The Morphology of Disk Galaxies in Galaxy Clusters with Dark Matter Self-Interactions

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ABSTRACT

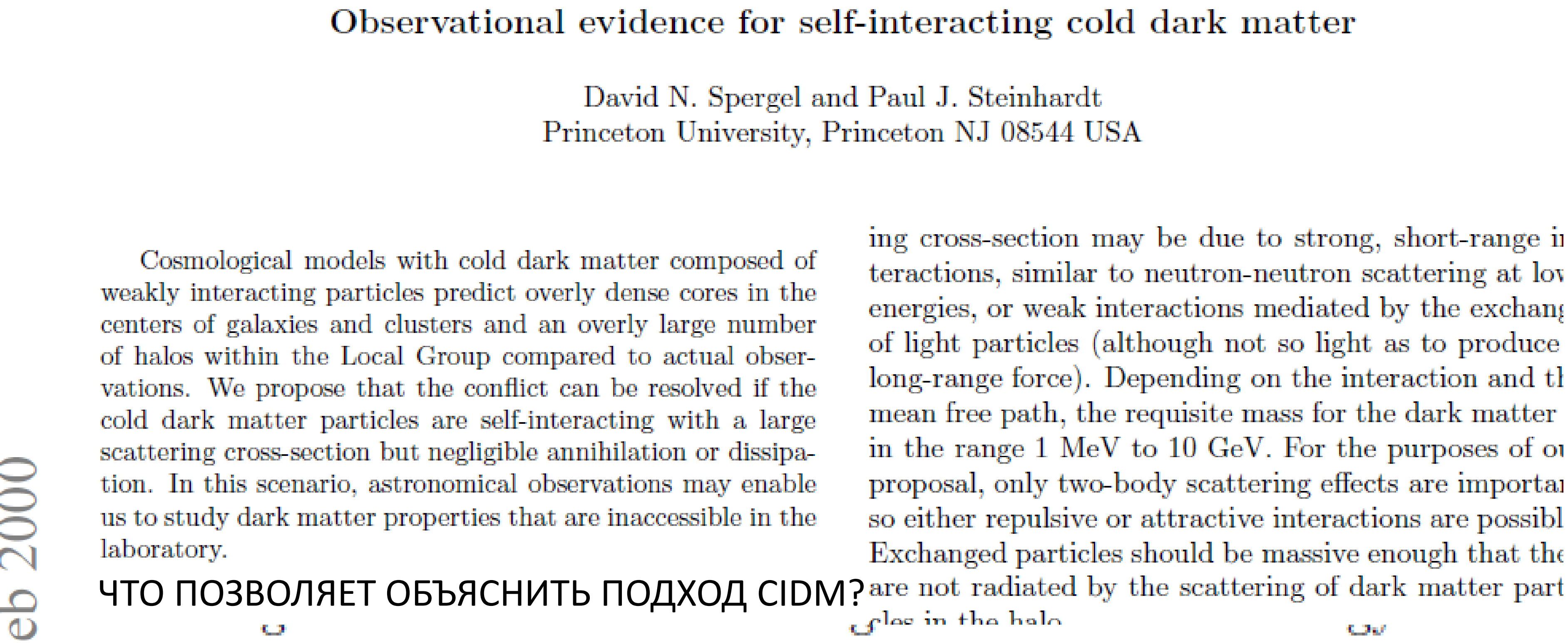
Self-Interacting Dark Matter (SIDM) has long been proposed as a solution to small scale problems posed by standard Cold Dark Matter (CDM). We use numerical simulations to study the effect of dark matter interactions on the morphology of disk galaxies falling into galaxy clusters. The effective drag force on dark matter leads to offsets of the stellar disk with respect to the surrounding halo, causing distortions in the disk. For anisotropic scattering cross-sections of 0.5 and $1.0\,\mathrm{cm}^2\mathrm{g}^{-1}$, we show that potentially observable warps, asymmetries, and thickening of the disk occur in simulations. We discuss the connection between these observational tests of SIDM and the follow up work needed with simulations in order to obtain detailed predictions.

Key words: astroparticle physics – dark matter – galaxies: kinematics and dynamics – galaxies: clusters: general

1 INTRODUCTION

The successful standard cosmological paradigm assumes that the dominant fraction of the matter contained in the universe is in the form of a non-luminous, nearly collisionless component called *dark matter* (DM). Furthermore, the clus-

that only $\mathcal{O}(10)$ satellites have been found around our galaxy led these mismatches to be named the "core-cusp problem" and the "missing satellites problem" respectively (Kravtsov 2010; Bullock & Boylan-Kolchin 2017). Proper modeling and implementation of baryonic physics into simulations (Wetzel



Observational evidence for self-interacting cold dark matter

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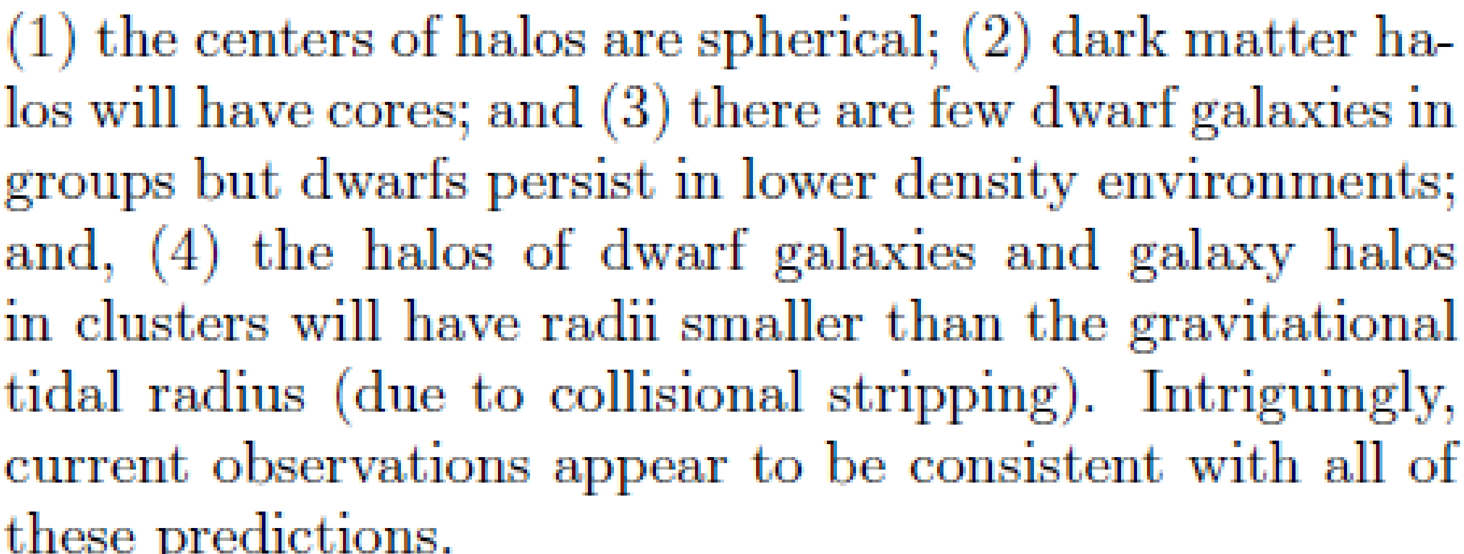
Cosmological models with cold dark matter composed of weakly interacting particles predict overly dense cores in the centers of galaxies and clusters and an overly large number of halos within the Local Group compared to actual observations. We propose that the conflict can be resolved if the cold dark matter particles are self-interacting with a large scattering cross-section but negligible annihilation or dissipation. In this scenario, astronomical observations may enable us to study dark matter properties that are inaccessible in the laboratory.

ing cross-section may be due to strong, short-range i teractions, similar to neutron-neutron scattering at lov energies, or weak interactions mediated by the exchan of light particles (although not so light as to produce long-range force). Depending on the interaction and tl mean free path, the requisite mass for the dark matter in the range 1 MeV to 10 GeV. For the purposes of o proposal, only two-body scattering effects are importa so either repulsive or attractive interactions are possib Exchanged particles should be massive enough that th are not radiated by the scattering of dark matter part cles in the halo

ЧТО ПОЗВОЛЯЕТ ОБЪЯСНИТЬ ПОДХОД CIDM?



(1) the centers of halos are spherical; (2) dark matter halos will have cores; and (3) there are few dwarf galaxies in groups but dwarfs persist in lower density environments; and, (4) the halos of dwarf galaxies and galaxy halos in clusters will have radii smaller than the gravitational tidal radius (due to collisional stripping). Intriguingly, current observations appear to be consistent with all of these predictions.

Self-interacting dark matter (SIDM)

- Общая идея: рассеяние частица-частица DM

$$\delta v_{\parallel} = -v(1-\cos\theta), \quad \frac{F_{\rm drag}}{m_{\rm dm}} = -\frac{1}{4}\left(\frac{\tilde{\sigma}}{m_{\rm dm}}\right)\rho v^2$$

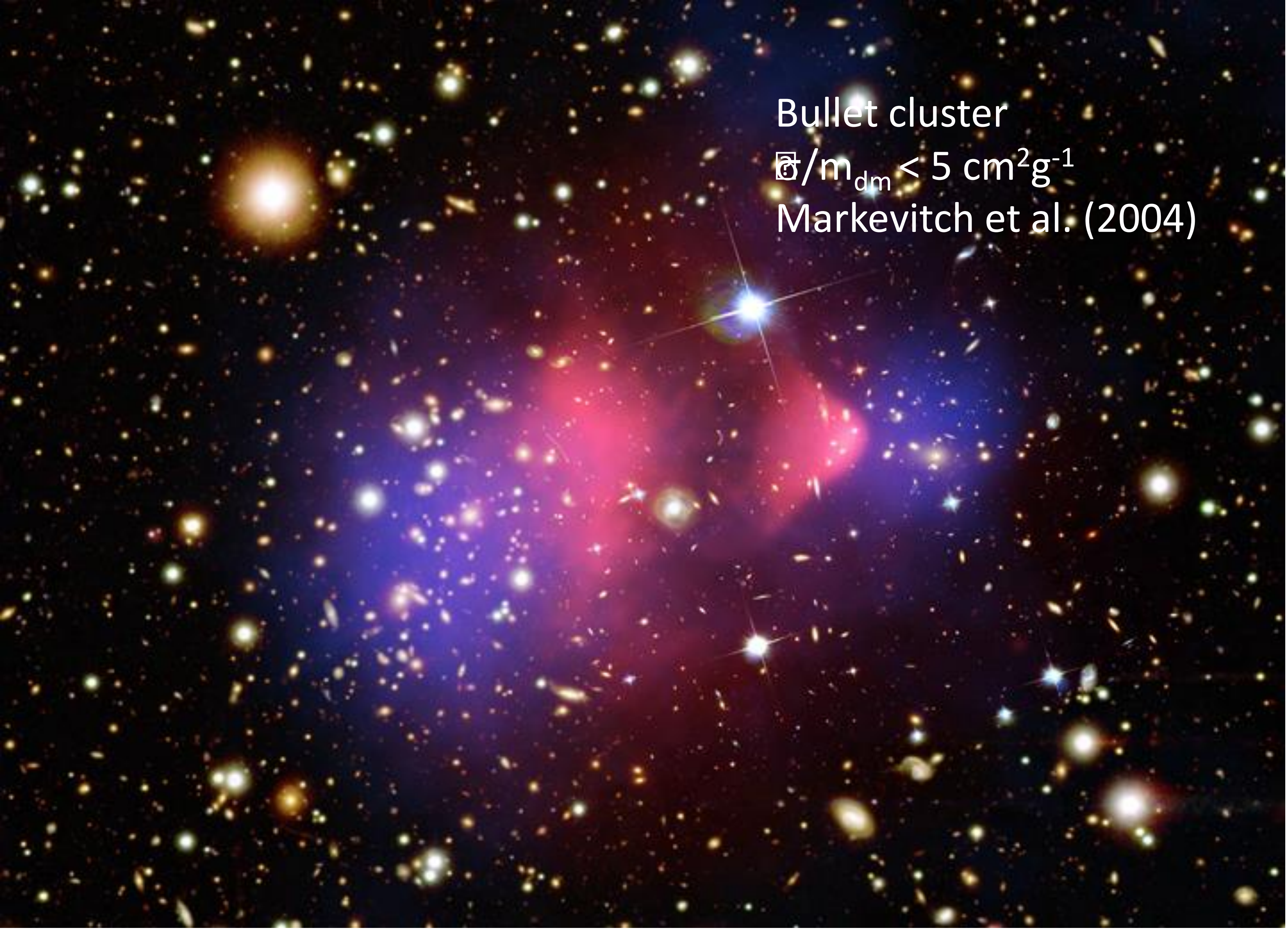
- Как результат – испарение частиц субгало + drag.

- It is commonly asserted that the desired range of cross-sections necessary to explain the observed mass profiles of galaxies is around σ/m_{dm} 0.5 – 5.0 cm^2g^{-1} (Tulin &Yu,2017)

- Spergel D. N., Steinhardt P. J., 2000:

«размыв» каспа требует 0.45-450 cm^2/gю

- В работе принимается σ/m_{dm} = 1 – 0.5 cm^2g^{-1}



Bullet cluster
$\sigma/m_{dm} < 5\ \mathrm{cm}^2\mathrm{g}^{-1}$
Markevitch et al. (2004)

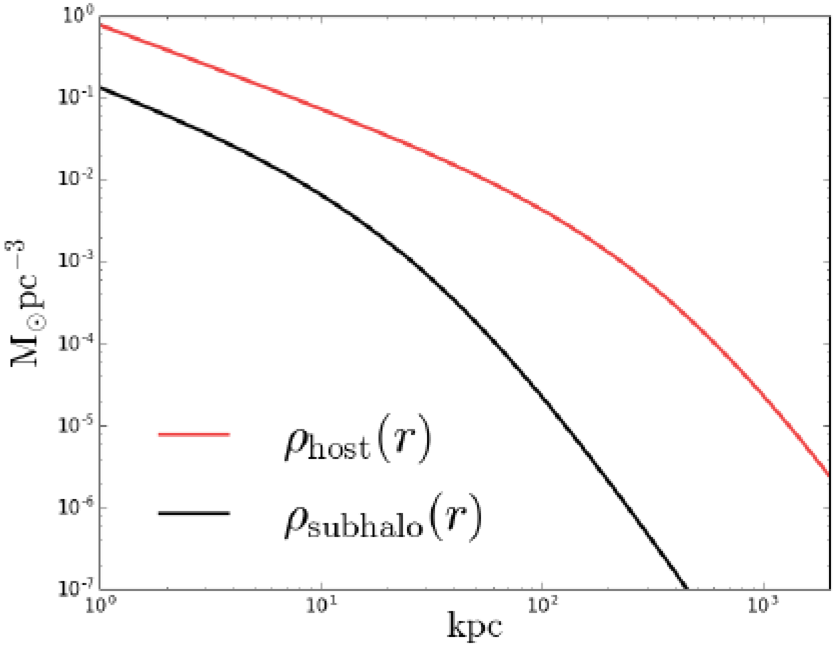


Figure 2. Radial density profiles of the subhalo (black) and the host halo (red). The host has a Hernquist profile defined by equation (11), with virial mass $M_{\rm h} = 10^{15}\,\mathrm{M_\odot}$ and concentration $c = 5$. The subhalo is also a Hernquist profile with virial mass $M_{\rm sh} = 10^{12}\,\mathrm{M_\odot}$ and concentration $c = 8$.

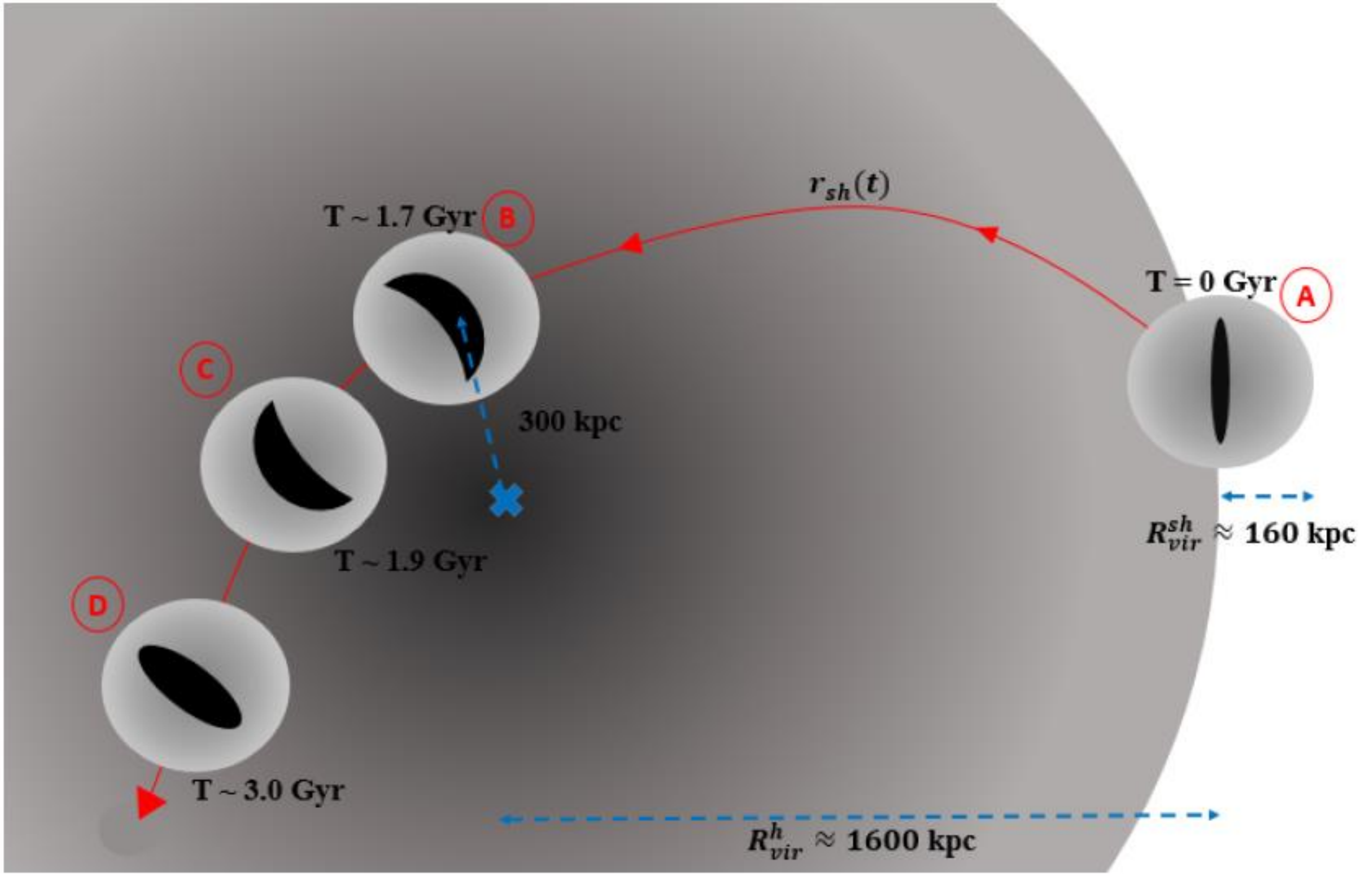


Figure 1. A schematic view of the simulated system (not to scale). With the fiducial choices detailed in Section 2.2, the virial radius of the host is around $R^{\mathrm{h}}_{\mathrm{vir}} = 1600\,\mathrm{kpc}$ and that of the subhalo is around $R^{\mathrm{sh}}_{\mathrm{vir}} = 160\,\mathrm{kpc}$. The curved red line corresponds to the trajectory of the subhalo though the host, $r_{\mathrm{sh}}(t)$. On (A), the thin galaxy disk is at the center of the subhalo at time $T = 0\,\mathrm{Gy}$. Both start infalling from the virial radius of the host with nonzero tangential velocity. On (B), at around $T = 1.7\,\mathrm{Gy}$ (exact time values are slightly dependent on the impact parameter chosen) the system is at closest approach from the host center and, shortly after that, the galaxy is maximally warped. On (C), a couple hundreds of My after the initial forward warp, the distortion oscillates backwards. At much later times, (D), around $T = 3\,\mathrm{Gy}$, the subhalo is close to its second turnaround or "splashback radius" , and the disk is considerably thicker than it was at the start.

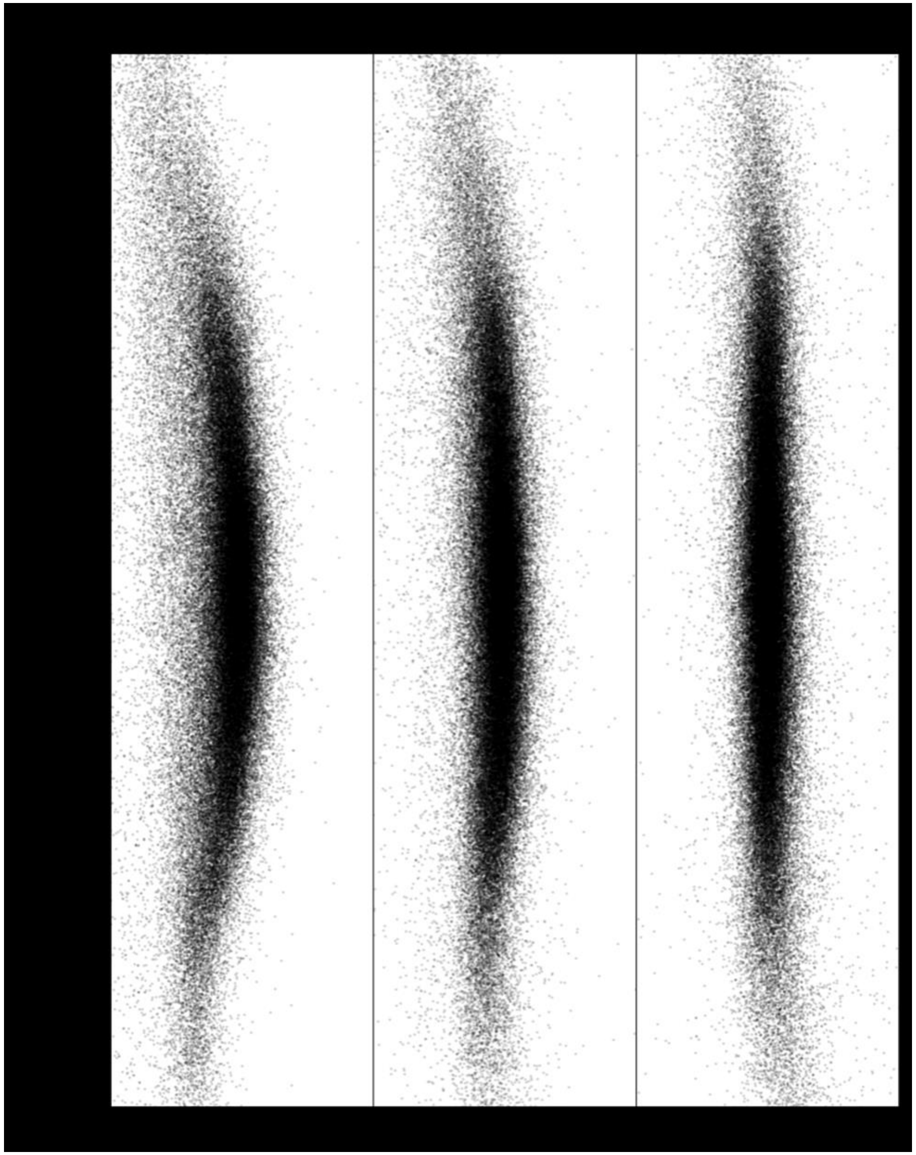


Figure 3. Snapshots from the simulations with 300 kpc impact parameter and orientation angle 0°. From left to right, we display the two SIDM cross-sections analyzed and the standard CDM

Поведение звёздного диска

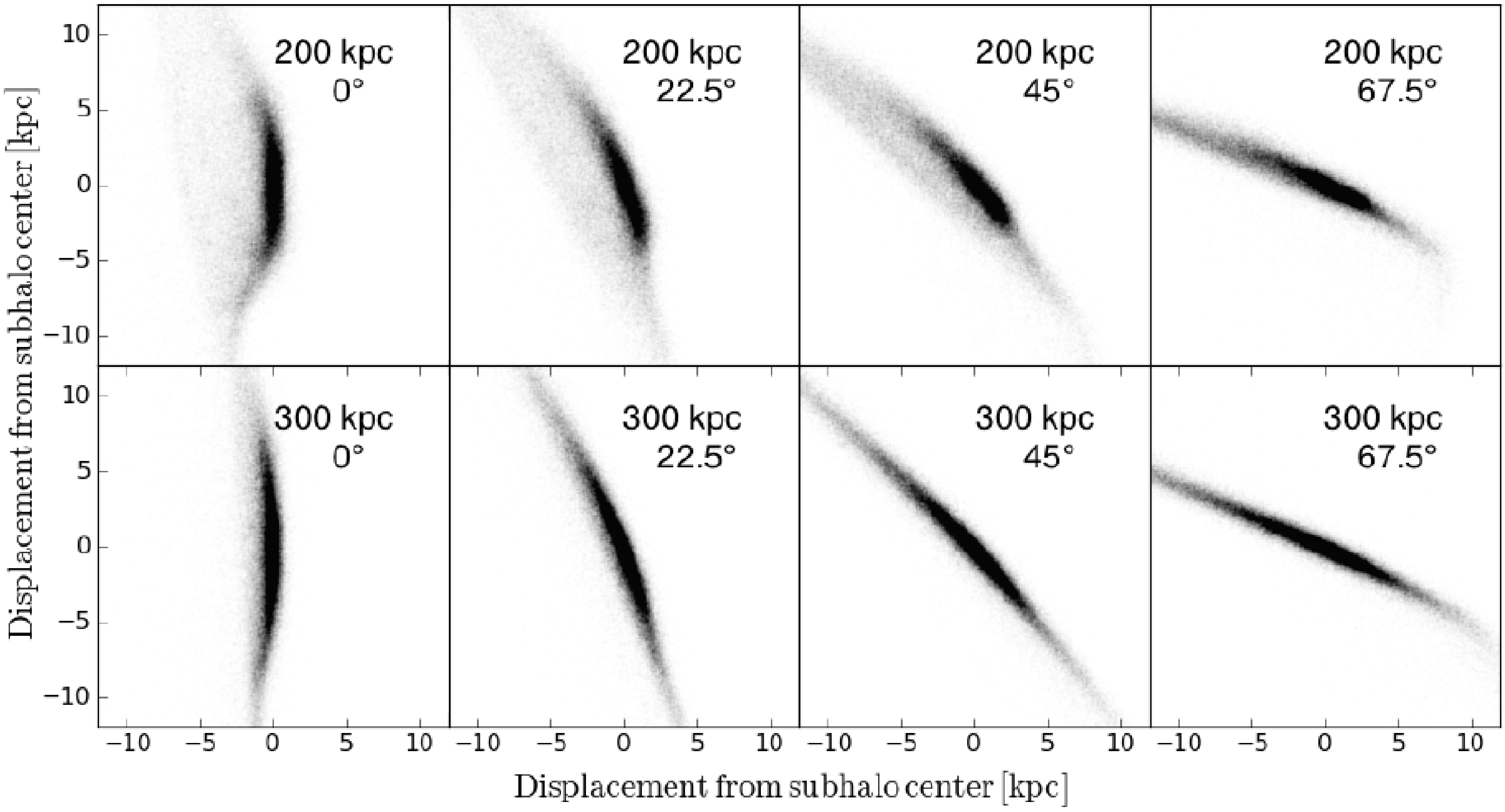


Figure 6. Snapshots of the maximum forward warp in 8 simulations with different impact parameters and orientation angles, for $\tilde{\sigma}/m_{\rm dm} = 1.0\,{\rm cm}^2{\rm g}^{-1}$. Black dots correspond to individual stars on the disk that inhabits an SIDM subhalo. The same initial conditions were used for the galaxies on each panel. The U-shaped warp is more prominent for lower impact parameters (when the subhalo probes a higher ambient density $\rho_{\rm h}$) and lower orientation angles (when the collision is closer to face-on as seen by the host halo). We also note, but leave for a future study, the fact that there is a skewness in the light distribution of disk galaxies at orientation angles larger than 0 degrees.

Распределение плотности частиц с высотой

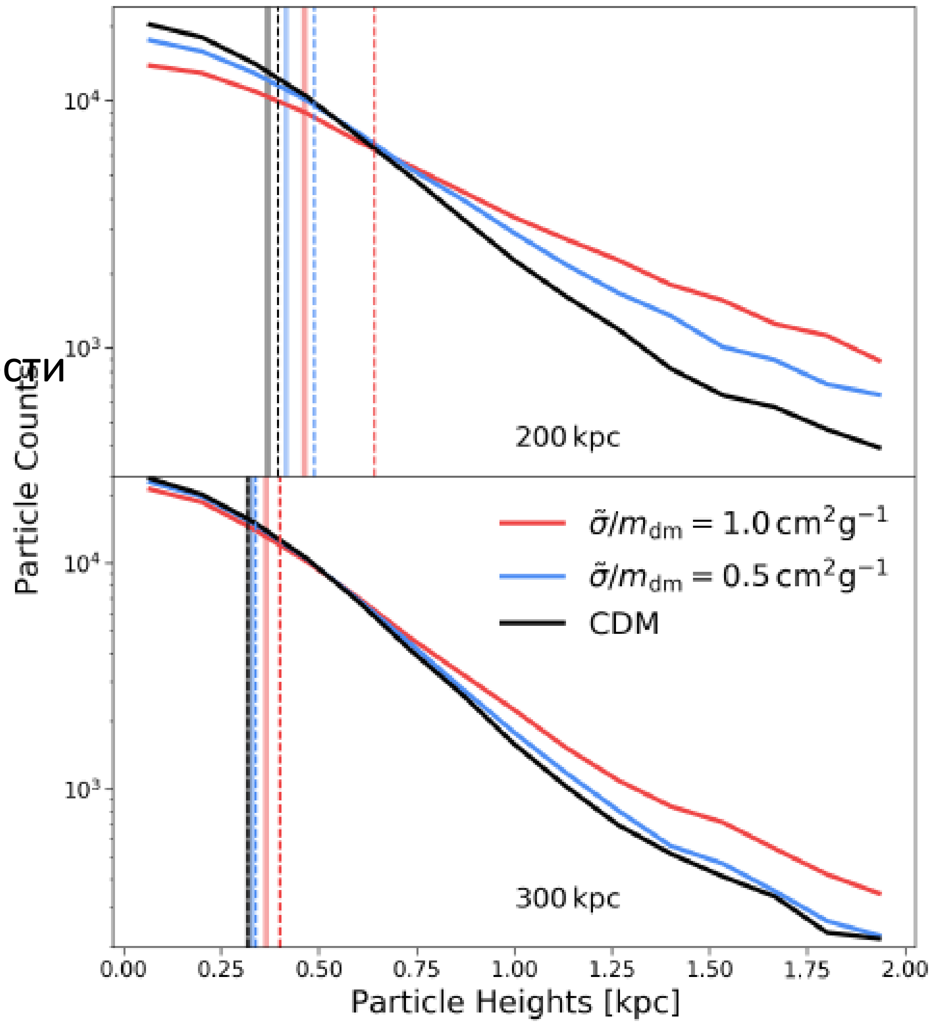


Figure 9. Histograms of disk particles selected to lie within a box of 3 scale radii and 5 scale heights from the galaxy center. Vertical bands correspond to the measurement of disk thickness as given by the standard deviation of the histograms, while dashed lines are scale height estimates from an exponential profile fit (see text). The uncertainty in the standard

Основной вывод

For SIDM cross-sections of 0.5 to 1 cm^2g^{-1}, we find that a disk galaxy gets significantly warped, and the warp oscillates on a timescale of a few hundred million years (F before decaying and leaving a thickened disk (Figure 9).

Thus we have identified the warping and thickening as distinct signatures of SIDM; more generally asymmetries in the light distribution arise once the disk is offset from the dark matter.

THE EFFECT OF FILAMENTS AND TENDRILS ON THE HI CONTENT OF GALAXIES

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ABSTRACT

We use the ALFALFA HI survey to examine whether the cold gas reservoirs of galaxies are inhibited or enhanced in large-scale filaments. Our sample includes 9947 late-type galaxies with HI detections, and 4236 late-type galaxies with well-determined HI detection limits that we incorporate using survival analysis statistics. We find that, even at fixed local density and stellar mass, and with group galaxies removed, the HI deficiency of galaxies in the stellar mass range $8.5 < \log(M/M_{\odot}) < 10.5$ decreases with distance from the filament spine, suggesting that galaxies are cut off from their supply of cold gas in this environment. We also find that, at fixed local density and stellar mass, the galaxies that are the most gas-rich are those in small, correlated "tendril" structures within voids: although galaxies in tendrils are in significantly denser environments, on average, than galaxies in voids, they are not redder or more HI deficient. This stands in contrast to the fact that galaxies in tendrils are more massive than those in voids, suggesting a more advanced stage of evolution. Finally, at fixed stellar mass *and color*, galaxies closer to the filament spine, or in high density environments, are more deficient in HI. This fits a picture where, as galaxies enter denser regions, they first lose HI gas and then redden as star formation is reduced.

Subject headings: galaxies: evolution — galaxies: groups — galaxies: ISM — galaxies: spiral — galaxies: statistics — large-scale structure of the universe

- We might expect cold gas accretion to depend on large-scale structure as well as local density.

- Cold gas accretion from the cosmic web is likely to be a dominant factor in the growth of galaxies. At the same time, cold gas is expected to be removed or cut off from galaxies through a variety of physical mechanisms that depend on large-scale environment.

- A particular question regarding the physical effect of large-scale filaments is whether they primarily act as conduits of cold gas that can replenish galaxies, or alternatively, as regions where galaxies are cut off from cold gas.

Данные противоречивы…..

- Kleiner et al. (2017 use spectral stacking of galaxies in the HI Parkes All-Sky Survey to show that high-mass galaxies within 0.7 Mpc of filament spines have a higher HI fraction than a control sample of galaxies more than5 Mpc from filament spines.
- Kuutma et al. (2017) find that at fixed density, high-mass galaxies (Mr < 20 mag) within filaments have reduced star formation rates (but not higher masses) and are more likely to have early-type morphologies.
- In this paper, we use HI observations from the ALFALFA survey (Giovanelli et al. 2005) to examine the cold gas content of galaxies as a function of large scale structure.
- HI deficiency is the logarithmic difference between the observed HI mass and the HI mass expected based on galaxy size:

HIDef = logMexpHI - logMobsHI.

log(MHI/Msun) = 8.72+1.25 logD25 (Toribio et al.,2011).

Цель работы

- Our goal is to compare galaxies that are very similar except for their large-scale environment. We consider the environmental dependence of three properties: stellar mass, color at fixed stellar mass, and HI deficiency at fixed stellar mass.
- In this paper, we use HI observations from the ALFALFA survey (Giovanelli et al. 2005) to examine the cold gas content of galaxies as a function of large scale structure.
- HI deficiency is the logarithmic dierence between the observed HI mass and the HI mass expected based on galaxy size:

$HI_{Def} = \log M_{exp}HI - \log M_{obs}HI.$

$\log(M_{HI}/M_{sun}) = 8.72+1.25 \log D25$ (Toribio et al.,2011).

- HI deficiency is fit as a function of three independent variables: heliocentric distance, log stellar mass , and perpendicular distance from the filament spine D_{fil}. The purpose is to find functions that remove the dependence on distance and stellar mass, leaving only the residual dependence on the environmental variable of interest, the distance to the filament spine.

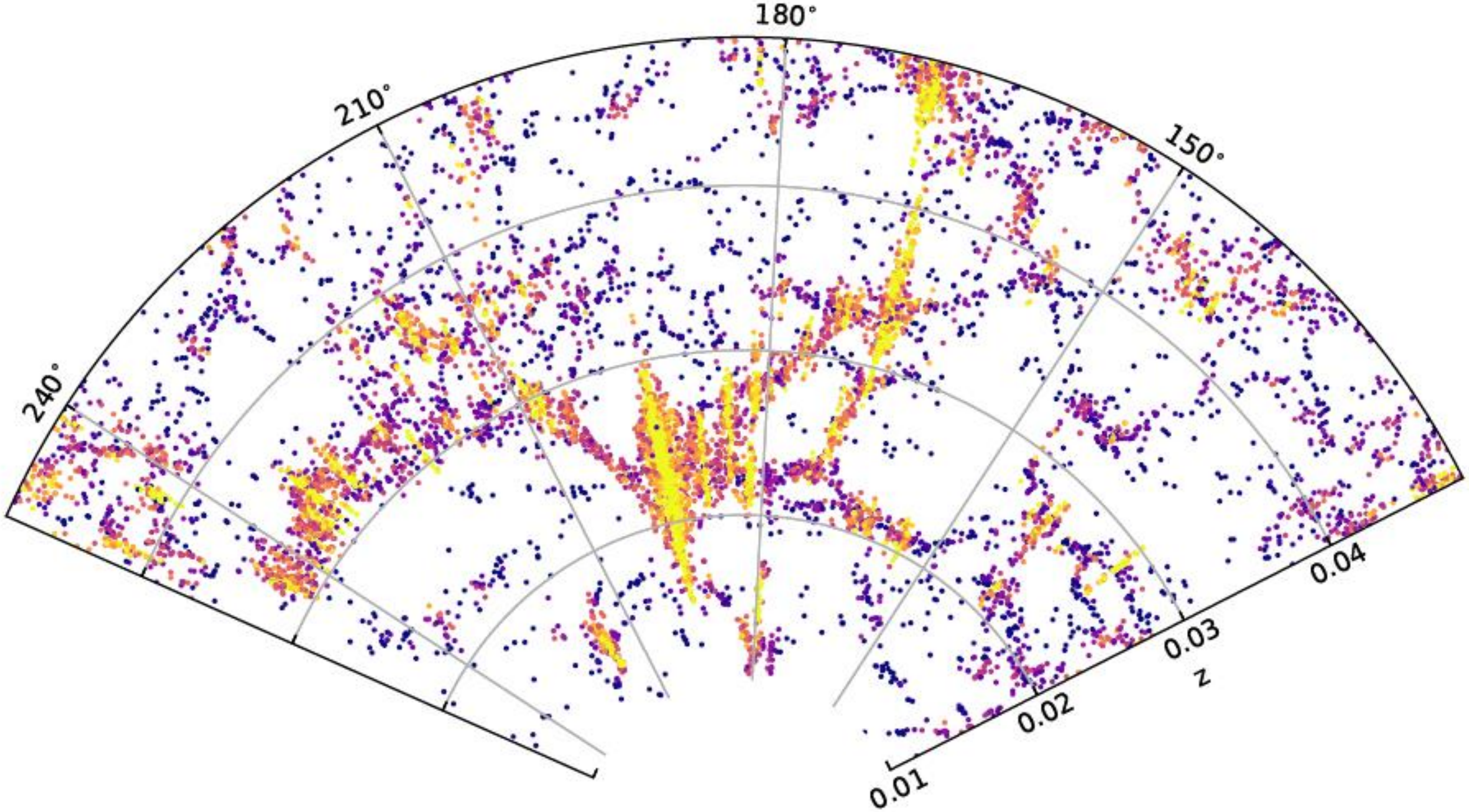


FIG. 3.— Like Figure 2, but including all galaxies in the slice, color-coded by nearest-neighbor density.

- Два параметра, характеризующих environment:
- Площадь до 3-го по расстоянию члена
- Расстояние от оси ближайшего филамента.

Между ними есть корреляция.

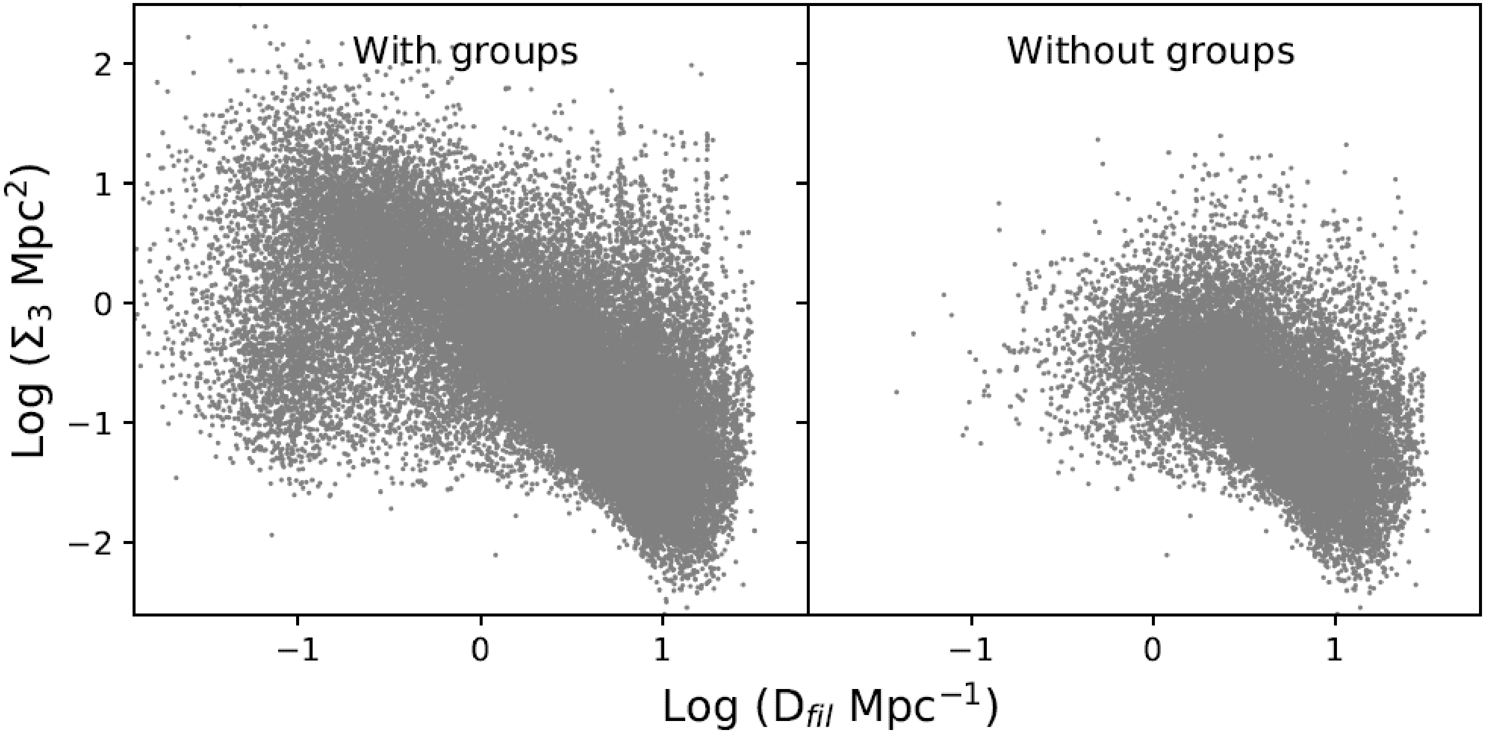


FIG. 5.— Relationship between local density Σ_3 and distance from the filament spine D_{fil} for all the galaxies (left) and for only galaxies that are not in groups (right). An exception to the approximately inverse relationship between Log Σ_3 and Log D_{fil} is the concentration of galaxies at moderate density but $D_{fil} \sim -1$; these galaxies are in groups that are relatively small but that define the filament spine.

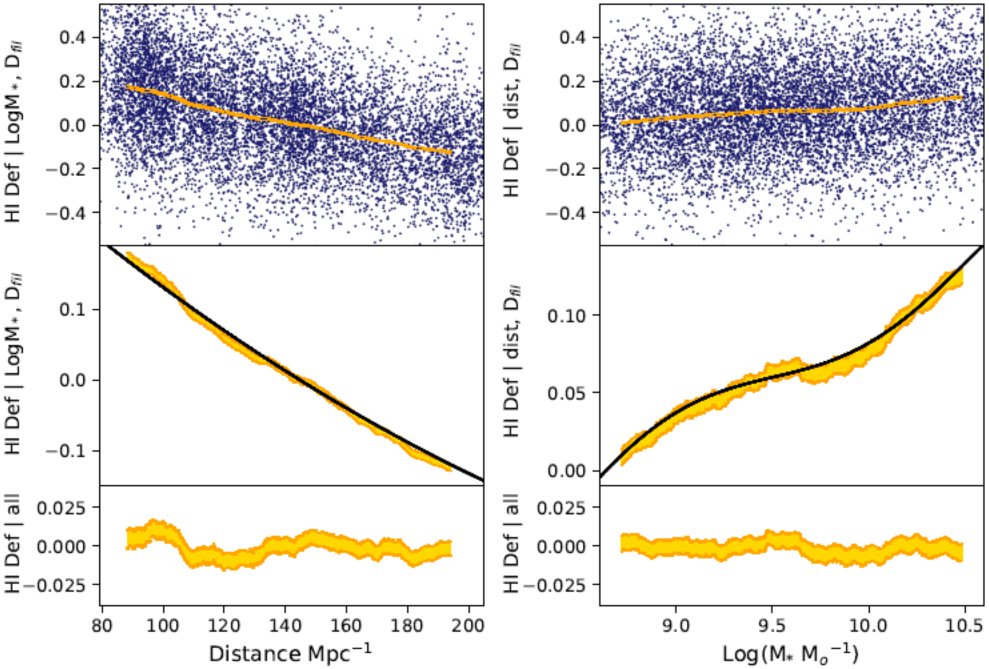
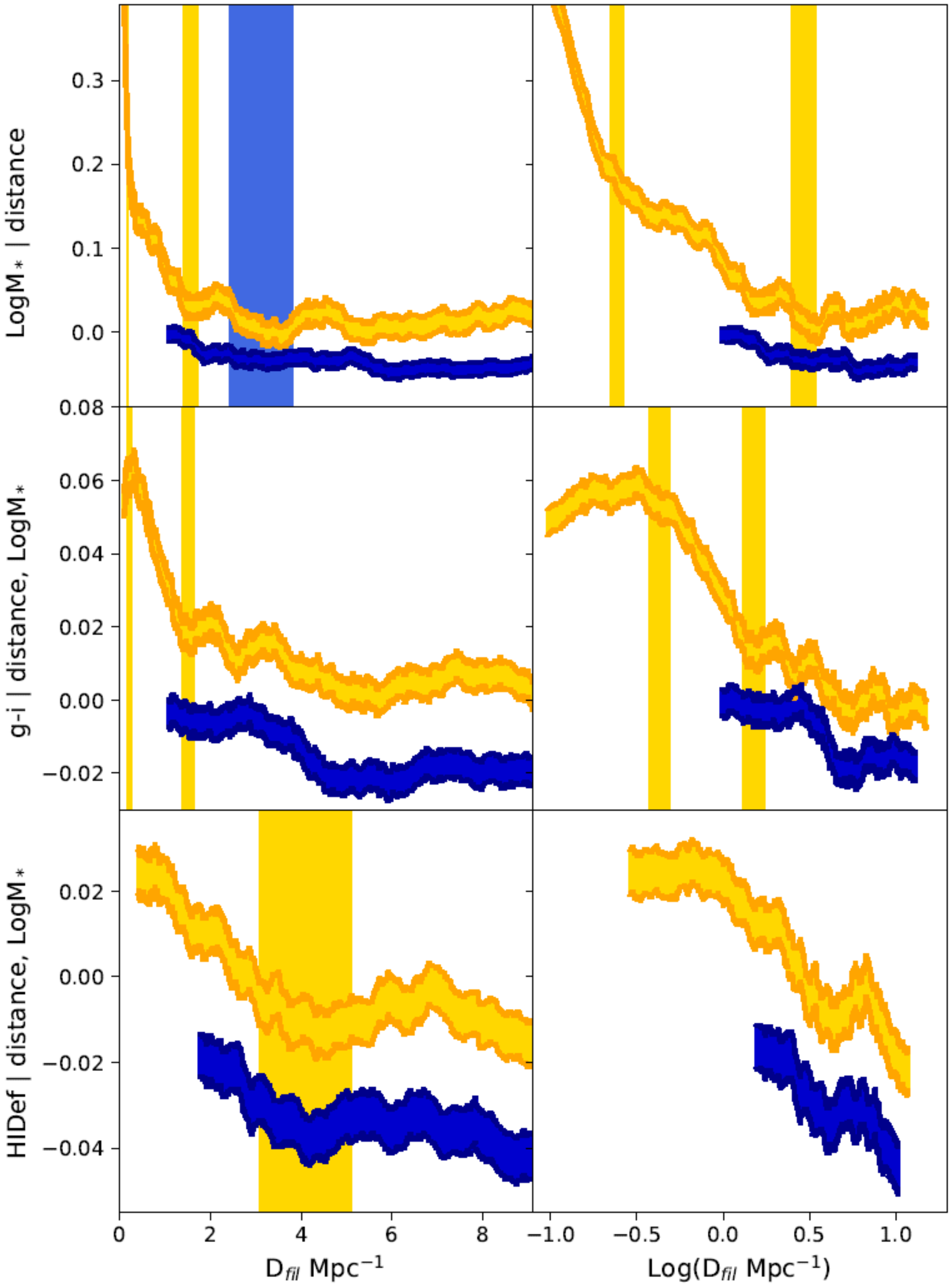
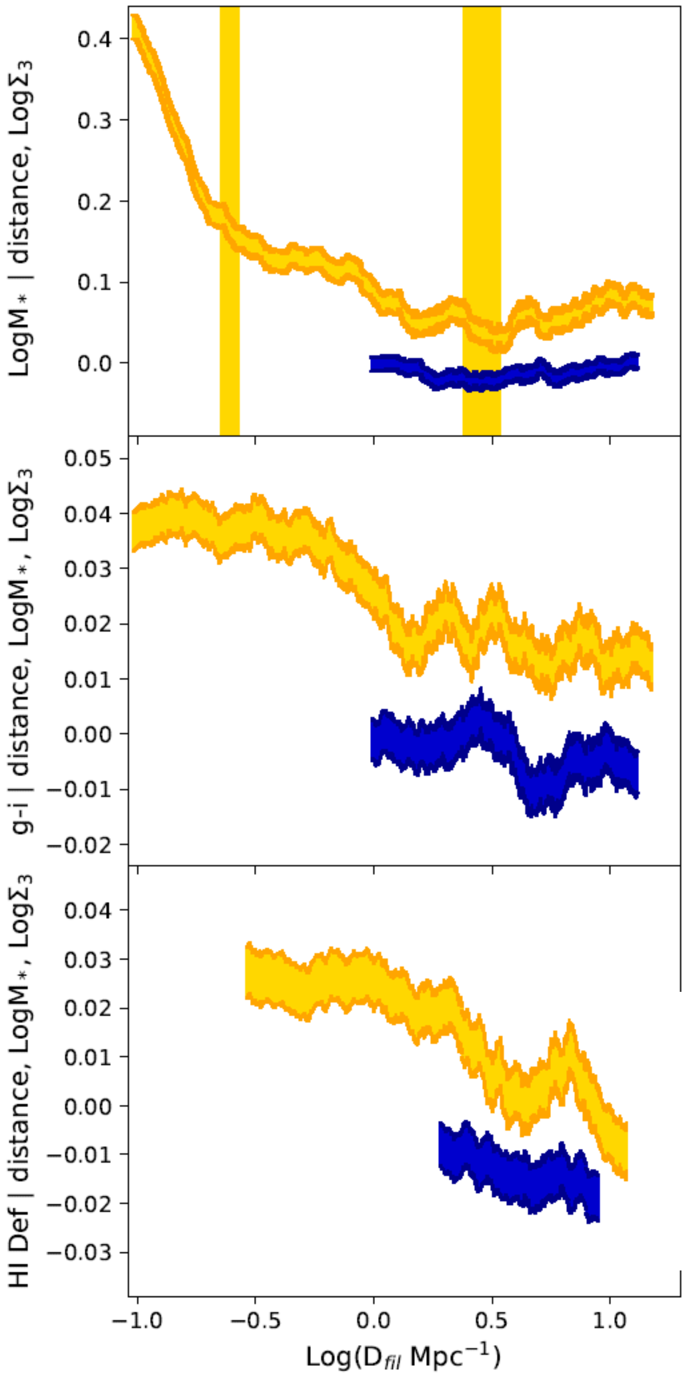


FIG. 6.— Residuals for HI deficiency, illustrating the process for estimating HI deficiency as a function of the perpendicular distance D_{fil} to the nearest filament spine, at fixed heliocentric distance and stellar mass. The top two rows show partial residuals based on regressions for HI deficiency as a function of distance, log stellar mass Log $M_\star$, and D_{fil}. The left column shows residuals relative to only Log $M_\star$ and D_{fil}, leaving the remaining dependence on distance. The right column shows residuals relative to only distance and D_{fil}, leaving the remaining dependence on mass. In the top row, blue dots indicate individual galaxies, while orange lines indicate the mean value with N=2000 boxcar smoothing. The width of the orange lines gives the standard error in the mean. The second row is a closeup of the same smoothed residuals, with black lines showing the best polynomial fits to the unsmoothed data. The bottom row shows the full residuals, where the dependences on both of these variables have been successfully removed. The quantity of interest, the HI deficiency as a function of D_{fil} at fixed distance and stellar mass, is the residual relative to distance and Log $M_\star$ leaving the remaining dependence on D_{fil}. This is shown in Figure 7.



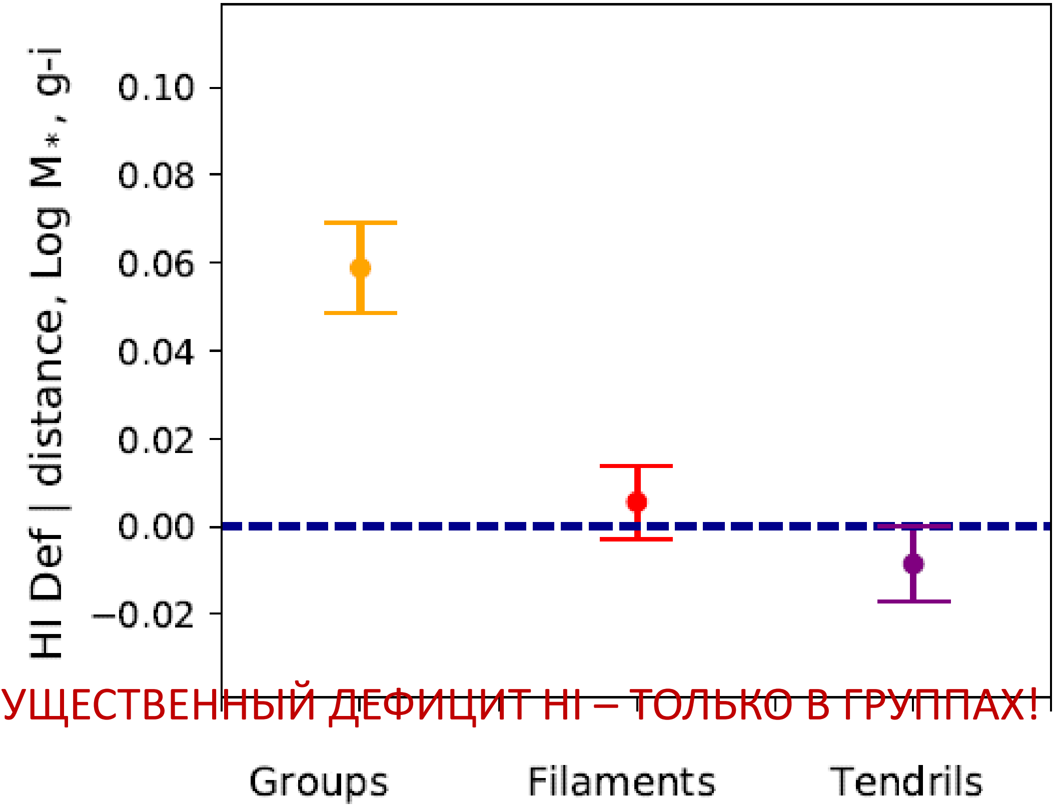
Голубая полоса –группы исключены, для удобства смещена вниз.



Голубая полоса –группы исключены,

для удобства смещена вниз.

FIG. 10.— Like the second column of Figure 7, but for fits that include local density as an additional independent variable. At fixed local density, there is still a statistically significant overall decrease with LogD_{fil} at small values of LogD_{fil} for the full sample (orange) and, in the case of HI deficiency, for both samples.



СУЩЕСТВЕННЫЙ ДЕФИЦИТ HI – ТОЛЬКО В ГРУППАХ!

FIG. 13.— Like Figure 9, but for fits to HI deficiency that include g-i color as an additional independent variable. At fixed color and stellar mass, HI deficiency still tends to decrease from groups to tendrils (left to right).

Самые главные выводы

- Хотя цвет и HI в звёздо-образующих галактиках зависит от их звёздной массы, даже при фиксированных значениях массы дефицит HI выше в более плотном окружении.
- Галактики «теряют» газ и замедляют SF в группах и в филаментах (на расстоянии нескольких Мпс от оси). Этот эффект заметен даже в пределах «голубого облака» галактик.
- Дефицит HI зависит как от локальной плотности, так и от расстояния до филамента.
- Если дефицит HI начиная с $D_{fil} < 4$ Mpc, цвет становится краснее с $D_{fil} < 1.5$ Mpc. This could be interpreted as reddening after gas loss as the galaxies move closer to the lament spine.
- At fixed local density and stellar mass, the galaxies that are the most gas-rich are those in small “tendril" structures within voids: although they are in signicantly denser environments, on average, than galaxies in voids, they are not redder or more HI deficient.