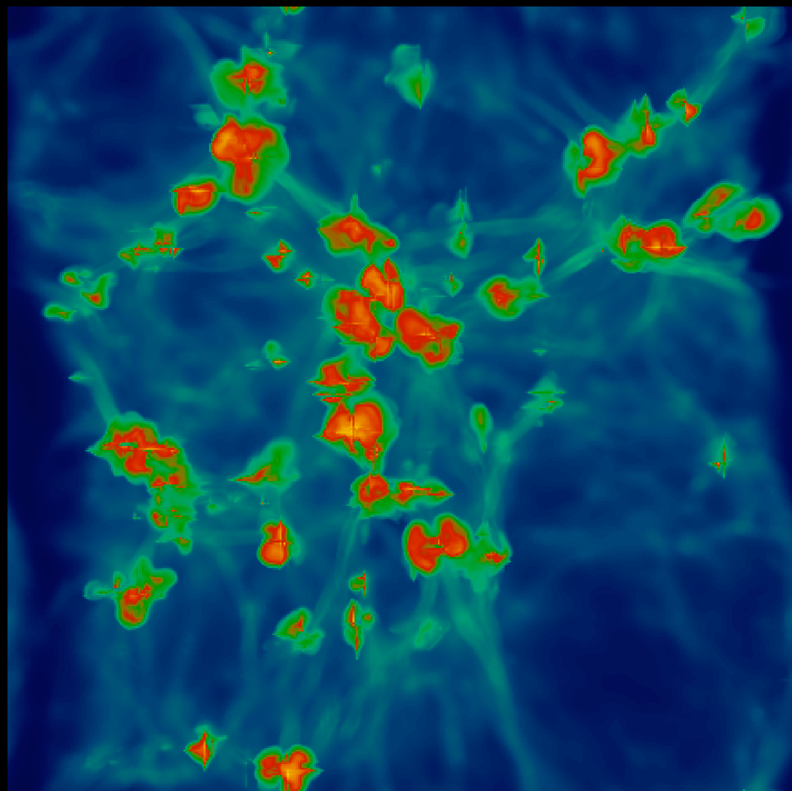
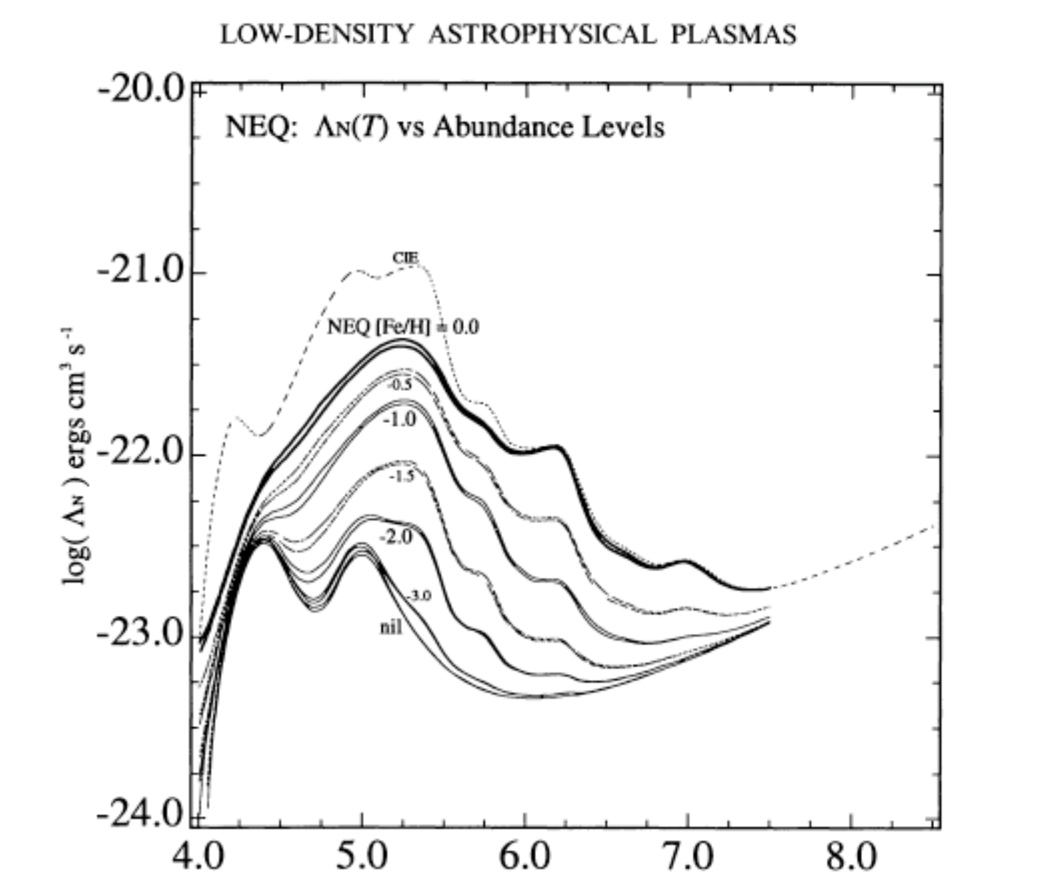

Mechanisms of Galaxy Evolution
Self-inflicted mechanisms:
Gas cooling
Star Formation
Feedback

# Recall…

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



# What happens to the IGM?



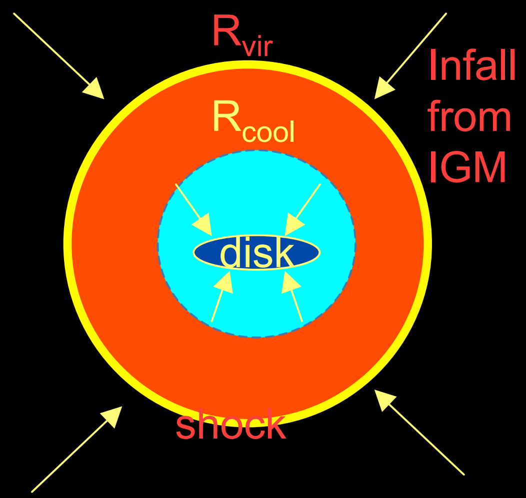

Log T

- 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

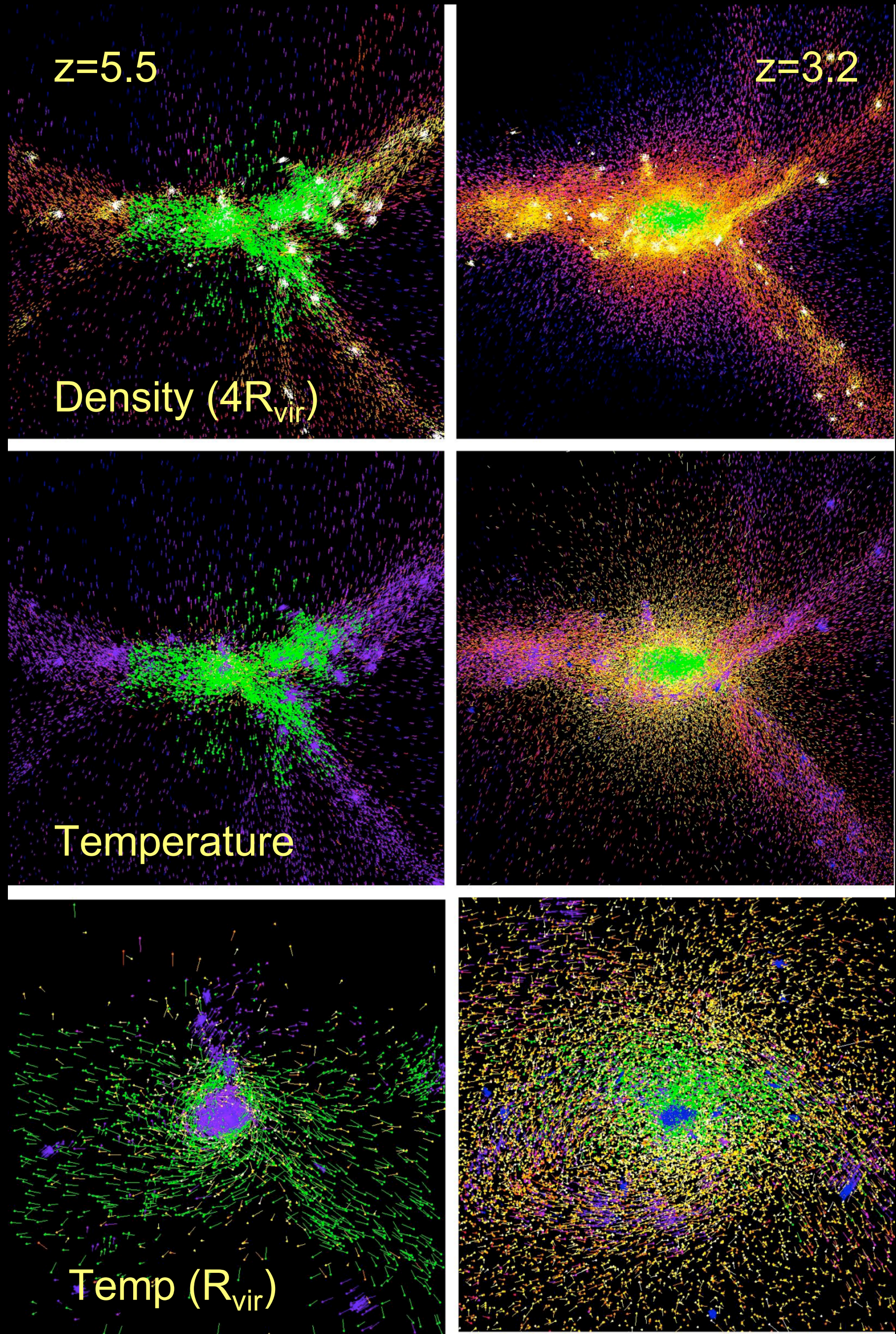
- Modes of Gas Accretion (Keres et al 05):
  - Hot Mode: (White&Rees 78) Gas shock heats at halo's virial radius up to $T_{vir}$, cools slowly onto disk. Limited by $t_{cool}$. Hydrostatic eqm $kT/m \sim v^2$
  - Cold Mode: (Binney 77) Gas radiates its potential energy away in line emission at $T << T_{vir}$, and never approaches virial temperature. Limited by $t_{dyn}$. $kT/m << v^2$

- 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

Heidelberg
March-April 2008

# Star formation

- ----> go to THINGS talk
- 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, in prep)

# 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

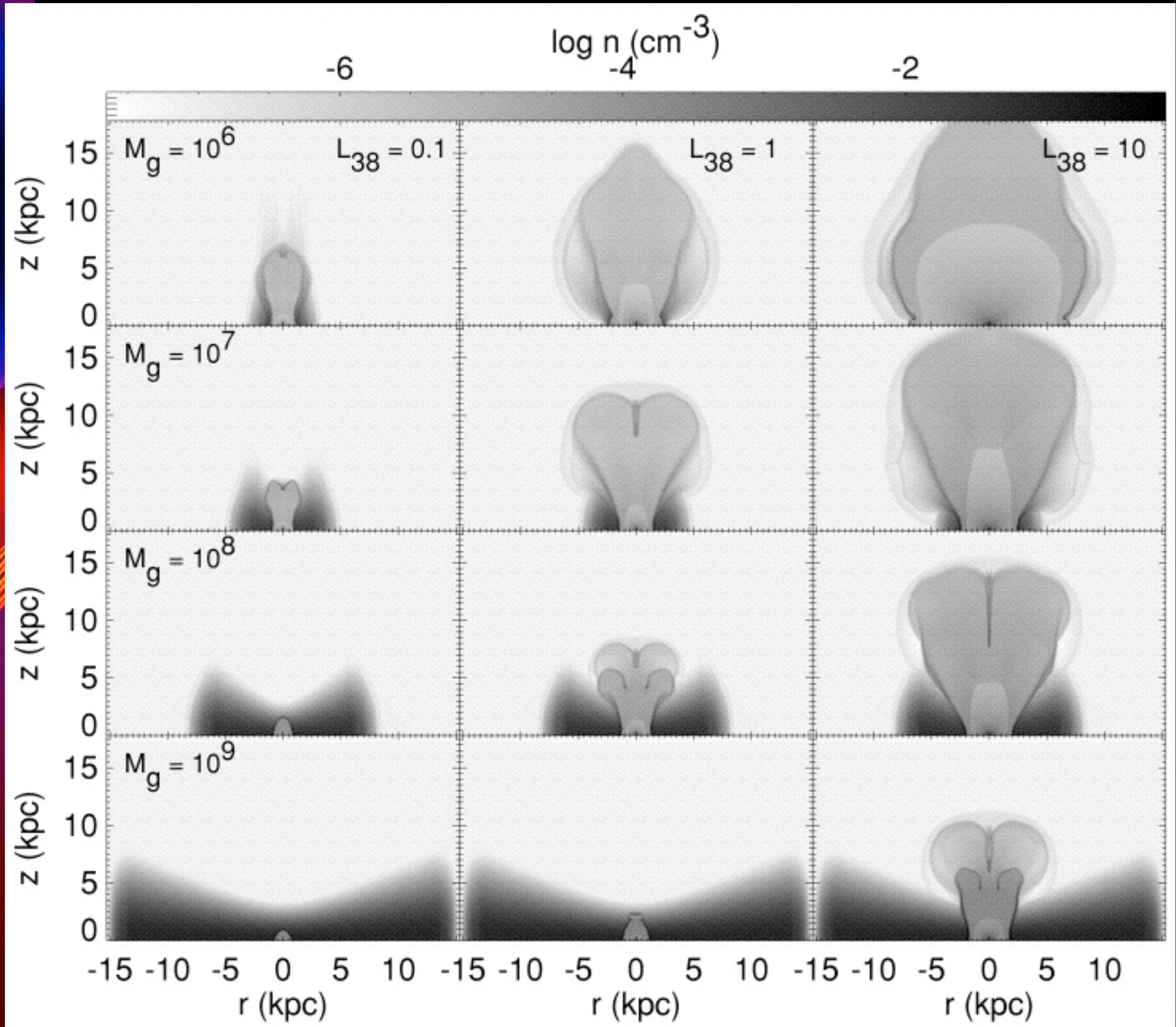
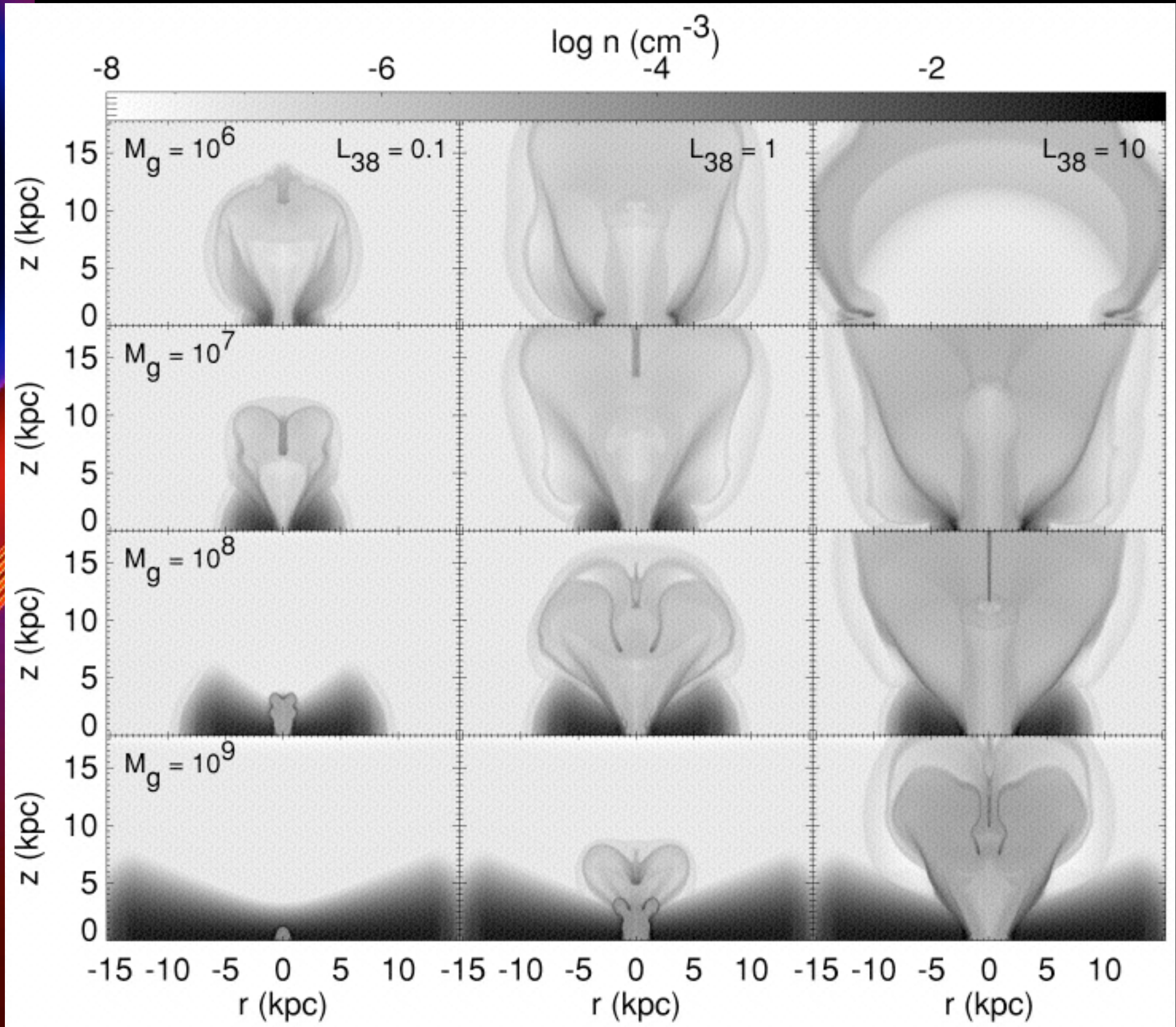



Fig. 2.— Density distributions for models with the given initial visible masses $M_{g}$ and mechanical luminosities L38 in limits of 1038 ergs s−1 at times (a) 50 Myr, (b) 75 Myr, (c) 100 Myr, and (d) 200 Myr, with the values of the density given at the top of each figure. Note that energy input ends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

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

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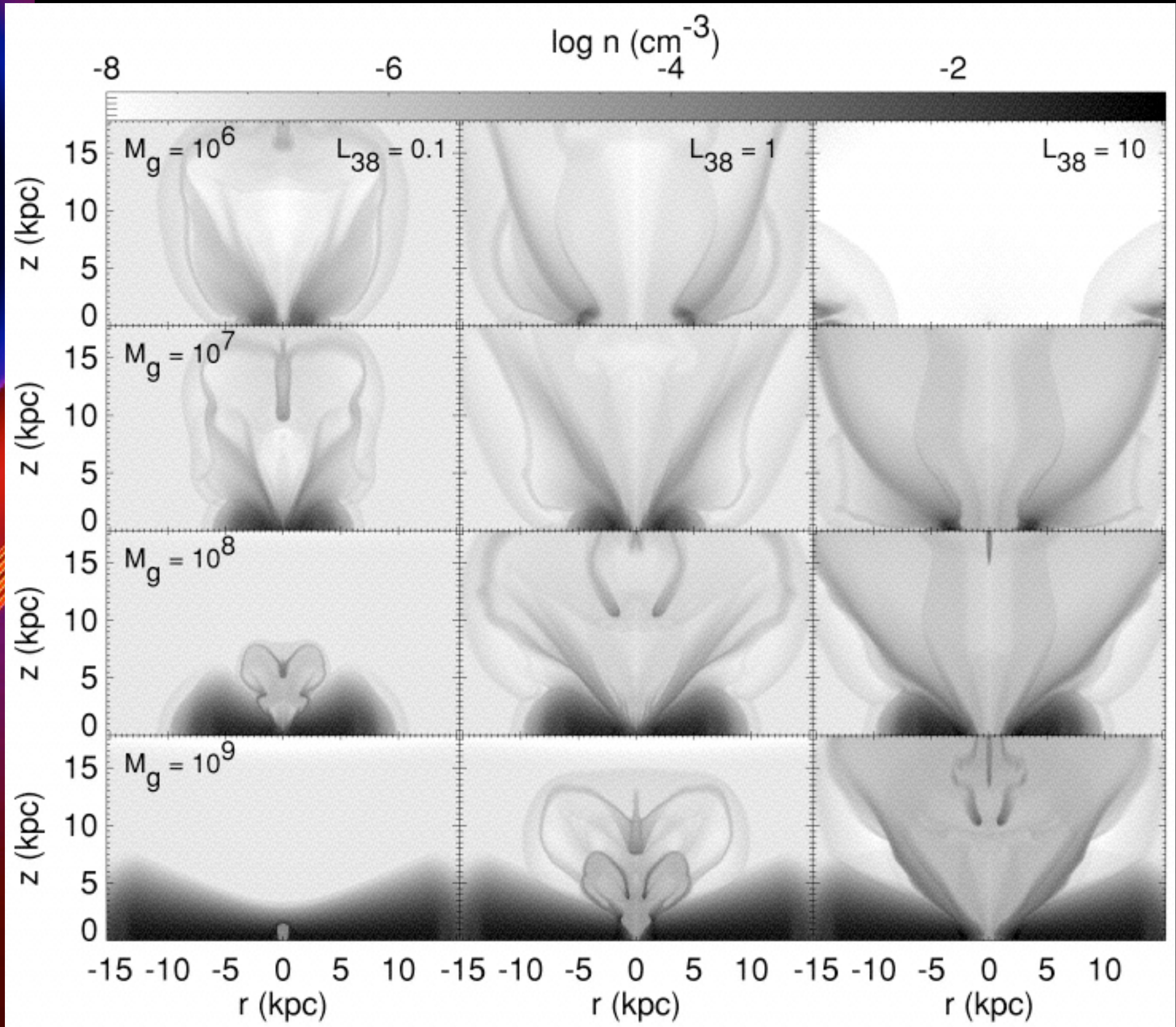
CHICAGO JOURNALS

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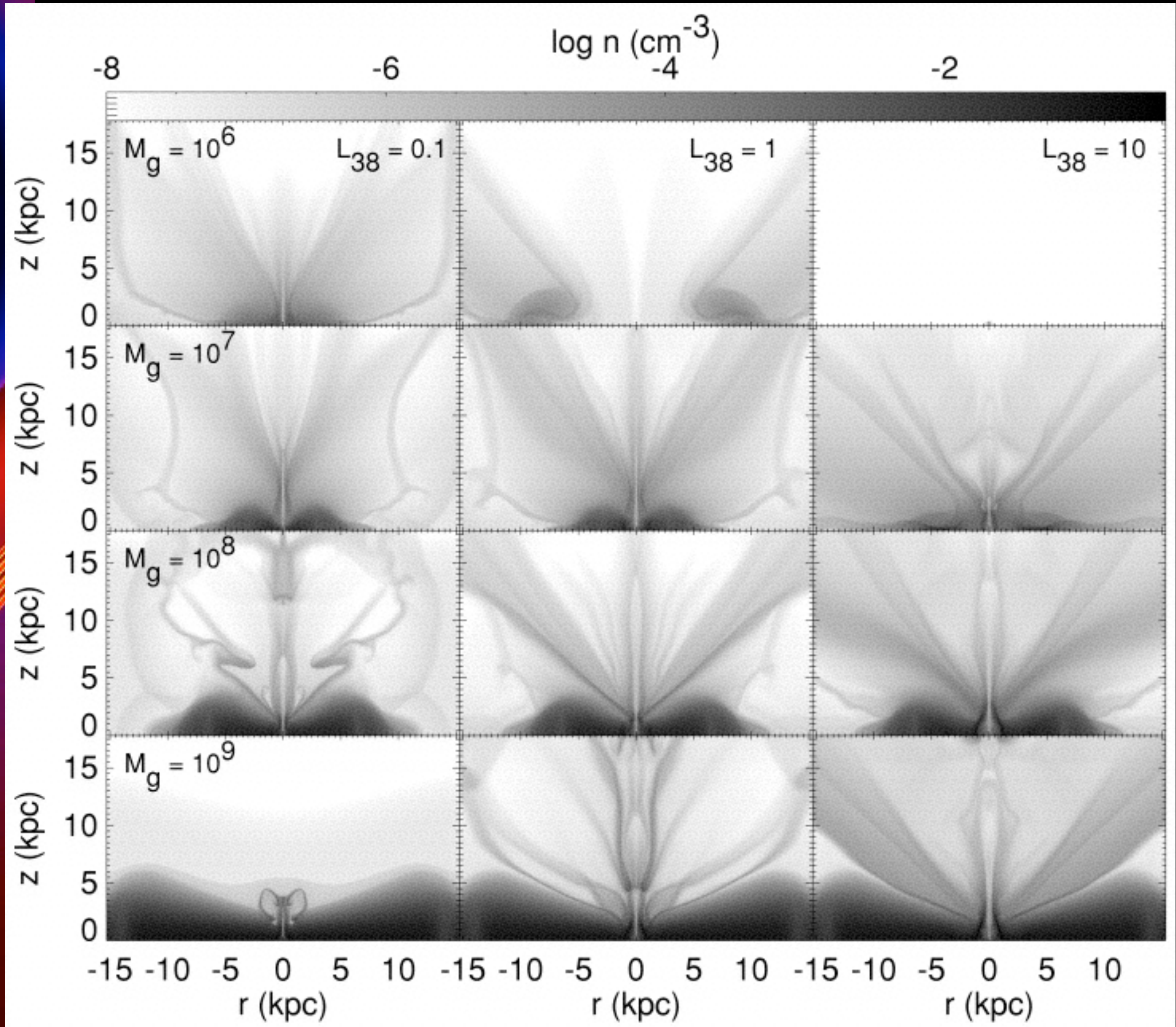


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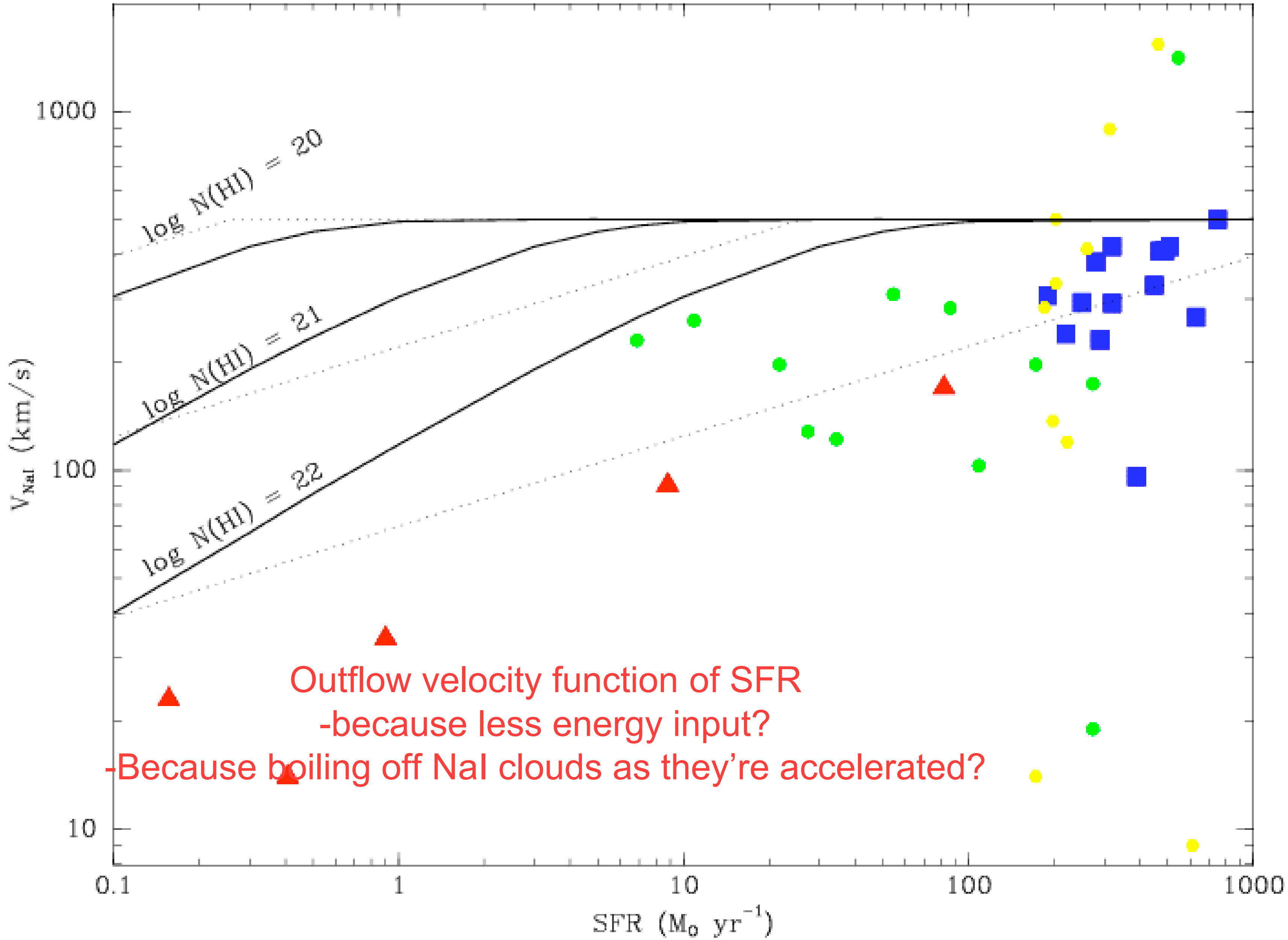



Outflow velocity function of SFR

-because less energy input?

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

Martin, 2007 Heidelberg conference talk

# How Far Do ULIRG Winds Travel?

## Dynamics of Entrained (Cool) Gas

- Radiatively-Driven Wind

  (?) Motivated by $V_w \sim$ few $V_c$; but dwarfs probably not luminous enough

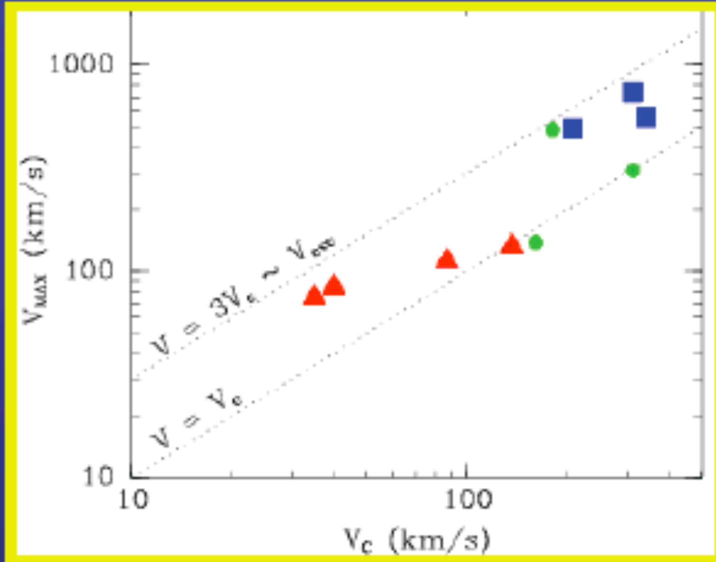
  (-) Low density (smooth) wind + measured UV/FIR requires very low NaI/Na. Measured NaI then implies large dM/dt.

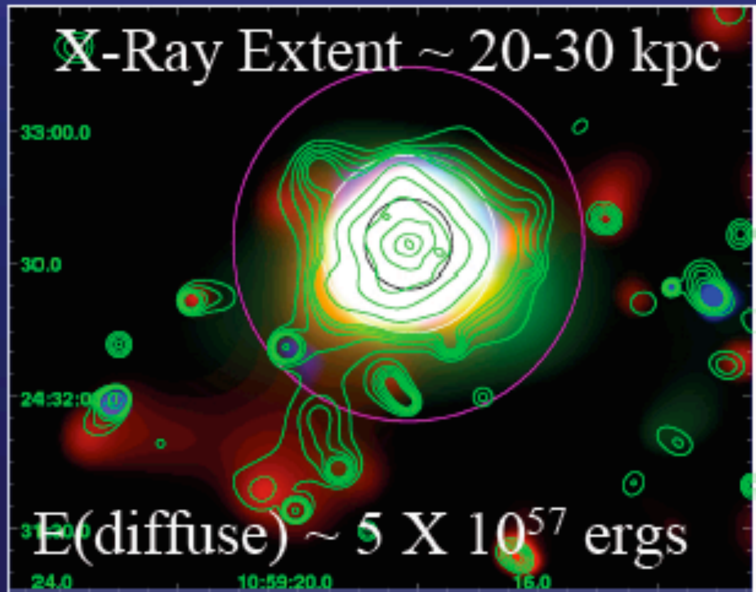
- Ram Pressure-Driven Wind

  (+) See hot phase in x-rays now but hard to prove it's outflowing

  (+) High density (pressure eq. $n_c = T_x n_x / T_c$) wind + measured UV/FIR requires modest ionization correction NaI/Na ~0.1. Measured NaI then imples dM/dt ~ few tenths SFR

  (+) Covering Factors



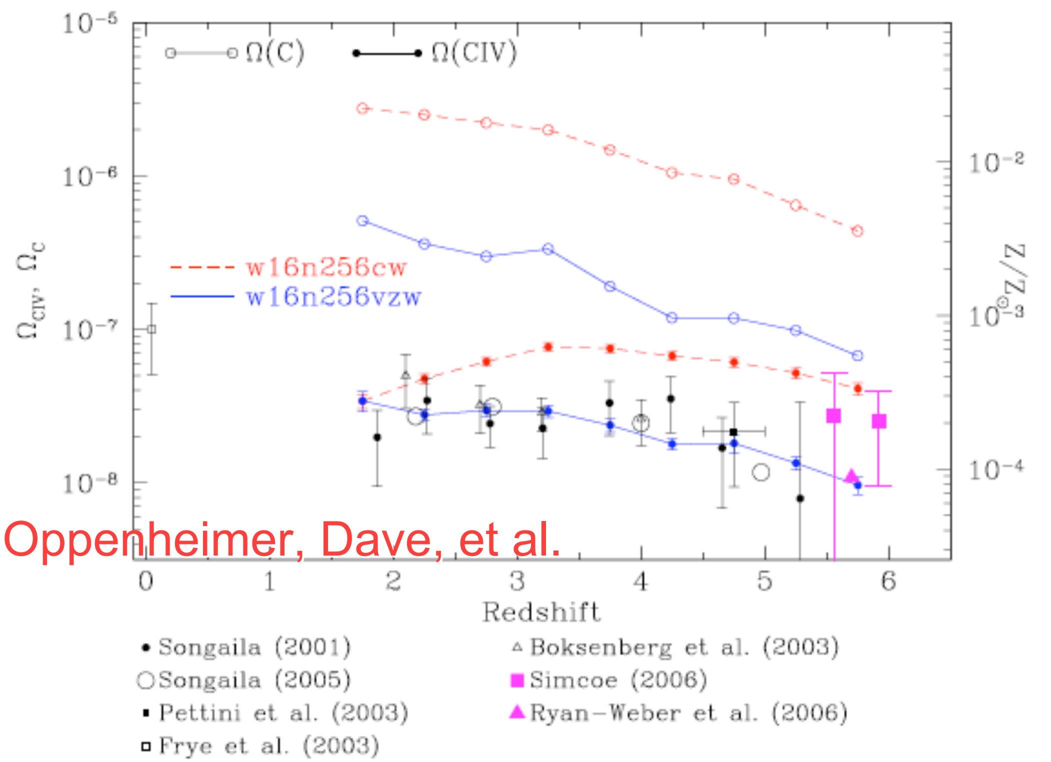



# Feedback : discussion

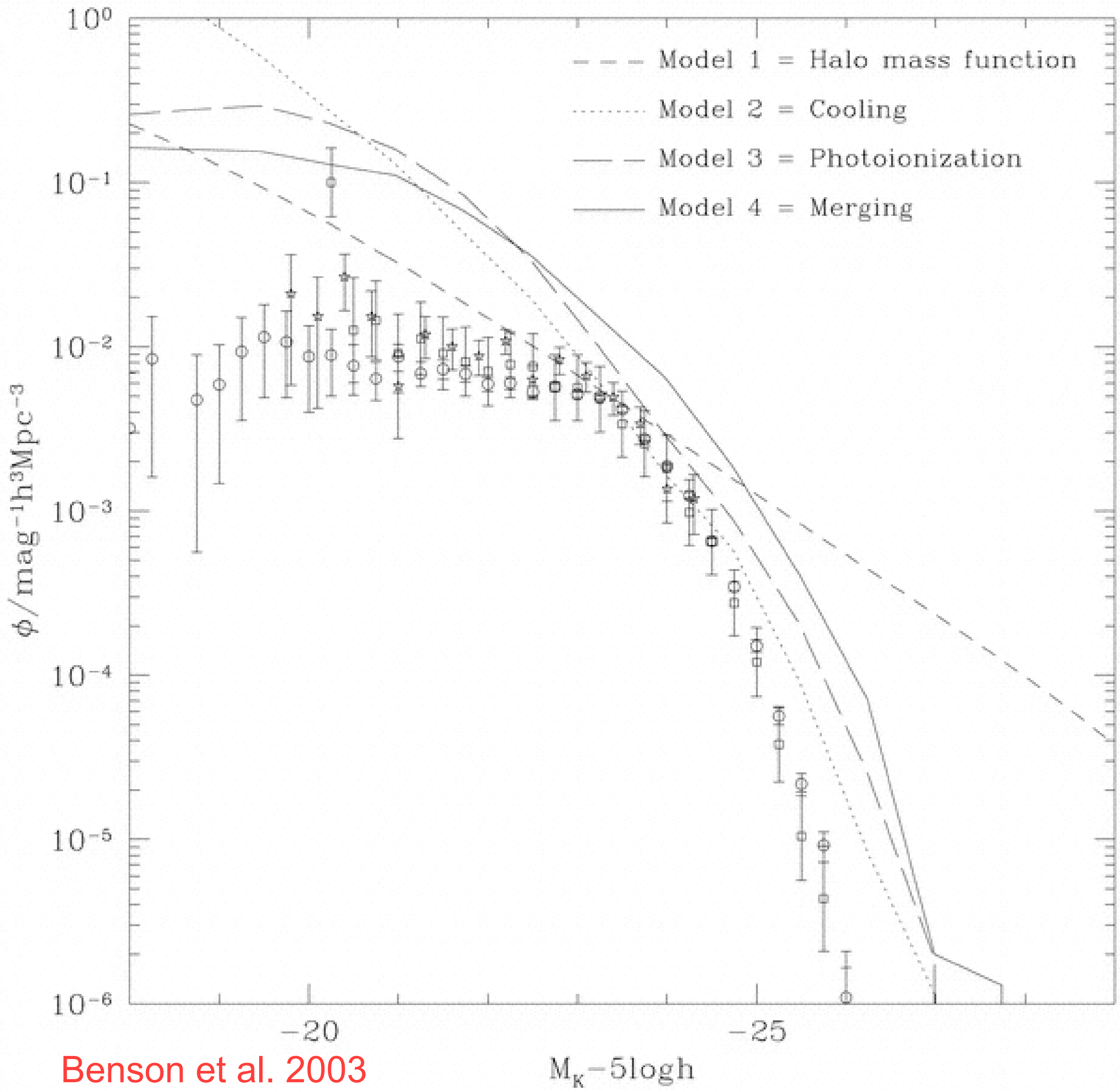
- Important at all masses
  - Regulating SF efficiency
  - Some cycling of the ISM
- For high SF intensities / low masses, looks likely to lead to outflows
  - Issue: *plausible* that they escape, but not clear that they *actually* do escape…
- ULIRGS
  - outflow rate >~ 1/4 SFR
  - energy >~ 1/4 SN energy

# Consequences of feedback

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

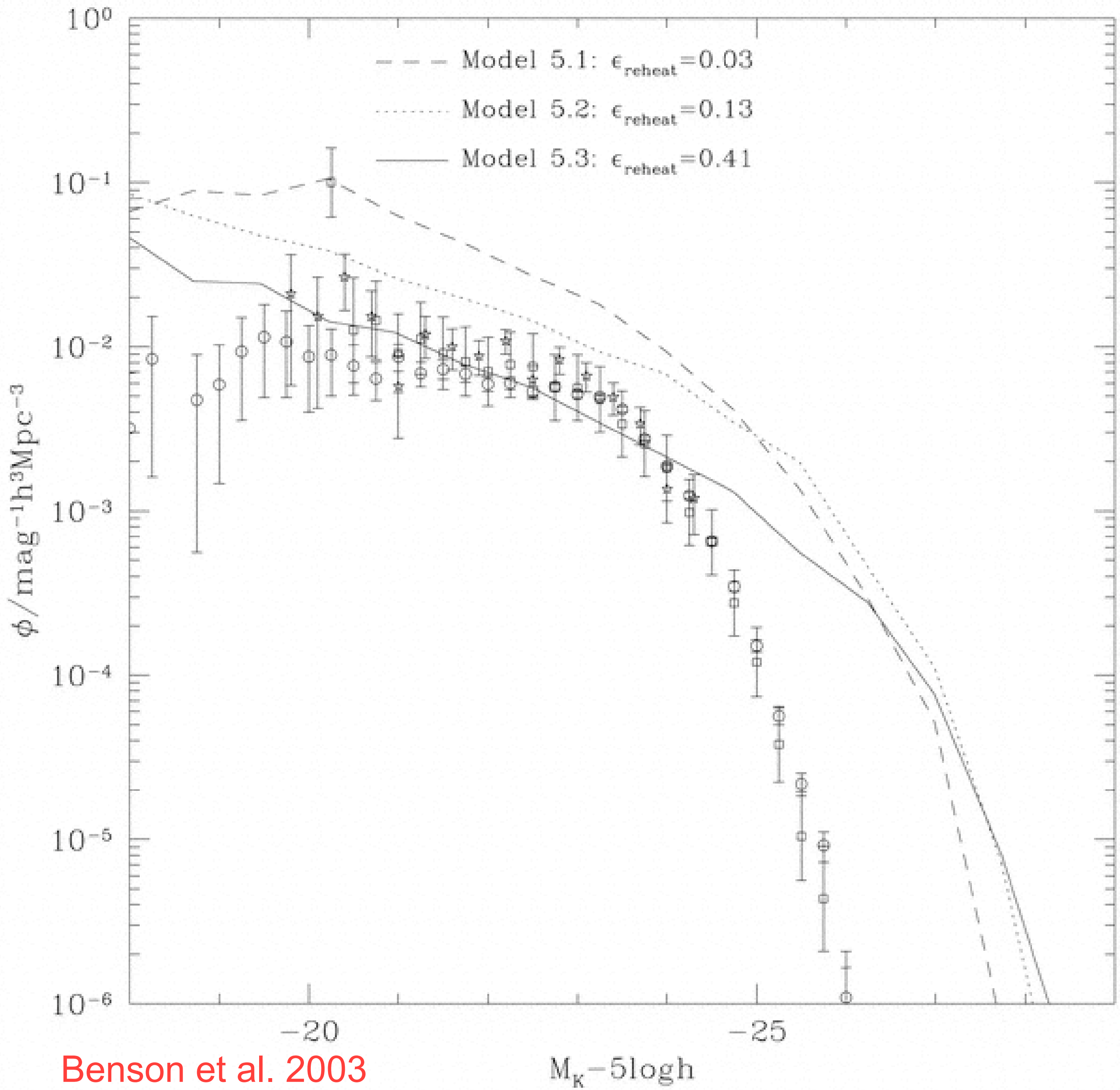



Oppenheimer, Dave, et al.




Benson et al. 2003

ic Bell

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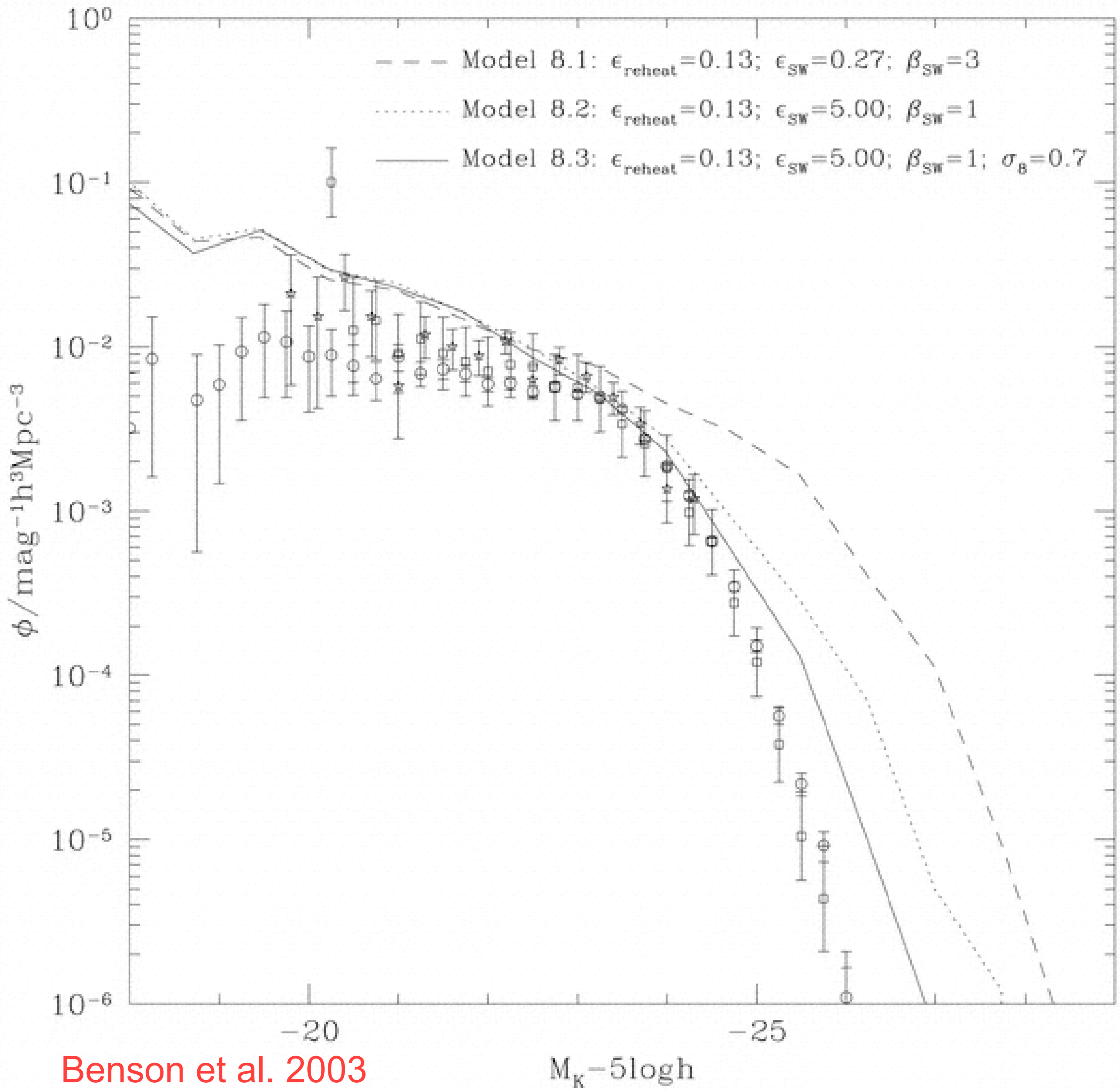



Benson et al. 2003

ic Bell

# Summary I

- Gas accretion / cooling from cosmic web
  - Gas cooling rate $\propto n^2$
  - Depends on metallicity
  - Hot mode (virial temp) / cold mode
- 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


Mechanisms of Galaxy Evolution
Things that happen to galaxies…
Galaxy merging

# Galaxy merging : basics

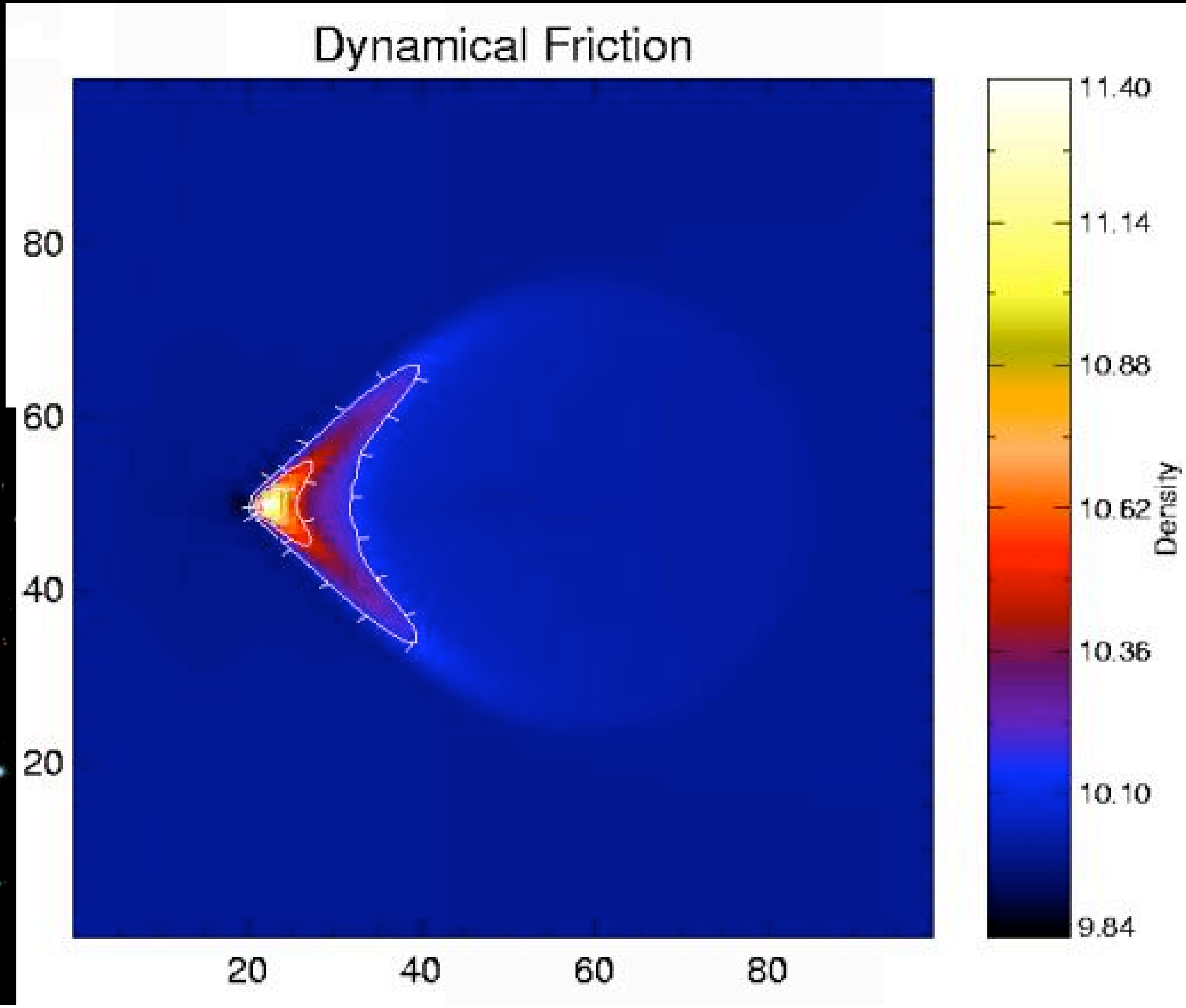
- Same physics as gravitational slingshot, just backwards….
  - M = secondary mass, going at speed $v_M$
  - $\rho$ = local density
  - C depends on how $v_M$ compares with velocity dispersion of the matter around it…

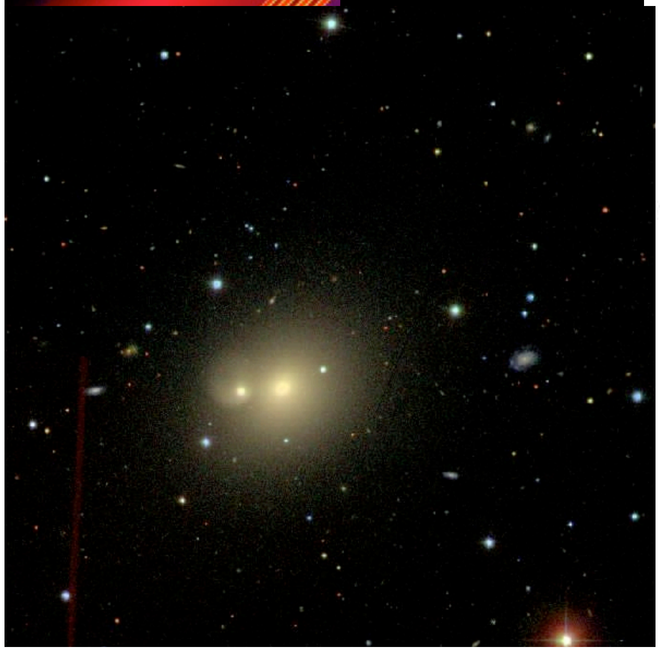
$$f_{dyn} \approx C \frac{G^2 M^2 \rho}{v_M^2}$$

- Dark matter is important contributor to dynamical friction for galaxy mergers…

# Galaxy merging : dynamical friction

Piontek, AIP



# The effects of galaxy merging

i) Mergers create spheroids

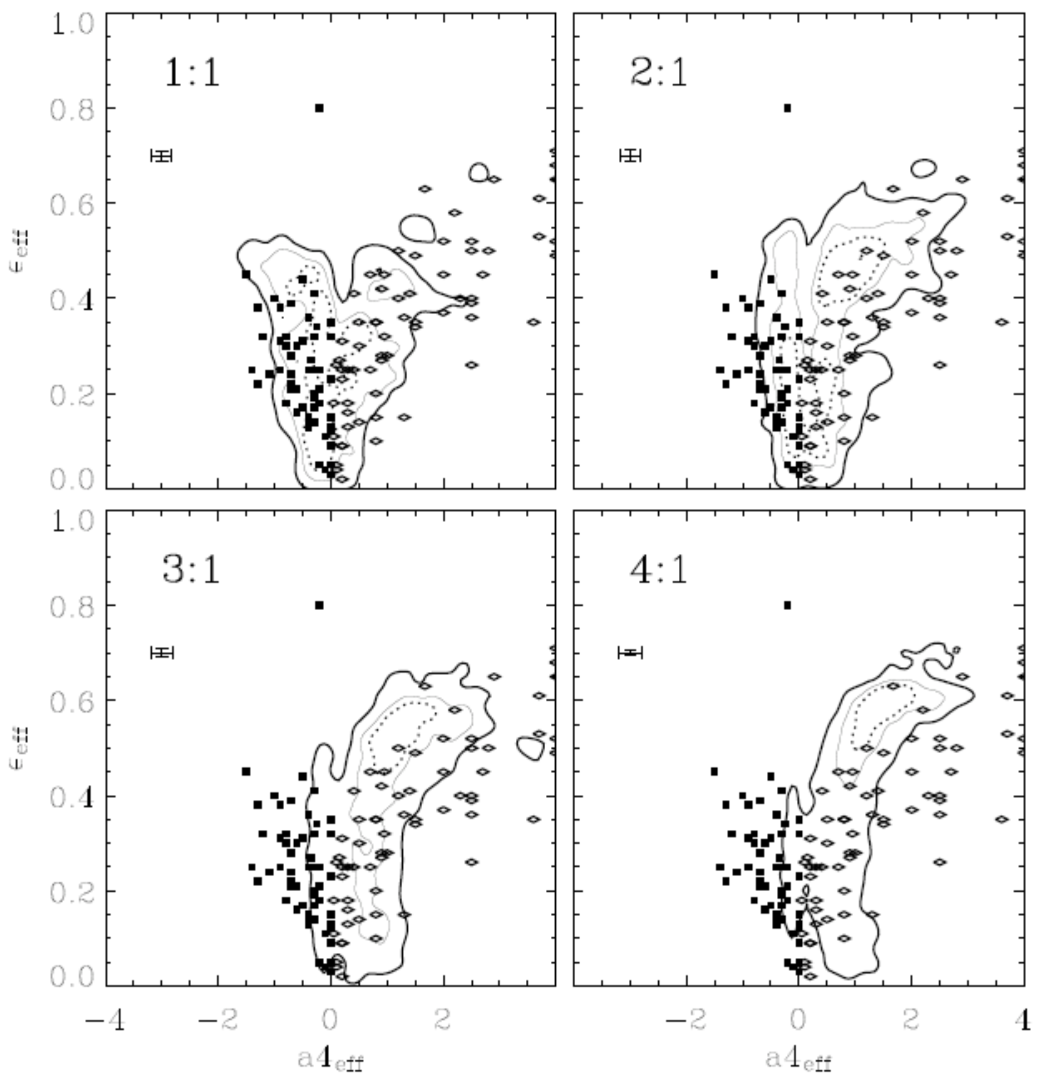
ii) Drives inflow of gas, burst of star formation

ii) Merger initiates feedback which quenches SF

(recall spheroids empirically associated with quenched SF)

Springel, MPA

# Mergers and spheroid creation

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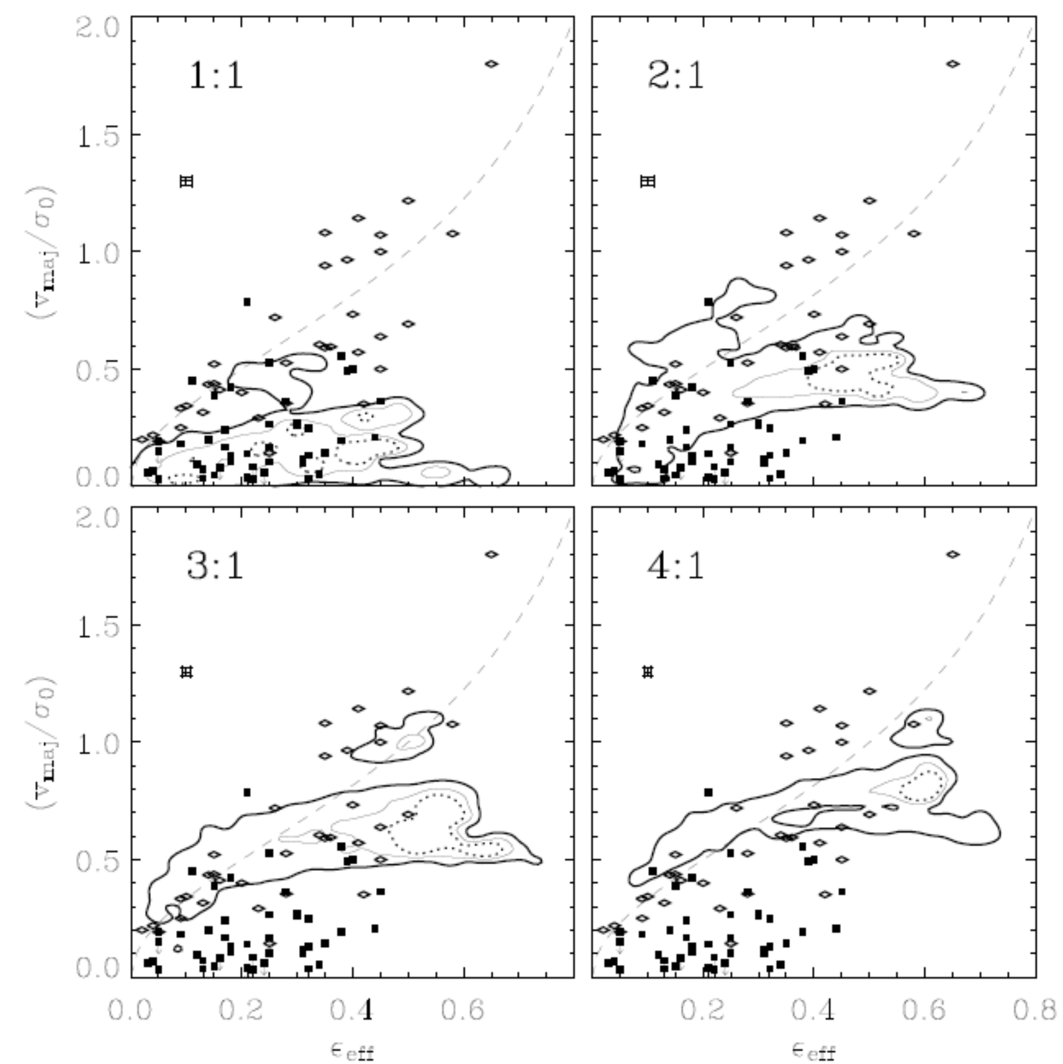
# Mergers and spheroid creation

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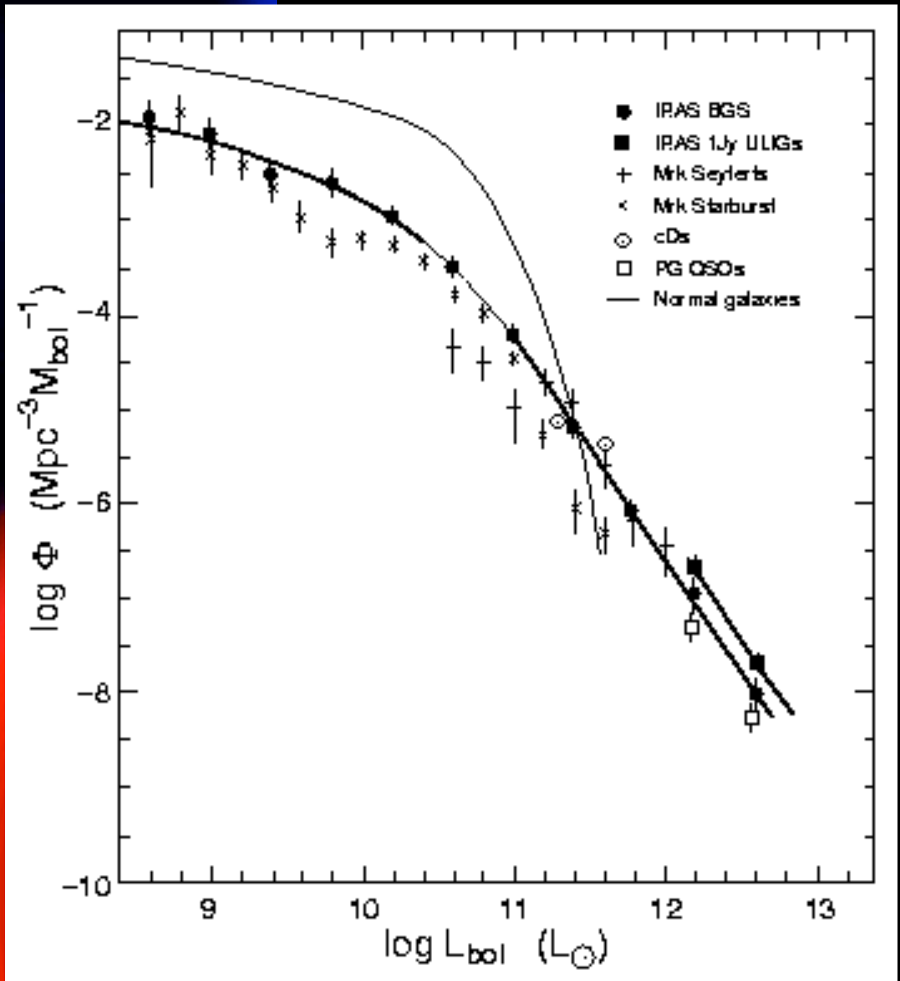
# Mergers and driving star formation

- Robaina’s work (z~0.6), Li et al. (z~0.1)
  - For star-forming galaxies, factor of 2-3 enhancement in star formation rate with interacting and merging (averaged over all galaxies, over whole *recognisable* interaction and merger phase)
  - Most very intense SF events
    - Associated with interactions and mergers
    - Sanders & Mirabel 1996 is a decent review
- At present day, significant number of mergers between elliptical galaxies.

# High end of the luminosity function

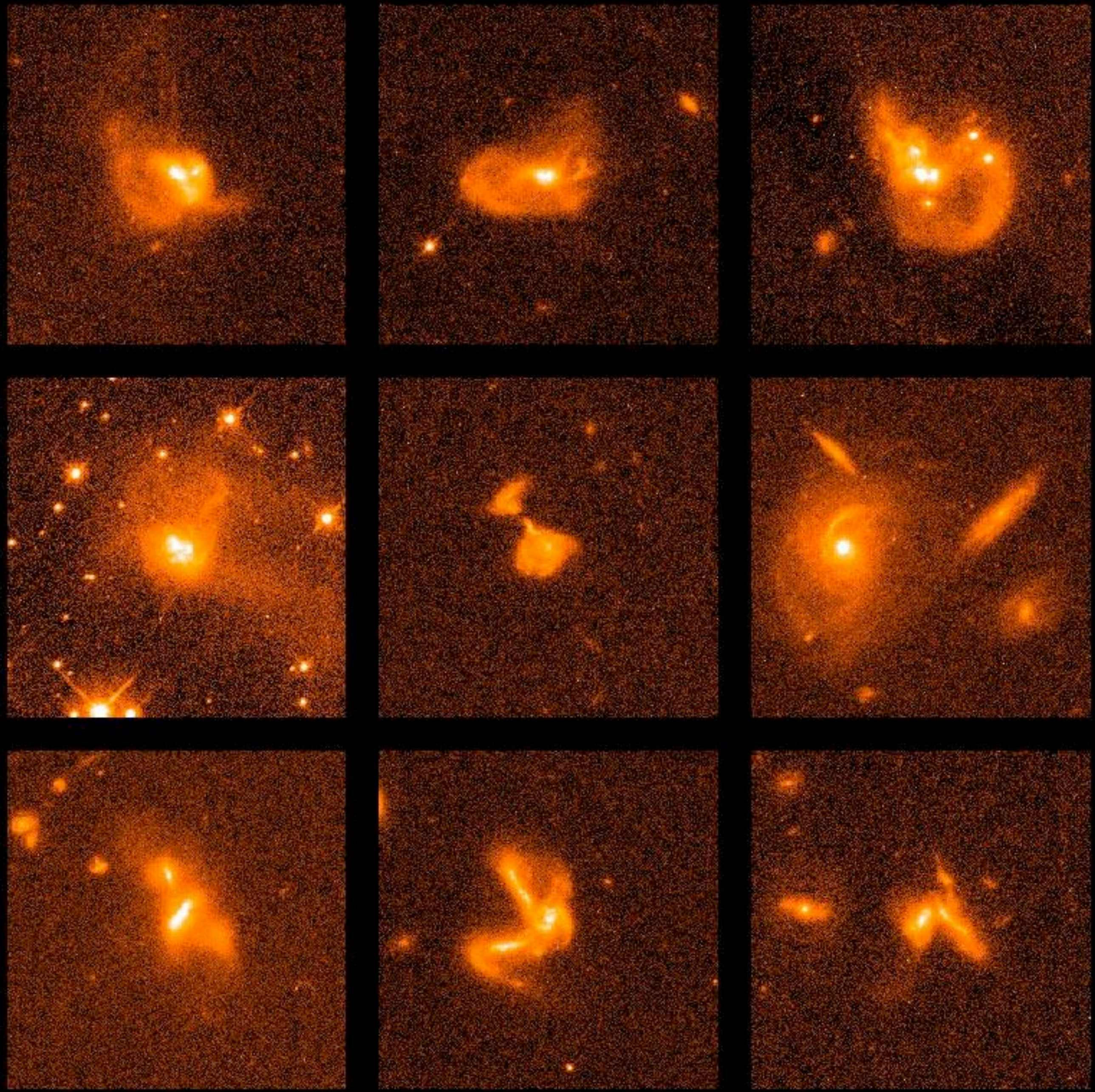



At $L > 10^{11}$ $L_o$ infrared galaxies are the dominant population z<0.3

more abundant than QSOs

Energy from starbursts
at $L> 10^{12}L_o$, all major mergers

In some cases, an AGN is superposed



Borne et al 99

HST WFPC2

ULIRGS

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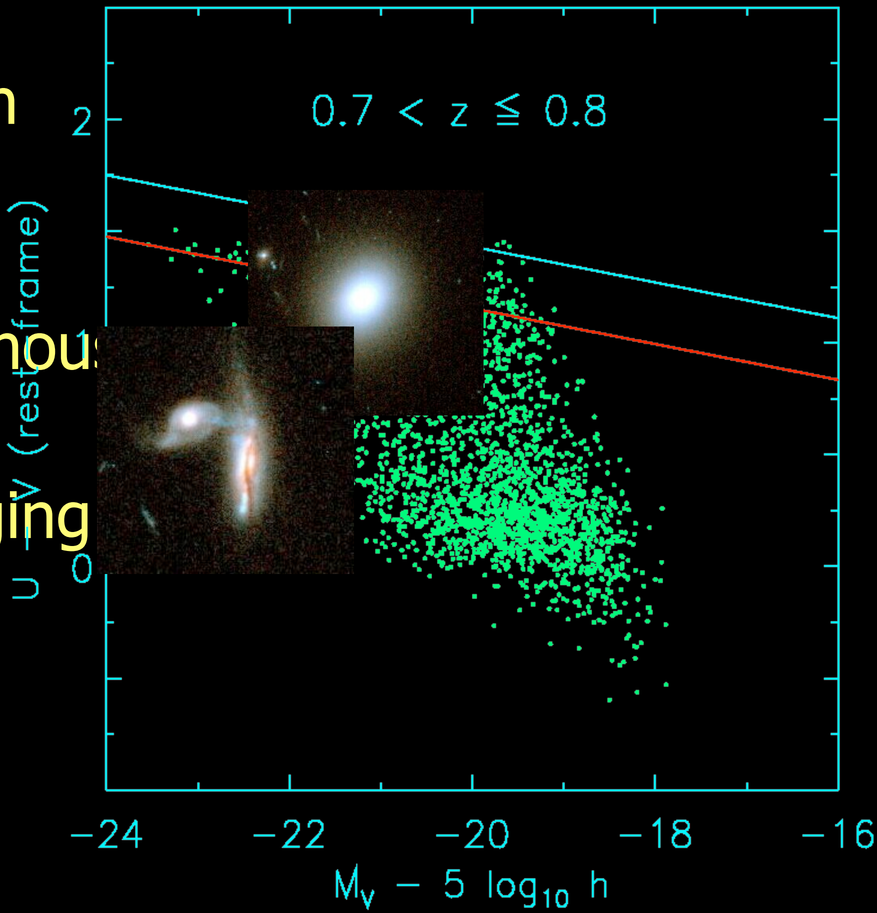
# Dry mergers…

- Can build-up even the most massive galaxies
- No room for luminous blue progenitors
- → gas poor merging is required…



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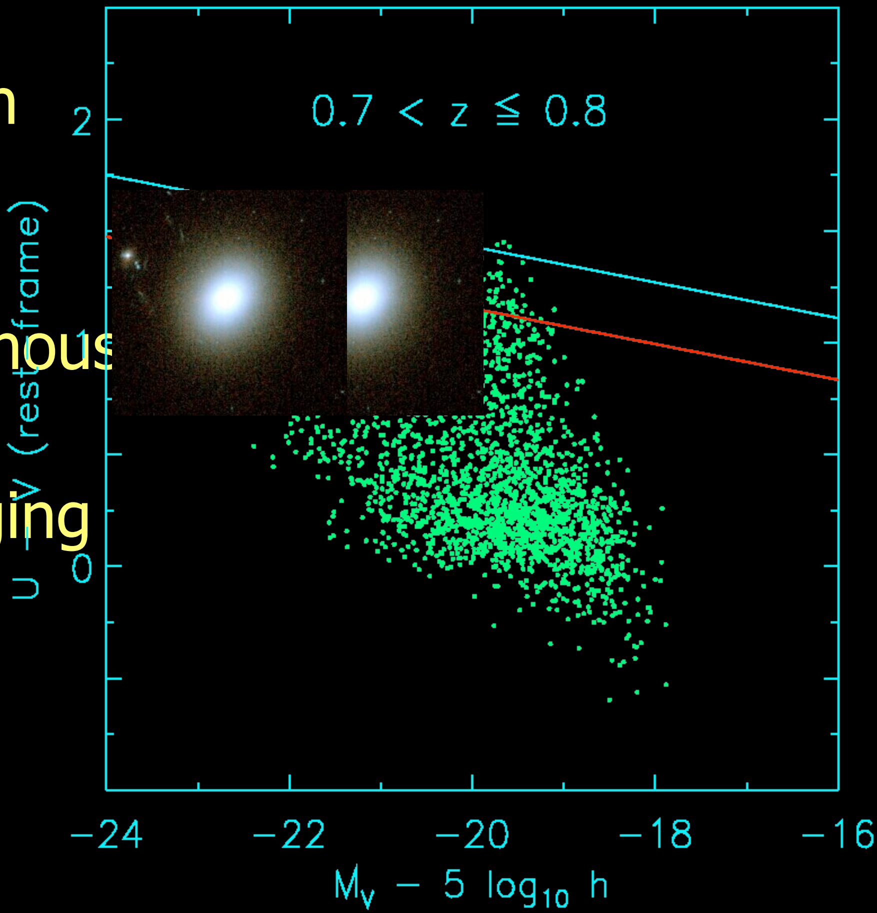
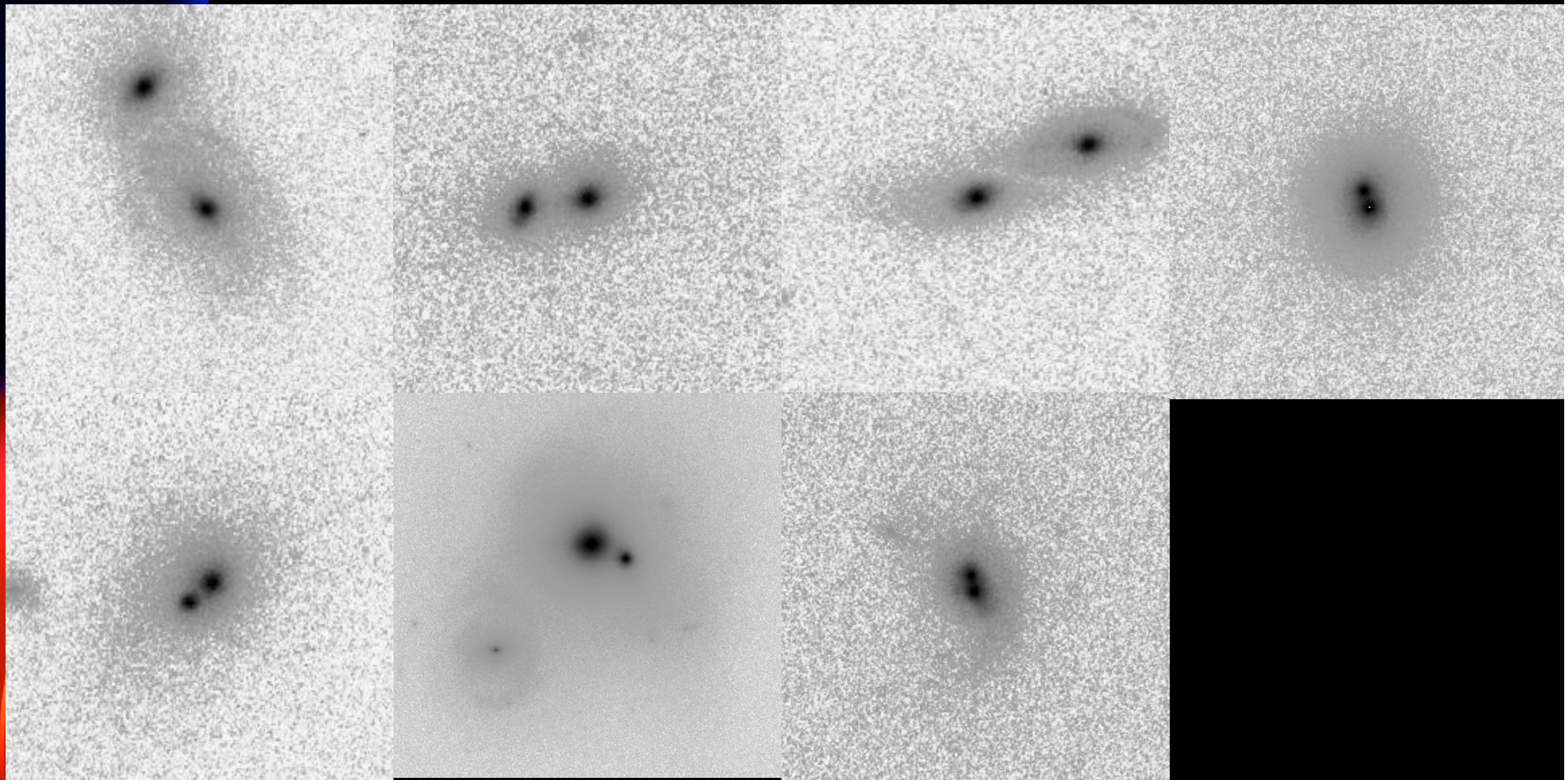


# Dry Mergers at z<0.7



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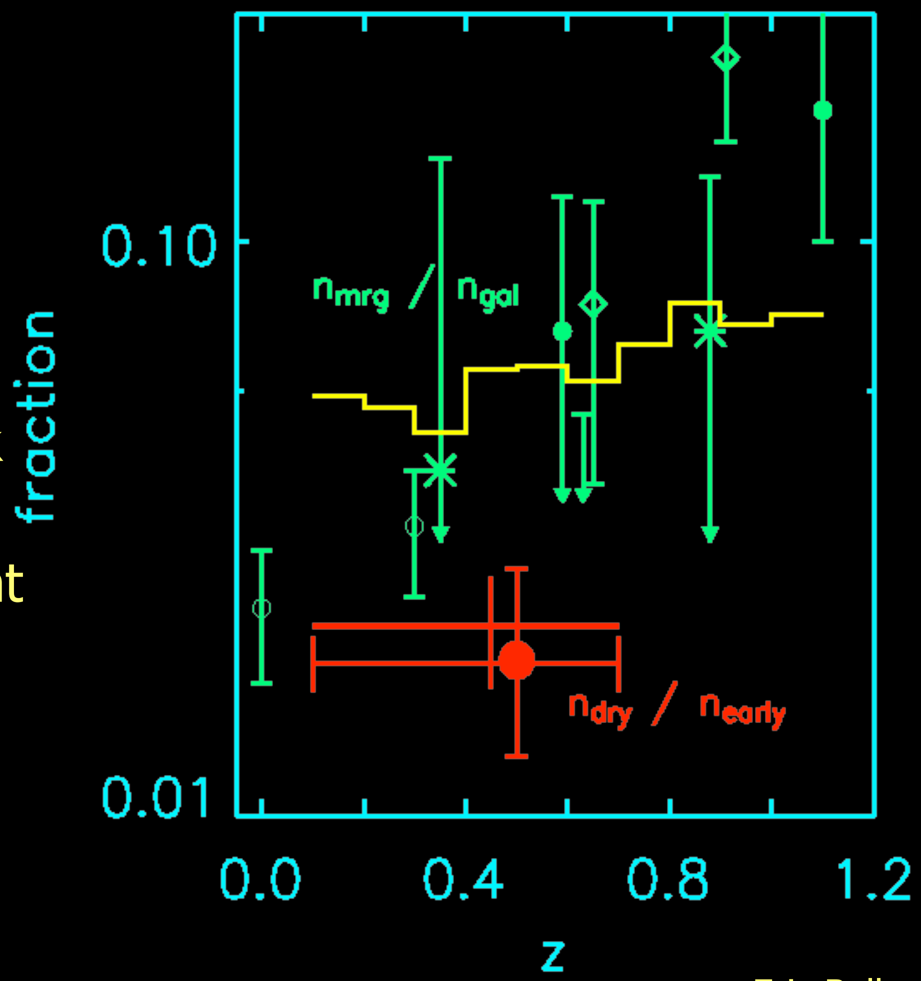
# Dry Mergers at z<0.7

- Using 150 Myr timescale
  - 0.5-1.5 dry merger for L>L* galaxies since z~0.7 with mass ratios from 4:1 to 1:1
- Consistent with Somerville et al. (2008) AGN feedback model
- Rate consistent with current CMR and stellar mass size relation limits

Bell et al. 2006

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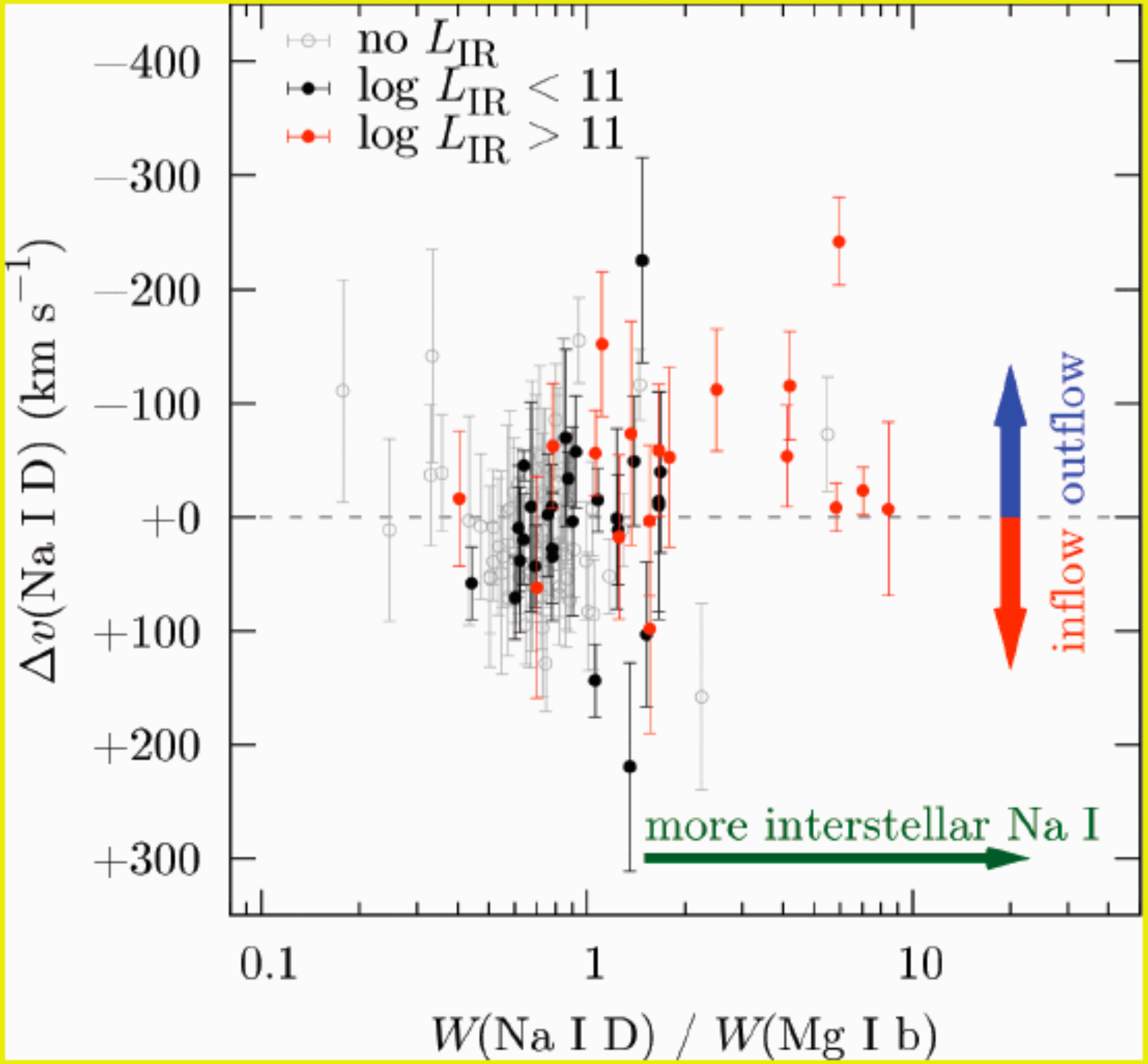
# Spectroscopic Wind Survey in EGS

Na I Survey @ z~ 0.4 with DEEP2 (Work in Progress)

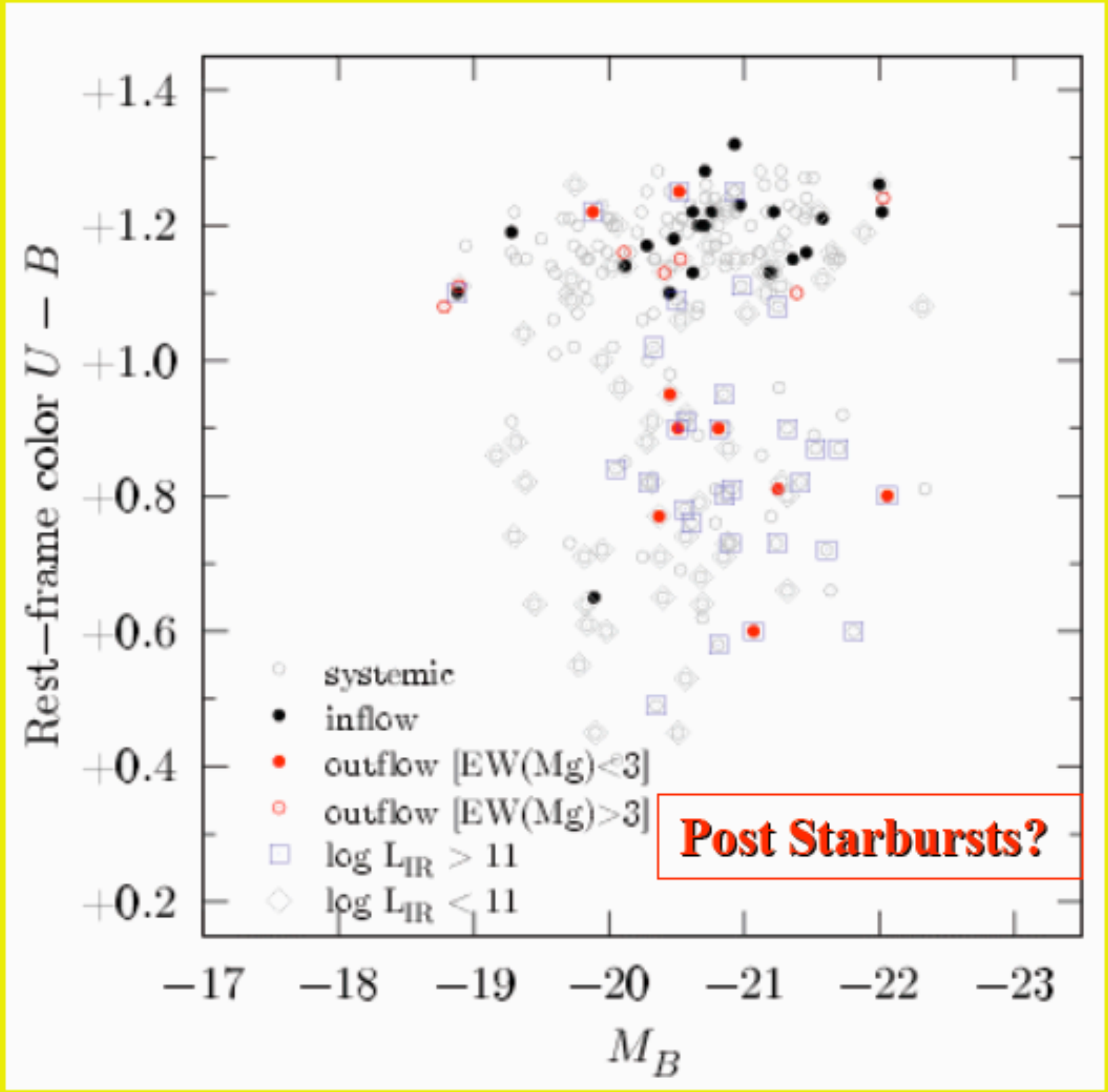
Work of **Taro Sato**

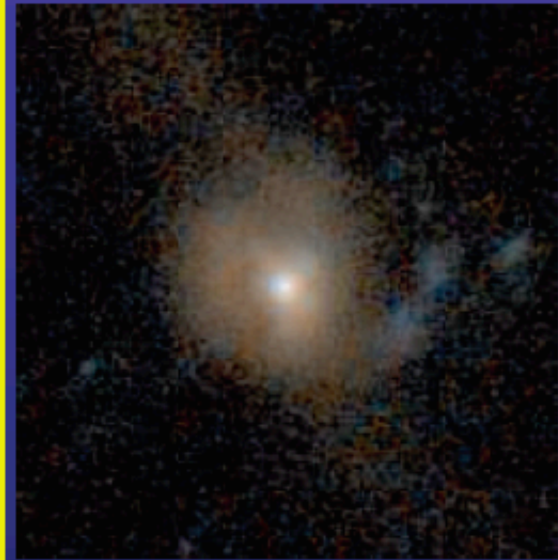



**Line Strength ~ Doppler Parameter**

# Find Outflows in Blue Cloud and on Red Sequence

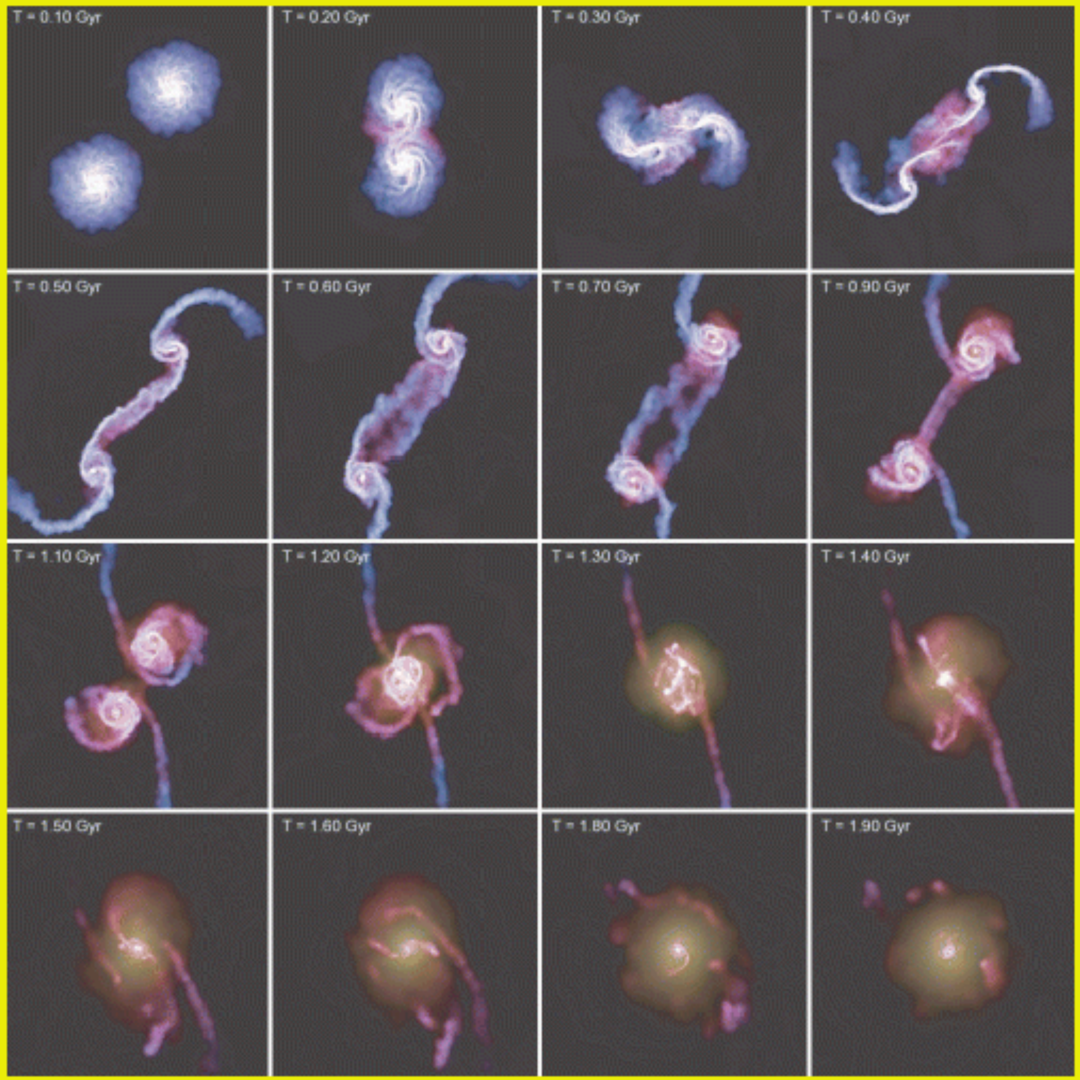
**Find outflows in high fraction of LIRGs ($L_{IR} > 10^{11} L_O$)**



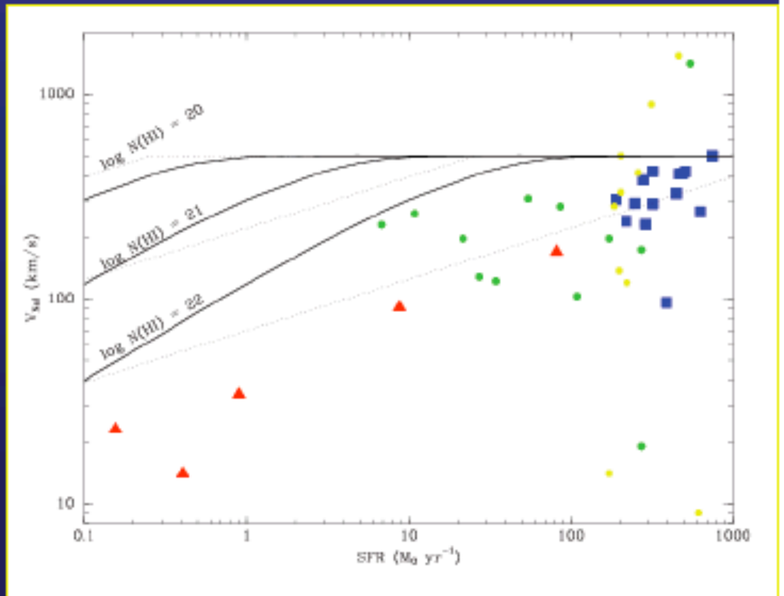



# Gas-Rich Disks => Cool ULIRGs => Warm ULIRGs ==> Field E

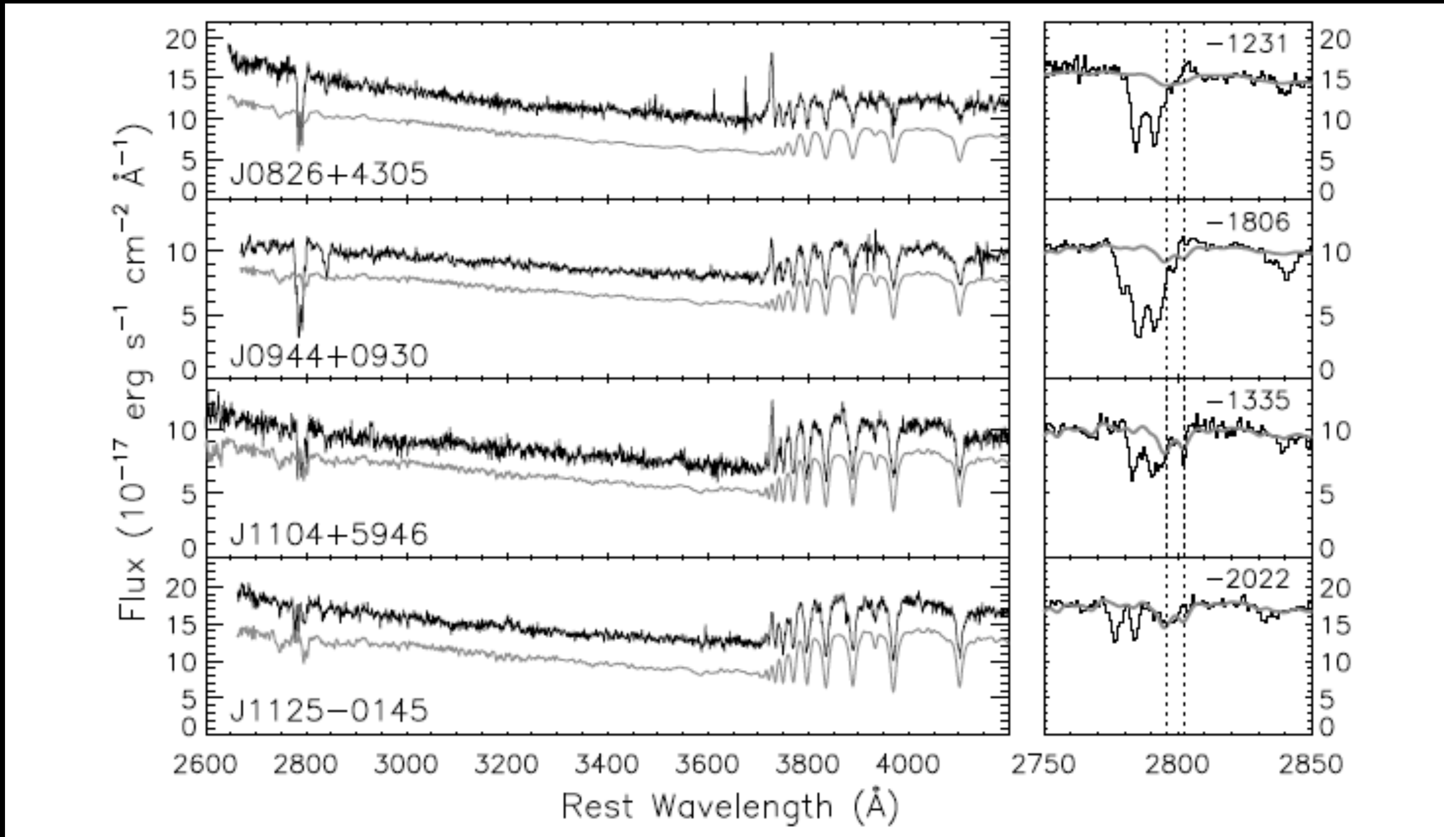
Local Analogy to : Springel et al. 2005




- Ultraluminous Infrared Galaxies ($L > 10^{12} L_O$) discovered with IRAS; Rare today (Soifer; Sanders)
- $R^{1/4}$ profile; high $\sigma/v$ (Genzel & Tacconi)
- Na I Doppler Shifts 200-600 km/s2 (CLM 2005, 2006; Rupke et al. 2005)



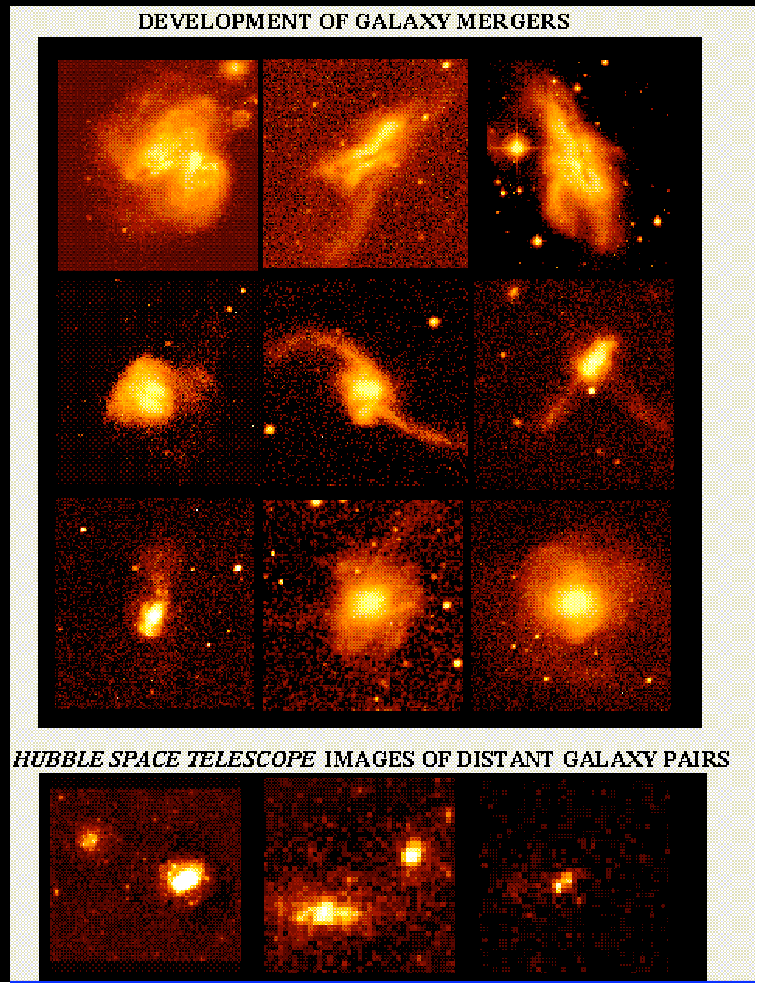
# AGN feedback from post-starbursts?




Tremonti et al. 2007

# I. Merger rates

- Messed up morphologies?

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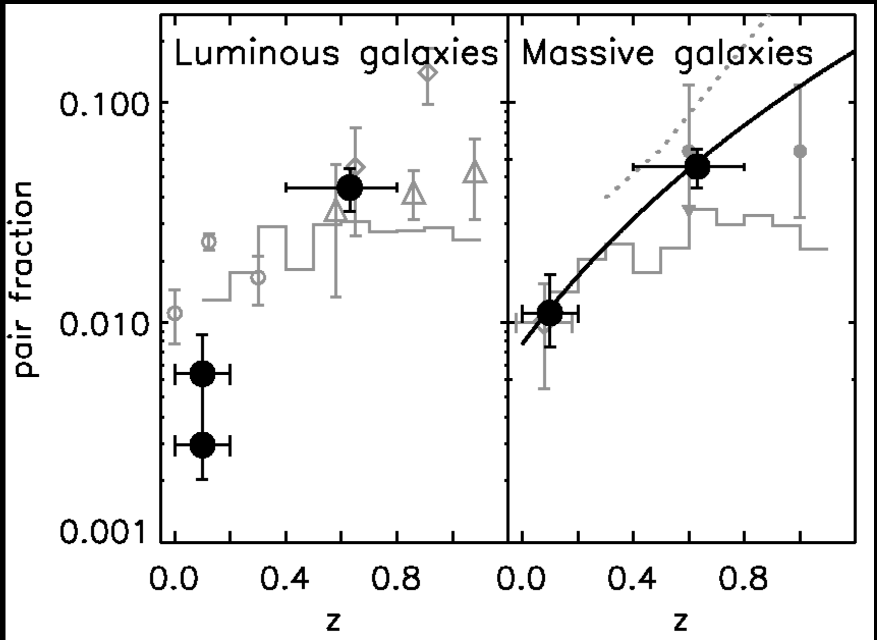
# I. Merger rates

- Merger rates
  - 2 point correlation function --> fraction of galaxies in close pairs in 3D space (through deprojection)

$M_B < -20$

z~0.6 COMBO-17
z~0.1 2dFGRS




$M > 2.5 \times 10^{10}\ M_{\odot}$

z~0.6 COMBO-17
z~0.1 SDSS/2MASS

Bell et al. 2006

Introduction

The growth of the red sequence

Can mergers drive growth of the red sequence?

introduction
merger rates
assumptions
results

Summary

# II. Assumptions

- Assume
  - Mergers between galaxies $2.5\times10^{10}\ M_\odot$ galaxies → red galaxies with > $5\times10^{10}\ M_\odot$
  - All r<30kpc pairs merge (limit)
  - Timescale ~ 2πr / v
    - $r_{av}$ ~ 15kpc, v ~ 150km/s → timescale ~ 0.4Gyr
    - Very uncertain
  - Only way to make z<1 $5\times10^{10}\ M_\odot$ galaxy is through merging
- Predict rate of growth of number of red galaxies with > $5\times10^{10}\ M_\odot$

Introduction

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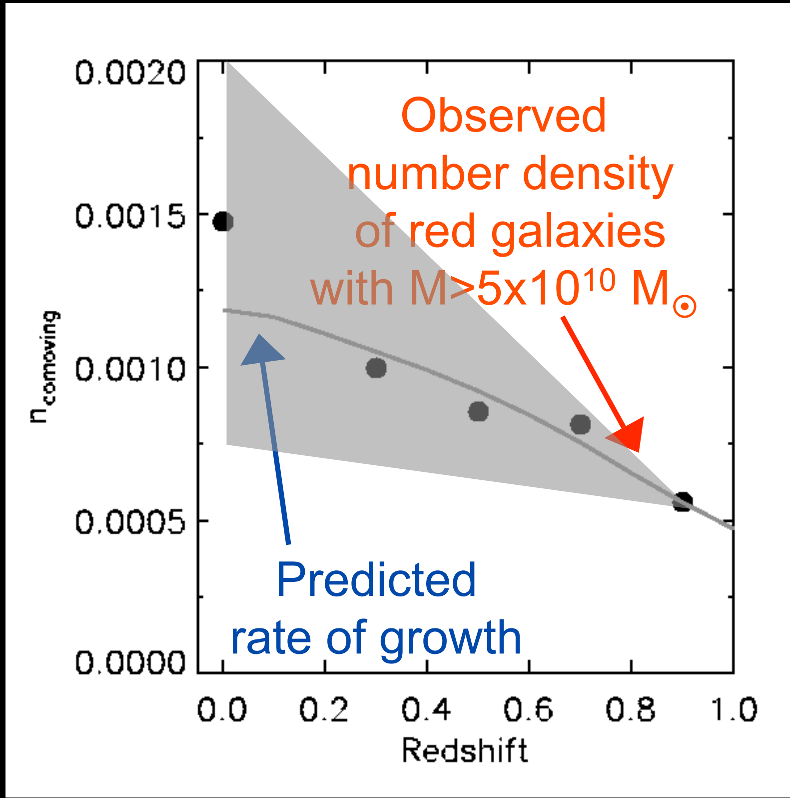
# III. Results

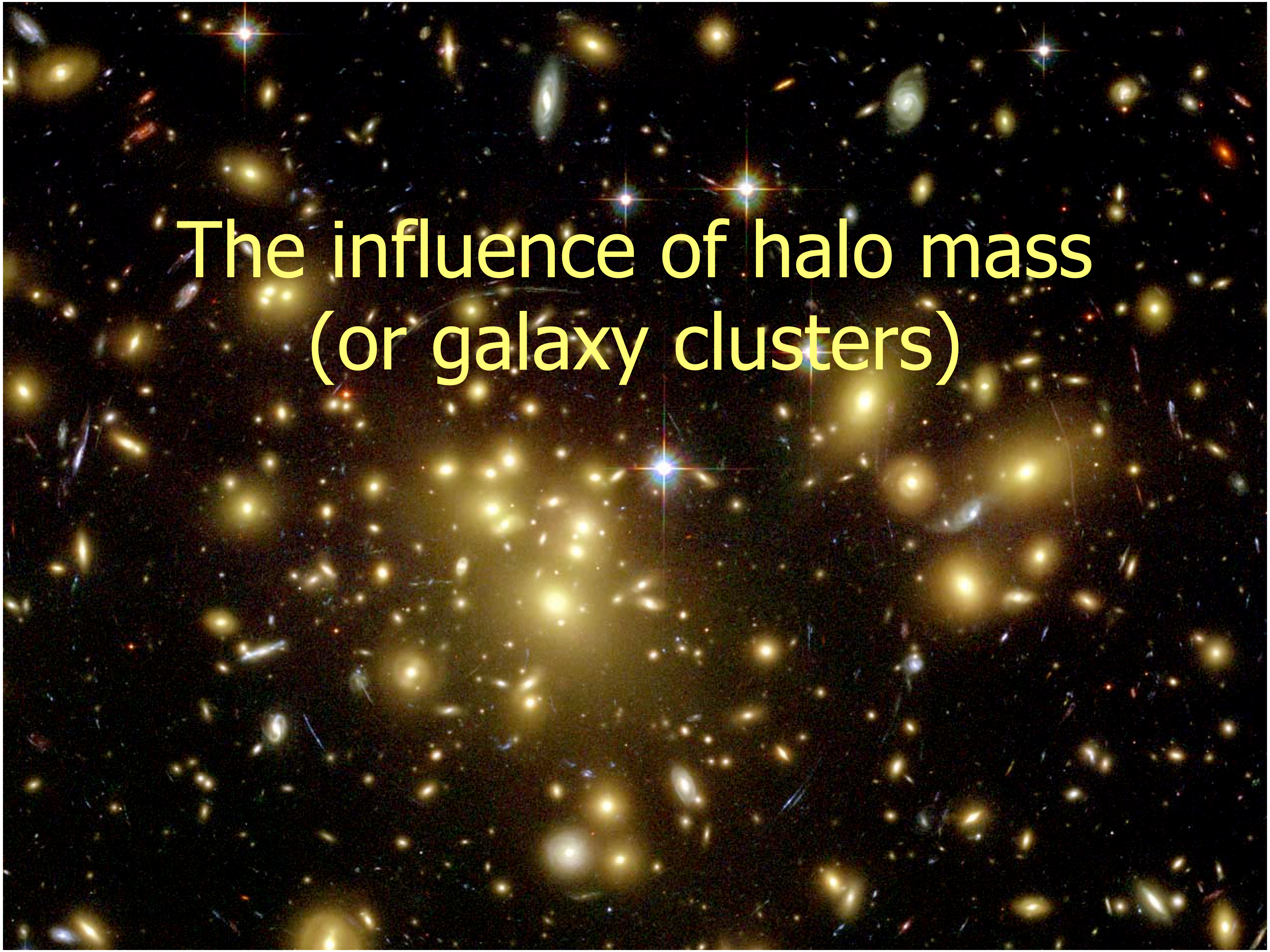
- IF all mergers between gals with $M > 2.5\times10^{10}\ M_\odot$ → red sequence galaxy $M>5\times10^{10}\ M_\odot$
  - There are enough mergers to plausibly feed the growth of red sequence



# Galaxy Mergers

- Galaxy Merging
  - From dynamical friction (wake of particles behind secondary)
    - $\propto M_{secondary}^2/v^2$
  - Makes spheroidal structures
  - If gas, enhances star formation (x2-3 on average)
  - Drives intense stellar and AGN feedback
  - Early-type galaxies merge, produce very massive elliptical galaxies…

  - ~ 0.5-1 merger per massive galaxy z<1…


The influence of halo mass
(or galaxy clusters)

- Moore et al. 1999
  - DM halo of a Milky Way galaxy
  - DM halo of a large galaxy cluster

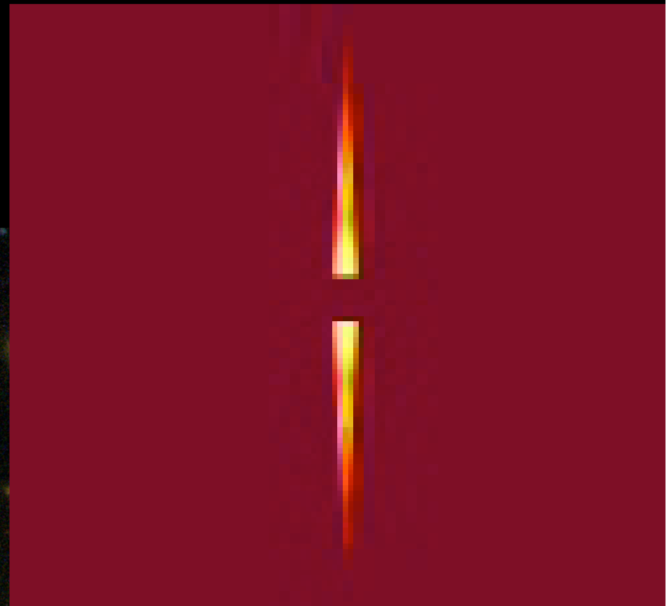
## What is different between a galaxy cluster and a galaxy (with little satellites)?

- The behaviour of the baryons is the main thing that is different…
  - Efficiency of galaxy formation low for low-mass halos/subhalos
  - Efficiency of galaxy formation maximal at $10^{12}$ solar masses

- Some minor differences in assembly history (rather more recent assembly for a cluster)

- Clusters filled with $>10^7$K gas

# Cluster-specific physical processes



- Ram pressure stripping
  - $P \sim \rho_{hot} v^2$
  - Restoring force $2\pi G \Sigma_g \Sigma_*$
  - Stripping if ram pressure > restoring force…
- Gunn & Gott 1972

# An almost halo mass-independent physical process…

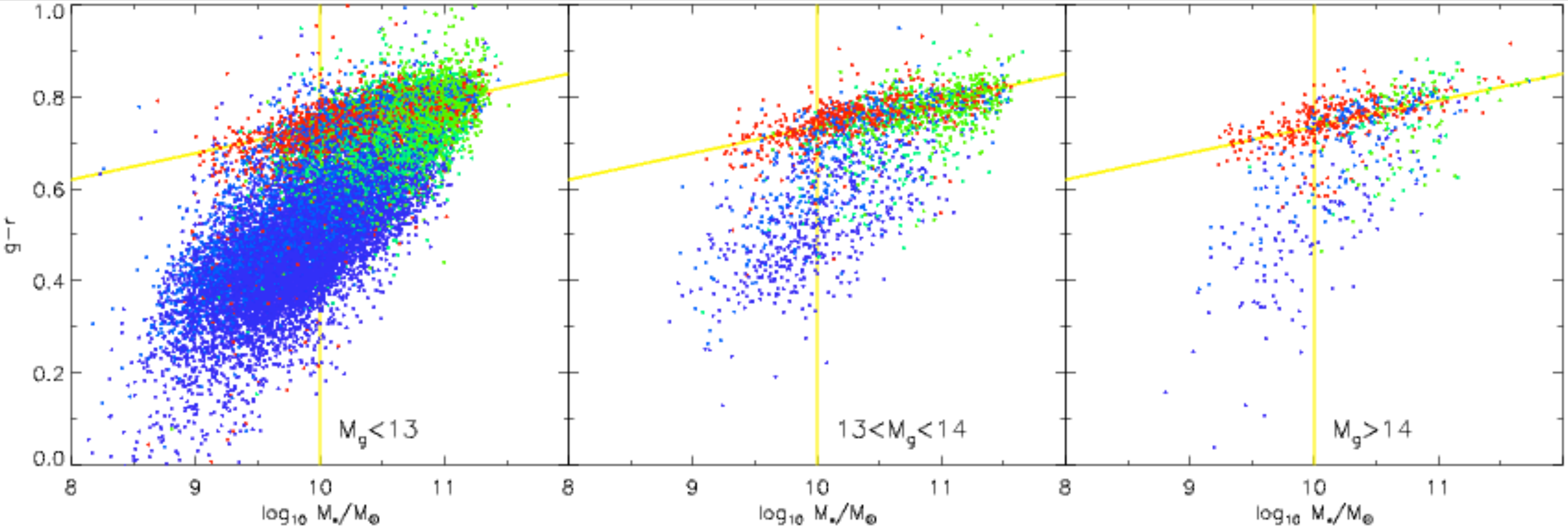
- Galaxy tidal interactions / harassment
  - Interactions with dark matter halo / individual galaxies in the cluster
  - Tidal interactions
    - Drive gas to middle
    - Thicken disk (increase vel. disp)
  - Ben Moore, Kenji Bekki…

# Galaxy clusters

- Higher red galaxy fraction
  - Also higher early-type galaxy (elliptical) fraction, Blanton argues this is mostly because of higher red fraction (at least at L*)
- Luminosity function slightly different
  - more high-mass and low-mass red galaxies
- Evolution:
  - Tendency towards older stellar populations

# Question

- Why are red sequence galaxies red?
  - Merging + AGN feedback
    - This happens at $10^{12}$-$10^{13}$ solar masses
  - Environment (ram pressure stripping, harassment)
    - This happens just in massive halos $>10^{14}$



# Summary

- Dark matter scale-free
  - Behaviour baryons very scale-dependent
- Galaxy clusters
  - Lots of ~L* galaxies --> tides / harassment
  - Lots of hot gas --> ram pressure
- Appears that properties of L* galaxies determined before fall into a cluster
  - Clusters are a second-order effect for L* galaxies
  - Decisive for low-mass galaxies
- Only <~1Mpc scales matter for galaxy formation
  - Support for the halo model

# Questions for Friday

- If there were dark matter halos without galaxies in them, how could you go about finding out?
- Massive galaxies are red, massive galaxies are in dense environments. How could one tackle the problem of best finding out what is 'driving' this correlation?
- In simulations of merger --> obscured star-burst --> optically bright QSO phase, this is the time ordering. How would you go about figuring out whether nature obeys this time order?
- If you had the, say, Andromeda galaxy perfectly resolved into stars (to make CMDs) etc, what (broadly) interesting questions would you ask of the data?

# Questions for Friday (cont)

- How would you go about estimating the ratio of 'dry' mergers (mergers with no new stars), vs. 'wet' mergers (i.e. mergers that go along with possibly obscured, IR-bright star-bursts)?

- How would you go about running an ab-initio (dark matter) simulation that actually resembles our Local Group (Milky Way, M31, M33, etc...)?

- How could you go about finding out whether spiral arms or bars are long-lived phenomena (would retain their 'shape' for longer than t_dyn)?

- If (some) galaxies contained not yet merged binary black holes, how could you tell?
  - (What should their orbital velocities be?)