Missing baryons in thick disks: edge-on galaxies seen through the Spitzer Survey of Stellar Structure in Galaxies (S⁴G)

Sébastien Comerón*, Bruce G. Elmegreen, Johan H. Knapen, Heikki Salo, Eija Laurikainen, Jarkko Laine, E. Athanassoula, Albert Bosma, Kartik Sheth, Michael W. Regan, Joannah L. Hinz, Armando Gil de Paz, Karín Menéndez-Delmestre, Trisha Mizusawa, Juan-Carlos Muñoz-Mateos, Mark Seibert, Taehyun Kim, Debra M. Elmegreen, Dimitri A. Gadotti, Luis C. Ho, Benne W. Holwerda, Jani Lappalainen, Eva Schinnerer and Ramin Skibba

seb .comeron@gmail.com

***Korea Astronomy and Space Science Institute, 776 Daedeokdae-ro, Yuseong-gu, Daejeon 305-348, Republic of Korea**

Abstract

Most disk galaxies are thought to have a thin (classical) and a thick disk. Thick disks are in many models thought to be a necessary consequence of the disk formation and/or evolution. They are made of old stars and their origin is still a matter of debate.

We have integrated the equations of two stellar and one gaseous isothermal coupled disks in equilibrium for a grid of models with different mid-plane density ratios for the stellar disks (ρ_{0T}/ρ_{0t}) and velocity dispersion ratios in the z axis (σ_t/σ_T). Forty-six edge-on S⁴G galaxies have then been compared to that grid of models in order to deduce their disk properties. We have found that the stellar mass of thick disks is comparable to or larger than that in the thin disks for the galaxies in our sample. Our results suggest an *in situ* thick disk formation or a creation from stars stirred from giant star formation clumps during the epoch of peak star formation in the Universe. Our results are highly dependent on the assumed mass-to-light ratio of the thin and the thick disk (Υ_t and Υ_T), but we find that even if the thin and thick disk had the same mass-to-light ratio (Υ_t/Υ_T=1), the thick disk mass would be comparable or larger than that of the thin disks. We suggest that thick disks may contain part of the "missing baryons".

What is the S⁴G?

The Spitzer Survey of Stellar Structure in Galaxies (S⁴G; Sheth et al. 2010) is a survey made using the Spitzer Space Telescope's IRAC 3.6μm and 4.5μm images of 2331 galaxies meeting the following selection criteria:

- V_{radio} < 3000 km/s (D < 40 Mpc).
- m_{Bcorr} < 15.5 mag.
- D_{25} > 1.0 arcmin.
- |b| > 30°.

The S⁴G is especially well suited for tracing the underlying stellar population of galaxies as it is not strongly affected by dust. In addition, its surface brightness sensitivity of $\mu_{3.6\mu m}$(AB) ~ 27 mag arcsec^{-2} is unprecedentedly deep for such a large number of galaxies. Thus, the S⁴G is ideal for studying the vertical distribution of stellar mass in edge-on galaxies down to very low luminosity levels.

The fitting procedure

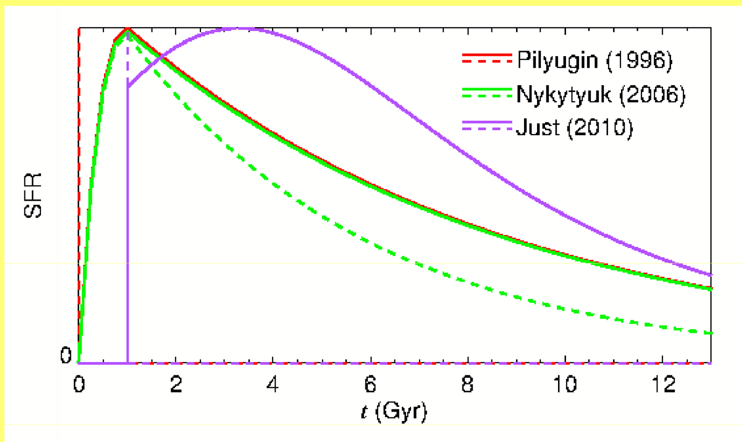
We have solved the equations of two stellar and one gaseous isothermal coupled disks for a grid of models with different ρ_T/ρ_t and σ_T/σ_t:

- $d^2\rho_i/d^2z = -4G\pi\rho_i(\rho_t+\rho_T+\rho_g)/\sigma^2_i + (1/\rho_i)(d\rho_i/dz)^2$

where *t*, *T*, and *g* stand for the thin, the thick and the gaseous disks and *i* can be either *t*, *T*, or *g*. We then transformed the mass distribution into a light distribution by assuming a ratio of the mass-to-light ratios of the thin and the thick disk (Υ_T/Υ_t). The resulting luminosity profiles were then scaled to have a mid-plane luminosity equal to one and to have a luminosity equal to 0.1 at z=200. They were then compared to observed luminosity profiles which had been scaled the same way. The best fitting synthetic profile was chosen by using a least squares fitting method.

A caveat: which Υ_T/Υ_t should we use?

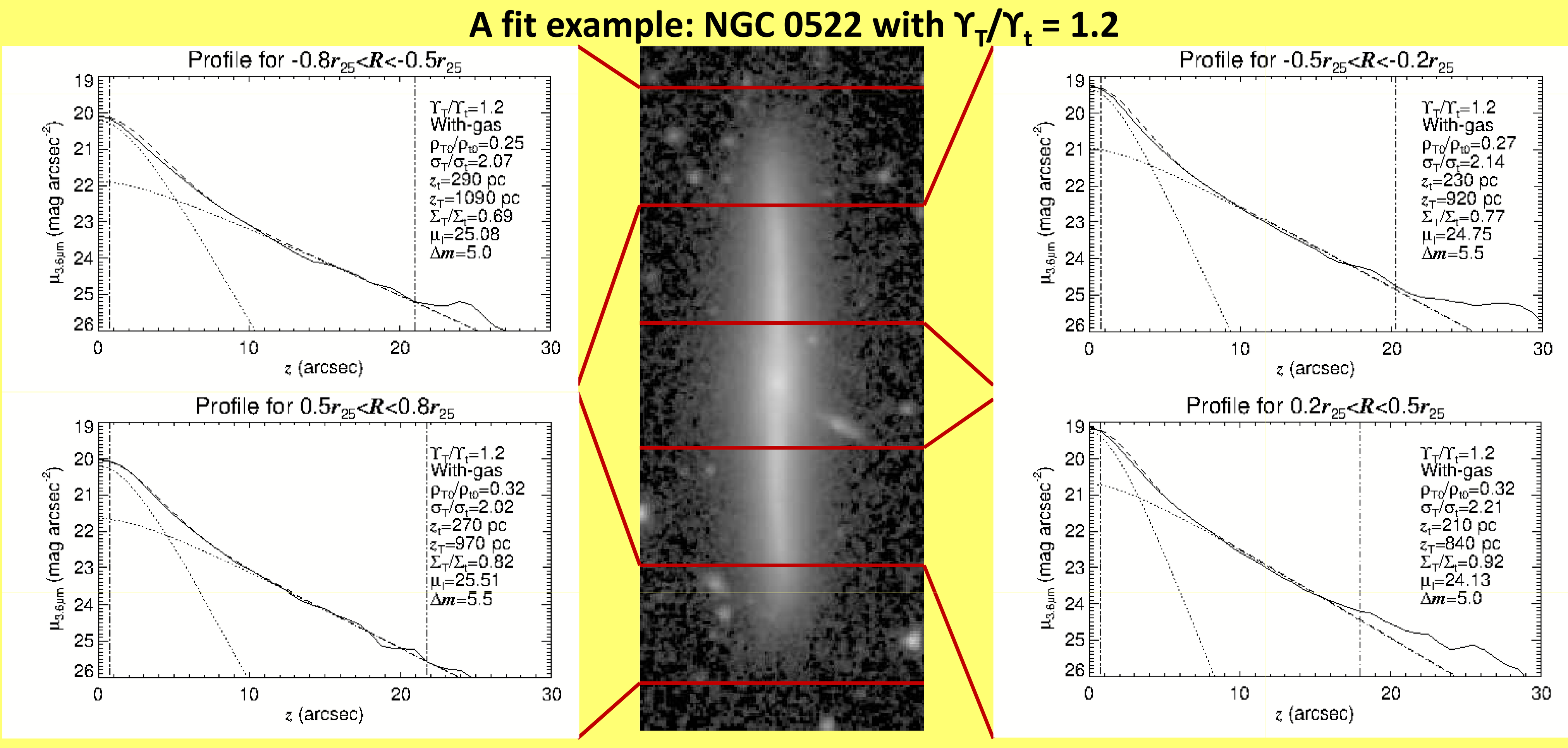
The main caveat in our process is the assumption of a given Υ_T/Υ_t. We searched for star formation (SF) histories of the two disks of the Milky Way in the literature and we computed the 3.6μm Υ_T/Υ_t they would yield using synthetic spectra made with Bruzual & Charlot (2003) libraries. When using the SF history from Pilyugin & Edmunds (1996; Pi96 in the plot below) we obtained Υ_T/Υ_t = 2.4, when using that from Nykytyuk & Mishenina (2006; Ny06) we obtained Υ_T/Υ_t = 1.2 and when using that from Just and Jahreiβ (2010; Ju10) we obtained Υ_T/Υ_t = 2.4. We thus see a large variation in Υ_T/Υ_t when using Milky Way SF histories from different papers.



Four thick disk formation mechanisms in literature

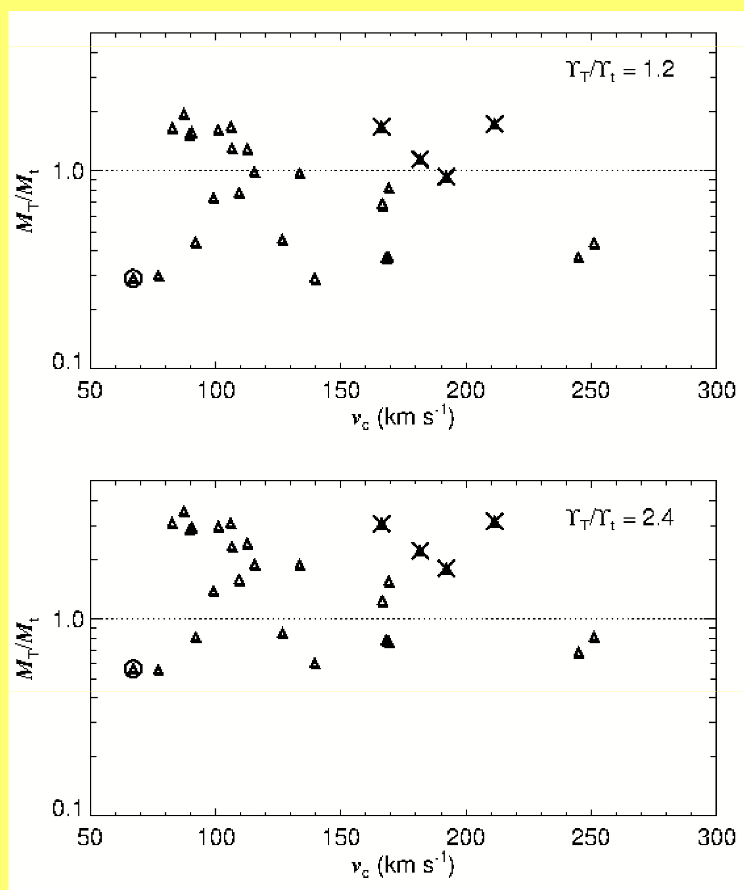
1) **Thin disk internal heating:** dynamical heating of a thin disk by its own overdensities (giant molecular clouds, spiral arms…). This mechanisms would create a thick disk with at maximum 30% of the thin disk mass (Bournaud et al. 2009).
2) **Thin disk external heating:** dynamical heating of a thin disk by having it crossed by dwarf galaxies and/or dark matter subhaloes. This mechanism would create substantial flares (Bournaud et al. 2009).
3) **Thick disk forms first:** thick disks form originally thick at high redshift and a thin disk is formed afterwards within them (Elmegreen & Elmegreen 2006; Brook et al. 2007).
4) **Thick disk from tidally stripped material:** Thick disks formed from tidally stripped stars. The mass of a thick disk formed through this mechanism would be on the order of 10% of the thin disk mass and would leave dynamical signatures (Read et al. 2008).

A fit example: NGC 0522 with Υ_T/Υ_t = 1.2



The continuous lines correspond to the real luminosity profiles, the dashed lines correspond to the fitted synthetic luminosity profiles and the dotted lines correspond to the thin and the thick disk. The vertical lines represent the limits of the fitting region.

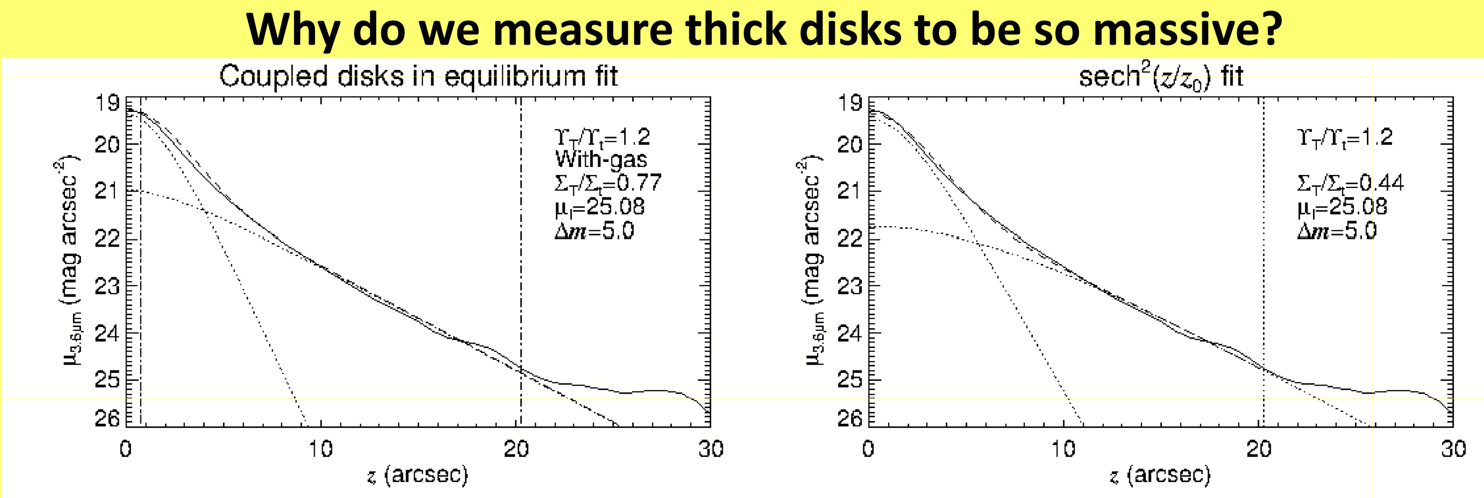
Thick to thin disk mass ratios (M_T/M_t)



We calculated M_T/M_t for each galaxy and have plotted it against v_c which is the maximum circular velocity. Once the galaxies with an X-shaped bulge are removed (indicated with an X in the plots) we reproduce the M_T/M_t – v_c trend found by Yoachim & Dalcanton (2006).

We found that 40% of the galaxies have a stellar thick disk more massive than the thin disk if Υ_T/Υ_t = 1.2 (top panel). The fraction goes up to 70% if we consider Υ_T/Υ_t = 2.4 (lower panel). This in sharp contrast with previous studies in which the stellar mass of the thin disk are usually larger than that of the thick disk.

Why do we measure thick disks to be so massive?



Many previous studies fit the luminosity profiles with a sum of sech²(z/z_0) functions. As seen in the plots above, this approach assigns some of the light of the thick disk to the thin disk. This is because the sech²(z/z_0) function is more rounded close to z=0 than the fitting functions we have used. As the fitting functions we used are physically motivated and not *ad hoc* analytical approaches to the problem we think our results are the most accurate so far.

Discussion and conclusions

We find that the stellar mass of thick disks is comparable to or larger than that of the thin disks for the galaxies in our sample. We also found that disks do not usually flare significantly. The only thick disk formation mechanism able to yield these thick disk masses is an *in situ* thick disk formation at high redshift.

Since thick disk masses have been historically underestimated and their light has been assigned to thin disks which have lower *M/L* we argue that part of the missing baryons at a galactic scale is found in thick disks.

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