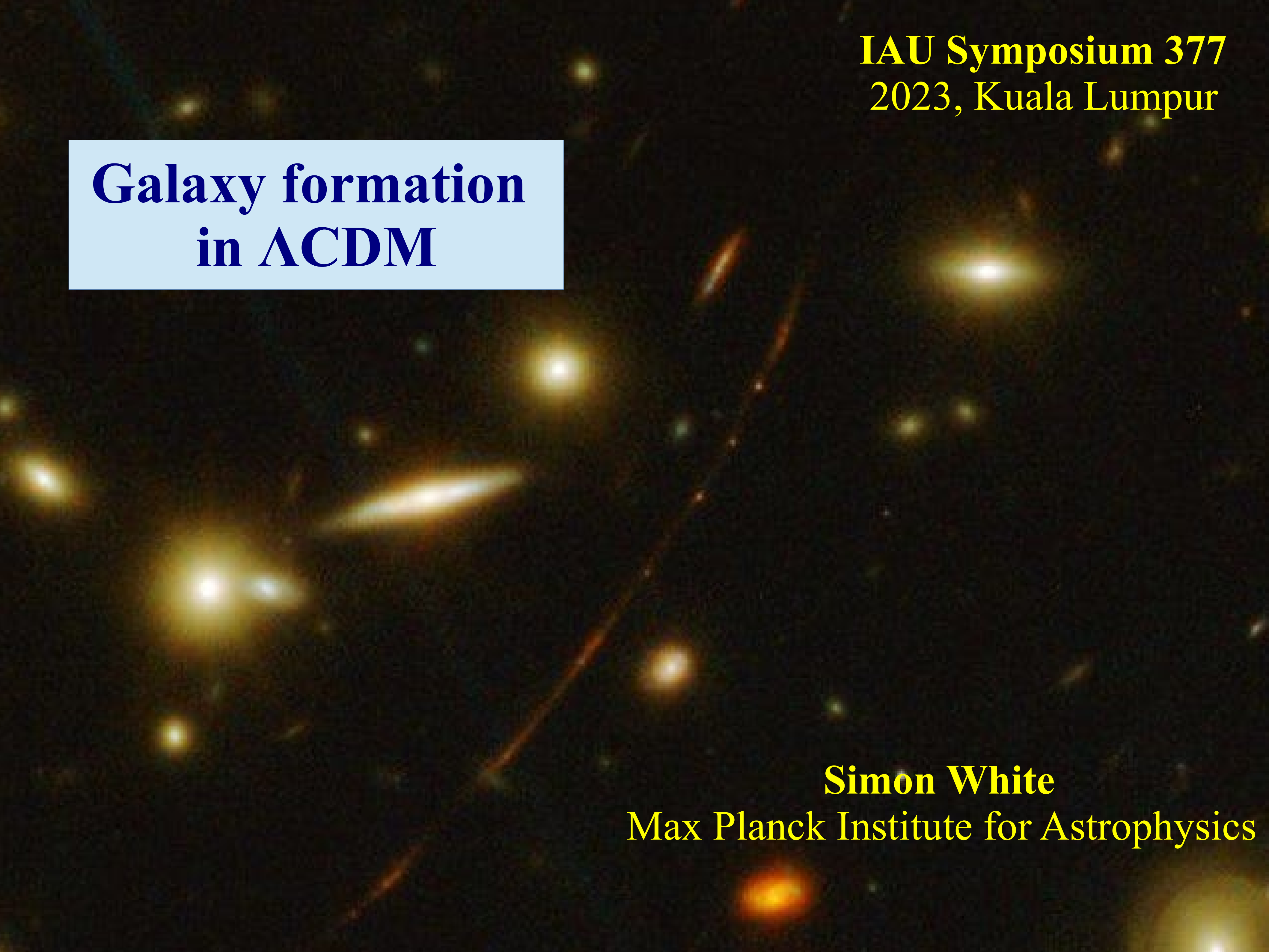

IAU Symposium 377
2023, Kuala Lumpur

Galaxy formation in ΛCDM

Simon White
Max Planck Institute for Astrophysics

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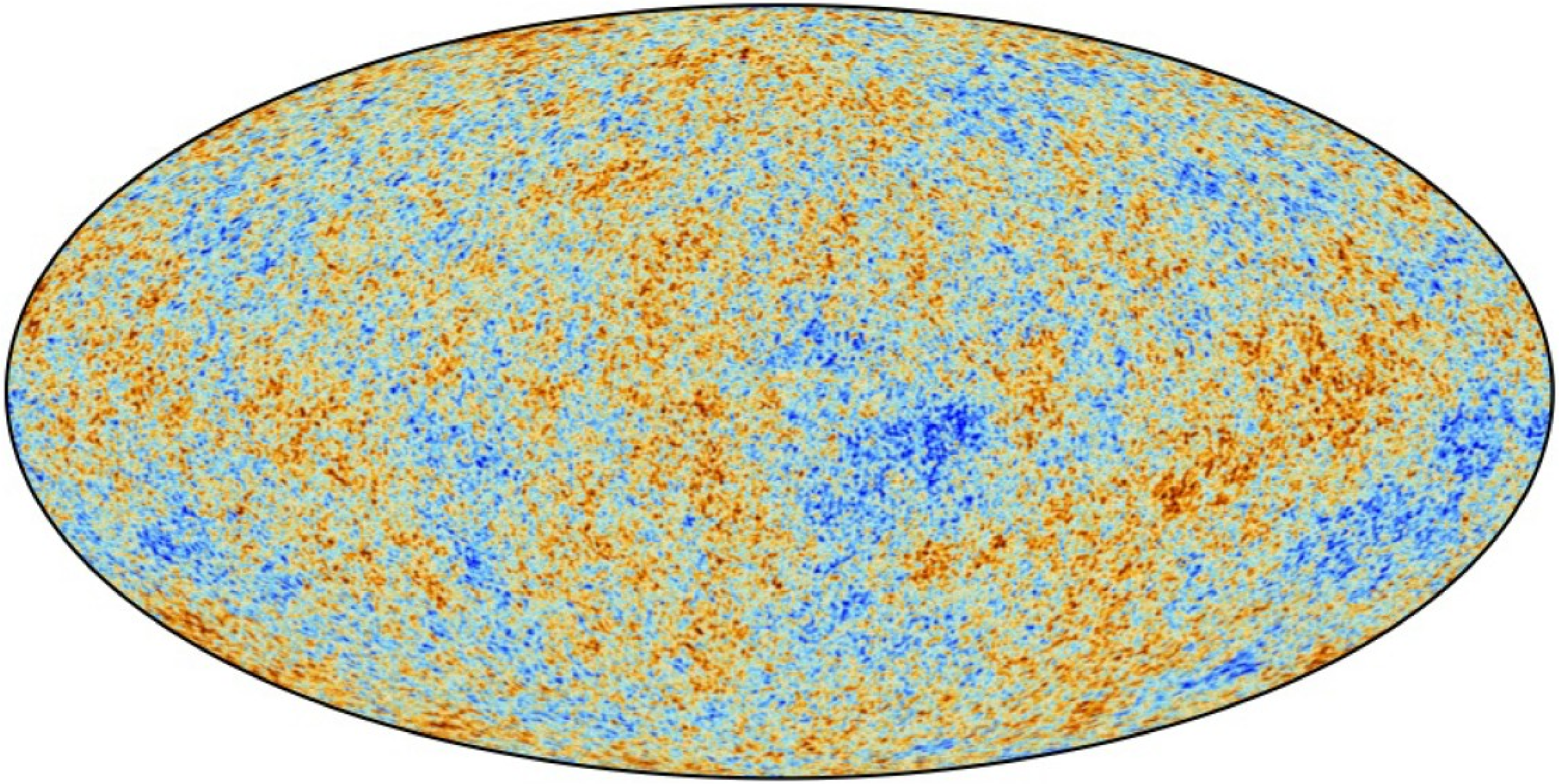

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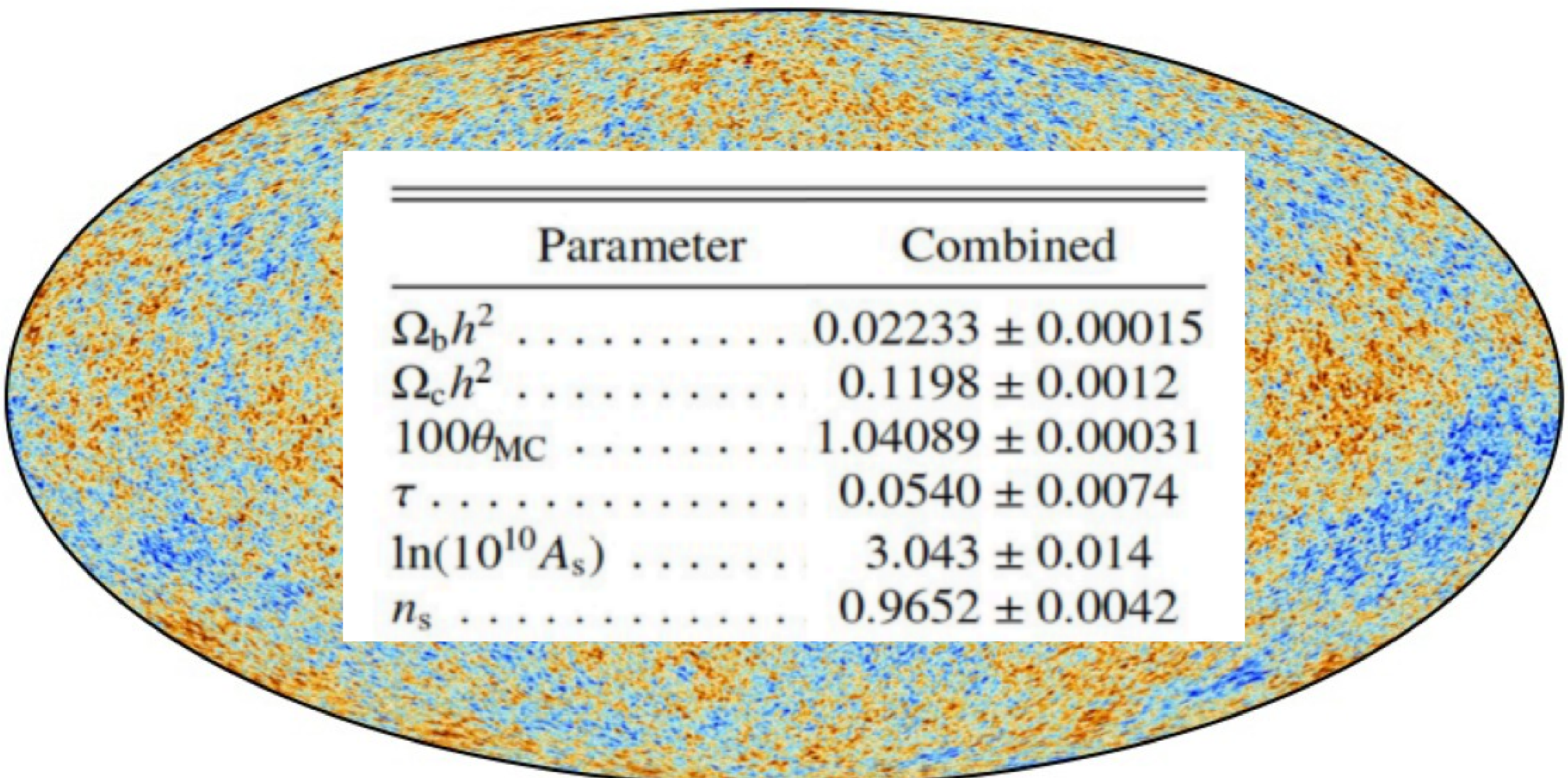
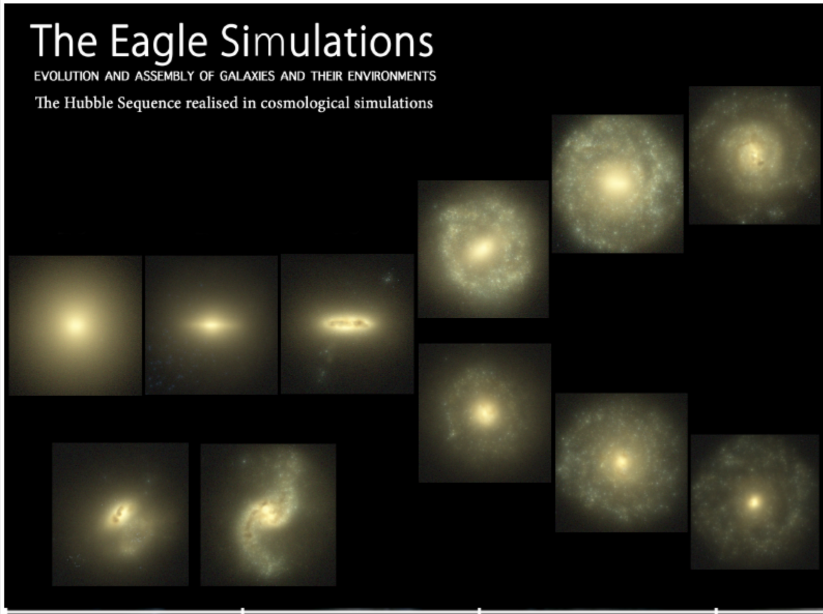
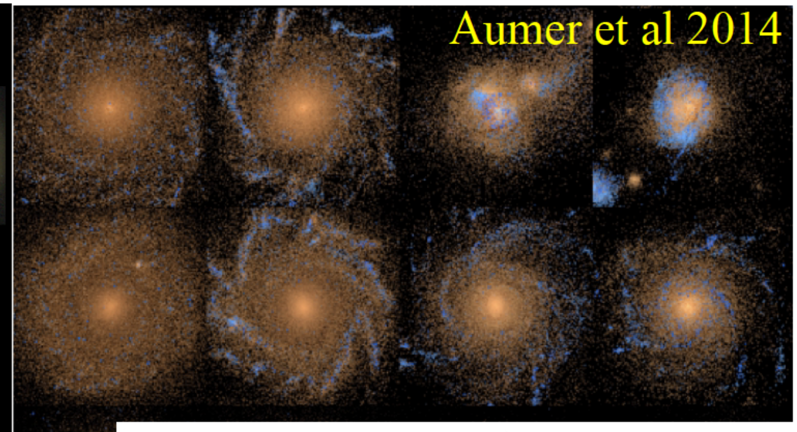
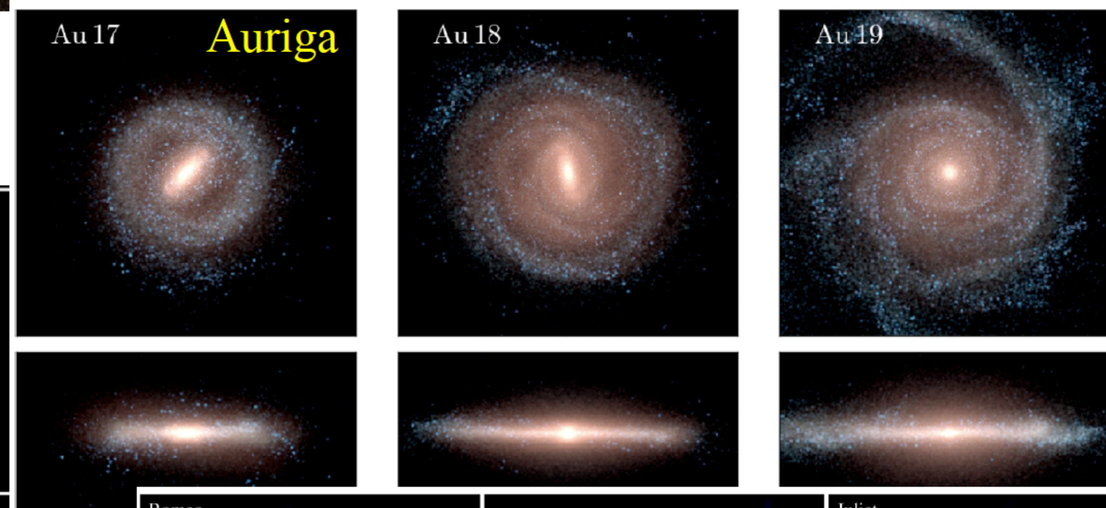


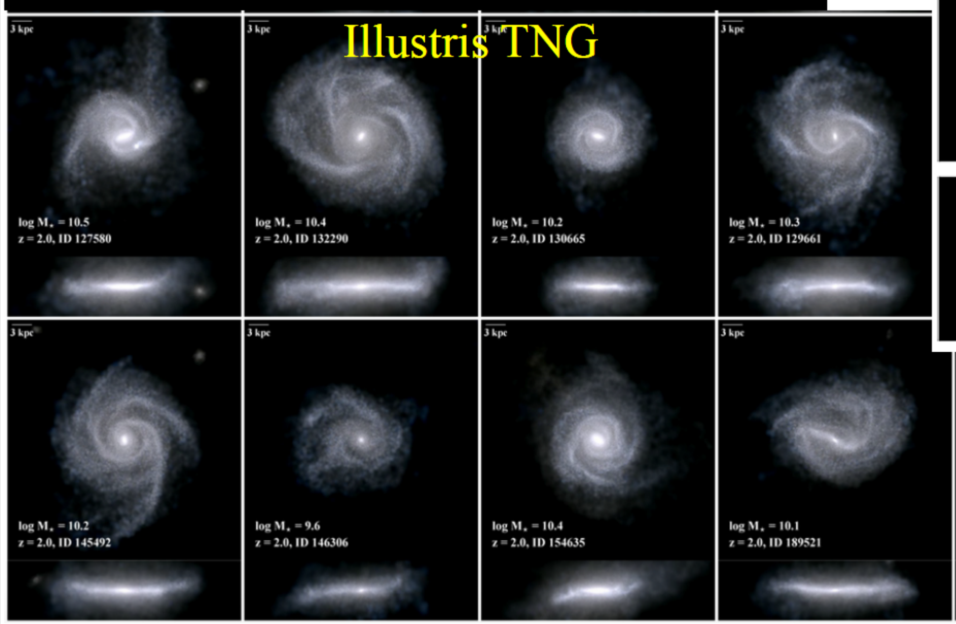
Parameter	Combined
$\Omega_b h^2$	0.02233 ± 0.00015
$\Omega_c h^2$	0.1198 ± 0.0012
$100\theta_{MC}$	1.04089 ± 0.00031
τ	0.0540 ± 0.0074
$\ln(10^{10} A_s)$	3.043 ± 0.014
n_s	0.9652 ± 0.0042

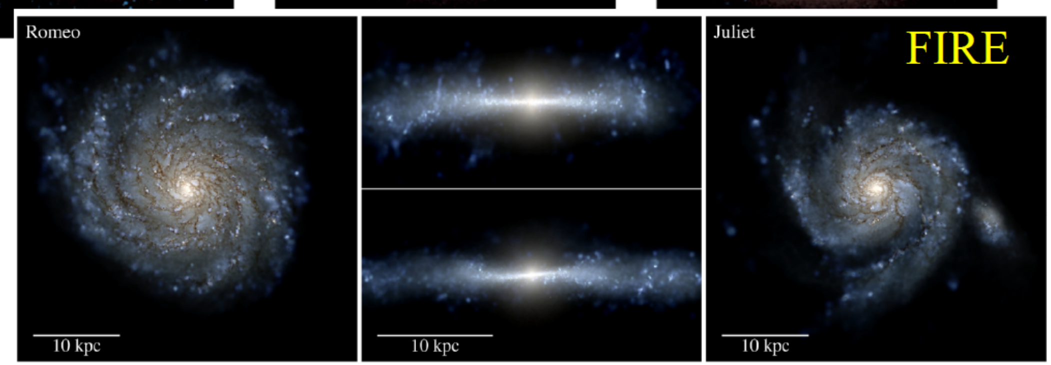
Simulating the structure of galaxies











Recent cosmological (magneto)hydrodynamical simulations reproduce many aspects of the observed internal structure of galaxies....

When is a galaxy formation theory good enough?

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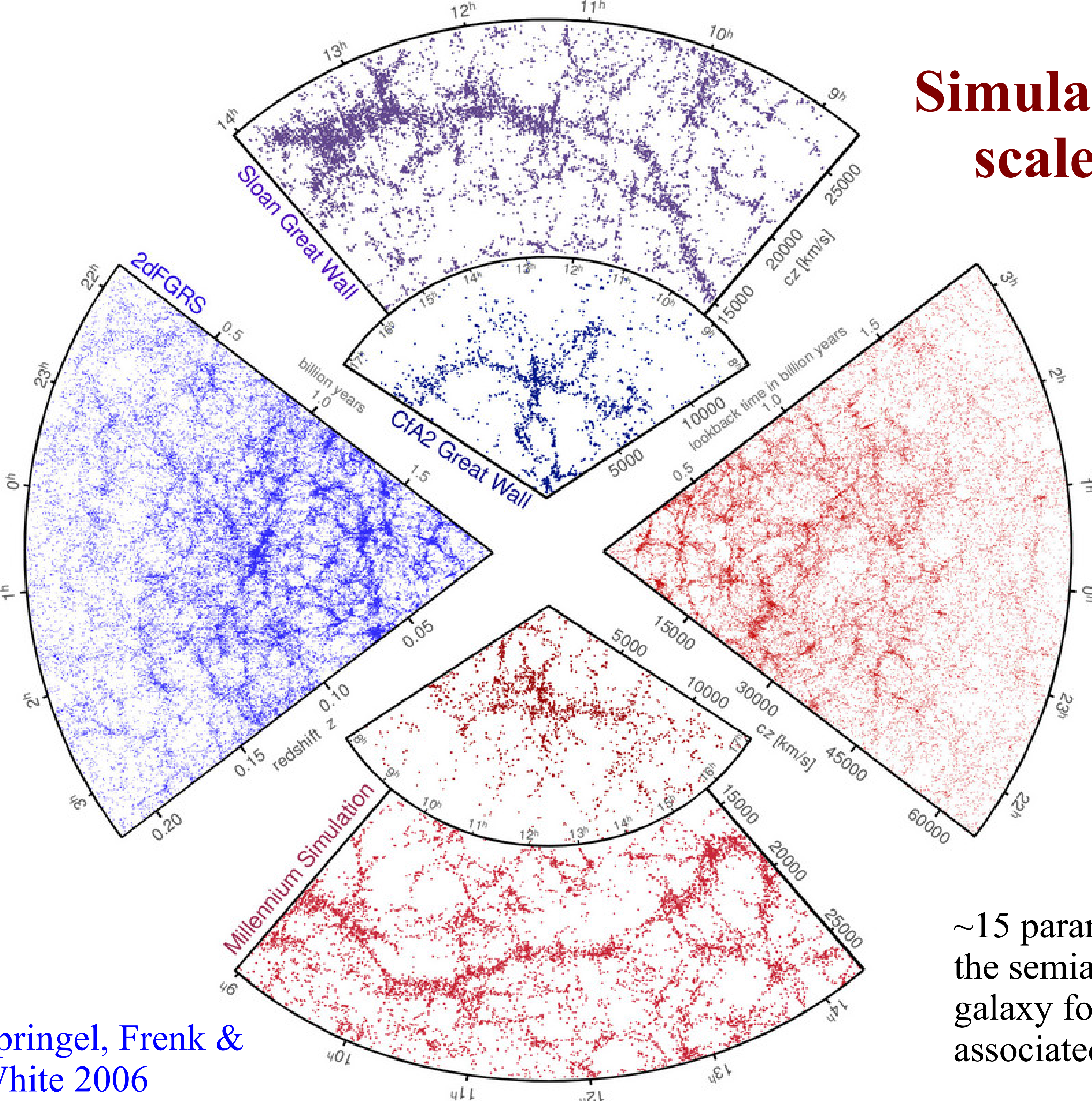
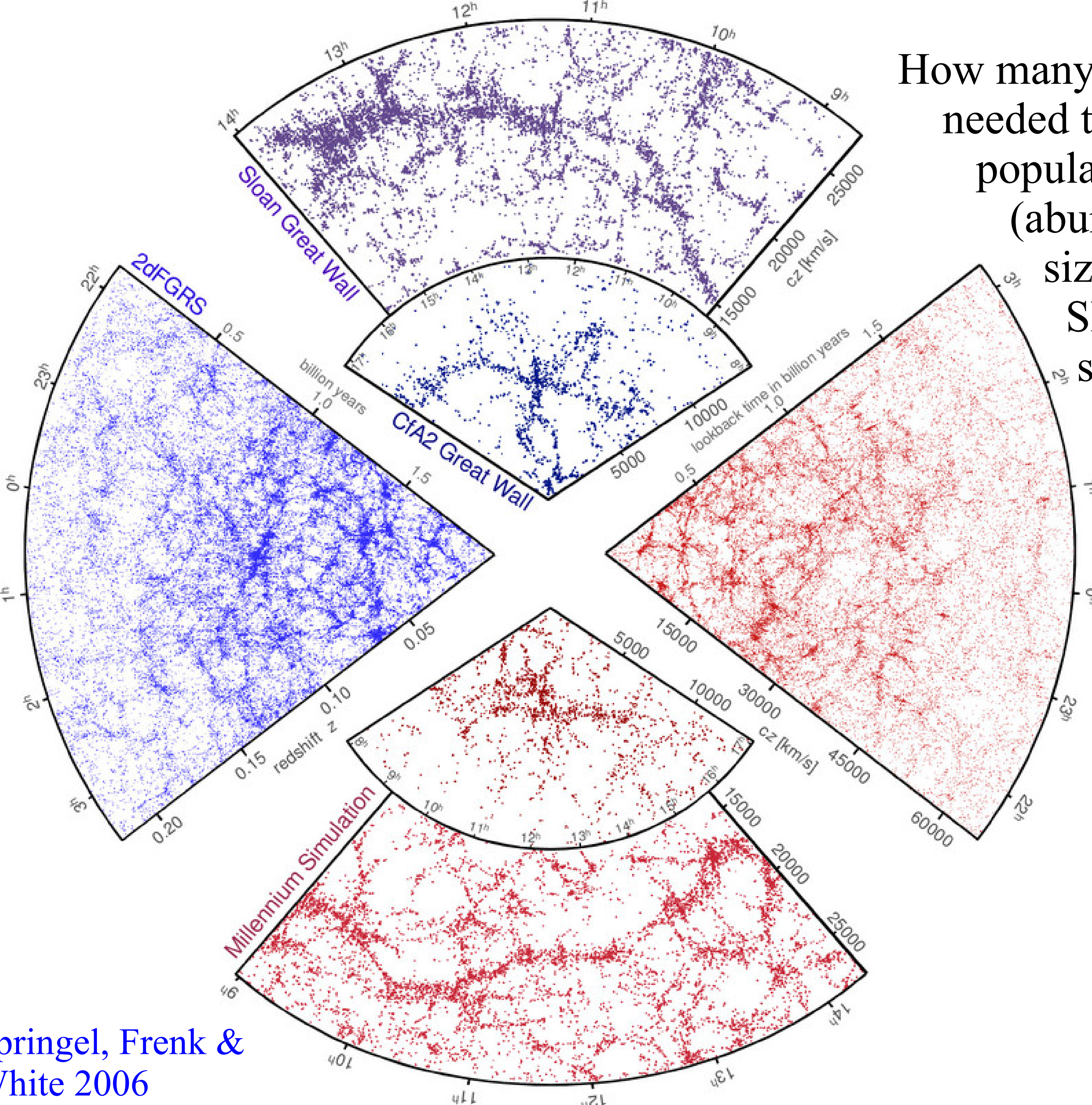
Galactic archaeologists focus on the detailed assembly history of nearby galaxies, particularly our own Milky Way.

Simulating large-scale structure



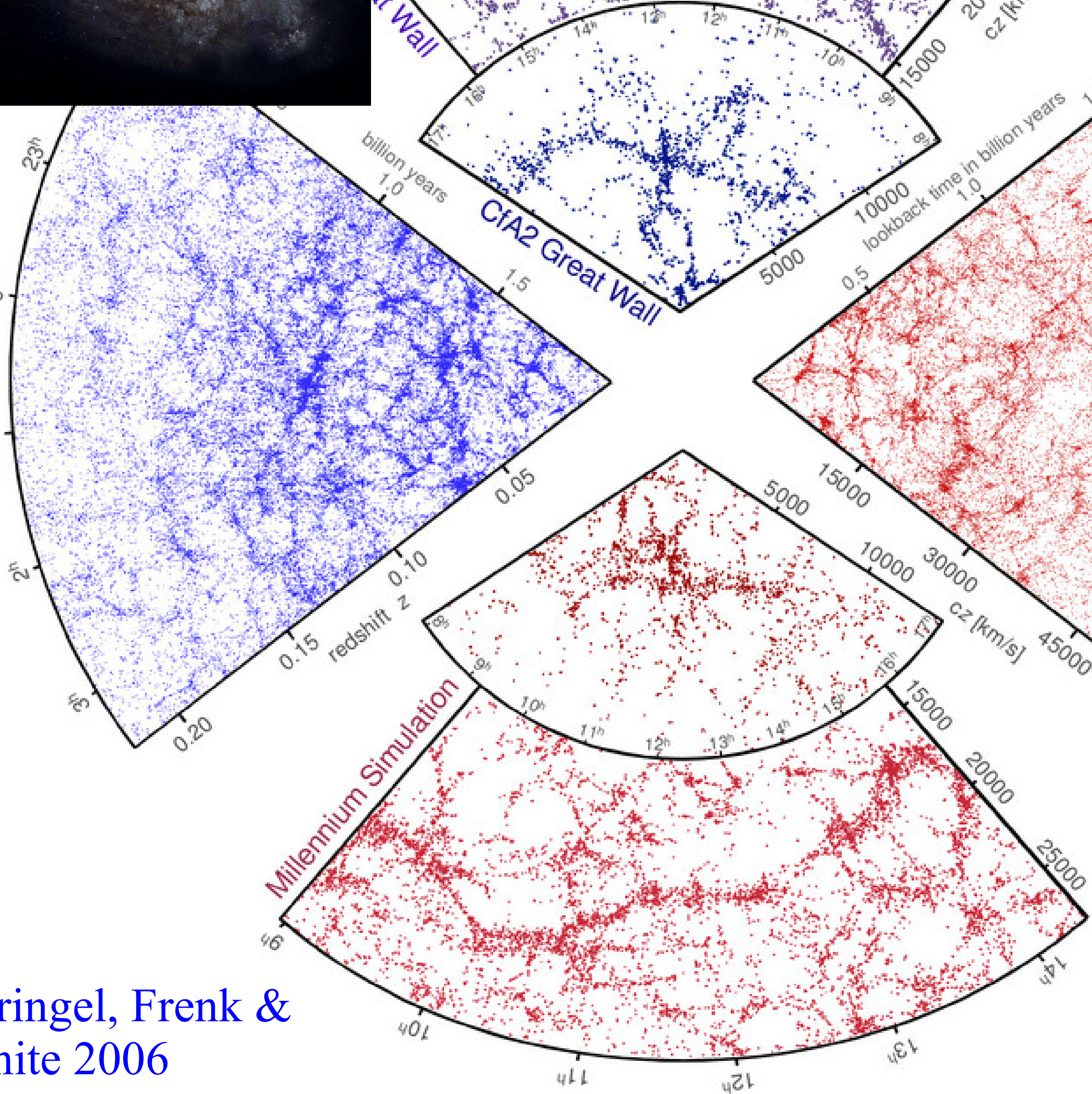
Springel, Frenk & White 2006

~15 parameters "tuned" in the semianalytic model for galaxy formation. None associated with clustering.



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

Springel, Frenk & White 2006



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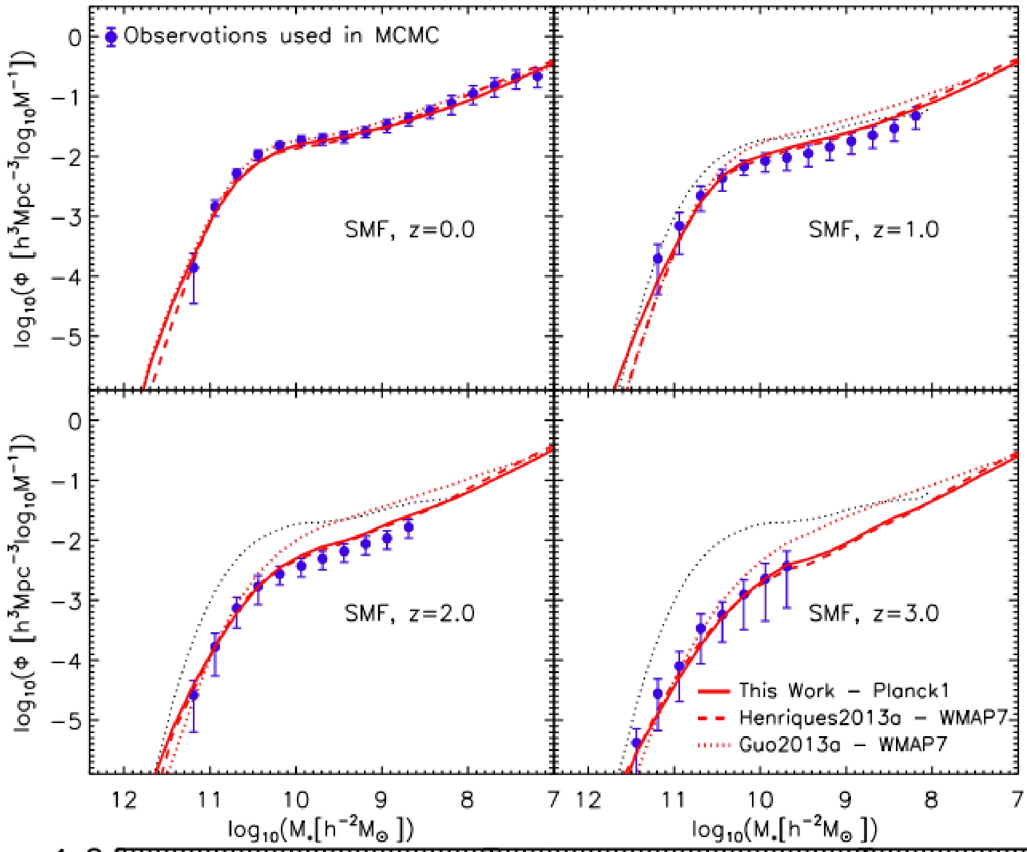
(abundance by mass, size, gas content, SFR, B/T, AGN; scaling relations; clustering; evolution...)

Do the parameters have useful *physical* content?

Springel, Frenk & White 2006

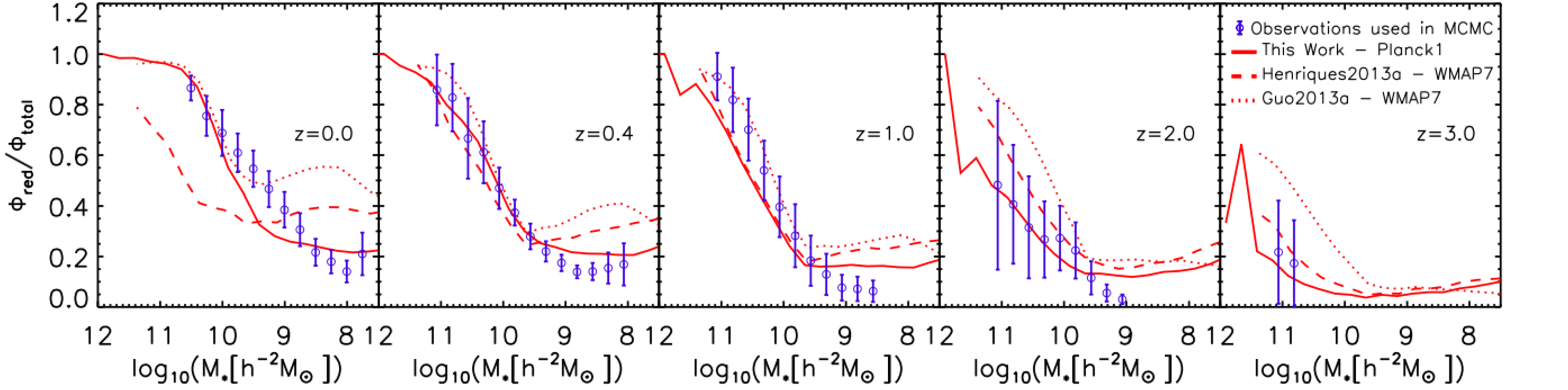
Calibrating galaxy formation models



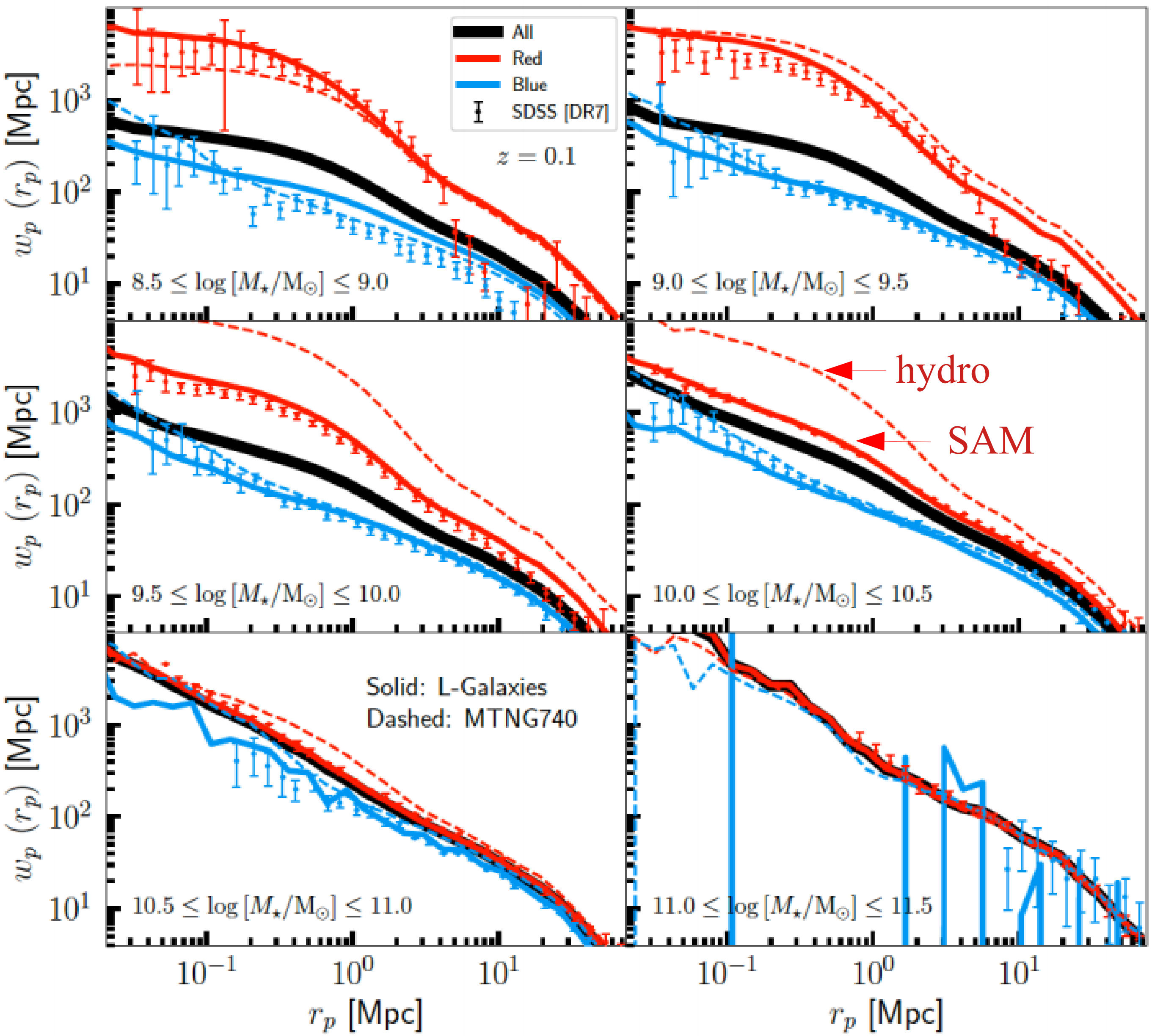
Henriques et al (2015)

17 galaxy formation parameters determined to moderate accuracy and without degeneracies by the observed mass function and passive fraction over $0 \leq z \leq 3$.

Galaxy clustering was not used and so provides a test.



Clustering and galaxy formation



Clustering of red and blue galaxies as a function of stellar mass in modern large-scale simulations compared to SDSS

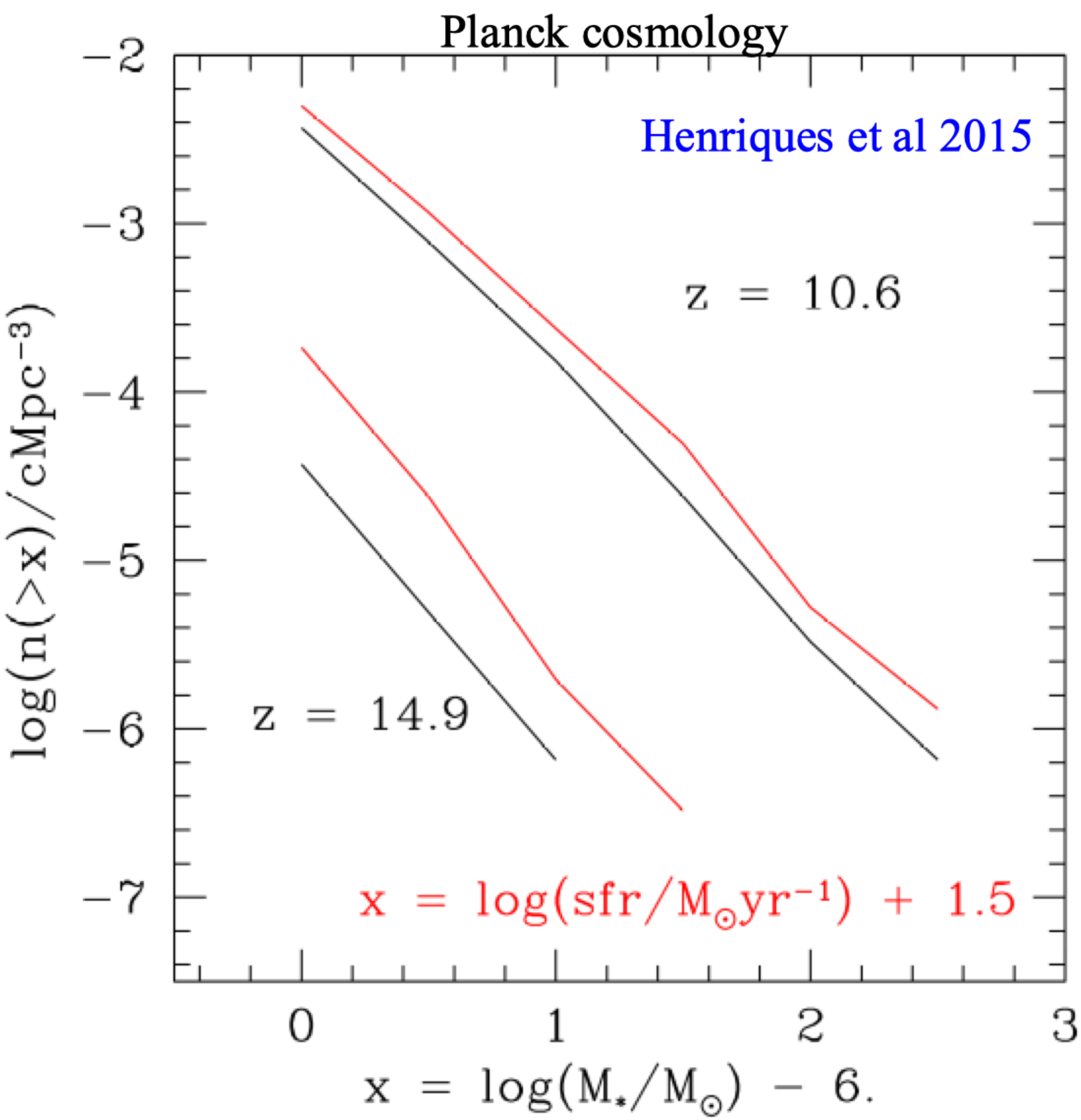
Both semianalytic and hydro simulations fit data without colour split

The SAM fits observation also when split by colour, but the hydro model fails at intermediate mass.

This reflects details of quenching by feedback in this particular hydro model

Bose et al 2022 – M-TNG hydro- and semianalytic simulations

High-z galaxy formation in 2015 simulations



At z = 10.6, 14.9, 24.6

M* ranges up to $10^{8.5}$, $10^{7.0}$, $10^{5.3}$ M⊙.

$\dot{M}$* ranges up to 10, 1.0, 0.02 M⊙/yr.

M*/(t . $\dot{M}$*) ~ 0.05, 0.05 , 0.05

M* /M_{ISM} ~ 0.15, 0.10 , 0.05

R* ~ 0.3, 0 .1, 0.05 kpc

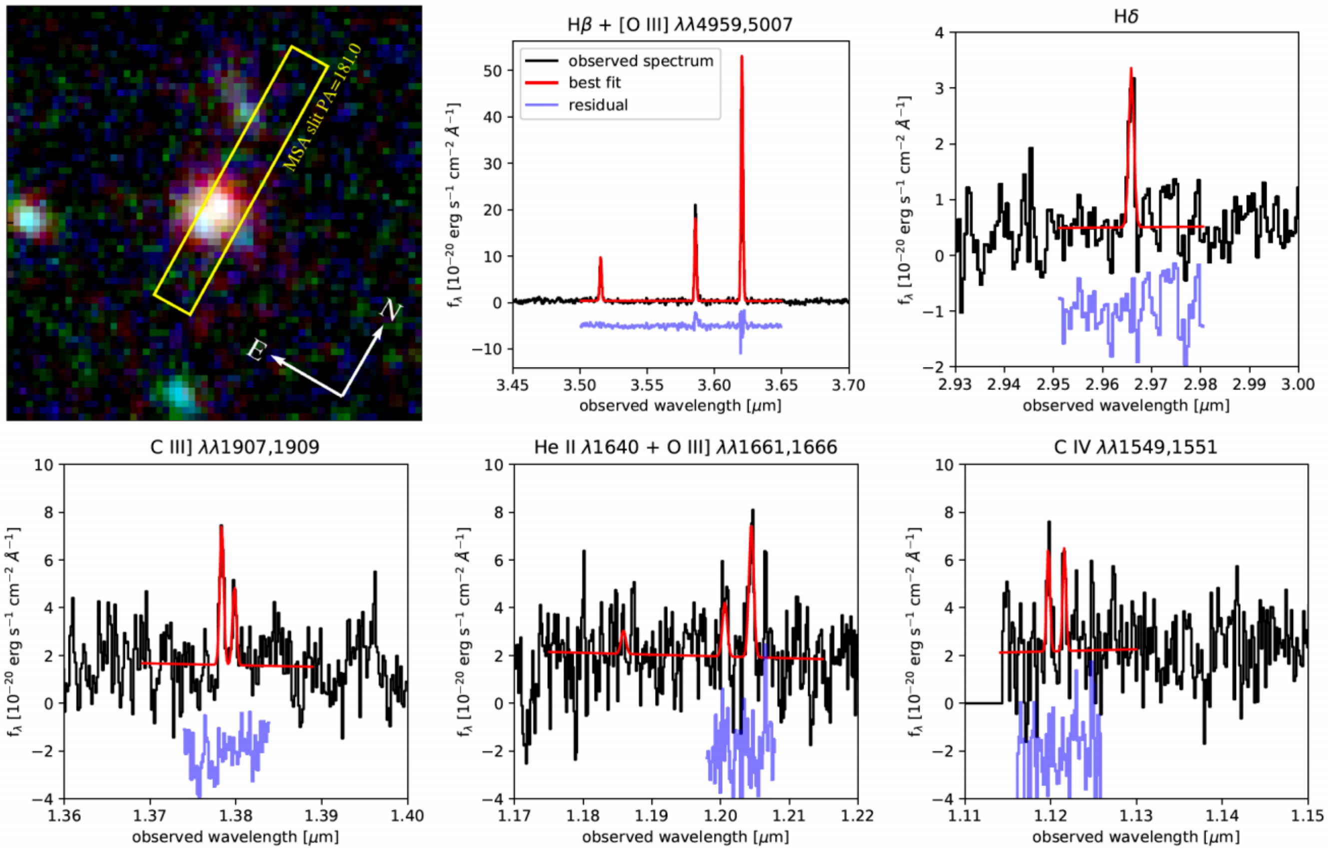
Z_{ISM} ~ 0.1y, 0.08y , 0.05y

V_{max} ~ 130, 100, 40 km/s

M_{halo} ~ $10^{10.3}$, $10^{9.7}$, $10^{8.5}$ M⊙

JWST spectroscopy and photometry of a young galaxy

Jones et al 2023



Property	Value
RA	00:14:24.607
Dec	−30:25:09.24
z	6.22895 ± 0.00007
μ	$2.59^{+0.04}_{-0.03}$
log M_* ($M_\odot$)[a]	$8.41^{+0.35}_{-0.19}$
SFR_{SED} ($M_\odot$ yr^{-1})[a]	$5.3^{+6.2}_{-1.1}$
$SFR_{H\beta}$ ($M_\odot$ yr^{-1})	10^{+14}_{-5}
Age_{par} (Myr)[a]	126^{+375}_{-70}
$Age_{non-par}$ (Myr)[b]	99^{+132}_{-63}

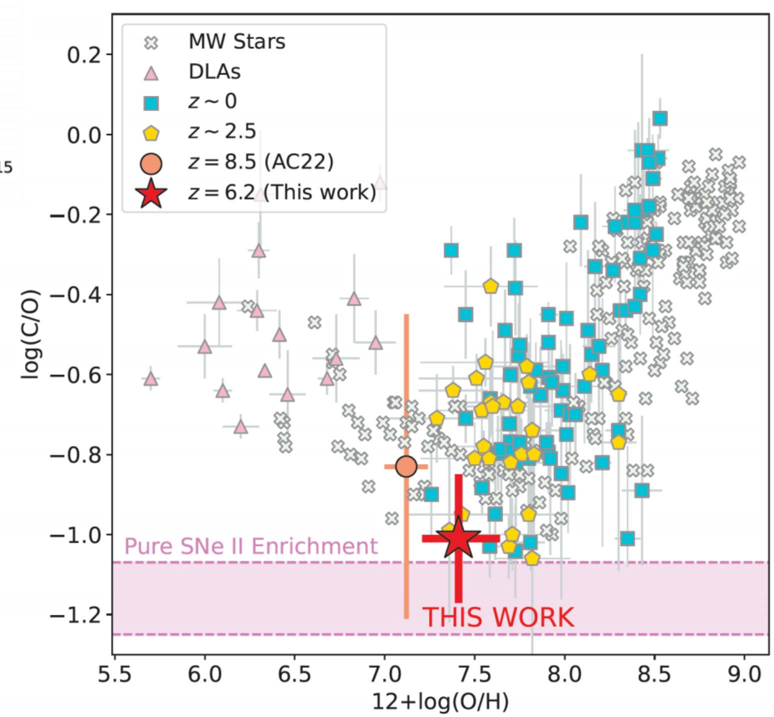
$z = 6.23$

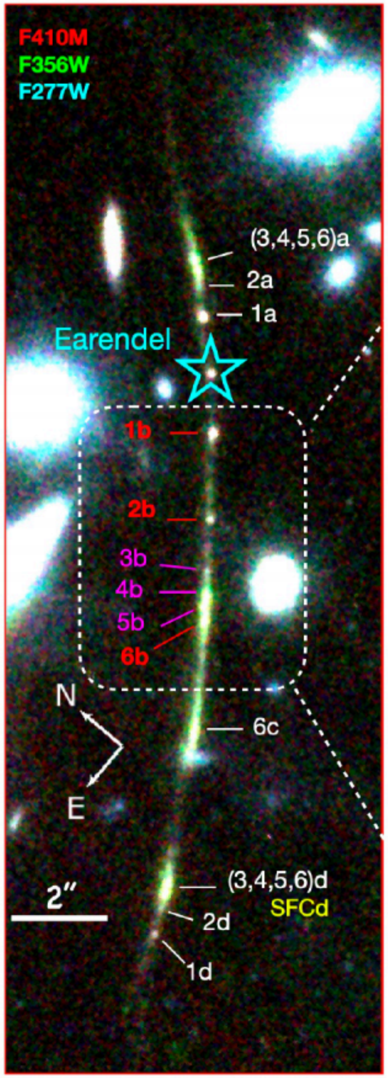
$M^* \sim 2.5 \times 10^8\ M_\odot$

$\dot{M}^* \sim 7\ M_\odot$ /yr

$M^* / \dot{M}^* t \sim 0.04$

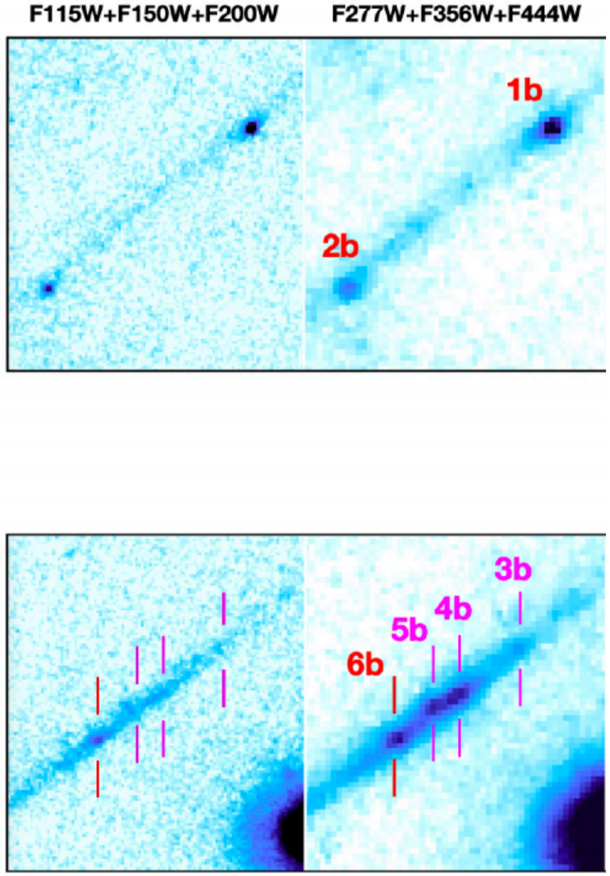
Pure SNII C/O abundance





Globular cluster formation in a z=6 galaxy

Vanzella et al 2022



Six young clusters marginally resolved

Masses and radii of massive GC's

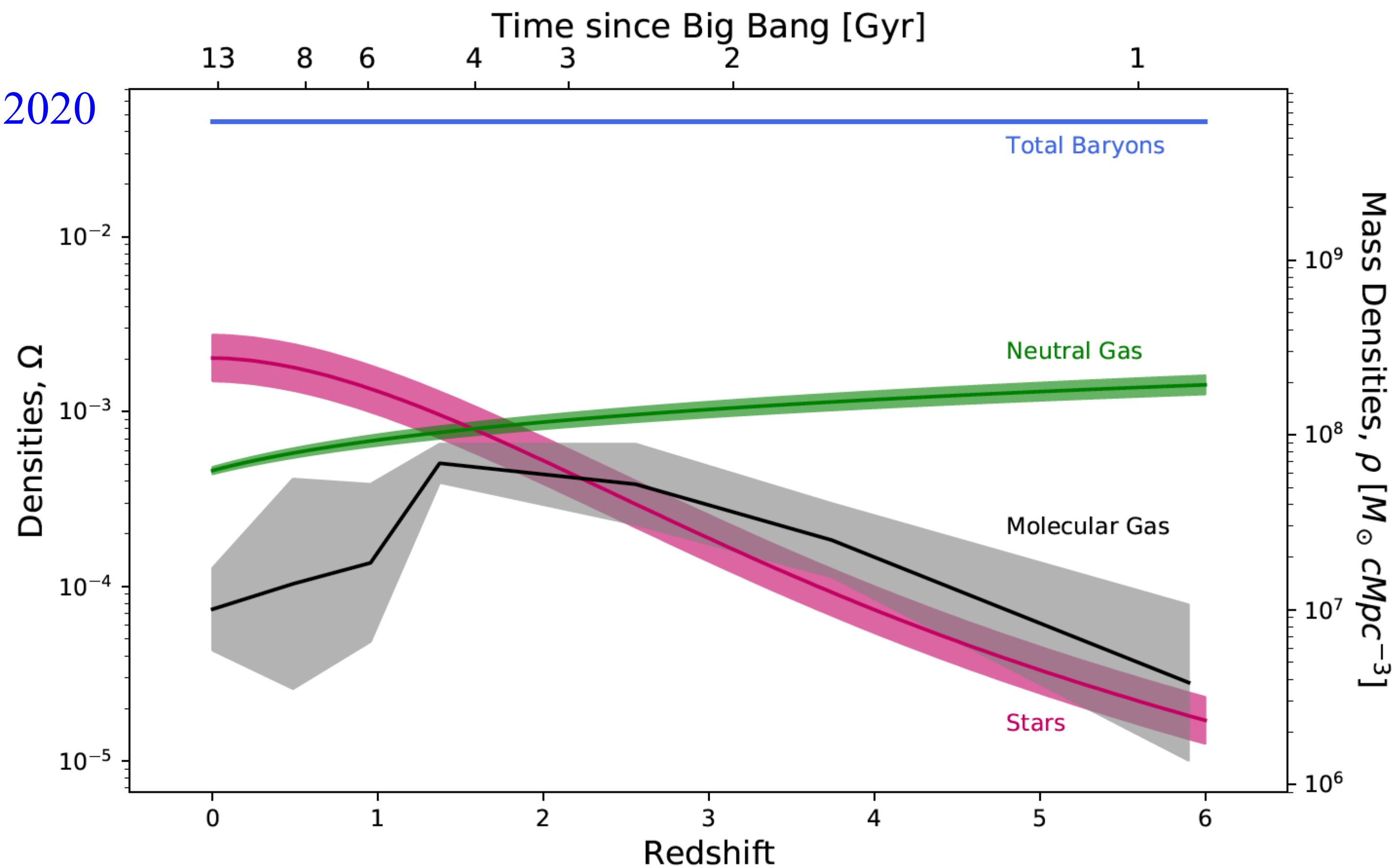
Ages of a few million years

Dynamical ages greater than unity

ID	Stellar Mass	Age	E(B-V)	R_{eff}	Π	Σ_{Mass}	μ_{tot}
	$[10^6\ M_\odot]$	[Myr]		[pc] [mas]		$[10^3\ M_\odot\ pc^{-2}]$	
(1)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1b	$7.1^{+1.6}_{-4.6}$	30^{+0}_{-22}	$0.00^{+0.10}_{-0.00}$	$1.4^{+0.3}_{-0.7}$ [15]	$314.1^{+297.6}_{-155.8}$	$311.3^{+445.5}_{-158.1}$	$\gtrsim 66$
2b	$3.9^{+0.2}_{-1.3}$	10^{+0}_{-1}	$0.10^{+0.00}_{-0.05}$	$6.3^{+1.1}_{-1.3}$ [30]	$8.3^{+3.1}_{-1.9}$	$8.7^{+4.8}_{-2.7}$	$\gtrsim 30$
3b⋆	$1.1^{+8.7}_{-0.5}$	4^{+36}_{-3}	$0.25^{+0.20}_{-0.20}$	$6.1^{+12.5}_{-3.6}$ [29]	$1.9^{+15.7}_{-0.9}$	$2.7^{+16.3}_{-2.3}$	$\gtrsim 30$
4b⋆	$10.1^{+11.0}_{-0.2}$	1^{+3}_{-0}	$0.15^{+0.15}_{--0.05}$	$24.8^{+62.6}_{-12.3}$ [117]	$0.2^{+0.4}_{-0.1}$	$1.5^{+2.1}_{-0.8}$	$\gtrsim 30$
5b⋆	$3.1^{+10.2}_{-2.0}$	6^{+74}_{-5}	$0.40^{+0.25}_{-0.30}$	$4.9^{+10.6}_{-1.7}$ [23]	$6.6^{+62.6}_{-3.3}$	$11.8^{+41.6}_{-9.1}$	$\gtrsim 30$
6b	$3.3^{+3.2}_{-0.8}$	4^{+2}_{-3}	$0.15^{+0.05}_{-0.10}$	$8.5^{+2.1}_{-3.0}$ [40]	$2.0^{+2.2}_{-1.1}$	$4.1^{+5.6}_{-2.4}$	$\gtrsim 30$

Baryon fraction in galaxies since z = 6

Péroux & Howk 2020



- Fraction of baryons in galaxies has grown from ~2% (z = 6) to ~5% (z = 0)
- Galaxies are mostly cold gas at z > 1; M_*/M_{ISM} ~ 1% at z = 6
- Cold ISM gas is mostly HI, strongly so at z < 1 and z > 3.
- Molecular gas tracks stars at z > 3

Conclusions?

- Galaxy formation is understood in considerable detail in the ΛCDM paradigm, and has been for some time.
- Nevertheless, the process is sufficiently complex that many quantitative aspects of interest cannot be reliably computed *a priori*.
- As a result, suggested "tensions" between observation and the standard paradigm are generally not robust to uncertainties in astrophysics.
- The great majority of the mass in galaxies at high z is in the cold ISM and is in the form of HI. Currently, it is not observed directly.
  → cross-correlate HI line-intensity maps at high z with other surveys?
- JWST is now able to see directly the formation of globular clusters and to measure Z for the star-forming gas in galaxies at $z > 6$.