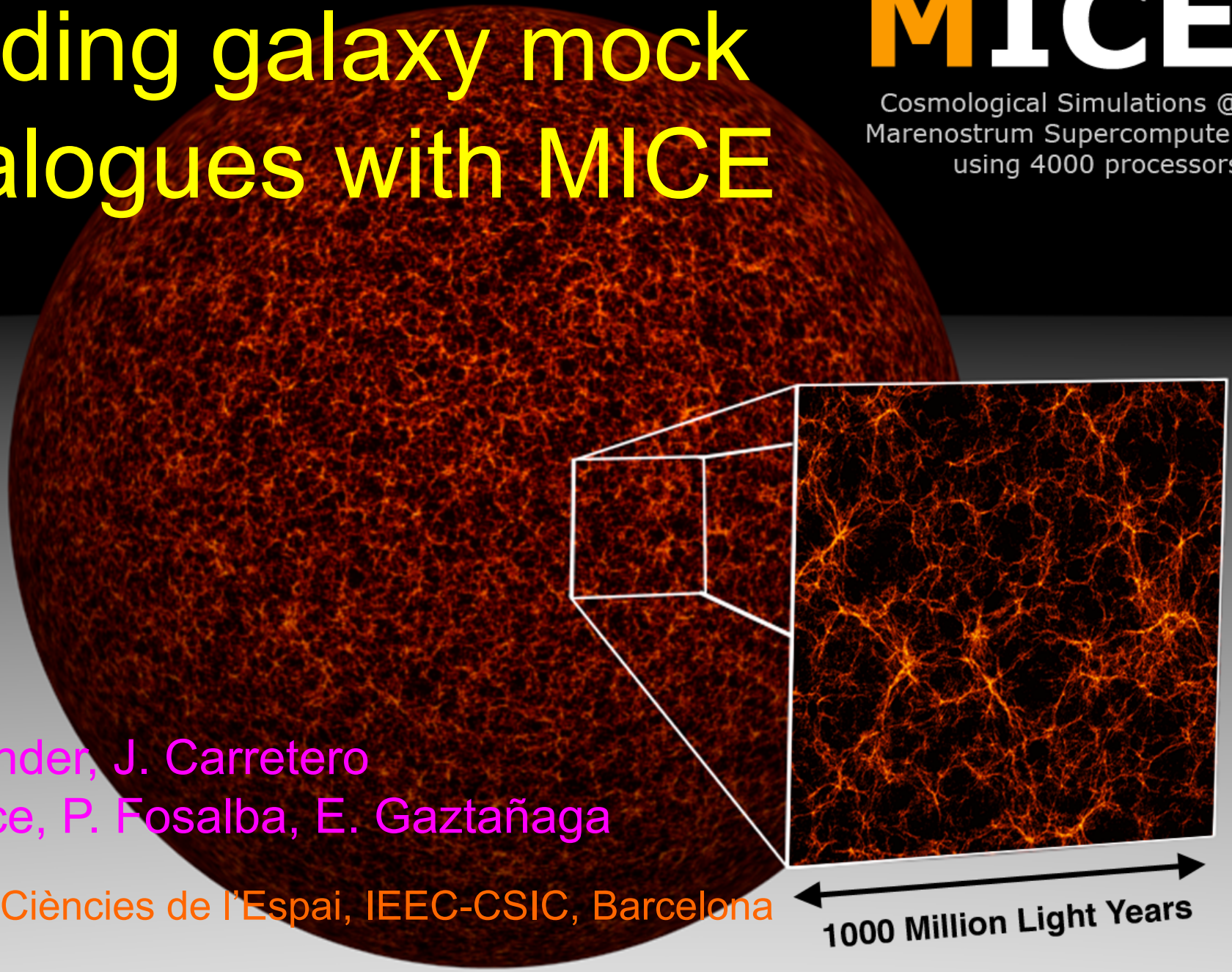
Building galaxy mock catalogues with MICE

MICE

Cosmological Simulations @
Marenostrum Supercomputer
using 4000 processors



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www.ice.cat/mice

Motivation

Mock galaxy catalogues

- understand and interpret observations
  - selection effects (magnitude, colour, extinction, seeing, masks,…)
  - systematic effects
  - errors and covariances
  - galaxy formation process
- design and optimize surveys
- test, validate and improve reduction and analysis pipelines

Methods

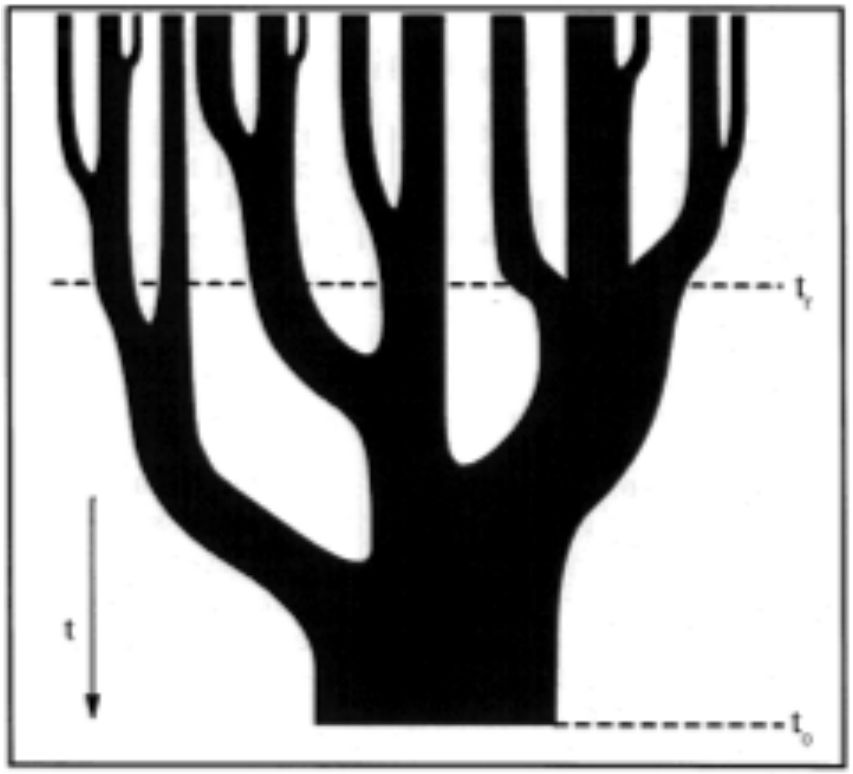
Mock galaxy catalogues with clustering

- In general start from a halo catalogue generated with a numerical simulation
  - hydrodynamical codes
  - semi-analytic models
  - halo-galaxy connection models
    - halo occupation distribution (HOD)
    - conditional luminosity function (CLF)
    - sub-halo abundance matching (SHAM)
    - local density correlations

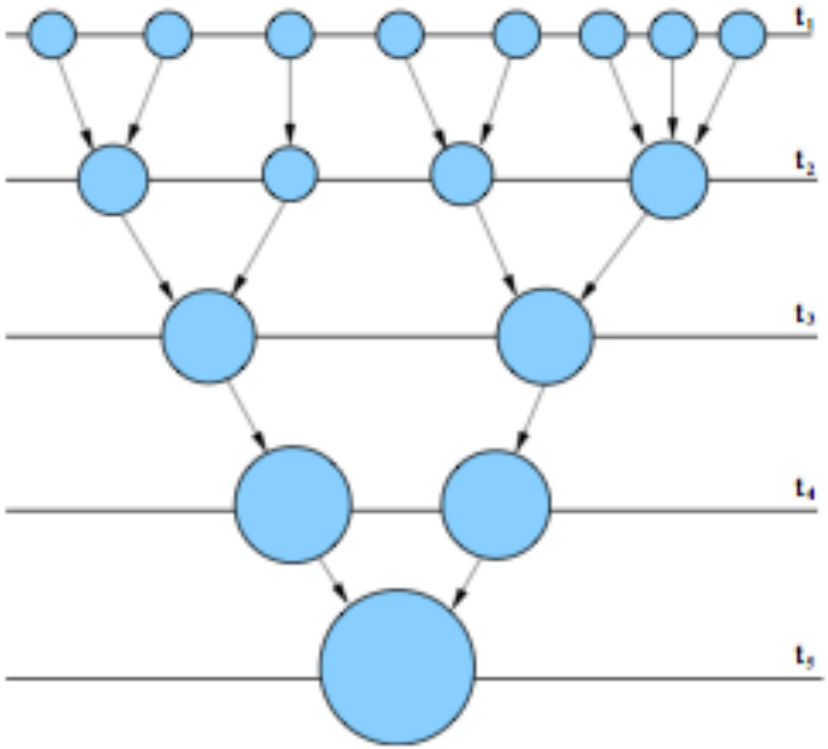
Methods

Semi-analytics models

- Start from a halo merger tree



Lacey & Cole 02

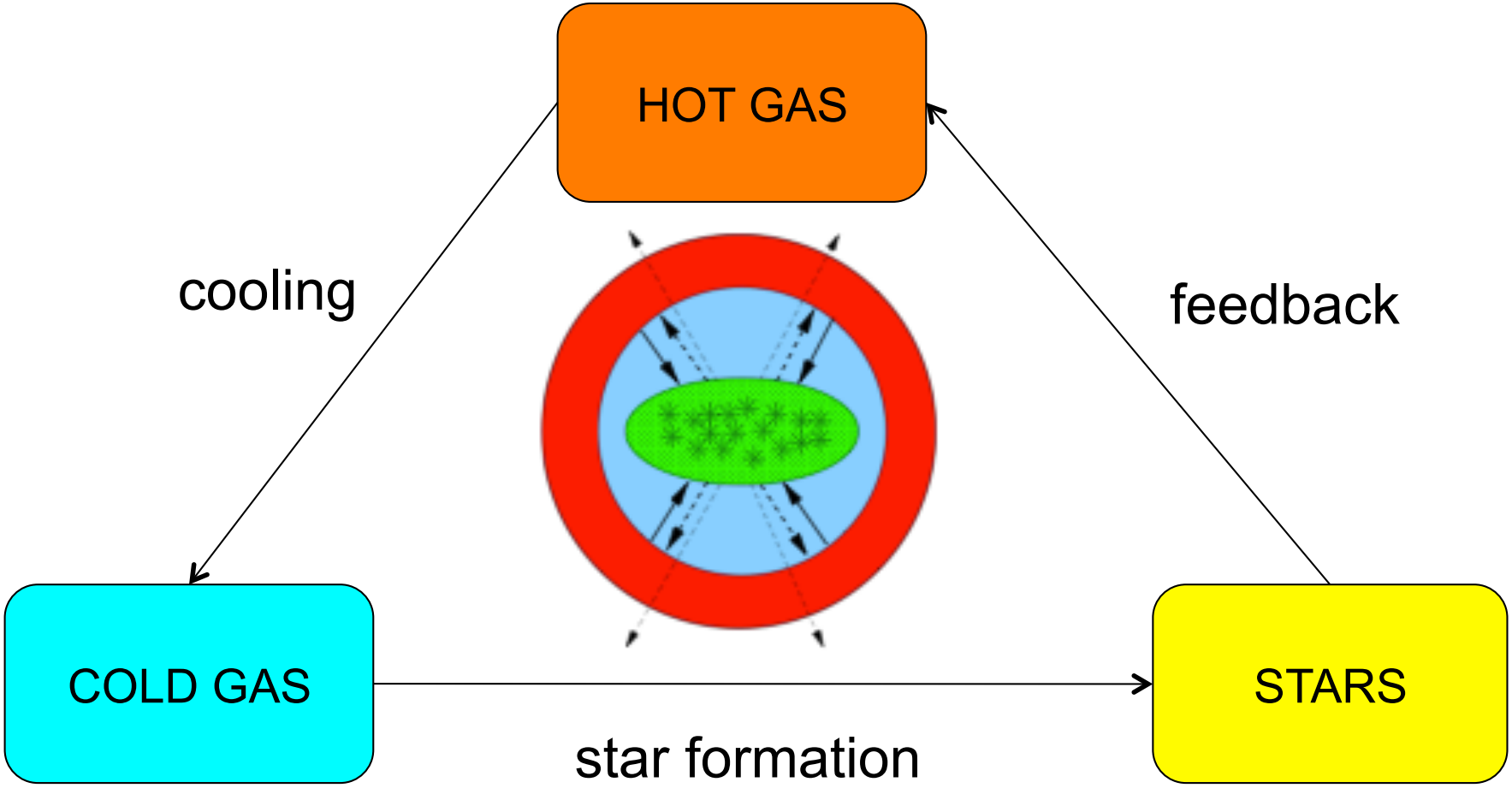


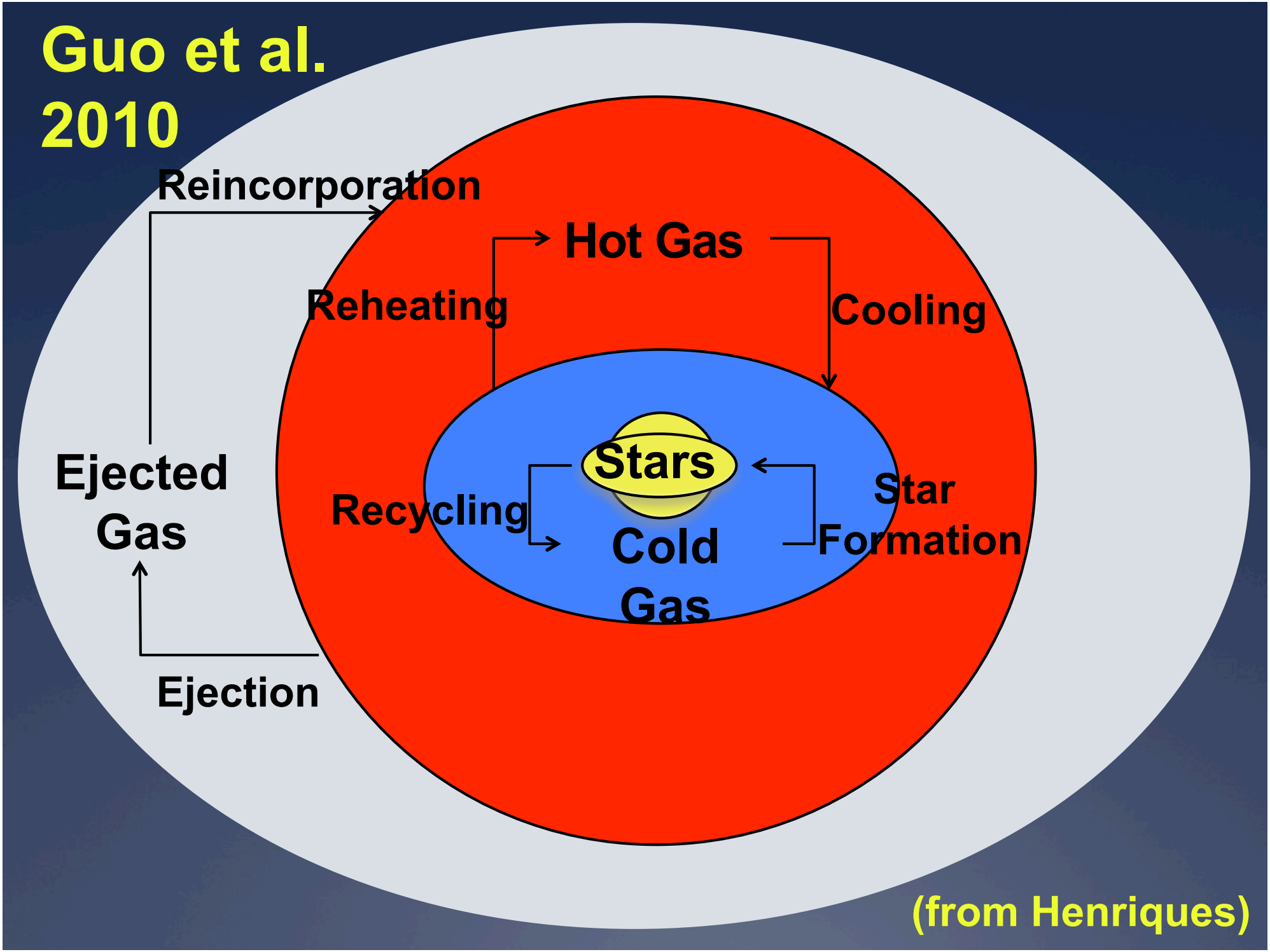
Baugh06

Methods

Semi-analytics models

- model the physical behaviour of baryons

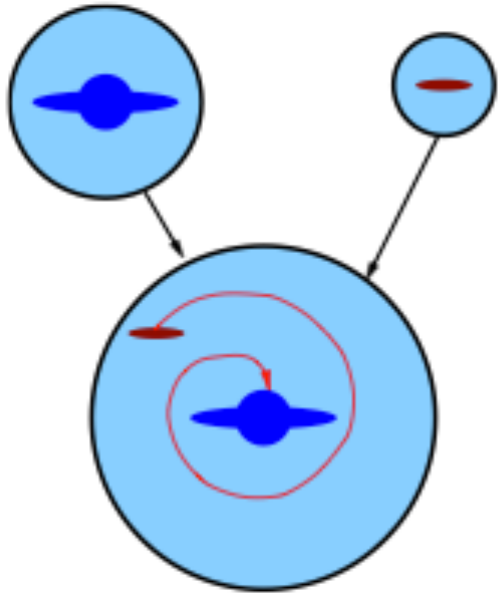



Guo et al.
2010
Reincorporation
Hot Gas
Reheating
Cooling
Ejected
Gas
Stars
Recycling
Star
Formation
Cold
Gas
Ejection
(from Henriques)

Methods

Semi-analytics models

- determine galaxy shapes and sizes
  - what happens when halos form/collapse
  - what happens when halos merge
  - what happens when halos accrete

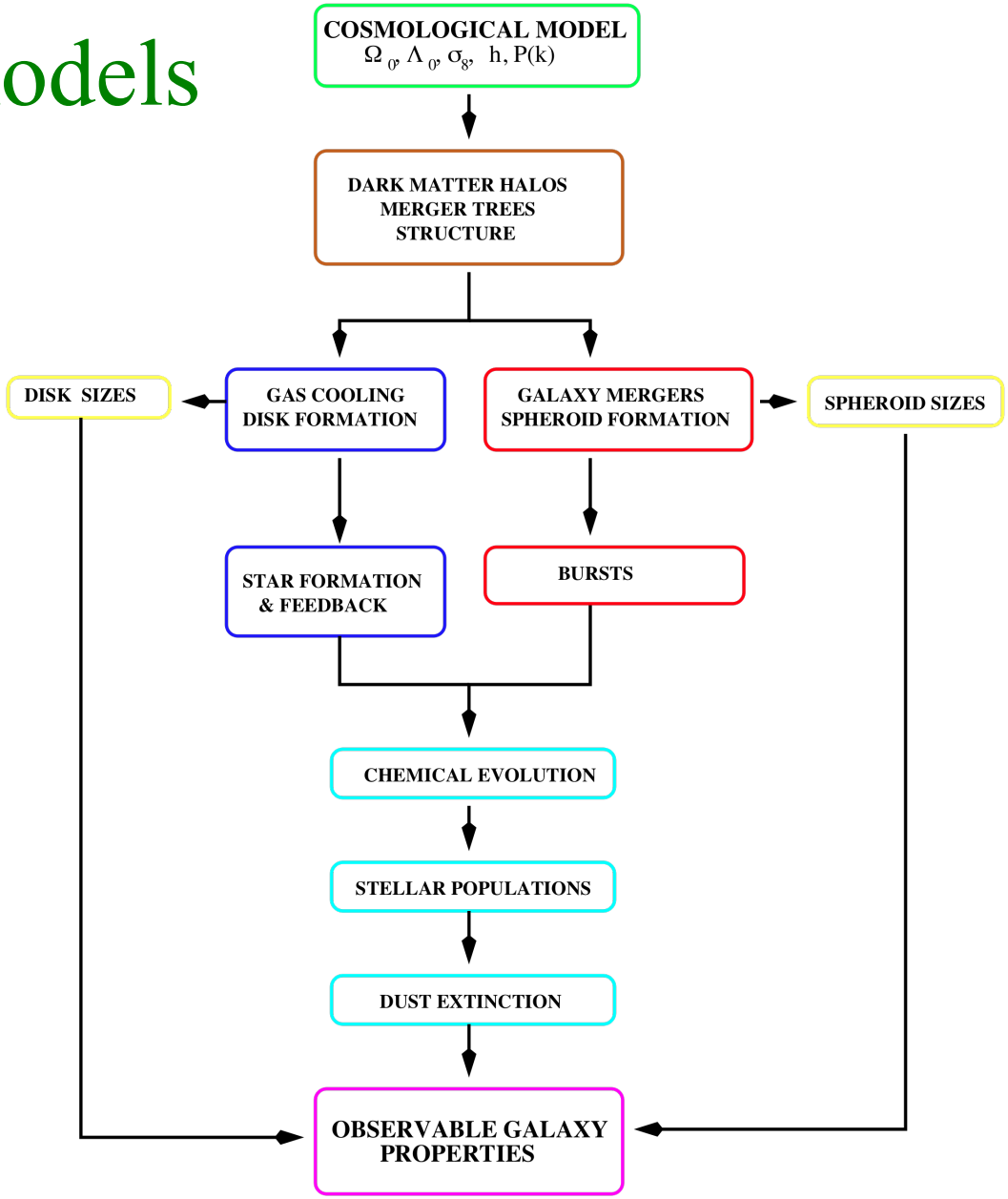


Baugh06

Methods

Semi-analytics models

- Example of processes



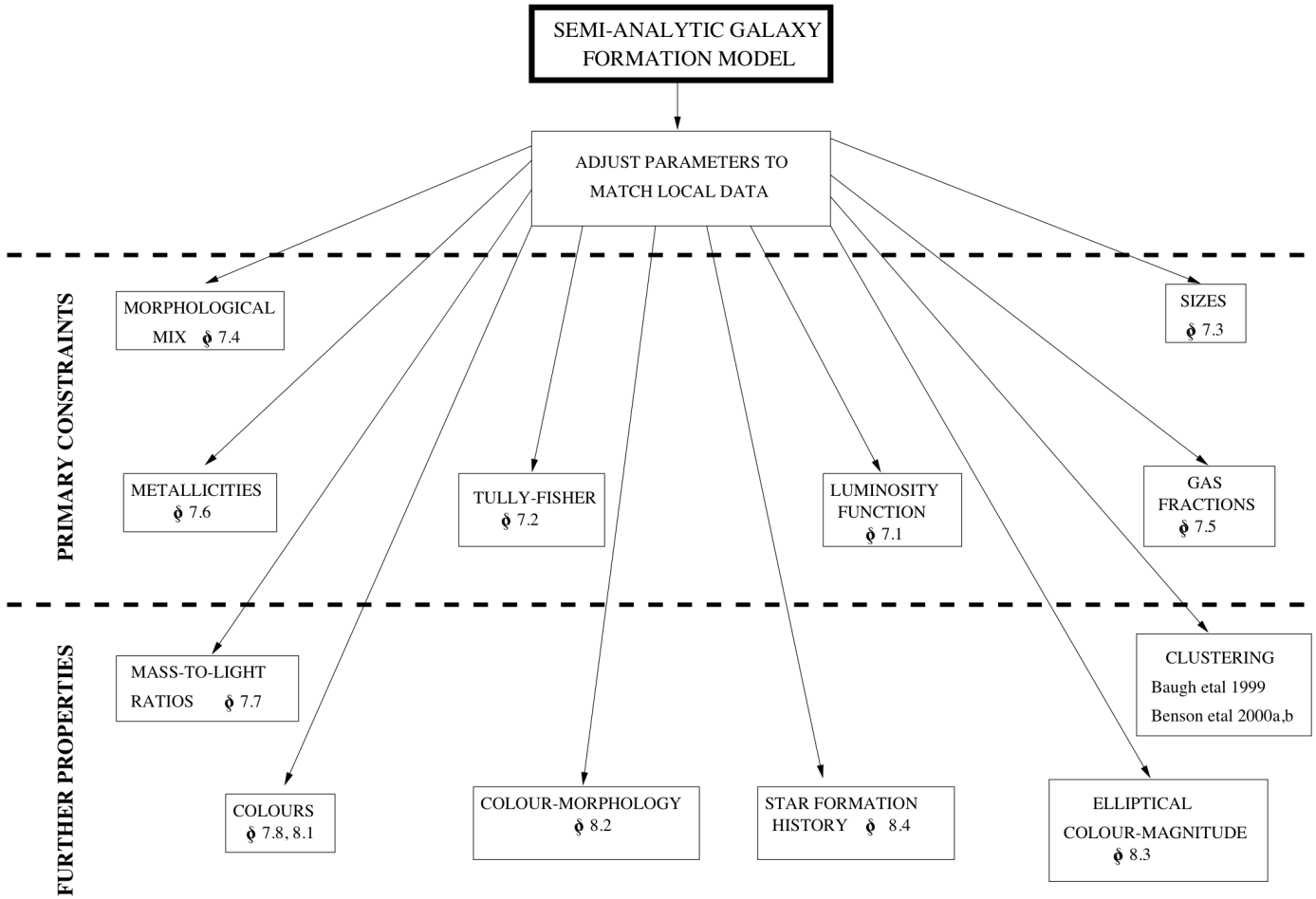
Cole00

Baugh06

Methods

Semi-analytics models

- Typical constraints



Cole00

Methods

Semi-analytics models

- Several models with different ways of implementing processes
  - galics Hatton 2003
  - galform Cole 2000
  - galacticus Benson 2010
  - L-galaxies de Lucia & Blaziot 2007
  - Morgana Monaco 2007
  - Menci 2006, Kang 2006, Somerville 2008, …..
- widely used Millenium mocks: Croton 2006, Bower 2006, Guo 2011, de Lucia & Blaizot 2007
- Review: Baugh 2006

Methods

Galaxy-halo connection models

- Normally start from a catalogue of halos found in an N-body simulation.
- However, there are faster schemes to generate halo catalogues like PTHalos (Scoccimarro & Sheth 2002; see Manera's talk)

Methods

Halo Occupation Distribution models

- Provides probability of having N galaxies in a halo of mass M_h : $P(N_{gal} \mid M_h)$
- Halo galaxies: centrals and satellites (Kratsov 2004)
- Normally given with 3 parameters (Berlind & Weinberg 2002):

$$N_{gal} = \begin{cases} 0 & \text{if } M_h < M_{min} \\ (M_h/M_1)^{\alpha} & otherwise, \end{cases}$$

- More recently 5 parameters used (Zheng 2005):

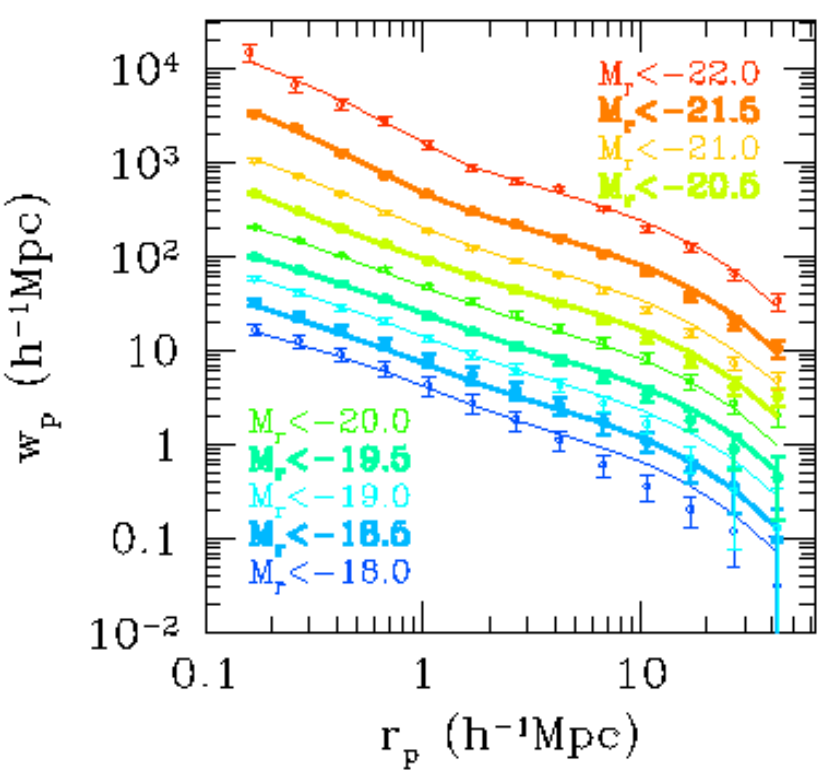
$$\langle N_{gal} \rangle = N_{cen} + N_{sat} = \frac{1}{2}\left[1 + erf\left(\frac{\log M_h - \log M_{min}}{\sigma_{\log M_h}}\right)\right]\left[1 + \left(\frac{M_h - M_0}{M_1'}\right)^{\alpha}\right]$$

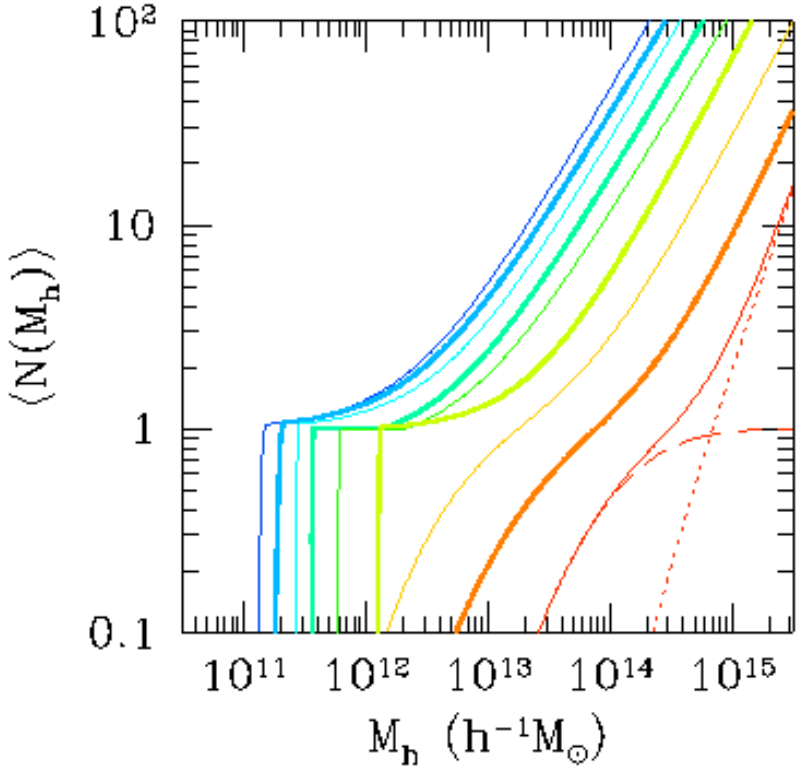
- find parameters that best fit the observed clustering as a function of luminosity

Methods

Halo Occupation Distribution models

- SDSS/DR7 Zehavi et al 2011:





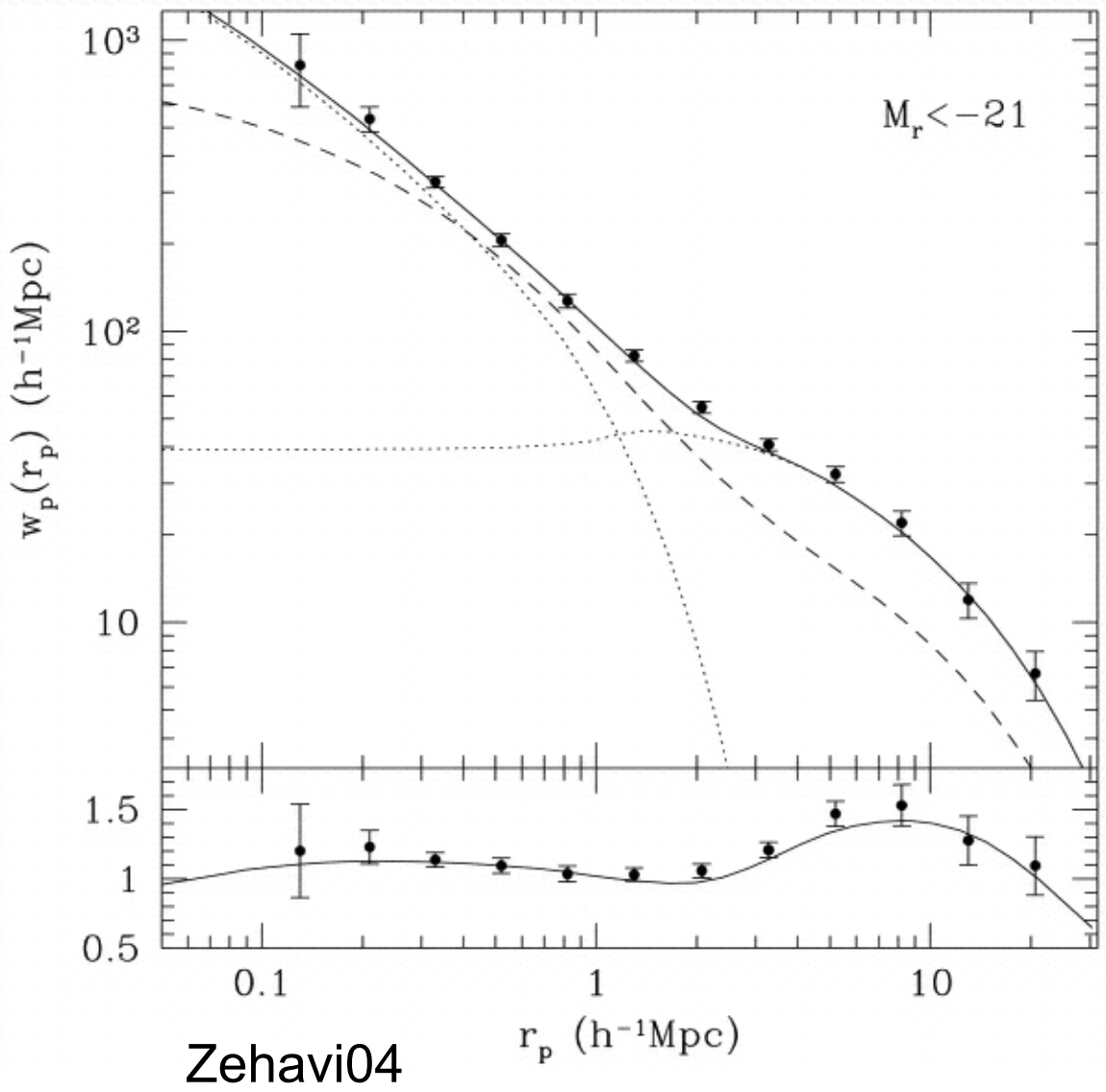
$$\langle N_{gal}\rangle = N_{cen} + N_{sat} = \frac{1}{2}\left[1 + erf\left(\frac{\log M_h - \log M_{min}}{\sigma_{\log M_h}}\right)\right]\left[1 + \left(\frac{M_h - M_0}{M_1'}\right)^{\alpha}\right]$$

Methods

Halo Occupation Distribution models

- clustering: 1-halo + 2-halo terms

- Jing98, Benson00, Seljak00, Scoccimarro01, Berlind & Weinberg02, Bullock02, Zheng02, Berlind03, Zehavi05, Skibba&Sheth09,…



Zehavi04

Methods

Conditional luminosity models

- Similar to HOD: $P(N_{sat} \mid M_h) \Rightarrow \Phi(L \mid M_h)$
- $\Phi(L \mid M_h)$ density of galaxies with luminosity L +dL in halos of mass M_h
- $\Phi(L \mid M_h) = \Phi_{cen}(L \mid M_h) + \Phi_{sat}(L \mid M_h)$
- Luminosity function

$$\Phi(L) = \int_0^\infty \Phi(L|M_h) \frac{dn}{dM_h} dM_h$$

- Peacock&Smith00, Yang03, van den Bosch03, Cooray05, Cooray06, van den Bosch07, Wang11

Methods

Sub-halo abundance matching

- match cumulative luminosity function to cumulativve halo mass function
- assign luminosities to halos in an rank-ordered fashion from most massive-luminous to least
- By construction reproduces LF
- Need to add scatter otherwise the 2pt correlation function is not well fit
- Kratsov 04, Tasitsiomi 04, Vale&Ostriker04, Conroy 06, Behroozi10, Trujillo-Gomez 11, Nuza 12,….

Methods

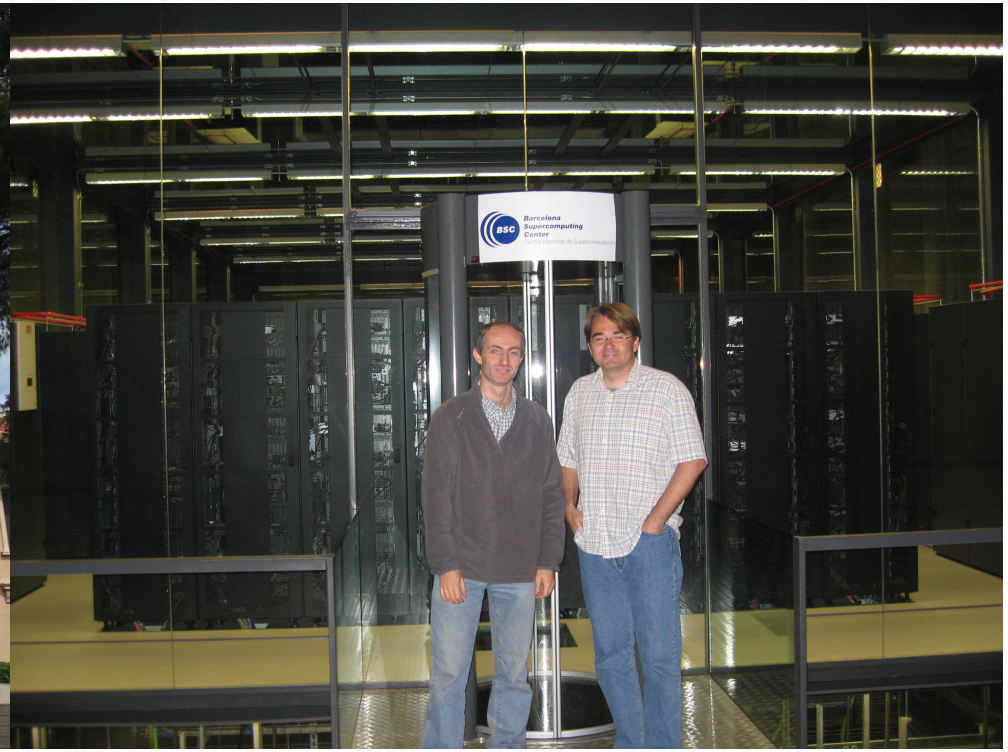
Local density correlations

- add galaxies to dark matter particles based on dark matter local density
- ADDGALS: Weschler, Busha, et al (see Evrard's talk)

Mock Galaxy catalogues with MICE

MICE: Marenostrum Institut de Ciències de l'Espai

- Project to develop very large numerical cosmological simulations using the Marenostrum supercomputer @ Barcelona
  - 10000 processors, 20TB RAM, 100 Teraflops



Mock Galaxy catalogues with MICE

MICE: Marenostrum Institut de Ciències de l'Espai

- Project to develop very large numerical cosmological simulations using the Marenostrum supercomputer @ Barcelona
  - 10000 processors, 20TB RAM, 100 Teraflops
- Simulations to support the science and projects of the cosmology ICE group (DES, PAU, Euclid)
- Run Gadget N-body simulations with 10^9-10^{11} dark matter particles in volumes 1-500 Gpc^3 => 5 orders of magnitude dynamical range
- Terabytes of simulated data stored at Port d'Informació Científica (PIC: LHC Tier1 data center & Euclid data center at Barcelona)

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Simulations

MICE simulations

Simulations run

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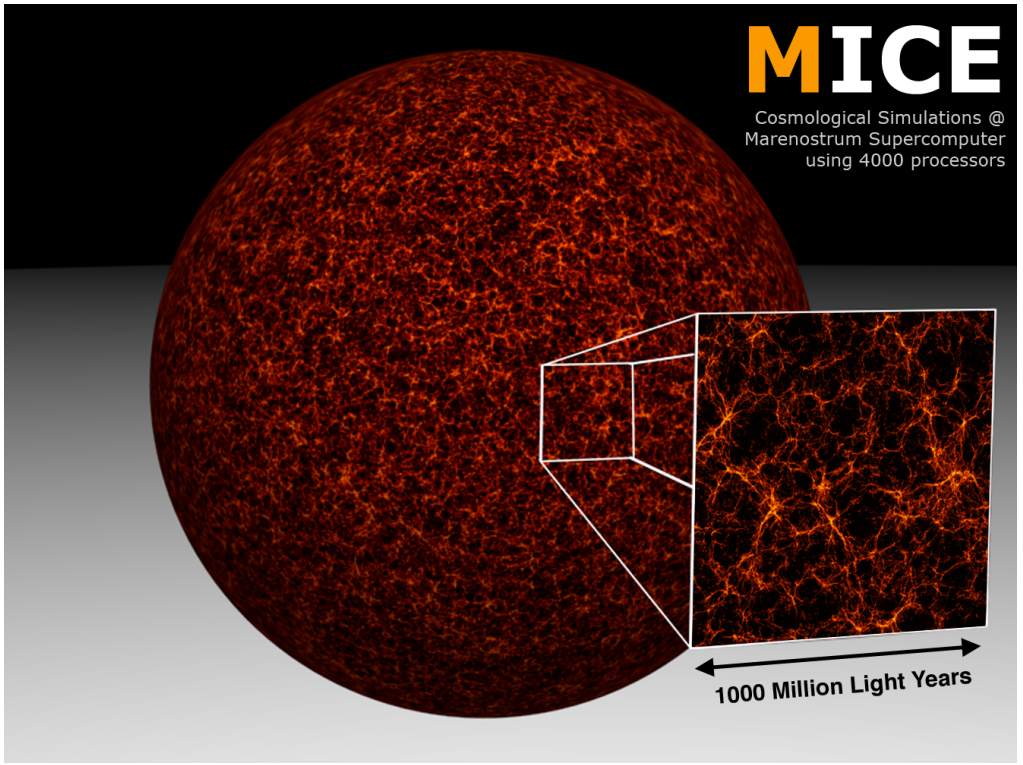
N	Box	Mass[Msun/h]	
800^3	1200 Mpc/h	2.3×10^{11}	(x20 realizations)
1024^3	1500 Mpc/h	2.3×10^{11}	
1024^3	3000 Mpc/h	1.9×10^{12}	
1200^3	4500 Mpc/h	3.7×10^{12}	
2048^3	3000 Mpc/h	2.3×10^{11}	
2048^3	7700 Mpc/h	3.7×10^{12}	
4096^3	3000 Mpc/h	3.0×10^{10}	

- Produce lightcones
- All-sky lensing maps
- generate halo catalogues
- produce galaxy catalogues



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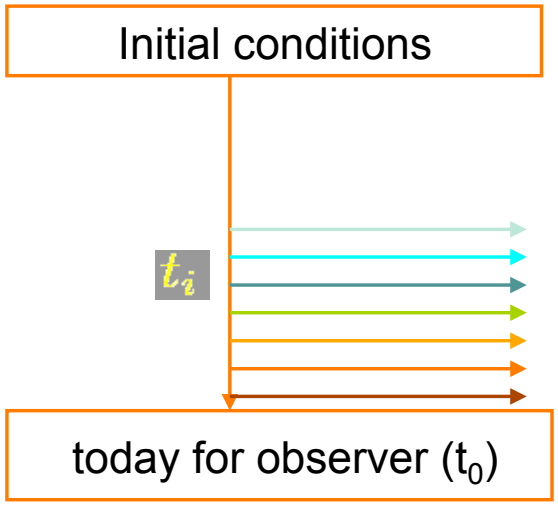
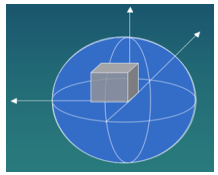
MICE simulations

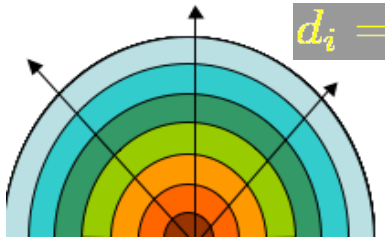
Lightcone

- Built-in within Gadget: place galaxies in lightcone based on their position as time progresses and the light travel time





Box replication
to fill up LC volume



- Depending on simulation size: lightcone box replication

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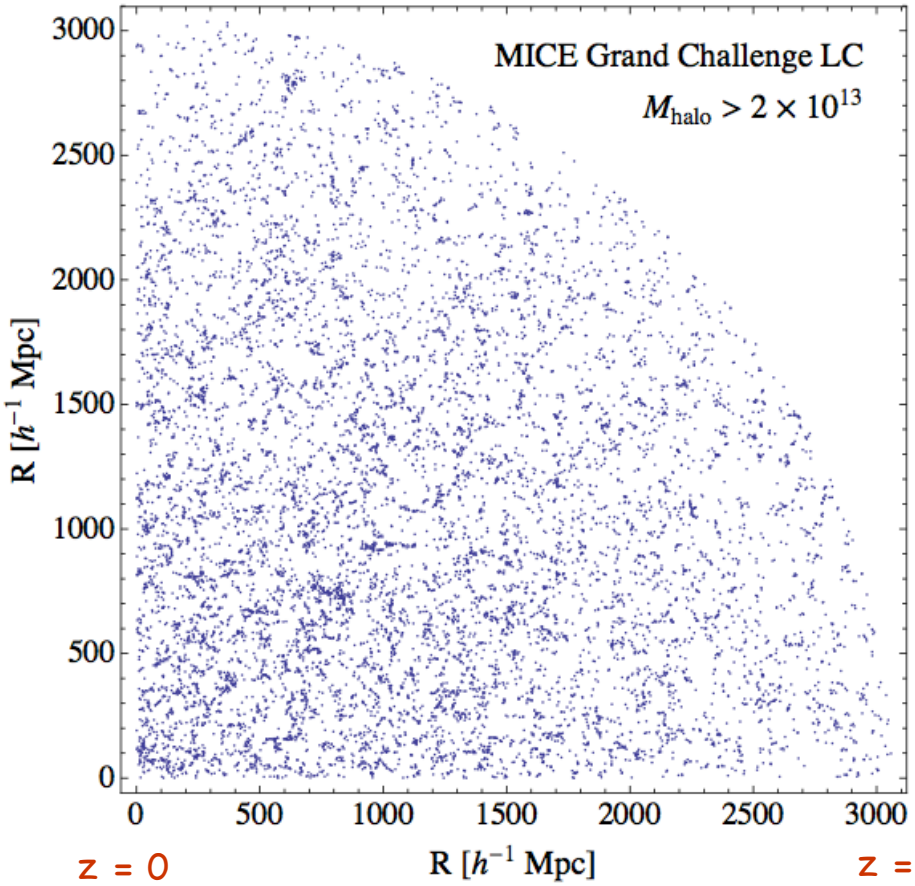
MICE simulations

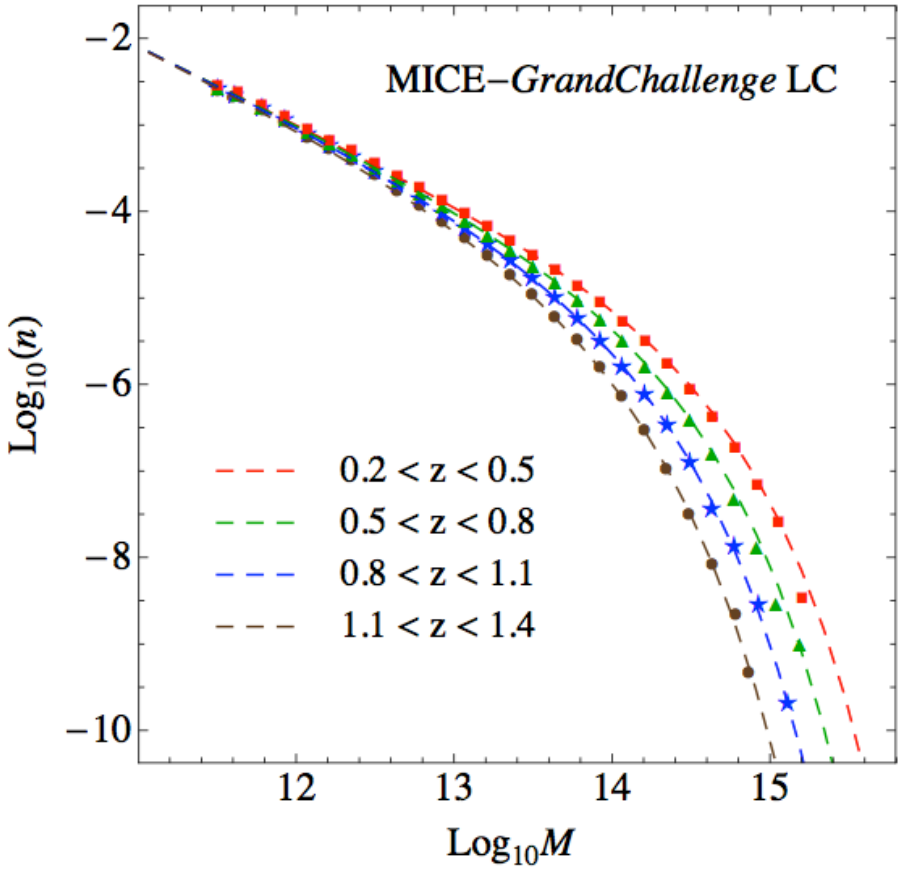
Halo catalogue & Mass function

- Halos with Friend-of-Friends (b=0.2/0.164)
- Mass function: massive halos Crocce et al 2010



z = 0

z = 1.4



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MICE simulations

Halo catalogue & Mass function

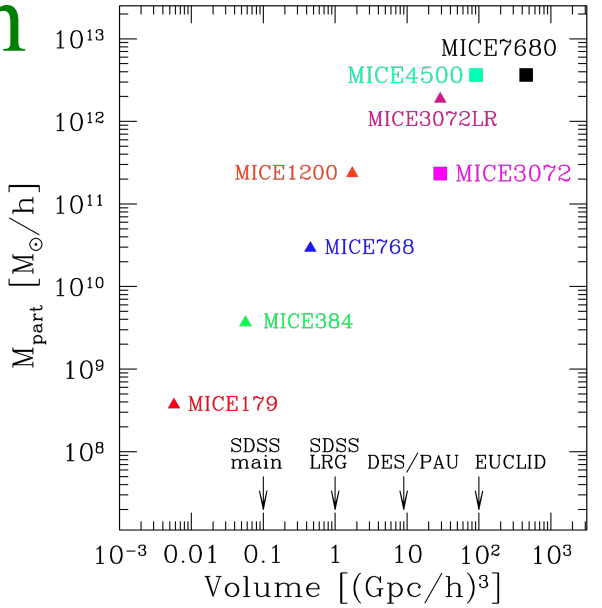
- combining several simulations with different volumes and particle mass

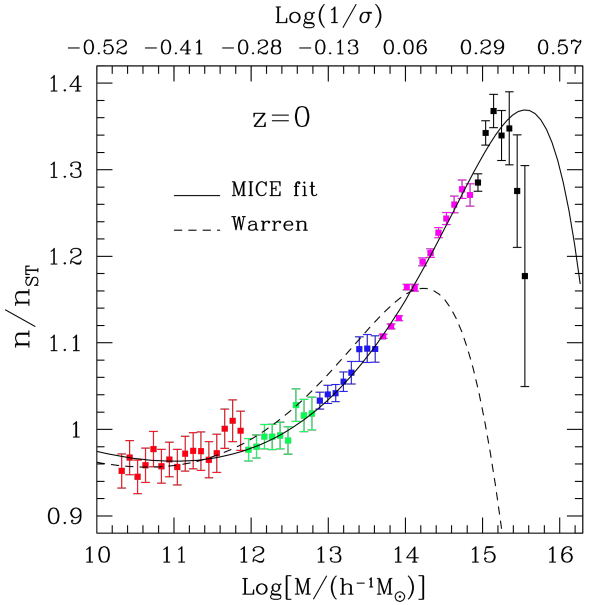
$$f(\sigma, z) = \frac{M}{\rho_b} \frac{dn(M,z)}{d\ln\sigma^{-1}(M,z)}$$

- Crocce et 10 fitting formula

$$f_{\rm MICE}(\sigma, z) = A(z)\left[\sigma^{-a(z)} + b(z)\right]\exp\left[-\frac{c(z)}{\sigma^2}\right] \qquad (22)$$

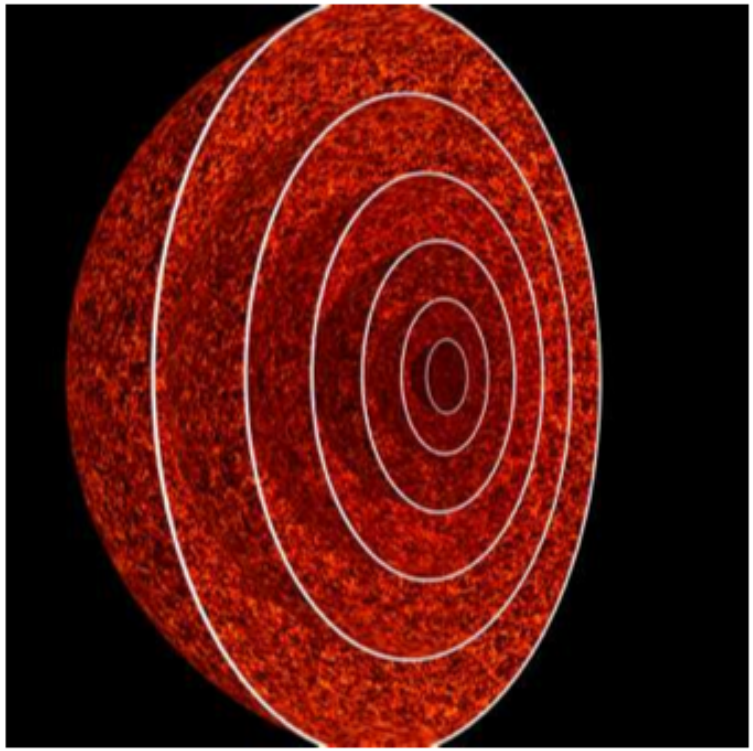
with $A(z) = 0.58(1+z)^{-0.13}$, $a(z) = 1.37(1+z)^{-0.15}$, $b(z) = 0.3(1+z)^{-0.084}$, $c(z) = 1.036(1+z)^{-0.024}$.





Lensing in MICE simulations

"The onion universe: all sky light-cone simulations in spherical shells"
Fosalba et al, MNRAS, **391**, 435 (2008)



- Split the data into thin shells.
- Interpolate into (Healpix) pixels
- Combine to produce convergence maps

$$\kappa(\theta) = \frac{3H_0^2\Omega_m}{2c^2} \int dr\ \delta(r,\theta) \frac{(r_s - r)r}{r_s\ a}$$

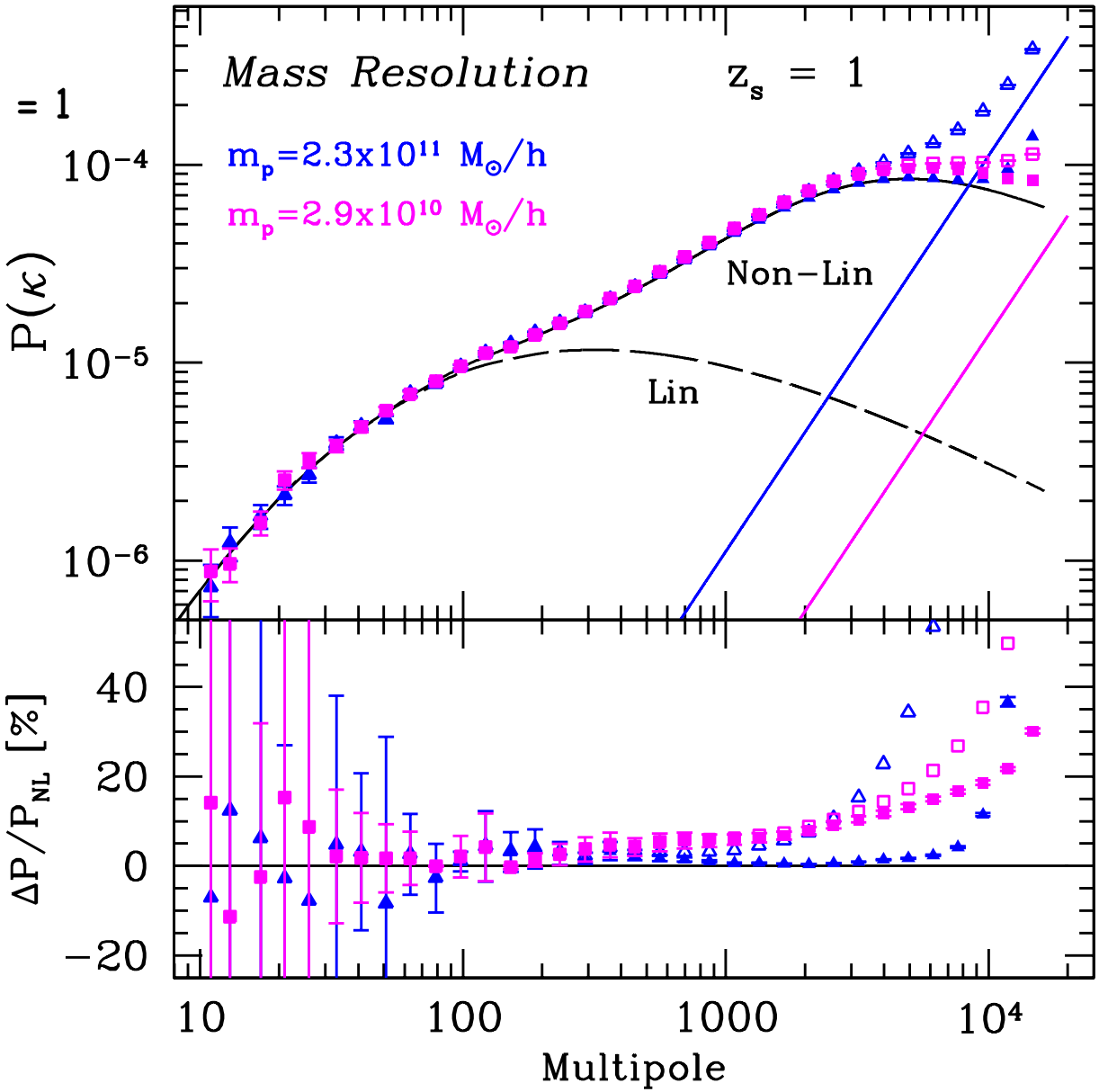
$$\kappa(i) = \frac{3H_0^2\Omega_m}{2c^2} \sum_j \delta(i,j)\ \frac{(r_s - r_j)r_j}{r_s a_j}\ dr_j$$

- From this it is possible to obtain other lensing observables, e.g. shear, magnification, flexion, etc *in the Born approximation*

Lensing in MICE simulations

- Convergence power spectrum for sources at z = 1 (sub arc-min resolution)

$$P(\kappa) = \frac{1}{2\pi}\ell(\ell+1)C_\ell$$



MICE Galaxy Catalogue

- ✓ uses MICE *Grand Challenge simulation*
  70 billion particles, 3 Gpc/h box, $m_p = 3 \times 10^{10}\ M_\odot$
- ✓ Lightcone without repetition up to z=1.4
- ✓ FoF halos with b=0.2 (150 millions, $n_{part}>10$)
- ✓ All-sky lensing maps
- ✓ 1 octant (5000 sq.deg.) filled with HOD galaxies
- ✓ apply lensing properties to each galaxy

Box Size (Mpc/h)	Number of Particles	Particle Mass (x10^{10} Msun/h)	PMGrid size	Initial conditions	Initial redshift	l_{soft} (kpc/h)	MaxSize Timestep
3072	4096^3	2,927	4096^3	ZA	100	50	0,02

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MICE simulations

General Plan

- Build mock galaxy catalogues from N-body halos using an HOD prescription
- Generate: positions, luminosities, colours and lensing
- Start at z=0 where constraints more stringent
- Constraints
  - luminosity function
  - colour-magnitude diagram
  - clustering as a function of luminosity and colour
- Implement recipes to higher redshifts

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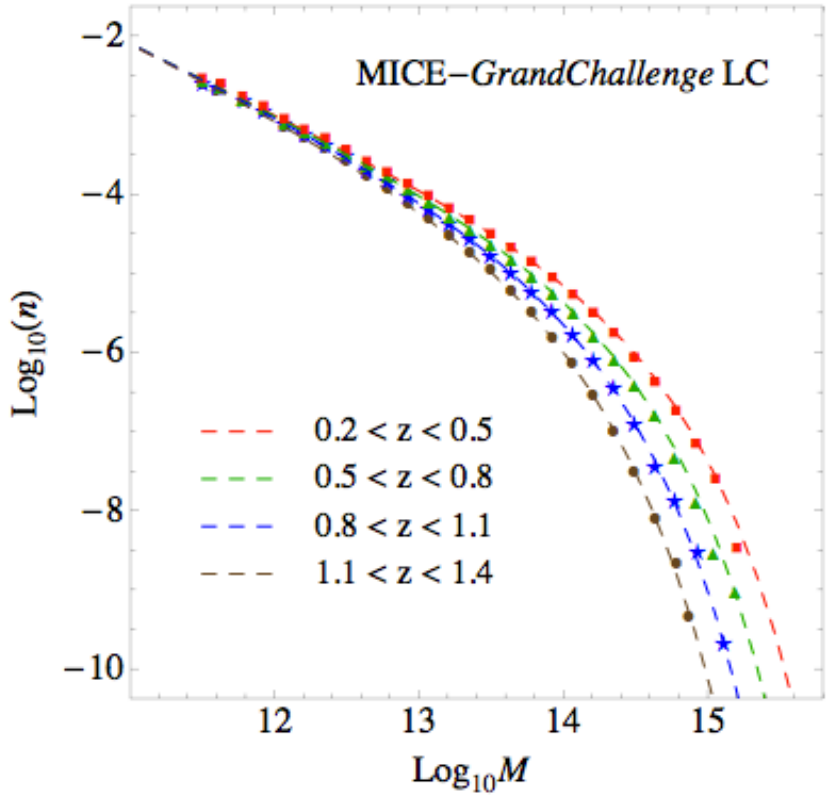
Mock galaxy catalogues

Starting point

- Large N-body MICE simulation provides halos both in the lightcone and in snapshots
- Use snapshots first to calibrate method then apply to lightcone



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Mock galaxy catalogues

Assign luminosities and HOD

- Each halo contains one central galaxy and maybe some satellite galaxies
- Compute how many satellite galaxies populate each halo (HOD) $<N_{sat}> = (M/M_1)^{\alpha}$
- Assign luminosities to central and satellite galaxies conserving the luminosity function
- Use an abundance matching technique to obtain a relation between galaxy luminosity and halo mass
- Apply that relation to obtain luminosities for central galaxies

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Mock galaxy catalogues

Assign luminosities and HOD

- Compute the resulting luminosity function for satellite galaxies
- Draw random luminosities for satellites galaxies from the LF of satellites

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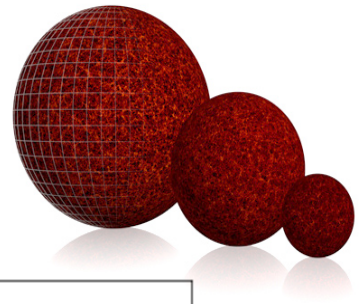
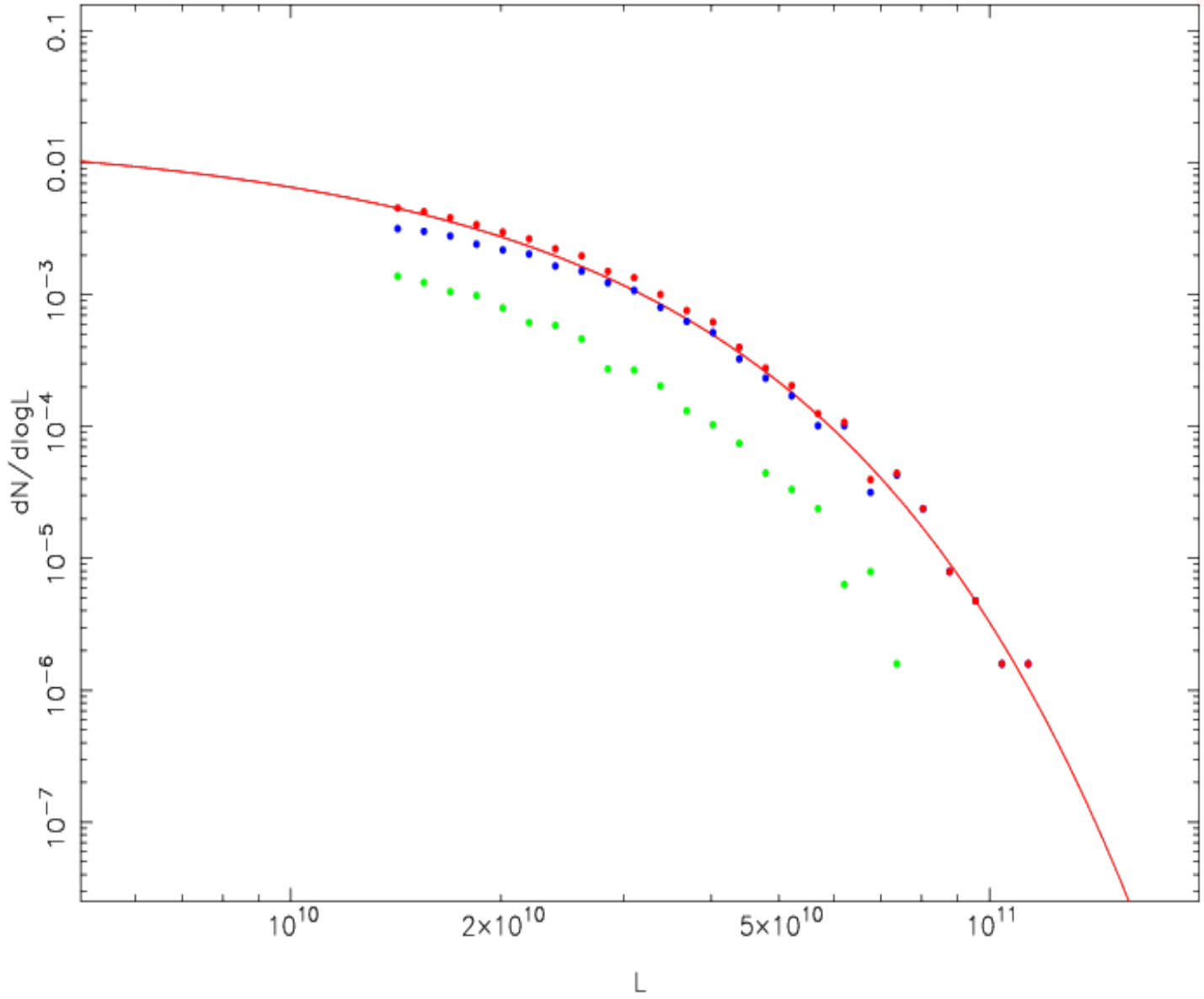
Mock galaxy catalogue





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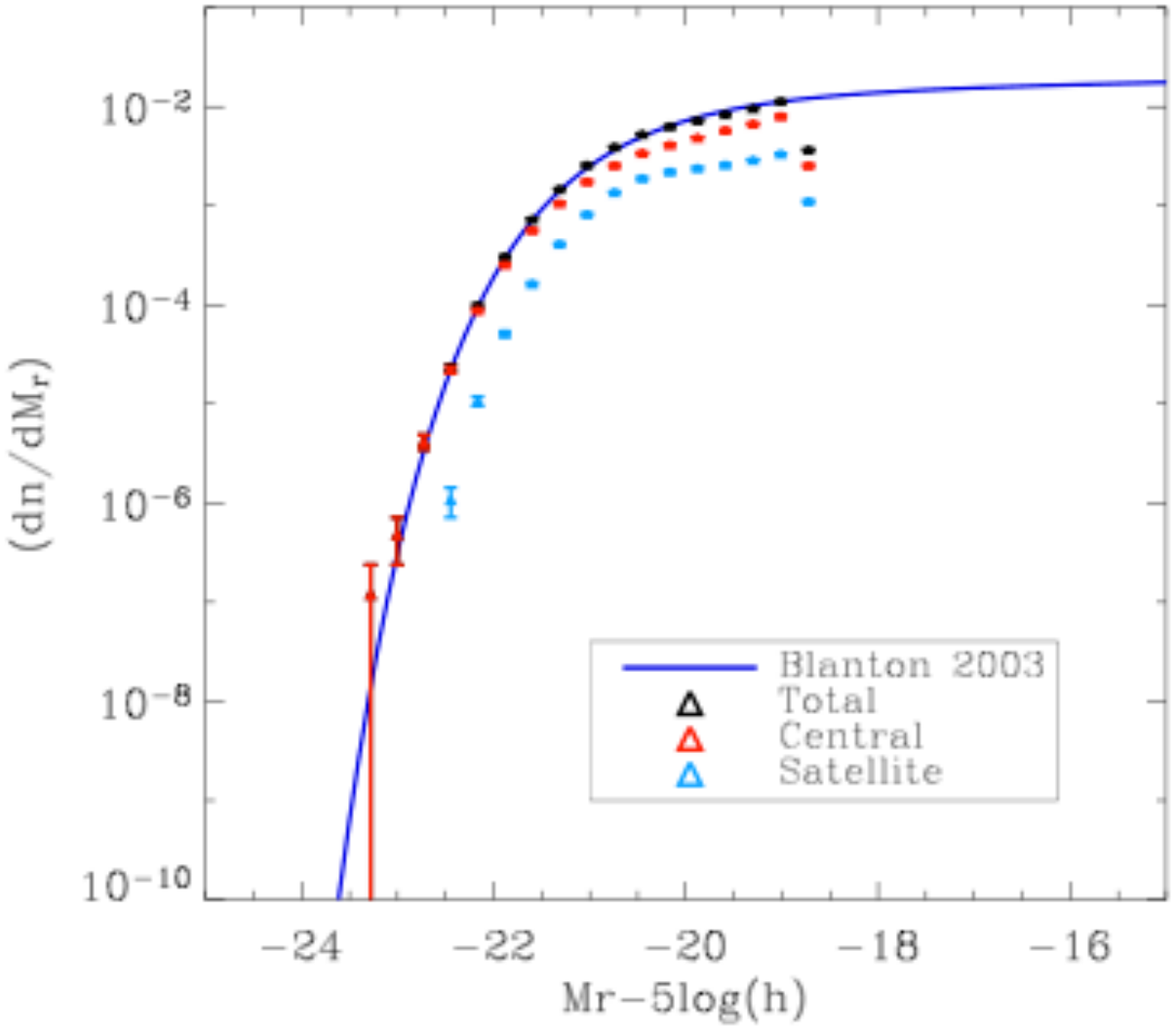
Mock galaxy catalogue



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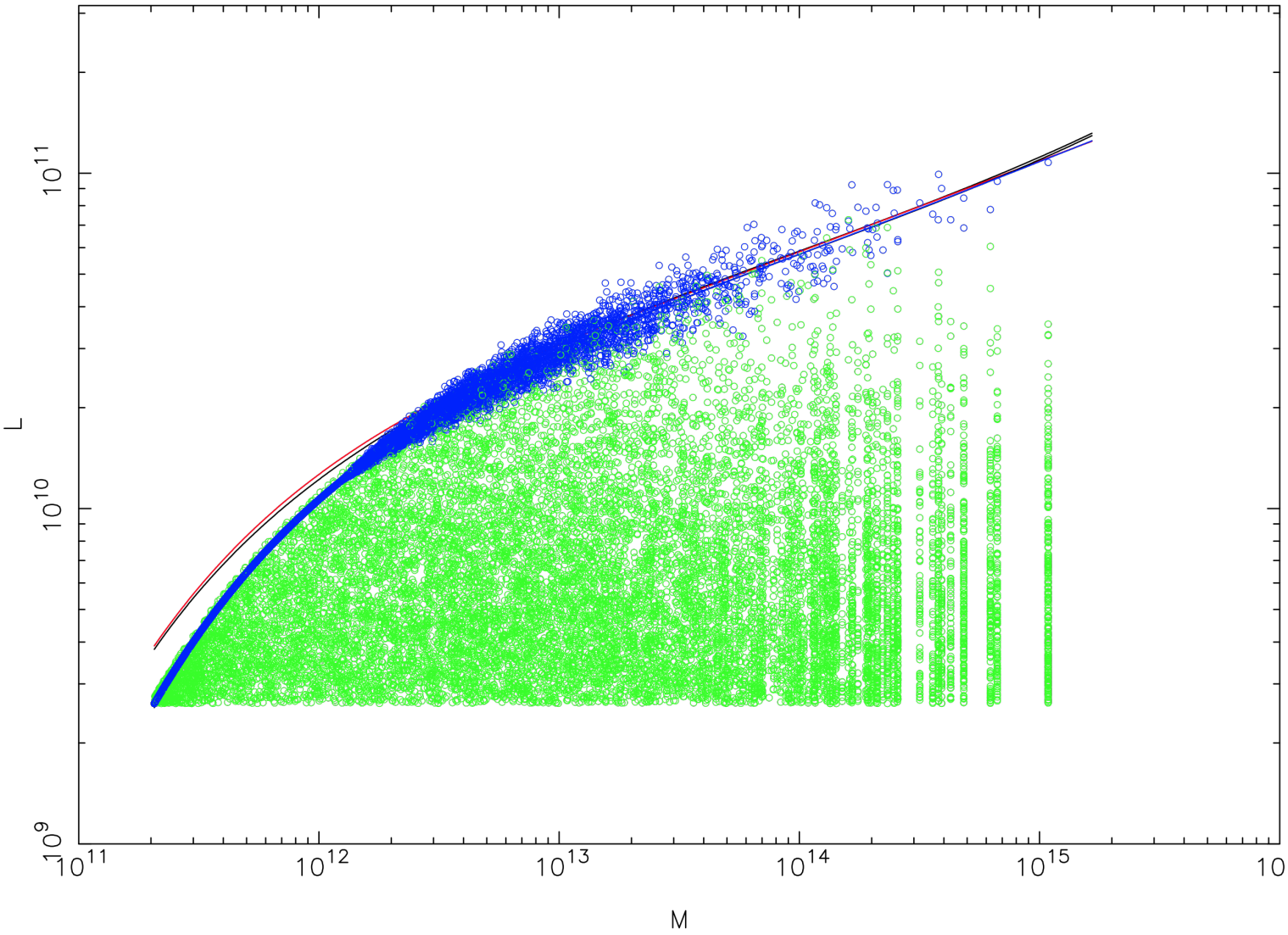
Mock galaxy catalogue

central=blue satellite=green



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Mock galaxy catalogues

Assign positions and velocities

- Centrals are placed at the center of the halos
- Satellites are positioned within the halos following a NFW profile using a concentration parameter: c=c(M,z)
- Bullock 2001, Gao2008, Munoz-Cuartas2011
- Triaxial NFW are used
- Velocities are assigned assuming Virial equilibrium

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Mock galaxy catalogues

Assign luminosities and HOD

- Compute projected correlation functions and compare to observations
- Teak HOD parameters until a good fit is achieved
- NO good fit to the clustering as a function of luminosity is achieved
- Solutions:
  - Scatter in the luminosity-halo mass relation
  - More complicated HOD parameterization

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Mock galaxy catalogues

Assign positions and velocities

- In order to improve the fit to the clustering we need to:
- Change the concentration parameter as a function of luminosity
- Add a probability for satellites to be in a halo of a given mass as a function of the luminosity

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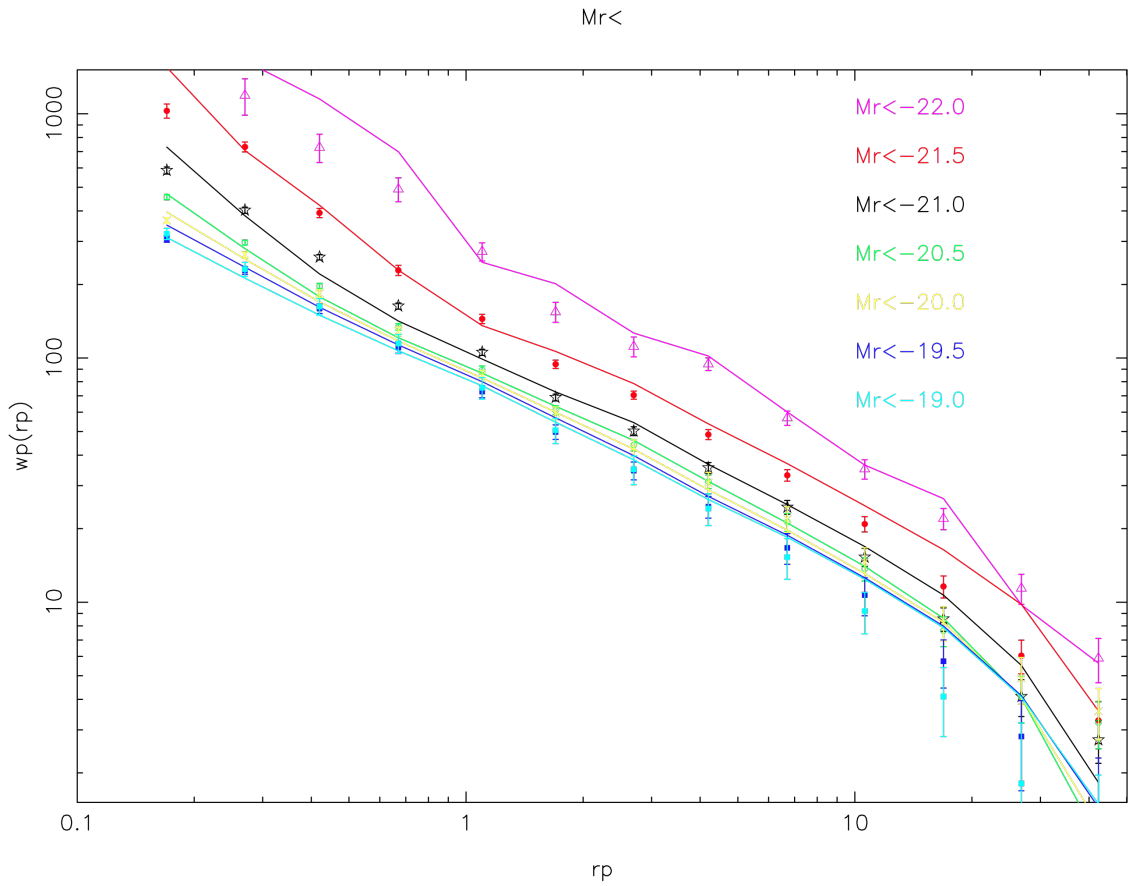
Simulations

Mock galaxy catalogues



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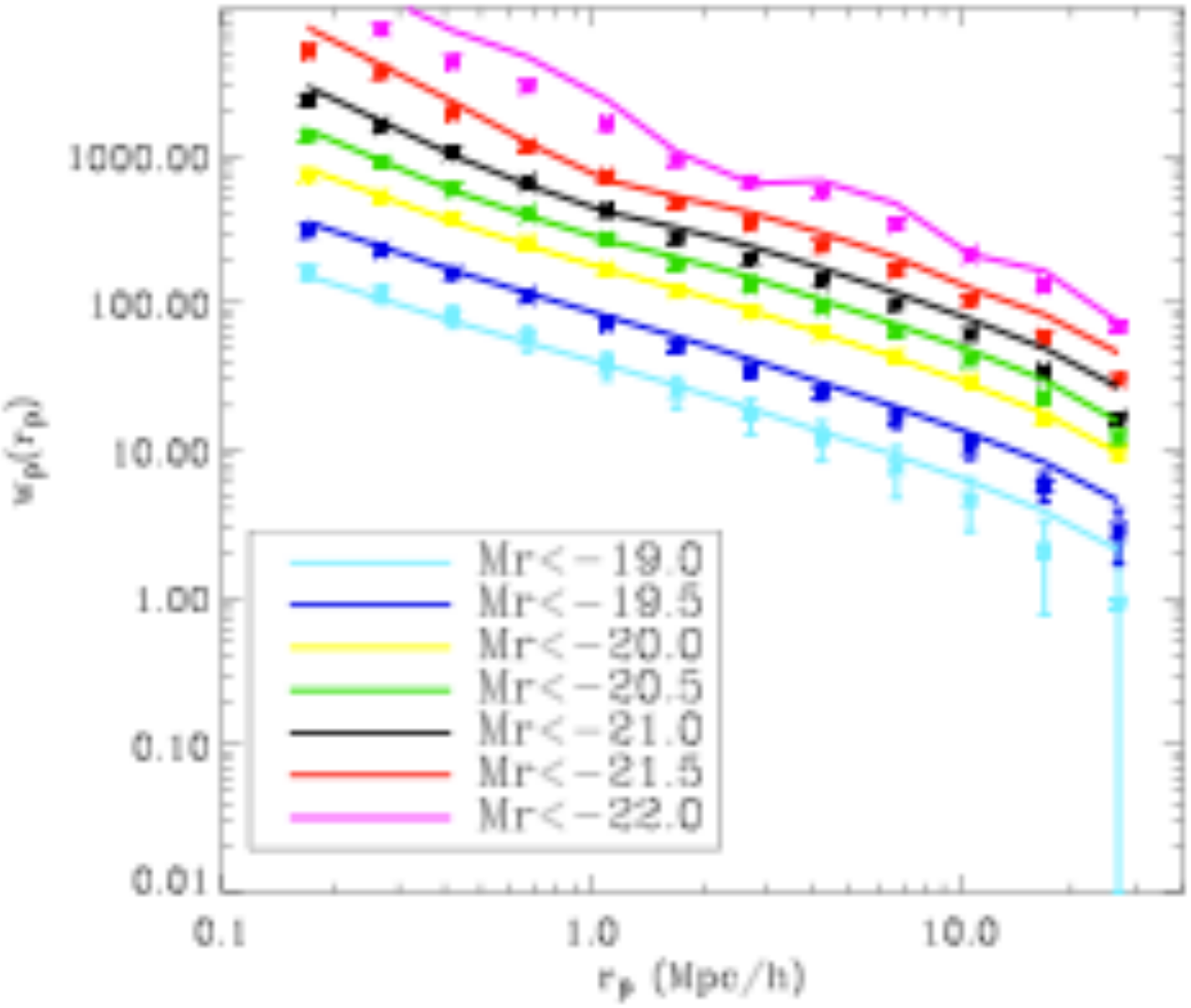
Simulations

Mock galaxy catalogues



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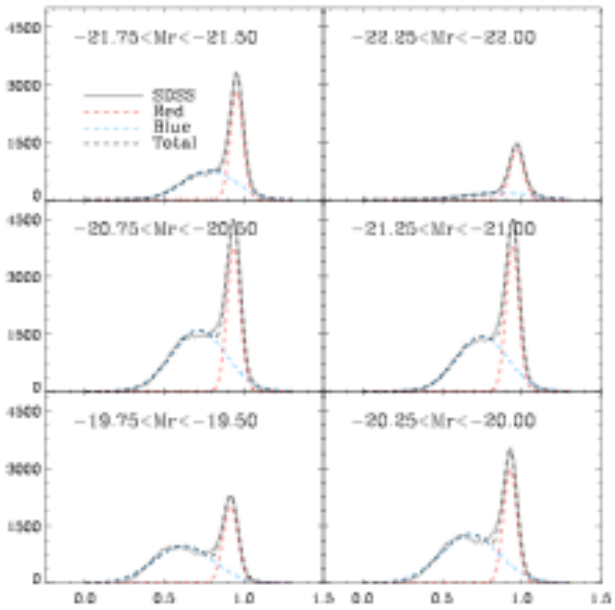
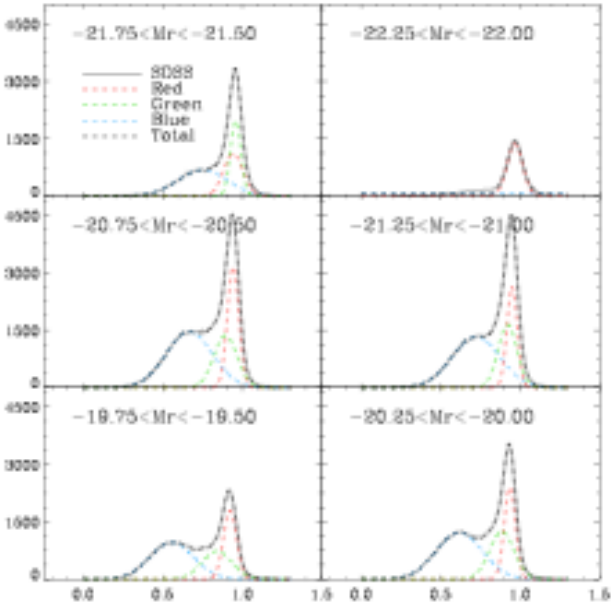
Mock galaxy catalogues

Assign colours

- Separate the galaxy population in the components: red, green and blue
- Fit them with Gaussians as a function of luminosity





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Mock galaxy catalogues

Assign colours

- We distribute centrals and satellites between these populations in a way that the clustering as a function of colour is as observed
- We start assigning colours to satellites
  - We define the fraction of satellites that are red and green
  - The fraction of blue satellites is then given
- The fraction of centrals that are red, green or blue are then given by the CM and the HOD

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Mock galaxy catalogues

Assign colours

- fsatred = f (luminosity)
- fsatgreen = g (luminosity)
- fsatblue = 1 – (fsatred + fsatgreen)
- ftotred = fcenred * fcen + fsatred * fsat
- fcenred = (ftotred + fsatred * fsat) / fcen
- fcengreen = (ftotgreen + fsatgreen * fsat) / fcen
- fcenblue = 1 – (fcenred + fcengreen)

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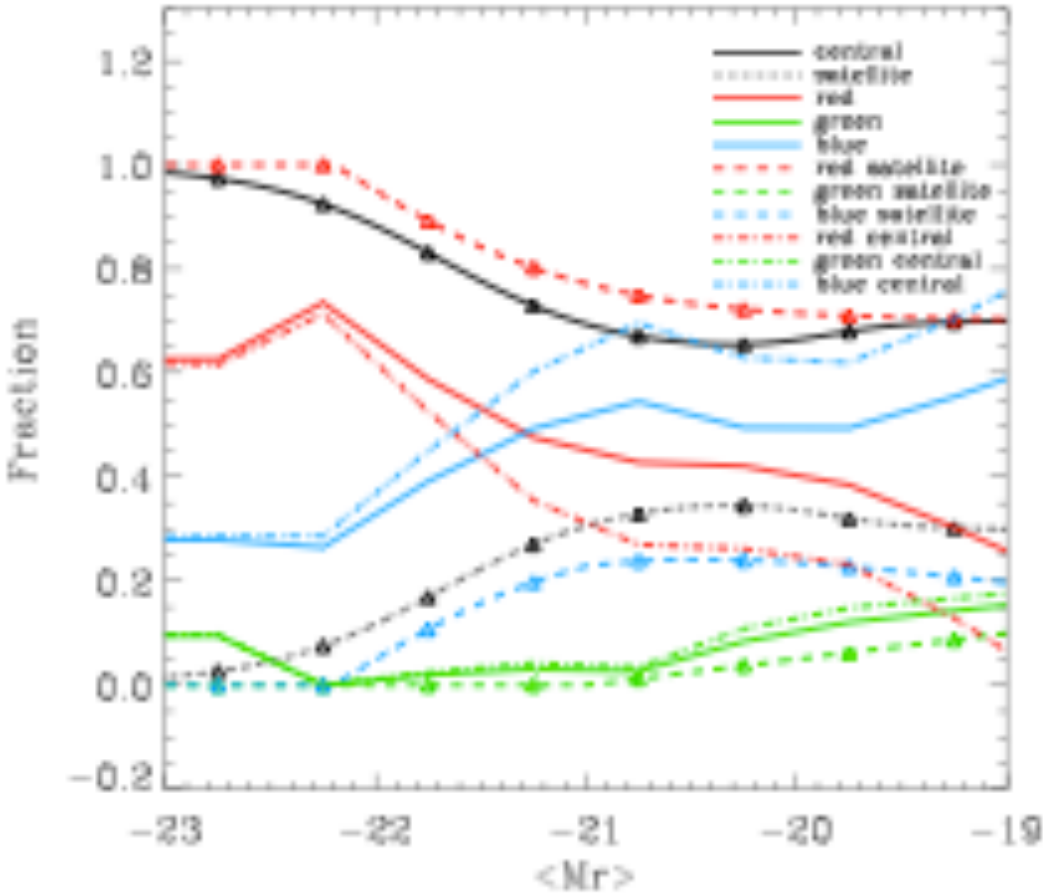
Mock galaxy catalogues

Assign colours



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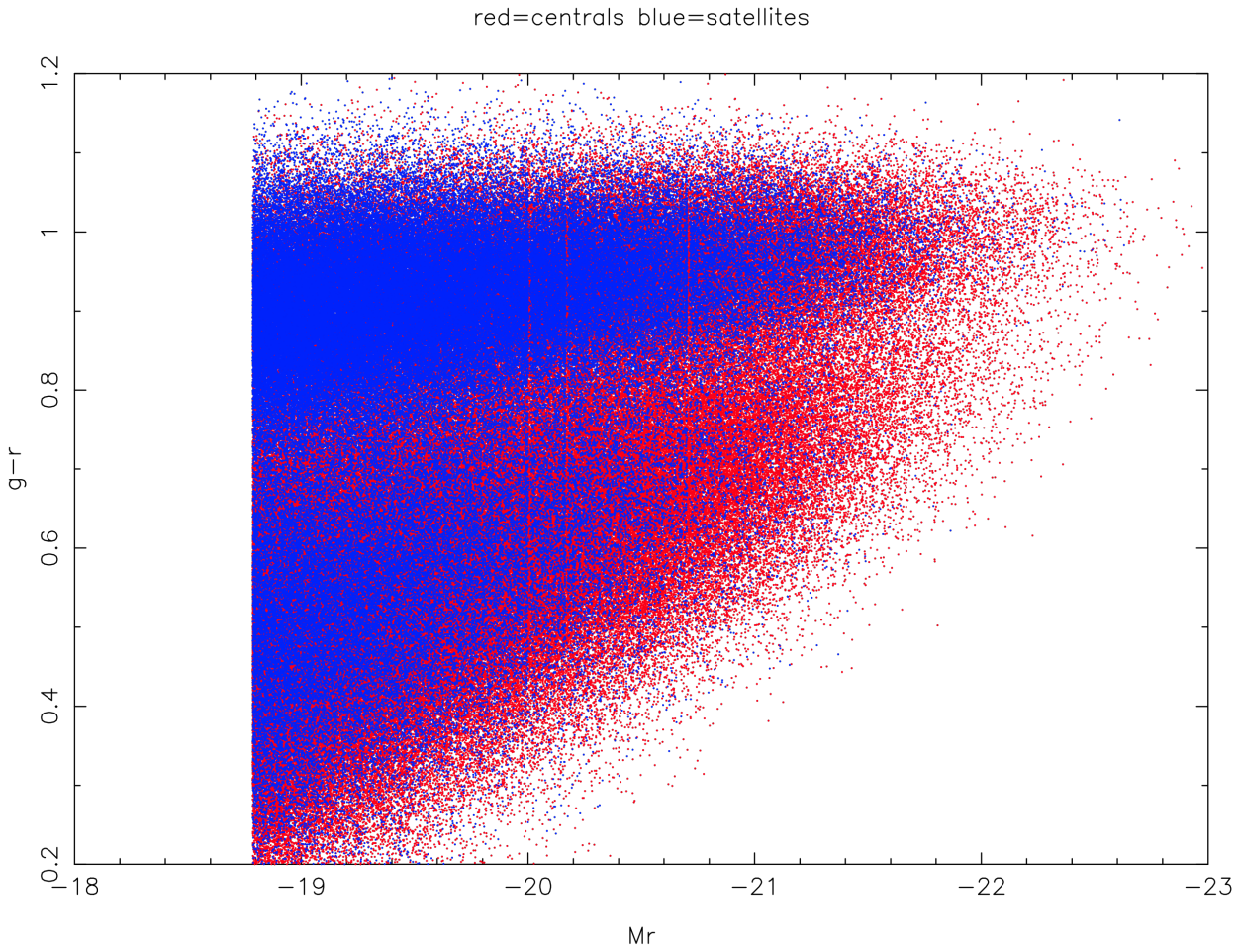
Mock galaxy catalogues

Assign colours



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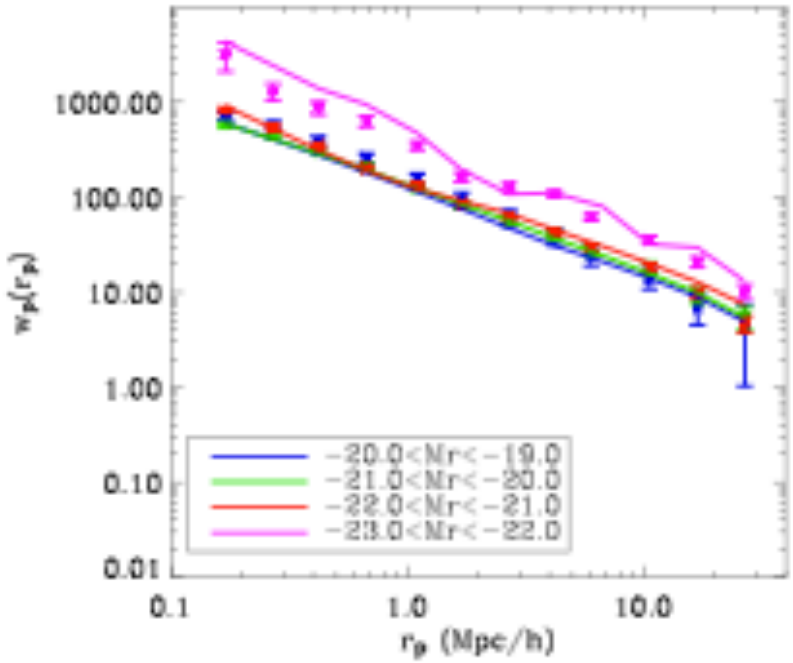
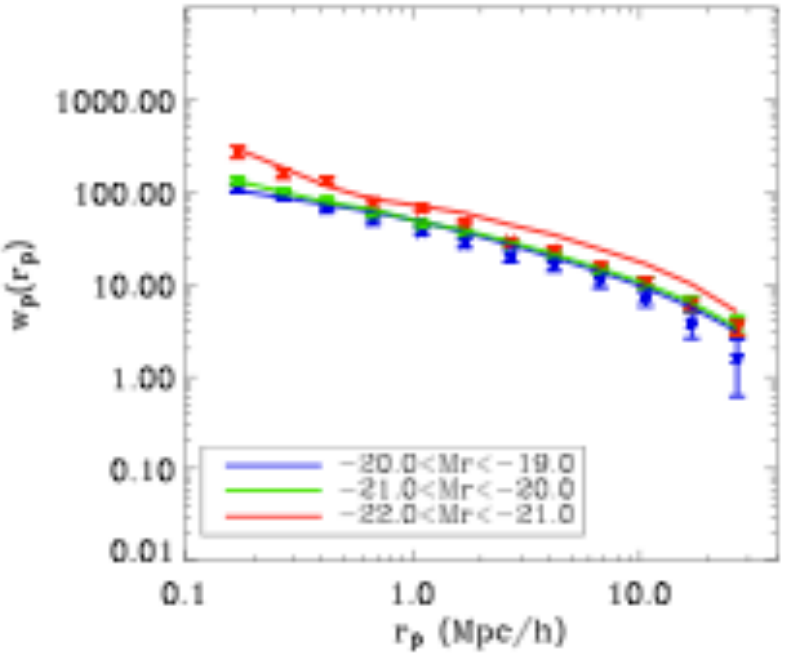
Mock galaxy catalogues

Assign colours

- Adjust the functions fsatred and fsatgreen until the clustering as a function of colour (and luminosity) is well fit to observations





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Mock galaxy catalogues

Last steps

- Assign SEDs
- Apply to lightcone

To Do

- Adjust model parameters at higher z
- Assign sizes and shapes

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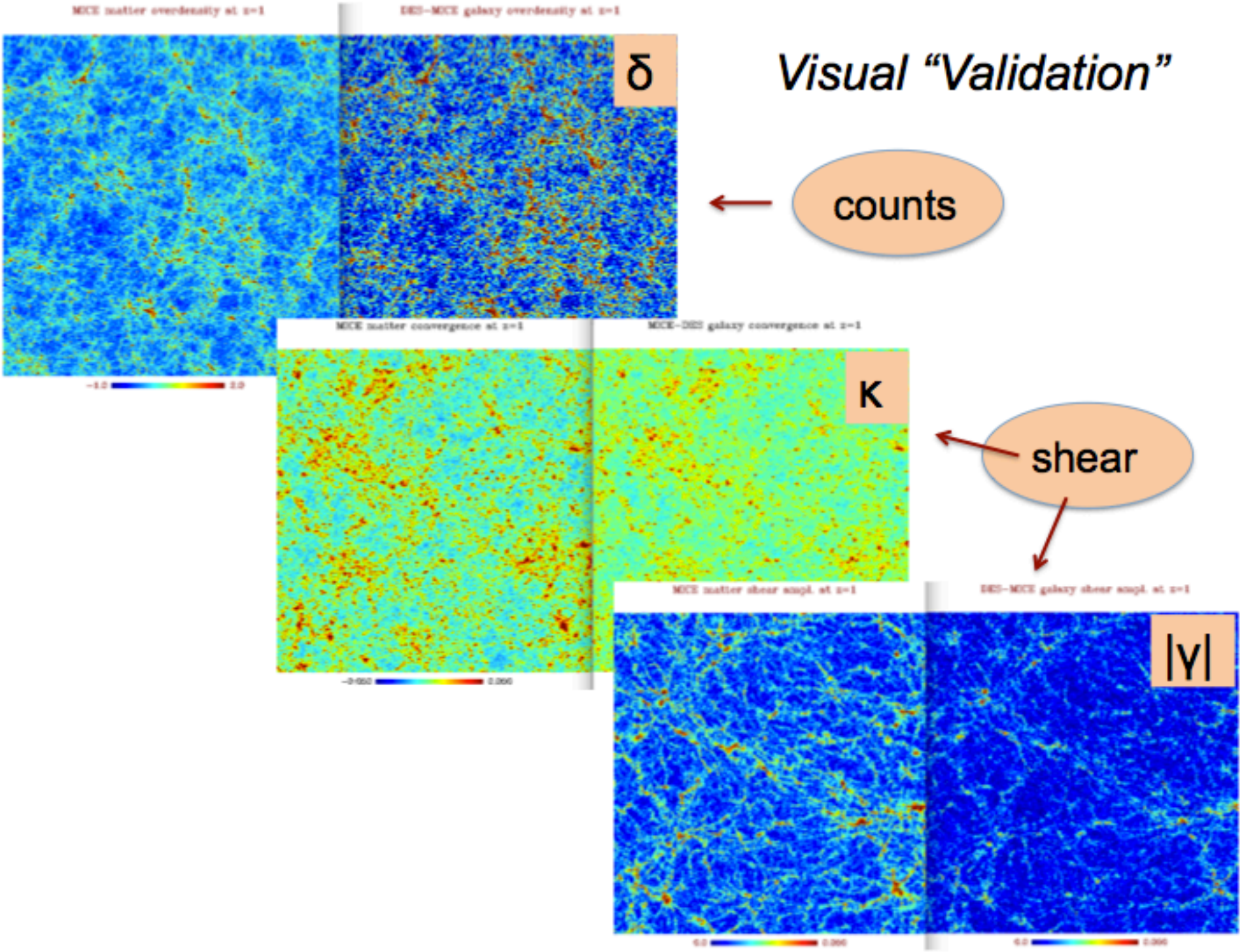
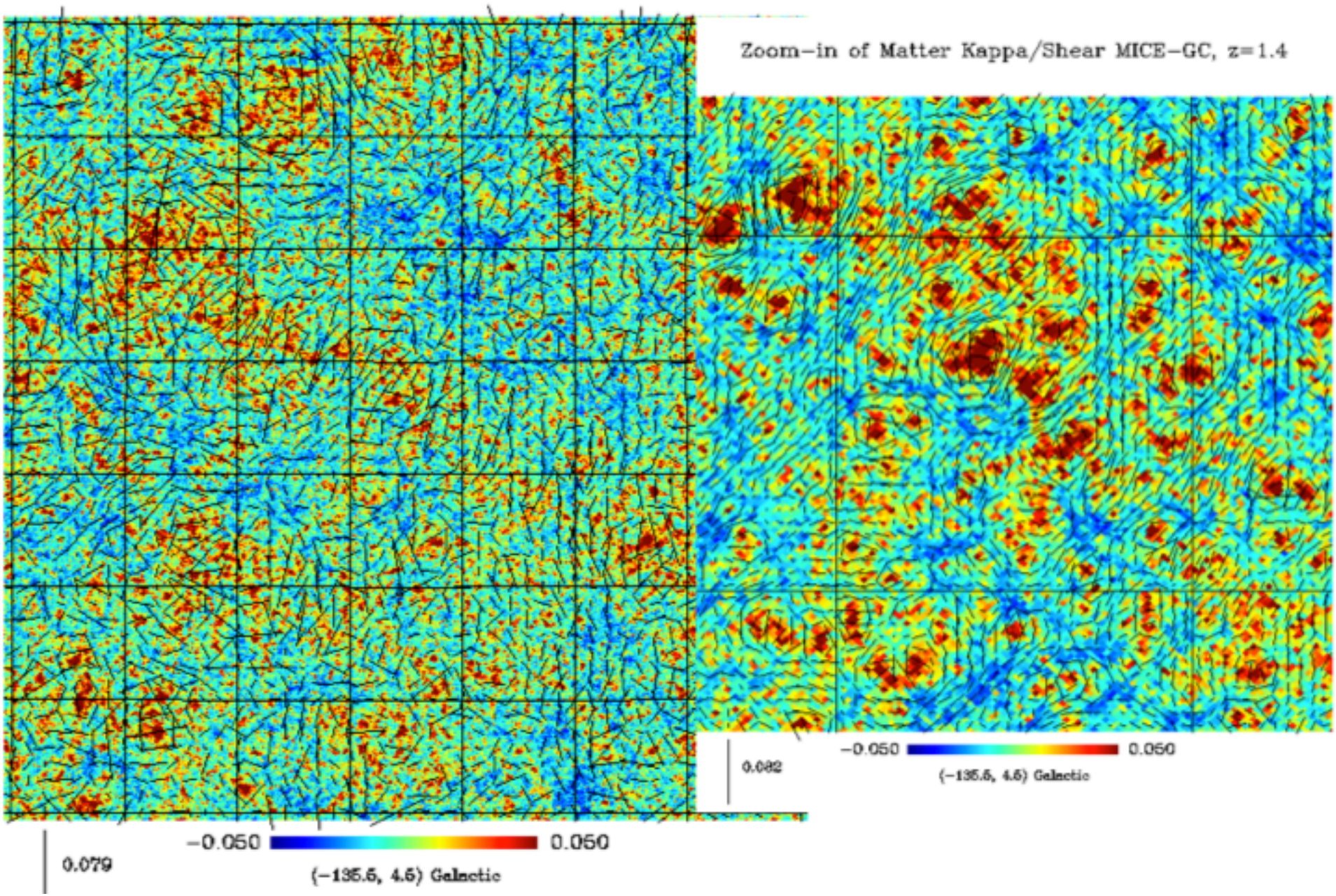
Mock galaxy catalogues

Lensing

- Build all-sky convergence (κ) maps (Fosalba et al 2008)
- Shear coefficients are obtained in harmonic space from convergence $\gamma_{lm} = -f(l)\,\kappa_{lm}$
- Assume B-mode is zero
- Obtain (γ1,γ2) transforming back to real space
- Assign convergence and shear to galaxies


MICE matter overdensity at z=1
DES+MICE galaxy overdensity at z=1
δ
Visual "Validation"
counts
MICE matter convergence at z=1
MICE+DES galaxy convergence at z=1
κ
shear
MICE matter shear ampl. at z=1
DES+MICE galaxy shear ampl. at z=1
|γ|


Matter Kappa/Shear MICE−GC, z=1.4
Zoom−in of Matter Kappa/Shear MICE−GC, z=1.4
0.079
−0.050
0.050
(−135.5, 4.5) Galactic
0.082
−0.050
0.050
(−135.5, 4.5) Galactic

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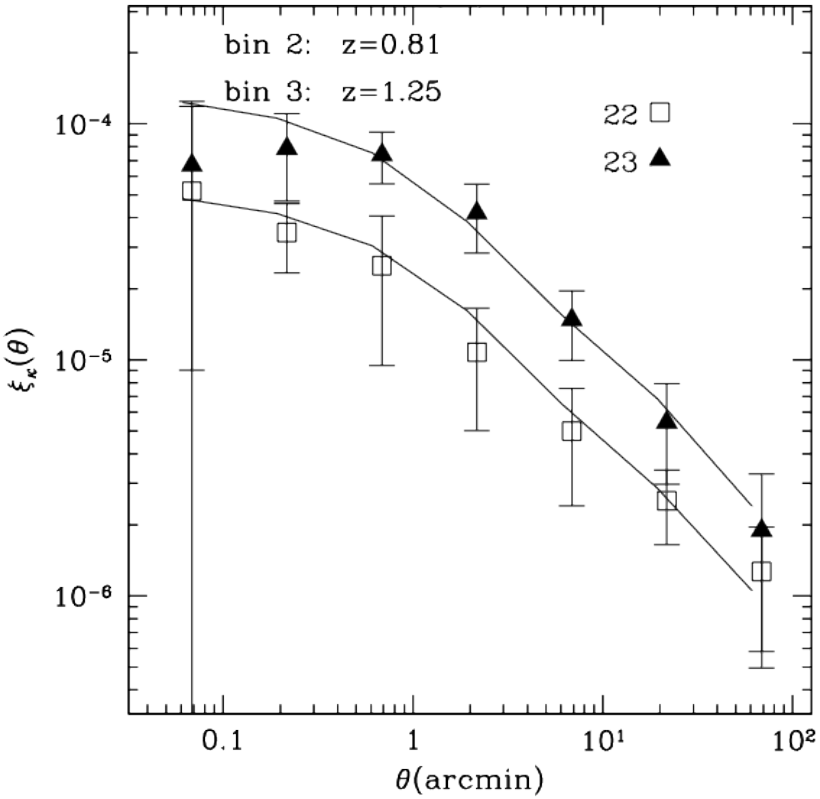
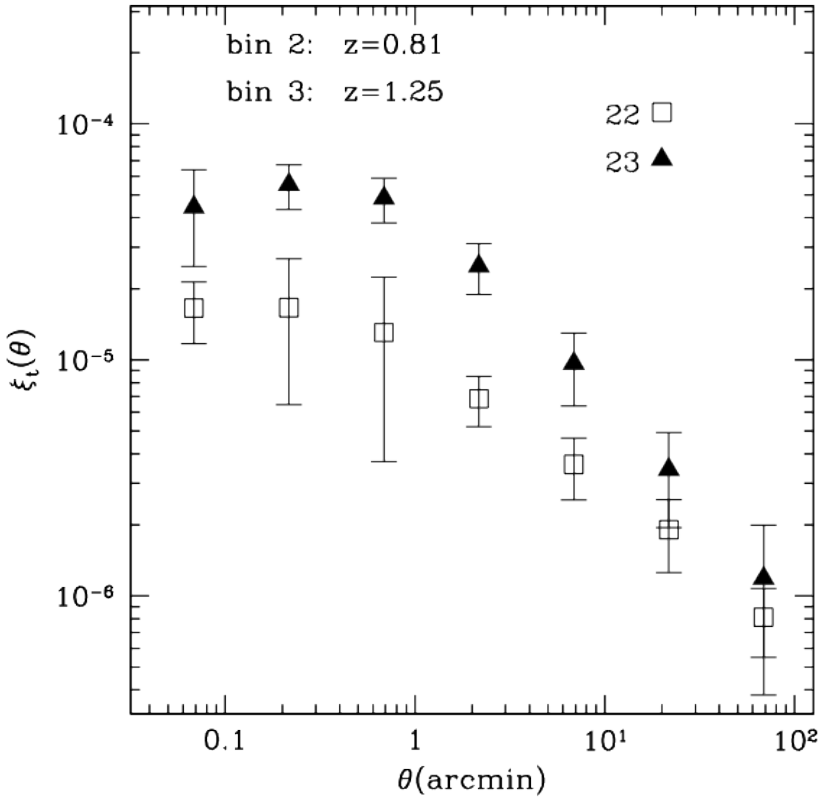
Mock galaxy catalogues

Lensing

- Convergence and tangential shear autocorrelation and cross-correlation





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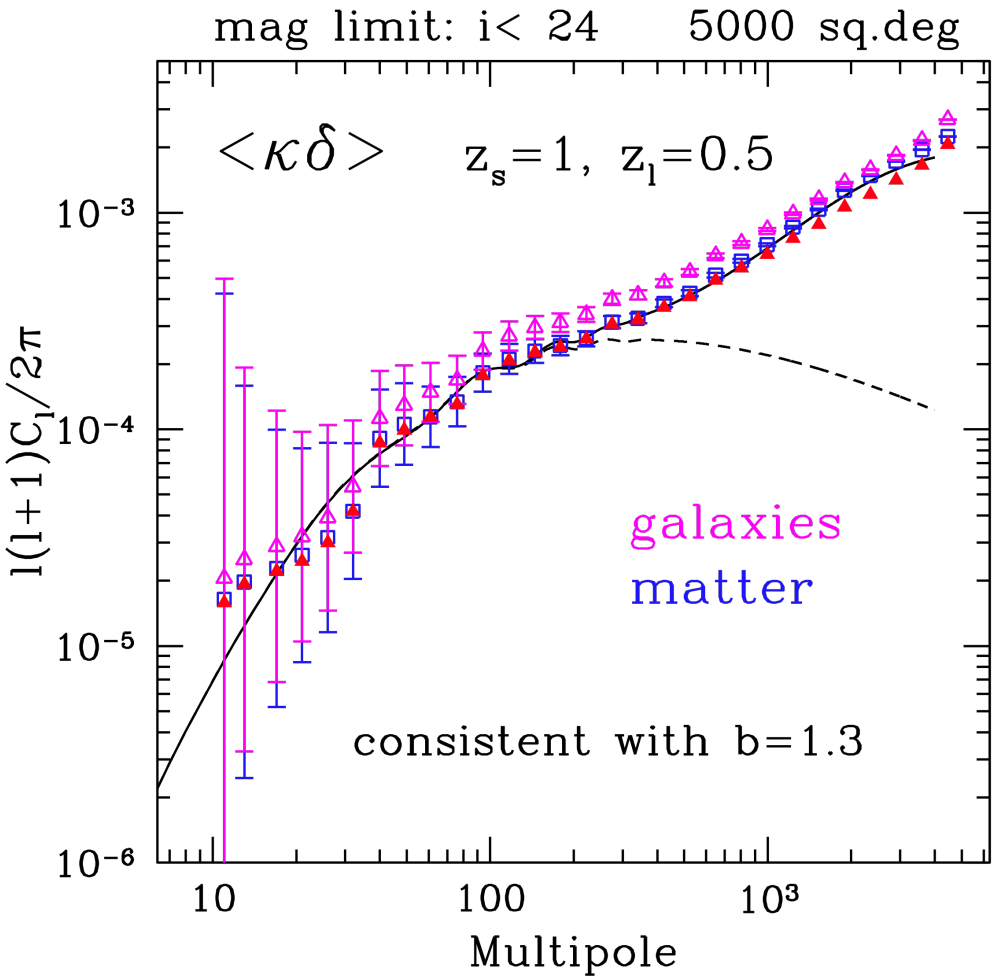
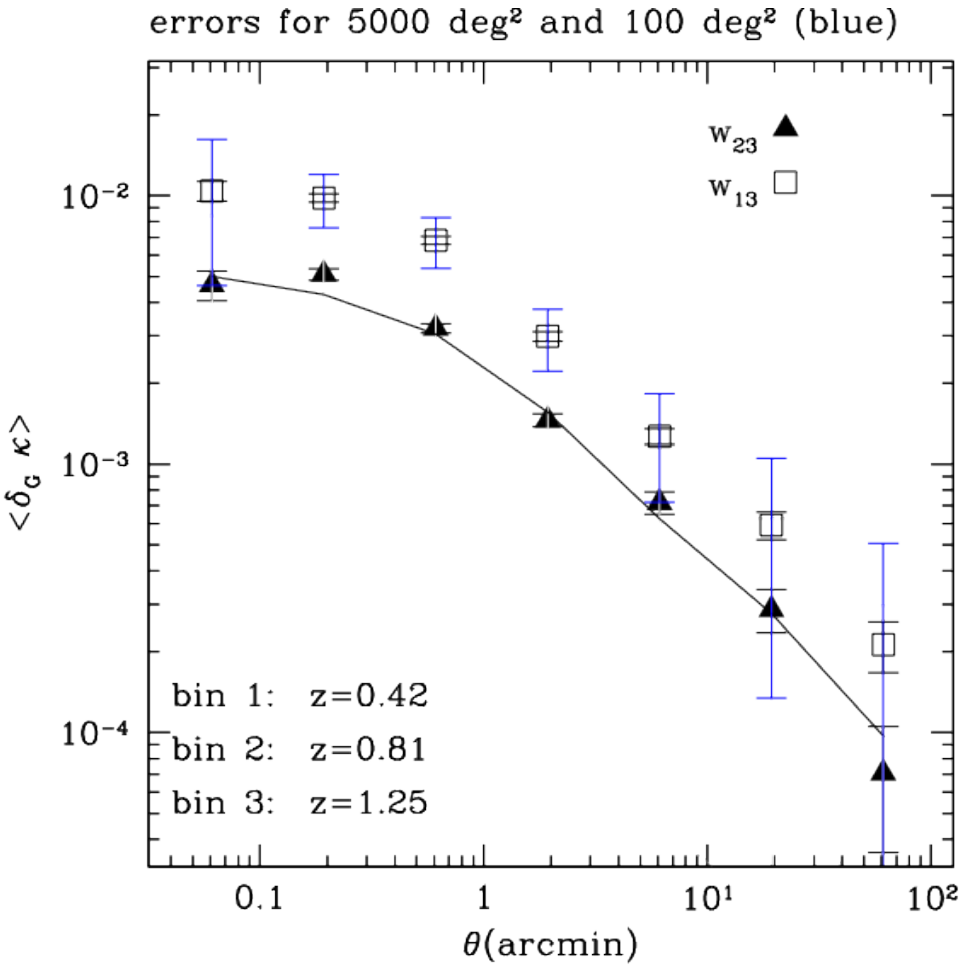
Mock galaxy catalogues

Lensing

- Convergence-overdensities cross-correlations





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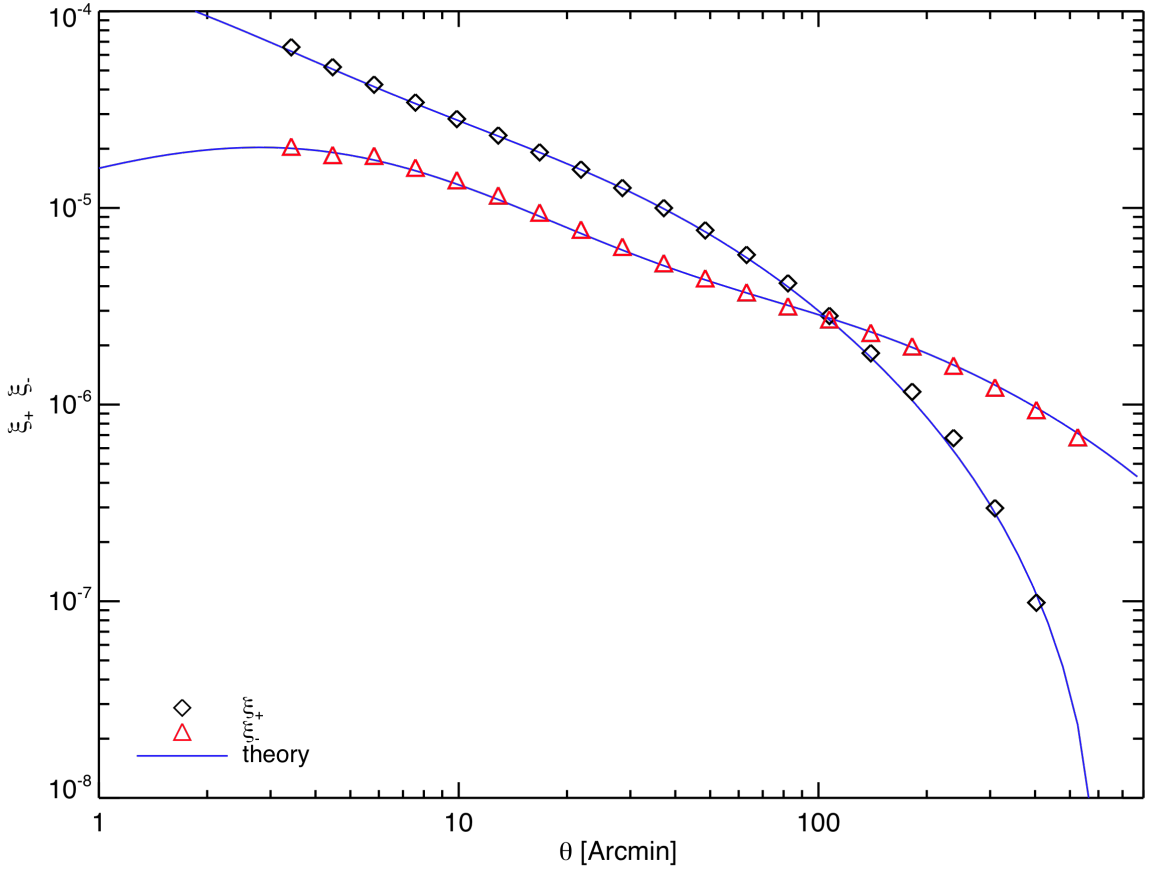
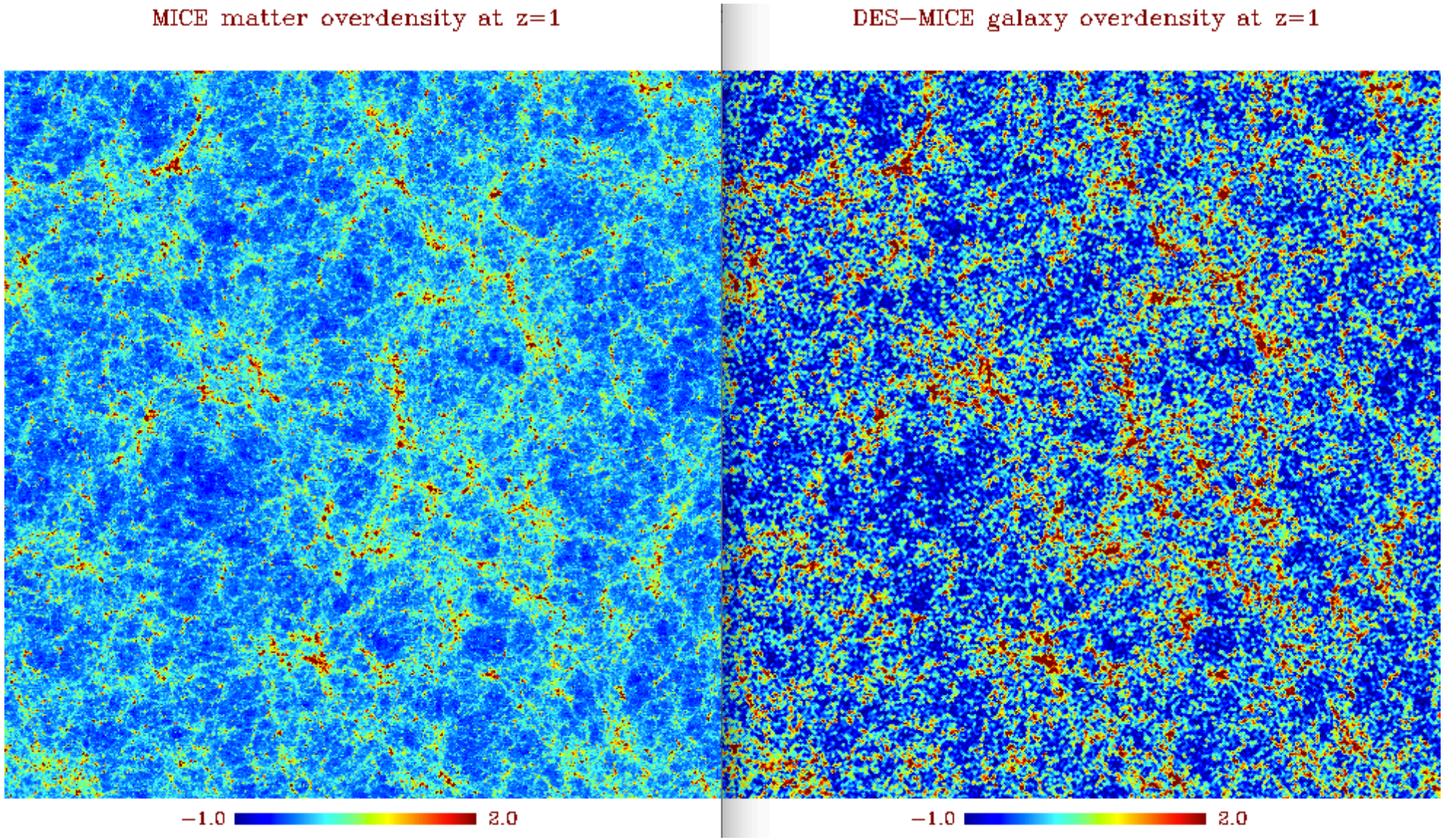
Mock galaxy catalogues

Lensing

- Shear correlations ξ_+ and ξ_-

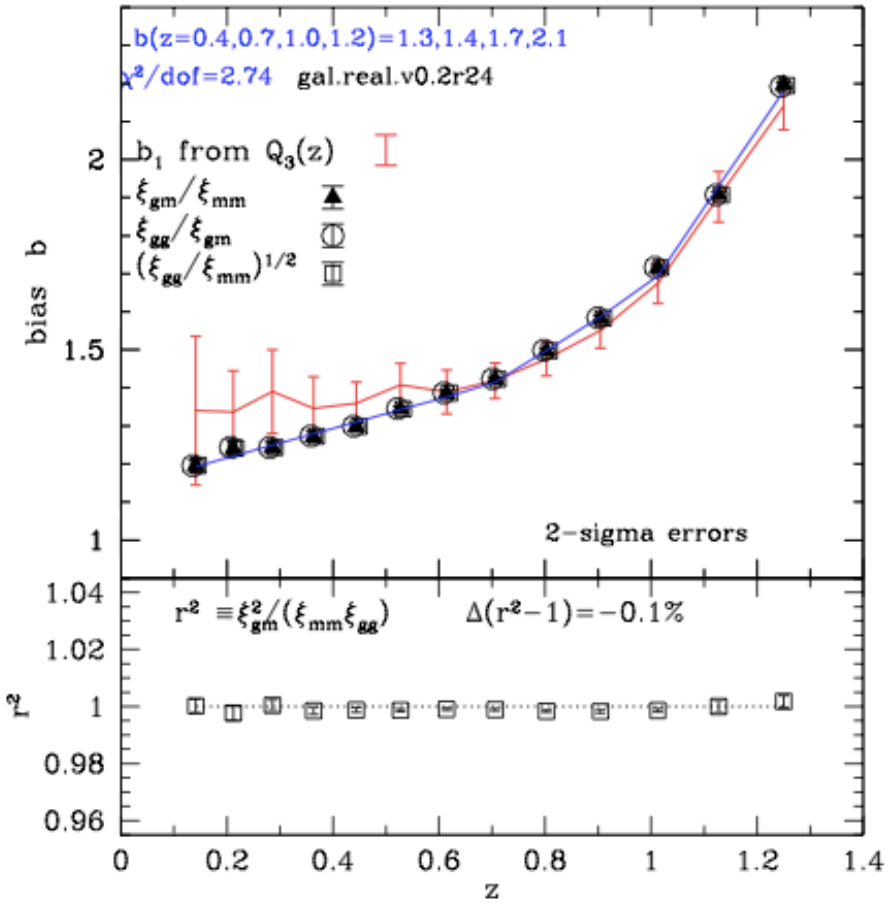


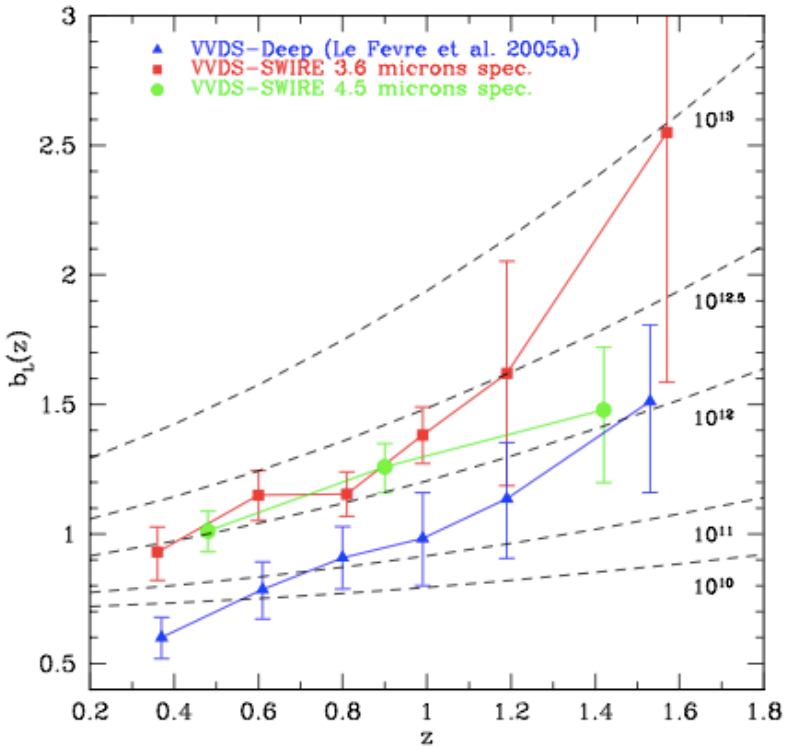
MICE Galaxy Catalogue



MICE Galaxy Catalogue

- Bias evolution (3D DM vs Gal correlations)

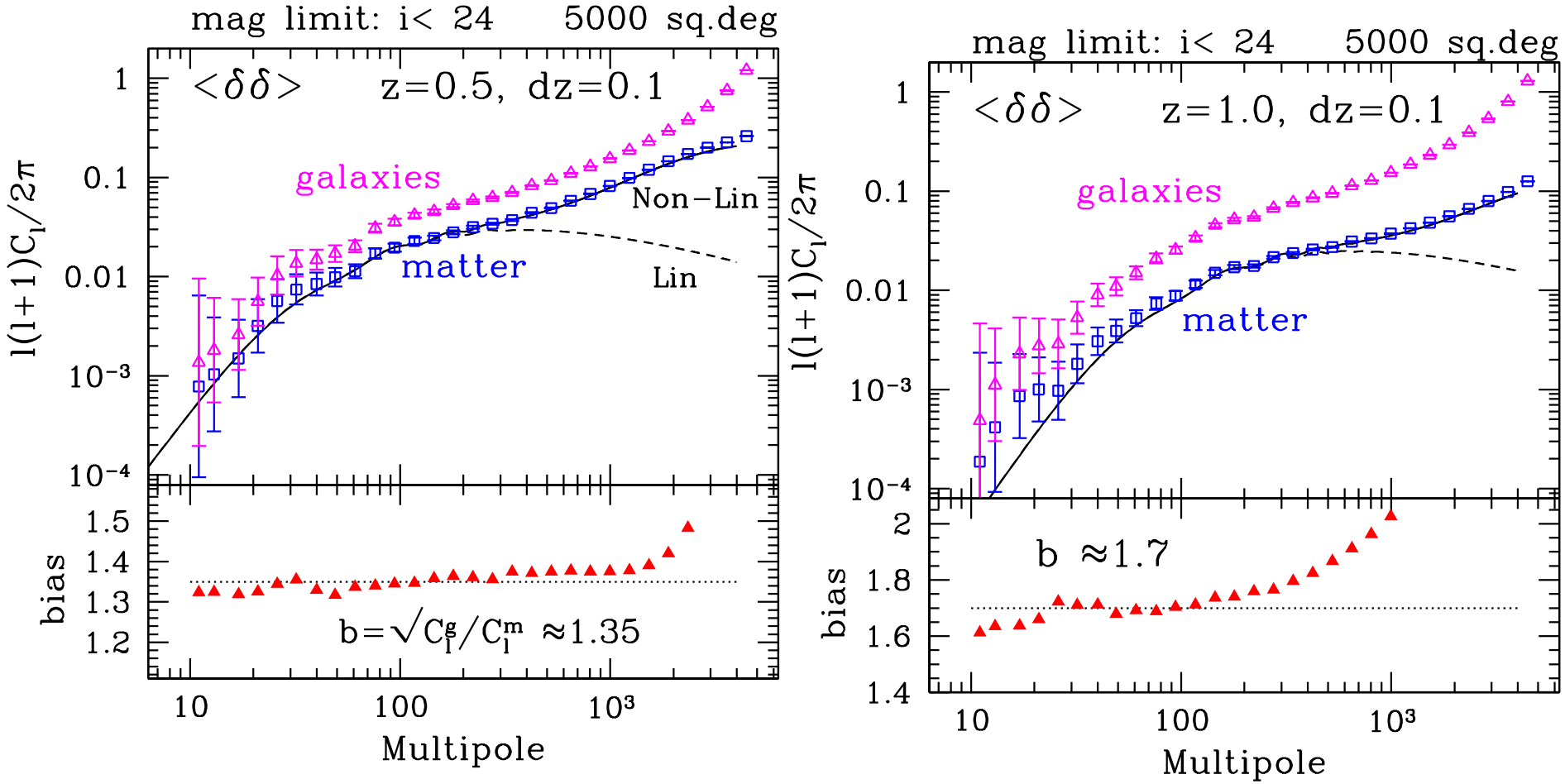




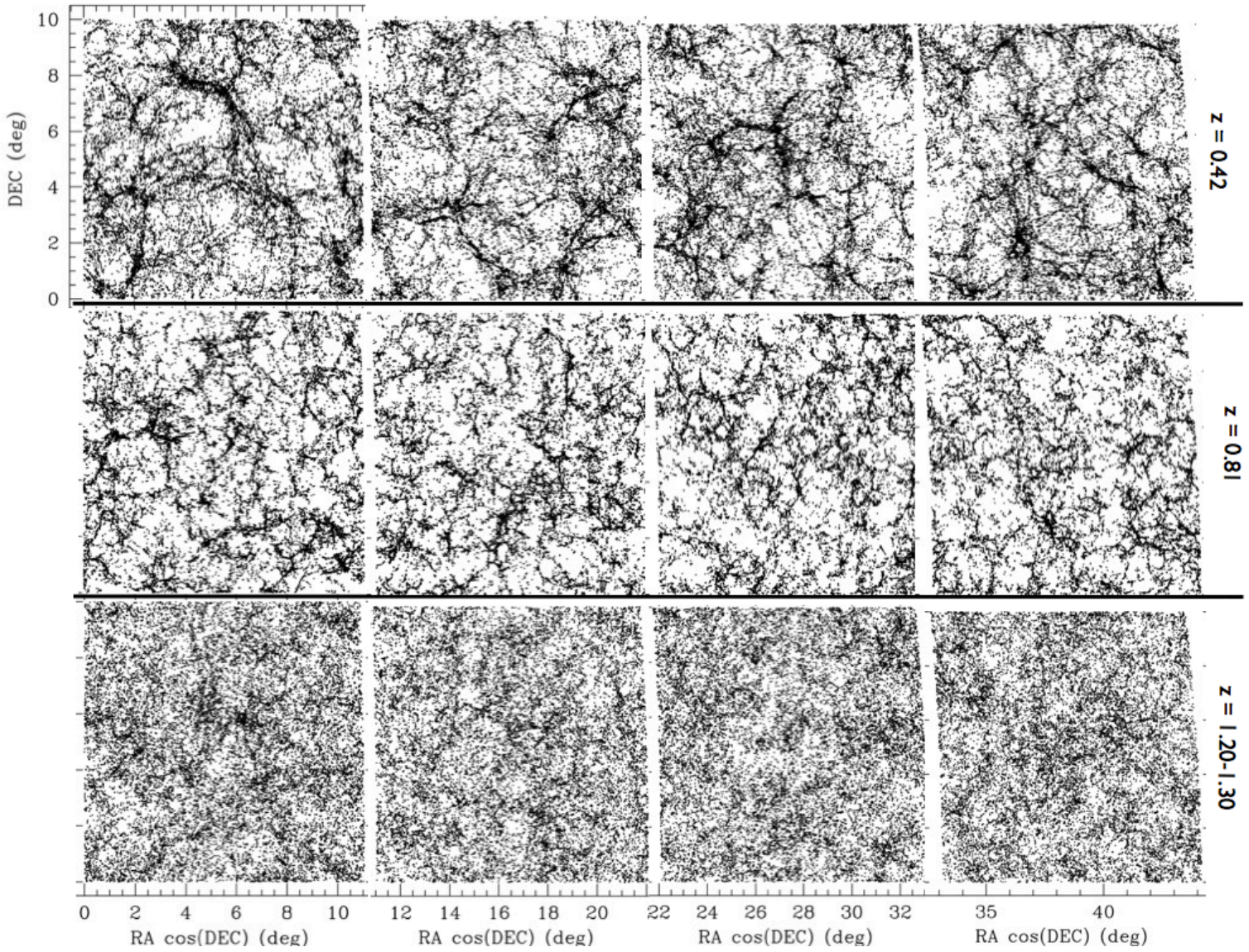
DES-MICE M>2.9 10^{11}
r<24

MICE Galaxy Catalogue

- Bias evolution (3D DM vs Gal power spectra)

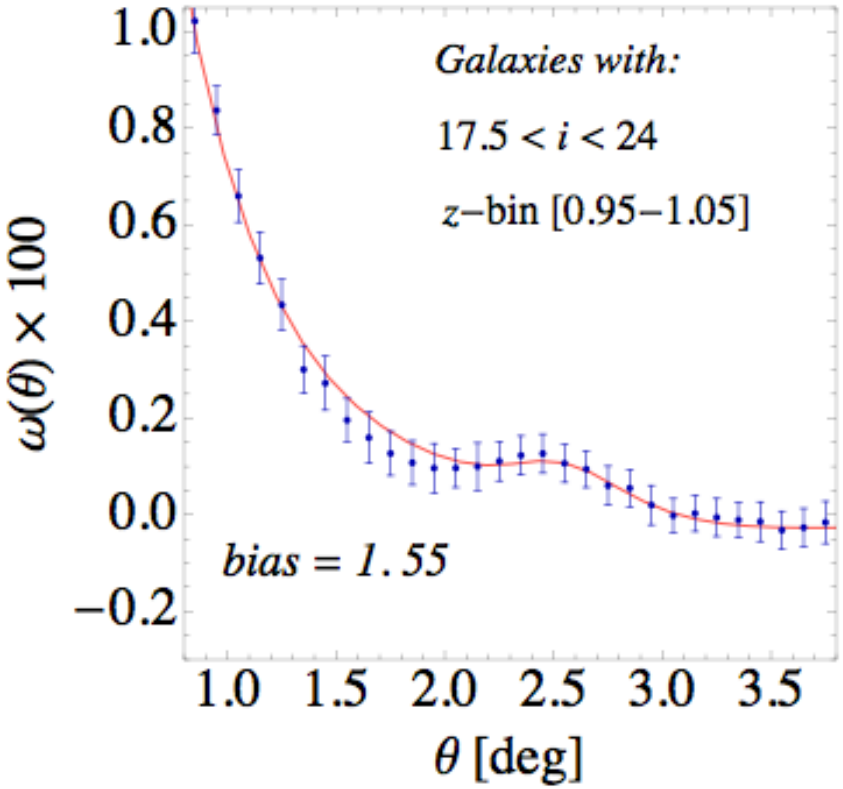


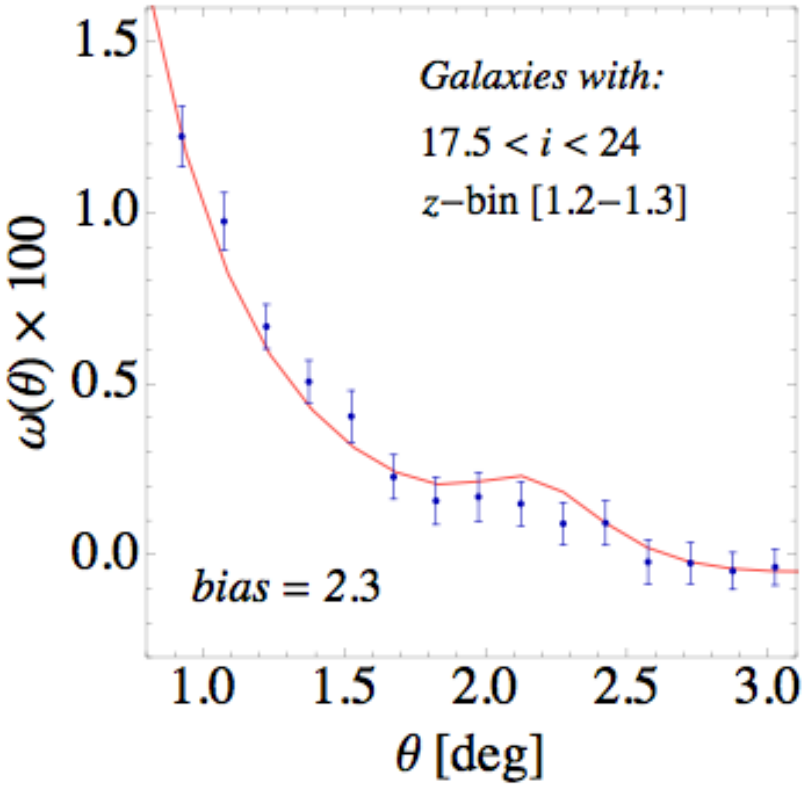
MICE Galaxy Catalogue



MICE Galaxy Catalogue

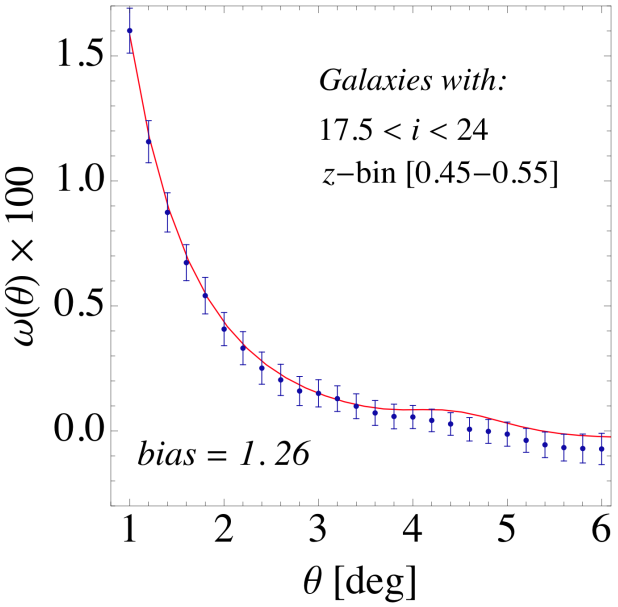
- Large scales (BAO)

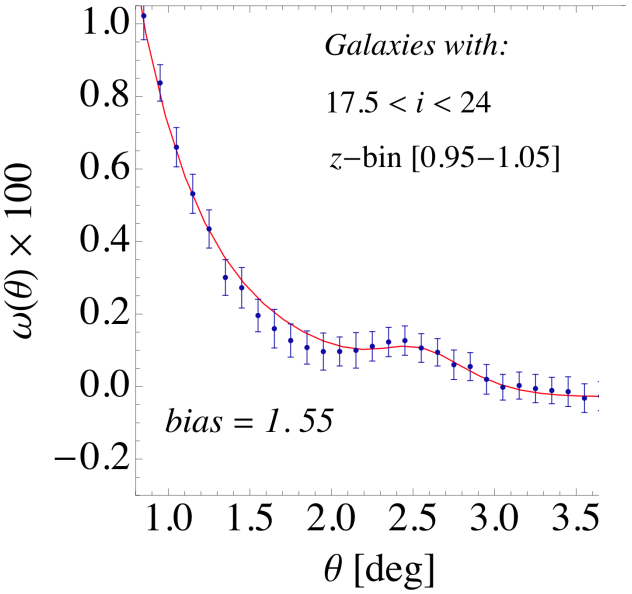


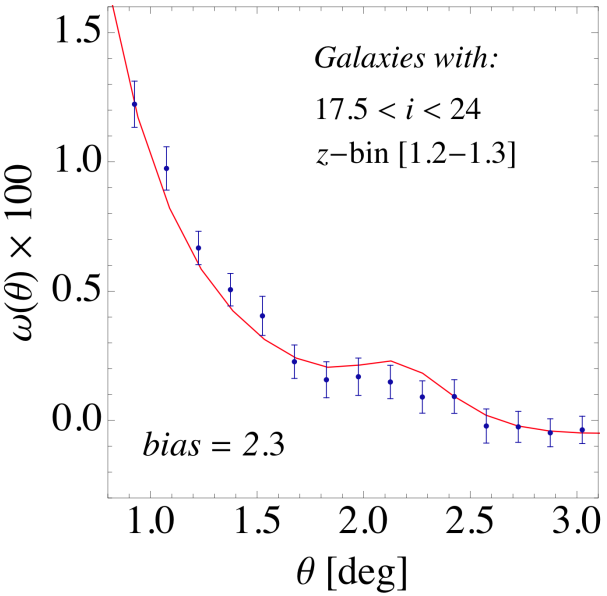


MICE Galaxy Catalogue

- Large scales (BAO)







MICE Galaxy Catalogue

- Large scales (BAO)

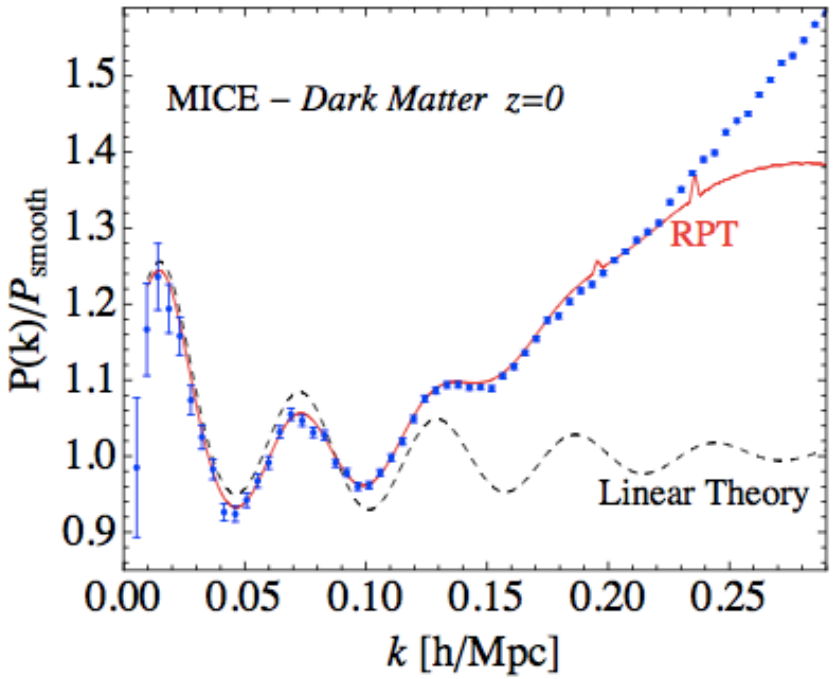


Figure 1. Baryon Oscillations : large scale clustering in MICE compared to linear theory (dashed) and RPT (solid red). The match with the later cross-validate the account of nonlinear effects on these scales.

MICE Galaxy Catalogue

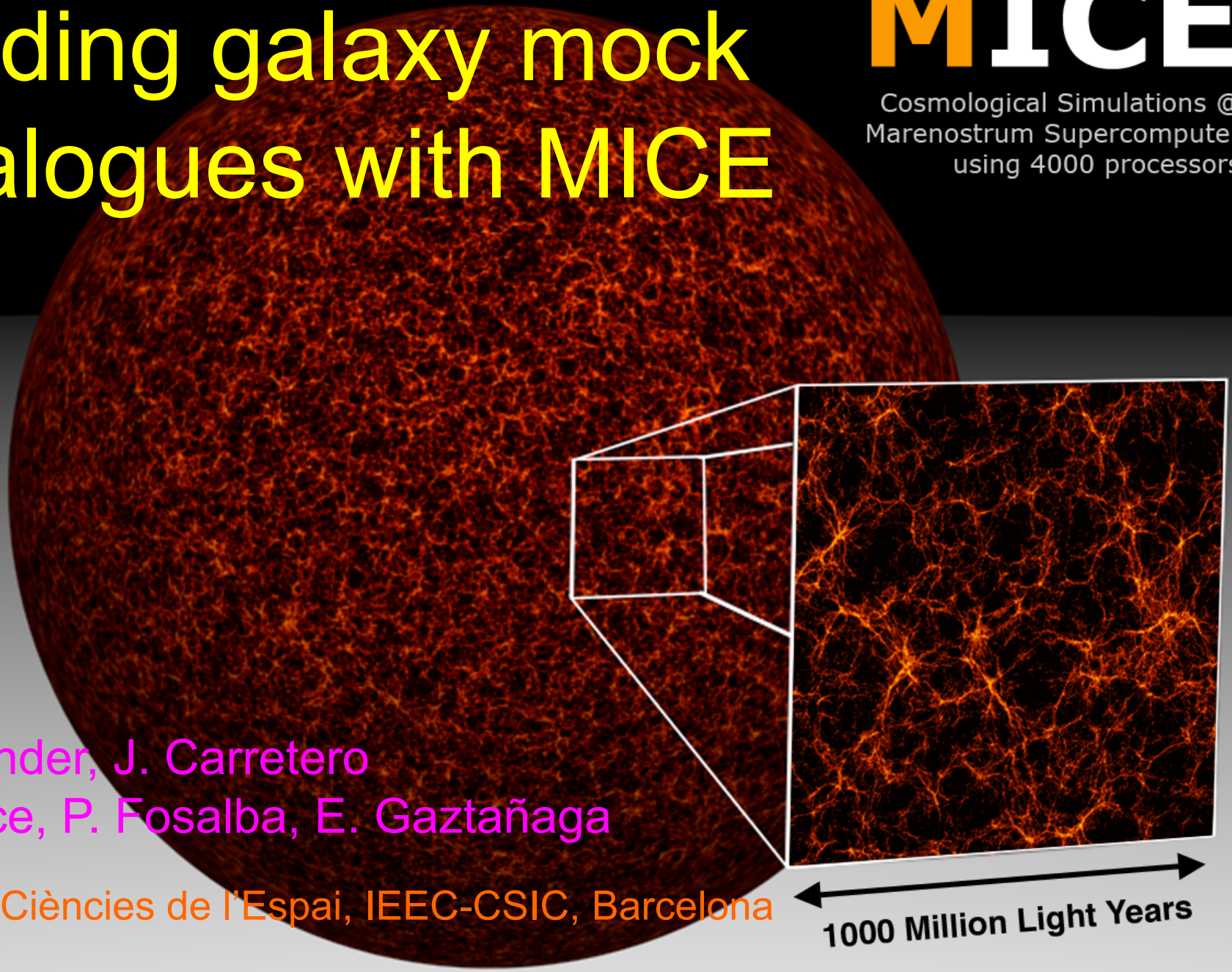
- Contains 117 million galaxies
- One octant of the sky (~5000 deg^2)
- Contents
  - Positions (RA, DEC & z)
  - Magnitudes
  - Photo-z's
  - Lensing (convergence & shear)
- Web page

  www.ice.cat/mice

Building galaxy mock catalogues with MICE

MICE

Cosmological Simulations @
Marenostrum Supercomputer
using 4000 processors



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