DM clustering 1: Stellar vs AGN feedback

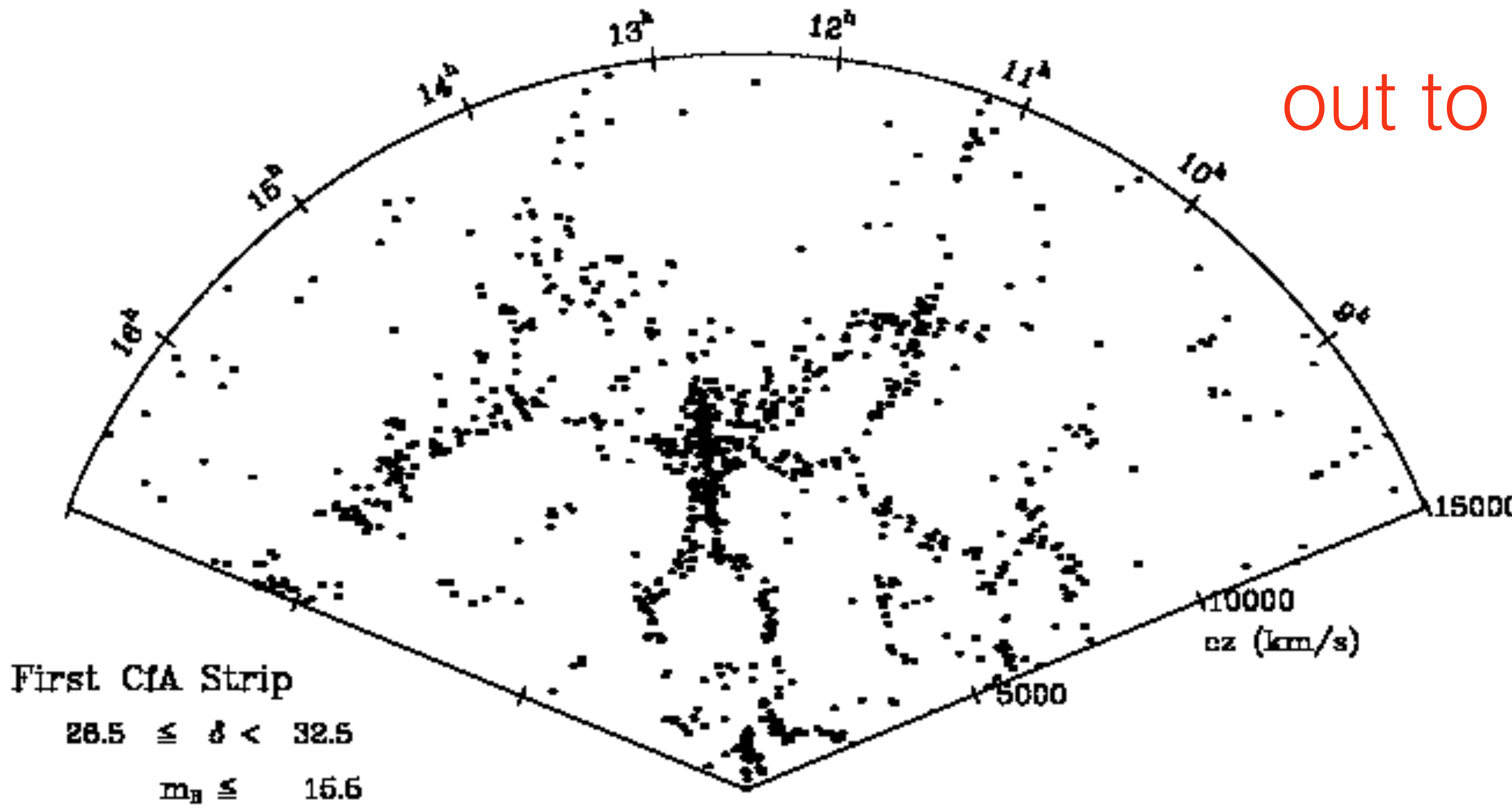
Galaxy clustering and fundamental physics

Tom Theuns
ICC, Durham

Contents:

- Galaxy redshift surveys
- Characterising clustering
- The Eagle hydrodynamical simulations
- Impact of galaxy formation on clustering

Galaxy clustering anno 1985: the CfA survey



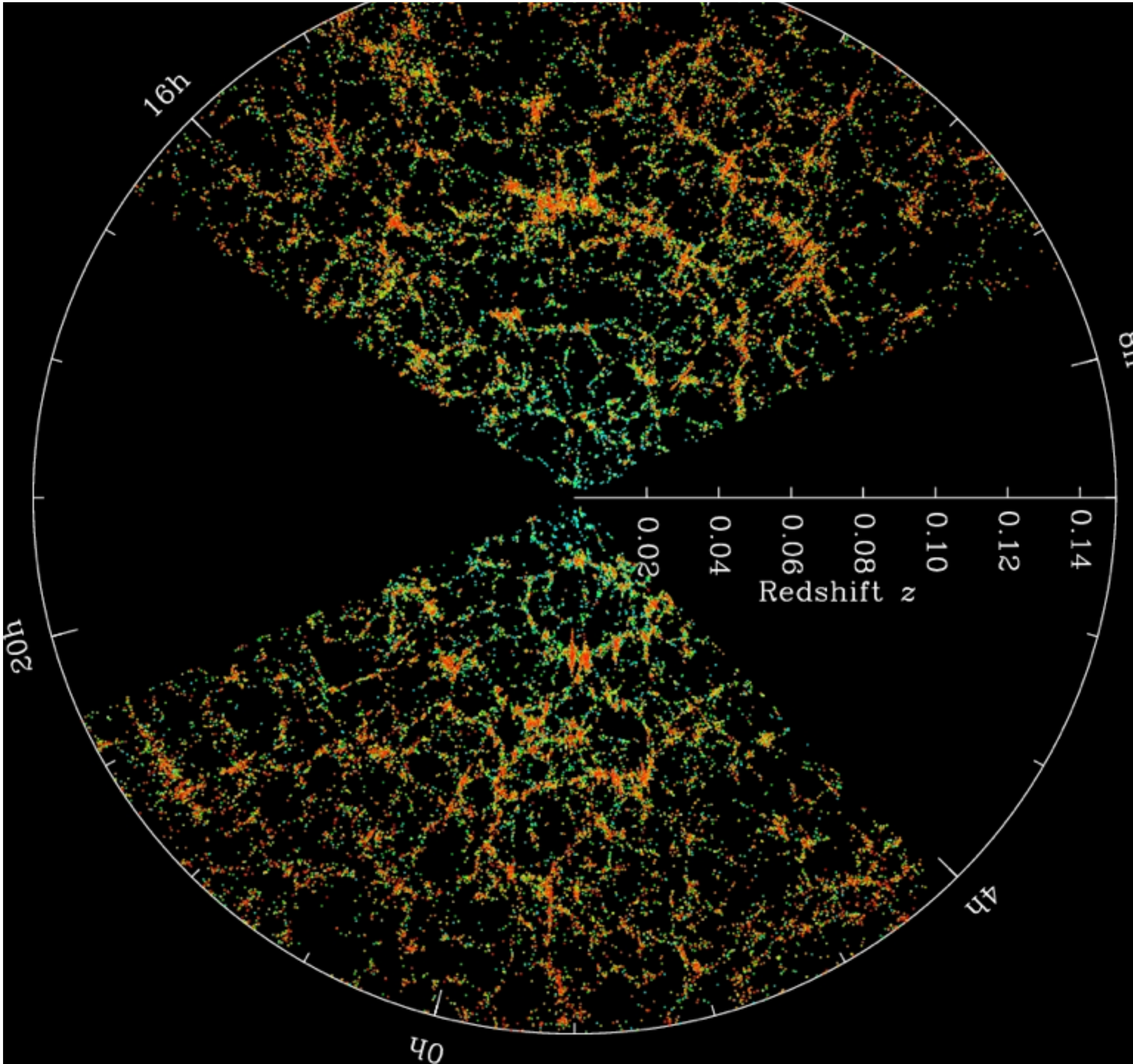
out to z=0.06

De Lapparant+'85

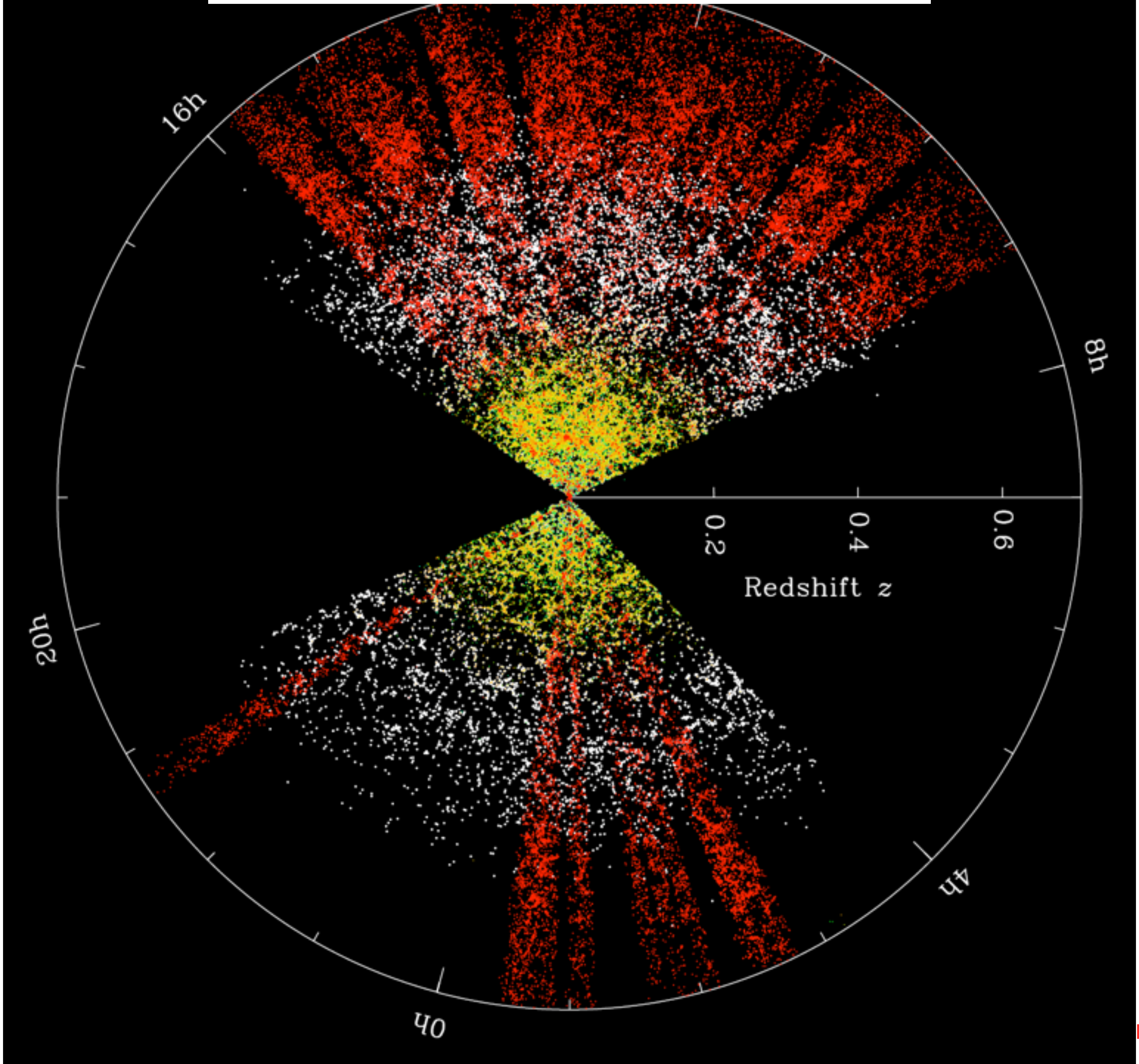
Copyright SAO 1998

Huchra, Davis, Latham and Tonry, 1983, ApJS 52, 89

Sloan Digital Sky Survey (SDSS) Map of galaxies



SDSS + Boss Map of galaxies



Measuring galaxy clustering from redshift surveys

What is clustering? And what can we learn from it?

2-point correlation function: excess of pairs over a random distribution:

$$\xi(r) = \frac{1}{\langle n \rangle}\frac{\mathrm{d}P}{\mathrm{d}V} - 1$$

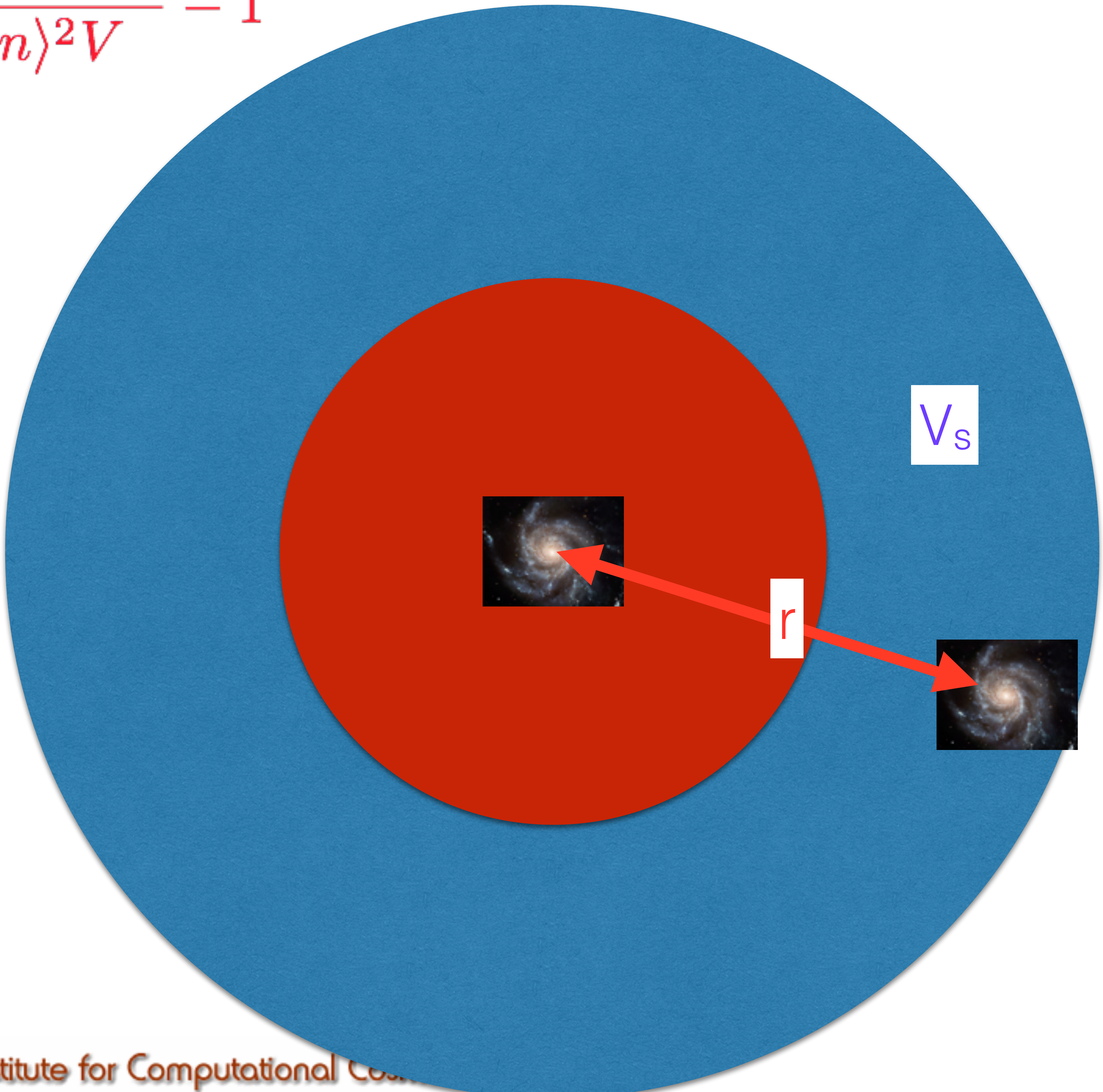
2-point correlation function is Fourier transform of power spectrum:

$$\begin{aligned} < \delta(\mathbf{r})\, \delta(\mathbf{r}+\boldsymbol{\Delta}) > &= \xi(\boldsymbol{\Delta}) \\ &\propto \int P(k)\, \exp(-i\mathbf{k}\cdot\boldsymbol{\Delta})\, d\mathbf{k} \end{aligned}$$

Growth of structure. In **linear** theory:

$$\delta(k,t) \propto a \propto t^{2/3} \quad \text{in EDS Universe}$$

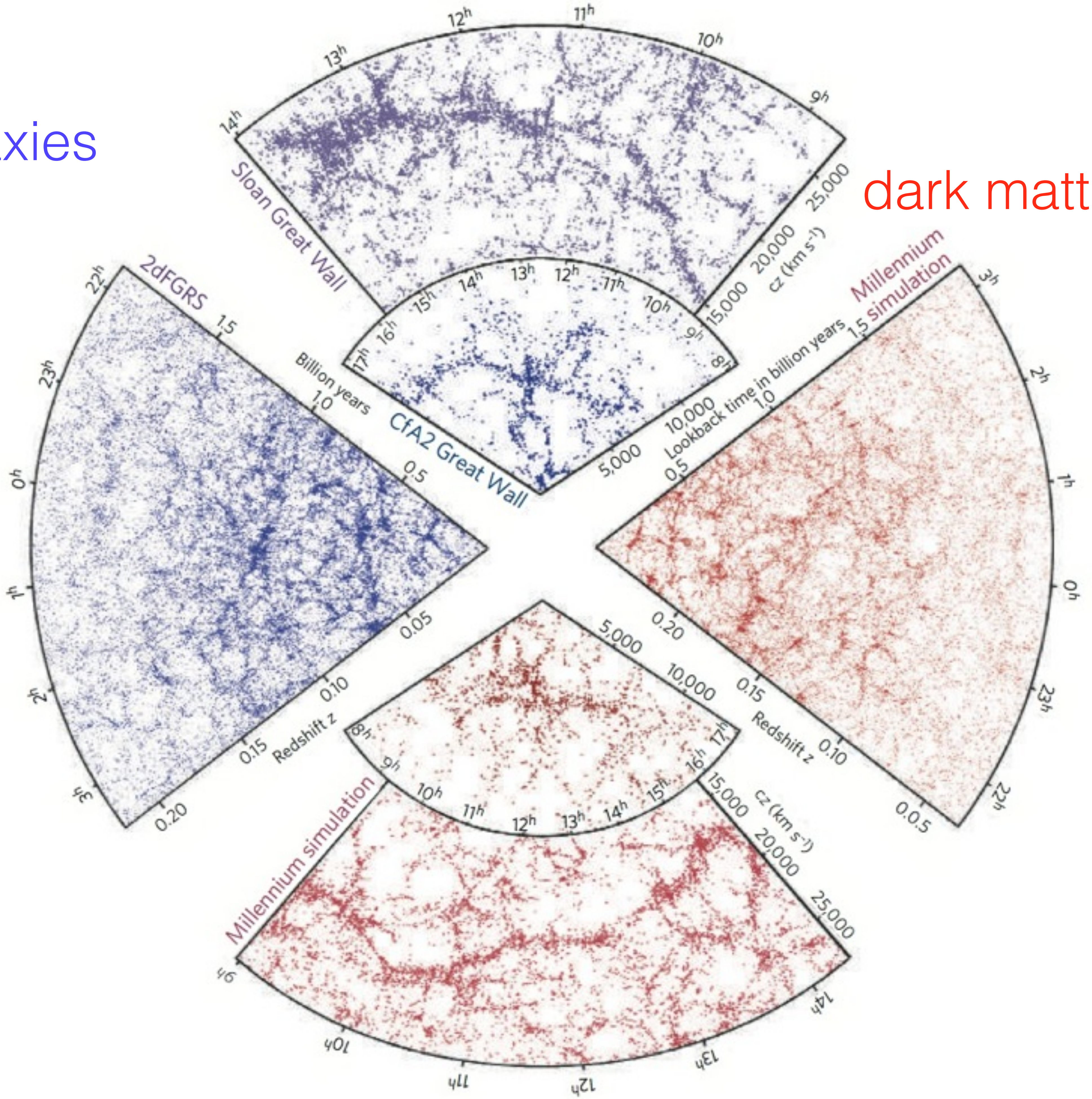
$$\xi(r) = \frac{N_s(r)/V_s}{\langle n \rangle^2 V} - 1$$



Springel +05

galaxies

dark matter haloes



Springel+08

(Re)Overviews:

- Cole et al., 2005, MNRAS, 362, 505
- Eisenstein et al., 2005, ApJ, 633, 560
- Blake et al, 2012, MNRAS, 425, 505

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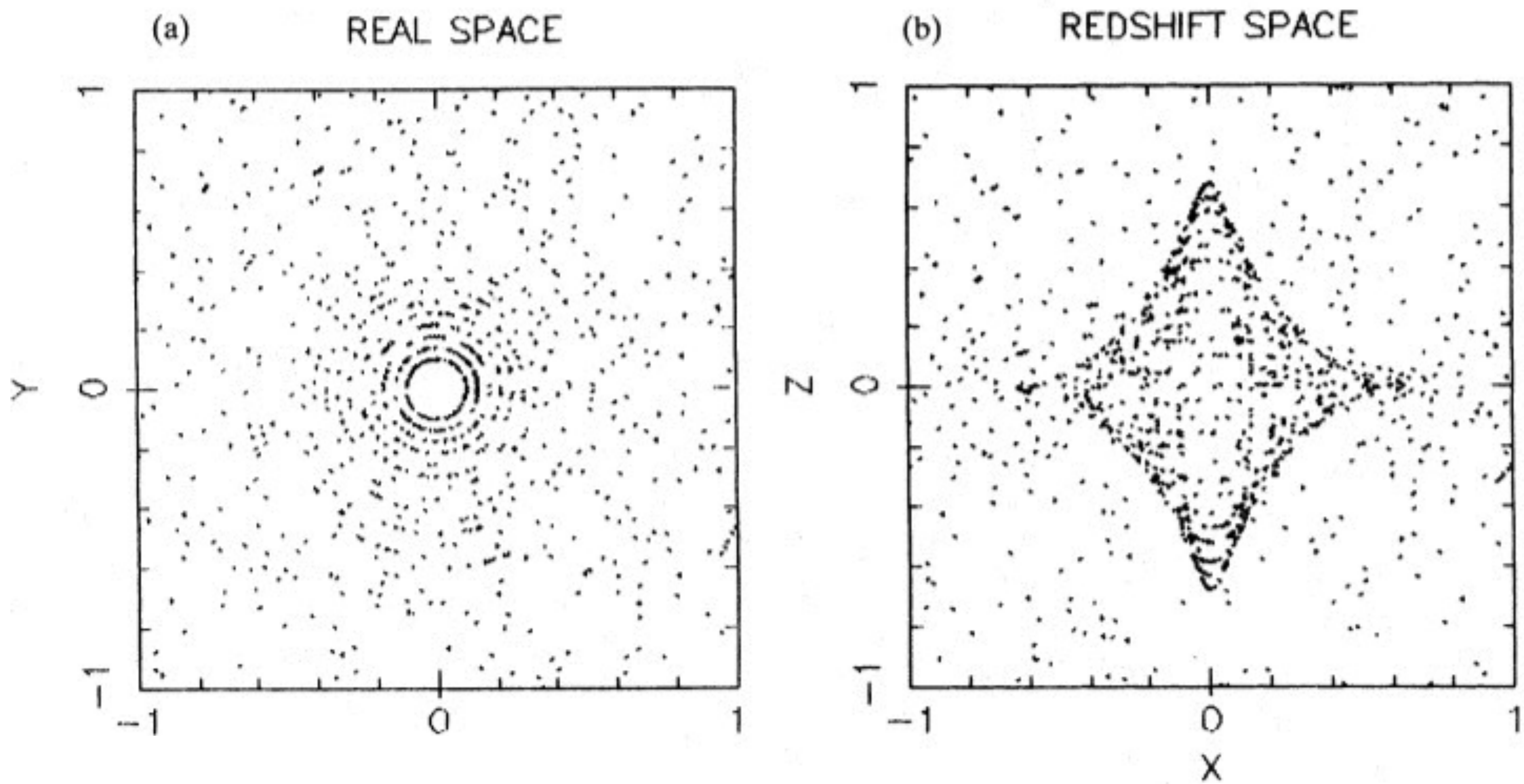
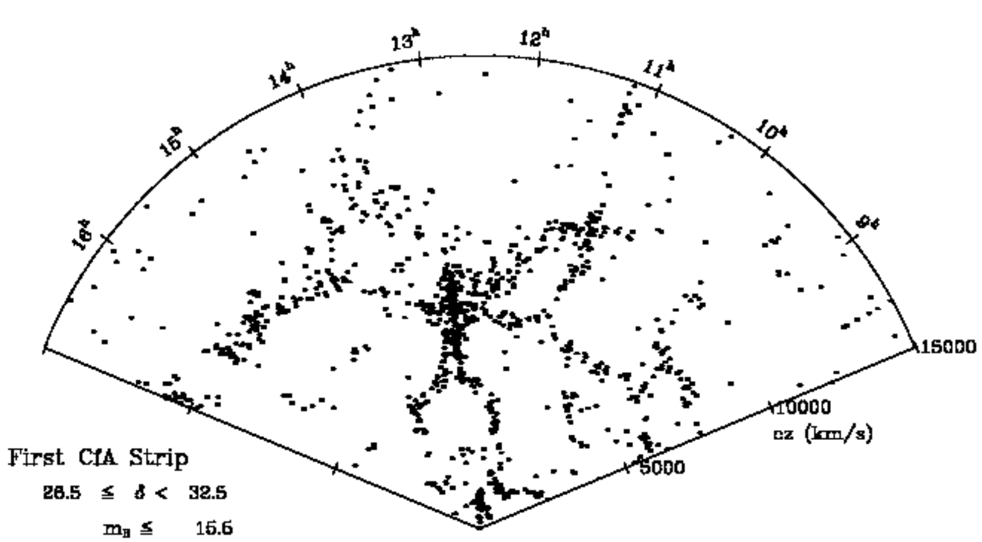
- linear growth also reflects initial conditions

Clustering in real space and in redshift space

Kaiser '87





Measuring galaxy clustering with redshift surveys

2-point correlation function in real space

$$\xi(r) = \frac{1}{\langle n \rangle} \frac{\mathrm{d}P}{\mathrm{d}V} - 1$$

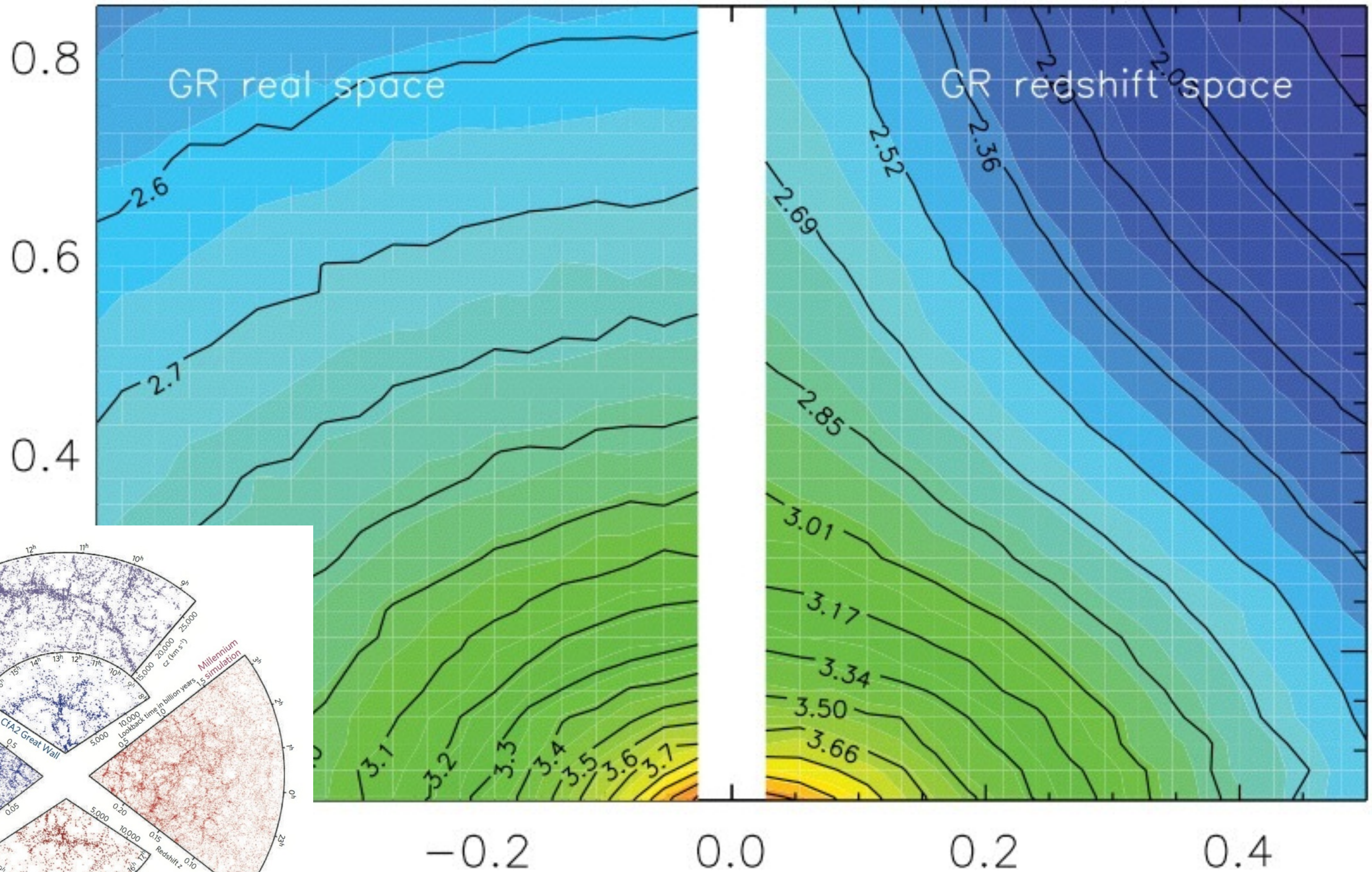
2-point correlation function in redshift space

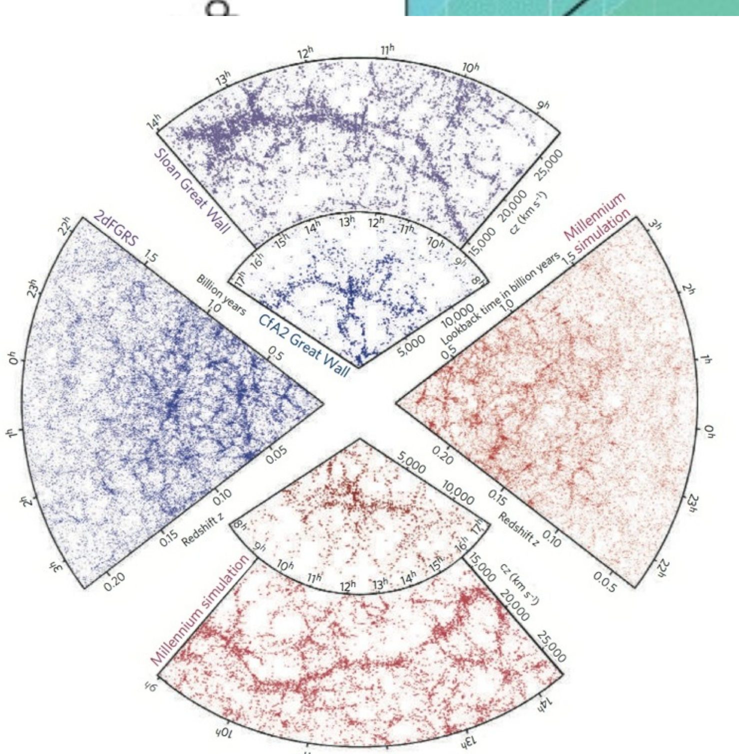
$$\begin{aligned} r^2 &= r_p^2 + \pi^2 \\ \xi(r) &= \xi(r_p, \pi) \end{aligned}$$

projected correlation function in real space

$$w_p(r_p) = \int \xi(r_p, \pi)\, d\pi$$

2D power spectrum



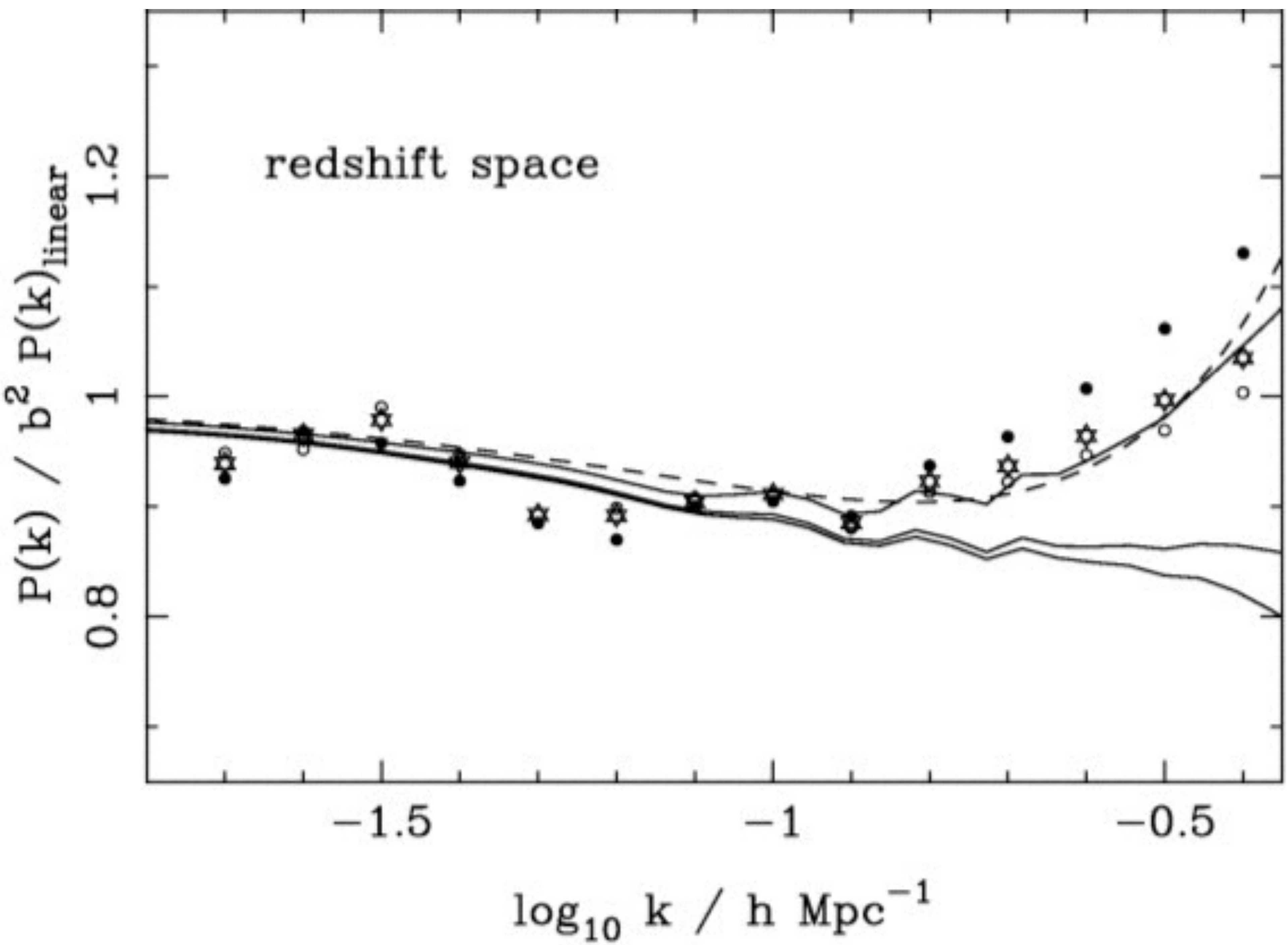


Jennings+12

2dF galaxy power spectrum

The 2dF Galaxy Redshift Survey: power-spectrum analysis of the final data set and cosmological implications

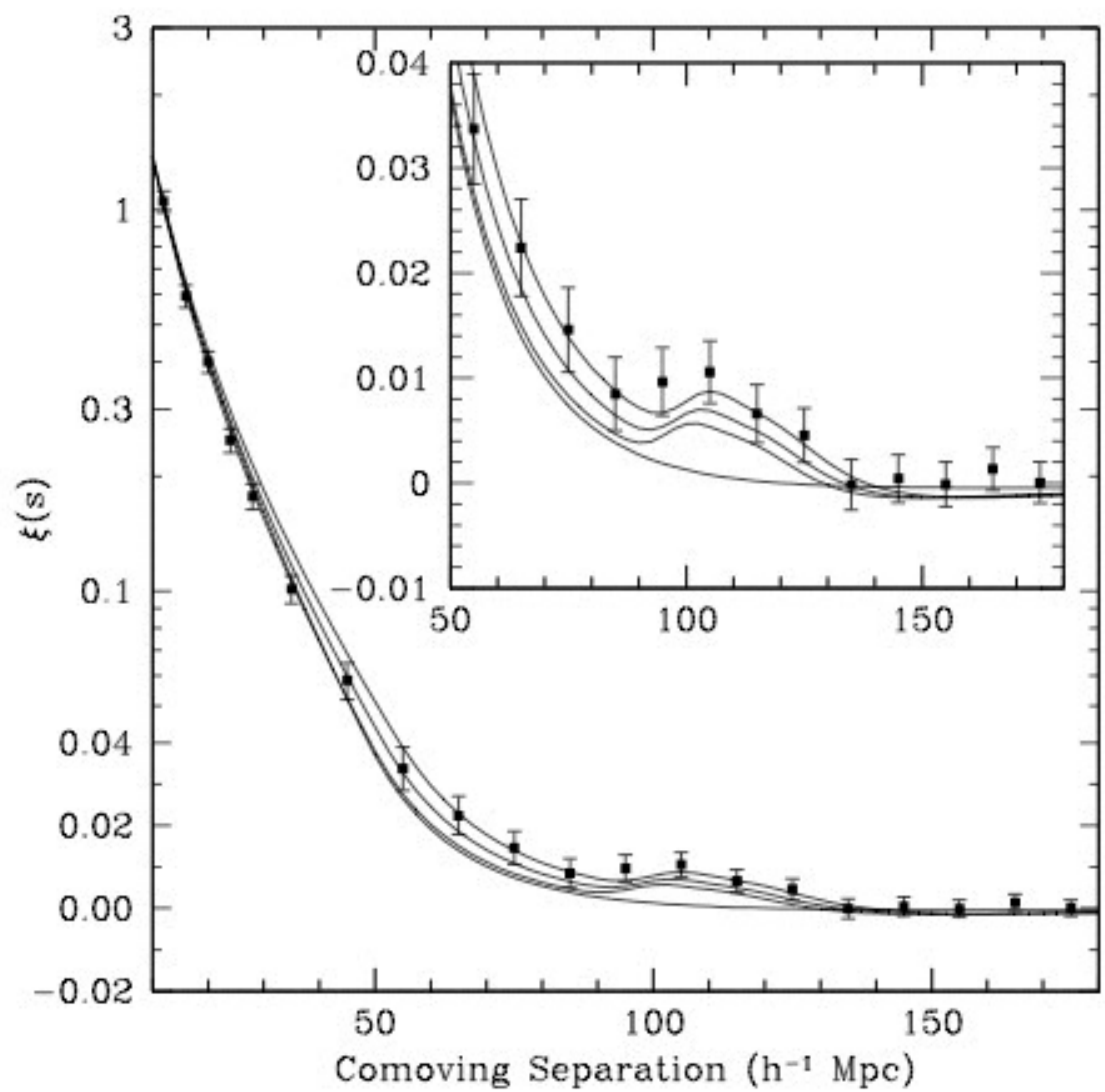
Shaun Cole,[1★] Will J. Percival,[2] John A. Peacock,[2] Peder Norberg,[3] Carlton M. Baugh,[1]



Cole +05

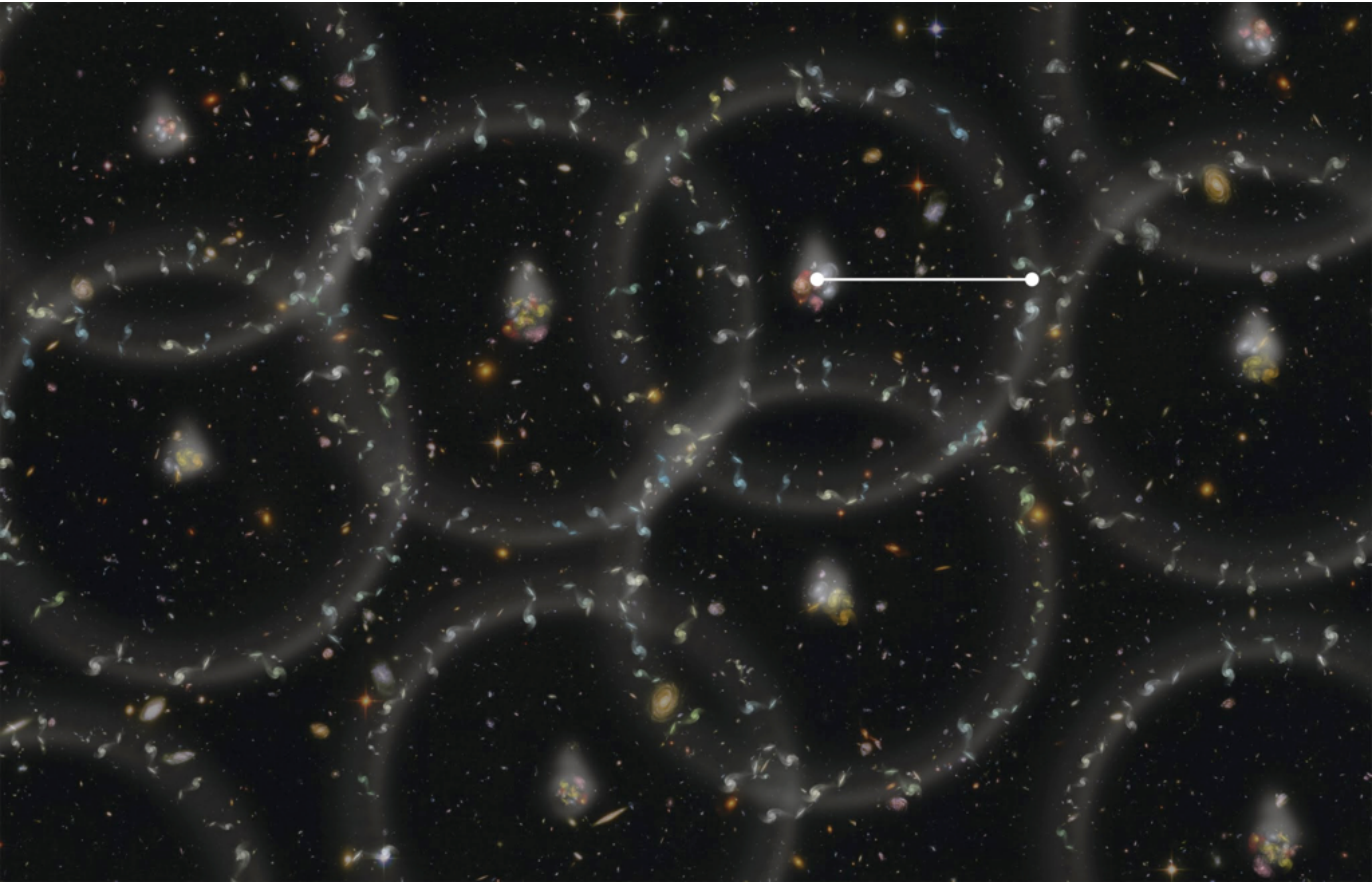
DETECTION OF THE BARYON ACOUSTIC PEAK IN THE LARGE-SCALE CORRELATION FUNCTION OF SDSS LUMINOUS RED GALAXIES

DANIEL J. EISENSTEIN,[1,2] IDIT ZEHAVI,[1] DAVID W. HOGG,[3] ROMAN SCOCCIMARRO,[3] MICHAEL R. BLANTON,[3] ROBERT C. NICHOL,[4]



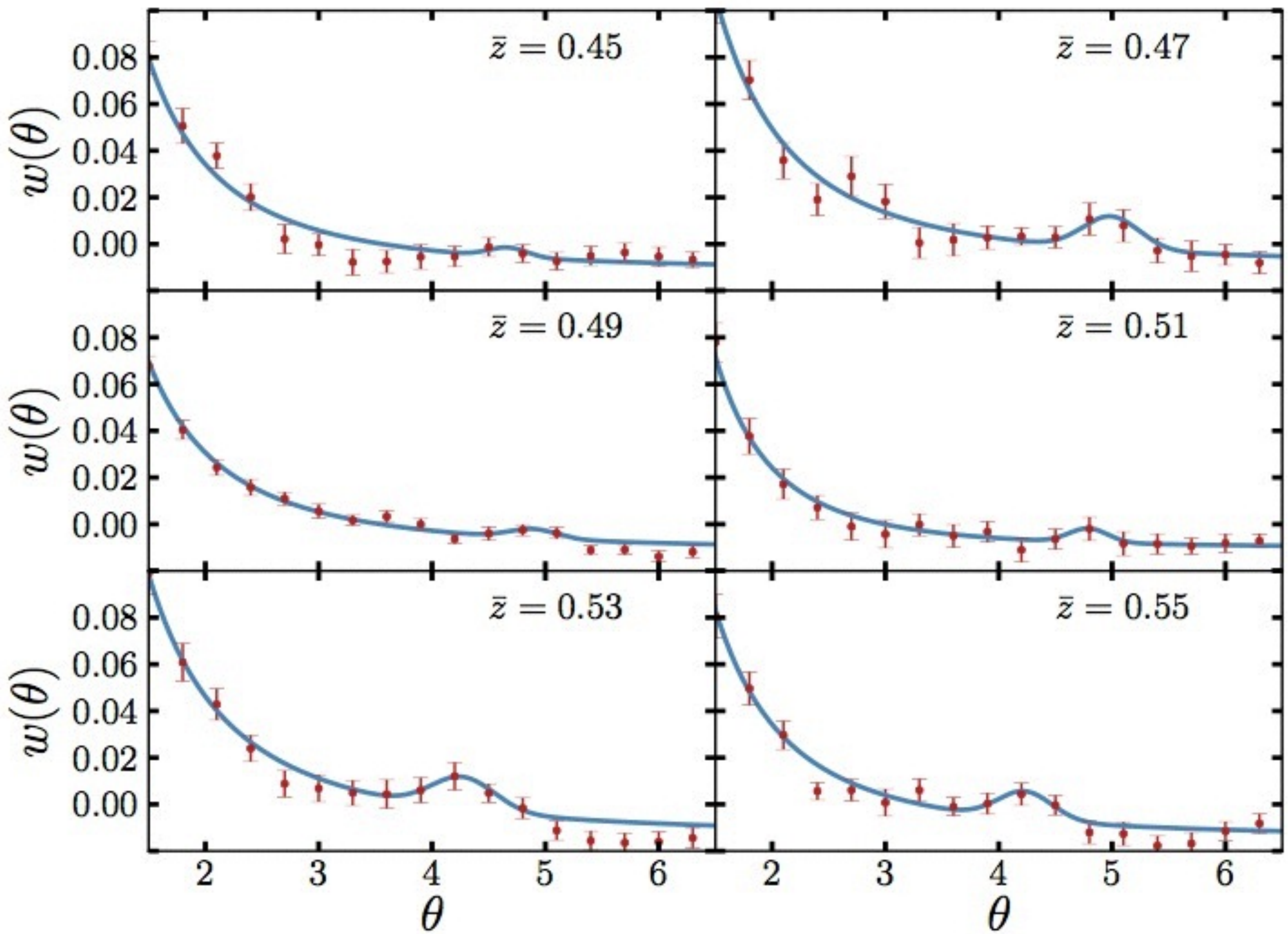
Eisenstein+05

Origin of baryon acoustic scale in galaxy clustering

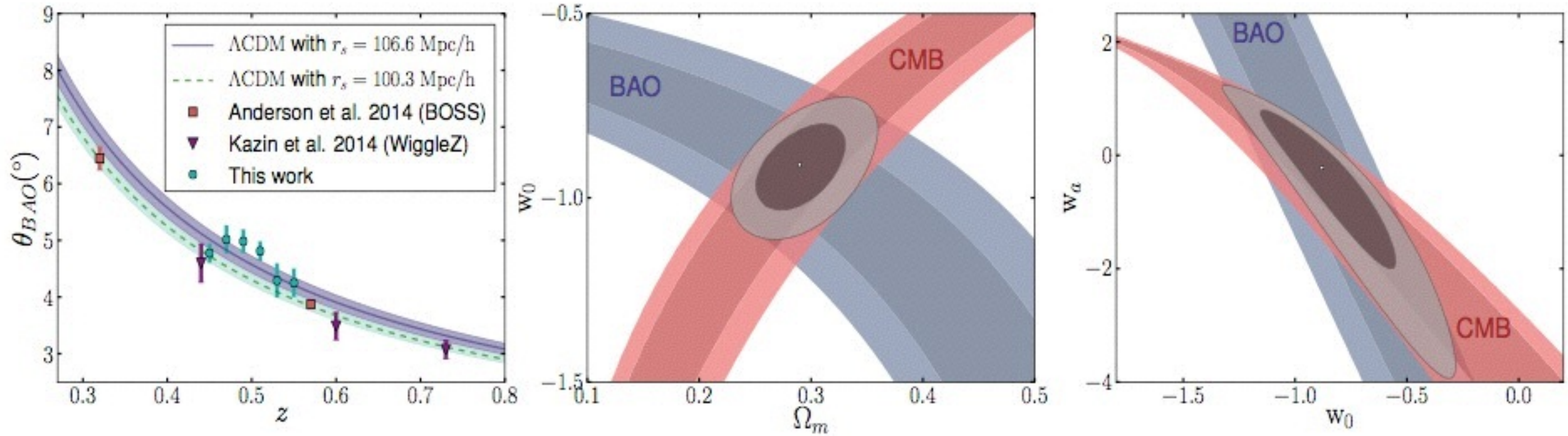


Baryon Acoustic Oscillations from the SDSS DR10 galaxies angular correlation function

G. C. Carvalho,* A. Bernui,† M. Benetti,‡ J. C. Carvalho,§ and J. S. Alcaniz¶



Carvalho+15



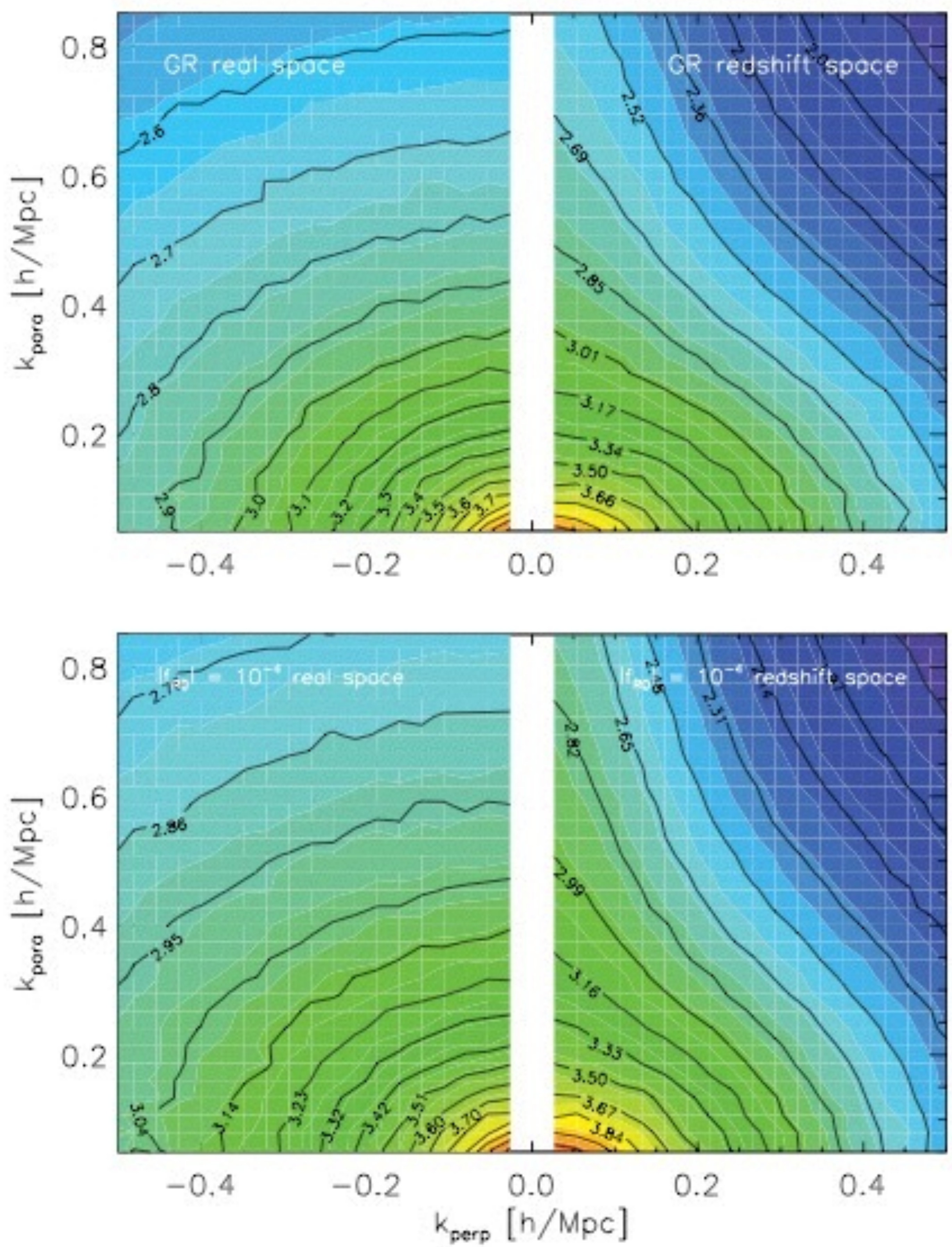
ΛCDM with $r_s = 106.6$ Mpc/h
ΛCDM with $r_s = 100.3$ Mpc/h
Anderson et al. 2014 (BOSS)
Kazin et al. 2014 (WiggleZ)
This work
$\theta_{BAO}(°)$
z
BAO
CMB
w_0
Ω_m
BAO
CMB
w_a
w_0

Carvalho+15

2d correlation function in f(R) gravity

GR

f(R)



Institute fo

Jennings+12

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What is clustering? And what can we learn from it?

- clustering is deviation of mass distribution from random
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- linear growth also reflects initial conditions

Problems:

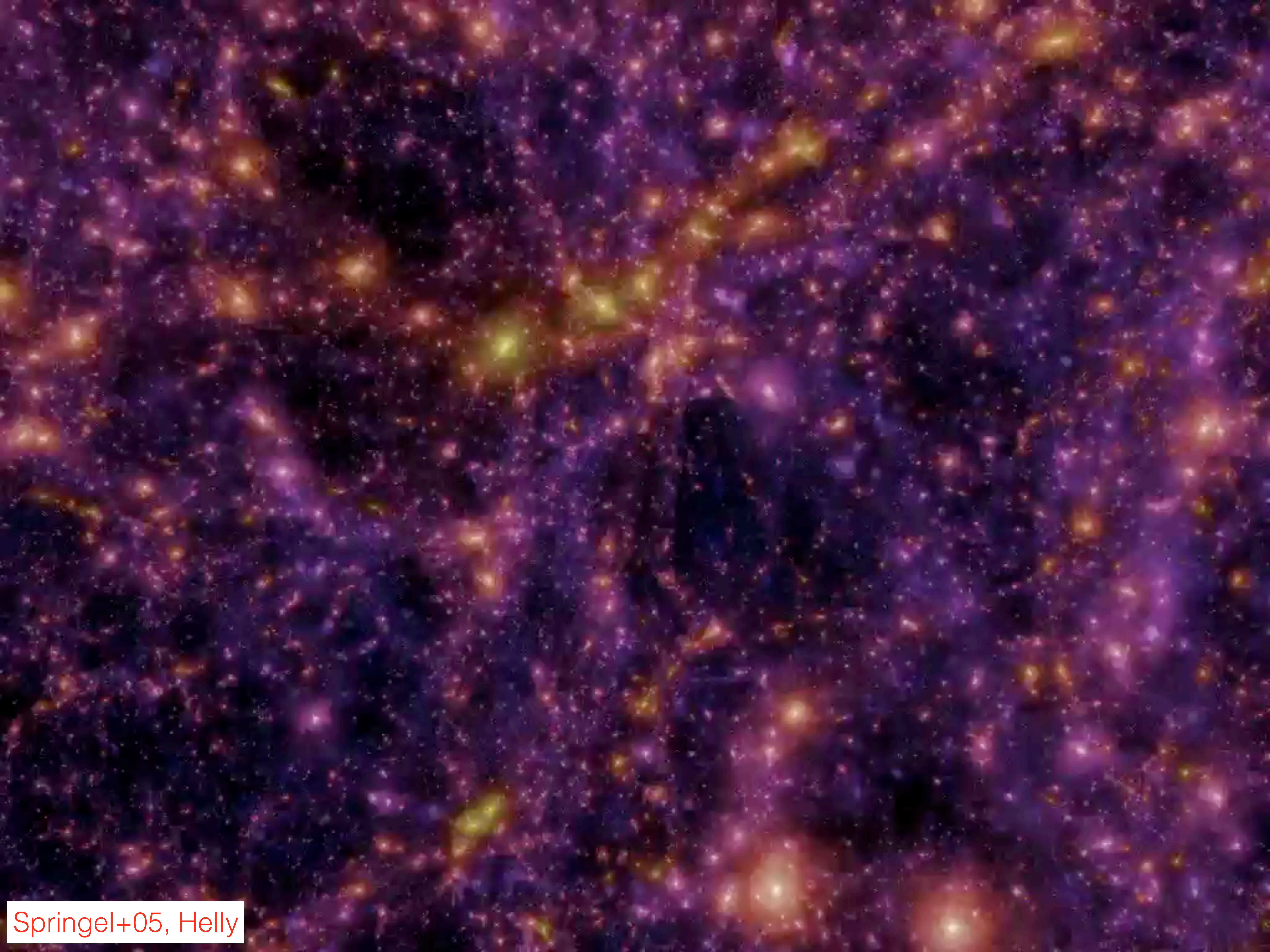
- matter is not directly observable (yet)
- galaxies do not cluster the same as mass
- clustering is not just linear
- forming galaxies affect clustering

galaxies cluster different from mass

bias: $\xi_{g,g}(r) = b^2\,\xi(r)$

galaxies (feedback) affects clustering

$$\xi_{DM}(r) \neq \xi_{DMO}(r)$$



Springel+05, Helly

galaxies cluster different from mass

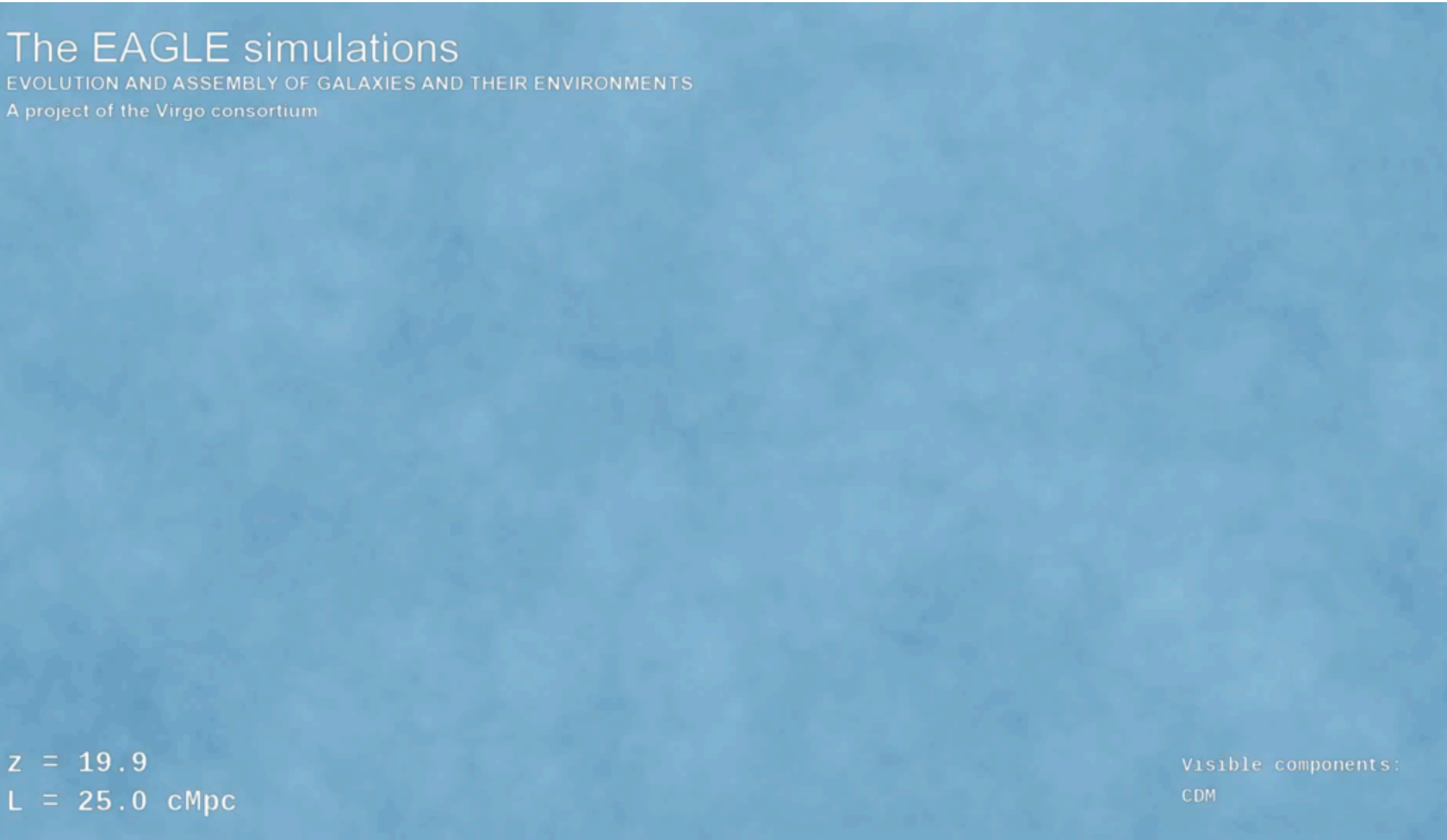
bias: $\xi_{g,g}(r) = b^2\,\xi(r)$

galaxies (feedback) affects clustering

$$\xi_{DM}(r) \neq \xi_{DMO}(r)$$

Hydrodynamical simulations: the Eagle project

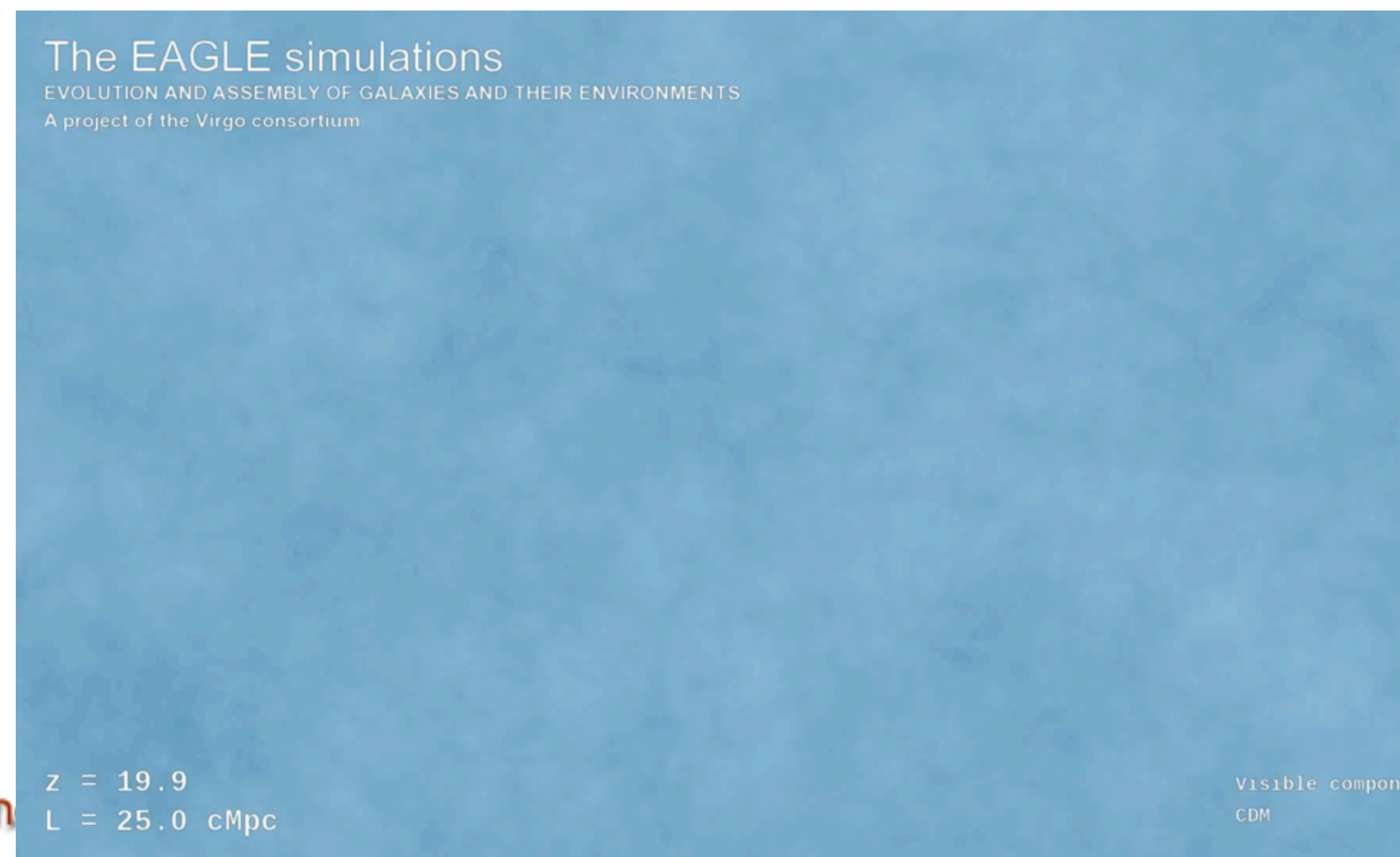
http://icc.dur.ac.uk/Eagle/



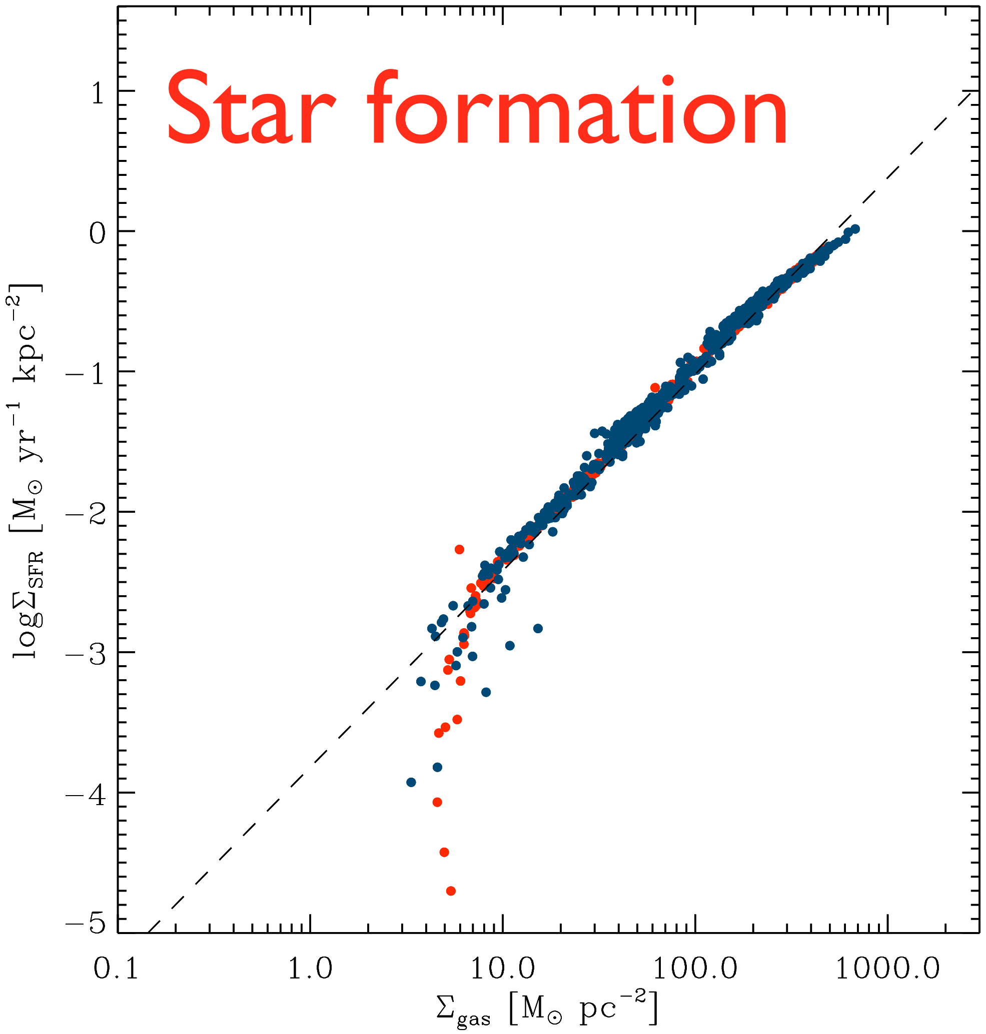
The EAGLE project: Simulating the evolution and assembly of galaxies and their environments

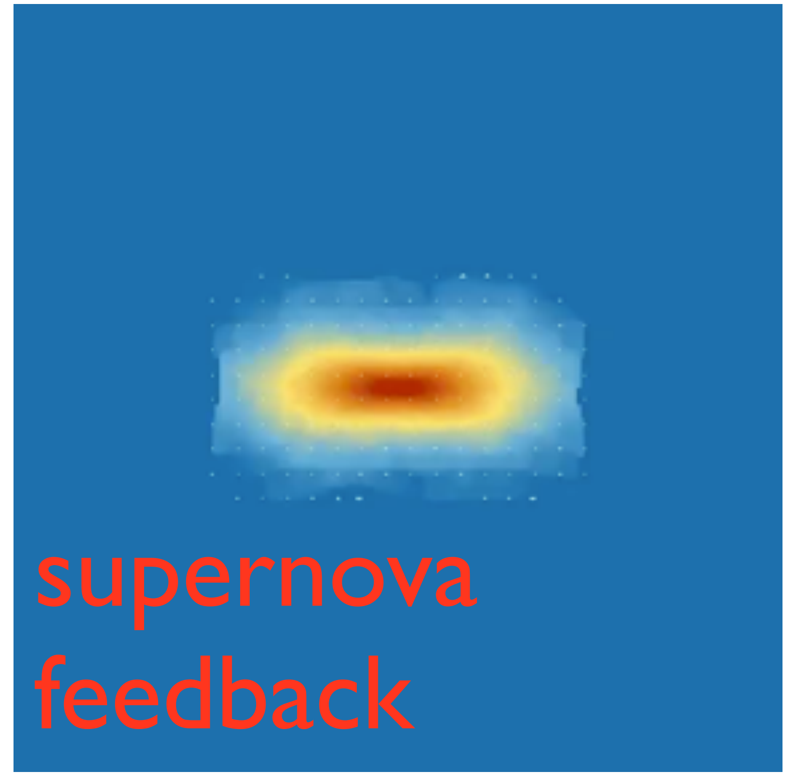
Joop Schaye,[1*] Robert A. Crain,[1] Richard G. Bower,[2] Michelle Furlong,[2] Matthieu Schaller,[2] Tom Theuns,[2,3] Claudio Dalla Vecchia,[4,5] Carlos S. Frenk,[2] I. G. McCarthy,[6] John C. Helly,[2] Adrian Jenkins,[2] Y. M. Rosas-Guevara,[2] Simon D. M. White,[7] Maarten Baes,[8] C. M. Booth,[1,9] Peter Camps,[8] Julio F. Navarro,[10] Yan Qu,[2] Alireza Rahmati,[7] Till Sawala,[2] Peter A. Thomas,[11] James Trayford[2]
[1] Leiden Observatory, Leiden University, P.O. Box 9513, 2300 RA Leiden, the Netherlands

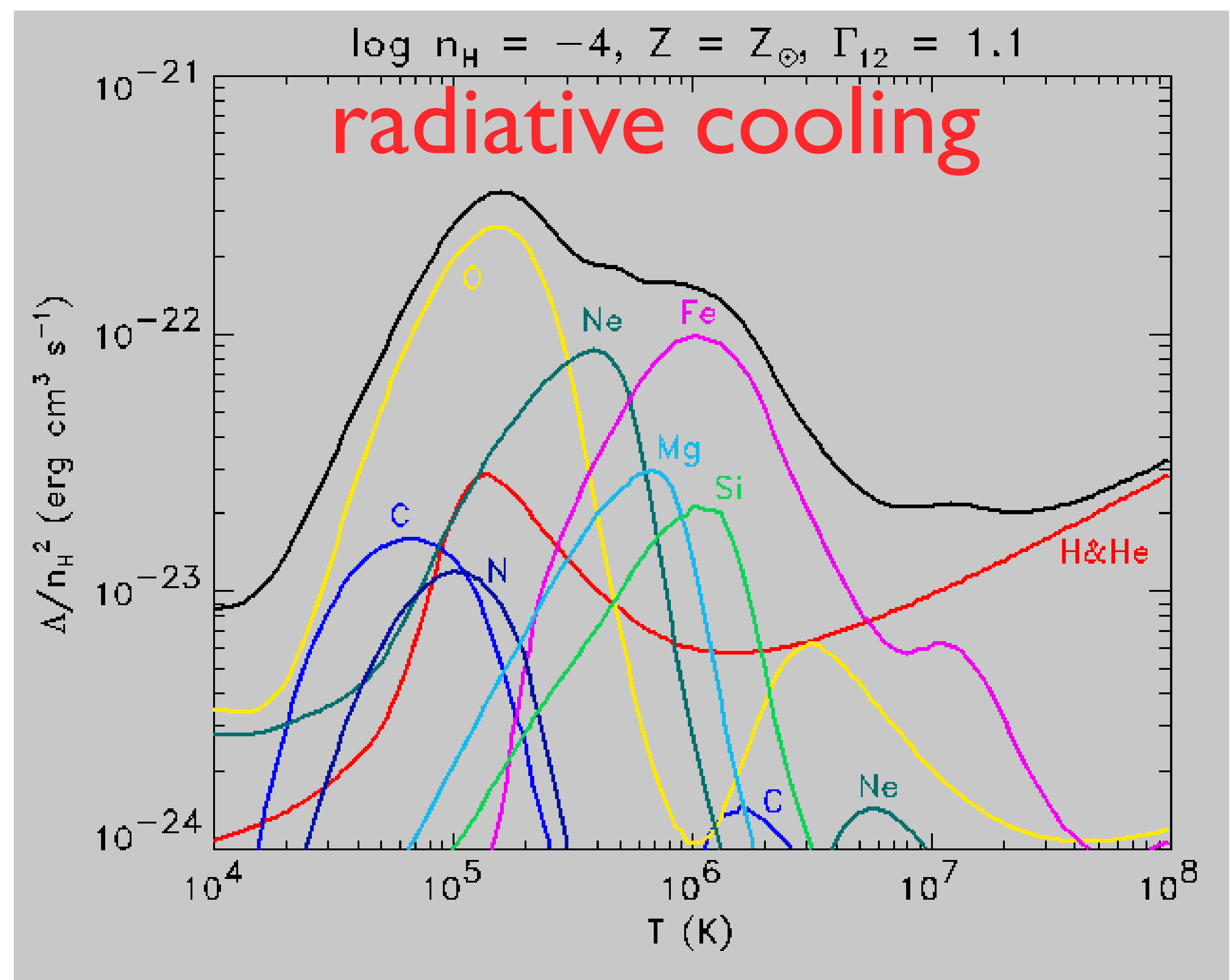
- 1504^3 Gadget 3 simulation
- $(100\ \mathrm{Mpc})^3$ volume
- baryonic mass $10^6\ M_{sun}$
- Calibrated to stellar MF
- Local physics

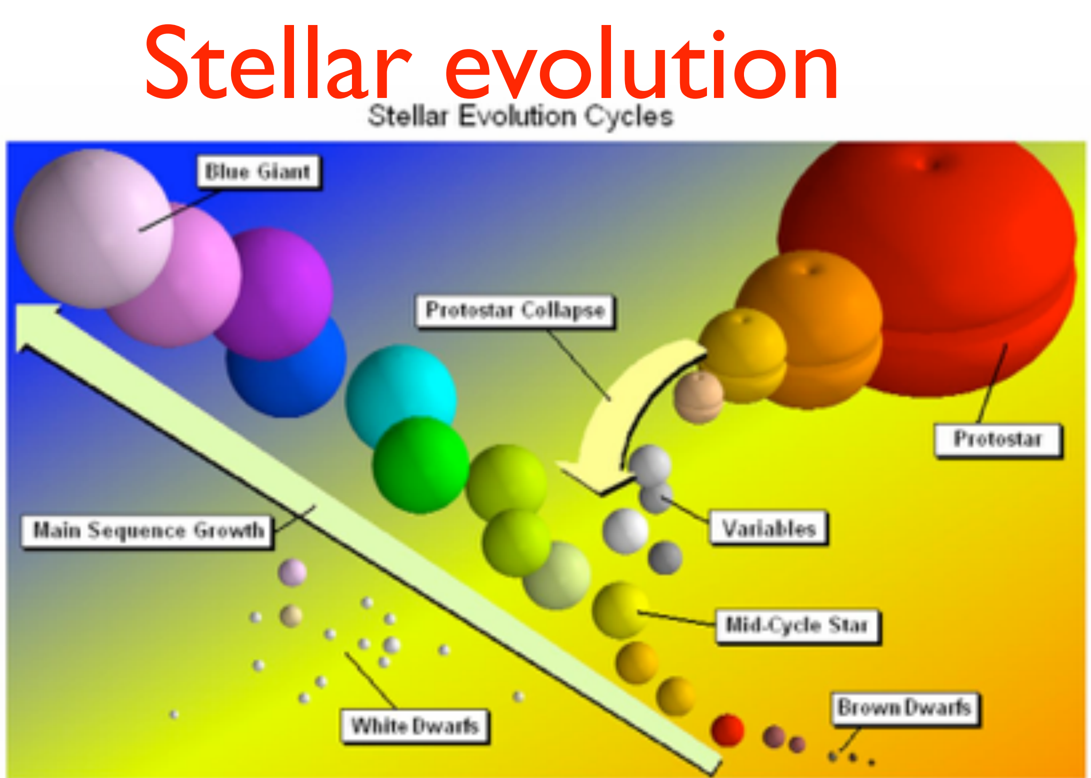


The subgrid physics in cosmological codes





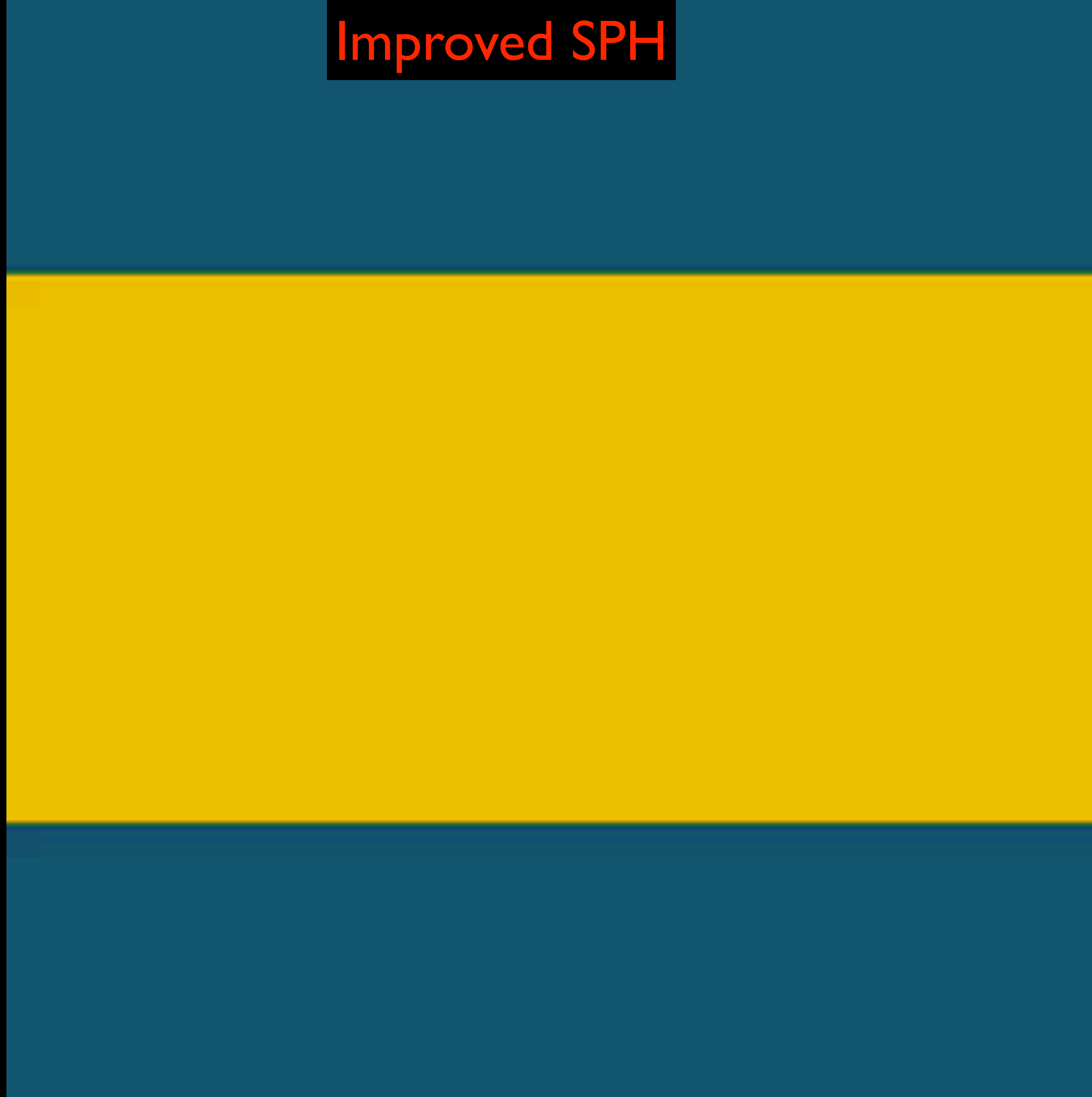


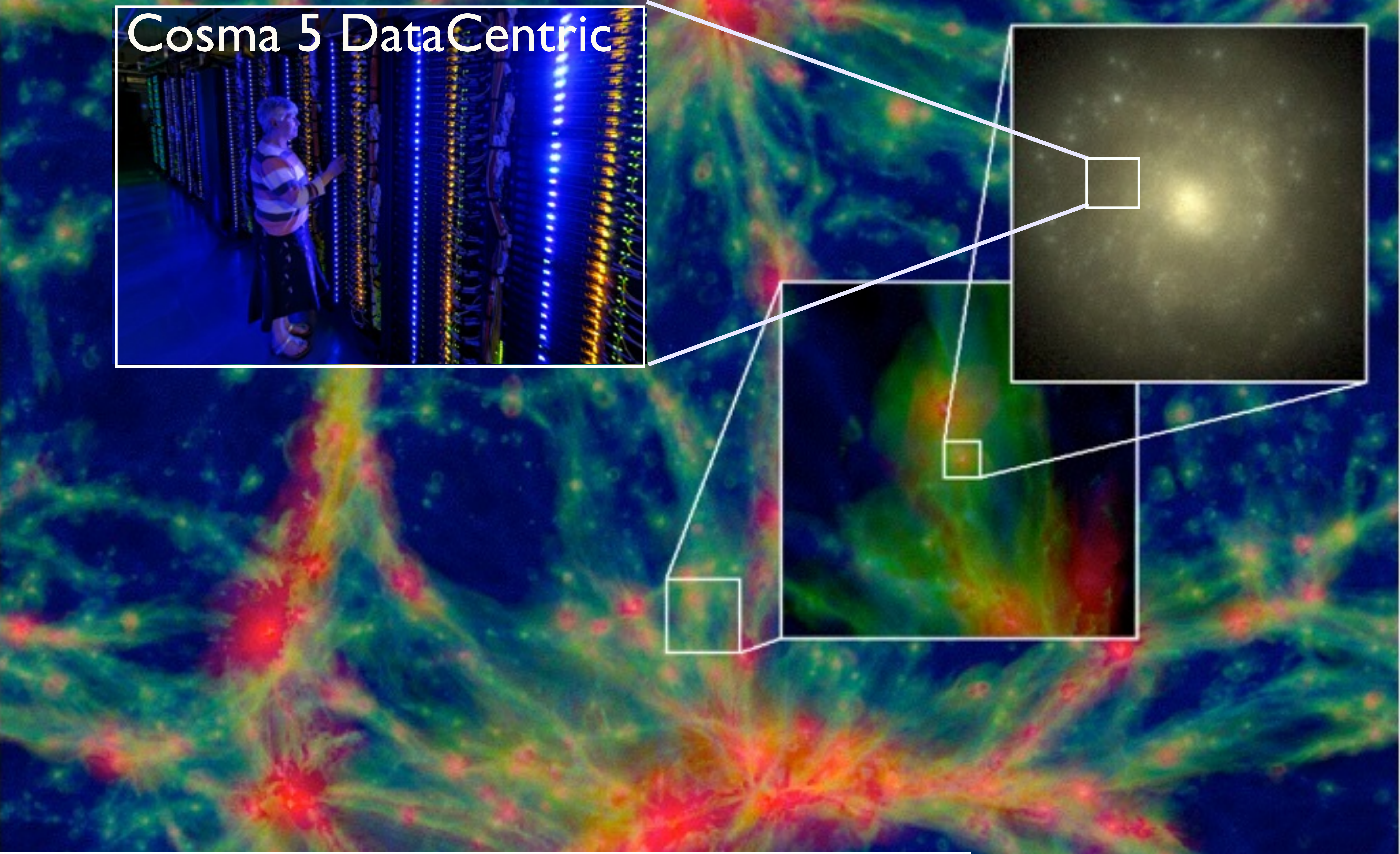


Improved SPH

"Anarchy" (Dalla Vecchia+)

Kelvin-Helmholtz instability





Name	L (comoving Mpc)	N	m_g ($M_\odot$)	m_{dm} ($M_\odot$)	ϵ_{com} (comoving kpc)	ϵ_{prop} (proper kpc)
L025N0376	25	376^3	1.81×10^6	9.70×10^6	2.66	0.70
L025N0752	25	752^3	2.26×10^5	1.21×10^6	1.33	0.35
L050N0752	50	752^3	1.81×10^6	9.70×10^6	2.66	0.70
L100N1504	100	1504^3	1.81×10^6	9.70×10^6	2.66	0.70

7 M CPU hours

Schaye +15

Eagle philosophy:
some properties cannot be predicted from first principles (yet?):

stellar mass
black hole mass

these are set by feedback efficiency which needs calibrating

Calibrate on:

- z=0.1 galaxy stellar mass function
- z=0.1 $M_* - M_{\text{black hole}}$ relation
- z=0 galaxy sizes

Energy injection (from SNe or AGN)

$$\Delta M_\star \rightarrow \Delta E_\star = \frac{\Delta M_\star}{100 M_\odot} 10^{51} \, \mathrm{erg}$$

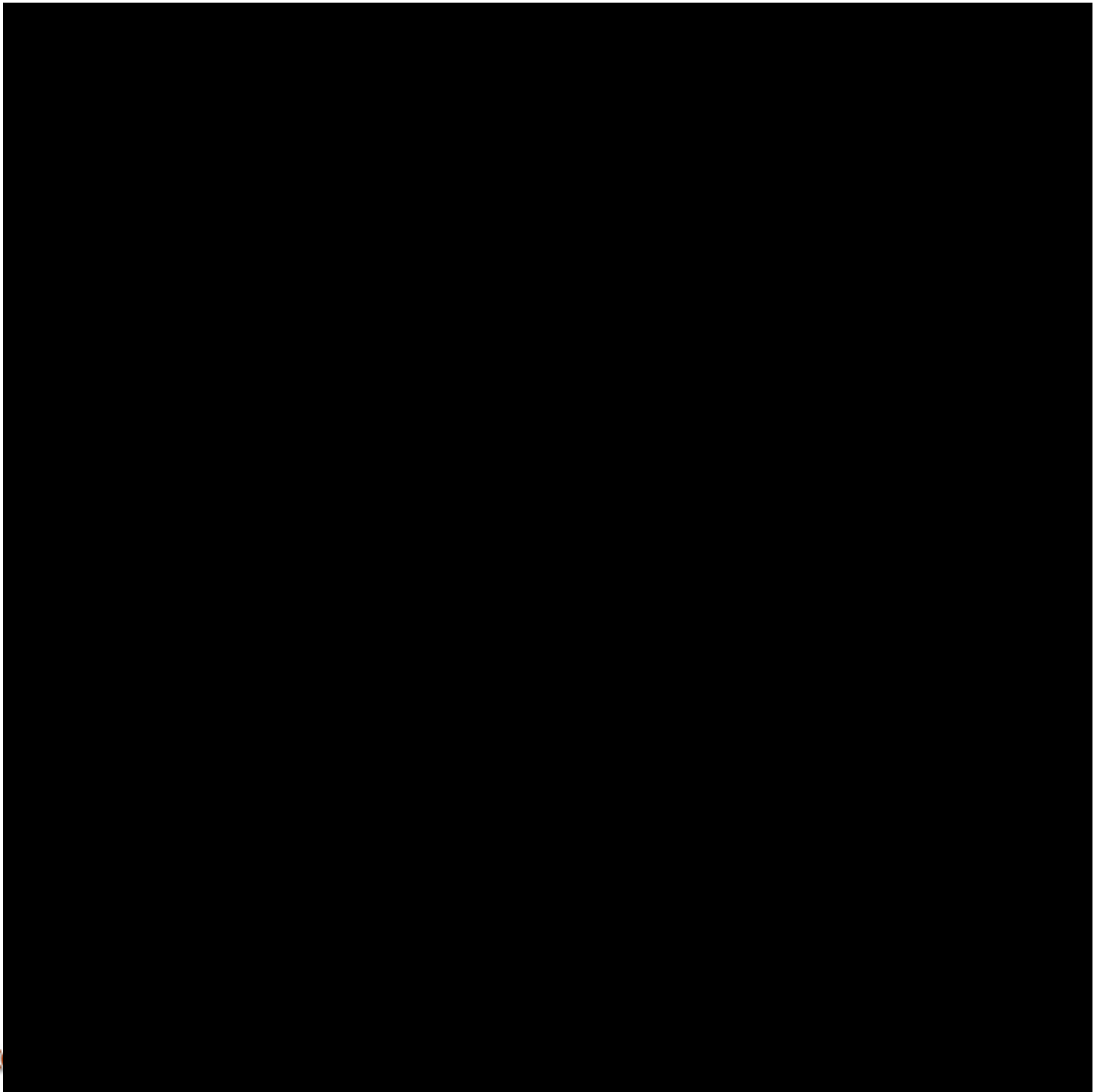
- some energy is lost in cooling
- how much energy is lost depends on density, temperature, and metallicity
- getting this fraction right requires very high resolution

$$f_{\mathrm{th}} = f_{\mathrm{th,min}} + \frac{f_{\mathrm{th,max}} - f_{\mathrm{th,min}}}{1 + \left(\frac{Z}{0.1 \mathrm{Z}_\odot}\right)^{n_Z} \left(\frac{n_{\mathrm{H,birth}}}{n_{\mathrm{H,0}}}\right)^{-n_n}},$$

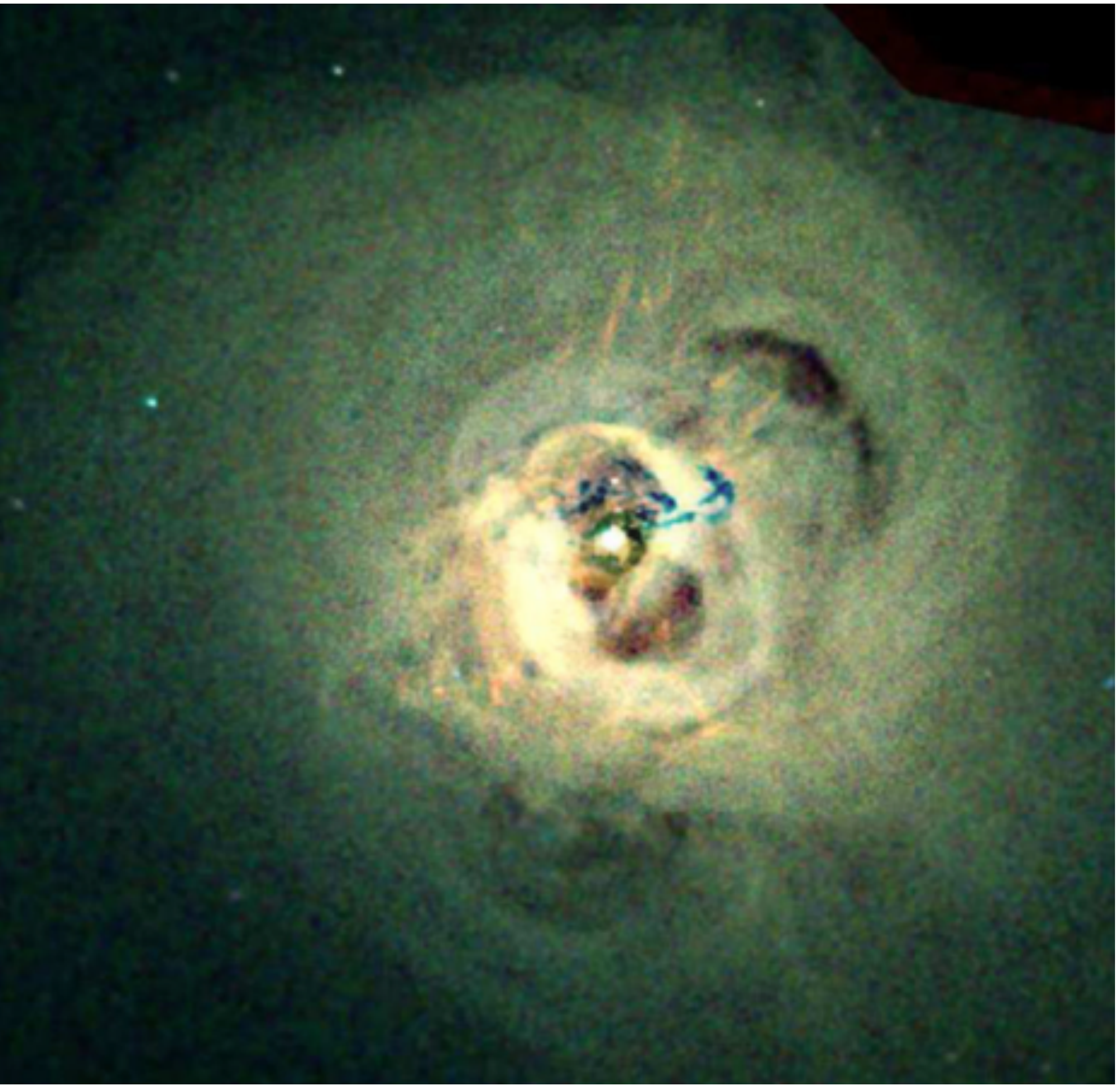
- effective amount of input energy used to heat gas
- main calibration function in Eagle

Gas outflows in Eagle due to AGN and SNe

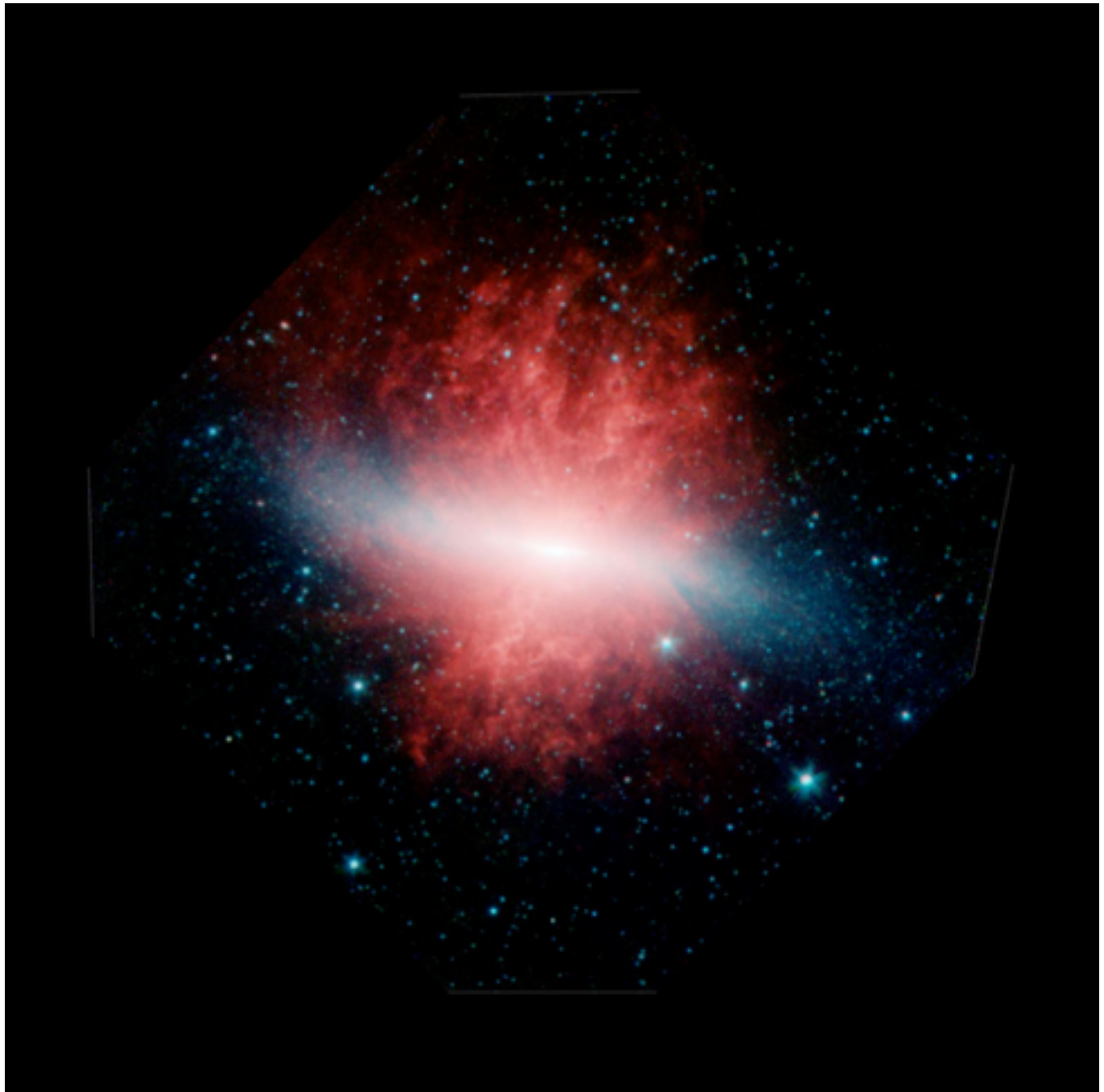
cold gas hot gas



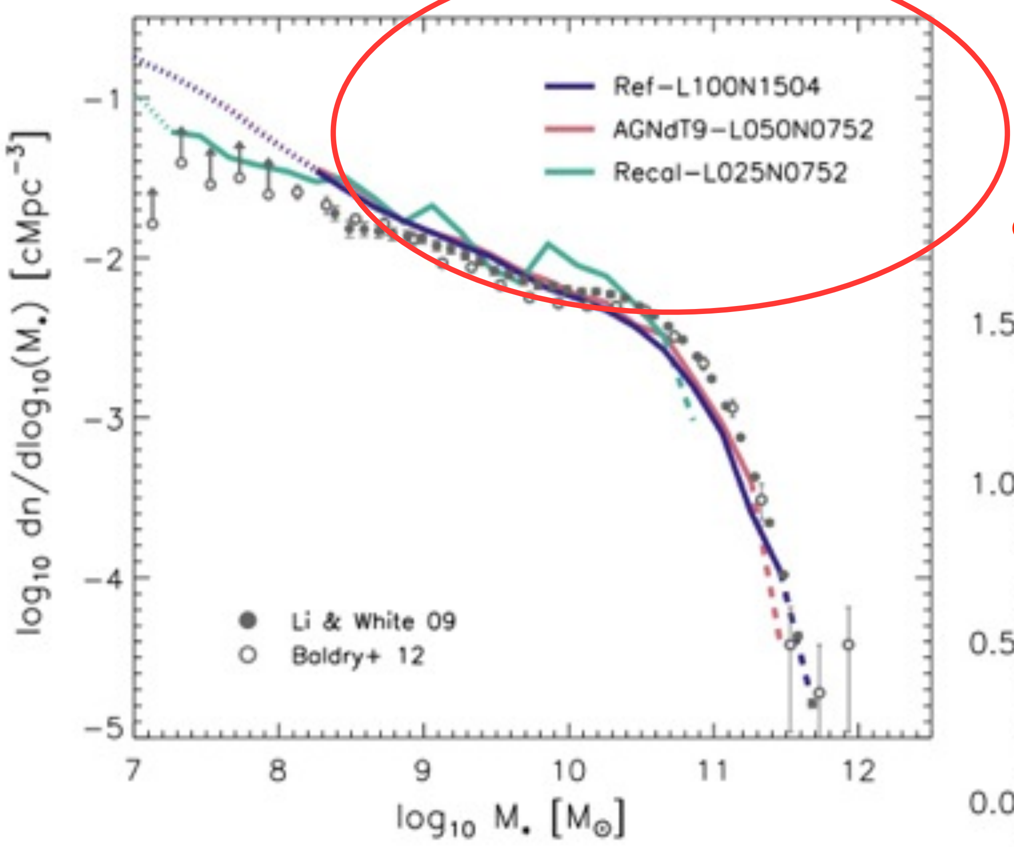
X-ray cavities in Perseus cluster: AGN events



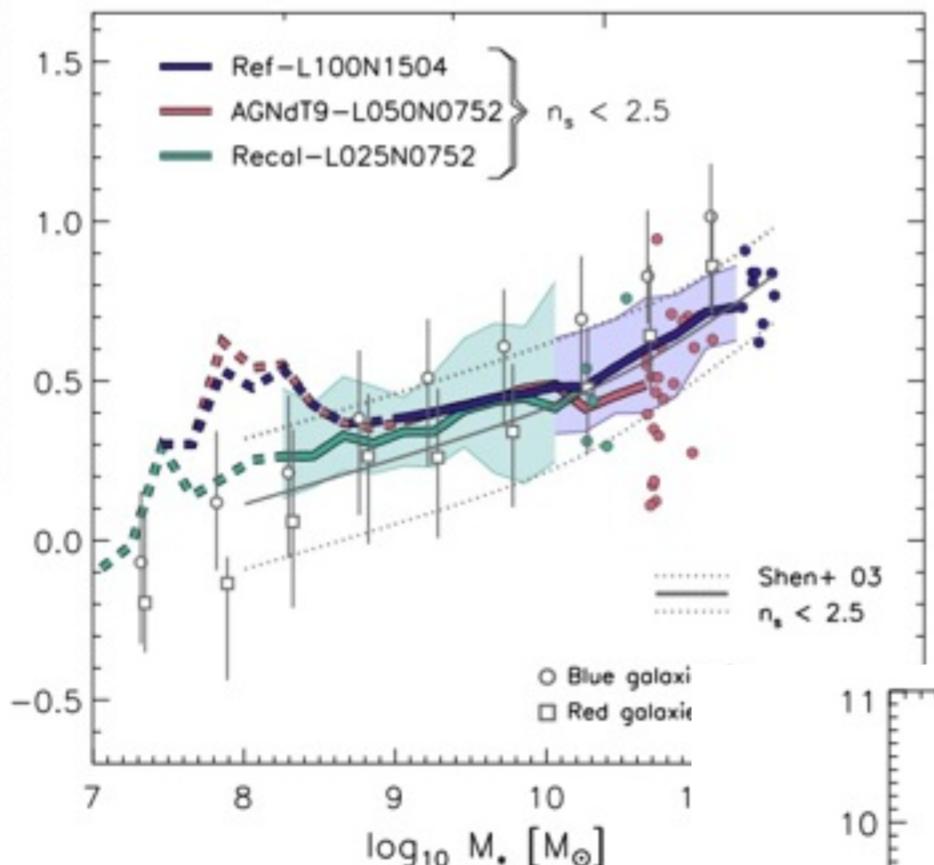
Galaxy outflows: M82



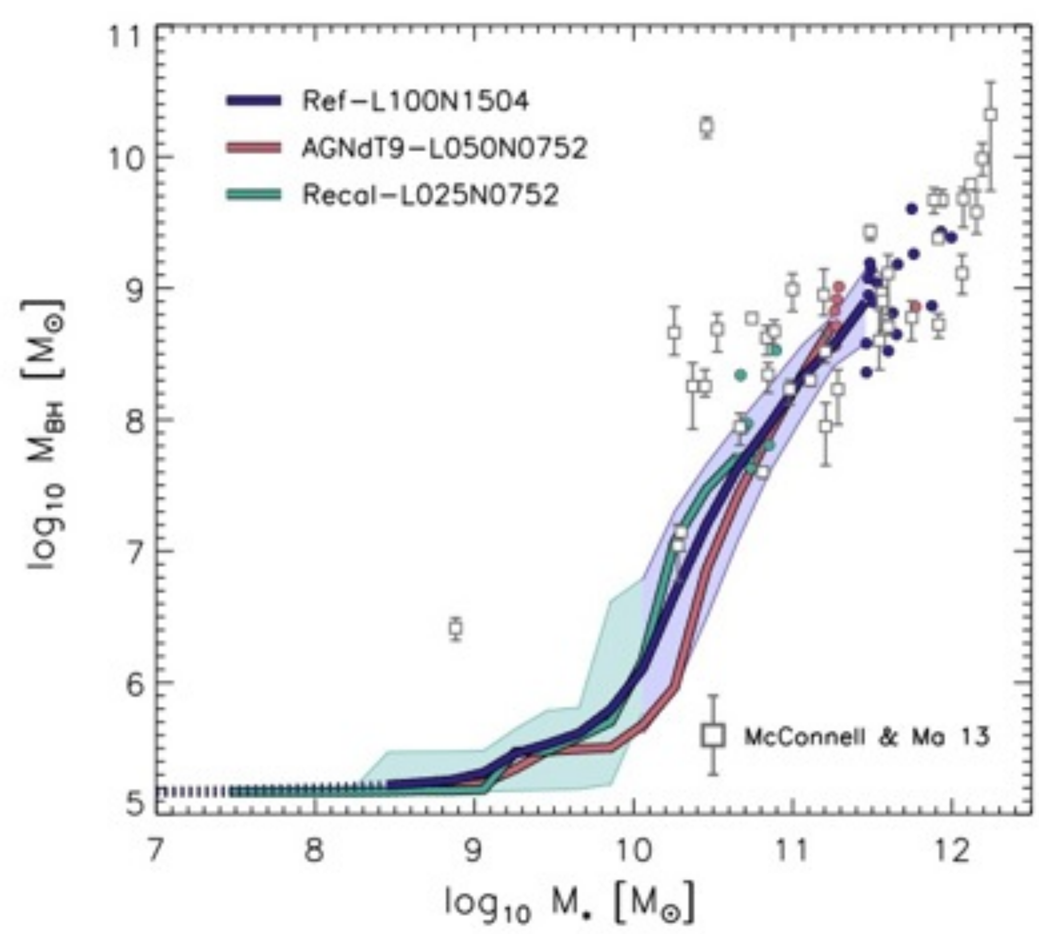
stellar mass function



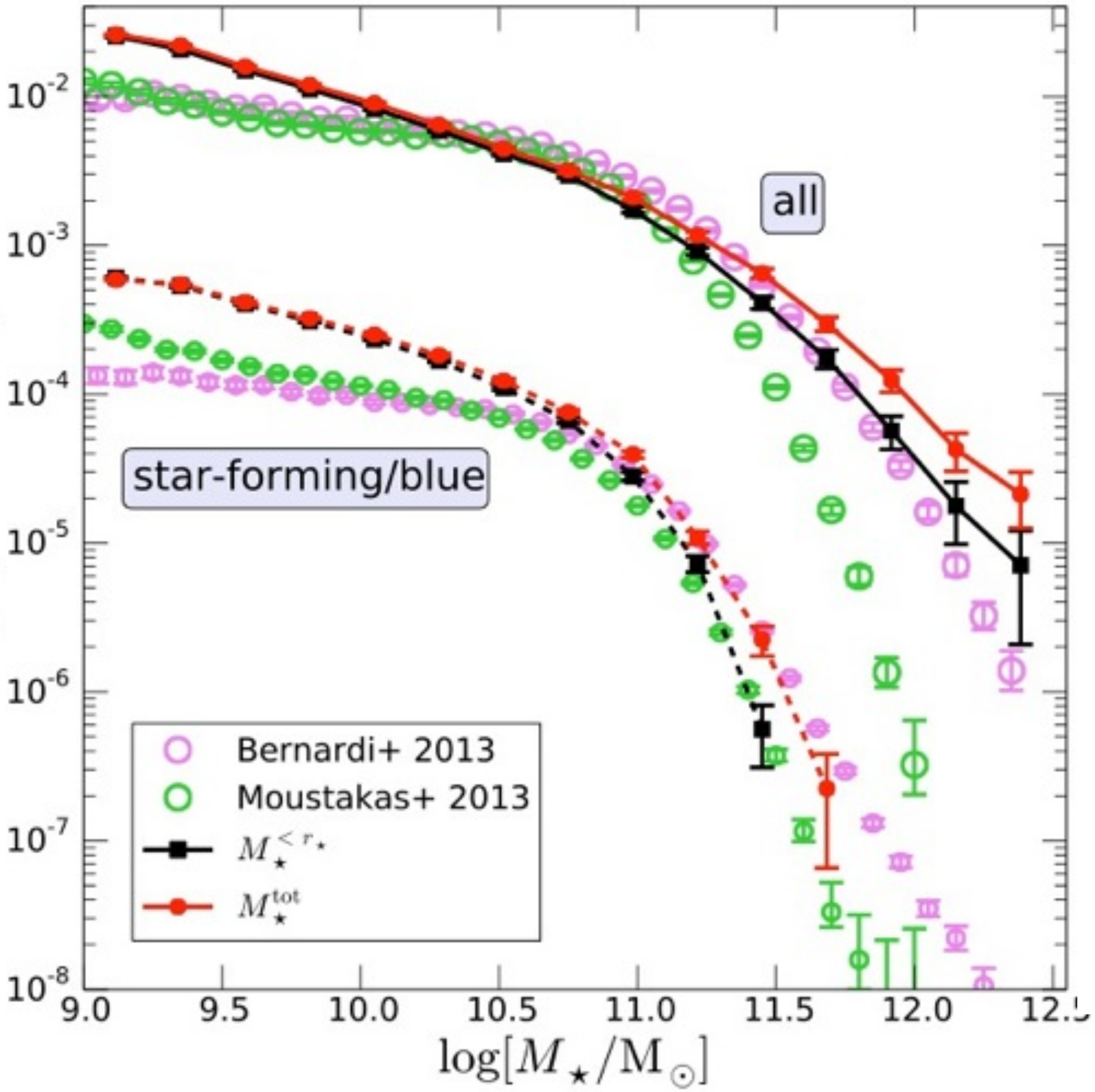
galaxy sizes



black hole masses

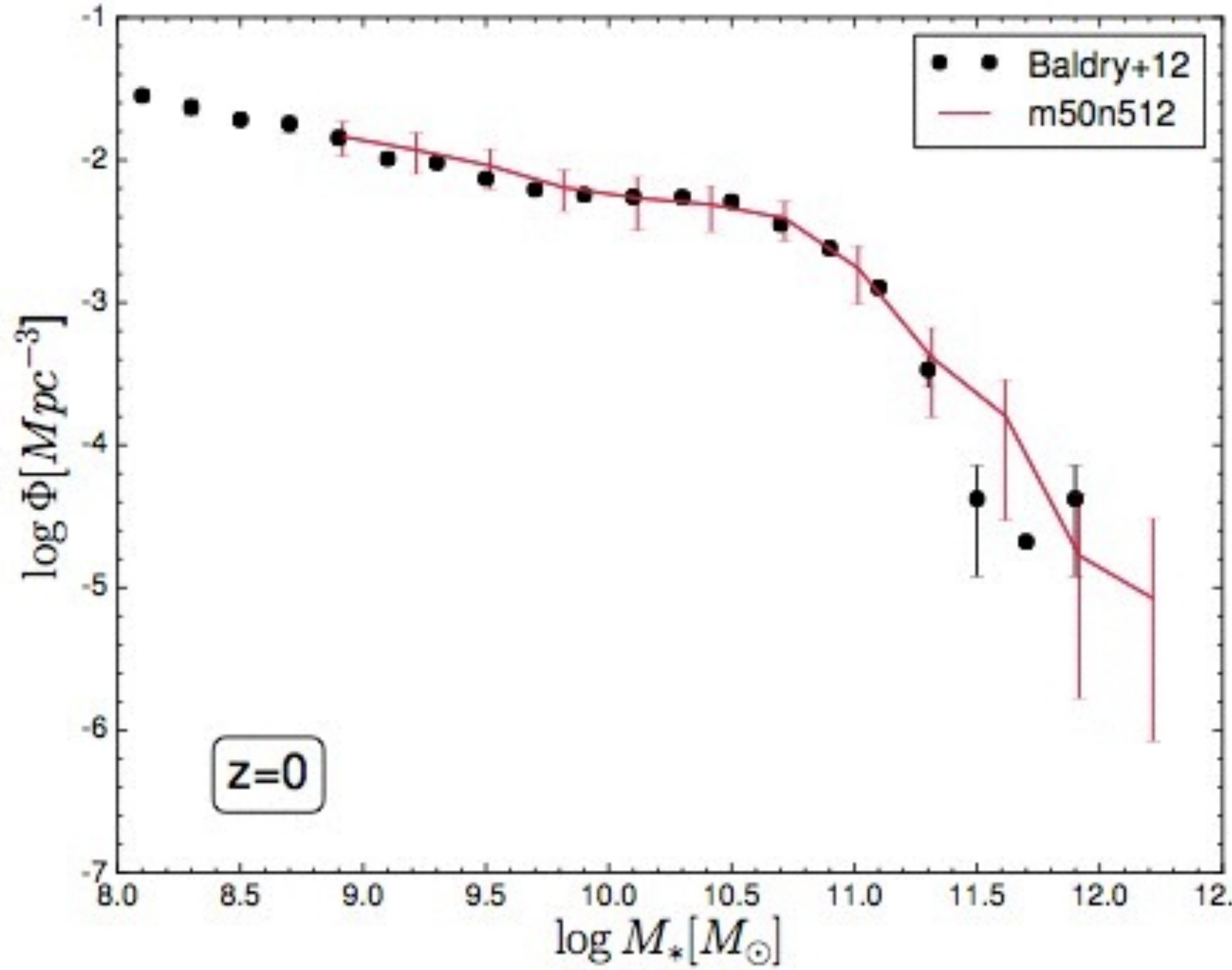


Illustris



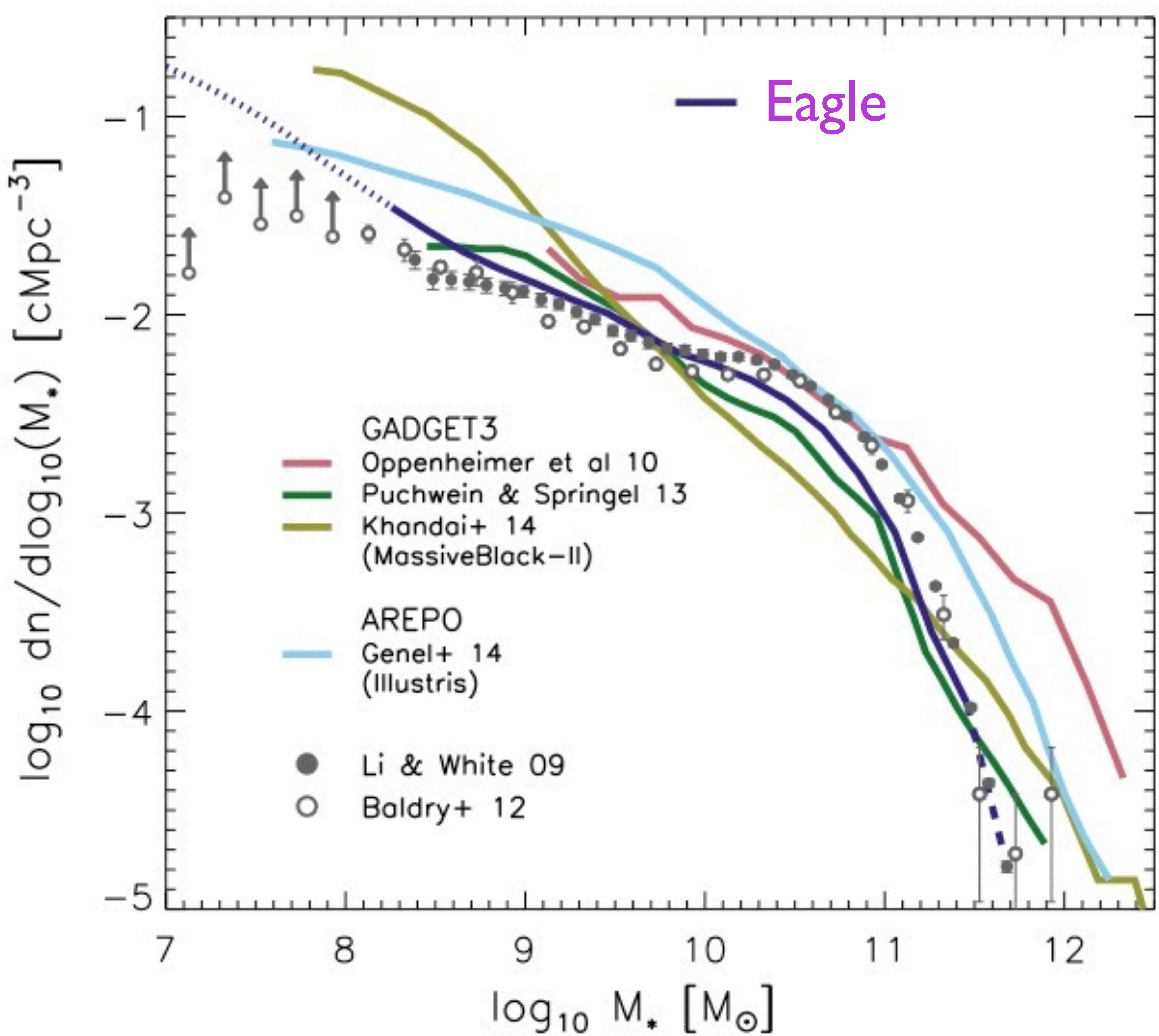
Vogelsberger+14

Mufasa



Dave+16

Galaxy stellar mass function: sims vs obs



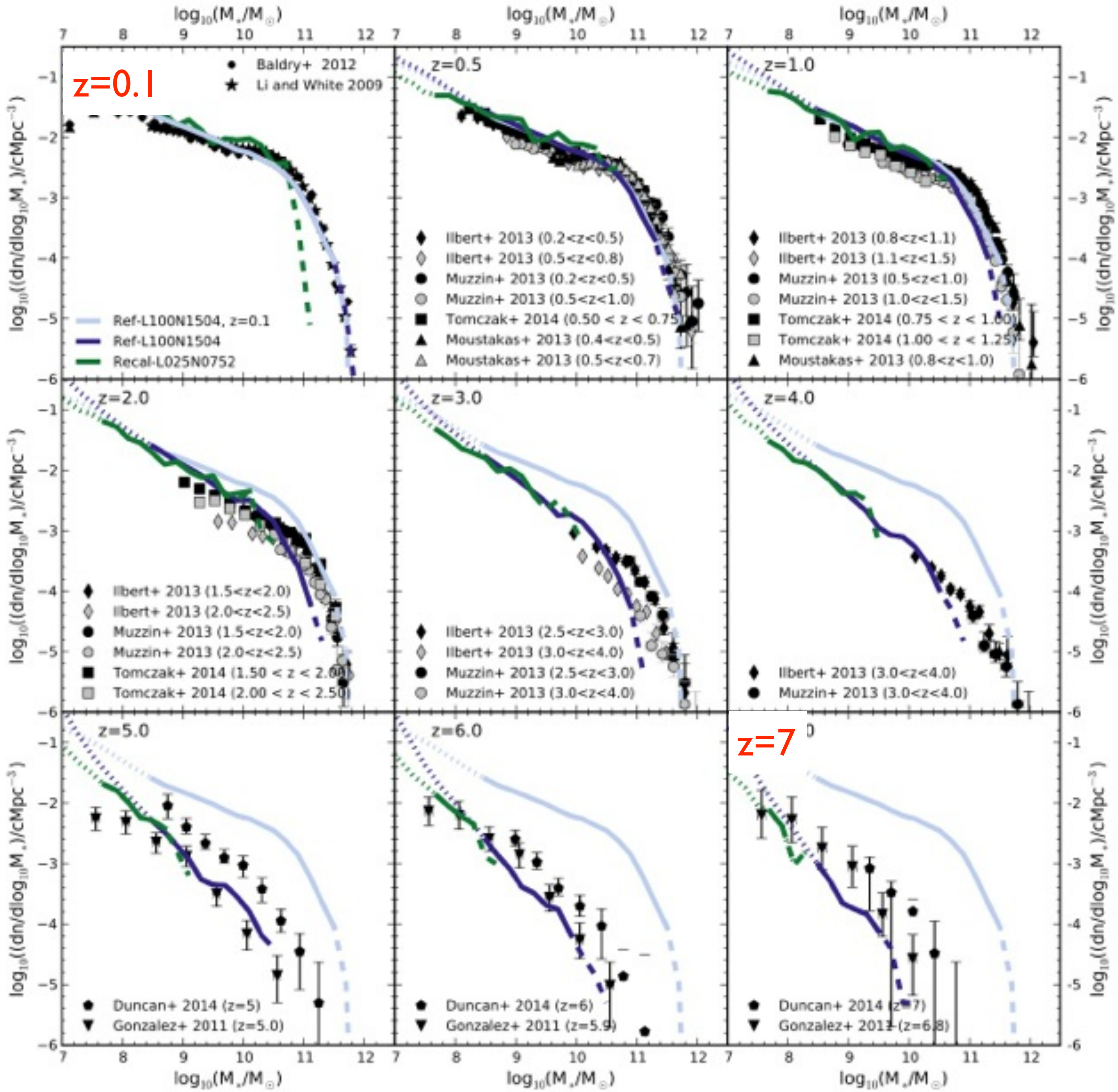
Schaye+15

Evolution of galaxy stellar mass function

Furlong+15

eagle high resolution

eagle standard resolution



ICC Instit

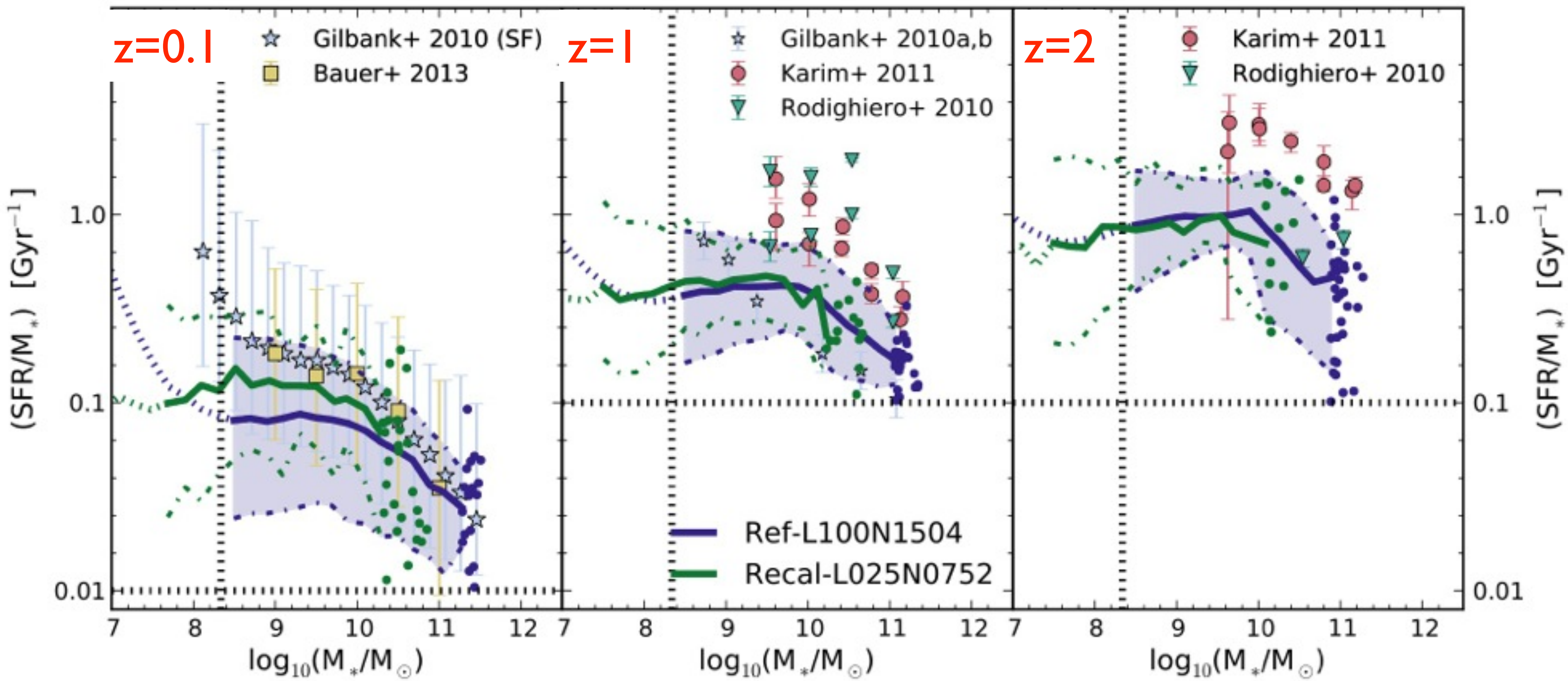
Tom Theuns

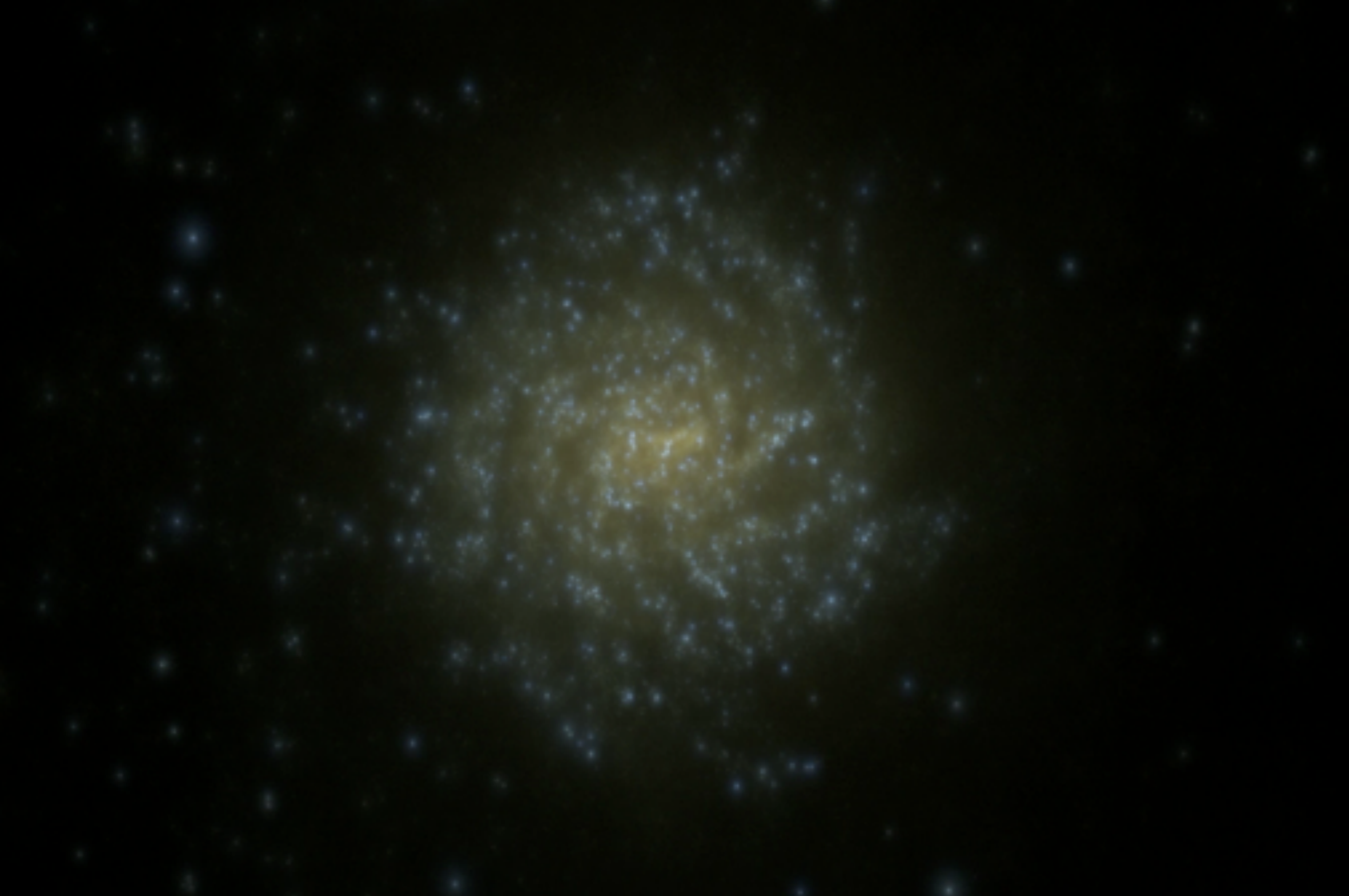
Evolution of sSFR

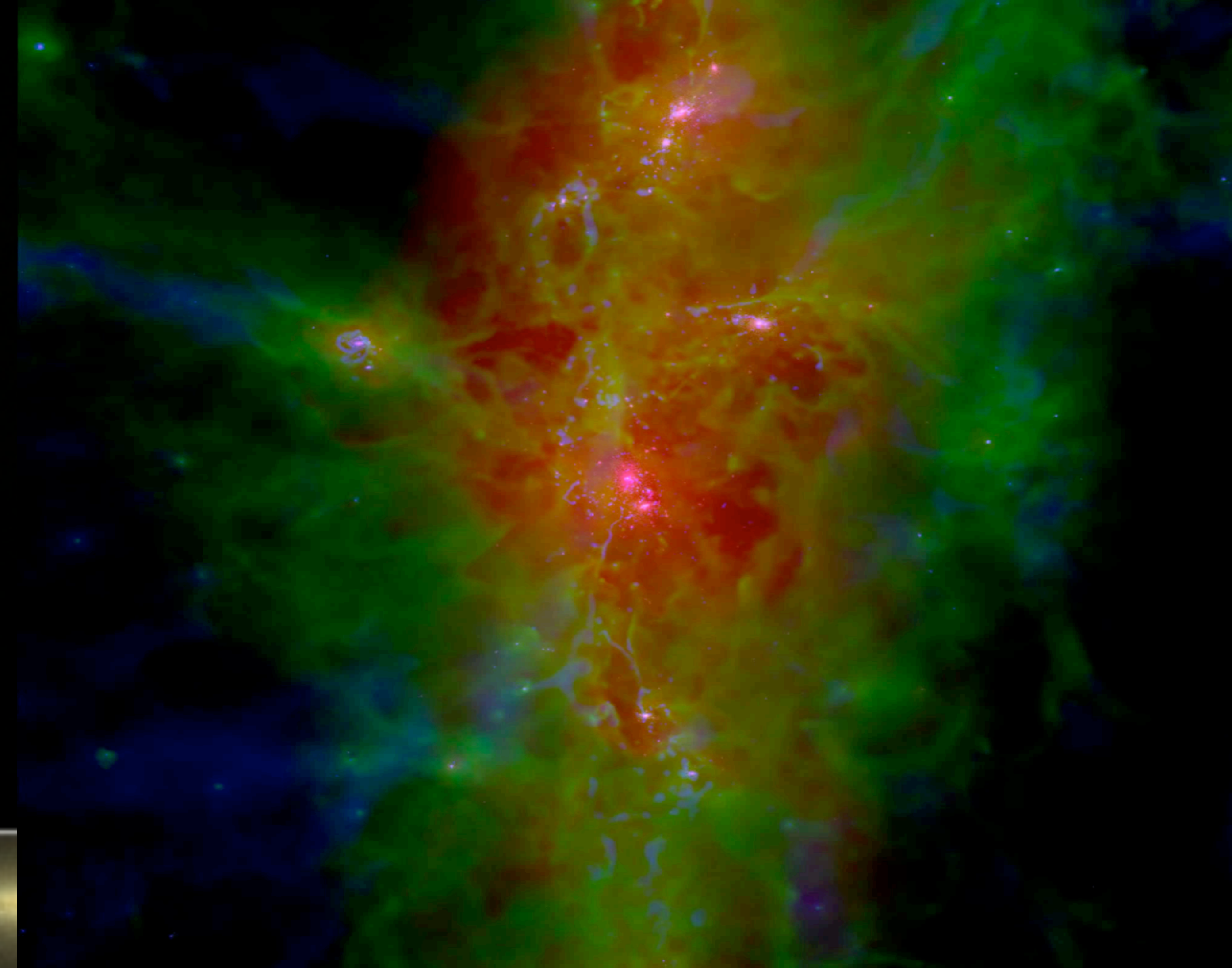
Furlong+15

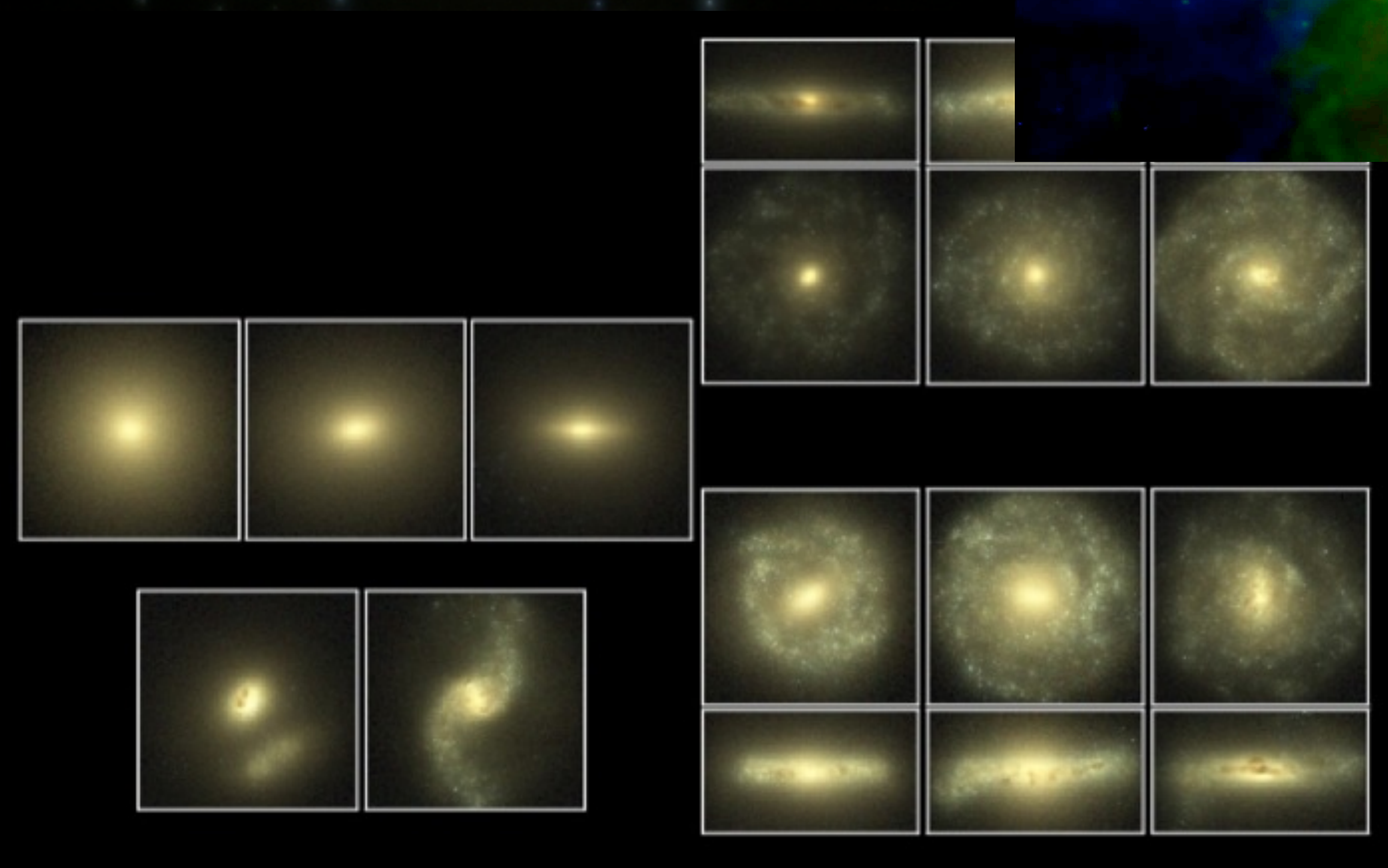
eagle high resolution
eagle standard resolution

specific star formation rates always too low by factor 1.5-3









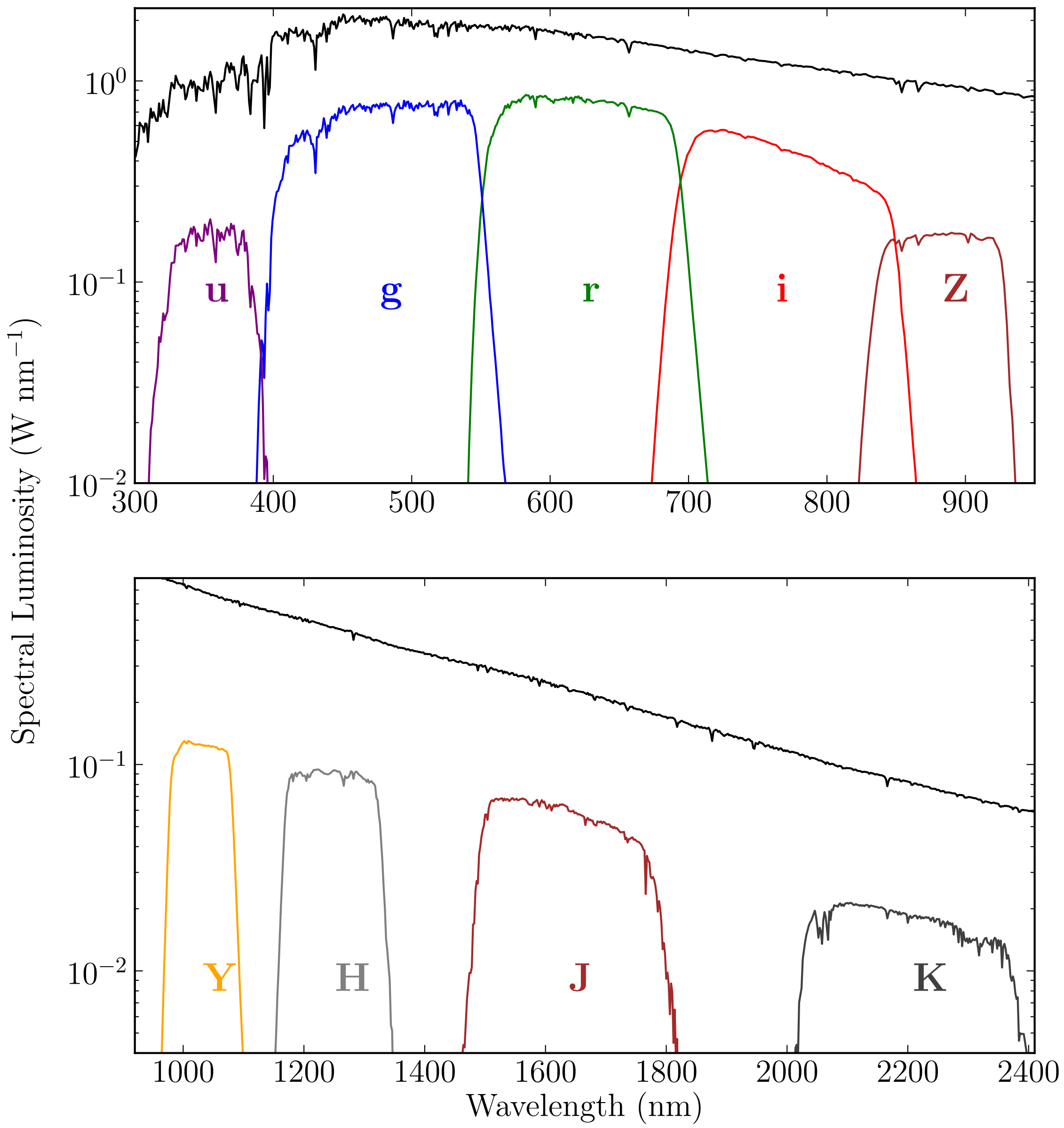
Trayford+15ab

Tully-Fisher relation

Sales+16

Colours and luminosities of $z = 0.1$ galaxies in the EAGLE simulation

James W. Trayford[1*], Tom Theuns[1], Richard G. Bower[1], Joop Schaye[2], Michelle Furlong [1], Matthieu Schaller[1], Carlos S. Frenk[1], Robert A. Crain[3], Claudio Dalla Vecchia[4,5], Ian G. McCarthy[3]



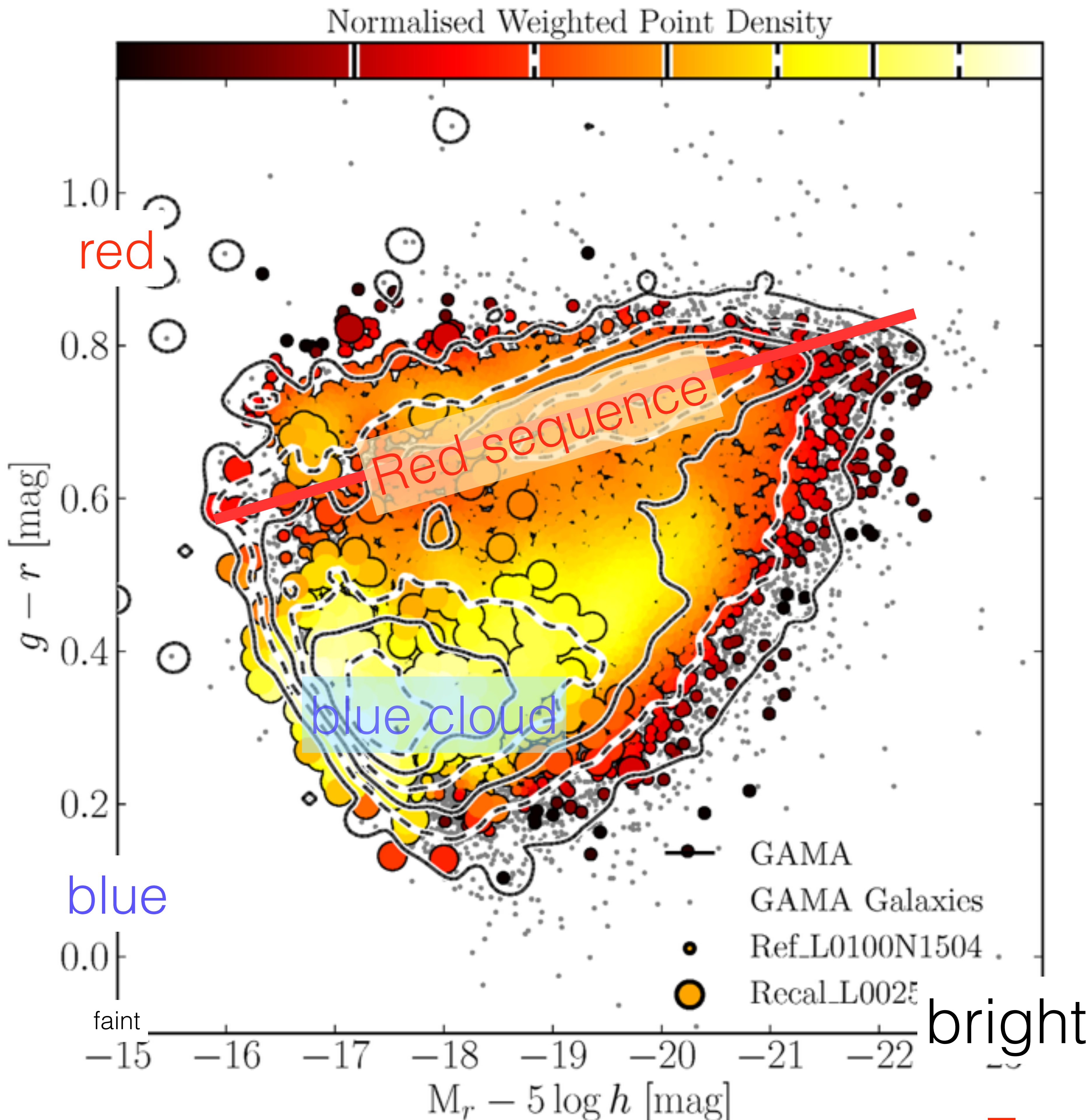
Eagle:

- stellar masses
- stellar ages
- stellar luminosities

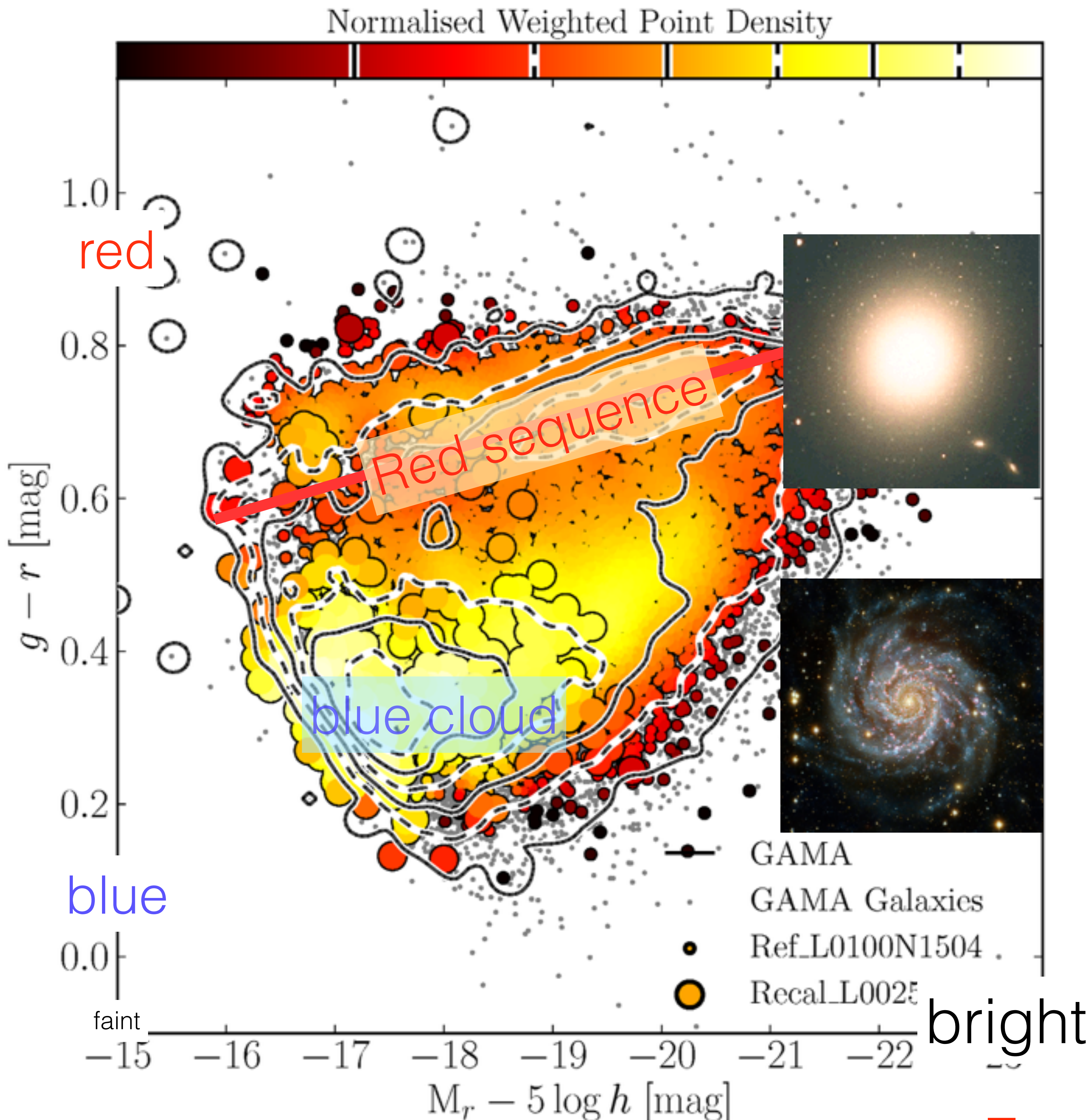
+ Chabrier '03 IMF

+ Bruzual & Charlot '03 Pop. Synt

+ Charlot & Fall-like dust model


Normalised Weighted Point Density
1.0
0.8
0.6
0.4
0.2
0.0
g − r [mag]
red
blue
Red sequence
blue cloud
GAMA
GAMA Galaxies
Ref_L0100N1504
Recal_L0025
faint
bright
−15
−16
−17
−18
−19
−20
−21
−22
M_r − 5 log h [mag]

Trayford +15



Normalised Weighted Point Density
red
Red sequence
blue cloud
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1.0
0.8
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0.2
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g − r [mag]
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−21
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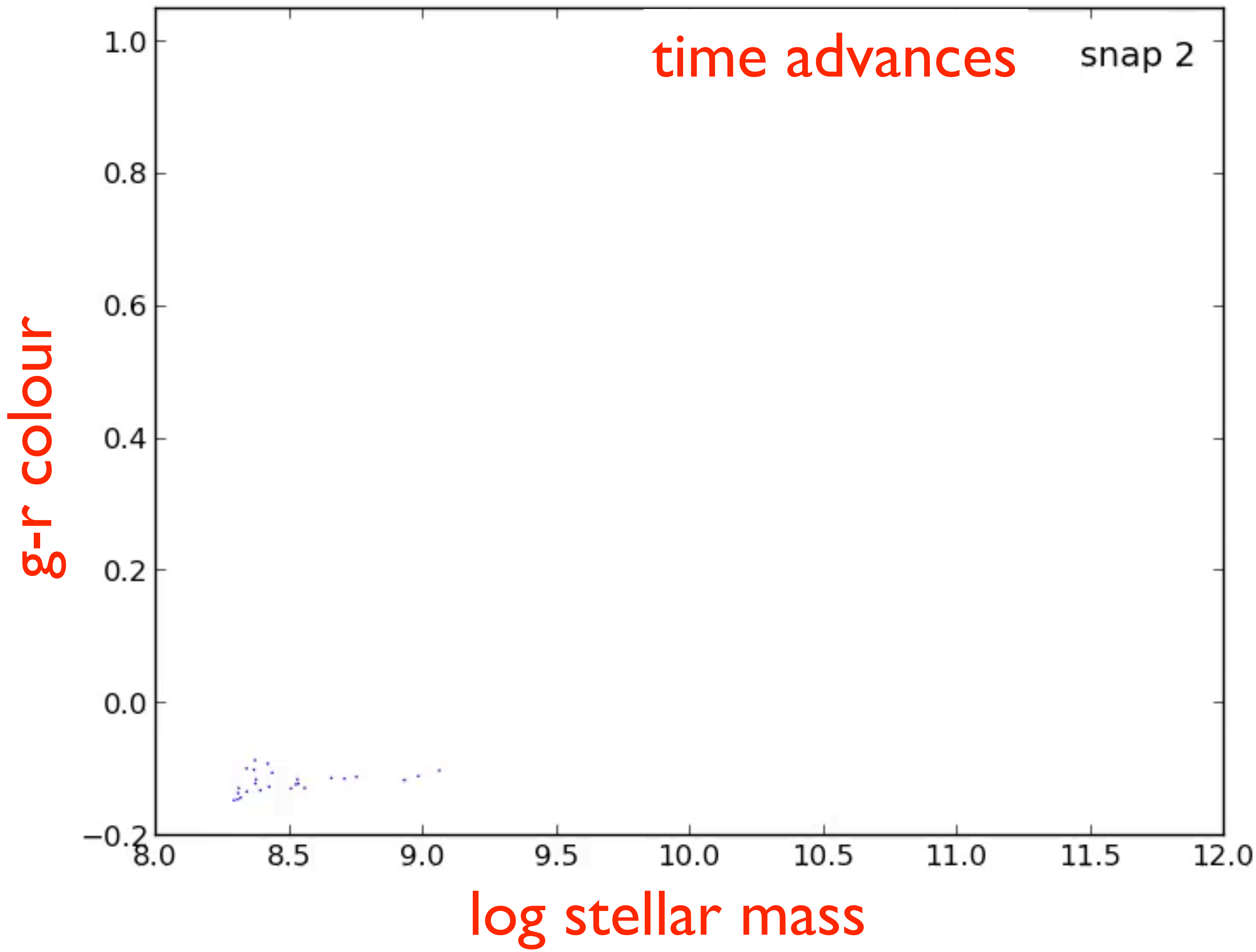
M_r − 5 log h [mag]
GAMA
GAMA Galaxies
Ref_L0100N1504
Recal_L0025

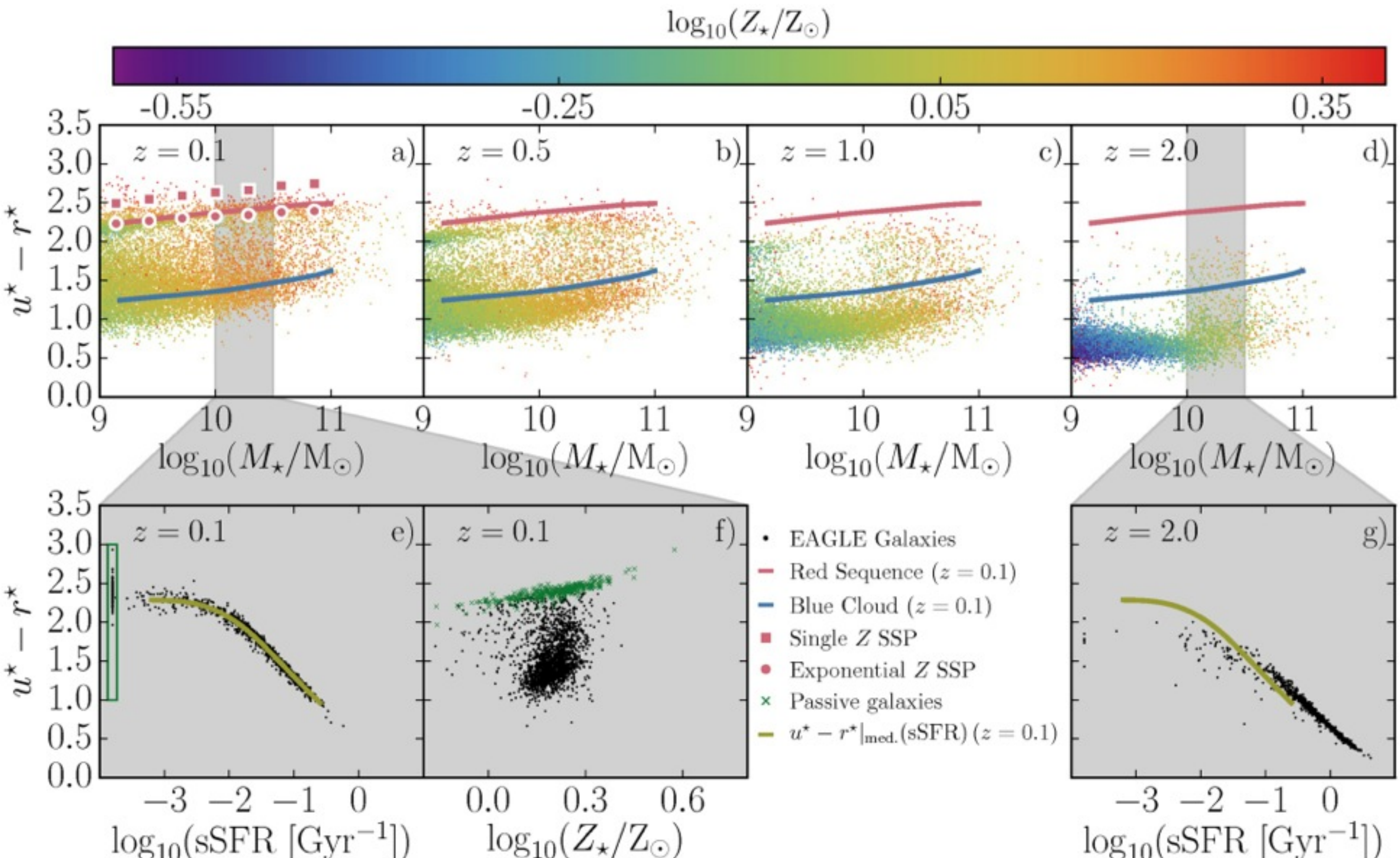
Trayford +15

Evolution of intrinsic colours:



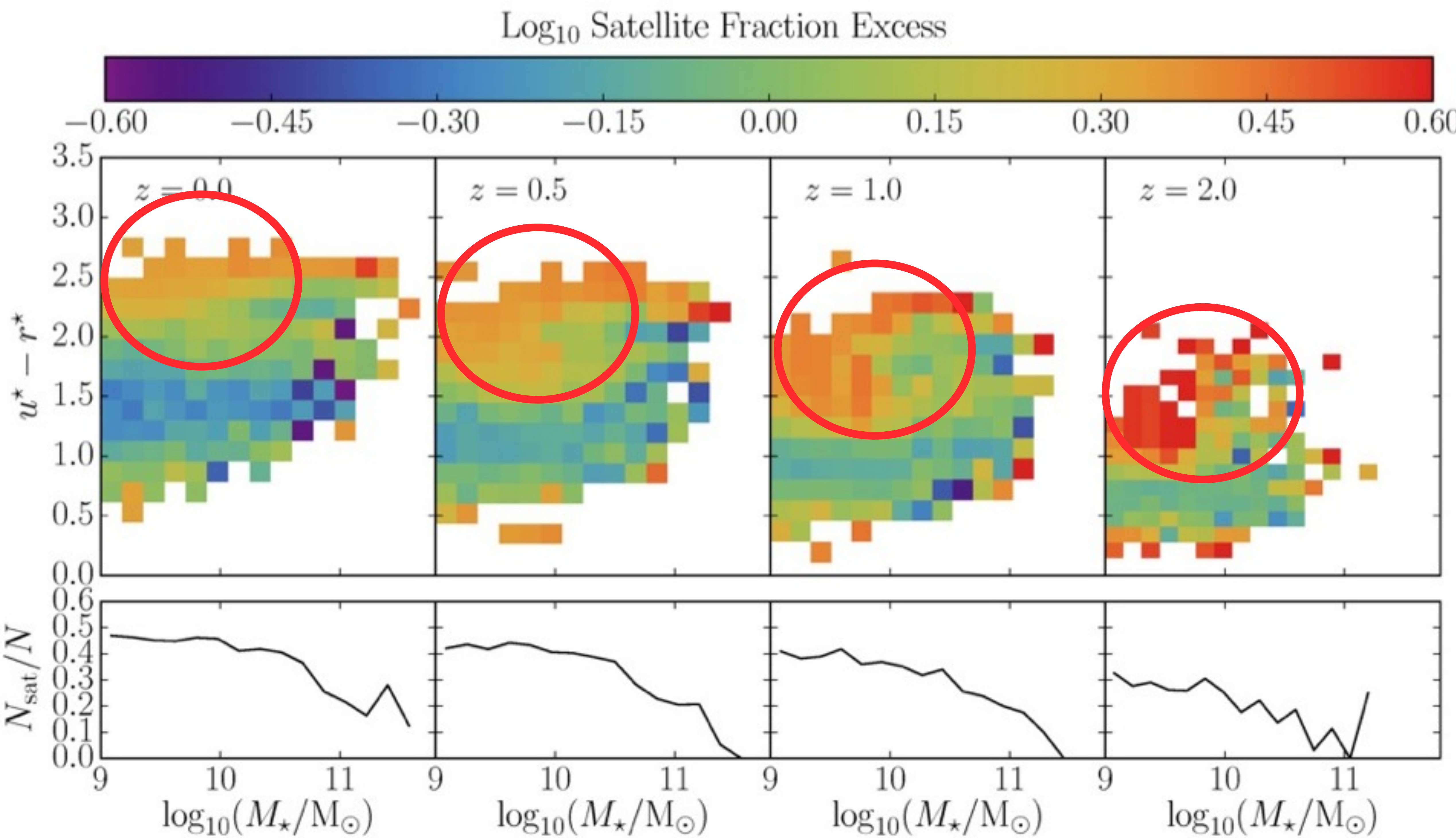
Evolution of intrinsic colours:

It's not easy being green: The evolution of galaxy colour in the EAGLE simulation Trayford +16, arXiv:1601.07907



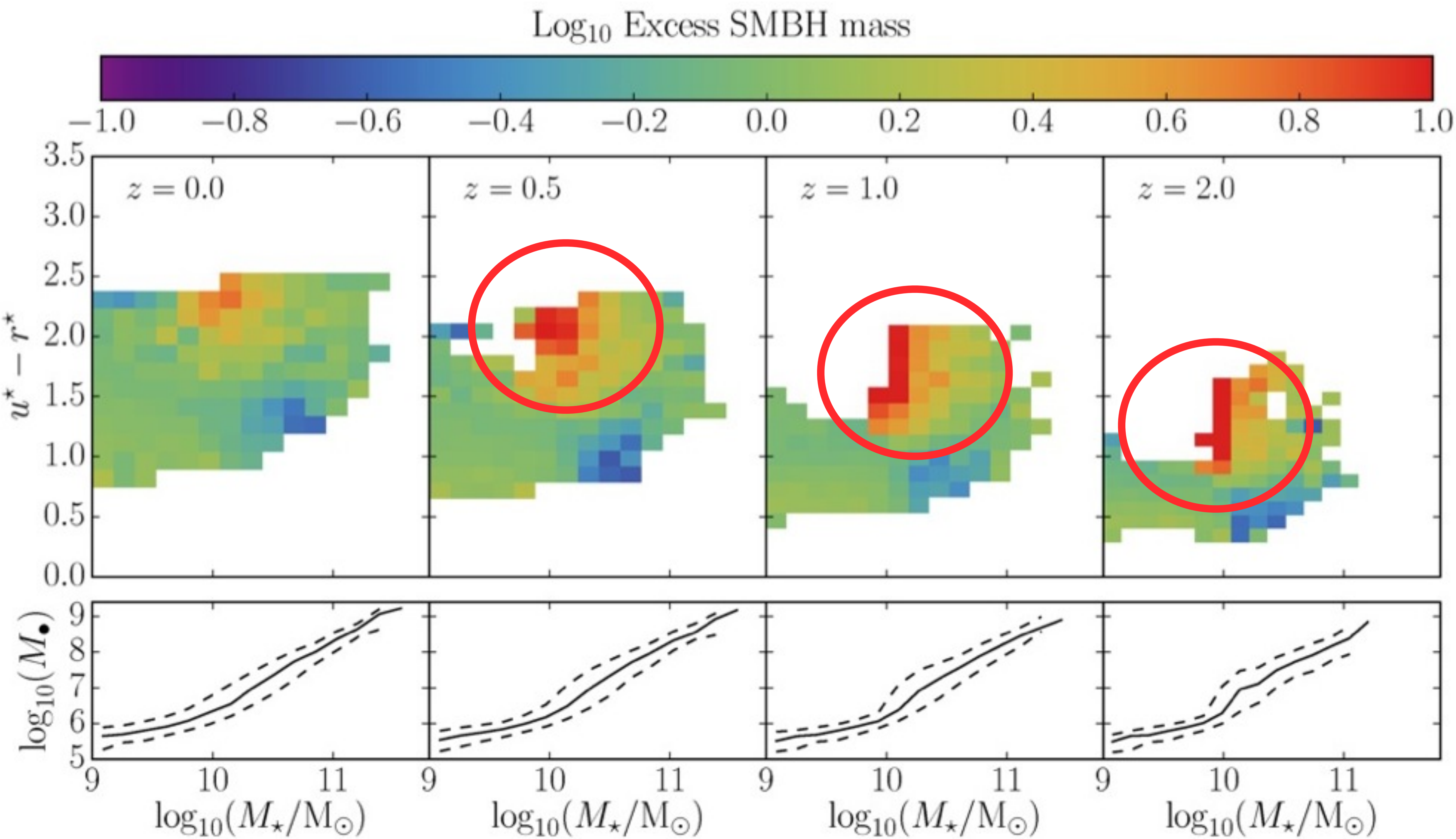
Trayford +16

Why do galaxies become red 1: satellite quenching



Trayford +16

Why do galaxies become red II: AGN quenching



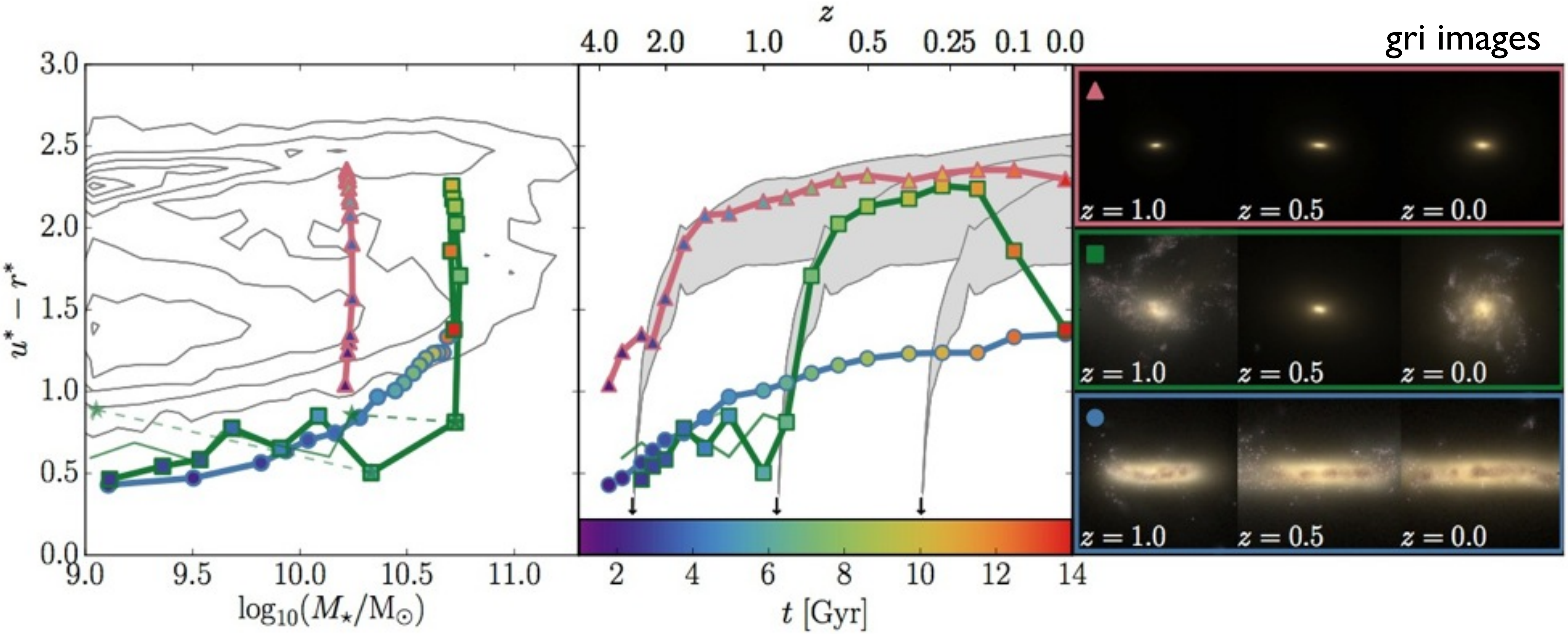
Trayford +16

Mean motion of galaxies in colour-stellar mass plane during 1Gyr

to z=0 to z=1

Trayford +16

Characteristic evolutionary tracks



grey: passively evolving population

red: rapidly quenched elliptical galaxy

blue: quiescently star forming spiral

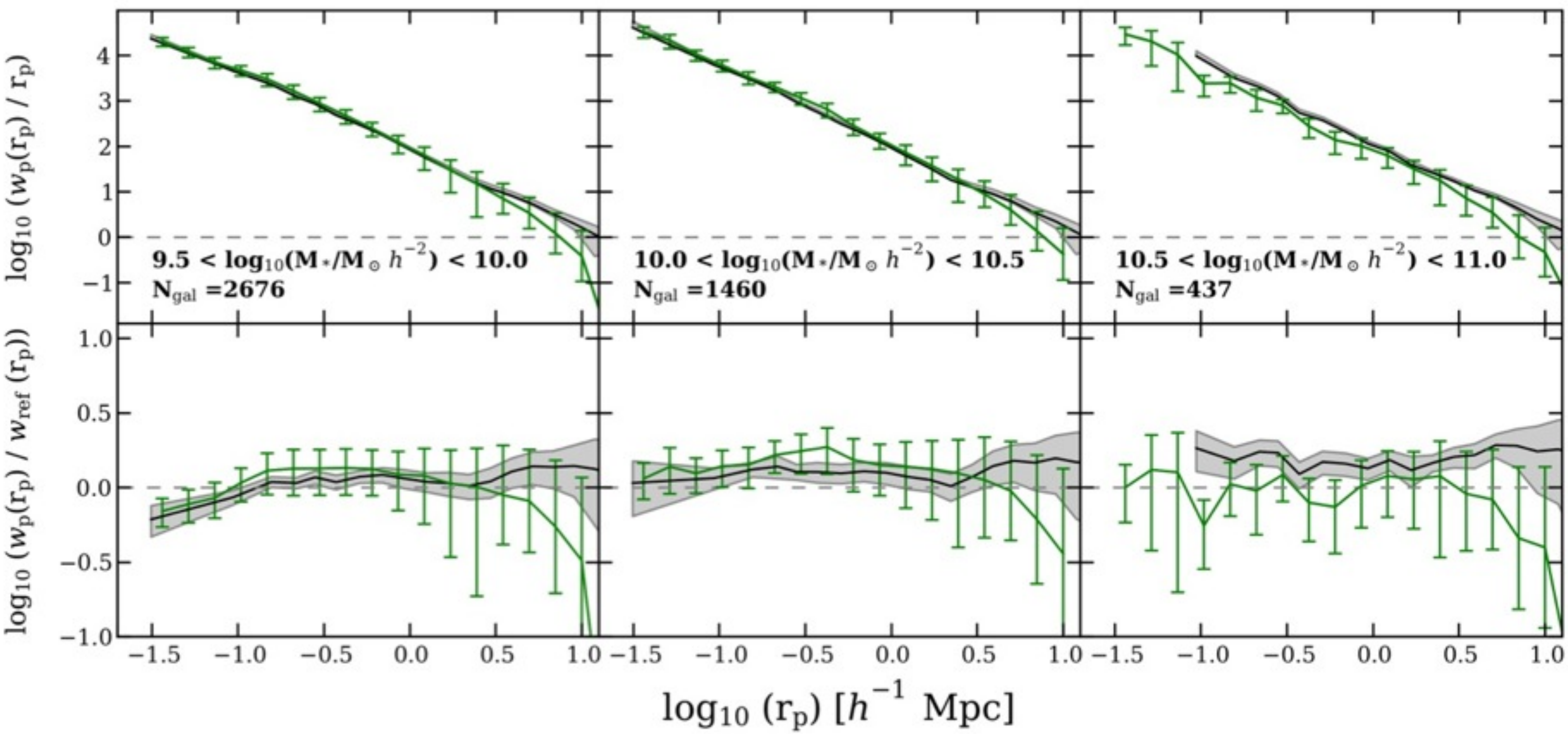
green: rejuvenating galaxy

Trayford +16

Clustering of galaxies as function of mass at z=0.1

Artale+16

Eagle simulation GAMA data



talk tomorrow!

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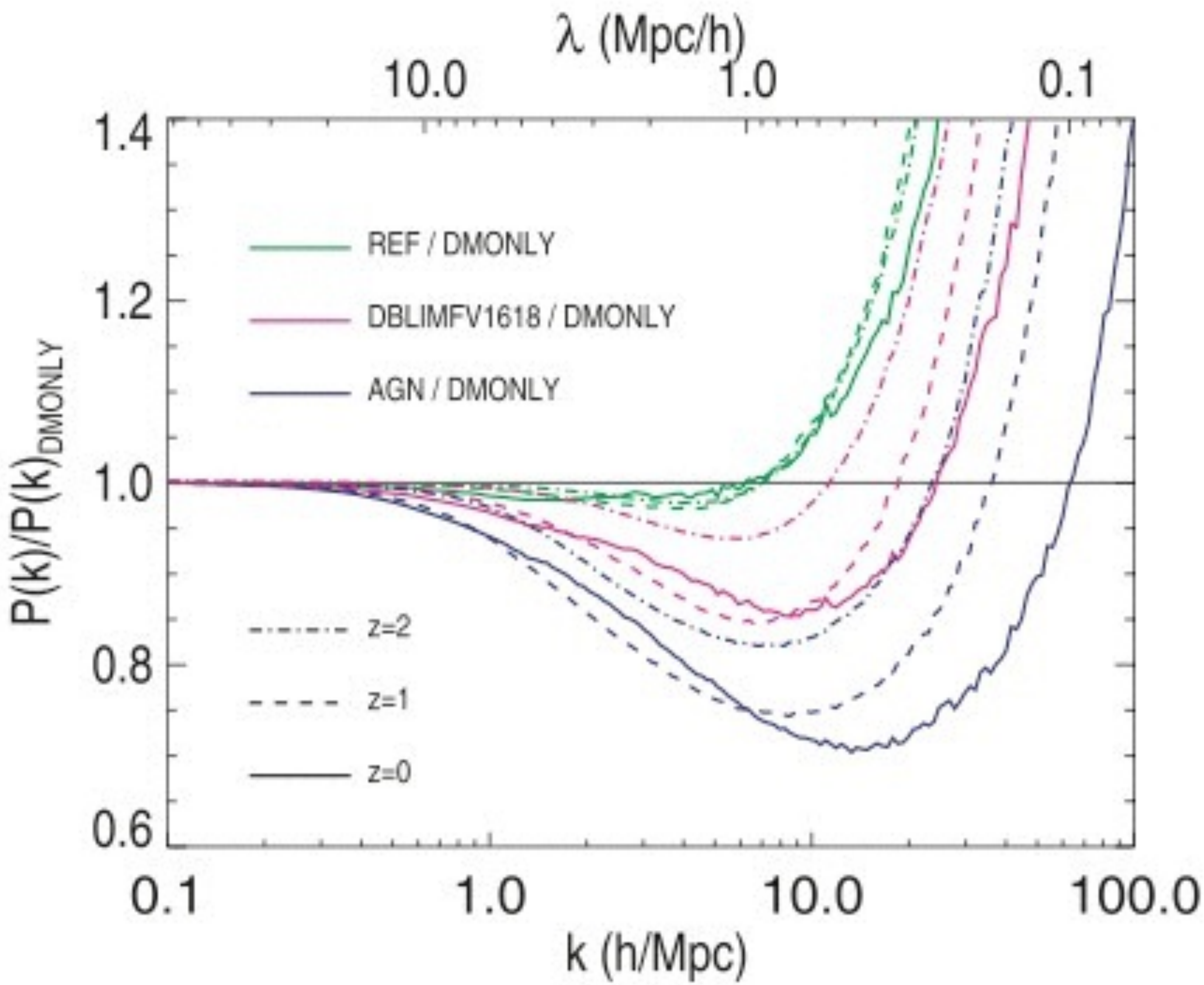
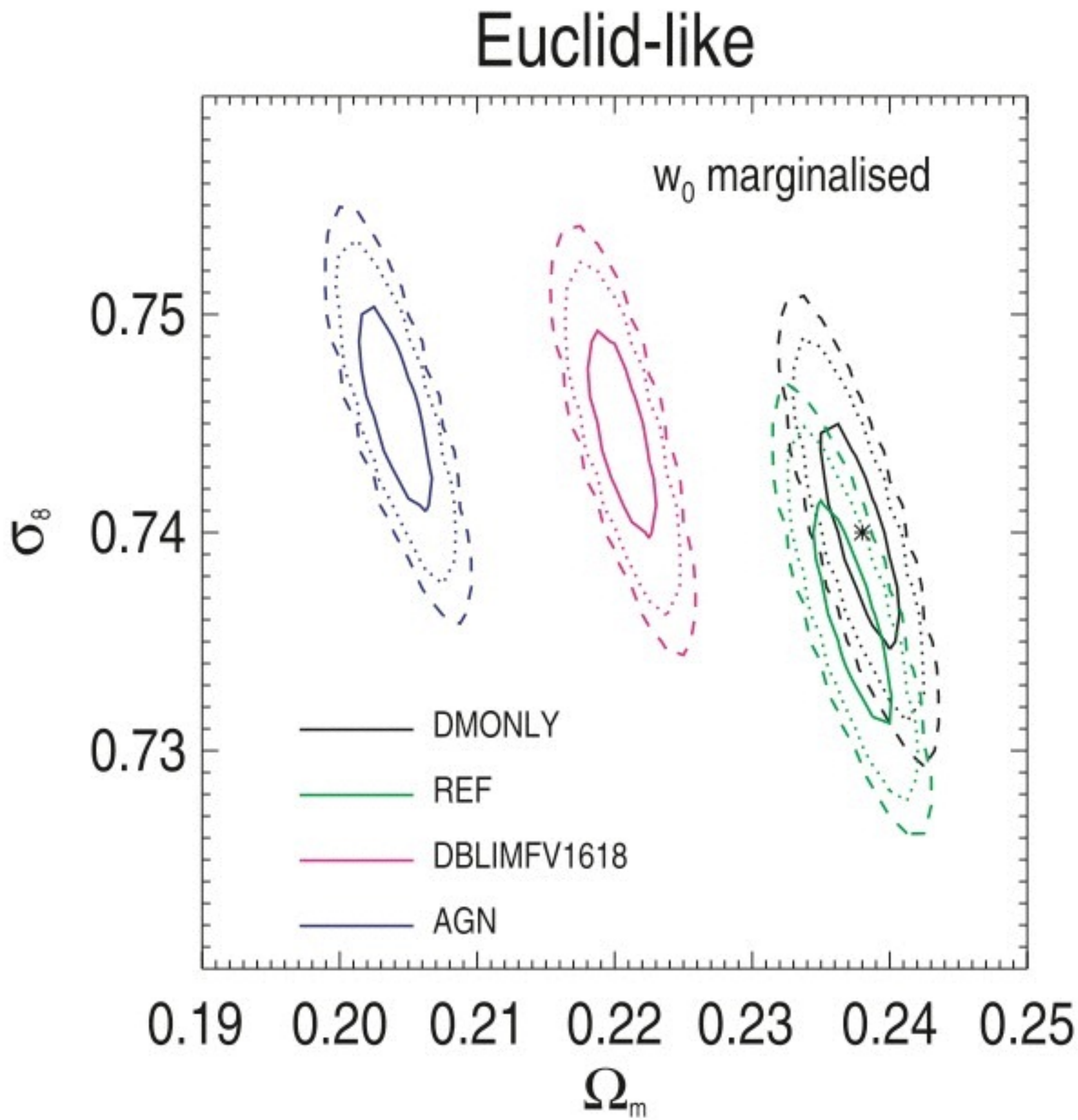
Quantifying the effect of baryon physics on weak lensing tomography

Elisabetta Semboloni,[1★] Henk Hoekstra,[1] Joop Schaye,[1] Marcel P. van Daalen[1,2] and Ian G. McCarthy[3]

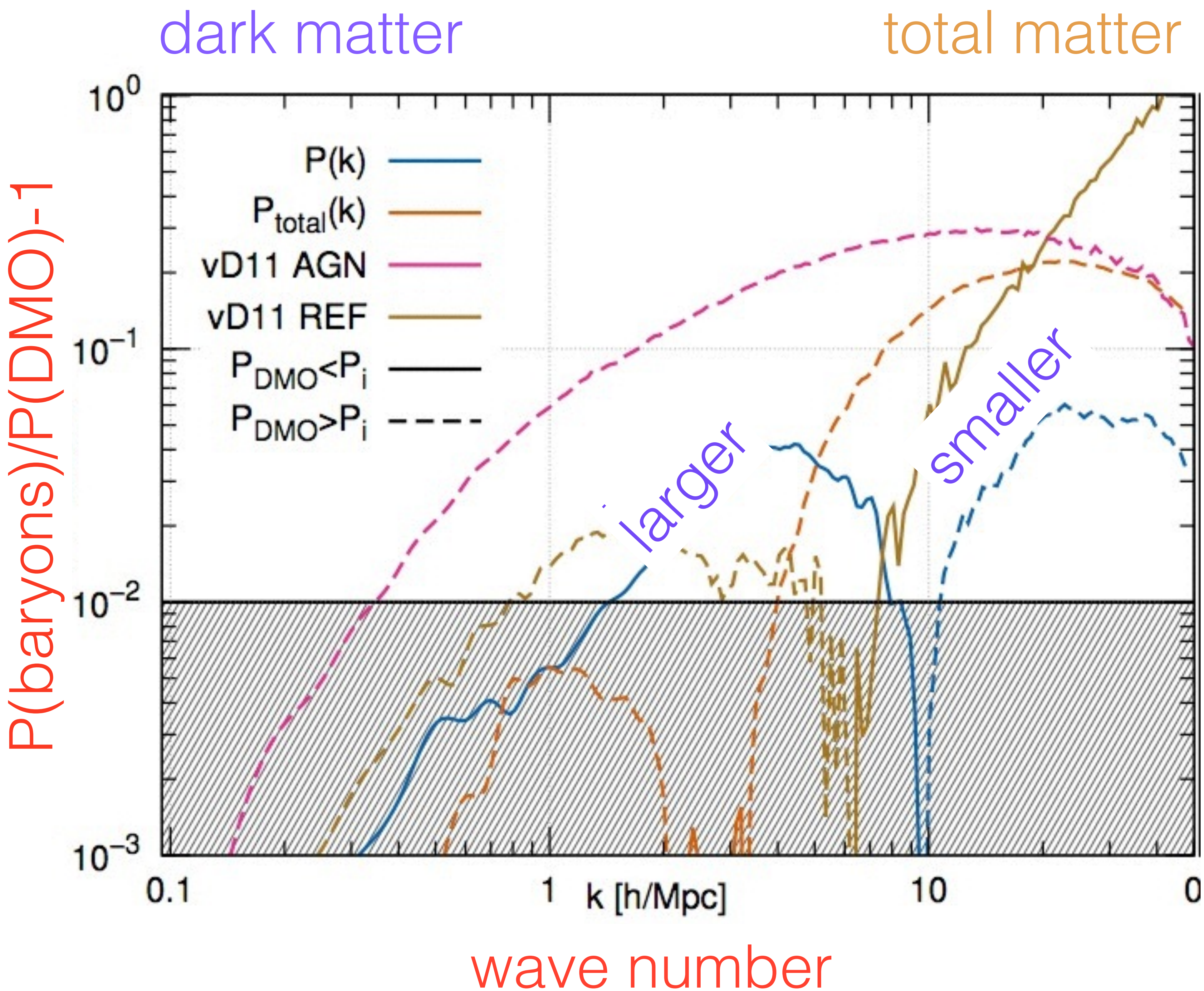


impact on “precision” cosmology



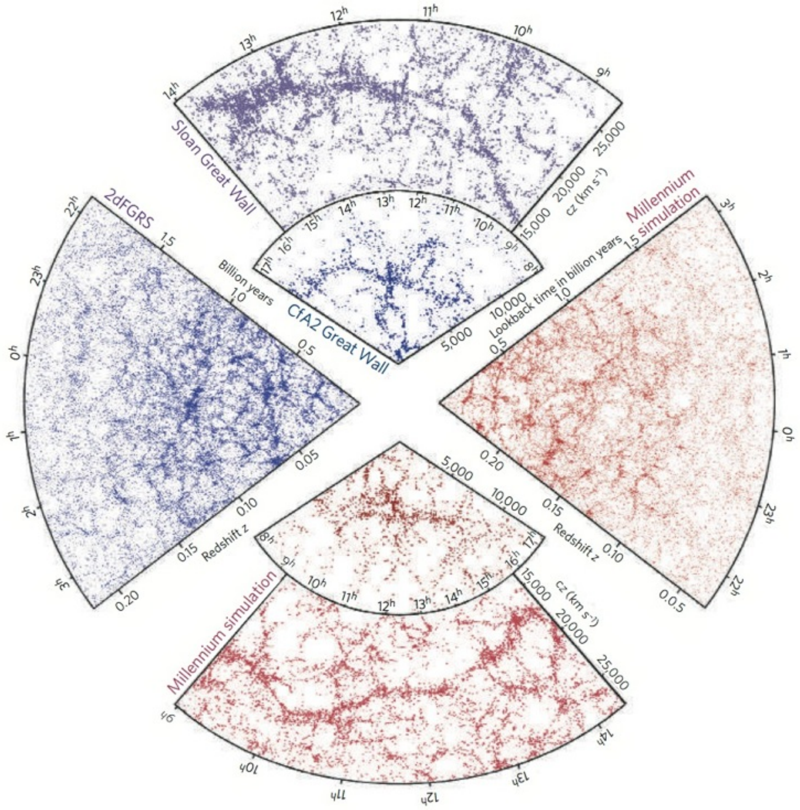
Semboloni+11

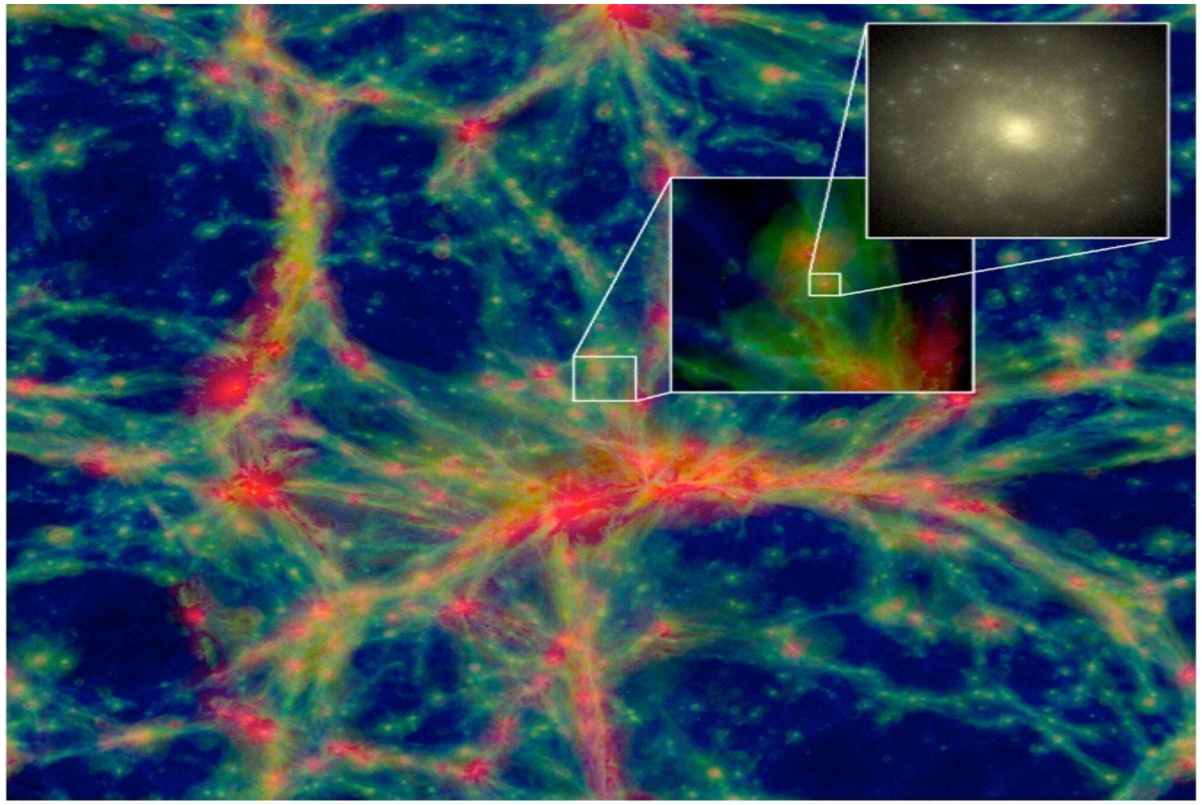
Effect of galaxy formation on power spectrum

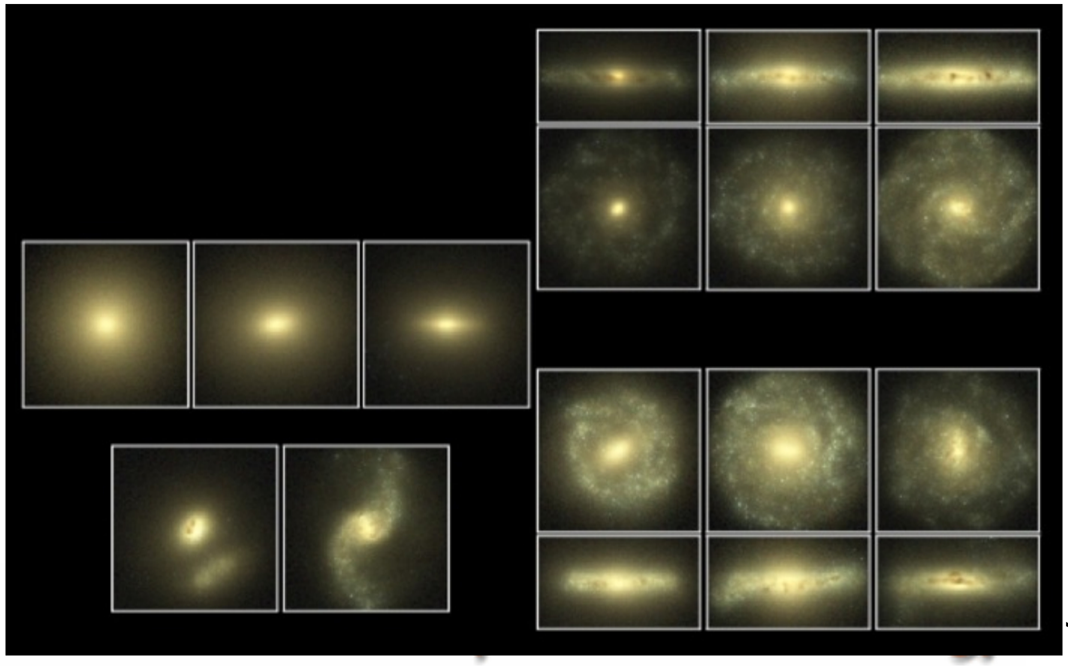


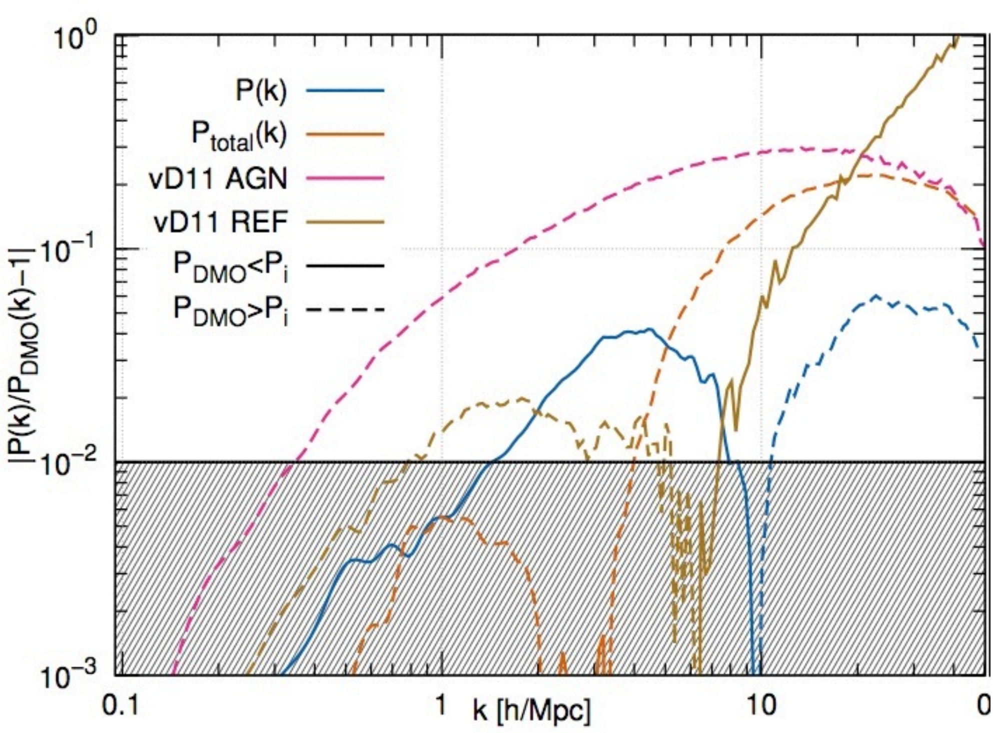
Hellwing+16

Summary









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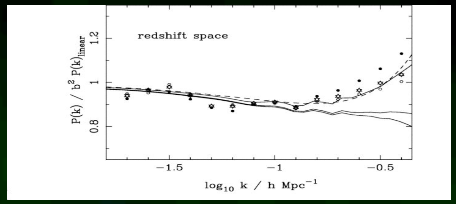
DM clustering I:
Stellar vs AGN feedback



Galaxy clustering and fundamental physics

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