A unified model of galaxy evolution in the UV & IR

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Collaborators

Galaxy formation models (GALFORM):

Carlton Baugh	Durham
Carlos Frenk	Durham
Andrew Benson	Caltech
Juan Gonzalez	ESO

+ other members GALFORM team

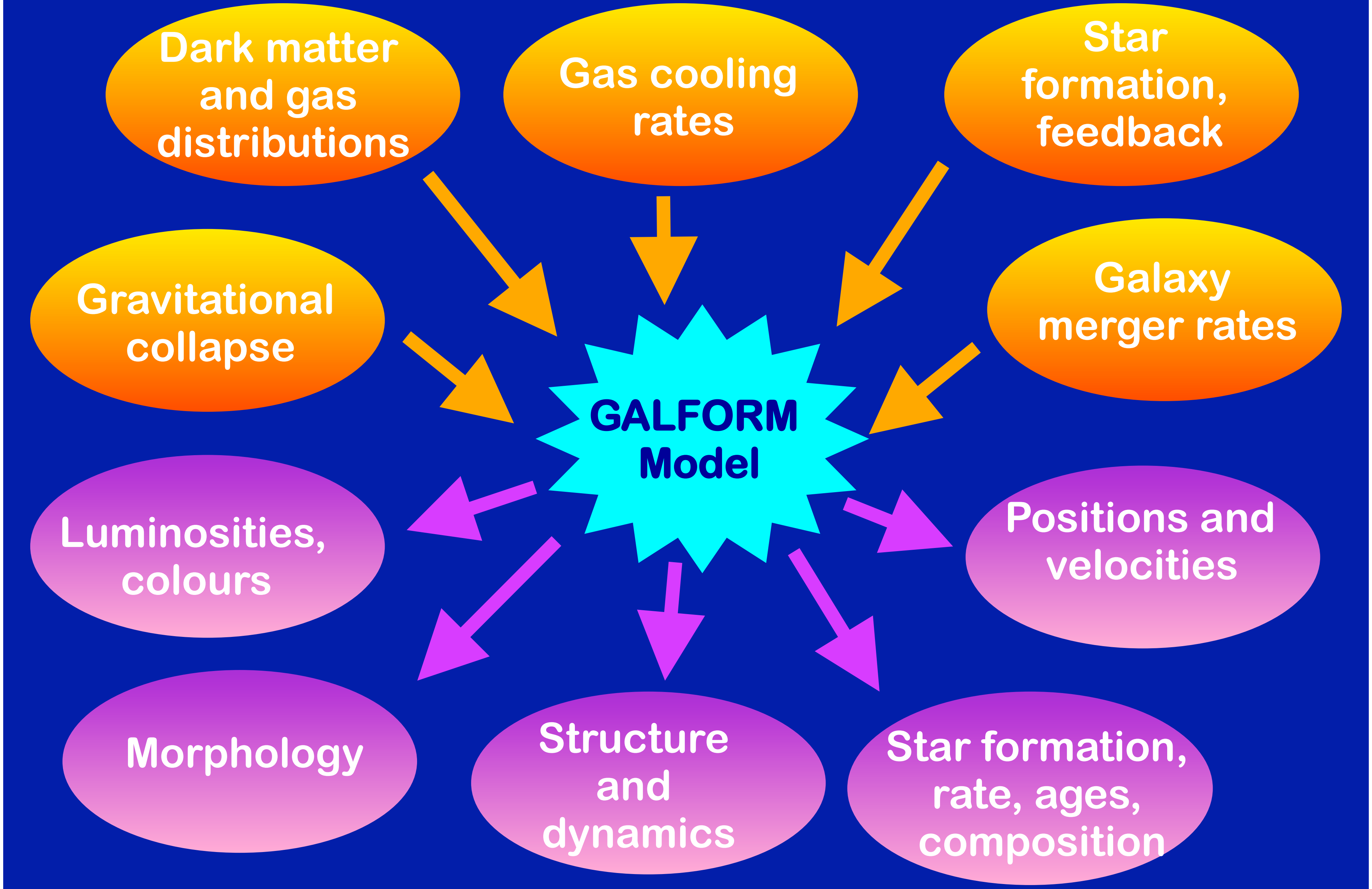
Dust Modelling (GRASIL):

Gian Luigi Granato	Trieste
Laura Silva	Trieste
Alessandro Bressan	Padova

Outline

- Semi-analytical modelling of galaxy formation
  - Goals & methods
- Multi-wavelength modelling of galaxy SEDs
  - Stars, dust and radio emission
- Sub-mm galaxies
  - Need for IMF variations?
- Evolution in the UV
  - Lyman-break galaxies
- Evolution in the IR
  - Spitzer & Herschel
- Conclusions

GALFORM: inputs and outputs



Dark matter and gas distributions

Gas cooling rates

Star formation, feedback

Gravitational collapse

Galaxy merger rates

GALFORM Model

Luminosities, colours

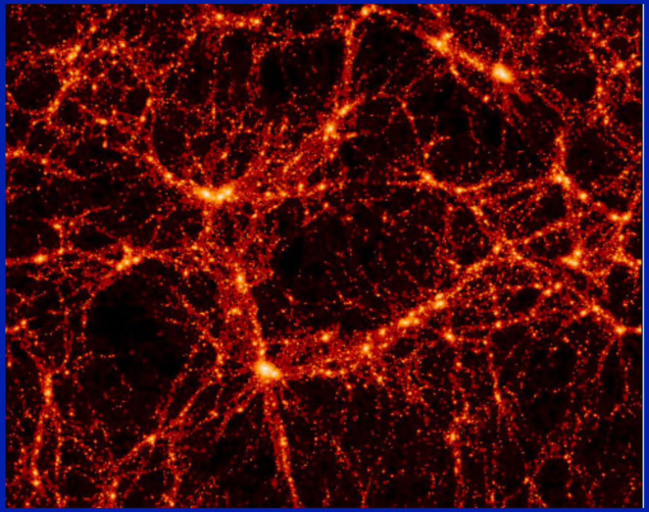
Positions and velocities

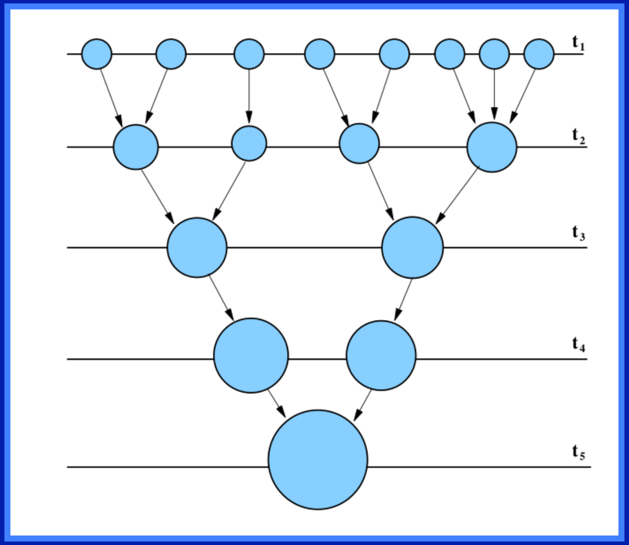
Morphology

Structure and dynamics

Star formation, rate, ages, composition

Assembly of dark matter halos: Merger trees





- **Monte Carlo - based on Extended Press-Schechter (EPS)**

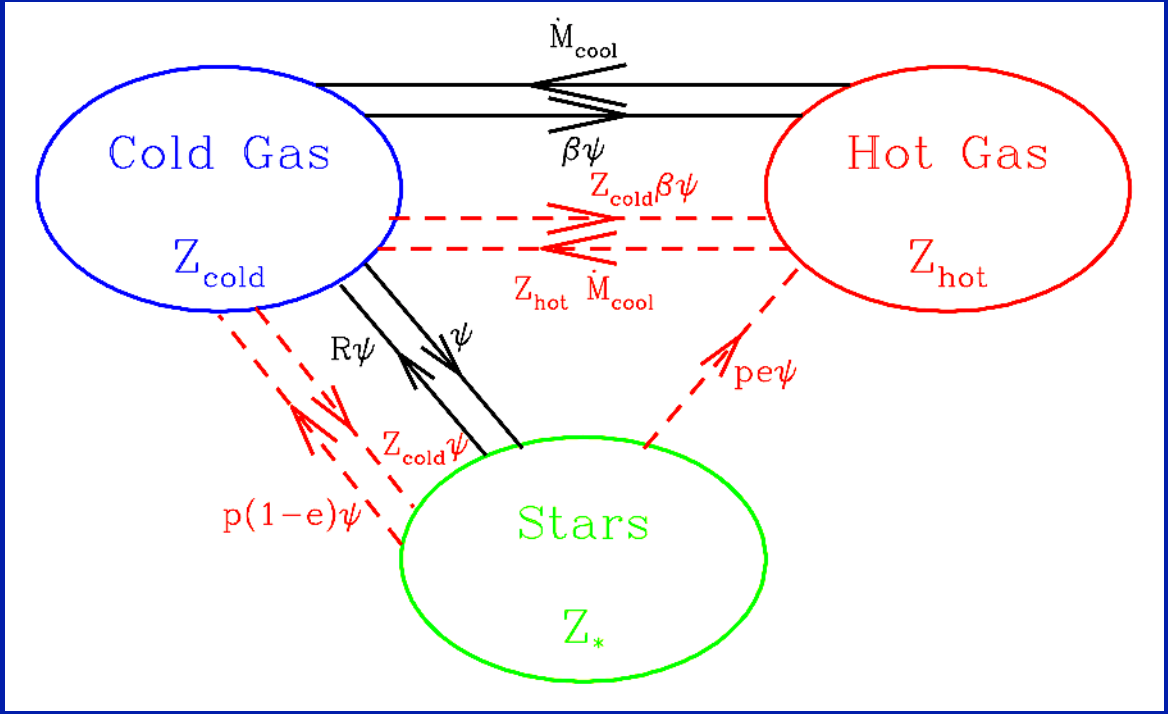
OR

- **Extract from N-body simulations**

EPS conditional mass function

$$f_{12}(M_1, M_2)dM_1 = \frac{1}{\sqrt{2\pi}} \frac{(\delta_{c1} - \delta_{c2})}{(\sigma_1^2 - \sigma_2^2)^{3/2}} \times \exp\left(-\frac{(\delta_{c1} - \delta_{c2})^2}{2(\sigma_1^2 - \sigma_2^2)}\right) \frac{d\sigma_1}{dM_1} dM_1$$

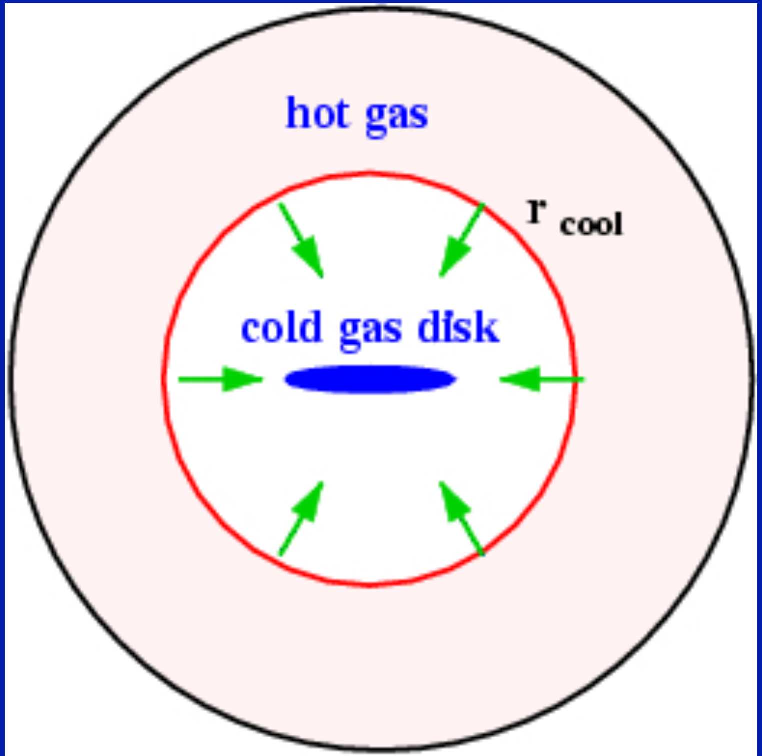
Evolution of baryons



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

Cole+00

Cooling & infall of gas in halos



$$T_{\mathrm{gas}} = T_{\mathrm{vir}} = \frac{1}{2}\frac{\mu m_{\mathrm{H}}}{k}V_{\mathrm{halo}}^2$$

$$\rho_{\mathrm{gas}}(r) \propto 1/(r^2 + r_{\mathrm{core}}^2)$$

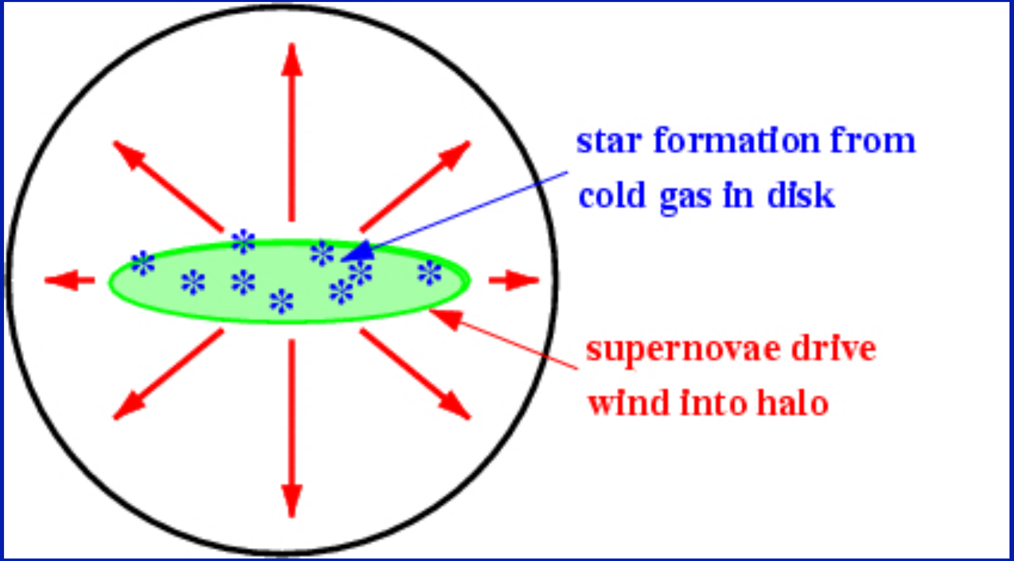
$$\tau_{\mathrm{cool}}(r) = \frac{3}{2}\frac{\mu m_{\mathrm{H}}}{\rho_{\mathrm{gas}}(r)}\frac{kT_{\mathrm{gas}}}{\Lambda(T_{\mathrm{gas}}, Z_{\mathrm{gas}})}$$

$$\begin{aligned} \tau_{\mathrm{cool}}(r) &= t - t_{\mathrm{form}} \quad \Rightarrow \quad r = r_{\mathrm{cool}}(t) \\ r_{\mathrm{acc}}(t) &= \min[r_{\mathrm{cool}}(t), r_{\mathrm{ff}}(t)] \end{aligned}$$

$$\dot{M}_{\mathrm{cool}} = 4\pi r_{\mathrm{acc}}^2\, \rho_{\mathrm{gas}}(r_{\mathrm{acc}})\, \dot{r}_{\mathrm{acc}}$$

Cole+00

Star formation & SN feedback



SFR & mass ejection

SFR

$$\begin{aligned} \psi &= \frac{M_{\rm cold}}{\tau_\star(r_{\rm disk}, V_{\rm disk})} \\ \dot{M}_{\rm eject} &= \beta(V_{\rm disk})\,\psi \end{aligned}$$

SFR timescale

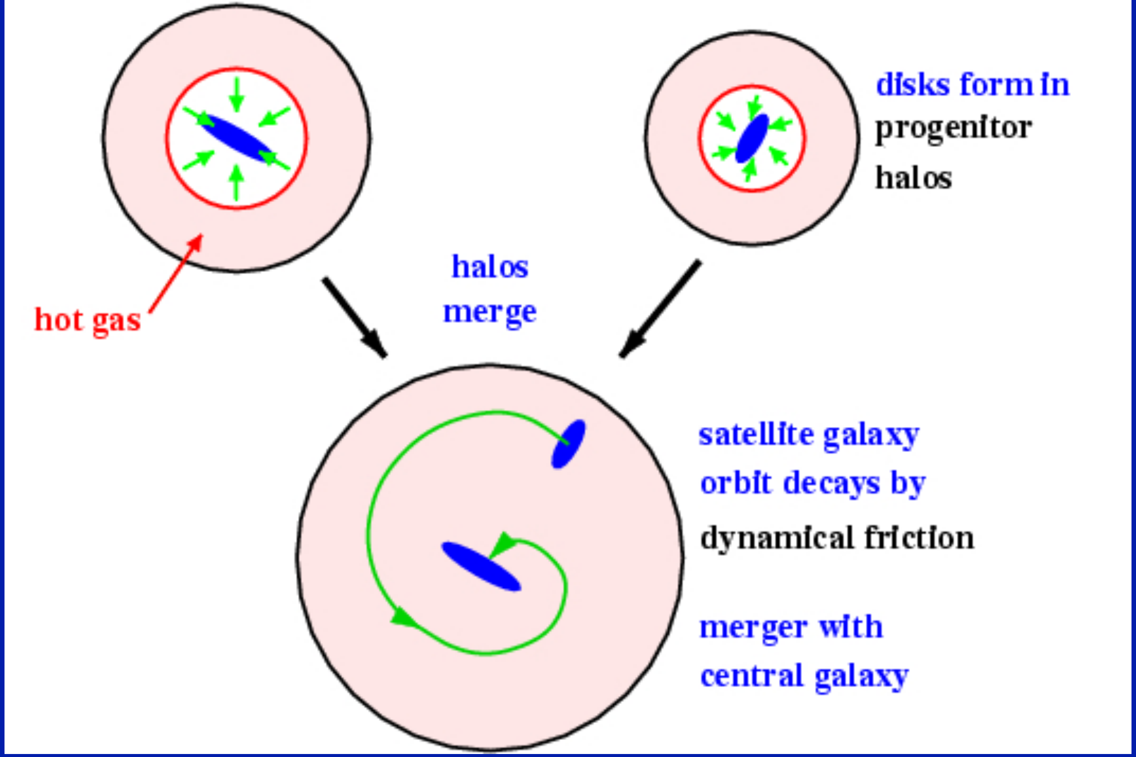
$$\begin{aligned} \tau_\star &\propto V_{\rm disk}^{\alpha_\star} \\ \tau_\star &\propto \tau_{\rm dyn,disk}\, V_{\rm disk}^{\alpha_\star} \end{aligned}$$

SN feedback efficiency

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

Cole+00

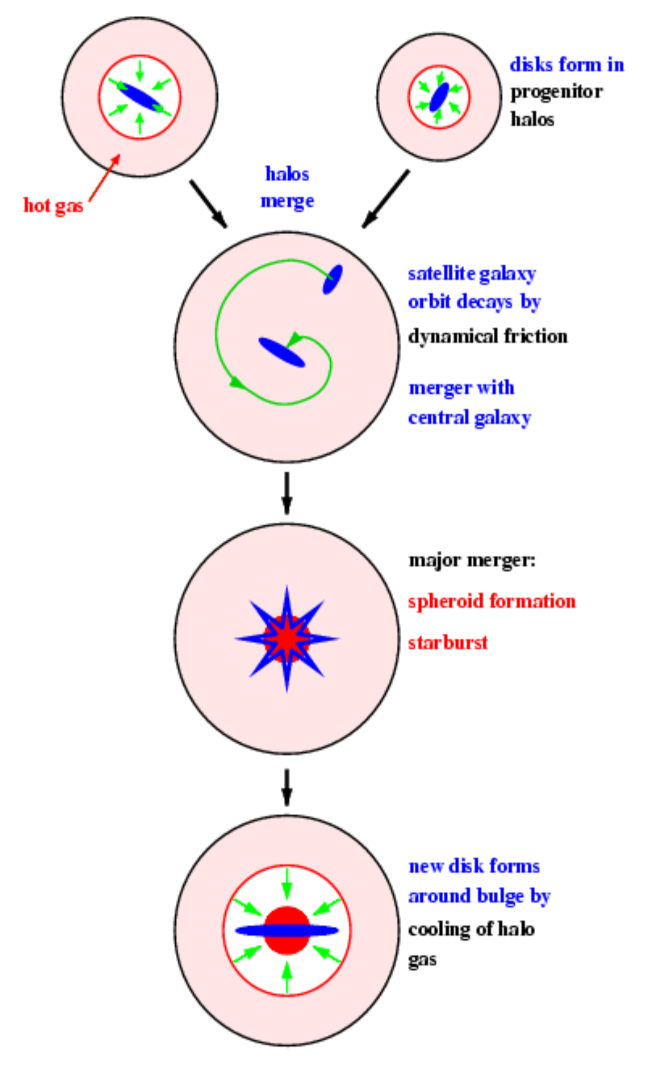
Galaxy mergers



Dynamical friction timescale

$$\tau_{\rm merge} = \left(\frac{J}{J_{\rm c}(E)}\right)^{0.78} \left(\frac{r_{\rm c}(E)}{r_{\rm vir}}\right)^{2} \frac{0.37}{\ln(\Lambda_{\rm Coulomb})} \frac{M_{\rm halo}}{M_{\rm sat}} \frac{r_{\rm vir}}{V_{\rm halo}}$$

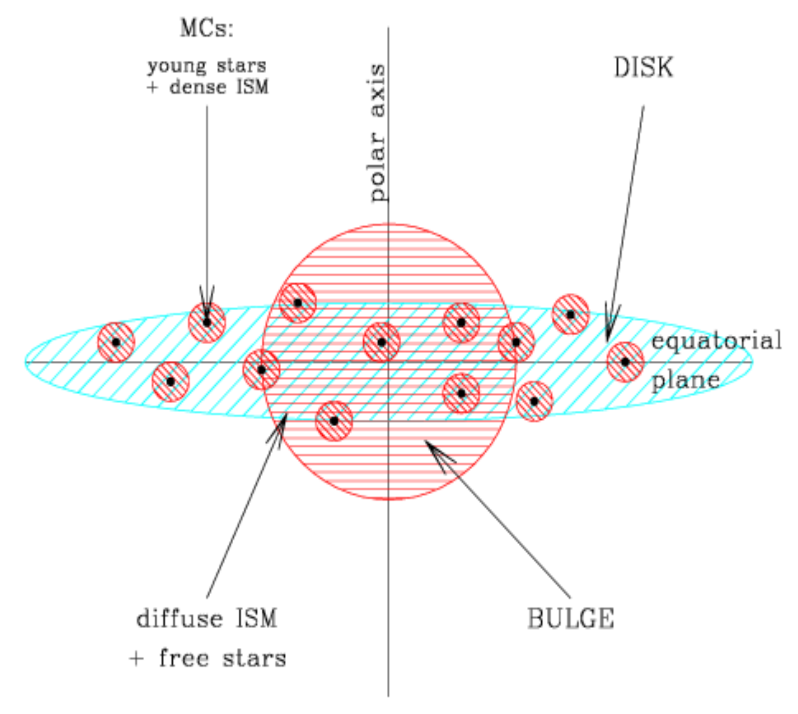
Mergers, morphology & starbursts



- halos merge
- galaxies merge driven by dynamical friction in halo
- major mergers make galactic spheroids from disks
- major and (some) minor mergers trigger starbursts
- spheroids can grow new disks

Modelling galaxy SEDs with dust

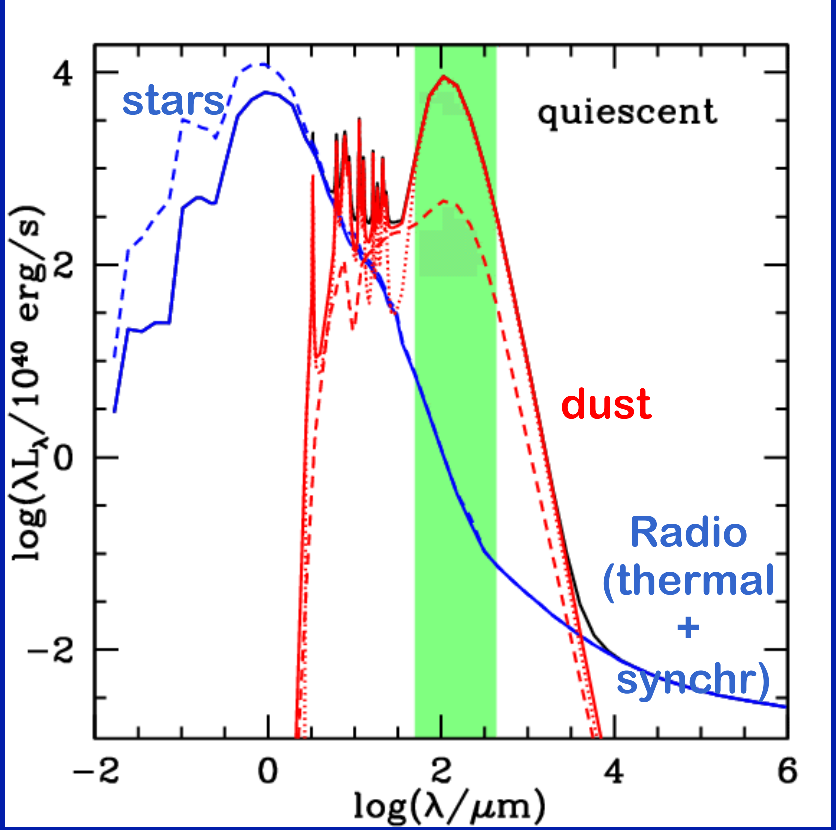
- dust in diffuse medium and molecular clouds
- stars form in clouds and leak out
- Stellar luminosity from pop synthesis
- radiative transfer of starlight through dust
- physical dust grain model, distribn of sizes
- heating of dust grains -> dust temperature distribution -> IR/sub-mm emission



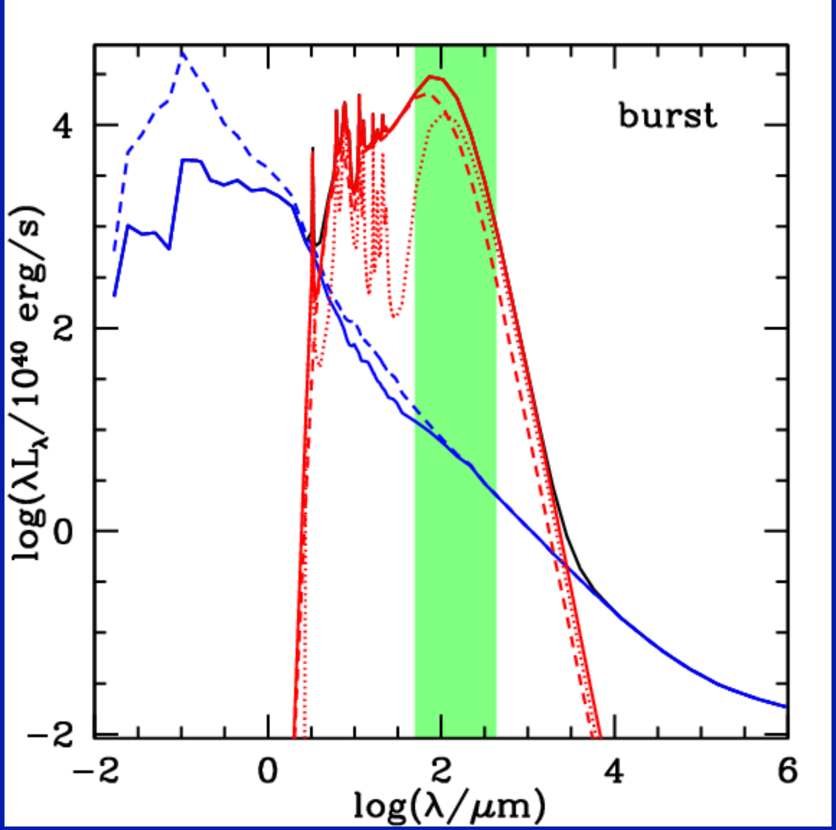
GRASIL: Silva et al 1998

Example SEDs of galaxies from GALFORM+GRASIL model

Quiescent spiral

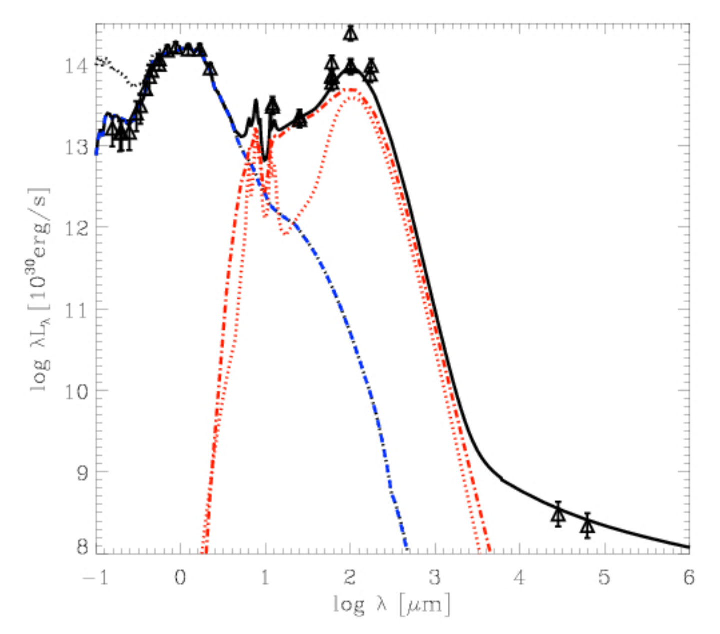


Ongoing burst

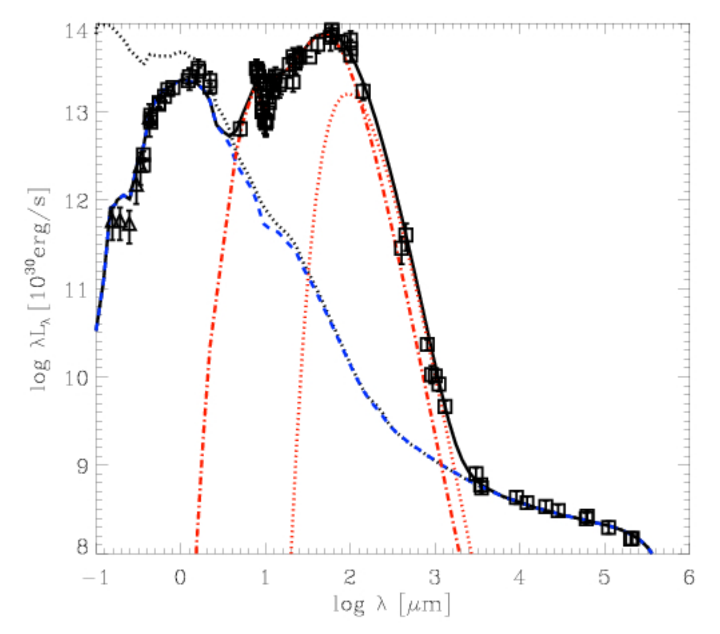


GRASIL SEDs compared to local galaxies

M51 (spiral)



M82 (starburst)



- GRASIL model can reproduce observed SEDs of local galaxies, for suitable dust model parameters & SF history (Silva et al 1998, Bressan et al 2002, Vega et al 2008)

Model with variable IMF

- Quiescent SF in disks:
  - Standard solar neighbourhood IMF
- Starbursts:
  - Top-heavy IMF

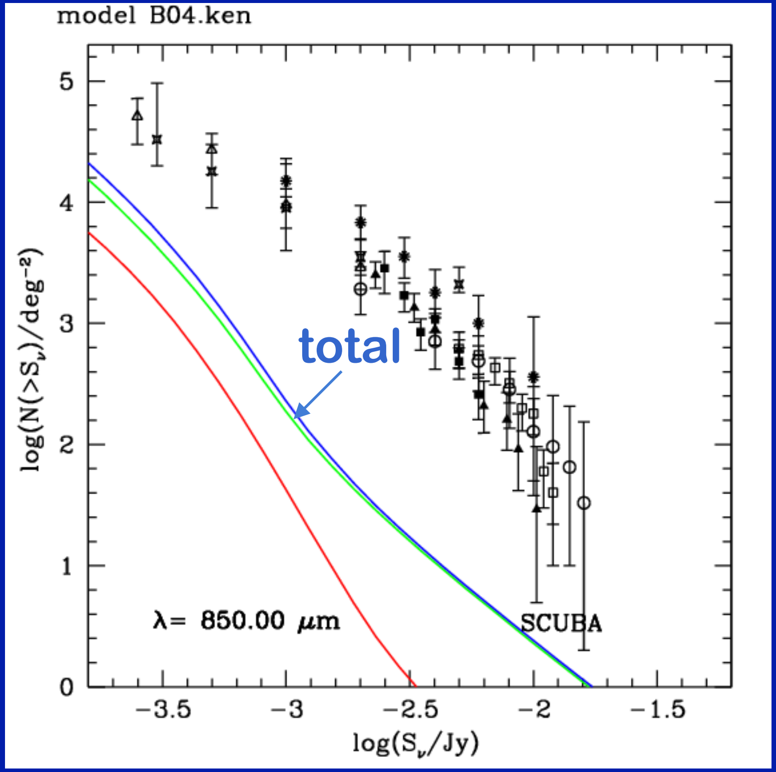
$$dN/d\ln m \propto m^0$$

  - Increases UV luminosities & metal production (hence dust masses) by ~ 5x
  - Would get similar effect with Salpeter IMF truncated below ~ $5M_o$

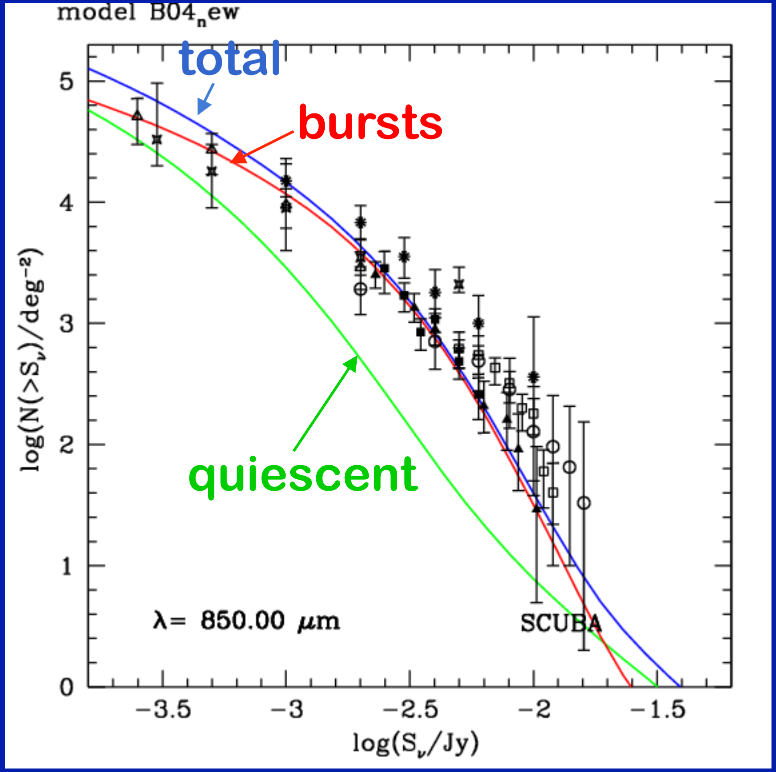
(Baugh+05, Lacey+08)

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

normal IMF



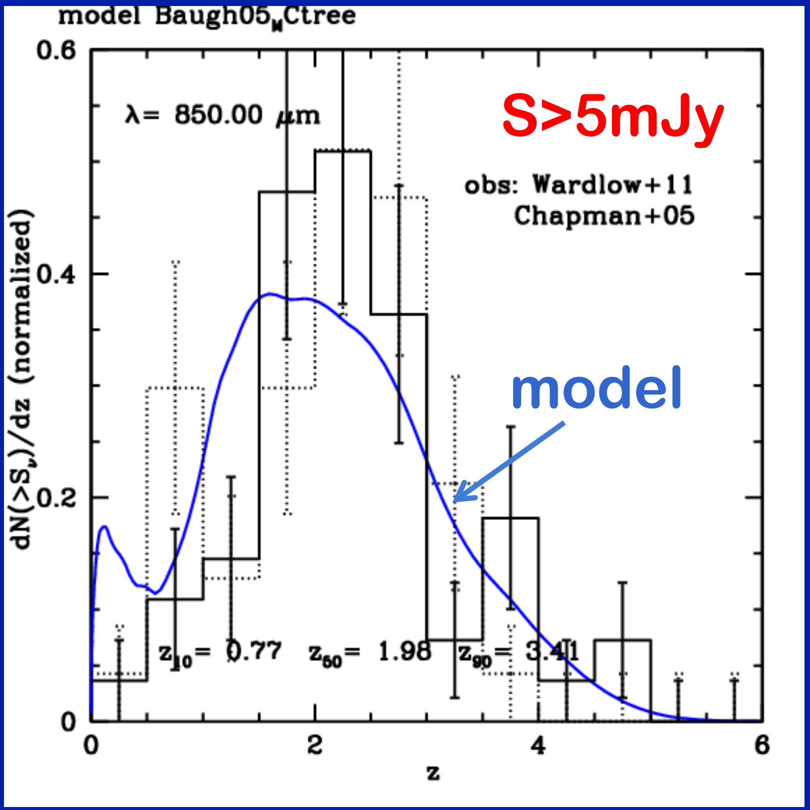
top-heavy IMF



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

Baugh+05

Redshifts of sub-mm galaxies



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

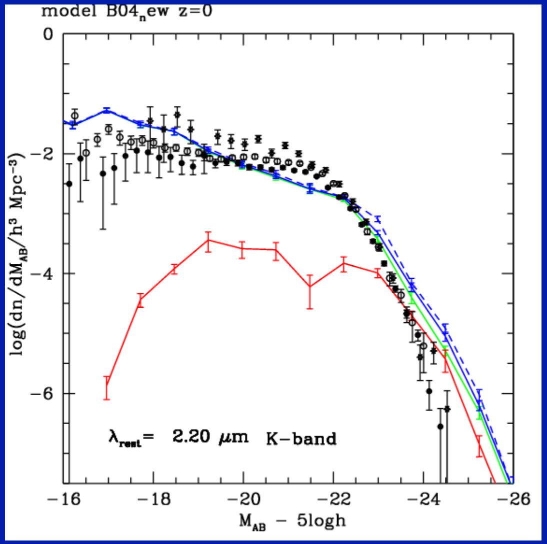
For model to reproduce simultaneously:

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

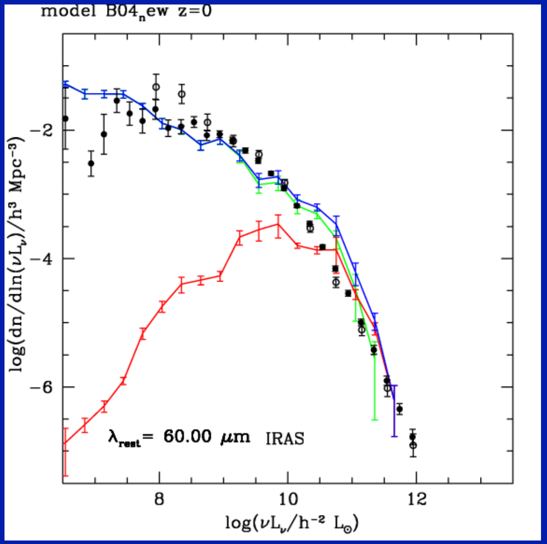
- need top-heavy IMF

Obs constraints at z=0

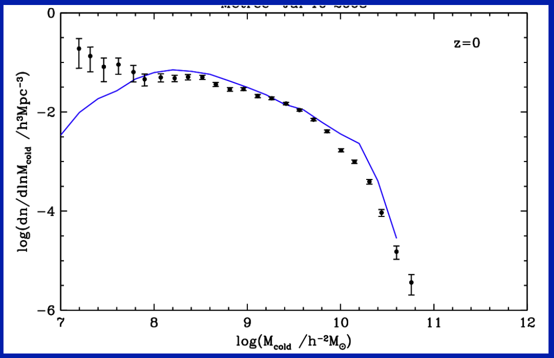
K-band LF



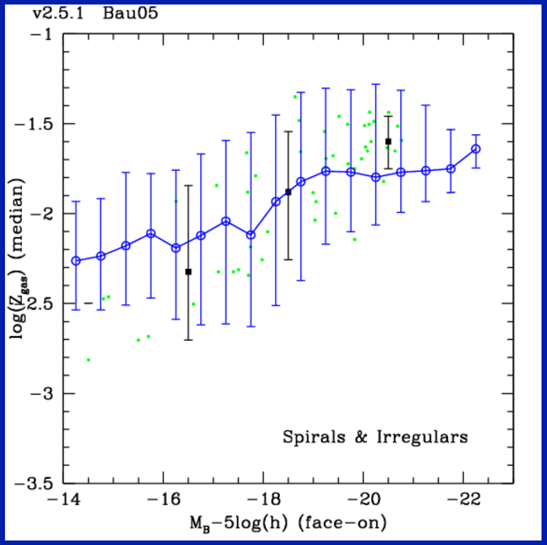
60 μm LF



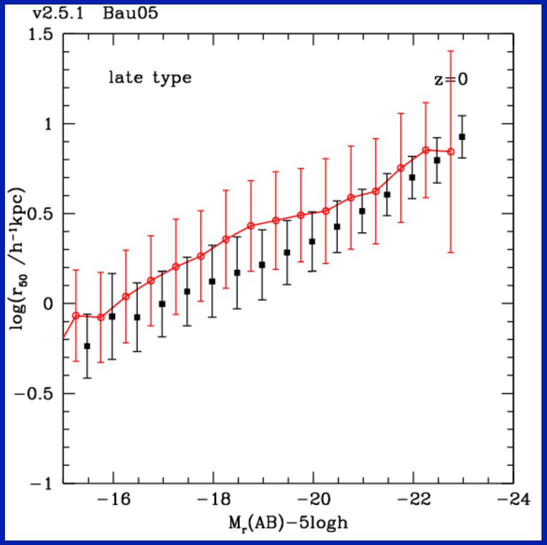
HI mass function



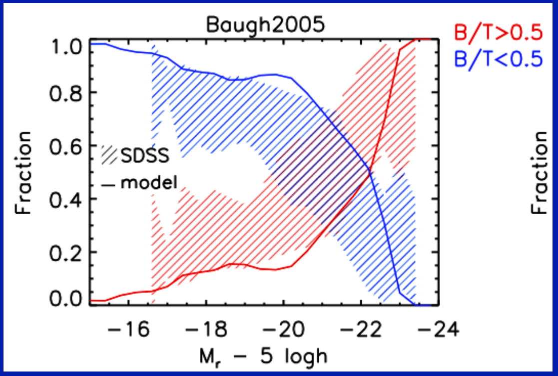
gas metallicity in disks



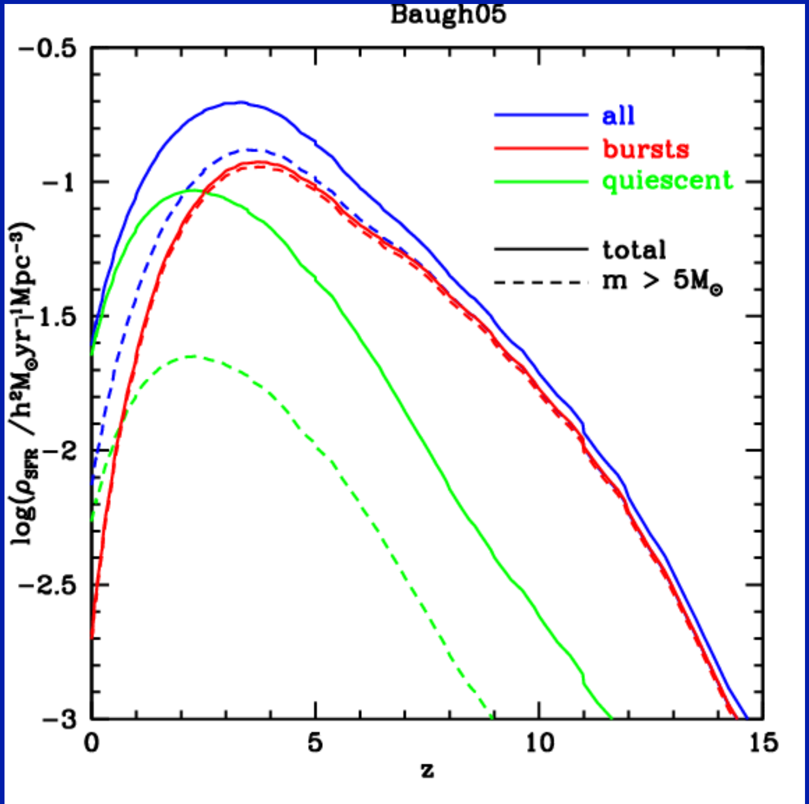
disk radii



early/late-type fractions



Cosmic star formation history - theory

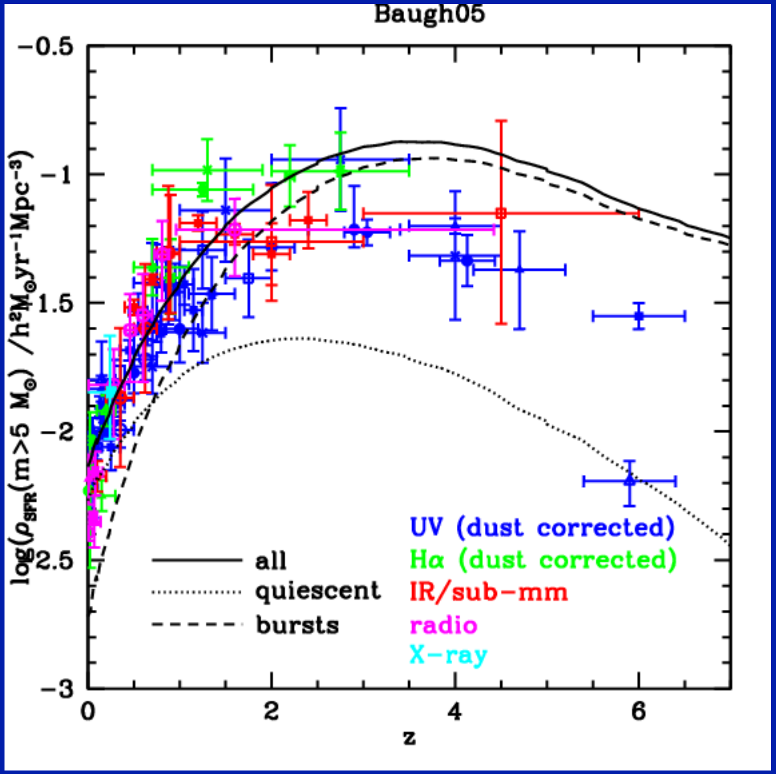


- Model predicts quiescent SF in disks dominates at low z<3, and merger-triggered starbursts at high z>3
- Rise from high-z due to buildup of DM halos
- Decline at low-z due longer gas cooling times in halos

Lacey+11

Cosmic star formation history - observations

SFR in m>5M_o stars



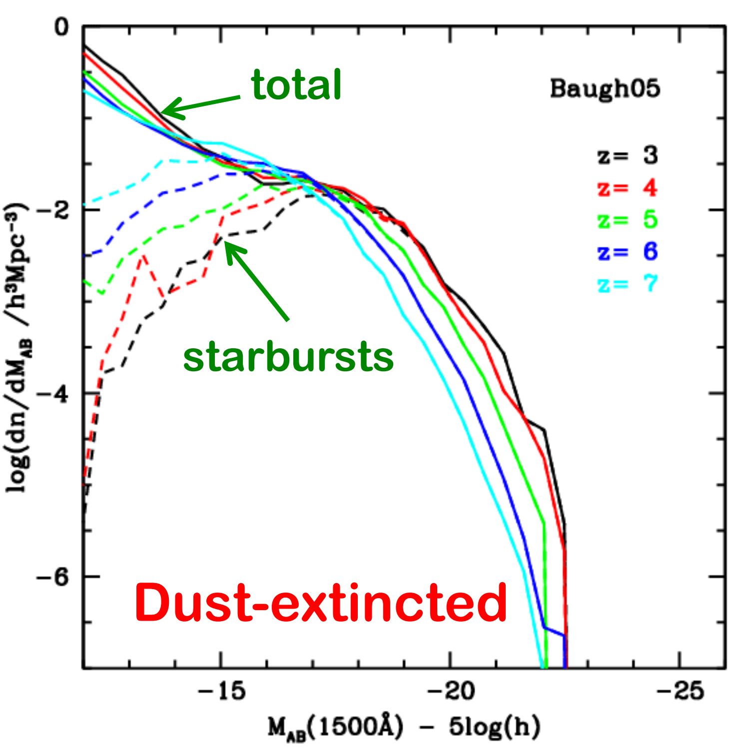
- High-mass (m>5M_o) SFR predicted by model broadly consistent with obs
- HOWEVER, many uncertainties in obs estimates:
  - Dust extinction (UV)
  - SED shape (IR/sub-mm)
  - SF histories
  - Extrapoln of LFs to low L
  - IMF

=> Need more direct obs comparisons

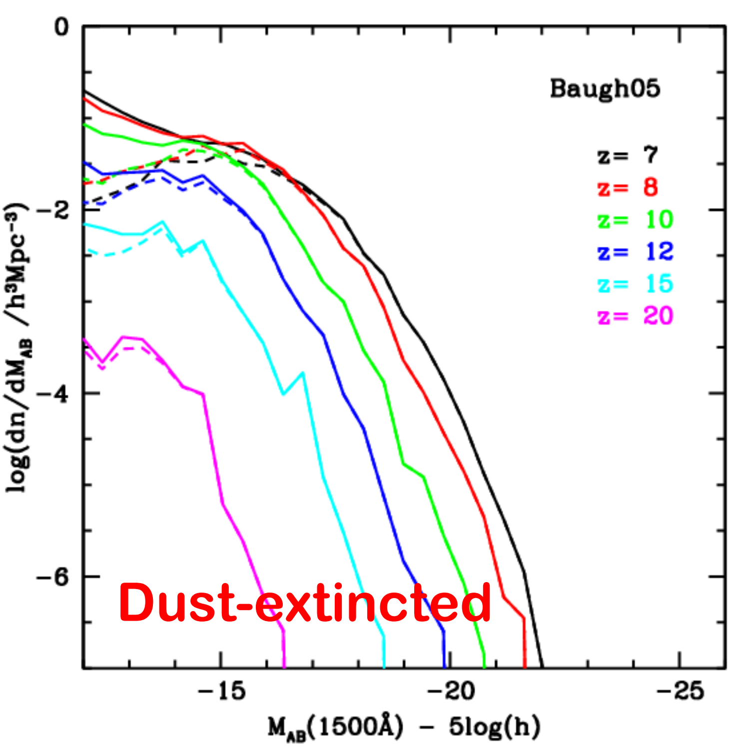
Obs compilation: Hopkins 2006

Evolution of luminosity function in far-UV - model

z=3-7



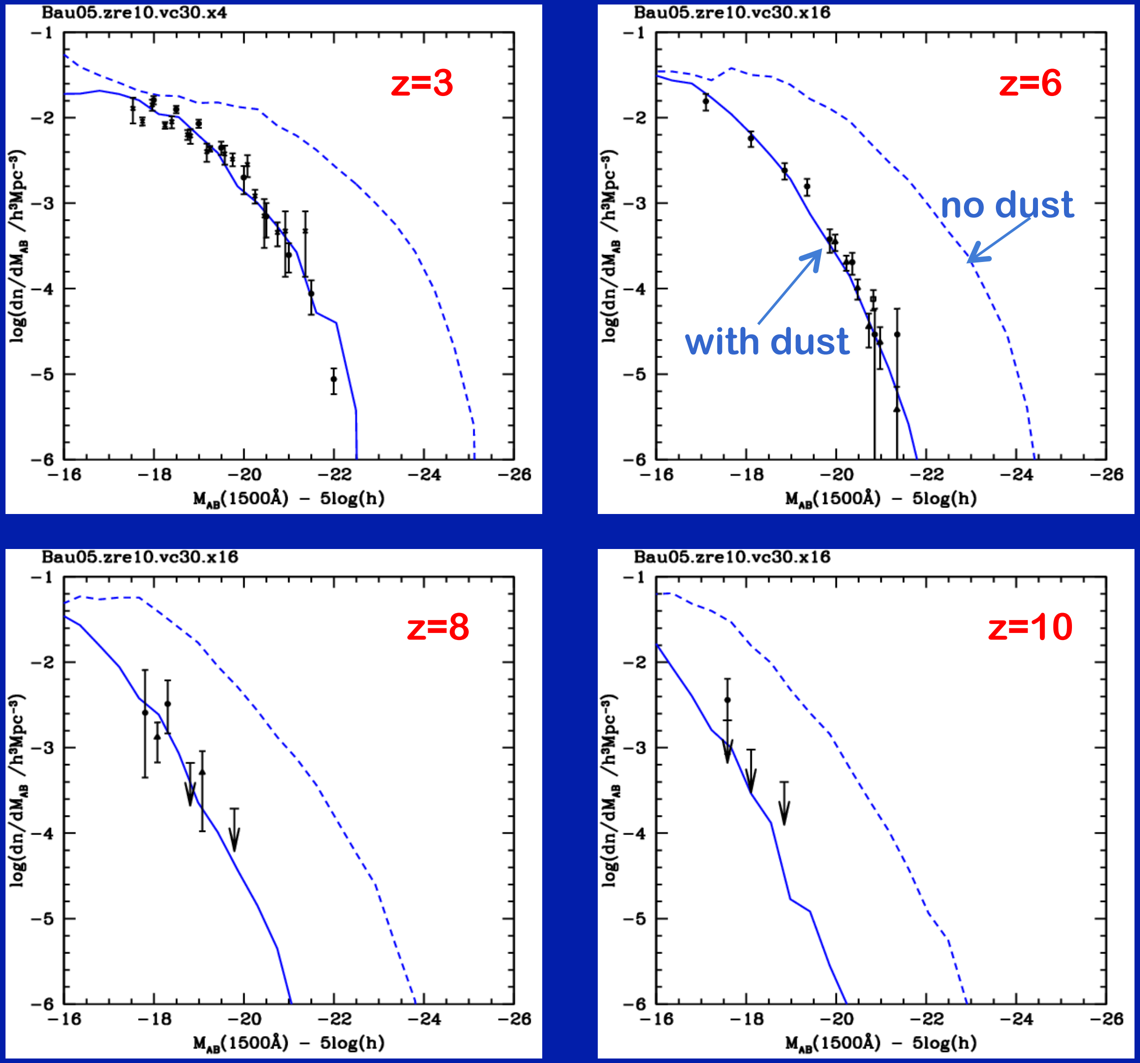
z=7-20



- UV LF at high L dominated by merger-triggered starbursts
- rapid decline at z>8 driven by buildup of DM halos

Lacey+11

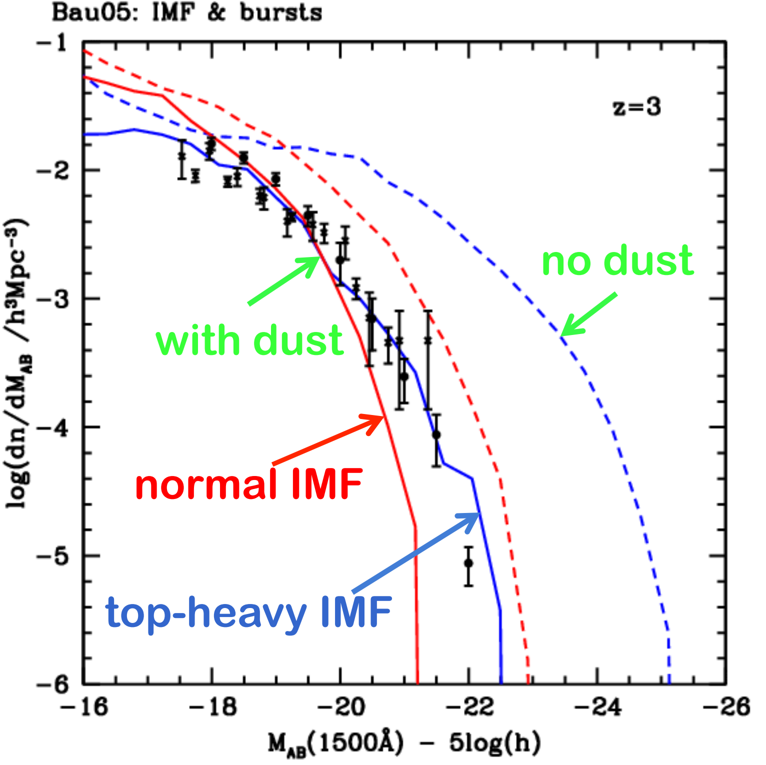
Evolution of far-UV LF – comparison with LBGs



- Extends original agreement of model with LBG obs for z=3 (Baugh+05) up to z=10 (including new HST WFC3 data)
- predict large UV extinctions (~ 2 mag)

Lacey+11

Effect of top-heavy IMF on far-UV LF

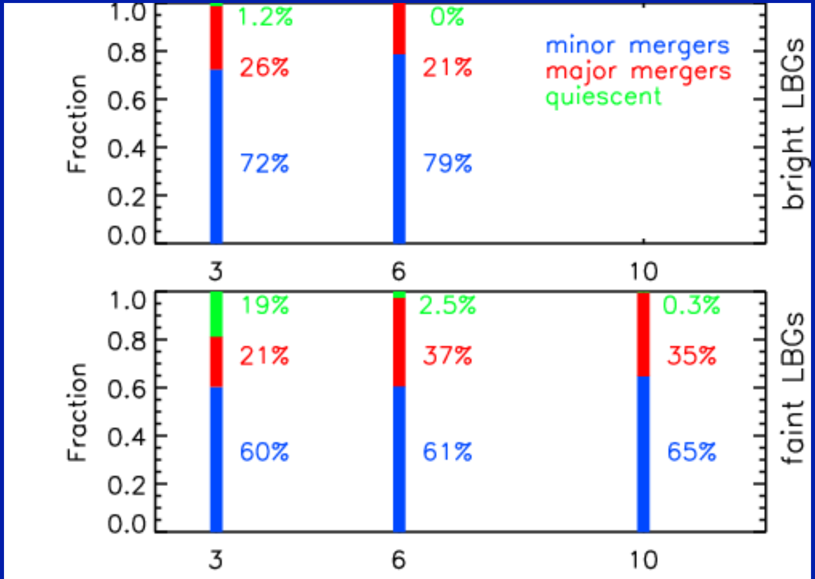


- replacing top-heavy IMF in bursts by normal IMF has only modest effect on far-UV LF
- decrease in stellar UV luminosities partly compensated by decrease in dust extinction

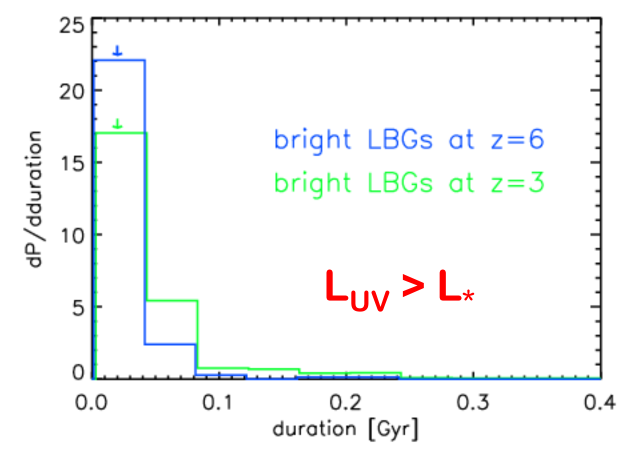
Lacey+11

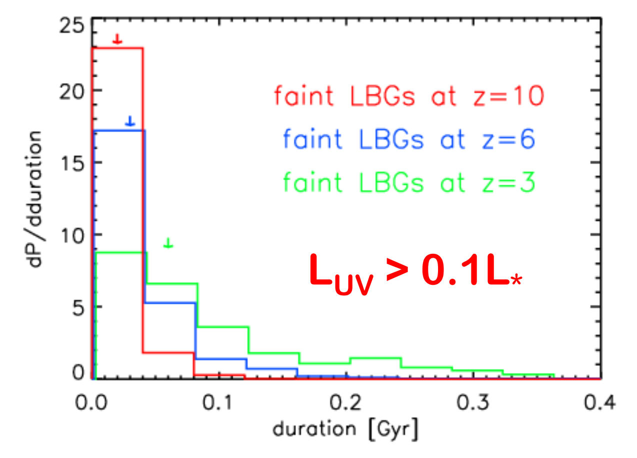
Triggering & duration of LBG phase

Triggering



Duration





- predict most LBGs are bursts triggered by minor mergers

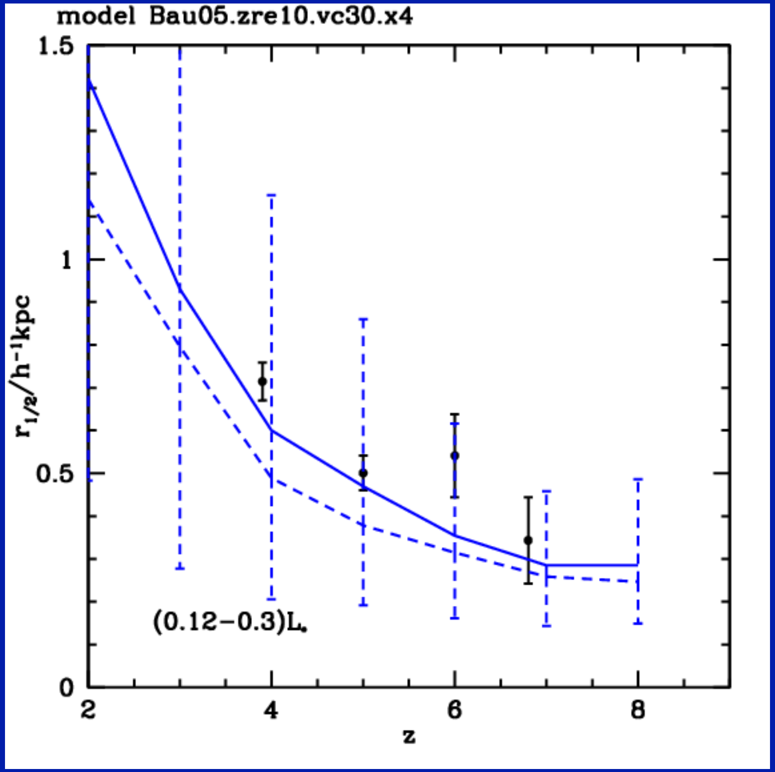
- roughly consistent with obs morphologies

- typical duration ~ 20-50 Myr

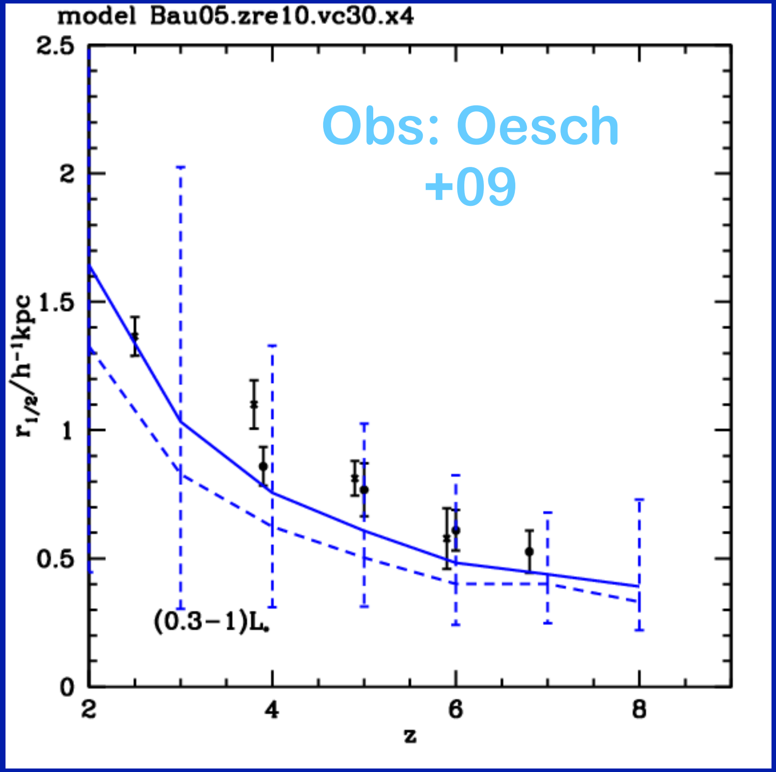
Gonzalez+11

Evolution of UV half-light radii

$0.12<L_{UV}/L_*<0.3$



$0.3<L_{UV}/L_*<1$

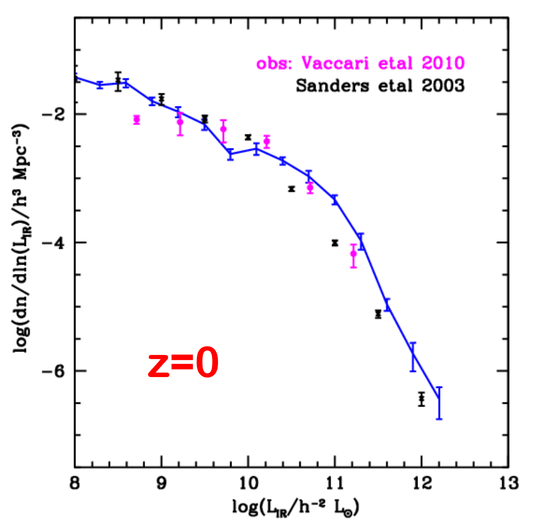


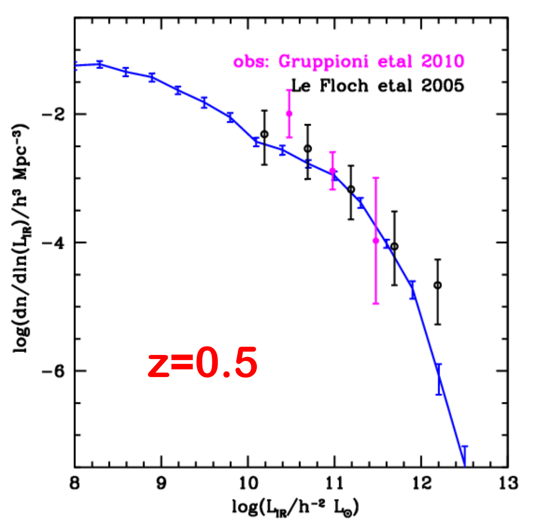
Obs: Oesch +09

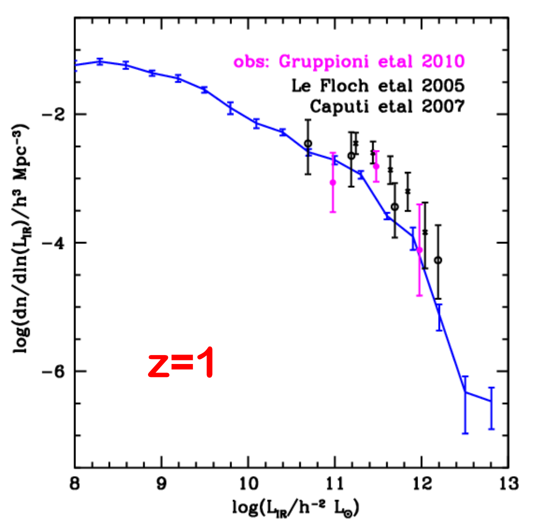
Model predicts sizes in excellent agreement with HST obs

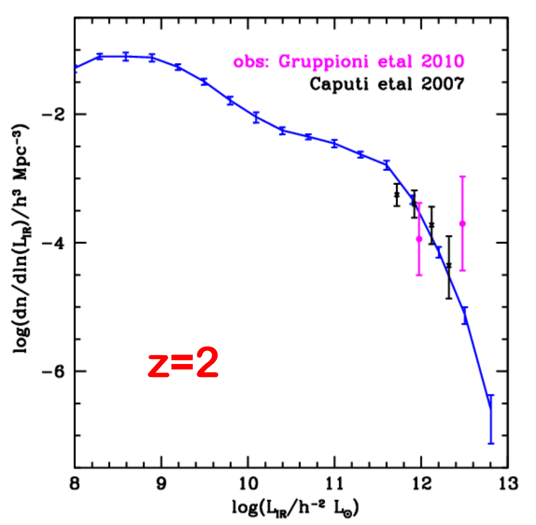
Lacey+11

Evolution of far-IR LF





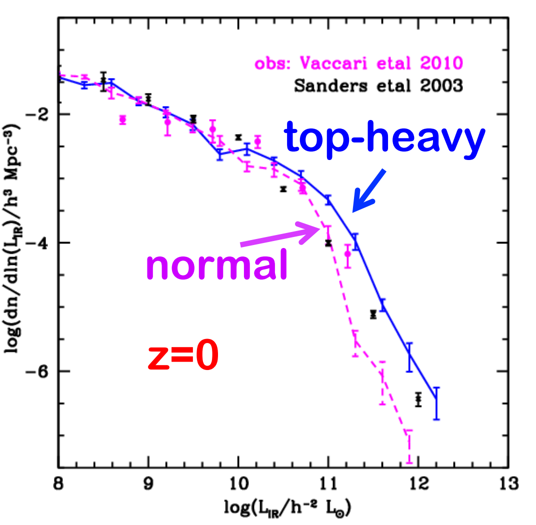


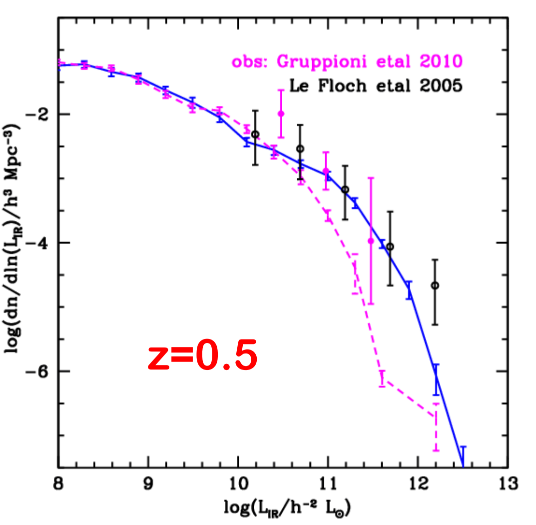


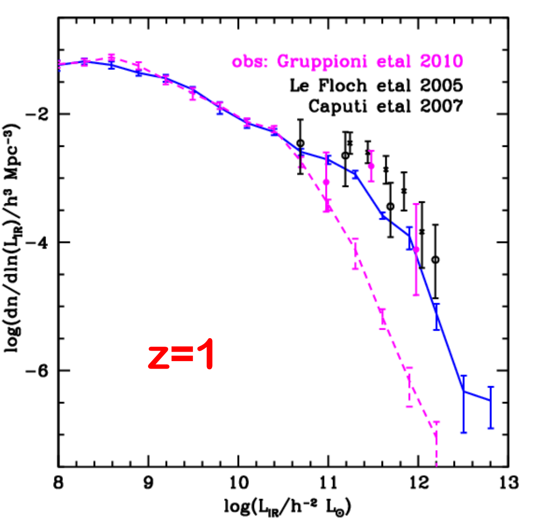
Model predictions in good agreement with total (8-1000 μm) IR LF inferred from IRAS, Spitzer & Herschel obs for z = 0-2

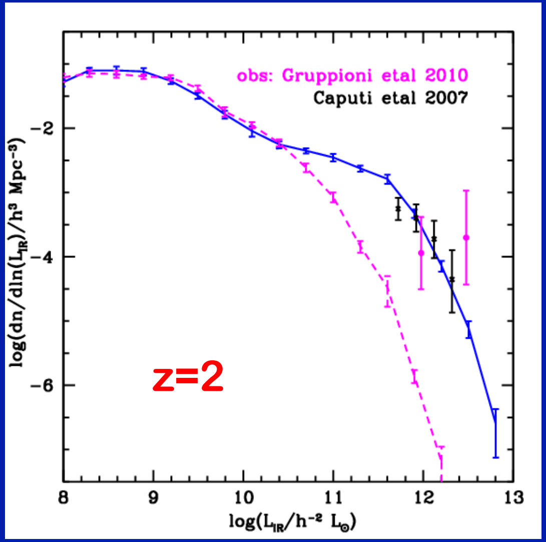
Lacey+11, in prep

Evolution of total IR LF – effect of starburst IMF





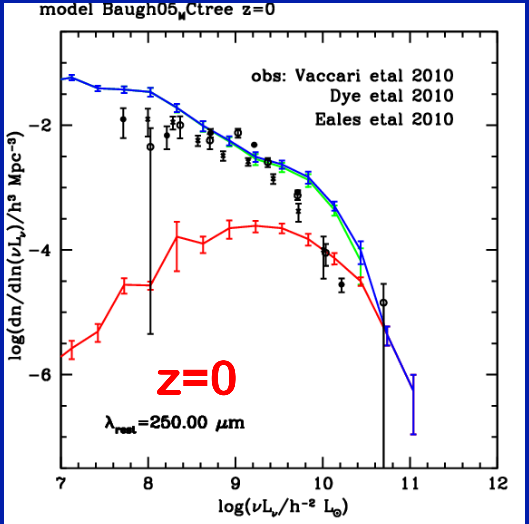


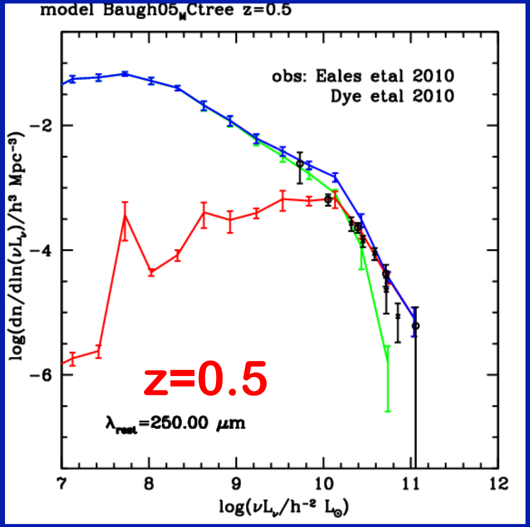


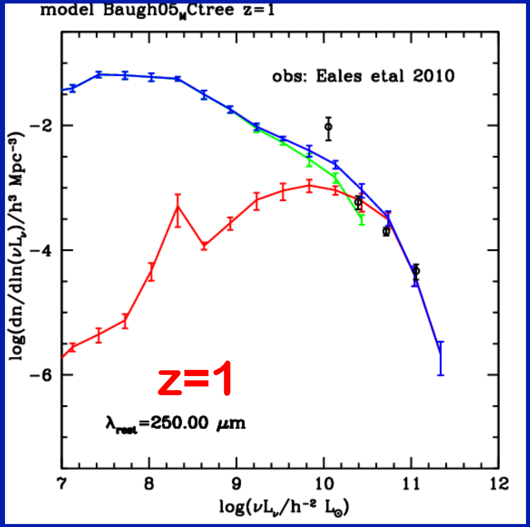
- Effect of top-heavy IMF in bursts on bright end of LF increases with z
- model with normal IMF in bursts does not match obs evoln

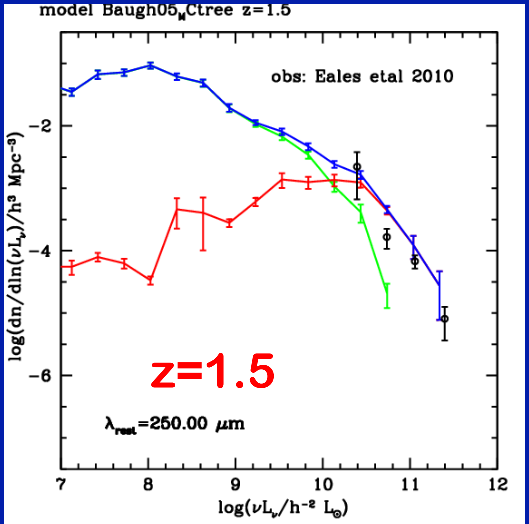
Lacey+11, in prep

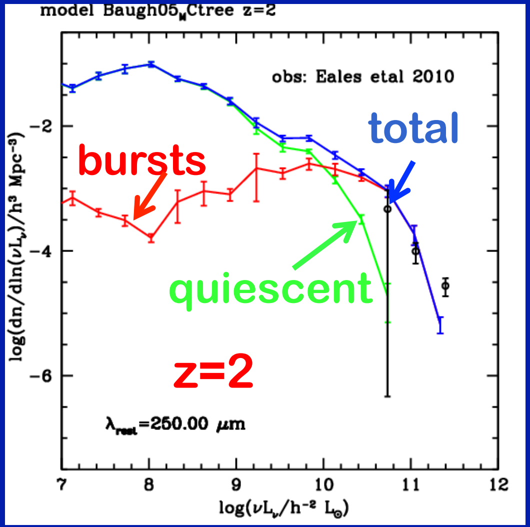
Evolution of 250 μm LF







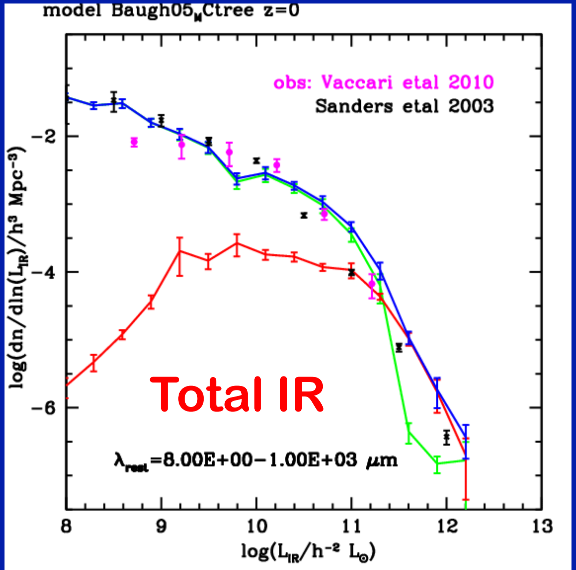


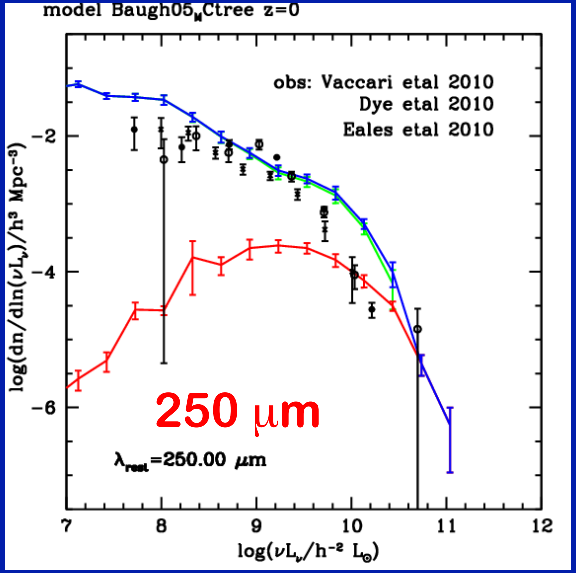


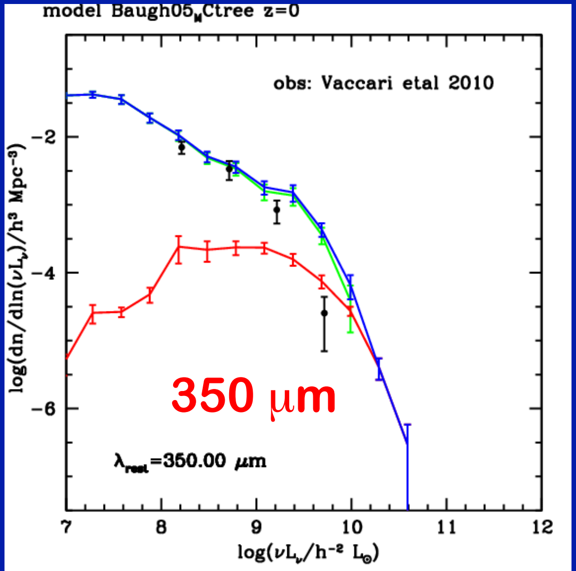
- 250 μm predictions agree better with Herschel obs at z>0.5, where LF more dominated by bursts
- overpredict 250 μm LF at z=0

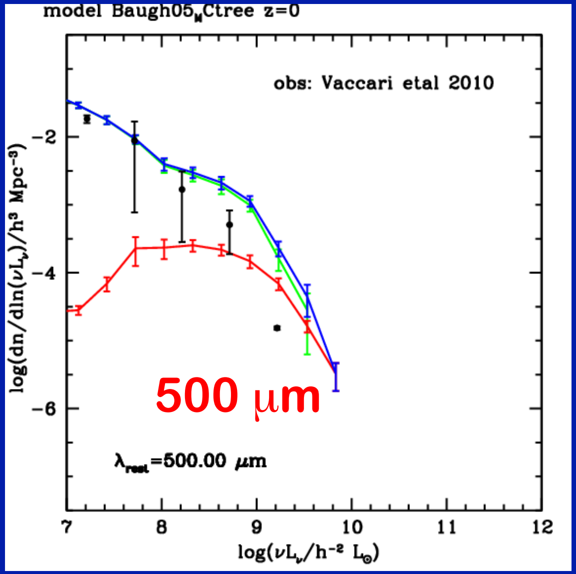
Lacey+11, in prep

Total IR & 250-500 μm LFs at z=0









- at z=0, model agrees better with bolometric than monochromatic IR LFs
- problem with predicted dust SEDS in quiescent galaxies at low-z?

Lacey+11, in prep

Conclusions

- CDM based models can explain wide range of galaxy properties in unified framework
- Sub-mm galaxies seem to require top-heavy IMF in bursts, once impose other obs constraints as well
- Same model reproduces numbers & sizes of LBGs to z~10
- And evolution of total IR LF to z~2
- However, possible problems with stellar masses at high z & dust SEDs at low z