GALAXY FORMATION

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IAP/Oxford

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SUMMARY OF LECTURE 2

- Linear theory of density fluctuations
- Non-linear theory
- Galaxy luminosity function
- Disk galaxy formation
- Spheroidal galaxy formation
- Feedback
- Cold flows
- First star formation

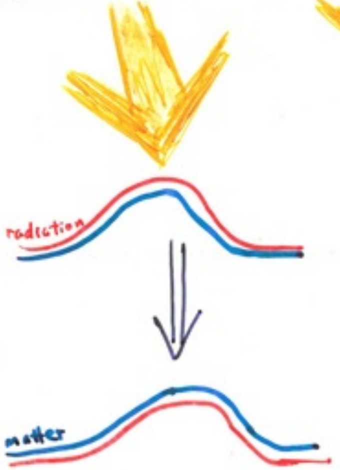
FLUCTUATION MODES

SCALAR → curvature, entropy

VECTOR → vorticity → decays

TENSOR → gravitational waves → incompressible;

decay (M-D)



$\rho_\gamma a^4 = \text{const}$

$\rho_m a^3 = \text{const}$ $+\delta S = 0$

$\uparrow$

$\delta\left(\frac{\rho_\gamma}{\rho_m}\right)_{4/3} = 0$

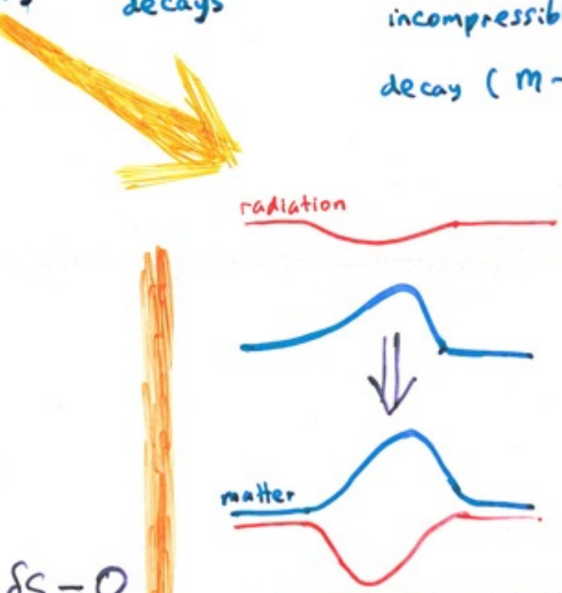
$\Downarrow$

$$\boxed{\frac{\delta\rho_m}{\rho_m} = \frac{3}{4}\frac{\delta\rho_\gamma}{\rho_\gamma}}$$

constant entropy:

predicted if $\frac{n_\gamma}{n_b} = \text{const}$;

inflation (and baryogenesis)



$$\boxed{\delta\rho_m + \delta\rho_x = 0}$$

primordial isocurvature or entropy fluctuations (e.g. phase transition)

$$\frac{\delta\rho_m}{\rho_m} = \frac{\rho_\gamma}{\rho_m}\underbrace{\delta S}_{}$$

$$\frac{\delta\rho_\gamma}{\bar{\rho}_\gamma} = \frac{\delta\rho_m}{\bar{\rho}_m}\frac{4}{3}$$

NEWTONIAN ANALYSIS ($\ell \ll ct$, $v \ll c$)

$$\frac{\partial\rho}{\partial t} + \nabla\cdot[(\rho+P)\vec{V}] = 0,$$

$$\frac{\partial V}{\partial t} + (\vec{V}\cdot\nabla)\vec{V} = -\frac{\rho}{\rho+P}\nabla\Phi - \frac{1}{\rho+P}\nabla P$$

$$\nabla^2\Phi = 4\pi G(\rho+3P)$$

$$\frac{\ddot{a}}{a} = -4\pi G(\rho + 3p/c^2)$$

$$\rho a^3 = \text{constant}$$

Linearize about Friedmann background

Define comoving coordinate : $x = \dfrac{\text{physical coordinate}}{a(t)} = \dfrac{r}{a}$

[redacted]

Eliminate ϕ via Poisson eqn, $\underline{v}$ via continuity eqn,

$$\delta \equiv \delta\rho/\rho$$

$$\frac{\partial^2}{\partial t^2}\delta + \underbrace{2\frac{\dot a}{a}\frac{\partial\delta}{\partial t}}_{\text{Hubble damping}} = \underbrace{4\pi G\rho\delta}_{\text{Self-gravity destabilizes}} + \underbrace{\frac{1}{a^2}\frac{dp}{d\rho}\nabla^2\delta}_{\text{pressure gradient stabilizes}}$$

Let $\delta(x,t) = \Sigma\, \delta_k \exp(i\underline{k}\cdot\underline{x})$

Define physical wavelength $\lambda = 2\pi\frac{a}{\underline{k}}$

UNSTABLE IF $\lambda > \lambda_J = c_s\left(\frac{\pi}{G\rho_0}\right)^{\frac{1}{2}}$ $\quad c_s^2 = \frac{\nabla\delta P}{\nabla\delta\rho}$

GROWTH RATE : $\delta \propto t^{2/3}, t^{-1}$ (matter domination) allows density fluctuation growth when $\rho_m > \rho_{rad}$

$$\frac{d^2\delta_m}{dt^2} + 2\frac{\dot{a}}{a}\frac{d\delta_m}{dt} = 4\pi G \rho_m \delta_m$$

$$\Rightarrow \delta_m \equiv \delta\rho_m/\rho_m = 1 + \frac{3}{2}\frac{\rho_m}{\rho_{rad}}$$

$$\delta K \sim \frac{G\,\delta M}{L c^2} \sim \frac{G\,\delta\rho\, L^2}{c^2}$$

$$\sim \left(\frac{\delta\rho}{\rho}\right)\left(\frac{L}{ct}\right)^2$$

$$\frac{\delta\rho}{\rho} \sim \delta K \left[\frac{ct}{a(t)}\right]^2 \left(\frac{a(t)}{L}\right)^2$$

$$\propto t^{2/3} M_{\text{comoving}}^{-2/3}$$

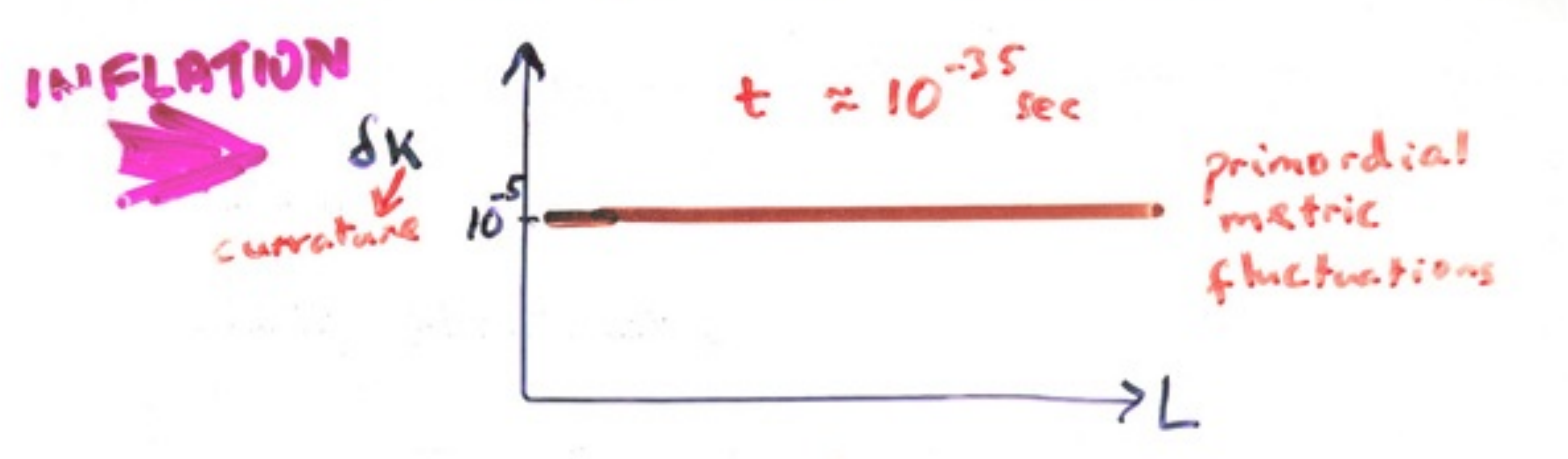
for $a \propto t^{2/3}$

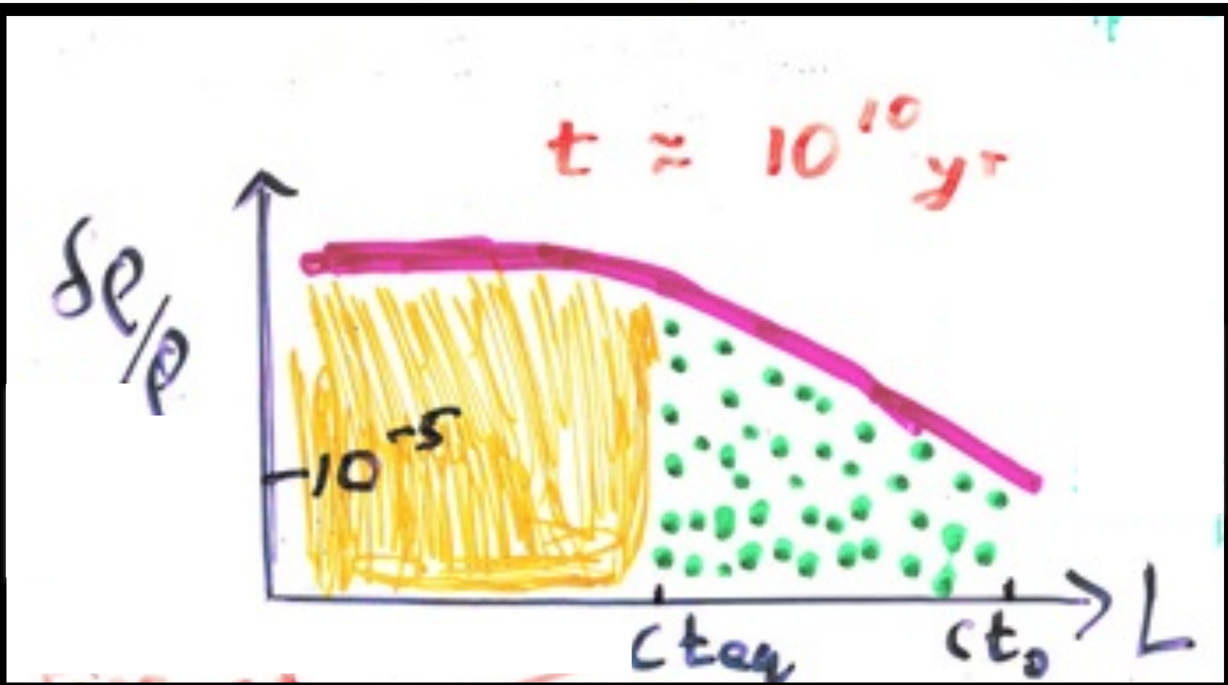
(matter-dominate regime

if δK = constant

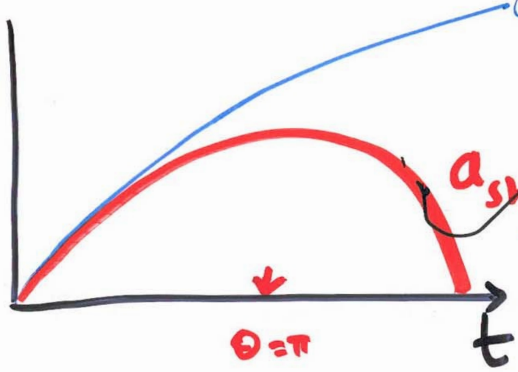
$\Uparrow$

scale invariance : $\begin{cases} \text{Harrison, Zeldovich} \\ \text{Inflation} \end{cases}$


INFLATION
δκ
curvature
10^-5
t ≈ 10^-35 sec
primordial metric fluctuations
L


t ≈ 10^10 yr
δρ/ρ
10^-5
ct_eq
ct_0
L

spherical top hat



$$a(t) = \left(\frac{t}{t_i}\right)^{2/3}$$

$$x_i = x_{i0}\, a_s(t)$$

$$\frac{a_{shell}(t)}{a(t)} \approx \frac{1-\cos\Theta}{(\Theta - \sin\Theta)^{2/3}} \cdot \frac{2^{1/3}}{3^{2/3}}$$

$$\frac{\ddot{a}_s}{a_s} = -\frac{4\pi G}{3}\rho$$

$$= -\frac{4\pi G}{3}\rho_0 (1+\delta)$$

$$\Downarrow$$

$$a_s = \frac{1-\cos\Theta}{2\delta}$$

$$t/t_0 = \frac{3}{4}\frac{\Theta - \sin\Theta}{\delta^{3/2}}$$

$$\frac{\rho_{\text{max expansion}}}{\rho} = \frac{9\pi^2}{16}$$

$$\text{at } \frac{t_{max}}{t_i} = \frac{3\pi}{8}\frac{1}{\delta_i^{3/2}}$$

FINAL RADIUS (no dissipation)

$$= \frac{1}{2} R_{max}$$

galaxy "formation" epoch

$$\boxed{= \frac{3\pi}{4}\delta_i^{-3/2} t_i}$$

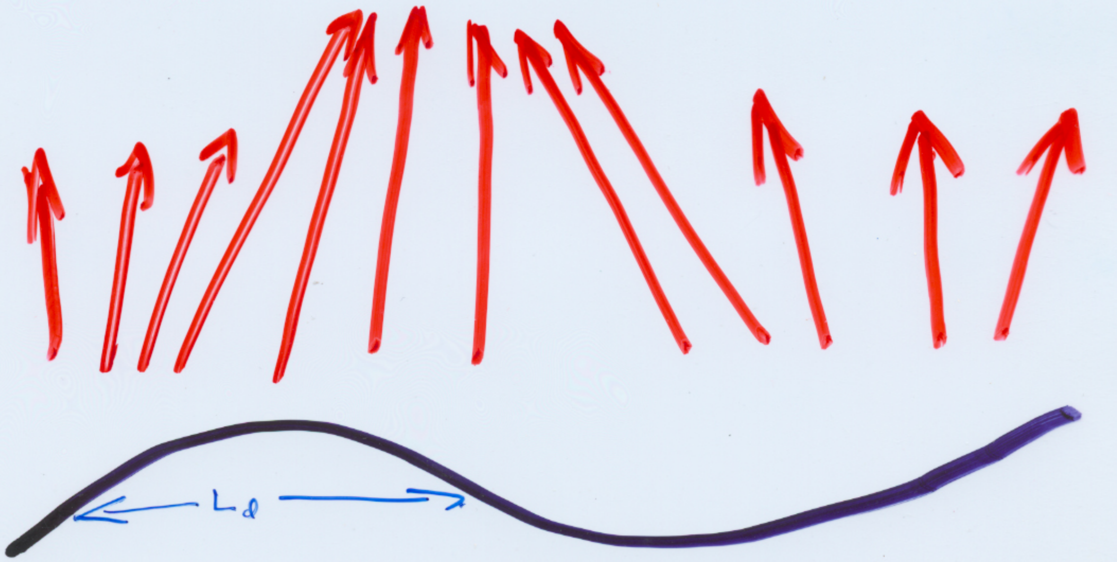
"FINAL" ($t_{virialization} = 2\, t_{R_{max}}$)

$$\frac{\rho_{virial}}{\rho(t_{virial})} = \frac{9\pi^2}{16} \times \frac{8}{1/4} = 18\pi^2$$

pancake

1-D solution (Zel'dovich)

$$Z(t,z_i) = a(t)\left[z_i - \frac{a(t)}{a_p}\frac{L_d}{\pi}\sin\left(\pi\frac{z_i}{L_d}\right)\right]$$

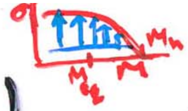


Velocity perturbation

1-D trajectories

Caustic develops

$$\rho = \frac{\rho_0}{1-\frac{a(t)}{a_p}\cos\frac{\pi z_i}{L_d}}$$



$$\frac{\left\langle \left(\frac{\delta\rho}{\rho}\right)^2 \right\rangle^{1/2}_{mass}}{\left\langle (\delta\rho/\rho)^2 \right\rangle^{1/2}_{light\ at\ z=0}} \equiv \sigma(M) \propto t^{2/3} \quad (\text{IF } \Omega = 1)$$

~1 averaged over 8h^{-1}Mpc spheres

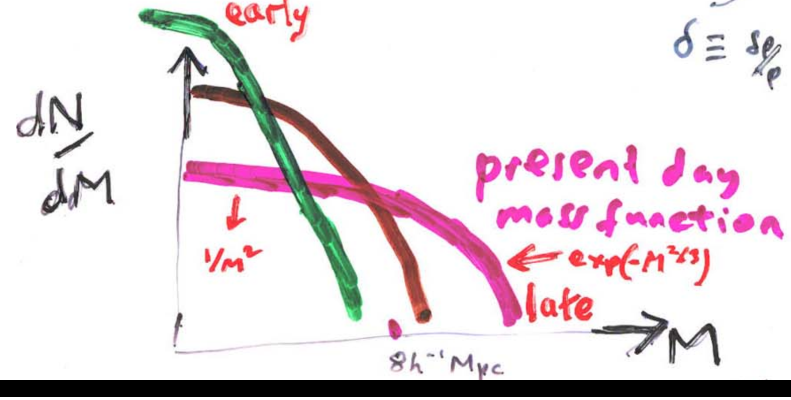
growth suppressed at $1+z < \left(\frac{\Omega}{\Omega_m}\right)$ if $\Omega_m < 1$ ⇒ need larger σ at specified M

calculate number of newly non-linear objects

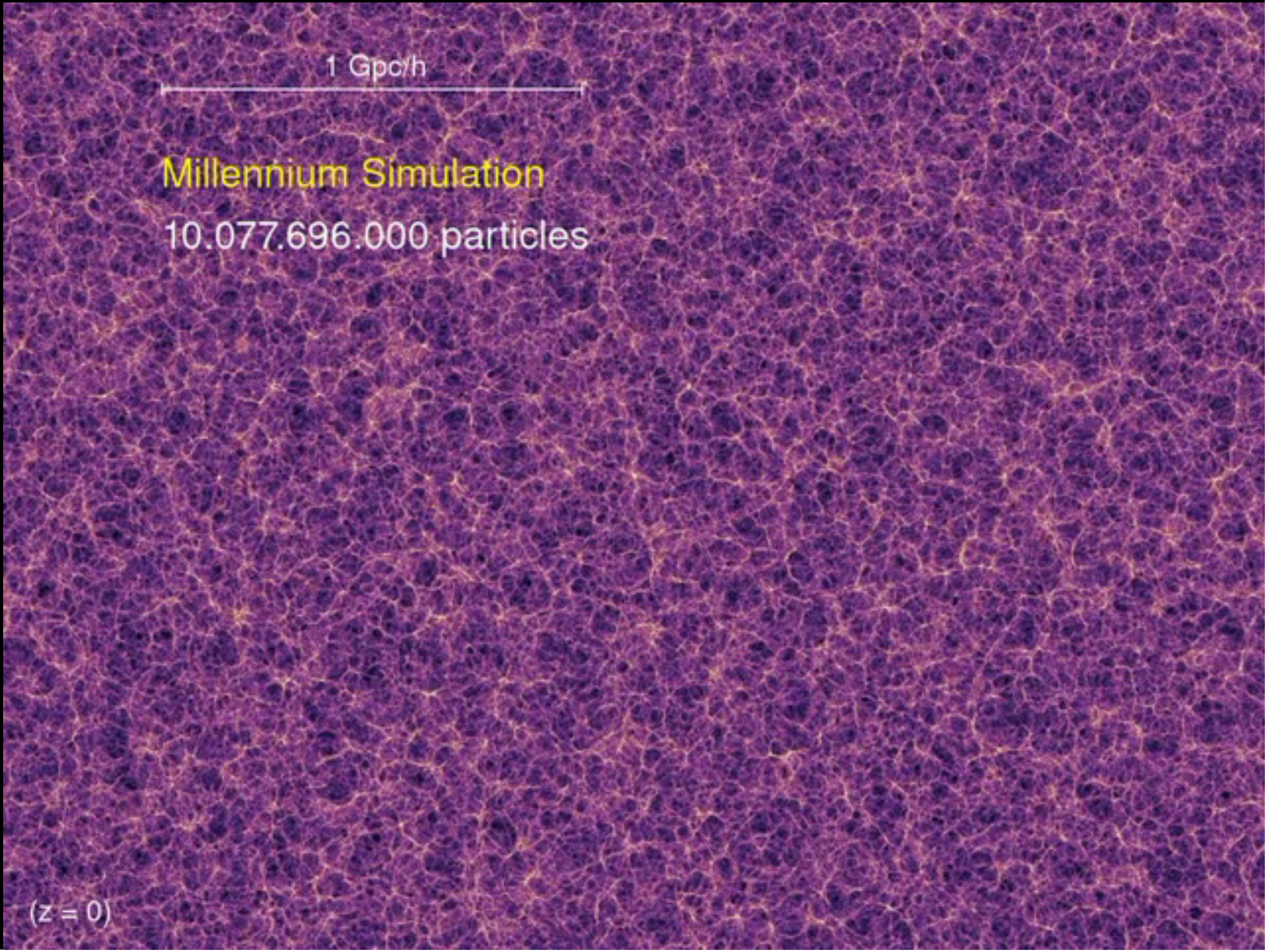
sensitive to gaussian tail i.e. rare peaks

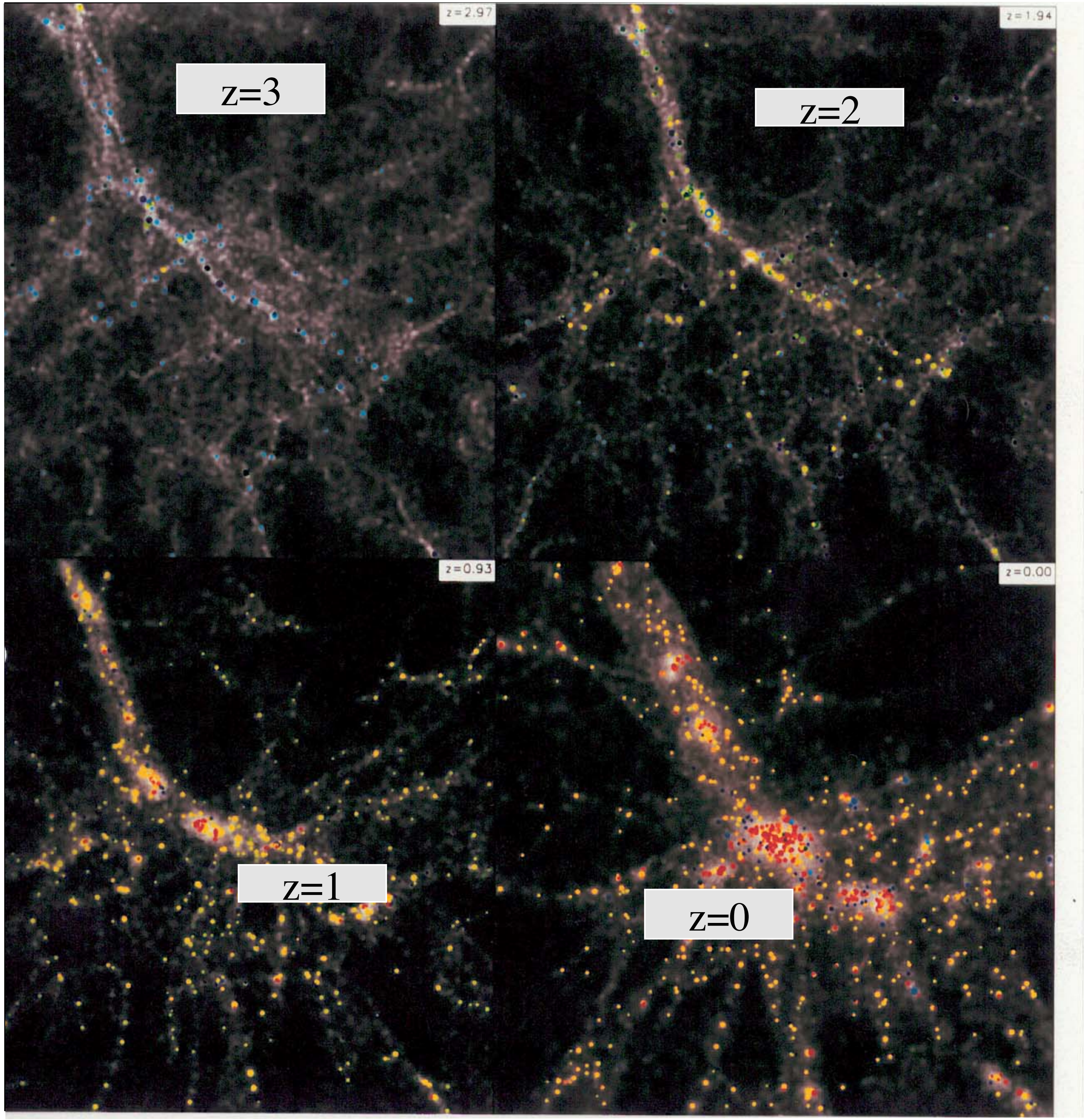
$$\text{NONLINEAR MASS FRACTION} \sim \int^{\infty} e^{-\delta^2/\sigma^2}\, d\delta$$

$\delta \equiv \delta\rho/\rho >$ threshold for collapse $= 1.68$



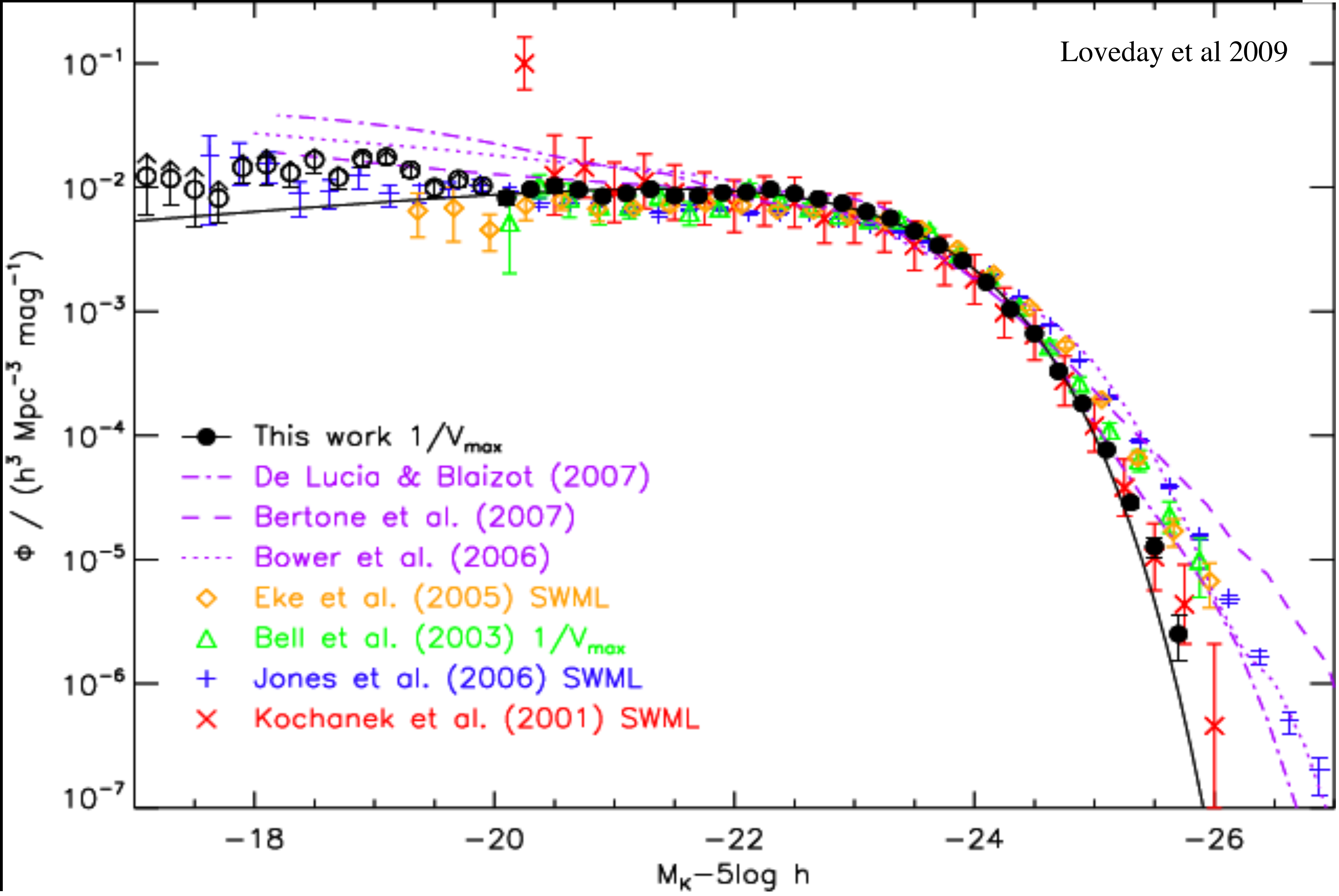
$$\sigma^2 \propto M^{-\frac{n+3}{3}} (1+z)^{-1}$$
$$\simeq M^{-2/3}\, t^{2/3}$$


1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)



G, Kauffmann 2008

Luminosity function of galaxies



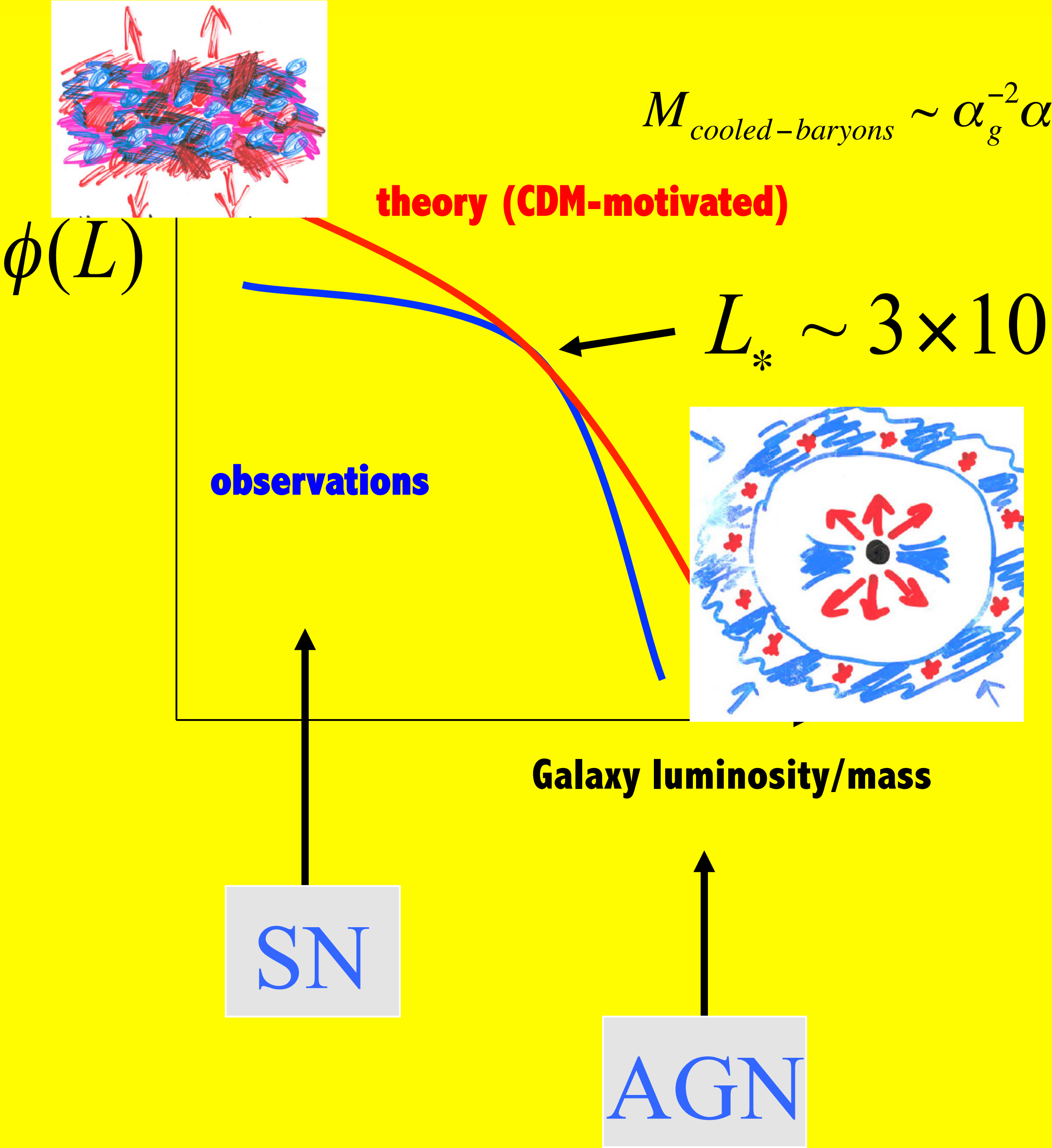
Feedback is needed

$$M_{cooled-baryons} \sim \alpha_g^{-2} \alpha^3 \left(\frac{m_p}{m_e} \right) \left(\frac{t_{cool}}{t_{dyn}} \right) T^{1+2\beta}$$

$$\alpha_g = Gm_p^2/e^2$$

$$t_{cool} \sim \frac{nkT}{\Lambda(T)n^2}$$

$$t_{dyn} \sim \frac{1}{\sqrt{Gm_p n}}$$



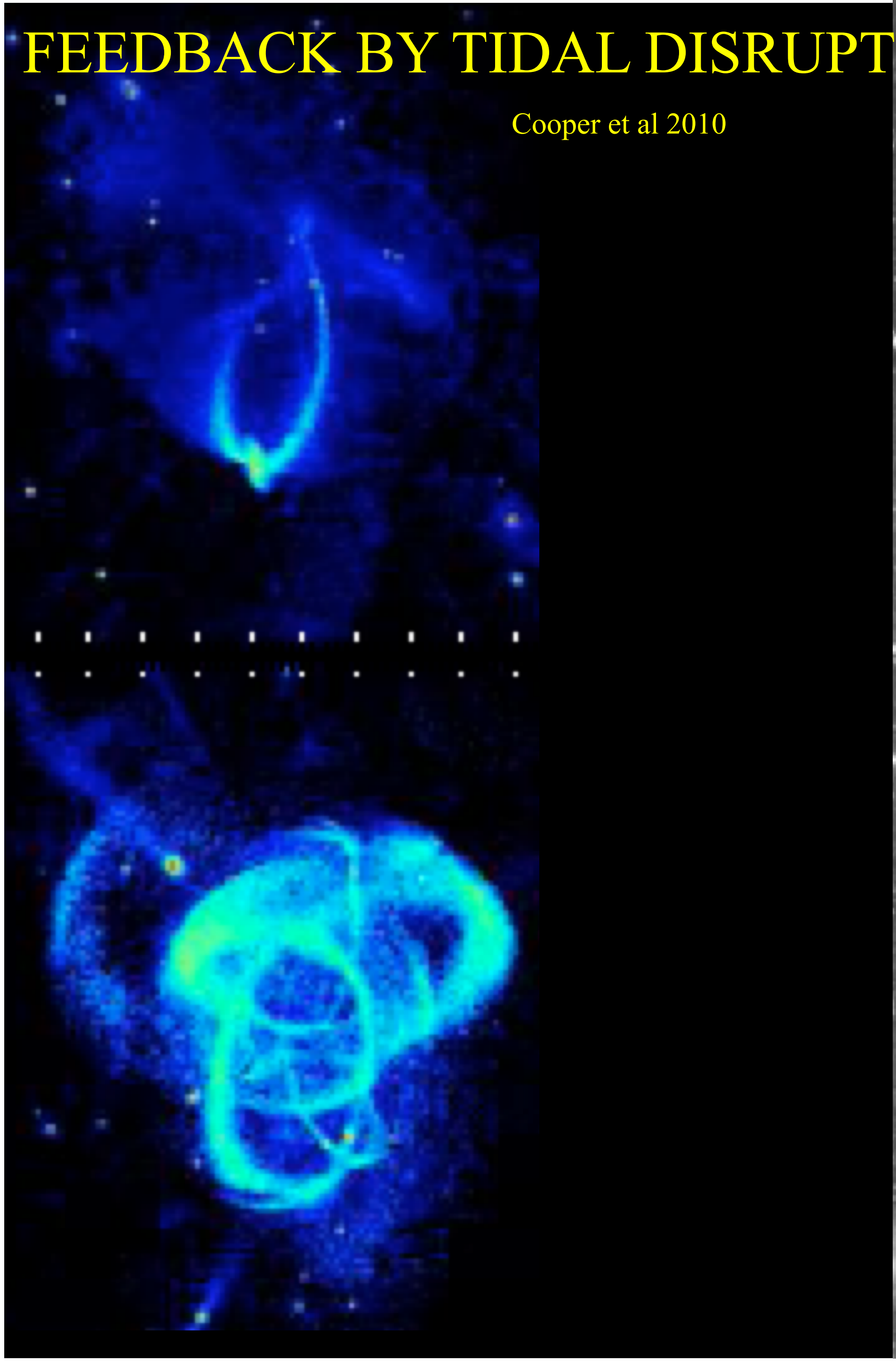
$$L_* \sim 3 \times 10^{10} L_\odot$$

Memories of the epoch of the first galaxies in the luminosity function of dwarfs…

FEEDBACK IS ESSENTIAL

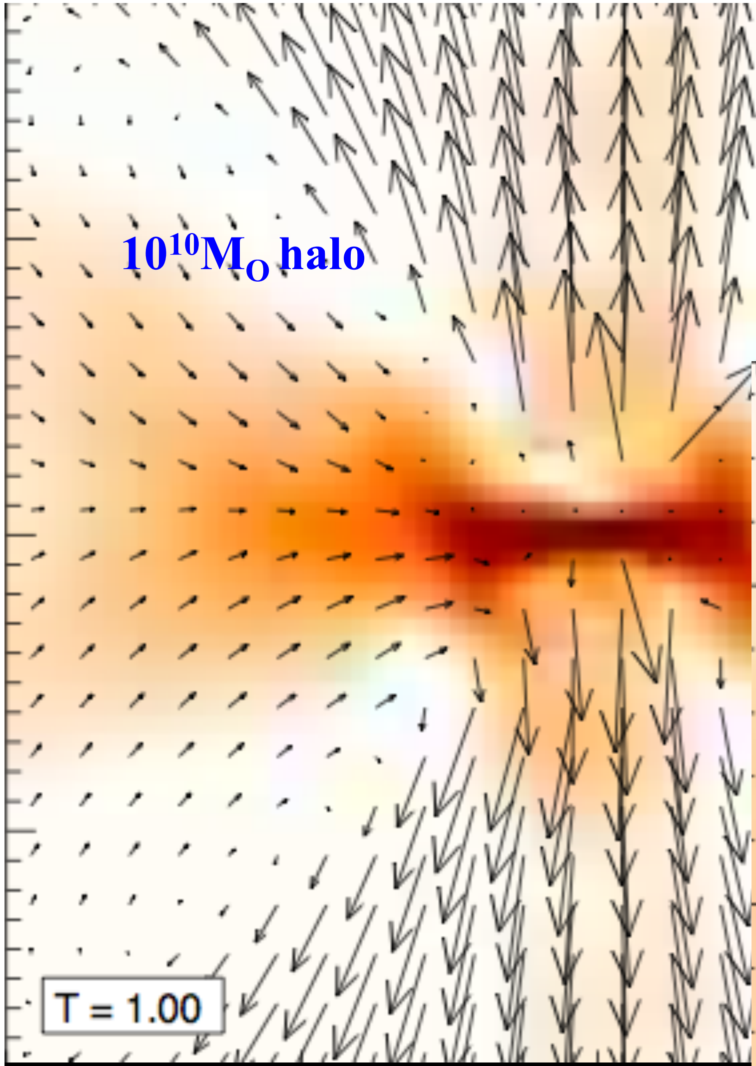
Reionization
Supernovae
Tidal stripping
Active galactic nuclei

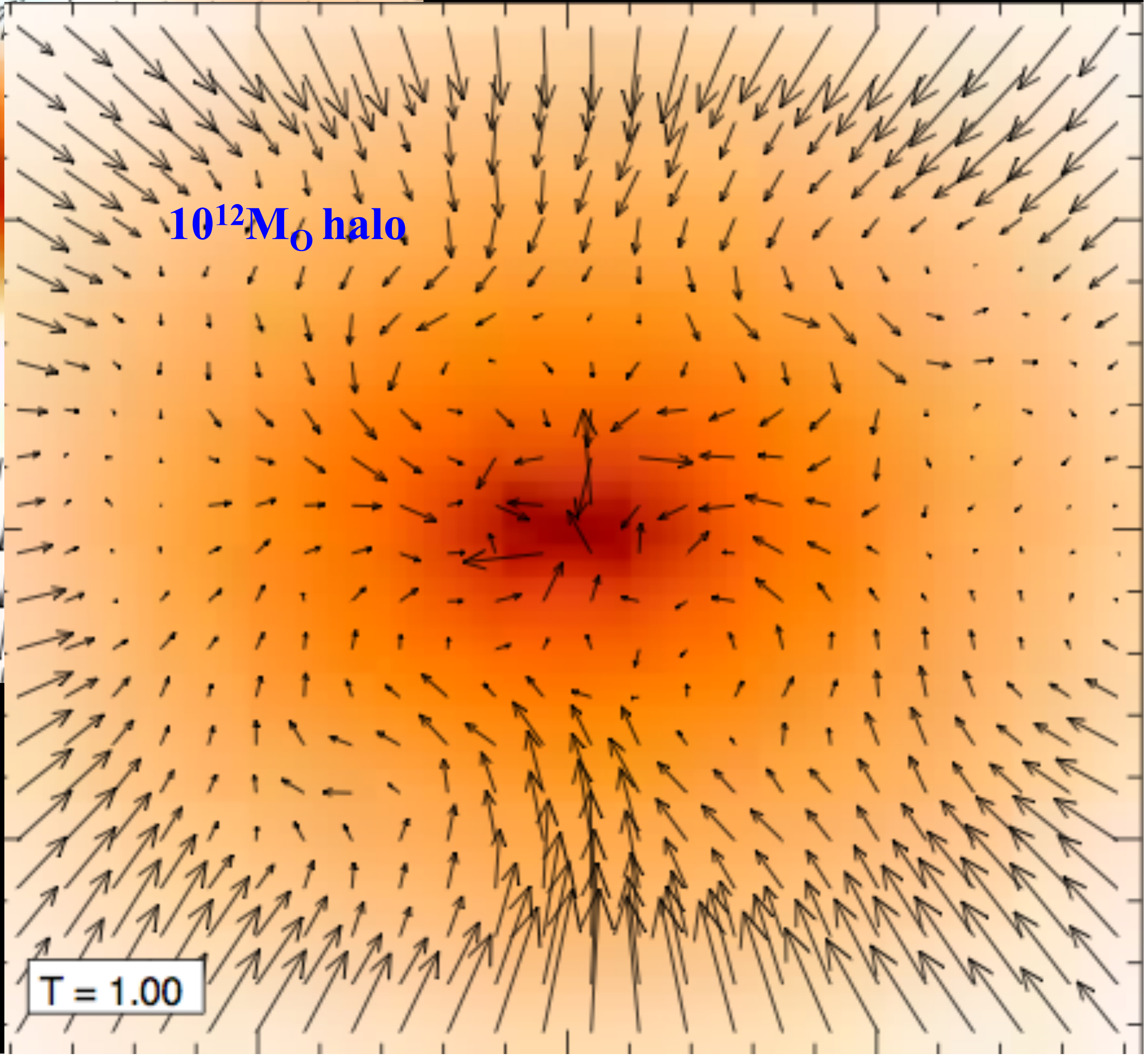
FEEDBACK BY TIDAL DISRUPTION


Cooper et al 2010


Martinez-Delgado et al 2008

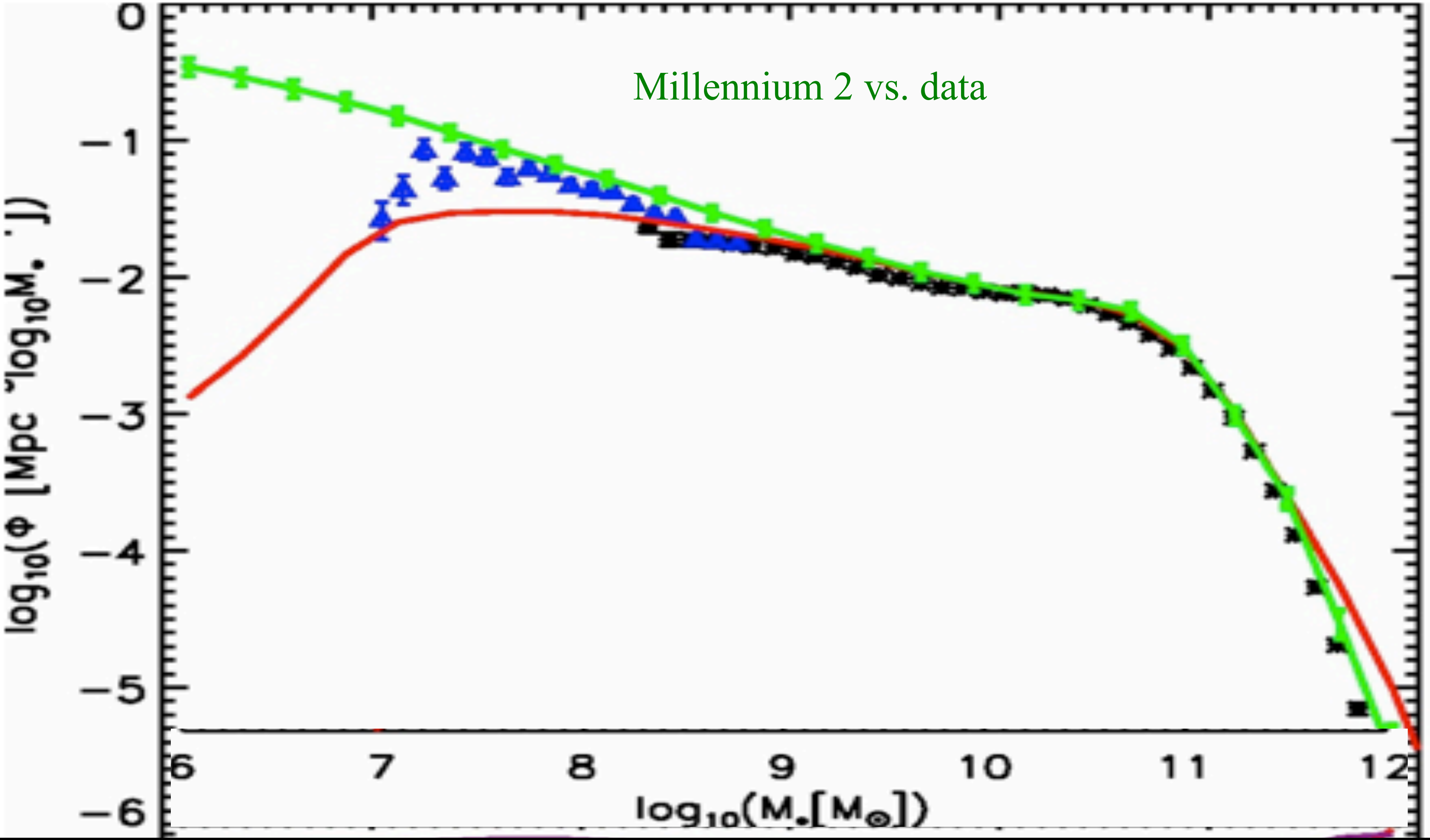
Springel and Hernquist 2003





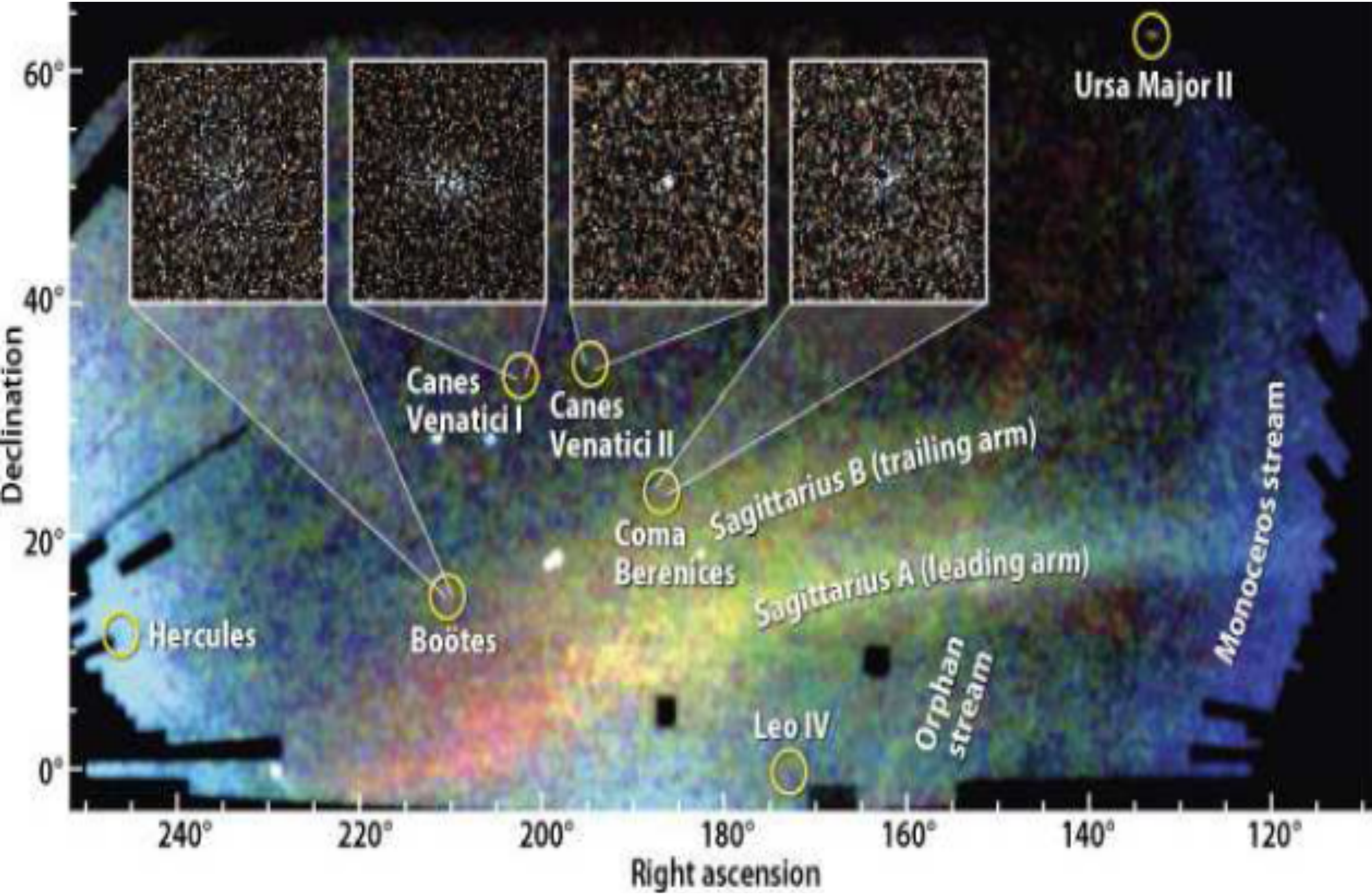
SNe feedback does not drive winds from massive galaxies

Semi-analytical models or hydro simulations

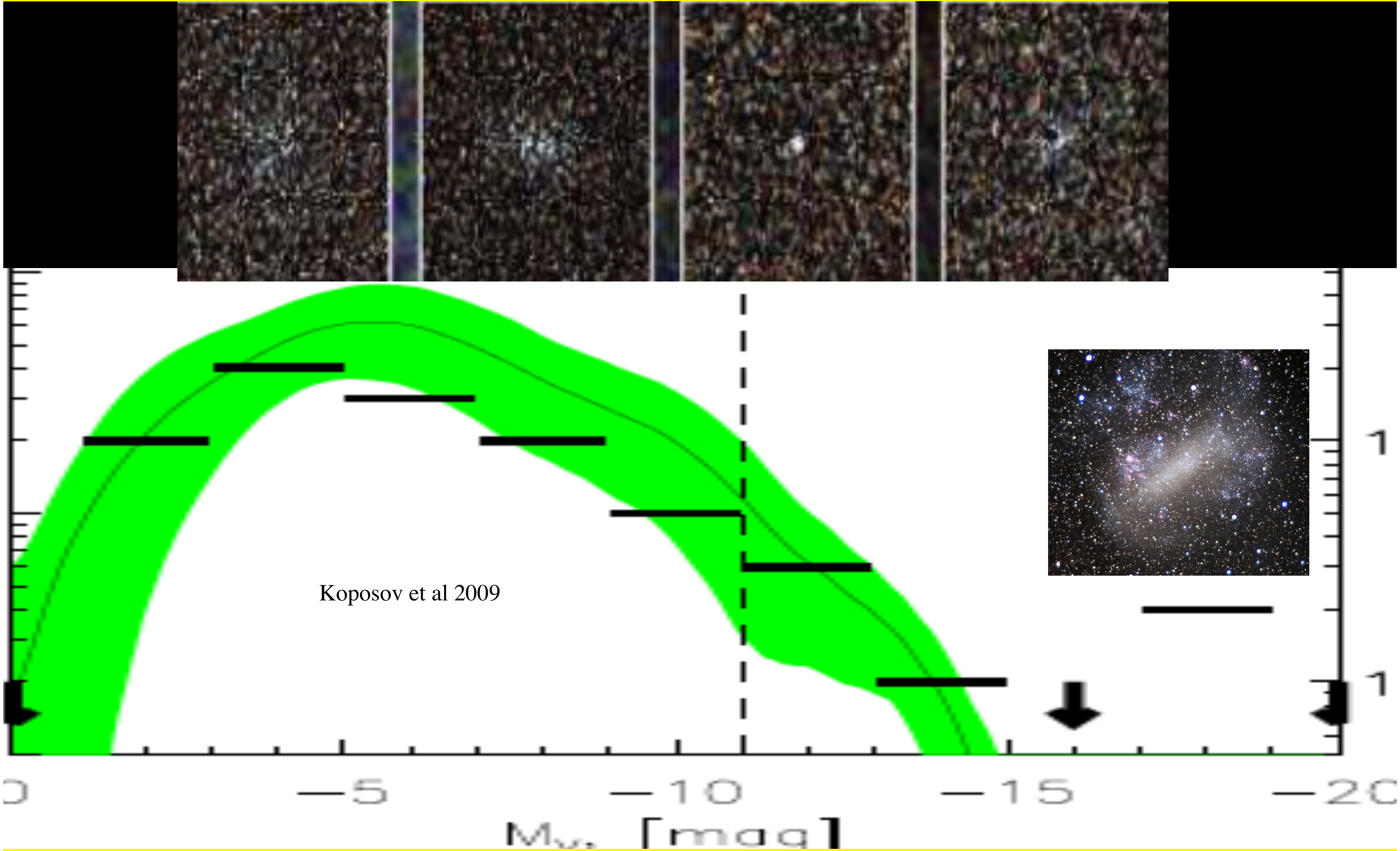


Guo et al 2010

Galaxy luminosity function

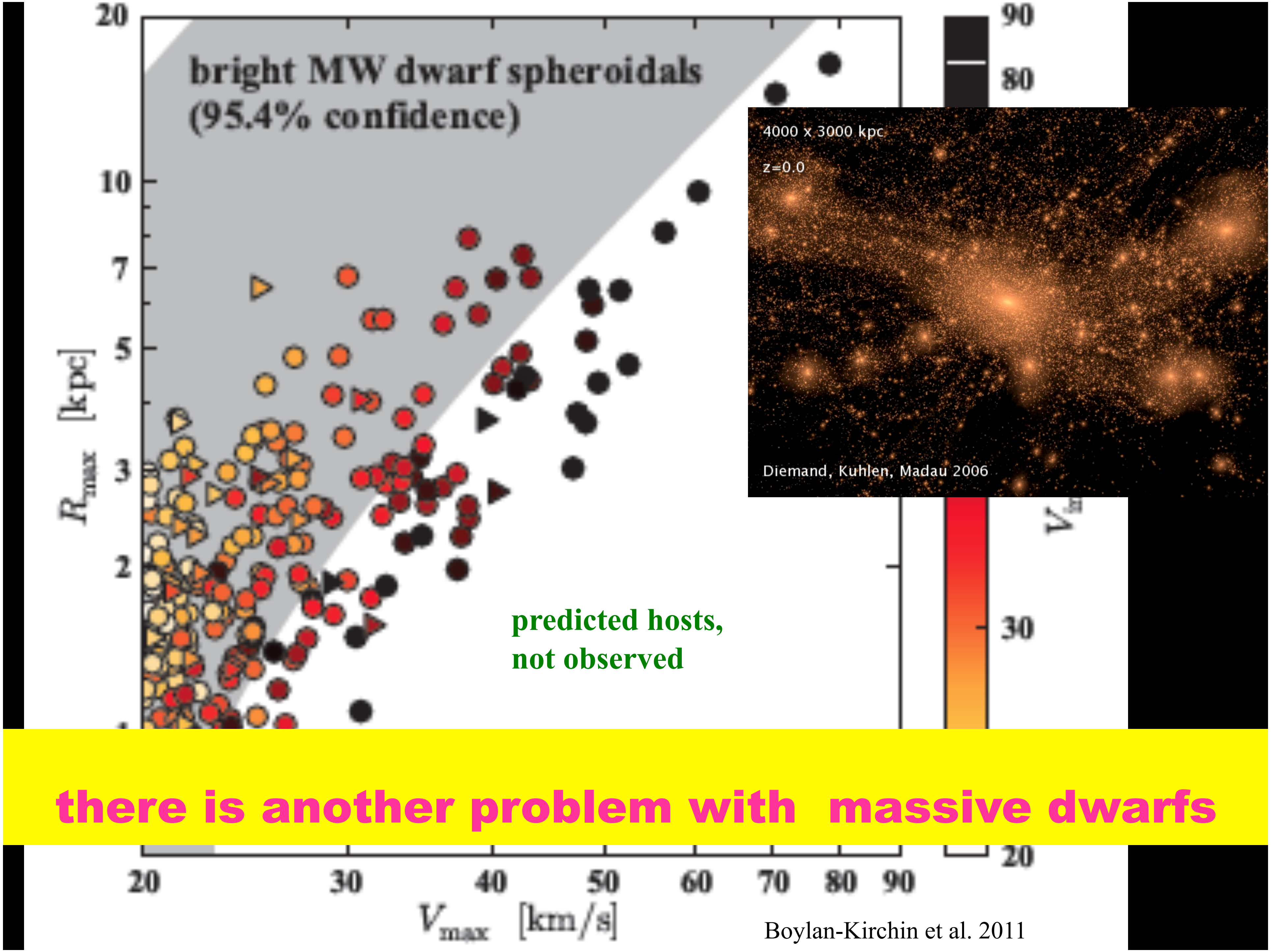

Ursa Major II
60°
40°
20°
0°
Declination
Canes Venatici I
Canes Venatici II
Coma Berenices
Sagittarius B (trailing arm)
Sagittarius A (leading arm)
Monoceros stream
Hercules
Boötes
Leo IV
Orphan stream
240°
220°
200°
180°
160°
140°
120°
Right ascension

the galaxy luminosity function



Koposov et al 2009

there is a problem with massive dwarfs



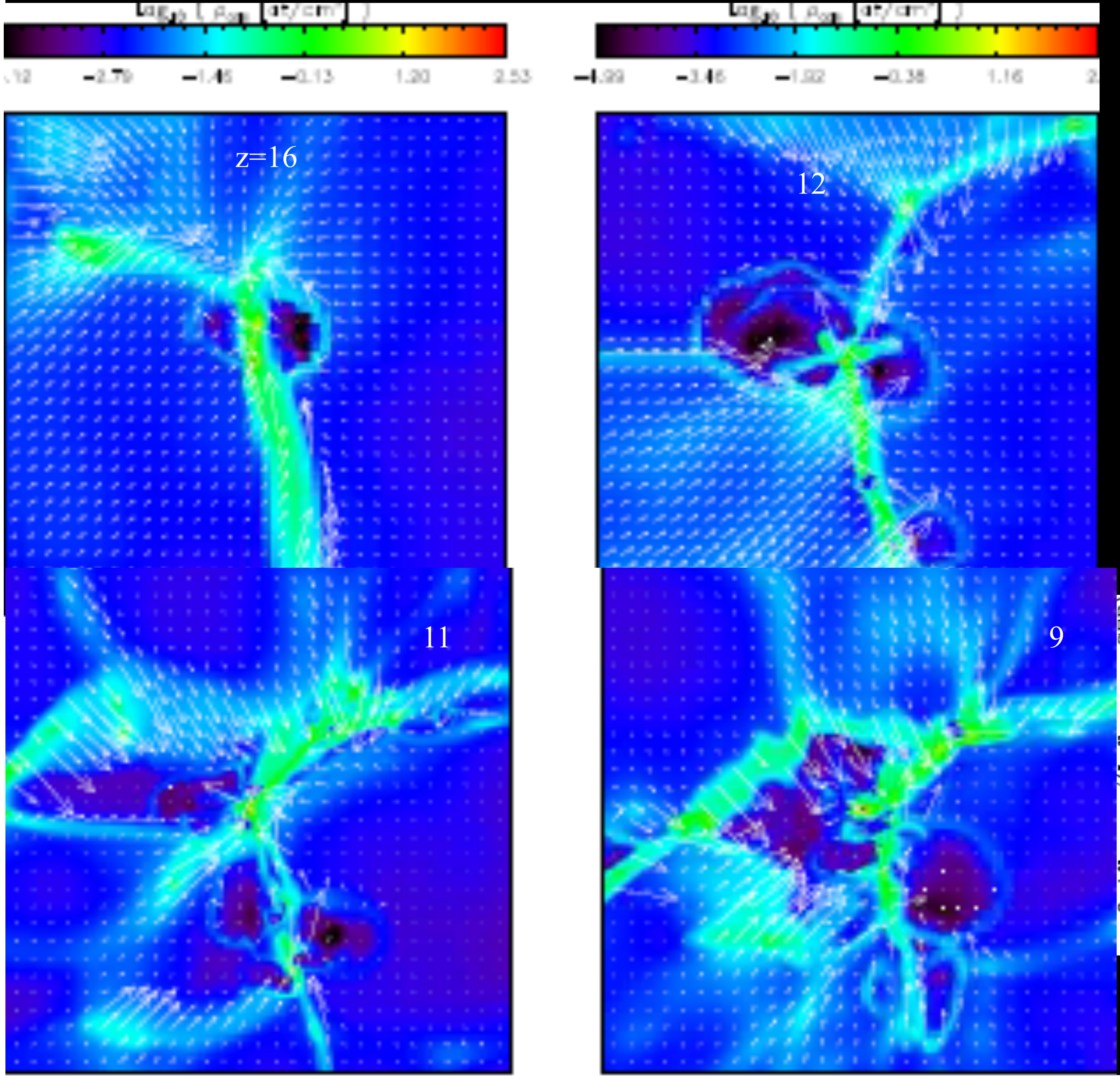
Diemand, Kuhlen, Madau 2006

predicted hosts,
not observed

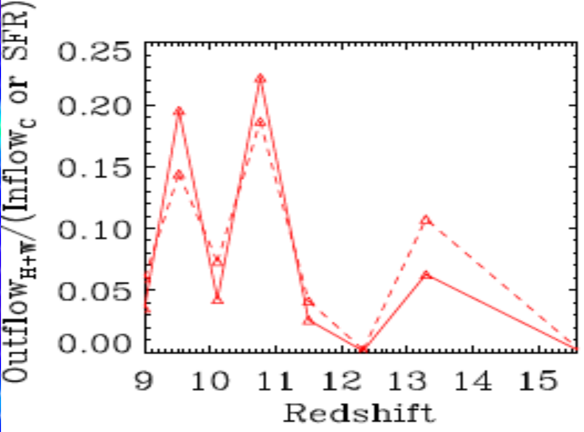
Boylan-Kirchin et al. 2011

there is another problem with massive dwarfs

Semi-analytical models or hydro simulations



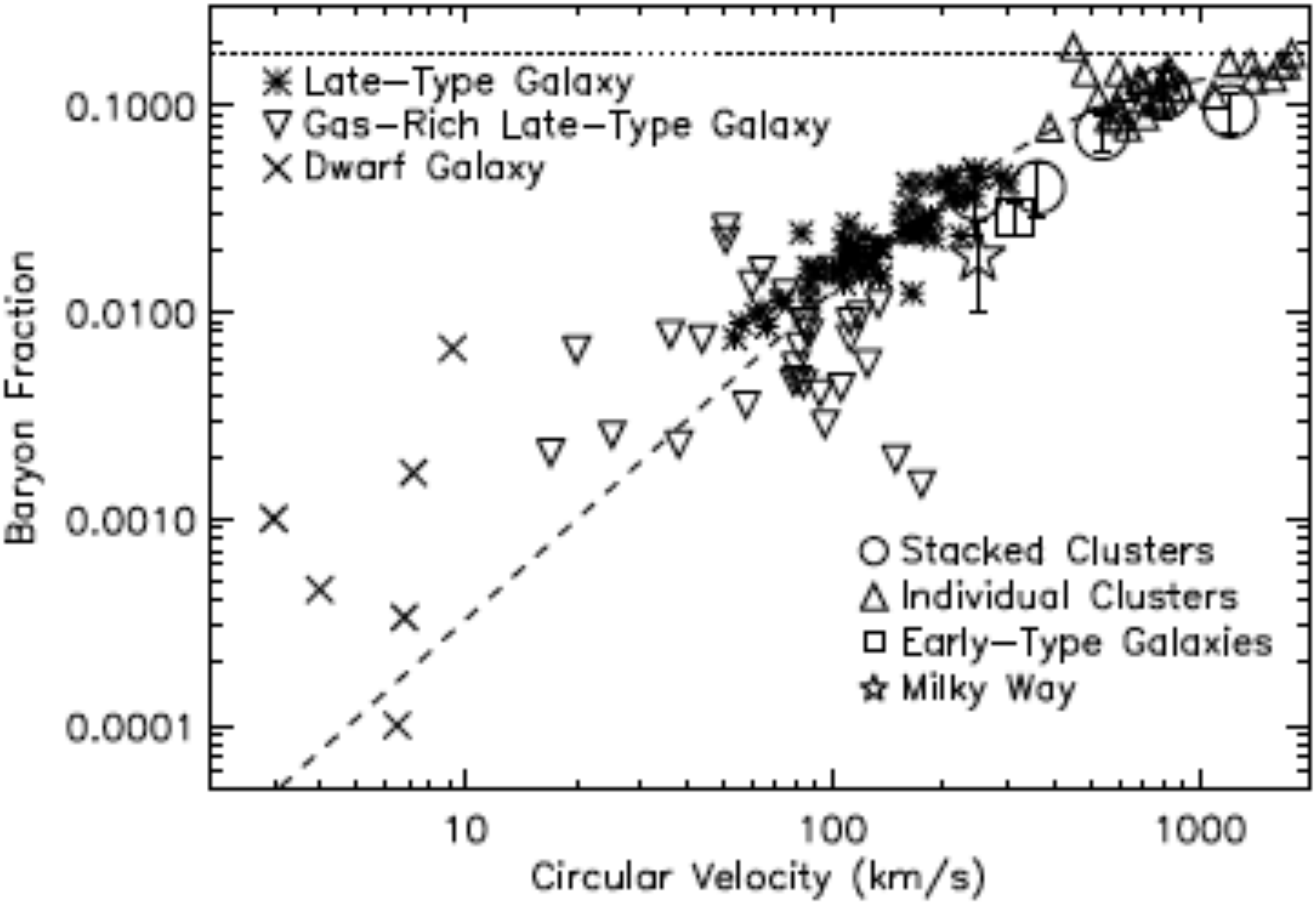
SNe do not eject enough baryons even from dwarfs



Powell et al 2011
Fujita et al 2004

BARYON FRACTION

Dai et al 2010



Disk galaxies

feedback by massive stars

Cloud disruption locally controlled by
OB stars: SFE= 2%

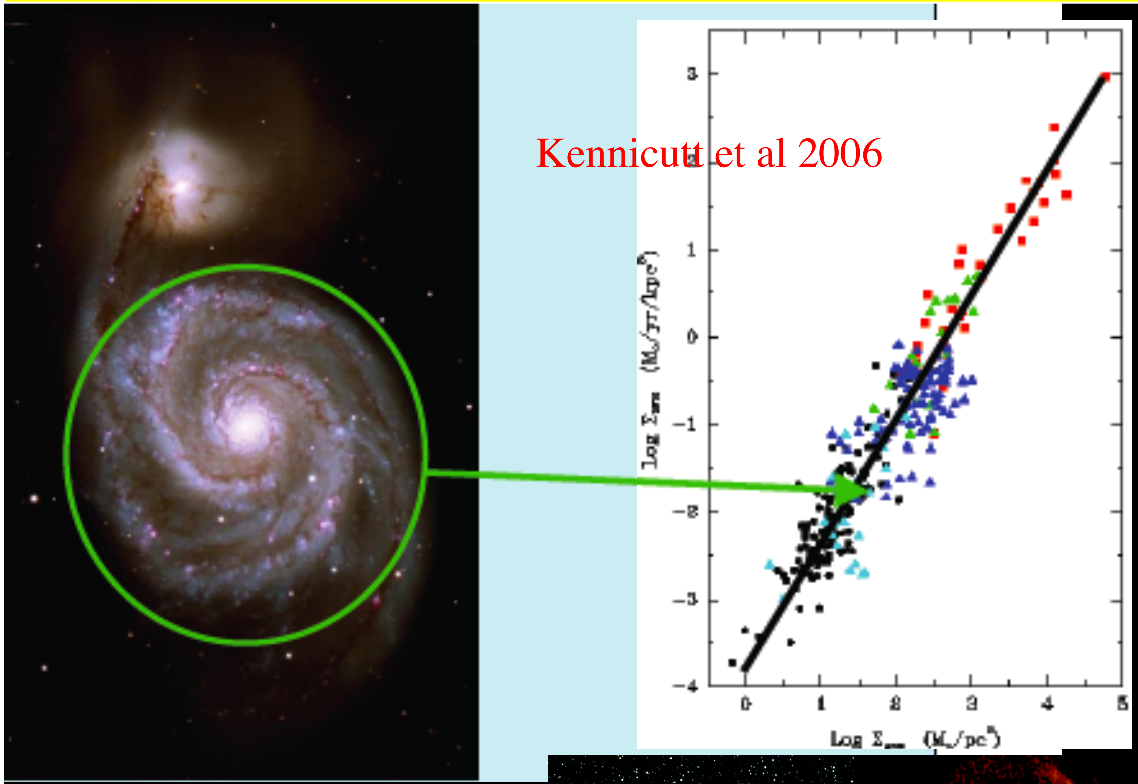
Cloud formation globally controlled by
supernova-driven turbulence: SFE= 2%

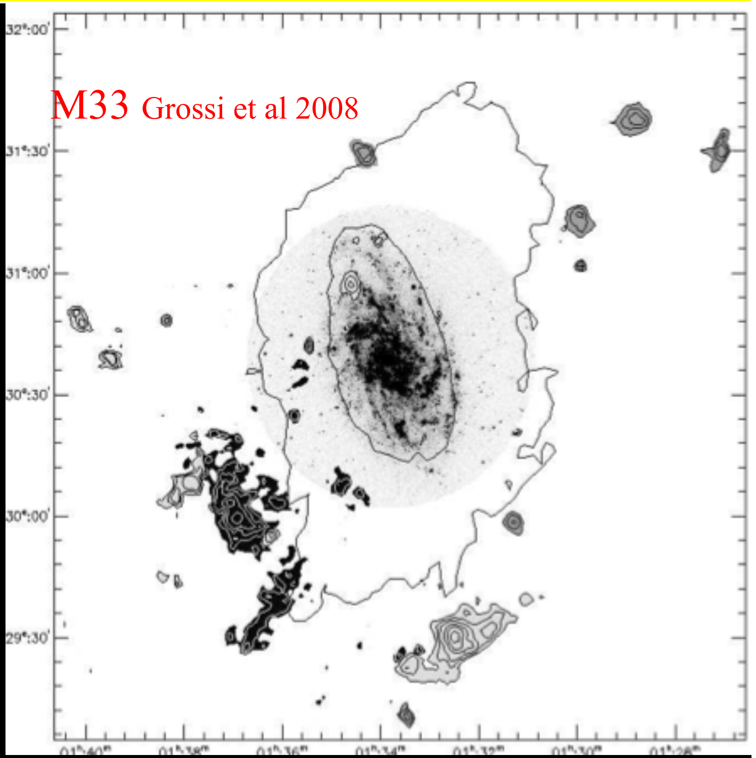
motivated by gravitational instability of cold disks

SFR= SFE . (GAS DENSITY)/t_{dyn}

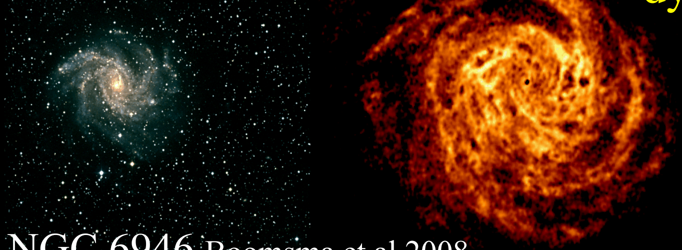
$$\mathrm{SFE} = \frac{\sigma_{gas}\ v_{cool}\ m_{*,SN}}{E_{SN}} \approx 0.02$$

A GLOBAL STAR FORMATION LAW

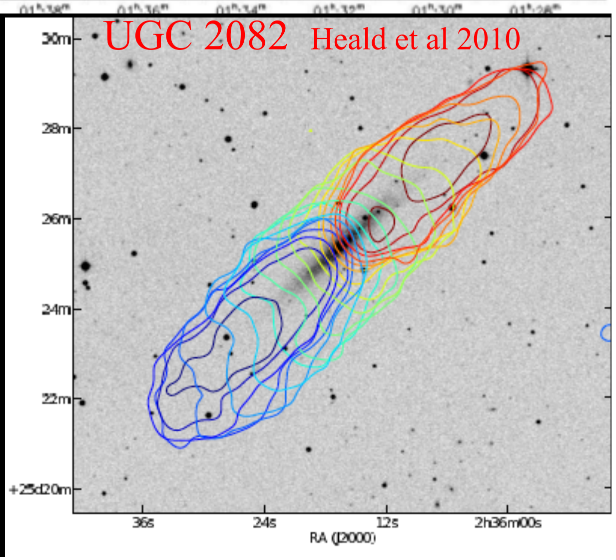




SFR=0.02 (GAS SURFACE DENSITY)/t_{dyn}

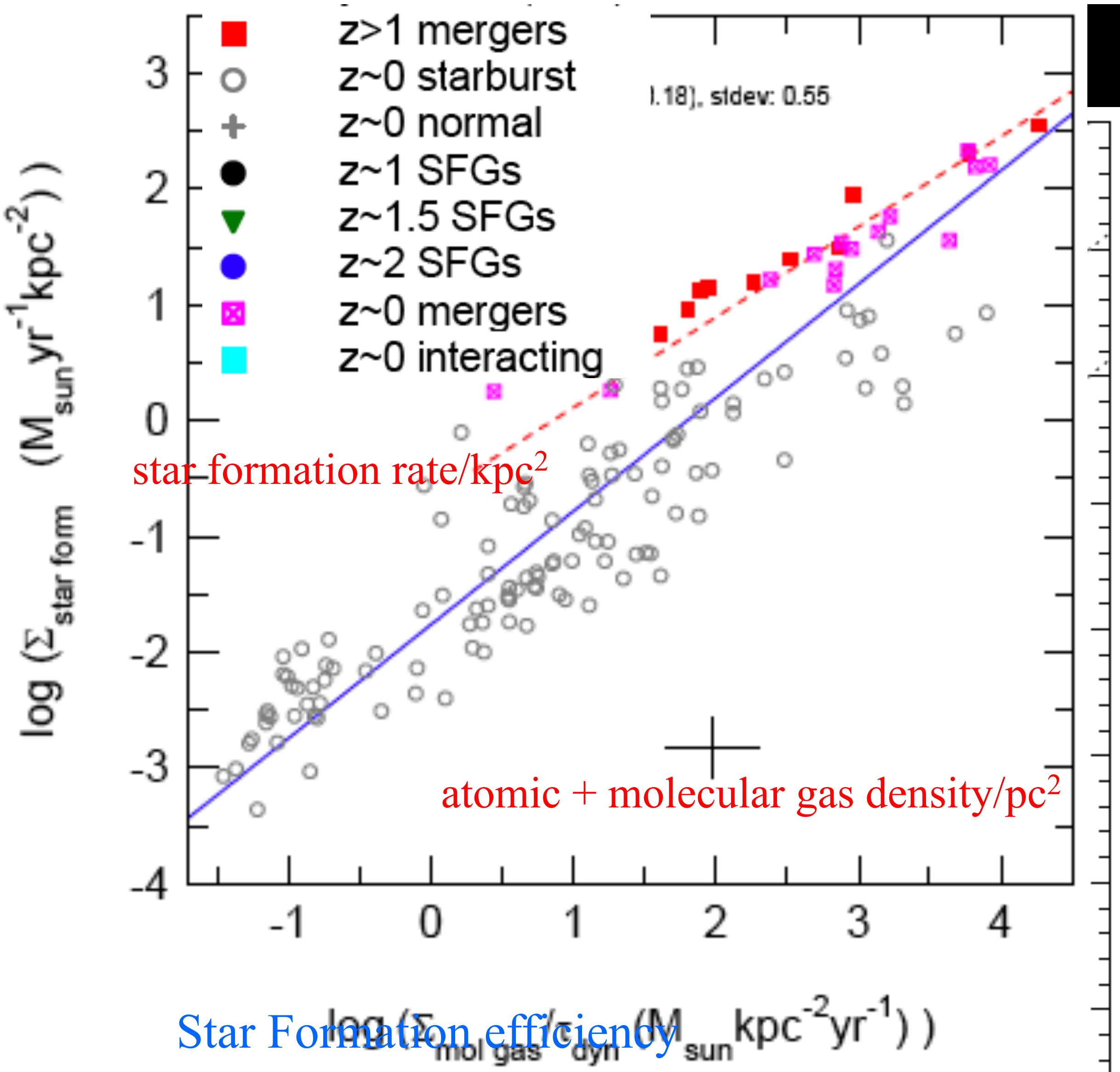


NGC 6946 Boomsma et al 2008



low efficiency due to SN feedback

+ cold gas accretion/global disk instability



star formation rate/kpc^2

atomic + molecular gas density/pc^2

Star Formation efficiency
=SFR/GAS MASS x ROTATION TIME
=2.5%

Genzel et al 2010

Molecular 'Elmegreen-Silk'-relation for mergers and SMGs. Symbols

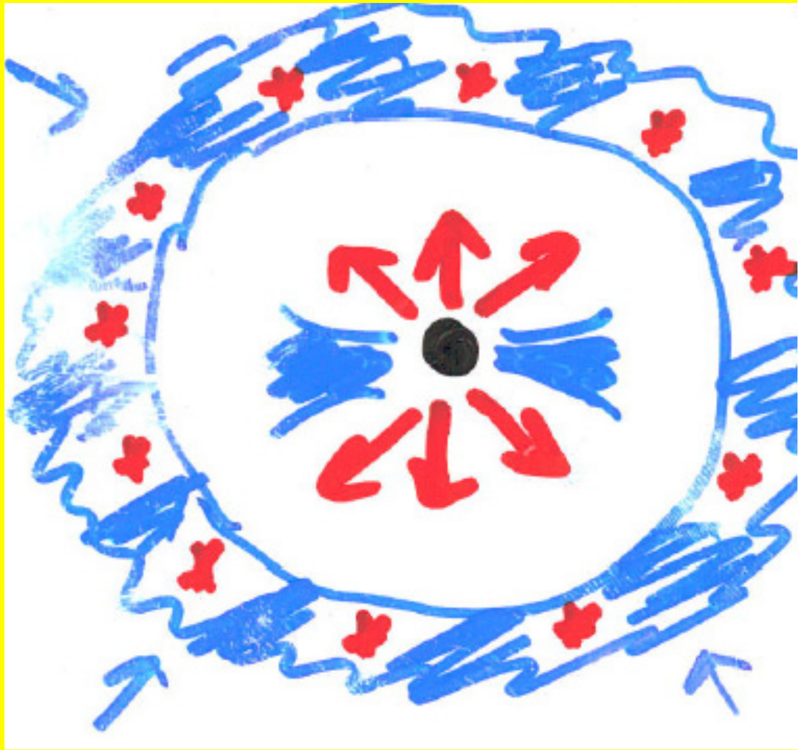
Spheroidal galaxies

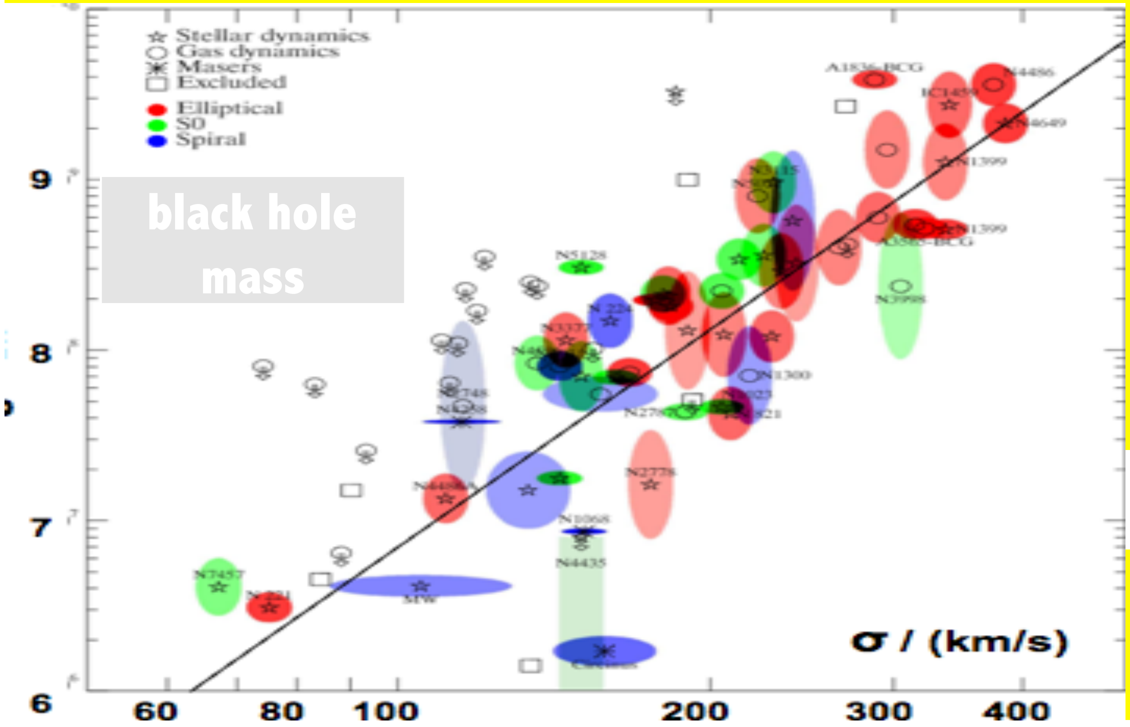
Feedback by massive black holes

$$L_{Edd}/c = GMM_{gas}/r^2$$

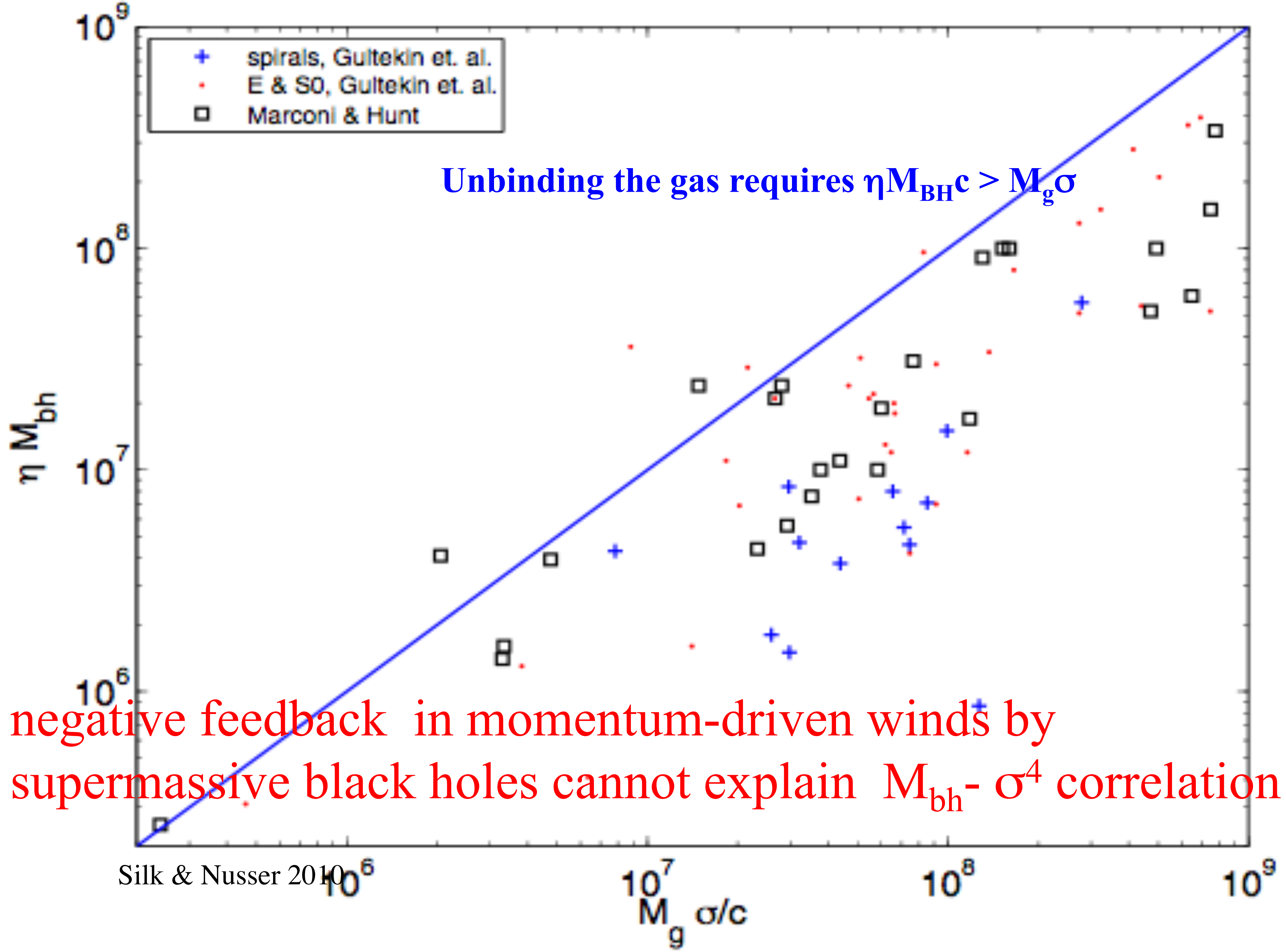
$$M_\bullet = 3\times10^9\,Msun\left(\frac{\sigma}{300\,\frac{\mathrm{km}}{\mathrm{s}}}\right)^4$$

Blowout occurs/star formation terminates when SMBH-σ relation saturates





$$L_{Edd} = 4\pi cGM_{BH}m_p/\sigma_T$$



Unbinding the gas requires $\eta M_{BH} c > M_g \sigma$

negative feedback in momentum-driven winds by supermassive black holes cannot explain M_{bh}- σ^4 correlation

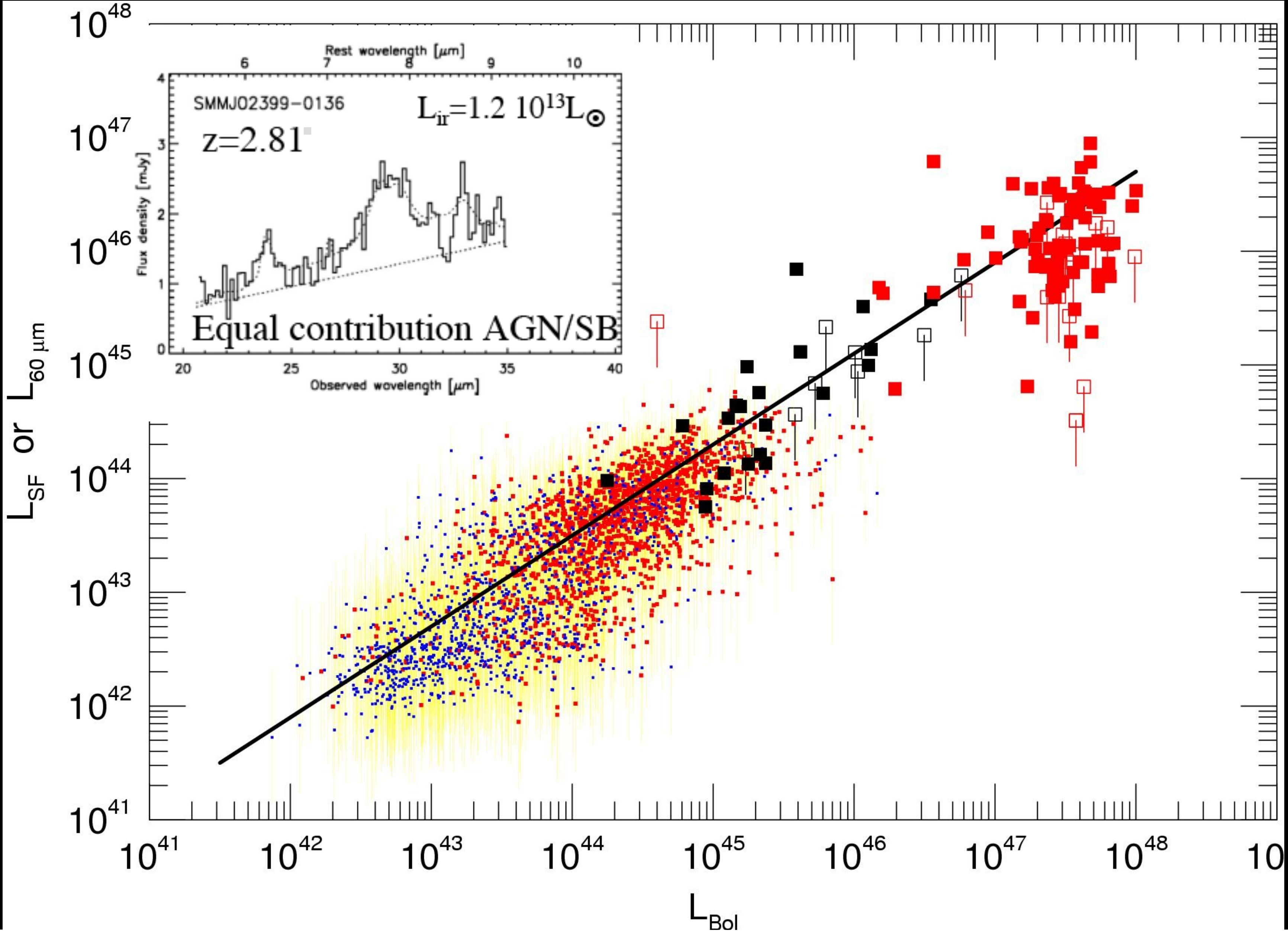
Silk & Nusser 2010

1) Porosity is a killer for SNe

2) Its not AGN, momentum deficit

3) maybe its both! AGN
+ triggering of star formation

connection between AGN and starbursts



star formation rate is boosted by AGN

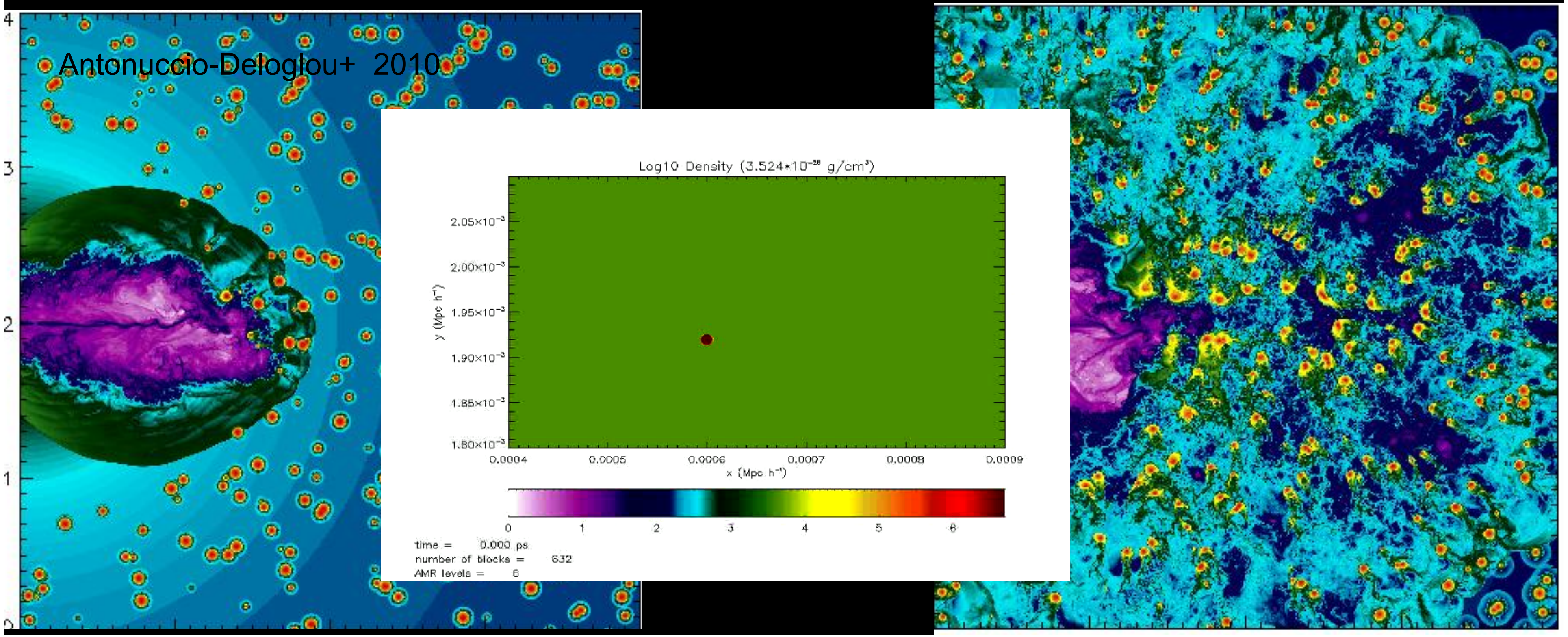
If AGN-driven outflows trigger star formation,

JS + C. Norman 2008

star formation rate boost factor ~ v_{cocoon}/σ ~10-100
+ outflow momentum amplified by supernovae

$$(p_{AGN}/p_g)^{1/2} \approx v_{jet}/\sigma$$

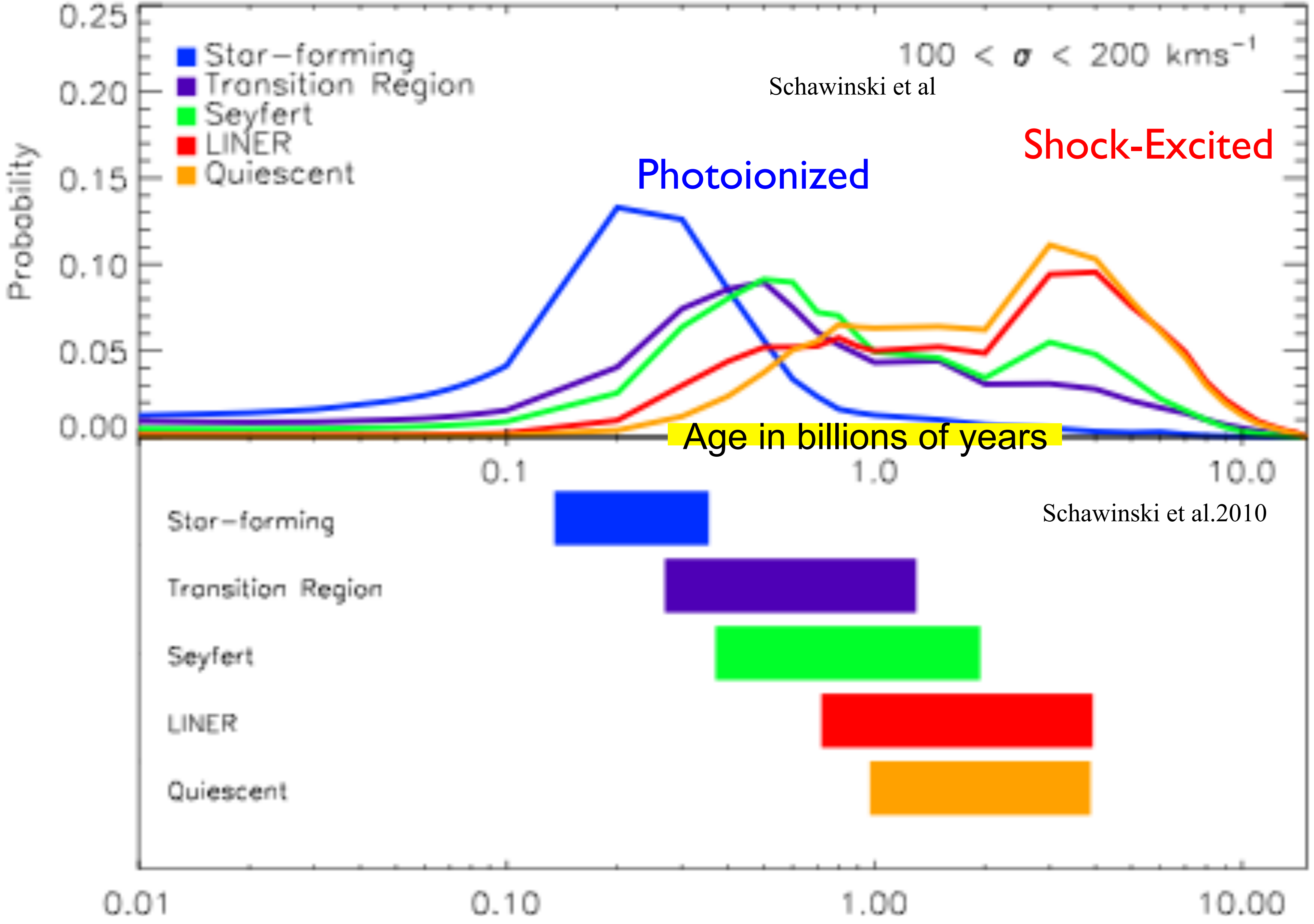
$$\dot{M}_* = (\epsilon_{SN}/\sigma) M_g (G p_g)^{1/2}$$



Antonuccio-Deloglou+ 2010

time = 0.000 ps
number of blocks = 632
AMR levels = 6

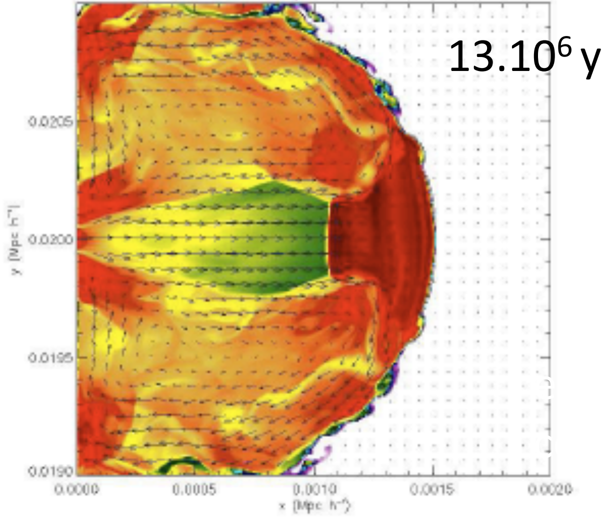
AGN are observed to quench star formation….



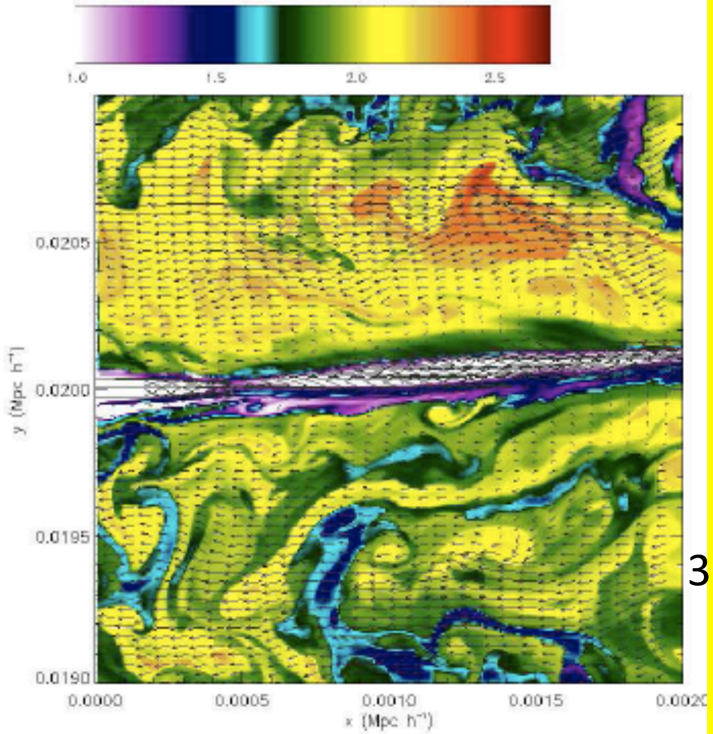
Schawinski et al

Schawinski et al.2010

AGN jet-induced backflow feeds the SMBH



13.10^6 yr



30.10^6 yr

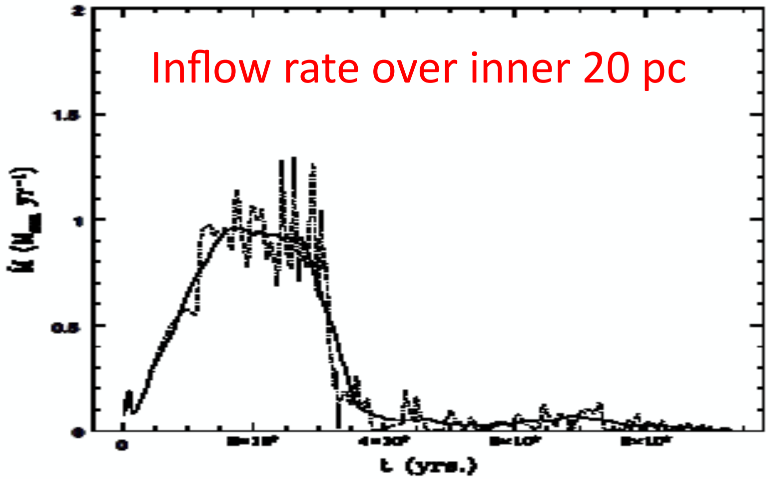
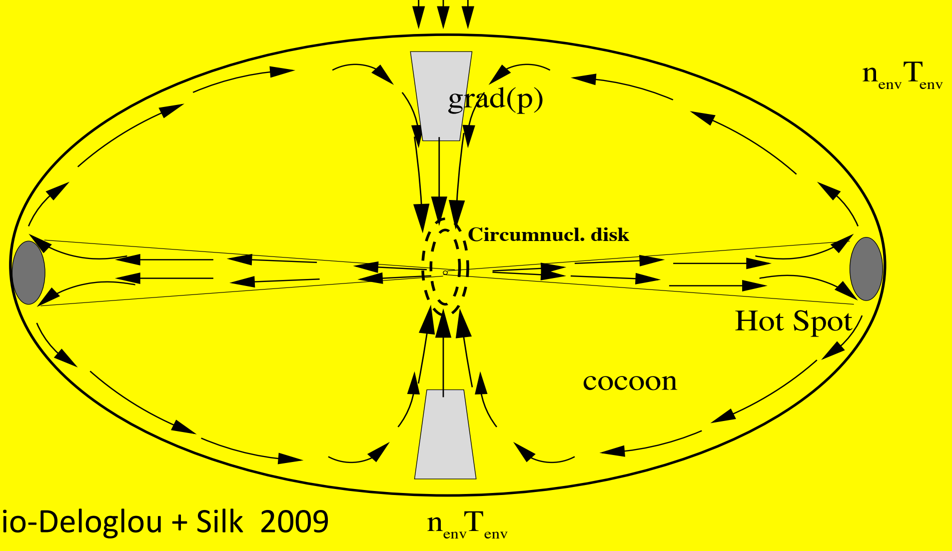


Figure 7. Mass flow in the circumnuclear region for run *sim800ss*. We show the averaged flux (continuous line) and the instantane[illegible] (dotted line). [illegible]sed by the intermittent behaviour of the flux inside the cocoon, during the evolved phase of the flow.



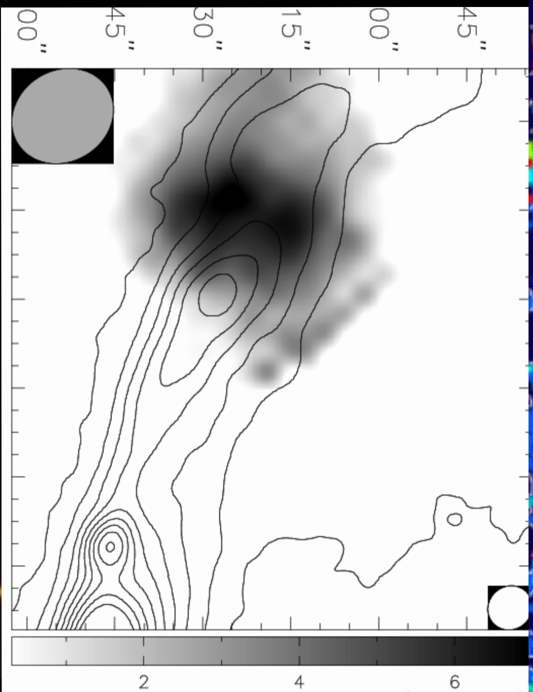
Antonuccio-Deloglou + Silk 2009

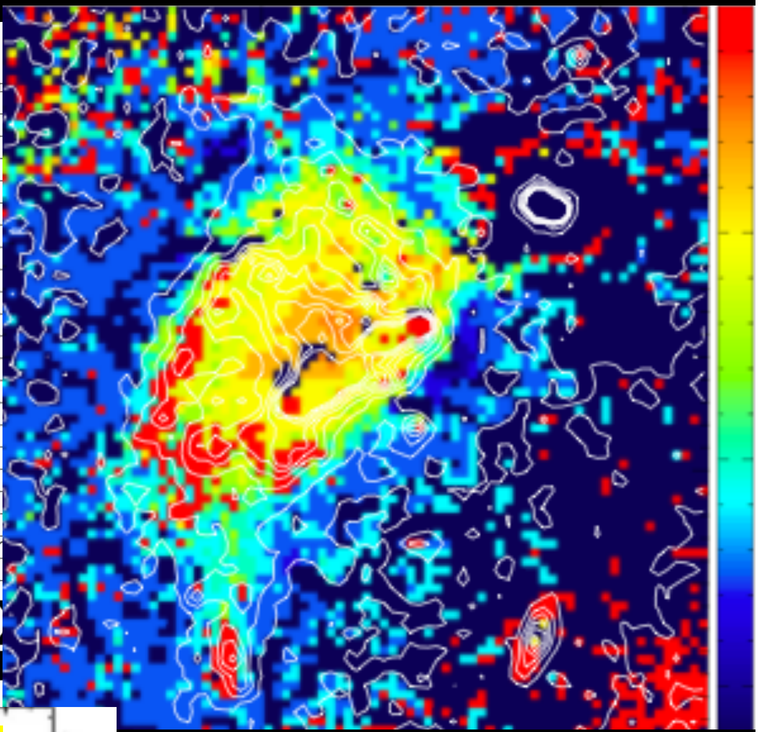
ram pressure

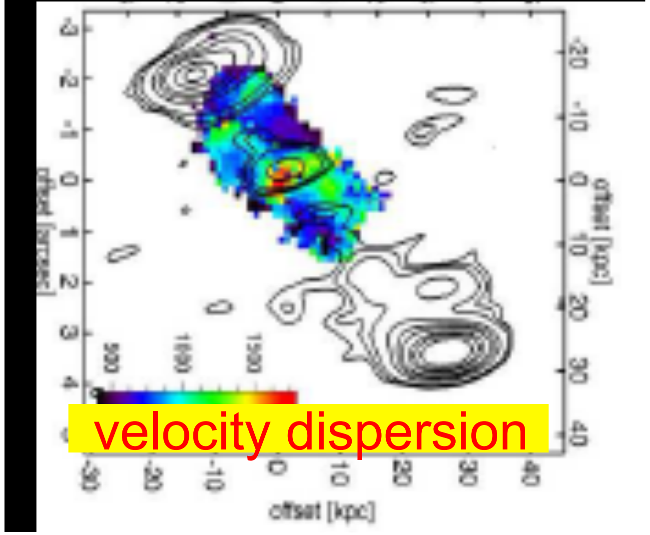
TRIGGERING IS OBSERVED

Minkowski's Object

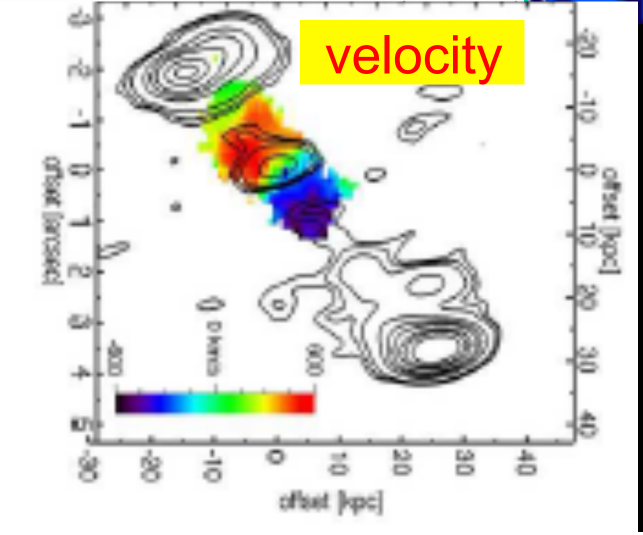
Croft et al. 2006







velocity dispersion



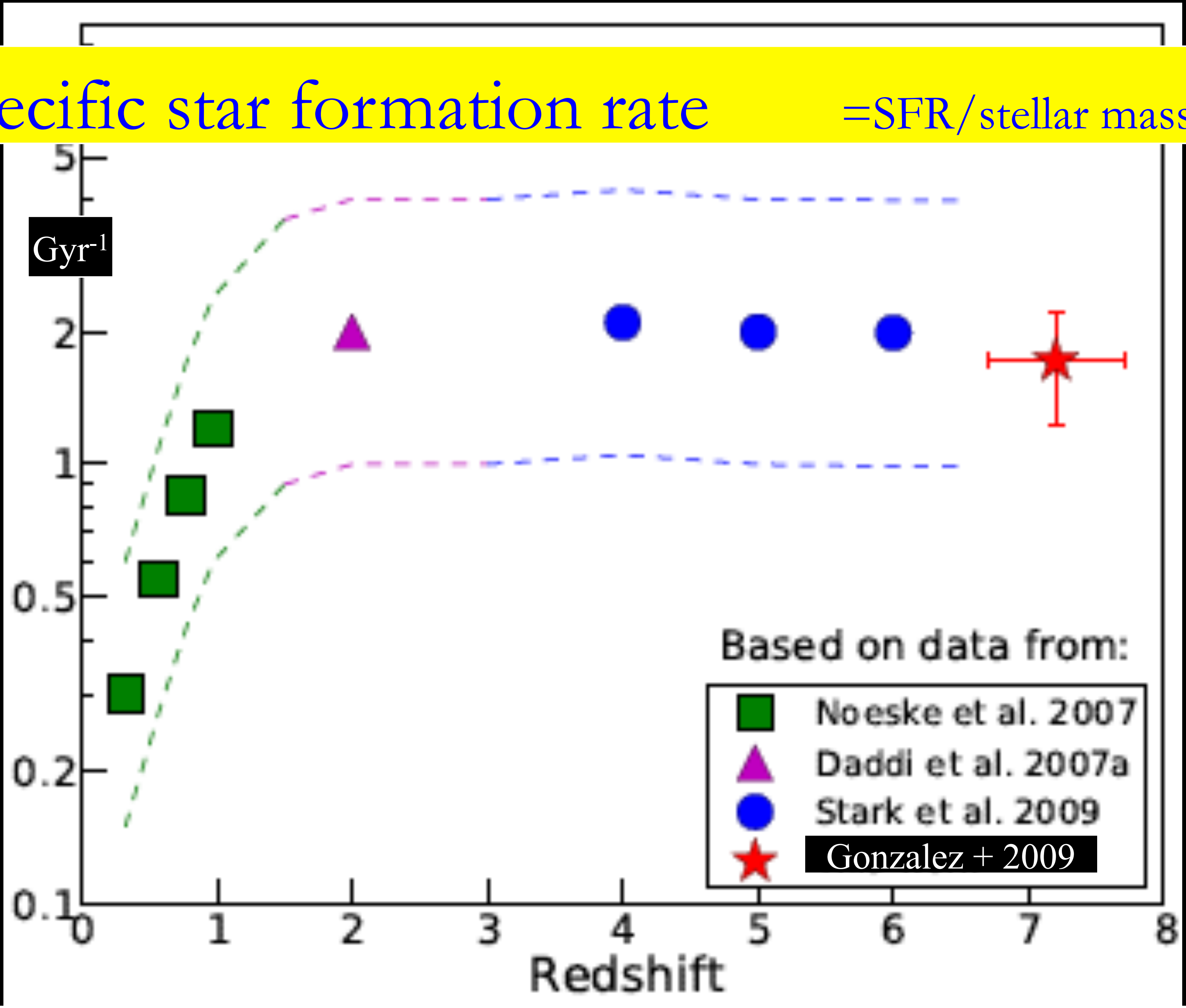
velocity

A ULIRG

Nesvadba 2009

PERHAPS WE NEED TRIGGERING AT HI z

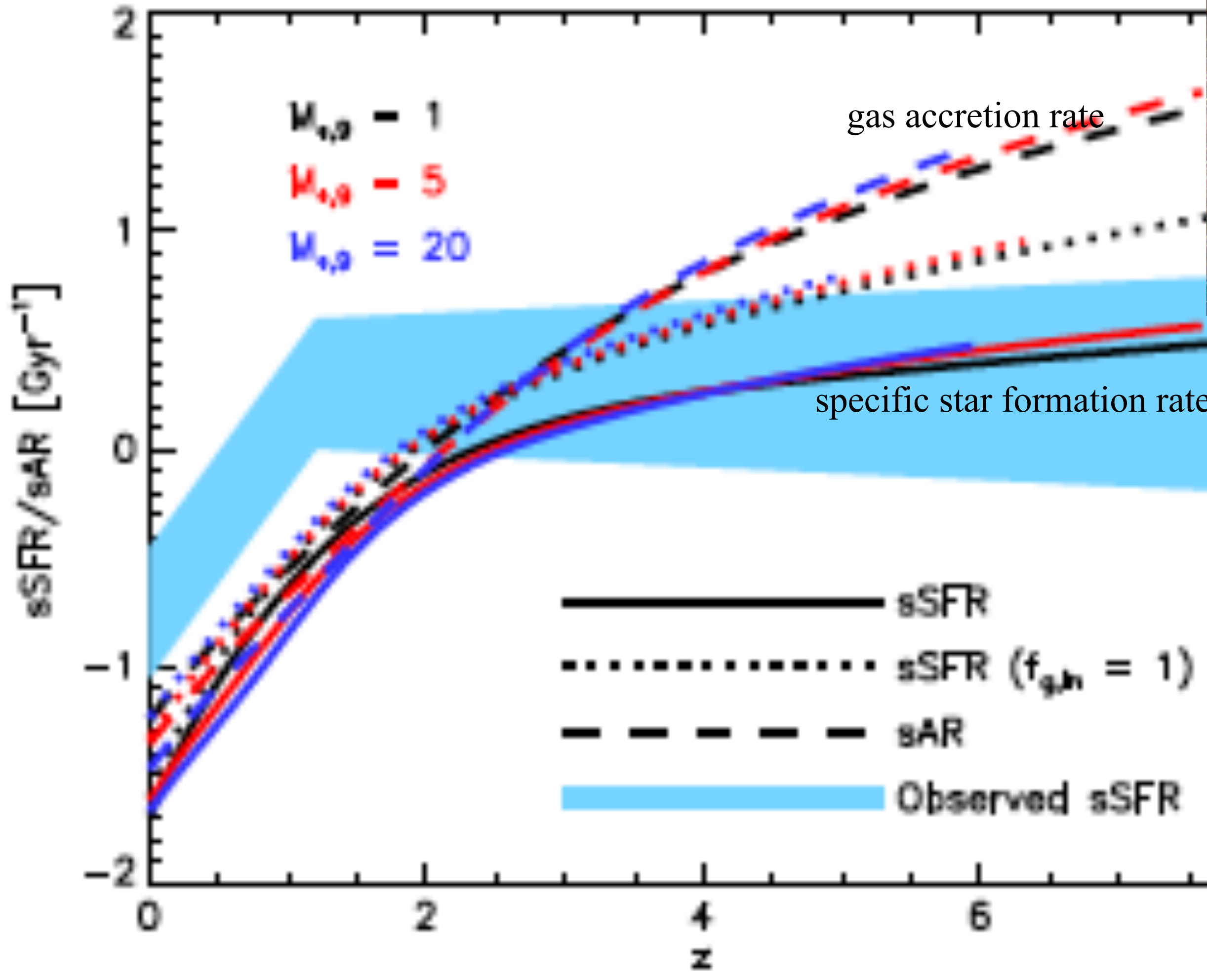
specific star formation rate =SFR/stellar mass

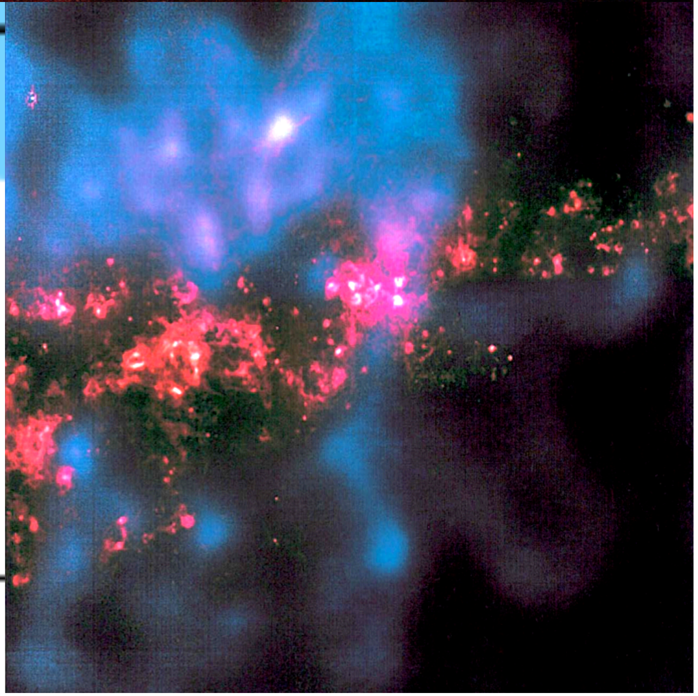


Star formation quenching via H_2 and Z(t)

No ejection of baryons (& fails at low z)

Krumholz and Dekel 2011



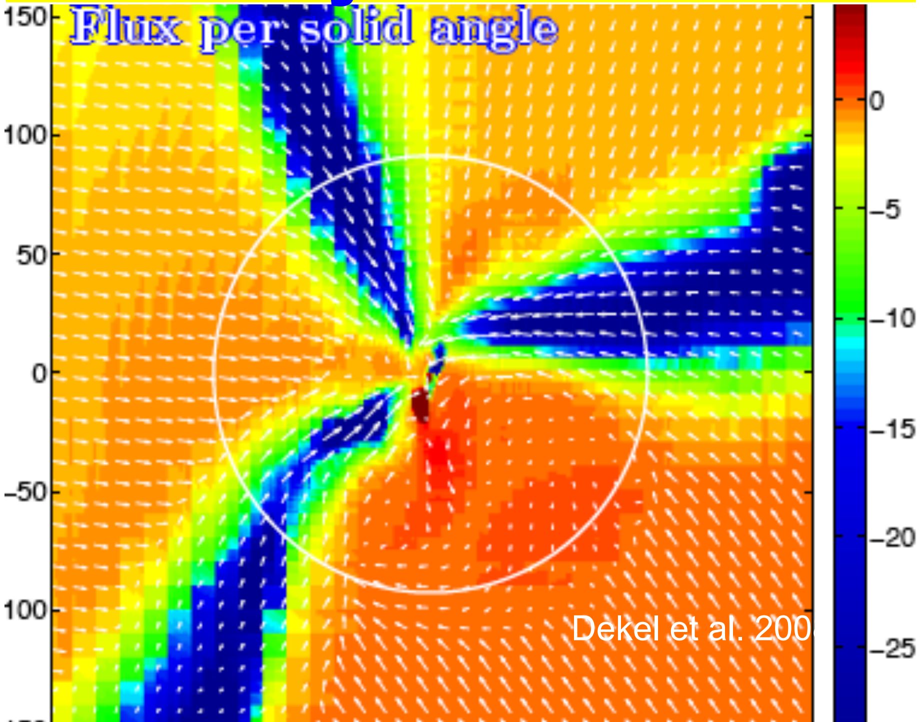


star formation, gas accretion and gas ejection

two modes of star formation
A: without active galactic nuclei (SMBH)
B: with active galactic nuclei

two modes of gas accretion:
A: cold streams/minor mergers
B: major mergers/cooling flows

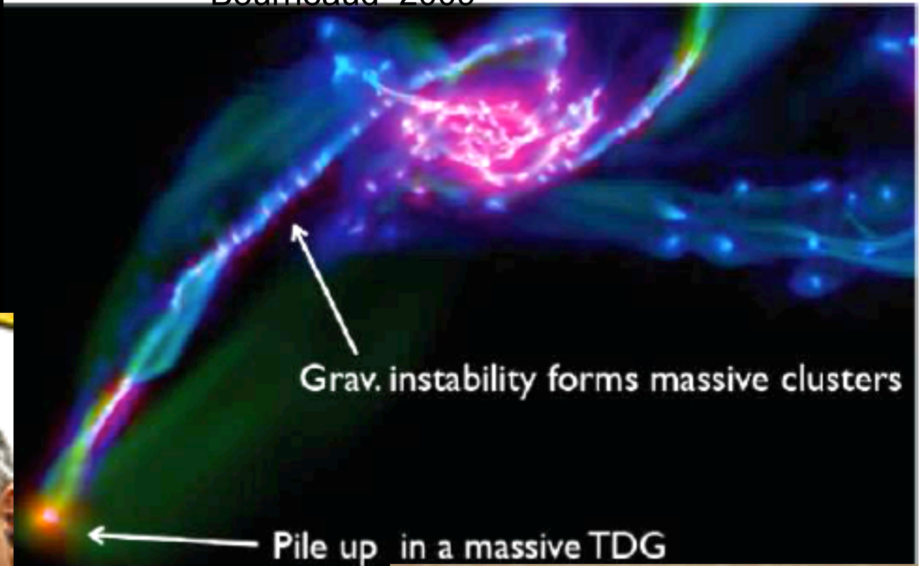
Infall by cold streams



Dekel et al. 200

major mergers

Bournaud 2009

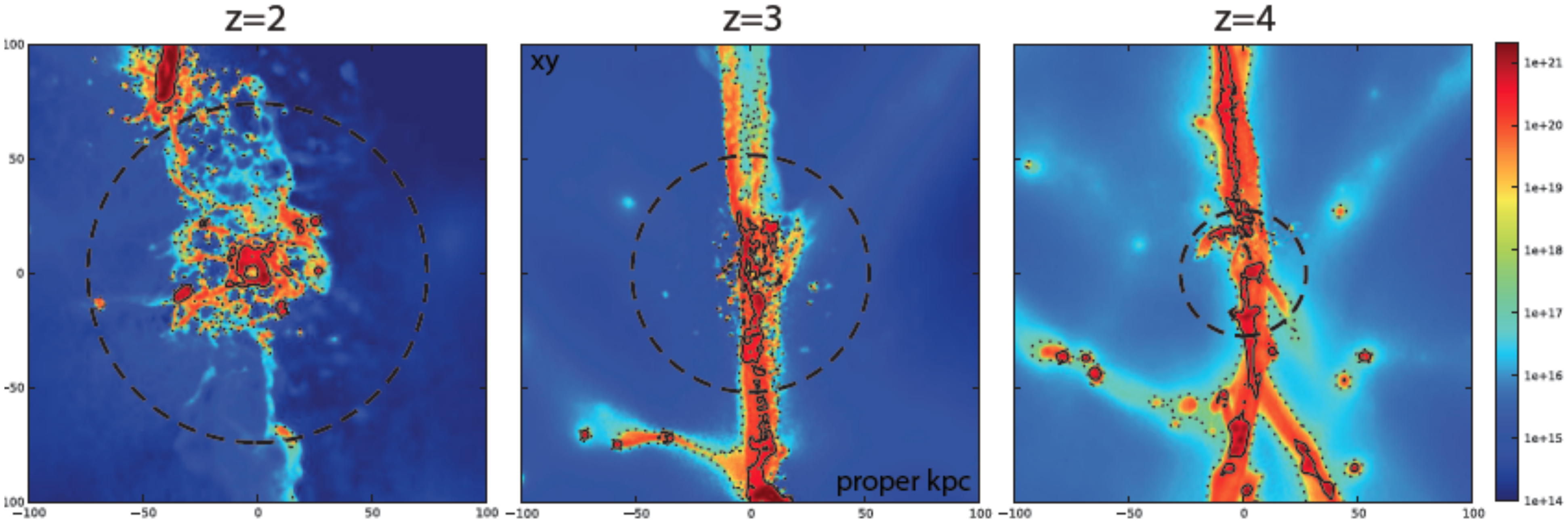


Grav. instability forms massive clusters

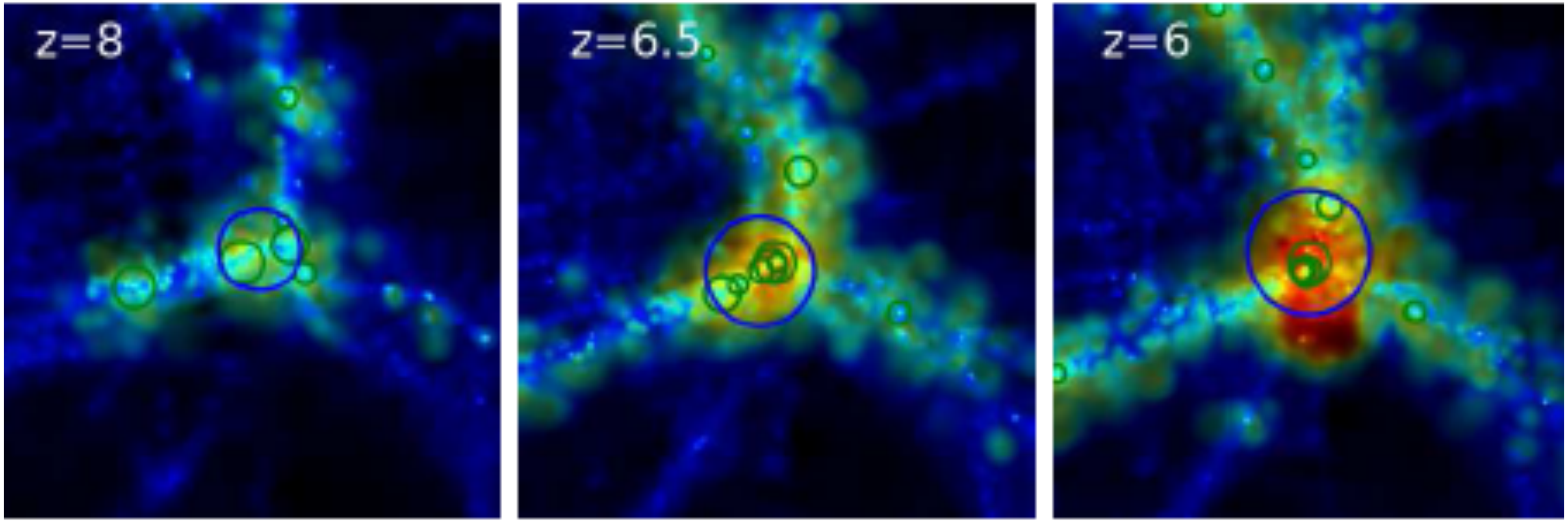
Pile up in a massive TDG

Where are the cold flows?

Faucher-Giguer & Keres 2010

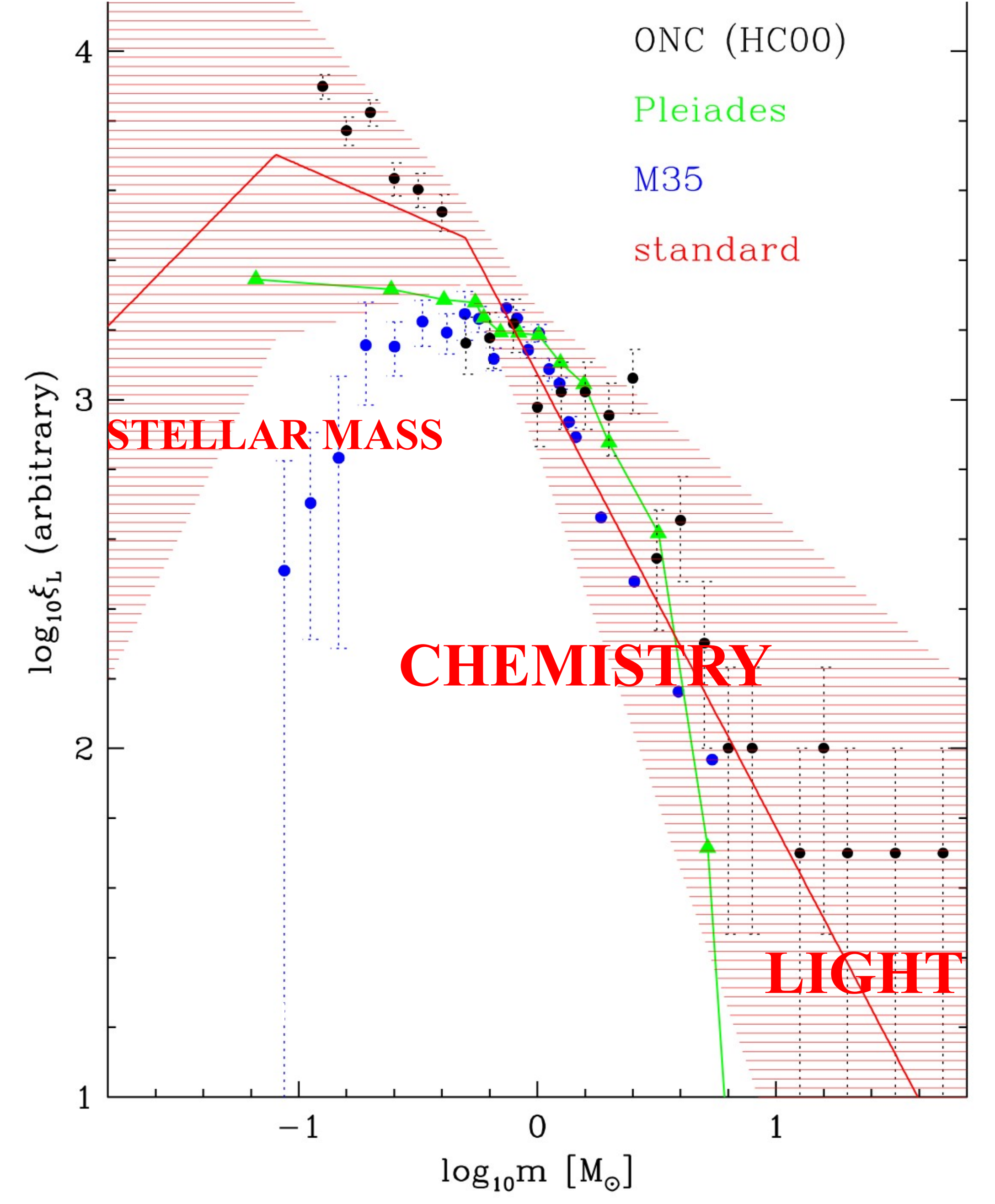


Feeding the monster



Di Matteo et al. 2011

The initial stellar mass function is a key assumption



imagine a physicist calculating on a cloud-bound planet and ending with the dramatic conclusion, "What 'happens' is the stars."

"We can imagine a physicist on a cloud-bound planet who has never heard tell of the stars calculating the ratio of radiation pressure to gas pressure for a series of globes of gas of various sizes, starting, say, with a globe of mass 10 gm., then 100 gm., 1000 gm., and so on, so that his *n*th globe contains 10^n gm. . . . Regarded as a tussle between matter and aether (gas pressure and radiation pressure) the contest is overwhelmingly one-sided except between Nos. 33-35, where we may expect something interesting to happen.

What 'happens' is the stars.

We draw aside the veil of cloud beneath which our physicist has been working and let him look up at the sky. There he will find a thousand million globes of gas nearly all of mass between his 33rd and 35th globes – that is to say, between $\frac{1}{2}$ and 50 times the sun's mass."

Sir Arthur S. Eddington: The Internal Constitution of the Stars, 1926

[redacted]

The life of a star depends on its mass and composition

Gravity versus electromagnetic forces (pressure)

The dimensionless constant that controls the masses of stars

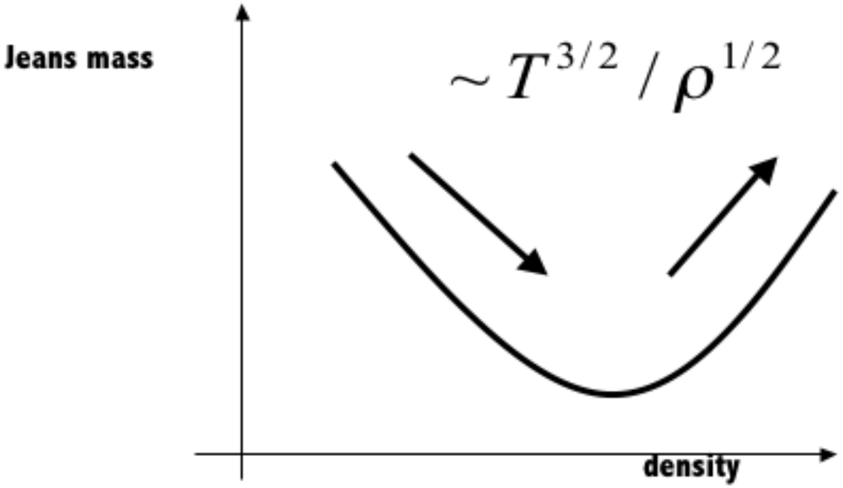
$$\alpha_g \equiv G m_p{}^2 e^{-2} \approx 3.10^{-37}$$

mass of the most massive star….the Eddington mass $\alpha_g{}^{-5/3}\alpha^{2/3}$

mass of a white dwarf star…the Chandrasekhar mass $\alpha_g{}^{-3/2}\alpha^{-3/2}$

G is Newton's constant, m_p is the mass of a proton, m_e is the mass of an electron

Stars



- Fundamental theory applied to a diffuse interstellar cloud that is collapsing under self-gravity
- Minimum fragment mass $\approx \alpha_g^{-3/2}\alpha m_p \approx 0.01 M_{sun}$

This is a robust but wrong result!

- Resolution: ***fragmentation*** + continuing ***accretion*** of cold gas, halted by ***feedback*** that taps stellar energy via magnetic turbulence

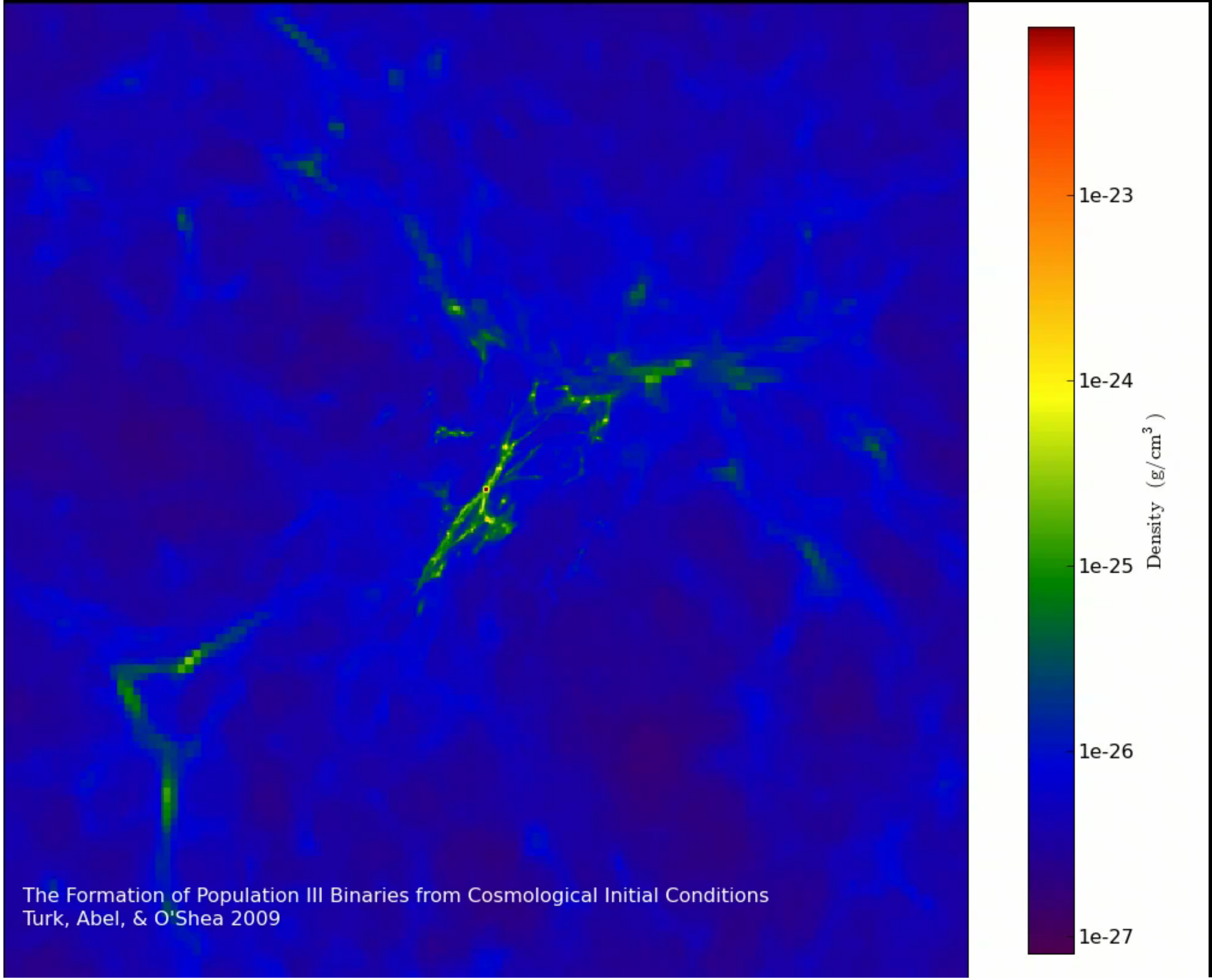
- accretion rate=(sound speed)^3/G

$\Rightarrow$ first stars were massive

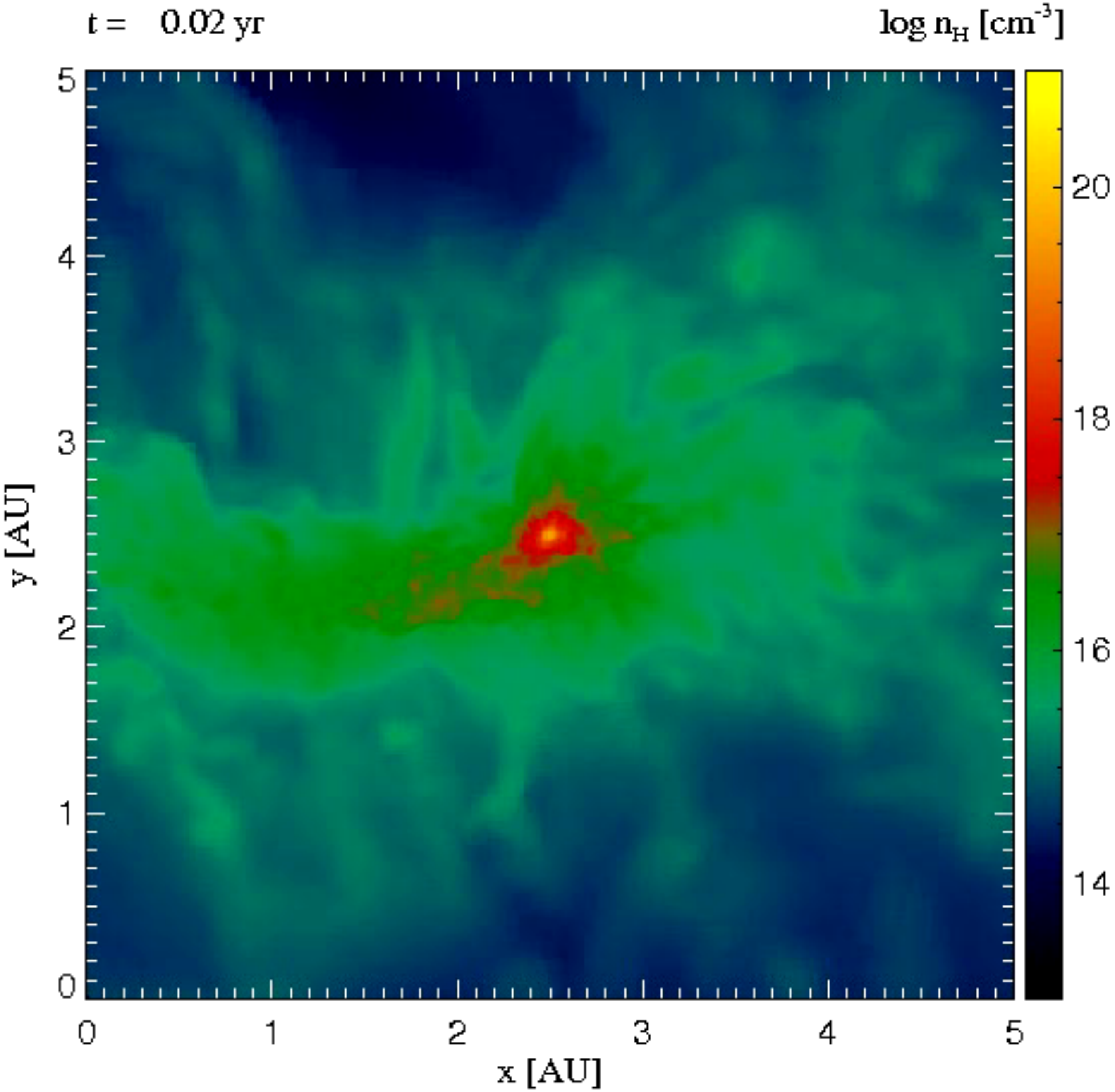
α is the fine-structure constant =1/137 m_p is the mass of a proton

$$\alpha_g \equiv G m_p{}^2 e^{-2} \approx 3.10^{-37}$$

The first stars: fragmentation



The Formation of Population III Binaries from Cosmological Initial Conditions
Turk, Abel, & O'Shea 2009



Greif 2011

a hybrid model

cold gas flows via filaments/minor mergers
lead to disk formation/pseudobulges

low efficiency

major mergers + hot infall + cooling
forms massive spheroids

high efficiency

Is star formation mechanism the same?
Is IMF universal?

AGN quenching of star formation
Intracluster gas heating by AGN
Baryon ejection: AGN role?
Triggering of star formation by AGN?
SMBH formation?

improved resolution in theory & observation will help…