Lectures

Dwarf Galaxies & Dark-Dark Halos: Feedback Processes

- The "fundamental line"
- Origin of scaling relations:
  supernova feedback

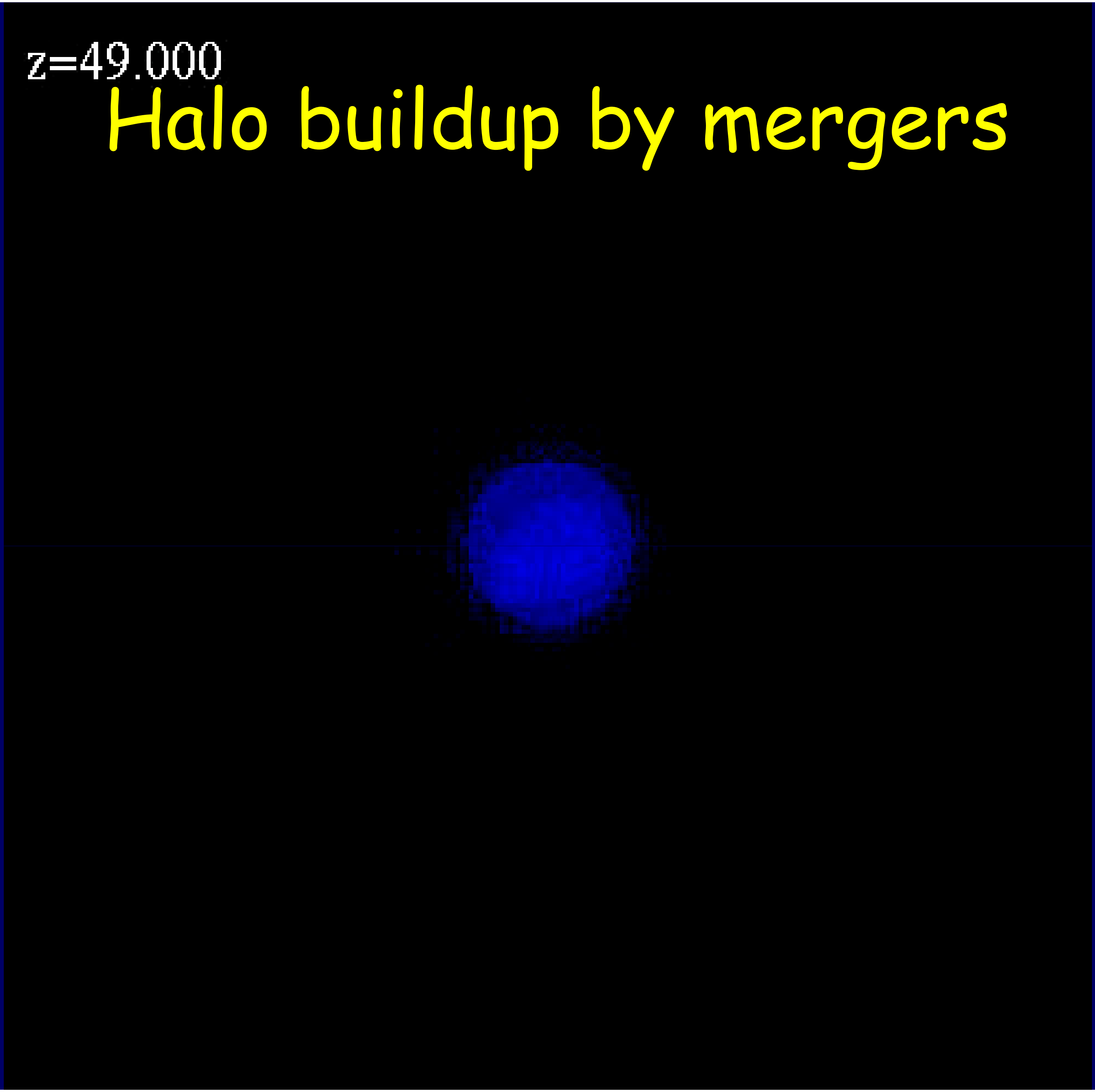
- Dark-dark halos (DDH) must exist
- Origin of DDH by photoionization

- Halo substructure: phase-space density

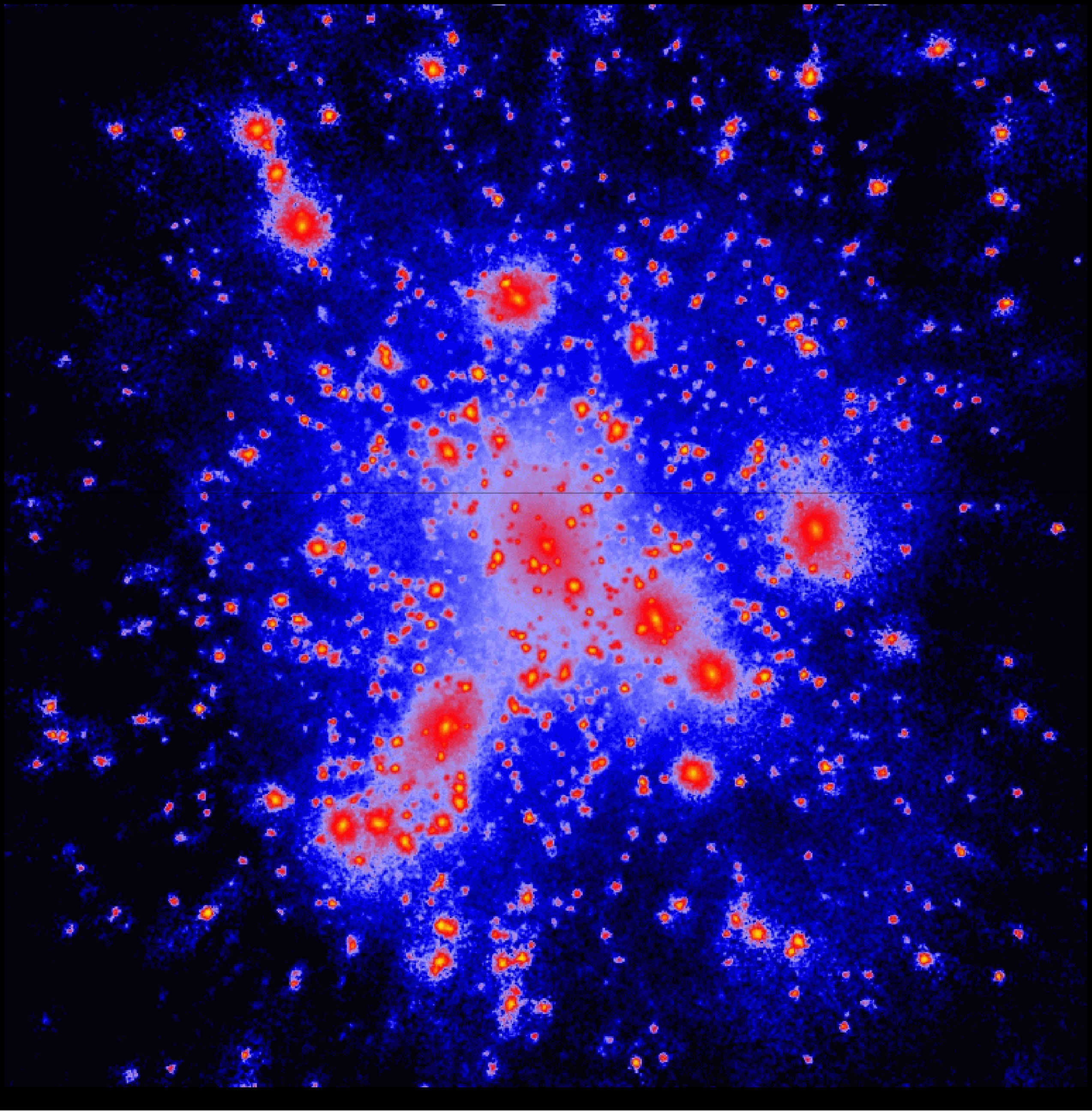
1. Missing Dwarfs & the “Fundamental Line”

Dekel & Woo 2003

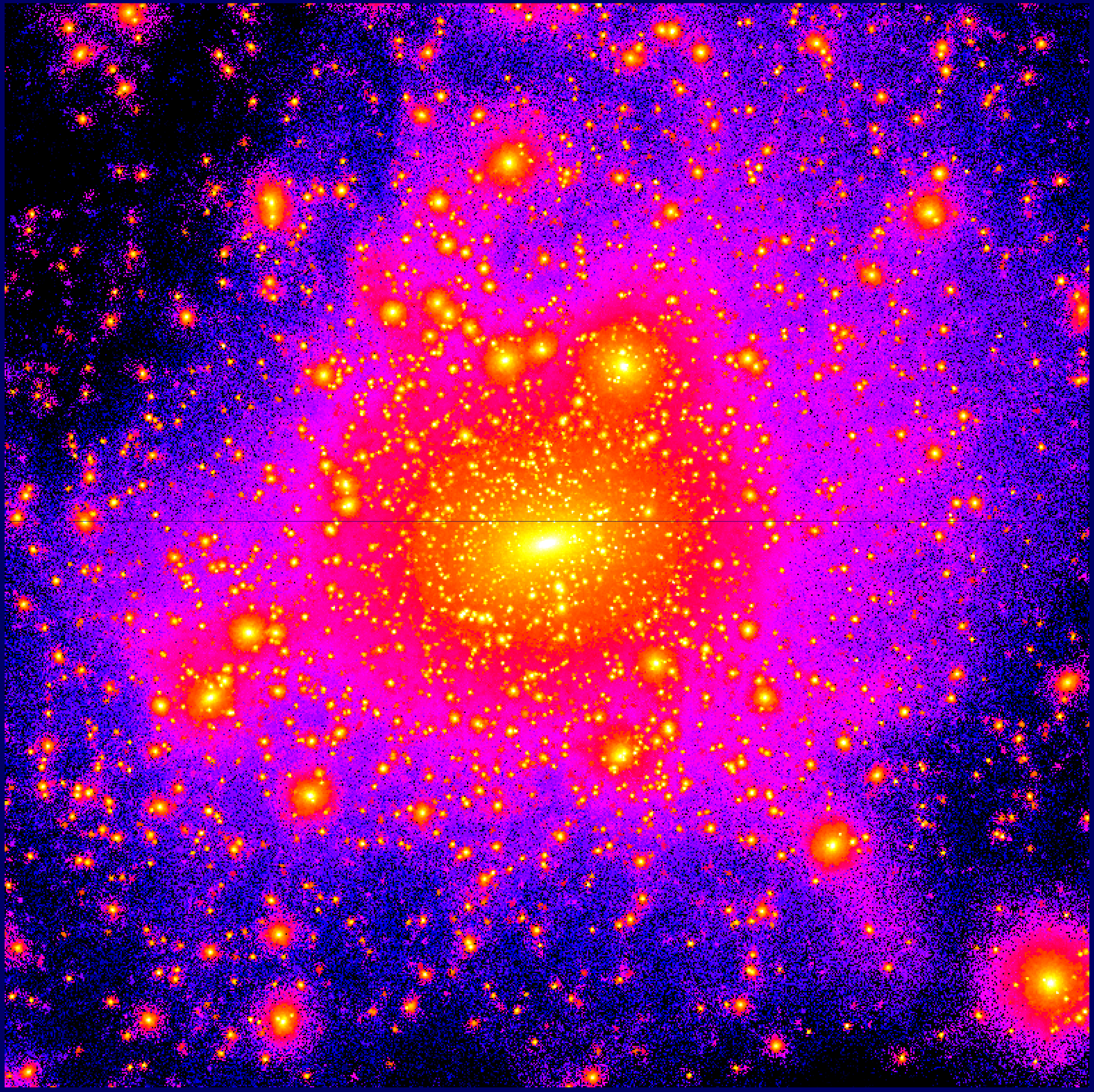
Halo buildup by mergers



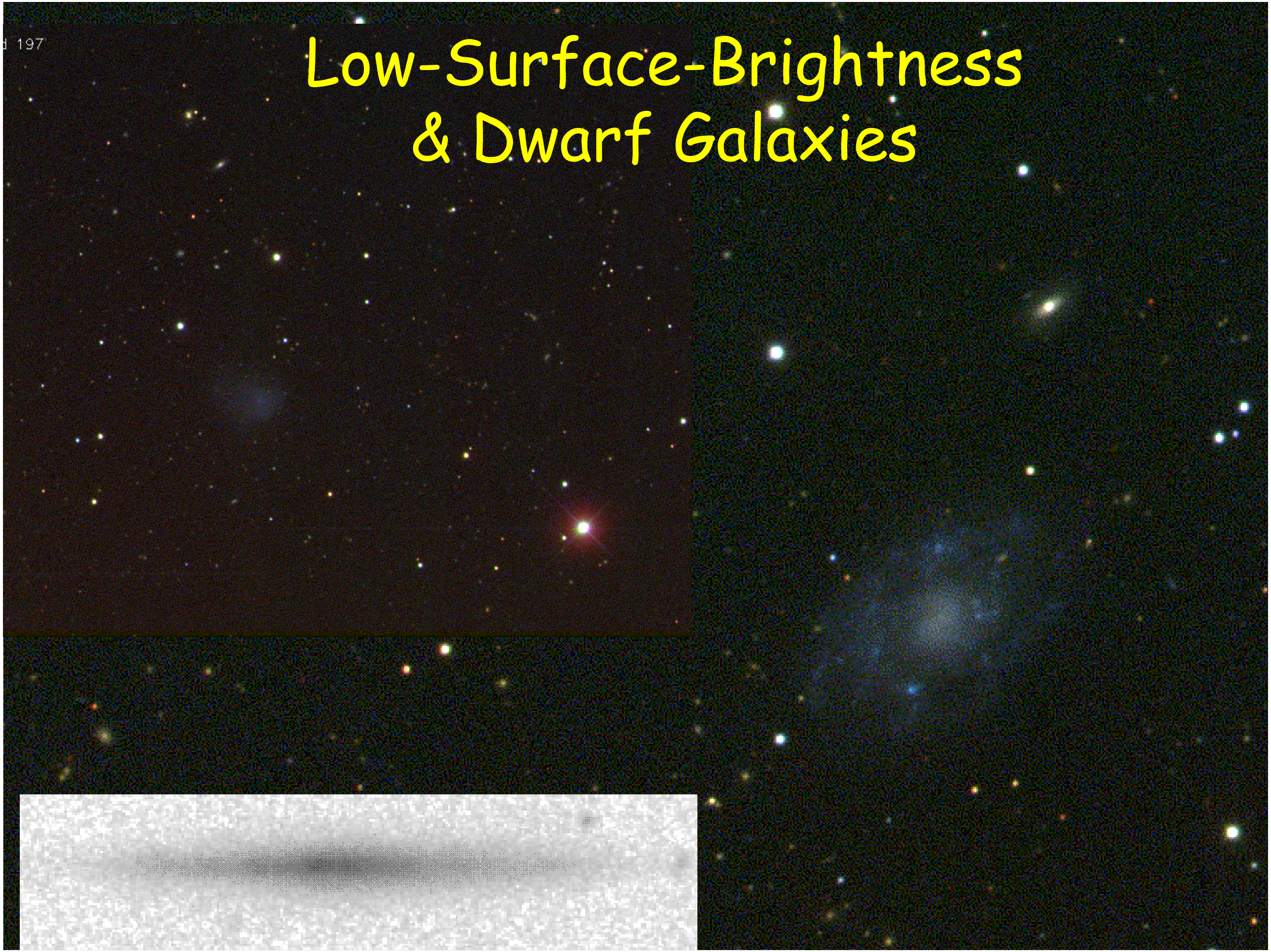
ΛCDM model: many dwarf satellites



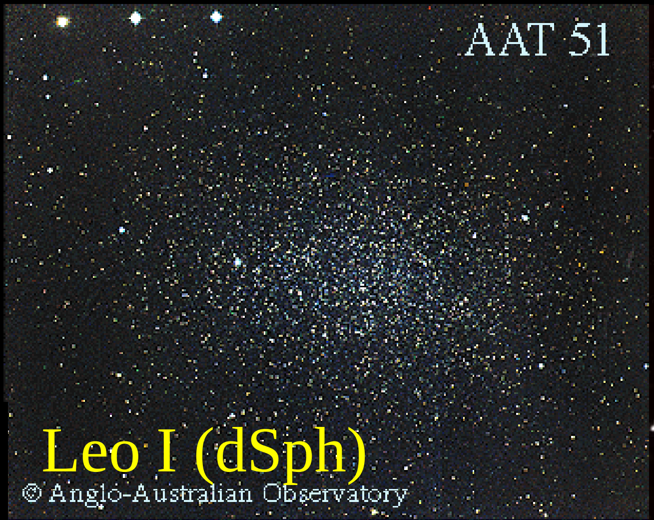
Moore et al



Low-Surface-Brightness & Dwarf Galaxies

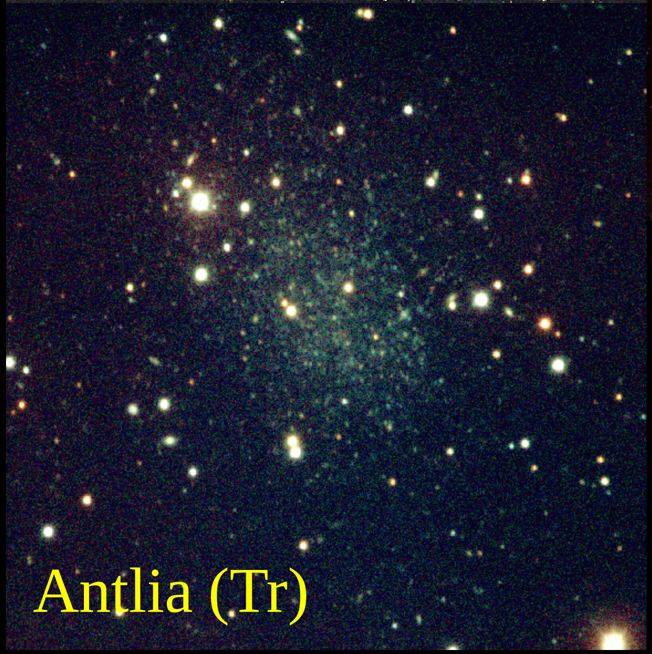


Only a few faint dwarf satellites



Leo I (dSph)

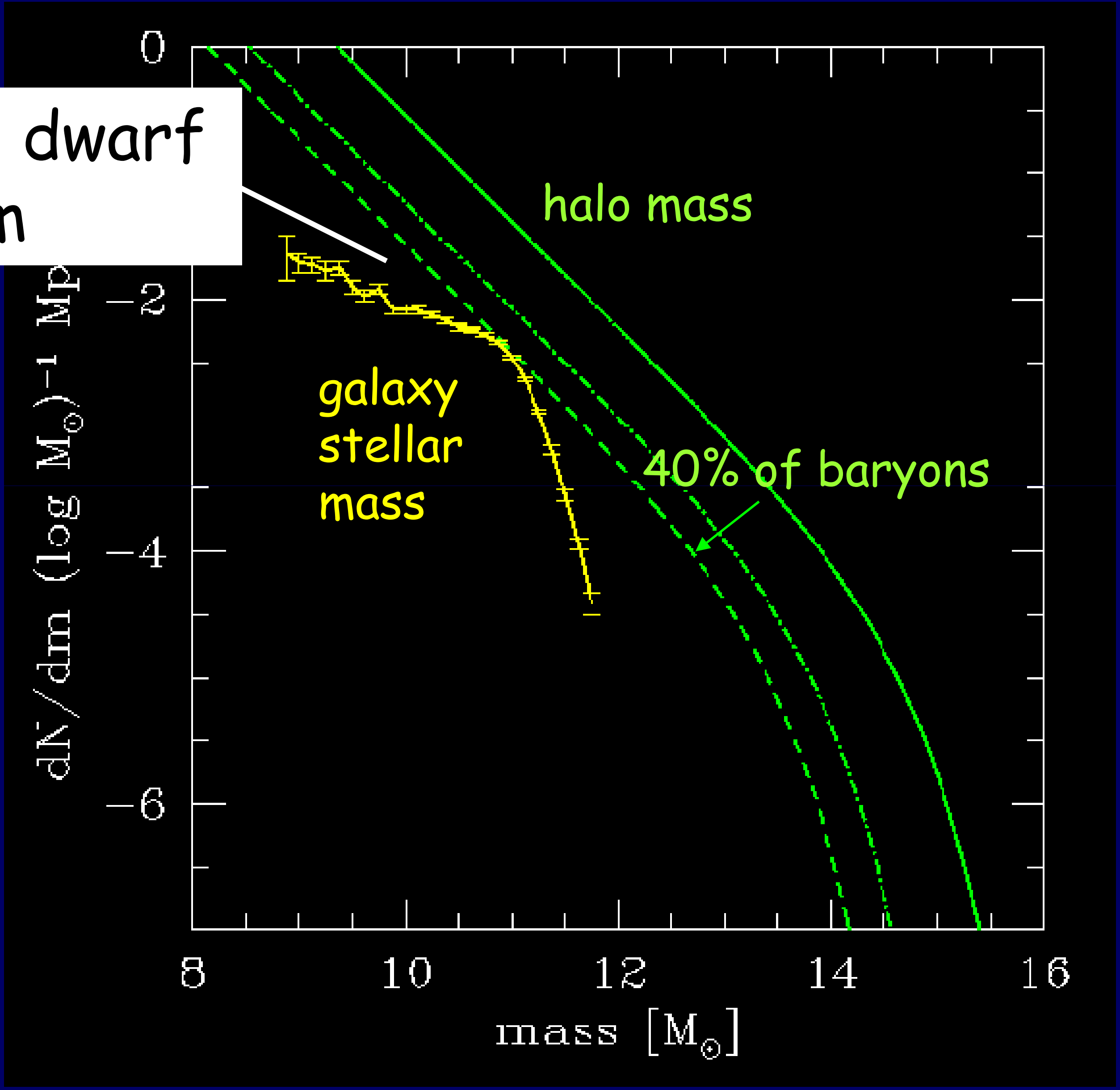
© Anglo-Australian Observatory



Antlia (Tr)

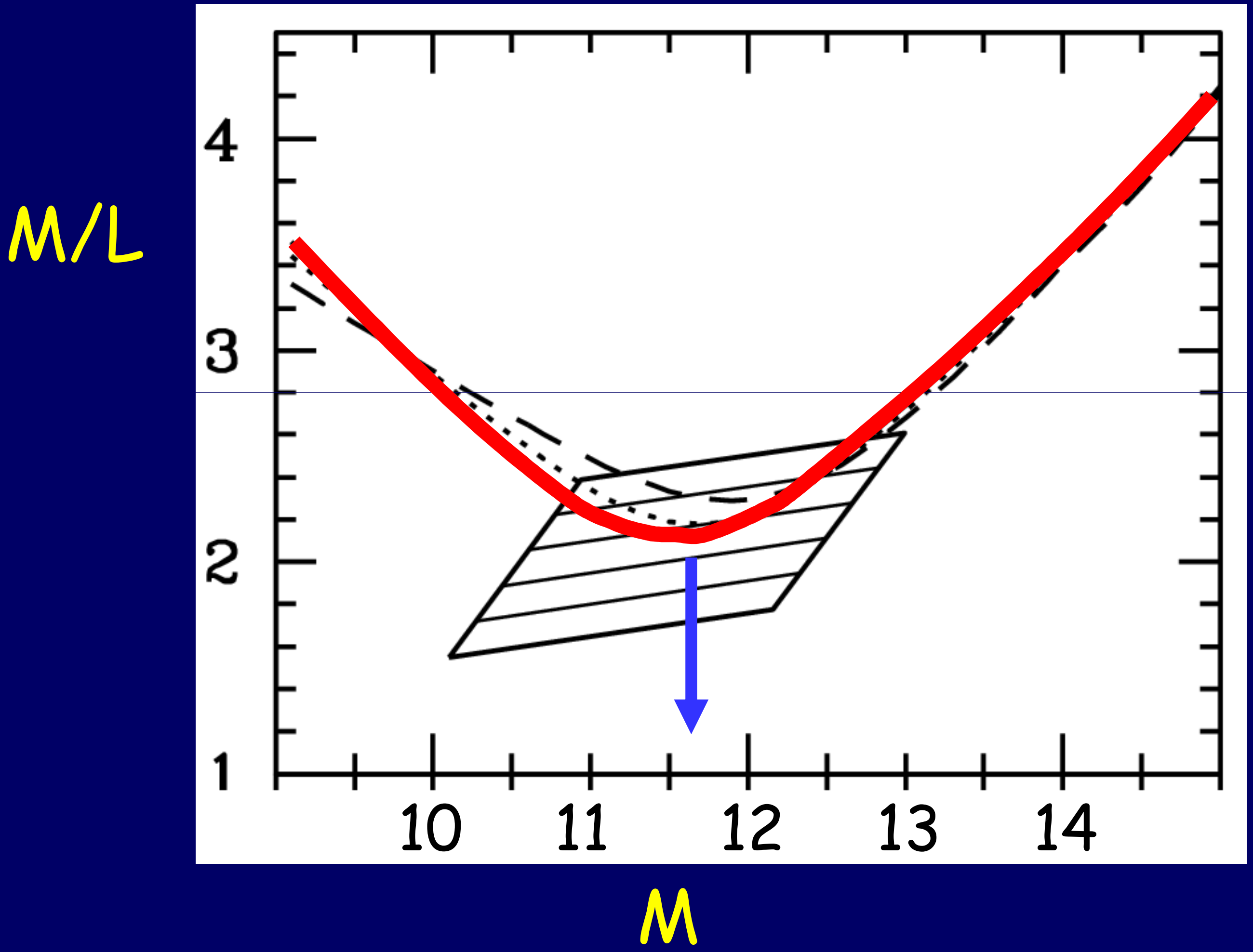
NGC 205 (dE)

Mass versus Light Distribution



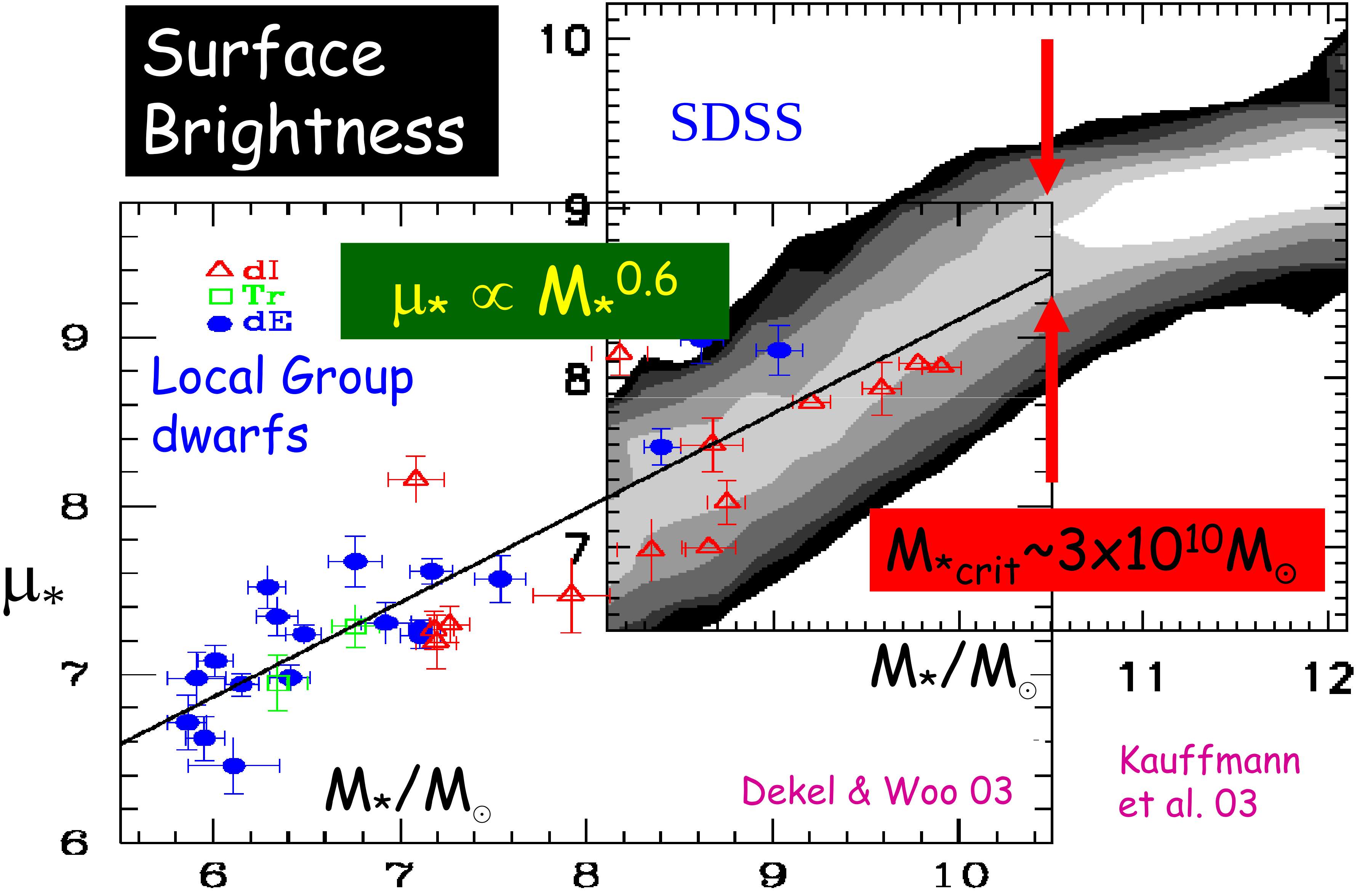
missing dwarf problem

<M/L> vs M for halos in 2dF assuming ΛCDM

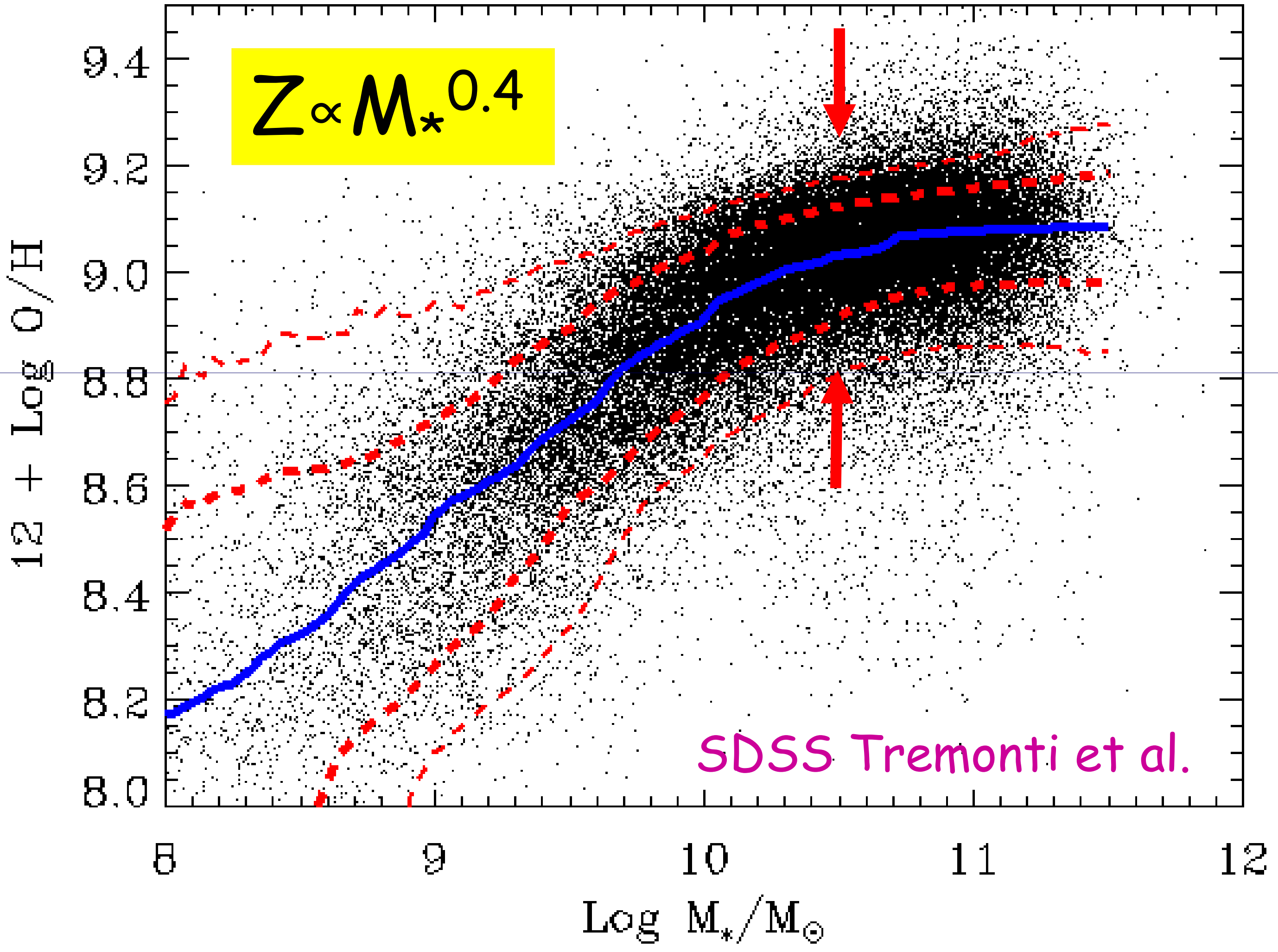


Using conditional luminosity function: Van den Bosch, Mo, Yang 03

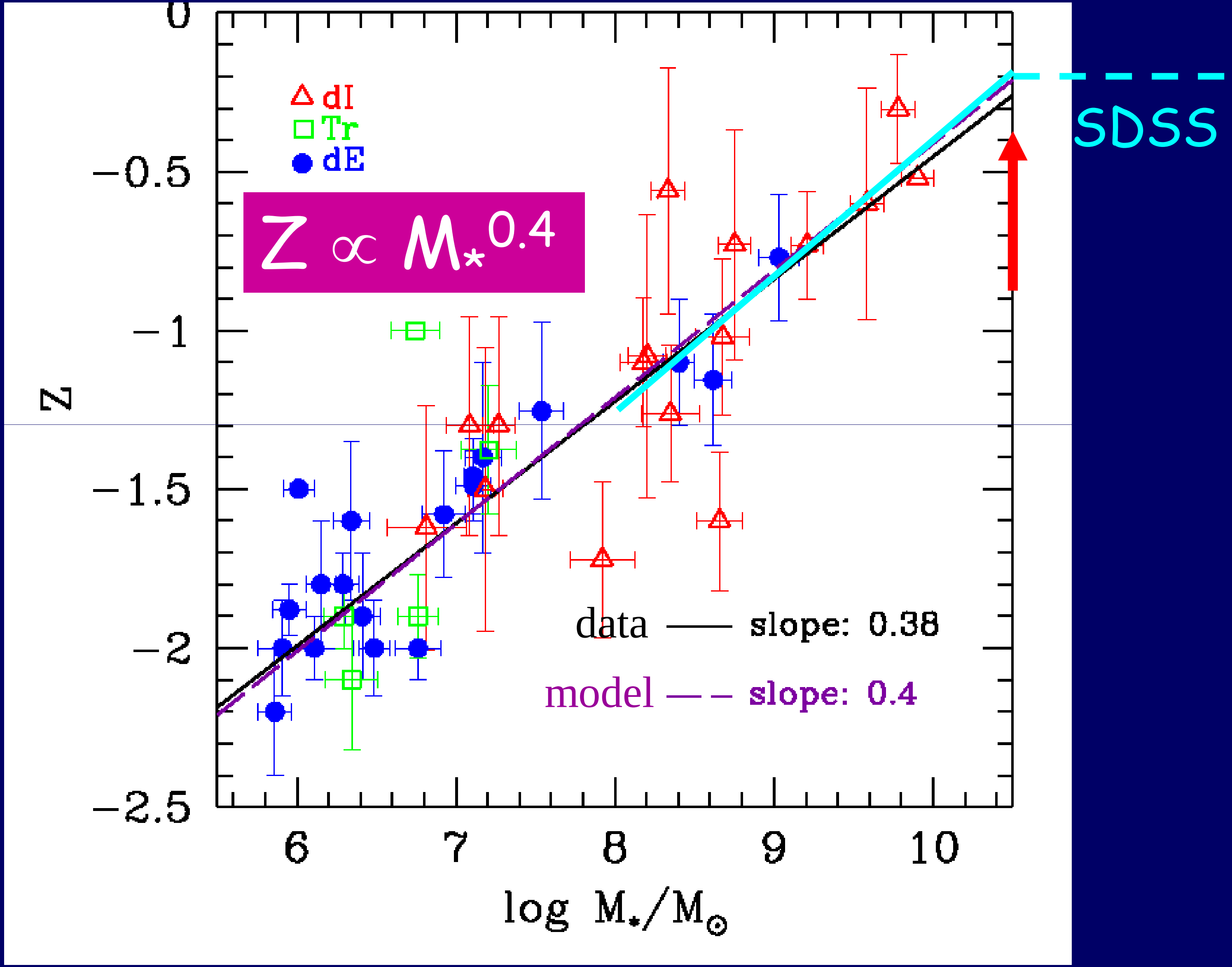
The "Fundamental Line" of LSB/Dwarfs



Metallicity

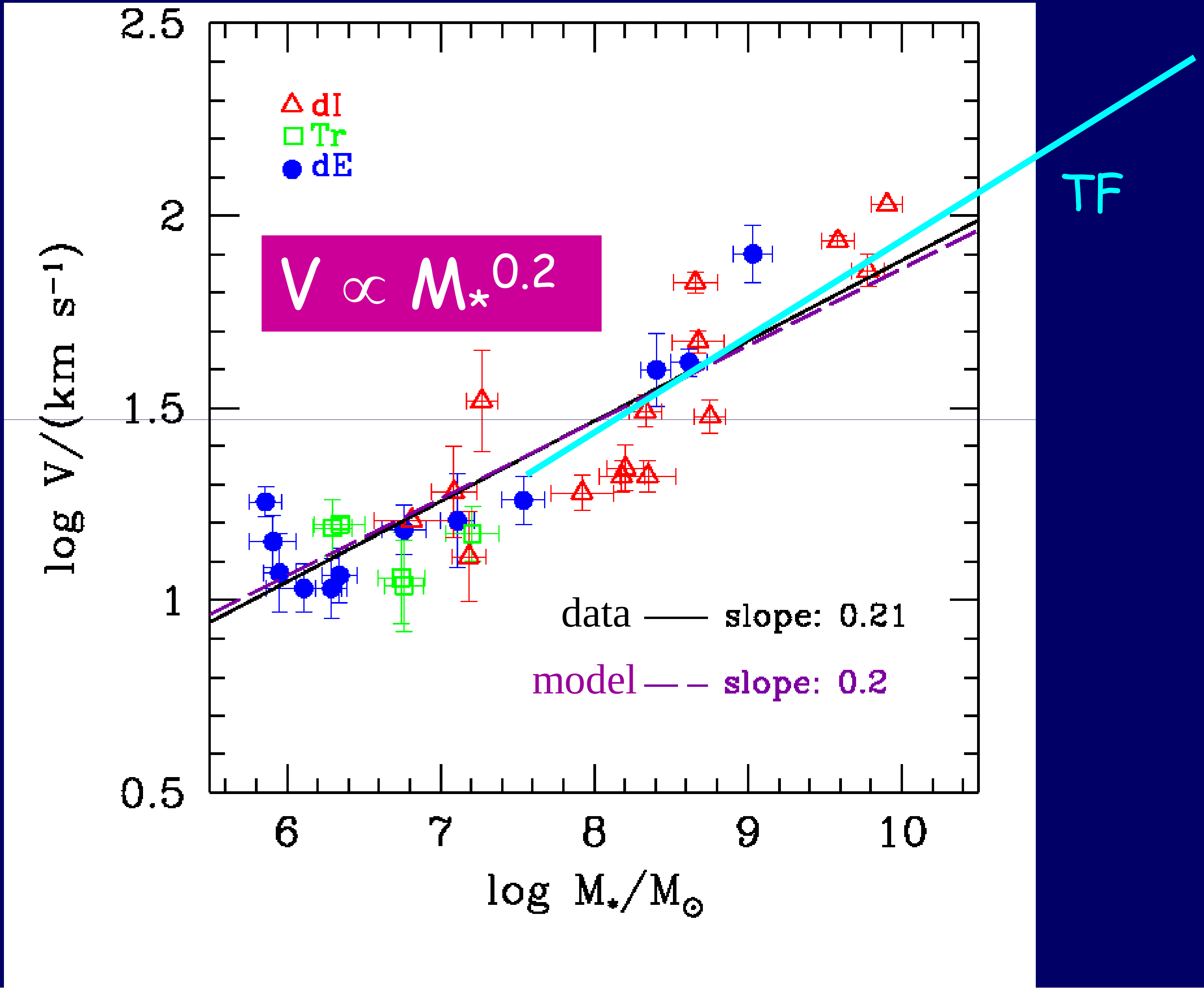


Local Group Dwarfs: Metallicity



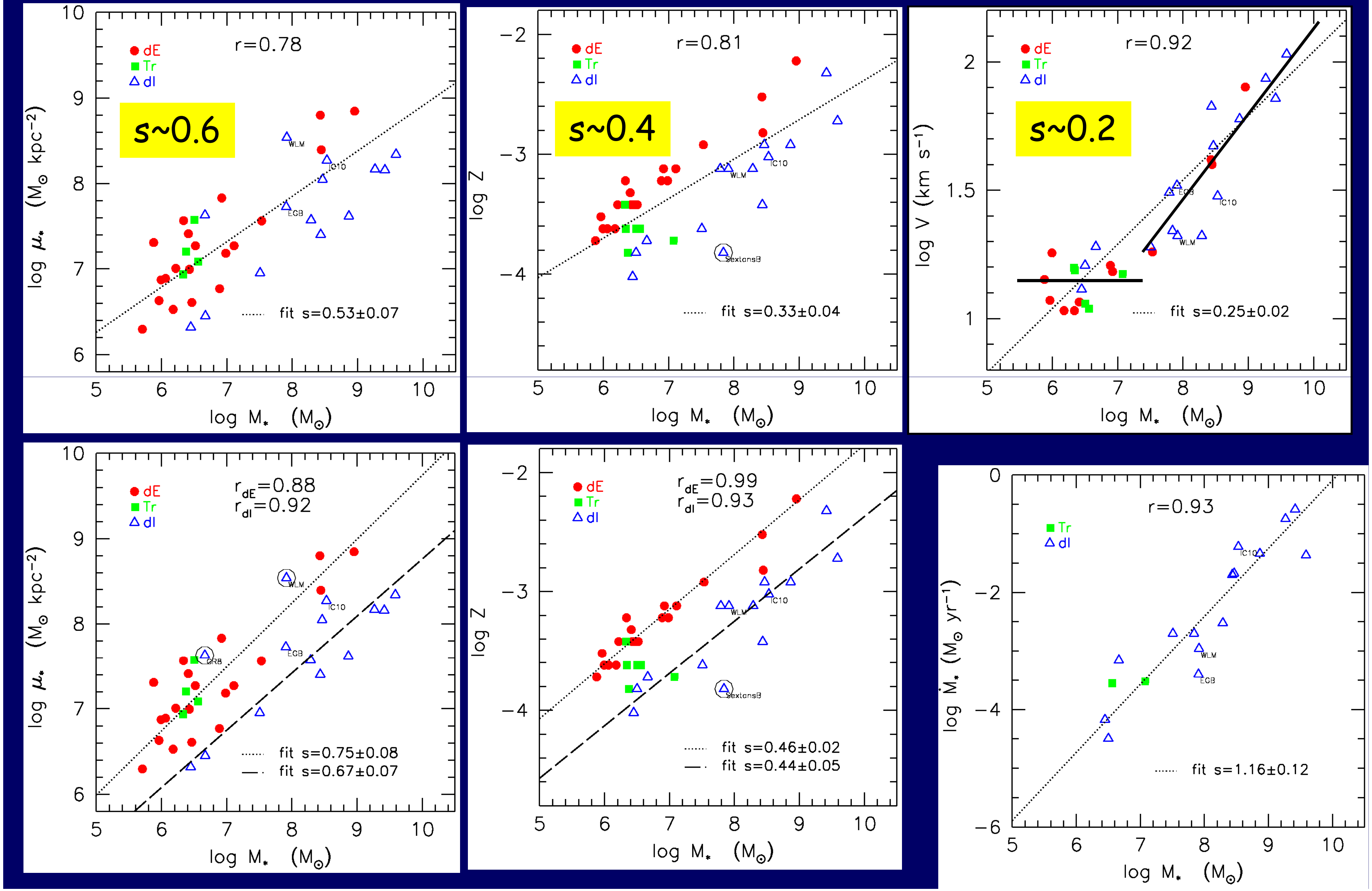
$Z \propto M_*^{0.4}$

LG Dwarfs: Velocity

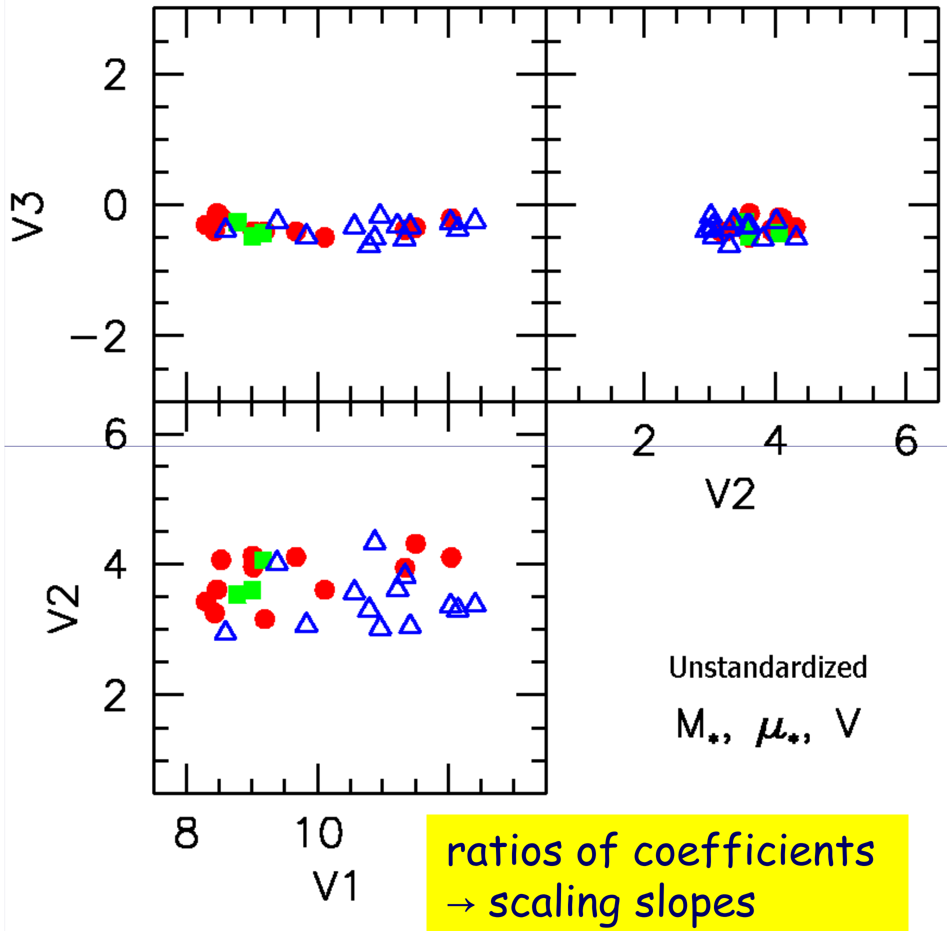


Fundamental Line: LG dwarfs

Woo, Courteau & Dekel 05
data: Mateo 98; Grebel 03



PCA Analysis: 3 structure variables

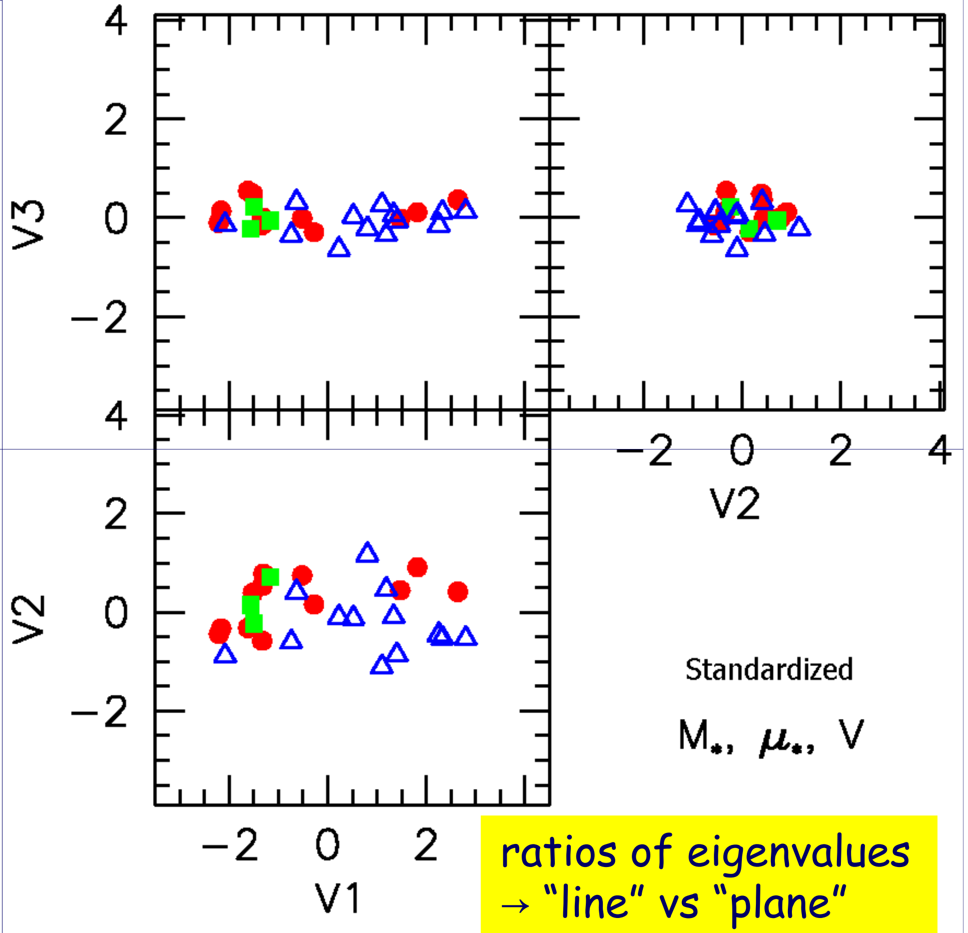


Unstandardized

M_*, μ_*, V

ratios of coefficients
→ scaling slopes

	$\log M_*$	$\log \mu_*$	$\log V$	Eigenvalue (%)
$\mathbf{V}_1$	0.88 ± 0.03	0.43 ± 0.06	0.22 ± 0.02	90.5 ± 2.1
$\mathbf{V}_2$	-0.41 ± 0.06	0.90 ± 0.03	-0.13 ± 0.06	8.8 ± 2.0
$\mathbf{V}_3$	-0.25 ± 0.03	0.03 ± 0.05	0.97 ± 0.01	0.7 ± 0.2



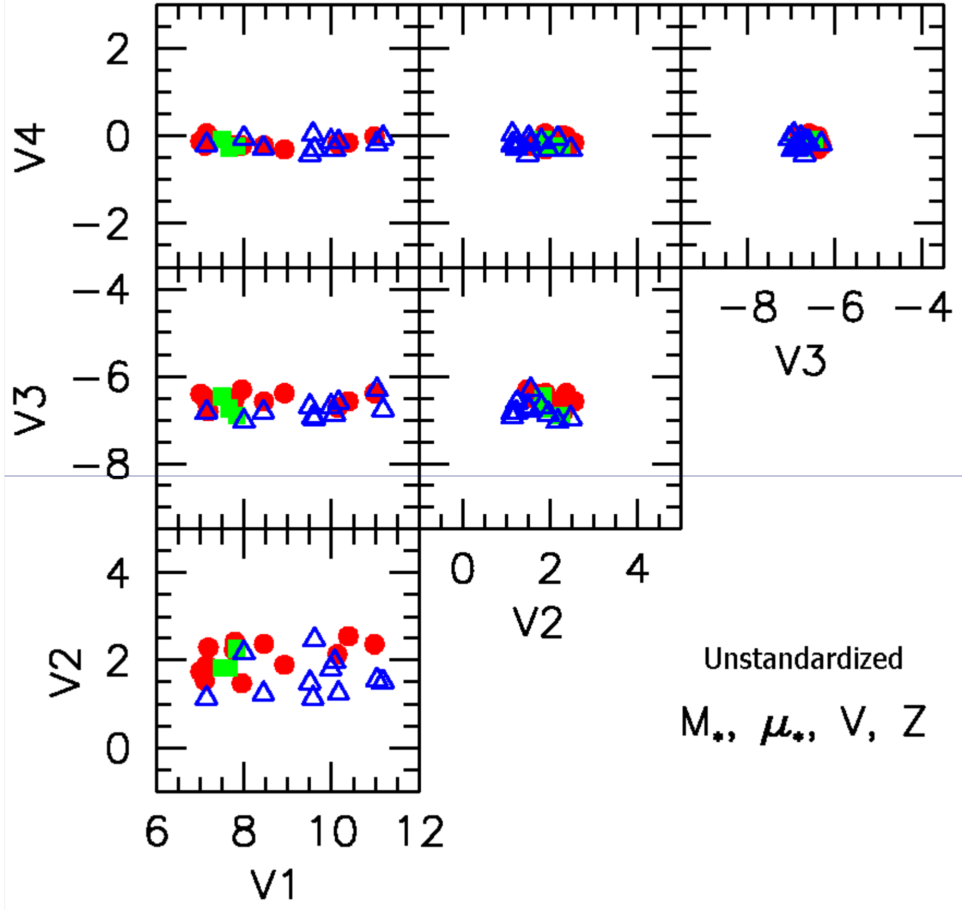
Standardized

M_*, μ_*, V

ratios of eigenvalues
→ “line” vs “plane”

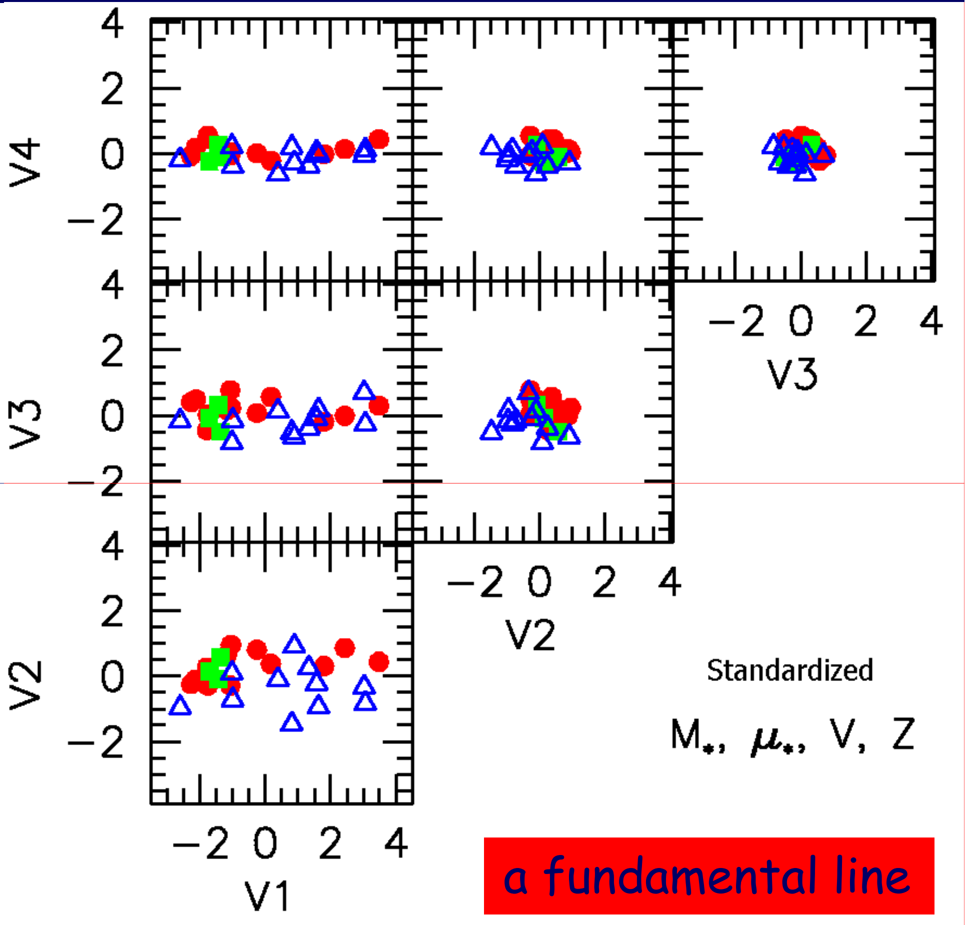
	$\log M_*$	$\log \mu_*$	$\log V$	Eigenvalue (%)
$\mathbf{V}_1$	0.60 ± 0.01	0.54 ± 0.02	0.59 ± 0.01	85.6 ± 3.2
$\mathbf{V}_2$	-0.27 ± 0.28	0.83 ± 0.80	-0.48 ± 0.46	12.1 ± 3.0
$\mathbf{V}_3$	-0.75 ± 0.74	0.13 ± 0.15	0.65 ± 0.64	2.3 ± 0.8

PCA: 3 Structure Variables + Metallicity



Unstandardized

M_*, μ_*, V, Z



Standardized

M_*, μ_*, V, Z

a fundamental line

	$\log M_*$	$\log \mu_*$	$\log V$	$\log Z$	Eigenvalue (%)
$\mathbf{V}_1$	0.83 ± 0.03	0.43 ± 0.06	0.20 ± 0.02	0.29 ± 0.03	88.5 ± 2.3
$\mathbf{V}_2$	-0.47 ± 0.07	0.84 ± 0.05	-0.14 ± 0.06	0.23 ± 0.12	8.9 ± 2.0
$\mathbf{V}_3$	-0.14 ± 0.08	-0.34 ± 0.11	0.00 ± 0.19	0.93 ± 0.08	2.0 ± 0.5
$\mathbf{V}_4$	-0.24 ± 0.05	0.03 ± 0.08	0.97 ± 0.06	-0.02 ± 0.18	0.7 ± 0.2

	$\log M_*$	$\log \mu_*$	$\log V$	$\log Z$	Eigenvalue (%)
$\mathbf{V}_1$	0.52 ± 0.01	0.48 ± 0.01	0.50 ± 0.01	0.50 ± 0.01	83.7 ± 3.6
$\mathbf{V}_2$	-0.36 ± 0.35	0.65 ± 0.67	-0.58 ± 0.55	0.33 ± 0.32	10.1 ± 2.7
$\mathbf{V}_3$	-0.08 ± 0.23	-0.58 ± 0.20	-0.16 ± 0.24	0.79 ± 0.16	4.3 ± 1.3
$\mathbf{V}_4$	-0.77 ± 0.67	0.08 ± 0.19	0.63 ± 0.55	0.10 ± 0.23	1.9 ± 0.6

2. Origin of Scaling Relations:

virial theorem & spherical halo collapse

angular momentum

feedback

Bright Galaxies

- virial halo

  top hat

$$V^2 \propto \frac{GM}{R} \qquad \frac{M}{R^3} \propto 200\rho_u \qquad \rightarrow \quad M \propto V^3 \propto R^3$$

initial

- $M_* \propto M_{\rm gas} \propto f_{\rm bar} M$

$$\rightarrow \quad M_* \propto V^3$$

spin

- disk size $R_* \approx \lambda R$ $\quad \lambda \approx \text{const.}$

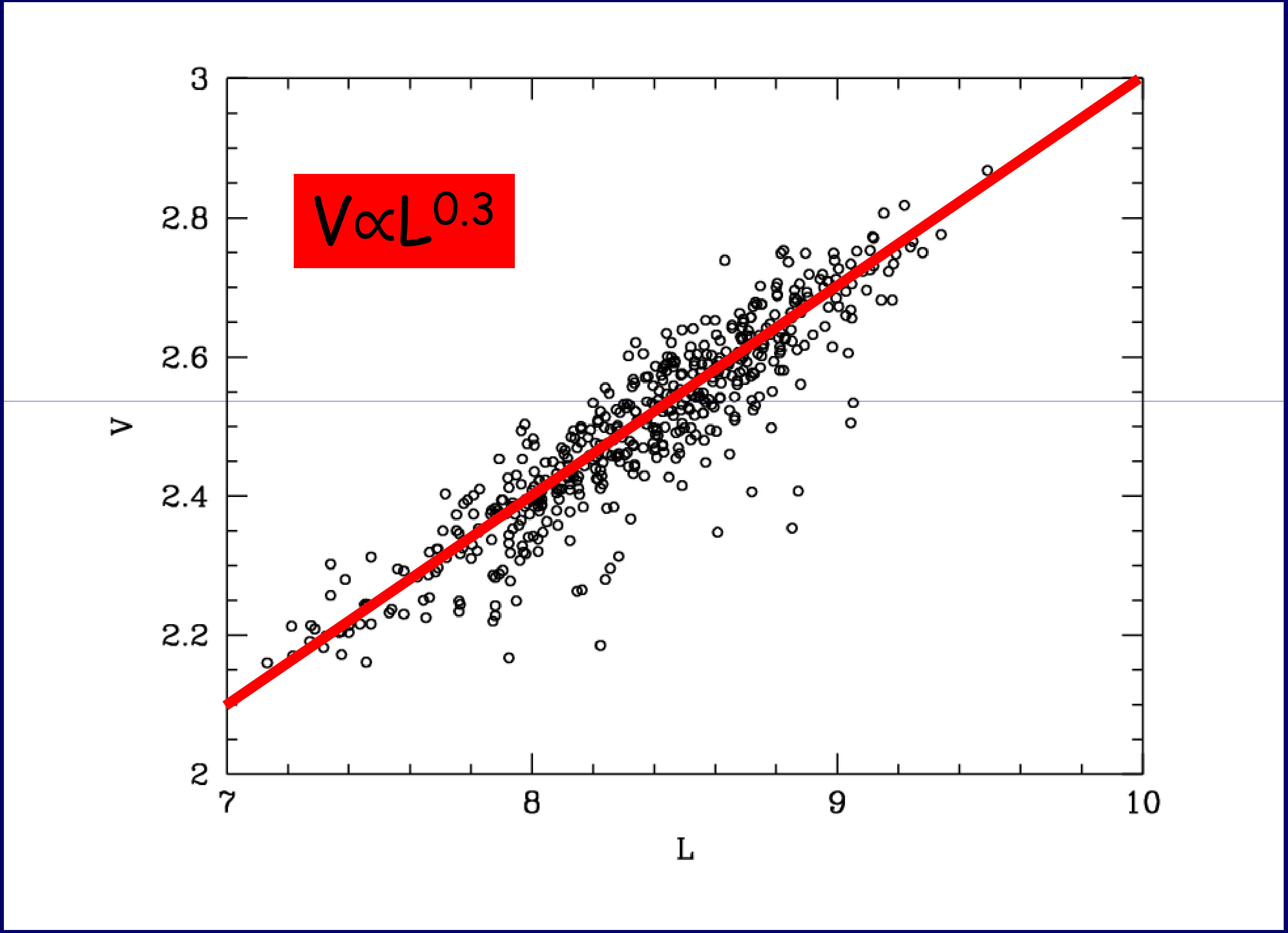
$$\mu_* \propto M_* / R_*^{\,2} \propto \lambda^{-2} M_*^{\,1/3}$$

$$\rightarrow \quad \mu_* \propto M_*^{\,1/3}$$

- $Z \propto M_* / M_{\rm gas}$

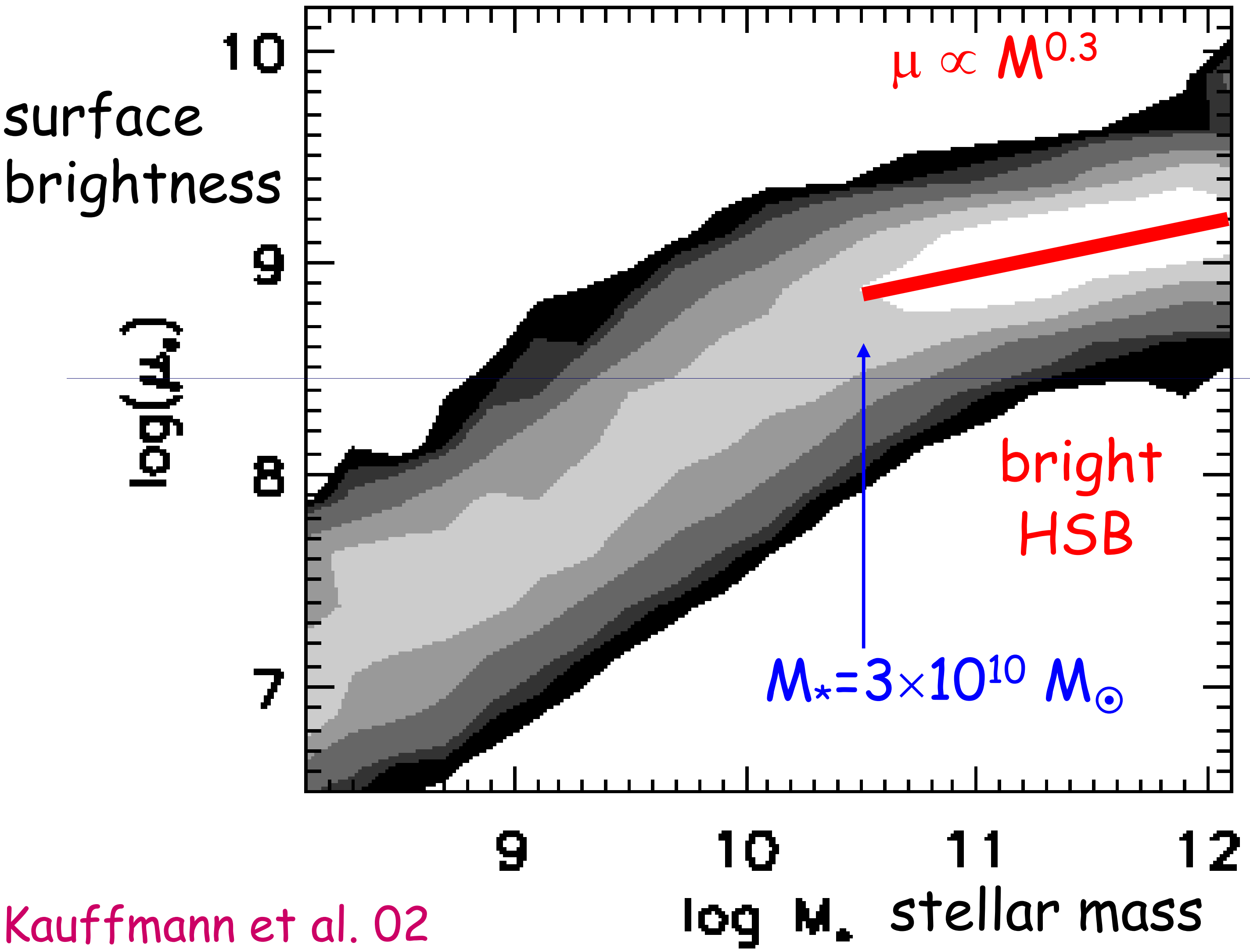
$$\rightarrow \quad Z \propto \text{const.}$$

Bright Galaxies: Tully Fisher Relation



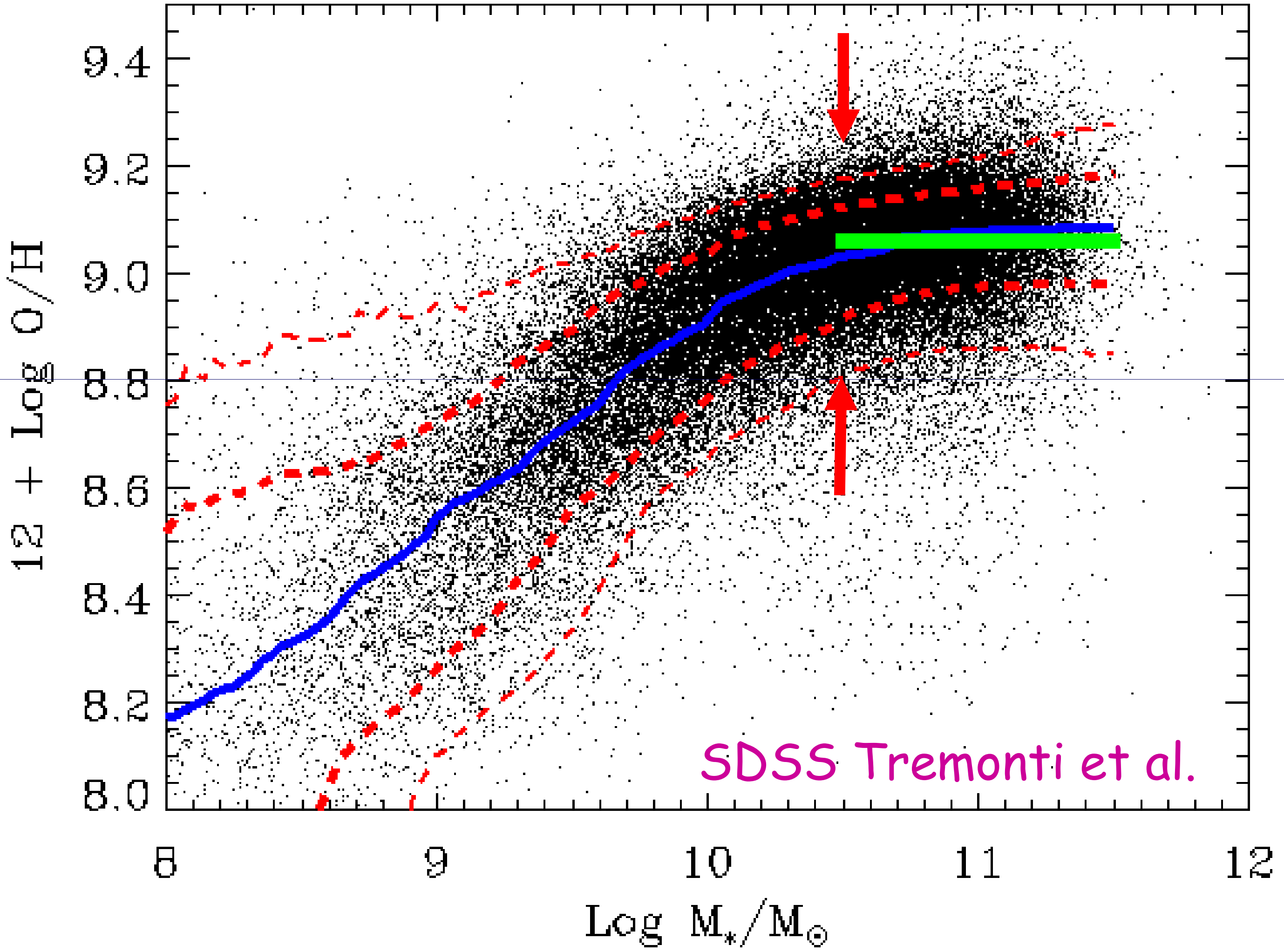
Courteau et al. 04

Surface Brightness: SDSS



Kauffmann et al. 02

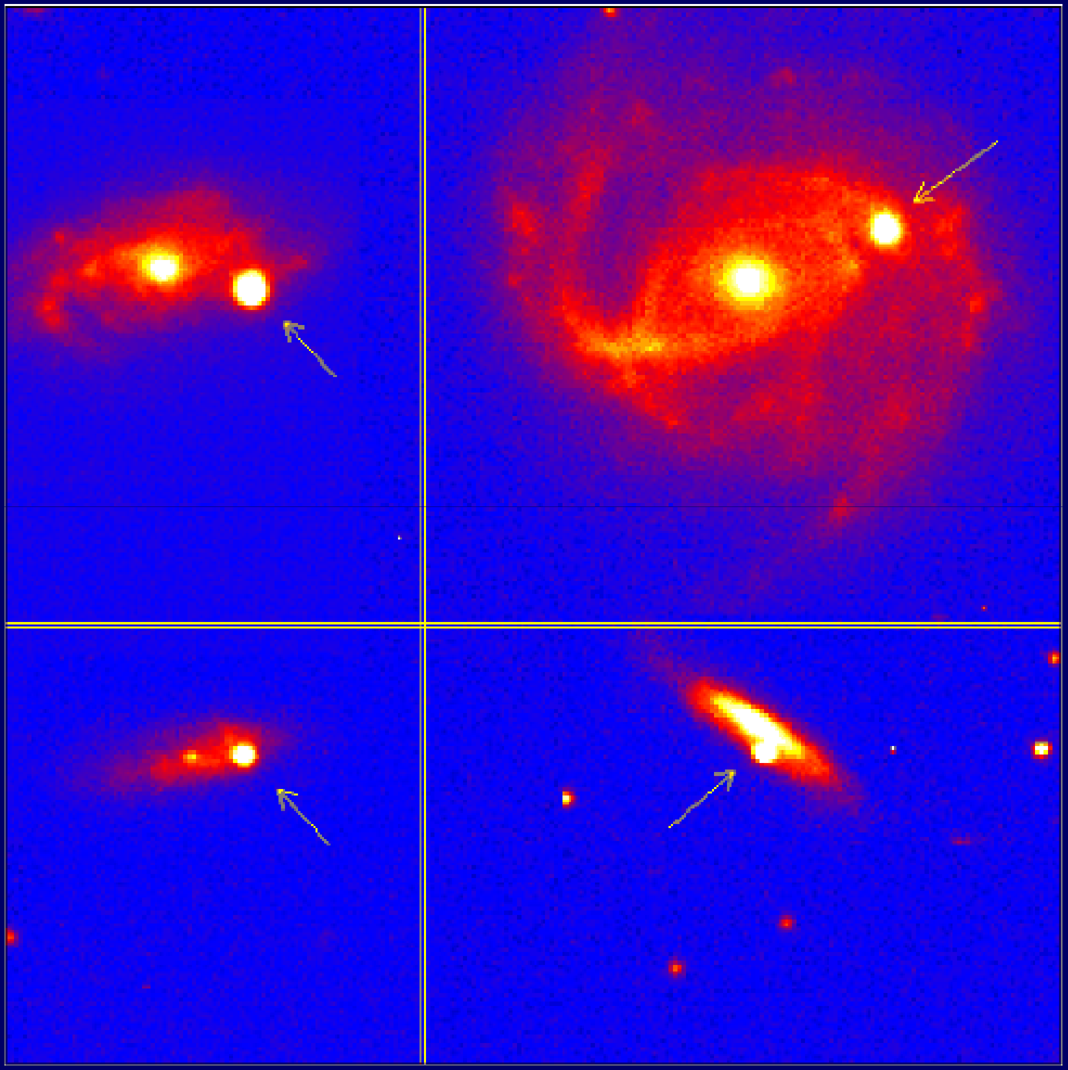
Metallicity SDSS



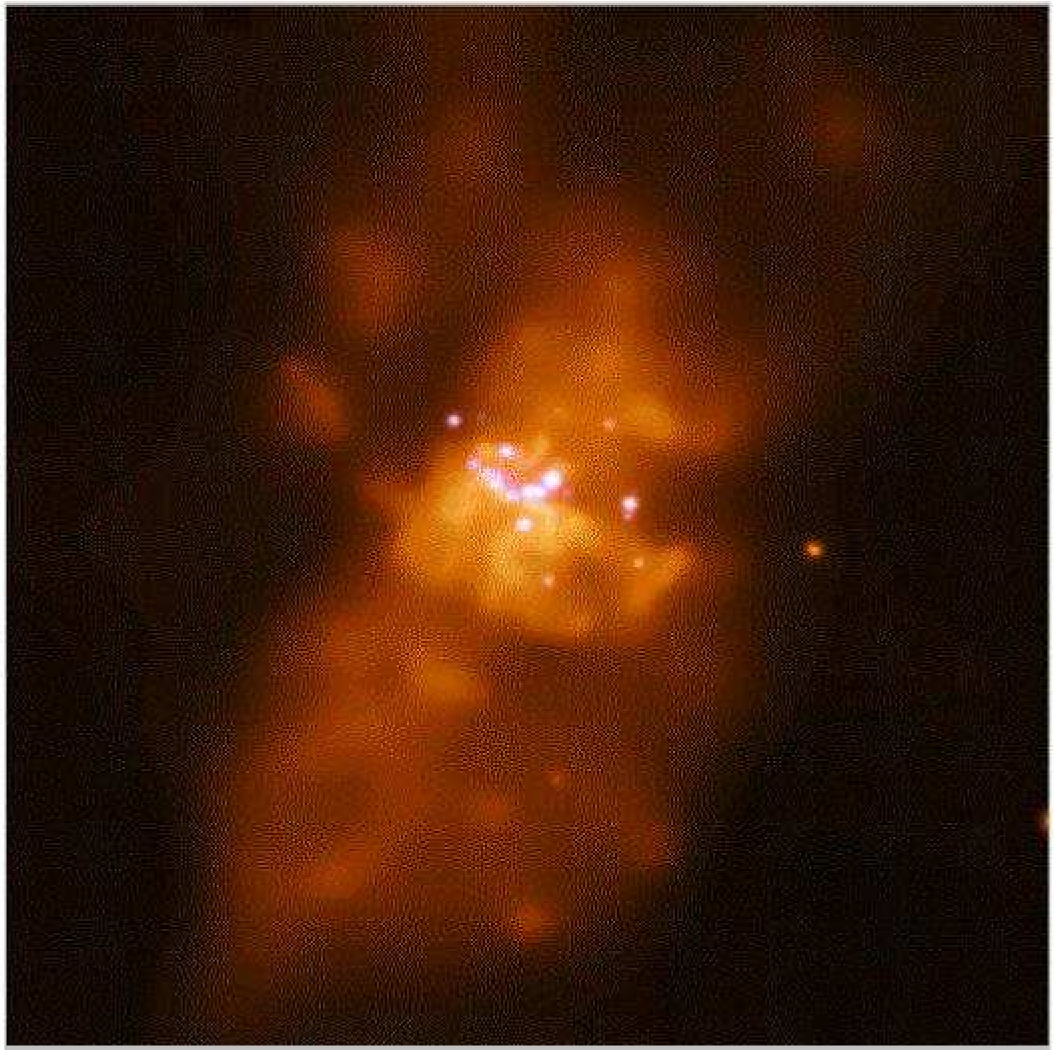
Supernova Feedback

Dekel & Silk 86
Dekel & Woo 03

Much energy in SNe



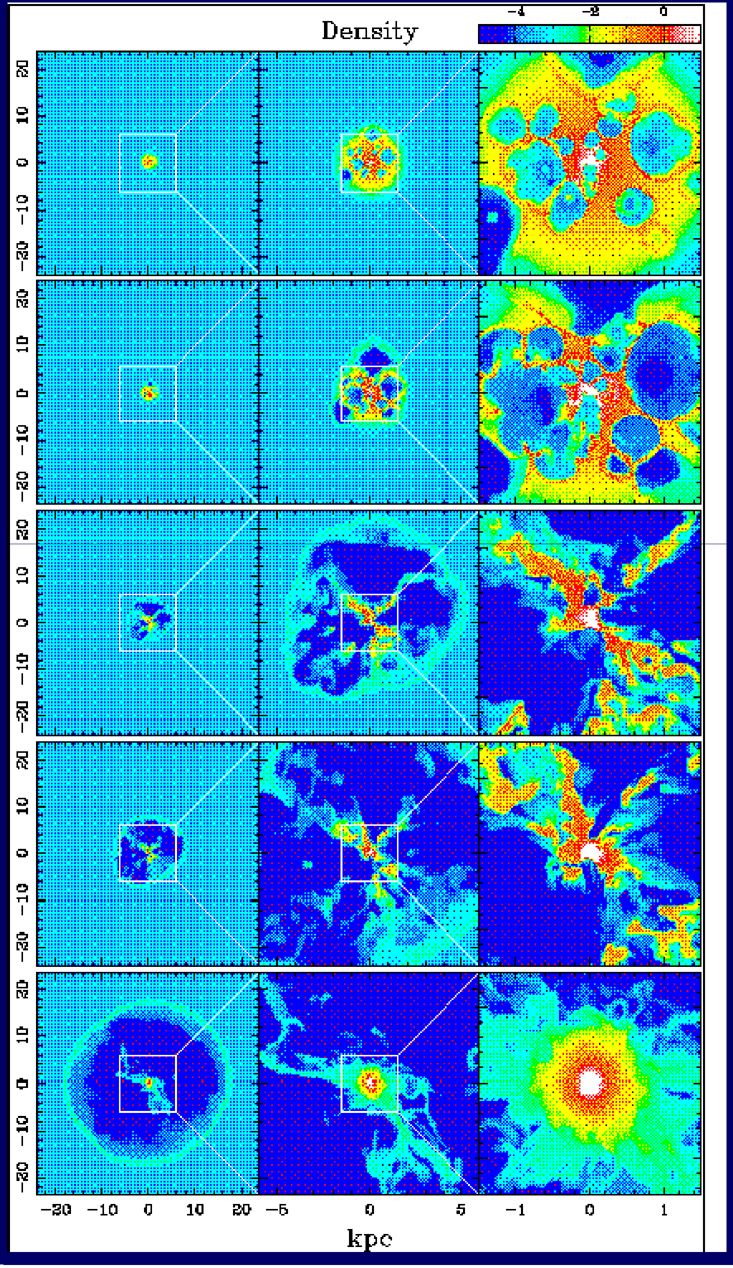
Galactic wind M82



Chandra X-Ray Observatory image of M82

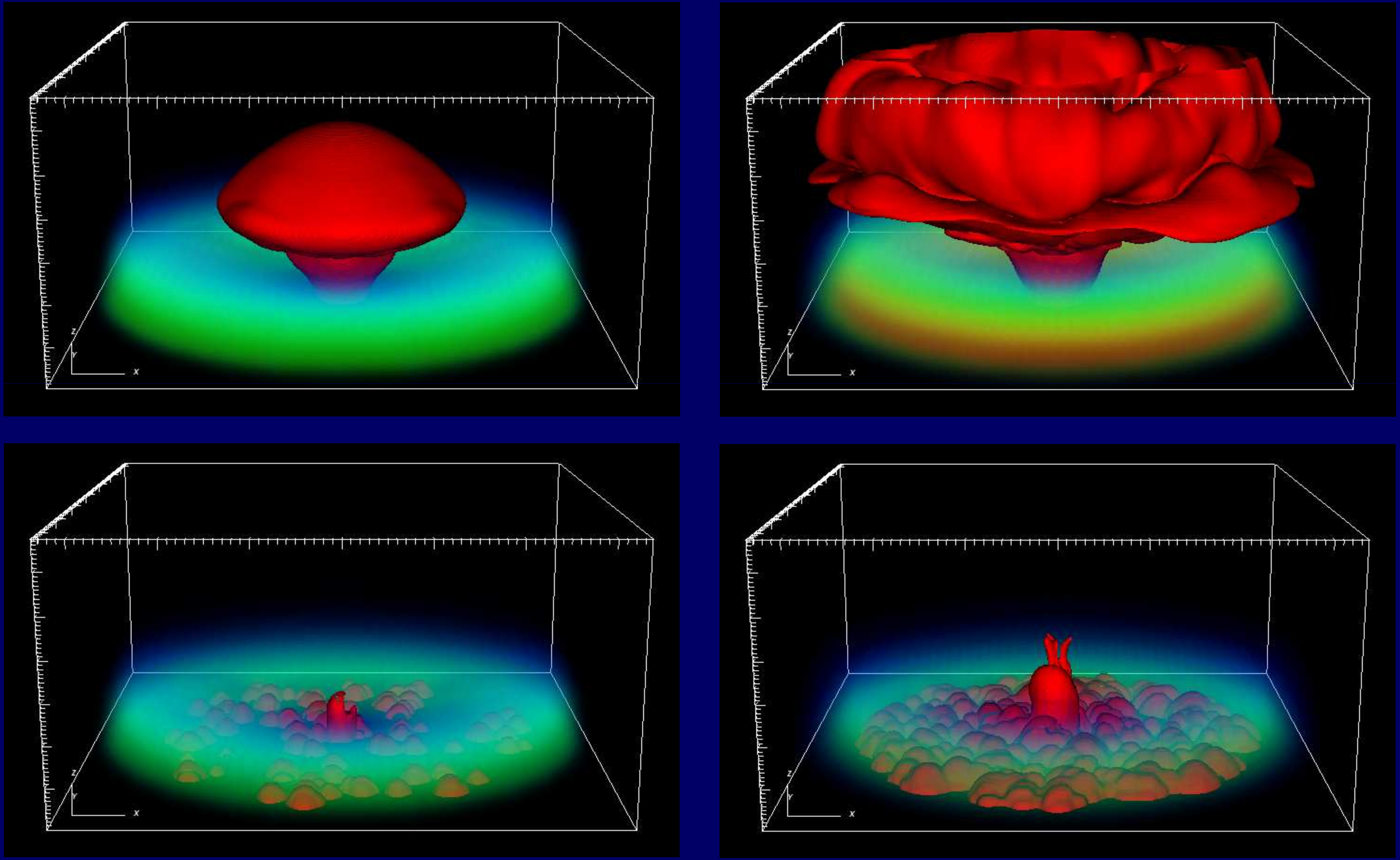
Simulation of supernova blowout

time



Mori et al.

Supernova Feedback



Fragile, Murray, Lin 04

Supernova Feedback Scale

(Dekel & Silk 86)

Energy fed to the ISM during the “adiabatic” phase:

$$E_{\rm SN} \approx \nu\varepsilon \dot{M}_* \, t_{\rm rad} \quad \propto M_* (t_{\rm rad}/t_{\rm ff})$$

$$\dot{M}_* \approx M_*/t_{\rm ff}$$

$$\approx 0.01$$

for $\Lambda \propto T^{-1}$ at $T \sim 10^5 K$

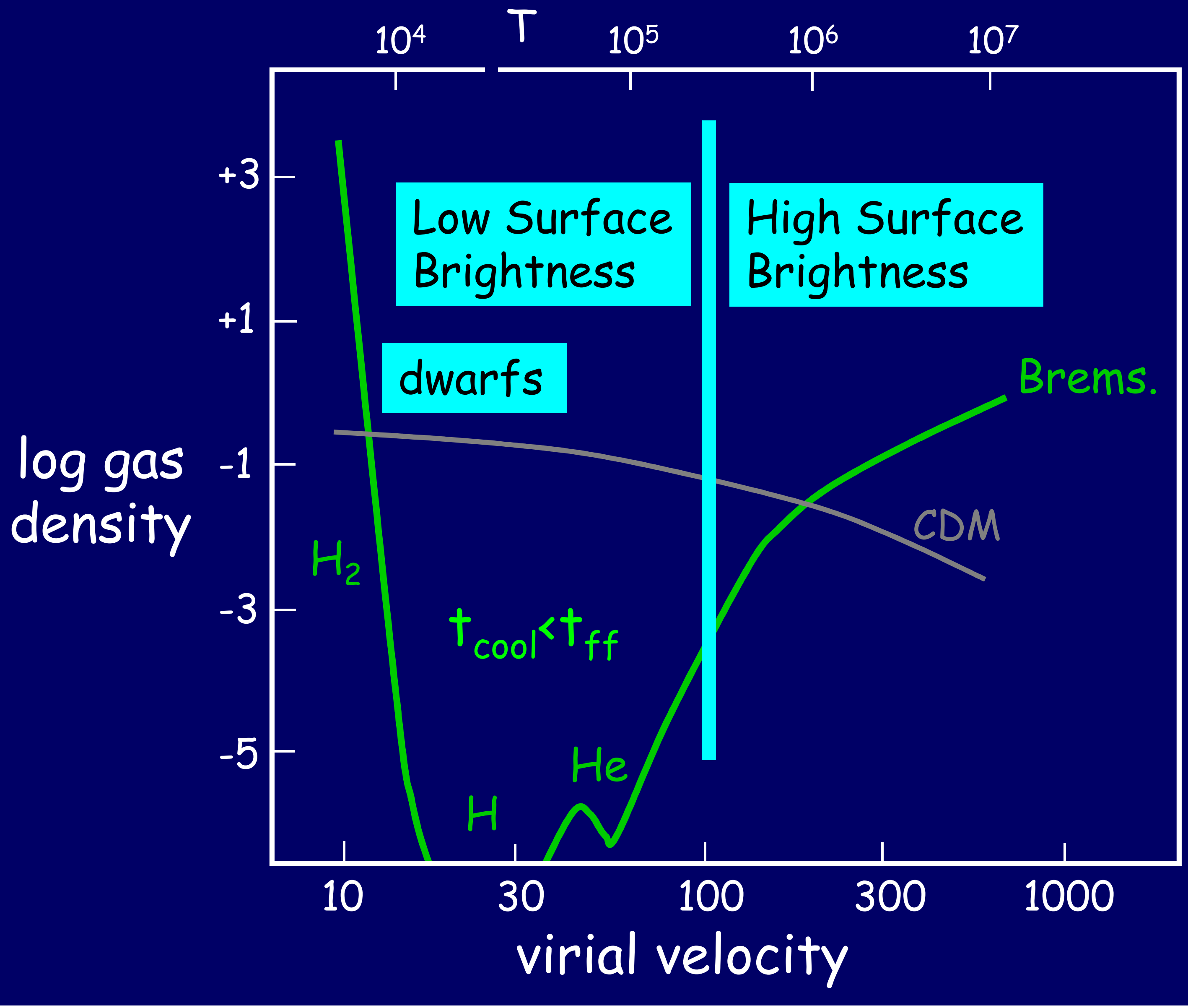
Energy required for blowout:

$$E_{\rm SN} \approx M_{\rm gas} V^2$$

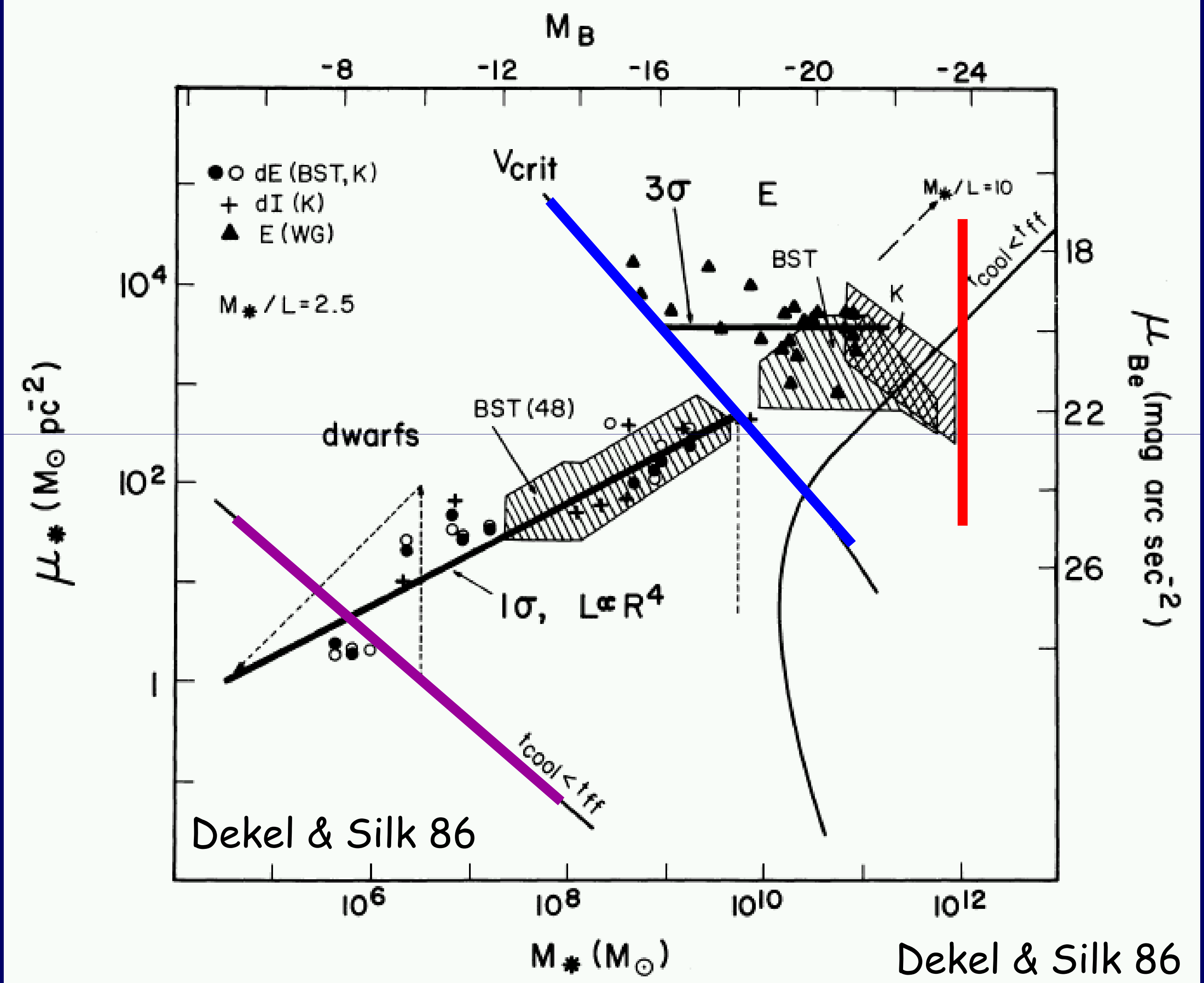
$$\rightarrow \quad V_{\rm crit} \approx 100 \text{ km/s} \quad \rightarrow \quad M_{*\rm crit} \approx 3\times 10^{10} M_{\circ}$$

Supernova Feedback Scale

Dekel & Silk 86



LSB vs HSB



Dekel & Silk 86

Model: fundamental line of LSB/Dwarfs

(Dekel & Woo 03)

- Energy: $E_{\rm SN} \propto M_* \propto M_{\rm gas} V^2$
- Virial halo: $V^3 \propto M \propto R^3$

$M_* / M_{gas} \propto V^2$

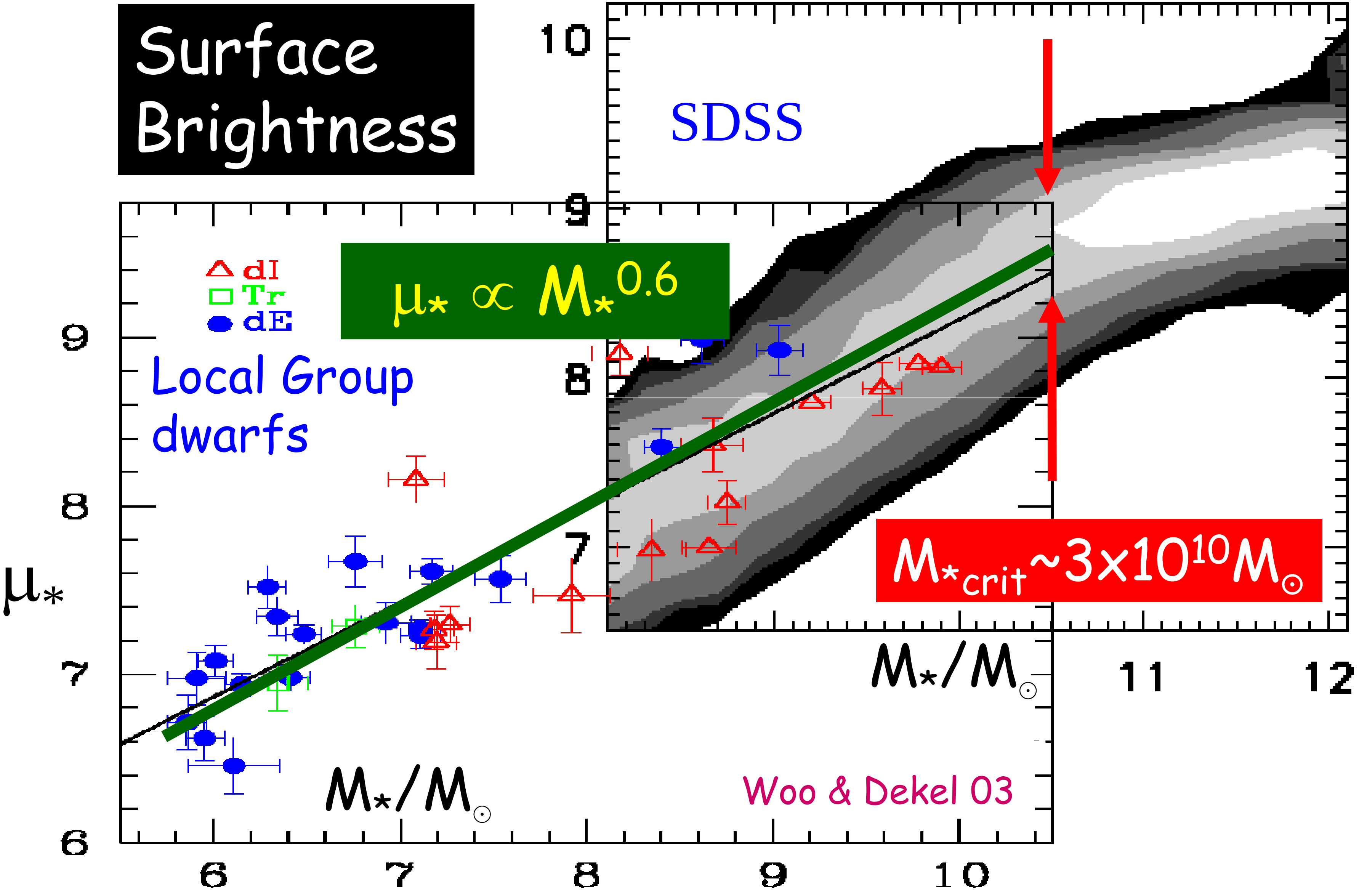
$<<1$

$\longrightarrow$ $V \propto M_*^{1/5}$ "Tully Fisher"

$Z \propto M_* / M_{gas}$ $\longrightarrow$ $Z \propto M_*^{2/5}$ metallicity

$R_* \approx \lambda R$ $\longrightarrow$ $\mu \propto \lambda^{-2} M_*^{3/5}$ surface brightness

The “Fundamental Line” of LSB/Dwarfs



Surface Brightness

$\mu_* \propto M_*^{0.6}$

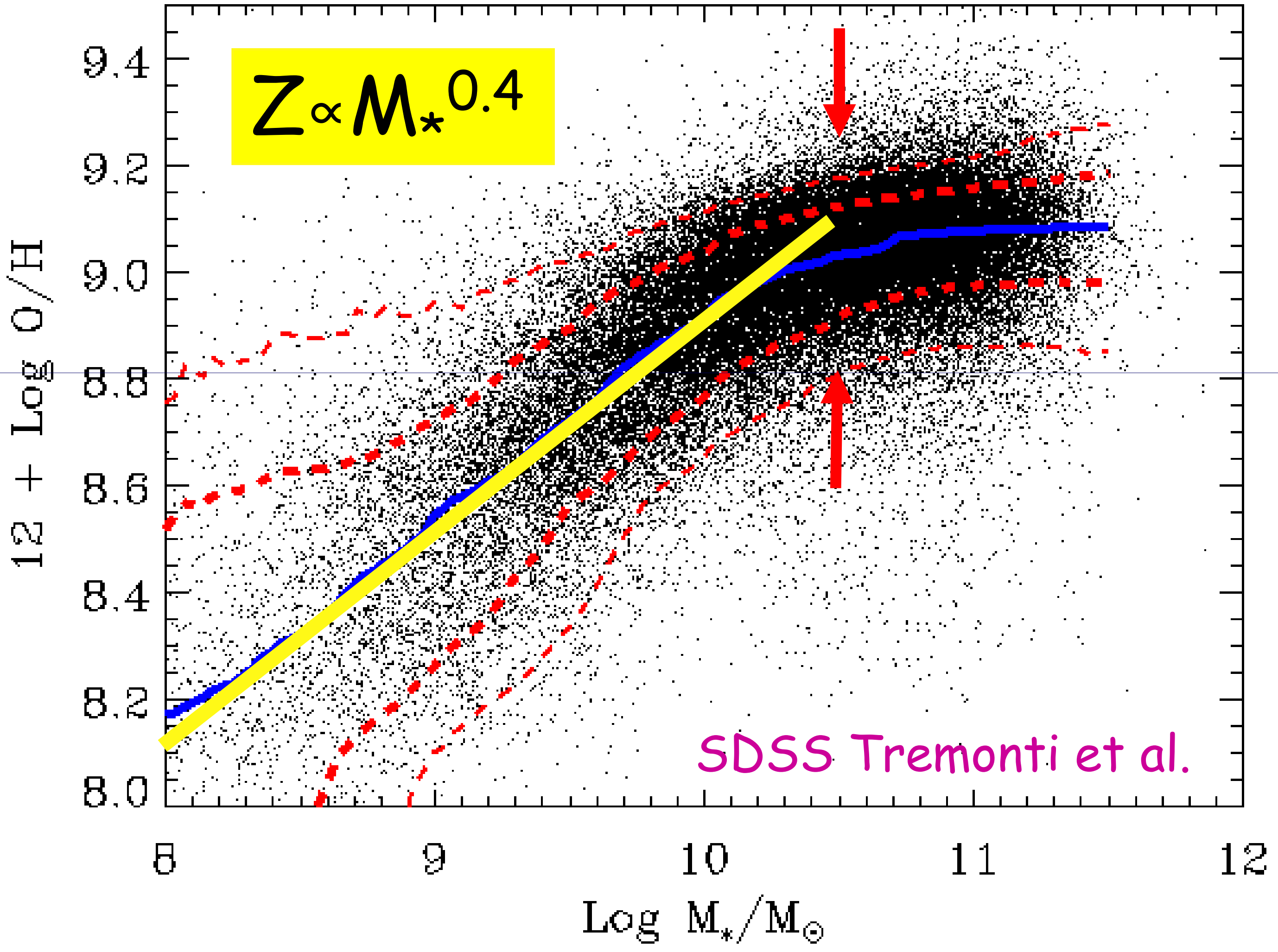
SDSS

Local Group dwarfs

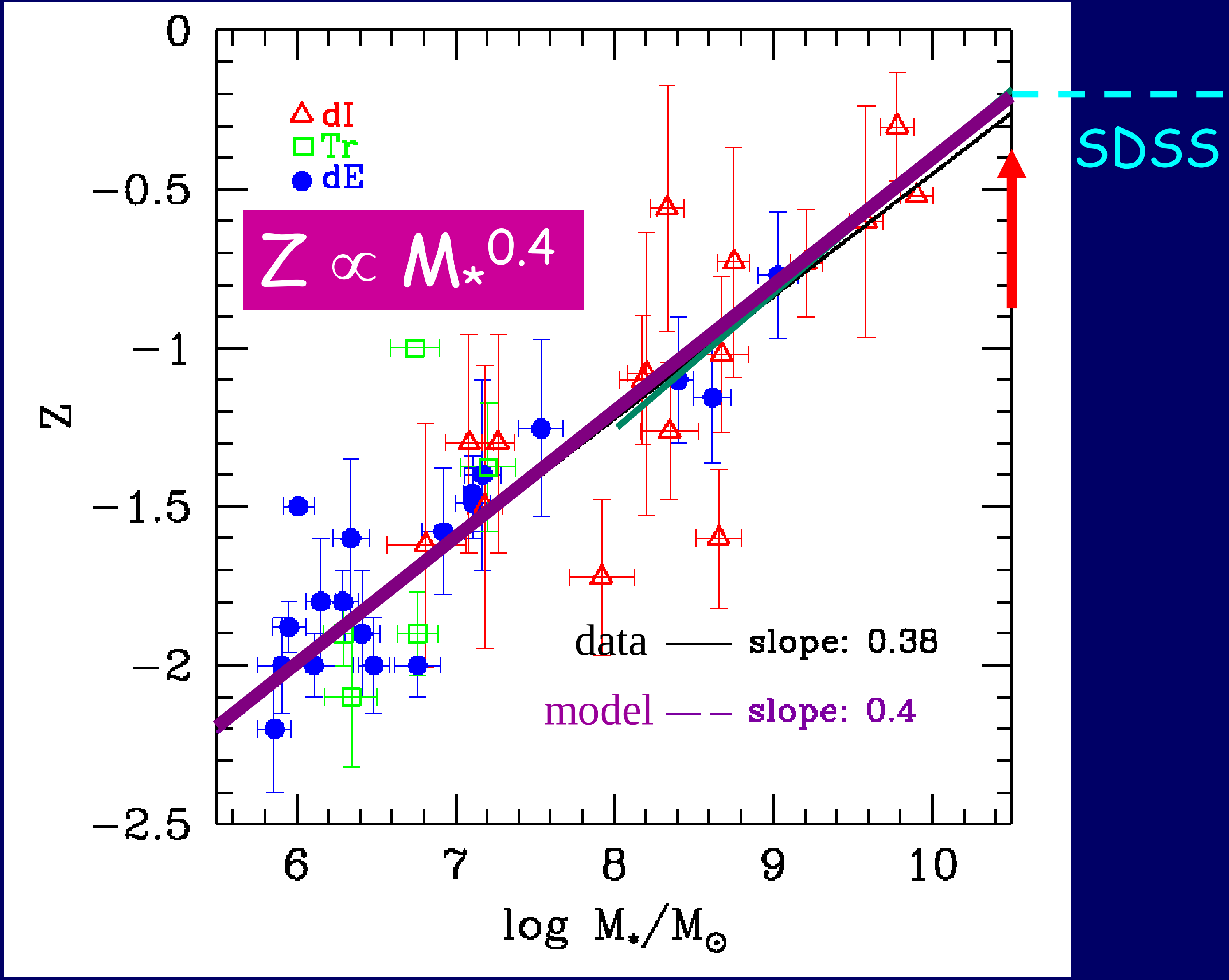
$M_{*crit} \sim 3 \times 10^{10} M_\odot$

Woo & Dekel 03

Metallicity

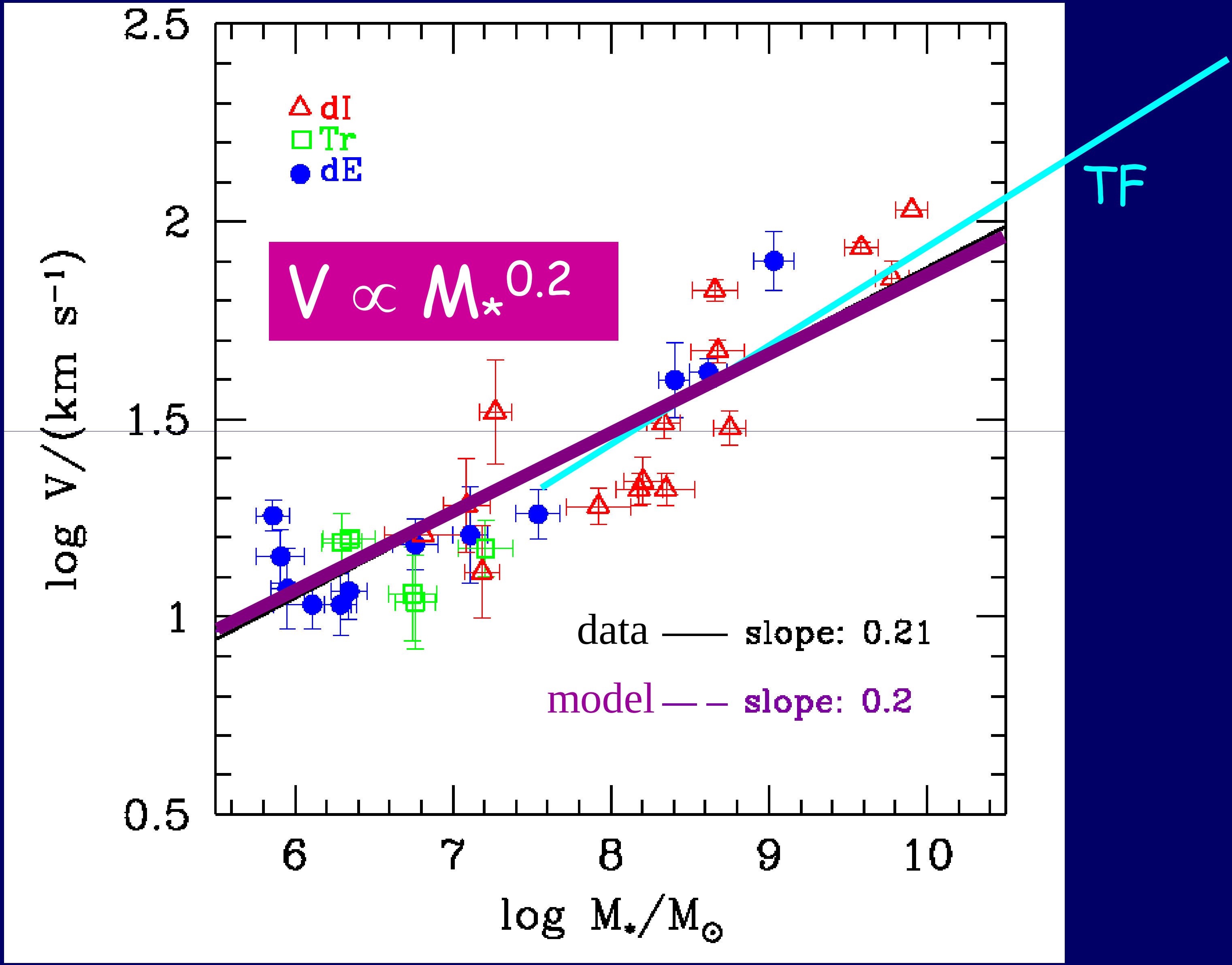


Local Group Dwarfs: Metallicity



$Z \propto M_*^{0.4}$

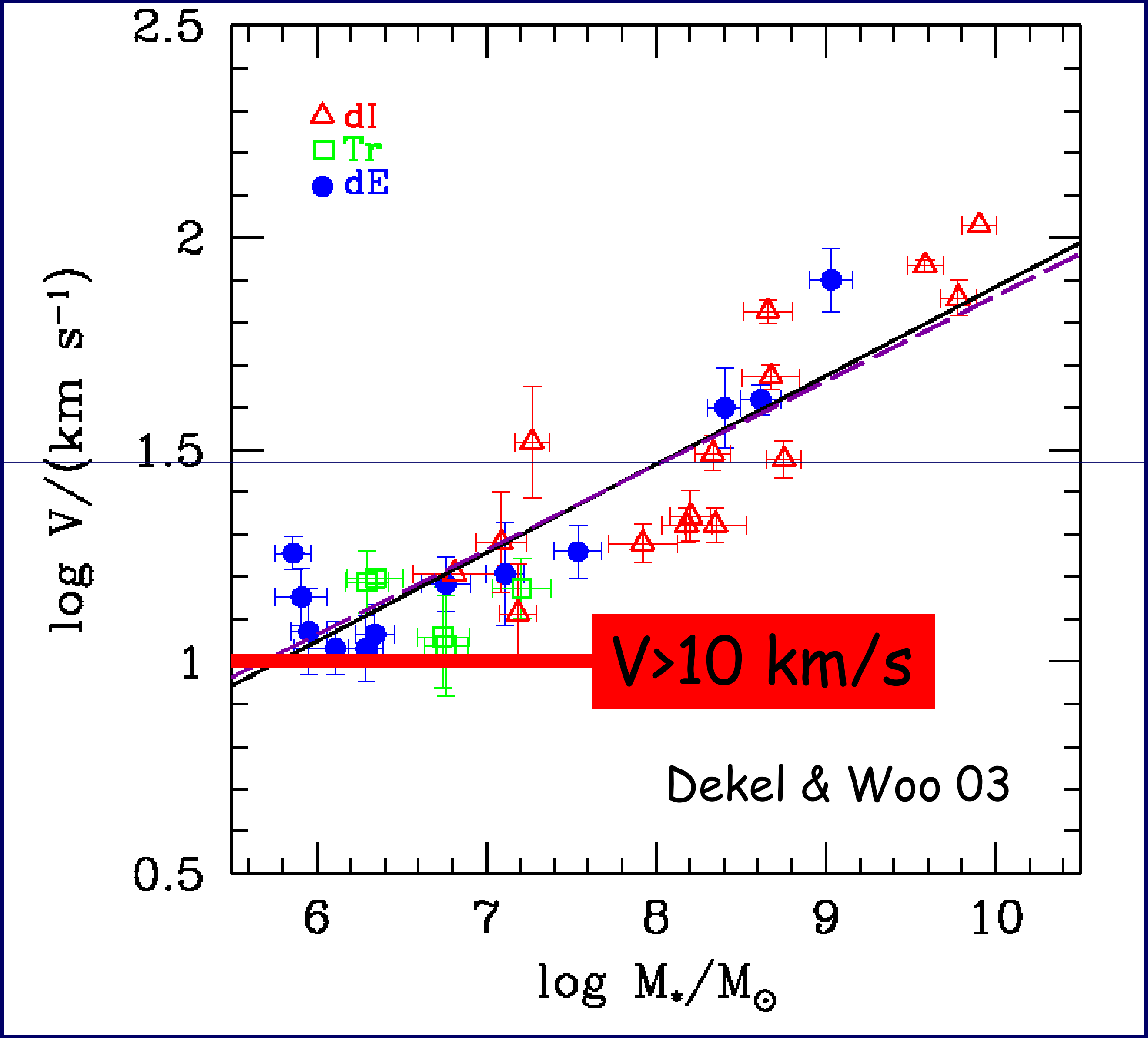
LG Dwarfs: Velocity



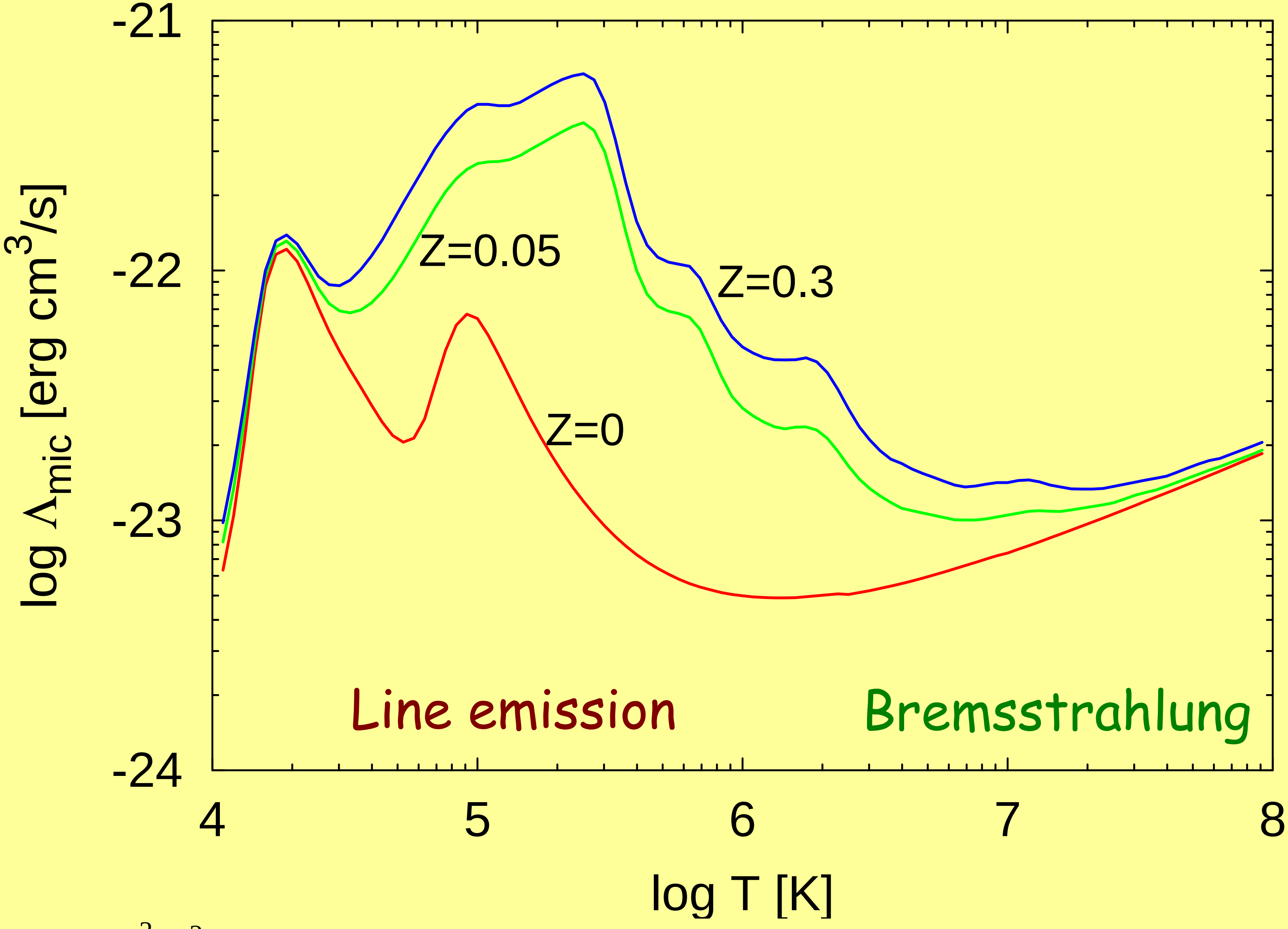
Summary: SN feedback

Could be responsible for the transition scale at $M_*=3\times10^{10}$, and the "fundamental line" of LSB/dwarf galaxies, $M^*/M \propto V^2$.

A lower bound for galaxies



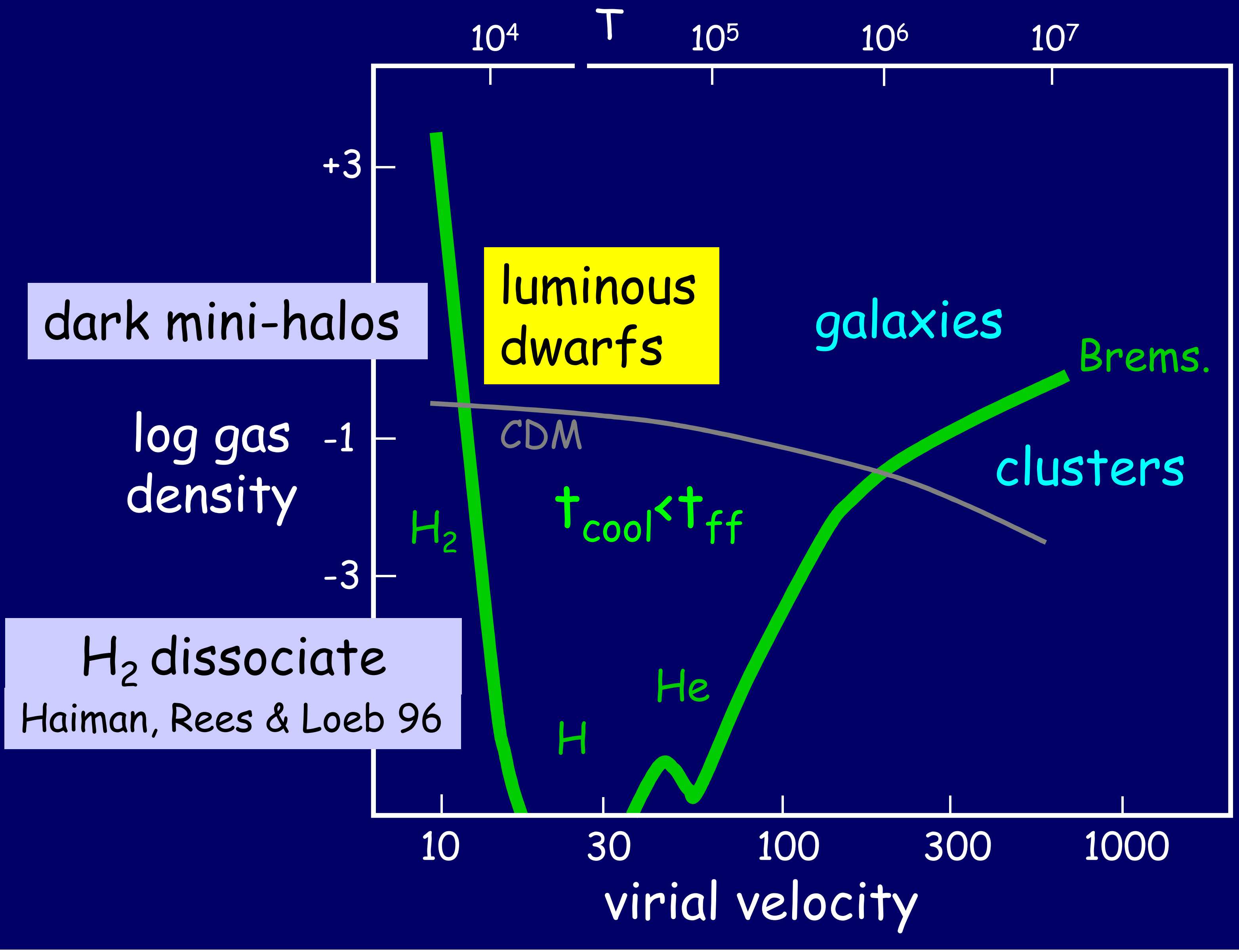
Cooling rate



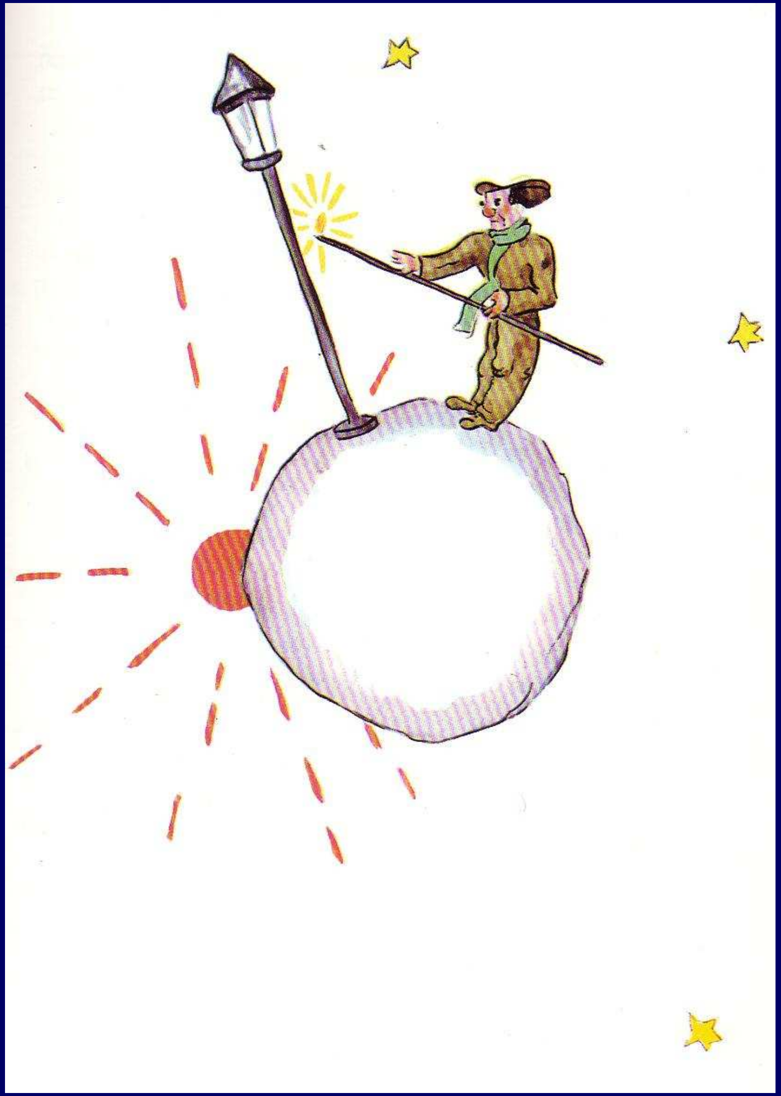
$q = \frac{N_A{}^2 \chi^2}{\mu^2} \Lambda(T) \rho$ [erg g^{-1} s^{-1}] N_A / μ molecules per g χ e$^-$ per particle

The Cooling Barrier

Rees & Ostriker 77, Silk 77, White & Rees 78



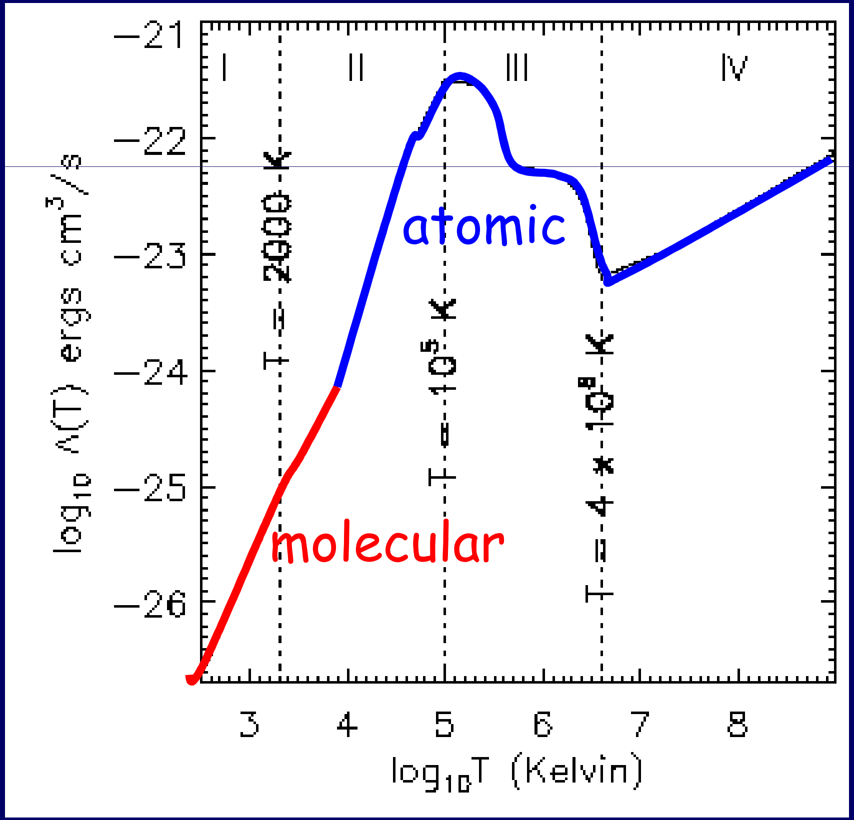
It isn't that simple to turn on the light

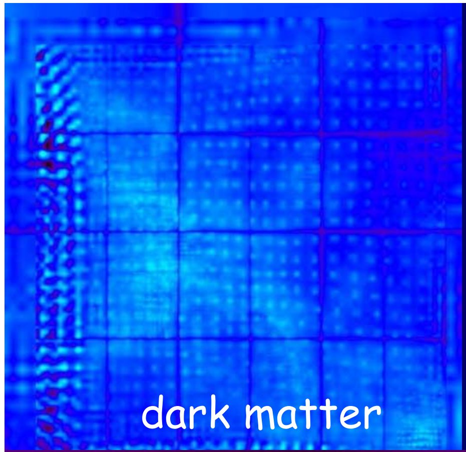


Cosmological hydro simulations of high-z dwarfs
Slyz & Devriendt

- molecular cooling below 10^4K

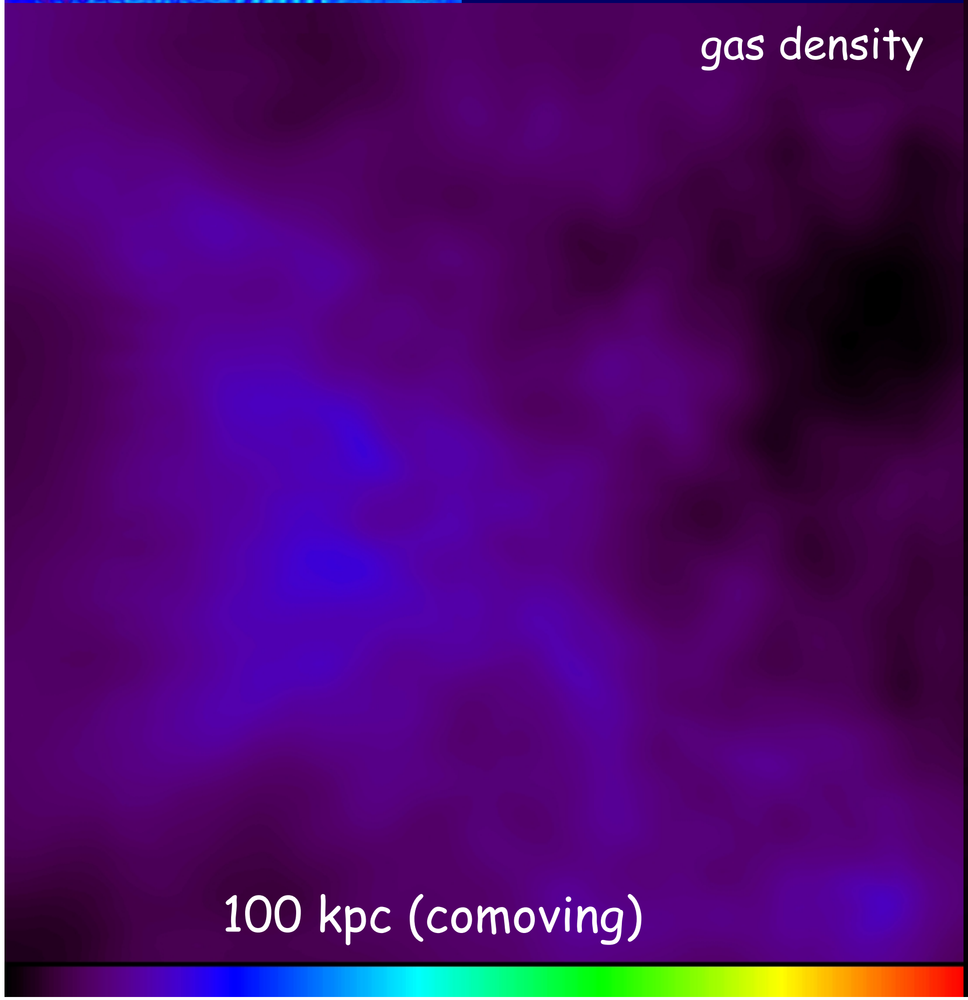
- star formation and supernova feedback

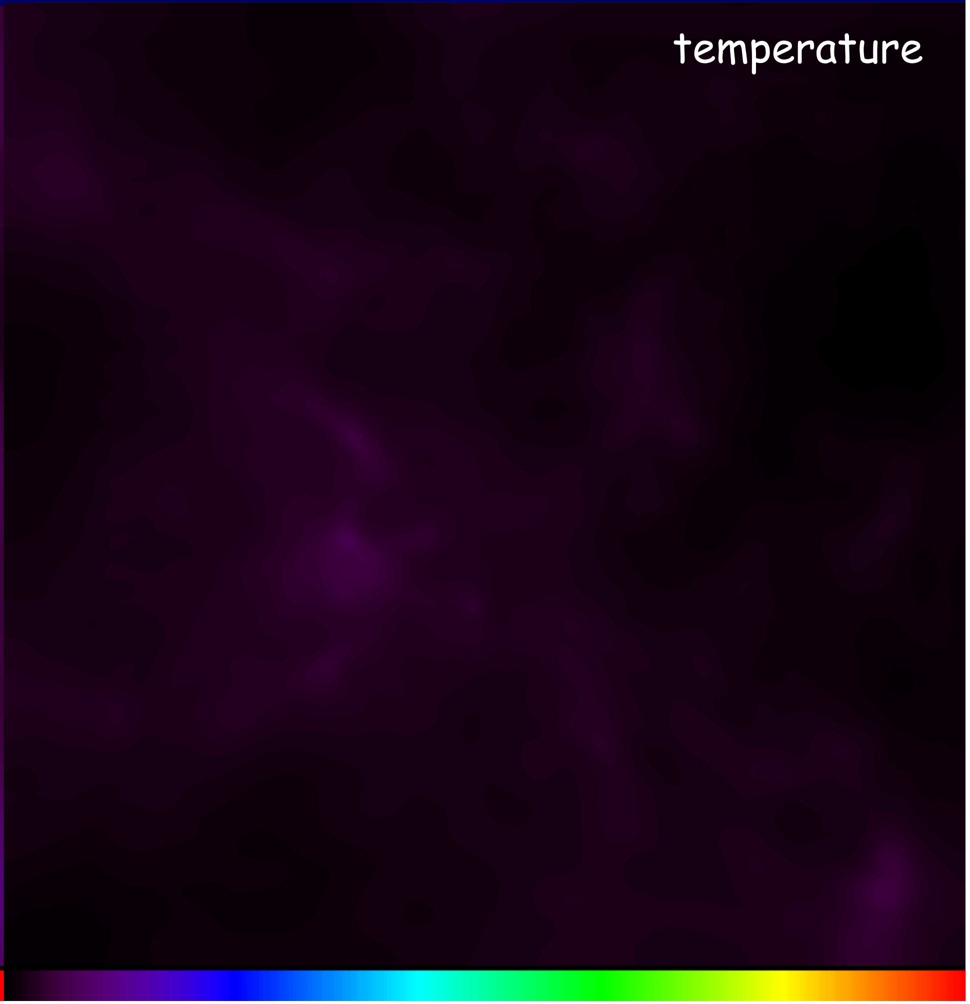


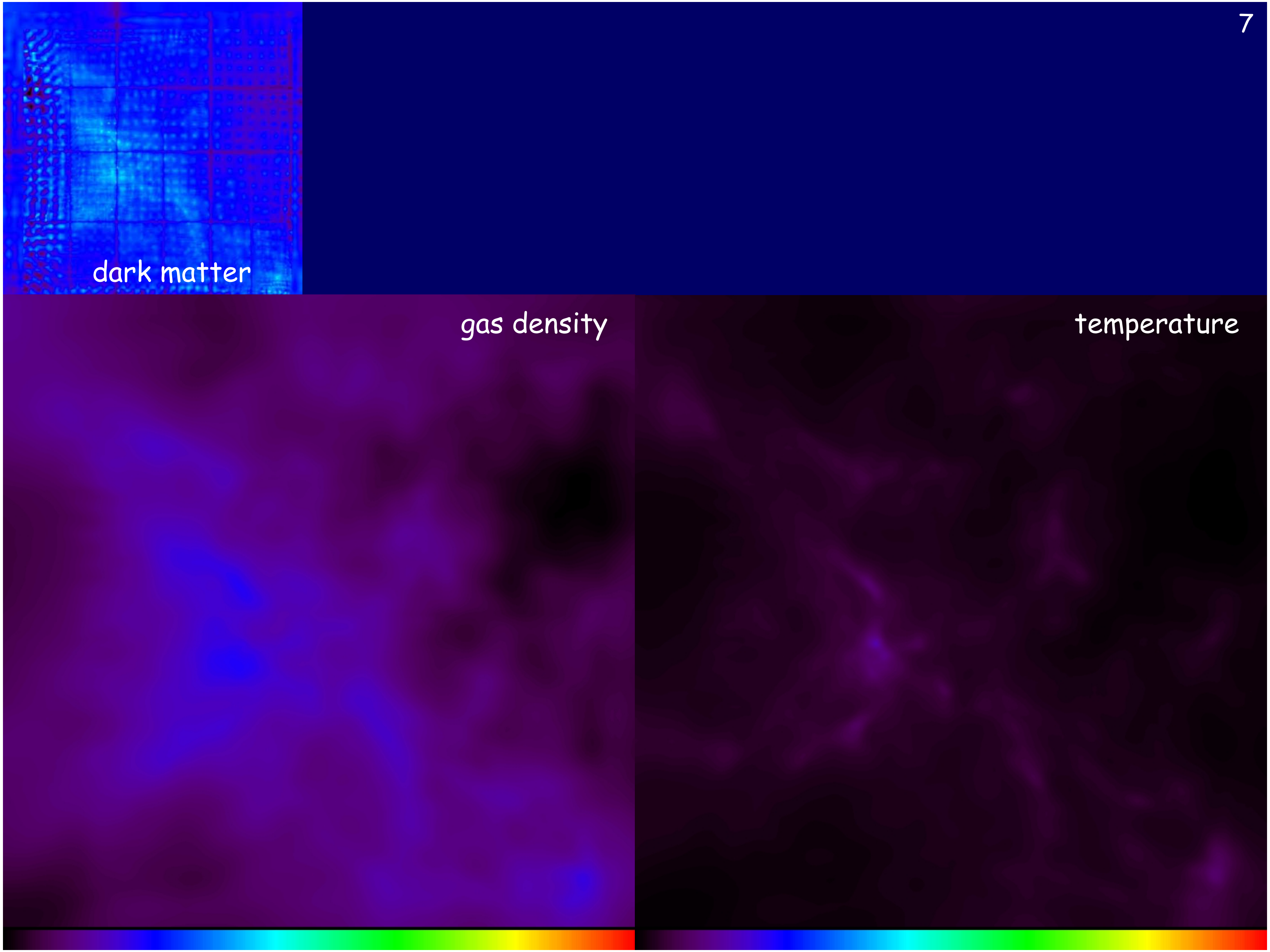


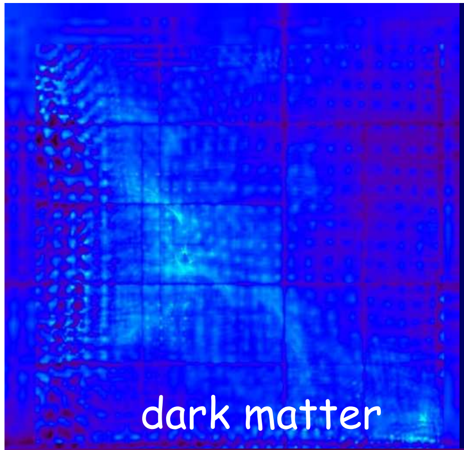
Cosmological hydro simulations
Slyz & Devriendt 2005

z~50

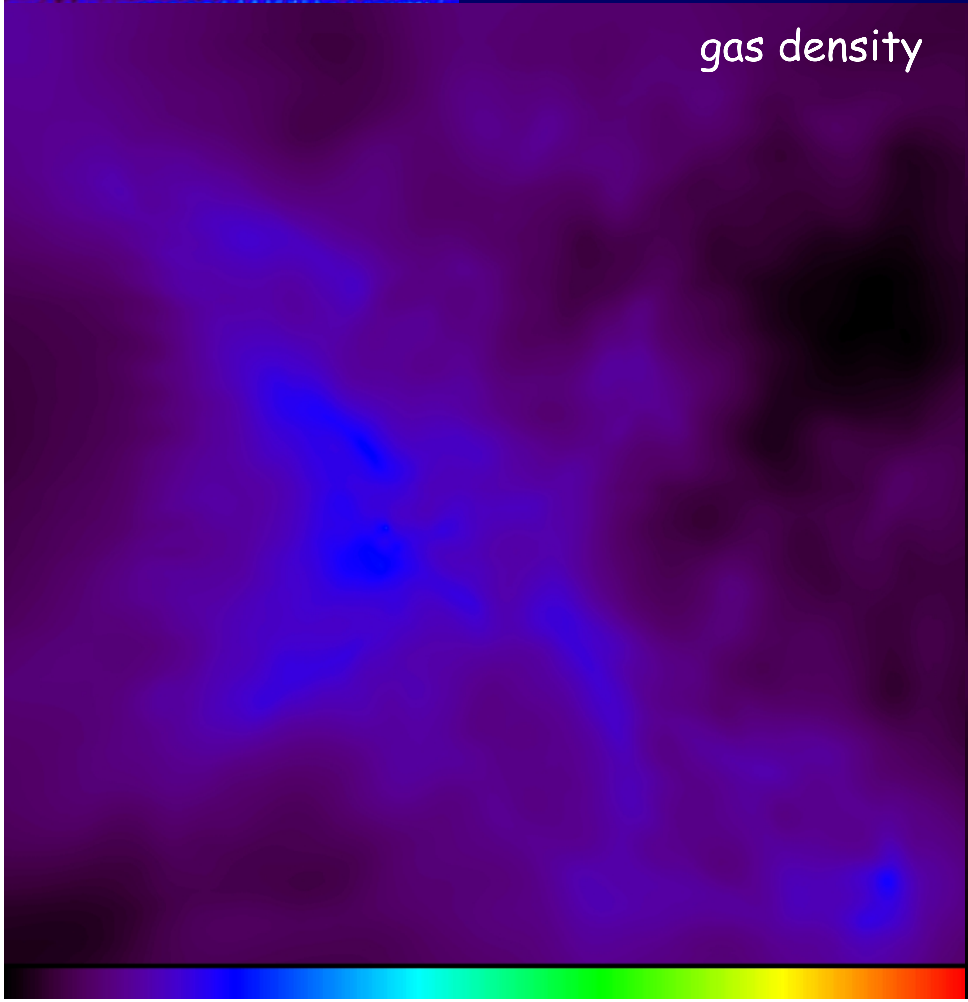




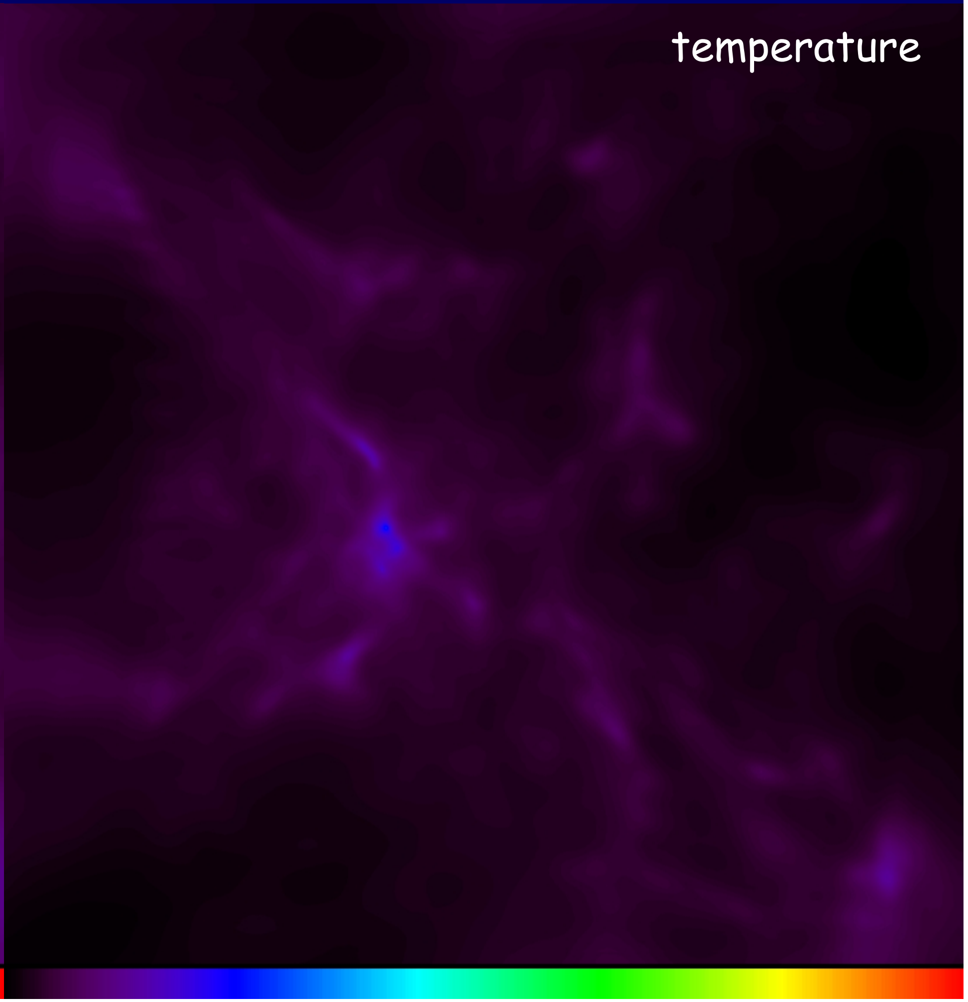

dark matter
gas density
temperature



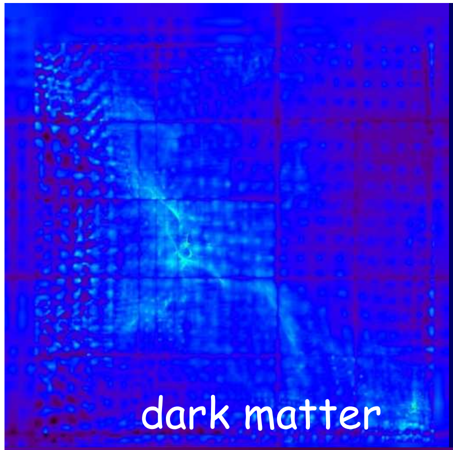
dark matter

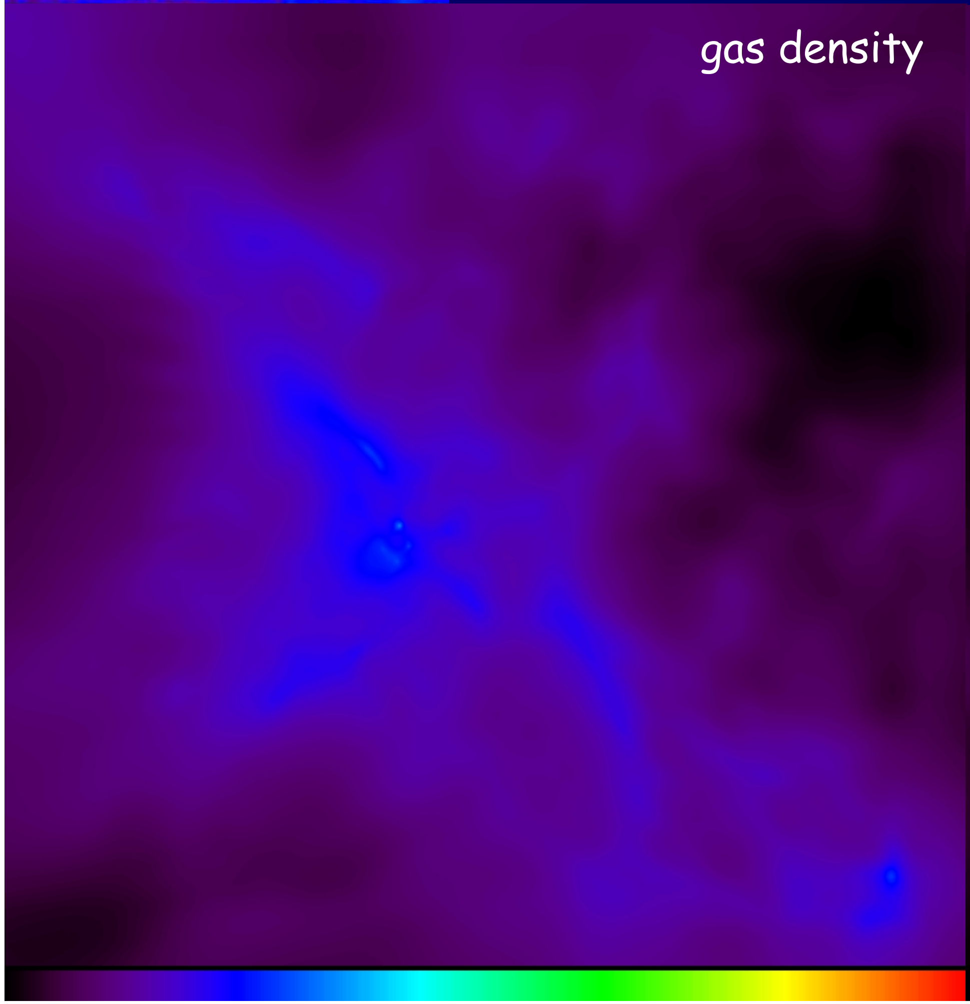


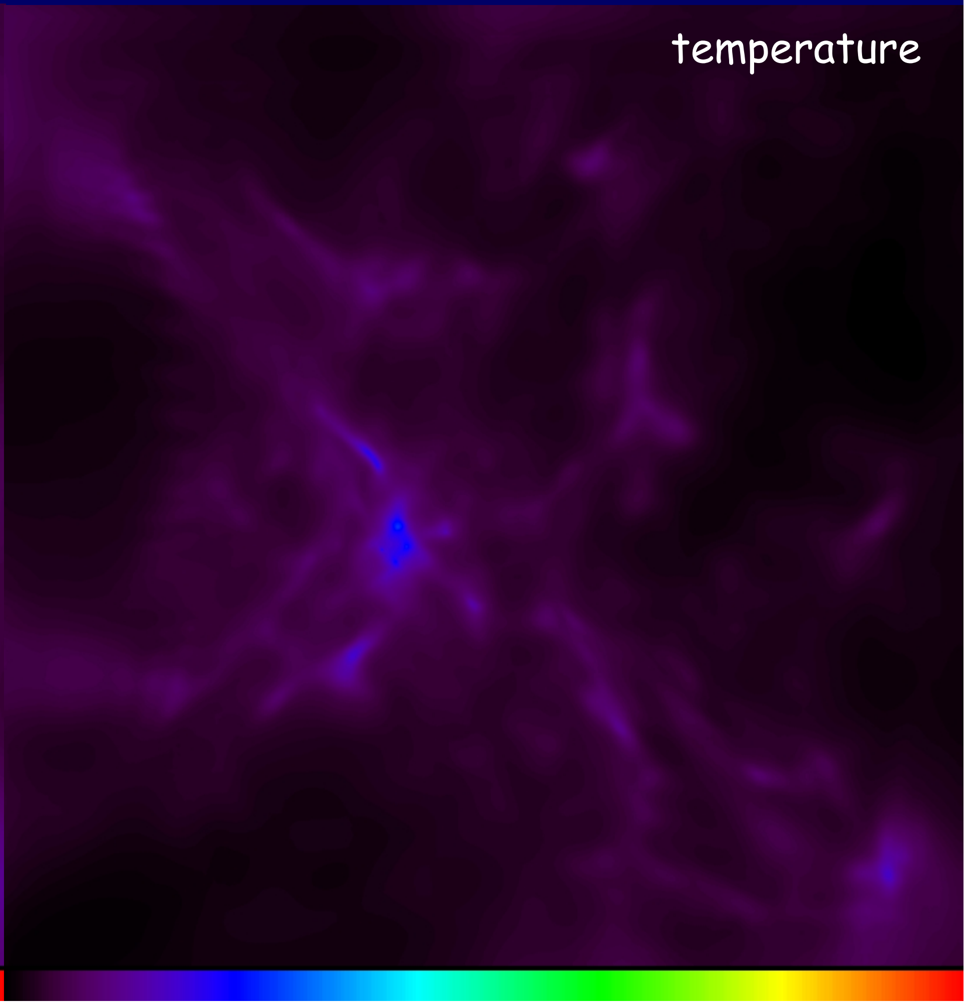
gas density

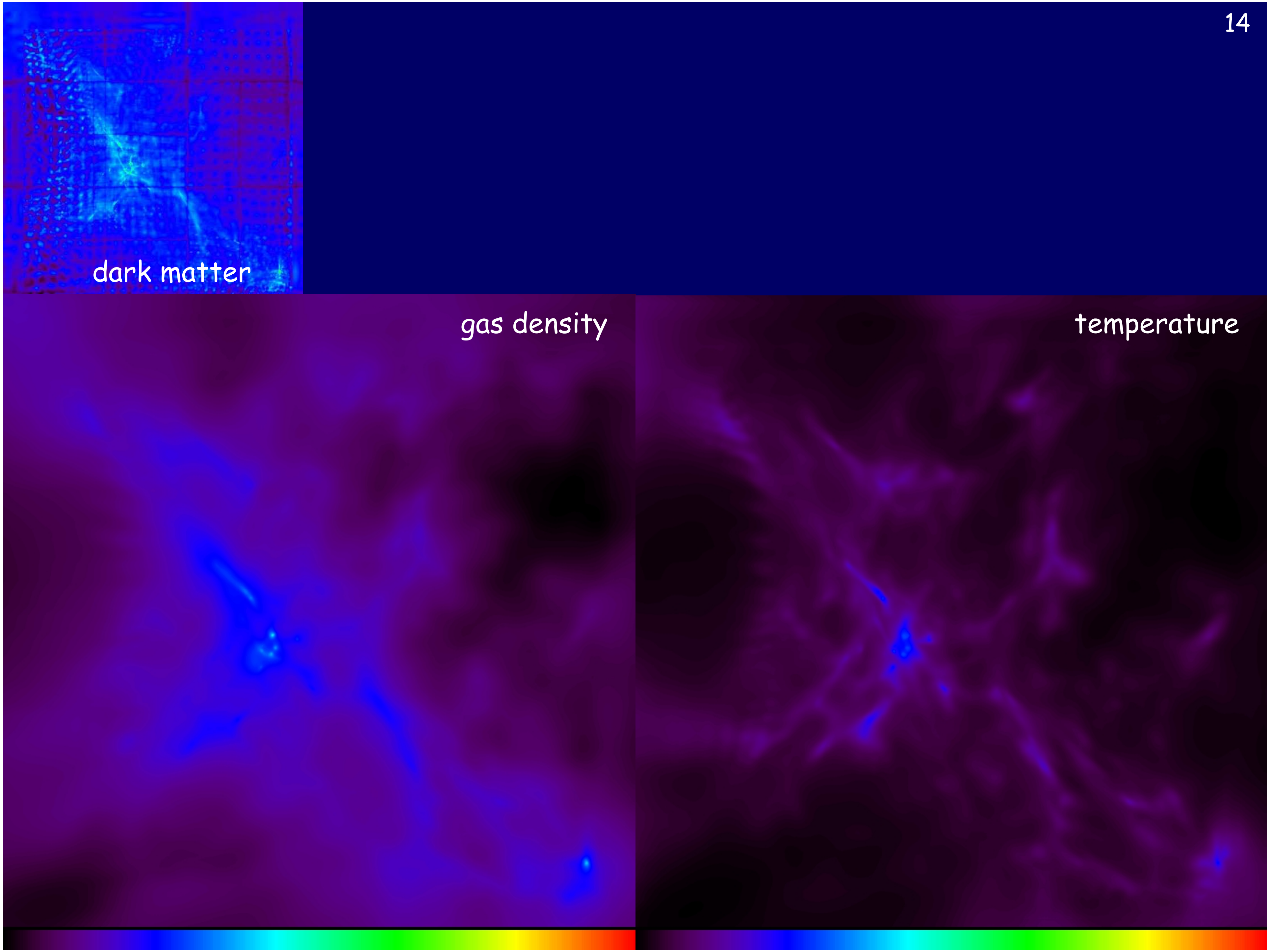


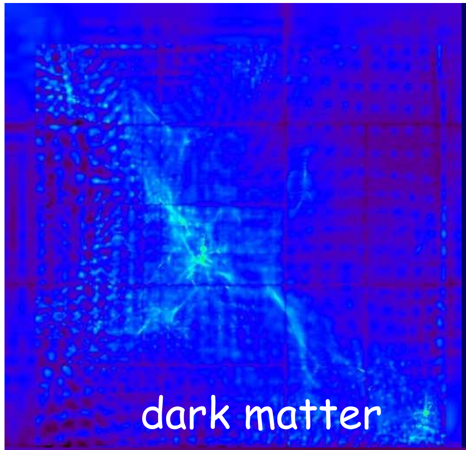
temperature

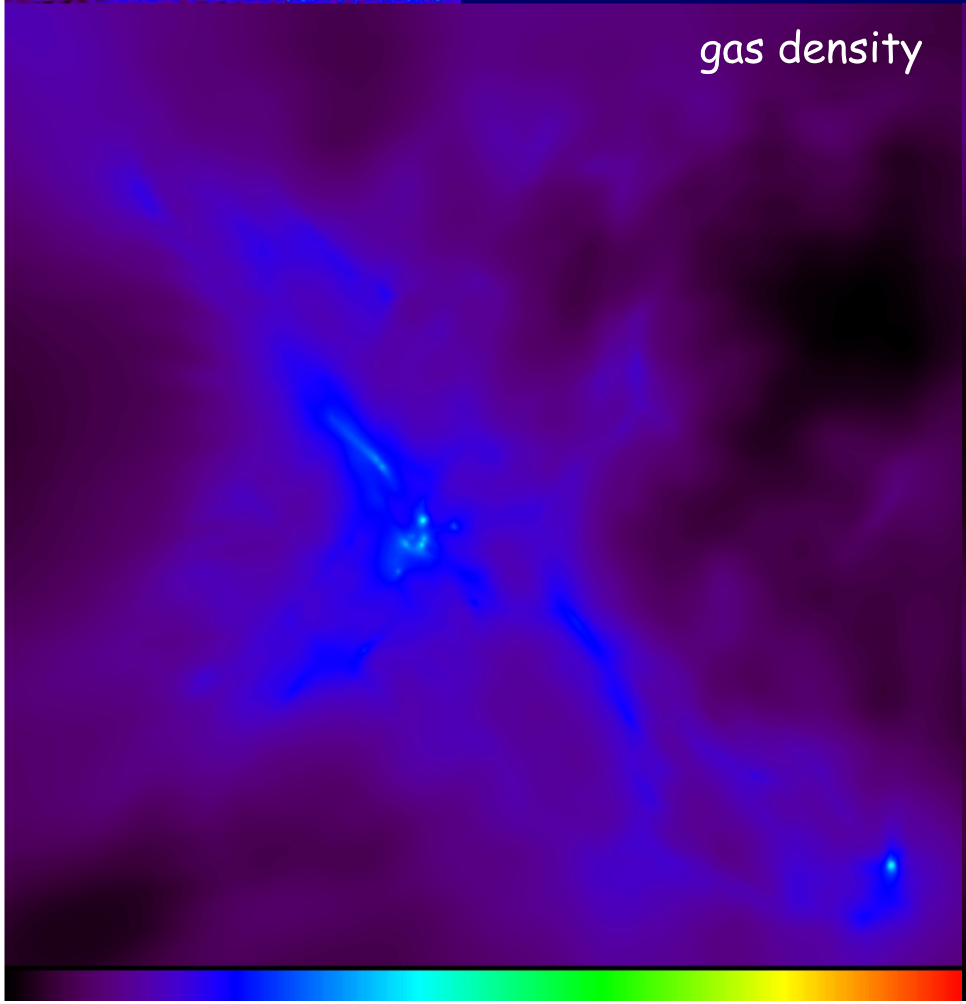

dark matter

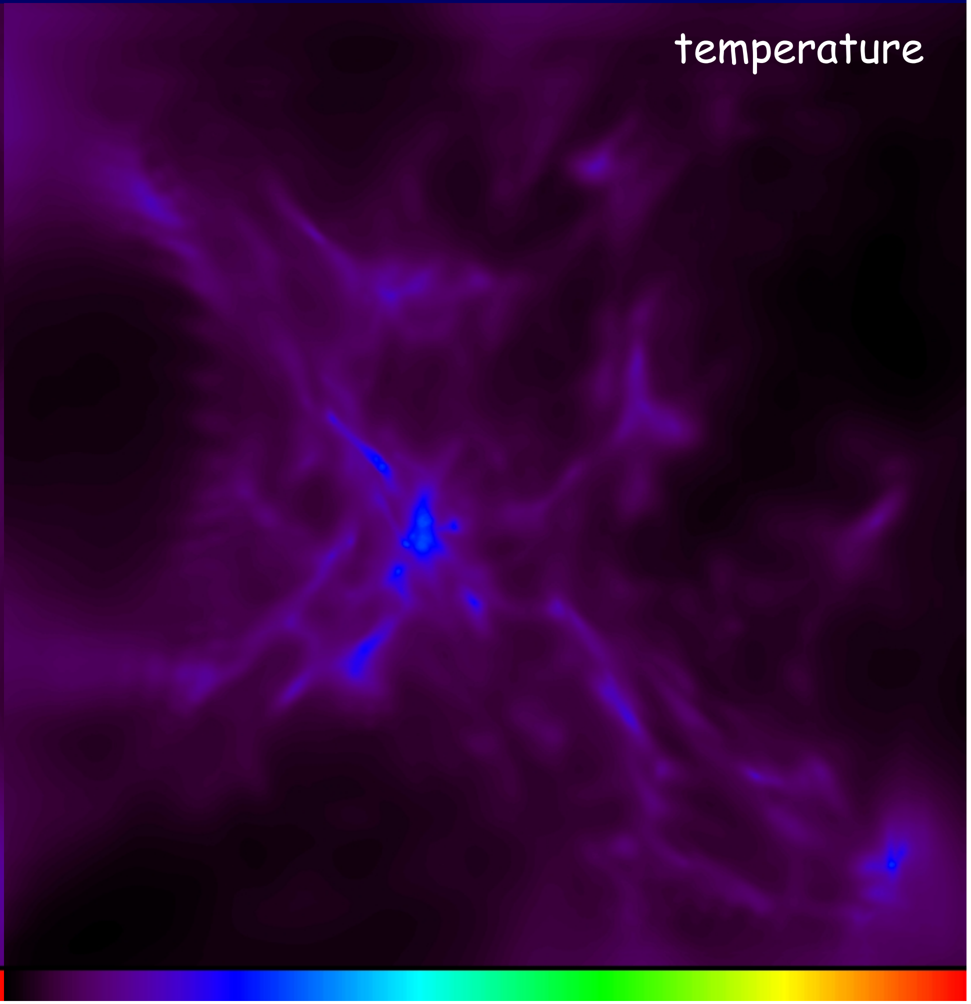

gas density

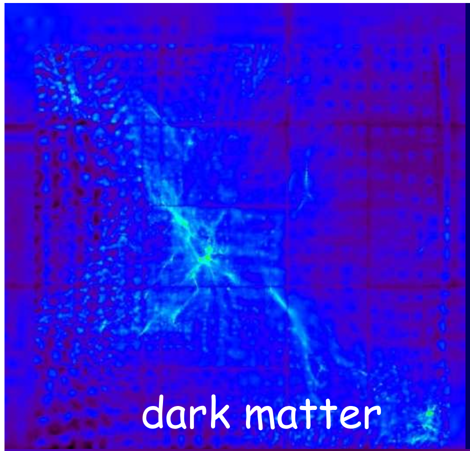

temperature

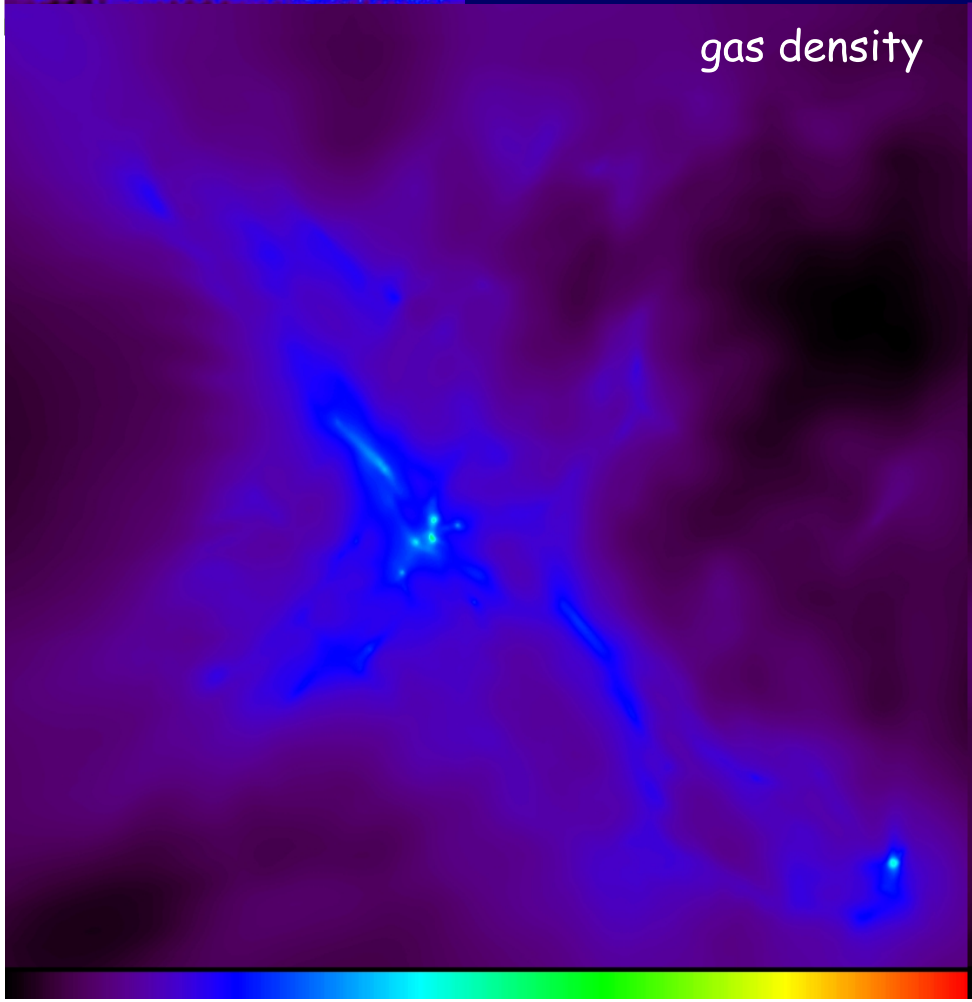

dark matter
gas density
temperature

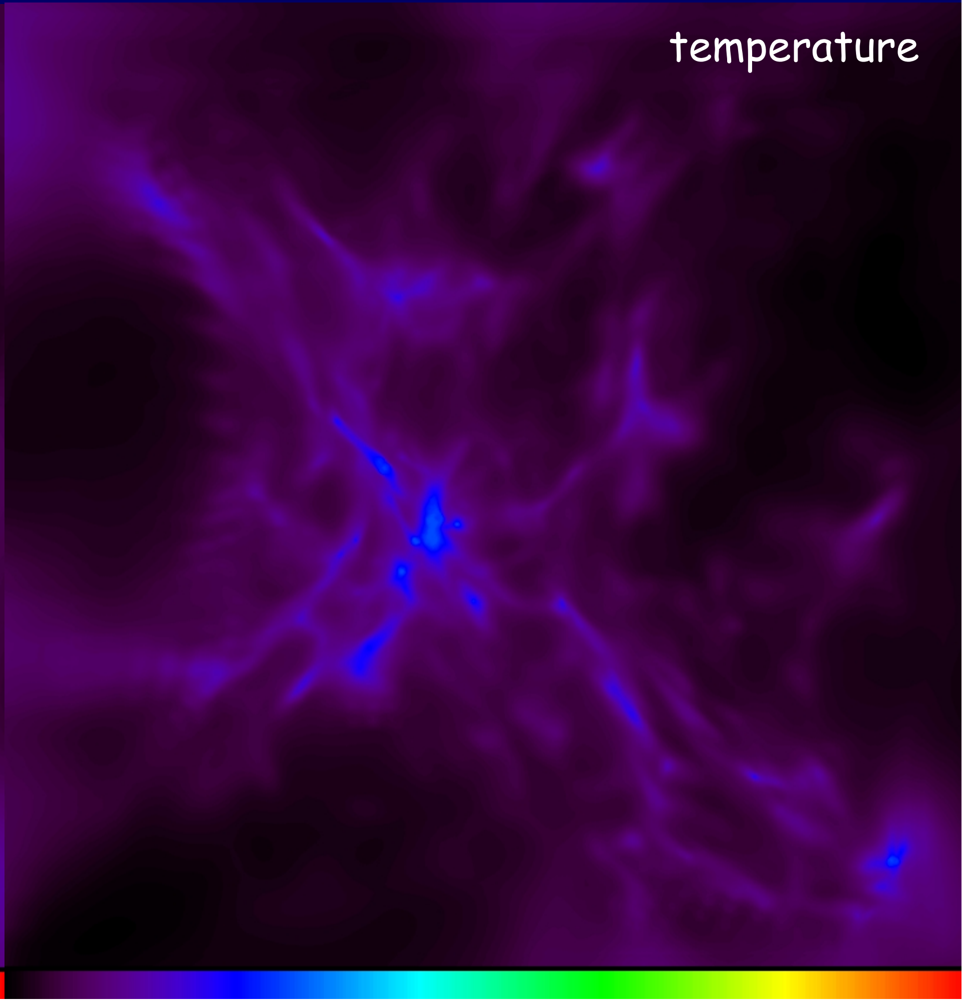

dark matter

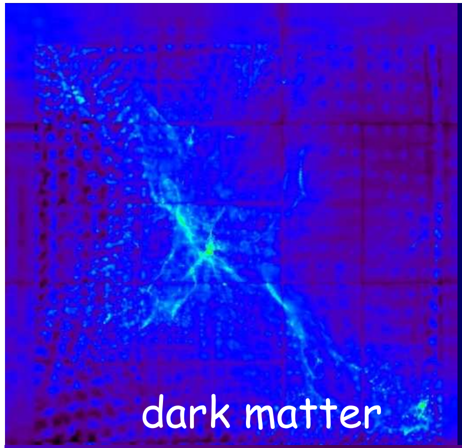

gas density


temperature

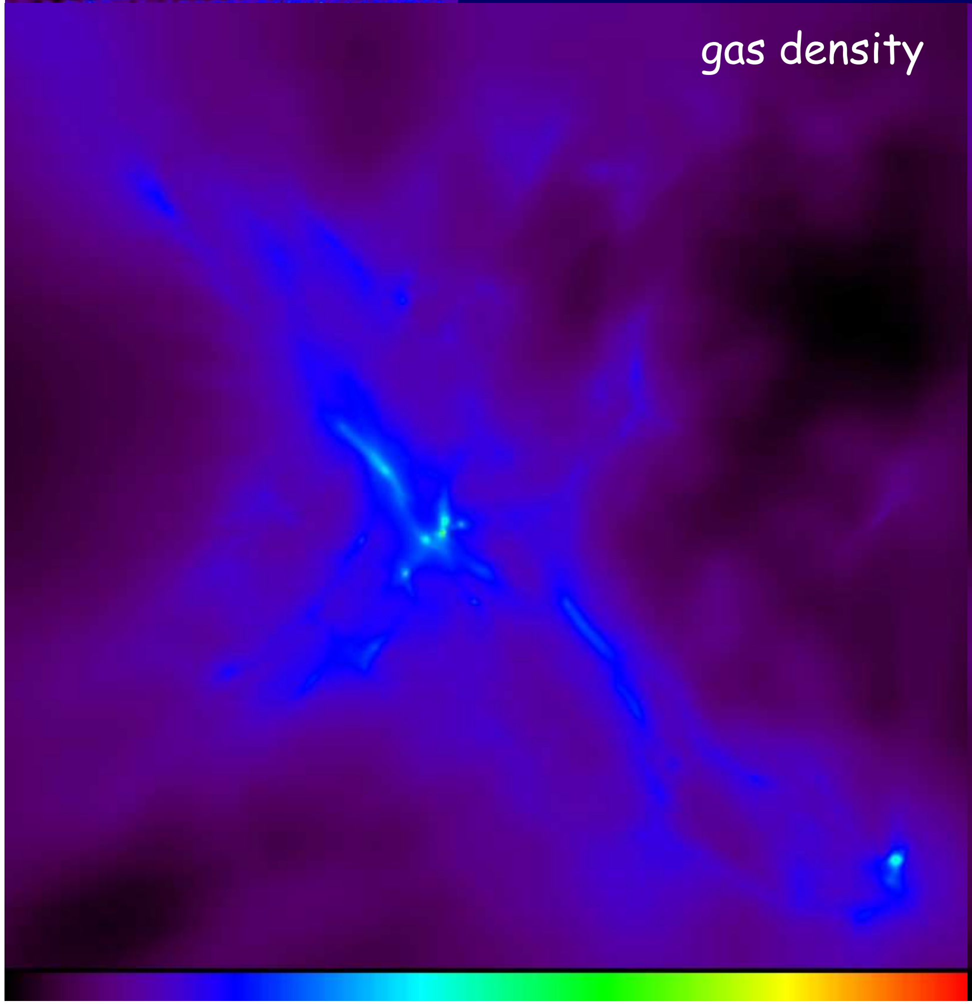

dark matter


gas density

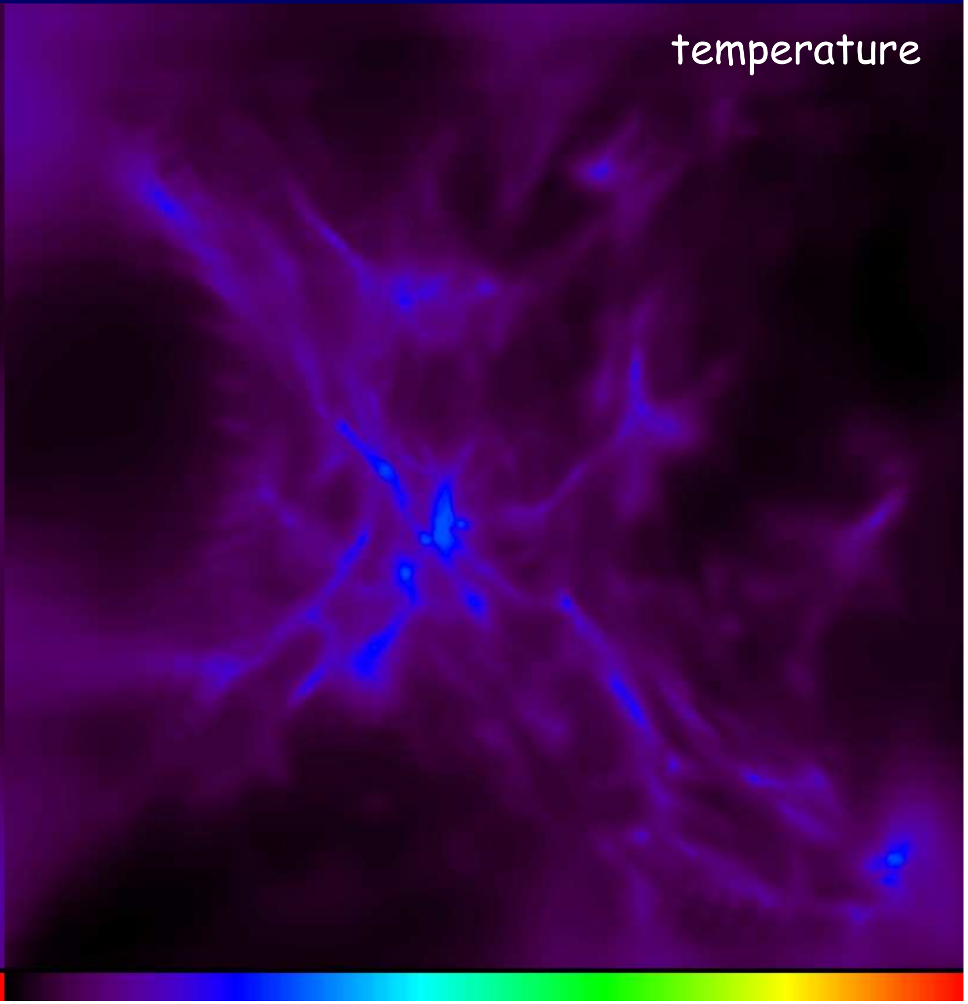

temperature



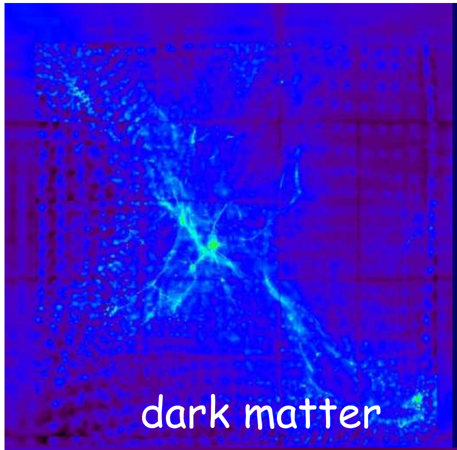
dark matter



gas density



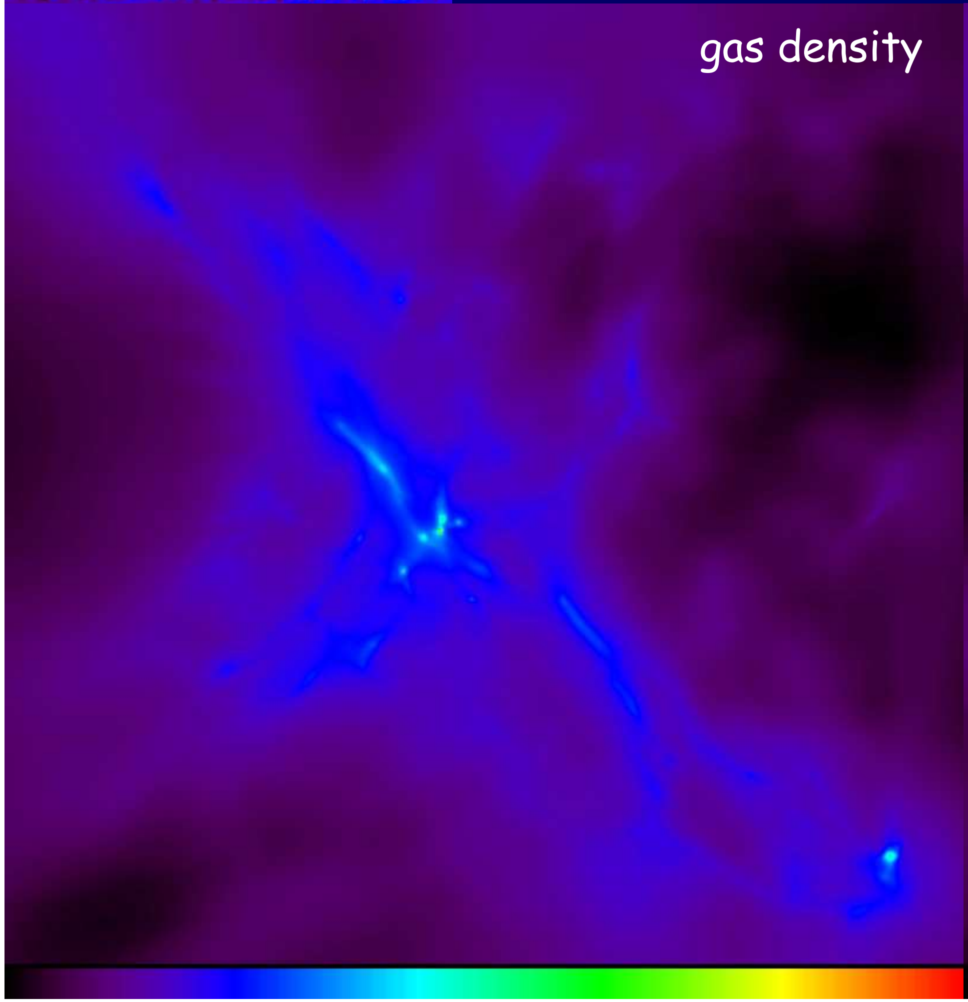
temperature

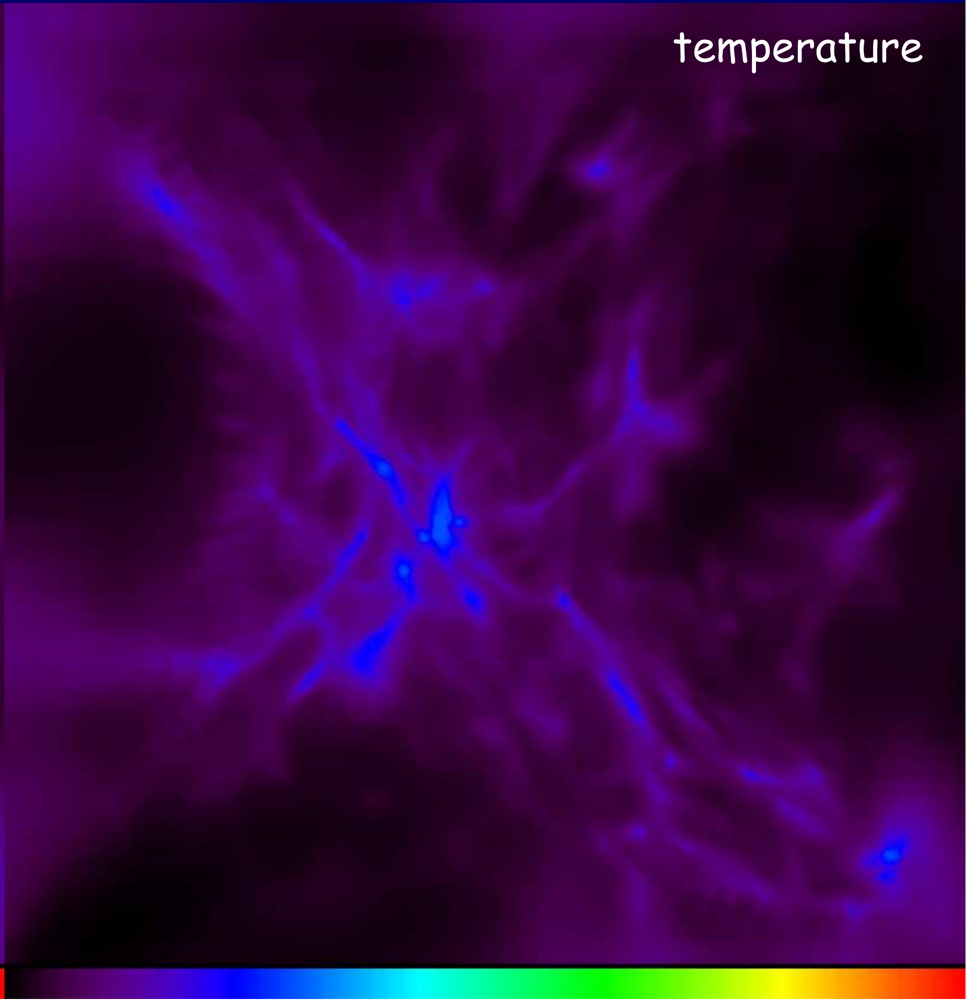


dark halos $10^{5-6}\ M_\odot$

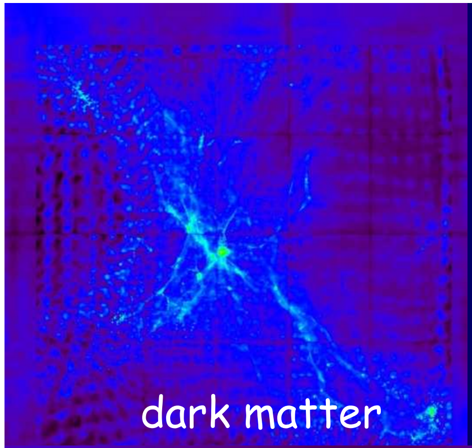
dense, cooled gas clumps $10^{4-5}\ M_\odot$

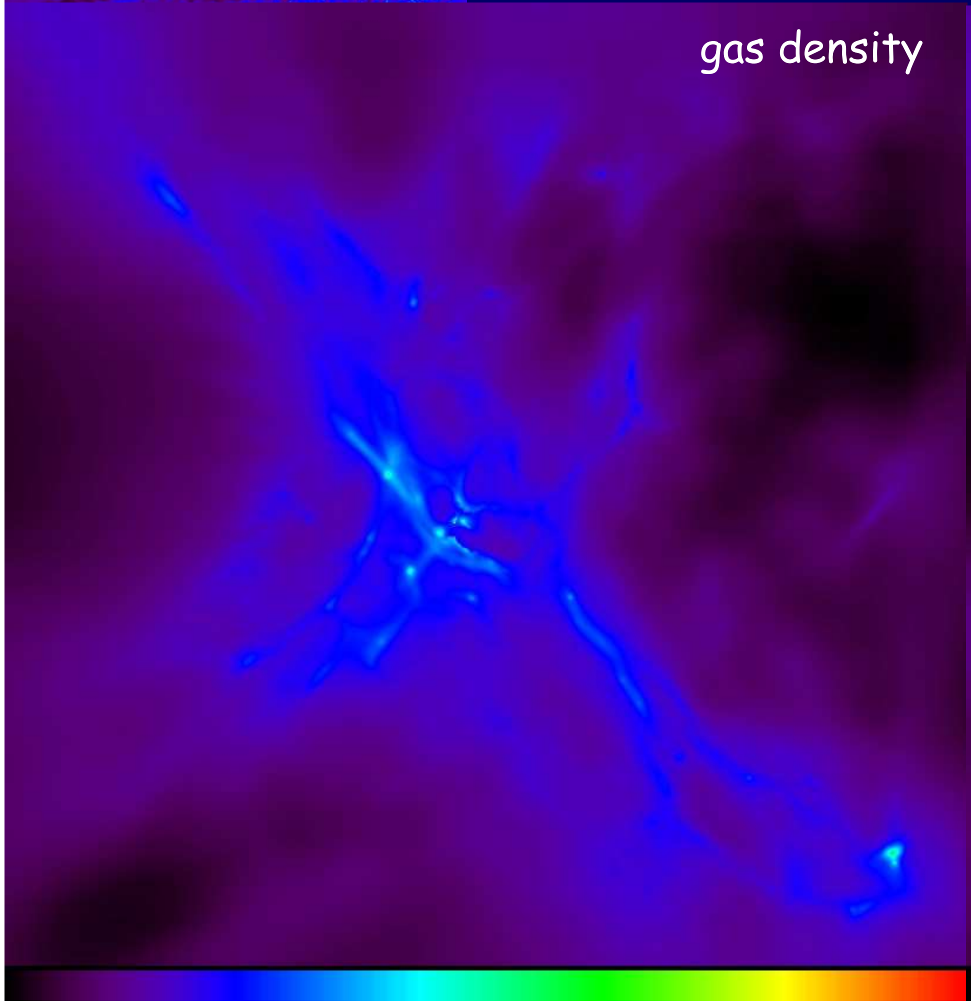
z~20

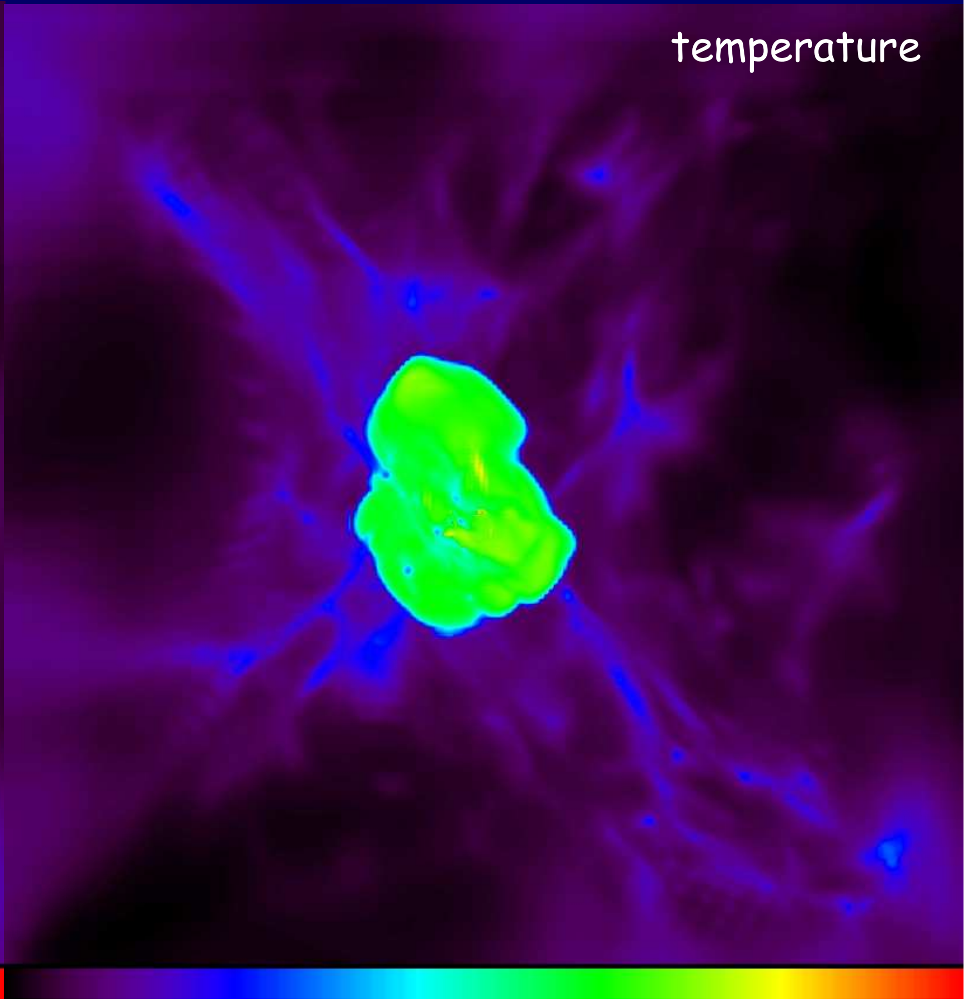




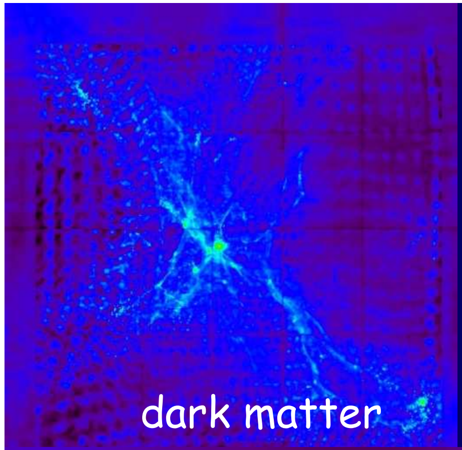
First burst: supernovae

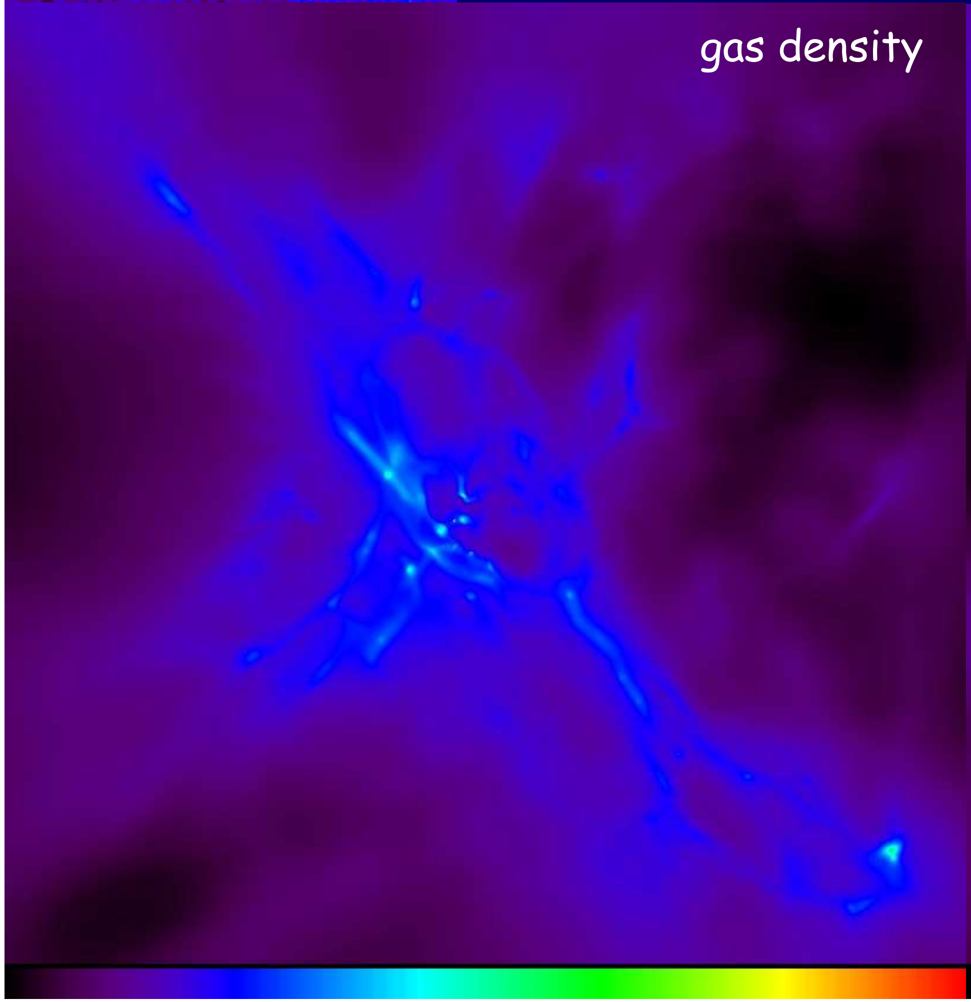


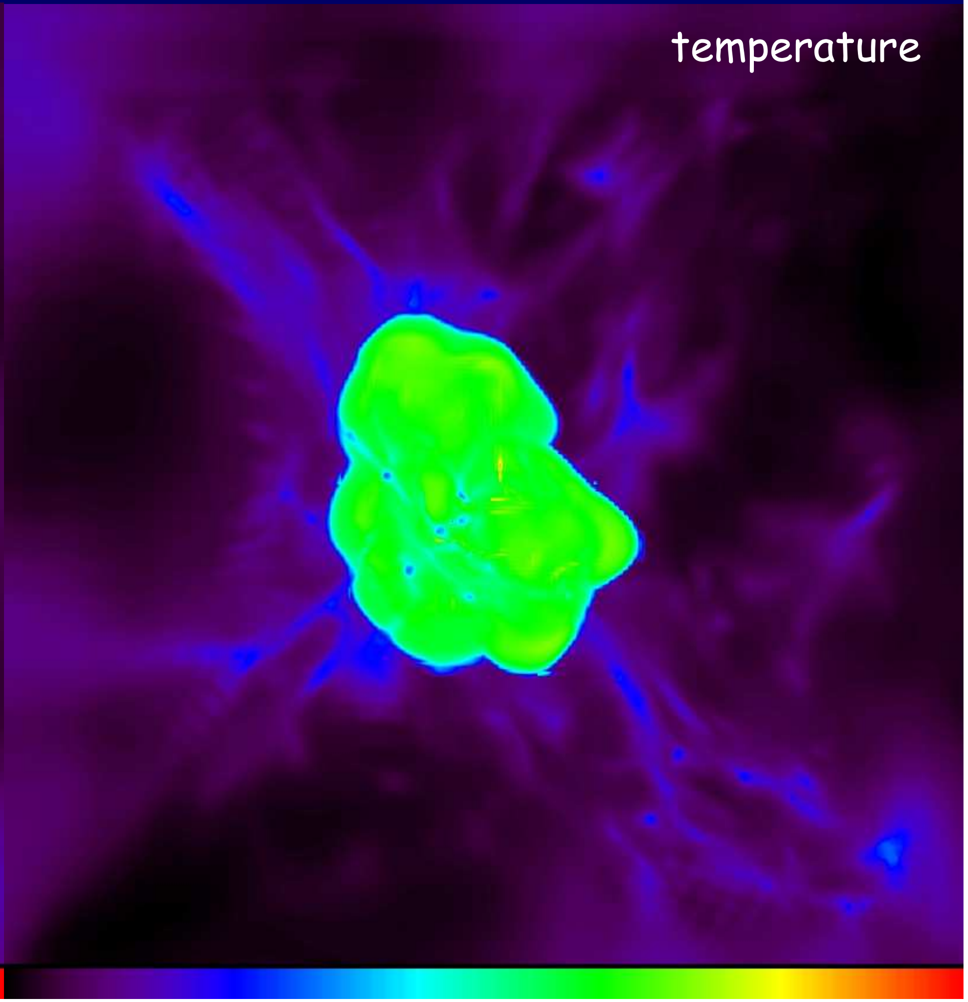




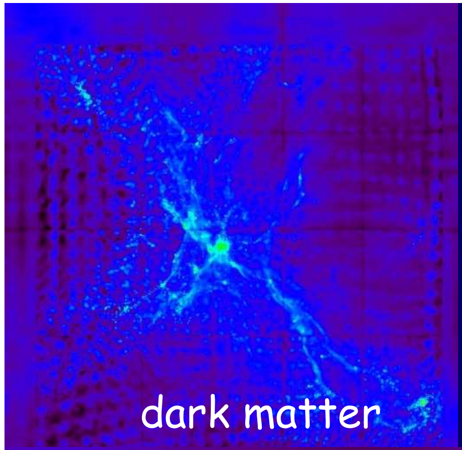
clouds are shielded: remain dense and cold

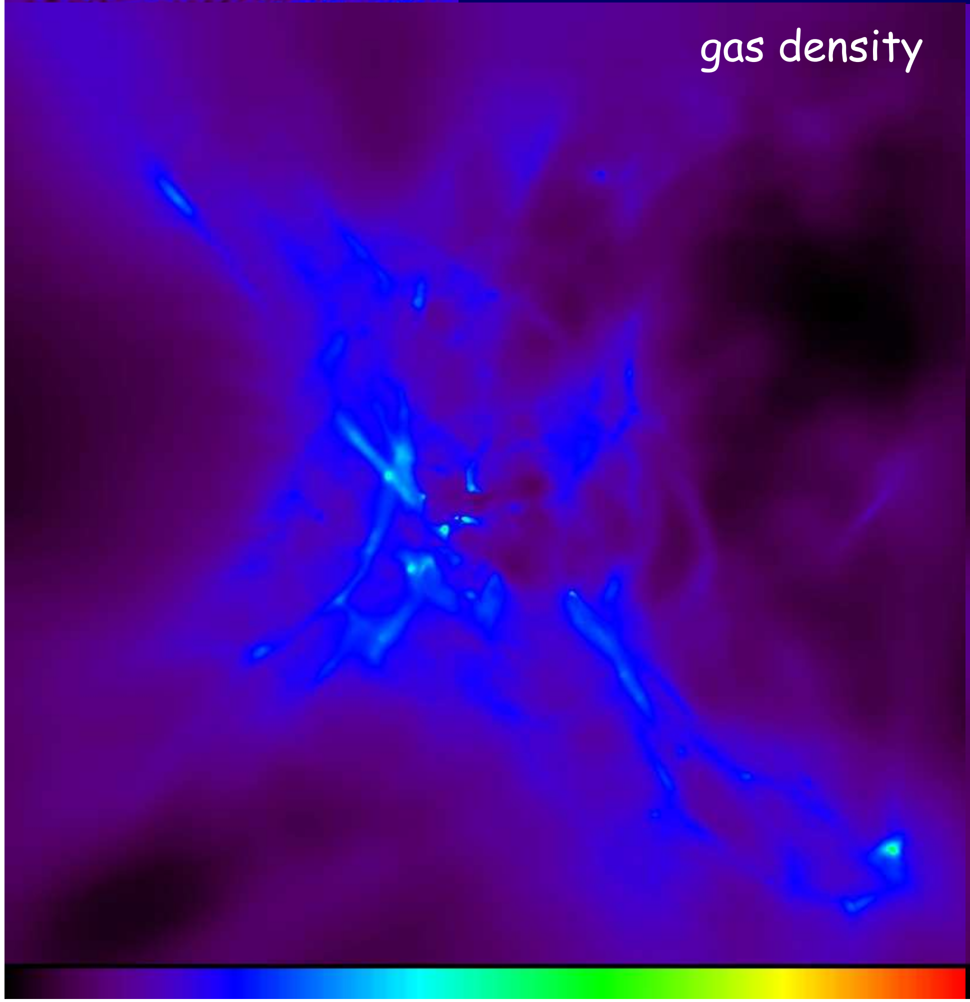


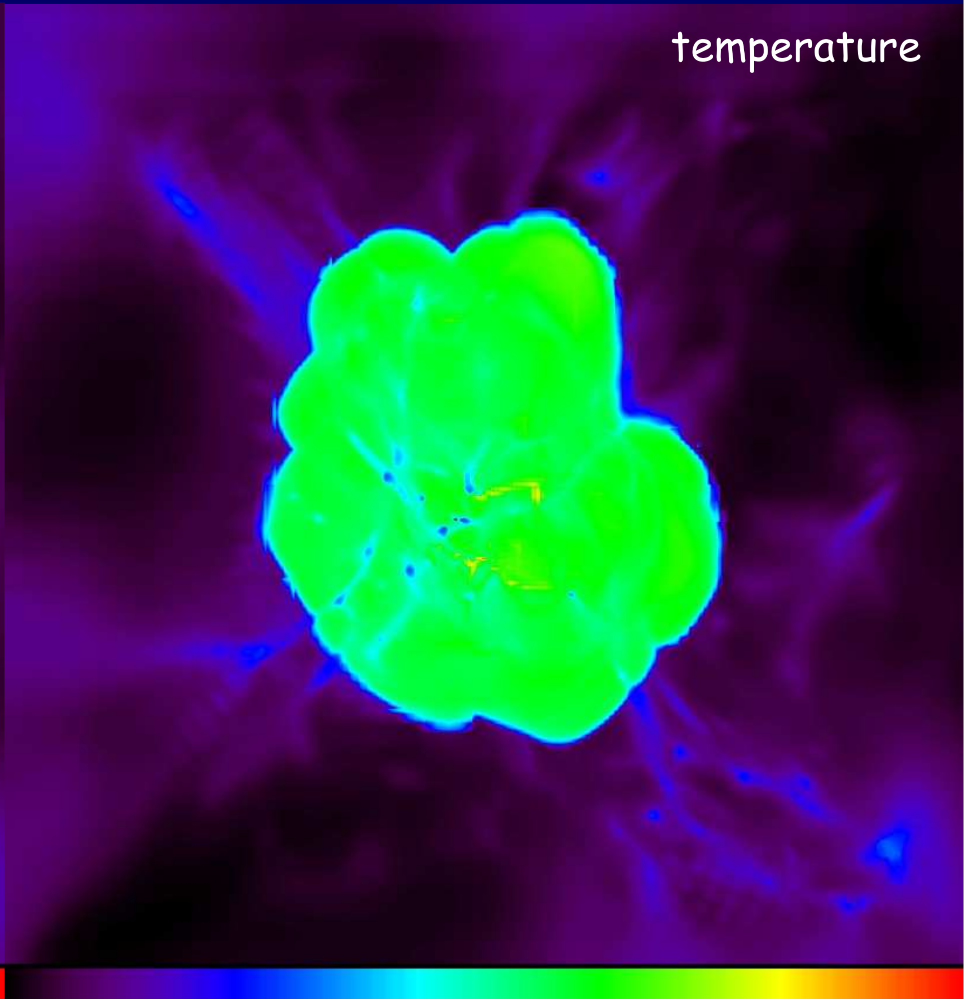


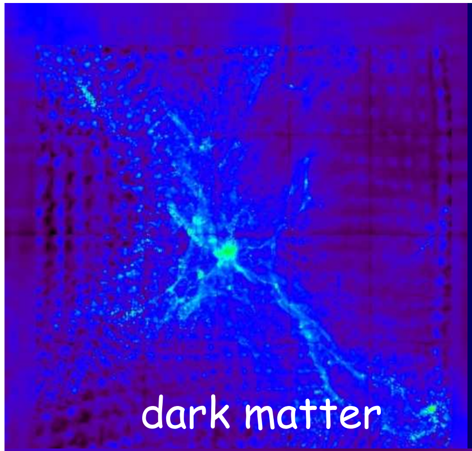


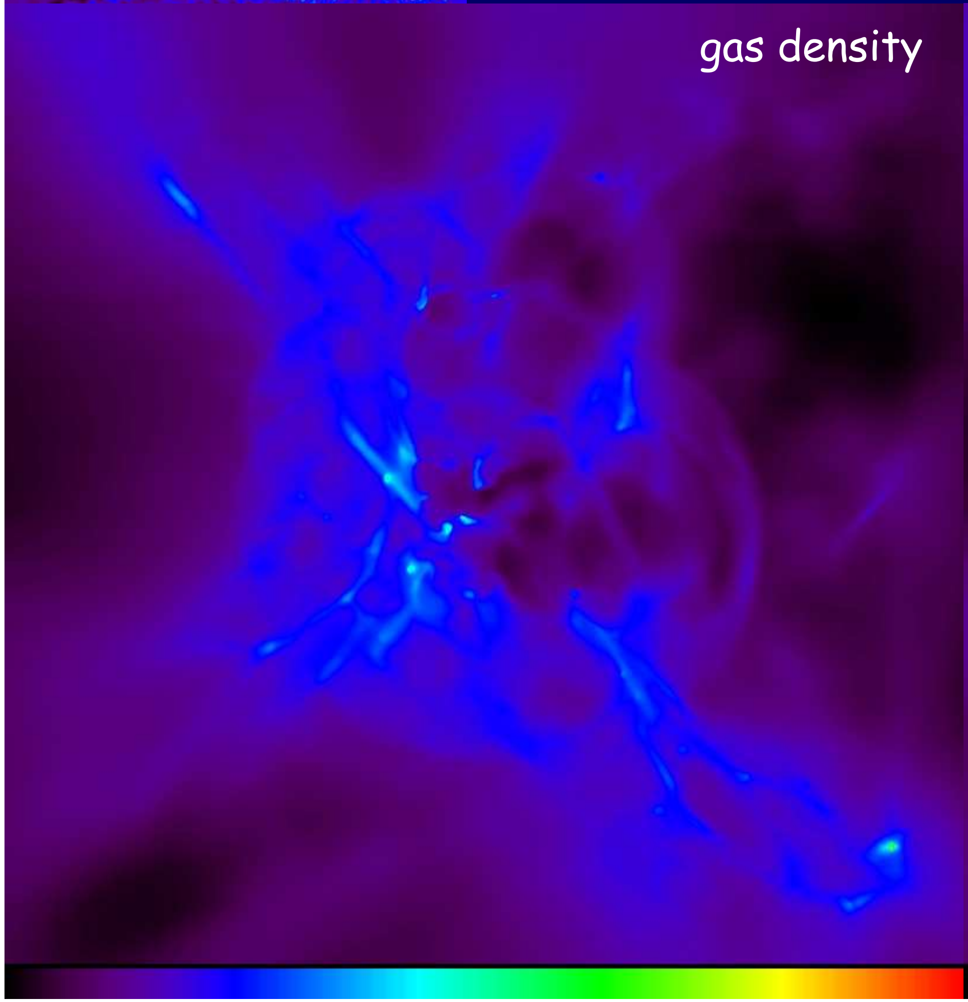
dilute gas is heated and pushed away: void

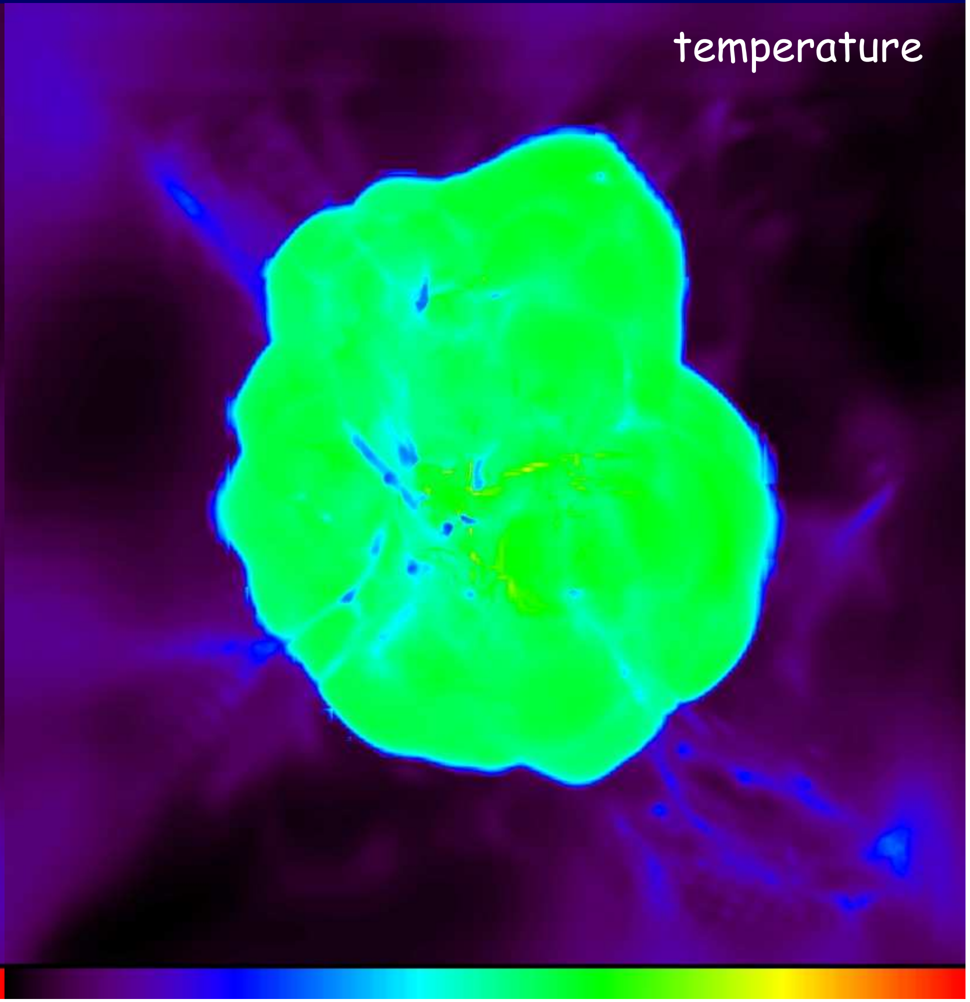


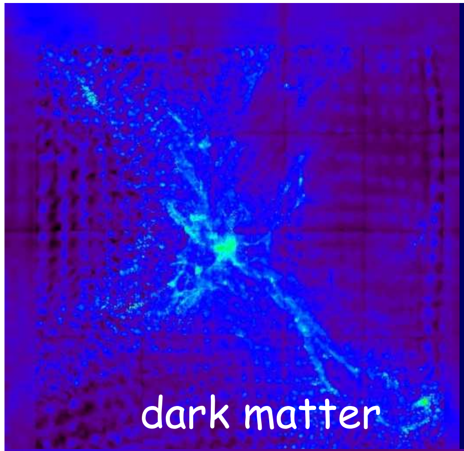


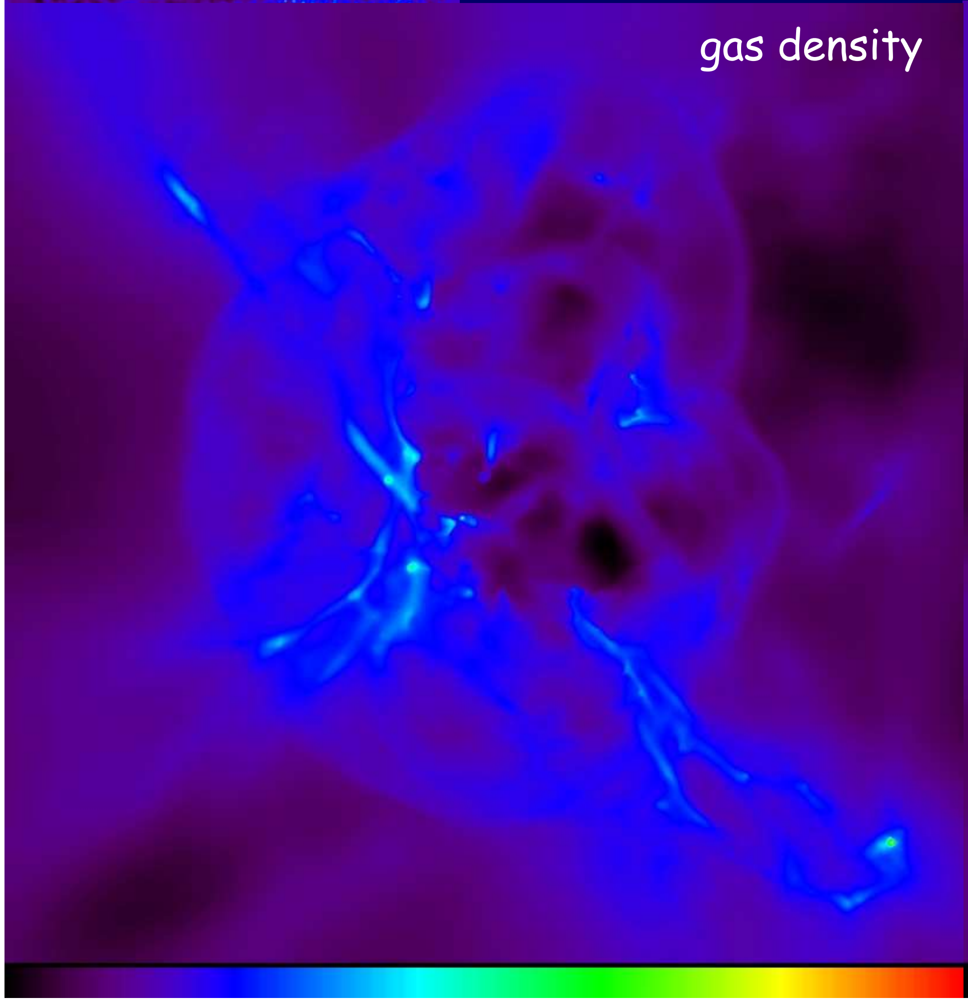


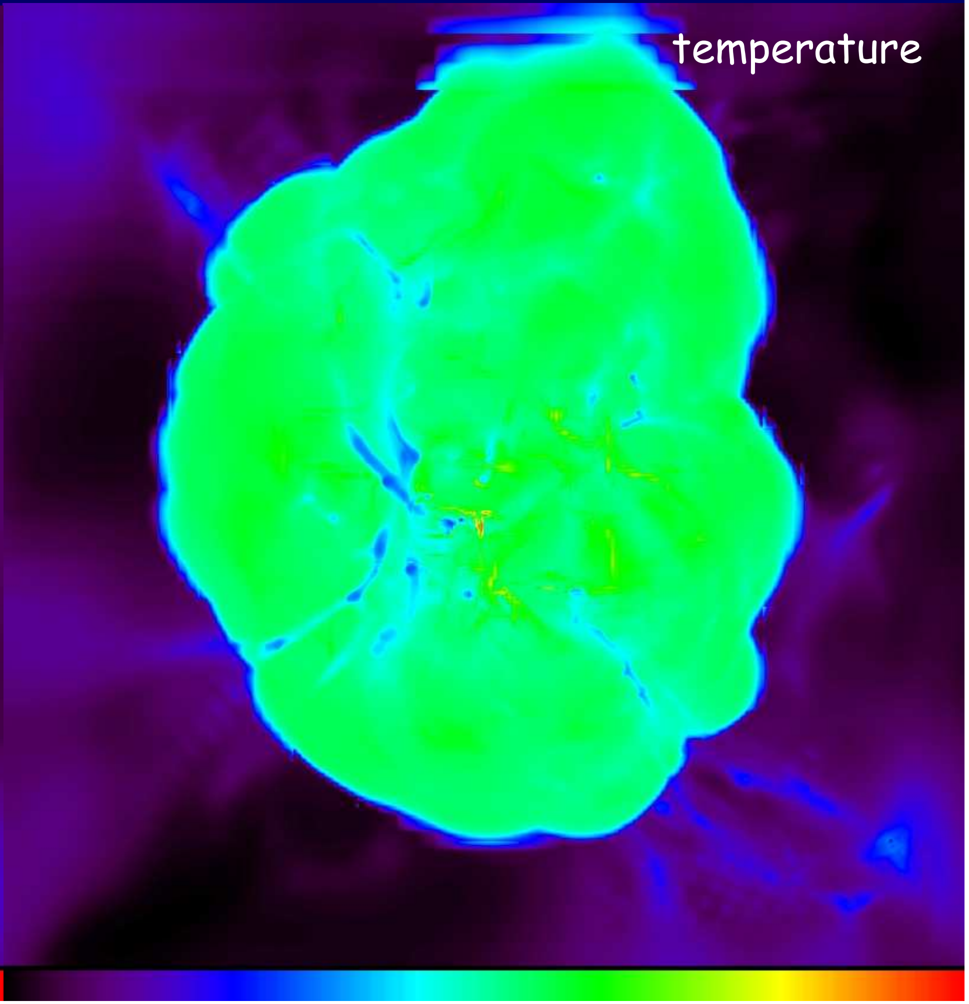

dark matter


gas density

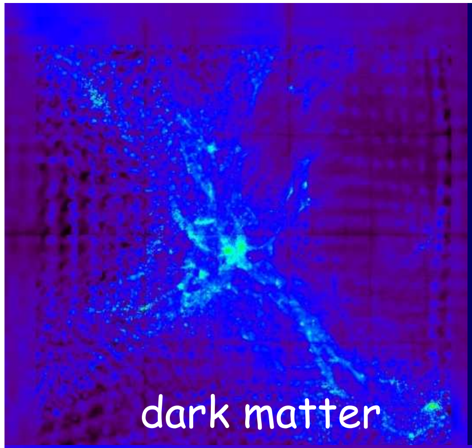

temperature

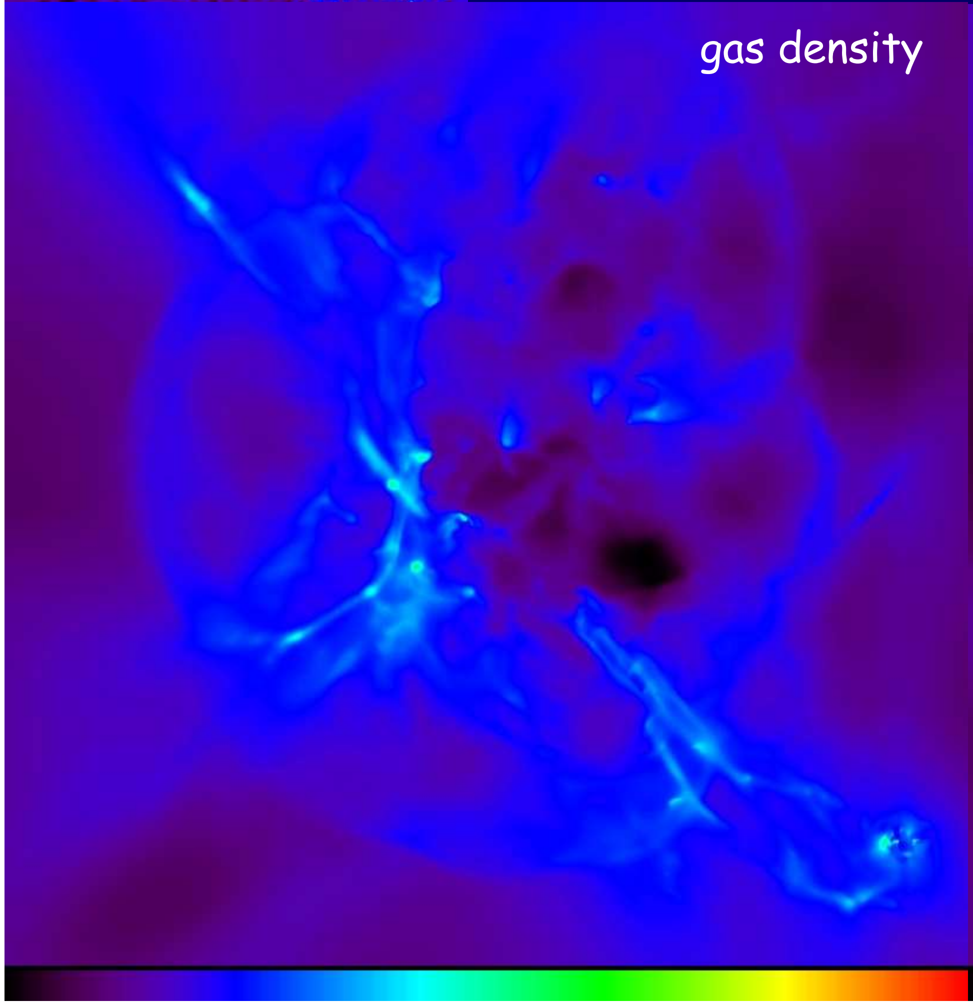

dark matter

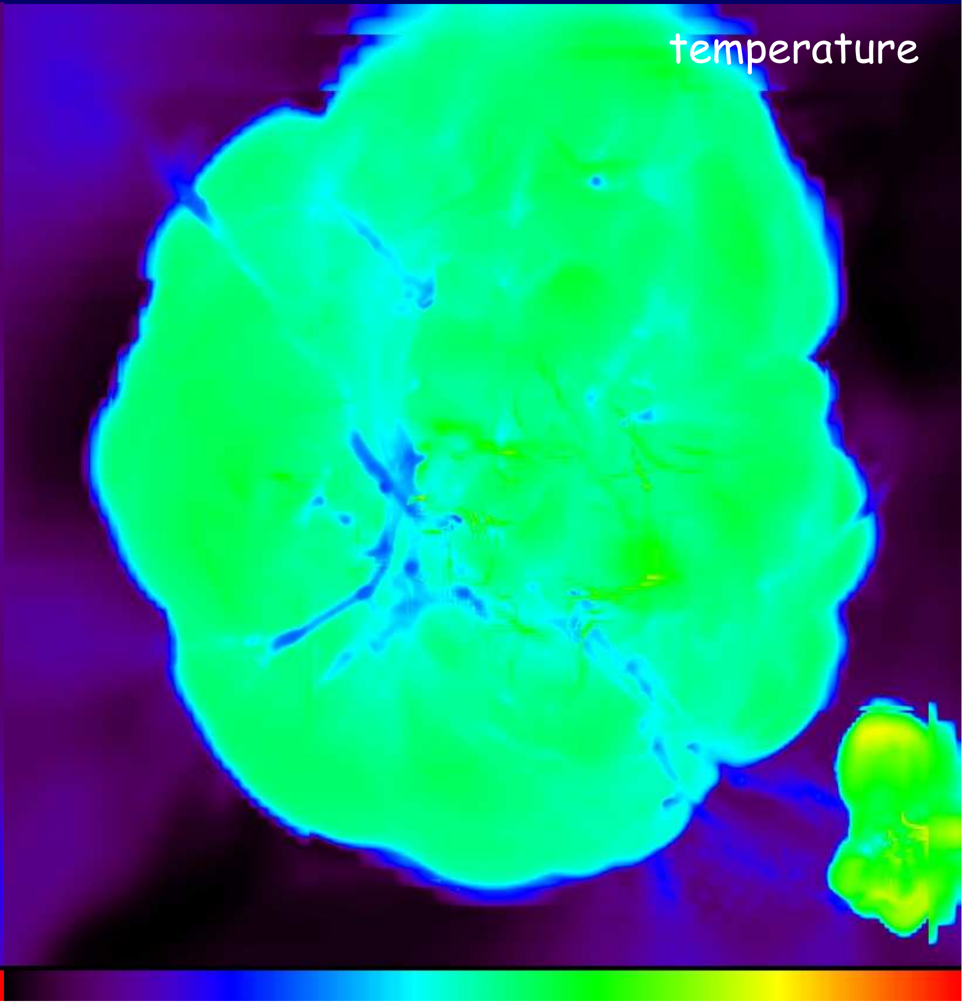

gas density

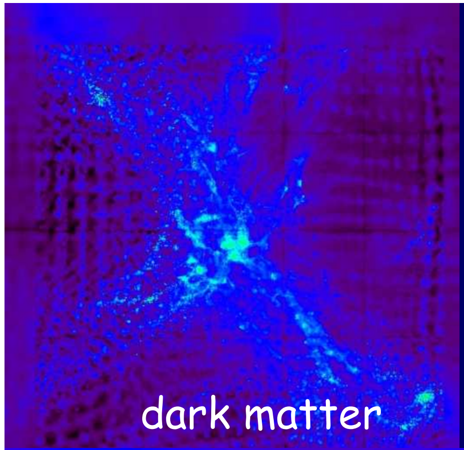

temperature

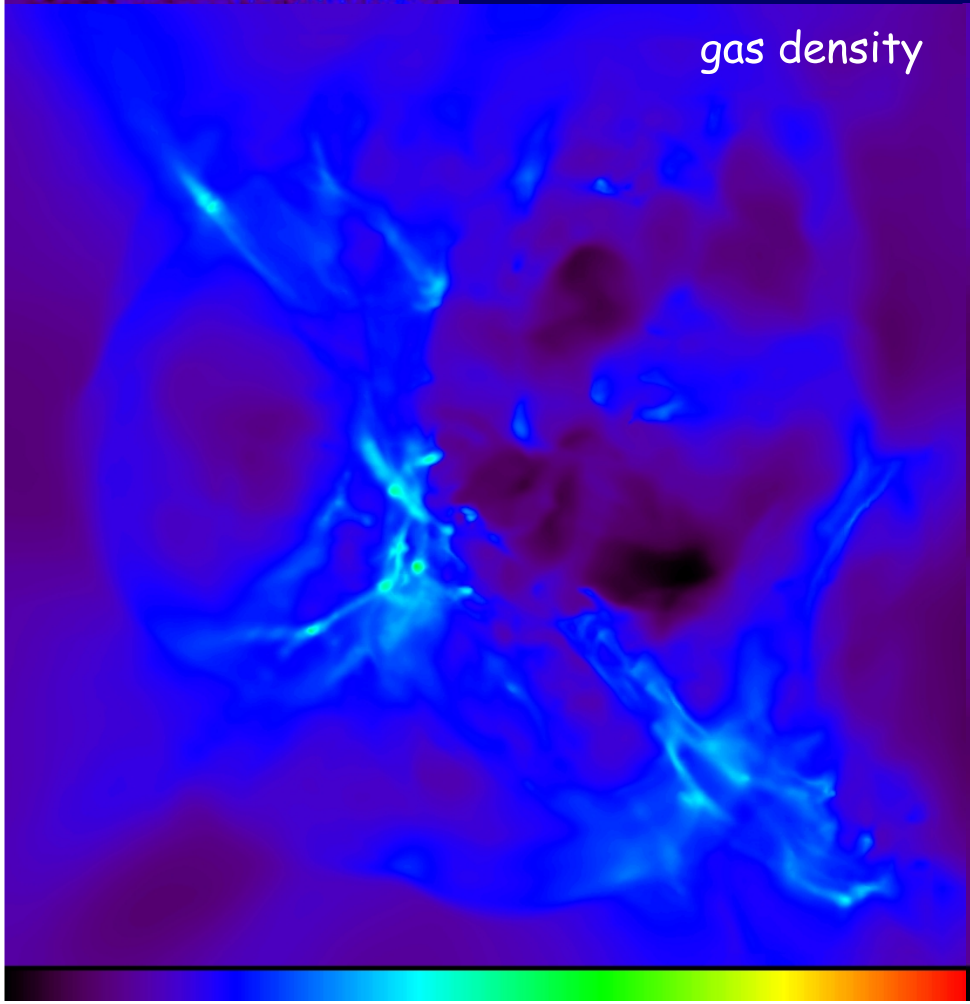
a second burst

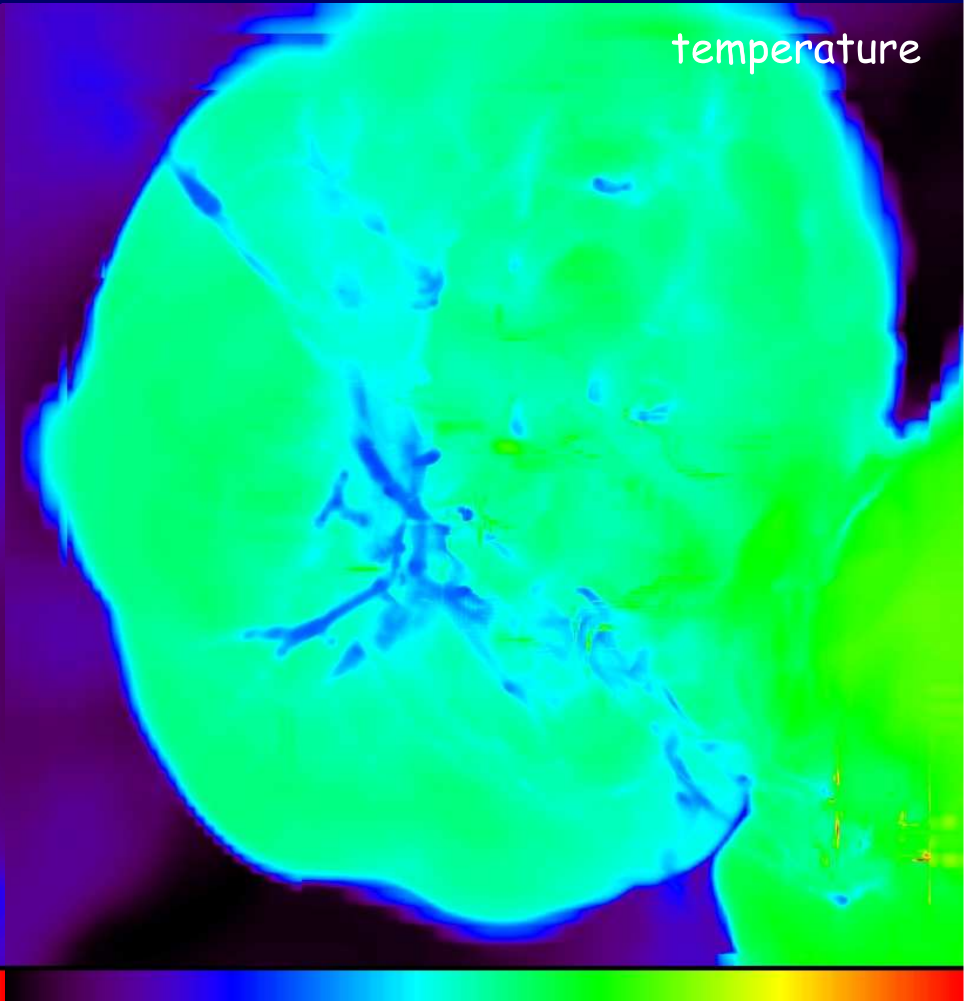


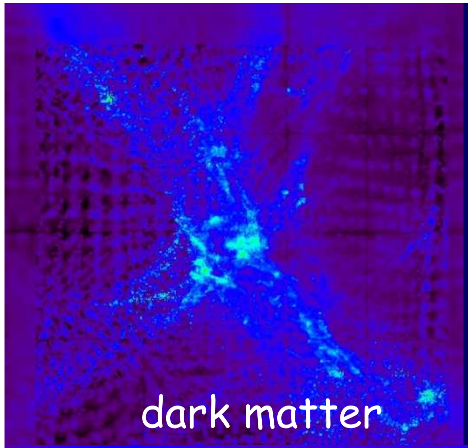


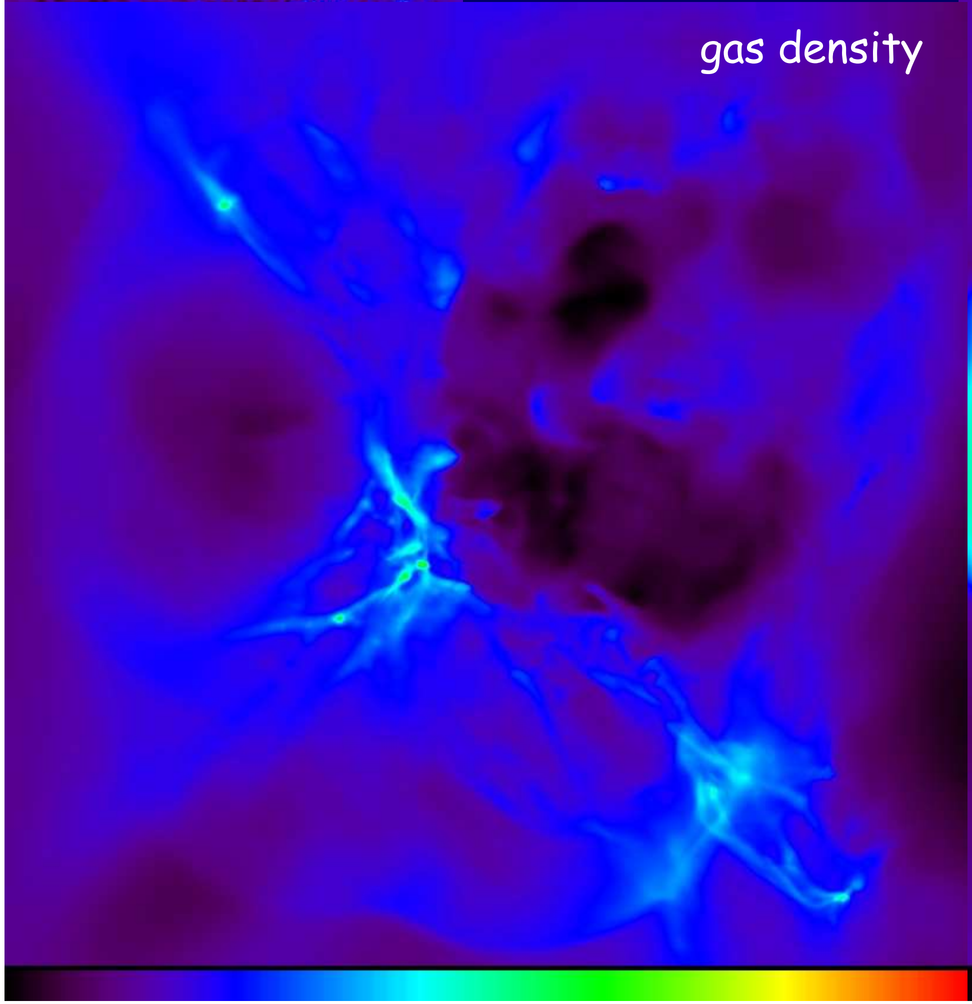


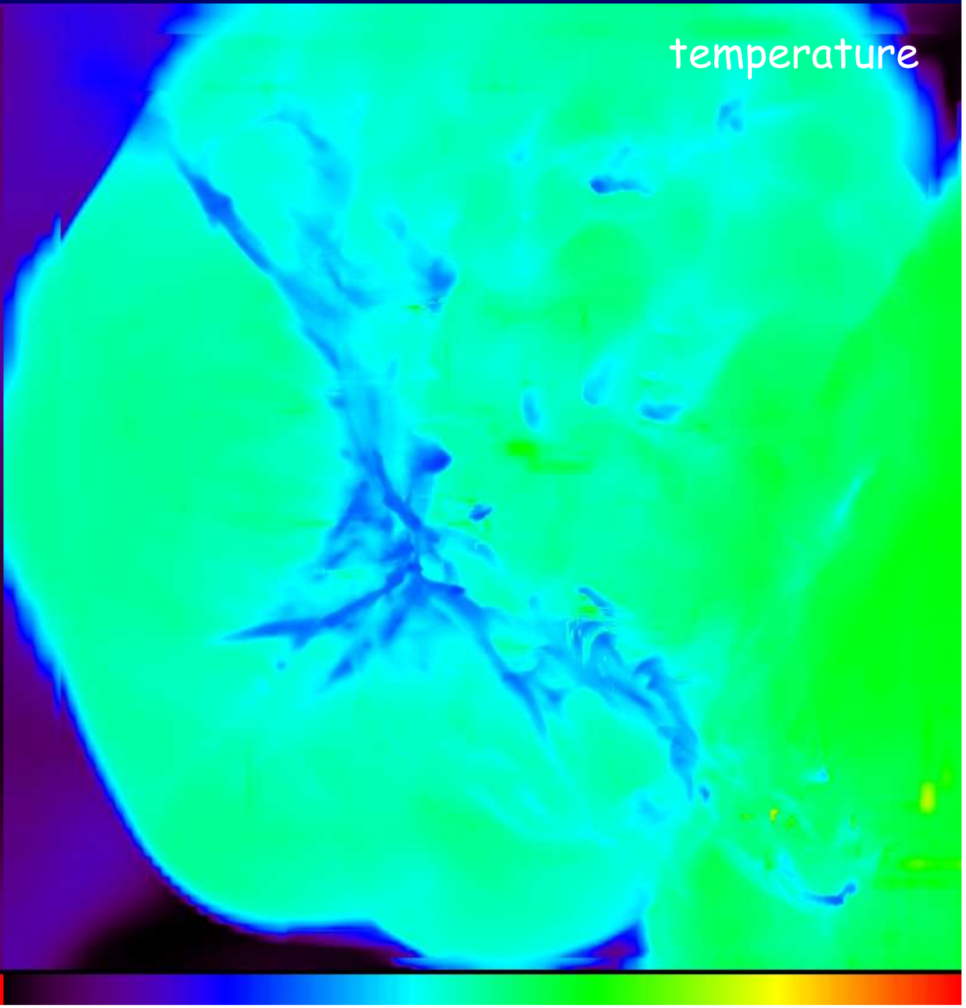

dark matter

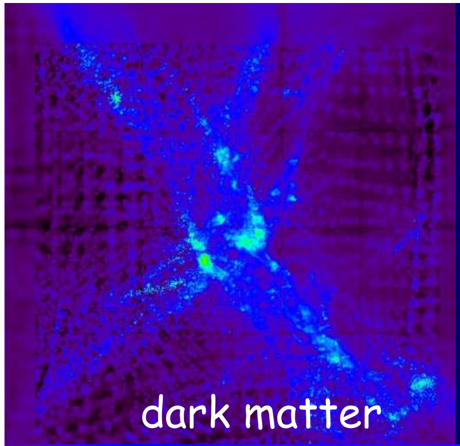

gas density

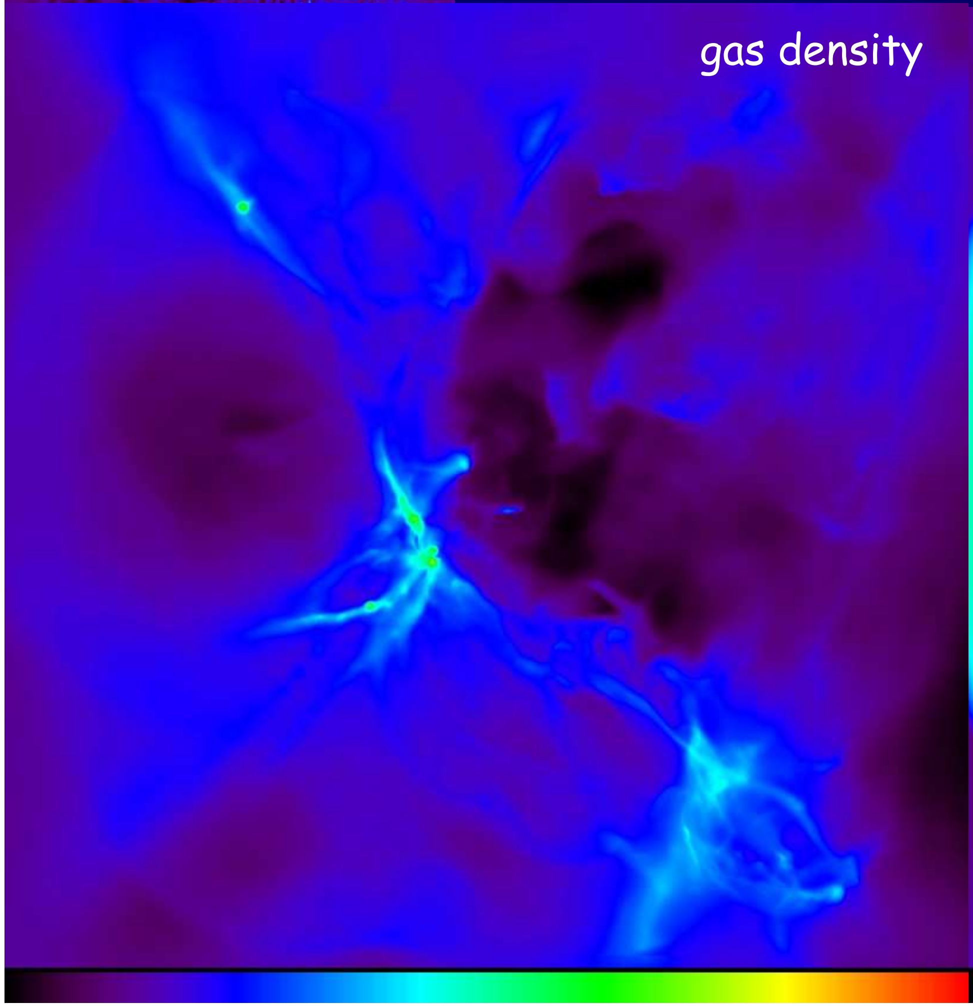

temperature

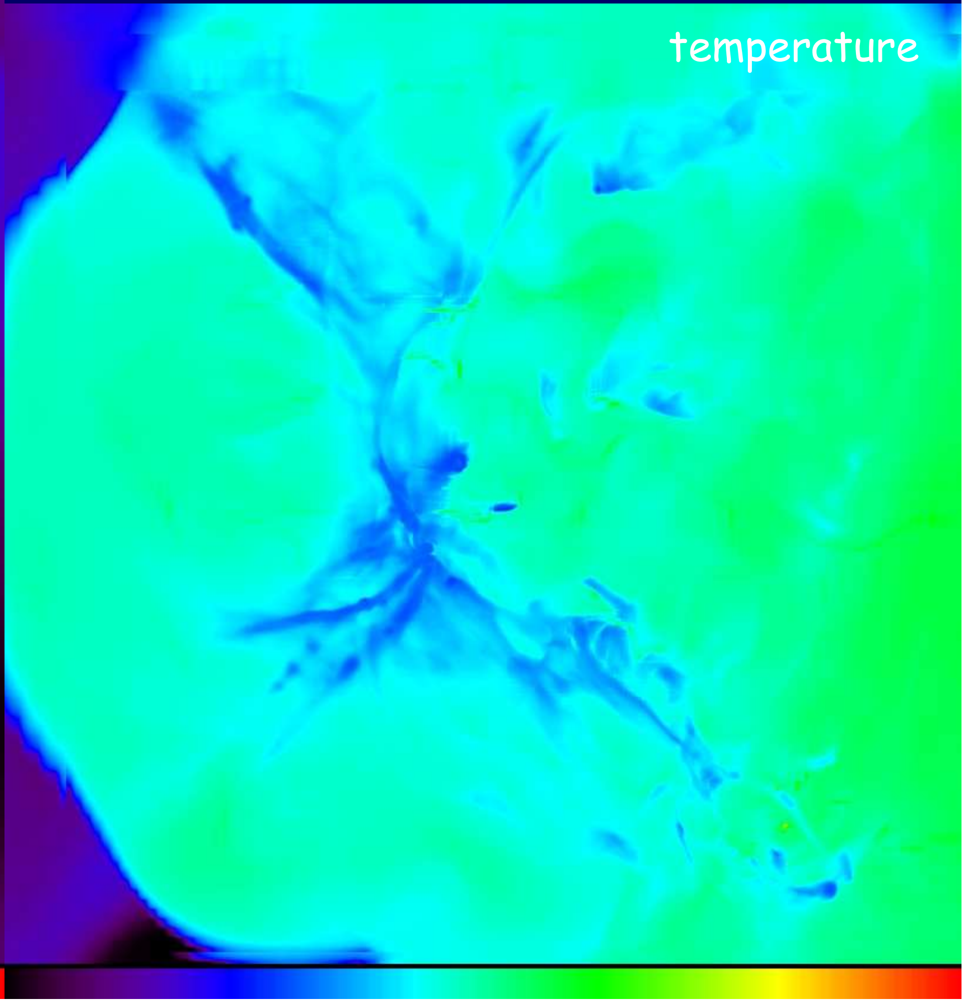

dark matter


gas density

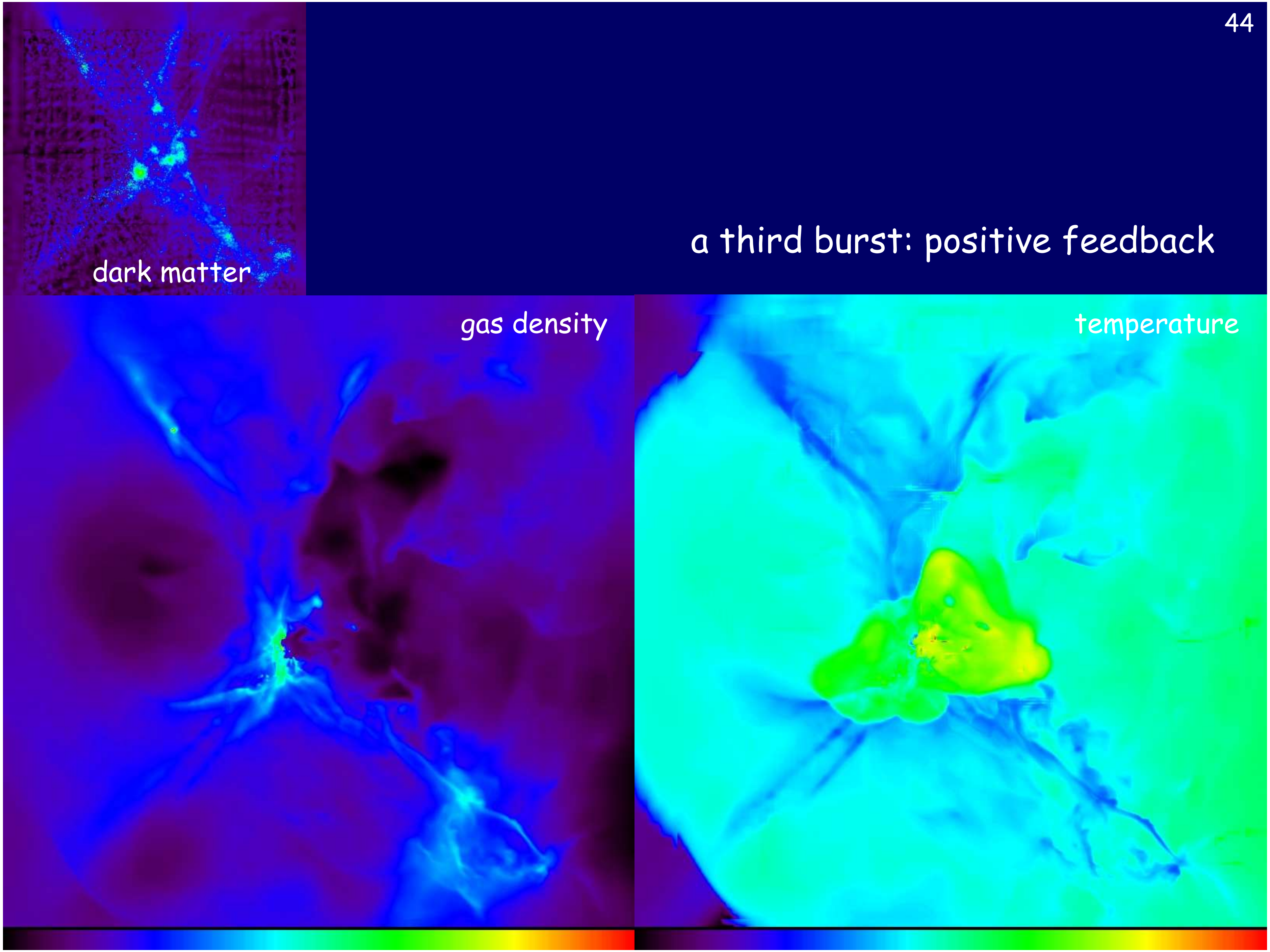

temperature

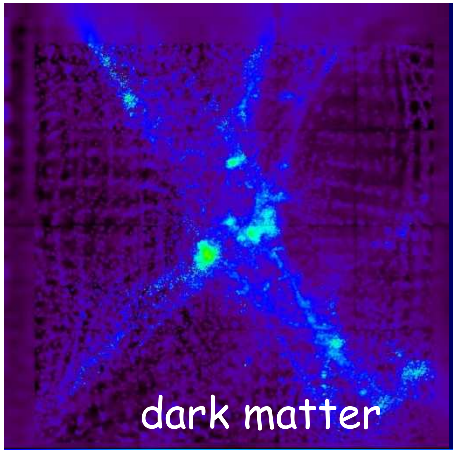

dark matter


gas density


temperature

a third burst: positive feedback

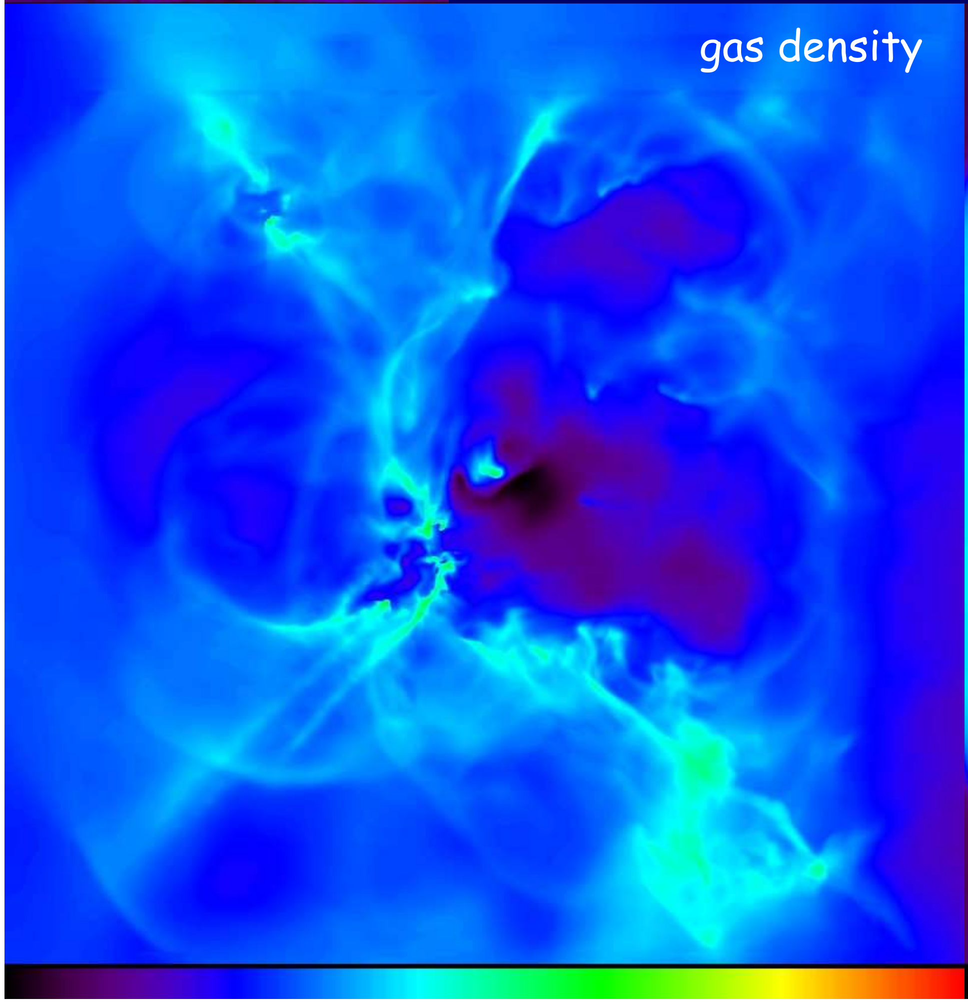


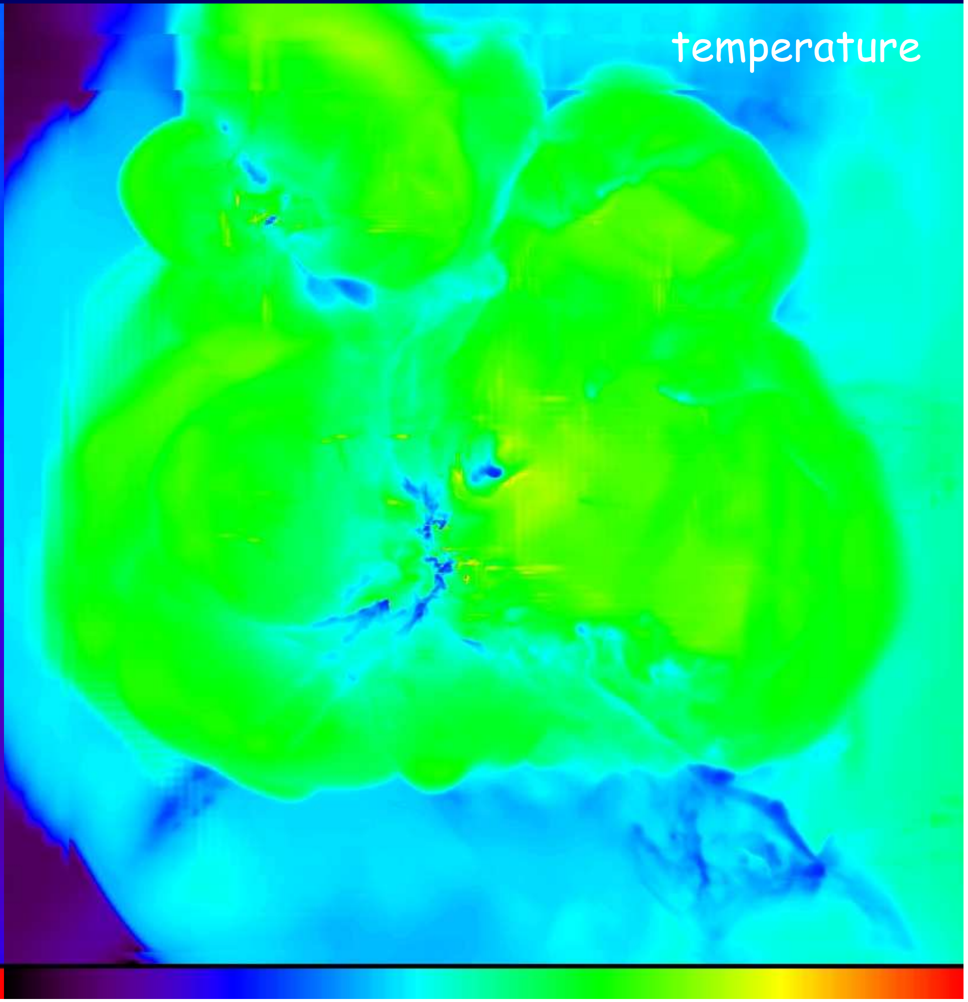


dark halo 10^7 $M_\odot$

gas left 10^4 $M_\odot$ (similar to small dwarf galaxies)

z~11





Main Features

- Two-phase medium driven by gravity and cooling
- Dense clouds survive SN feedback; SFR enhanced
- Dilute gas is removed

3. Dark-Dark Halos Must Exist

Dark-Dark Halos at V<30 km/s

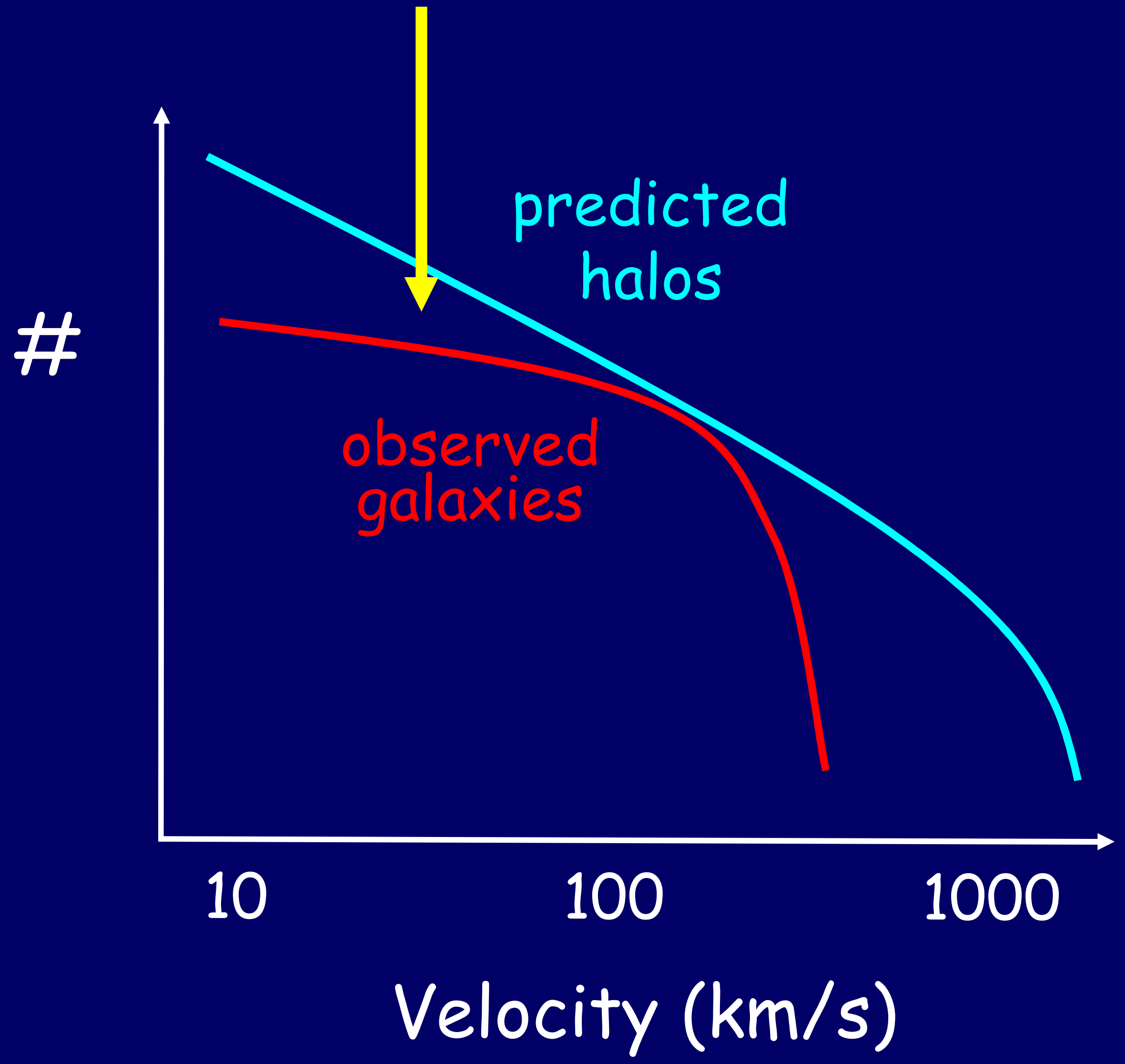
TF: $L \sim V^4$

Virial: $M \sim V^3$

$\psi(M) \sim M^{-2}$

$\varphi(L) \sim L^{-1}$

Cannot be reconciled !



Dark Dark Halos must exist !

virial, top-hat: $M \propto V^3$

Tully Fisher: $L \propto M^x \propto V^{3x} \quad 3x \approx 5$ $\rightarrow dL/dM \propto M^{x-1}$

luminosity function: $\varphi(L) \propto L^{-\alpha} \quad \alpha \approx 1.2$

mass function: $\psi(M) \propto M^{-\beta} \quad \beta \approx 1.8$

$$\enclose{circle}{f_L(M)}\,\psi(M)dM = \varphi(L)dL \rightarrow dL/dM \propto M^{\alpha x-\beta\enclose{circle}{+\gamma}}$$

$$\Rightarrow (\alpha-1)x = \beta-1-\gamma \qquad \rightarrow \gamma \approx 0.5-0.8$$

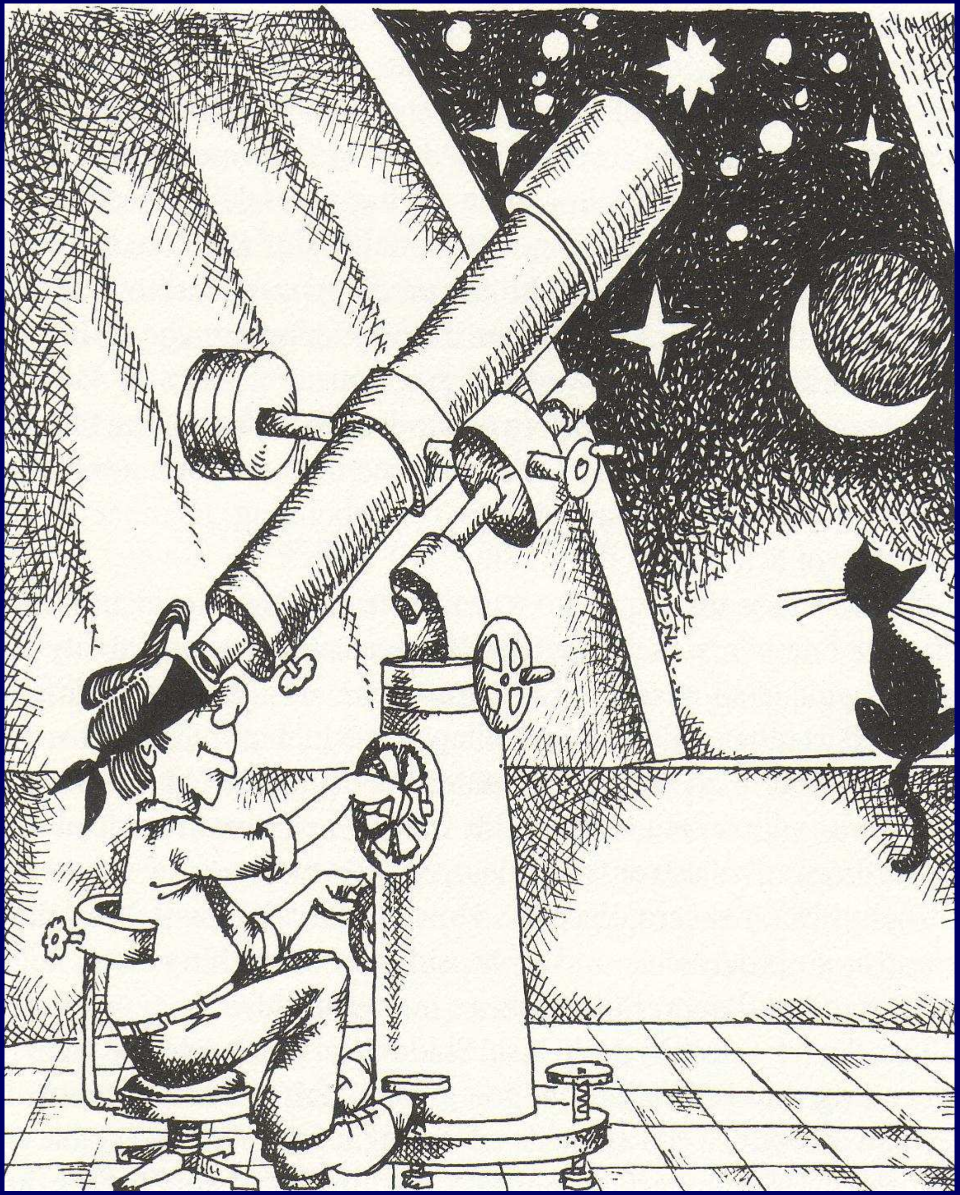
Cannot reconcile TF with luminosity and mass functions !

fraction of halos with luminous component: $f_L \propto M^{\gamma}$

$$\boxed{\rightarrow f_L \propto M^{0.5-0.8} \propto V^2 \qquad L/M \propto V^2}$$

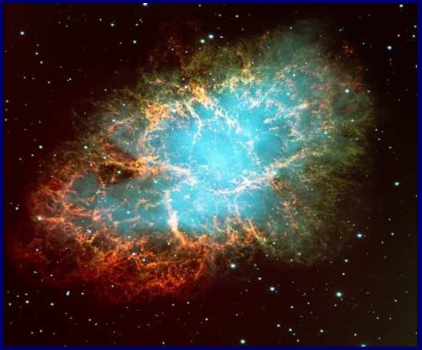
completely dark halos SN feedback

Search for DDH



Complete removal of gas from proto-halos?

By SN outflow? unlikely



By ram pressure due to outflow from a nearby galaxy (Scannapieco, Ferrara & Broadhurst 00) ?

By radiative feedback?

4. Evaporation by Thermal Winds

Shaviv & Dekel 2003

Radiative Feedback

Reionization of H by UV flux from stars and AGN
by z_{ion}~10 → heating gas to $T \approx (1\text{-}2)\times 10^4$K

Jeans scale – **no** infall into halos of **V<30** km/s

Efstathiou 92; Thoul & Weinberg 96; Gnedin & Ostriker 97; Gnedin 00

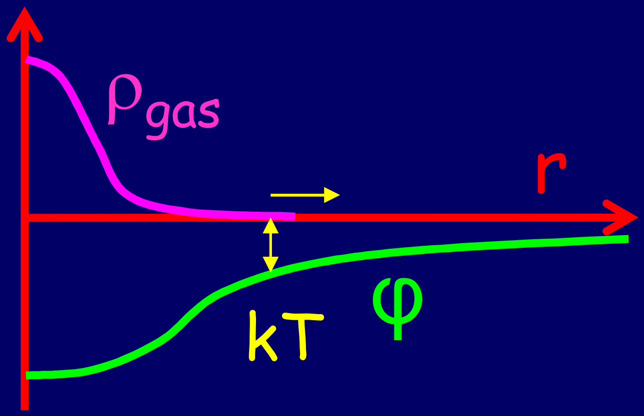
But complete gas removal?

Evaporation from halos of **V<~~10~~** km/s Barkana & Loeb 99

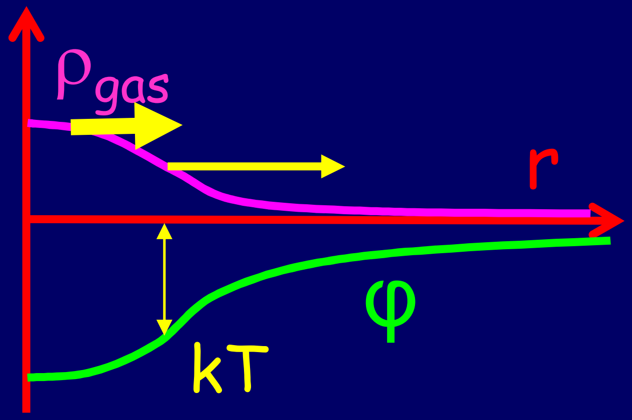
V<30 km/s Shaviv & Dekel 03

May eliminate luminous dwarfs in small halos, 10<V<30

Evaporation of hot gas



cold gas



hot gas

Mass loss from top of potential well $\boxed{t_{\text{evap}} \approx t_{\text{dyn}} e^{\phi/kT}}$

It is continuously replenished and lost

Continuous energy input by the ionizing flux
→ steady wind

Steady Thermal Wind

In stars: Parker 1960. In galaxies: extended potential well

Hydrodynamics:

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v})$$

$$\rho \frac{D\mathbf{v}}{Dt} = -\nabla P + \mathbf{f}_{\mathrm{grav}}$$

$$P = c_{\mathrm{s}}^2 \rho$$

Assume:
spherical, c_s=const., steady state $\dot{M}(r) = \mathrm{const.} \rightarrow \dot{\rho} = 0 \quad \dot{\mathrm{v}} = 0$

→ wind equation: $\left(\mathrm{v}(r) - \frac{c_{\mathrm{s}}^2}{\mathrm{v}(r)} \right) \mathrm{v}'(r) = -\phi'(\mathrm{r}) + \frac{2 c_{\mathrm{s}}^2}{r}$

→ the sonic radius: $\phi'(r_{\mathrm{s}}) = 2 c_{\mathrm{s}}^2 / r_{\mathrm{s}}$ → $r_{\mathrm{s}} \approx GM / c_{\mathrm{s}}^2$

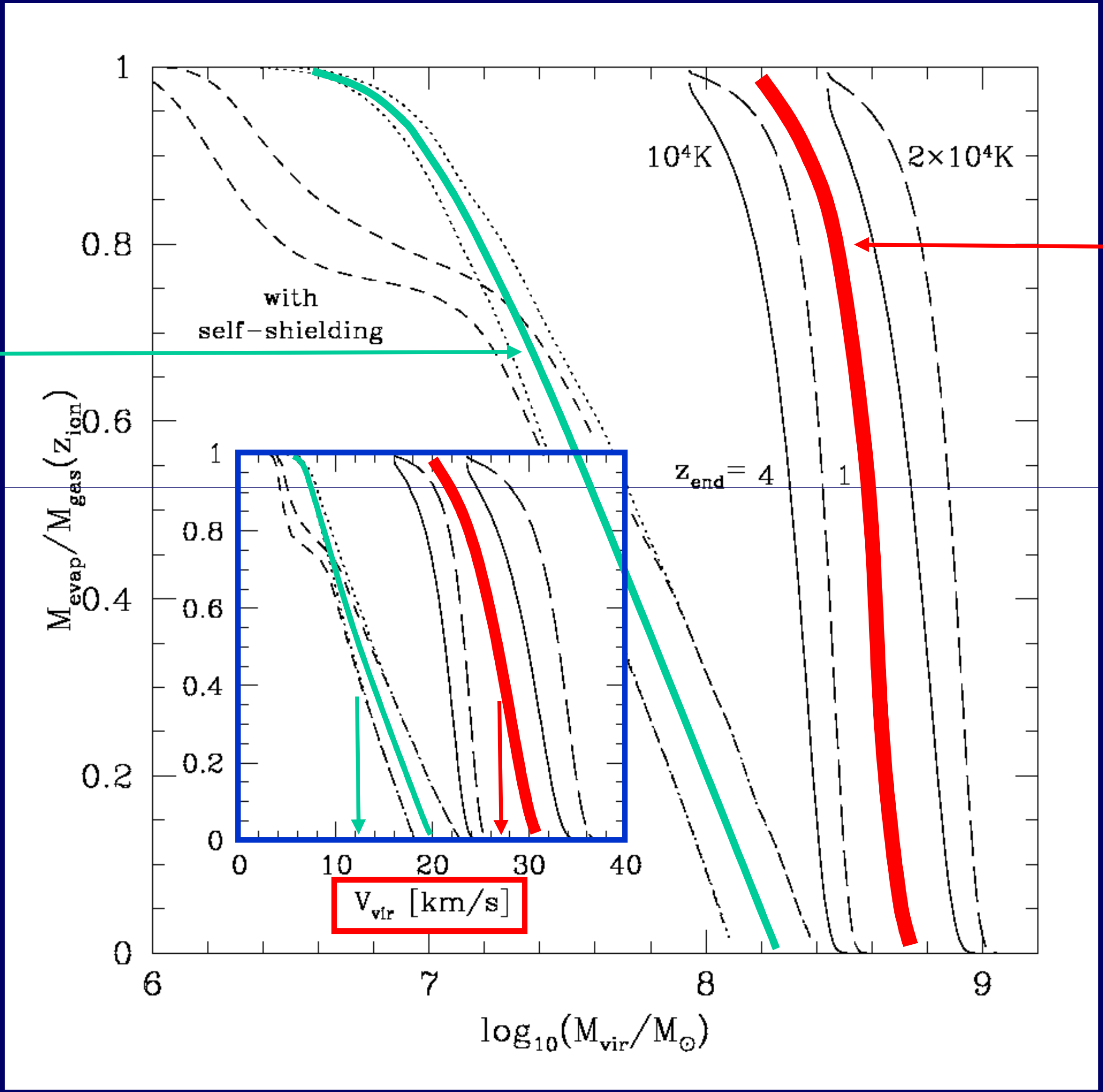
wind parameter (NFW): $\psi \equiv \frac{GM_{\mathrm{c}} / r_{\mathrm{c}}}{c_{\mathrm{s}}^2}$ $t_{evap} / t_{dyn} \approx 10^{\psi - 1}$

ψ>>1 tightly bound, no evaporation

ψ>1 bound, but steady wind >> t_{dyn}

$\psi \leq$1 rapid evaporation ~t_{dyn}

Evaporated Mass Fraction



Barkana & Loeb 99

instant

Shaviv & Dekel 03

wind

$z_{ion}=8$

$z_{end}=2$

Summary Dwarf Halos

Dark-dark halos must exist at V<30 km/s

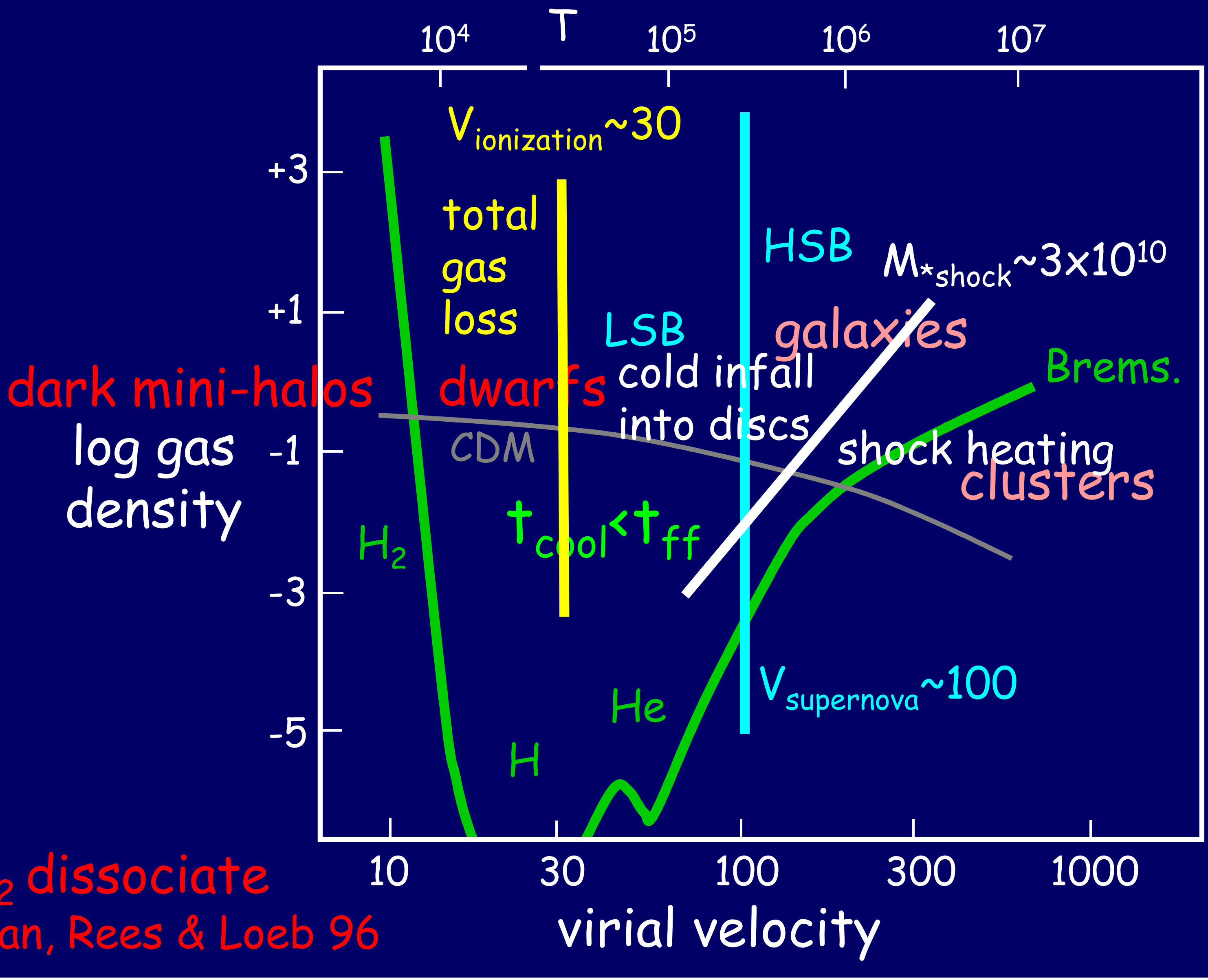
Half the photo-ionized gas evaporates by steady winds from halos of V<30 km/s.

Halos in the range 10<V<30 could be:
- gas-poor dSph /dE
- or totally dark

No galaxies V<10 becasue of cooling barrier

Cooling vs Free Fall

Rees & Ostriker 77, Silk 77, White & Rees 78

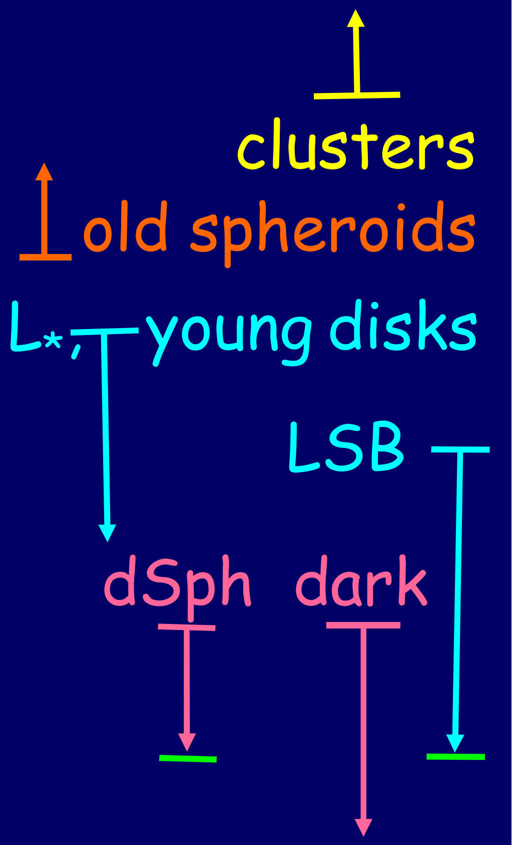


H_2 dissociate

Haiman, Rees & Loeb 96

Summary: Characteristic Scales

	V (km/s)	$M_*(M_\odot)$	$M(M_\odot)$
Cooling (Brems.)	300	2×10^{11}	10^{13}
Shock heating	100	3×10^{10}	6×10^{11}
Supernovae	100	3×10^{10}	6×10^{11}
Photoionization	30	10^{8}	2×10^{10}
Cooling (H)	10	3×10^{5}	6×10^{8}



clusters

old spheroids

L_*, young disks

LSB

dSph dark

Phase-Space Density & Halo Substructure

Arad & Dekel, in progress

Phase-Space Density

$$f(\vec{x},\vec{v})$$

$$\rho(\vec{x}) = \int d\vec{v}\ f(\vec{x},\vec{v})$$

Vlasov eq.

$$\partial_t f + \vec{v}\cdot\vec{\nabla}_x f - \vec{\nabla}_x \phi \cdot \nabla_v f = 0$$

Poisson eq.

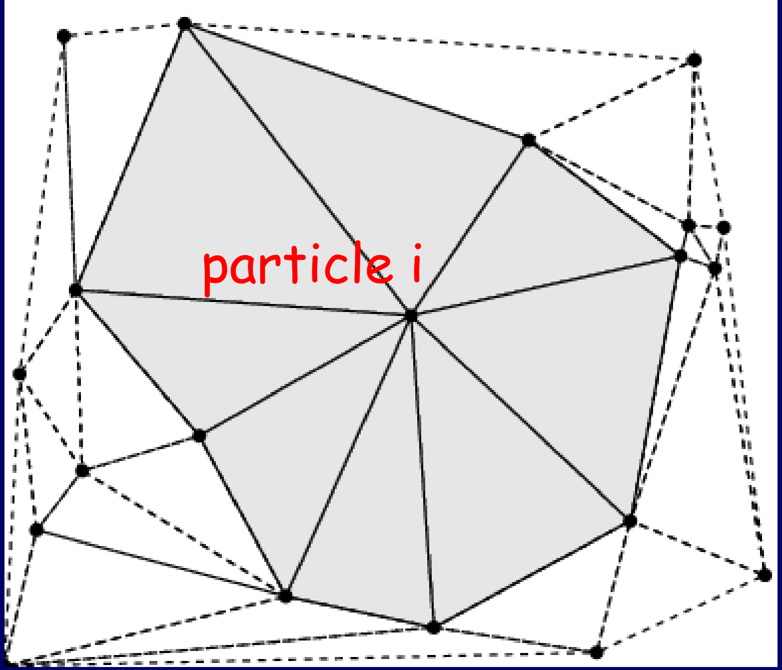
$$\phi(\vec{x}) = -G\int d\vec{x}'\,d\vec{v}\ \frac{f(\vec{x}',\vec{v})}{|\vec{x}-\vec{x}'|}$$

Distribution function of f:

$$V(f = f_0) \equiv \int d\vec{x}d\vec{v}\ \delta_{Dirac}[f(\vec{x},\vec{v},t) - f_0]$$

V(f)df = volume of phase space occupied by f in the range (f,f+df)

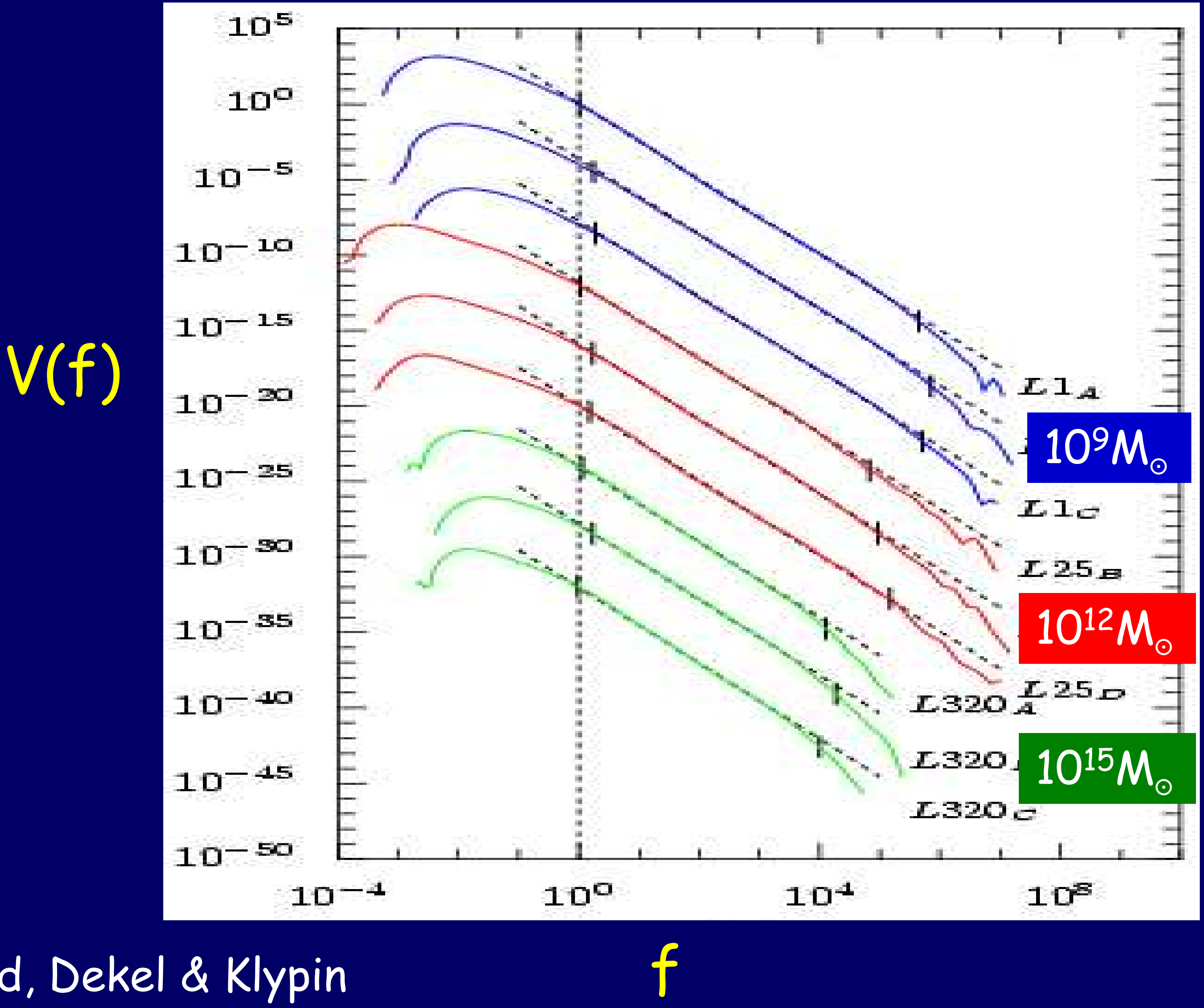
Measuring f(x,v) using an adaptive "grid"
Delaunay Tesselation



$$f_i = (d+1)\frac{m}{V_i}$$

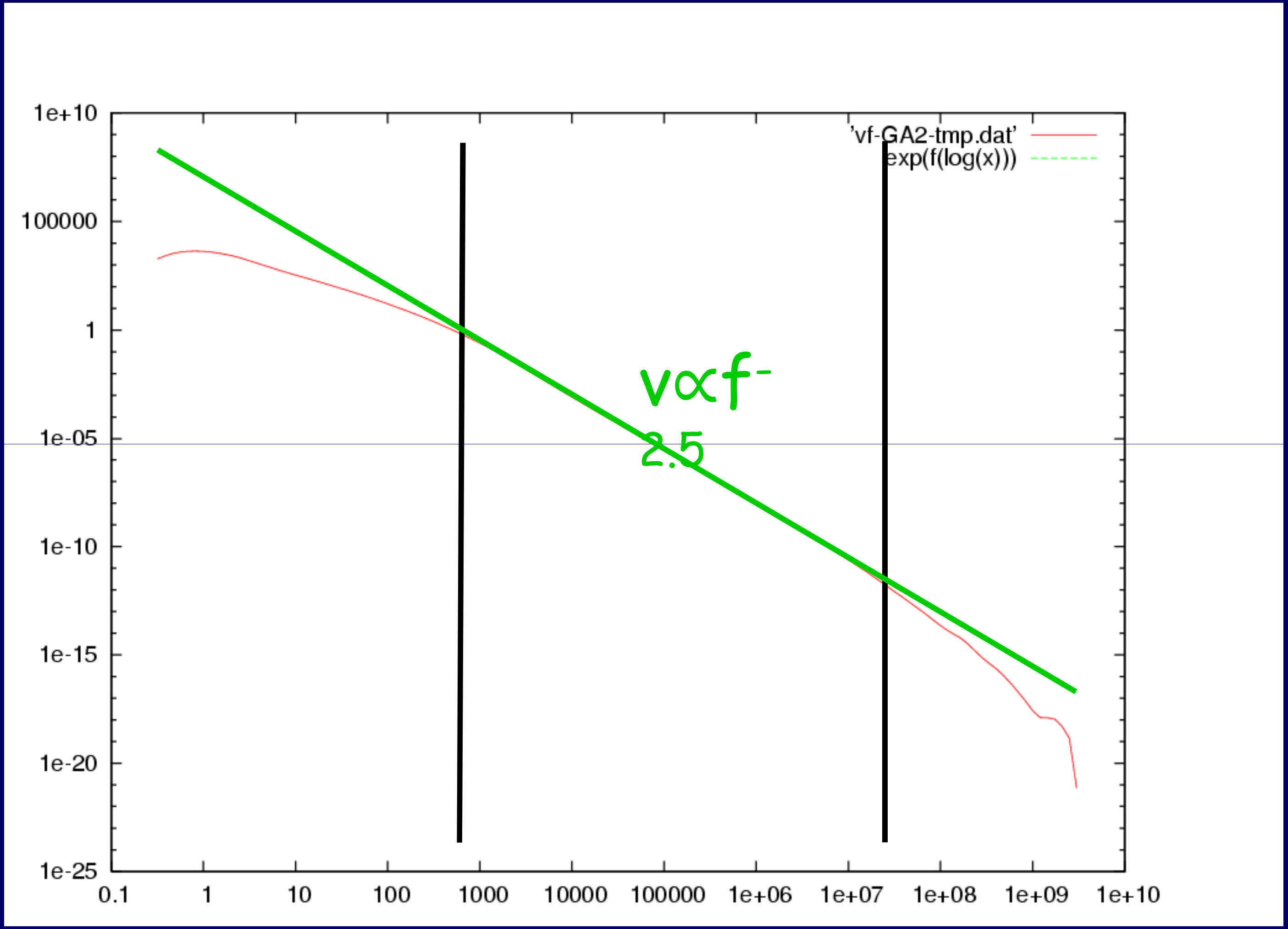
Arad, Dekel & Klypin

PDF of Phase-Space Density



Arad, Dekel & Klypin

PDF of Phase-Space Density



V(f)

f

Arad, Dekel & Klypin

V(f) related to ρ(r)?

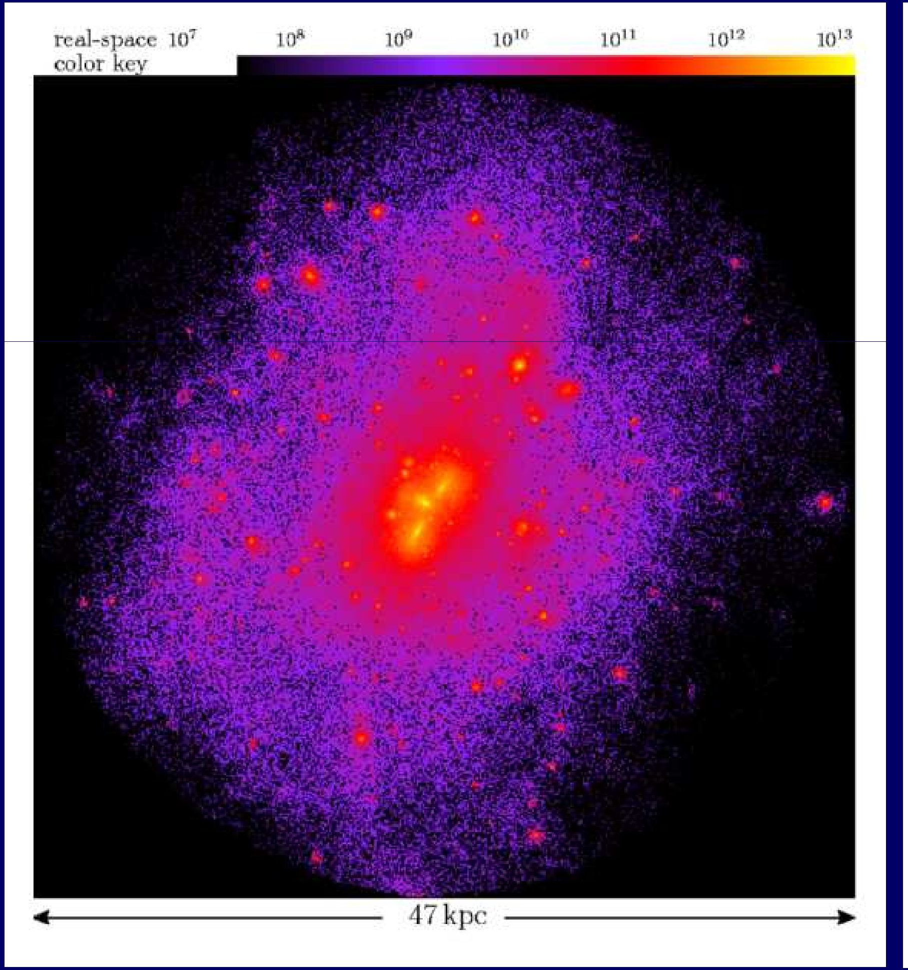
if $f(\vec{x},\vec{v}) \xcancel{=} f(E)$ e.g., spherical & isotropic

$$\rho(r) \propto r^{-\alpha}, \quad V(f) \propto f^{-\beta}, \quad \beta = \frac{18-4\alpha}{6-\alpha}$$

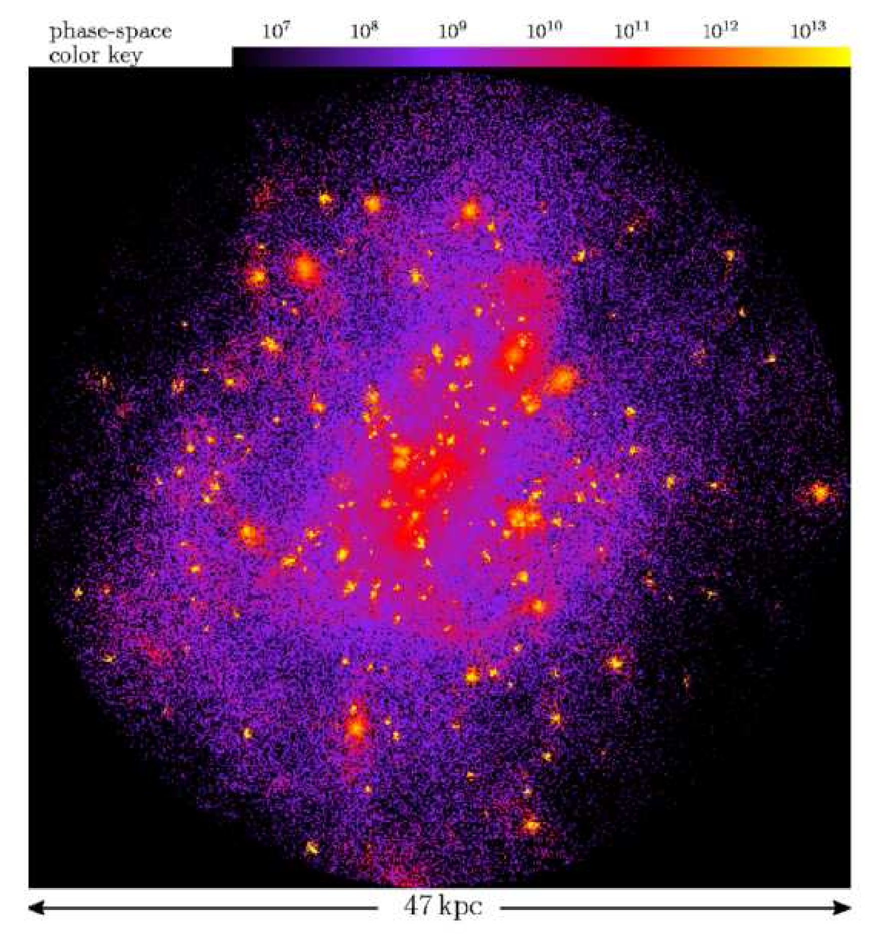
$$\alpha = 3 \leftrightarrow \beta = 2$$
$$\alpha = 2 \leftrightarrow \boxed{\beta = 2.5}$$
$$\alpha = 1 \leftrightarrow \beta = 2.8$$
$$\alpha = 0 \leftrightarrow \beta = 3$$

Halo Phase-Space Density

Real Density

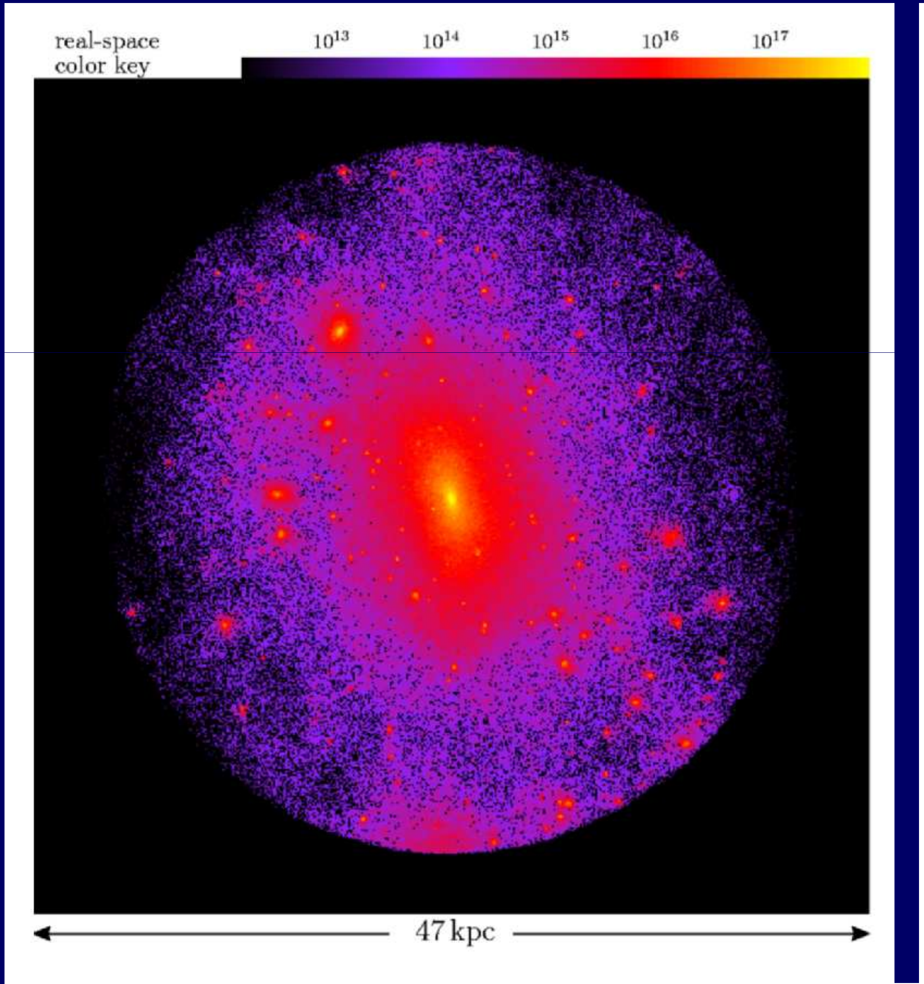


Phase-Space Density

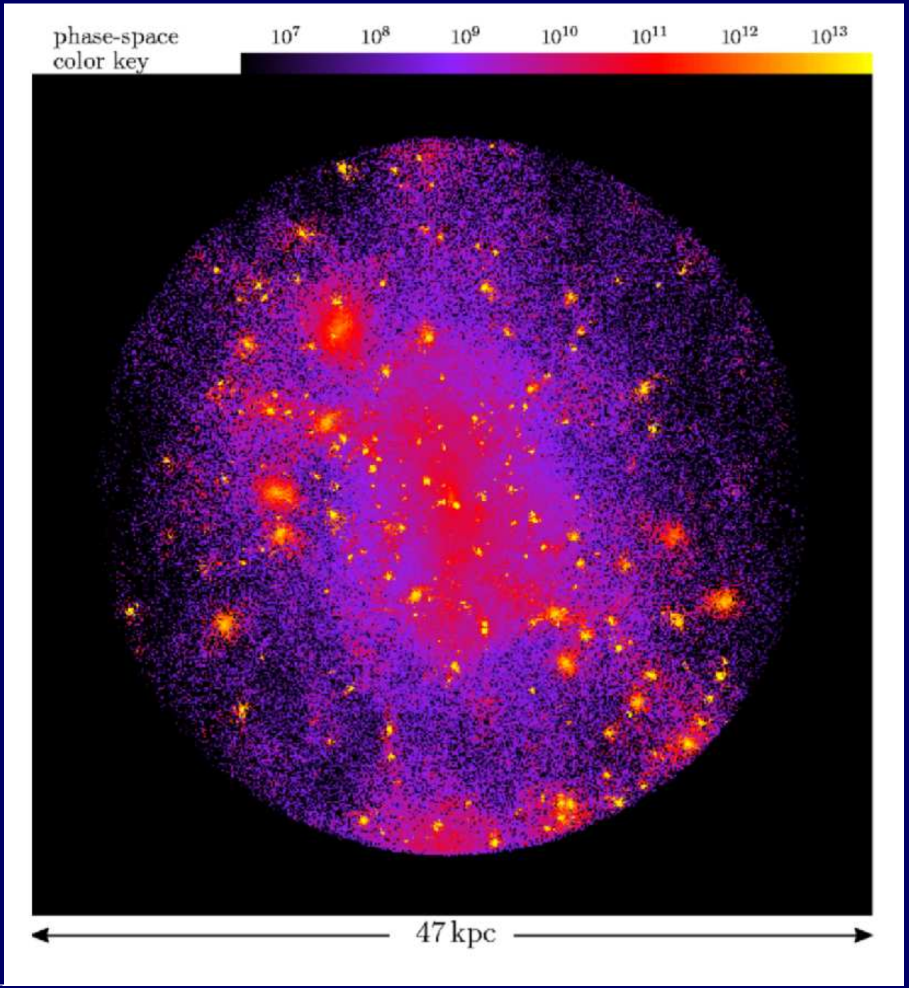


Halo Phase-Space Density

Real Density

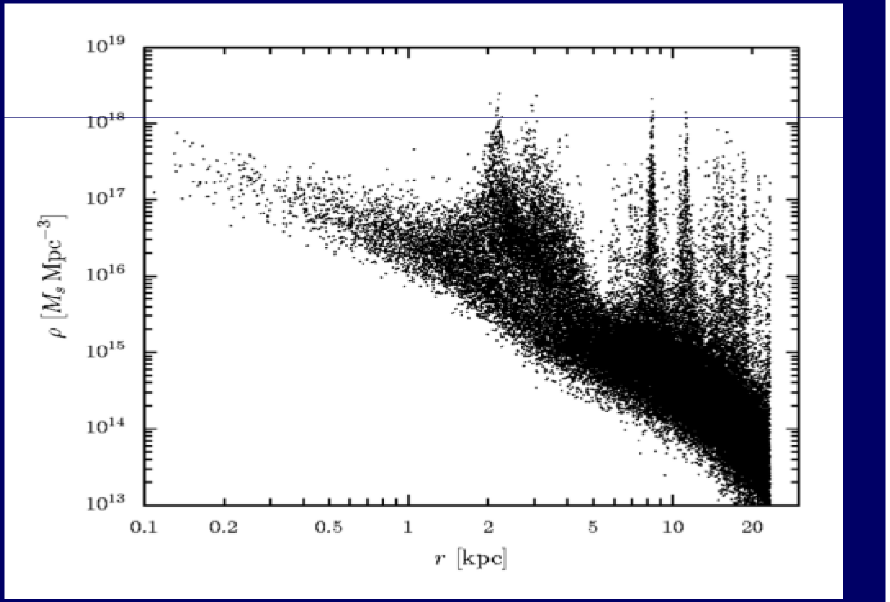


Phase-Space Density



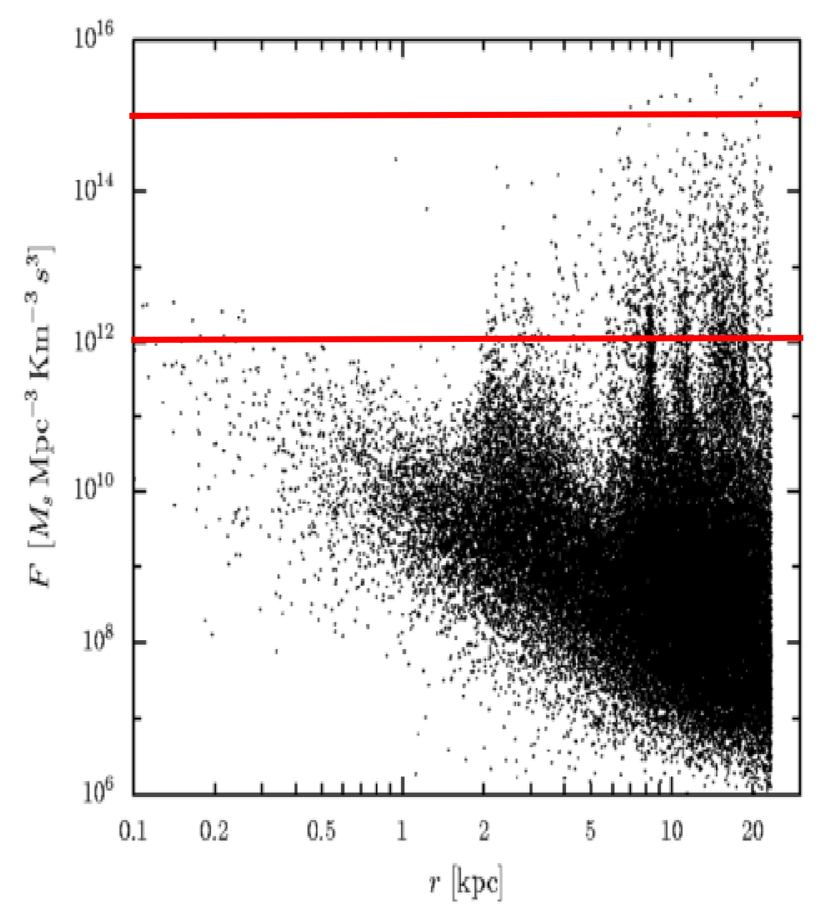
Profiles in Real Space and Phase Space

ρ(r)



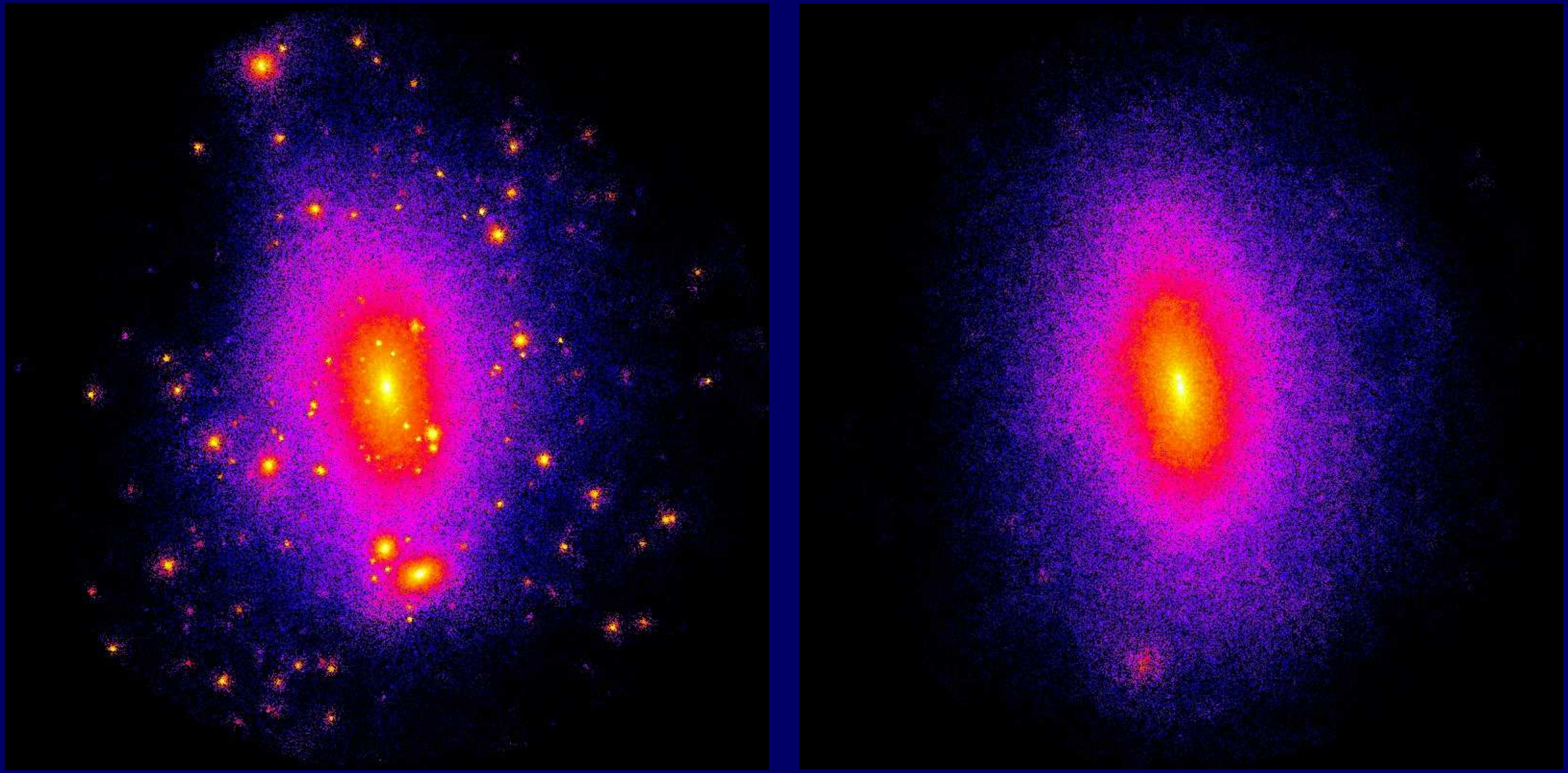
radius

f(r)



radius

Is v(f)$\propto$f$^{-2.5}$ determined by substructure?

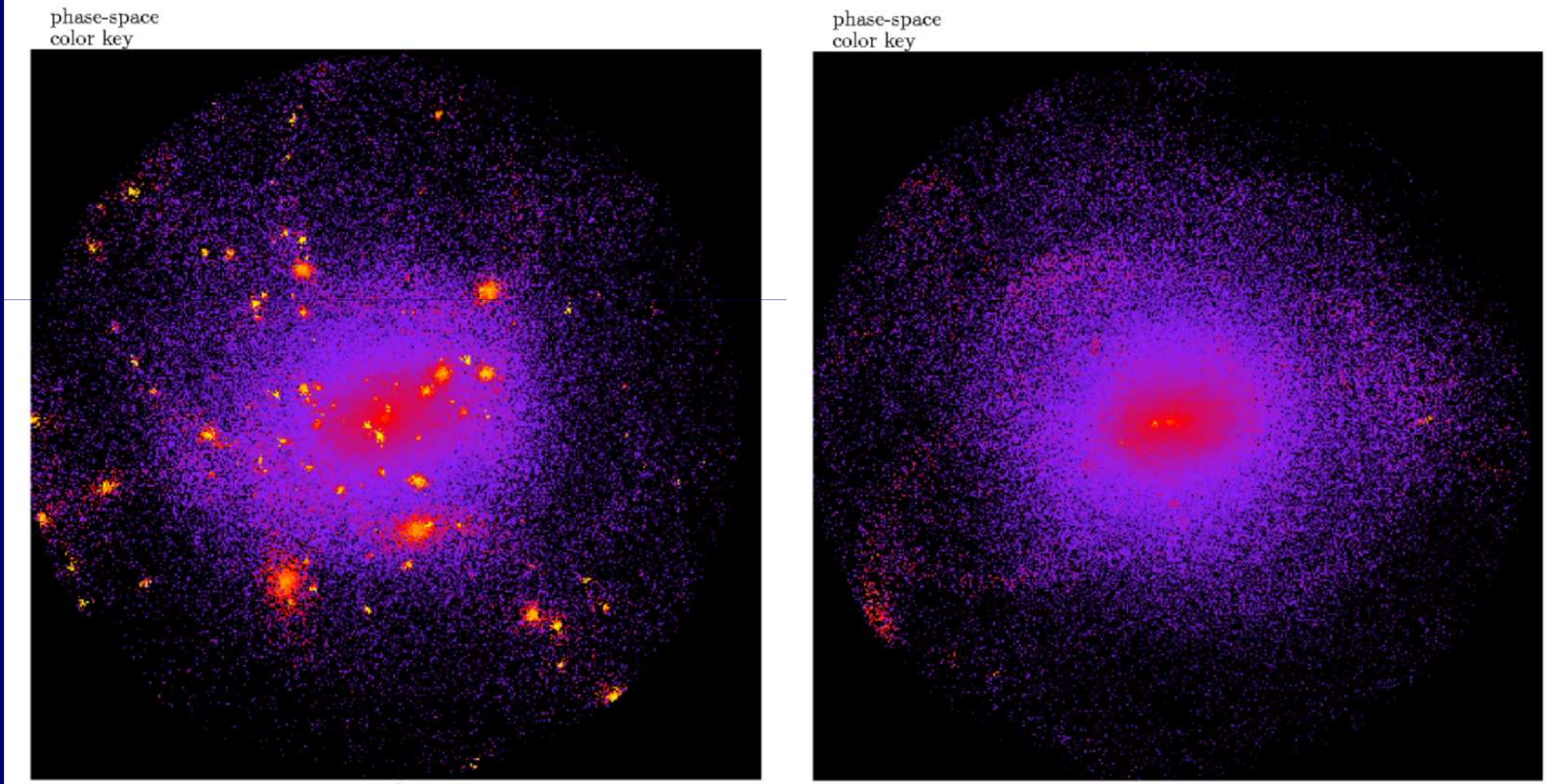


Real-Space Density

Moore et al.

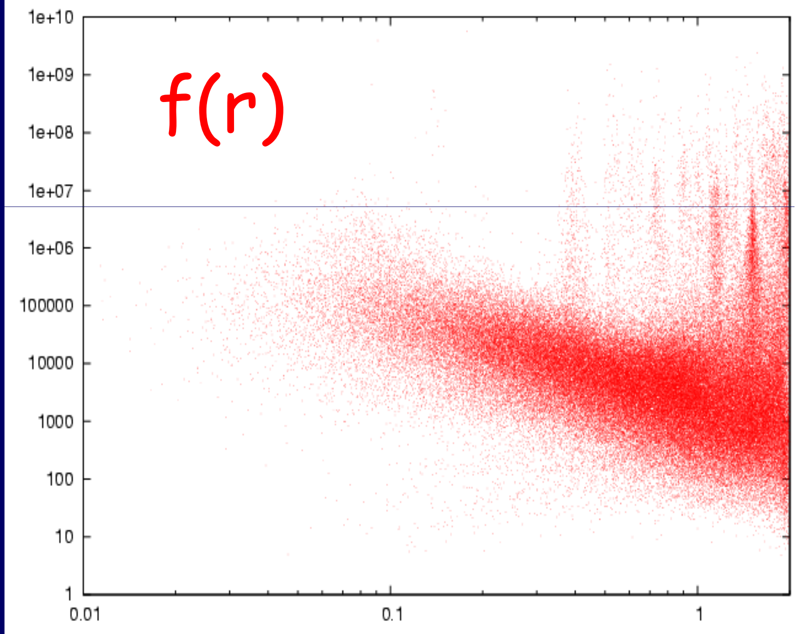
Phase-Space density

ΛCDM No short waves



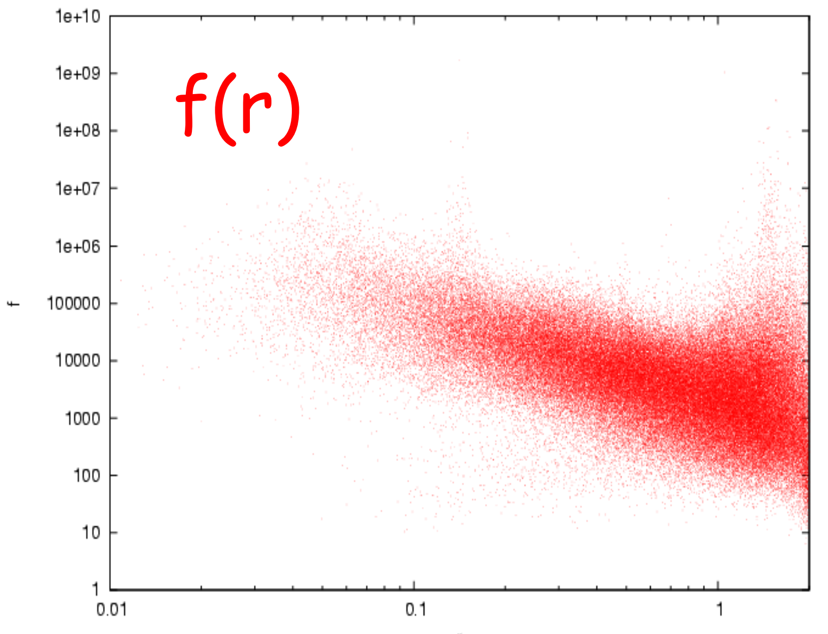
Phase-Space Density Profile

ΛCDM



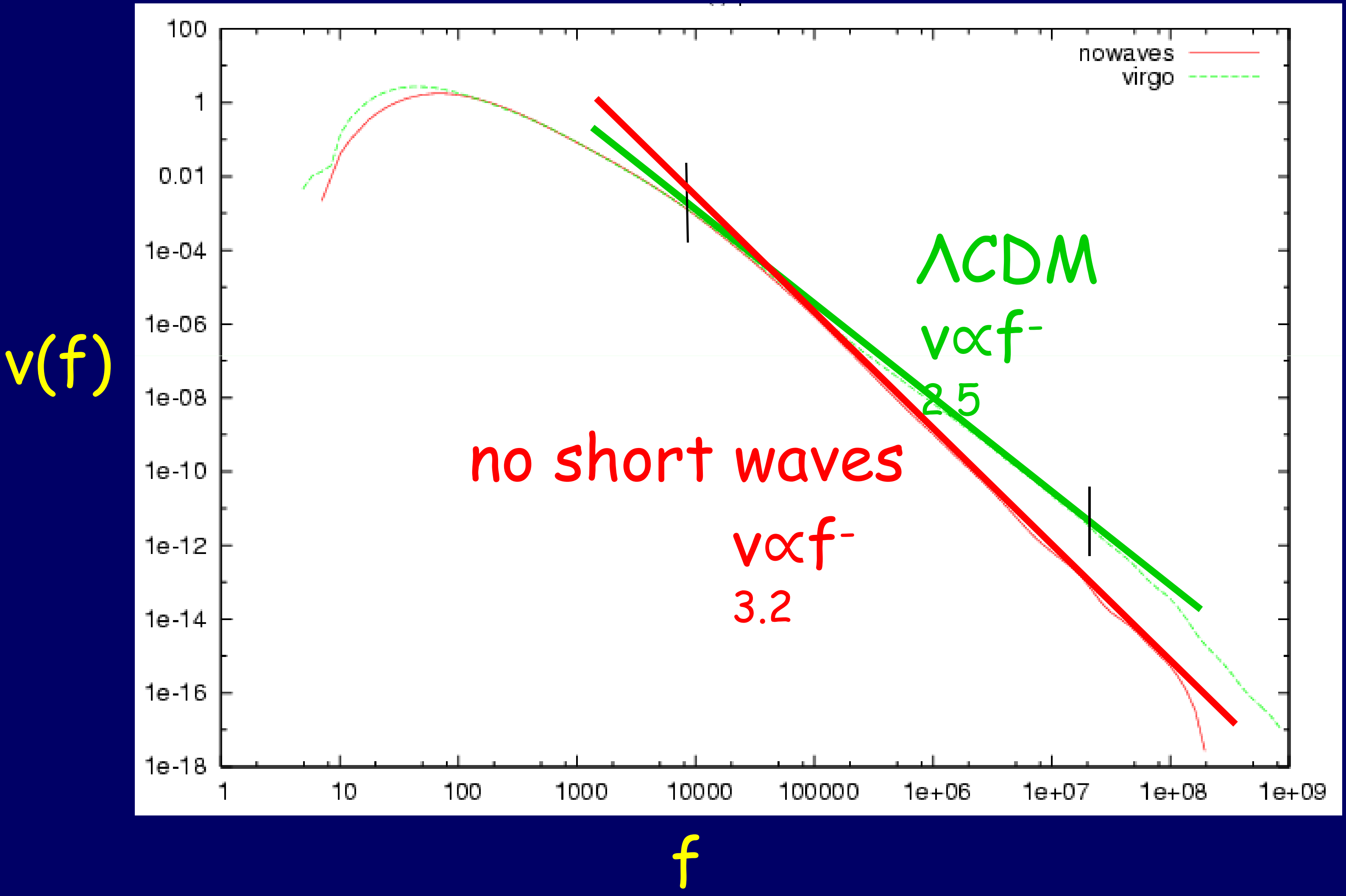
radius

No short waves

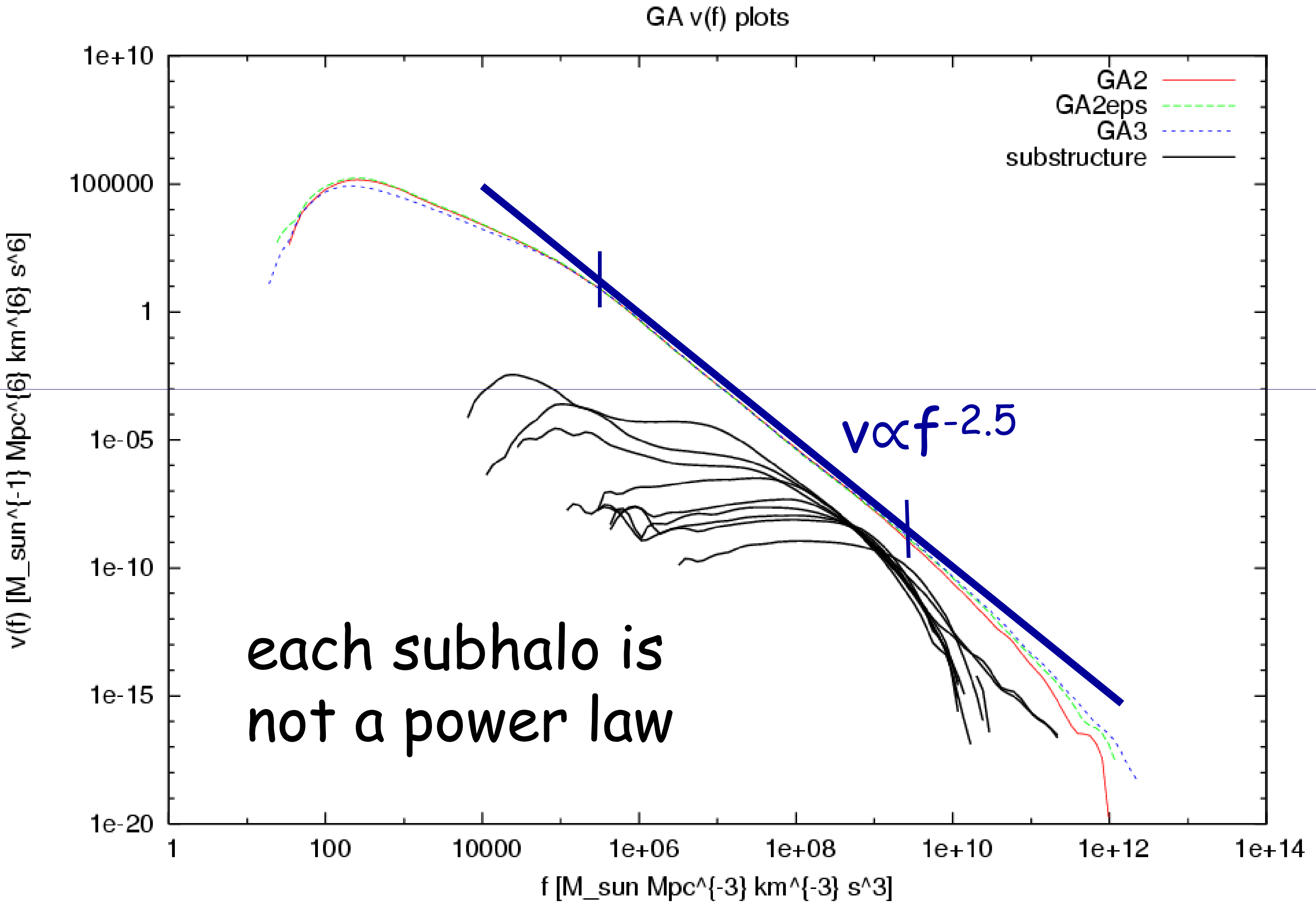


radius

Same power law v(f)?

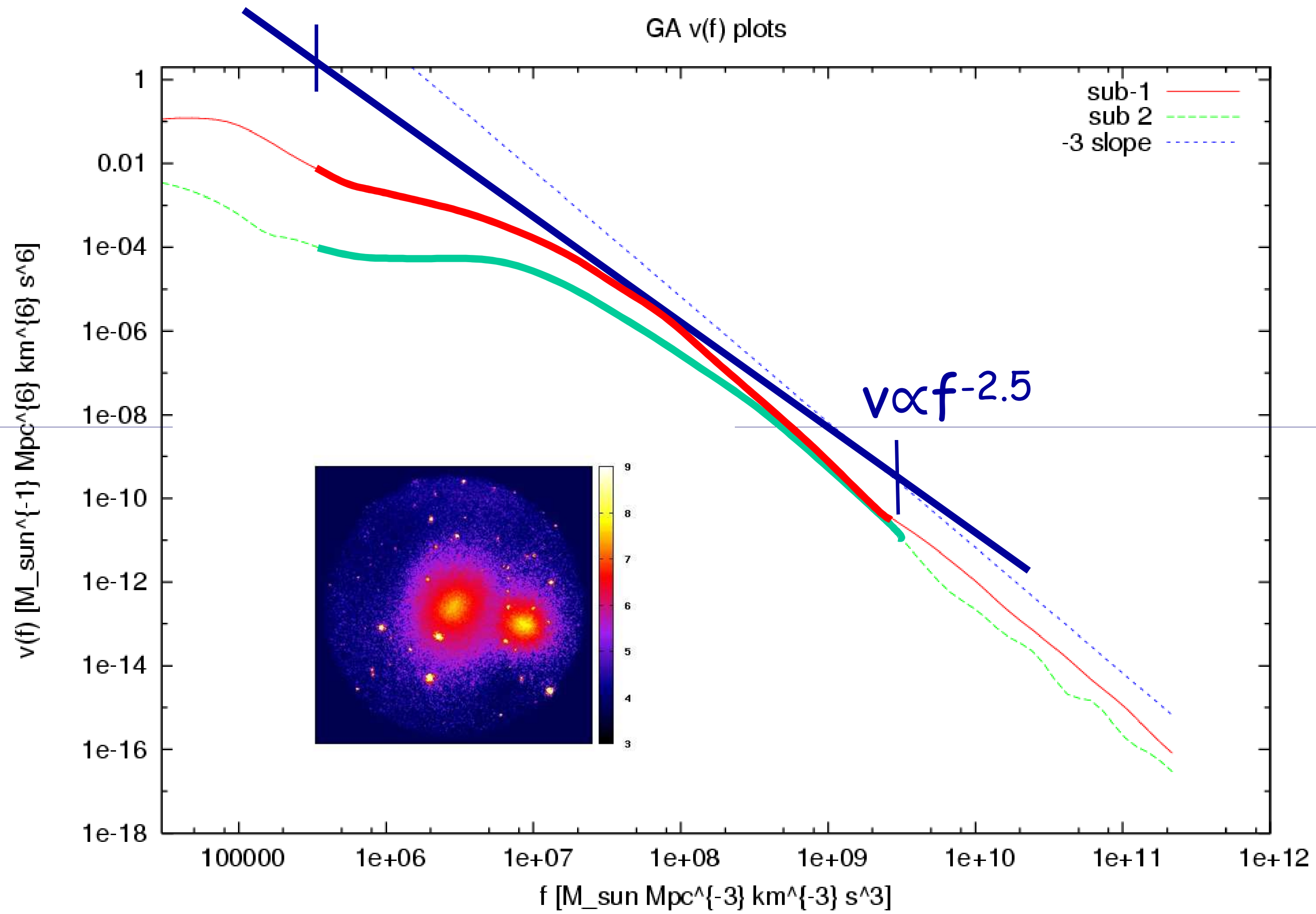


Additive Contribution of Subhalos

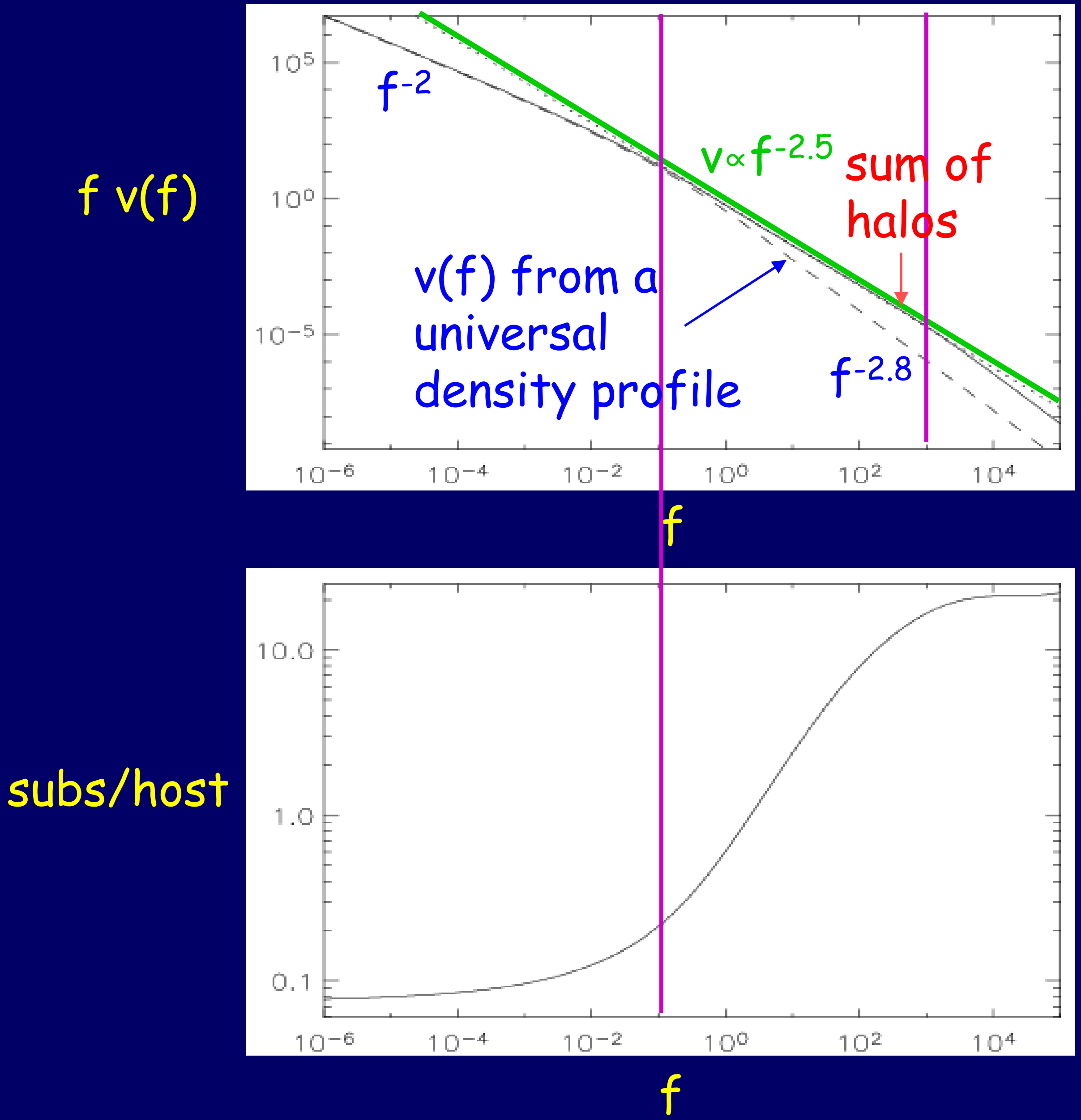


each subhalo is
not a power law

The Two Most Massive Subhalos



Adding up Sub-halos



$\rho(r) \rightarrow v(f)$

halo mass function:

$$\phi(m) \propto m^{-\gamma} \quad \gamma \approx 1.8$$

Scaling of halos:

$$\rho \propto m / r^3 = const.$$

$$r \propto m^{1/3} \qquad \sigma \propto m^{1/3}$$

Boylan-Kolchin, Ma, Arad, Dekel

Tentative Conclusions

In hierarchical clustering, robust PDF: $v(f) \propto f^{-2.5}$ doesn't depend on power-spectrum slope, or on method of simulation

The power-law $v(f)$ is driven by substructure.
How exactly? Yet to be understood !

Phase-space density is a unique tool for studying substructure and its evolution

Adding up small CDM halos leads to $v(f) \propto f^{-2.5}$?
How robust? How dependent on subhalo density profile and mass function?