The Physical Thickness of Stellar Disks to z ∼ 2

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ABSTRACT

In local disk galaxies such as our Milky Way, older stars generally inhabit a thicker disk than their younger counterparts. Two competing models have attempted to explain this result: one in which stars first form in thin disks that gradually thicken with time through dynamical heating, and one in which stars form in thick disks at early times and in progressively thinner disks at later times. We use a direct measure of the thicknesses of stellar disks at high redshift to discriminate between these scenarios. Using legacy *HST* imaging from the CANDELS and GOODS surveys, we measure the rest-optical scale heights of 491 edge-on disk galaxies spanning $0.4 \leq z \leq 2.5$. We measure a median intrinsic scale height for the full sample of 0.74 ± 0.03 kpc, with little redshift evolution of both the population median and scatter. The median is consistent with the thick disk of the Milky Way today ($0.6 - 1.1$ kpc), but is smaller than the median scale height of local disks ($\sim$1.5 kpc) which are matched to our high-redshift sample by descendant mass. These findings indicate that (1) while disks as thick as the Milky Way's thick disk were in place at early times, (2) to explain the full disk galaxy population today, the stellar disks in galaxies need to on average physically thicken after formation.

Keywords: Galaxy evolution(594), Scale height(1429), Disk galaxies(391), High-redshift galaxies(734)

1. INTRODUCTION

In present-day disk galaxies like our own Milky Way,

comprise its flatter "thin disk" (scale height $\sim$ 270 pc) (Gilmore & Reid 1983; Bland-Hawthorn & Gerhard 2016 and references therein). In reality, the relation between

Галактика:

- толстый диск h~ 1 kpc, наиболее старые звезды
- Тонкий диск h~270 pc
- Вопрос: толстый диск – это динамически разогретый тонкий,

или же предшественник тонкого?

Допустимы оба варианта

Цель работы: проследить на обширном материале тенденцию изменения толщины дисков со временем в интервале **z = 0.4 – 2.5**

- В РАБОТЕ ДИСКИ НЕ РАЗДЕЛЯЮТСЯ НА ТОЛСТЫЙ И ТОНКИЙ,
- Рассматриваются наиболее вероятные значения толщины диска НА ЭФФЕКТИВНОМ РАДИУСЕ ГАЛАКТИКИ.
- Материал: archival Hubble Space Telescope (HST) IR imaging from the CANDELS (Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey) and GOODS (Great Observatories Origins Deep Survey) surveys
- The galaxies in this sample span a stellar mass range of logM= 9 -11.
- Fixed rest-optical wavelengths (0.46-0.66 mkm)

- Parent sample для $z = 0.4\text{-}2.5$ – 6933 галактики
- Из них отбираются:
- галактики с well-defined major and minor axis and pos.angles, so that we can reliably orient the plane of the galaxy (около 3000 галактик).
- Отношение фотометрических осей < 0.4 (для ожидаемых толщин диска это в пределах $i \sim 10^0$ от edge-on).
- We remove galaxies with a sufficiently close neighbor (< 2’’).
- The final sample includes 491 galaxies.

- Из 6933 галактик отобраны

491 галактик с b/a<0.4

и без близких соседей.

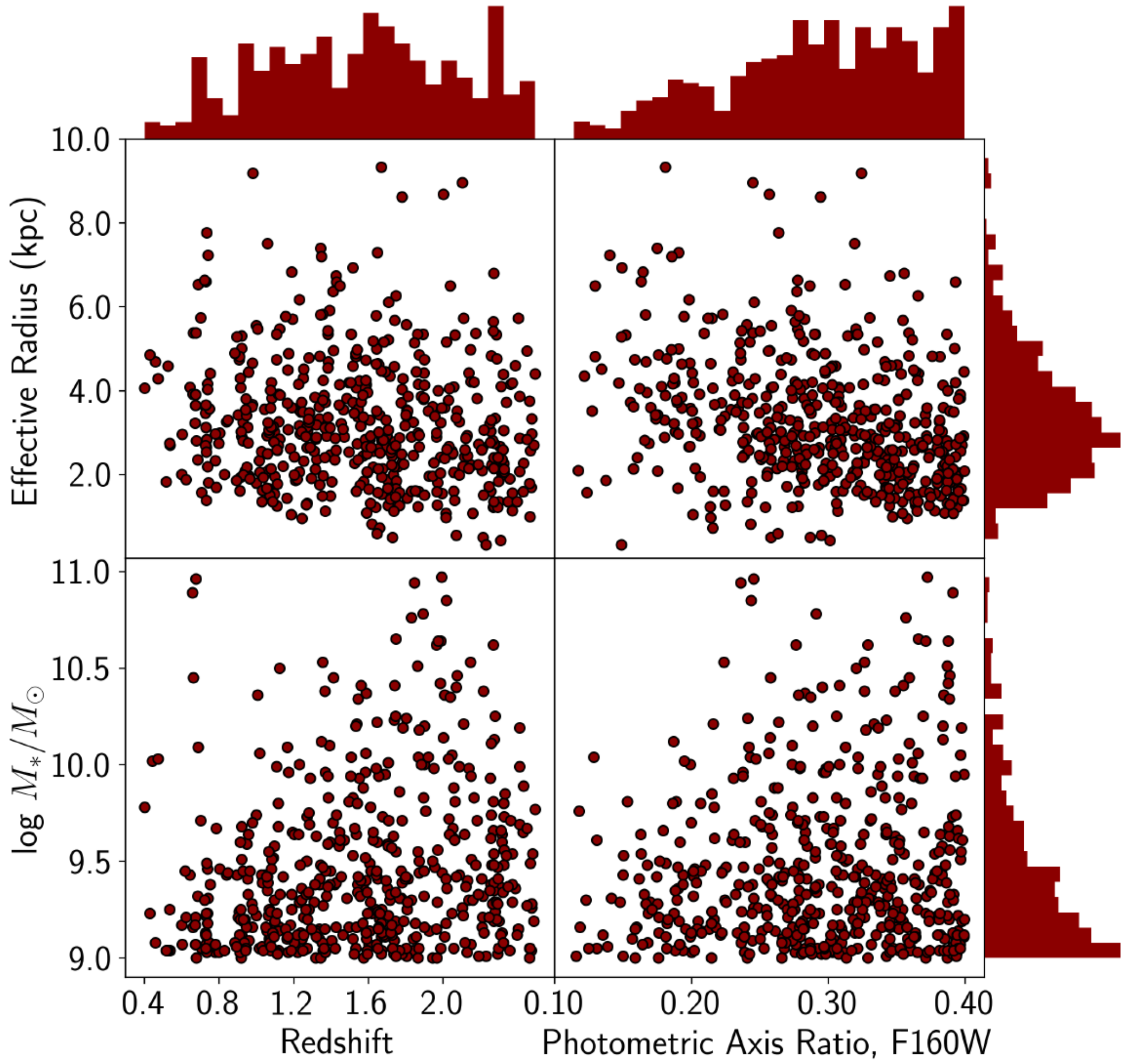

Figure 1. The distributions of stellar mass, redshift, WFC3/F160W effective radius, and WFC3/F160W photometric axis ratio for the galaxies in our sample are shown. Our sample spans a relatively uniform distribution in redshift. The majority of the galaxy sample have low stellar mass ($9 < \log M_*/M_\odot < 10$). To include galaxies that are sufficiently edge-on, we select galaxies with a WFC3/F160W photometric axis ratio less than 0.4.

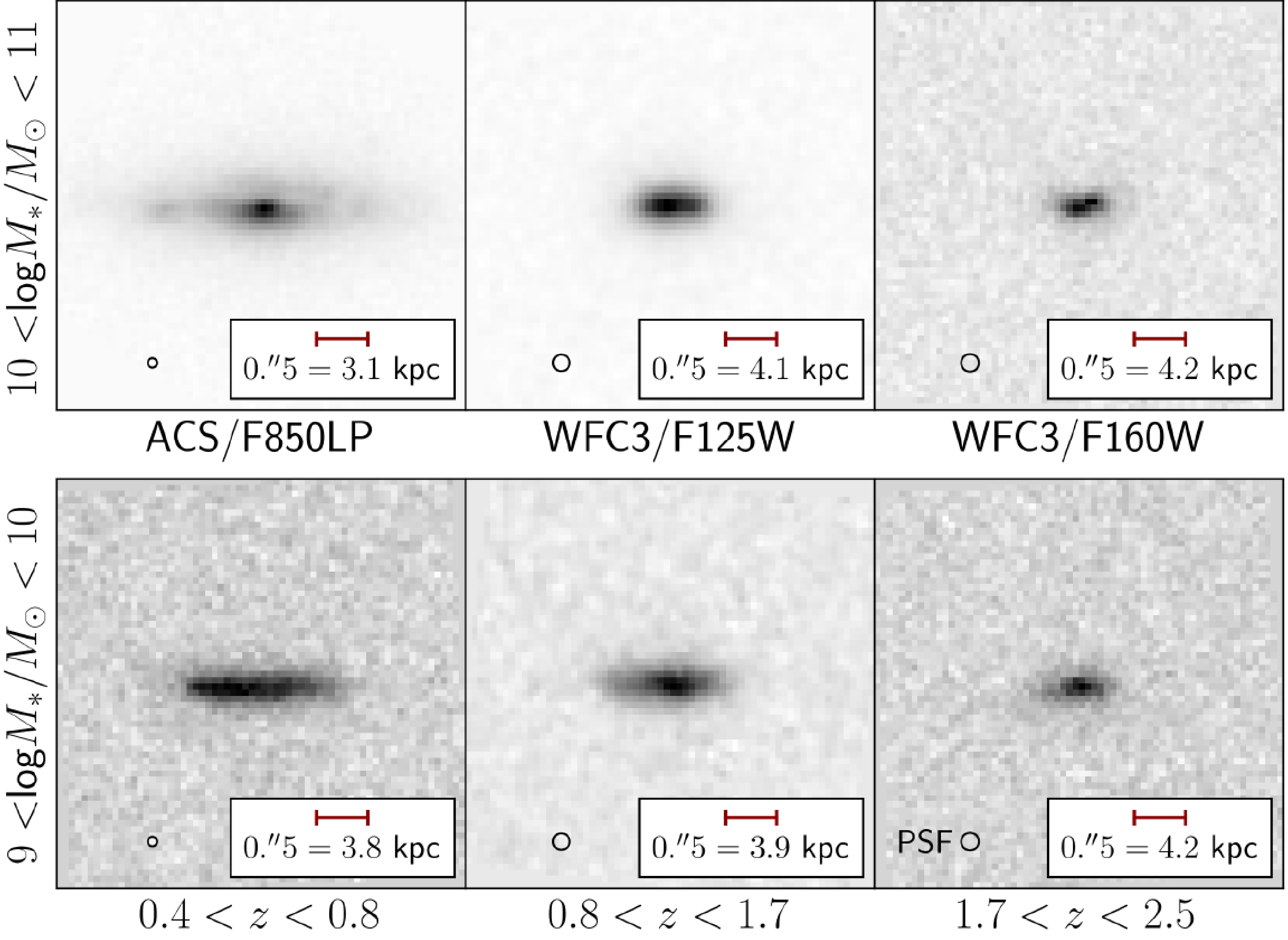

Figure 2. *HST*/ACS+WFC3 postage stamps for a random subset of the galaxies in the sample are shown. We select edge-on galaxies using a cut on axis ratio. The top row are high-mass galaxies ($10 < \log M_*/M_\odot < 11$) and the bottom row are low-mass galaxies ($9 < \log M_*/M_\odot < 10$). Redshift increases from left to right. The filters shown (and used to make the measurements in this paper) vary with redshift to target a fixed rest frame wavelength of $0.46 - 0.66\mu m$ (see Figure 3 and

Оценка шкалы высот

- We extract vertical surface brightness (and uncertainty) profiles along each vertical column.
- The columns are separated by 0.0006'' which corresponds to 0.33 kpc at z = 0.4 and 0.52 kpc at z = 2.
- We fit each of the observed surface brightness profiles using a model that includes a 1D convolution of the HST point-spread function (PSF) and a 1D sech^2 surface brightness profile.
- For every vertical column we derive the probability distribution of the scale height. (в рамках принятой модели).
- We do not consider the effect of dust attenuation on the observed surface brightness proles.(Bizyaev et al. (2014) inferred that dust attenuation leads to a

  < 15% increase in the observed disk thickness).
- Не понял, как быть с балджами?

We consider a galaxy sufficiently edge-on if it has a photometric axis ratio of b/a <0.4. This corresponds to an inclination of < 20^0 from edge-on for disks with intrinsic axial ratios (commonly denoted q) of 0.25. We then use simulations of randomly-inclined galaxy disks to calculate the bias to the median of the measured scale heights due to the residual inclination

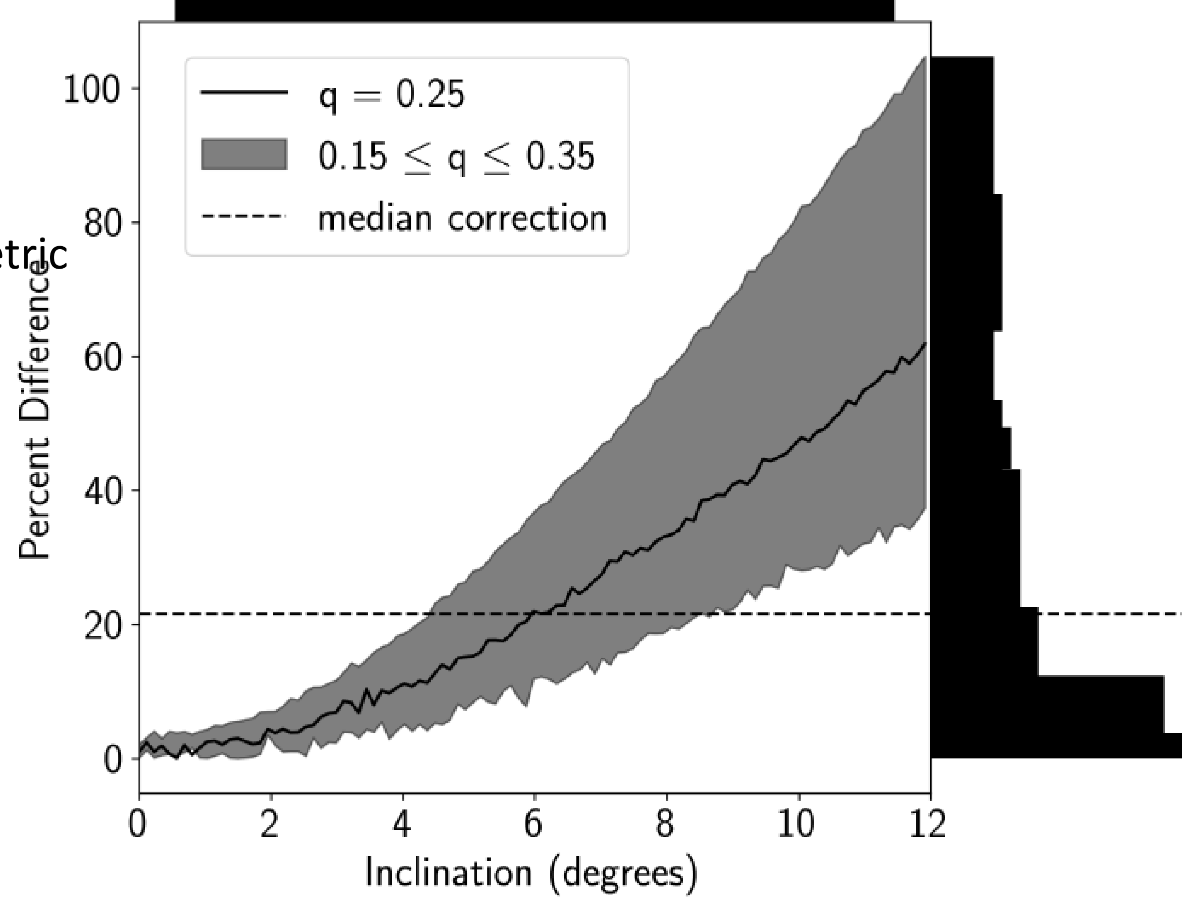

Figure 7. This figure shows the percentage difference between the intrinsic and recovered scale heights for toy models of disk galaxies that are randomly inclined to our line-of-sight. The toy models have ratios (q) of intrinsic scale height to scale length that vary between 0.15 and 0.35 The horizontal line represents the median of the models, 22%. We use the results shown here to correct the population median of the observed scale heights measured in this paper.

Простая модель для зависимости отношений толщины диска к радиальной шкале диска от отклонения от “edge-on” .

В среднем отличие от edge-on увеличивает оценку толщины диска на 22%.

z	$z_{0,\rm median}$	$z_{0,\rm median}^{\rm incl-corr}$	Δz_0
	(kpc)		
$1.7 < z \leq 2.5$ (N = 198)	0.96 ± 0.07	0.75 ± 0.05	0.47
$0.8 < z \leq 1.7$ (245)	0.88 ± 0.04	0.69 ± 0.03	0.40
$0.4 \leq z \leq 0.8$ (48)	1.15 ± 0.15	0.90 ± 0.12	0.80
$0.4 \leq z \leq 2.5$ (491)	0.94 ± 0.04	0.74 ± 0.03	0.35

Table 1. The population median ($z_{0,\rm median}$), inclination-corrected median ($z_{0,\rm median}^{\rm incl-corr}$), and scatter ($\Delta z_0$) of the galaxy scale height as measured at one effective radius is reported for different bins in redshift (top three rows) and for the full sample (bottom row). The scatter is defined as $(z_{0,84\rm th} - z_{0,16\rm th})/2$. The reported uncertainties are the standard error on the median.

- Выборка нормальных галактик - по работе Bizyaev, D. V., Kautsch, S. J., Mosenkov, A. V., et al.2014 (g-band), $9.5 < \log M/M_s < 10.5$.
- We fit each of the observed surface brightness profiles using a model that includes a 1D convolution of the HST point-spread function (PSF) and a 1D $sech^2$ surface brightness profile.

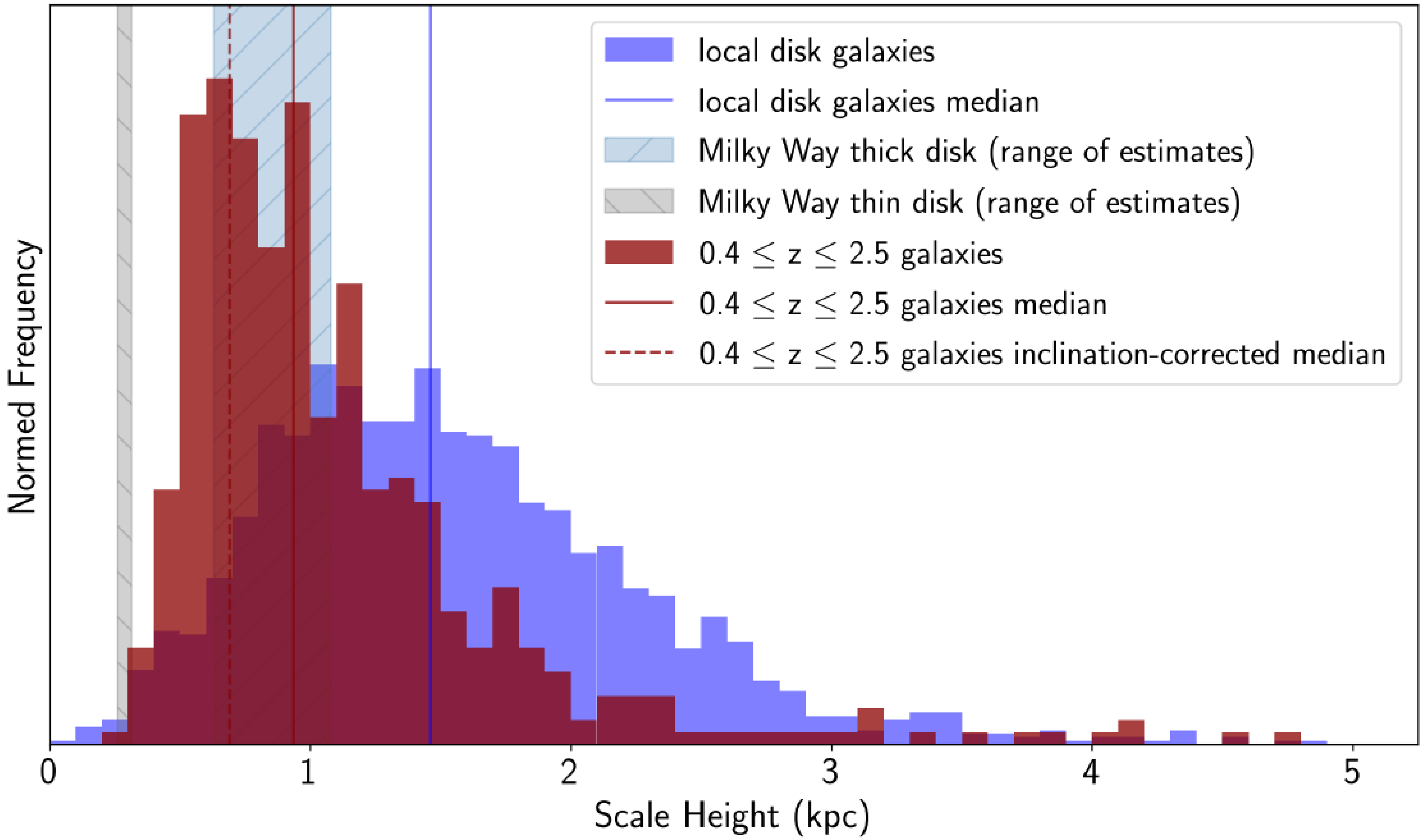

Figure 6. The distribution of the galaxy scale heights of our sample is shown in red. The sample spans $0.4 \leq z \leq 2.5$. The measurements are carried out at one effective radius from the center of each galaxy. The distribution of a population-matched sample of disk galaxies in the local universe (SDSS; Bizyaev et al. 2014) is shown in blue. The median and inclination-corrected median of our high redshift sample are shown with solid and dashed red lines, respectively. The median of the local sample is indicated with a vertical blue line. The range of estimates for the thick (light blue) and thin (grey) disks of the Milky Way are also shown (Bland-Hawthorn & Gerhard 2016 and references therein). The inclination-corrected median scale height of the high-redshift galaxies (~ 750 pc) is smaller than that of the disk galaxies today (~ 1500 pc) but is similar to that of the thick disk of the Milky Way ($\sim 600 - 1100$ pc).

As a whole, we draw two conclusions: (1) disks as thick as the Milky Way are established as early as cosmic noon at $z \sim 2$, but also that (2) these high-redshift stellar disks are as thin or thinner than their (expected) descendant galaxies today. This suggests that the thickest components of today's galaxy disks start thick, and subsequently thicken at later times. This is consistent with the scenario outlined in Bird et al. (2021), where stars are formed in thicker disks (with higher velocity dispersion) at higher redshifts *and also* subsequently thicken at later times.

Еще один вывод

- From $z \sim 2.5$ to $z \sim 0.4$, we find no evidence for an evolution in the median and scatter of the scale heights of the galaxy population with redshift. We suggest that the bulk of the scale height evolution that is implied by the comparison with SDSS above must occur at cosmic times later than $z \sim 1$, where our sample loses statistical power.