Feedback and galaxy formation

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Collaborators

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T Okamoto	ICC Durham
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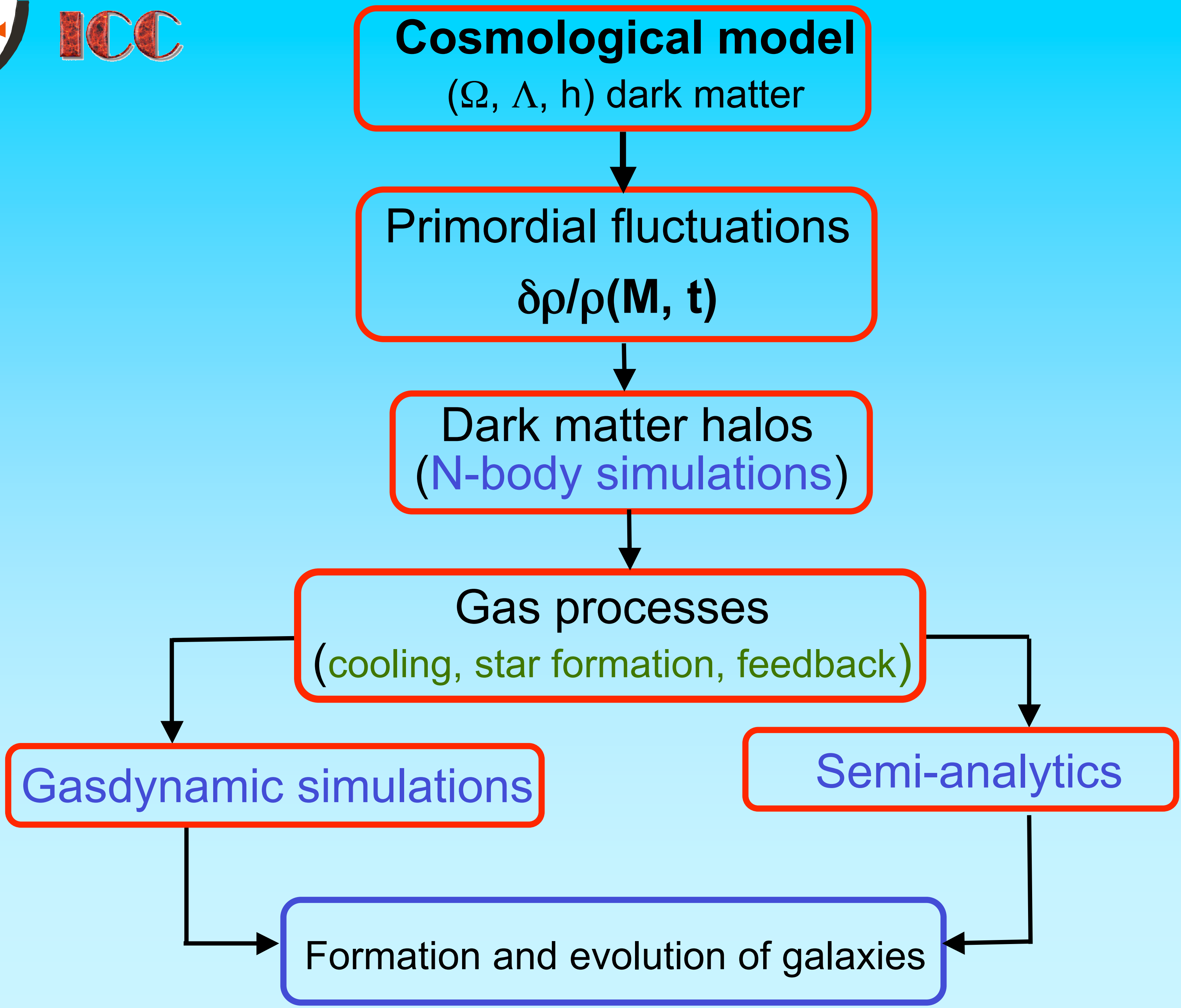
Cosmological model
(Ω, Λ, h) dark matter
Primordial fluctuations
δρ/ρ(M, t)
Dark matter halos
(N-body simulations)
Gas processes
(cooling, star formation, feedback)
Gasdynamic simulations
Semi-analytics
Formation and evolution of galaxies

Modelling galaxy formation

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- **Aim:** follow history of galaxy formation ***ab initio***, i.e starting from a cosmological model for structure formation so as to predict observables
- **Main Physical processes**:
  - Assembly of dark matter halos
  - Shock-heating and radiative cooling of gas within halos
  - Star formation and feedback
  - Production & mixing of metals
  - Evolution of stellar populations
  - Dust obscuration
  - Black hole format'n, AGN feedback
  - Galaxy mergers

Sub-grid physics

Phenomenological models

In semi-analytics and simulations

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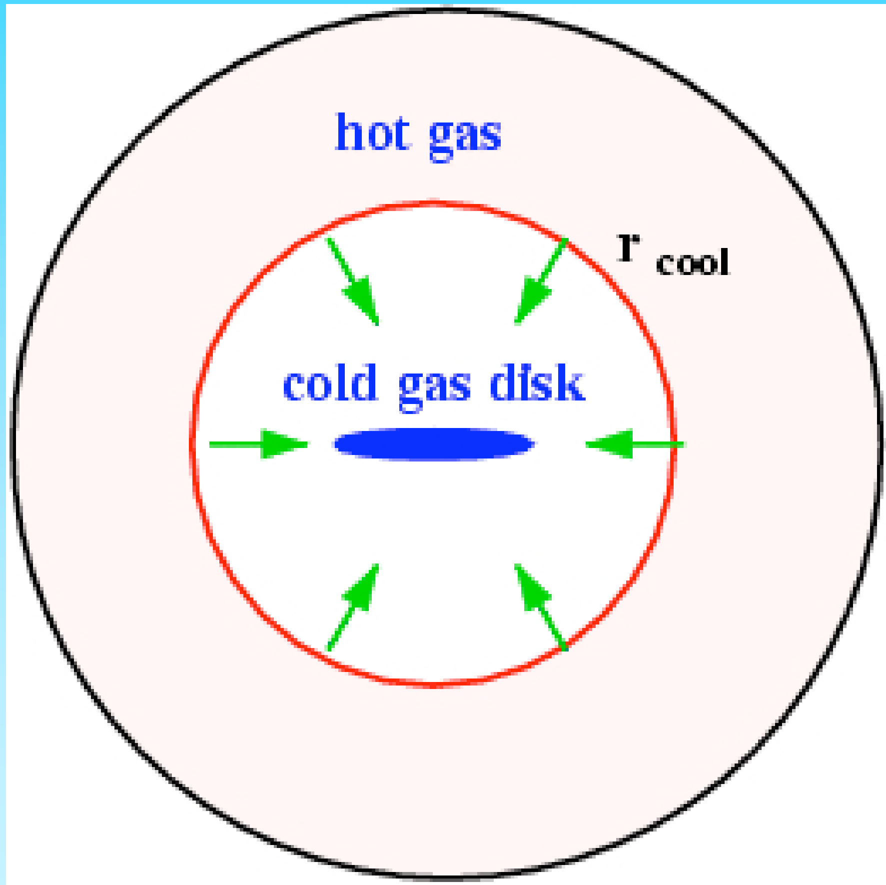
Shock heating & cooling of gas in halos

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



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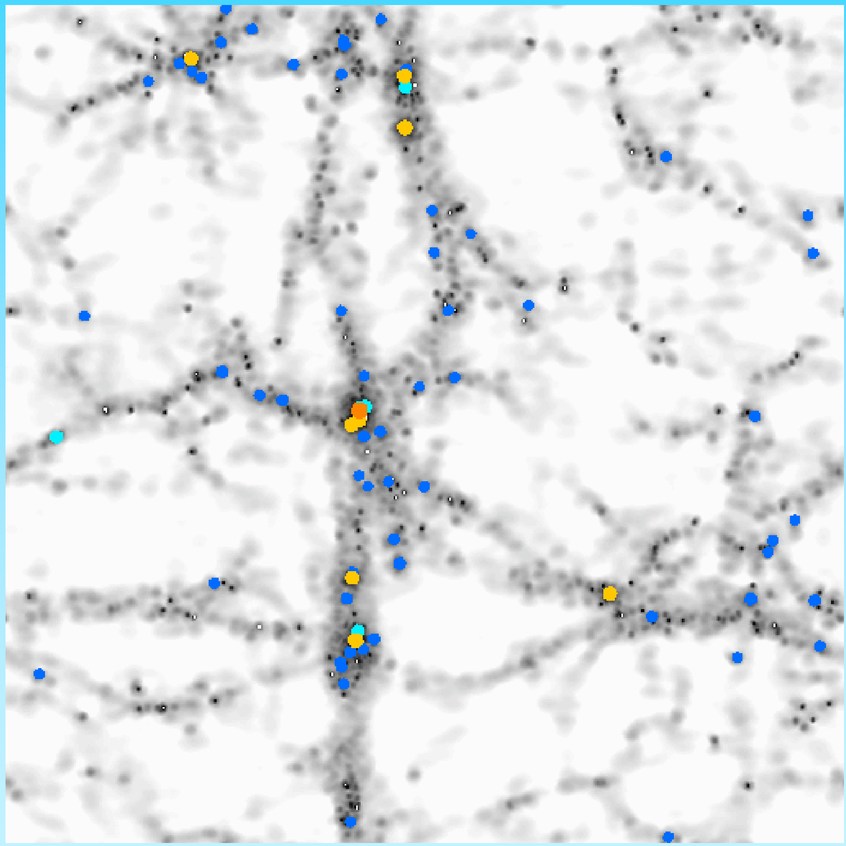
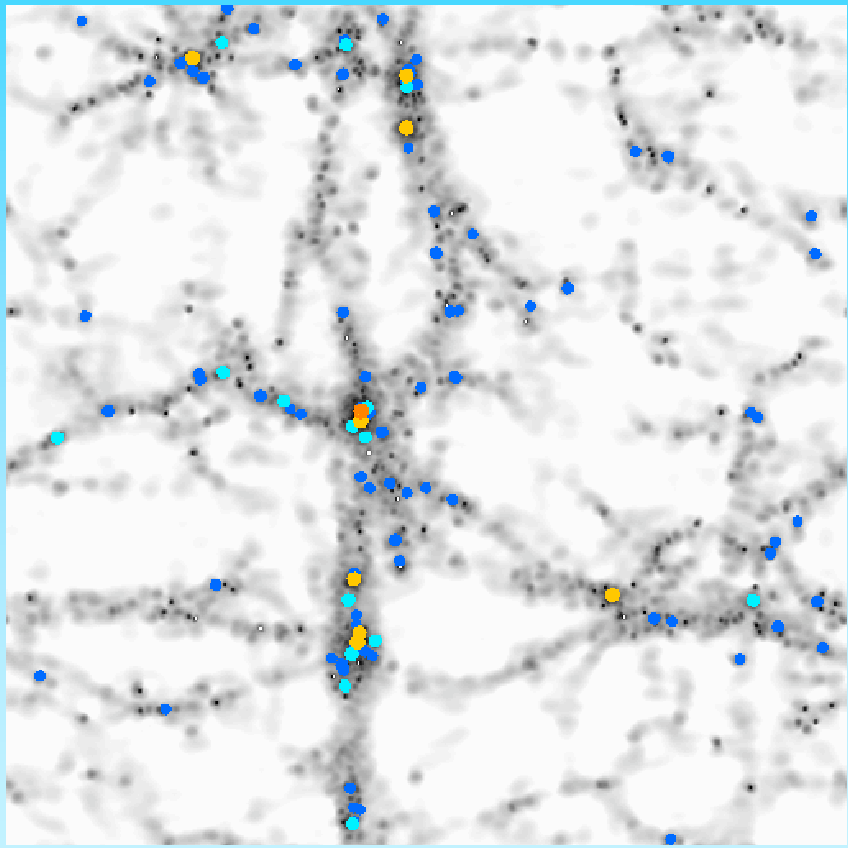
Gas cooling in SPH and semi-analytics

SPH



Semi-analytics



Gas cooling only

Helly, Cole, Frenk, Benson, Baugh, Lacey ’03
(see also Benson etal 00, Yoshida etal ’03)

Semi-analytic vs SPH cooling

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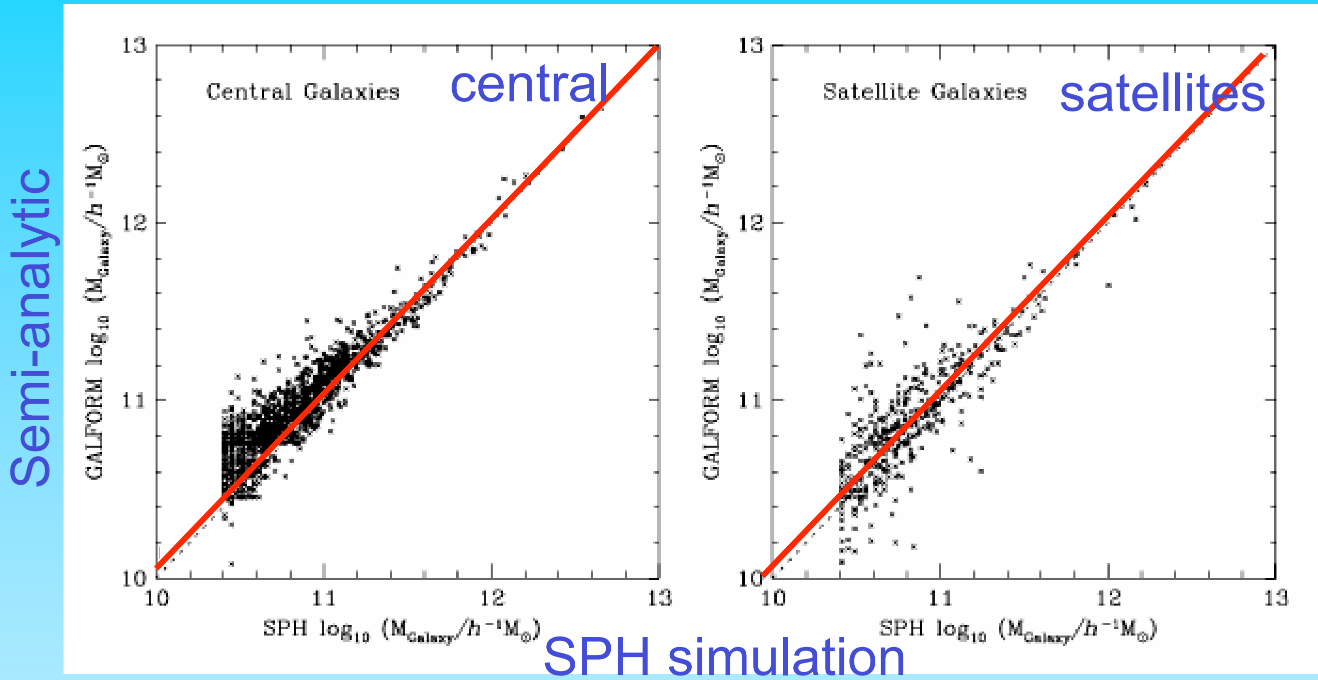
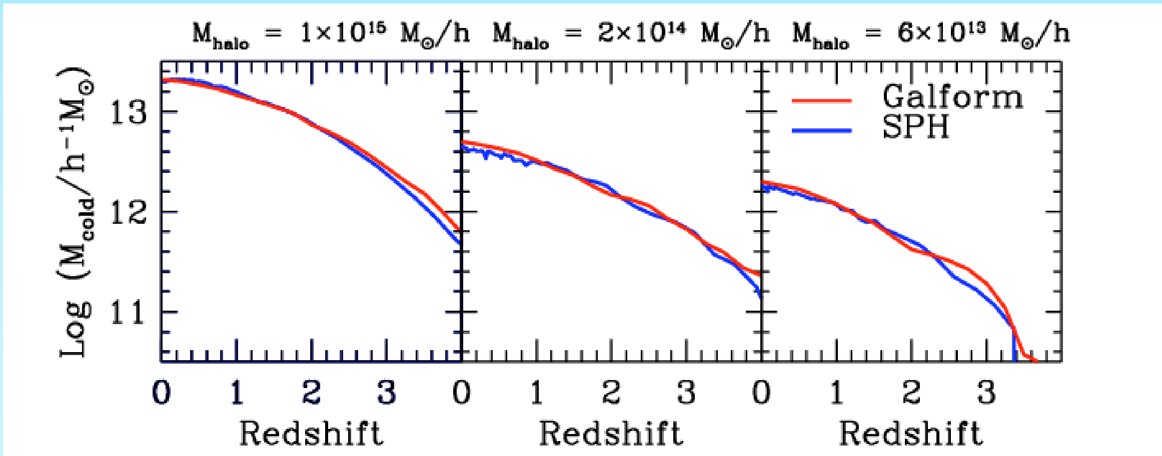
Mass in cold gas in halos at z=0

no star formation of feedback



Agreement between mass that cools in halos in SPH and SA



Helly etal '03
Yoshida etal '03

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Modelling galaxy formation

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  - Black hole format'n, AGN feedback
  - Galaxy mergers

Sub-grid physics

Phenomenological models

In semi-analytics and simulations

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The galaxy luminosity function

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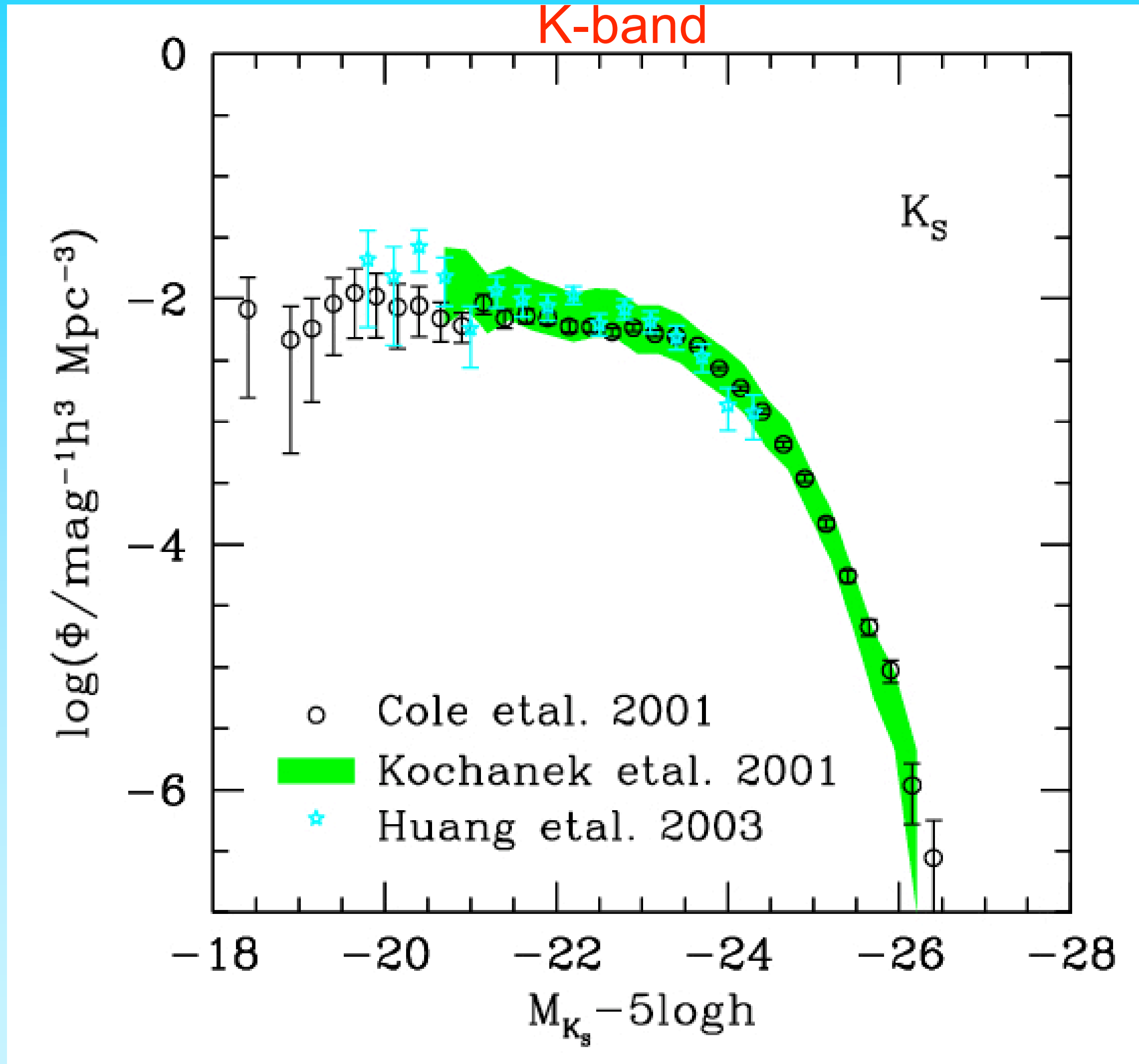
Cole etal:
2MASS+2dFGRS

Kochanek etal:
2MASS+SDSS

Huang etal:
Z=0.1



Cole, Norberg, Frenk, Baugh + 2dFGRS ‘01

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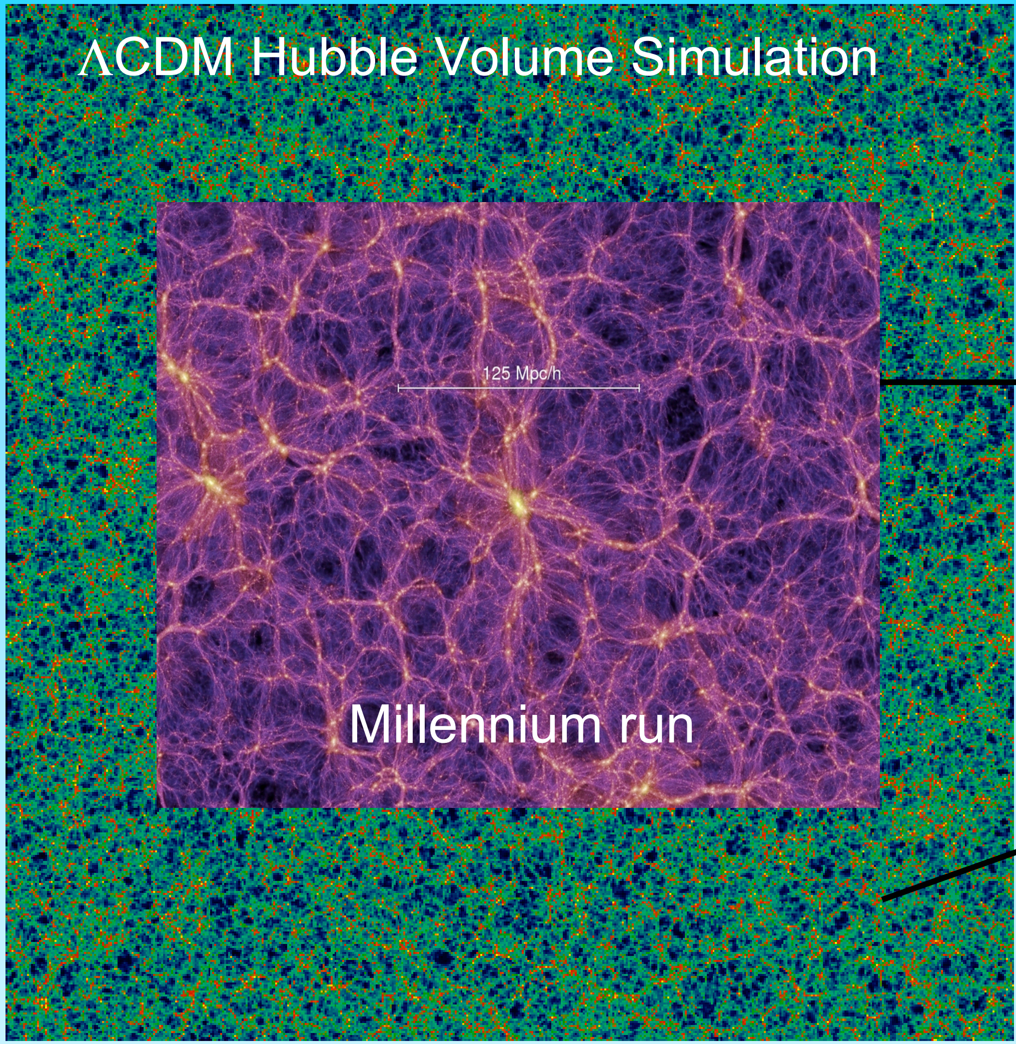
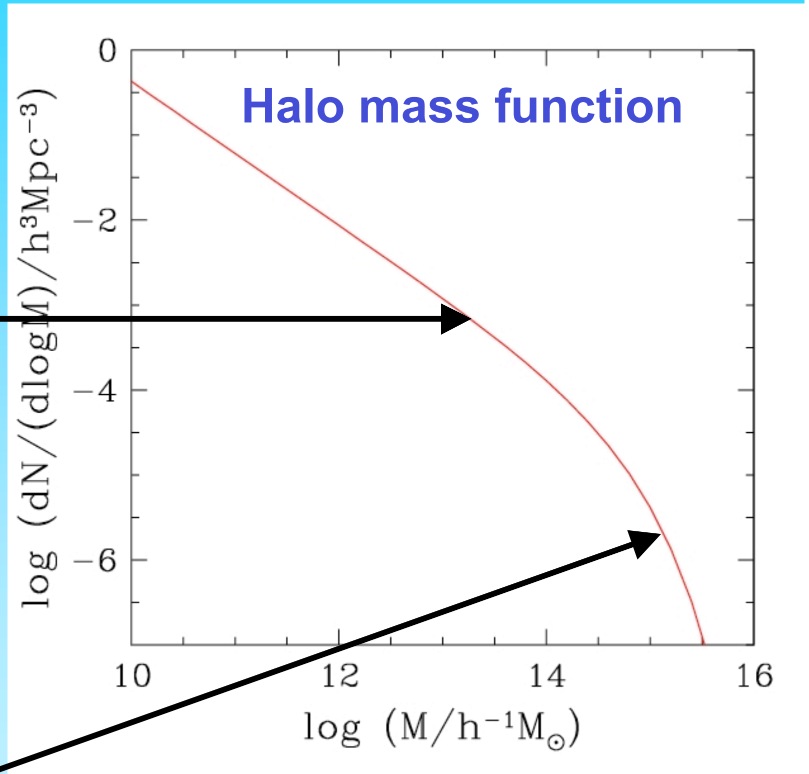
The abundance of dark halos



3000 Mpc/h

ΛCDM



Jenkins etal '99

Virgo consortium

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The galaxy luminosity function

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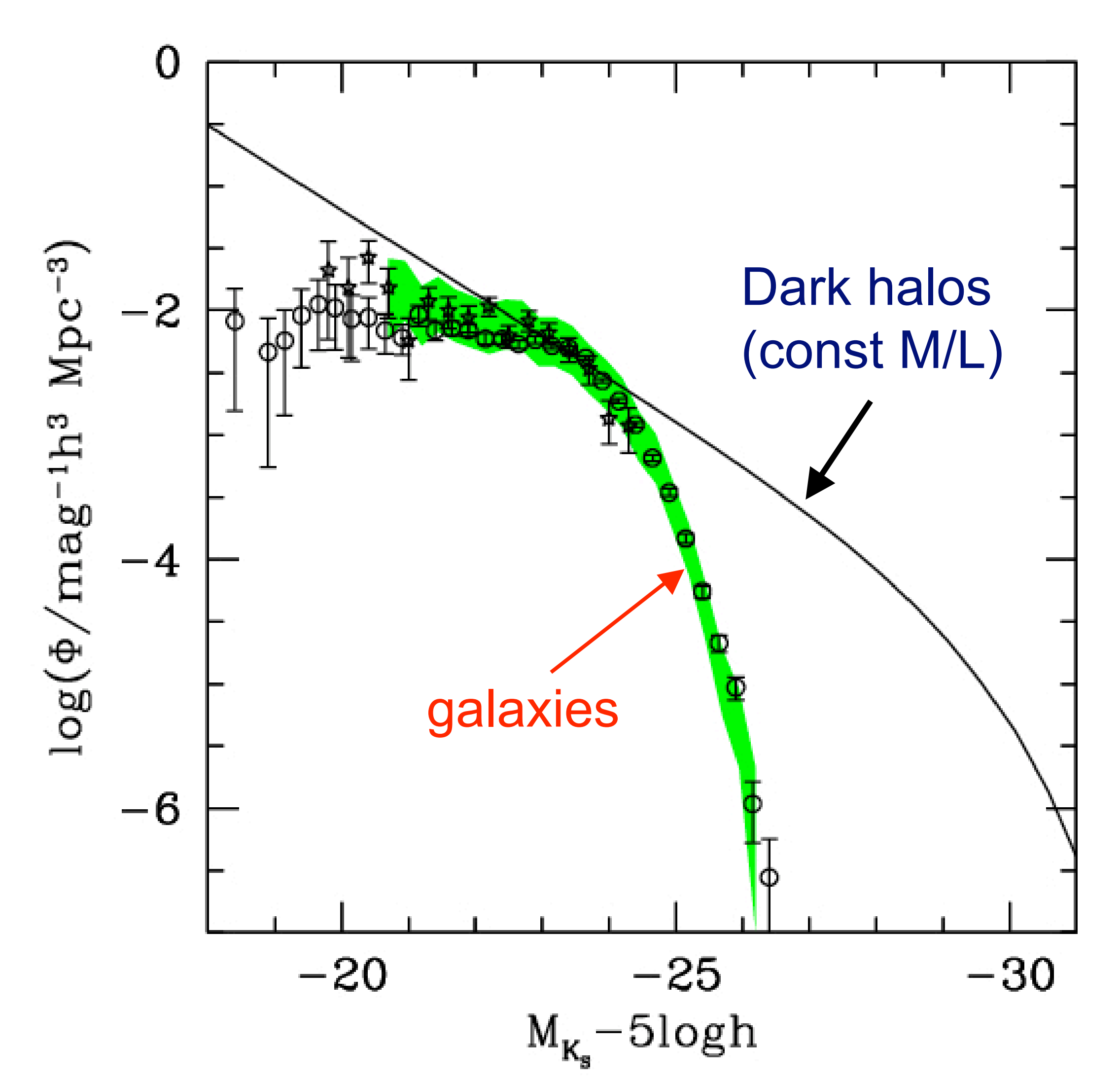
The halo mass function and the galaxy luminosity function have different shapes

⇒

Complicated variation of M/L with halo mass



Benson, Bower, Frenk, Lacey, Baugh & Cole '03

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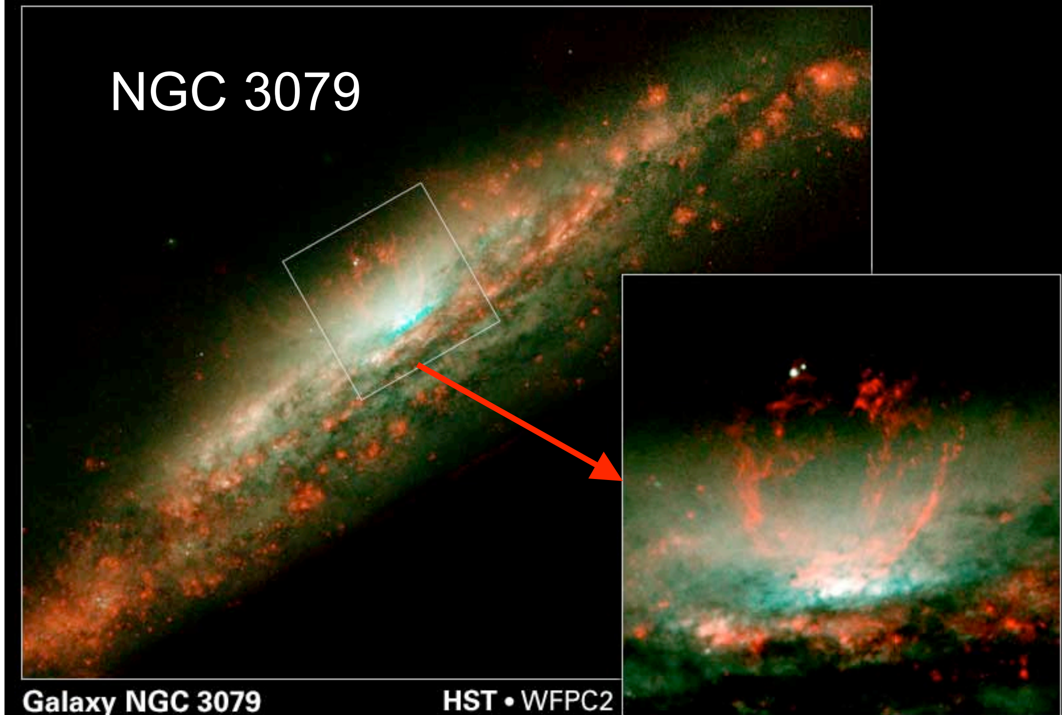
Feedback in galaxy formation

Traditional forms of feedback:

- Injection of supernovae/stellar wind energy
- Photoionisation of IGM at high-z

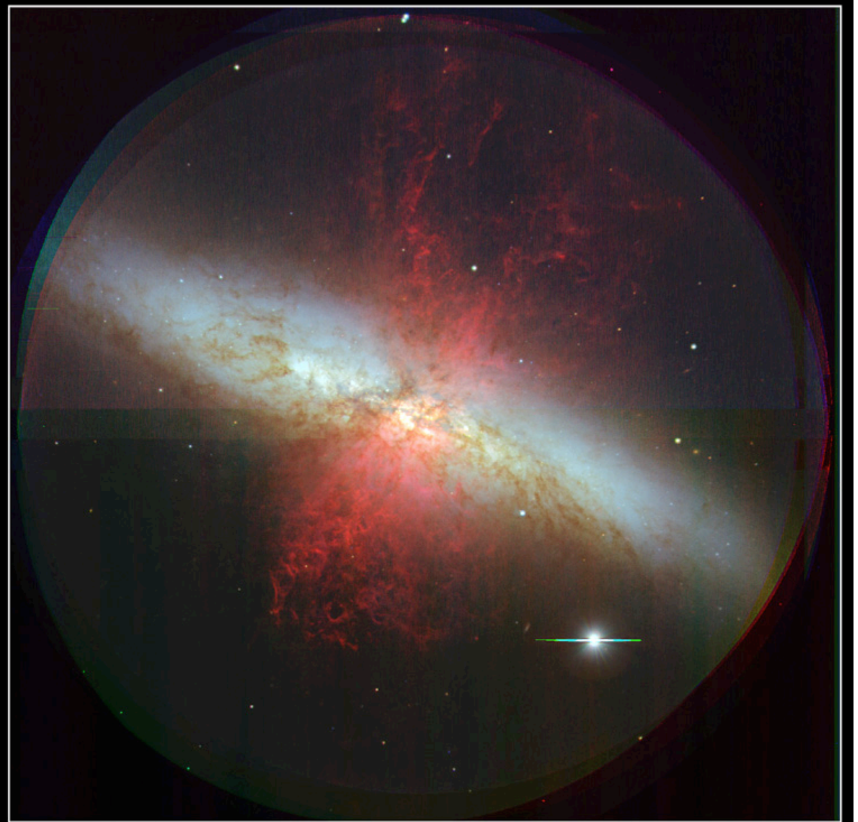
These are not enough to explain galaxy luminosity fn

$\Longrightarrow$ Need AGN feedback as well



Galaxy NGC 3079 **HST** • WFPC2

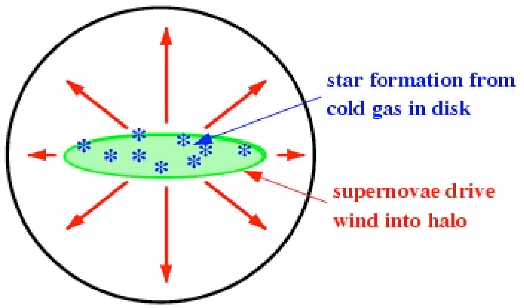
NASA and G. Cecil (University of North Carolina) • STScI-PRC01-28



M 82 (NGC 3034) FOCAS (B, V, Hα)

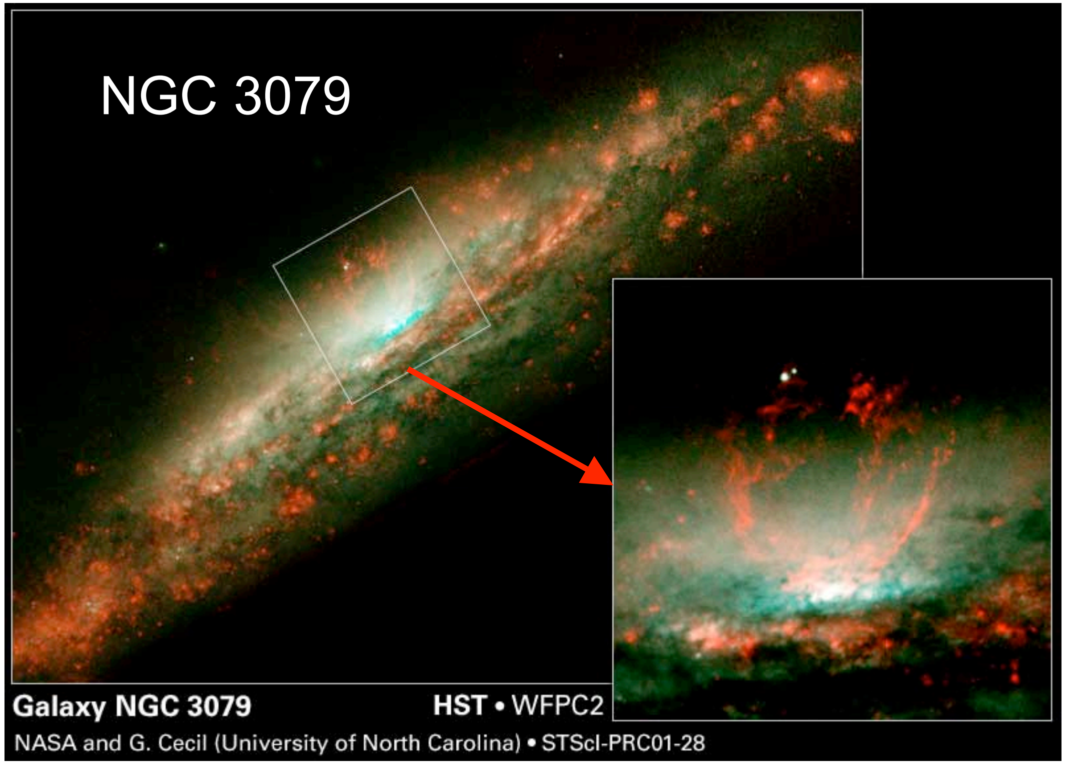
Subaru Telescope, National Astronomical Observatory of Japan March 24, 2000

STAR FORMATION & FEEDBACK IN DISKS



Supernovae and stellar winds inject energy which can:

1. Reheat cold disk gas and eject into halo
2. Cause the gaseous halo to expand
3. Drive a superwind



$$\dot{M}_{reheat} = \beta_{rh} \dot{M}_*$$

$$\dot{M}_{halo} = \beta_h \dot{M}_*$$

$$\dot{M}_{sw} = \beta_{sw} \dot{M}_*$$

e.g. $\beta_{rh} = (V_{disk} / V_{hot})^{-2}$ etc

1. and 3. are most important

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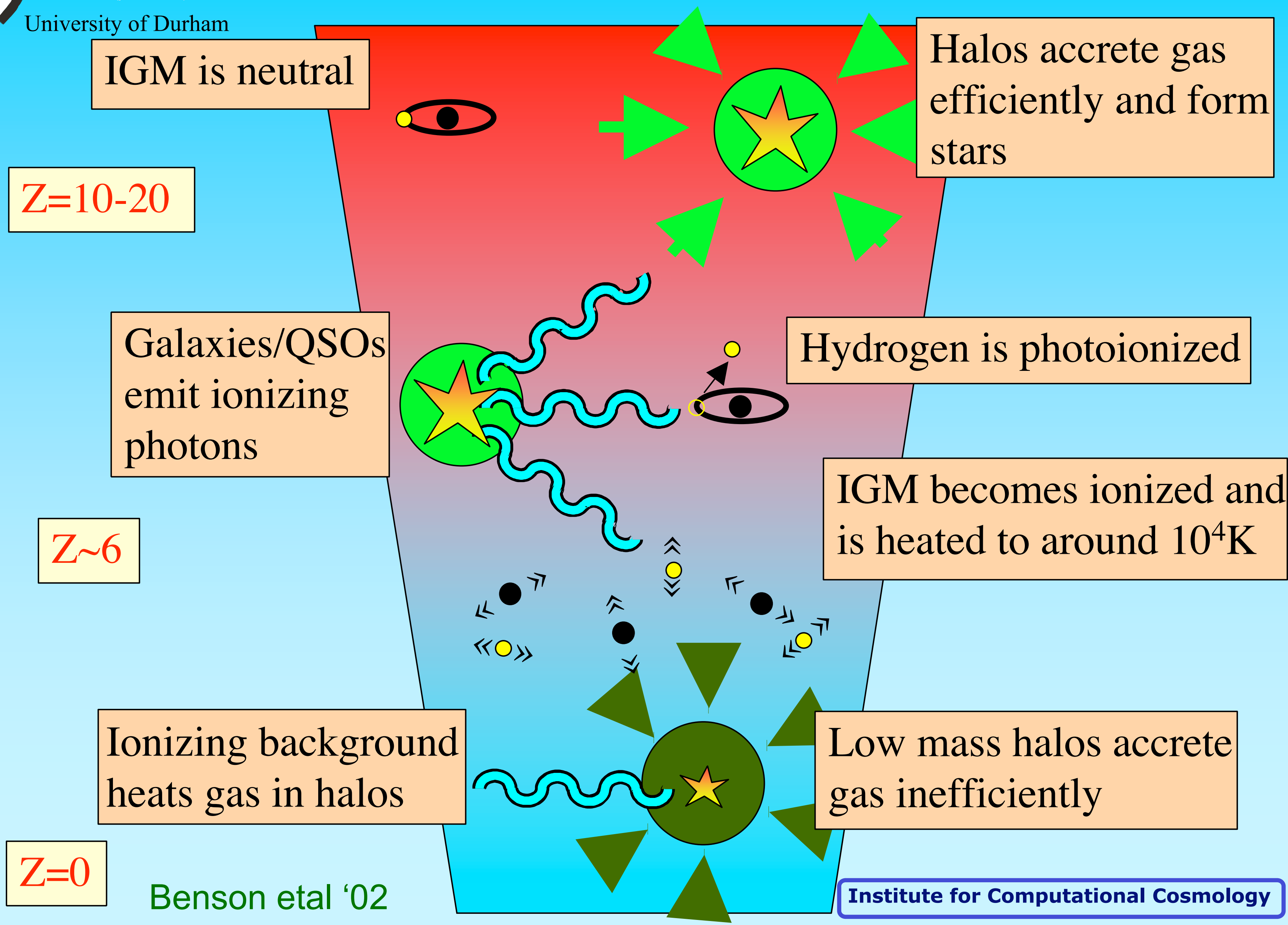
Photoionization



Benson etal '02

Deconstructing the galaxy LF

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ICC

Gas cooling only

No energy injection, ie:

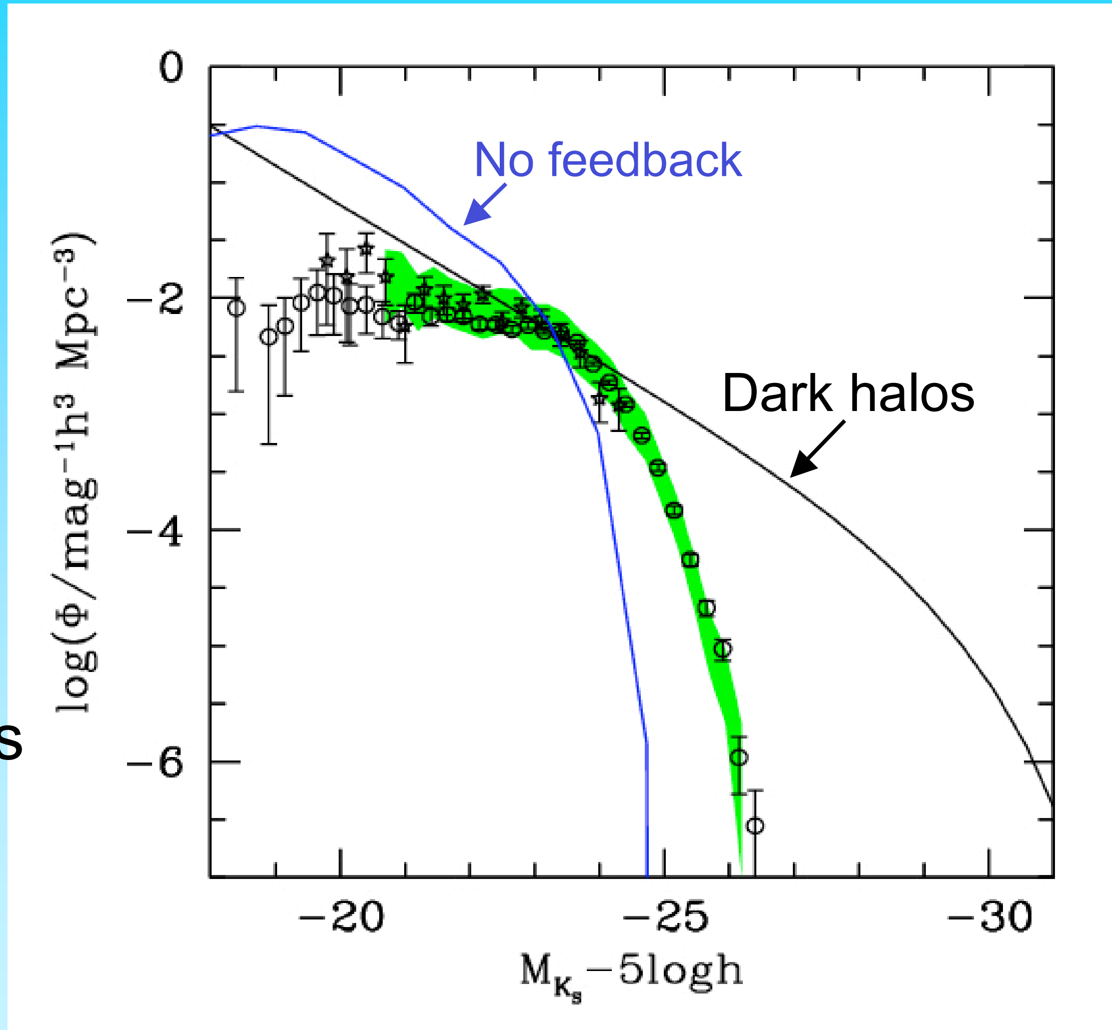
- No SN feedback
- No Photoionization

➡

Gas cools into small halos

Faint end – too steep

Bright end – two few gals



Benson, Bower, Frenk, Lacey, Baugh & Cole '03

Deconstructing the galaxy LF

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<u>Cooling + photoionisation</u>

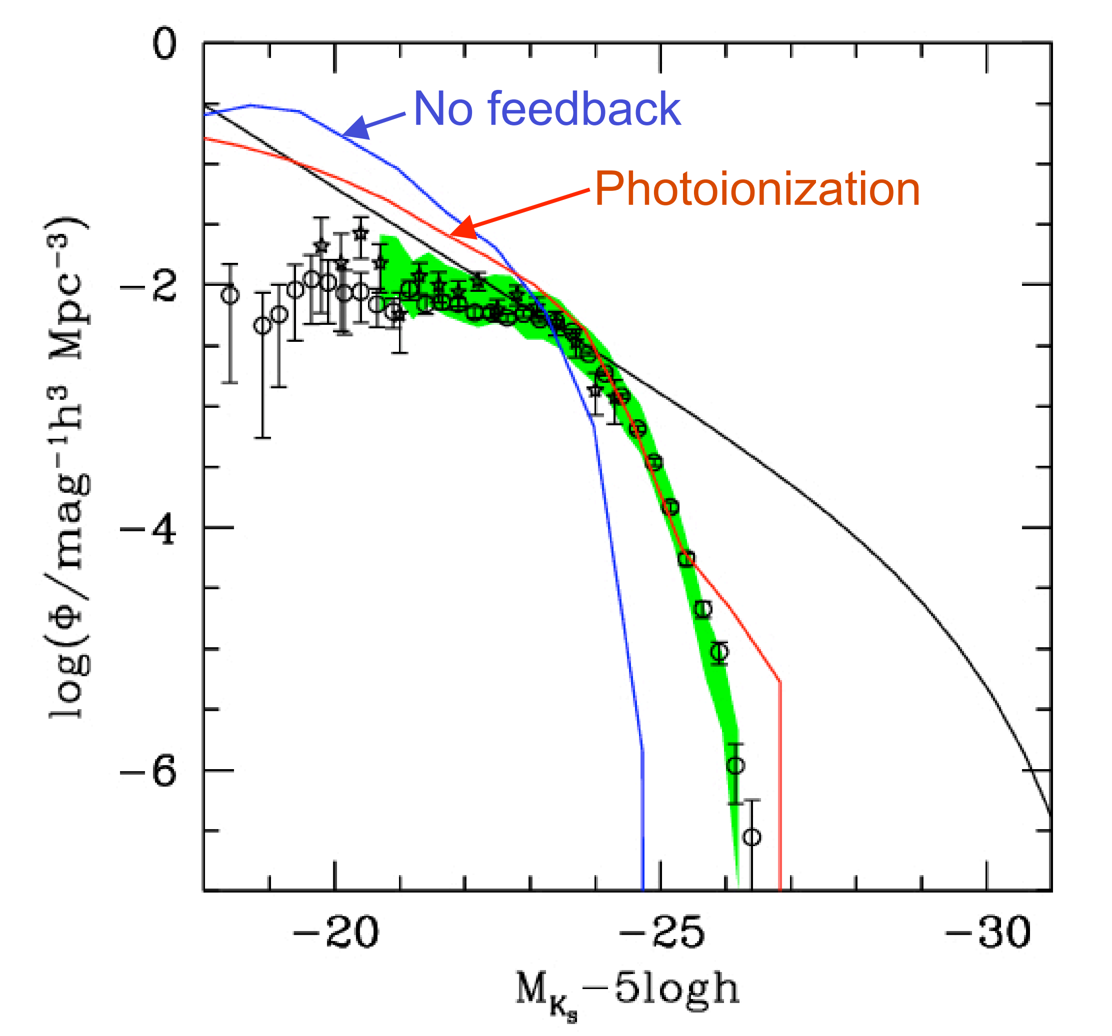
No energy injection, ie:

No SN feedback

Photoionization flattens faint end, leaving enough gas to make bright gals.

(Main effect: gas pressure)

Need additional source(s) of feedback



Benson, Bower,Frenk, Lacey, Baugh & Cole ‘03

Deconstructing the galaxy LF

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Cooling + photoionisation +energy feedback (reheat)

Faint end:

Can be explained by

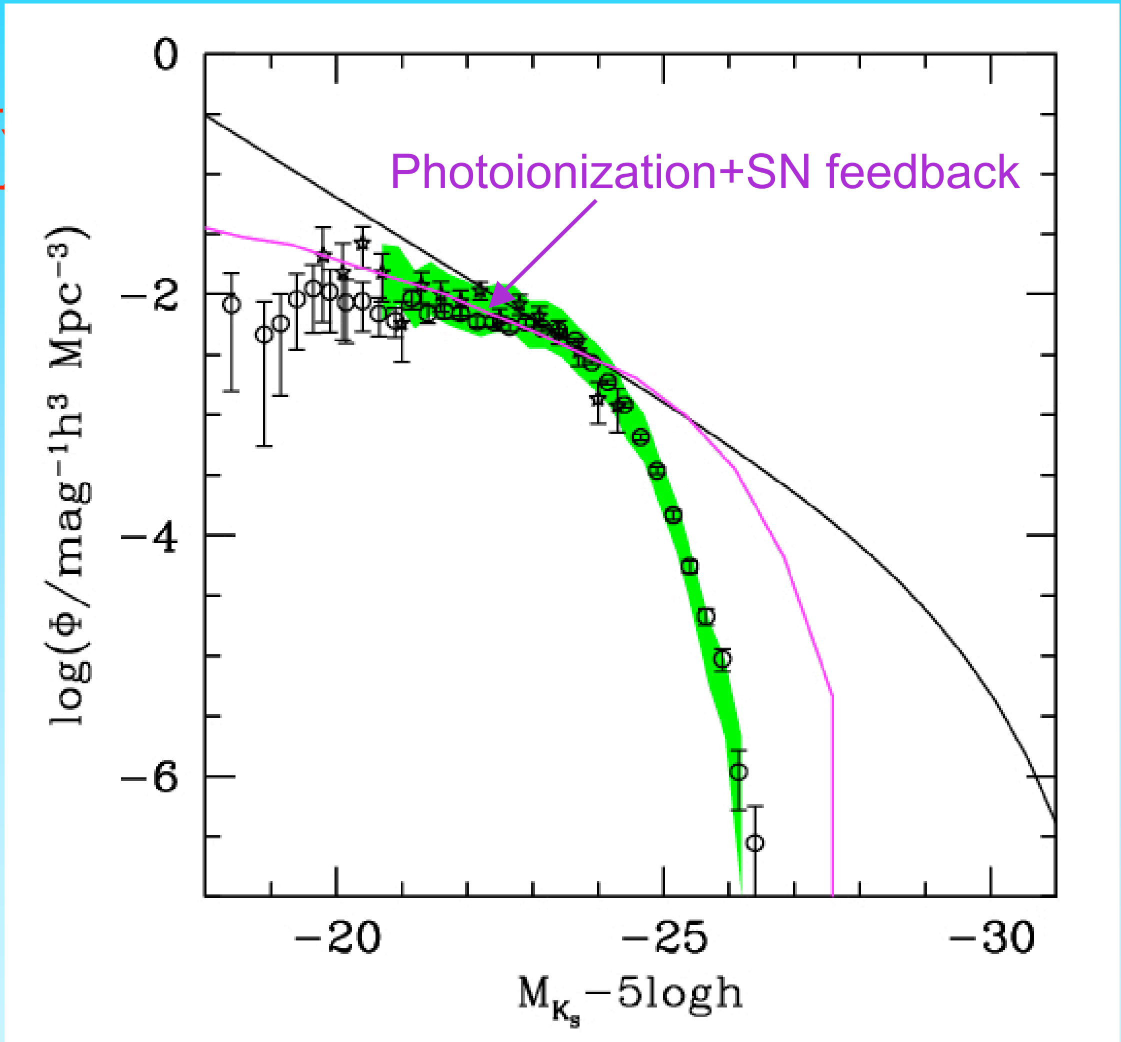
✓ Reionization

✓ SNe feedback

Bright end:

→ Too many bright galaxies

Need to prevent too much gas cooling in large halos



Benson, Bower, Frenk, Lacey, Baugh & Cole '03

Deconstructing the galaxy LF

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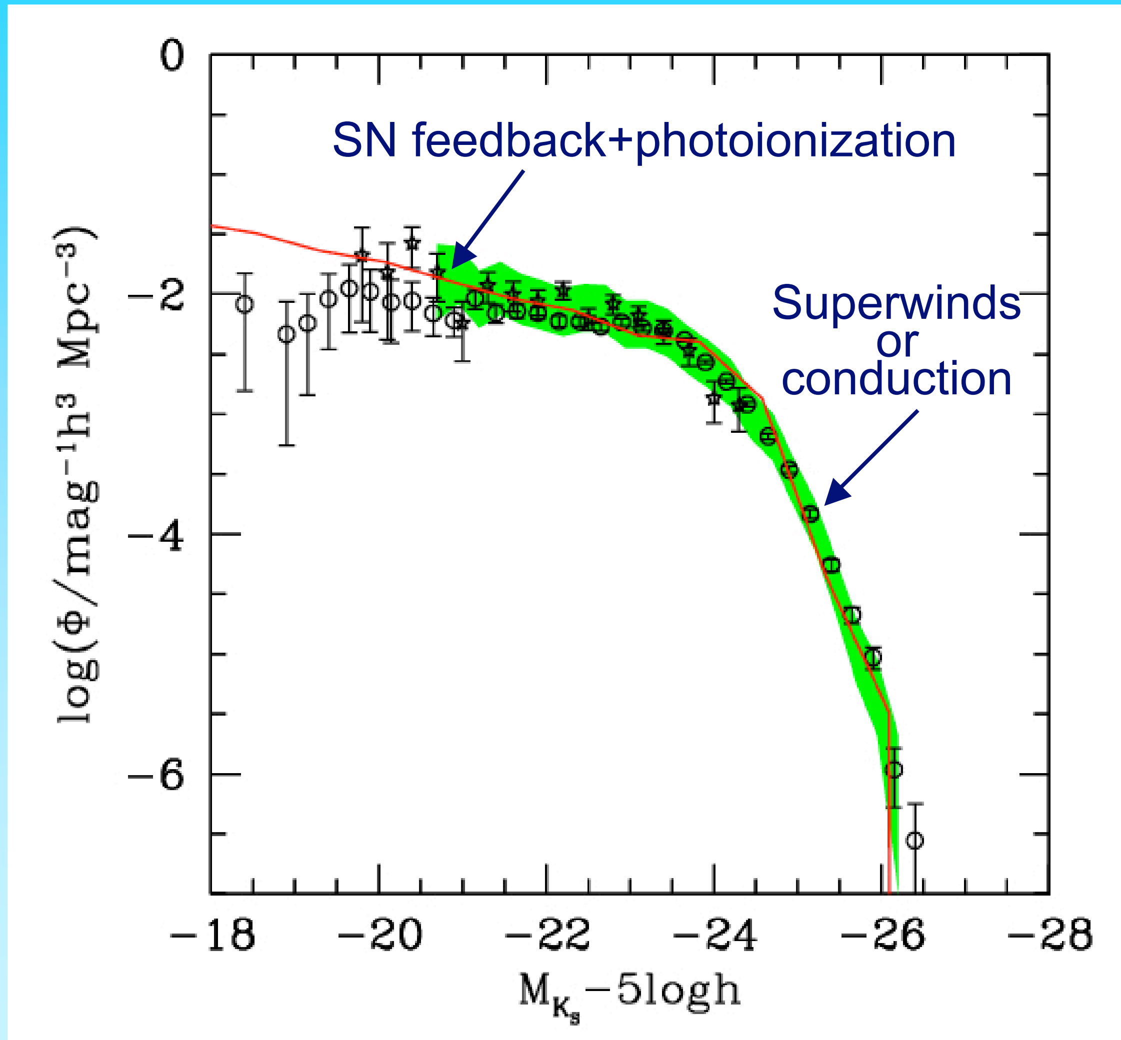
Faint end:

Photoionization + reheating of cold disk gas by SN

Bright end:

Either:

- Superwinds ($E>E_{SN}$)
- Conductivity (high efficiency)



Benson, Bower, Frenk, Lacey, Baugh & Cole '03

Deconstructing the galaxy LF

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Bright end: superwinds?

Weak: gas is recaptured and cools again

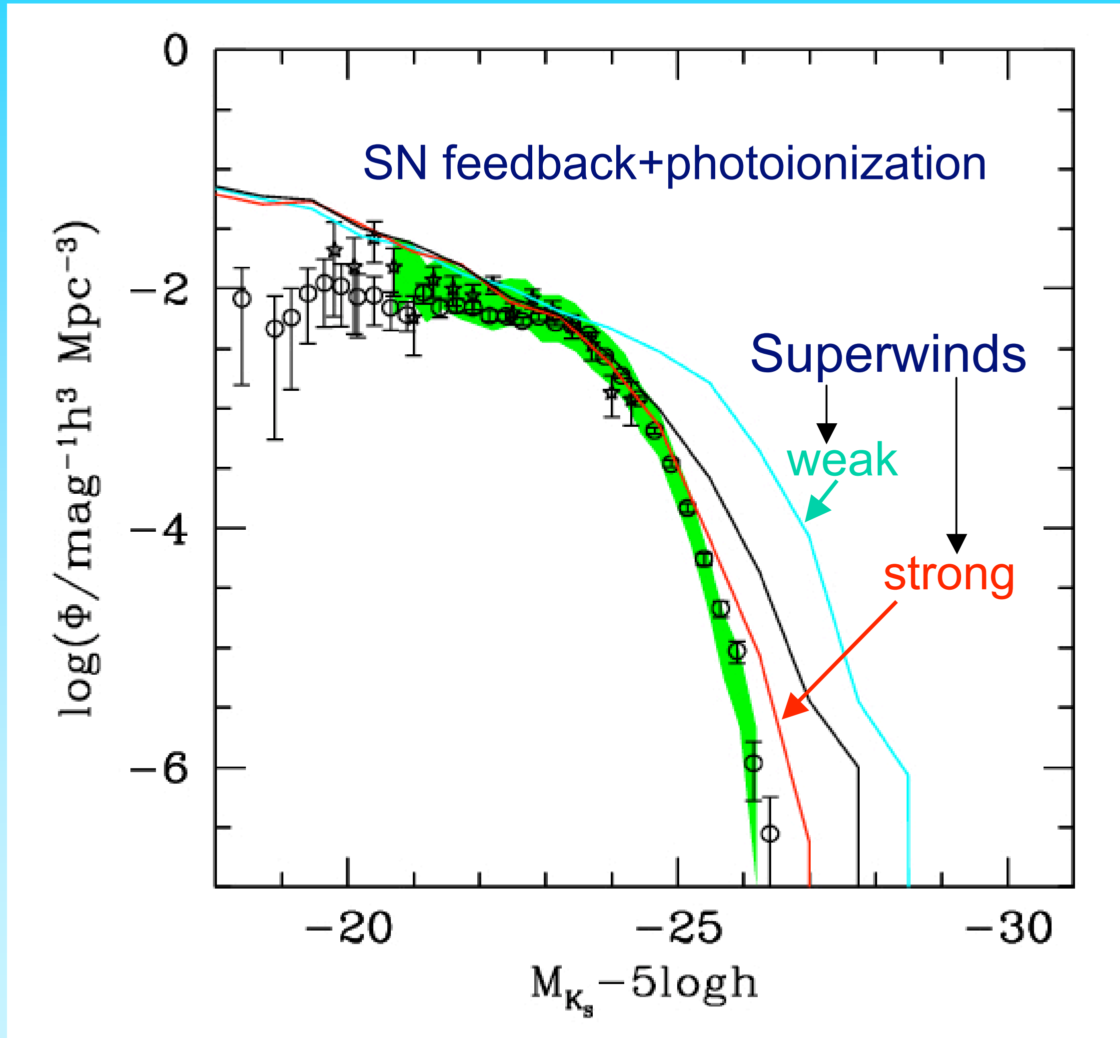
Strong: if E_{av}=15keV per particle, winds escape and never recaptured

~10% baryons ejected (~mass turned into ∗s)

$E_{SW} \sim 5 \times E_{SN}$

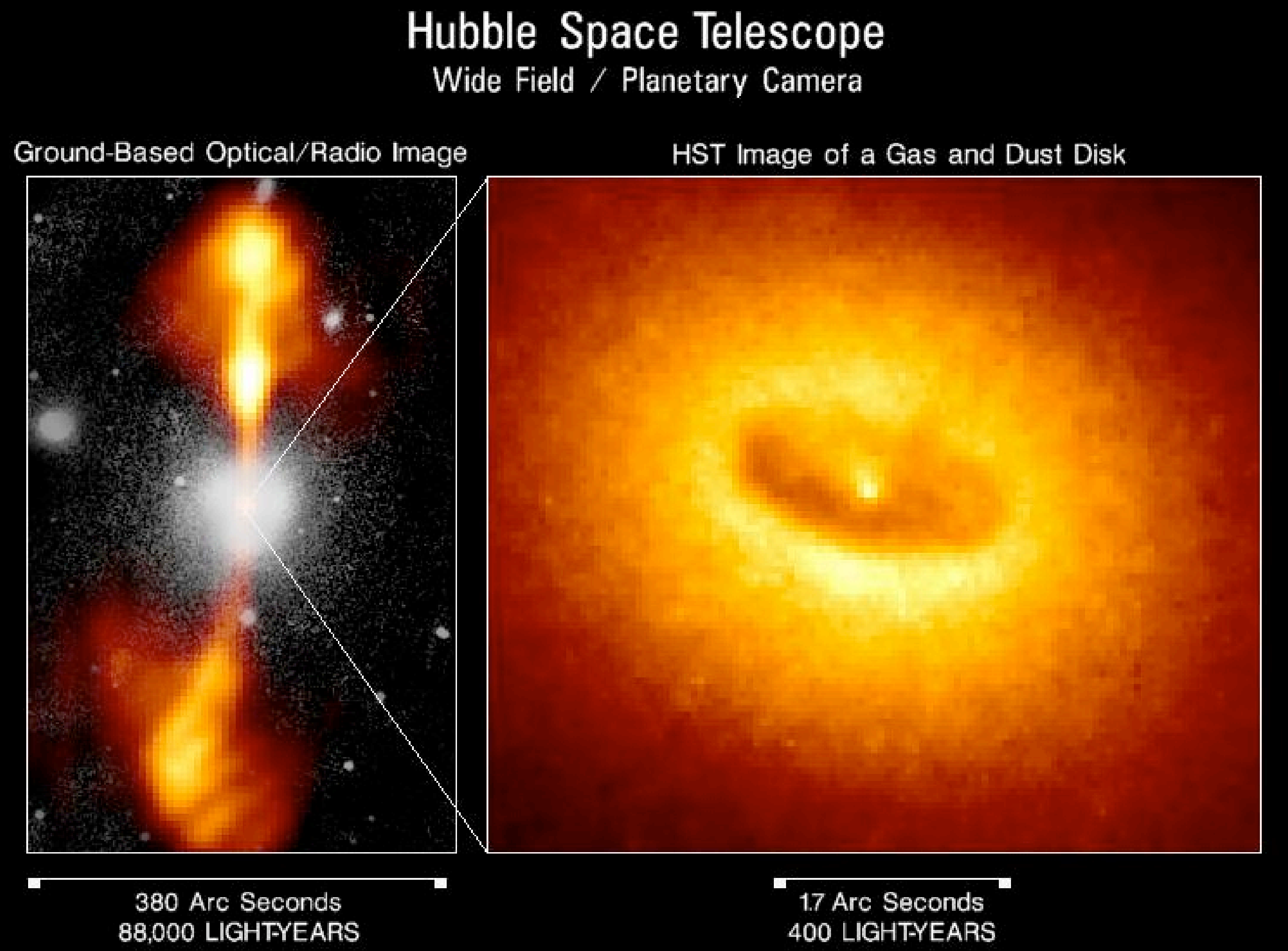
→ Need energy from black hole formation

(low σ_8 ~0.7 helps)



Benson, Bower, Frenk, Lacey, Baugh & Cole '03

Core of Galaxy NGC 4261



Radio jets → to bubbles that rise buoyantly and deposit energy into the ICM (eg Perseus – Fabian etal '00)

Quenching cooling flows in clusters

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By AGN "feedback"

- FLASH Adaptive Mesh Refinement hydro code
- NFW potential $M_{200}=3x10^{14}\,M_o$, c=4, h=0.7, r_{200}=1.4 Mpc
- Isothermal, non-gravitating gas in hydro eq at T=3.1 Kev
- Cooling fn includes H, He metals ($Z=Z_o/3$)
- Bubbles created every 10^8 yr by injecting energy at constant rate over 10^7yrs at random positions, r<50 kpc
- Energy in each bubble: $(1x10^{59}$ -- $3x10^{60})$ erg
- Each simulation run for 1.5 Gyr

Dalla Vecchia, Balogh, Bower, Frenk & Theuns '04

Blowing bubbles in a cluster

temperature

Dalla Vecchia etal 05

Quenching cooling flows in clusters

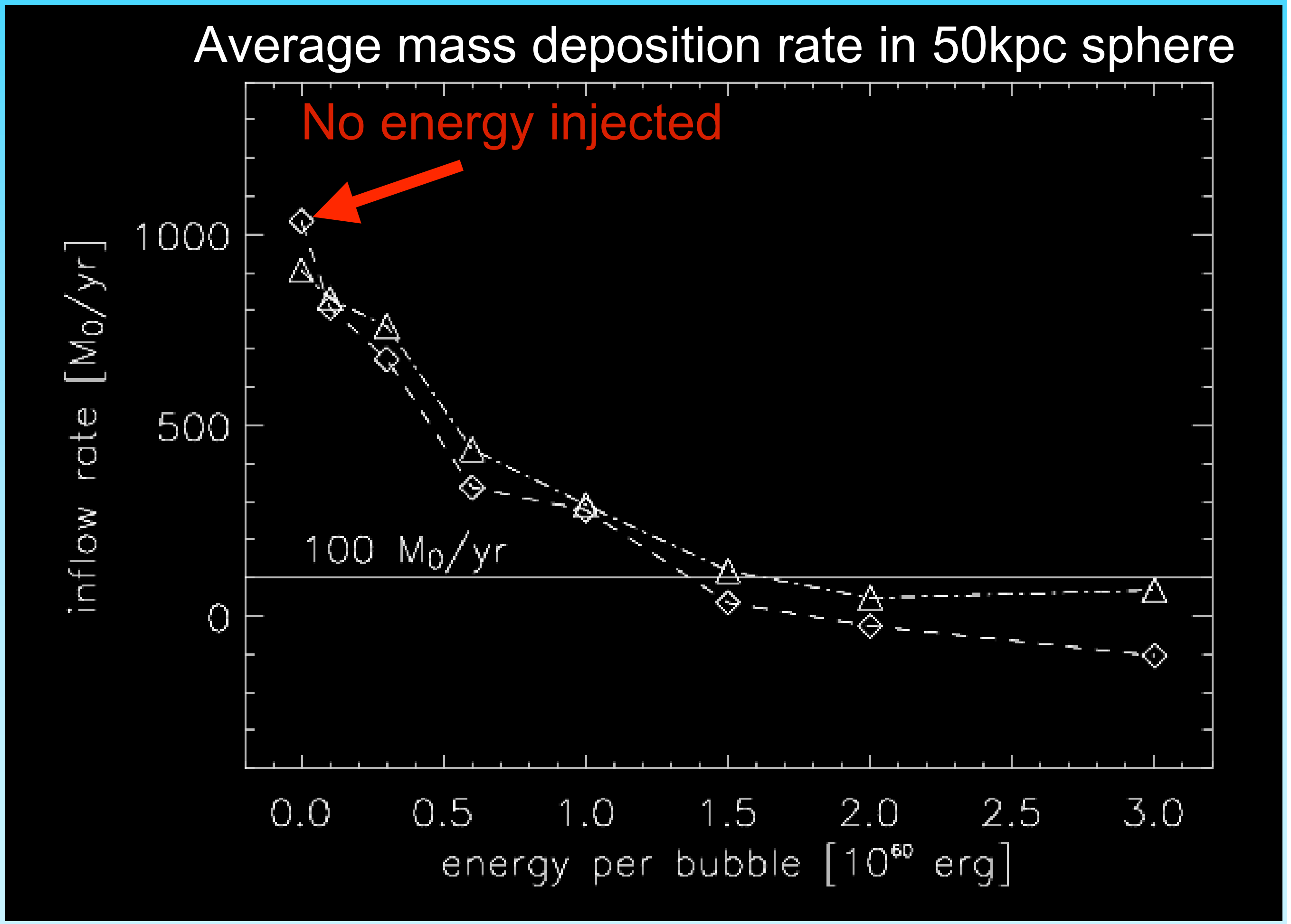
University of Durham

By AGN “feedback”

Bubbles every 10^8 yr at random in 50kpc sphere.

Each event lasts 10^7 yr

Recurrent bubbles (ea of 6×10^{44} erg/s) ($\sim2\times10^{62}$ erg total) stop cooling flow onto cluster centres



Dalla Vecchia, Balogh, Bower, Frenk & Theuns etal 04

Turbulence – effects of numerical resolution

Dalla Vecchia, Balogh, Bower, Frenk & Theuns 04

Sound Waves

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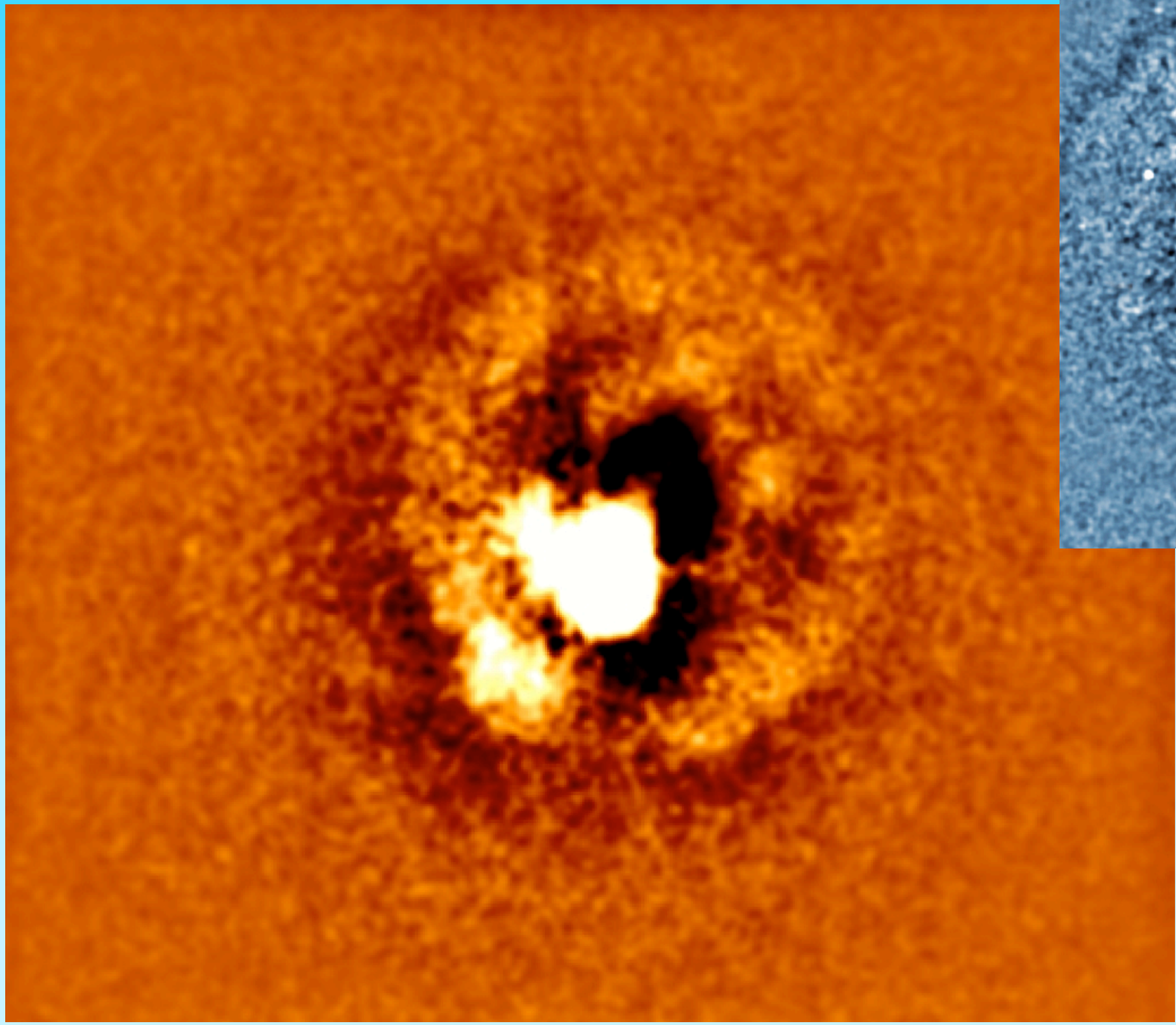
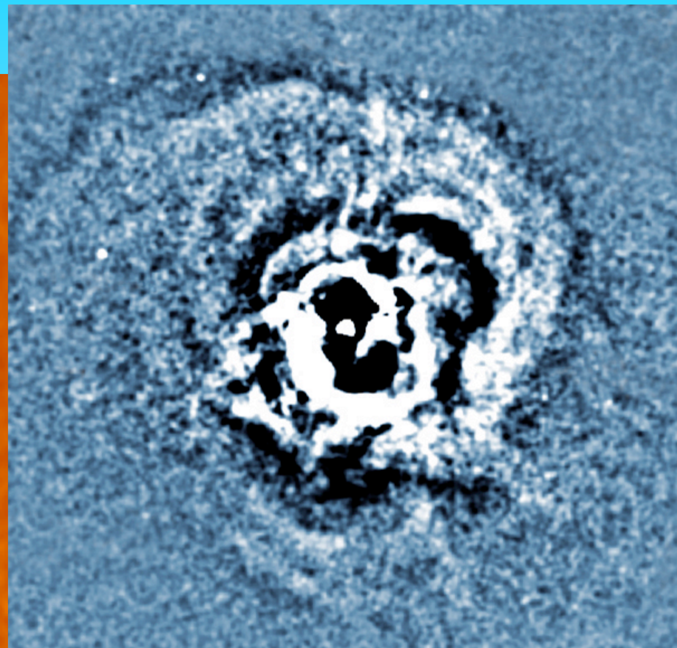


Simulation



Perseus

(Fabian etal 03)

Dalla vecchia etal 04

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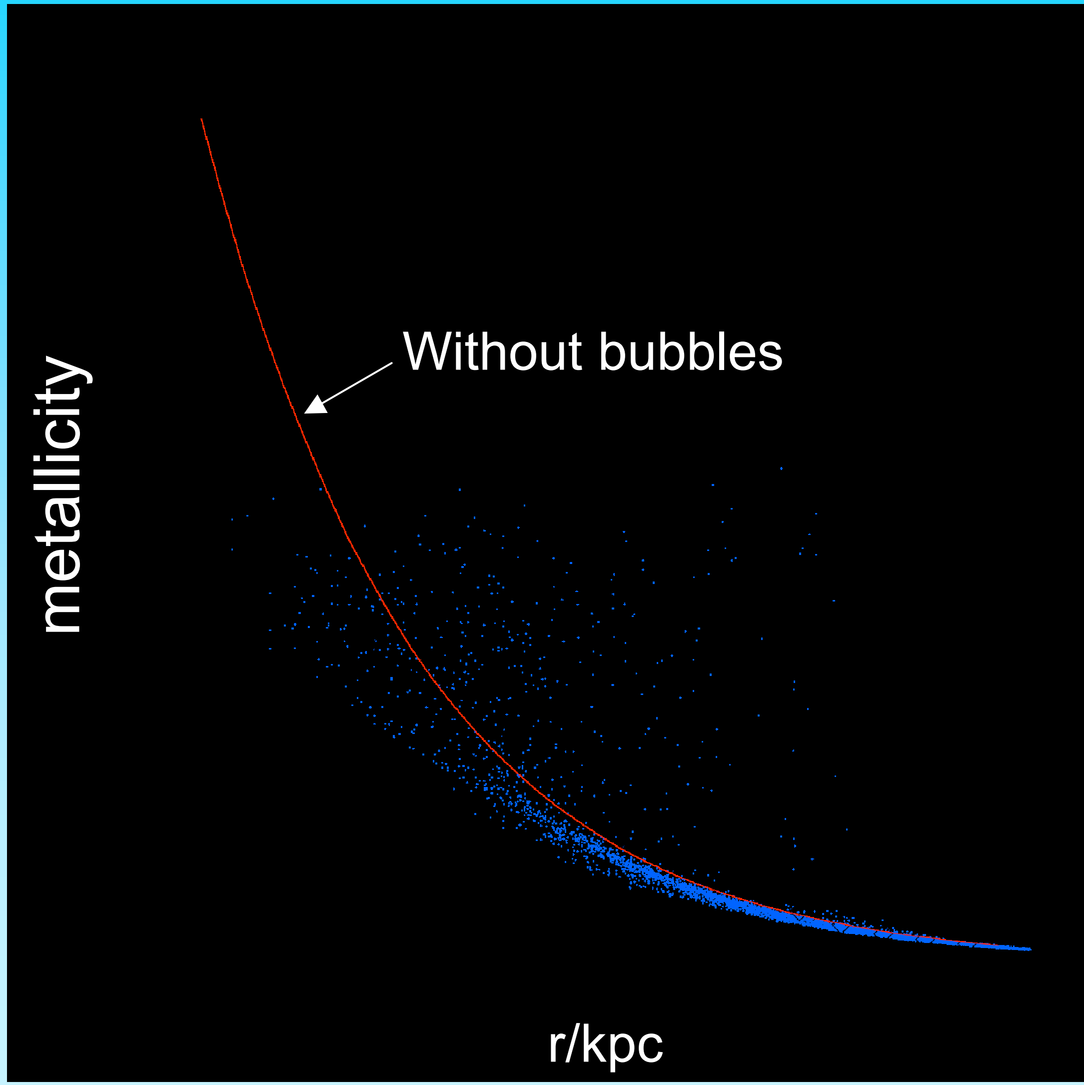
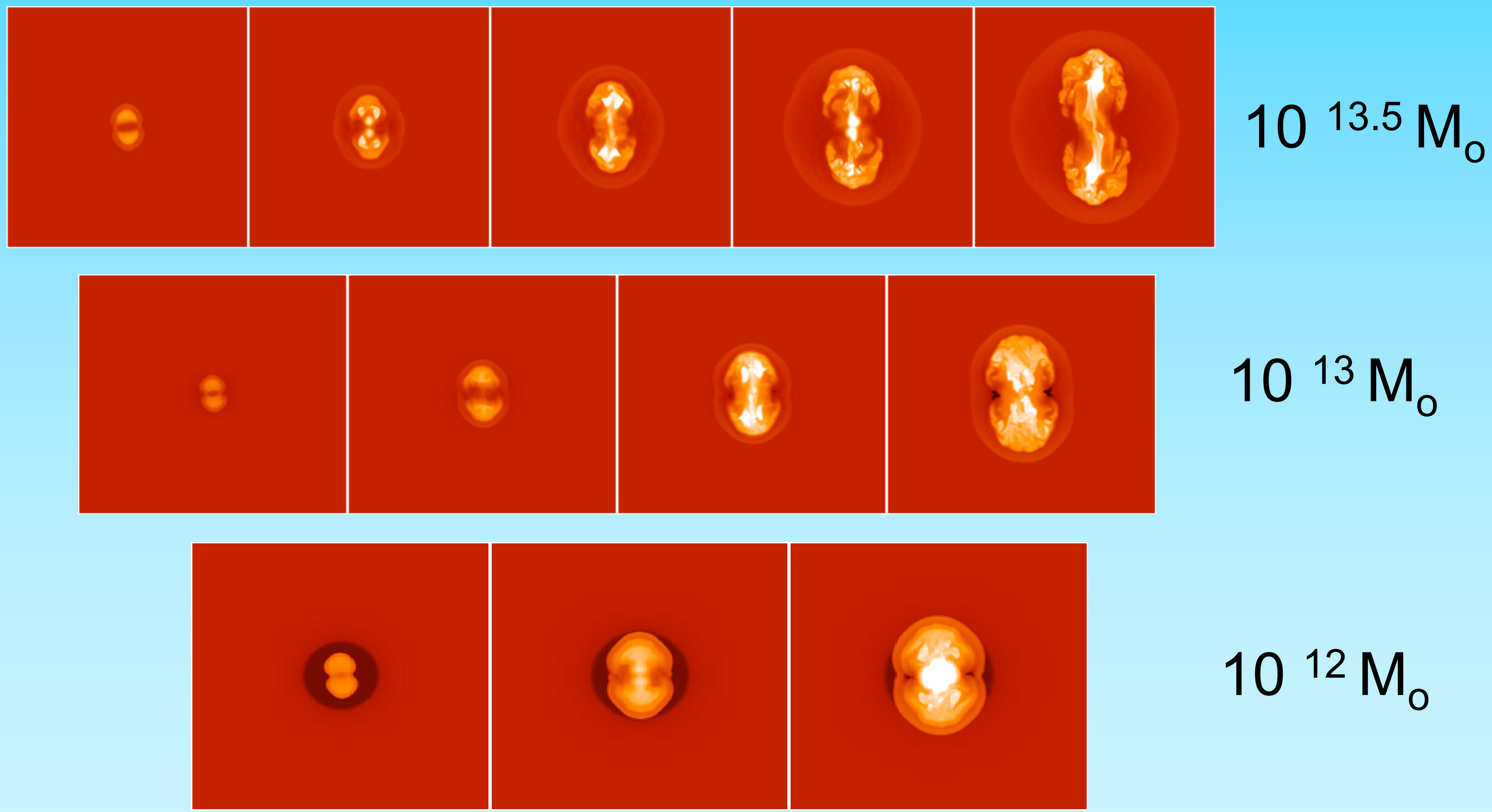
Can metallicity gradients survive?

Yes!



Dalla Vecchia et al 2005; see also Bruggen 02

“Bubble” feedback in halos of different mass



Dalla Vecchia, Bower, Frenk & Theuns 05

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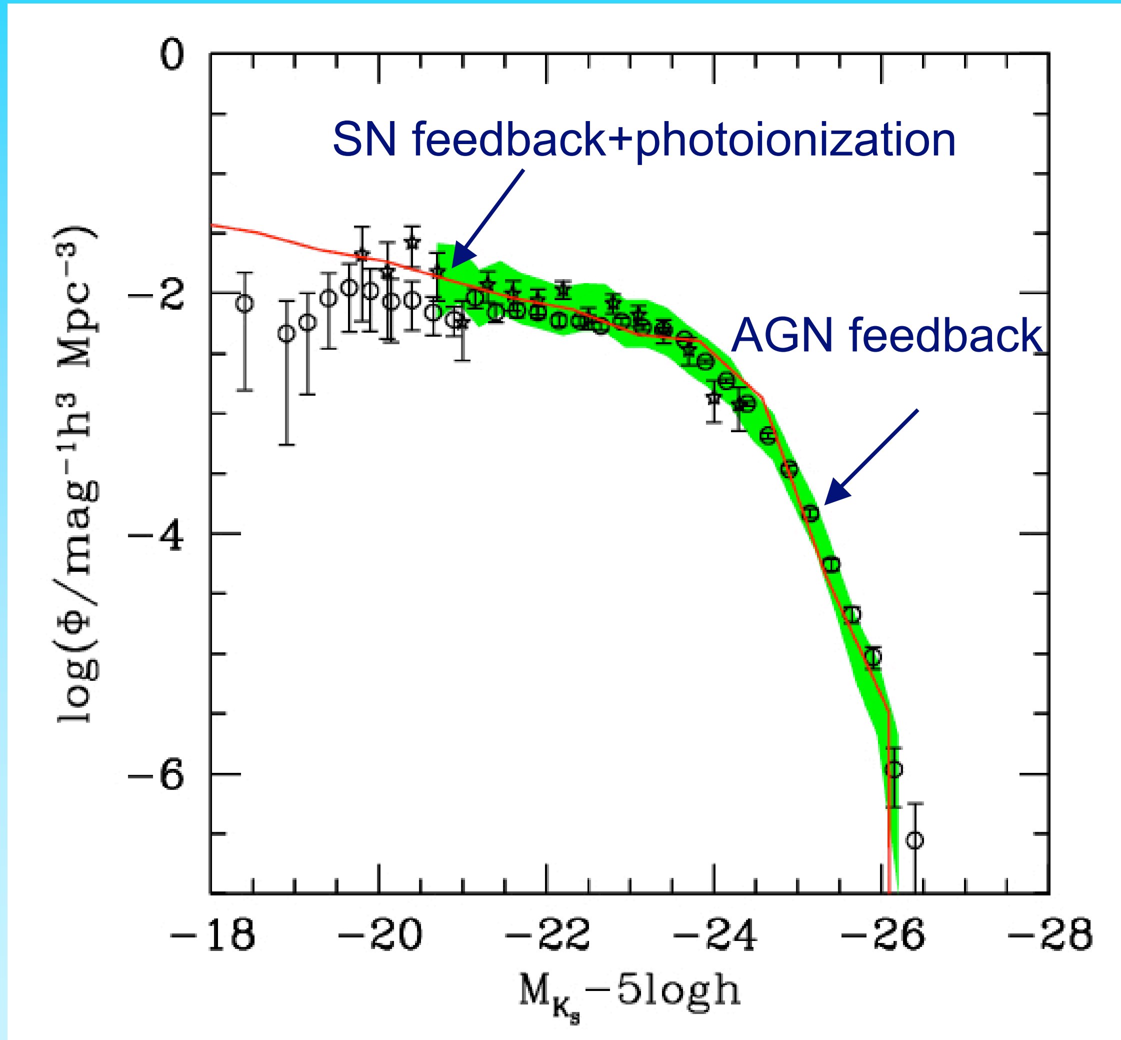
Deconstructing the galaxy LF Summary



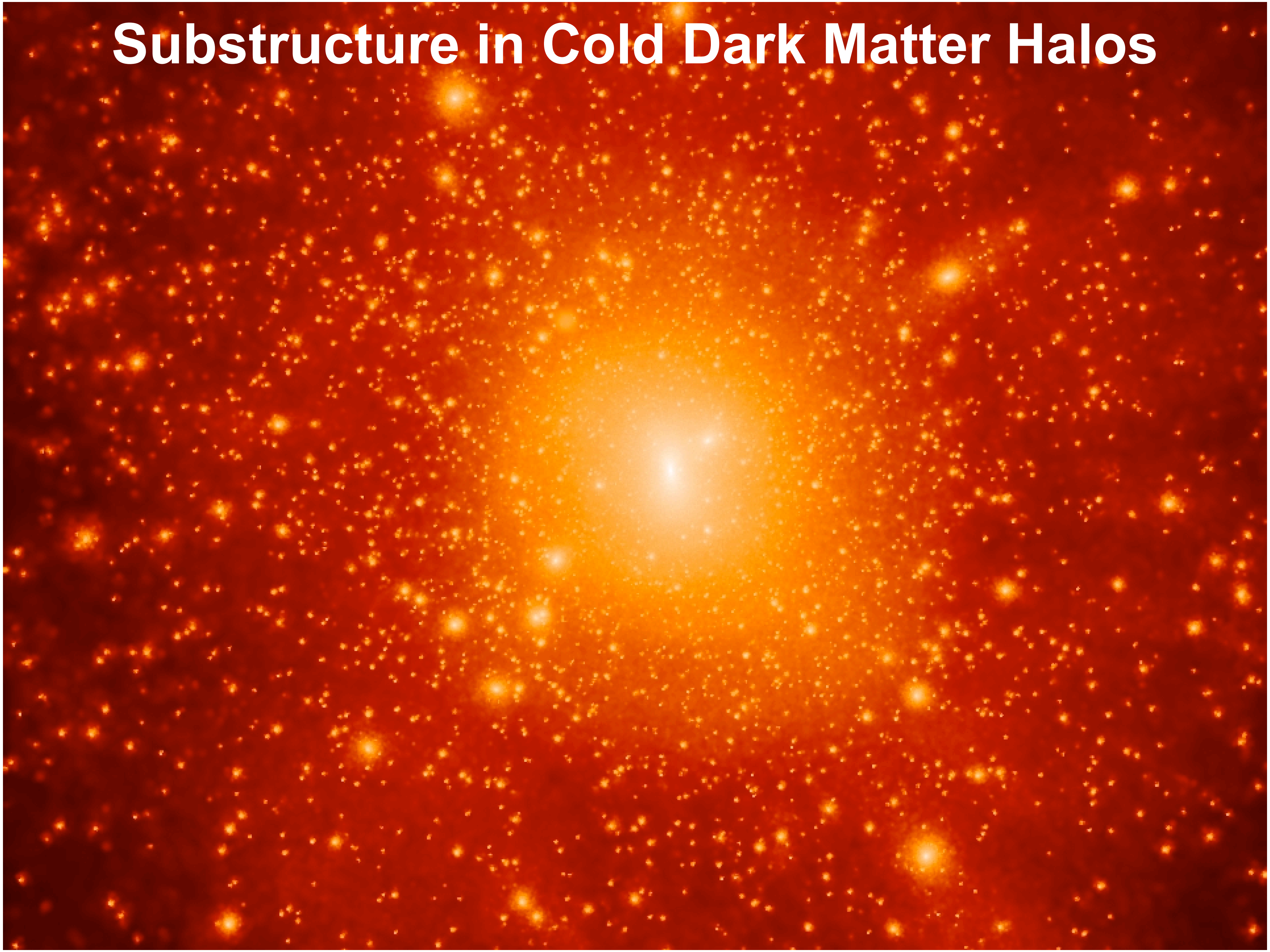
Faint end:

Photoionization + reheating of cold disk gas by SN

Bright end:

AGN energy transported by bubbles (?)

Dalla Vecchia, Bower, Frenk & Theuns 05


Substructure in Cold Dark Matter Halos

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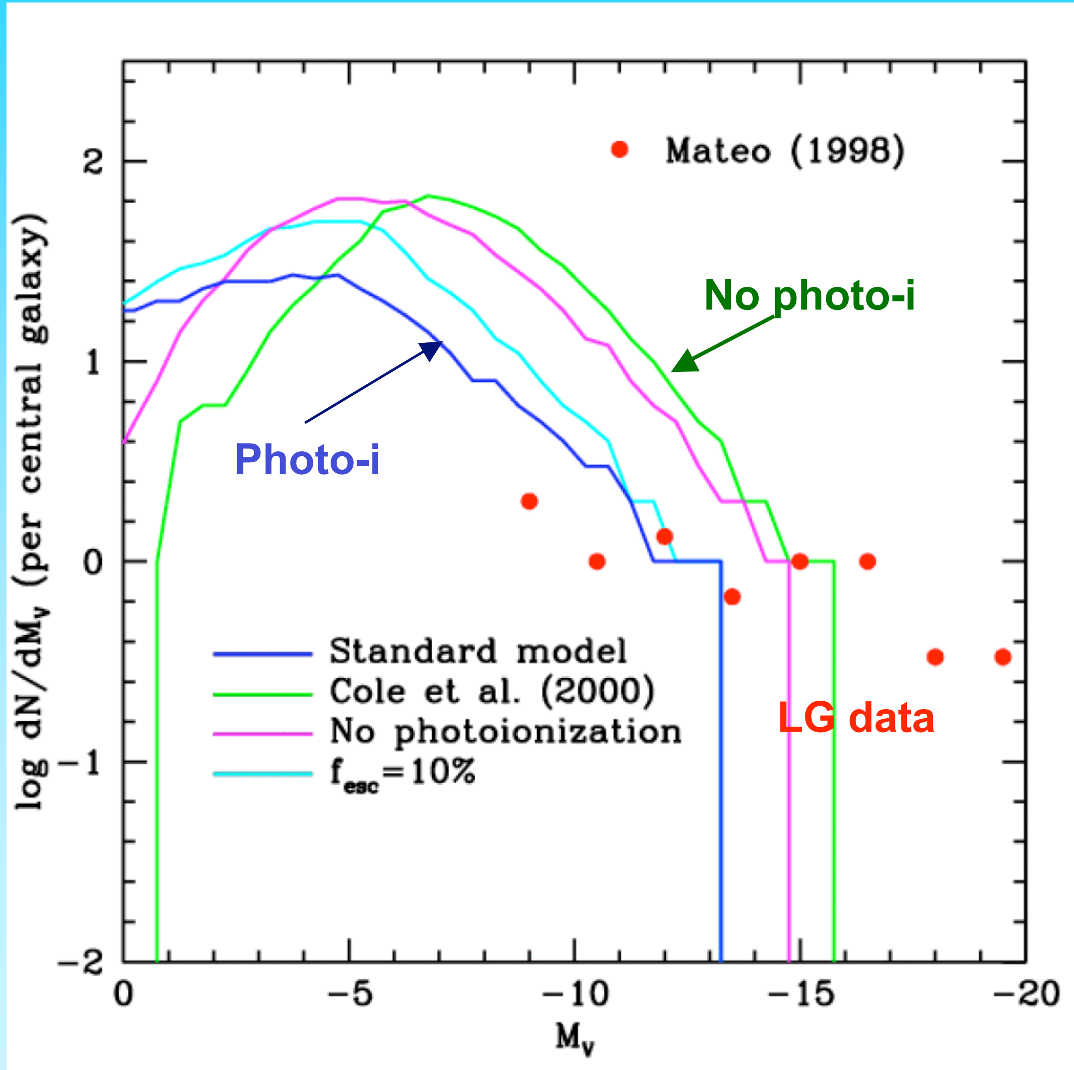
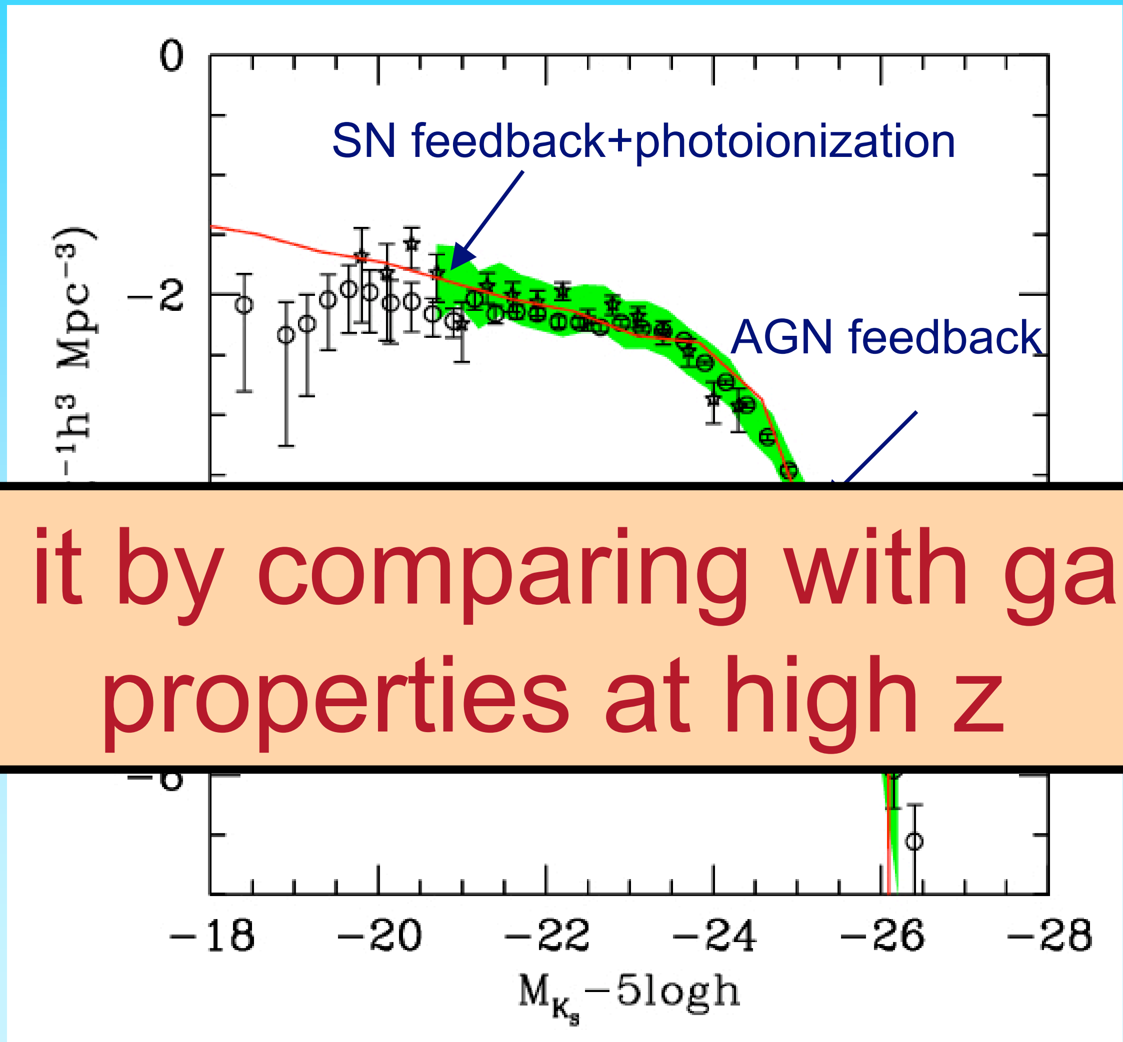
Luminosity Function of Local Group Satellites

- Photoionization inhibits the formation of satellites
- Abundance reduced by factor of 10
- Main effect due to reduced cooling because of increased IGM pressure



Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman etal '93, Bullock etal '01)

Model successful at low z



Test it by comparing with galaxy properties at high z

The abundance of galaxies at high redshift

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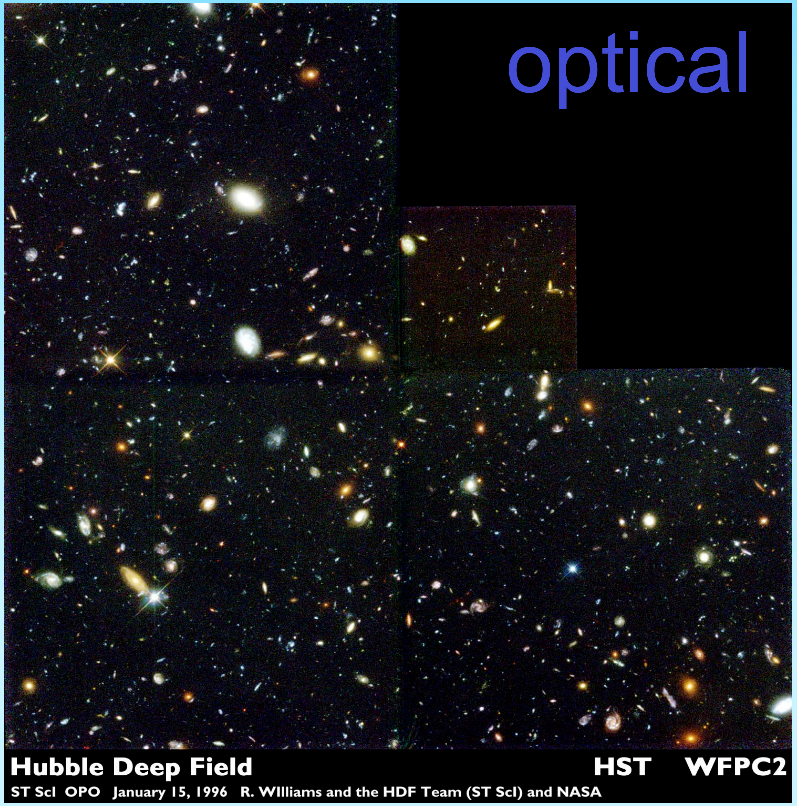
Statistical samples difficult to obtain.

Focus on:

- UV-selected galaxies (eg LBGs, seen in rest-frame UV)
- Sub-mm sources (SMGs, seen (SCUBA) in rest far-IR)



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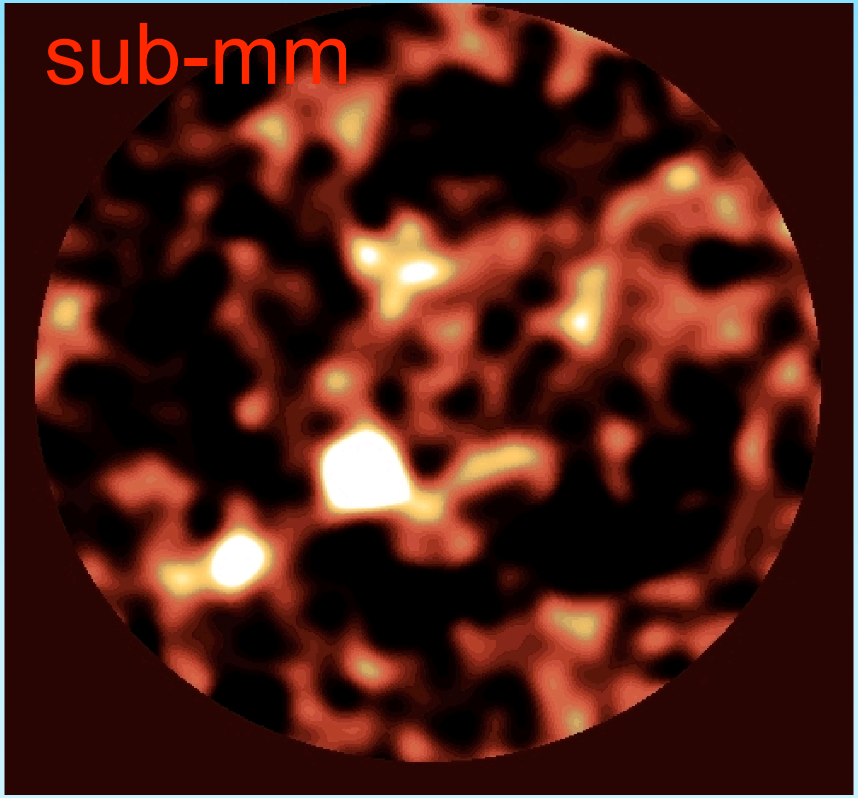
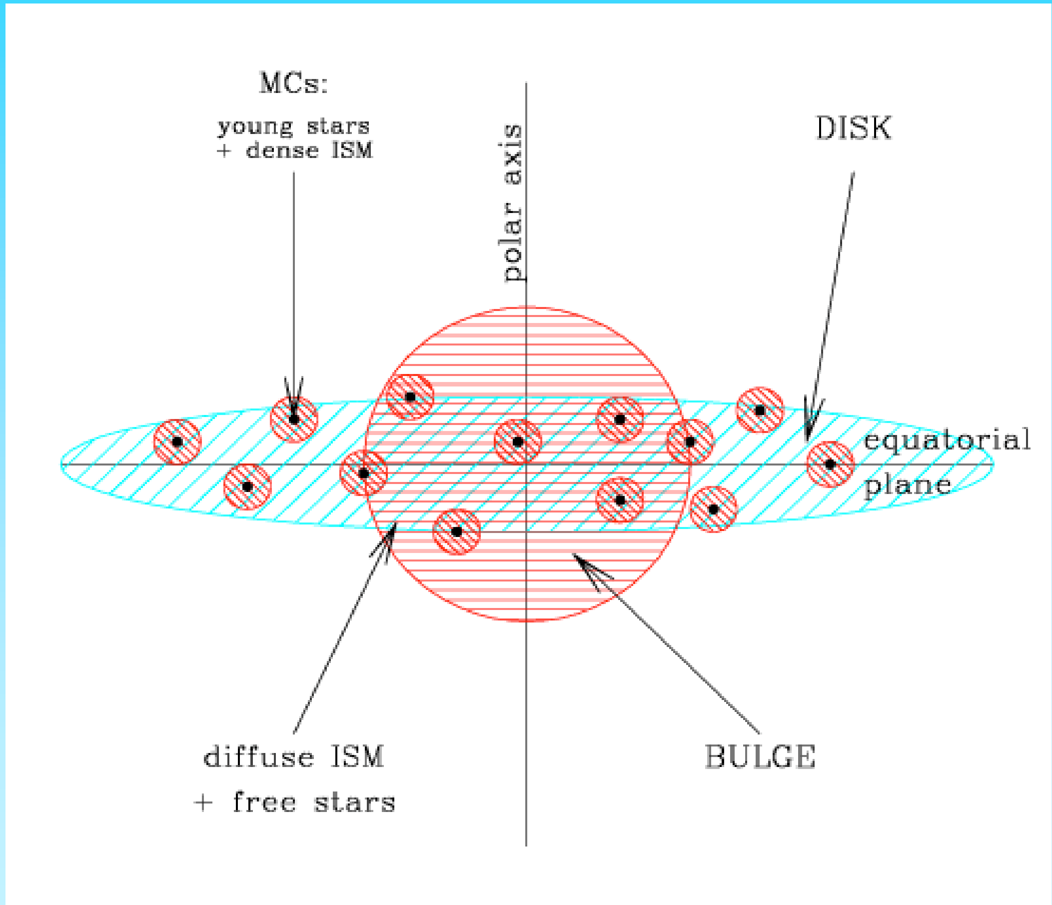


Modelling dust

- dust in diffuse medium and molecular clouds
- stars form in clouds and leak out
- radiative transfer of starlight through (clumpy) dust distribution
- heating of dust grains

  → dust temperature distribution



Complicated but partly understood?

Granato, Lacey, Silva, Baugh, Bressan, Cole & Frenk '00

Sub-mm galaxies

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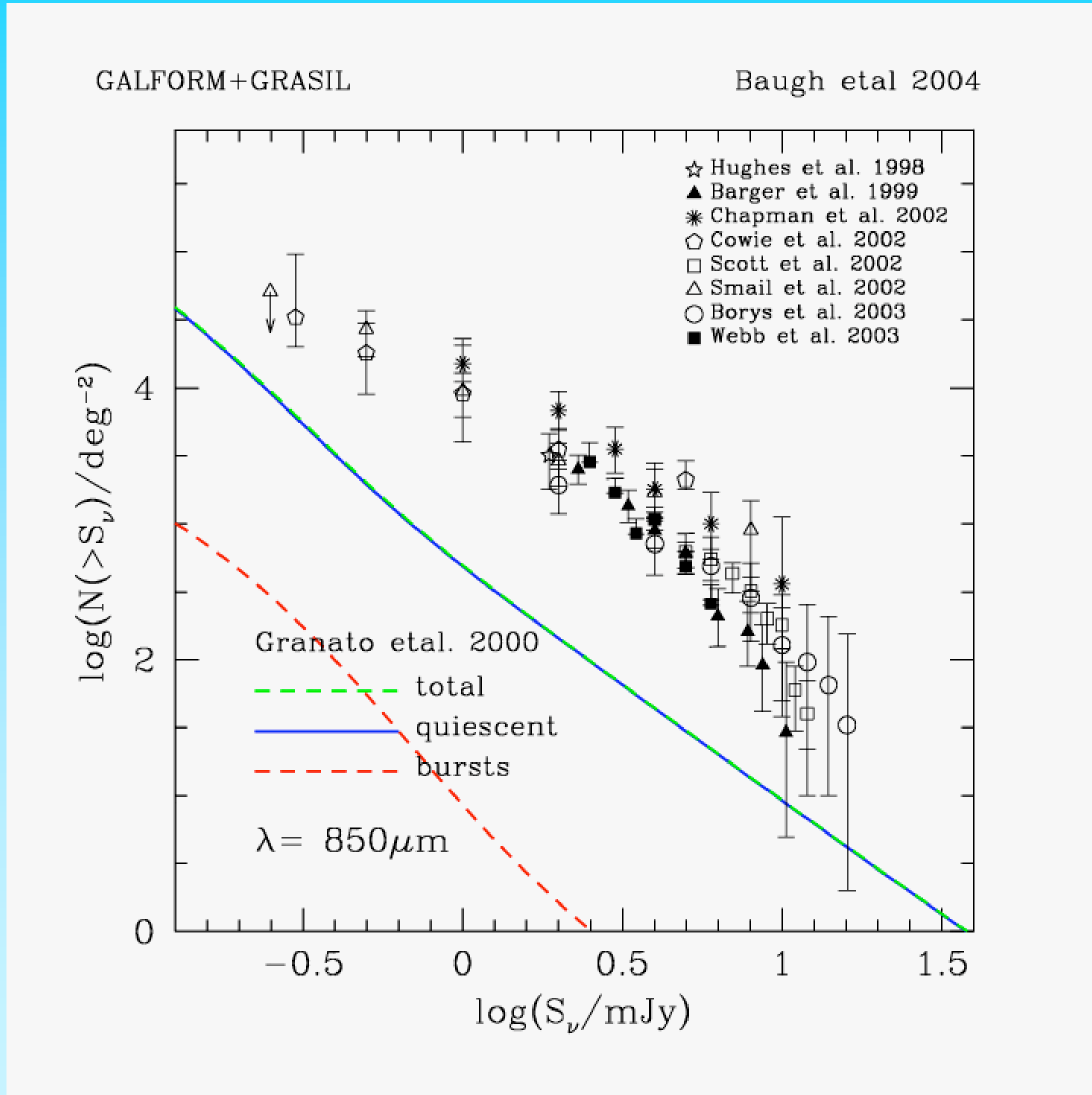
Cole etal/Benson etal model underpredicts Scuba counts by about x10

Not enough large starbursts at high-z!

⟹ Insufficient feedback

Baugh etal 04

Counts per deg^{-2}



Flux/Janskys

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Galaxies at high redshift

The model that works at z=0 underpredicts the number of SCUBA sources by x10

Modifications:

1. Star formation timescale in quiescent disks: t(SFR) ~ const

(instead of scaling with dynamical time)

→ quiescent disks are high-z are gas-rich

→ gas-rich mergers at high-z

2. Top-heavy IMF in bursts:

quiescent disks: solar neighbourhood IMF (dN/dlnm ~ $m^{-1.5}$)

bursts: 'top heavy' (dN/dlnm ~ $m^{-0.35}$)

→ bursts much more luminous

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Galaxies at high redshift

Modifications

1. Star form s

2. Top-hea

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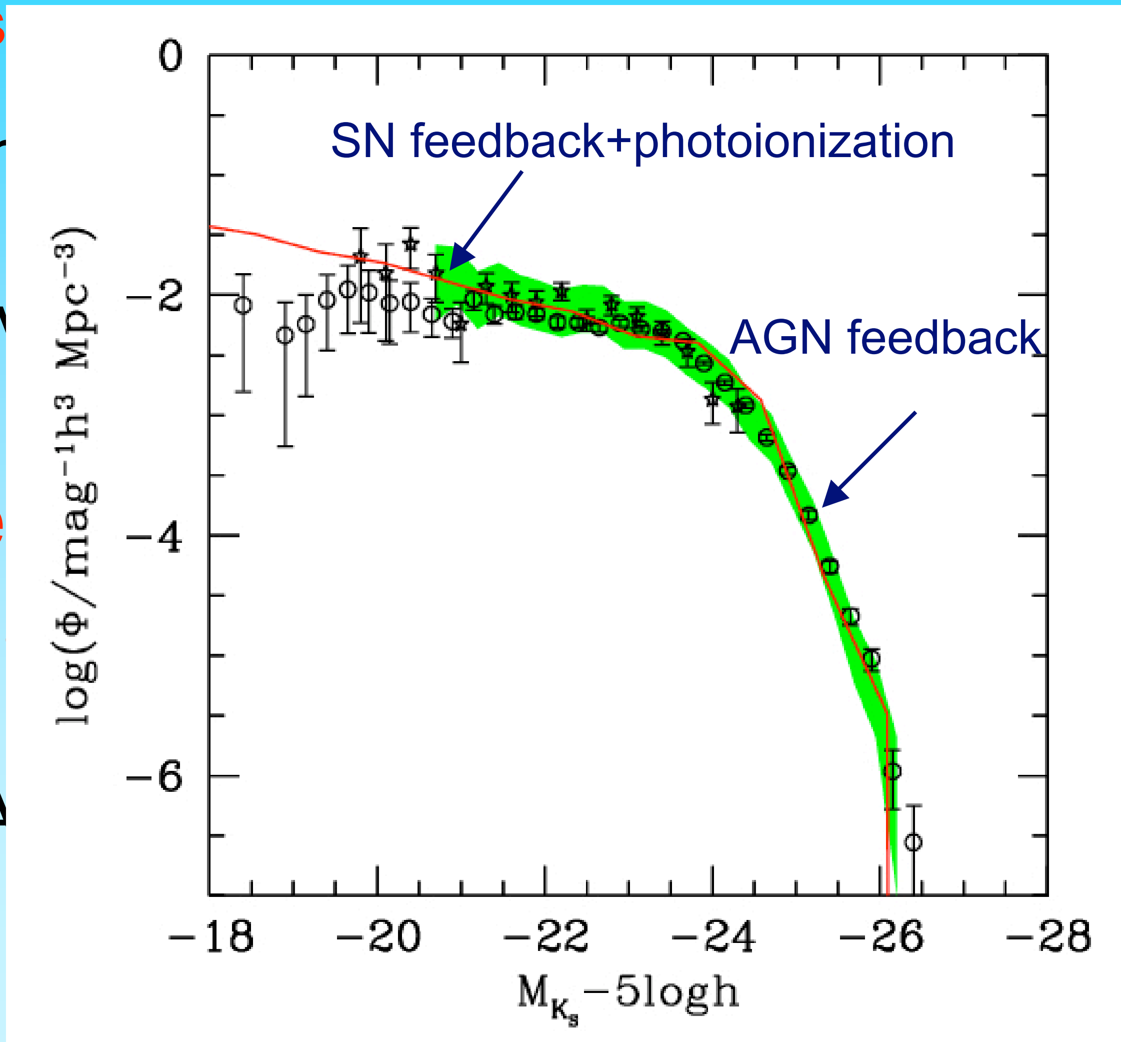

Sub-mm galaxies

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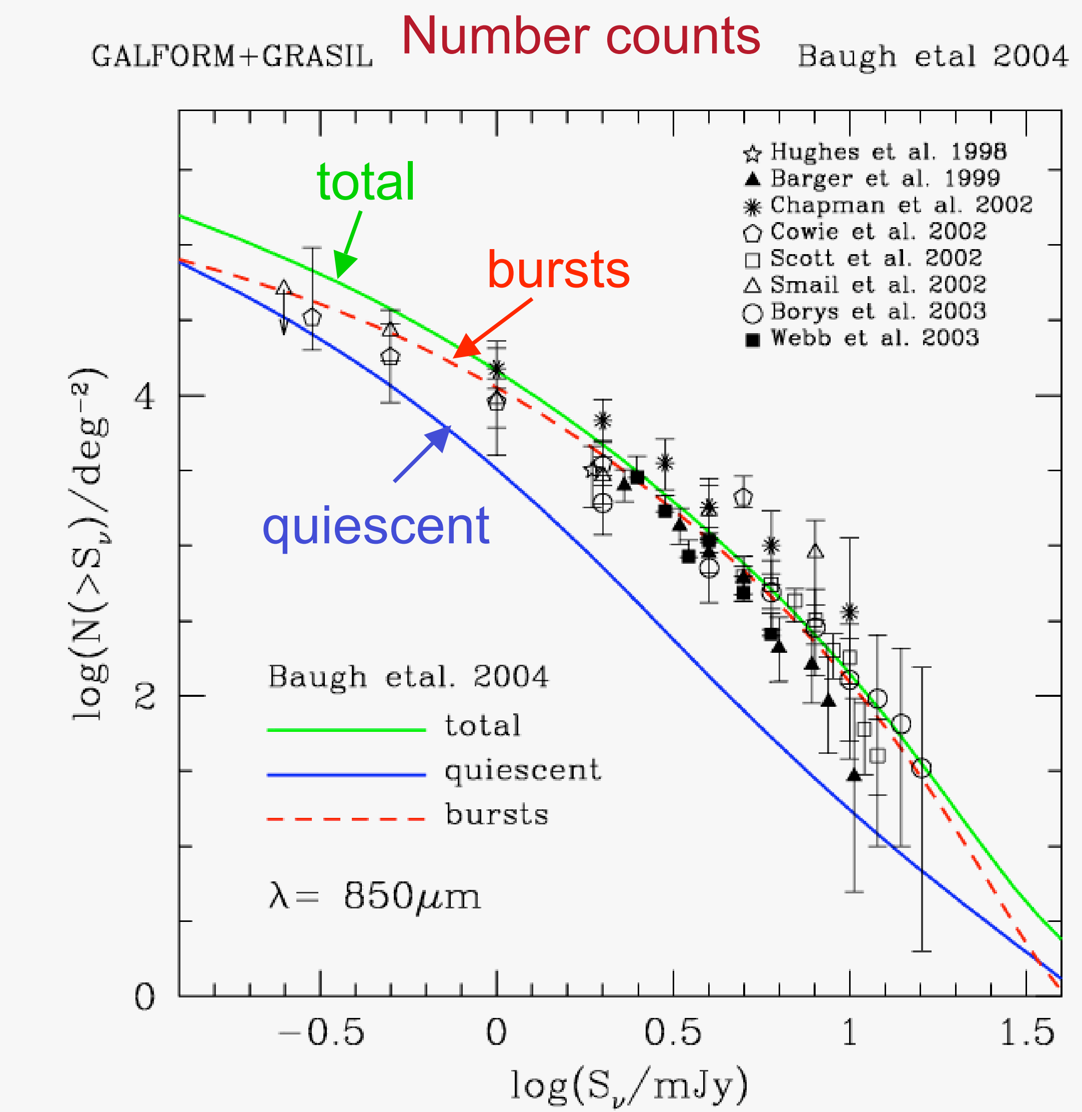
New model with:

- Constant star formation timescale
- Top-heavy IMF in bursts

Gives correct SCUBA counts



Baugh, Lacey, Frenk, Cole, Benson, Bressan, Granato, Silva 04

Sub-mm sources galaxies

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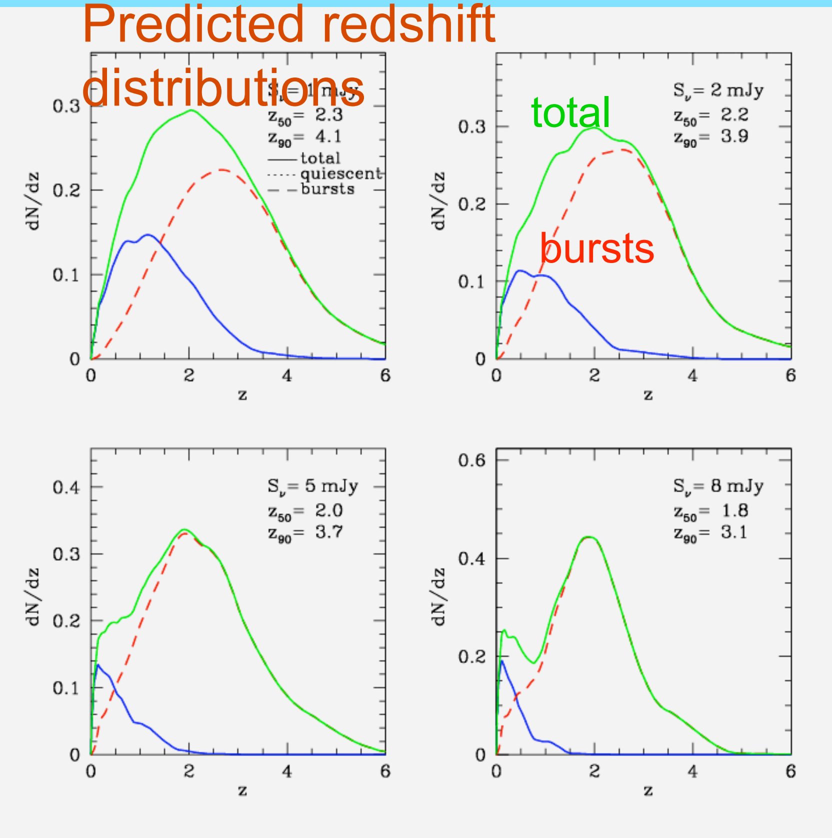
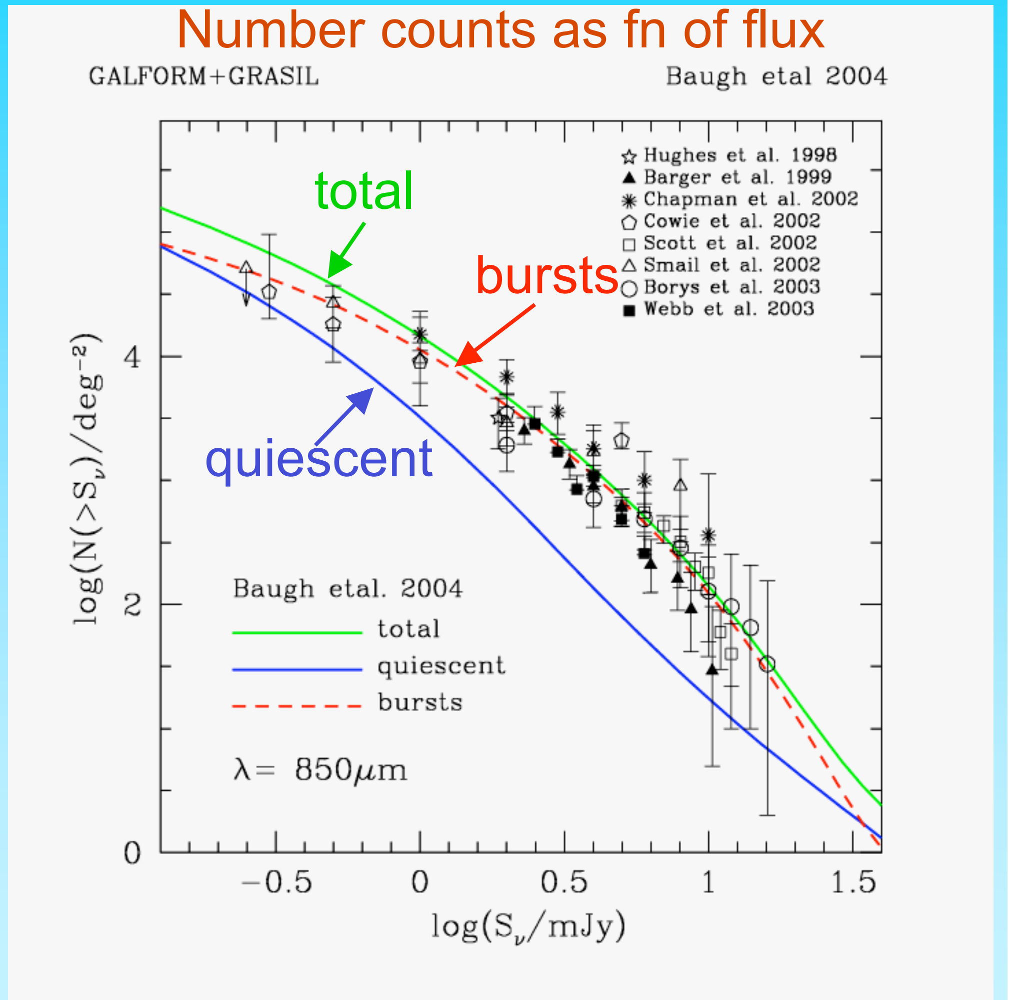
- Counts dominated by recent bursts (mergers)
- Predicted median z~1.8-2.2 for S_ν = (1-8)mJy





Baugh, Lacey, Frenk, Benson, Bressan, Cole, Granato & Silva '04

Sub-mm sources galaxies

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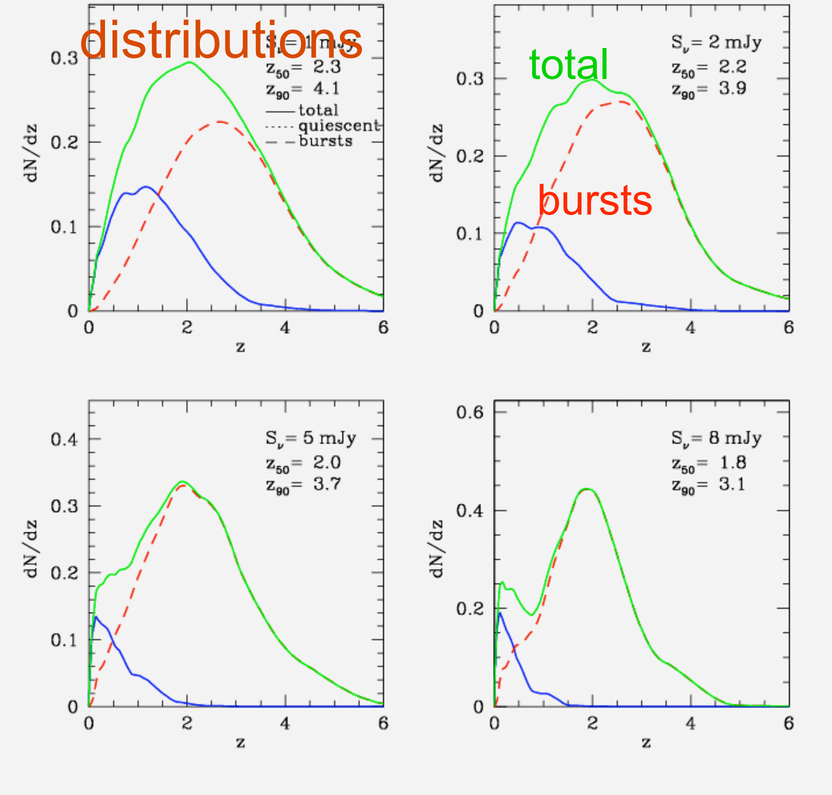
- Counts dominated by recent bursts (mergers)
- Predicted median z~1.9-2.3 for S_ν = (1-8)mJy

Predicted redshift distributions



$\Rightarrow$

consistent with observational determinations

(e.g. Chapman etal 2005, z_{median}=2.0 at S=5mJy)

Baugh, Lacey, Frenk, Benson, Bressan, Cole, Granato & Silva '04

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Galaxy LF in rest-frame UV

Lyman-break galaxies

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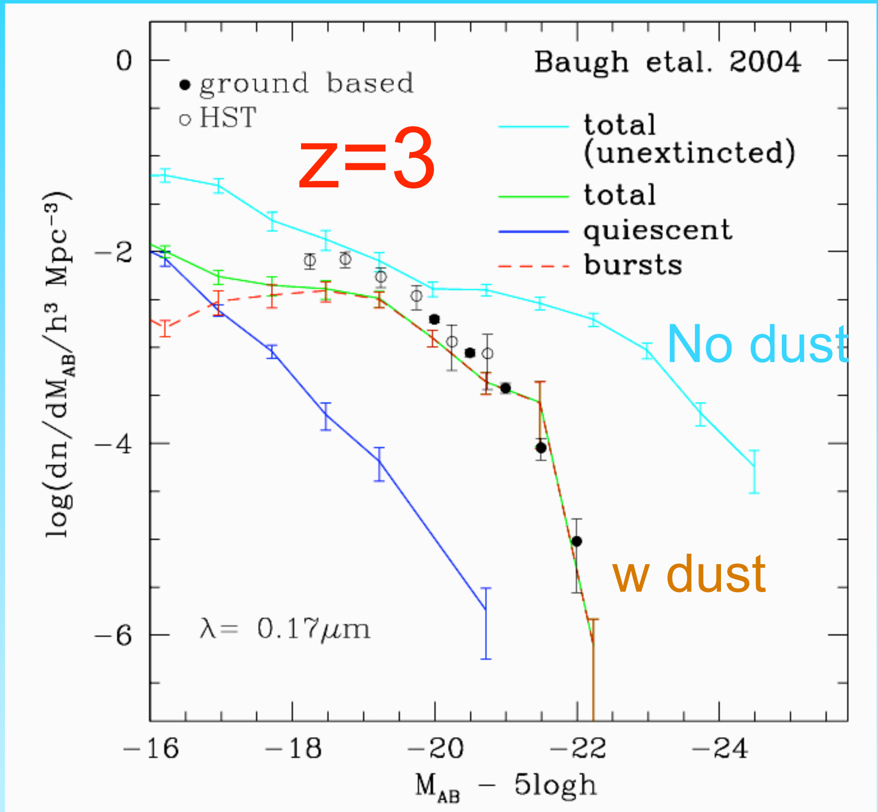
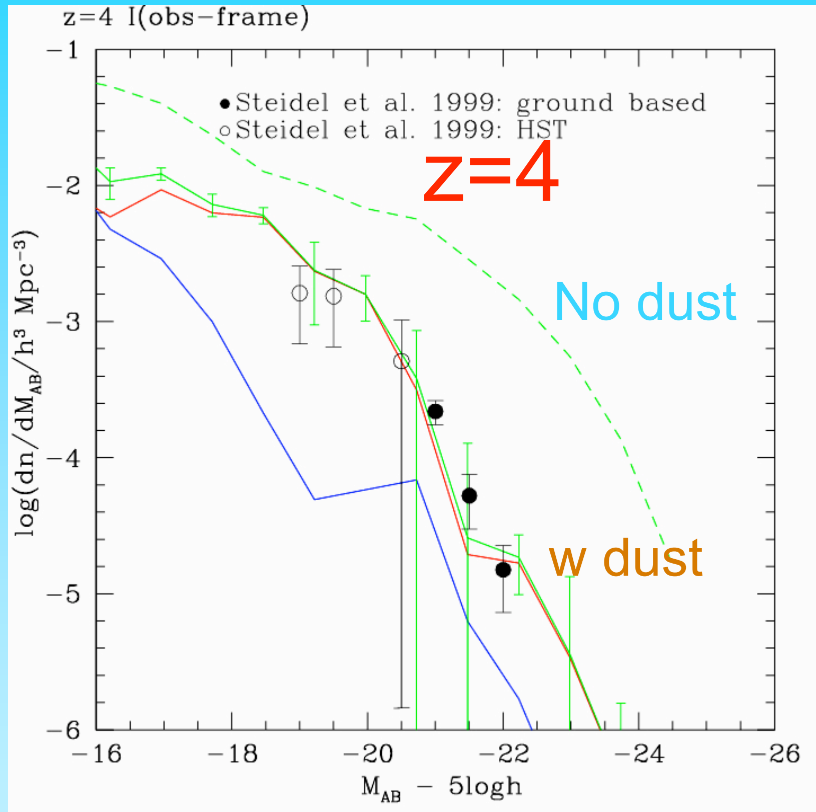


LBG luminosity function



- Dust extinction has huge effect on LBG luminosity function
- Most of UV radiation emitted by stars is absorbed by dust
- CDM model agrees well with data at z=3 and z=4

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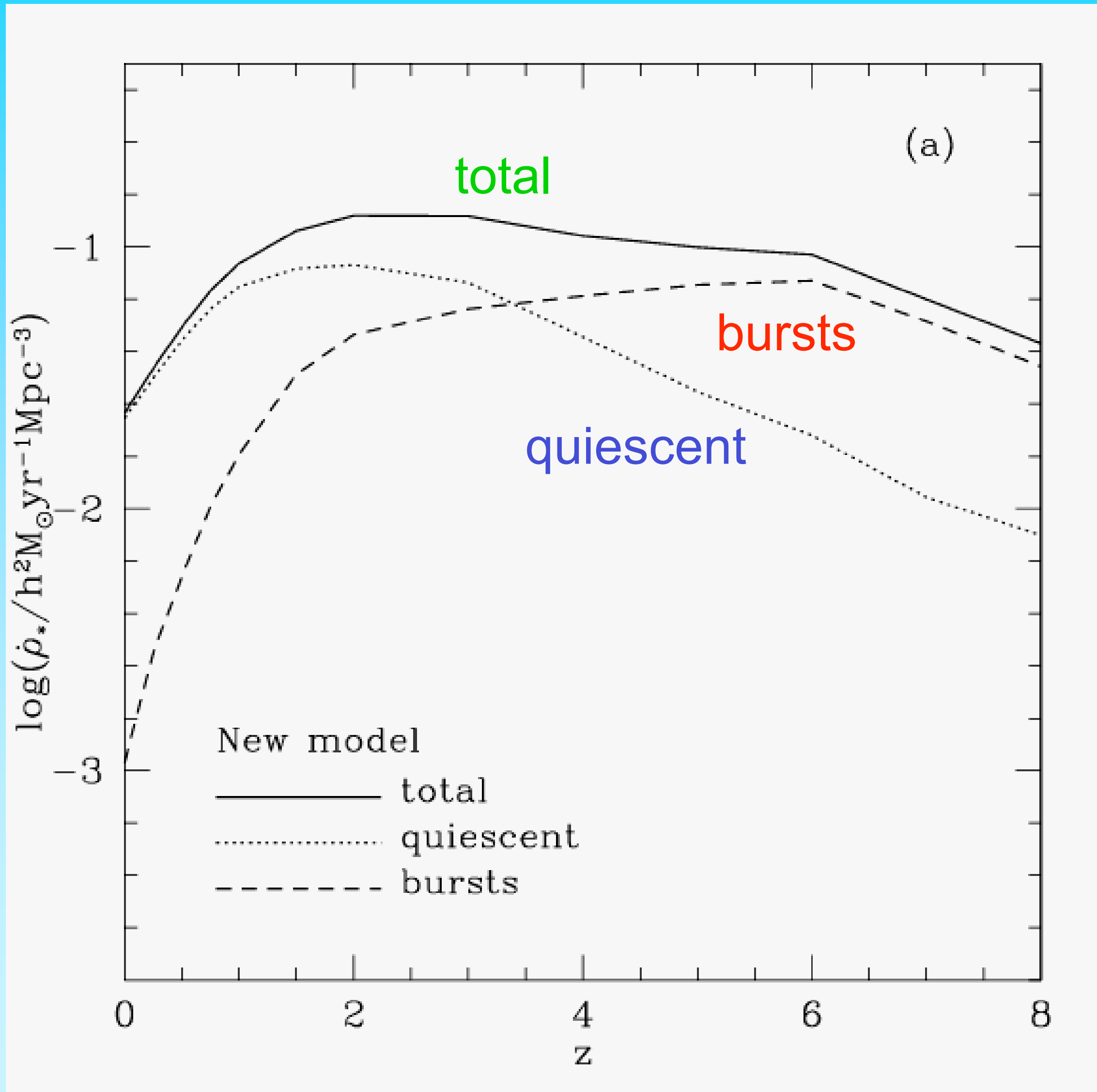
The cosmic star formation history

- $z>4$ → SFR in bursts ~ quiescent
- $z<4$ → quiescent dominates

20% of all the stars are made in bursts (with top-heavy IMF),

but only 5% of mass locked up in stars was made in bursts



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Clustering of LBGs and SMGs

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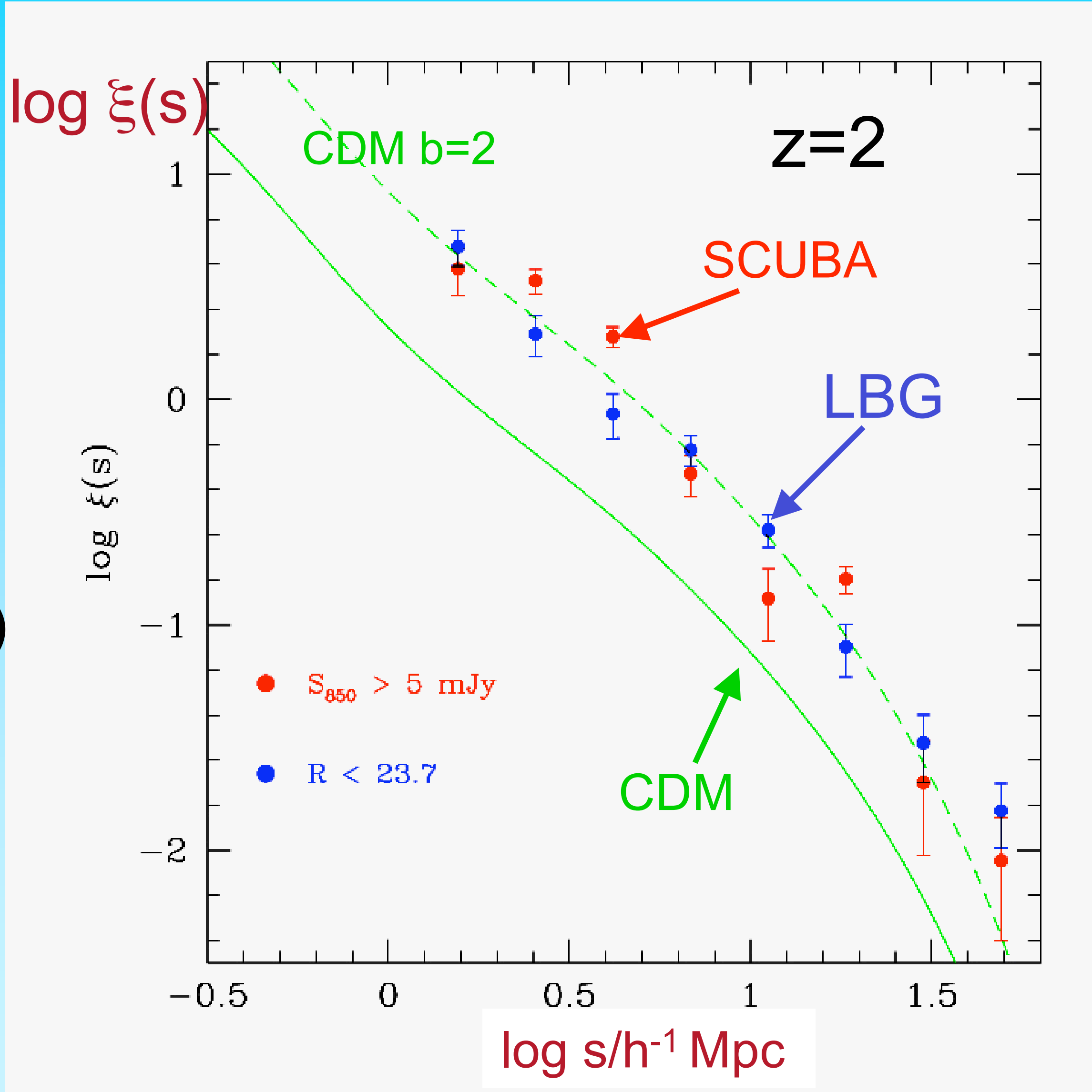
- 5 mJy LMGs (z=2) → characterstic clustering length, $r_0 \sim 6$ Mpc/h
- Similar to R< 23.5 LBGs (which have same density)



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A top-heavy IMF in bursts?

20% of all the stars are made in bursts
(with top-heavy IMF),

but only 5% of mass locked up in stars
today was made in bursts

Look for evidence in metallicity of intracluster gas
→ all gas still there

The metallicity of the intracluster gas

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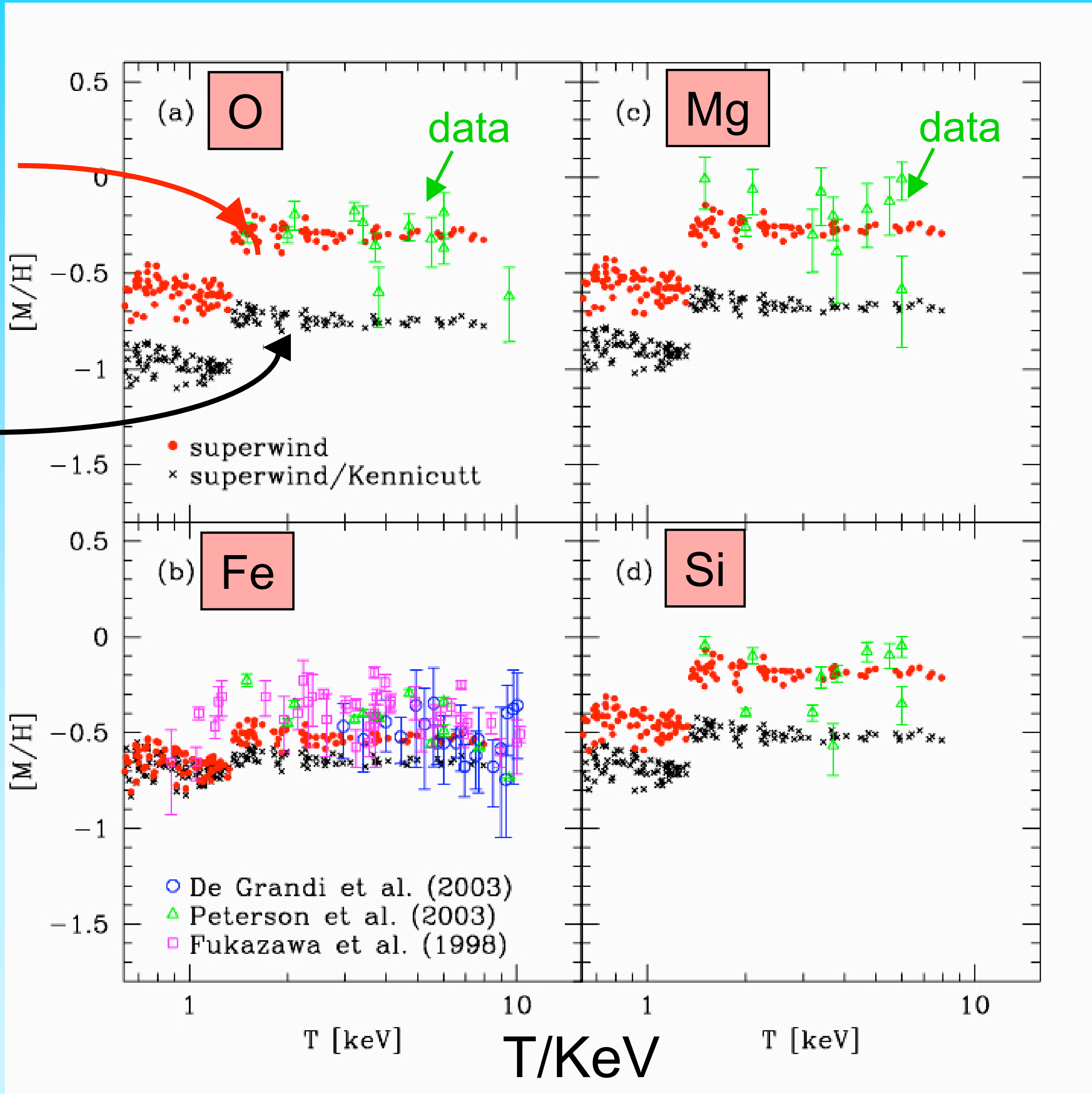
- Bursts: top-heavy IMF
  Quiescent: Kennicutt
- Bursts: Kennicutt IMF
  Quiescent: Kennicutt

Standard IMF results in too few metals in ICM

→ Top-heavy IMF in bursts needed

Nagashima, Lacey, Frenk, Baugh, Cole '04



The metallicity of the intracluster gas

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- Bursts: top-heavy IMF
  Quiescent: Kennicutt

- Bursts: Kennicutt IMF
  Quiescent: Kennicutt

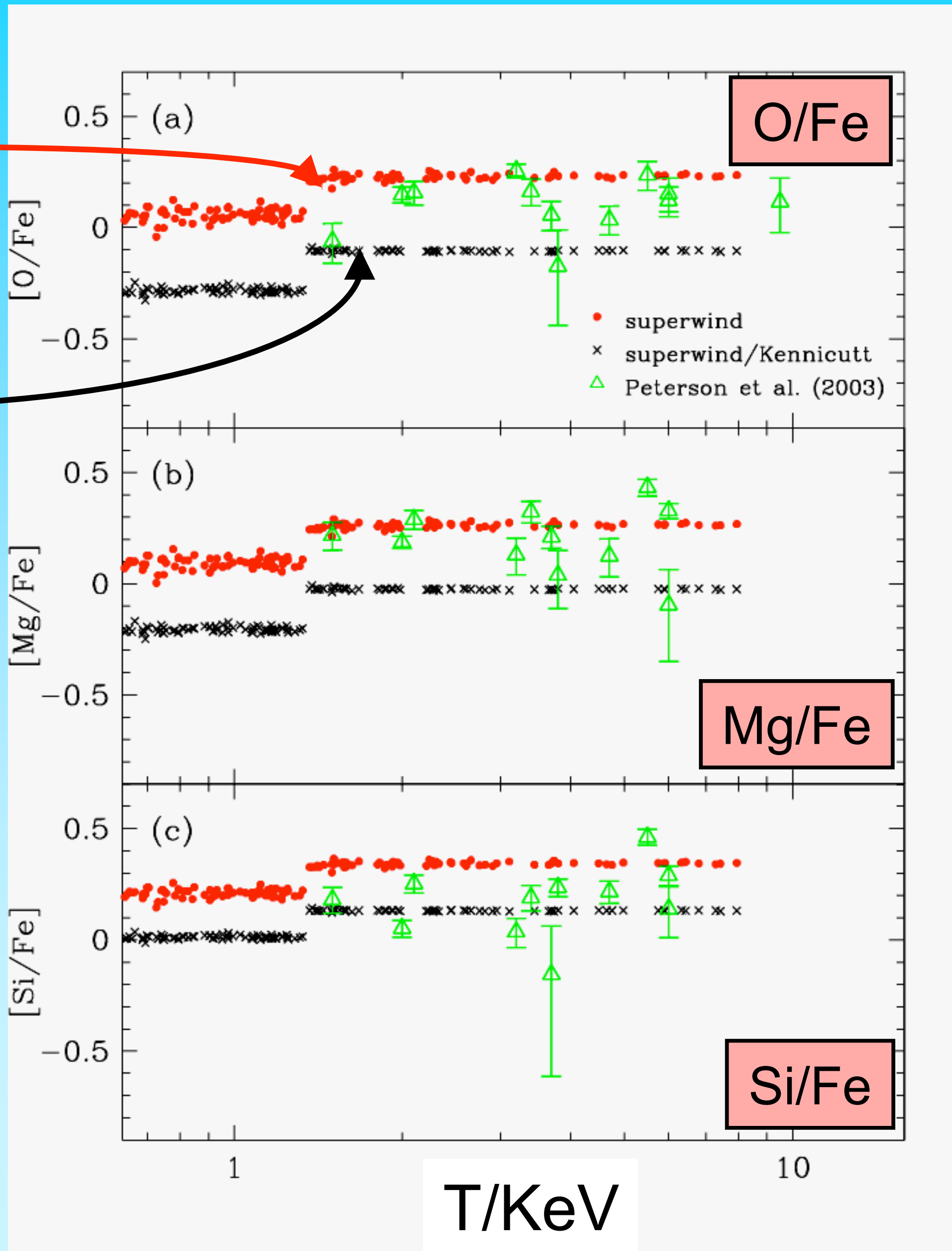
α elements (O, Mg, Si) produced mostly in SNII

Fe produced mostly in SNIa

→ α/Fe probes IMF

α/Fe consistent with top-heavy IMF in bursts

Nagashima, Lacey, Frenk, Baugh, Cole '04



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Simulations of disc galaxy formation

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Simulations of disk galaxy formation

Simulate formation of a spiral galaxy in a ΛCDM model

using SPH *and* same star formation modes (similar subgrid physics) as in the semi-analytic model

Simulations of disk galaxy formation

Two star formation modes just as in semianalytics:

- Quiescent
  - Self-regulated star formation
  - Kennicutt IMF
- Burst
  - High star formation efficiency
  - Top-heavy IMF $\Rightarrow$ large feedback energy in merging galaxies

Simulations of disk galaxy formation

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Gadget2 (Parallel TreePM SPH code by V. Springel)

- Multi-phase gas model
- Phase decoupling (Okamoto et al. 2004)
- Metallicity dependent cooling (Sutherland & Dopita 1993).
- Photoionizing background at z<6 (Haardt & Madau 1996)
- SNeII
  - Chemical yield (Portinari et al. 1998)
- SNeIa (Greggio & Renzini 1983)
  - Chemical yield (W7 of Nomoto et al. 1997)
- Stellar pop synthesis (Pegasse; Fioch & Rocca-Volmerange '02)

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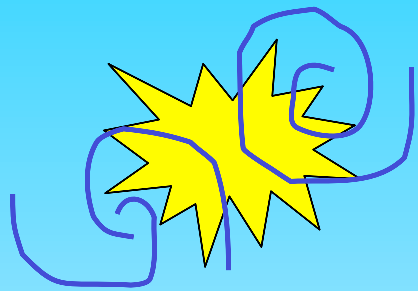
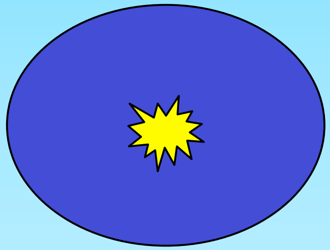
What triggers a burst?

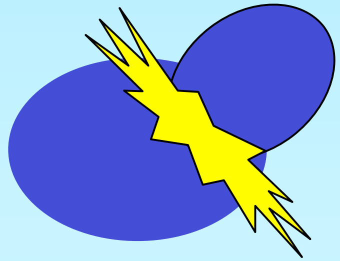
- In SA models
  - Major merger



- In simulations
  - High density ($\rho > \rho_{burst}$)
    - Nuclear starburst



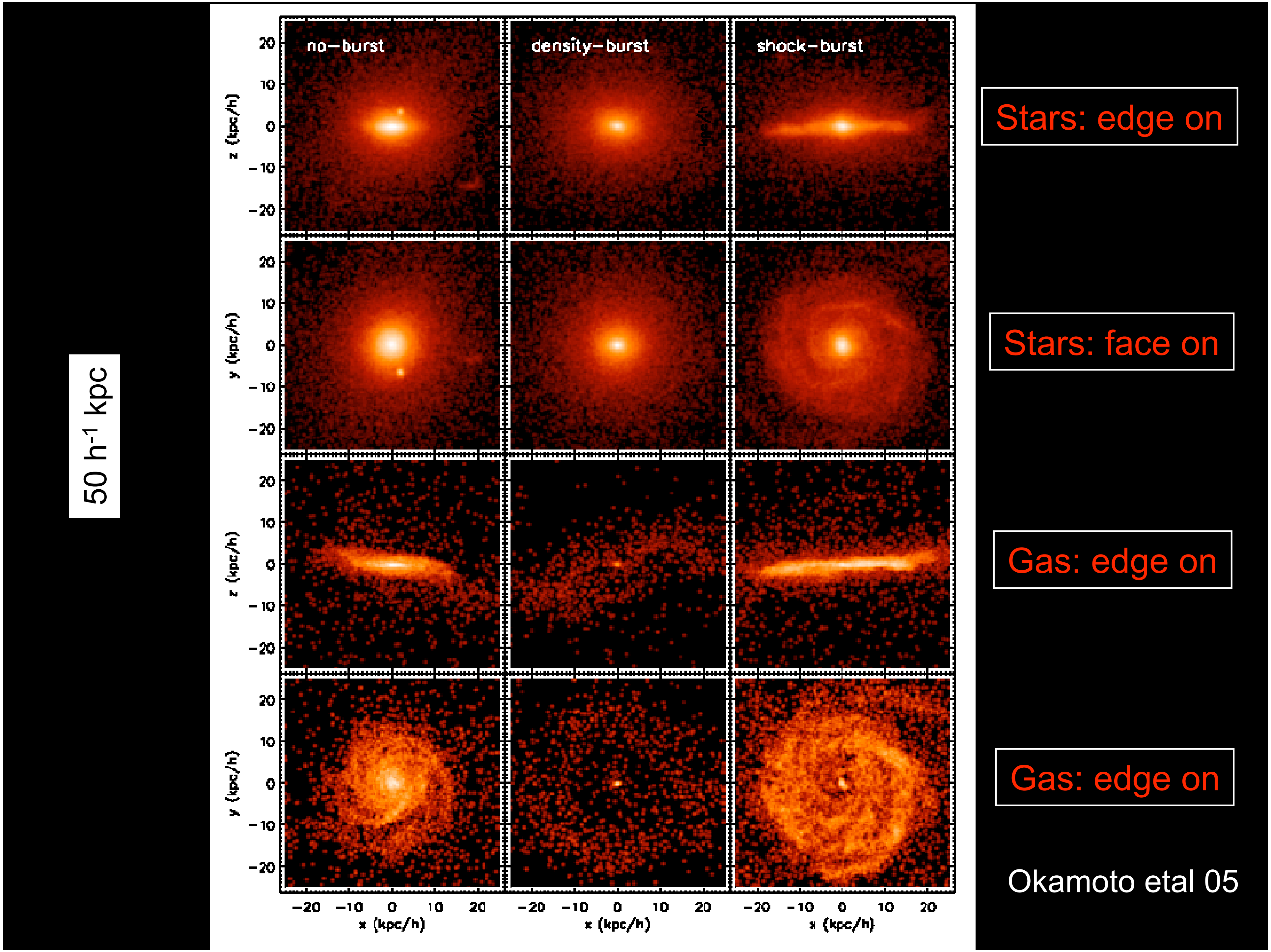
  - Strong shock ($\dot{s} > \dot{s}_{burst}$)
    - Extended starburst



Shock-induced burst

stars

gas



Okamoto etal 05

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Surface brightness profile

All models produce $r^{1/4}$ spheroids and exponential disks

No-burst

- Medium-size disk

$(L_D/L_{tot})_B = 0.63$ (Sa)

Density-induced bursts

- Small disk

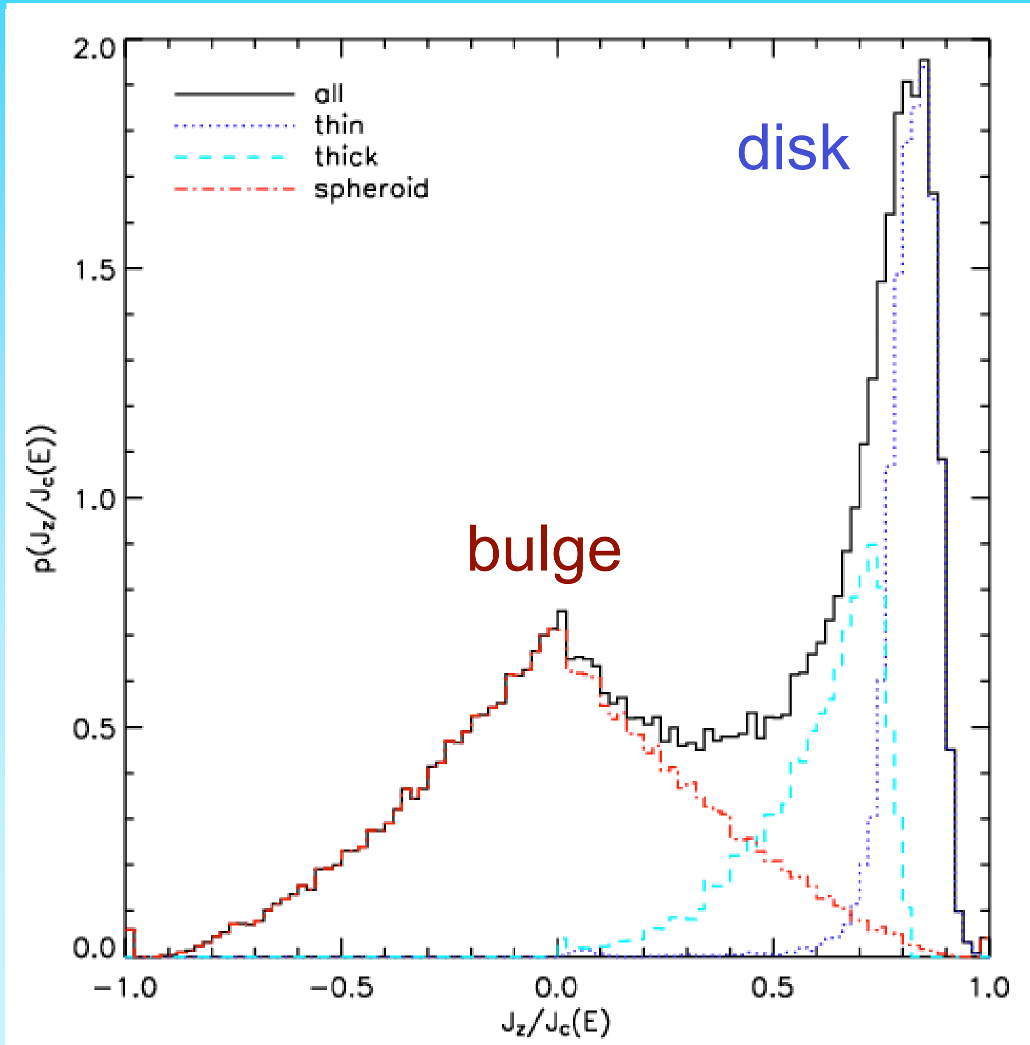
$(L_D/L_{tot})_B = 0.22$ (E)

Shock-induced bursts

- Very large disk

$(L_D/L_{tot})_B = 0.84$ (Sc)

Orbital circularity



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Star formation history

No-burst

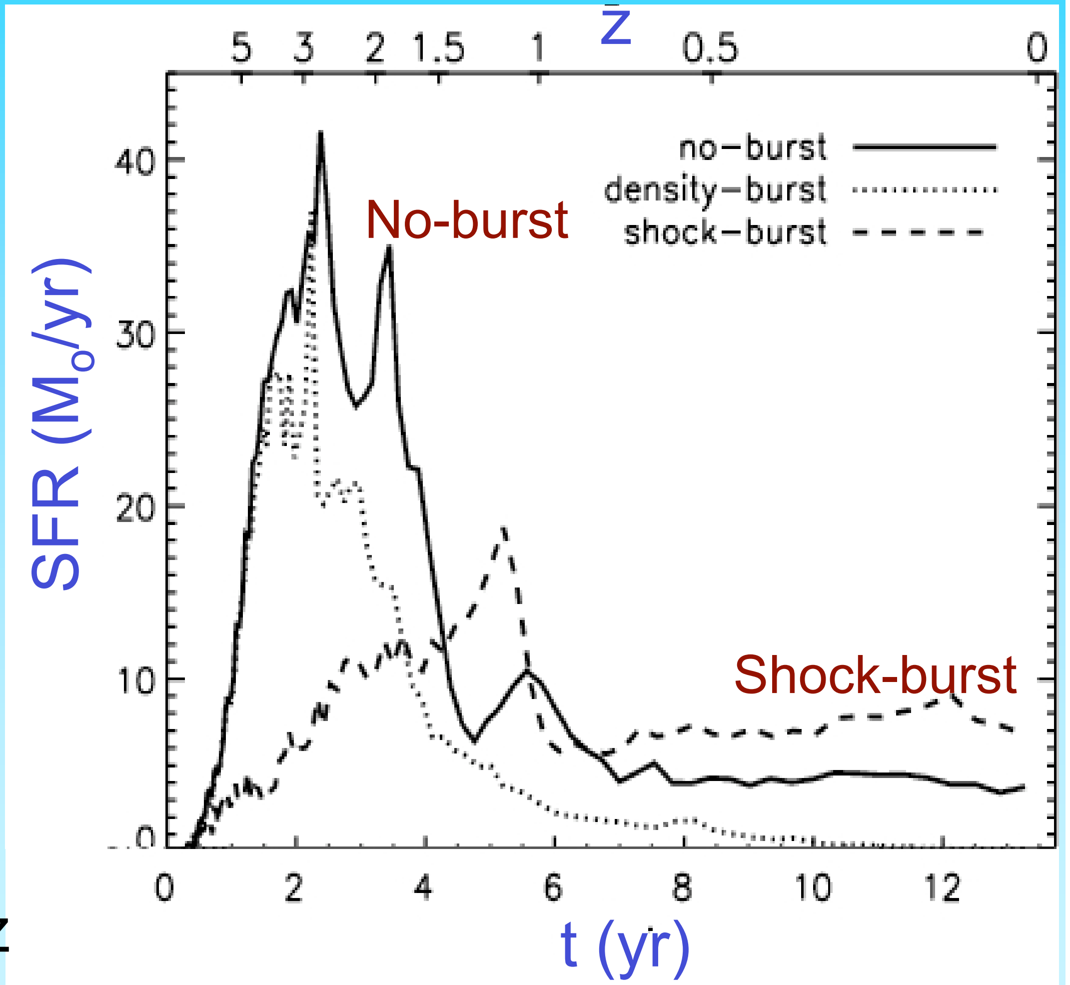
- SF peaks at high z and most of gas is used up

Density-induced bursts

- Similar to no-burst model until gas density reaches threshold.
- Once bursts occur, SF strongly suppressed.
- Almost no SF after z = 0.5

Shock-induced bursts

- Burst fraction high at high-z → SF strongly suppressed.
- Burst fraction gradually ↘



Galactic winds

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No-burst

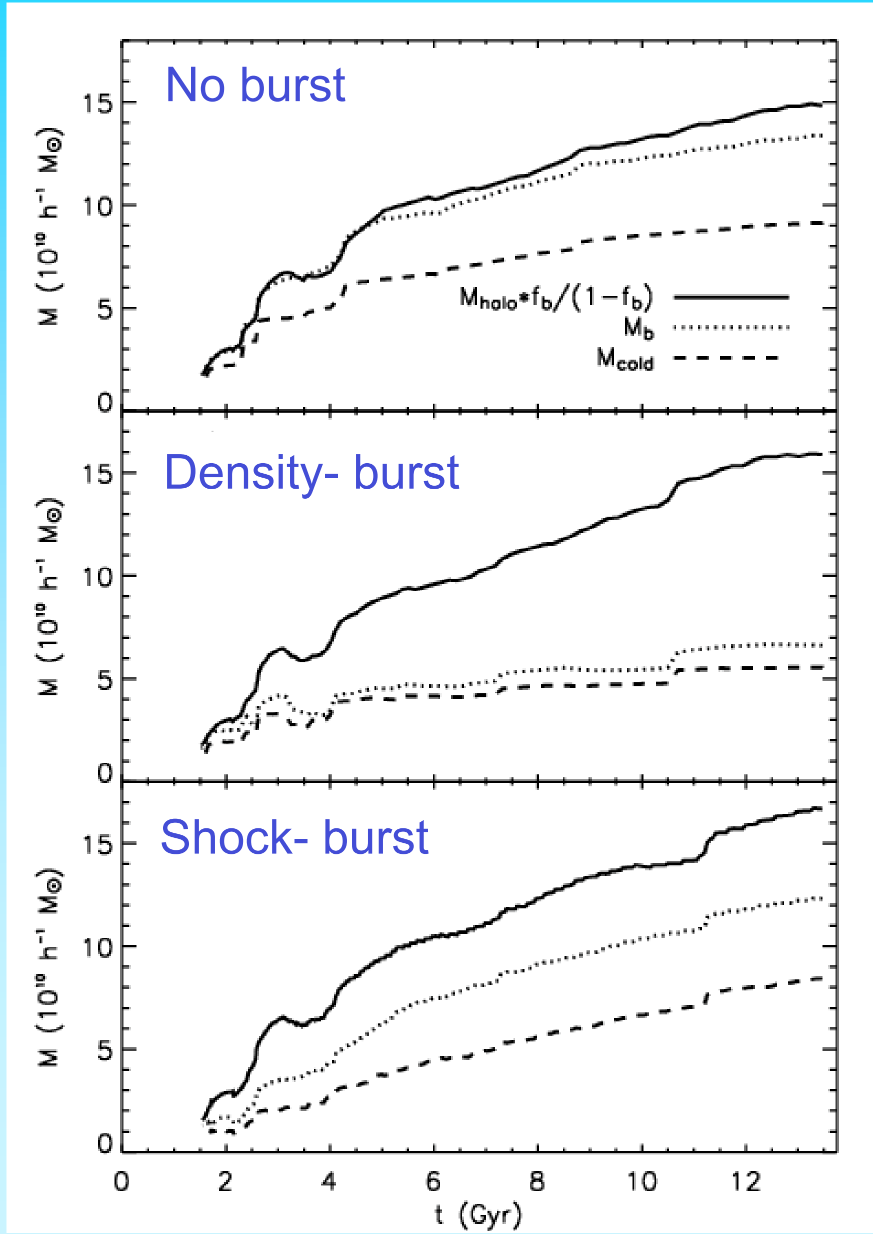
- Almost no gas lost
- Gal baryons: 2/3 cold, 1/3 hot

Density-induced bursts

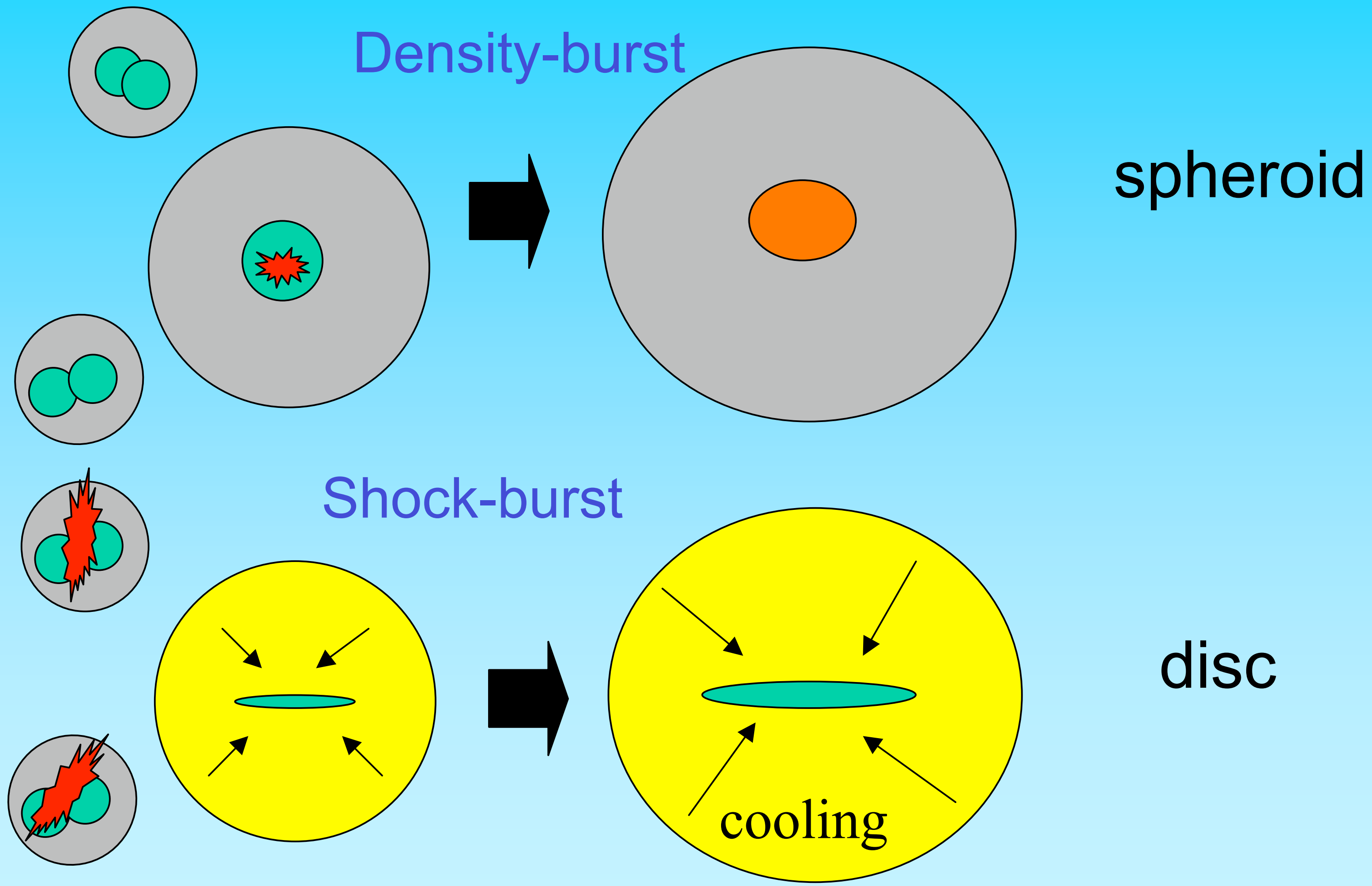
- 2/3 of gas lost in winds
- Gal baryons: all cold

Shock-induced bursts

- 1/3 of gas lost in winds
- Gal baryons: 1/4 hot, 3/4 cold



Summary



SF & feedback determine galaxy evolution

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CONCLUSIONS

Semi-analytics and N-body/gasdynamics simulations are complementary methods for modelling galaxy formation

LF and high-z study → required semi-analytics

Heating of ICM
Spiral galaxy formation
} required simulations

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CONCLUSIONS

1. The galaxy luminosity function

- In CDM, it is determined by feedback processes
- Faint end: photoionization & SNe feedback

(Satellites of Local Group: not a problem for ΛCDM)

- Bright end: mergers, starbursts, AGN (?)

2. Galaxies at high redshift

- Model requires top-heavy IMF in bursts
- Sub-mm and Lyman-break galaxies are star-bursting gals

$\Longrightarrow$ Evidence for top-heavy IMF in ICM and E gals

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CONCLUSIONS

3. Simulations of galaxy formation in ΛCDM

Using same SF model as in semi-analytics $\Longrightarrow$

- "Angular momentum problem" can be overcome
- For same ics, morphology depends strongly on feedback