Formation & evolution of galaxies & SMBHs

Cedric Lacey

Durham University

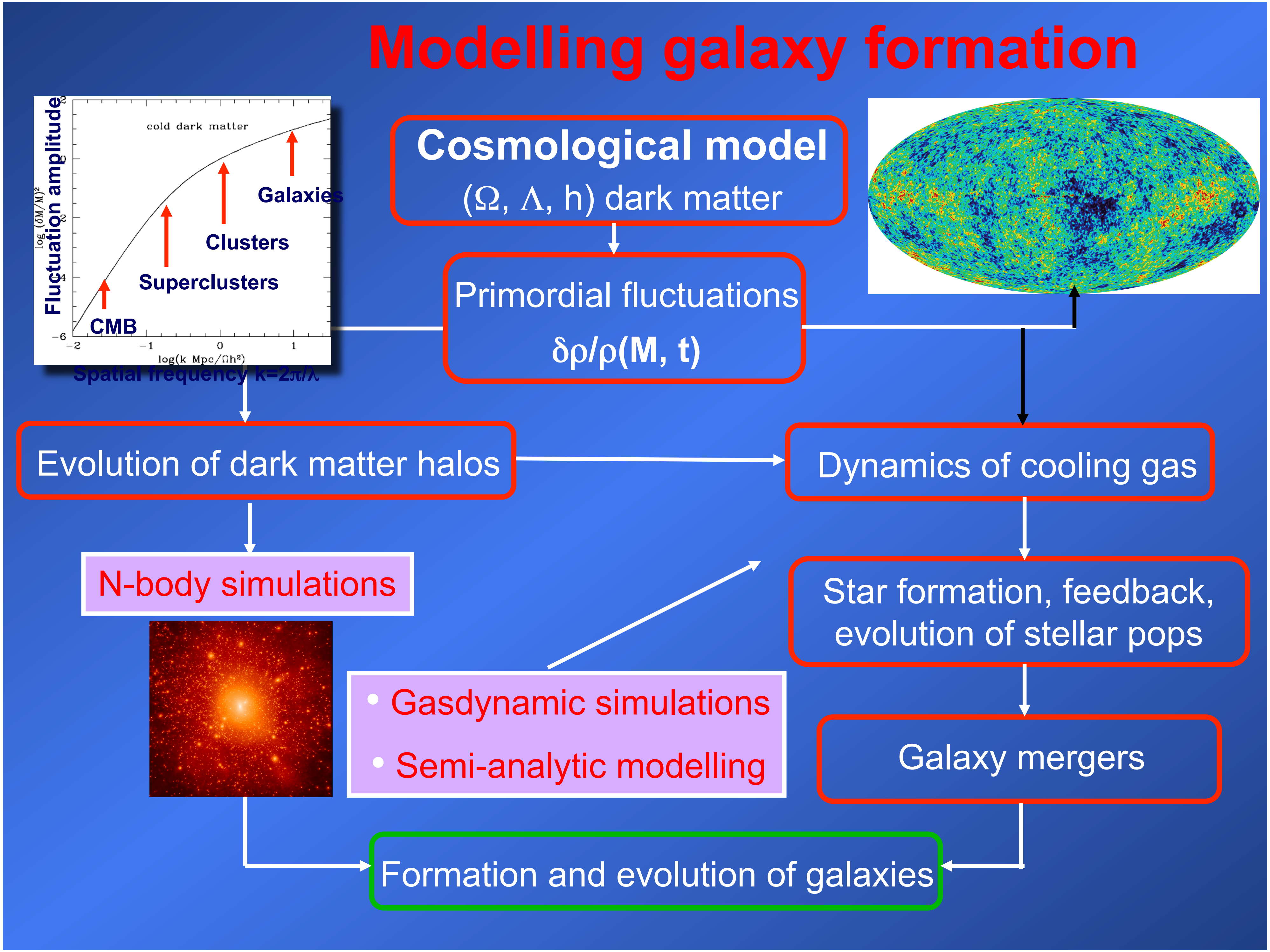
Outline of lectures

1. Structure formation & assembly of dark halos
2. Gas cooling & angular momentum
3. Star formation & feedback
4. Galaxy mergers & morphologies
5. Cosmic evolution of galaxies
6. Formation of black holes
7. BH binaries & spin
8. Co-evolution of galaxies & AGN

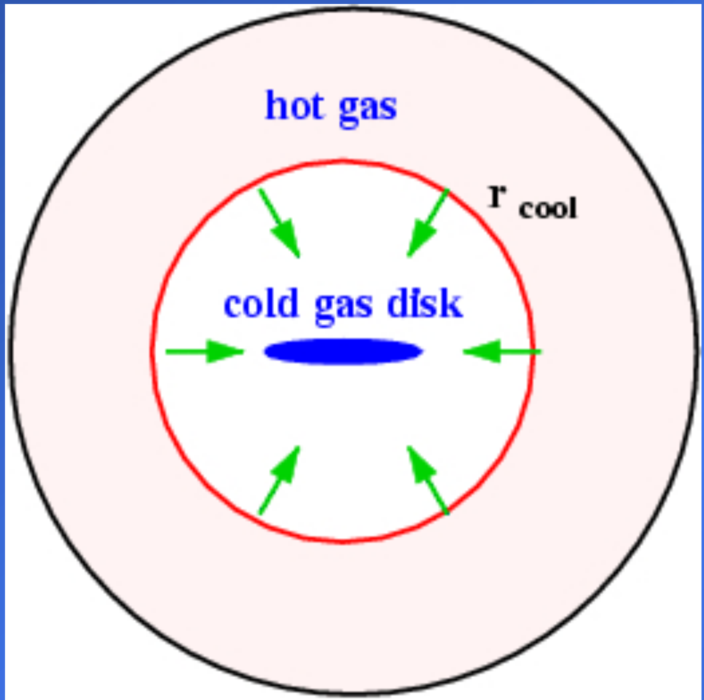
Lecture 3:
Star formation & feedback

Lecture 3 outline

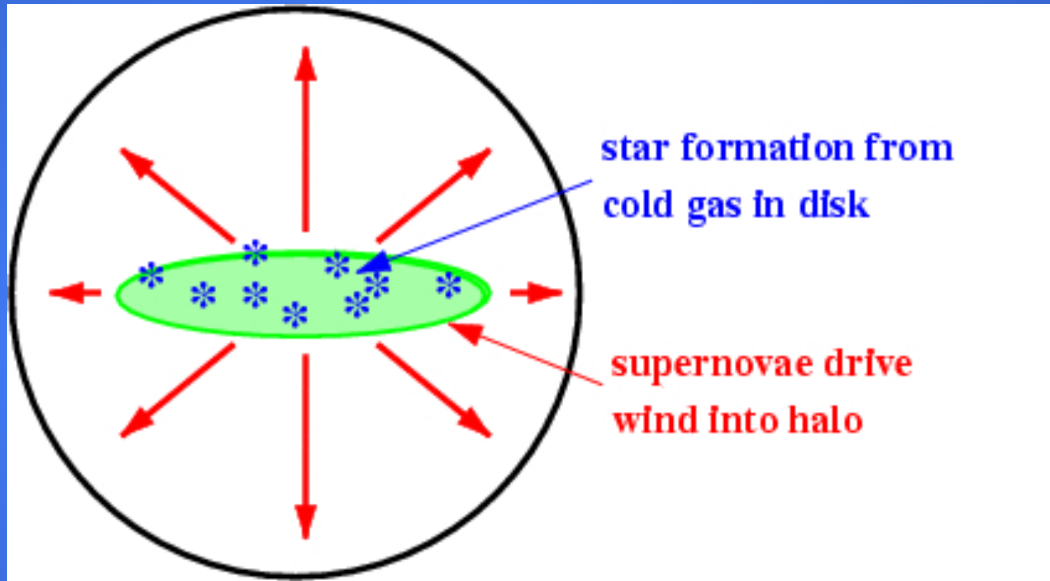
- Star formation
  - Observational & theoretical clues to the star formation law
- Feedback
  - Why it is needed
  - Photoionization
  - Supernovae


Modelling galaxy formation
Cosmological model
(Ω, Λ, h) dark matter
Primordial fluctuations
δρ/ρ(M, t)
cold dark matter
Fluctuation amplitude
Galaxies
Clusters
Superclusters
CMB
−6
−2
−1
0
1
log(k Mpc/Ωh²)
Spatial frequency k=2π/λ
Evolution of dark matter halos
Dynamics of cooling gas
N-body simulations
Star formation, feedback, evolution of stellar pops
• Gasdynamic simulations
• Semi-analytic modelling
Galaxy mergers
Formation and evolution of galaxies

gas cooling & collapse in halos



star formation & feedback in disks

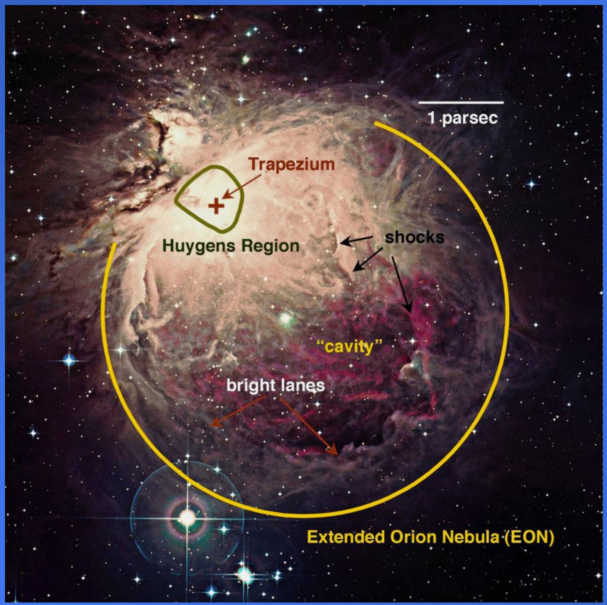


Star formation

Star formation - overview

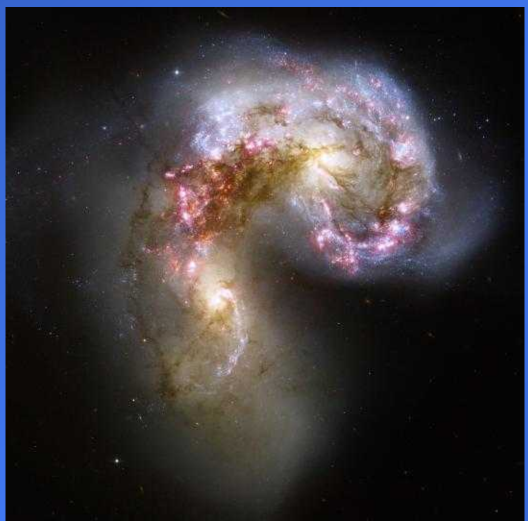
- Gravity tends to make gas collapse to higher & higher densities, end result is star formation
- but collapse inhibited by:
  - pressure support -> radiative cooling, ambipolar diffusion of B-fields
  - rotational support -> gravitational, hydrodynamical or magnetic torques
- also inhibited by energy injection in ISM from earlier generations of stars
  - photoionization
  - stellar winds
  - supernova explosions
- star formation thus very complex process to model theoretically

Star formation & GMCs



- Star formation involves processes on very wide range of scales, from ~ kpc to << 1 pc
- present-day galaxies: 2 stages
  - large scale aggregation/collapse of ISM to Giant Molecular Clouds (GMCs)
  - collapse & fragmentation of GMCs to protostellar cores which collapse to stars
  - star formation in individual GMCs appears quite inefficient – only few % of gas converted to stars
- too complicated to model all this theoretically – need observational clues

Star formation modes in the present-day universe



- Appear to be 2 distinct modes of SF on galaxy-wide scales:
- Quiescent (in disks of spiral & irregular galaxies)

  $\tau_* = M_{gas}/SFR \sim 10^9 - 10^{10}$ yr

- Starburst (usually triggered by major dynamical disturbances - galaxy mergers & tidal interactions, galactic bars)

  $\tau_* \sim 10^7 - 10^8$ yr

What do observations of local galaxies tell us about the SFR law?

- early studies (Kennicutt 1998) suggested simple relation between surface densities of SF and TOTAL gas (i.e. HI + H_2), with quiescent & starburst galaxies on same relation
- global mean surface densities of SF and gas within galaxy nearly equally well fit by either:

(A) $$\dot{\Sigma}_* = K\,\Sigma_{gas}^{\;N} \quad with\ N = 1.4$$

  - Close to N=3/2 expectation from local gravitational collapse timescale of gas

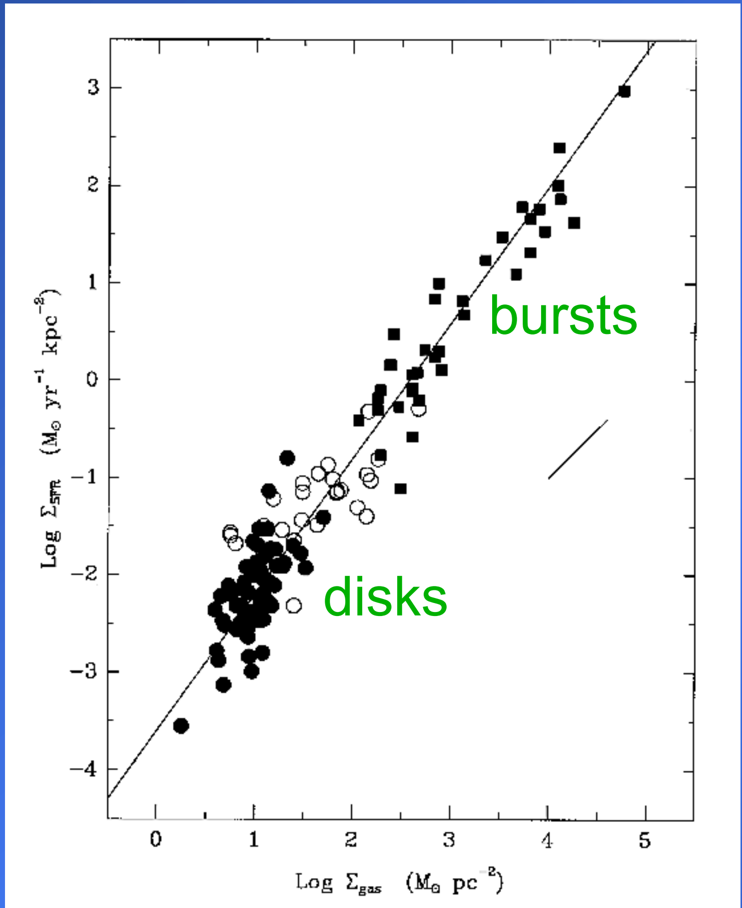
(B) $$\dot{\Sigma}_* = \varepsilon\,\Sigma_{gas} / \tau_{orb} \quad with\ \tau_{orb} = r / V_c$$

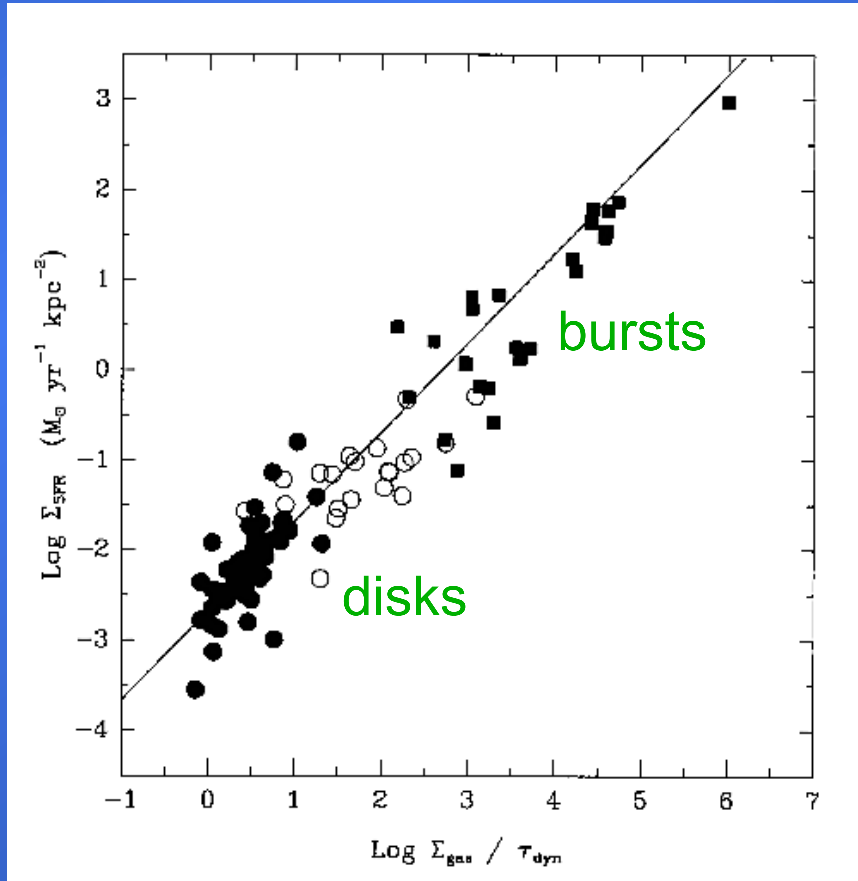
and $\varepsilon \sim 10^{-2}$, i.e. $\tau_* \sim 10^2\, \tau_{orb}$

Observed global SFR laws

$$\dot{\Sigma}_* = K\,\Sigma_{gas}^{\ N} \qquad N = 1.4$$

$$\dot{\Sigma}_* = \varepsilon\,\Sigma_{gas} / \tau_{orb}$$

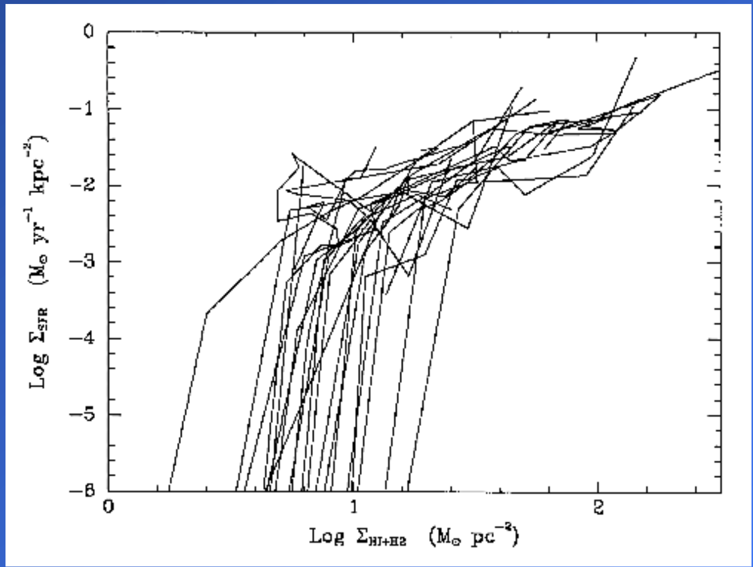




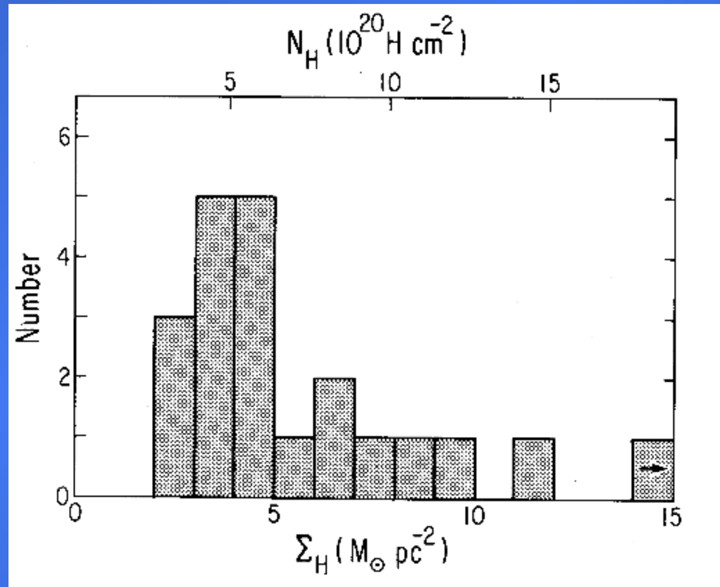
Kennicutt 1998

Observed star formation thresholds in disks

Σ_{SFR}

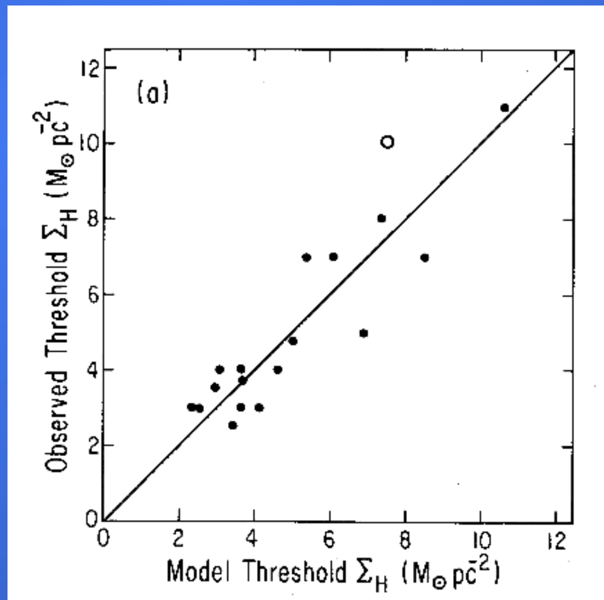


Σ_{gas}



Model:

$$\Sigma_{thresh} = \alpha \frac{\kappa\, c_s}{\pi G}$$



Kennicutt 1989

Star formation thresholds in disks & gravitational instability

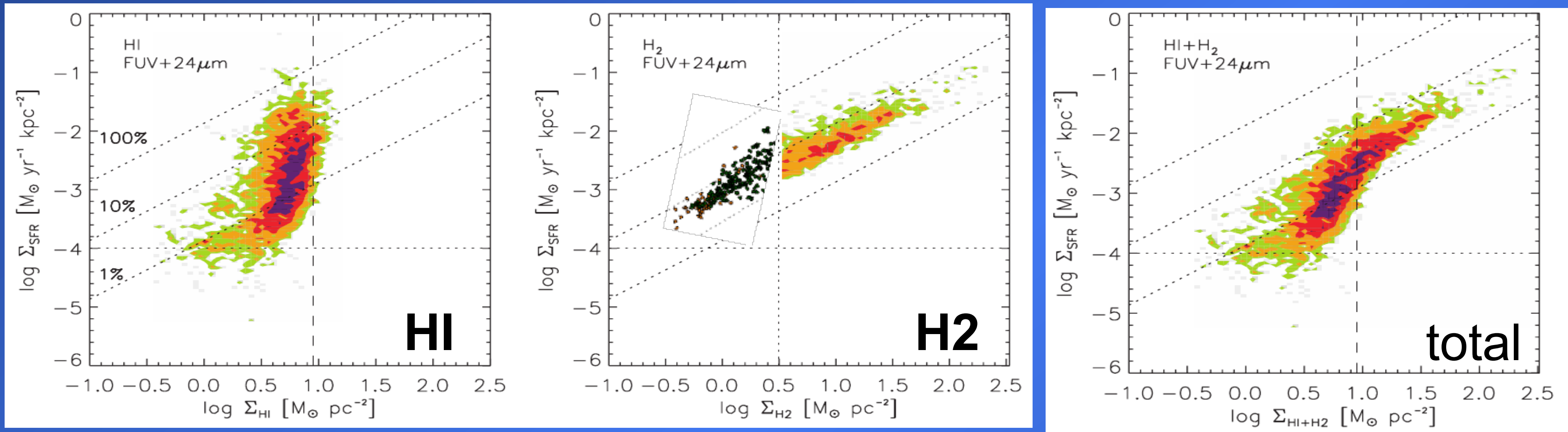
- Thin rotating gaseous disk predicted to be gravitationally unstable to axisymmetric perturbns if (Toomre 1964)

$$\Sigma_{gas} > \Sigma_{crit} = \frac{\kappa\, c_s}{\pi G}$$

- Where c_s is sound speed & κ is epicyclic frequency, $\kappa = 2^{1/2} V_c/r$ for flat rotation curve
- Observed star formation thresholds fit with

$\Sigma_{thresh} = \alpha\, \Sigma_{crit}$ with α=0.7 (Kennicutt 1989)

Observed local SFR-gas relation

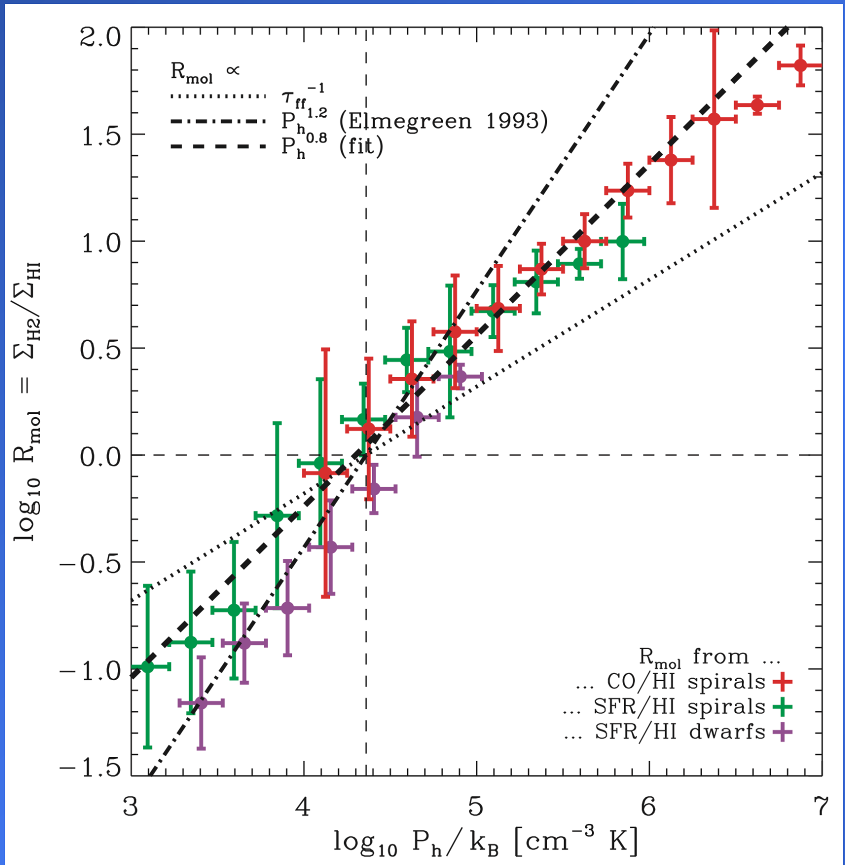


- more recent studies of SFR, HI & H_2 on sub-kpc scales in local disk galaxies indicate:
  - no correlation SFR with HI surface density
  - non-linear, non power-law relation with total gas surface density
  - linear relation between SFR and H_2 surface density

$$\Sigma_{SFR} \propto \Sigma_{H_2}$$

Leroy et al 2008, Schruba et al 2011

What determines the H_2/HI ratio?



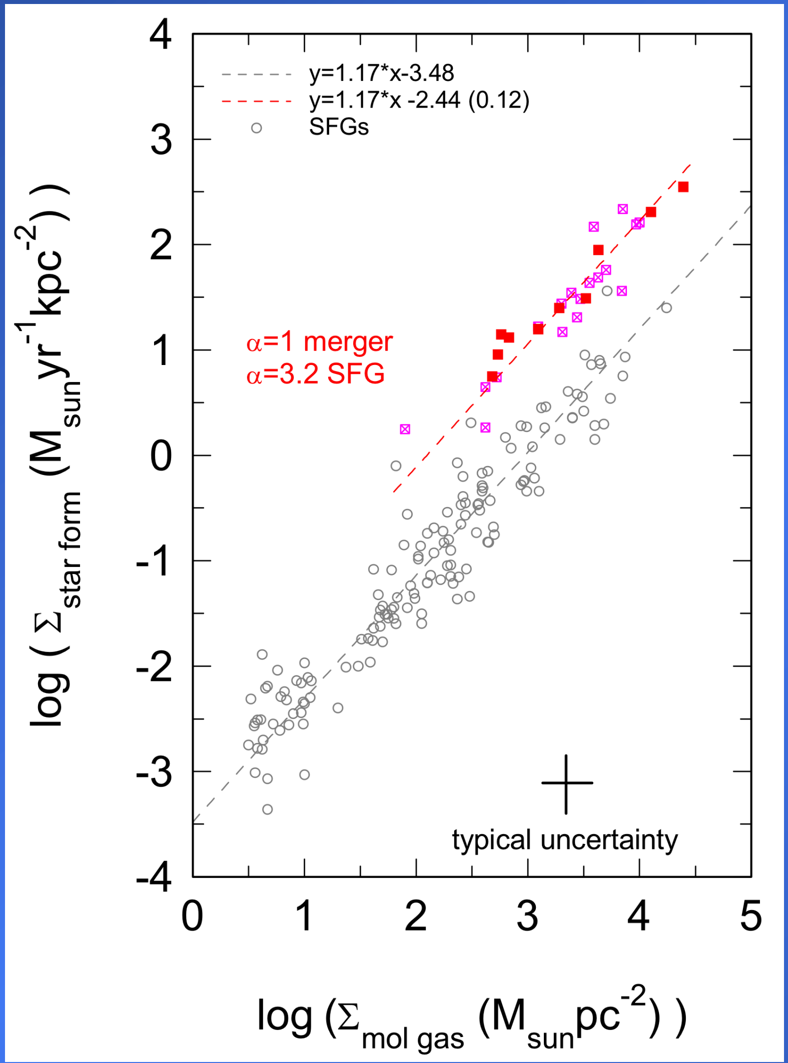
- observations of nearby spiral galaxies well fit by

$$R_{mol} = \Sigma_{H_2} / \Sigma_{HI} = (P_{gas} / P_0)^{\alpha}$$

(Blitz & Rosolowsky 2006, Leroy et al 2008)

- but not clear theoretically that pressure is the real physical variable driving this

A different SFR law in starbursts?



- recent obs have been interpreted as showing different (offset) SFR laws in starburst & spiral galaxies
- but depends on assumed CO-H_2 conversions

Genzel et al 2010

Including star formation in galaxy formation models

- due to lack of complete theoretical description forced to use relations/prescriptions for SFR inferred from observations of (mostly) nearby galaxies
  - observational relations not unique
  - not clear over what range of physical conditions or redshifts they are valid
- remains major uncertainty in models, especially at high redshifts

Feedback in galaxy formation

What is feedback?

- most general definition:
  - some kind of back-reaction (positive or negative) from galaxy formation on the later stages of formation of the same galaxy, or of other galaxies
- more restrictive definition (what is usually meant in galaxy formation context)
  - Negative feedback on the amount of baryons which are able to condense into galaxies (in the form of either cold gas or stars), due to some form of energy input from stars or AGN

Why is feedback needed?

- Condensed baryon fraction
- Faint end of galaxy luminosity function (LF)
- Sizes of galaxy disks
- Bright end of galaxy luminosity function

- first 3 of these are due to efficient cooling of gas in halos with $T_{vir} \sim 10^4 - 10^5$ K
- In hierarchical models, most of mass passes through such halos at some time

Condensed baryon fraction

- Predict: in absence of any feedback process, atomic cooling of gas in galaxy halos would lead to ~ 80% of all baryons being condensed into galaxies (in form of stars & neutral gas) by present day - COOLING CATASTROPHE (e.g. Cole 1991)
- Observe: only ~ 5% of baryons condensed at z=0 (of which 90% are stars) (inferred from K-band LF for stars, HI & CO obs for gas) (e.g. Fukugita et al 1998, Cole et al 2001, Balogh et al 2001)

Faint end of galaxy LF

- Halo mass function at low M has slope

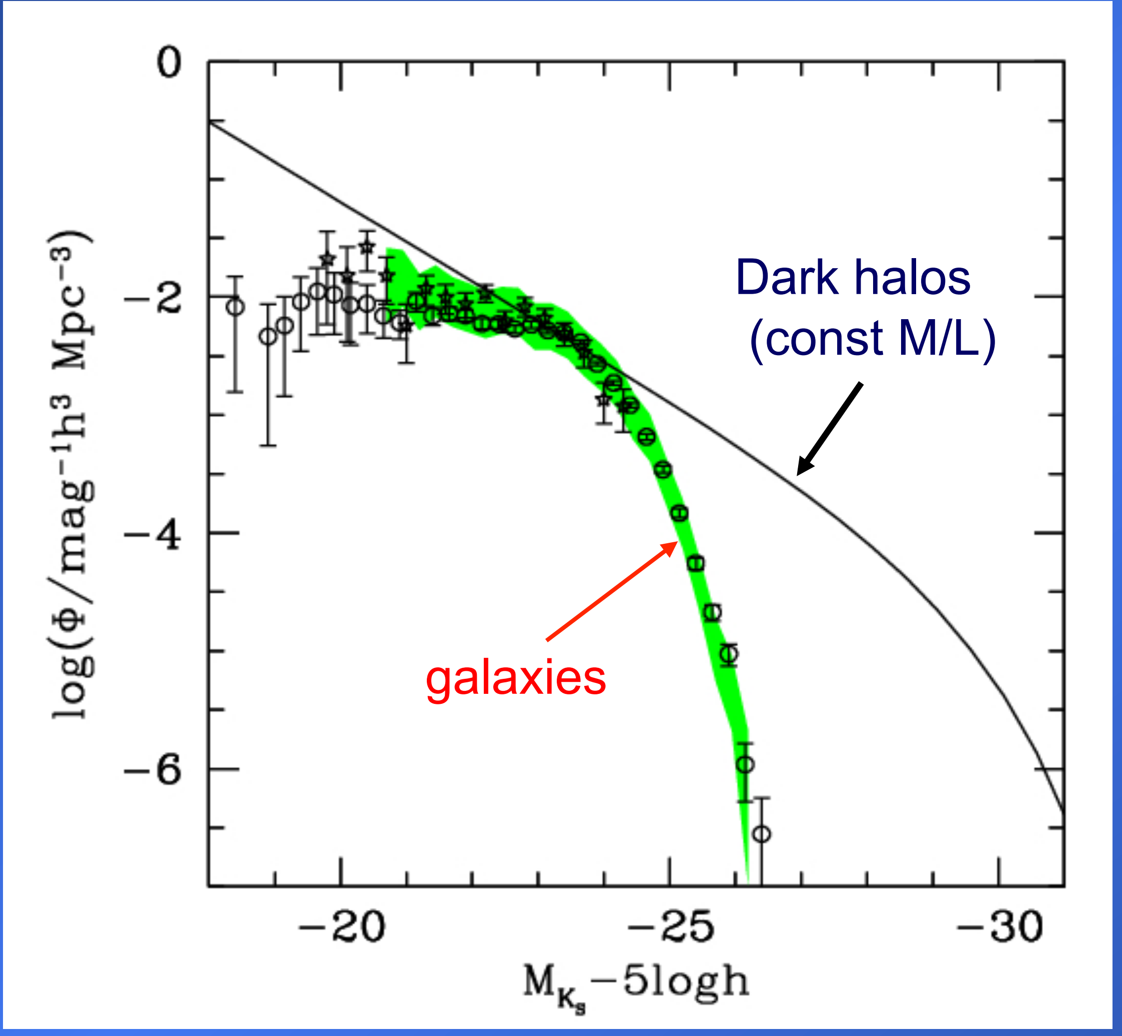
$$dn/dM \propto M^{-2}$$

- Observed galaxy luminosity function has faint-end slope

$$dn/dL \propto L^{-\alpha} \quad with\ \alpha \approx -1$$

- Difference in slopes shows that M/L must increase & condensed baryon fraction must decrease with decreasing halo mass

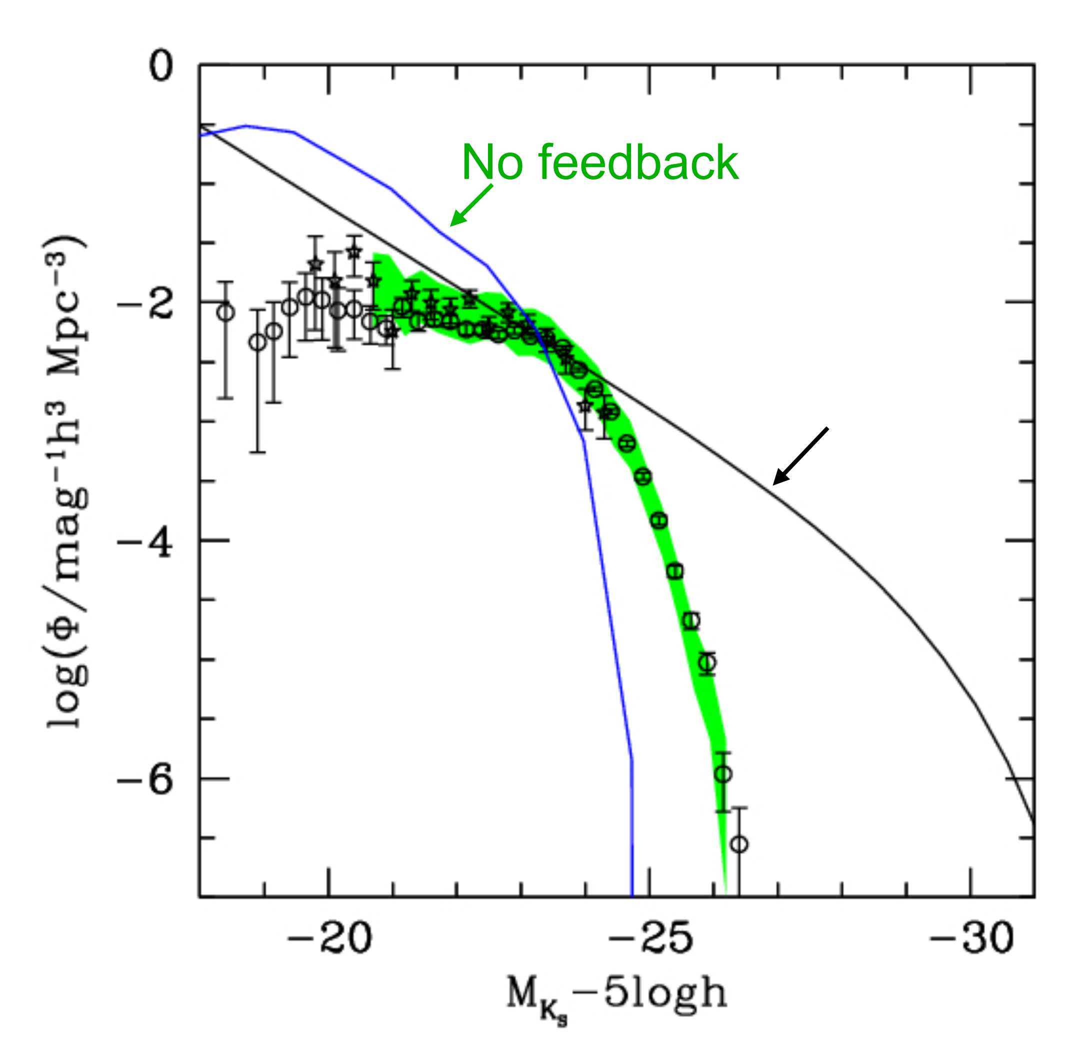
Galaxy luminosity function



- K-band LF approximately traces distribution of stellar masses of galaxies
- halo mass function & galaxy LF have different shapes

=> M/L and fraction of condensed baryons must vary with halo mass

Theoretically predicted galaxy LF with gas cooling & no feedback



Benson etal 2003

- no feedback => too many faint galaxies
- these produce the excess condensed fraction of baryons

Sizes of galaxy disks

- In absence of feedback, most of gas cools early in small halos (~ 10^8 -10^{10} Mo)
- Larger galaxies then all assembled by merging smaller galaxies
- If gas in small galaxies has already turned into stars, this produces mostly spheroidal galaxies (while most galaxies observed to be disks)
- Even if small galaxies remain gaseous, galaxy mergers lead to disks which are much smaller than is observed (Navarro et al 1995)

Types of feedback in galaxy formation (1)

- Photo-ionization/photo-dissociation feedback
  - Photo-ionization of H & He in IGM & galaxy halos
  - Photo-dissociation of H_2 in early objects
  - Ionizing photons can be produced by either massive young stars or AGN

Types of feedback (2)

- Supernova feedback
  - Energy injection by supernova (SN) explosions or stellar winds from massive stars
  - Ejecting gas from galaxies & halos
  - Heating gas in halos, thus inhibiting cooling

Types of feedback (3)

- AGN feedback
  - Energy injection by winds & jets from AGN
  - AGN activity driven by accretion of gas onto central supermassive black holes (SMBHs) in galaxies
  - AGN winds may eject gas from galaxies
  - Relativistic jets may heat halo gas

Photo-ionization feedback

- Observed absence of absorption by neutral hydrogen in IGM in spectra of z<6 quasars shows IGM must have been reionized at z>6
- WMAP measurement of CMB polarization implies reionization at z~10
- Most likely mechanism of reionization is photo-ionization by stars in early galaxies
- So what is the effects of this on galaxy formation?

Photoionization

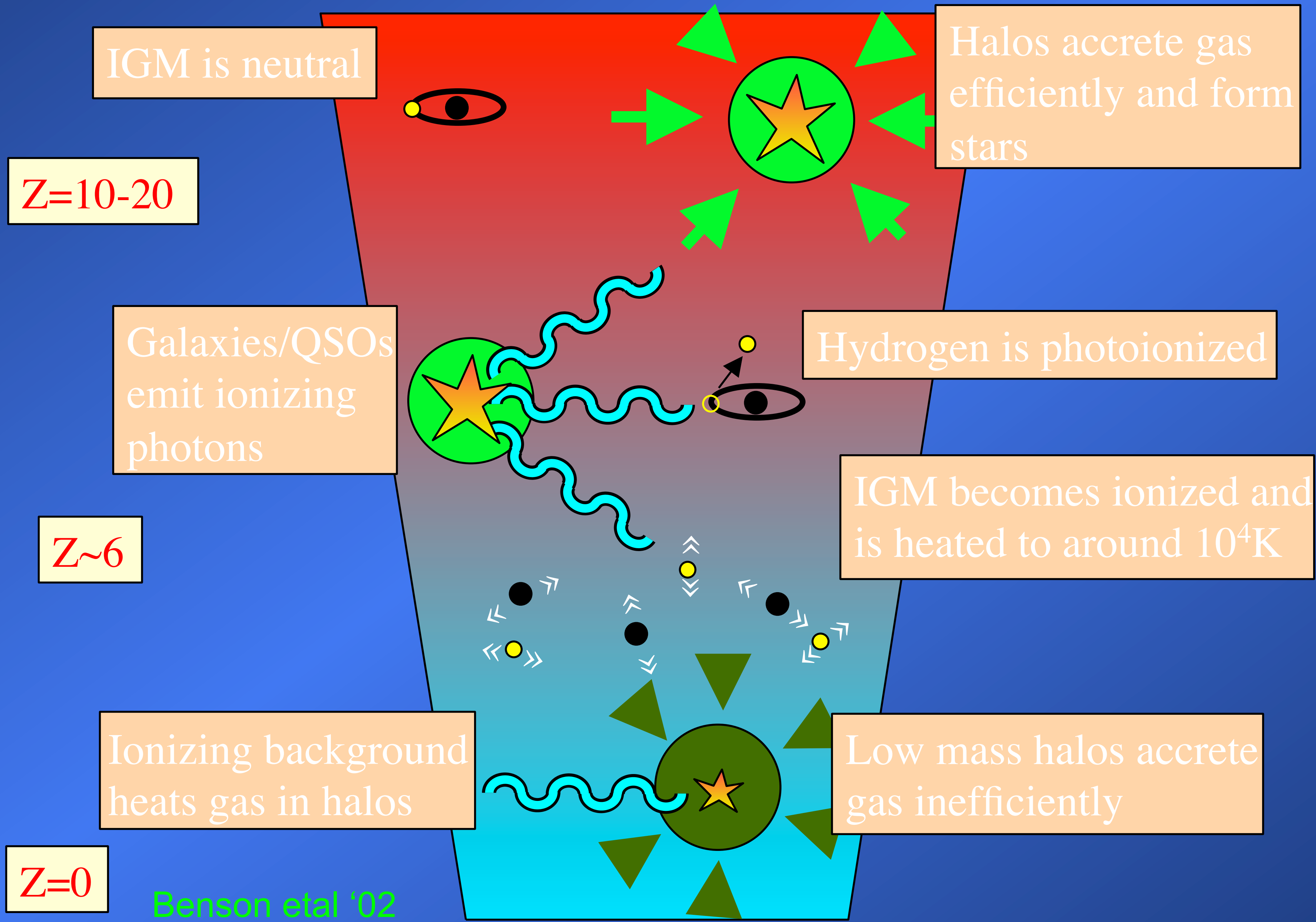


Photo-ionization inhibits galaxy formation in 2 ways:

- IGM pressure:
  - Photo-ionizn heats IGM, resulting gas pressure inhibits collapse of gas into halos
- Reduction in gas cooling:
  - Gas which has collapsed into halos still photo-ionized & photo-heated, reducing amount of gas which can cool into galaxy

(Efstathiou 1992, Thoul & Weinberg 1996, Okamoto etal 2008)

Simple estimate of photo-ionization feedback

- Photo-ionizn heats gas to $T \sim 2 \times 10^4$ K
  - So expect to suppress collapse/cooling of gas in halos with $T_{vir} < 2 \times 10^4$ K
  - This corresponds to $V_{vir} < 20$ km/s
- Numerical simulns => collapse of gas into halos supressed for $V_{vir} < V_{crit} \sim 30$ km/s
- Effect is to supress formation of galaxies in halos with $M \sim 10^8 - 10^{10}\ M_o$ after reionization
- Important for understanding dwarf galaxies
- But quantitatively not enough to solve any of the primary feedback problems

reminder about virial temperature T_{vir}

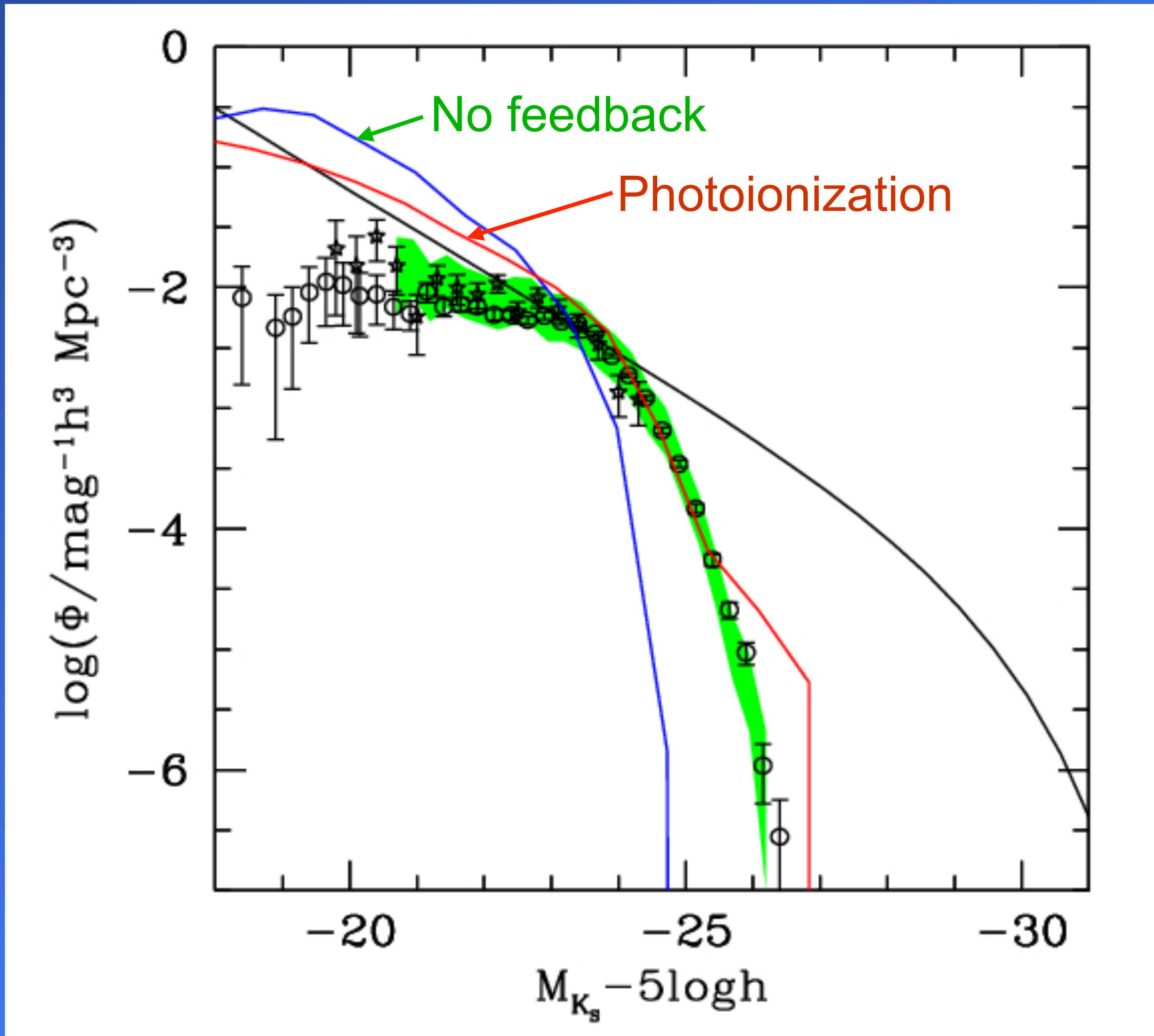
characteristic temperature for gas which falls into DM halo if NOT able to cool radiatively

$$T_{vir} = \frac{1}{2}\frac{\mu m_H}{k} V_{vir}^{\ 2} = \frac{1}{2}\frac{\mu m_H}{k}\frac{GM_{halo}}{r_{vir}}$$

$$T_{vir} \approx 4 \times 10^5 K \left(\frac{V_{vir}}{100 km/s}\right)^2$$

$$T_{vir} \approx 6 \times 10^5 K \left(\frac{M_{halo}}{10^{12} M_o}\right)^{2/3} (1+z)$$

Predicted galaxy LF including photoionization feedback



- including photoionization feedback in model reduces number of faint galaxies, but not enough to match observations

=> need additional feedback mechanism

Benson etal 2003

Supernova feedback

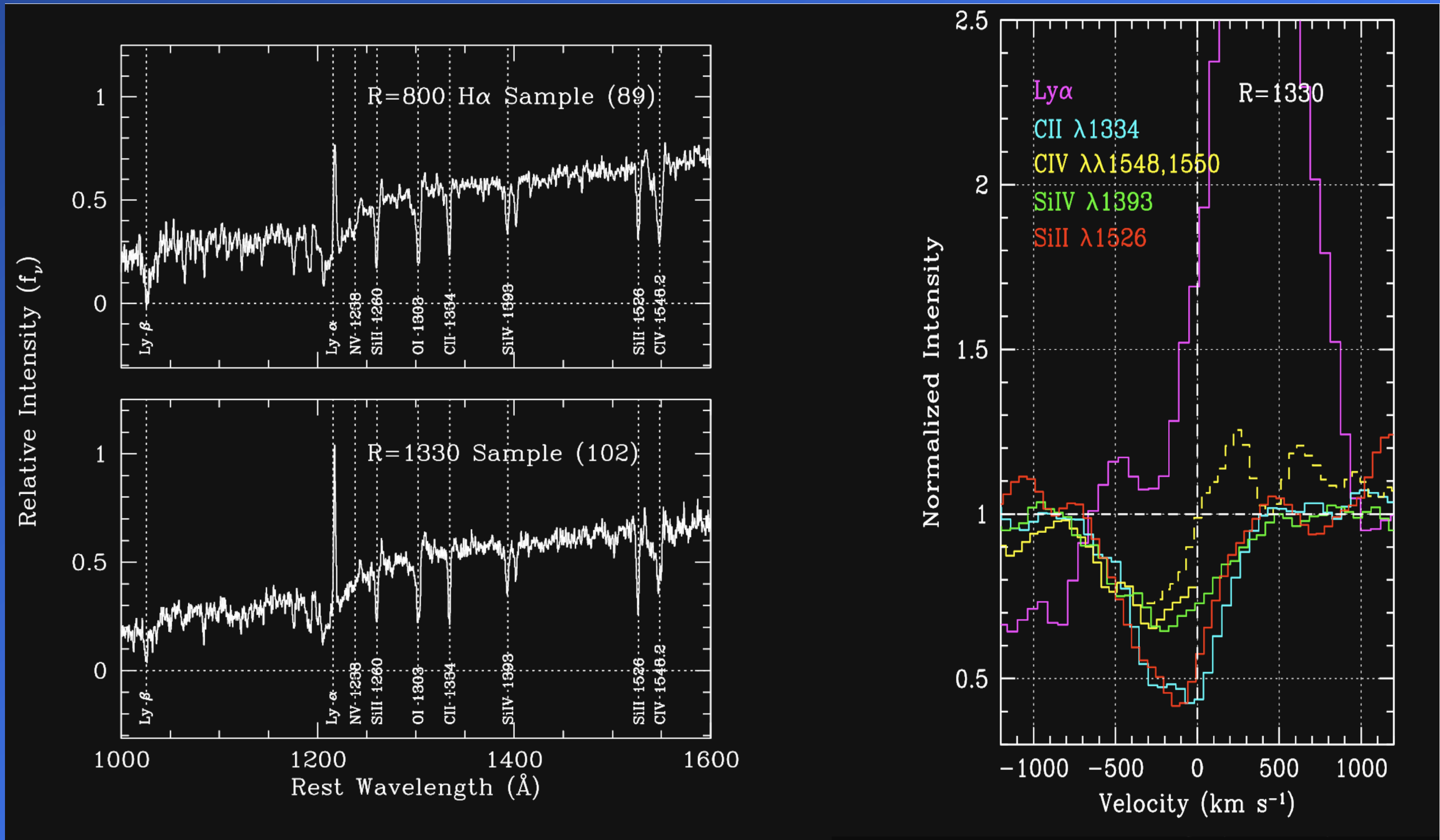
Observational evidence for gas ejection from galaxies due to supernova explosions:

- Galactic fountain in Milky Way halo
- Outflows from local starburst galaxies
- Winds from Lyman-break galaxies at high-z

Outflows from starburst galaxies

- large SFRs & SN rates
- hot gas seen in X-rays
- Hα filaments show outflowing gas to many kpc
- outflow in cone perpendicular to disk
- outflow velocity > circular velocity
- mass outflow rate ~ SFR

Outflows from high-z galaxies



Composite spectra of z~2-2.6 UV-selected galaxies

Velocity profiles in selected transitions relative to z_{sys}

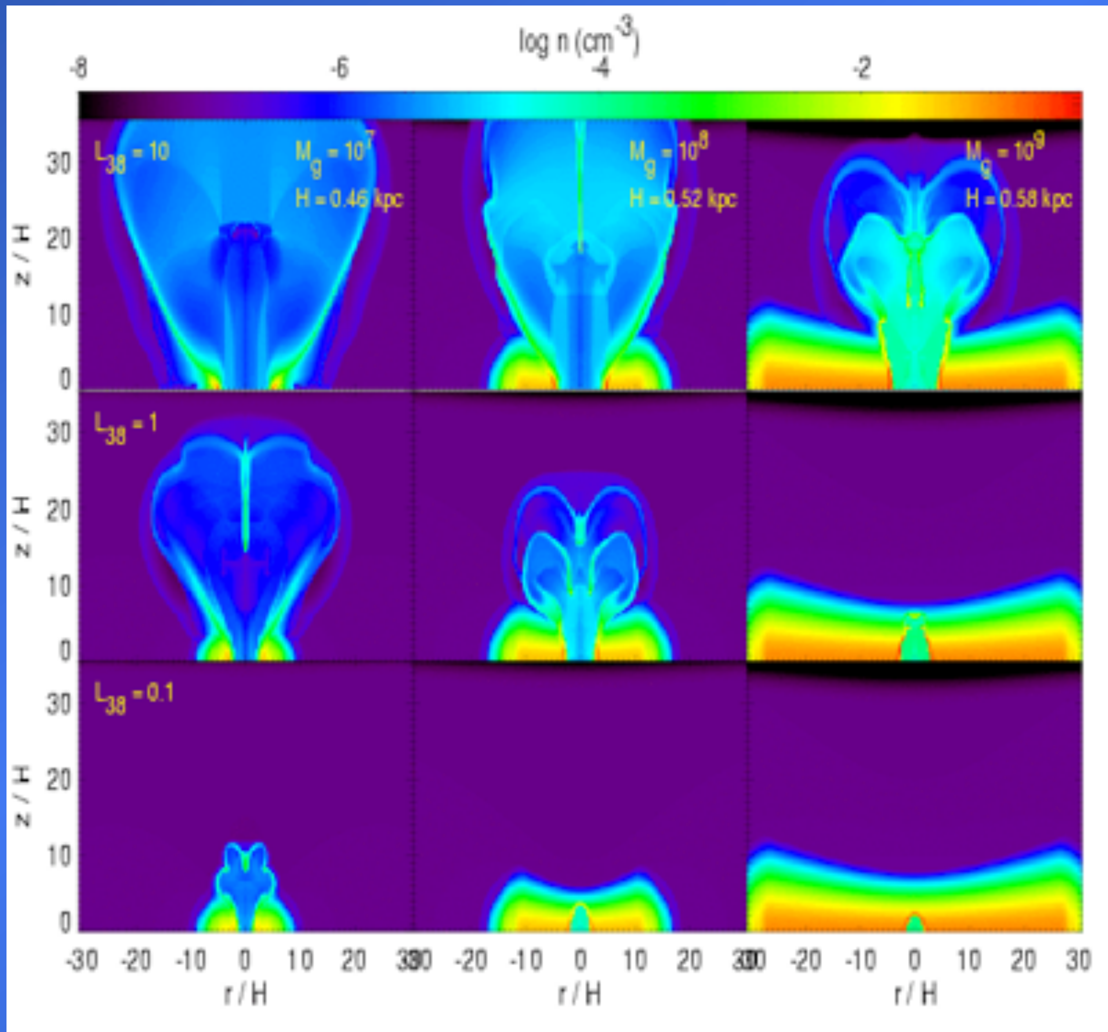
- blueshifted interstellar absorption lines & redshifted Lyα emission
- => outflows ubiquitous in high-z starforming galaxies

Steidel etal 2010

Numerical simulations of supernova feedback in dwarf disk galaxies

Blow-away

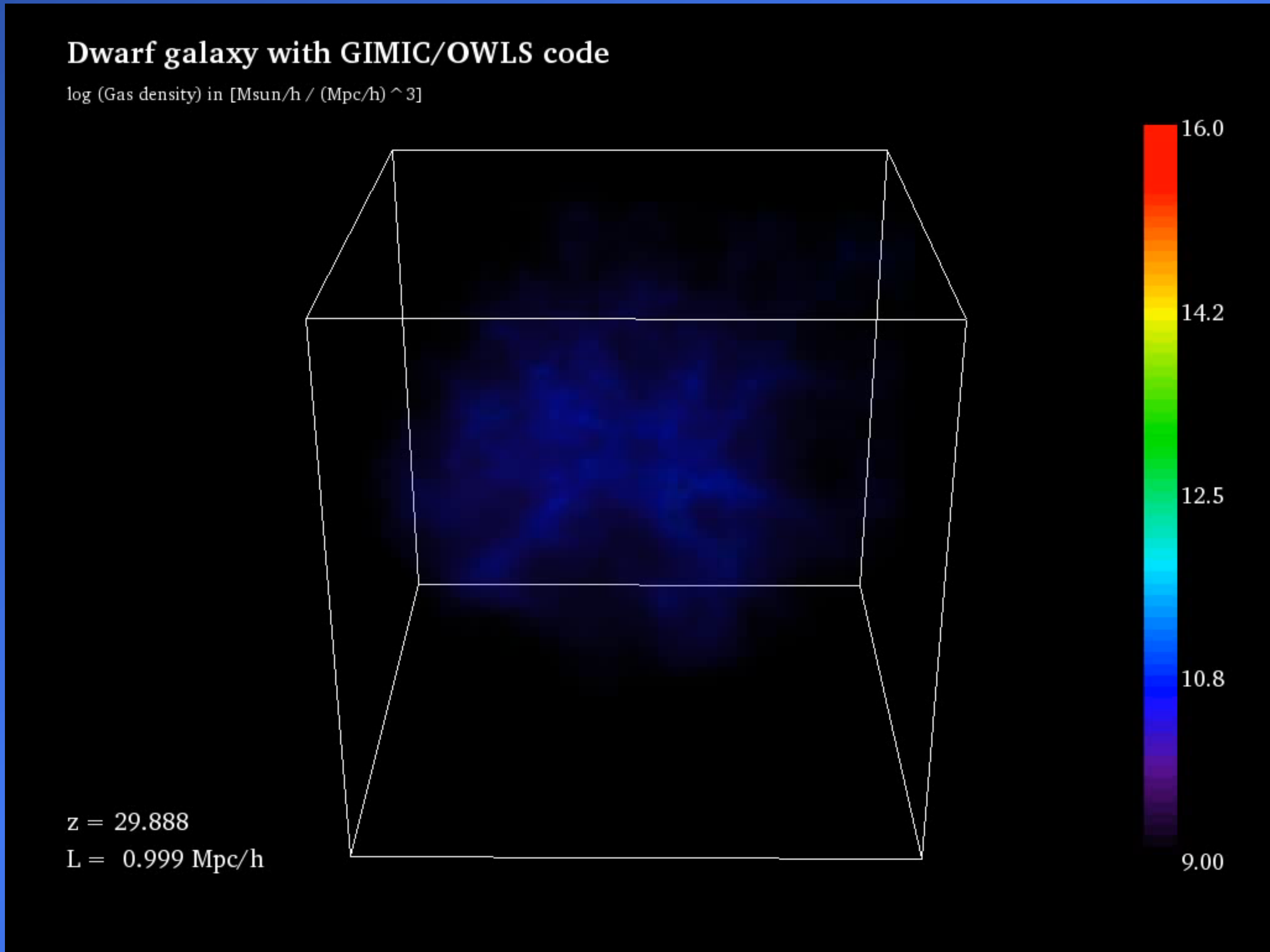
Blow-out



Injection of wind from central star cluster in disk

MacLow & Ferrara 1999

Numerical simulation of dwarf galaxy formation with photo-ionizn and SN feedback



Crain et al 2007

Simple estimate of supernova feedback

(Larson 1974, Dekel & Silk 1987)

- If form mass M_* of new stars, then total energy of Type II SN explosions is $\eta M_* E_{SN}$, where $E_{SN} = 10^{51}$ erg, and η = 1 SN/(100 M_o) for normal IMF
- Assume fraction ε_{ej} of this goes into driving outflow at escape speed V_{esc} , then total mass ejected is

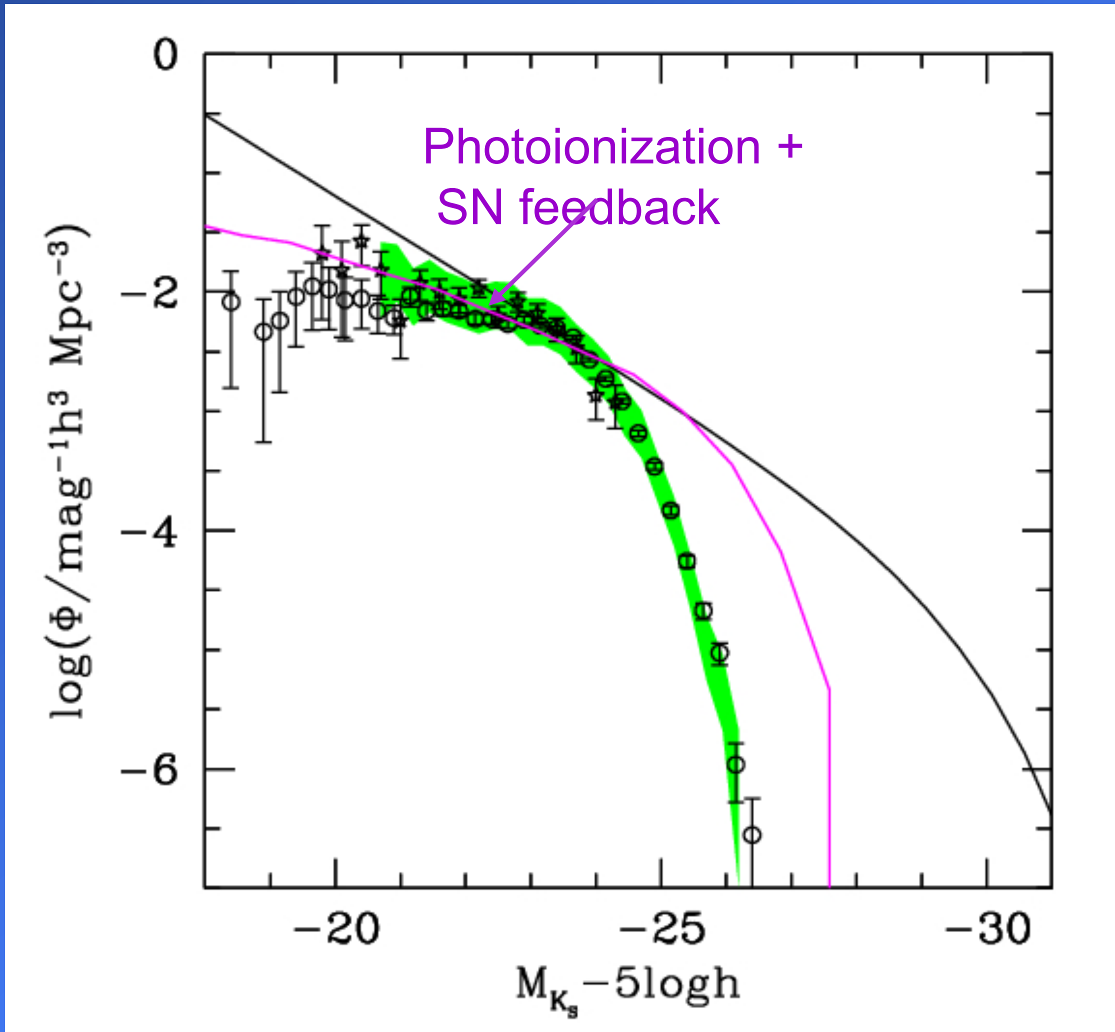
  $$1/2\ M_{ej} V_{esc}^2 = \varepsilon_{ej}\, \eta\, M_*\, E_{SN}$$

- Take $V_{esc} = 2\ V_c$, then ejected mass is

  $$M_{ej} = M_* (V_{crit}/V_c)^2$$

  where $V_{crit} = 500\ \varepsilon_{ej}^{1/2}$ km/s
- for plausible ε_{ej}~0.1, V_{crit}~200 km/s => large effect on most galaxies

Predicted galaxy LF including SN feedback



- include gas cooling + photoionization + SN feedback

=> can explain faint end of LF & condensed baryon fraction

- however, too many bright galaxies

=> additional feedback – AGN?

Benson etal 2003