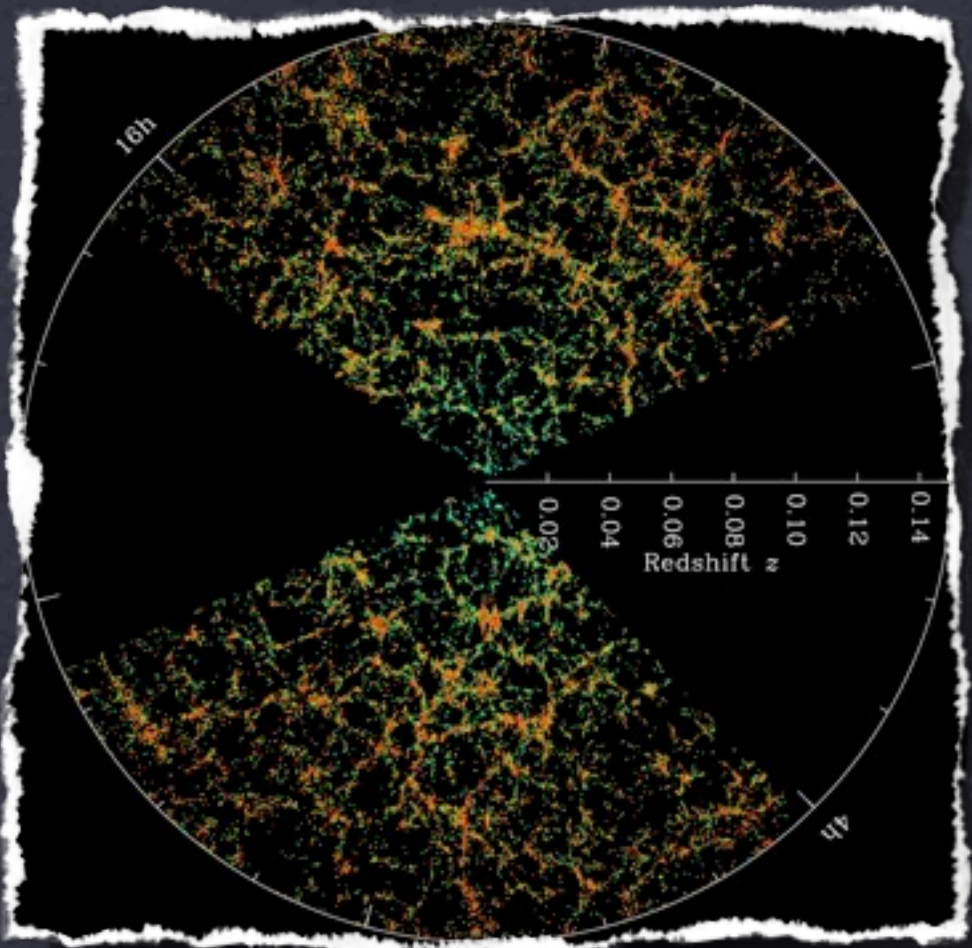
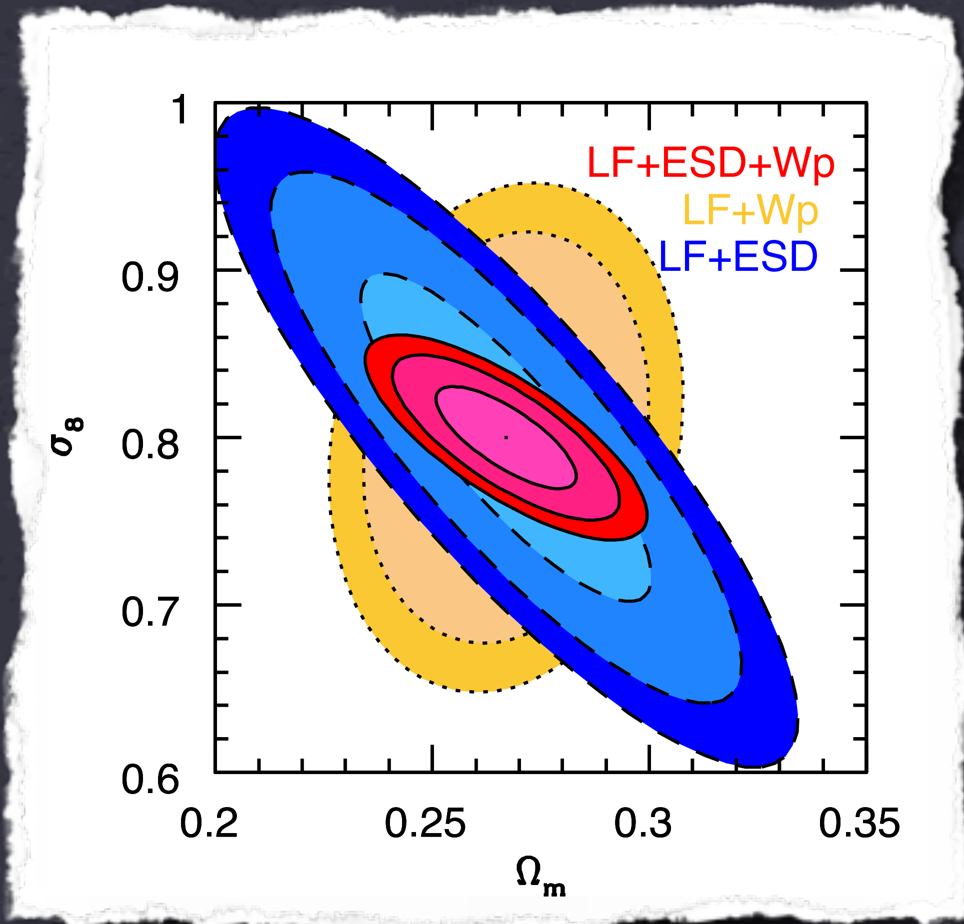
Galaxy-dark matter connection: a cosmological perspective

Surhud More (KICP)

Together with: Frank van den Bosch (Yale), Marcello Cacciato (HUJI), Houjun Mo (UMass), Xiahou Yang (SHAO)

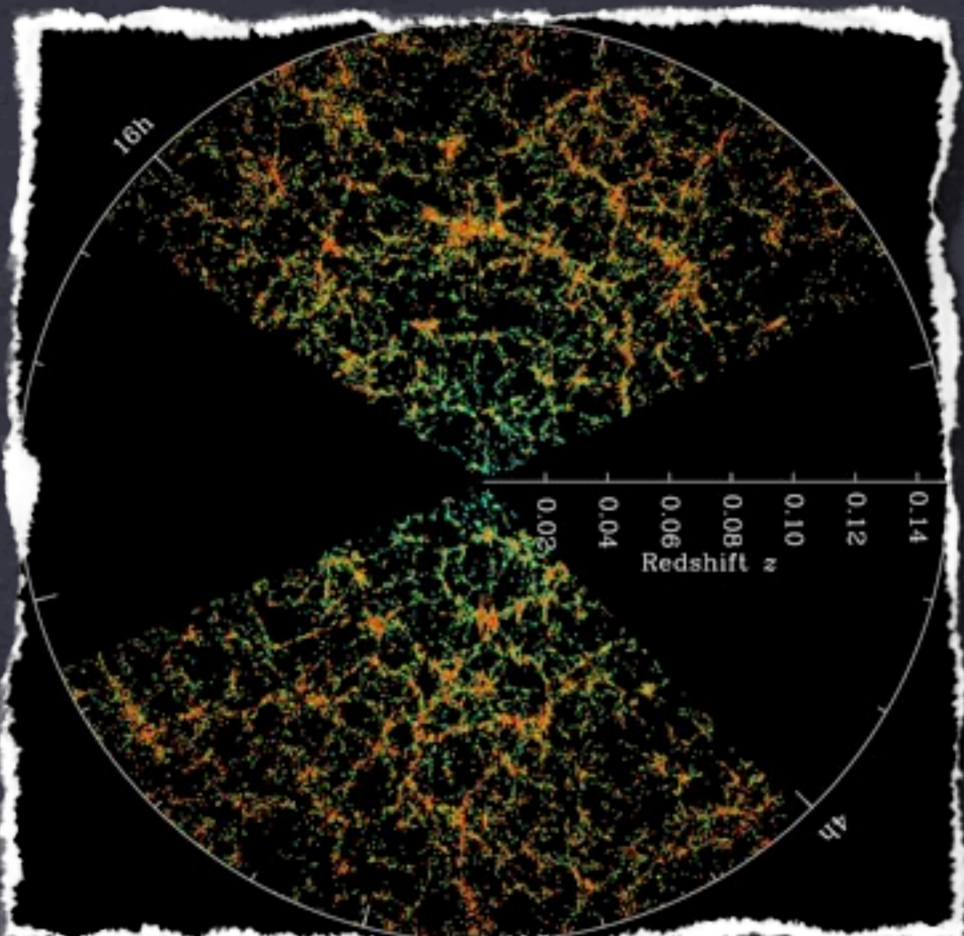
Take home message

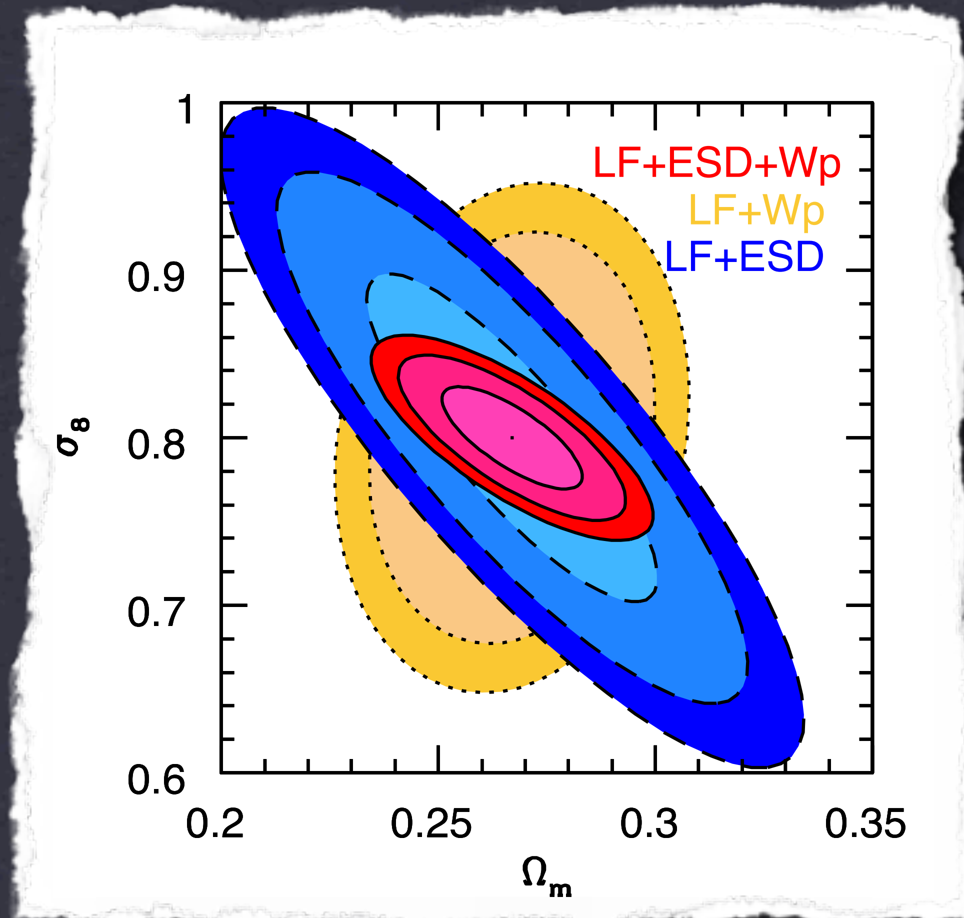




Galaxy observations can be used to constrain cosmological parameters!

Take home message





Galaxy observations can be used to constrain cosmological parameters!

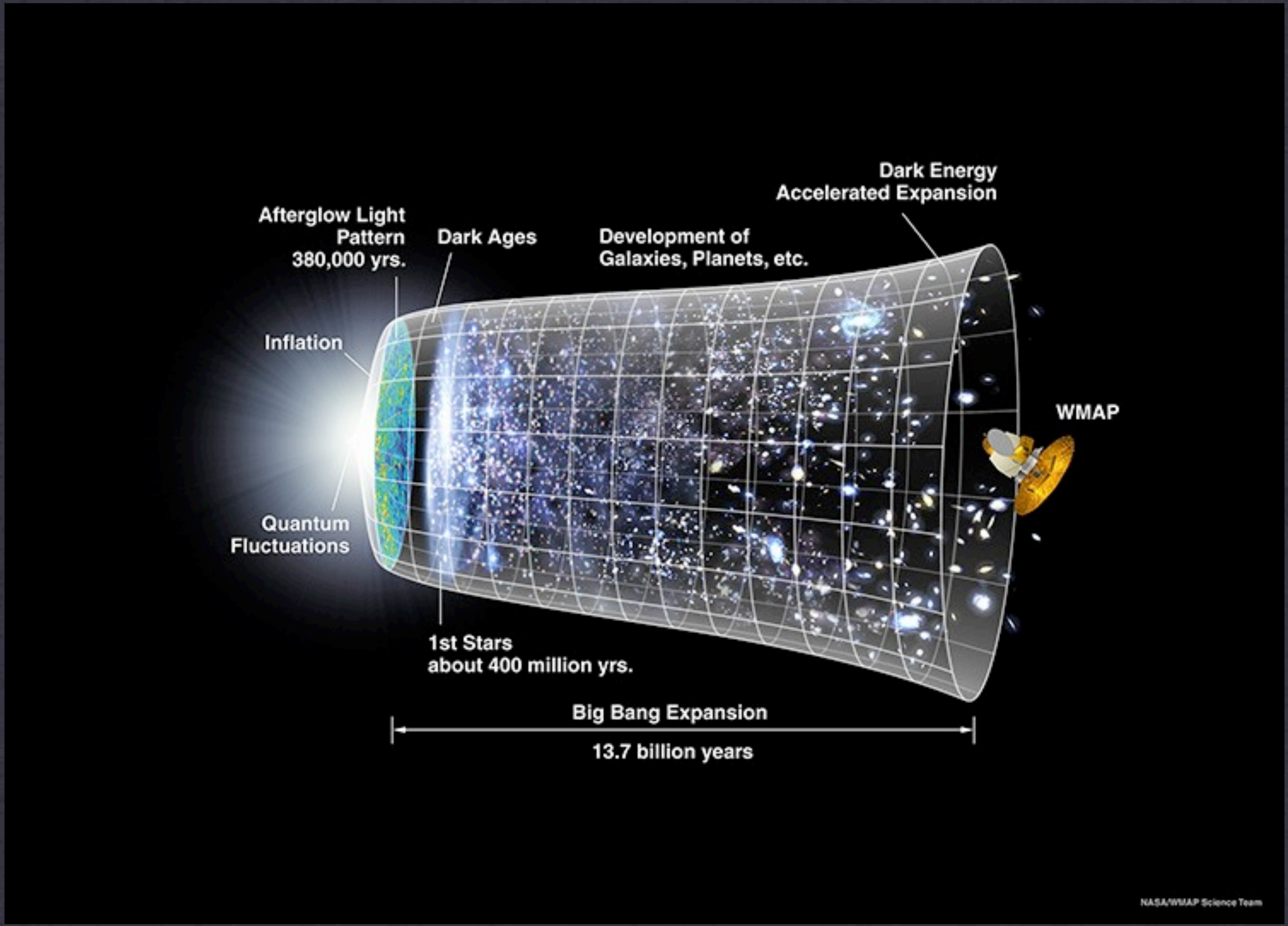
What kind of?

How?

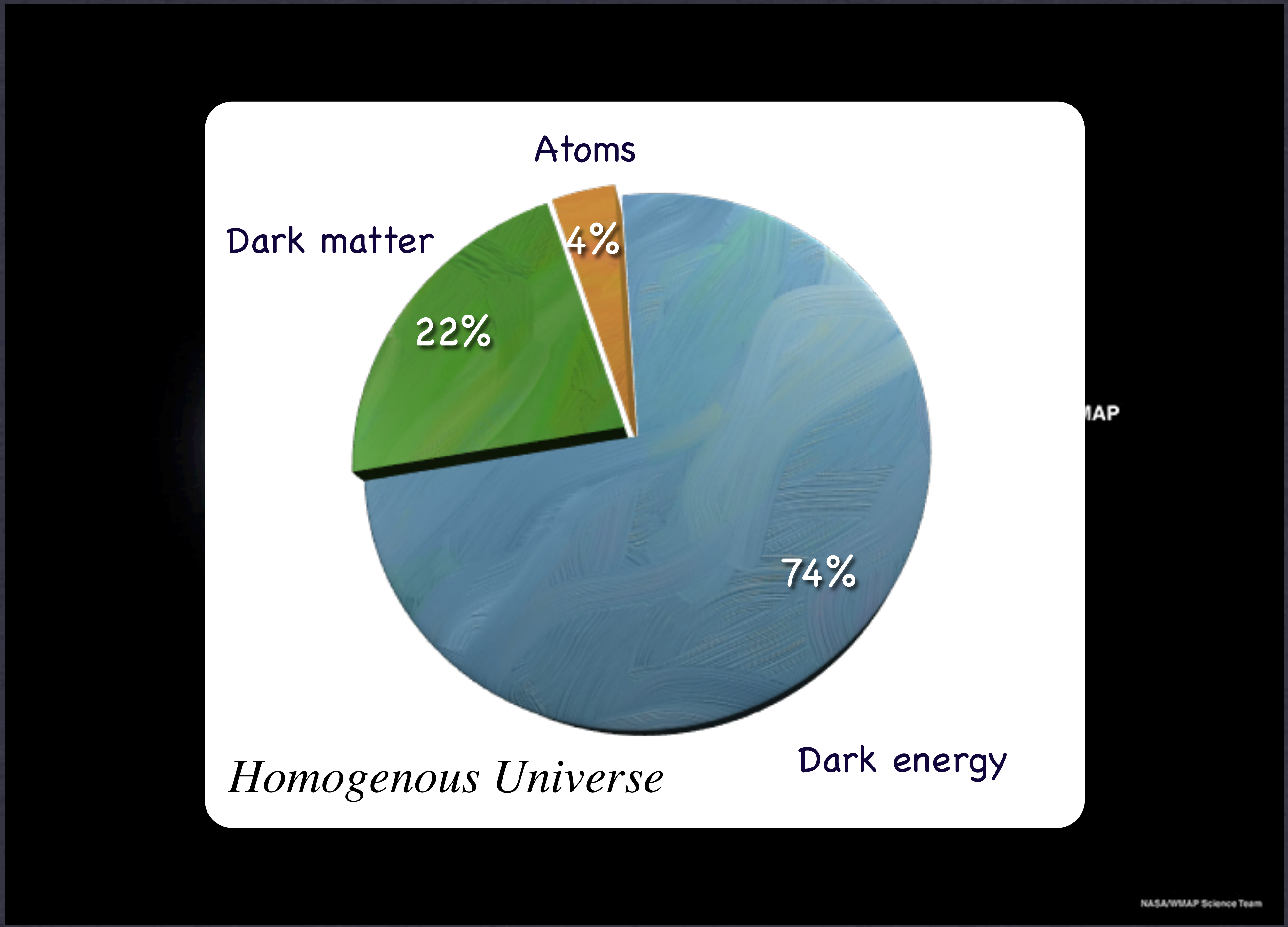
Outline of the talk

- Concordance cosmology: ΛCDM model
- Galaxy distribution
  - Observables: Galaxy abundance, galaxy clustering and galaxy-galaxy lensing
- The halo model and the conditional luminosity function
- Results: ΛCDM model and beyond!

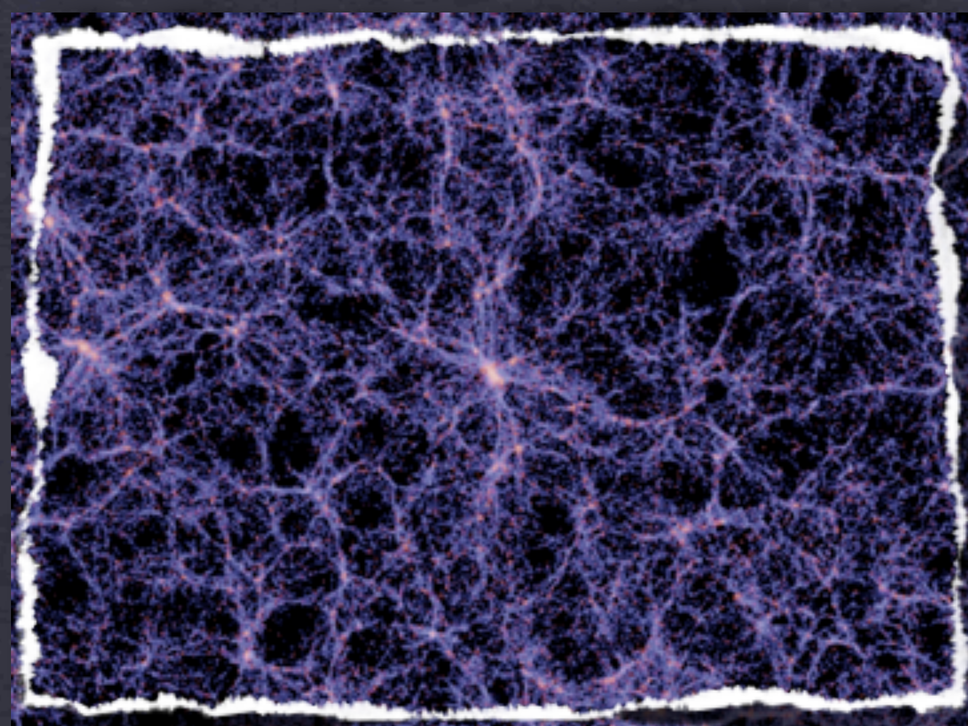
Cosmological paradigm

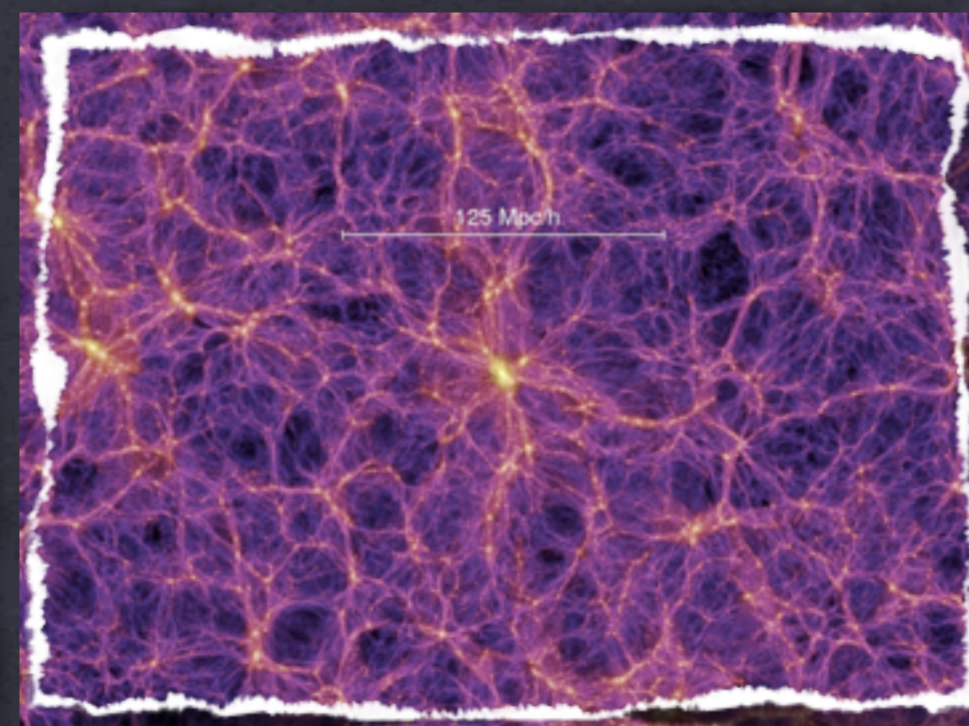


Cosmological paradigm



Galaxy-dark matter connection



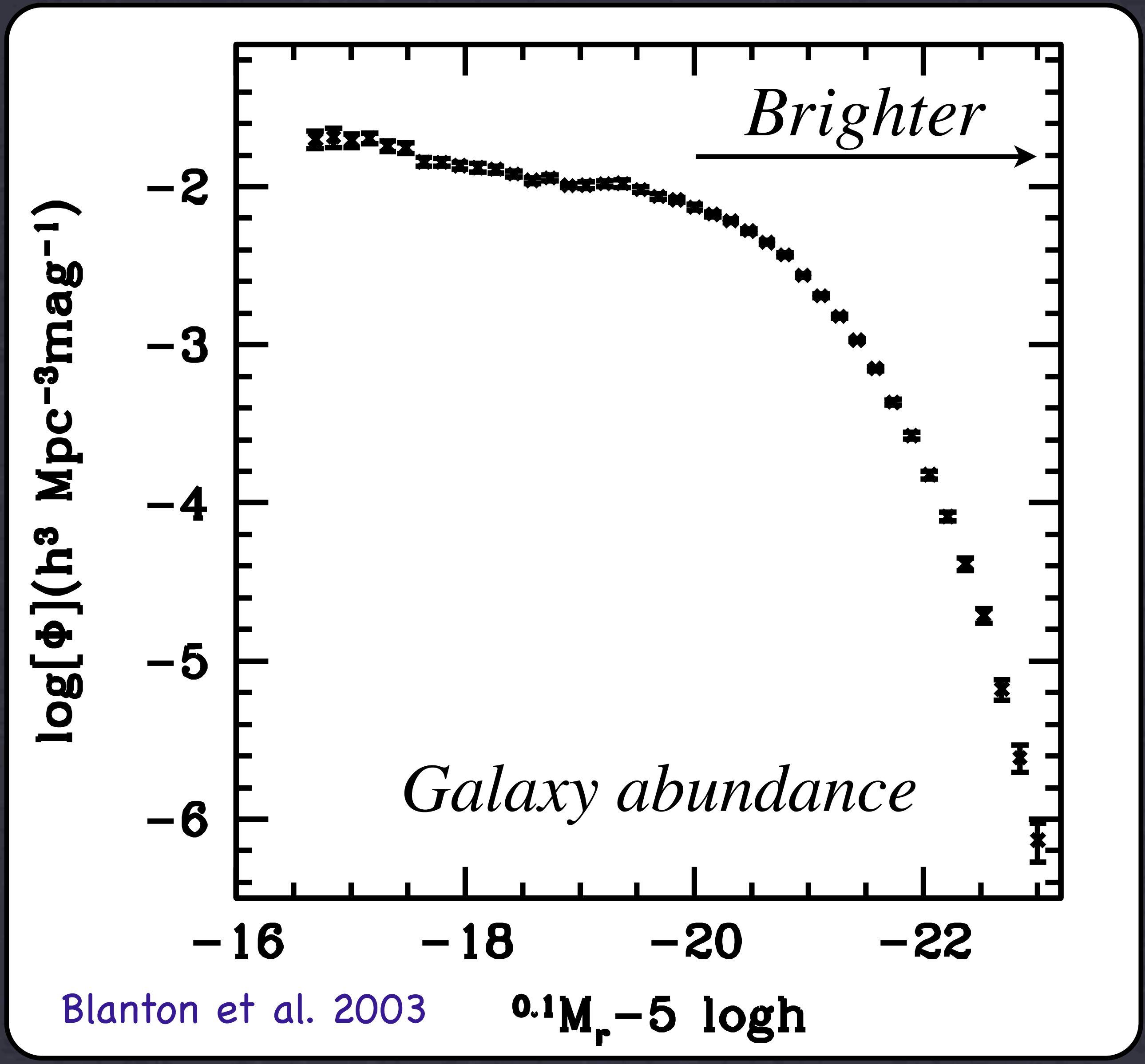


Millenium simulation, Springel et al. 2005 Galaxies Dark Matter

HOW DO GALAXIES OCCUPY DARK MATTER HALOES?

- Kinematics of satellite galaxies
- Strong gravitational lensing
- Abundance and clustering of galaxies
- Weak gravitational lensing

Galaxy luminosity function



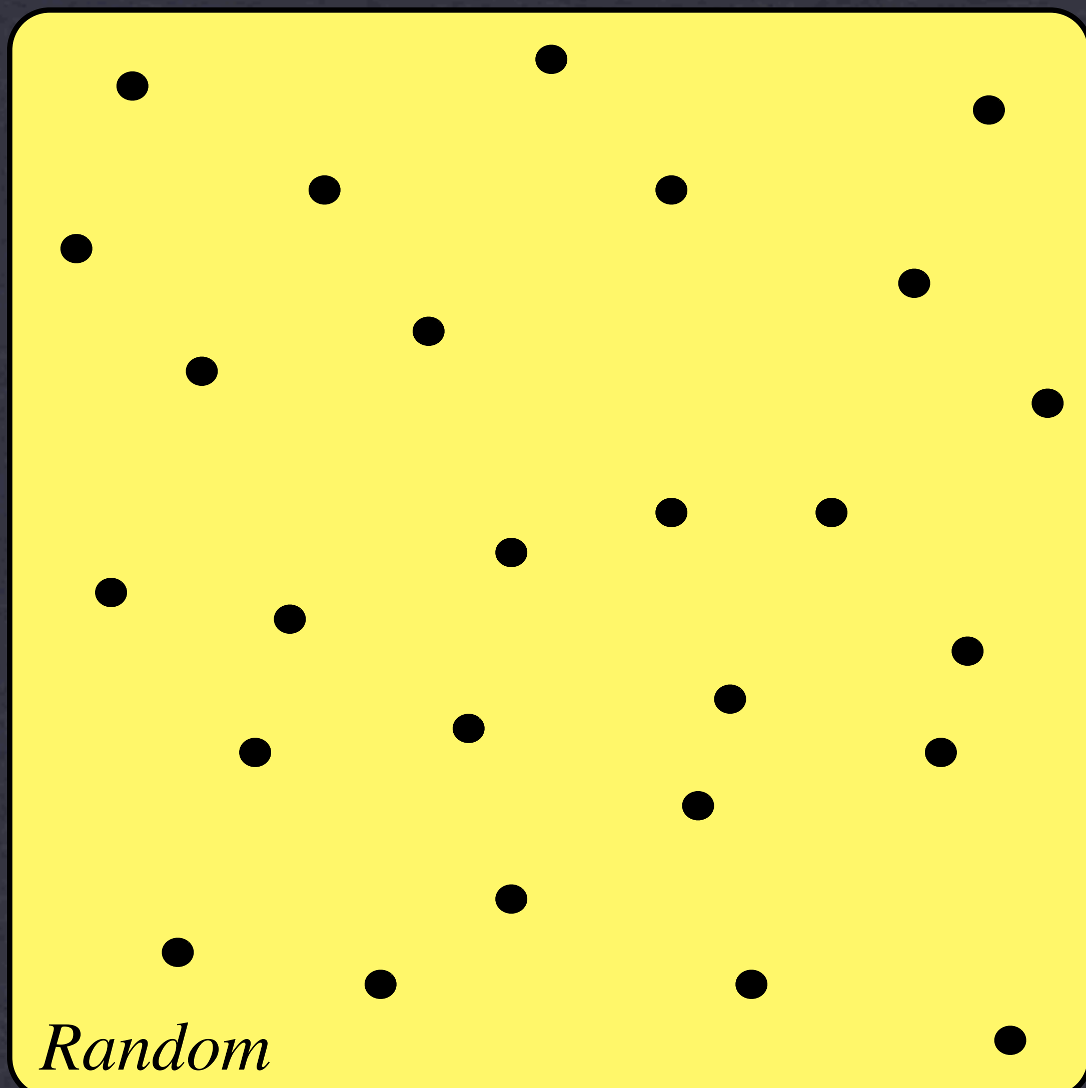
- Average number density of galaxies as a function of brightness.

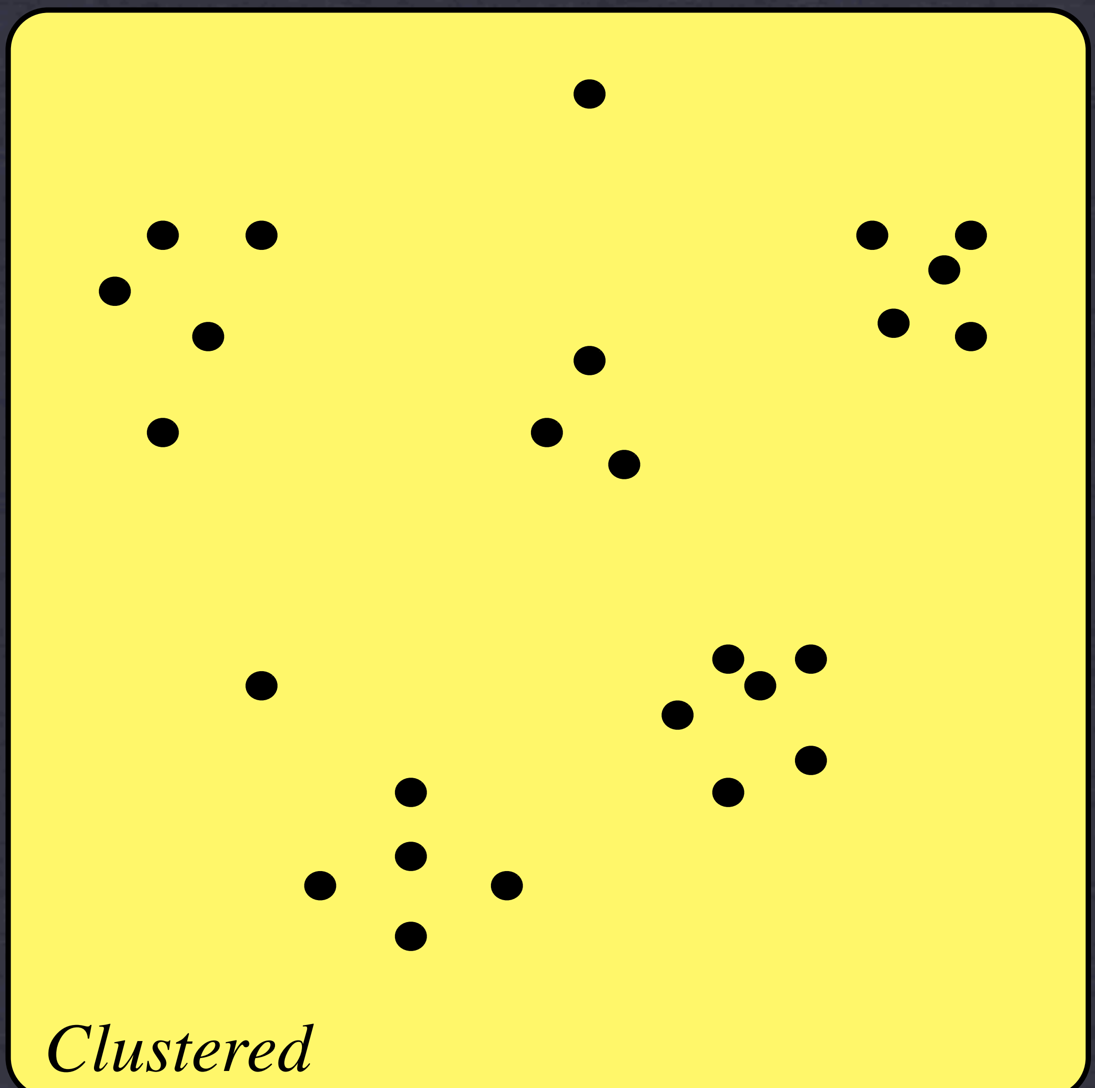
Galaxy clustering: the two point correlation function

$$\xi(r) = \frac{DD(r, r+dr)}{RR(r, r+dr)} - 1$$

$RR(r, r+dr) \rightarrow \bar{n}^2 dV 4\pi r^2 dr$

Galaxy clustering: the two point correlation function





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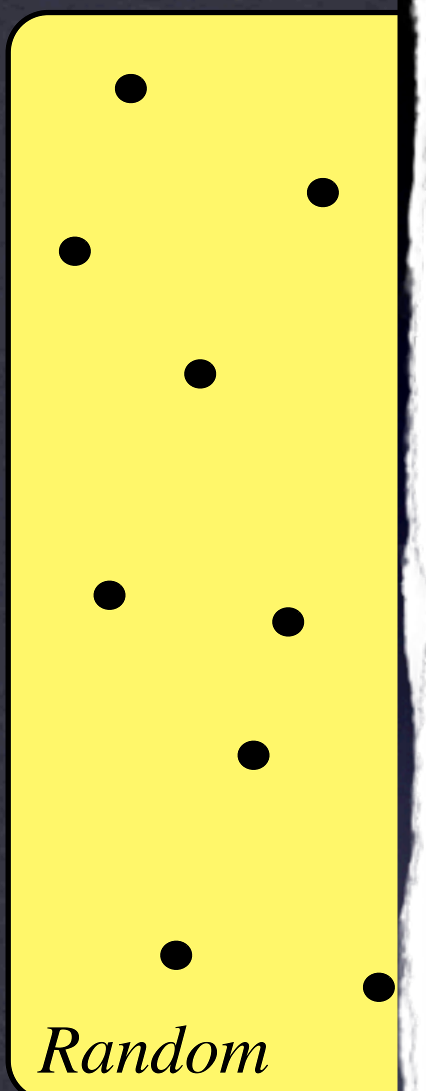
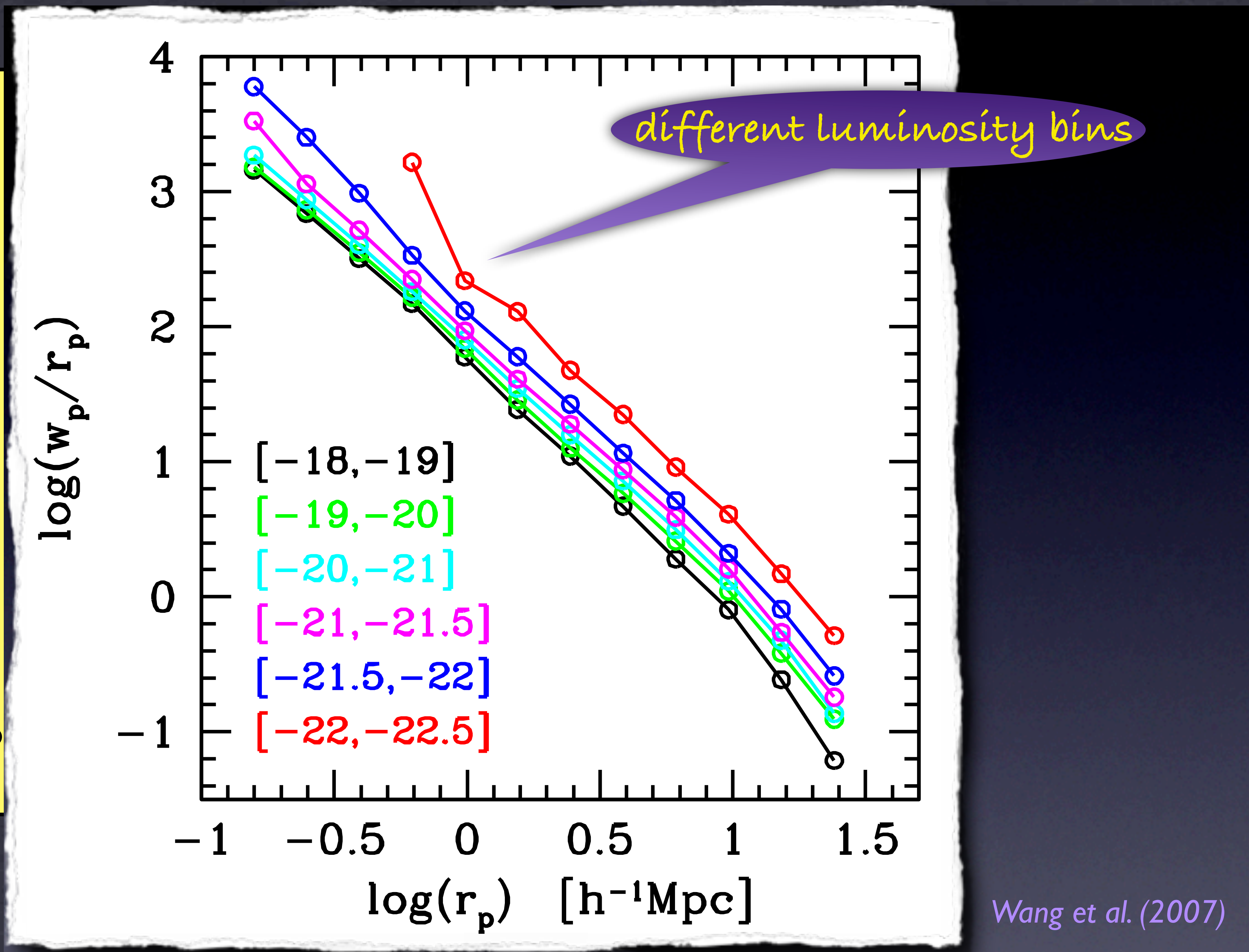
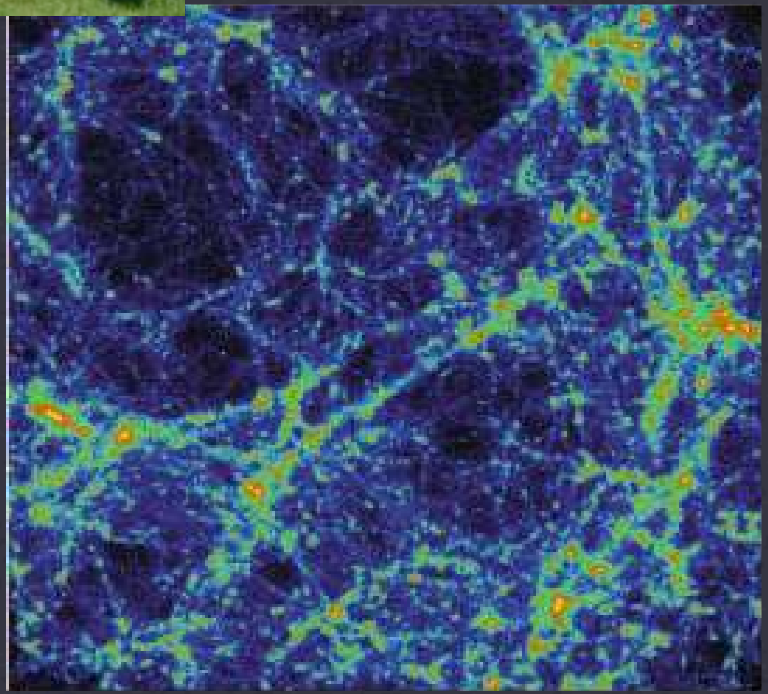


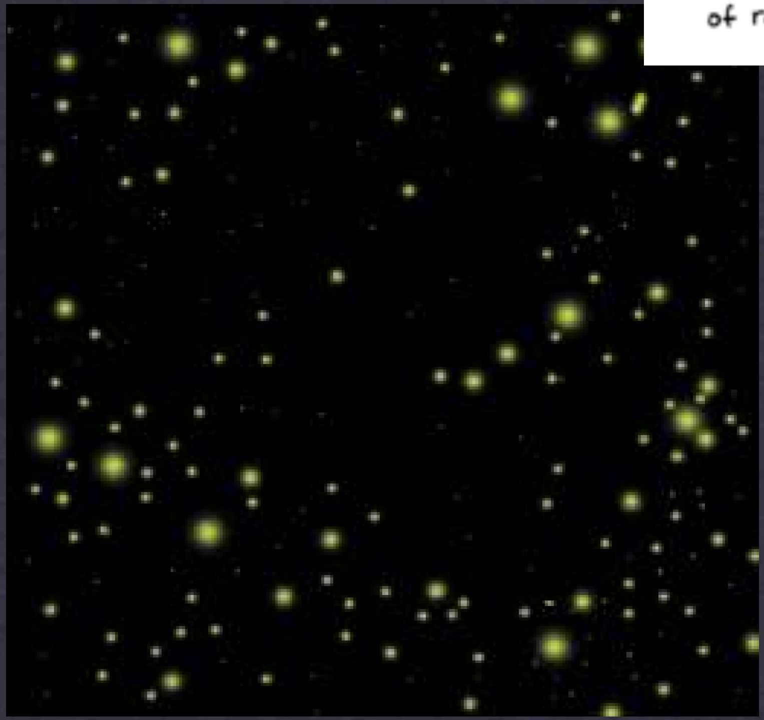


$$\xi(r) = \frac{\quad}{RR(r, r+dr)} - 1$$

$RR(r, r+dr) \rightarrow \bar{n}^2 dV 4\pi r^2 dr$

Halo model





Cooray & Sheth (2002)

- Structure in dark matter distribution
- Theorist's simplification :)

Halo model ingredients

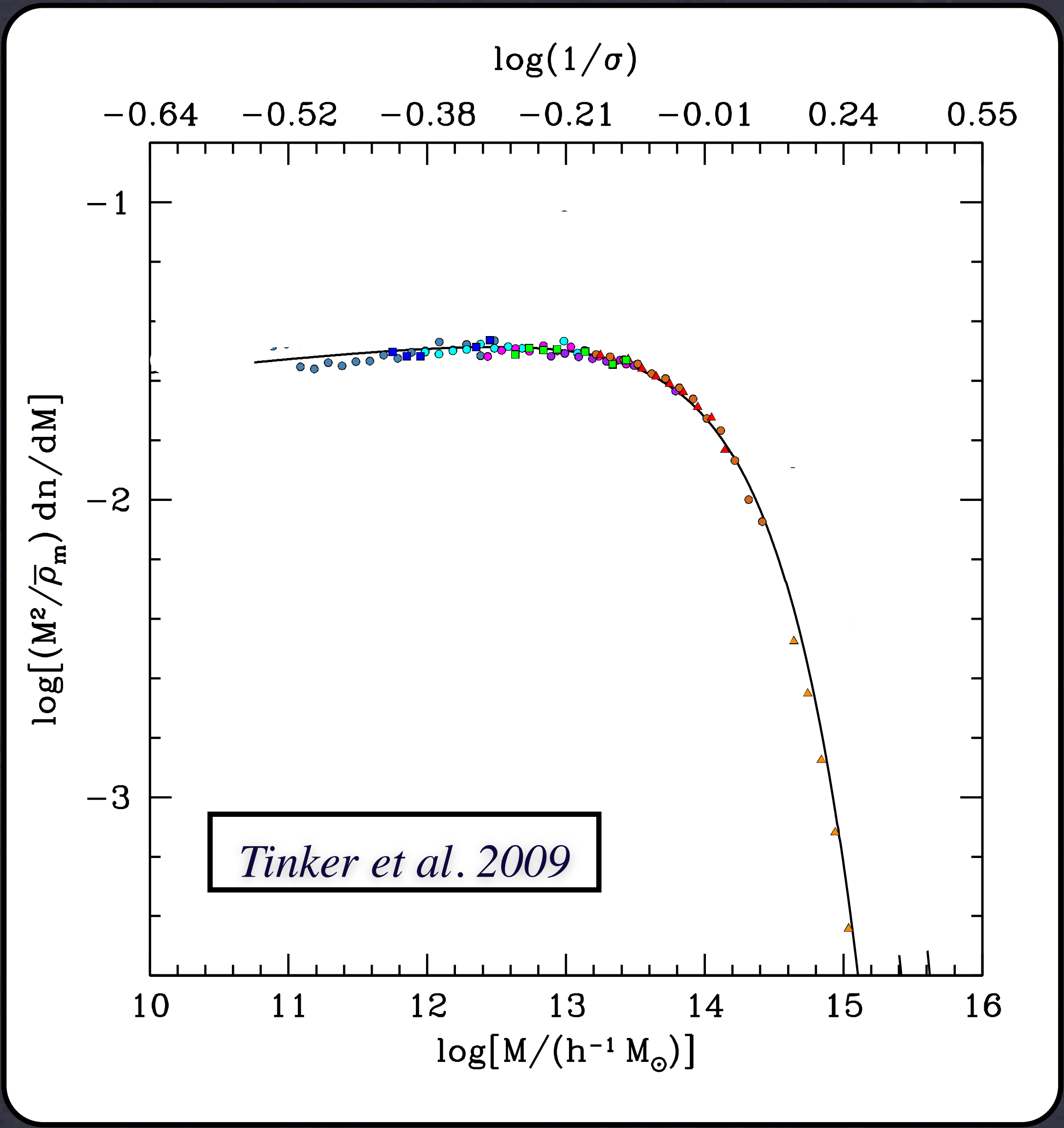
- Abundance of dark matter halos and its clustering properties

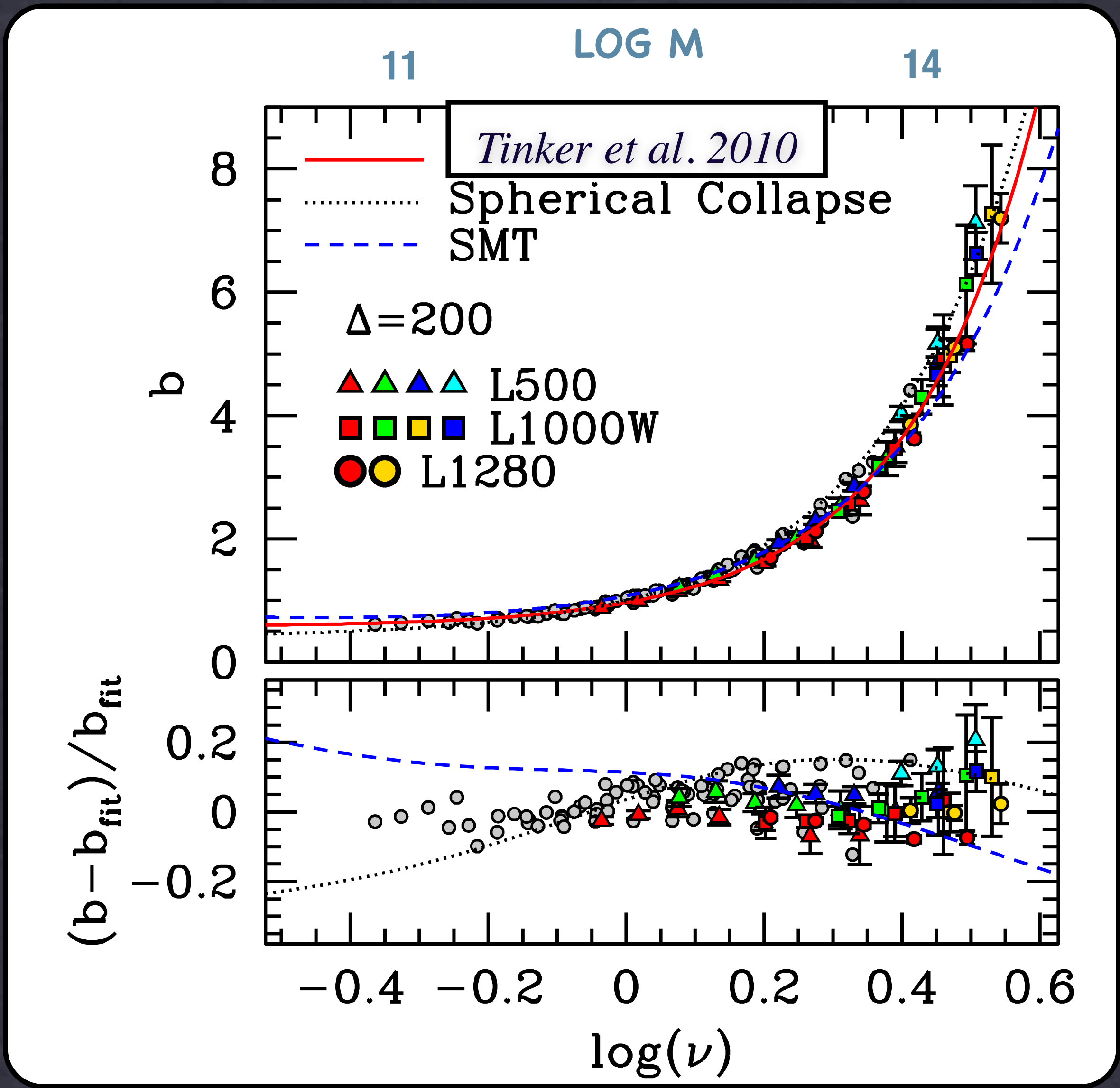
Cosmological information

- The connection between galaxies and dark matter

Galaxy formation physics

Dark matter distribution



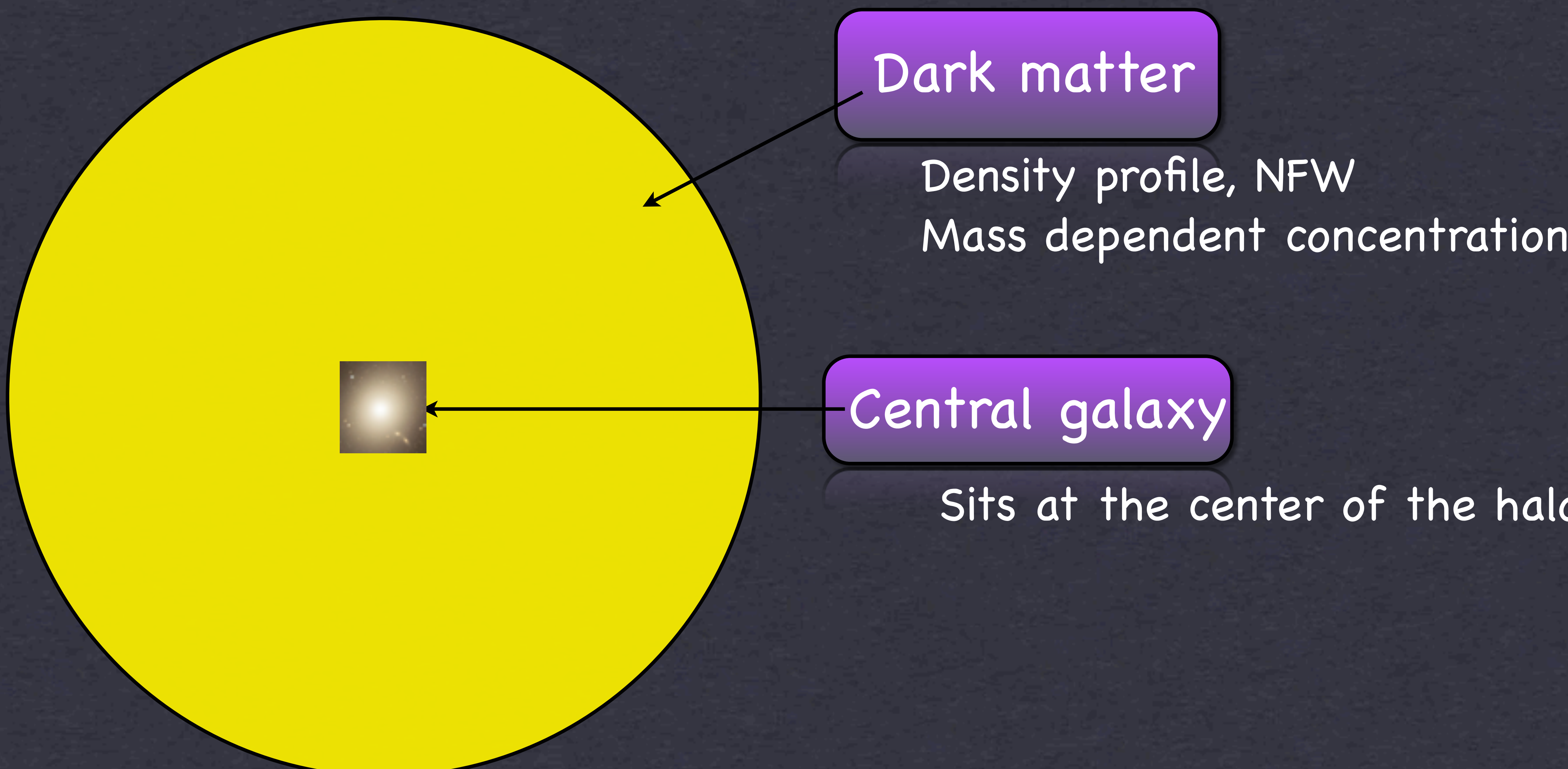


- Halo mass function
- Halo bias function

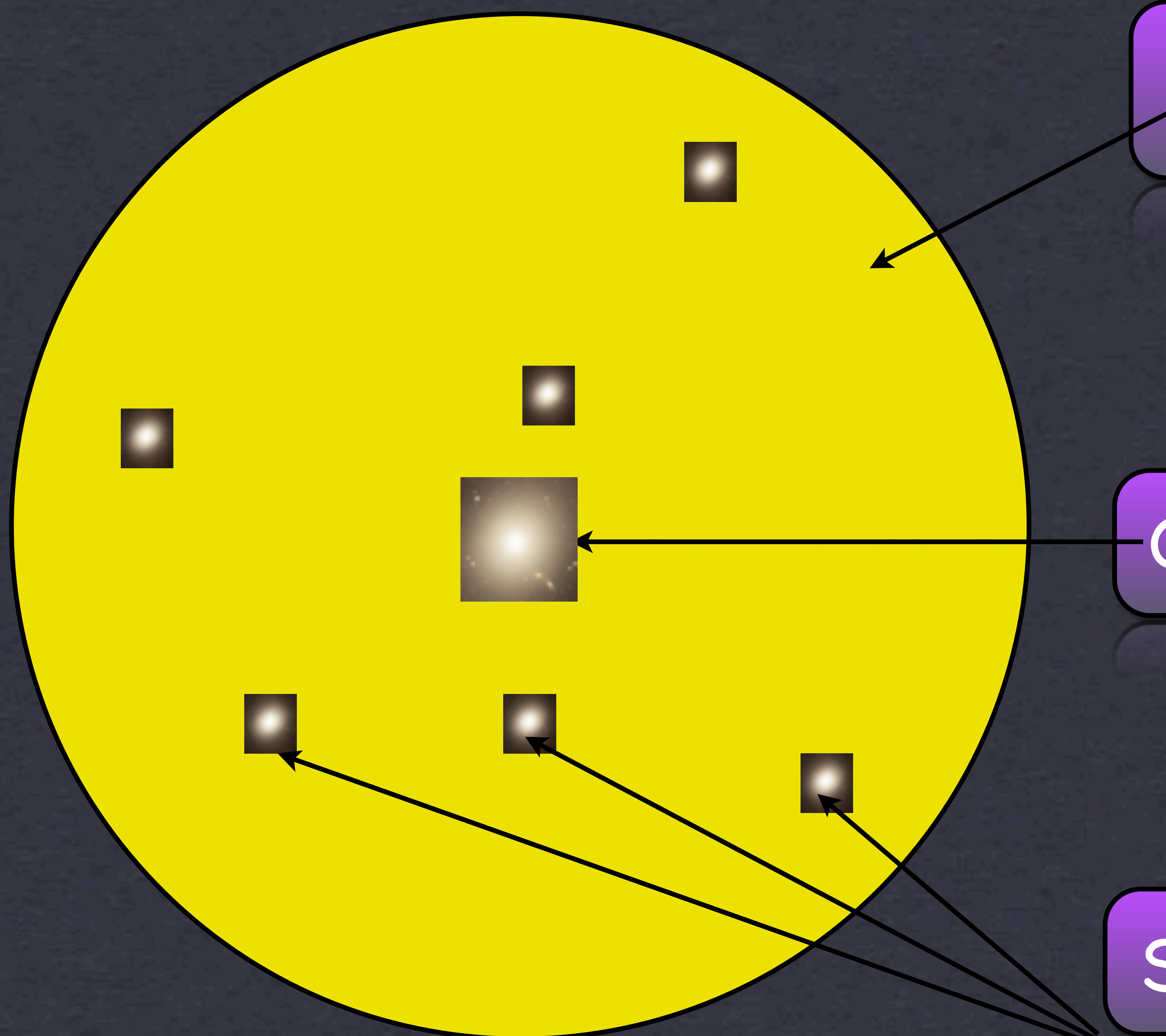
Inside a dark matter halo

Density profile, NFW
Mass dependent concentration

Inside a dark matter halo



Inside a dark matter halo



Dark matter

Density profile, NFW
Mass dependent concentration

Central galaxy

Sits at the center of the halo

Satellite galaxies

Roughly follow the dark matter

Conditional luminosity function

- Average number of galaxies of luminosity L living in halos of mass M
  - Central CLF
  - Satellite CLF

$$\Phi(L|M) = \Phi_c(L|M) + \Phi_s(L|M)$$

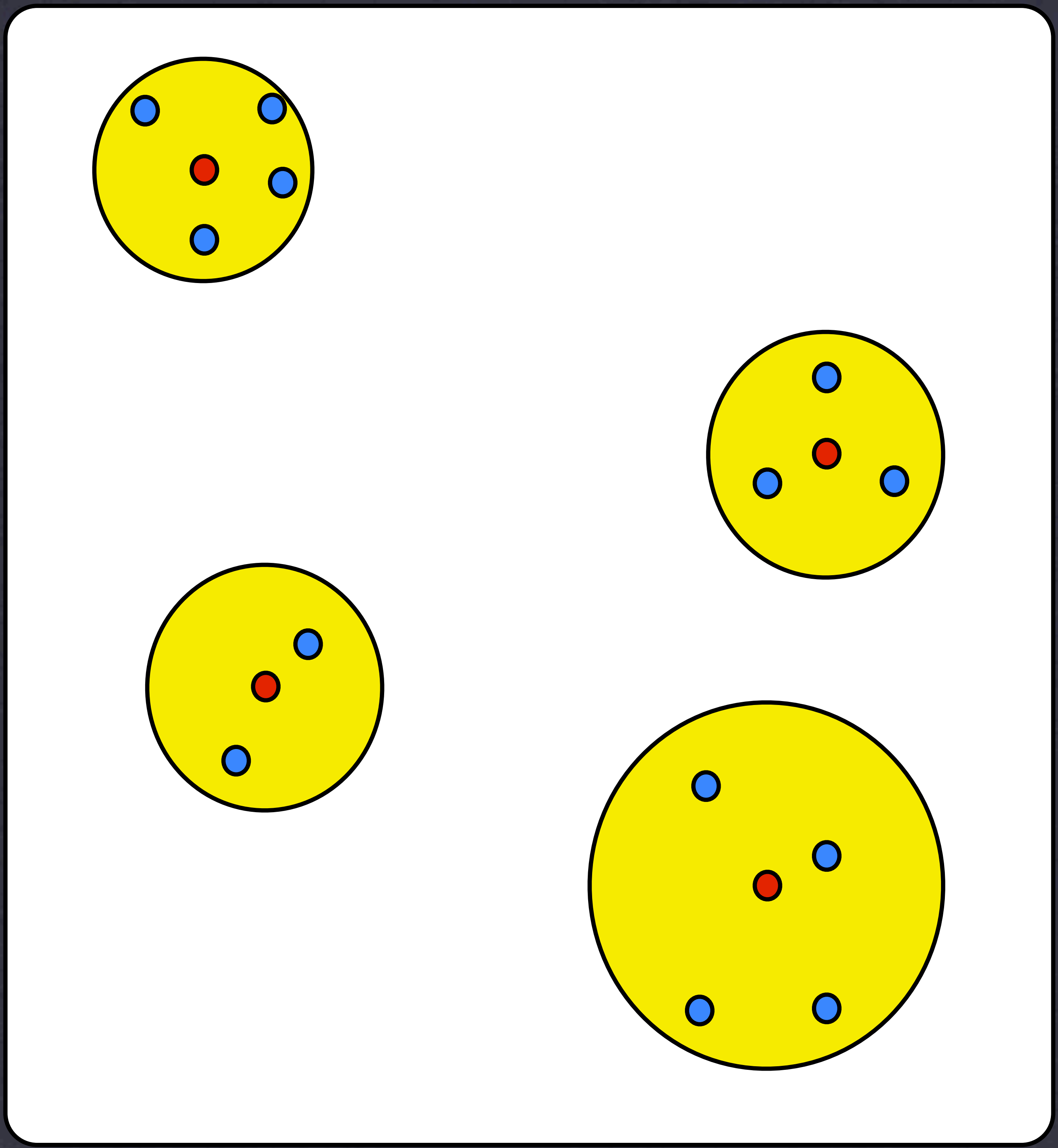
- Abundance of galaxies $\Phi(L) = \int \Phi(L|M) n(M) dM$
- Average number of galaxies in a luminosity bin

$$\langle N_c \rangle_{[L_1,L_2]}(M) = \int_{L_1}^{L_2} \Phi_c(L|M) dL$$

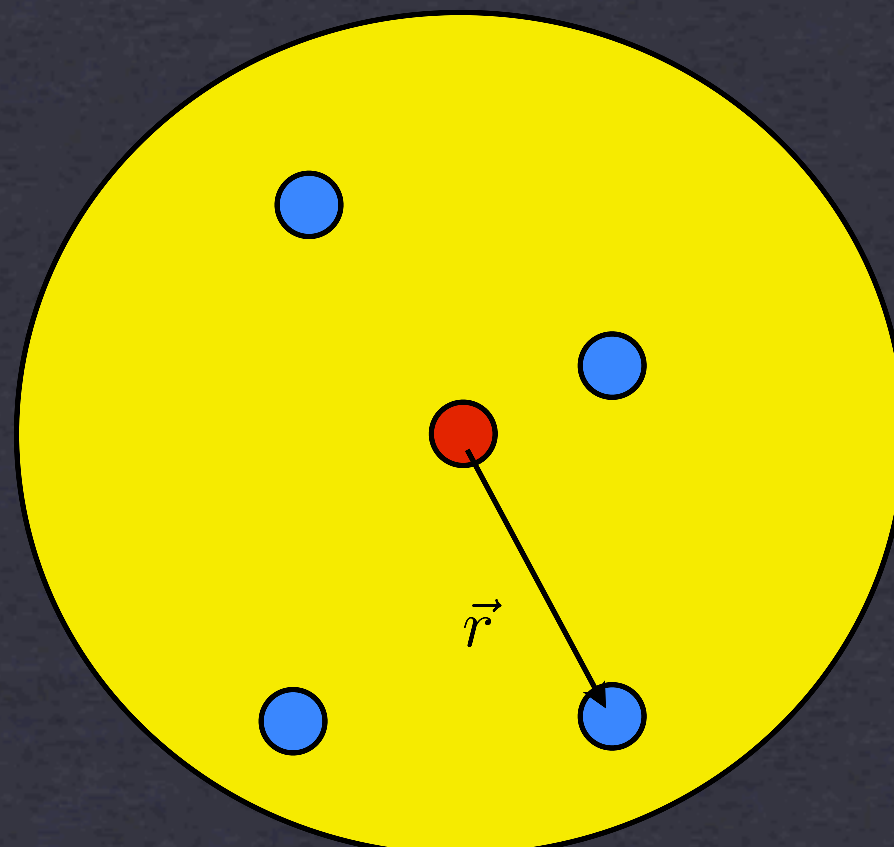
$$\langle N_s \rangle_{[L_1,L_2]}(M) = \int_{L_1}^{L_2} \Phi_s(L|M) dL$$

Galaxy clustering

- Galaxy pairs from the same halo
    - central-satellite
    - satellite-satellite
- Galaxy pairs from different halos
    - central-central
    - central-satellite
    - satellite-satellite



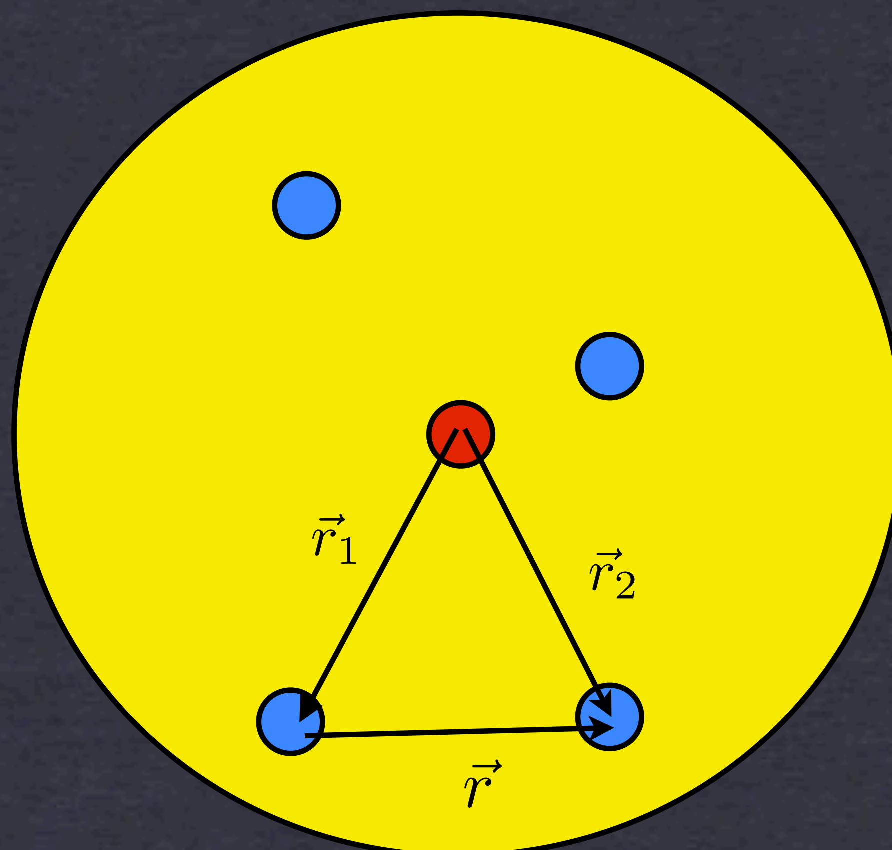
One halo central-satellite



$$\langle N_c \rangle_M \langle N_s \rangle_M u(r|M) n(M)$$

$\rightarrow n_s(r)$

One halo satellite-satellite



$$\frac{1}{2}\langle N_s\rangle_M u(\vec{r}_1|M)\langle N_s\rangle_M u(\vec{r}_2|M)n(M)$$

Pair counting 1-halo terms

- 1 halo central-satellite $\langle N_c \rangle_M \langle N_s \rangle_M u(r|M)$
- 1 halo satellite-satellite $\frac{1}{2}\langle N_s \rangle_M u(\vec{r}_1|M) \langle N_s \rangle_M u(\vec{r}_2|M)$

$$|\vec{r}_1 - \vec{r}_2| = r$$

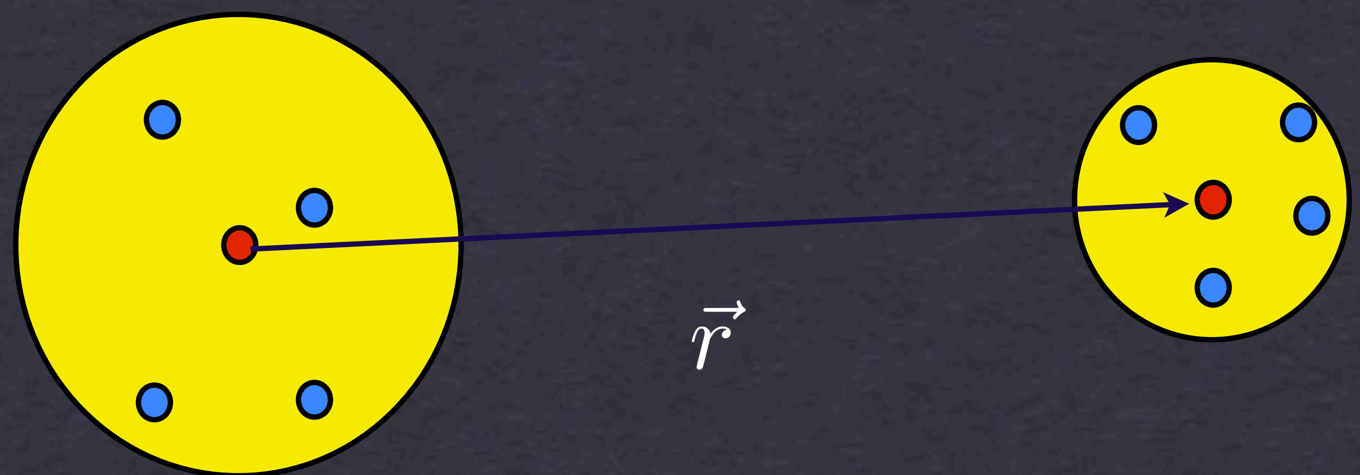
Convolution!!!
Easiest to handle in Fourier space

- Total 1 halo pairs

$$\int \left[\langle N_c \rangle_M \langle N_s \rangle_M u(r|M) + \frac{1}{2}\langle N_s \rangle_M \underline{u(\vec{r}_1|M)} \langle N_s \rangle_M \underline{u(\vec{r}_2|M)} \right] n(M) dM$$

$$|\vec{r}_1 - \vec{r}_2| = r$$

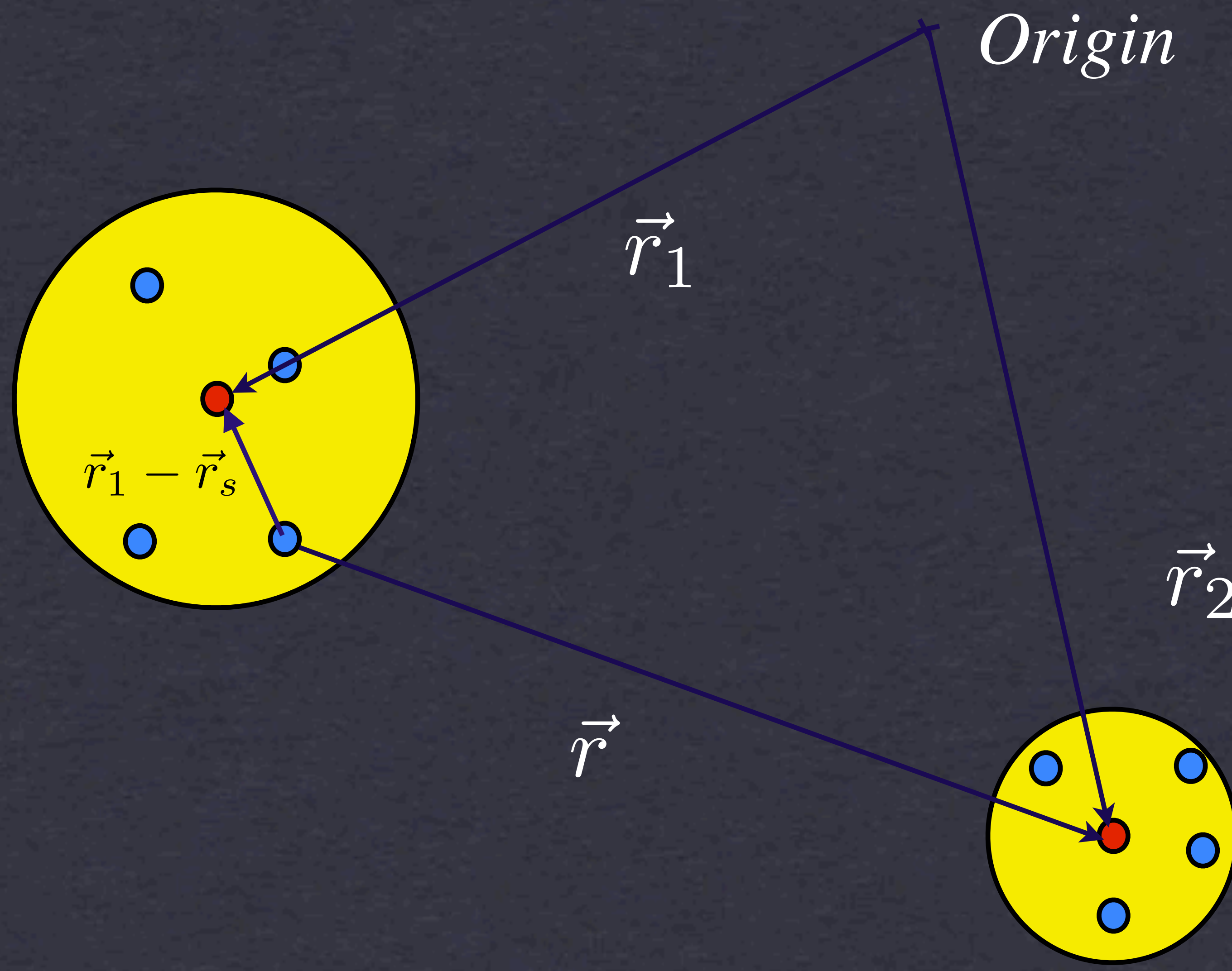
Two halo central-central



$$\frac{1}{2}\langle N_c\rangle_{M_1}\langle N_c\rangle_{M_2}\left[1+\xi^{hh}(r,M_1,M_2)\right]n(M_1)n(M_2)$$

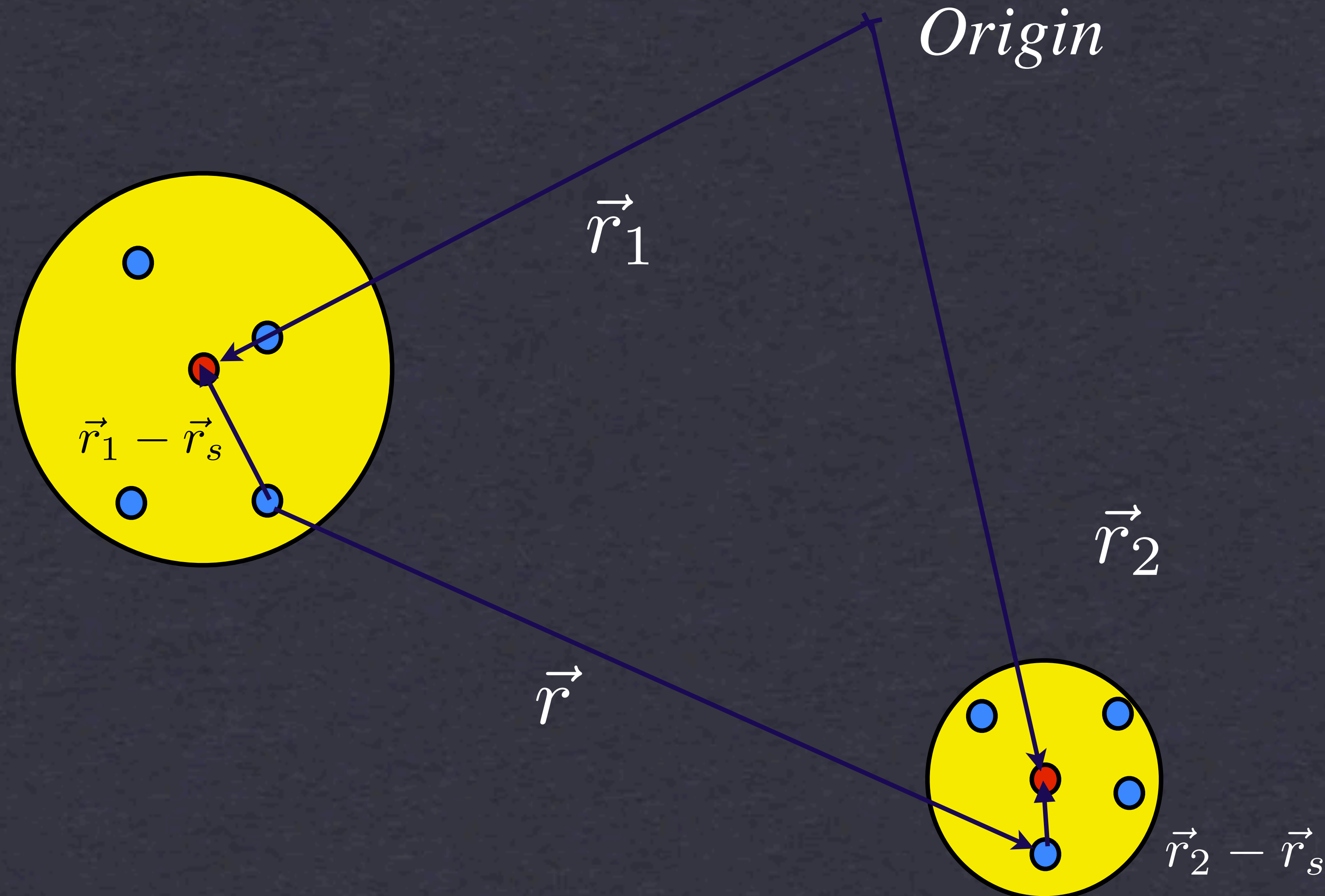
- An accurate treatment of the halo clustering: a mathematically consistent treatment of radial dependence and halo exclusion!

Two halo central-satellite



$$\langle N_c \rangle_{M_2} \langle N_s \rangle_{M_1} u(\vec{r}_1 - \vec{r}_s | M_1) \left[1 + \xi^{hh}(|\vec{r}_1 - \vec{r}_2|, M_1, M_2) \right]$$

Two halo satellite-satellite



$$\frac{1}{2}\langle N_s\rangle_{M_1} u(\vec{r}_1 - \vec{r}_{s_1}|M_1)\langle N_s\rangle_{M_2} u(\vec{r}_2 - \vec{r}_{s_2}|M_2)\left[1+\xi^{hh}(|\vec{r}_1 - \vec{r}_2|, M_1, M_2)\right]$$

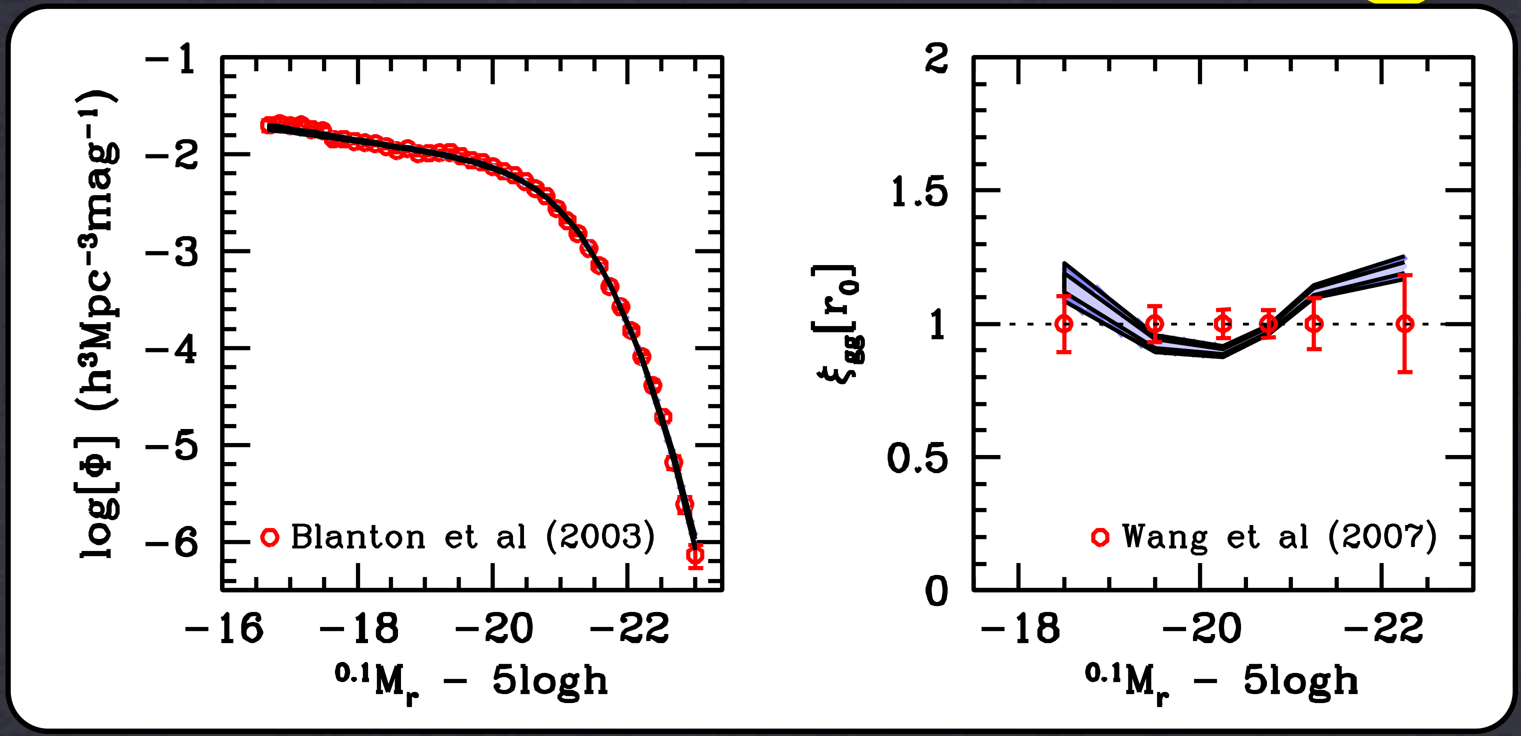
Putting it all together

- Numerical simulations
  - Abundance of haloes
  - Clustering of haloes
  - Density profile of dark matter
    - Concentration-Mass relation
- Conditional luminosity function
  - Halo occupation distribution of central and satellite galaxies as a function of halo mass

Cosmology sensitive

Galaxy formation physics

Fixed cosmology



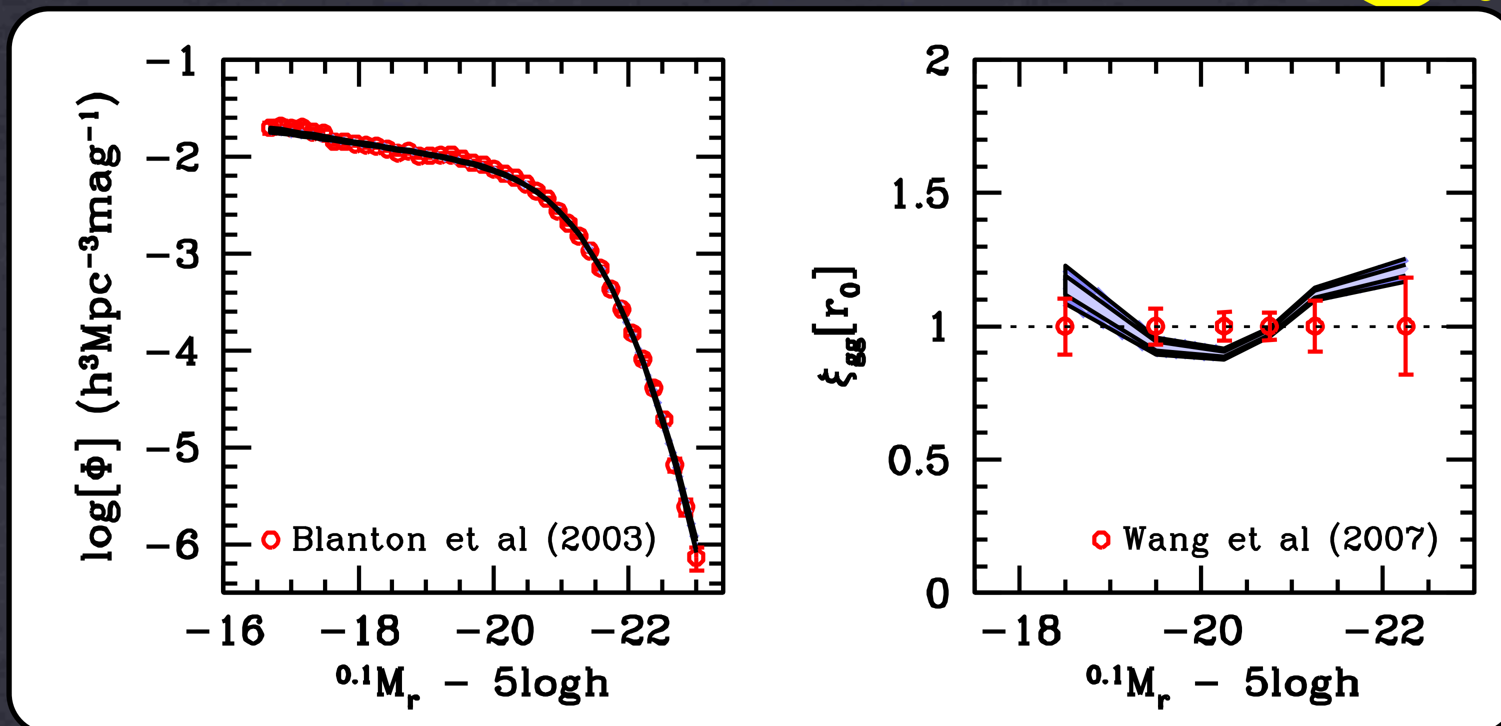
WMAP3

$\Omega_m = 0.27$

$\sigma_8 = 0.74$

Cacciato, vdB, SM et al. 2009

Fixed cosmology



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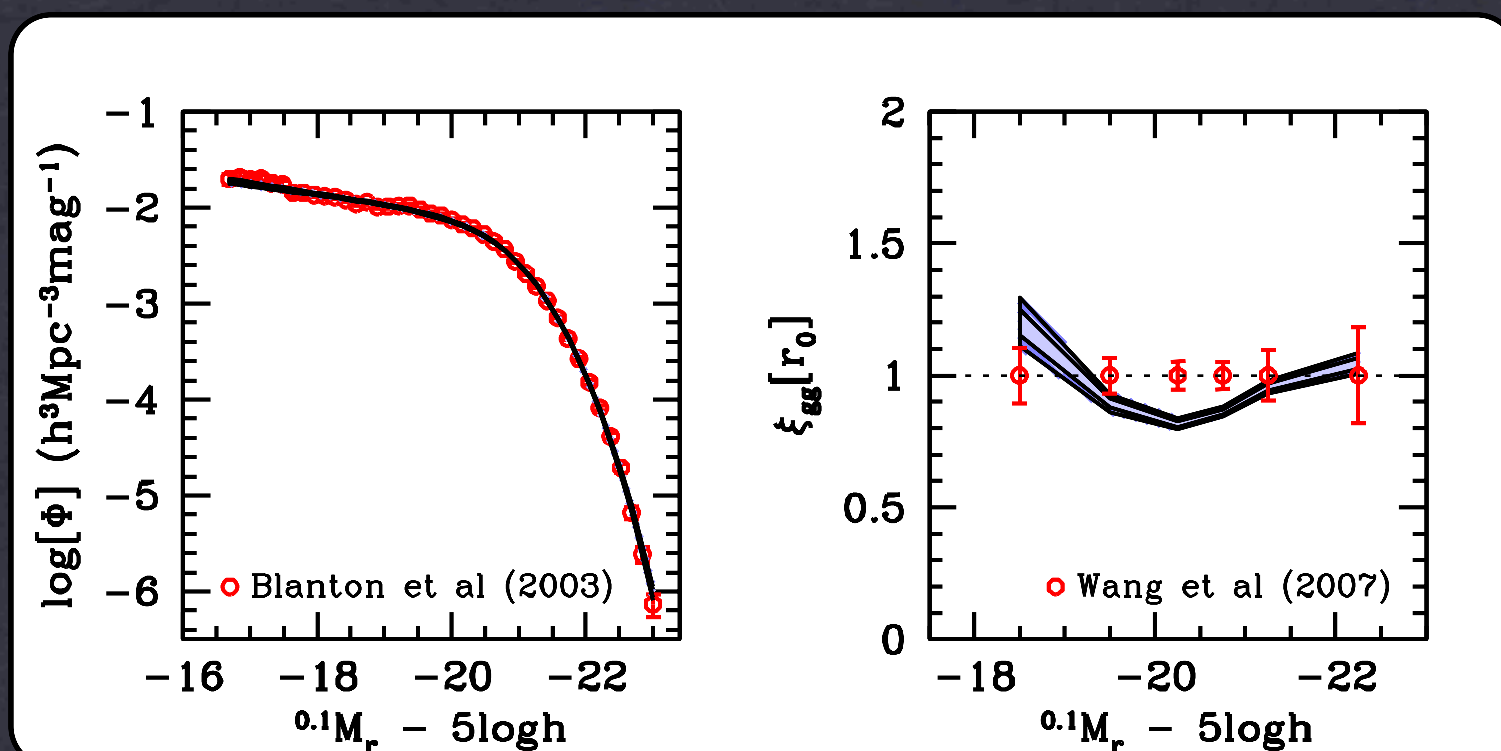


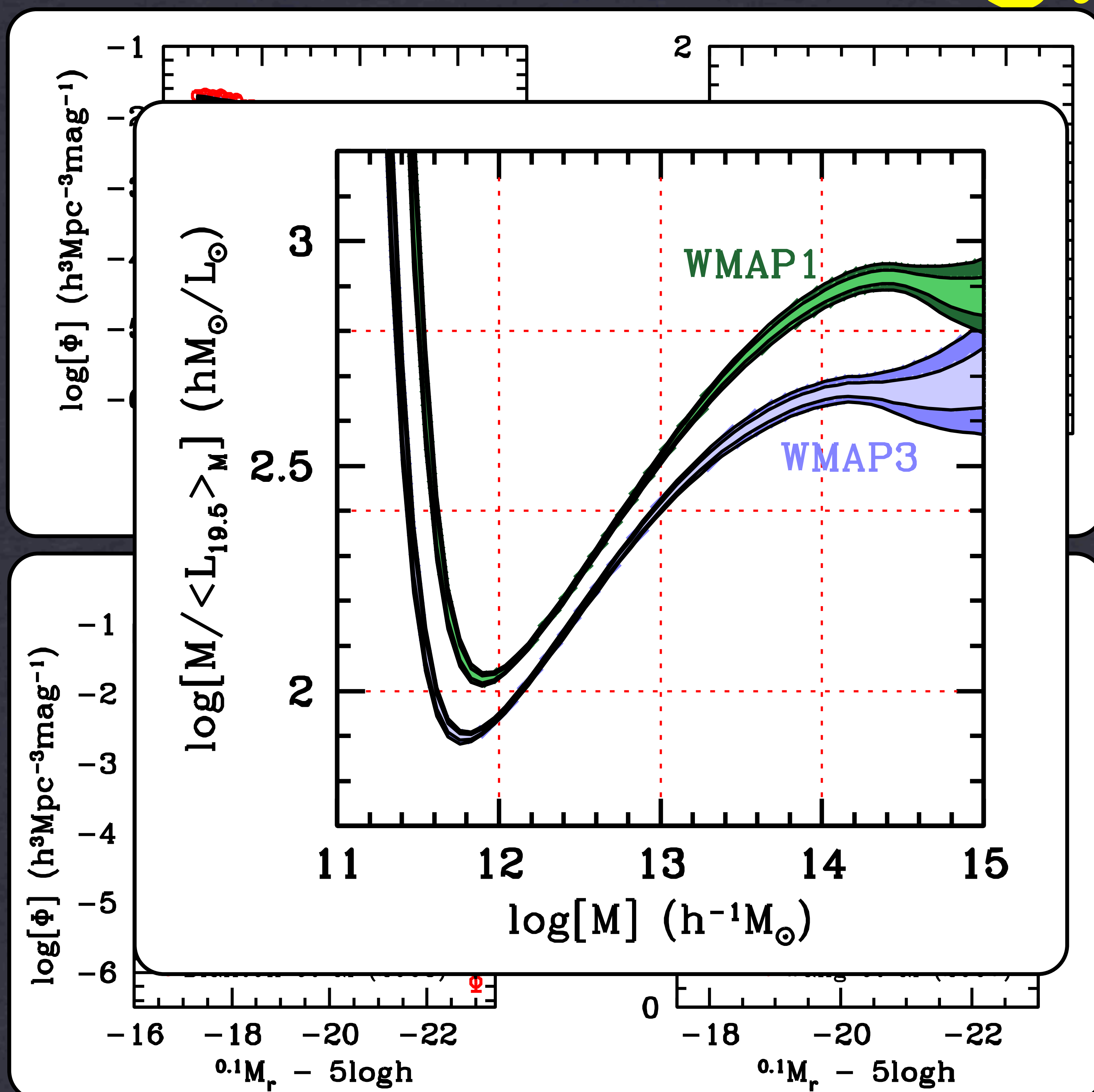
WMAP1

$\Omega_m = 0.3$

$\sigma_8 = 0.9$

Cacciato, vdB, SM et al. 2009

Fixed cosmology



WMAP3

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WMAP1

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Cacciato, vdB, SM et al. 2009

Galaxy-galaxy lensing

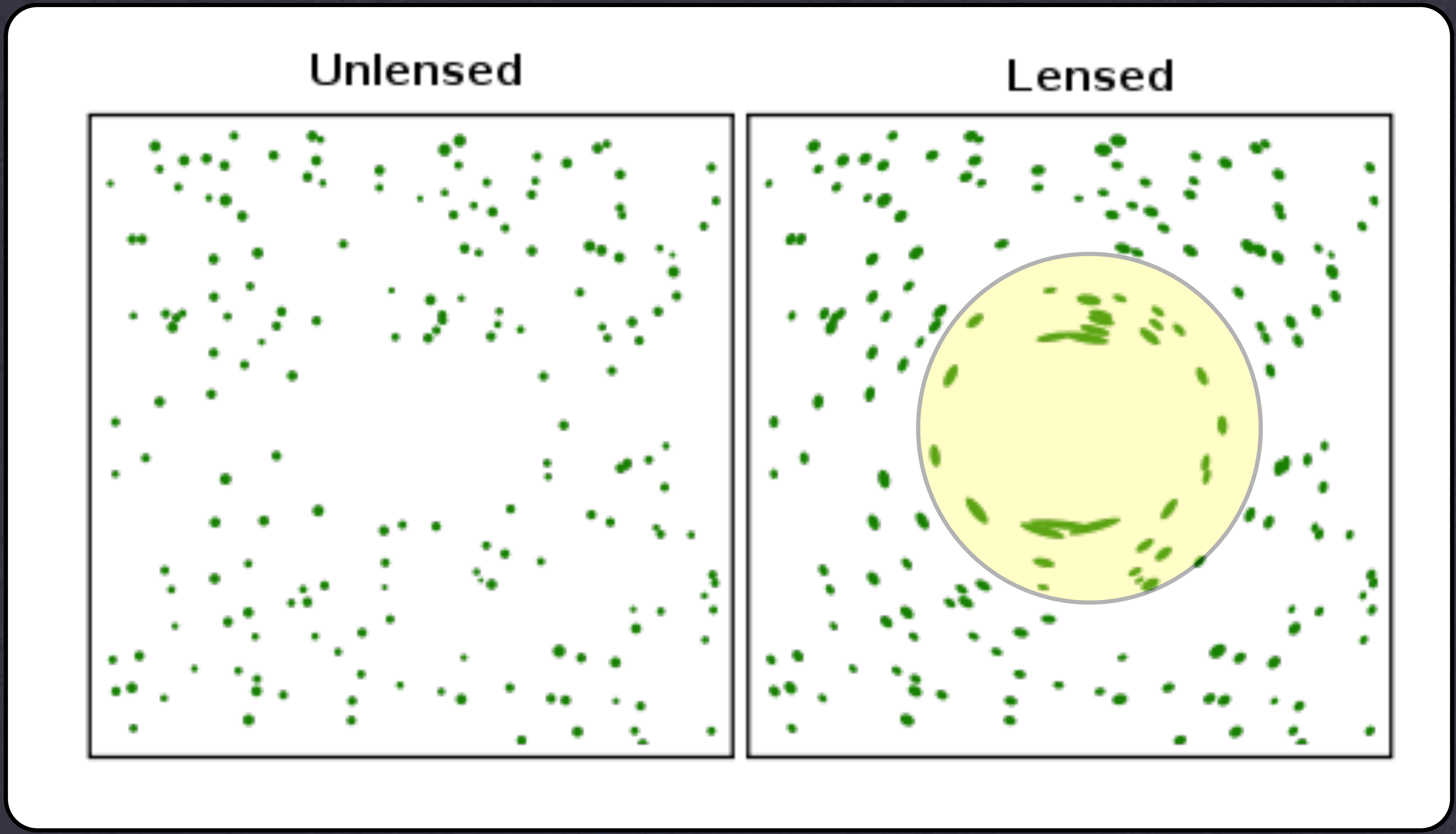
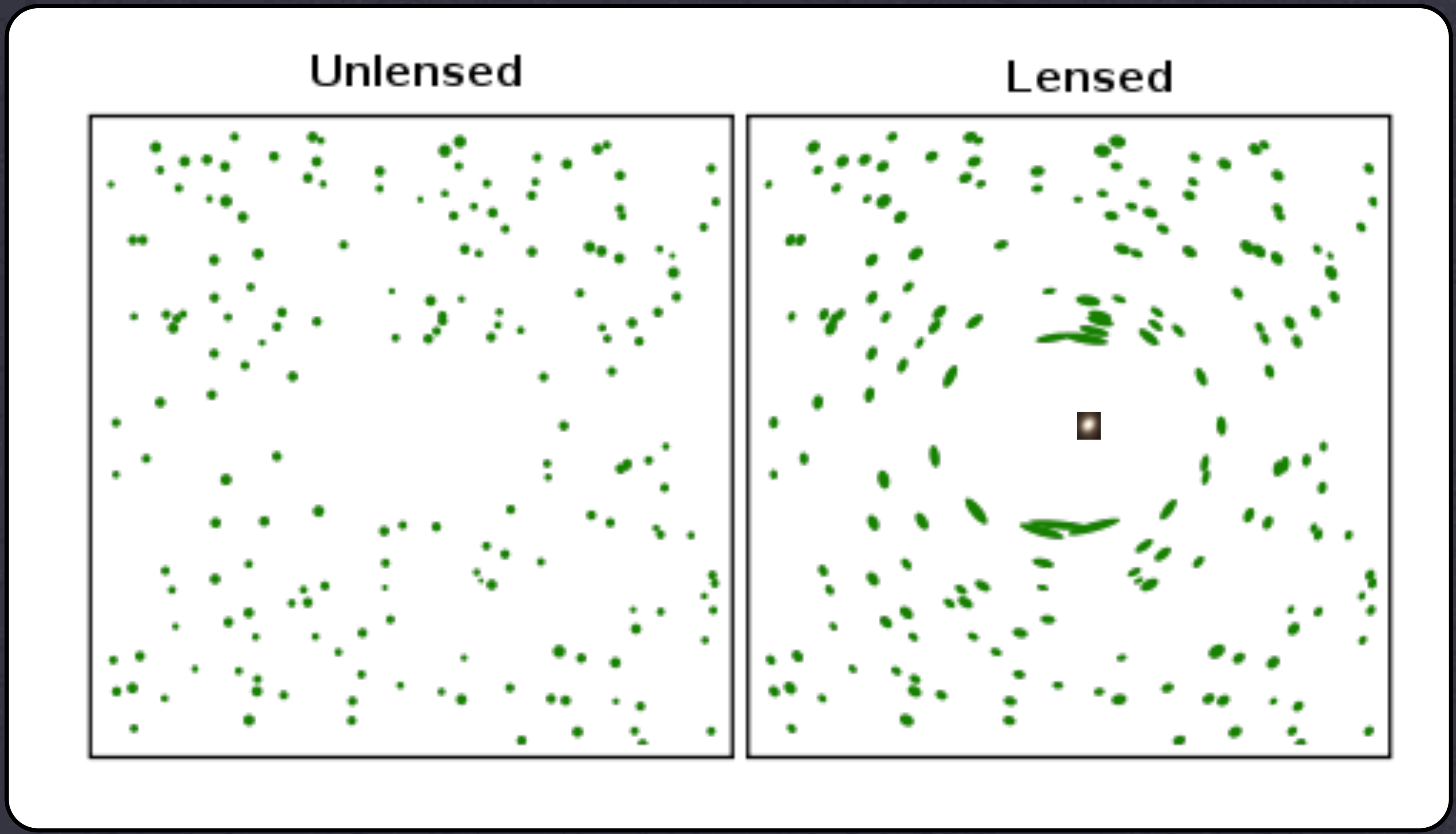
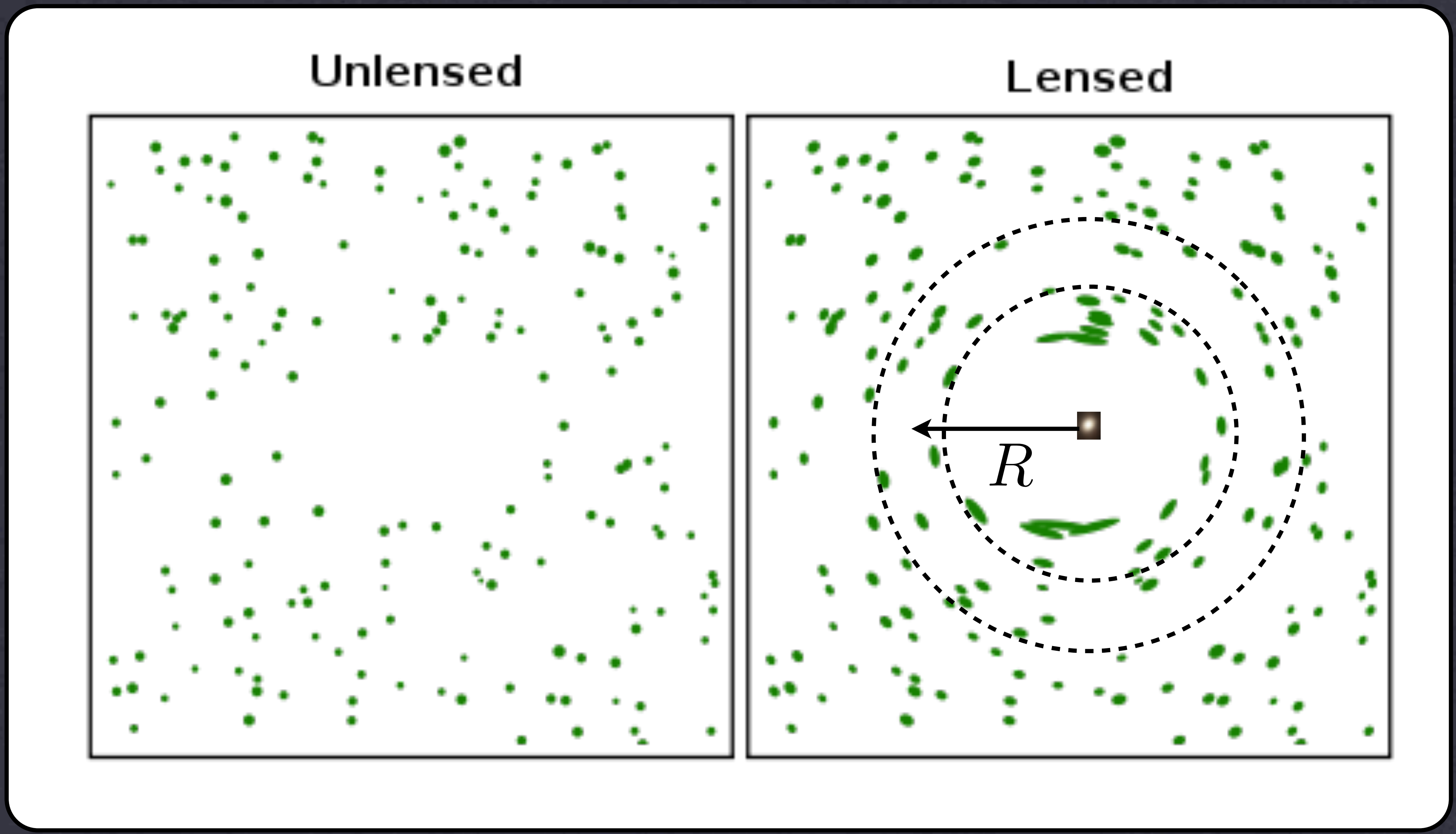


Image adapted from Wikipedia

Galaxy-galaxy lensing

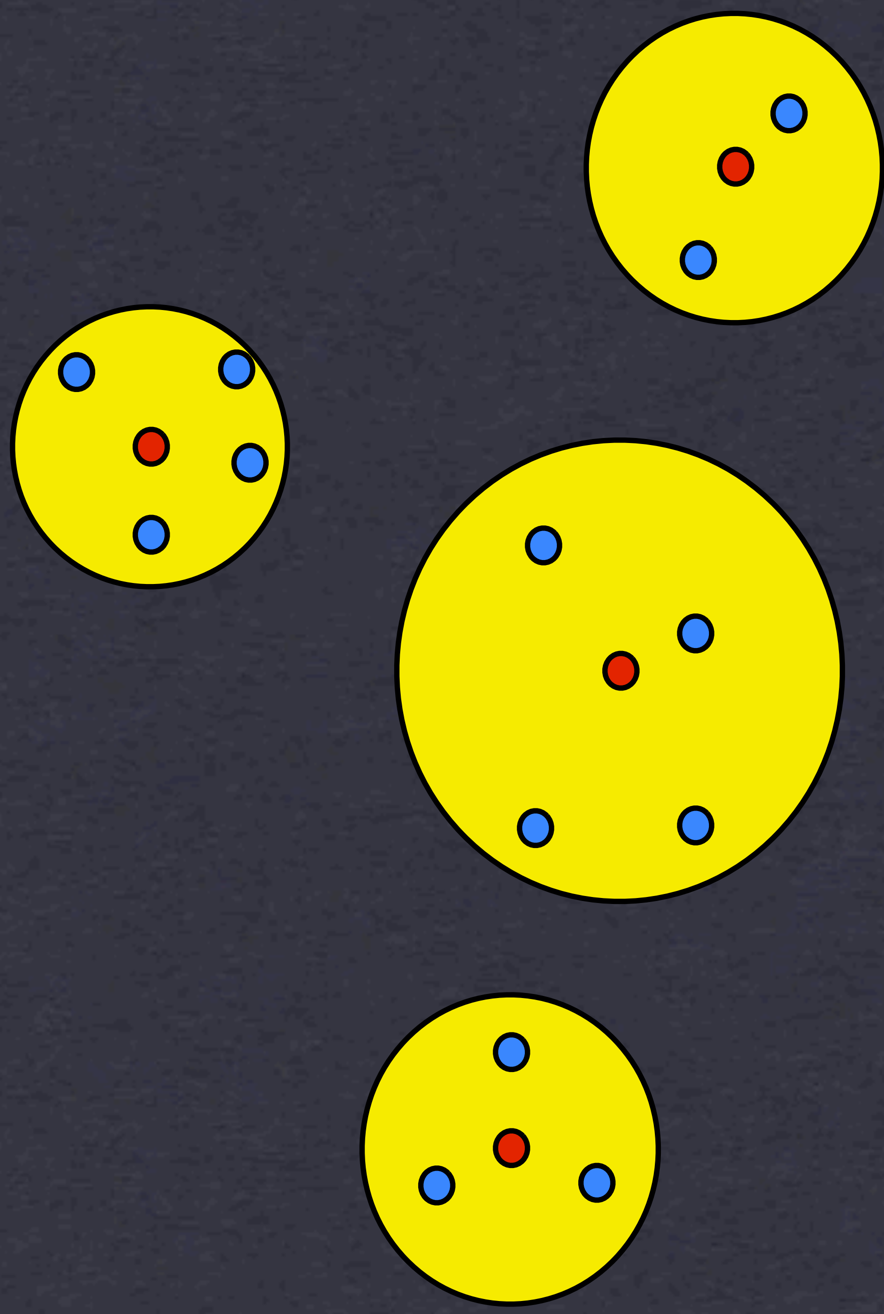


Galaxy-galaxy lensing

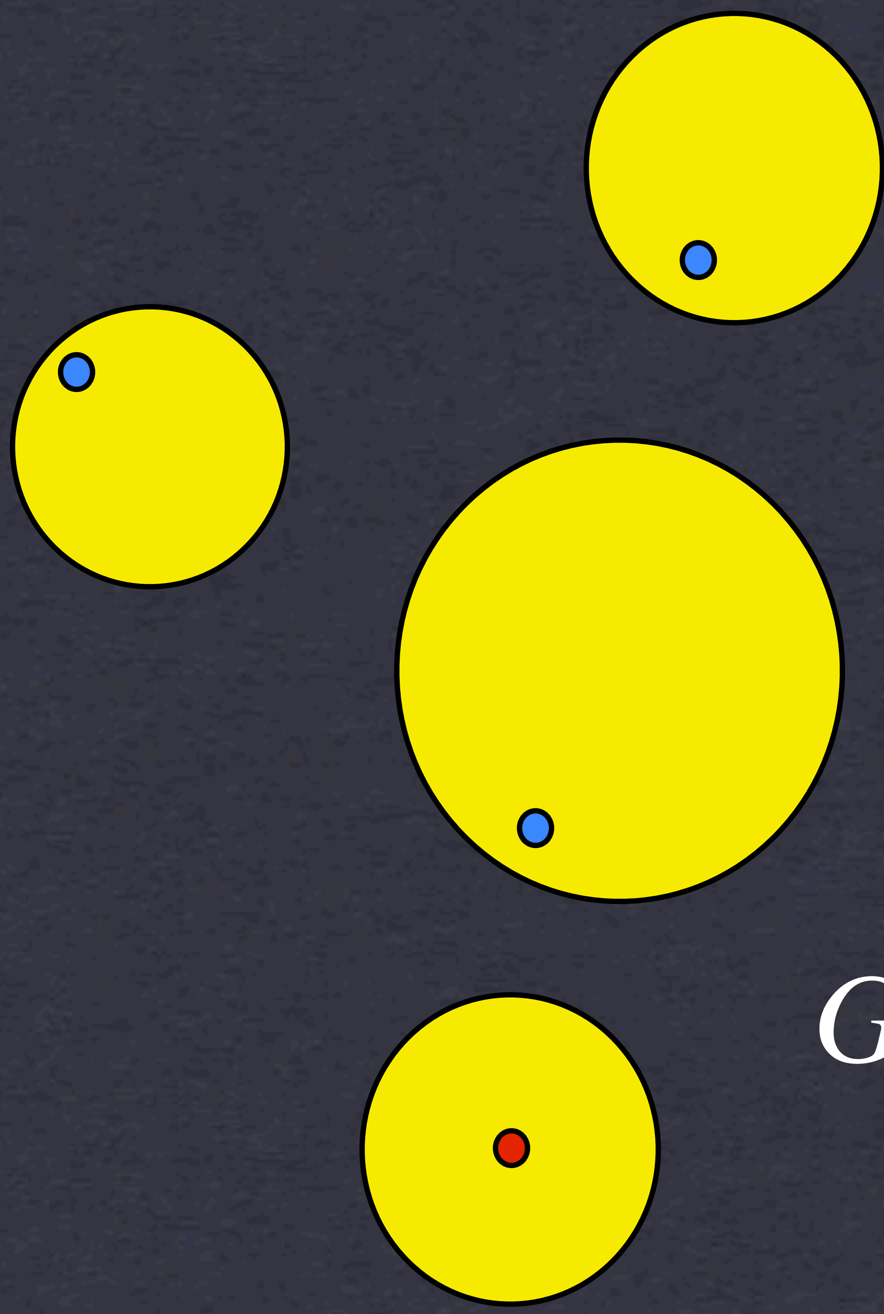


$$\langle \epsilon \rangle = \gamma_t(R) \qquad \gamma_t(R) = \frac{\bar{\Sigma}(< R) - \Sigma(R)}{\Sigma_{\rm crit}}$$

Galaxy-galaxy lensing

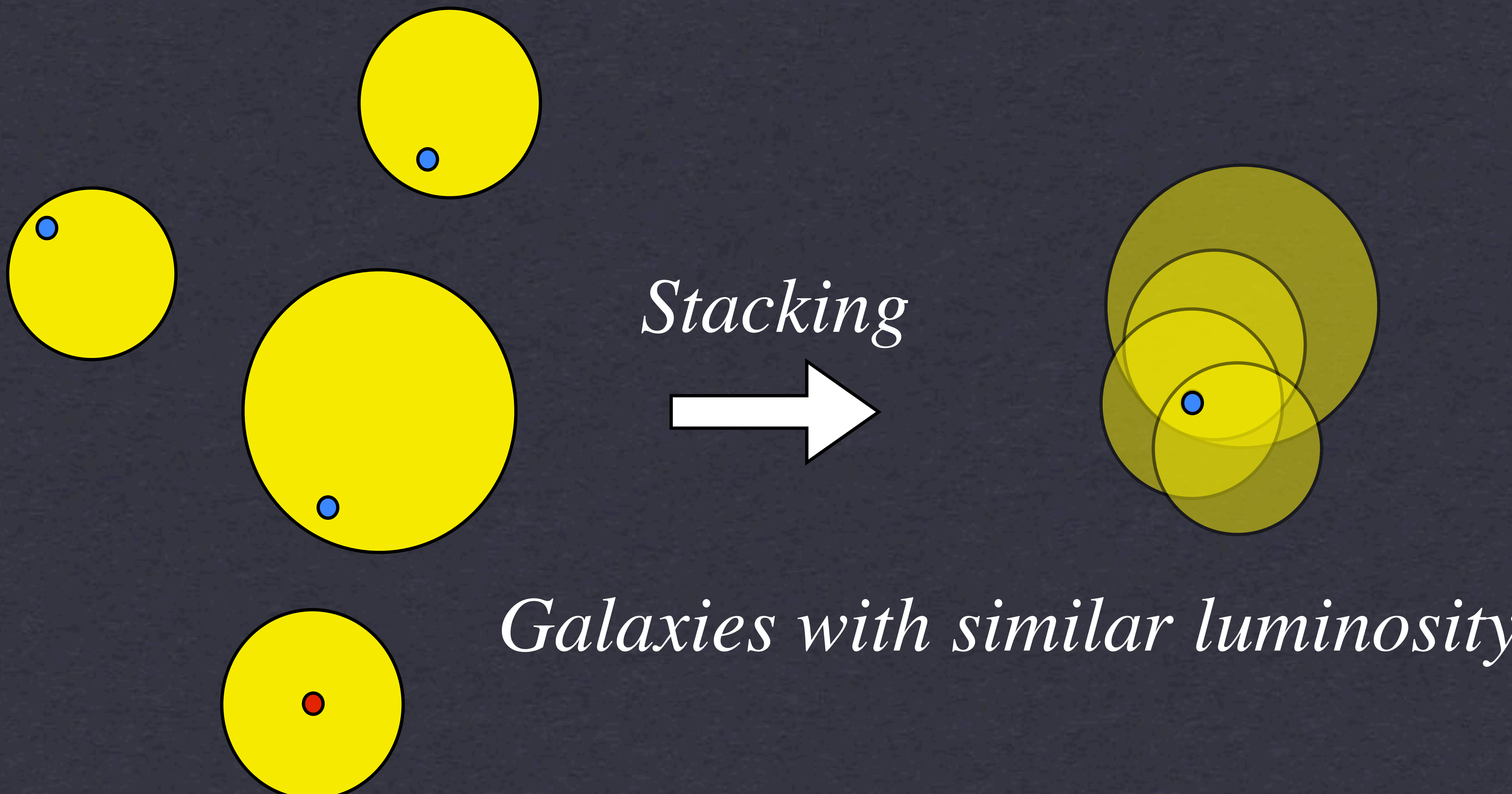


Galaxy-galaxy lensing

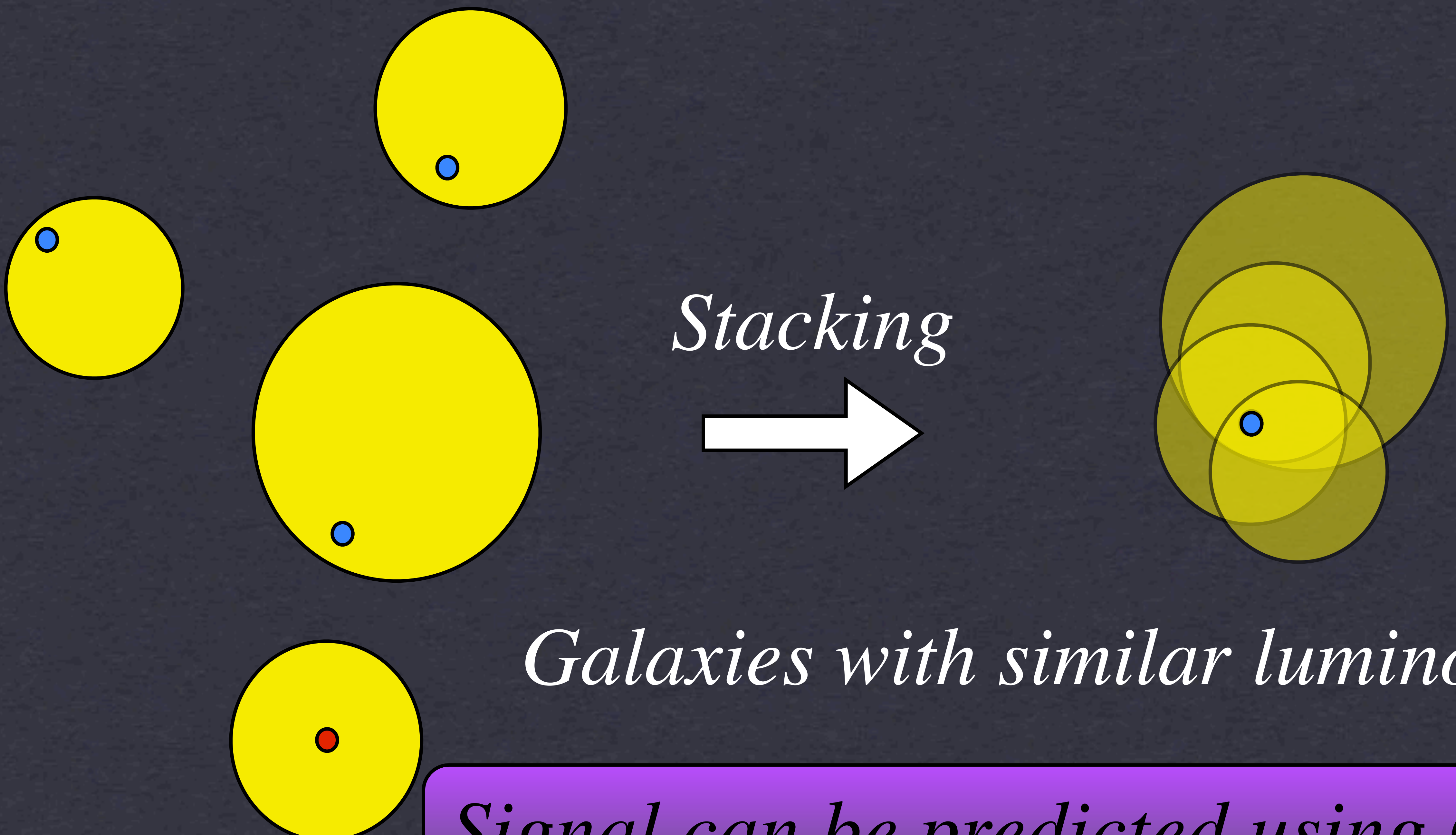


Galaxies with similar luminosity

Galaxy-galaxy lensing



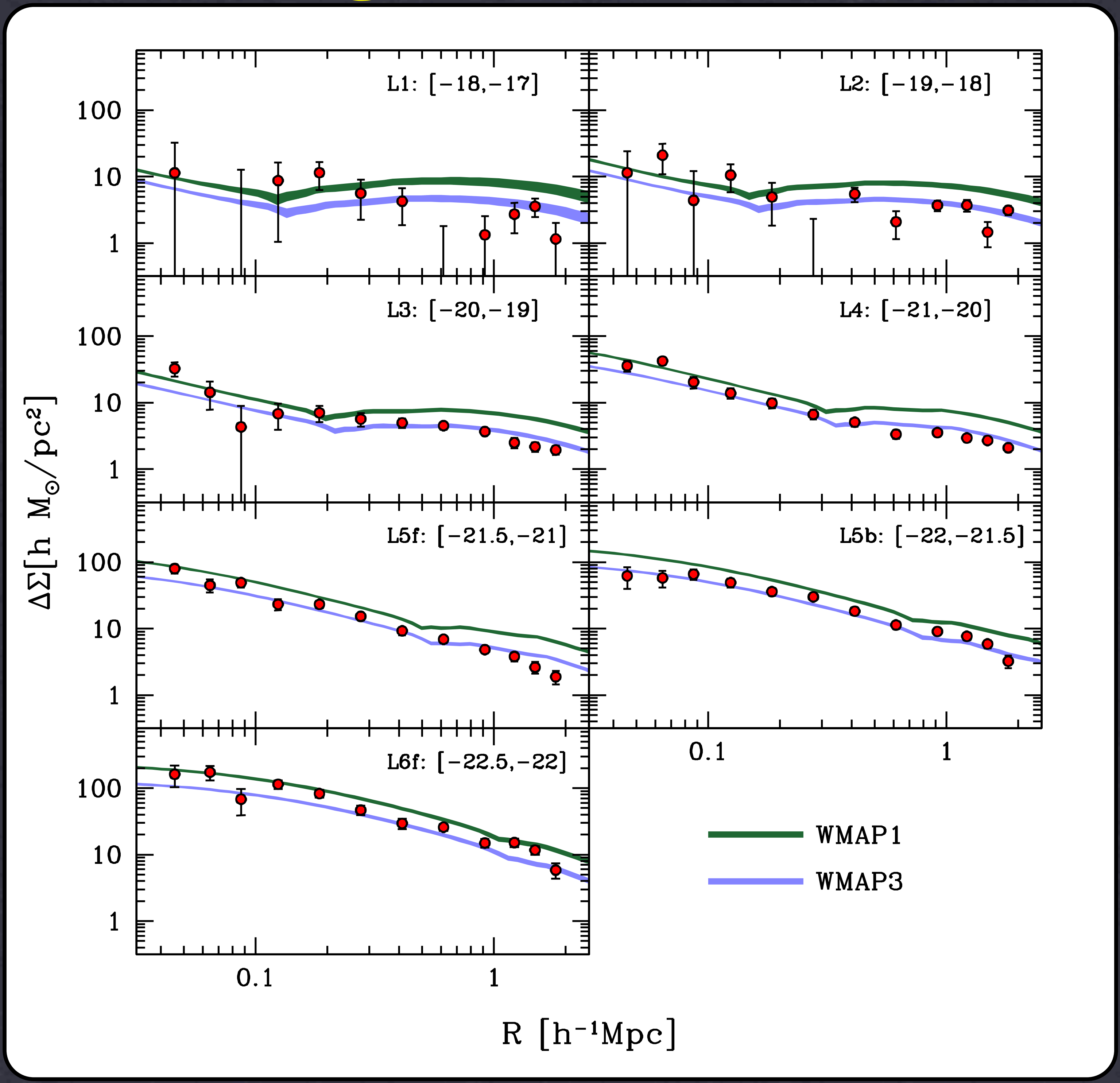
Galaxy-galaxy lensing



Galaxies with similar luminosity

Signal can be predicted using CLF!

Galaxy-galaxy lensing



Cacciato, vdB, SM et al. 2009

Model parameters

- Central CLF

$$L_{\rm c}(M): \quad 4 \text{ parameters}, \;\; \sigma_{\log L}: \quad 1 \text{ parameter}$$

- Satellite CLF

$$\Phi * (M): \; 3 \text{ parameters}, \;\; \alpha: \; 1 \text{ parameter}$$

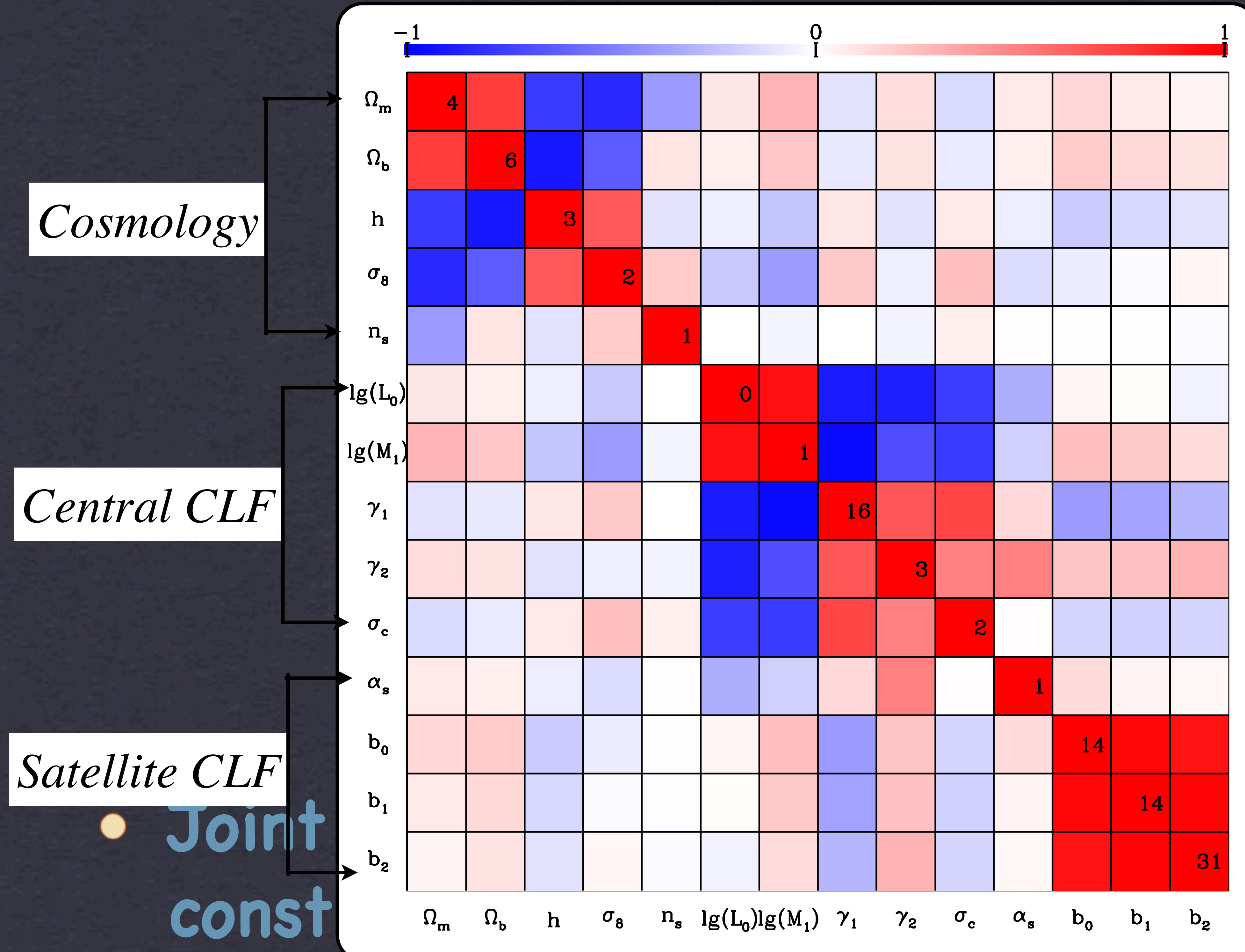
- Cosmology

$$\Omega_{\rm m}, \sigma_8 \quad \text{free, WMAP7 priors on } \Omega_b, h, n_s$$

Fisher forecasts

- Joint analysis is a promising way to constrain cosmological parameters *SM, vdB, Cacciato et al., in prep*

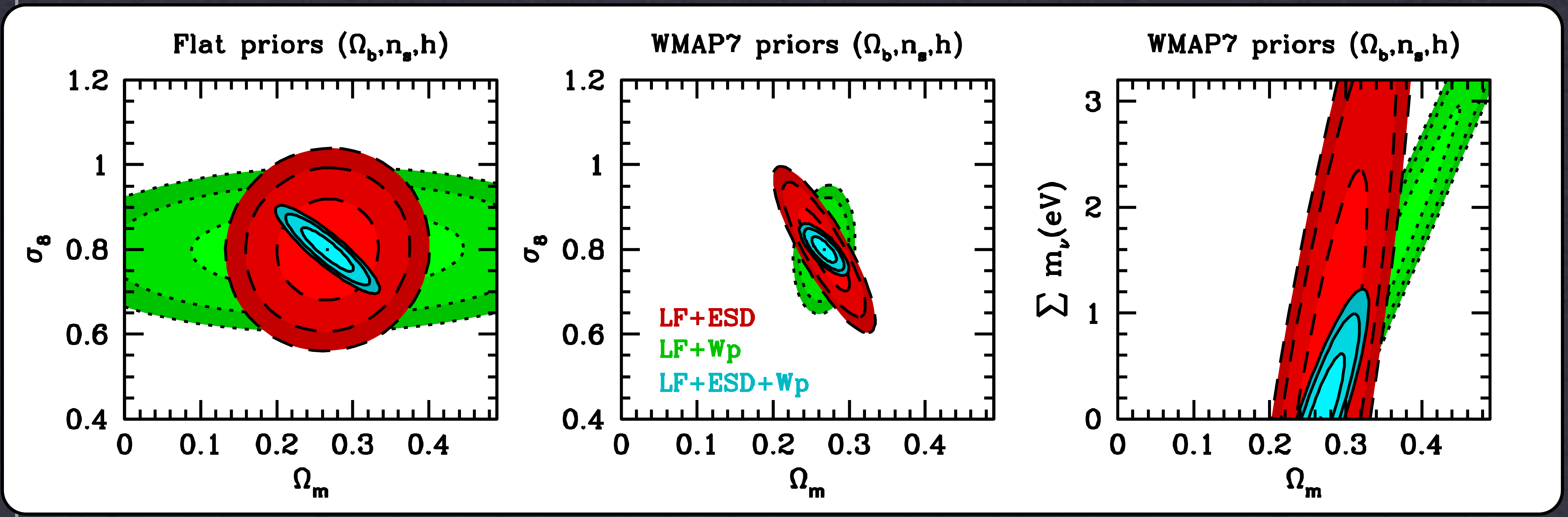
Fisher forecasts



- Joint ... to
  const ...

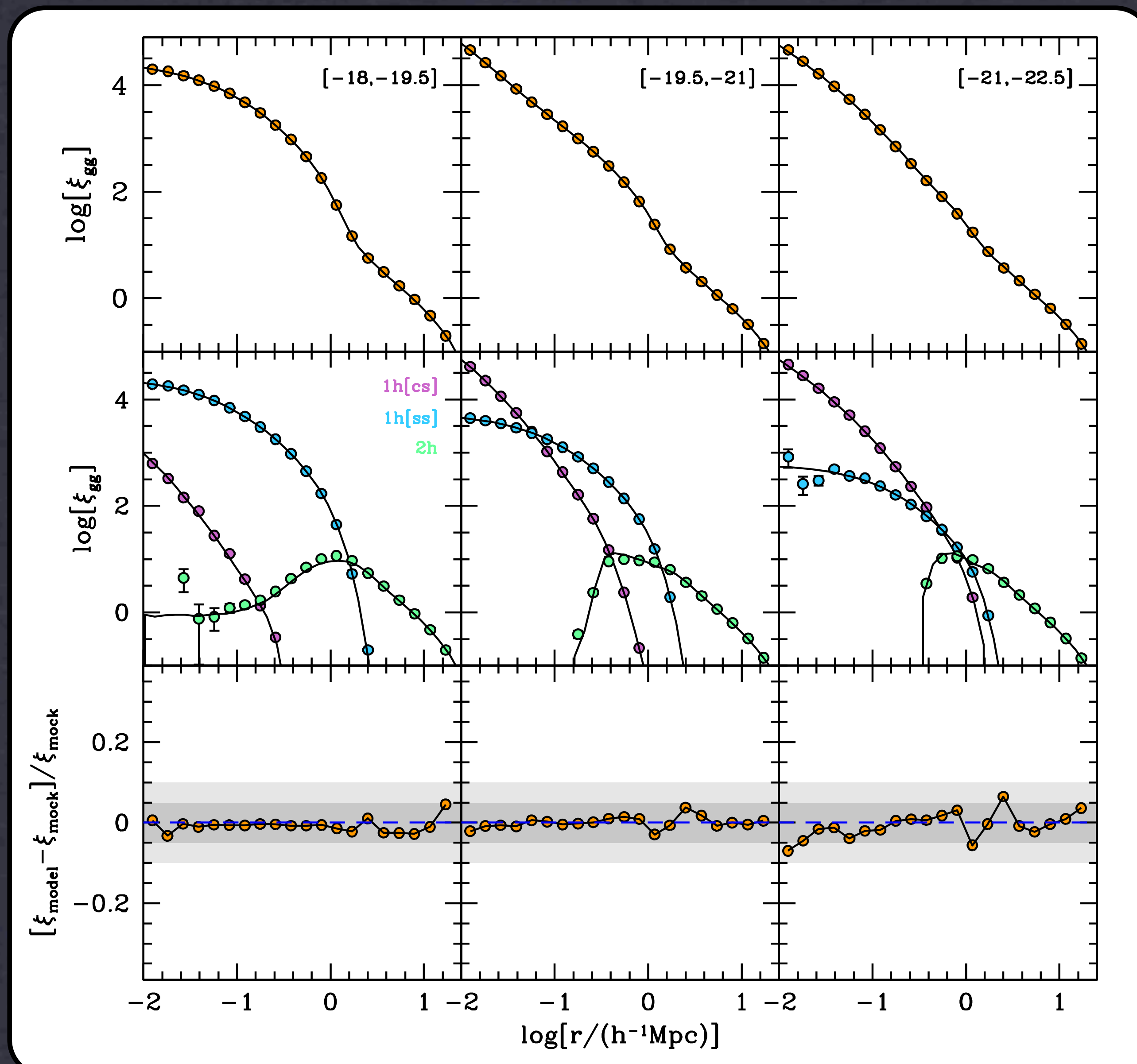
SM, vdB, Cacciato et al., in prep

Fisher forecasts



- Joint analysis is a promising way to constrain cosmological parameters *SM, vdB, Cacciato et al., in prep*

Mock catalog tests



vdB, SM et al. in prep

- Galaxy-galaxy clustering signal

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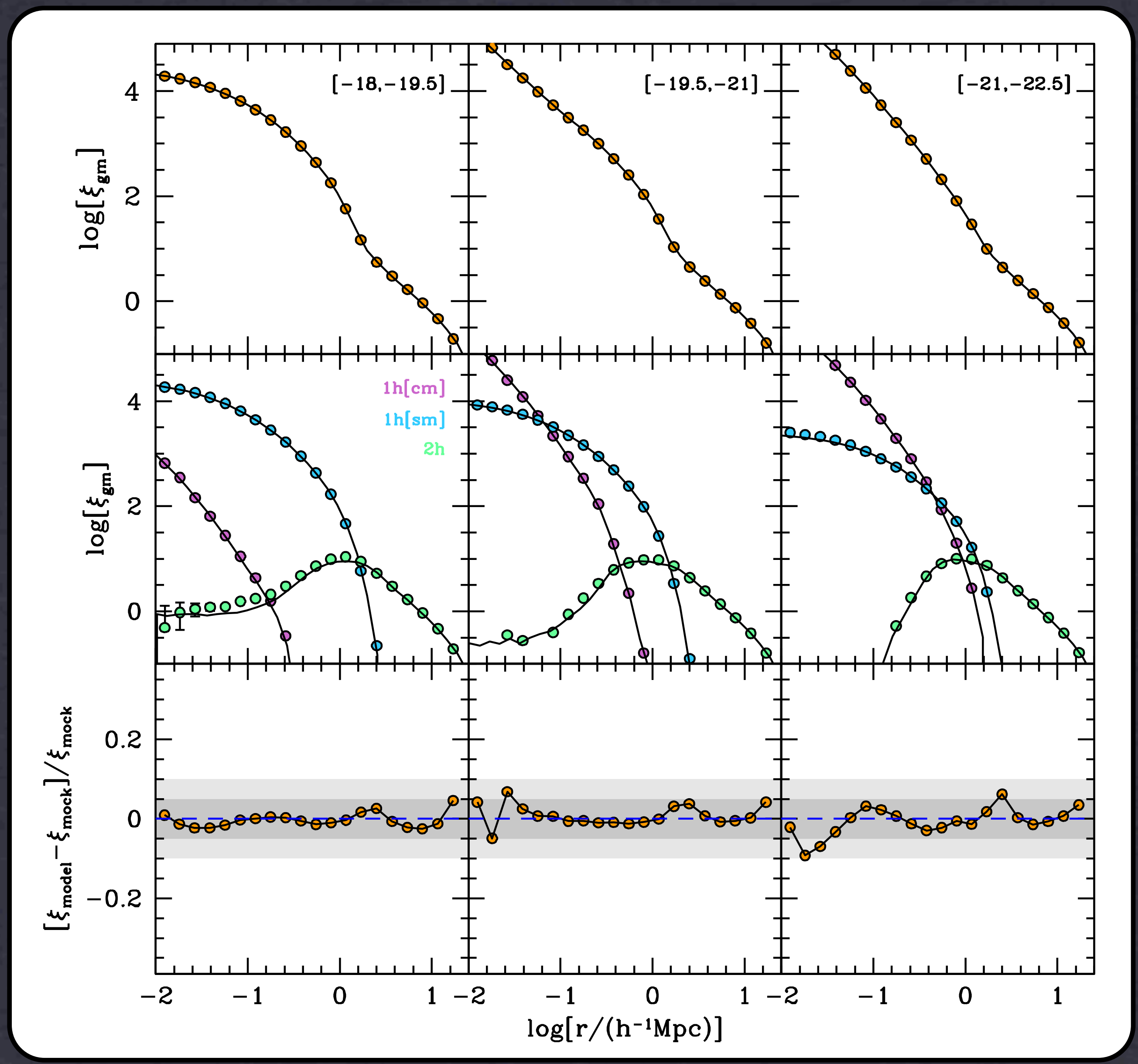
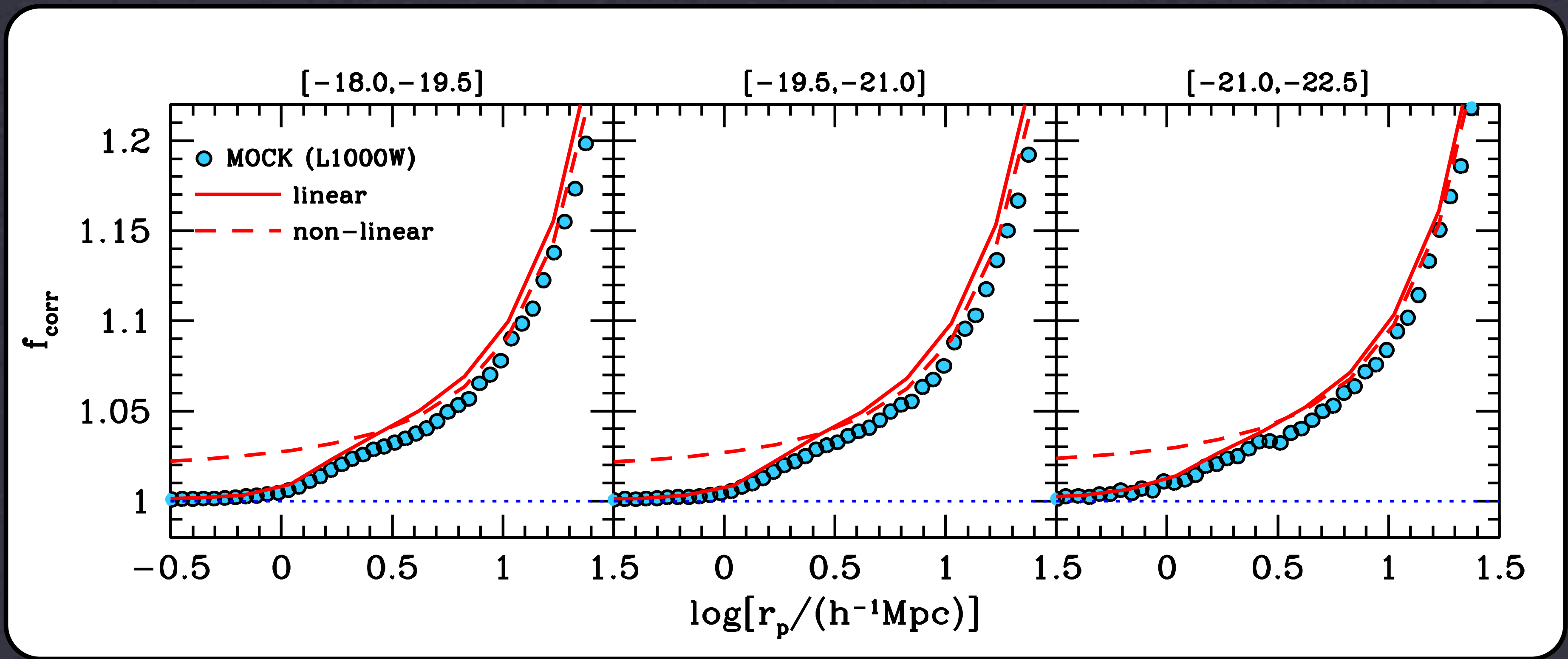


vdB, SM et al. in prep

- Galaxy matter clustering signal

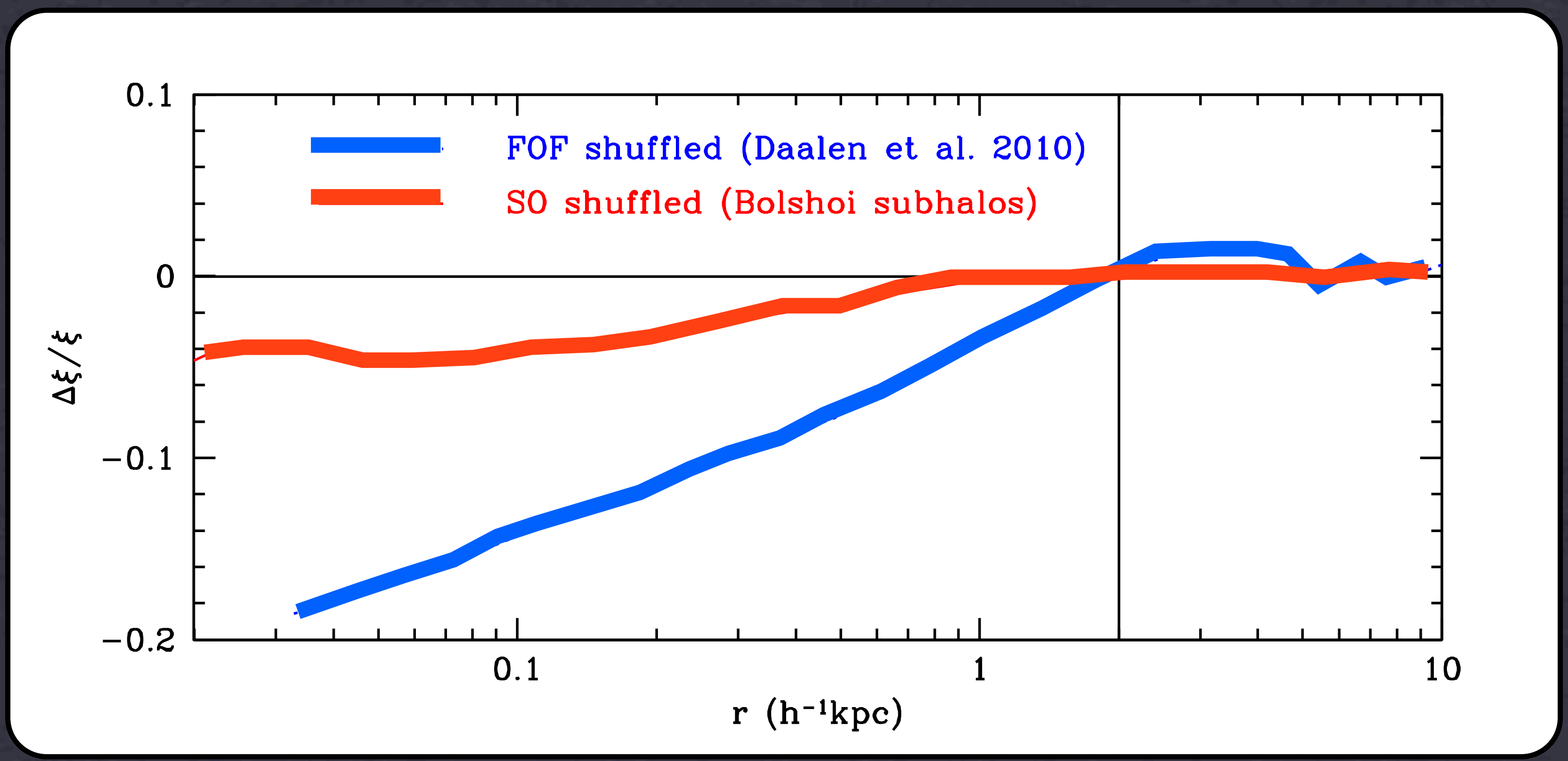
Redshift space distortions



vdB, SM et al. in prep
SM, 2011, ApJ, 741, 19

- The redshift space correlation function was integrated along the line-of-sight to 40 Mpc.

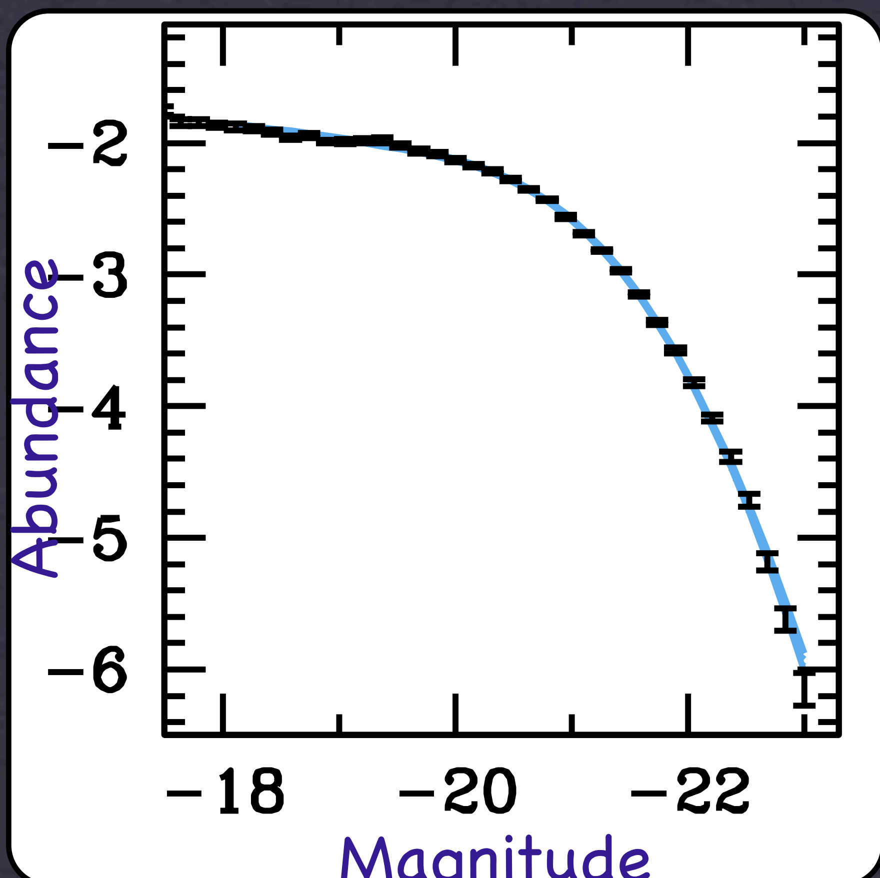
Sphericity assumption



SM, in prep

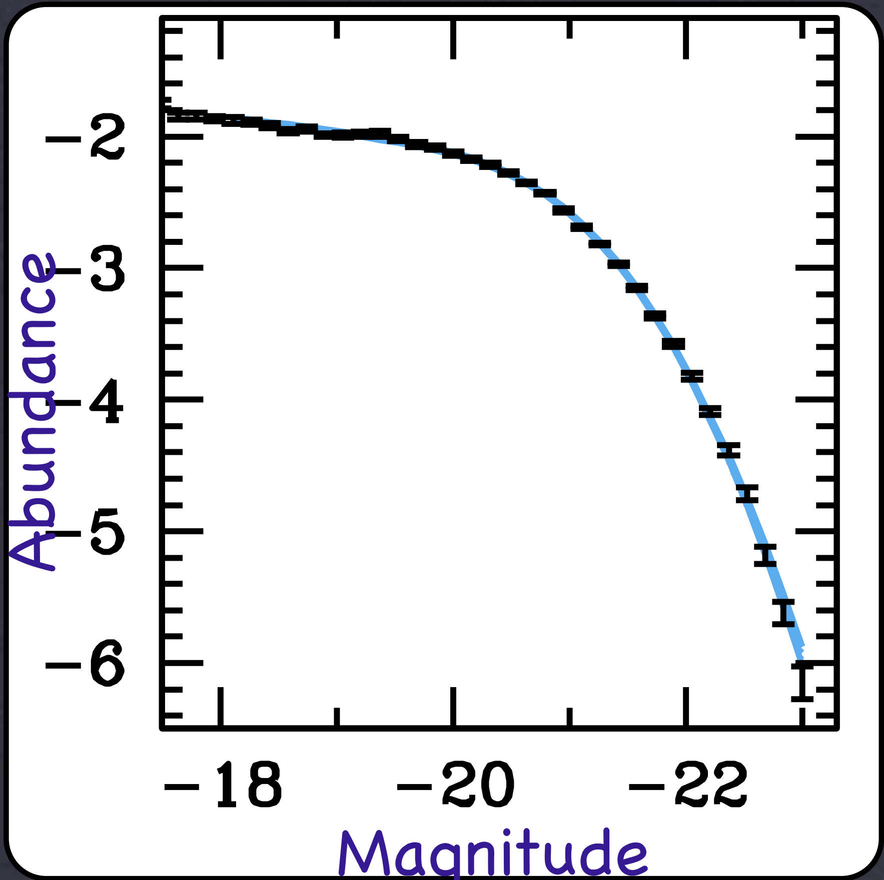
- Sphericity assumption is good enough to predict the two point correlation function to about 5%: however use Spherically Overdense halos!

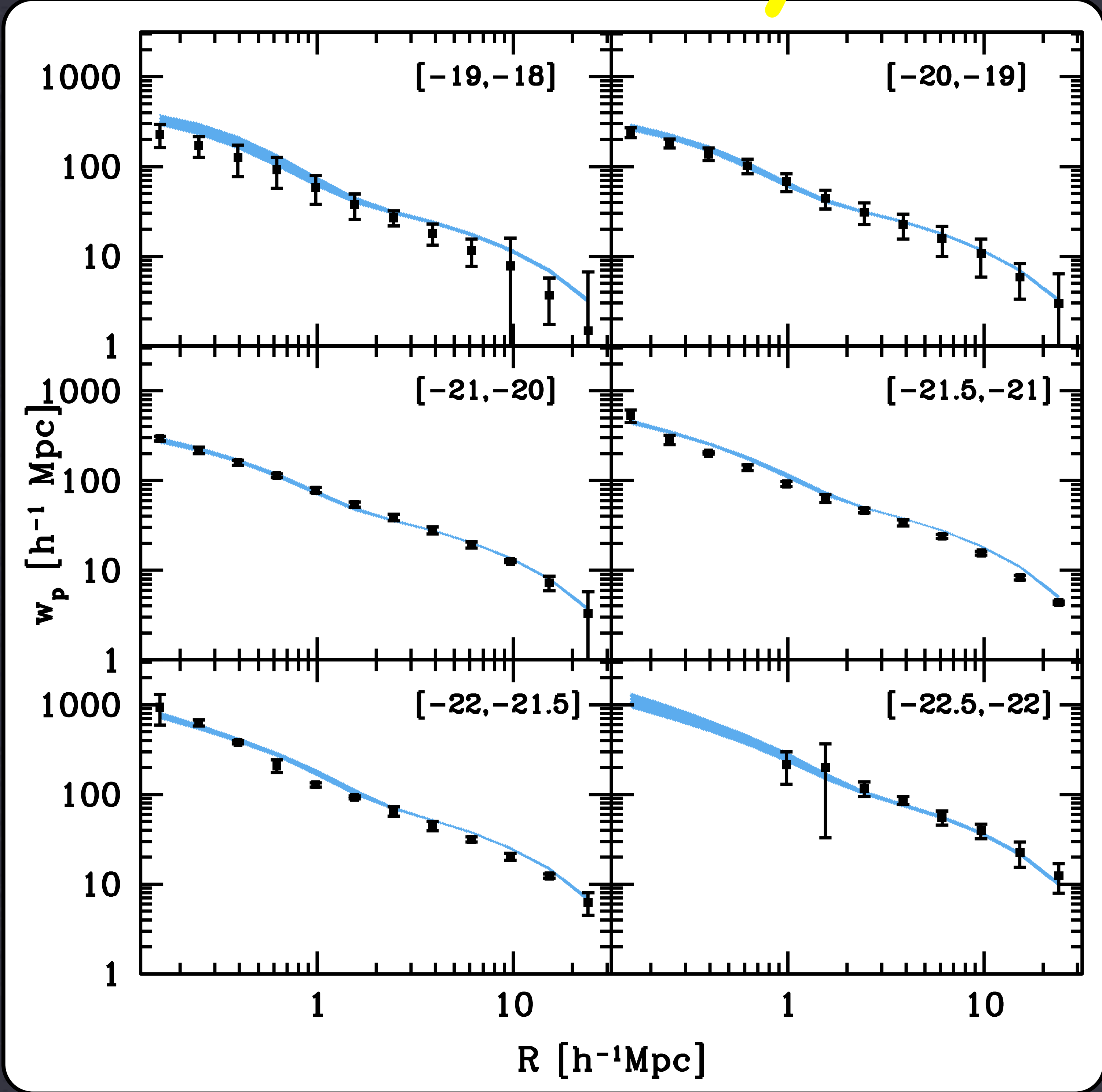
Results from a MCMC analysis



Cacciato, SM, vdB (in prep)

Results from a MCMC analysis





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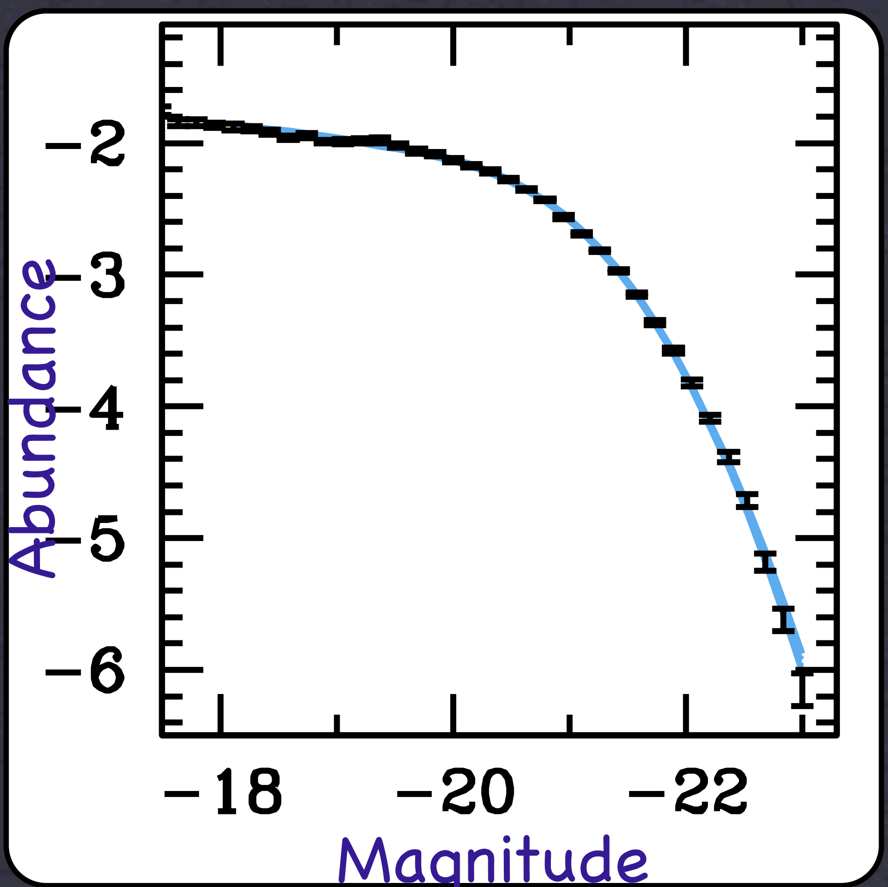
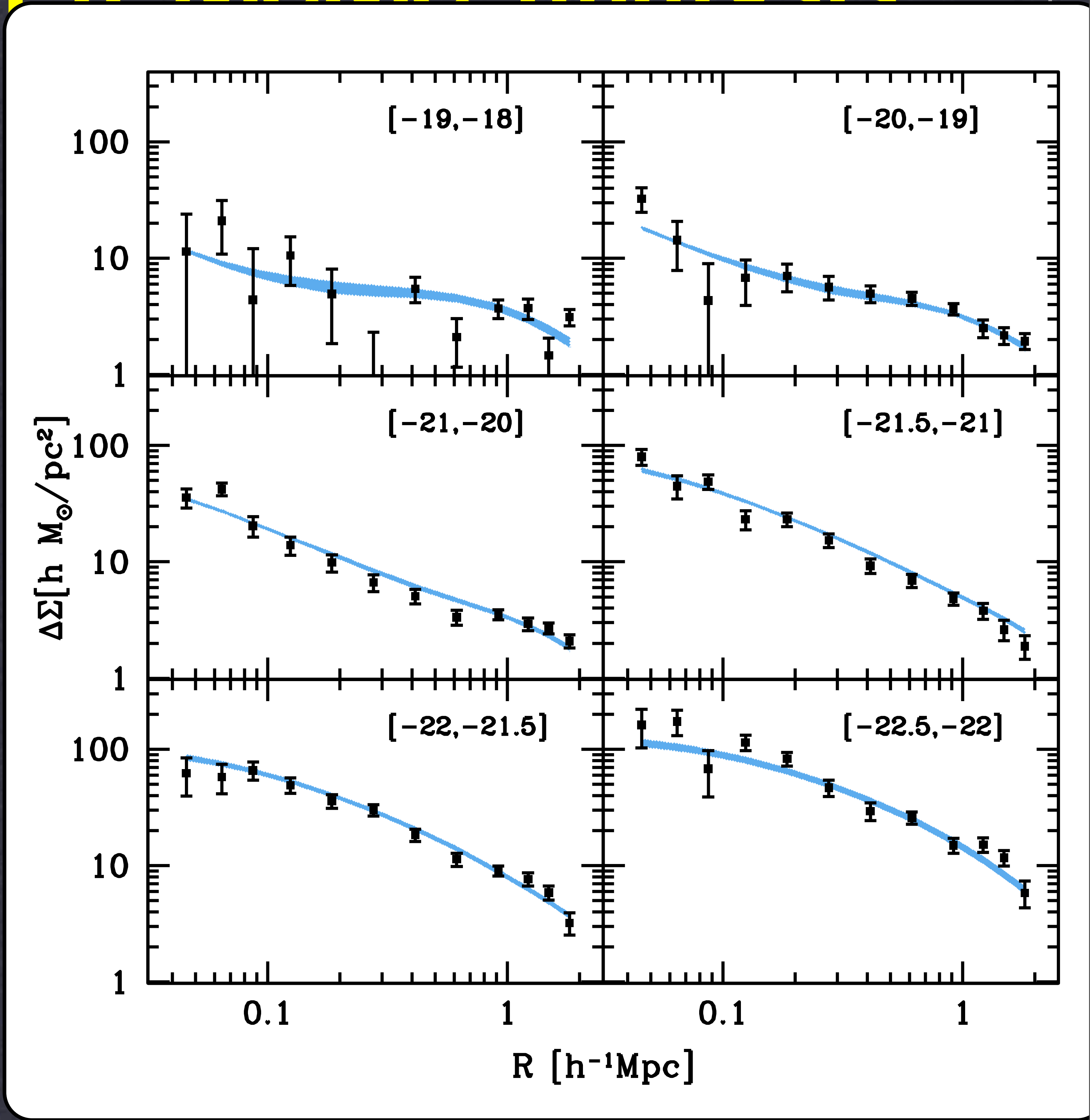
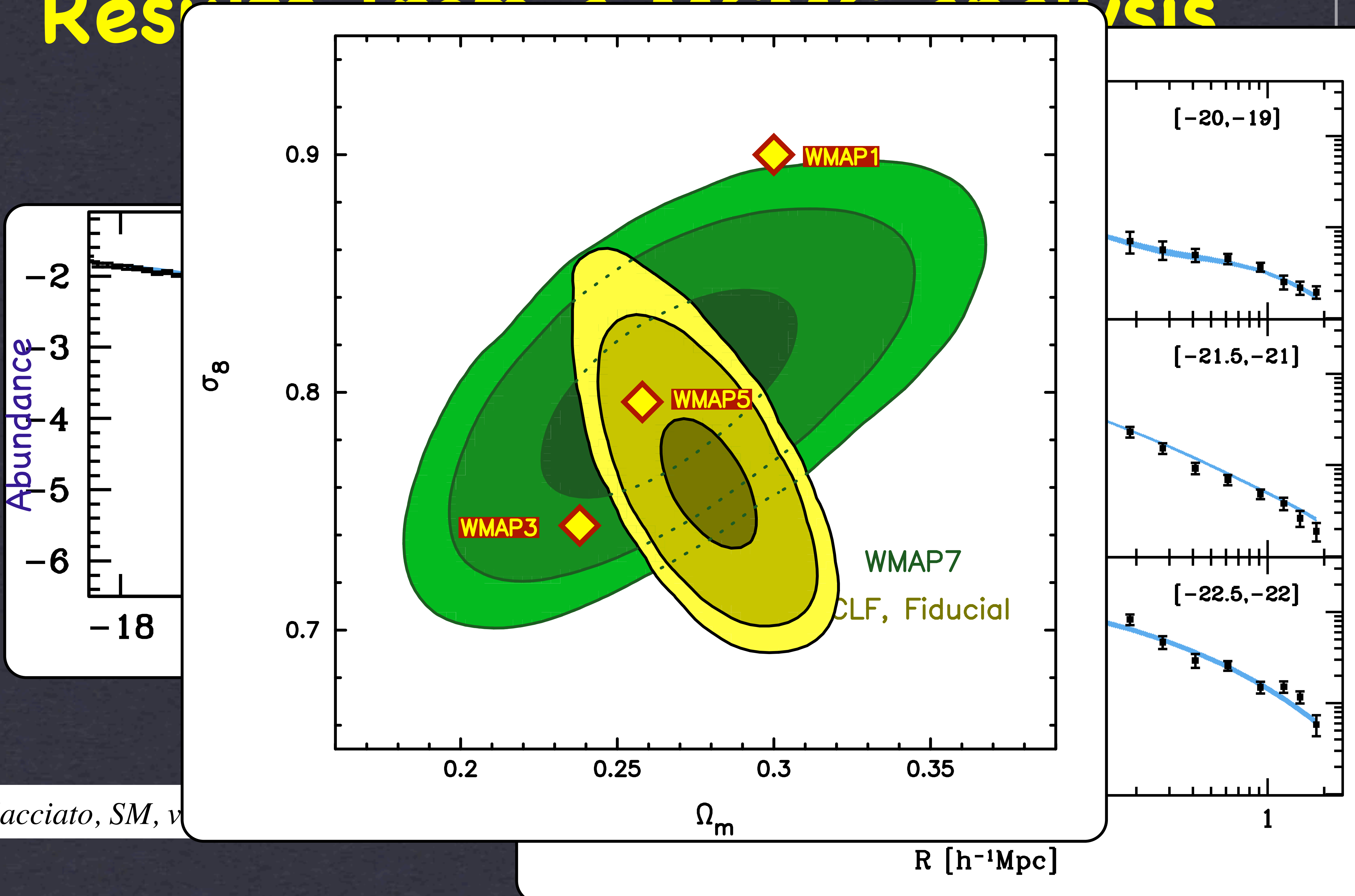




Cacciato, SM, vdB (in prep)

Results from a MCMC analysis



Cacciato, SM, v

Some ideas for the future!!!

- Modified gravity models: f(R) gravity
- Generalize the Einstein-Hilbert action

$$S = \int d^4x \left(\frac{1}{2\kappa}[R + f(R)] + \mathcal{L}_M \right) \sqrt{-|g|}$$

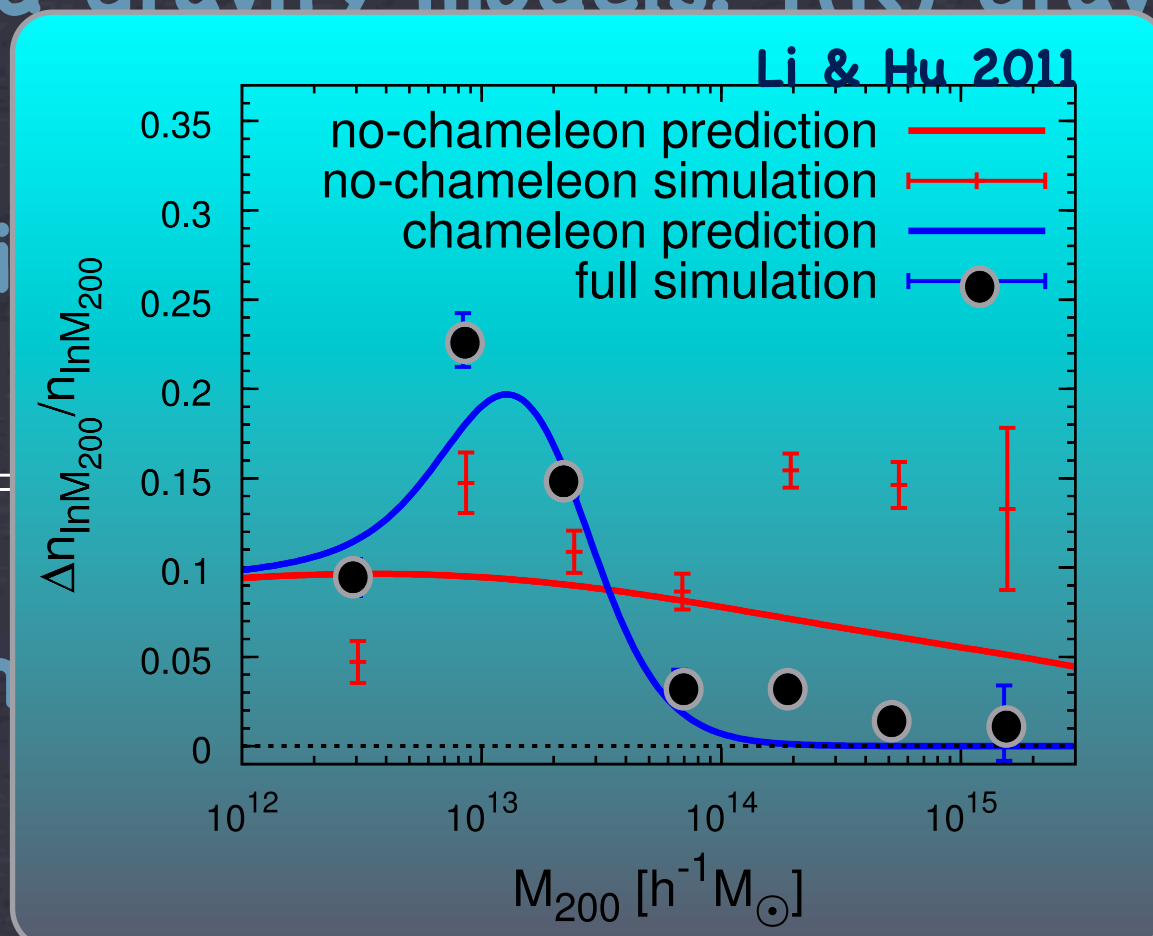
- Can mimic the effects of dark energy for specific choices of the function f(R)
- However, it has to reduce to GR on small scales to obey solar system constraints.

Some ideas for the future!!!

- Modified gravity models: f(R) gravity
- Generali ... ion

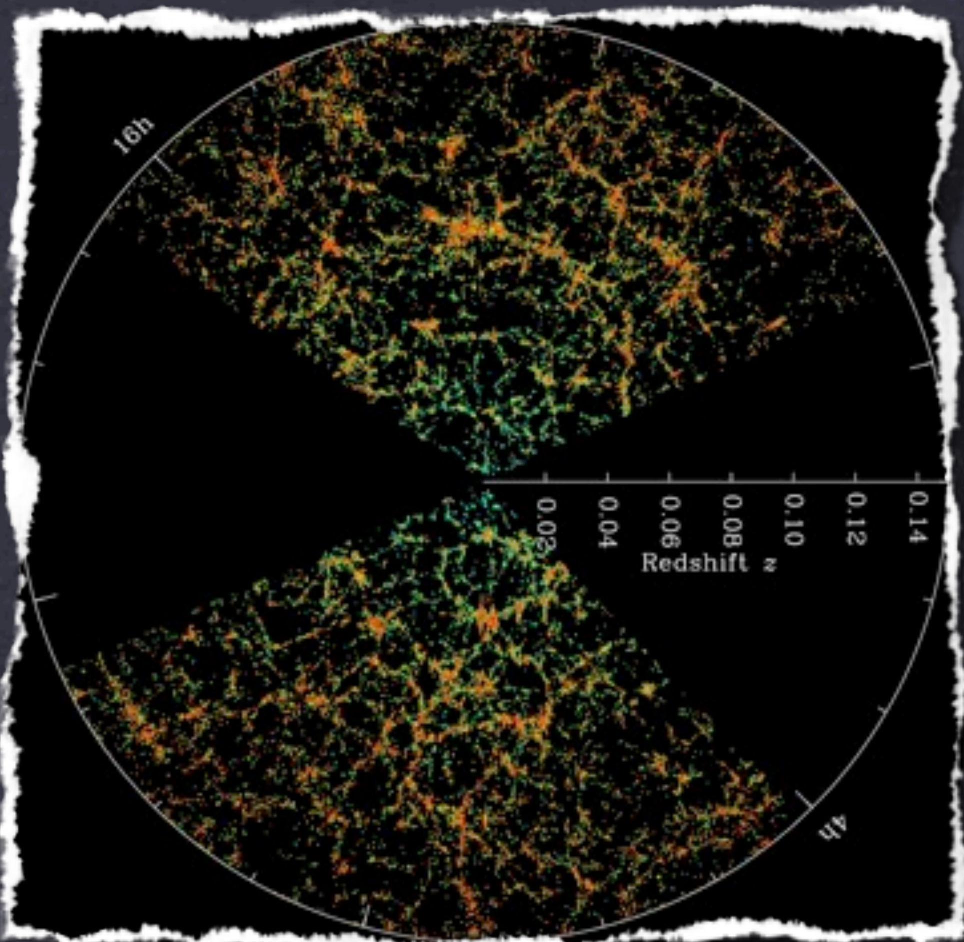
$S = \ldots |g|$

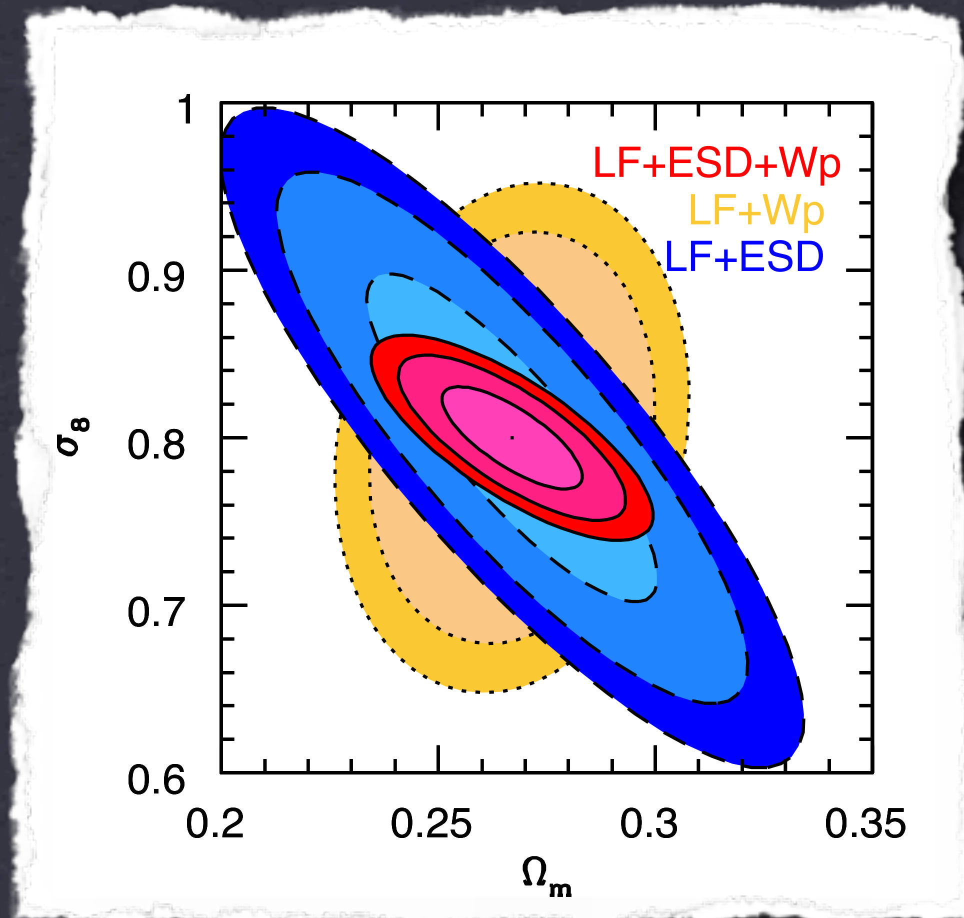
- Can mim ... rgy for specific ... R)



- However, it has to reduce to GR on small scales to obey solar system constraints.

Take home message



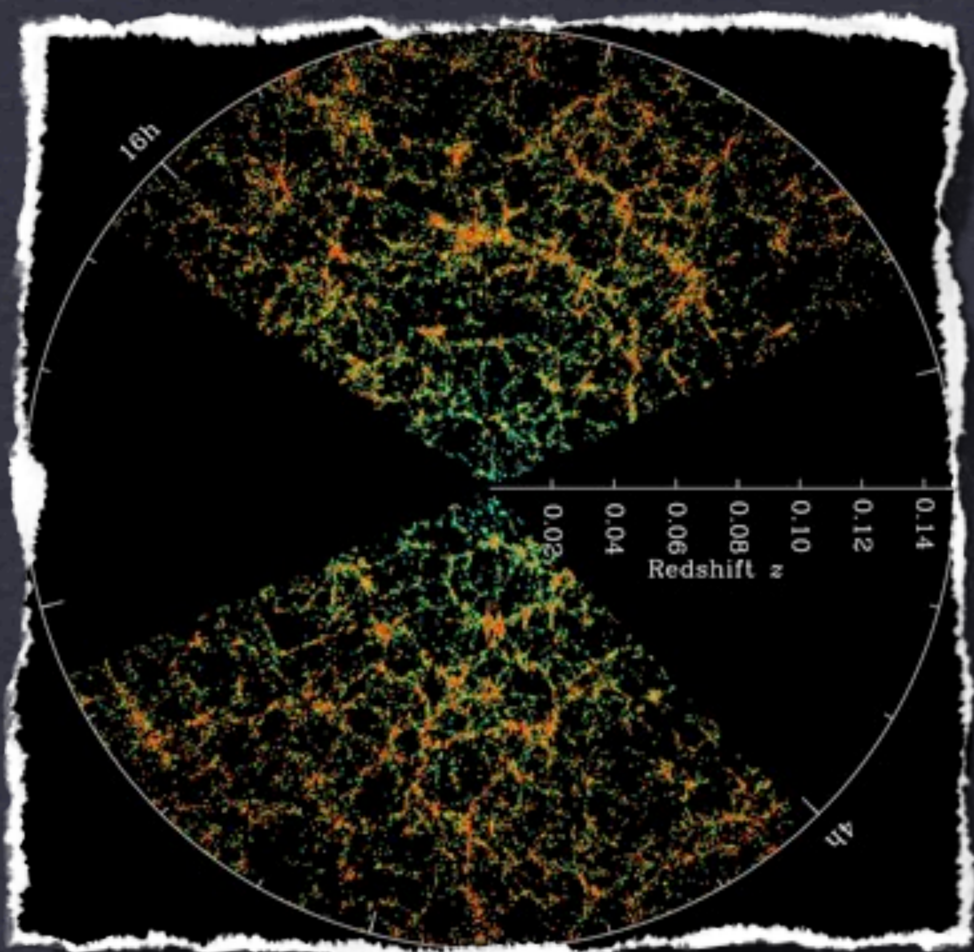


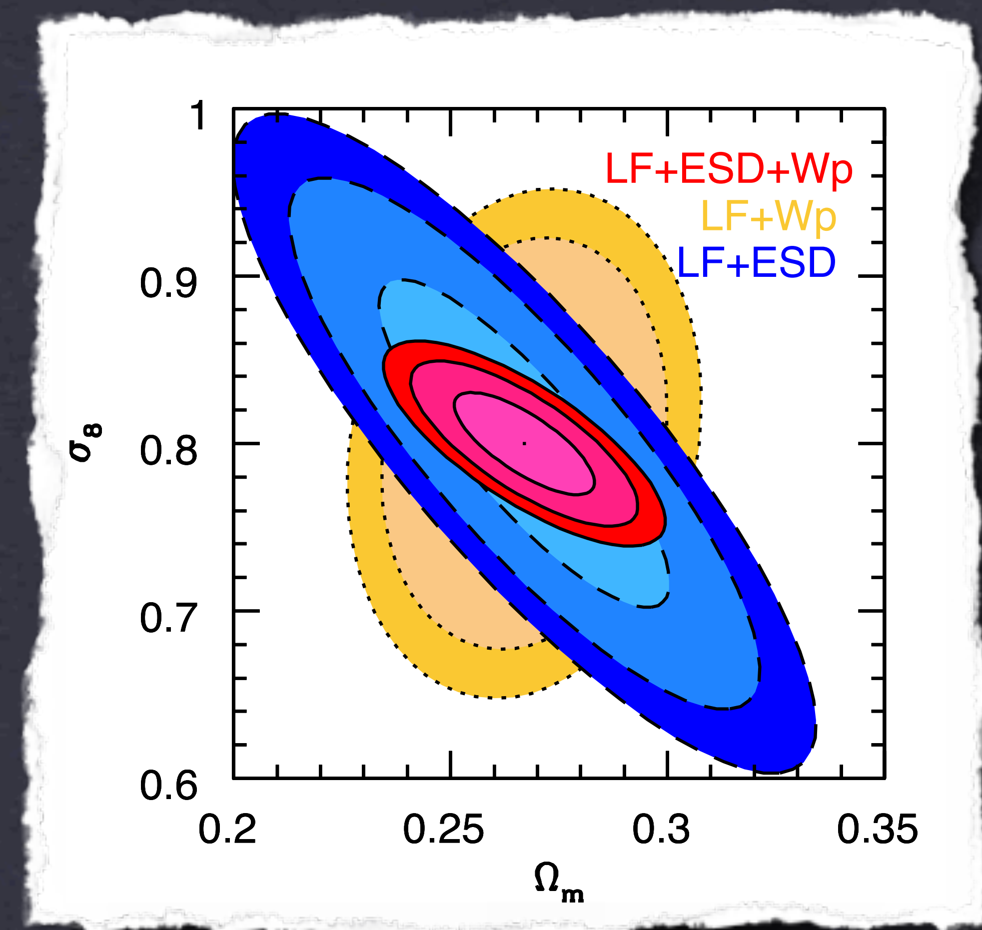
Galaxy observations can be used to constrain cosmological parameters!

What kind of?

How?

Take home message





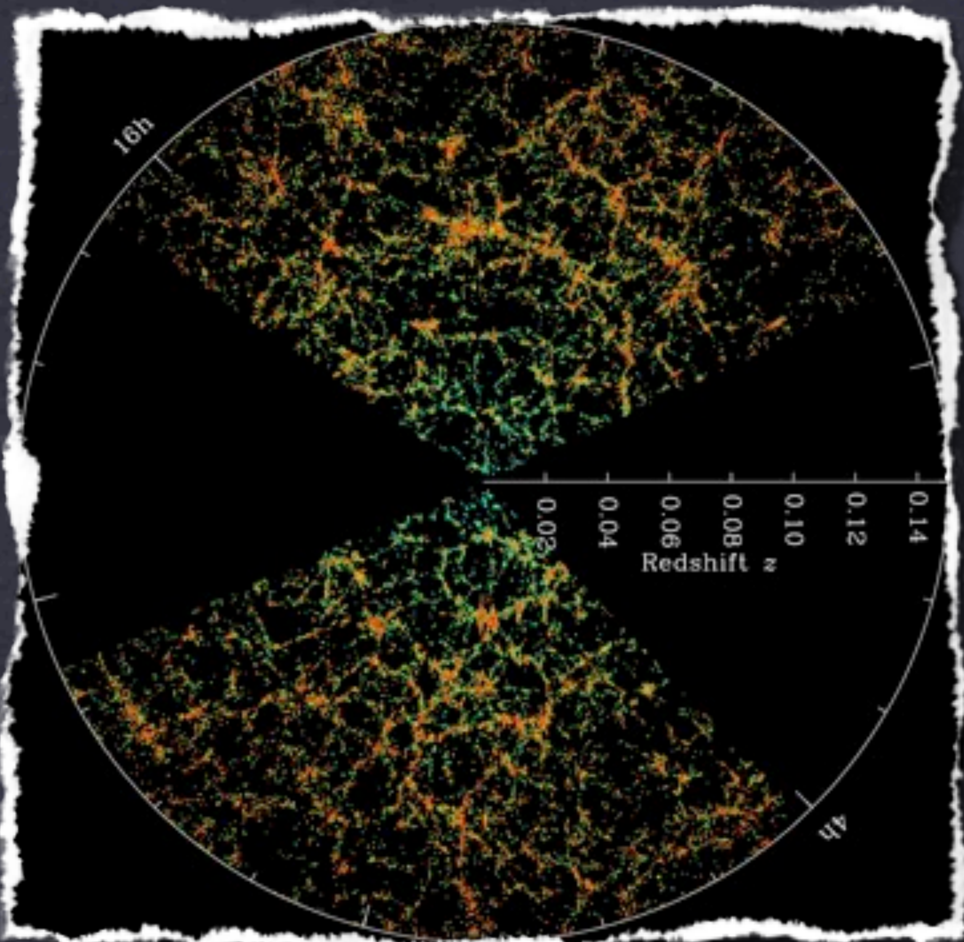
Galaxy observations can be used to

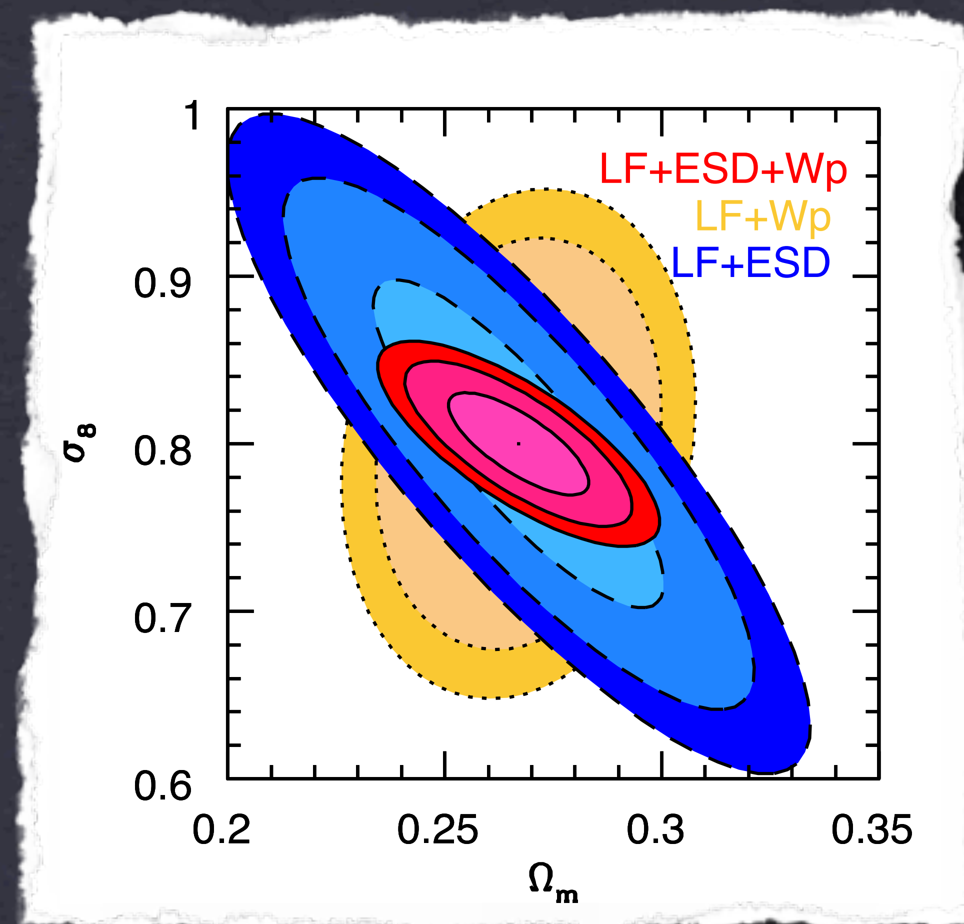
logical parameters!

Galaxy abundance
Galaxy clustering
Galaxy-galaxy lensing

How?

Take home message





Galaxy observations can be used to

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Galaxy abundance
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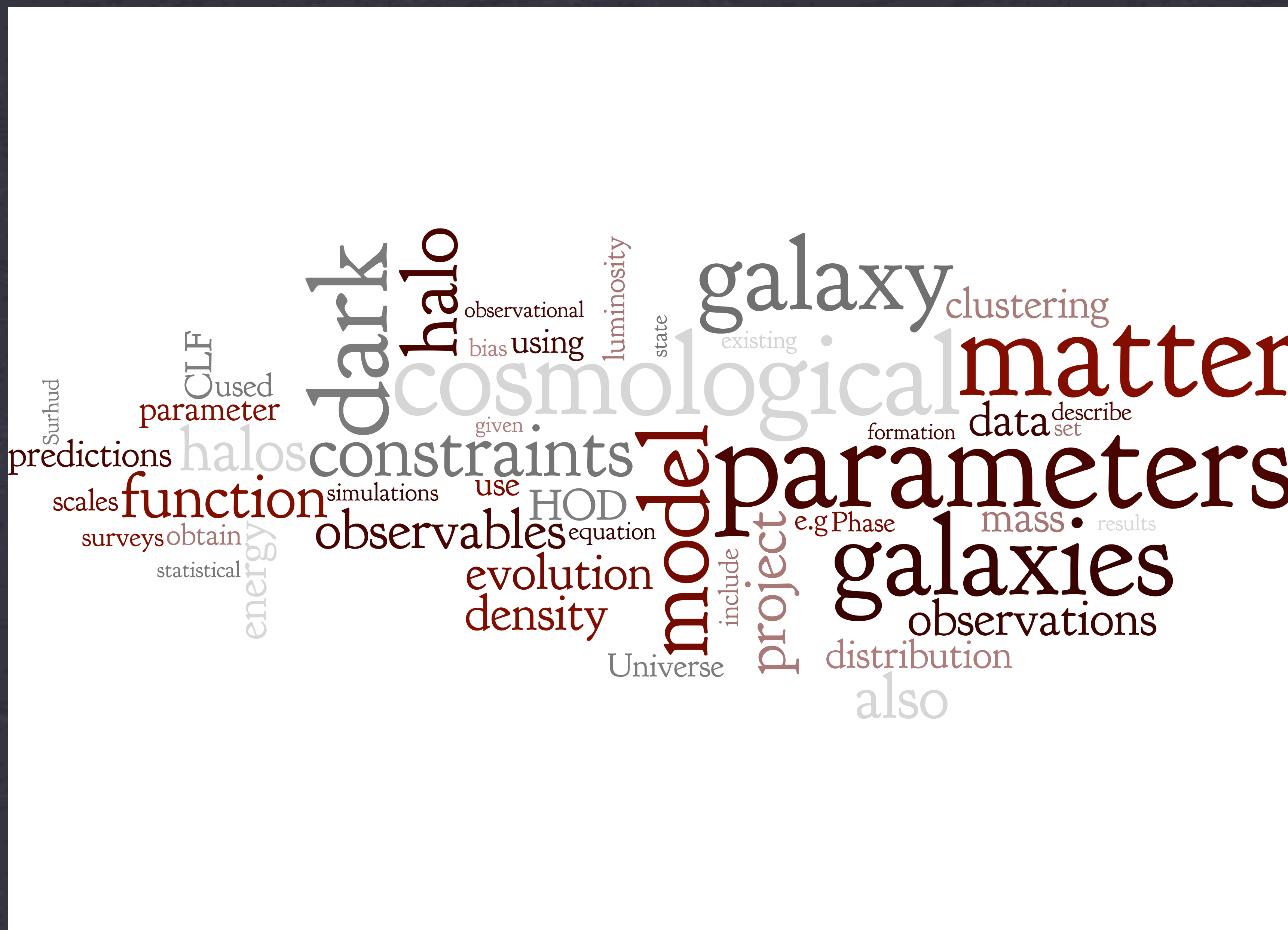
Halo occupation modeling with CLF!!!

Word cloud



Thank you!!!