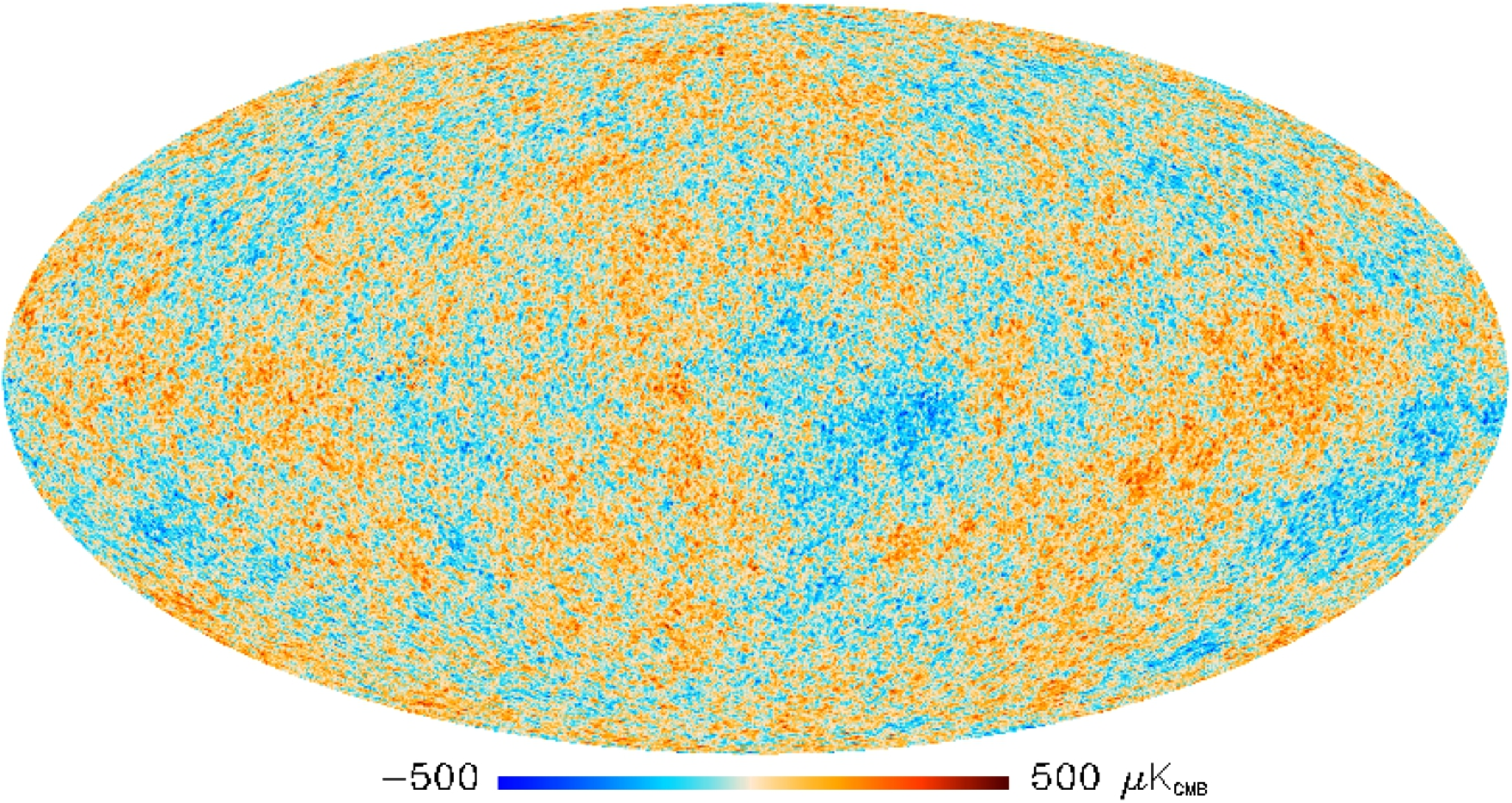
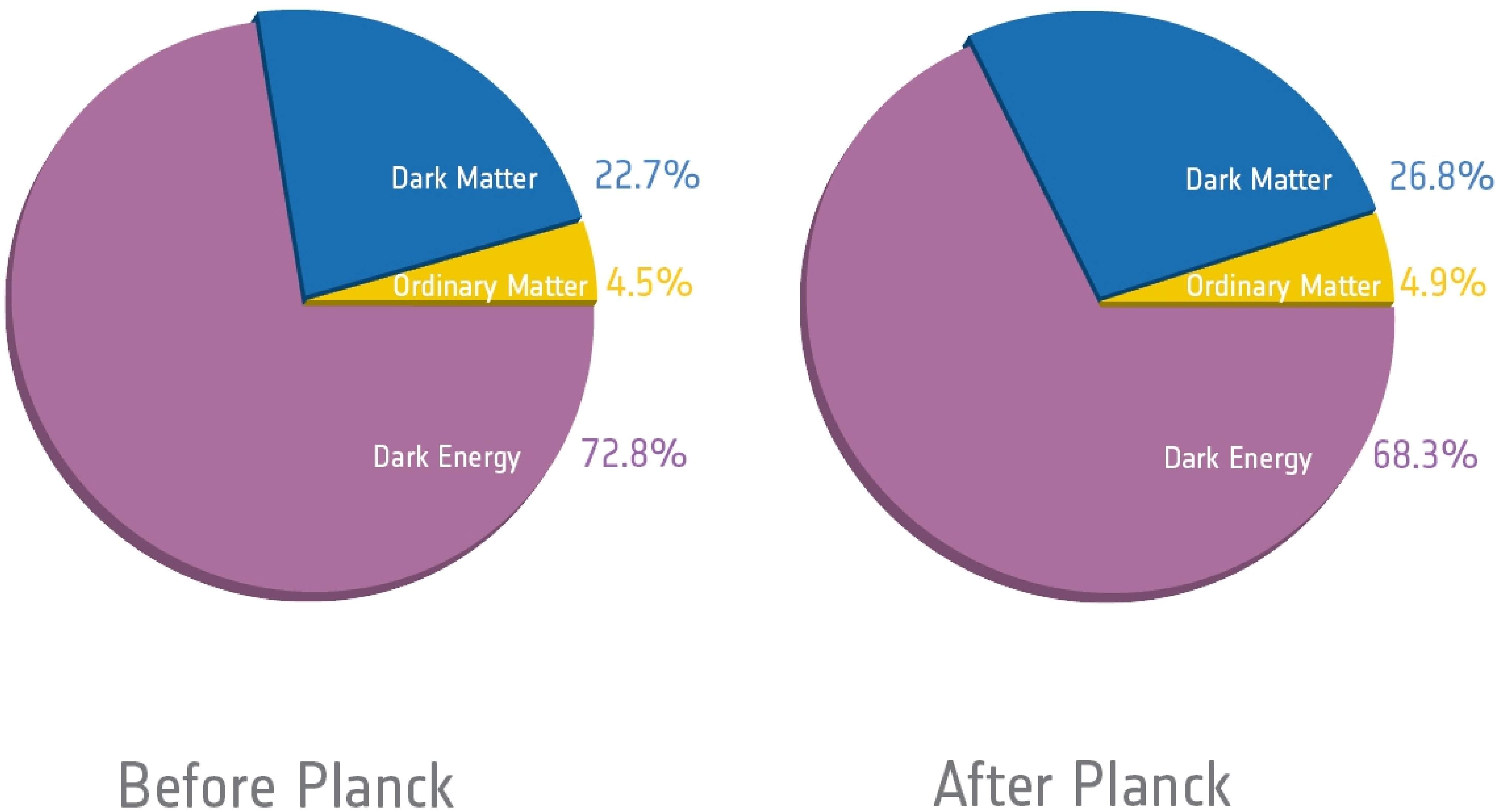
?

Revisit of the state-of-the-art in simulating galaxy formation?

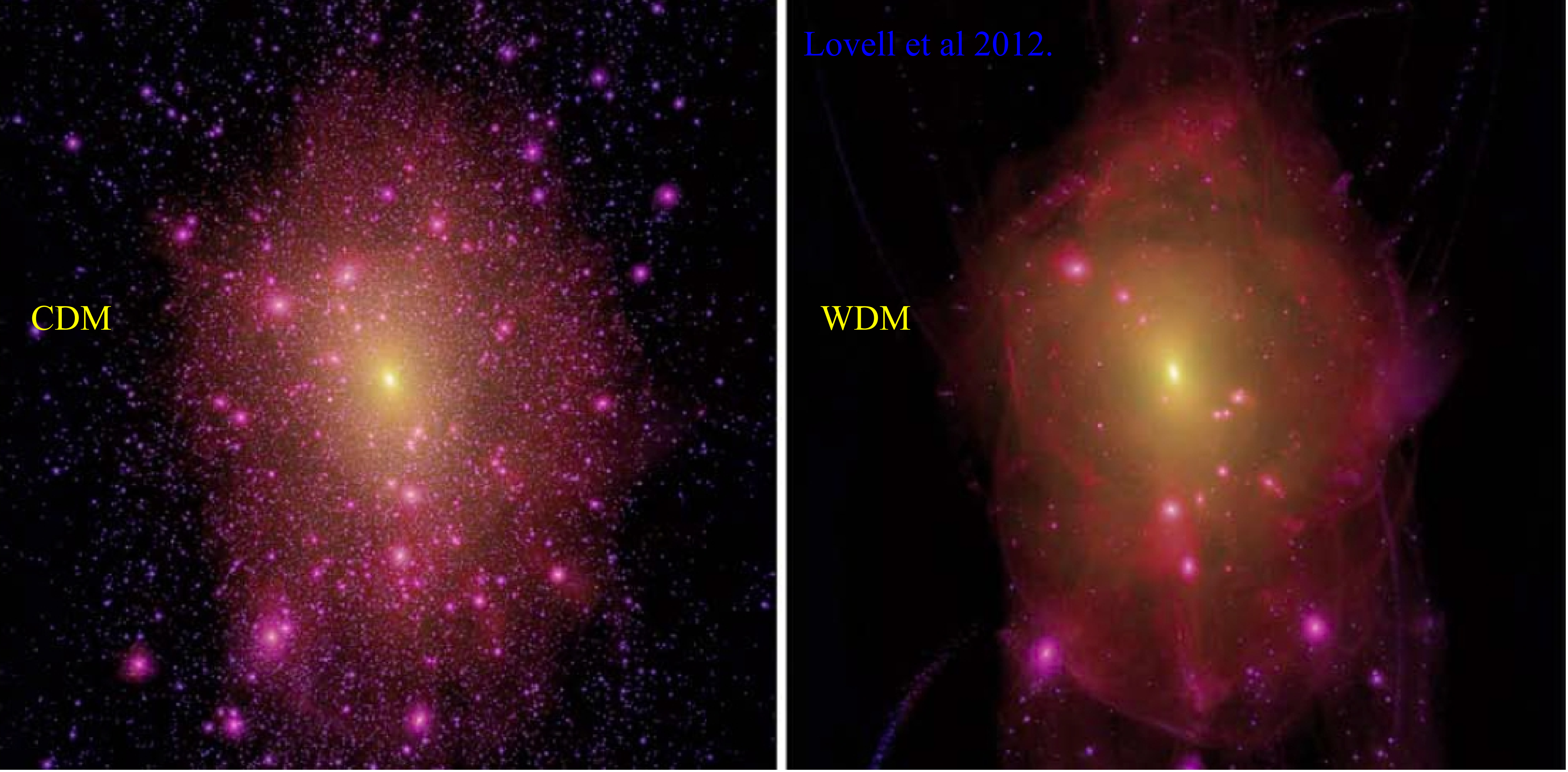
Simon White, MPI for Astrophysics

Planck CMB map: the IC's for structure formation

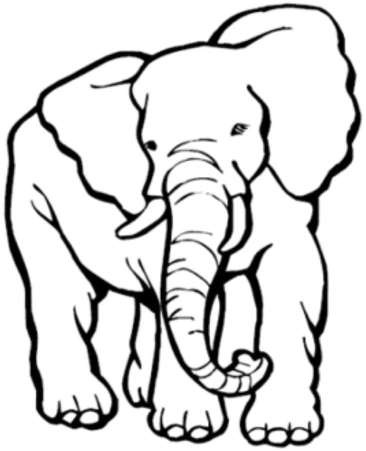




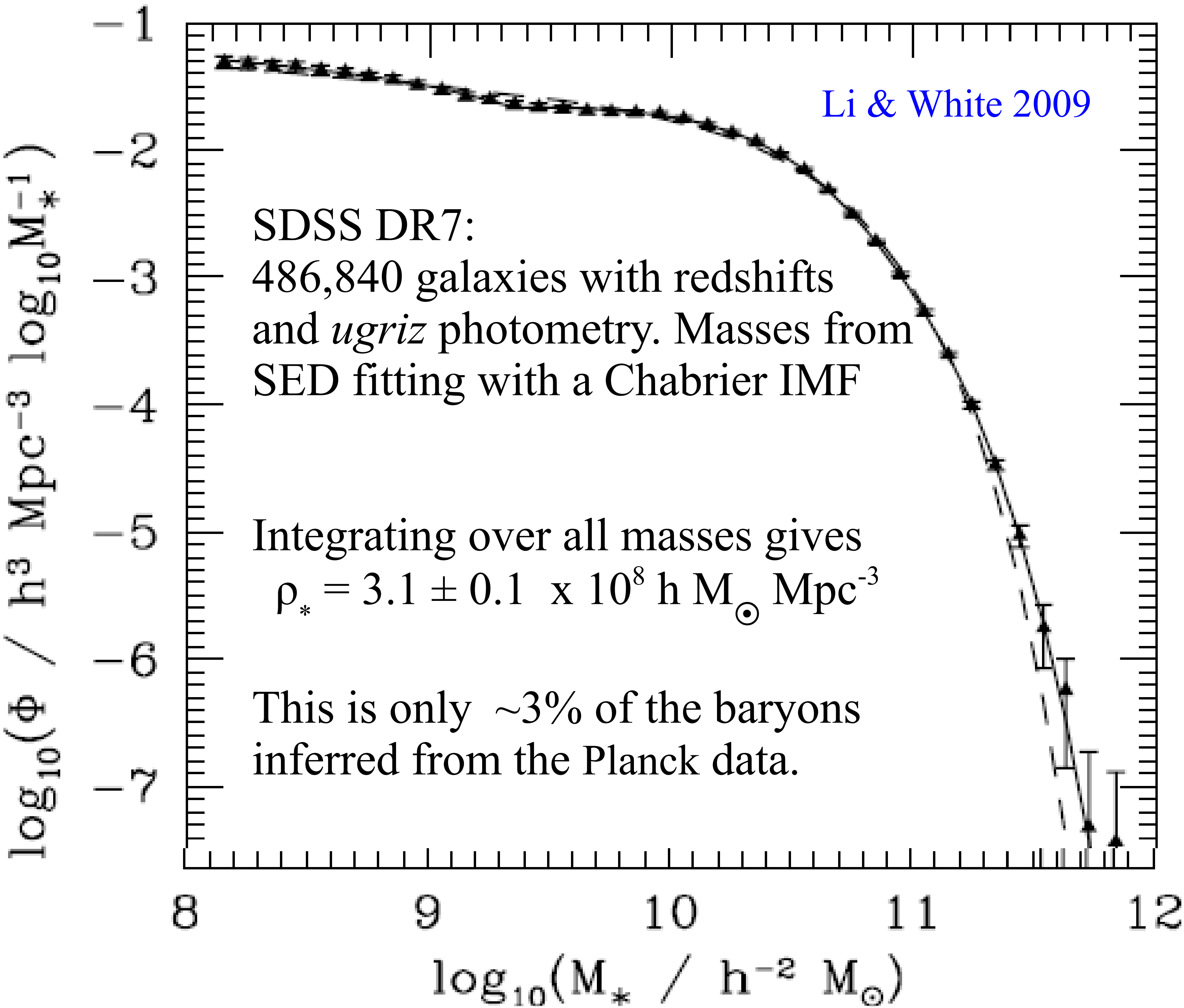
$\Omega_m = 0.315 \pm 0.015$ $\quad \Omega_{bar} = 0.049 \pm 0.003$ from CMB data *alone* if the Universe is flat. $\longrightarrow$ $F_{bar} = 0.154 \pm 0.005$



A “Milky Way” halo in CDM and WDM (a 1.4 keV thermal relic)

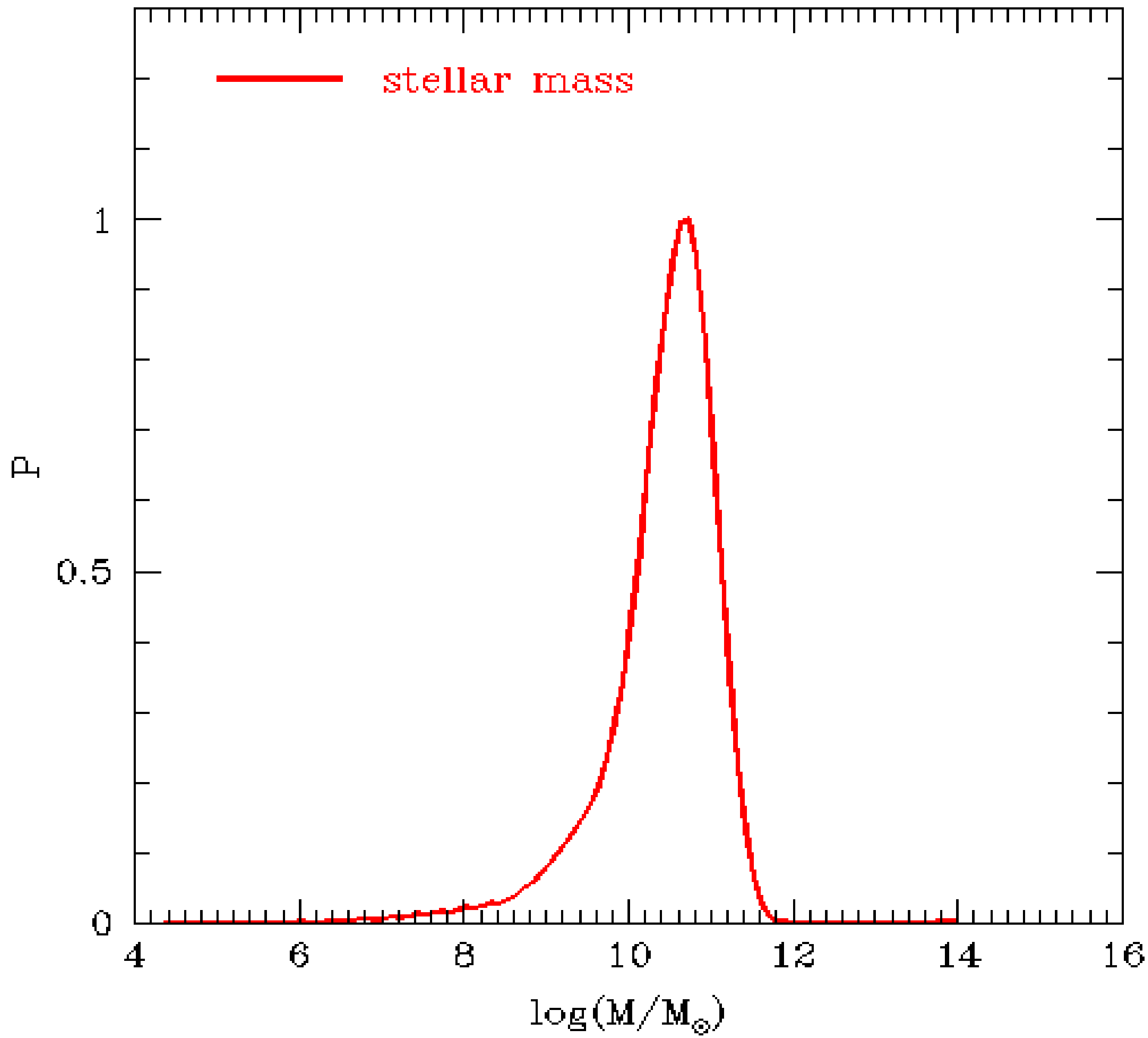


- What is the Dark Matter?   the Dark energy?
- Does this affect galaxy formation?
  (...dwarfs? first stars? reionization?)

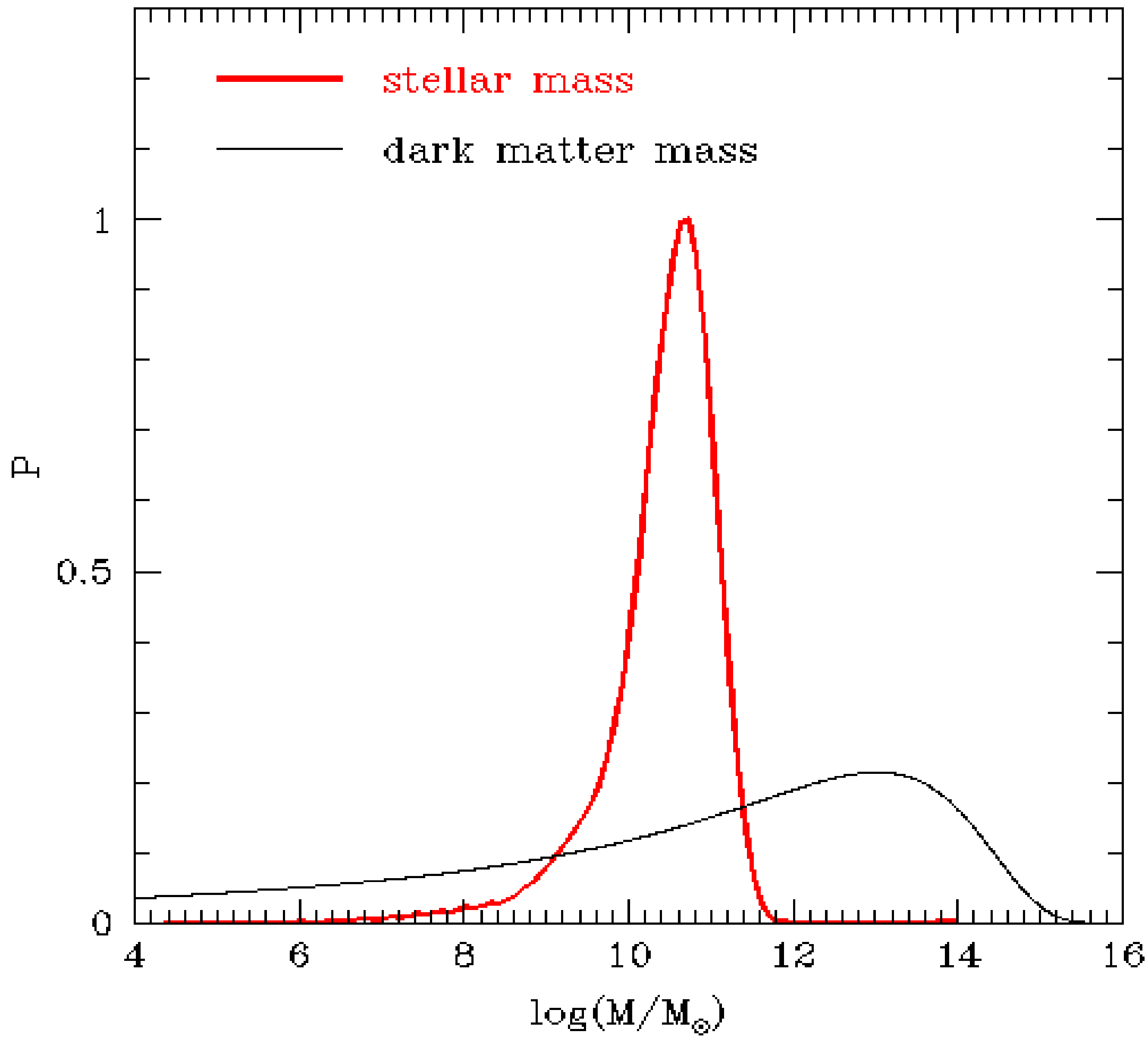


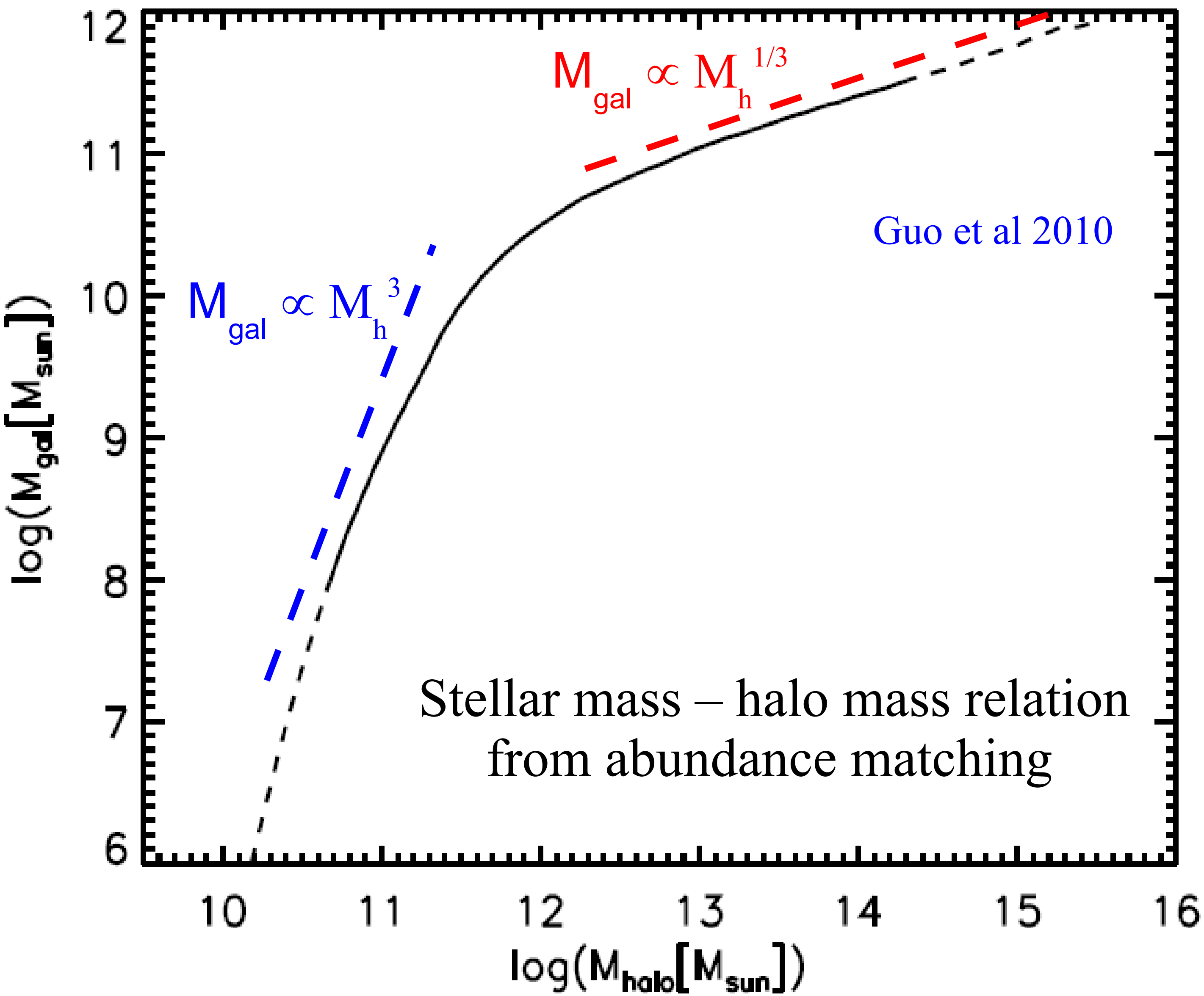
Li & White 2009
SDSS DR7:
486,840 galaxies with redshifts
and *ugriz* photometry. Masses from
SED fitting with a Chabrier IMF
Integrating over all masses gives
$\rho_* = 3.1 \pm 0.1 \times 10^8\ h\ M_\odot\ \mathrm{Mpc}^{-3}$
This is only ~3% of the baryons
inferred from the Planck data.
$\log_{10}(\Phi\ /\ h^3\ \mathrm{Mpc}^{-3}\ \log_{10}M_*^{-1})$
$\log_{10}(M_*\ /\ h^{-2}\ M_\odot)$
−1
−2
−3
−4
−5
−6
−7
8
9
10
11
12

Most stars are in galaxies with similar stellar mass to the Milky Way



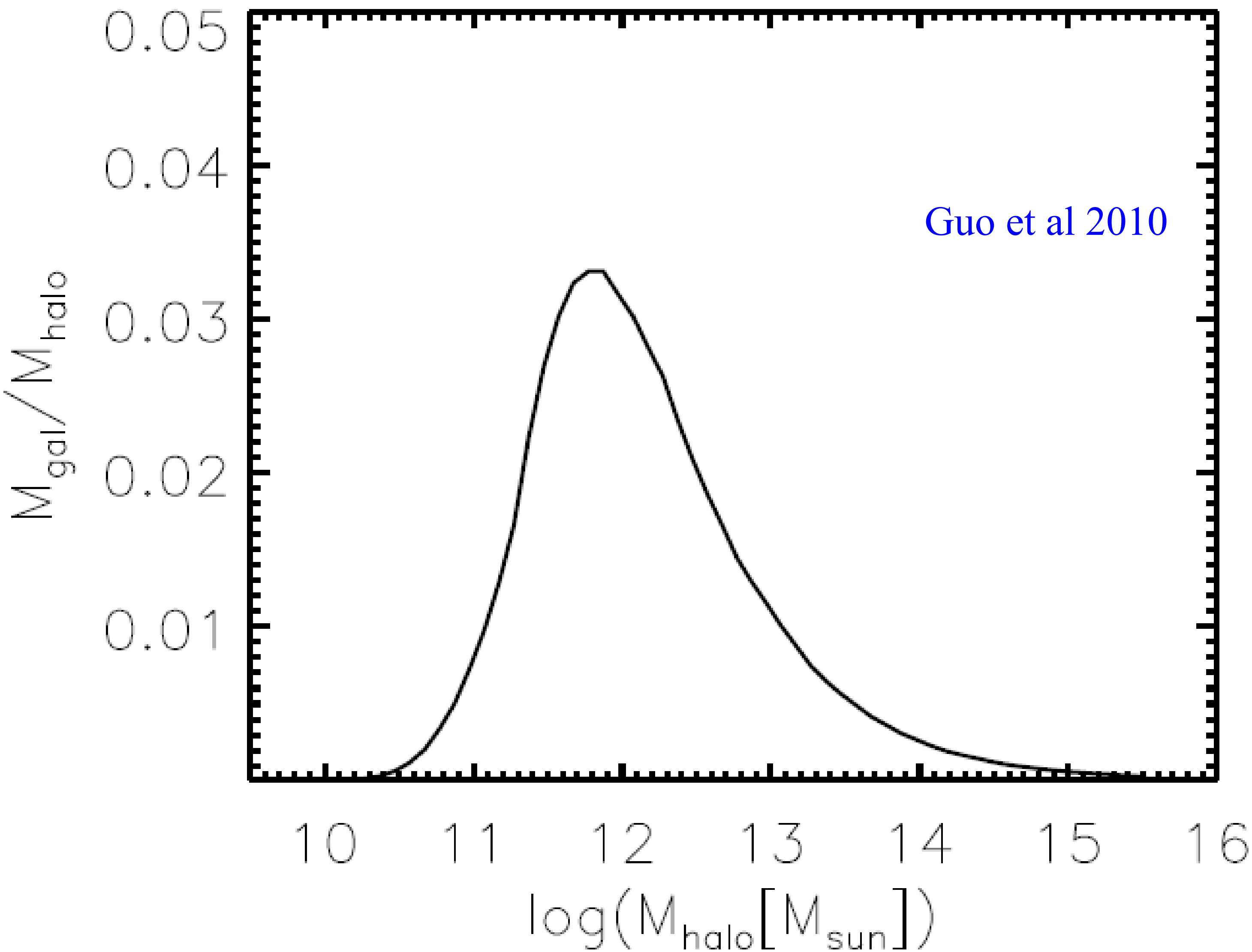
Most stars are in galaxies with similar stellar mass to the Milky Way
Dark matter (and baryons) are *much* more broadly distributed across halo mass in the Planck cosmology





The stellar mass of the central galaxy increases rapidly with halo mass at small halo mass, but slowly at large halo mass

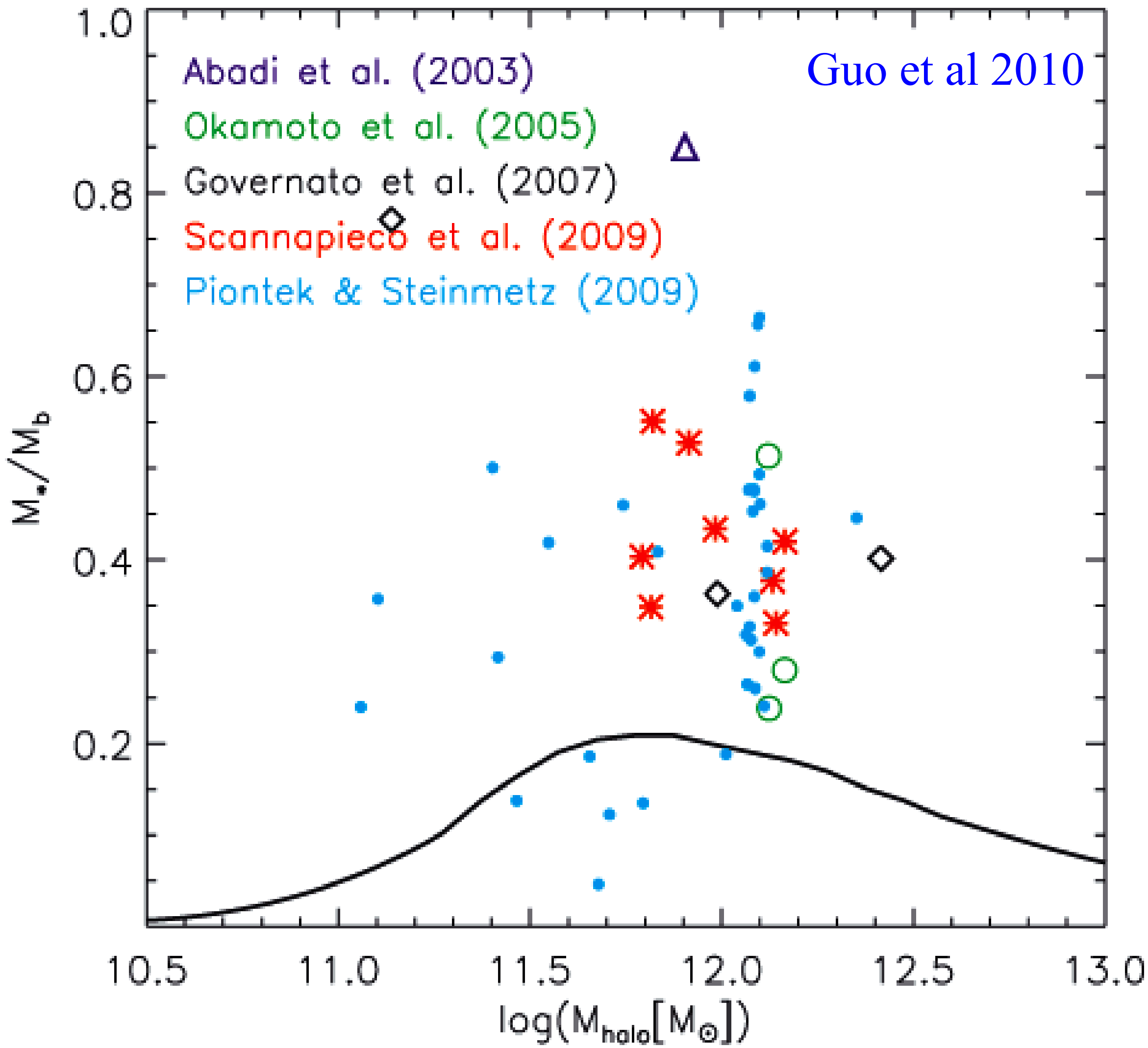
The characteristic halo mass at the bend is $5 \times 10^{11}\ M_{\odot}$



The maximum halo mass fraction in central galaxy stars is <4%

This is attained for halos similar in mass to the Milky Way's halo

The fraction drops very rapidly to higher and lower masses

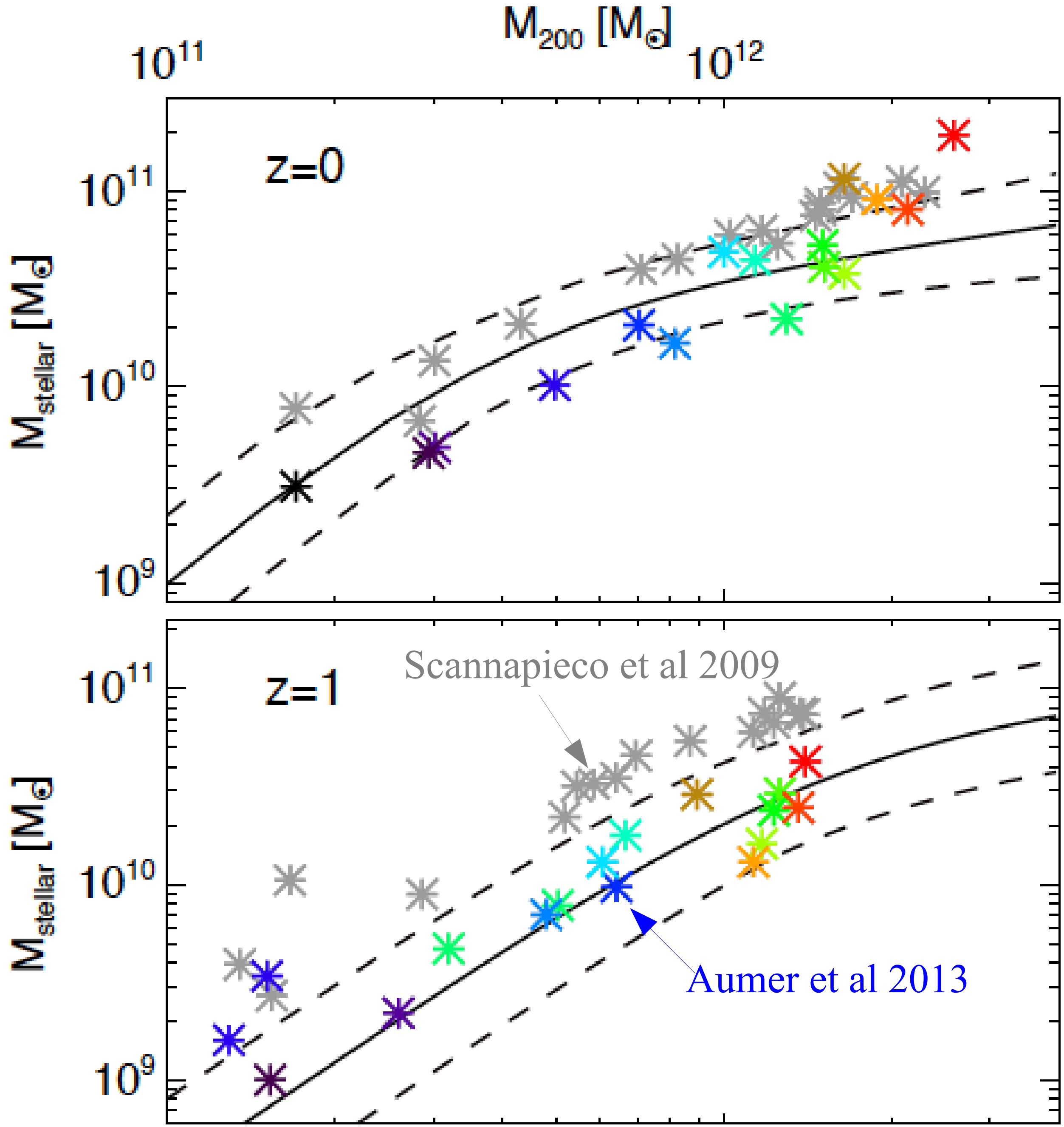


Galaxy formation efficiency is: $\varepsilon = M_* \;/\; (\Omega_b\, M_{h,max} \;/\; \Omega_m\,)$

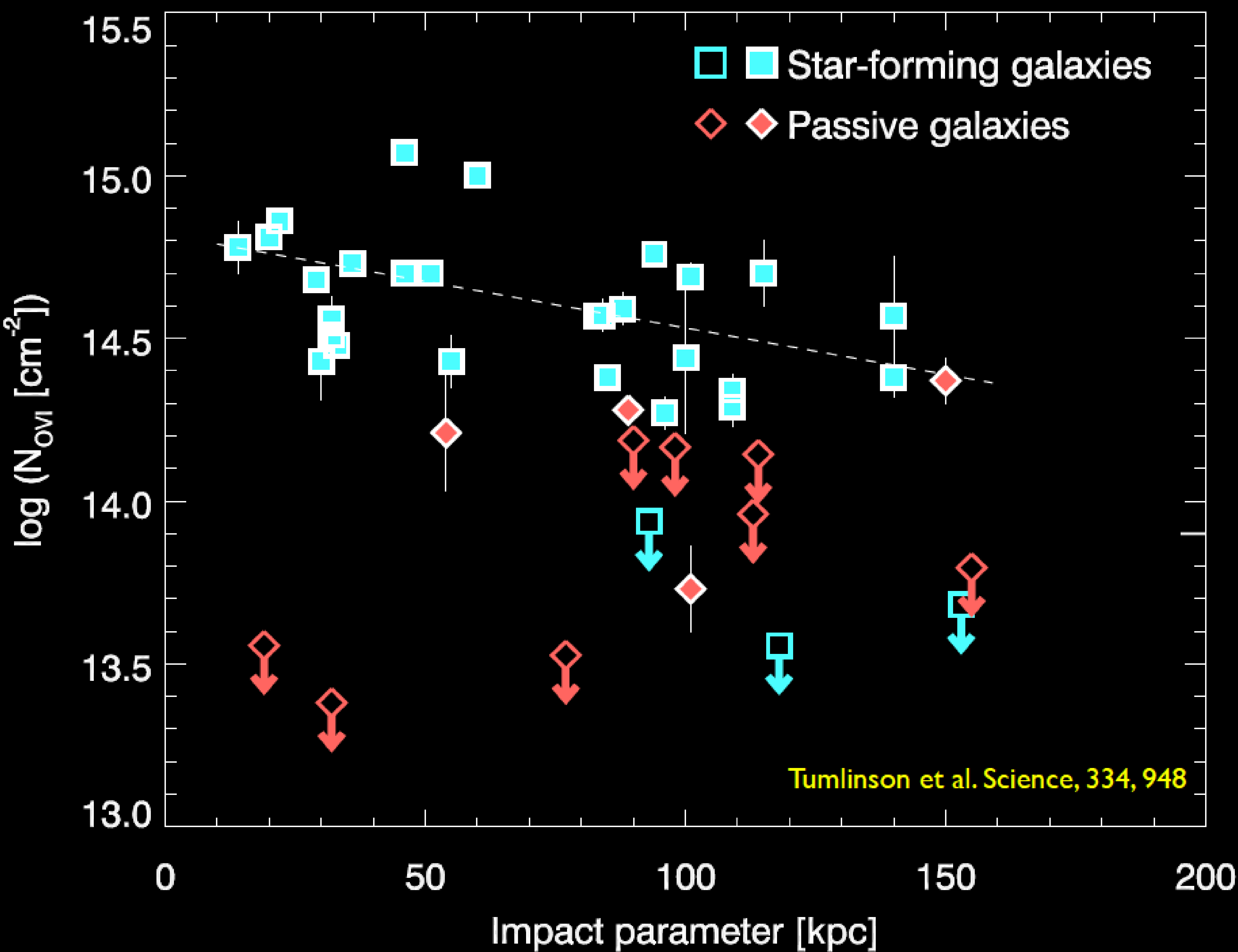
This *maximises* at about 25%

It is substantially lower than in early galaxy formation simulations

In the Milky Way about $2 \times 10^{11}\, M_\odot$ of baryons are “missing”

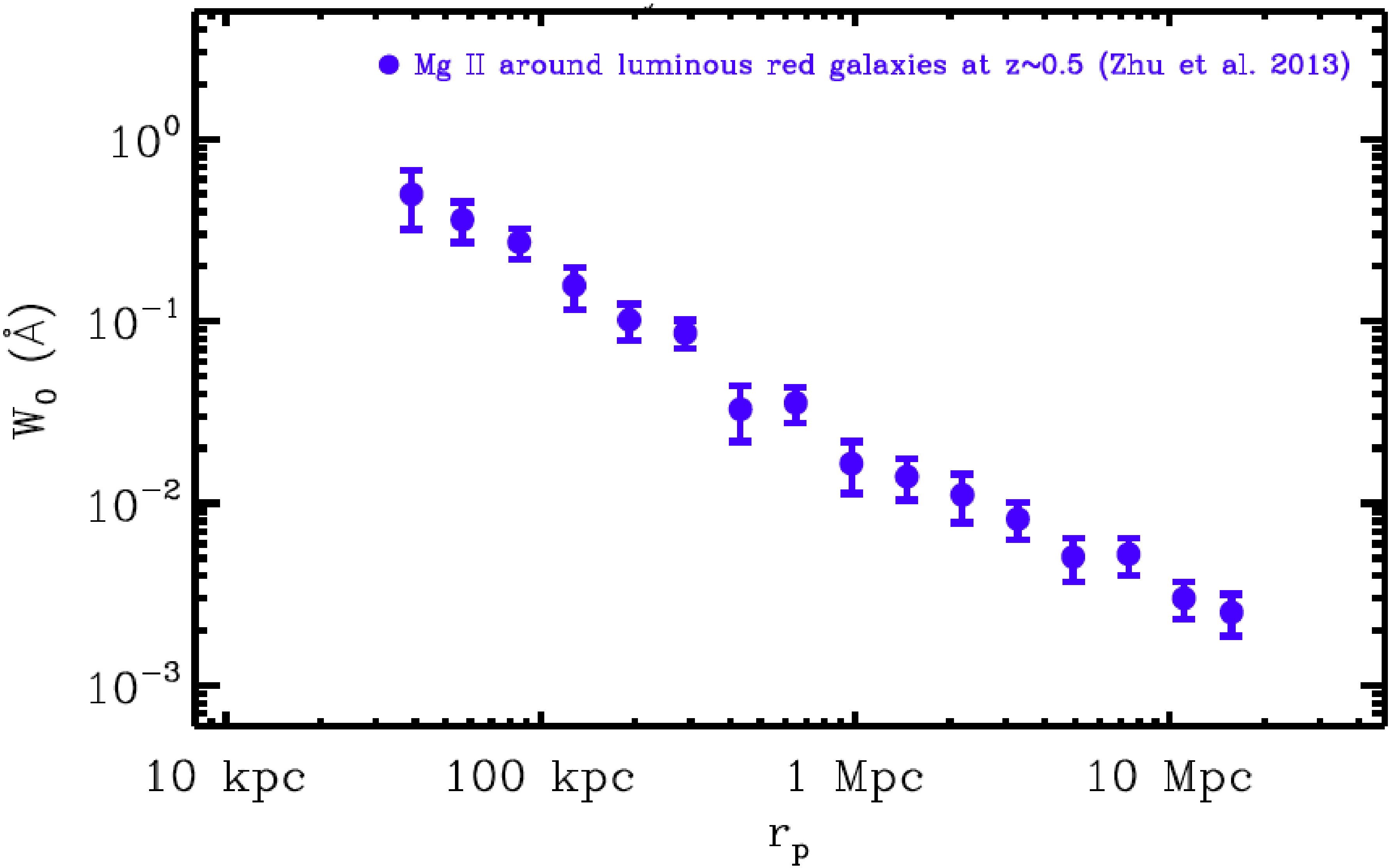


More recent simulations have retuned to better match the observed (in)efficiency



At least as much oxygen is estimated in the CGM as in the ISM of galaxies

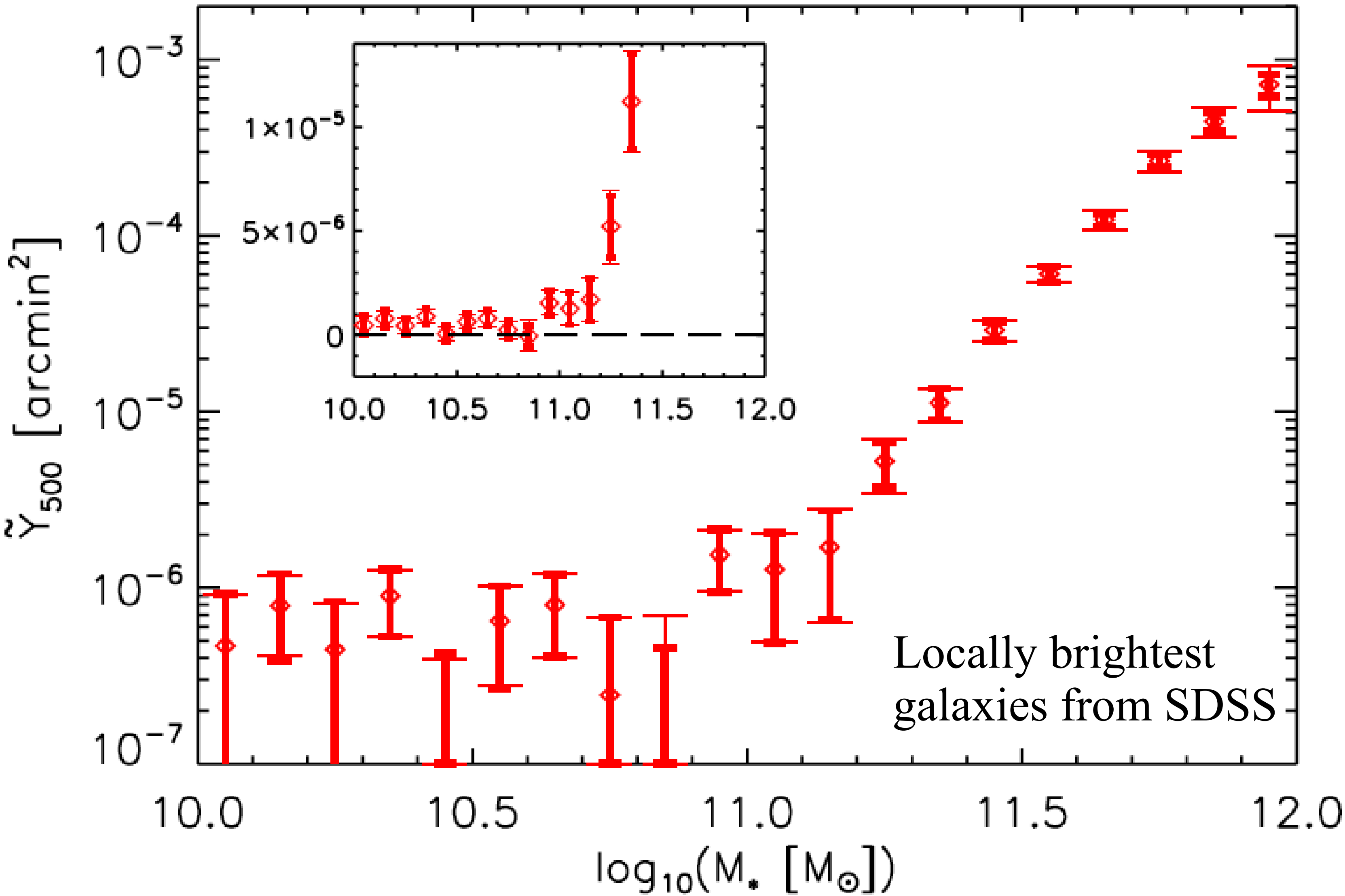
The galaxy-gas correlation function



MgII is distributed around passive galaxies similarly to the dark matter
(from Guangtun Zhu & Brice Ménard)

Stacked $Y_{500}(M_*)$ for Locally Brightest Galaxies

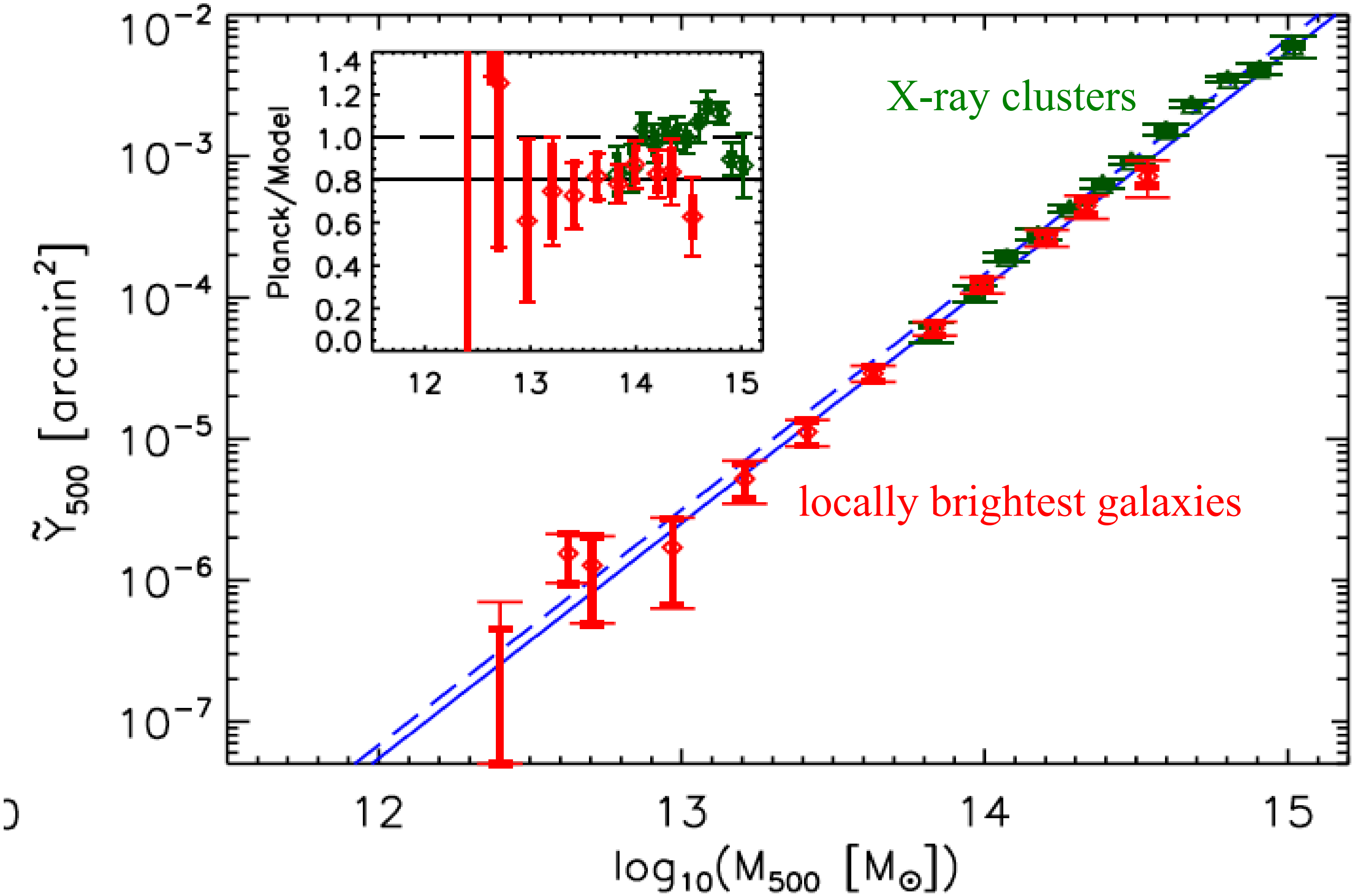
Planck Collaboration 2013: PIP-XI



Signal is detected down to $\log M_* / M_\odot \sim 11.0$

Inferred Y–M_h compared to X-ray cluster result

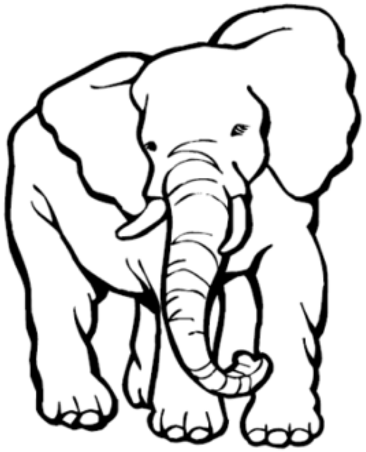
Planck Collaboration 2013: PIP-XI



LBG and MCXC results consistent to 20%

Scaling continues down to log M_h / $M_\odot$ ~ 12.5 <u>with no break</u>.

Planck sees all(?) the cosmic baryons associated with galaxy halos!



- Only a small fraction of all baryons are in galaxies
- Only a small fraction of the baryons which participated in galaxy formation are still in galaxies
- Most of the heavy elements produced by galactic stars are no longer in galaxies
- The structure of the CGM is complex, including multiple phases, inflows and outflows
- Feedback is regulating galaxy formation, but *not* the same feedback that regulates GMC star formation!

- Infall and radiative cooling
  - -- mixing and interface effects between inflow and outflow
  - -- photo-, collisional and nonequilibrium ionization
  - -- metallicity and dust effects

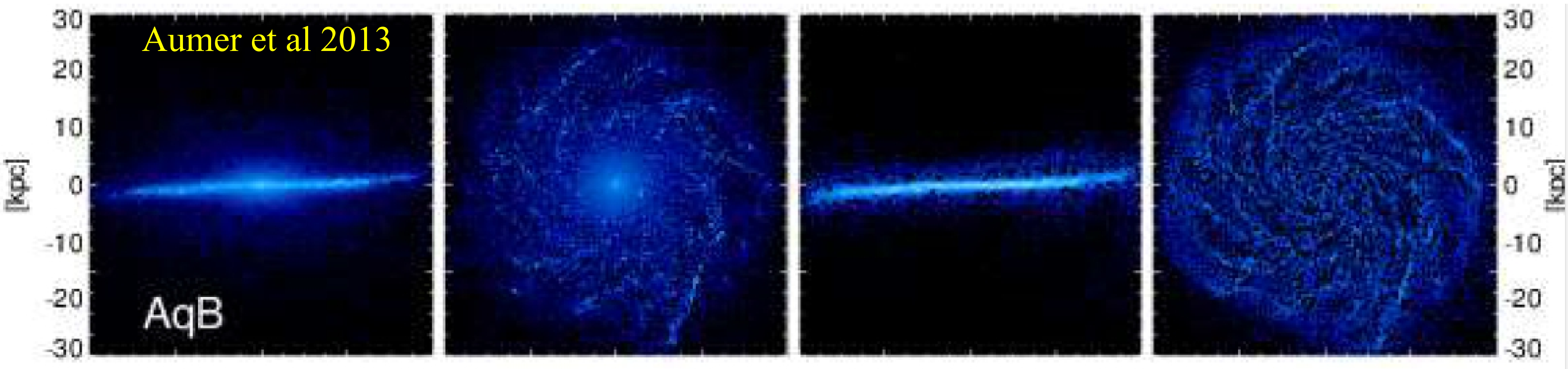
- Star formation
  - -- threshold density/surface density, low efficiency
  - -- metallicity and environment dependences, IMF
  - -- starburst mode

- Input from stars
  - -- injection of radiative/kinetic/thermal energy, mass and metals
  - -- interaction with ISM structure, wind generation, mass loading

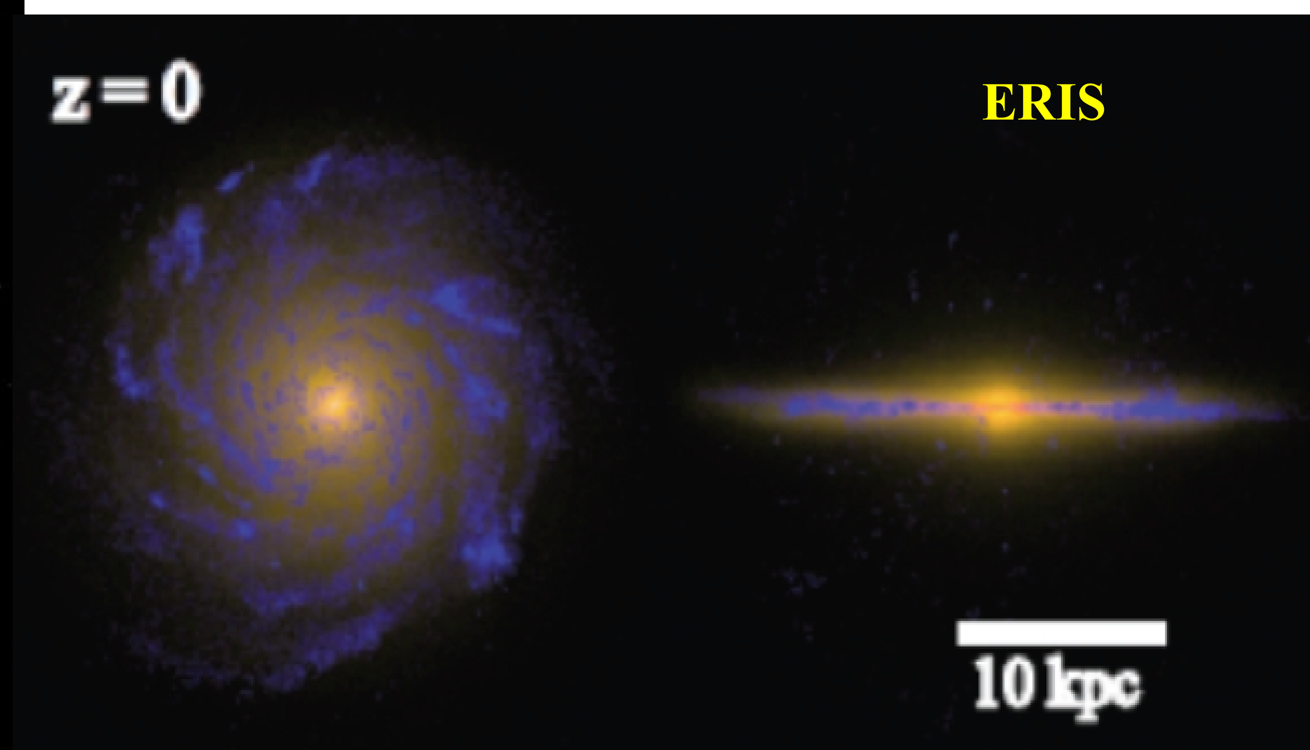
- Accretion onto and output from AGN (radiative, hydrodynamic..)

- Effects of cosmic rays and B fields

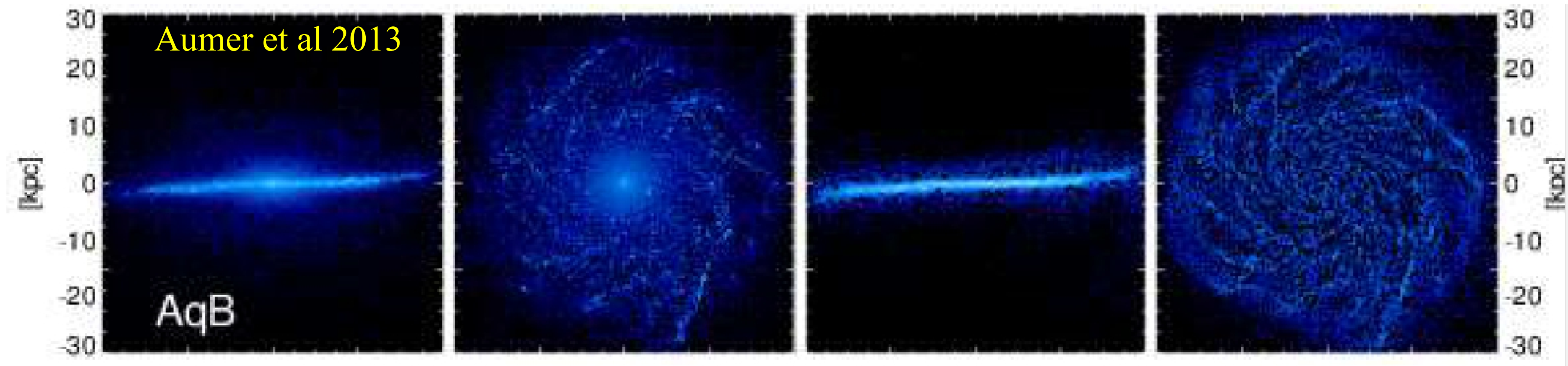
- Environment effects (interactions, mergers, stripping, irradiation)



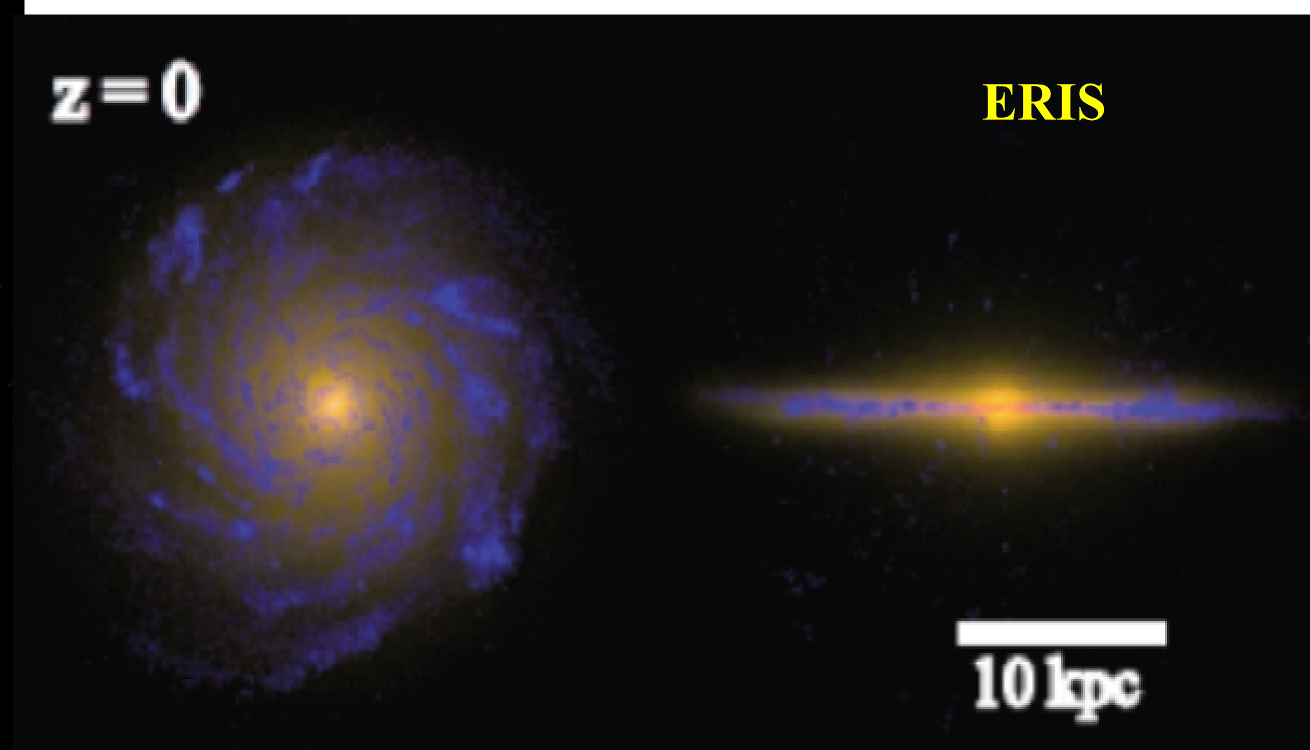
Several groups now make viable Milky Ways



Guedes et al. 2011, 2012



Several groups now make viable Milky Ways. They have different, differently implemented and incomplete "subgrid" phenomenology. The agreement is a result of parameter tuning



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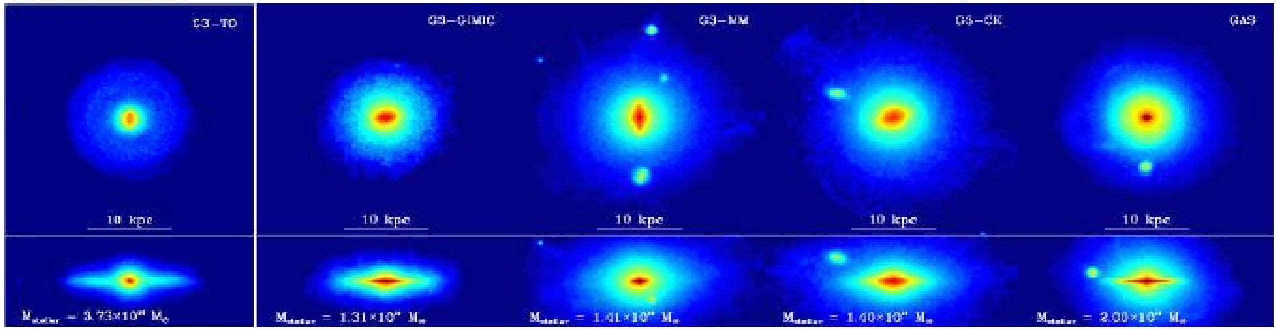
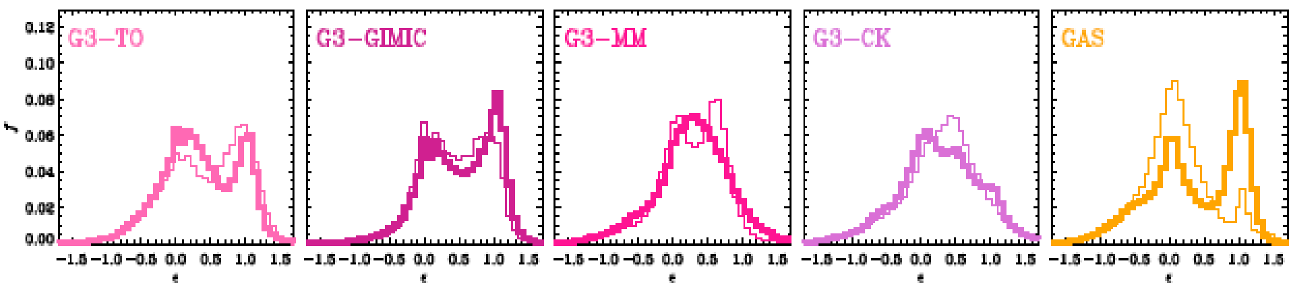
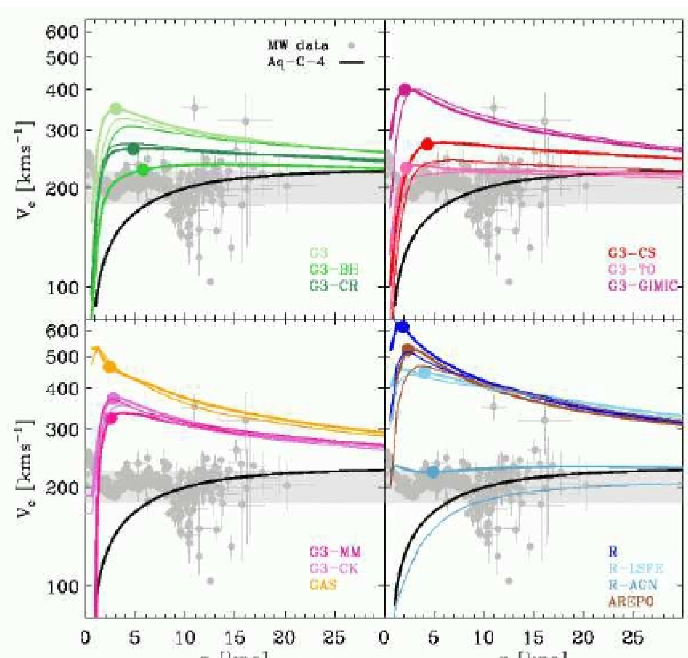
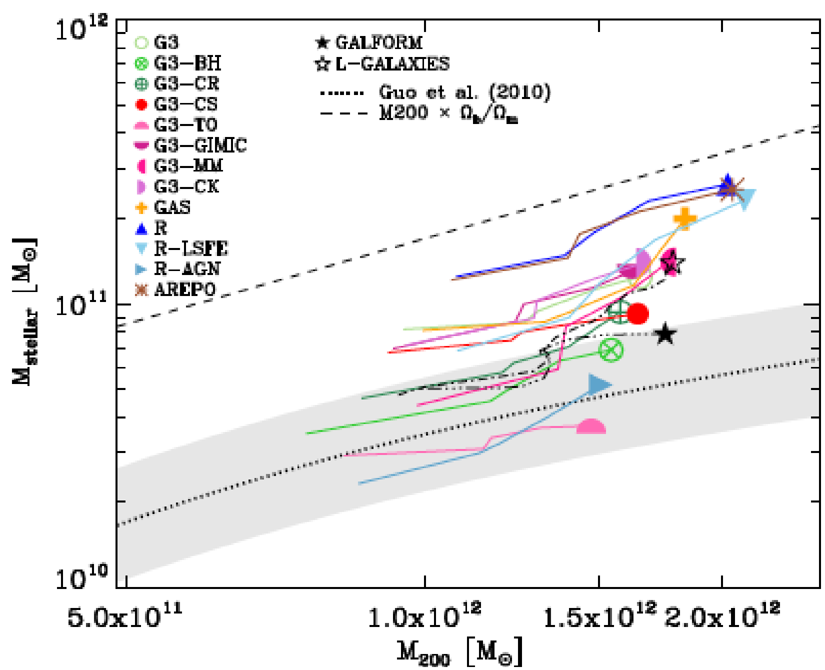


Different baryonic physics codes give very different galaxies when applied to the <u>same</u> initial conditions

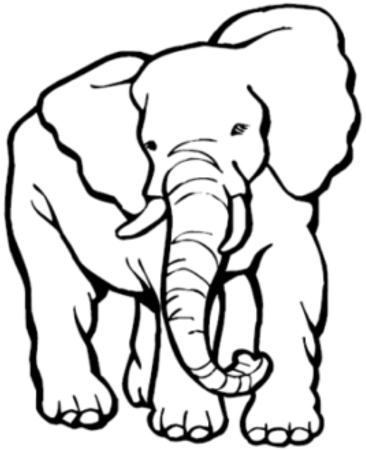


→ clues to galactic astro-physics or just a need to tune parameters?

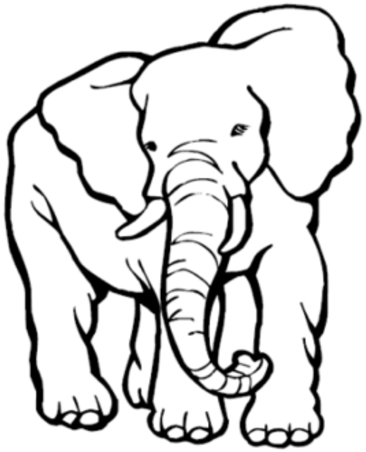




The Aquila Project
Scannapieco et al 2012



- Many interacting physical processes are important and span a very wide range of physical scales
- Many cannot be resolved and so *must* be handled by phenomenological “subgrid” models
- These are typically highly simplified, incomplete and uncertain, involving various undetermined parameters
- Parameter tuning may give a good fit to observation but this does *not* necessarily imply correctness of the model



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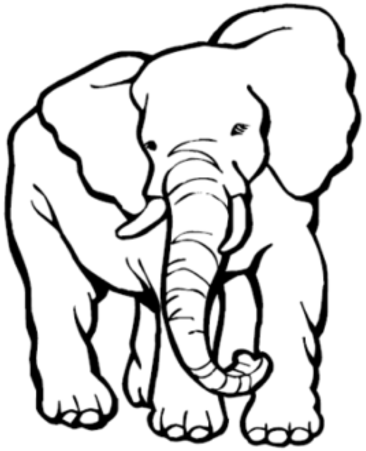
HOW DO WE MAKE PROGRESS?



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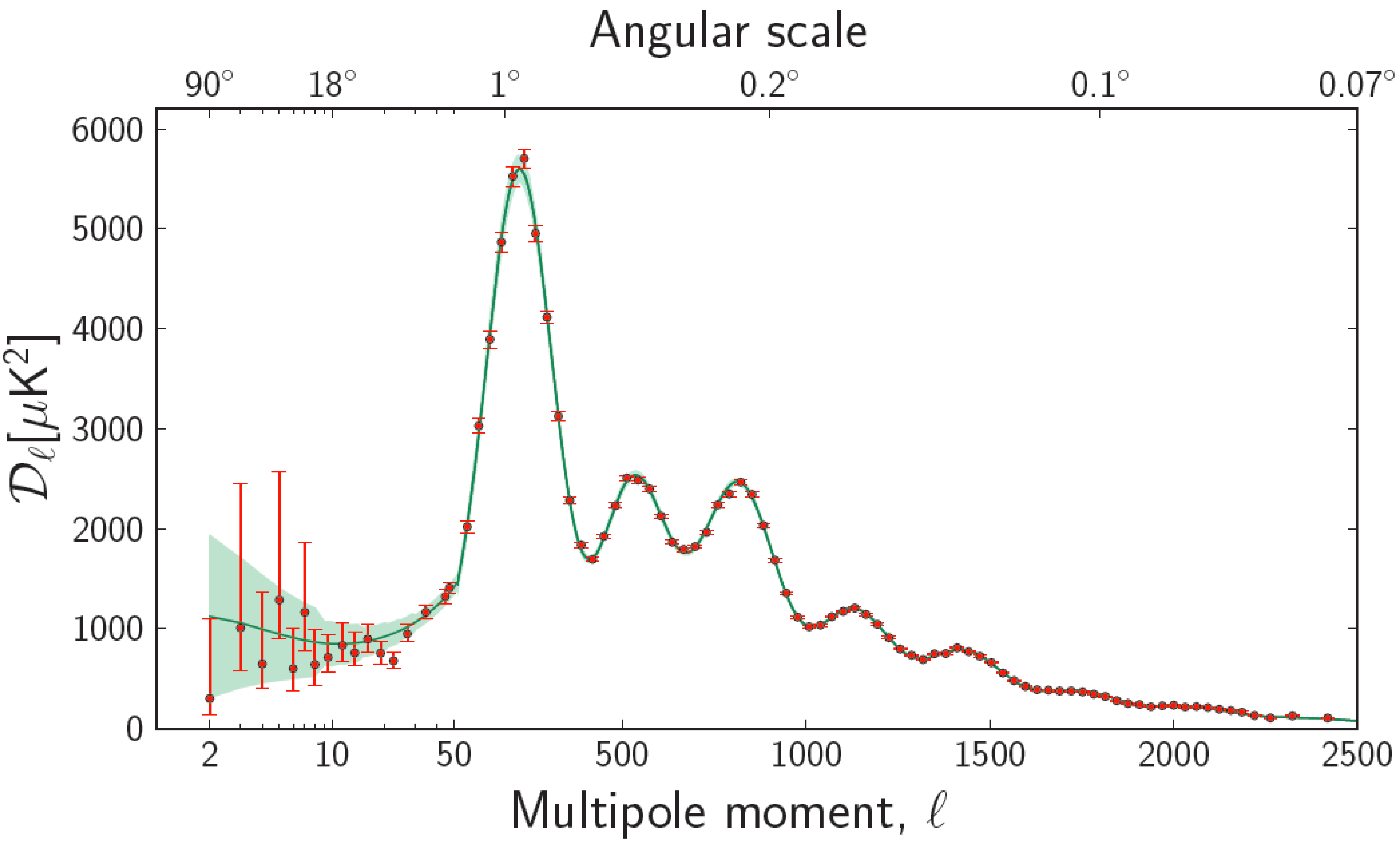
HOW DO WE MAKE PROGRESS?

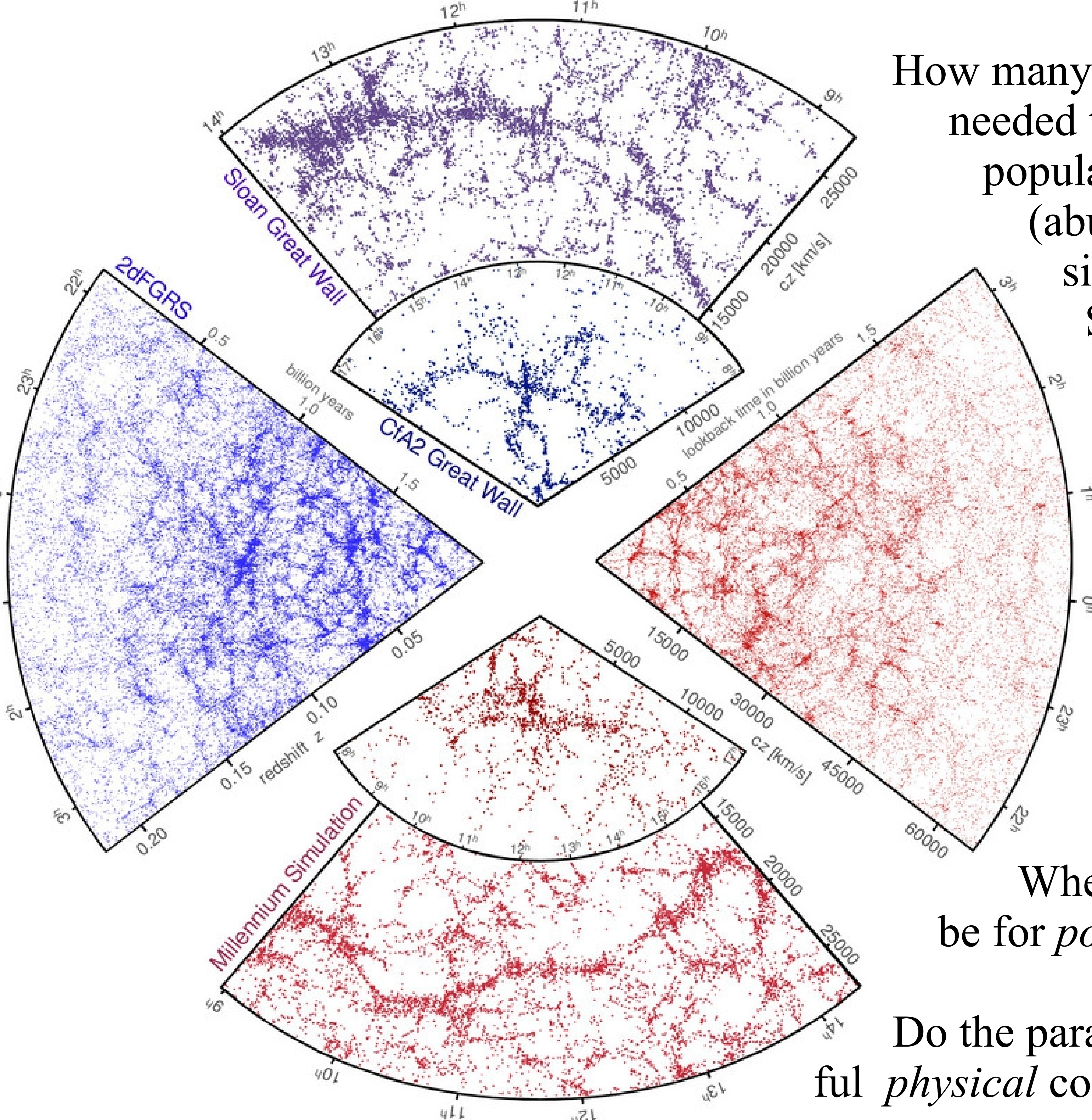
- Improve understanding by tests for physical consistency and against data of <u>different</u> kinds

Information content of the *Planck* CMB map



Six parameters fine-tuned to fit a single curve

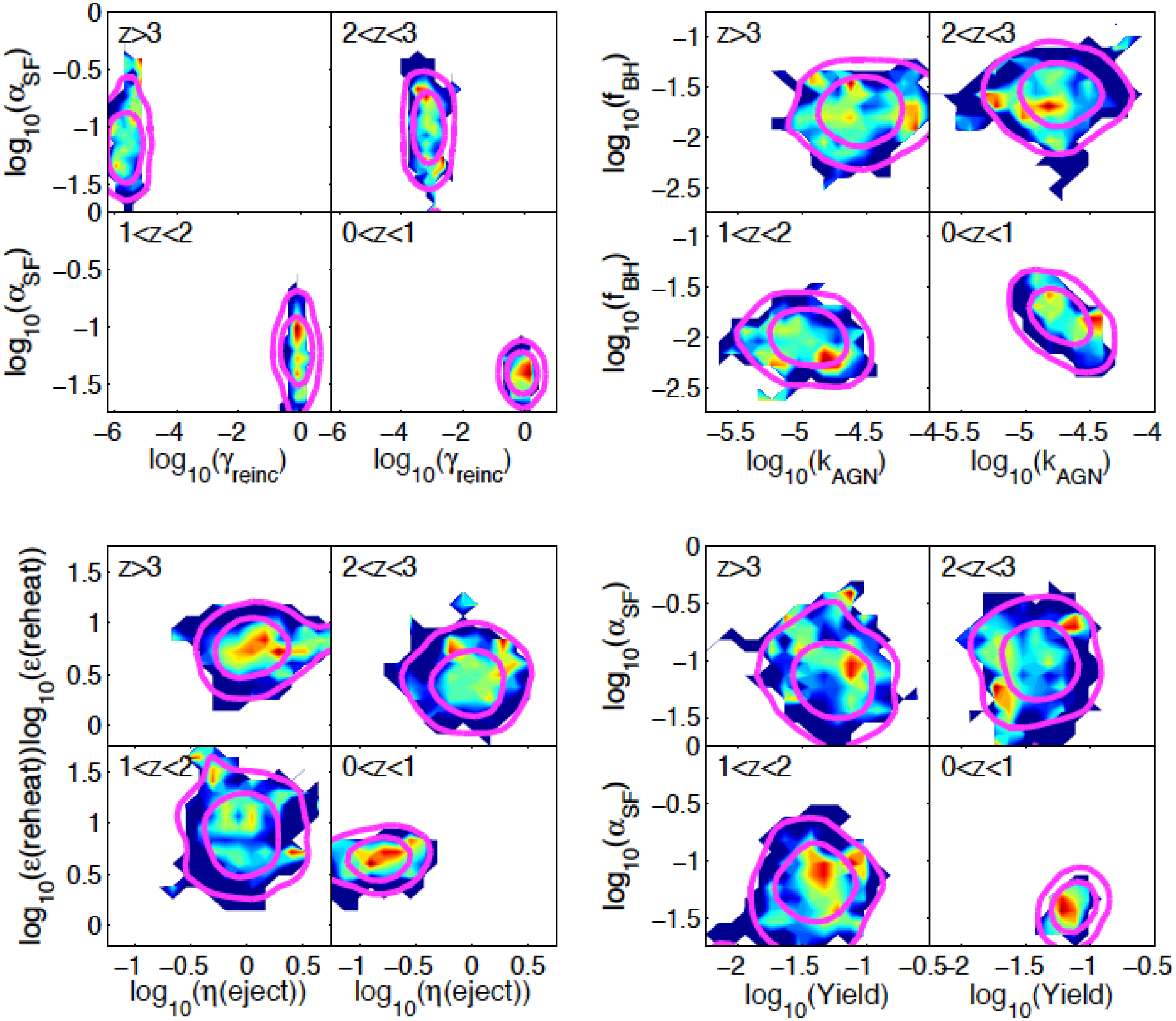
	Planck+WP	
Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063
τ	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$



How many parameters are needed to fit the galaxy population?
(abundance by mass, size, gas content, SFR, B/T, AGN; scaling relations; clustering...)

Where should the gap be for *population* studies?

Do the parameters have useful *physical* content?



Henriques et al 2013

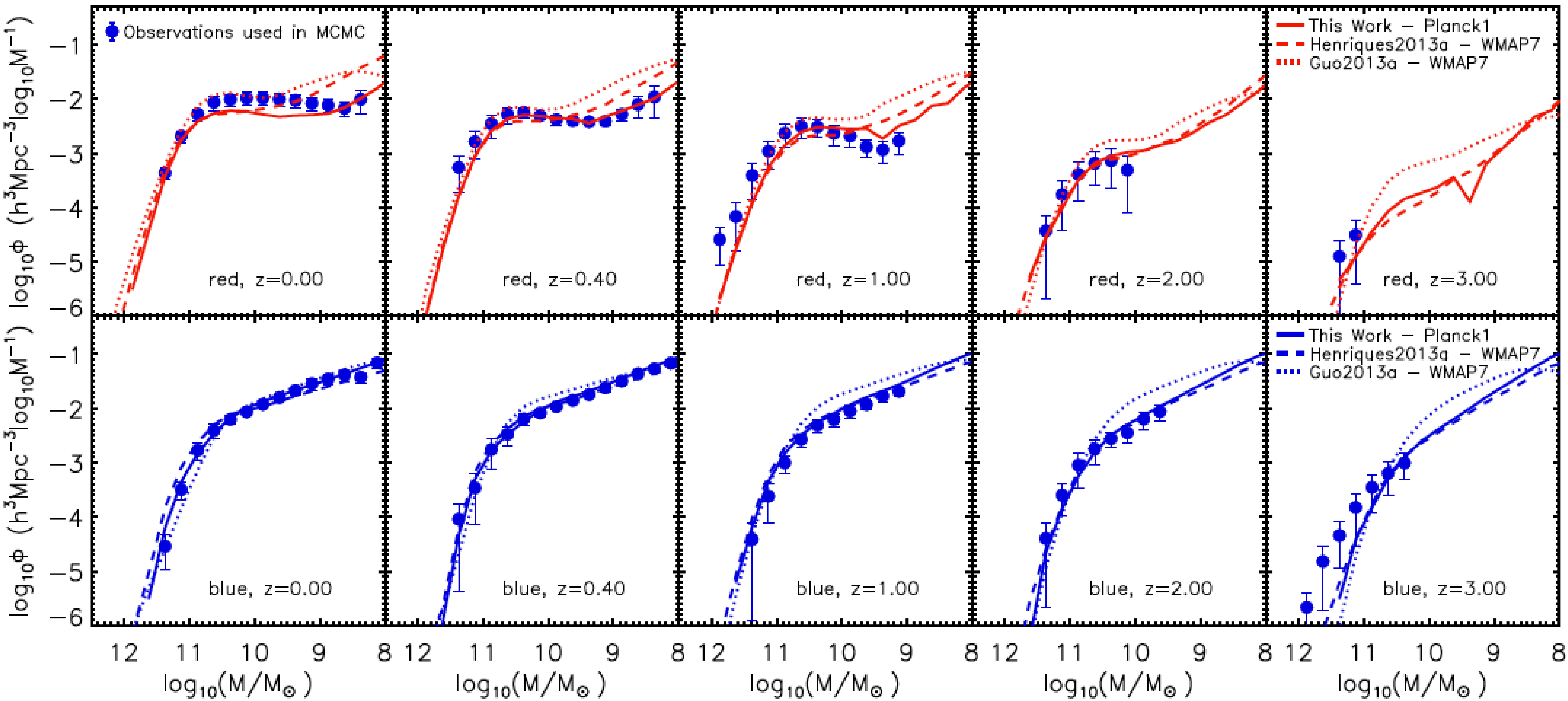
SA model of Guo et al (2011) constrained by observed stellar mass and luminosity functions at z = 0, 1, 2 and 3

Parameters are determined by data at each individual redshift

No parameter set is consistent with data at all redshifts

(At least) one parameter is required to vary with redshift

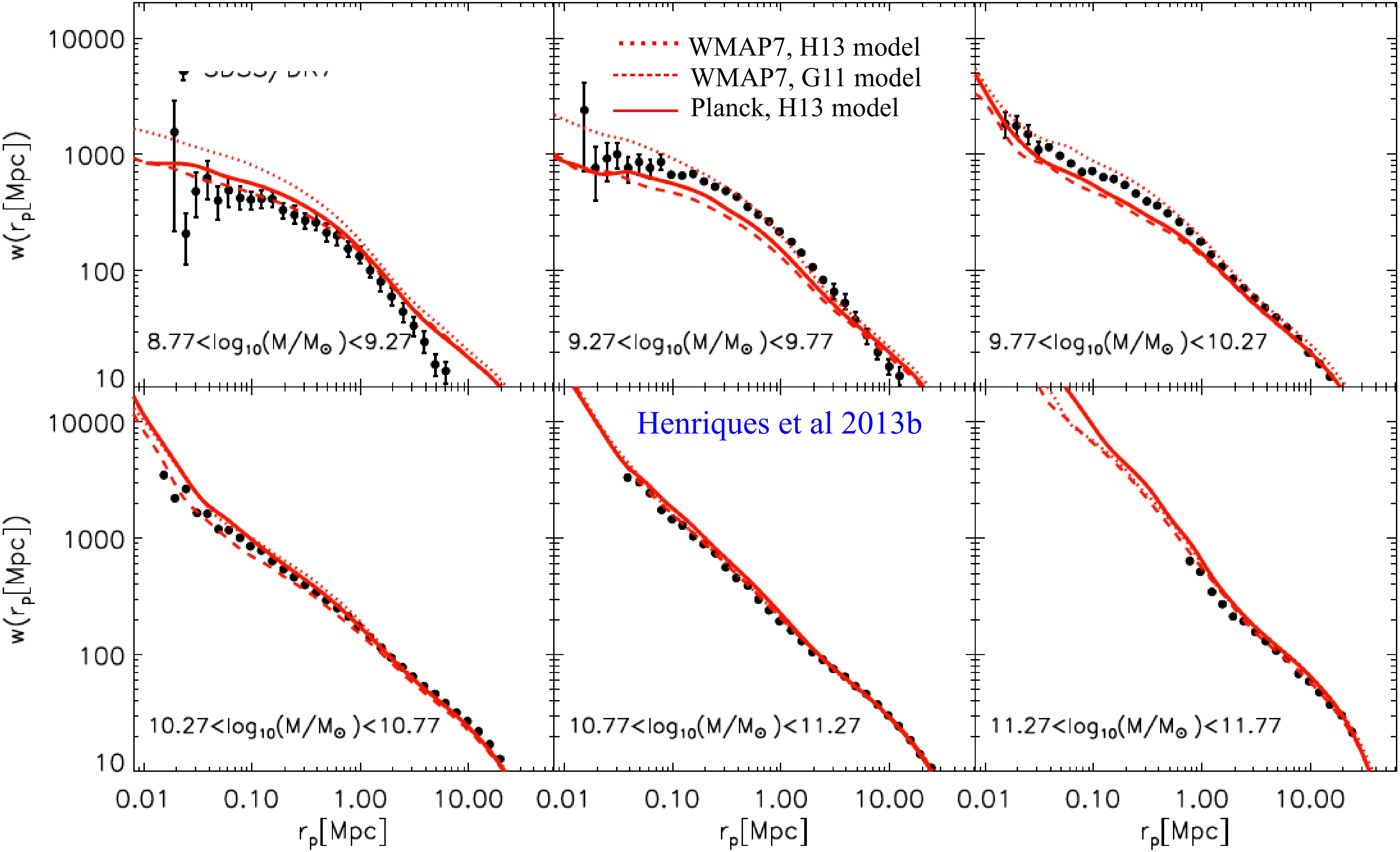
Henriques et al 2013b, Planck cosmology



Changing the assumed timescale for reincorporation of wind ejecta

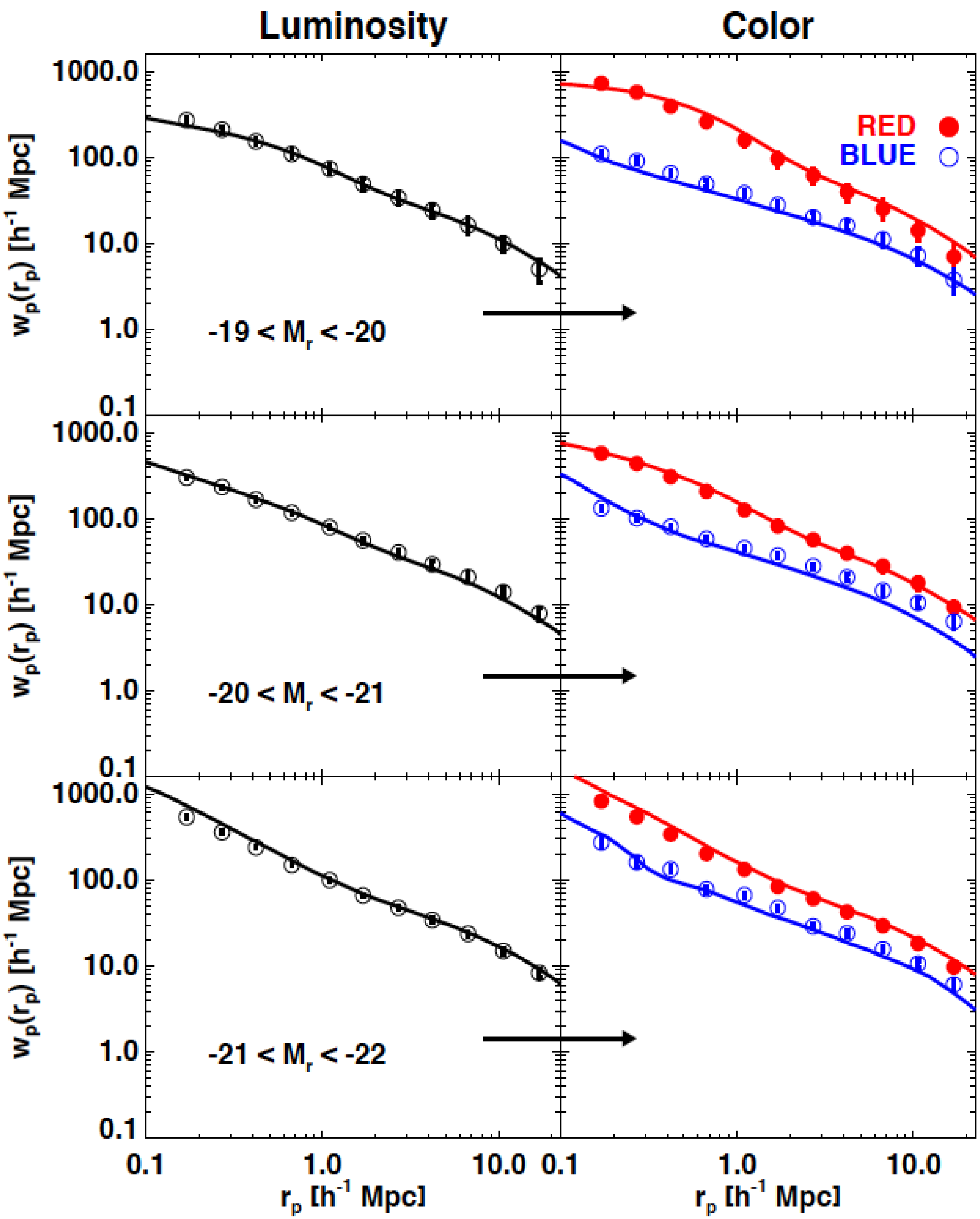
$$t_{return} = \text{const.} / H(z)\, V_{halo} \longrightarrow t_{return} = \text{const.} / M_{halo}$$

allows a good fit to data at all redshifts for the same # of parameters

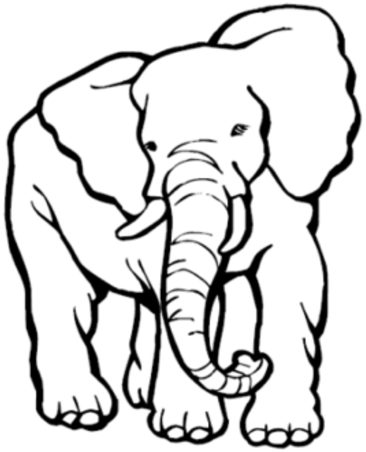


Clustering predictions depend weakly and at a similar level on cosmology and galaxy formation model

Hearin & Watson 2013



- *Assume* that L of the galaxy in each subhalo in a DM simulation is a monotonic function of its V_{peak}
- *Assume* that galaxy colour is a monotonic function of subhalo age
- Abundance matching can then be used to populate the simulation
- Comparing to real clustering tests assumptions + cosmology + simulation accuracy, but does not separate them
- Observed luminosity and colour distributions are *input*, so are not used to constrain formation physics



It is important (but not always easy) to separate

- assumption from deduction
- physics from fitting
- astrophysics from cosmology from numerics

- Galaxy abundances put *strong* constraints on formation processes -- better to use them!
- SA models typically have only as many free parameters as needed to fit the adopted constraints
- To date they have been <u>by far</u> the most predictive and most highly tested of all astrophysical simulations

Virgo - Millennium Database

Documentation

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FAQ

Public Databases

- DGalaxies
- DHaloTrees
- Guo2010a
- Guo2013a
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- MField
- MillenniumII
- millimil
- miniMilII
- MMSnapshots
- MPAGalaxies
- MPAHaloTrees
- MPAMocks
- Snapshots

Private (MyDB) Databases

- sampling_db (r)
- swhite_db (rw) (context)

VIRGO

Welcome Simon White.
Streaming queries return unlimited number of rows in CSV format and are cancelled after 420 seconds.
Browser queries return maximum of 1000 rows in HTML format and are cancelled after 30 seconds.

- The MS halo and galaxy databases have been public since 2006

Query (stream) | Query (browser) | Help

Maximum number of rows to return to the query form: 10

Demo queries: click a button and the query will show in the query window.
Holding the mouse over the button will give a short explanation of the goal of the query. These queries are described in some more detail on this page.

Mainly Halos: H 1 | H 2 | H 3 | H 4 | H 5 | HF 1 | HF 2 | HF 3

Mainly Galaxies: G 1 | G 2 | G 3 | G 4 | G 5 | G 6 | HG 1 | HG 2 | GF 2

Metadata queries: The SQL statements under these buttons provide examples for querying and managing the state of a private database.
Holding the mouse over the button will give a short explanation of the goal of the statement.

ShowTables | Show Views | Show Columns | Show Indexes | MyDB Size | MyDB Table Size

Create View | Drop Table | Create Index

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Help

...scribed in some more detail on this page.

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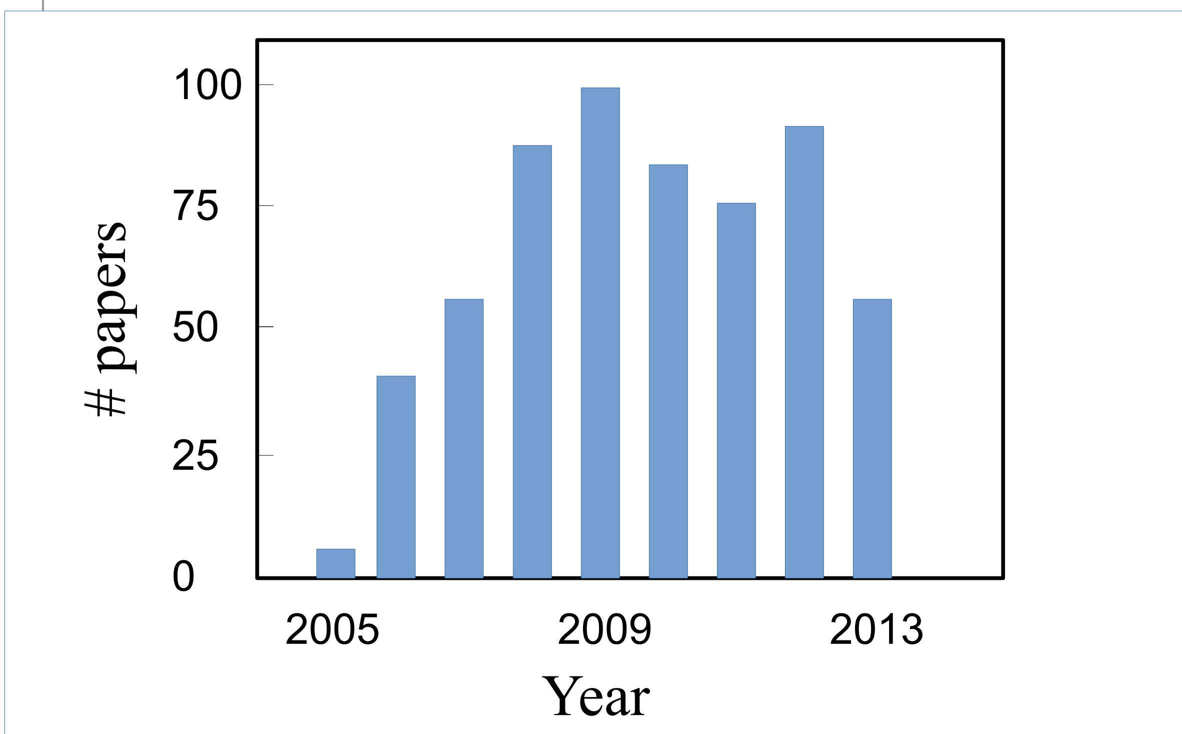

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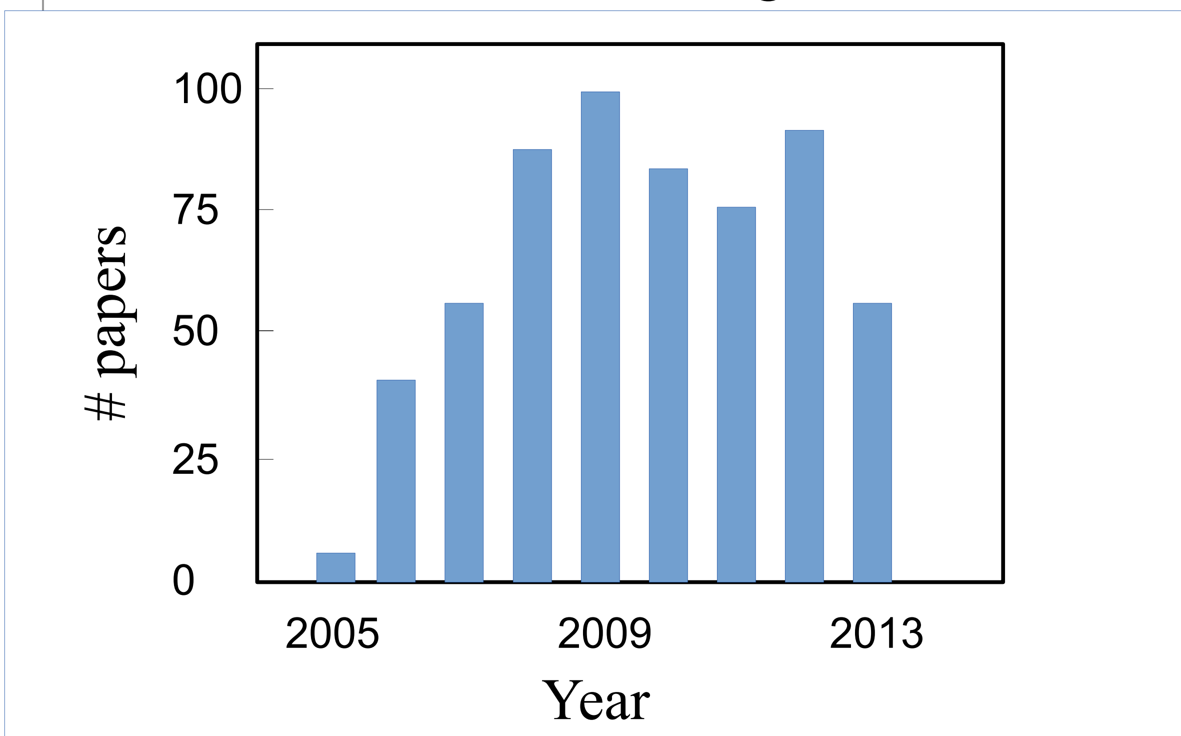
- >580 papers have used these predictions
- Most use the galaxies and are by authors unassociated with the Virgo Consortium

Query (stream)

Query (browser)

Help



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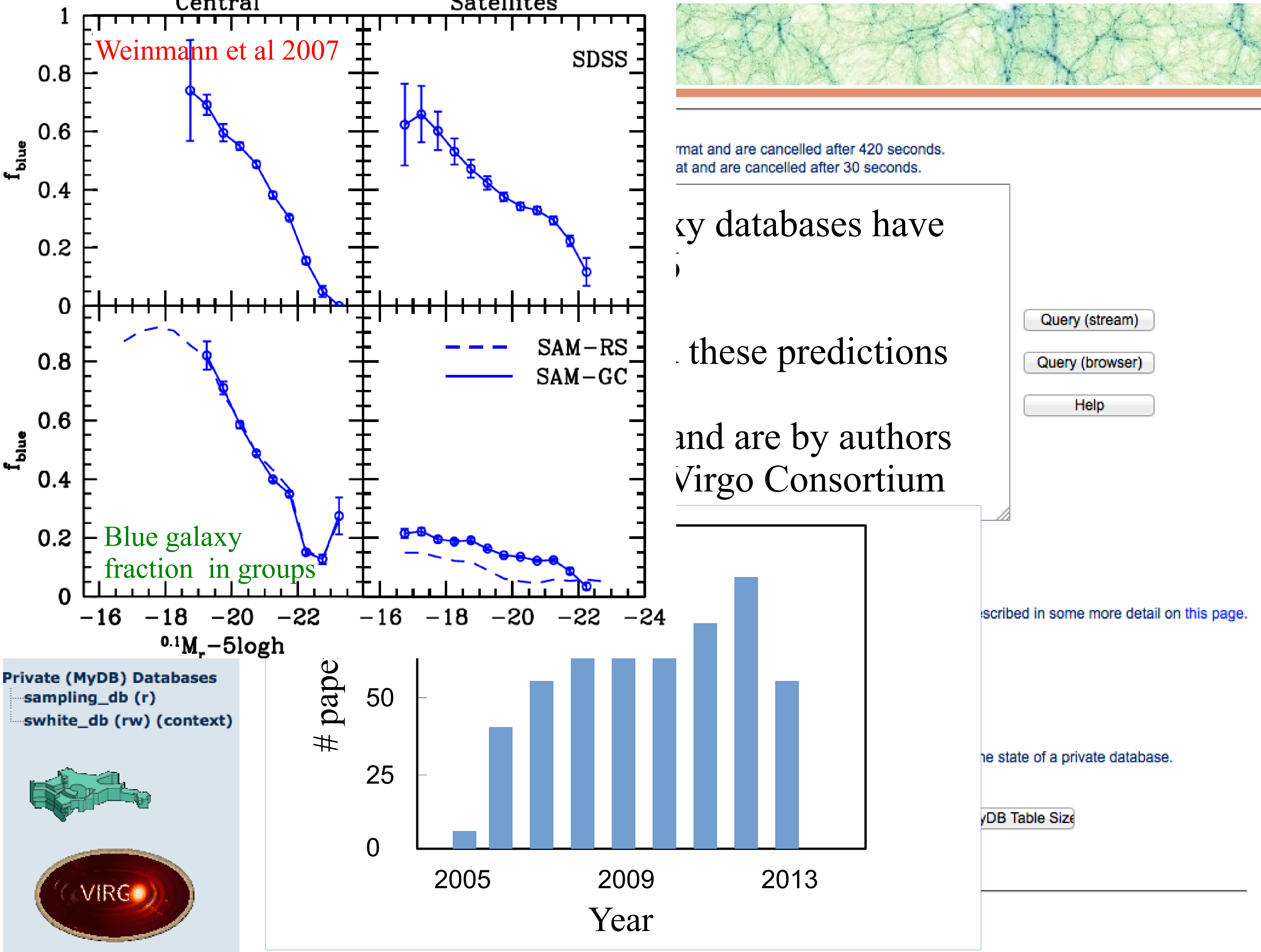
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SDSS
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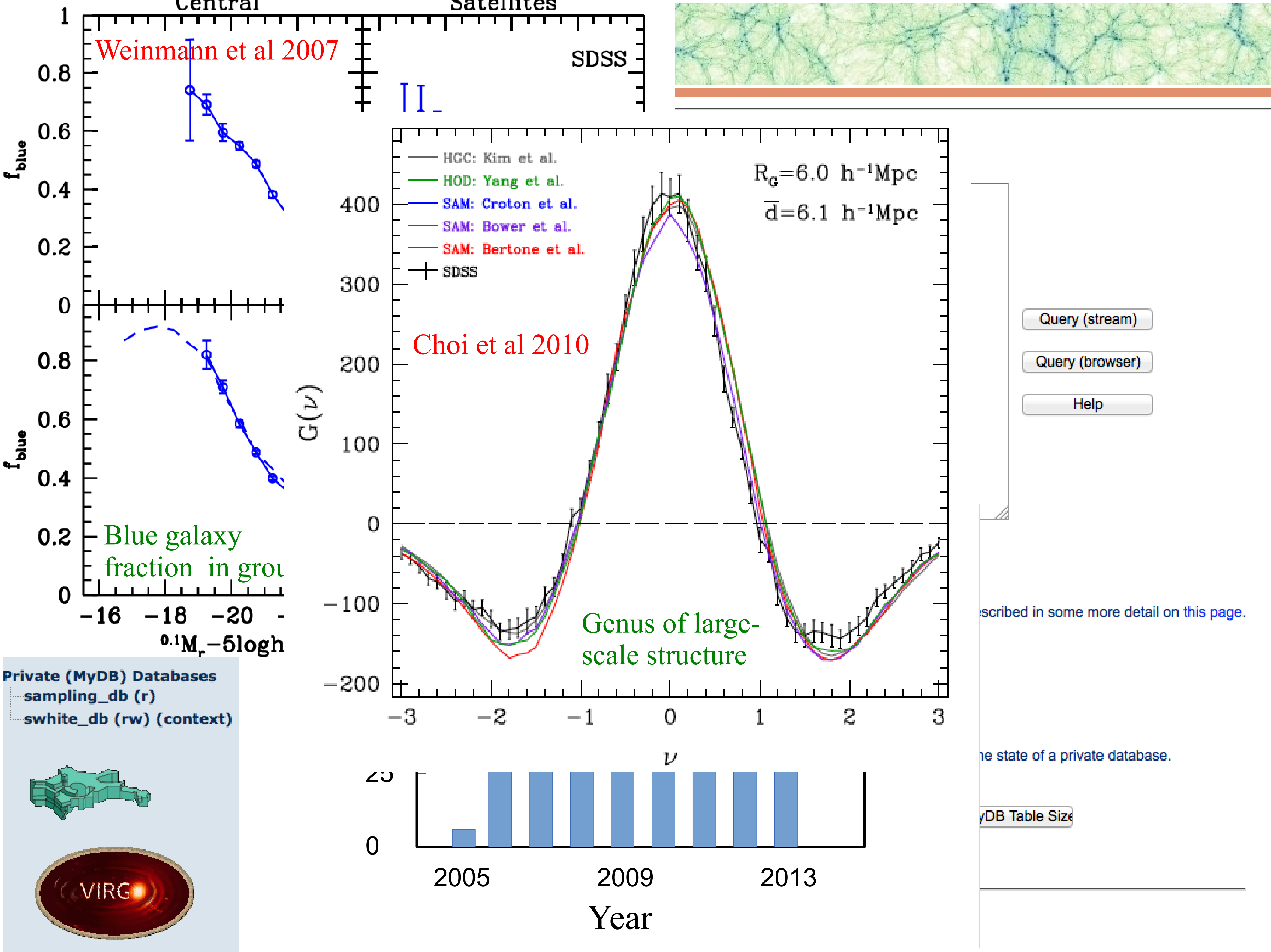

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HOD: Yang et al.
SAM: Croton et al.
SAM: Bower et al.
SAM: Bertone et al.
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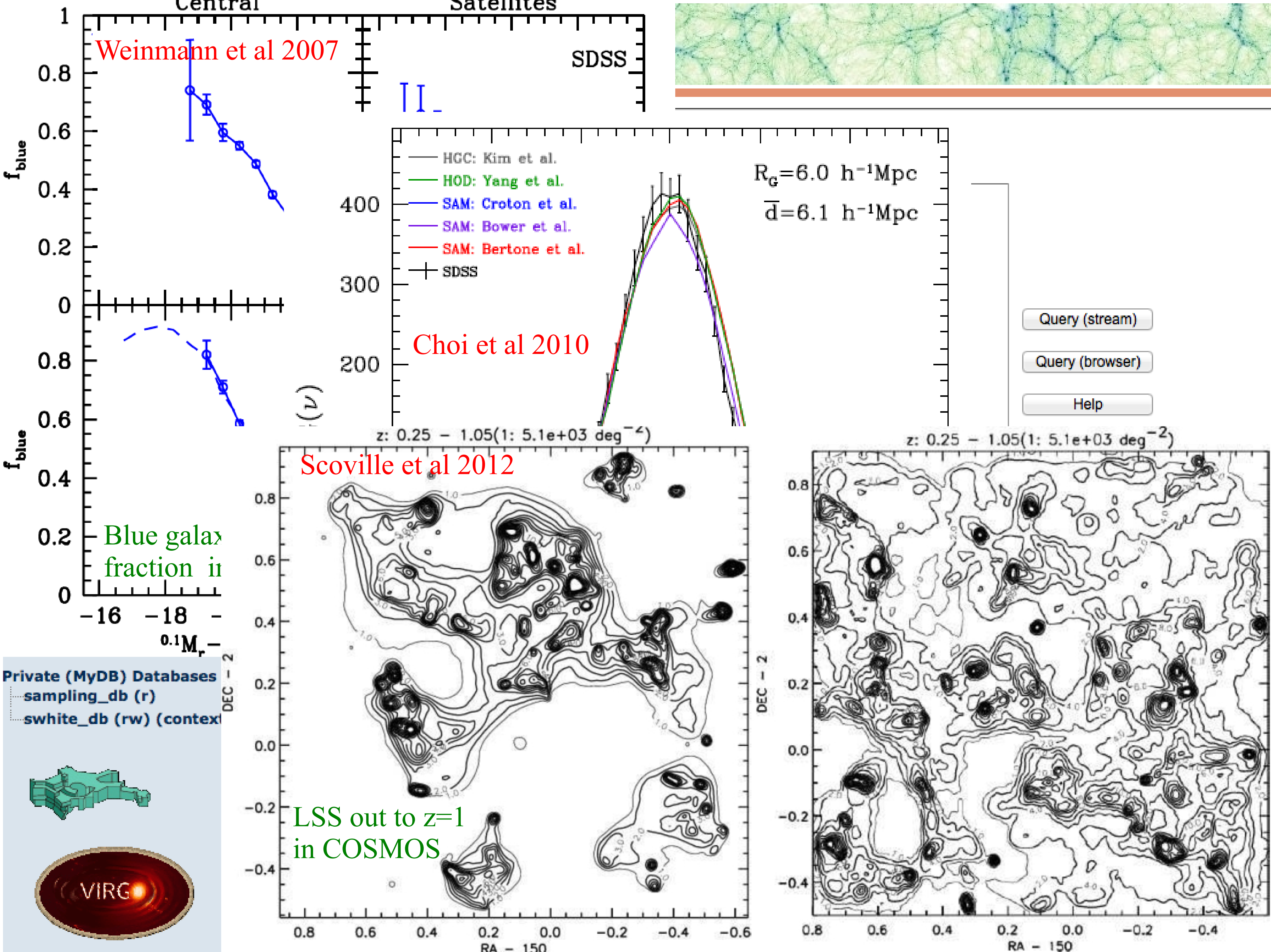

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Choi et al 2010
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Scoville et al 2012
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DEC – 2
RA – 150
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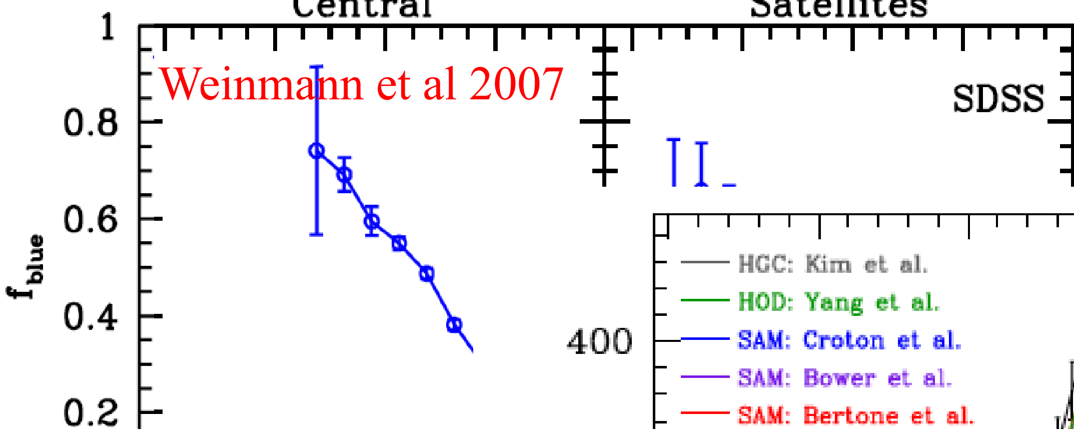
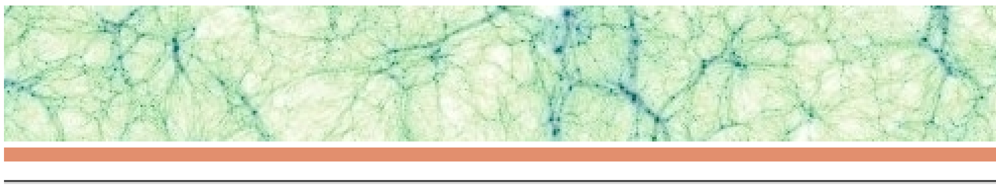
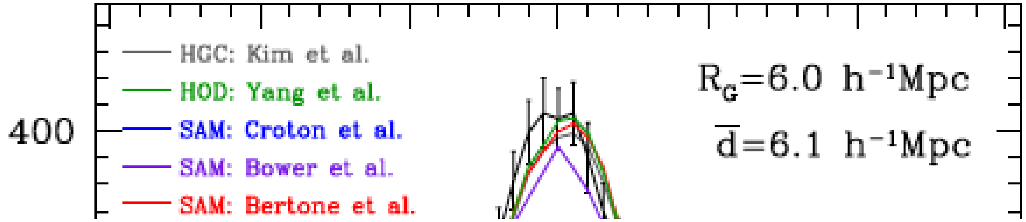
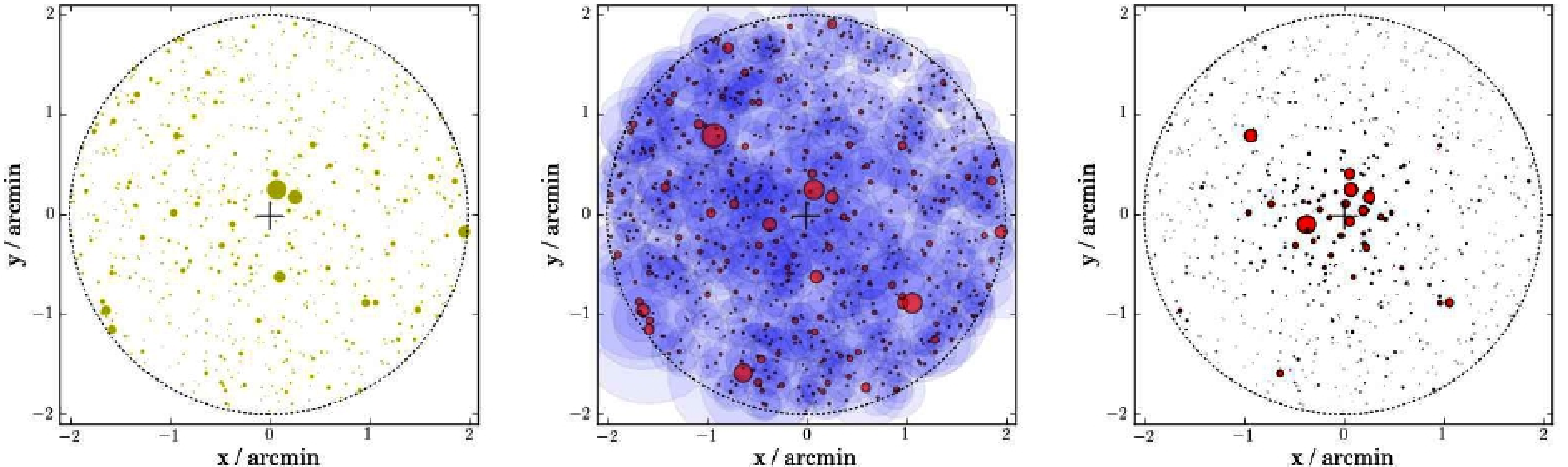
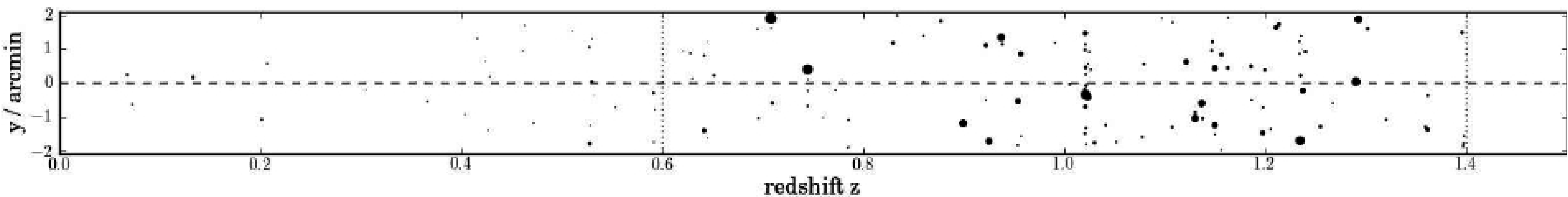


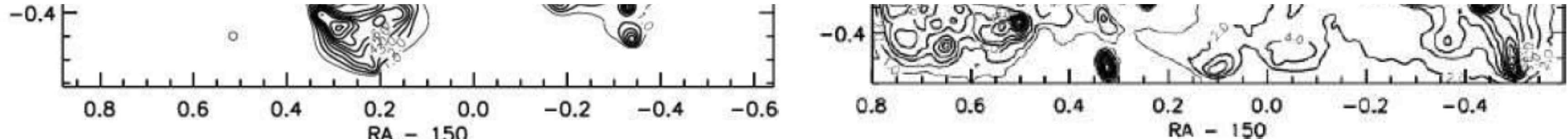






Reconstructing the cosmic lensing mass distribution
Collett et al 2013





Virgo - Millennium Database

Documentation

CREDITS/Acknowledgments

Registration

News

FAQ

Public Databases

- DGalaxies
- DHaloTrees
- Guo2010a
- Guo2013a
- Henriques2012a
- MField
- MillenniumII
- millimil
- miniMilII
- MMSnapshots
- MPAGalaxies
- MPAHaloTrees
- MPAMocks
- Snapshots

Private (MyDB) Databases

- sampling_db (r)
- swhite_db (rw) (context)

VIRGO

Welcome Simon White.
Streaming queries return unlimited number of rows in CSV format and are cancelled after 420 seconds.
Browser queries return maximum of 1000 rows in HTML format and are cancelled after 30 seconds.

The MS halo and galaxy databases have been heavily used because

(i) they are publicly available

(ii) they are easy to use

(iii) they provide data in the form needed to calibrate and interpret observations

Query (stream)

Query (browser)

Help

Maximum number of rows to return to the query form: 10

Demo queries: click a button and the query will show in the query window.
Holding the mouse over the button will give a short explanation of the goal of the query. These queries are described in some more detail on this page.

Mainly Halos: H 1 H 2 H 3 H 4 H 5 HF 1 HF 2 HF 3

Mainly Galaxies: G 1 G 2 G 3 G 4 G 5 G 6 HG 1 HG 2 GF 2

Metadata queries: The SQL statements under these buttons provide examples for querying and managing the state of a private database.
Holding the mouse over the button will give a short explanation of the goal of the statement.

ShowTables Show Views Show Columns Show Indexes MyDB Size MyDB Table Size

Create View Drop Table Create Index

Scaling Simulations to neighboring cosmologies

Angulo & White 2010

For example: \`WMAP1' – $\Omega_m = 0.25$, $\Omega_b = 0.045$, $\sigma_8 = 0.9$

to \`WMAP3' – $\Omega_m = 0.238$, $\Omega_b = 0.0416$, $\sigma_8 = 0.76$

1) Scale simulation size to match power spectrum slopes of original and target cosmologies on the scales of the target z=0 halos

-- 685 Mpc 593 Mpc

2) Reassign redshifts to match linear amplitudes on these scales

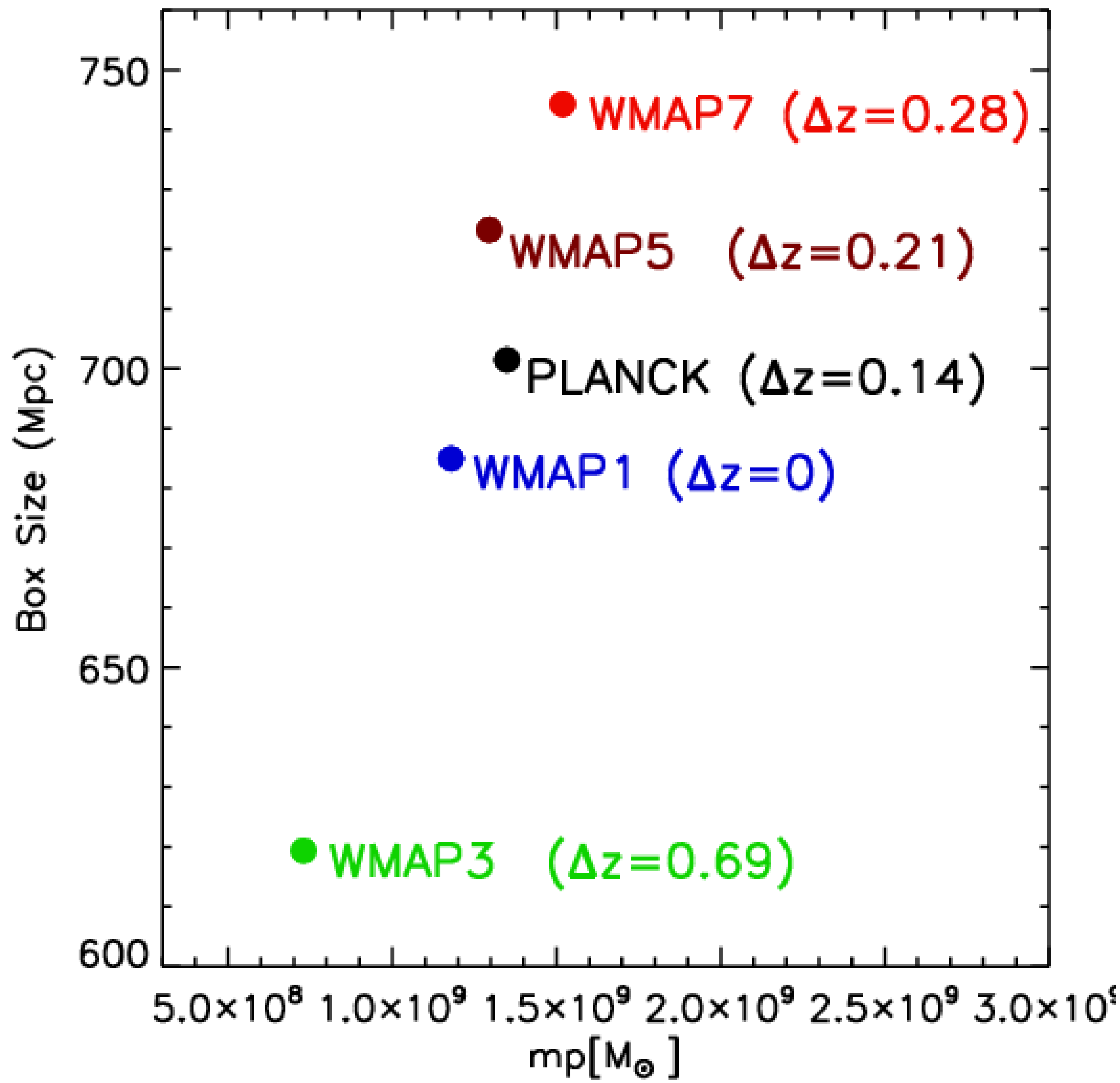
-- $z = 0.57, 1.68, 2.92$ $z = 0, 1, 2$

3) Scale particle masses and velocities to match Ω_m and new size

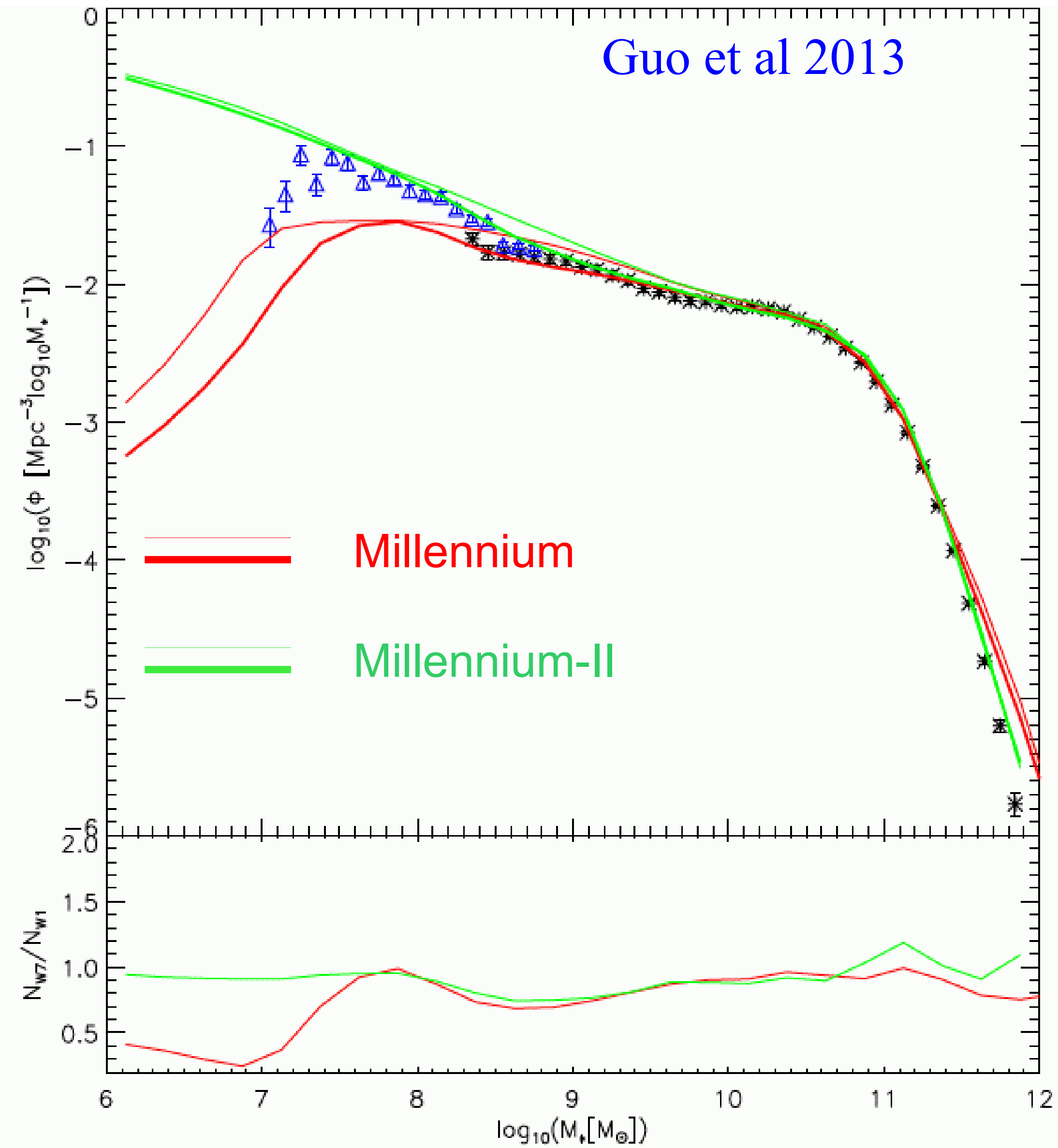
-- $1.2 \times 10^9\ M_\odot$ $7.7 \times 10^8\ M_\odot$

4) Adjust for the difference between amplitudes of original and target power spectra on large scales using linear theory.

Effect of changing cosmology on structure growth



Scalings needed to adapt the MS to changing CMB cosmologies



Switching from **WMAP1** to **WMAP7**

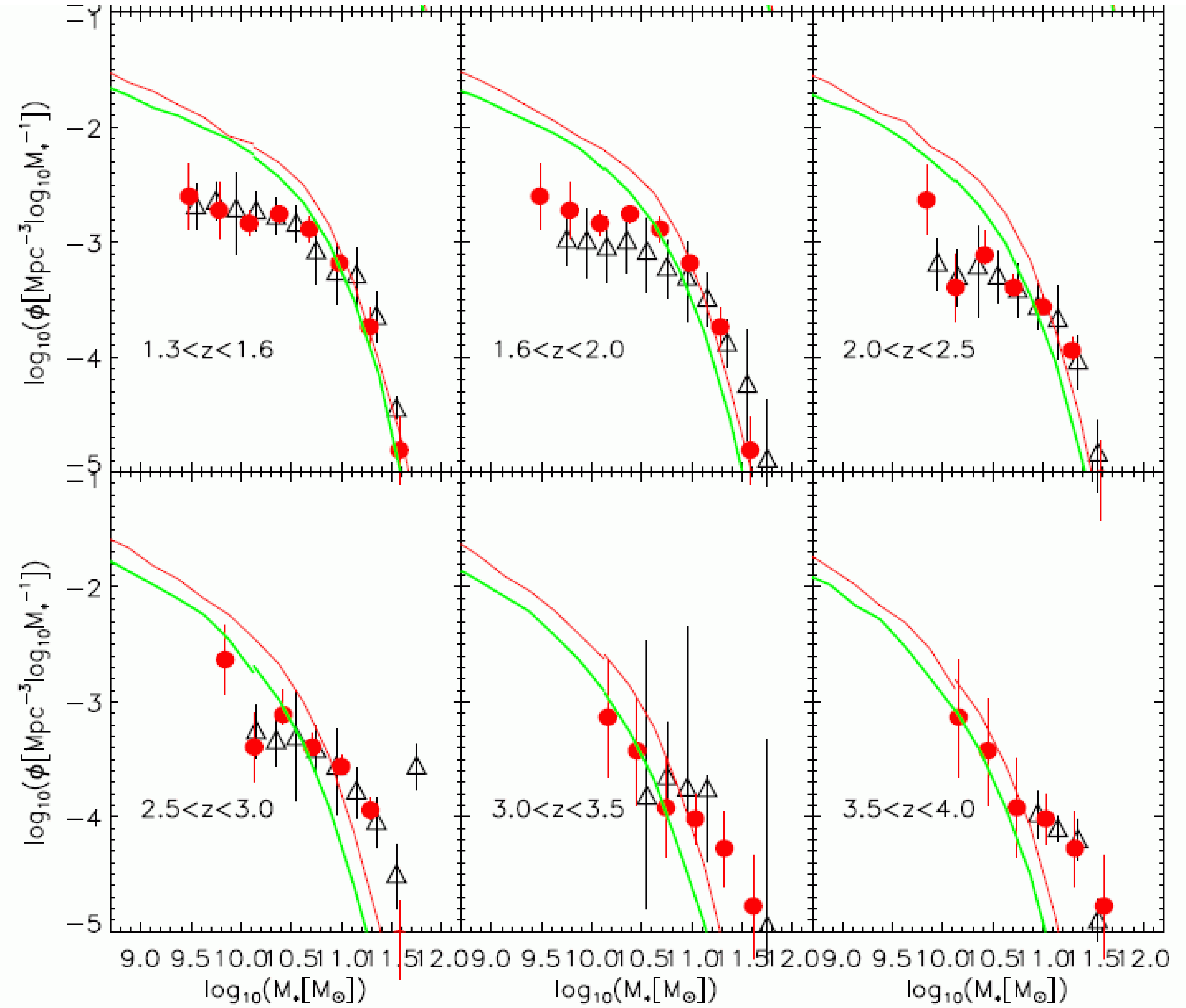
Small shifts in the parameters of the galaxy formation model allow the galactic stellar mass function to be fit equally well in the two cosmologies despite

$\sigma_8 = 0.90 \longrightarrow \sigma_8 = 0.81$

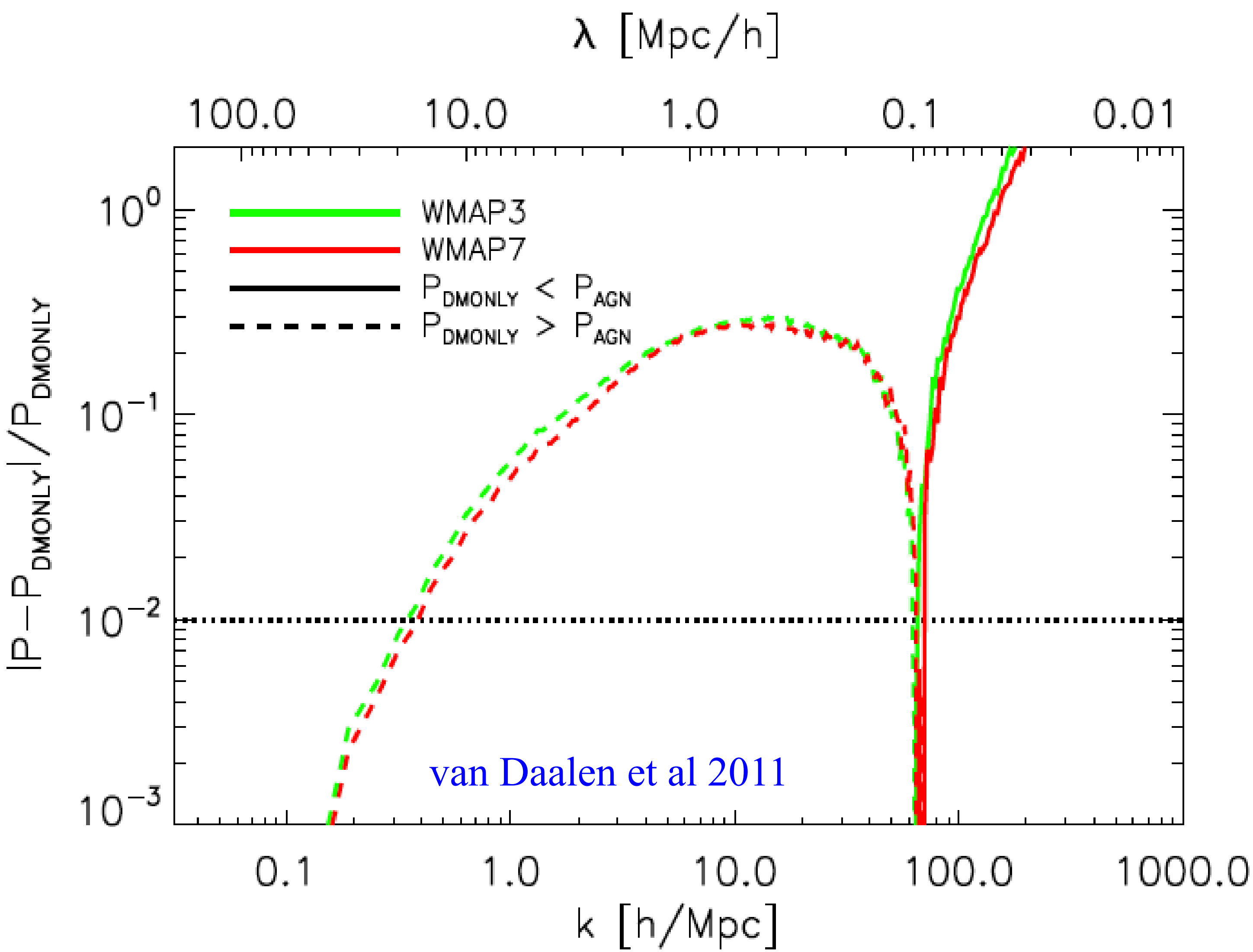
Parameter	Description	WMAP1	WMAP7
α	Star formation efficiency	0.02	0.015
ϵ	Amplitude of SN reheating efficiency	6.5	4.5
β_1	Slope of SN reheating efficiency	3.5	4
V_{reheat}	normarlization of SN reheating efficiency dependence on Vmax	70	80
η	Amplitude of SN ejection efficiency	0.32	0.33
β_2	Slope of SN ejection efficiency	3.5	6.5
V_{eject}	normarlization of SN ejection efficiency dependence on Vmax	70	80
κ	Hot gas accretion efficiency onto black holes	1.5×10^{-5}	6.0×10^{-6}

Switching from WMAP1 to WMAP7

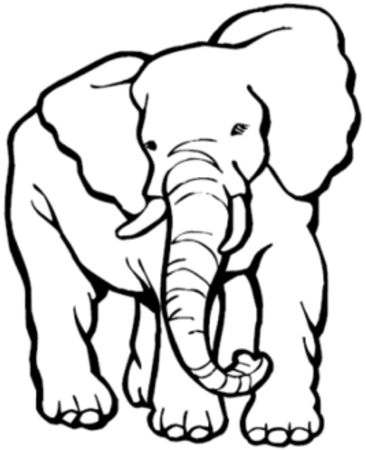
Guo et al 2013



..but the galaxy formation sequence is wrong in both

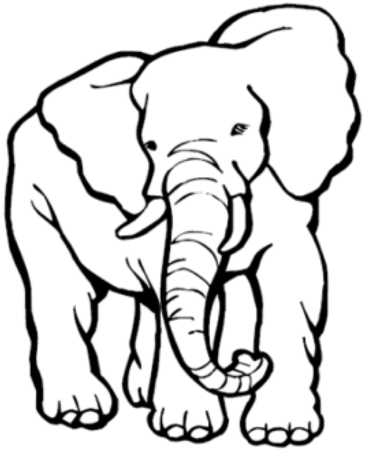
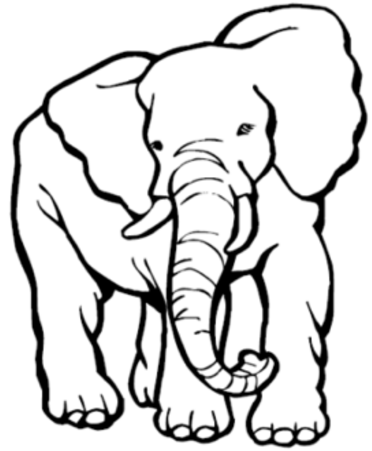
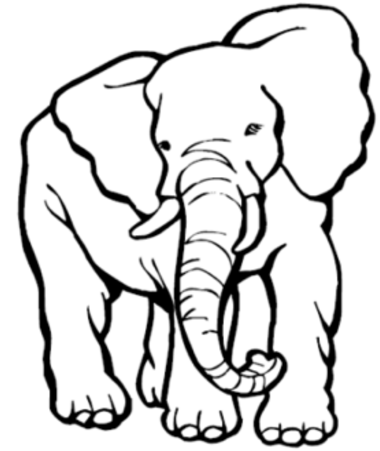
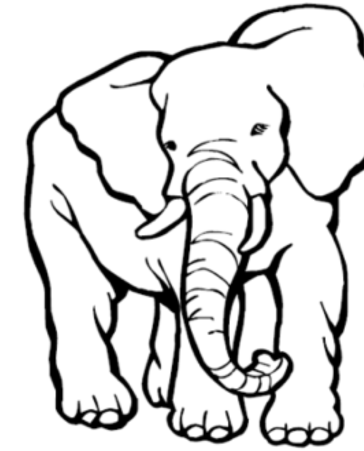


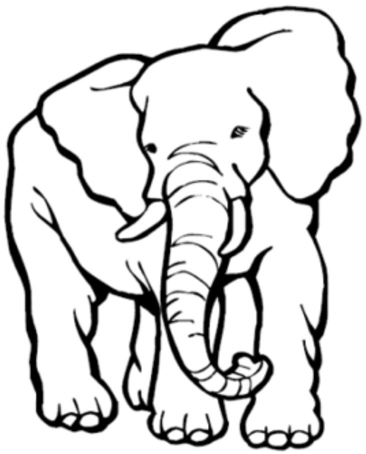
Feedback effects in a realistic galaxy formation model affect the mass power spectrum at the several percent level even at λ ~ 10 Mpc
This poses a problem for "precision" cosmology



Galaxy formation is highly nonlinear and sensitive to subgrid recipes, to numerical implementations and to cosmology

- These are not easily separated
- The galaxy distribution is much more strongly affected by formation physics than by cosmology
- Even “clean” probes like lensing (and BAOs?) are affected by galaxy formation at a level which may compromise “precision” cosmology.



In complex, multi-scale and highly nonlinear subjects like galaxy and star formation, true progress is possible only if modelling is combined with close attention to OBSERVATION

Observers are needed if we are to bridge the gap!