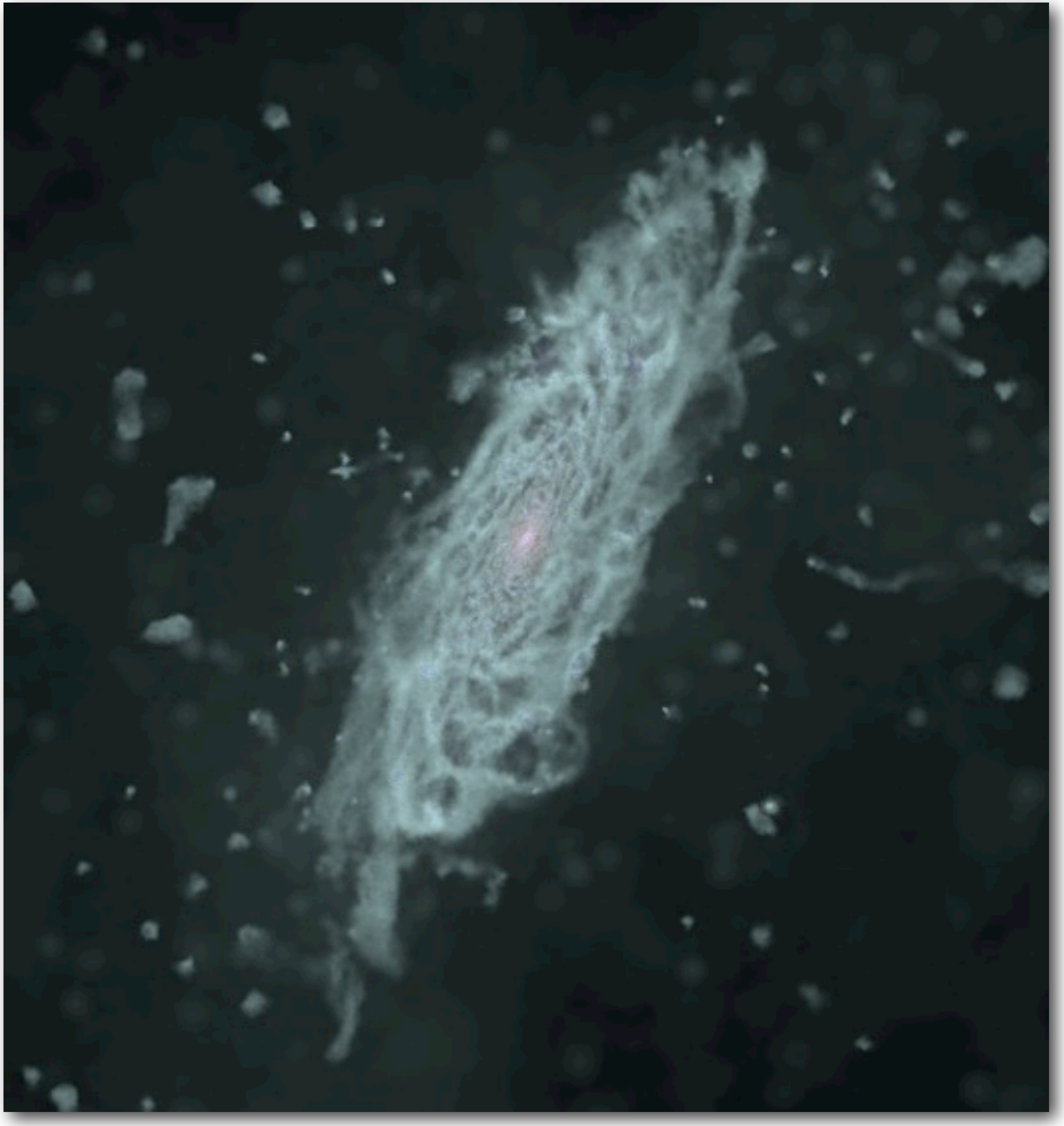
Ερις

The soldiers fought like wolves while Eris, the Lady of Sorrow, watched with pleasure. -- The Iliad



Javiera Guedes
Simone Callegari
Annalisa Pillepich
Sijing Shen
Michael Kuhlen
Piero Madau
Lucio Mayer
Marcella Carollo
+ *Gasoline Community*

SC Galaxy Formation Workshop
August 17th, 2012

This talk is based on:

Guedes et al. 2011b
Shen, Madau, Aguirre, Guedes et al. 2012
Shen, Madau, Guedes et al. 2012
Kuhlen, Guedes, et al. 2012 (in prep)
Guedes et al. 2212 (in prep)

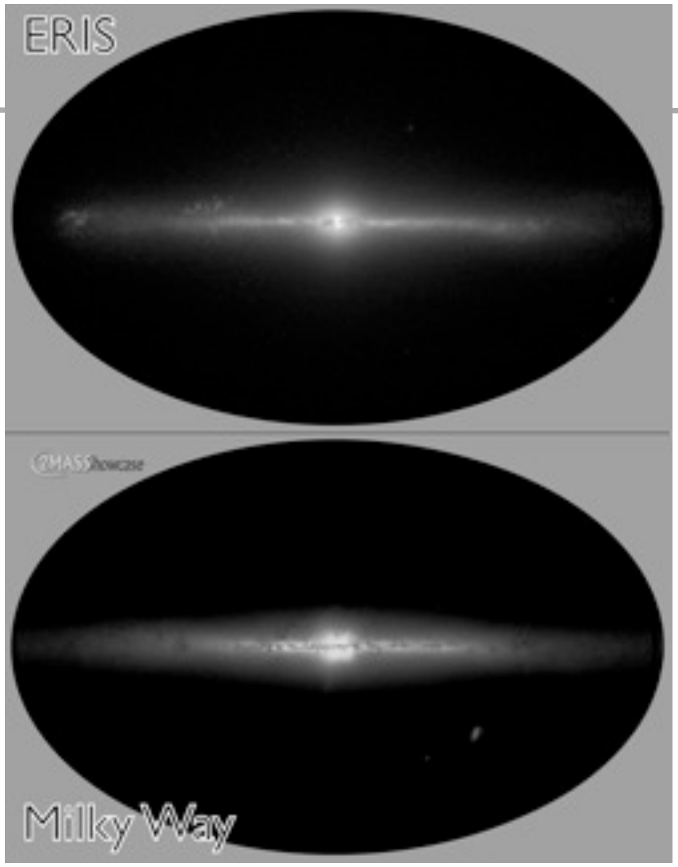
Philosophy

Is it possible to produce a realistic Milky Way-like galaxy in a fully cosmological context?

✳ Quality over quantity: we simulate ***one*** spiral galaxy at very high resolution, and at a very high computational cost.

✳ Follow the star formation recipe that produced the bulgeless dwarf of Governato et al. 2010, .i.e. high SF threshold.

What do we mean by "realistic"?



> "Be skeptical of your simulation until you prove yourself wrong."
> -- *Fabio Governato at HIPACC summer school*

✳ Tully-Fisher relation
✳Rotation curve
✳SF History
✳K-S relation
✳M_{star} - M_{halo} relation
✳Cold gas mass

✳B/D ratio
✳Angular momentum distribution
✳Dispersion measure (hot halo gas)
✳Surface brightness breaks
✳The size of HI holes in the gaseous disk
✳Outflows / CGM

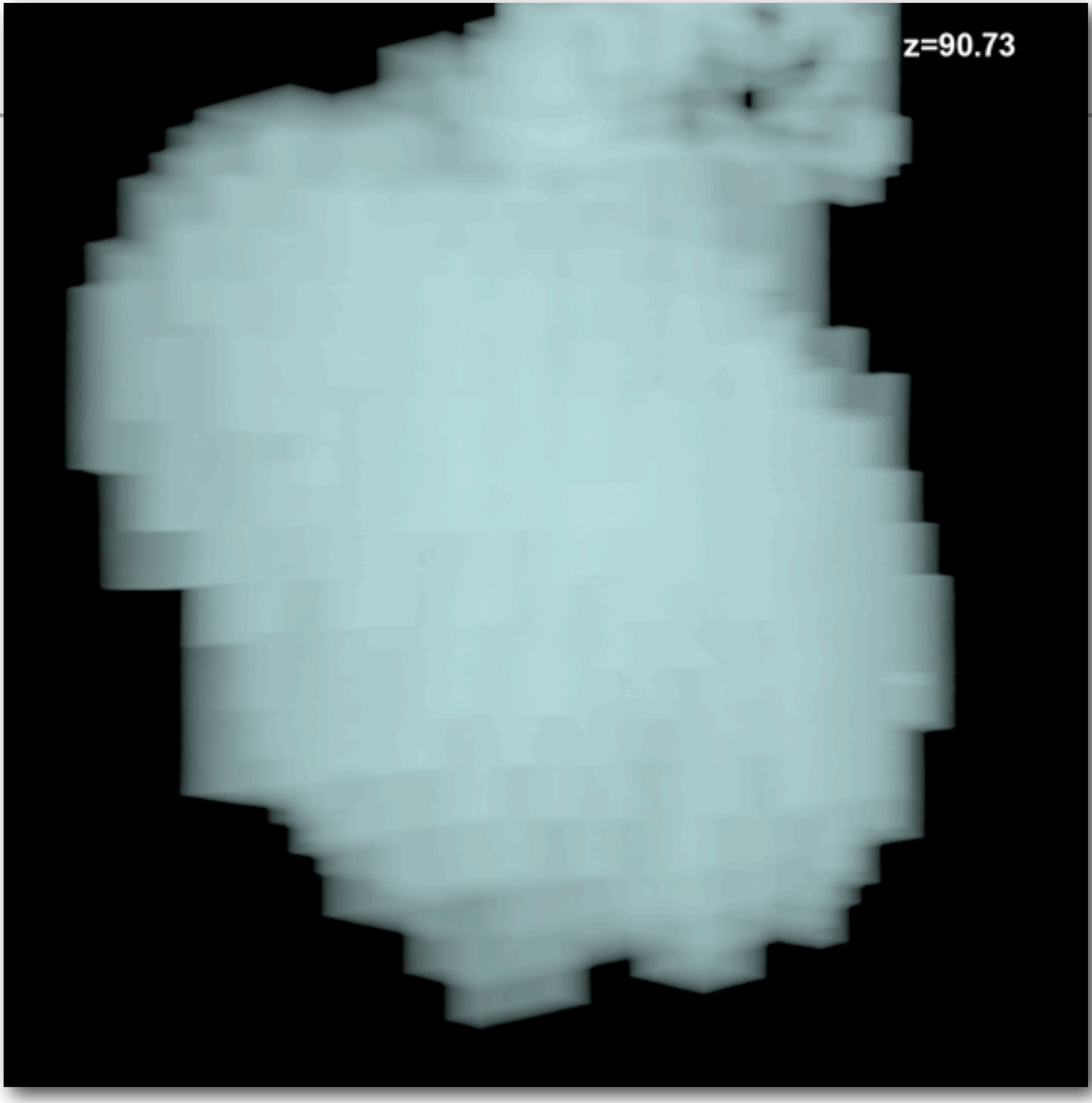
What can we learn?

✳ Formation mechanisms of the major components of the galaxy: bulge, disk, bar, thick disk, stellar halo.

✳Predictions: Observability of cold flows around MW-sized galaxies, dark halo shape, dark disk formation, offset in the DM annihilation signal.

✳Evolution, redistribution of stellar populations due to e.g. stellar migration.

ERIS: The Basics



✳ Eris is a product of **GASOLINE.**

✳ Follows the formation of a light Milky Way galaxy of mass
$M_{vir} = 8x10^{11}\ M_{sun}$

✳ Selected to have a quiet merger history. No mergers larger than 1:10 after z=3.

✳High mass and spatial resolution: 18.6 million particles within the virial radius. ε_G=120 pc.

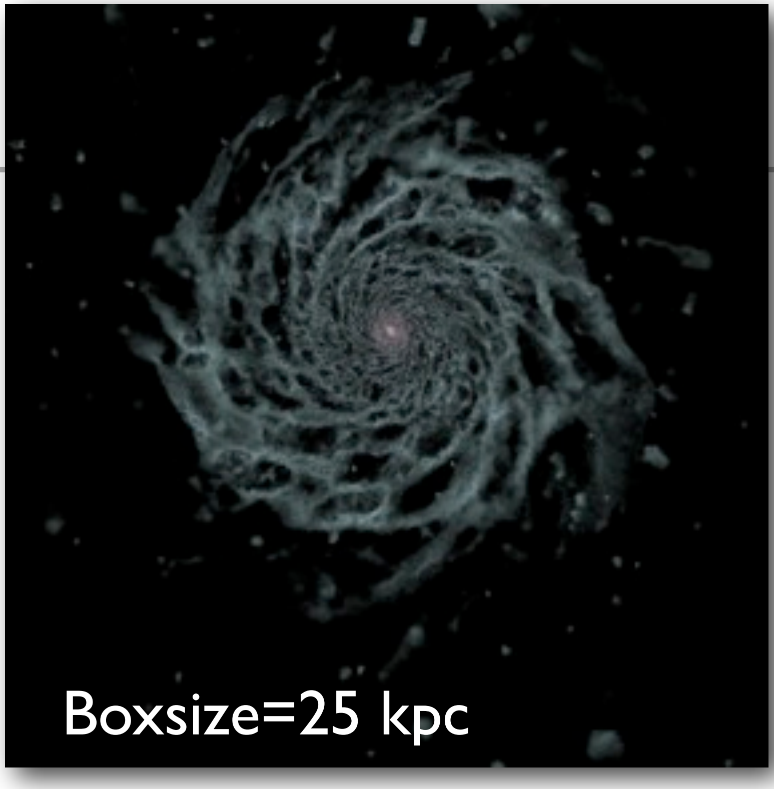
✳ Physics: lowT metal dependent gas cooling, UVB heating, SN Type Ia and Type II thermal feedback. No explicit wind prescriptions.

✳ High SF gas density threshold:
nSF=5 atoms cm^{-3}

✳ Expensive: 9 months at NASA Pleiades and Rosa Cray using 512 cores.

What is missing: High Temperature metal cooling, H_2 star formation (see Charlotte Christensen's talk), metal diffusion, stellar radiation, AGN. Some of these ingredients are included in ongoing new simulations.

Eris: The Basics



	M_{vir} [$10^{12}M_{sun}$]	V_{sun} [km/s]	M* [$10^{10}M_{sun}$]	f_b	B/D	R_d [kpc]	M_i	SFR [M_{sun} yr^{-1}]
Eris	0.79	206	3.9	0.12	0.35	2.5	-21.7	1.1
MW	1±0.2	221±18	4.9-5.5	?	0.33	2.3±0.6	?	0.68-1.45

	N	ε [kpc]	m_{dark} [10^4 M_{sun}]	m_{gas} [10^4 M_{sun}]	n_{SF} [cm^{-3}]
Eris (Guedes et al. 2011b)	18.6 M 3M+7M+8.6M (gas+dark+star)	0.12	9.8	2	5
Brooks et al. 2010 (h258)	2.8 M	0.35	1200	21	0.1
Scannapieco et al. 2009, 2010	1 M	0.7-1.4	2600	56	0.05

Gasoline: Star Formation Recipe

Galaxy	$M_{\rm vir}$	$V_{\rm peak}$	M_*	f_b	$f_{\rm cold}$
Eris ($z = 0$)	7.9	238	3.9	0.121	0.12
Eris ($z = 1$)	5.4	237	2.9	0.126	0.40
ErisLT ($z = 1$)	5.5	308	3.4	0.158	0.18

The K-S relation of each particle:

$$\frac{d\rho_*}{dt} = \frac{\epsilon_{\rm SF}\rho_{\rm gas}}{t_{\rm dyn}} \propto \rho_{\rm gas}^{1.5} \qquad \rho > \rho_{\rm thres}$$

SN feedback (blast-wave):

$$E_{\rm SN} = \epsilon_{SN} \times 10^{51}\,{\rm erg\,s^{-1}}$$

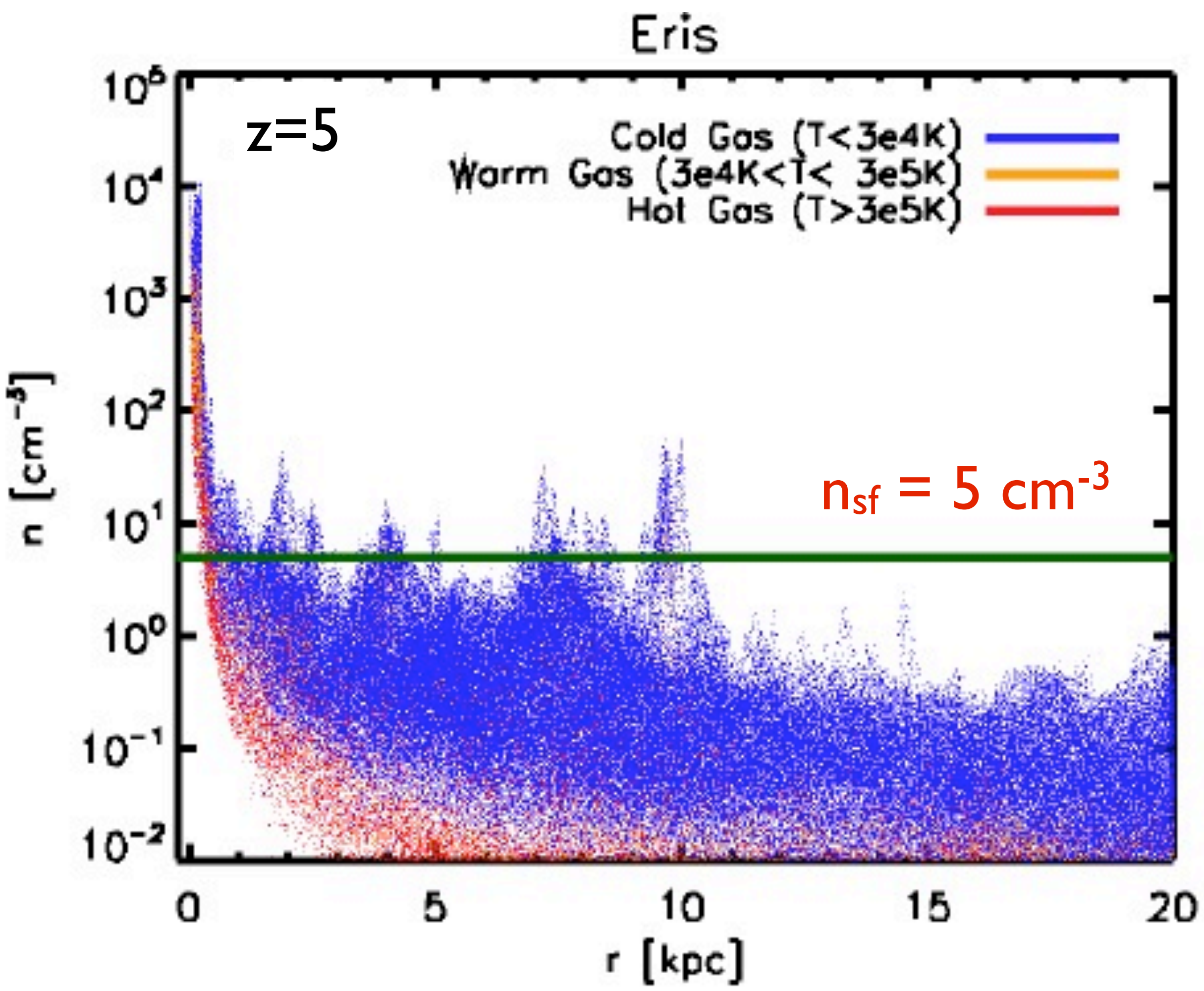
$$\tau_{\rm off} \sim 0.5\ \epsilon_{\rm SN}^{0.31}\ {\rm Myr}$$

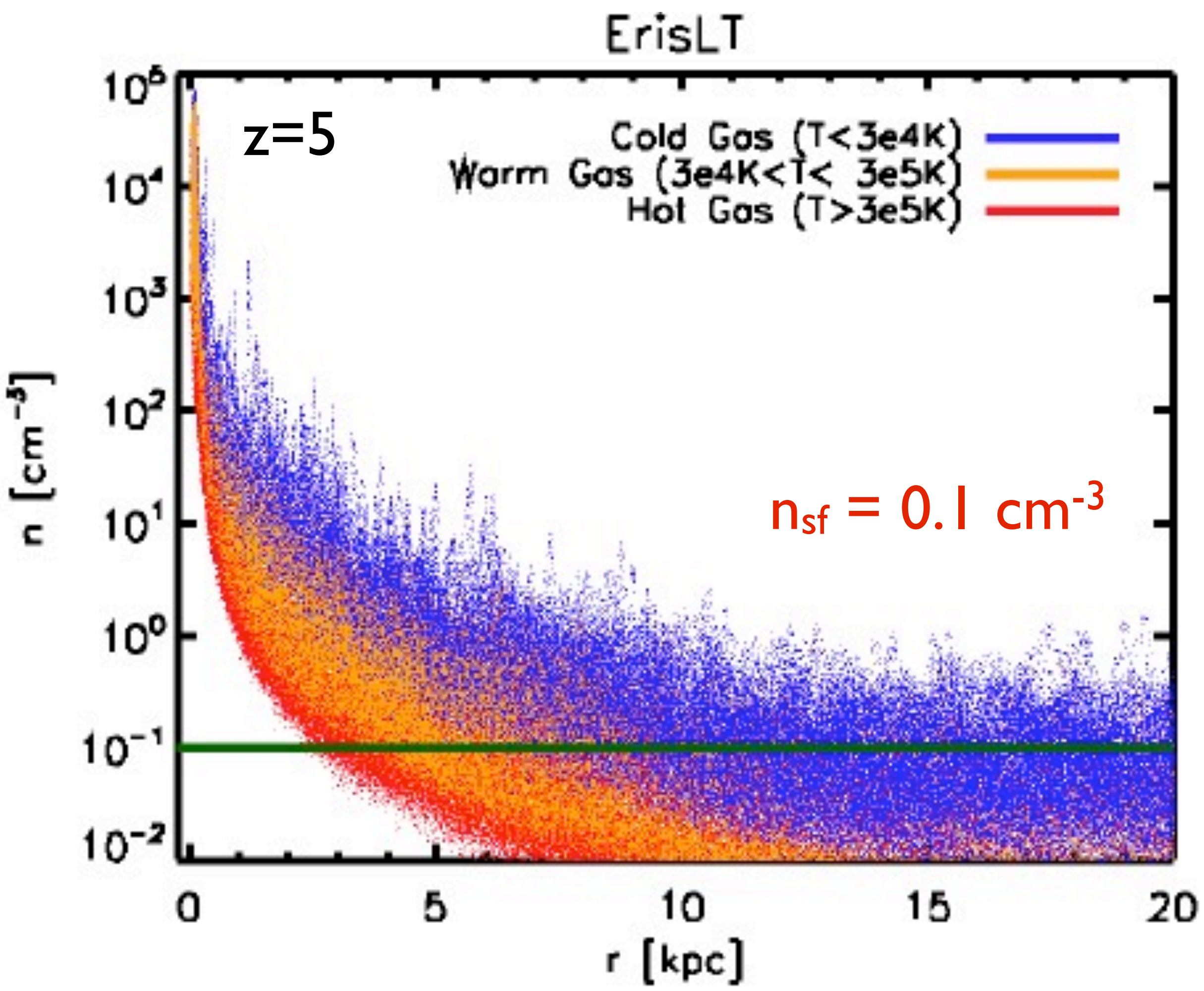
In reality, stars form in cold high-density H_2 clouds that sit at the peaks of the HI distribution.

$$\Sigma_{\rm SFR} \propto \Sigma_{\rm H2}^{1.0\pm0.2}$$

Bigiel et al. 2008

$$\frac{{\rm N_{new*}}}{{\rm m_{gas}}} \propto \sqrt{n_{\rm SF}}$$

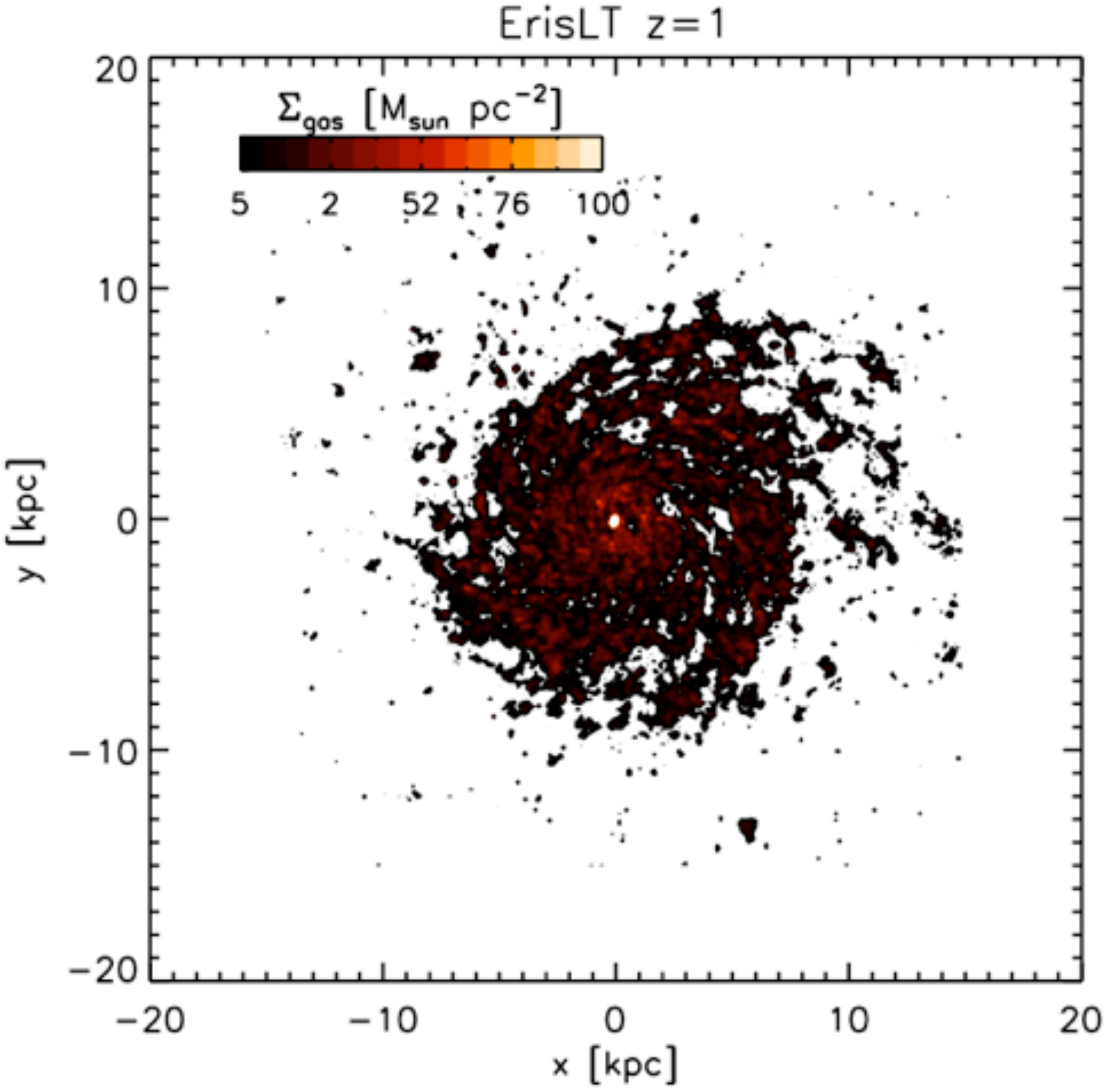


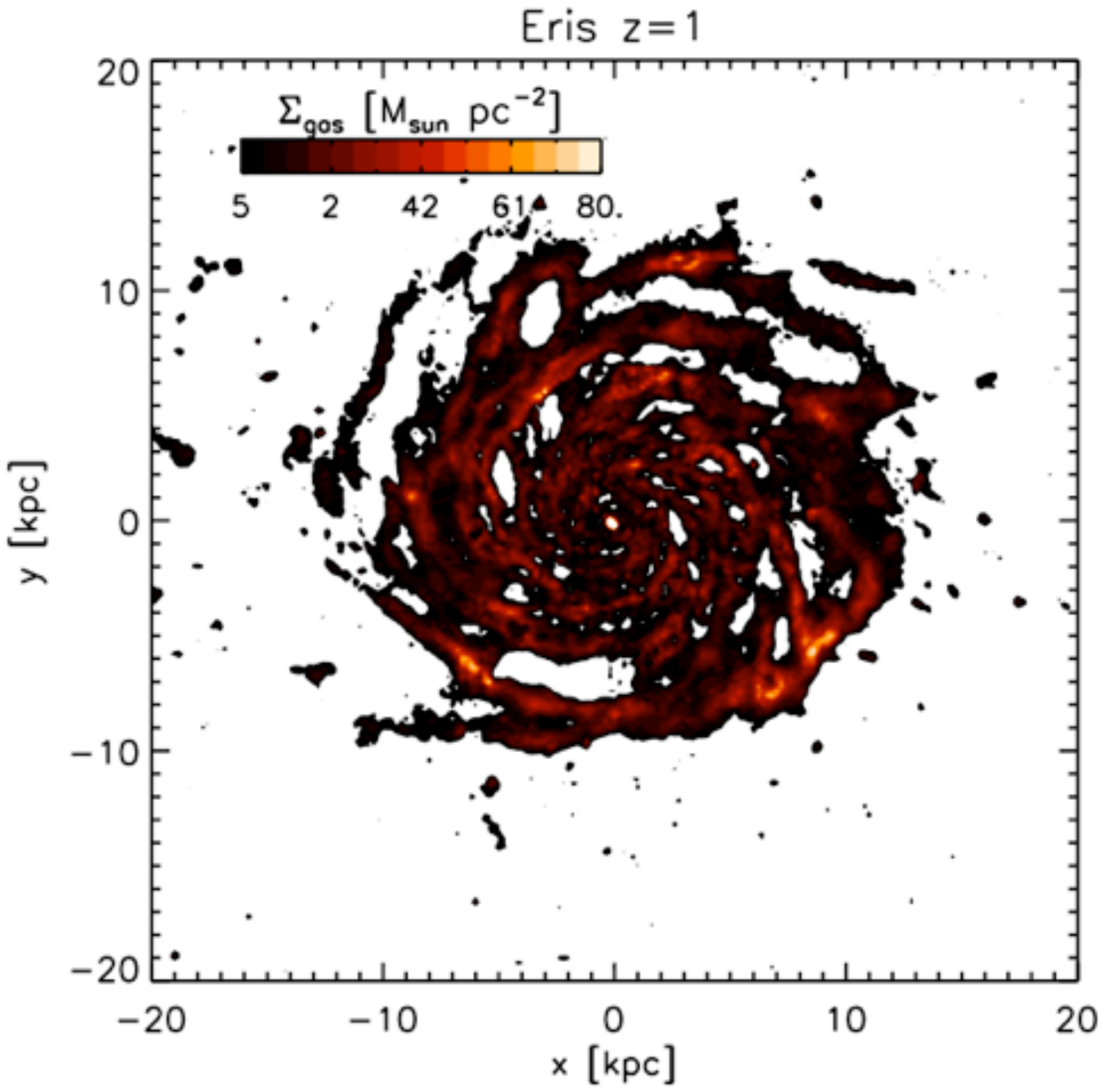


Low vs. high star formation threshold

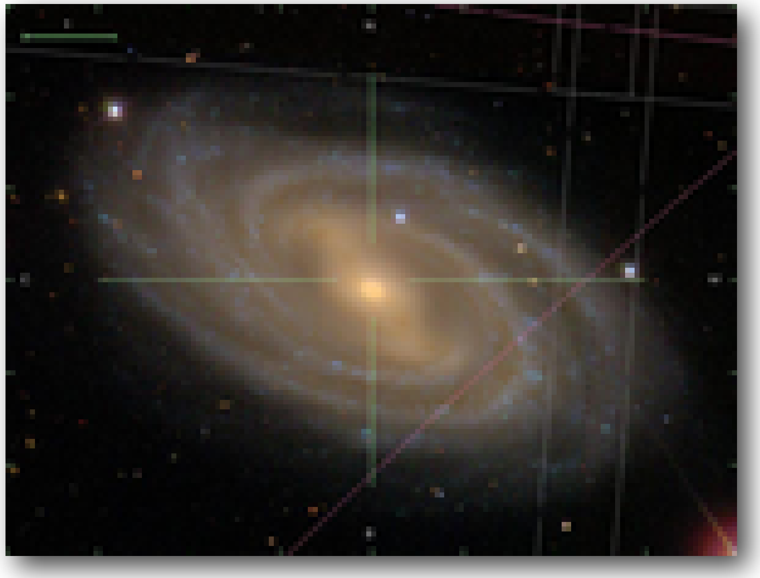
With higher threshold, Eris’ disk at z=2 is

50% larger
30% less massive
30% higher gas fraction
5x lower density at r < 1 kpc

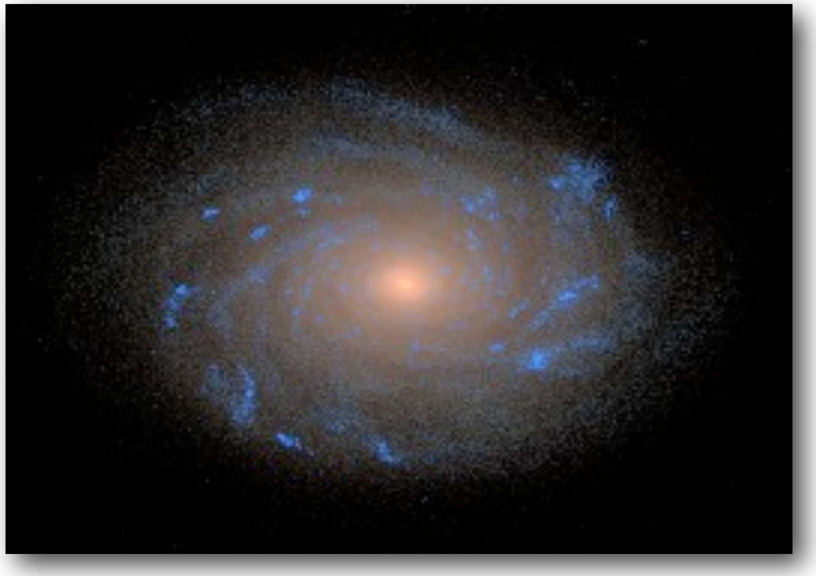




Comparison To Observations



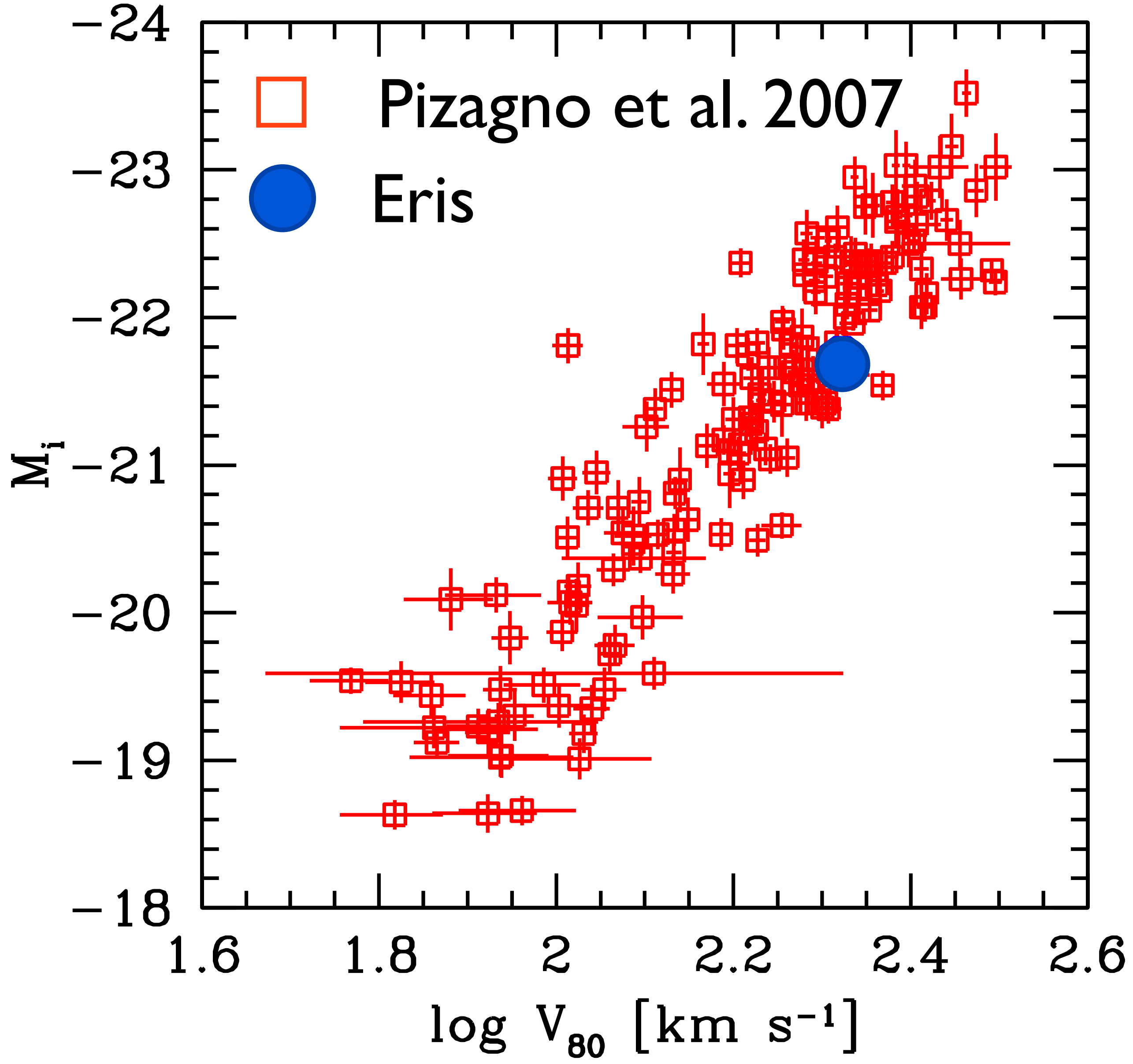
Real

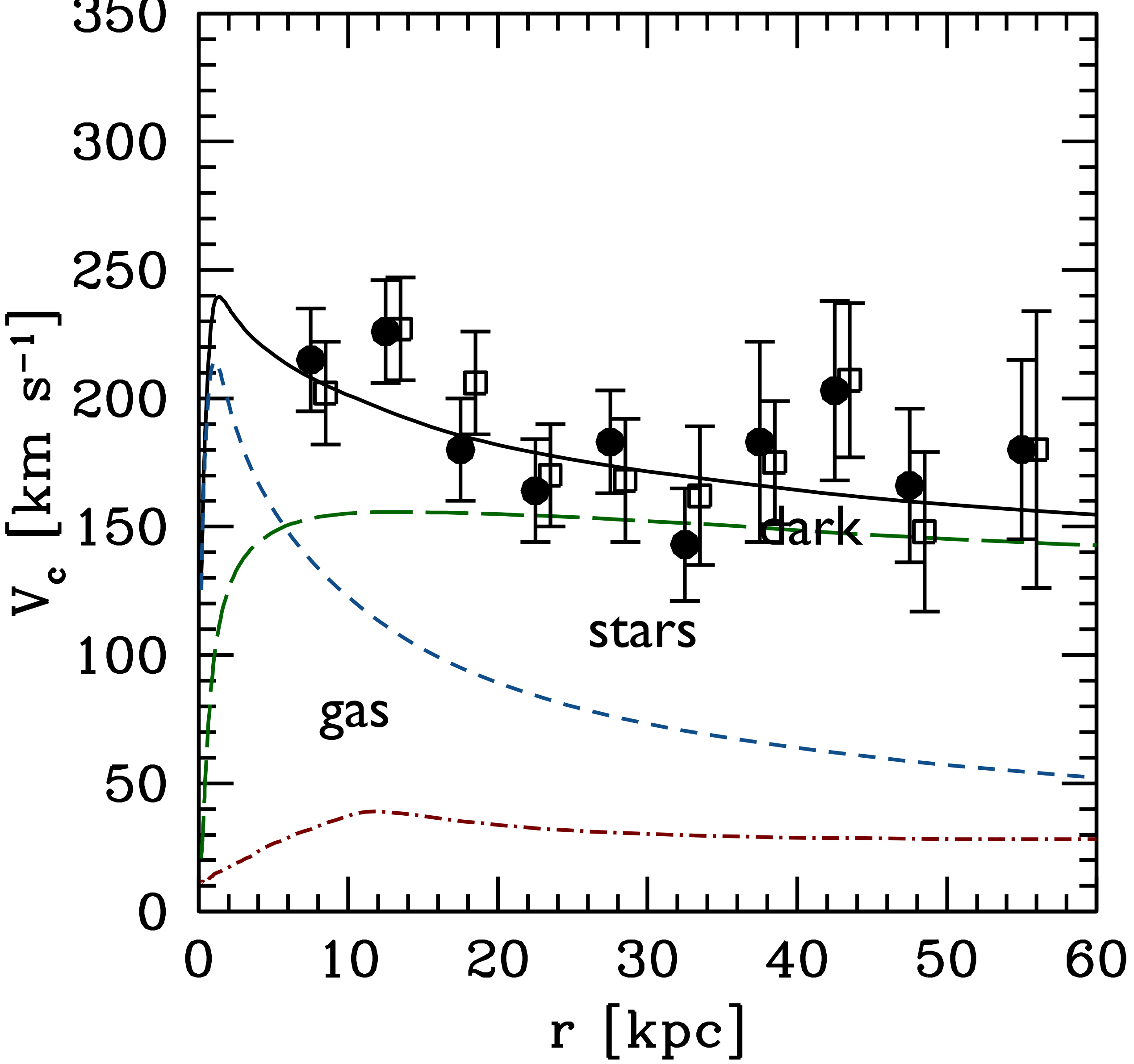


Realistic

Mass and Light Distribution

Tully-Fisher Relation and rotation curve: the distribution of the stellar mass in the galaxy is in agreement with observed nearby spirals.

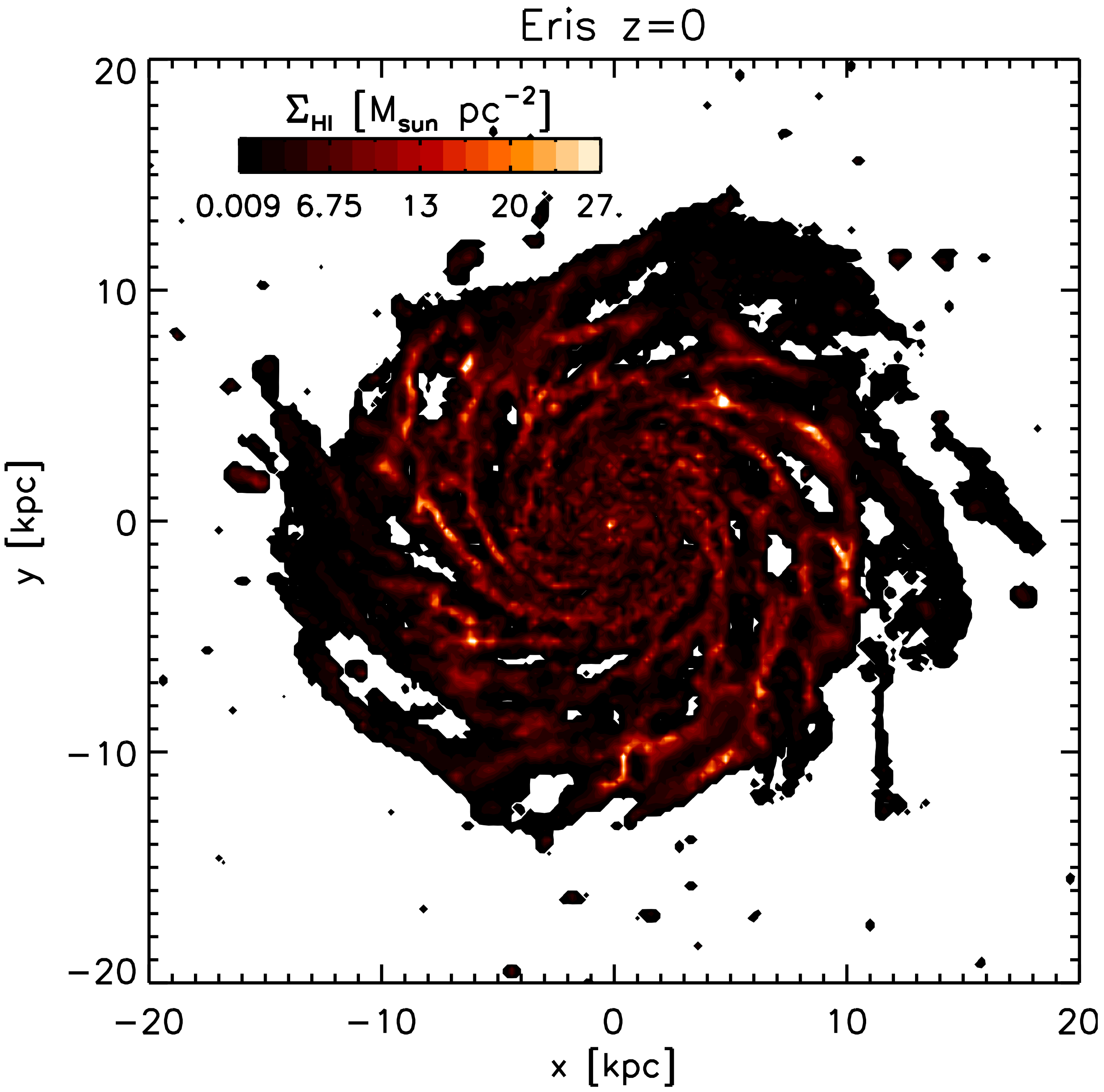


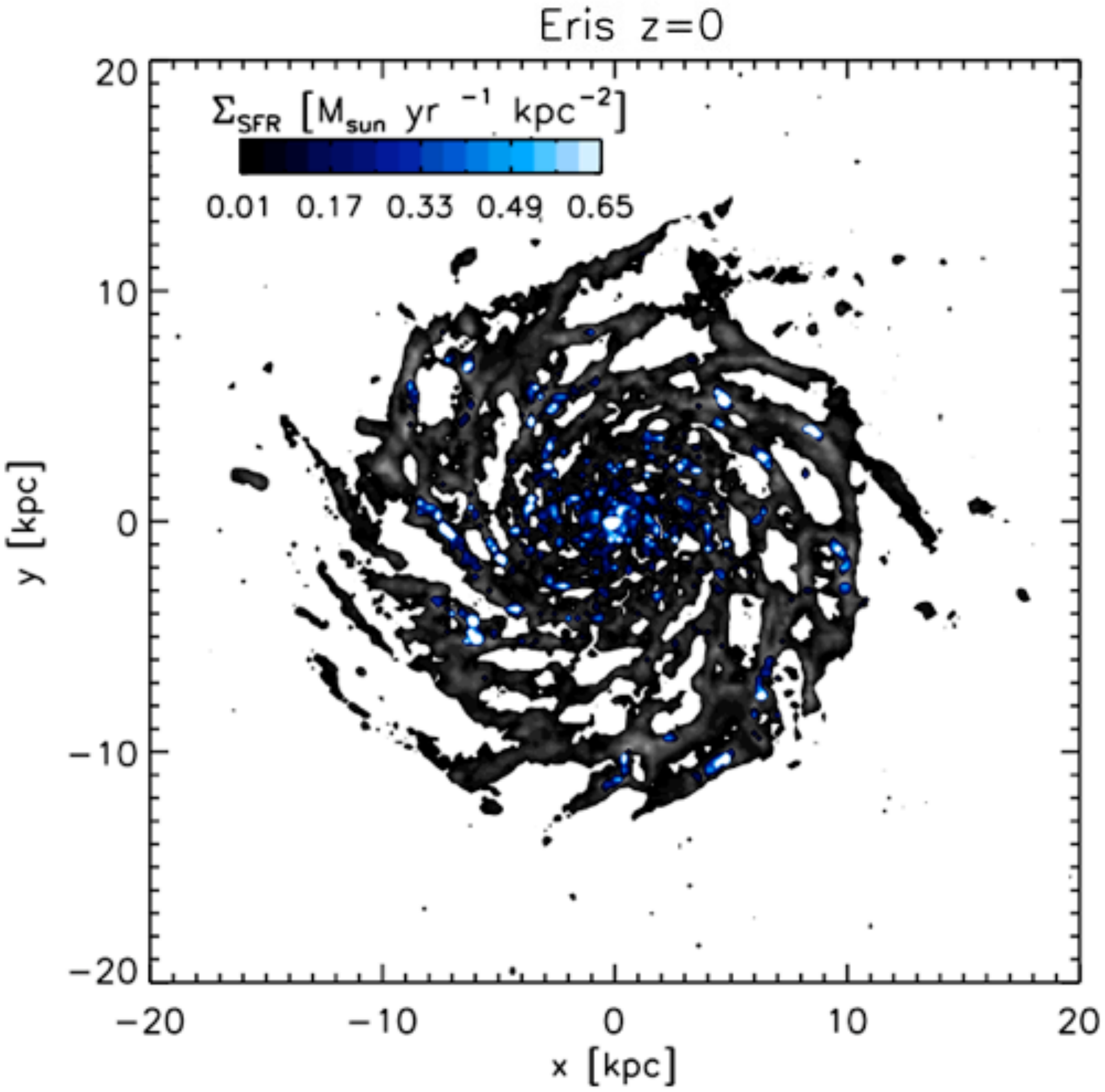


data points from SDSS blue HB stars (Xue et al. 2008)

Gas Content and Star Formation

Star formation occurs at the peaks of the HI distribution.

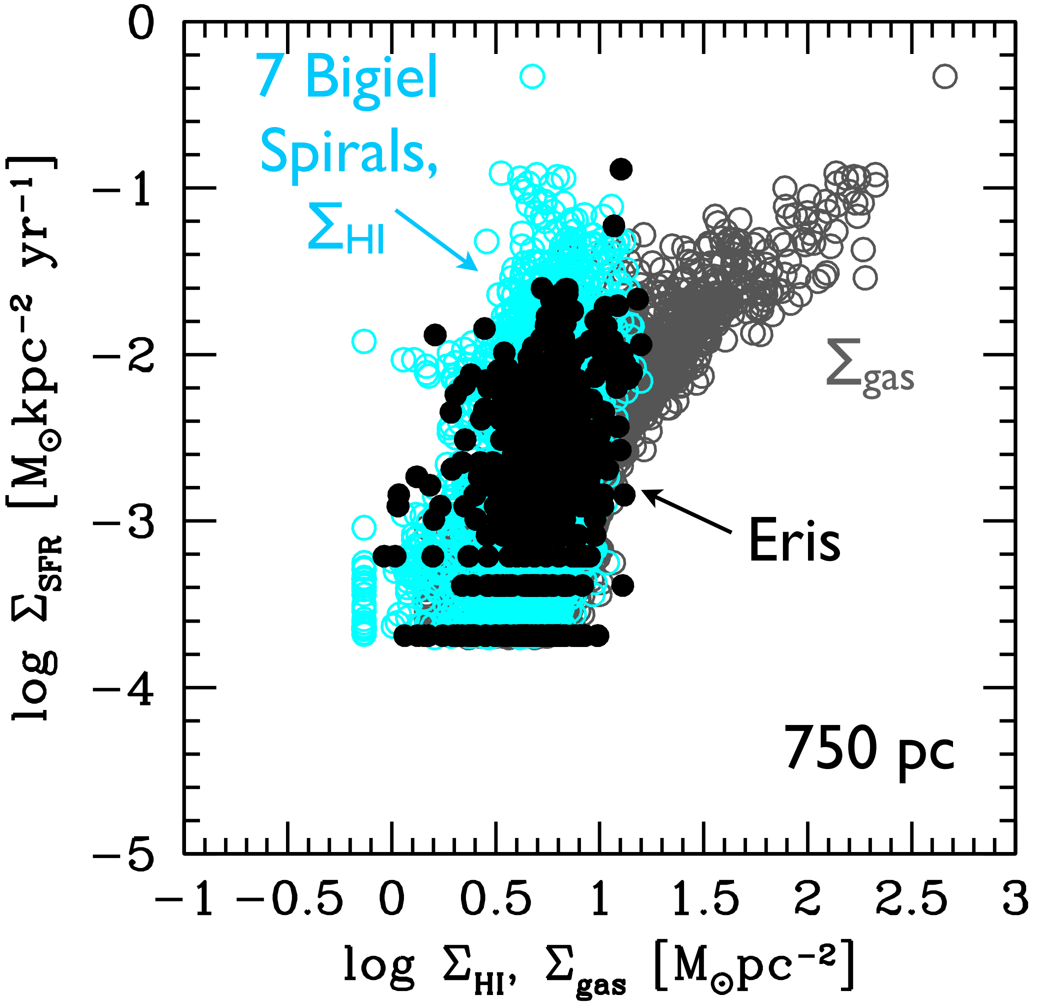


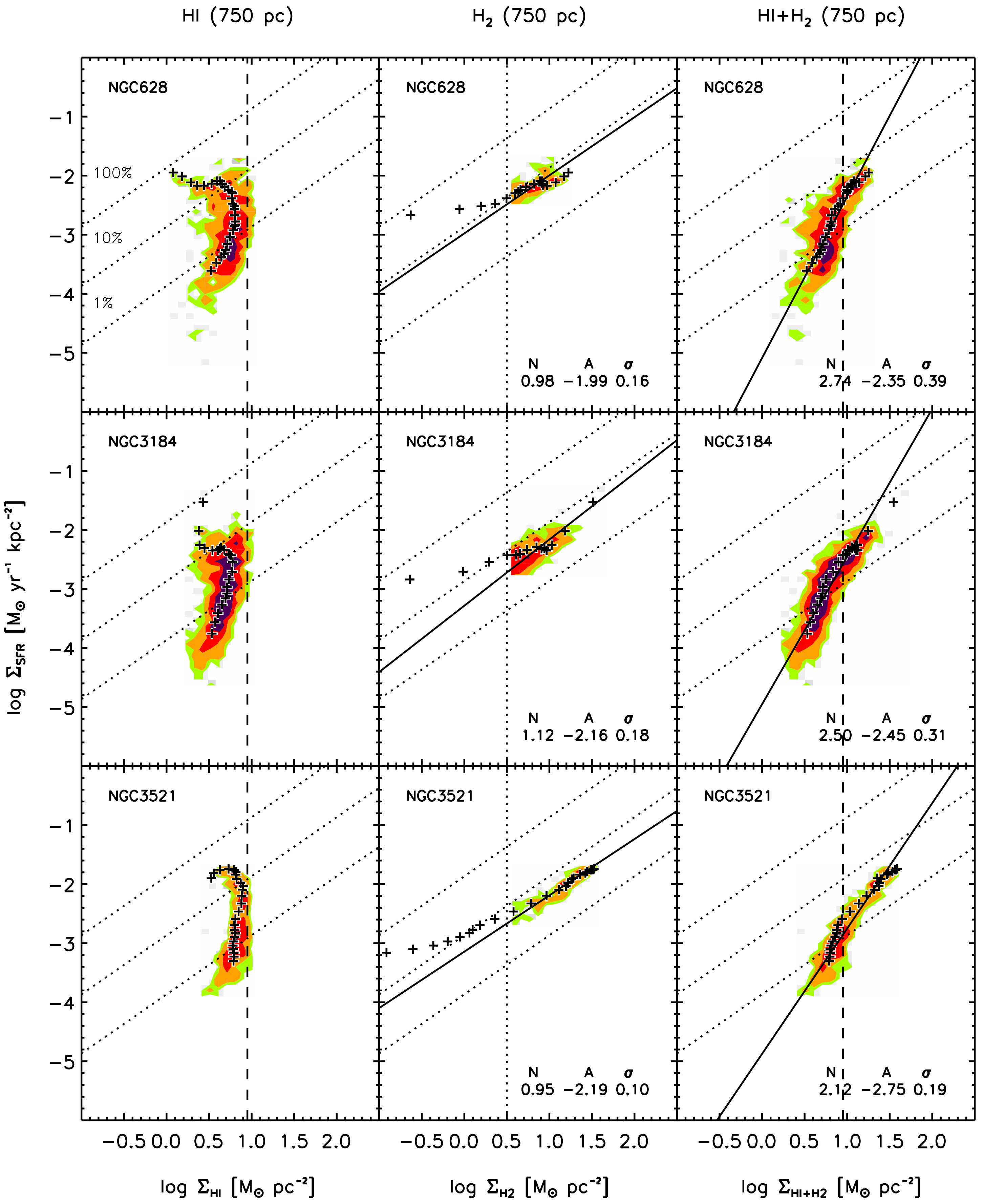


Gas Content and Star Formation: K-S Relation

Star formation rate as a function of surface density of HI (left), H2 (middle), and gas (right) from Bigiel et al. 2008.

- ✳No correlation between Σ_{SFR} and Σ_{HI}.
- ✳Strong correlation between Σ_{SFR} and Σ_{H2}.
- ✳At high densities, gas is mostly molecular.
- ✳No H2 in the simulations, in fact we kill the high-density regions by forming stars at a threshold density.
- ✳Yet, we match the observed Σ_{SFR}-Σ_{HI} data.





Structural Properties: Bulge-to-Disk Ratio

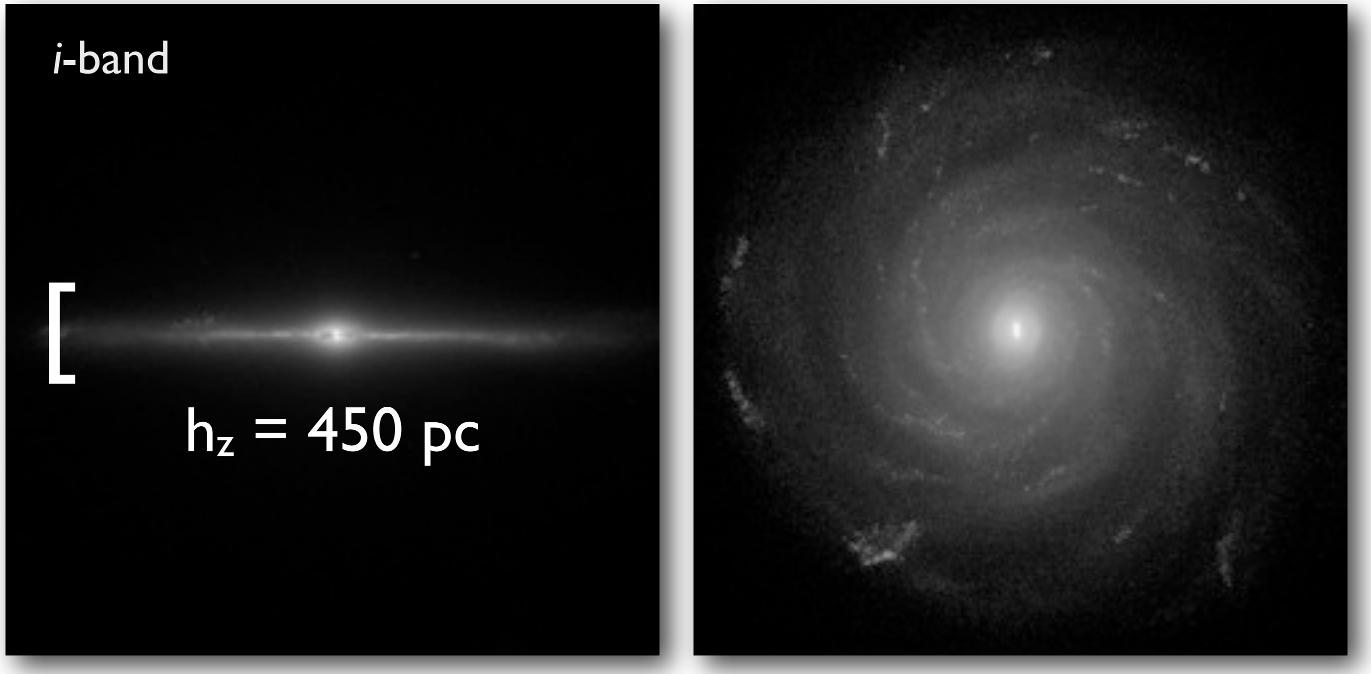
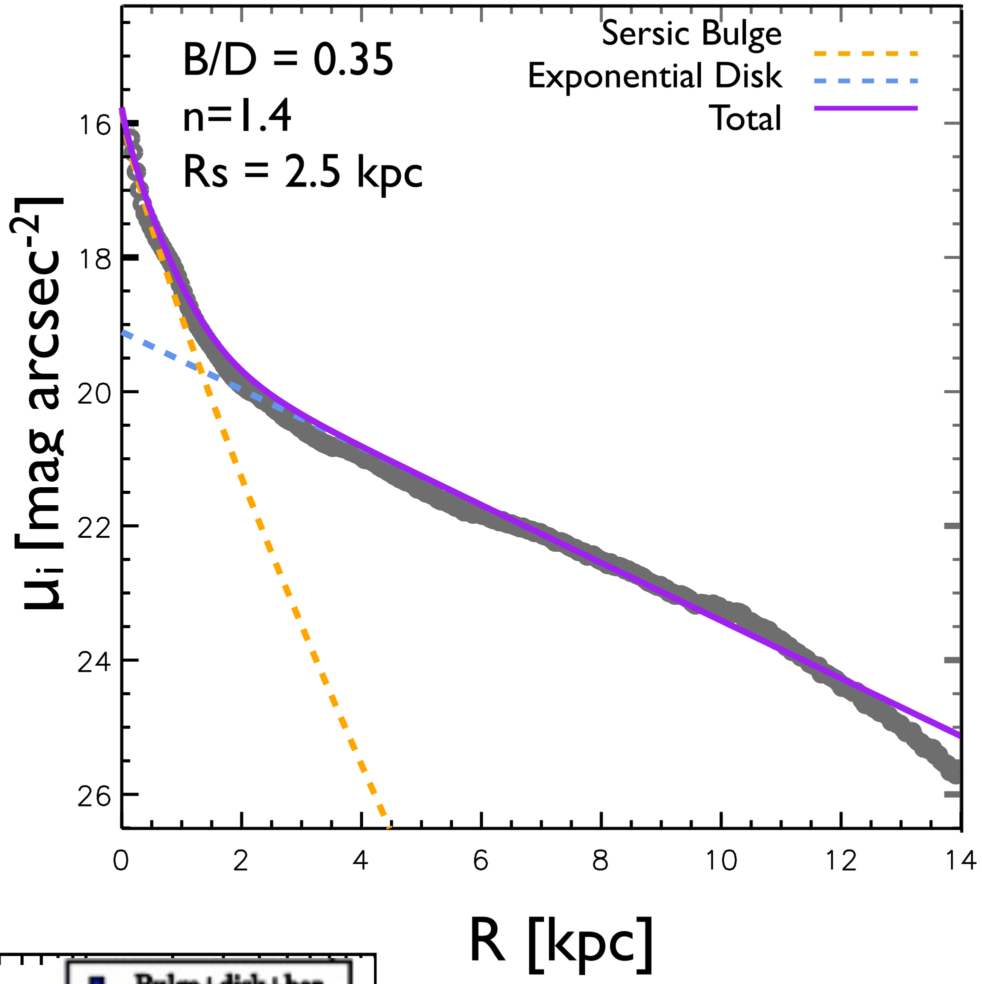
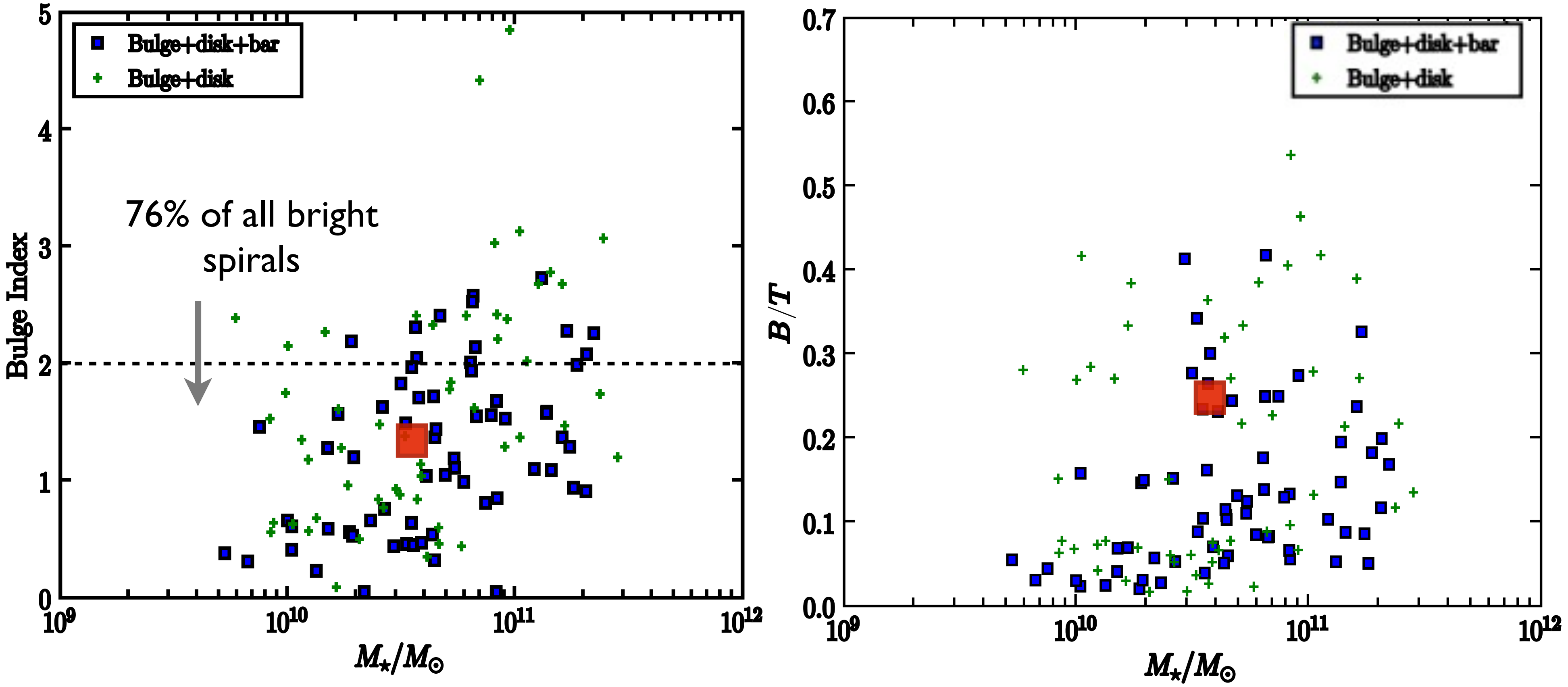


Image produced using SUNRISE (Jonsson et al. 2006)



Weinzirl et al. 2009

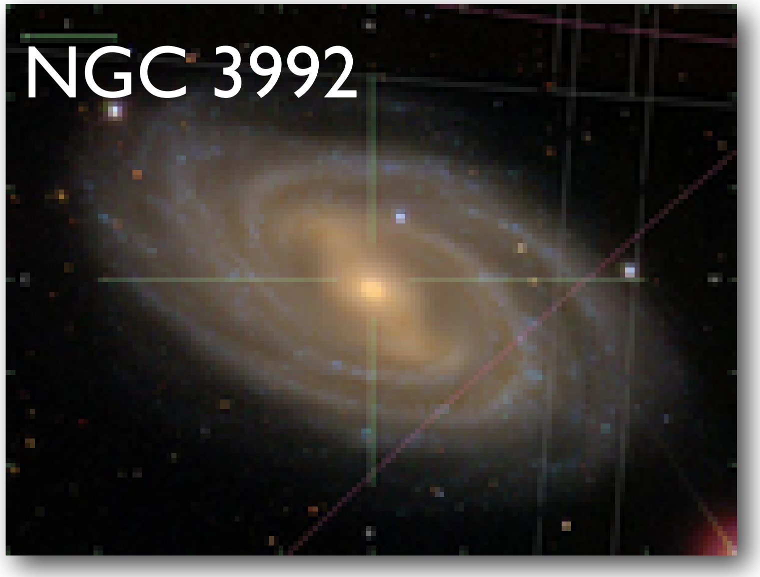


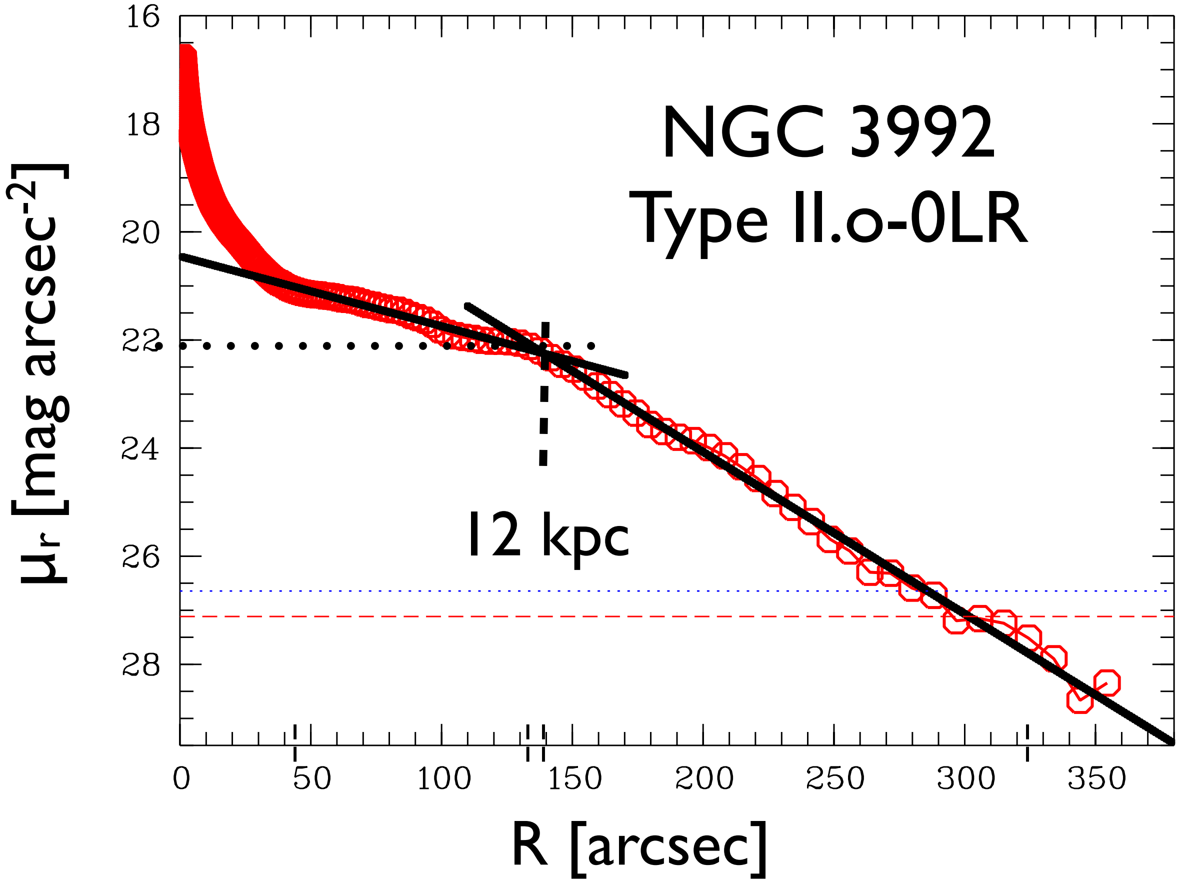
Photometric decomposition in i-band using Galfit (Peng et al. 2002)

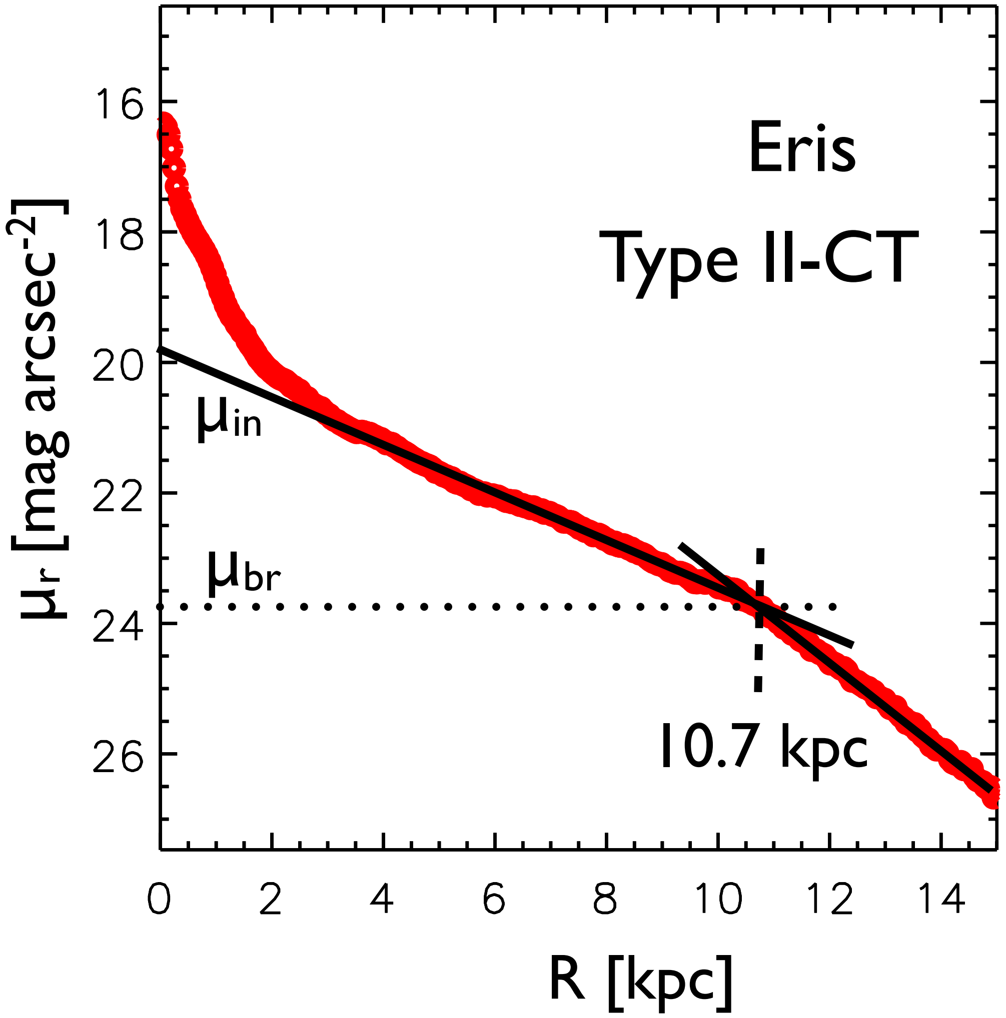
🟥 Eris

Structural Properties: Galactic Disk

Pohlen & Trujillo 2006

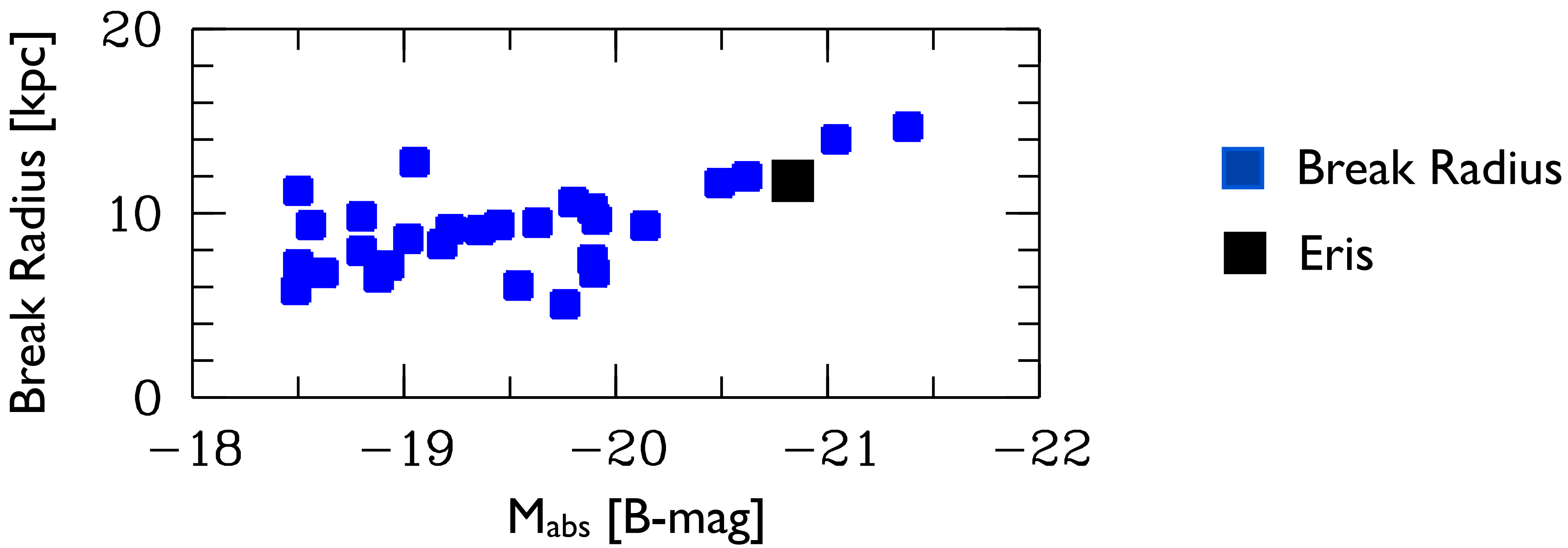


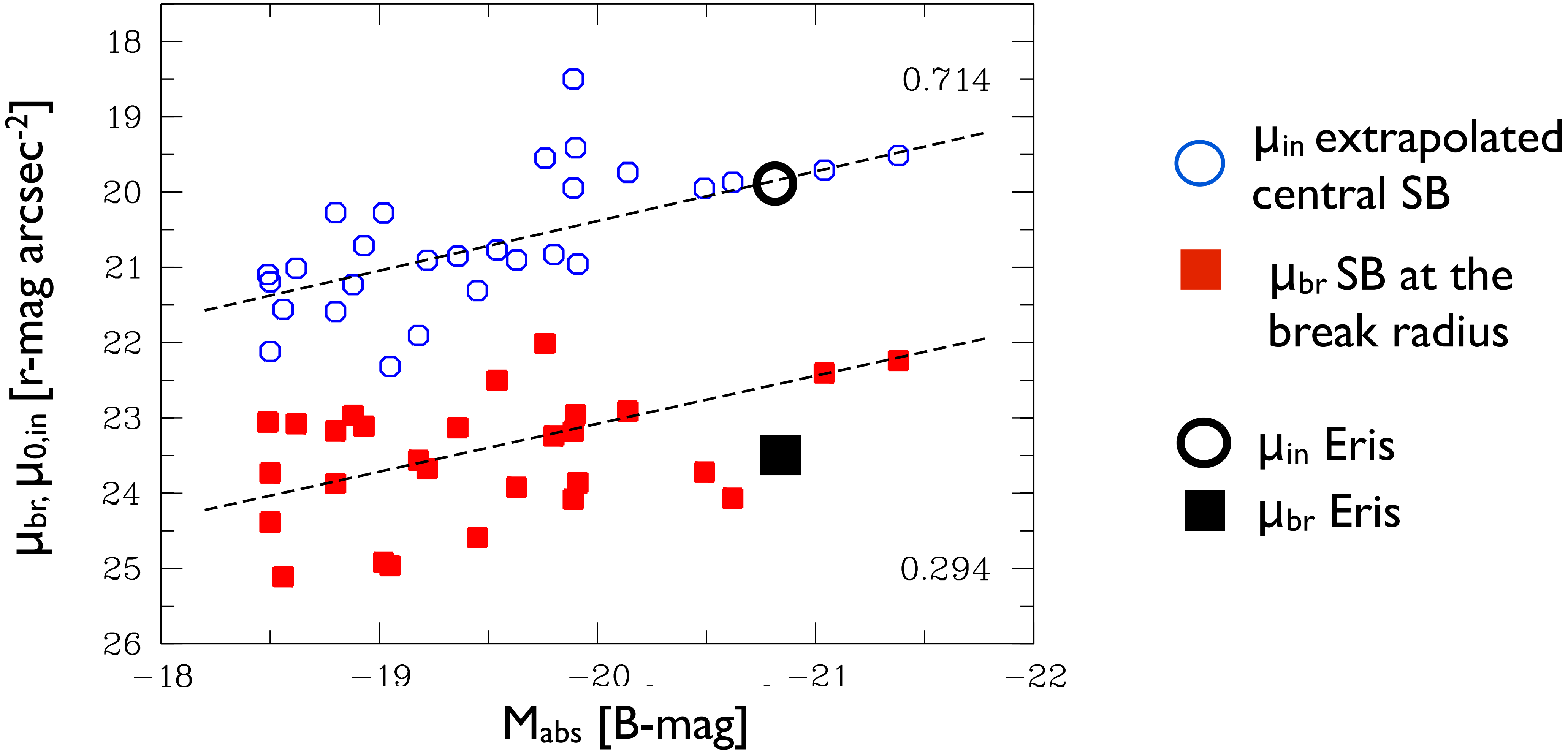




Structural Properties: Galactic Disk

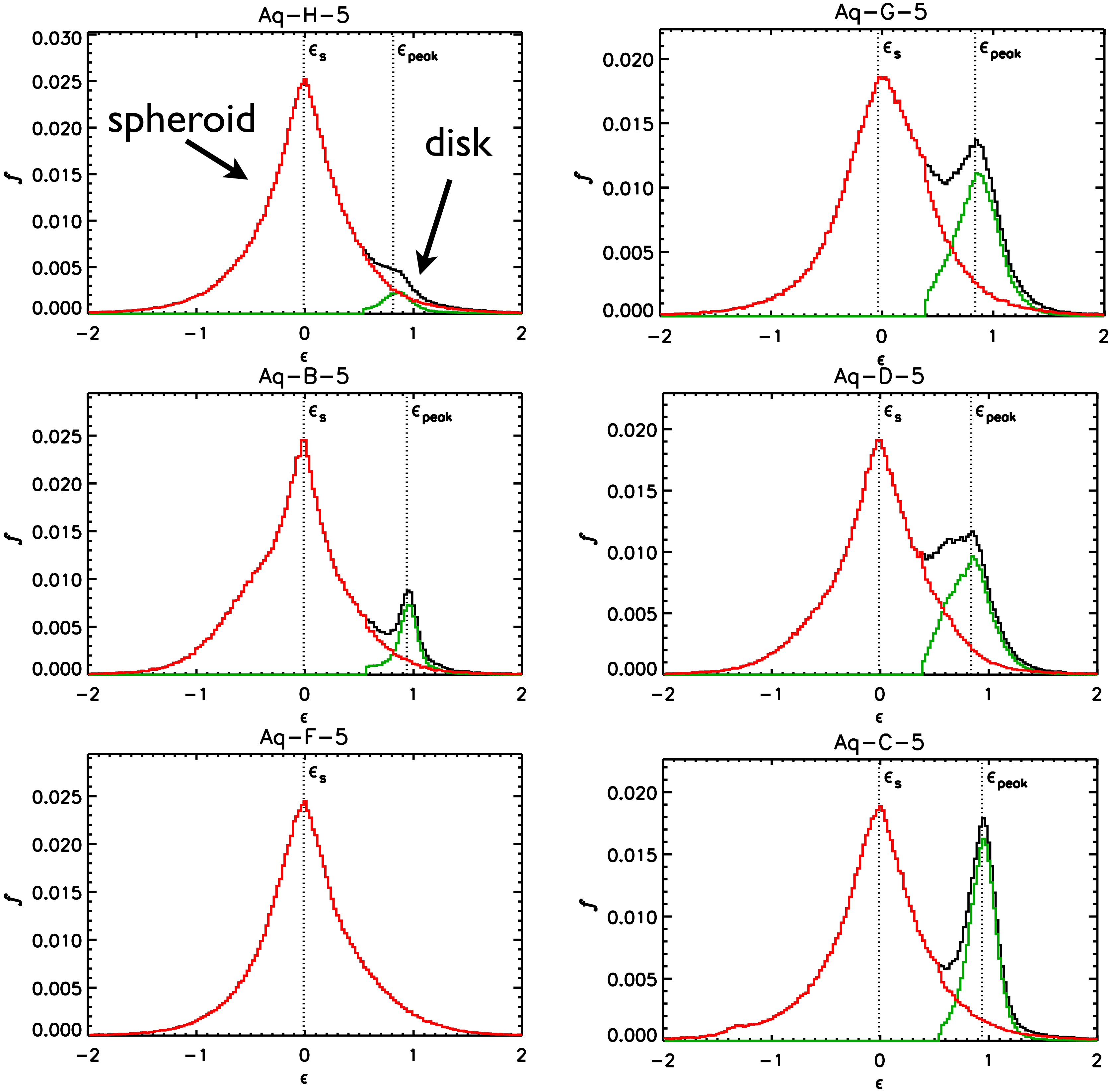
Pohlen & Trujillo 2006





Structural Properties: Kinematic Decomposition

A simple kinematic decomposition can be used to identity the disk and spheroid component (Scannapieco et al. 2009)


Aq−H−5

Aq−G−5

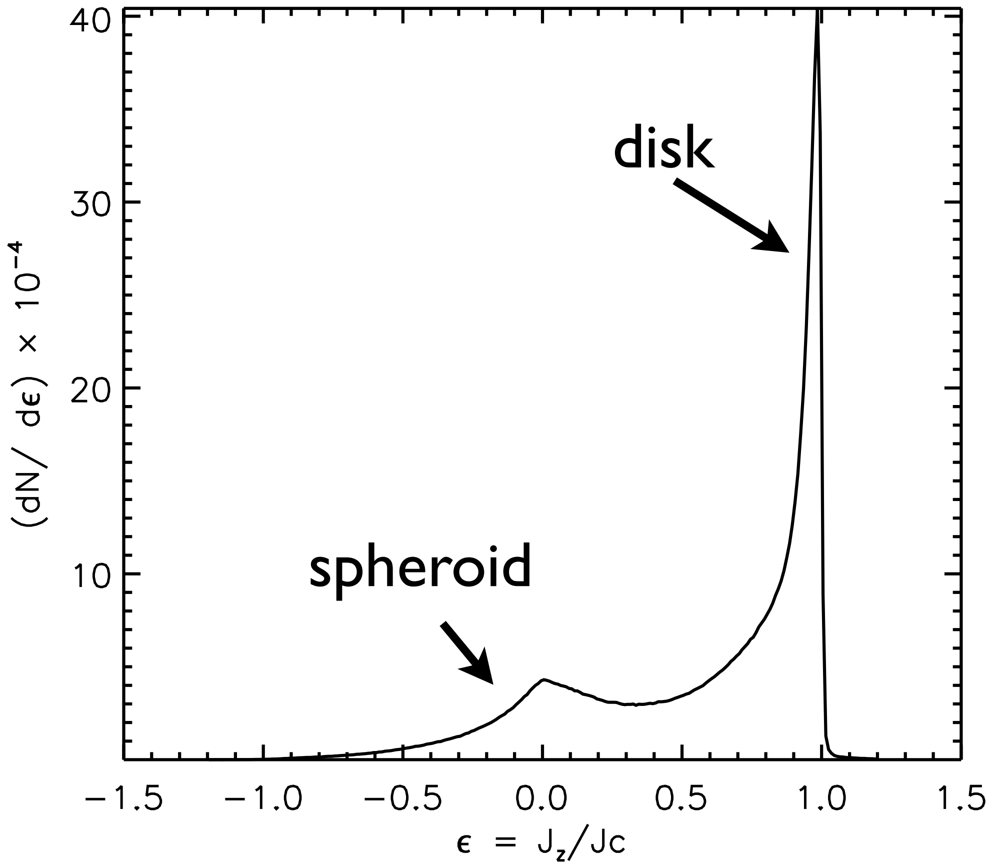
Aq−B−5

Aq−D−5

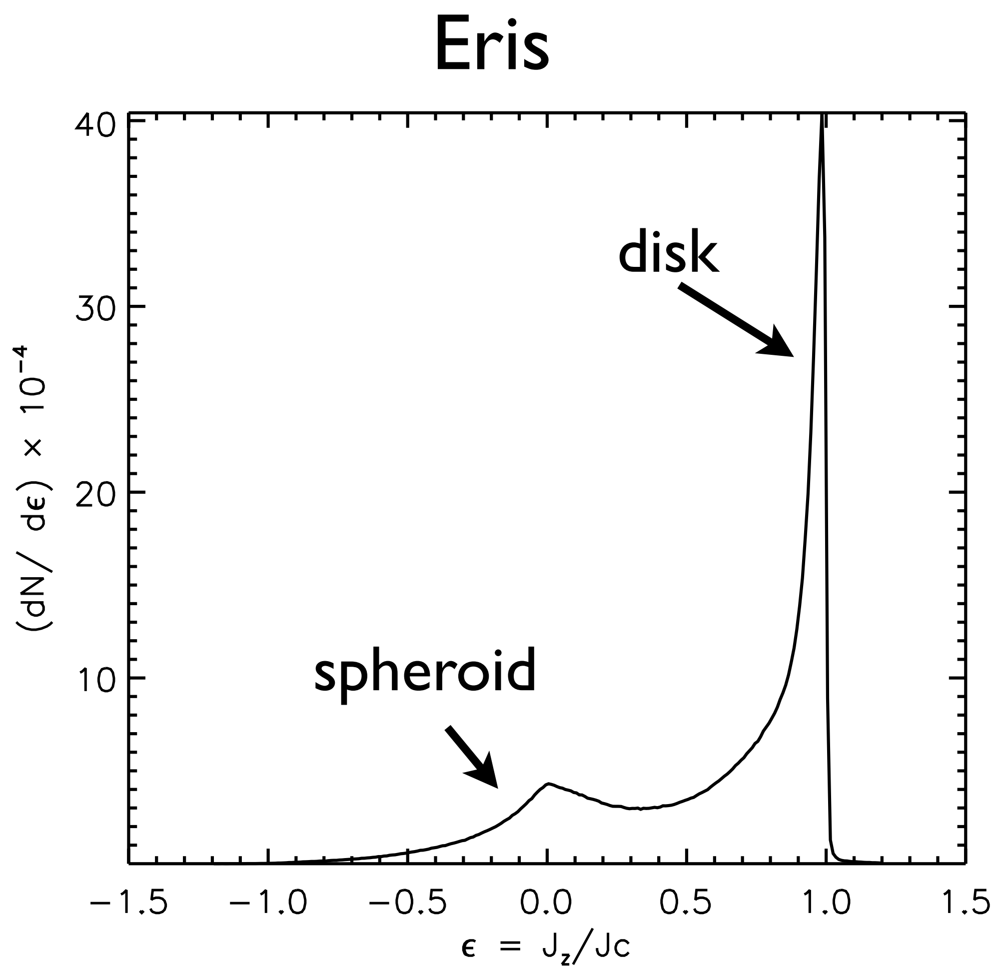
Aq−F−5

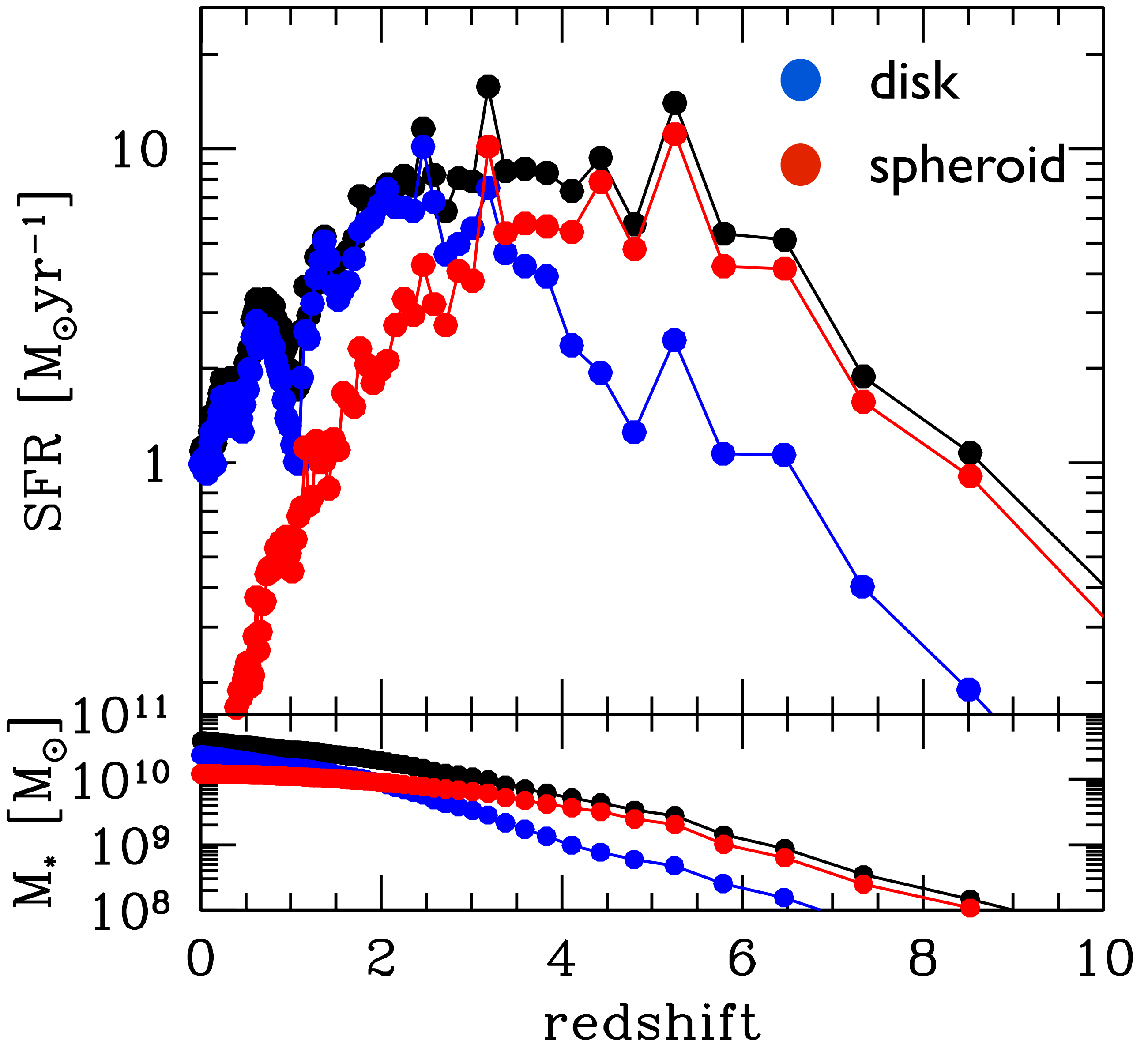
Aq−C−5

Eris



Structural Properties: Kinematic Decomposition



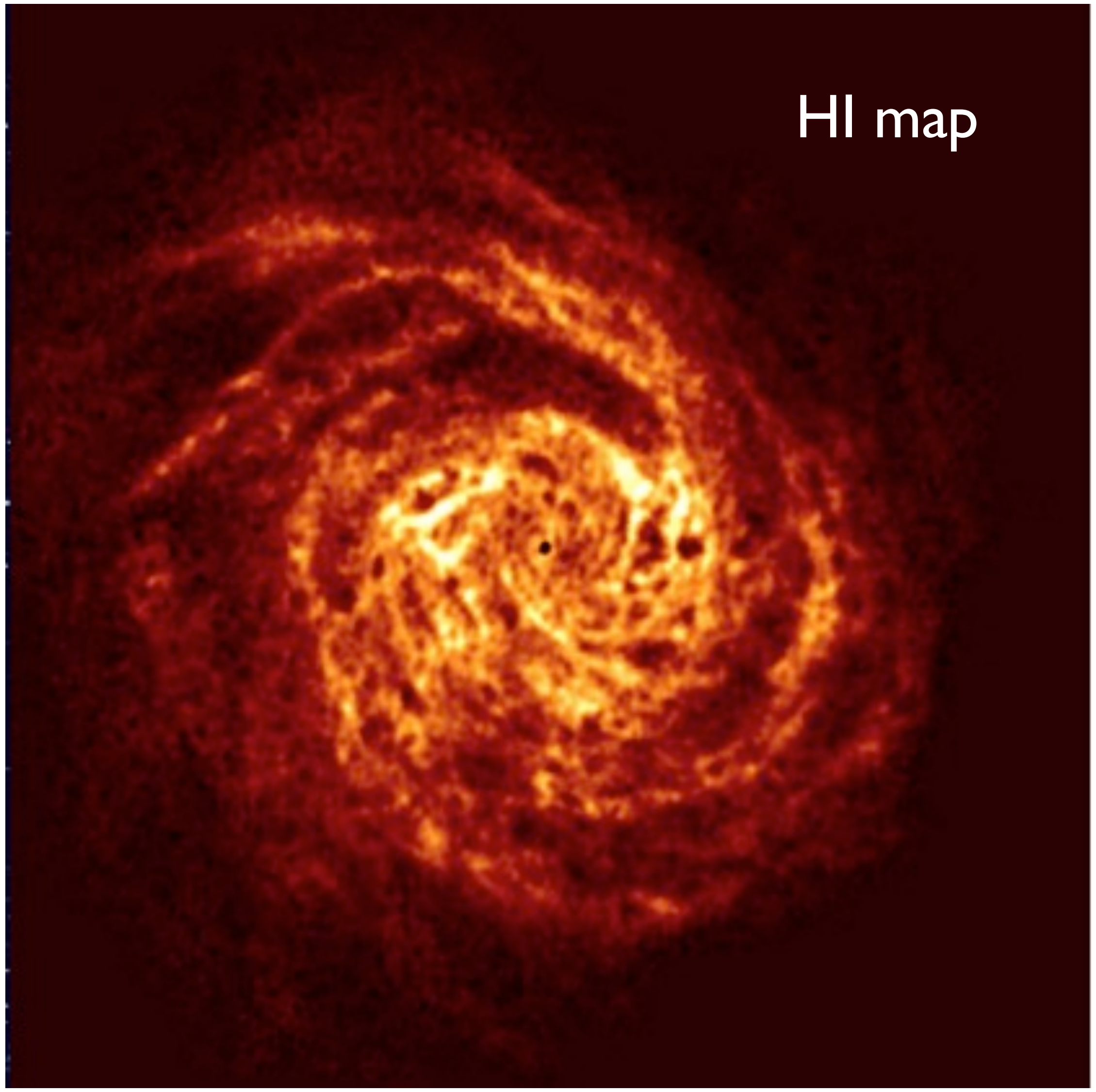


- ✳ The spheroid forms early and is quenched today.
- ✳The formation of the disk begins later, but it is sustained down to z=0 at a rate of 1.1 M_{sun} yr^{-1}

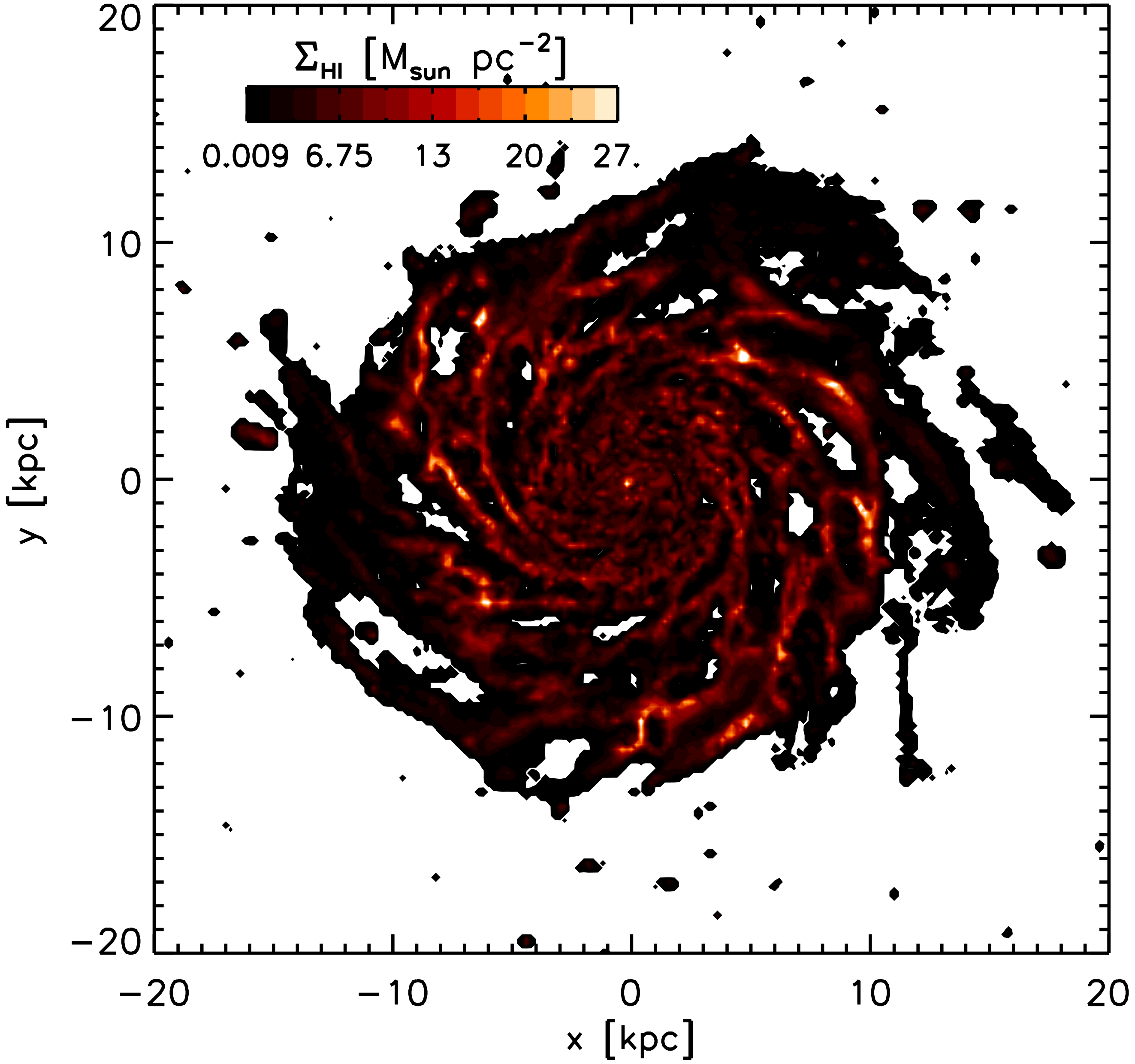
Gas Disk “Holiness”

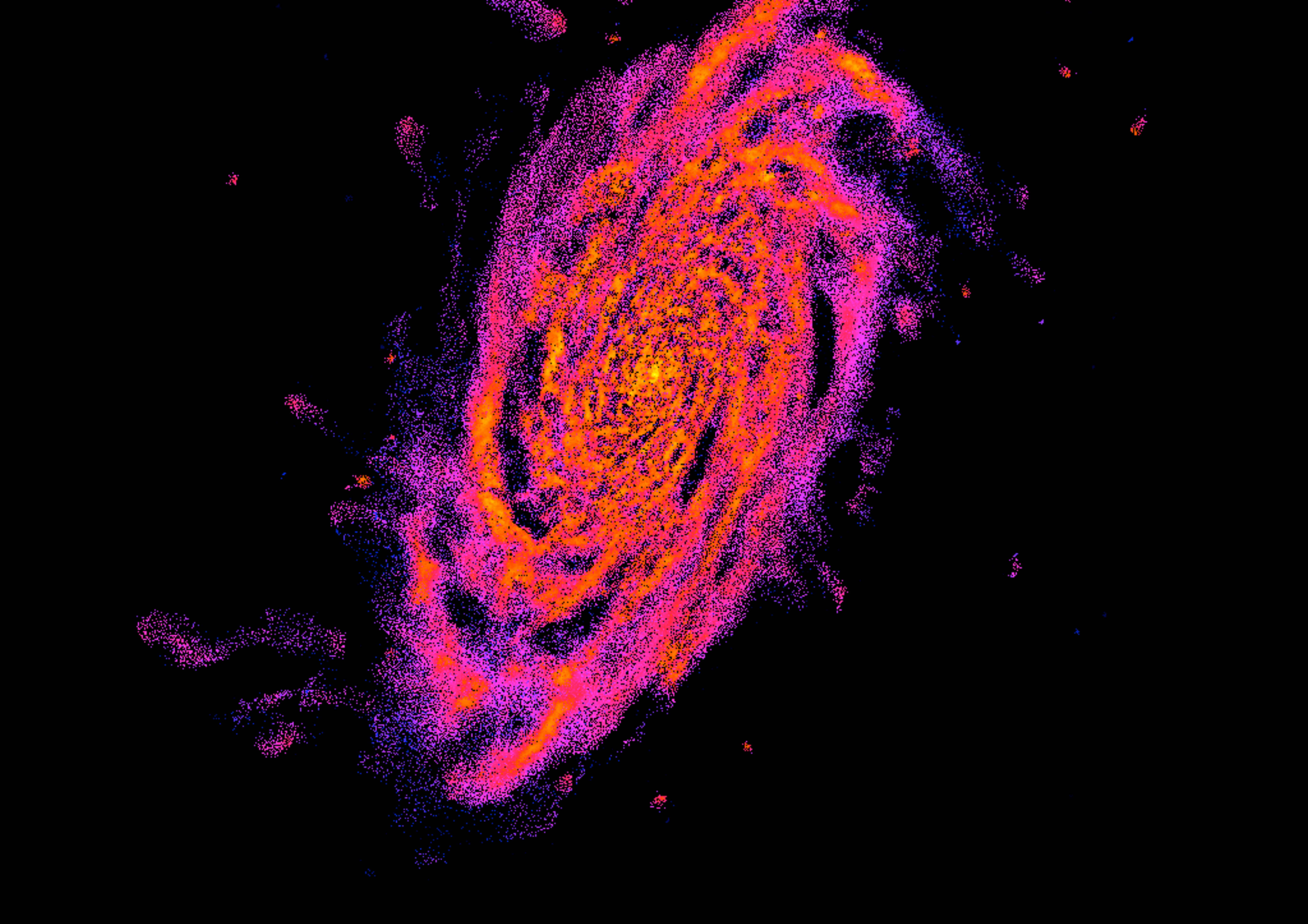
HI disks observed in nearby face-on spirals extend further than the stellar disk have a distribution of holes with mean diameter ~1 kpc. Boomsma et al. 2008

NGC 6946



Eris z=0

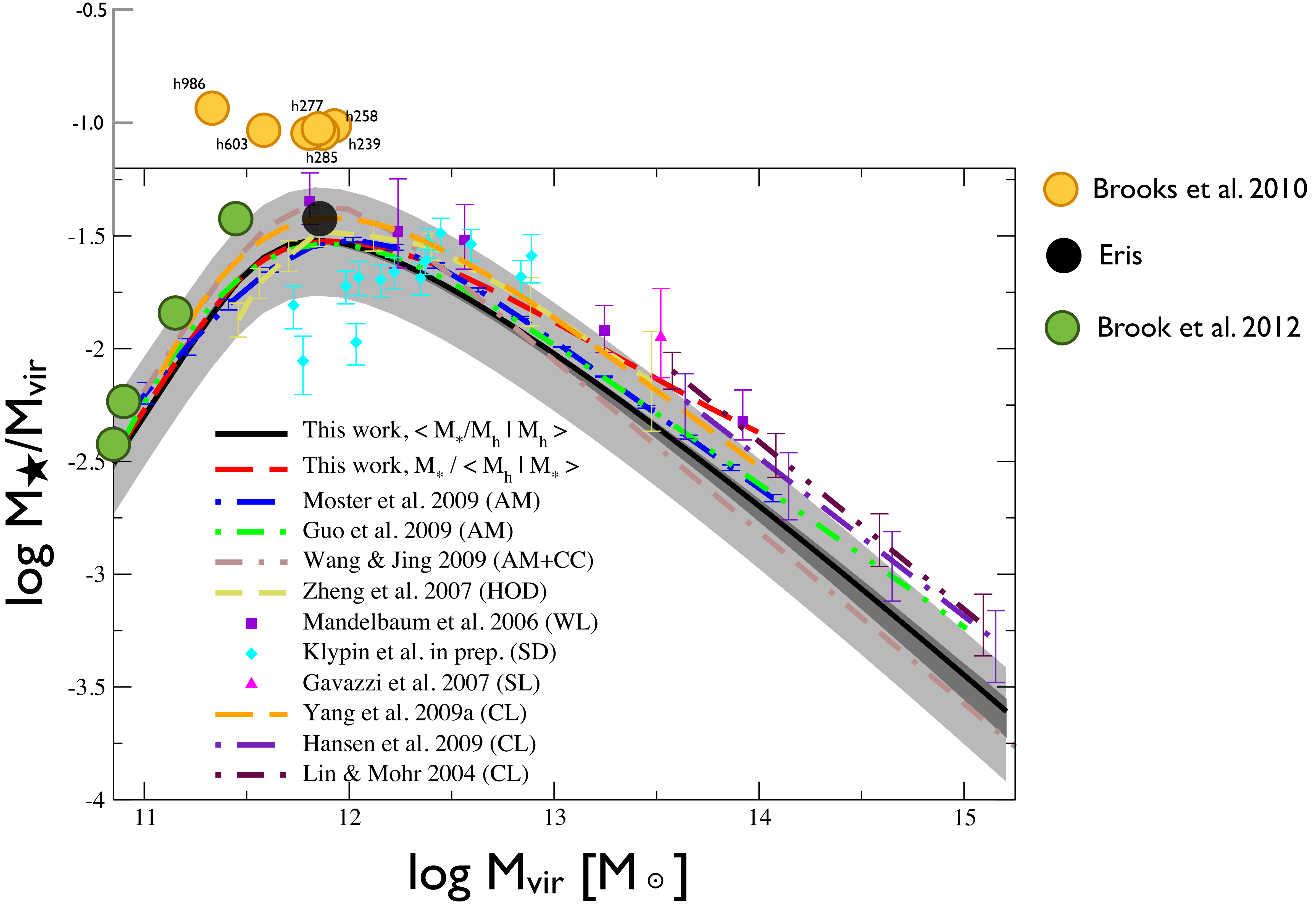




r = 18 kpc

The M_{star}-M_{halo} Relation

Behroozi et al 2010



The forming-too-many-stars-at-high-z catastrophe?

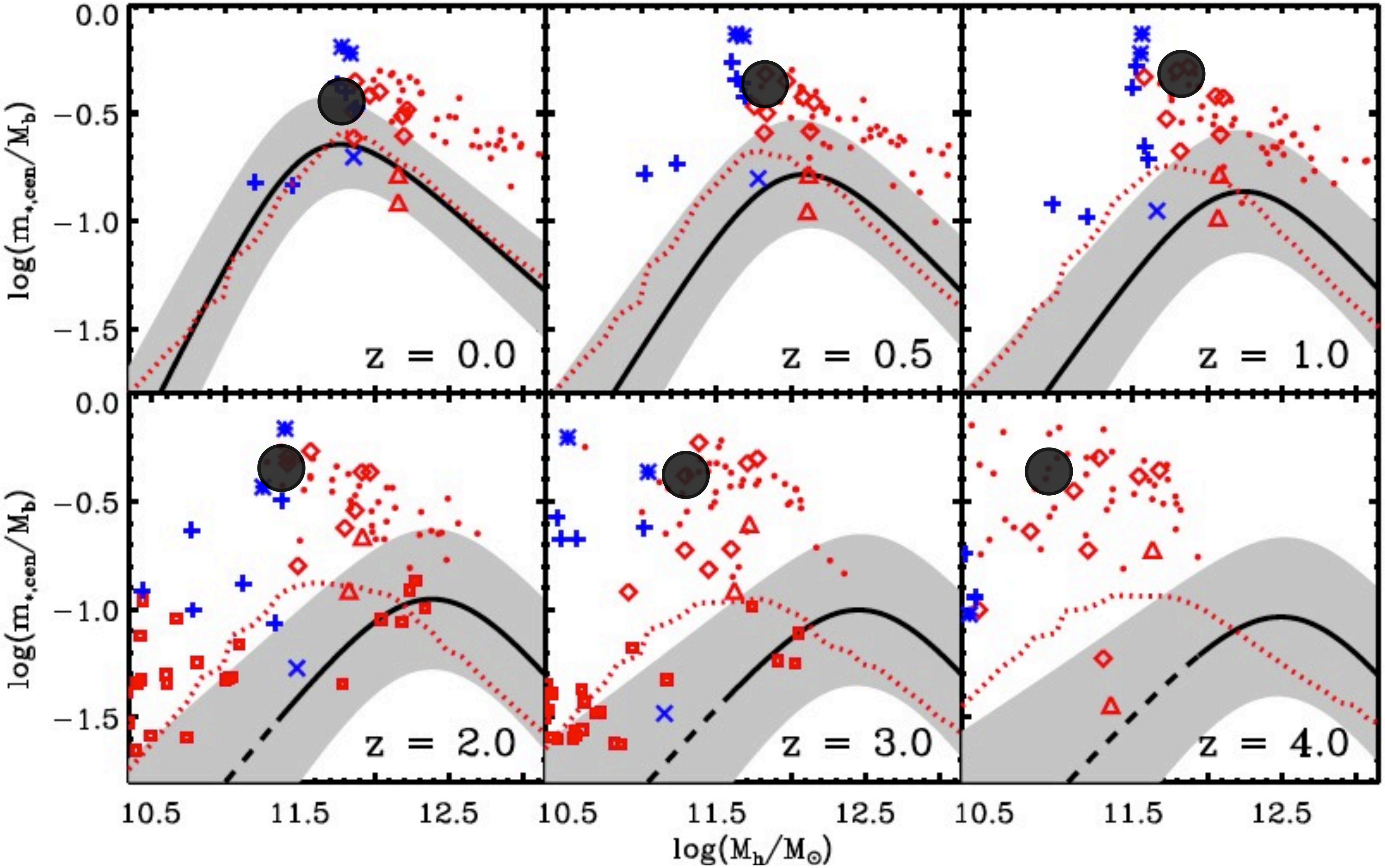
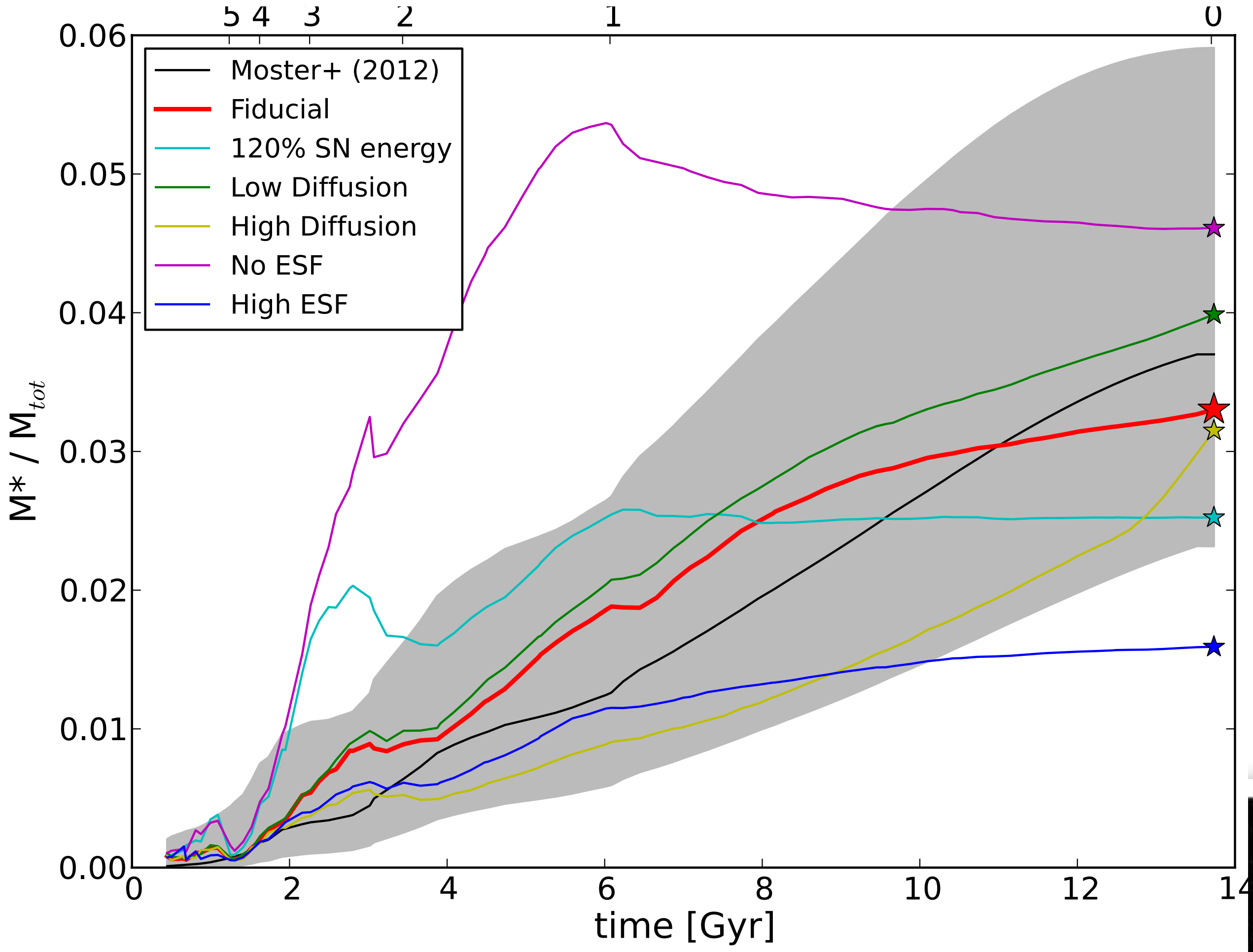


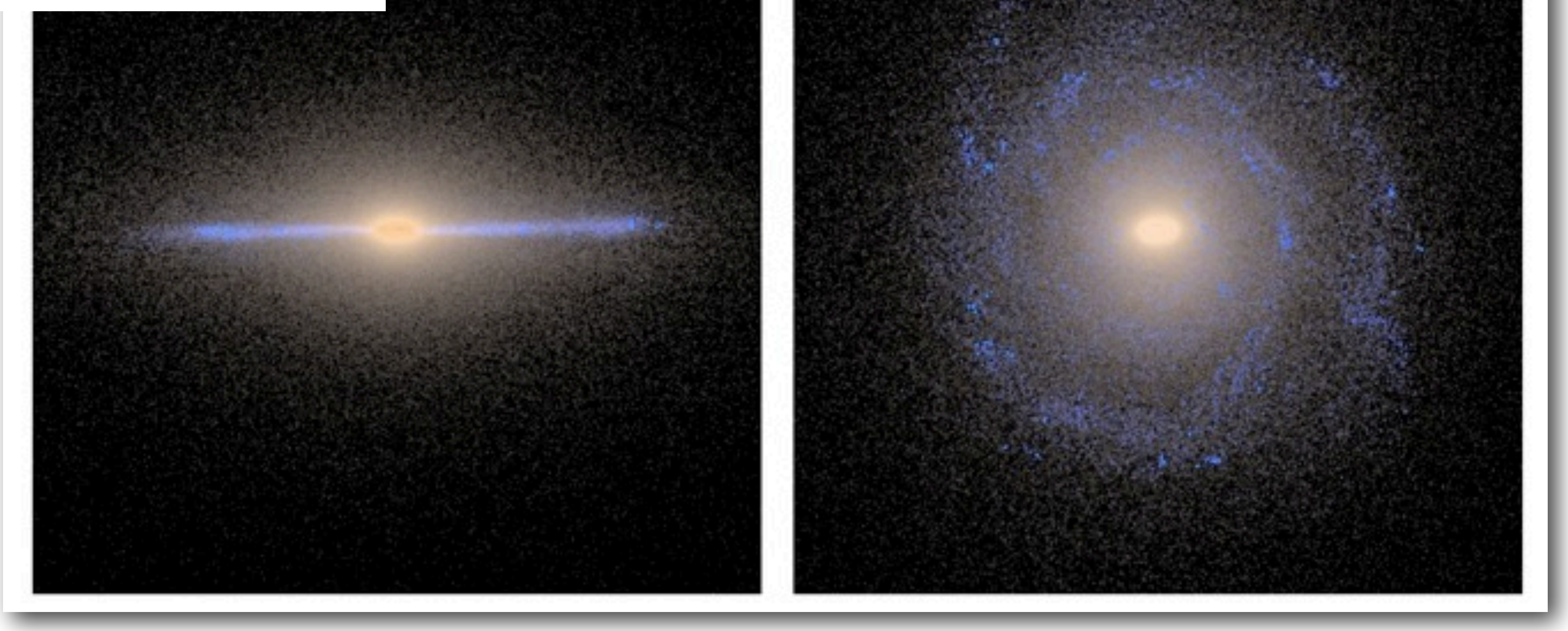
Figure 12. Comparison between central galaxy formation efficiencies found in numerical simulations at different redshifts. Each panel corresponds to the indicated redshift. The solid black lines give the average conversion efficiencies needed to fit the observed SMFs and the shaded areas indicate the 1σ confidence levels. The symbols show the results of hydrodynamical zoom-in simulations run with the GASOLINE code (blue asterisks: Brooks et al. 2011, pluses: Governato et al. 2012, crosses: Stinson et al. in prep.) and the GADGET code (red dots: Oser et al. 2010, diamonds: Scannapieco et al. 2011, squares: Genel et al. 2012, triangles: Okamoto 2012). The colored lines show the conversion efficiencies predicted by the semi-analytic model by Guo et al. (2011, red dotted line). While many simulations agree well with the predicted conversion efficiency at $z = 0$, most have too high values at earlier epochs, indicating that they form their stars too early.

Need Early Stellar Feedback?



Simulation that include early stellar feedback from massive stars in addition to SNe helps alleviate the over production of stars at high redshift.

Stinson et al. 2012

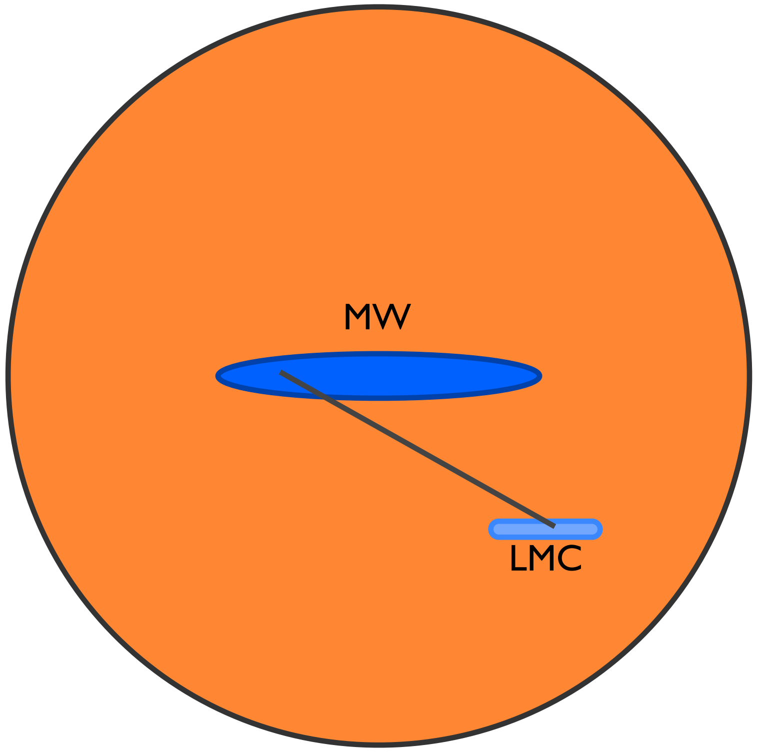


Distribution of the Hot Gas: Pulsars

Pulsars can be used to probe the ISM
the interstellar plasma disperses radio waves, causing a delay between low and high-frequency waves. The *dispersion measure* (DM) is the total column density of electrons along the line of sight:

$$\mathrm{DM} = \int_0^D n_e(l)dl \simeq 70\,\mathrm{cm}^{-3}\mathrm{pc}$$

Manchester et al. 2006, Anderson & Bregman 2010



$$\mathrm{DM} = 62 \pm 3\,\mathrm{cm}^{-3}\mathrm{pc}$$

in Eris

along lines of sight from the Sun's location to the LMC, 50 kpc away.

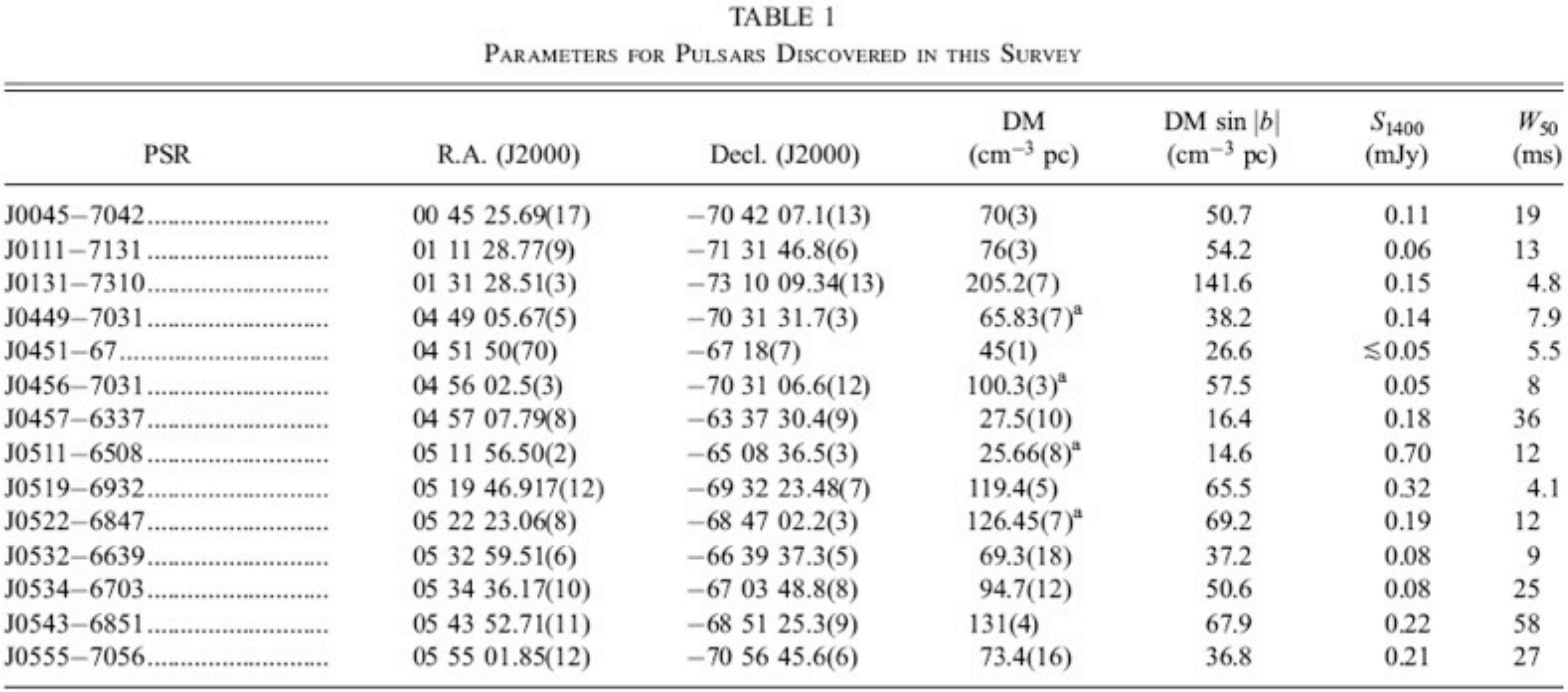


TABLE 1

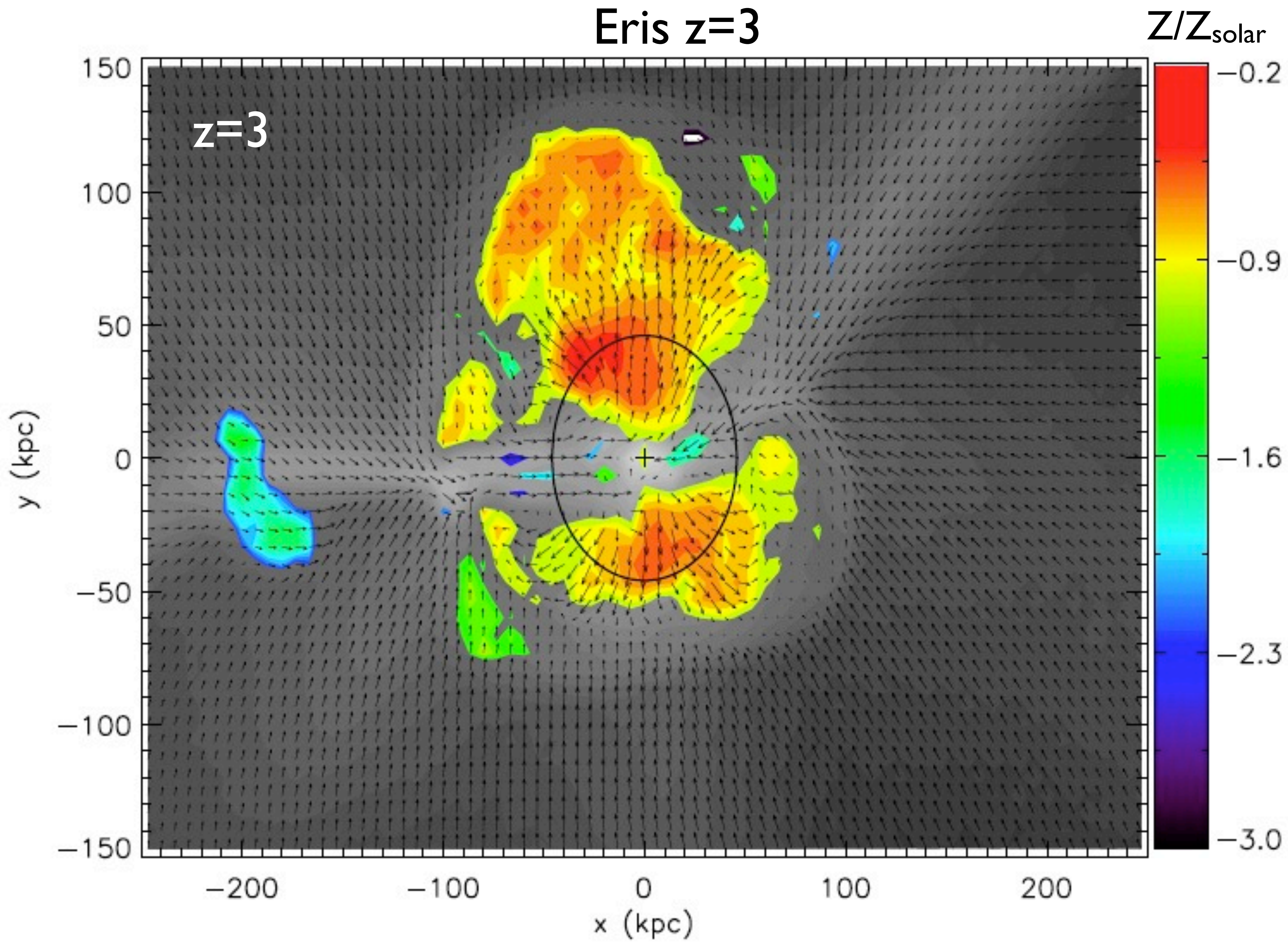
Parameters for Pulsars Discovered in this Survey

PSR	R.A. (J2000)	Decl. (J2000)	DM (cm^{-3} pc)	DM sin $\lvert b \rvert$ (cm^{-3} pc)	S_{1400} (mJy)	W_{50} (ms)
J0045−7042	00 45 25.69(17)	−70 42 07.1(13)	70(3)	50.7	0.11	19
J0111−7131	01 11 28.77(9)	−71 31 46.8(6)	76(3)	54.2	0.06	13
J0131−7310	01 31 28.51(3)	−73 10 09.34(13)	205.2(7)	141.6	0.15	4.8
J0449−7031	04 49 05.67(5)	−70 31 31.7(3)	65.83(7)[a]	38.2	0.14	7.9
J0451−67	04 51 50(70)	−67 18(7)	45(1)	26.6	≤0.05	5.5
J0456−7031	04 56 02.5(3)	−70 31 06.6(12)	100.3(3)[a]	57.5	0.05	8
J0457−6337	04 57 07.79(8)	−63 37 30.4(9)	27.5(10)	16.4	0.18	36
J0511−6508	05 11 56.50(2)	−65 08 36.5(3)	25.66(8)[a]	14.6	0.70	12
J0519−6932	05 19 46.917(12)	−69 32 23.48(7)	119.4(5)	65.5	0.32	4.1
J0522−6847	05 22 23.06(8)	−68 47 02.2(3)	126.45(7)[a]	69.2	0.19	12
J0532−6639	05 32 59.51(6)	−66 39 37.3(5)	69.3(18)	37.2	0.08	9
J0534−6703	05 34 36.17(10)	−67 03 48.8(8)	94.7(12)	50.6	0.08	25
J0543−6851	05 43 52.71(11)	−68 51 25.3(9)	131(4)	67.9	0.22	58
J0555−7056	05 55 01.85(12)	−70 56 45.6(6)	73.4(16)	36.8	0.21	27

Metallicity Distribution: Outflows

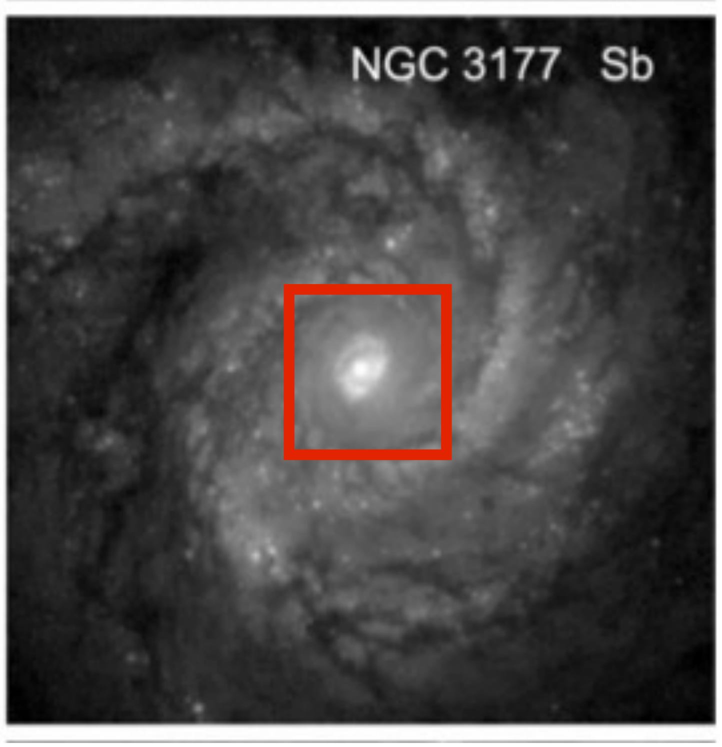
Shen et al. 2012

Eris z=3

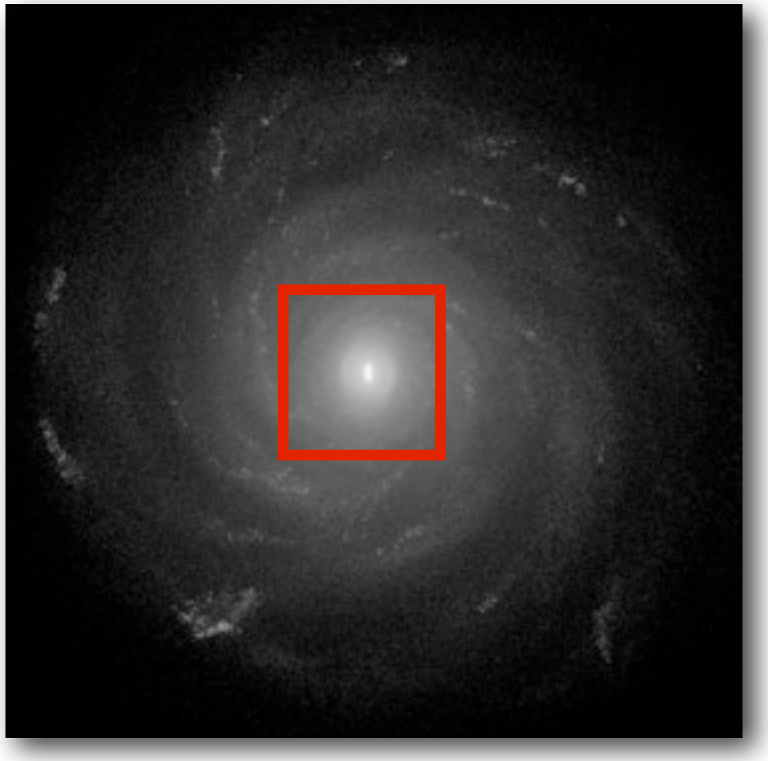


What can we learn?

Pseudo / disk-like bulges



HST image by
Carollo et al. 1998

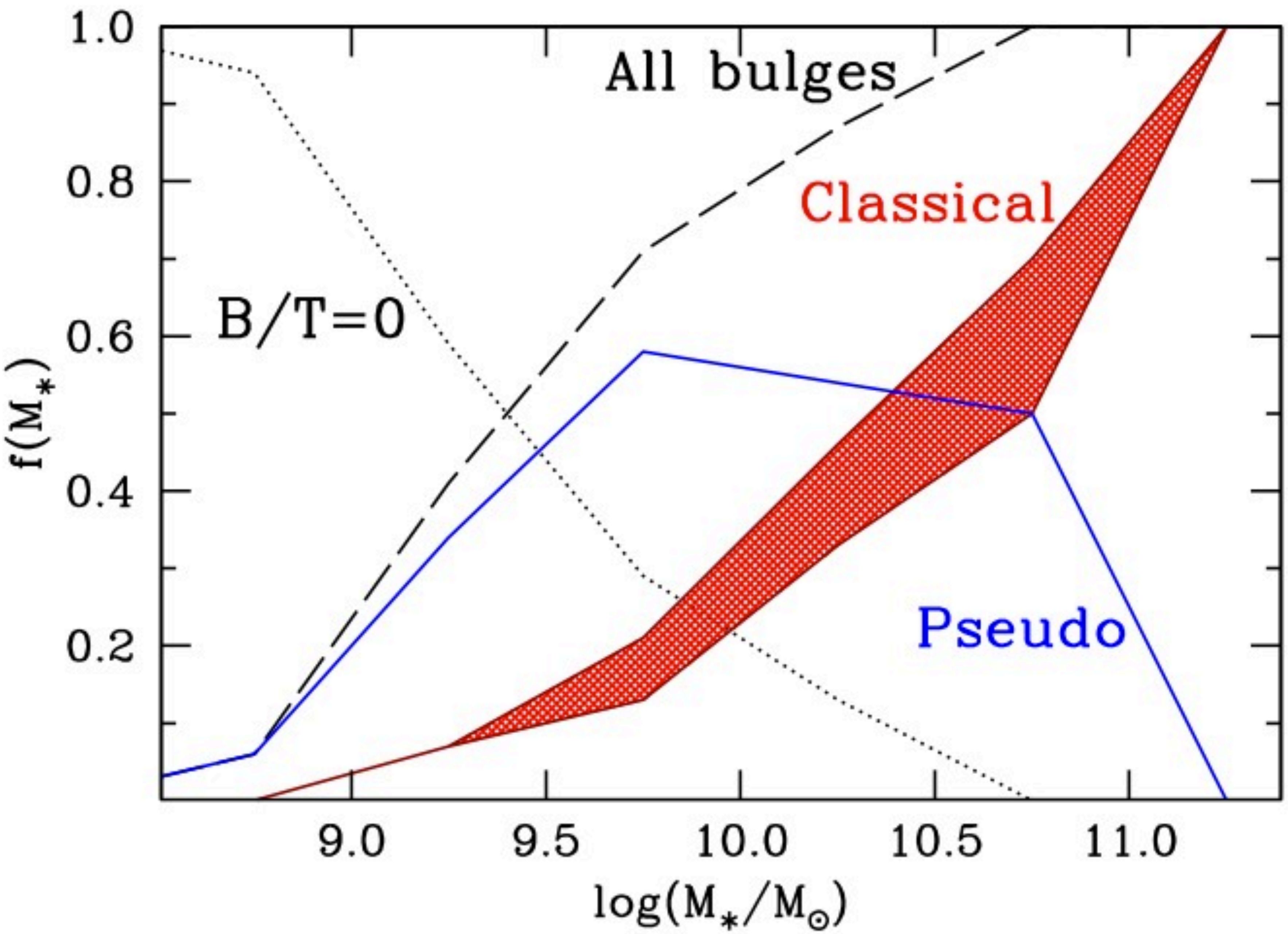


Eris

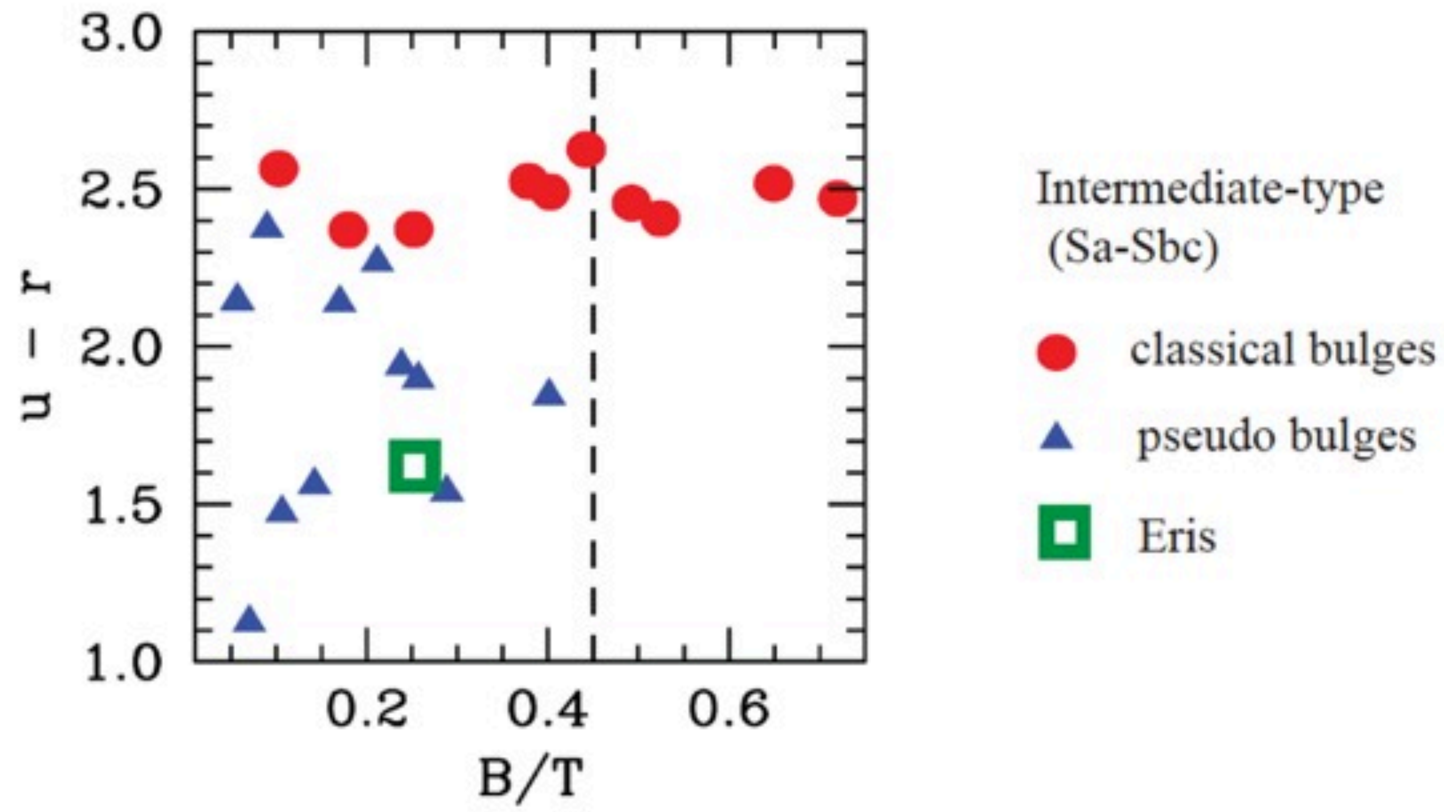
Bulges vs. Pseudobulges

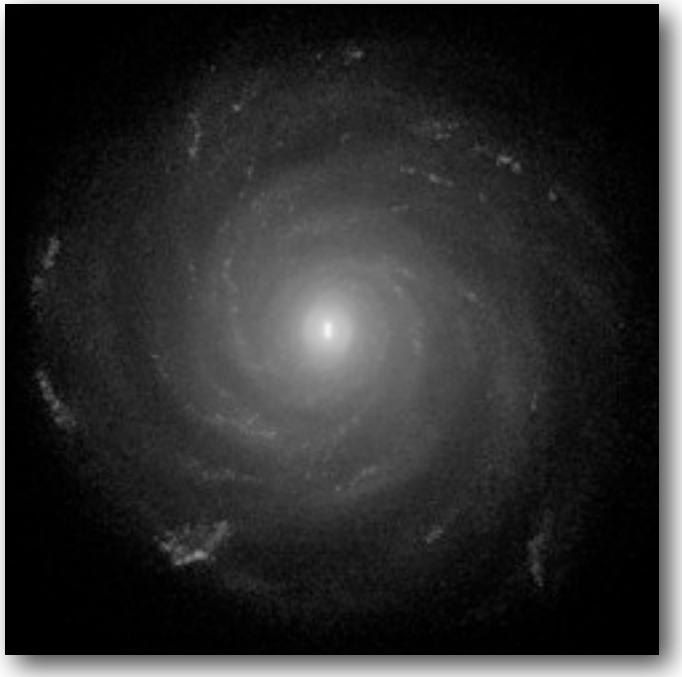
Classical bulges: Can be treated as "mini ellipticals" (Renzini+), high Sersic indices (n>2) , believed to have formed early via mergers.
Pseudobulges: Flattened or disk-like bulges that are thought to have formed predominately via secular evolution (e.g. Combes et al. 1993, Raha+1999, Debattista+2005), high-z starbursts (e.g. Okamoto 2012), and clumpy disks (Noguchi 1998; Immeli & Gerhard 2001; Bournaud+)

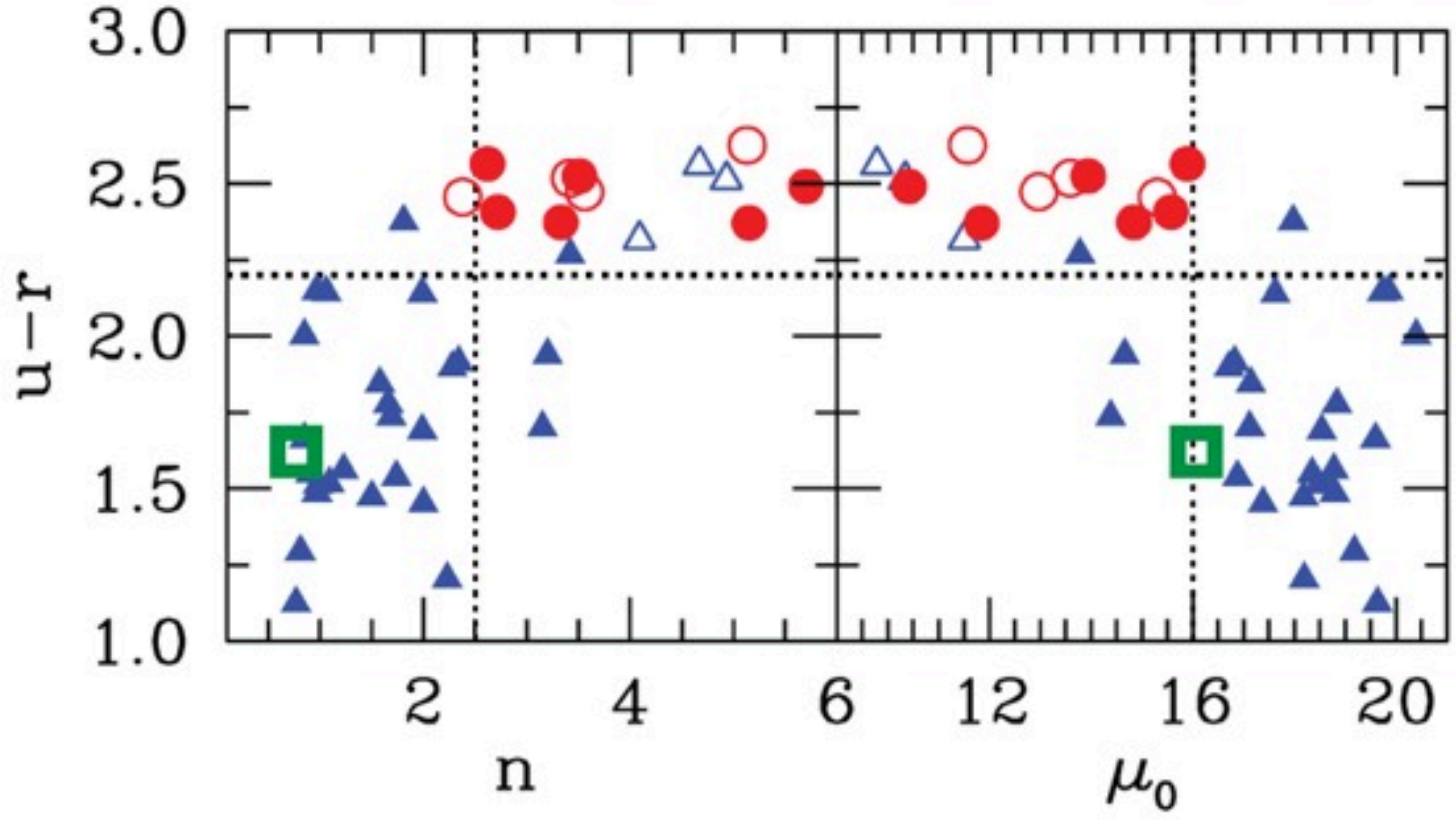
Drory & Fisher 2011



Eris has a pseudo-bulge



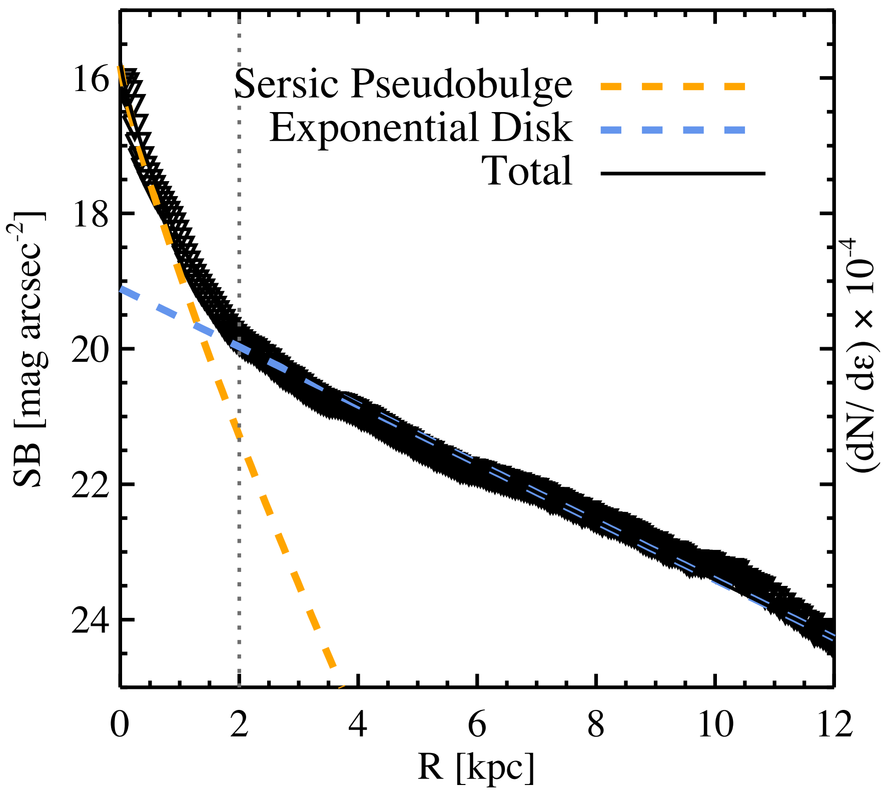


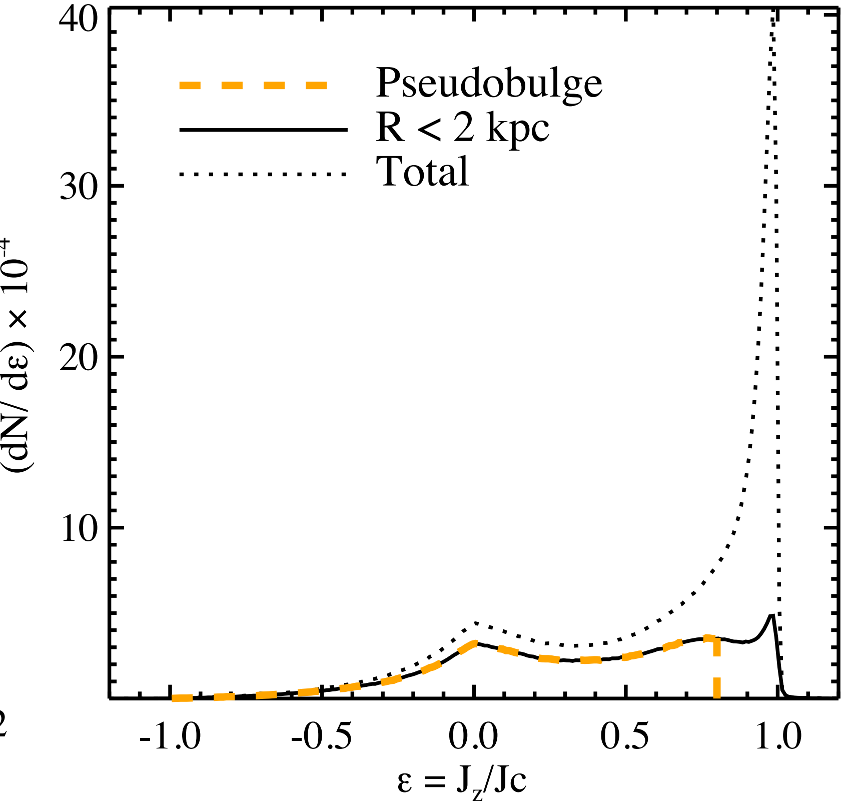


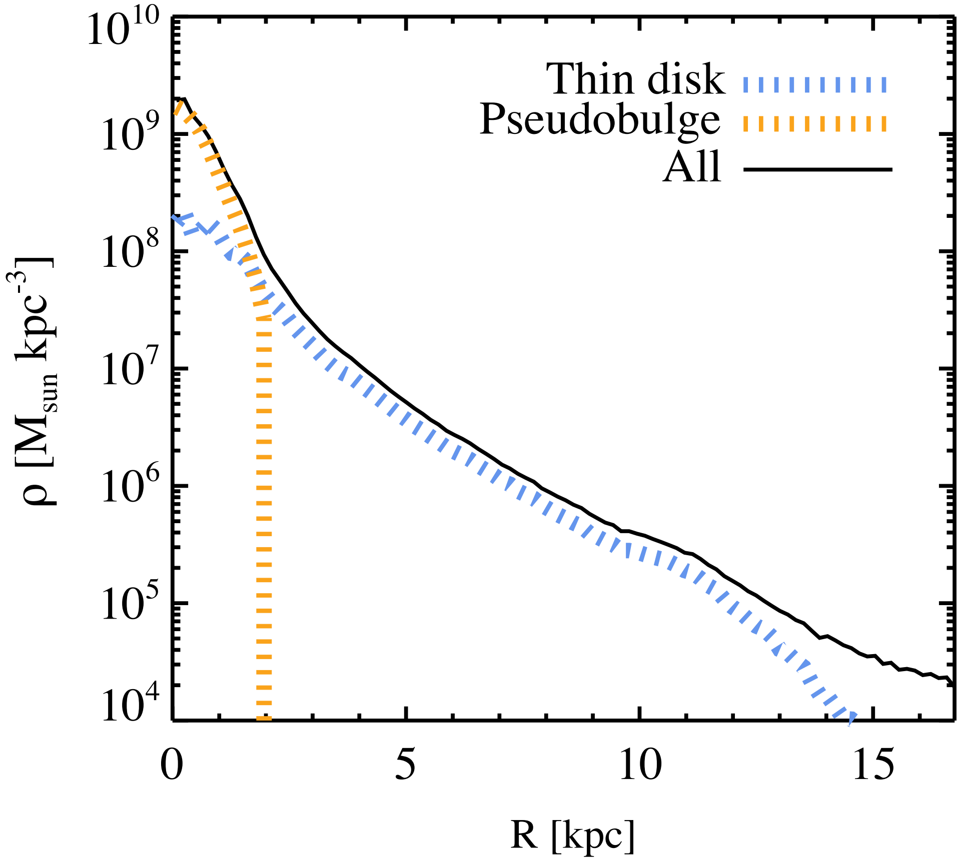
data from
Drory & Fisher 2007

Selection of pseudobulge particles

We select the pseudobulge based on the photometric profile of the galaxy as having R < 2 kpc and epsilon < 0.8





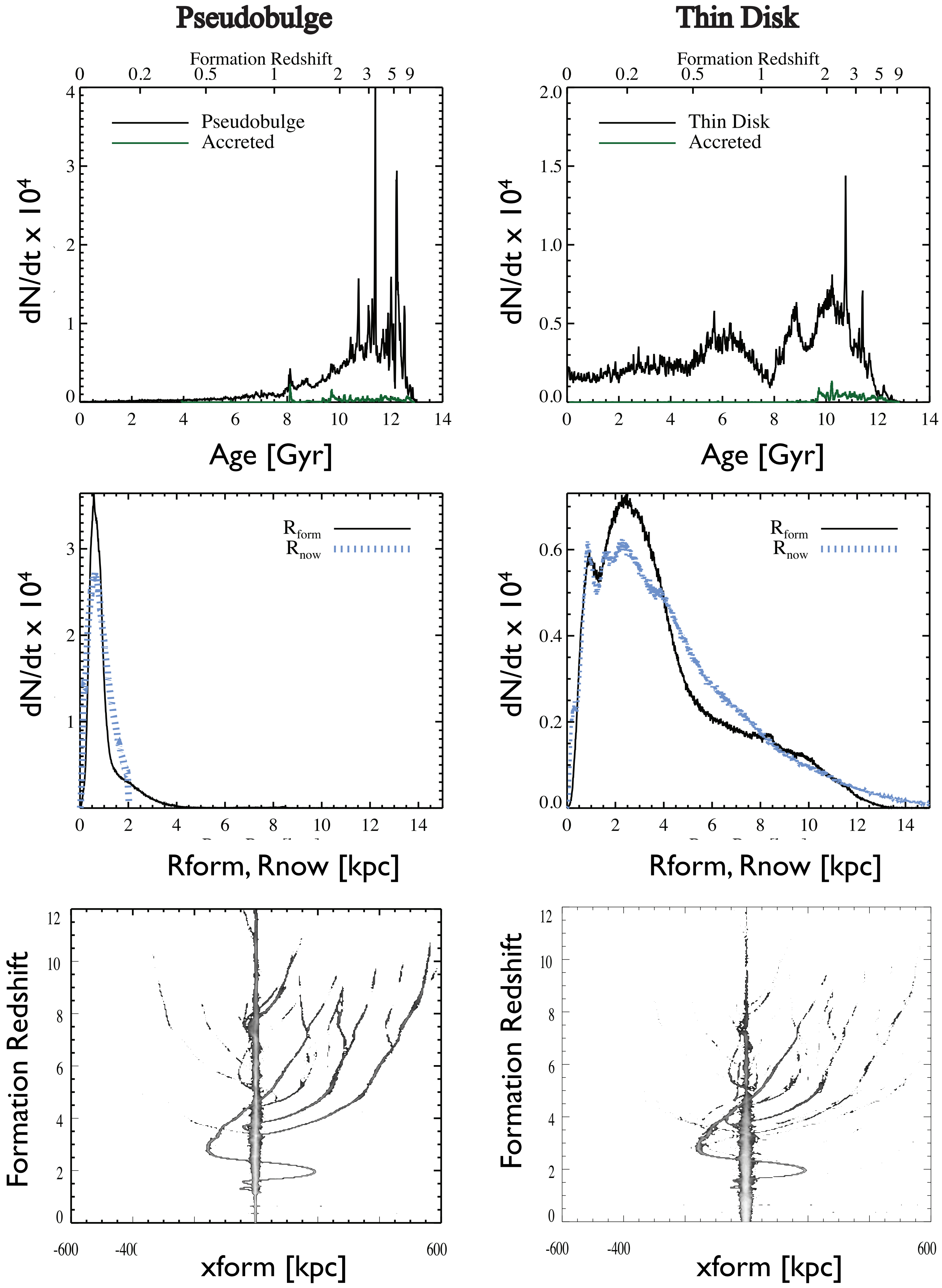


Origin

- The bulk of the pseudobulge stars form in situ in a burst of star formation at high redshift (z~4).

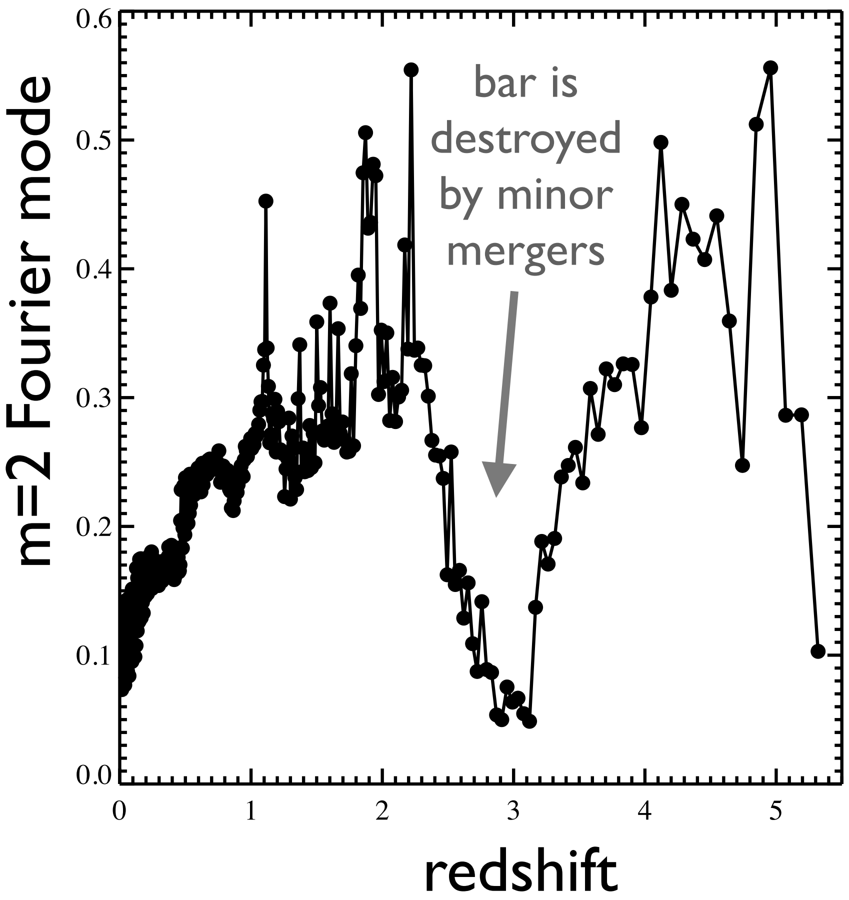
- Only 4% of pseudobulge particles are accreted (but Eris has a quiet merger history).

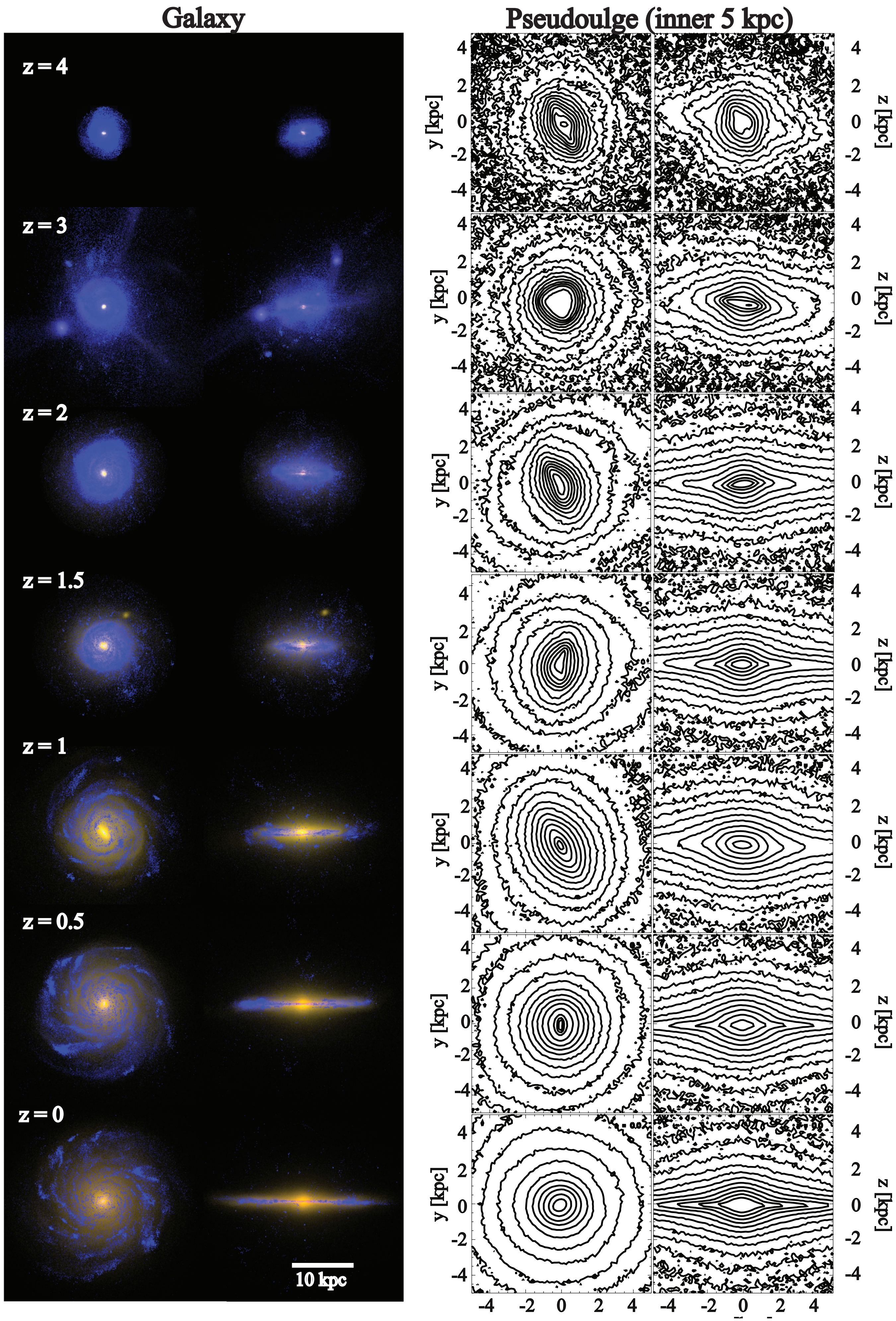
- The formation path of the pseudobulge is not distinct to that of the disk in terms of merging history



Evolution

- Early bar formation triggered at z=5, and sustained until several minor mergers destroy it at z=3.
- The bar quickly reforms, but many stars lose angular momentum and become part of a ‘heated’ inner disk component, aka pseudobulge.
- At late time (z<1) when the bar is again fully fledged, gas inflow becomes important, again destroying the bar and growing the pseudobulge.





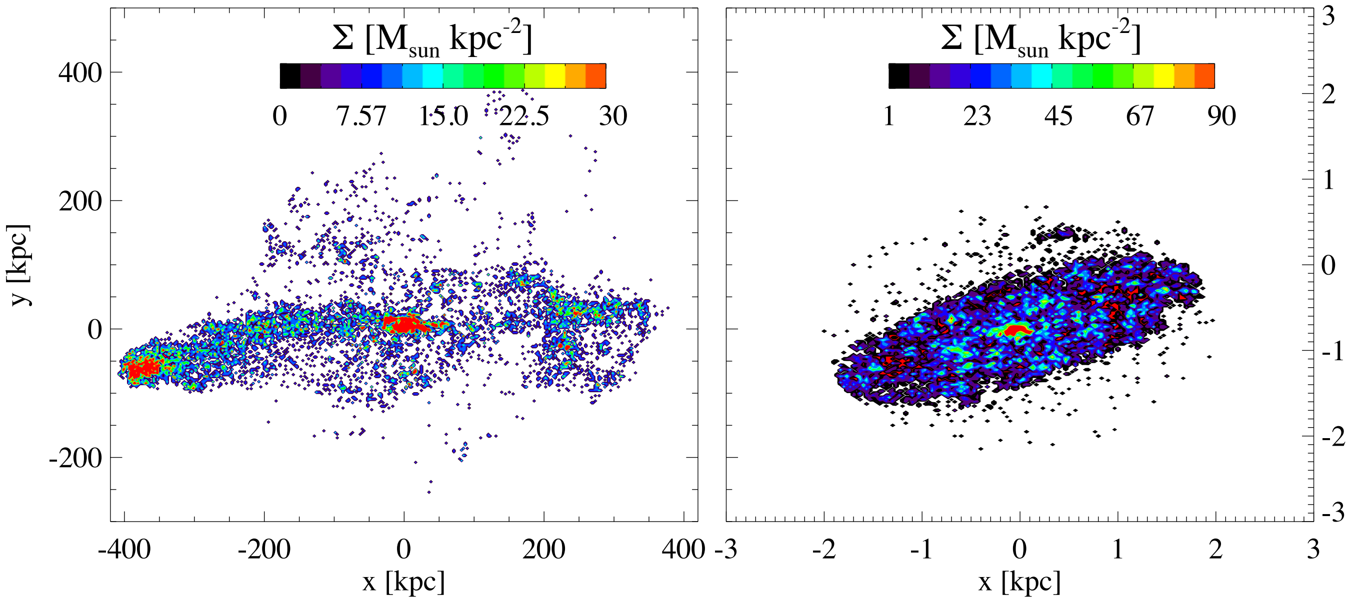
Evolution

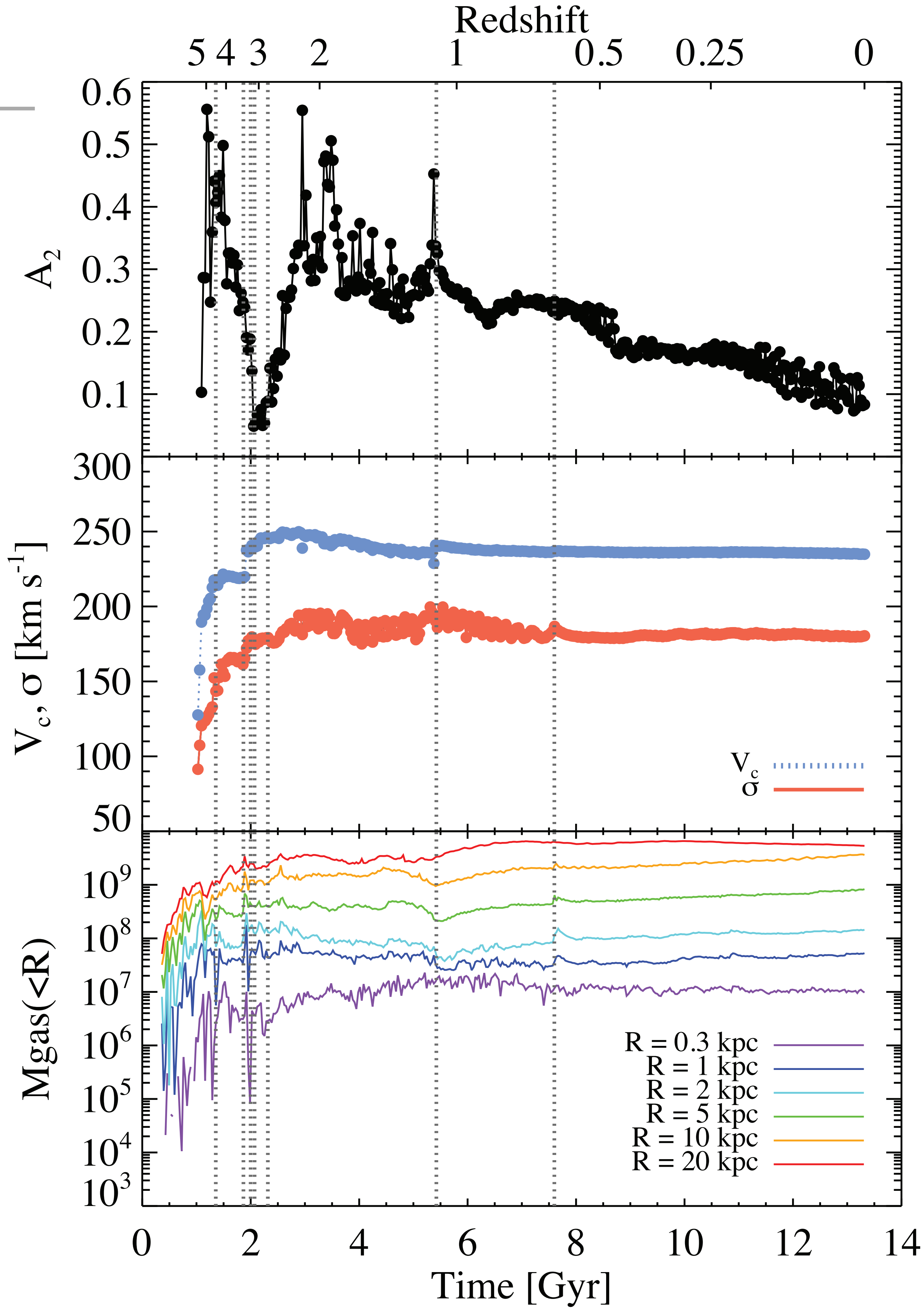
- The first structure to form is a bar at z~5

- The bar is destroyed due to heavy bombardment by minor mergers at z~3, and reforms quickly by z~2.

- The velocity dispersion in the inner 2 kpc increases during this bombardment and remains constant afterwards

- The amount of gas in the inner regions increases by a factor of ~2, however the star formation after z=2 takes almost exclusively in the disk

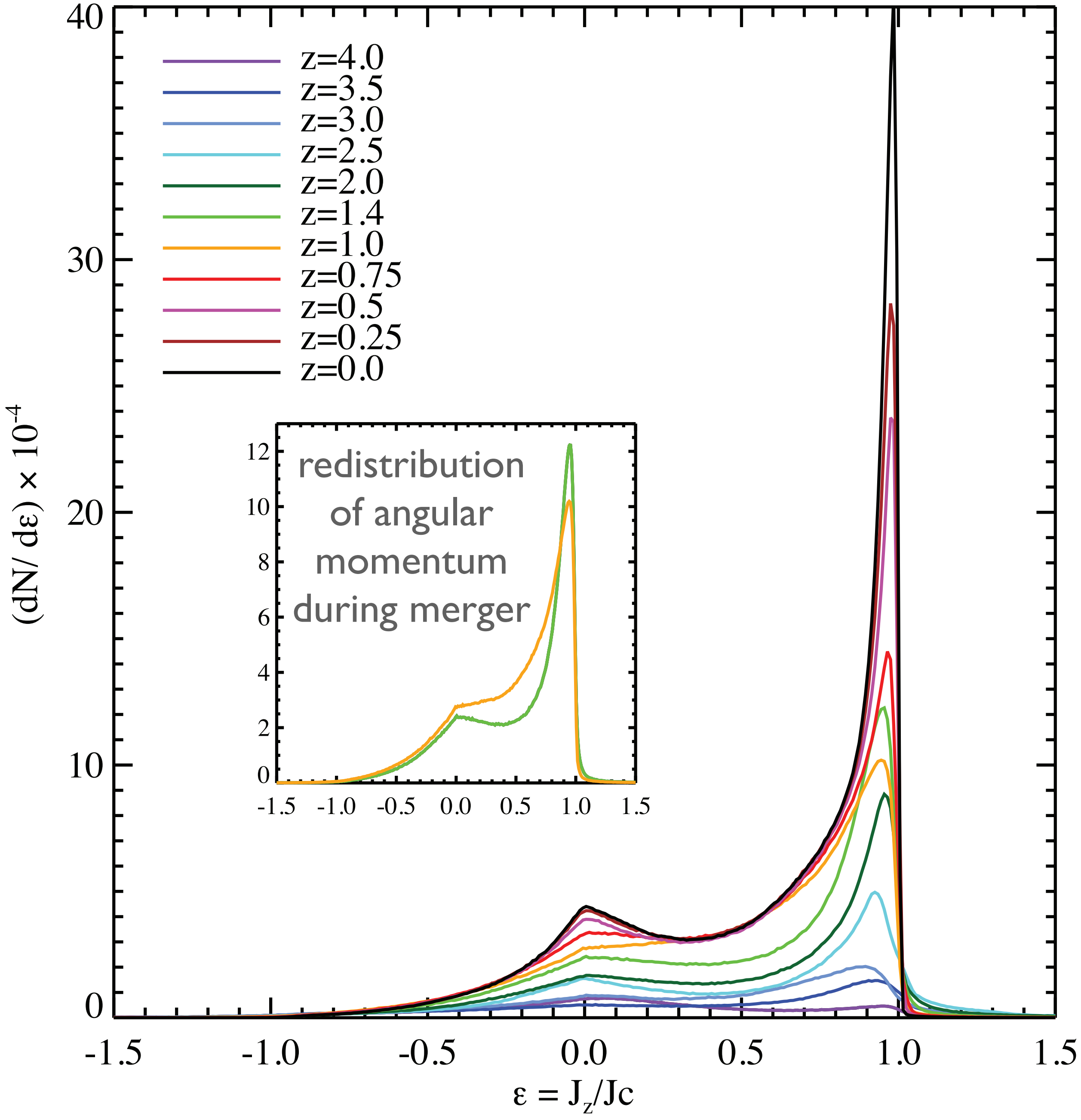


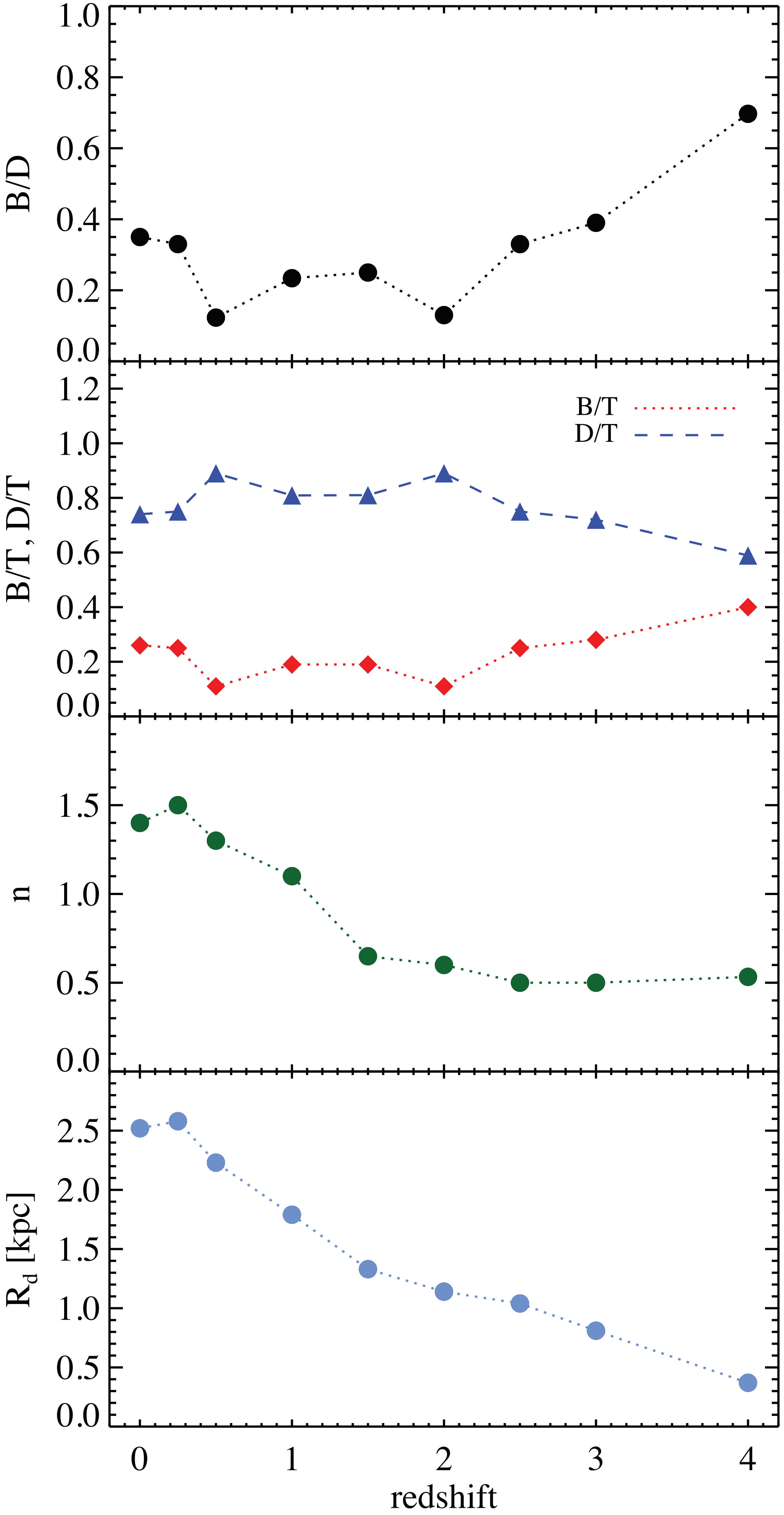


Evolution

Guedes et al. 2012 (in prep)

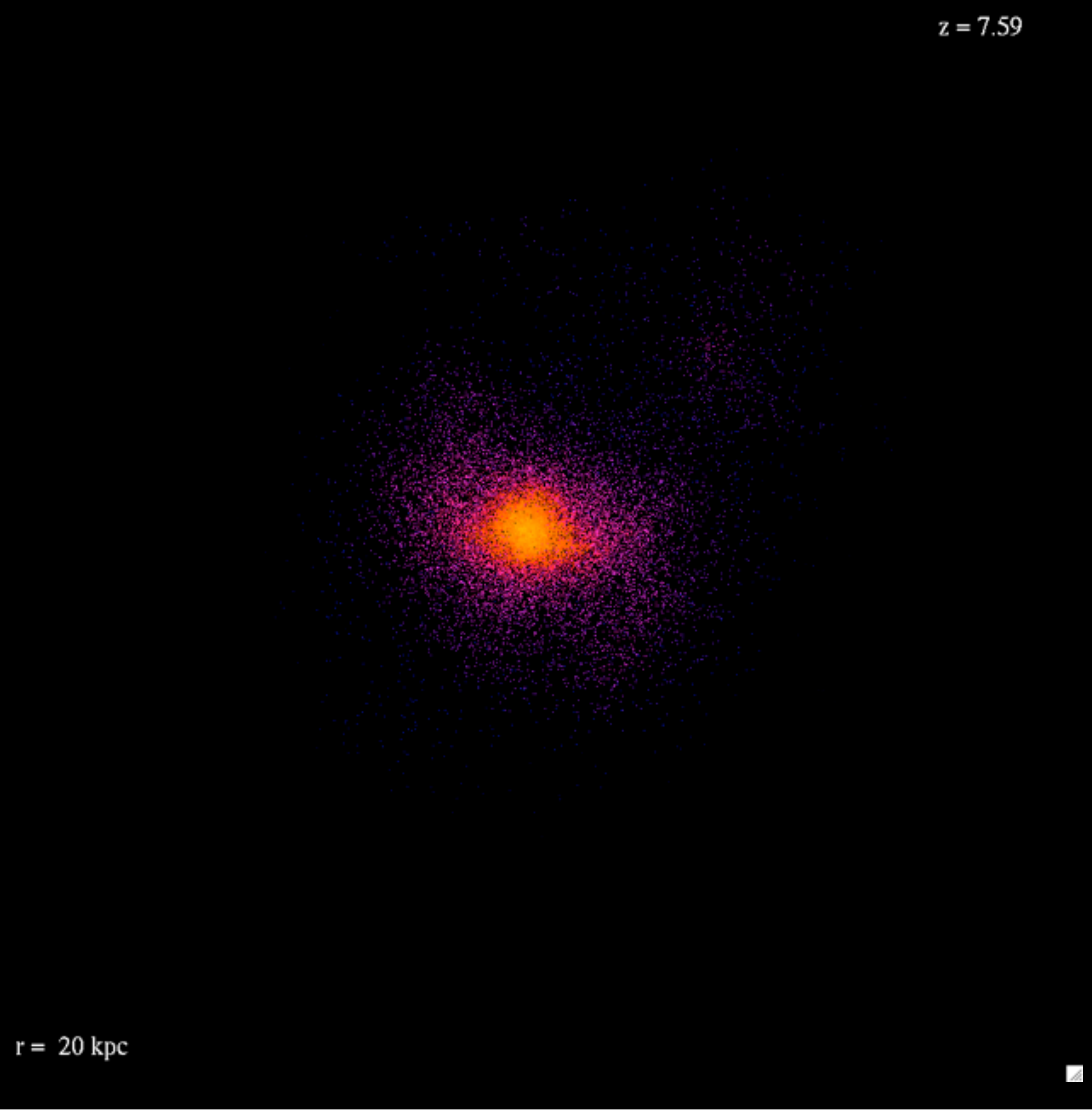
The evolution of the B/D ratio is non-monotonic. The bulge's Sersic index and the disk's exponential scale length do not grow independently from each other.





Tracing back the pseudobulge

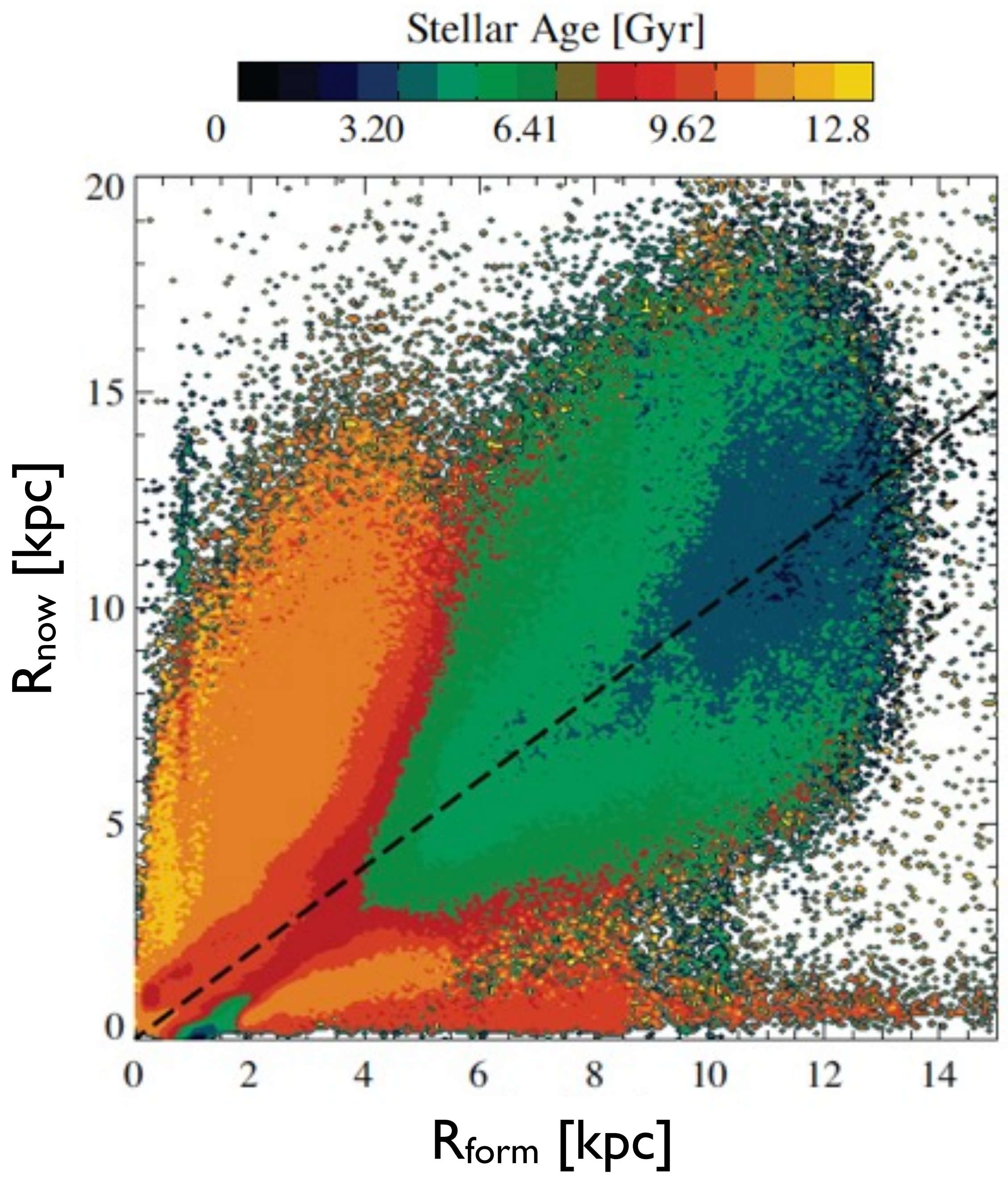
Guedes et al. 2012 (in prep)

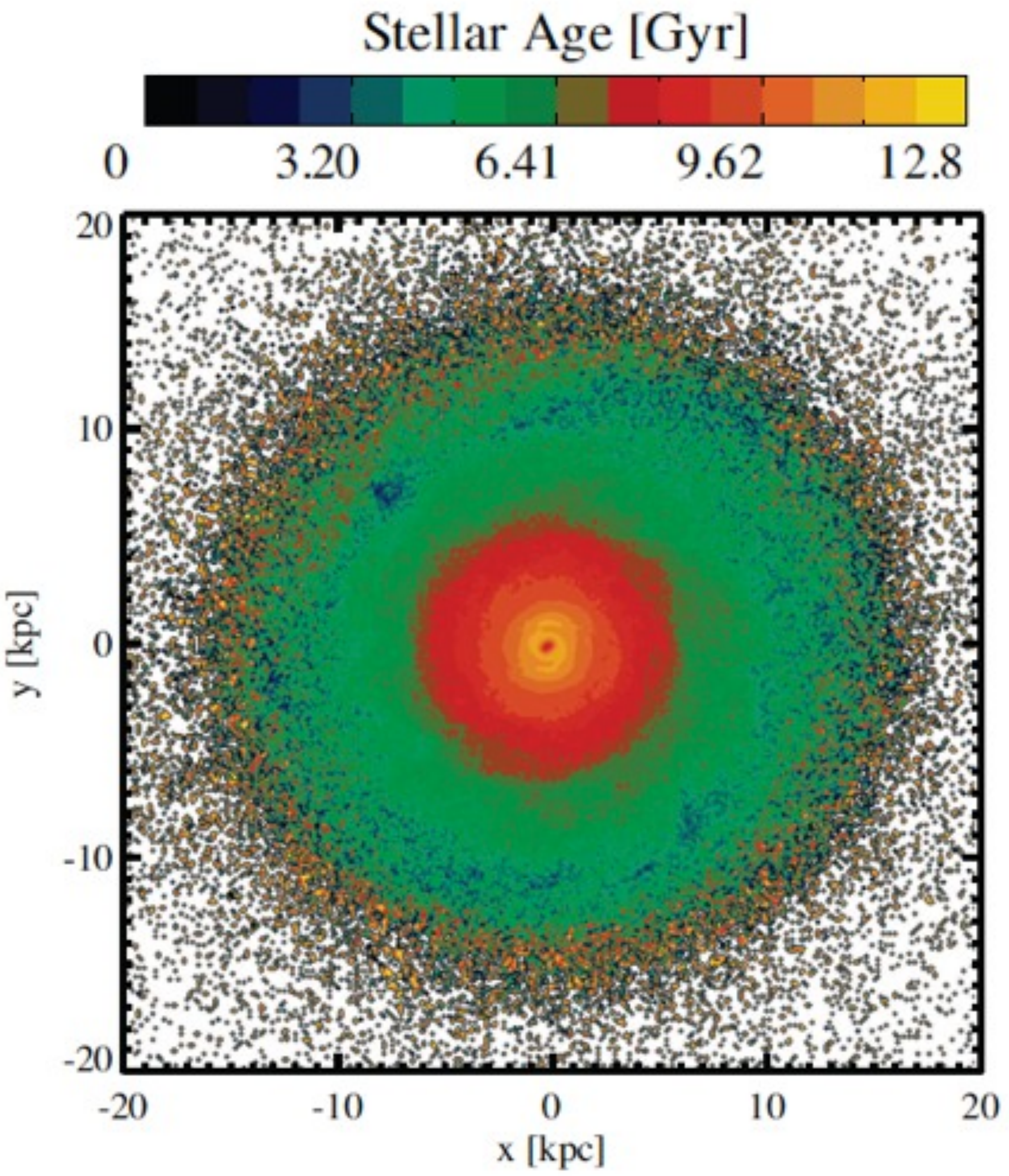


Stellar Migration in the disk

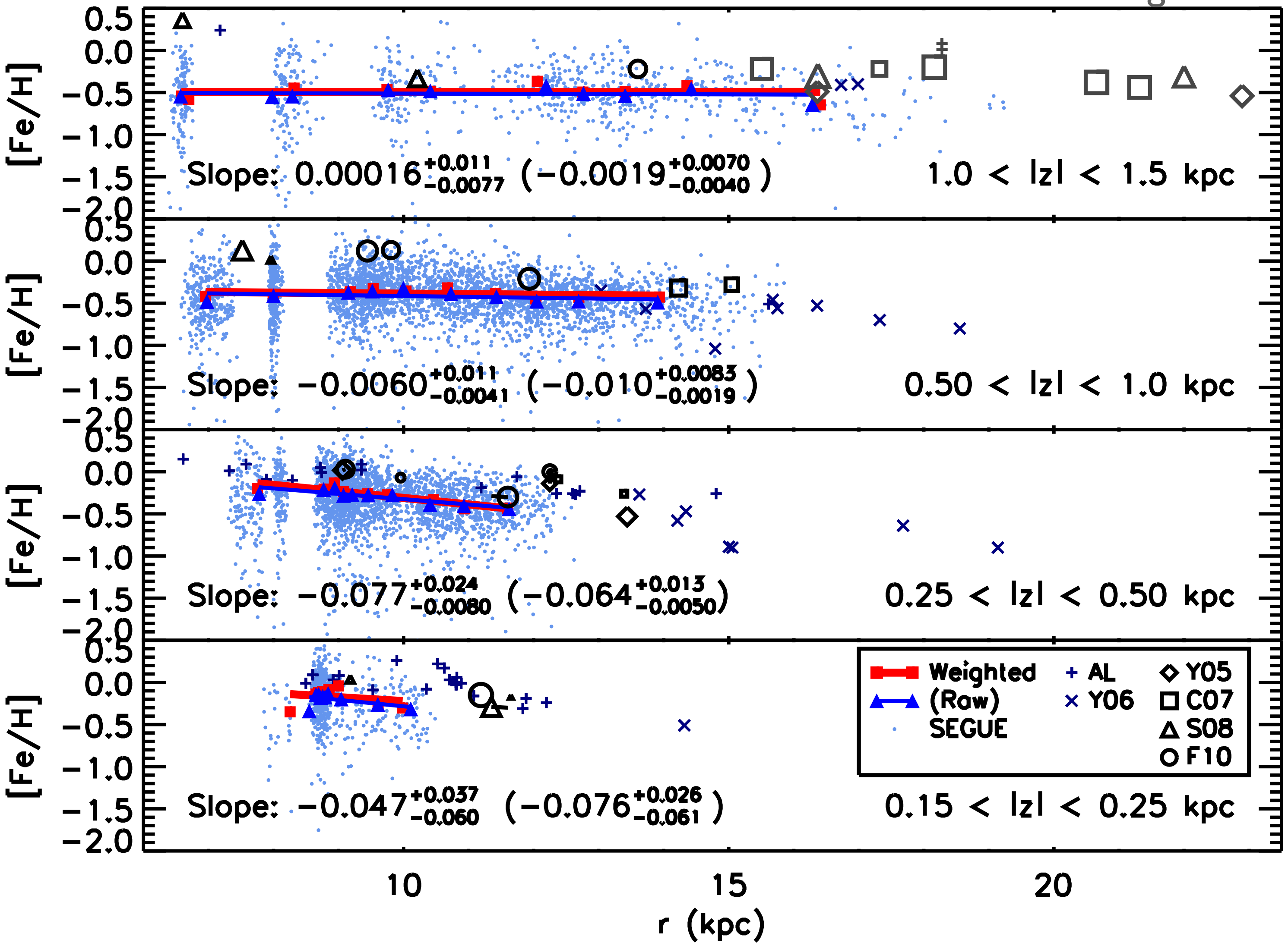
The disk forms inside-out, and stellar migration is mildly important.

11% of all stars that formed within 4 kpc migrated outwards.





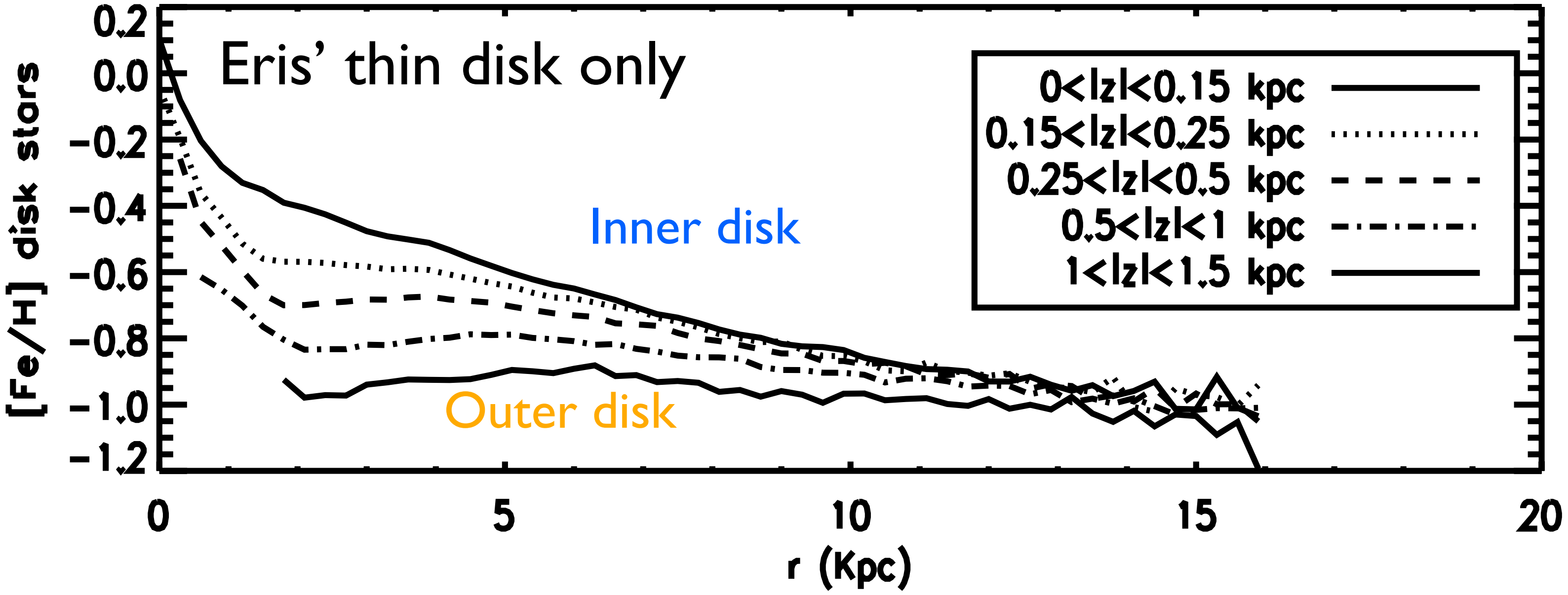
Metallicity gradients in the disk



Cheng+ 2012

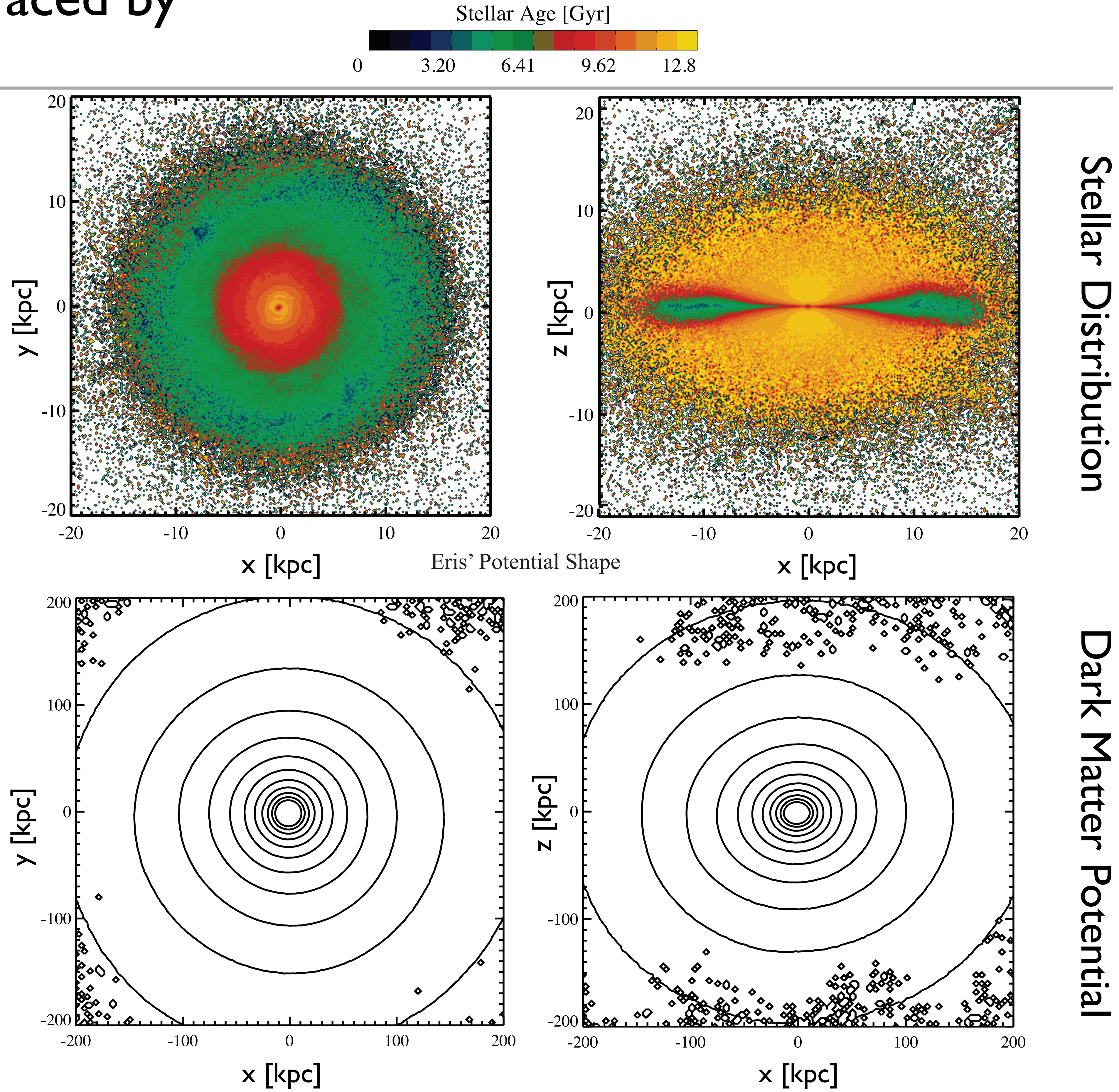
Outer disk

Inner disk

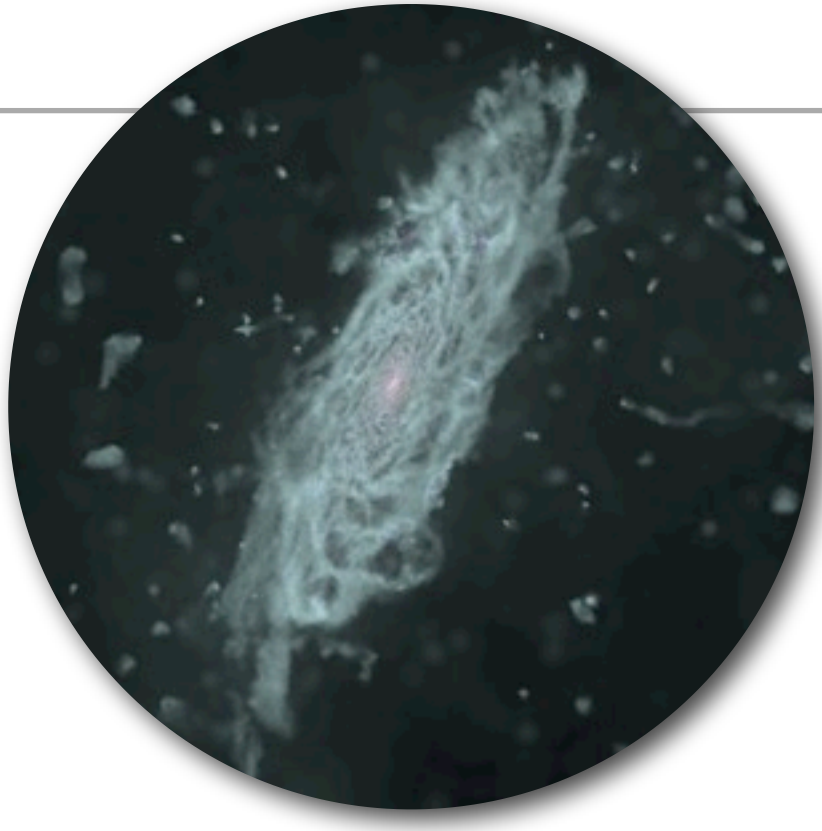


DM halo shape is traced by inner halo stars

Detail simulations of the formation of Milky Way analogs can give clues on the formation of the inner / outer stellar halo and provide kinematic tracers that could help constraint the shape of the dark matter halo.



Summary



- ✳ We have successfully formed a late-type spiral galaxy in the LCDM framework without fine tuning of parameters, or invoking alternate feedback mechanisms (e.g. AGN).

- ✳ Eris is the first cosmological simulation to match a large variety of observable parameters, both in terms of correlation relations and structural properties.

- ✳ The key to the success of Eris is in its high resolution which allowed us to use a high threshold for star formation. The interplay between star formation and feedback is crucial in producing realistic massive disks with localized star formation regions.

- ✳The pseudobulge forms in situ, at high redshift, and undergoes several structural transformations.

- ✳ Moving forward -- many problems should be accounted for in the next generation of simulations. In particular, artificial clumps, over production of stars at high redshift.

- ✳Questions: Do we worry about solving the forming-too-many-stars-at-high-z catastrophe (is it a catastrophe?). Is it fair to measure stellar masses in our simulations by just counting stars, or should we do it photometrically from SED fitting?