Galaxy Formation

par Avishai Dekel

The Hebrew University of Jerusalem
& Chaire Internationale de Recherche Blaise Pascal, Paris

Une série de cours (en anglais) pour les étudiants en thèse (et M2) et les chercheurs

les mercredis, de 17h00 à 19h00 à l'amphithéâtre de l'IAP

98bis Bd Arago - Paris 14ème - M° St Jacques ou Denfert-Rochereau

20 octobre

1. The standard cosmology
2. Linear growth of fluctuations by gravitational instability

A special lecture series on Galaxy Formation

by Avishai Dekel (Chaire Internationale Blaise Pascal)

for graduate students and researchers; IAP/OP Wednesdays 17:00-19:00

Octobre 20	1. the standard cosmology
	2. linear growth of fluctuations by gravitational instability
Novembre 17	3. statistics of density fluctuations: the CDM scenario
	4. nonlinear growth: spherical model, filamentary structure
Decembre 8	5. numerical simulations of structure formation
	6. hierarchical clustering: Press-Schechter formalism, biasing
Decembre 15	7. dark-matter halos: density profile, cusp/core problem
	8. halo substructure: dynamical friction, tidal effects, HOD
Janvier 5	9. angular momentum problem: tidal torques, disk formation
	10. the origin of galaxy scaling relations and their scatter
Janvier 12	11. semi-analytic modeling: cooling, star formartion, mergers
	12. feedback processes: supernova, AGN and black holes
Fevrier 9	13. cold flows versus shock heating
	14. origin of bi-modality in galaxies
Fevrier 16	15. dwarf galaxies and the "fundamental line"
	16. dark-dark halos: effect of cosmological photoionization

Lectures 15-16 (some 8,12)

Dwarf Galaxies & Dark-Dark Halos: Feedback Processes

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

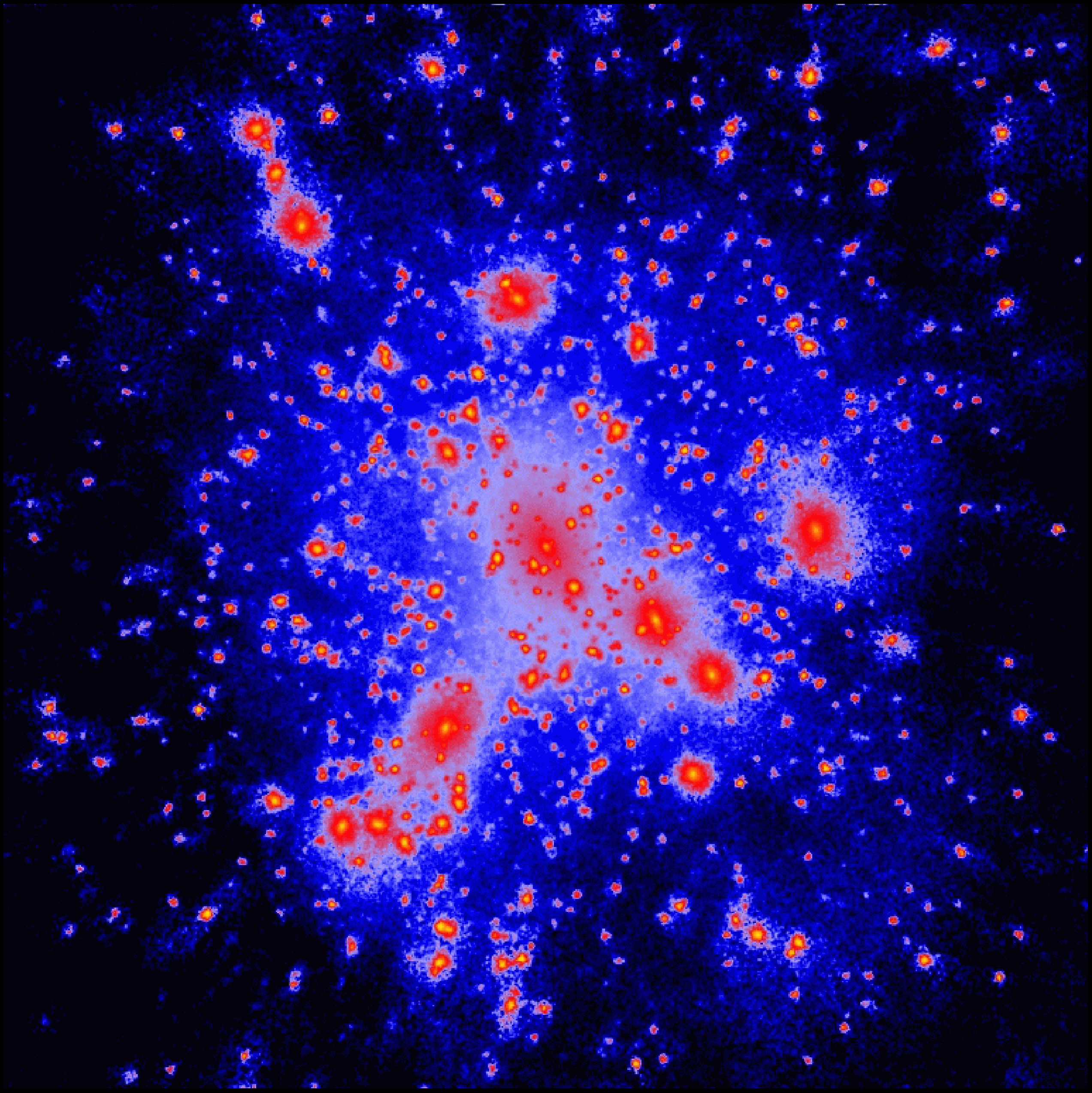
- Dark-dark halos (DDH) must exist
- Origin of DDH by photoionization

- Halo substructure: phase-space density

1. Missing Dwarfs & the "Fundamental Line"

Dekel & Woo 2003

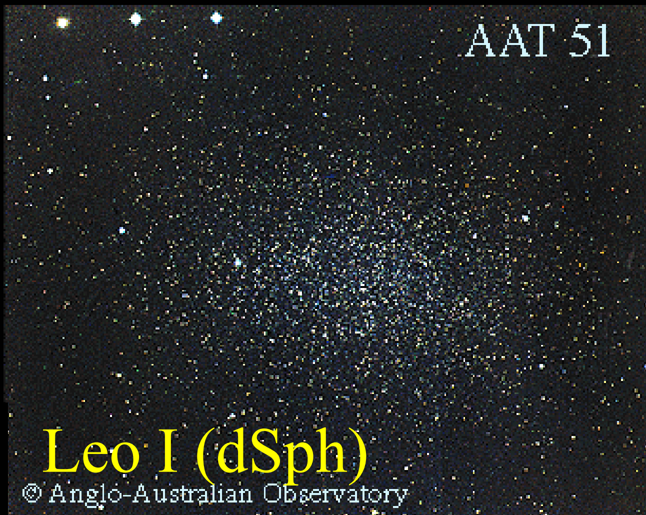
ΛCDM model: many dwarf satellites

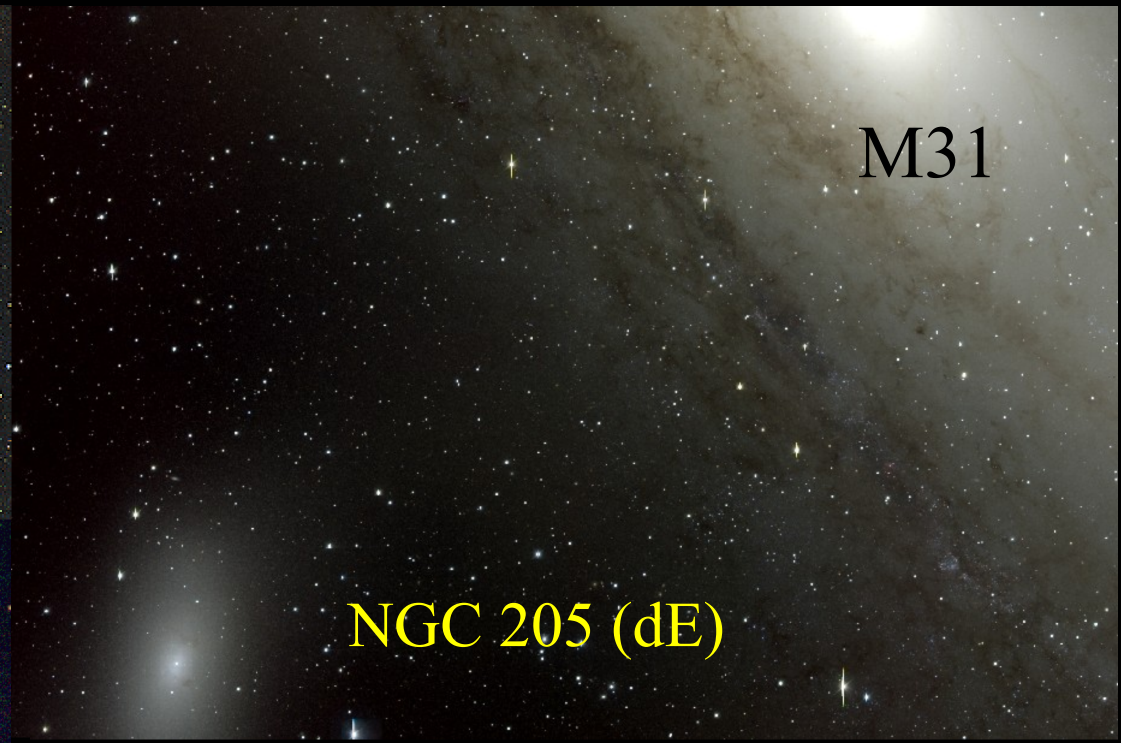


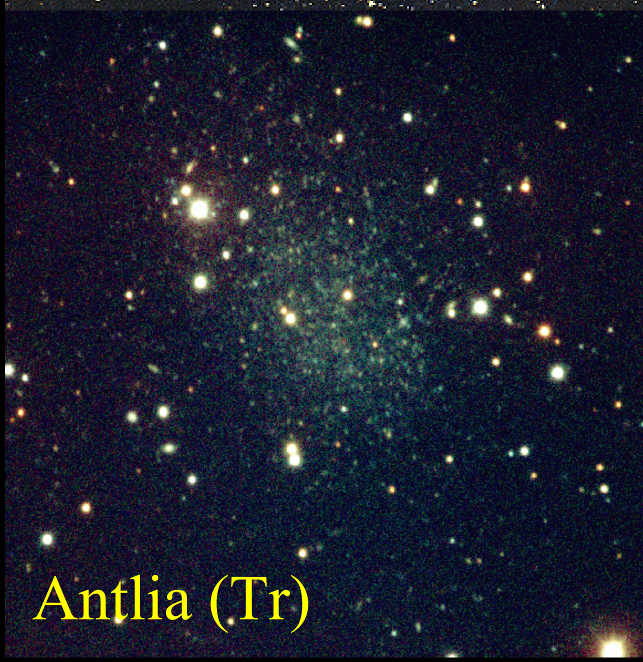
Moore et al

Low-Surface-Brightness & Dwarf Galaxies

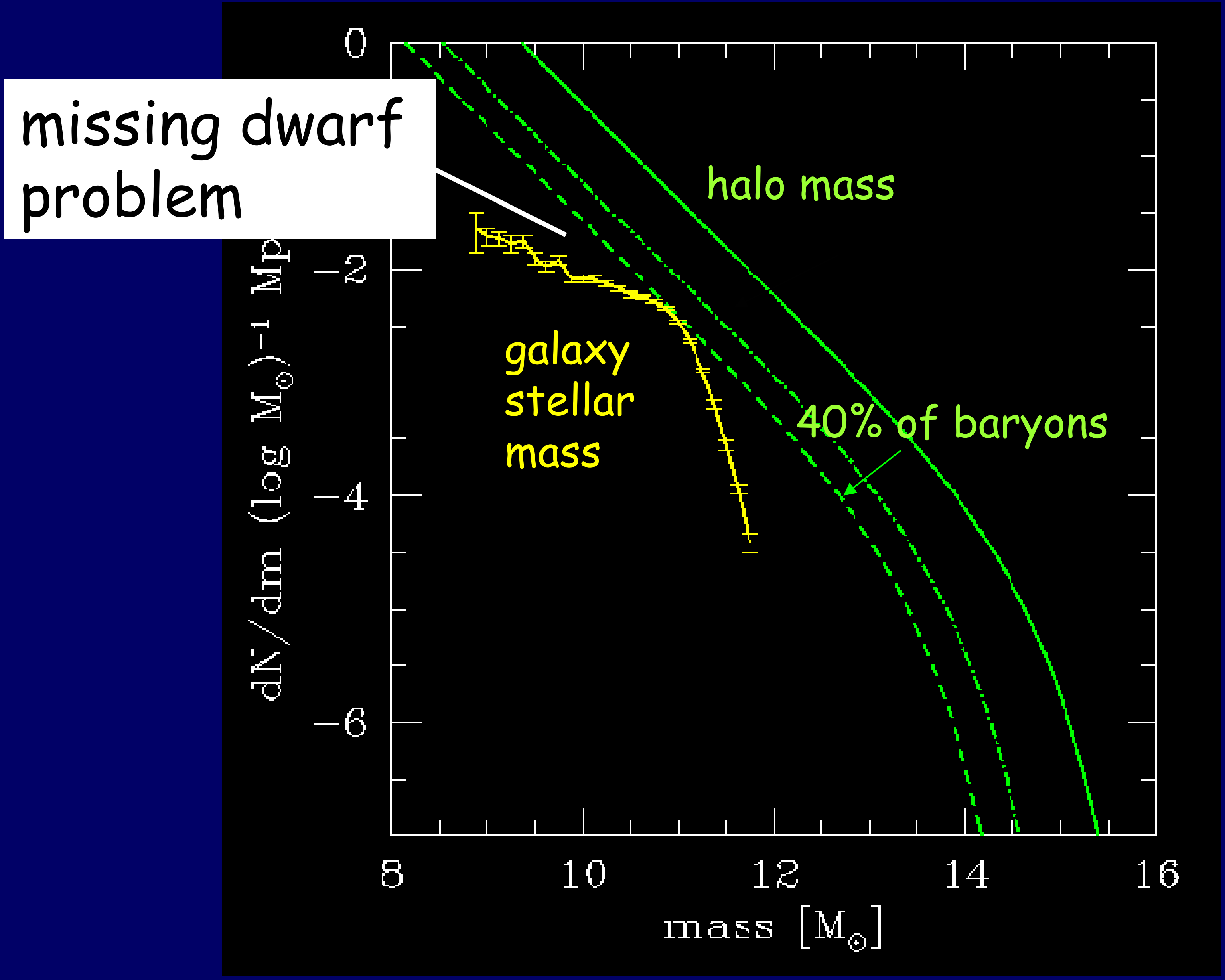
Only a few faint dwarf satellites





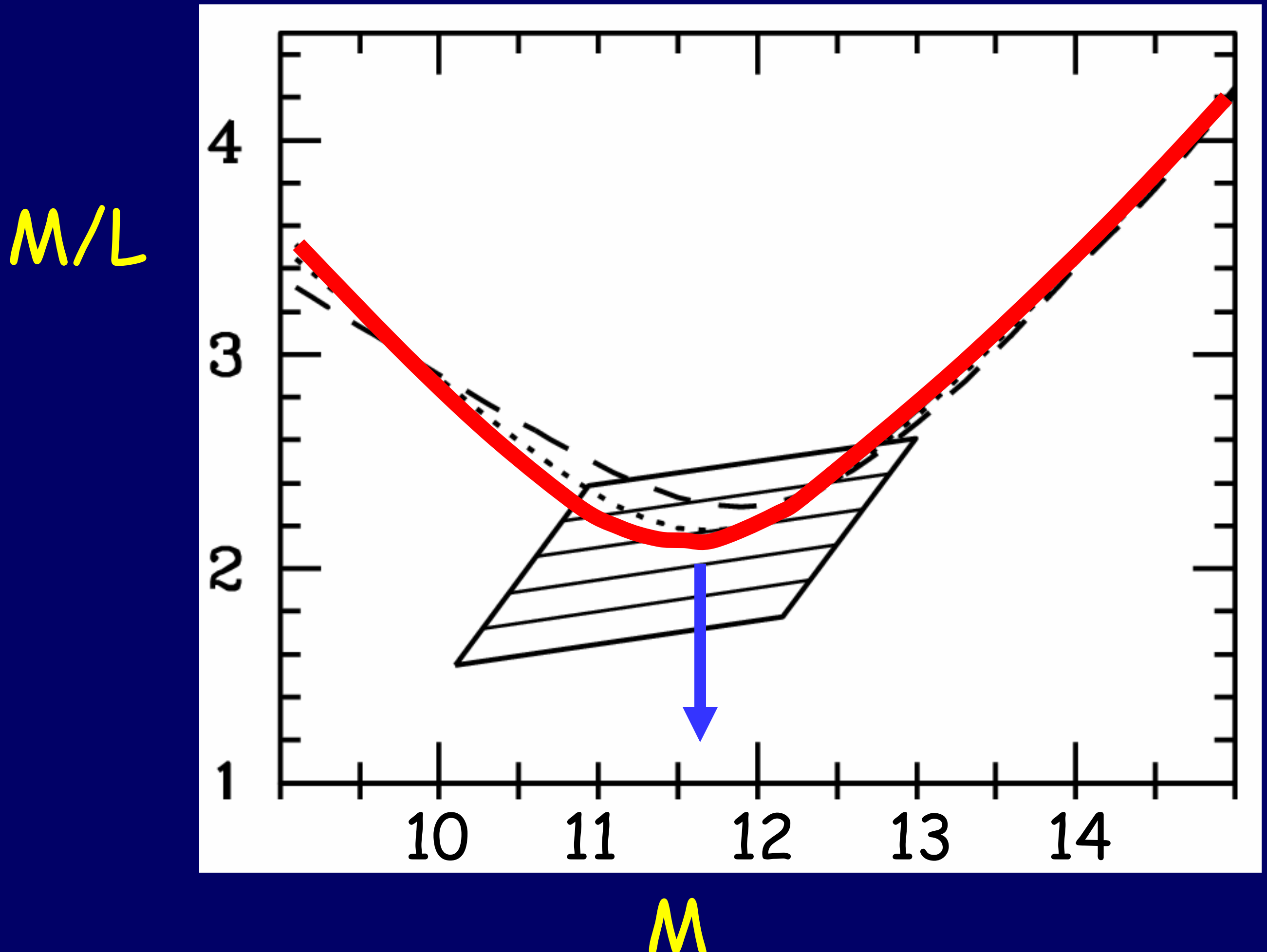


Mass versus Light Distribution



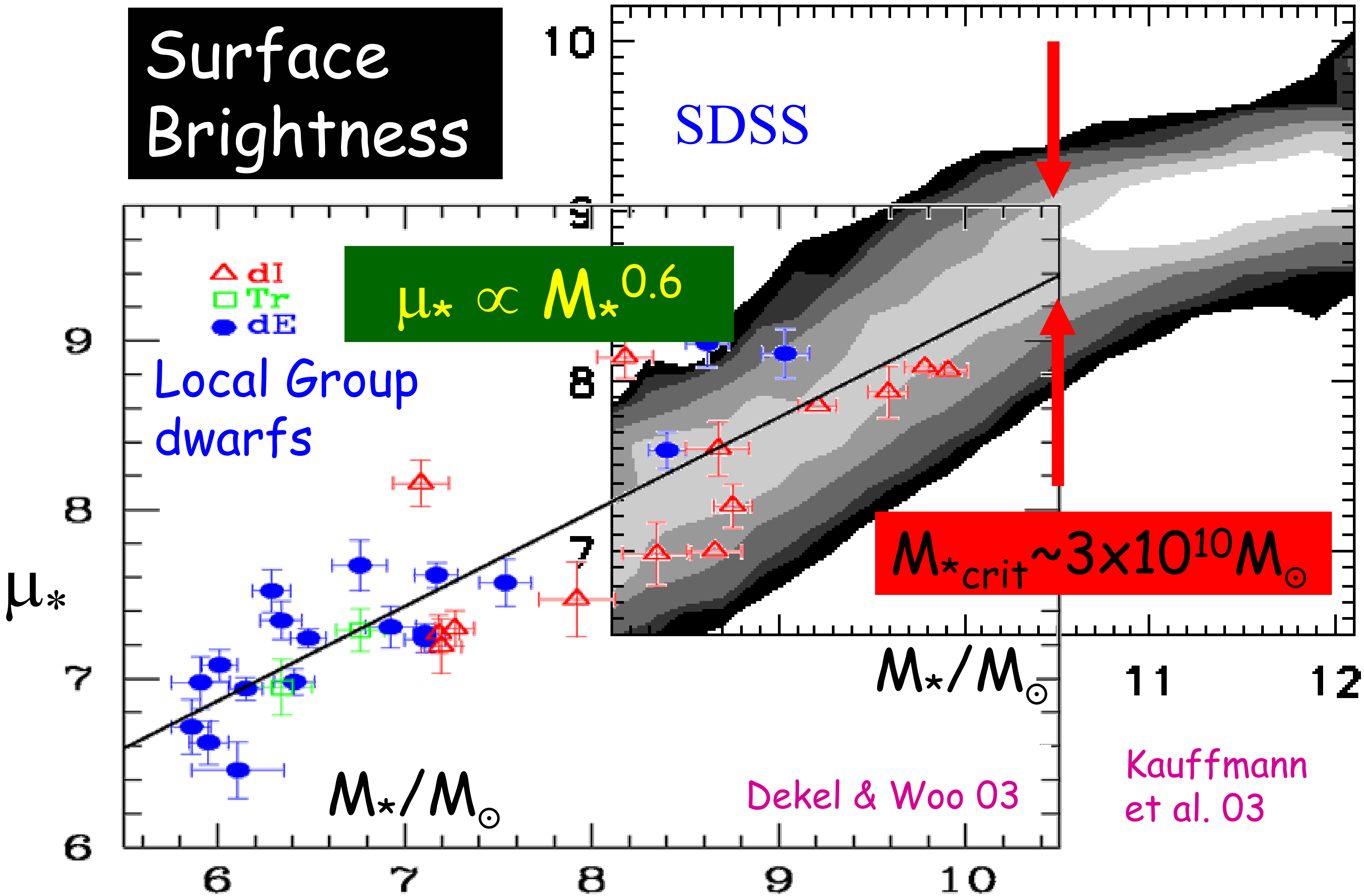
<M/L> vs M for halos in 2dF

assuming ΛCDM

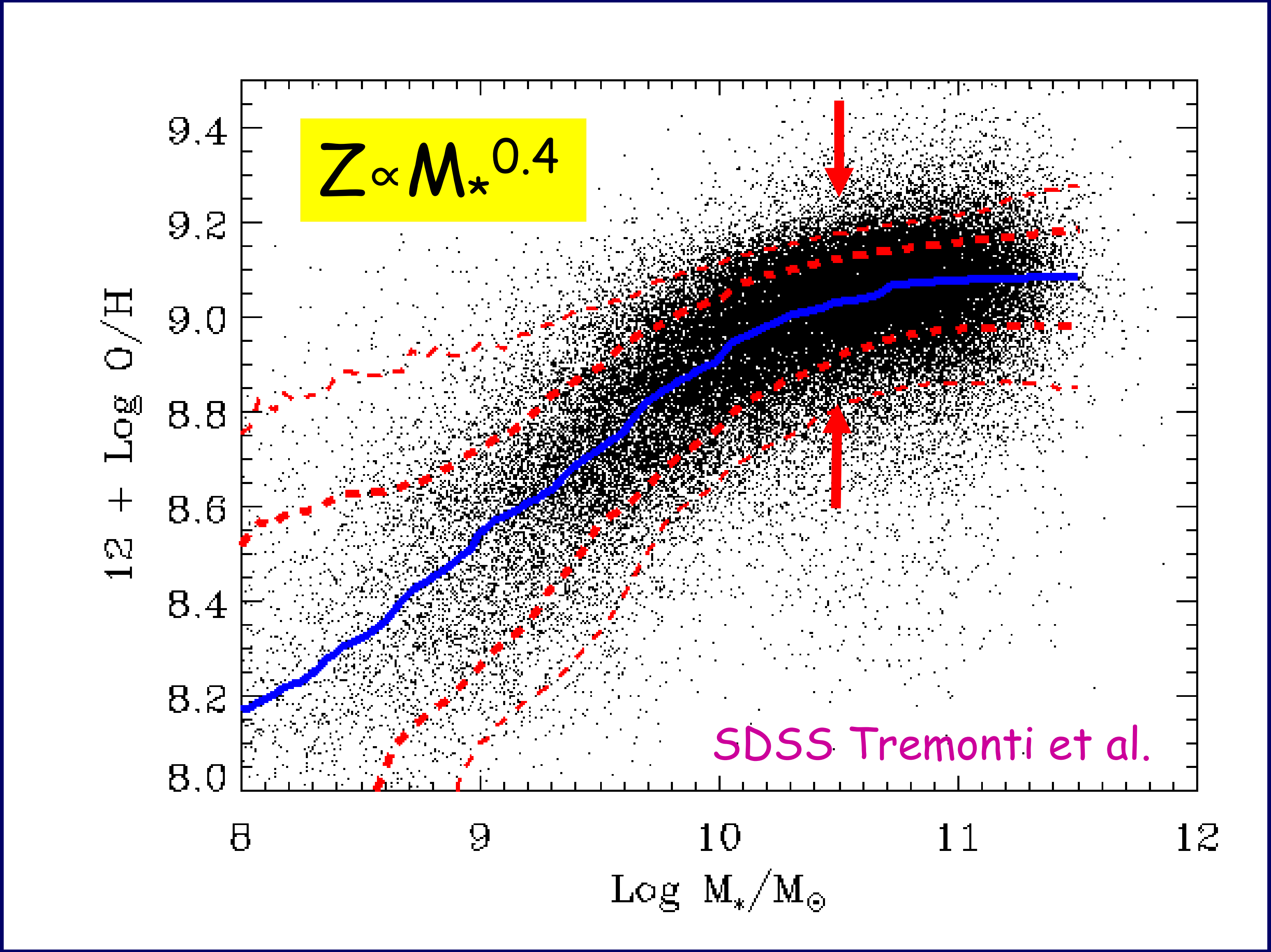


Using conditional luminosity function: Van den Bosch, Mo, Yang 03

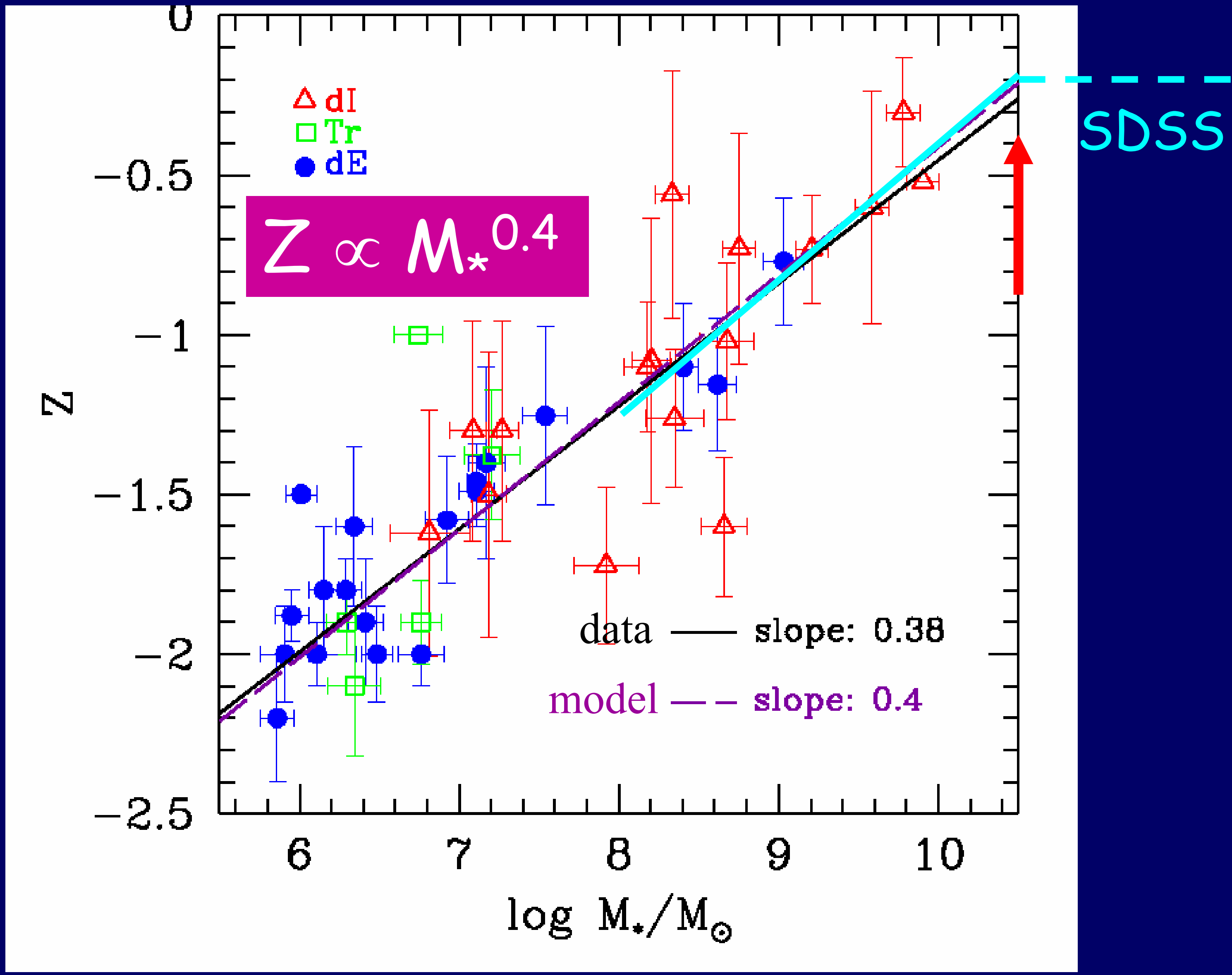
The "Fundamental Line" of LSB/Dwarfs



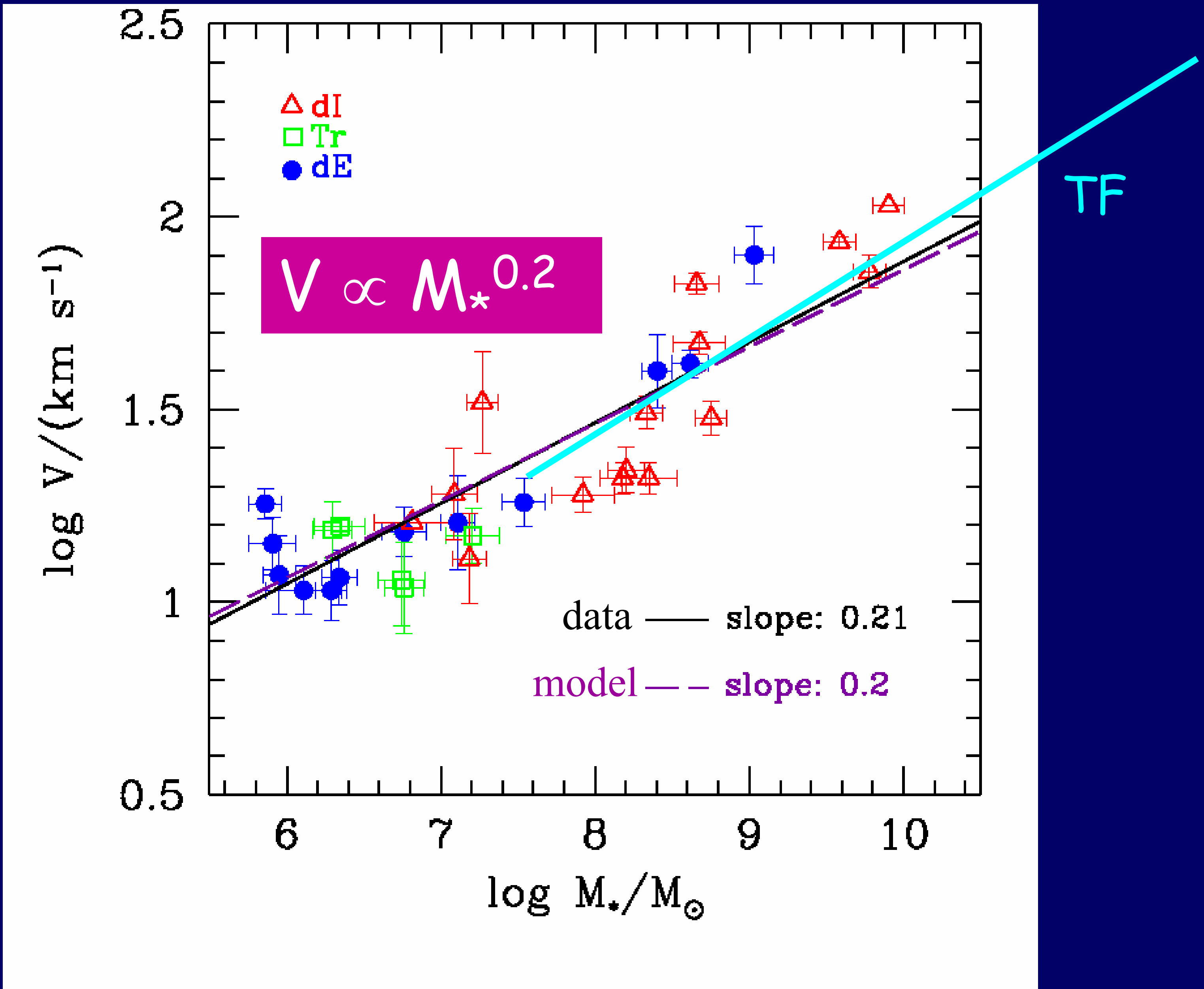
Metallicity



Local Group Dwarfs: Metallicity



LG Dwarfs: Velocity



2. Origin of Scaling Relations:

virial theorem & spherical halo collapse

angular momentum

feedback

Bright Galaxies

- virial halo $V^2 \propto \frac{GM}{R}$ top hat $\frac{M}{R^3} \propto 200\rho_u$ $\rightarrow \quad M \propto V^3 \propto R^3$

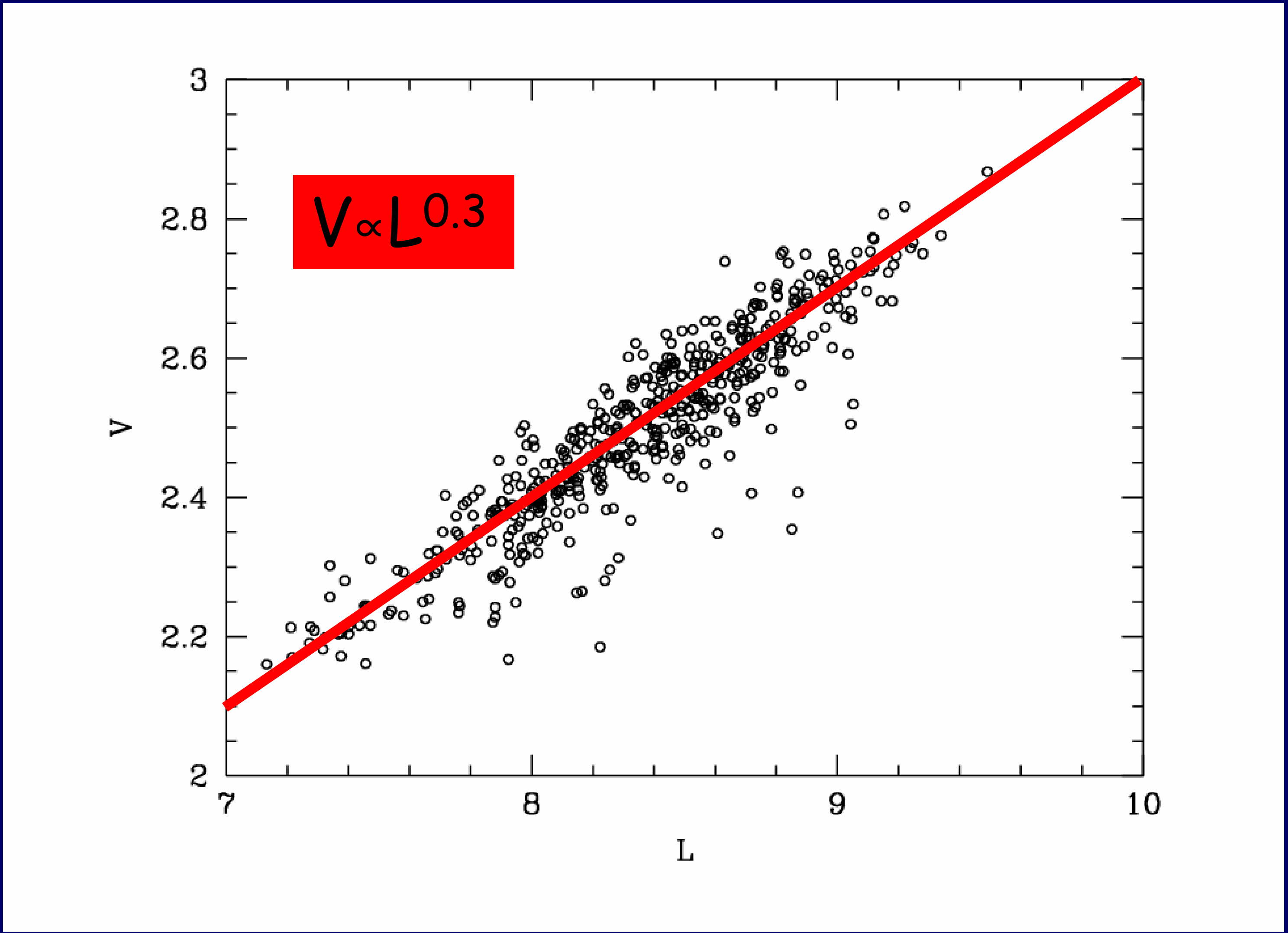
- initial
  $M_* \propto M_{gas} \propto f_{bar} M$ $\rightarrow \quad M_* \propto V^3$

- disk size $R_* \approx \lambda R$ (spin) $\lambda \approx \text{const.}$

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

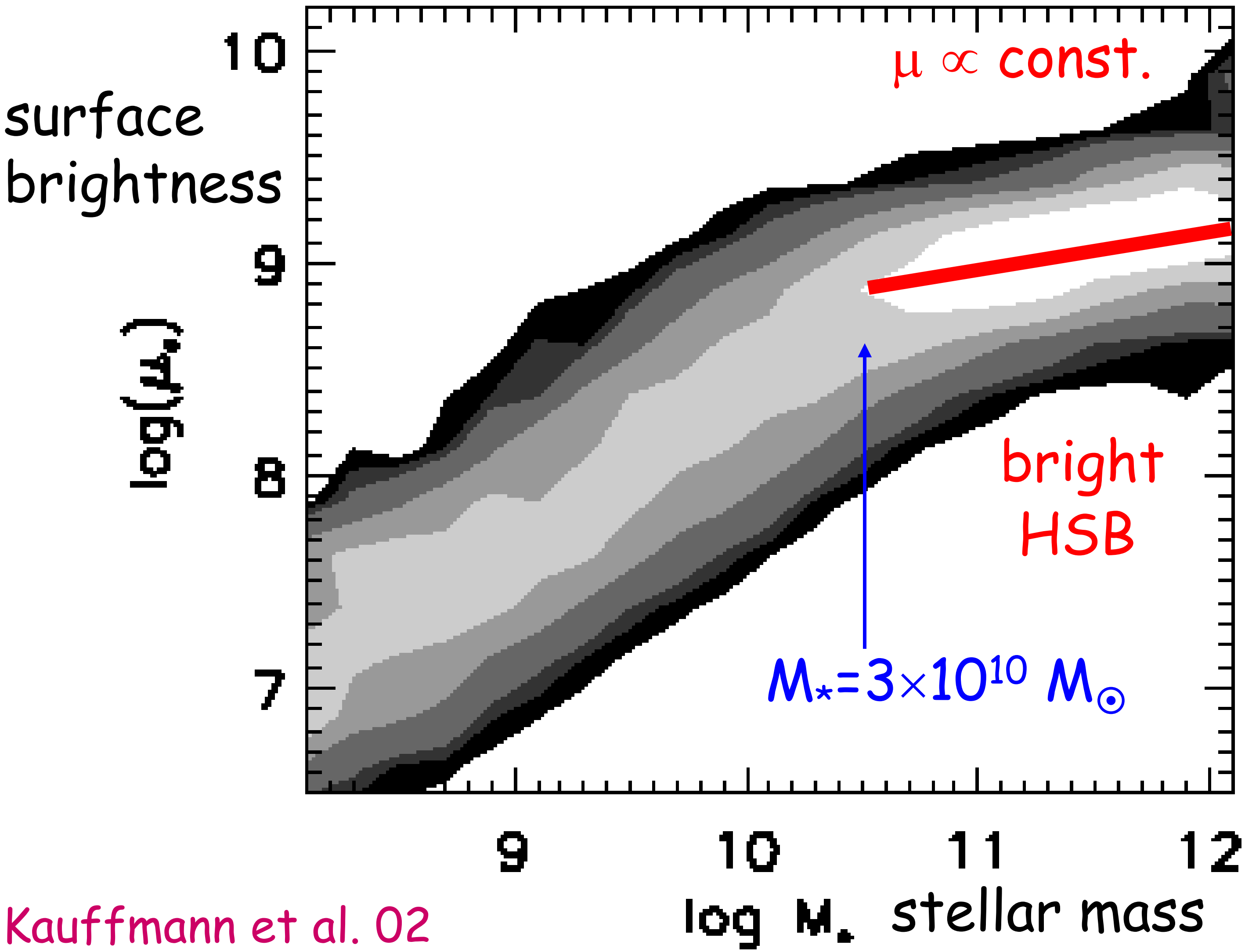
- $Z \propto M_* / M_{gas}$ $\rightarrow \quad Z \propto \text{const.}$

Bright Galaxies: Tully Fisher Relation



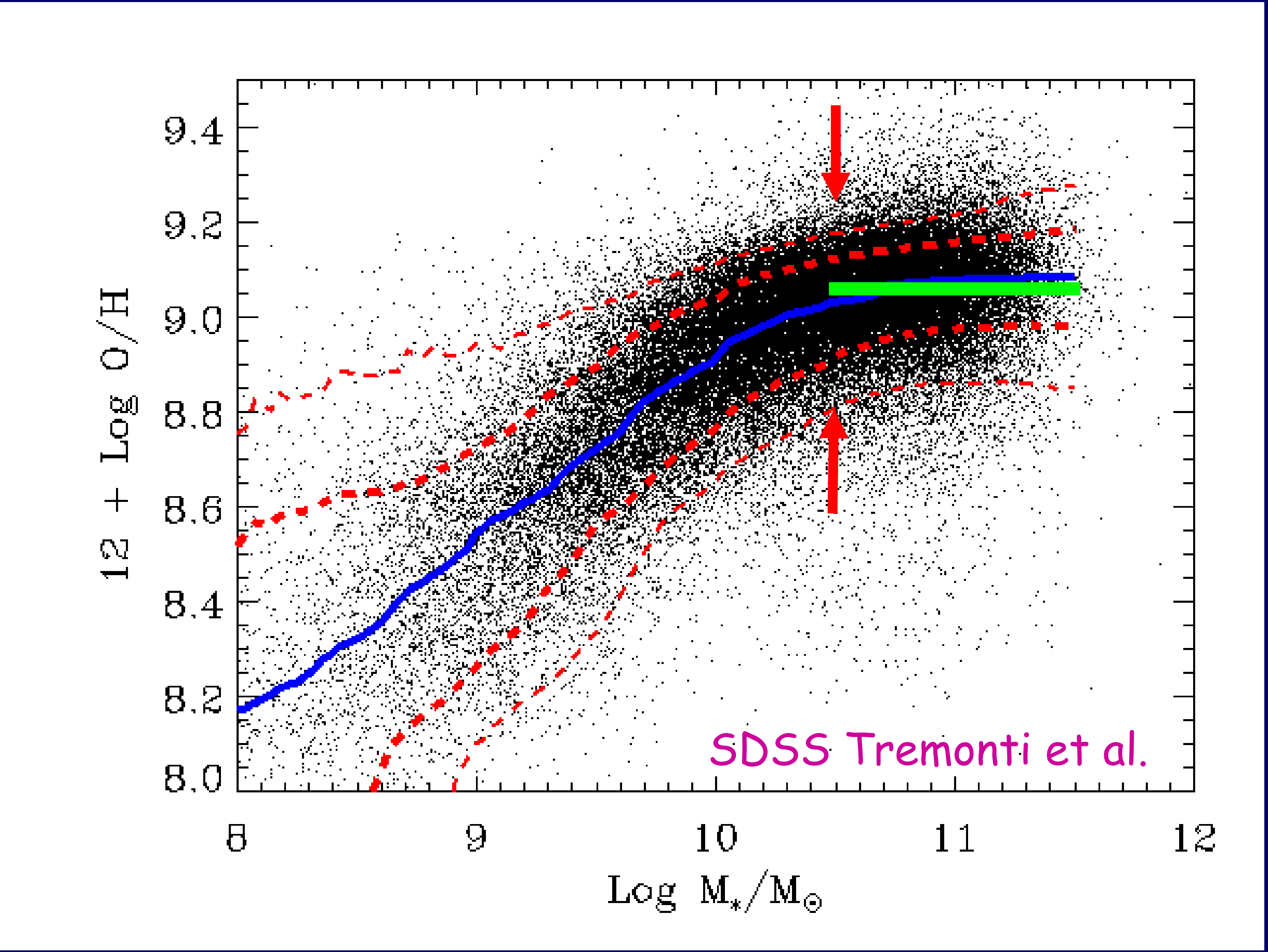
Courteau et al. 04

Surface Brightness: SDSS



Kauffmann et al. 02

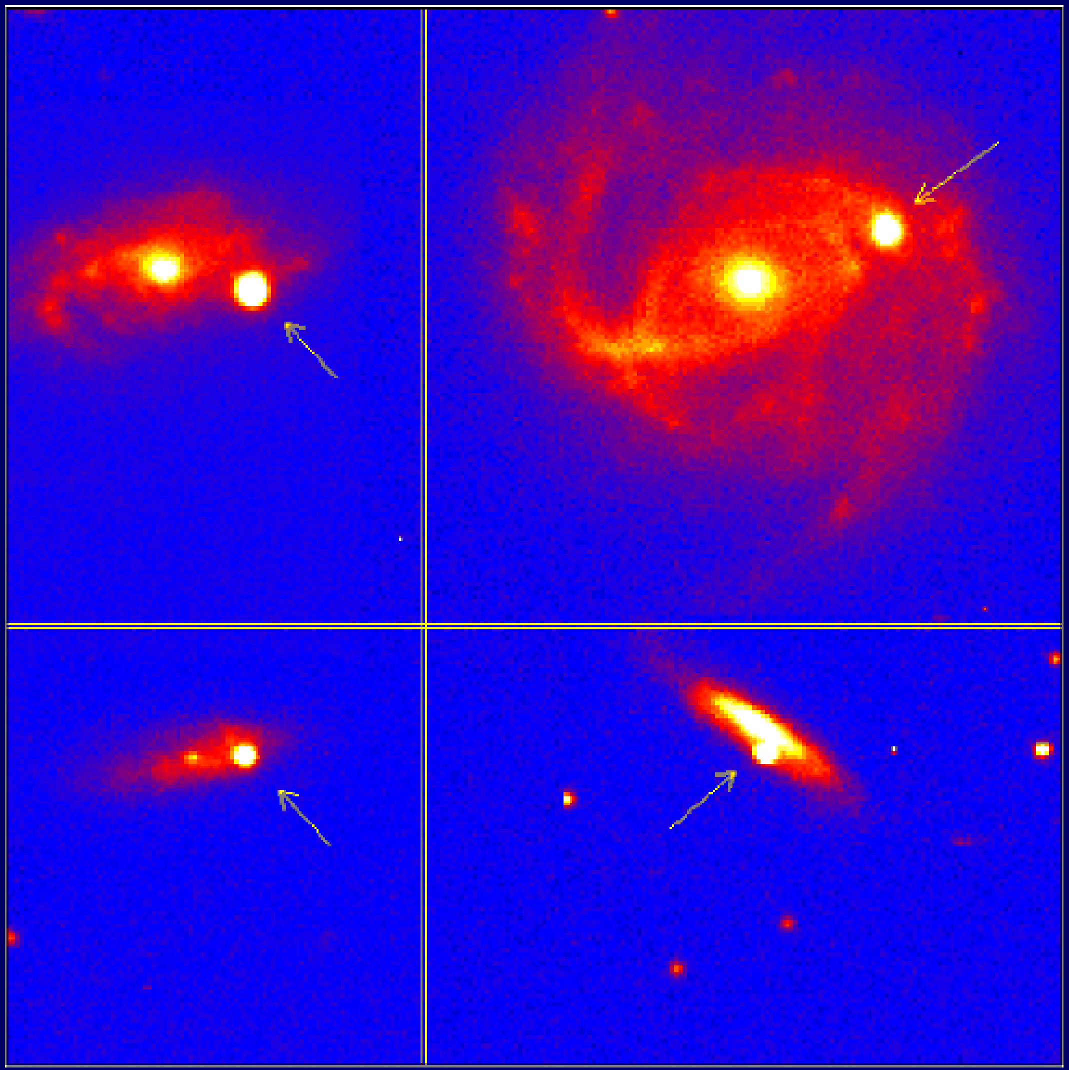
Metallicity SDSS



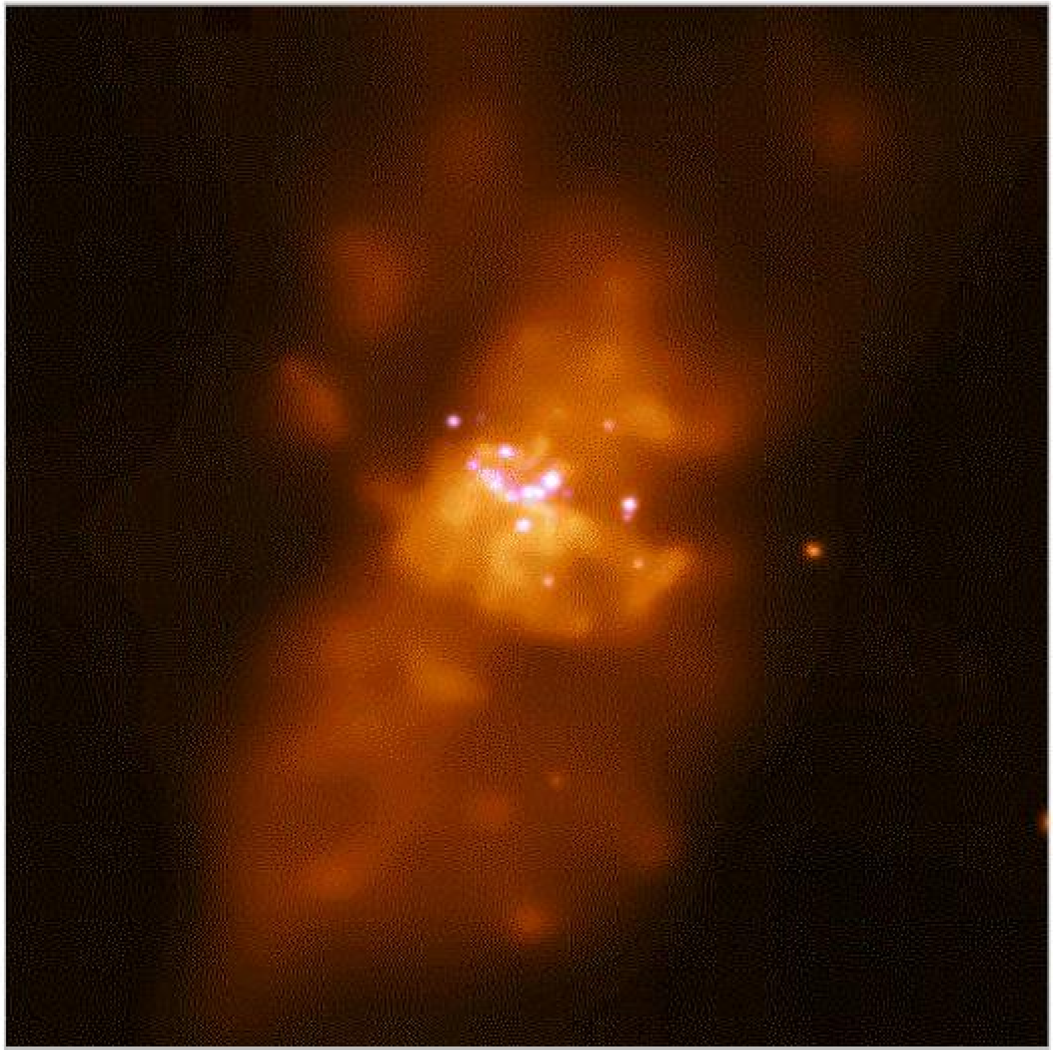
Supernova Feedback

Dekel & Silk 86
Dekel & Woo 03

Much energy in SNe



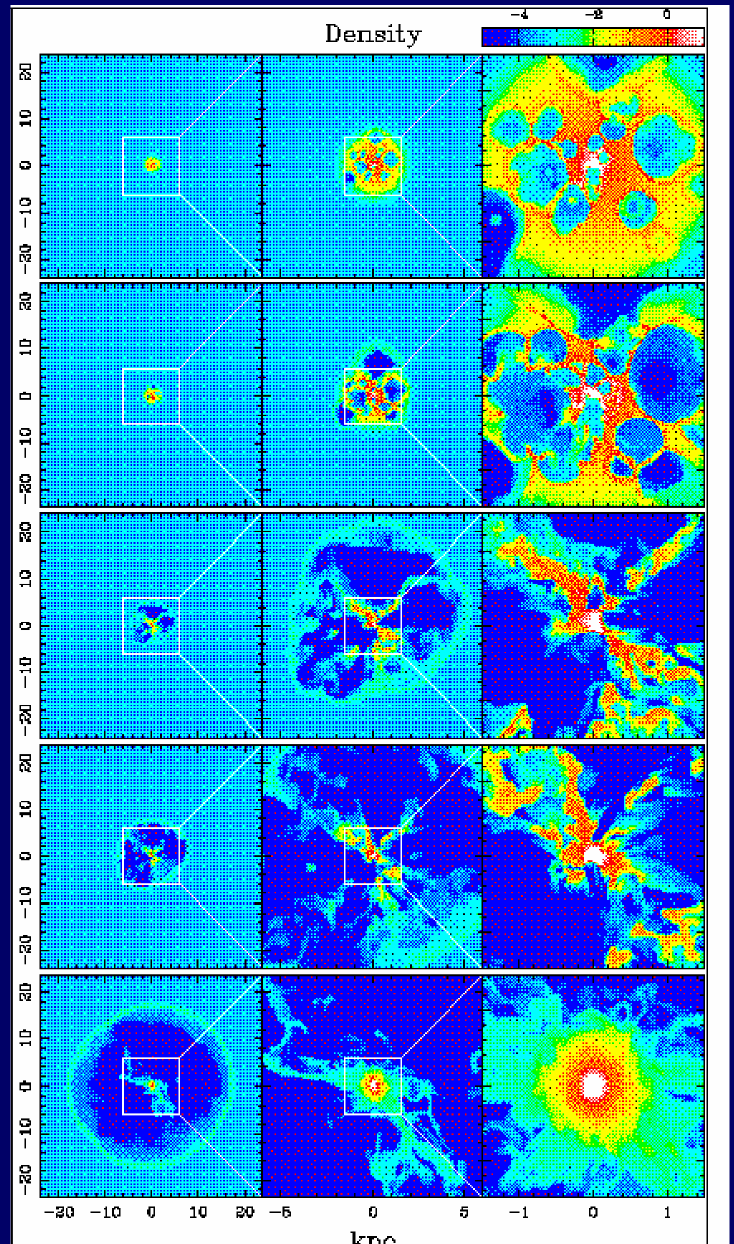
Galactic wind M82



Chandra X-Ray Observatory image of M82

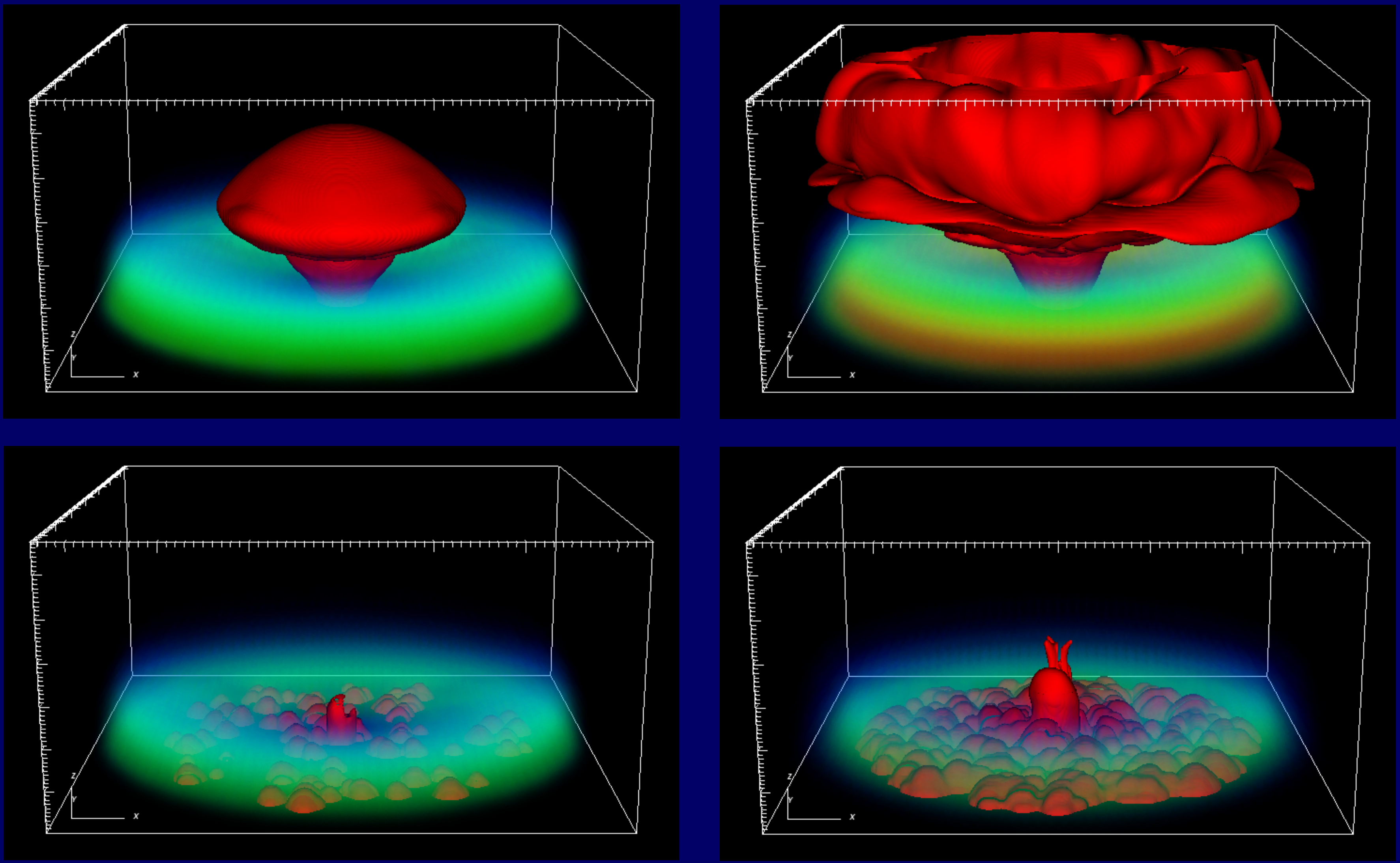
Simulation of supernova blowout

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:

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

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

≈ 0.01

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

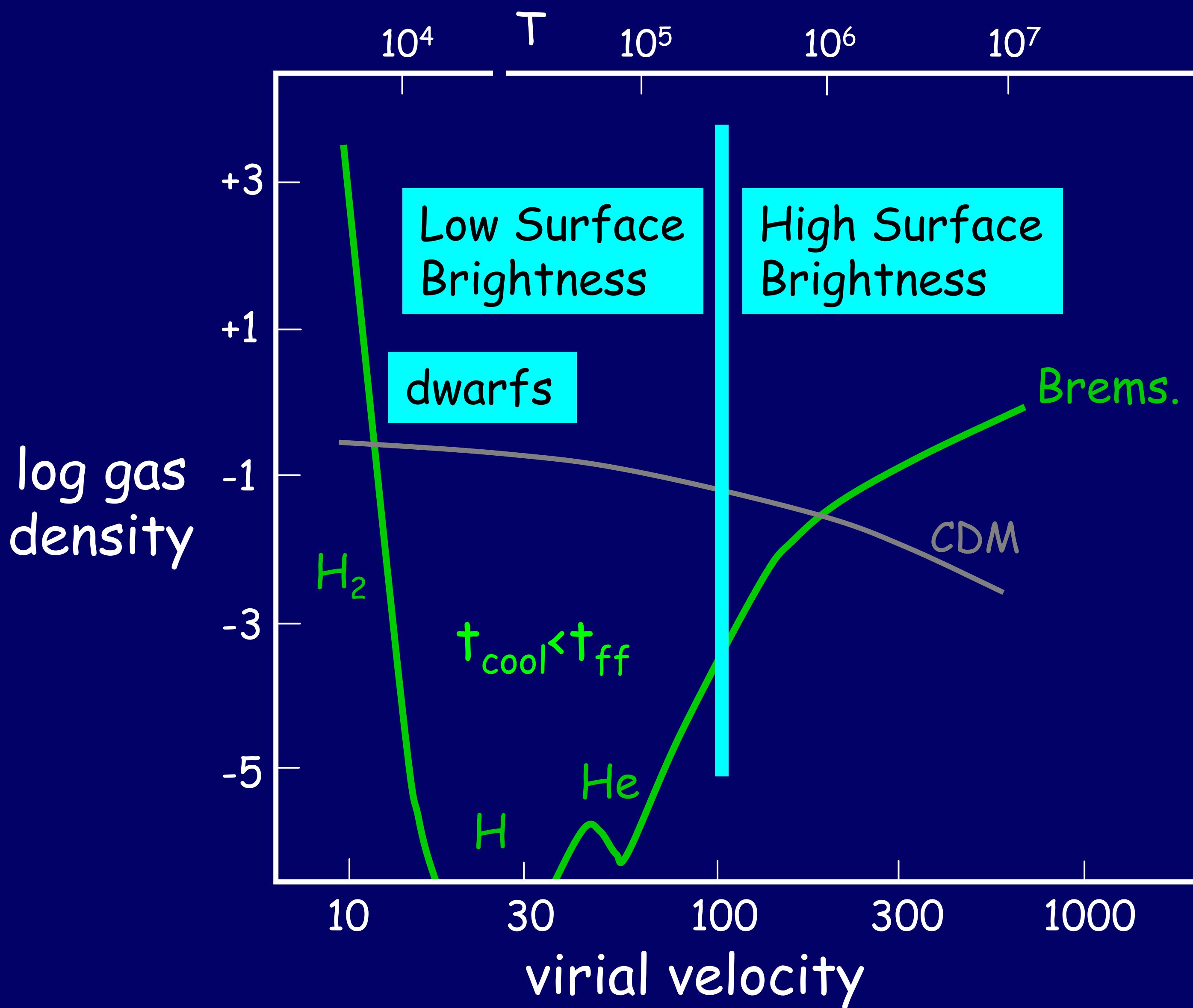
Energy required for blowout:

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

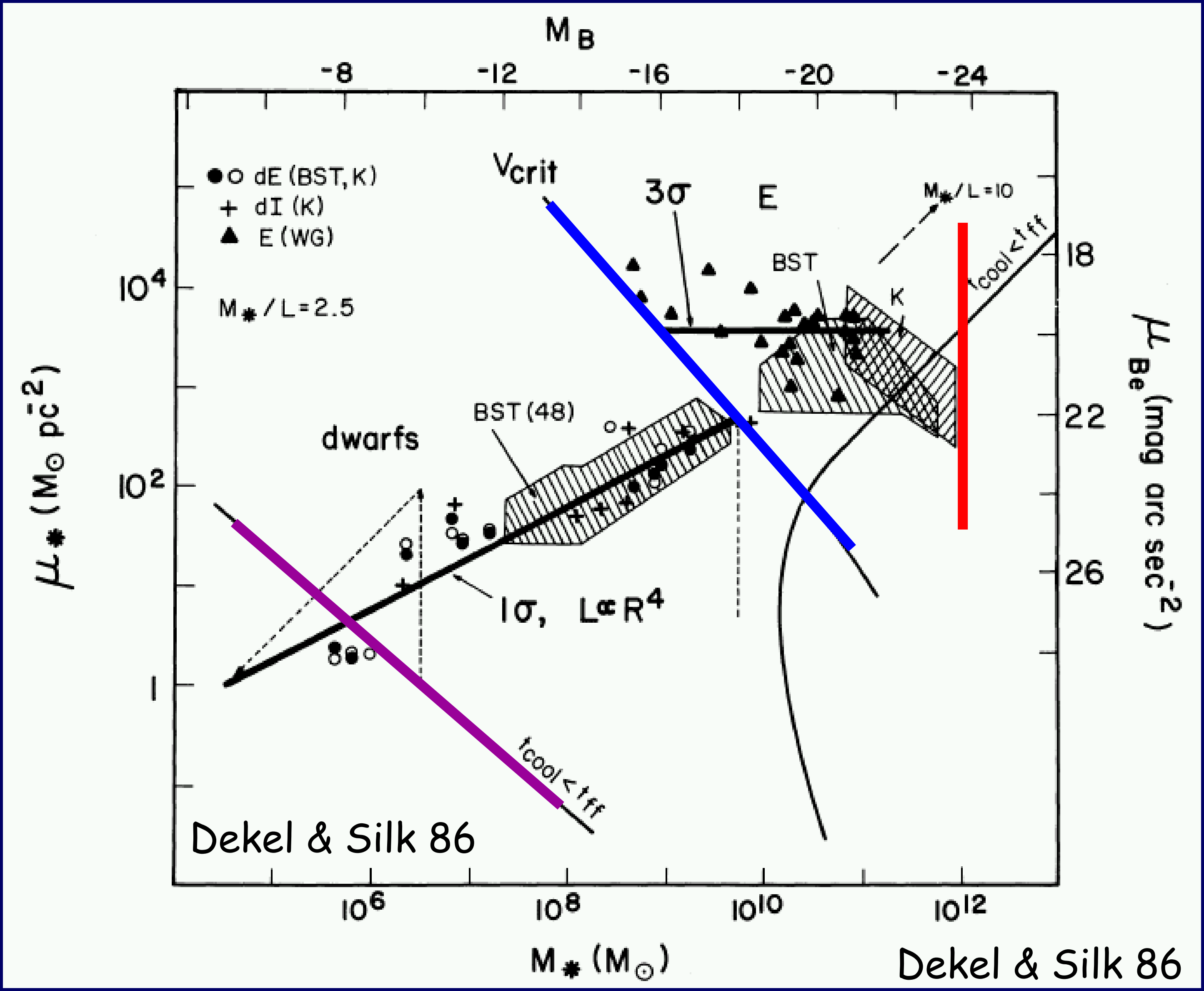
$$\rightarrow \quad V_{\rm crit} \approx 100 \text{ km/s} \quad \rightarrow \quad M_{*\rm crit} \approx 3\times10^{10} M_\odot$$

Supernova Feedback Scale

Dekel & Silk 86



LSB vs HSB



Dekel & Silk 86

Model: fundamental line of LSB/Dwarfs

(Dekel & Woo 03)

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

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

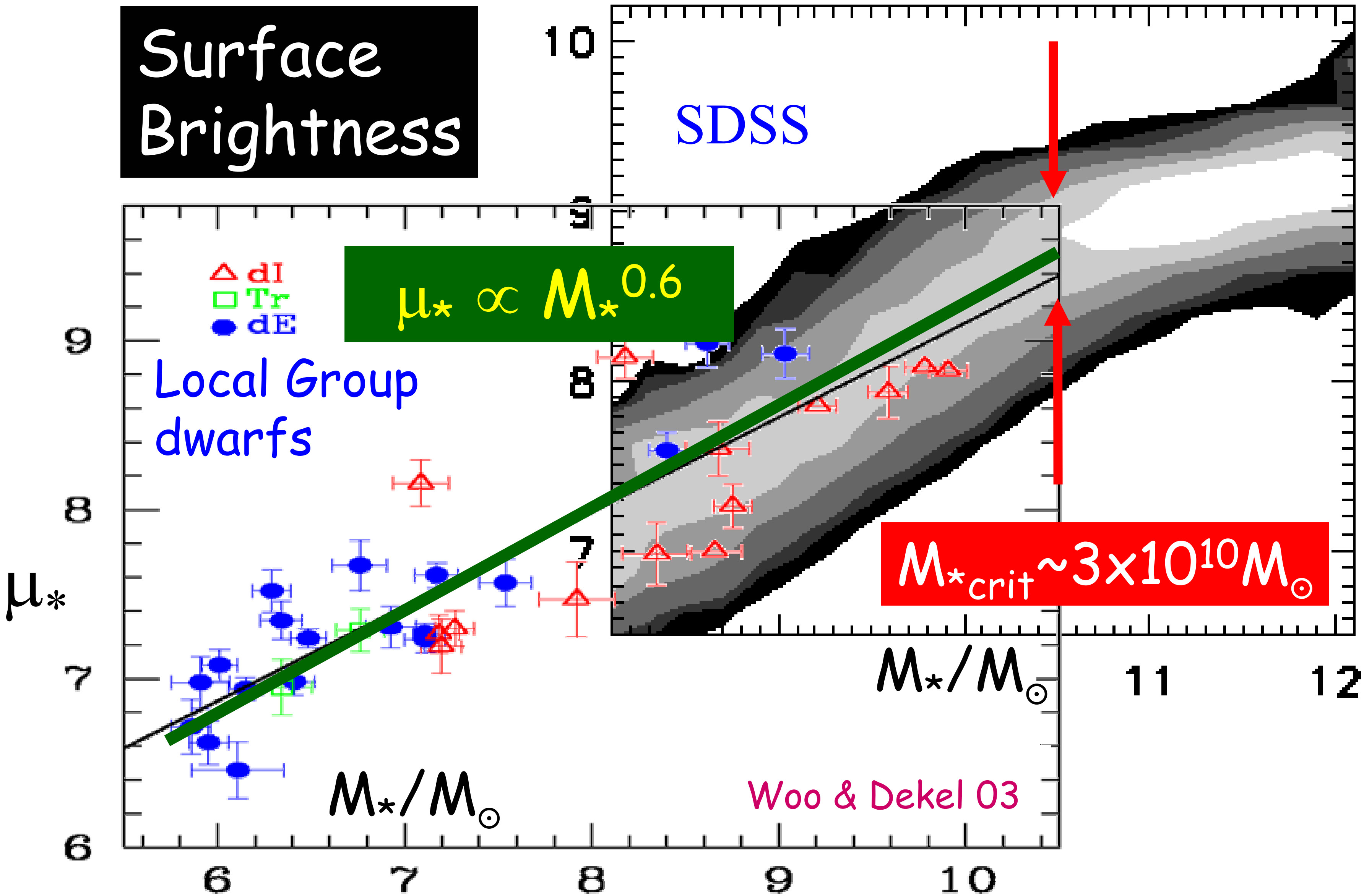
<<1

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

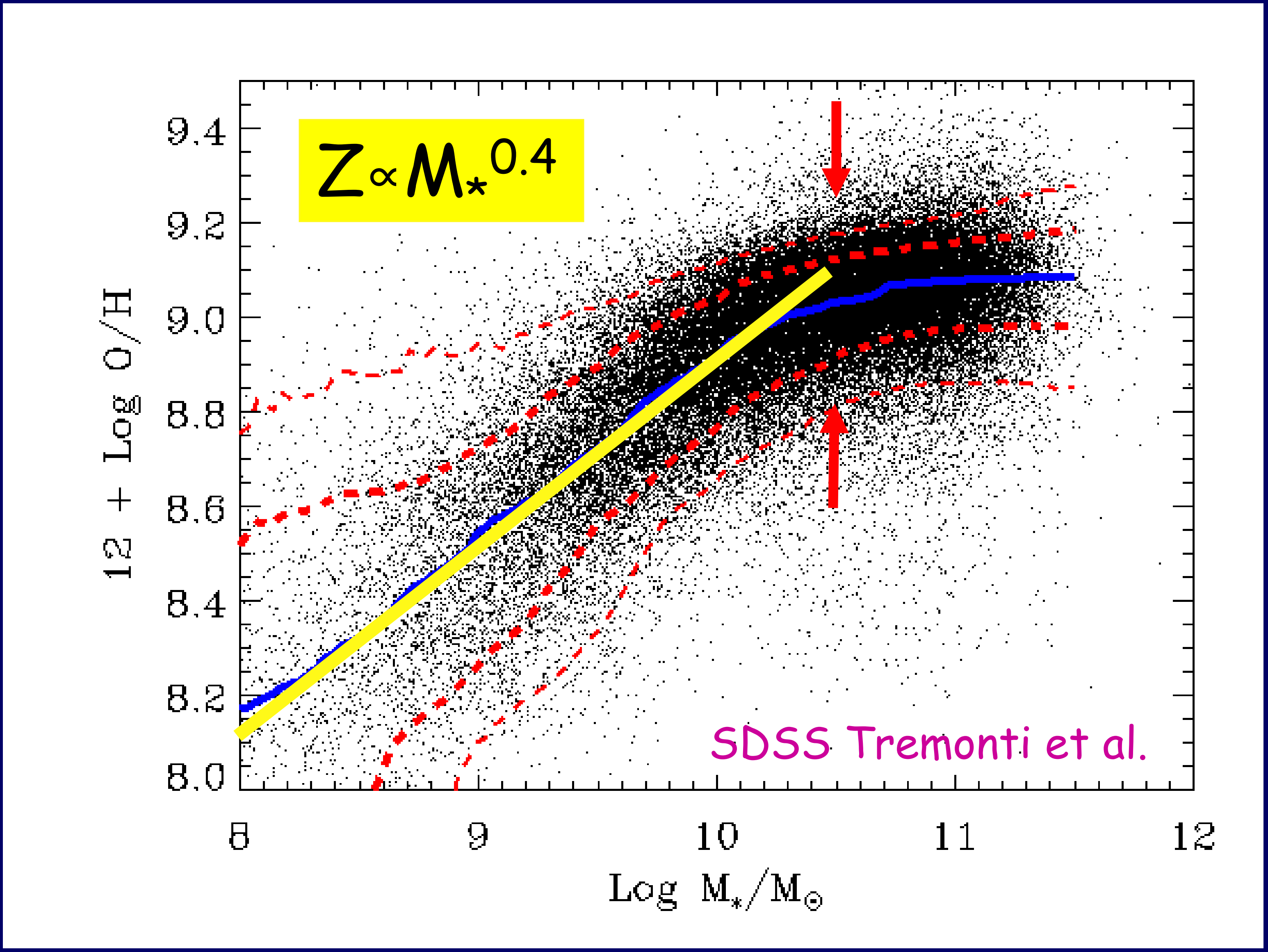
$Z \propto M_* / M_{gas}$ $\longrightarrow$ $Z \propto M_*^{2/5}$ metallicity

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

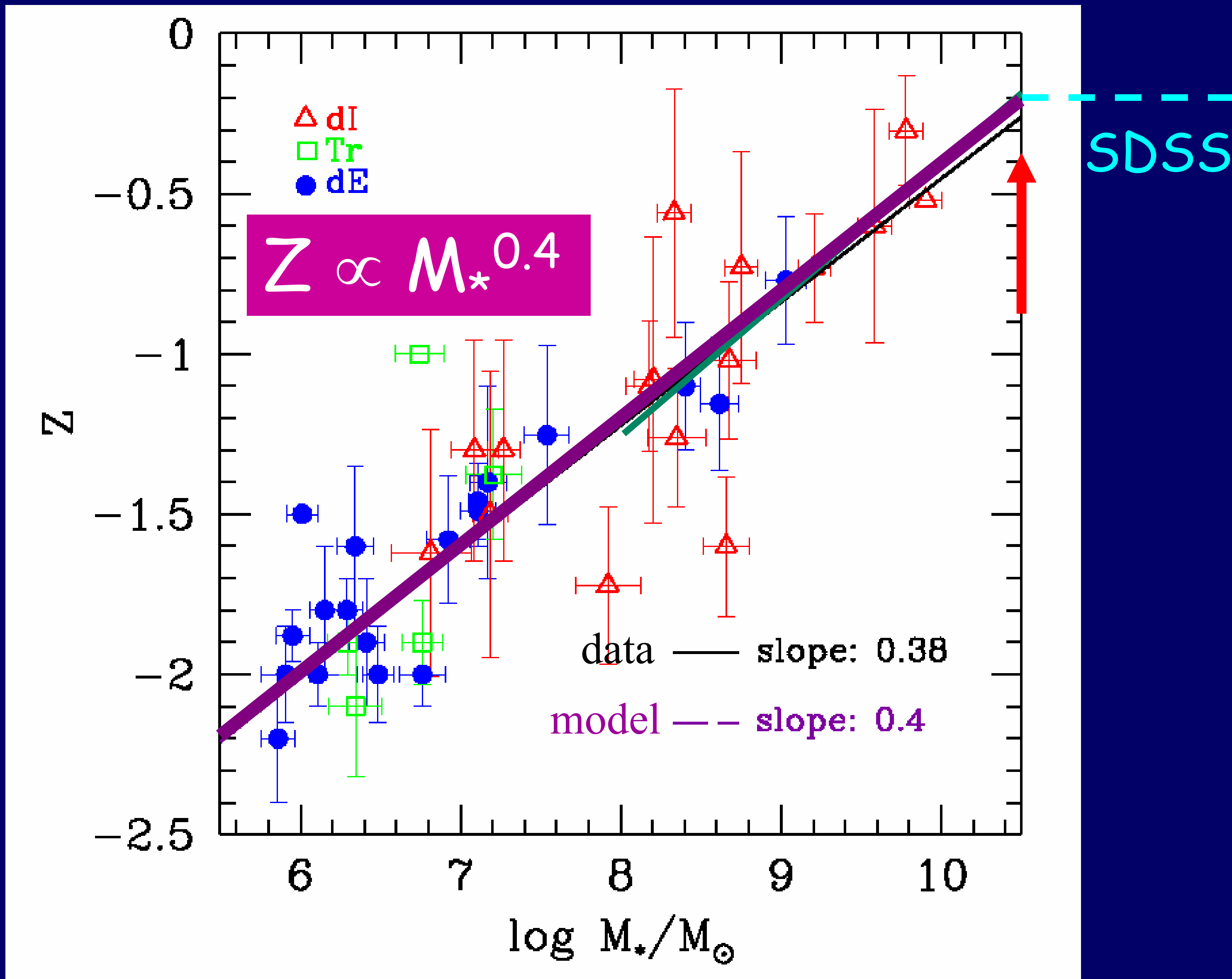
The “Fundamental Line” of LSB/Dwarfs



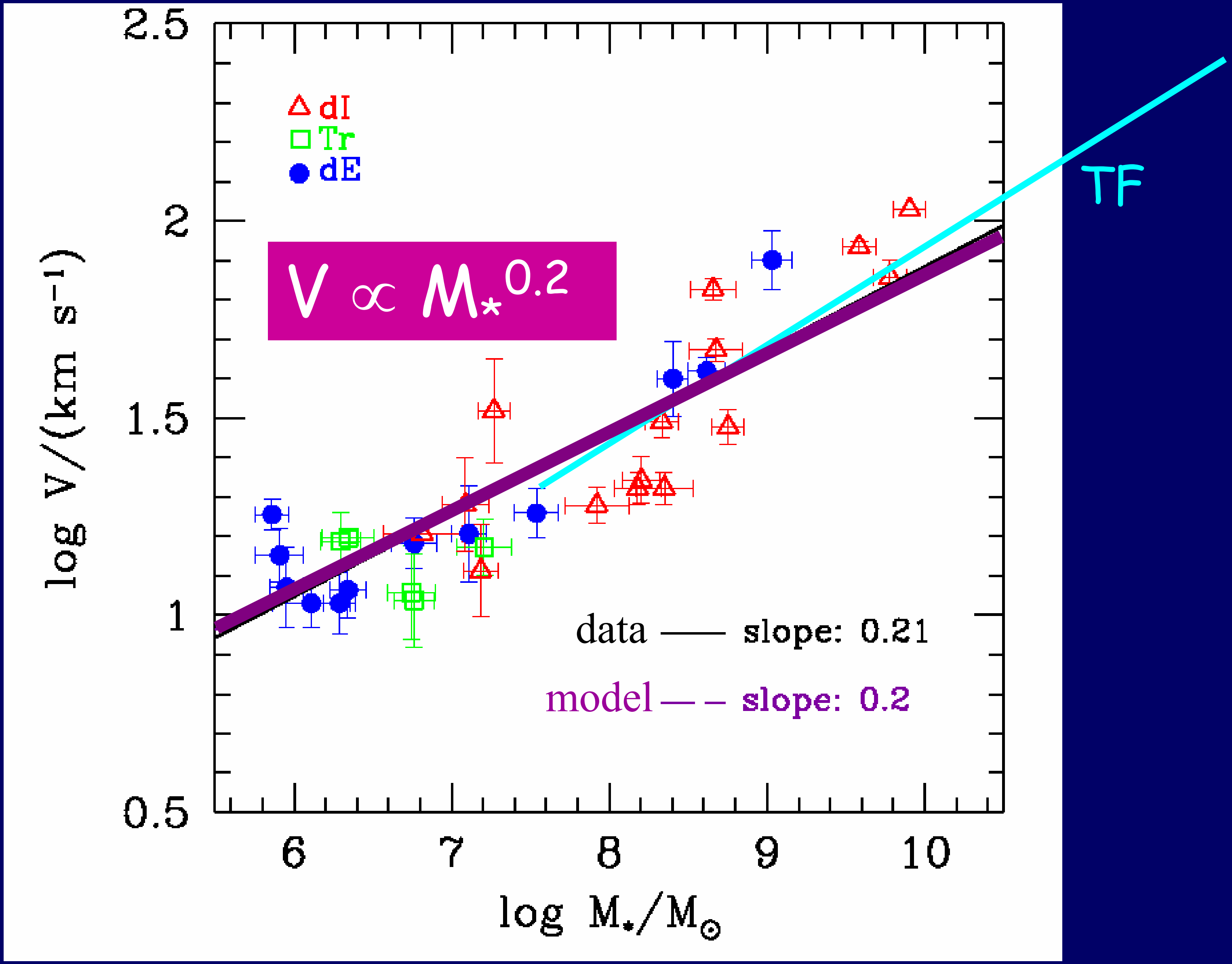
Metallicity



Local Group Dwarfs: Metallicity



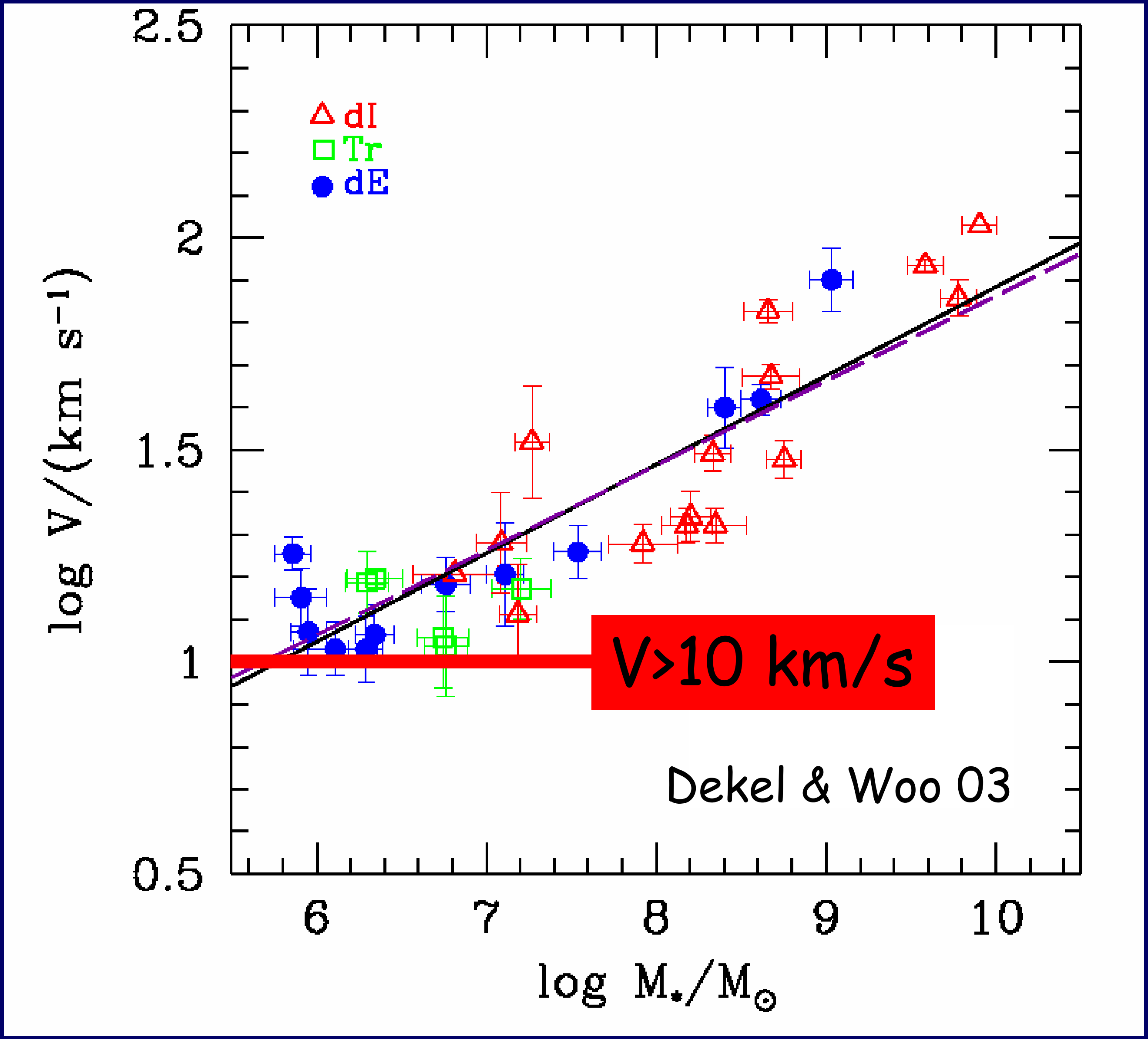
LG Dwarfs: Velocity



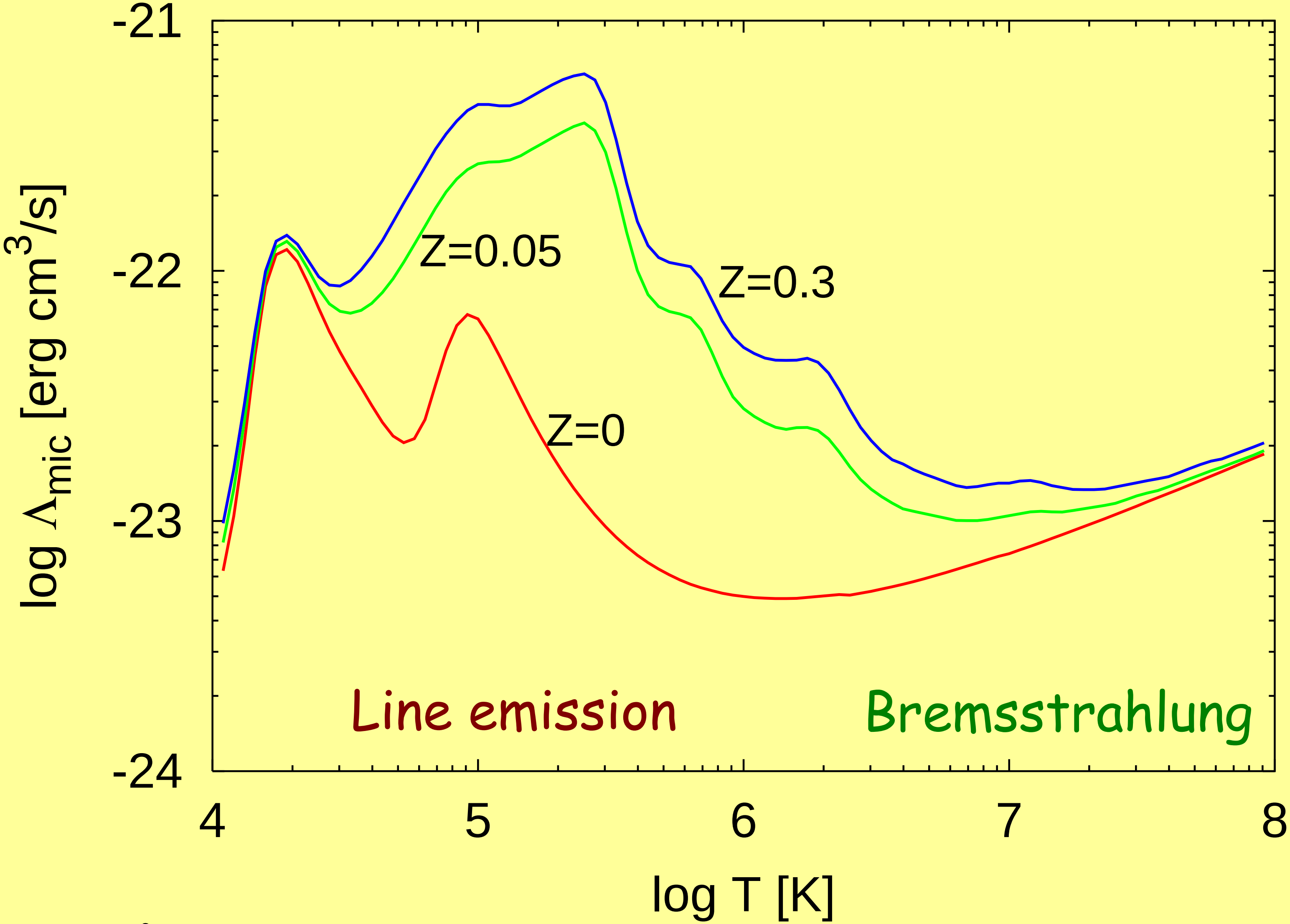
Summary: SN feedback

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



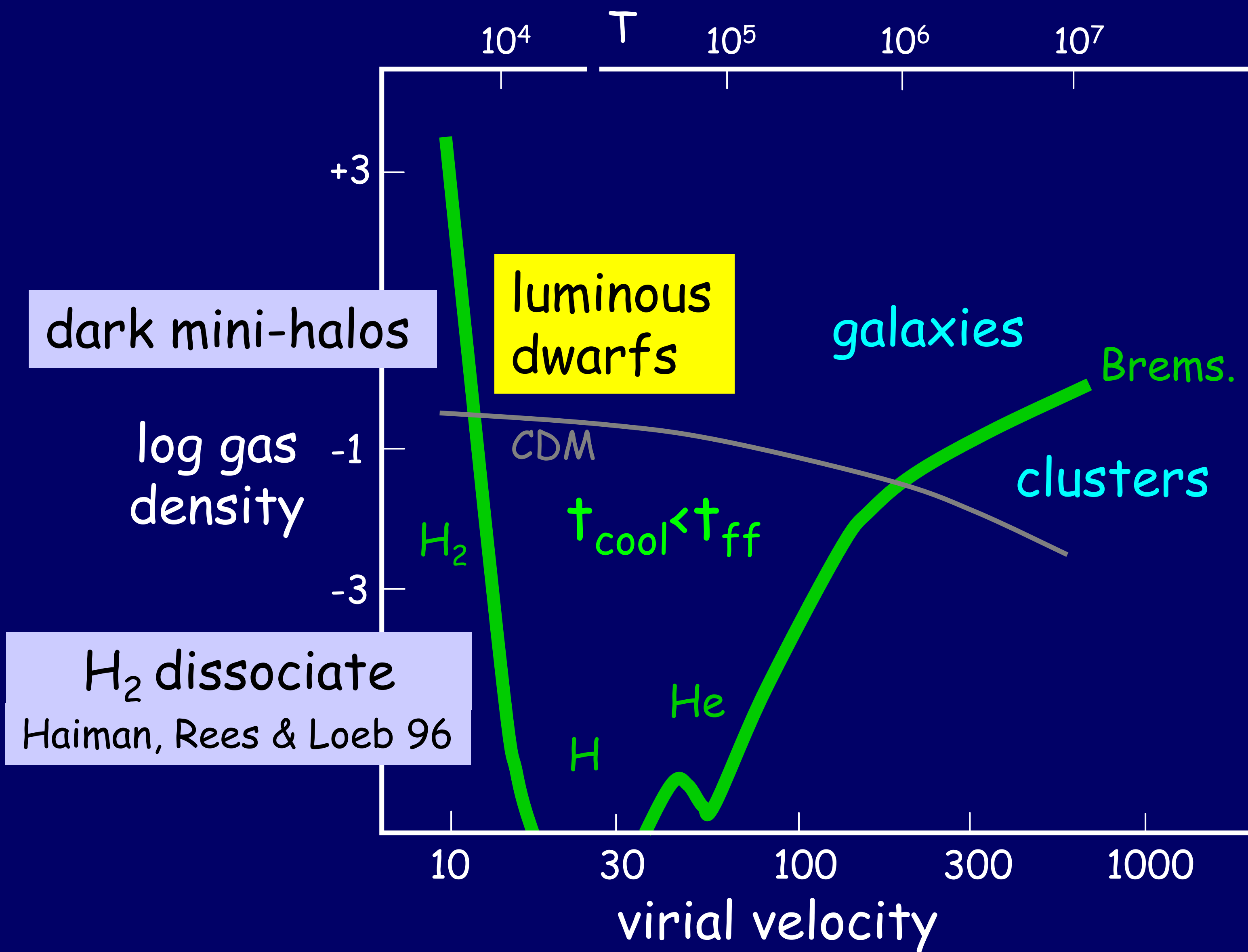
Cooling rate



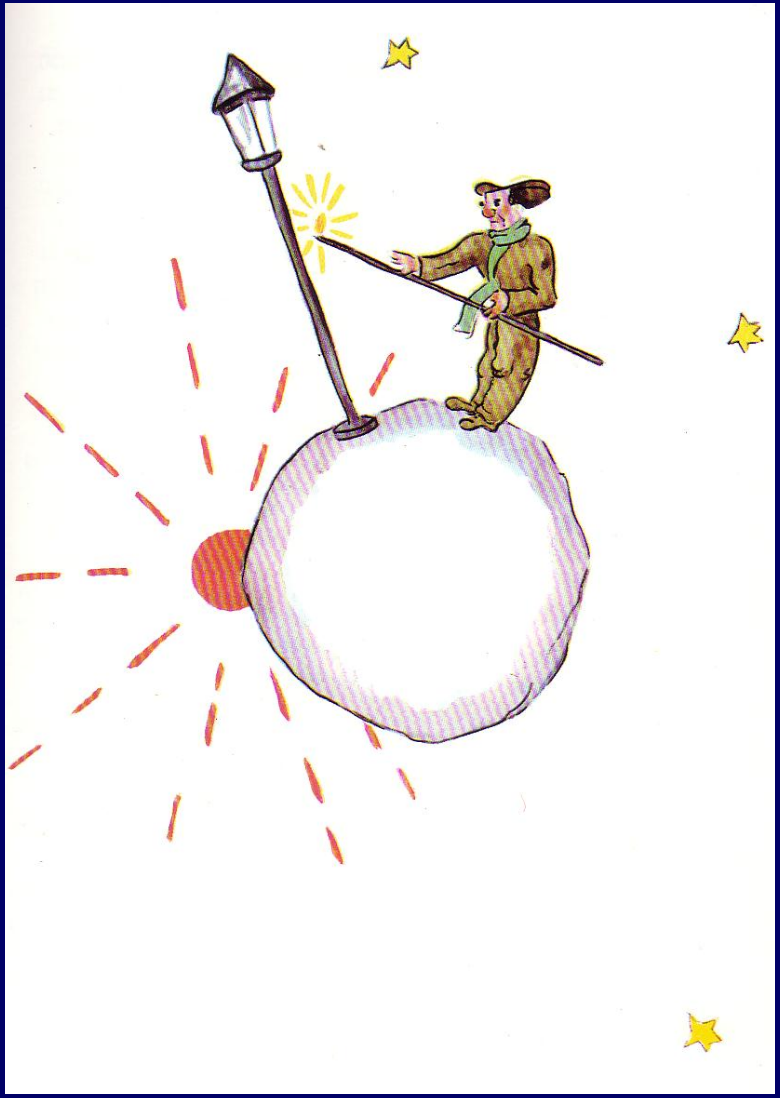
$$q = \frac{N_A{}^2 \chi^2}{\mu^2} \Lambda(T) \rho \quad [\mathrm{erg\ g^{-1}\ s^{-1}}] \qquad N_A / \mu \ \text{molecules per g} \qquad \chi \ e^- \ \text{per particle}$$

The Cooling Barrier

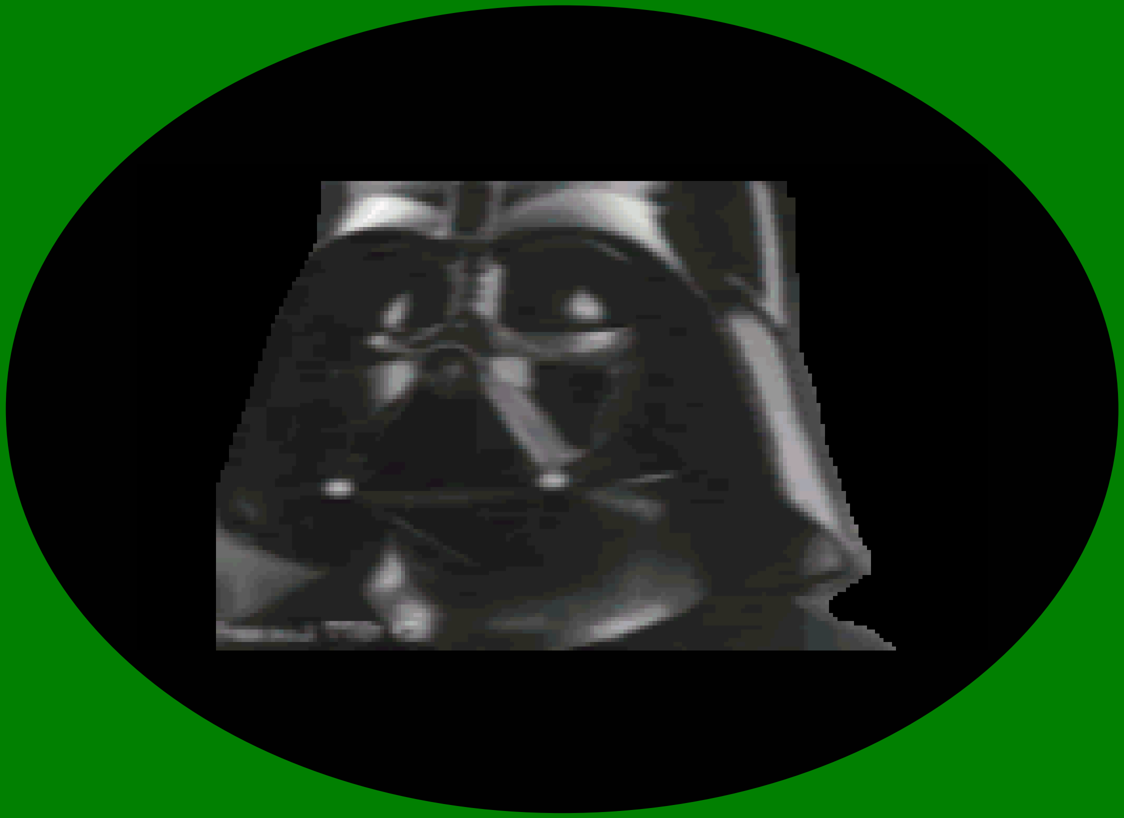
Rees & Ostriker 77, Silk 77, White & Rees 78



It isn't that simple to turn on the light



3. Dark-Dark Halos Must Exist



Dark-Dark Halos at V<30 km/s

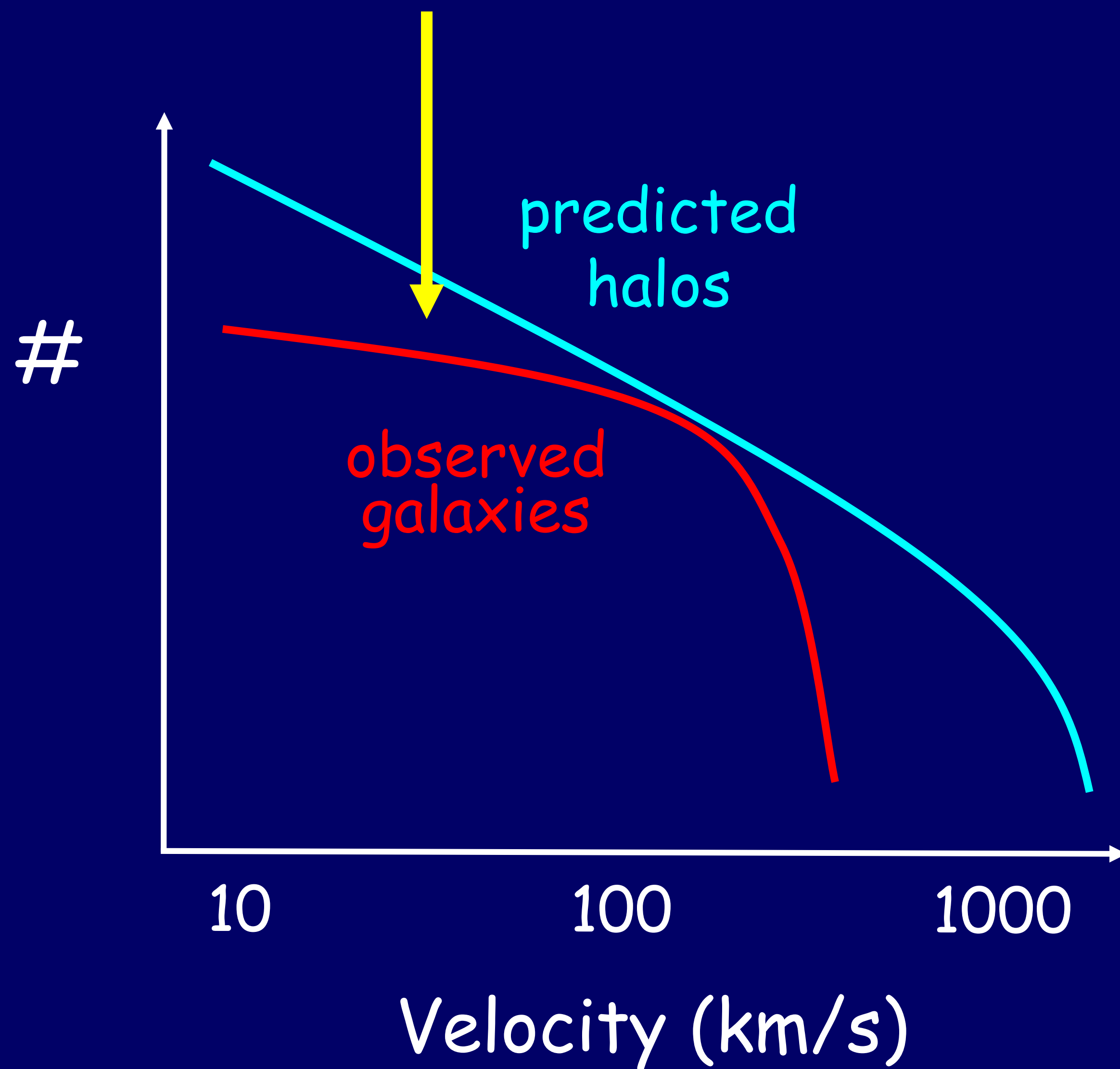
TF: $L \sim V^4$

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

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

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

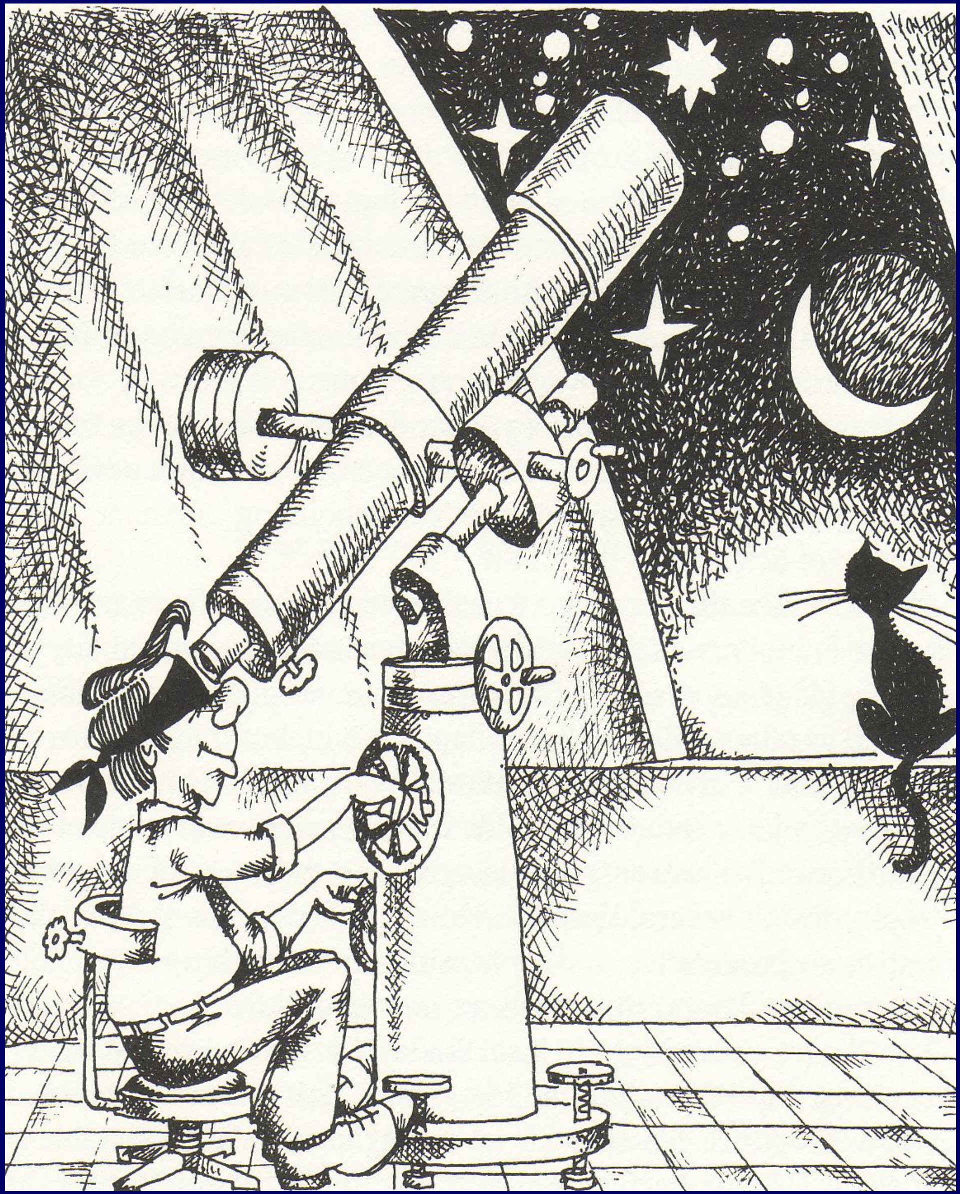
Cannot reconcile TF with luminosity and mass functions !

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

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

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 $\rightarrow$ 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

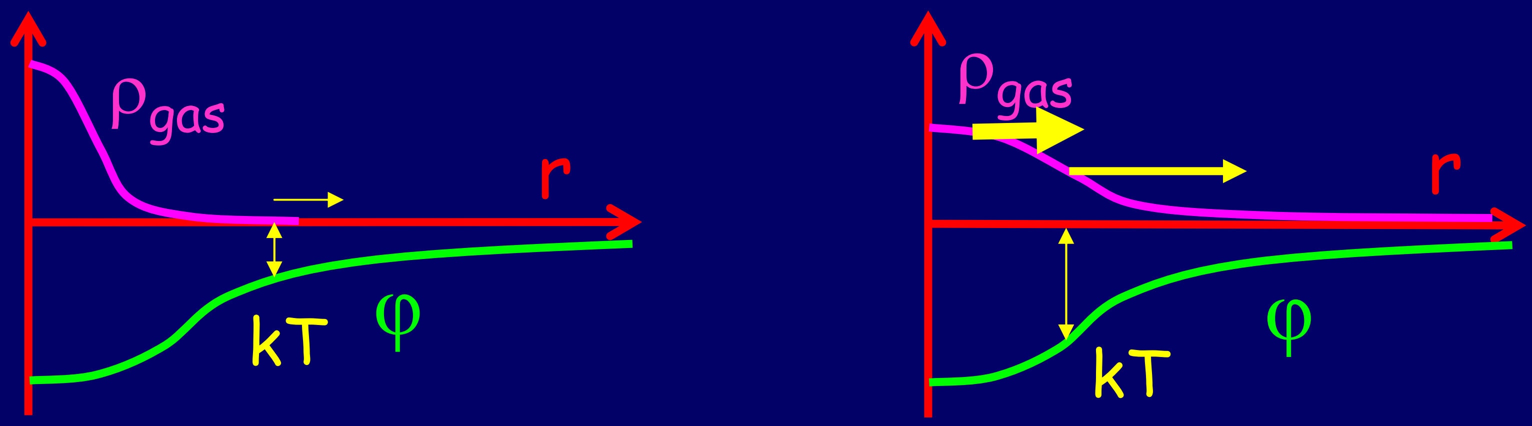
But complete gas removal?

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 $t_{\rm evap} \approx t_{\rm dyn} e^{\phi / kT}$

It is continuously replenished and lost

Continuous energy input by the ionizing flux
$\rightarrow$ steady wind

Steady Thermal Wind

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

Hydrodynamics:

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

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

$$P = c_s^2 \rho$$

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

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

→ the sonic radius: $\phi'(r_s) = 2c_s^2 / r_s$ → $r_s \approx GM / c_s^2$

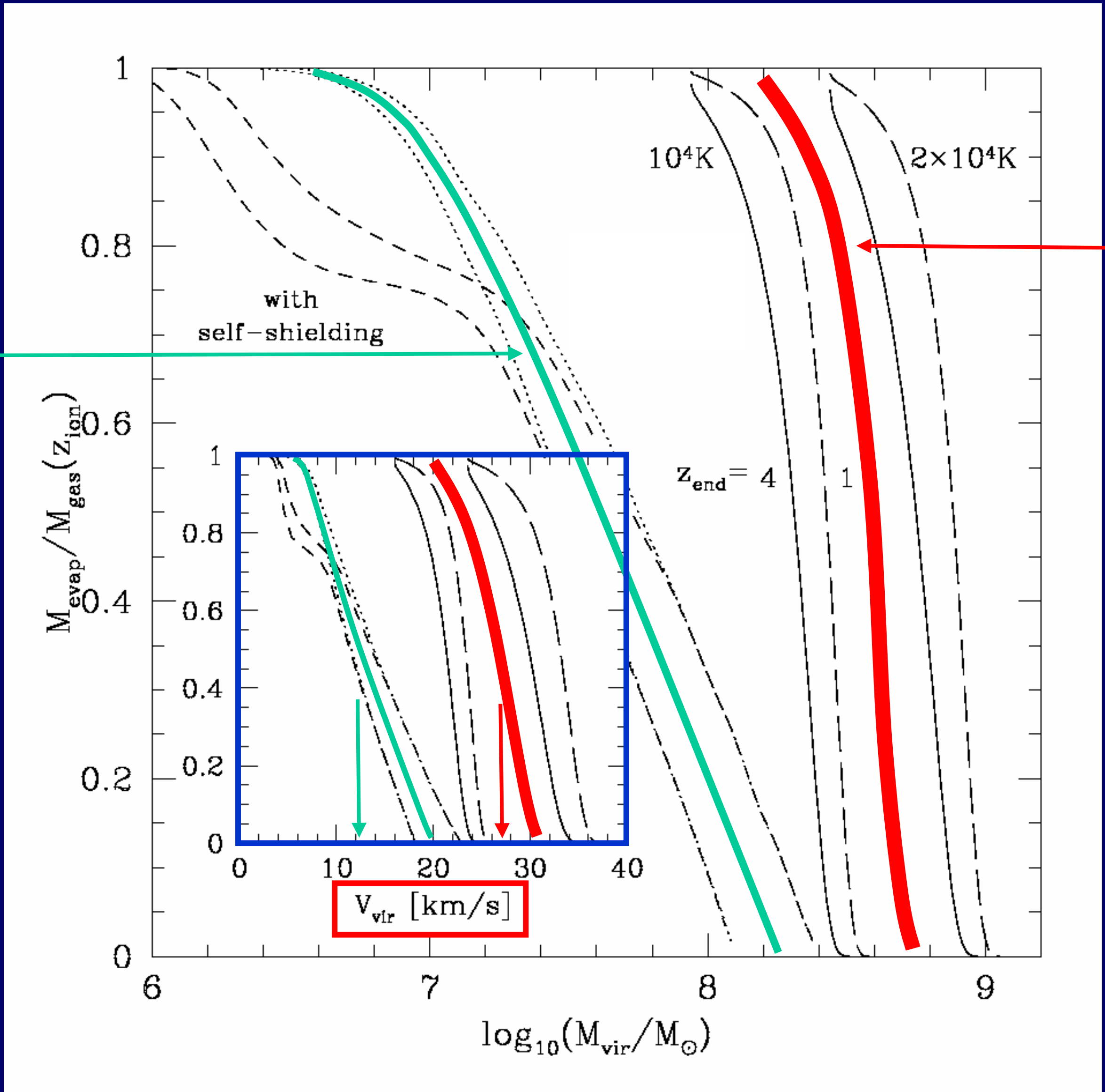
wind parameter (NFW): $\psi \equiv \frac{GM_c / r_c}{c_s^2}$ $\quad t_{evap} / t_{dyn} \approx 10^{\psi - 1}$

ψ>>1 tightly bound, no evaporation

ψ>1 bound, but steady wind >> t_{dyn}

ψ≤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

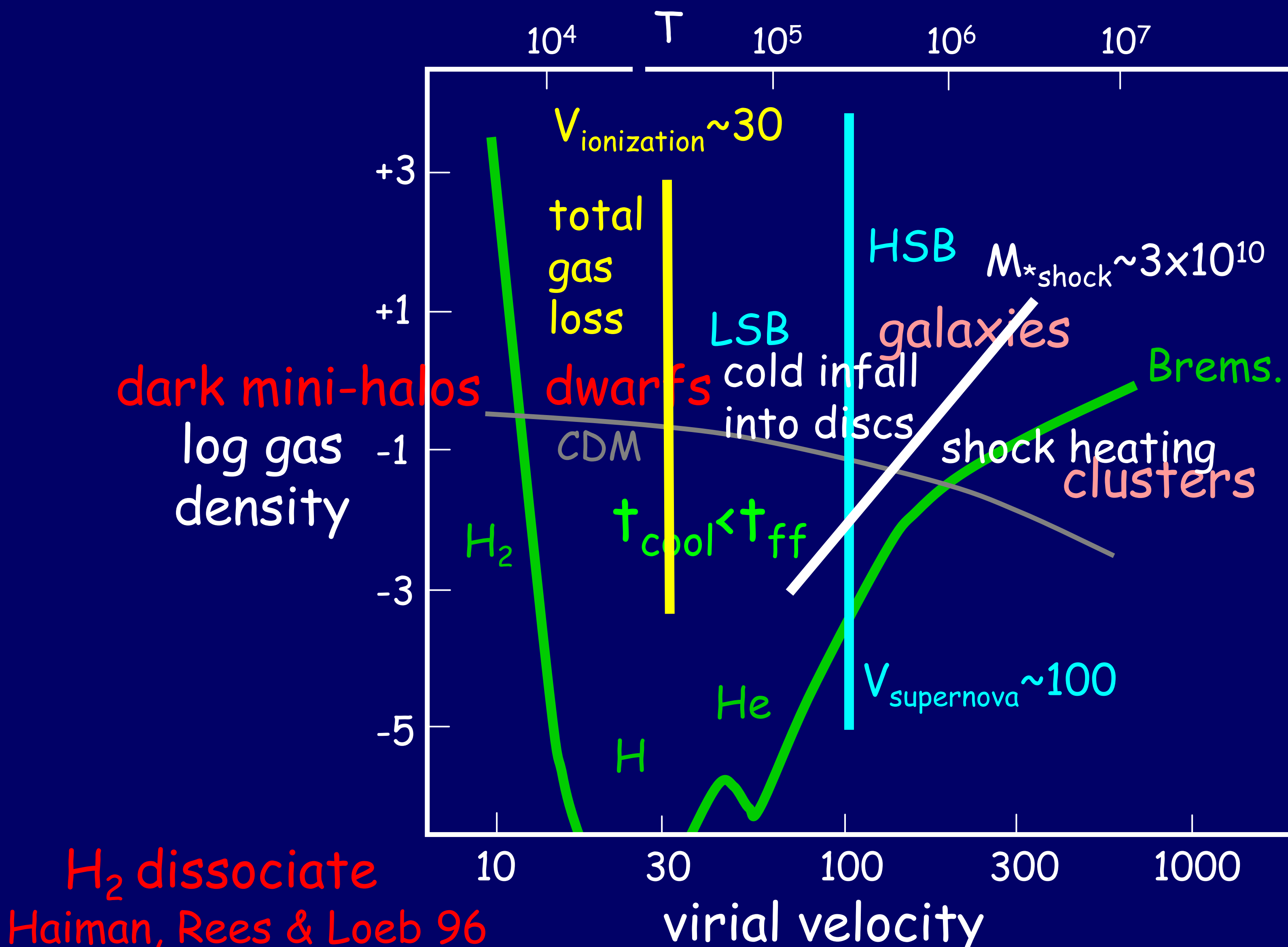
Half the photo-ionized gas evaporates by steady winds from halos of $V<30$ km/s.

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

No galaxies $V<10$ becasue of cooling barrier

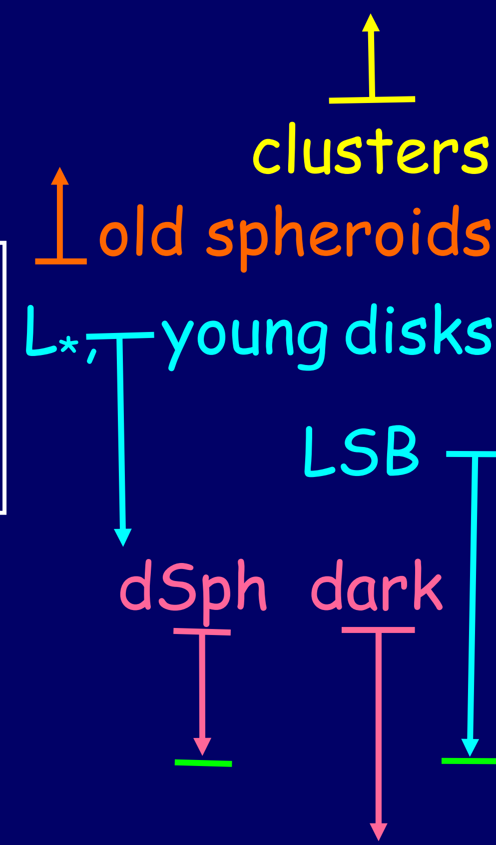
Cooling vs Free Fall

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



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}



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.

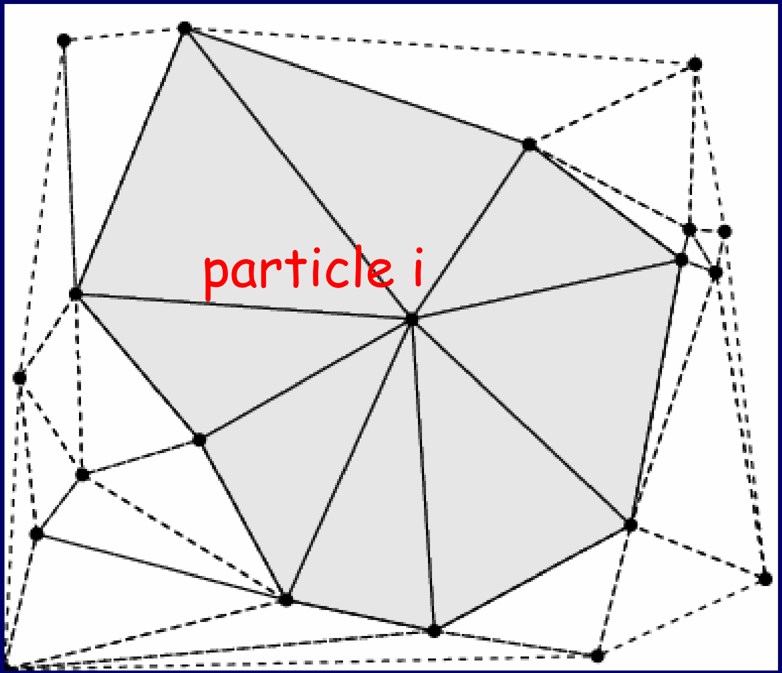
$$\phi(\vec{x}) = -G\int d\vec{x}'\, d\vec{v}\, \frac{f(\vec{x}',\vec{v})}{|\vec{x}-\vec{x}'|}$$

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

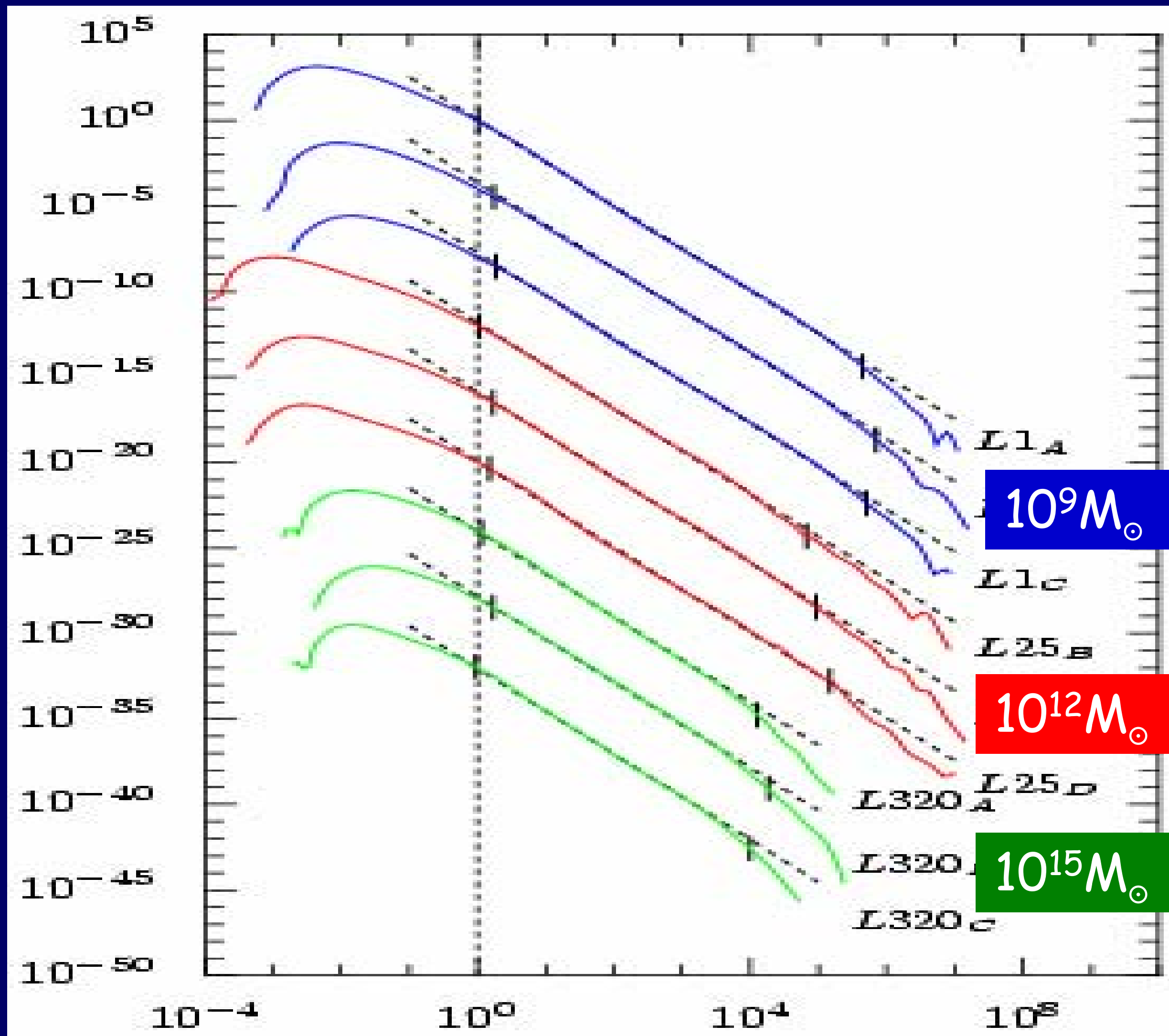


$$f_i = (d+1)\frac{m}{V_i}$$

Arad, Dekel & Klypin

PDF of Phase-Space Density

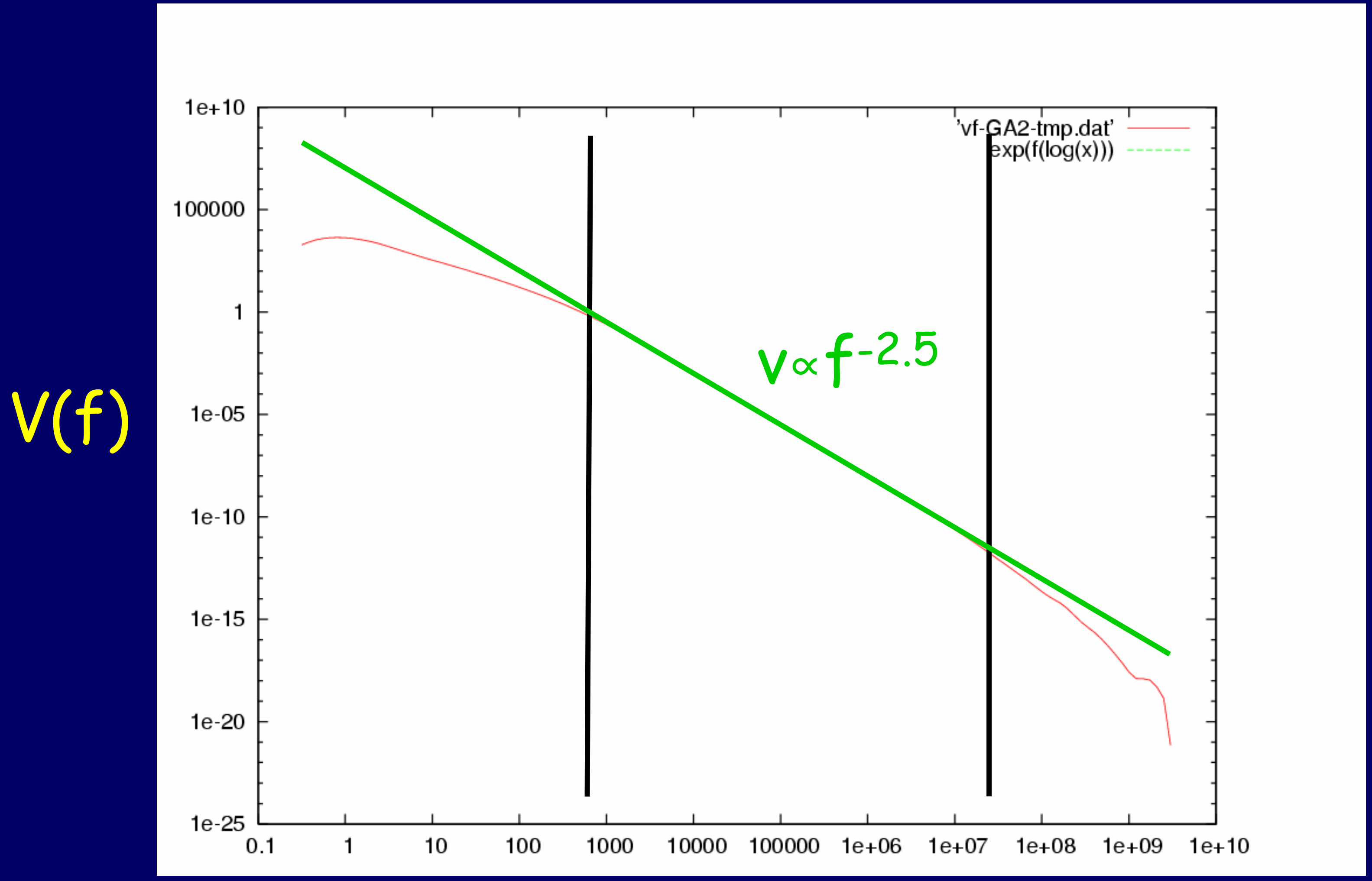
V(f)



f

Arad, Dekel & Klypin

PDF of Phase-Space Density



Arad, Dekel & Klypin

V(f) related to ρ(r)?

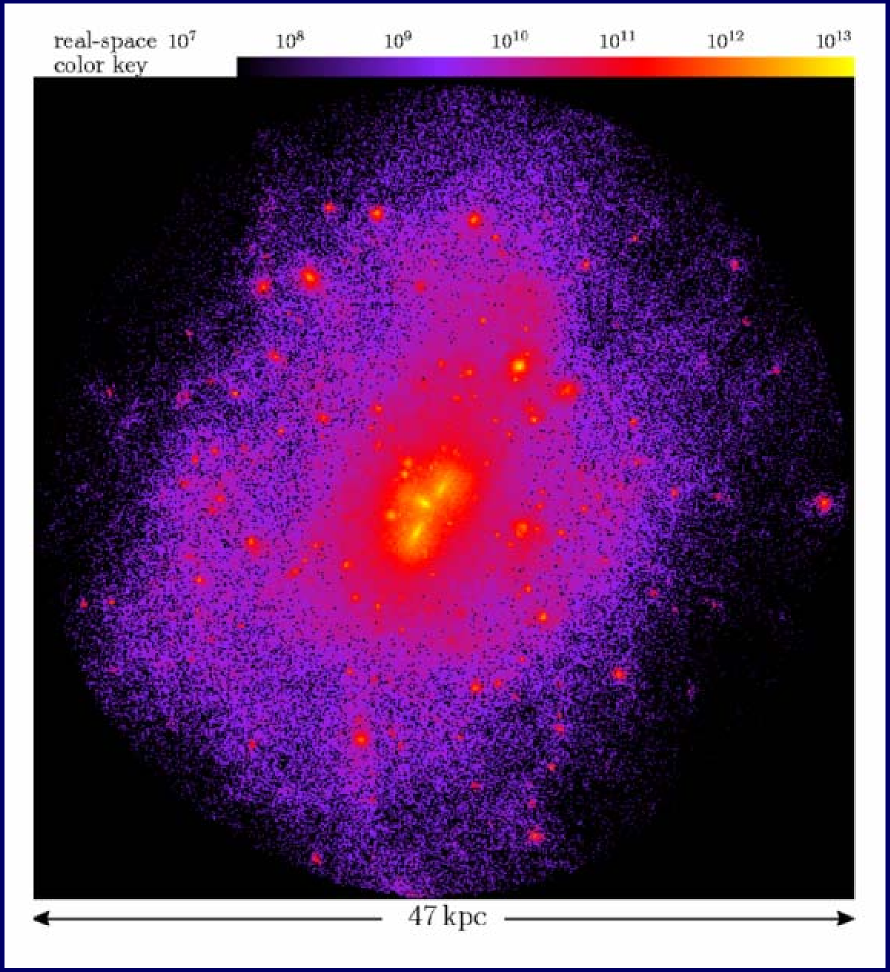
if $f(\vec{x},\vec{v}) = f(E)$ e.g., spherical & isotropic

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

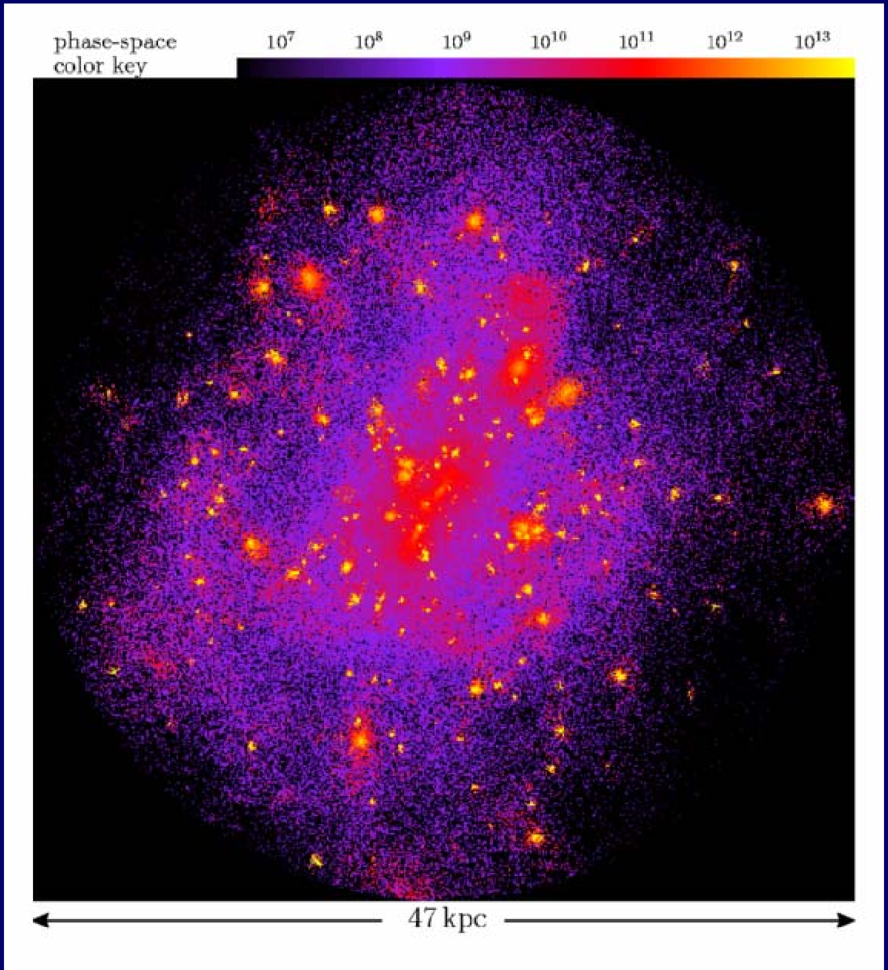
$$\alpha = 3 \leftrightarrow \beta = 2$$
$$\alpha = 2 \leftrightarrow \beta = 2.5$$
$$\alpha = 1 \leftrightarrow \beta = 2.8$$
$$\alpha = 0 \leftrightarrow \beta = 3$$

Halo Phase-Space Density

Real Density

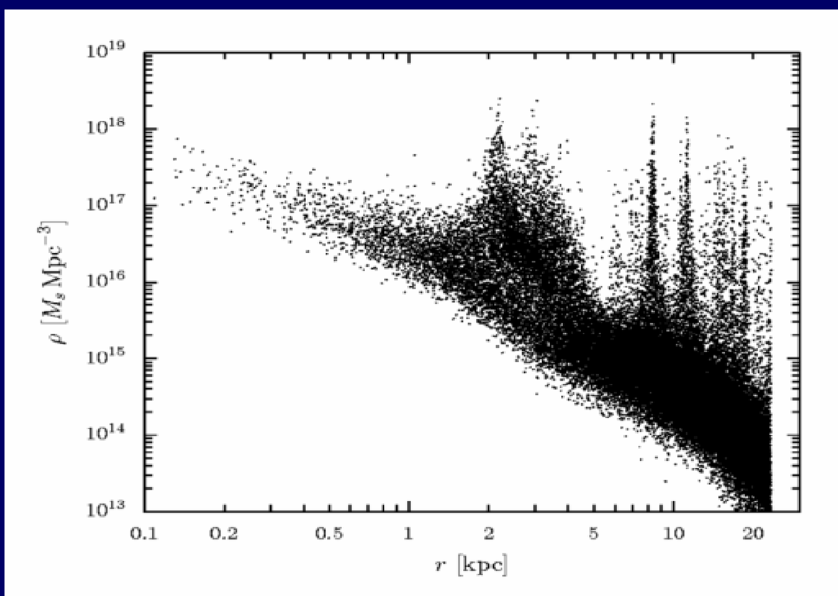


Phase-Space Density



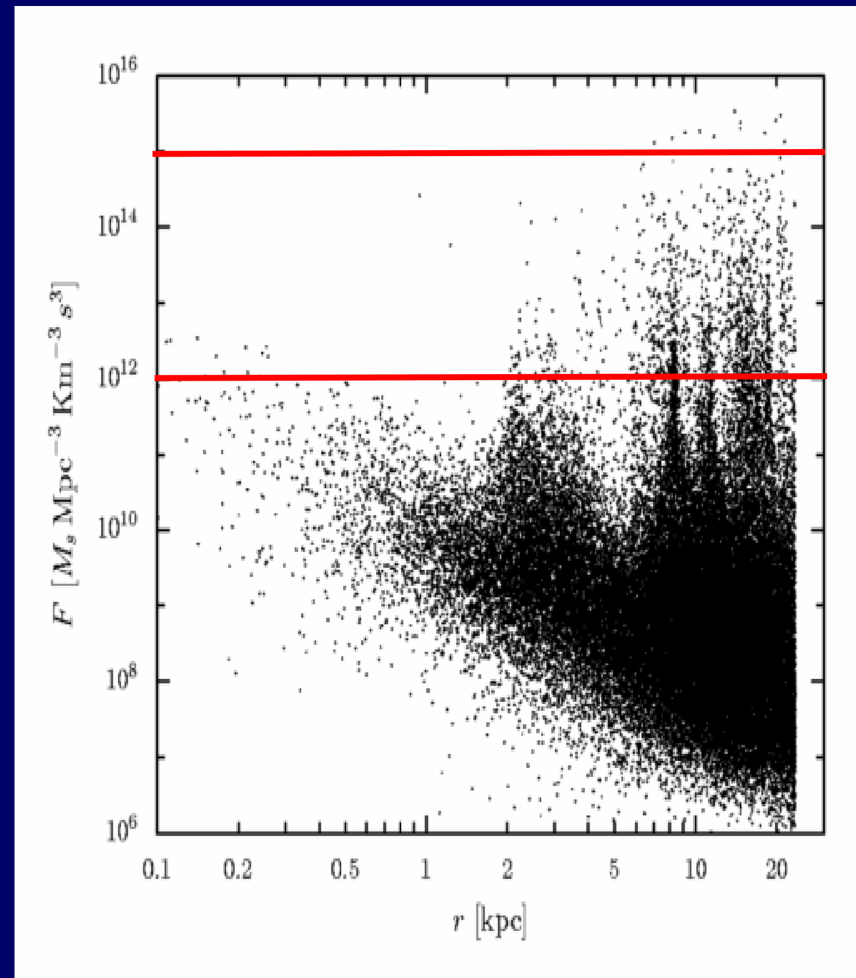
Profiles in Real Space and Phase Space

ρ(r)



radius

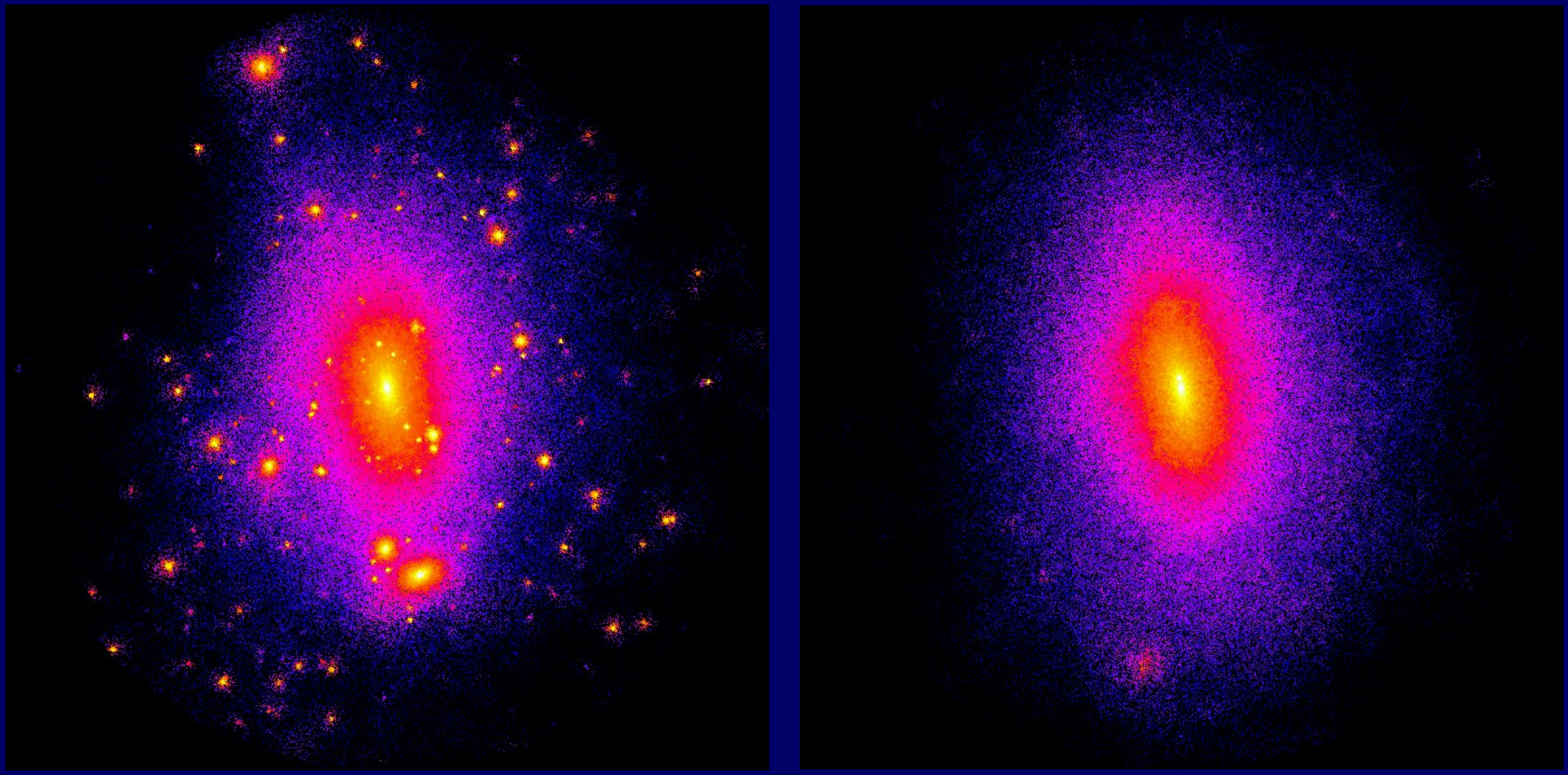
f(r)



radius

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

ΛCDM | No short waves

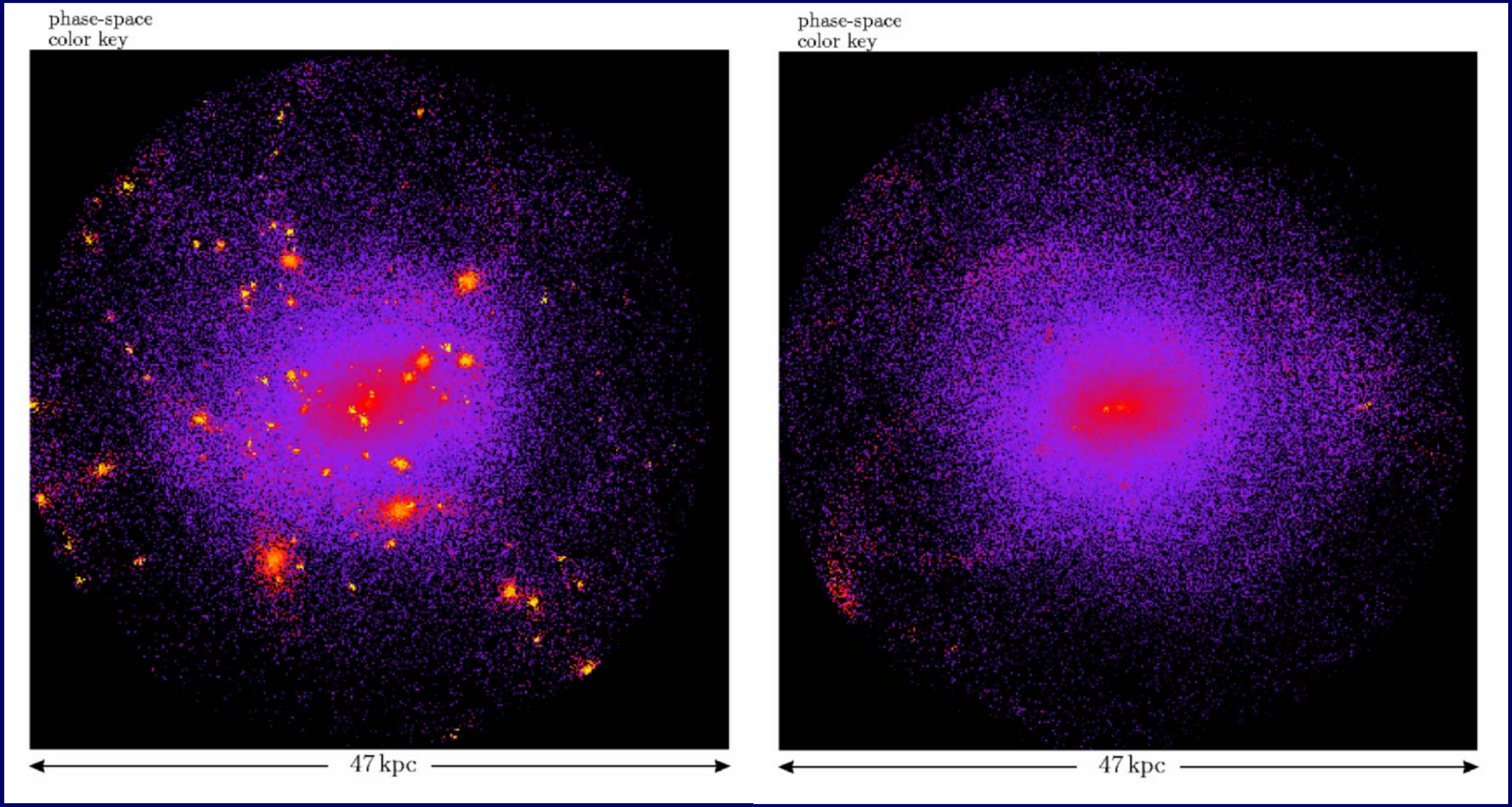


Real-Space Density

Moore et al.

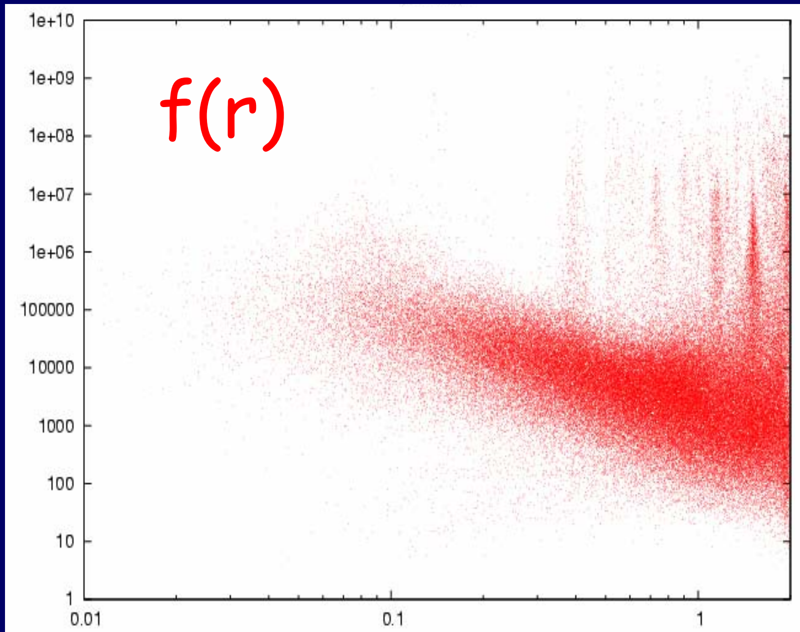
Phase-Space density

ΛCDM | No short waves



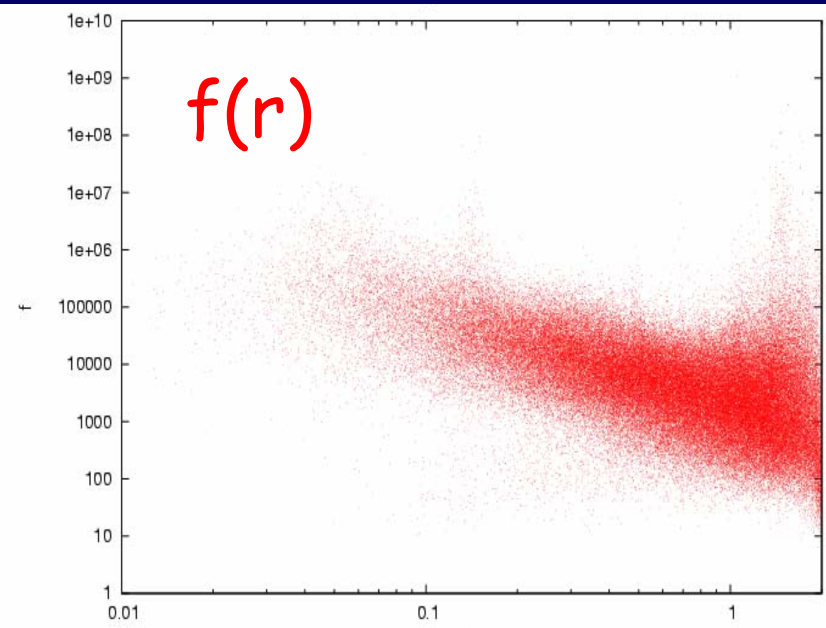
Phase-Space Density Profile

ΛCDM



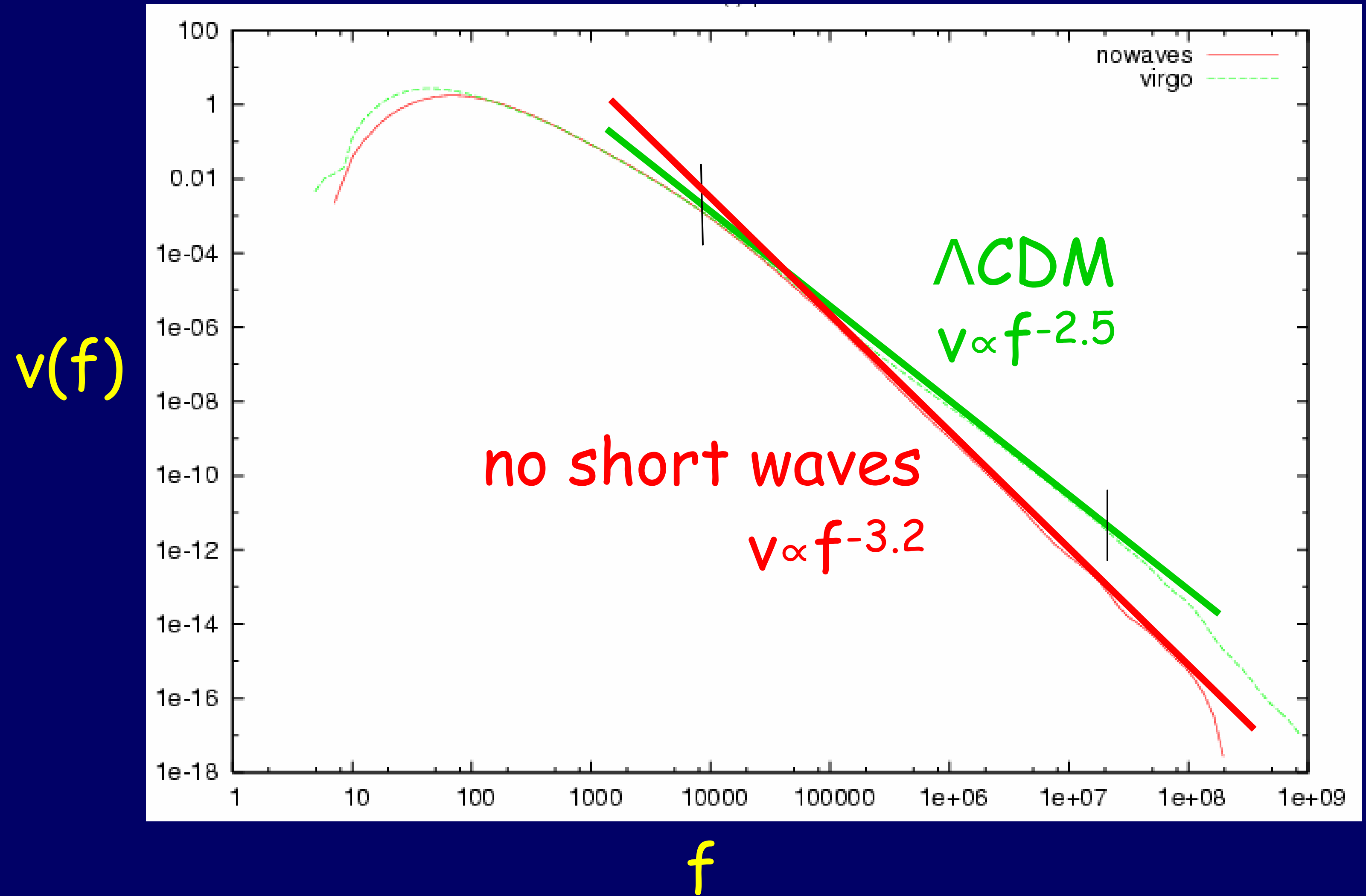
radius

No short waves

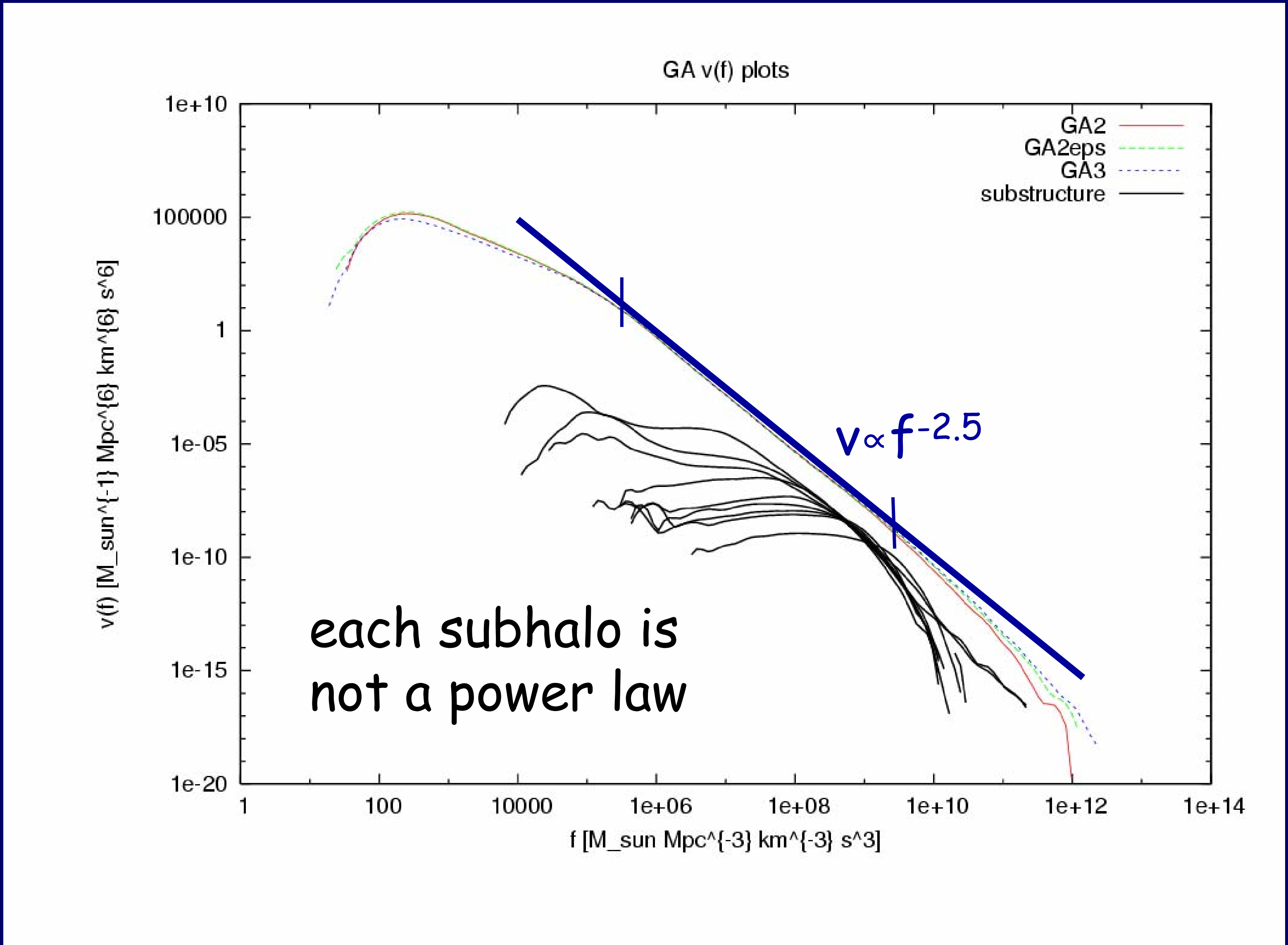


radius

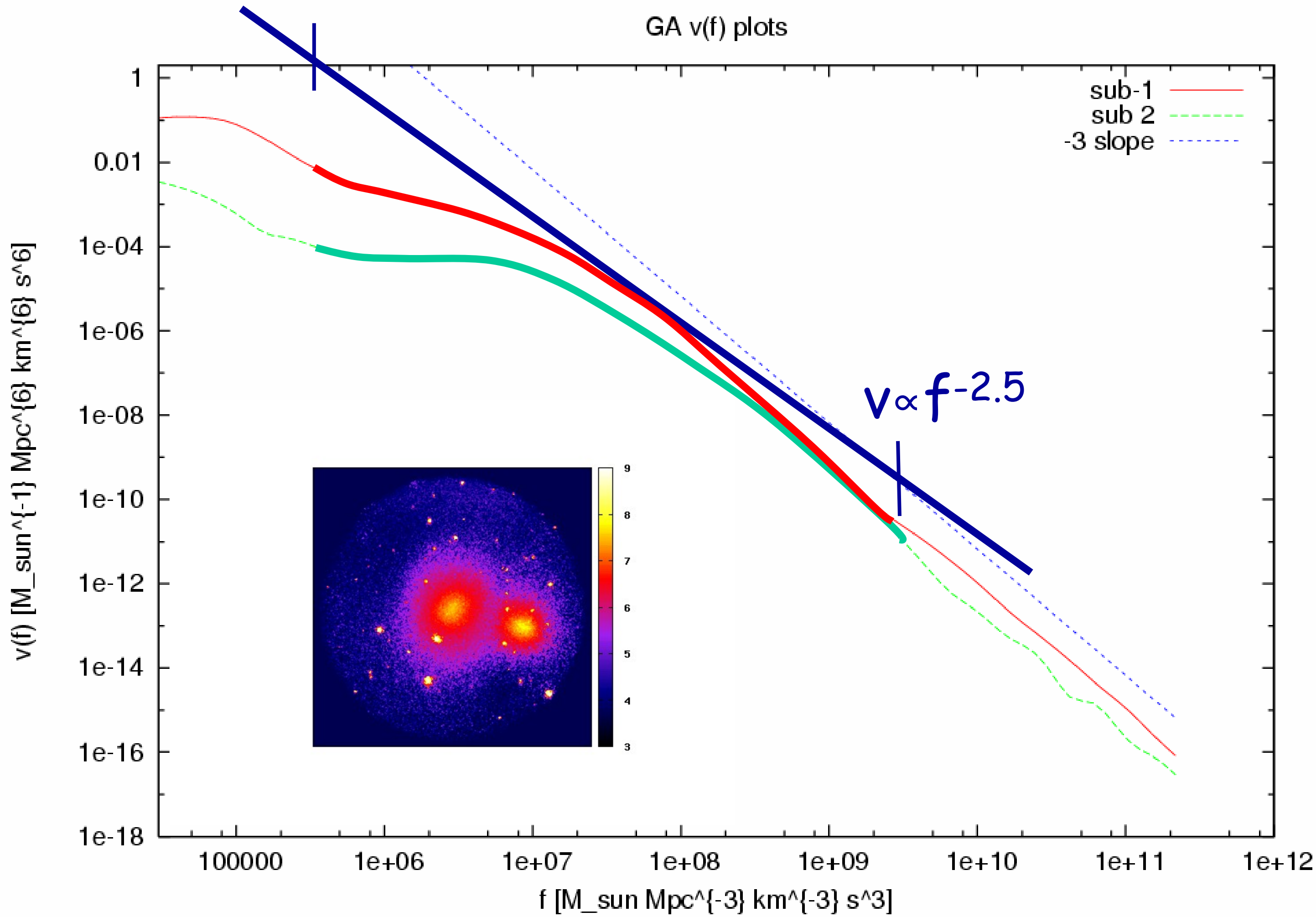
Same power law v(f)?



Additive Contribution of Subhalos

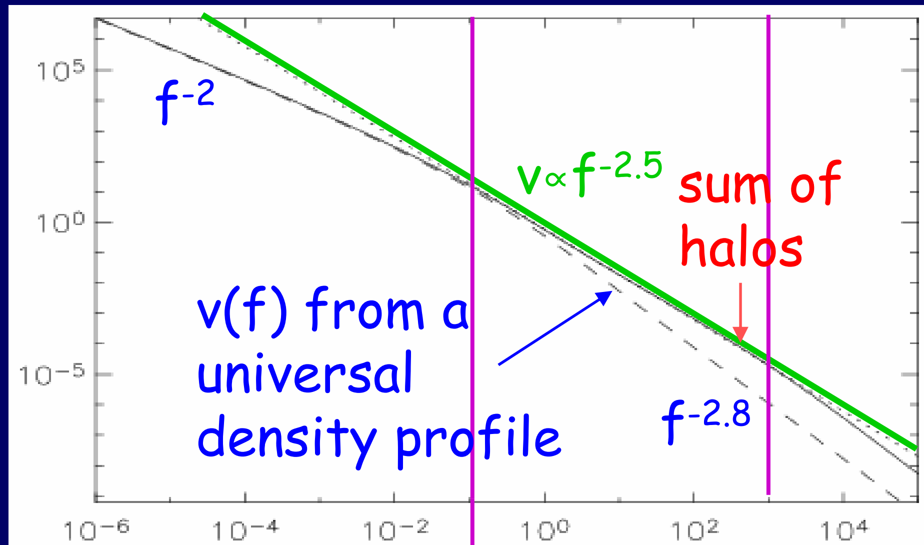


The Two Most Massive Subhalos



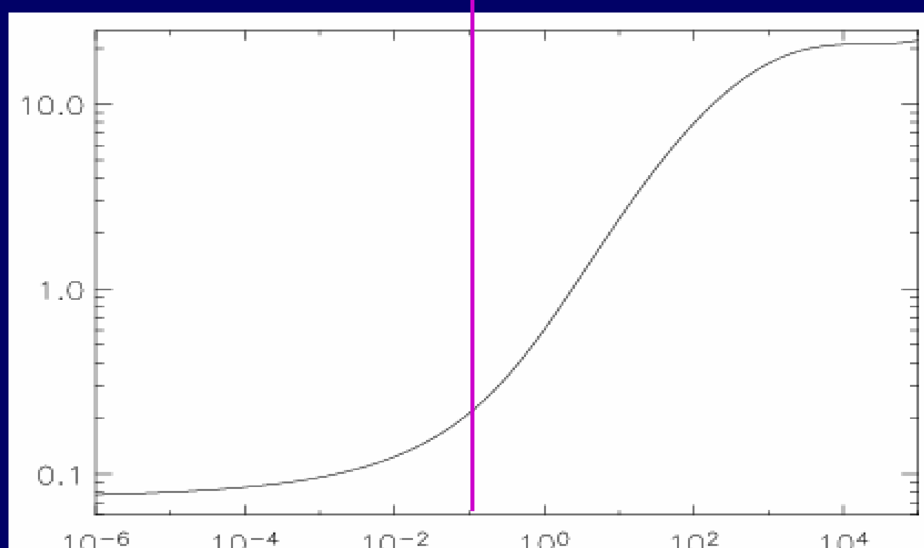
Adding up Sub-halos

f v(f)



f

subs/host



f

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

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?