Effects of the stochasticity of galaxy angular momentum growth on star formation

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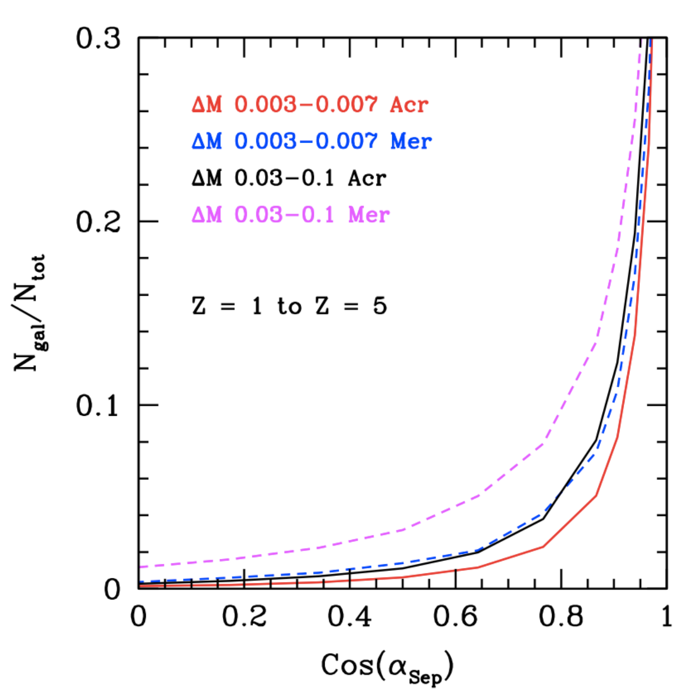
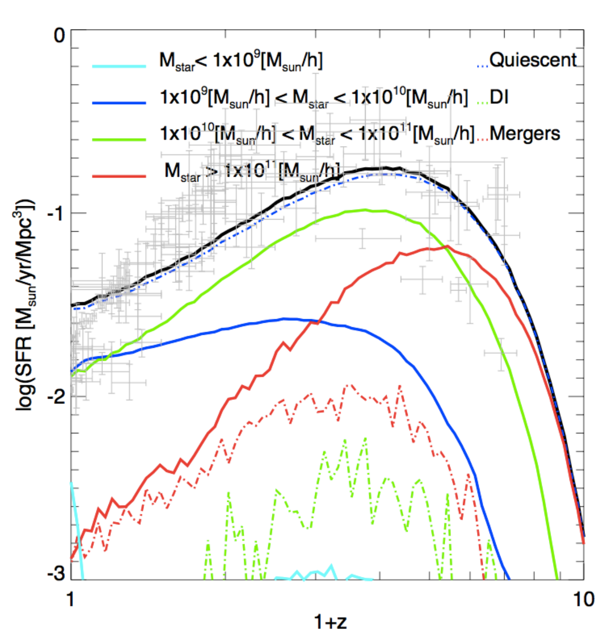
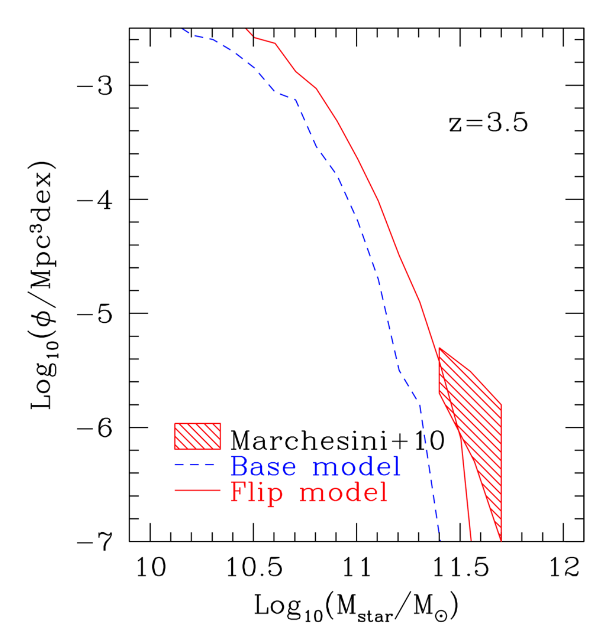
MARIE CURIE ACTIONS

OUTLINE

- 1 Models of galaxy formation
- 2 Angular mom. of infalling material and its effect in a SAM
- 3 Results







1) MODELS OF GALAXY FORMATION

Hydrodynamical simulations:

- Detailed processes of gas cooling, turbulence, preheating, star-formation, feedback (SN and AGN).
- Difficulties: over cooling, no grand-design spirals, difficulty to obtain statistical samples, lack of universality in codes.

Sales+12, Scannapieco+12, Marinacci+13, Crain+09, Powell+11, Brook+11, Nagamine10, Hopkins+11, Tasker+11, Kannan+13

Semi-analytic models

- Baryons via a set of equations per sub-halo of a merger tree extracted from cosmological DM-only simulations.
- Difficulties: simplified assumptions do not contain full complexity of galaxy evolution; e.g., by fitting z=0 LF, they make little SF at high-z.

Springel+01, Lagos, Cora & Padilla 08, Lagos, Padilla & Cora 09, Tecce+10, Lagos+11, Padilla+13

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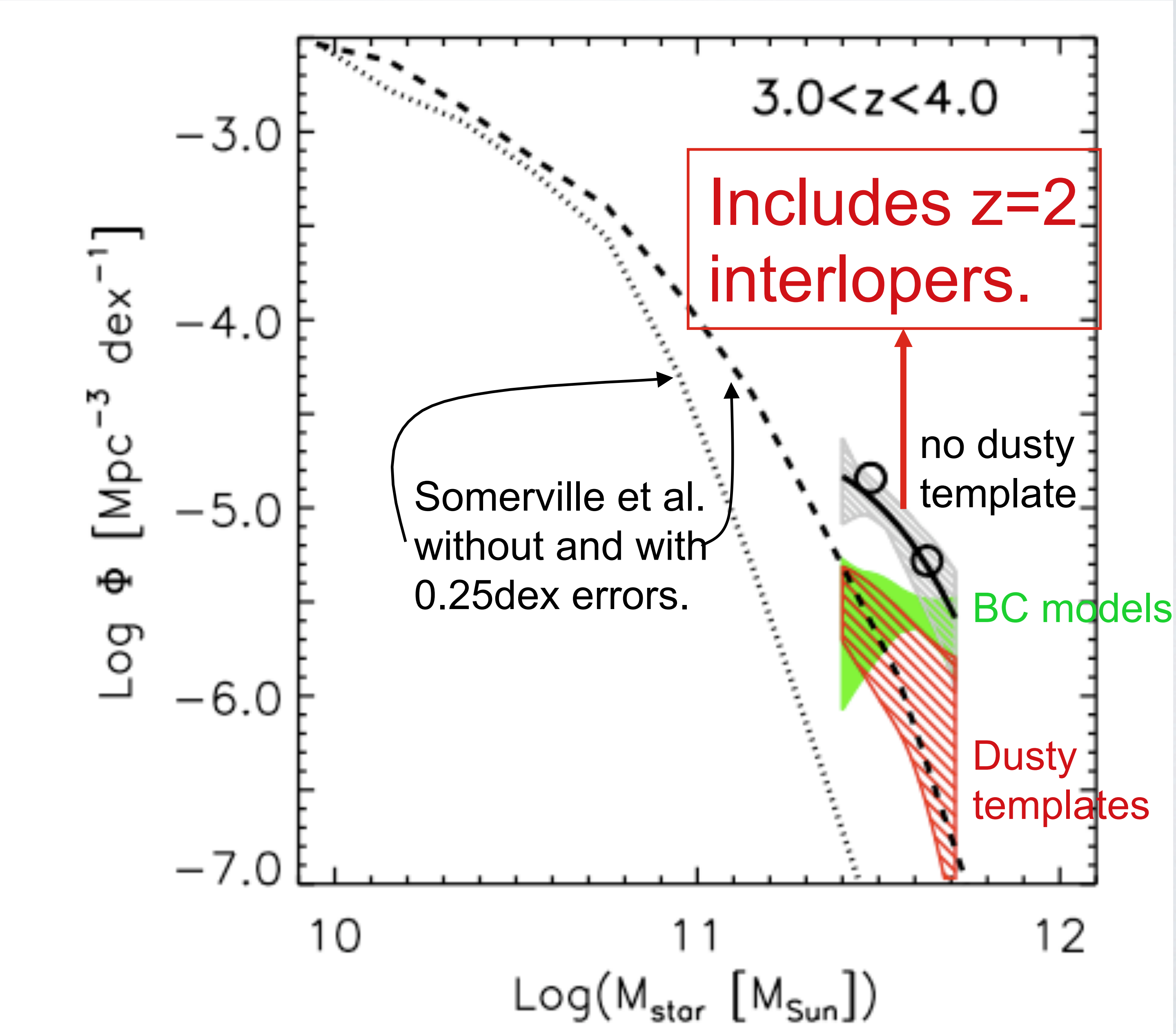
1) SAM PERFORMANCE AT HIGH-Z

General deficit of high-z massive galaxies

Example:
NEWFIRM Medium Band Survey
Marchesini et al. (2010)

By fitting the z=0 LF, and having large initial angular momenta in discs, SAMs slow down the high-z SF



2) ANGULAR MOMENTUM

Simplified assumption in SAM: dimensionless spin parameter is constant due to limited resolution in large cosmological volume simulations.

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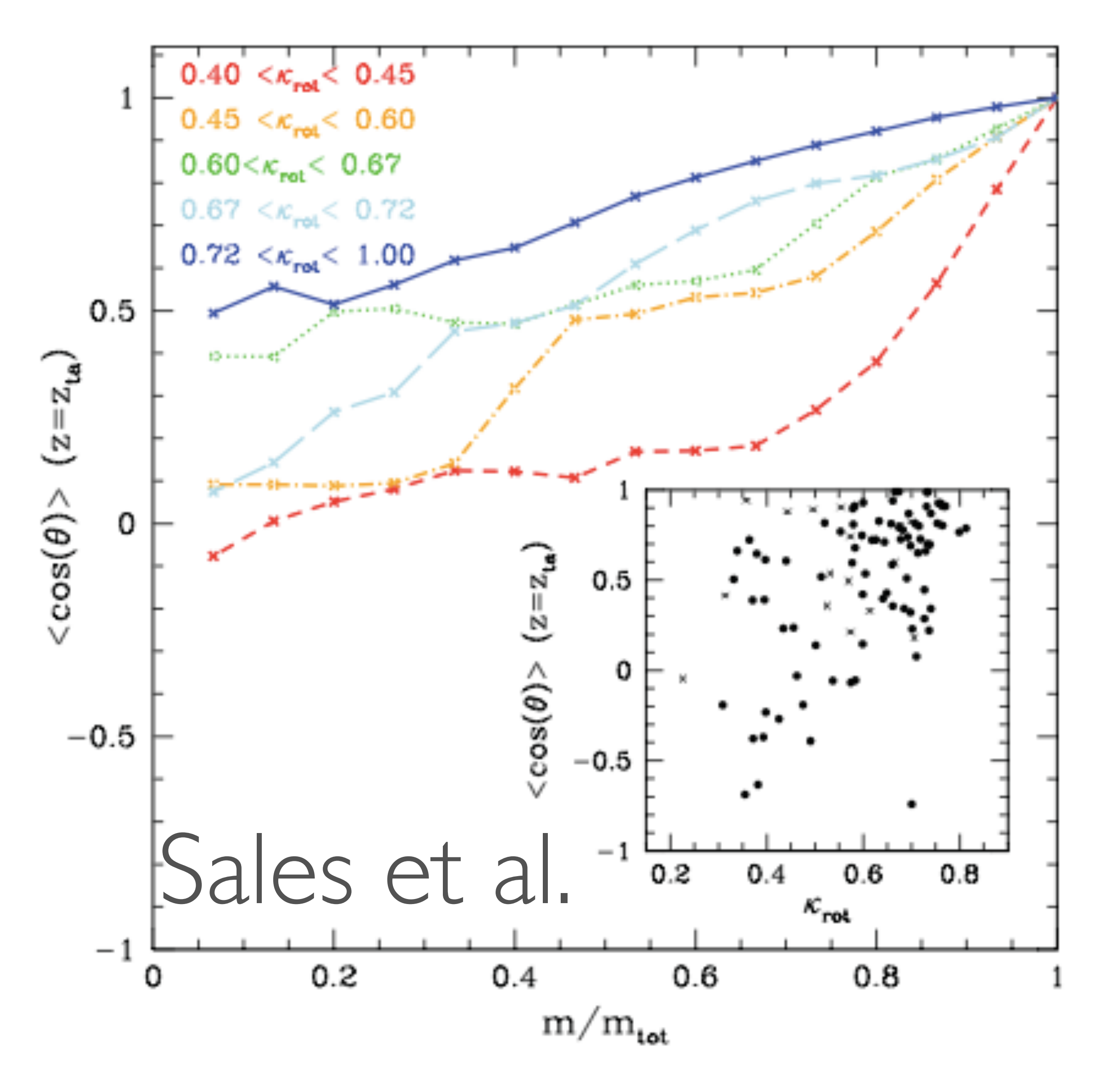
Using Hydro, Sales et al. (2012) show that surviving discs (k_rot high) in GIMIC show good alignment of angular momentum of mass enclosed in given radius (m/m_tot) with total angular momentum at time of turn-around.

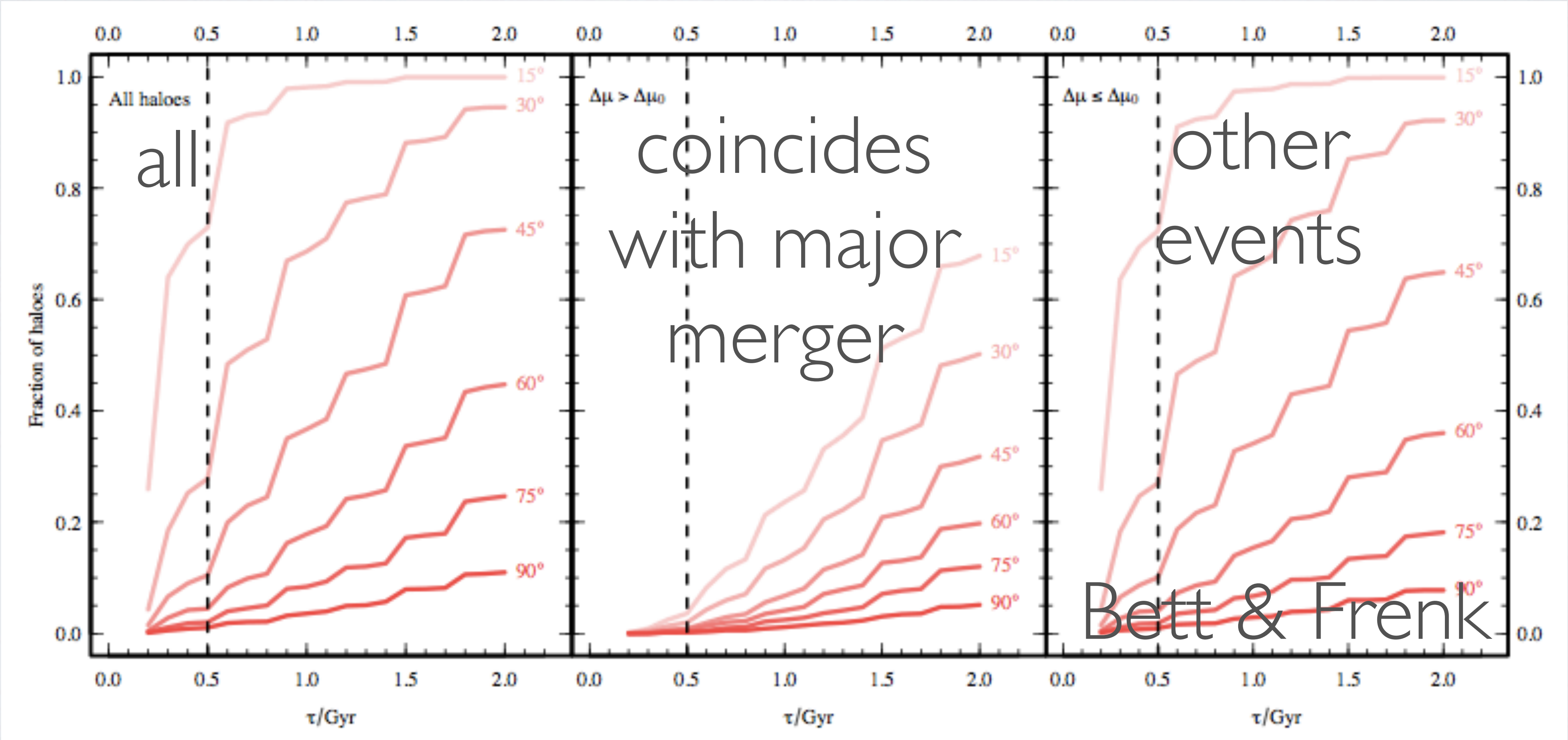
Missalignments by accretion of material destroy the disc, and a new disc starts to form. Discs are episodic and their spins not constant.



GIMIC

2) ANGULAR MOMENTUM

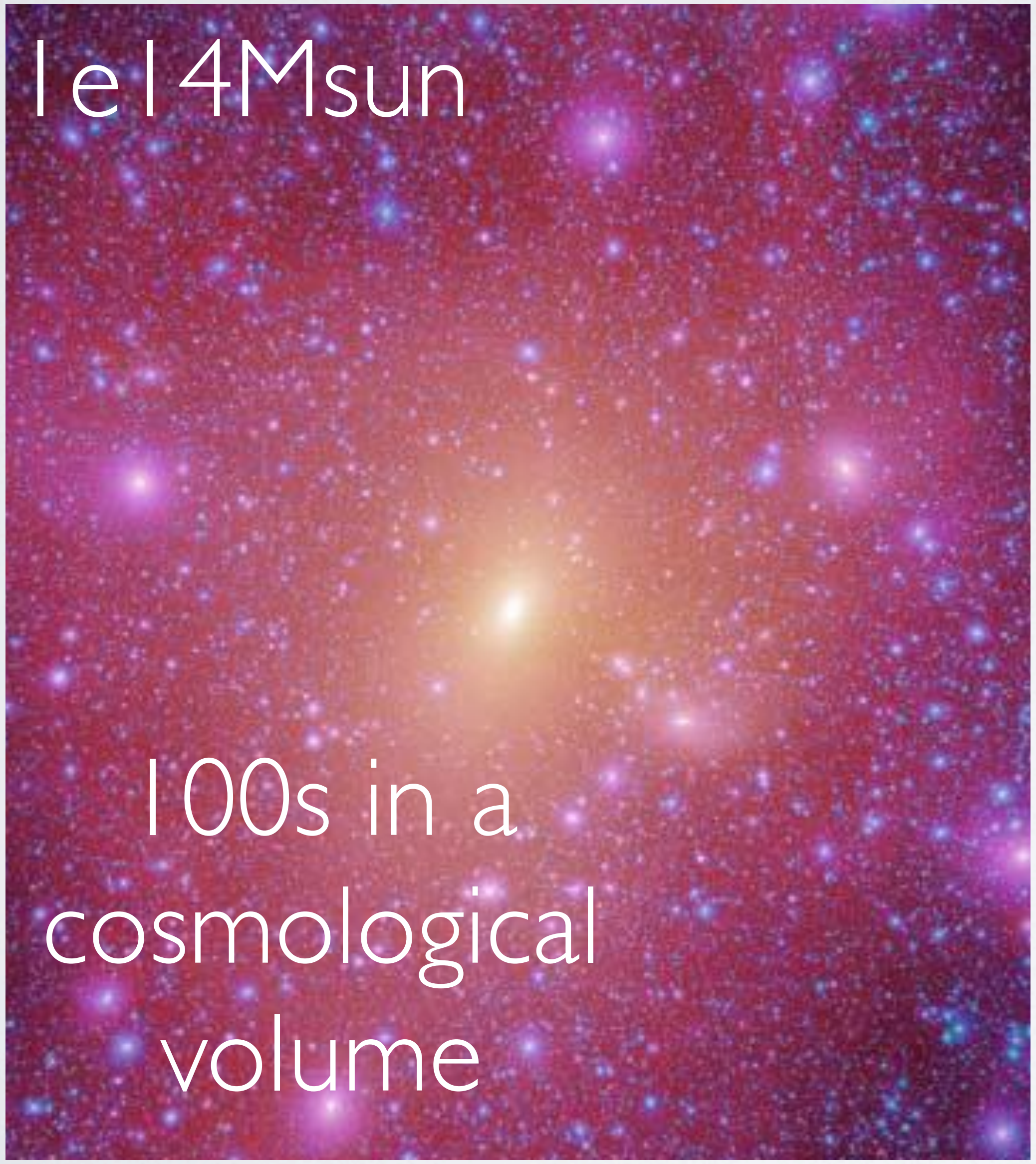
SAMs do not follow gas: Bett & Frenk (2011) study the occurrence of spin flips in DM halos in a high resolution simulation (using enough particles per halo):



flips produced by infalling material with angular momentum misaligned with that of DM halo.

2) ANGULAR MOMENTUM IN SAMS

In a SAM there are no particles tracing a disk, they trace DM halos. The angular momentum is easy to measure for well resolved ones.



But halos in SAMs are sometimes resolved with 10 particles

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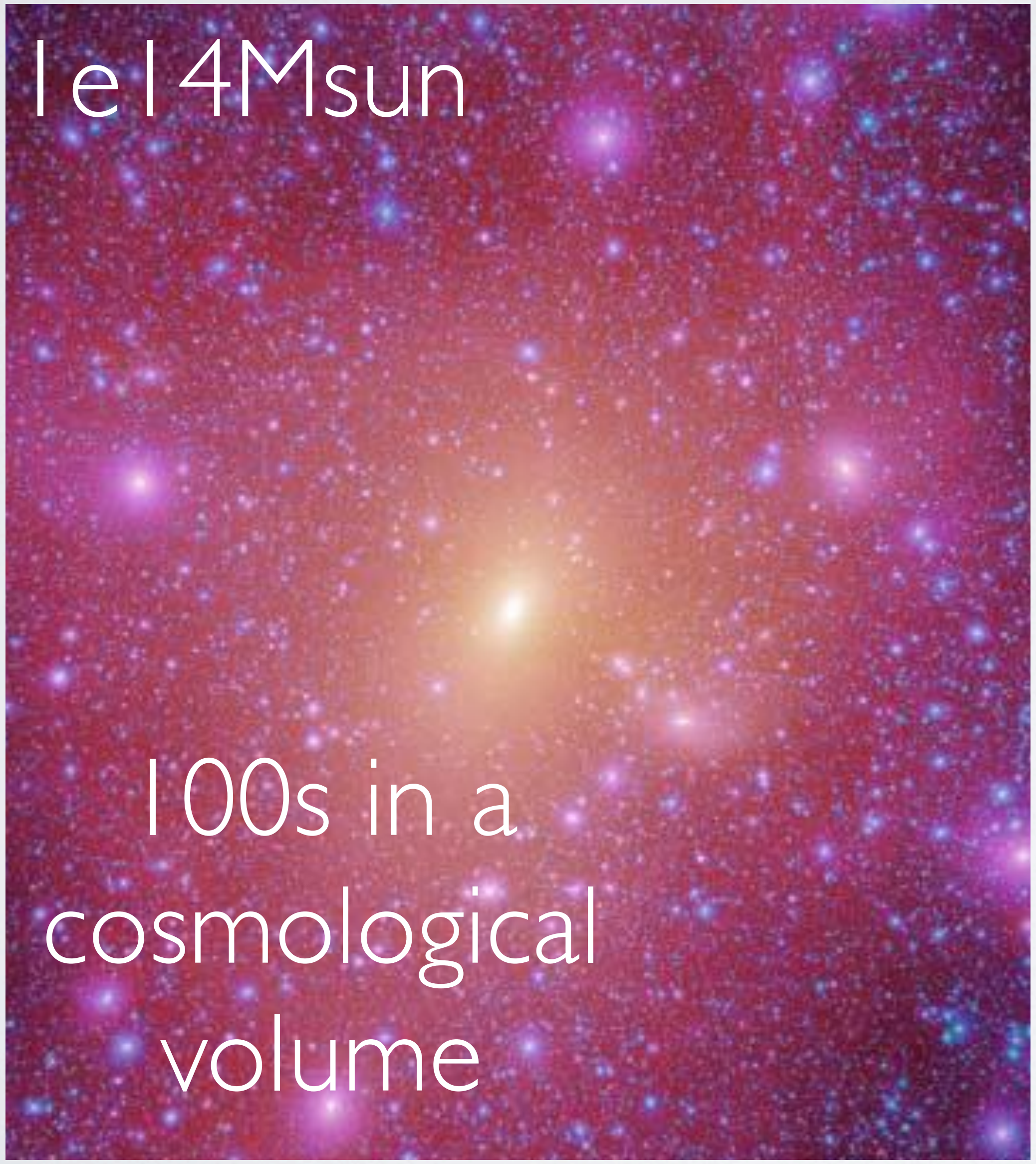

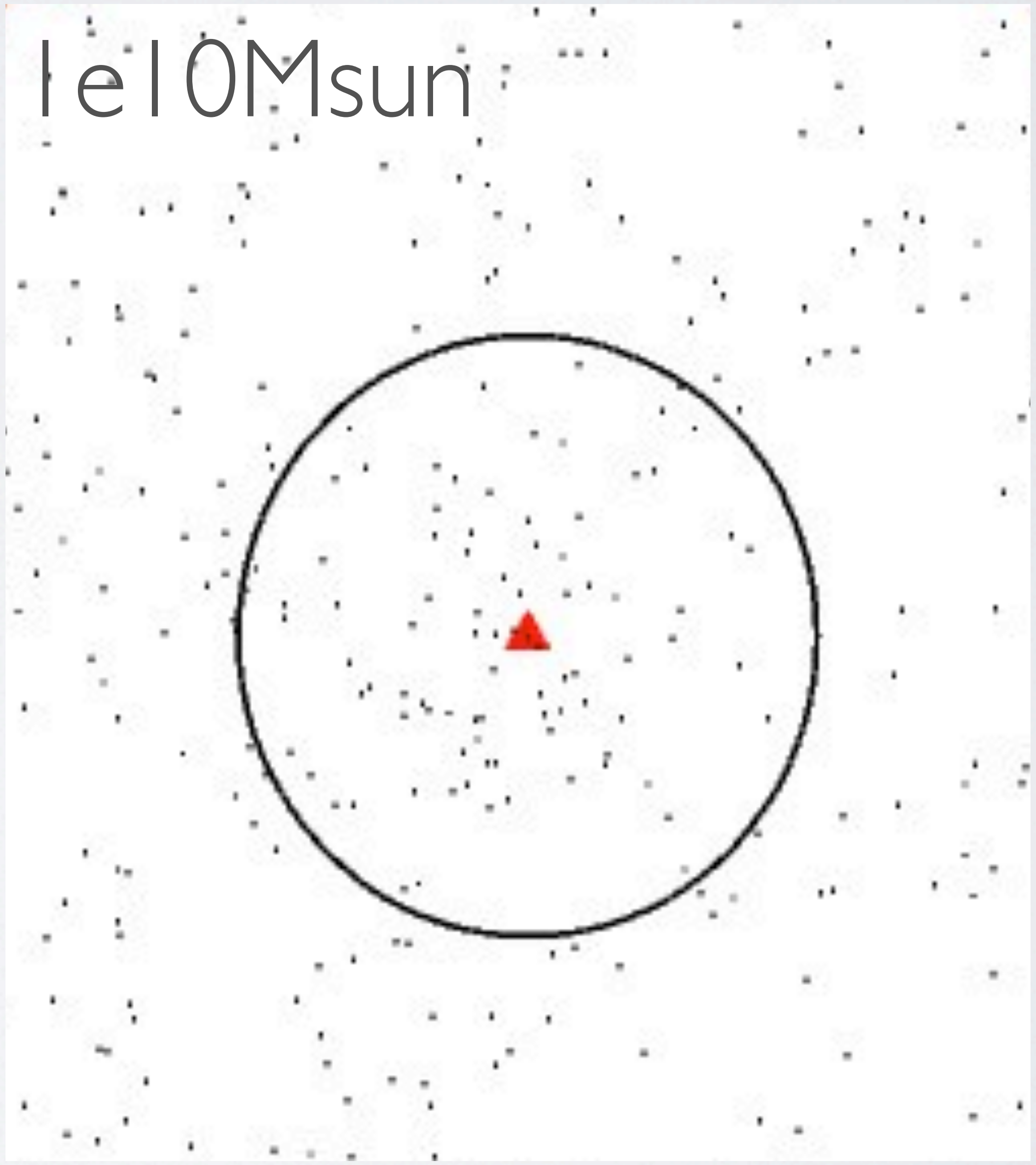

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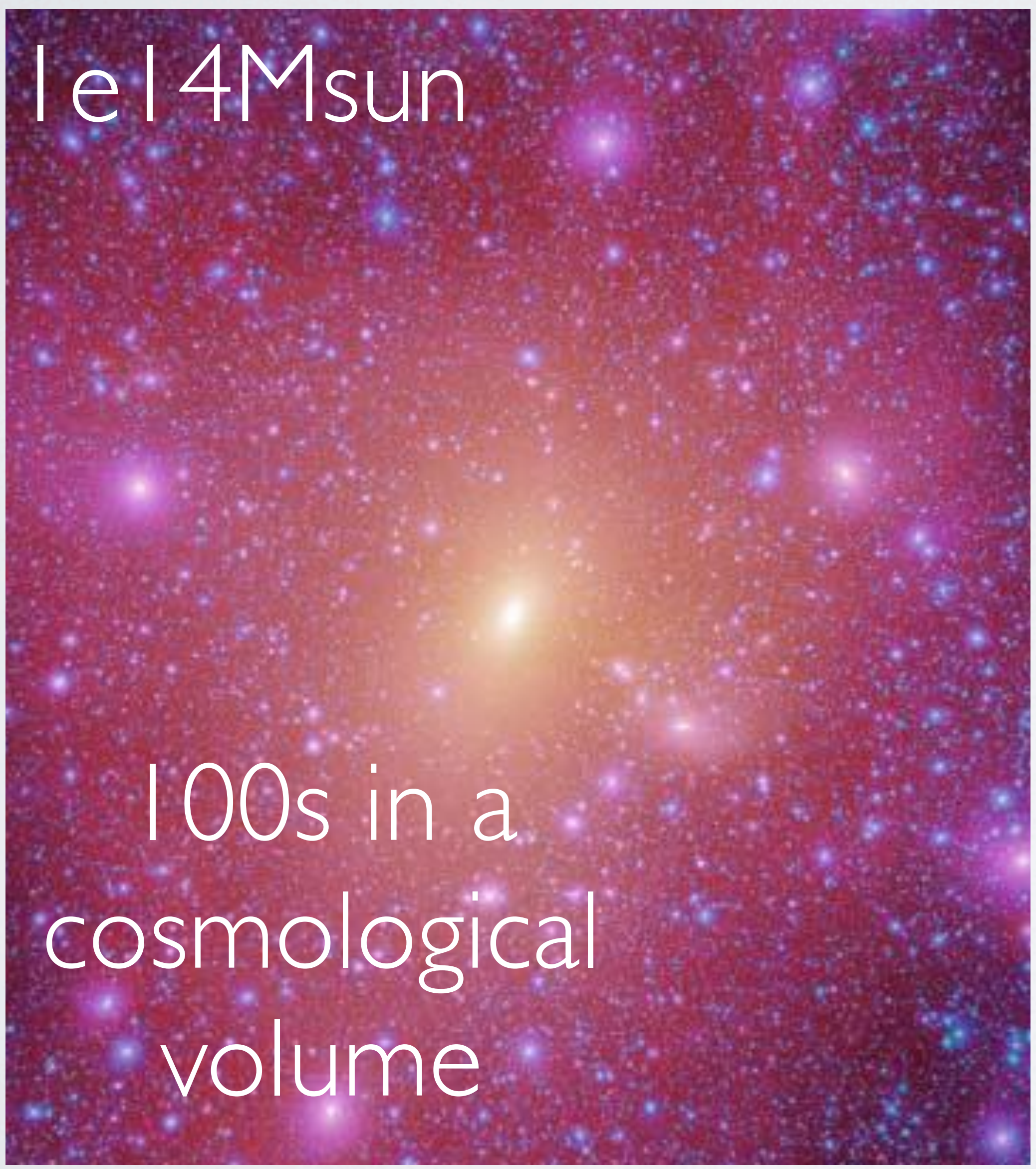
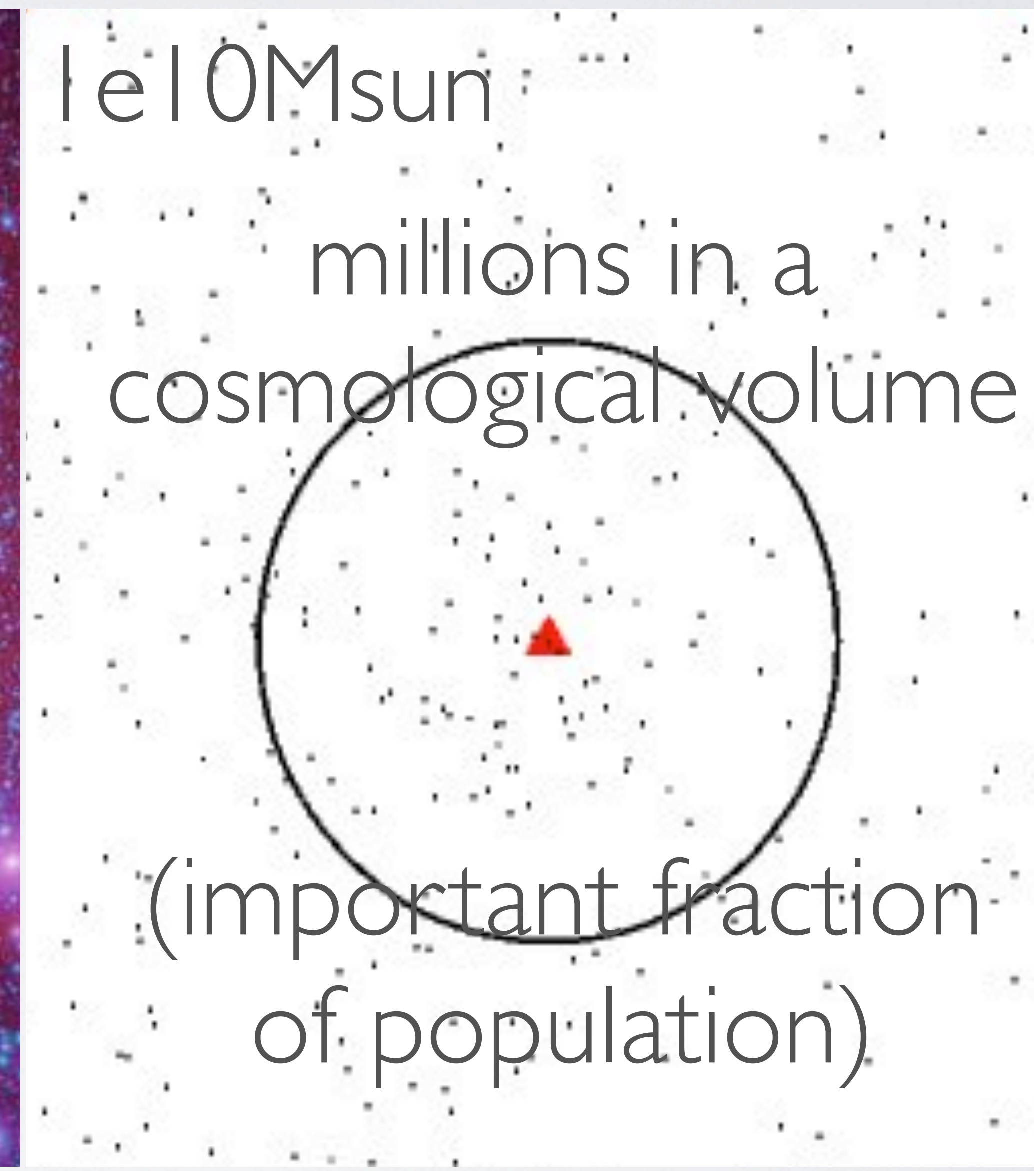




But halos in SAMs are sometimes resolved with 10 particles

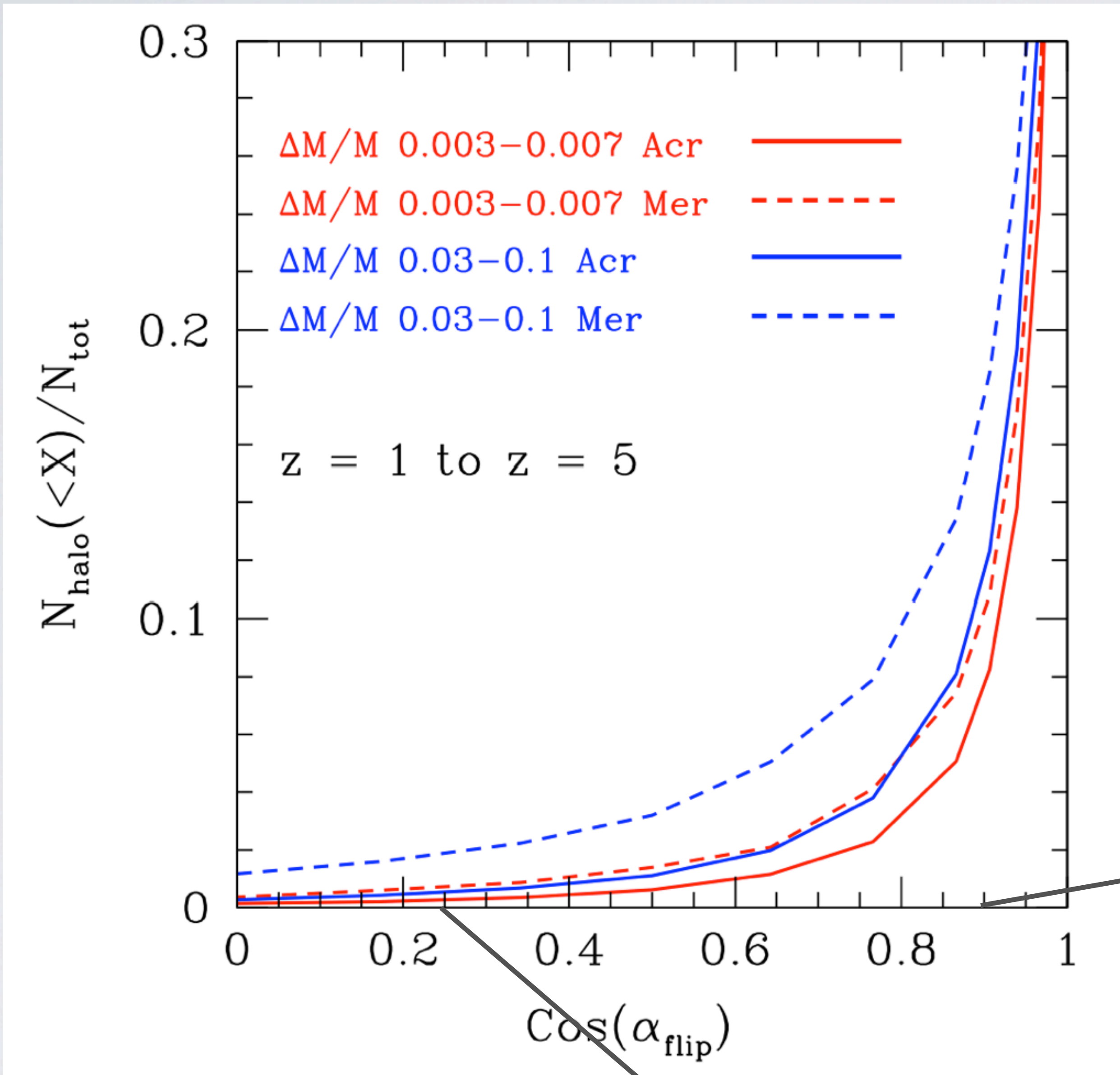
2) ANGULAR MOMENTUM IN SAMS

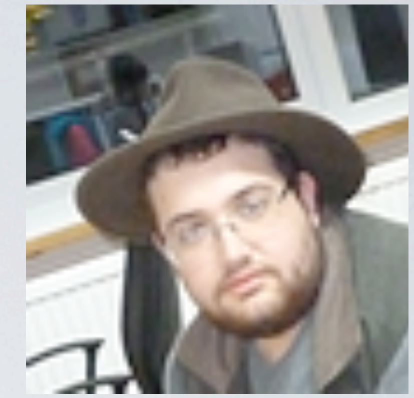
Use high resolution Millennium II simulation:
Angular momentum followed numerically
A halo needs to have at least 1000 particles for a reliable measurement of the three components of its angular momentum vector.

Low resolution (SAMs):
Directions of spins assigned using MC simulations

Lagos, Cora & Padilla (2008), Lagos, Padilla & Cora (2009), Tecce et al. (2010)

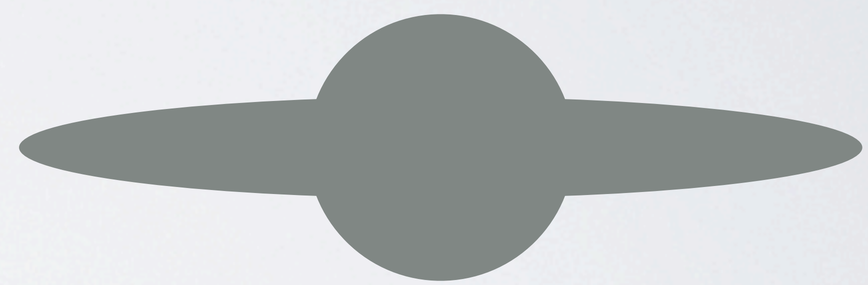
2) ANGULAR MOMENTUM IN SAMS

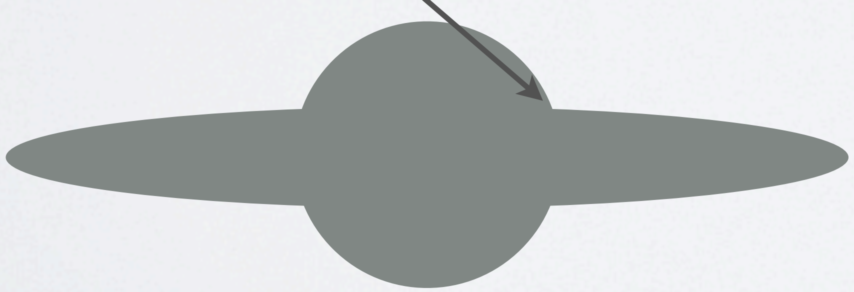




S. Contreras

Interpretation for a semi-analytic galaxy:





Convert into probability of alpha_sep for a given accretion event.

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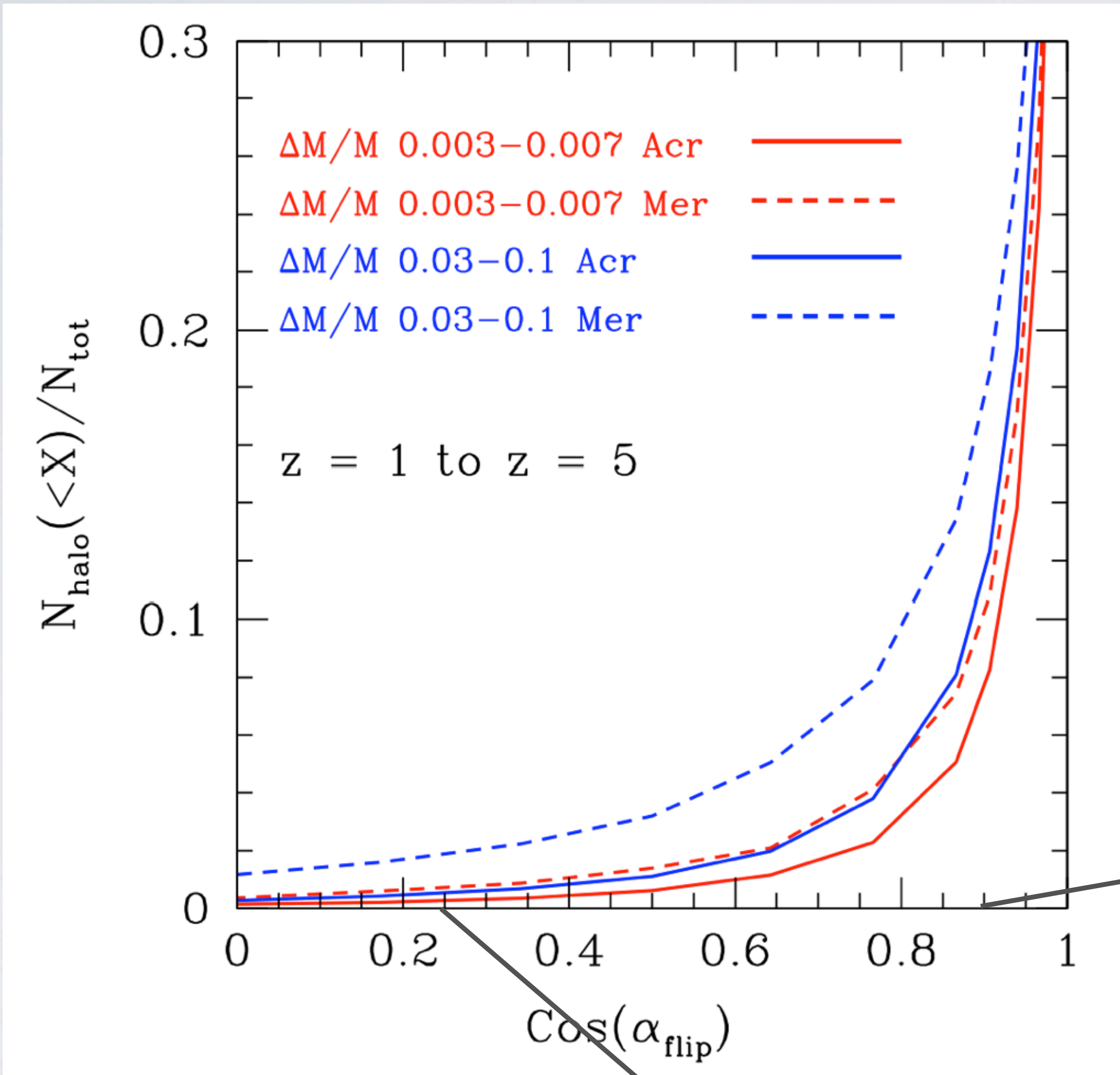

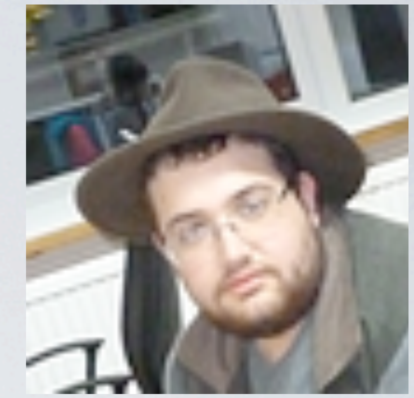

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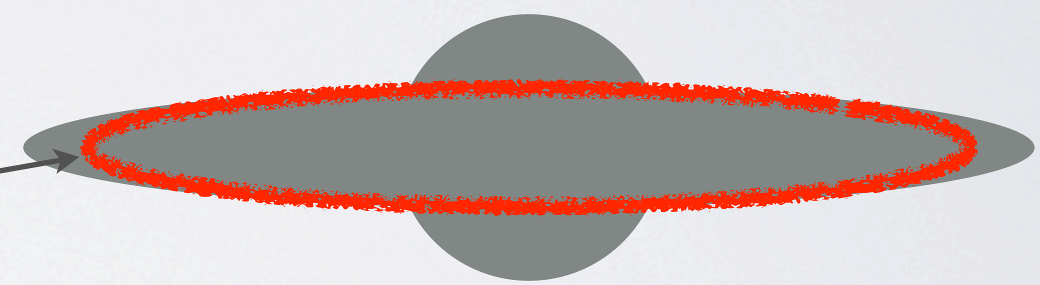
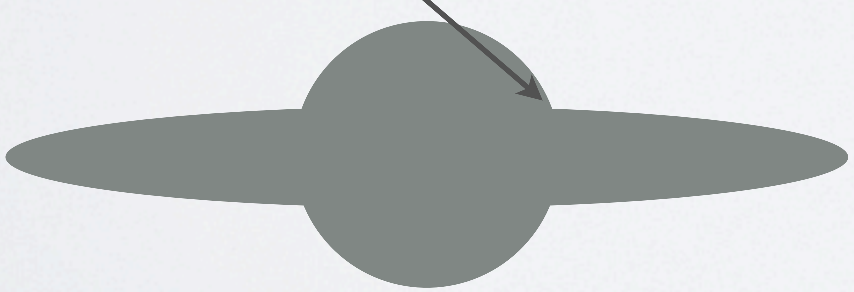


Angular momentum and size increase



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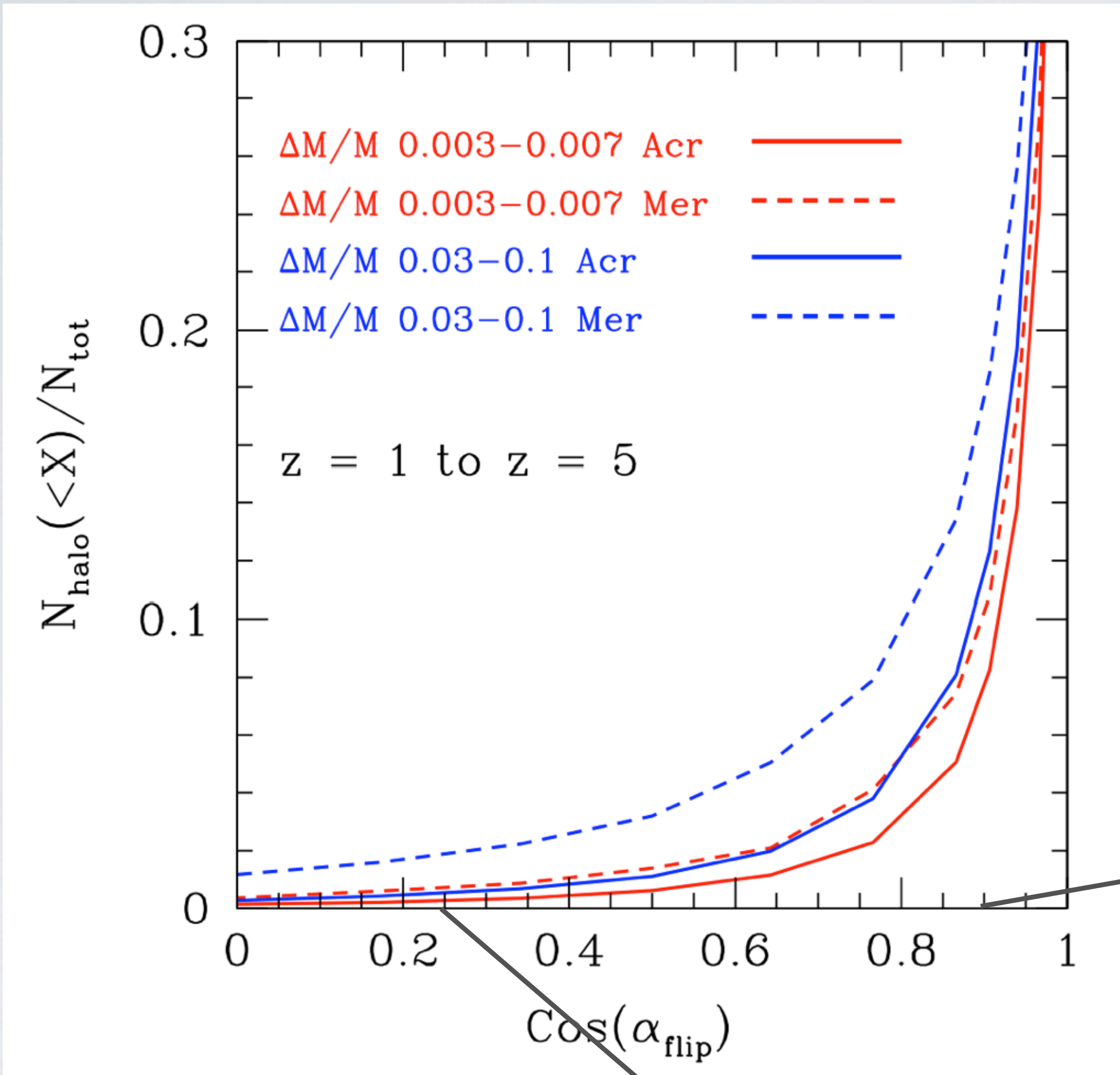

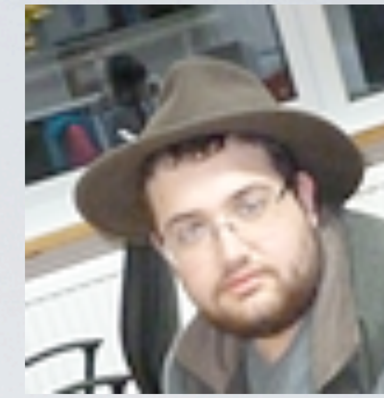

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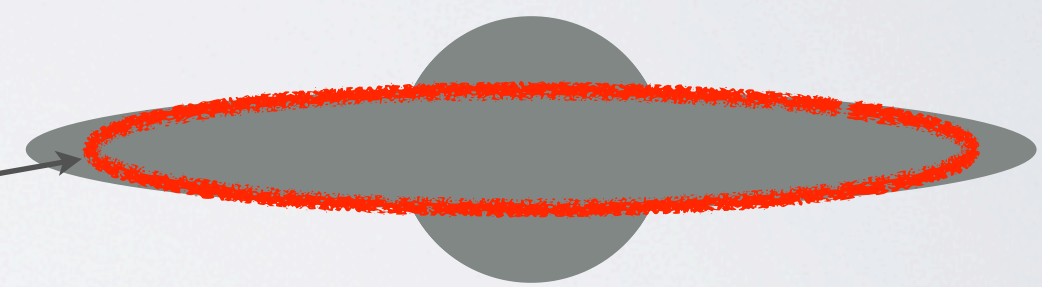

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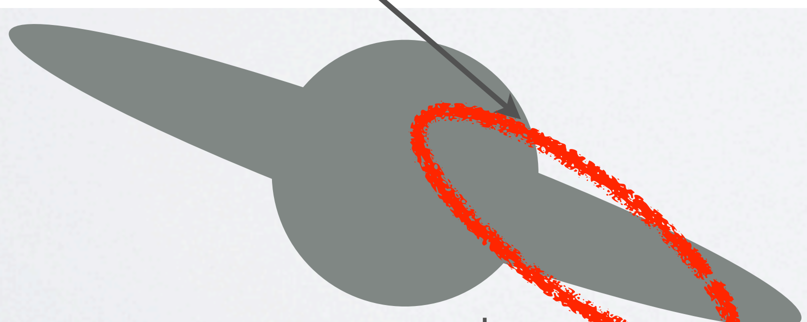

Angular momentum does not increase

Convert into probability of alpha_sep for a given accretion event.

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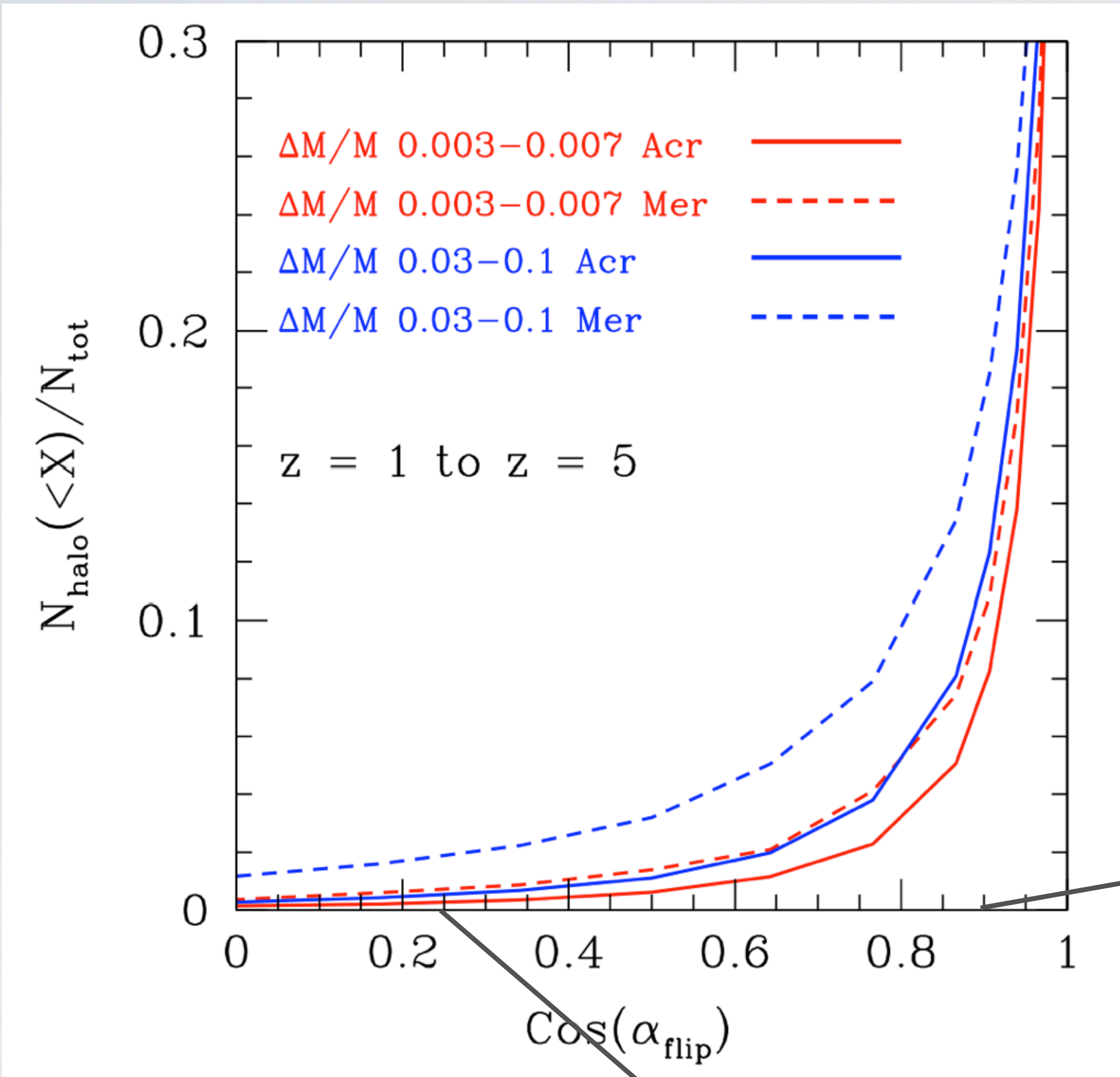

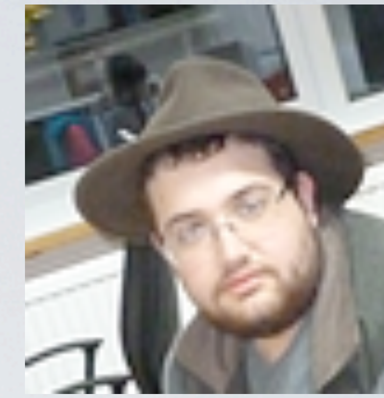

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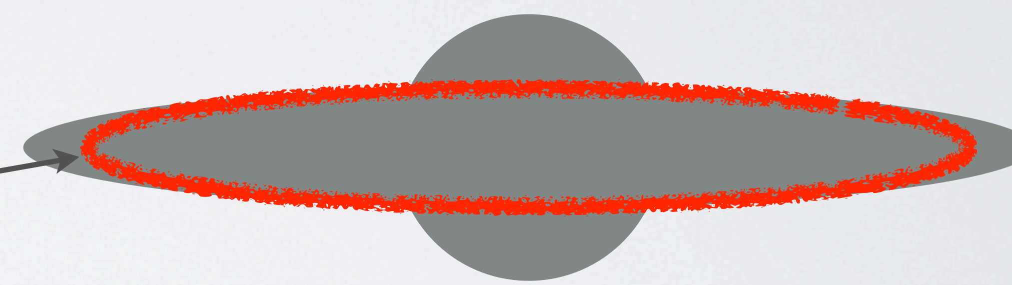

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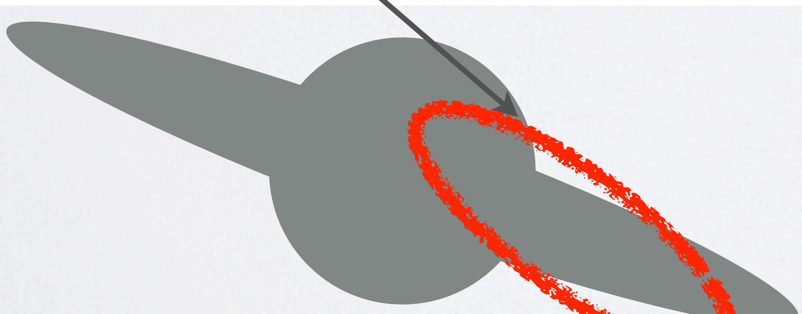


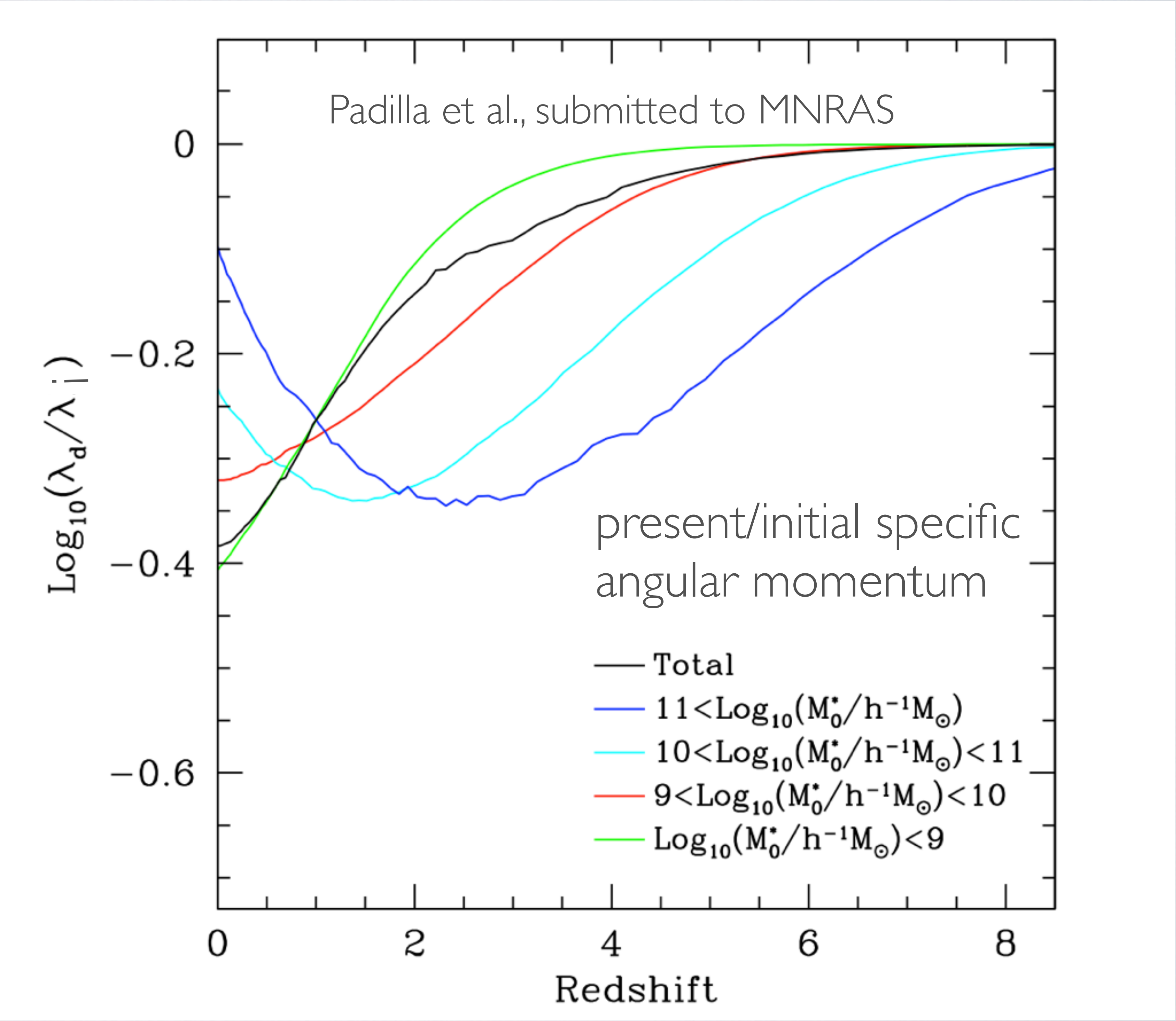
Angular momentum does not increase

Convert into probability of alpha_sep for a given accretion event.

Rd_new=Rd_init*cos(alpha_flip)

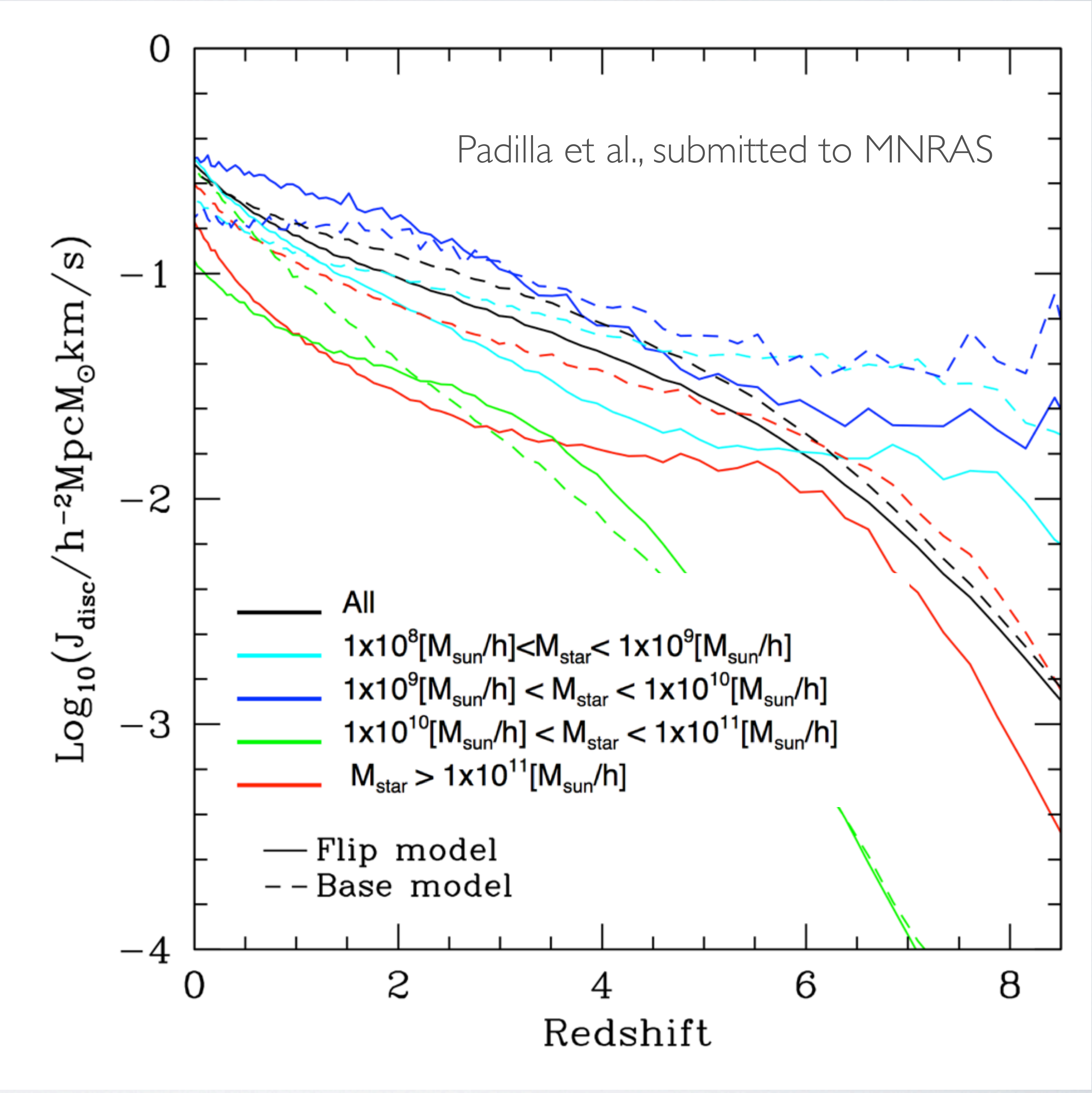
2) ANGULAR MOMENTUM IN SAMS

Resulting ratios between present-day and initial specific angular momentum of disc



2) ANGULAR MOMENTUM IN SAMS

Resulting slower increase of disc angular momentum



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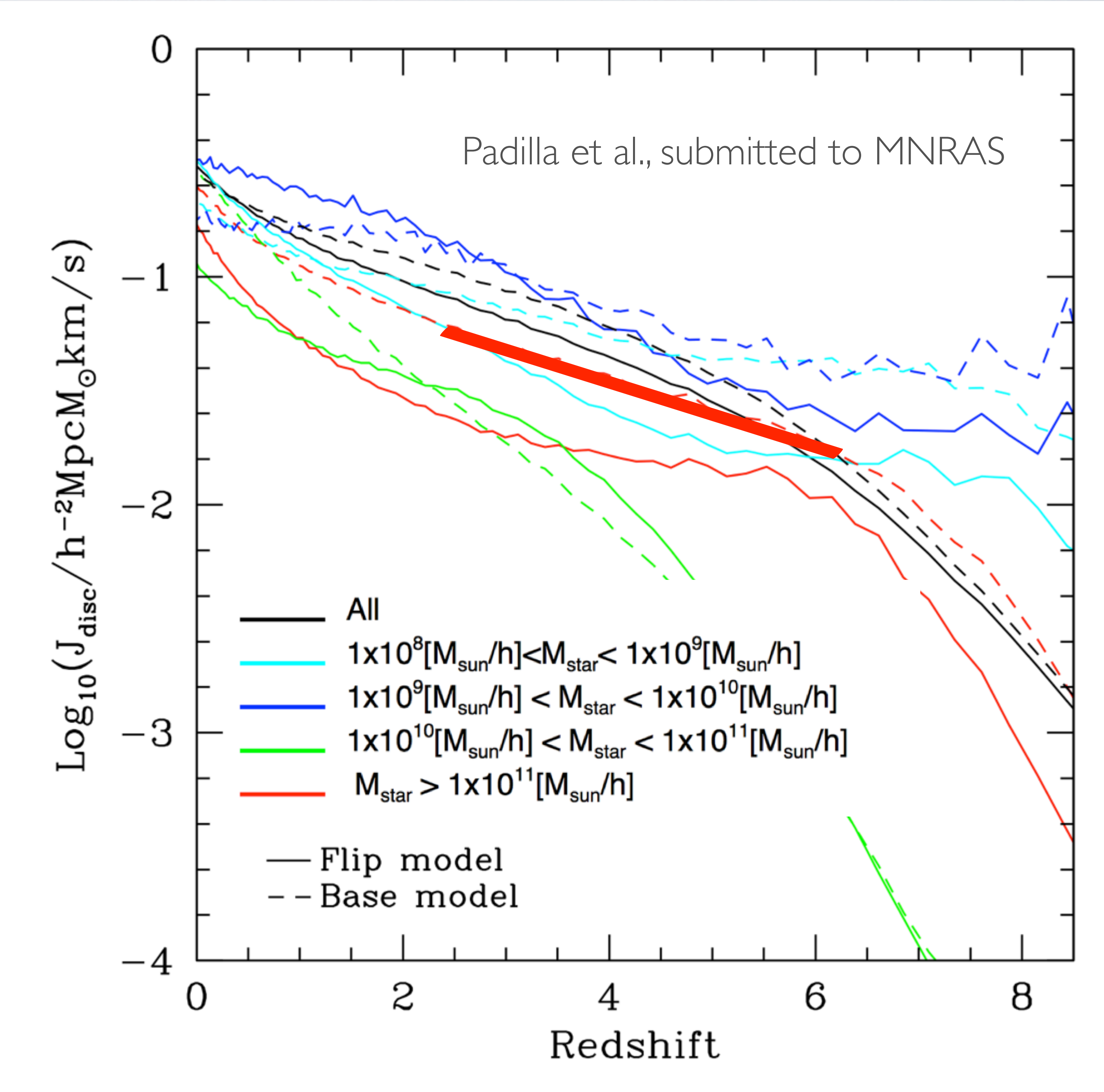

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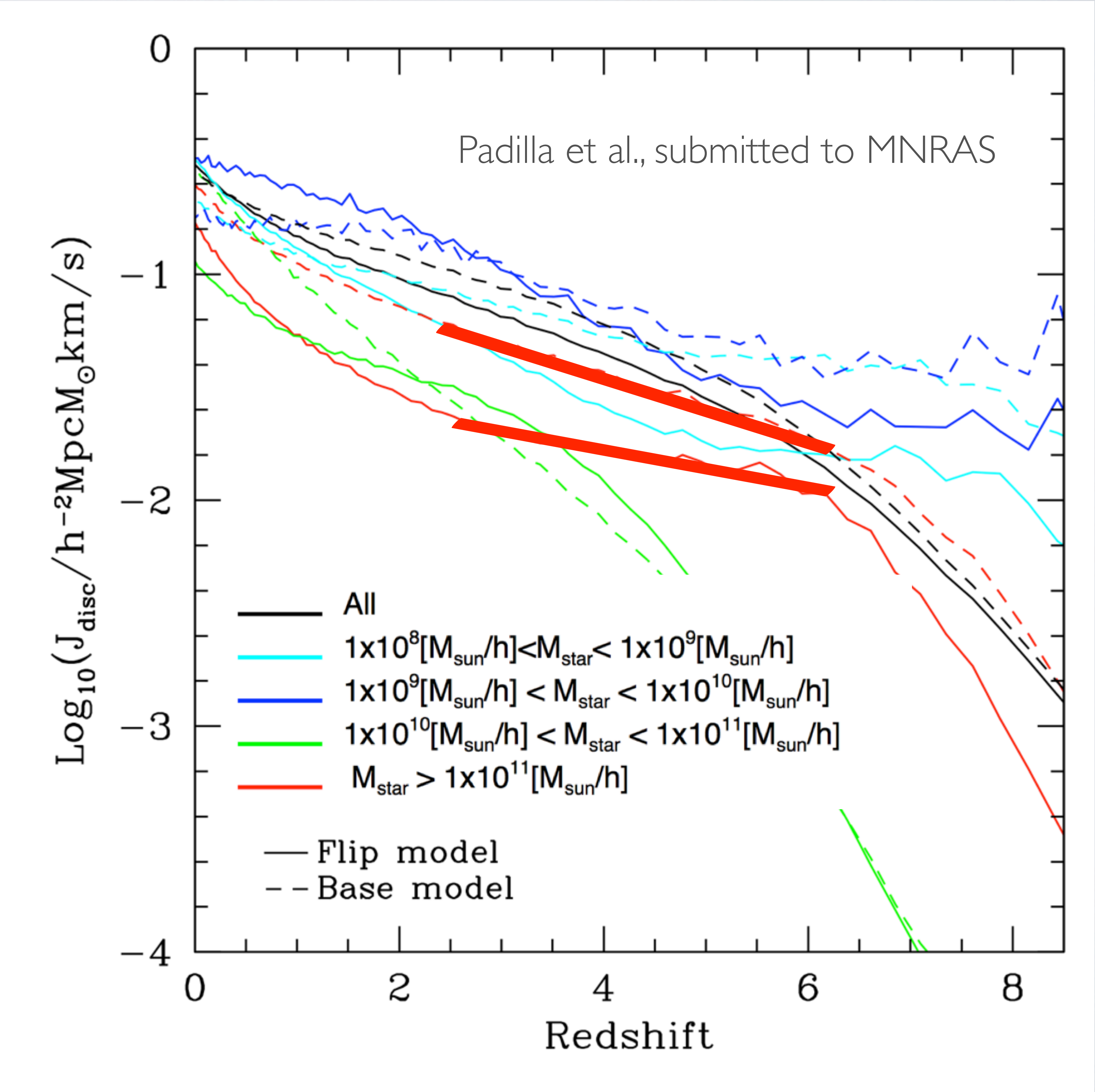

2) EFFECT ON SF

Using the SF law from Croton et al. (2006) which considers a threshold surface density of gas to form stars.

$$R_d = \frac{1}{\sqrt{2}}\left(\frac{j_d}{m_d}\right)\lambda r_{\rm vir} f_c^{-1/2} f_R(\lambda, c, m_d, j_d)$$

MMW

$$f_c \simeq \frac{2}{3} + \left(\frac{c}{21.5}\right)^{0.7} \qquad f_R(\lambda, c, m_d, j_d) = 2\left[\int_0^\infty e^{-u} u^2 \frac{V_c(R_d u)}{V_{\rm vir}} du\right]^{-1}$$

Star formation on dense enough discs (Croton+06):

$$m_{\rm crit} = 3.8 \times 10^9 \left(\frac{V_{\rm vir}}{200\ {\rm km\ s^{-1}}}\right)\left(\frac{r_{\rm disc}}{10\ {\rm kpc}}\right) {\rm M_\odot}$$

$$\dot{m}_* = \alpha_{\rm SF}(m_{\rm cold} - m_{\rm crit})/t_{\rm dyn,disc}$$

t_dyn= $r_{\rm disc}/V_{\rm vir}$

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$$\dot{m}_* = \alpha_{\mathrm{SF}}(m_{\mathrm{cold}} - m_{\mathrm{crit}})/t_{\mathrm{dyn,disc}} \qquad \text{t\_dyn}= r_{\mathrm{disc}}/V_{\mathrm{vir}}$$

Smaller disc size => higher star formation rates

2) EFFECT ON SF

Disk instabilities:

$$\epsilon = \frac{V_{\rm max}}{(GM_{\rm disc}/r_{\rm disc})^{1/2}},$$

if lower than critical value
disc is unstable

Smaller radius makes
more frequent instabilities

After a disk instability driven starburst, disc forms again with initial halo angular momentum.

2) EFFECT ON SF

Disk instabilities:

$$\epsilon = \frac{V_{\rm max}}{(GM_{\rm disc}/r_{\rm disc})^{1/2}},$$

if lower than critical value disc is unstable

Flip from merger lowers rdisk and triggers instabilities

After a merger driven starburst, disc forms again with initial halo angular momentum.

2) EFFECT ON SF

Disk instabilities:

$$\epsilon = \frac{V_{\rm max}}{(GM_{\rm disc}/r_{\rm disc})^{1/2}},$$

Disc instability as the only driver of bursts in the model.

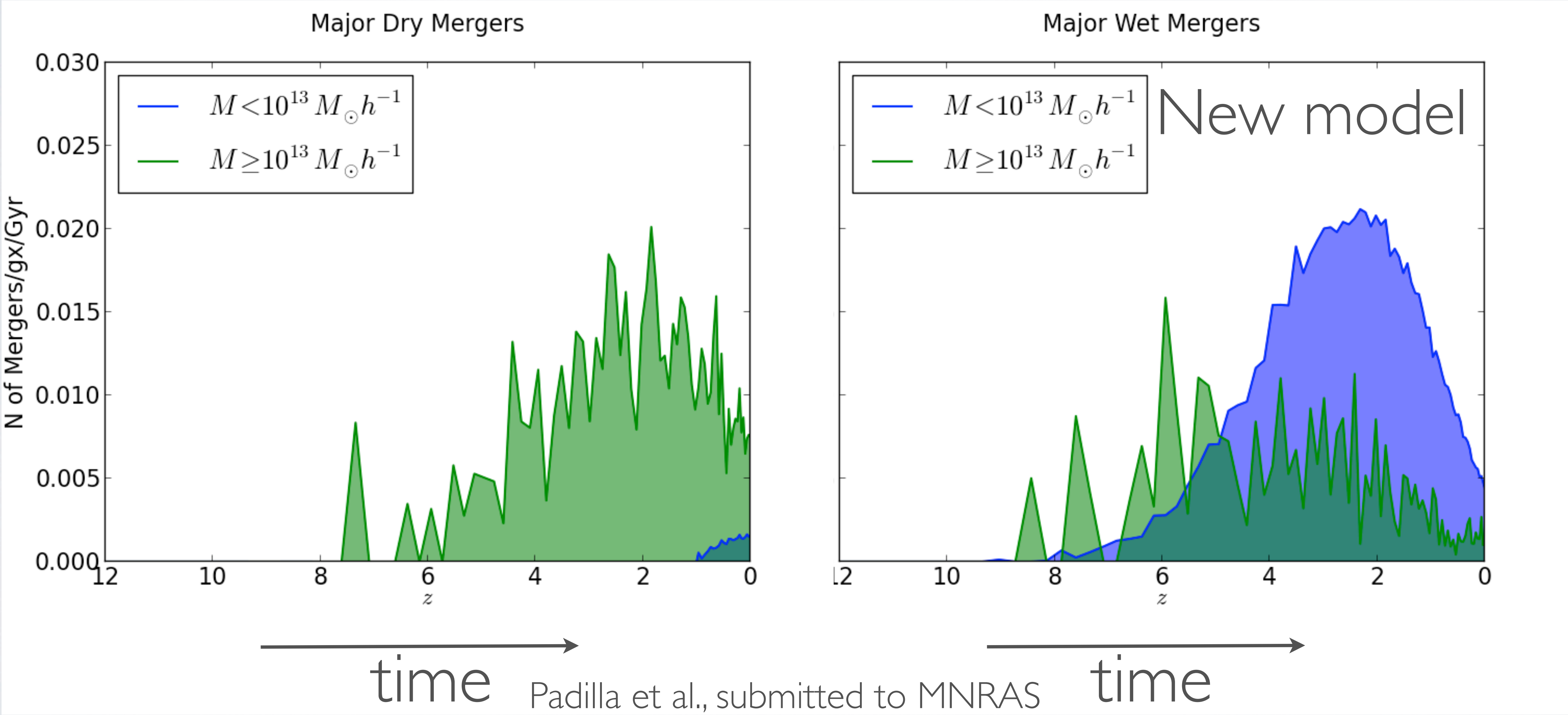
if lower than critical value disc is unstable

Flip from merger lowers rdisk and triggers instabilities

After a merger driven starburst, disc forms again with initial halo angular momentum.

2) EFFECT ON MERGERS

S. Salazar



Padilla et al., submitted to MNRAS

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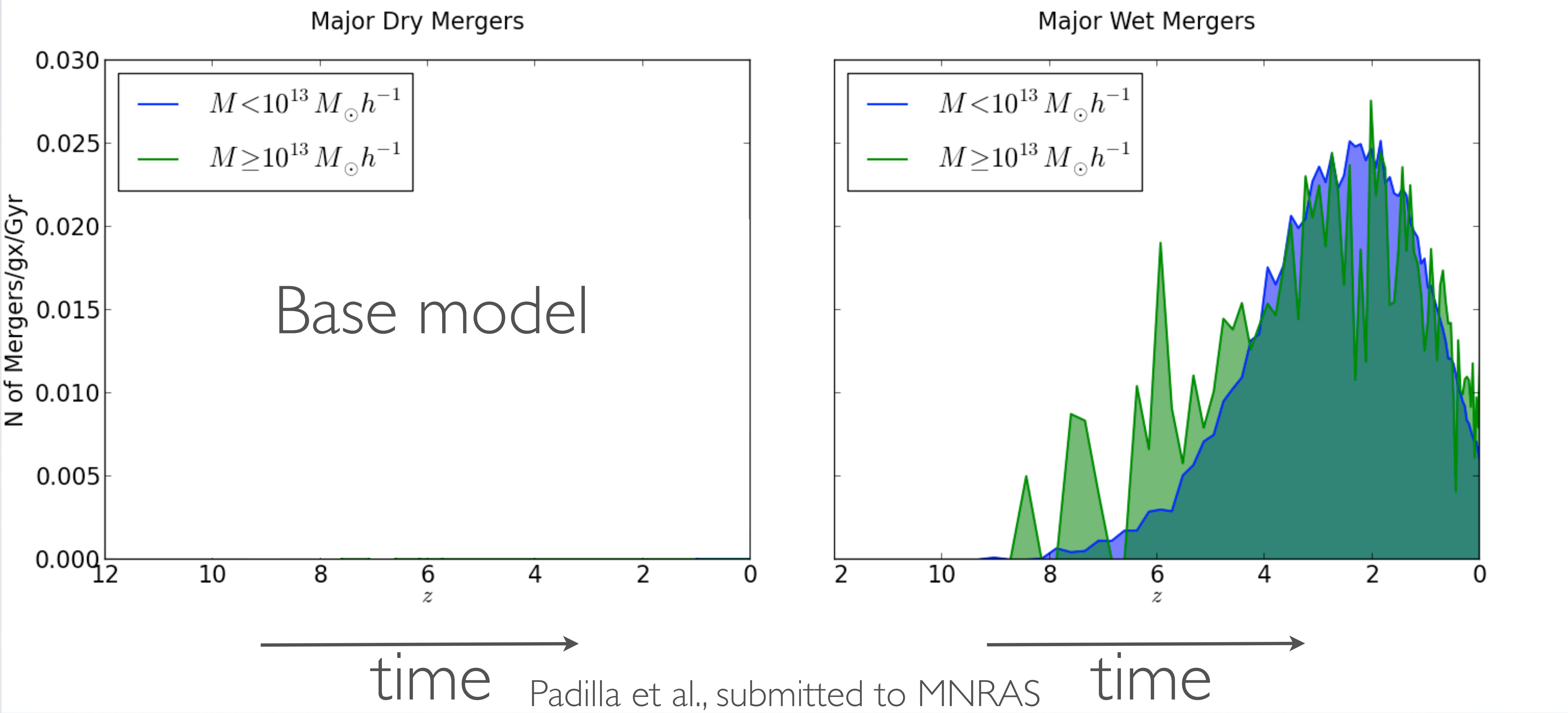

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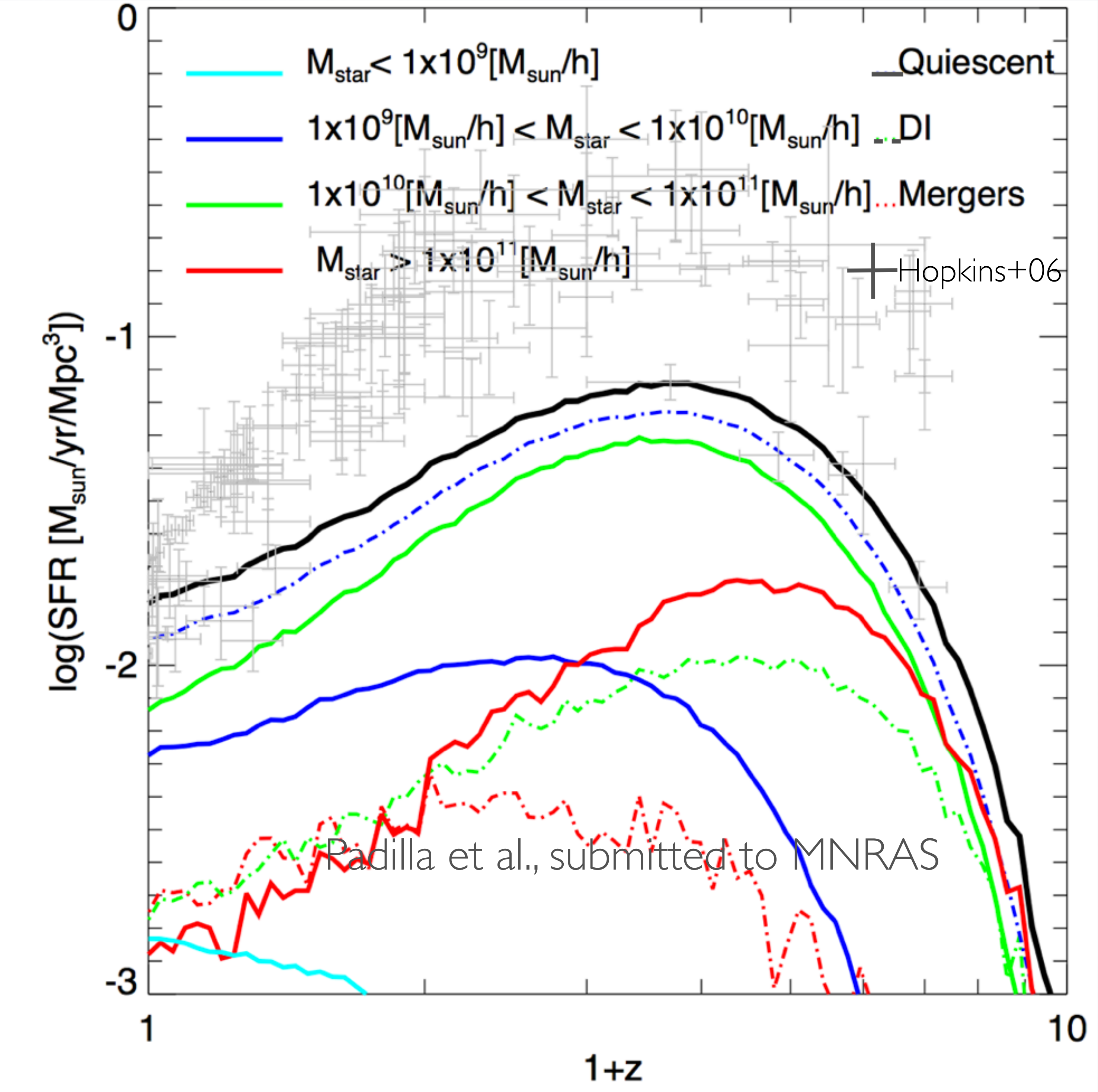
2) EFFECT ON SF

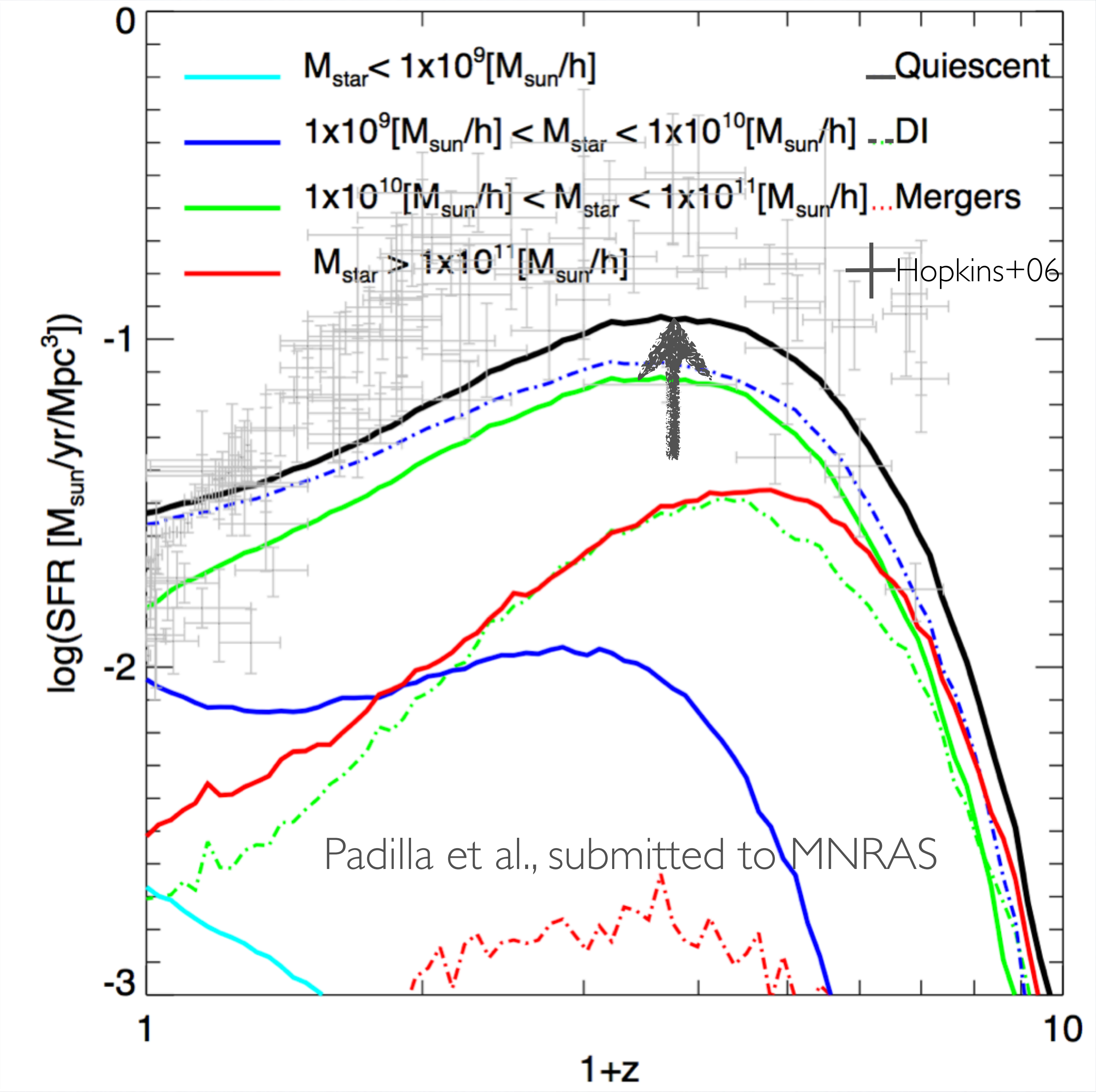
Smooth growth in disc size



2) EFFECT ON SF

With episodic discs

Rdisk is smaller,
Tdyn is smaller,
SFR is higher,
comparatively

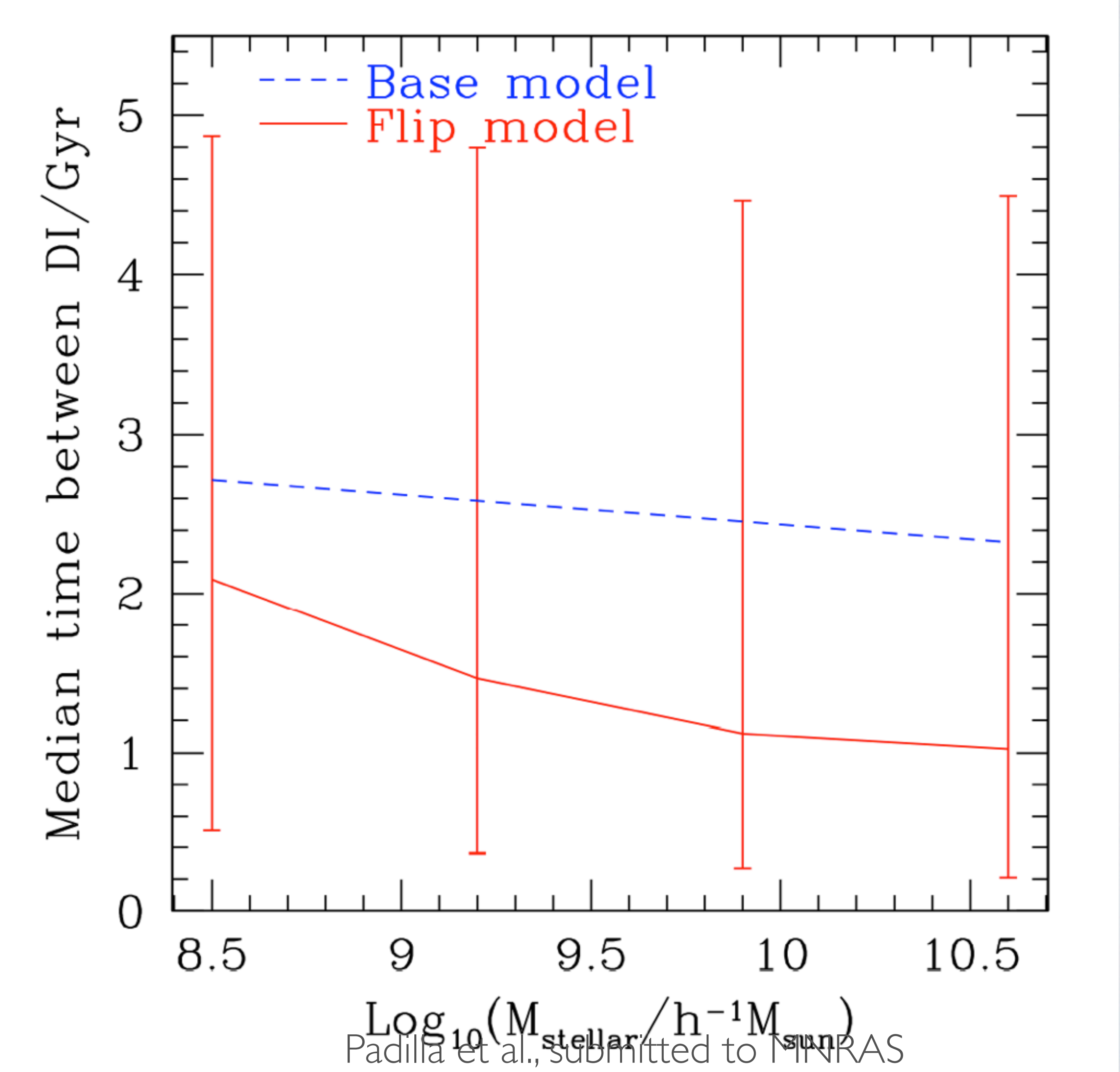


2) EFFECT ON SF

Disc life-times

Base Model

With episodic discs



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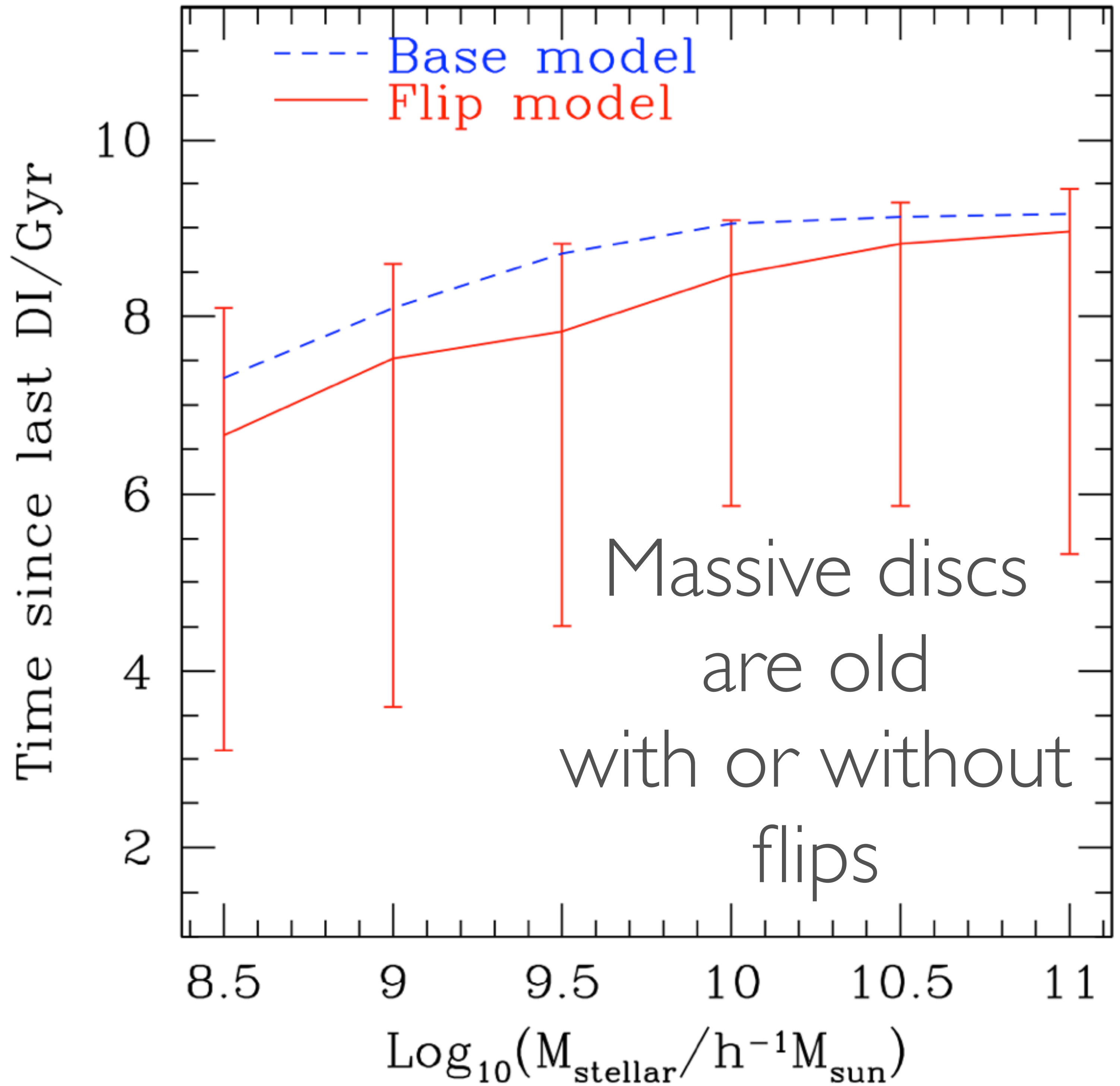
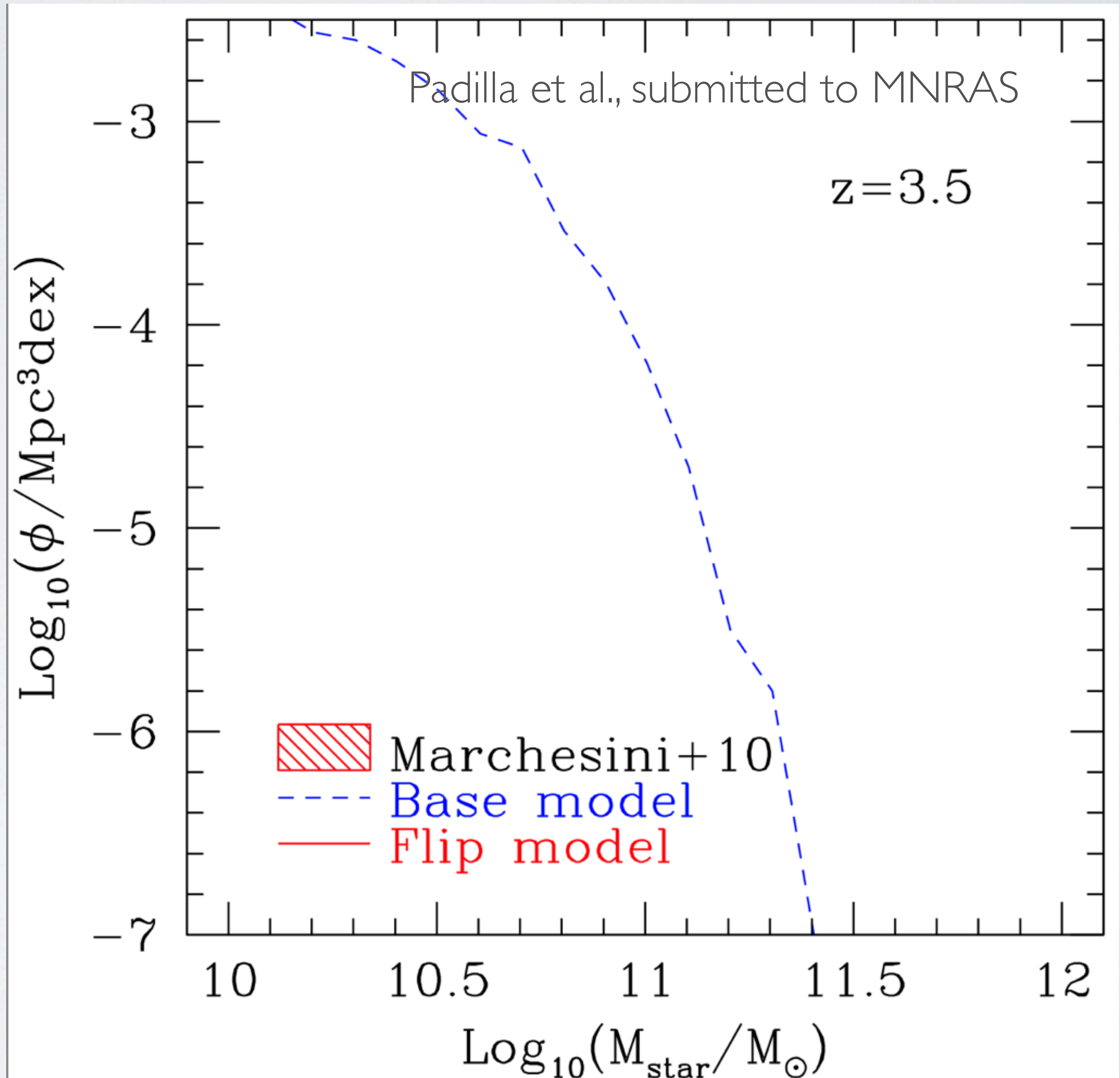


Massive discs are old with or without flips

Padilla et al., submitted to MNRAS

3) RESULTS: HIGH-Z MASSES

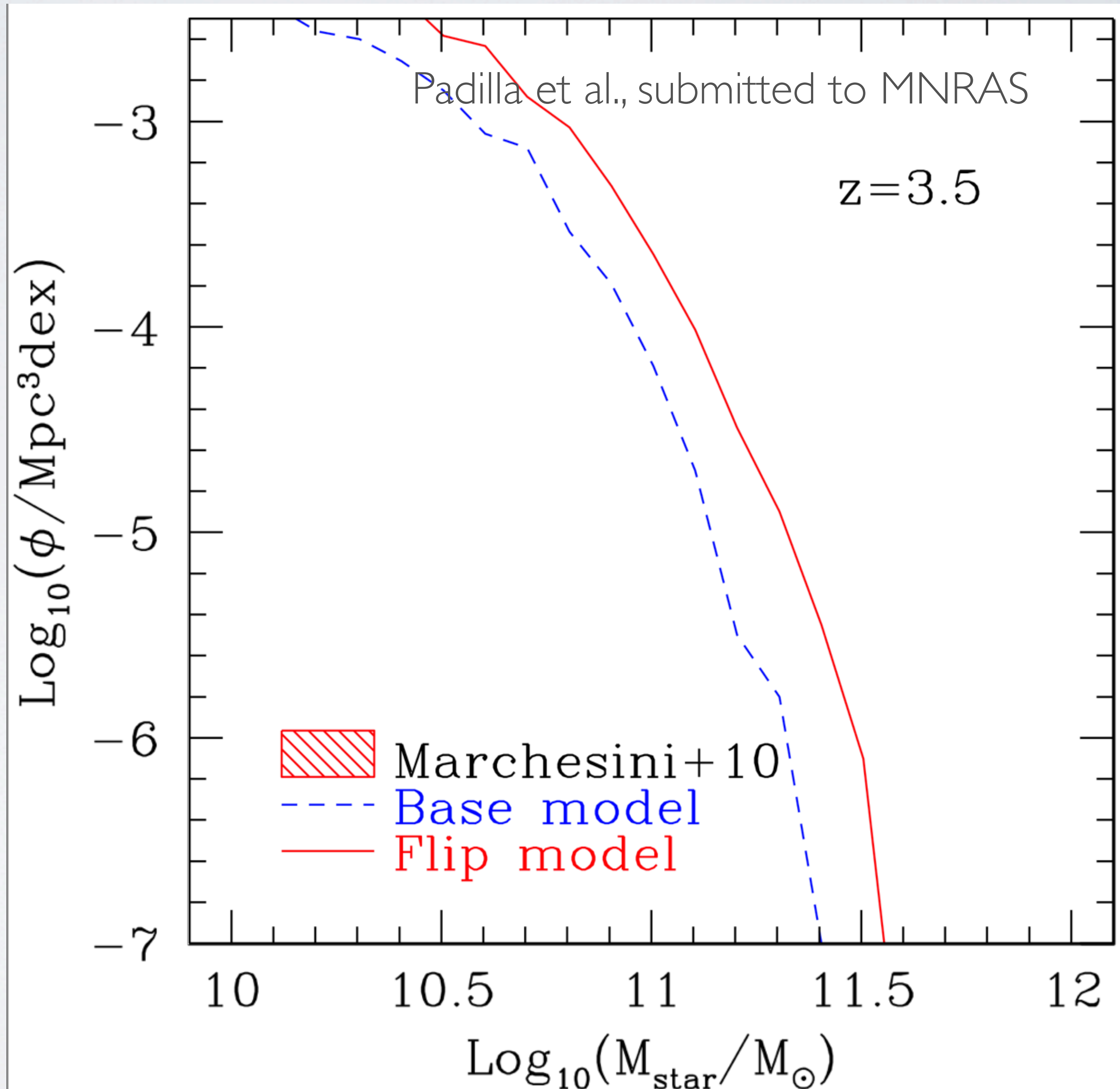
The stellar mass function at z=3.5



3) RESULTS: HIGH-Z MASSES

The stellar mass function at z=3.5

Stellar mass growth is faster at high z due to the more frequent instabilities of discs.



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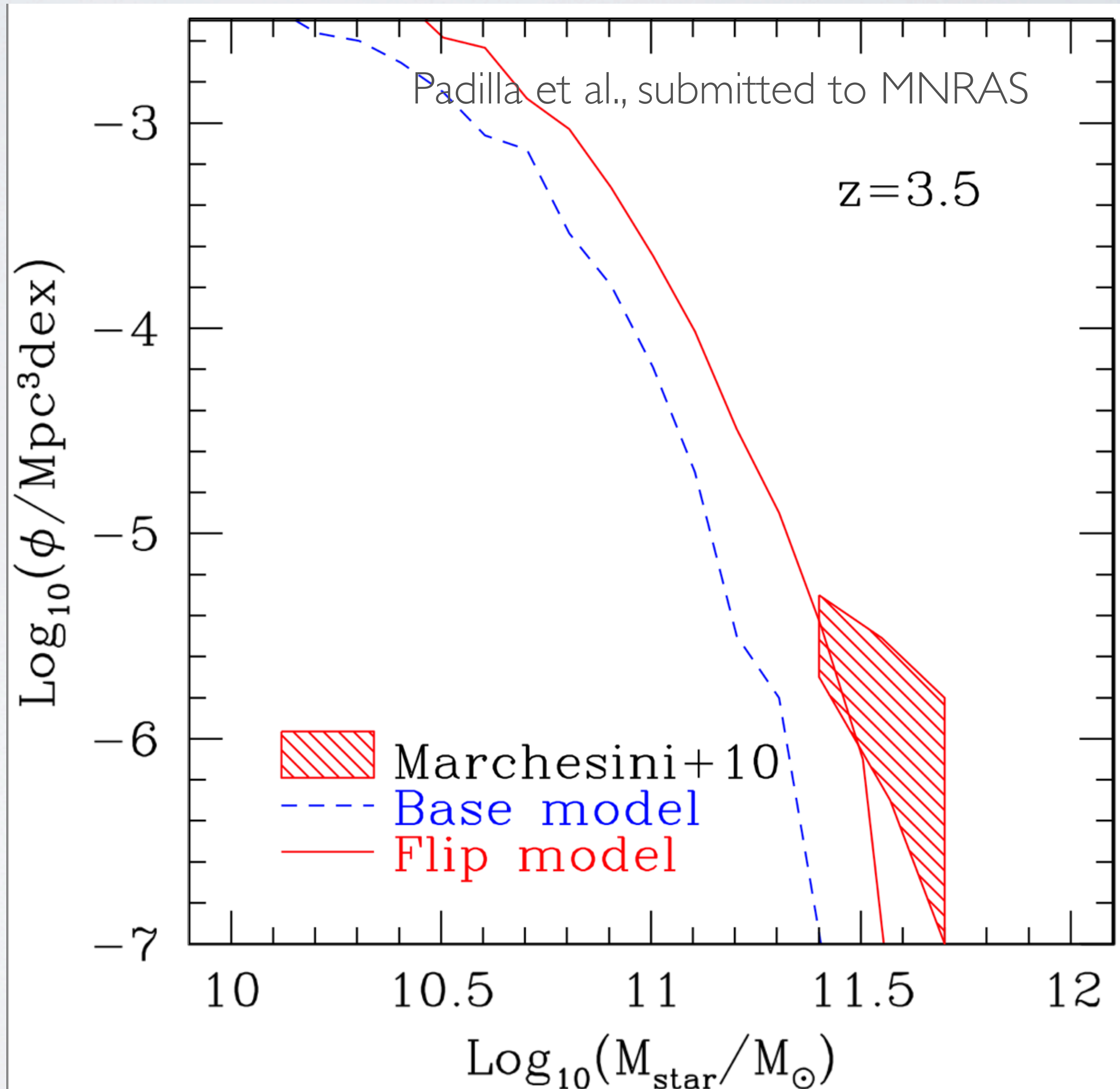


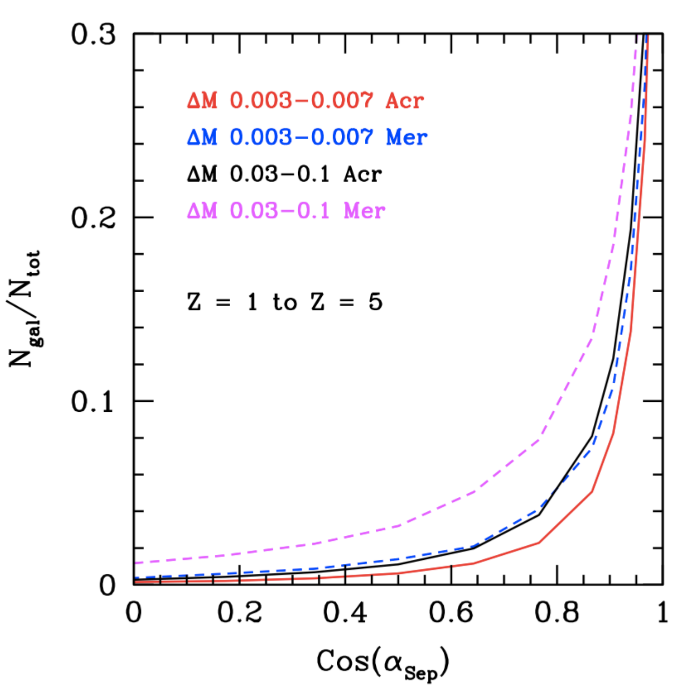
CONCLUSIONS

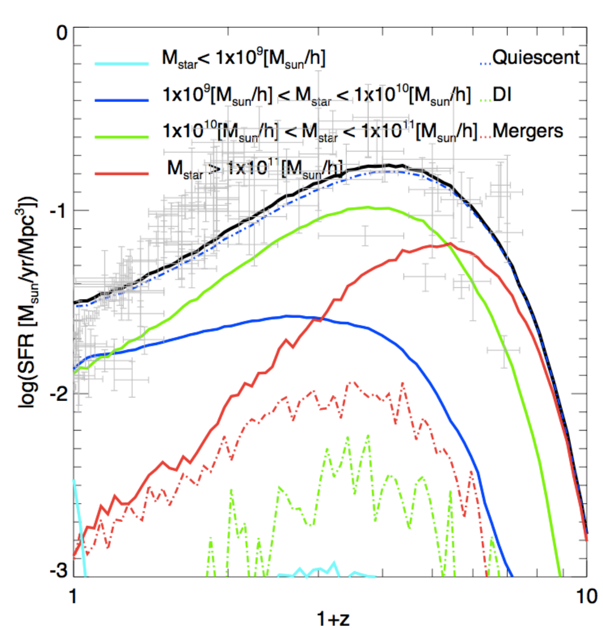
Padilla et al., tonight in arXiv!

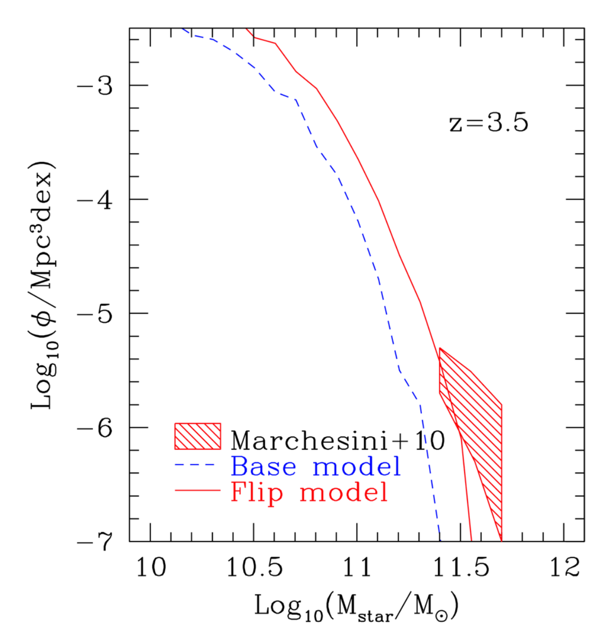
- High redshift abundances in models and observations have been difficult to reconcile. Observational and modeling techniques are still evolving...

- The infalling material carries only a small contribution to the increase of the angular momentum, with a strong stochastic component => discs become short-lived. Merger driven starbursts are obtained naturally.

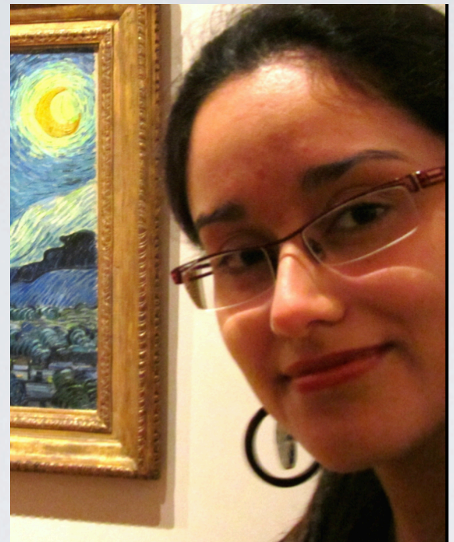
- Galaxy sizes are more compatible with observations at low and high redshift and stellar mass grows more rapidly at high redshifts..



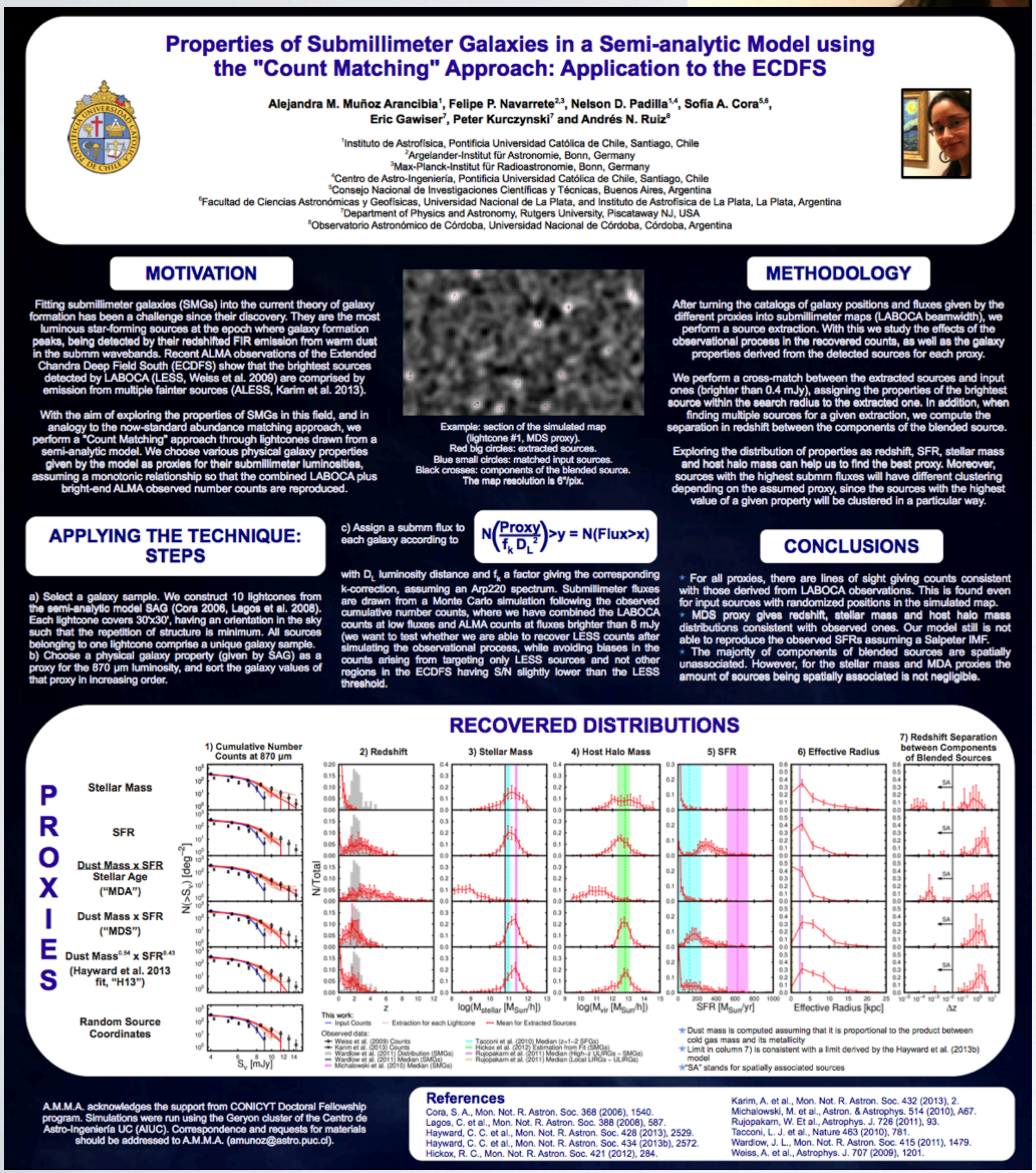


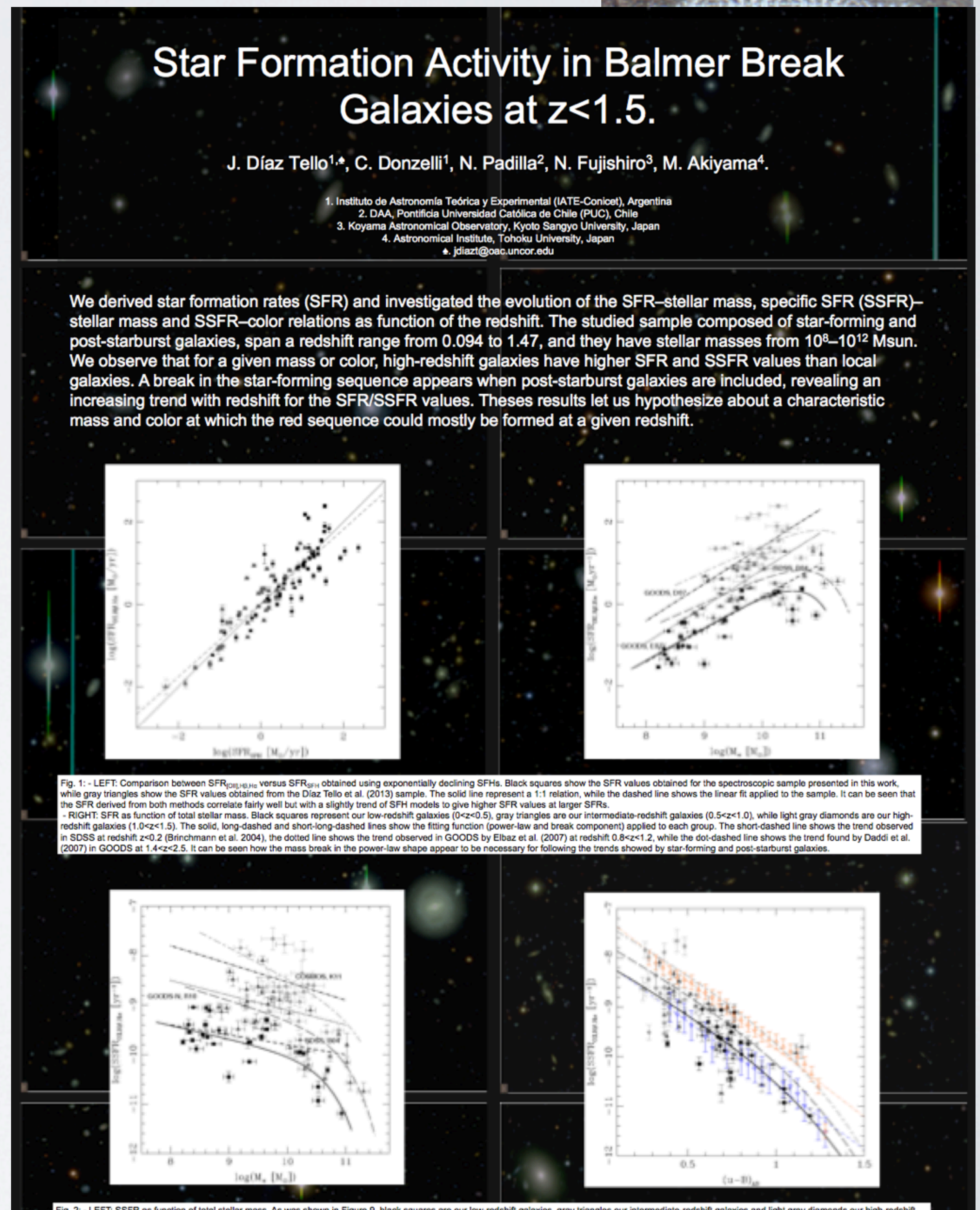


Alejandra Muñoz



Jorge Diaz





1A) MODELS OF GALAXY FORMATION

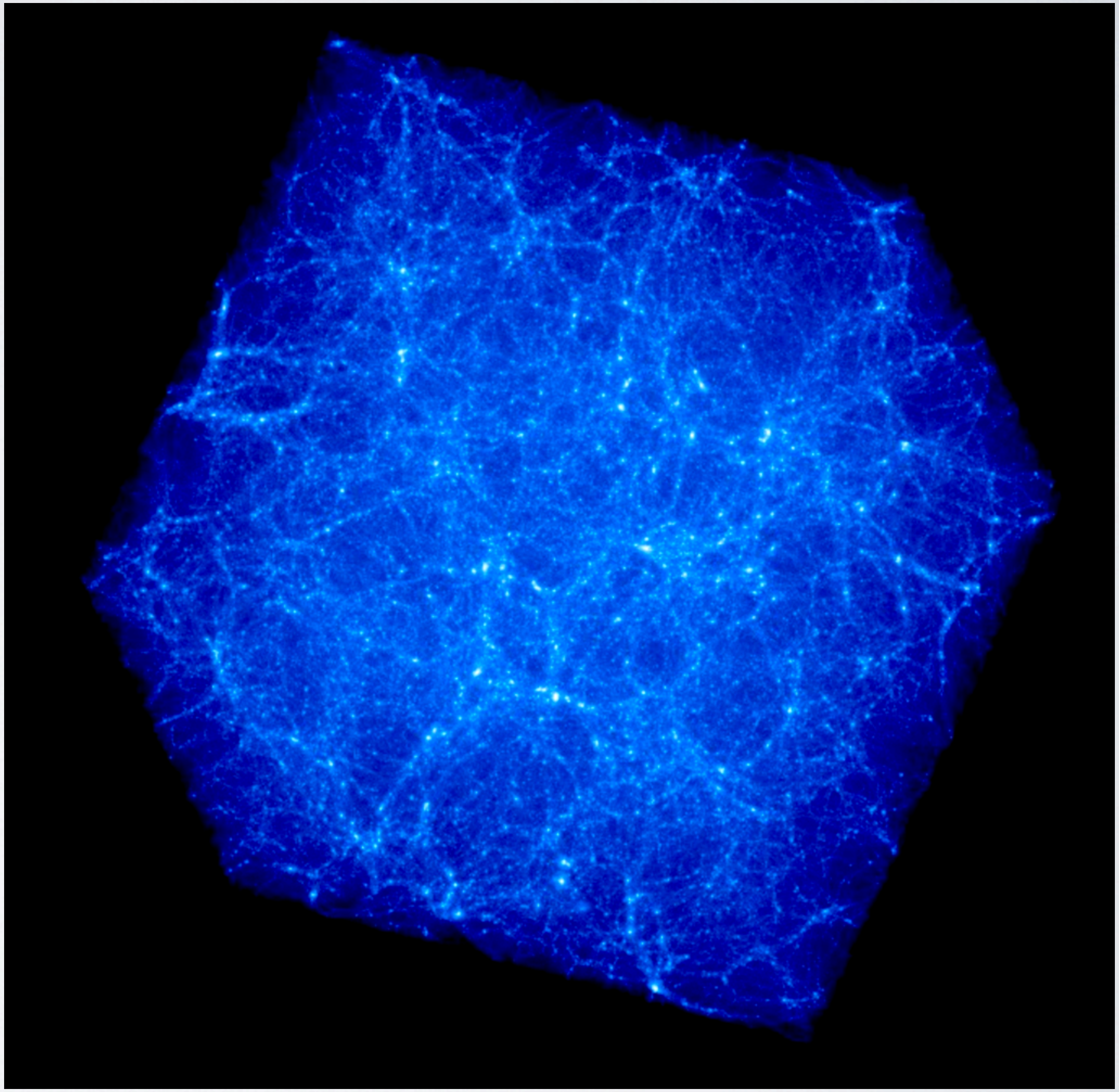
Cosmological
periodic
comoving
boxes.

DM-only:
halos of 1e10Msun and up.

Our sim: 640^3 particles

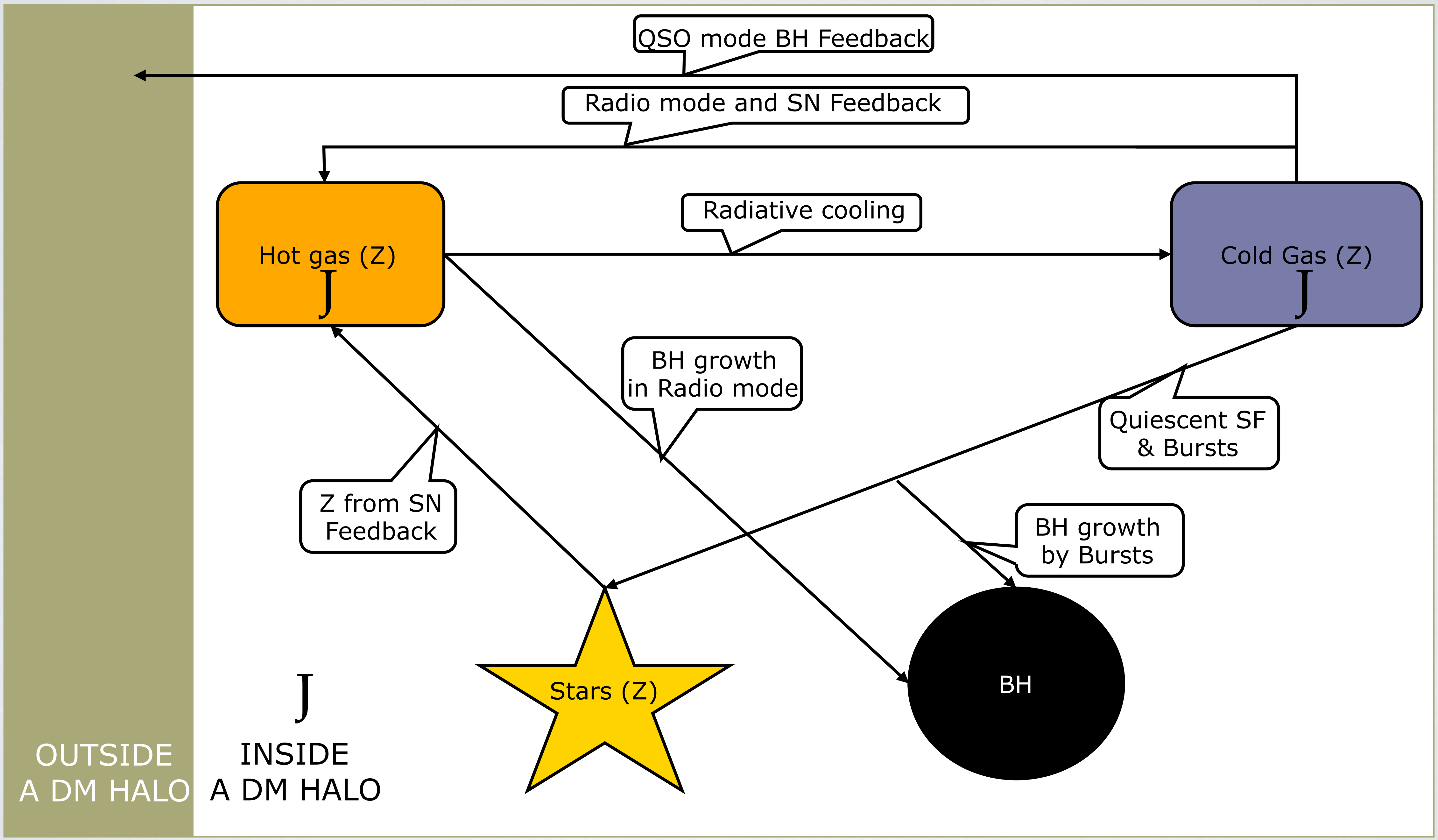
Millennium II:
2000^3 particles

MII 100xparticles per halo of
equal mass



1B) SEMI-ANALYTIC MODELS

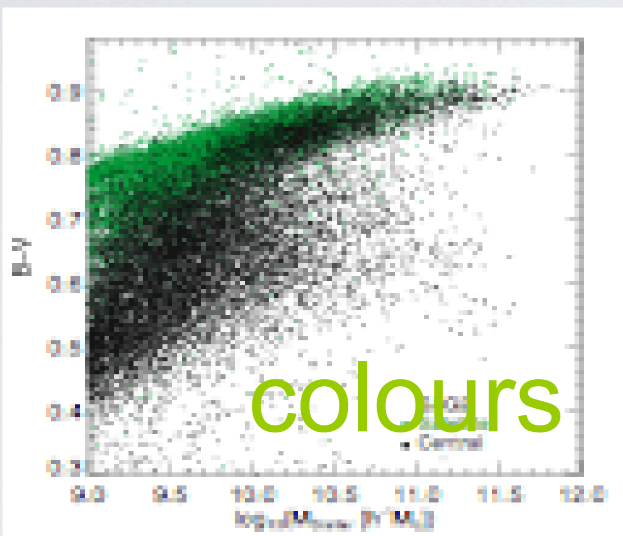
Summary of processes:



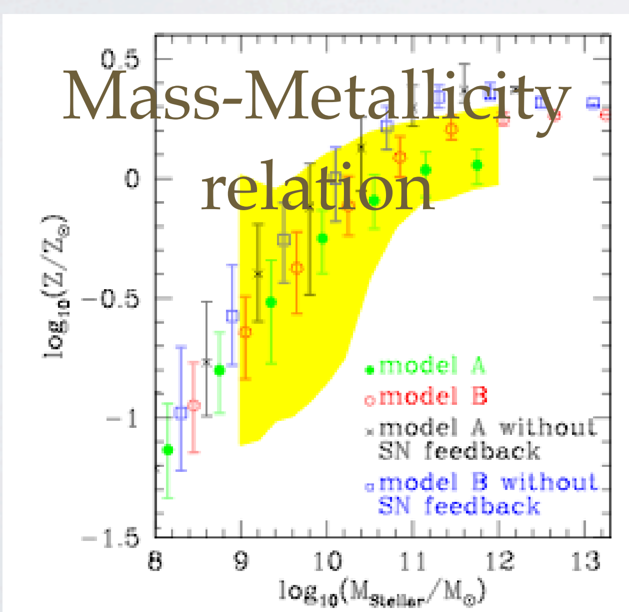
Lagos, Cora & Padilla (2008), Lagos, Padilla & Cora (2009), Tecce et al. (2010)

1B) SEMI-ANALYTIC MODEL

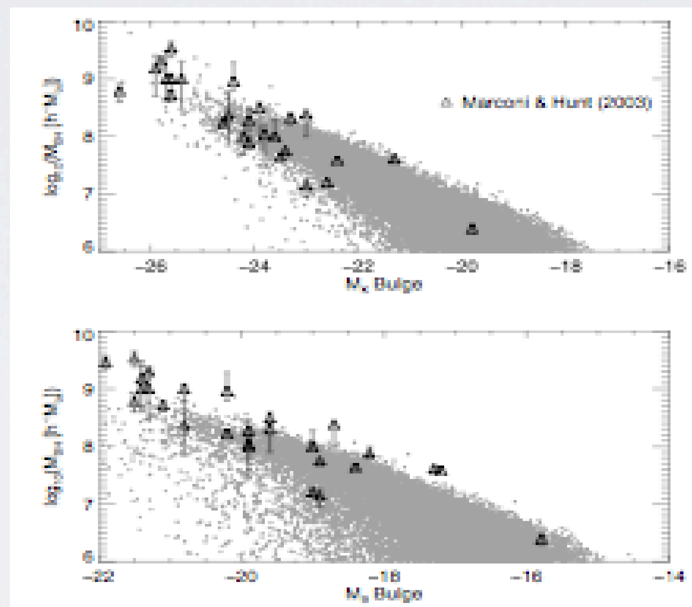
Fix free parameters using a set of z=0 statistics:

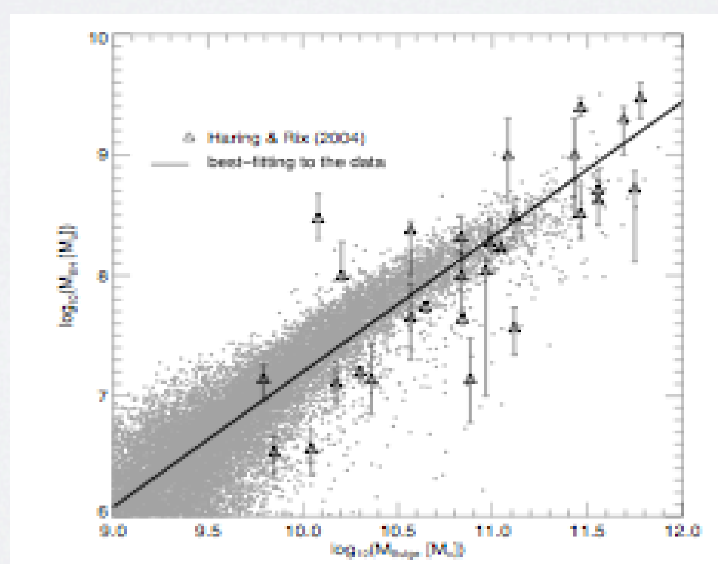


colours

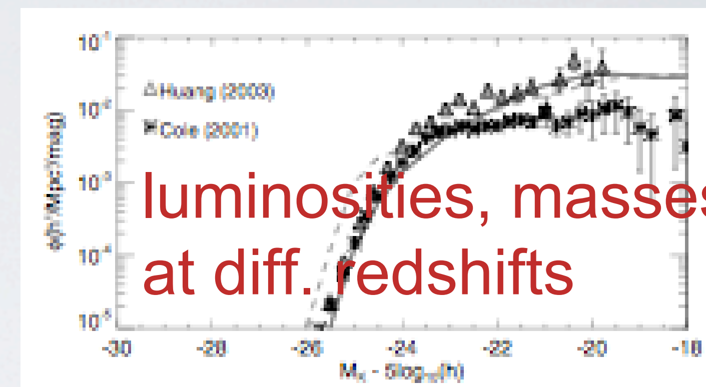


Mass-Metallicity relation

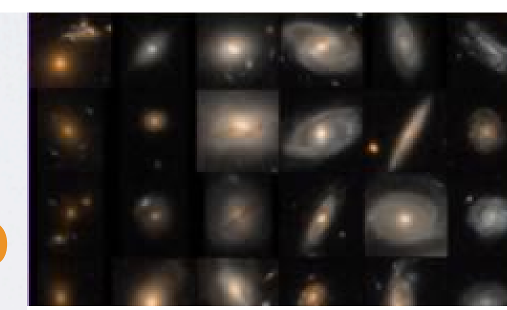


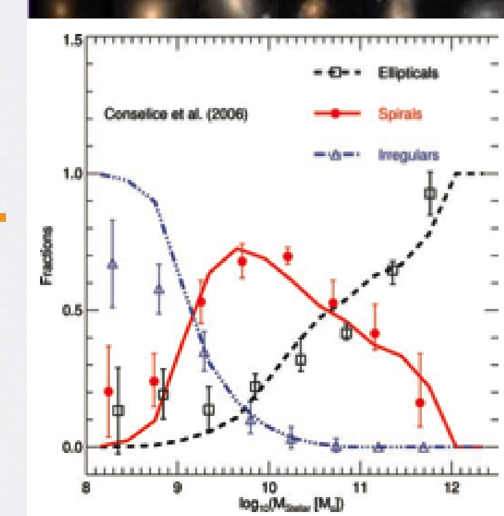


Black hole-host relations



luminosities, masses at diff. redshifts



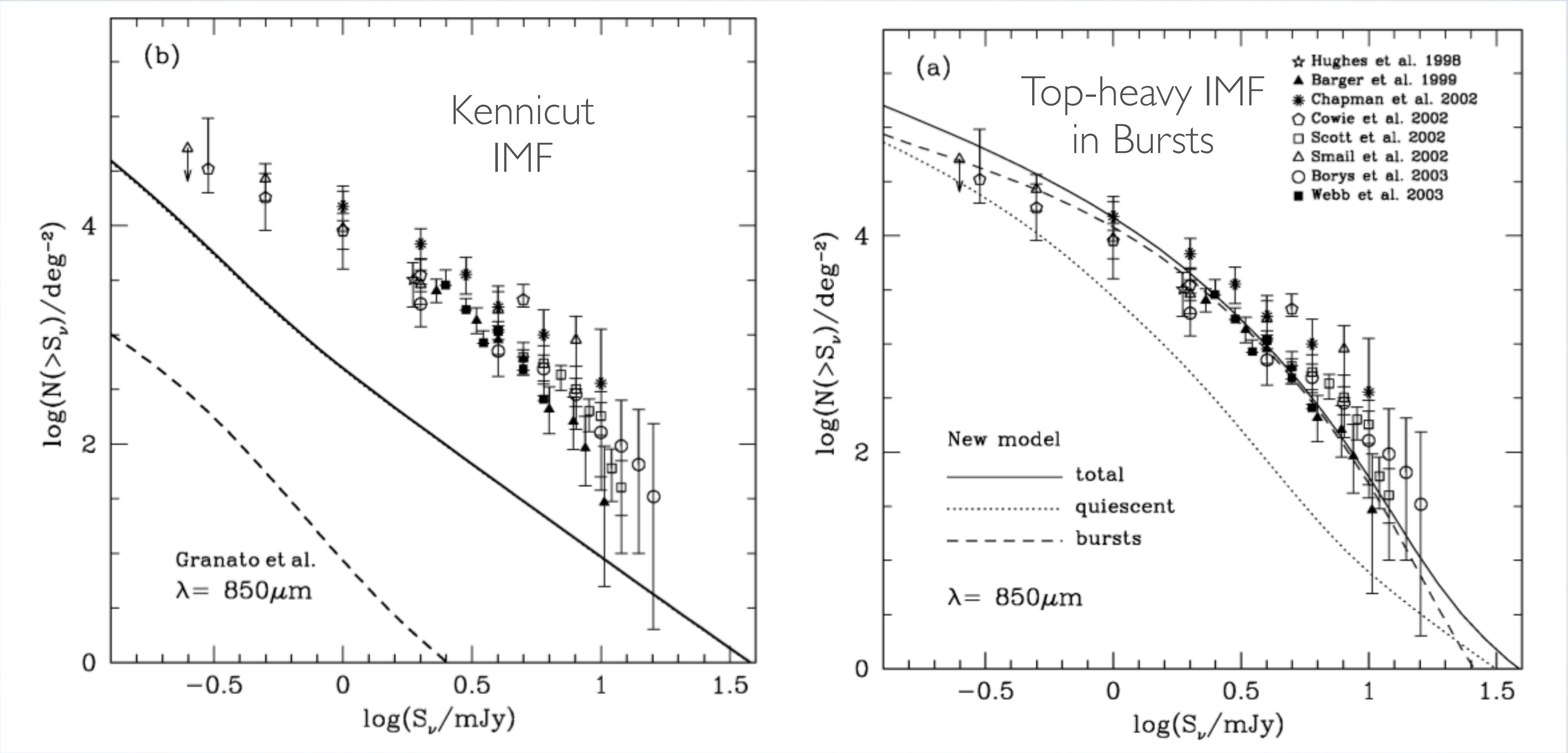


morphologies

Springel et al. (2001), Lagos, Cora & Padilla (2008), Lagos, Padilla & Cora (2009), Tecce et al. (2010)

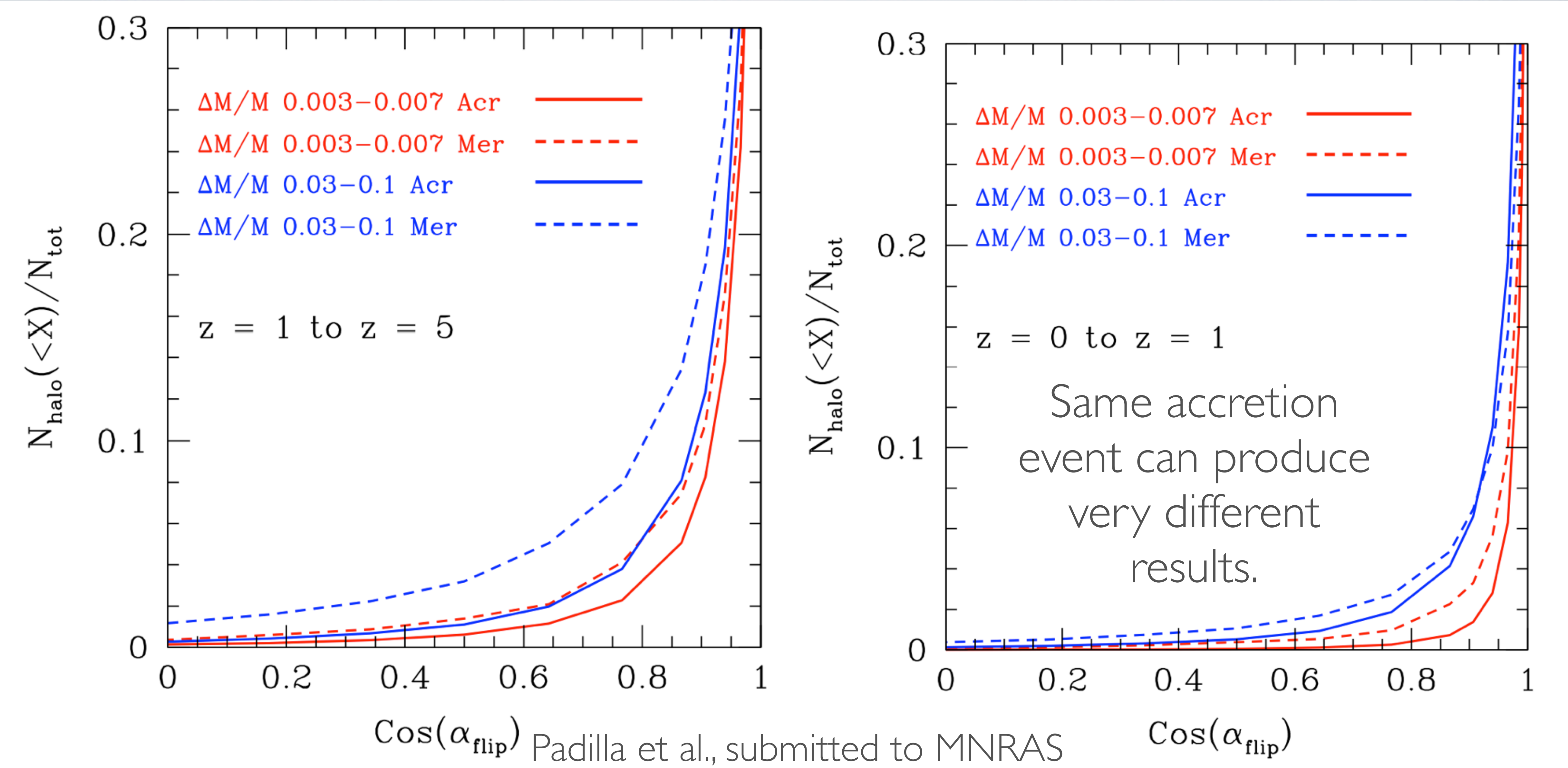
1C) MODELS PERFORMANCE AT HIGH-Z

Submm counts:



Baugh et al. 2005

2) MILLENNIUM II ANALYSIS



Padilla et al., submitted to MNRAS

- Notice that change in direction is larger for mergers.
- Cos(alpha_sep) as a function of fraction of accreted mass.

S. Contreras

2) ANGULAR MOMENTUM IN SAMS

Assumption:

The angular momentum of the dark matter is carried by the baryons.

Flips in DM => Flip in baryons

Cooling baryons will find a disc with a different L.

Missaligned accretion prevents the angular momentum of the disc from growing.

(i.e., no need to follow the amplitude of the angular momentum of DM haloes).

2) EFFECT ON MERGERS

Disc instability
as the only driver of bursts in
the model naturally produces
short-lived discs when loss of
angular momentum due to
accretion is considered.

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Disc instability
as the only driver
of bursts in the
model.

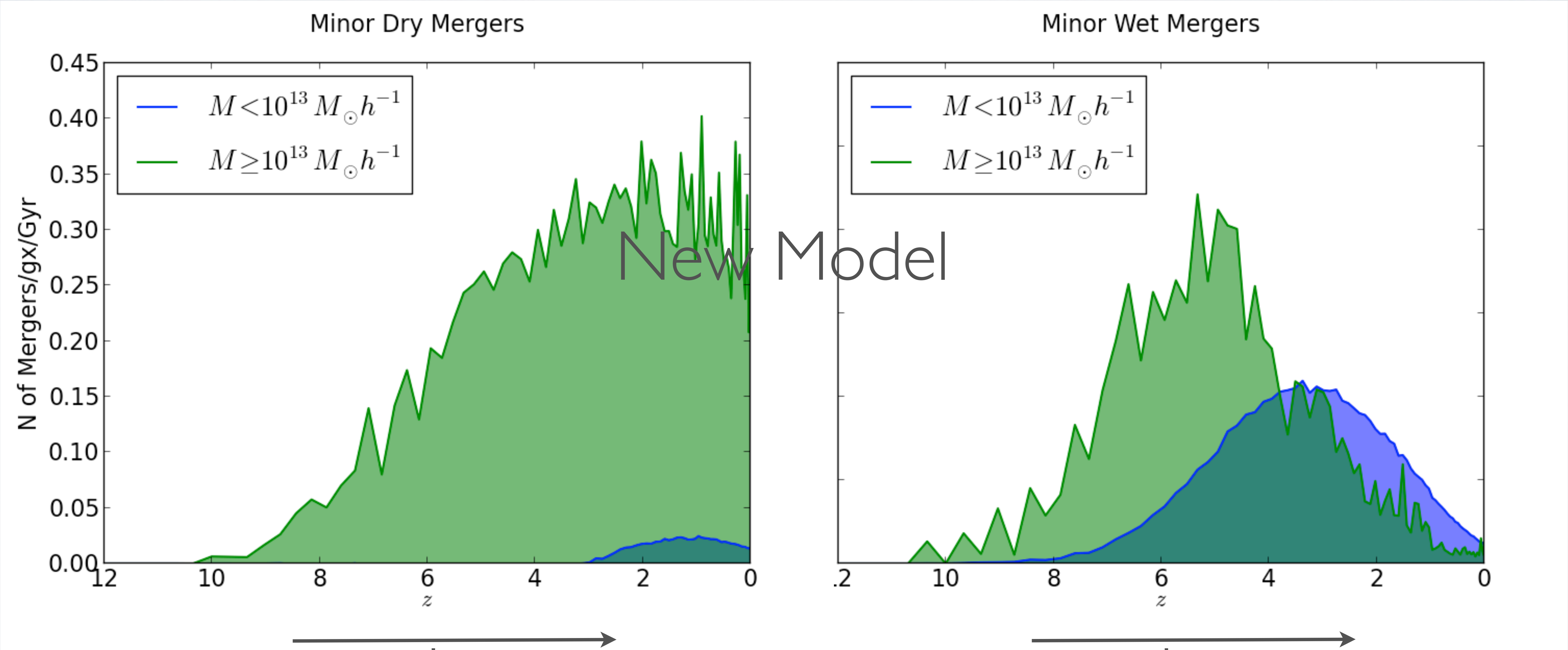
$$\epsilon = \frac{V_{\rm max}}{(GM_{\rm disc}/r_{\rm disc})^{1/2}},$$

if lower than critical value
disc is unstable

Mergers also
which make epsilon very low

2) EFFECT ON MERGERS

S. Salazar



Padilla et al., submitted to MNRAS

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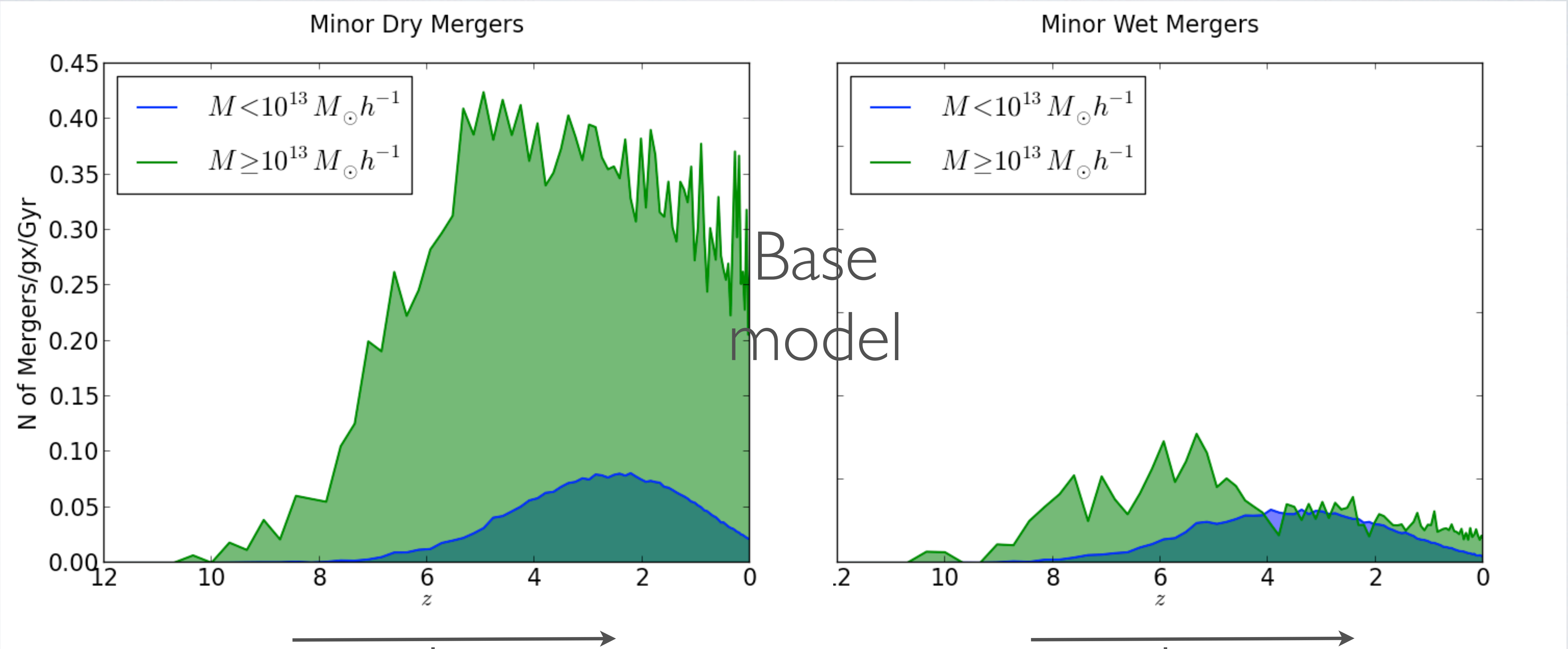

Padilla et al., submitted to MNRAS

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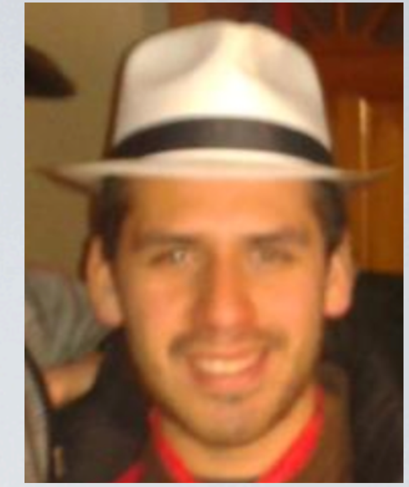
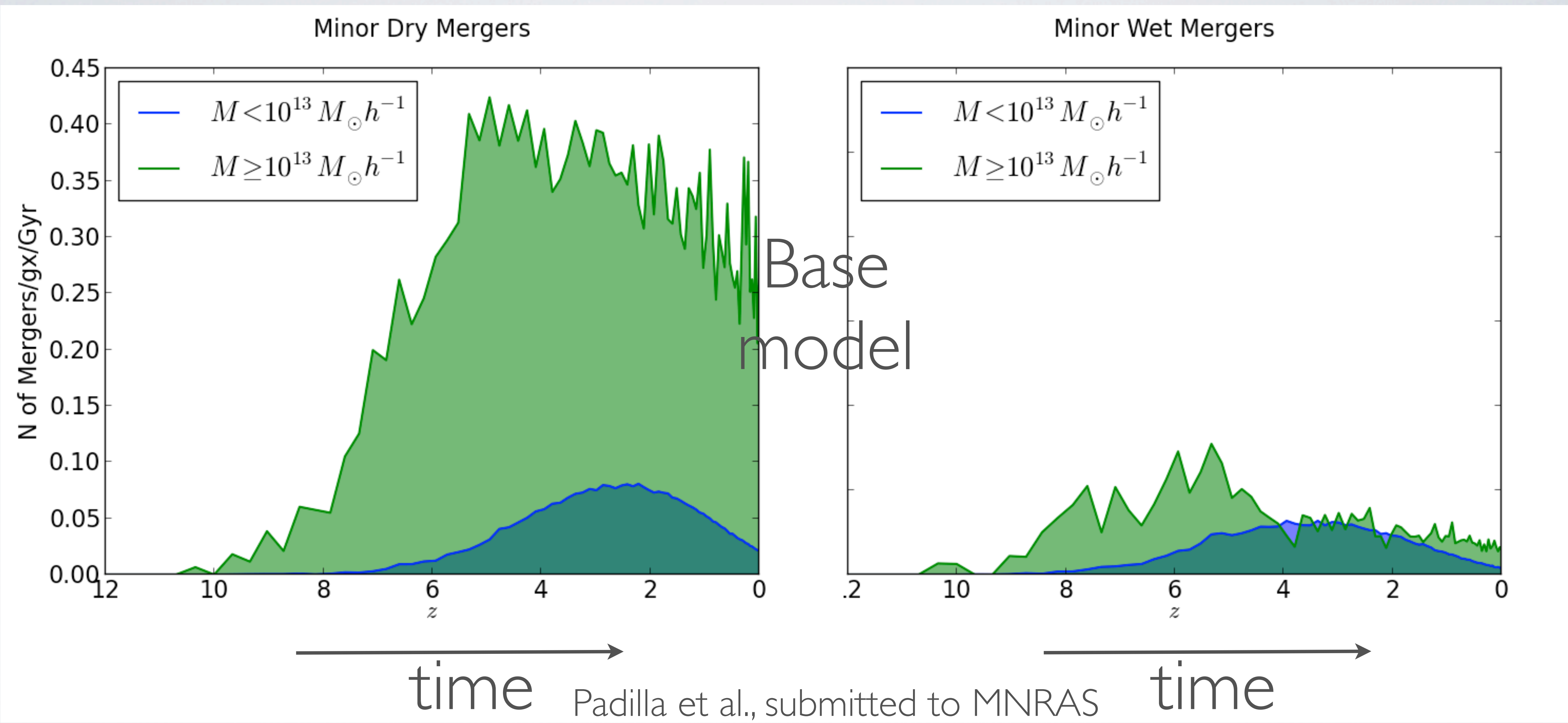


S. Salazar



Padilla et al., submitted to MNRAS

Mergers+DI produce similar frequency of bursts (except for minor mergers)

f_major, f_gas, f_disc no longer needed as parameters.

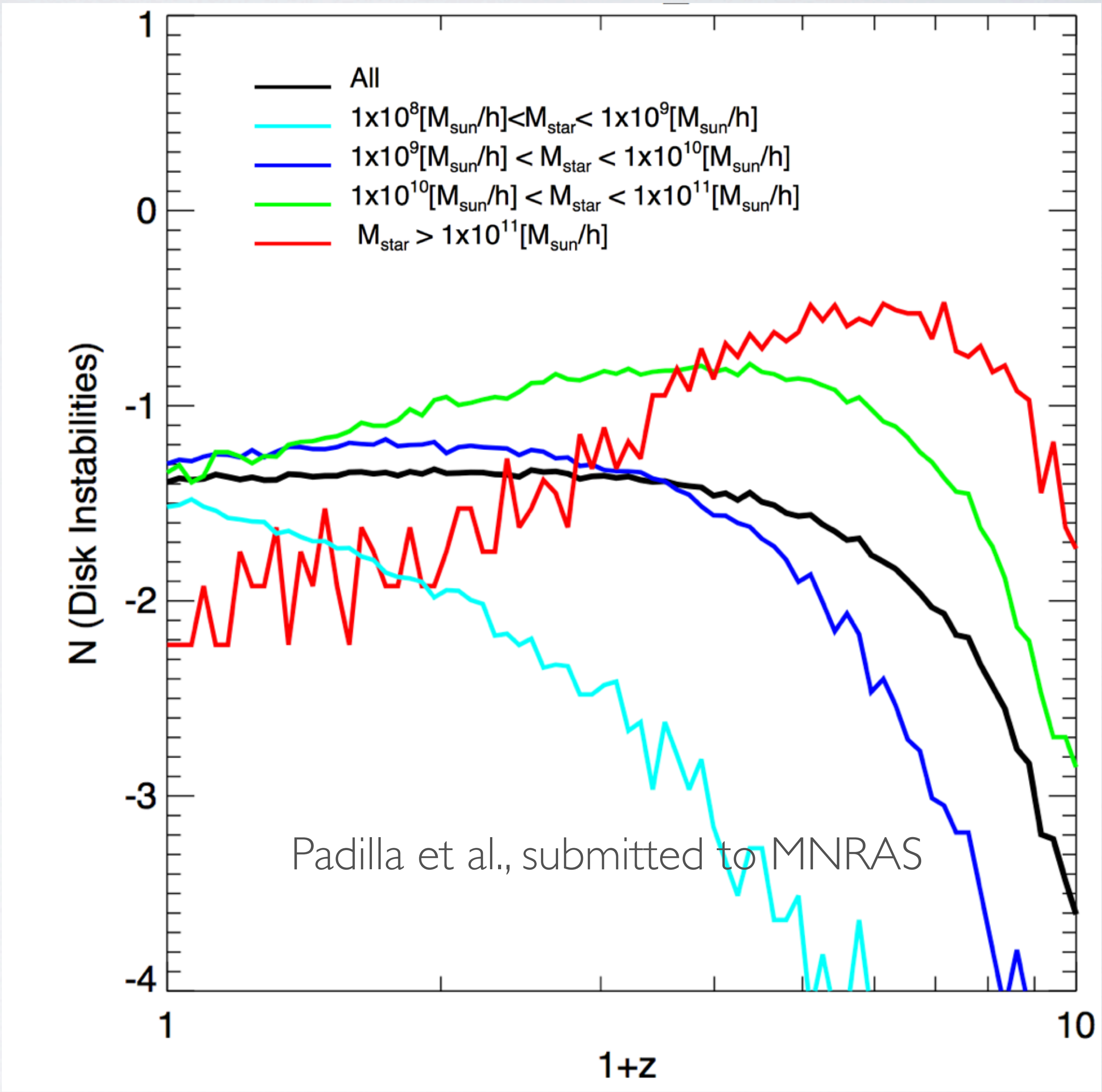
2) EFFECT ON SF

Number of disc instabilities

$$\epsilon = \frac{V_{\max}}{(GM_{\rm disc}/r_{\rm disc})^{1/2}},$$

if lower than critical value disc is unstable

r_disc is now subject to changes due to accretion which make epsilon very low



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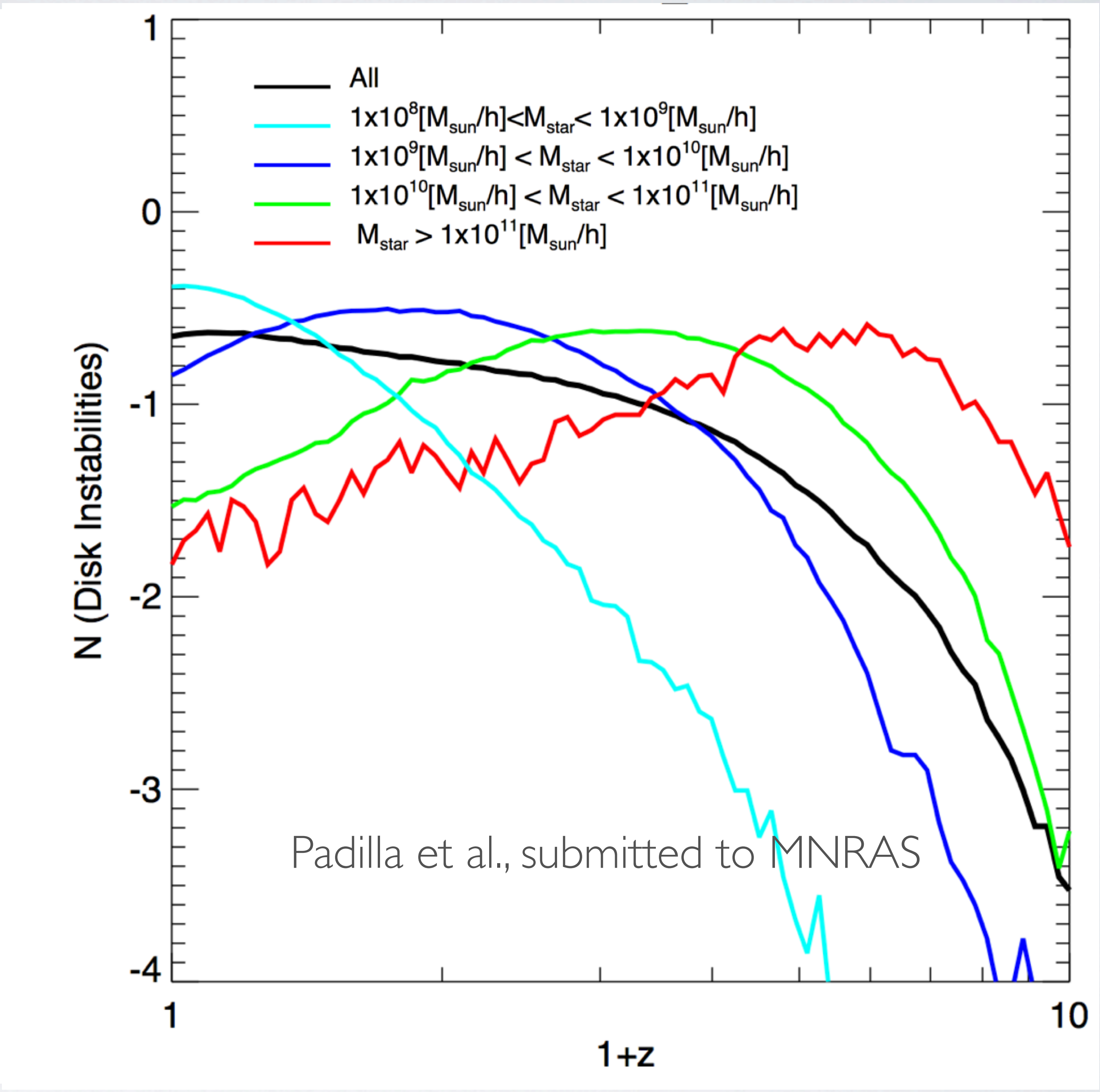
With episodic discs:
* 50% global increase in instabilities at high masses
* 8% of galaxies with DI



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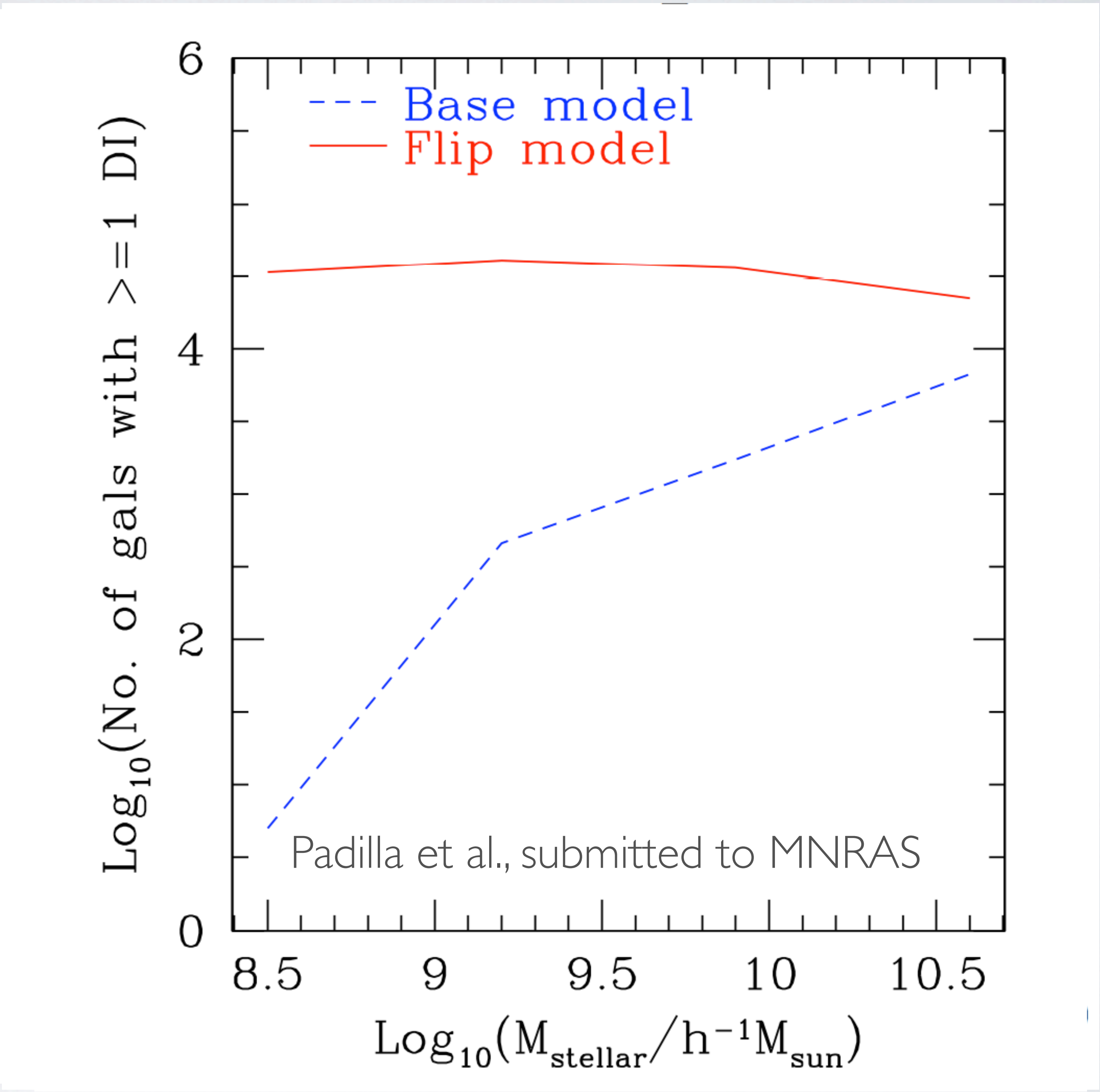
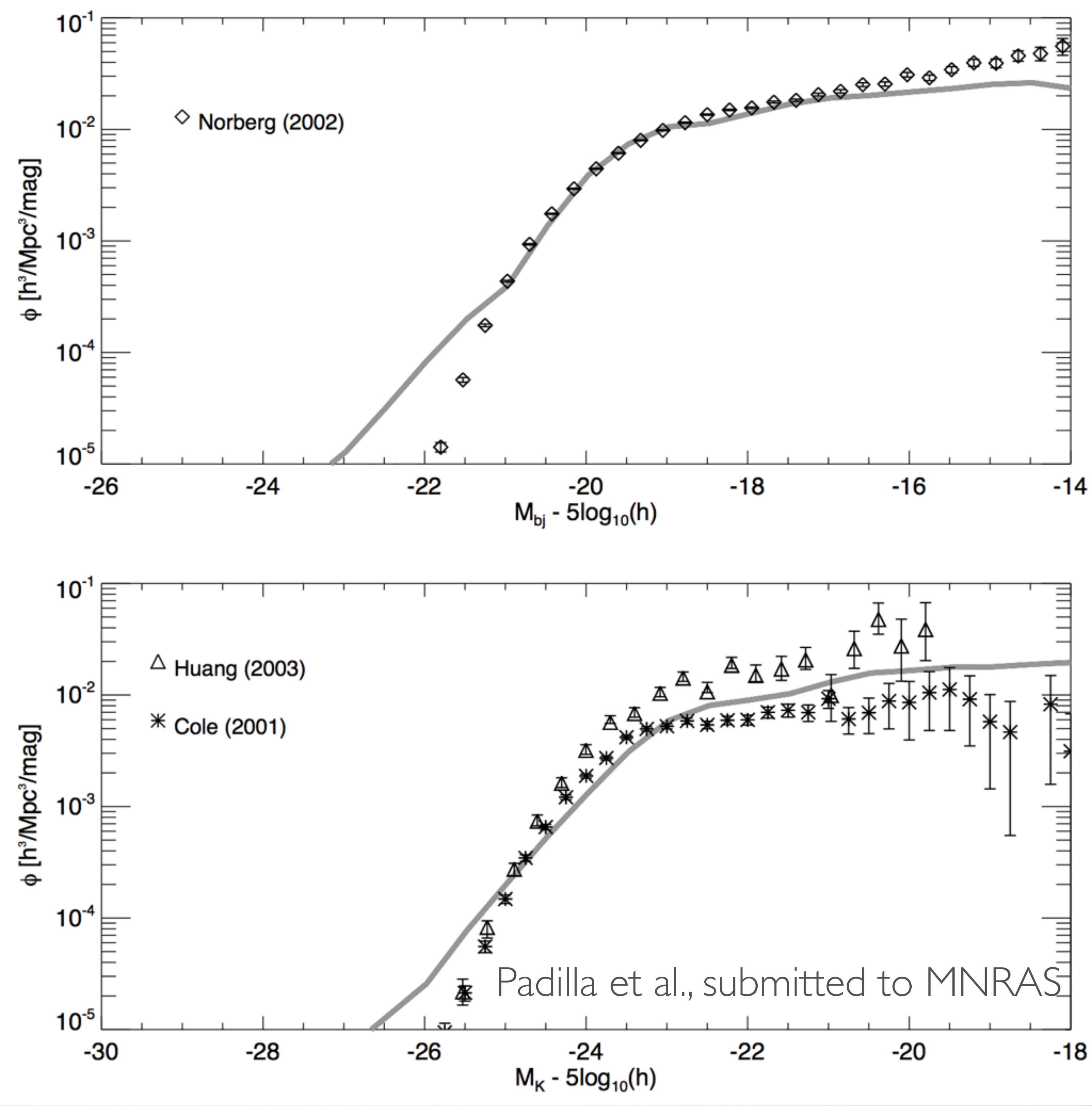


SAM PARAMETERS FIXED WITH LF

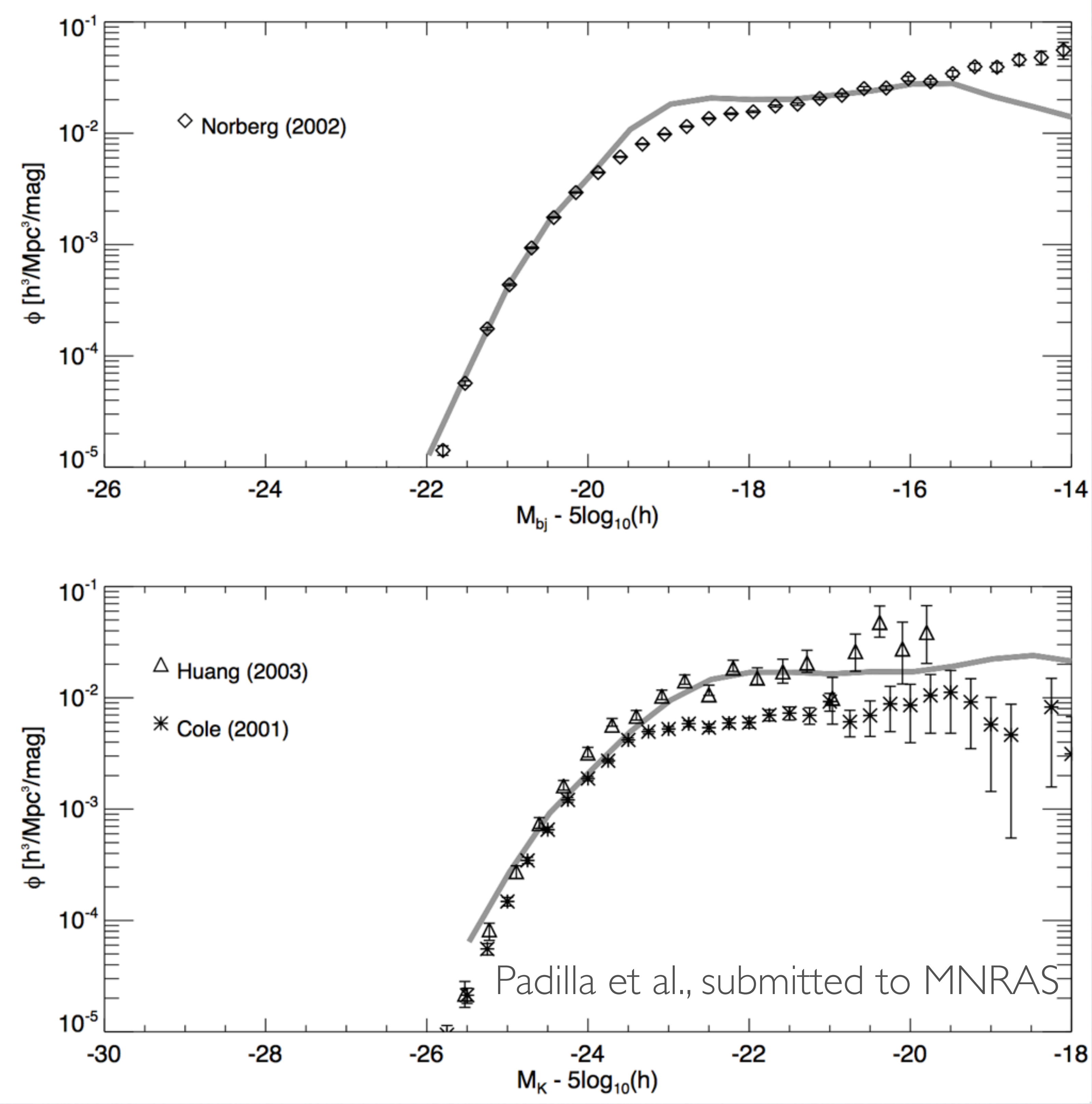
Smooth growth in disc size



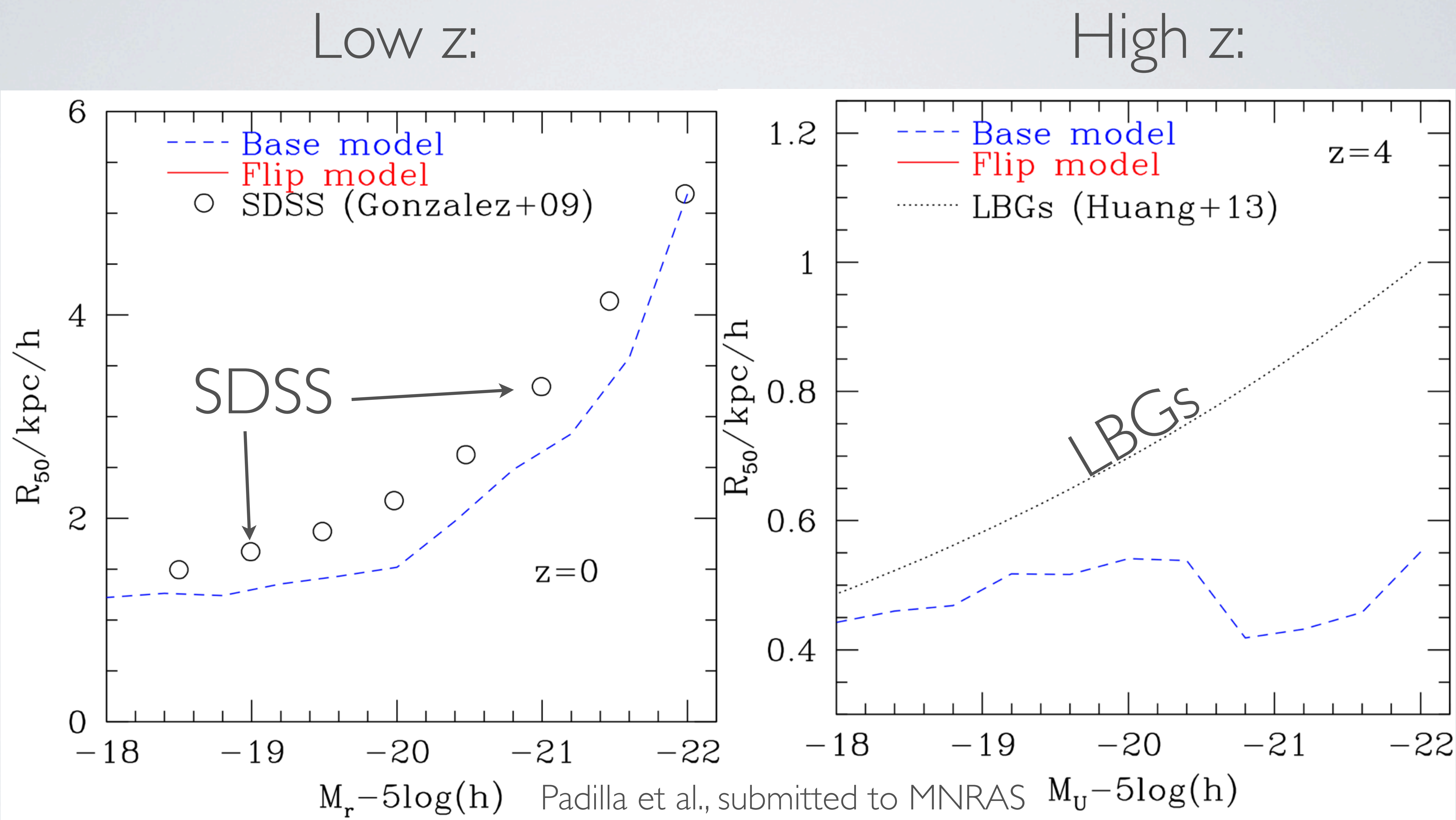
SAM PARAMETERS FIXED WITH LF

With episodic discs

SF efficiency lowered to reproduce LF at z=0



3) RESULTS: GALAXY SIZES

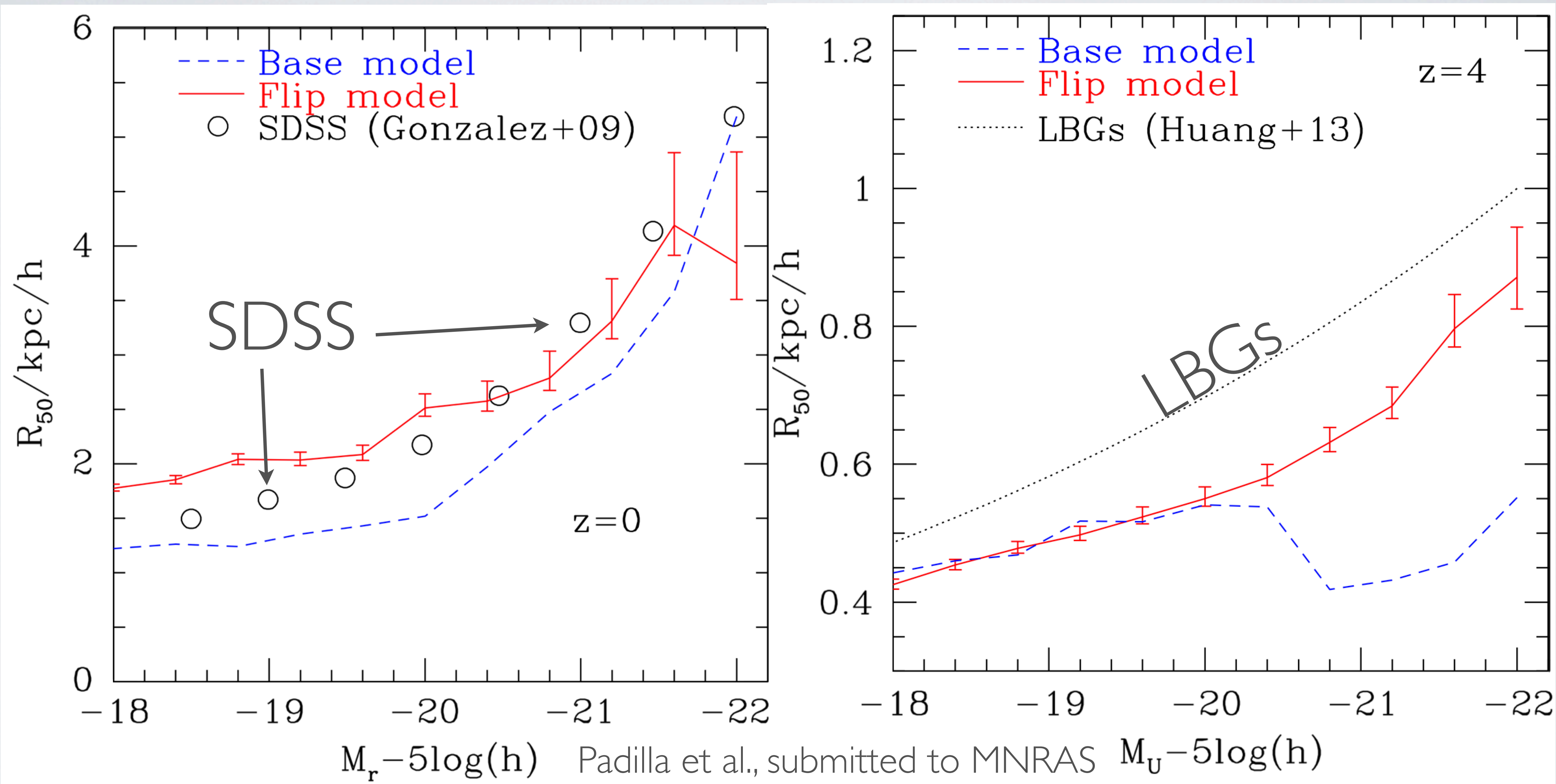


Padilla et al., submitted to MNRAS

Even though discs would become smaller along with their spins, this makes only large discs survive perturbations: larger discs in the population.

3) RESULTS: GALAXY SIZES

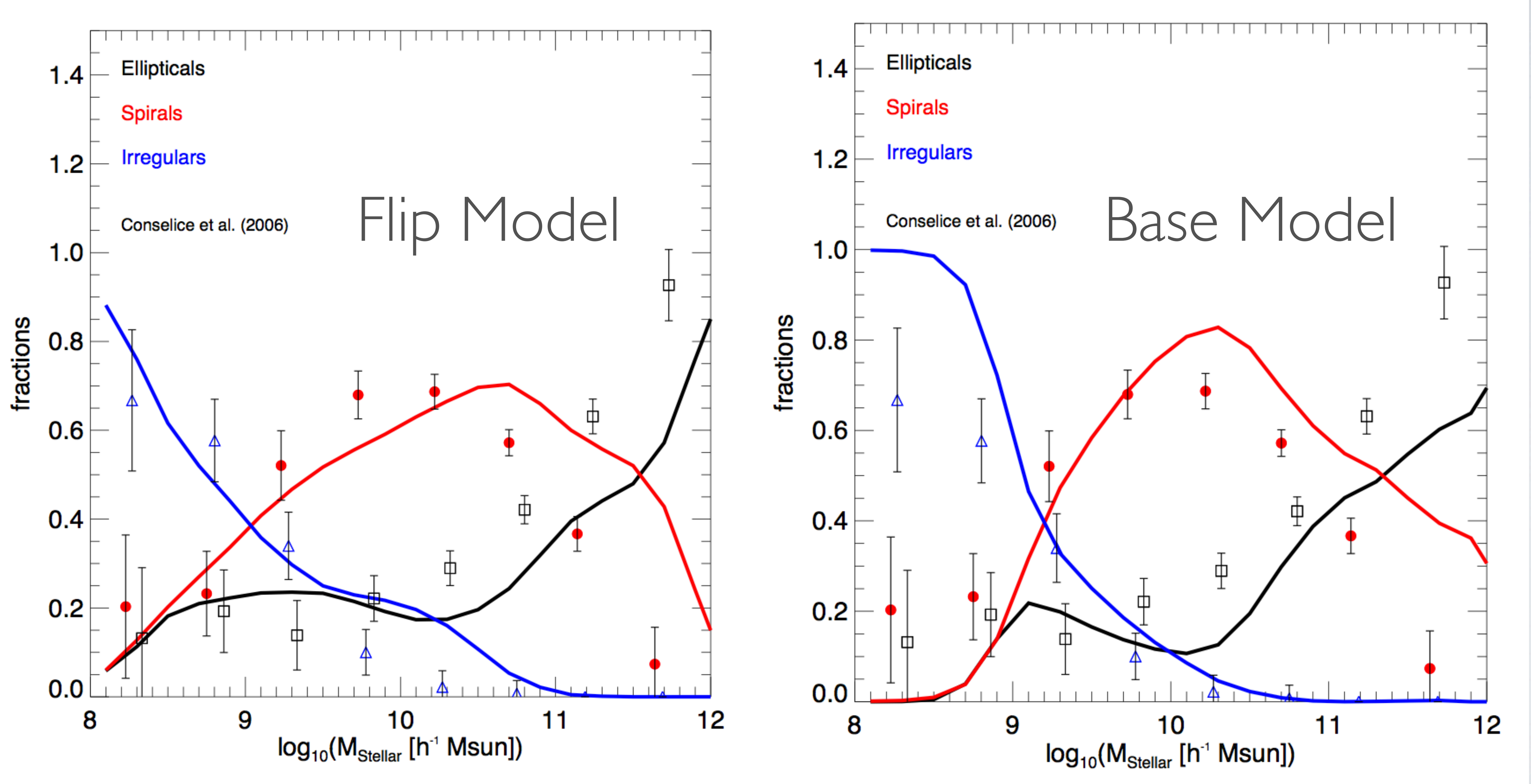
Low z: High z:



Padilla et al., submitted to MNRAS

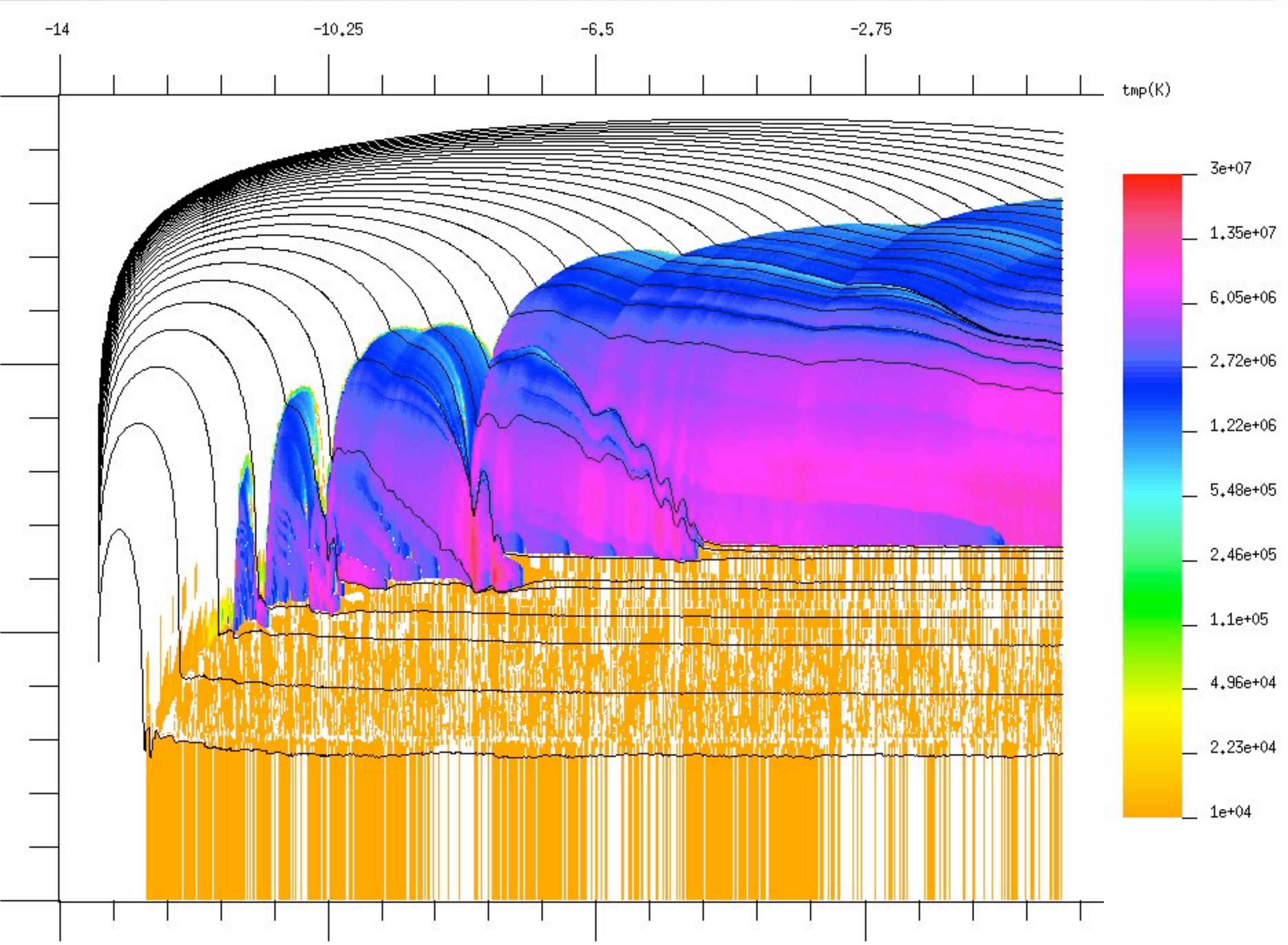
Even though discs would become smaller along with their spins, this makes only large discs survive perturbations: larger discs in the population.

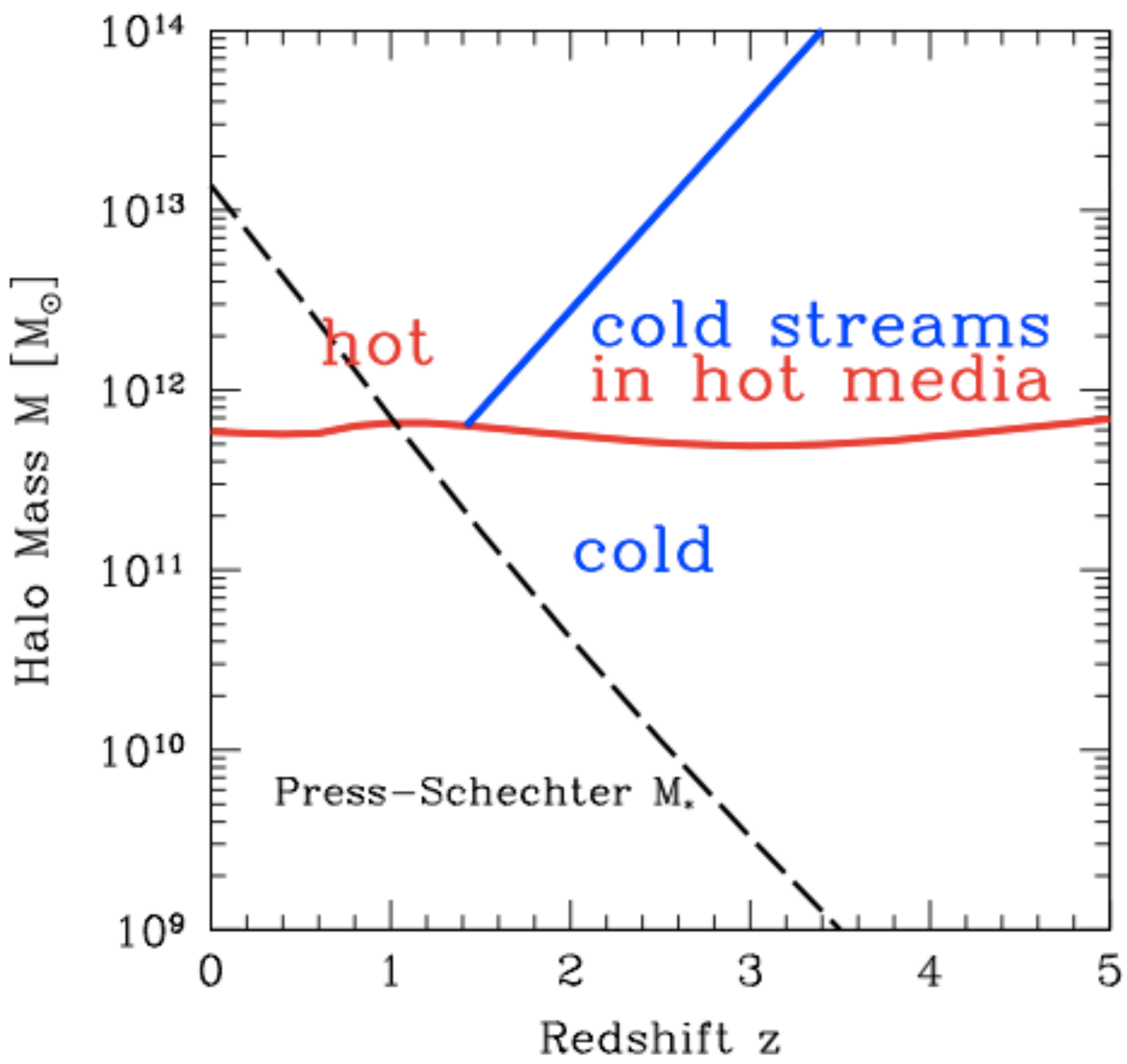
3) RESULTS: MORPHOLOGIES



4) COLD GAS INFLOWS

High-z low mass halos: most of the gas reaching the center of a galaxy is able to arrive cold without going through a heating phase.





Dekel, Birnboim, et al., 2009

see also Keres et al., 2009, van de Voort et al., 2011, etc.

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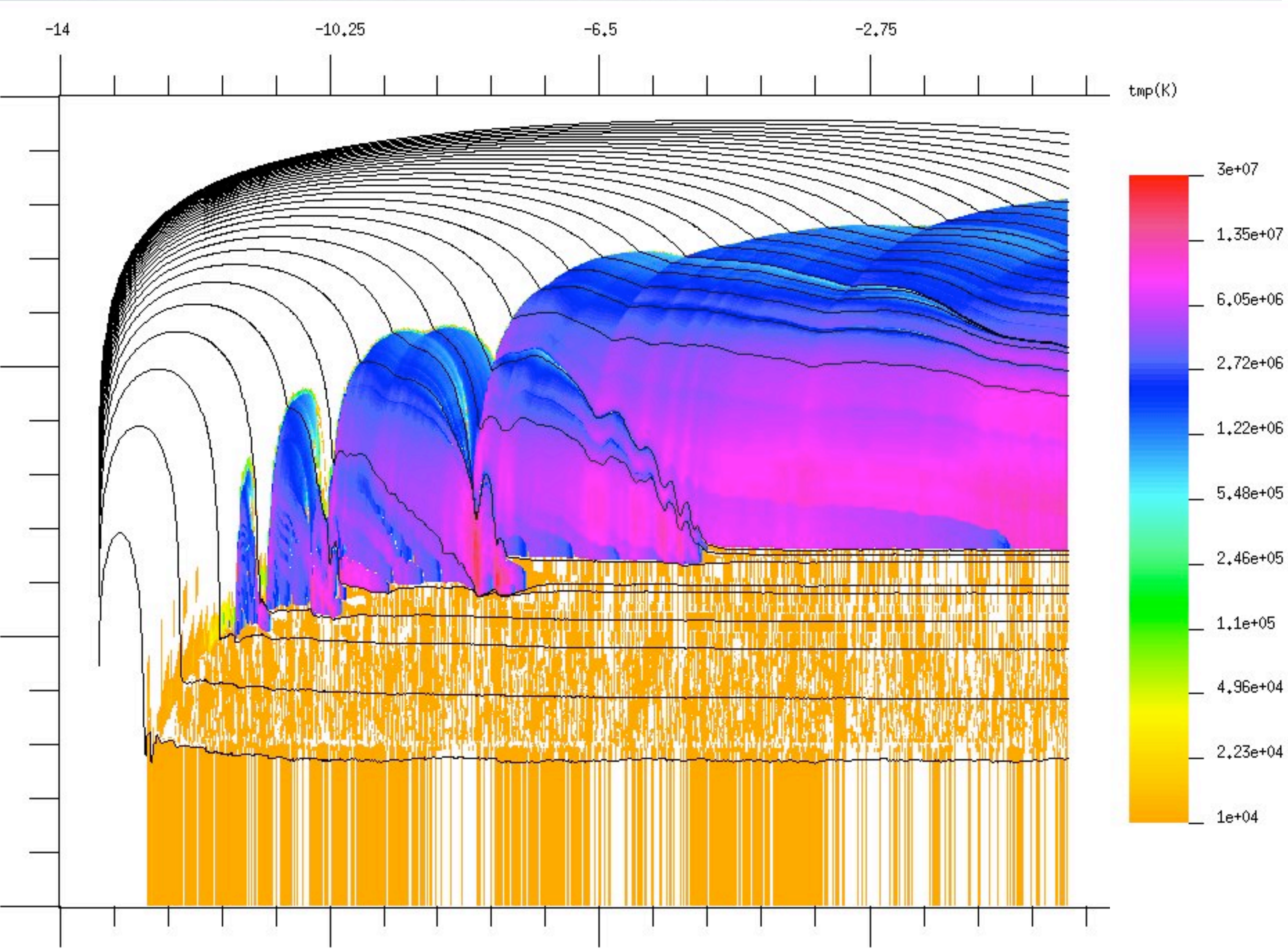

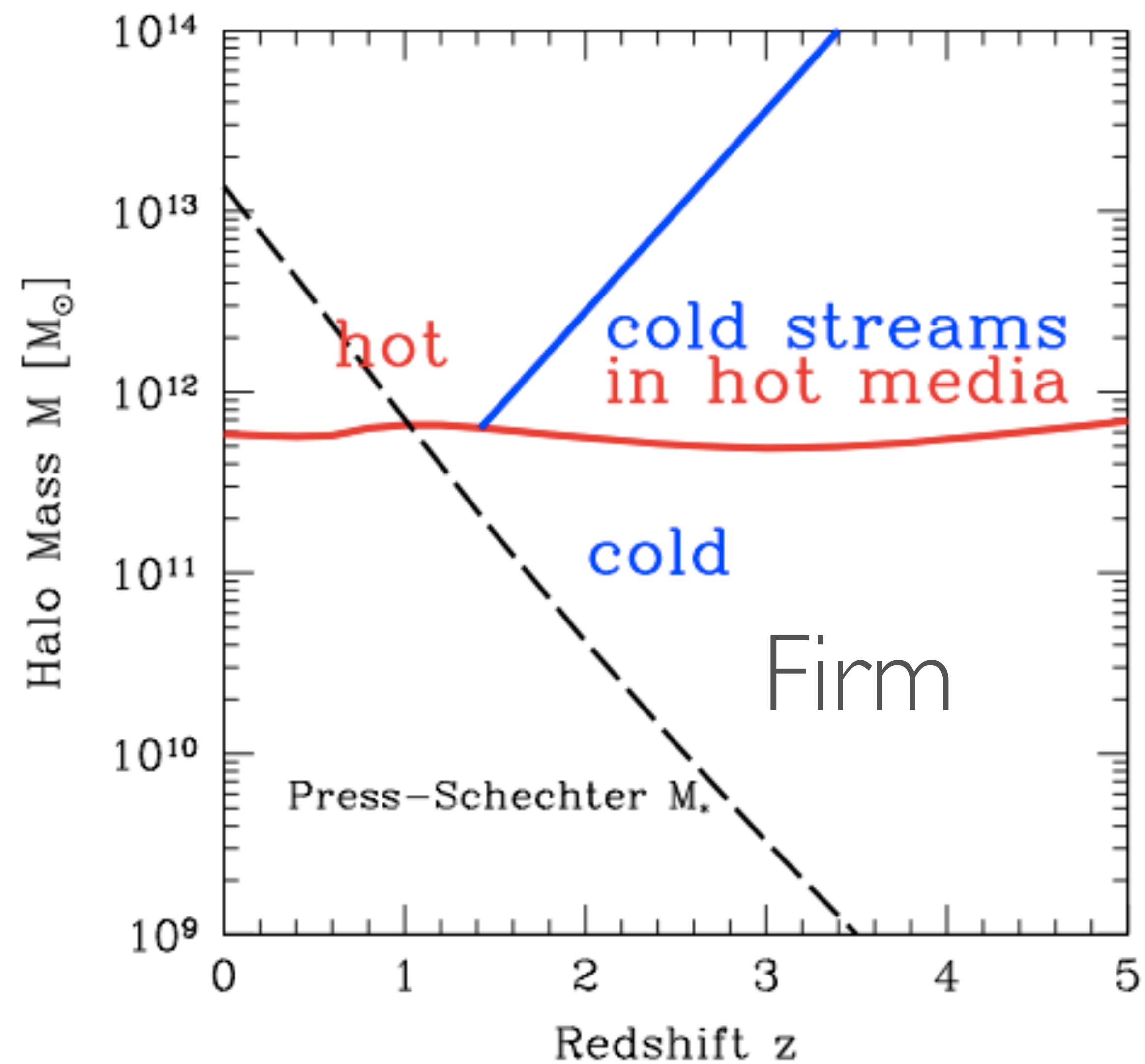

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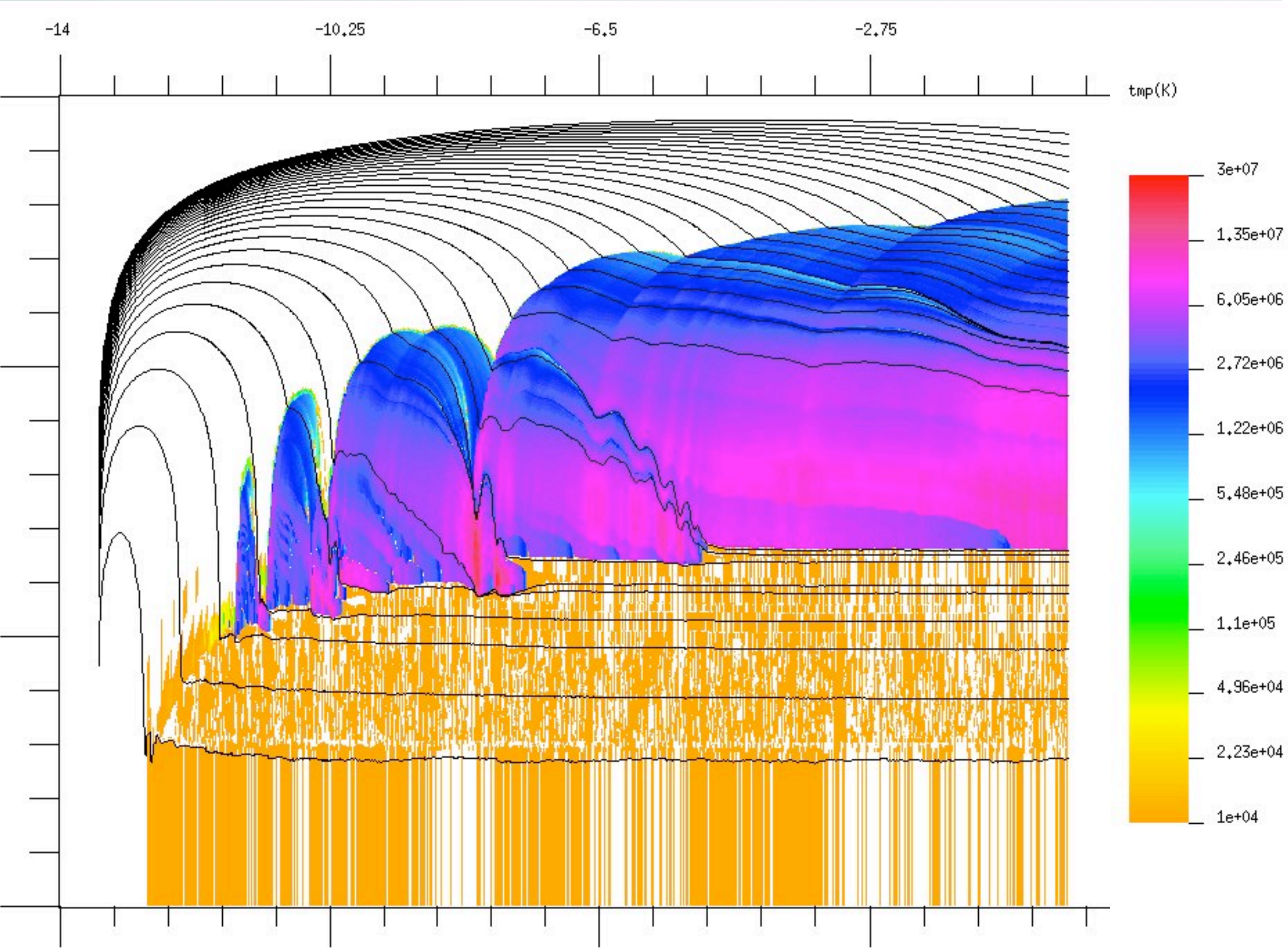

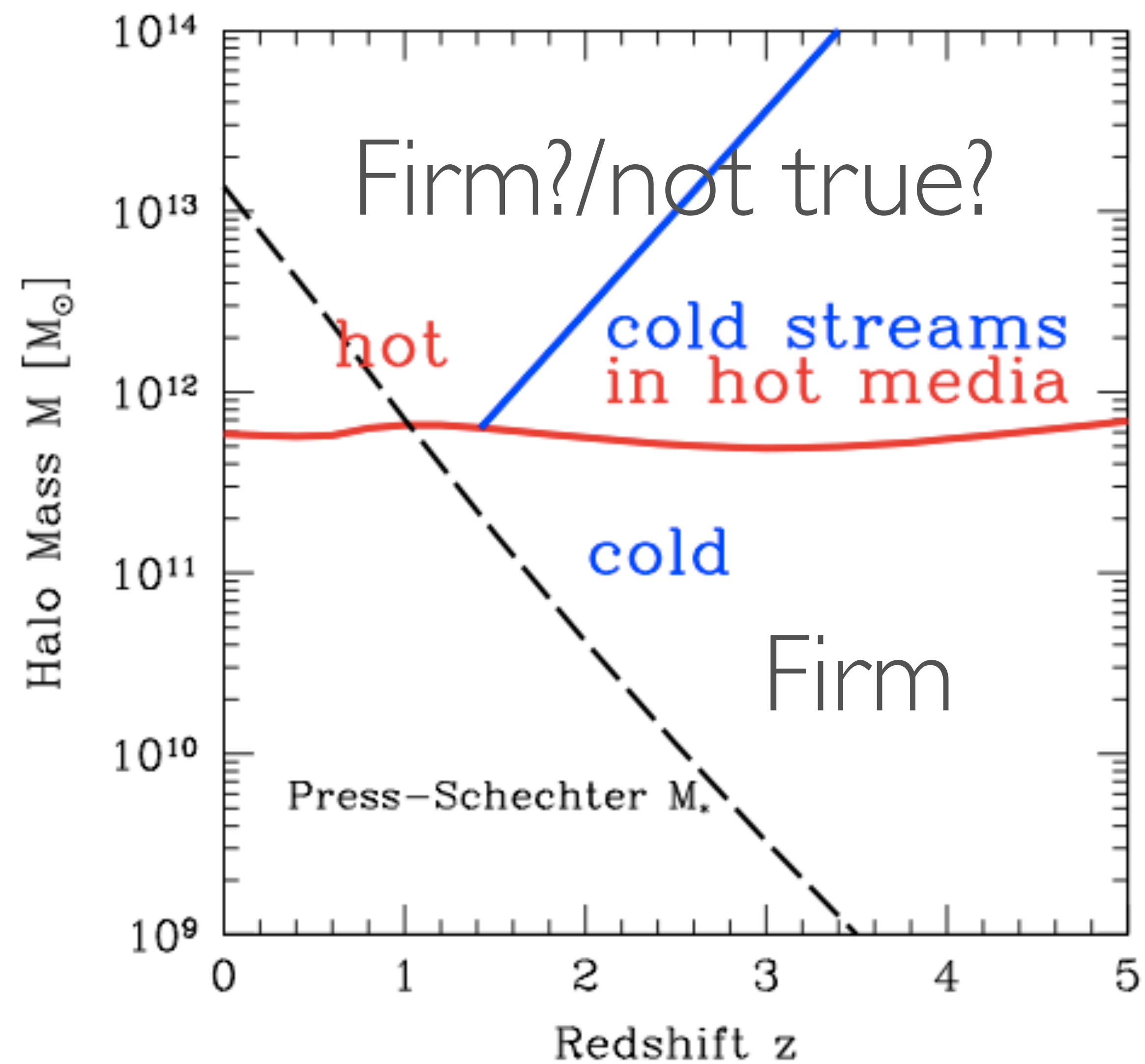

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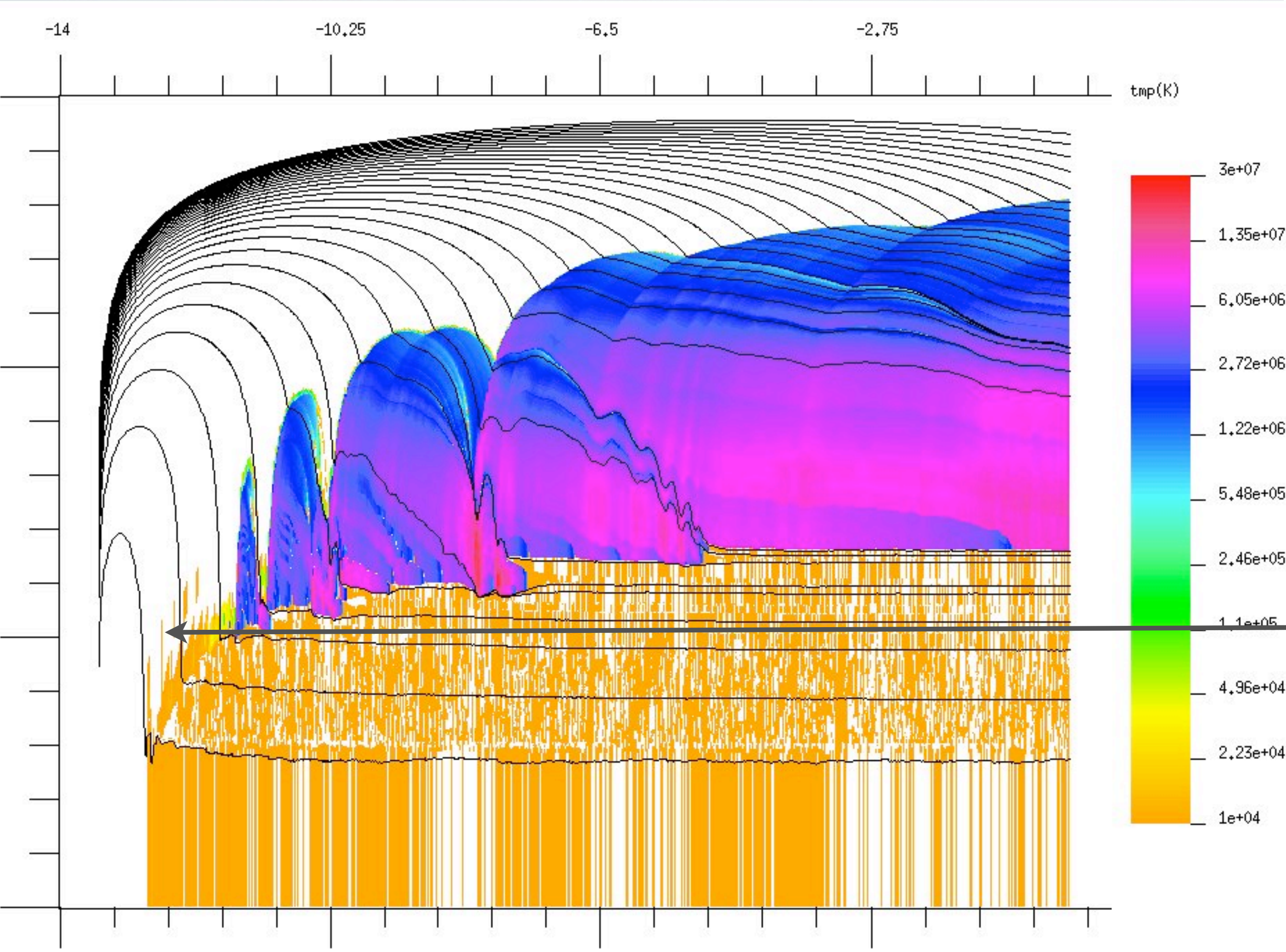
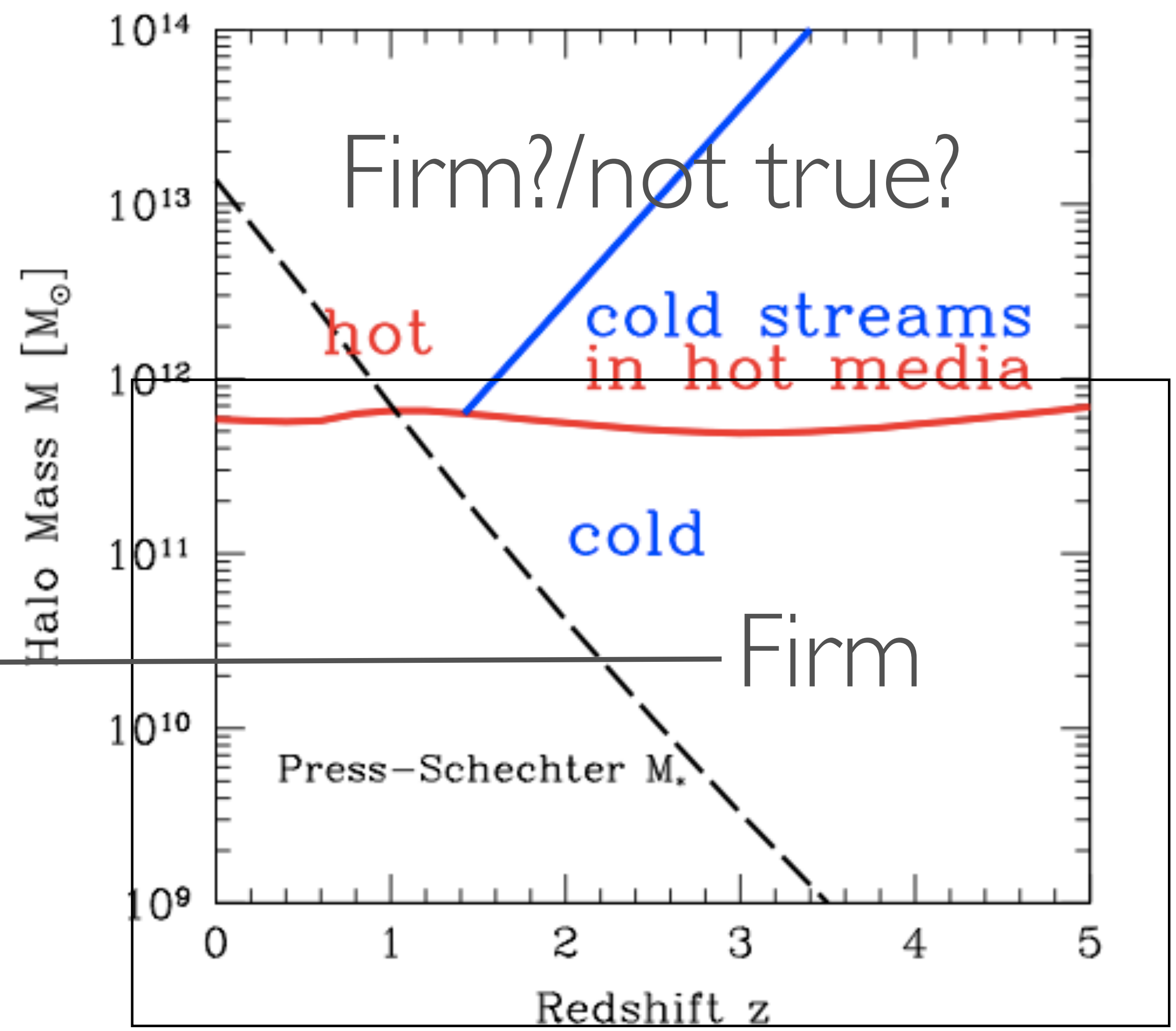




Dekel, Birnboim, et al., 2009

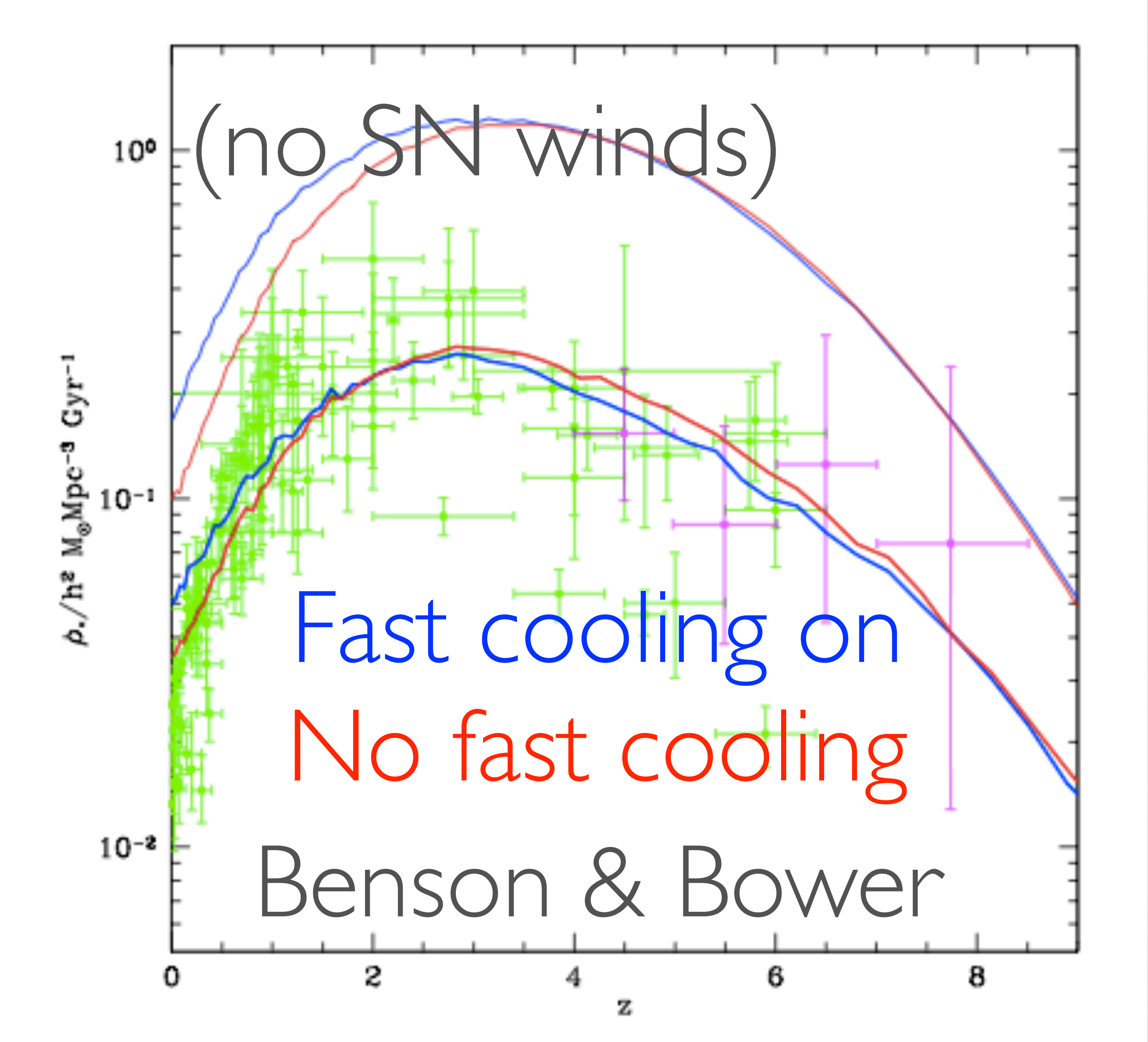
see also Keres et al., 2009, van de Voort et al., 2011, etc.

4) COLD GAS INFLOWS

Implemented in the GALFORM semi-analytic model by Benson & Bower (2010):

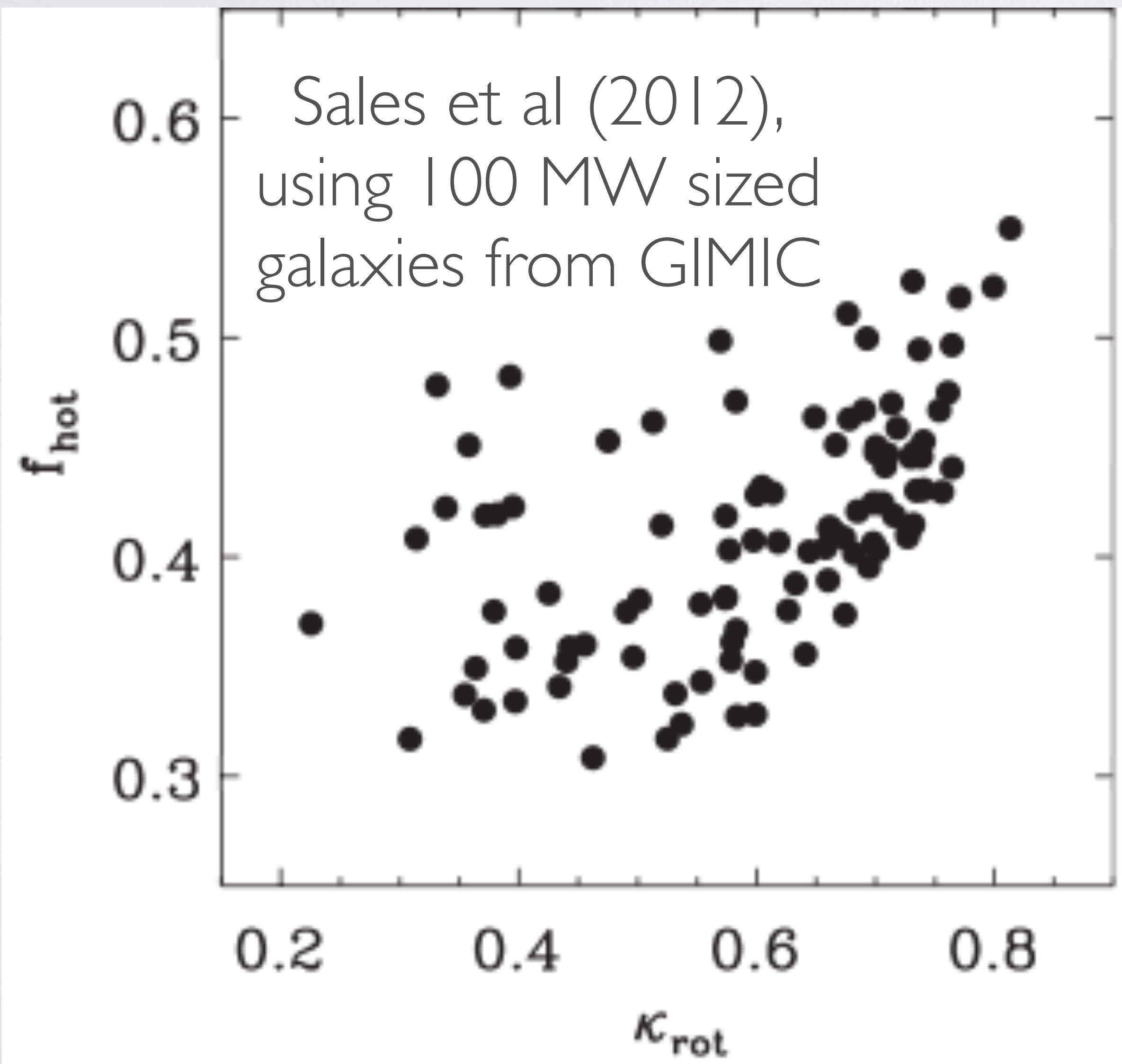
- Analytic approximation.
- Assume infalling cold gas relaxes in halo (also relaxed).

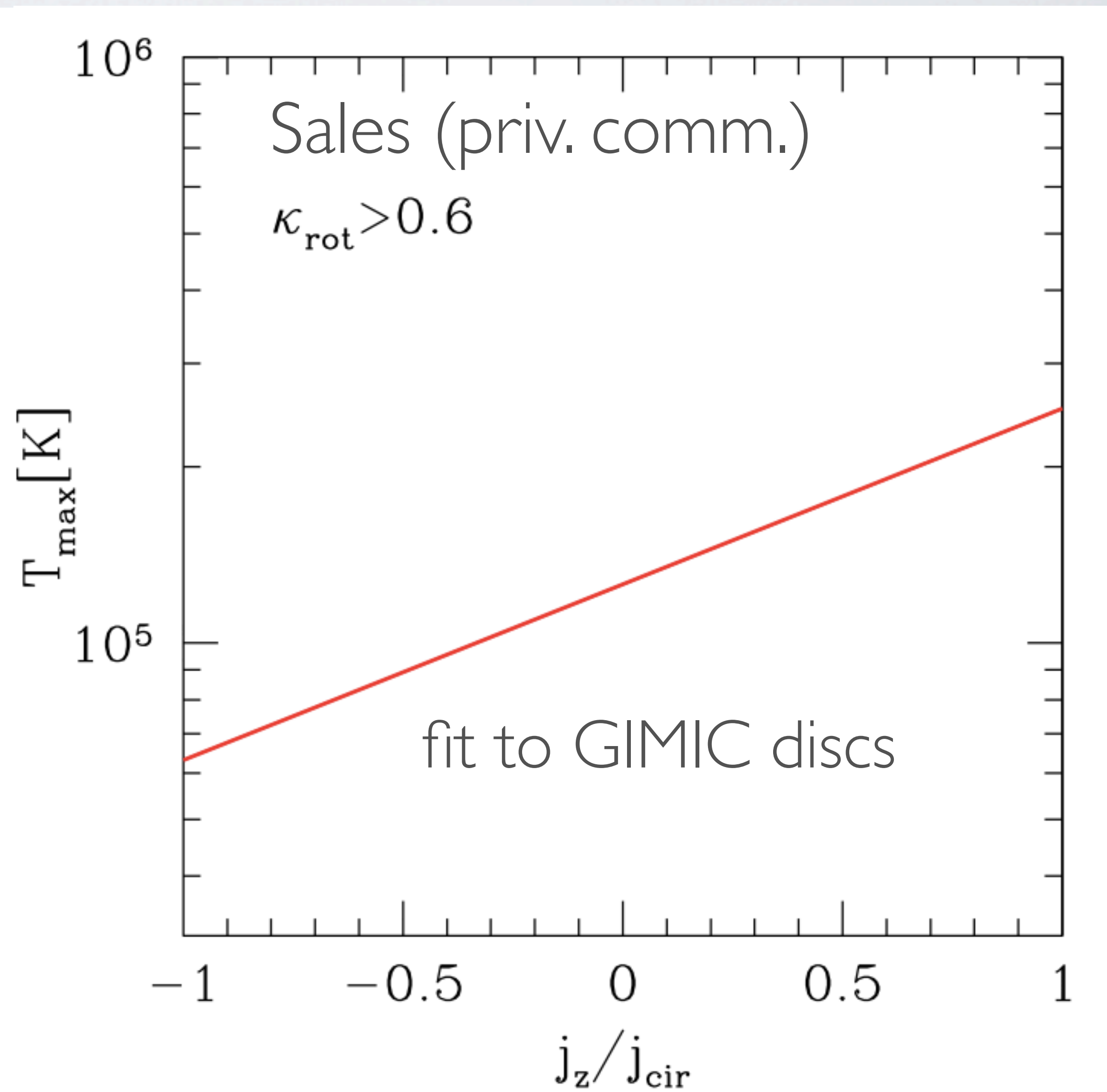
As a result, even though there is more cold gas in galaxies at high-z, the discs are larger: not an important effect on the SFR.



4) COLD GAS INFLOWS

However, in gas simulations most of the gas that forms discs has been in a hot phase, indicating that cold flows are somehow responsible for the existence of a spheroid component.





4) EFFECT ON SF

We adopt two different treatments:

- Angular momentum of filament gas as that of a relaxed DM halo: more angular momentum, more gas, larger disc, may not increase SF.

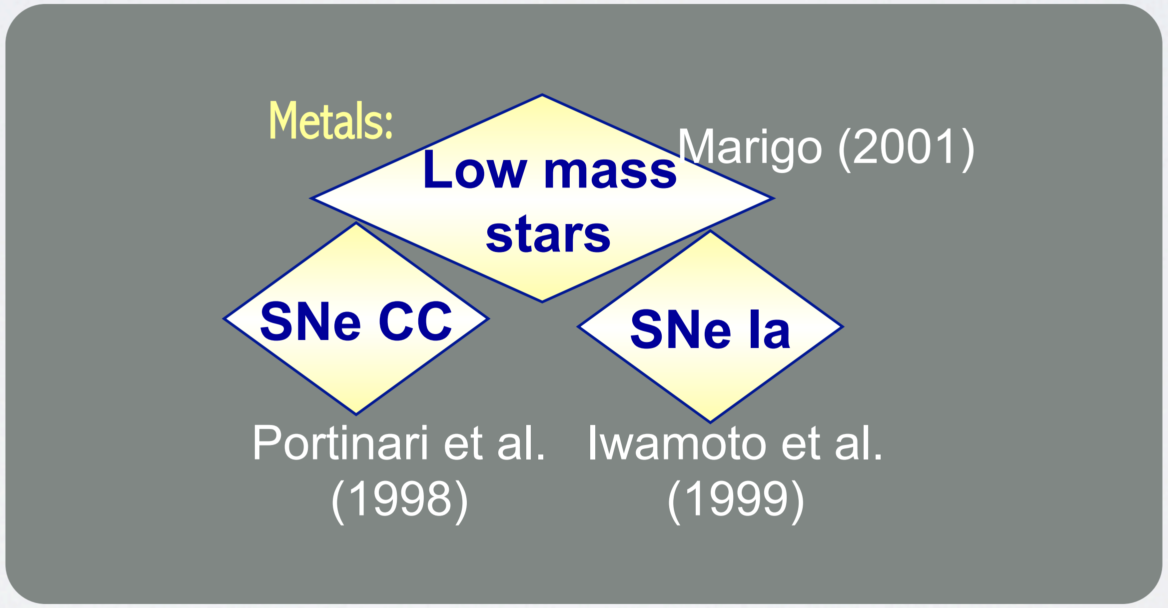
- Angular momentum assumed to follow **flips** according to the baryonic mass coming with the cold inflows: comparatively smaller gas disc.

4) COLD GAS INFLOWS IN SAG

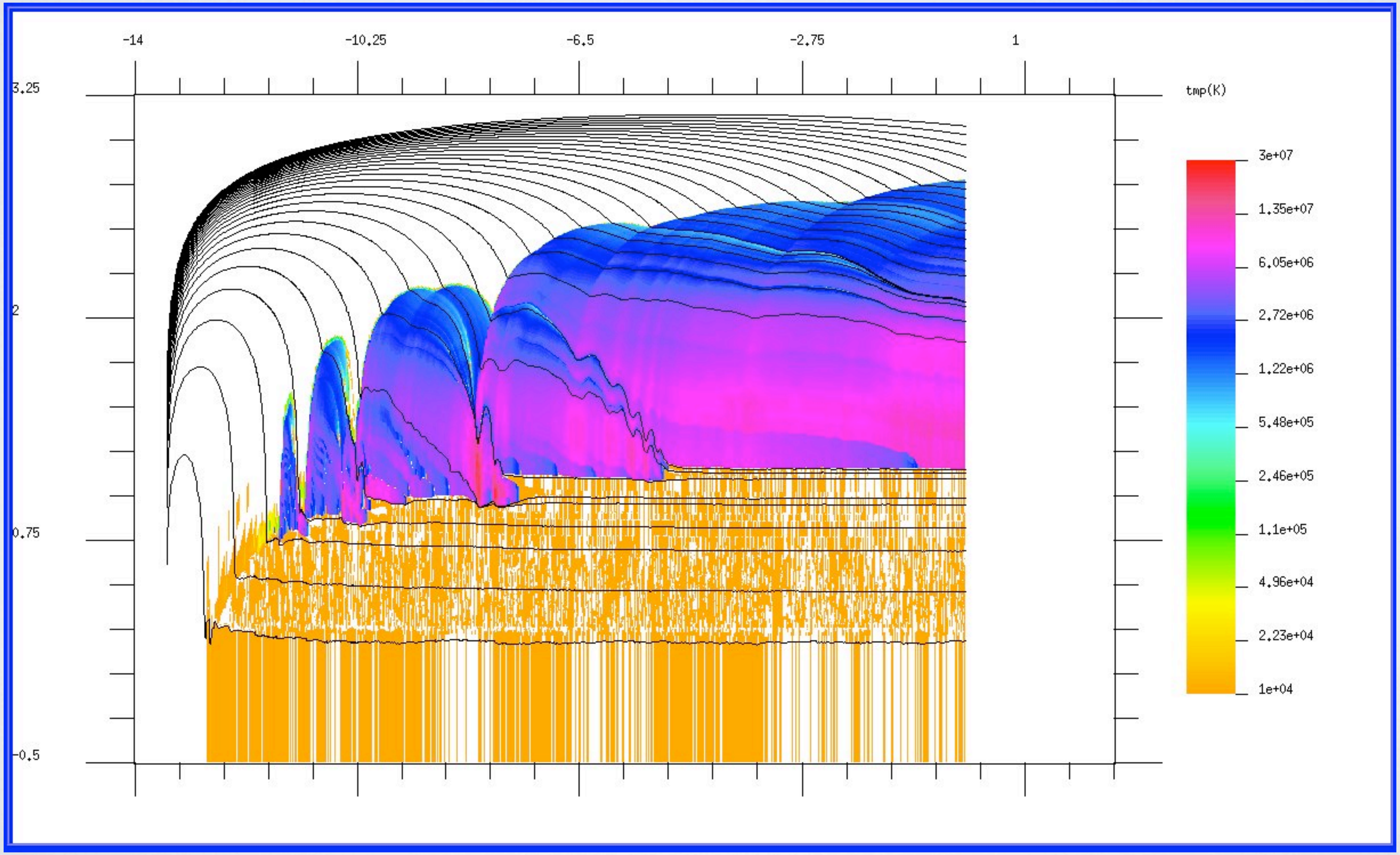
In SAG, we use the Sutherland and Dopita metallicity dependent cooling rates:

$$\frac{\mathrm{d}M_{\mathrm{cool}}}{\mathrm{d}t} = 4\pi r_{\mathrm{cool}}^2 \frac{\mathrm{d}r_{\mathrm{cool}}}{\mathrm{d}t}$$

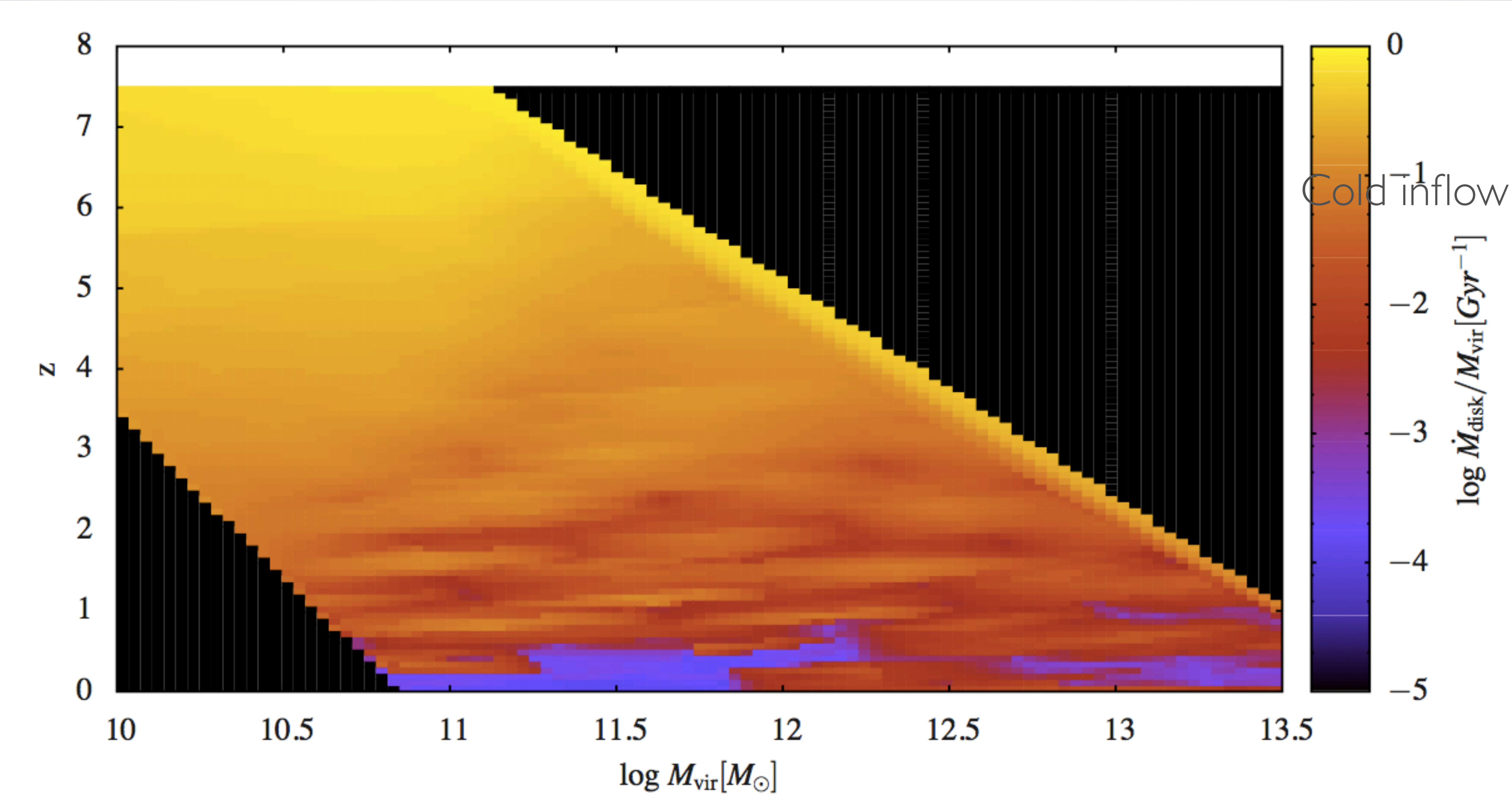
$$t_{\mathrm{cool}}(r) = \frac{3}{2} \frac{k T \rho_{\mathrm{g}}(r)}{\mu m_{\mathrm{p}} n_{\mathrm{e}}^2(r) \Lambda(T, Z)}$$



4) COLD INFLOWS FROM HYDRODYNAMICAL SIMULATIONS:



4) RATE OF COLD GAS INFLOW:



Cold inflow

incorporated in SAG via metallicity dependent fit (variables: metallicity, mass, redshift) keeping the SD cooling rates for slow cooling

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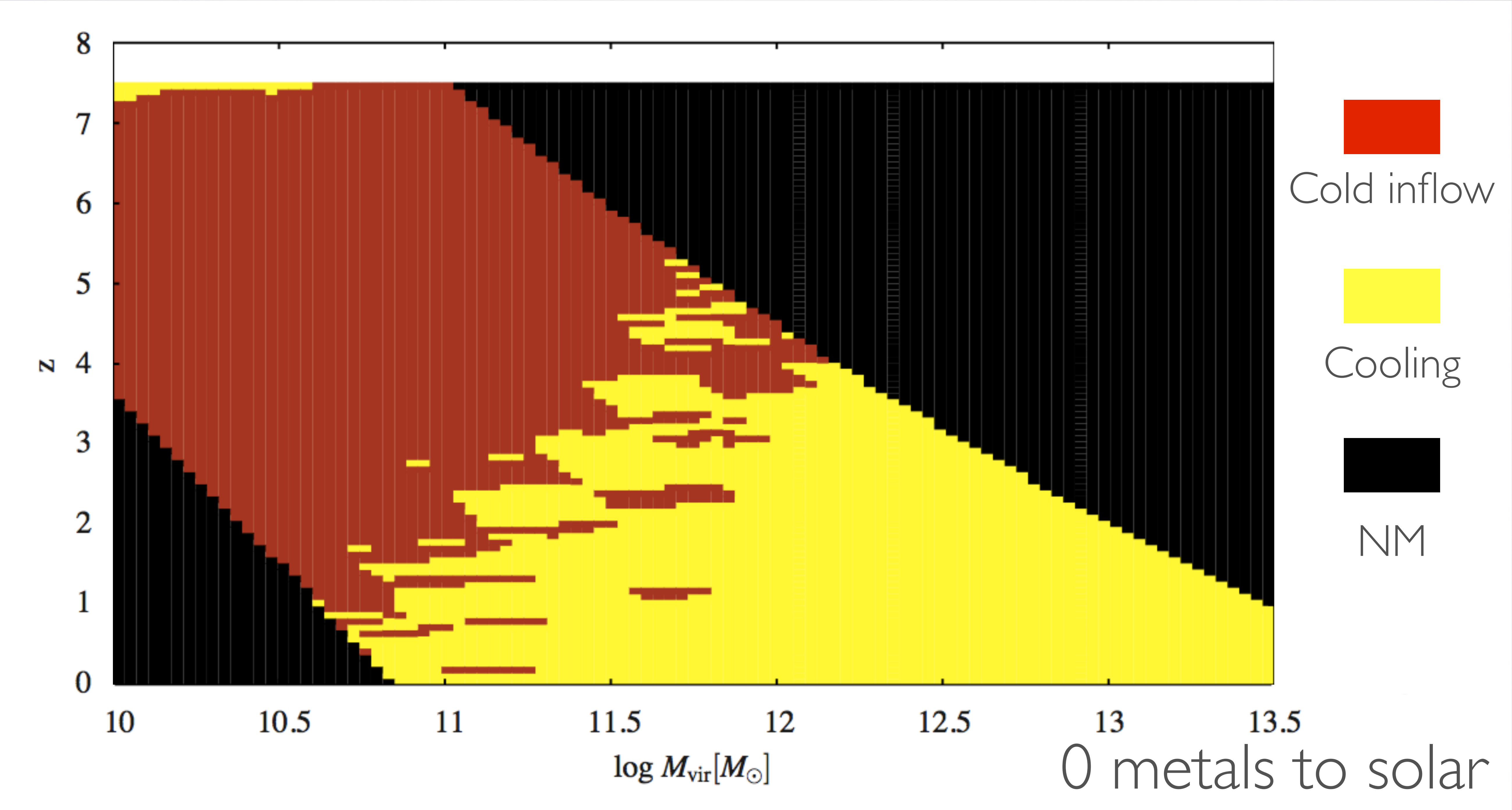

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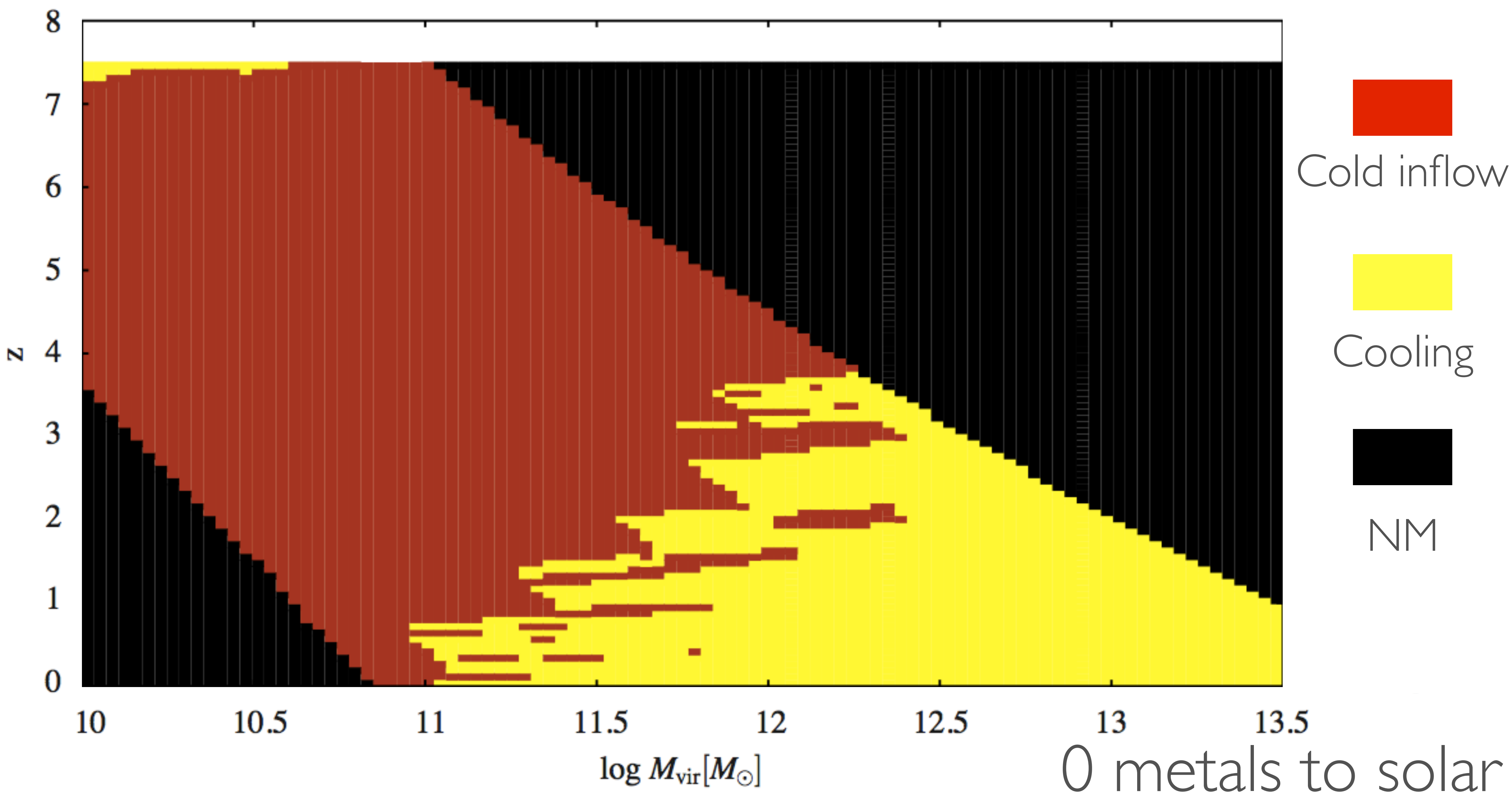

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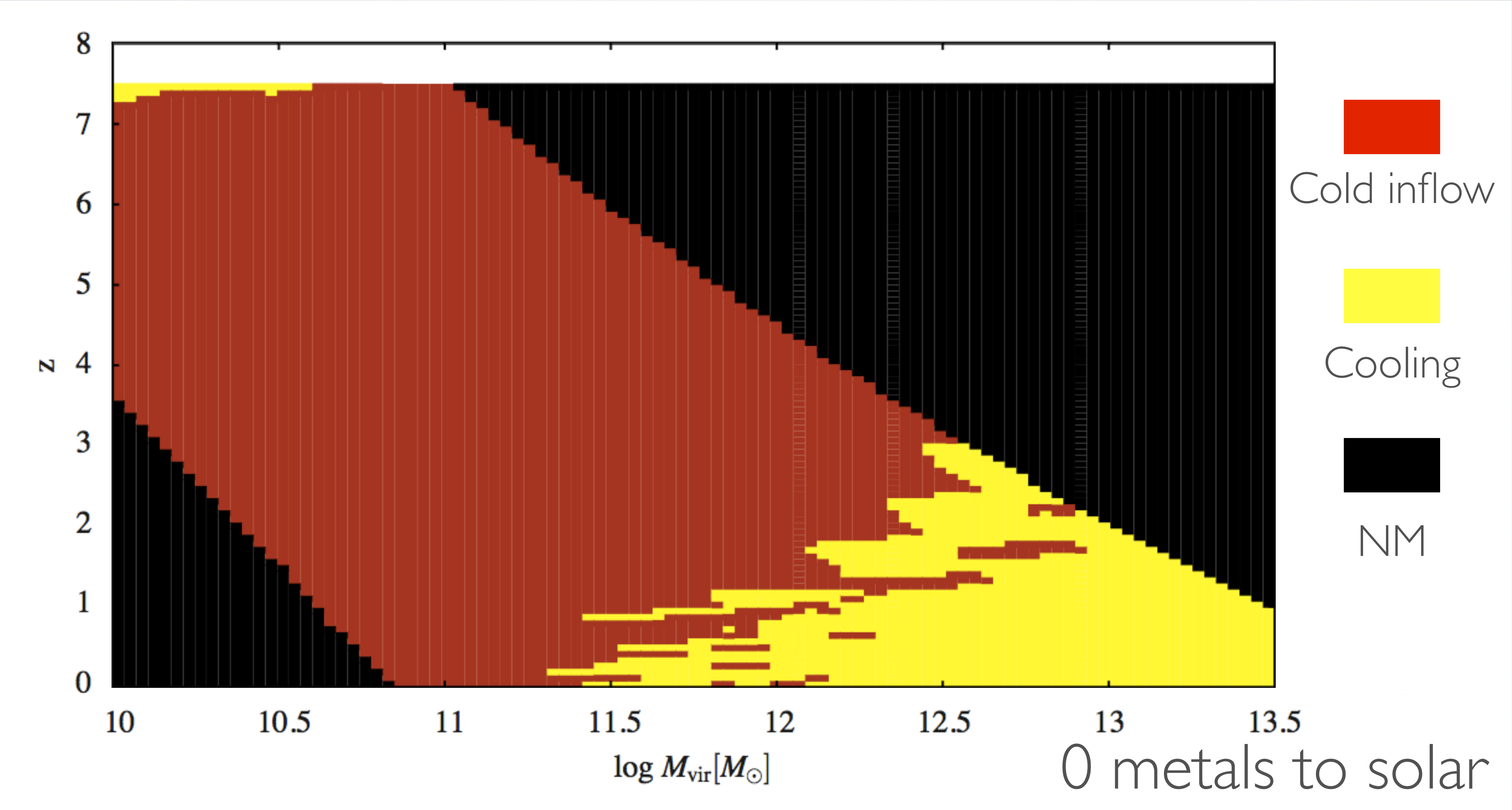

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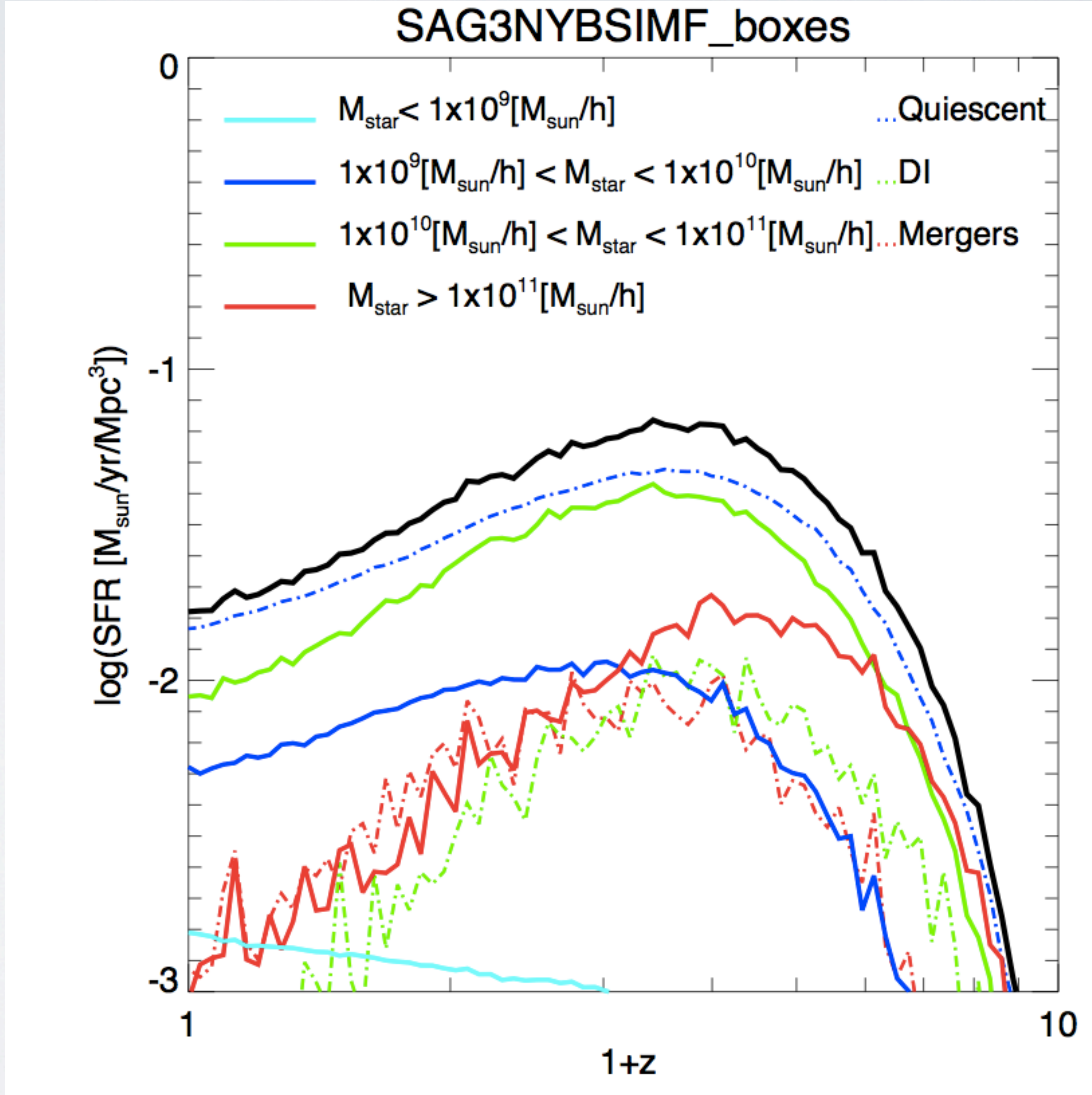
4) RESULTS: MADAU PLOT

- Almost no effect from cold-inflows when relaxing filaments and no flips.
- Factor of up to x2 increase in high-z SFR in flips case.



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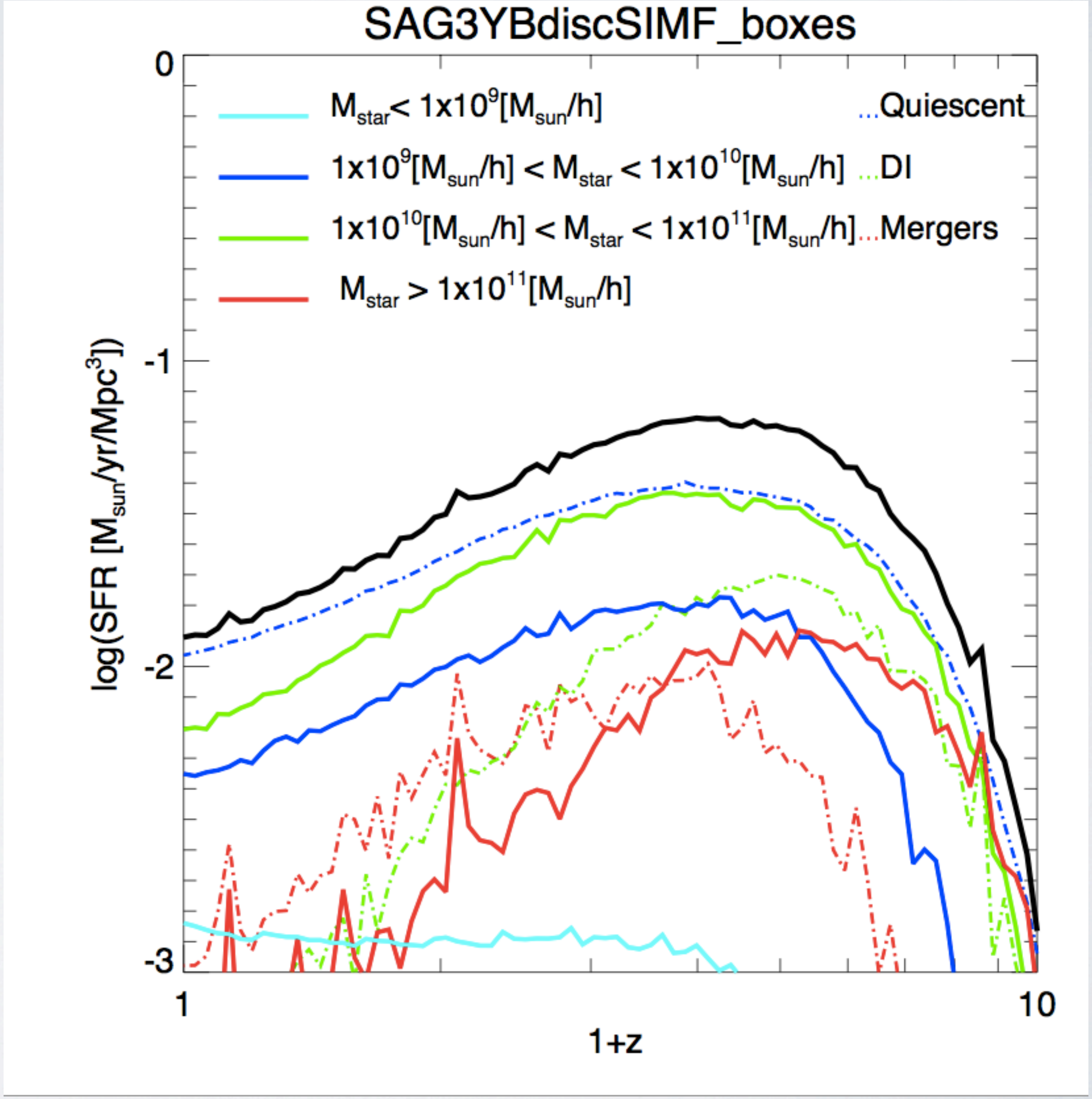


SAG

HOT GAS

$$M_{\mathrm{hot}} = \Omega_{\mathrm{b}} M_{\mathrm{vir}} - \sum_i \left(M^{(i)}_{\mathrm{star}} + M^{(i)}_{\mathrm{cold}}\right)$$

COLD GAS

$$\frac{\mathrm{d}M_{\mathrm{cool}}}{\mathrm{d}t} = 4\pi r^2_{\mathrm{cool}} \frac{\mathrm{d}r_{\mathrm{cool}}}{\mathrm{d}t}$$

$$t_{\mathrm{cool}}(r) = \frac{3}{2} \frac{k\,T\,\rho_{\mathrm{g}}(r)}{\mu\, m_{\mathrm{p}}\, n^2_{\mathrm{e}}(r)\,\Lambda(T,Z)}$$

STARS

$$\frac{dM_*}{dt} = \alpha \left(\frac{V_{\mathrm{vir}}}{220\,\mathrm{km\,s^{-1}}}\right)^n \frac{M_{\mathrm{cold}}}{t_{\mathrm{dyn}}}$$

Option 1

$$\frac{dM_*}{dt} = \alpha \frac{(M_{\mathrm{cold}} - M_{\mathrm{crit}})}{t_{\mathrm{dyn}}}$$

Option 2: Croton et al. (2006)

FEEDBACK

$$\Delta M_{\mathrm{reheat}} = \frac{4}{3} \varepsilon \frac{\eta_{\mathrm{SNCC}} E_{\mathrm{SNCC}}}{V^2_{\mathrm{vir}}} \Delta M_*$$

Metals:

Low mass stars — Marigo (2001)

SNe CC — Portinari et al. (1998)

SNe Ia — Iwamoto et al. (1999)

Simple degenerate model (Lia et al. 2002)

Stellar life time:

Padovani & Matteucci (1993)

Cora (2006)

Improvement

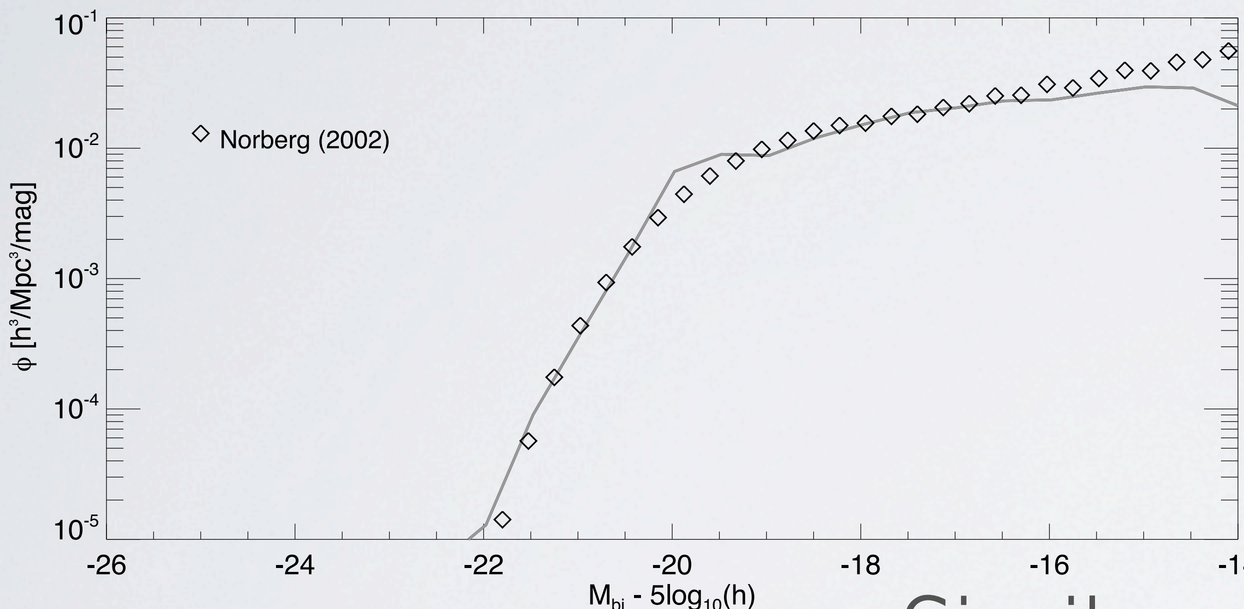
AGN FEEDBACK

Lagos, Cora & Padilla (2008)

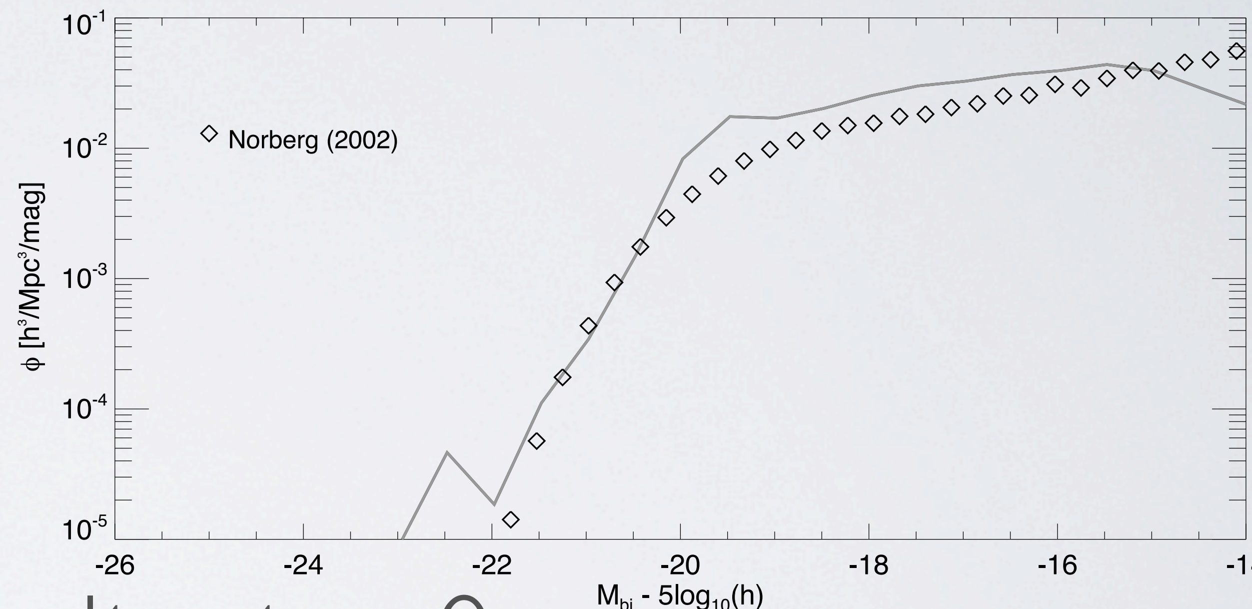
4) RESULTS: Z=0 LF

Do we still reproduce z=0 properties?

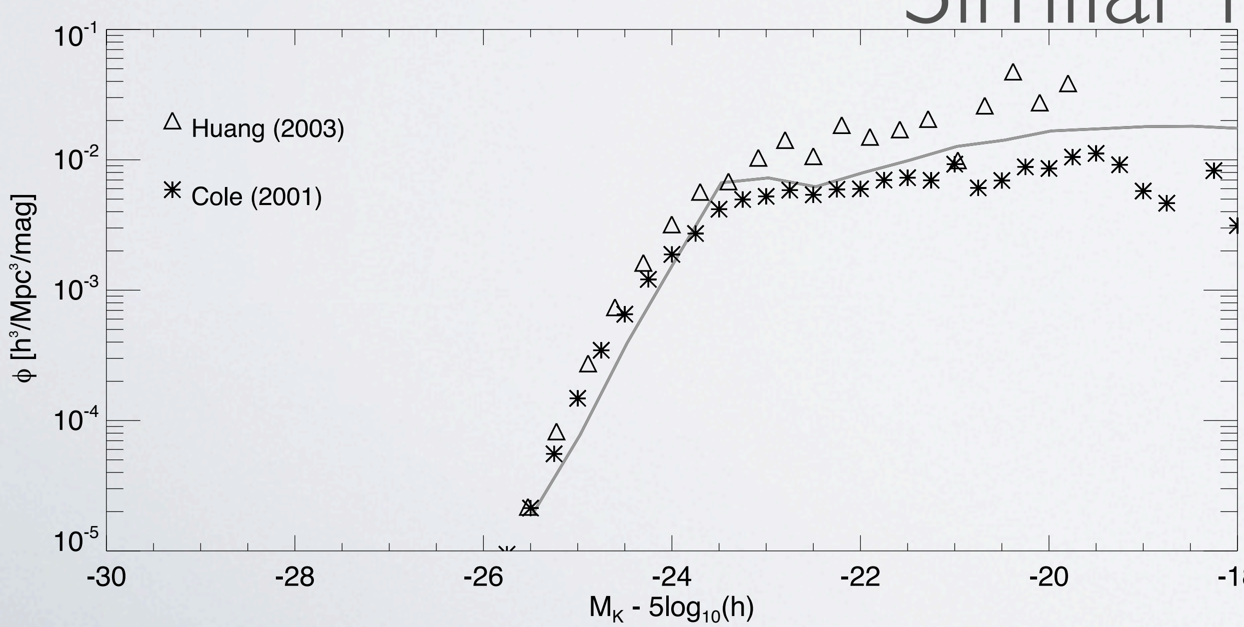
No cold inflows

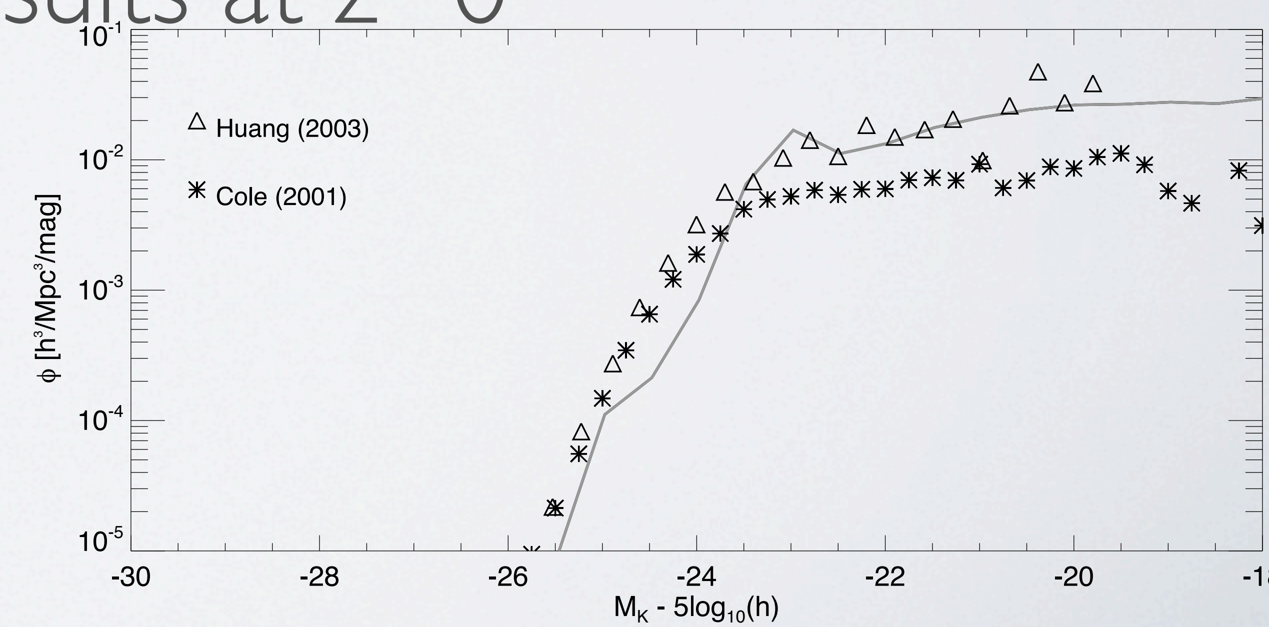


Cold inflows zero J



Similar results at z=0





4) SPIN OF BHS:

Base model:

We have 3 different mechanism of BH growth: Bondi-Hoyle

- The QSO mode

$$\dot{M}_{\rm BH} = \frac{f_{\rm BH}}{\Delta T} \times \frac{M^{\rm sat}}{M^{\rm central}} \times \frac{M_{\rm ColdGas}}{1 + (200\,{\rm km\,s^{-1}}/V_{\rm vir})^2},$$

  with $f_{\rm BH} = 0{,}76$.

- The Radio mode

$$\dot{M}_{\rm BH} = \kappa_{\rm AGN} \frac{M_{\rm BH}}{10^8 M_\odot} \times \frac{f_{\rm hot}}{0{,}1} \times \left(\frac{V_{\rm vir}}{200\,{\rm km\,s^{-1}}}\right)^3,$$

  with $\kappa_{\rm AGN} = 6 \times 10^{-2}\ {\rm M_\odot\,yr^{-1}}$.

- Mergers of BHs

$$M_{\rm BH}^{\rm final} = M_{\rm BH}^1 + M_{\rm BH}^2$$

- The BH luminosity

$$L_{\rm BH} = \eta \dot{M}_{\rm BH},$$

  with $\eta = 0{,}1$.

- The modification of the cooling rate is given by

$$\dot{M}'_{\rm cool} = \dot{M}_{\rm cool} - \frac{L_{\rm BH}}{V_{\rm vir}^2/2}$$

- We limit the luminosity by the "Eddington limit"

$$L_{\rm edd} = \frac{4\pi G m_p}{\sigma_T} M_{\rm BH}$$

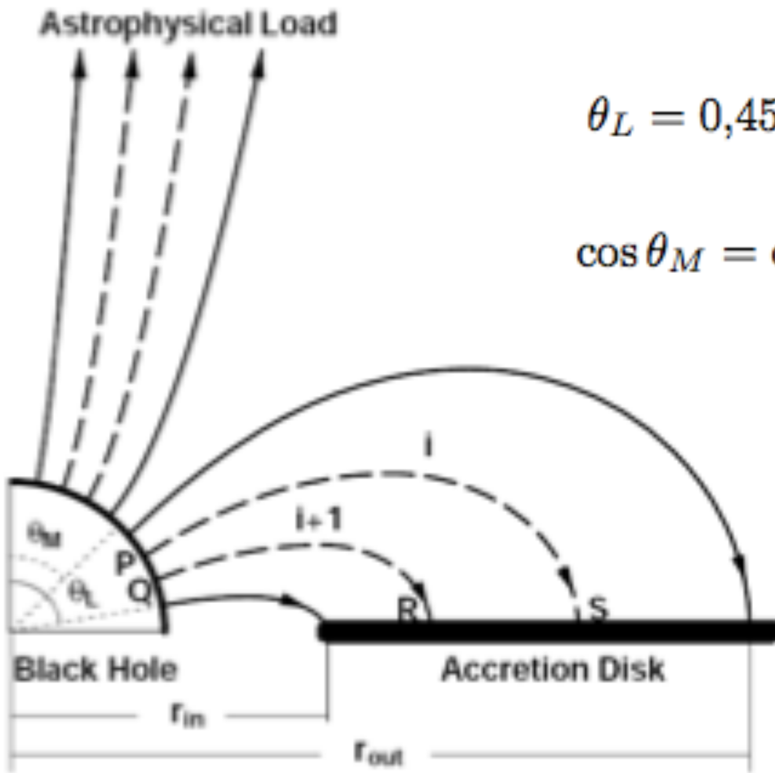
Model with BH spin:

Spin:
last stable orbit
lies further in.

$$F(r) = \frac{\dot{M}_0}{4\pi r} f + \frac{1}{r} \frac{-\Omega_{,r}}{(E^+ - \Omega L^+)^2} \int_{r_{\rm ms}}^{r} (E^+ - \Omega L^+) H r dr,$$

Higher accretion
disc flux.

We use the model of Wang, Xiao & Lei (2002), with the improvement of Wang et al. (2003)



$$\theta_L = 0{,}45\pi$$

$$\cos\theta_M = \cos\theta_L + \int_1^{\xi_{\rm out}} G(a_*, \xi, n) d\xi.$$

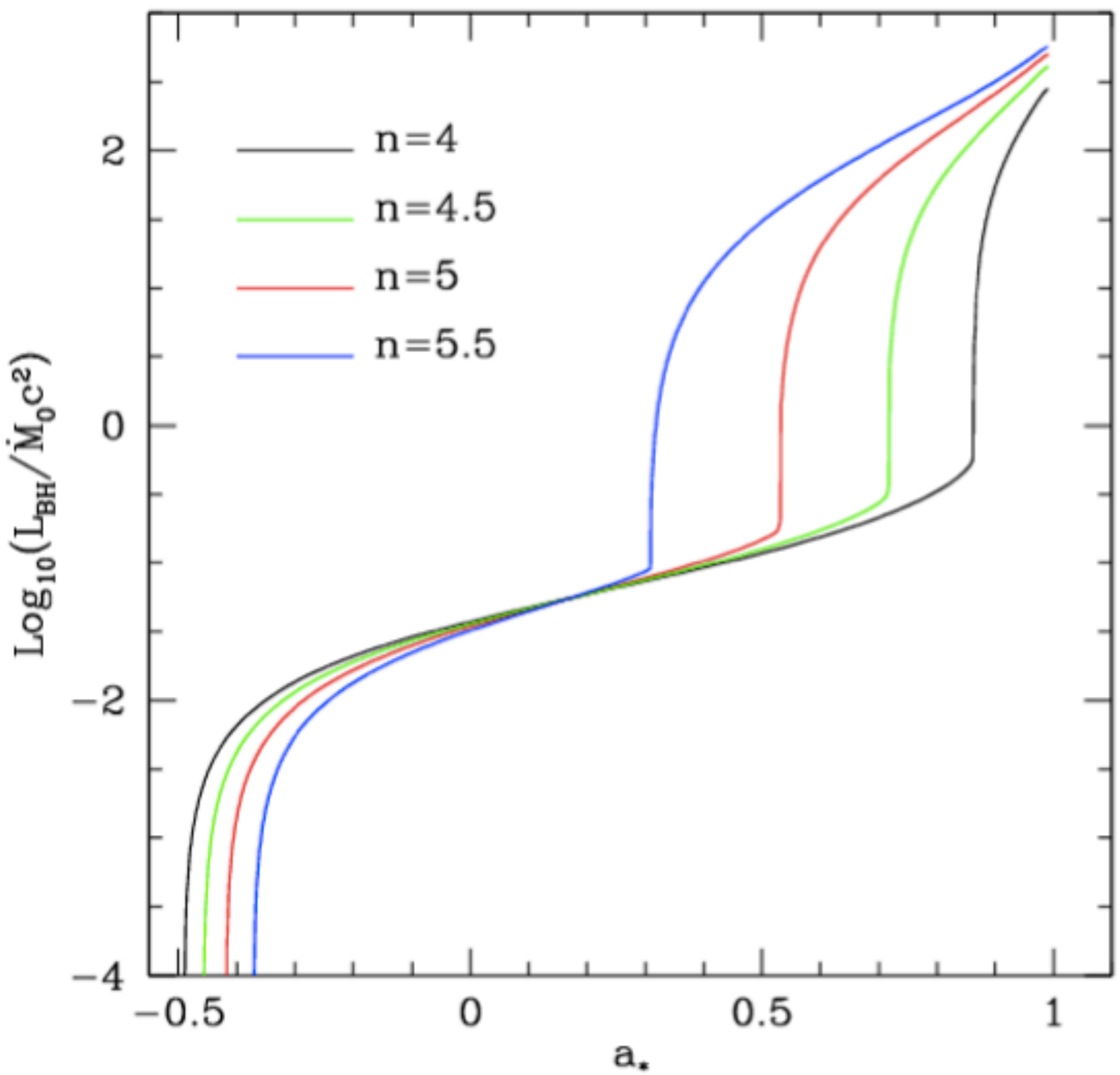
This model allows the coexistence of the BZ and MC processes (CEBZMC).

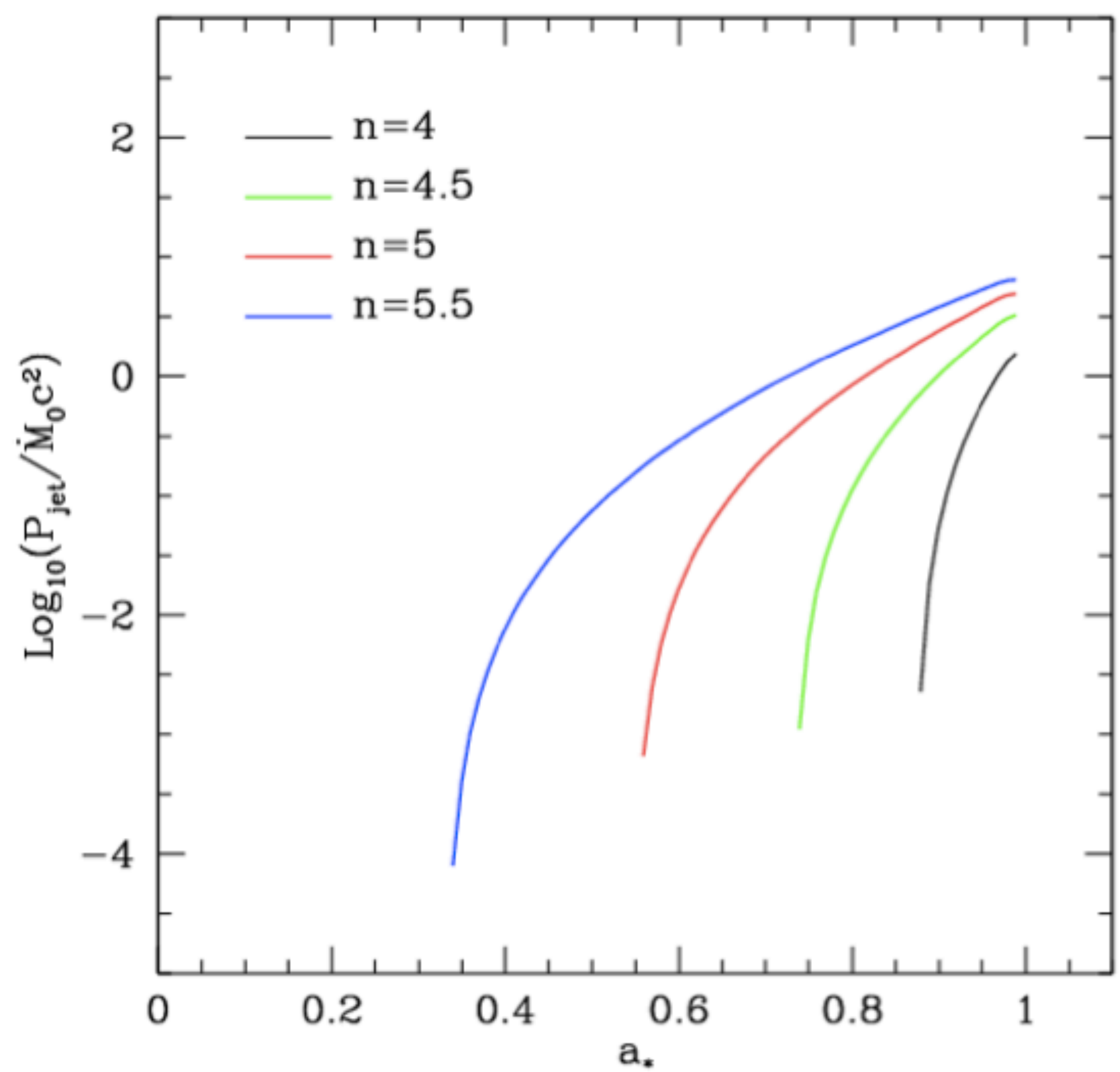
The magnetic field on the horizon

$$B_{\rm H}^2 = \frac{2\dot{M}_0}{r_{\rm H}^2}$$

$$\begin{aligned} L_{\rm BH} &\equiv 2\int_{r_{\rm ms}}^{\infty} FE^+ 2\pi r dr \\ &= \dot{M}_0(1 - E_{\rm ms}^+) + 4\pi \int_{r_{\rm ms}}^{\infty} H\Omega r dr \\ &= \epsilon_0 \dot{M}_0 + L_{\rm MC} \end{aligned}$$

4) SPIN OF BHS:

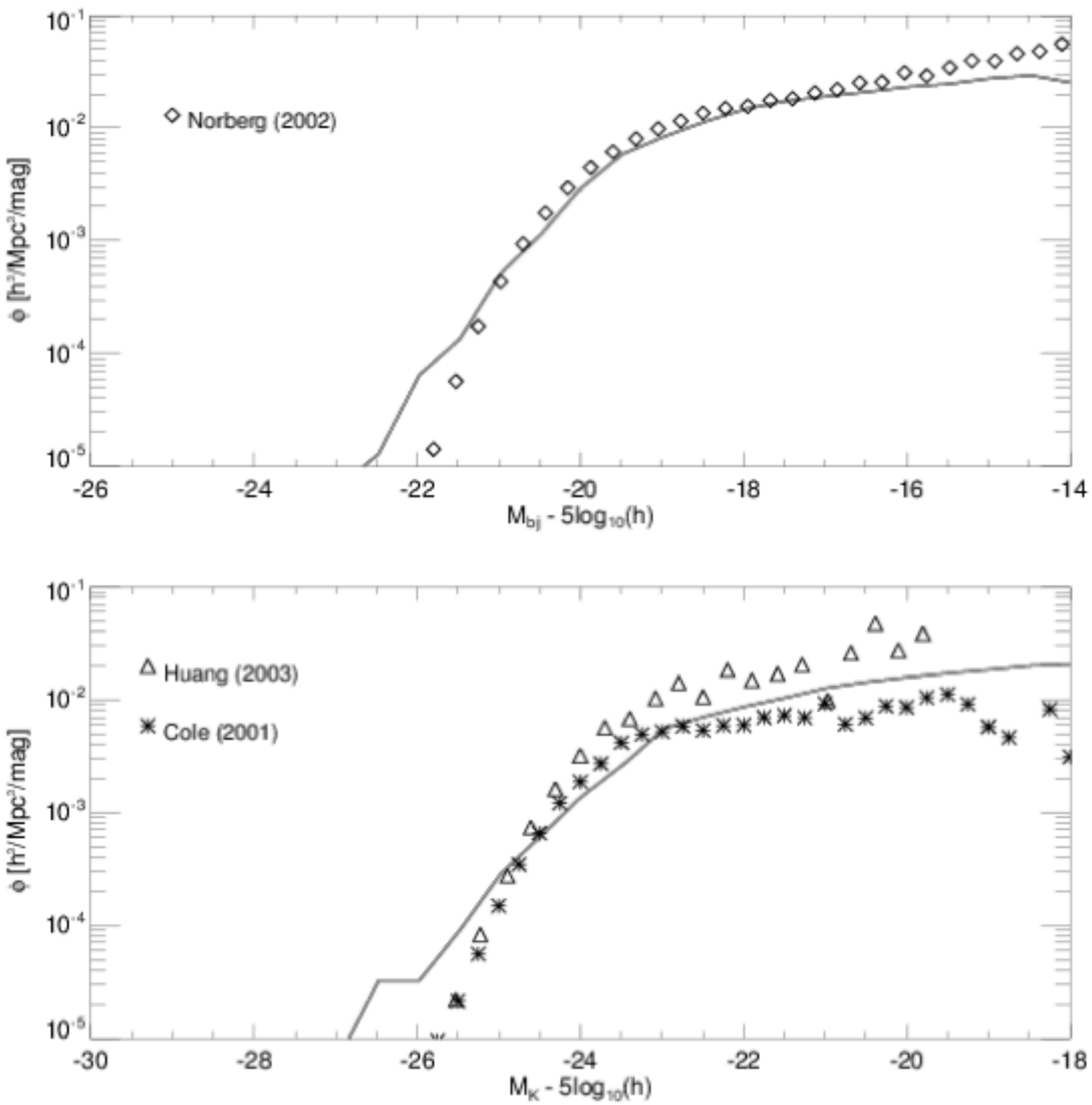




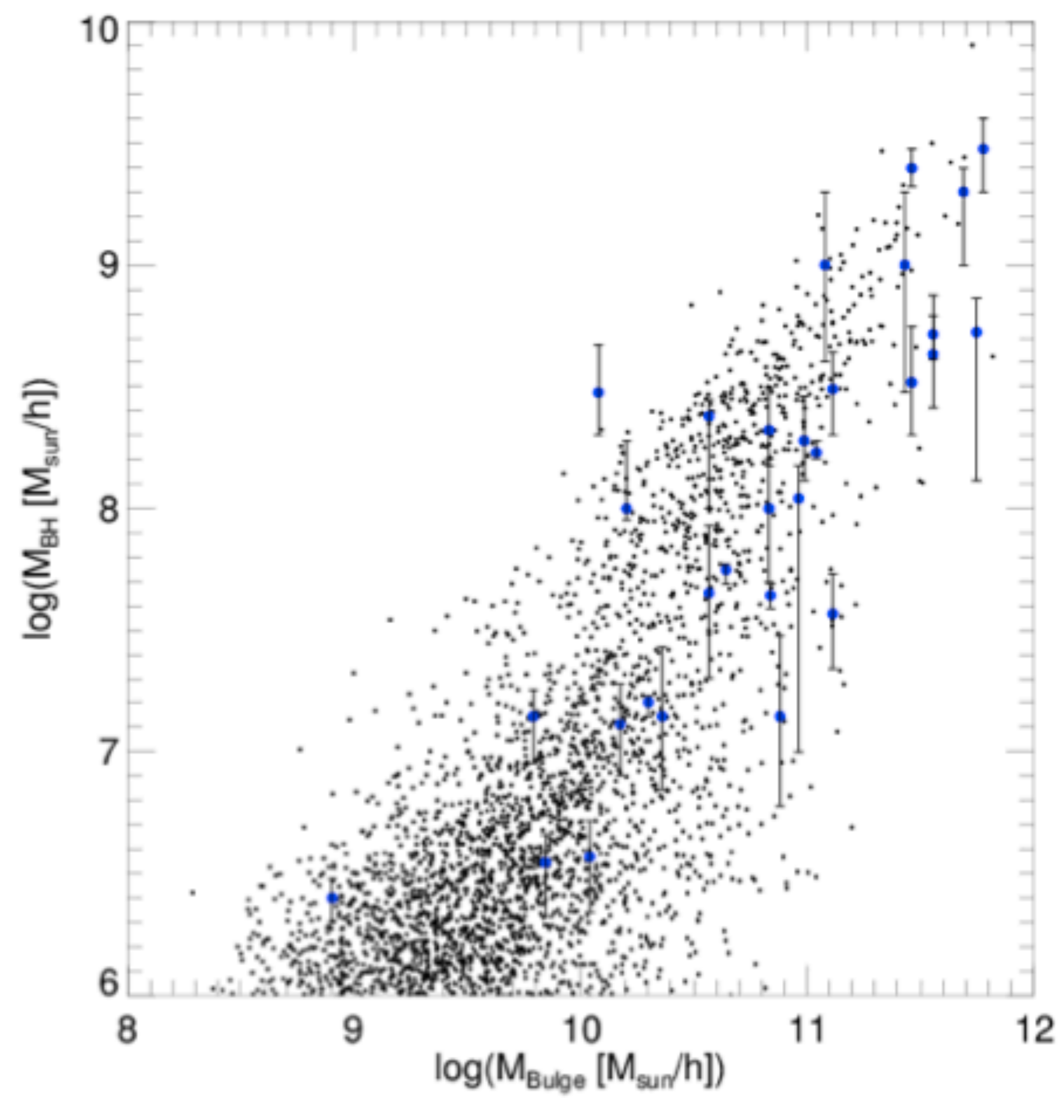
$$(\Delta M_{\mathrm{reheated}})_{\mathrm{AGN}} = \eta_{\mathrm{BH}} \frac{L_{\mathrm{BH}}}{V_{\mathrm{vir}}^2/2}$$

$$\dot{M}'_{\mathrm{cool}} = \dot{M}_{\mathrm{cool}} - \eta_{\mathrm{FB}} \frac{P_{\mathrm{jet}}}{V_{\mathrm{vir}}^2/2}$$

4) SPIN OF BHS:



Norberg (2002)
ϕ [h³/Mpc³/mag]
M_{bj} - 5log$_{10}$(h)
Huang (2003)
Cole (2001)
ϕ [h³/Mpc³/mag]
M_K - 5log$_{10}$(h)



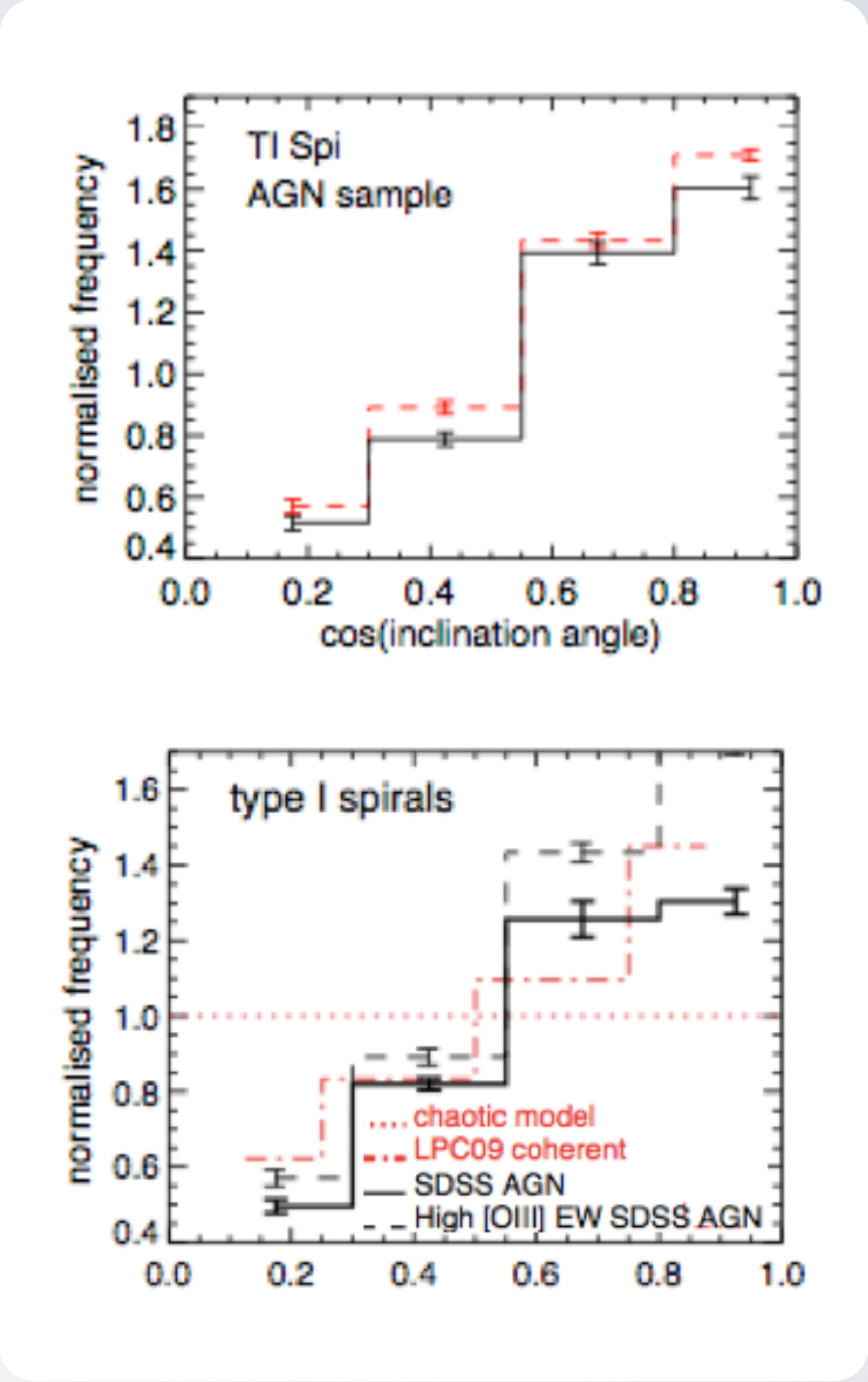
log(M_{BH} [M_{sun}/h])
log(M_{Bulge} [M_{sun}/h])

4) IS THERE EVIDENCE OF ALIGNMENTS?:

Evidence is conflicting:

Possitive in Schmitt et al. (2002) and in Battye & Browne (2008)

Lagos et al. (2011):



dotted horizontal: random orientations

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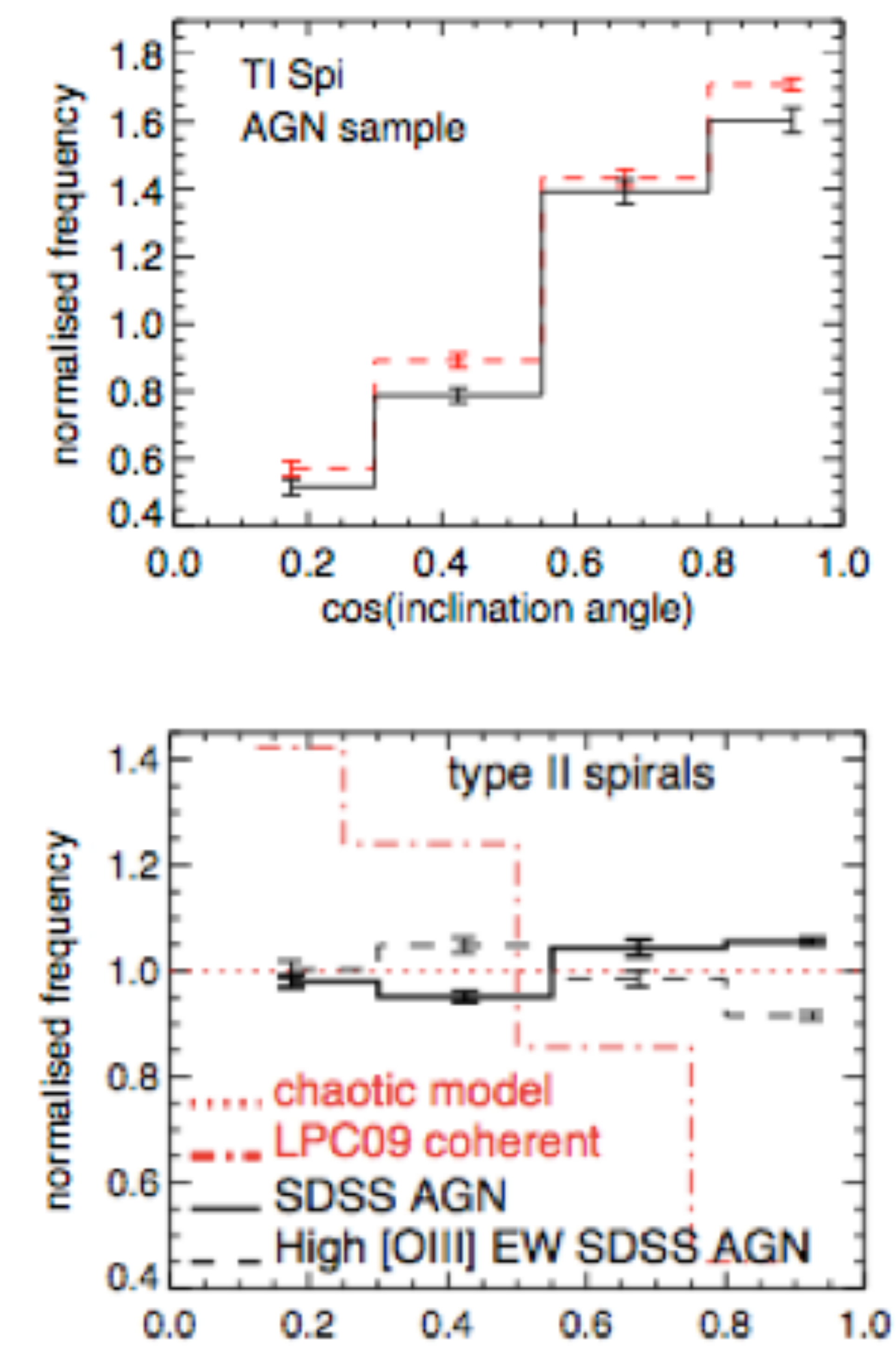
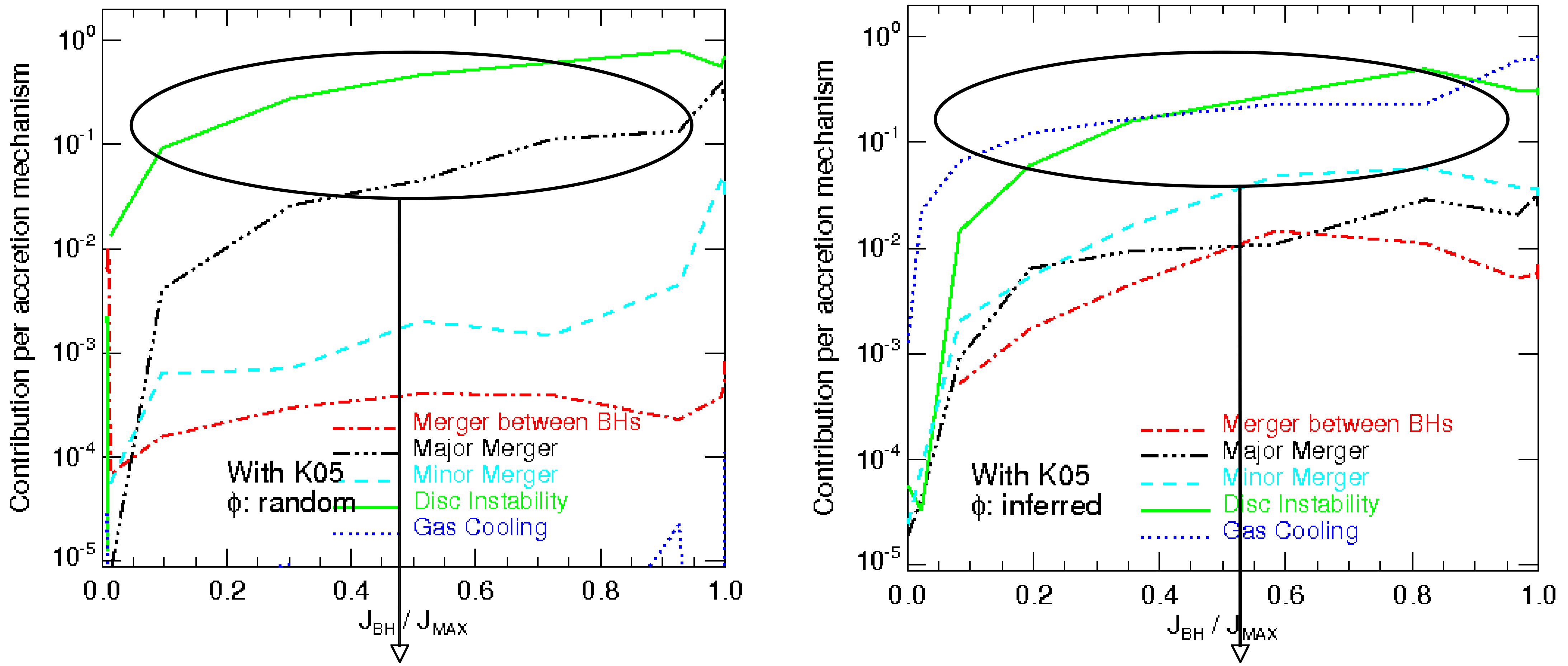


dotted horizontal: random orientations

4) IS THERE AN EFFECT OF ALIGNMENTS IN THE MODEL?:

→ One of the main advantages in use a SAM is to **follow the baryon physics** and to distinguish between different phenomena in the galaxy SFH

Lagos, Padilla & Cora (2009a)



same mechanisms that produce the main BH growth

processes involving same galaxy components