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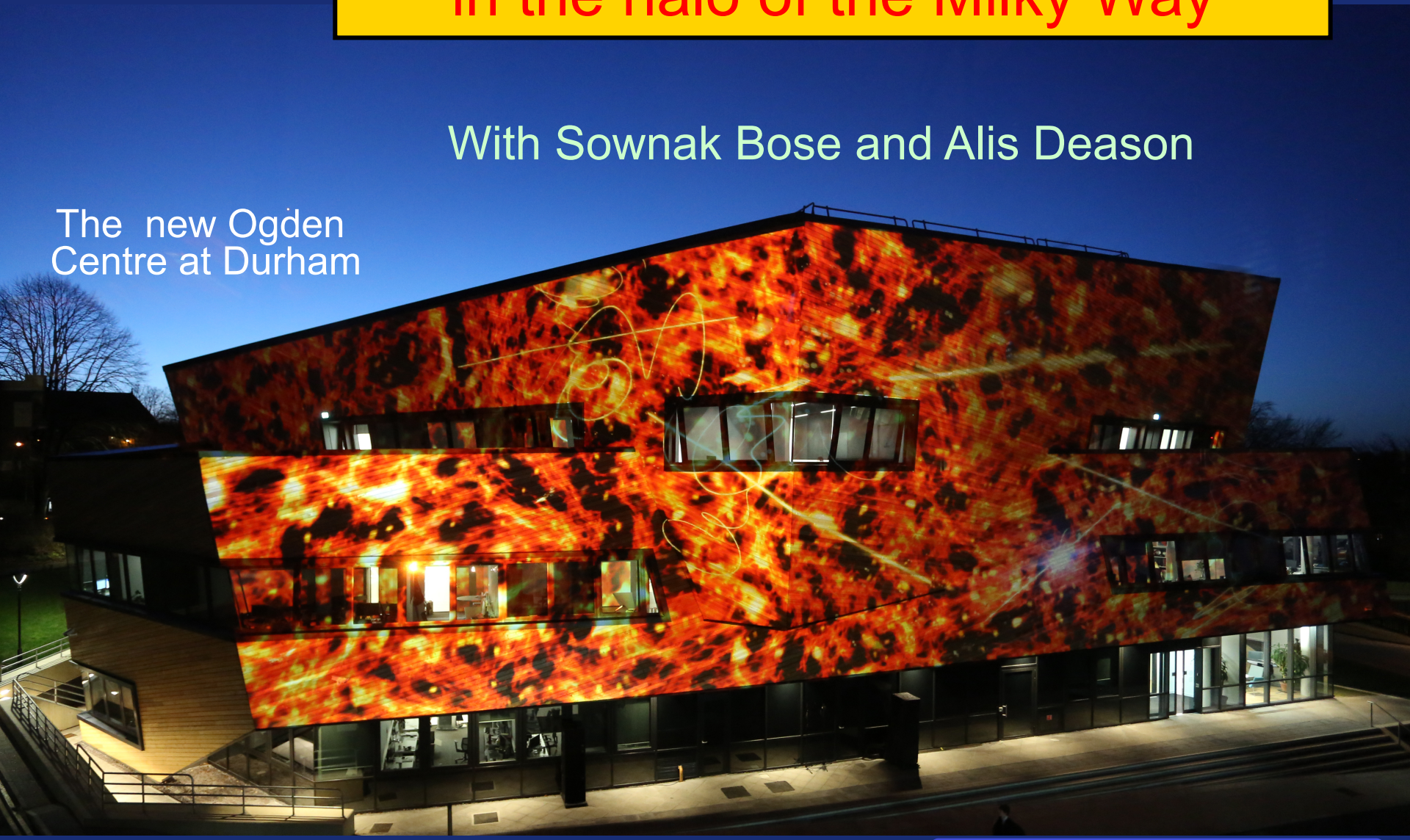
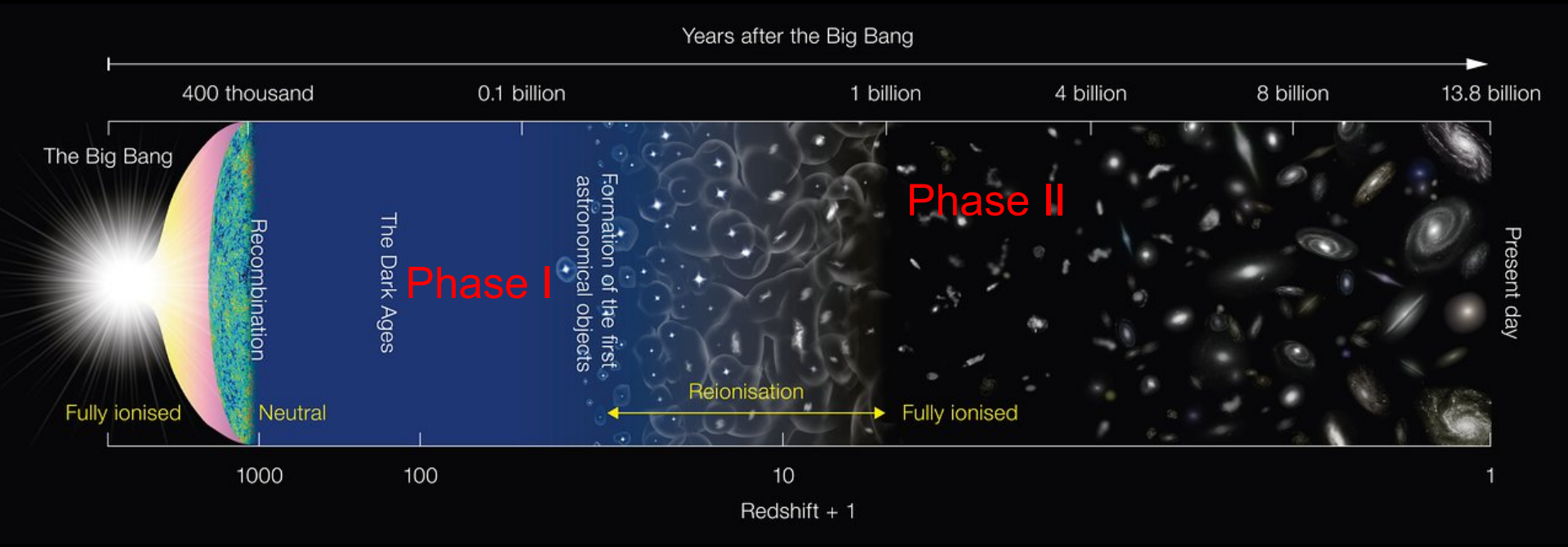
The imprint of cosmic reionisation in the halo of the Milky Way

With Sownak Bose and Alis Deason



The two phases of galaxy formation



Phase I: Galaxies begin to form during the "dark ages"

First stars reionize H and heat it up to 10^4K → prevents gas from cooling in halos of "T_{vir}" < 10^4K – galaxy formation is interrupted

Phase II: Halos with "T_{vir}" > 10^4K form → galaxy formation resumes

Is there evidence for these 2 phases of galaxy formation?

YES! We can see the two phases of galaxy formation in the halo of the Milky Way: the ultra-faint satellites formed during Phase I (i.e. before reionization) and the bright ones during Phase II.

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Galaxy formation theory

Two approaches:

1. Cosmological hydrodynamic simulations
2. Semi-analytic modelling

Hydro simulations cannot resolve the ultrafaints (yet)

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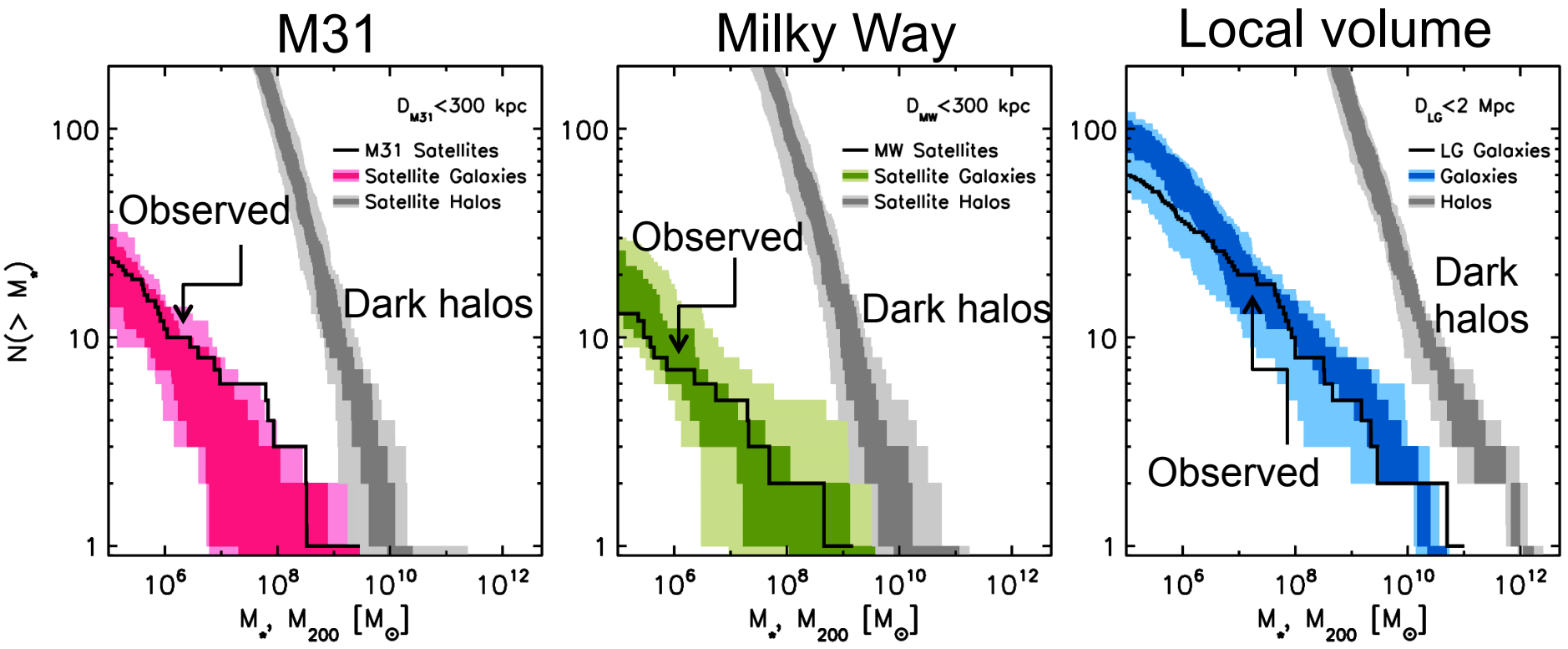
EAGLE Local Group simulation

APOSTLE

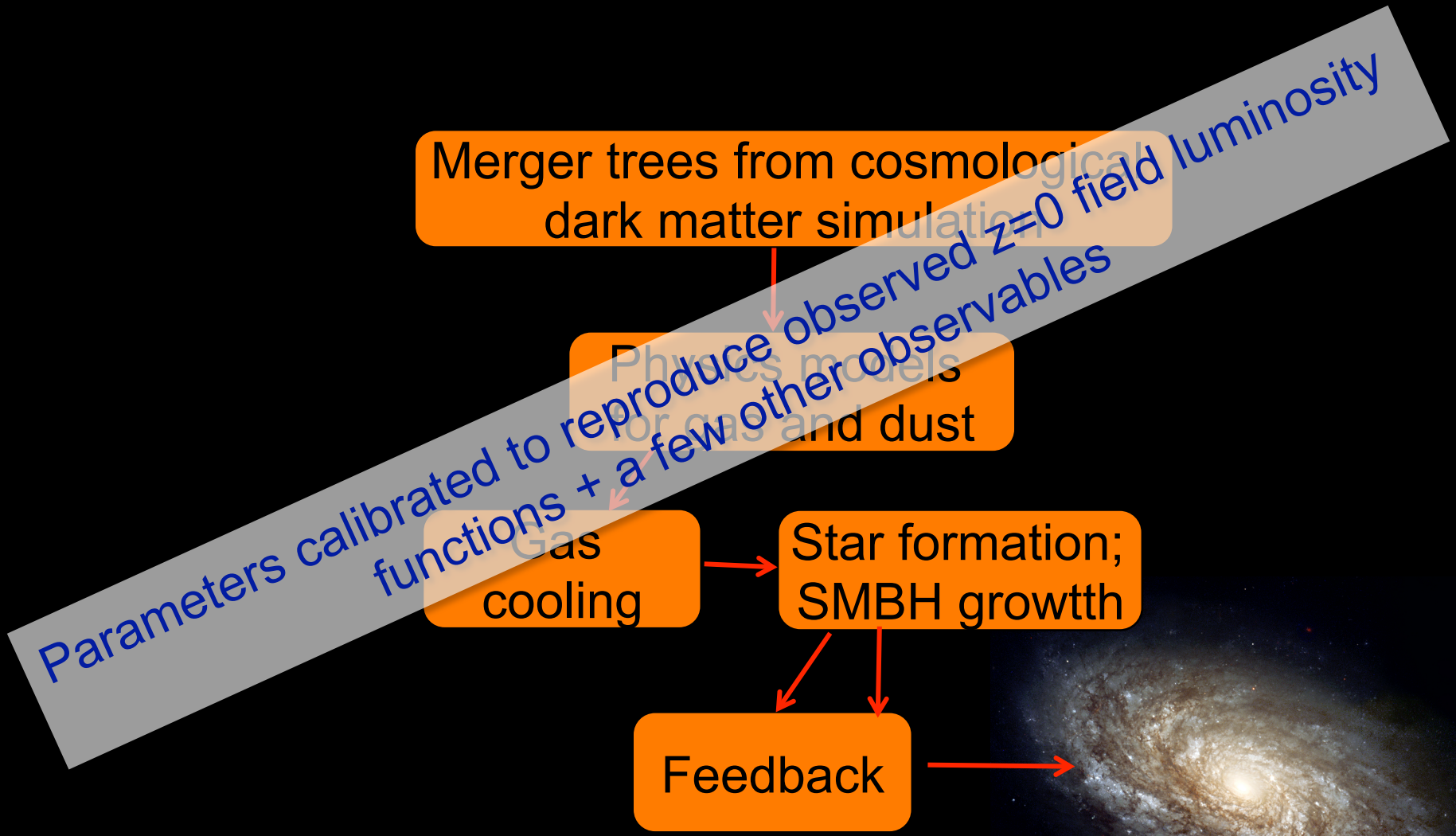


LCDM correctly predicts satellite luminosity function

Sawala, CSF et al '16

Institute for Computational Cosmology

The GALFORM model



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Photoionization & the filtering mass

Linear theory for the growth of a baryonic perturbation (Gnedin & Hui 98)

$$\ddot{\delta}_{\rm b} + 2H(a)\dot{\delta}_{\rm b} = 4\pi {\rm G}\bar{\rho}(f_{\rm DM}\delta_{\rm DM} + f_{\rm b}\delta_{\rm b}) - \frac{c_{\rm S}^2}{a^2}k^2\delta_{\rm b}$$

Instantaneous Jeans wavenumber given by $k_{\rm J} = \frac{a}{c_{\rm S}}\sqrt{4\pi {\rm G}\bar{\rho}}$

Expand baryonic overdensity in wavenumber:

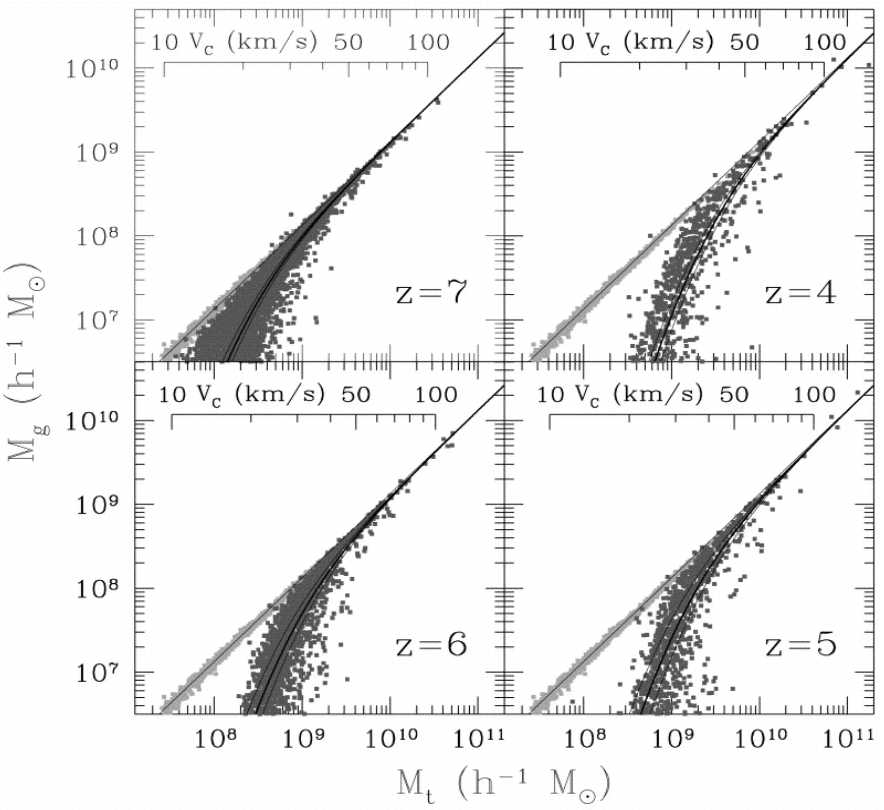
$$\frac{\delta_{\rm b}(t,k)}{\delta_{\rm DM}(t,k)} = 1 - \frac{k^2}{k_{\rm F}^2}$$

$$\frac{1}{k_{\rm F}^2}(t) = \frac{1}{D_+(t)}\int_0^t {\rm d}t' a^2(t')\frac{\ddot{D}_+(t') + 2H(t')\dot{D}_+(t')}{k_{\rm J}^2(t')}\int_{t'}^t \frac{{\rm d}t''}{a^2(t'')}$$

Filtering mass used in fitting formula for total mass of gas accreted by halos (Gnedin '00):

$$M_{\rm gas} = \frac{f_{\rm b}M_{\rm total}}{[1 + (2^{1/3} - 1)M_{\rm F}(z)/M_{\rm total}]^3}$$

Benson, CSF+ '02



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The GALFORM model

Modelling reionization: full model well approximated by:

Turn off cooling in halos of circular velocity V_c for:

$$V_c < V_{cut} \quad \text{at} \quad z < z_{cut}$$

Controls the characteristic scale below which reionisation is effective

[fiducial value: $V_{cut} = 30$ kms^{-1}]

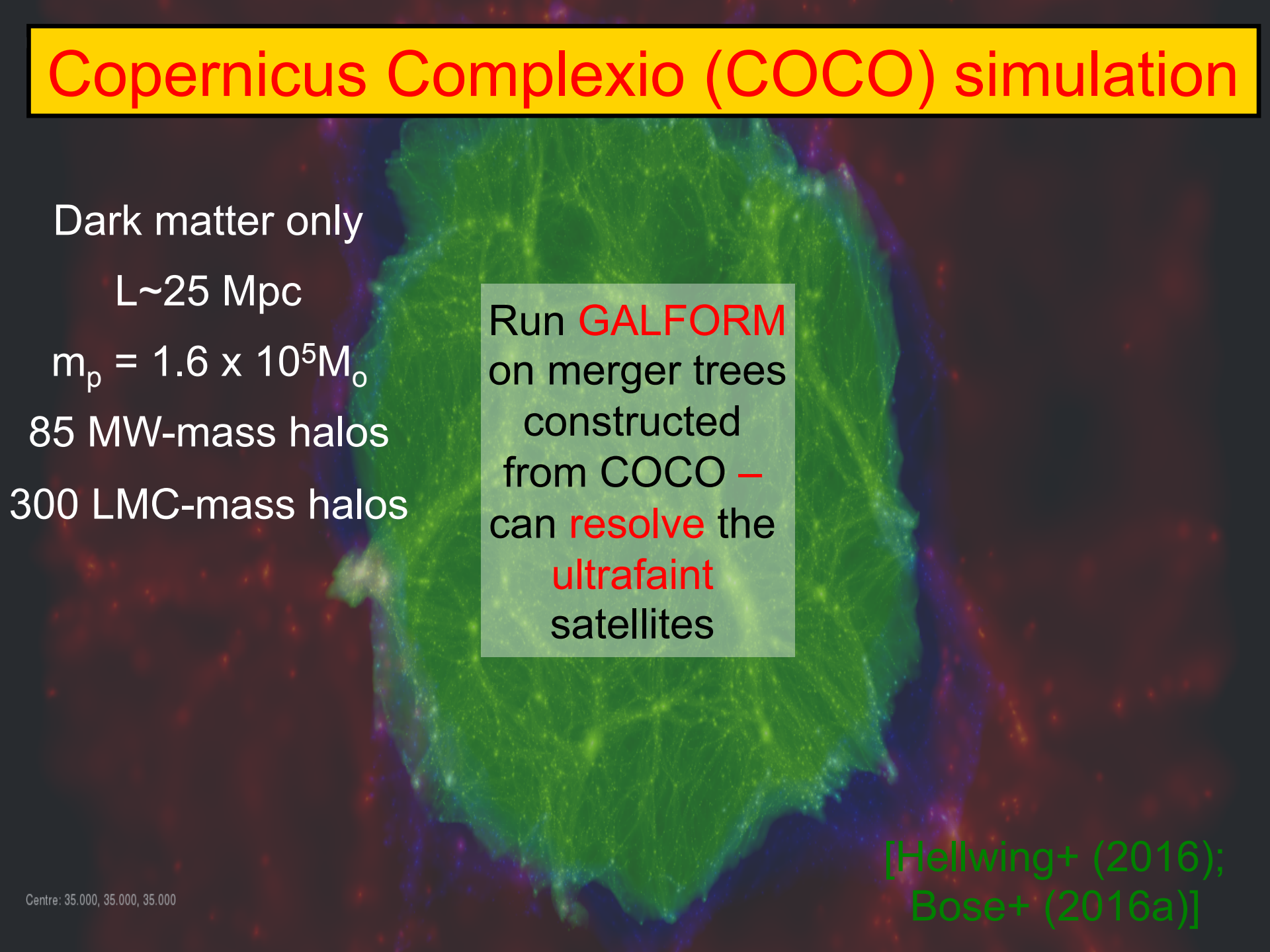
Controls when reionisation happens

[fiducial value: $z_{cut} = 6$]

[calibrated by hydrodynamical sims. of Okamoto+ '08]

[c.f. a full, self-consistent calculation of reionisation by Benson+ (2002a); also employed by Bullock+ 00; Somerville '0 etc.]

Copernicus Complexio (COCO) simulation



Dark matter only

L~25 Mpc

$m_p = 1.6 \times 10^5 M_o$

85 MW-mass halos

300 LMC-mass halos

Run GALFORM on merger trees constructed from COCO – can resolve the ultrafaint satellites

[Hellwing+ (2016); Bose+ (2016a)]

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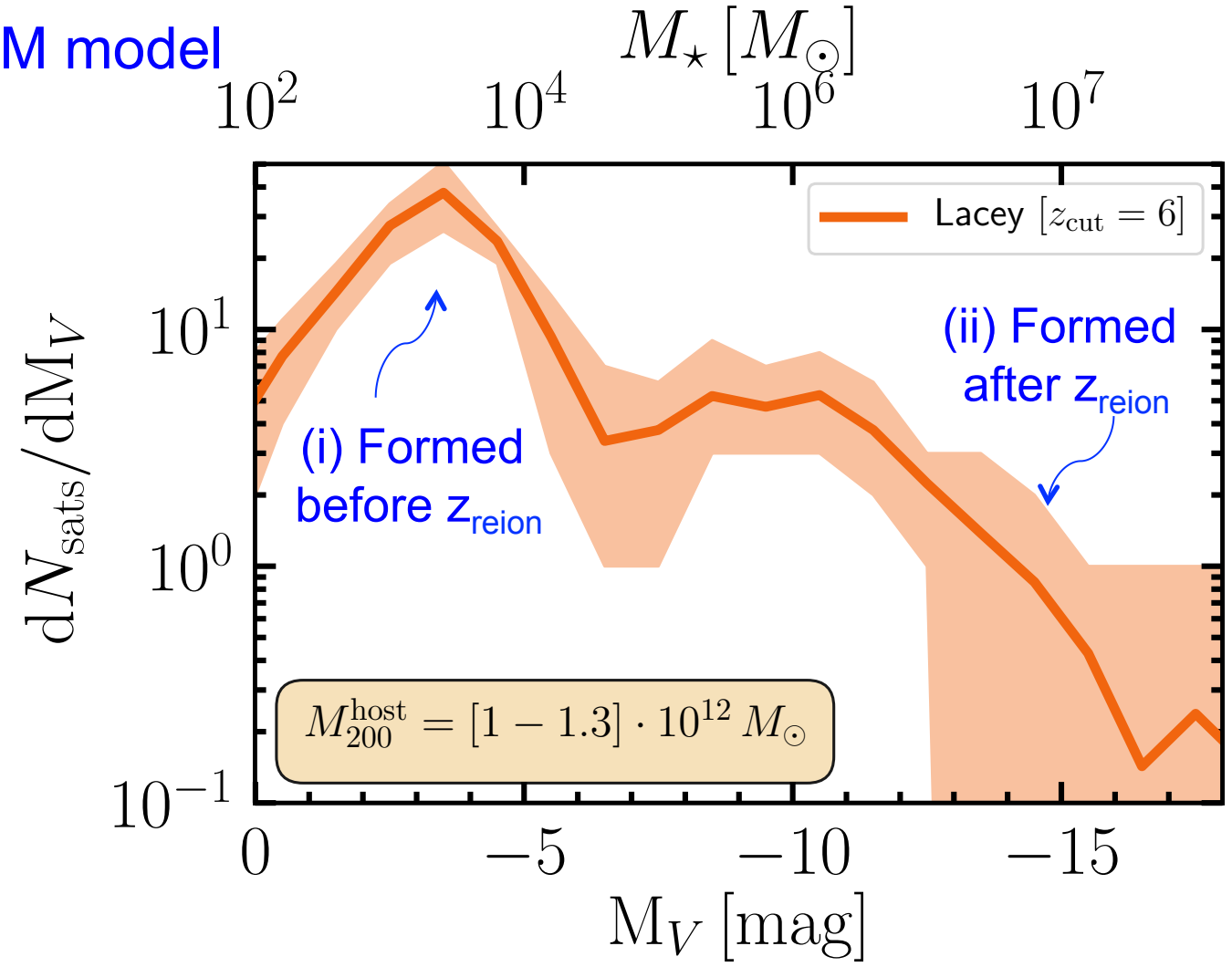
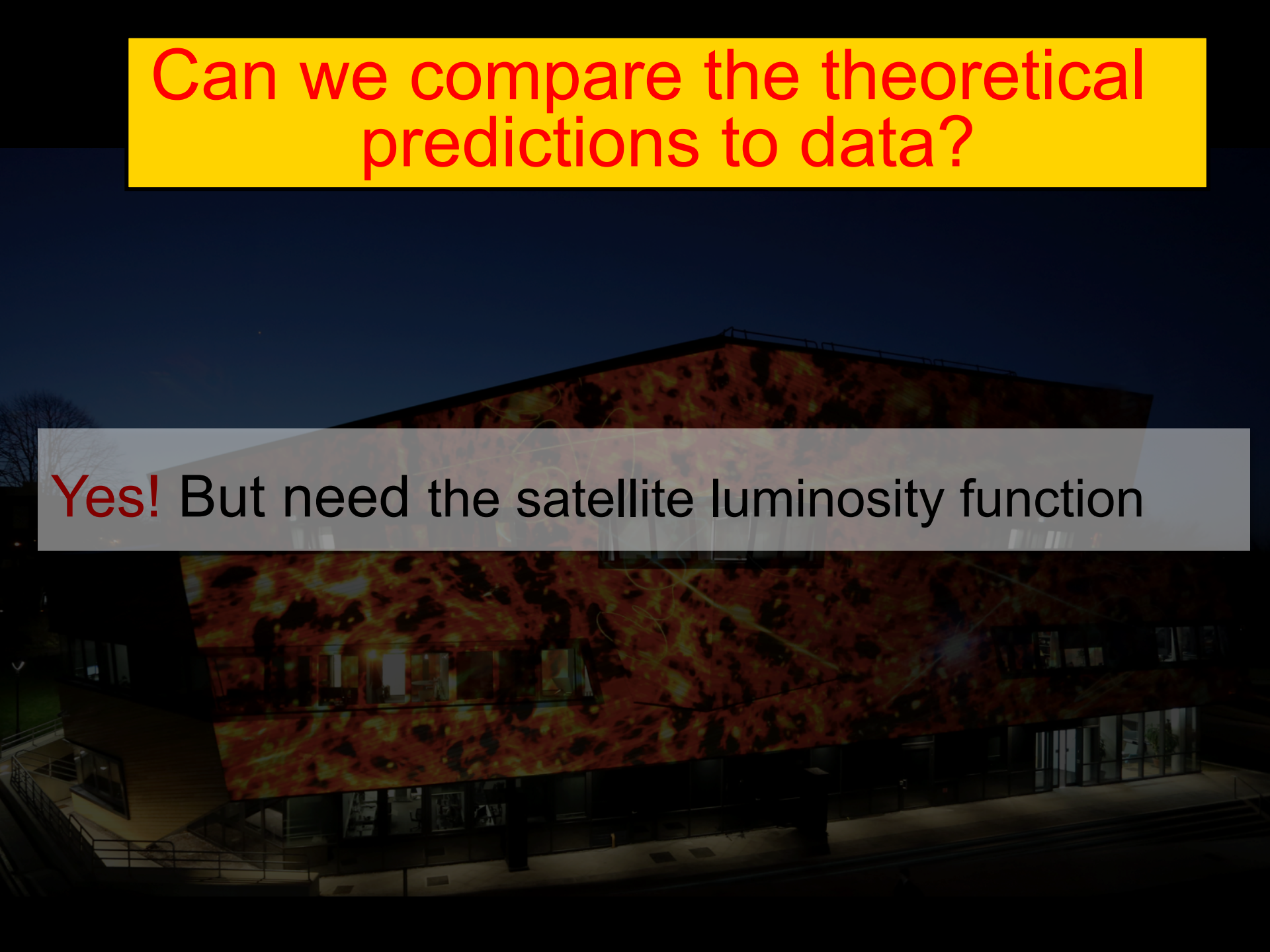
The satellite luminosity function

Two populations of sats formed: (i) before and (ii) after reionization

GALFORM model



Can we compare the theoretical predictions to data?



Yes! But need the satellite luminosity function

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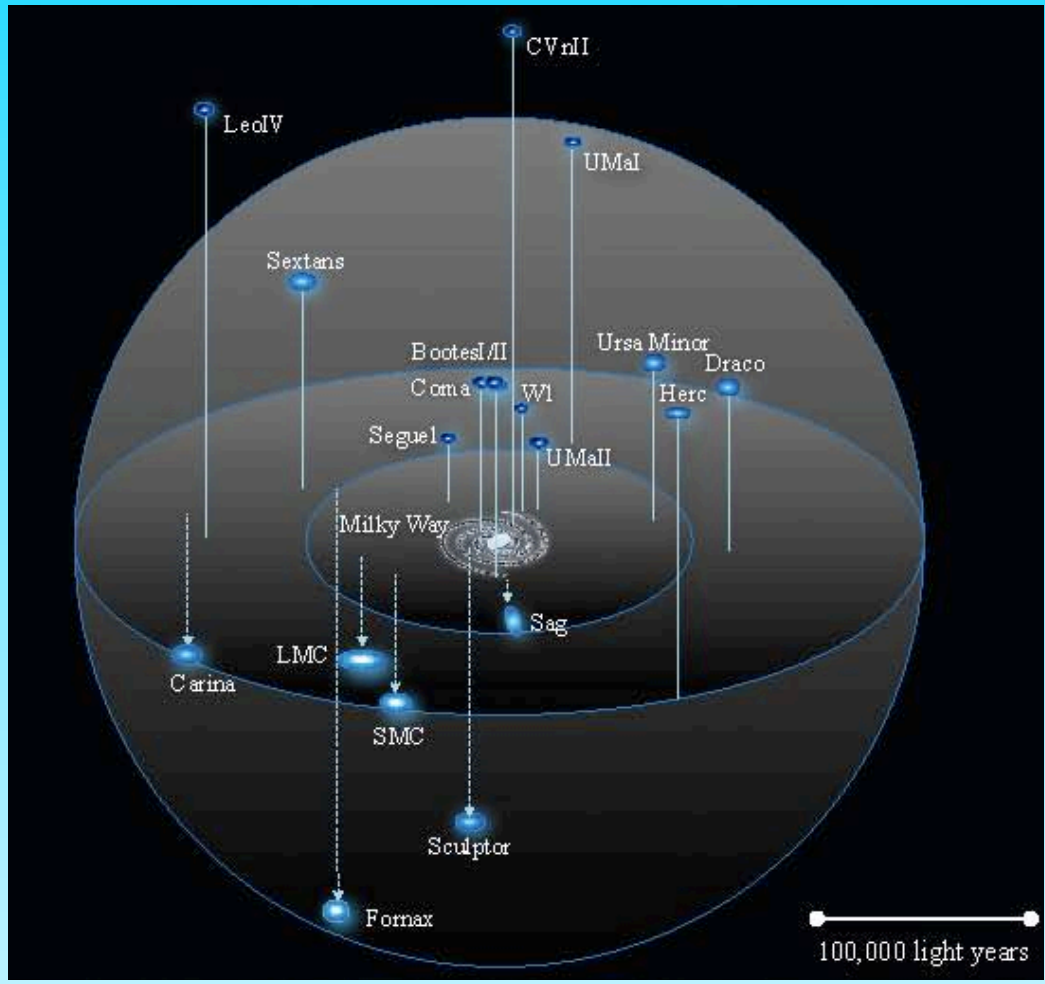
The MW satellite luminosity function

~55 satellites discovered so far in MW

About 55 satellites known in the MW so far from partial surveys (e.g. SDSS, Pan-STARRS, DES)

Can infer total population from survey selection function, assuming a radial distribution (from simulations)

(Newton+18, Koposov+08, Tollerud+08, Hargis+14)



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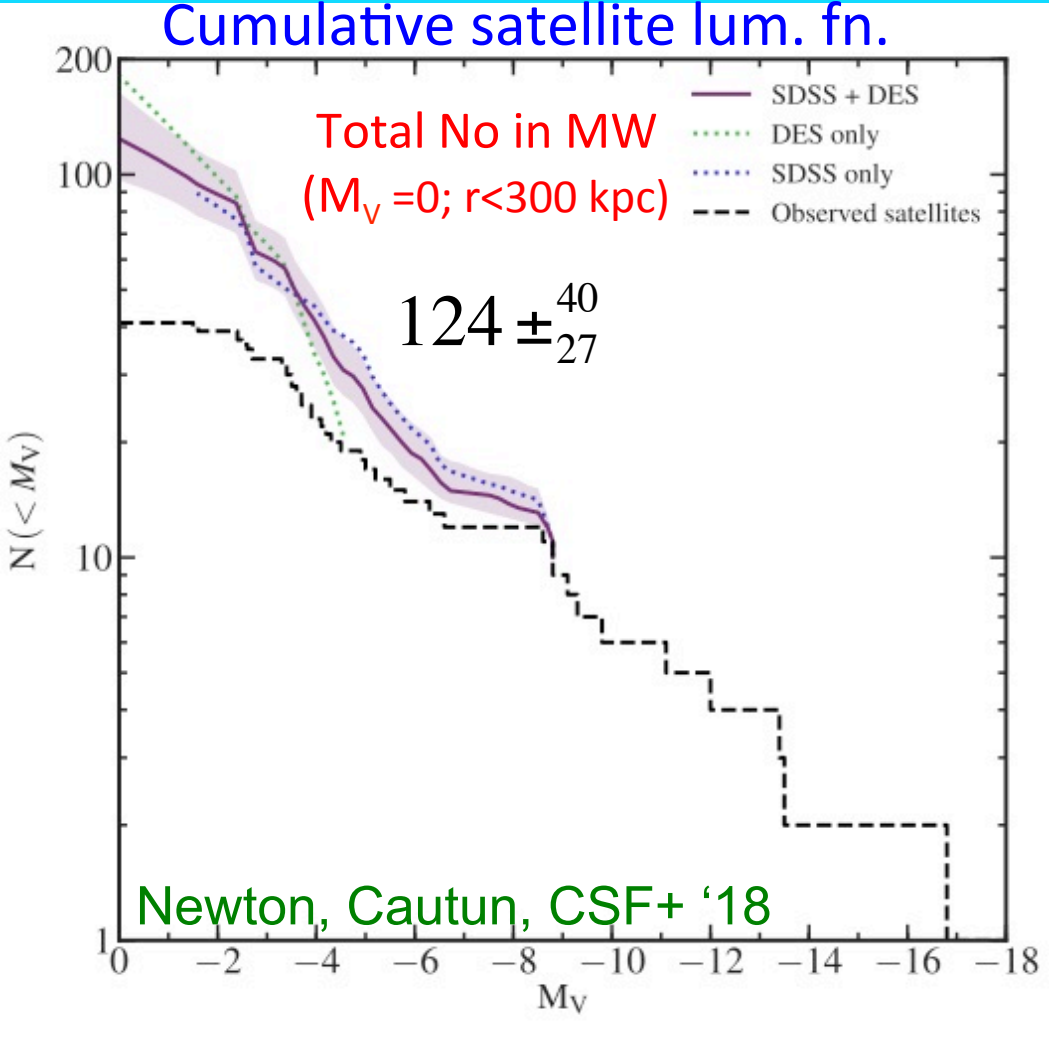
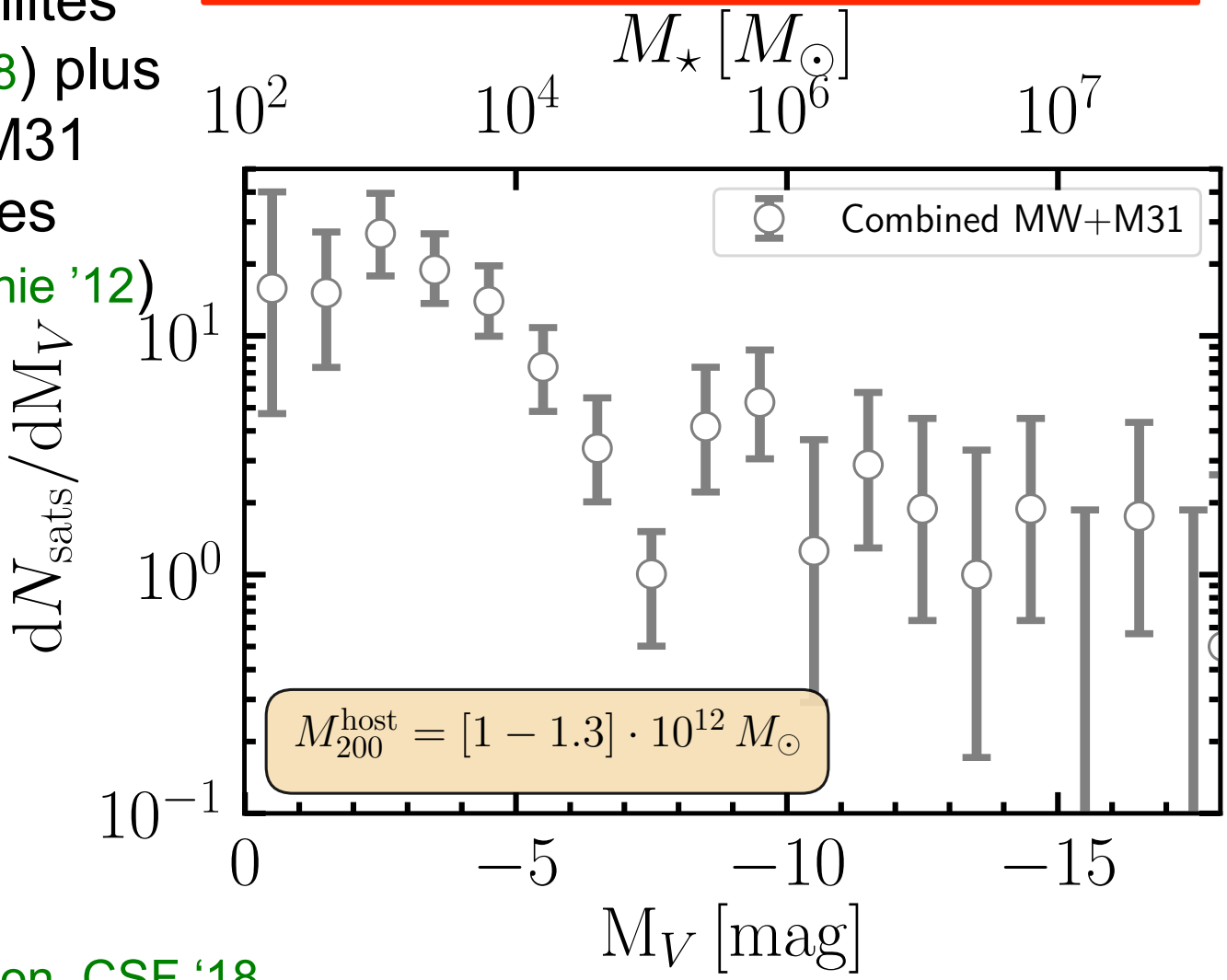


The MW/M31 sat. luminosity function

MW satellites (Newton+ '18) plus M_V<-8 M31 satellites (Mcconnachie '12)

Differential satellite luminosity function



Bose, Deason, CSF '18

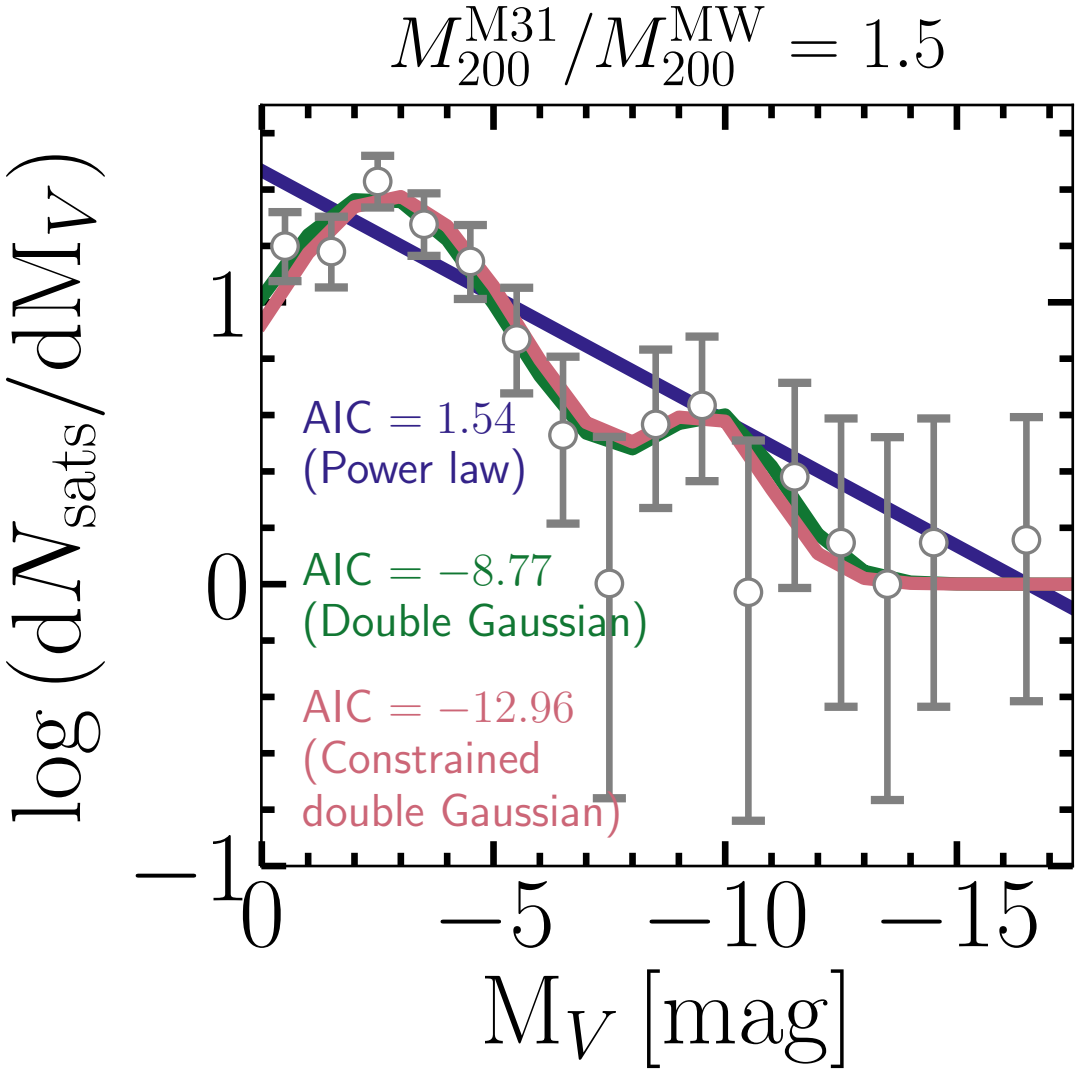
The 2 populations of galactic satellites

Fit 3 models and compare using Akaike Information Criterion (AIC)

Model	AIC
Power law	-1.5
Double Gaussian	-8.8
Constrained DG*	-13.0

*Assumes V_{cut}=30 km/s

Bose, Deason, CSF '18



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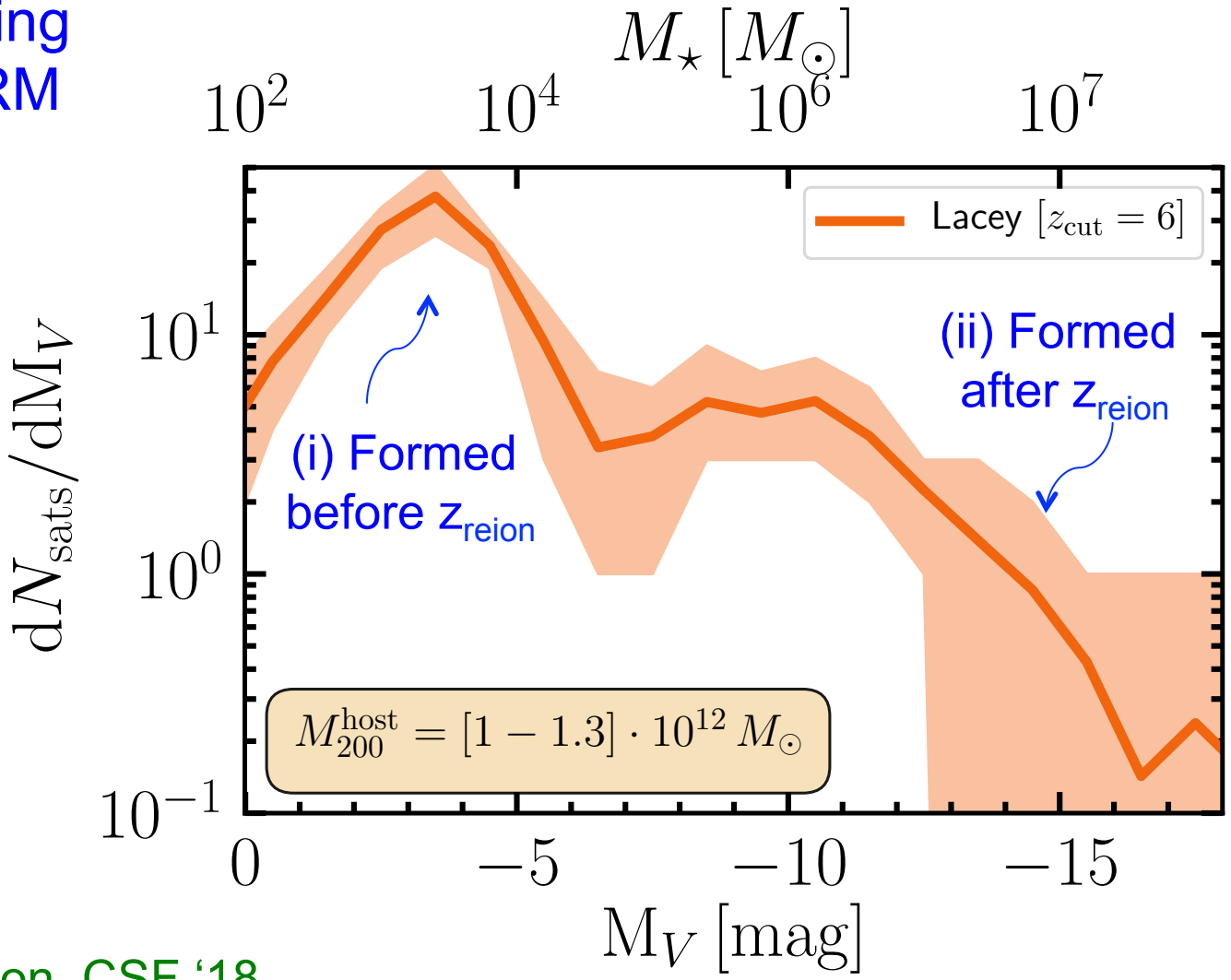
Theory *vs* data

Pre-existing GALFORM model



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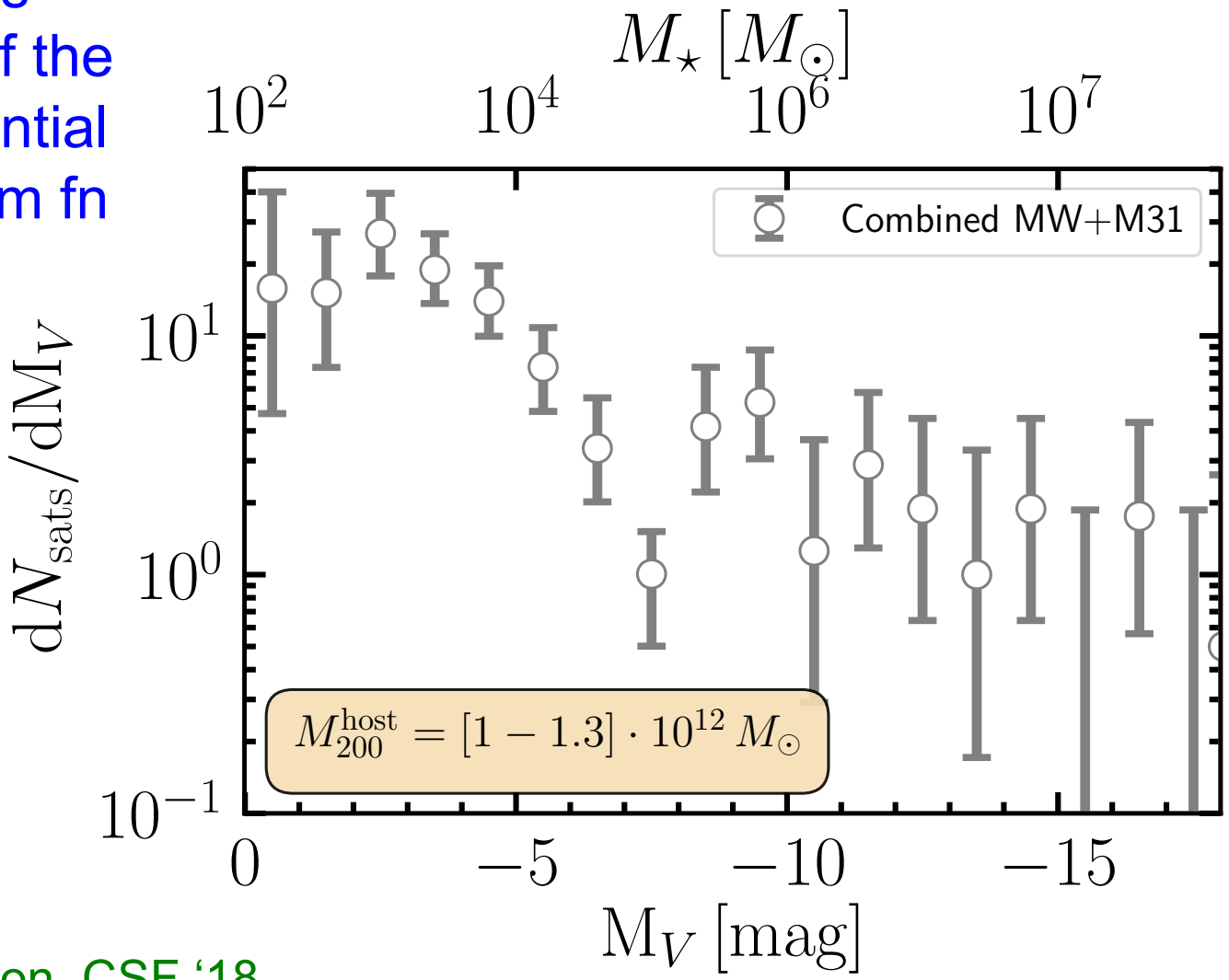
Theory *vs* data

Newtons' estimate of the MW differential satellite lum fn



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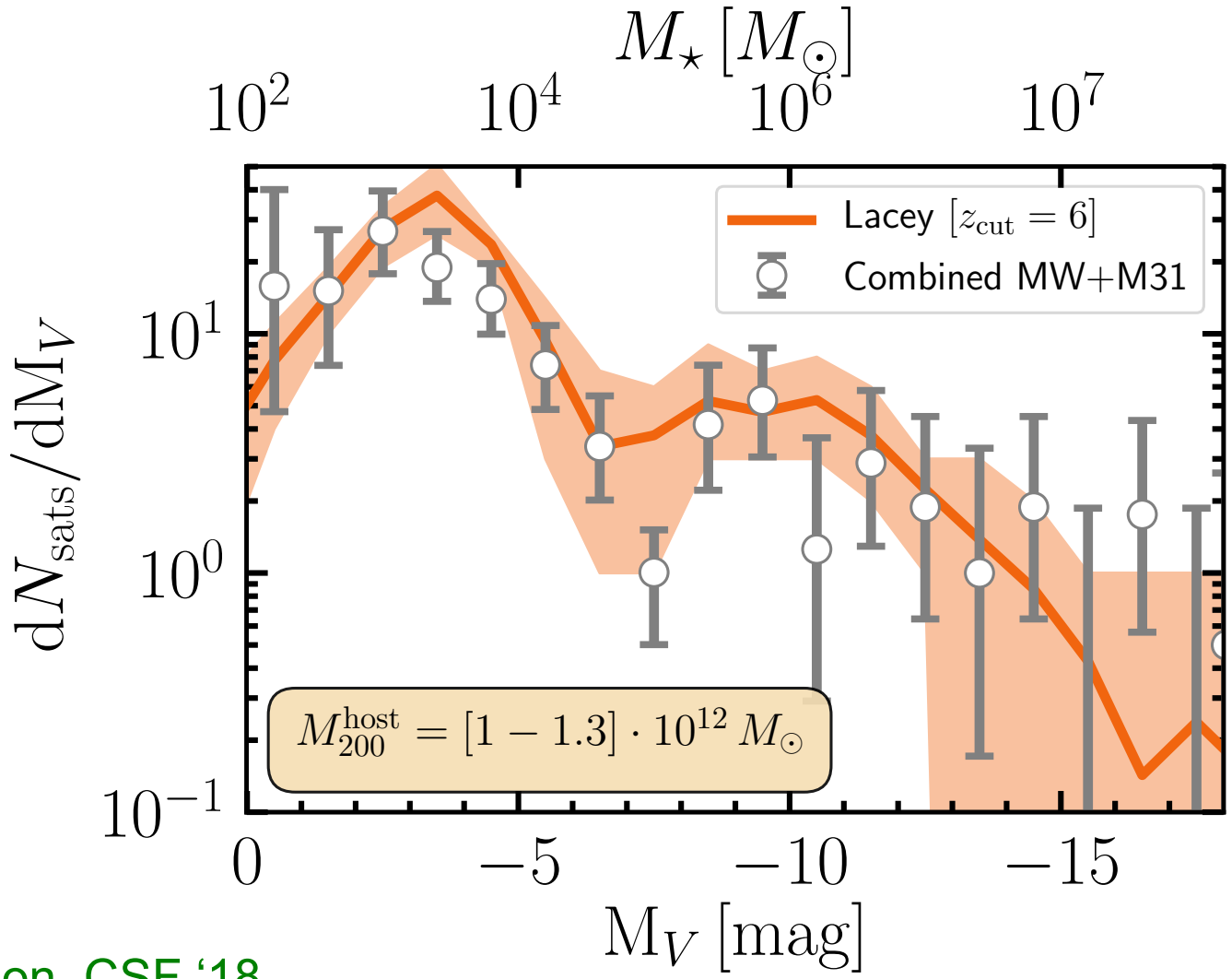
Theory *vs* data



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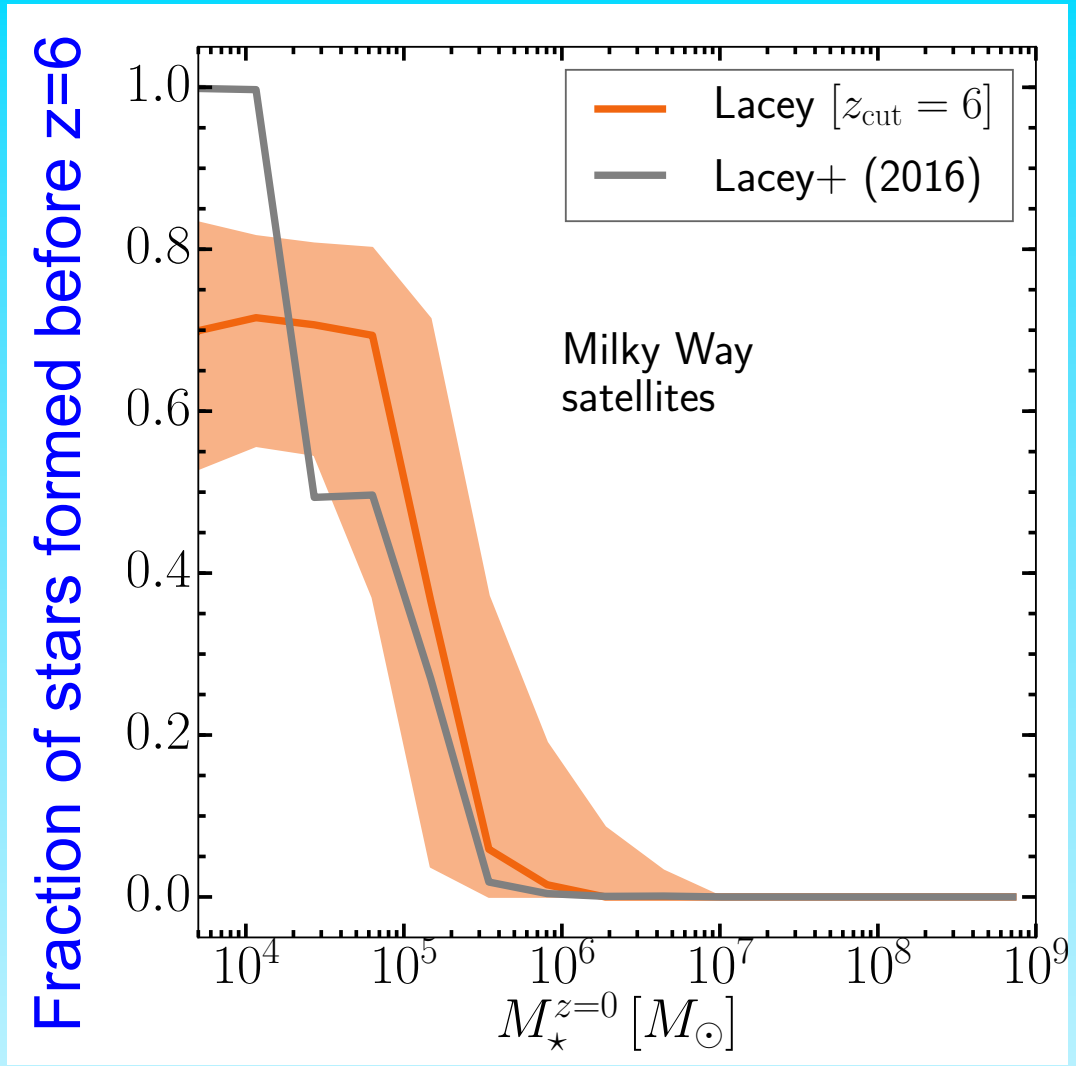
Stars formed before reionisation

Ultra-faint satellites ($M_* < 10^5\ M_\odot$) form ~70% of their stars before reionization

Bright galaxies assemble much later: they know nothing about reionisation.



Bose, Deason, CSF '18

Conclusions

1. Galaxy formation theory predicts 2 populations of gal. satellites, formed (i) before and (ii) after reionization
2. We have estimated the total luminosity function of satellites in Milky Way (124 w. $M_V<0$, within 300kpc)
3. Combining MW sats with bright M31 sats, we have detected the two populations at high signficance
4. The (pre-existing) model agrees perfectly with the data