate galaxy populations in cosmological volumes

Physical ingredients in semi-analytical models

- Assembly of dark matter halos
- Shock-heating and radiative cooling of gas within halos
- Star formation
- Feedback from supernovae & AGN
- Production of heavy elements
- Galaxy mergers
- Stellar populations
- Dust absorption & emission

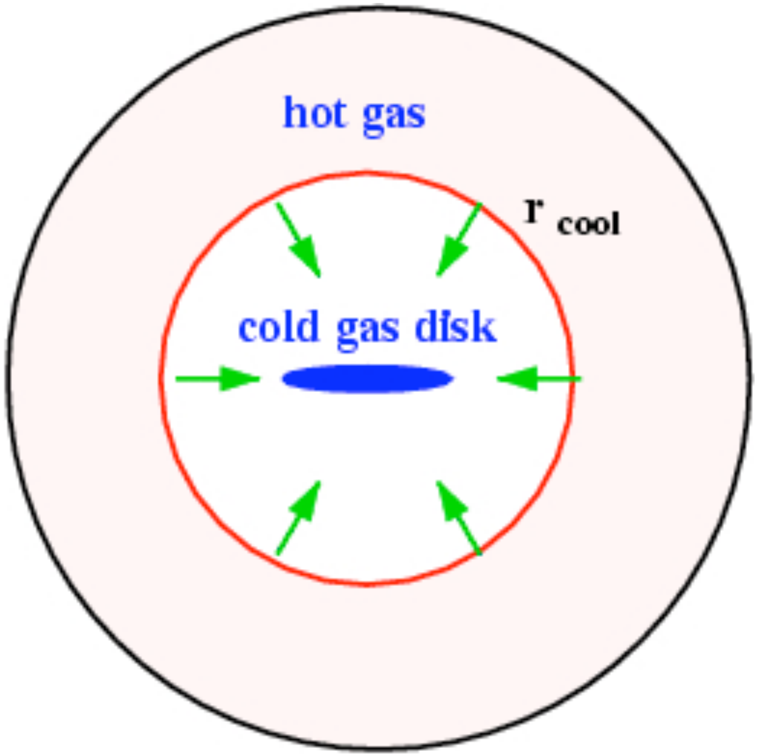
Assembly of dark matter halos: Merger trees



- 2 approaches:
- **Monte Carlo** based on (analytical) conditional Press-Schechter mass function

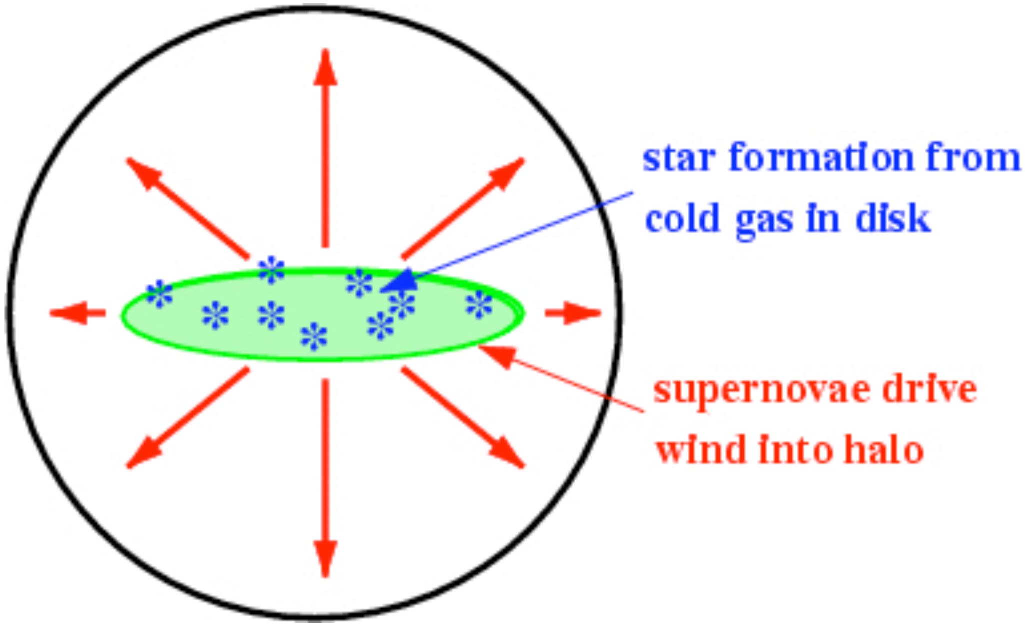
  OR
- **Extract** from **N-body simulations**
- very similar results from both approaches

Shock-Heating & cooling of gas in halos



- Infalling gas shock-heated to T_{vir}
- Radiative cooling of gas from static spherical distribution
- If $t_{cool} < t_{ff}$ gas falls in on free-fall timescale - cold accretion
- Disk size related to angular momentum of gas which cools

Star formation & feedback



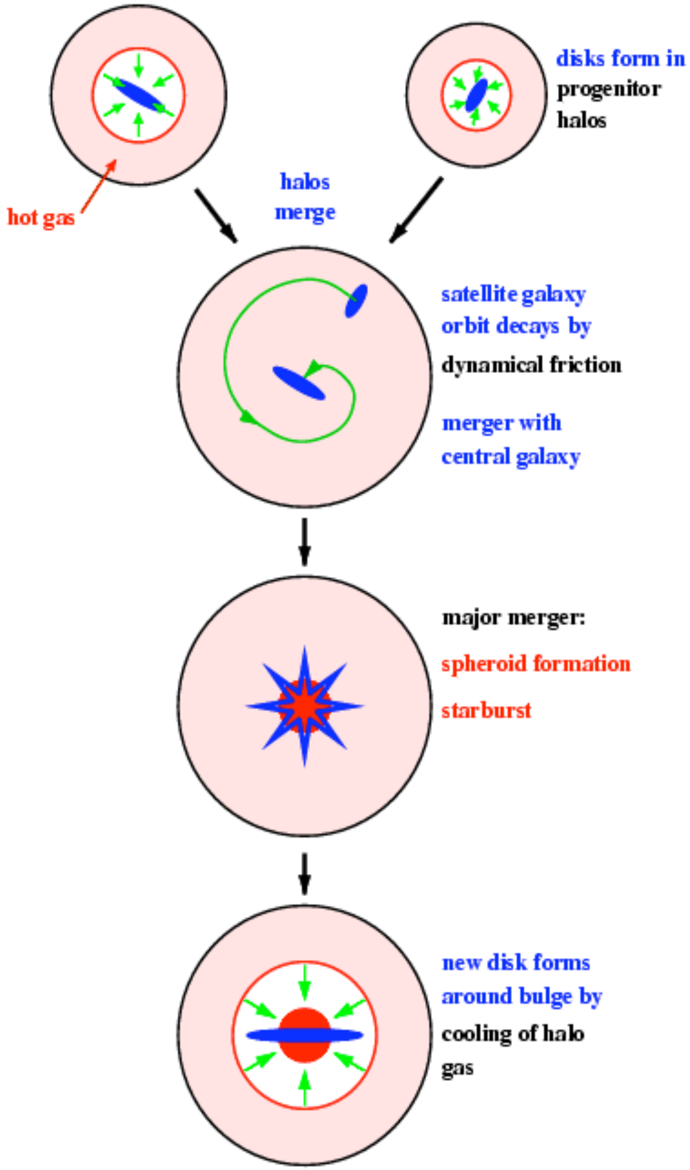
- stars form in disks

$$SFR = M_{gas} / \tau_*$$

- supernova feedback ejects gas from galaxies

$$\dot{M}_{eject} = \beta(V_c)\, SFR$$

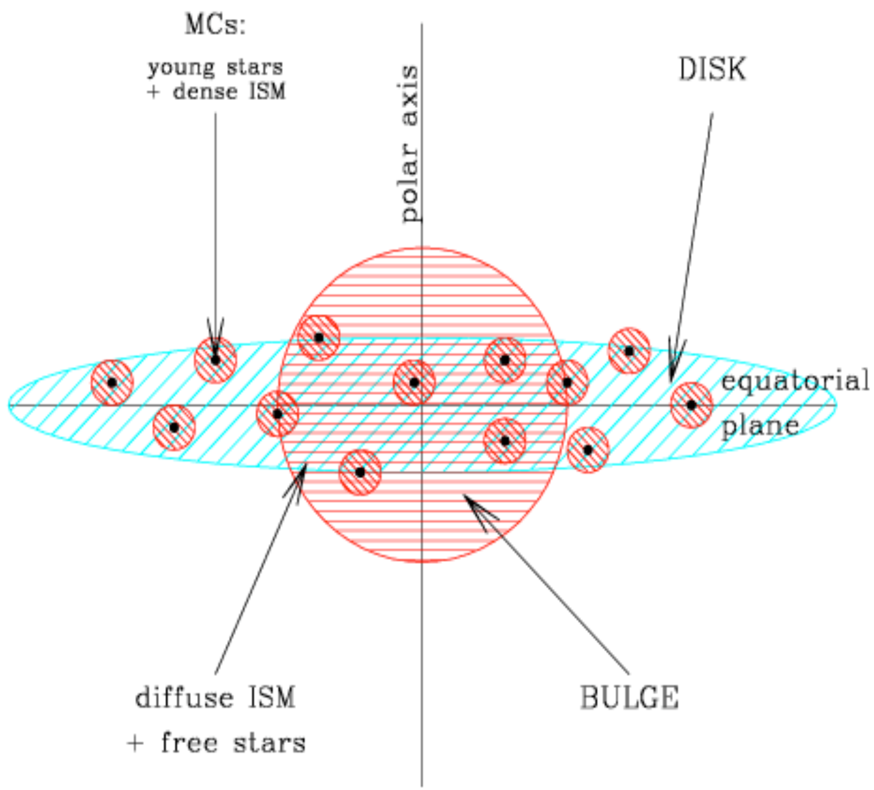
Galaxy mergers & morphology



- halos merge
- galaxies merge by dynamical friction
- major mergers make galactic spheroids from disks
- mergers trigger starbursts
- spheroids can grow new disks

Modelling galaxy SEDs with dust

- dust in diffuse medium and molecular clouds
- stars form in clouds and leak out
- radiative transfer of starlight through dust distribution
- physical dust grain model
- heating of dust grains –> dust temperature distribution
- IR/sub-mm emission from grains w distrib of size & T



GRASIL: Silva et al 1998, Granato et al 2000, Vega et al 2005

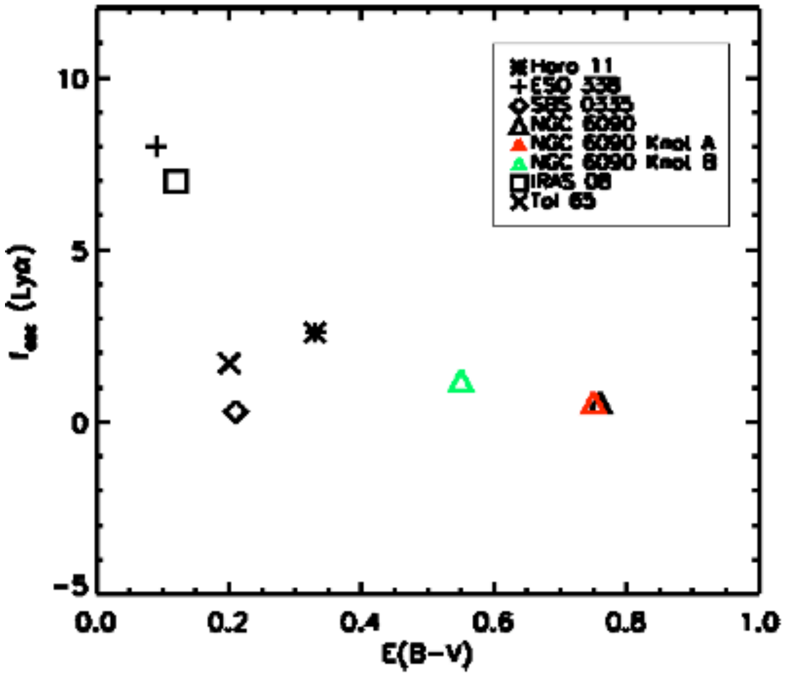
Modelling Lyα emission

- Model predicts SED for each galaxy including effects of SF history, metallicity & IMF
- Integrate over SED to get Lyc luminosity
- Assume all Lyc absorbed by H within galaxy & produces Lyα according to Case B recombination

Lyα escape fraction f_{esc}

- Calculating escape fraction from galaxy from 1st principles is very complicated radiative transfer problem
- Depends on spatial distribution and kinematics of neutral gas & dust in galaxy & surrounding halo
- We adopt simpler approach - assume constant f_{esc} for all galaxies (ignore scatter & possible dependence on L & z)
- Normalize to match number of LAEs at z~3 (for f ~ 2e-17 erg/cm^2/s or L ~ 1e42 erg/s) => f_{esc}= 0.02 in our standard model

Is f_{esc}~ 0.02 reasonable?



- Atek et al 2008 measure Lyα escape fractions for sample of z~0 LAEs
- use measured Lyα, Hα & Hβ fluxes
  - NO assumptions about IMF or SED
- wide range f_{esc} ~ 0.025 - 0.08
- median f_{esc} only ~ 0.02

Hayes (this meeting) finds average f_{esc} = 4.5% @ z=2 from Lα & Hα LFs

Aims of semi-analytical modelling

- Want single model which can reproduce galaxy masses, SFRs, sizes, luminosities, colours, gas contents etc over whole range of redshifts observed
- i.e. not only LF of LAEs at z~3-6, but also
  - Galaxy population at z~0
  - Other types of high-z galaxies (e.g. LBGs, SMGs)

Our standard model

(Baugh+ 2005, Lacey+ 2008)

- Model with standard solar neighbourhood IMF can explain wide range of properties for present-day galaxies
- But then fails to reproduce main populations of star-forming galaxies at high-z:
  – Sub-mm galaxies (SMGs) at z~1-4
  – Lyman-break galaxies (LBGs) at z~3-7

Solution - a variable IMF?

- Normal (solar nhd) IMF in star-forming disks

  $$dN / d\ln m \propto m^{-x}$$

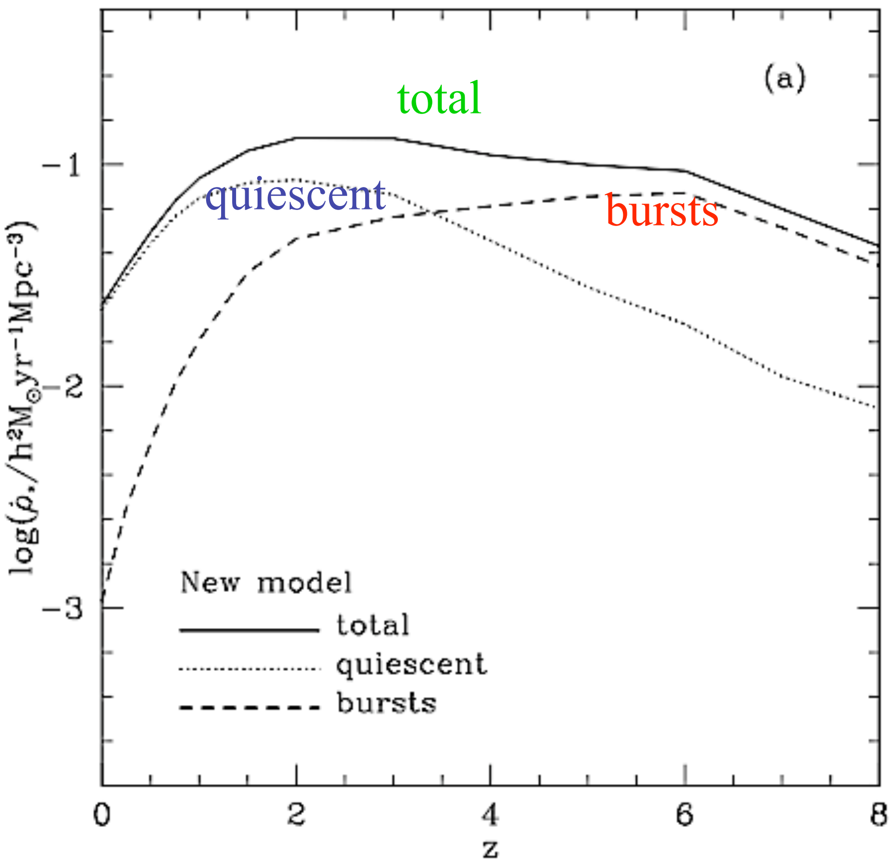
  - with x=0.4 for m < Mo, x=1.5 for m >Mo (Kennicutt 1983)
  - c.f x=1.35 for Salpeter

- Top-heavy IMF in bursts triggered by mergers

  $$dN / d\ln m \propto m^{0}$$

  - Increases both stellar luminosities & chemical yields by ~ 5x

Cosmic star formation history



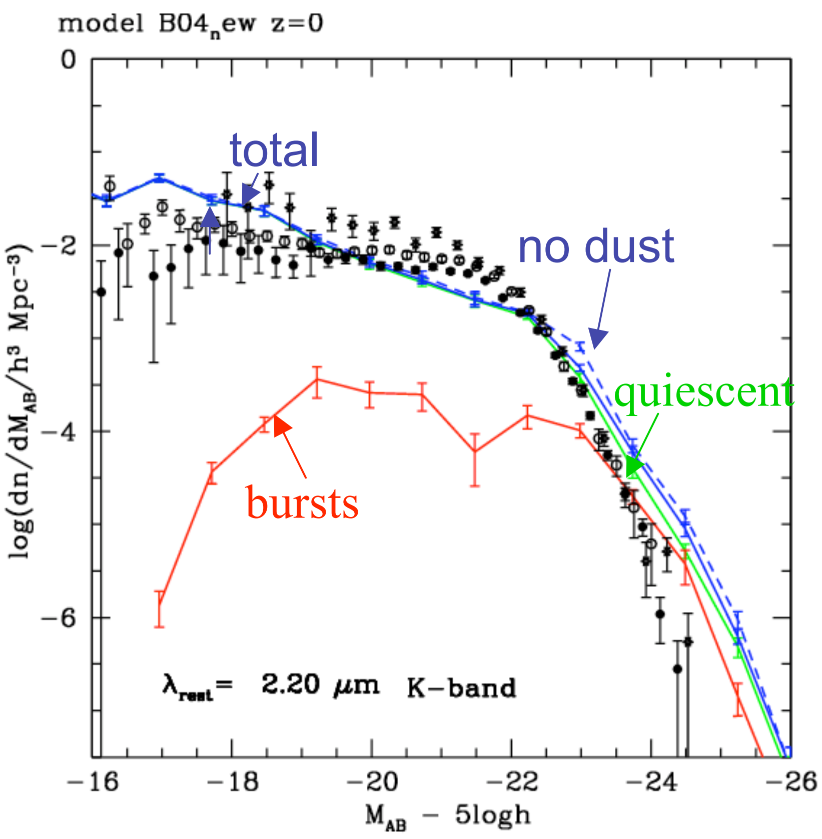
Bursts dominate total SFR at high z

=> Shift from normal to top-heavy IMF

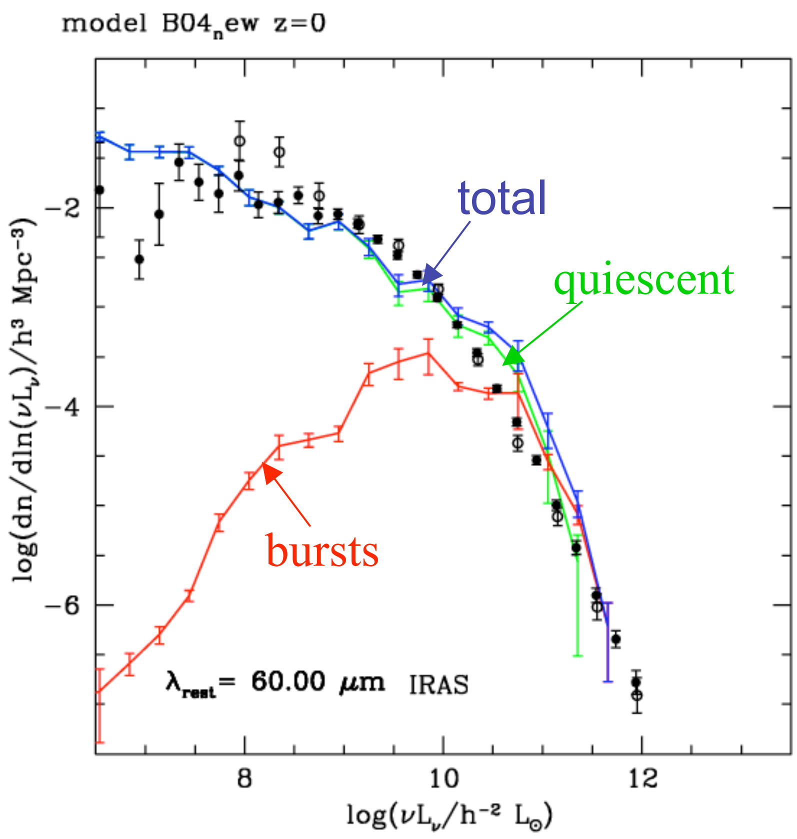
Validation of model against non-LAE obs data

galaxy luminosity functions @ z=0 in near-IR & far-IR

K-band (stars)

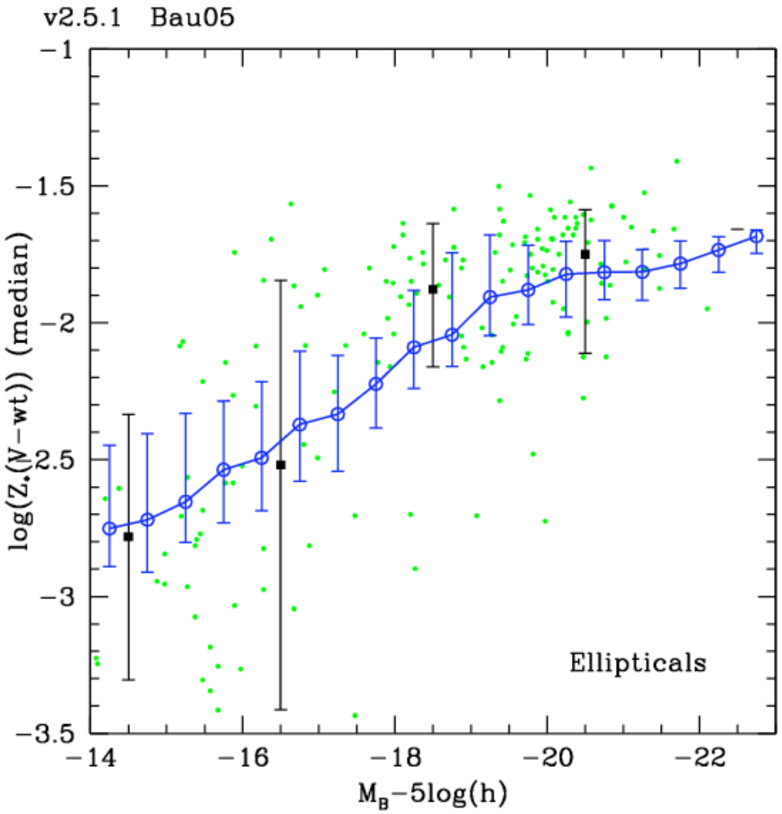


60 μm (dust)

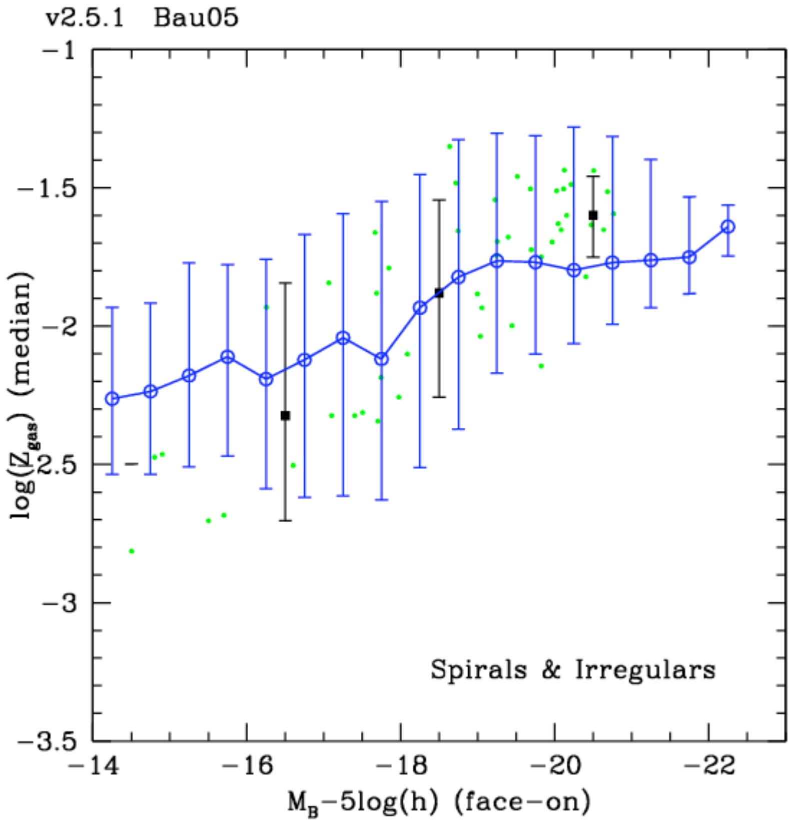


Metallicities of stars & gas @ z=0

Stars in ellipticals



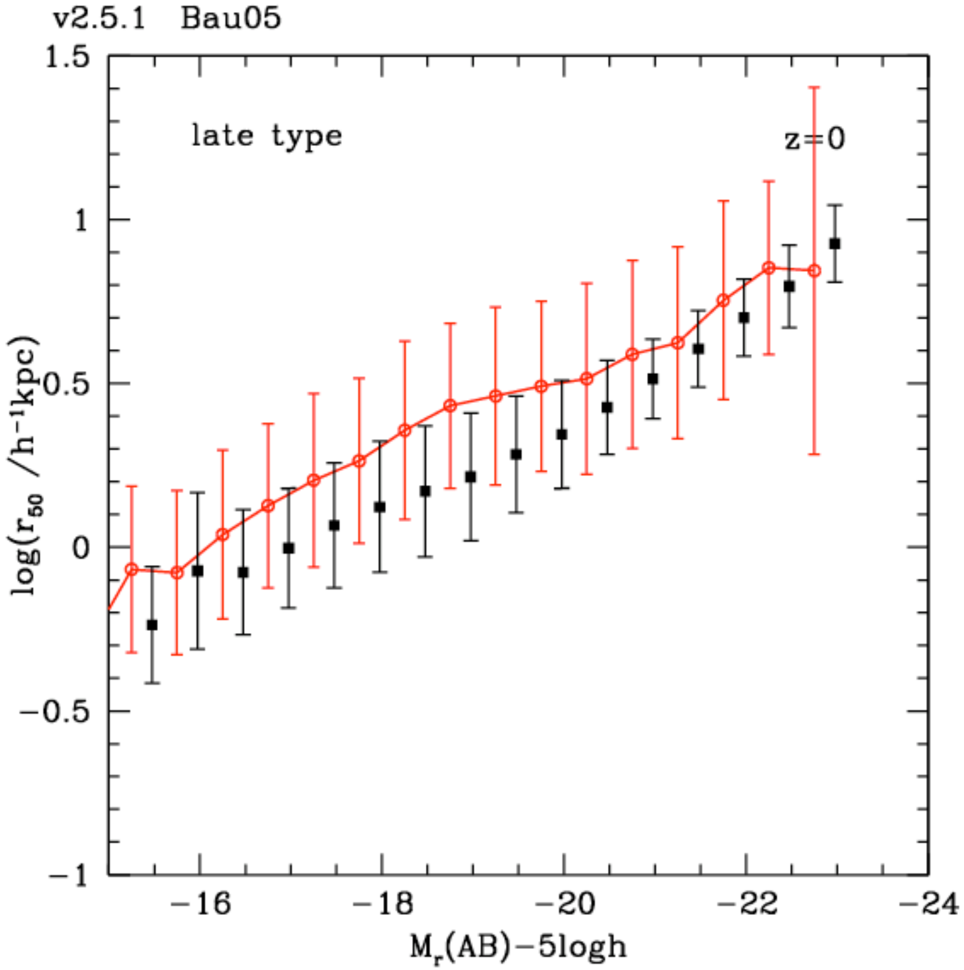
Gas in spirals



Correct metallicities using yields predicted by stellar evolution + IMF - yield NOT adjustable parameter

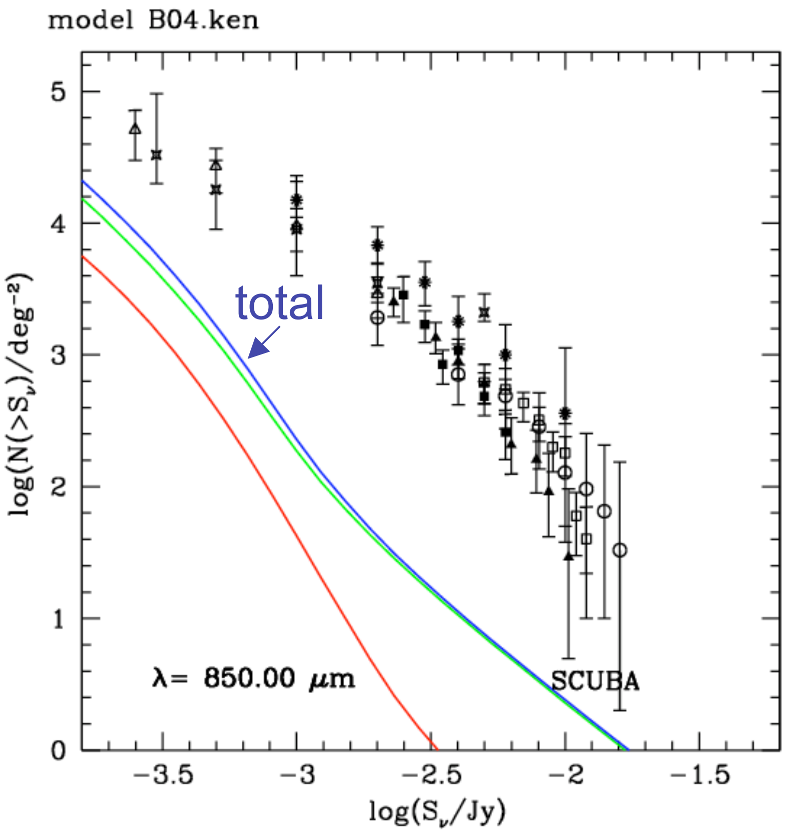
Galaxy disk sizes @ z~0

Size vs luminosity

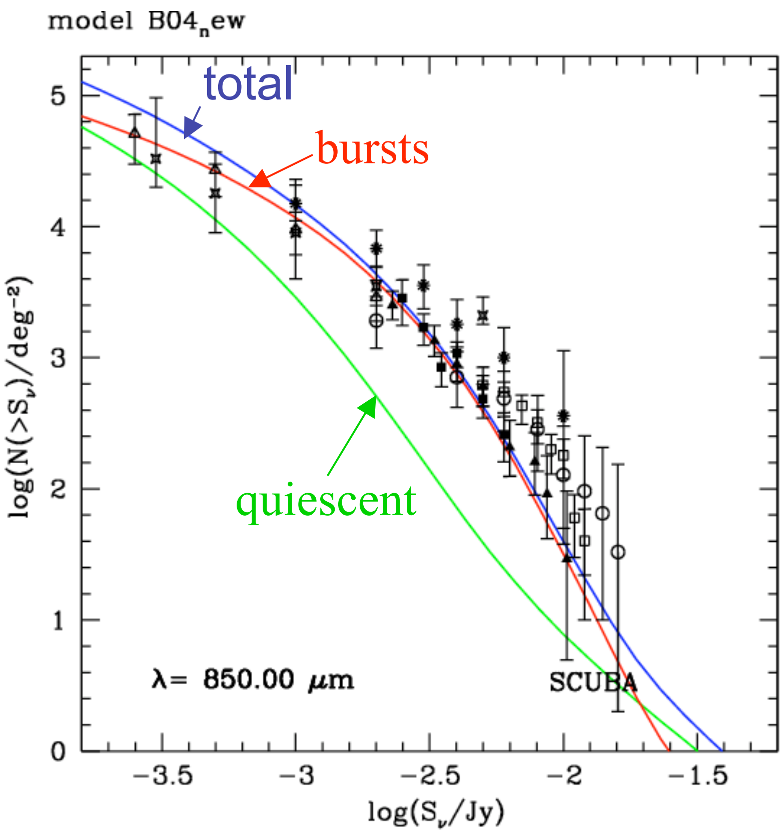


Why a top-heavy IMF?
(a) Sub-mm source counts

normal IMF



top-heavy IMF

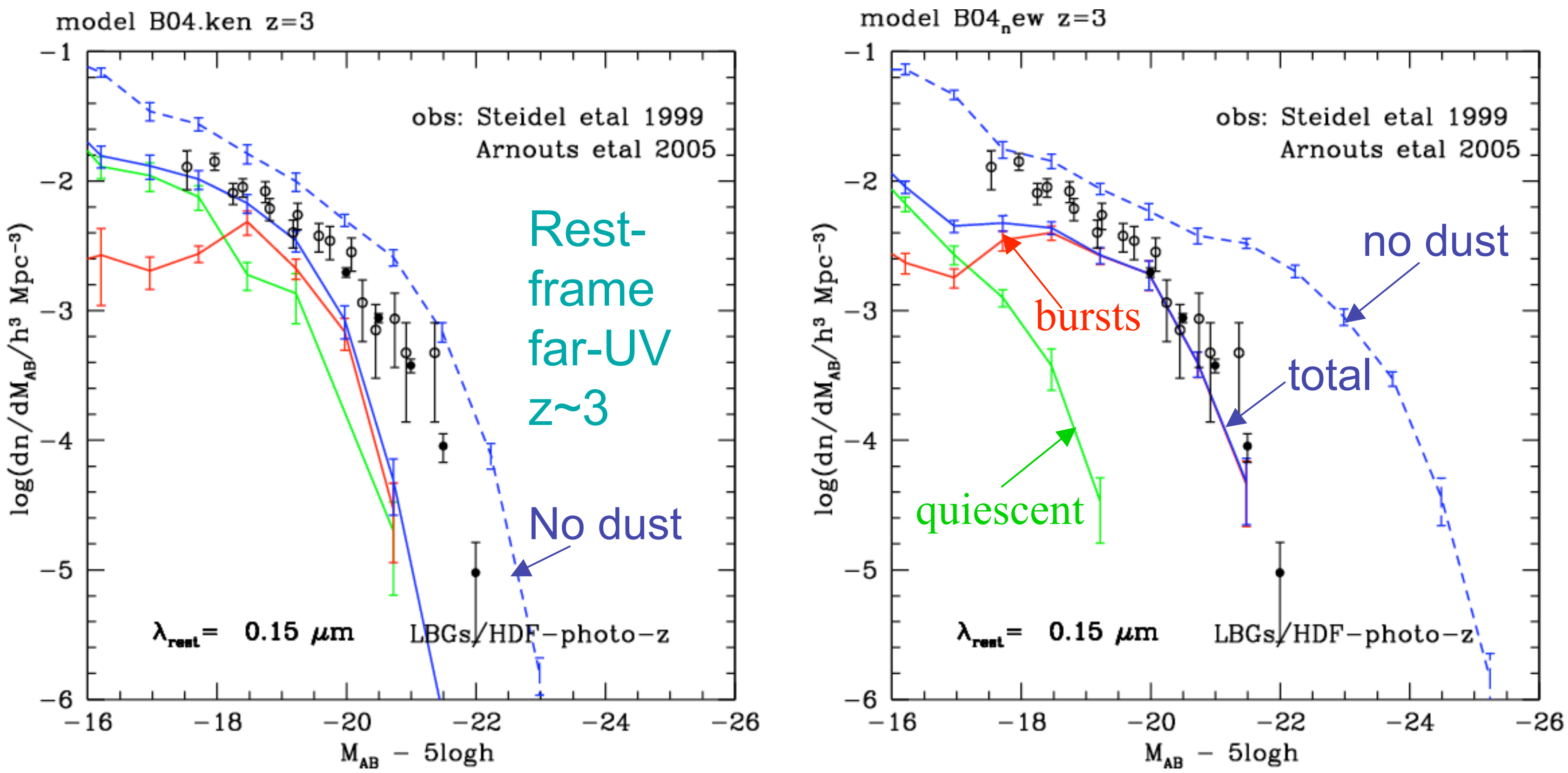


Sub-mm counts too low by factor ~50 for normal IMF

Why a top-heavy IMF?
(b) Lyman-break galaxies

normal IMF

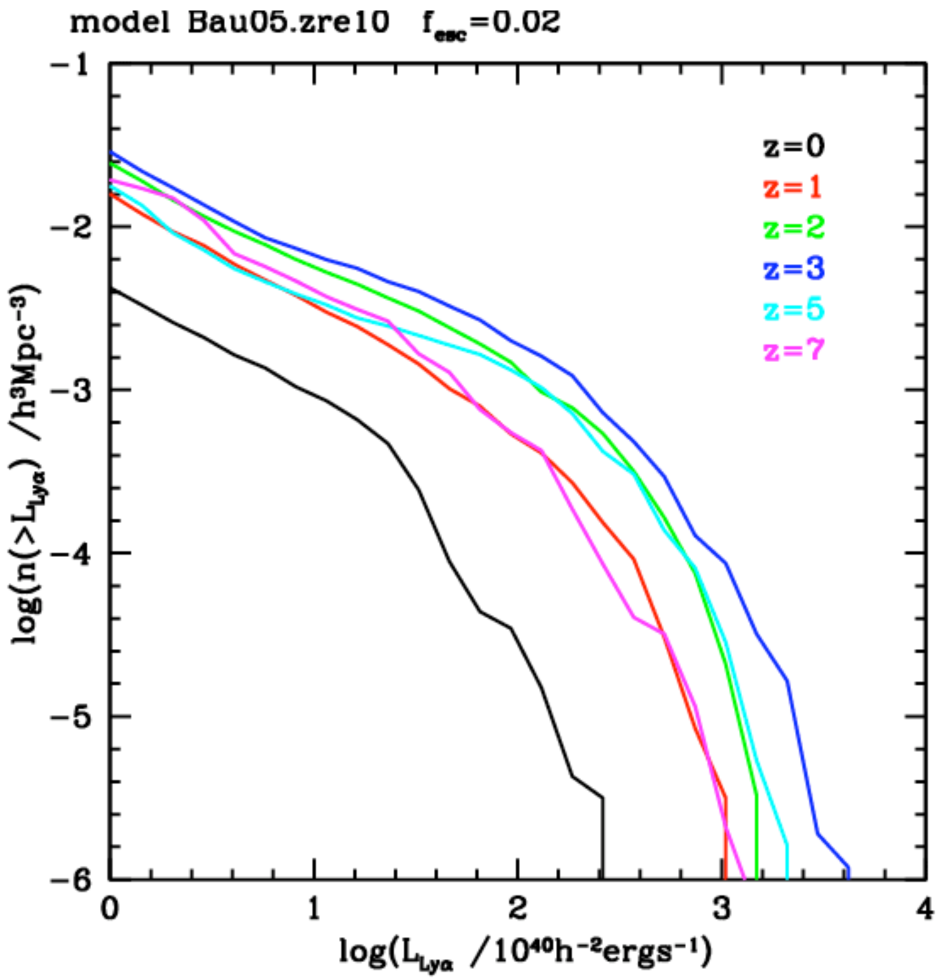
top-heavy IMF



LBGs too faint for normal IMF, once include dust extinction

Model predictions for LAE LF evoln

Evolution of LAE luminosity function

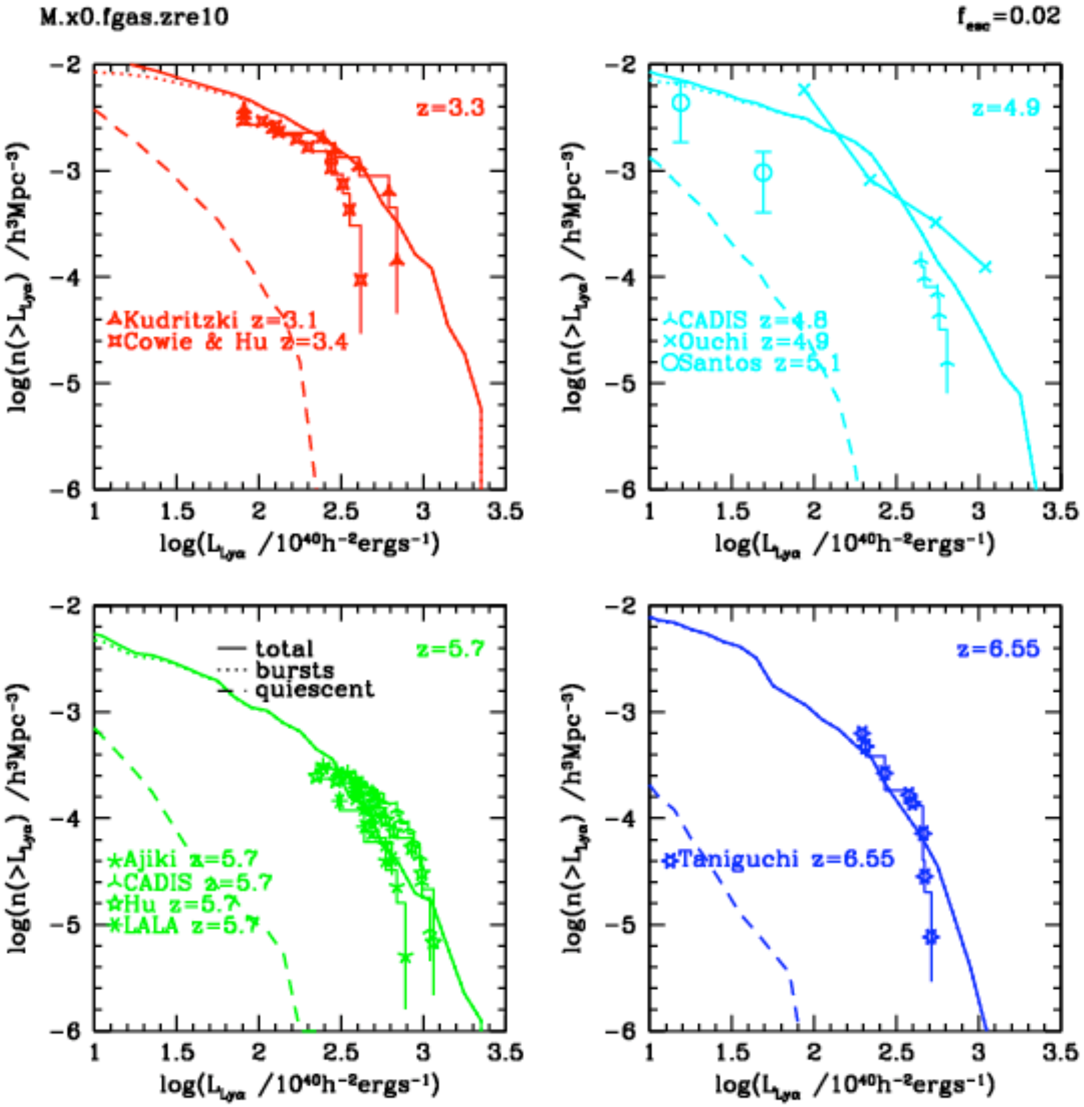


Top-heavy burst IMF

f_{esc}=0.02

- no of LAEs peaks around z~3
- characteristic L increases by ~ 10x from z=0 to z=3

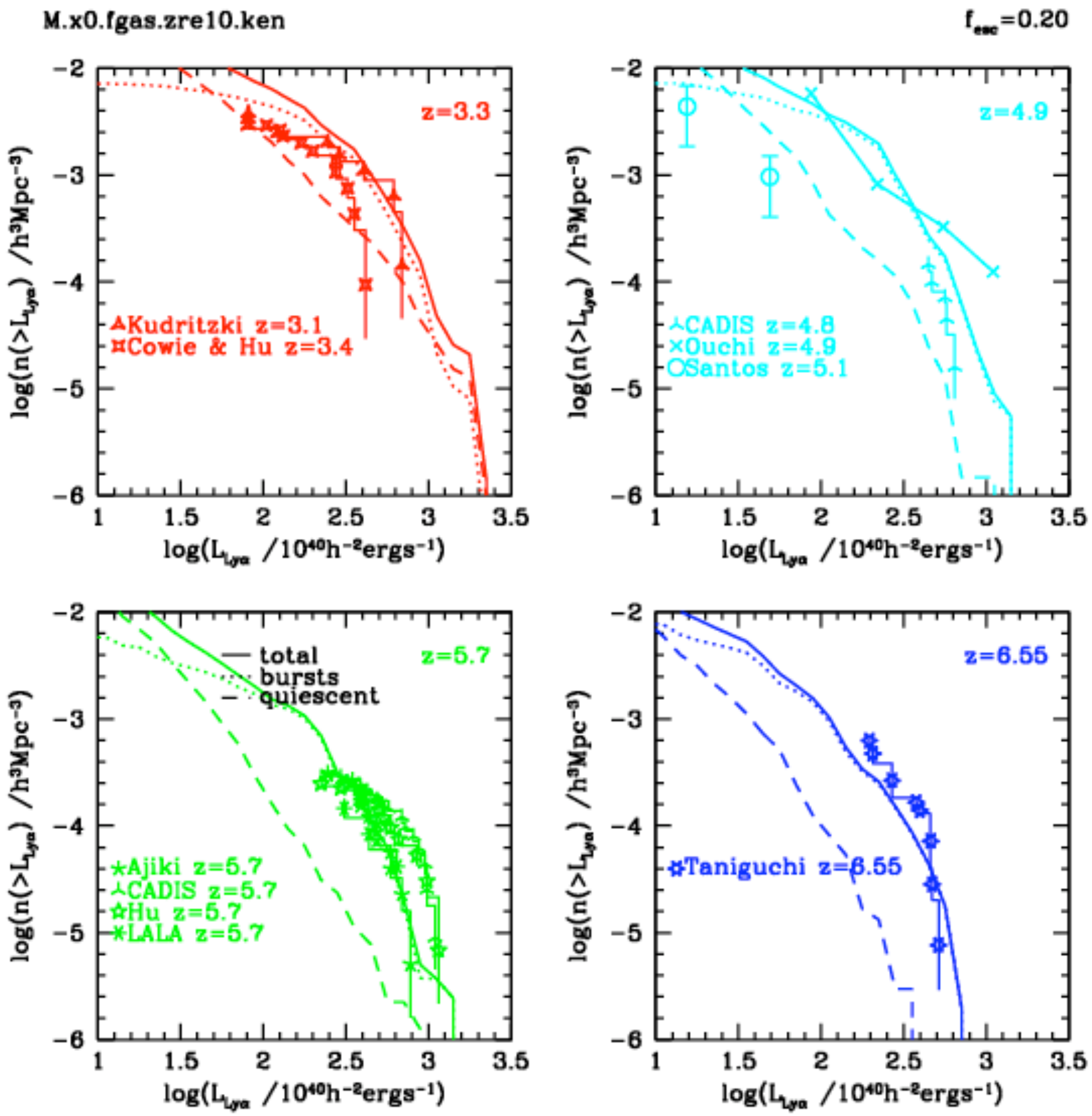
Comparison with observed LF



(Le Delliou+ 2006)

- Model with top-heavy IMF in bursts & fixed f_{esc}=0.02 agrees well with obs for z~3-7
- Observed LAE popn dominated by merger-driven starbursts

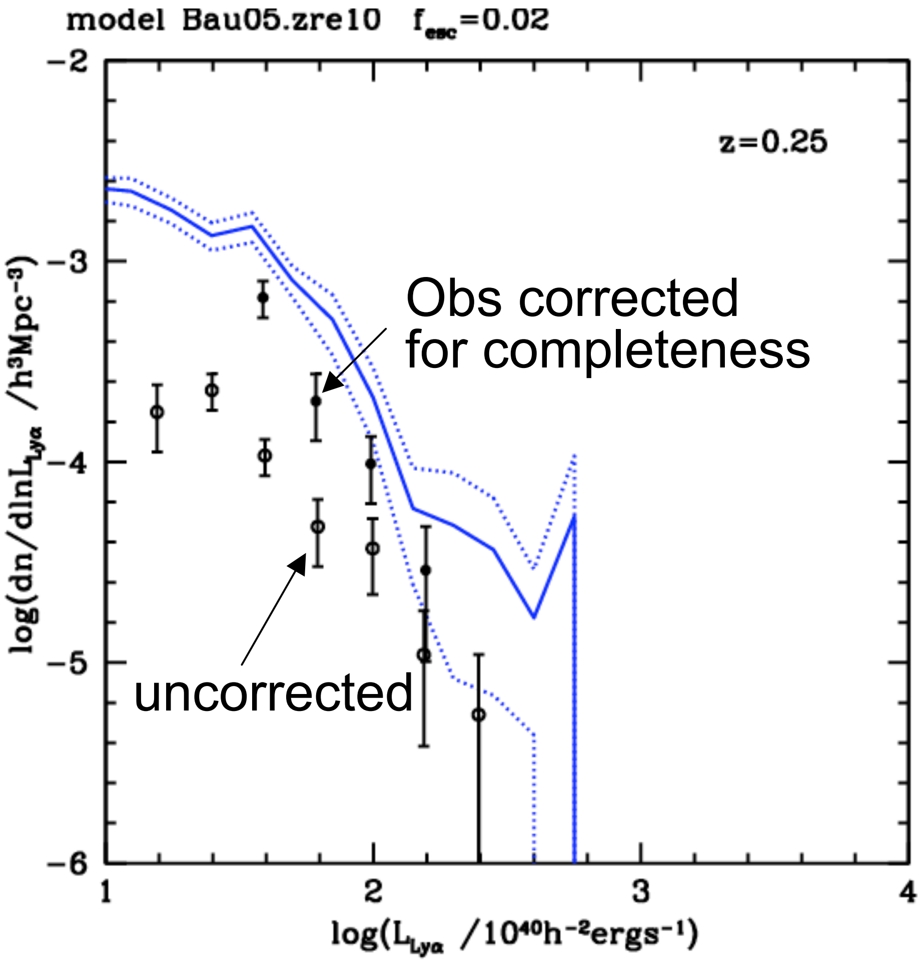
LAE LFs in model with normal IMF



(Le Delliou+ 2006)

- Alternative model with normal IMF works nearly as well for LAEs but needs f_{esc}~0.2
- however, would not fit obs of LBGs & SMGs

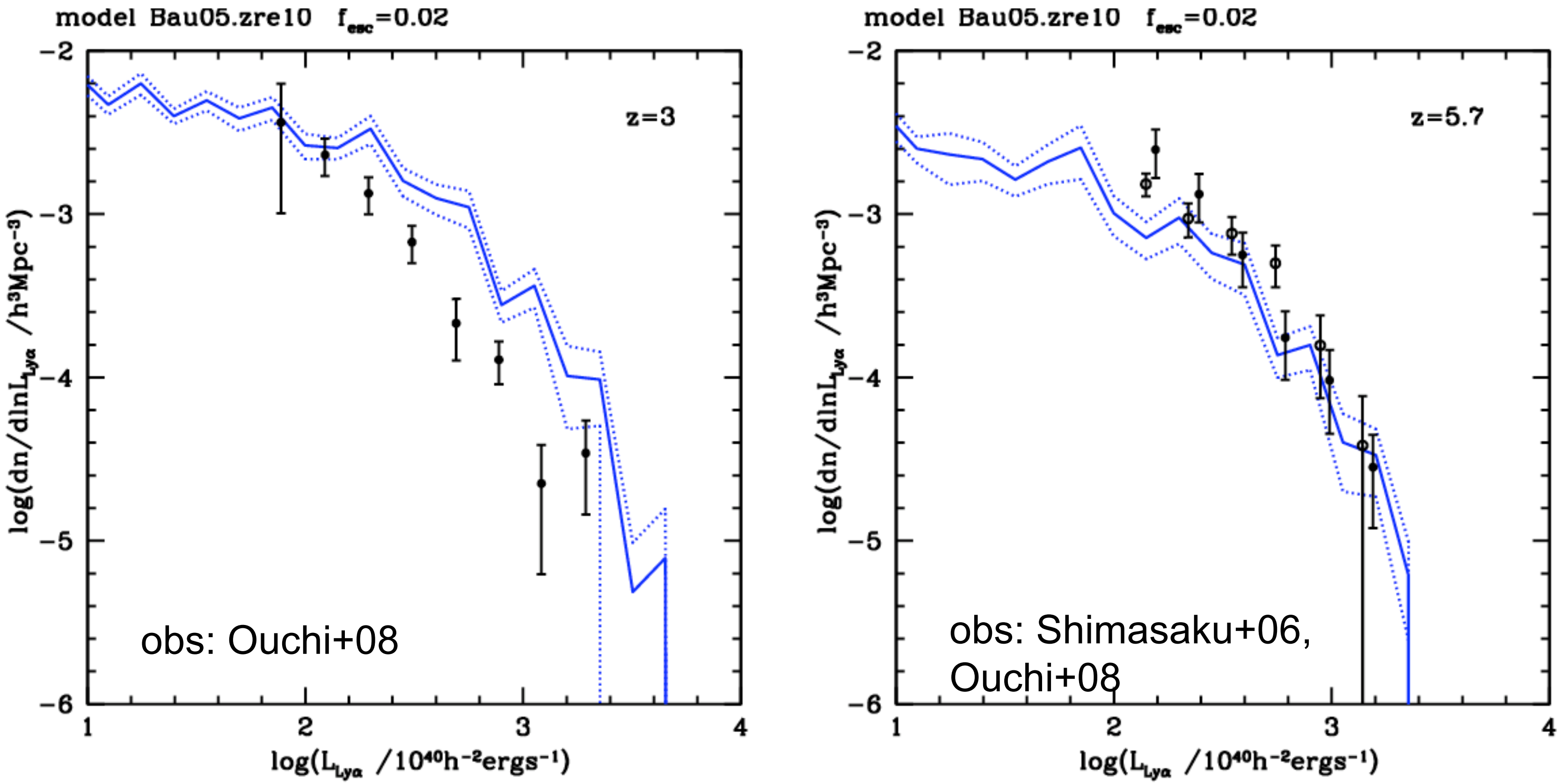
Updated LF comparison - z~0.3



- comparison to GALEX survey (Deharveng 2008+)
- 2006 model prediction remarkably close to obs @ z~0.3 - WITHOUT any adjustment!

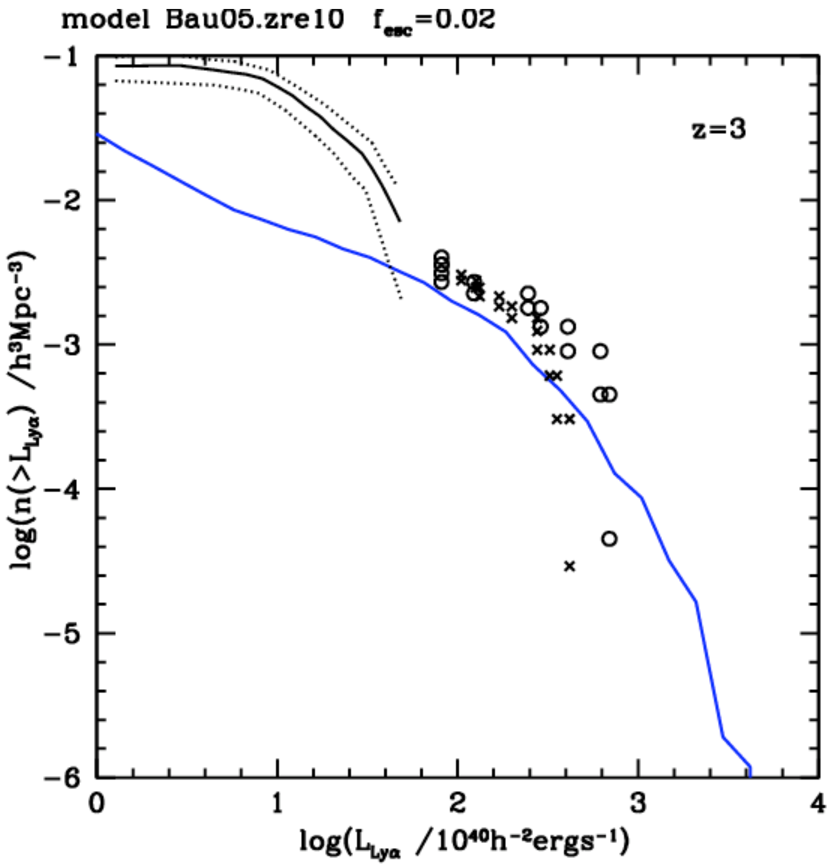
- naturally predict strong evoln from z~0 to z~3

Updated LF comparison - z=3.1 & z=5.7



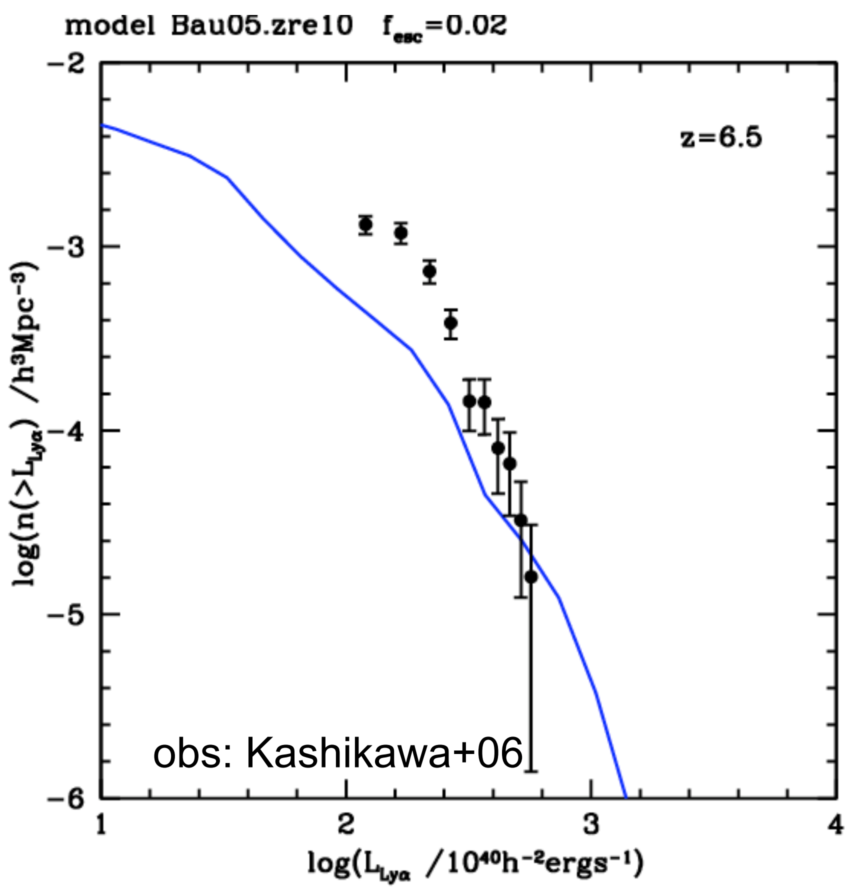
Excellent agreement with newer data at z~6, not as good at z~3

LAE LF at faint L @ z~3



- Rauch+08 data => many more faint LAEs than in model
- also LeFevre (this conf) finds steeper faint slope in VVDS
- suggest larger f_{esc} at low L, or weaker feedback than assumed in model

Updated LF comparison - z=6.5



- model LF below new obs at low L
- discrepancy could be due to either:

- error in predicted dn/d(SFR)

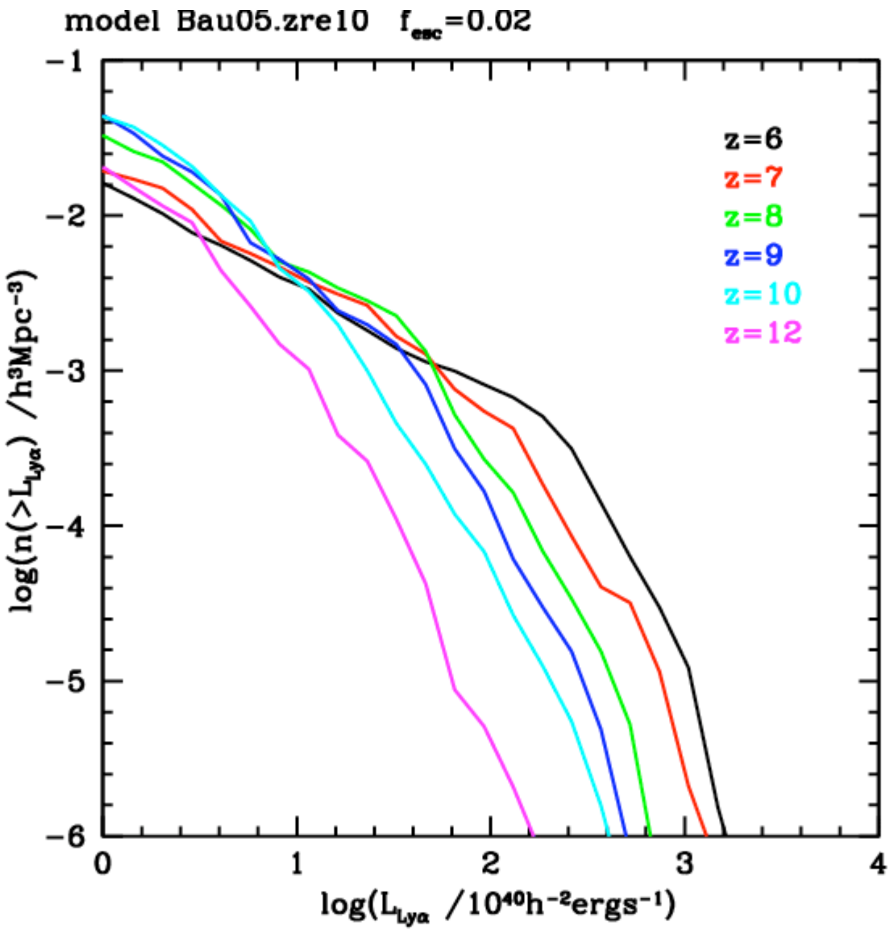
- or variation in f_{esc}

- degenerate in effect on LAE LF

Comparison with observed LAE LF evoln - summary

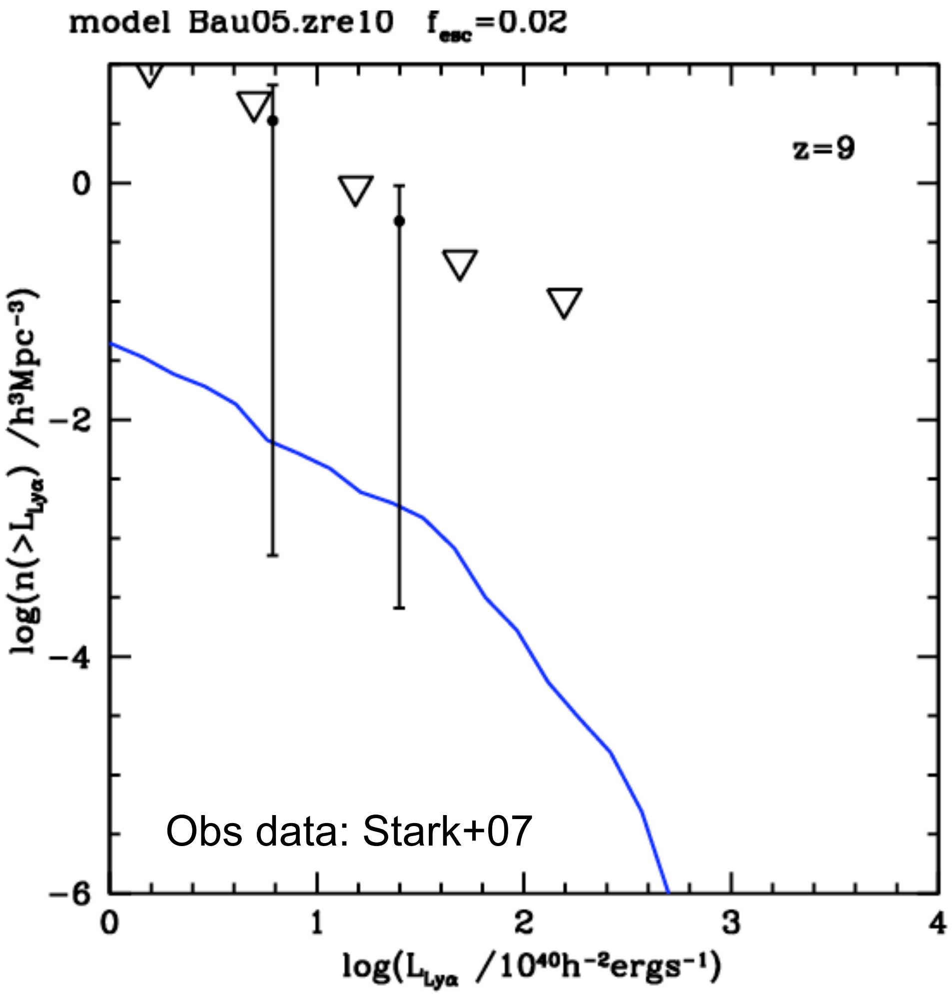
- Model with top-heavy IMF in bursts & fixed f_{esc}=0.02 roughly agrees with observed LAE LF for z~0-7
- Discrepancies might be explained by weak L and/or z-dependence of f_{esc}
- In this model, observed LAE population dominated by merger-driven starbursts
- Alternative model with normal IMF agrees nearly as well for LAEs (only) at high z, but needs f_{esc} ~ 0.2

Evolution of LF to high z



Very rapid decline in LAE LF at z>10 - due to buildup of halo mass fn

LAE LF at z~9

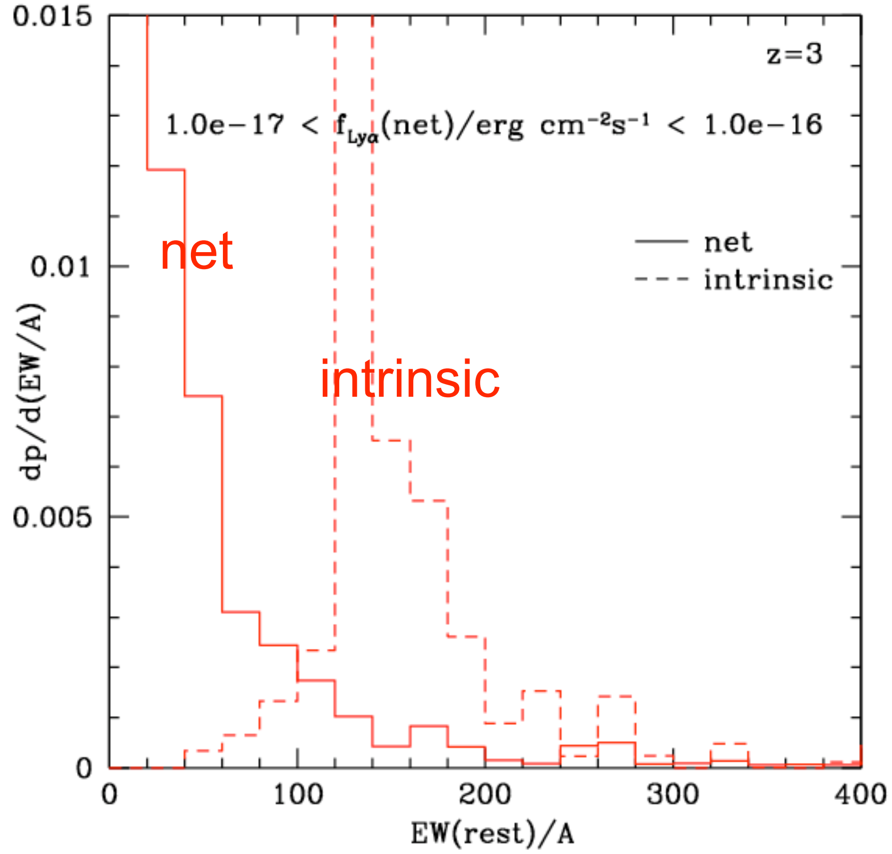


- Predicted LF at z~9 >10x below upper limits from Cuby+07, Willis+06,08, Sobral+09
- but ~100x lower than Stark+07 obs estimate (if 2 of their LAE candidates real)

EWs & UV continuum luminosities of LAEs

Lyα equivalent widths

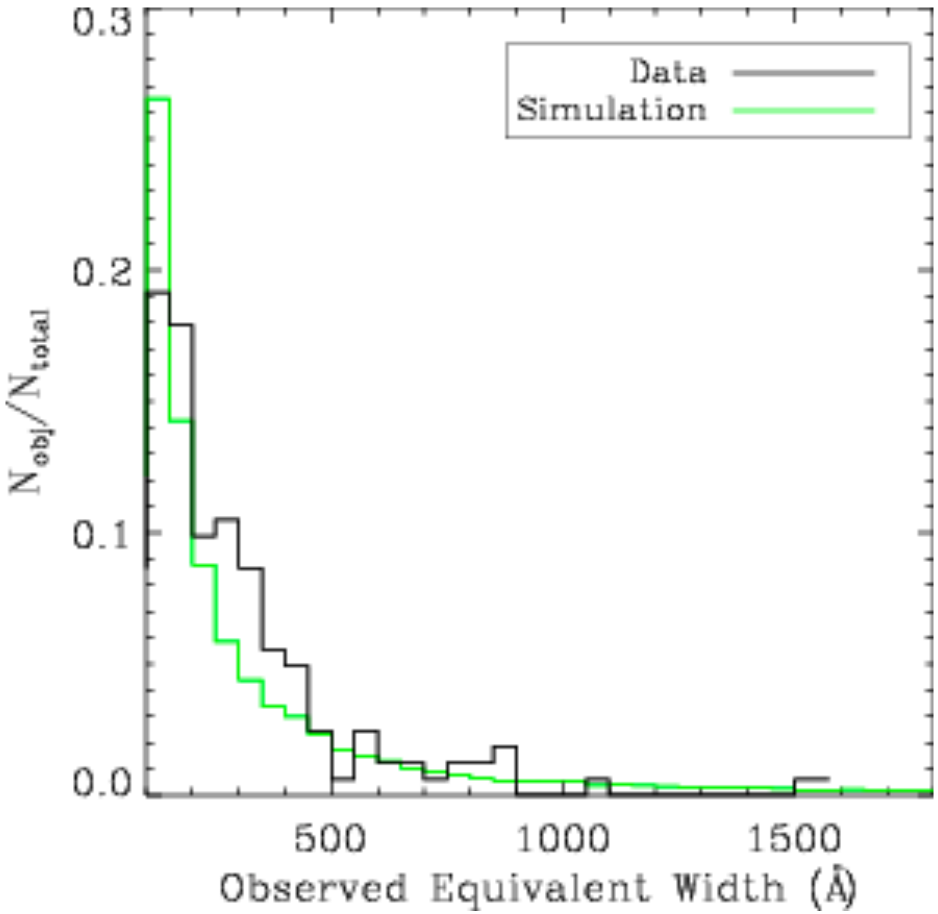
Model prediction



- intrinsic EW: no attenuation of Lyα or dust extinction of stellar continuum
- net EW: attenuation & dust extinction both included

Lyα equivalent widths

Comparison with MUSYC survey at z~3

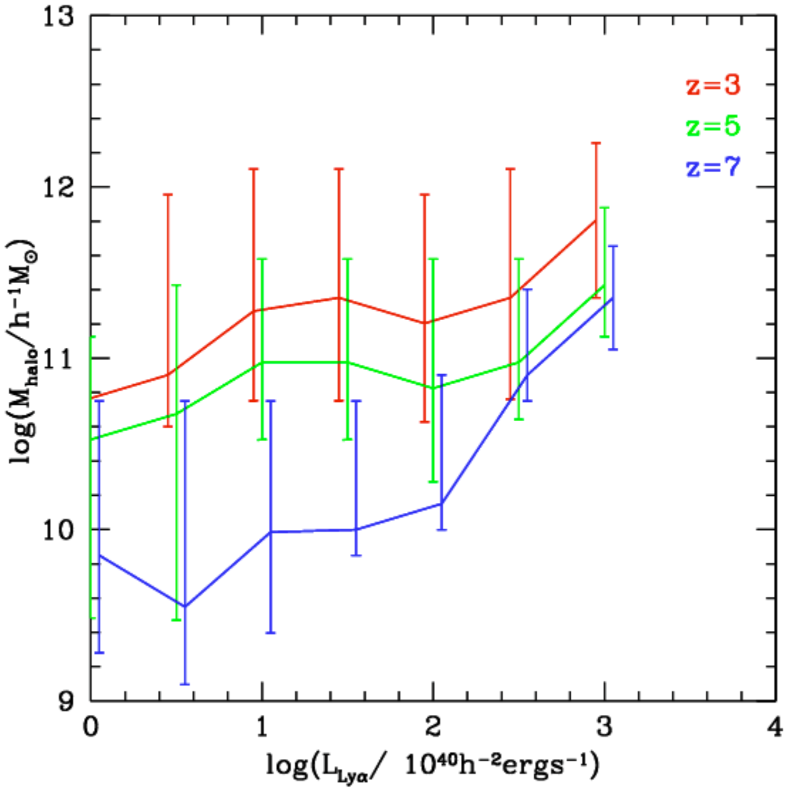


Orsi, Lacey & Baugh 08

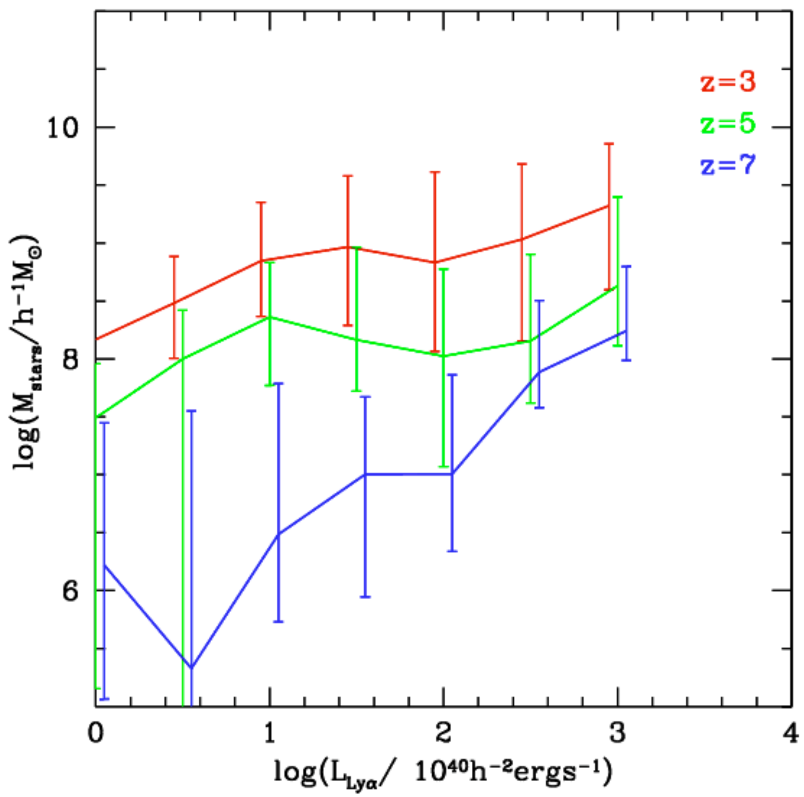
Other predicted properties of LAEs

Halo & stellar masses

DM halos

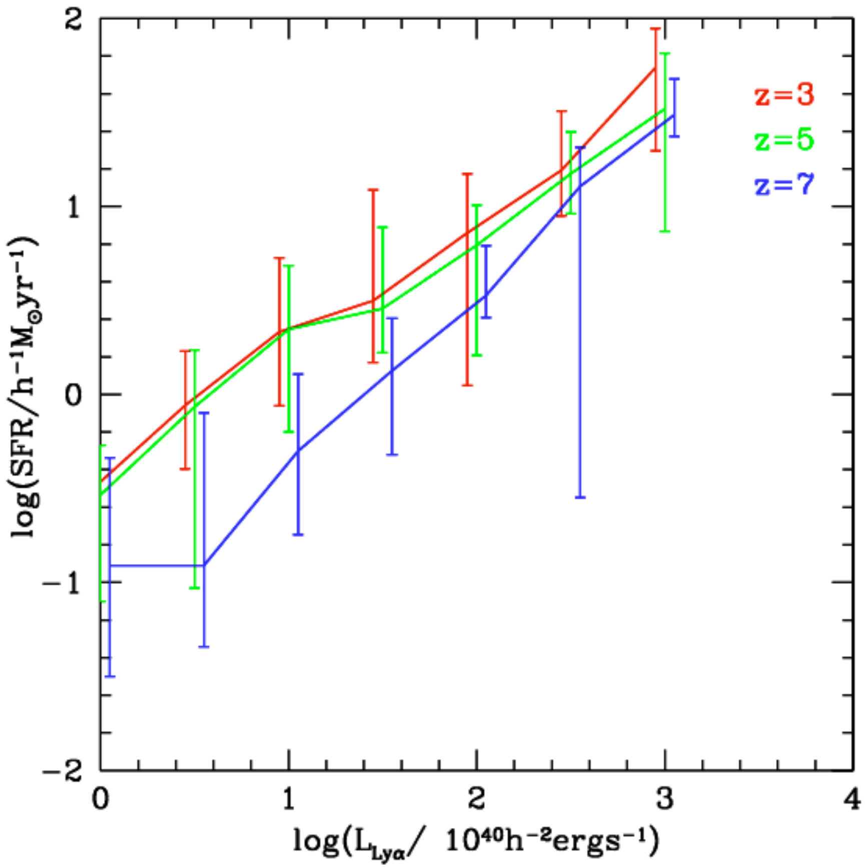


stars



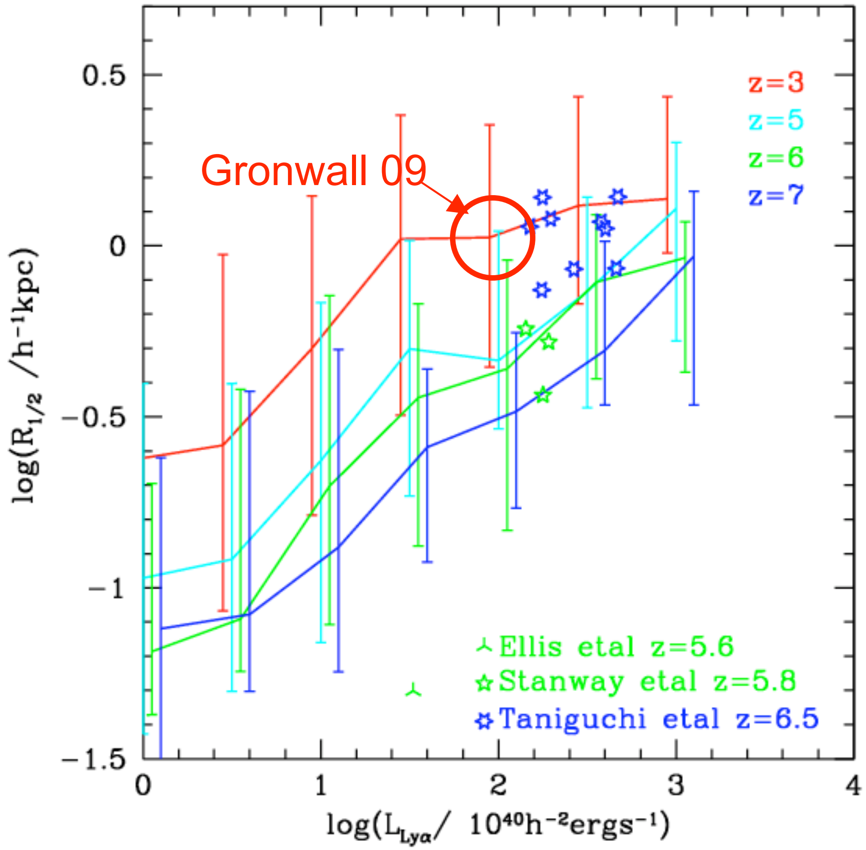
DM & stellar masses decrease at fixed L as z increases

SFRs



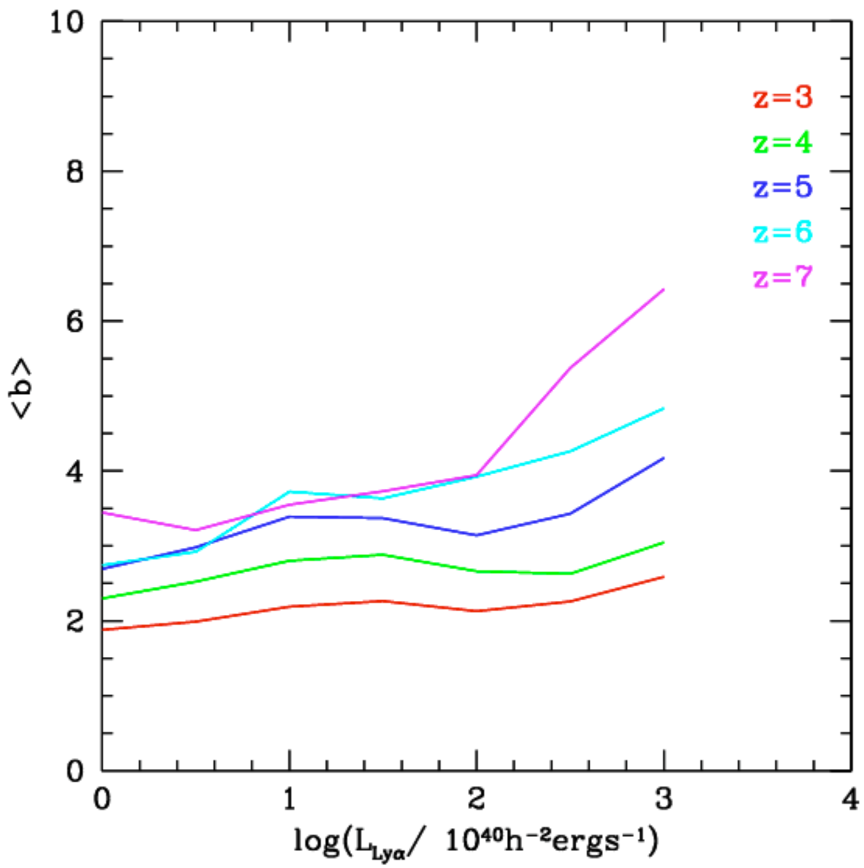
Due to top-heavy IMF in bursts, SFR ~ 10x lower at given L(Lyα) than for normal IMF (for same f_{esc})

Stellar radii



- predict stellar radii compact < 1 kpc - agrees with obs
- sizes decrease as z increases
- obs indicate that Lyα radii may be larger than stellar radii

Galaxy clustering bias



$$\xi_{gal} = b^2 \xi_{DM}$$

- Large-scale bias can be approximated by analytical linear halo bias
- predict LAEs strongly biased at high z
- bias increases with z

SEE ALVARO'S TALK TOMRROW!

Conclusions

- Model based on CDM with top-heavy IMF in bursts which matches local universe & LBGs & SMGs at high-z also approximately reproduces LFs of LAEs at z~0-7, with assumption of constant f_{esc} ~0.02
- Also agrees with obs EW distribn & stellar continuum sizes
- Predicted clustering also agrees with obs - see Alvaro’s talk