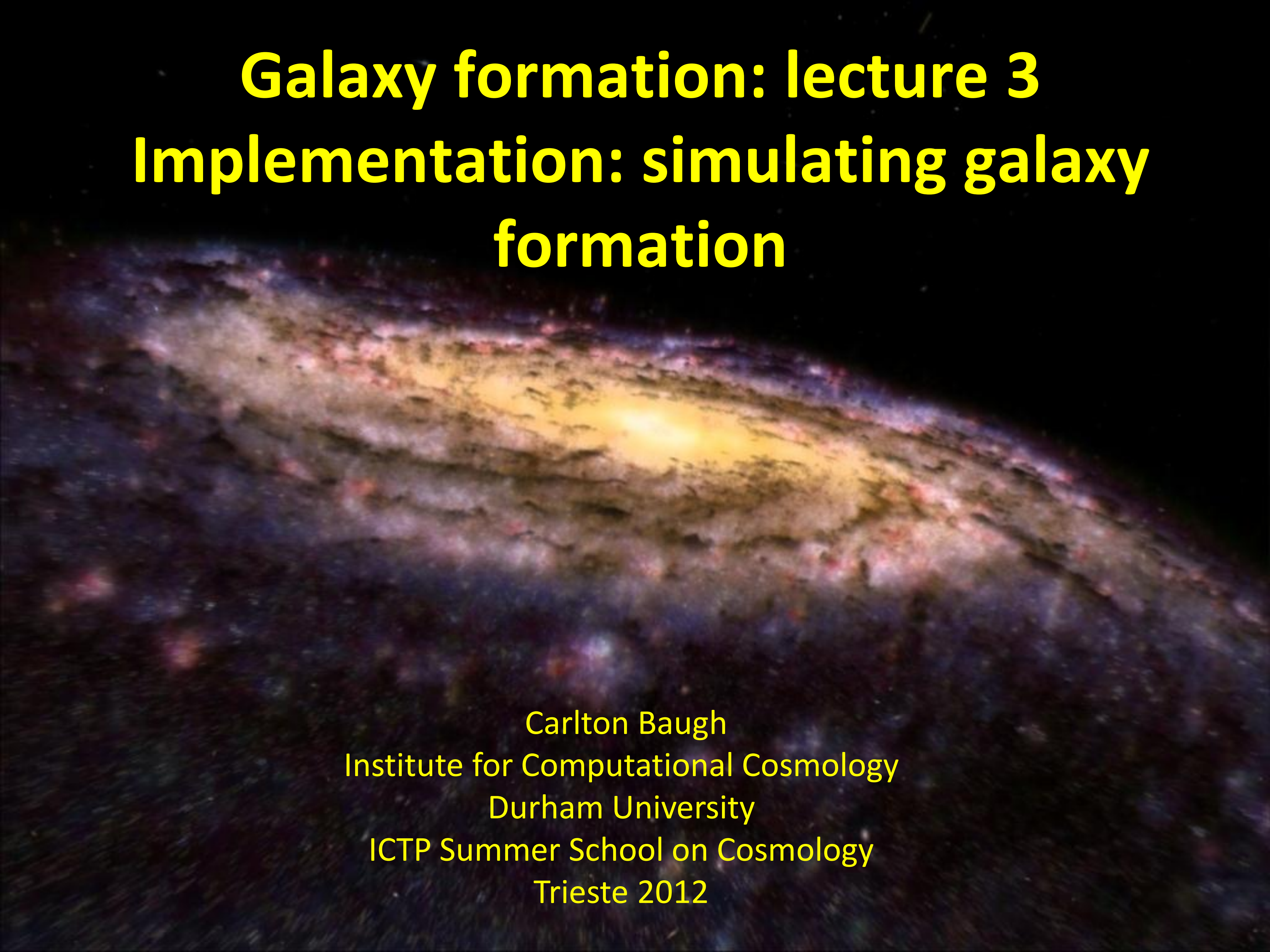


# Galaxy formation: lecture 3
# Implementation: simulating galaxy formation

Carlton Baugh
Institute for Computational Cosmology
Durham University
ICTP Summer School on Cosmology
Trieste 2012

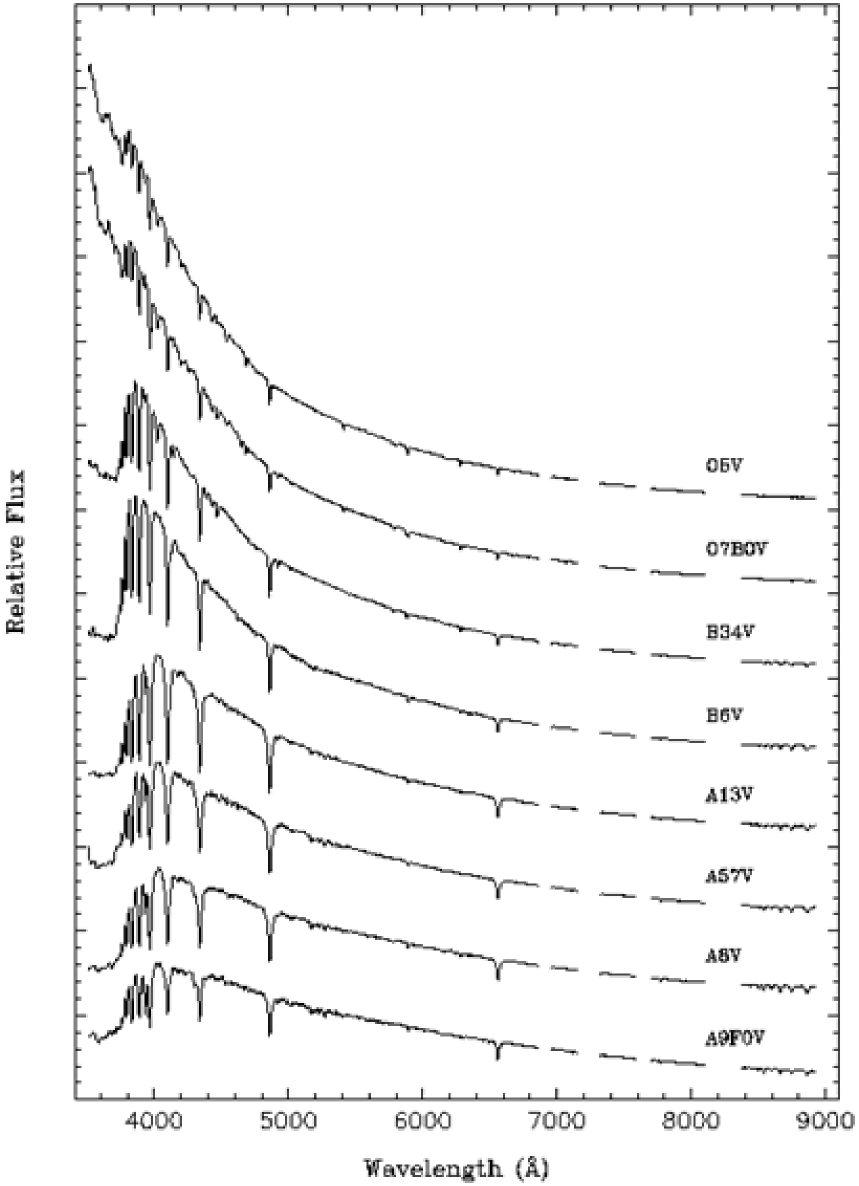
Hot O, B and A type stars.

Steeply rising continua to the blue (Surf T ~ 10-30K).

Dominated by absorption lines of Hydrogen (n=2 gr state).

The Balmer break at 3646 angstrom marks the termination of the hydrogen Balmer series and is strongest in A-type stars. The break strength does not monotonically increase with age, but reaches a maximum in stellar populations of intermediate ages (0.3 - 1 Gyr).

For very high redshift galaxies, the Lyman break (n=1) may be used.

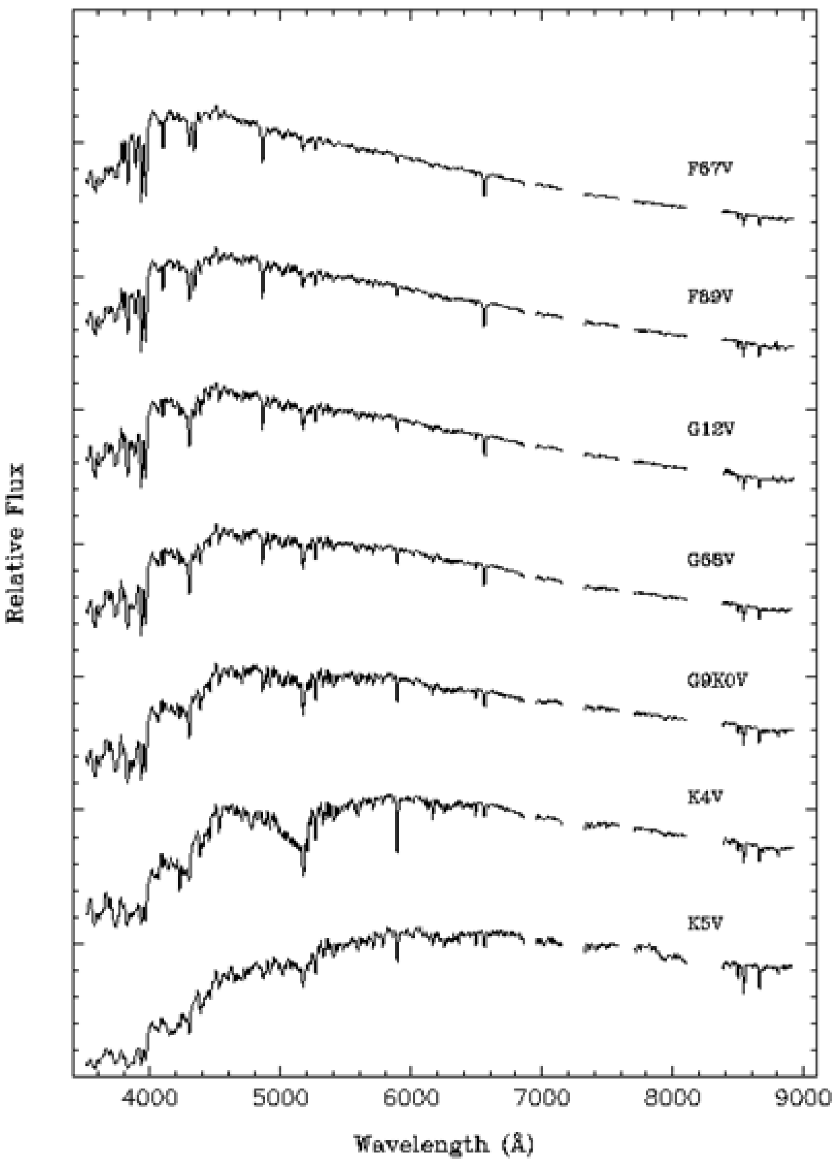


(slide from Margaret Hanson)

Cool stars: F, G and K type.

Hydrogen less prominent.
Ionized metals begin to appear (H and K lines of Ca II 3933, 3968A).

The 4000 angstrom break arises because of an accumulation of absorption lines of mainly ionized metals. As the opacity increases with decreasing stellar temperature, the 4000 angstrom break gets larger with older ages, and it is largest for old and metal-rich stellar populations.



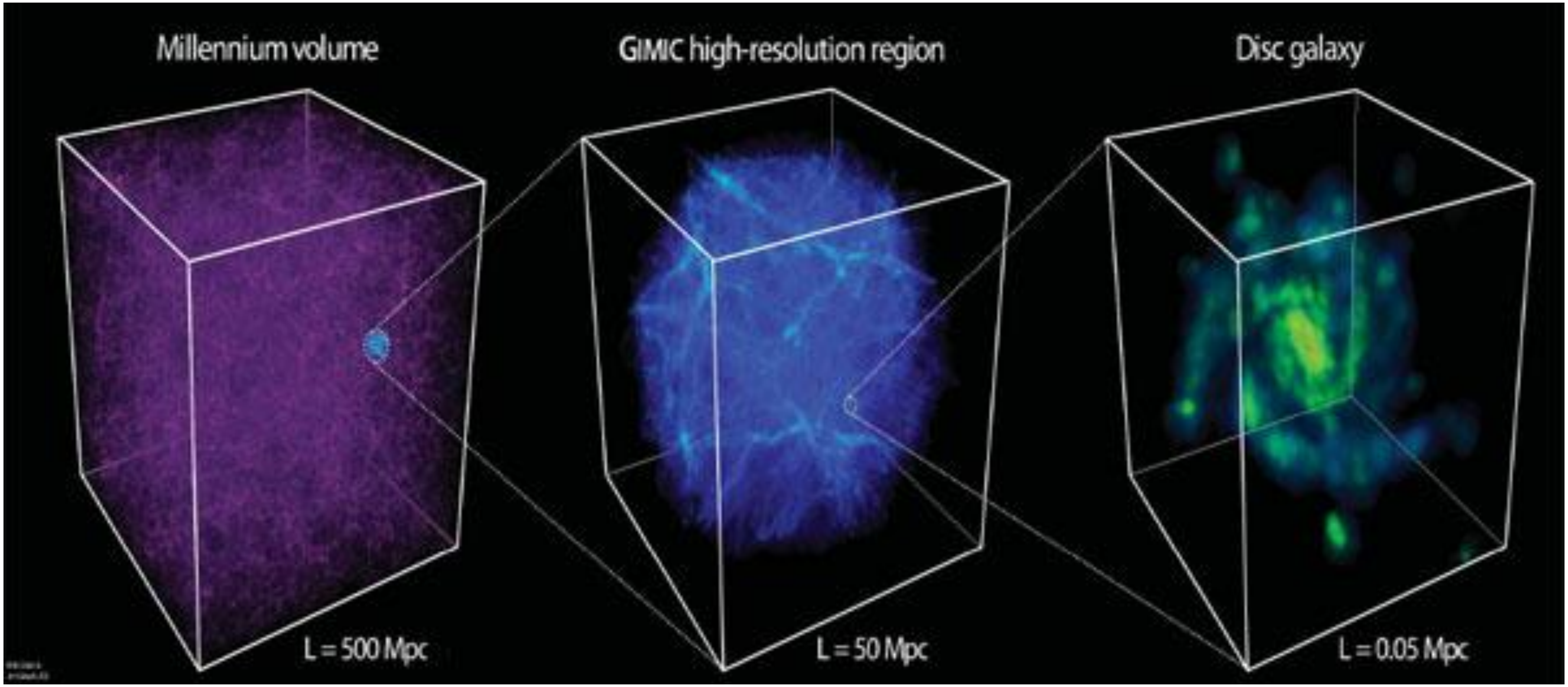
(slide from Margaret Hansen)

# Sub-grid physics

“ …..a theoretical swindle…..”

Silk & Mamon 2012

# Why do we need sub-grid physics?



Huge dynamic range required to follow structure in cosmological setting

Graphic by Rob Crain & Jim Geach

# Formation of the first star

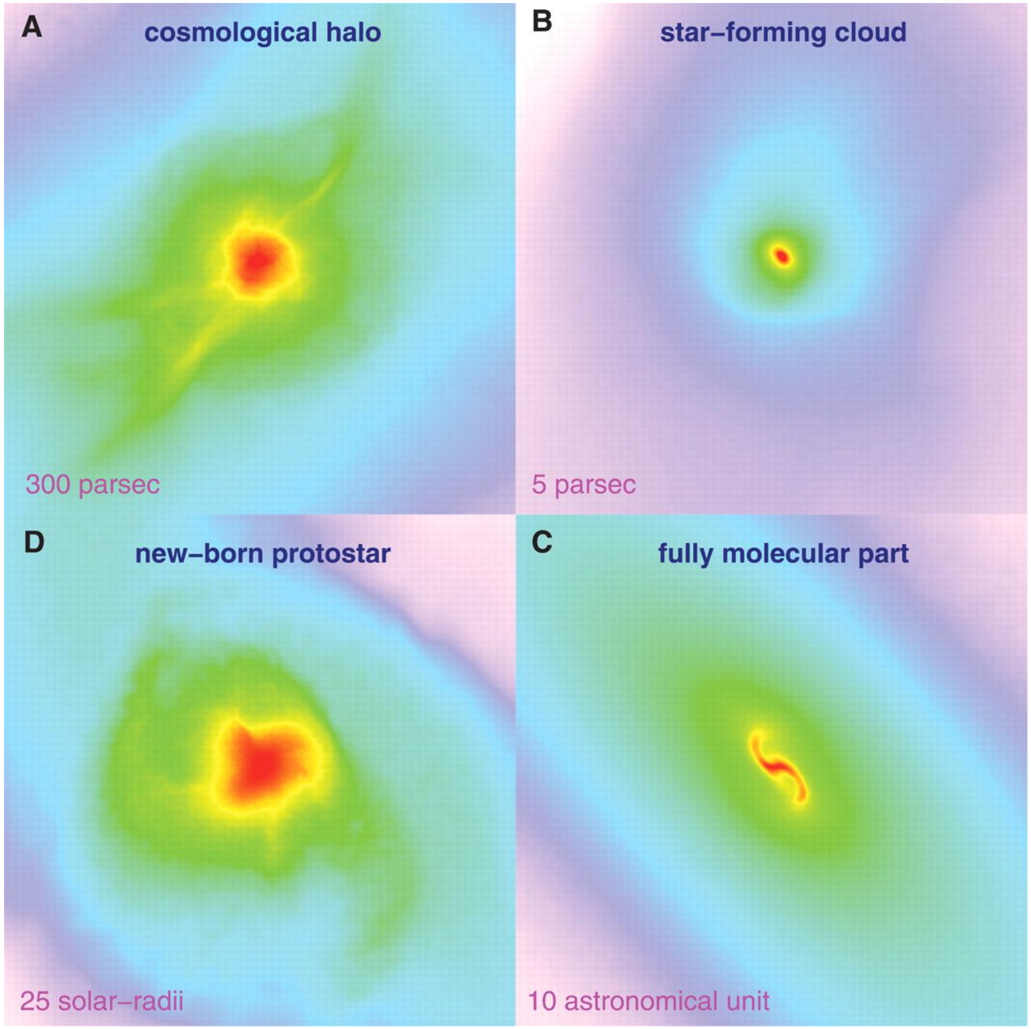
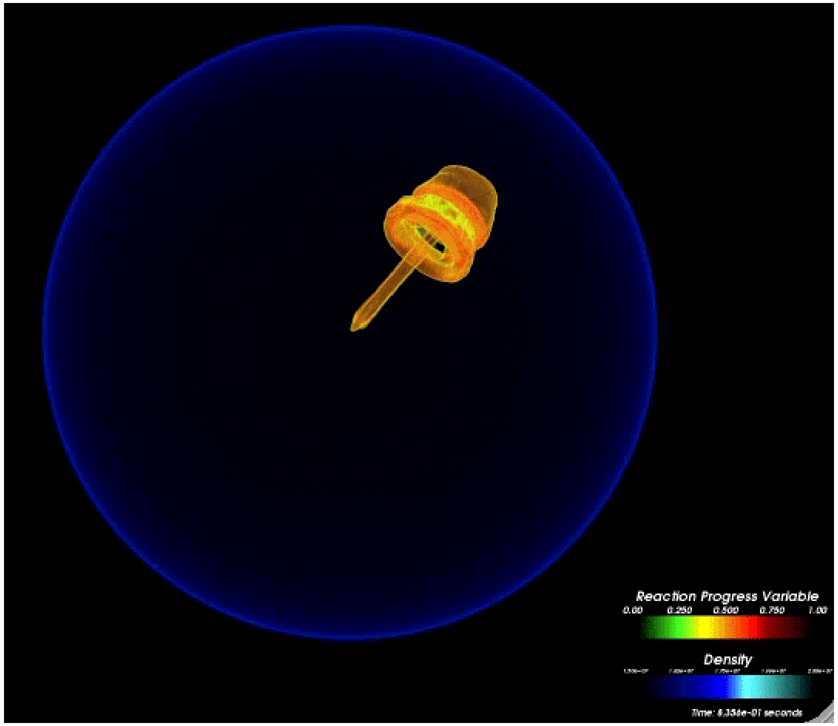
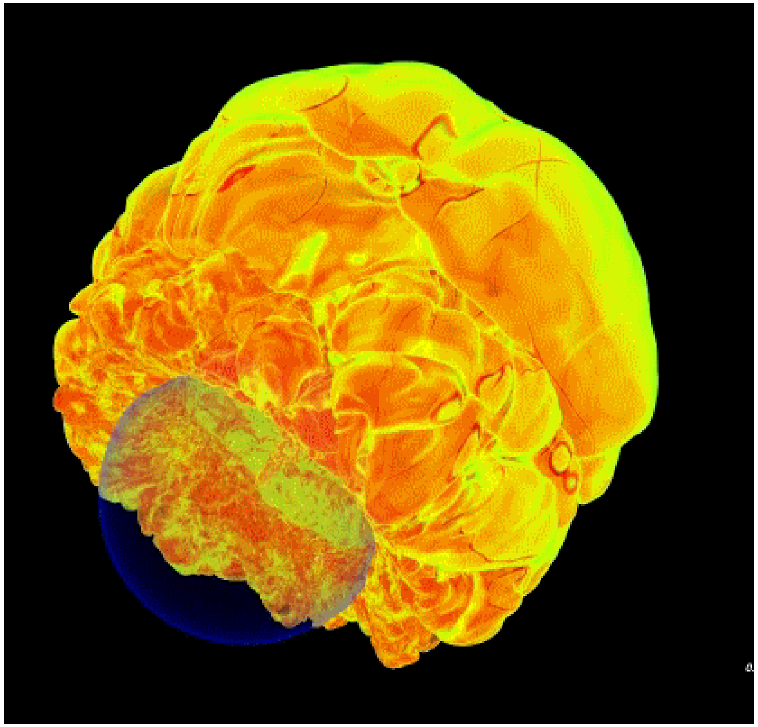


**Fig. 1. Projected gas distribution around the protostar**

**N. Yoshida et al., Science 321, 669 -671 (2008)**

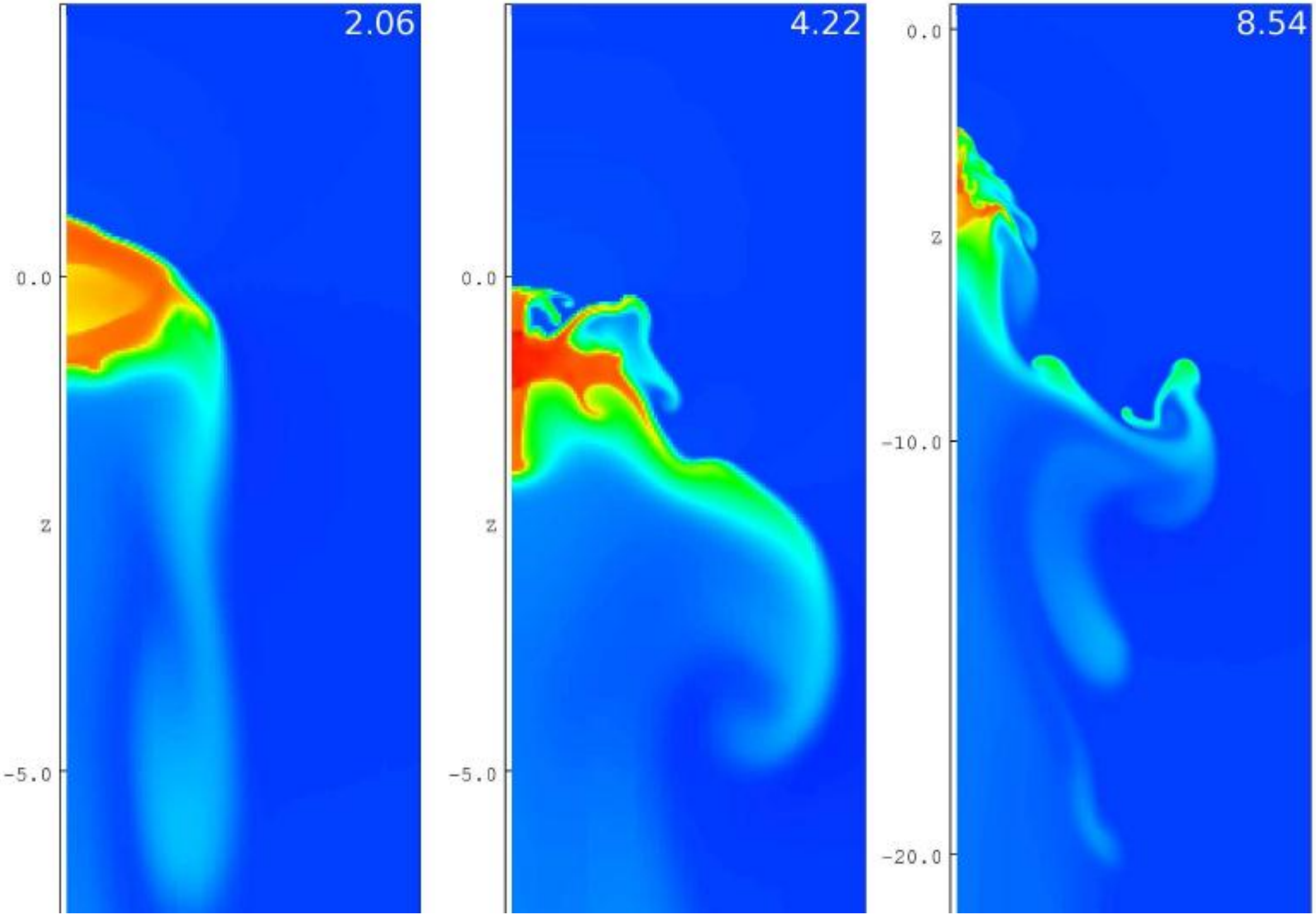
# Simulating the end of a massive star





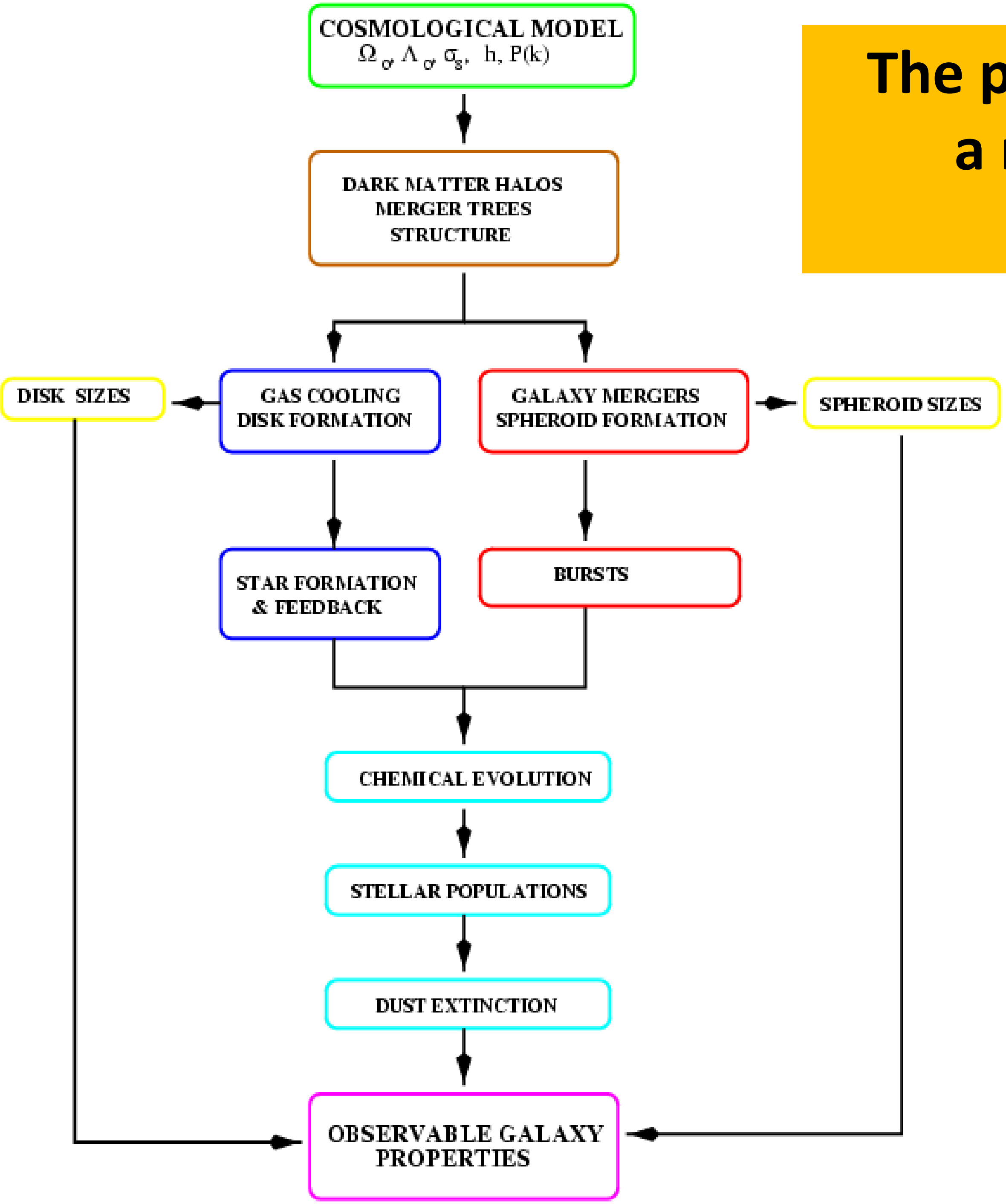
FLASH AMR simulation of off-centre SN – multiscale physics – peta scale computing

# Wind/cloud interactions in the ISM



Pittard et al. 2010

# The physics processes in a model of galaxy formation



COSMOLOGICAL MODEL
$\Omega_0, \Lambda_0, \sigma_8$, h, P(k)

DARK MATTER HALOS
MERGER TREES
STRUCTURE

DISK SIZES

GAS COOLING
DISK FORMATION

GALAXY MERGERS
SPHEROID FORMATION

SPHEROID SIZES

STAR FORMATION
& FEEDBACK

BURSTS

CHEMICAL EVOLUTION

STELLAR POPULATIONS

DUST EXTINCTION

OBSERVABLE GALAXY
PROPERTIES

# Numerical techniques

**Dissipationless gravitational instability**

- N-body simulation

**Dissipative baryonic physics:**

- Gas dynamics simulations
  - Smooth Particle Hydrodynamics
  - Adaptive Mesh Refinement
  - Deformable meshes
- Semi-analytical modelling

# The N-body method uses a finite set of particles to sample the underlying distribution function

## "MONTE-CARLO" APPROACH TO COLLISIONLESS DYNAMICS

We discretize in terms of N particles, which approximately move along characteristics of the underlying system.

$$\ddot{\mathbf{x}}_i = -\nabla_i \, \Phi(\mathbf{x}_i)$$

$$\Phi(\mathbf{x}) = -G \sum_{j=1}^{N} \frac{m_j}{[(\mathbf{x} - \mathbf{x}_j)^2 + \epsilon^2]}$$

The need for **gravitational softening**:

- Prevent large-angle particle scatterings and the formation of bound particle pairs.
- Ensure that the two-body relaxation time is sufficiently large.
- Allows the system to be integrated with low-order intergations schemes.

Needed for faithful collisionless behaviour

(from Volker Springel)

# Two conflicting requirements complicate the study of **hierarchical** structure formation

## DYNAMIC RANGE PROBLEM FACED BY COSMOLOGICAL SIMULATIONS

Want **small particle mass** to resolve internal structure of halos

Want **large volume** to obtain respresentative sample of universe

*need large* N

*where N is the particle number*

**Problems due to a small box size:**

- Fundamental mode goes non-linear soon after the first halos form. ⇨ Simulation cannot be meaningfully continued beyond this point.
- No rare objects (the first halo, **rich** galaxy clusters, etc.)

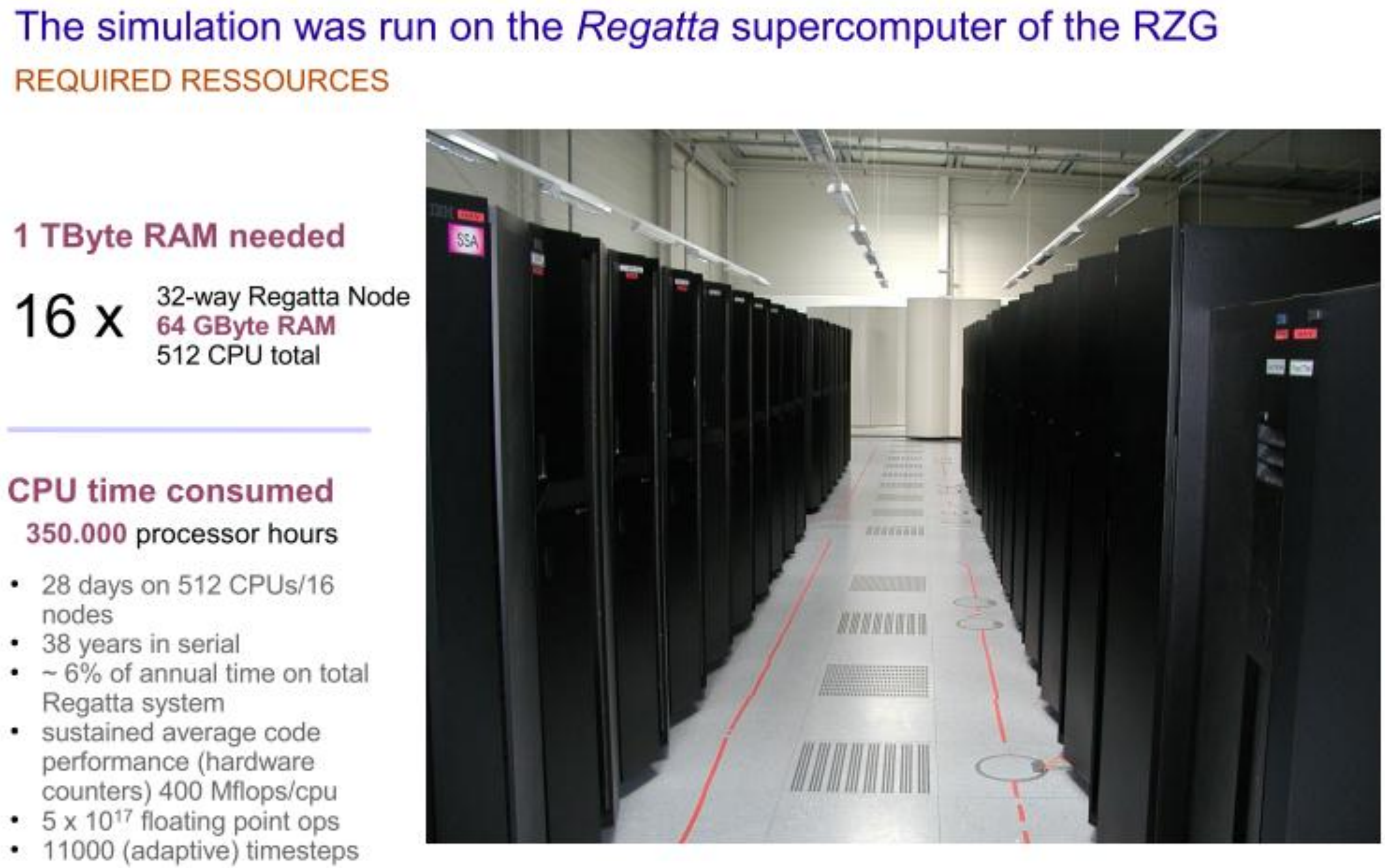
**Problems due to a large particle mass:**

- Physics cannot be resolved.
- Small galaxies are missed.

At any given time, halos exist on a large range of mass-scales !

(from Volker Springel)

# The Millennium Simulation



The simulation was run on the *Regatta* supercomputer of the RZG

REQUIRED RESSOURCES

**1 TByte RAM needed**

16 x 32-way Regatta Node
**64 GByte RAM**
512 CPU total

**CPU time consumed**

**350.000** processor hours

- 28 days on 512 CPUs/16 nodes
- 38 years in serial
- ~ 6% of annual time on total Regatta system
- sustained average code performance (hardware counters) 400 Mflops/cpu
- $5 \times 10^{17}$ floating point ops
- 11000 (adaptive) timesteps

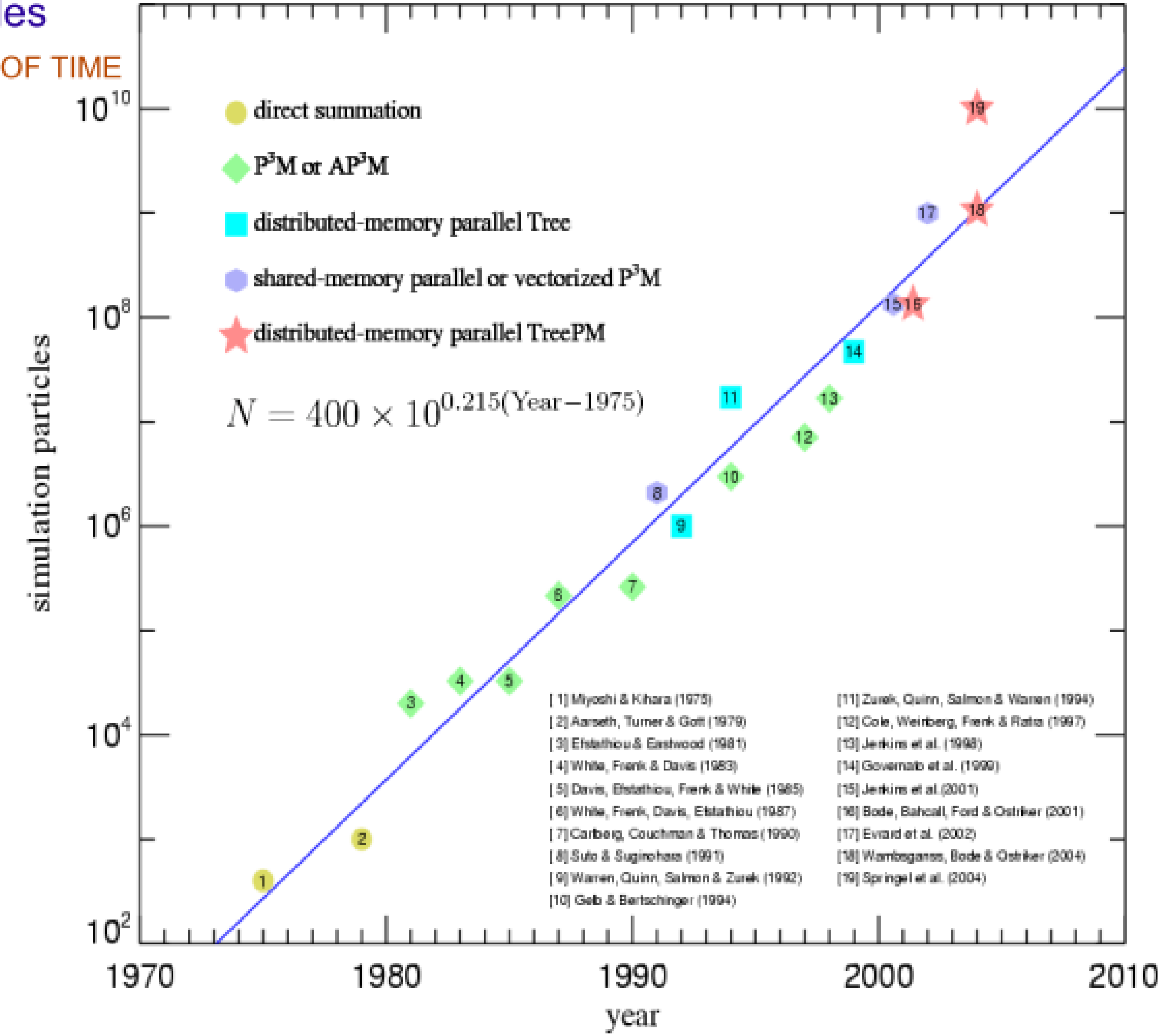
**Springel et al. 2005**

# Cosmological N-body simulations have grown rapidly in size over the last three decades

"**N**" AS A FUNCTION OF TIME

- Computers double their speed every 18 months (Moore's law)
- N-body simulations have doubled their size every 16-17 months
- Recently, growth has accelerated further.

  The Millennium Run should have become possible in 2010 – we have done it in 2004 !



(from Volker Springel)

# SPH

Solve fluid dynamics equations using Lagrangian scheme with particles:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} + \rho \nabla \cdot \mathbf{v} = 0,$$

$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} + \frac{\nabla P}{\rho} = 0,$$

$$\frac{\mathrm{d}u}{\mathrm{d}t} + \frac{P}{\rho} \nabla \cdot \mathbf{v} = 0,$$

Estimation of continuum fluid properties from particles:

$$\rho_i = \sum_{j=1}^{N} m_j W(\mathbf{r}_i - \mathbf{r}_j, h_i).$$

Usually a cubic spline is adopted with $W(r, h) = w(\frac{r}{2h})$, and

$$w_{3\mathrm{D}}(q) = \frac{8}{\pi} \begin{cases} 1 - 6q^2 + 6q^3, & 0 \le q \le \frac{1}{2}, \\ 2(1-q)^3, & \frac{1}{2} < q \le 1, \\ 0, & q > 1, \end{cases}$$

**SPH cannot follow shocks unless artificial viscosity invoked**

Springel Annual Reviews A&A 2010

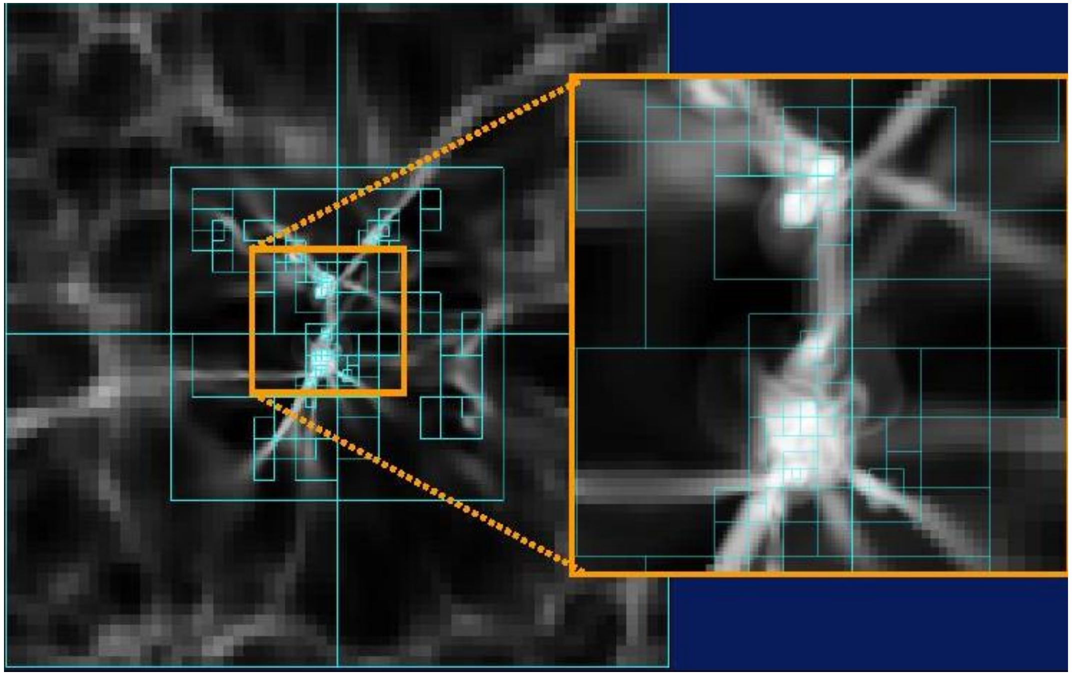
# AMR

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} + \rho \nabla \cdot \mathbf{v} = 0,$$

$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} + \frac{\nabla P}{\rho} = 0,$$

$$\frac{\mathrm{d}u}{\mathrm{d}t} + \frac{P}{\rho} \nabla \cdot \mathbf{v} = 0,$$

**Solve discretized version of fluid equation on mesh**



(image from Miniati)

# Gas simulations & Semi-analytic modelling

**Gas simulations:**

- More direct
- (Sometimes) more information
- Challenged by dynamic range
- Still use ‘sub-grid’ physics (=semi-analytics)

**Semi-analytic models:**

- More generalised calculation e.g. Spherical symmetry
- Faster
- Flexible
- Modular
- Hybrid approach?

# Semi-analytic models - are we kidding ourselves?

The 11th Birmingham-Nottingham Extragalactic Workshop

June 24-25th 2008

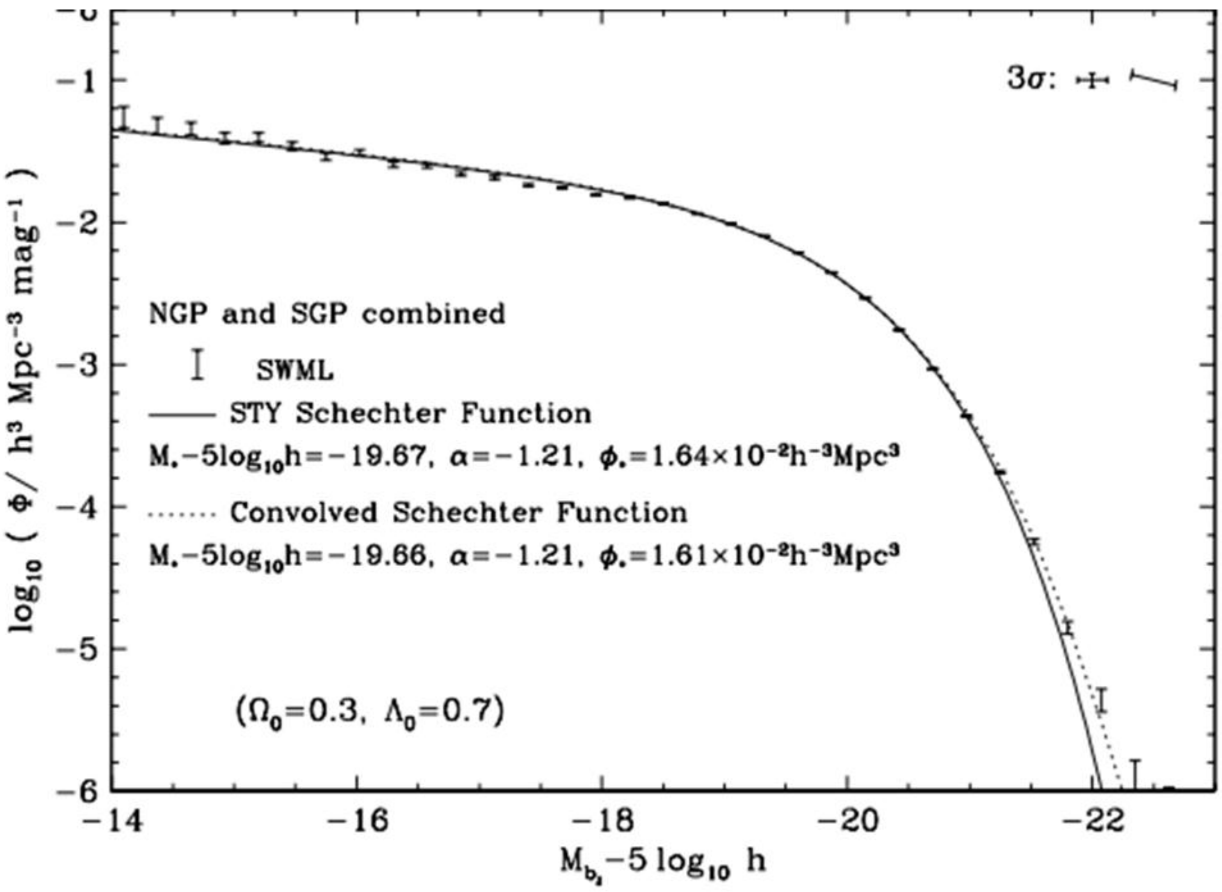
www.sr.bham.ac.uk/workshop/2008/

# Sub-grid physics

- Precise physics uncertain
- Can write down physically motivated differential equations to solve e.g. for star formation
- Parameters are set by requiring model predictions to match observations
- Not statistical parameters

# An example of statistical parameters

$$\frac{\mathrm{d}\Phi}{\mathrm{d}M} = 0.921\,\Phi^*\,(L/L^\star)^{\alpha+1}\,\exp(-L/L^\star)$$



# An example:
# Modelling star formation in galaxies

**Parametric form for the SF law**

(total cold gas mass/SF timescale)

$$\psi = \frac{M_{\rm cold}}{\tau_\star}$$

What is $\tau_\star$? →

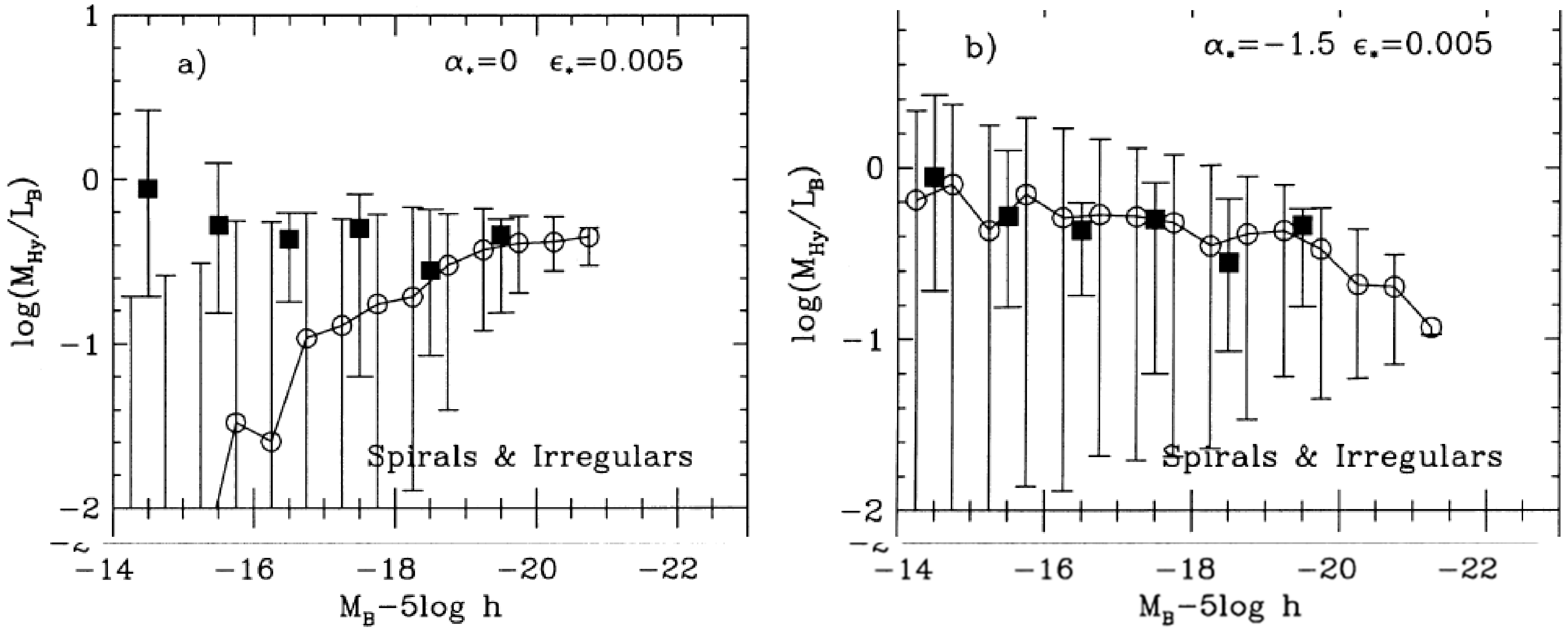
$$\tau_\star = \frac{\tau_{\rm disk}}{\boxed{\epsilon_\star}} \left(V_{\rm disk}/V_0\right)^{\boxed{\alpha_\star}}$$

**Cole et al. (2000)**

**Two free-parameters to model the SF activity**

**Lagos et al. 2011**

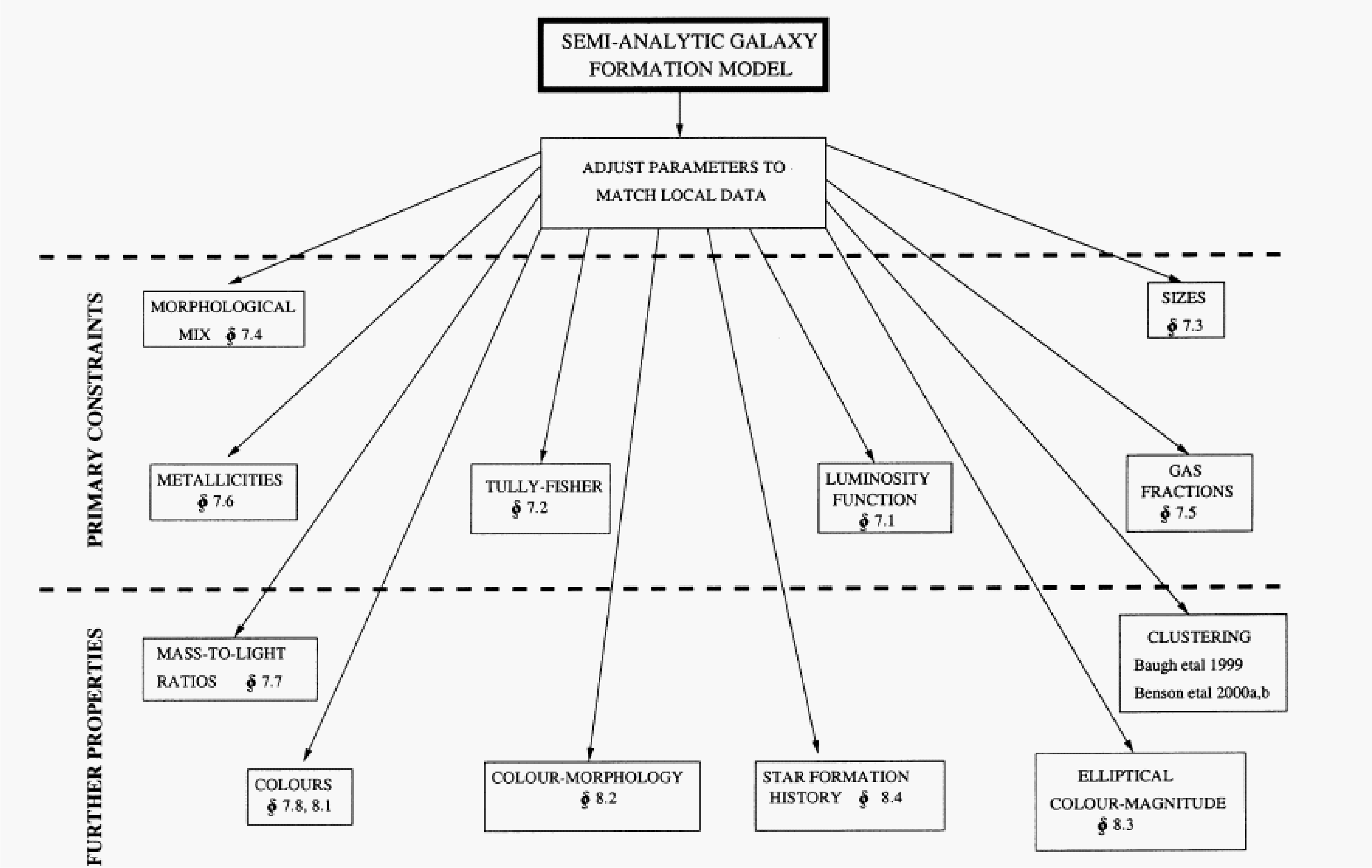
# Fitting “physical” parameters



**By changing slope, longer timescale for SF in faint galaxies, higher gas content**

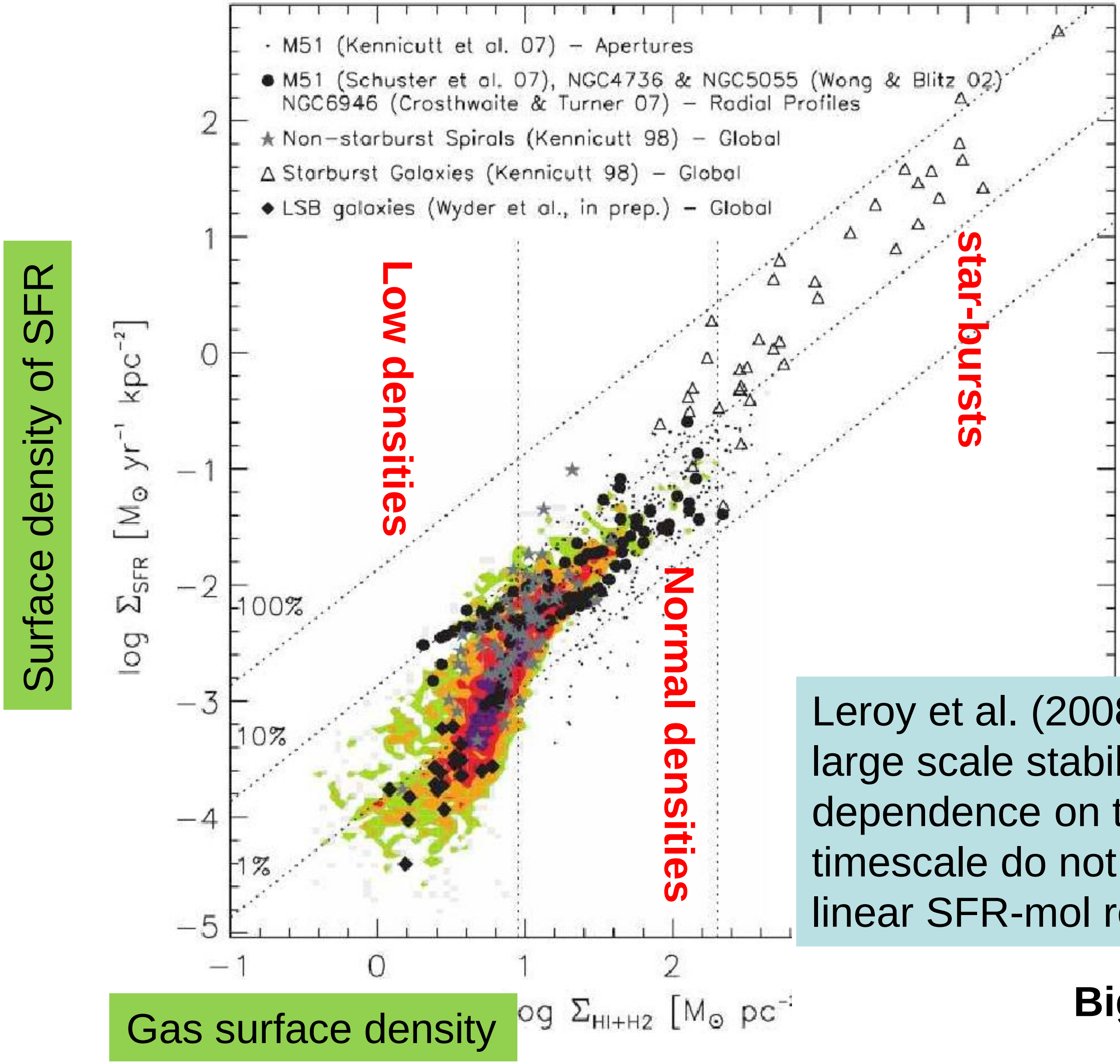
**Cole et al. 2000**

# Setting model parameters



Cole et al. 2000

# An improved SF model



Leroy et al. (2008): thresholds of large scale stability, or single dependence on the orbital or free-fall timescale do not offer good fit to linear SFR-mol relation.

**Bigiel et al. (2008)**

# Empirical and theoretical SF laws to test

parameter-free

## Empirical laws

(ii) The Kennicutt-Schmidt law (KS) →

$$\Sigma_{\rm SFR} = A\,\Sigma_{\rm gas}^{1.4}$$

$$\Sigma_{\rm crit}$$

**(i) The Blitz & Rosolowski law (BR)**

**Leroy et al. (2008), Bigiel et al. (2008)** →

$$\frac{\Sigma({\rm H_2})}{\Sigma({\rm HI})} = \left(\frac{P_{\rm ext}}{P_0}\right)^{\alpha}$$

$$\Sigma_{\rm SFR} = \nu_{\rm SF}\,\Sigma_{\rm mol}$$

---

## Theoretical laws

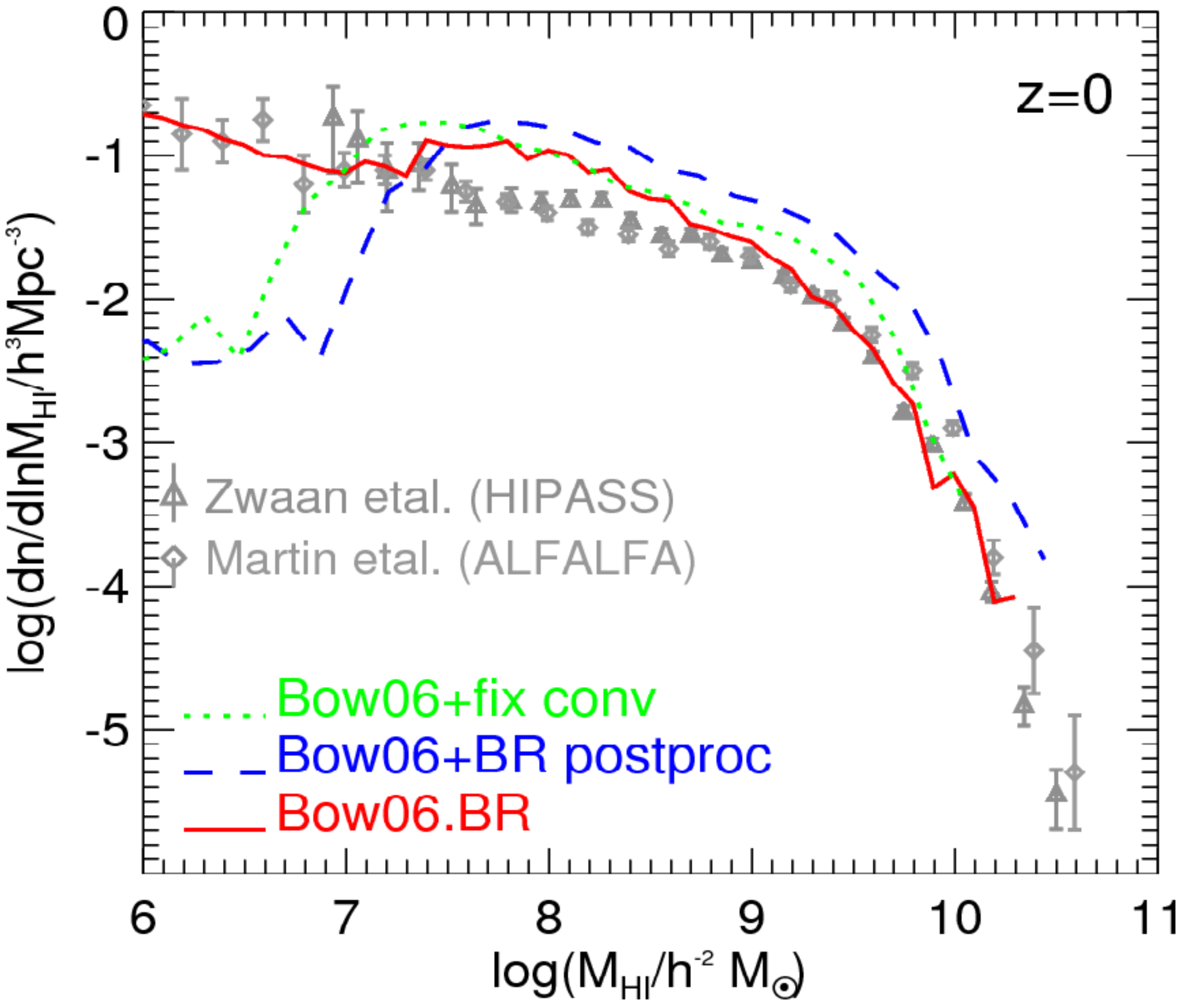
**(iii) The Krumholz, McKee & Tumlinson theoretical law (KMT)**

$$\Sigma_{\rm SFR} = \nu_{\rm SF}(\Sigma_{\rm gas})\, f_{\rm mol}\,\Sigma_{\rm gas}$$

$$\nu_{\rm SF}(\Sigma_{\rm gas}) = \nu_{\rm SF}^{0} \times \begin{cases} \left(\frac{\Sigma_{\rm gas}}{\Sigma_0}\right)^{-0.33}, & \frac{\Sigma_{\rm gas}}{\Sigma_0} < 1 \\ \left(\frac{\Sigma_{\rm gas}}{\Sigma_0}\right)^{0.33}, & \frac{\Sigma_{\rm gas}}{\Sigma_0} > 1 \end{cases}$$

**Lagos et al. 2011**

# New predictions from improved model: The mass function of atomic hydrogen



**Lagos et al. 2011**

# More on feedback

# Parameterized outflow models

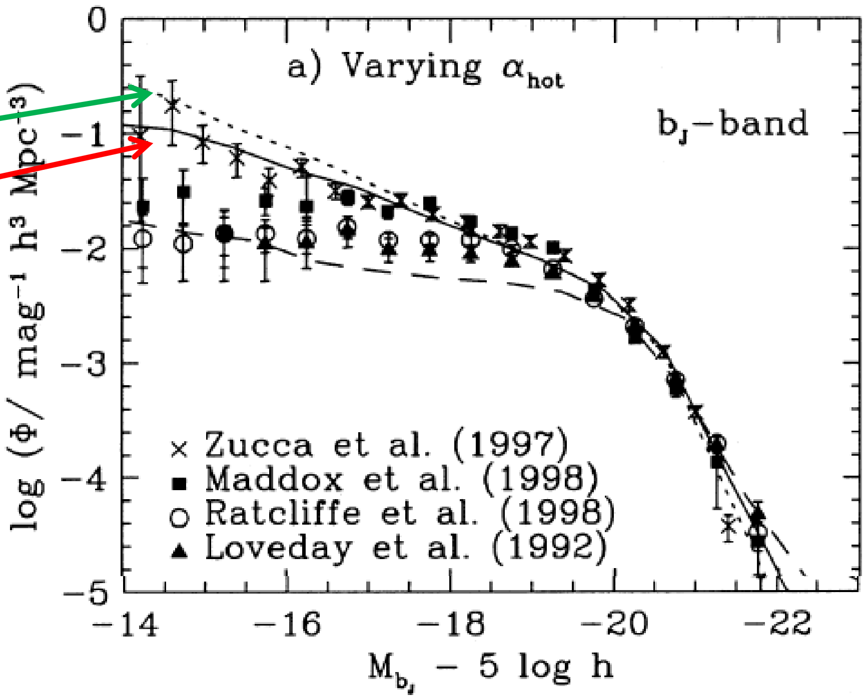
**Wrote down a mass outflow rate in terms of the SFR (which traces SNeII rate)**

$$\dot{M}_{\rm eject} = \beta\psi.$$

$$\beta = (V_{\rm H}/V'_{\rm hot})^{-\alpha'_{\rm hot}}$$

Simple arguments for the exponent:

alpha_hot = 1 (momentum cons.)
alpha_hot = 2 (energy cons.)



**Cole et al 2000**

# A dynamical model of Sne winds

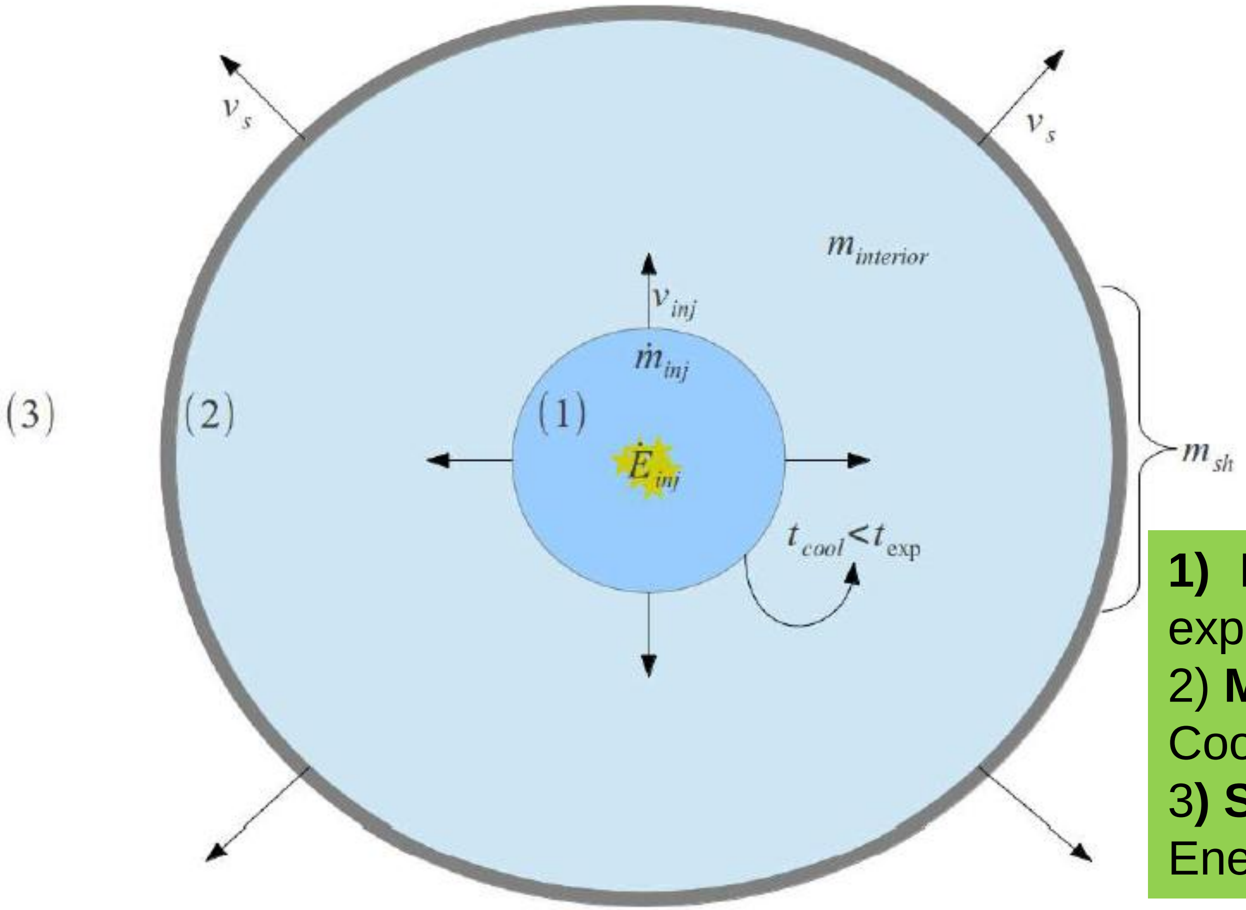


**Figure 1.** Schematic view of the inner structure of bubbles in the dynamical model described in §2. The energy injection point at the centre of the bubble is from SNe, which inject energy at a rate $\dot{E}_{\rm inj}$. The pressurised region right next to the energy injection point expands adiabatically (zone 1 in the diagram). When the expansion time exceeds the cooling time (represented by change of colour from the inner to the outer filled circle), the bubble losses energy radiatively and expands through momentum conservation (zone 2 in the diagram). The shock front driven by the wind interaction with the ISM is represented by the dense region in contact with the diffuse ISM (zone 3 in the diagram; dark grey ring).

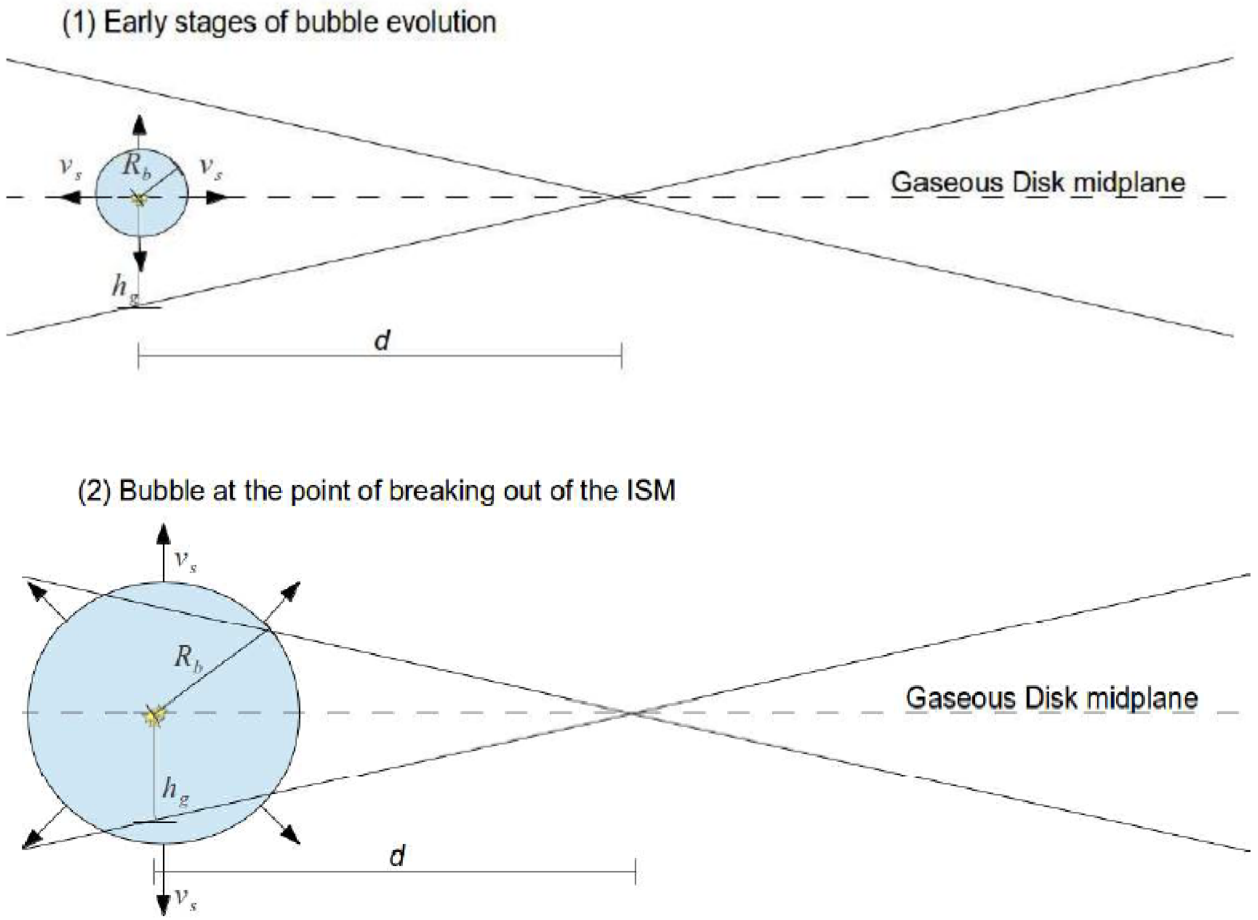
1) **Energy conserving**: expansion time << cooling time

2) **Momentum conserving**: Cooling time << expansion time

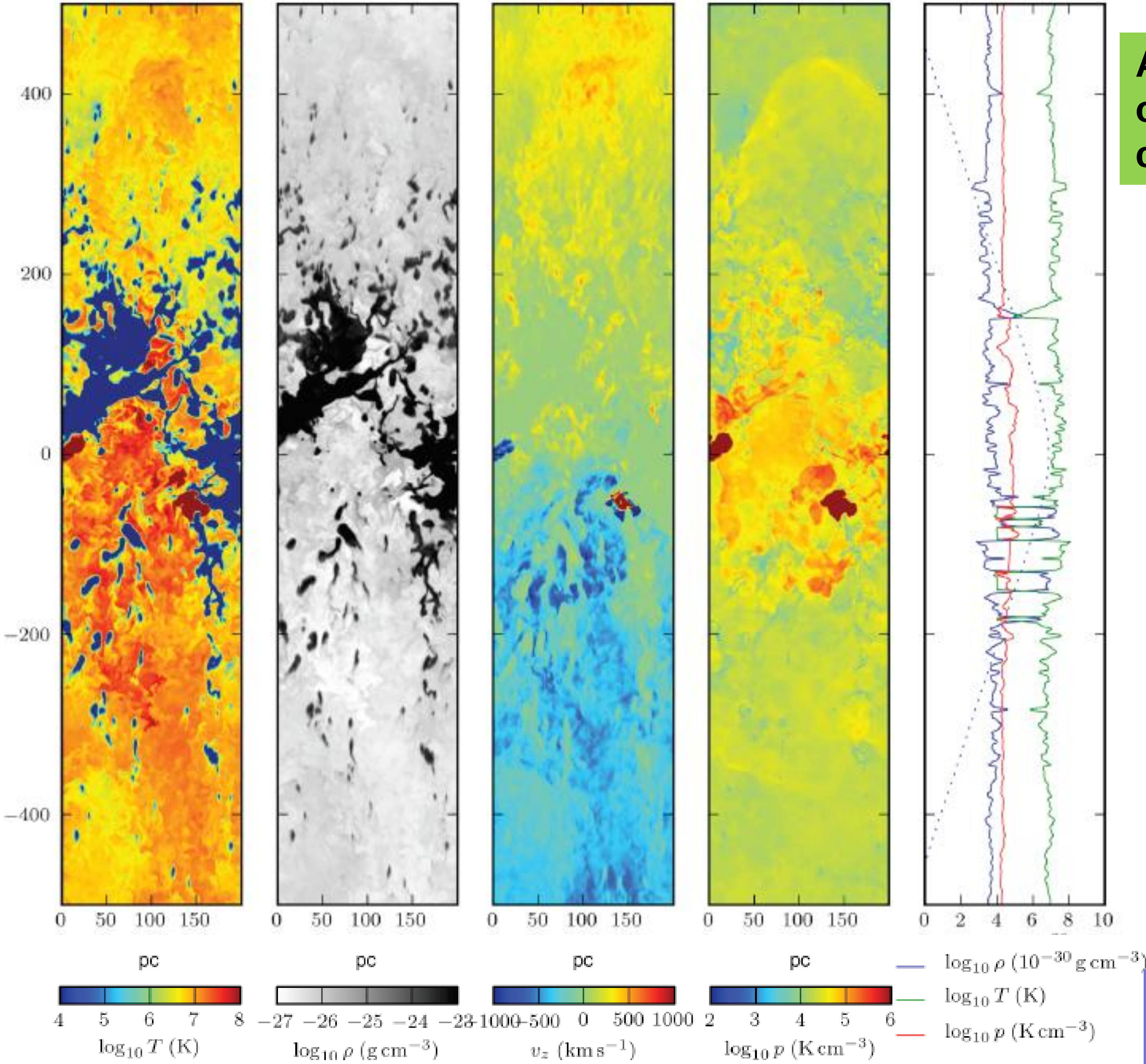
3**) Self-similar expansion**: Energy injection switches off

Monaco 2004
Bertone et al. 2005
**Lagos et al. 2012**
See review by:
McKee & Ostriker 2007

# Bubble expansion and escape



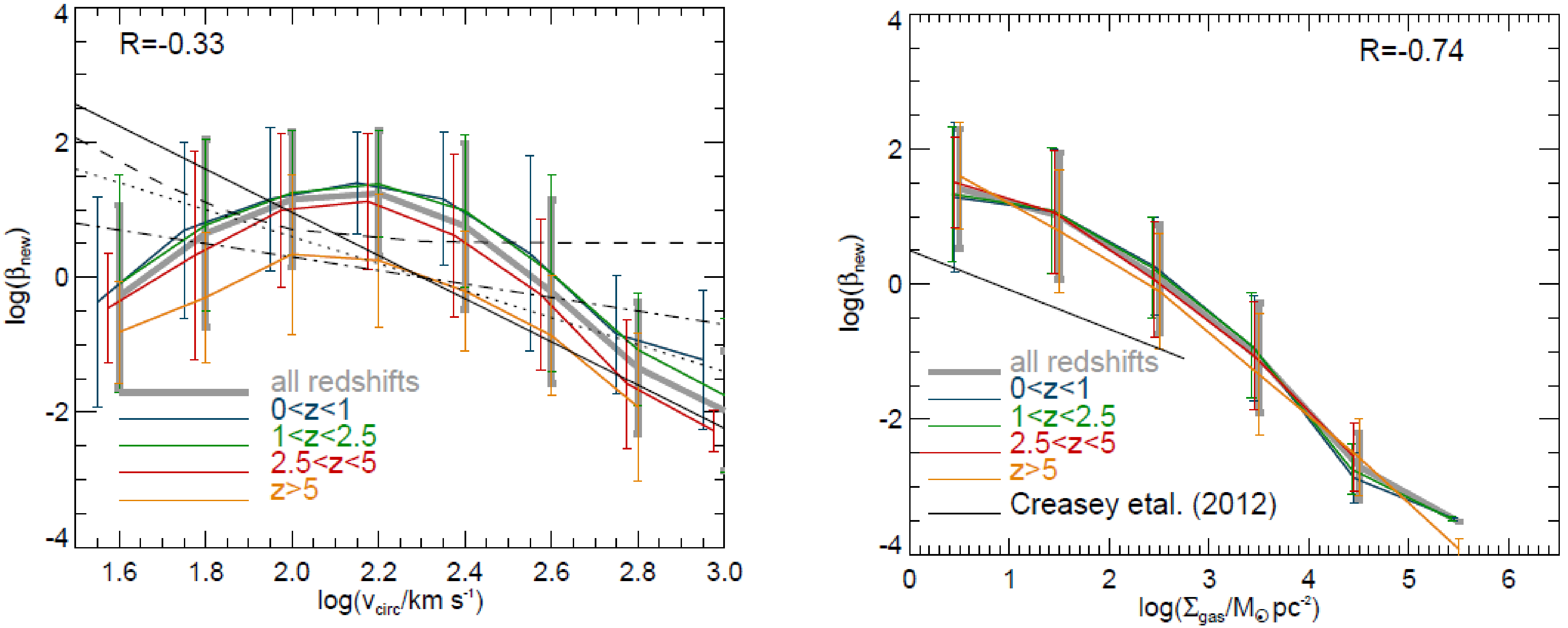
**Lagos et al. 2012**



**AMR simulation of Sne in a cylinder of the ISM**

**Creasey, Theuns & Bower 2012**

# What do these dynamical calculations imply for the outflow rate?

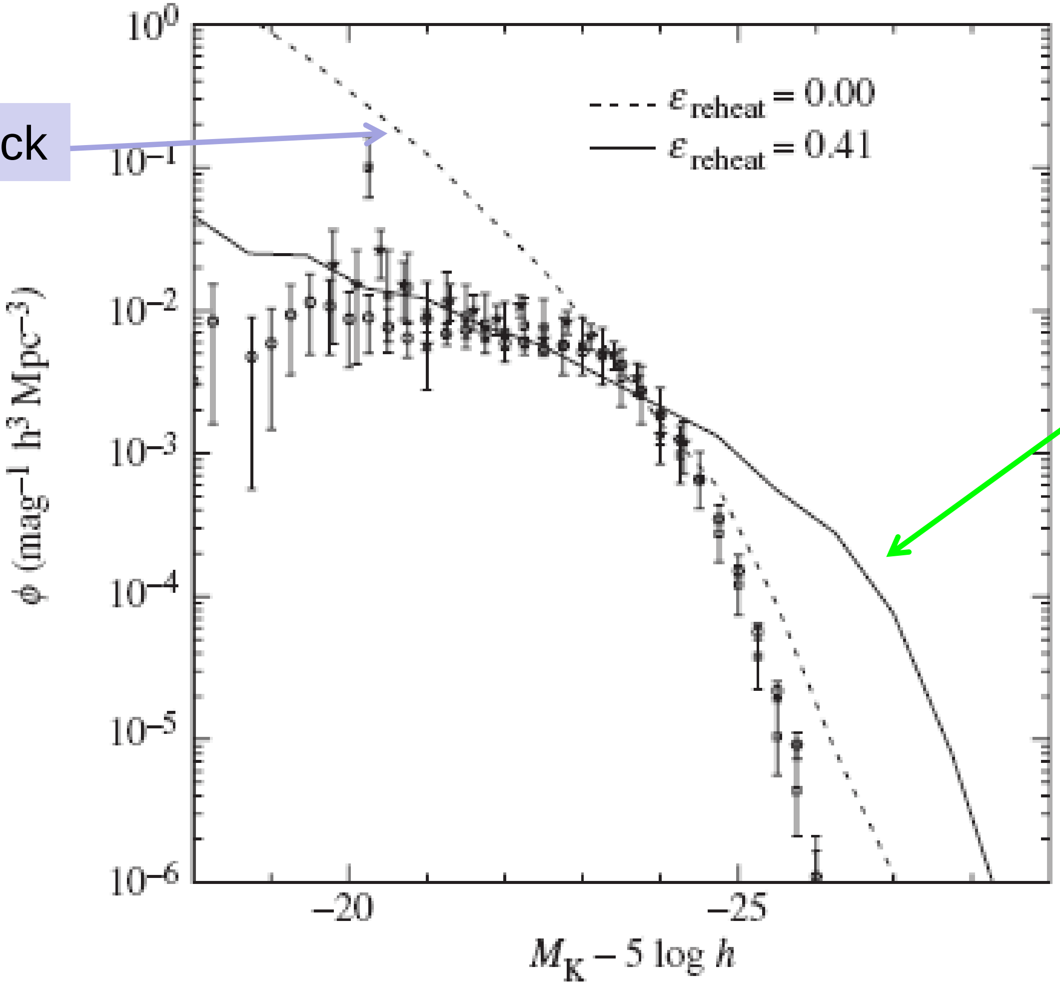


**Tighter correlation with other properties, such as surface density of gas**

**Lagos et al. 2012**

# Regulation of SFR in massive haloes

# A problem with massive galaxies?



No feedback

With Sne feedback

Benson et al. 2003

# Possible mechanisms to suppress formation of bright galaxies

- Regulate gas cooling in massive halos
  - turn off gas cooling ``by-hand''
  - conduction of heat in halo gas
  - change density profile of hot halo
  - inject energy to balance cooling flow
- Drive out cooled gas in a superwind
  - driven by quasar activity
  - driven by star formation

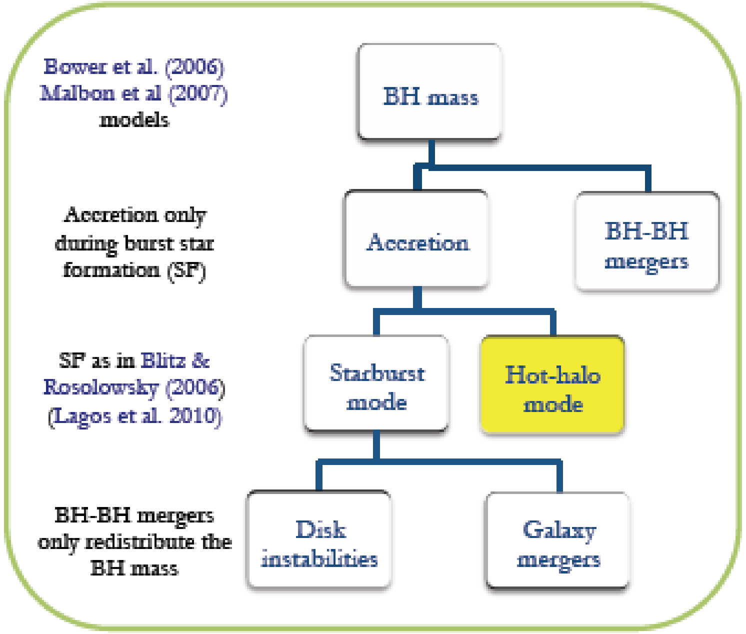
# An alternative source of energy accretion onto SMBH

Bower et al. 2006

- Need model to track growth of black holes
- Haloes with quasi-static hot gas halo: t(cool) > t(free-fall)
- Rate at which gas cools is quenched, depending on size of black hole
- AGN emits luminosity that balances cooling luminosity radiated by gas

See also Croton et al. 2006, MNRAS; de Lucia et al. 2006, MNRAS
Quasar mode feedback: Granato et al 2004, Hopkins et al 2006a,b,….
Cattaneo et al 2006; Lagos, Cora & Padilla 2008; Monaco et al 2007

# The growth of BHs in **GALFORM**



Bower et al. (2006)
Malbon et al (2007)
models

BH mass

Accretion only during burst star formation (SF)

Accretion

BH-BH mergers

SF as in Blitz & Rosolowsky (2006) (Lagos et al. 2010)

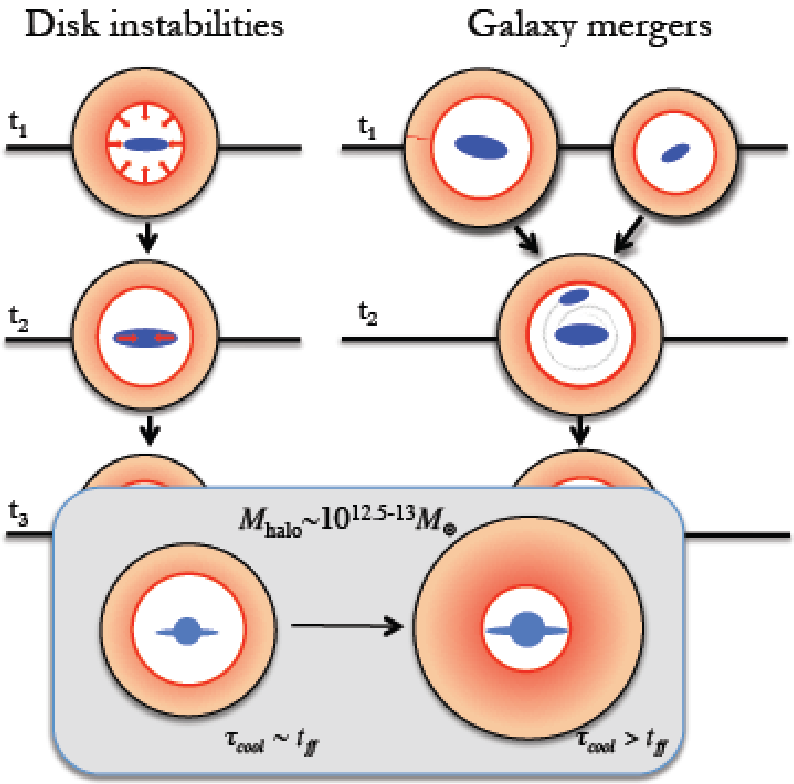
Starburst mode

Hot-halo mode

BH-BH mergers only redistribute the BH mass

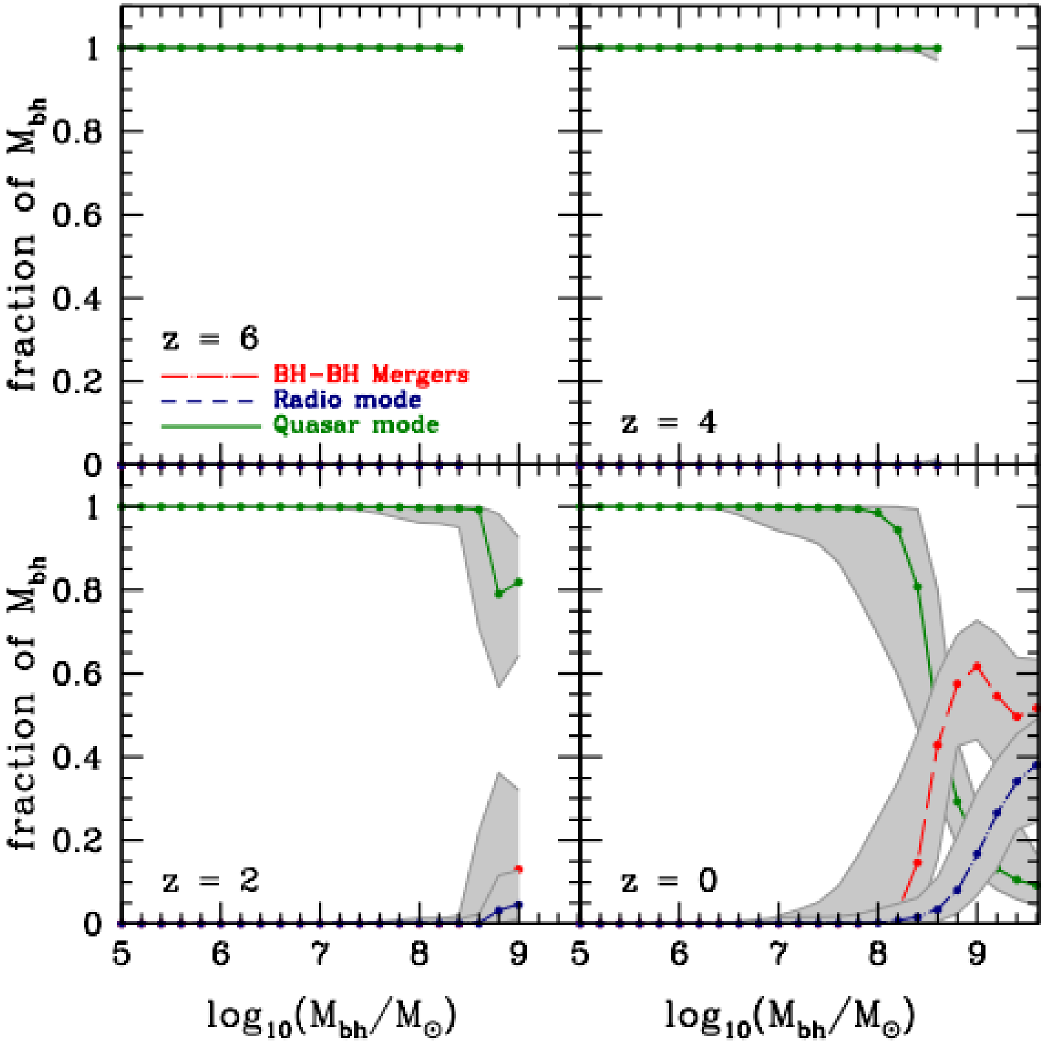
Disk instabilities

Galaxy mergers



**Fanidakis et al.2011**

# Tracking the growth of black holes



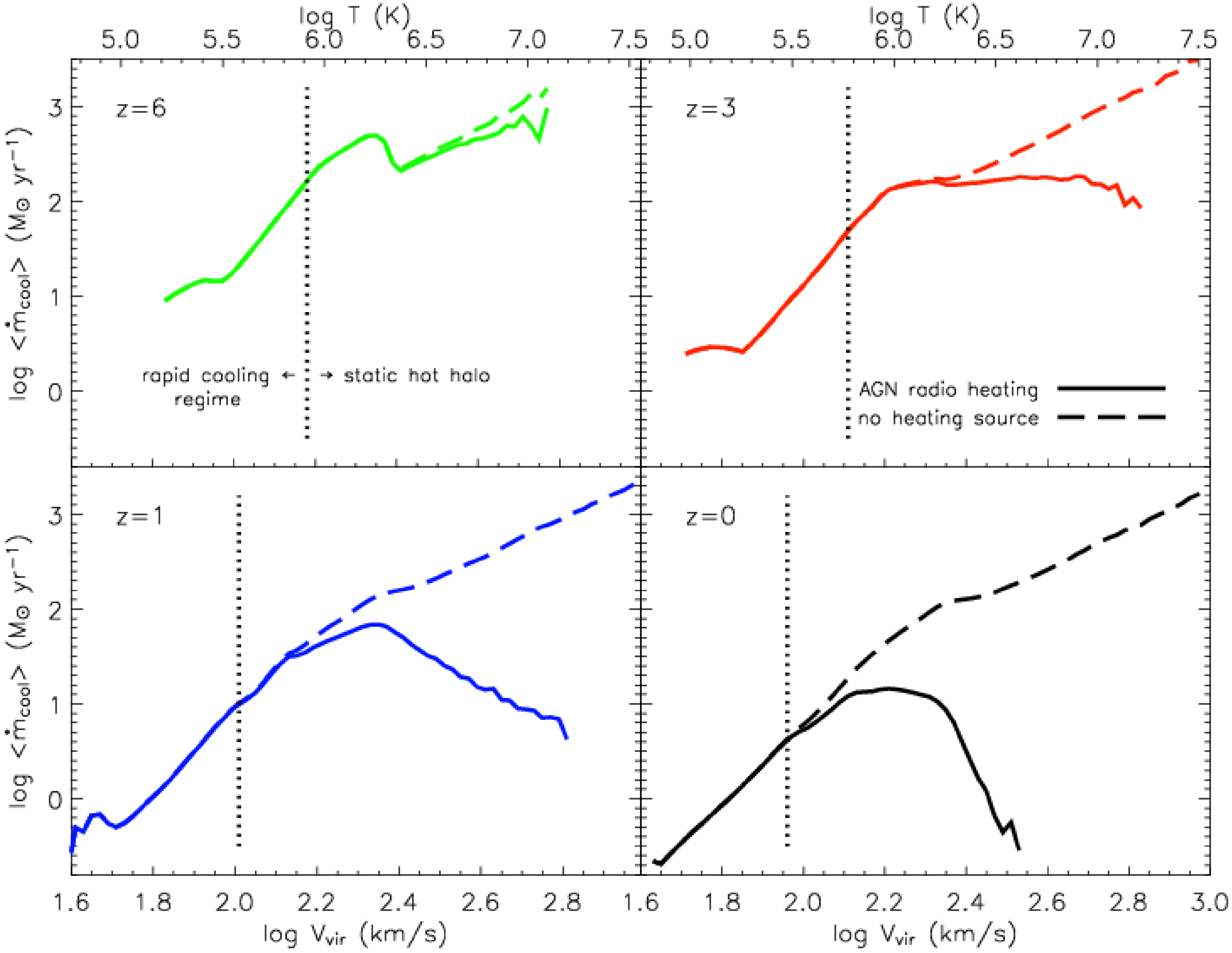
Luminosity released by accretion of material onto SMBH balances cooling luminosity in haloes where cooling time is long (hydrostatic equilibrium)

Stops gas cooling in massive haloes, so no fuel for star formation.

**Radio mode feedback**

**Nikos Fanidakis et al. 2010**

# The impact of AGN feedback on gas cooling

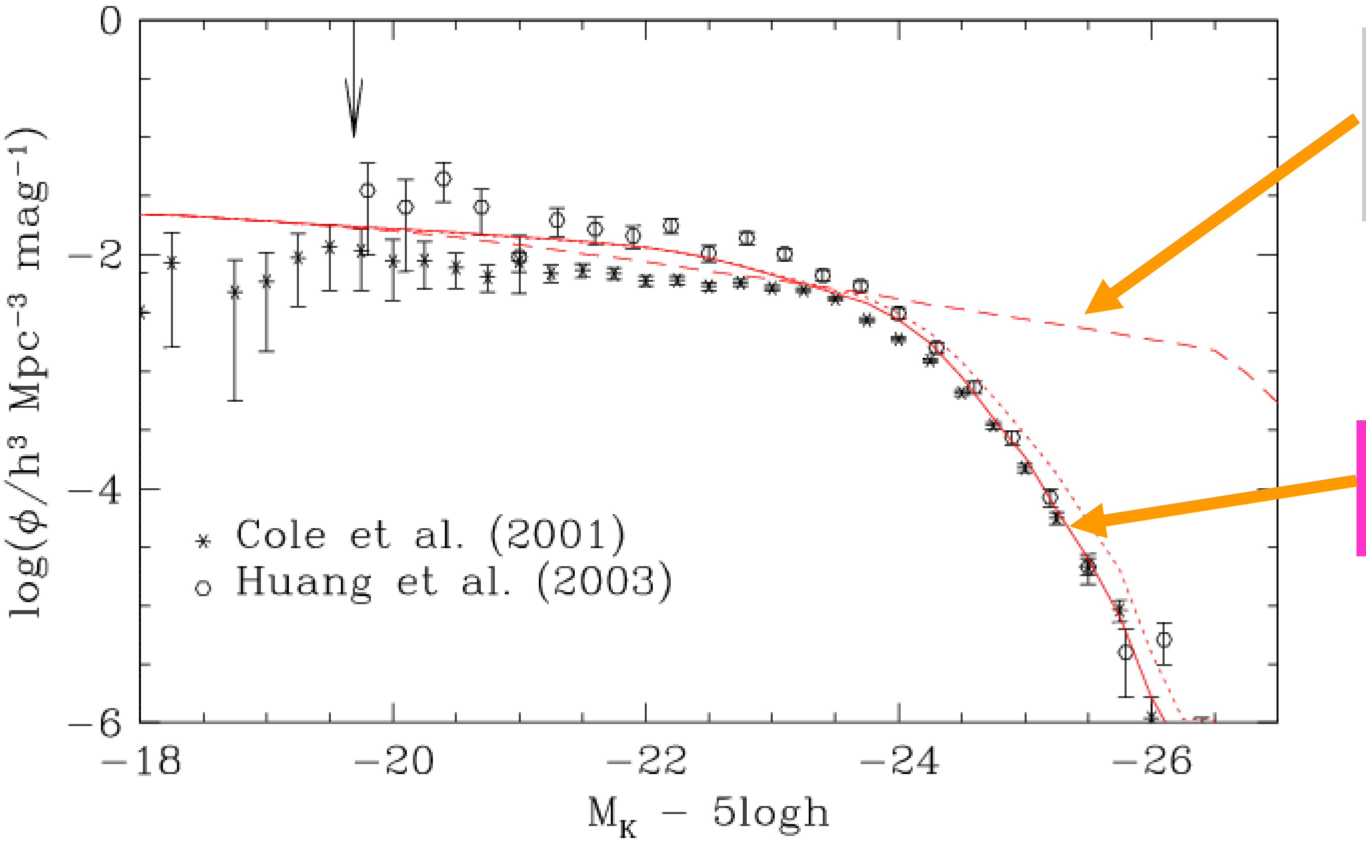


**Gas cooling rate**

**Halo virial velocity**

**Croton et al. 2006**

# The luminosity function with suppression of cooling by AGN



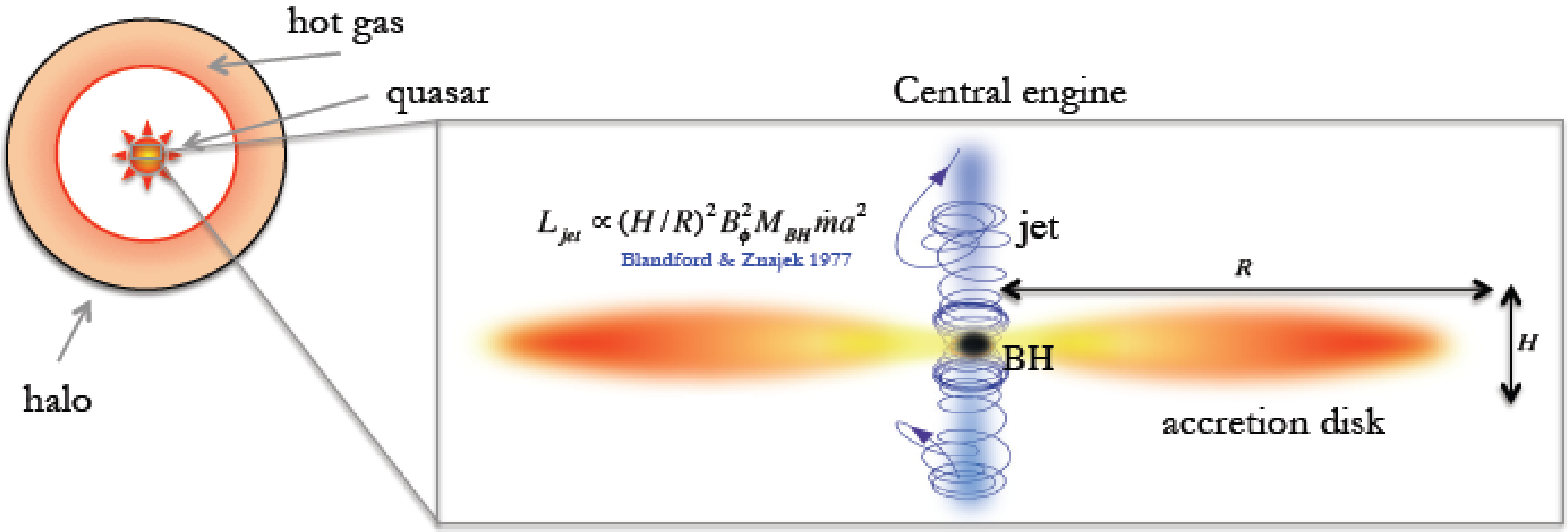
Same parameters but turn off AGN feedback

With AGN feedback

Present day K-band field luminosity function

Bower et al. 2006

# Modelling the active nucleus



$$L_{jet} \propto (H/R)^2 B_\phi^2 M_{BH} \dot{m} a^2$$

Blandford & Znajek 1977

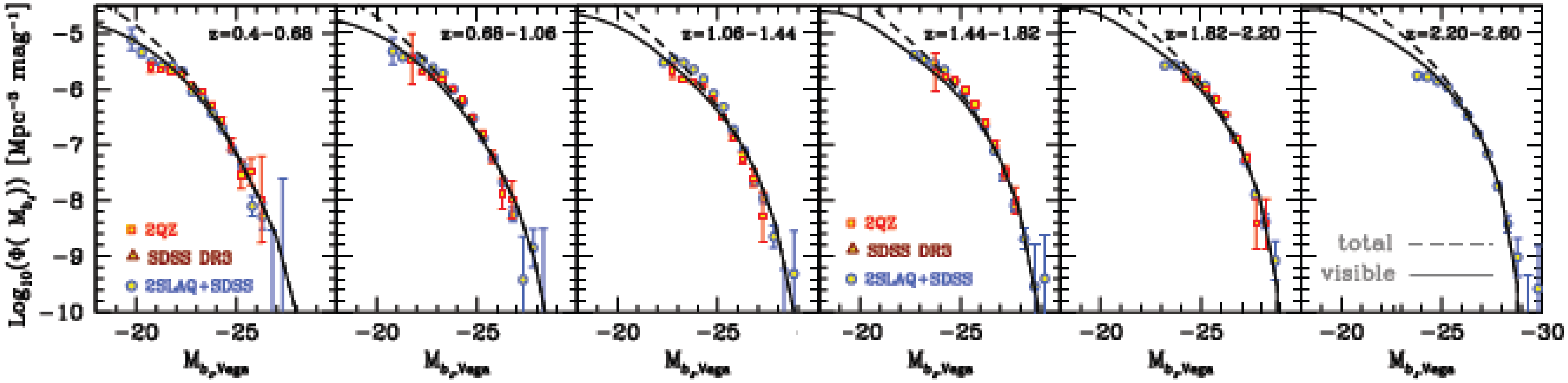
Basic ingredients

1) Accretion rate calculation
2) Disk structure (thin-disk/ADAF) Shakura & Sunyaev (1973); Mahadevan (1997)
3) BH spin evolution (accretion and BH-BH mergers) King et al. (2005)
4) Bolometric corrections for optical, x-ray, UV emission Marconi et al. 2005)
5) Empirical obscuration Hasinger (2008)
6) Jet total and radio luminosity Blandford & Znajek (1977)

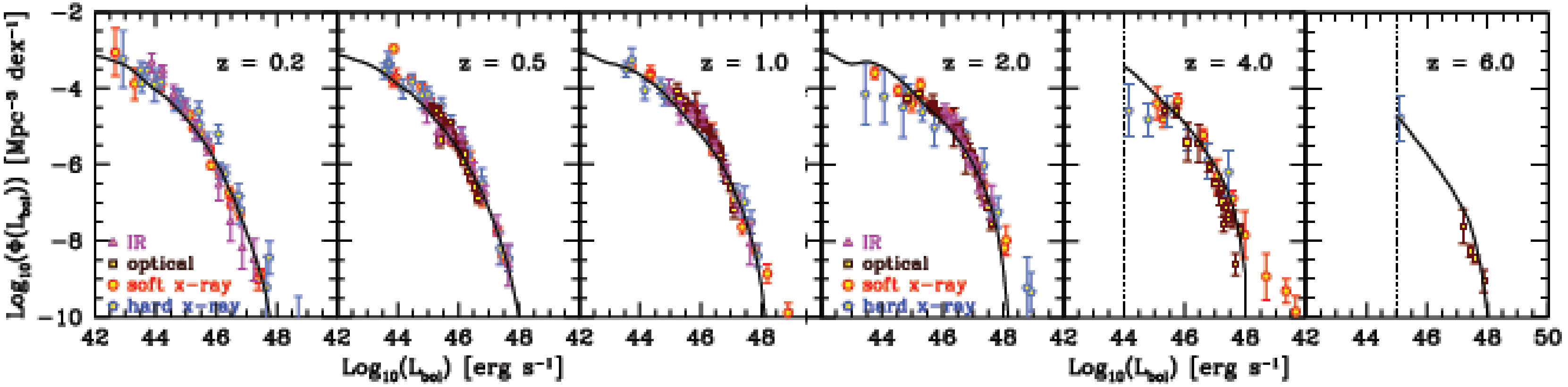
# Quasar luminosity functions

## Optical

AGN are strongly obscured in the optical (and soft X-rays): $f_{obsc}=f_{obsc}(z,L)$



## Bolometric (compilation of LF's from Hopkins et al. 2007)



NF et al. 2011 (arXiv:1011.5222 )

**Fanidakis et al 2011**

# Summary

- Galaxy formation cannot be modelled fully numerically: physics, dynamic range
- Semi-analytical modelling complementary to gas dynamic simulations
- Rapid exploration of different physical models and parameter space
- Modular nature: plug in improved recipes
- Only way to generate predictions for galaxy formation in CDM