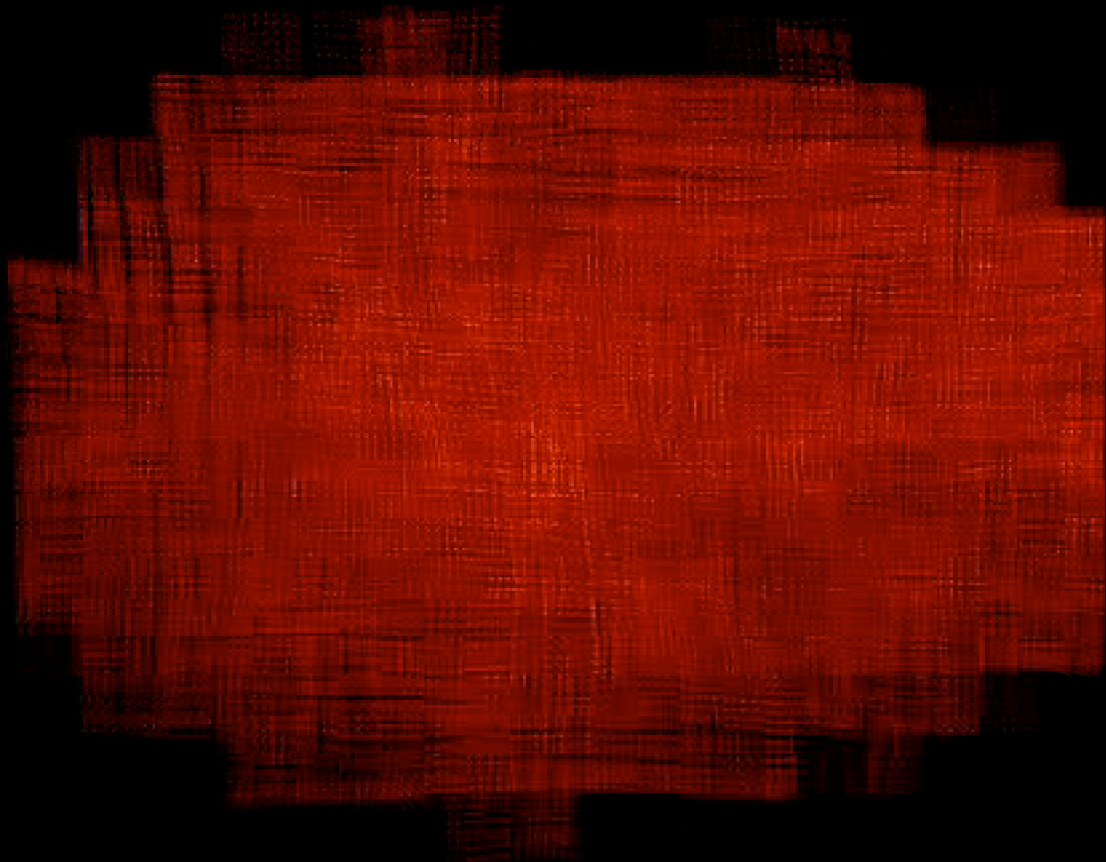
Galaxy Formation

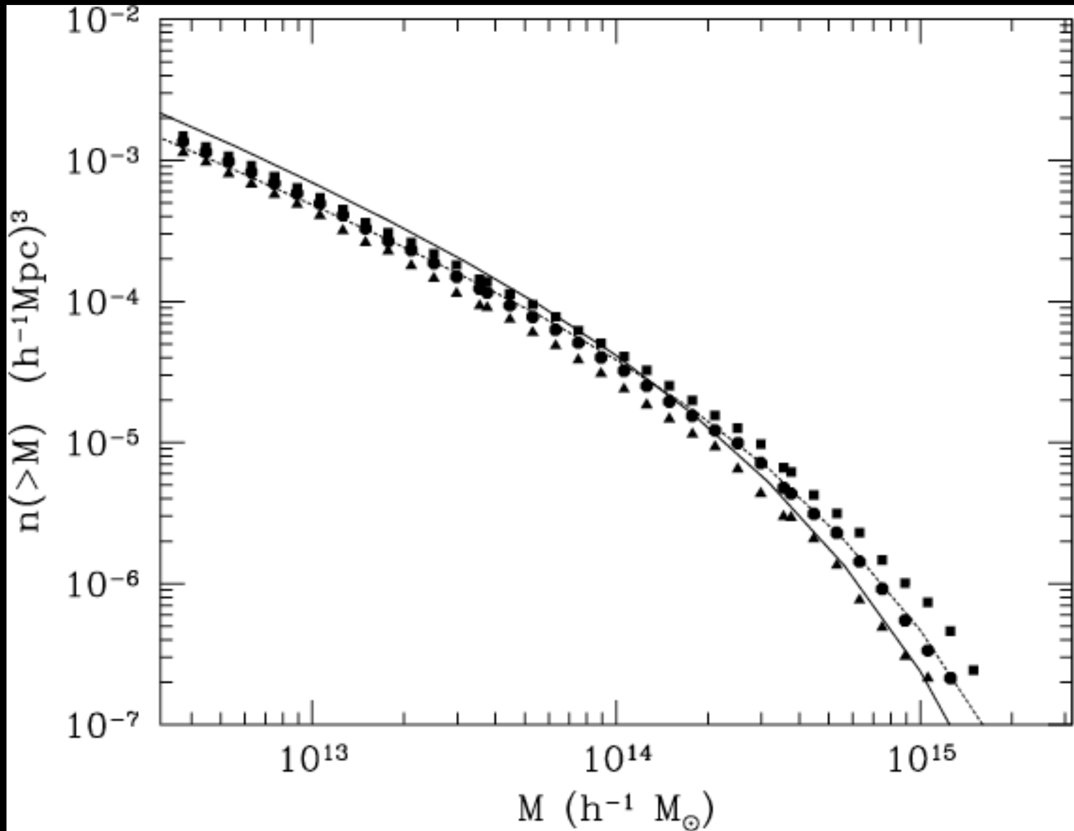
A quick overview of the key concepts

Dark Matter framework



Dark Matter halo masses

- Mass spectrum $dn/dM \propto M^{-2}$



M. White 2001

Dark Matter mass accretion histories

- Weak dependence on halo mass
  - Massive halos tend to build up later
  - Li et al. 2007

6 *Li, Mo, van den Bosch & Lin*

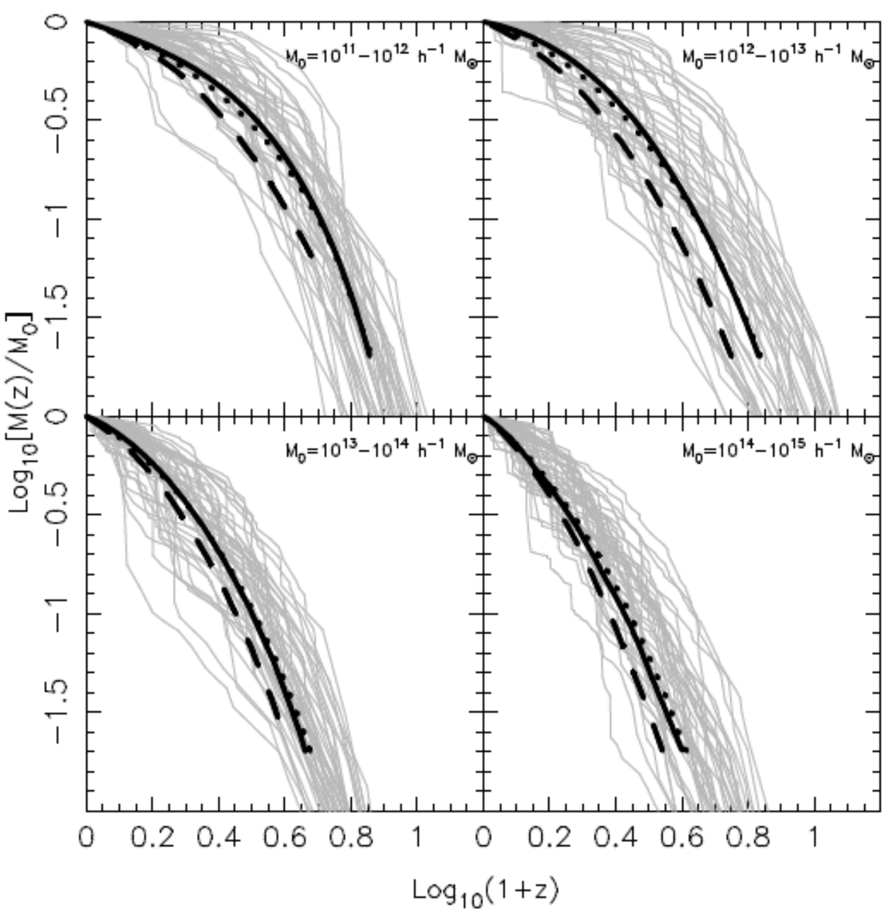
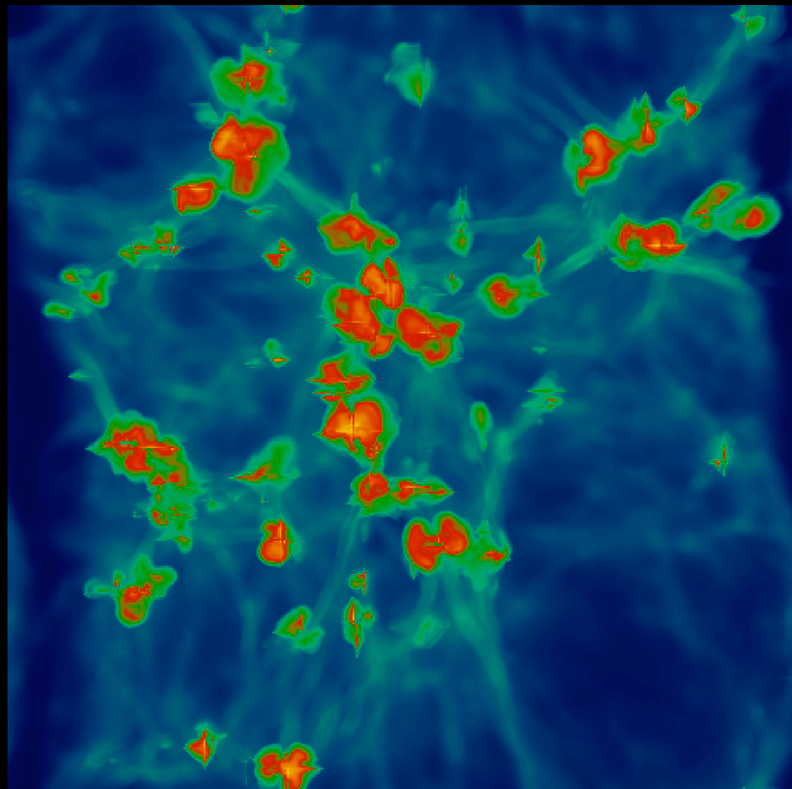


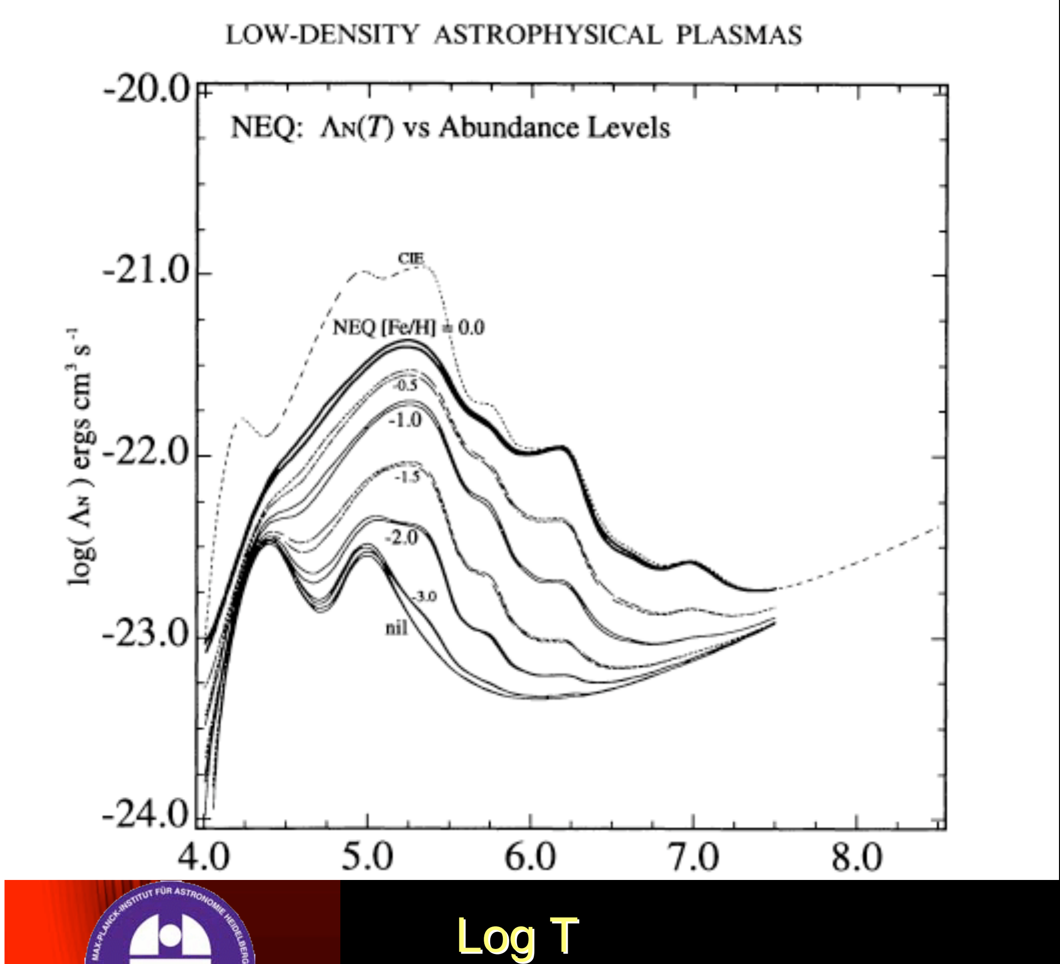
Figure 2. The mass assembly histories of dark matter haloes

Recall…

- Reionisation --> leads to warm/hot intergalactic medium >~10^6 K



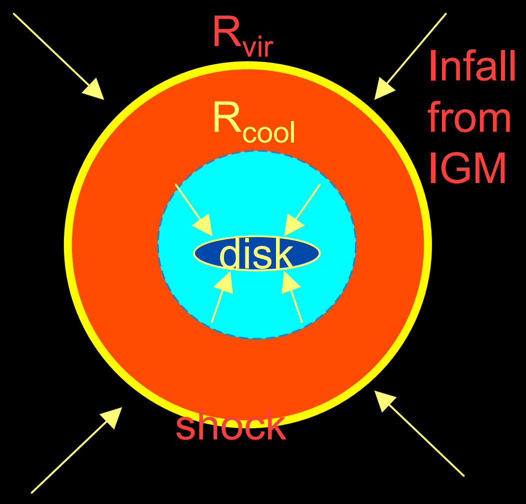
What happens to the IGM?



- Gas cooling strongly density (n^2 obviously) and metallicity dependent (>1 dex level)
- Y-axis is cooling rate / $n_i n_e$
- Sutherland & Dopita 1993

How Gas Gets Into Galaxies

- Modes of Gas Accretion (Keres et al 05):
  - Hot Mode: (White&Rees 78) Gas shock heats at halo's virial radius up to T_{vir}, cools slowly onto disk. Limited by t_{cool}. Hydrostatic eqm $kT/m \sim v^2$
  - Cold Mode: (Binney 77) Gas radiates its potential energy away in line emission at $T \ll T_{vir}$, and never approaches virial temperature. Limited by t_{dyn}. $kT/m \ll v^2$
- If $T_{igm} > T_{vir}$ little cooling happens (tiny halos)
- Cold mode dominates in small systems ($M_{vir} < 3\times10^{11} M_\odot$), and thus at early times.



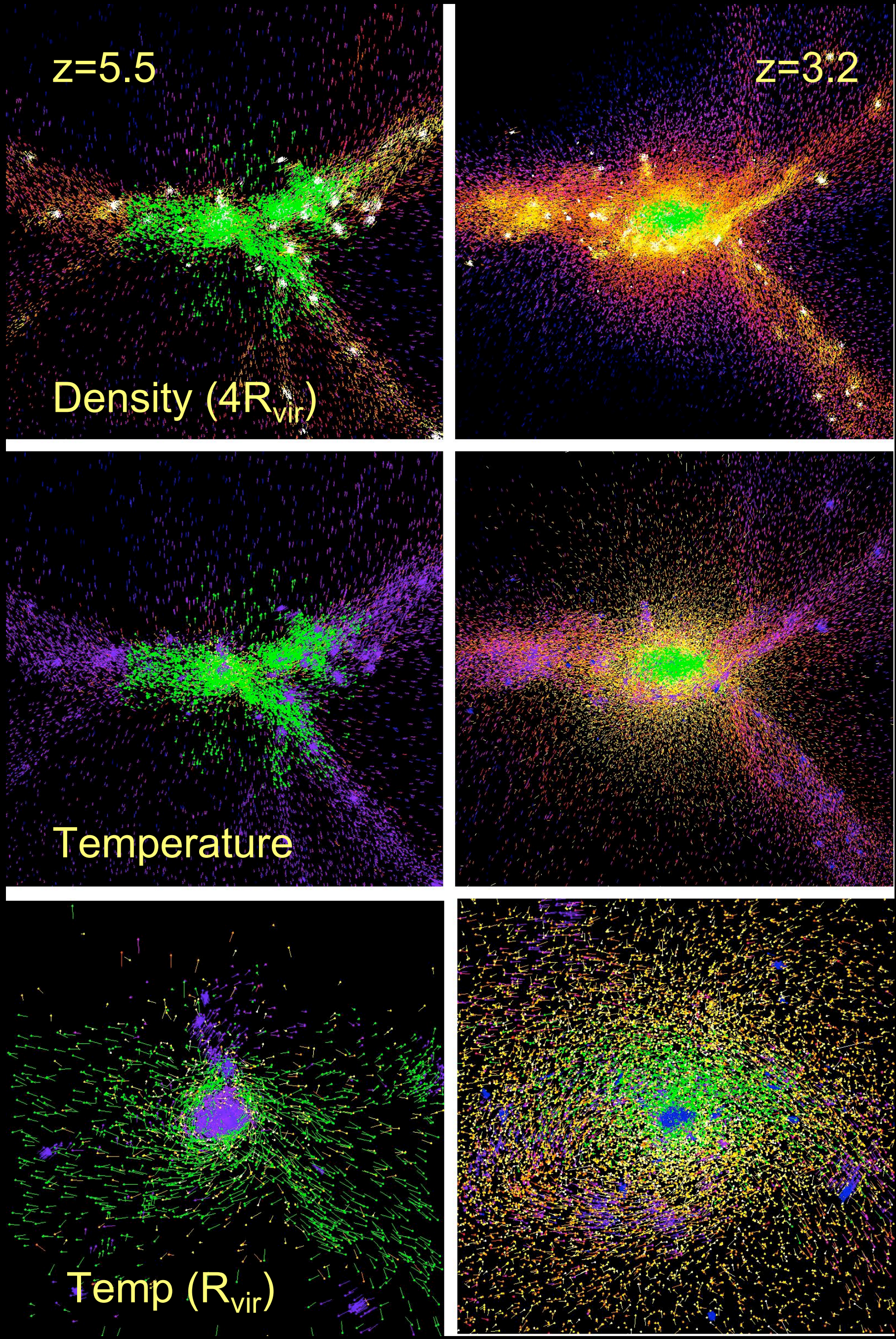
Accretion in a Growing Halo
(Keres at al 06; from Dave)

- Left panels: z=5.5,
- right panels: z=3.2.

- Halo grows from $M \sim 10^{11} M_{\odot} \rightarrow 10^{12} M_{\odot}$, changes from cold → hot mode dominated.

- Left shows cold mode gas as green; Right shows hot mode as green.

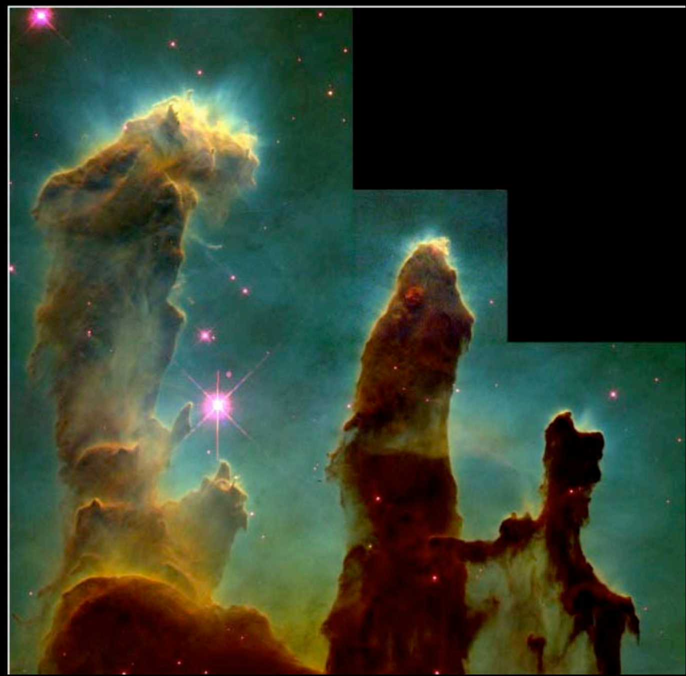
- Cold mode filamentary, extends beyond R_{vir}; hot mode quasi-spherical within R_{vir}. Filamentarity enhances cooling.



Keres et al 2005

Star Formation

- Local process
  - $n \sim 10^5 cm^{-3}$
  - Molecular cooling important low densities
  - Dust cooling takes over
- Turbulence
- Cloud core mass spectrum --> IMF
- Feedback critical (more later…)



The Star Formation Law on kpc scales…

This and next few slides from Bigiel, Leroy, Walter et al.

What is a SF law?

A relation connecting Σ_{SFR} to Σ_{gas}: $\Sigma_{SFR} = A \bullet \Sigma_{gas}^N$

(going back to Schmidt 1959)

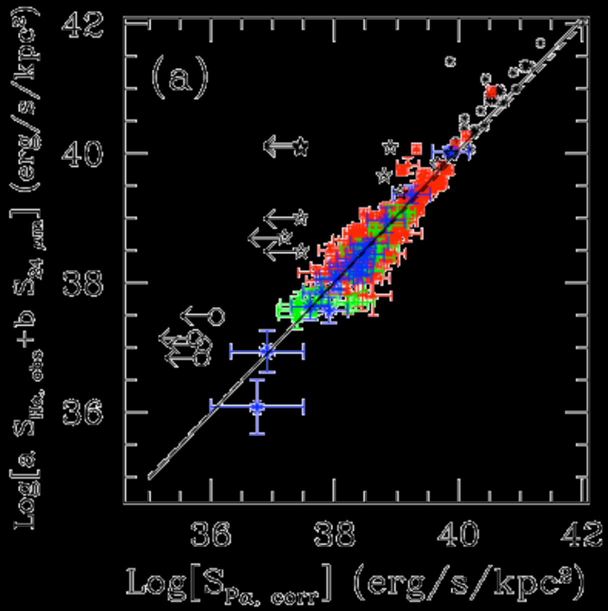
- Derive physical insight into what drives SF (e.g. by comparing empirical relations to predictions from theory)
- SPH modeling of galaxy formation
- Predictive power: measure the gas (surface) density and estimate the SFR (surface) density

Previous studies include e.g.

- Schmidt (1959): N≈2 (Milky Way)
- Kennicutt (1989,1998): N≈1.4 (sample of ~90 nearby galaxies)
- Wong & Blitz (2002): N=1.2-2.1 (6 nearby spiral galaxies)
- Boissier et al. (2003), Heyer et al. (2004): N≈2 (16 galaxies) and N≈3.3 (M33)

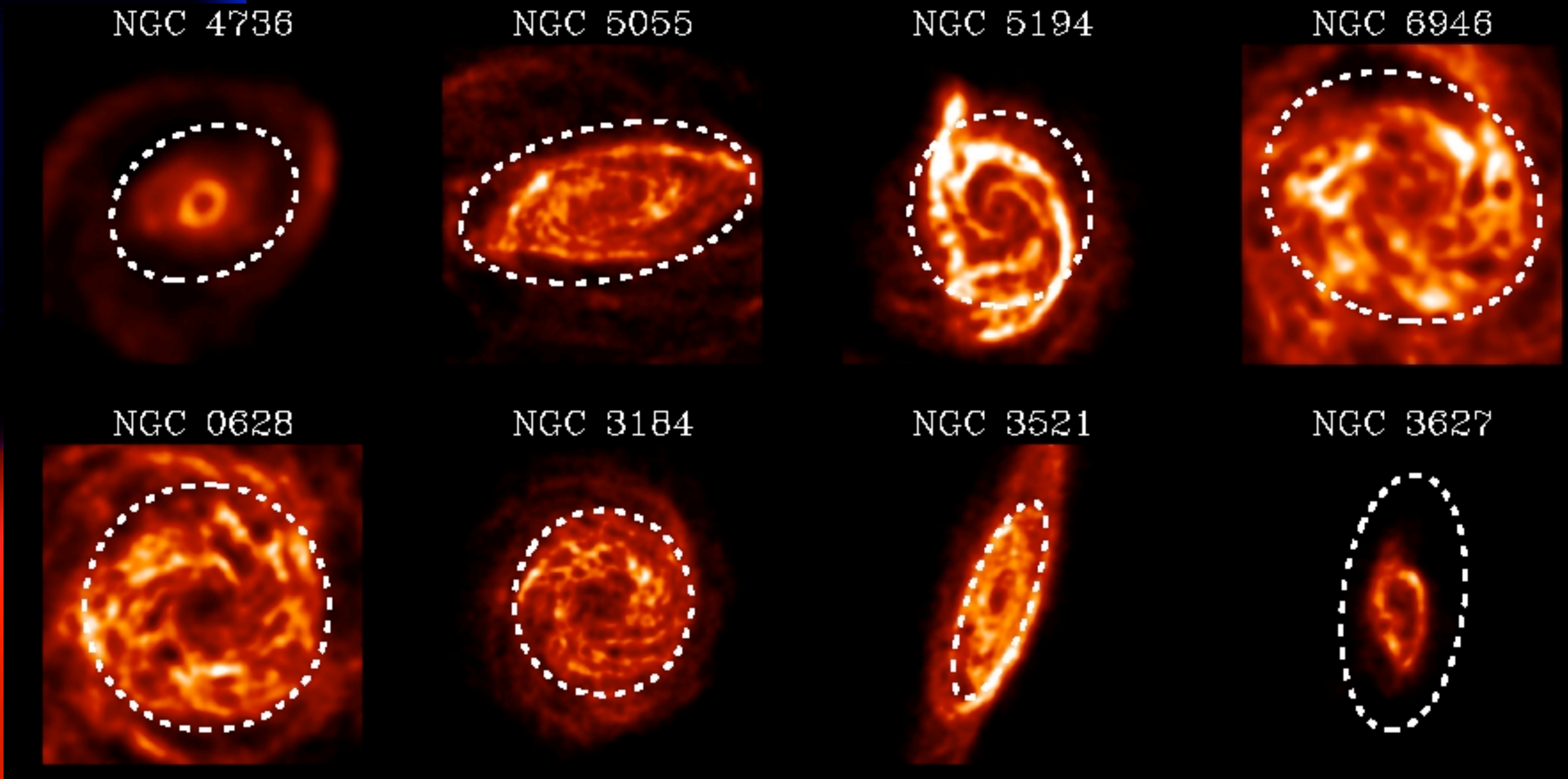
Calibrating SFRs

- Combined FUV and 24 μm maps:
  - A particular version of energy balance UV+IR.
  - Based on Hα + 24 μm calibration (Calzetti + 2007).
  - Pixel-by-pixel approach at 750 pc.



Calzetti et al. (2007) calibrated $H\alpha$ + 24 μm against $P\alpha$ in apertures.

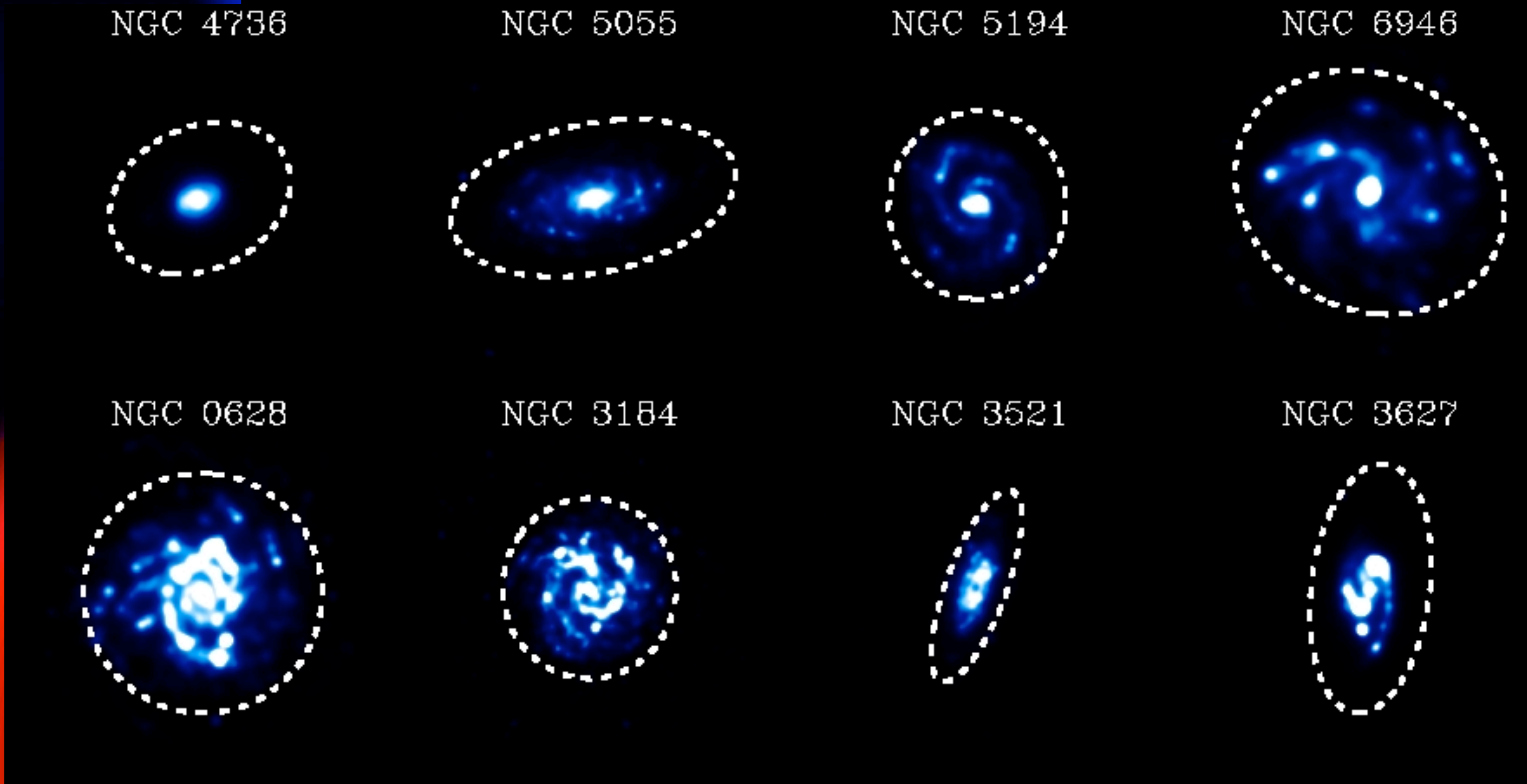
HI Maps



Heidelberg
March 2009

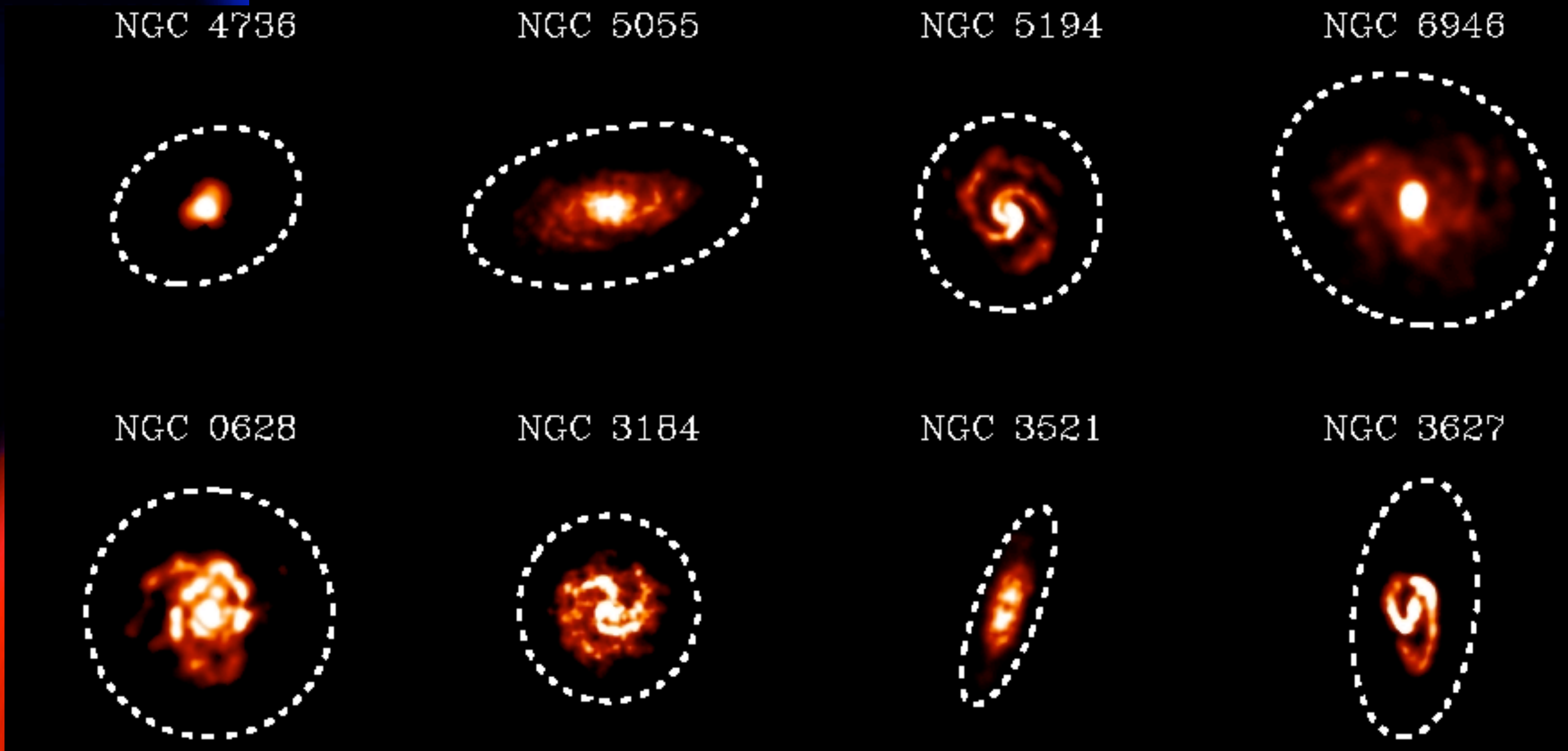
Eric Bell

SFR Maps

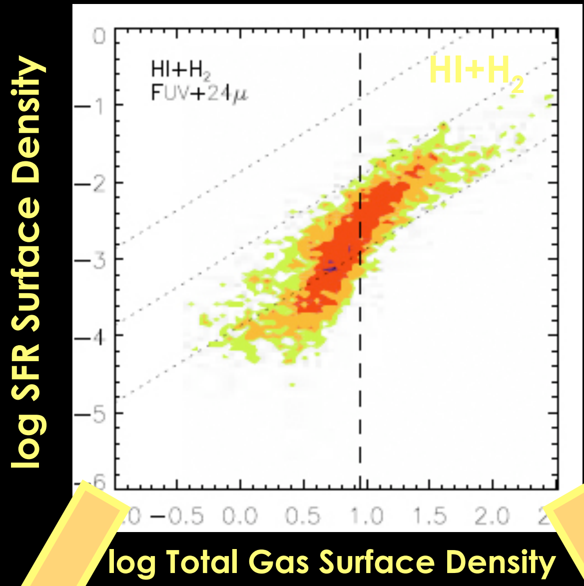


NGC 4736
NGC 5055
NGC 5194
NGC 6946
NGC 0628
NGC 3184
NGC 3521
NGC 3627

H_2 Maps


NGC 4736
NGC 5055
NGC 5194
NGC 6946
NGC 0628
NGC 3184
NGC 3521
NGC 3627

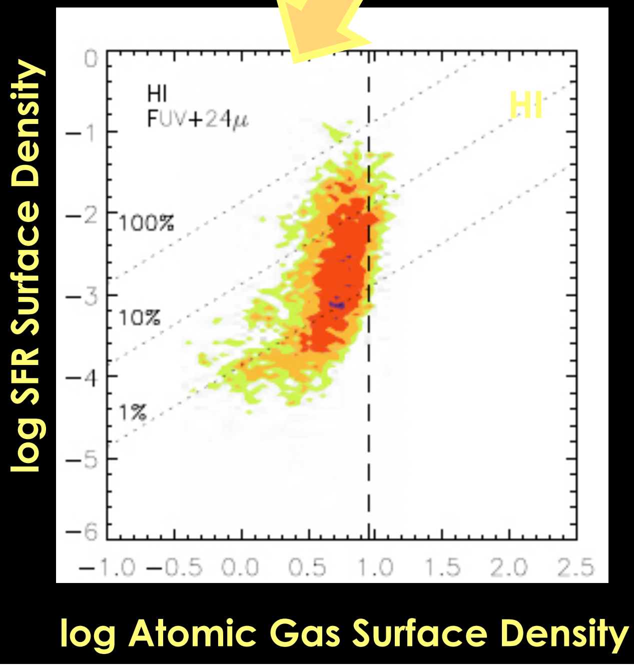
... And In All Spirals Combined

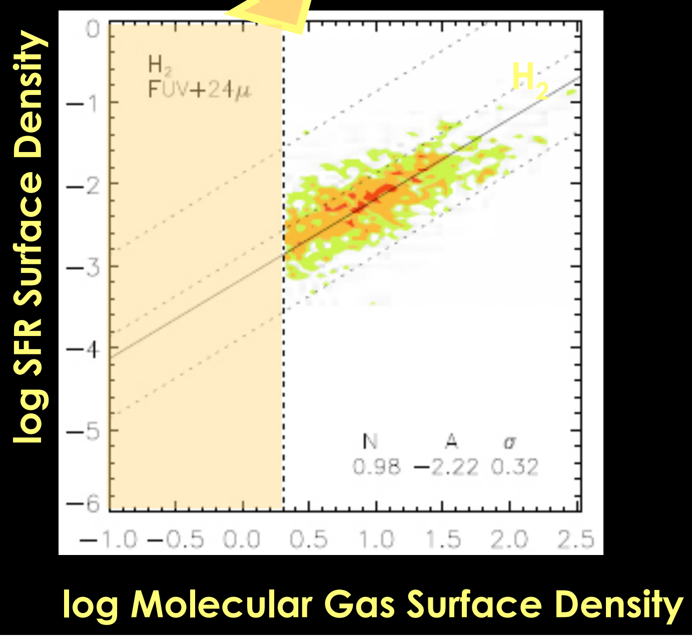


- A saturation of Σ_{HI} is evident at ~ 9 $M_{\odot}$ pc^{-2}

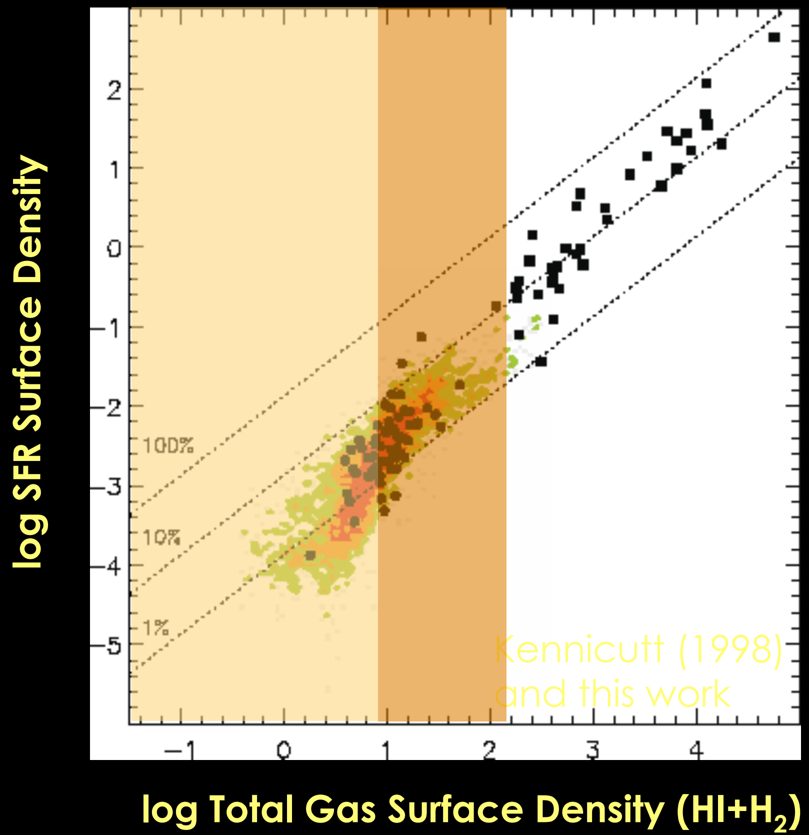
- Σ_{H2} is tightly correlated with Σ_{SFR} (N_{H2} = 1.0 ± 0.2)

- Data are compatible with a **molecular gas** Schmidt Law, showing a constant SFE (τ~2*10^9 yrs)





The Kennicutt / Schmidt Law …



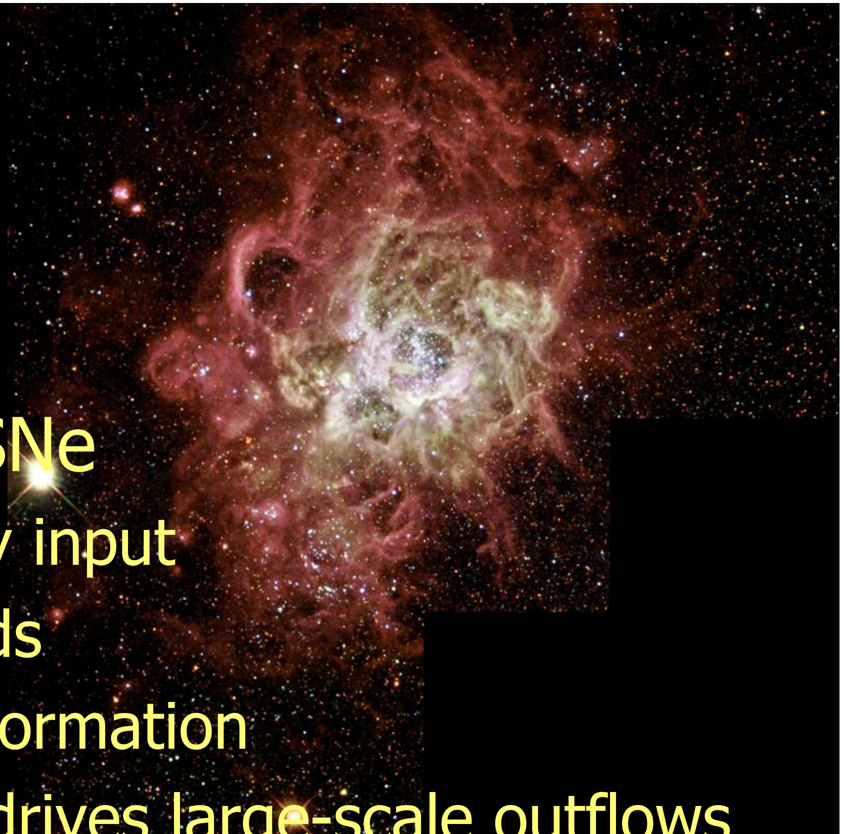
• Resolved data overlaps normal starforming spirals from Kennicutt (1998)

• Obtaining resolved data for high gas columns and SFRs is key for complete assessment of SF law

Star formation

- What does it look like on ~kpc scales? -->things
- Physical picture --
  - HI collapses to molecular hydrogen, then the H_2 turns into stars with characteristic gas depletion timescales 2Gyr (I.e., M_{H2}/SFR ~ 2Gyr)
  - What sets this HI to H_2 conversion?
- Empirical laws
  - SFR $\propto$ gas density $^{1.4}$ (Kennicutt 1998)
  - Threshold of ~10 solar masses per sq. pc. (Kennicutt 1989)
  - SFR $\propto$ gas density / t_{dyn} (Kennicutt 1998)
  - SFR/M_{gas} $\propto$ $M_*^{0.5}$ (Bell, won't publish)

Feedback



- Stellar winds and SNe
  - Comparable energy input
  - Disrupts birth clouds
  - Triggers new star formation
  - Intense cases --> drives large-scale outflows

Feedback (or, why doesn't star formation just use up all the gas straight away?)

- Energy / material / metals from stellar winds and supernovae
- Limits star formation efficiency at ~10% per dynamical time

- Key papers : Dekel & Silk 1986, Mac Low & Ferrara 1999

From The Astrophysical Journal 513(1):142–155.

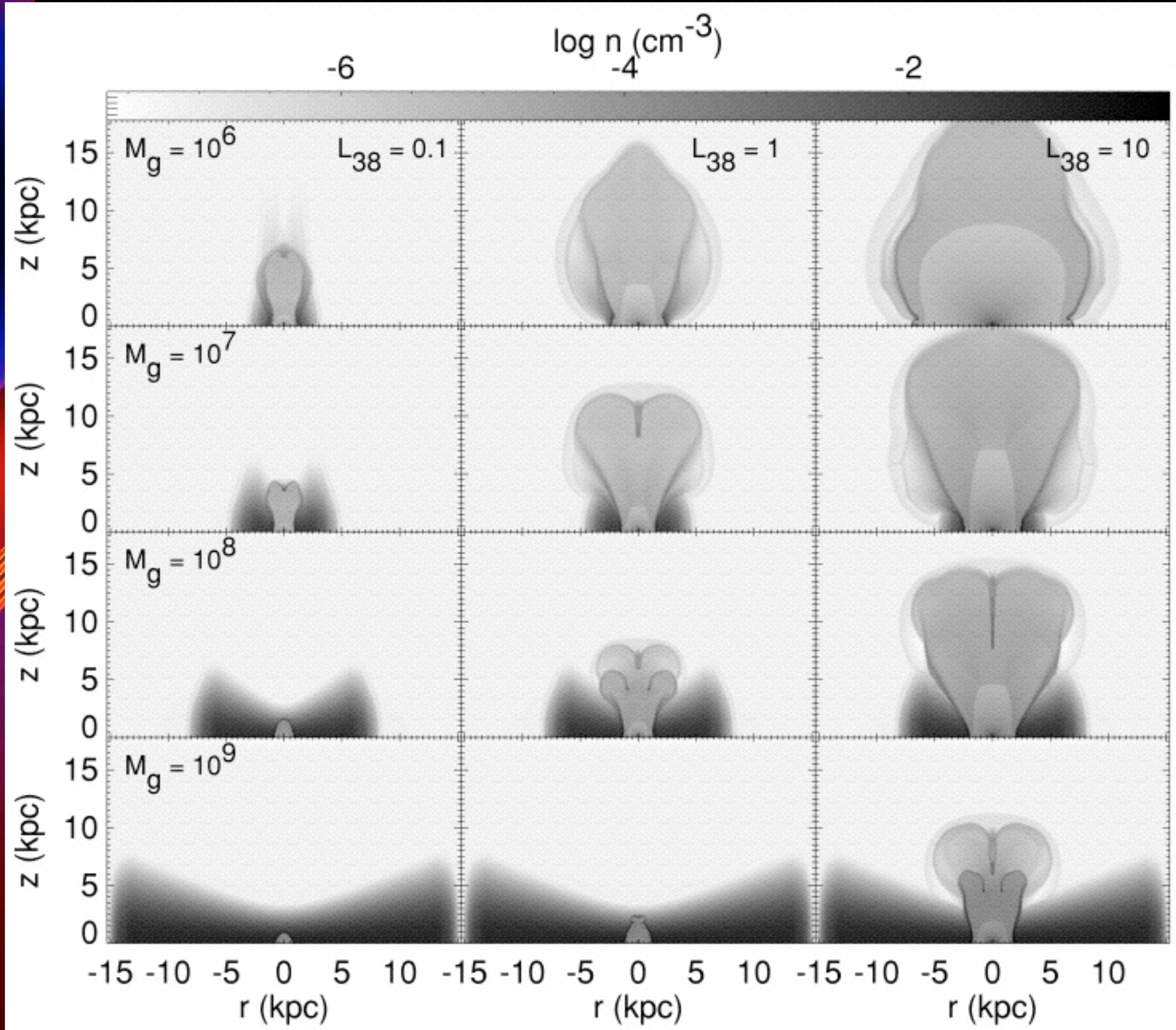
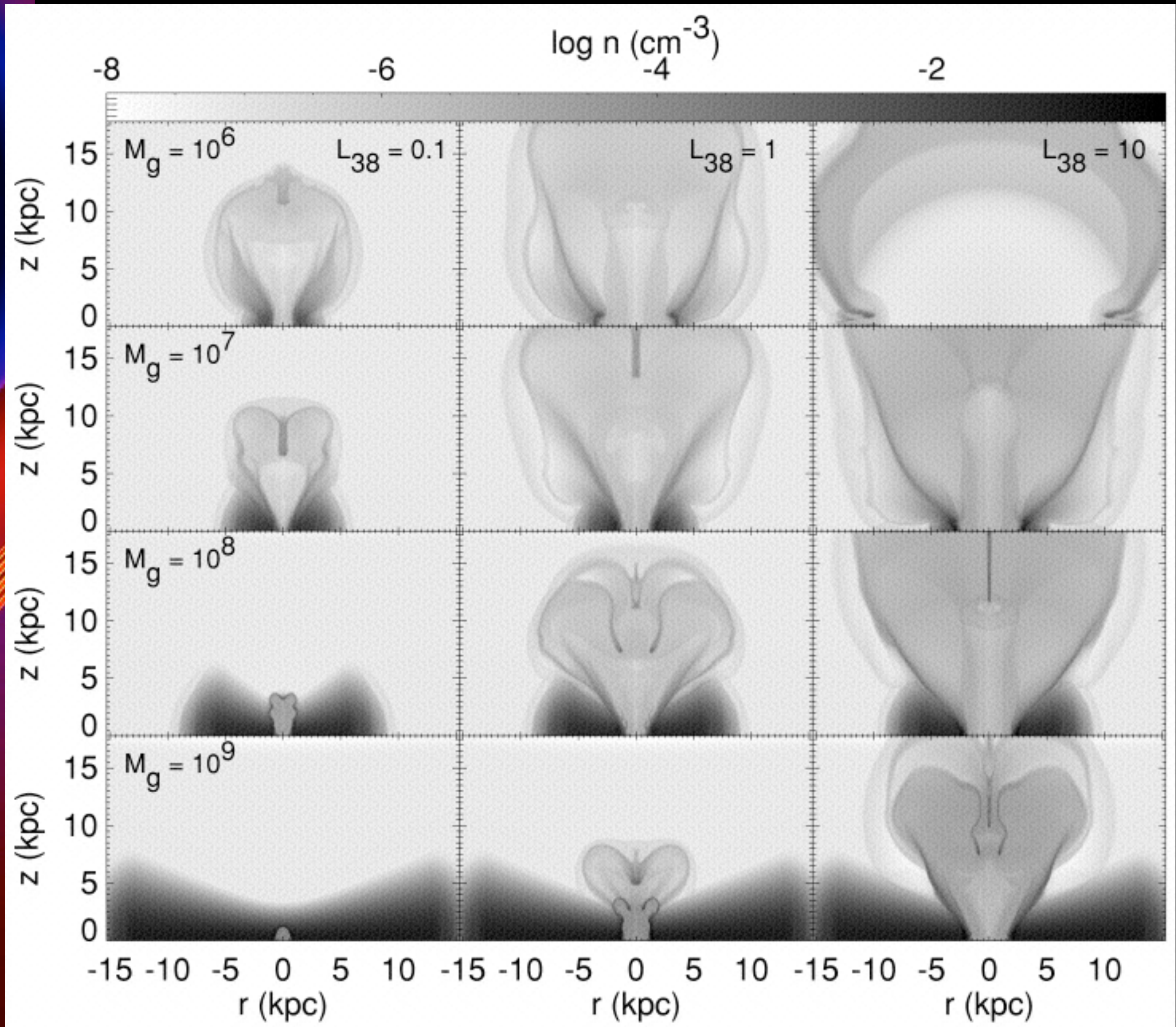


Fig. 2.— Density distributions for models with the given initial visible masses M_{g} and mechanical luminosities L38 in limits of 1038 ergs s−1 at times (a) 50 Myr, (b) 75 Myr, (c) 100 Myr, and (d) 200 Myr, with the values of the density given at the top of each figure. Note that energy input ends at 50 Myr.



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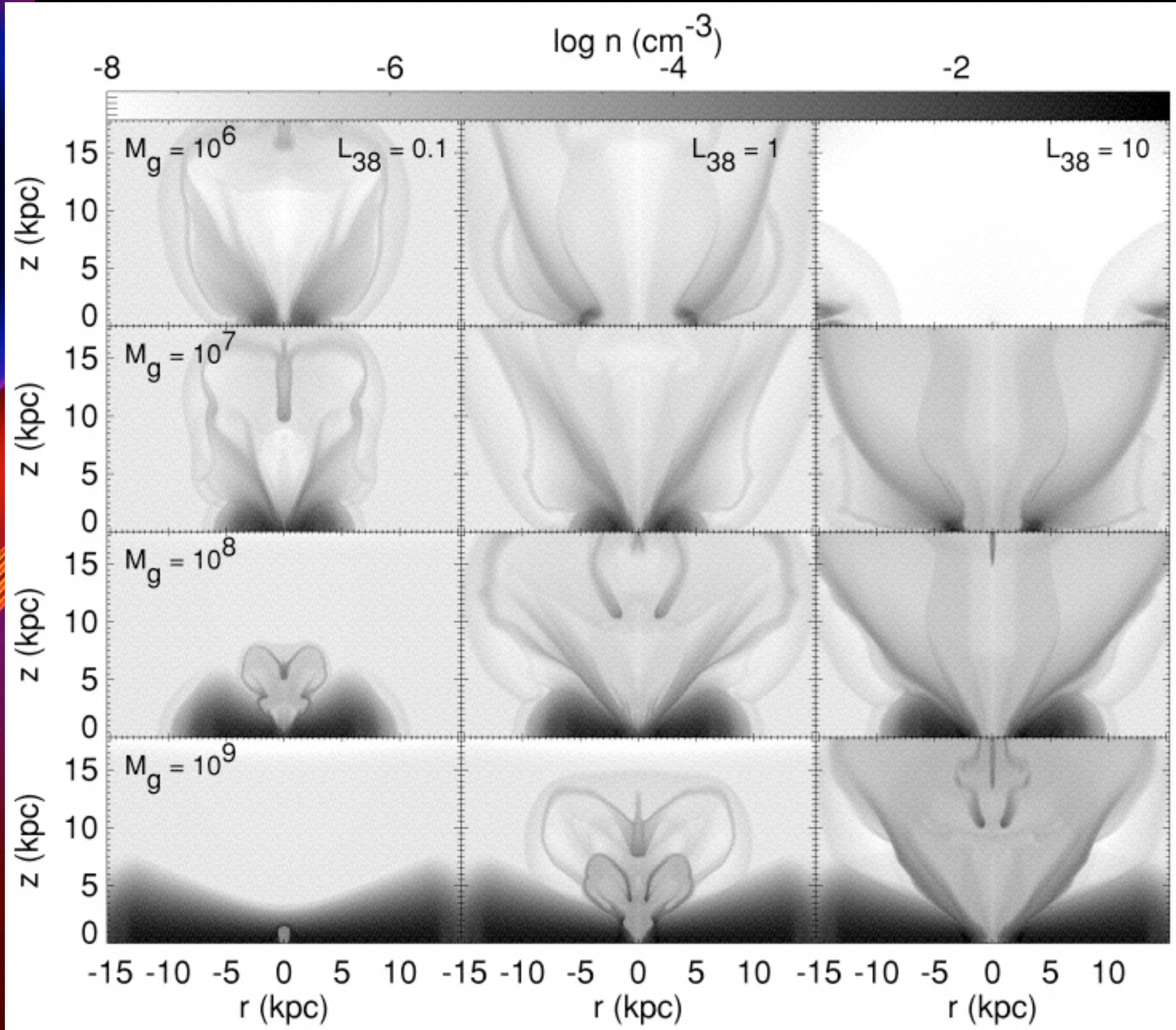

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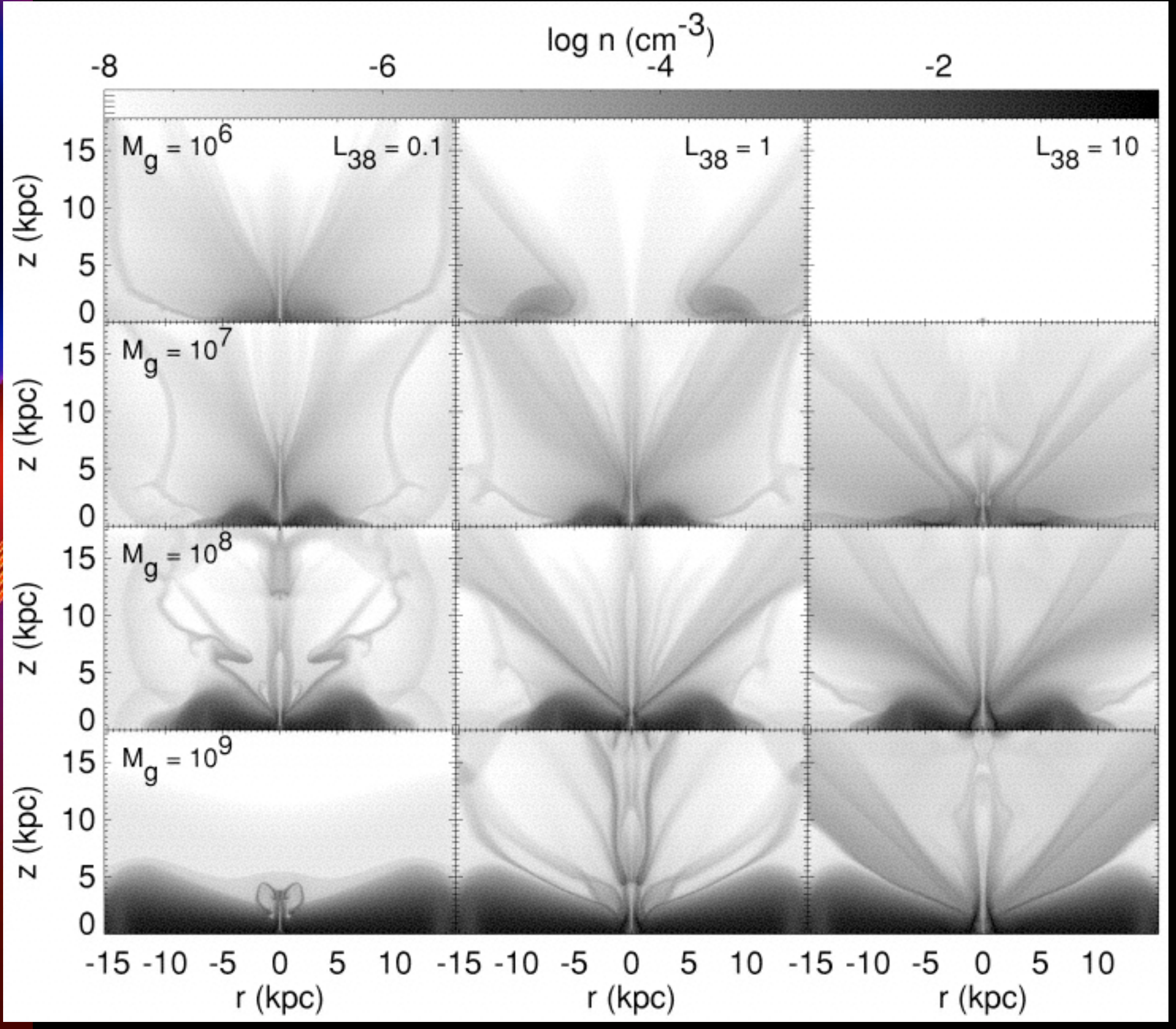

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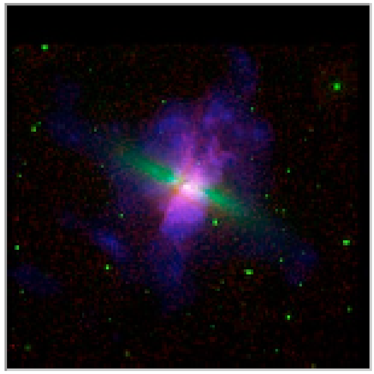
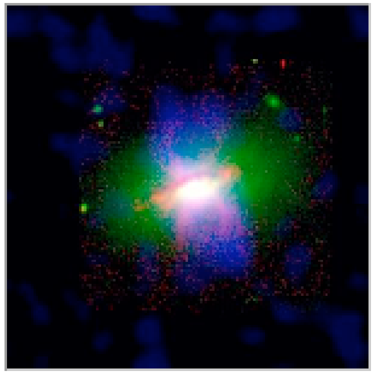
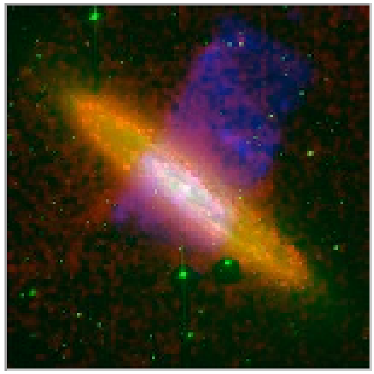


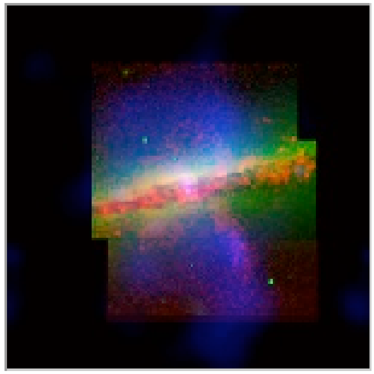
M82 (starburst)



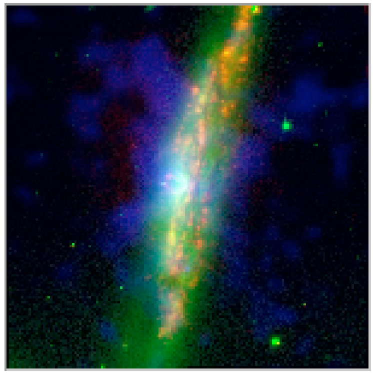
NGC 1482 (starburst)



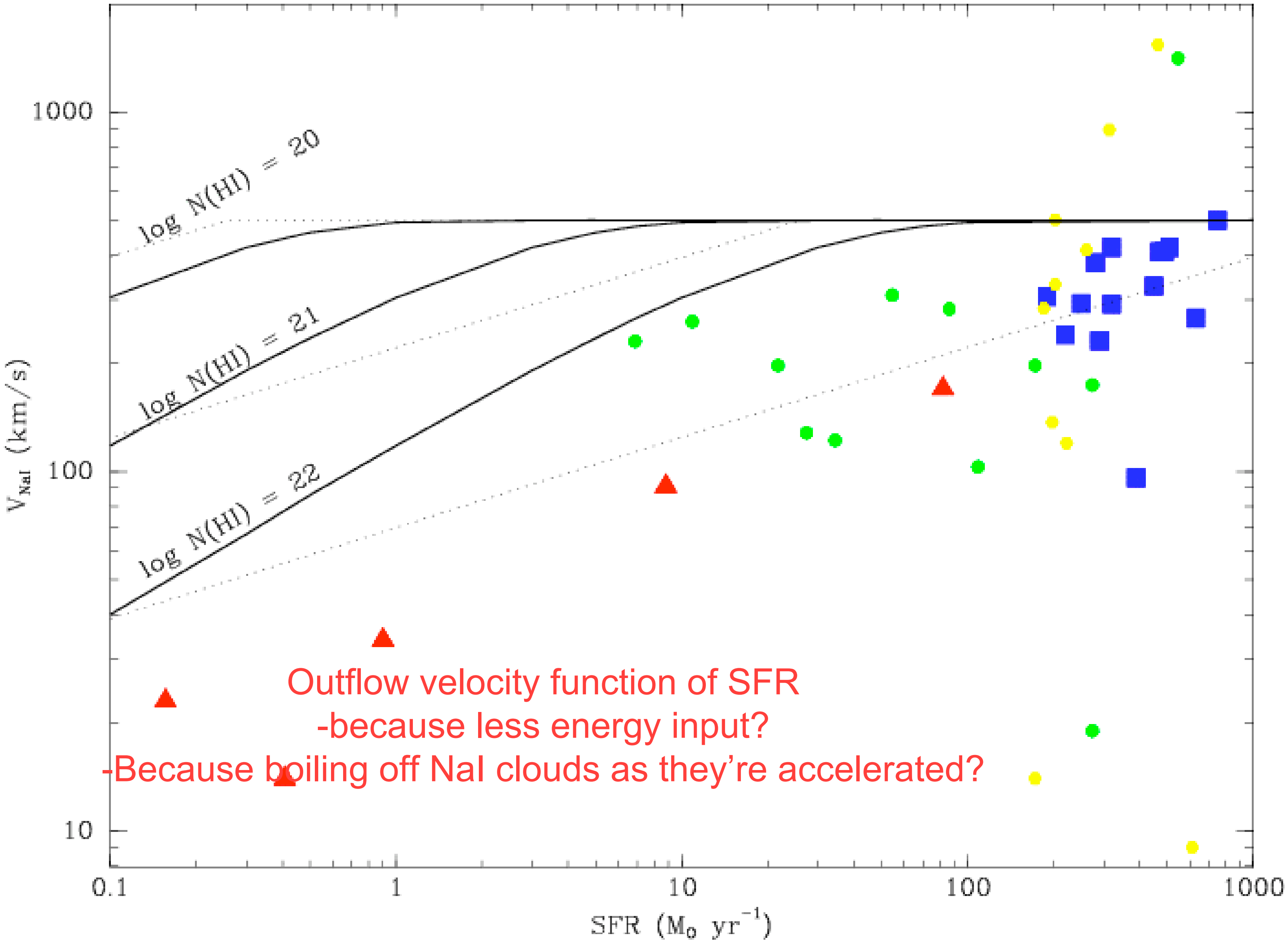
NGC 253 (starburst w/LLAGN)



NGC 3628 (starburst)



NGC 3079 (starburst w/LLAGN)



Outflow velocity function of SFR

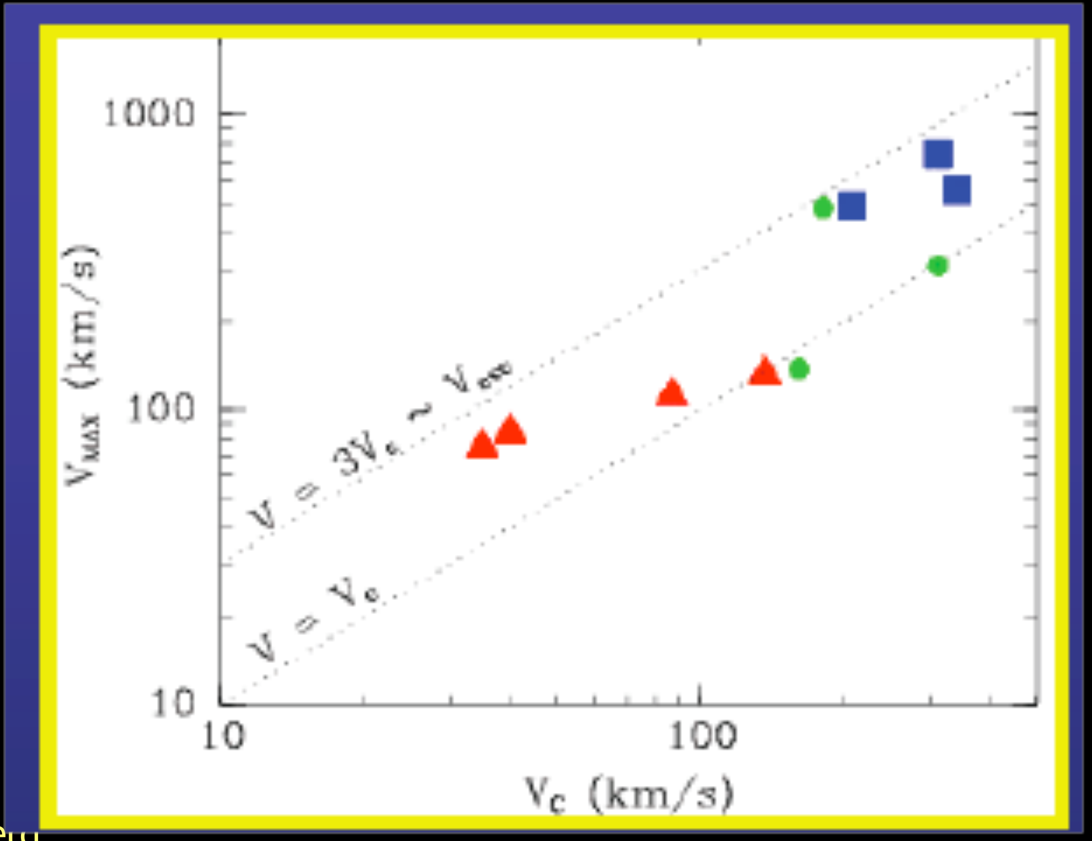
-because less energy input?

-Because boiling off NaI clouds as they're accelerated?

Martin, 2007 Heidelberg conference talk

Do winds escape?

- At least sometimes…

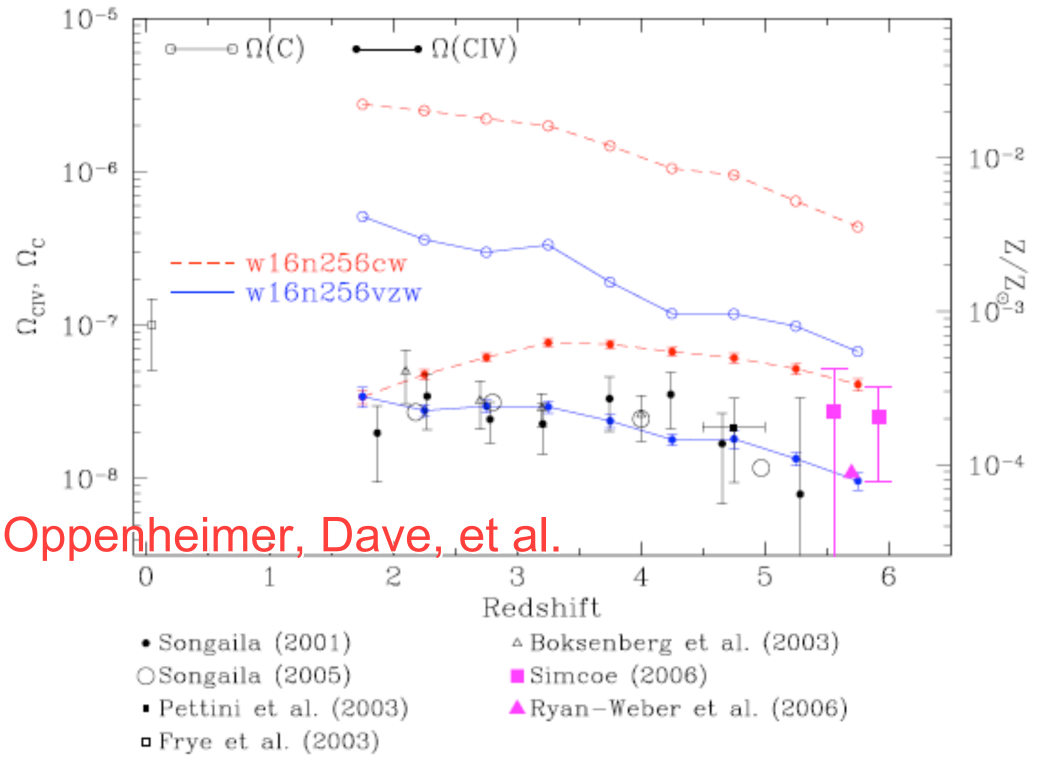


Feedback : discussion

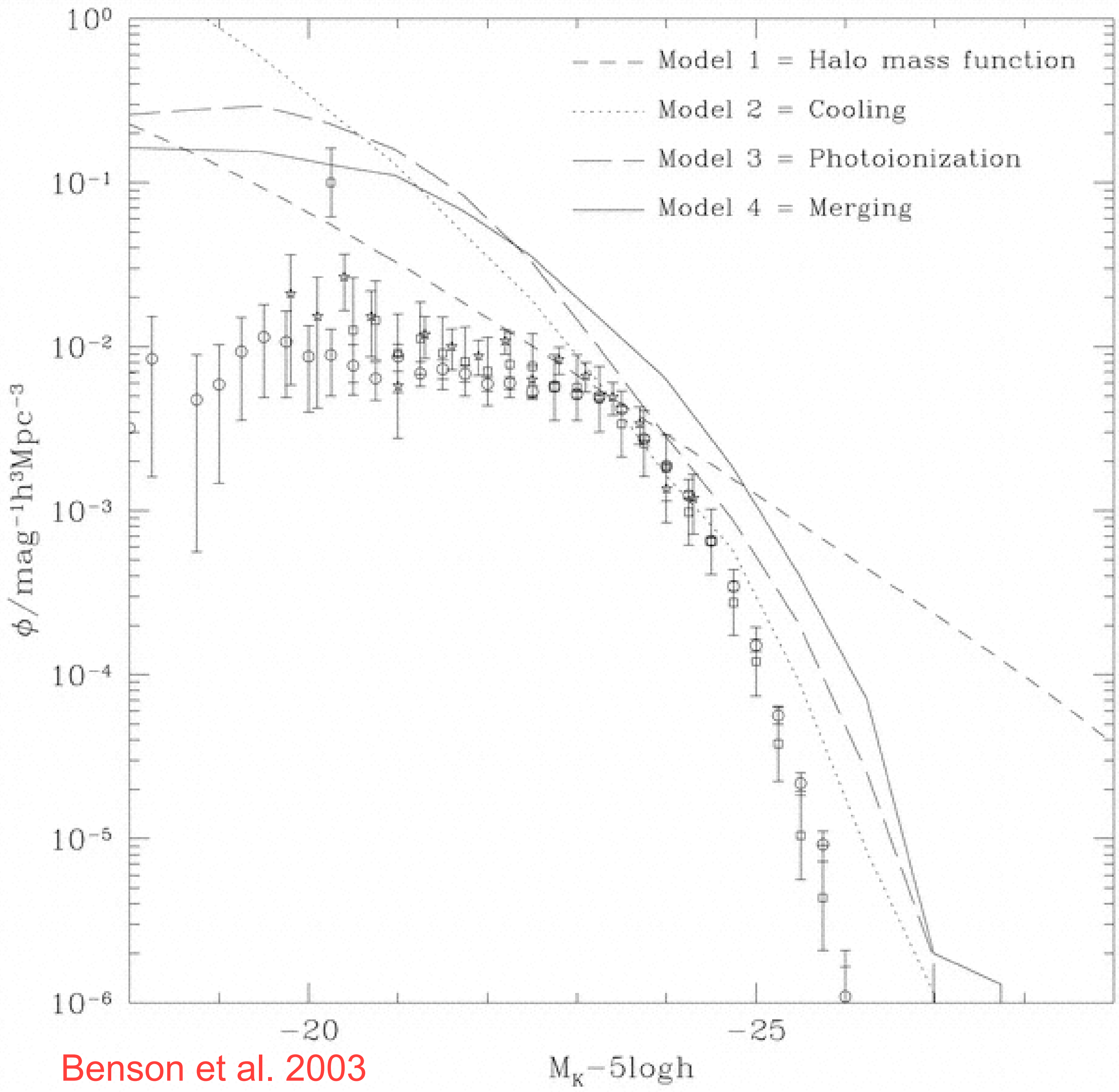
- Important at all masses
  - Regulating SF efficiency
  - Some cycling of the ISM
- For high SF intensities / low masses, looks likely to lead to outflows
  - Issue: *plausible* that they escape, but not clear that they *actually* do escape…
- Scaling (all v. uncertain…)
  - outflow rate ~ SFR
  - energy ~ SN energy
  - Velocities <~ escape velocity

Consequences of feedback

- Redistribution of metals / gas thoughout IGM
- Regulation of star formation rate
- Suppression of low-mass galaxies

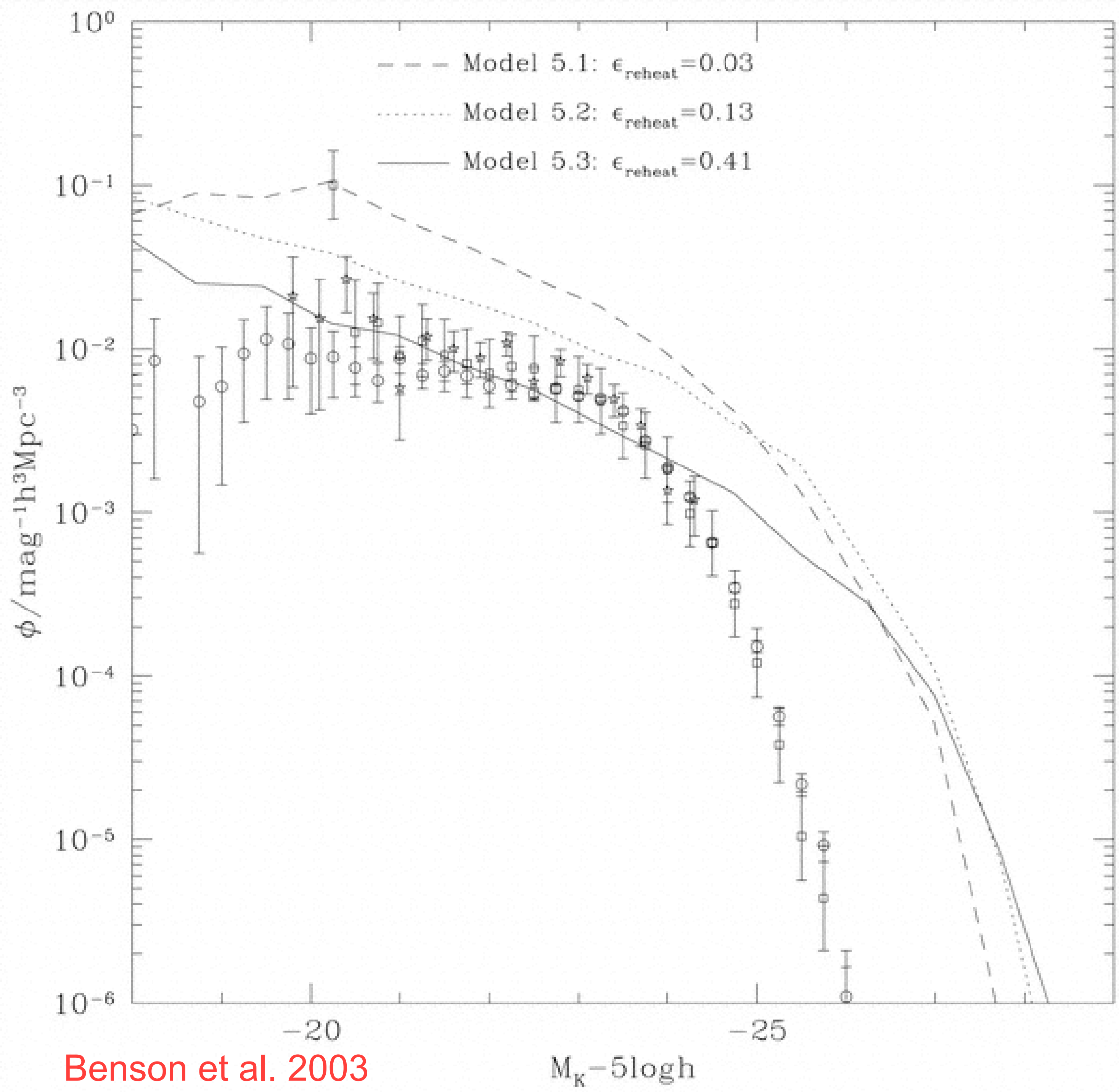


Oppenheimer, Dave, et al.



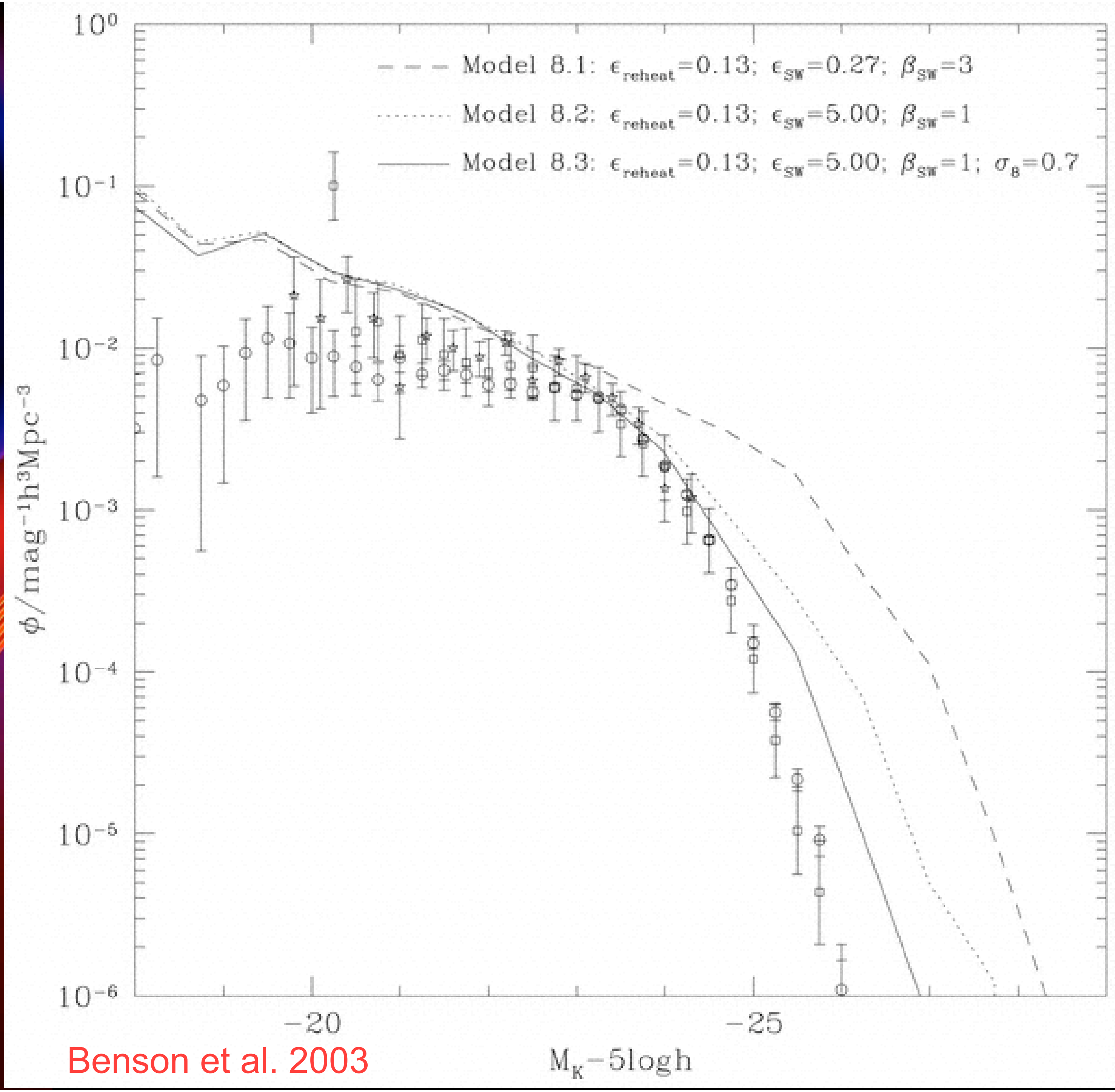
Benson et al. 2003

ic Bell



Benson et al. 2003

ic Bell



Benson et al. 2003

ic Bell

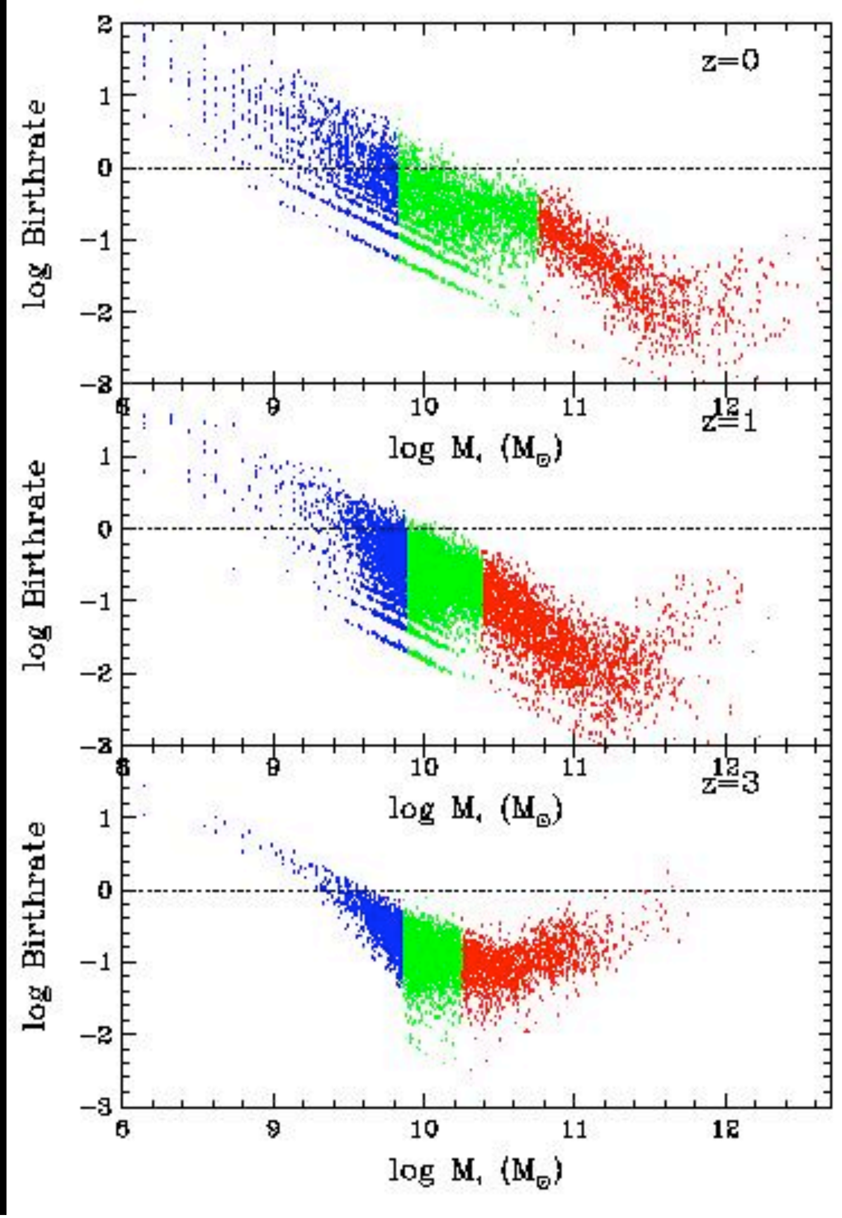
Galaxy Formation on a Postcard

- Dark matter accretion
  - Can collapse pre-recombination
  - Halo mass function $\propto M^{-2}$
  - Halos grow only through merging (mass accretion ~ scale free)
- Gas accretion / cooling from cosmic web
  - Gas cooling rate $\propto n^2$
  - Depends on metallicity
  - Hot mode (virial temp) / cold mode
  - Not tiny halos with $T_{vir} < T_{igm}$
- Star formation
  - SFR $\propto$ H_2 mass (Biegel, Leroy et al.)
  - Empirical star formation laws
    - SFR $\propto$ gas density $^{1.4}$ (Kennicutt 1998)
    - SFR $\propto$ gas density / t_{dyn} (Kennicutt 1998)
- Feedback
  - Flows follow line of least resistance
  - Redistributes metals
  - Regulation of SF
  - Suppresses low-mass galaxies
    - $E \sim E_{SN}$; $V \sim < V_{esc}$; $dM/dt \sim$ SFR

Predictions I

- Almost all galaxies have gas cooling --> star formation…
  - Davé et al.

- Natural state of all galaxies is to form stars…



Heidelberg
March 2009

Predictions II

Dynamical assembly history - a probe largely of DM and baryons
= disks, conservation AM
= spheroids, mergers/int

z: 49.5