Theoretical modelling of galaxy evolution in the far-IR & sub-mm

Cedric Lacey

collaborators: Carlton Baugh, Carlos Frenk, Andrew Benson, Richard Bower

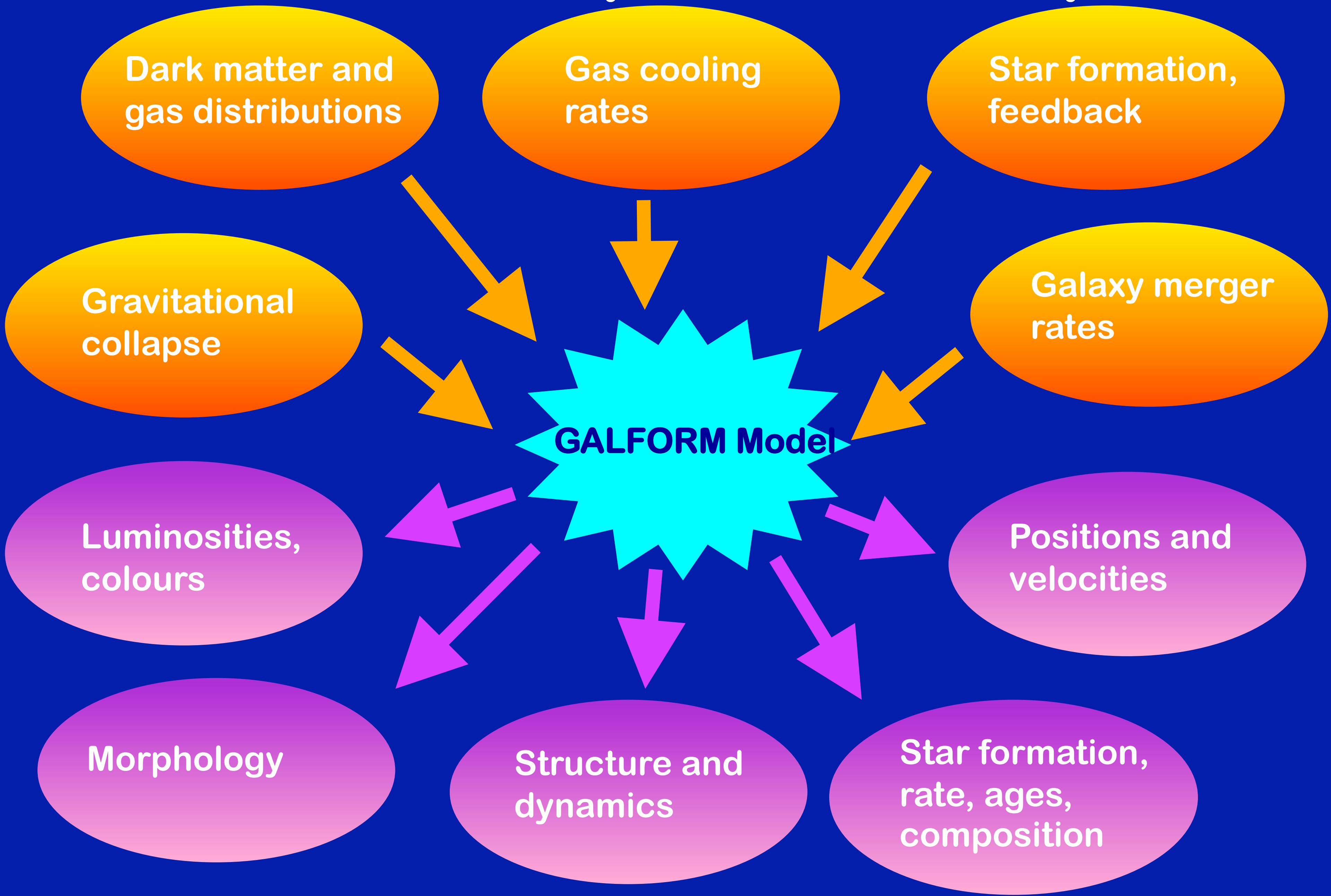
Durham University

ICC Institute for Computational Cosmology

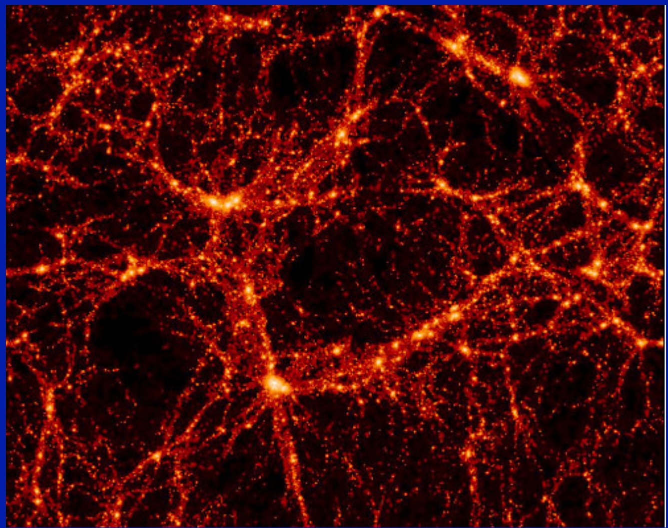
Outline

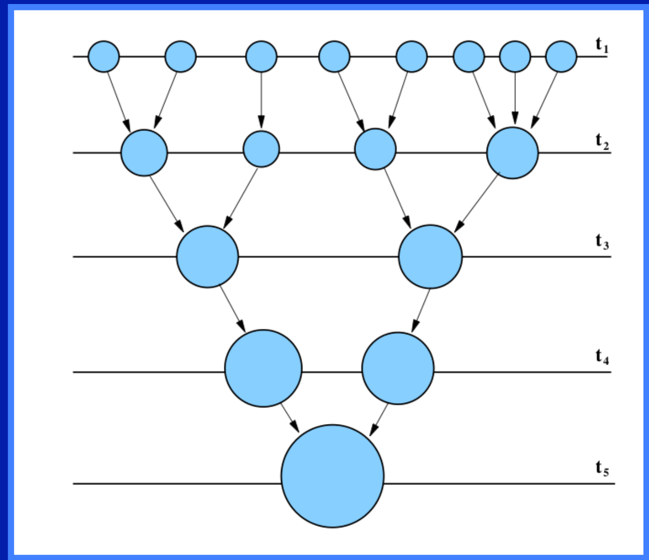
- modelling galaxy formation in ΛCDM
- SEDs & dust
- old model – successes & problems
- new model
- conclusions

GALFORM: inputs and outputs



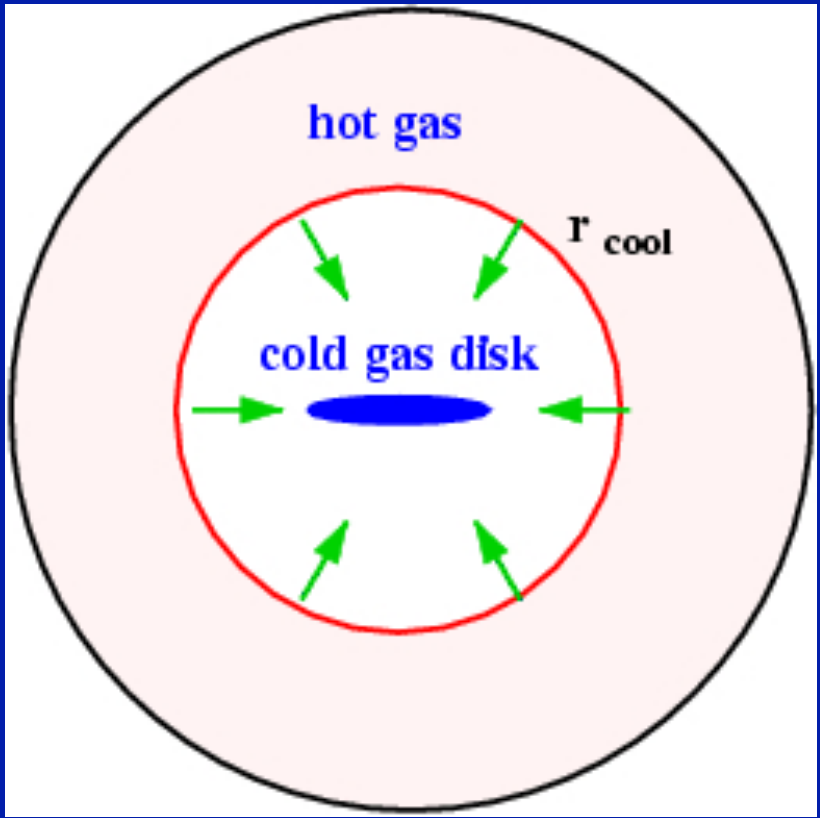
Assembly of dark matter halos: Merger trees





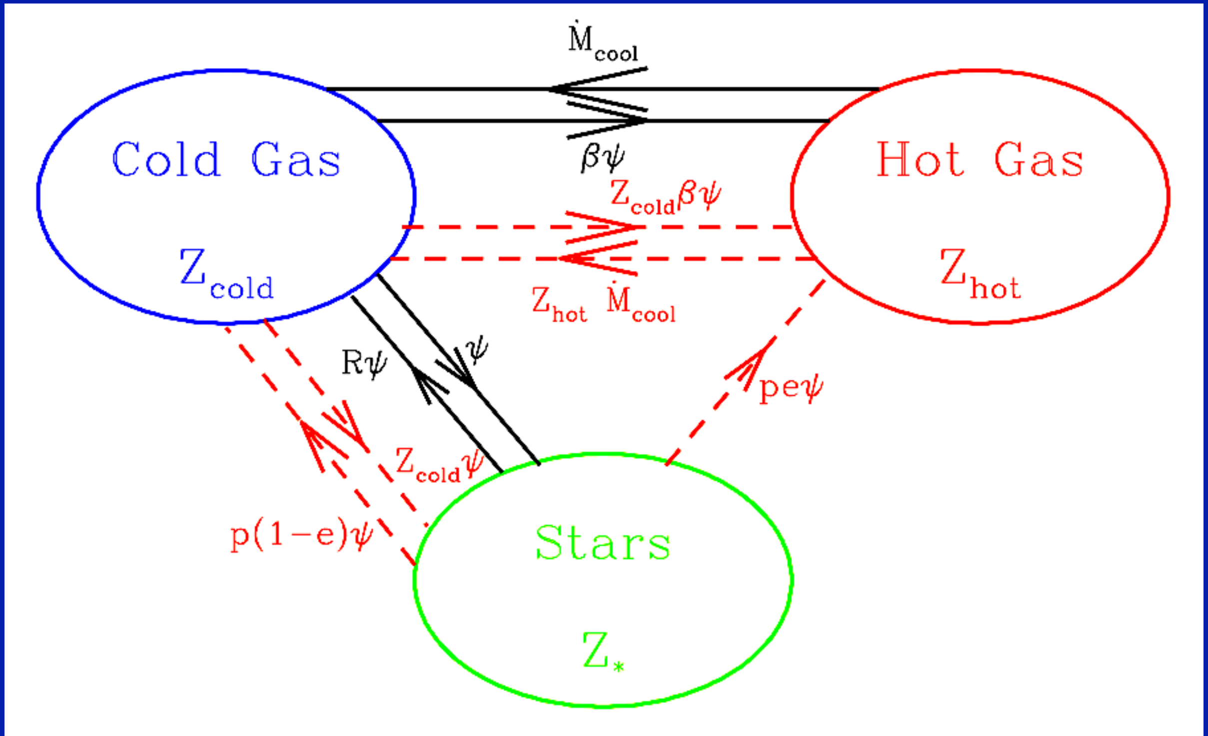
- **Monte Carlo - based on Extended Press-Schechter**
  OR
- **Extract from N-body simulations**

Shock-heating & cooling of gas in halos



- Infalling gas all shock -heated to halo virial temperature
- Radiative cooling and infall of gas from static spherical distribution
- Disk size related to angular momentum of gas which cools

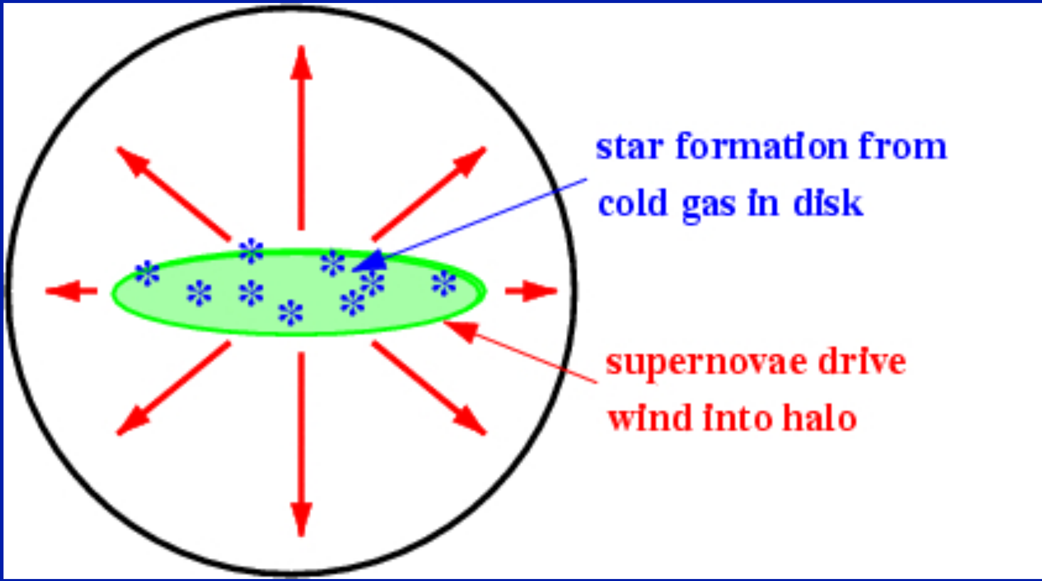
Evolution of baryons



$$\dot{M}_{cold} = \dot{M}_{cool} - (1 - R + \beta)\psi$$
$$\dot{M}_{\star} = (1 - R)\psi$$
$$\dot{M}_{hot} = -\dot{M}_{cool} + \beta\psi$$

Cole+00

Star formation & SN feedback



SFR & mass ejection

SFR

$$\psi = \frac{M_{\rm cold}}{\tau_\star(r_{\rm disk}, V_{\rm disk})}$$

$$\dot{M}_{\rm eject} = \beta(V_{\rm disk})\,\psi$$

SFR timescale

$$\tau_\star \propto V_{\rm disk}^{\alpha_\star}$$

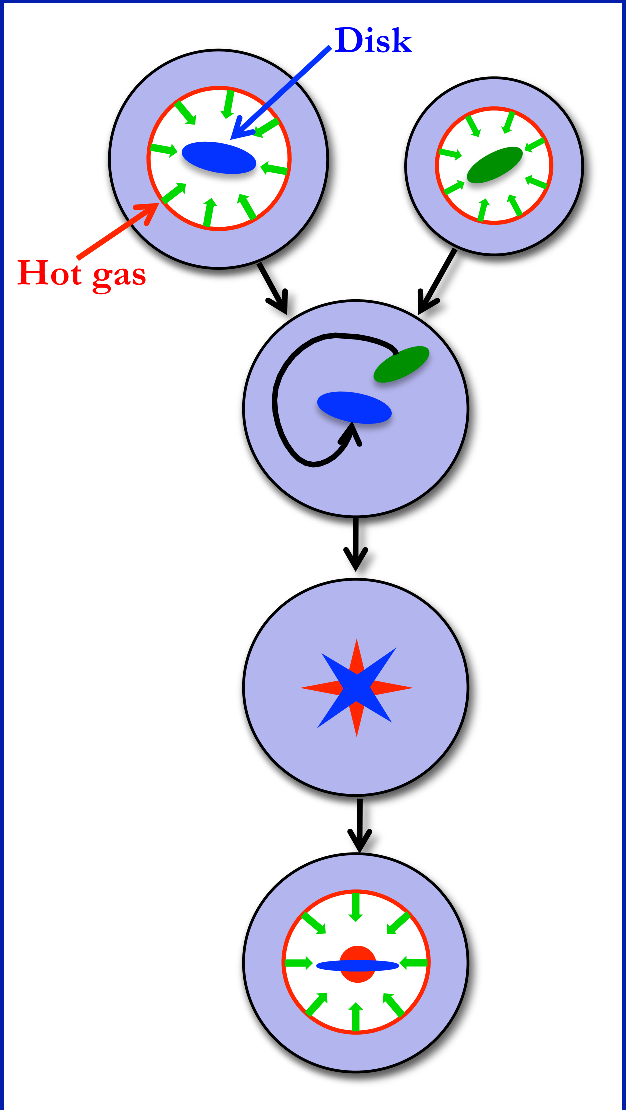
$$\tau_\star \propto \tau_{\rm dyn,disk}\, V_{\rm disk}^{\alpha_\star}$$

SN feedback efficiency

$$\beta = (V_{\rm disk}/V_{\rm hot})^{-\alpha_{\rm hot}}$$

Cole+00

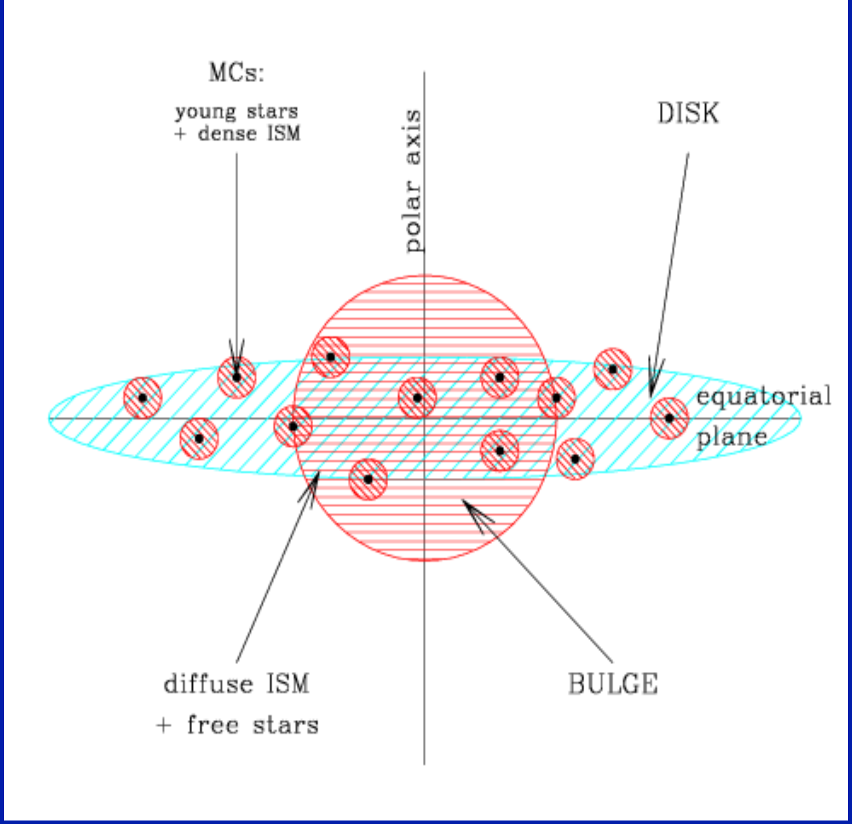
Mergers, morphology & starbursts



- gas cools in DM halos to form disks
- halos merge
- satellite galaxies sink by dynamical friction in halo & merge with central galaxy
- mergers trigger starbursts & spheroid formation
- spheroids can grow new disks by further gas cooling

Modelling galaxy SEDs with dust

- dust in diffuse medium and molecular clouds
- stars form in clouds and leak out
- Stellar luminosity from pop synthesis
- radiative transfer of starlight through dust
- physical dust grain model
- heating/cooling of dust grains
  -> dust temperature
  -> IR/sub-mm emission



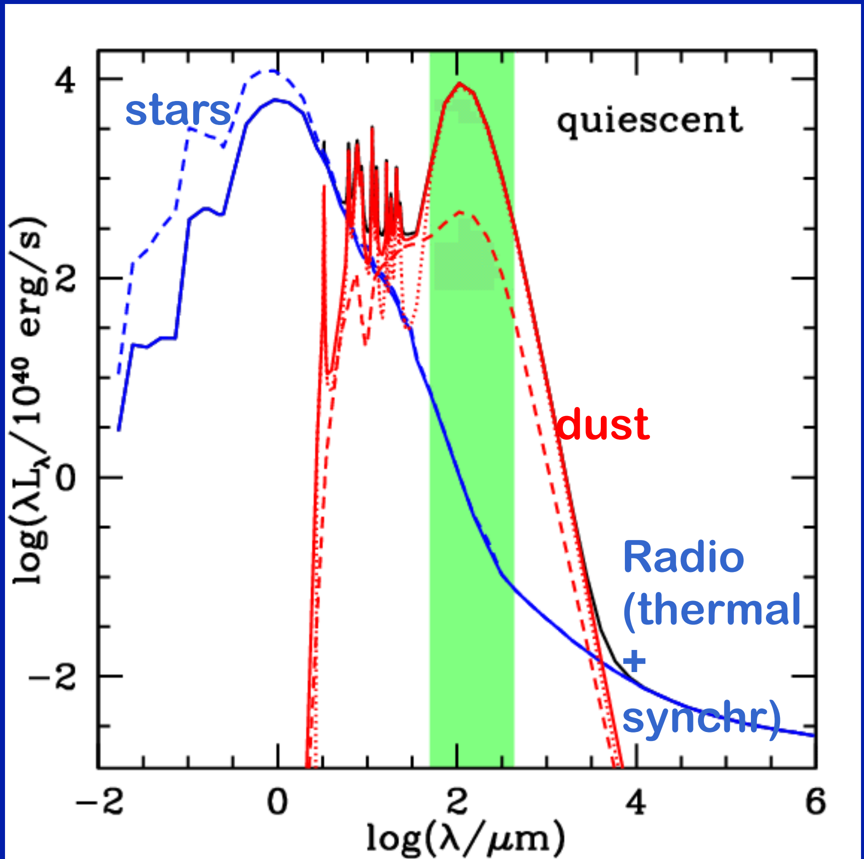
SEDs with dust

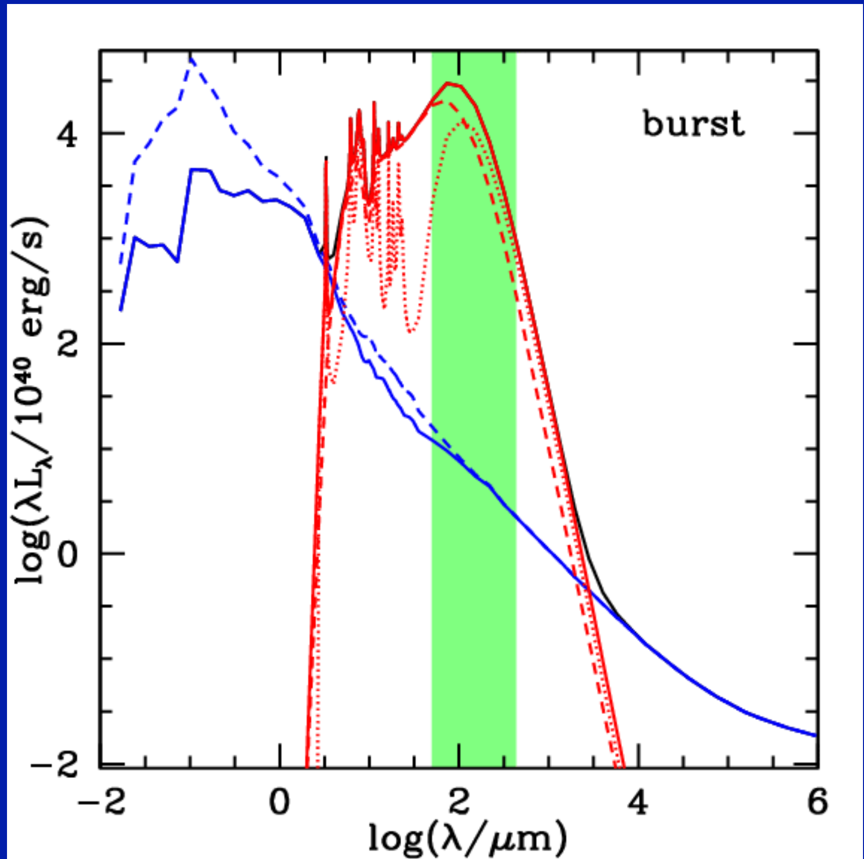
- dust grain model chosen to reproduce local ISM
- assume dust/gas proportional to gas metallicity
- optical depth for diffuse dust calcd from dust mass and galaxy radius (predicted by GALFORM)
- self-consistent calc of dust extinction & emission

- predicts range of extinctions for stars
- mean extinction depends on stellar age

Example SEDs of galaxies from GALFORM+GRASIL model

Quiescent spiral | **Ongoing burst**





Lacey+10

Sub-mm galaxies: a challenge to hierarchical galaxy formation models

- How to explain the number counts AND redshift distributions of faint sub-mm galaxies (SMGs)?
  - in the framework of ΛCDM structure formation
  - while ALSO reproducing properties of present-day galaxy population (optical, near-IR & far-IR LFs, gas fractions, metallicities, galaxy sizes etc)
- seem to need varying IMF

Baugh et al (2005) model

- Quiescent star formation timescale in disks

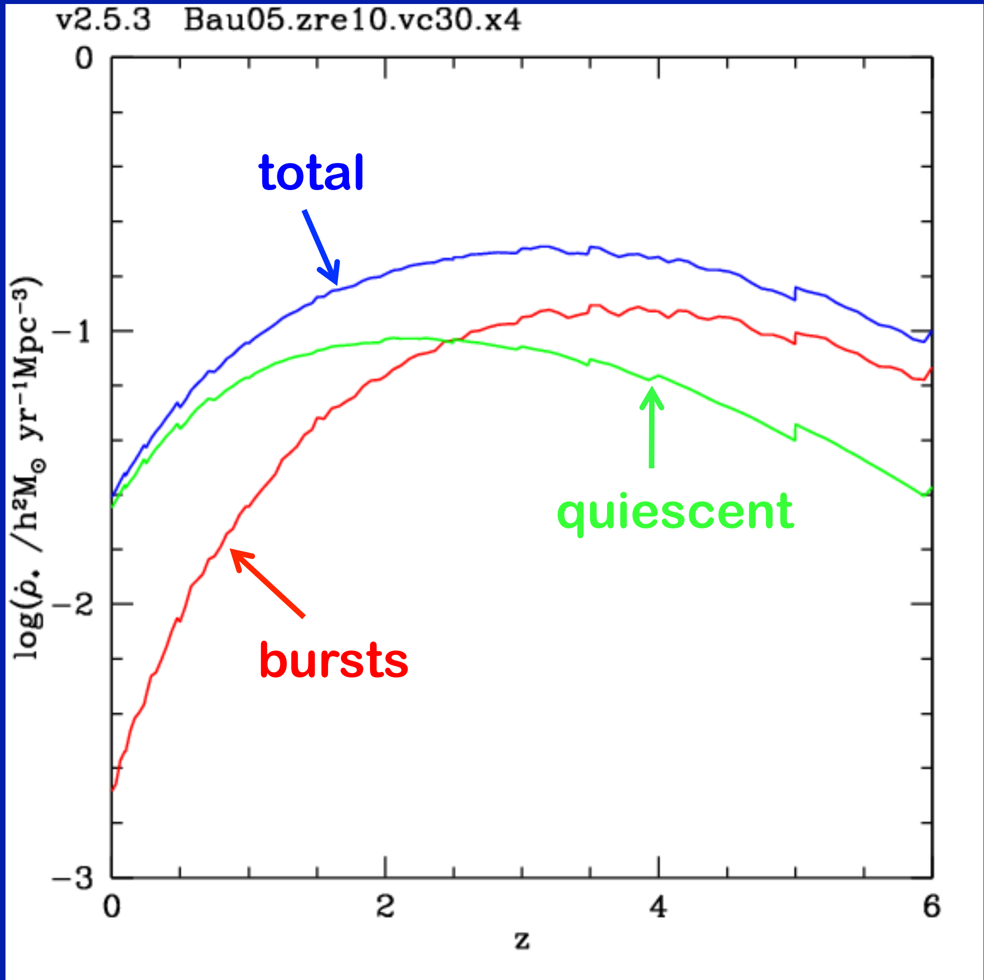
$$\tau_* \approx const$$

- Starbursts triggered by galaxy mergers
- SN-driven superwinds reduce gas density & inhibit cooling in massive halos
- Top-heavy IMF in starbursts (x=0, c.f. x=1.3-1.5 in solar neighbourhood)

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

Baugh, Lacey, Frenk etal 2005

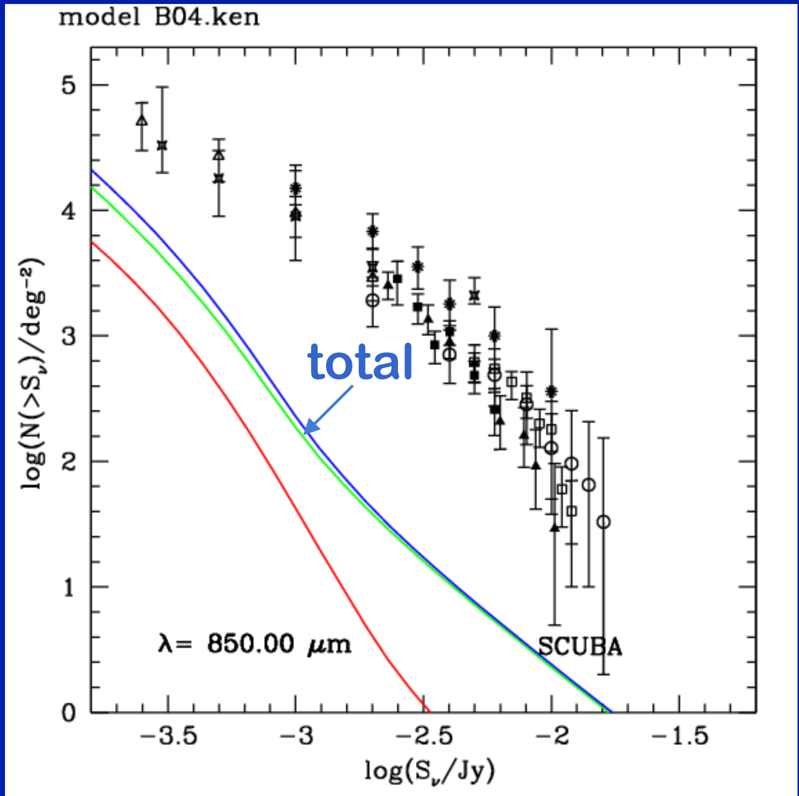
Cosmic SFR history – quiescent vs bursts

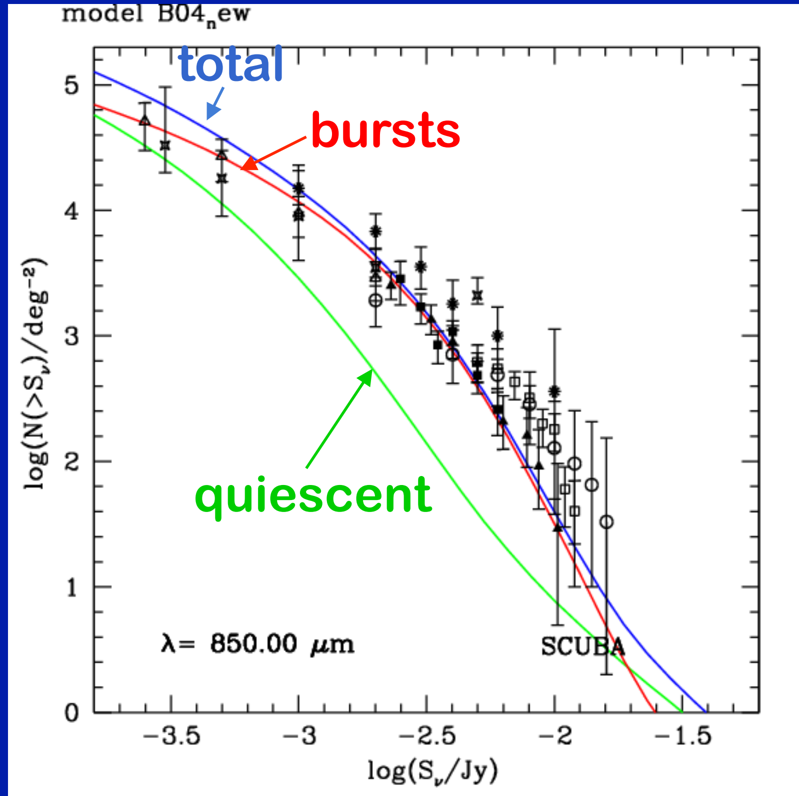


- model predicts SF mostly in quiescent mode (with normal IMF) at low z, but in burst mode (with top-heavy IMF) at high-z
- so average IMF changes with z

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

normal IMF | **top-heavy IMF**





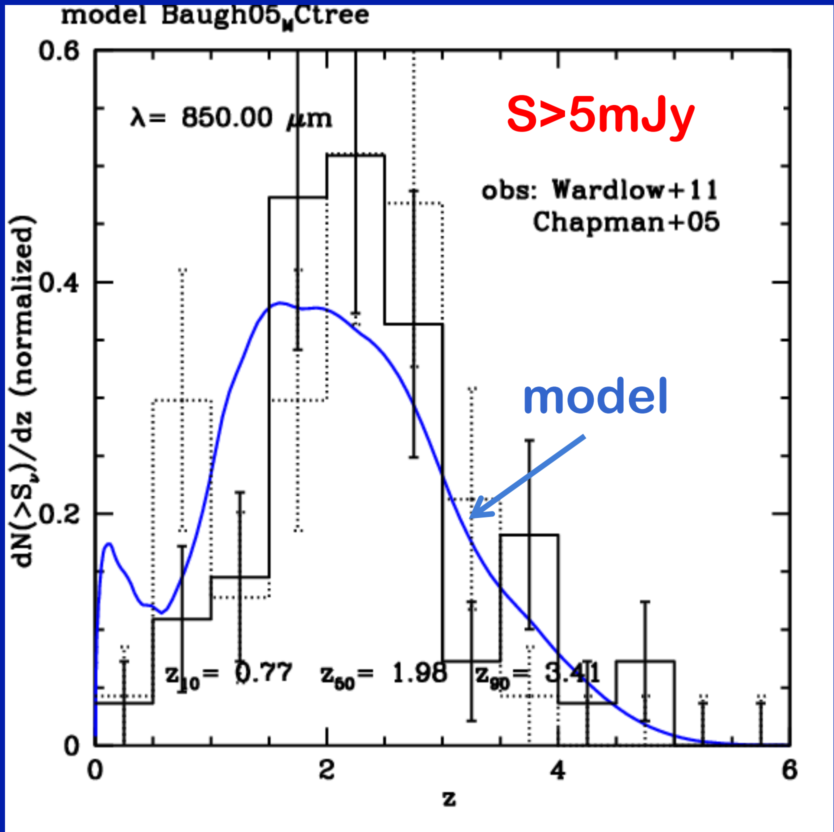
Sub-mm counts too low by factor ~50 for normal IMF

Baugh+05

How does top-heavy IMF help?

- starbursts have higher intrinsic UV luminosities for given SFR
- more metals from SNII => more dust => lower T_{dust}

Redshifts of sub-mm galaxies



Median z~2 for S(850)>5mJy

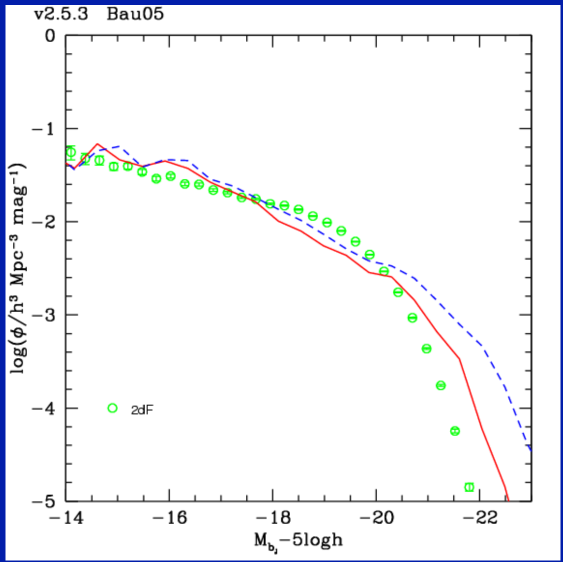
For model to reproduce simultaneously:

- observed SMG number counts AND redshifts
- present-day galaxy properties (including opt/NIR LFs)
- in CDM framework

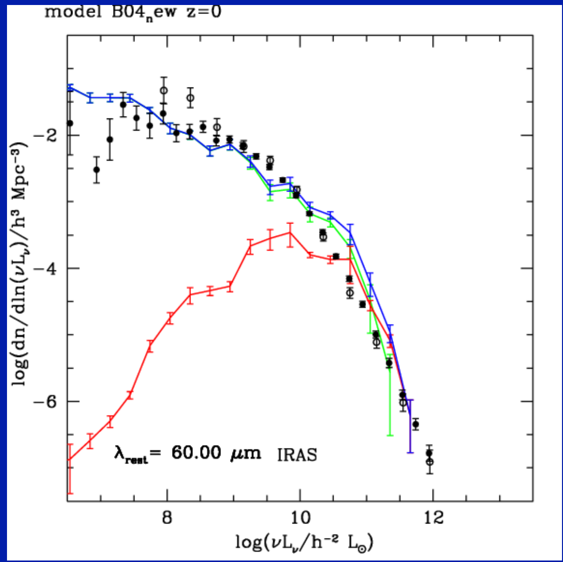
- need top-heavy IMF

Obs constraints at z=0

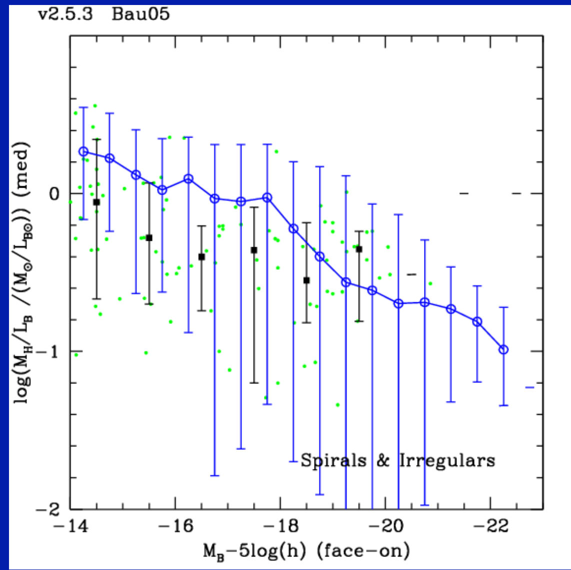
B-band LF



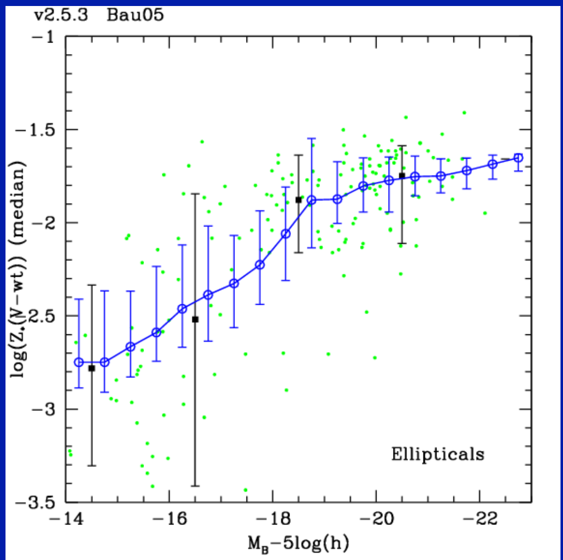
60 μm LF



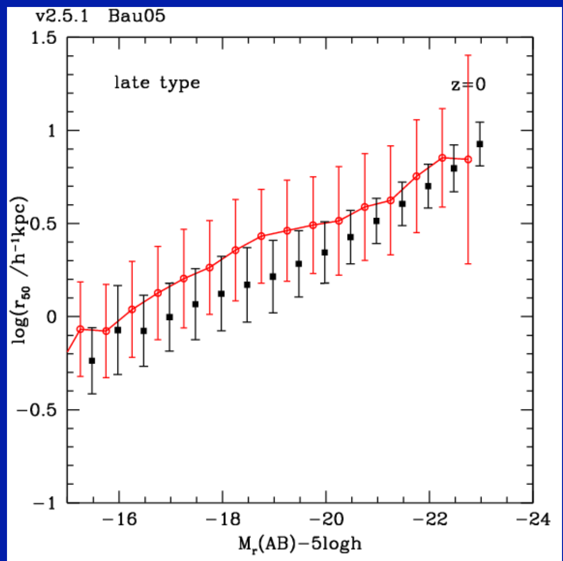
gas fractions



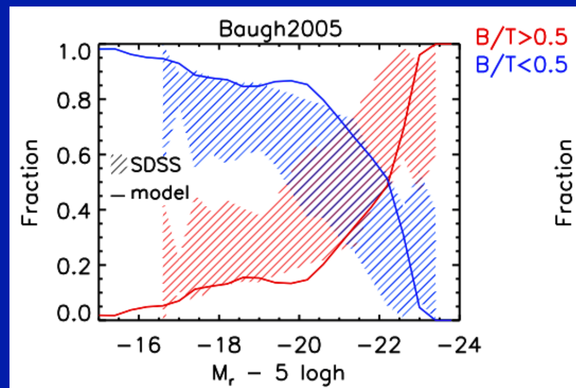
stellar metallicity in spheroids



disk radii

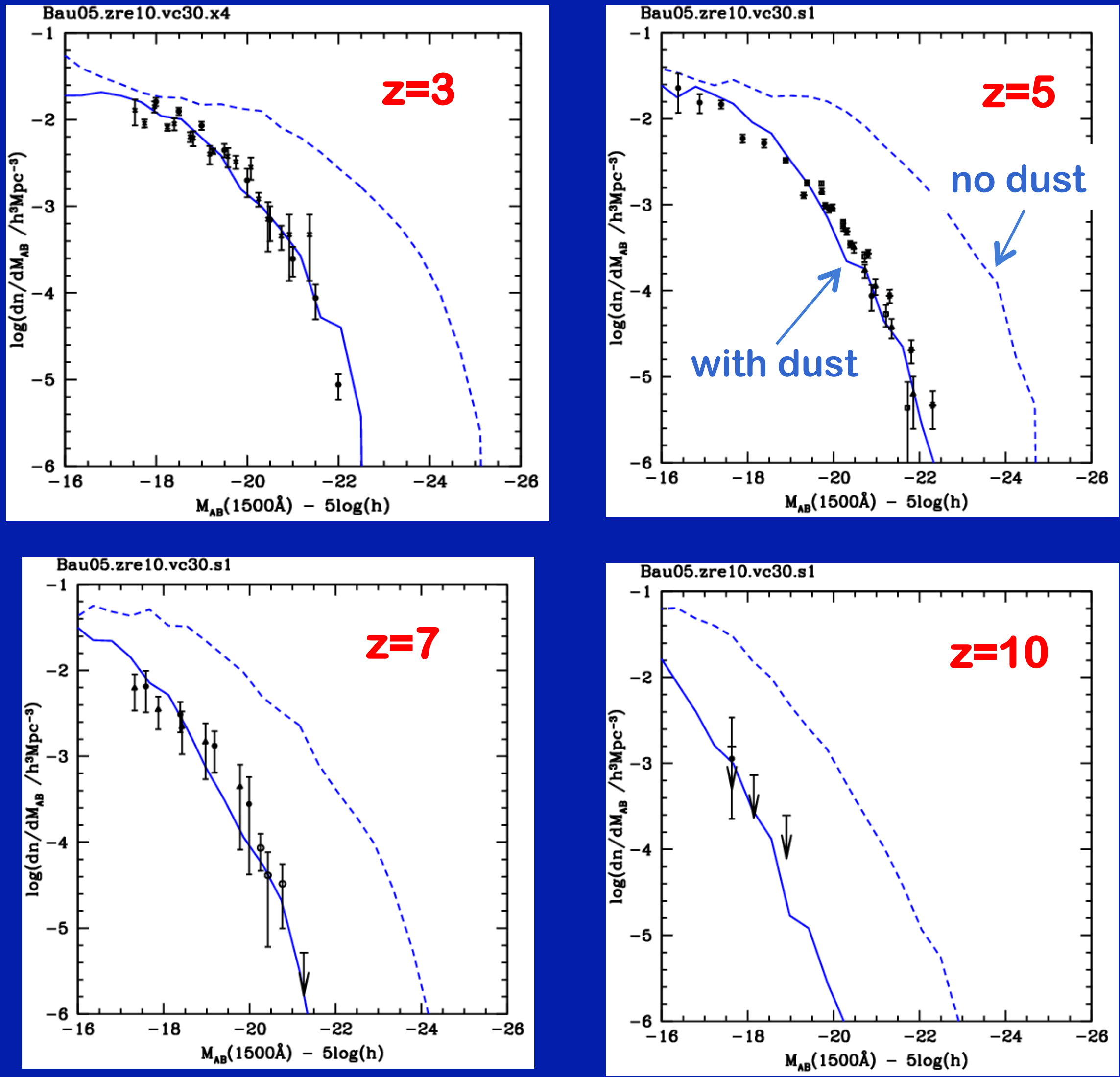


early/late-type fractions



Baugh05 model

far-UV LF – comparison with Lyman-break galaxies



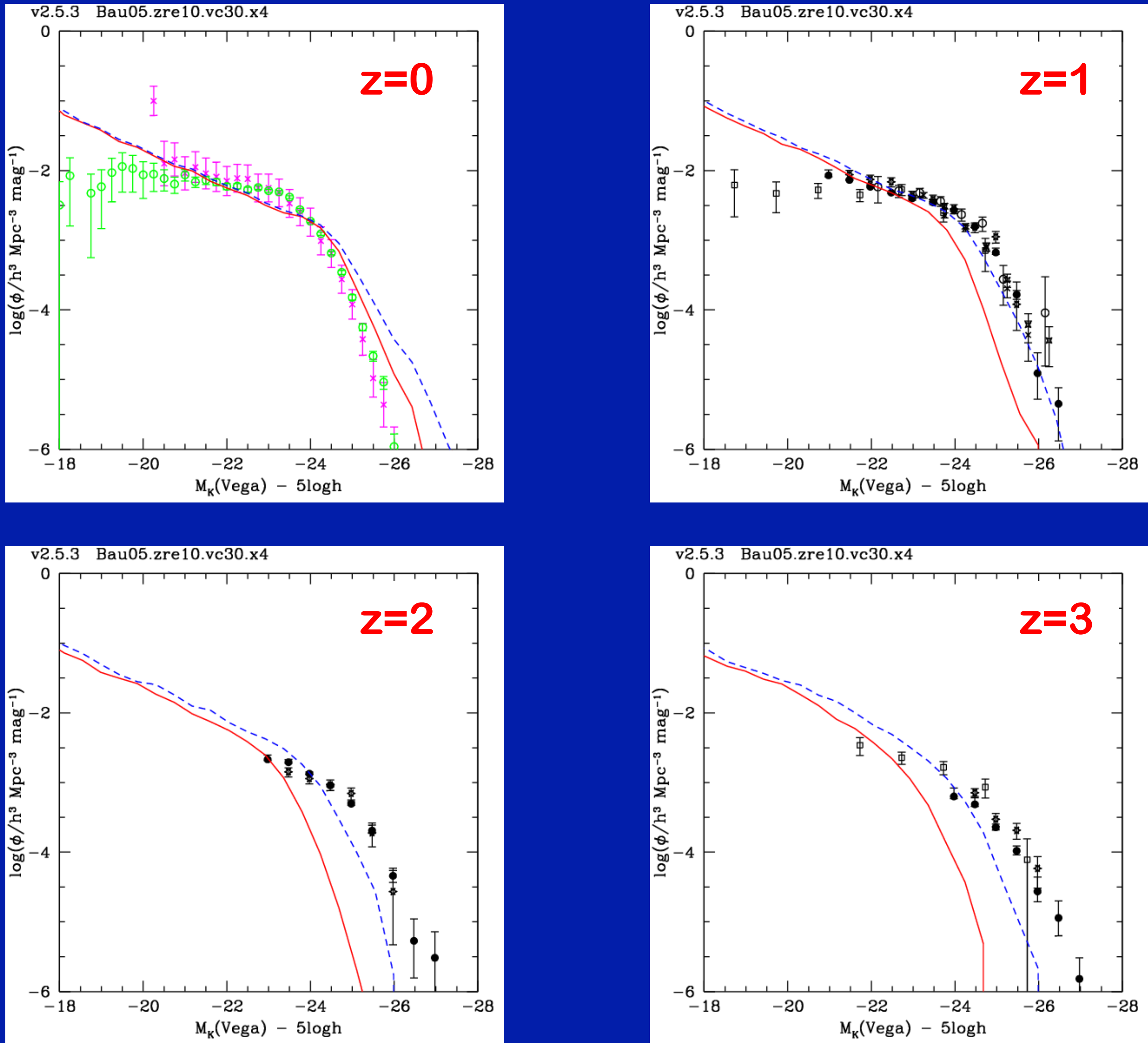
- Model based on CDM with top-heavy IMF in starbursts agrees with observed LF of Lyman-break galaxies from z=3 up to z=10
- model predicts large UV extinctions (~ 2 mag) due to large metal production by top-heavy IMF

Lacey+11

Some problems with old model

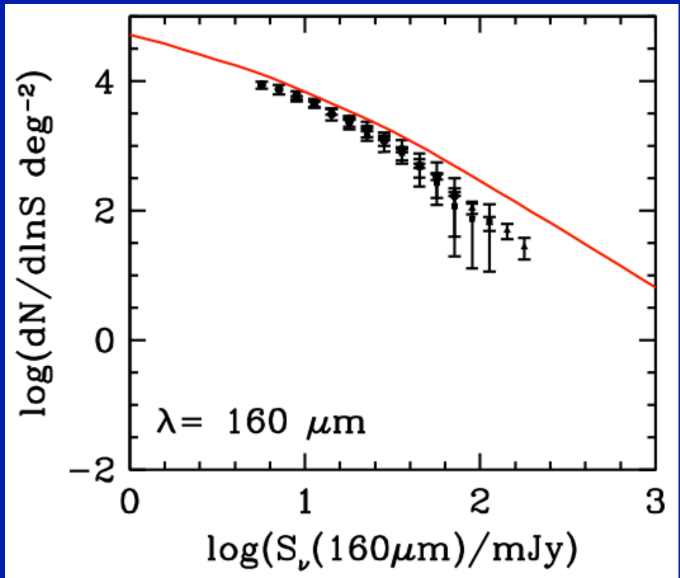
- evolution of K-band luminosity function
  - too few bright galaxies at higher z
  - stellar mass builds up too slowly in high-mass galaxies
- far-IR number counts & low-z LFs compared to Herschel data
  - counts too high at bright fluxes, due to too many bright galaxies in local FIR LF

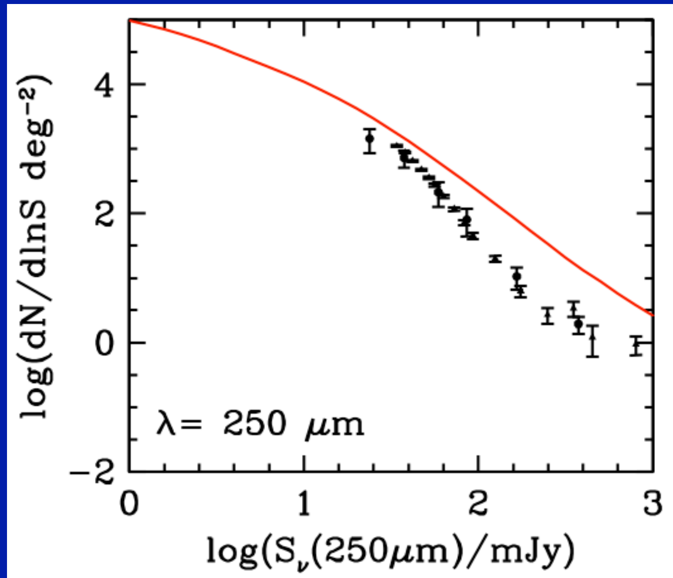
Evolution of K-band LF

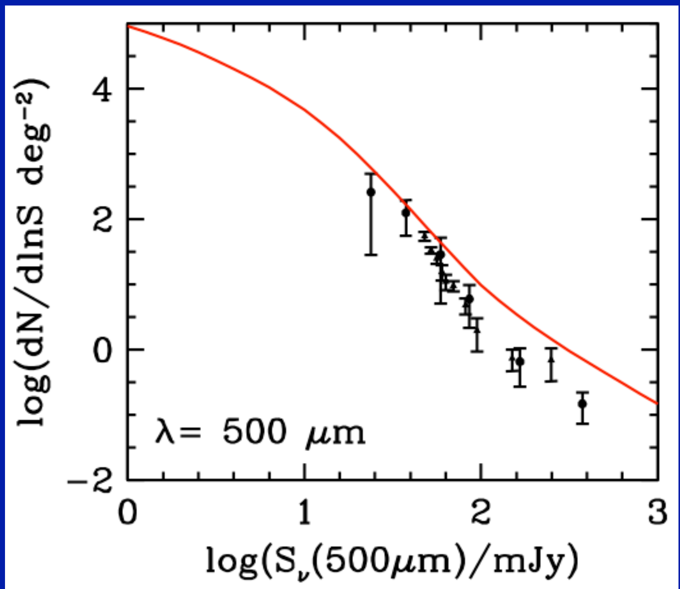


Baugh05 model

far-IR number counts







- counts in Herschel bands too high at bright fluxes
- due to too many bright galaxies in FIR LF at low z

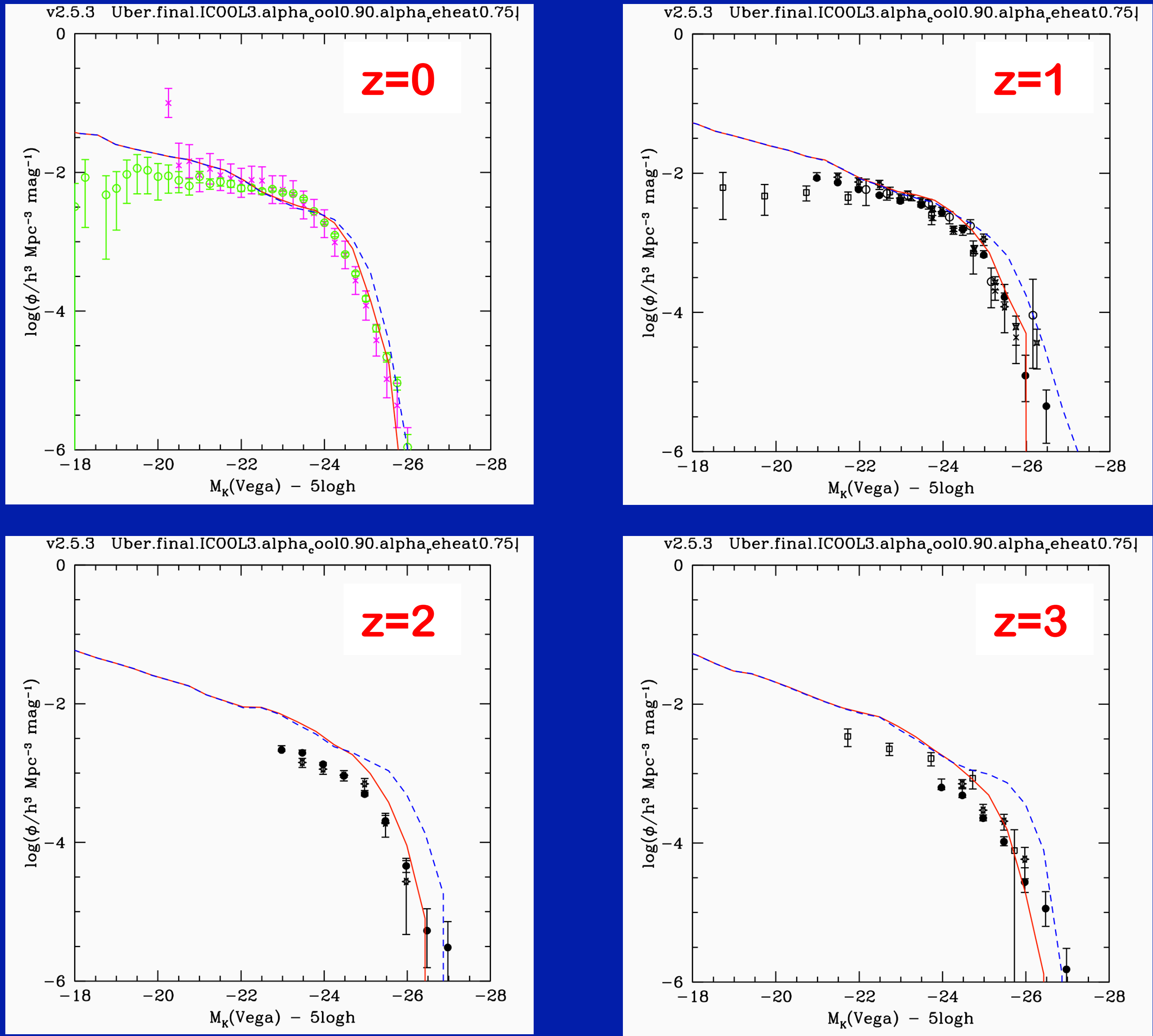
Lacey+10

New model

- includes AGN feedback & bursts triggered by disk instabilities (as in Bower+06)
- new star formation law (Lagos+11) (see Claudia Lagos' talk)
- also changes in SN feedback, return timescales for ejected gas, etc
- still need top-heavy IMF in bursts (as in Baugh+05)
  - but less extreme tilt (x=1 vs x=0)

Lacey+12, in prep

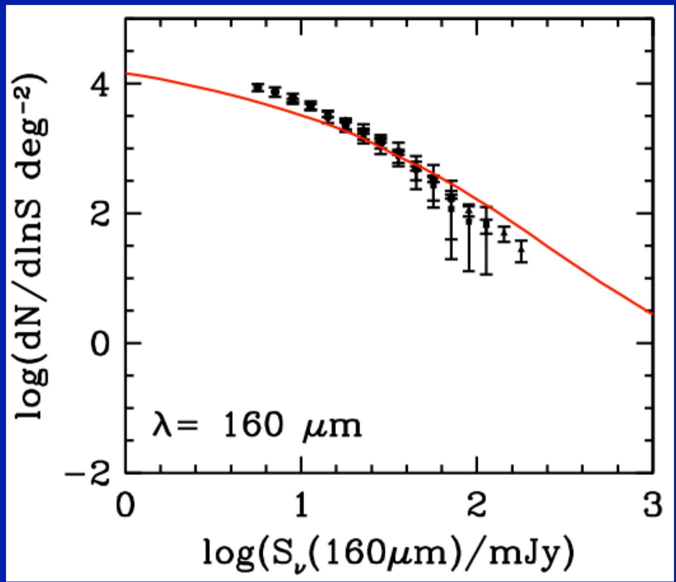
Evolution of K-band LF

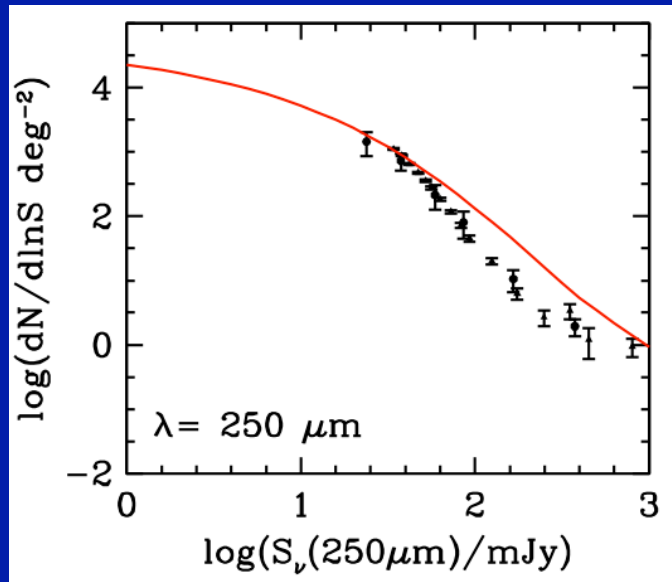


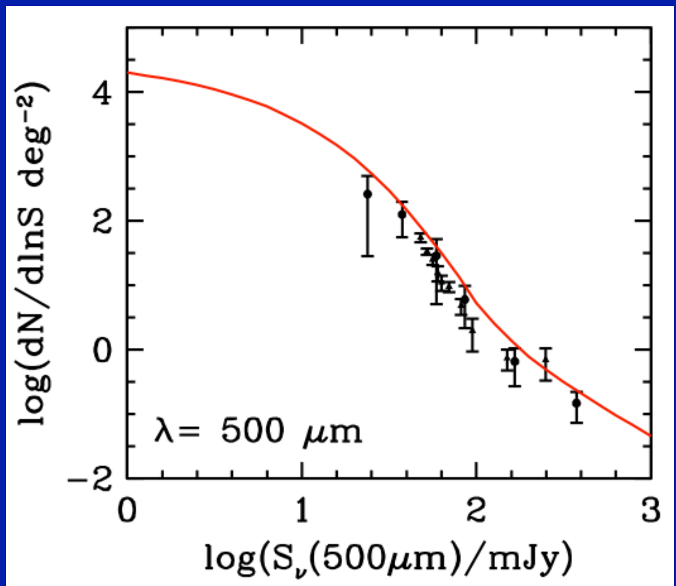
new model

Lacey+12

far-IR number counts







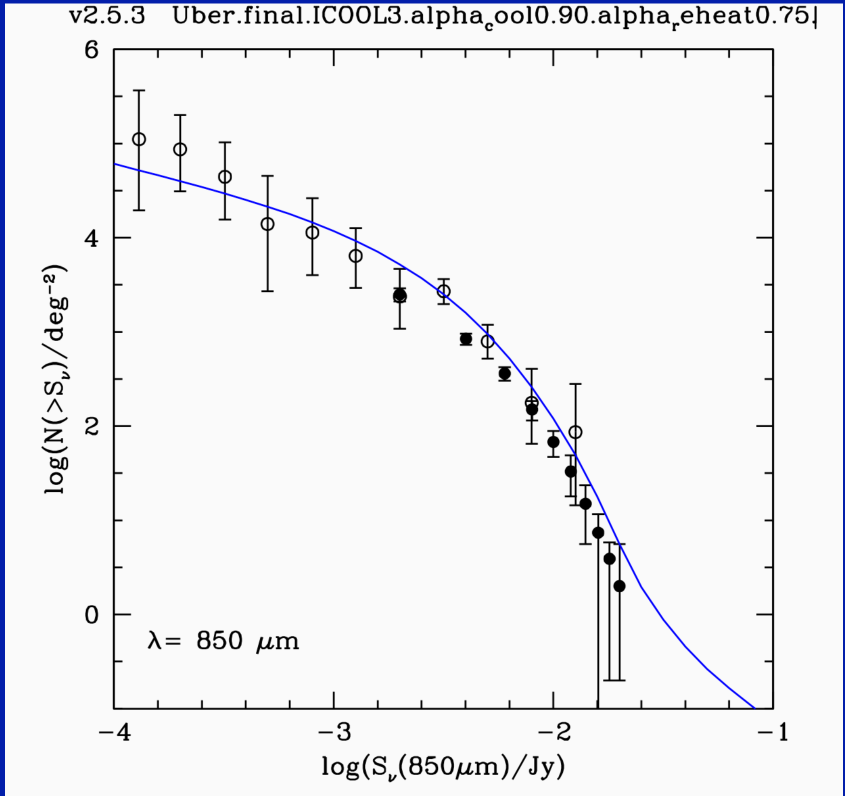
- improved match to bright Herschel counts, though still differences at 250 μm

new model

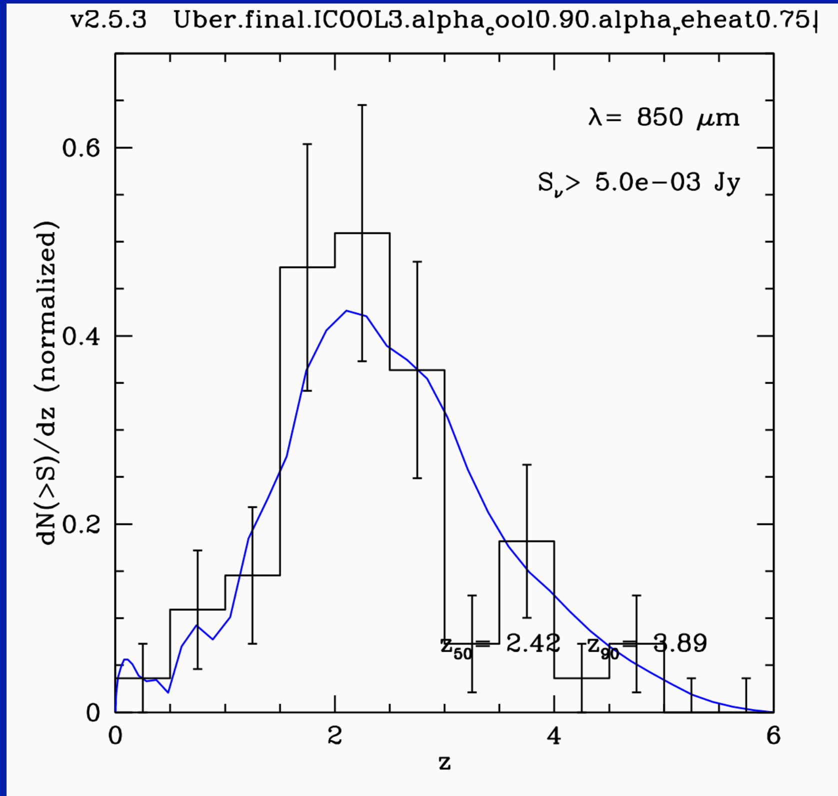
Lacey+12

Sub-mm galaxies

850 μm number counts



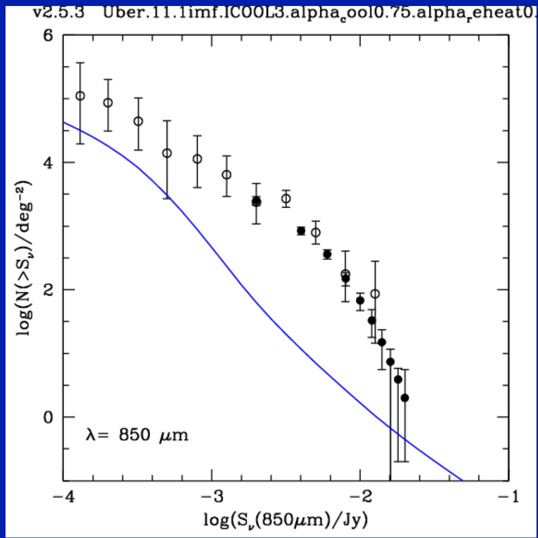
dN/dz for S(850)>5mJy



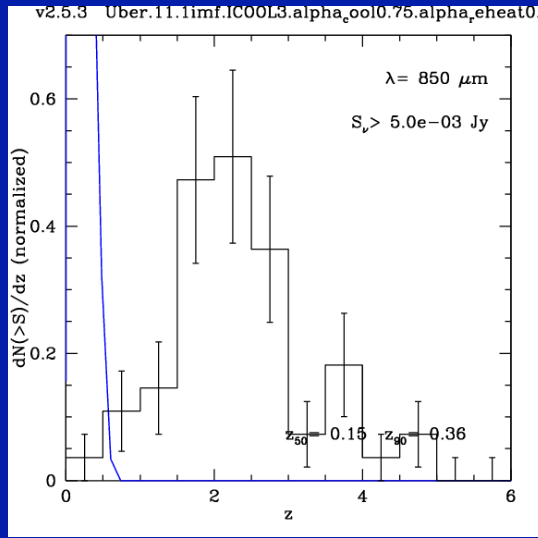
new model

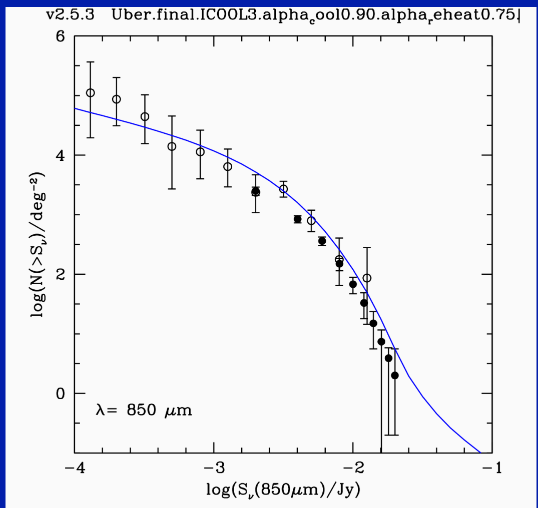
Sub-mm galaxies: effect of top-heavy IMF in bursts

counts | **dN/dz**

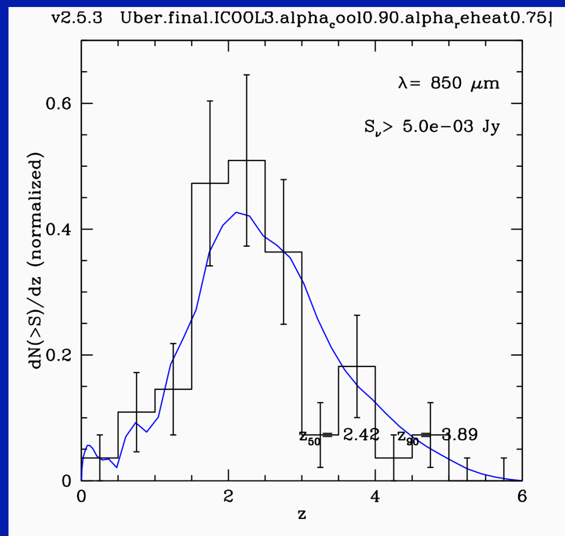


normal IMF (Kennicutt)





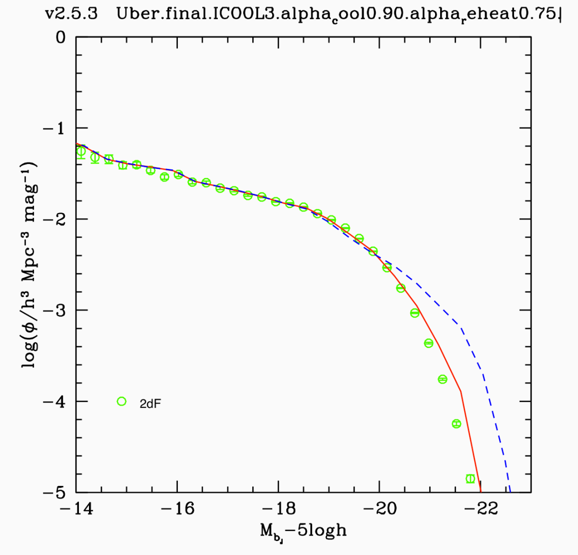
top-heavy IMF (x=1)



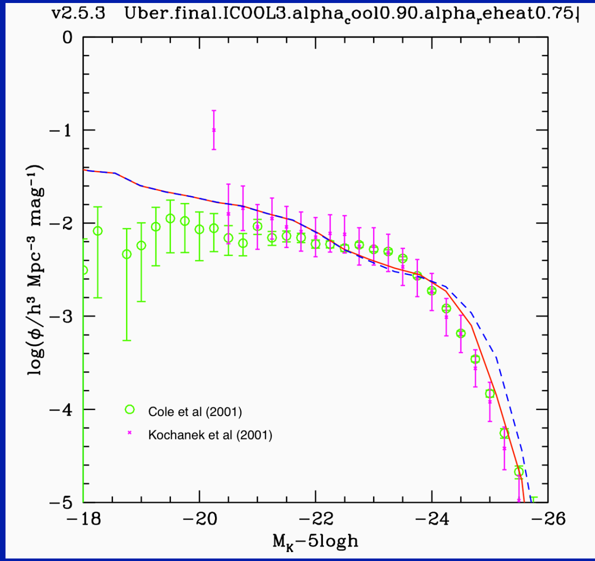
new model

Obs constraints at z=0

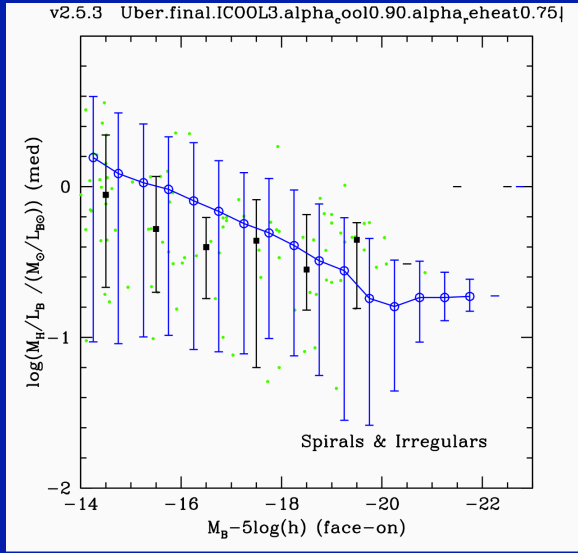
B-band LF



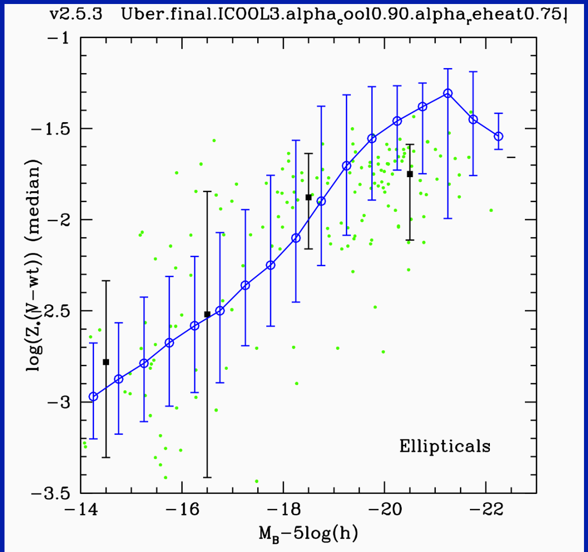
K-band LF



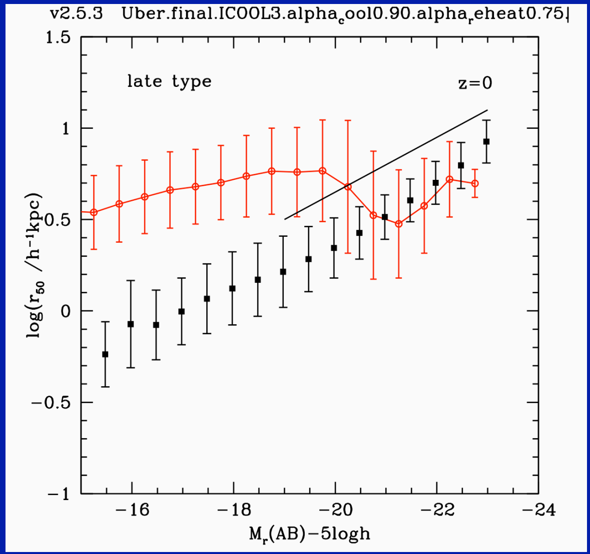
gas fractions



stellar metallicity in spheroids

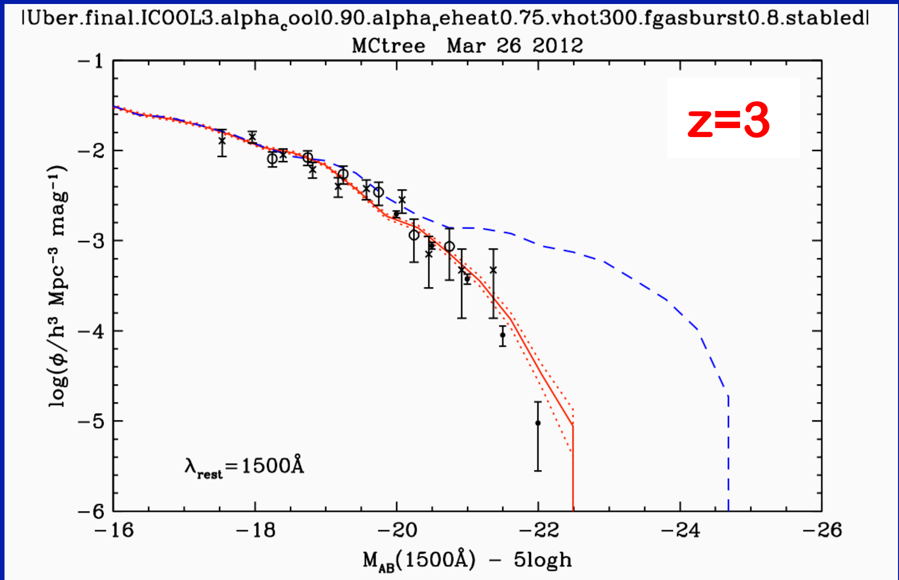


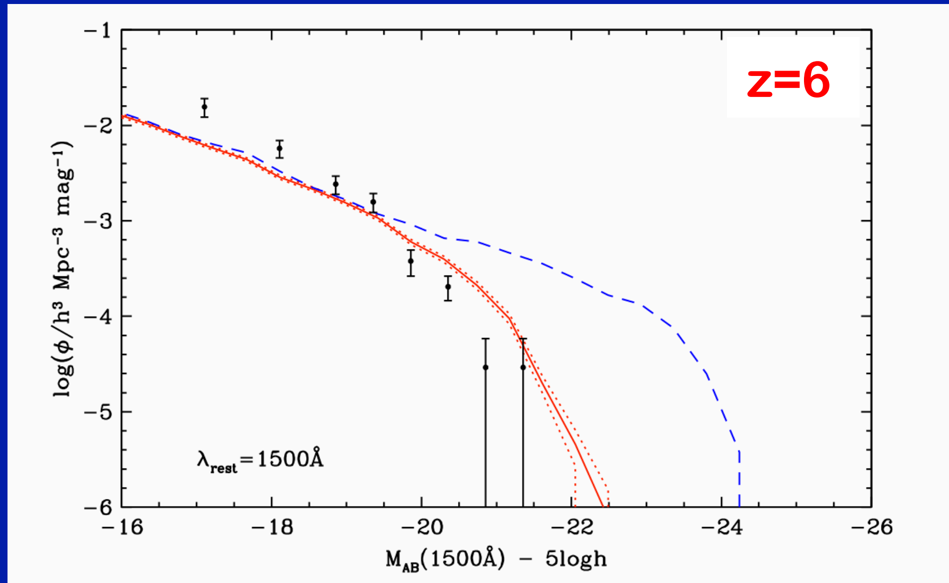
disk radii



new model

Lyman-break galaxies





new model

Conclusions

- explaining number counts & redshifts of SMGs in ΛCDM framework while also reproducing properties of present-day galaxies still seems to require variations in IMF, with top-heavy IMF in starbursts at high-z – but less extreme starburst IMF than before
- improved agreement with evolution of K-band LF & Herschel far-IR counts, due to AGN feedback and new SF law in disks