Cosmological simulations of galaxy formation: current progress and challenges

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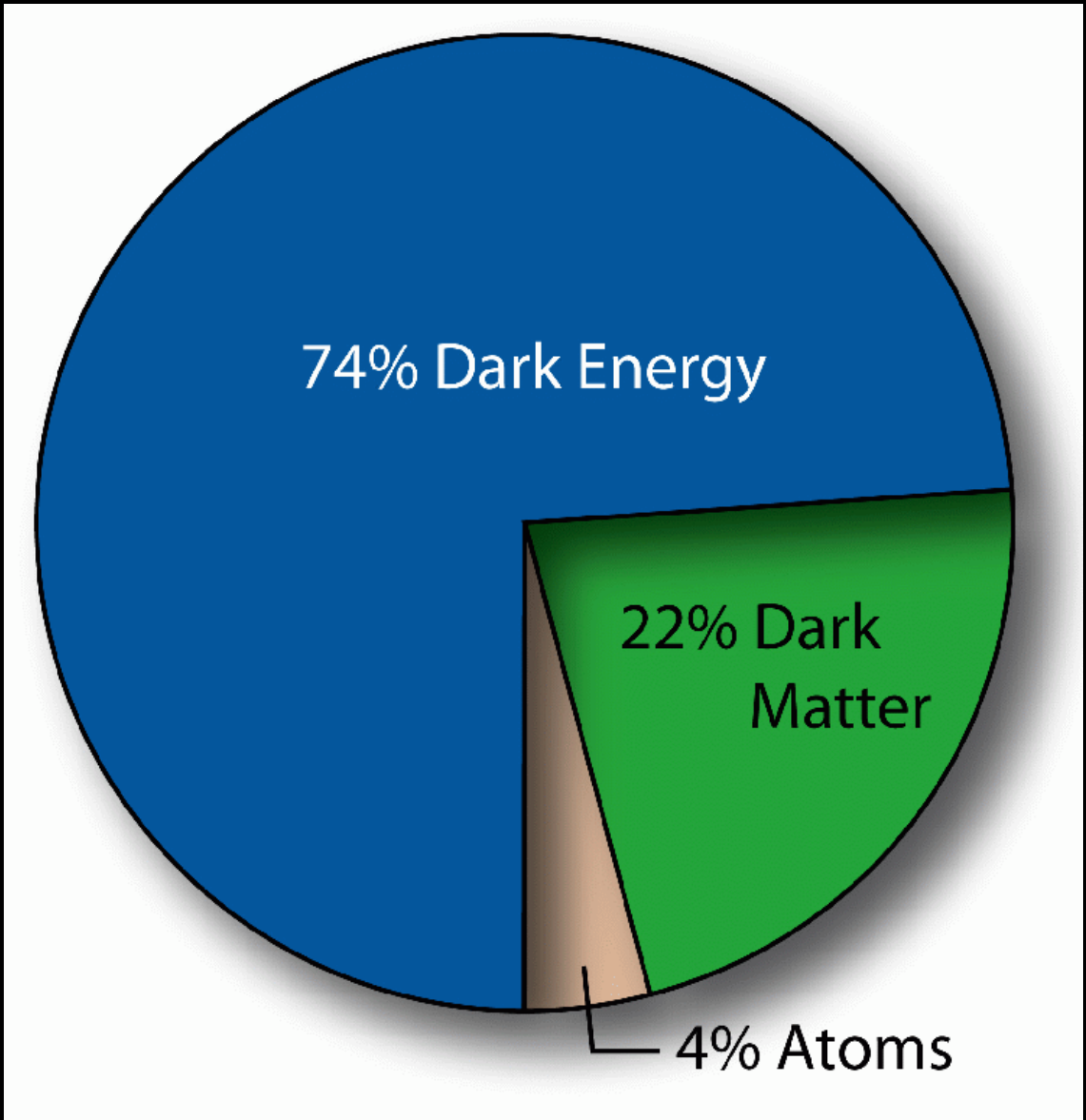
ASTRONUM'09

The current cosmological paradigm: the ΛCDM model



Cold Dark Matter (CDM) = weakly interacting particles (e.g WIMPs) with negligible thermal velocity, dynamics dictated by gravity

In ΛCDM cosmology cosmic structure forms BOTTOM-UP: Gravity rules

Primordial small matter density fluctuations amplified by gravitational instability in an expanding Universe
→ collapse into dark matter halos that then merge with other halos to form progressively larger halos

Formation of dark matter halo

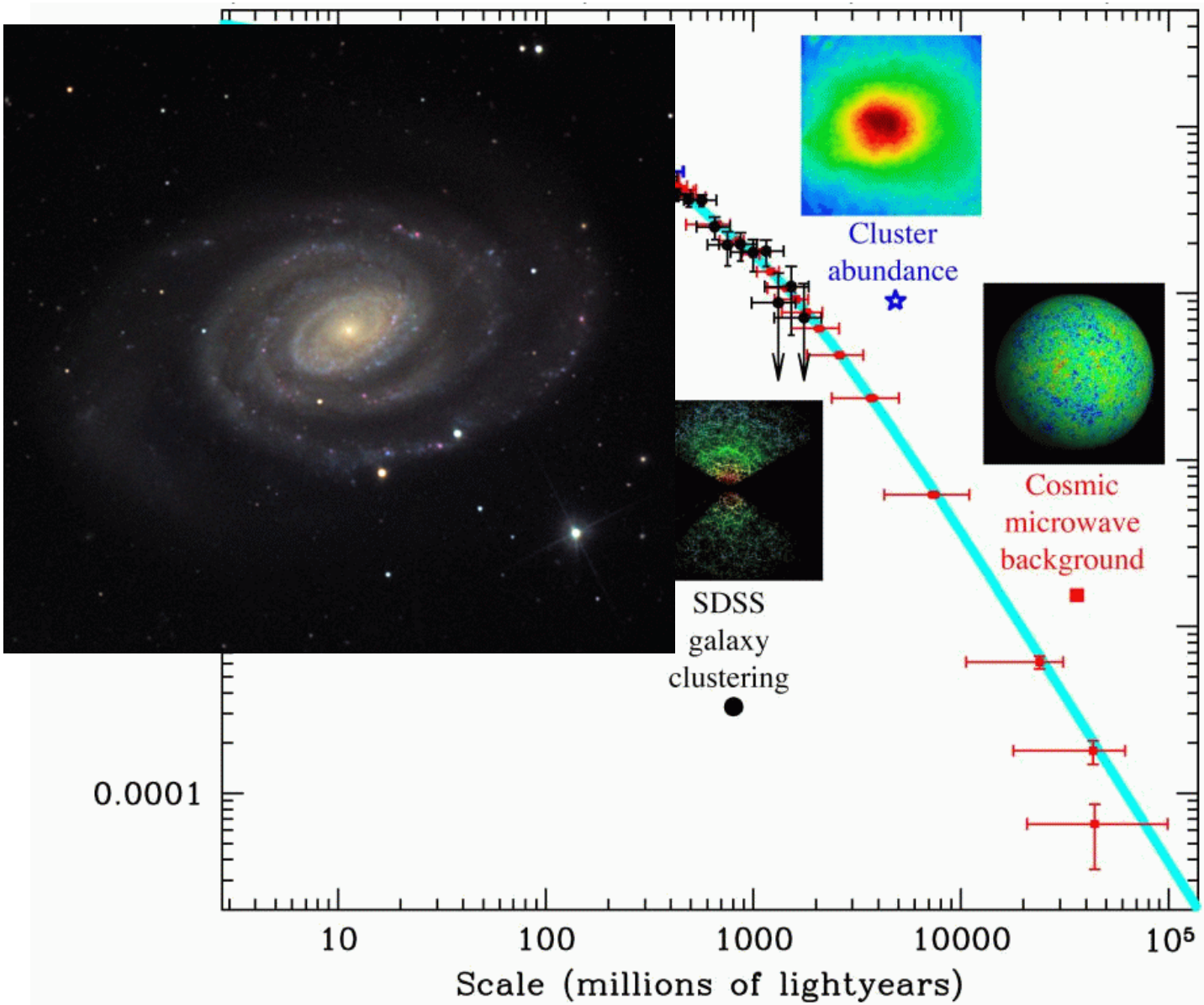
N-Body code PKDGRAV (hierarchical tree method)

Periodic box

VIA LACTEA simulation
(Diemand et al. 2007; 2008)

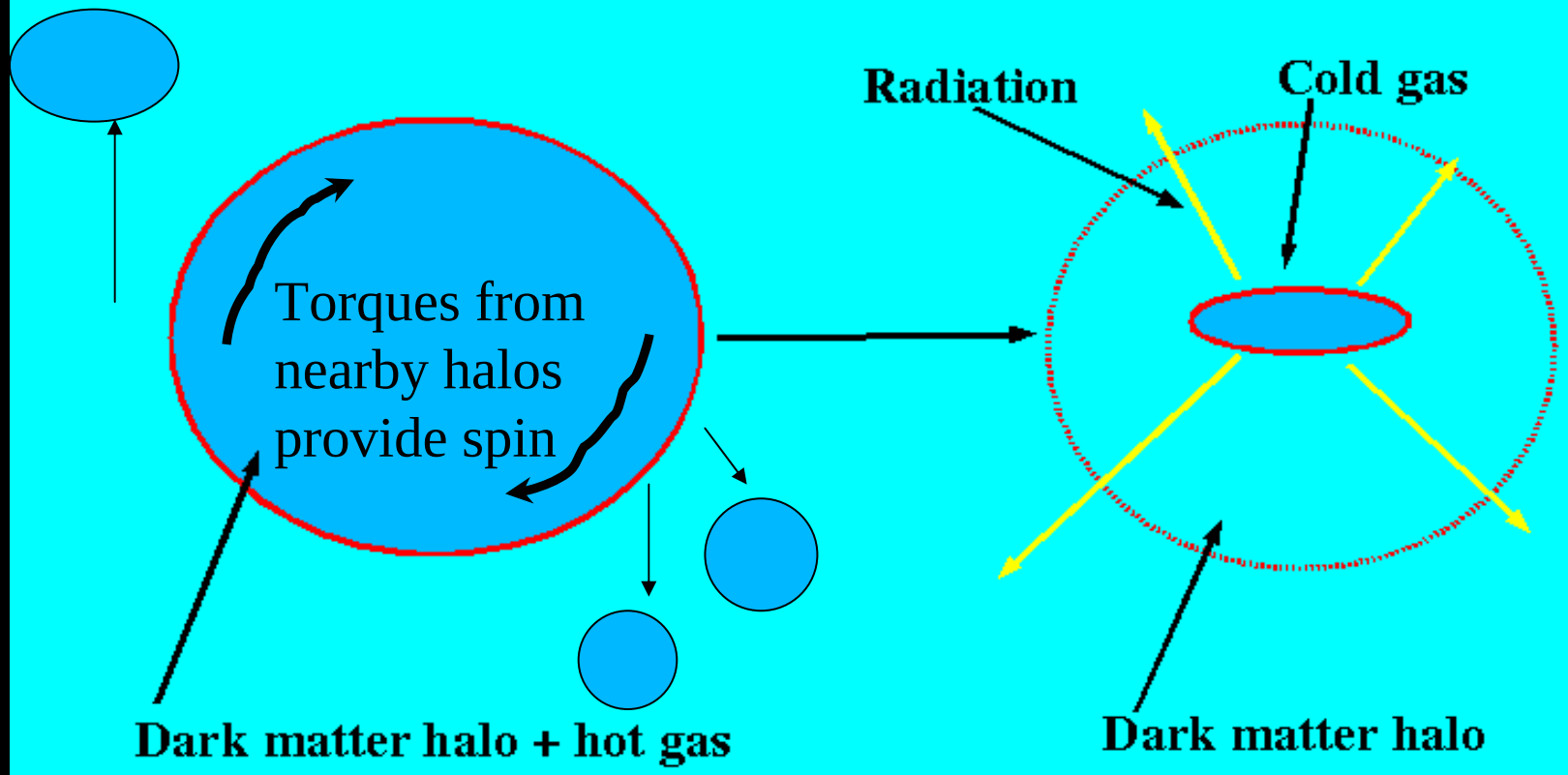
Observations of large scale structure of the Universe support power spectrum of density fluctuations predicted by ΛCDM model

But what about galactic scales (< 100 kpc ~ 10^5 light years)?
Can we reproduce observed galaxies in the ΛCDM model?



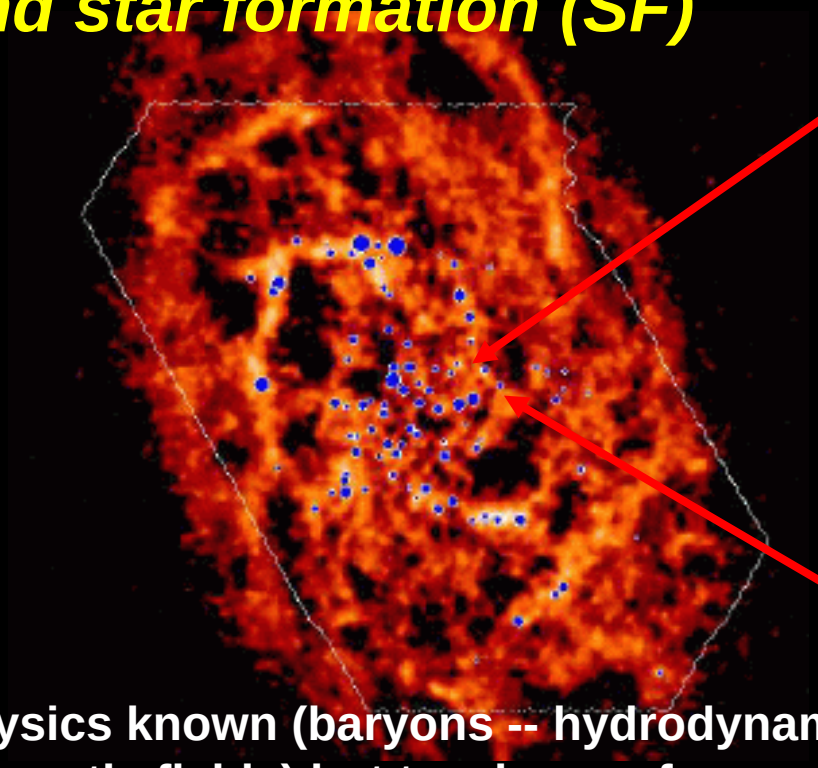
Galaxy formation in CDM Universe: baryons in dm halos

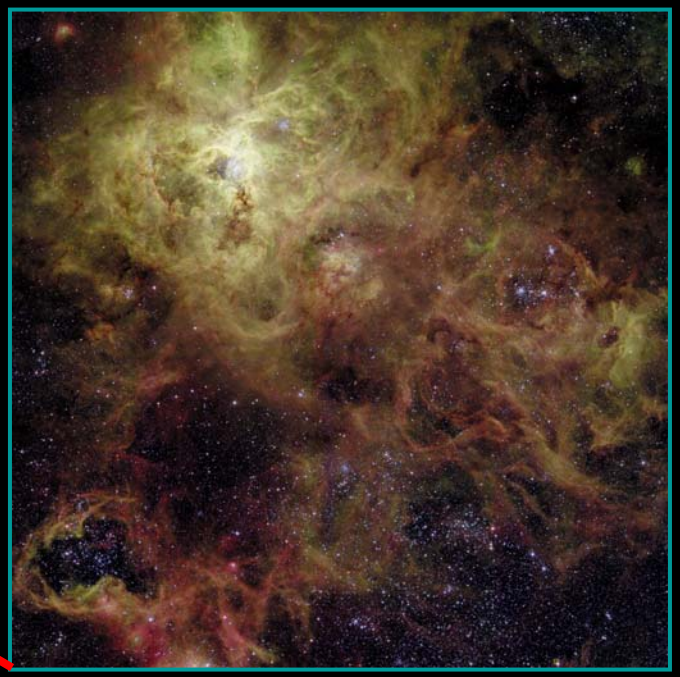
- Hot baryonic plasma (H, He, T ~ 10^5-10^6 K) falls into gravitational potential of dm halo
- Radiatively cools within halo ($T_{cool} << T_{hubble}$, *by recombination + radiative transitions)*
- Spinning disk form - gas settles at radius of centrifugal equilibrium because both gas and dark matter have angular momentum (from tidal torques)
- Gas disk forms stars out of the cold gas phase (Jeans unstable gas clouds)
- Stars reheat the gas via their radiation and supernovae exposions ("feedback")



(Fall & Rees 1977;White & Rees, 1978)

Complexity: *Physics of the interstellar medium (ISM) and star formation (SF)*



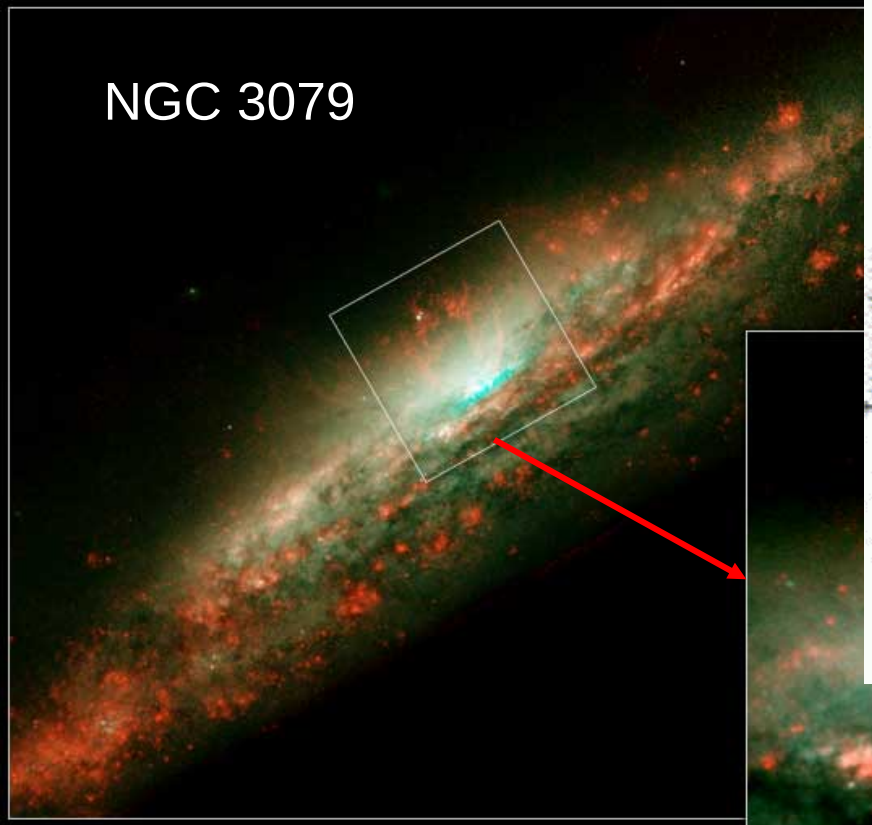


Physics known (baryons -- hydrodynamics, gravity, radiative mechanisms, magnetic fields) but two issues for modeling

- **Multi-scale (< 1 pc to 1 kpc) – resolution of numerical models of cosmic structure formation was only ~ 1 kpc till 2004, ~100 pc today**

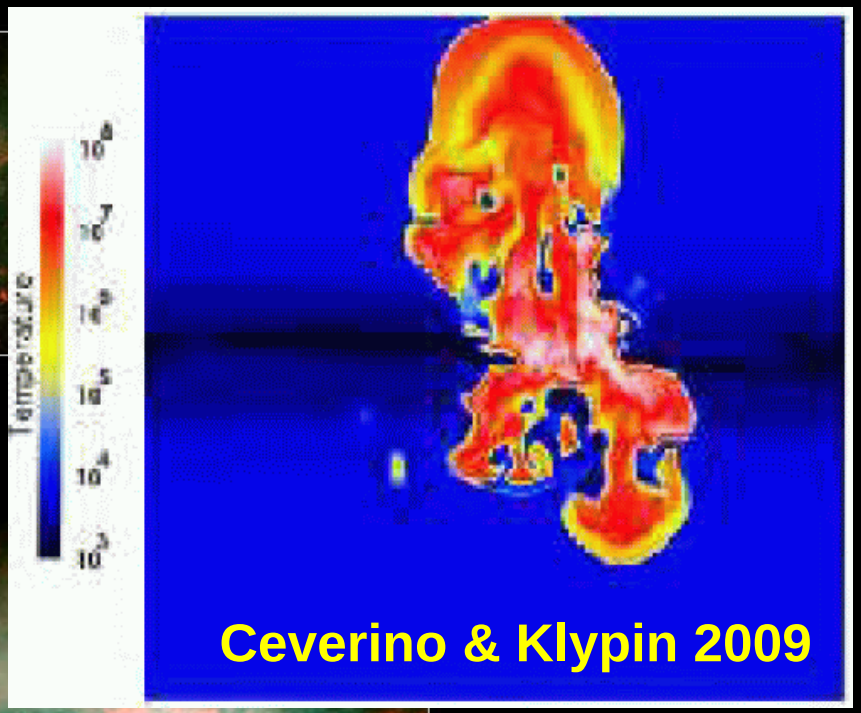
- **Multi-process: cooling, heating, phase transitions (e.g. from HI to H_2), star formation, stellar explosions, self-gravity, MHD phenomena, viscous phenomena (what source viscosity?). Some of these processes not completely understood plus require interplay between many scales**

Energy balance in the ISM; injection of energy by supernovae explosion (supernovae feedback)



Galaxy NGC 3079 HST • WFPC2

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



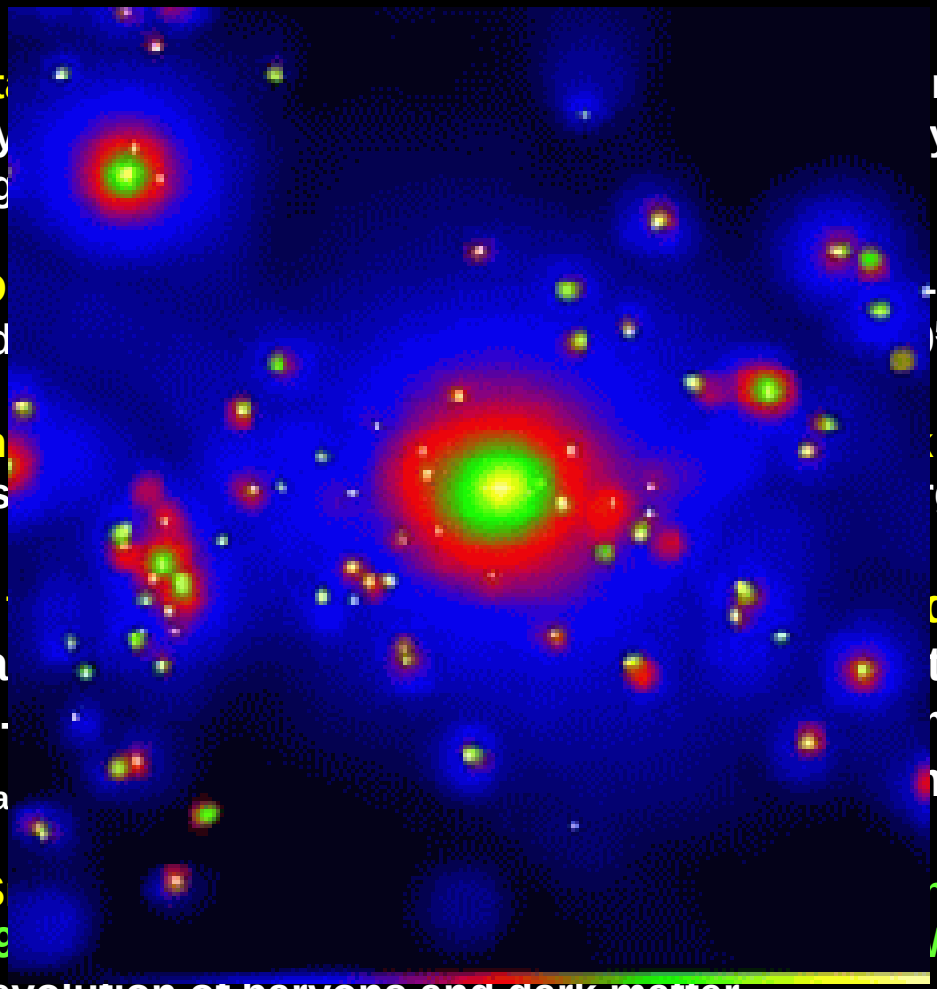
Explosions at sub-pc scales

What effect on 100 pc scales?

-Currently only local calculations (volume < 100 pc) can model directly the hydrodynamics and thermodynamics of supernovae blastwaves

- **Maintain hot intercloud medium (HIM) (f_V~ 0.5, T > 10^5 K, ρ < 10^{-2} atoms/cc)**
- **Observed to drive "bubbles" and "winds" on scales of 100 pc to 1 kpc**

Tool for galaxy formation: simulation with three-dimensional algorithms that solve for the coupled gravitational dynamics of the **dissipationless cold dark matter** component and the gravitational and radiative hydrodynamics of the **dissipative baryonic fluid**



- **Self-gravit** … rned by Euler equation + continuity … y equation with cooling and heating

- **SUB-GRID** … - star clusters form in coldest and … ^{5} Mo).

- **No supern** … - transfer fraction of sup. explos … gy (no wind/bubble)

Research … **d codes** because a … turally adaptive in space and time - … mic structure (in MW ρ_{ha} … ms/cm^3).

N-Body + S … nquist & Katz 1989; Navarro & Benz 199 … Nadsley et al. 2004)

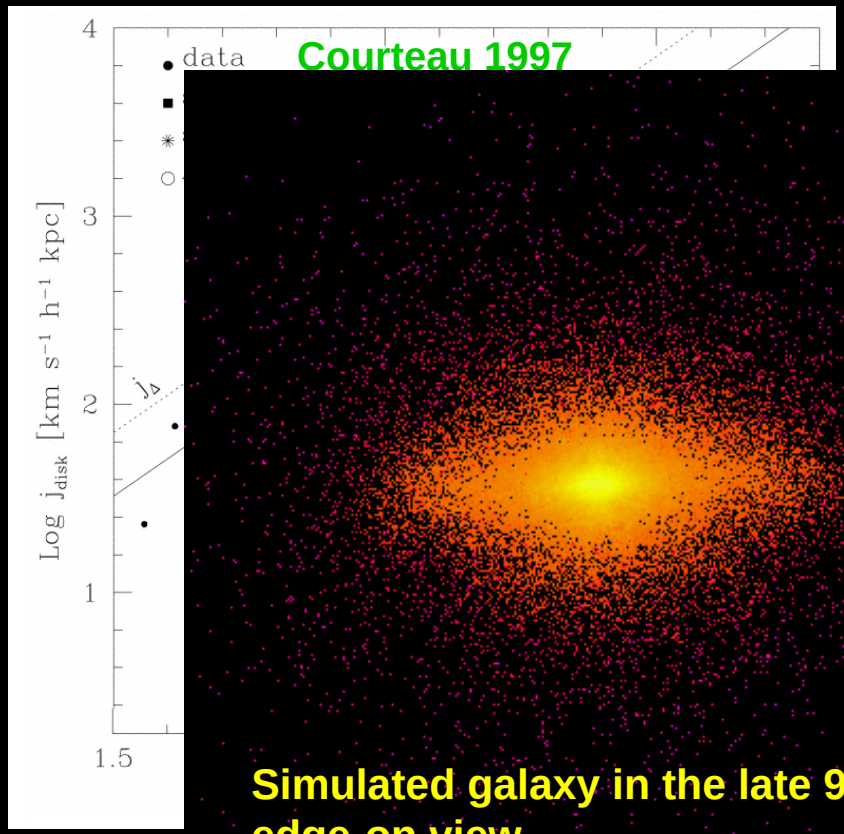
Follow co-evolution of baryons and dark matter

Dense "baryonic cores" (yellow) form at the center of dark matter halos as a result of cooling

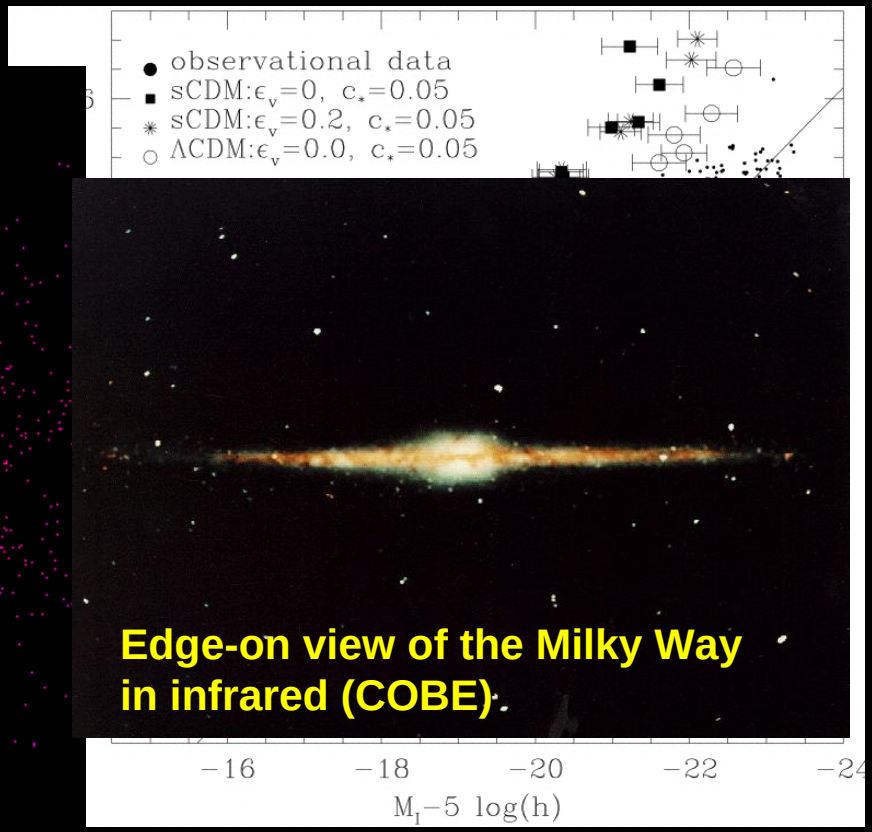
Simulated galaxies: Angular Momentum Problem

Disks are too small at a given rotation speed (Vrot measures mass)

Disks rotate too fast at a given luminosity -> disks too compact so Vrot ~ $(GM/R_{disk})^{1/2}$ too high



Simulated galaxy in the late 90s edge-on view



Edge-on view of the Milky Way in infrared (COBE).

Navarro & Steinmetz 2000

Both in observations and simulations J_{disk}~ R_{disk}*Vrot, where R_{disk} is computed by fitting an exponential profile to the stellar surface density

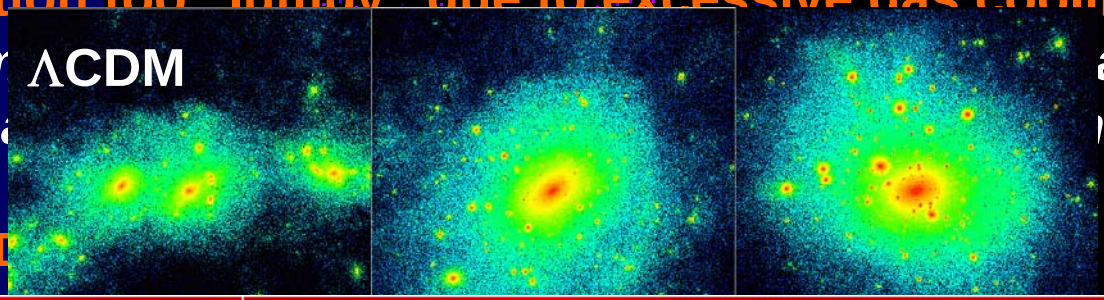
Is galaxy formation CDM model-compatible?

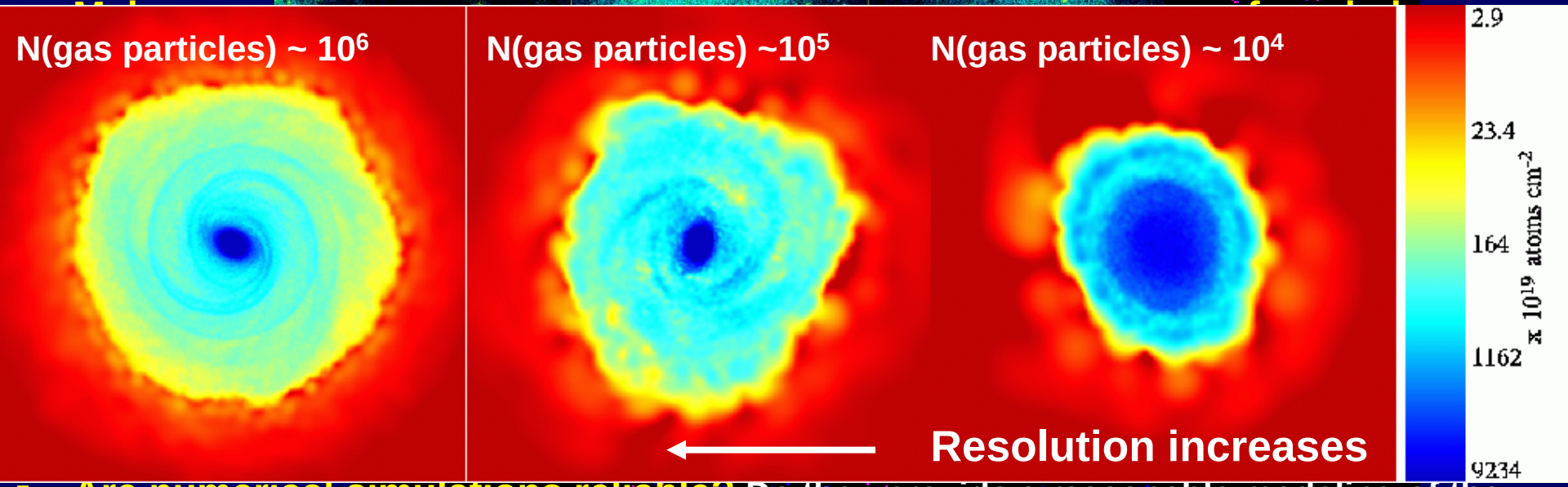
Original interpretation of angular momentum problem

(Navaro & Benz 1991, Navarro & White 1994):

gas distribution too "lumpy" due to excessive gas cooling -→ *dense lumps of dm* ag ("dynamical friction") a disk

PROPOSED





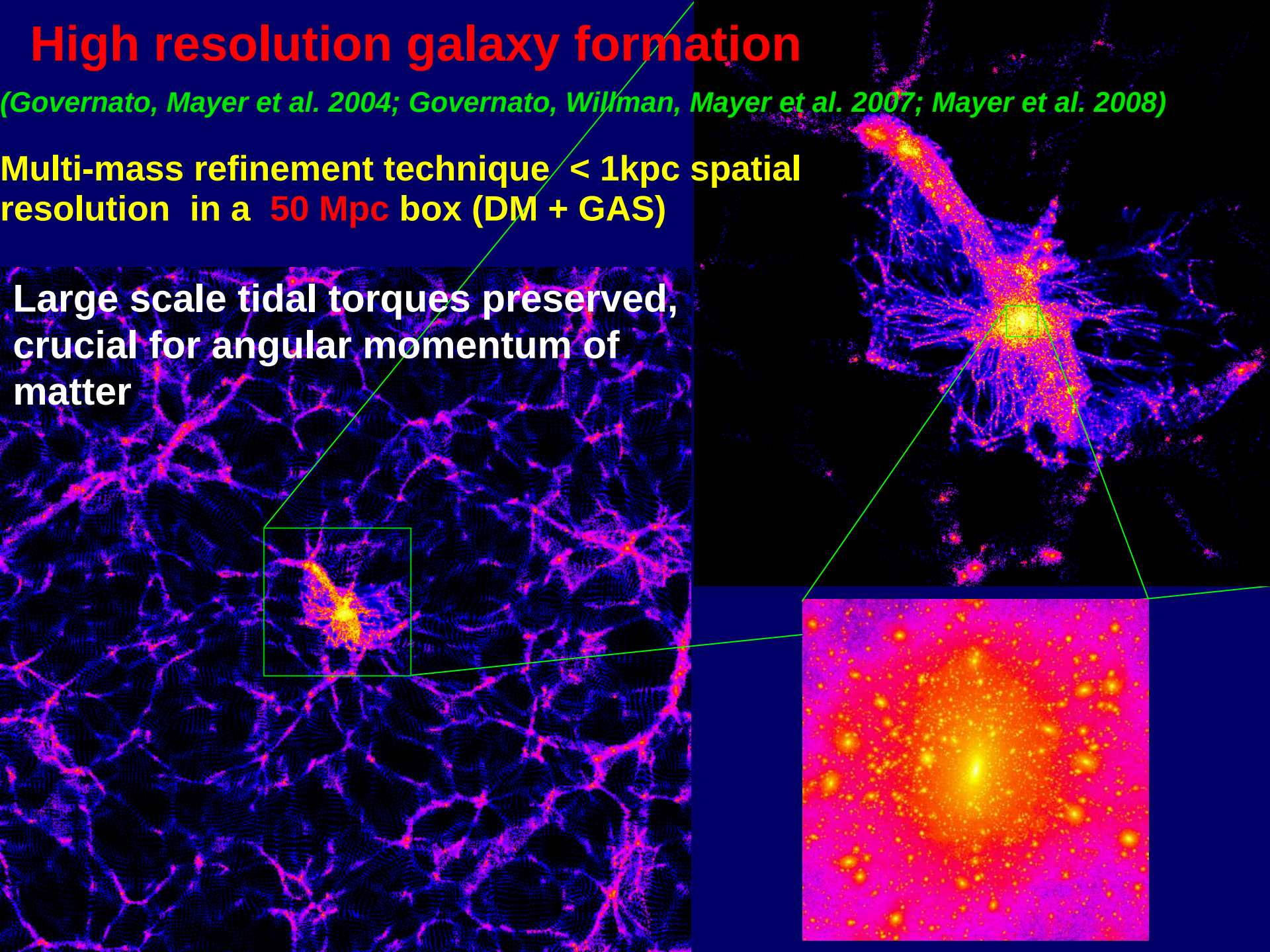
- **Are numerical simulations reliable?** Do they provide a reasonable modeling of the physical processes at play? We found numerical resolution is a major issue; with less than a million resolution elements per galaxy spurious loss of angular momentum (Governato, Mayer et al. 2004; Mayer 2004; Kaufmann, Mayer et al. 2007; Mayer et al. 2008)

High resolution galaxy formation

(Governato, Mayer et al. 2004; Governato, Willman, Mayer et al. 2007; Mayer et al. 2008)

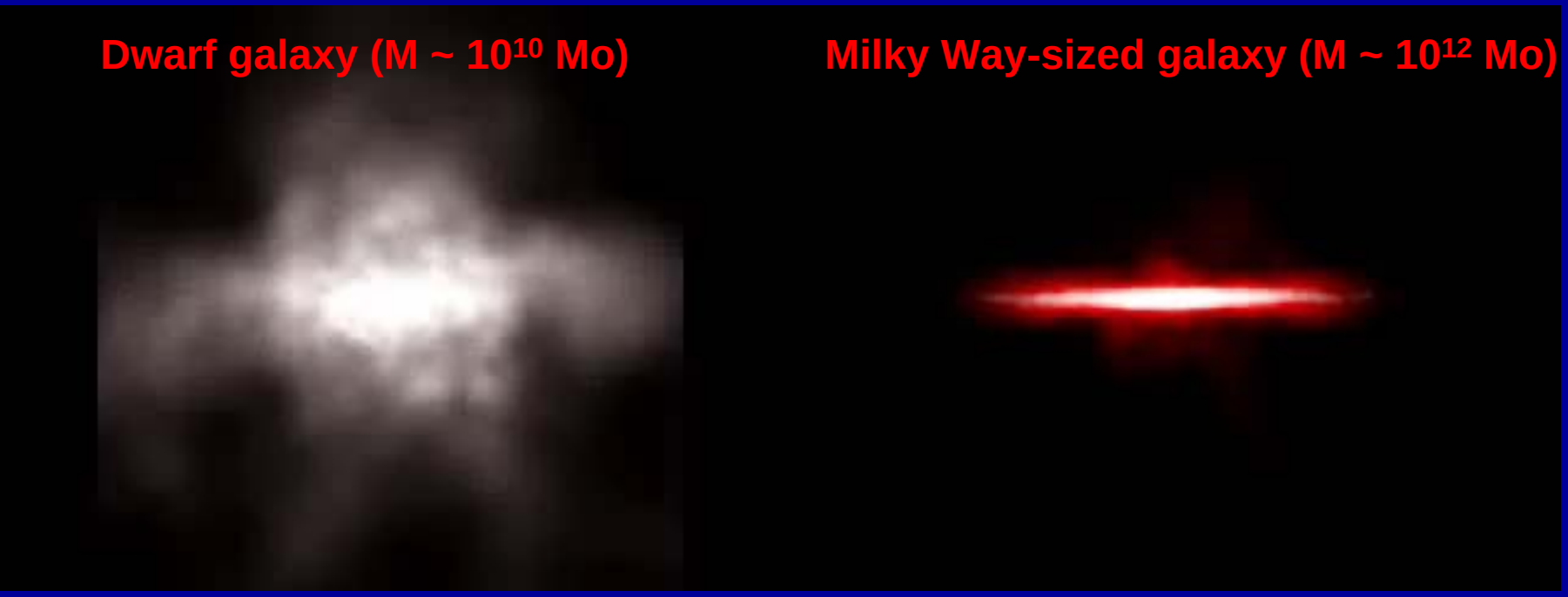
Multi-mass refinement technique < 1kpc spatial resolution in a 50 Mpc box (DM + GAS)

Large scale tidal torques preserved, crucial for angular momentum of matter



SUB-GRID Supernovae Feedback **: cooling stopped in region heated by supernovae blastwave for** ***t_s ~ 30 million years***

- ***Based on time of maximum expansion of supernova blast wave (Sedov-Taylor phase + snowplaugh phase). Radius of blastwave self-consistently calculated based on McKee & Ostriker (1977)***
- ***Blastwave generated by simultaneous explosion of many supernovae type II (time resolution limited as mass resolution – single star particle represents star cluster where many type II supernovae can explode)***



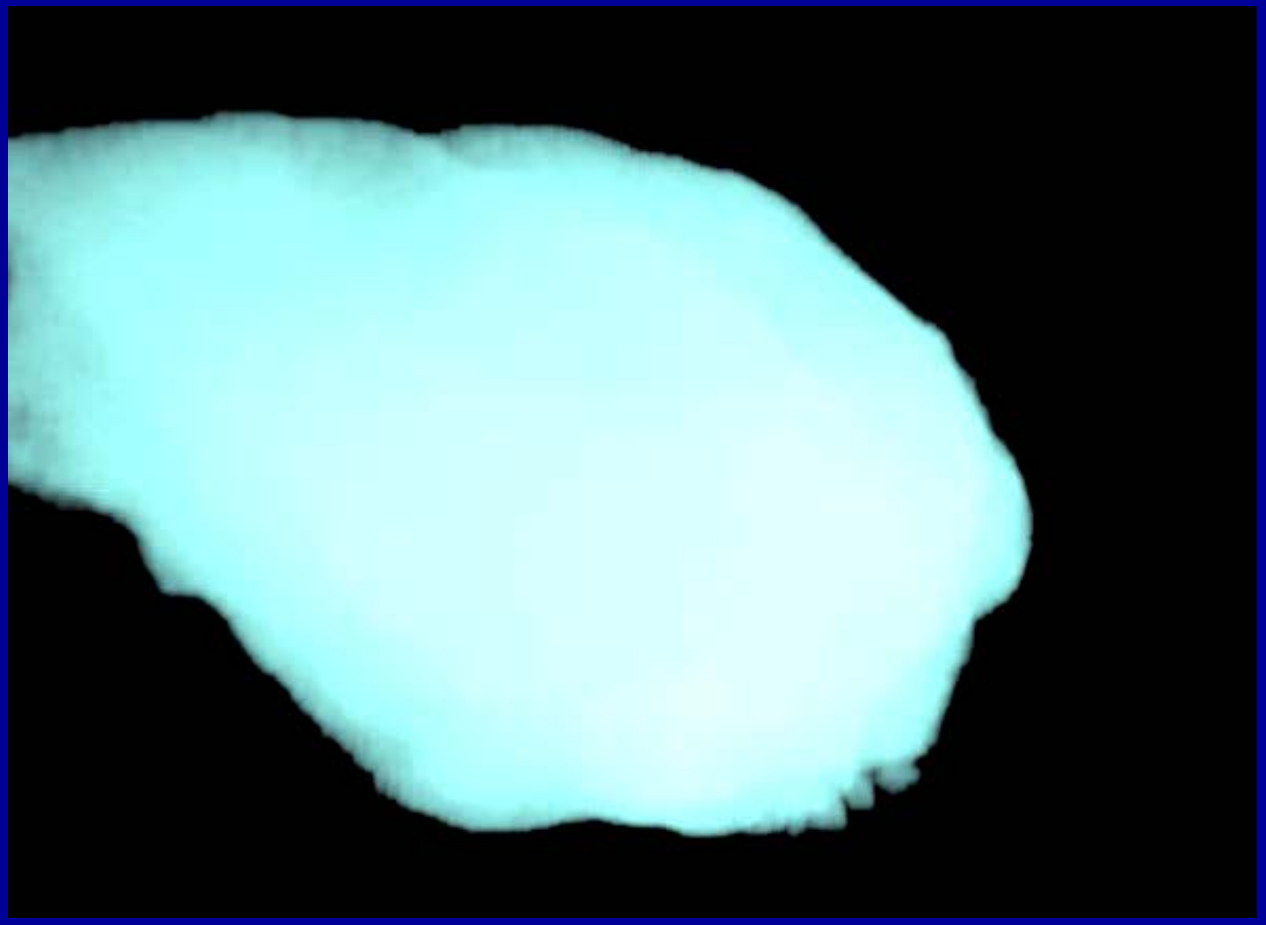
- **Free parameters (e.g. fraction of energy of supernovae explosions turned into gas heating) calibrated to reproduce star formation rate observed in real galaxies across a wide mass range**
- **Heating also by type Ia supernovae but without delayed cooling (no collective blastwave)**

Formation of Milky Way-sized galaxy

Last major merger at z ~ 1.5 plus several minor mergers at z < 0

(Ngas, Ndm > 10^6 within R < Rvir + blast-wave feedback model)

(Governato,Willman, Mayer et al. 2007)
Mayer, Governato and Kaufmann 2008;
Governato et al. 2008)



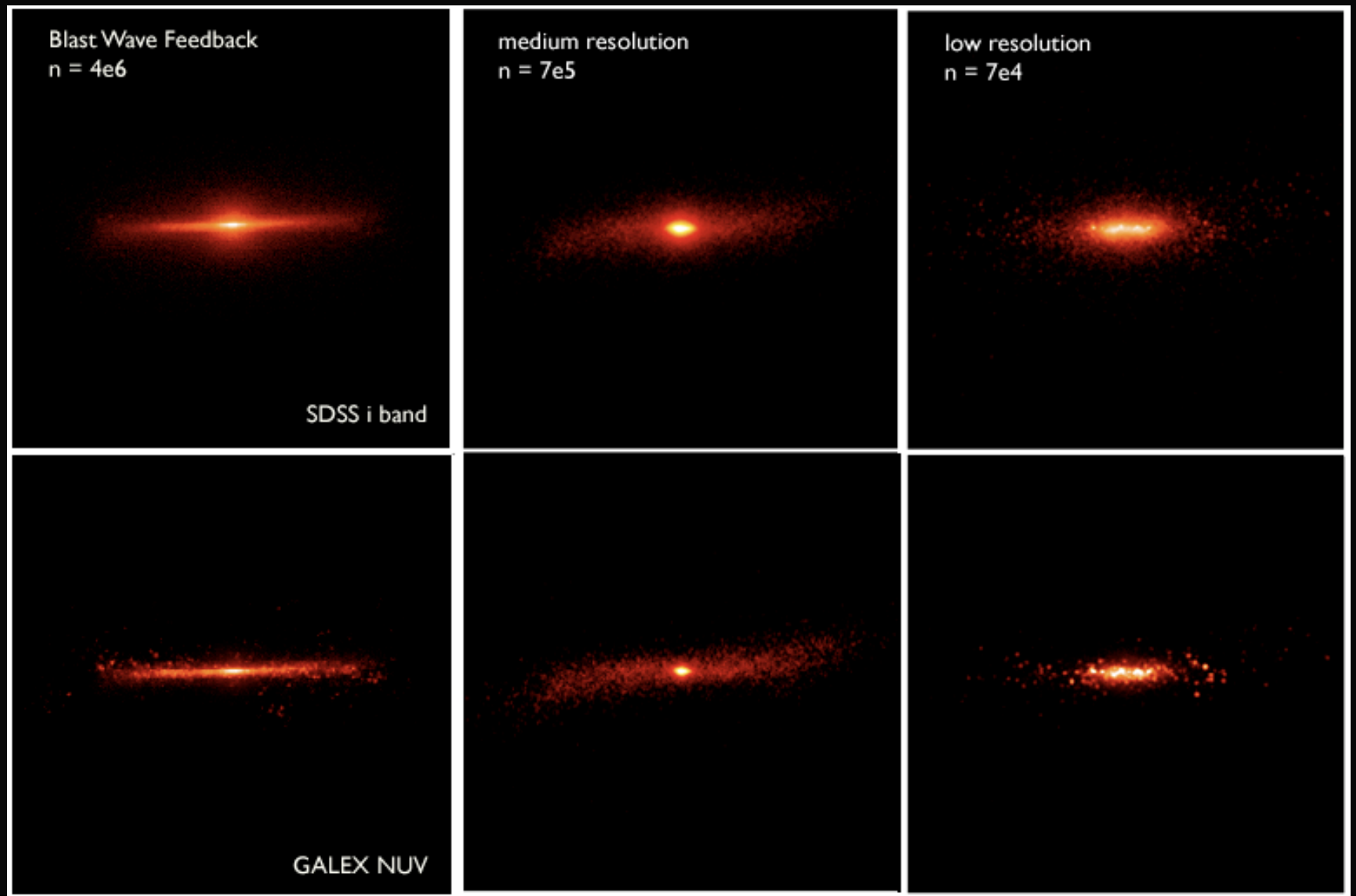
Green:gas
Blue:new stars
Red:old stars

Frame size = 100 kpc comoving

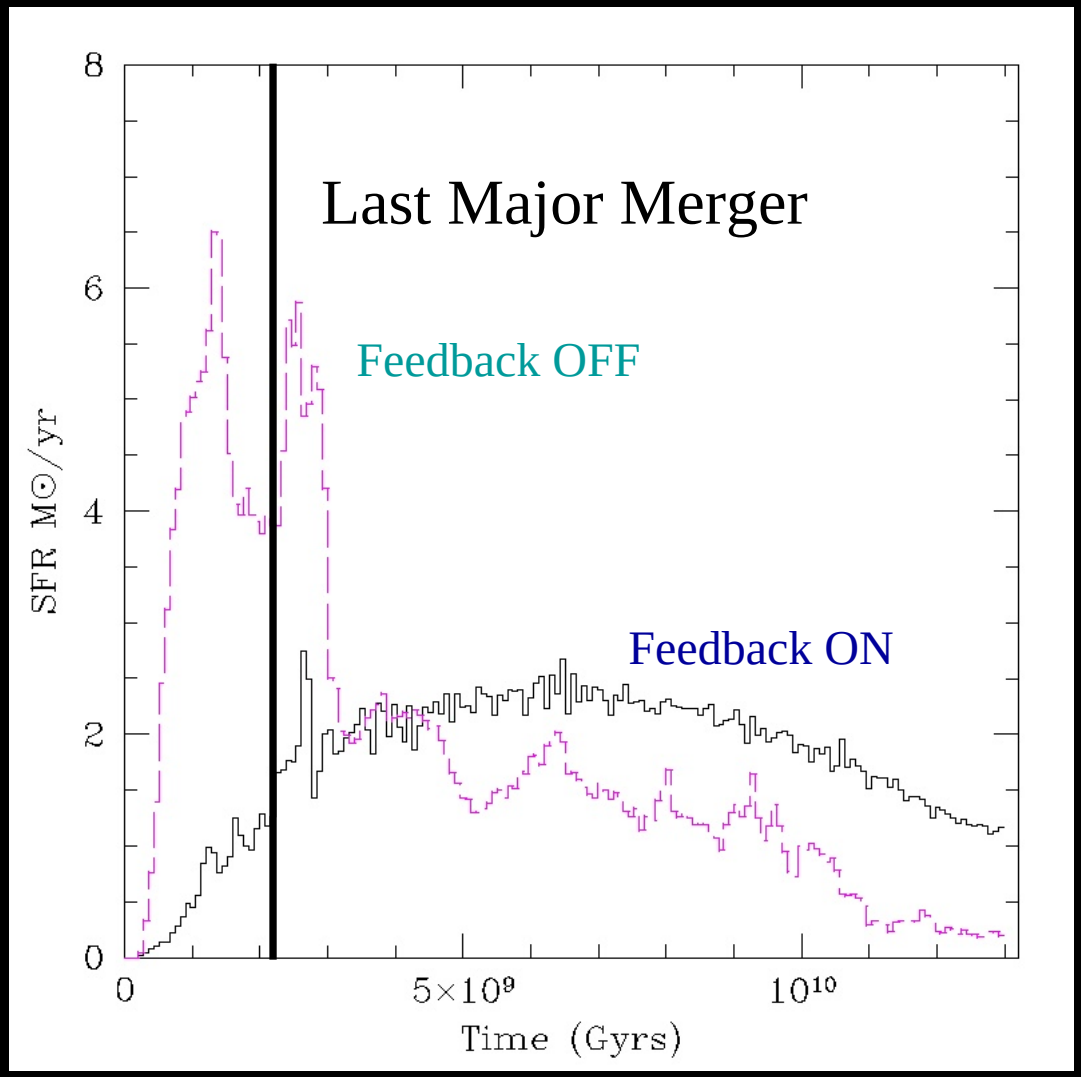
Images made with SUNRISE (P. Jonsson - UC Santa Cruz)

N=DM+Gas+stars

Boxes 50 kpc across



Effect of SN feedback on SFH of a 10^{11} Solar Masses Galaxy

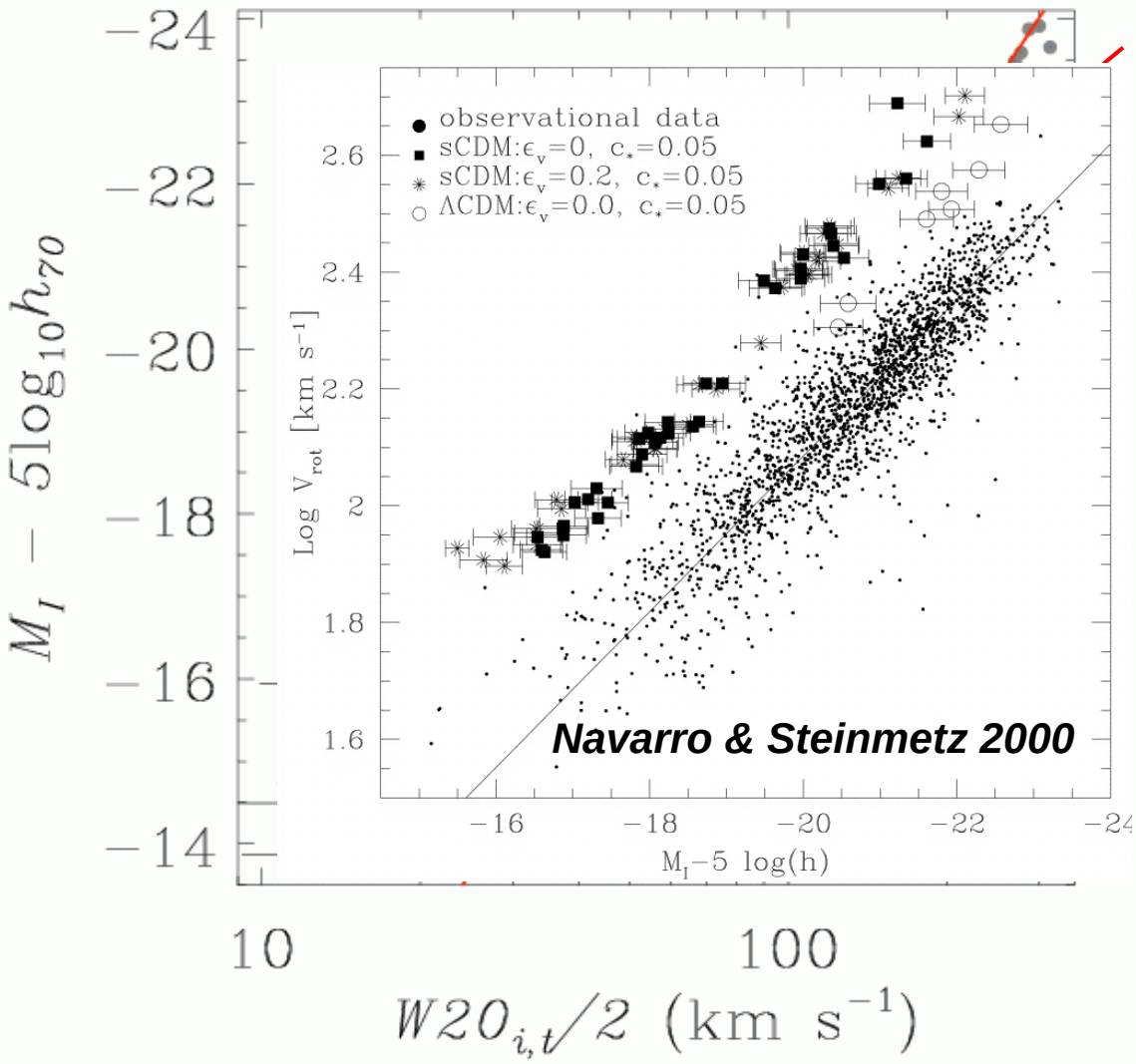


Without "blastwave" feedback star formation history follows dark matter assembly history

If "blastwave" feedback is on, star formation less efficient (no "bursts") + more extended in time as in real disk galaxies

SF significantly reduced in early mergers due to feedback in progenitors

SFH includes all progenitors at any given time



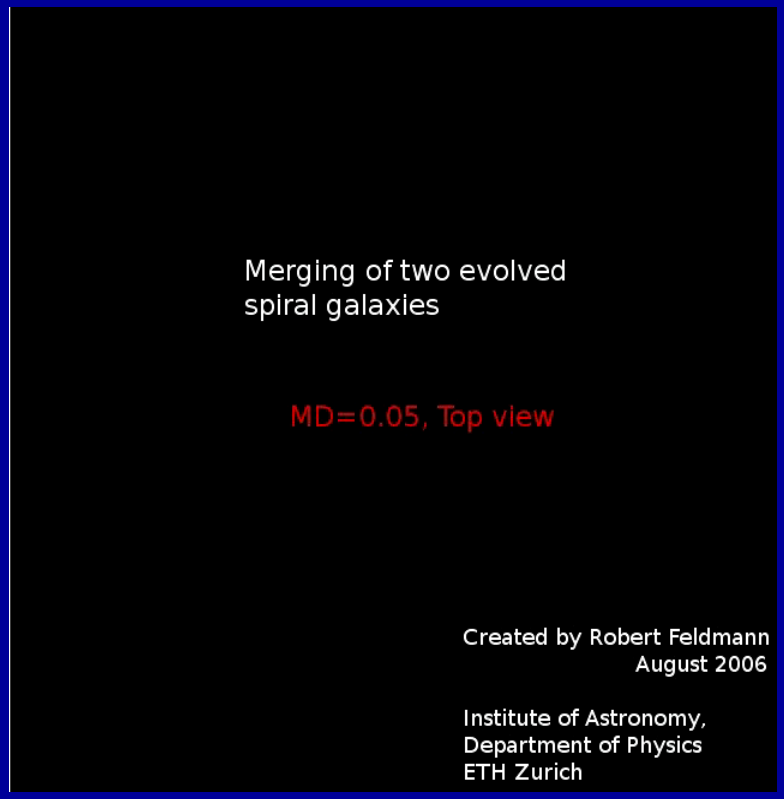
One simulated with AMR code RAMSES w/same sf/feedback model (Teyssier et al. 2009)

The Tully-Fisher Relation

The **simulated halos** (stars) on a plot of the Tully-Fisher relation from Geha et al. (2006), using measured HI widths and I-band magnitudes. The grey background points are from a variety of sources as cited in Geha et al. (2006).

Are recent major mergers a problem for formation of disk-dominated galaxy?

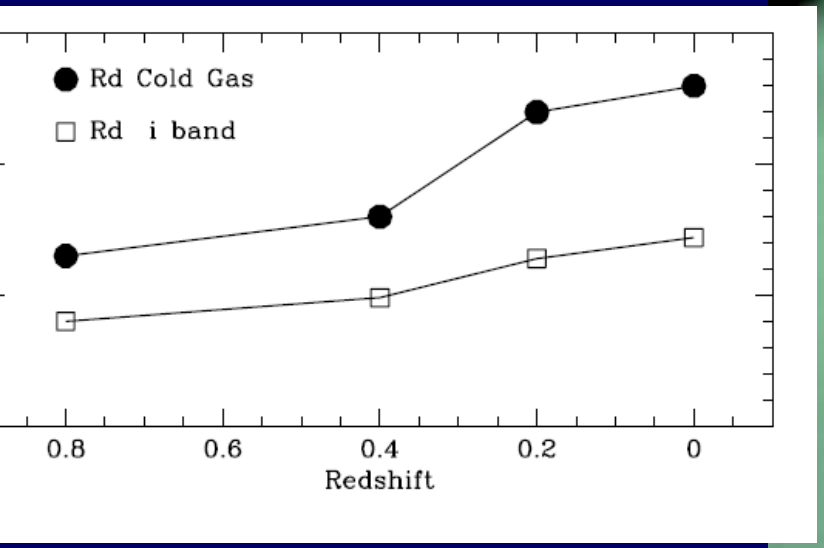
Disk-disk mergers are known to form ellipticals

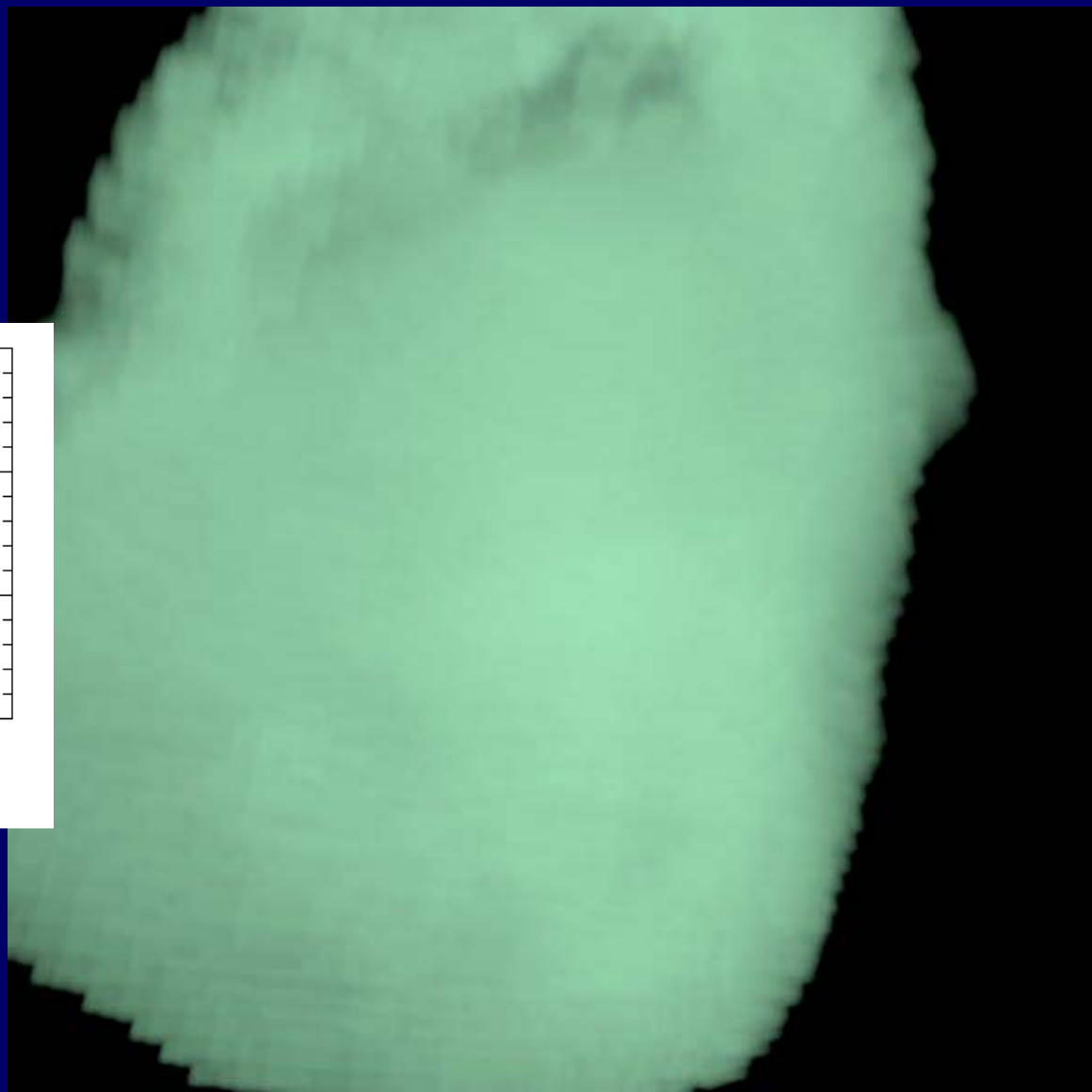


So is a "quiet" merging history a requisite?

Formation of a large disk galaxy from a gas-rich merger *(Governato, Brook, Brooks, Mayer et al. 2008)*

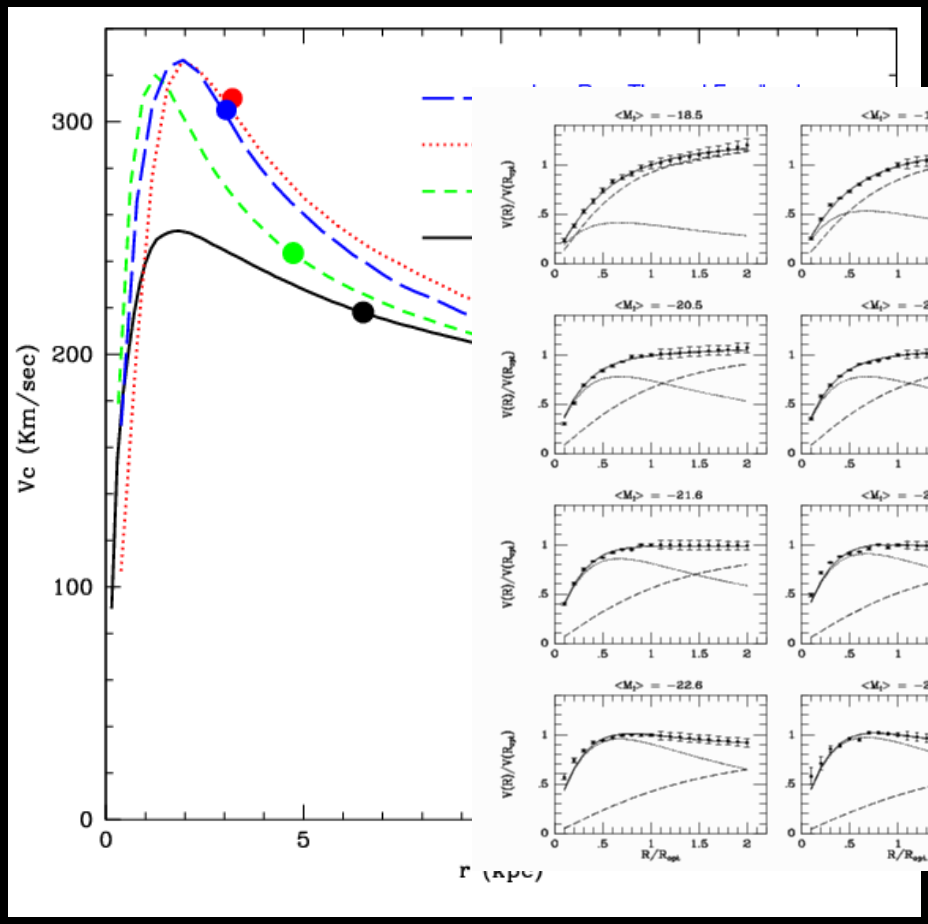
MW-sized galaxy
(M_{vir} ~ 10^{12} Mo)

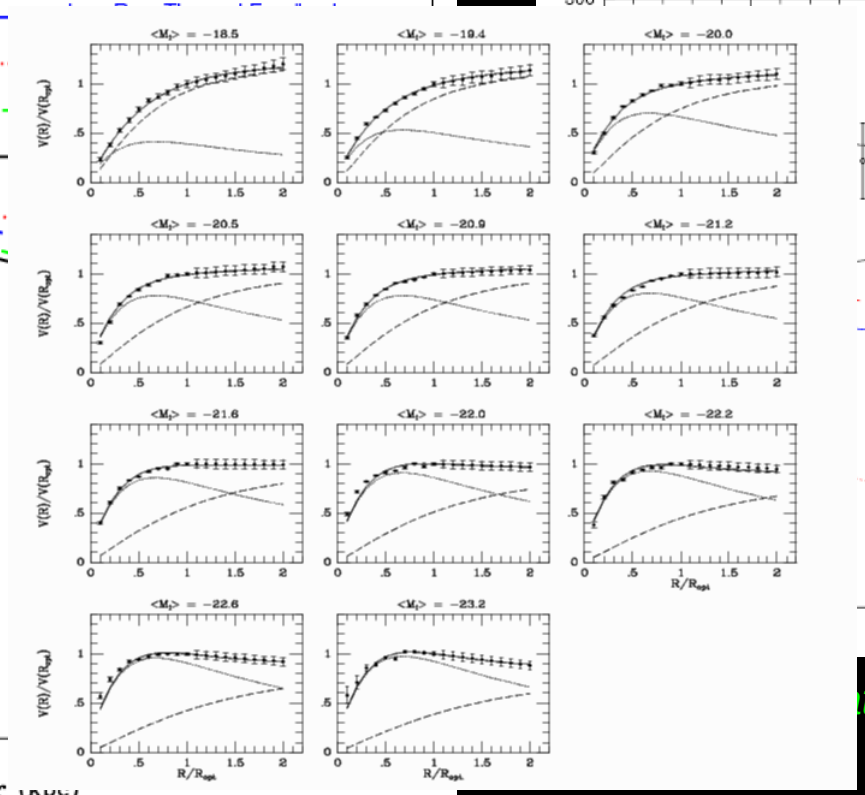


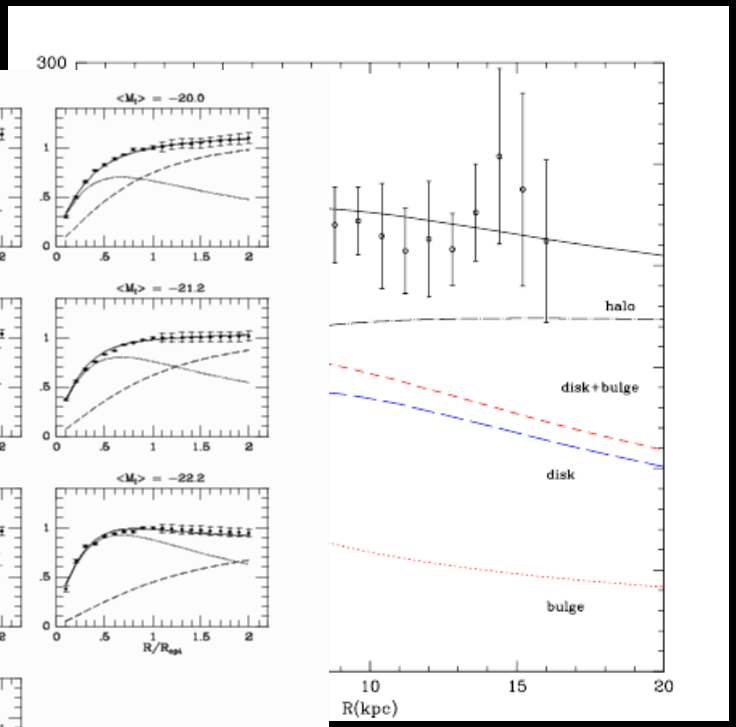


Mass distribution of simulated galaxies

The mass concentration problem: ***global size (global J) realistic but central region of galaxy still has too low J material (central stellar bulge too massive – in dwarf galaxies even no bulge!)***







to & Kaufmann,

How do we get rid of massive central "bulge"?

Resolution helps but does not solve. Bulge contains lowest angular momentum material that sinks closest to center of galaxy

“High” vs “Low” Resolution Star Formation

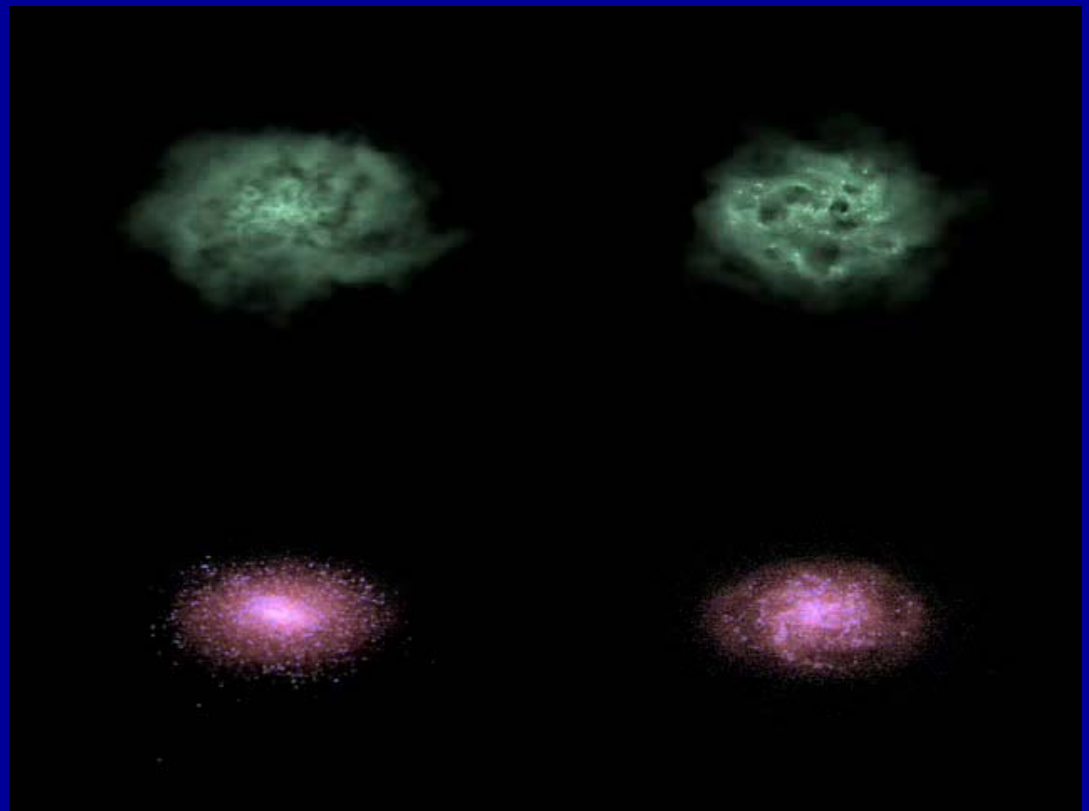
Star formation in galaxies is in molecular clouds (ρ ~ 100 atoms/cm^{-3})
So far limited resolution has forced simulations to use star formation density threshold corresponding to low-density, warm atomic medium (~ 0.1 atoms/cm^{-3})

With sufficiently high mass and force resolution (M_{SPH} ~ 10^3 Mo, Δs ~ 50 pc) we can now resolve high density peaks with masses 10^5-10^6 Mo and GMC densities in low mass galaxies-→ can now use realistic “molecular” star formation density threshold

Low SF Threshold 0.1 atoms/cc

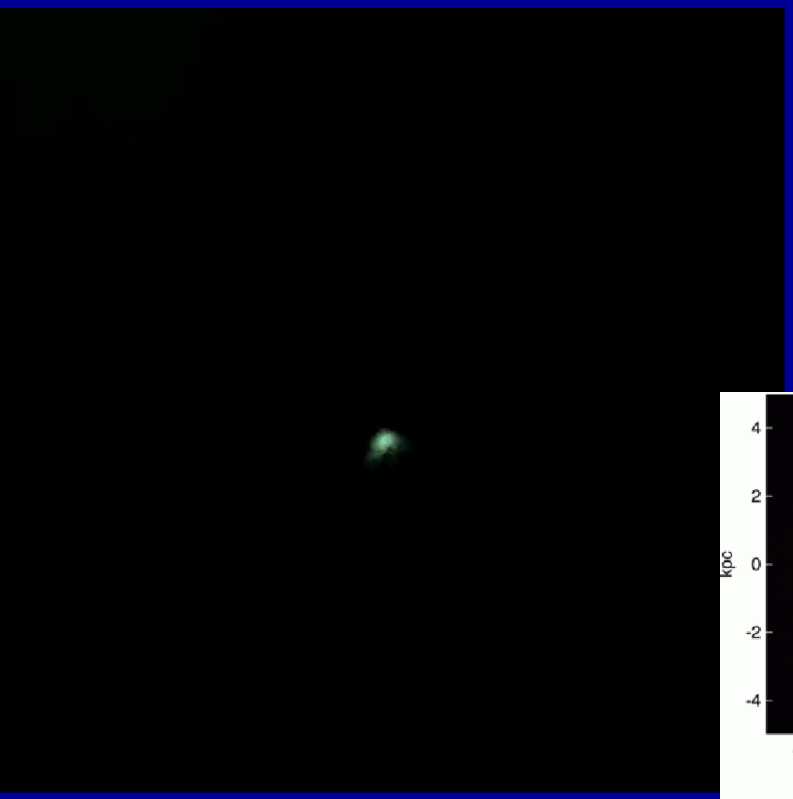
Top: gas Density

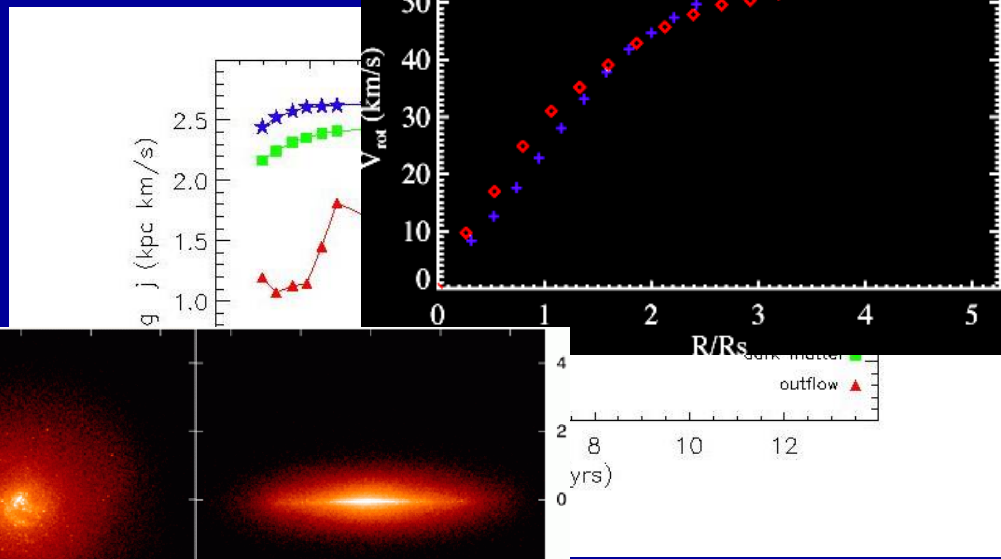
Bottom: stellar density

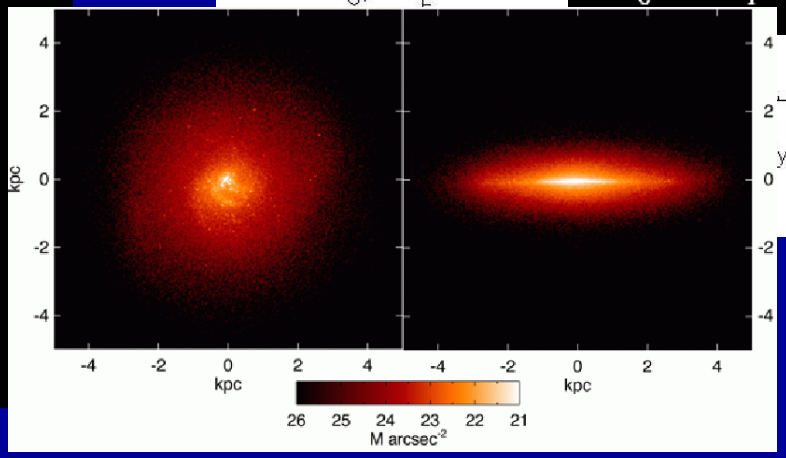


Hi SF Threshold 100 atoms/cc

Towards a solution of the mass concentration problem







Brook , Governato, Mayer et al., 2009,

With star formation in dense molecular phase:

- **star formation more localized, only in high density peaks -→ locally stronger effect of outflows because more energy deposited in smaller volume via blastwaves**

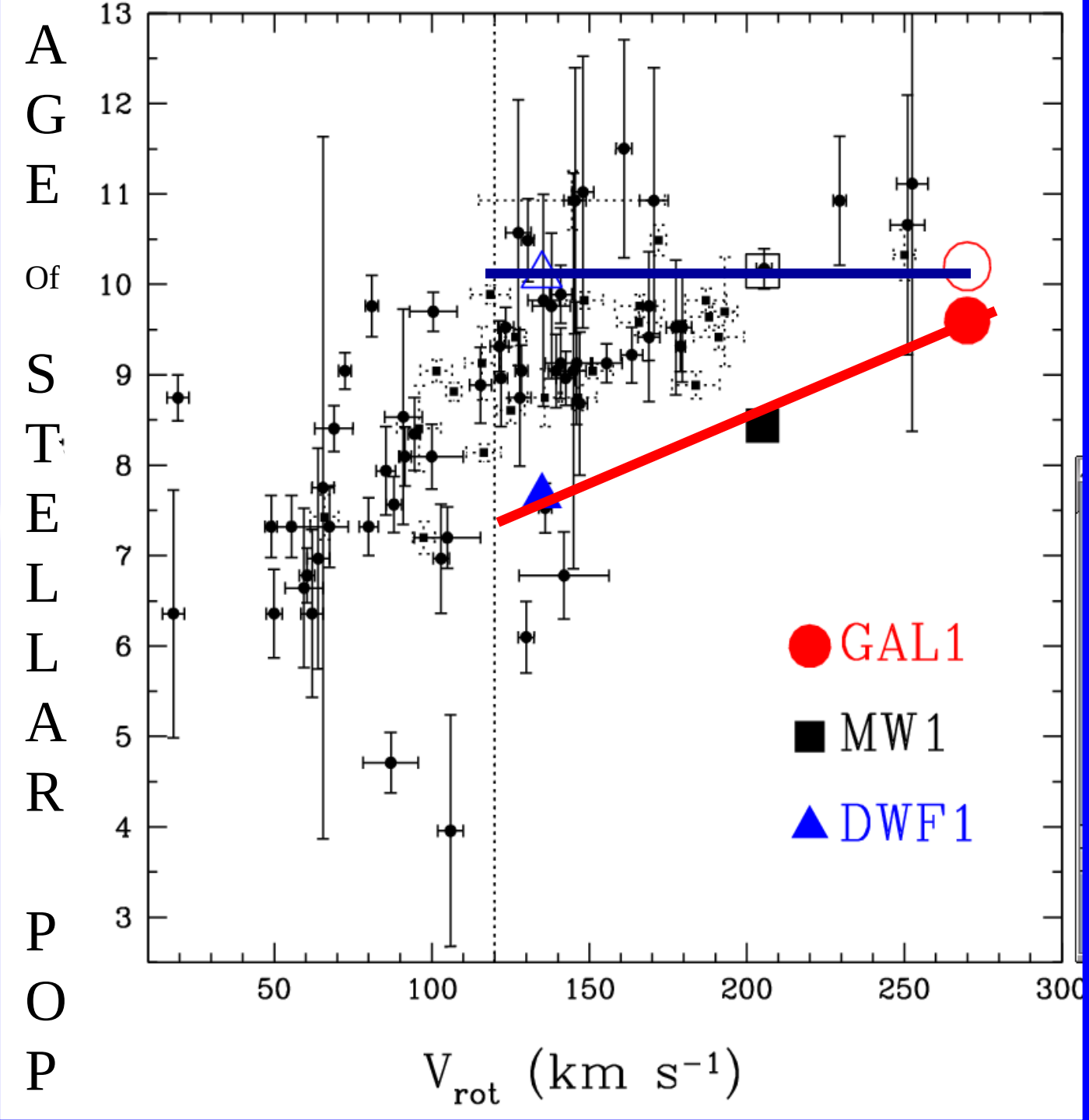
- **Outflows mostly in the center of galaxy where density higher -→ remove low angular momentum material -→ suppress bulge formation → produce realistic slowly-rising rotation curve**

Conclusions

Major improvements with higher resolution + more realistic sub-grid models --→ no need to change cosmology!

(1) Realistic disk galaxies resembling massive early-type spiral galaxies are now obtained in ΛCDM simulations through a combination of high resolution (which limits spurious angular momentum loss) and blastwave feedback (which avoids overcooling and regulates star formation)
Unrealistically small disk sizes disappear with more than a million resolution elements per galaxy + mean rotational velocities approach observed values

(2) Recent gain in resolution allows to follow regions with densities of GMCs
Star formation becomes more clustered and blastwaves stronger locally
--→ in low mass halo (Vc < 100 km/s) a galaxy with slowly rising rotation curve and no bulge obtained. ***Towards the solution of galaxy formation in CDM ?***



Data points from Mac Arthur Courteau and Bell 2004

We reproduce the observed ***anti-hierarchical*** trend of galaxy mass vs age trend.in a ***hierarchical*** Universe

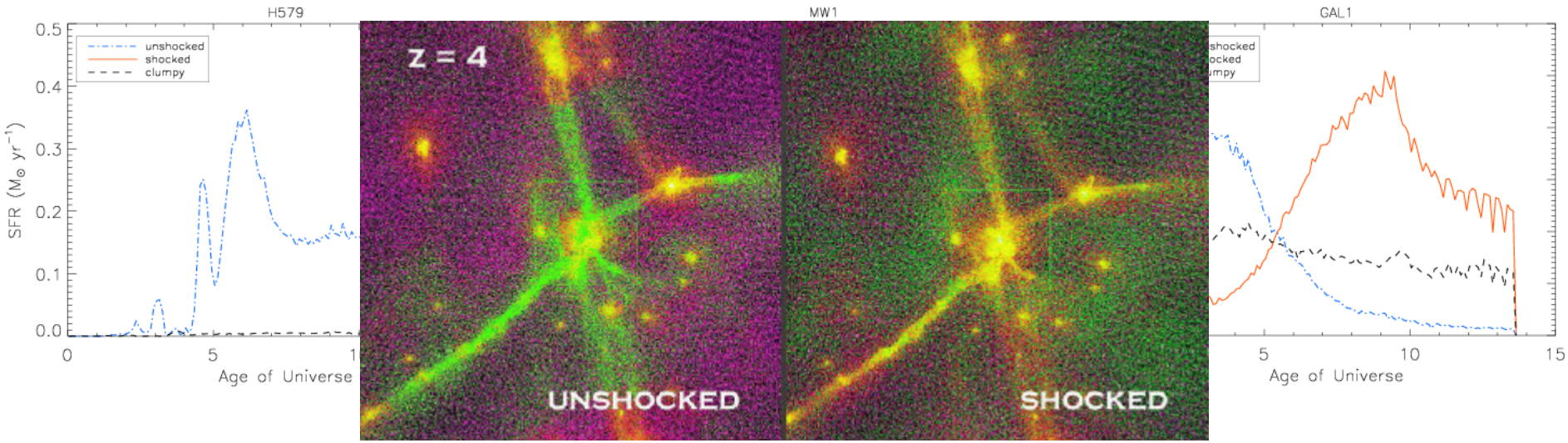
Star Formation delayed/suppressed more in lower mass galaxies

Hi-res cosmological dwarf galaxy formation simulation

NSPH ~ 5 x 10^6 particles
Ndm ~5 x 10^6 particles,
spatial resolution 50 pc
High SF threshold
100 atoms/cm^3

Star Formation History in galactic disks: imprint of cold and hot mode

Blue: Cold Flows. Orange: Shocked.

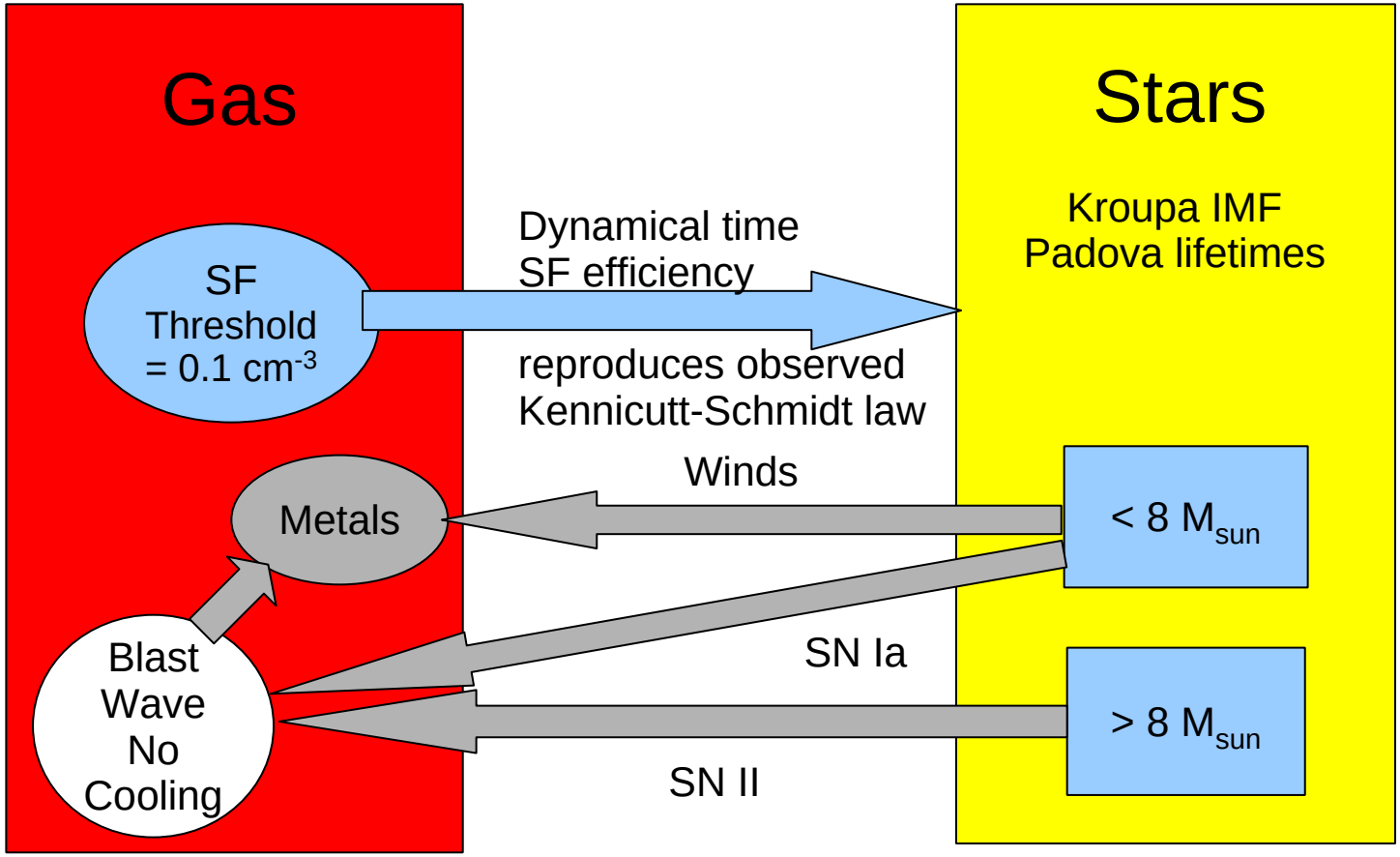


5e10 1e12 3e12

Cold Flows Shocked gas

A (sub-grid) phenomenological attempt model ISM + SF physics

Stinson et al 2006



Free parameters: C* (SF eff.), εSN (supernova heating eff.)

Supernova blast-wave model based on **McKee & Ostriker (1977)**

GALAXY FORMATION – A MULTI-FACETED PROBLEM

TO SOLVE IT WE NEED:

▪**RIGHT COSMOLOGY/STRUCTURE FORMATION** - provides the initial conditions (e.g. J, halo masses/densities) and the global dynamics (hierachical merging/accretion). Let us assume ΛCDM model is correct.

▪**"COMPLETE" INPUT PHYSICS** radiative cooling, star formation,heating mechanisms in interstellar medium (supernovae explosions, radiative backgrounds, e.g. cosmic UV bg) ---→ should yield right thermodynamics of baryons.

↕

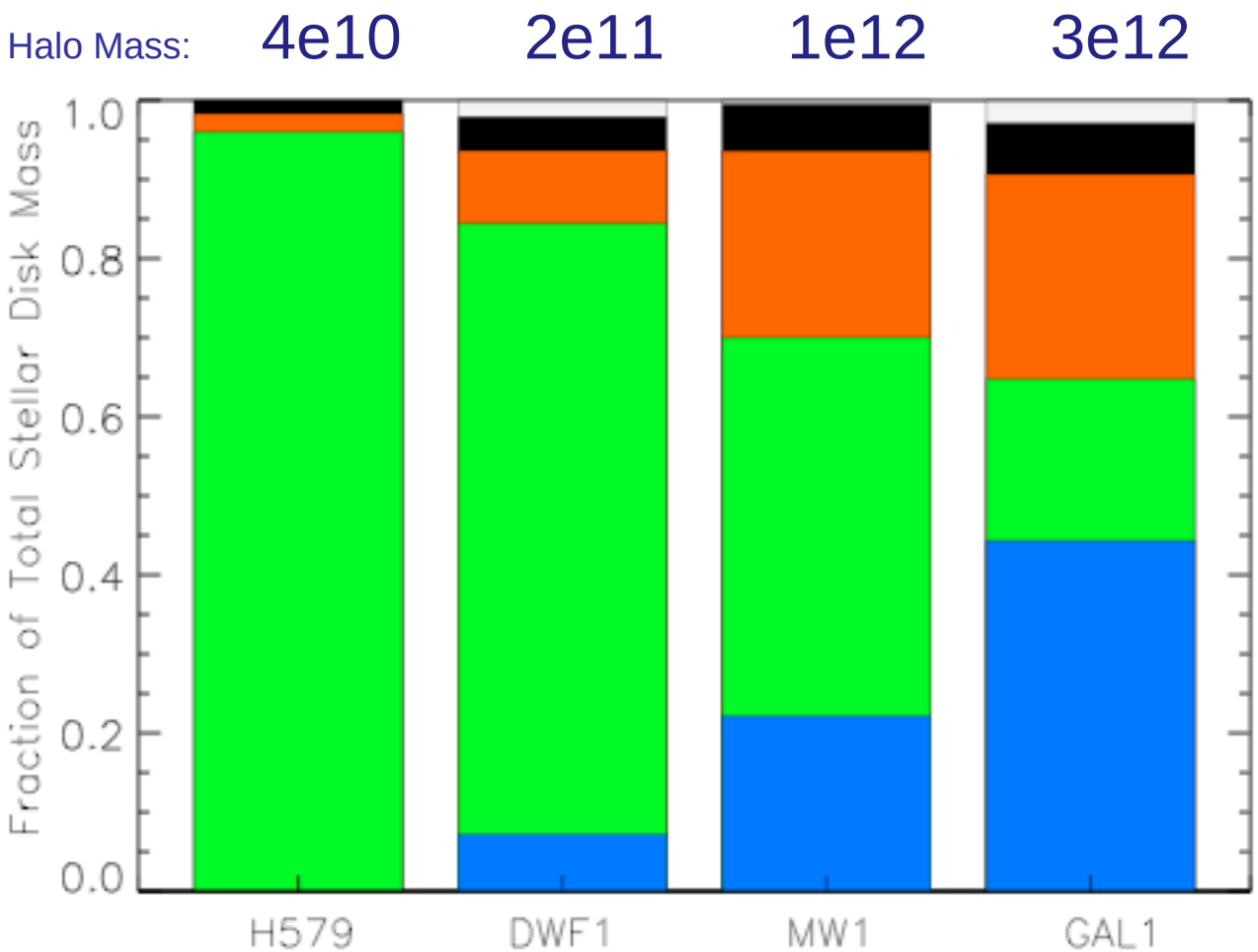
▪**RELIABLE NUMERICAL MODELS**

Numerical simulations (needed due to complexity) rely on discrete representation + solution of continuum CDM and baryonic fluid by particles/finite grid cells → solve exactly Collisionless Boltzmann Equation (CDM) and Euler equation (baryons) coupled with gravity only in the limit of infinite number of particles/grid cells…

Gas accretion : disk stars @ z=0

clumpy cold flows shocked

Brooks et al, in prep.



Confirms cold vs. hot mode accretion scenario by Dekel & Birnboim (2006;2008) and Keres et al. (2005)