modeling star formation in high-resolution cosmological simulations

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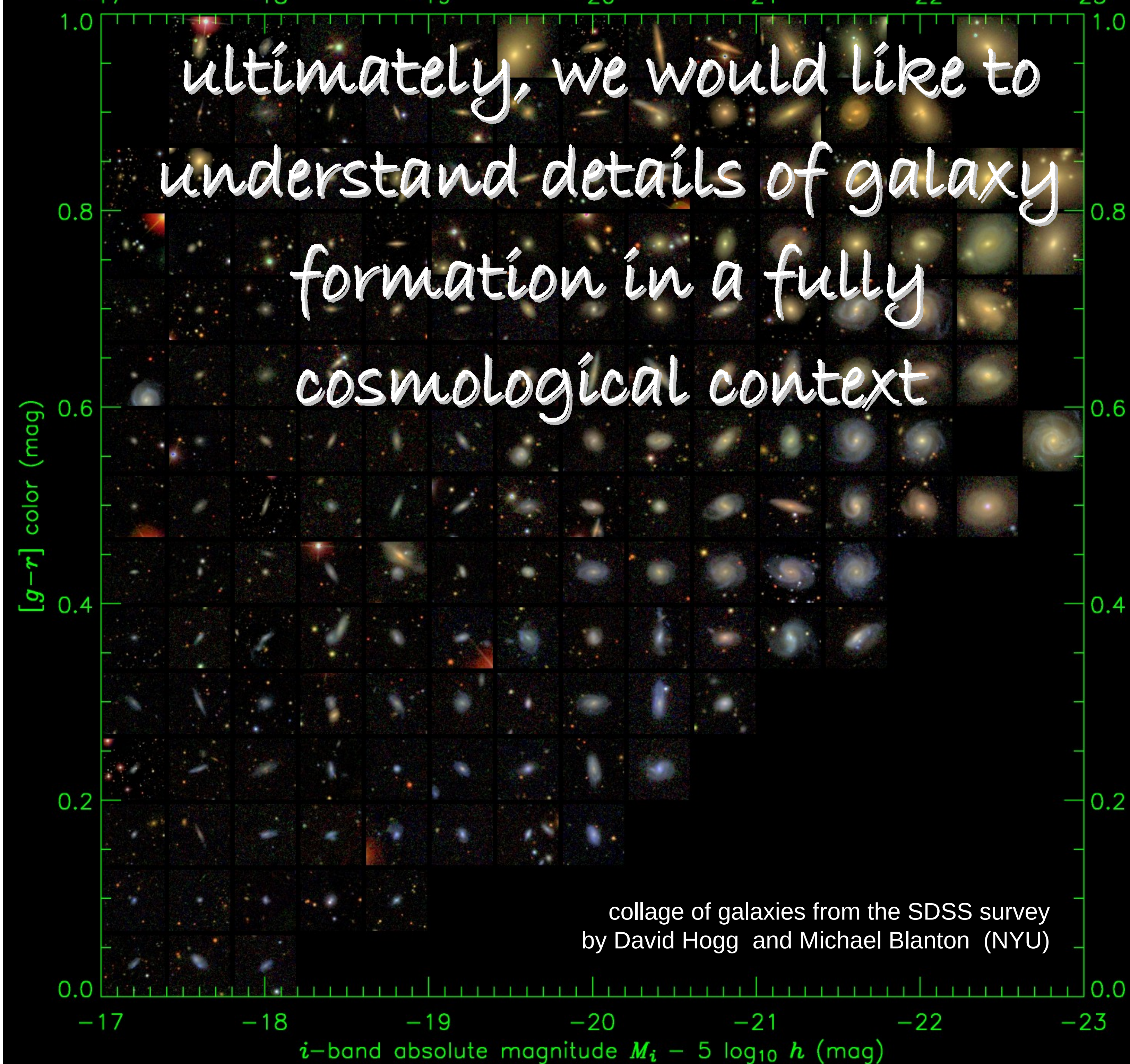
we have a robust framework for dark matter halo formation

Dark matter distribution in a simulation of LCDM cosmology (intensity = log of local DM density) ultimately, we would like to understand details of galaxy formation in a fully cosmological context



collage of galaxies from the SDSS survey
by David Hogg and Michael Blanton (NYU)

It's a difficult problem...

HST image of the Antennae galaxies

THE ASTROPHYSICAL JOURNAL, 399:L113–L116, 1992 November 10

GALAXY FORMATION AND PHYSICAL BIAS

RENYUE CEN AND JEREMIAH P. OSTRIKER
Princeton University Observatory, Princeton, NJ 08544
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Tag all mesh cells (or gas particles in an SPH simulation) for which the following set of conditions is satisfied:

$$\nabla \cdot v < 0 \Rightarrow \text{contracting} ,$$

$$t_{\rm cool} < t_{\rm dyn} \equiv \sqrt{\frac{3\pi}{32G\rho_{\rm tot}}} \Rightarrow \text{cooling rapidly}$$

$$m_b > m_J \quad \Rightarrow \text{gravity unstable}$$

Take mass from the gas mass of the cell and convert it into a stellar particle:

$$\Delta m_b = -m_b \Delta t / t_{\rm dyn} \quad \text{and} \quad m_* = +m_b \Delta t / t_{\rm dyn}$$

Stellar particles are assigned the momentum and position of their parent cell (or gas particle). Subsequently, they are followed as collisionless particles along with DM particles using standard N-body techniques.

another approach: subgrid models

assume a multi-phase model of ISM inside a computational gas element (grid cell or SPH particle)

Mon. Not. R. Astron. Soc. **284**, 235–256 (1997)

Hydrodynamical simulations of galaxy formation: effects of supernova feedback

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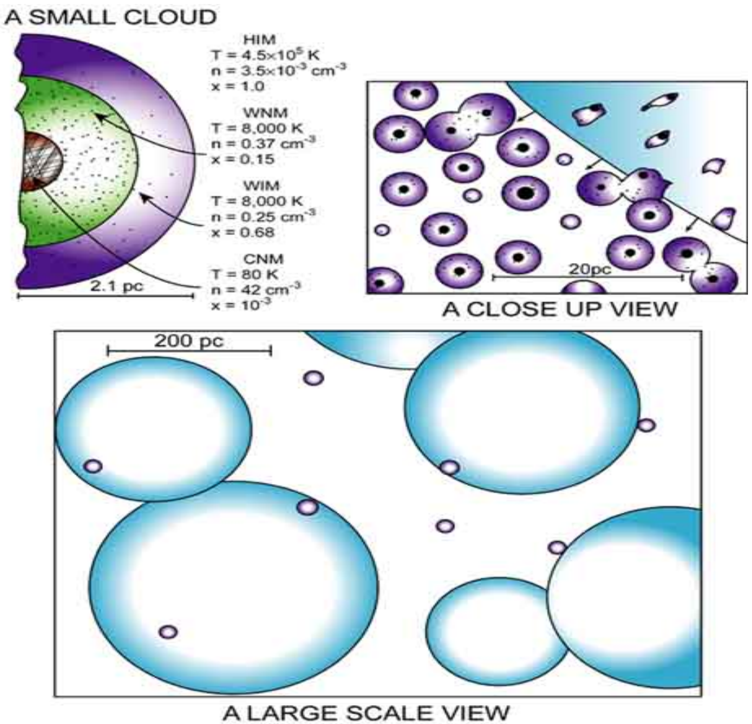

2.1 Multiphase medium

The matter in the simulated universe consists of four phases.

(1) The dark matter (labelled by a subscript 'dm') in the form of weakly interacting collisionless particles is the main contribution to the mean density of the universe ($\Omega_{\rm dm} = 1 - \Omega_{\rm bar}$). The baryonic component is described as a medium consisting of the following three interacting phases.

(2) Hot gas (labelled by subscript h, $T_{\rm h} > 2 \times 10^4$ K).

(3) Gas in the form of cold dense clouds (subscript c, internal temperature $T_{\rm c} = 10^4$ K) resulting from cooling of the hot gas.

(4) 'Stars' (subscript *), formed inside cold clouds and treated as collisionless particles. Thus, the total density $\rho(\boldsymbol{r})$ is the sum of four components:

$$\rho = \rho_{\rm dm} + \rho_{\rm h} + \rho_{\rm c} + \rho_{*}. \tag{1}$$

Stars are treated as collisionless particles, and thus their filling factor is zero. $\rho_{\rm c}$ represents the average density of cold gas clouds, which have negligible filling factors as well (McKee & Ostriker 1977). We also assume that the hot and cold gas components are dynamically linked. Thus, they share the same average velocity at the cell resolution.

Mon. Not. R. Astron. Soc. **339**, 289–311 (2003)

Cosmological smoothed particle hydrodynamics simulations: a hybrid multiphase model for star formation

Volker Springel[1★] and Lars Hernquist[2★]
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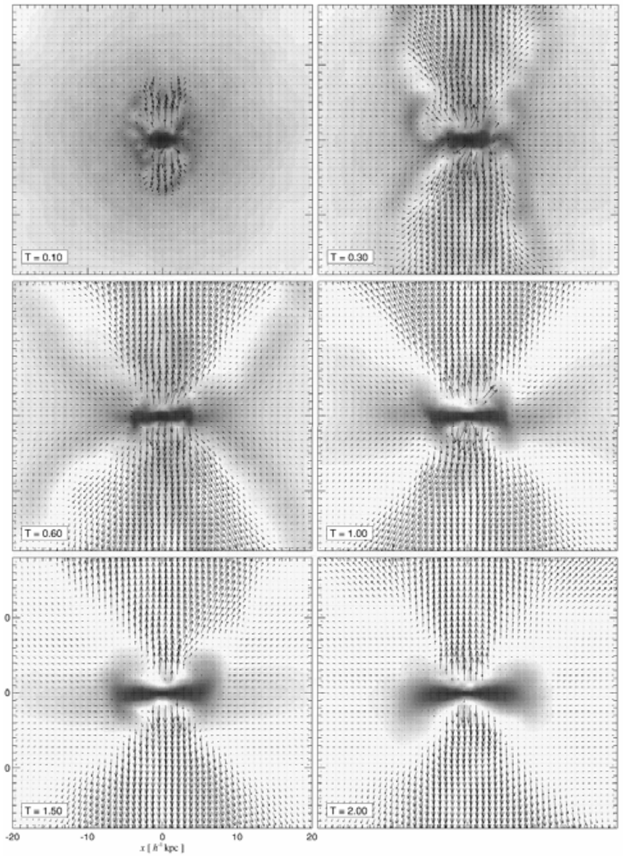
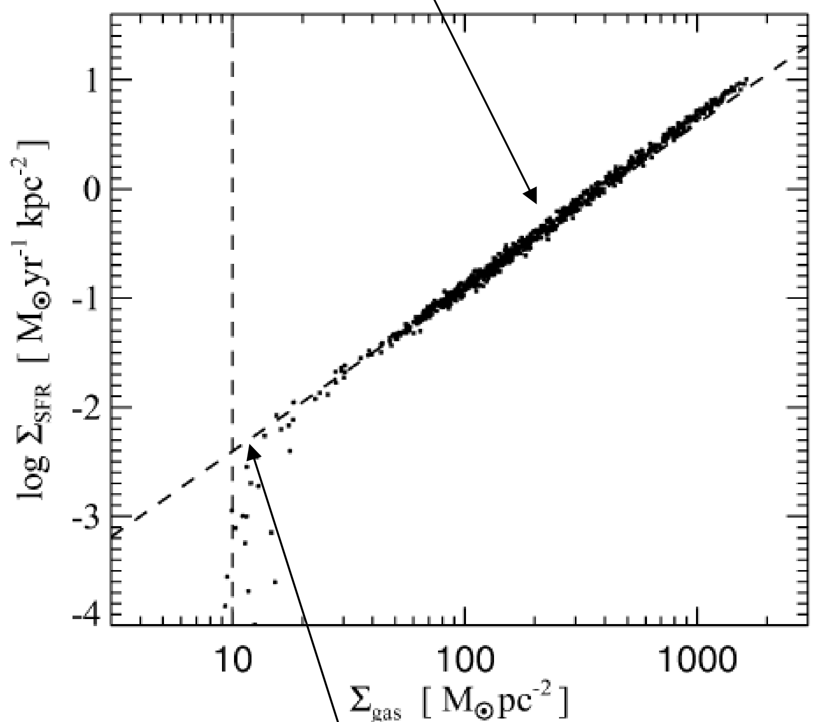


- ❑ implemented multi-phase subgrid (or rather sub-particle in this case) model of Yepes et al. 1997 in the SPH Gadget code
- ❑ extended the model by including galactic winds, presumably driven by the supernovae feedback (kinetic feedback)
- ❑ tune in for Joop Schaye's talk this afternoon for more on implementation of this model in Gadget.

The parameters of the starformation recipe are usually tuned to reproduce the observed Kennicutt law

SF rate as a function of gas surface
density in a controlled simulation of a gas disk

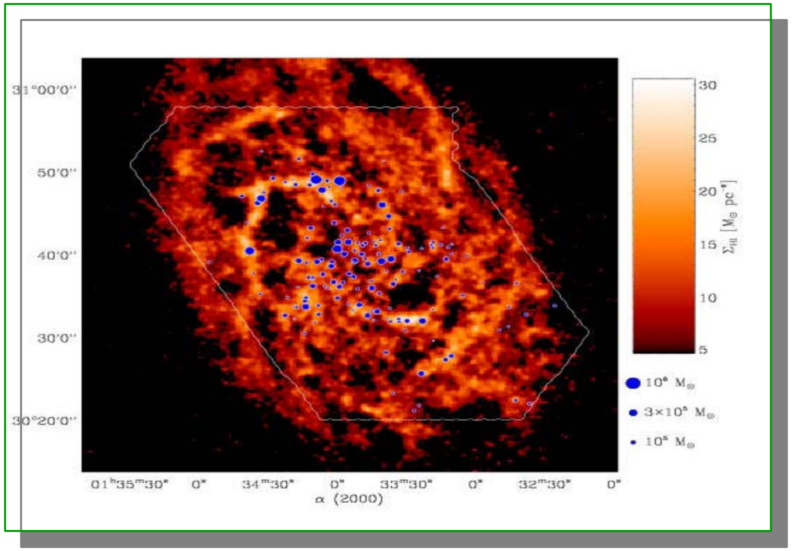


Springel & Hernquist 2003

observed law (Kennicutt 1998)

$$\Sigma_{\rm SFR} = (2.5 \pm 0.7) \times 10^{-4} \left(\frac{\Sigma_{\rm gas}}{1 \ {\rm M_\odot pc^{-2}}} \right)^{1.4 \pm 0.15} \ {\rm M_\odot yr^{-1} kpc^{-2}}$$

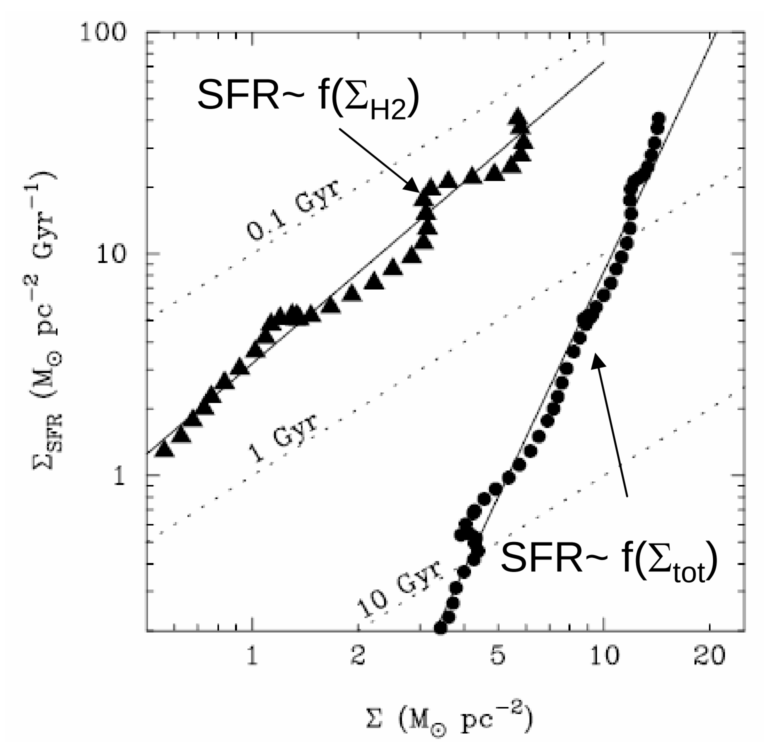
Star formation in simulations: challenges



HI/CO map of M33 courtesy of Leo Blitz

- ❑ It is not yet clear how universal is the K-S law, especially *locally* on scales < 100 pc in unusual environments of dwarf and starburst galaxies

- ❑ The recipes commonly used so far may be appropriate on scales >5 kpc, but are not applicable for scales smaller than 100 pc (e.g., statistical multi-phase ISM description)



case study – star formation in M33

Observed Schmidt Law $\Sigma_{SFR} = C\Sigma^n_{gas}$ in M33

Parameter	Total Gas	Molecular Gas
n	3.3 ± 0.07	1.36 ± 0.08
C	0.0035 ± 0.066	3.2 ± 0.2
Correlation Coefficient	0.99	0.98

Heyer et al. 2004
see also Boissier et al. 2003

Why high resolution?

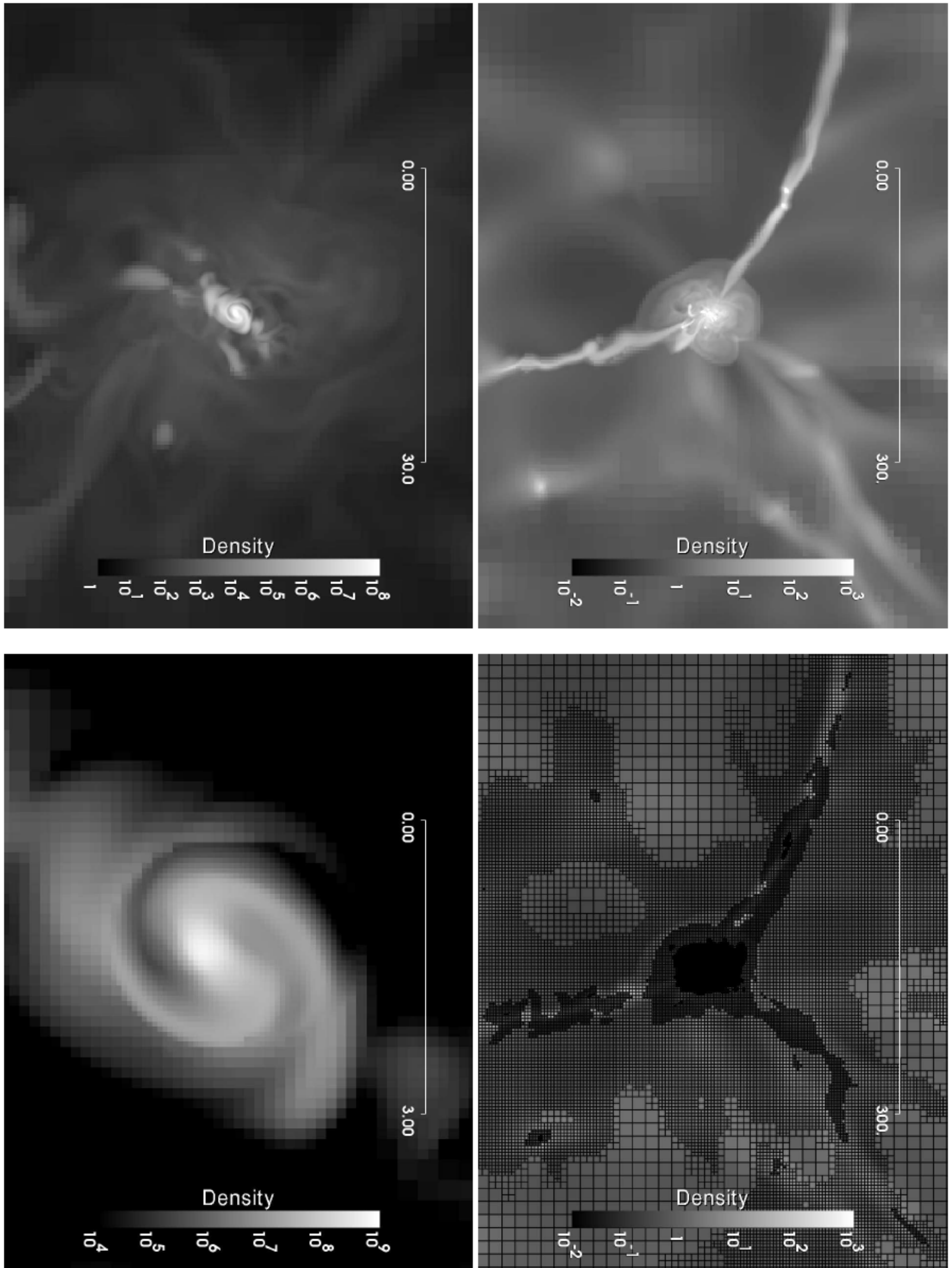
- *high* resolution is required to simulate internal structure of galaxies, star formation, and feedback *properly* in cosmological context:

Ideally need resolution element in star formation regions of ~1-10 pc (i.e., $>10^6$ dynamic range in a box of 10 Mpc). Why? Molecular clouds form on these scales. The scale-height of cold gas disk in the MW is ~100 pc.

Bar formation and dynamics requires ~10 pc resolution and millions of stellar particles to resolve the relevant orbital resonances properly (e.g., Debattista et al. 2005)

- currently, such dynamic range is achievable only at <u>*high redshifts.*</u> high-z's are also less complicated in certain physical aspects (e.g., low dust content) and very interesting overall…

Cosmological simulations of high-z galaxy formation



- Adaptive Refinement Tree (ART) code (Eulerian shock-capturing AMR hydro)

- *N*-body dynamics of DM and stellar particles

- radiative cooling and heating: Compton, UV background heating, density and *metallicity dependent net cooling/heating equilibrium rates taking into account line and molecular processes* (cooling rates down to 100 K)

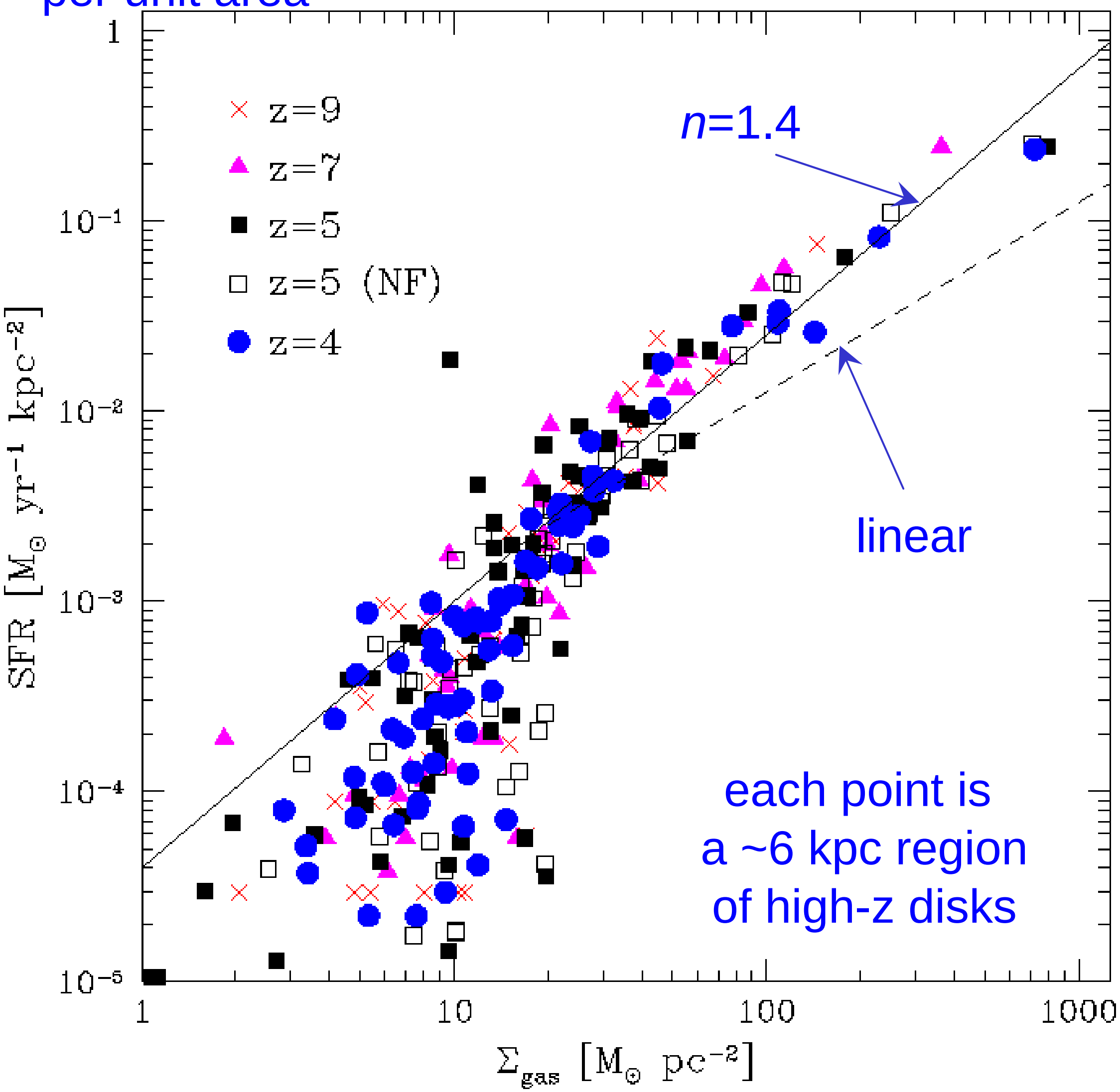
- Star formation only in the dense, cold, high-f_{H2} gas

- Thermal stellar feedback and metal enrichment by SNII/Ia, stellar mass loss

- Peak resolution in the disk region ~20-50 pc particle mass ~10^6 Msun

example of a different star formation implementation on small scales

star formation rate
per unit area



gas surface density

<u>star formation recipe</u>:
stars form only at molecular densities – local SFR is *linear* function of gas density:

$$\dot{\rho}_* \propto \rho_g$$

$$T < T_{SF} \text{ and } \rho_g > \rho_{SF}$$

$$(\rho_{SF}=50 \text{ cm}^{-3})$$

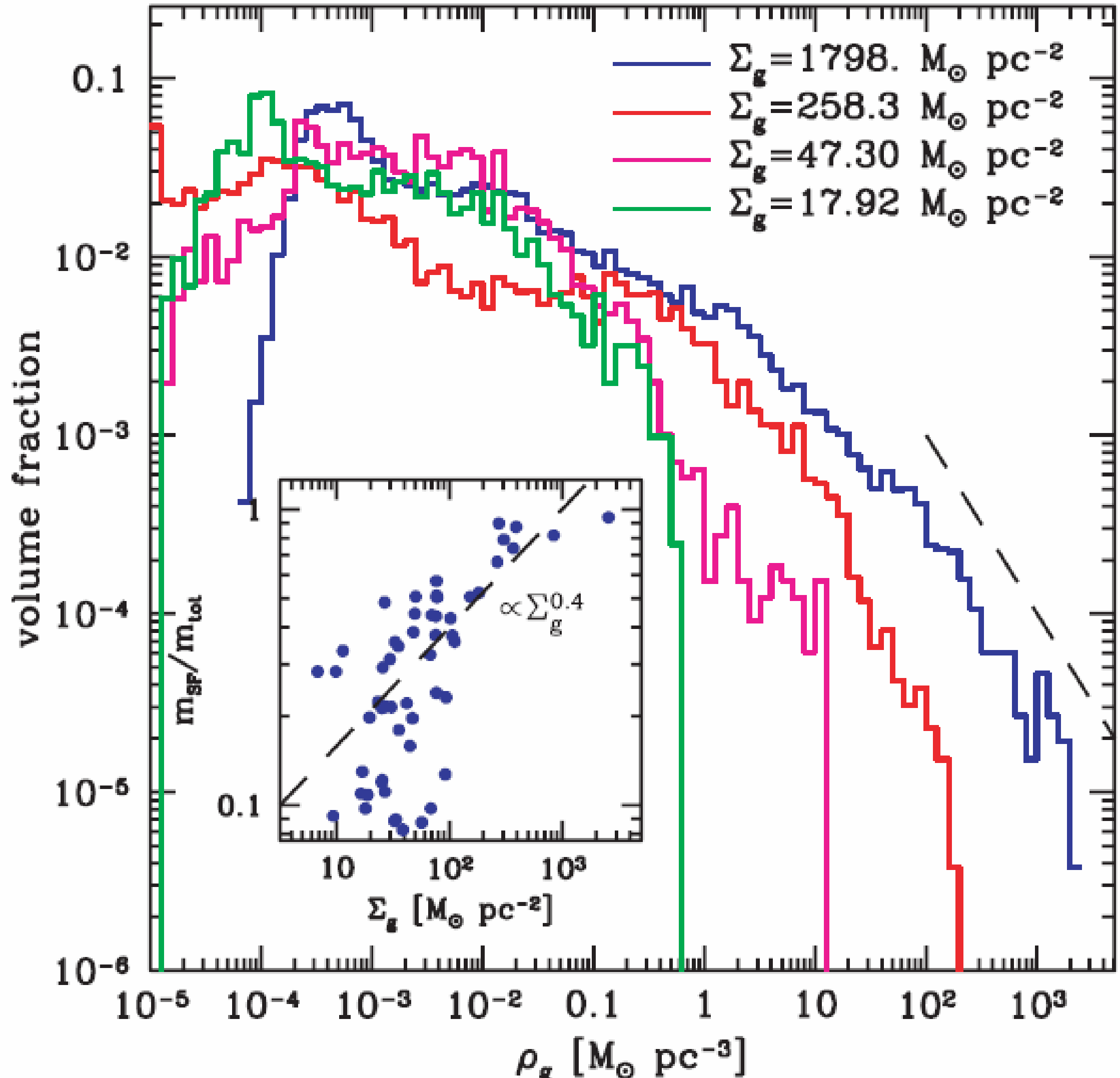
when averaged on 6 kpc scale get non-linear K-S correlation:

$$\text{SFR} \propto \Sigma_{gas}^n \text{ with } n \approx 1.4$$

Kravtsov 2003, ApJL, 590, L1

The origin of *n*=1.4 in the simulations

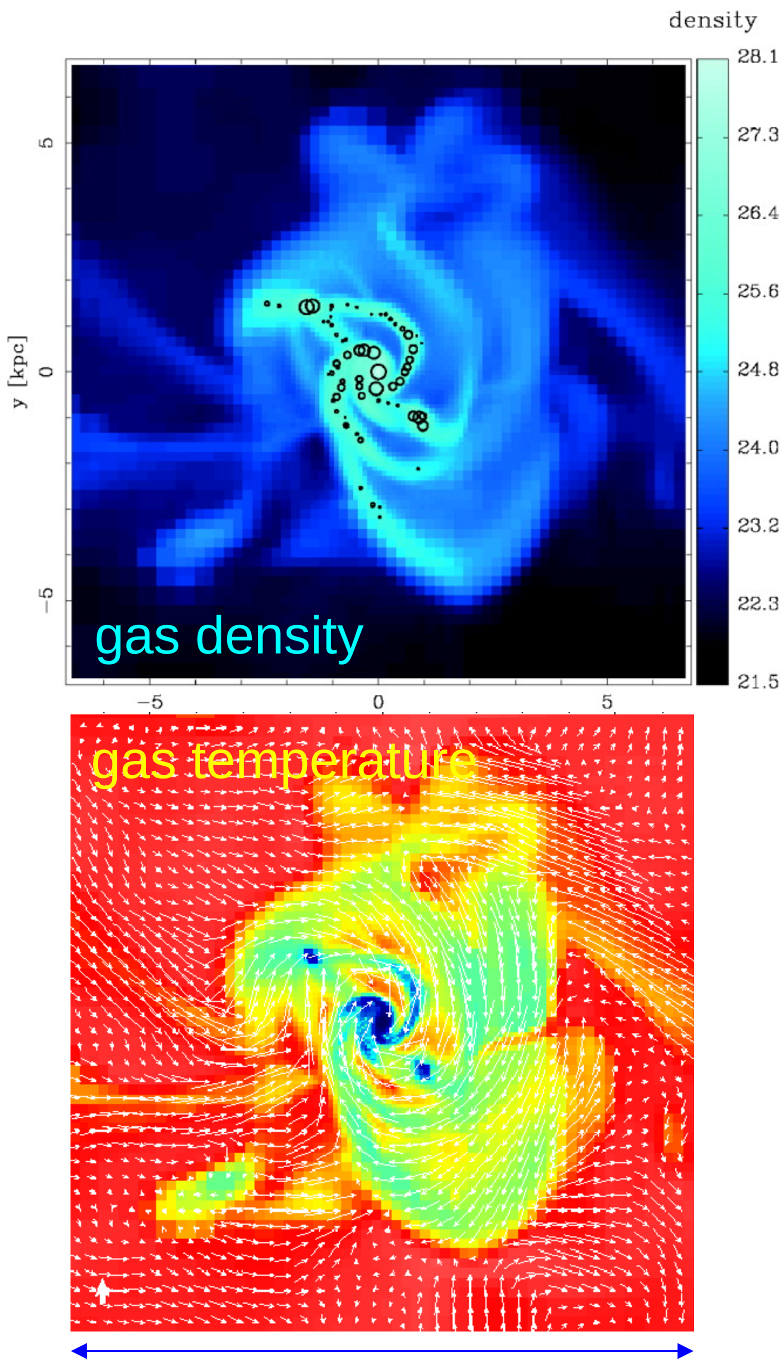
pdf of gas density and scaling of the fraction of gas at molecular densities as a function of total gas density on ~kpc scales



3D gas density

Kravtsov 2003, ApJL, 590, L1

Formation of star clusters



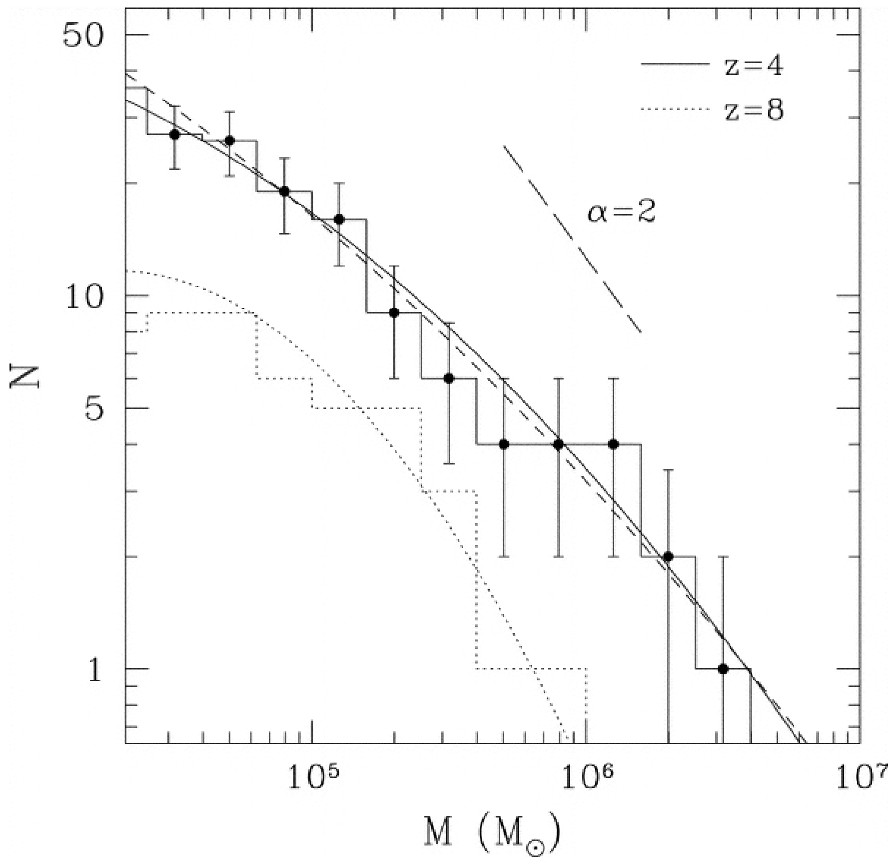
- Identify GMCs in the ISM of high-z galaxies
- *assume that massive star cluster forms in the densest cell of each identified GMC*
- assume an isothermal density profile (e.g., Williams et al. 2000) within the densest cell and formation of star cluster with efficiency e>0.5 at $\rho > \rho_{cl} \sim 10^4\ M_{sun}\ pc^{-3}$ (Elmegreen 2002), which corresponds to some radius R_{cl} (~3-5 pc)
- Simple model, but reasonable output mass function of GMCs and star clusters
- Implies that we could cluster mode of star formation in simulations

Kravtsov & Gnedin, O. 2005, ApJ 623, 650

see also Li, Mac Low & Klessen 2004

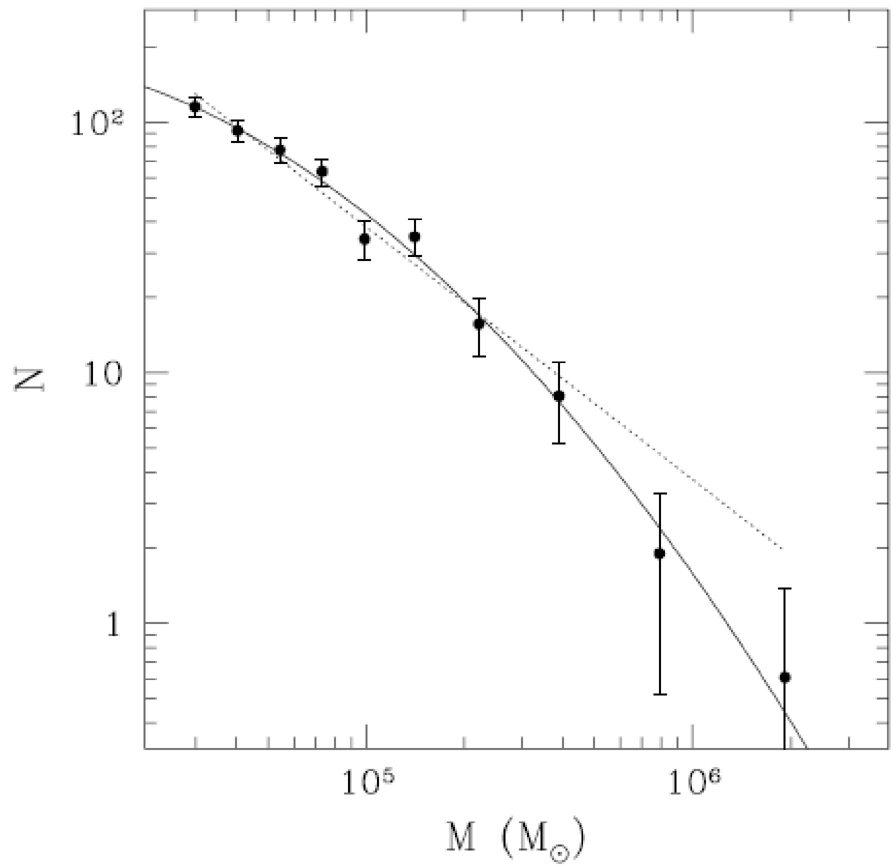
mass function of young star clusters

in sumulated high-z galaxies based on the cluster formation model



cluster mass

in Antennae (Zhang & Fall 2001)



cluster mass

Kravtsov & Gnedin, O. 2005, ApJ 623, 650

H_2 formation and star formation in molecular clouds

(work in progress; in collaboration with N. Gnedin)

- high-resolution AMR hydro simulations +

- *approximate 3D radiative transfer of UV continuum from local sources using the OTVET approximation* (Gnedin & Abel 2001) +

- prescription for H_2 formation on dust grains (Cazaux & Spaans 2004) +

- model H_2 self-shielding using the Sobolev approximation for line radiative transfer, assuming that the optical depth is controlled by dust which scales as $Z * N_{HI+H2}$, where Z is the mass fraction of gas in metals

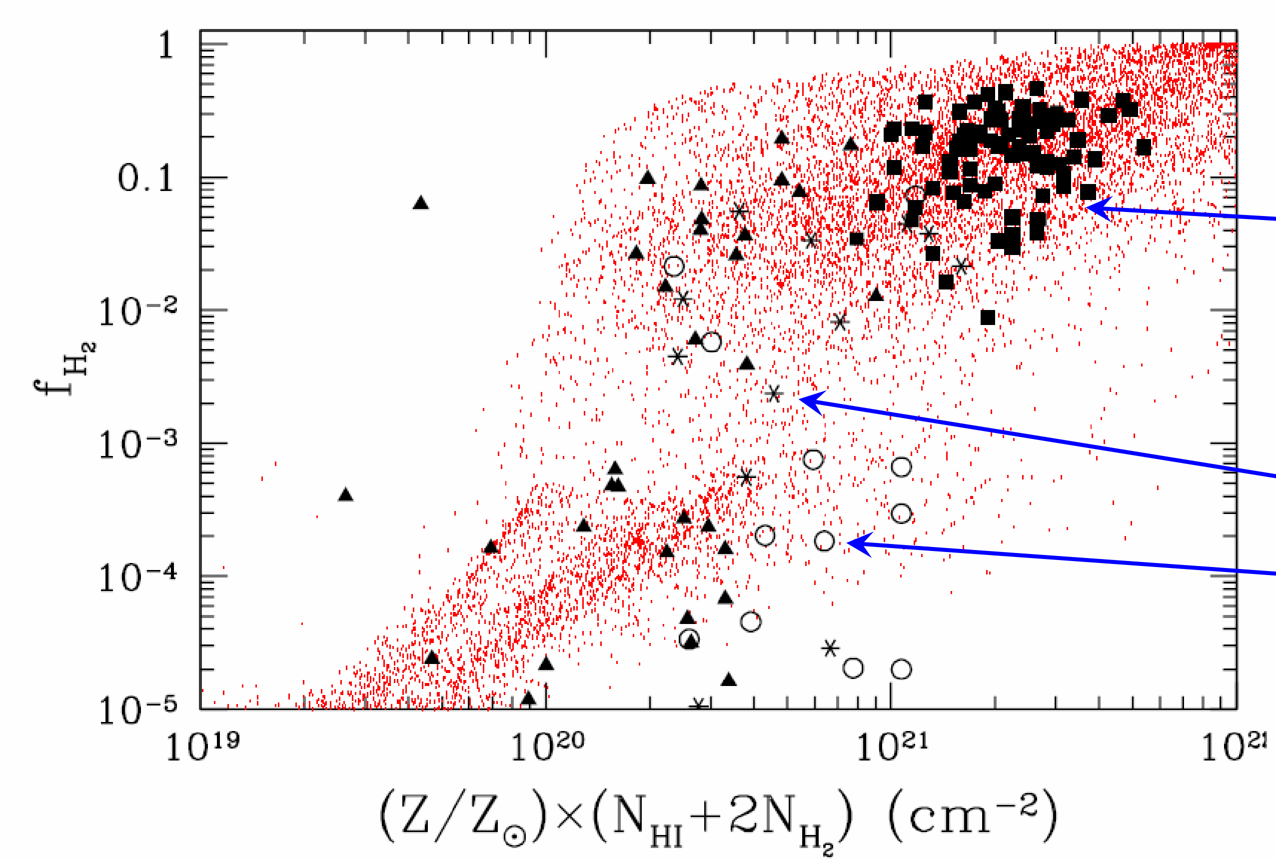
- identify star forming regions as regions of high H_2 fraction (star formation time scale is now controlled by the rate of H_2 formation)

- use an appropriate recipe to convert molecular gas into stars

Testing H_2 formation and self-shielding model

FUSE observations of translucent clouds (Browning et al. 03; Gillmon et al. 06)

H_2 fraction

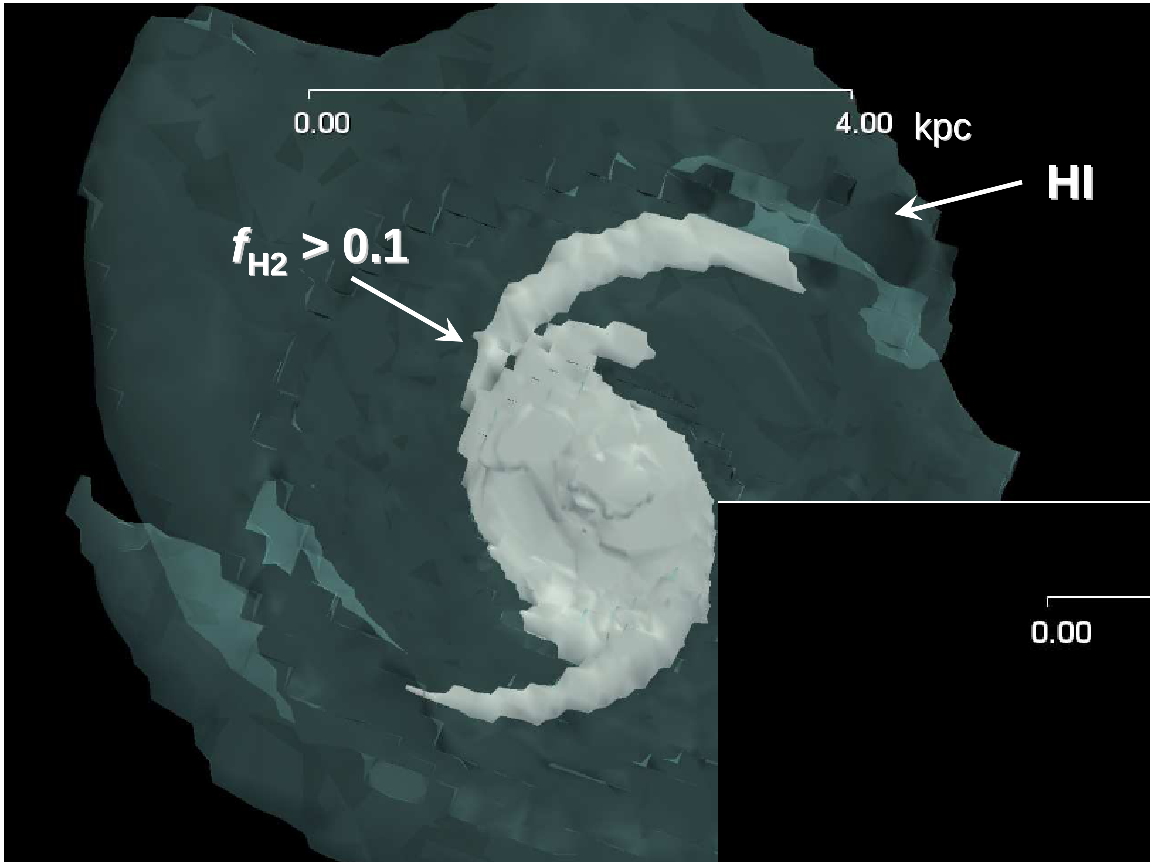


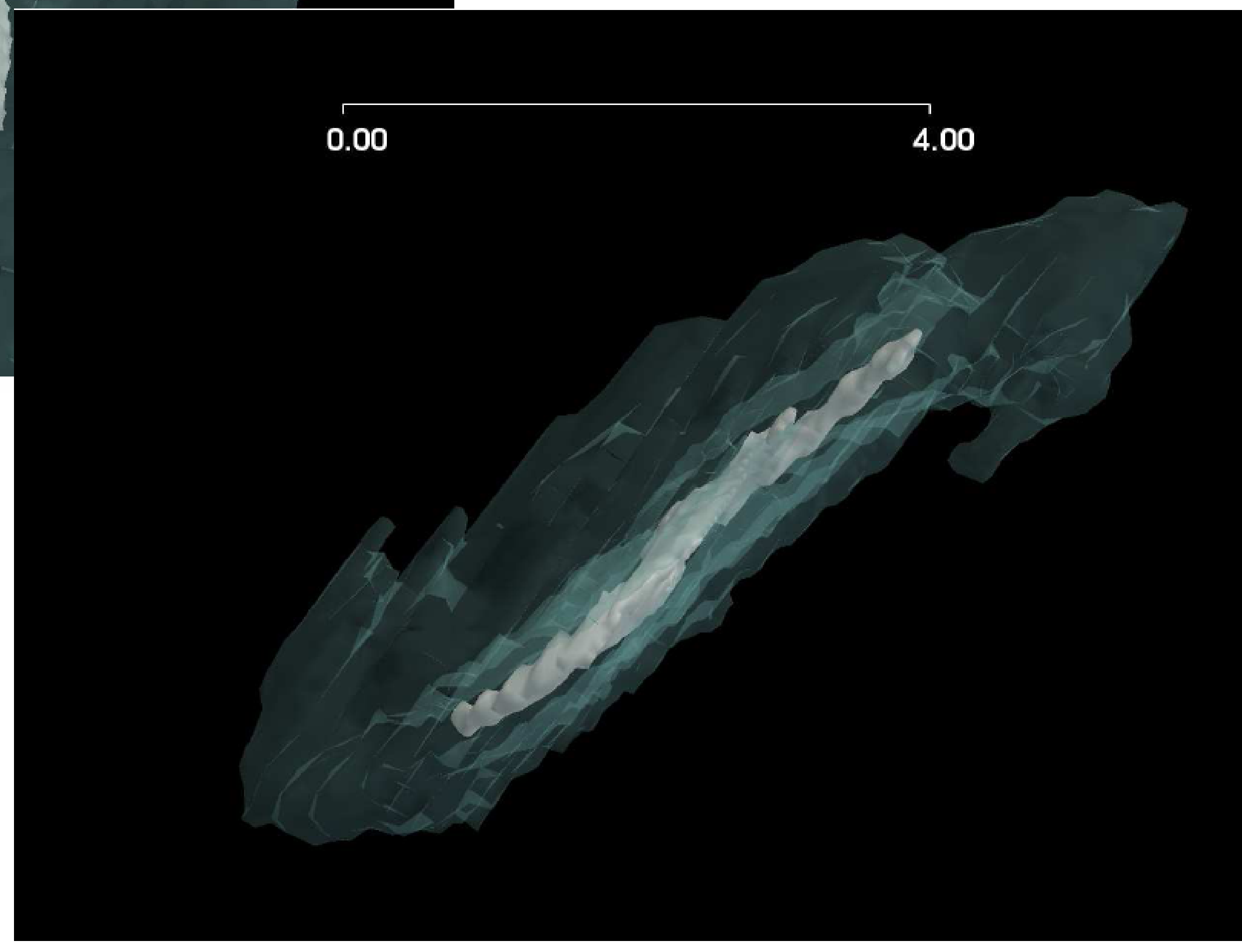
squares and triangles: MW

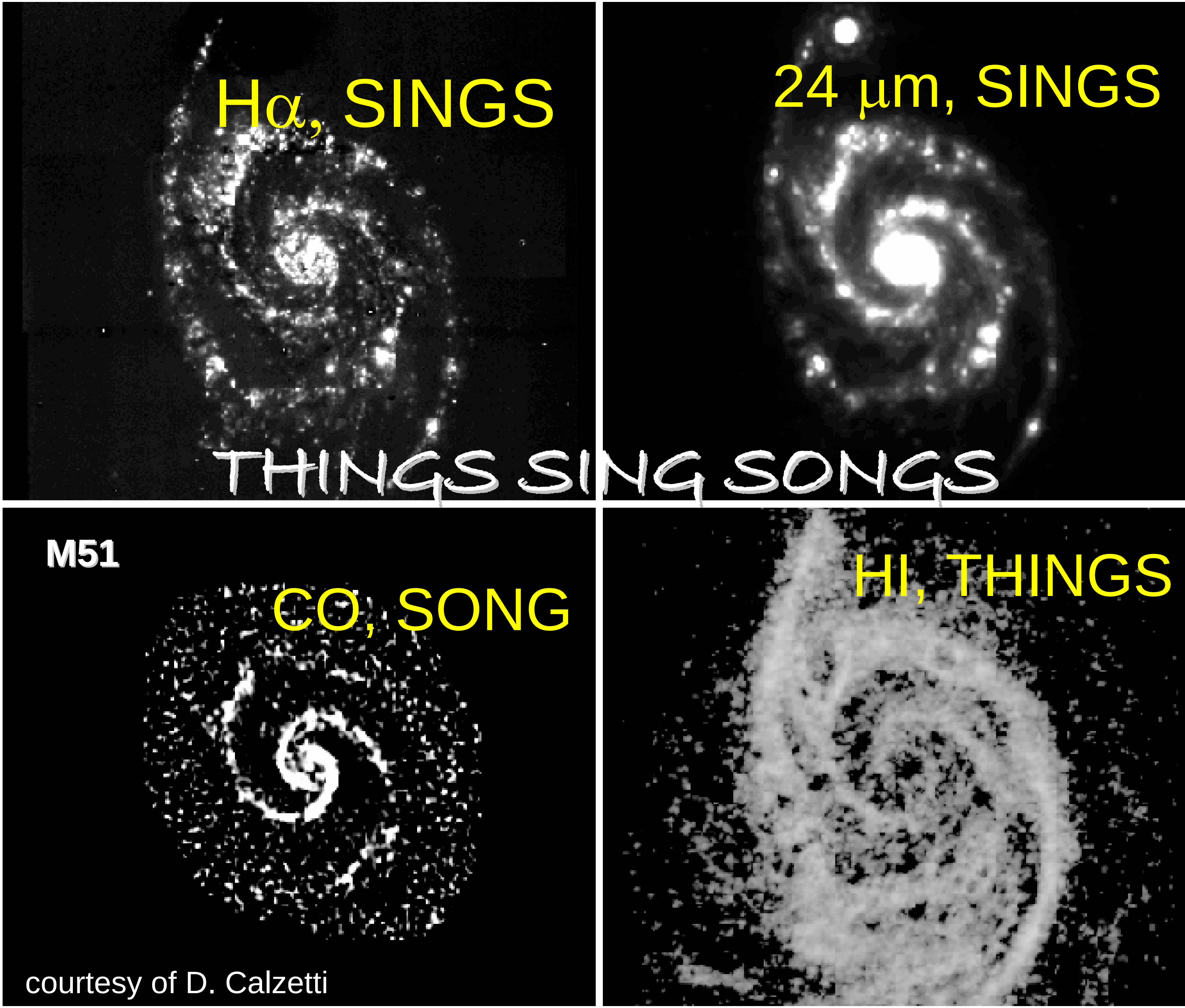
asterisks: LMC

circles: SMC

total gas column density scaled by metallicity *face-on and edge-on views of HI and H2 distribution in a z~4 gas disk*





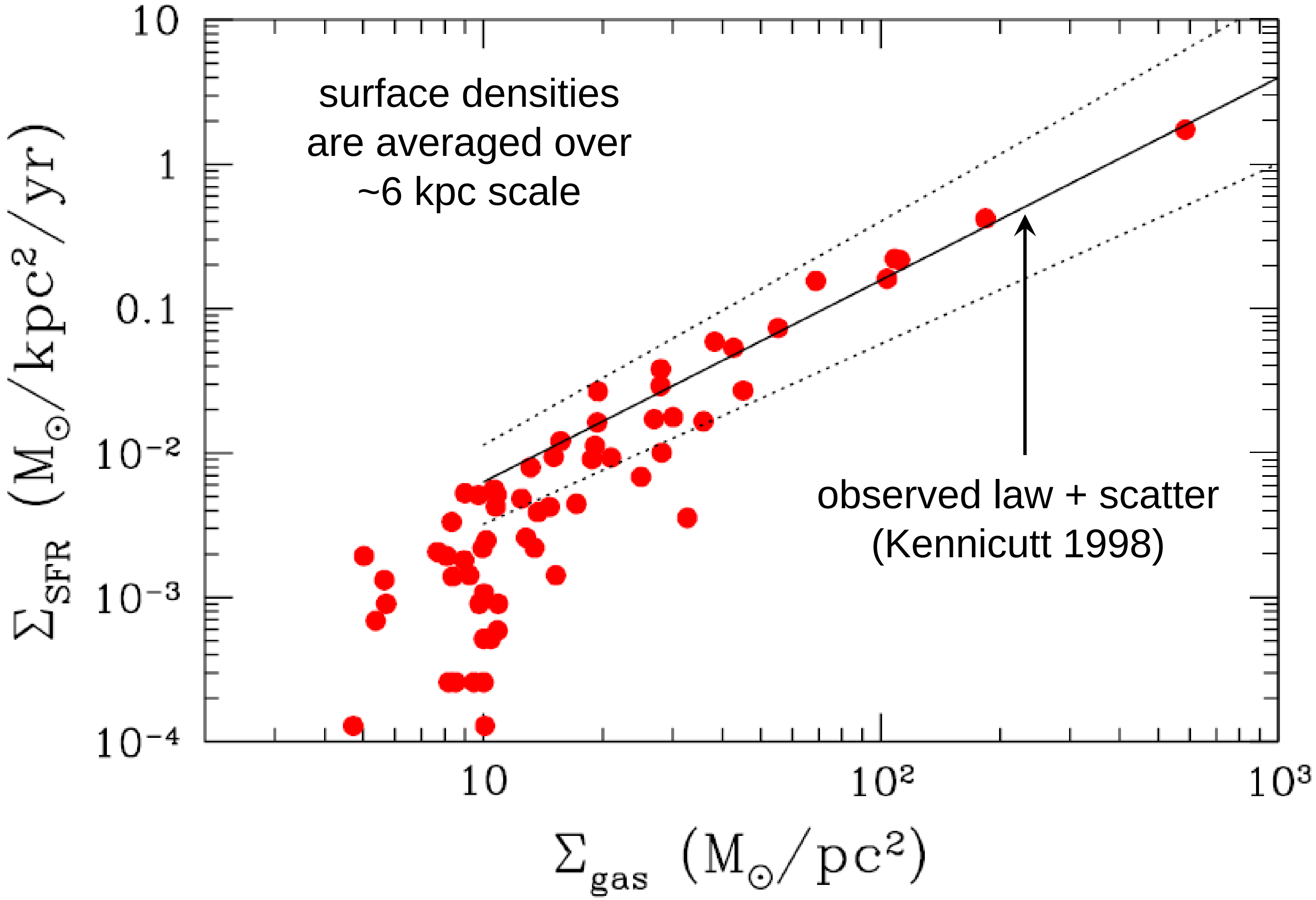


Hα, SINGS
24 μm, SINGS
THINGS SING SONGS
M51
CO, SONG
HI, THINGS
courtesy of D. Calzetti

The K-S law

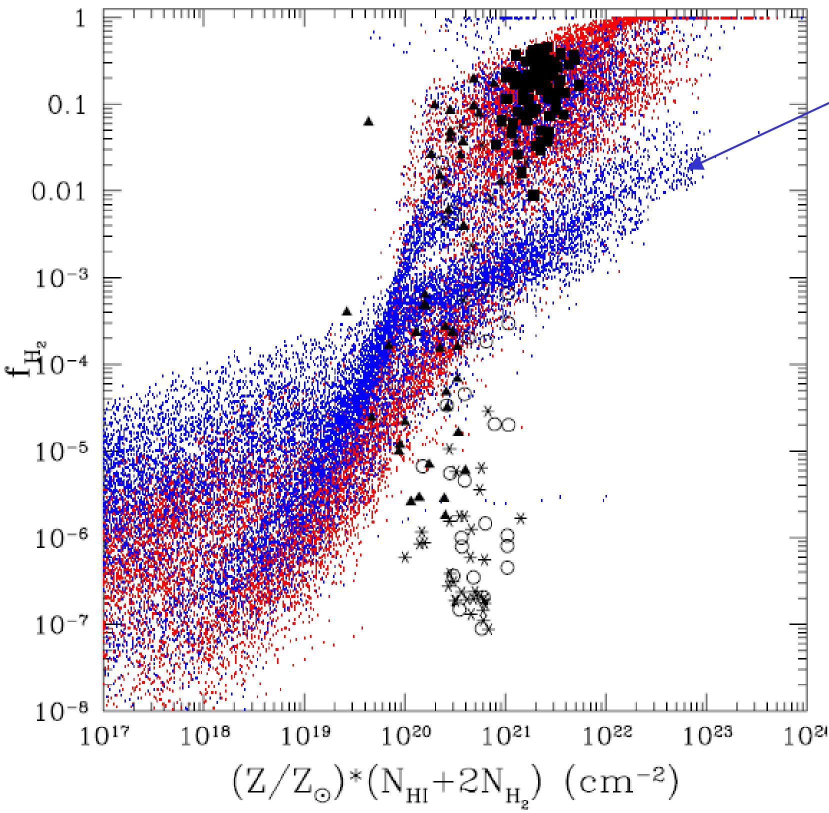
with the H_2 star formation recipe

assume SFR = const x ρ_{H2} in cells with f_{H2}>0.1



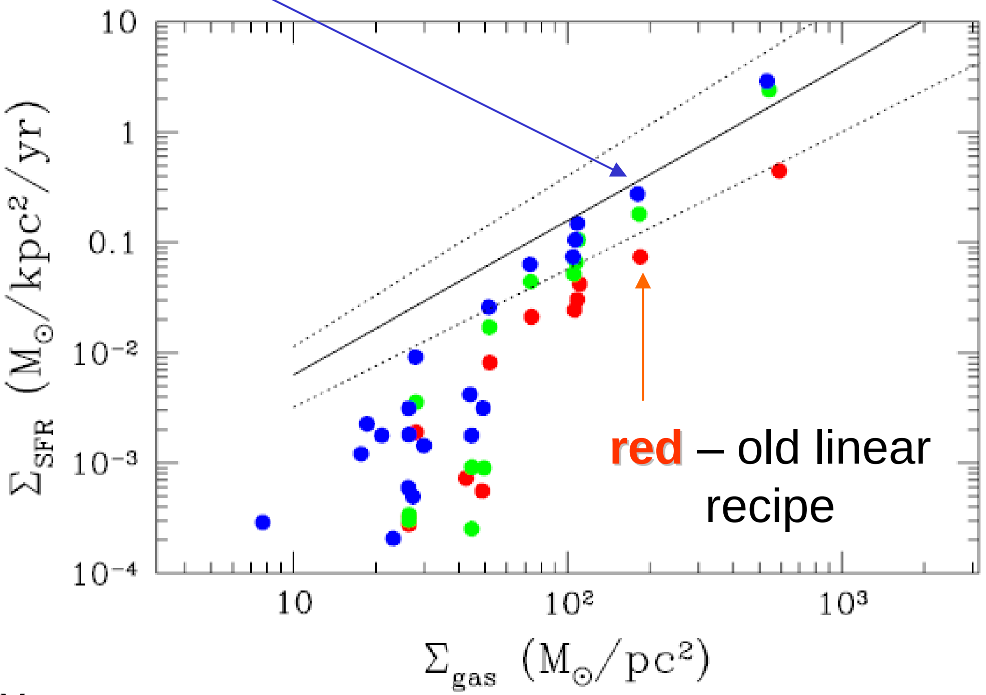
Reproducing both the K-S law and H_2 dependence on column density <u>is not trivial</u>

H_2 fraction at high column densities is sensitive to the molecular gas consumption rate and assumptions about feedback



total gas column density scaled by metallicity

blue – a simplified Krumholz & McKee (2005) prescription: SFR= 0.01 * M_{H2}/t_{dyn}



red – old linear recipe

How is this modeling useful?

- allows to tie the SF recipe of the simulation to a physical model of star formation in molecular clouds (e.g., *Elmegreen 2002; Krumholz & McKee 2005*)

- can be used to develop new SF recipes applicable on > kpc scales at different surface densities

- may provide useful clues on the relation between mass in dense molecular gas and mass of the ISM on kpc scales and on the role of gravitational instability for the K-S law

- we can study formation of H_2 and molecular content in z>2 galaxies and related SFR -> predictions for future CARMA and ALMA observations

+ *much more…*

Summary (in pictures)