Synthetic HI observations of spiral structure in the outer disk in galaxies

Sergey A. Khoperskov[1,2,3]†, Giuseppe Bertin[1]

[1]Dipartimento di Fisica, Università degli Studi di Milano, via Celoria 16, I-20133 Milano, Italy

[2]Institute of Astronomy, Russian Academy of Sciences, Pyatnitskaya st., 48, 119017 Moscow, Russia

[3]Sternberg Astronomical Institute, Moscow M.V. Lomonosov State University, Universitetskij pr., 13, 119992 Moscow, Russia

(Received 31/03/2015; revised: 18/10/2015; accepted 18/11/2015)

By means of 3D hydrodynamical simulations, in a separate paper we have discussed the properties of non-axisymmetric density wave trains in the outermost regions of galaxy disks, based on the picture that self-excited global spiral modes in the bright optical stellar disk are accompanied by low-amplitude short trailing wave signals outside corotation; in the gas, such wave trains can penetrate through the outer Lindblad resonance and propagate outwards, forming prominent spiral patterns. In this paper we present the synthetic 21 cm velocity maps expected from simulated models of the outer gaseous disk, focusing on the case when the disk is dominated by a two-armed spiral pattern, but considering also other more complex situations. We discuss some aspects of the spiral pattern in the gaseous periphery of galaxy disks noted in our simulations that might be interesting to compare with specific observed cases.

Как далеко могут уходить спирали от резонансов?

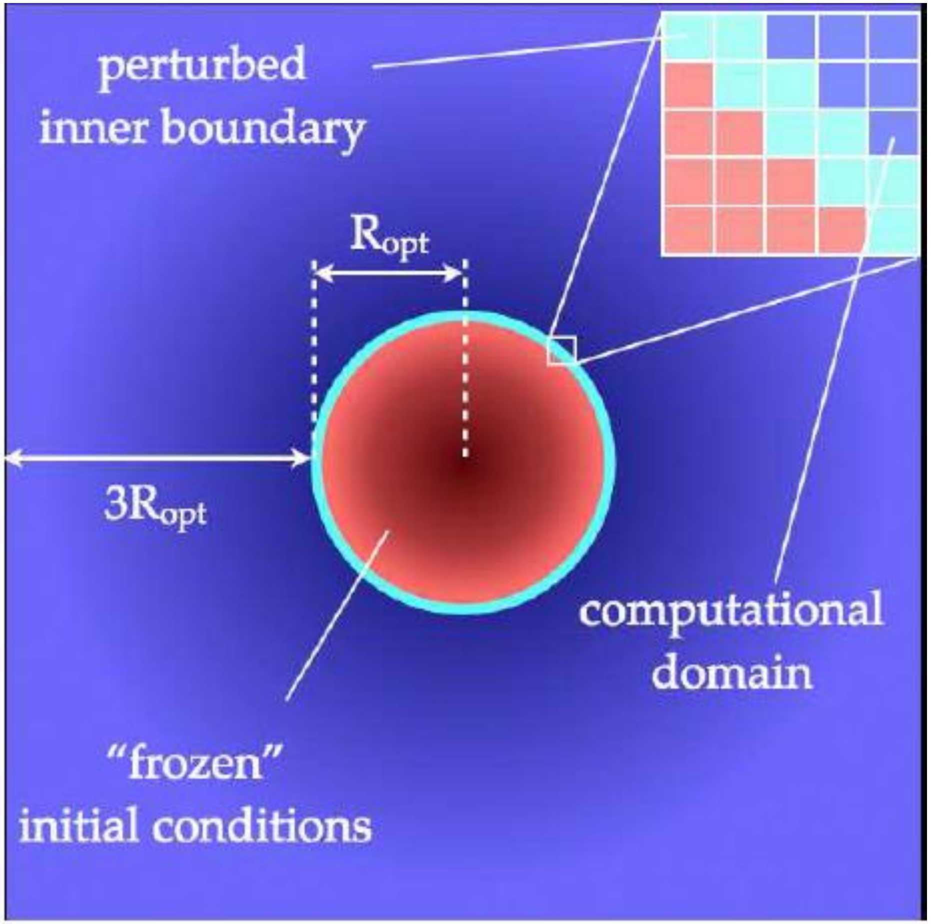
- **“We consider a hydrodynamical model of the galactic outer disk subject to perturbations beyond the outer Lindblad resonance”.**
- For the numerical simulations of the gaseous disk evolution, we make use of the TVD MUSCL (Total Variation Diminishing Multi Upstream Scheme for Conservation Laws) scheme (for a description of the structure of the code, see Khoperskov et al. 2014).
- Below we show the results of 3D simulations on a uniform 2048×2048×128 Cartesian grid. The computational box size is 144×144×9 kpc, which corresponds to a spatial resolution of ≈ 70 pc.

МОДЕЛЬ

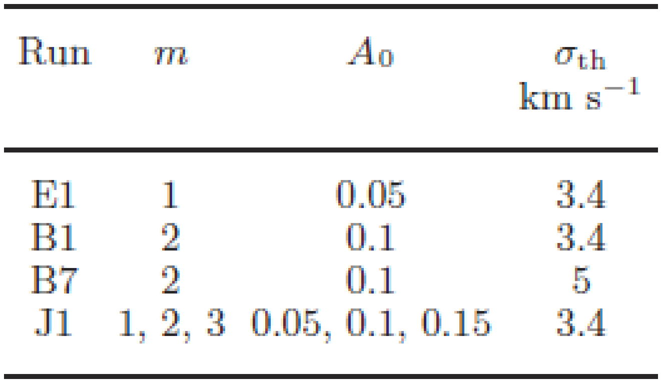
- Плоская кривая вращения, равновесный 3D диск, псевдоизотермическое гало.
- Начальное возмущение в кольце на r= 6h. $\hat{\mathrm{X}} \propto \cos\left(m\theta - \omega t\right)$
- m=1,2,3

Выбрано:

OLR=5.6h.



Картина спиралей через To = Trot at r = 6h. Узор сохраняет заданное на границе значение Ωp.



Run	m	A_0	$\sigma_{\rm th}$ km s^{-1}
E1	1	0.05	3.4
B1	2	0.1	3.4
B7	2	0.1	5
J1	1, 2, 3	0.05, 0.1, 0.15	3.4

P

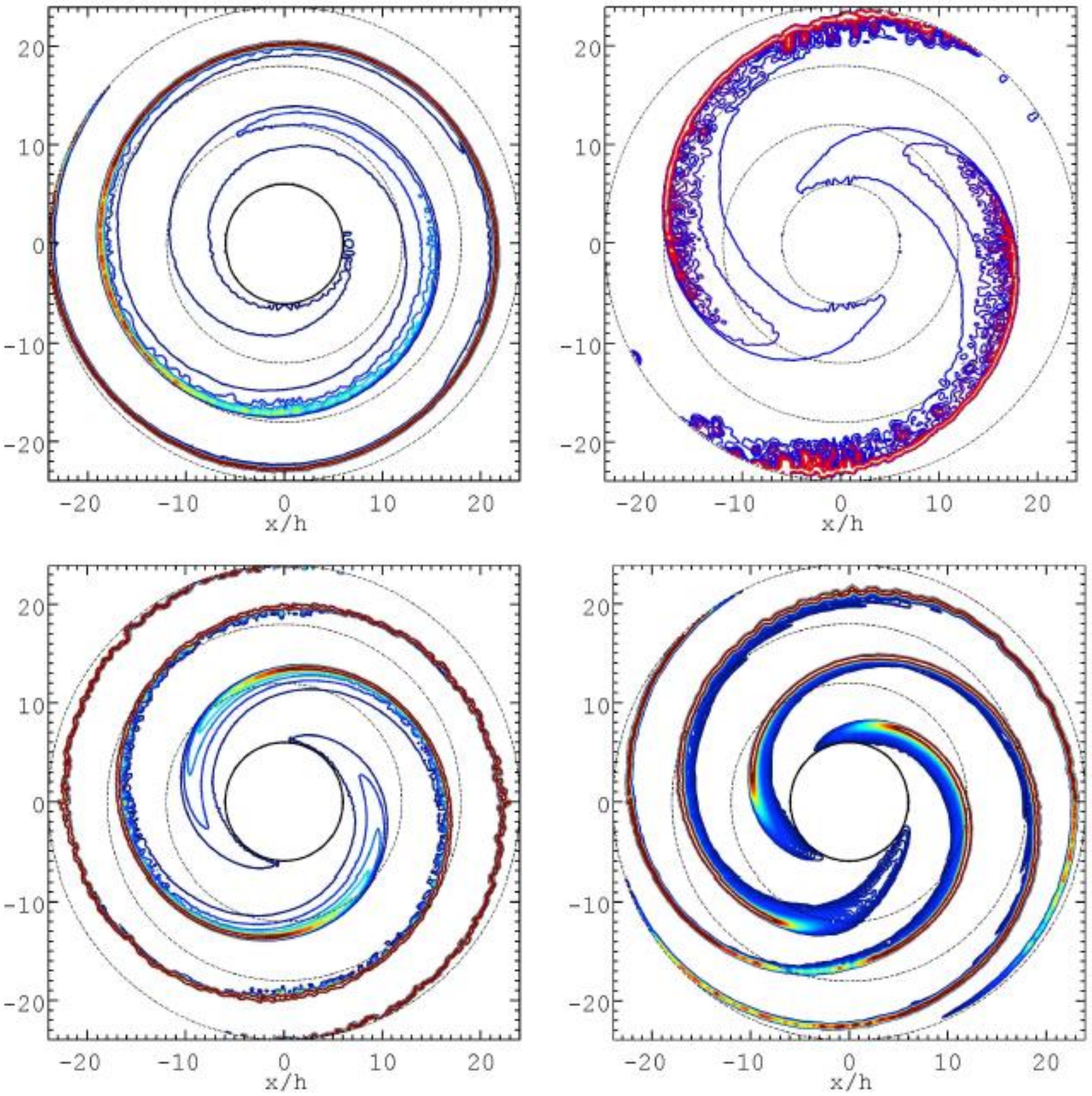
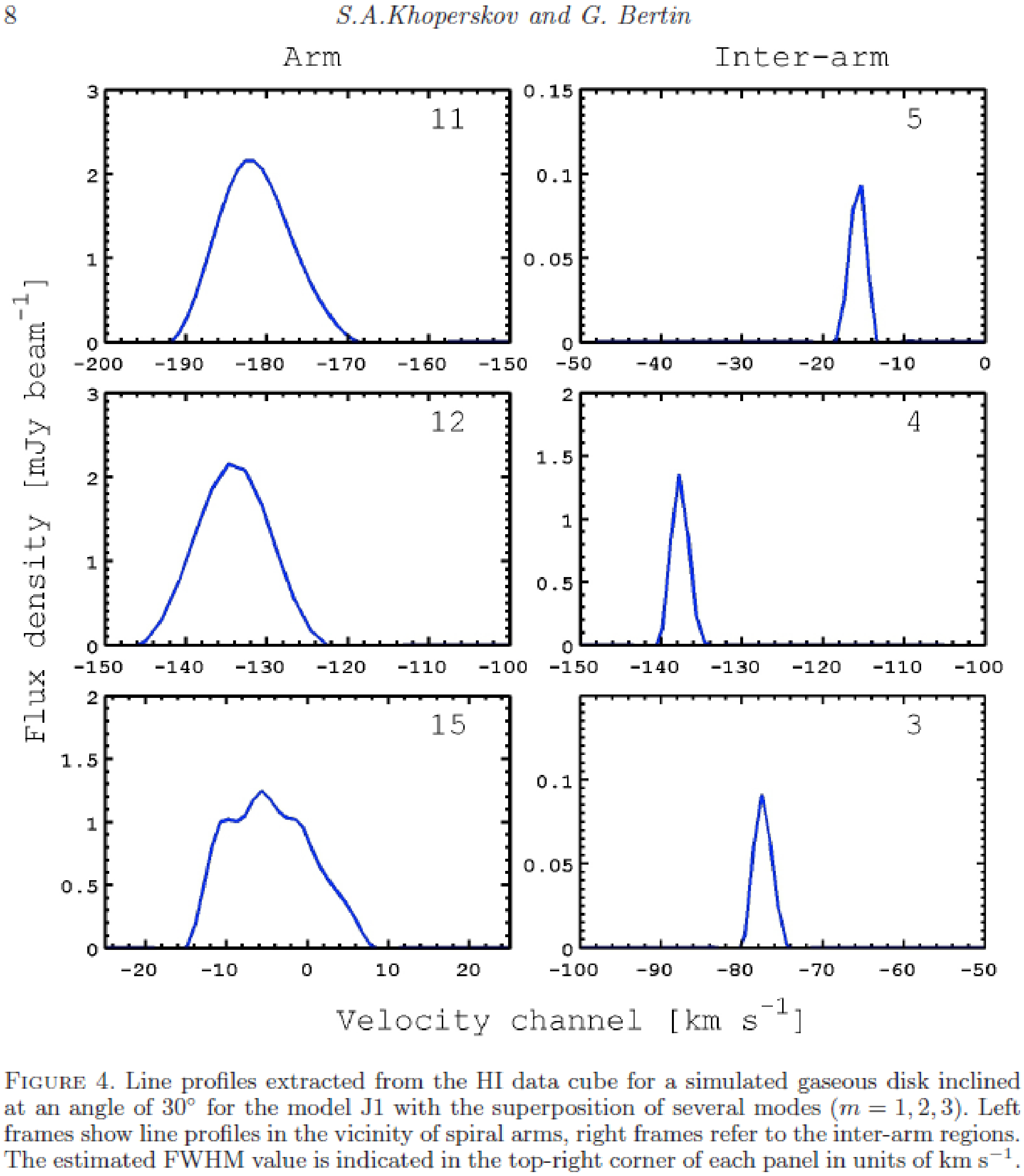


FIGURE 2. The relative surface density perturbations (positive part of the quantity $\Sigma_1/\langle\Sigma_g\rangle$) for models at time $t \approx T_0$, with different imposed perturbations. Top row: single $m = 1$ mode (left, model E1) and single $m = 2$ mode on a gaseous disk characterized by higher velocity dispersion (right, model B7). Bottom row: morphology produced by a single $m = 2$ mode (left, model B1) and by the superposition of three modes with $m = 1$, $m = 2$, and $m = 3$ (right, model J1). Contours vary from blue to red, which corresponds to values of the relative density perturbation in the range $0.01 - 1$. The plots are drawn in the inertial, nonrotating frame of reference. Black circles are drawn at radii $6h$, $12h$, $18h$, and $24h$.

Э то важно: внешние спирали сжимают газ!

- At radii beyond ≈ 12 – 15h, rather narrow shocks form because of the supersonic motion of the pattern across the disk. The shocks are unstable with respect to the wiggle instability, which develops behind the shock front

In the velocity channels the spectra show clear trace of the kinematic perturbations induced by the presence of prominent spiral structure. Features of this kind are often observed in grand-design spiral galaxies within the region occupied by the bright optical disk Comparable kinematical studies of the outermost gaseous disk are quite rare.



8 *S.A.Khoperskov and G. Bertin*

FIGURE 4. Line profiles extracted from the HI data cube for a simulated gaseous disk inclined at an angle of 30° for the model J1 with the superposition of several modes ($m = 1, 2, 3$). Left frames show line profiles in the vicinity of spiral arms, right frames refer to the inter-arm regions. The estimated FWHM value is indicated in the top-right corner of each panel in units of km s^{-1}.

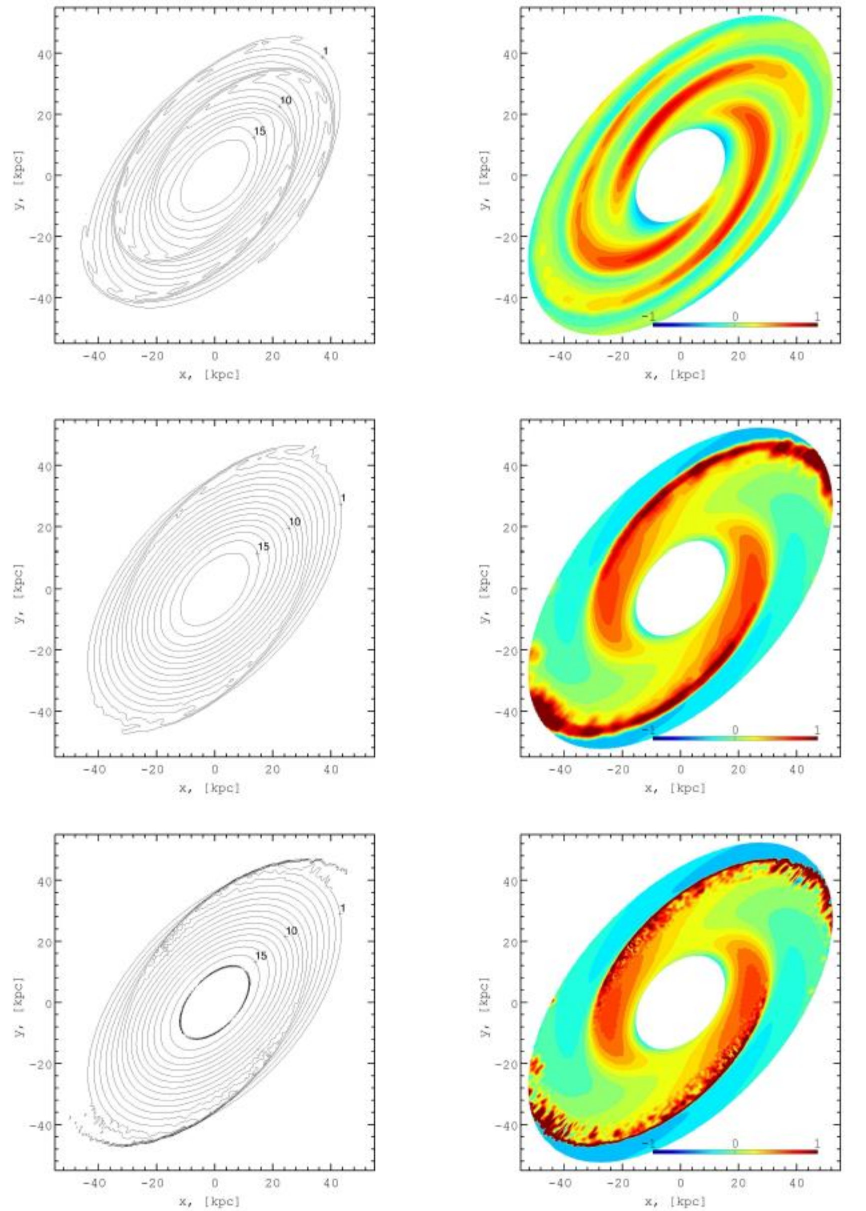


Figure 5. Synthetic HI column density maps (left) for a simulated galaxy. Contours are in the range $(1-15)\times10^{19}$ cm^{-2}. The right frames show residual maps of the column density relative to the initial unperturbed state. The inner boundary disk ($r < 6h = 18$ kpc) is masked by a white ellipse. Top row frames correspond to the model J1 with the superposition of several modes and small pitch angle; **the middle and bottom** frames are for the model with a single $m = 2$ more open spiral pattern (model B7). Top and middle frames show the effect of a Gaussian filter adopted in the HI spectra calculation, bottom frames correspond to a calculation without beam

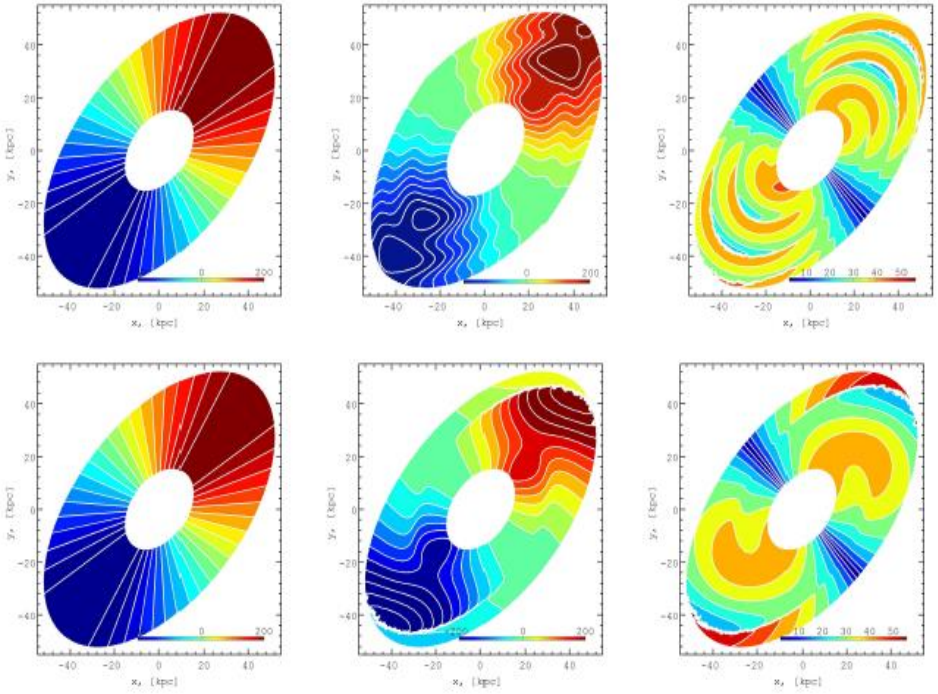


Figure 6. Synthetic LOS isovelocity contour maps for the initial state (left) and for the evolved state of the simulated gaseous disk (middle) for two simulated galaxies. The right frames show residual maps of the LOS velocity distribution relative to the initial unperturbed state. Top frames correspond to the galaxy with the superposition of several modes and small pitch angle (model J1); the bottom frames are for the model with a single $m = 2$ more open spiral pattern (model B7). The inner boundary disk ($r < 6h = 18$ kpc) is masked out.

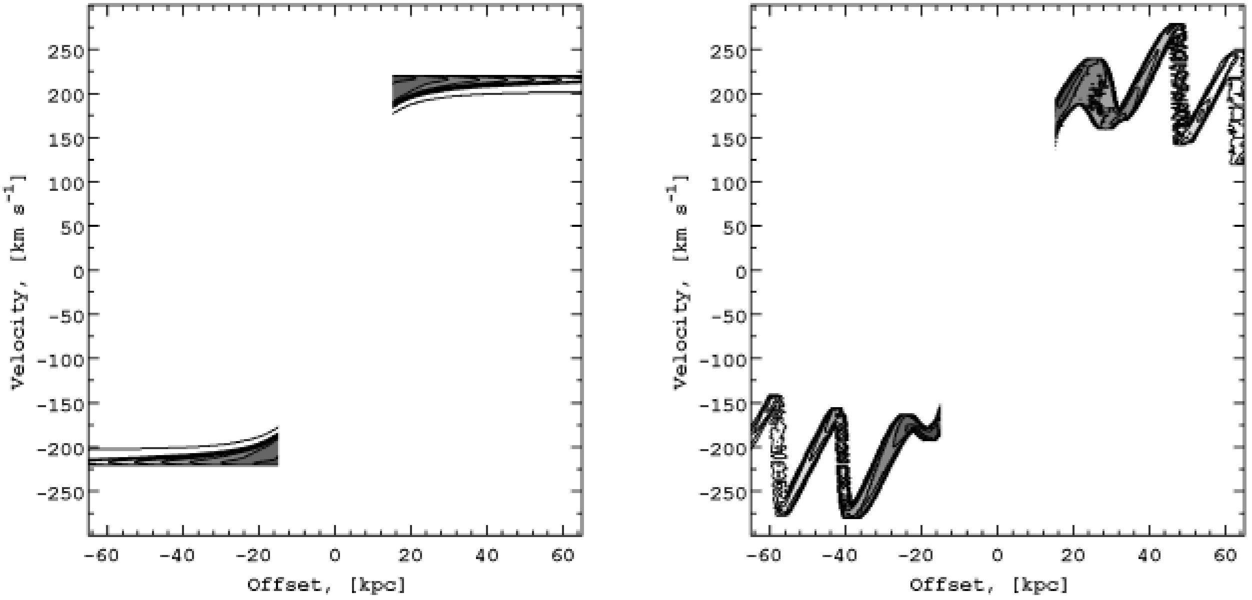


FIGURE 7. Position - velocity diagram along the major axis (corresponding to the top frames of Fig. 6): left — for the initial unperturbed state, right — for the evolved state of the simulated gaseous disk. Contours are at 0.5, 1, 2, 3, 4, 5, 6, 7, 9, and 10 in units of 10^{19} cm^{-2}. The inner boundary disk ($r < 6h = 18$ kpc) is masked out.

Such systematic variations, if found in 21 cm observations, would add strong support to the dynamical scenario

we are proposing

Главный вывод

- With the inner boundary acting as a source of density waves, after a relatively short time, a quasi-stationary spiral structure is established over the entire gaseous outer disk, well outside the bright optical disk. The amplitude of spiral structure is found to increase rapidly with radius, producing nonlinear shocks that become unstable with respect to shear-induced instabilities.

The distribution of atomic hydrogen in EAGLE galaxies: morphologies, profiles, and H I holes

Yannick M. Bahé*[1], Robert A. Crain[2,3], Guinevere Kauffmann[1], Richard G. Bower[4], Joop Schaye[3], Michelle Furlong[4], Claudia Lagos[5,6], Matthieu Schaller[4], James W. Trayford[4], Claudio Dalla Vecchia[7,8], and Tom Theuns[4]

[1] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild Str. 1, 85748 Garching, Germany*
[2] *Astrophysics Research Institute, Liverpool John Moores University, 146 Brownlow Hill, Liverpool, L3 5RF, UK*
[3] *Leiden Observatory, Leiden University, PO Box 9513, 2300 RA Leiden, The Netherlands*
[4] *Institute for Computational Cosmology, Department of Physics, University of Durham, South Road, Durham DH1 3LE, UK*
[5] *European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching, Germany*
[6] *International Centre for Radio Astronomy Research (ICRAR), M468, University of Western Australia, 35 Stirling Hwy, Crawley, Western Australia, 6009, Au*
[7] *Instituto de Astrofísica de Canarias, C/Vía Láctea s/n, E-38205 La Laguna, Tenerife, Spain*
[8] *Departamento de Astrofísica, Universidad de La Laguna, Av. del Astrofísico Francisco Sánchez s/n, E-38206 La Laguna, Tenerife, Spain*

17 November 2015

ABSTRACT

We compare the mass and internal distribution of atomic hydrogen (H I) in 2200 present-day central galaxies with $M_{\rm star} > 10^{10}\,{\rm M}_{\odot}$ from the 100 Mpc EAGLE "Reference" simulation to observational data. Atomic hydrogen fractions are corrected for self-shielding using a fitting formula from radiative transfer simulations and for the presence of molecular hydrogen using an empirical or a theoretical prescription from the literature. The resulting neutral hydrogen fractions, $M_{\rm H\,I+H_2}/M_{\rm star}$, agree with observations to better than 0.1 dex for galaxies with $M_{\rm star}$ between 10^{10} and 10^{11} $\rm M_{\odot}$. Our fiducial, empirical $\rm H_2$ model based on gas pressure results in galactic H I mass fractions, $M_{\rm H\,I}/M_{\rm star}$, that agree with observations from the *GASS* survey to better than 0.3 dex, but the alternative theoretical $\rm H_2$ formula from high-resolution simulations leads to a negative offset in $M_{\rm H\,I}/M_{\rm star}$ of up to 0.5 dex. Visual inspection of mock H I images reveals that most H I disks in simulated H I-rich galaxies are vertically disturbed, plausibly due to recent accretion events. Many galaxies (up to 80 per cent) contain spuriously large H I holes, which are likely formed as a consequence of the feedback implementation in EAGLE. The H I mass–size relation of all simulated galaxies is close to (but 16 per cent steeper than) observed, and when only galaxies without large holes in the H I disc are considered, the agreement becomes excellent (better than 0.1 dex). The presence of large H I holes also makes the radial H I surface density profiles somewhat too low in the centre, at $\Sigma_{\rm H\,I} > 1{\rm M}_{\odot}\,{\rm pc}^{-2}$ (by a factor of $\lesssim 2$ compared to data from the Bluedisk survey). In the outer region ($\Sigma_{\rm H\,I} < 1{\rm M}_{\odot}\,{\rm pc}^{-2}$), the simulated profiles agree quantitatively with observations. Scaled by H I size, the simulated profiles of H I-rich ($M_{\rm H\,I} > 10^{9.8}{\rm M}_{\odot}$) and control galaxies ($10^{9.1}\,{\rm M}_{\odot} > M_{\rm H\,I} > 10^{9.8}\,{\rm M}_{\odot}$) follow each other closely, as observed.

КОСМОЛОГИЧЕСКАЯ ЭВОЛЮЦИЯ HI В ГАЛАКТИКАХ

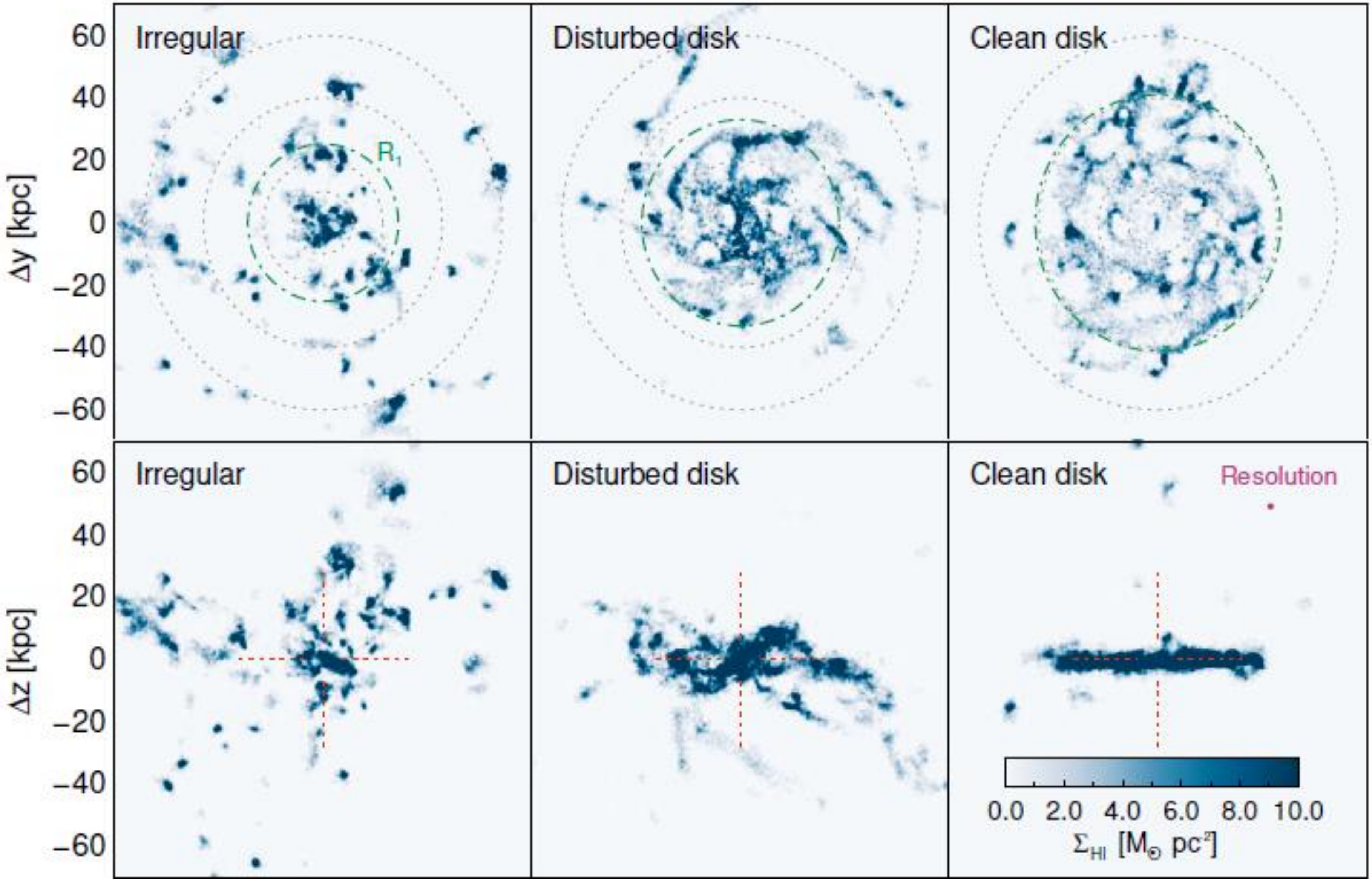
- A number of authors have studied low-redshift HI with cosmological hydrodynamical simulations in the past. However, a common problem of these simulations has been their inability to produce galaxies whose stellar component agrees with observations. In particular, angular momentum from infalling gas was typically dissipated too quickly and too severely to form realistic discs
- Incorporation of efficient supernova feedback and/or increased resolution has led to the formation of realistic disk galaxies.
- With these and other improvements, the **EAGLE** project (Schaye et al. 2015; Crain et al.2015) has yielded a cosmologically representative population of galaxies with realistic properties such as stellar masses and sizes.
- **Our aim is to analyse the distribution of HI within individual**

z = 0 galaxies;

Модель

- Куб L=100 mpc. Z_initial = 127
- N=1504^3., Mdm~5Mgas
- SFR определяется давлением газа (модель Schaue). Массы молек.газ/HI – пересчет а)через давление, б) по численной модели Гнедина-Кравцова.
- Отбирались галактики, имеющие на Z=0 M*>10^10Mc (много тысяч частиц)
- Сравнение с обзорами GASS (Galex-Arecibo-SDSS Survey) , 760 массивных г-к, и CJLD GASS (250 г-к в CO).

Примеры simulated galaxies



- Большие символы – наблюдения, маленькие – модель.

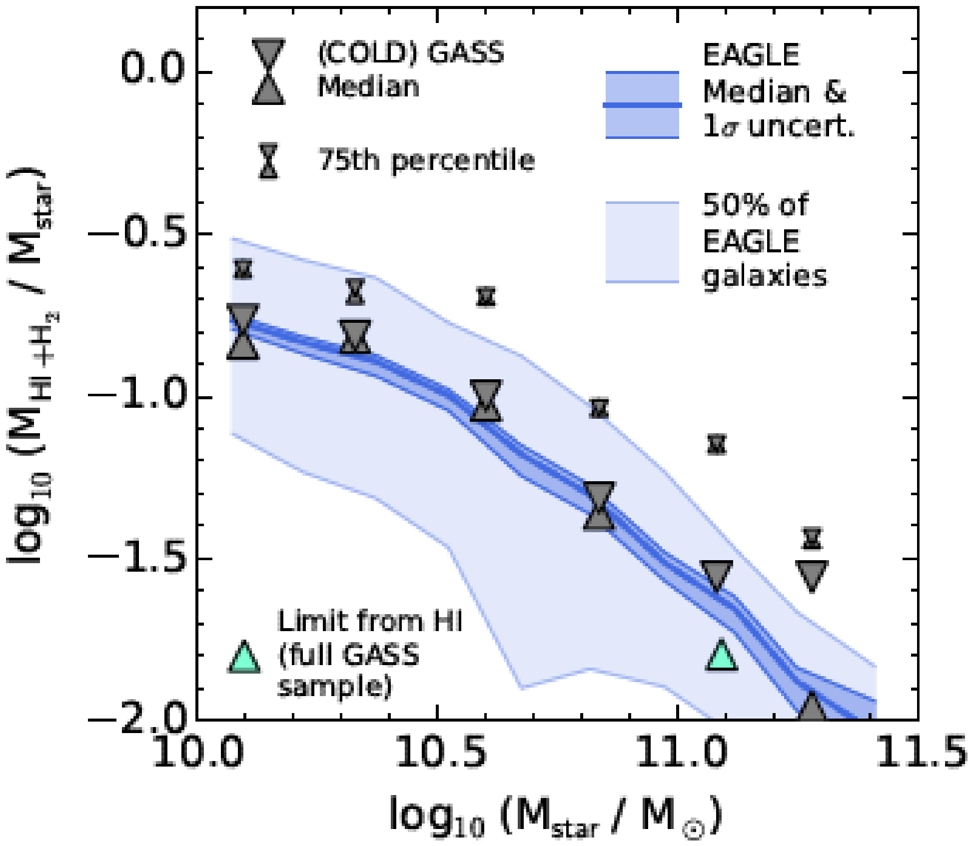


Figure 1. Neutral hydrogen mass fractions for our simulated galaxies as predicted by the Rahmati et al. (2013a) fitting formula (blue line, shaded bands show the 1σ uncertainty and 50 per cent scatter, respectively). For comparison, observational data from the combined *GASS* and *COLD GASS* surveys are shown as grey symbols, upward (downward) facing triangles differ in that non-detections are set to zero (upper limits). Large triangles show the observed medians, small ones the 75th percentile of the distribution. The light blue triangle shows an additional lower limit from H I masses in the full *GASS* survey (see text for details). The neutral hydrogen masses in EAGLE agree with observational constraints to within 0.1 dex, although there are large uncertainties on the observational median at $M_{\rm star} > 10^{11}\,{\rm M}_\odot$.

Сравнение моделейц с наблюдениями (темные линии)

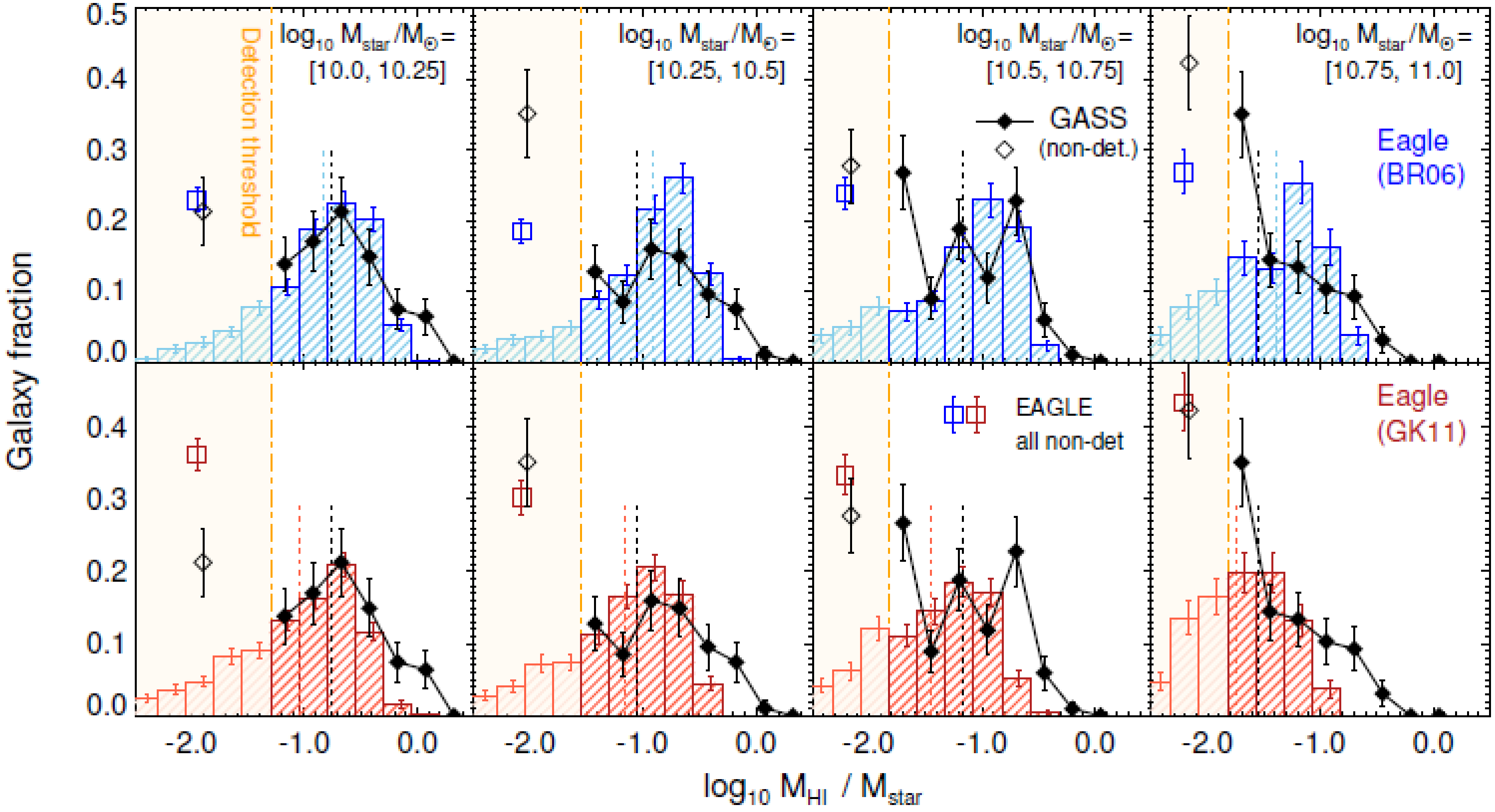


Figure 2. Comparison of the H I mass of EAGLE galaxies (blue/red histograms) with *GASS* observations (black lines); both samples include only central galaxies. In the top panel, the presence of H_2 in EAGLE is accounted for with the empirical Blitz & Rosolowsky (2006) pressure-law prescription, while the bottom panel shows the corresponding results from the theoretical Gnedin & Kravtsov (2011) partition formula. The shaded region on the left is below the (maximum) *GASS* detection threshold in each panel; all simulated galaxies in this regime (light blue/red) are combined into the blue/red open square for comparison to the observations. Vertical black (blue/red) dotted lines indicate the median H I mass fraction of all *GASS* (EAGLE) galaxies per stellar mass bin; in the third panel of the top row both lie on top of each other. Error bars show statistical Poisson uncertainties. Both H_2 prescriptions lead to broad agreement of the predicted H I masses with observations, but the detailed match is considerably better for the BR06 H_2 formula (top).

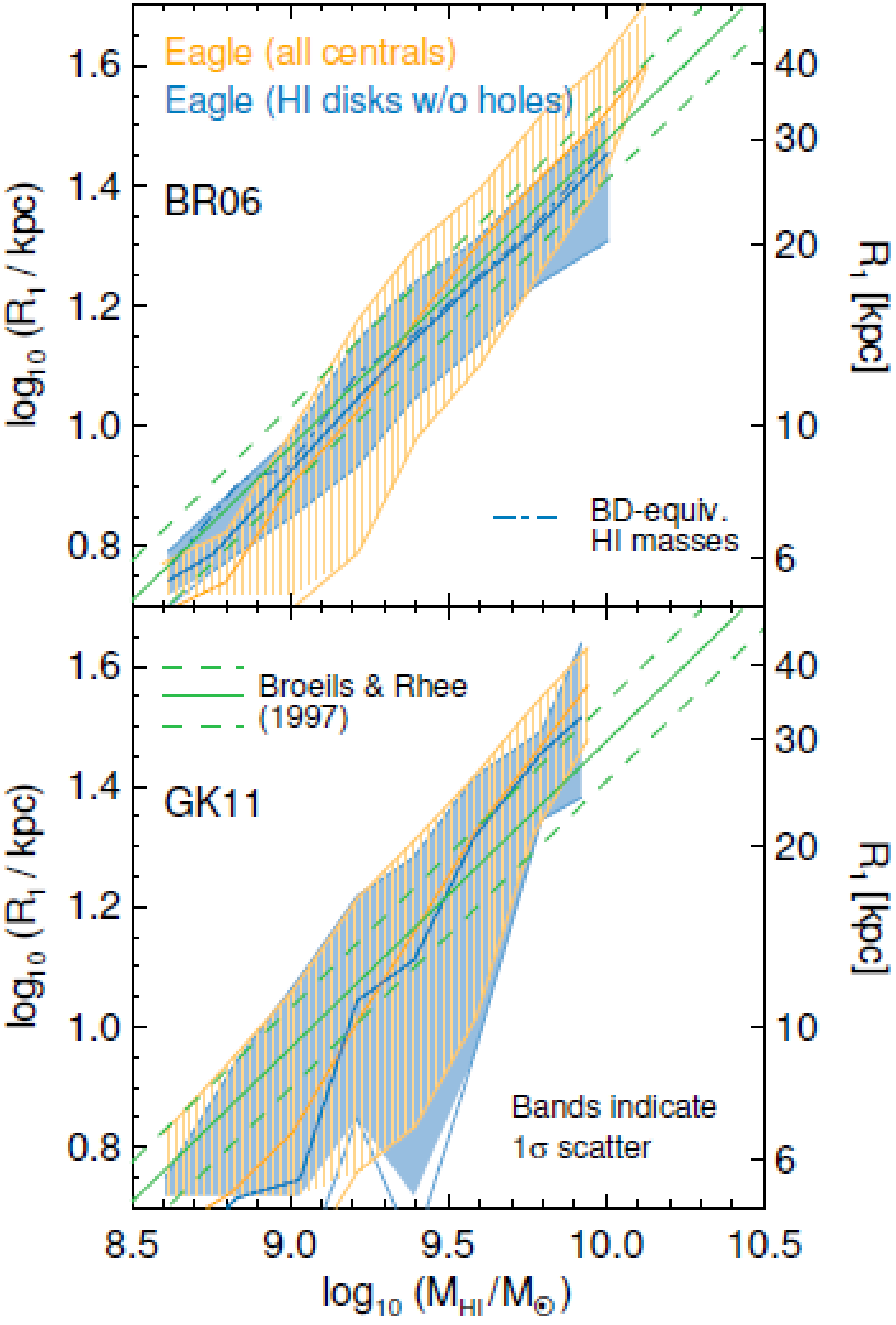
- R1- радиус до плотности 1Mc/pc^2

Оценки H2 двумя методами:

по Blits, Rosolowsky (вверху)

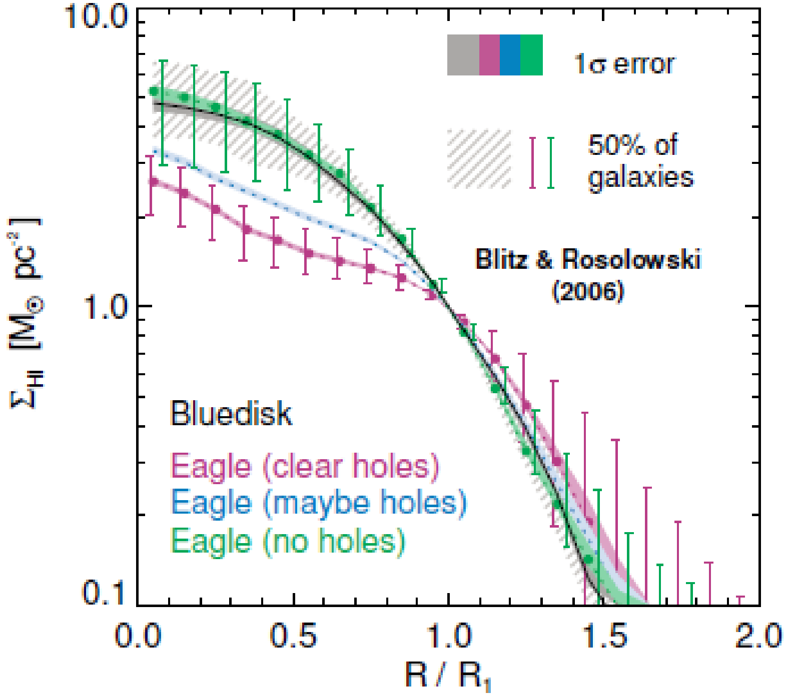
по Gnedin, Kravtsov (внизу).

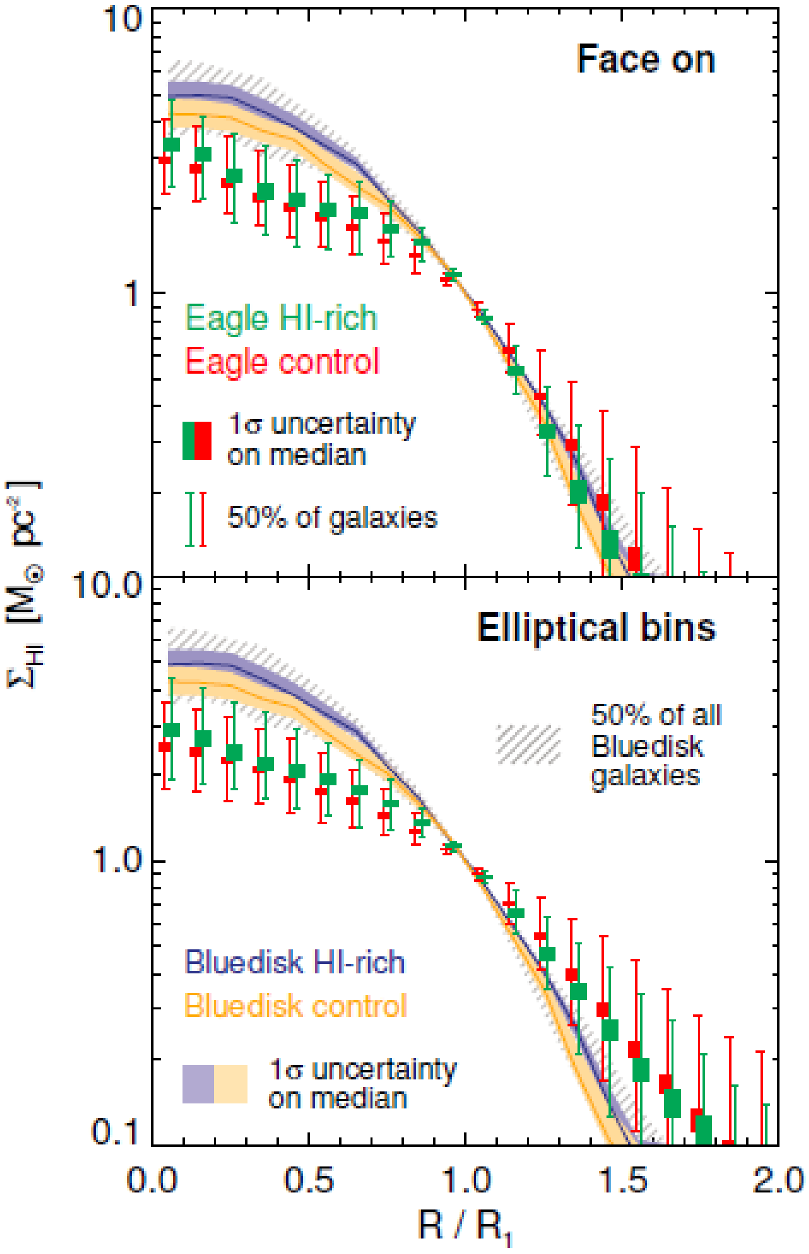
Синий цвет – модельные галактики без дыр в распределении HI.



- Согласие с наблюдениями плохое! Причина- нереально большие дыры HI.

No-holes galaxies





ОСНОВНОЙ ВЫВОД:

To our knowledge, this is the first time that such relatively detailed agreement of HI properties with observations has been demonstrated in self-consistent cosmological hydrodynamical simulations