Sub-mm galaxies

as a test of semi-analytical models

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Outline

- Physical processes
- Multi-wavelength modelling
  - Dust and radio emission
- Sub-mm galaxies
  - Why important?
  - Need for IMF variations?
- Multi-wavelength observational comparison with SMGs
- What have we learned & future directions

Collaborators

Galaxy formation models (GALFORM):

- Carlton Baugh Durham
- Carlos Frenk Durham

  + other members GALFORM team

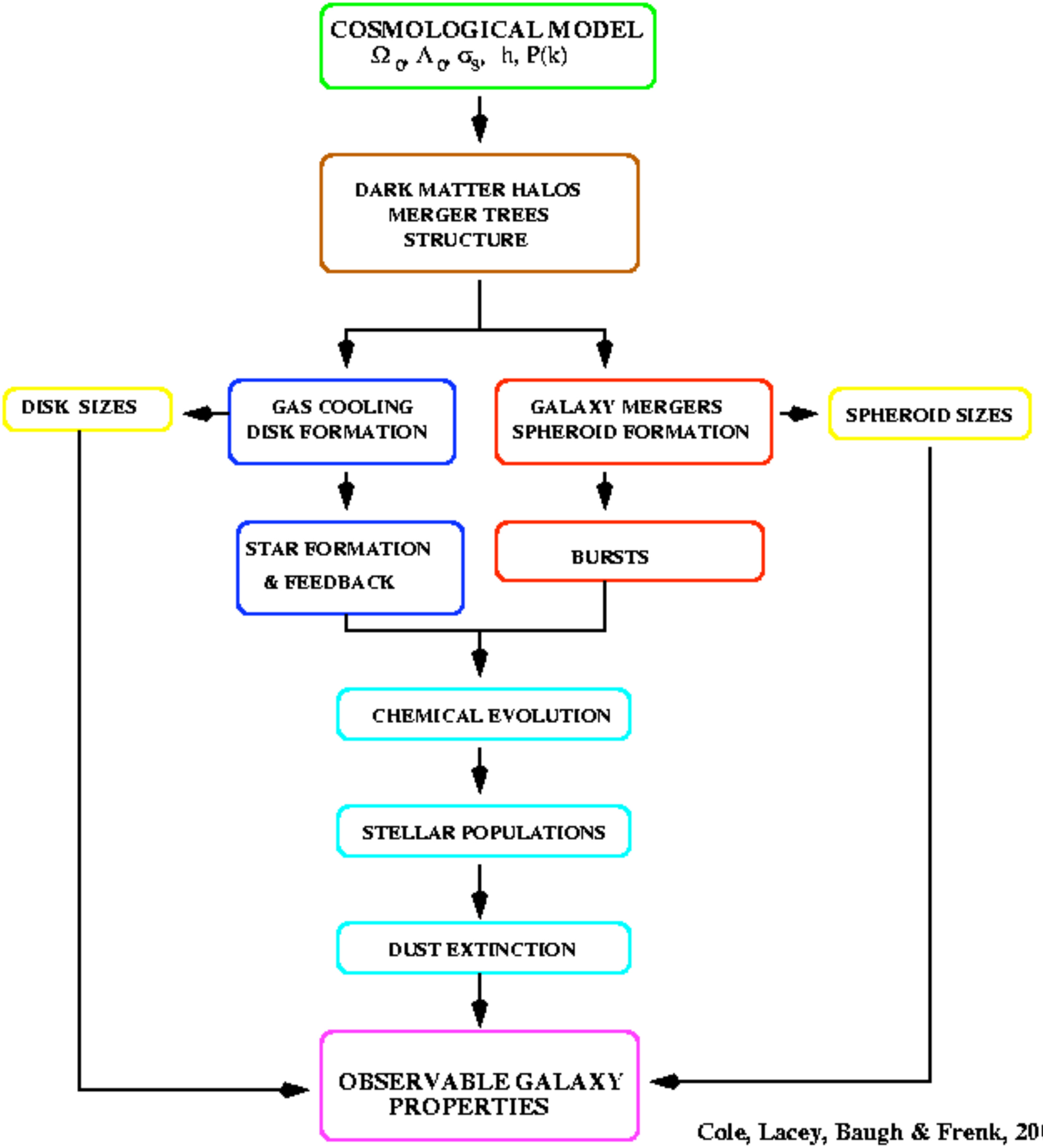
Dust Modelling (GRASIL):

- Alessandro Bressan Padova
- Gian Luigi Granato Trieste
- Laura Silva Trieste

SMG observational comparisons

- Mark Swinbank + Ian Smail Durham

HIERARCHICAL GALAXY FORMATION



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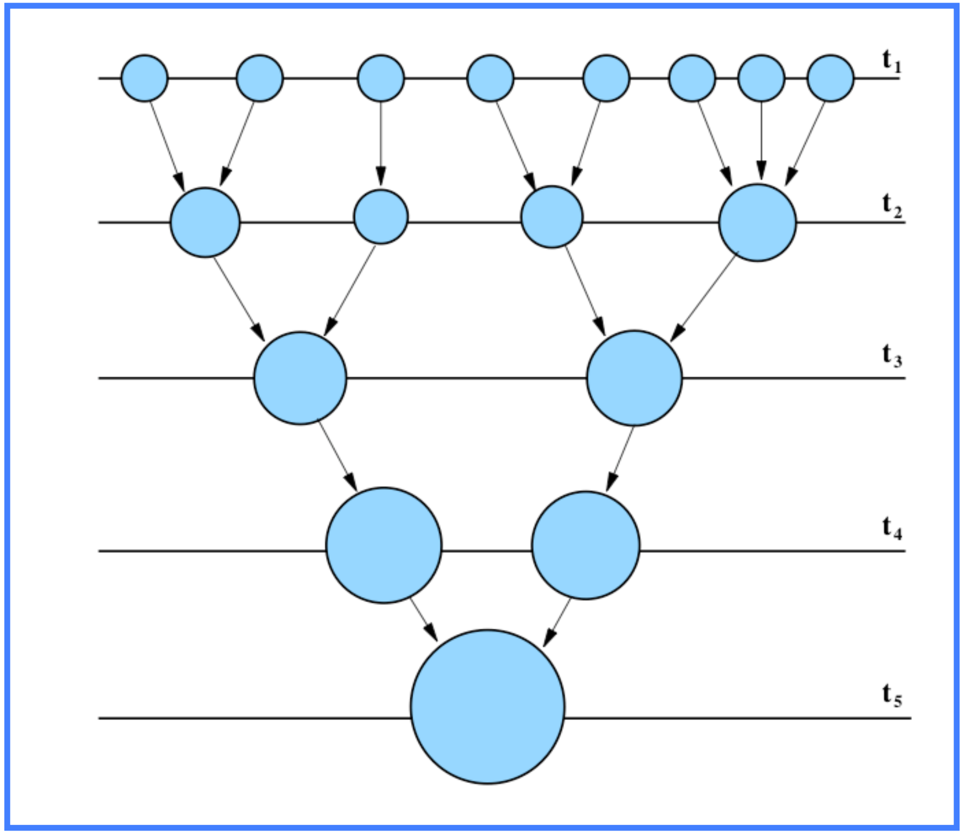
Cole, Lacey, Baugh & Frenk, 2000, MNRAS, 319, 168.

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

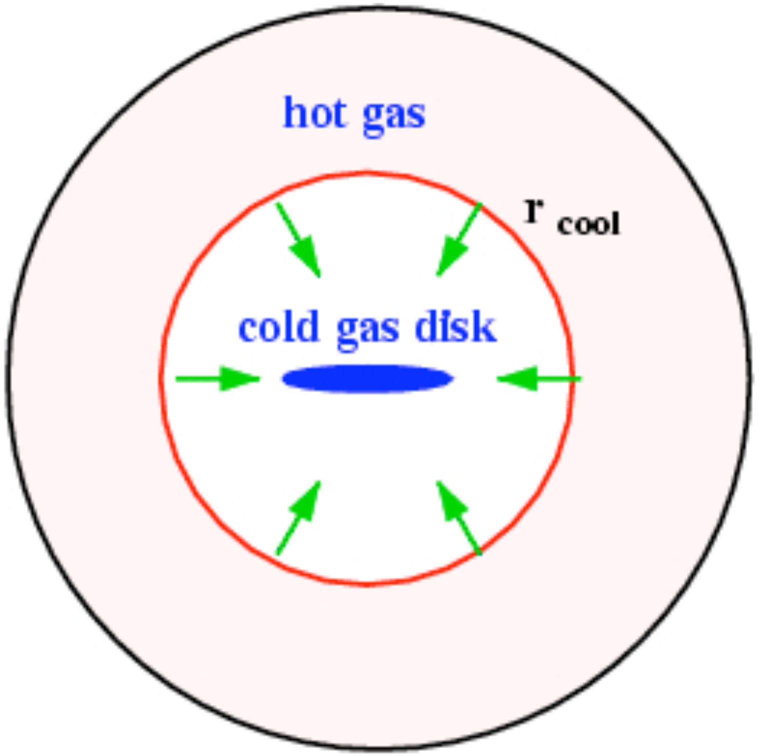
Assembly of dark matter halos: Merger trees



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

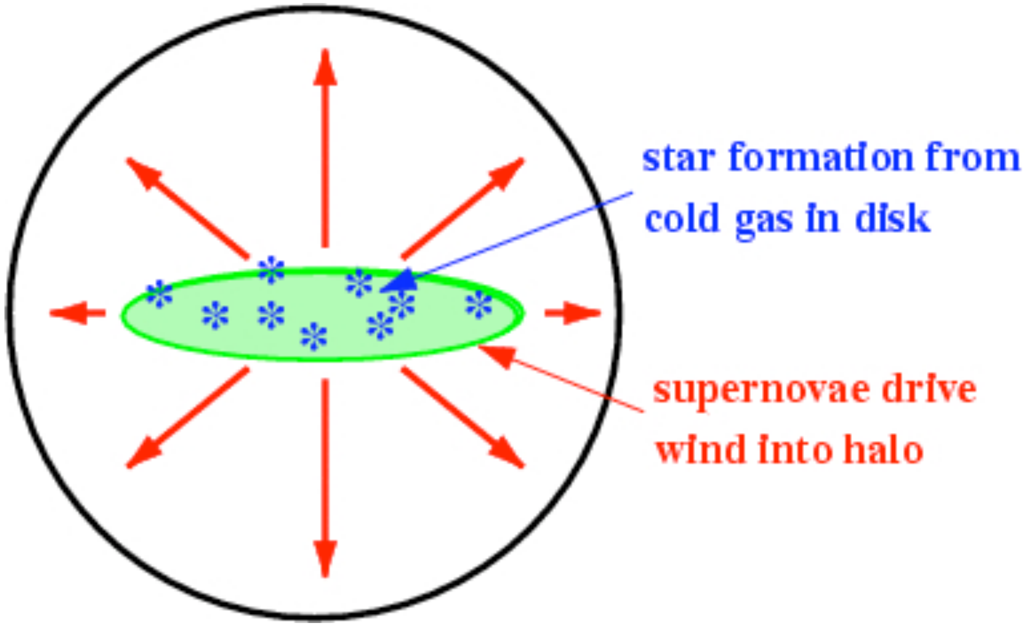
  OR
- **Extract** from **N-body simulations**
- very similar results from both approaches

Shock-Heating & cooling of gas in halos



- Infalling gas all shock-heated to T_{vir}
- Radiative cooling of gas from static spherical distribution
- Disk size related to angular momentum of gas which cools

Star formation & feedback



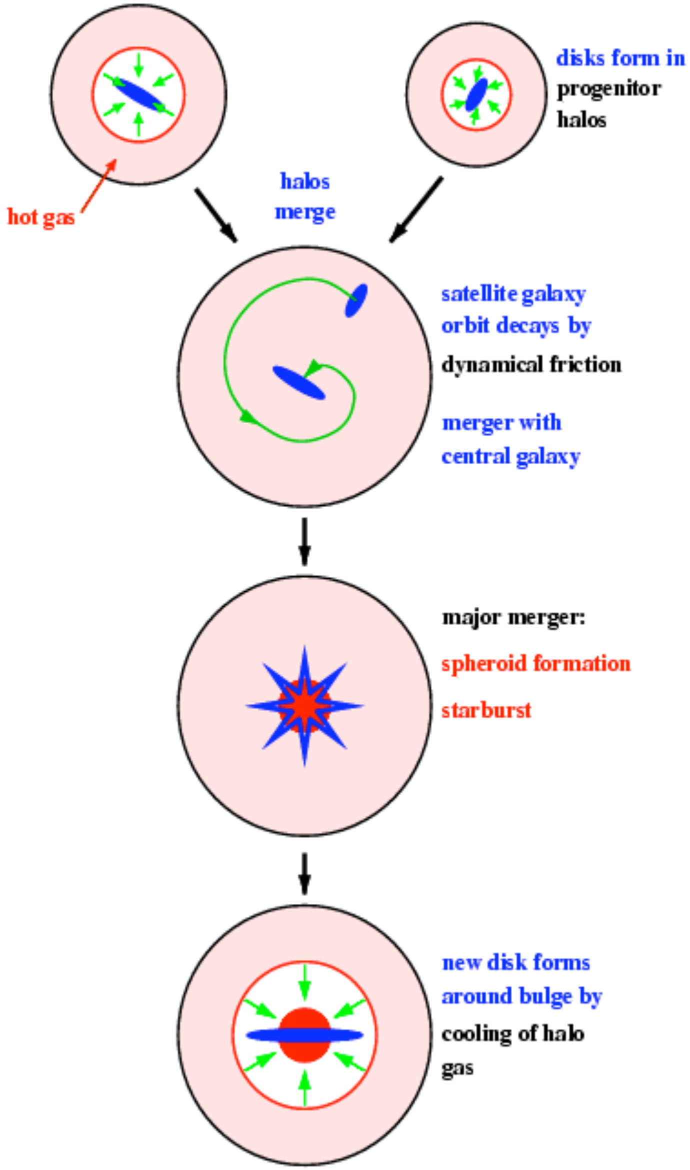
- stars form in disks

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

- supernova feedback ejects gas from galaxies

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

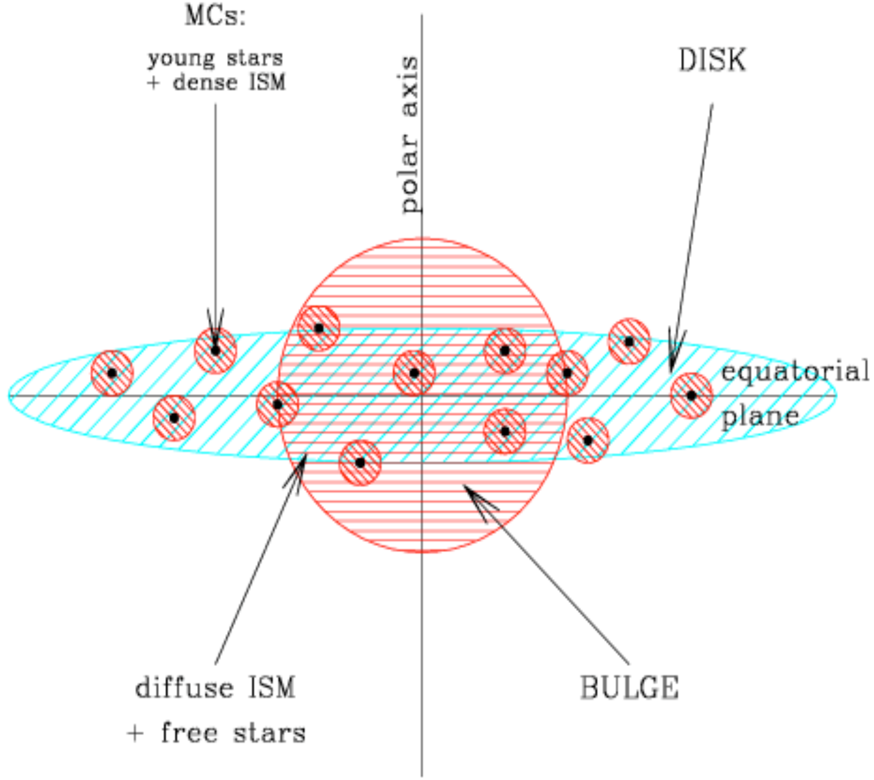
Galaxy mergers & morphology



- 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

SEDs with dust

- dust grain model chosen to reproduce local ISM
- assume dust/gas proportional to gas metallicity
- optical depth for dust depends on both dust mass and galaxy radius
- self-consistent calcn of dust extinction & emission
- model predicts range of extinctions for stars
- mean extinction depends on stellar age
- also range of dust temperatures in same galaxy

Model for radio emission

(Bressan, Silva & Granato 2002)

- Free-free radiation from HII regions ionized by young stars

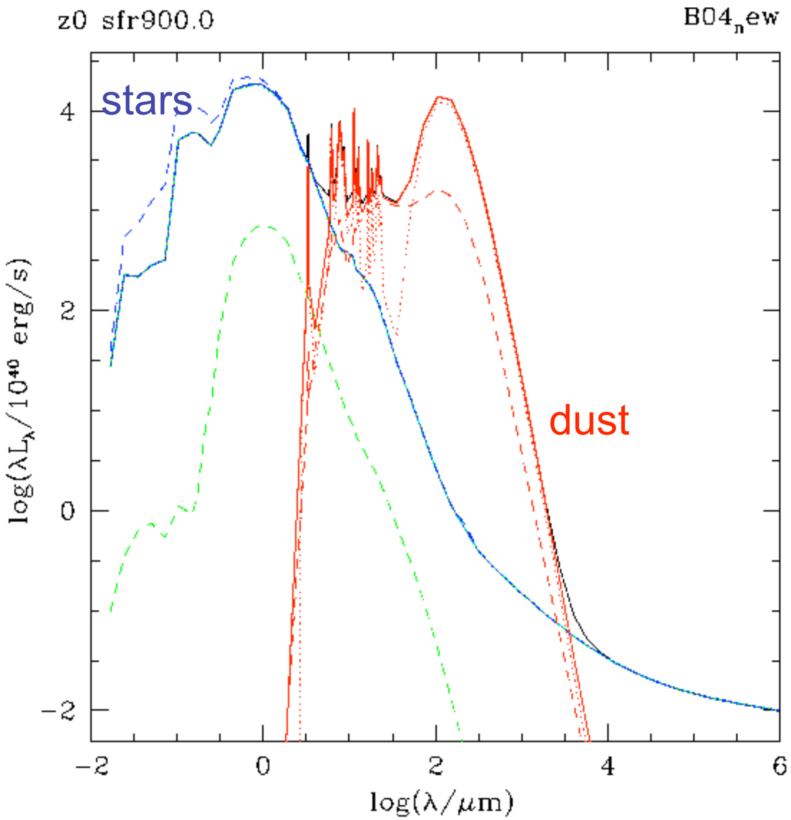
$$L_{\nu,free-free} \propto \dot{N}_{Lyc} \nu^{-0.1}$$

- Synchrotron radiation from relativistic electrons accelerated in supernova remnants – assume const frac of SN energy radiated

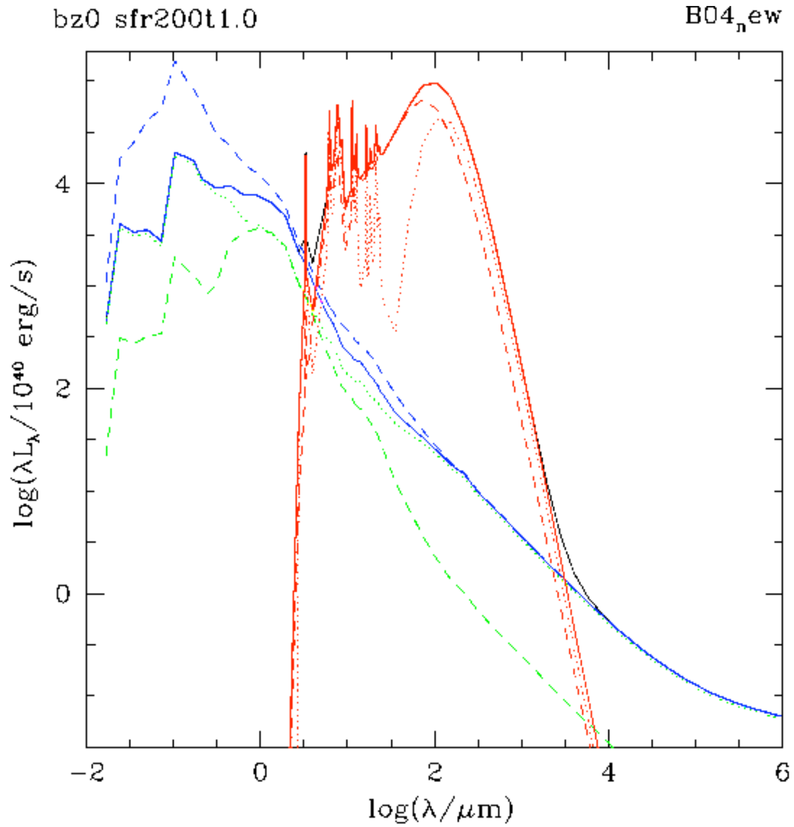
$$L_{\nu,sync} \propto \dot{N}_{SN} \nu^{-\alpha} \qquad \alpha \approx 0.8$$

Example SEDs of galaxies from CDM model

Quiescent spiral

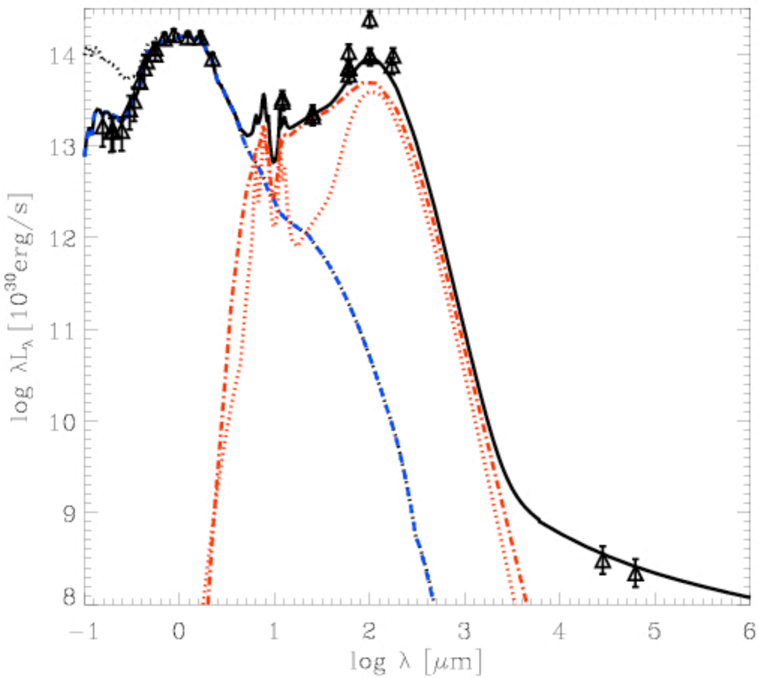


Ongoing burst

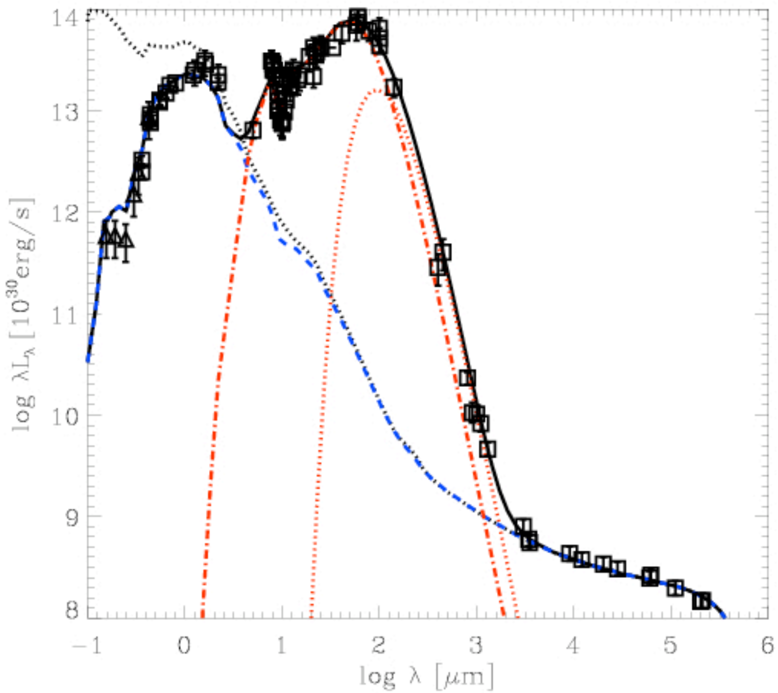


Model SEDs compared to observations

M51 (spiral)



M82 (starburst)

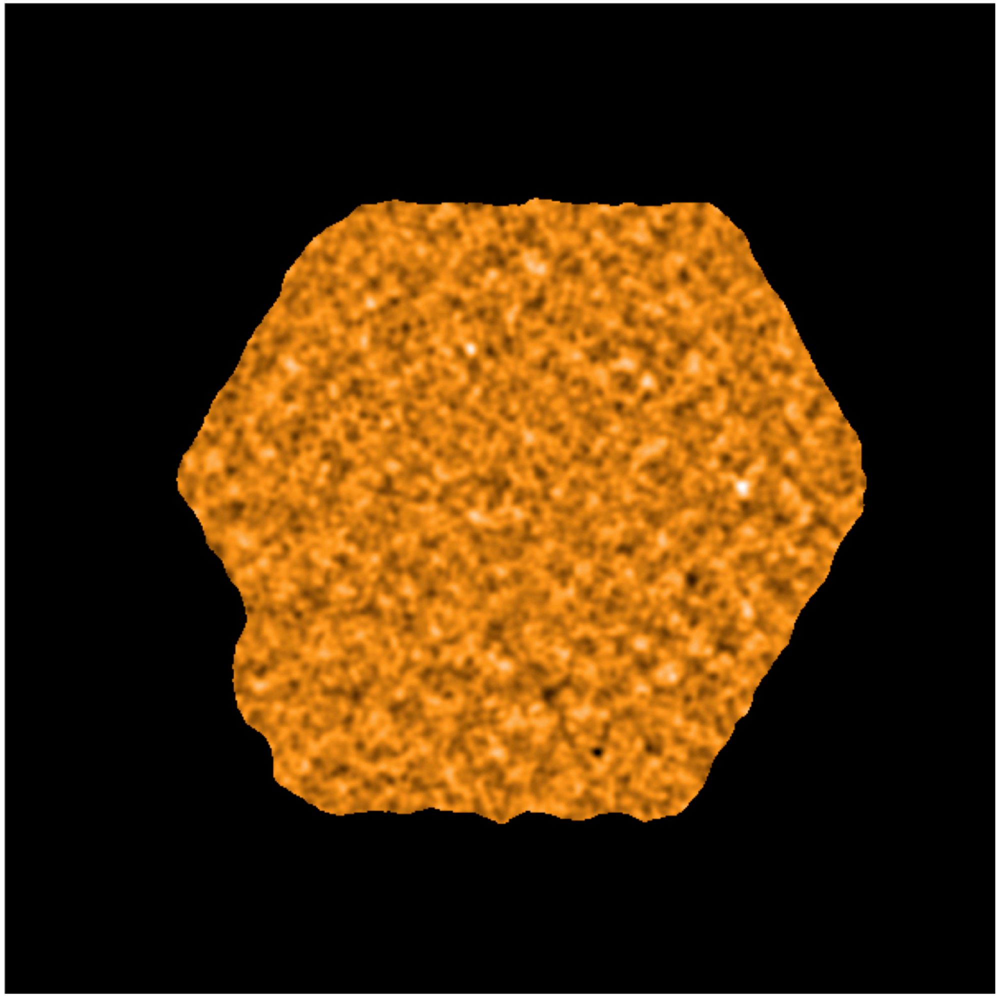


• GRASIL model can reproduce observed SEDs of local galaxies (Silva etal 1998, Bressan etal 2002)

Modelling approach

- Galaxy formation is complicated
- Large range of physical processes
- Many parameters in model
- Therefore essential to compare model to wide range of observational data to constrain parameters
- Just fitting e.g. optical LF is not enough!

Sub-mm galaxies (SMGs)



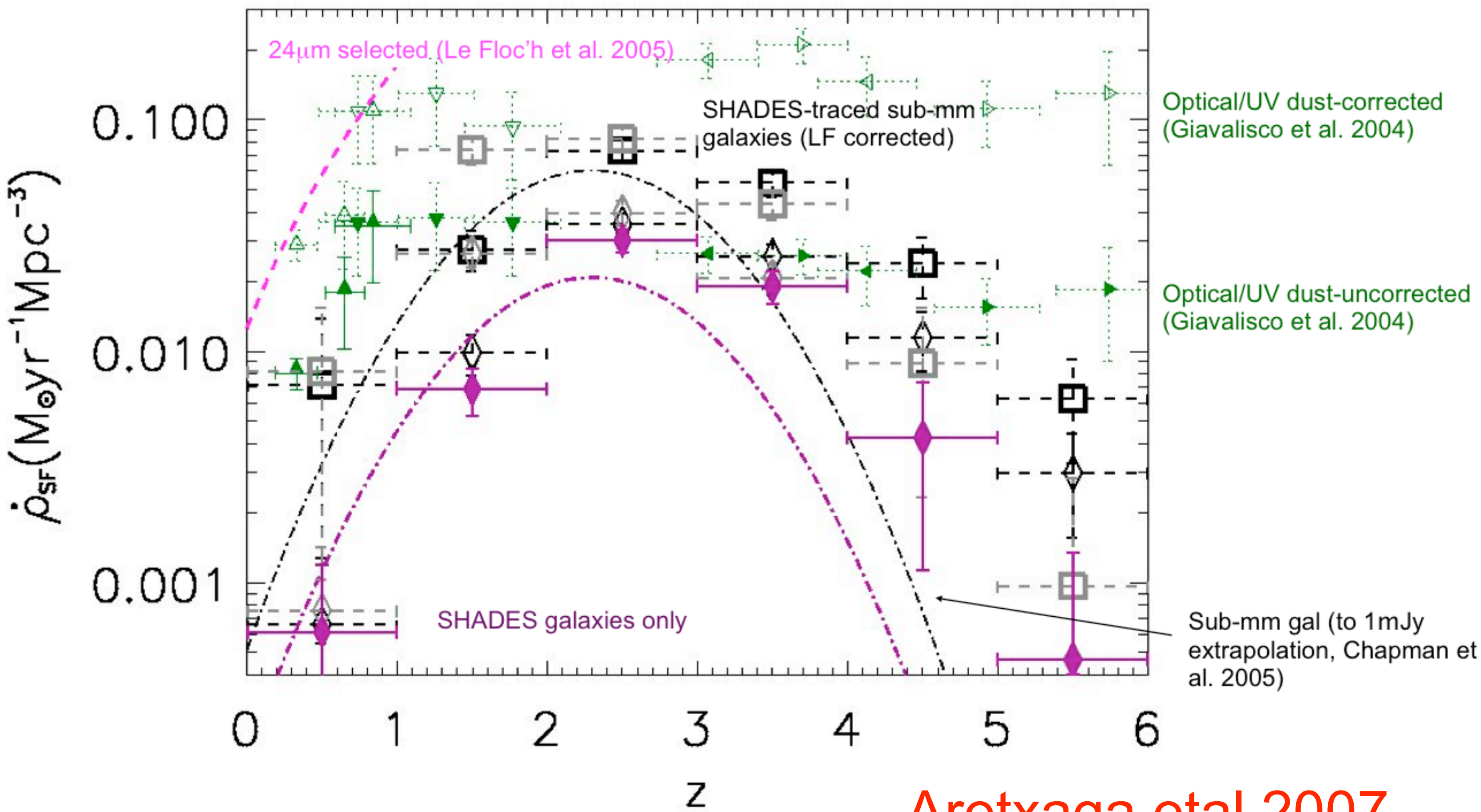
- popn seen in faint sub-mm surveys
- SMGs seem to be dust-enshrouded starbursts at z ~ 1-3

- SHADES 850μm survey of Subaru-XMM Deep Field (20 arcmin dia)
- ~ 60 sources detected down to S ~ 5 mJy

Sub-mm galaxies - why are they important?

- IF assume normal IMF, then implied SFRs ~ 1000 Mo/yr for S ~ 5 mJy @ z~2 - highest SFR objs in high-z universe
- Assuming fainter SMGs have similar z's to brighter ones, total SFR density @ z~1-3 dominates that of optically-detected populations (i.e. Lyman-break gals) if NO dust extinction correction
- So SMGs impt globally & appear to dominate at high SFRs

Cosmic SFR history including SMGs



Aretxaga etal 2007

Baugh et al (2005) model

(Baugh et al 2005, Lacey et al 2007)

- Version of GALFORM, no AGN feedback
- Starting point was model which reproduced wide range of properties for present-day galaxies, using standard IMF
- But this failed to reproduce numbers of main populations of star-forming galaxies at high-z:
  – Sub-mm galaxies (SMGs) at z~2
  – Lyman-break galaxies (LBGs) at z~3-6

Solution - a variable IMF?

- Normal IMF in star-forming disks

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

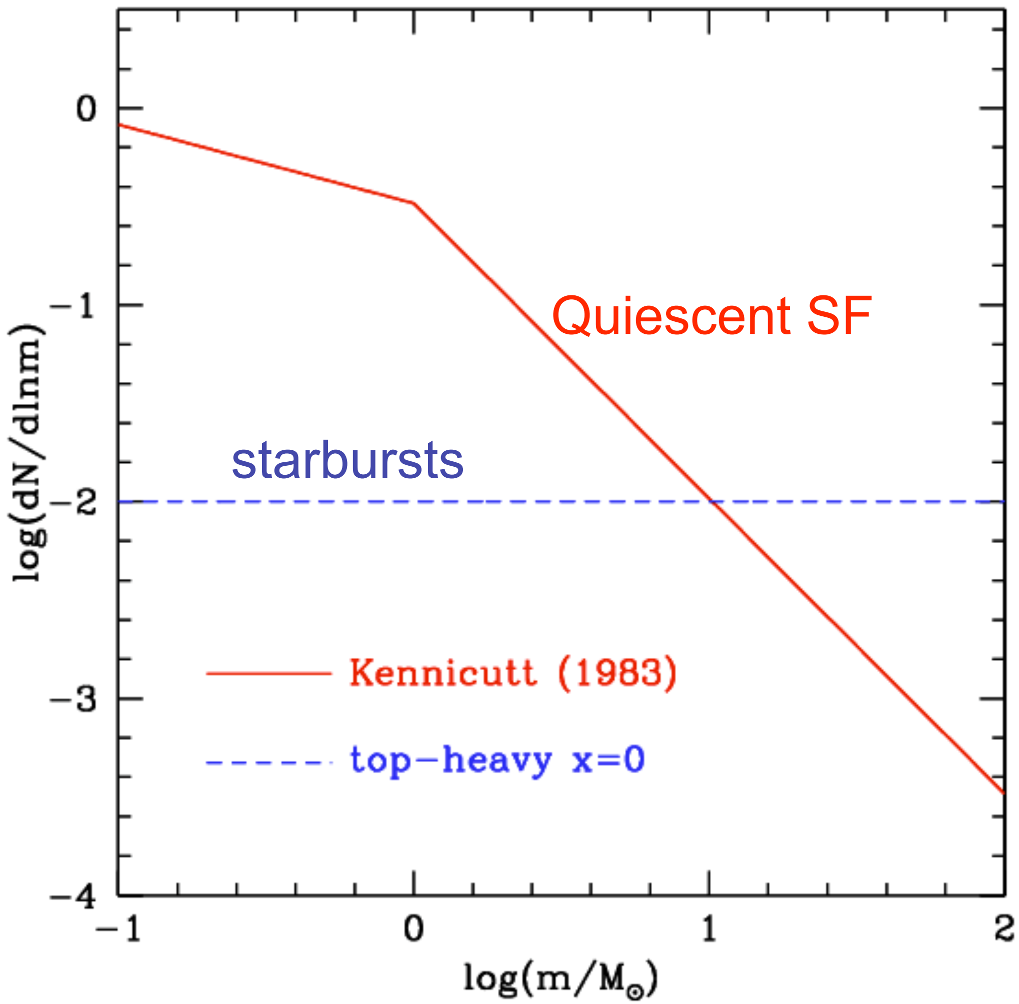
  - with x=0.4 for m < Mo, x=1.5 for m >Mo (Kennicutt 1983)
  - c.f x=1.35 for Salpeter

- Top-heavy IMF in bursts triggered by mergers

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

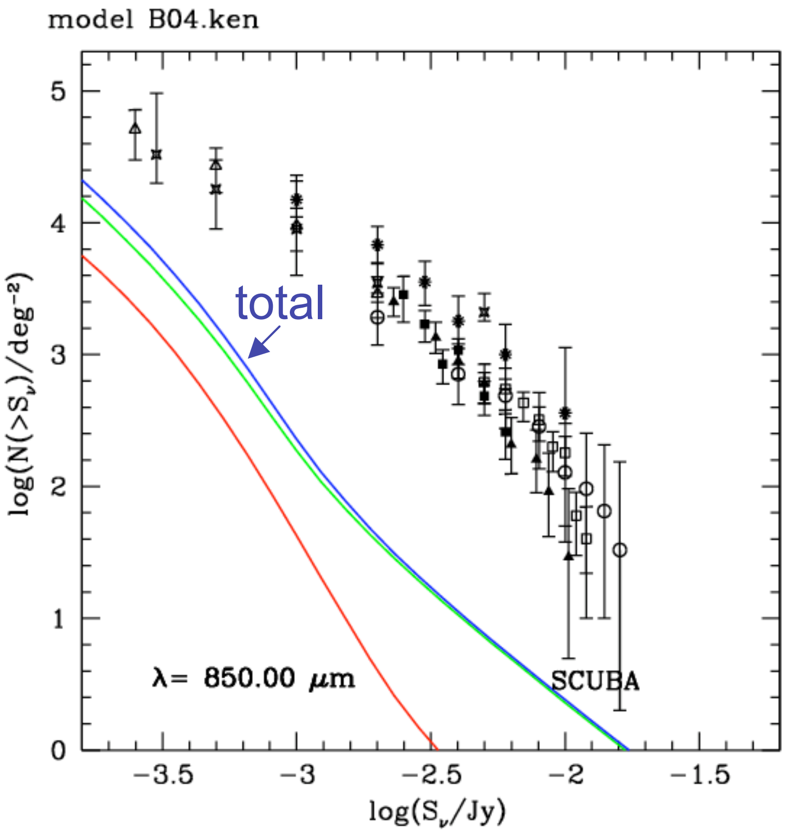
  - Increases both stellar luminosities & chemical yields by ~ 5x

Normal vs top-heavy IMF

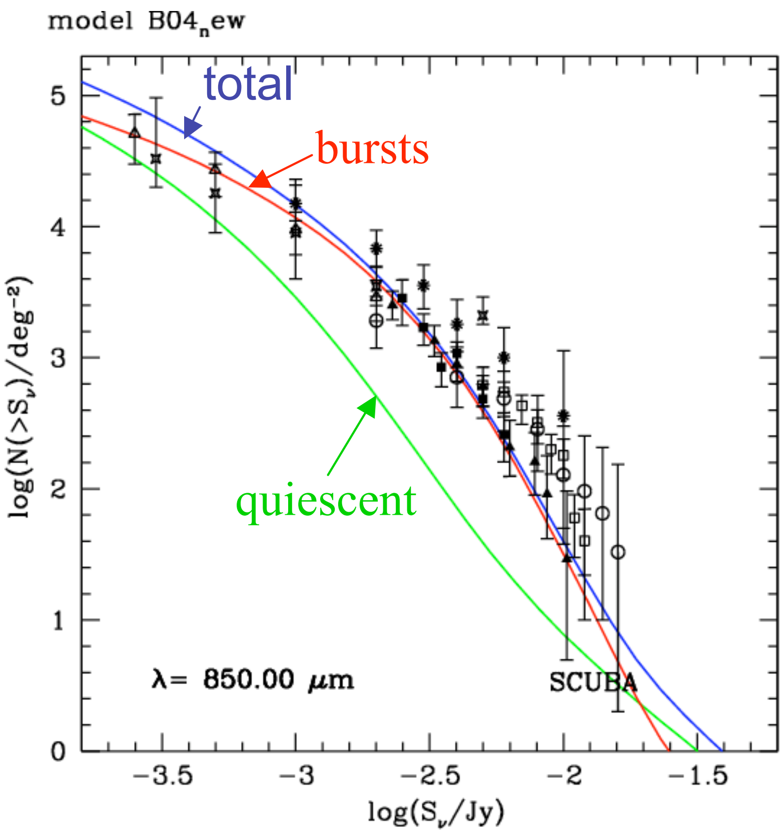


Why a top-heavy IMF?
(a) Sub-mm source counts

normal IMF



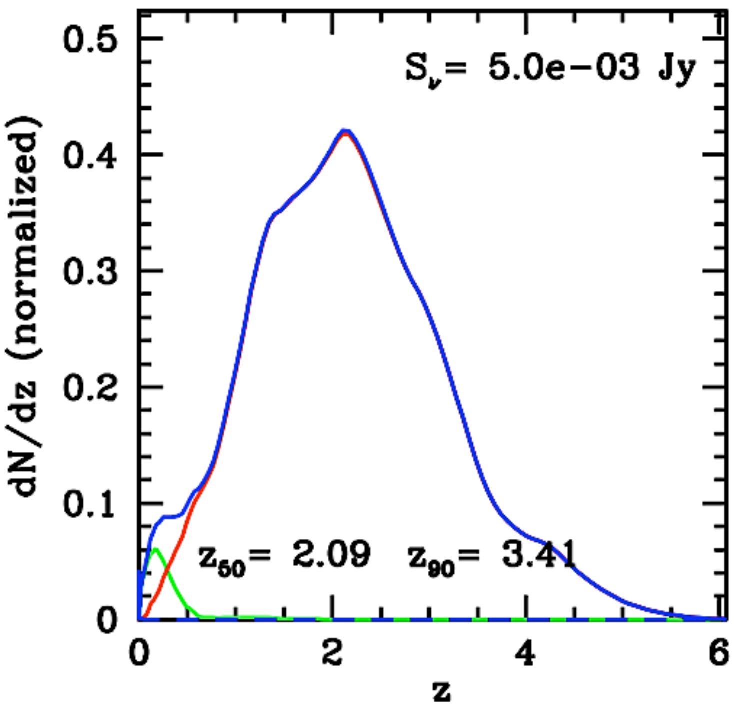
top-heavy IMF



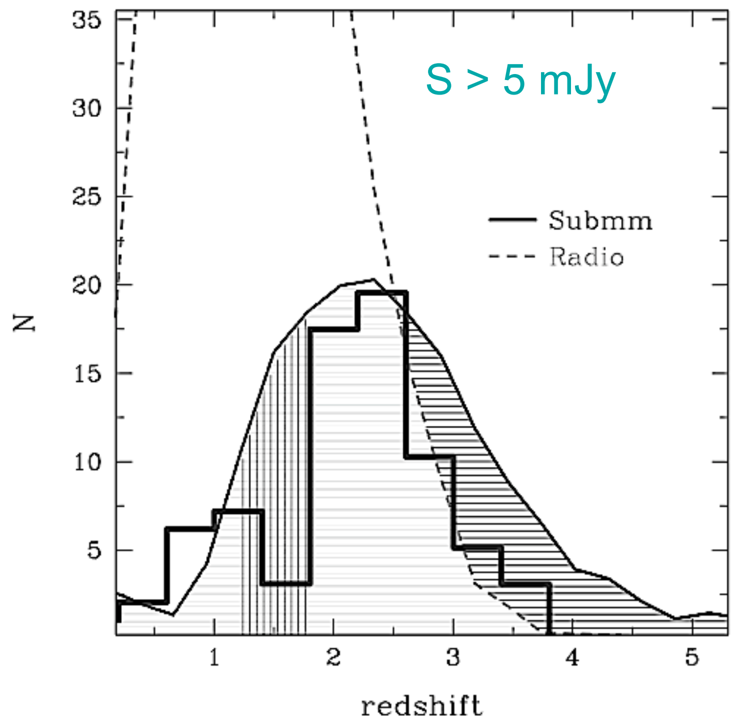
Sub-mm counts too low by factor ~50 for normal IMF

Redshifts of sub-mm galaxies

Model (top-heavy IMF)

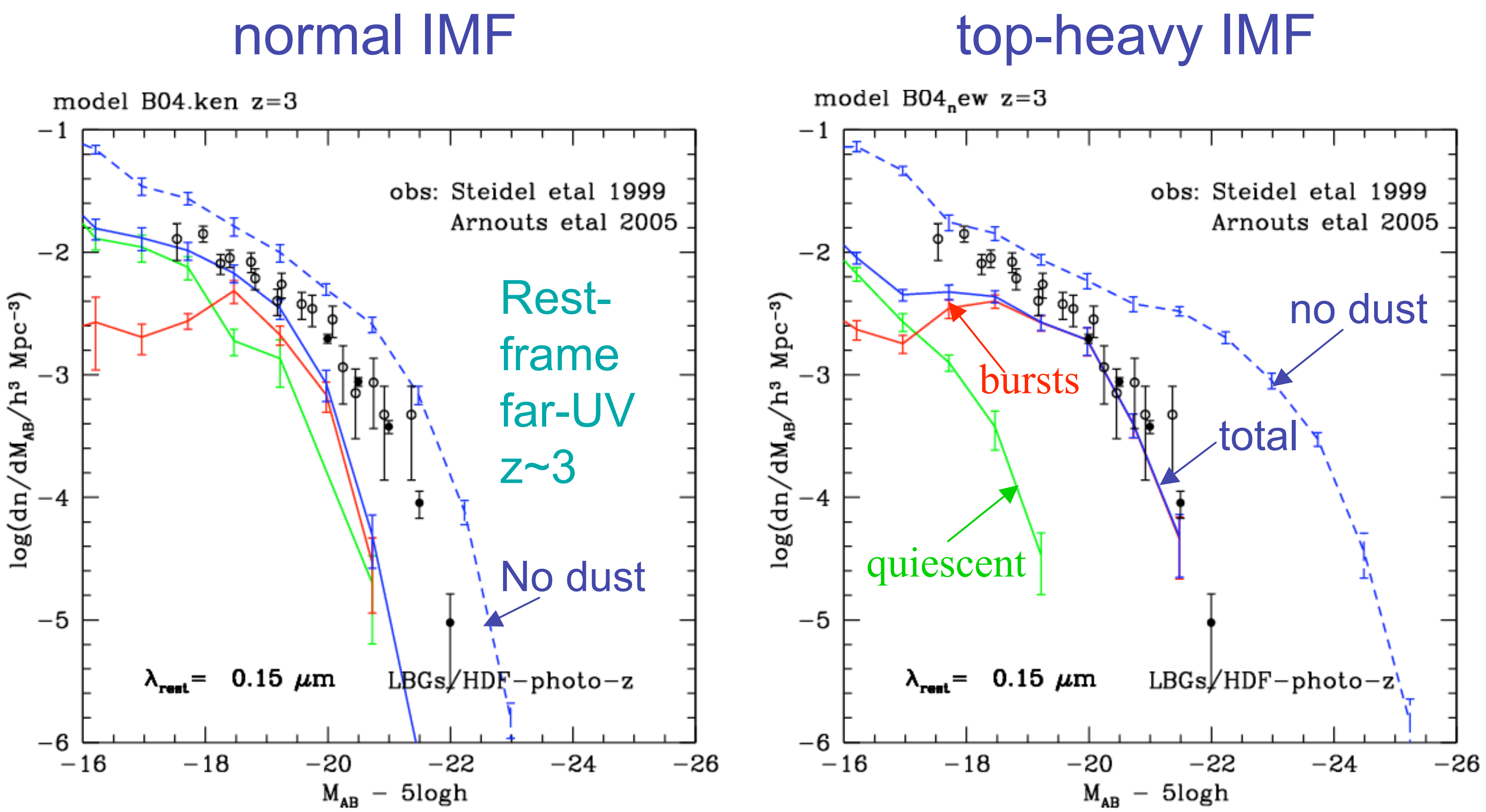


observed (Chapman etal 2005)



Model with top-heavy IMF predicts median z~2 for S(850) > 5mJy

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

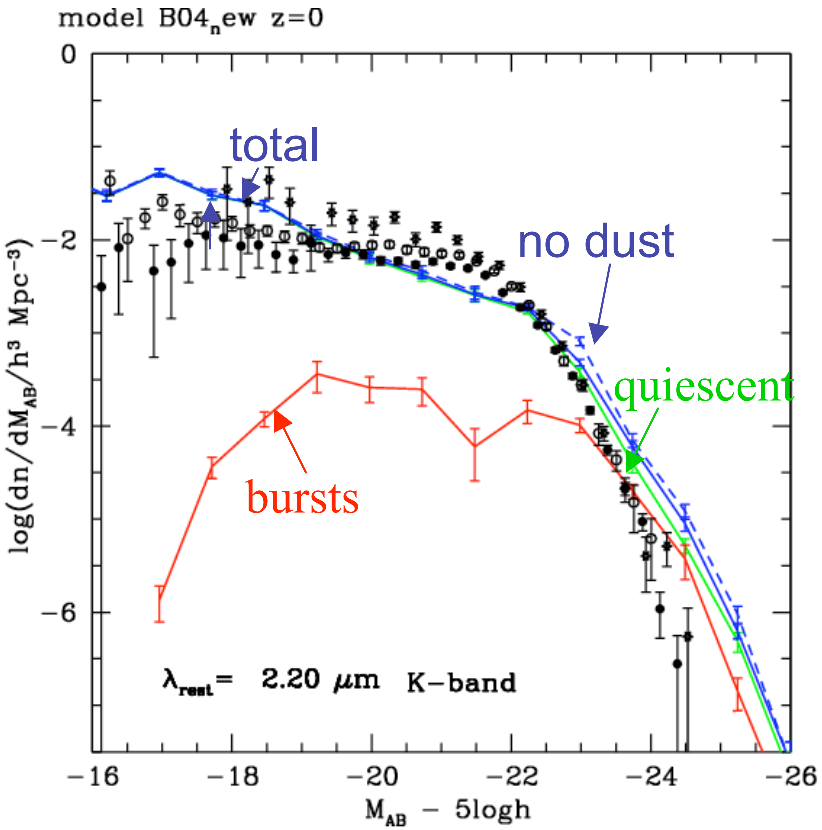


LBGs too faint for normal IMF, once include dust extinction

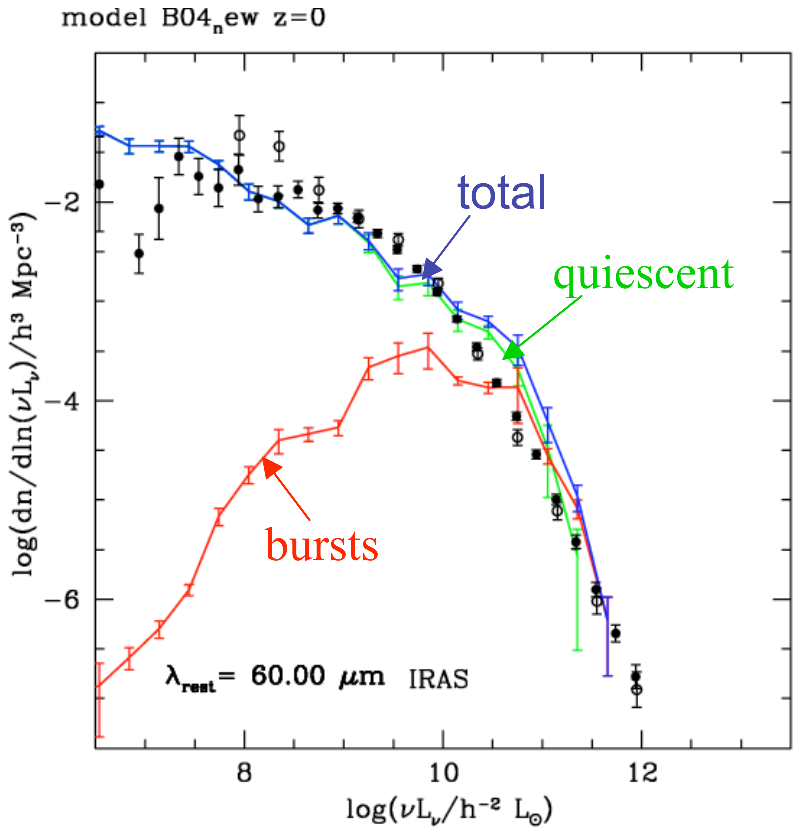
- So model works for SMGs & LBGs at high-z
- But what about properties of present-day galaxies?

Present-day galaxy luminosity functions in near-IR & far-IR

K-band (stars)

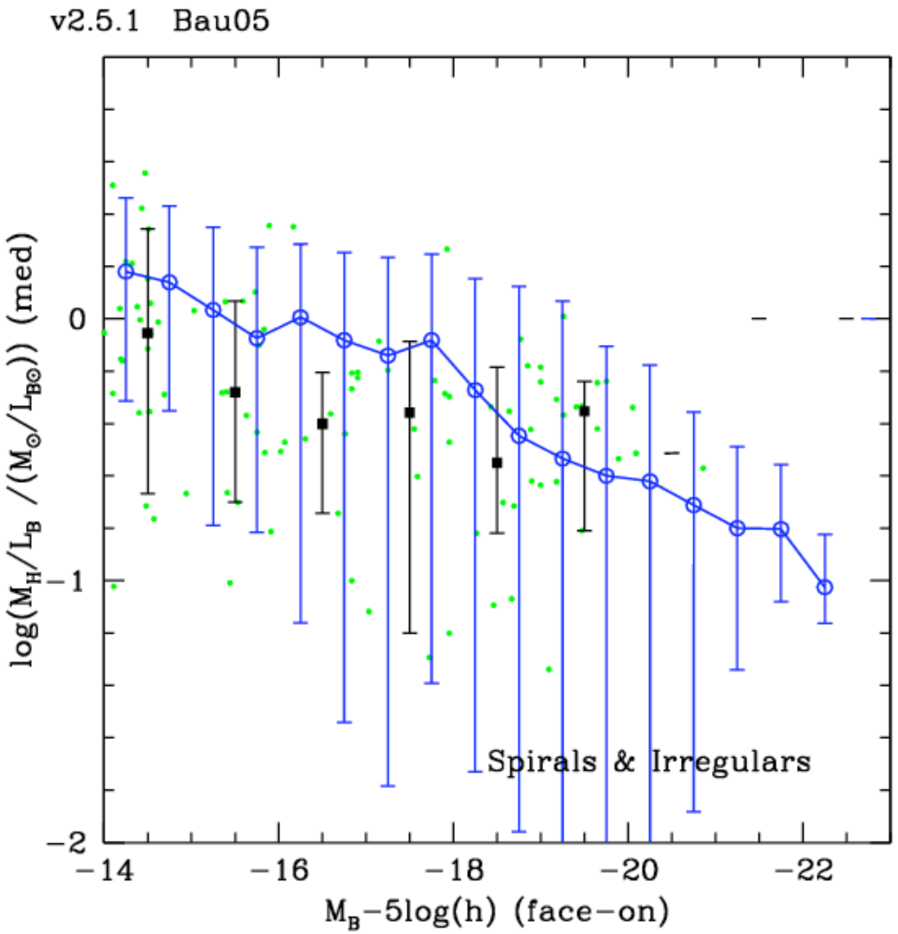


60 μm (dust)



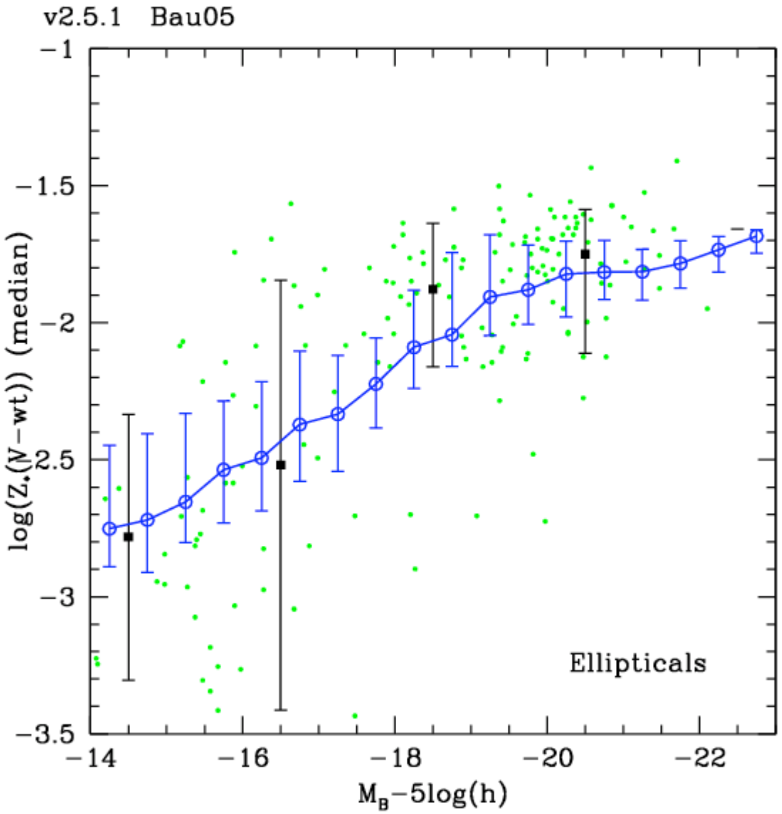
Gas fractions in disks

M_H/L vs luminosity

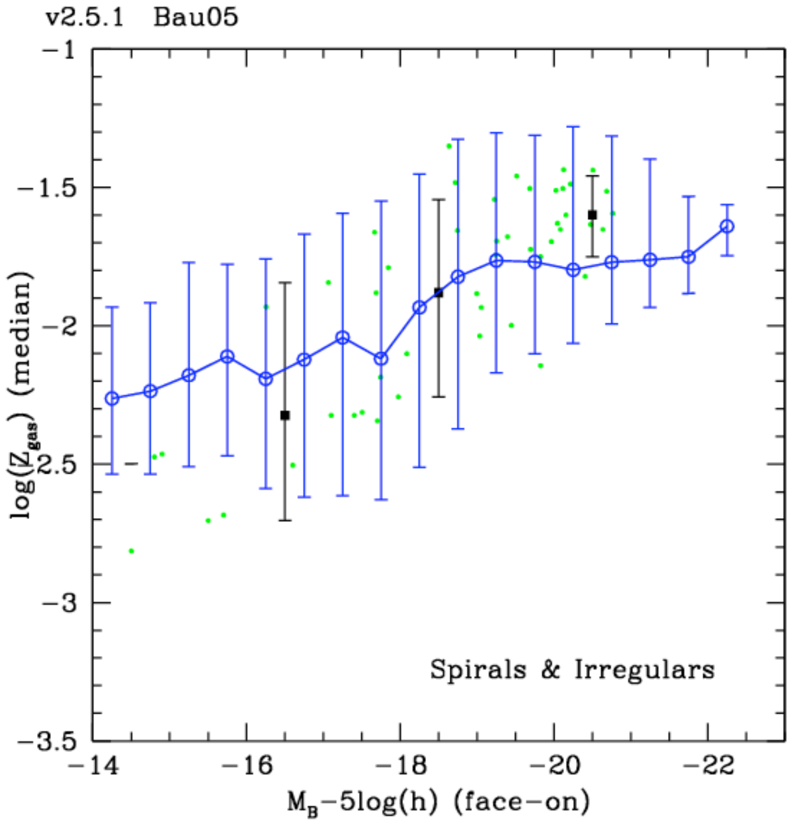


Metallicities of stars & gas

Stars in ellipticals

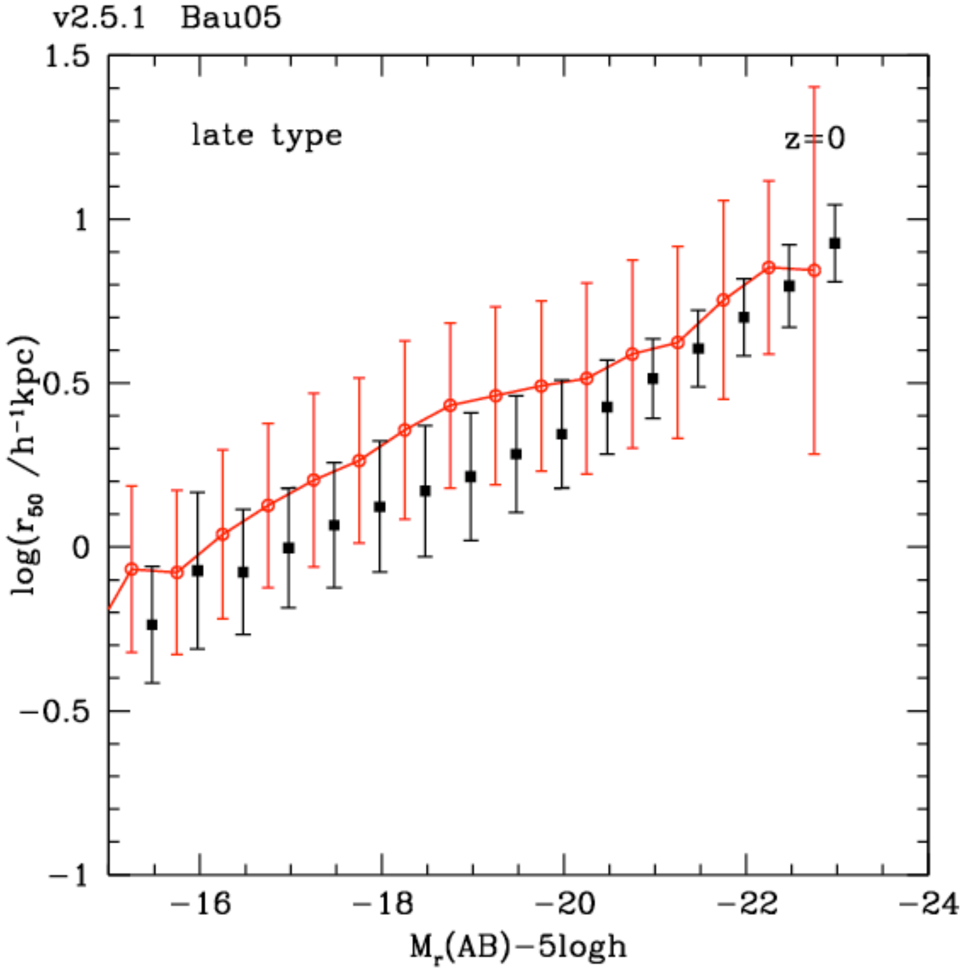


Gas in spirals



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

Galaxy disk sizes



Size vs luminosity

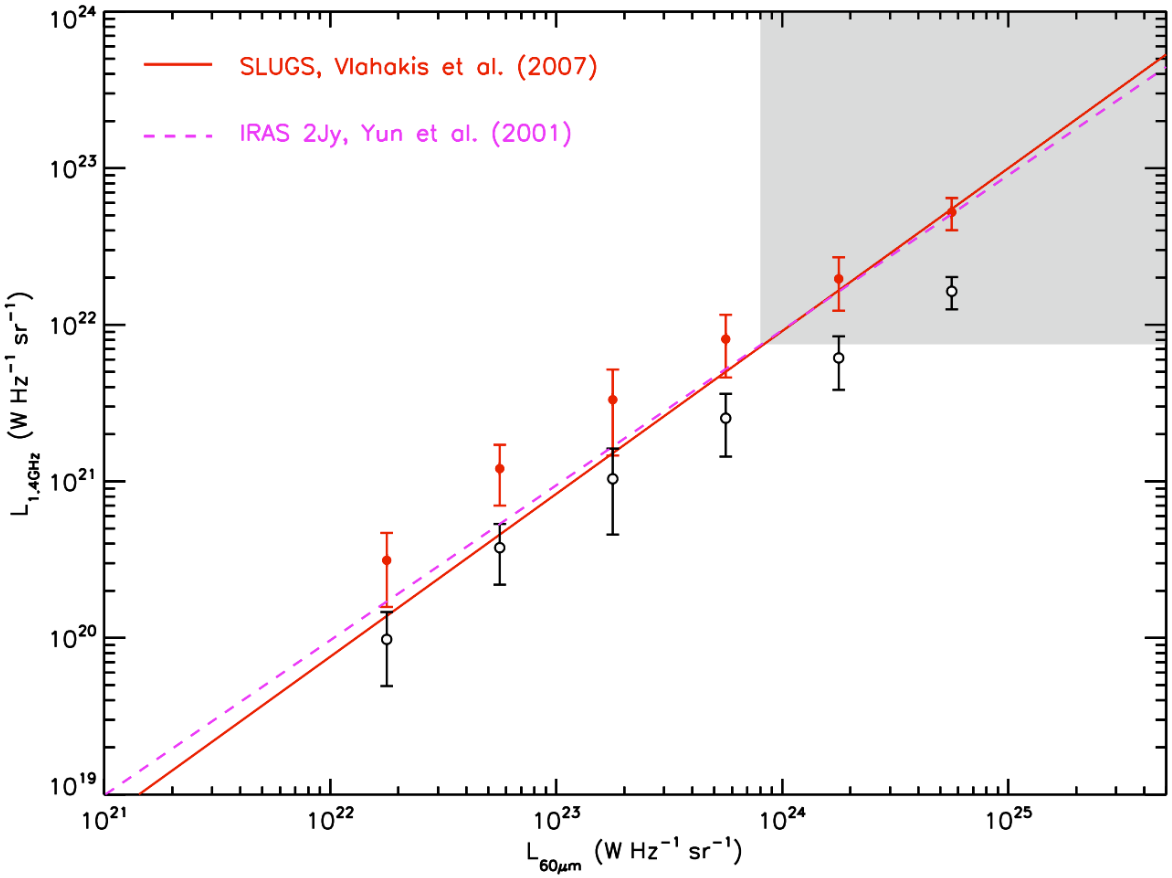
Comparison with SDSS data (see Juan's talk)

Detailed comparison of predicted SMG properties with observations

Swinbank etal (2008)

- Model parameters chosen to reproduce SMG number counts
- But do other predicted properties agree with observations?
- Use Chapman et al (2005) sample with spec z's & joint sub-mm (850 μm) & radio (1.4 GHz) selection: S_{850}>5 mJy & $S_{1.4}$>30 μJy

Normalization of radio emission in models

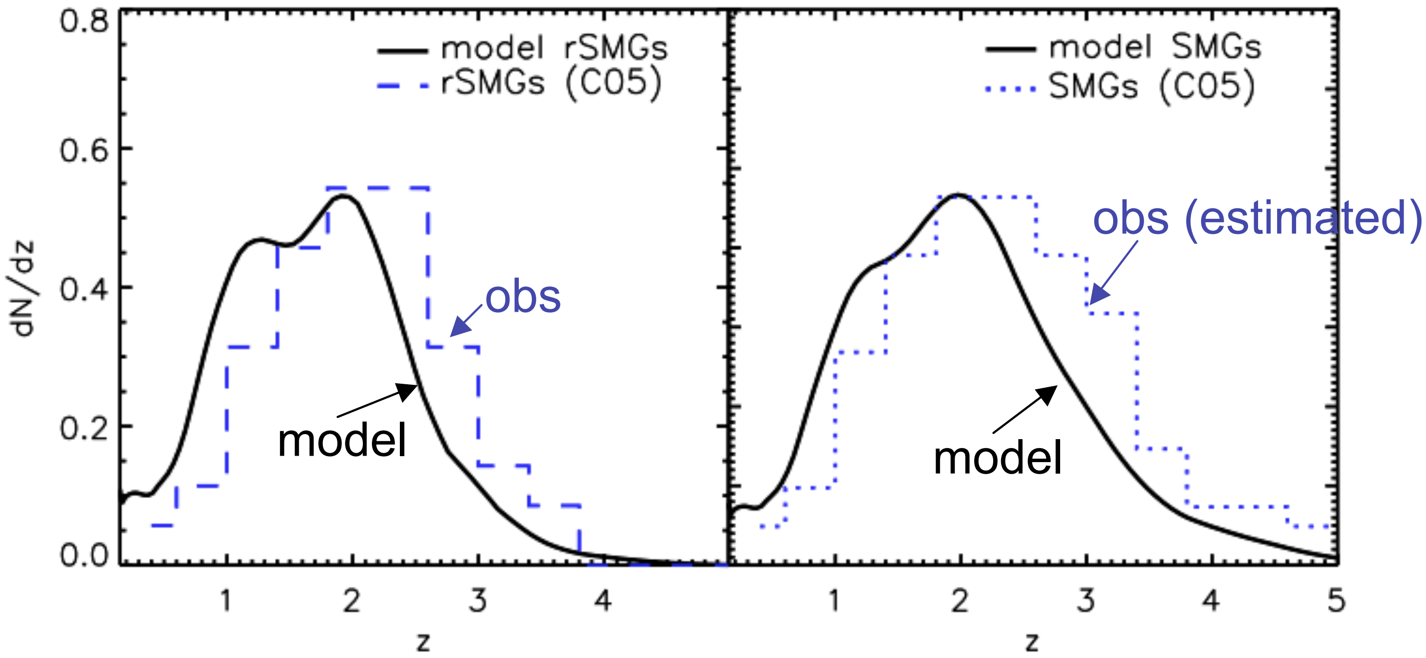


Normalize synchrotron radio emission in model to match radio-FIR reln for local ULIRGs

Redshift distributions with & without radio selection

sub-mm + radio | sub-mm only

S(850) > 5 mJy & S(1.4)>30μJy | S(850)>5mJy



Slightly lower median z for sub-mm+radio selection c.f pure sub-mm selection - consistent with obs

Bolometric luminosities & SFRs

- Model SMGs selected this way have

  $L_{bol} \sim 2 \times 10^{12}$ Lo

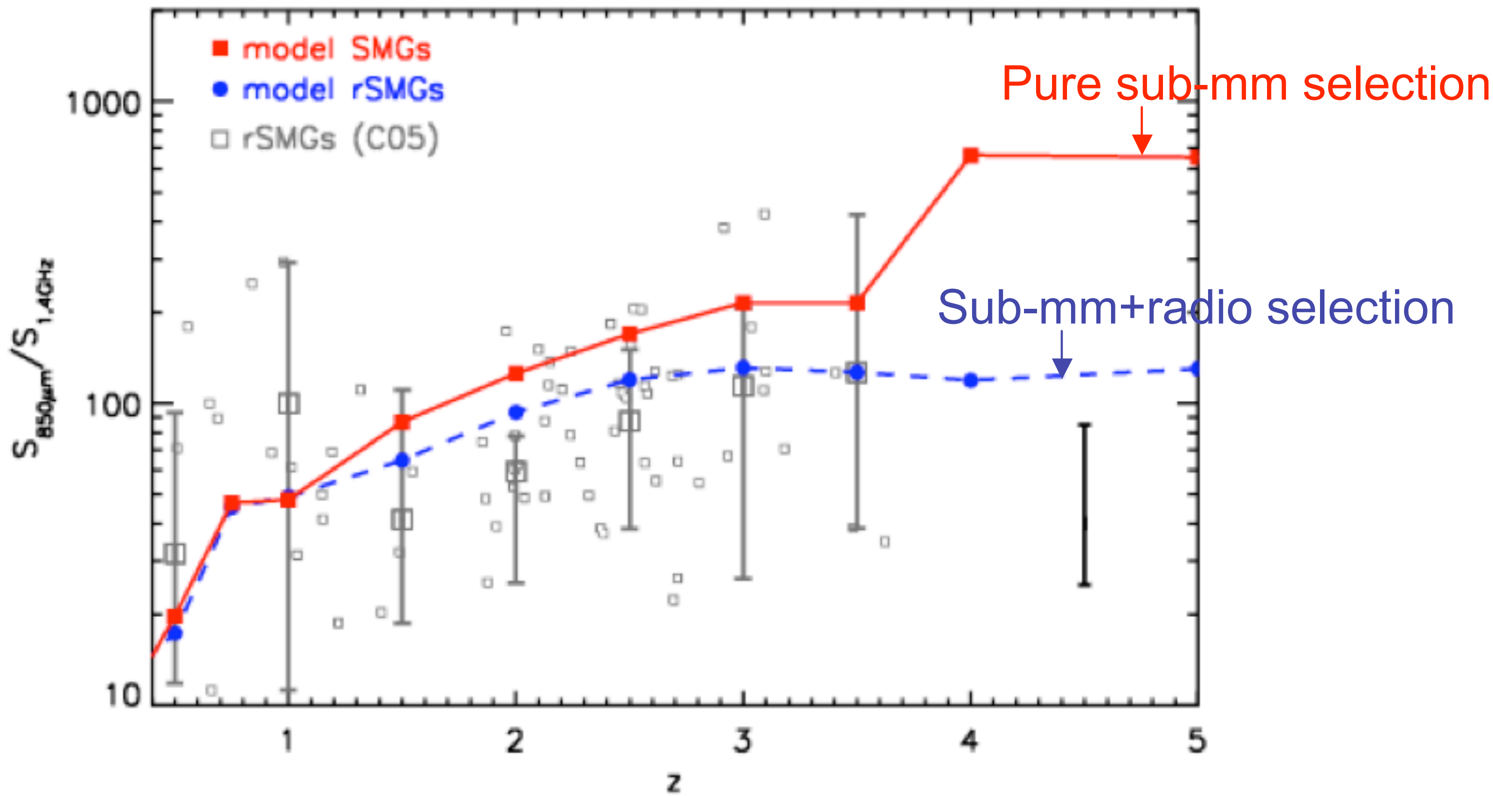
- For Salpeter (x=1.35, m=0.1-100 Mo) IMF, wd require

  SFR ~ 1000 Mo/yr

- BUT with top-heavy (x=0) IMF produce this with

  SFR ~ 100 Mo/yr

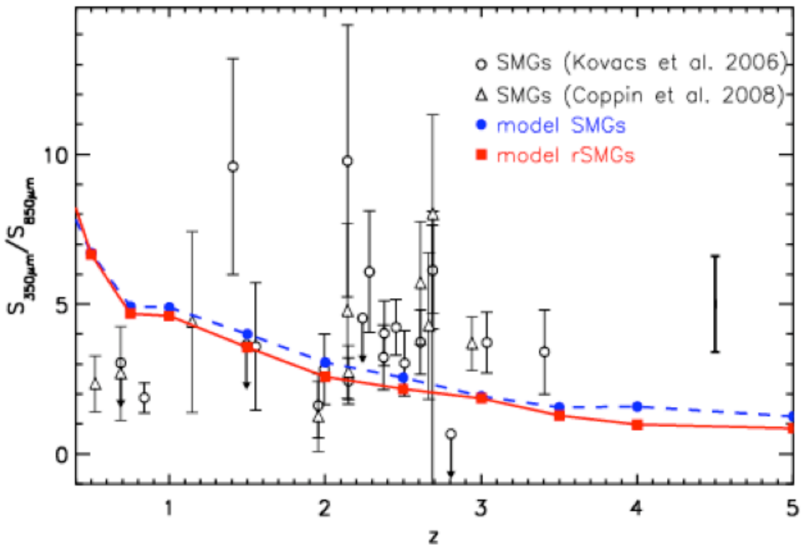
Radio/sub-mm flux ratios



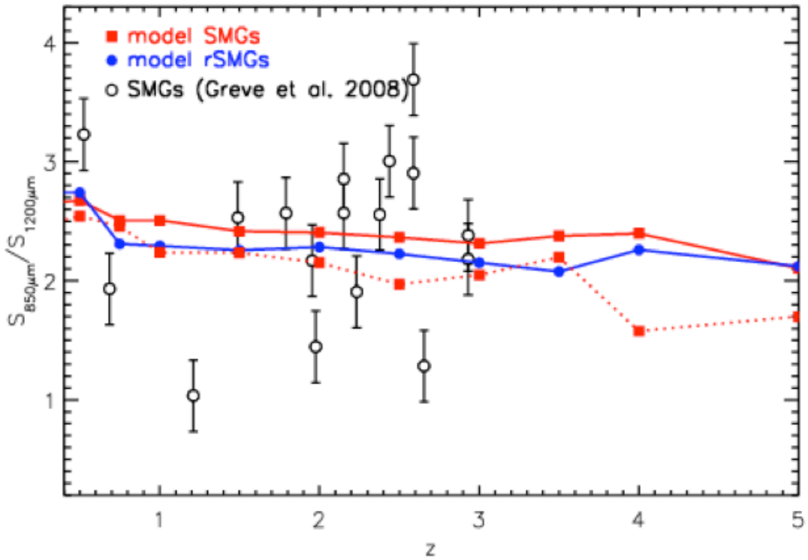
Good agreement with obs 850μm/1.4GHz ratios, once include radio selection

FIR/sub-mm dust SED & T_{dust}

S(350μm)/S(850μm)



S(850μm)/S(1200μm)



- 350/850 & 850/1200 ratios consistent with obs
- model FIR SEDs well fit by modified Blackbody w β=1.5 => EFFECTIVE dust temperature T_d~30K

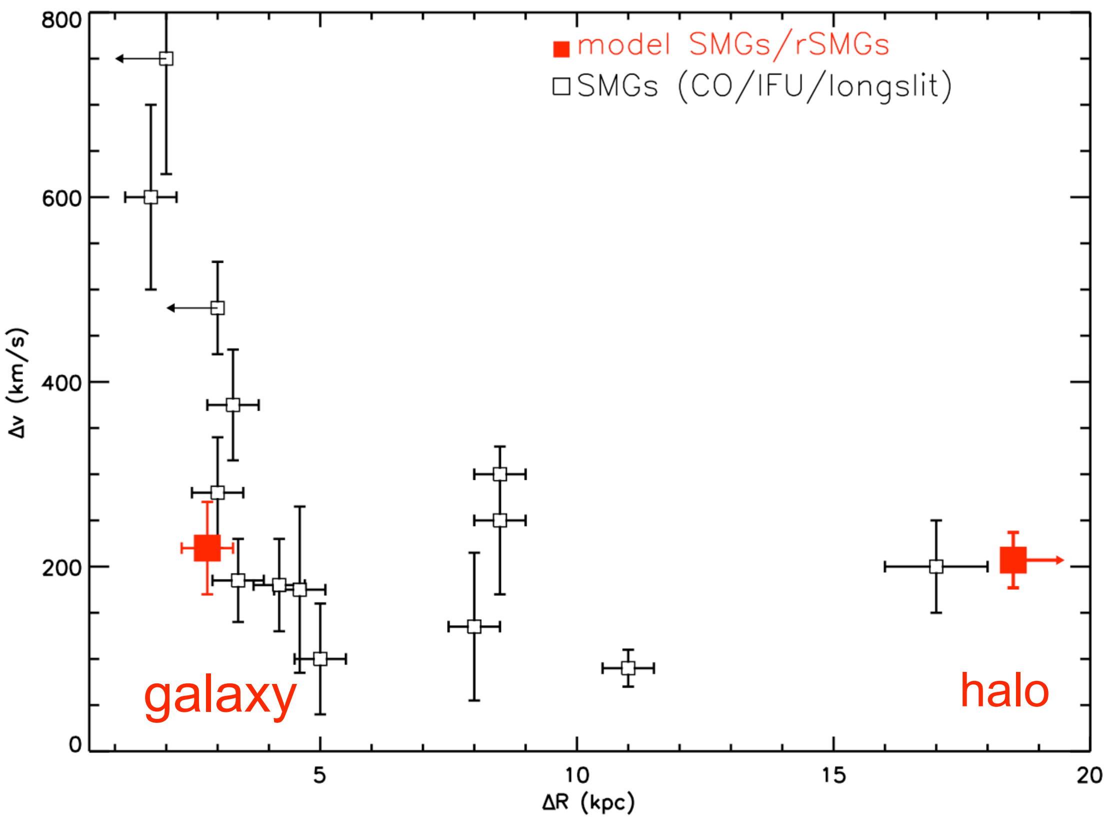
Gas masses

- Model SMGs with S>5mJy have total $M_{gas} = 3.4$ (+2.7,-1.7) $\times 10^{10}$ Mo (median)
- In good agreement with obs from CO $M_{gas} = 3.0$ (+/- 1.6) $\times 10^{10}$ Mo

  (Greve etal 2005, Tacconi etal 2008)

  – Assuming standard conversion for ULIRGs: $M(H_2+He)/L_{CO} = 0.8$ Mo (K kms^{-1} pc^{-2})$^{-1}$

Velocity widths



- provide constraint on dynamical mass
- obs:

  $\sigma_{H\alpha}$ = 170 +/- 30 km/s

  σ_{CO} = 200 +/- 45 km/s
- models:

  σ_{1D} = 160 +/- 30 km/s

- excellent agreement!

Halo masses & clustering

- Models predict S>5mJy SMGs hosted by DM halos with

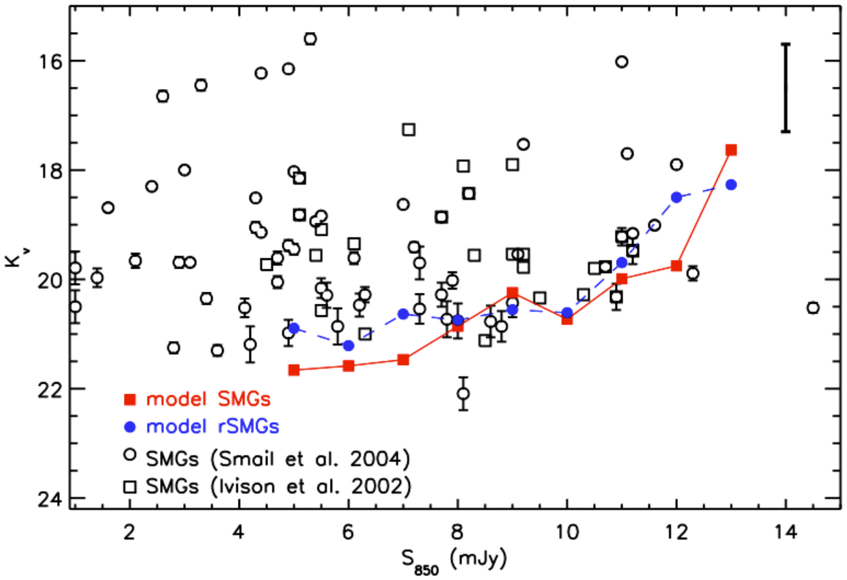
  M_{halo}= 4 (+6,-2) x10^{12} Mo (median)
- In ΛCDM, such halos @ z~2 have bias b ~ 2, so predict clustering length r_0= 8 Mpc for SMGs
- In excellent agreement with Blain etal 2005 obs estimate from pairs in N(z): r_0=10 (+/- 3) Mpc

Rest-frame UV properties

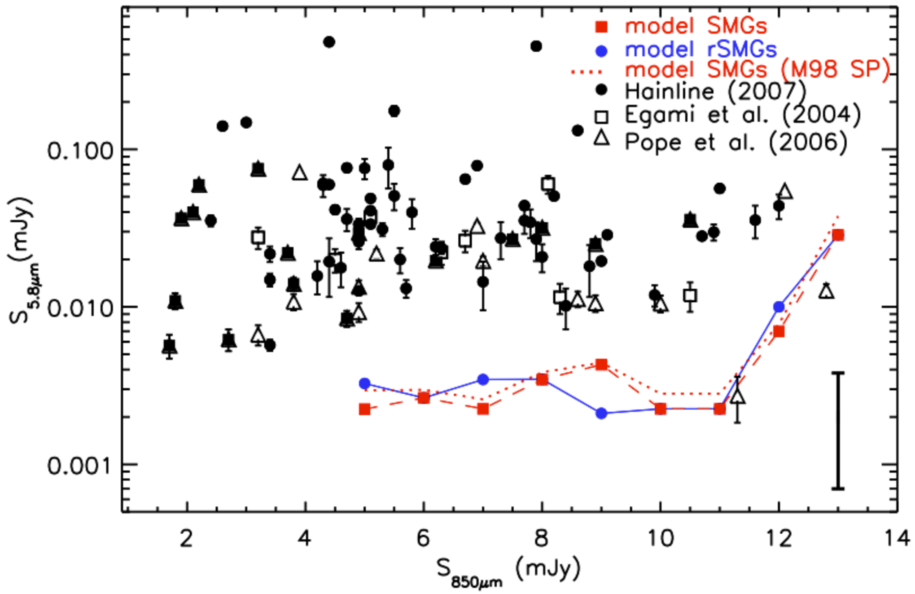
- Model SMGs with 0.9<z<3.5 have B~24.0, R~23.9 (AB)
- C.f. obs B~24.8, R~24.3
- i.e. similar, but model SMGs slightly brighter & bluer - too little dust extinction?
- ~60% model SMGs have colours of BX/BM gals - similar to obs

Rest-frame optical & NIR luminosities

K-band (~ rest R)



IRAC 5.8μm (~ rest K)



- model predicts K-band fluxes too low by 6x
- 5.8μm too low by 10x - serious problem !!

NIR luminosities & stellar masses

- NIR luminosities too low because too few post-MS m~2-3 Mo stars
- related to predicted stellar masses: M_{star}~ 2 (-1,+3) x10^{10} Mo
- These are ~ 10x lower than obs estimates assuming standard IMF (Borys etal 2005)
- But since IMF varying, comparison via obs 5.8μm fluxes much more robust

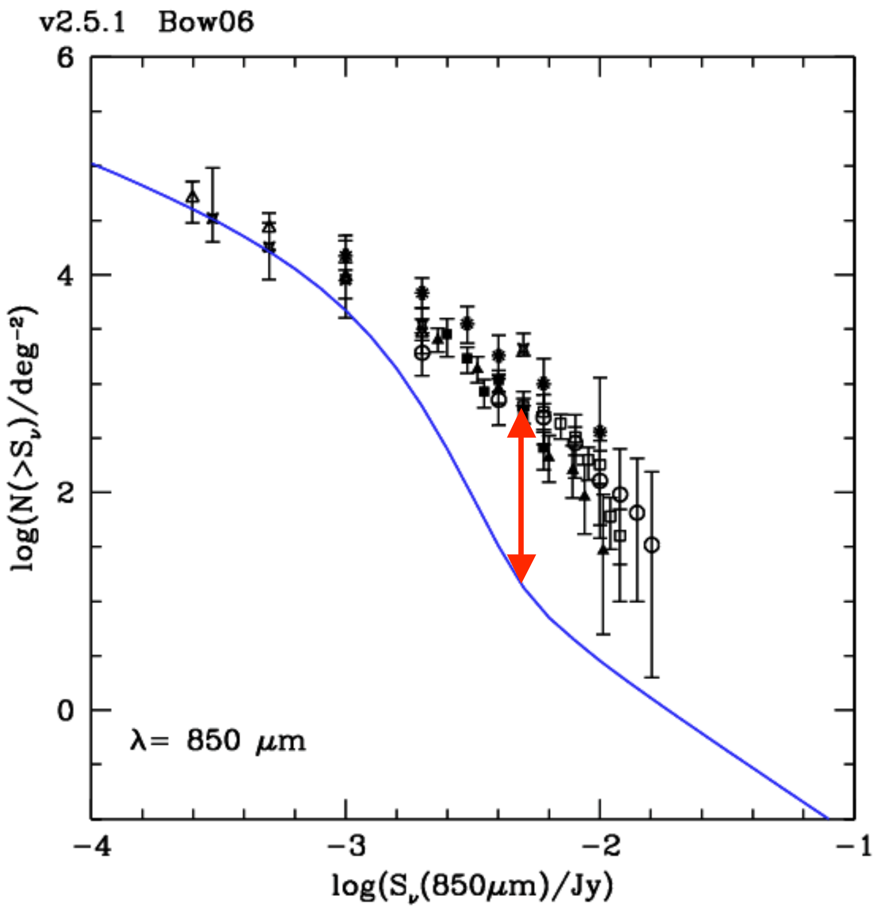
Could this be problem in stellar evolution models?

- Maraston (1998,2005) finds that improved modelling of TP-AGB stars leads to increased NIR luminosities compared to standard models (e.g. BC03), for SSP ages ~ 0.1-1 Gyr
- Have checked effect of using Maraston SSPs - increases 5.8μm fluxes of model SMGs by only ~ 20%
- Does not solve problem of low NIR L's

What about AGN feedback?

- Bower etal (2006) model with AGN feedback and standard IMF seems in better agreement with "observed" stellar mass function to z~4 (inferred from obs assuming solar nhd IMF)
- But underpredicts counts of SMGs by factor 30x

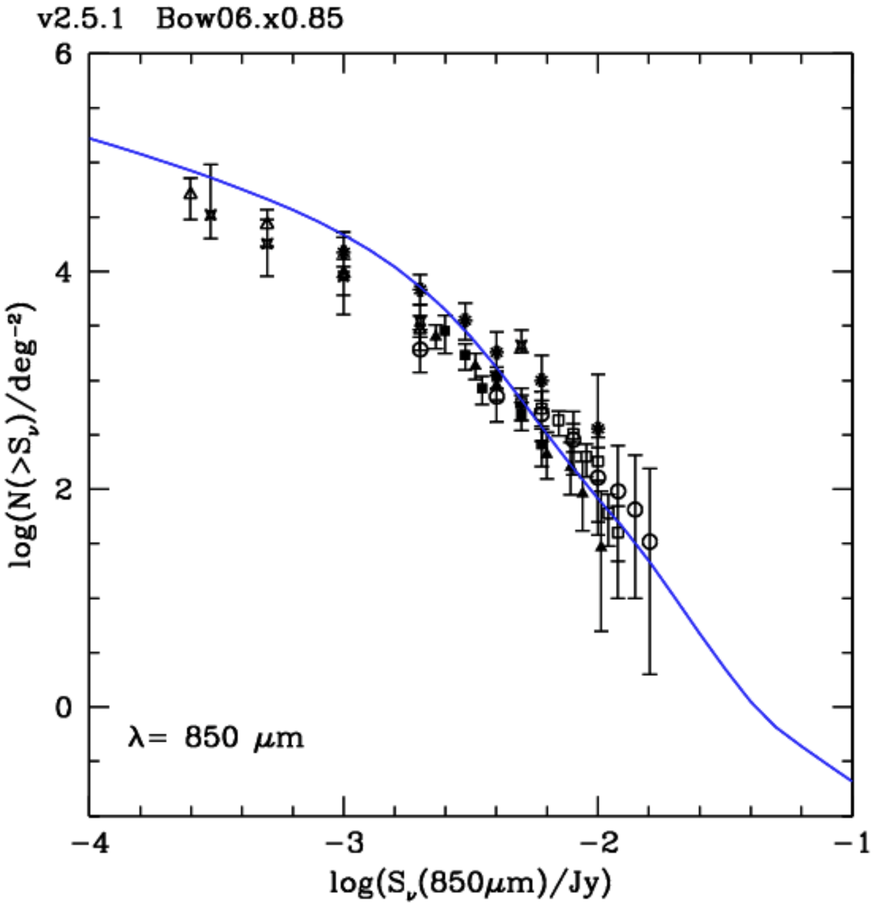
SMG number counts in standard Bower 06 model



SMG counts
30x too low
at S ~ 5 mJy

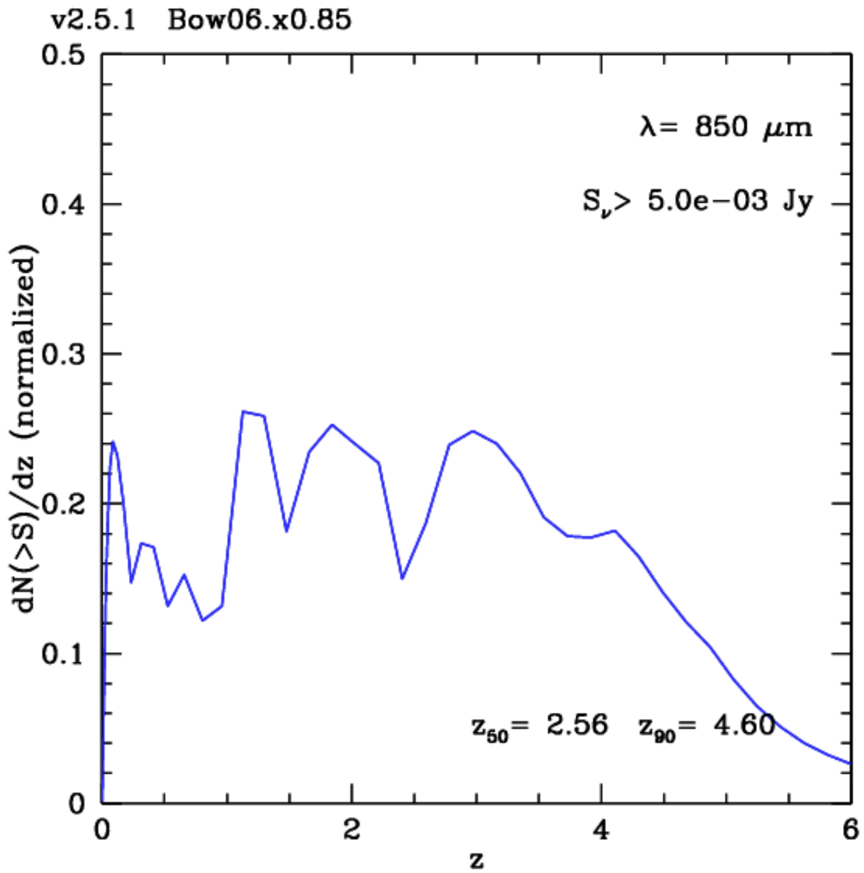
- Seems to be contradiction between observationally-inferred SFRs & stellar masses when assume standard IMF throughout
- What if add top-heavy IMF in bursts to AGN feedback model?

Bower 06 model + x=0.85 IMF in bursts



AGN feedback + top-heavy IMF gives good fit to SMG counts

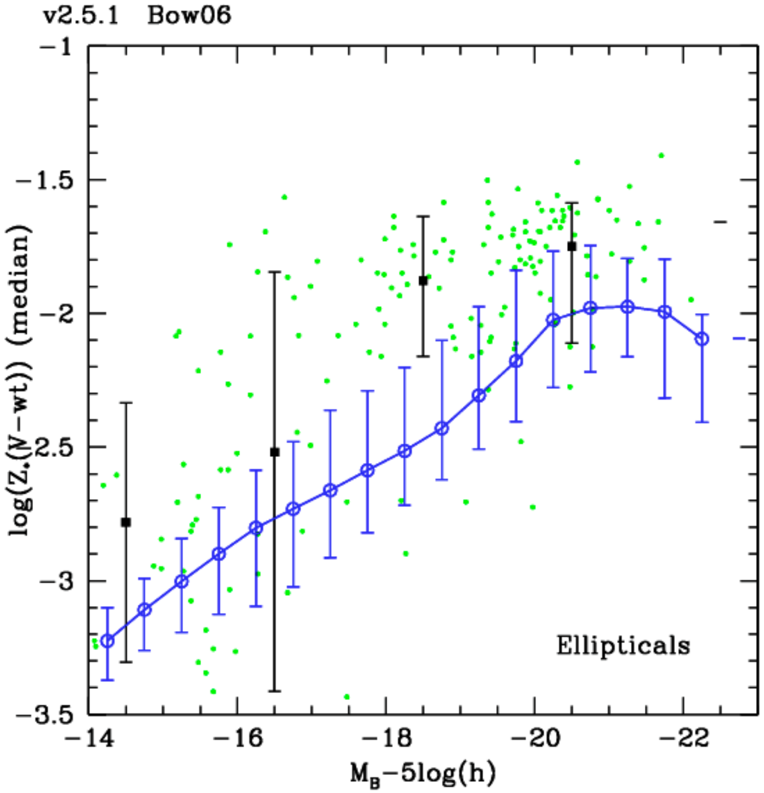
Bower 06 model + x=0.85 IMF in bursts



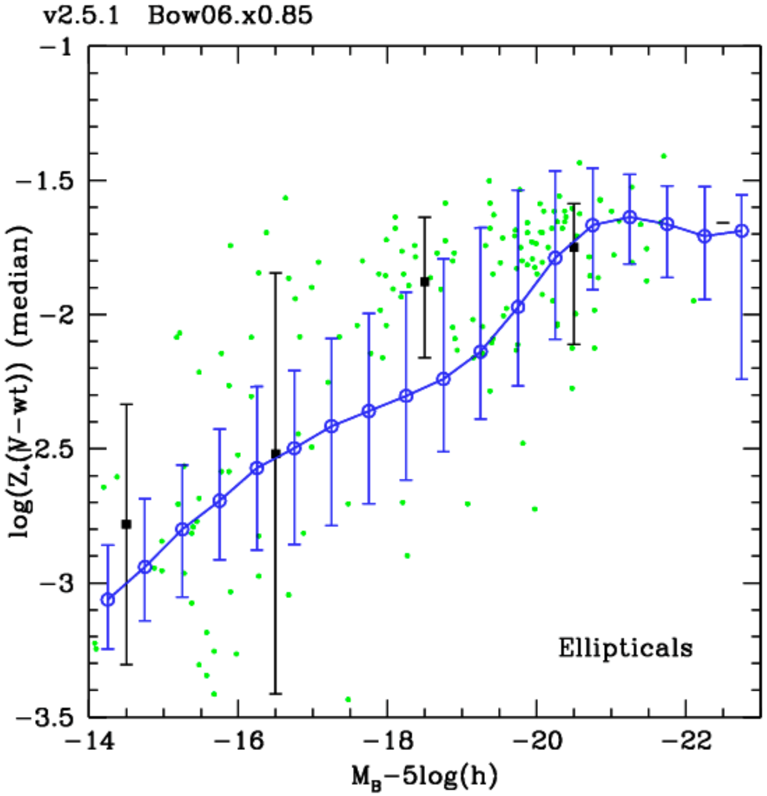
Redshift distribution of SMGs too broad c.f. obs

Stellar metallicities in Bower 06 model

Standard IMF



x=0.85 IMF in bursts

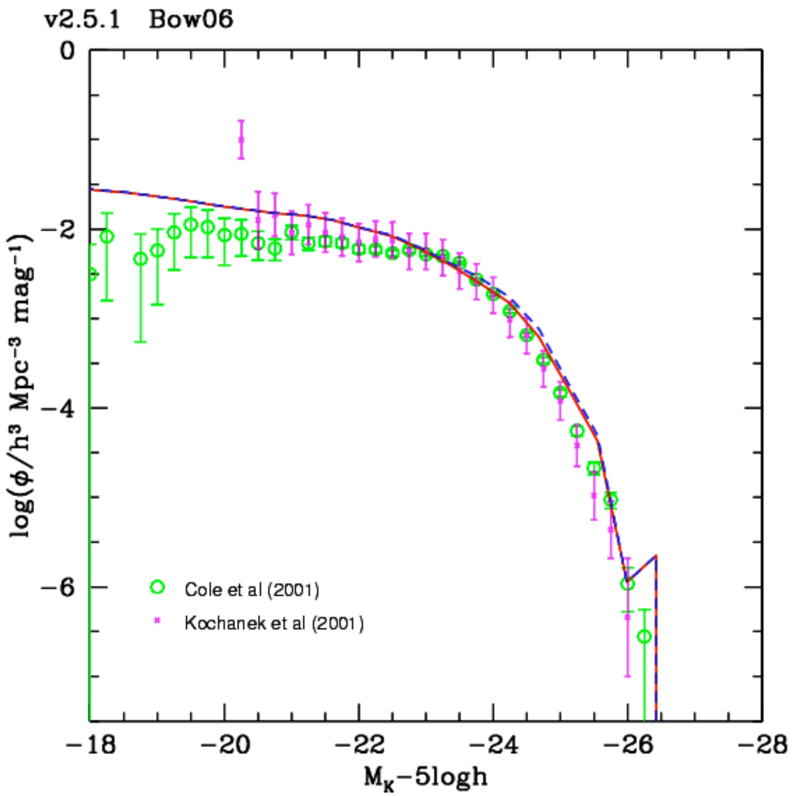


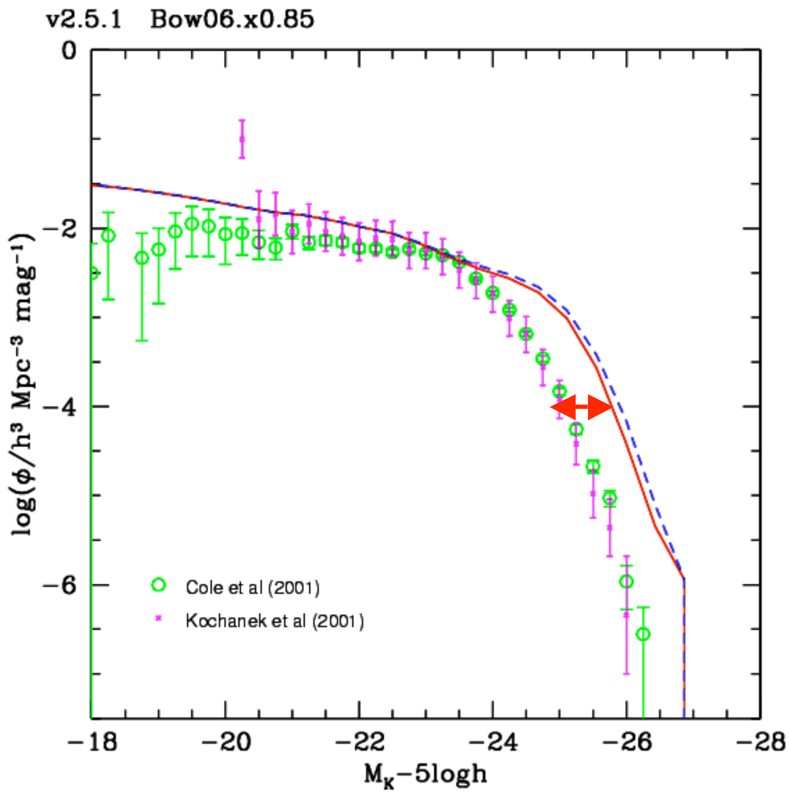
x=0.85 IMF in bursts gives better agreement with observed metallicities (using yields from stellar evoln)

K-band LF in Bower 06 model

Standard IMF

x=0.85 IMF in bursts





But x=0.85 IMF in bursts makes fit to z=0 K-band LF worse!

- Complicated interplay between different physical processes in model & different observational constraints
- Hard work finding model which satisfies all constraints!
- Search for improved model still underway….

Conclusions

- Model with top-heavy IMF in bursts reproduces many observed properties of SMGs: number counts, redshifts, dust SED shapes, gas masses, velocity widths, clustering length
- But predicts rest-frame NIR luminosities (& stellar masses) 10x too small
- Model combining AGN feedback + milder top-heavy IMF shows promise for reconciling these constraints - but no fully satisfactory model yet!