Modelling galaxies: from the luminosity function evolution to isolated pairs of galaxies as a cosmological test

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in collaboration with:
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Durham: **Cedric Lacey**, **Carlton Baugh**, **John Helly**
Christian Marinoni (CPT), **Elise Jennings** (Chicago), **Claudia Lagos** (ESO), etc

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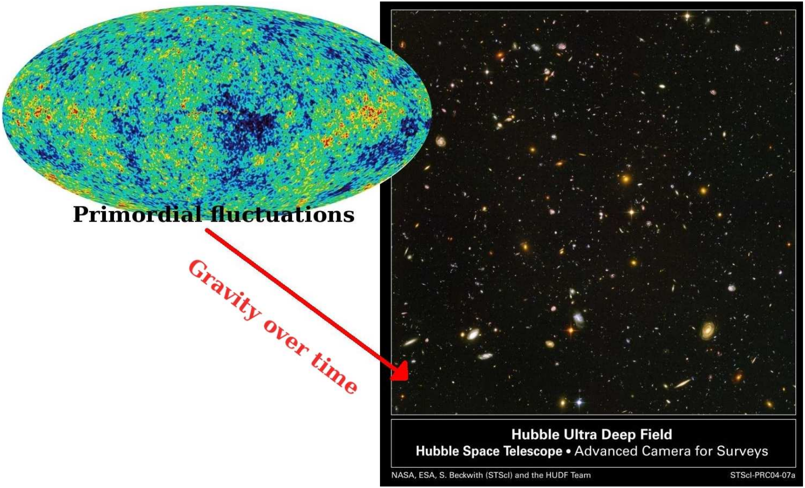
AGENCE NATIONALE DE LA RECHERCHE

Outline

1. The formation and evolution of galaxies
2. GALFORM, a semi-analytical model of galaxy formation
   - The Gonzalez-Perez et al. (2013) model
3. How sensitive are predicted LFs to the choice of SPS model?
   - The SPS models
   - Results
4. The predicted pairwise velocity of isolated galaxy pairs.
   - The Alcock-Paczynski test on isolated pairs of galaxies
   - Results so far

The formation and evolution of galaxies

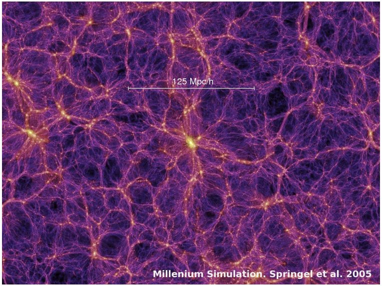
The cosmological parameters are very well constrained within the ΛCDM framework, for which:



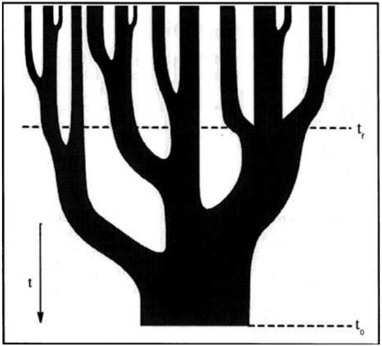
 Where do galaxies form?

Galaxies will form in large gravitational potential wells. Given a cosmology, we can identify those by:

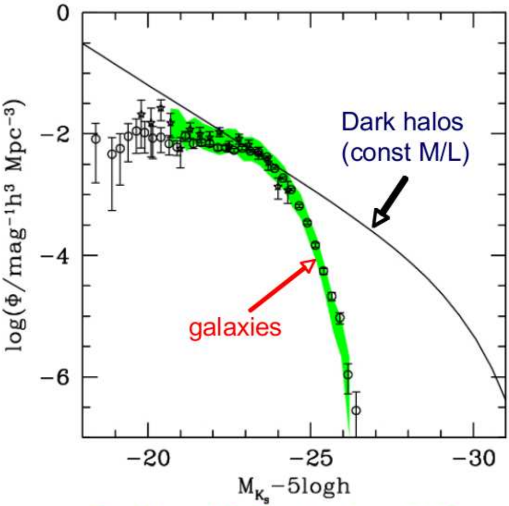
1. Make a simulation of DM only, which interacts gravitationally.



2. Identify the sites where galaxies form (haloes and subhaloes).
3. Construct the DM merger trees.

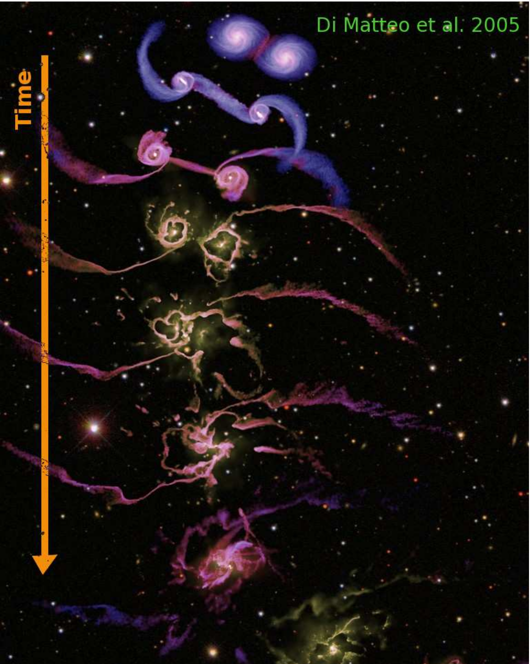


 How do galaxies form?



Tom Theuns, http://www.icc.dur.ac.uk/~tt/

- If we assume a simple approach: There are more DM halos than galaxies at the faint and bright ends.
- Galaxy formation is an inefficient process!



- If we assume a simple approach: There are more DM halos than galaxies at the faint and bright ends.
- Galaxy formation is an inefficient process!
- Galaxies are NOT shaped only by gravity. Gas physics, stellar formation and feedback, mergers, etc., also shape galaxies.

a) Following gas and dark matter together, for example with an hydrodynamic simulation.
b) Semi-analytical model of galaxy formation and evolution:

c) Subhalo abundance matching.
d) Halo occupation modelling.

The semi-analytical approach: Because galaxies are not only shaped by gravity

ΛCDM Cosmology

DM Merger trees

Galform

Observable galaxy properties

Test

Fit obs. at z=0?

NO

update free parameters

YES

Stable model

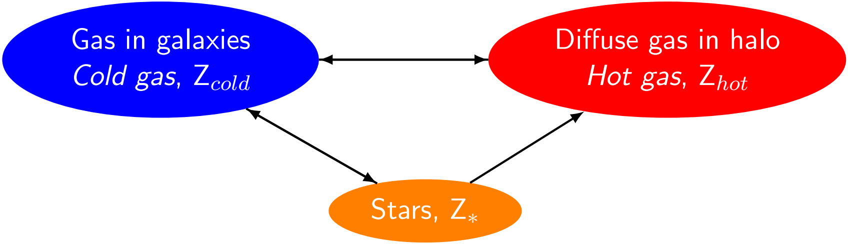
Using analytical equations, containing free parameters, GALFORM calculates the physical processes affecting the evolution of galaxies:

- Gas cooling $\Rightarrow$ Disk formation
- Galaxy mergers $\Rightarrow$ Spheroids
- SF & Feedback
- Chemical Evolution
- Stellar population & Extinction

Semi-analytical models account for complex processes

Galaxy formaiton is a messy business!

An example: the evolution of the mass and metal content of the 3 reservoirs needed to model the evolution of galaxies.



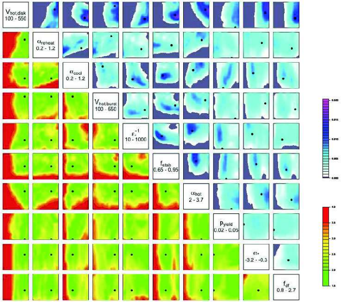
$$\begin{cases} \dot{M}_* = (1-R)\psi; \quad \dot{M}_*^Z = (1-R)Z_{cold}\psi \\ \dot{M}_{hot} = -\dot{M}_{cool} + \beta\psi; \quad \dot{M}_{hot} = -\dot{M}_{cool}Z_{hot} + (pe + \beta Z_{cold})\psi \\ \dot{M}_{cold} = \dot{M}_{cool} - (1 - R + \beta)\psi; \\ \qquad \dot{M}_{cold}^Z = \dot{M}_{cool}Z_{hot} - [p(1-e) - (1+\beta-R)Z_{cold}]\psi \end{cases}$$

ψ =instantaneous SFR, R =recycled mass, β = stellar fedback efficiency,

p = yield, e = ejected metals, $\dot{M}_{cool}$ = cooling rate, $Z_i = M_i^Z/M_i$

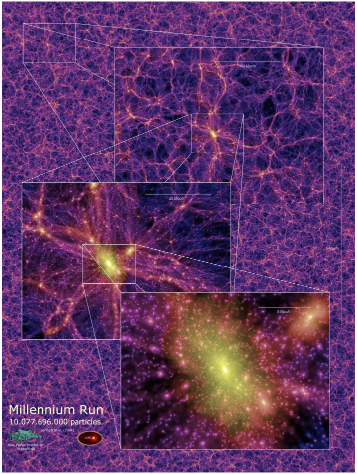
Issues with the semi-analytical approach

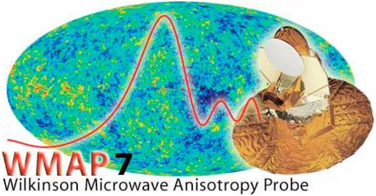
The semi-analytical approach is quite successful in reproducing galactic properties **but**:

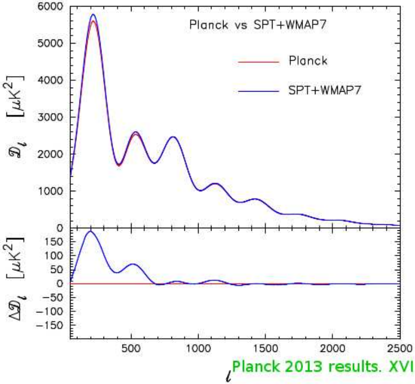
- A complete understanding is lacking in many areas of galaxy formation (e.g. the transformation of galaxy sizes in mergers).
- There are too many free parameters. This can be overcome for a given set of parameters by using statistical methods: such as the Monte Carlo Markov Chains (see Henriques et al. 2009), using a very simplistic approach (see Neistein et al. 2009), using 

emulators (see Bower 2010) or using more observational constrains!.

A new flavour of the GALFORM semi-analytical model







Gonzalez-Perez et al. (2013)

The new model based on a N-body simulation with WMAP7 cosmology

ΛCDM Cosmology

↓

DM Merger trees

↓

Galform

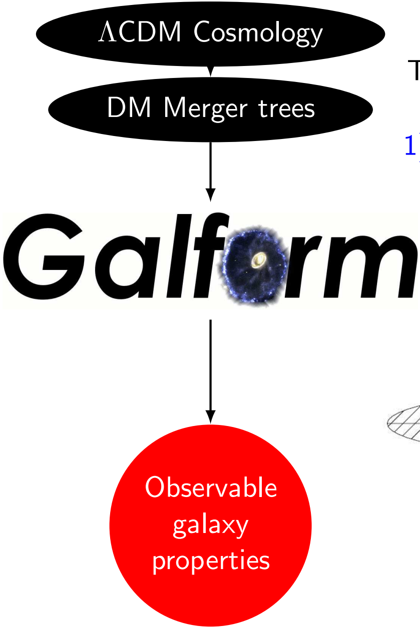
Using analytical equations, containing free parameters, GALFORM calculates the physical processes affecting the evolution of galaxies:

- Gas cooling $\Rightarrow$ Disk formation
- Galaxy mergers $\Rightarrow$ Spheroids
- SF* & Feedback
  from both SNe & AGN
- Chemical Evolution
- Stellar population & Extinction

* New improved treatment of SF in disks (Lagos et al. 2011) based on the empirical law from Blitz & Rosolowsky (2006), following explicitly the He, HI & H_2:

$$\Sigma_{SFR} = \frac{1}{\tau_{mol.\,gas}} \times \frac{\Sigma_{mol.\,gas}}{\Sigma_{total\;gas}}(\mathrm{P_{hydrostatic}\;of\;the\;disk}) \times \Sigma_{\mathrm{cold\;gas}}$$

The new model based on a N-body simulation with WMAP7 cosmology

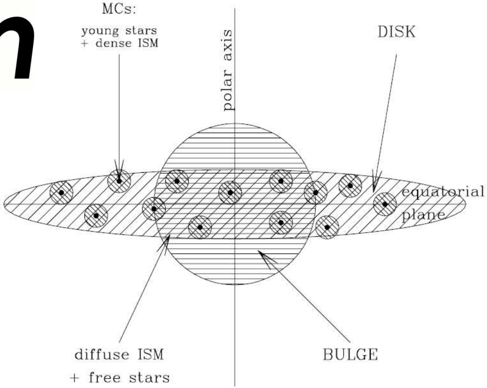


GALFORM gives M_*, SFH, Z, etc.

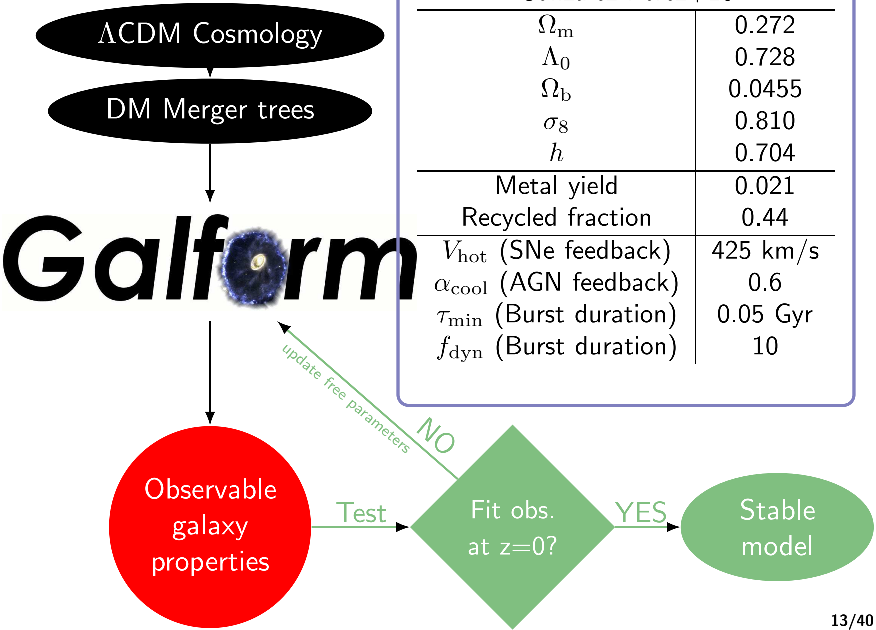
Thus, in order to obtain observables out of the model we need:

1) An SPS model to get luminosities

2) A dust model:

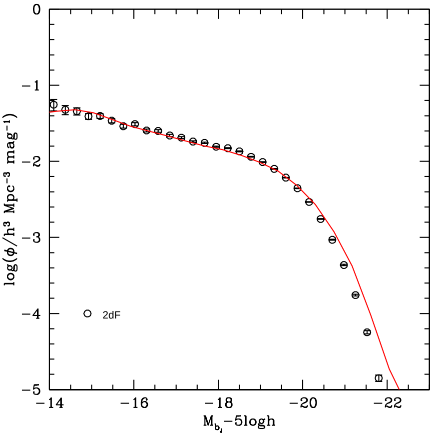


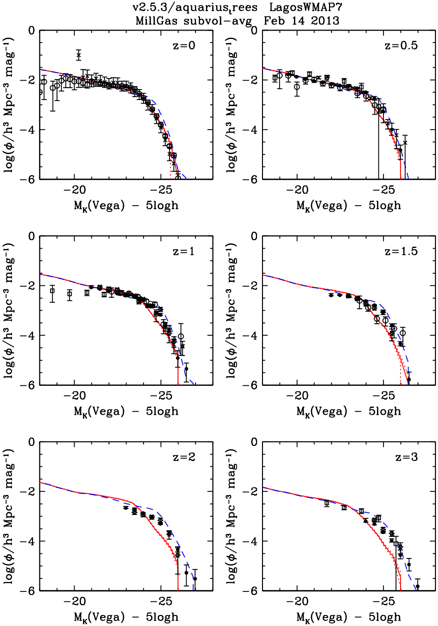
The new model based on a N-body simulation with WMAP7 cosmology



Gonzalez-Perez+13	
$\Omega_{\rm m}$	0.272
Λ_0	0.728
$\Omega_{\rm b}$	0.0455
σ_8	0.810
h	0.704
Metal yield	0.021
Recycled fraction	0.44
$V_{\rm hot}$ (SNe feedback)	425 km/s
$\alpha_{\rm cool}$ (AGN feedback)	0.6
$\tau_{\rm min}$ (Burst duration)	0.05 Gyr
$f_{\rm dyn}$ (Burst duration)	10

Free parameters tunned to reasonably match:





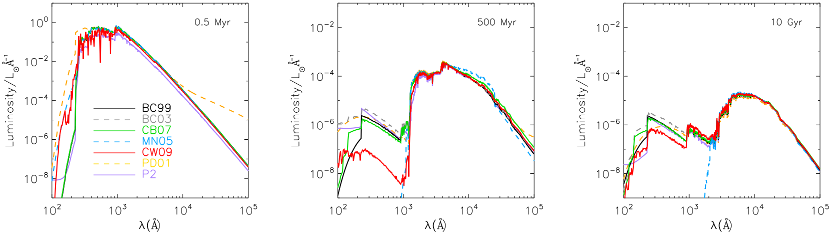
+ UV-LF at z∼3 and z∼6

Gonzalez-Perez et al. 2013

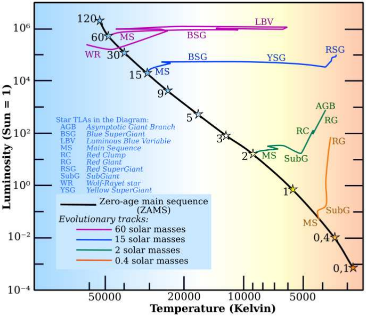
The SED of a galaxy is found by convolving the star formation history, $\dot{m}_*(t)$, with the SED of a single stellar population, ϕ_λ:

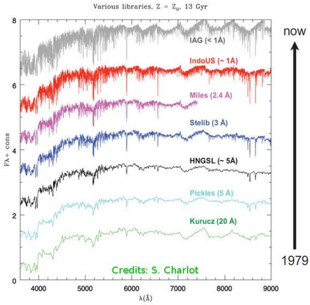
$$S_\lambda(t) = \int_0^t \phi_\lambda\left(t-t', Z(t')\right)\dot{m}_*(t')\mathrm{d}t',$$

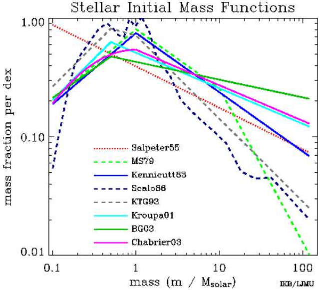
$\phi_\lambda\left(t-t', Z(t')\right)$ is obtained using a synthetic population stellar (SPS) model:

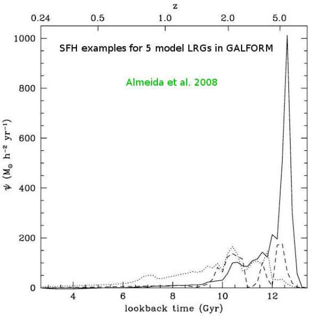


The ingredients of a SPS model

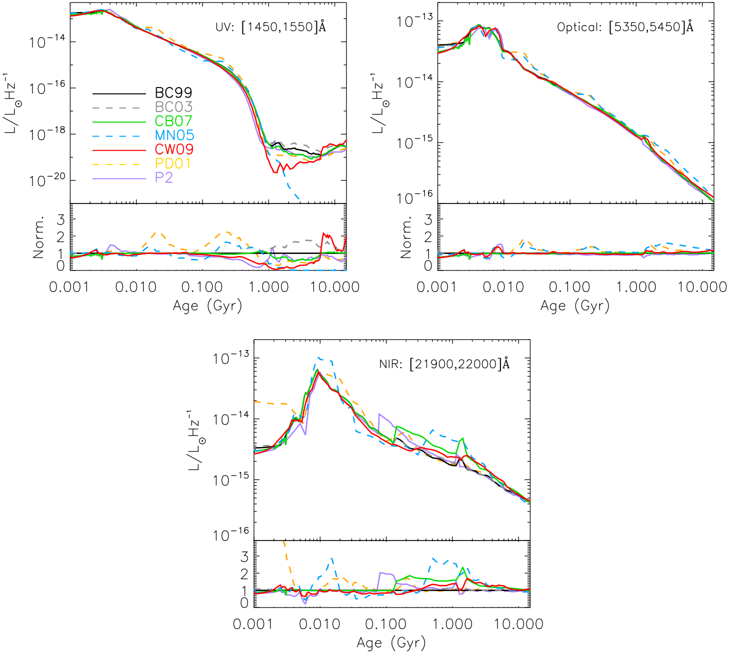




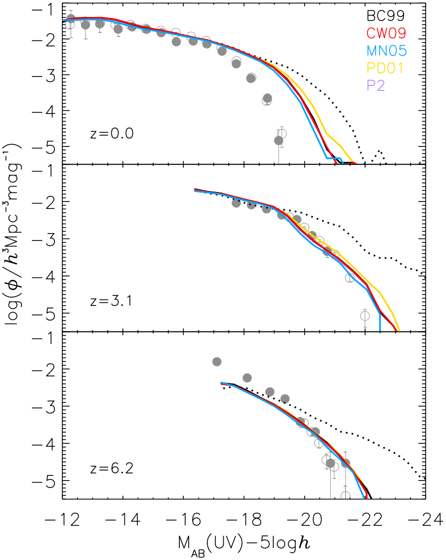




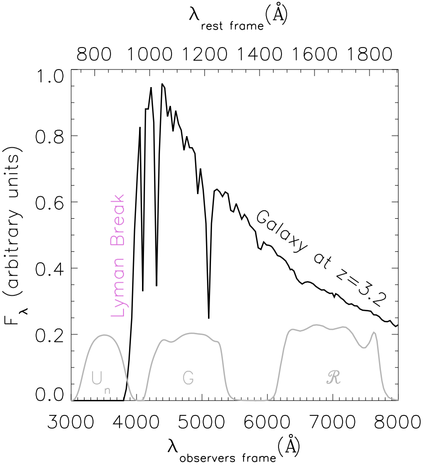
Comparing different SPS models

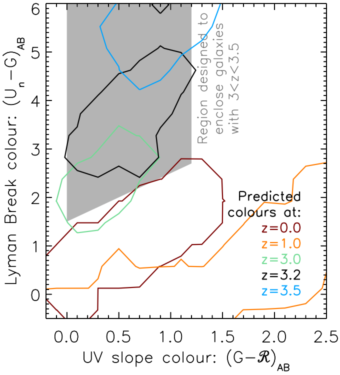


The evolution of the rest-frame UV luminosity function



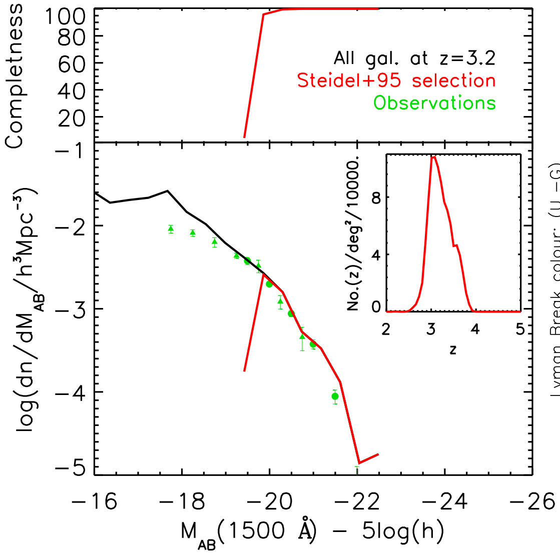
- The rest-frame UV LF is insensitive to the choice of SPS model.
- Similar results are expected for colour selected Lyman Break Galaxies.

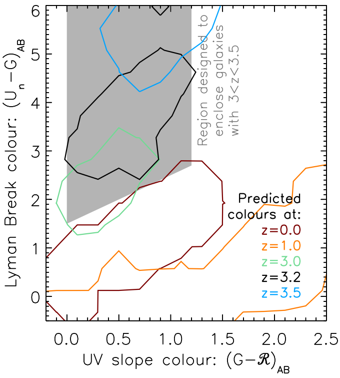




Gonzalez-Perez et al., MNRAS, 429, 2013

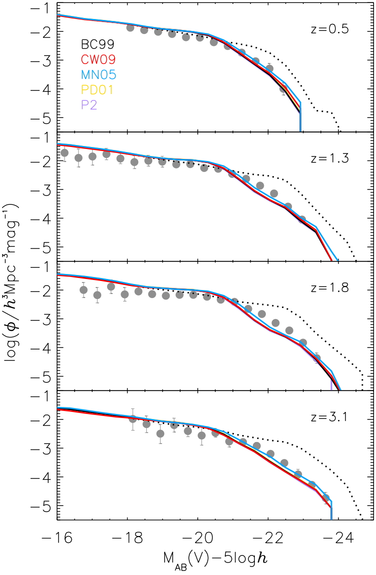
Lyman-break Galaxies: Selecting star forming galaxies





Gonzalez-Perez et al., MNRAS, 429, 2013

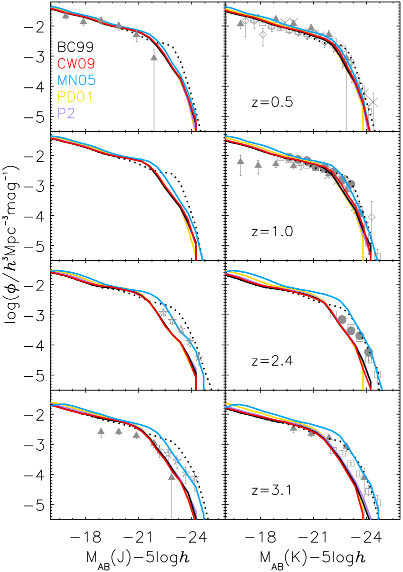
The evolution of the rest-frame optical luminosity function

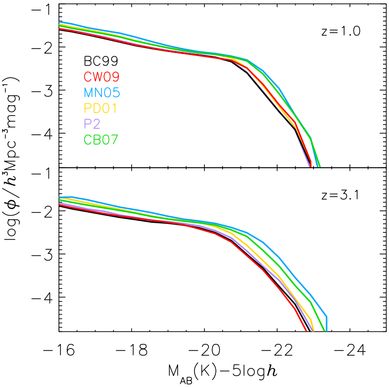


- The rest-frame optical LF is insensitive to the choice of SPS model.
- There is an increase in the dust attenuation with redshift. This is due to the dust attenuation in the model being directly related to τ_{V_0} and

$$\tau_{V_0} = 0.043 \left[\frac{M_{\rm cold}}{2\pi h_R^2} \frac{pc^2}{M_\odot} \right] \left(\frac{Z_{\rm cold}}{0.02} \right)$$

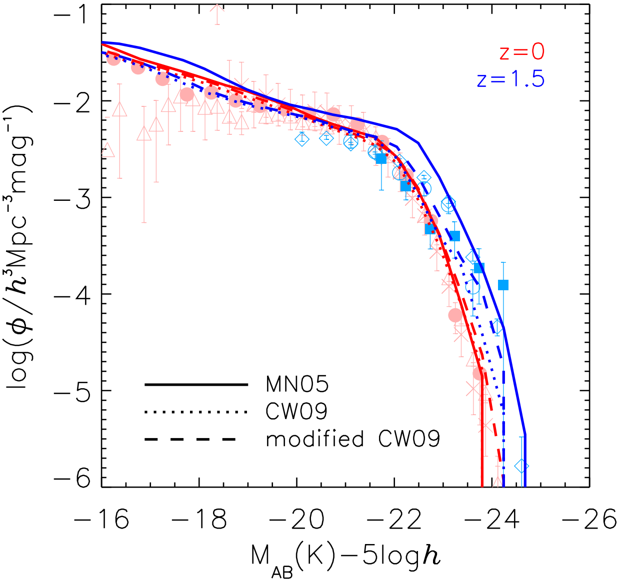
The evolution of the rest-frame NIR luminosity function





- Too many faint model galaxies at $z = 1$ (SN outflow treatment?)
- The treatment of the TP-AGB phase in the SPS model affects the predicted NIR LF evolution.

The evolution of the rest-frame NIR luminosity function



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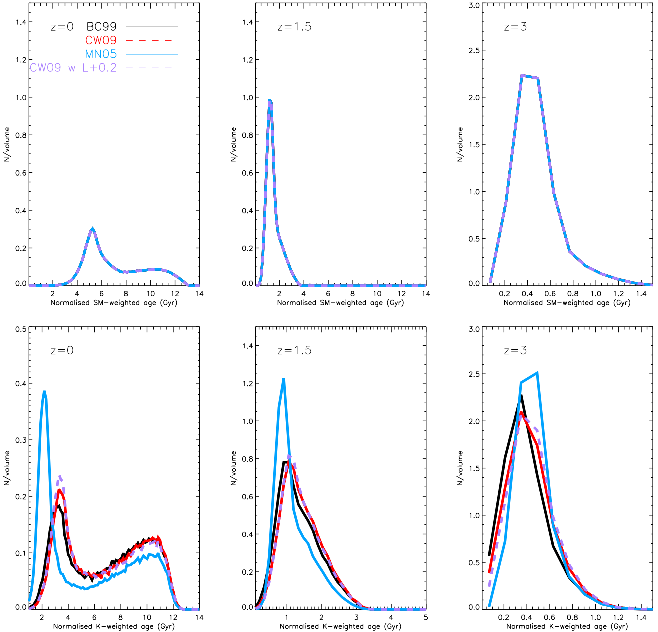

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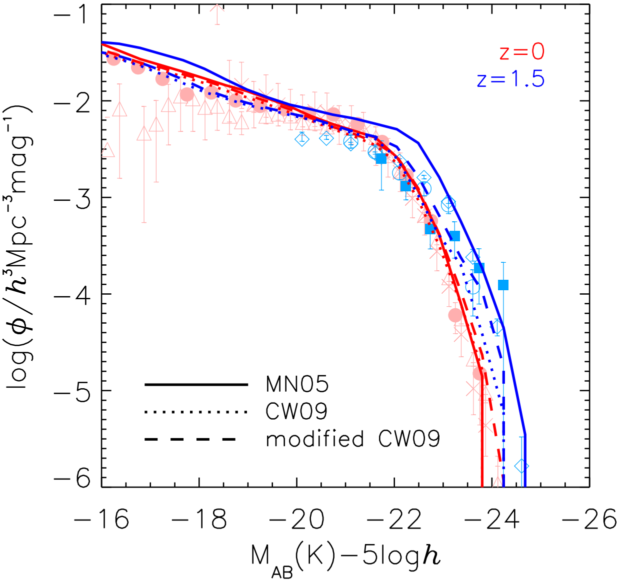
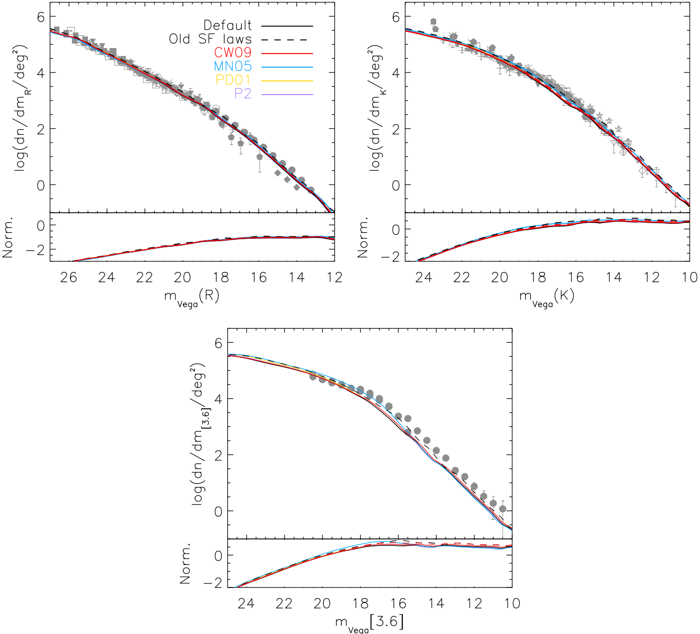


Predicted number counts

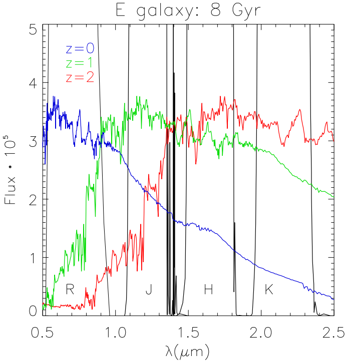


The number counts of EROs

EROs are galaxies which have been claimed to be particularly sensitive to the TP-AGB phase in SPS models.

Observationally EROs are:

- Redder than e.g. $(R - K) = 5$



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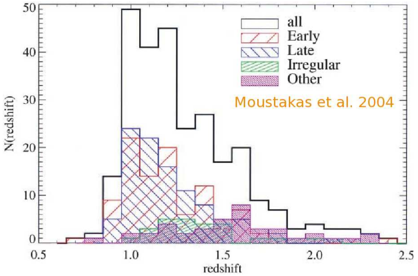

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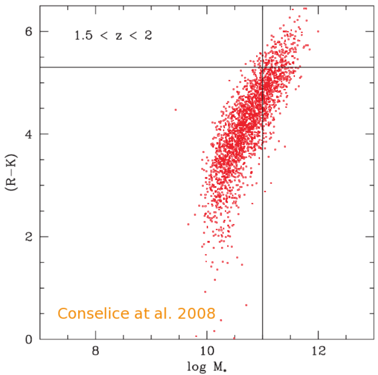

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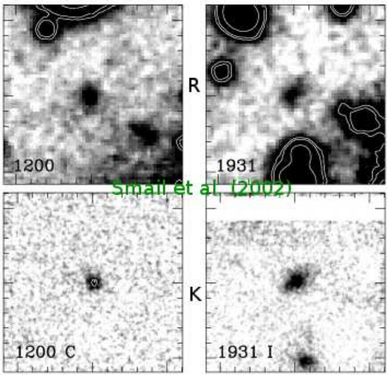
- Massive galaxies
- $\sim 50\%$ have an old stellar population



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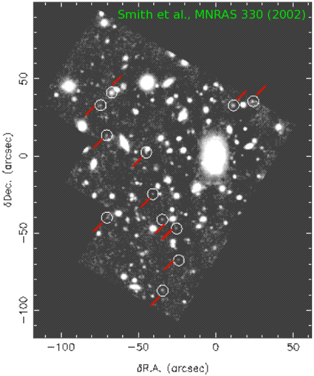
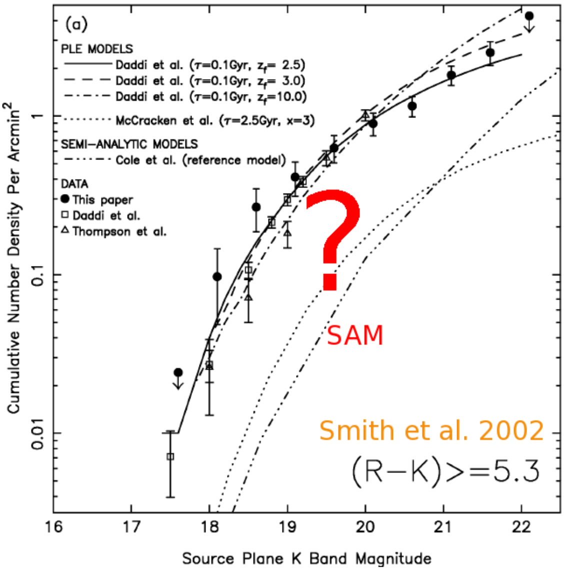
Observationally EROs are:

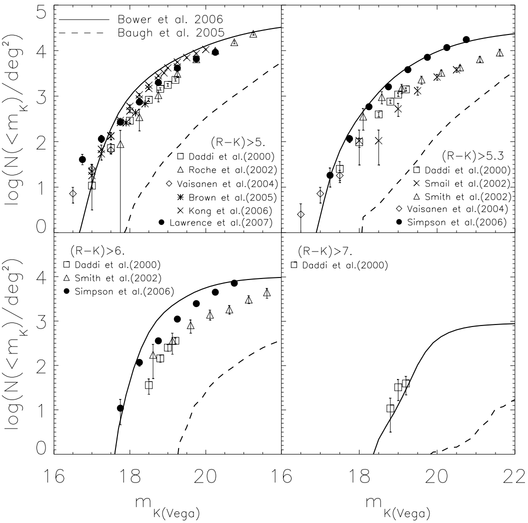
- Redder than e.g. $(R-K)=5$
- They appear at $z \sim 1$
- Massive galaxies
- $\sim 50\%$ have an old stellar population
- Inhomogeneously distributed in the sky: highly clustered



EROs are extreme galaxies in a hierarchical scenario



EROs number counts with previous GALFORM releases



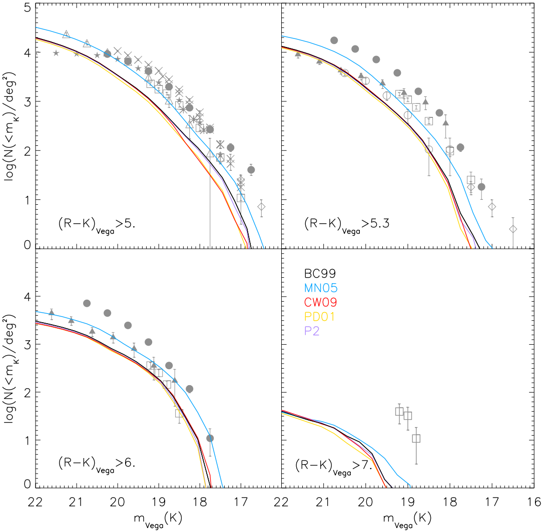
- Baugh et al. (2005) underestimation $\times 10$ and lacks a turn over
- Bower et al. (2006) fits good data. This model assumed

$$\psi = \frac{M_{cold}}{\tau_*}$$

- AGN feedback seems to be needed to understand massive galaxy evolution!

Gonzalez-Perez et al., MNRAS, 2009 and 2011

The predicted EROs number counts



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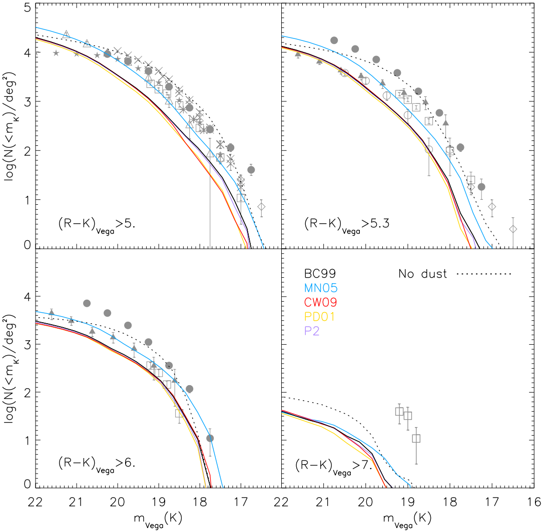

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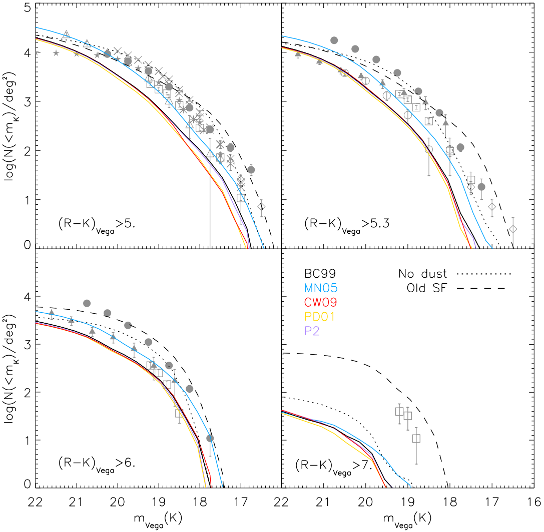
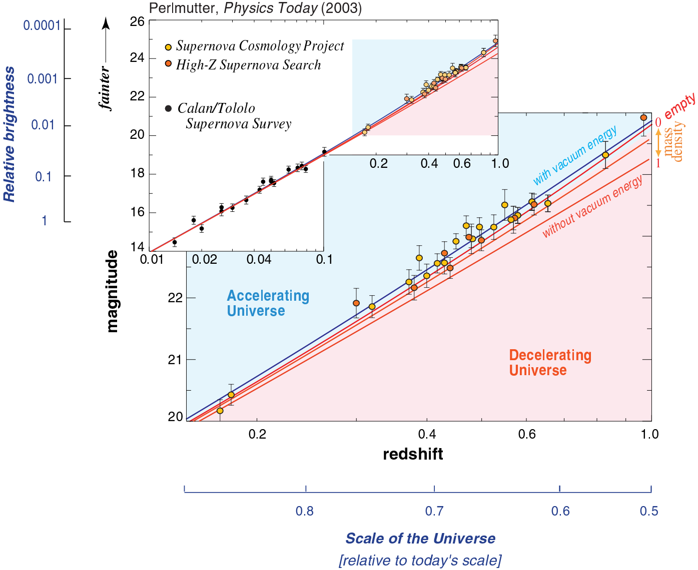


Concluding remarks on the predicted evolution of the LF

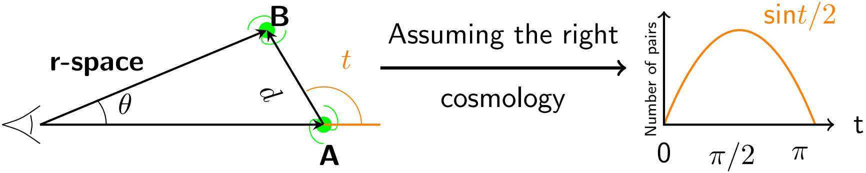
- The predicted rest-frame UV and optical LF are insensitive to the choice of SPS model.
- The evolution of the predicted rest-frame NIR LF strongly depends on the treatment of the TP-AGB phase in the SPS models:
  - The predicted evolution of the NIR LF from SPS models with a strong TP-AGB phase differs from observations.
- Predicted number counts up to MIR are insensitive to the choice of SPS model.
- EROs are sensitive to the treatment of TP-AGB phase in the SPS models, but are even more sensitive to the modelling of SF in disks.

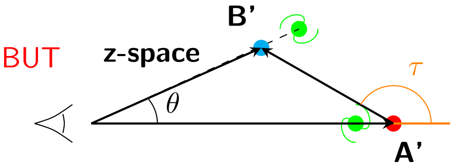
Gonzalez-Perez et al., 2013, submitted to MNRAS
See also Gonzalez-Perez et al., MNRAS, 2009, 2011, 2013.

Type Ia Supernovae

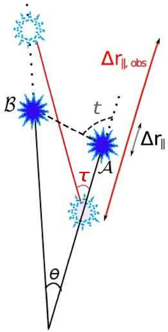


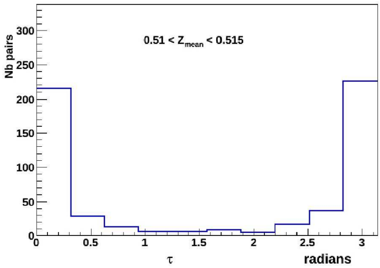
In a homogeneous and isotropic universe and for isolated pairs of galaxies we expect:





From the measured angles to the cosmological parameters





How the recovered distribution compares with the observed one?

$$\Phi(\tau)\mathrm{d}\tau = F(\mathrm{t})\mathrm{d}t; \qquad \frac{\tan t}{\tan\tau} = \frac{\Delta r_{\parallel,\mathrm{obs}}}{\Delta r_{\parallel}} = 1 + \frac{(1+z)}{H(z)}\frac{\Delta v_{\parallel}}{\Delta r_{\parallel}}$$

How can we determine the term $\Delta v_{\parallel}/\Delta r_{\parallel}$?

1. Measure the peculiar velocity of observational galaxies (this is only possible for a small subsample of BOSS).

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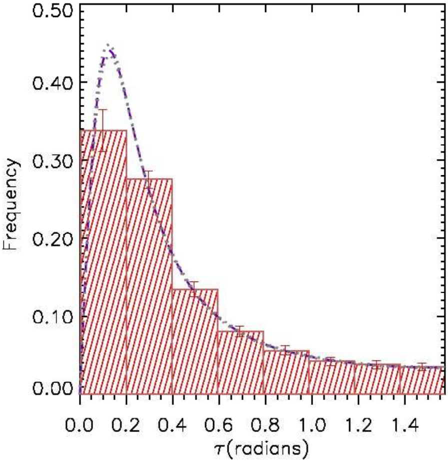
2. Normalize with observations at $z = 0$ (as done in Marinoni & Buzzi 2010).



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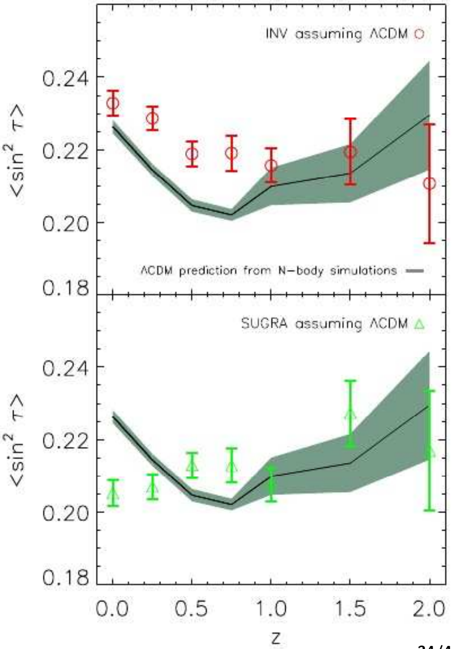
1. Measure the peculiar velocity of observational galaxies (this is only possible for a small subsample of BOSS).
2. Normalize with observations at $z = 0$ (as done in Marinoni & Buzzi 2010).
3. Make use of N-body simulations (as done in Jennings, Baugh & Pascoli 2011).



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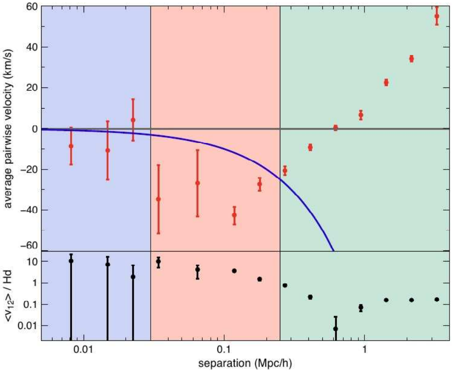
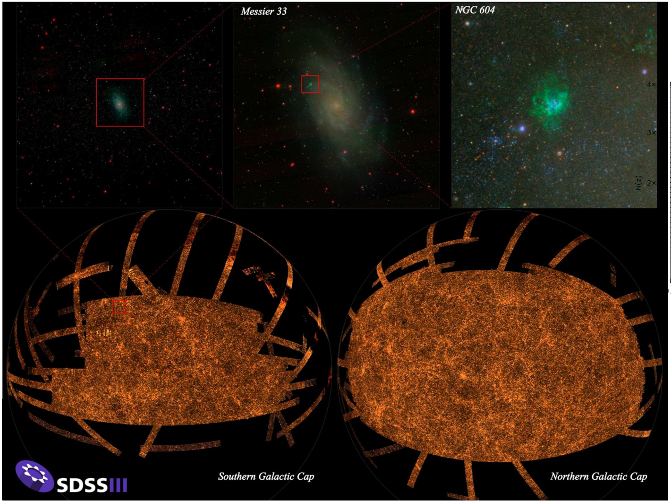
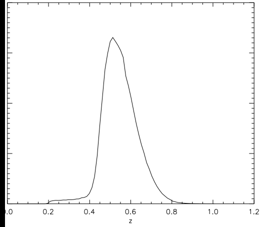
2. Normalize with observations at $z = 0$ (as done in Marinoni & Buzzi 2010).
3. Make use of N-body simulations (as done in Jennings, Baugh & Pascoli 2011).
4. Can we select pairs of galaxies with peculiar velocities such that the measured angle τ is minimally affected by the z-space distortion?. To try to answer this question we use GALFROM.



Focusing on galaxies at $z \sim 0.5$

We would like to apply the Alcock-Paczynksi test to isolated pairs of galaxies selected from the SDSS-III BOSS DR11

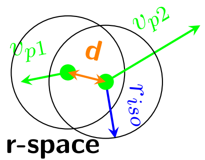




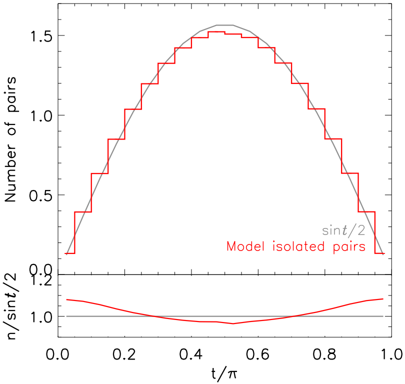
There are more than 800000 galaxies within BOSS DR10 with a measured spectra.

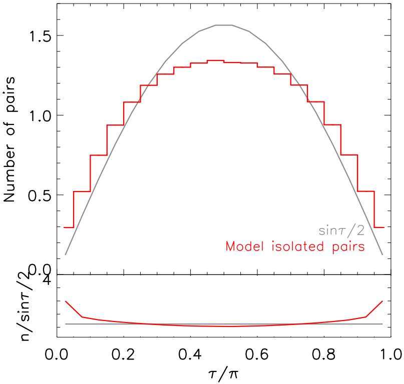
The predicted isolated pairs of galaxies

1. The isolation criteria: The number of neighbours a galaxy has within a sphere of a given comoving radius, r_{iso}, should be below a certain value.

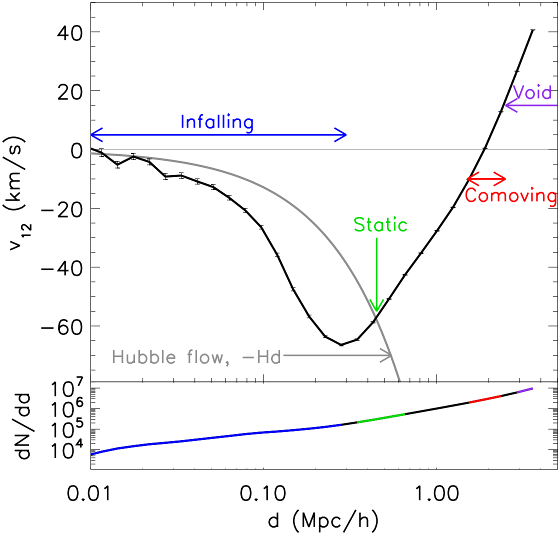


2. The predicted angles:

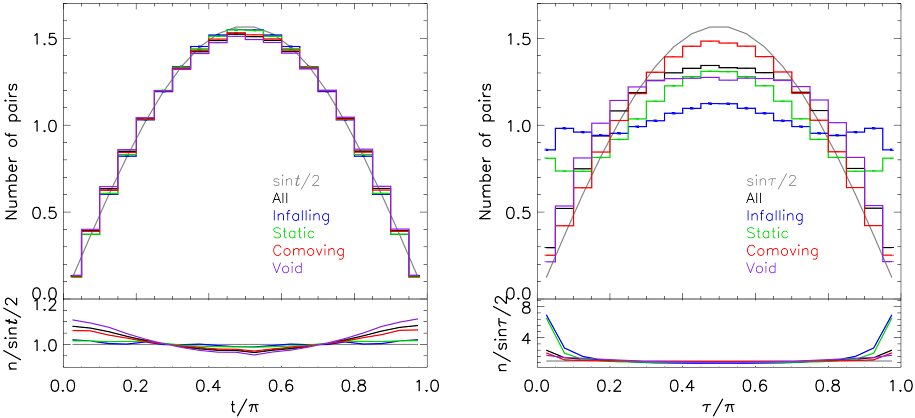




For a model snapshot at z, we can define the comoving velocity between two isolated galaxies as:
$v_{12} = (1+z)(\overrightarrow{v_{p2}} - \overrightarrow{v_{p1}})\hat{d}$



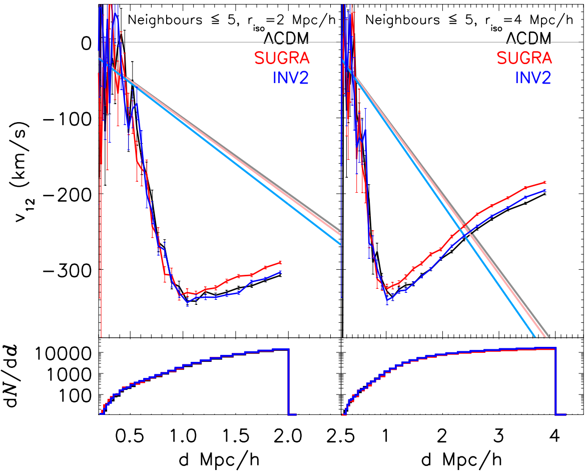
The predicted angles t and τ for different regimes



The distribution of τ for pairs in the *comoving regime* is minimally modified for $0.1 < t/\pi < 0.9$. Promising!

Step 1 to select galaxies in the *comoving regime*

The *comoving regime* can be defined in terms of the separation between pairs of galaxies such that $v_{12} \sim 0$.



The particular limits do not seem to be very sensitive to changes in the DE.

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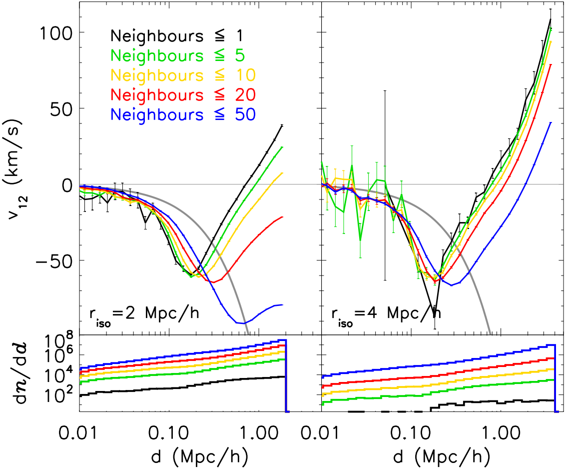

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But they do depend on:

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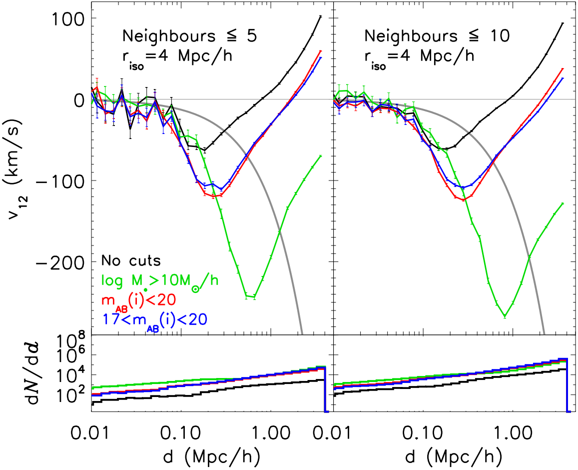

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But they do depend on:

- The isolation criteria: r_{iso} & maximum number of neighbours.
- Cuts in M_* or magnitude.

Next step: using a lightcone