HOW UNIVERSAL IS THE SCHMIDT LAW?

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In collaboration with

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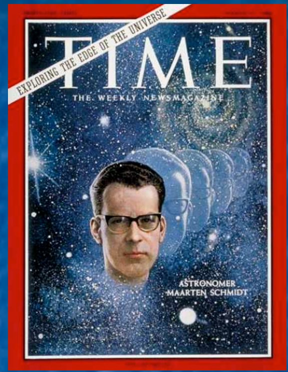
Topics

- "Surface" vs "volume" Schmidt law
- Where does the Schmidt law fail?
- A case of extremely low density gas
- A problem of the second parameter.

WHAT IS THE SCHMIDT LAW?



- Local Schmidt law: $SFR_v \sim \rho_g^n$

- Local (and azimuthally averaged) Kennicutt–Schmidt law: $SFR_s \sim \sigma_g^N$

- Global Schmidt law: $SFR_t \sim M_g^N$

(usually divided by the disk area)

Modifications of the Schmidt law

- The molecular Schmidt Law

  SFR versus σ_{H2} or σ_{HCN}
- Ryder-Dopita law

  SFR ~ $\sigma_{HI}^{n_1}$ $\sigma_{*}^{n_2}$
- "Dynamic" Schmidt law

  SFR ~ σ_{gas} V/R
- Free-fall time law

  SFR ~ σ_{gas} $(\rho_{gas})^{1/2}$

The list can be extended

The problem to pass from the surface to volume gas density:

- The density of stellar disks and the stellar velocity dispersion are needed, but usually they are badly known.
- Generally accepted assumption that the disc thickness remains constant with radius may be wrong.

Where do we observe a strong deviation (or dispersion) from the simple power law with the exponent N= 1-2?

- Some individual galaxies (*e.g. M33; n=3, M81, no SFR-*σ_{gas} *dependence etc*)
- Starburst galaxies, LIRGs/ULIRGs
- Inner regions of galaxies with heavy bulges (?)
- LSB-galaxies (?)

Kennicutt 98

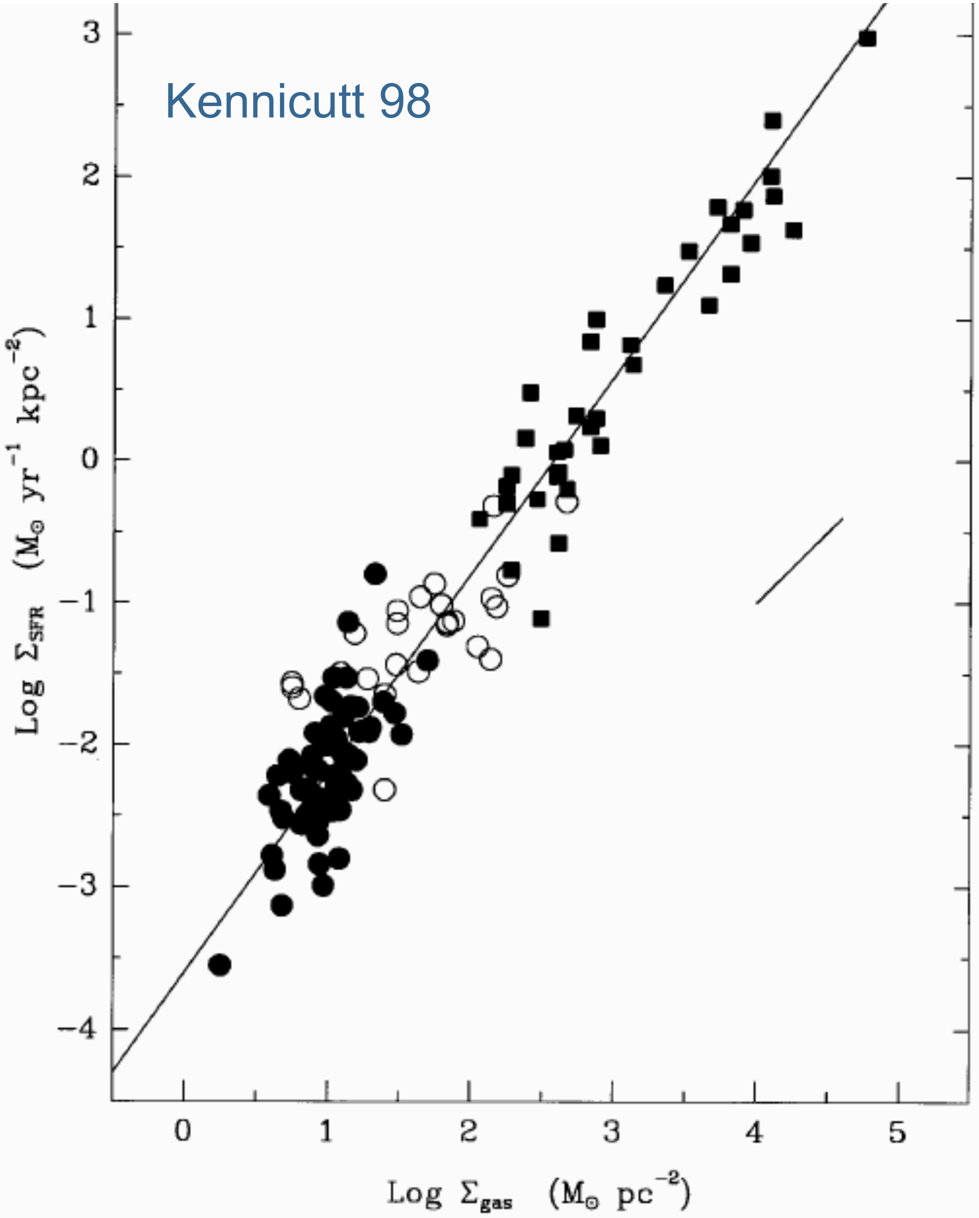


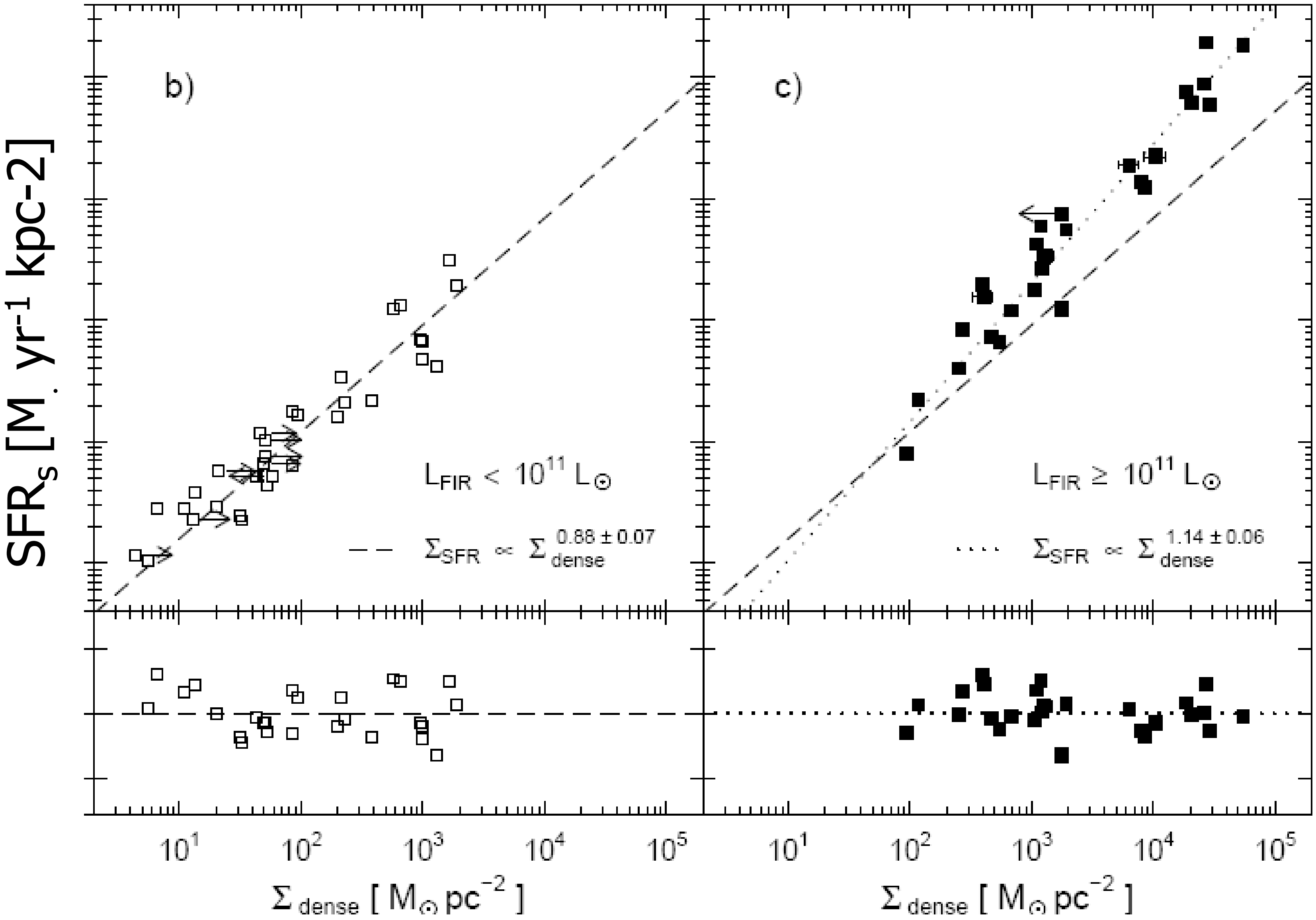
FIG. 6.—Composite star formation law for the normal disk (*filled circles*) and starburst (*squares*) samples. Open circles show the SFRs and gas densities for the centers of the normal disk galaxies. The line is a least-squares fit with index $N = 1.40$. The short, diagonal line shows the effect of changing the scaling radius by a factor of 2.

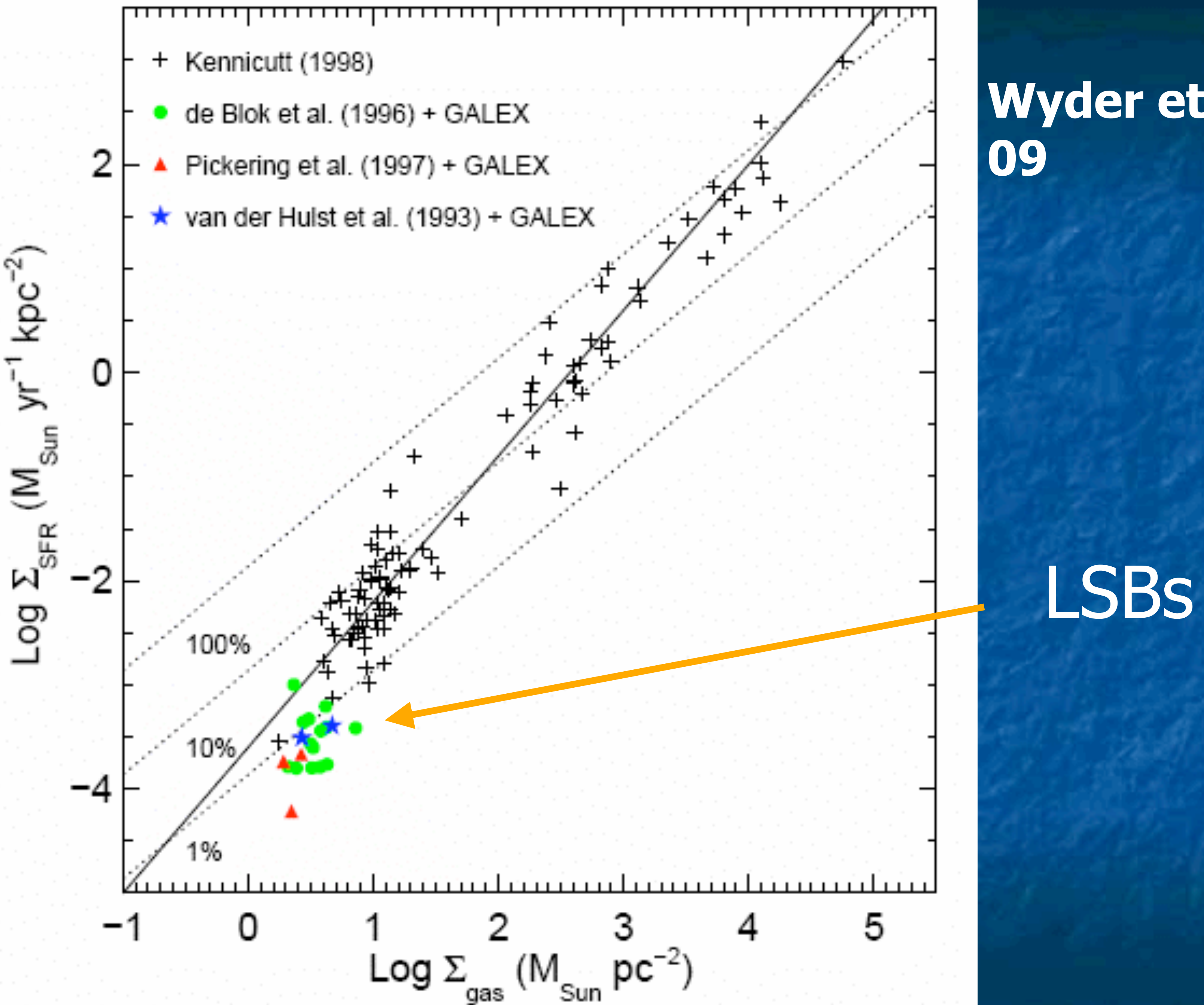
NOTE:

- The inclusion of both extremely high SFR galaxies (LIRGs, ULIRGs) and extremely low SFR galaxies (LSBs) tend to make the SFR–σ_{gas} relationship more steep.

J. Gracia-Carpio et al., 07

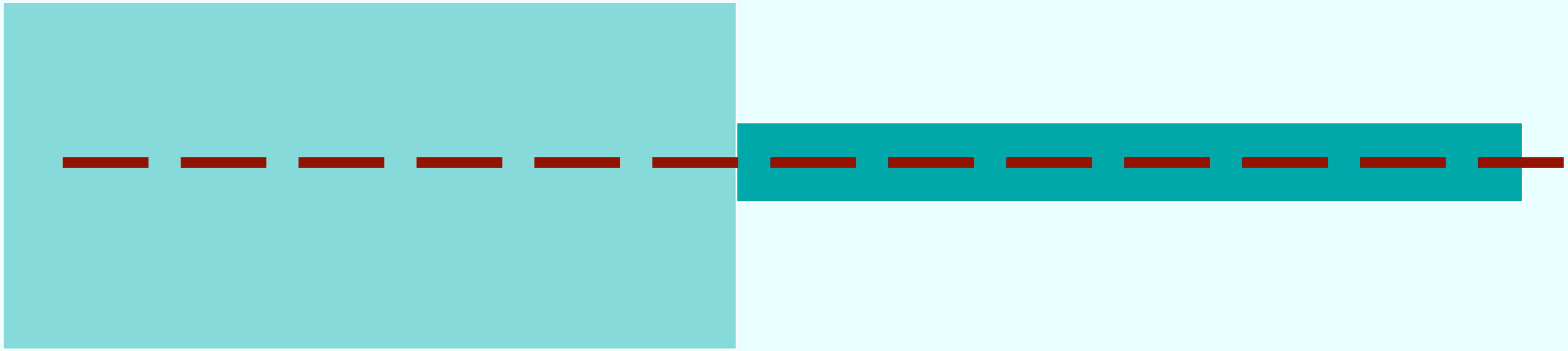
IRAM 30m, HCN





Wyder et al., 09

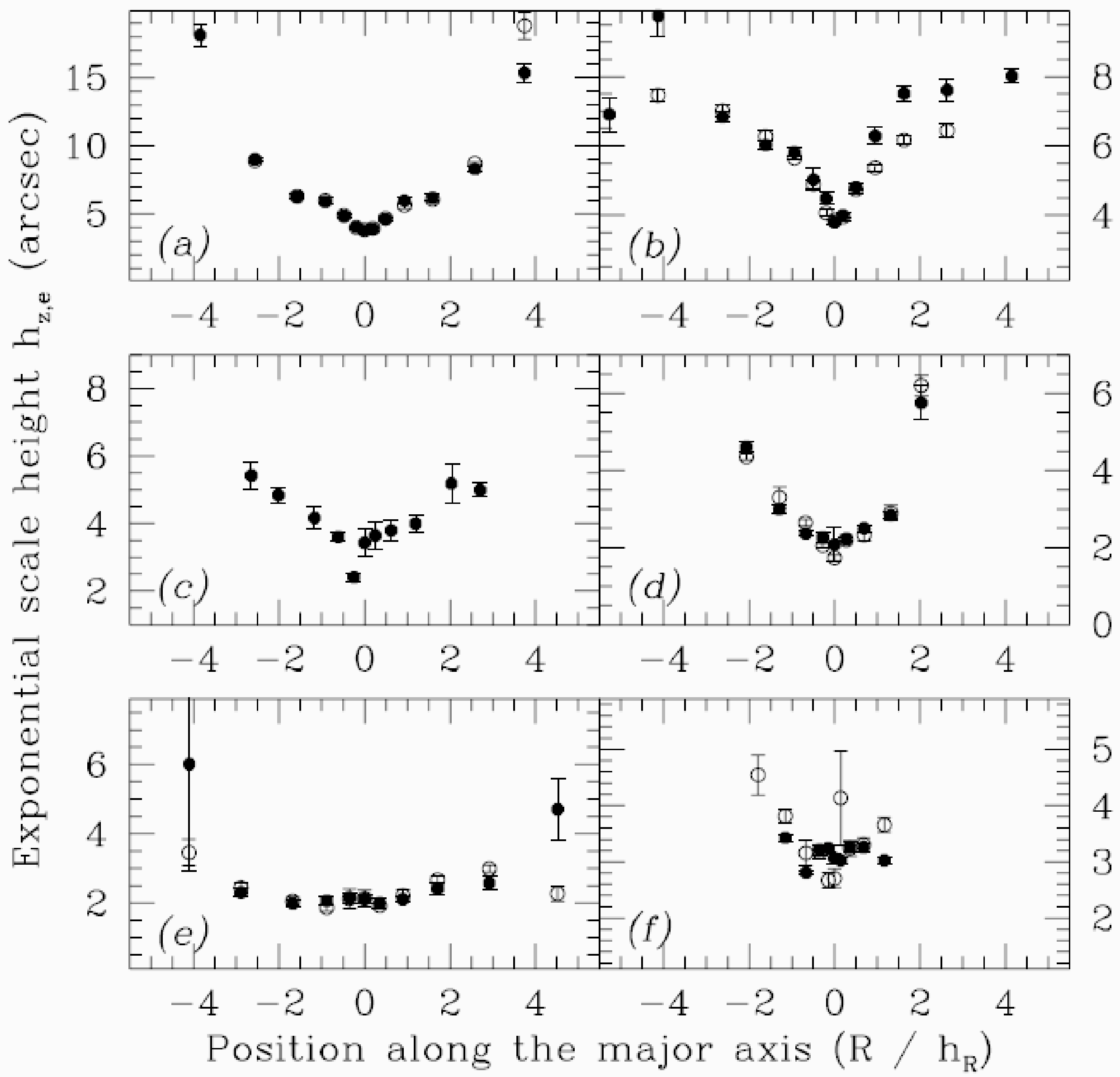
Two points have to be noted:



1. Thickness of gas disc evidently changes along the radius:
if some regions have the same surface gas density, their gas volume densities are different, so it is not evident that the observed SFR would be the same (even if N =1)

2. If $SFR_V \sim \rho^n$, the value of n may be different for radial $\rho(R)$ and vertical $\rho(z)$ profiles.

R. de Grijs and R.F. Peletier, 97
Edge on galaxies,   I-band



WE PROPOSE:
A STABILITY CONDITION as the method to find the upper limit of the disc density

A general idea:
For the disc to be stable, the radial velocity dispersion of stars should exceed some marginal value

THAT IS
A high density needs a high velocity dispersion!

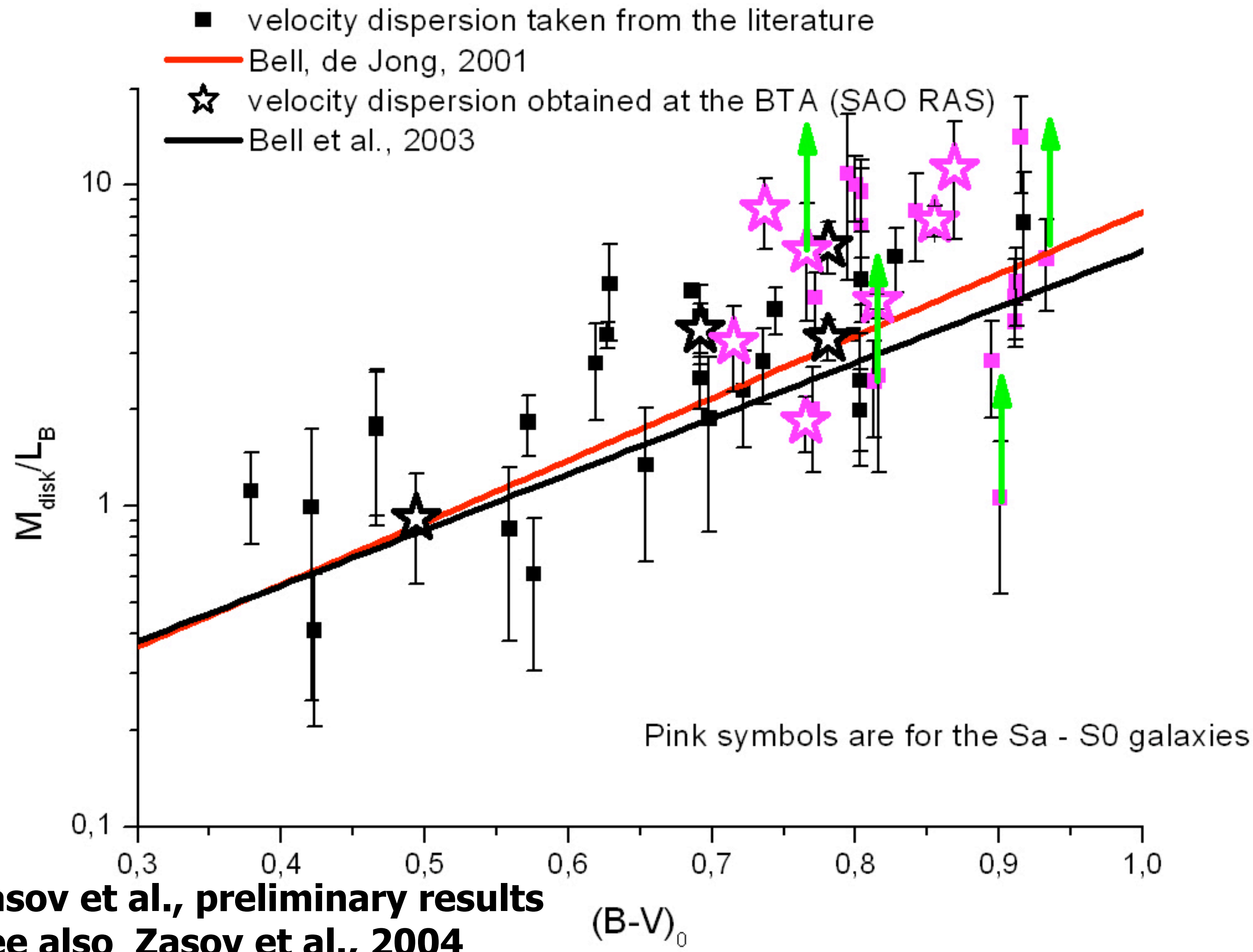
This is Moscow

What gives evidence of marginal stability of disks?

1. Masses of discs of S-galaxies, found assuming their marginal stability, agree with the estimates obtained by another methods (photometry;
decomposition of velocity curve).

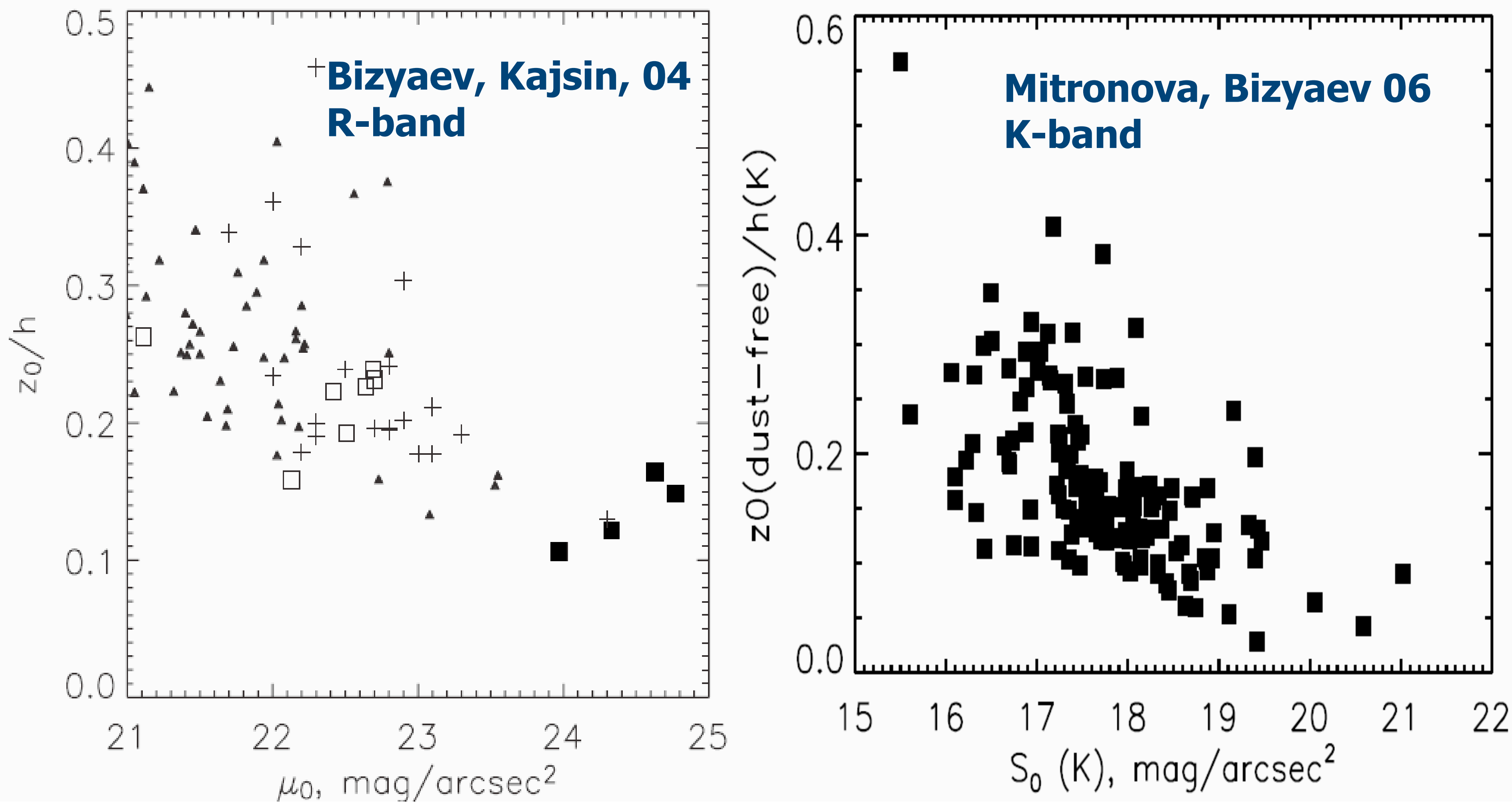
NOTE: some galaxies (usually S0) are definitely overheated.

Bottema 1993, 1997,
Zasov, Khoperskov, Tiurina, 2001, 2004



Zasov et al., preliminary results
See also Zasov et al., 2004

2.The observed disc thickness in the inner parts of edge-on galaxies depends on a de-projected surface brightness, in the same manner, as it follows from the disc marginal stability condition



WHAT WE HAVE TO KNOW:

$\sigma(r) = 1/Q \cdot C_r \cdot \kappa/3.36G$, ***where κ–epicyclic frequency***

- **ROTATION CURVE**
  (corrected for the asymmetric drift if necessary)

- **DISC SURFACE DENSITY**
  (rotation curve and/or disc colour, assuming M/L~const)

- **THE RATIO Cz/Cr = const**
  (assumed to be~0.6)

- **VELOCITY DISPERSION OF GAS**
  (V_{HI}~9 km/s, V_{H2}~6 rm/s)

- **TOOMRE PARAMETER Q_T corresponding to the marginal case**

Analytical local criteria of stability to the perturbations in the plane of a disc:

- "Classical" Toomre criterium

$(Cr)_{TOOMRE} = Q_T \bullet 3.36G\sigma/\kappa$

where $Q_T = 1$ **(radial perturbations only),**

- Modified Toomre' criterion

$Q_T = 2\Omega/\kappa$

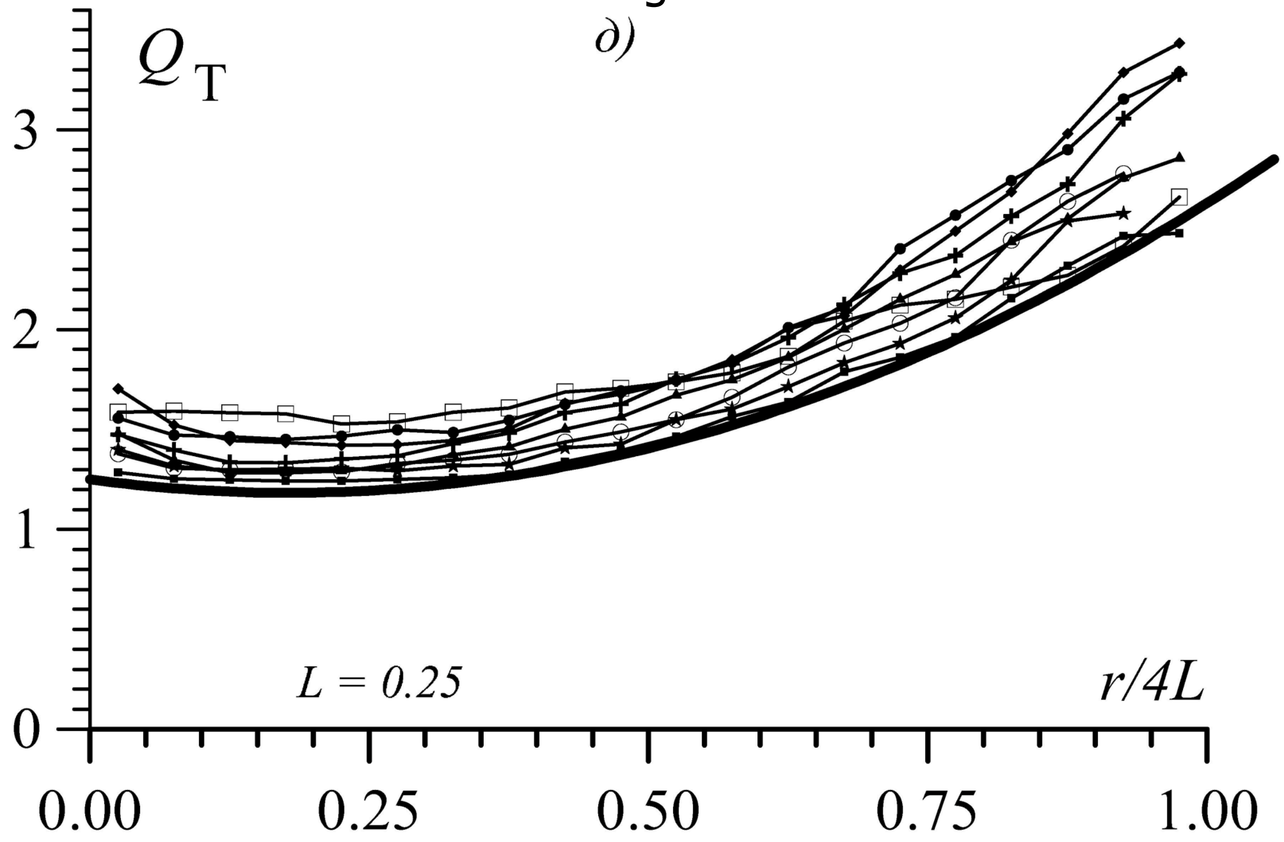
- Morozov' criterion

$Q_T = (2\Omega/\kappa)(1+F_M\ (Cr, \Omega, \kappa, d\sigma/dr, dC_r/dr, d\Omega/dr)$

- Polyachenko-Polyacheko-Strel'nikov criterion

$Q_T = F_P(d\ln\Omega/d\ln r)$

Different numerical 3D models are represented, evolving from the initial subcritical condition



A THEOREM OF MIDPLANE DENSITY of marginally stable disk

- **If to admit that the stellar disc of a galaxy is marginally stable, then the estimated values of scale height and midplane density of gas very weakly depend on both the adopted surface density or the adopted scale height of the stellar disc.**

It follows from the proportionality between C_r and C_z

__***The increasing of the surface density of stellar disk leads to the increasing of the stellar velocity dispersion and , in turn, to the increasing of disk scale height. As the result, the volume density of gas of fixed surface density , embedded into a disk, remains practically unchanged.***

Self-consistent model of a galaxy

Components:

HI (i=1); H2(i=2), stellar disc (i=3), spherical halo (d)

4 equilibrium equations :

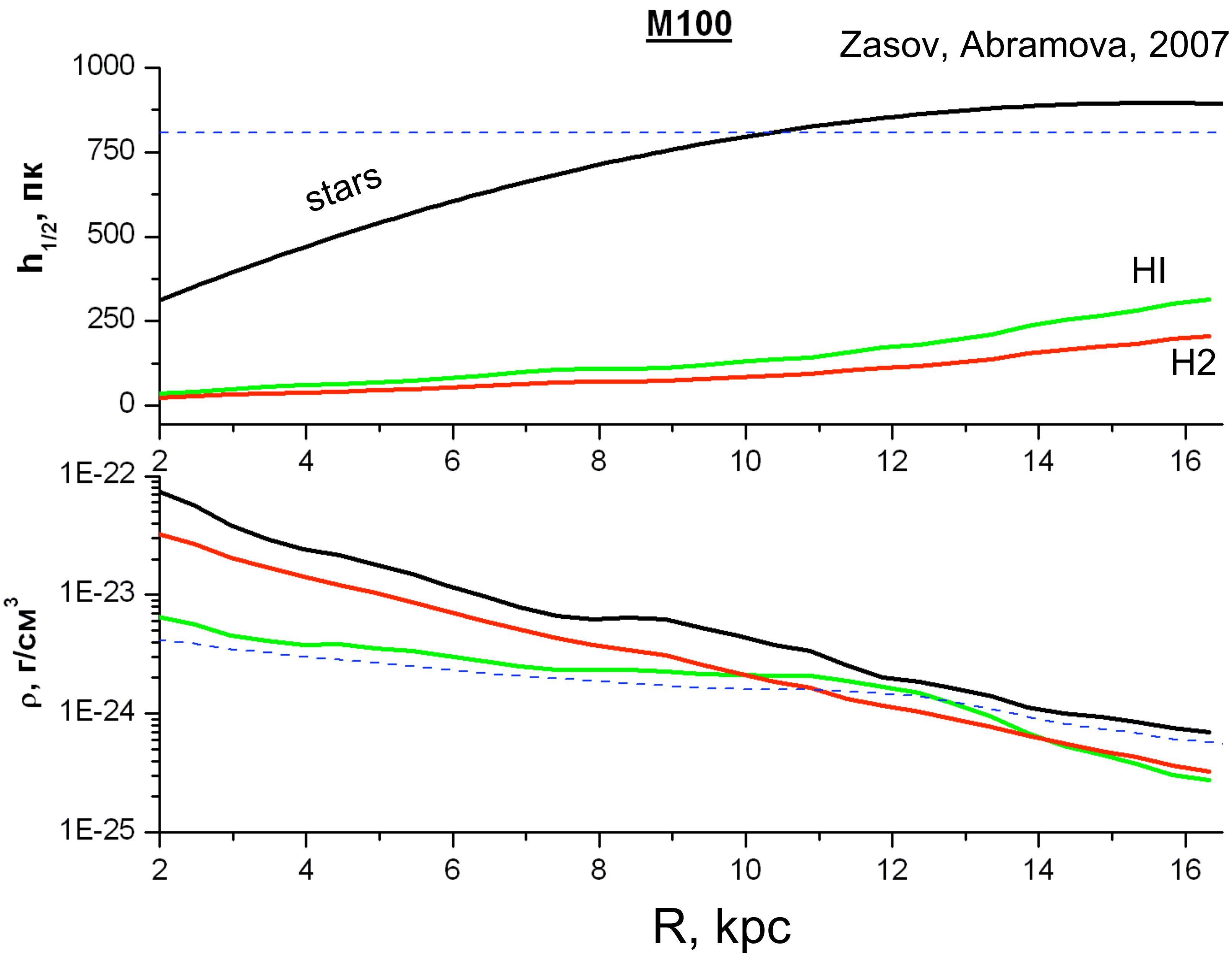
$$-(V_{z,i})^2/\rho_i \times (d\rho_i/dR) = \Sigma_i \, (\partial\varphi_i \, /\partial z) + \partial\varphi_{halo}/\partial z$$

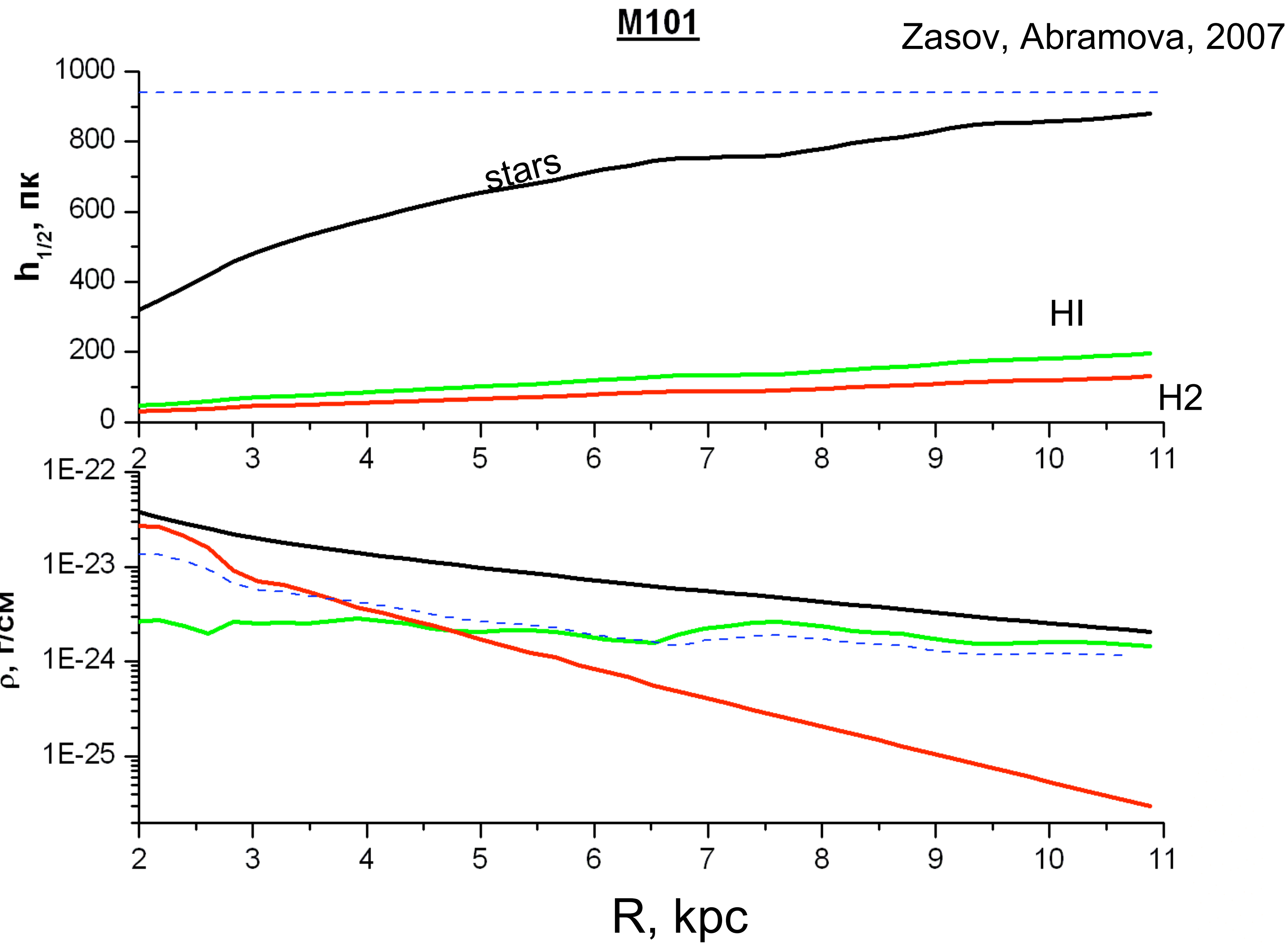
4 Poisson equations:

$$\Sigma_i \, (\partial^2 \varphi_i \, /\partial z^2) = 4\pi G \, \Sigma_i \, \rho_i$$

For z = 0:

$$\rho_i = (\rho_0)_i \, , \quad d\rho_i \, /dz = 0.$$


M100
Zasov, Abramova, 2007
1000
750
500
250
0
$h_{1/2}$, пк
stars
HI
H2
2
4
6
8
10
12
14
16
1E-22
1E-23
1E-24
1E-25
ρ, г/см3
R, kpc


M101
Zasov, Abramova, 2007
stars
HI
H2
h1/2, пк
ρ, г/см3
R, kpc
1000
800
600
400
200
0
1E-22
1E-23
1E-24
1E-25
2
3
4
5
6
7
8
9
10
11

Star formation rate

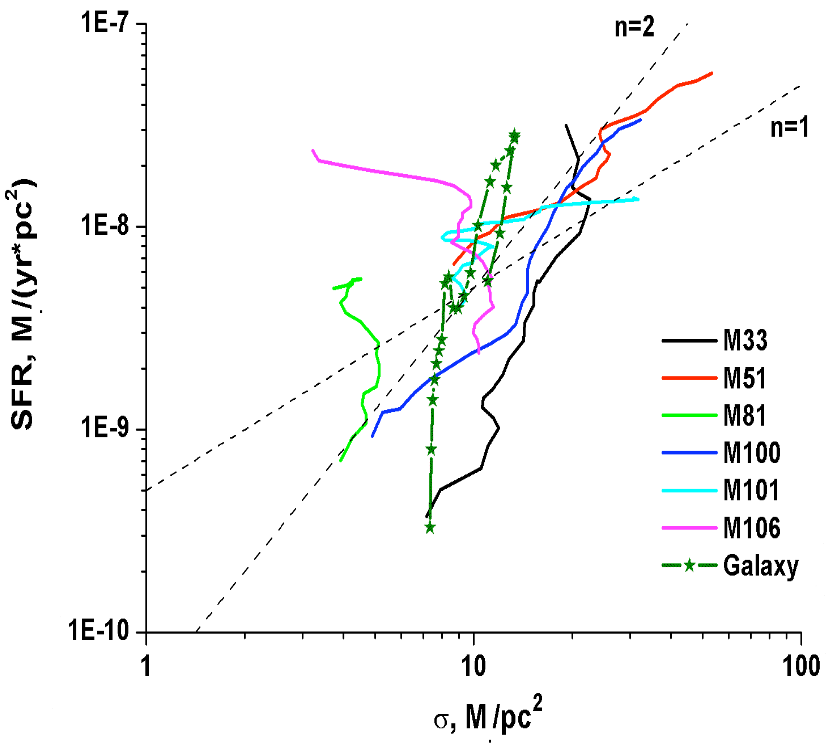
–a combination of UV+FIR

following the papers by

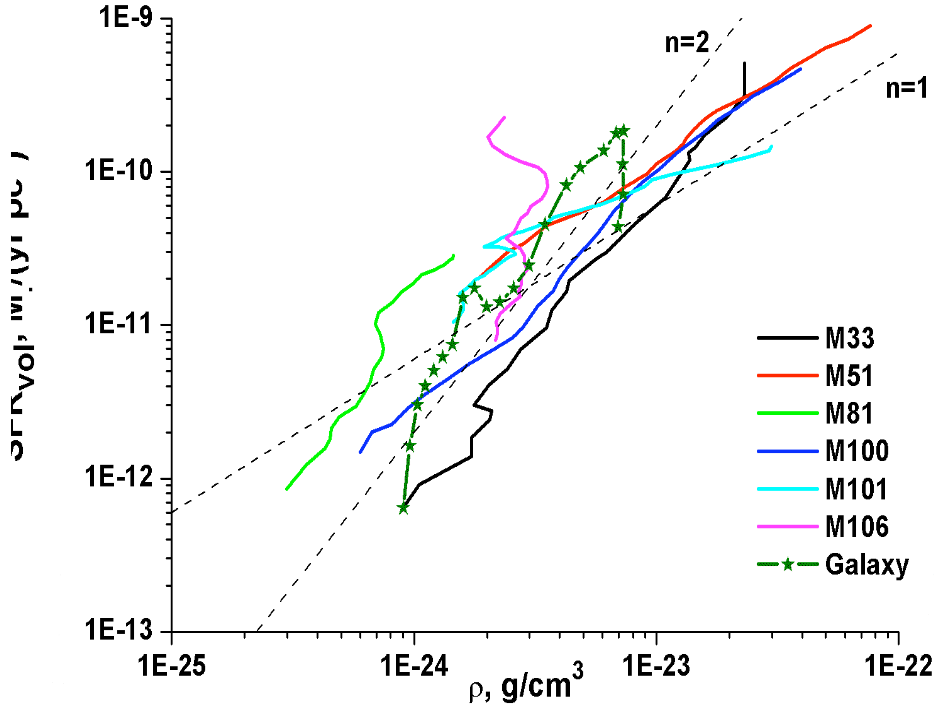
- Boissier et al, 2004; Hirashita et al, 2003:

The correlation is much better now and “n” is closer to unit

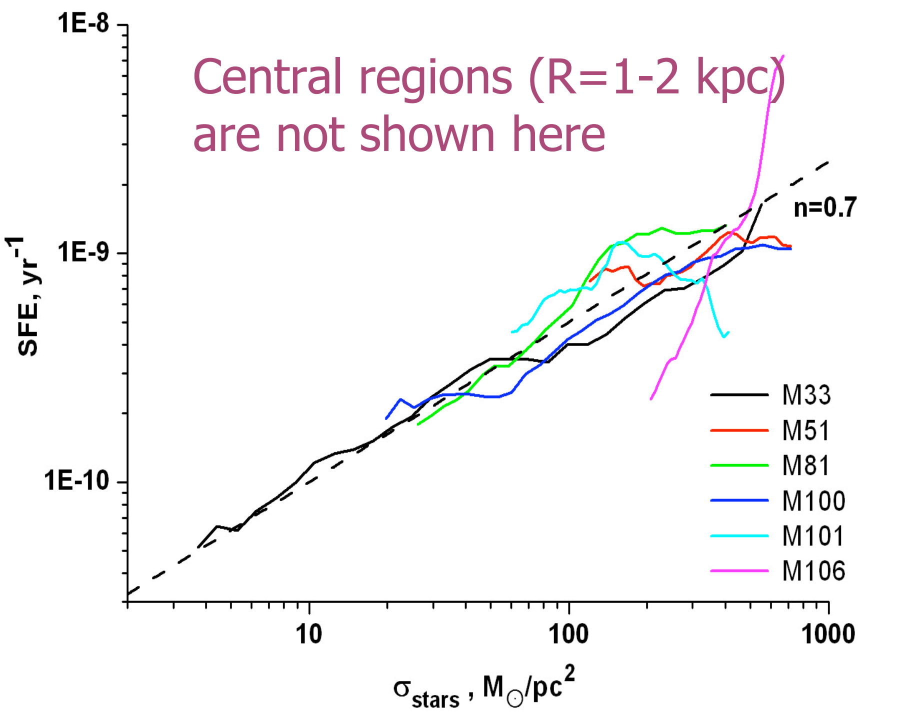
SFR-surface gas density

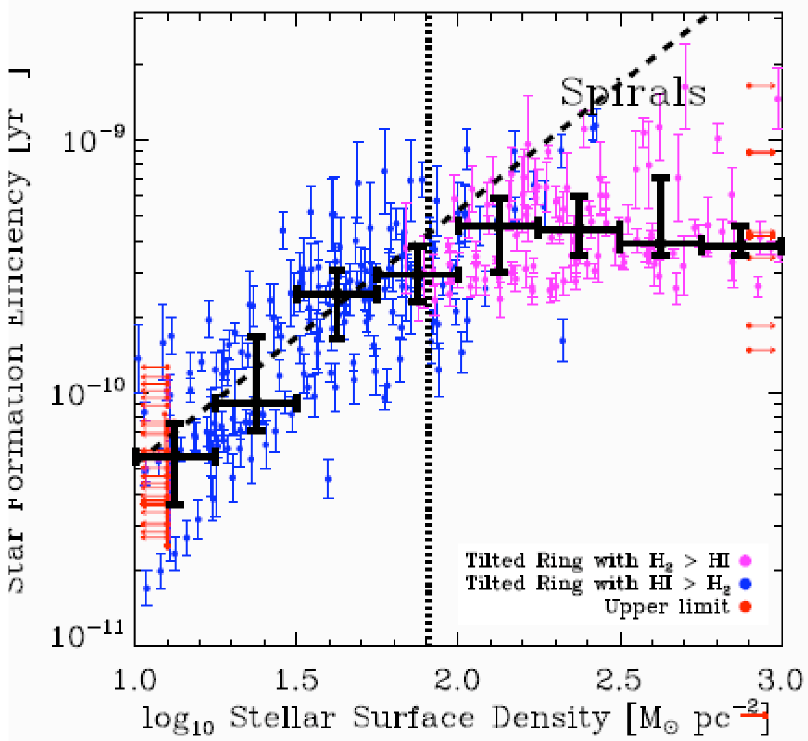


SFR-midplane volume gas density



The second parameter is the local surface density of stellar disc





Zasov, Abramova,2007

Leroy et al, 2008

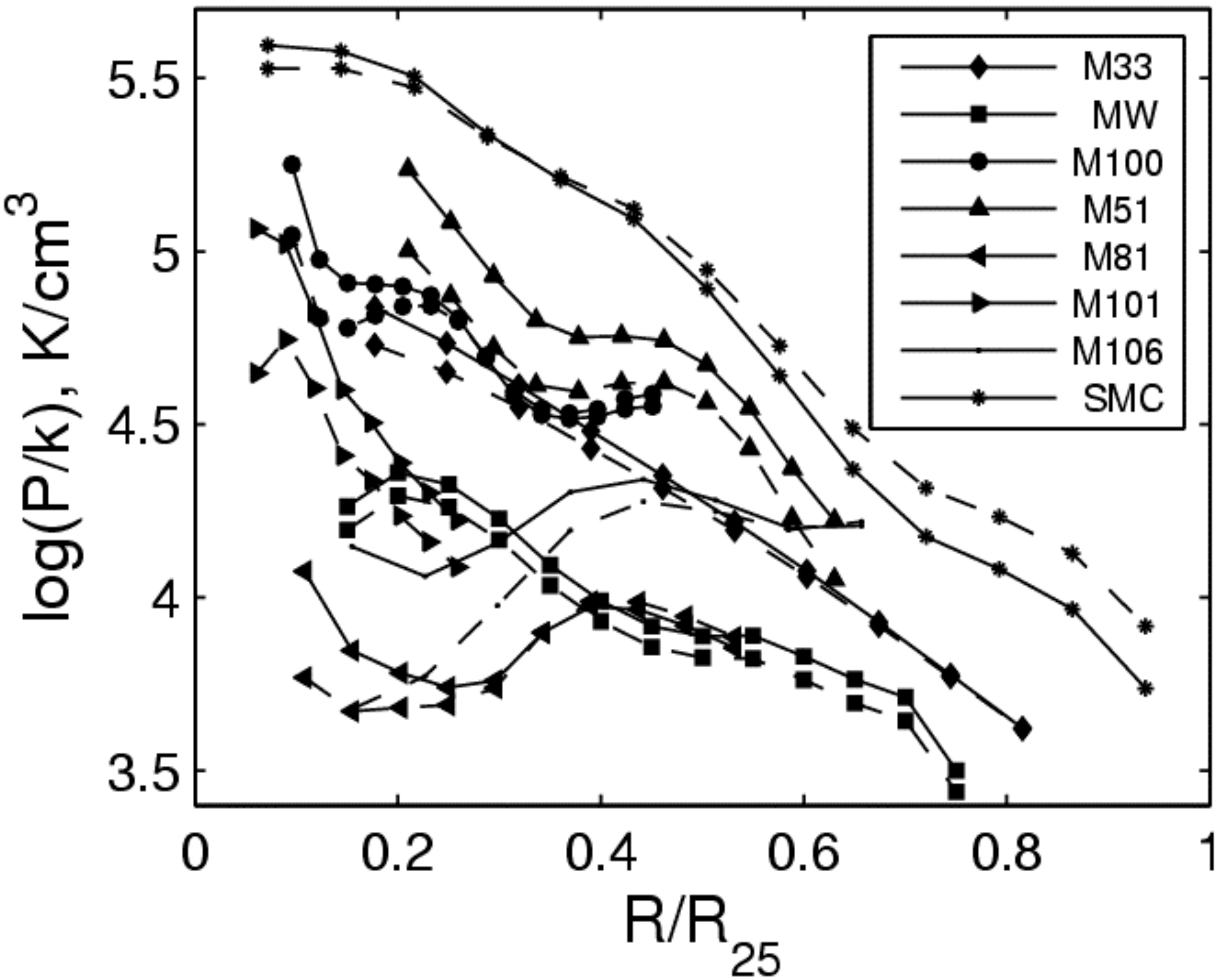
Is gas pressure a key factor?

- $P_{gas} \sim (G\Sigma_* / h_*)^{0.5} \Sigma_{gas} V_{gas}$
- *(Blitz, Rosolowsky, 2004, 2006)*

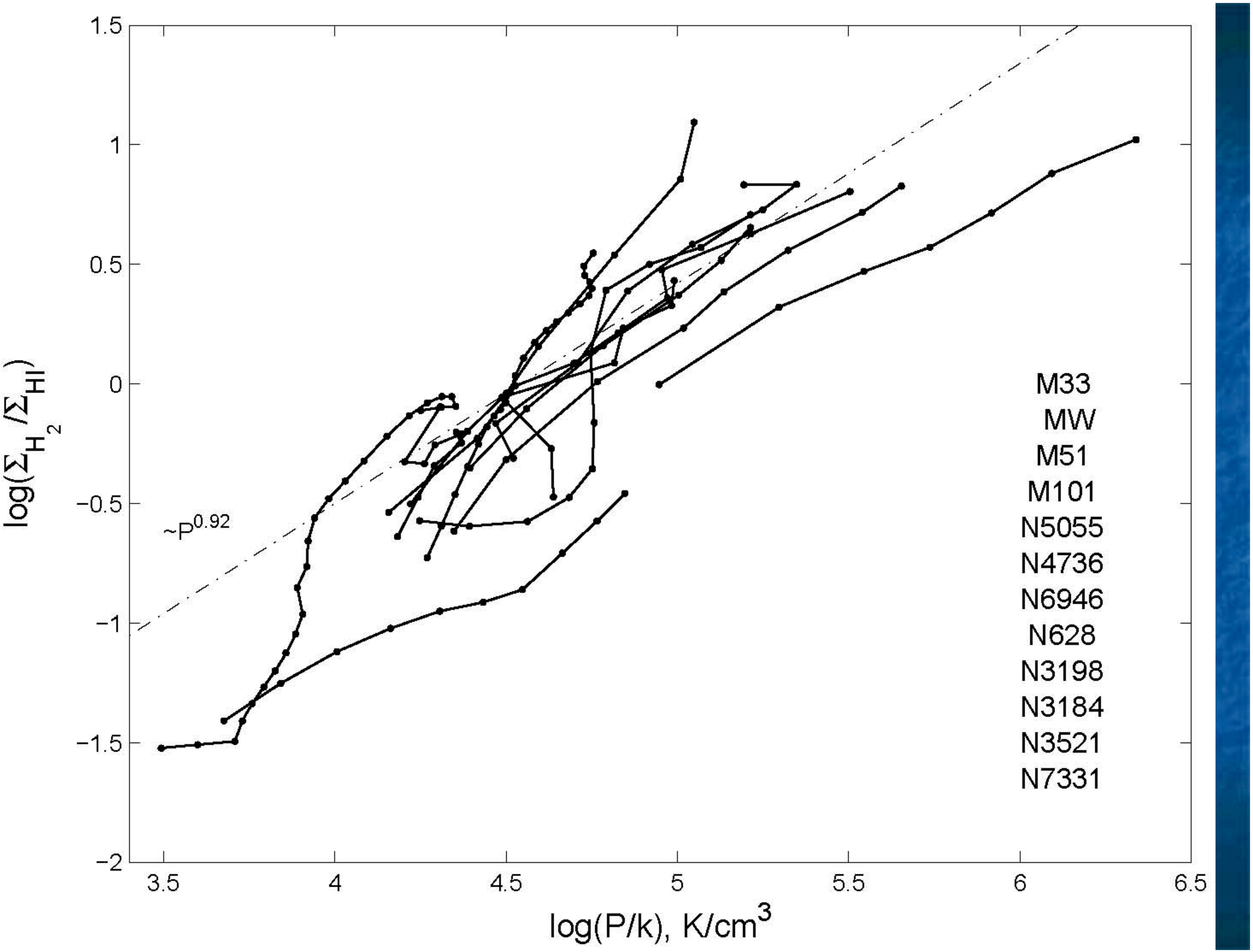
Custom assumptions:

- *V_{gas} is constant (in agreement with the observations)*
- *h_* is constant (rather arbitrary)*
- *Gas gravitation and self-gravitation are ignored*
- *A presence of dark halo , which makes the potential well more steep is ignored.*

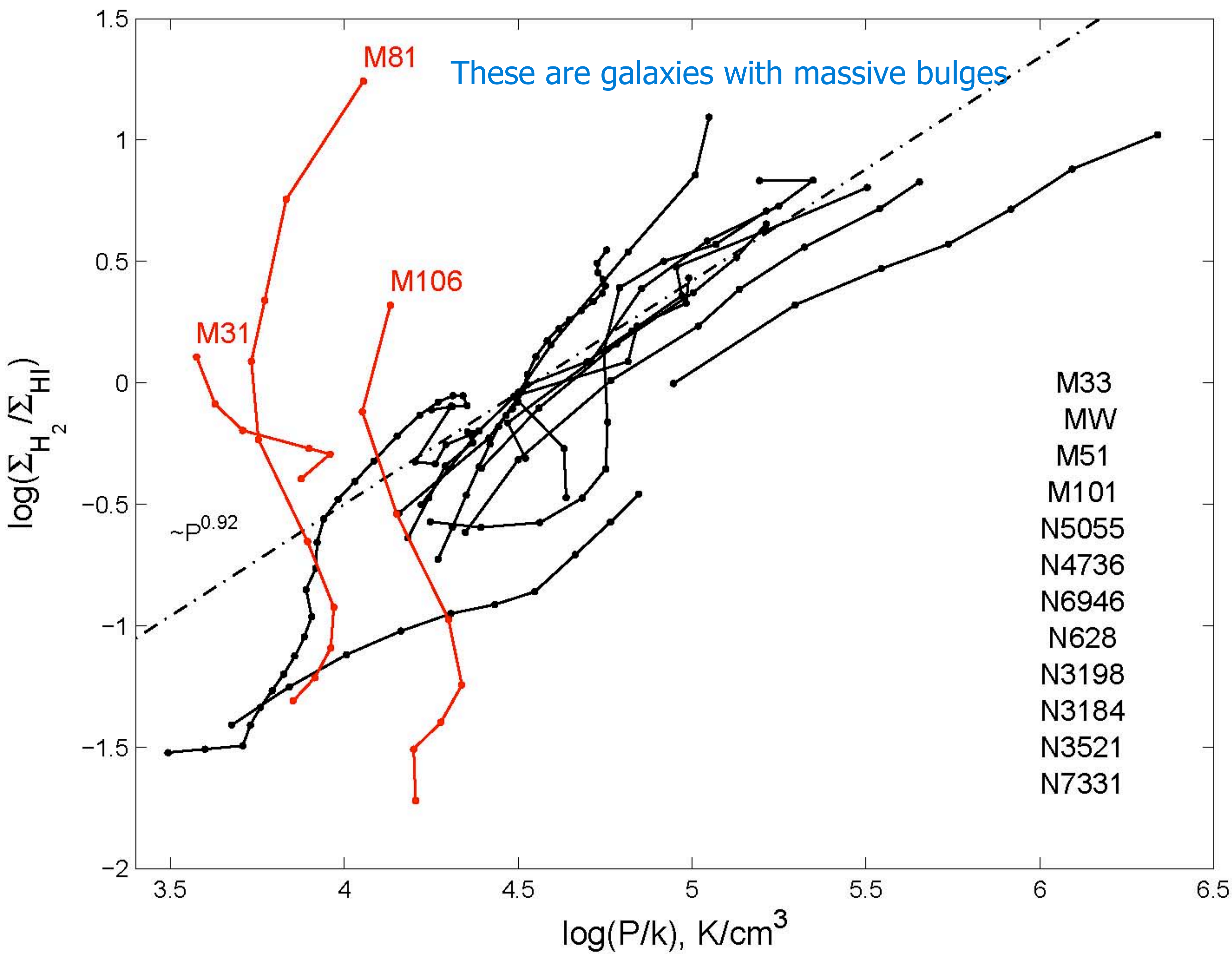
- *SELF-CONSISTENT SOLUTION IS PREFERRABLE*



log(P/k), K/cm^3
5.5
5
4.5
4
3.5
0
0.2
0.4
0.6
0.8
1
R/R$_{25}$
M33
MW
M100
M51
M81
M101
M106
SMC



1.5
1
0.5
0
−0.5
−1
−1.5
−2
3.5
4
4.5
5
5.5
6
6.5
log(Σ_H2/Σ_HI)
log(P/k), K/cm3
~P0.92
M33
MW
M51
M101
N5055
N4736
N6946
N628
N3198
N3184
N3521
N7331



These are galaxies with massive bulges
M81
M106
M31
~P^0.92
M33
MW
M51
M101
N5055
N4736
N6946
N628
N3198
N3184
N3521
N7331
log(Σ_H2 /Σ_HI)
log(P/k), K/cm^3
1.5
1
0.5
0
−0.5
−1
−1.5
−2
3.5
4
4.5
5
5.5
6
6.5


M81

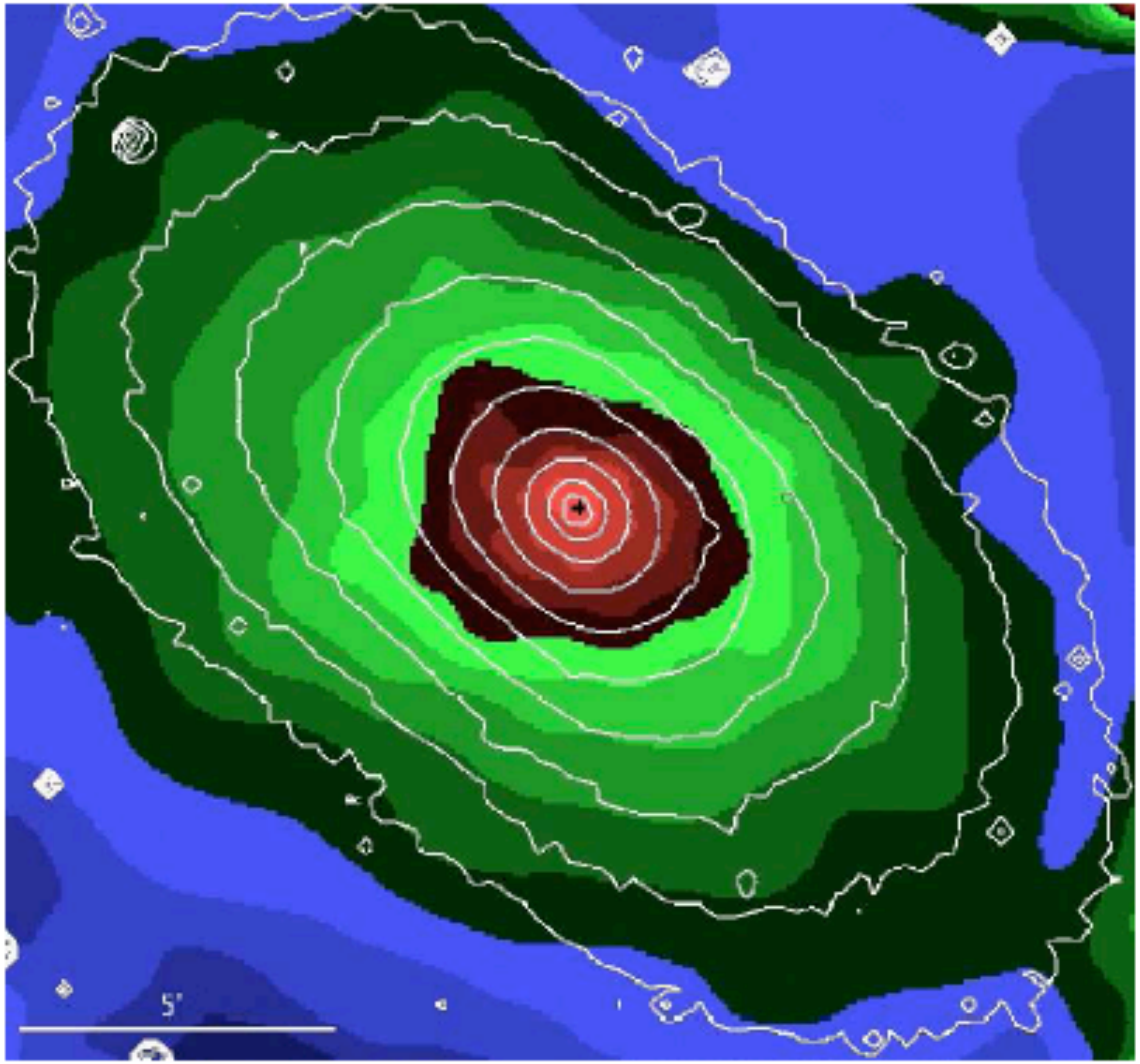


Figure 2. Adaptively smoothed Chandra image in the 0.5 – 1.2 keV band overplotted with K-band contours. The point sources were removed and their locations were filled with the local background value. Center of the M31 is marked with a cross. North is up and east is left.

Galaxy	T_{gas} keV	n_e	R_{lim} kpc	Log nT	Observatory	Ref
M31	0.3–1	10^{-2}–10^{-3}	2 KPC	**4 – 5**	Chandra	1
M81	0.18 0.64 0.4 0.26	0.01–0.07 M81	1 kpc 2 kpc 2 kpc	**4.5 – 5.5**	XMM-Newton Chandra	2 3
VIRGO Cluster	3	3×10^{-4}	250 kpc	~ 4	Rosat	4

1. A.Bogdan+2008; 2. M.Page+ 2002; 3. D.Swartz+ 2002 4. Nulsen+1995

It is the essential point:

- The external thermal pressure of gas squeezing the galaxy discs in the inner regions of bulges rich of hot-gas may be significant

SF IN LOW DENSITY REGIONS

- Outer regions of normal S-galaxies
- Disks of S0- galaxies
- Disks of LSB galaxies

LSB and S0 –galaxies: are they marginally stable?

- Discs of some of them are definitely overheated
- LSB: two possibilities:

  – Either they have underluminous disc with “normal” stellar population, or their disc is nearly maximal, and their M/L is larger than expected (Fusch, 2002).

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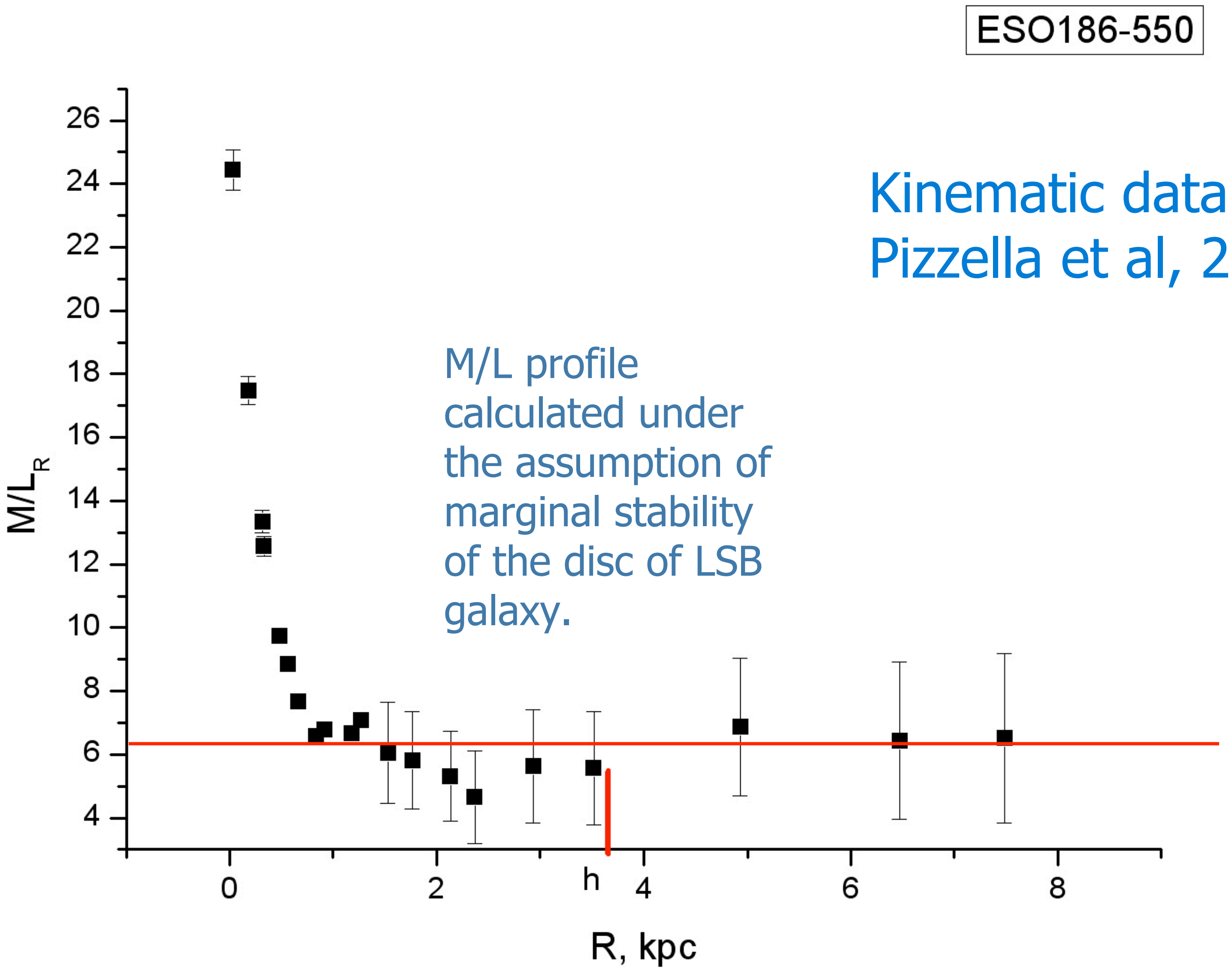
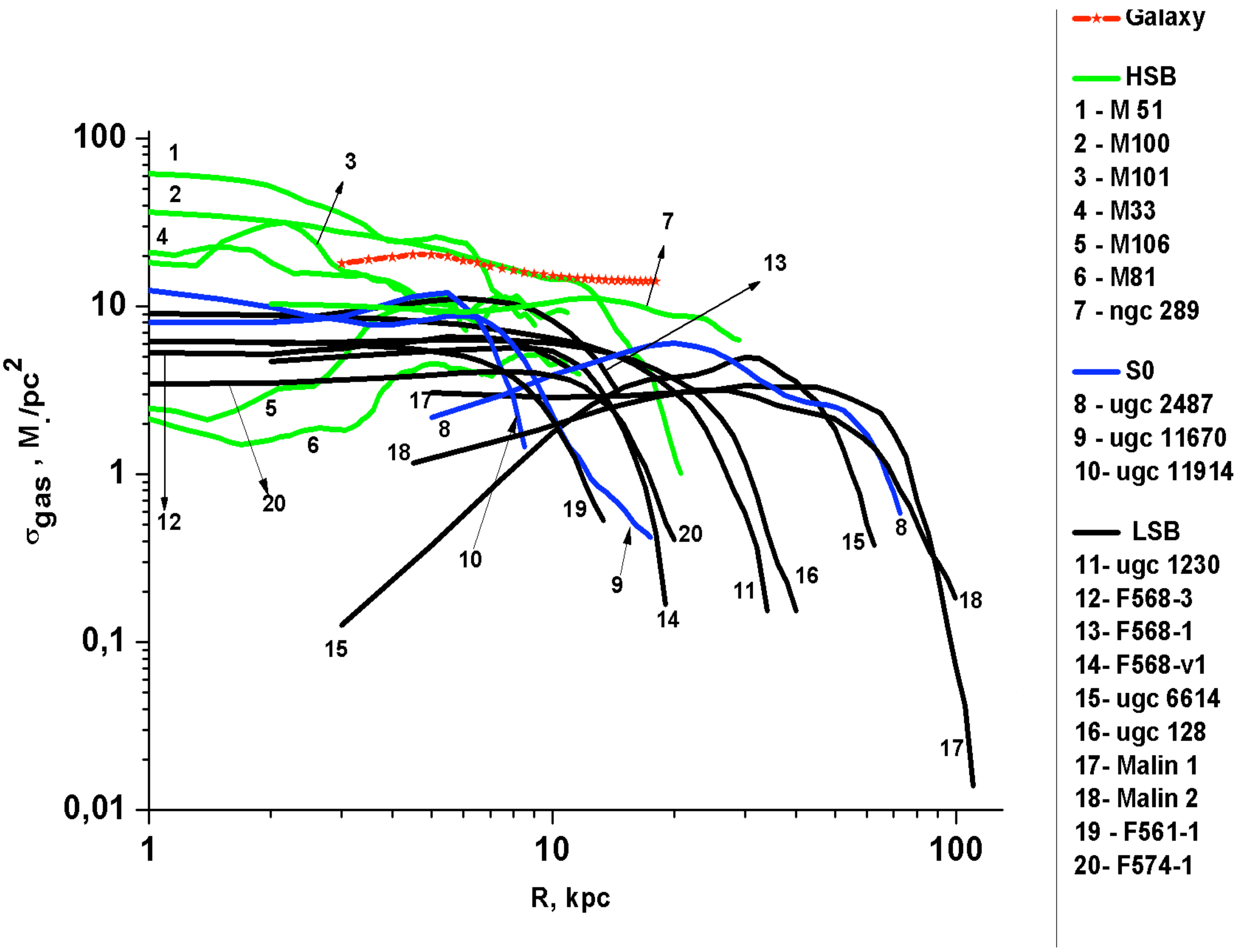
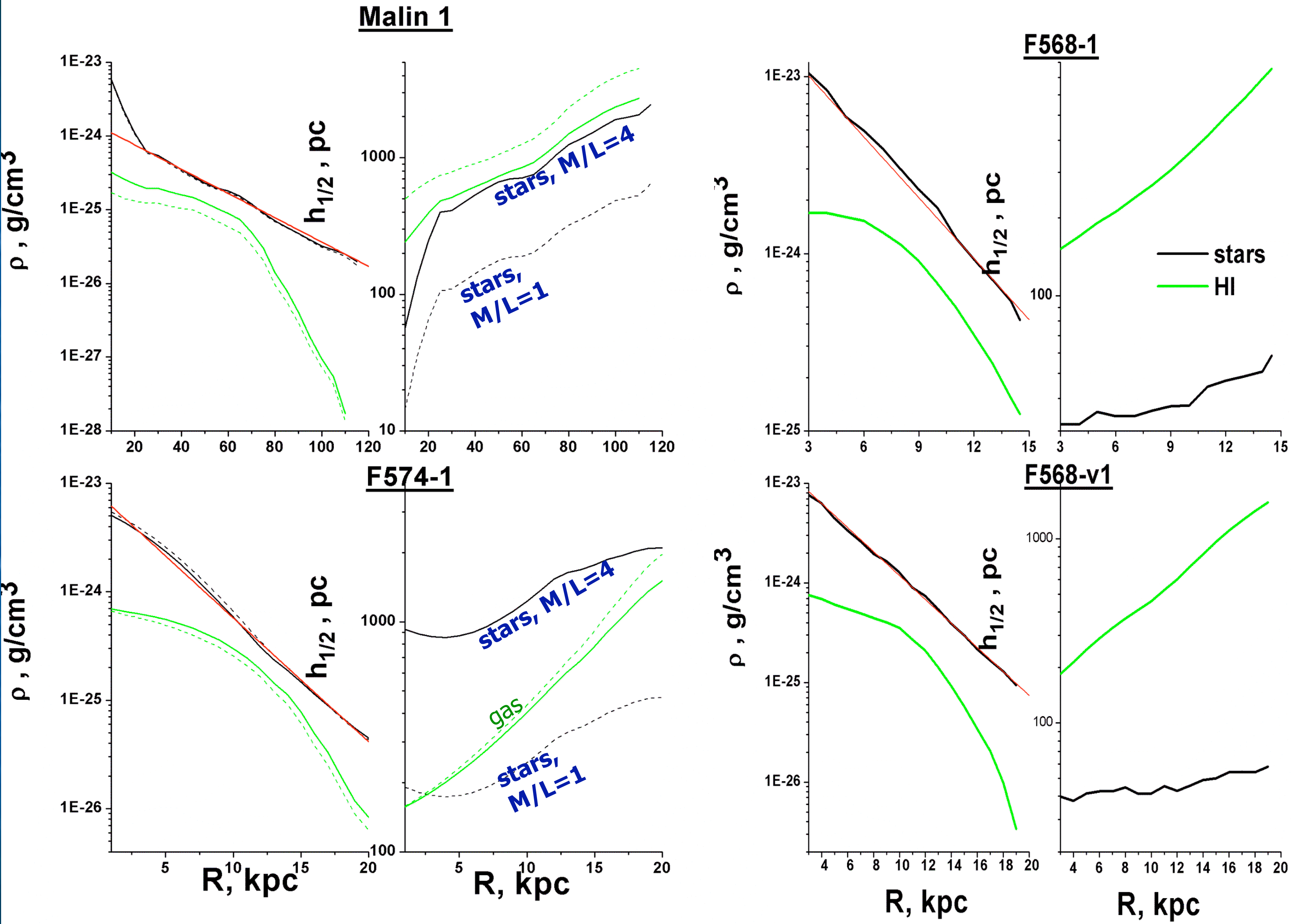
Kinematic data are from Pizzella et al, 2008



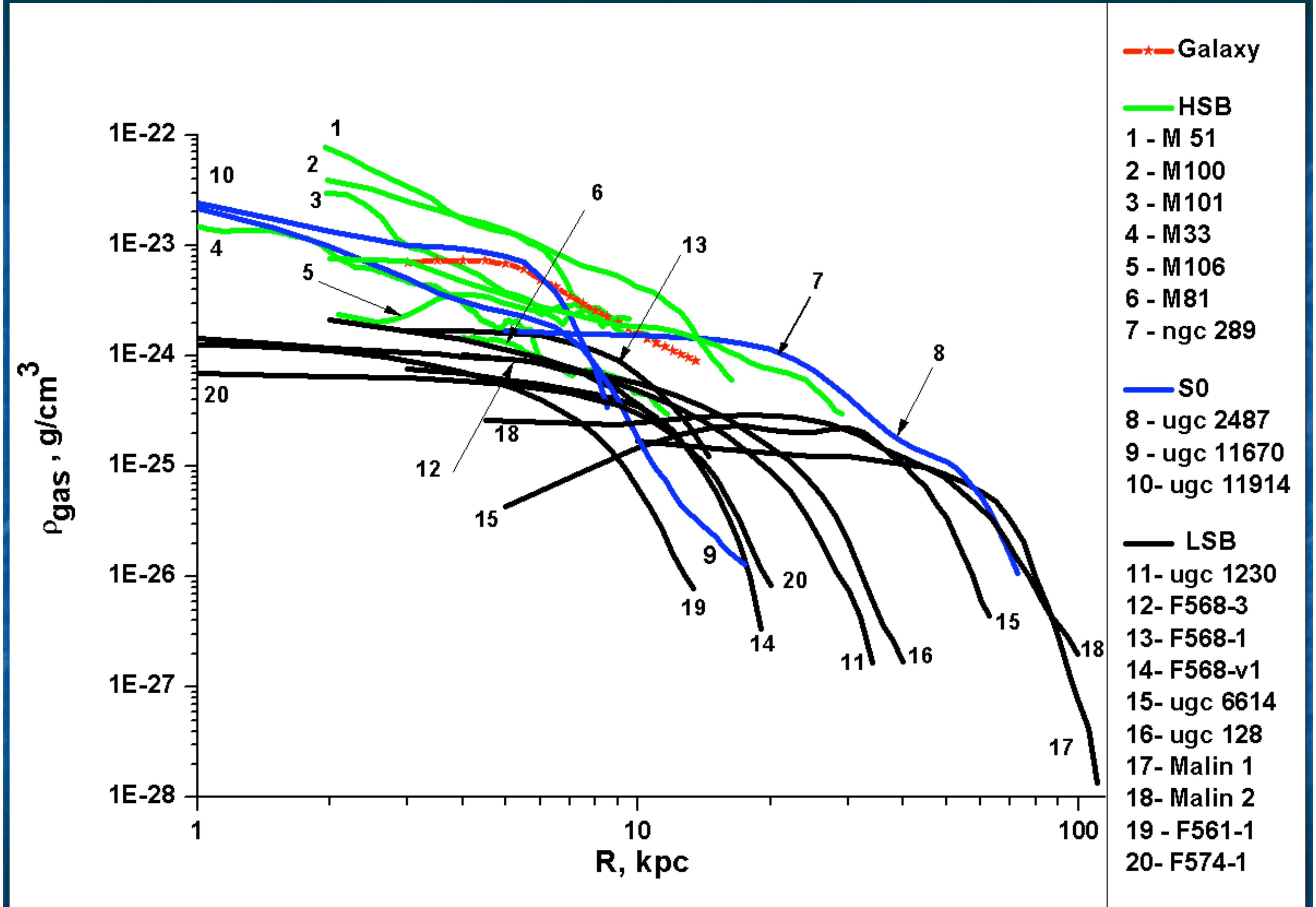


Galaxy
HSB
1 - M 51
2 - M100
3 - M101
4 - M33
5 - M106
6 - M81
7 - ngc 289
S0
8 - ugc 2487
9 - ugc 11670
10- ugc 11914
LSB
11- ugc 1230
12- F568-3
13- F568-1
14- F568-v1
15- ugc 6614
16- ugc 128
17- Malin 1
18- Malin 2
19 - F561-1
20- F574-1
100
10
1
0,1
0,01
R, kpc
σgas , M./pc2

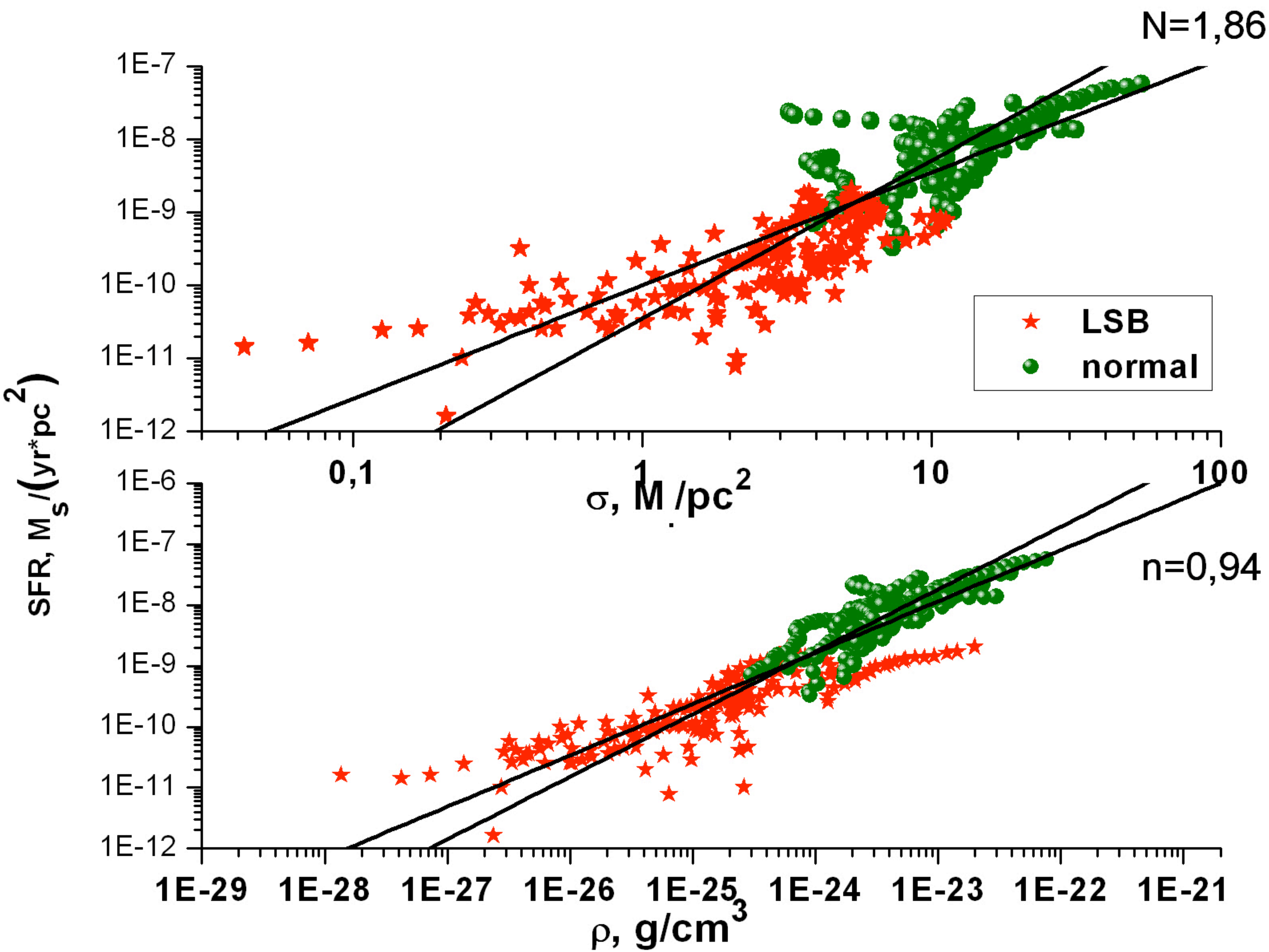


LSB-galaxies

S0-galaxies

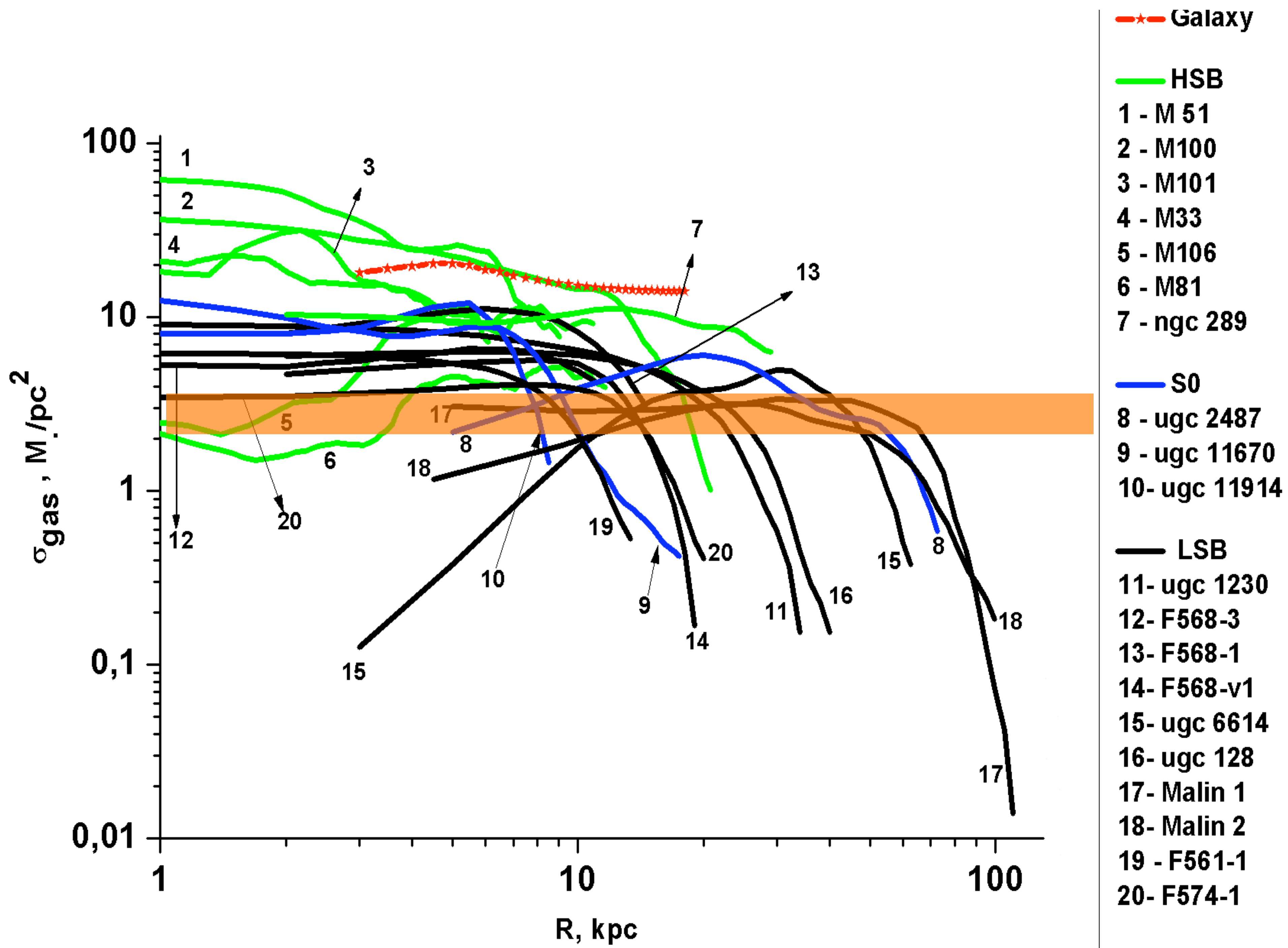


Galaxy
HSB
1 - M 51
2 - M100
3 - M101
4 - M33
5 - M106
6 - M81
7 - ngc 289
S0
8 - ugc 2487
9 - ugc 11670
10- ugc 11914
LSB
11- ugc 1230
12- F568-3
13- F568-1
14- F568-v1
15- ugc 6614
16- ugc 128
17- Malin 1
18- Malin 2
19 - F561-1
20- F574-1
ρ_{gas} , g/cm^3
R, kpc
1E-22
1E-23
1E-24
1E-25
1E-26
1E-27
1E-28
1
10
100

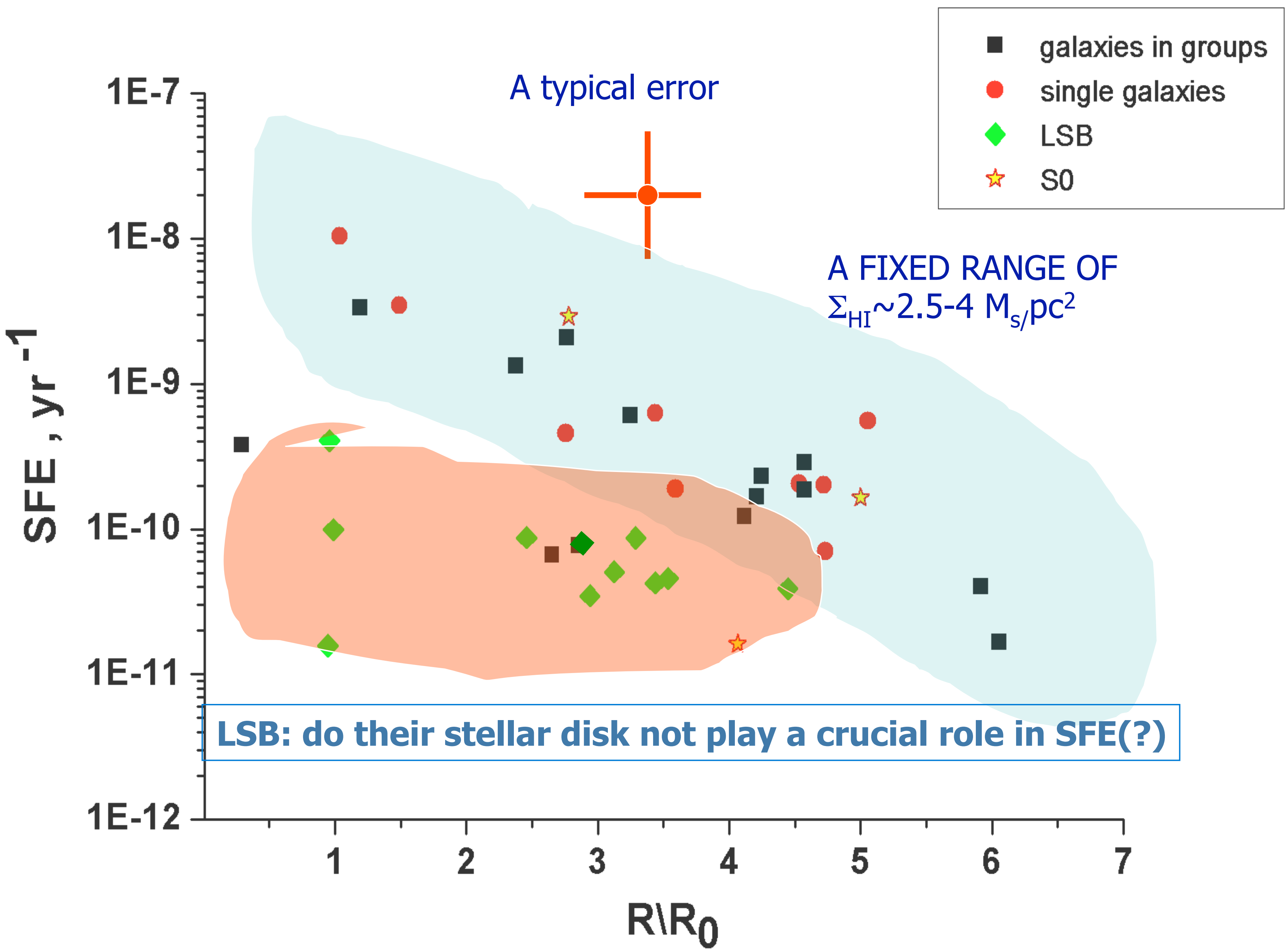


N=1,86
LSB
normal
SFR, M_s/(yr*pc^2)
σ, M /pc^2
0,1
1
10
100
n=0,94
ρ, g/cm^3
1E-29
1E-28
1E-27
1E-26
1E-25
1E-24
1E-23
1E-22
1E-21

- The decreasing of SFE in the outer parts of the disks is just the result of the radial increasing of thickness of gas layer, which in turn is caused by the low density of stellar discs.
- Although under the extremely low density conditions of the outer regions of LSB discs the situation may be more complicated.



Galaxy
HSB
1 - M 51
2 - M100
3 - M101
4 - M33
5 - M106
6 - M81
7 - ngc 289
S0
8 - ugc 2487
9 - ugc 11670
10- ugc 11914
LSB
11- ugc 1230
12- F568-3
13- F568-1
14- F568-v1
15- ugc 6614
16- ugc 128
17- Malin 1
18- Malin 2
19 - F561-1
20- F574-1
σ_{gas} , M./pc^2
R, kpc
100
10
1
0,1
0,01



galaxies in groups
single galaxies
LSB
S0
A typical error
A FIXED RANGE OF
Σ_{HI}~2.5-4 $M_{s/}pc^2$
1E-7
1E-8
1E-9
1E-10
1E-11
1E-12
SFE , yr -1
1
2
3
4
5
6
7
R\R0
LSB: do their stellar disk not play a crucial role in SFE(?)

- N>1 : a problem with SF history

- N>1 : a problem with the description
- of SF history

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THE RATE OF STAR FORMATION

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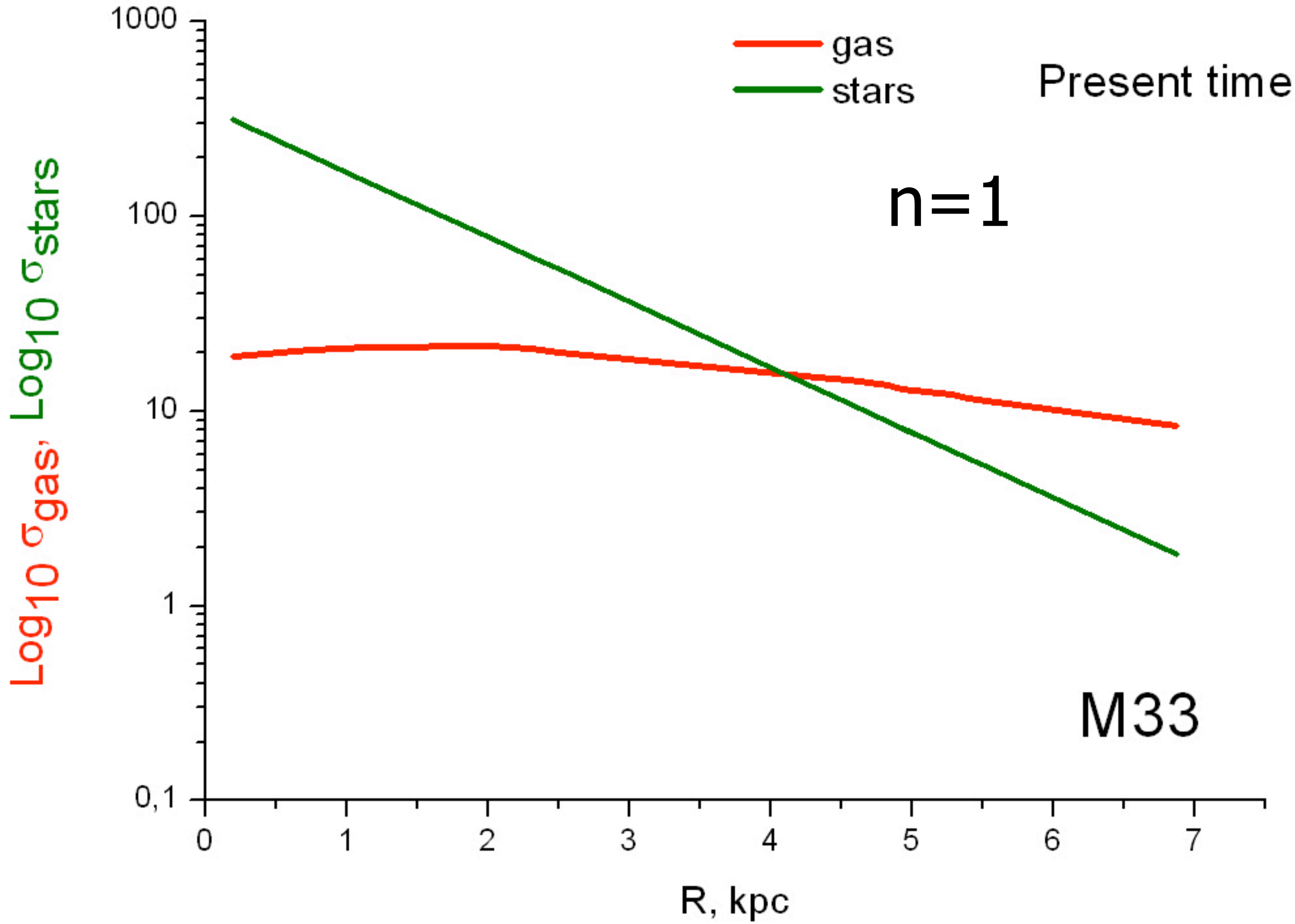
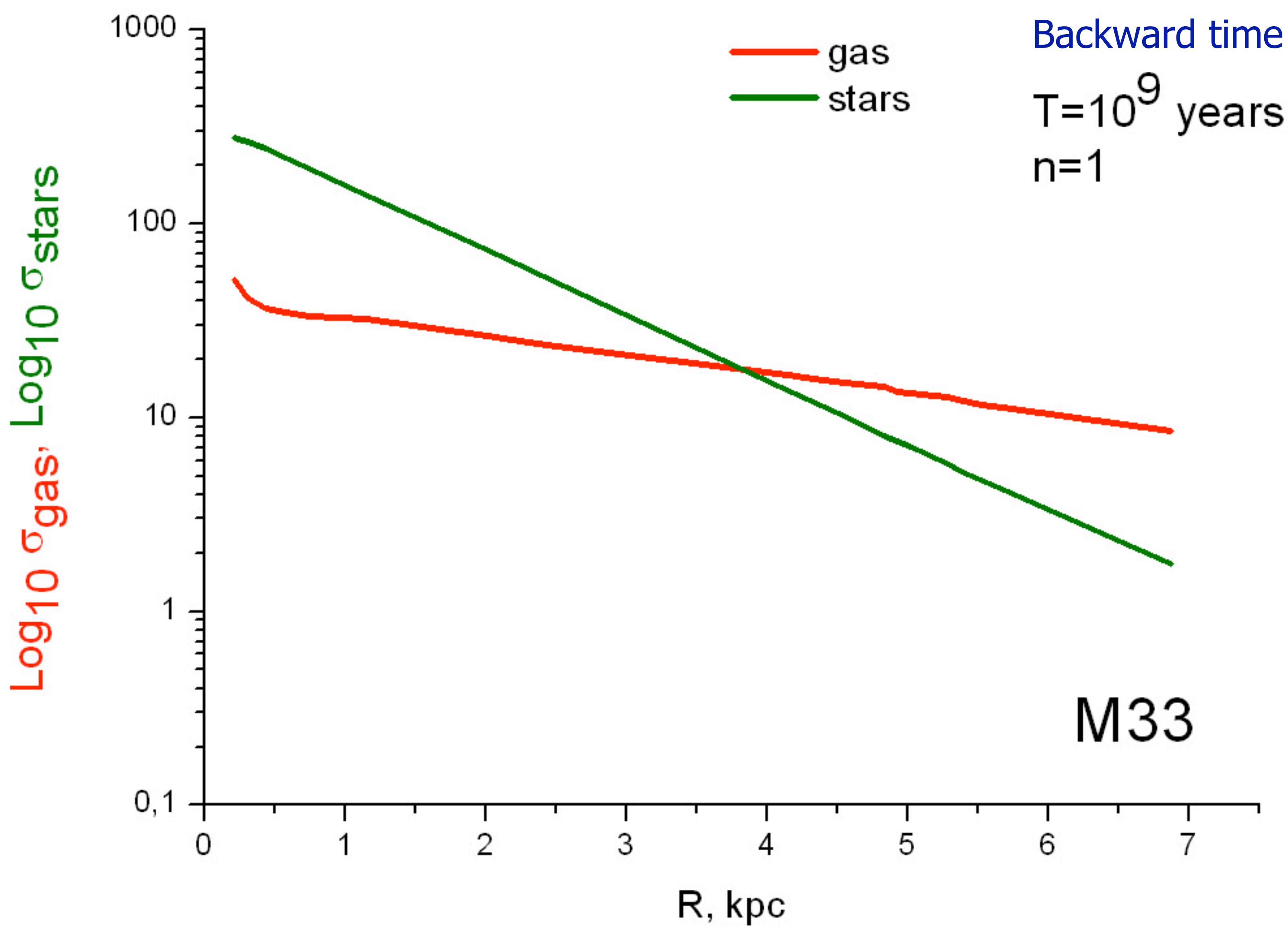
ABSTRACT

It is assumed that the rate of star formation for population I varies with a power n of the density of interstellar gas and that the initial luminosity function is time-independent. Direct evidence on the value of n is found in the relative distribution, perpendicular to the galactic plane, of gas and young objects. For various values of n, computations were made of the initial luminosity function, the rate of star formation, the exchange of gas between stars and interstellar medium, the number of white dwarfs and their luminosity function, and the abundance of helium. It is concluded, from a comparison of the results with observational data, that n is around 2. The present rate of star formation, then, is five times slower than the average rate. The interstellar gas, of which the surface density on the galactic plane was taken to be 11 $\mathfrak{M}_\odot$ per square parsec, loses 1.4 $\mathfrak{M}_\odot/\text{pc}^2$ per 10^9 years by the formation of stars but gains about one-third of this by ejection of gas from evolving stars. The present helium abundance of the interstellar gas may be explained if a star has burned, on the average, 53 per cent of its original hydrogen into helium at the time that ejection takes place. The ejected material was assumed to have a composition equal to the average composition of the star. The effect of star formation on the gas density in the galactic system and other galaxies is briefly discussed.

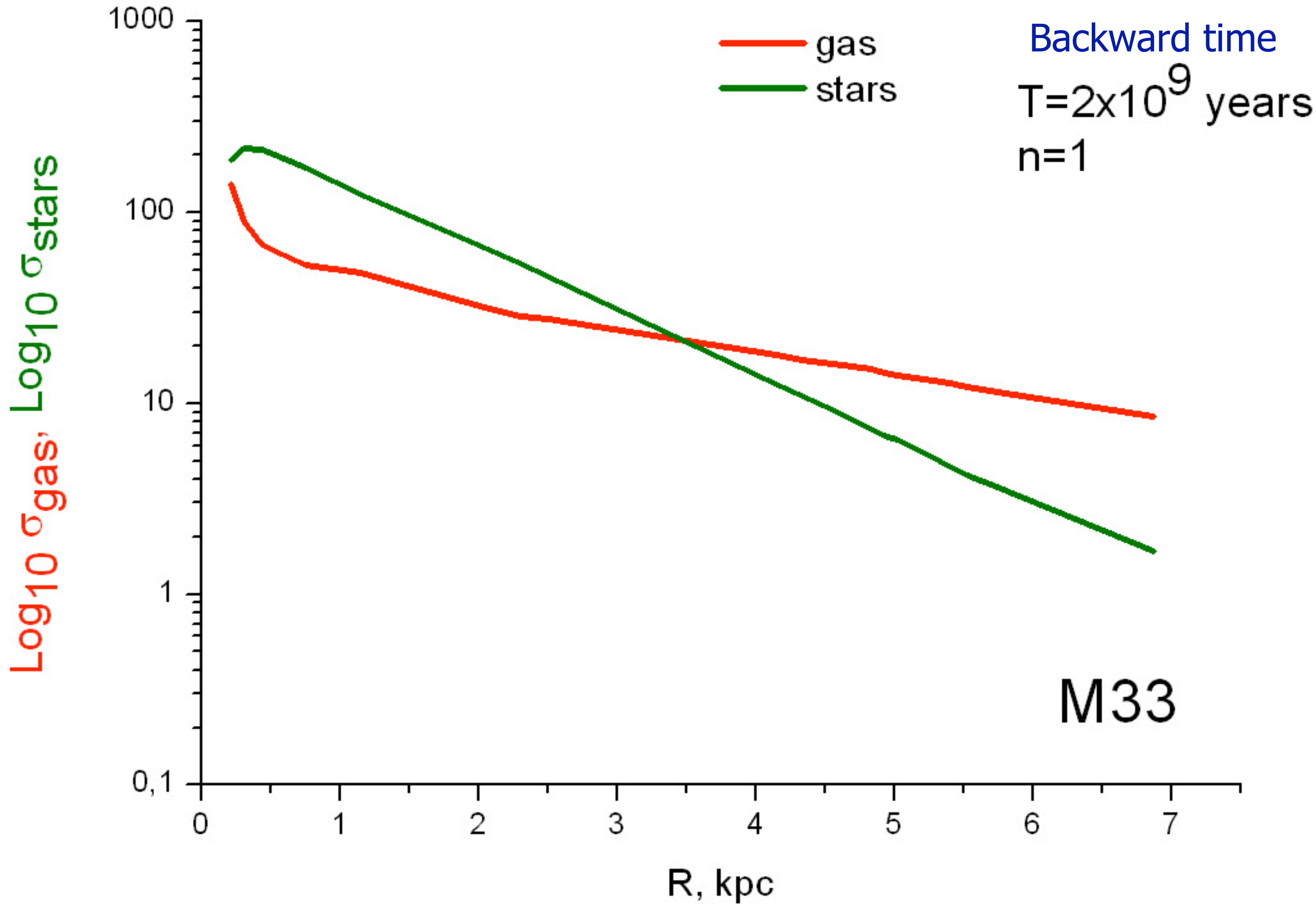
I. INTRODUCTION



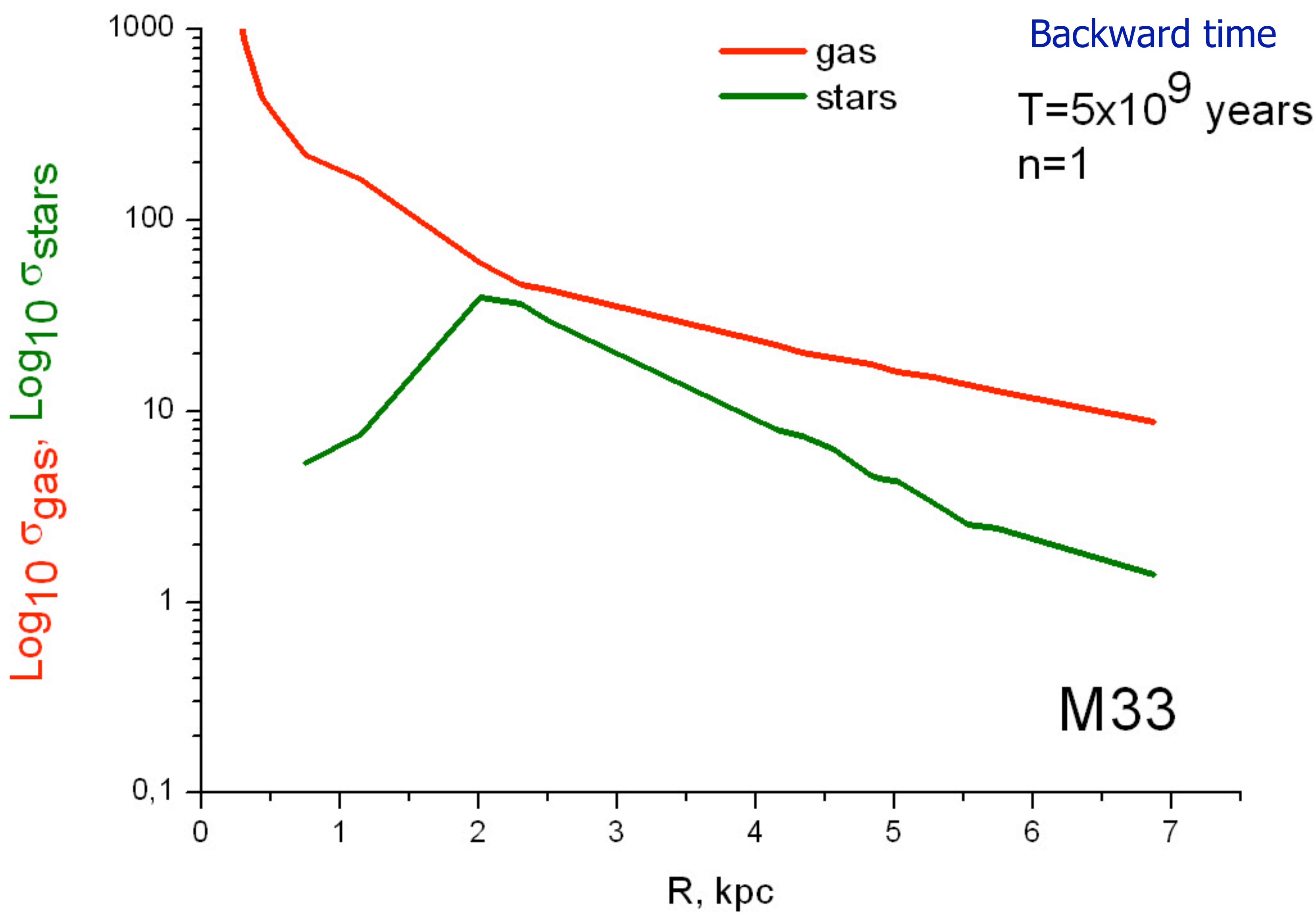
gas
stars
Present time
n=1
M33
$Log_{10}\ \sigma_{gas}$, $Log_{10}\ \sigma_{stars}$
1000
100
10
1
0,1
0
1
2
3
4
5
6
7
R, kpc



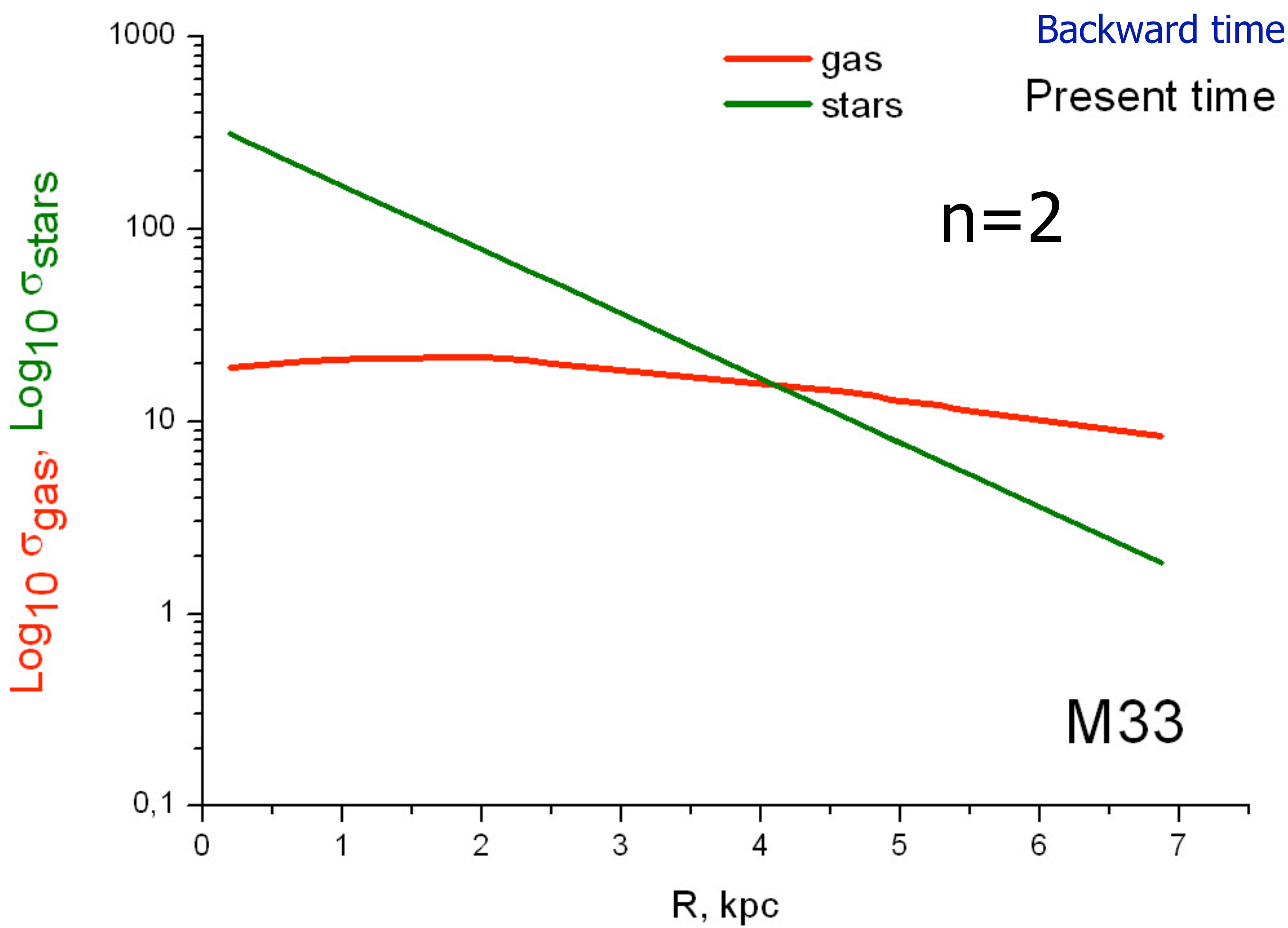
Backward time
T=10^9 years
n=1
gas
stars
M33
$Log_{10}\ \sigma_{gas}$, $Log_{10}\ \sigma_{stars}$
R, kpc
1000
100
10
1
0,1
0
1
2
3
4
5
6
7

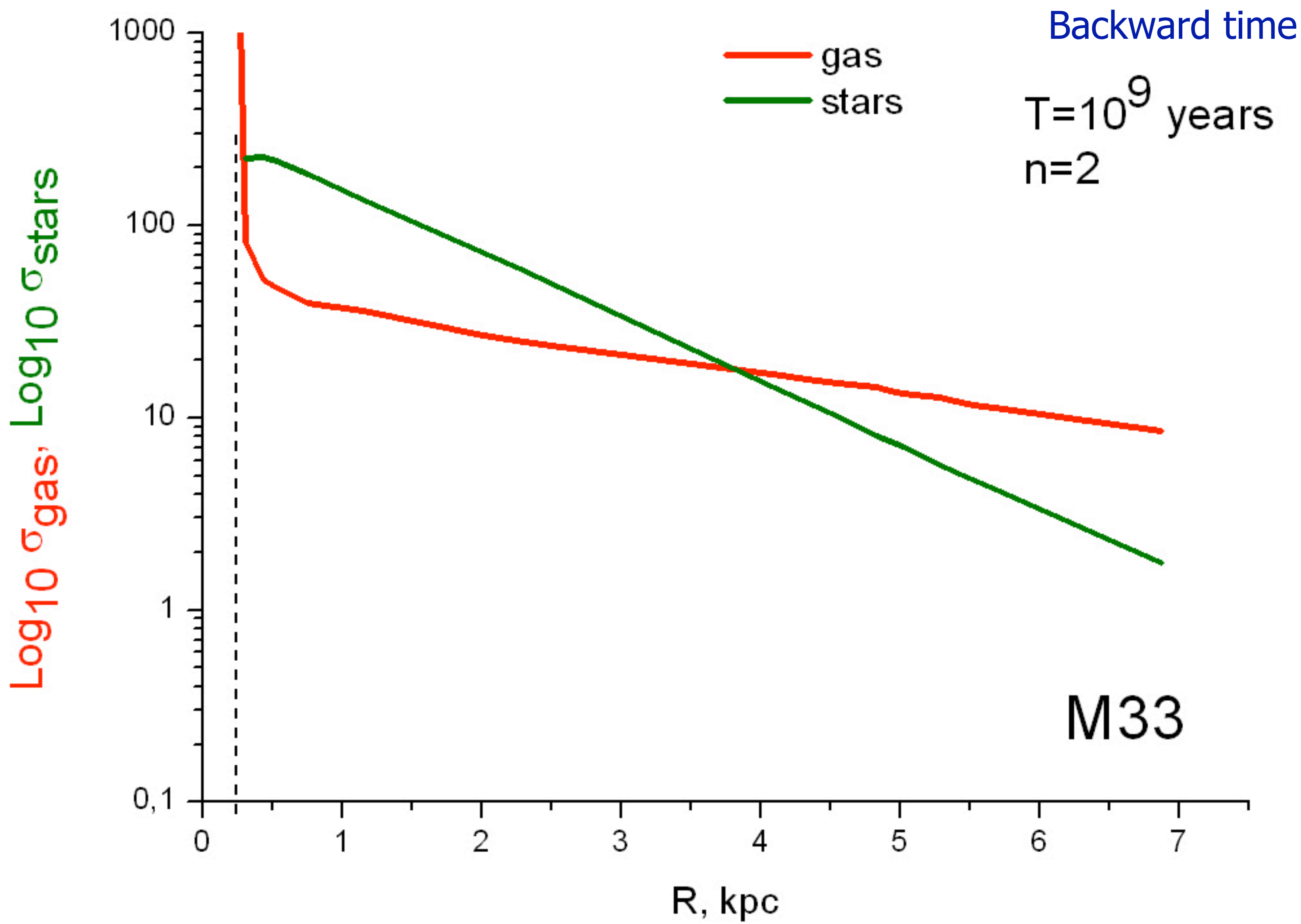


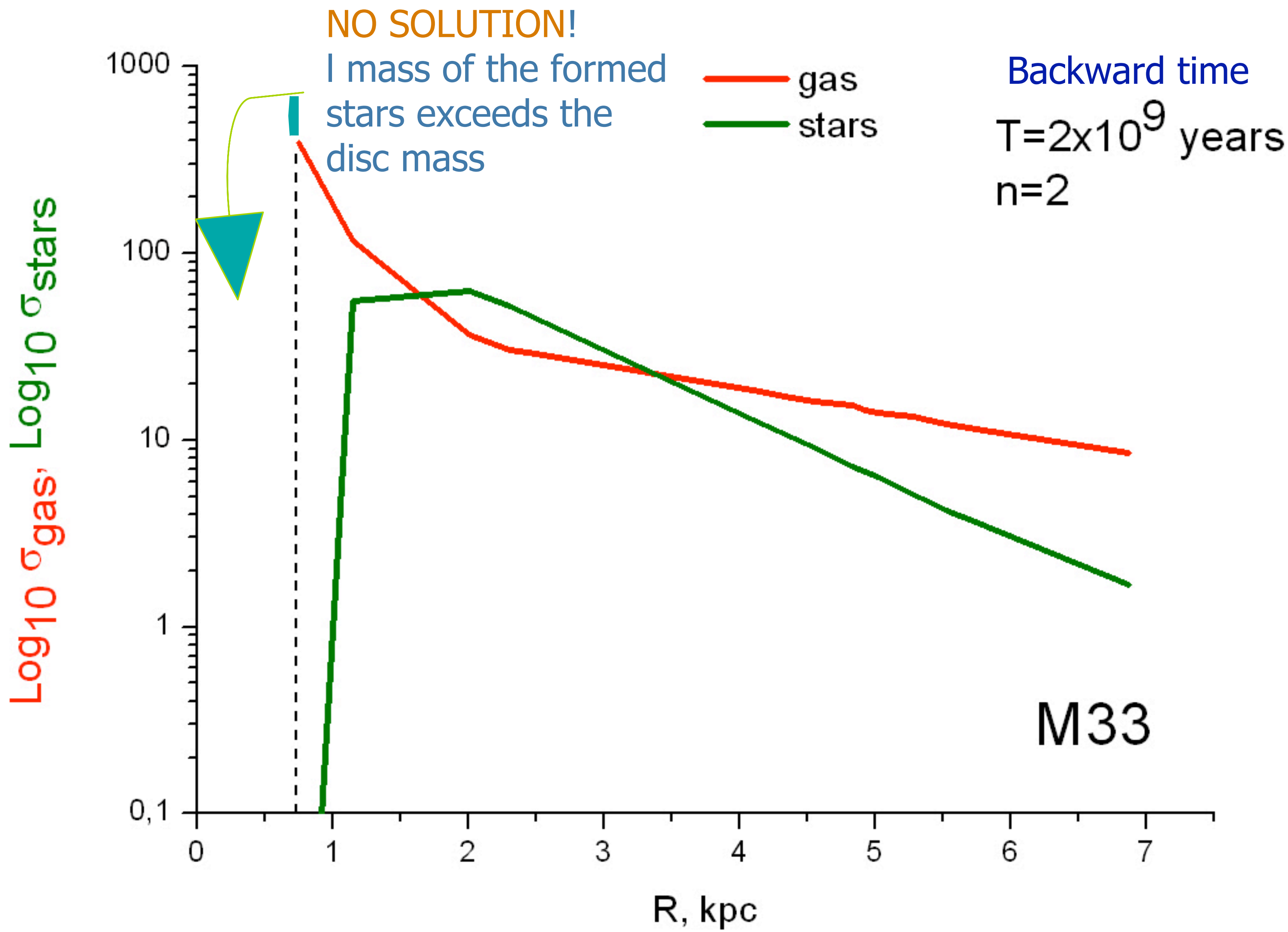
gas
stars
Backward time
T=2x10^9 years
n=1
M33
1000
100
10
1
0,1
0
1
2
3
4
5
6
7
R, kpc
Log10 σgas, Log10 σstars

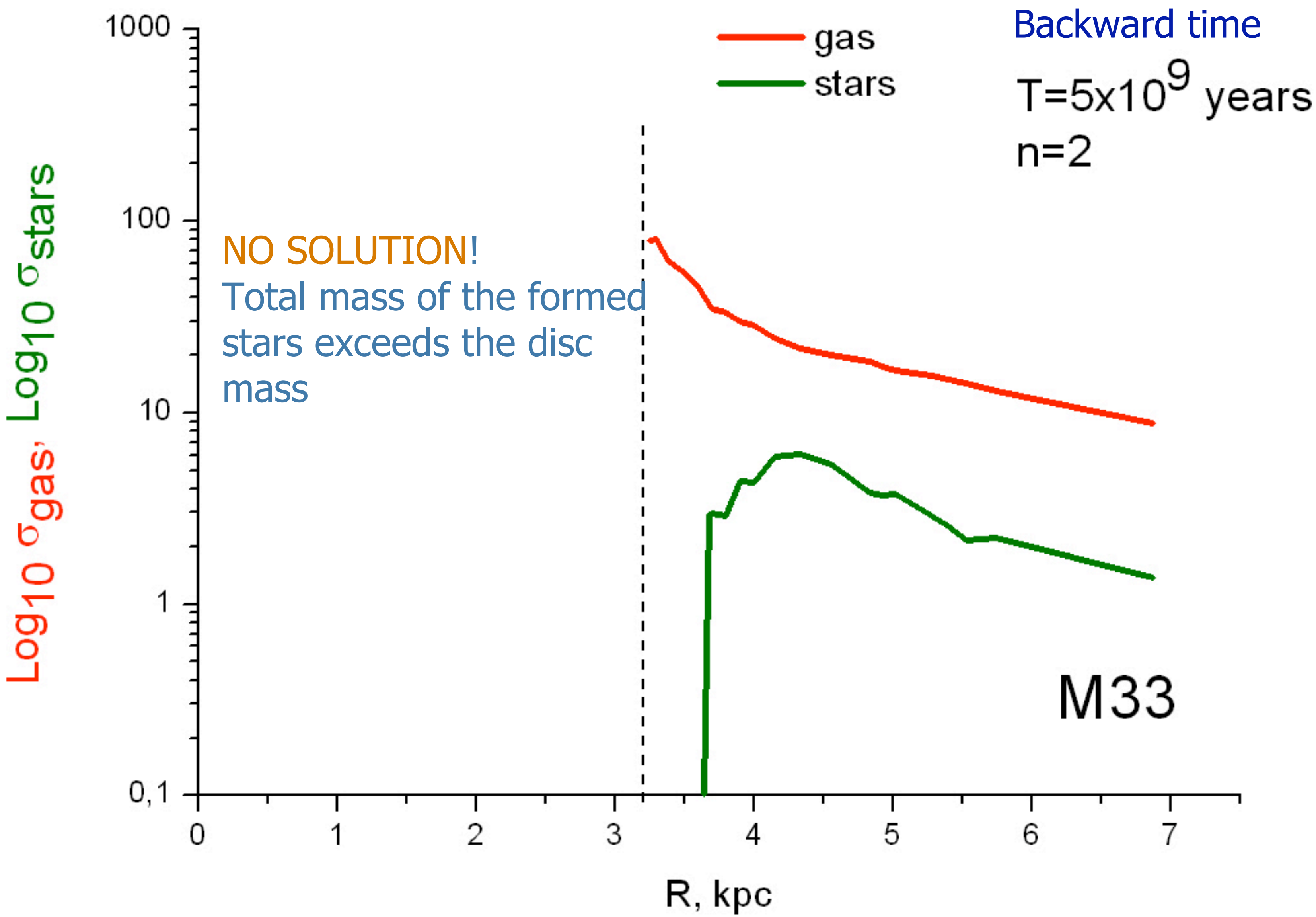


1000
100
10
1
0,1
0
1
2
3
4
5
6
7
R, kpc
Log10 σgas, Log10 σstars
gas
stars
Backward time
T=5x10^9 years
n=1
M33


Backward time
Present time
gas
stars
n=2
M33
1000
100
10
1
0,1
0
1
2
3
4
5
6
7
R, kpc
Log10 σgas, Log10 σstars

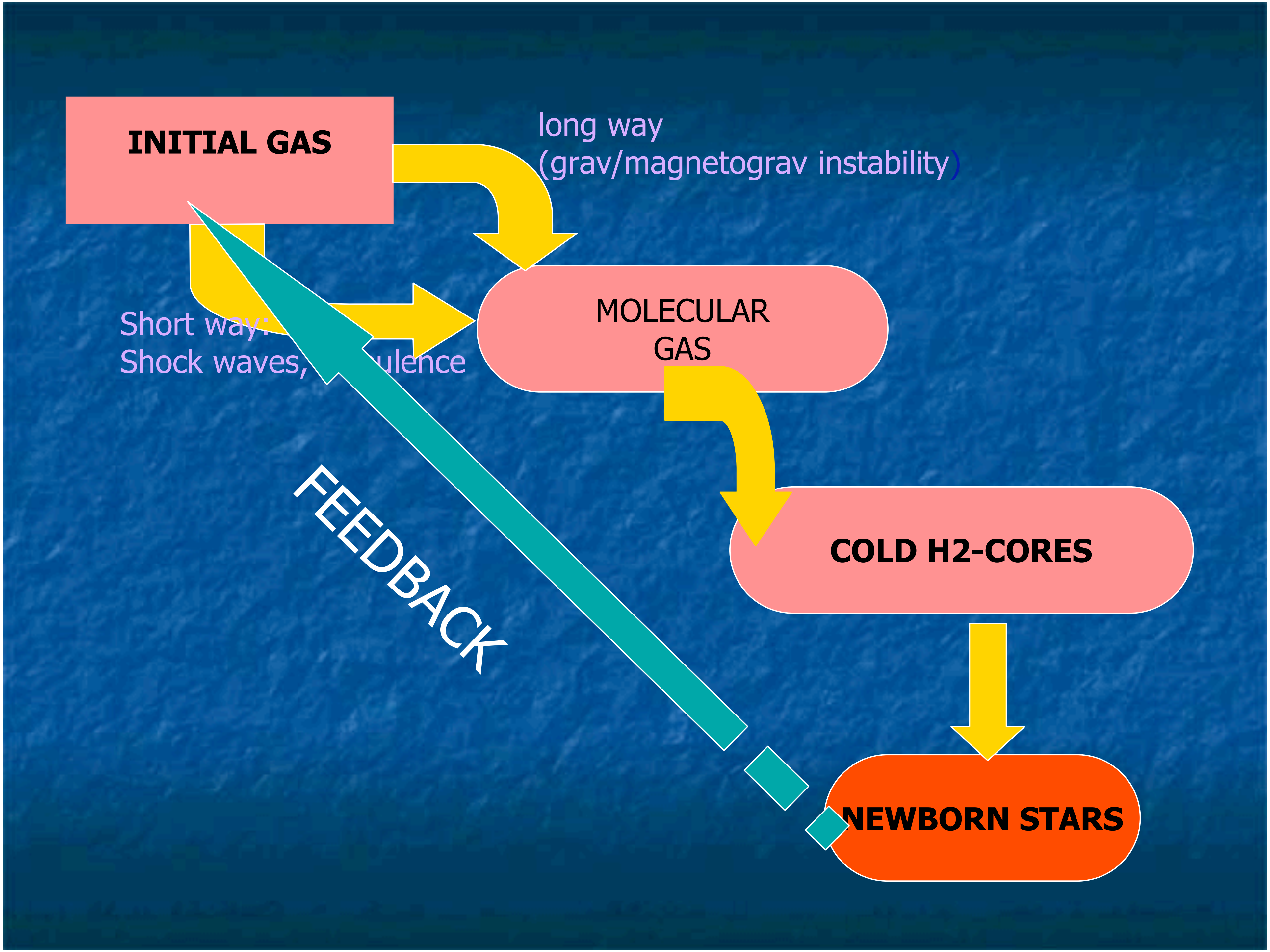

Backward time
gas
stars
T=10^9 years
n=2
M33
Log10 σgas, Log10 σstars
R, kpc
1000
100
10
1
0,1
0
1
2
3
4
5
6
7


NO SOLUTION!
I mass of the formed stars exceeds the disc mass
gas
stars
Backward time
T=2x10^9 years
n=2
1000
100
10
1
0,1
0
1
2
3
4
5
6
7
R, kpc
Log10 σgas, Log10 σstars
M33



gas
stars
Backward time
T=5x10^9 years
n=2
NO SOLUTION!
Total mass of the formed stars exceeds the disc mass
M33
1000
100
10
1
0,1
0
1
2
3
4
5
6
7
R, kpc
Log10 σgas, Log10 σstars

- One may propose that in the past, when σ_{gas} exceeded 10-20 Ms/pc^2, the SFR was linearly connected both with the surface and with the volume densities.
- The accretion seems to be inevitable to account for the observed disc mass density in the case of $n>1$.


INITIAL GAS
long way
(grav/magnetograv instability)
Short way:
Shock waves,
ulence
MOLECULAR
GAS
COLD H2-CORES
NEWBORN STARS
FEEDBACK

It also means the growing fraction of “spare” (non active) gas along the radius.

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- In the disc periphery, due to low stellar density and high scale height of the gas the time for its sinking into the mainplane may be too long for the gas to be involved into the starforming process.
- The fraction of this non-active gas should increase parallel with the decreasing of the surface density of disc.

Conclusions

- SFR correlates better with the volume gas (HI+H2) density than with the surface one. It explains at least partially the observed decreasing of SFE with R.
- Galaxies with extremely low SFR are in general at the same sequence at the "volume Schmidt law" diagram.
- The Schmidt power law is certainly not universal both "in space and time" , but it works!!!.

THANK YOU!