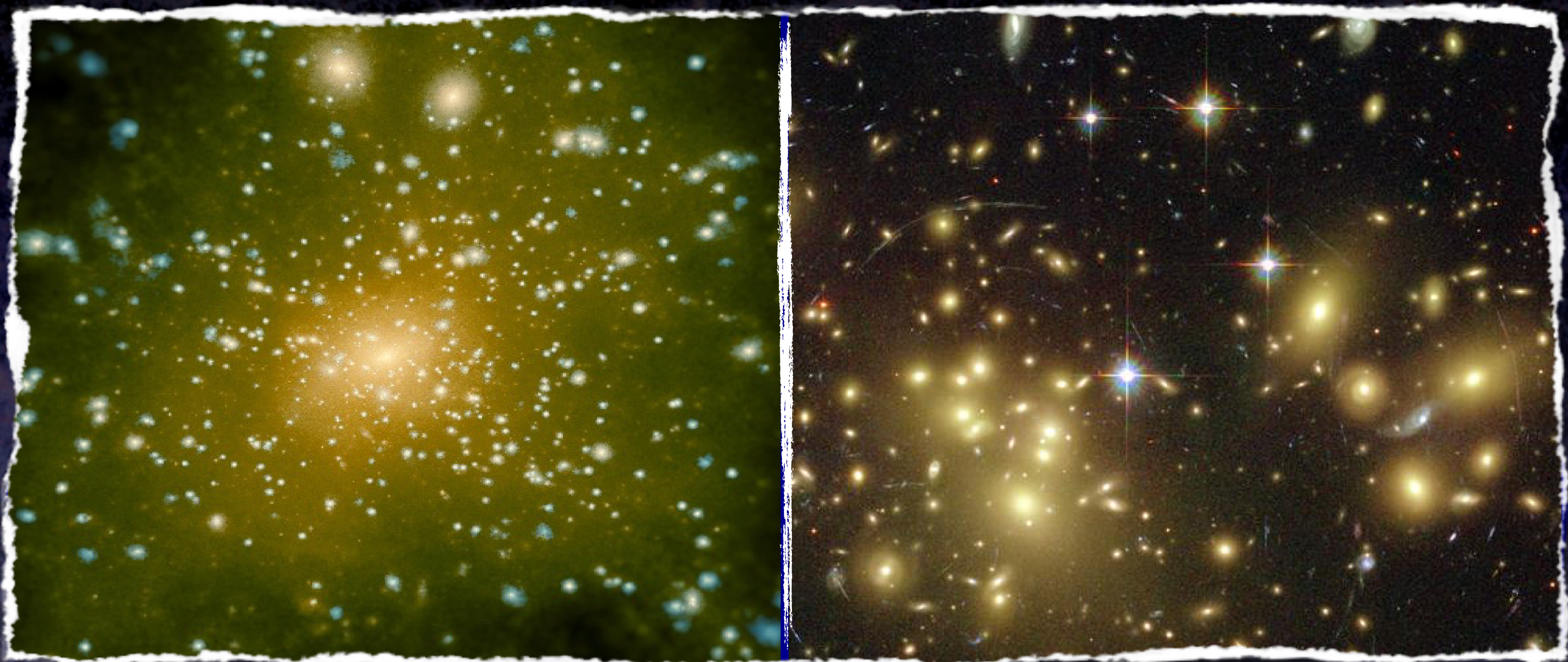
Cosmological Constraints from a Combined Analysis of Clustering & Galaxy-Galaxy Lensing in the SDSS

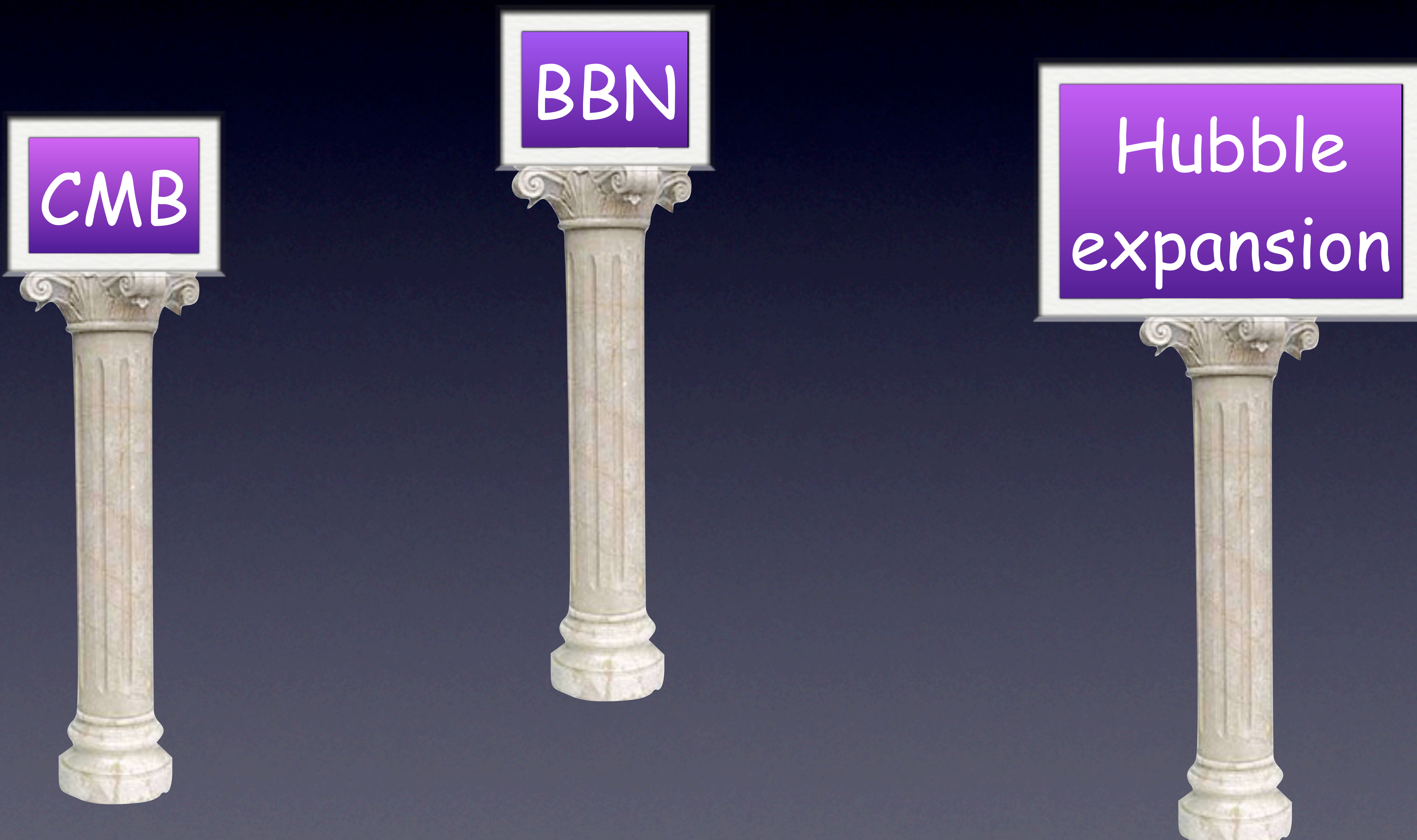


Frank van den Bosch

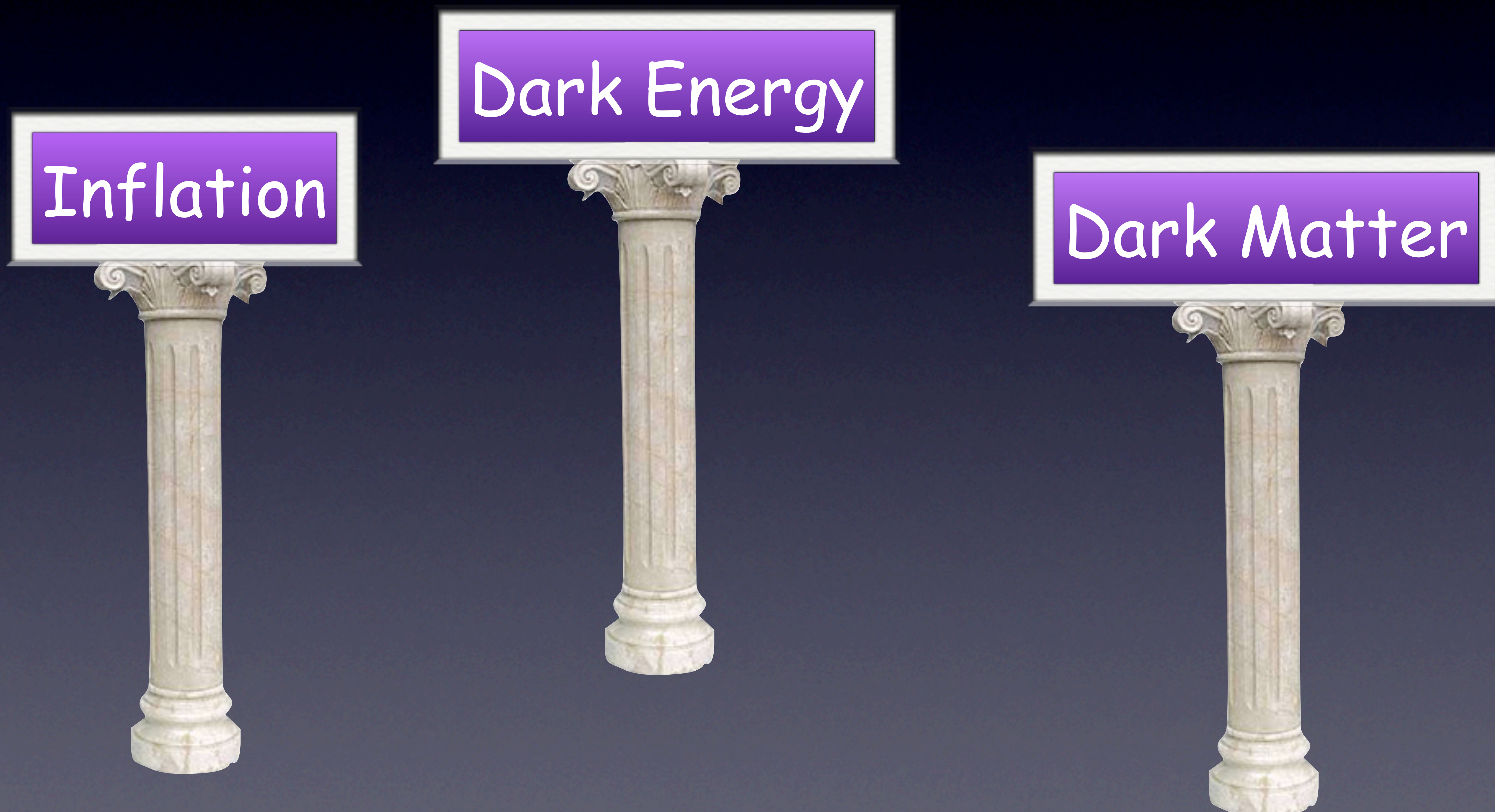
Yale University

In collaboration with:
Marcello Cacciato (HU), Surhud More (KICP),
Houjun Mo (UMass), Xiaohu Yang (SHAO)

The Three Observational Pillars of Classical Cosmology



The Three Theoretical Pillars of Modern Cosmology



The Standard Paradigm

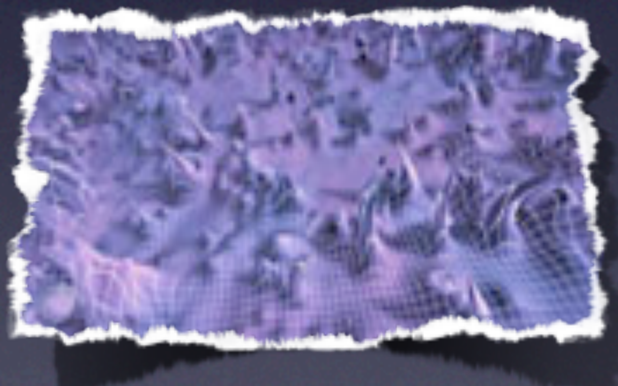
Hot Big Bang

The Standard Paradigm

Hot Big Bang

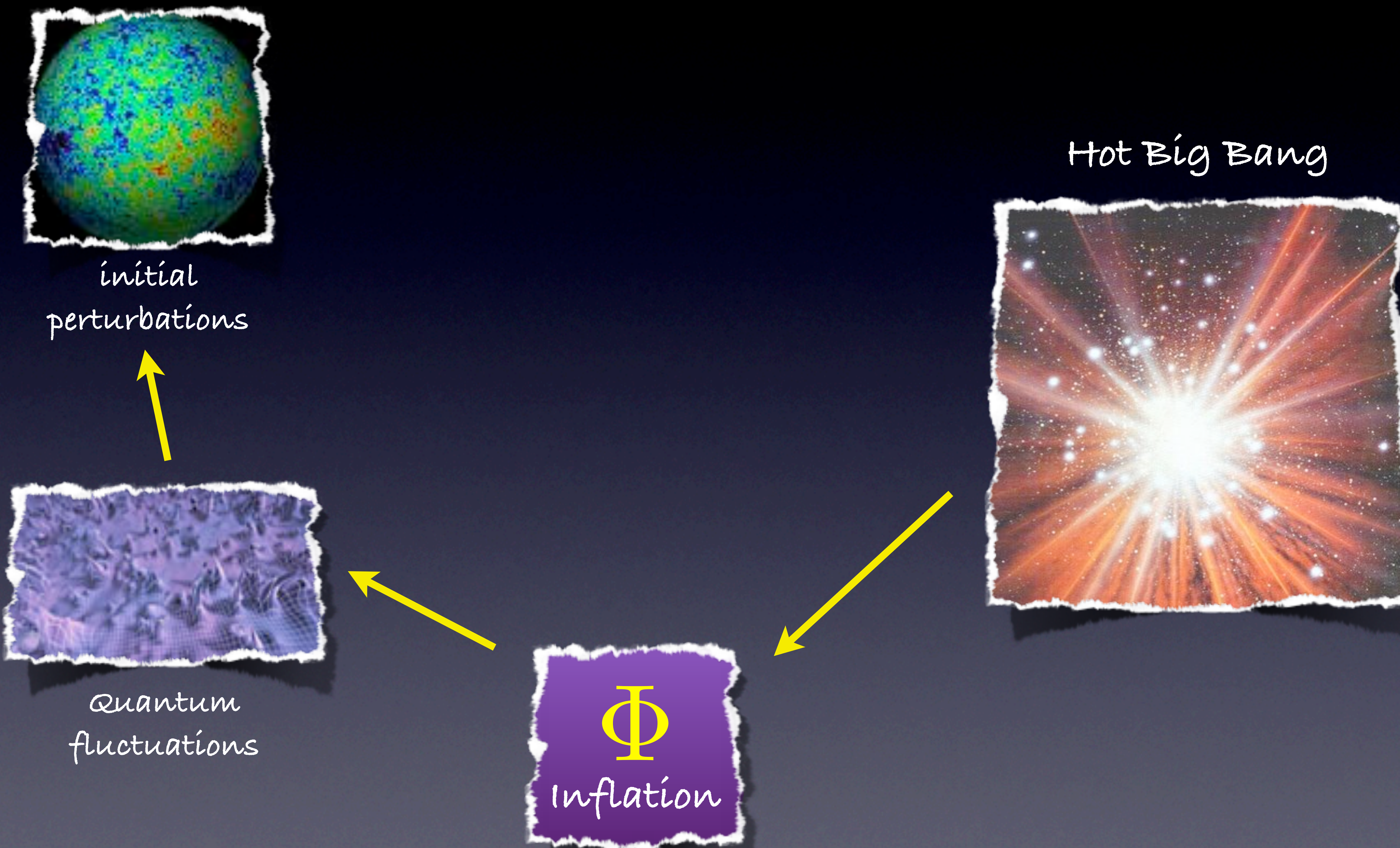
The Standard Paradigm

Hot Big Bang



Quantum fluctuations

The Standard Paradigm



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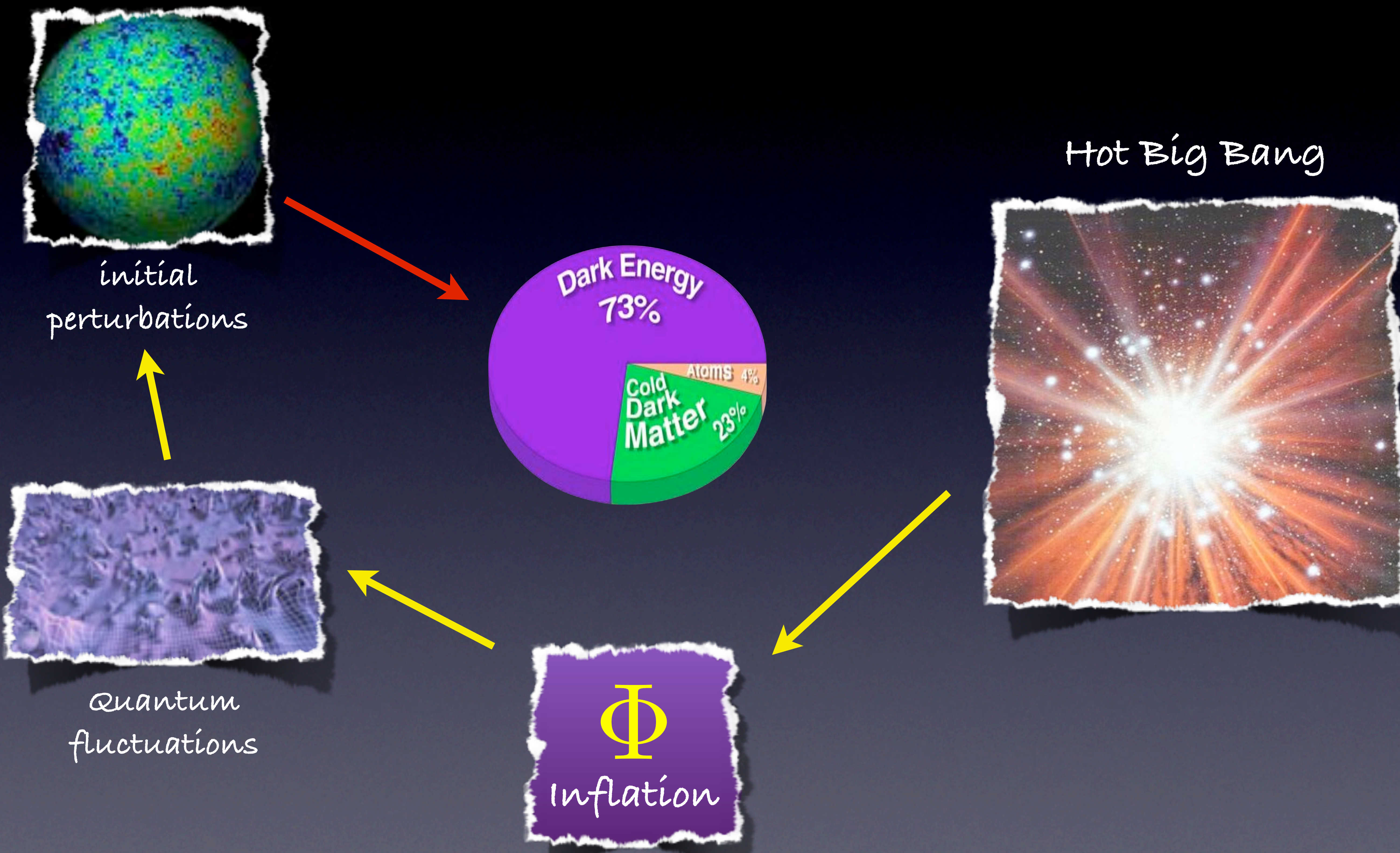

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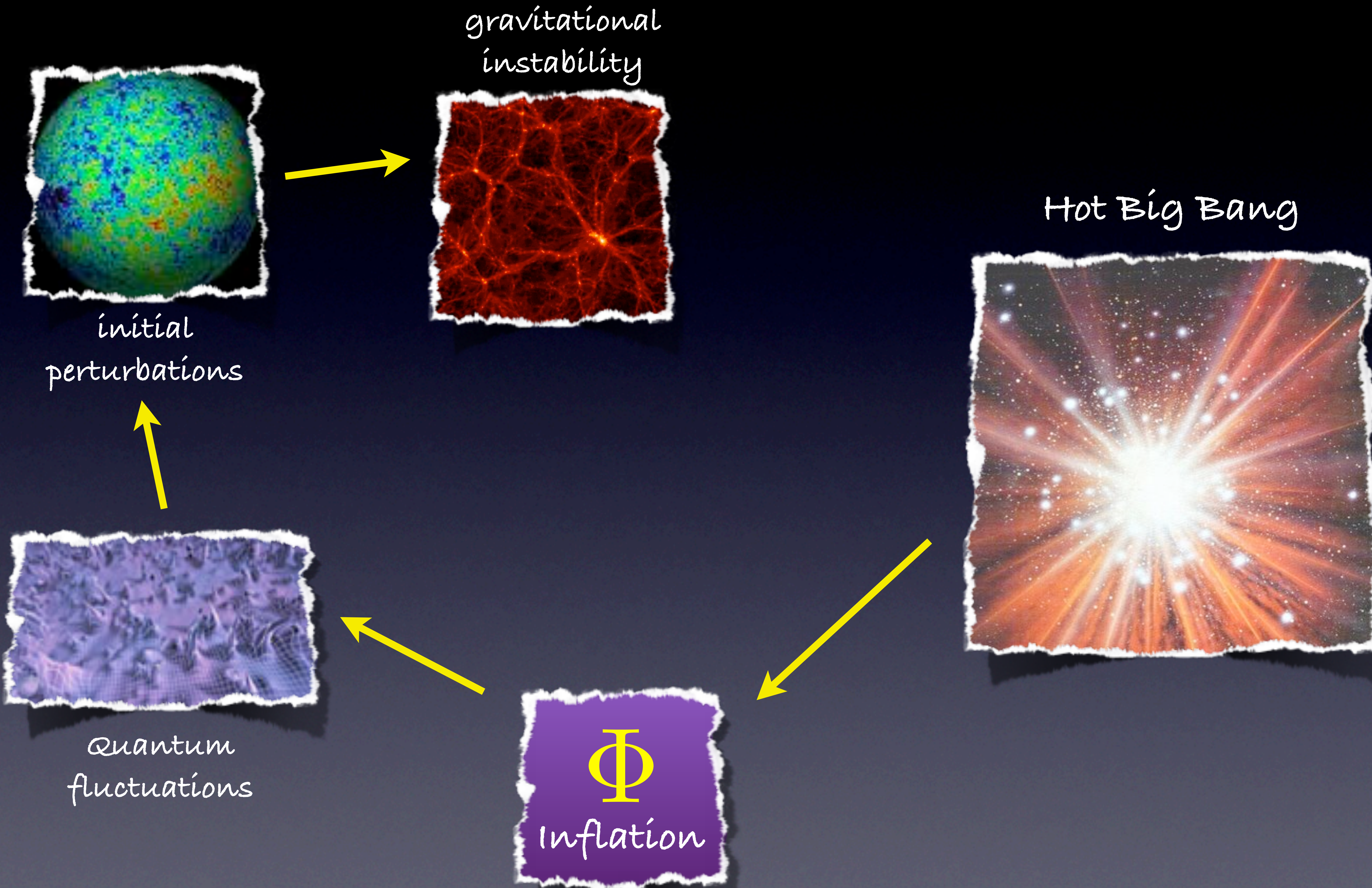

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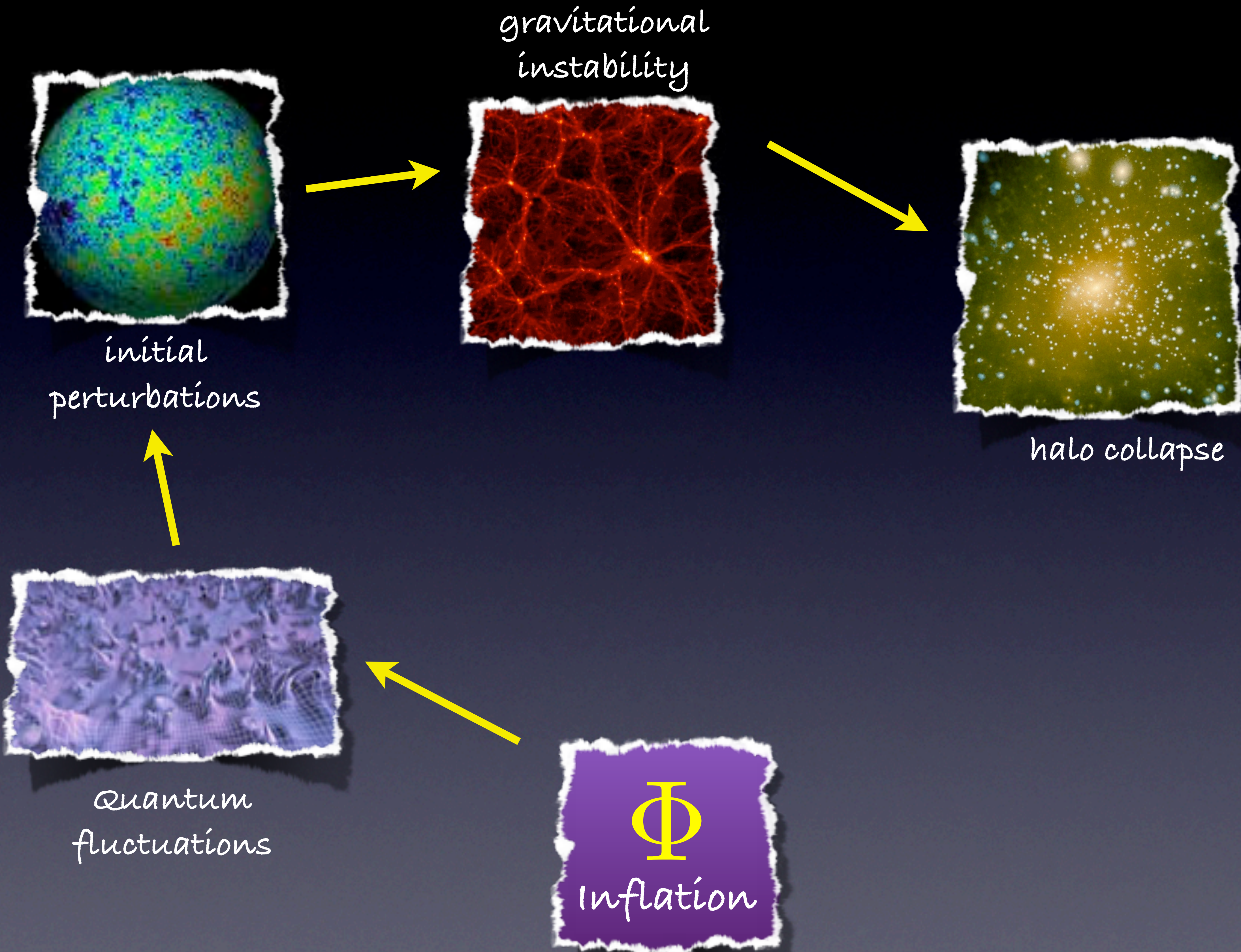
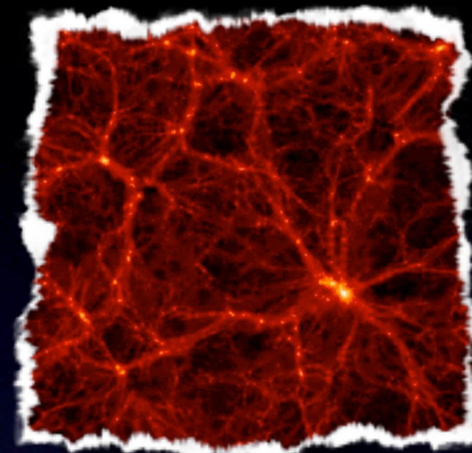
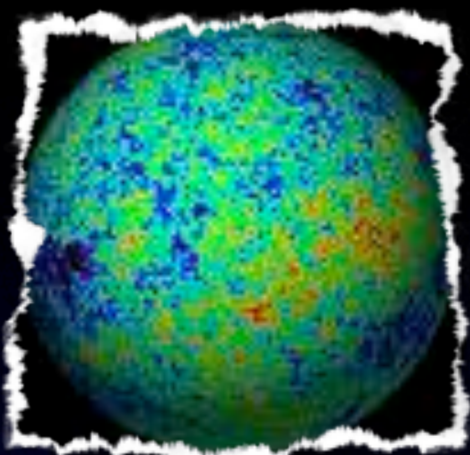


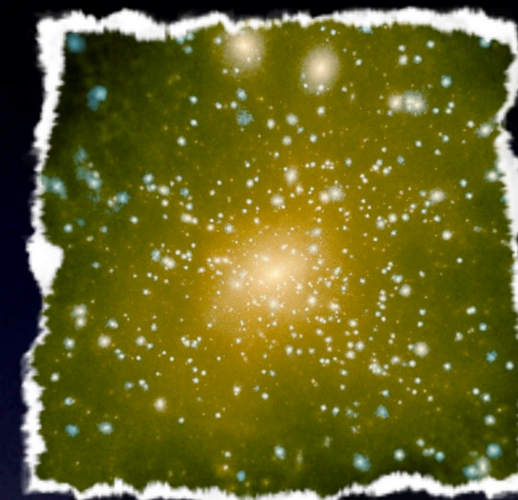
The Standard Paradigm

gravitational
instability





initial
perturbations



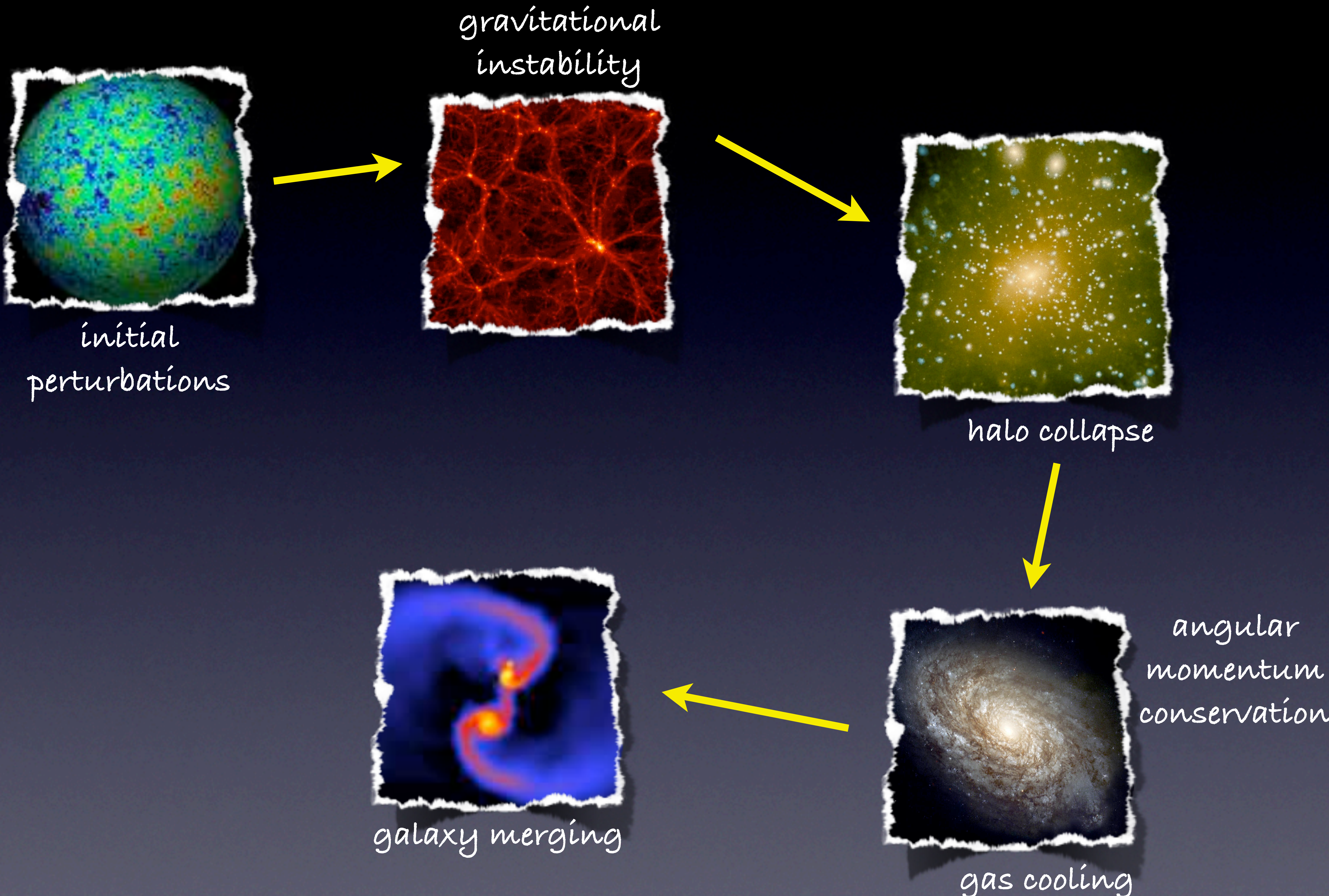
halo collapse

Quantum
fluctuations

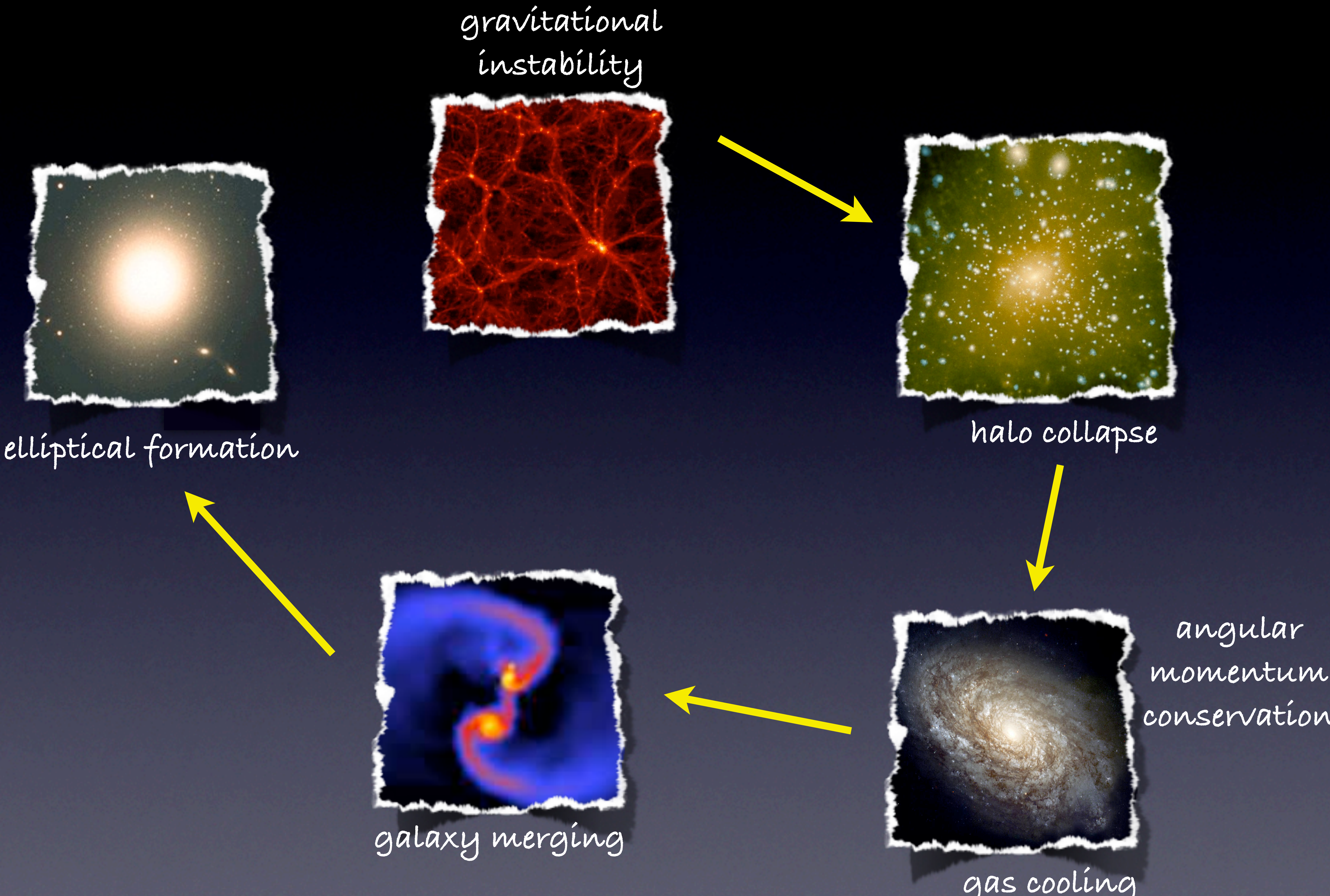
angular
momentum
conservation

gas cooling

The Standard Paradigm



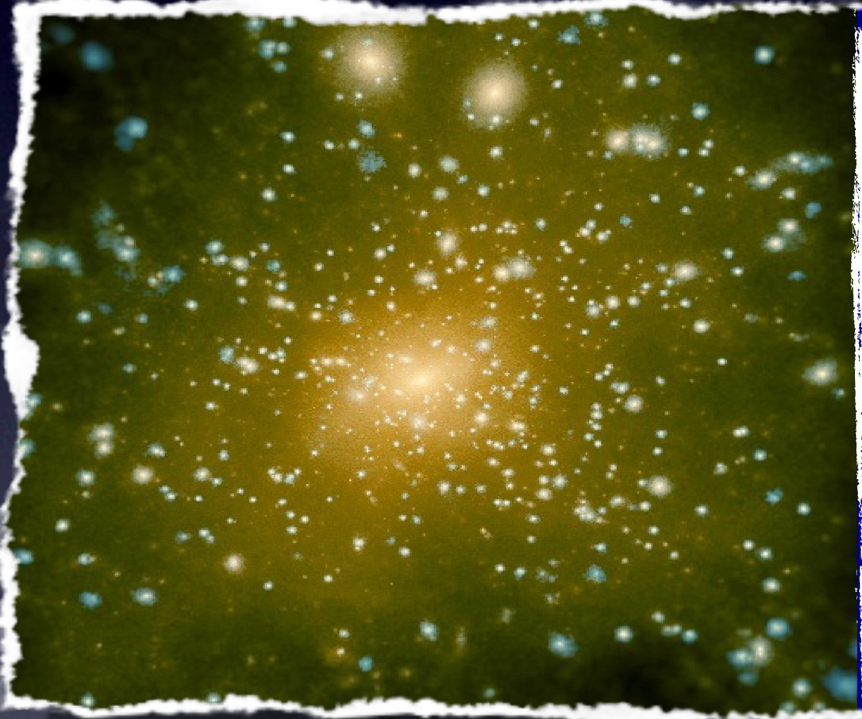
The Standard Paradigm



Introduction: Motivation & Goal

Our main goal is to study the Galaxy-Dark Matter connection;
i.e., what galaxy lives in what halo?

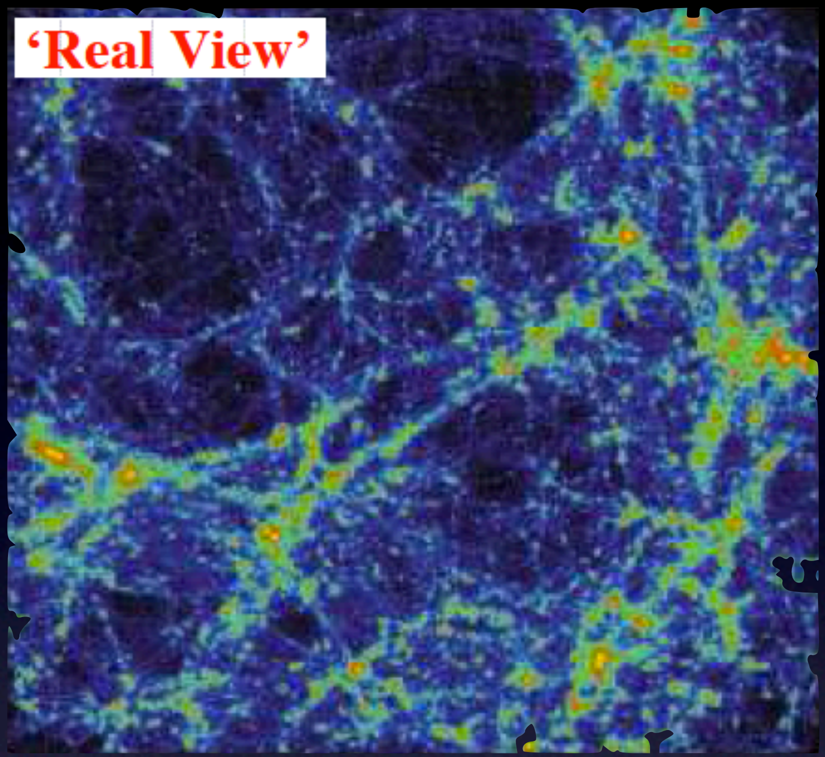
- To constrain the physics of Galaxy Formation
- To constrain cosmological parameters

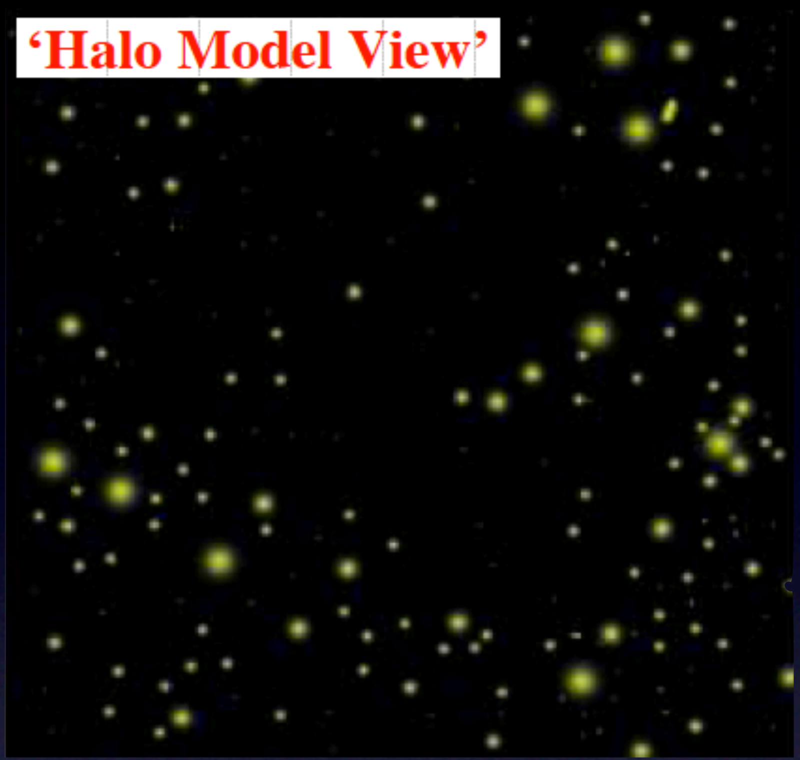


Four Methods to Constrain Galaxy-Dark Matter Connection:

- Large Scale Structure
- Galaxy-Galaxy Lensing
- Satellite Kinematics
- Abundance Matching

The Halo Model



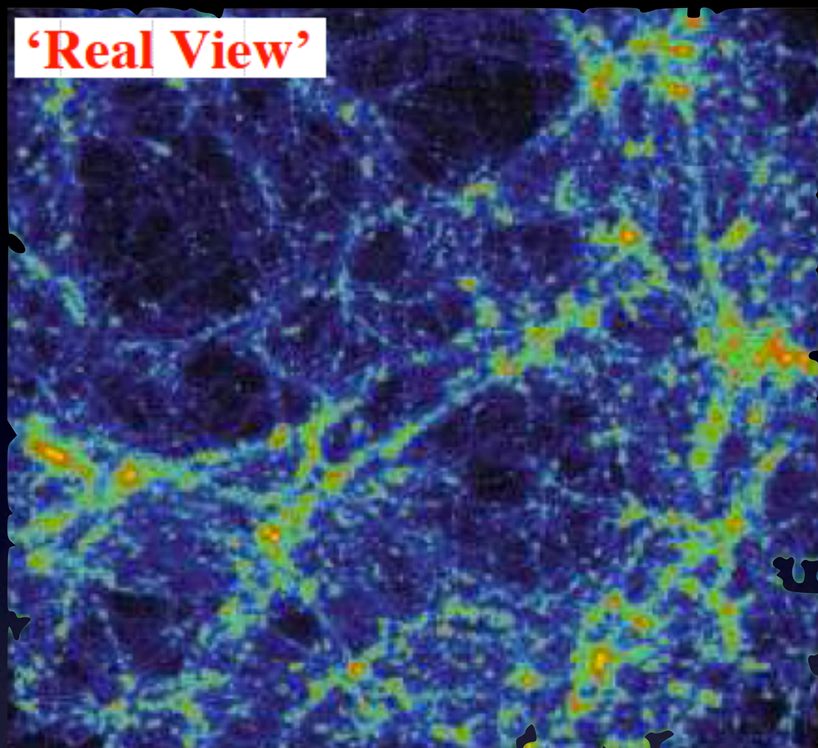


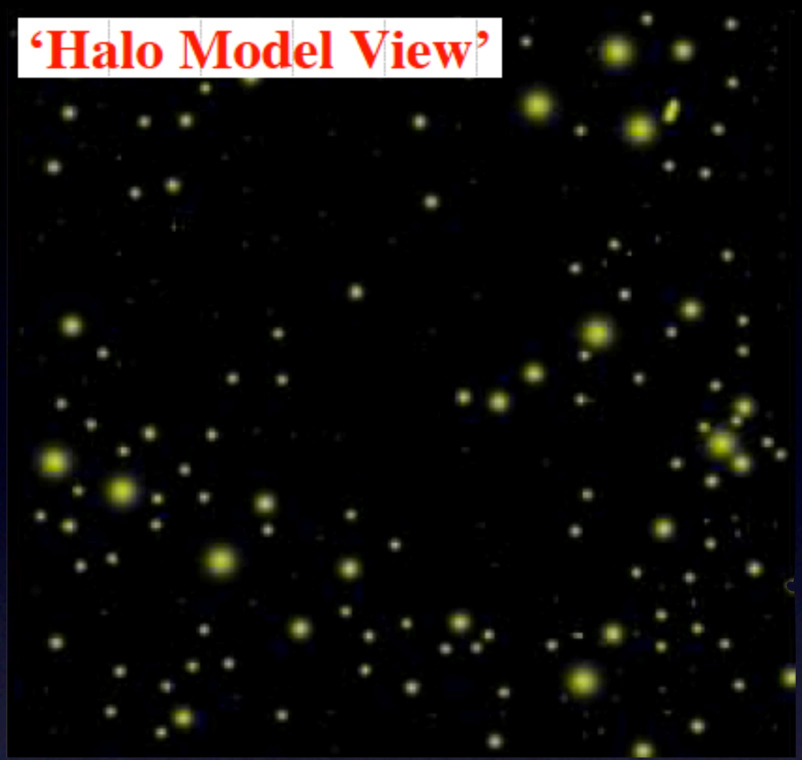
Halo model describes dark matter density distribution (correlation function or power spectrum) in terms of its halo building blocks, under ansatz that all dark matter is partitioned over haloes.

Halo Model Ingredients:

- the halo density profiles $\rho(r|M) = M u(r|M)$
- the halo mass function $n(M)$
- the halo bias function $b(M)$

The Halo Model





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- the halo density profiles $\rho(r|M) = M u(r|M)$
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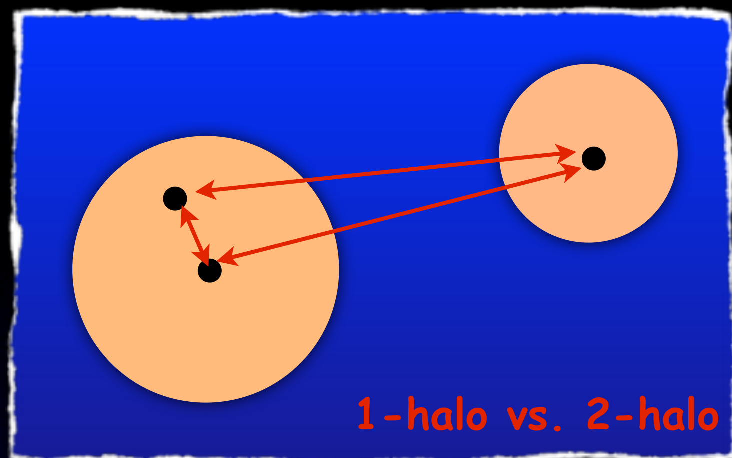
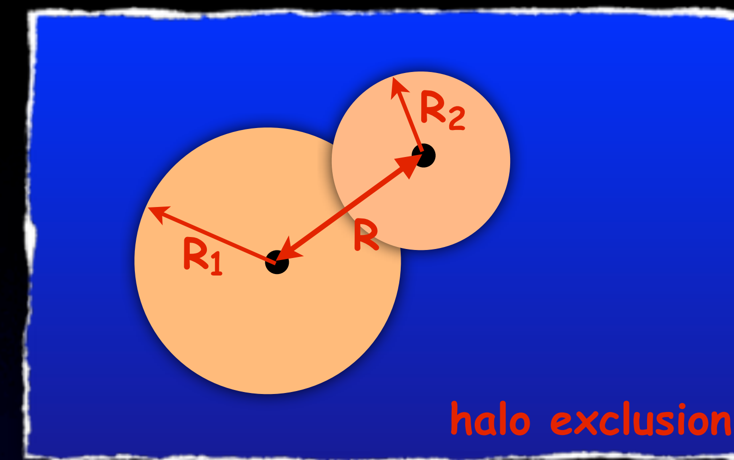
Dark matter halos are clustered: $\xi_{\rm hh}(r|M_1, M_2) \propto b(M_1)\, b(M_2)\, \xi_{\rm mm}(r)$

All of these are (reasonably) well calibrated against numerical simulations.

The Halo Model





$$P^{1h}(k) = \frac{1}{\bar{\rho}^2} \int \mathrm{d}M \, M^2 \, n(M) \, |\tilde{u}(k|M)|^2$$

$$P^{2h}(k) = \frac{1}{\bar{\rho}^2} \int \mathrm{d}M_1 \, M_1 \, n(M_1) \, \tilde{u}(k|M_1) \int \mathrm{d}M_2 \, M_2 \, n(M_2) \tilde{u}(k|M_2) \, Q(k|M_1, M_2)$$

Here $Q(k|M_1, M_2) = 4\pi \int_{r_{\rm min}}^{\infty} [1 + \xi_{\rm hh}(r|M_1, M_2)] \, \frac{\sin kr}{kr} r^2 \mathrm{d}r$

describes the fact that dark matter haloes are clustered, as described by the halo-halo correlation function, $\xi_{\rm hh}(r|M_1, M_2)$, and takes halo exclusion into account by having $r_{\rm min} = R_1 + R_2$

The Galaxy-Galaxy Correlation Function

$$P^{1h}(k) = \frac{1}{\bar{\rho}^2} \int \mathrm{d}M \, M^2 \, n(M) \, |\tilde{u}(k|M)|^2$$

$$P^{2h}(k) = \frac{1}{\bar{\rho}^2} \int \mathrm{d}M_1 \, M_1 \, n(M_1) \, \tilde{u}(k|M_1) \int \mathrm{d}M_2 \, M_2 \, n(M_2) \tilde{u}(k|M_2) \, Q(k|M_1, M_2)$$

The above equations describe the non-linear matter power-spectrum.

It is straightforward to use same formalism to compute power spectrum of galaxies:

Simply replace

$$\frac{M}{\bar{\rho}_{\mathrm{m}}} \rightarrow \frac{\langle N \rangle_M}{\bar{n}_{\mathrm{g}}}$$

$$\tilde{u}(k|M) \rightarrow \tilde{u}_{\mathrm{g}}(k|M)$$

where $\langle N \rangle_M$ describes the average number of galaxies (with certain properties) in a halo of mass M. Thus, the halo model combined with a model for the halo occupation statistics, allows a computation of $\xi_{\mathrm{gg}}(r)$

The Conditional Luminosity Function

The CLF $\Phi(L|M)$ describes the average number of galaxies of luminosity L that reside in a halo of mass M.

$$\Phi(L) = \int \Phi(L|M)\, n(M)\, \mathrm{d}M$$

$$\langle L \rangle_M = \int \Phi(L|M)\, L\, \mathrm{d}L$$

$$\langle N \rangle_M = \int \Phi(L|M)\, \mathrm{d}L$$

- Describes occupation statistics of dark matter haloes
- Links galaxy luminosity function to halo mass function
- Holds information on average relation between light and mass

see Yang, Mo & vdBosch 2003

The CLF Model

We split the CLF in a central and a satellite term:

$$\Phi(L|M) = \Phi_{\rm c}(L|M) + \Phi_{\rm s}(L|M)$$

For centrals we adopt a log-normal distribution:

$$\Phi_{\rm c}(L|M)\,{\rm d}L = \frac{1}{\sqrt{2\pi}\sigma_{\rm c}} \exp\left[-\left(\frac{\ln(L/L_{\rm c})}{\sqrt{2}\sigma_{\rm c}}\right)^2\right] \frac{{\rm d}L}{L}$$

For satellites we adopt a modified Schechter function:

$$\Phi_{\rm s}(L|M)\,{\rm d}L = \frac{\phi_{\rm s}}{L_{\rm s}} \left(\frac{L}{L_{\rm s}}\right)^{\alpha_{\rm s}} \exp\left[-(L/L_{\rm s})^2\right] {\rm d}L$$

Note: $\{L_{\rm c}, L_{\rm s}, \sigma_{\rm c}, \phi_{\rm s}, \alpha_{\rm s}\}$ all depend on halo mass

Free parameters are constrained by fitting data.

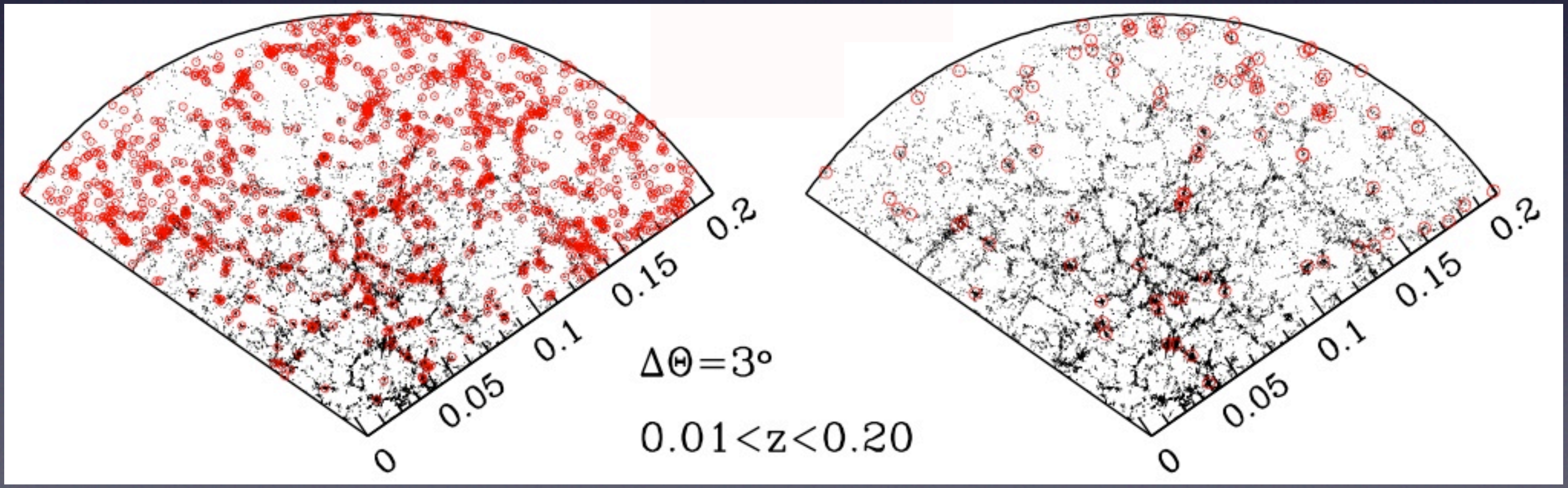
Galaxy Group Catalogues

Constructing Galaxy Group Catalogues

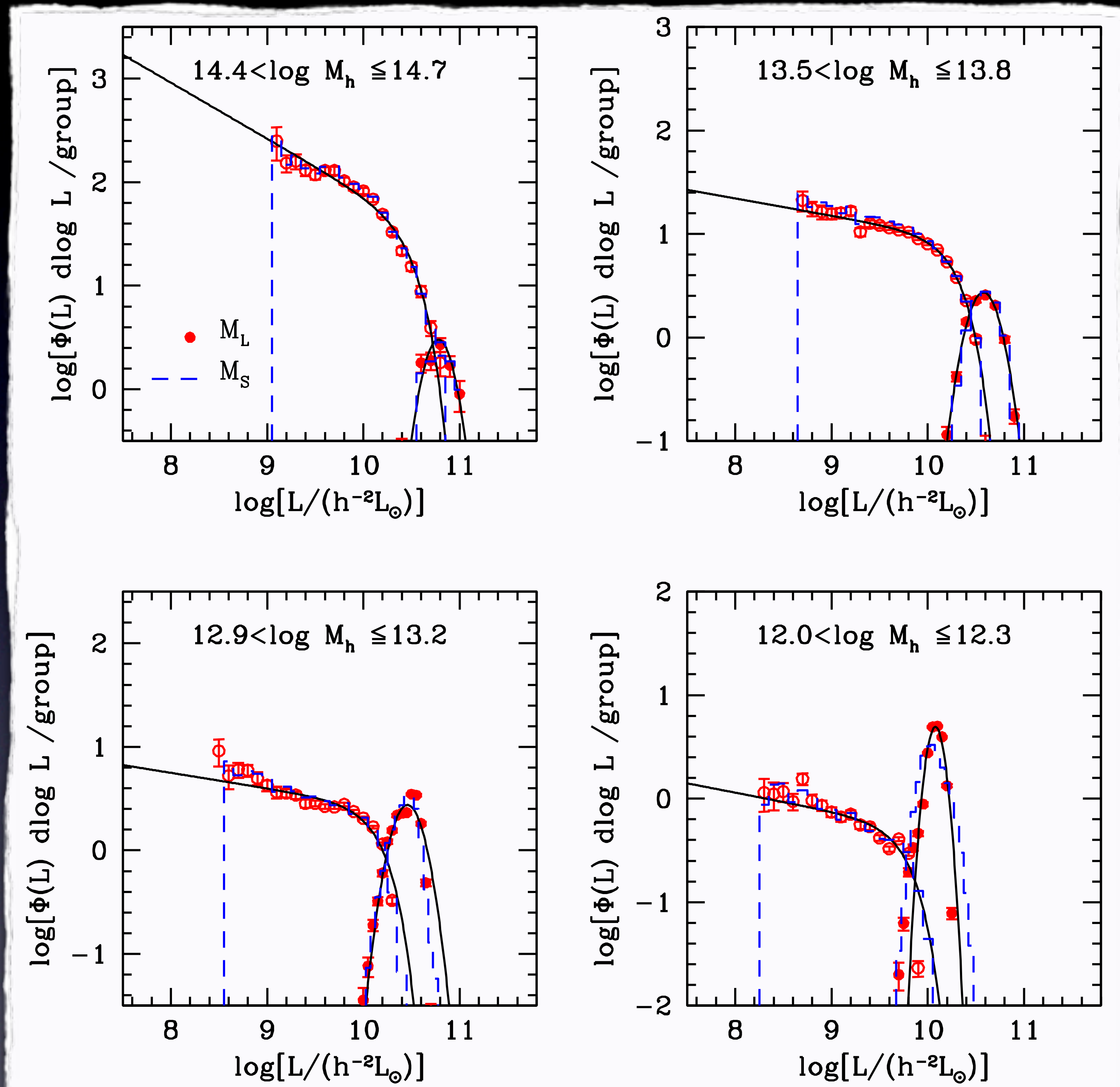
We have developed a new, iterative group finder which uses an adaptive filter modeled after halo virial properties.

- Calibrated & optimized using mock galaxy redshift surveys
- Low interloper fraction (<15%) & high completeness of members (>90%)
- Halo masses estimated from total group luminosity/stellar mass using abundance matching (...cosmology dependent....)
- Can also detect `groups' with single member; large dynamic mass range

For details see Yang et al. (2005) and Yang et al. (2007).



CLF Constraints from Group Catalogue



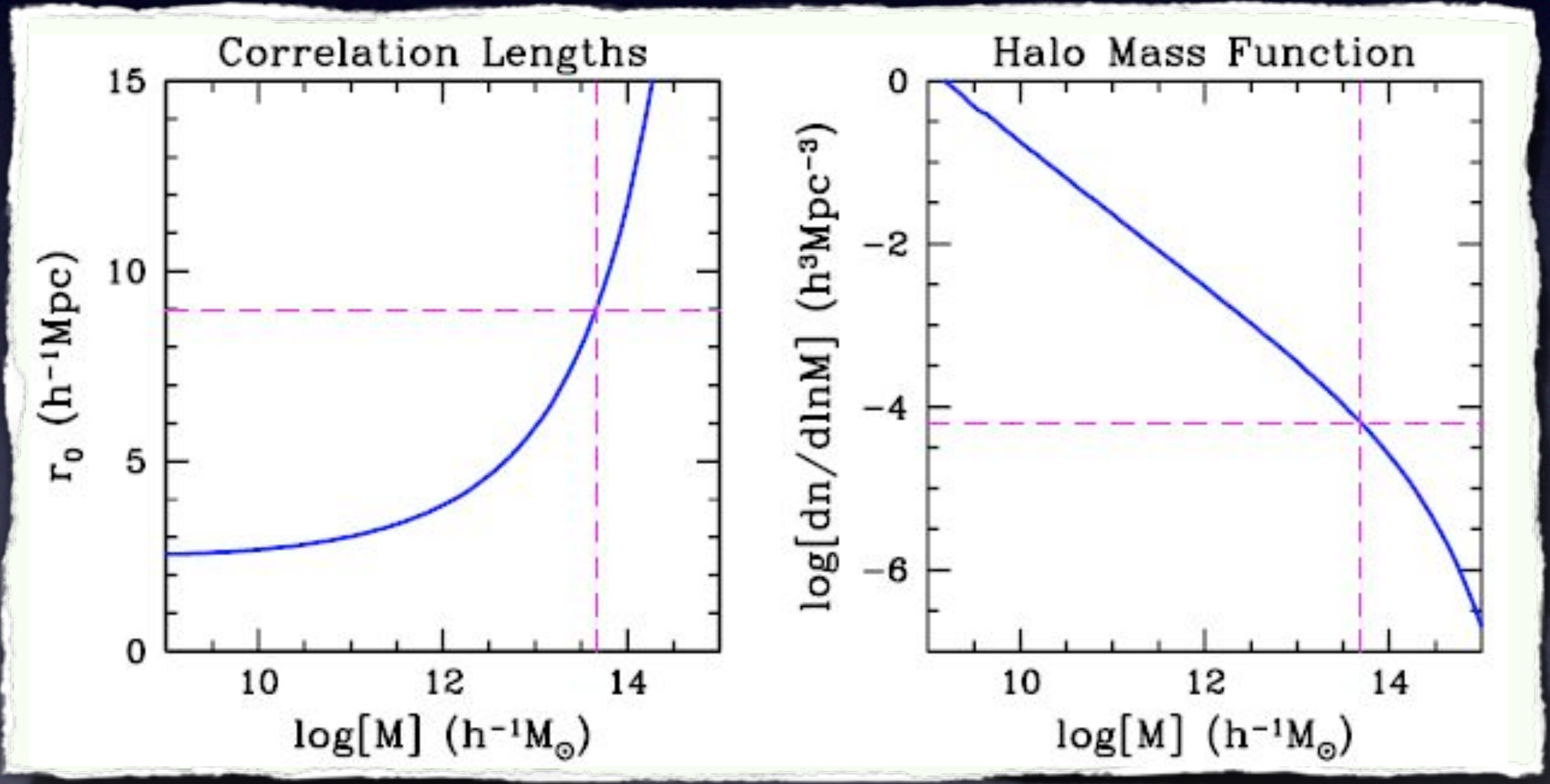
Yang, Mo & vdB (2008)

Galaxy Clustering

Occupation Statistics from Clustering

- Galaxies occupy dark matter halos
- CDM: more massive halos are more strongly clustered
- Clustering strength of given population of galaxies indicates the characteristic halo mass

Clustering strength measured by correlation length r_0



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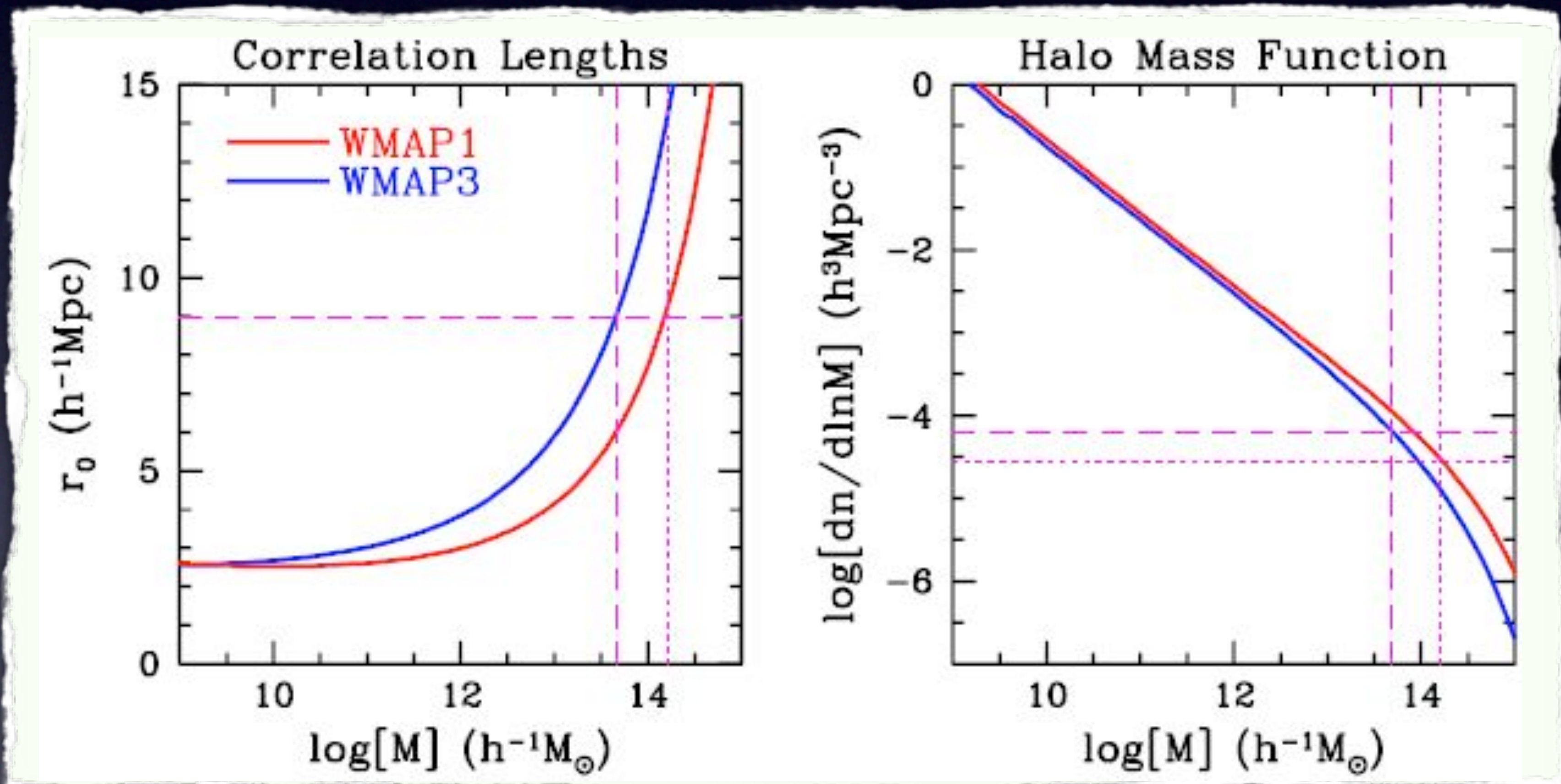


WMAP1

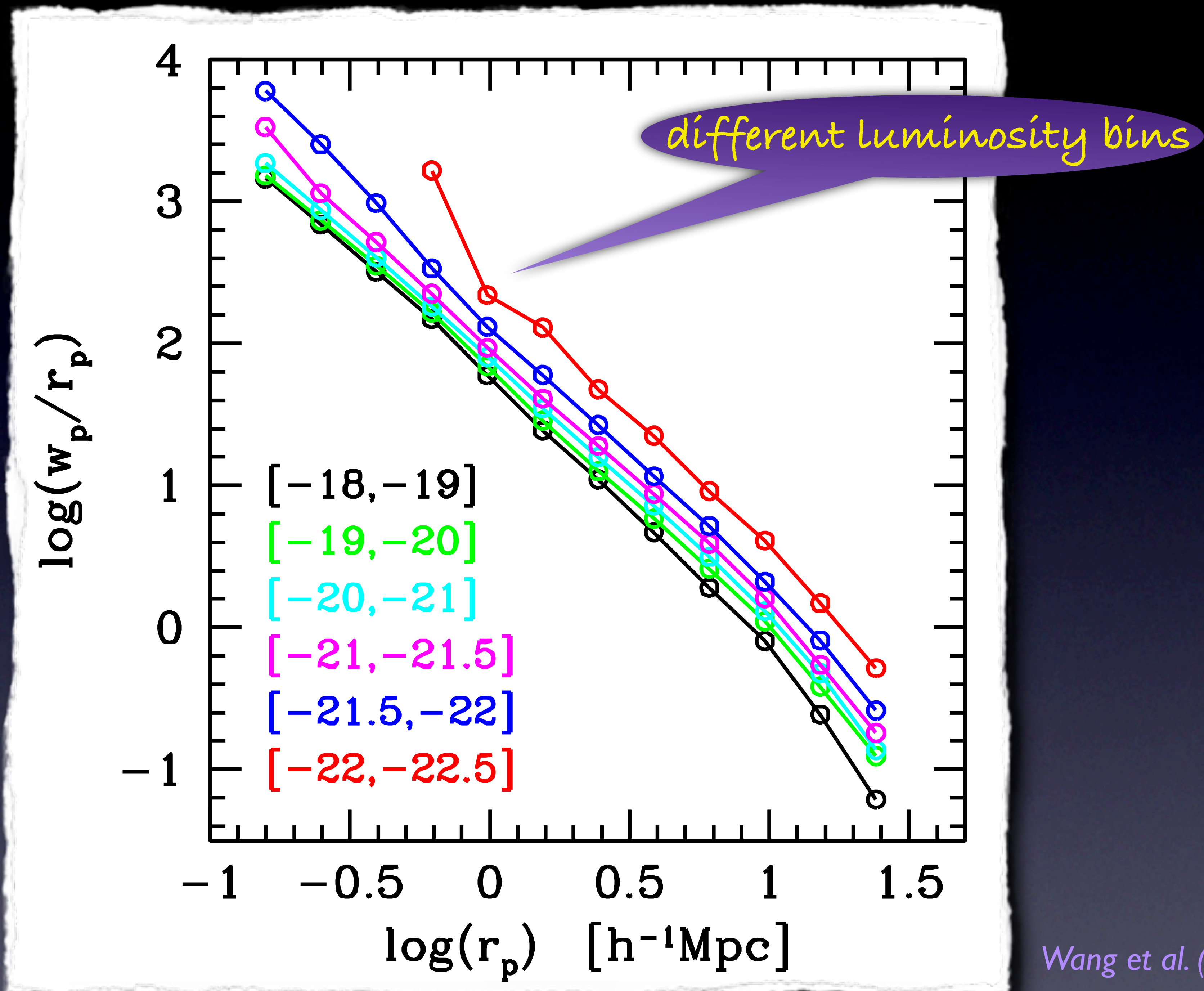
$\Omega_m = 0.30$
$\Omega_\Lambda = 0.70$
$\sigma_8 = 0.90$

WMAP3

$\Omega_m = 0.24$
$\Omega_\Lambda = 0.76$
$\sigma_8 = 0.74$

CAUTION: results depend on cosmology

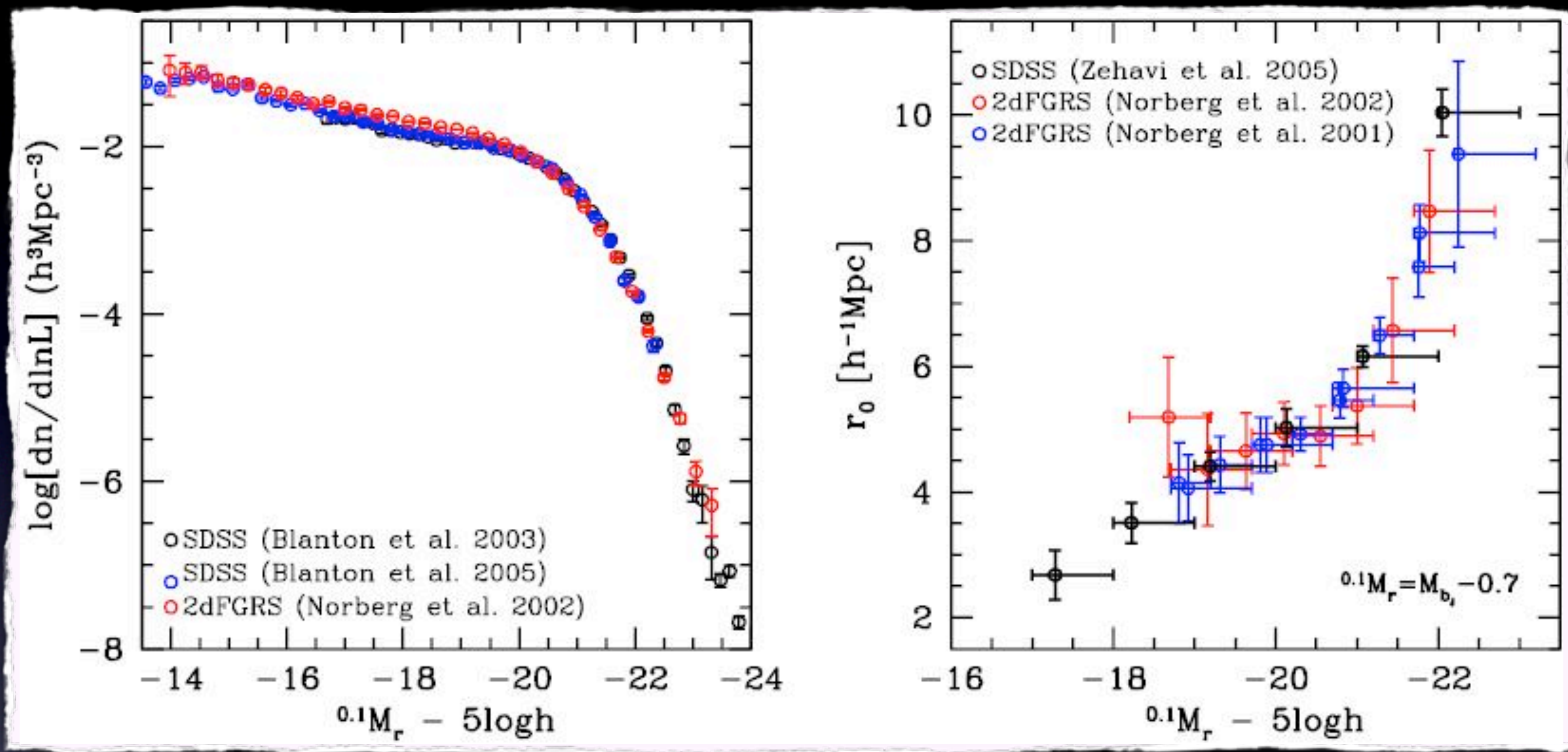
Galaxy Clustering: The Data



Wang et al. (2007)

More luminous galaxies are more strongly clustered

Luminosity & Correlation Functions

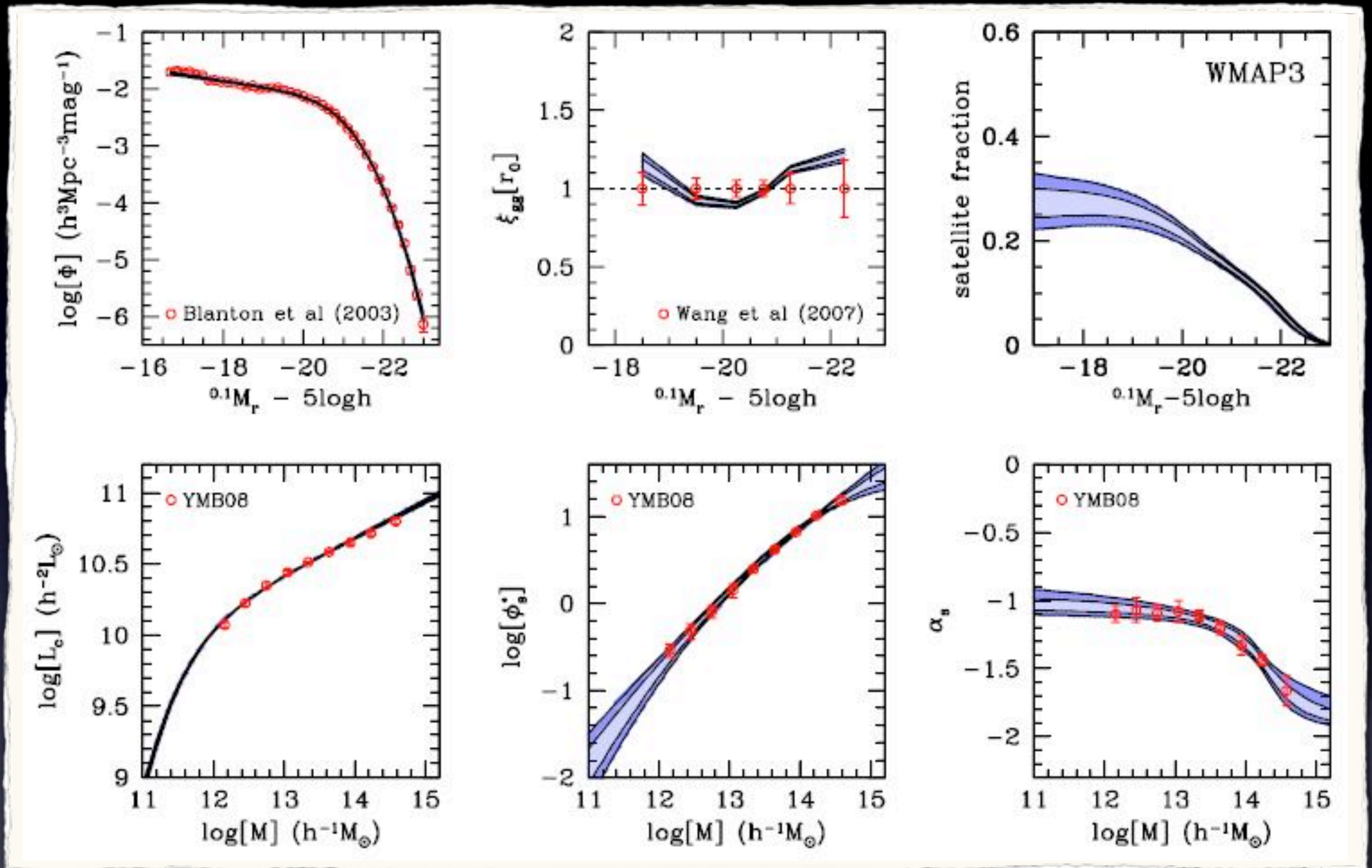


DATA: more luminous galaxies are more strongly clustered

LCDM: more massive halos are more strongly clustered

CONCLUSION: more luminous galaxies reside in more massive halos

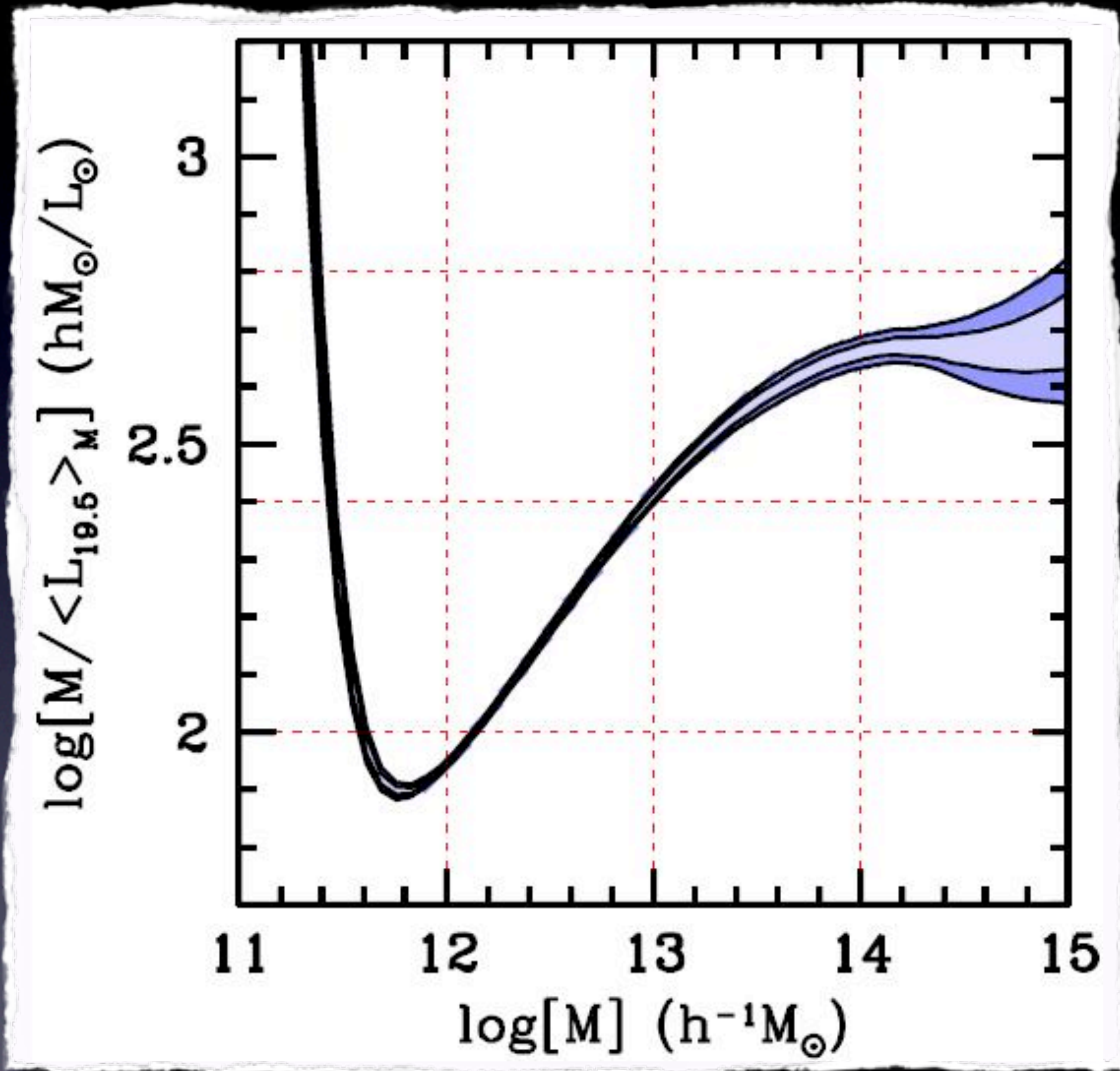
Results from MCMC Analysis



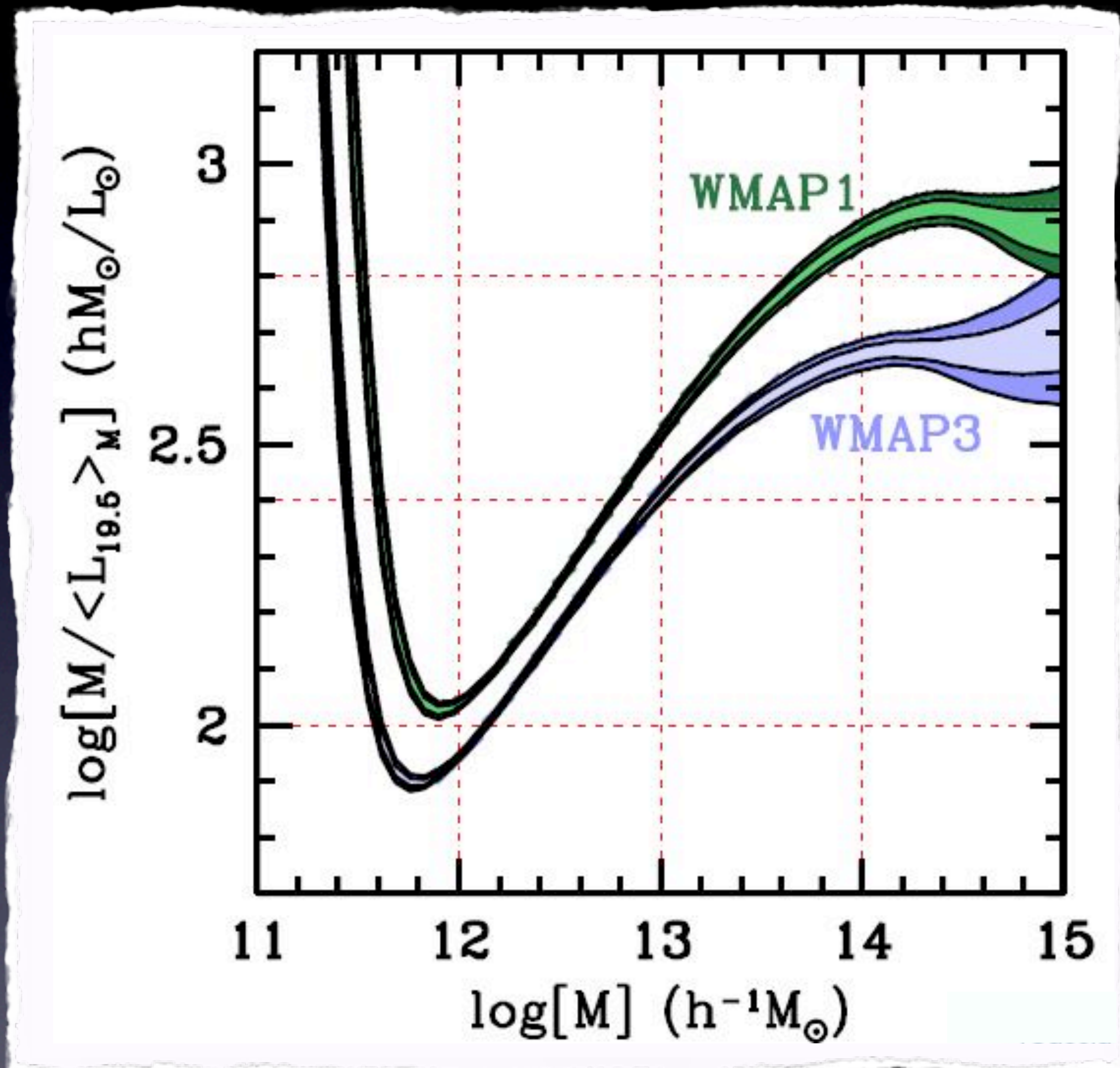
Cacciato, vdB et al. (2009)

- Model fits data extremely well with
- Same model in excellent agreement with results from SDSS galaxy group catalogue

Cosmology Dependence



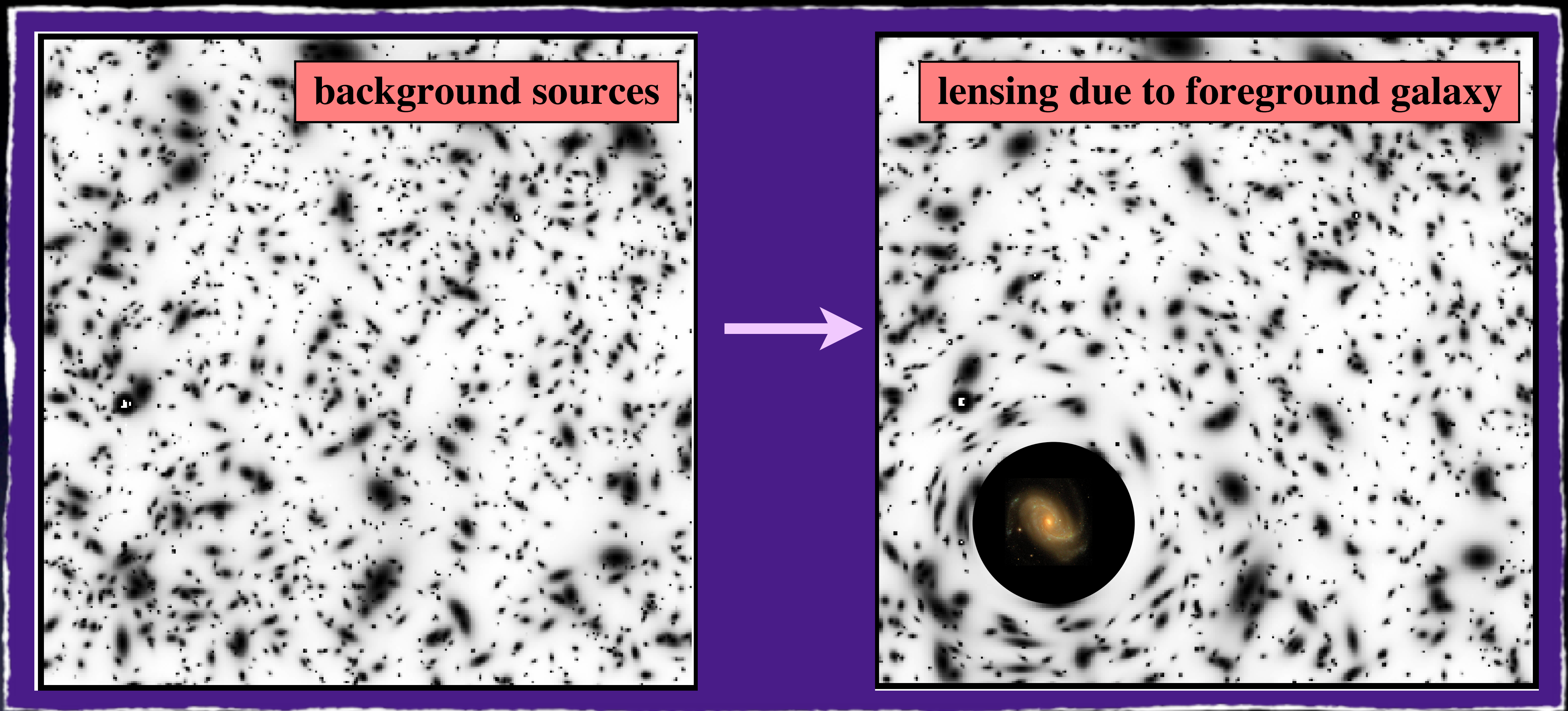
Cosmology Dependence



Galaxy-Galaxy Lensing

Galaxy-Galaxy Lensing

The mass associated with galaxies lenses background galaxies



Lensing causes correlated ellipticities, the tangential shear, $\gamma_{\rm t}$, which is related to the excess surface density, $\Delta\Sigma$, according to

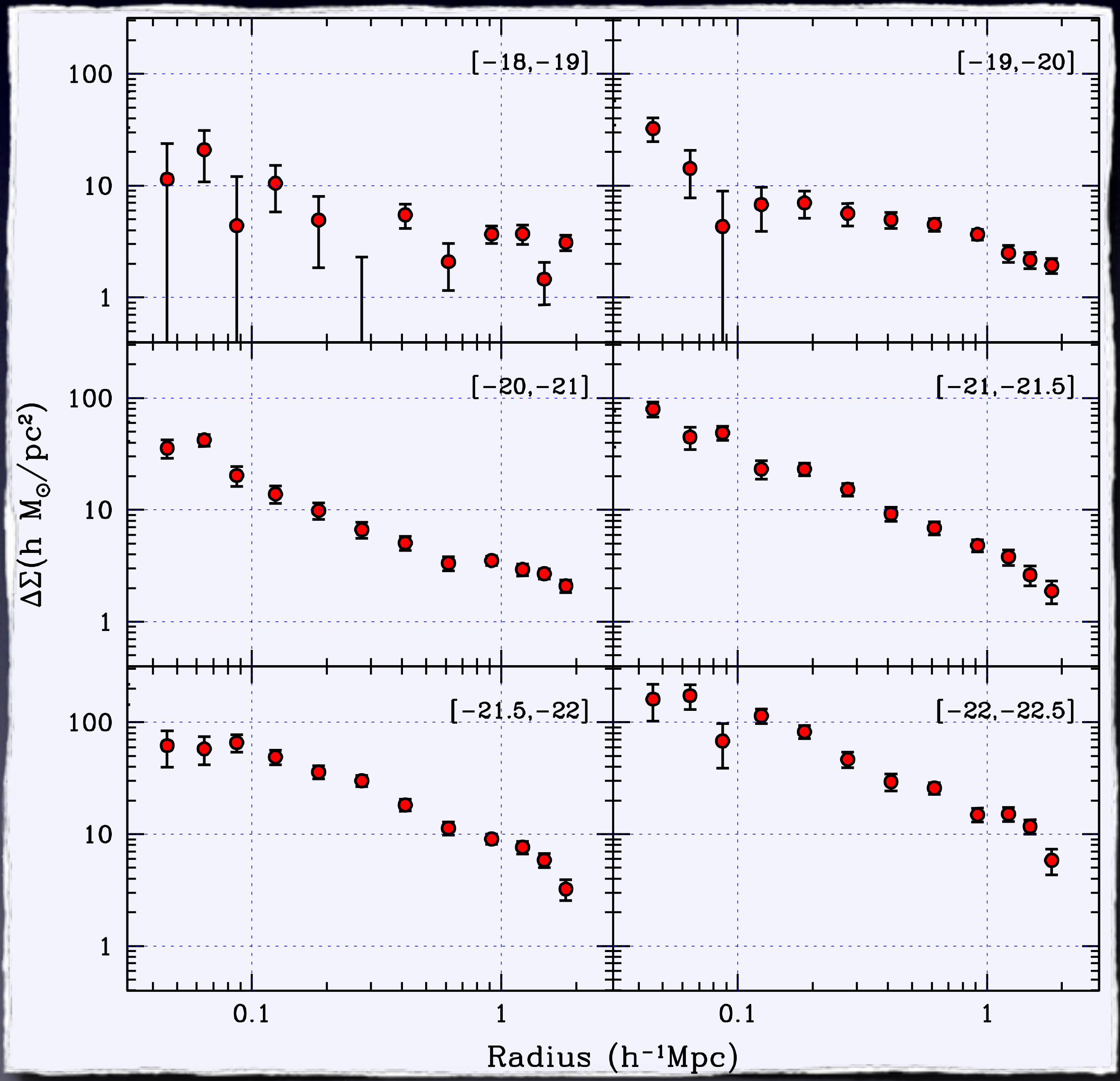
$$\gamma_{\rm t}(R)\Sigma_{\rm crit} = \Delta\Sigma(R) = \bar{\Sigma}(<R) - \Sigma(R)$$

$\Delta\Sigma$ is line-of-sight projection of galaxy-matter cross correlation

$$\Sigma(R) = \bar{\rho}\int_0^{D_{\rm s}} [1 + \xi_{\rm g,dm}(r)]\, {\rm d}\chi$$

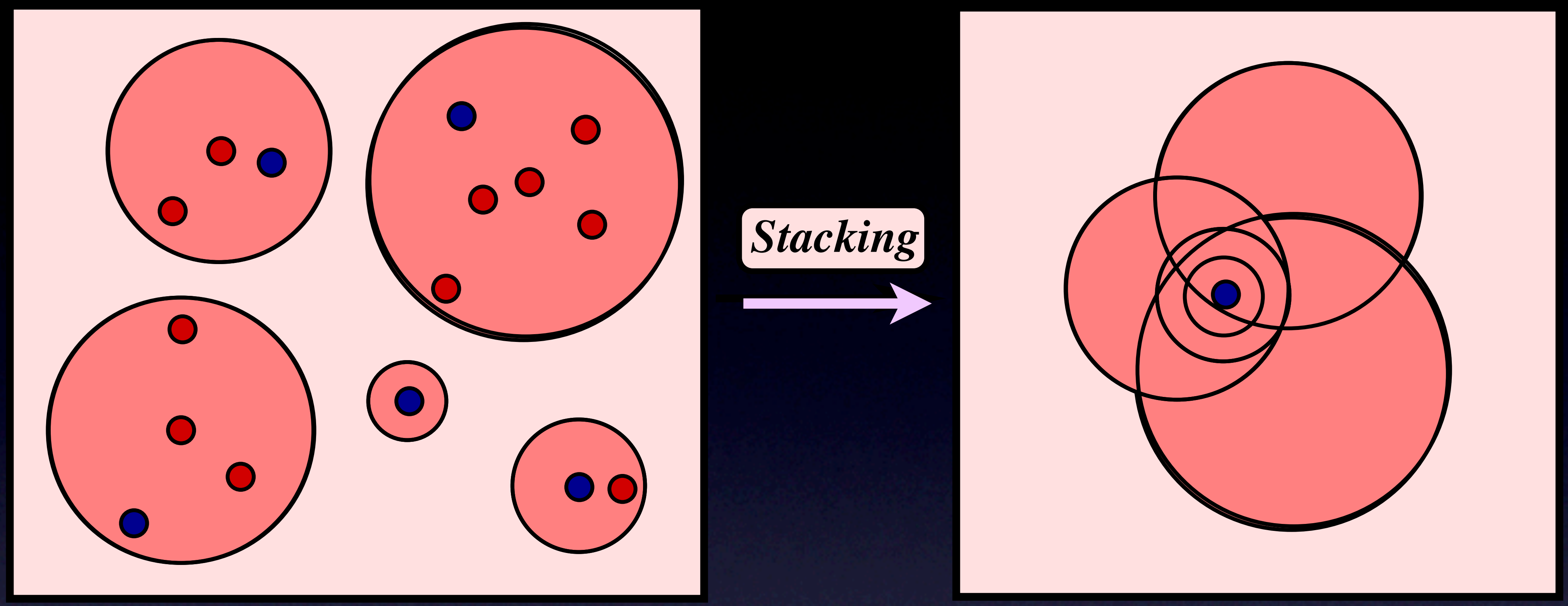
Galaxy-Galaxy Lensing: The Data

- Number of background sources per lens is limited
- Measuring shear with sufficient S/N requires stacking of many lenses
- $\Delta\Sigma(R|L_1, L_2)$ has been measured using the SDSS by Mandelbaum et al. (2006), using different bins in lens-luminosity



Mandelbaum et al. (2006)

How to interpret the signal?



Because of stacking the lensing signal is difficult to interpret

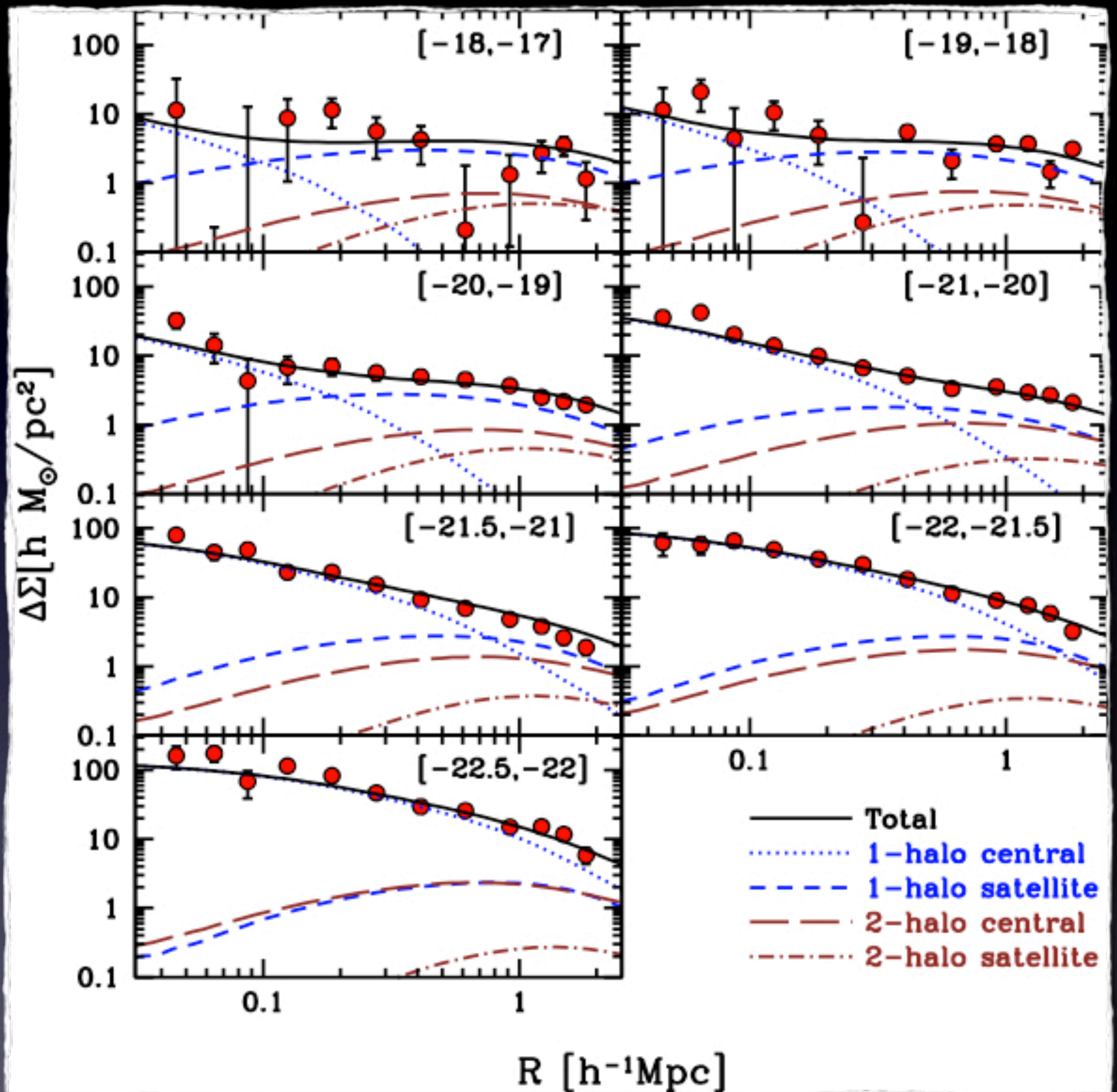
In order to model the data, what is required is:

$P_{\rm cen}(M|L)$ $P_{\rm sat}(M|L)$ $f_{\rm sat}(L)$

These can all be computed from the CLF...

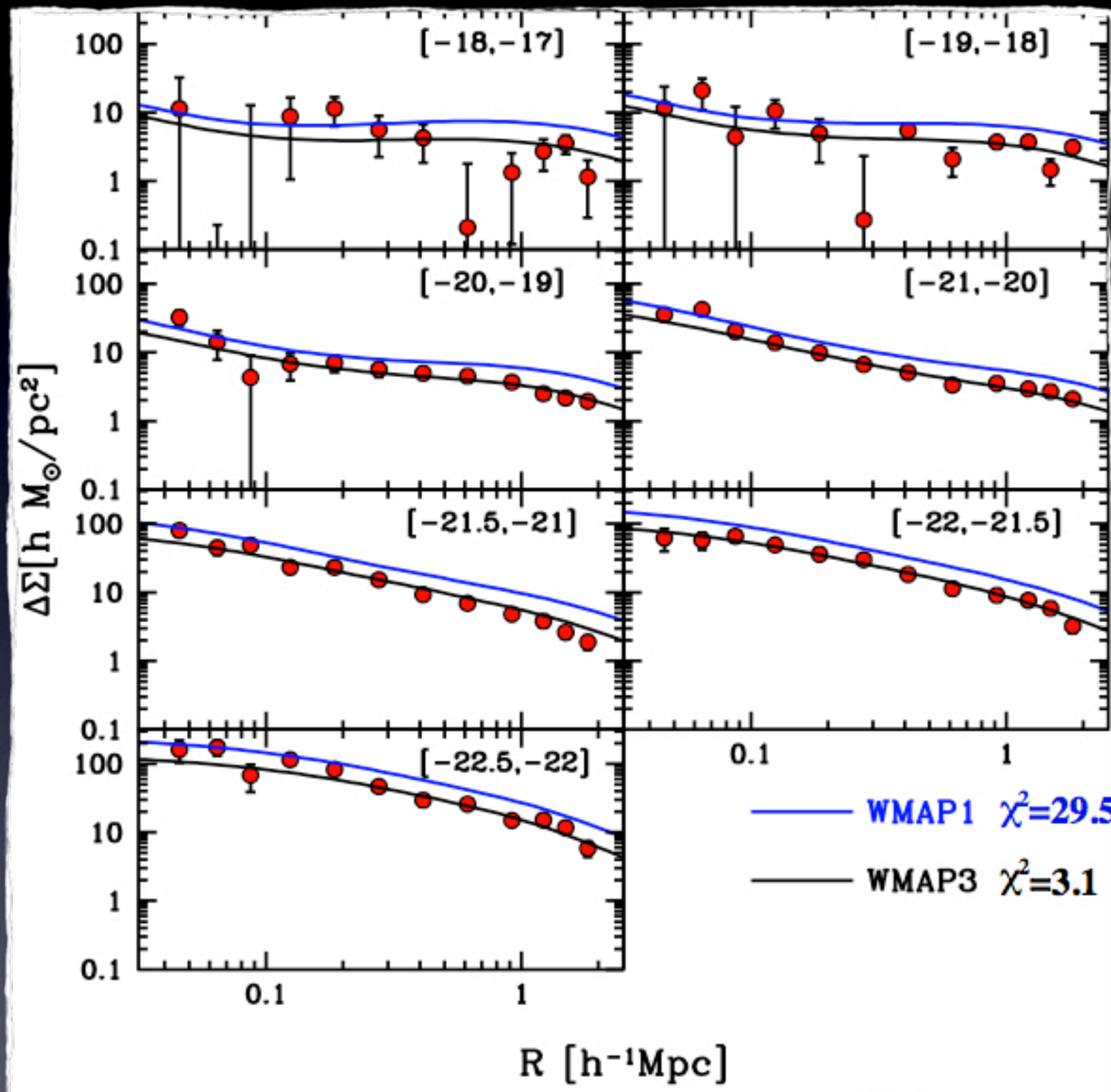
For a given $\Phi(L|M)$ we can predict the lensing signal $\Delta\Sigma(R|L_1, L_2)$

Galaxy-Galaxy Lensing: Results

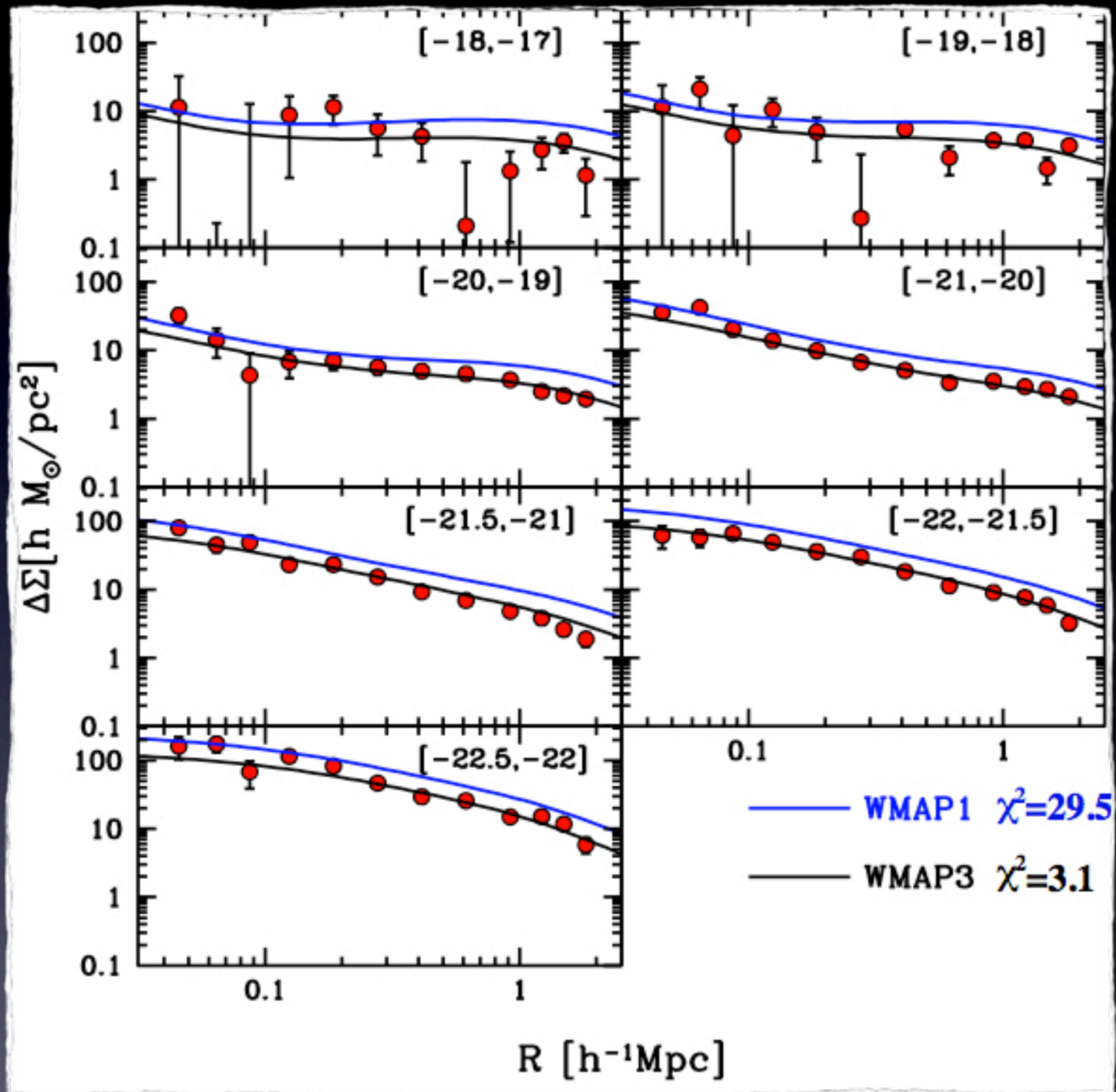


NOTE: this is not a fit, but a prediction based on CLF

Galaxy-Galaxy Lensing: Results



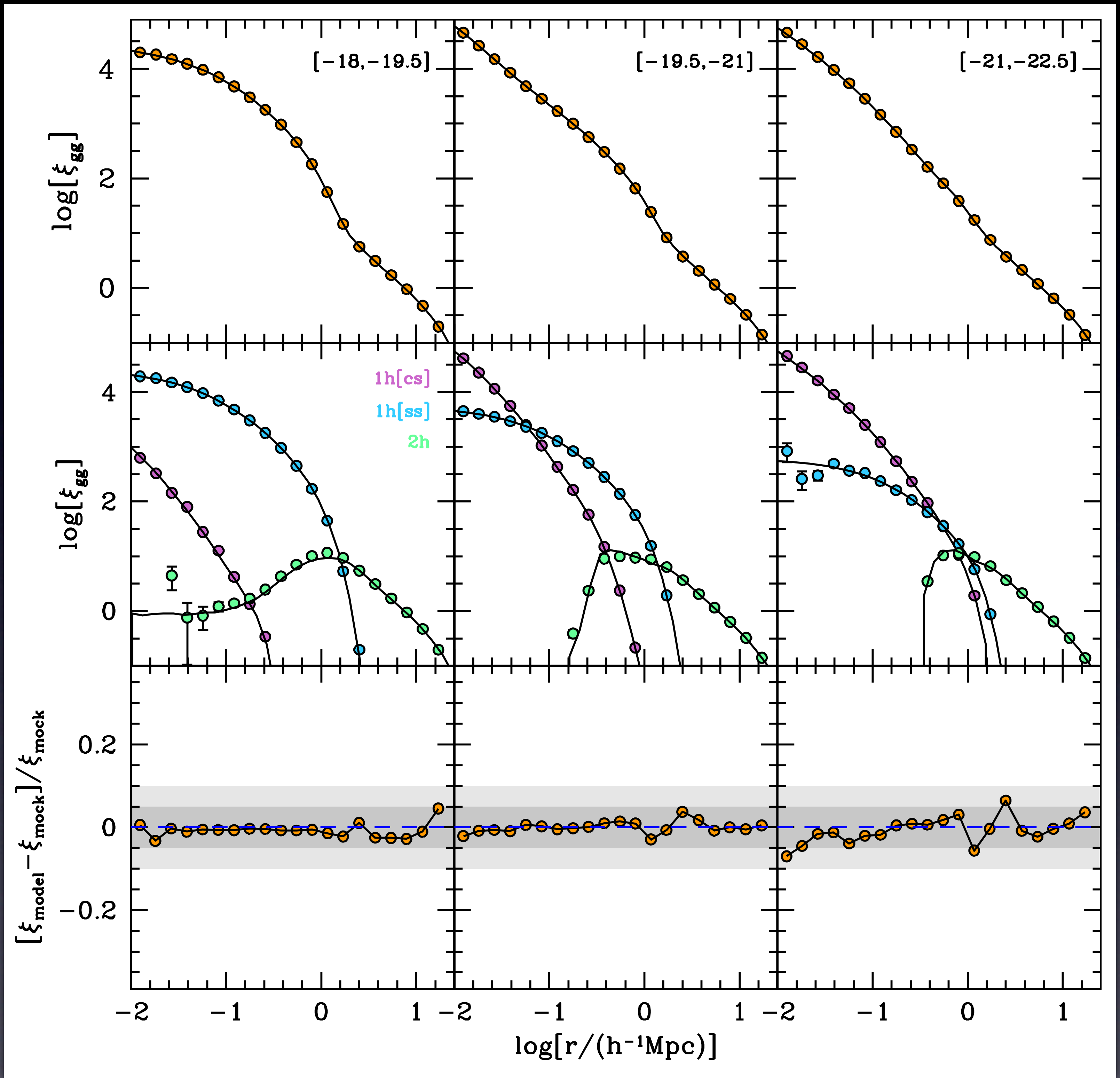
Galaxy-Galaxy Lensing: Results



Combination of clustering & lensing can constrain cosmology!!!

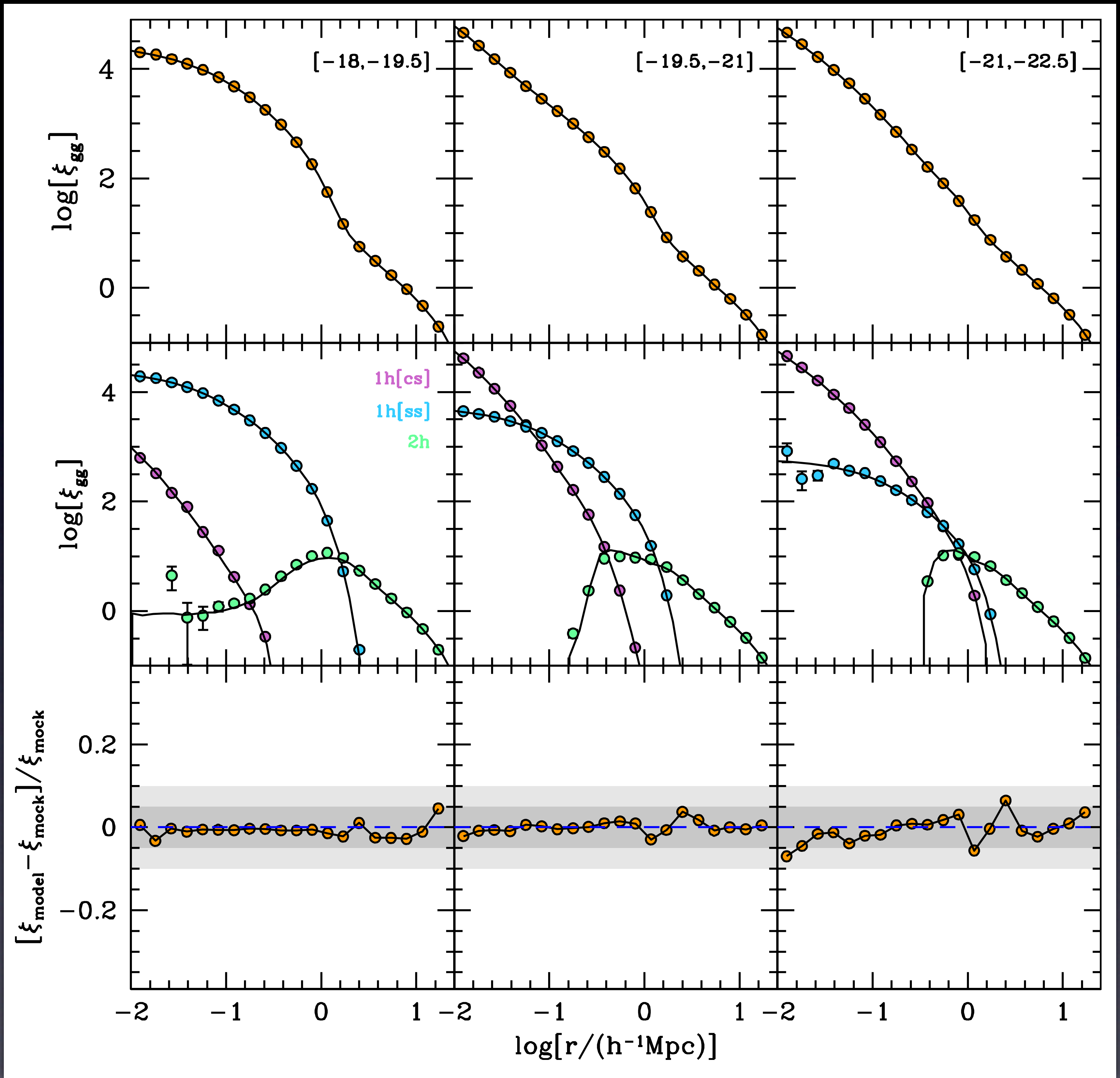
Constraining Cosmology

Comparison with Mock Catalogues



- Run numerical simulation of structure formation (DM only)
- Identify DM haloes, and populate them with galaxies using a model for the CLF.
- Compute galaxy-galaxy correlation functions for various luminosity bins.
- Use analytical model to compute the same, using the same model for the CLF.

Comparison with Mock Catalogues



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- Identify DM haloes, and populate them with galaxies using a model for the CLF.
- Compute galaxy-galaxy correlation functions for various luminosity bins.
- Use analytical model to compute the same, using the same model for the CLF.

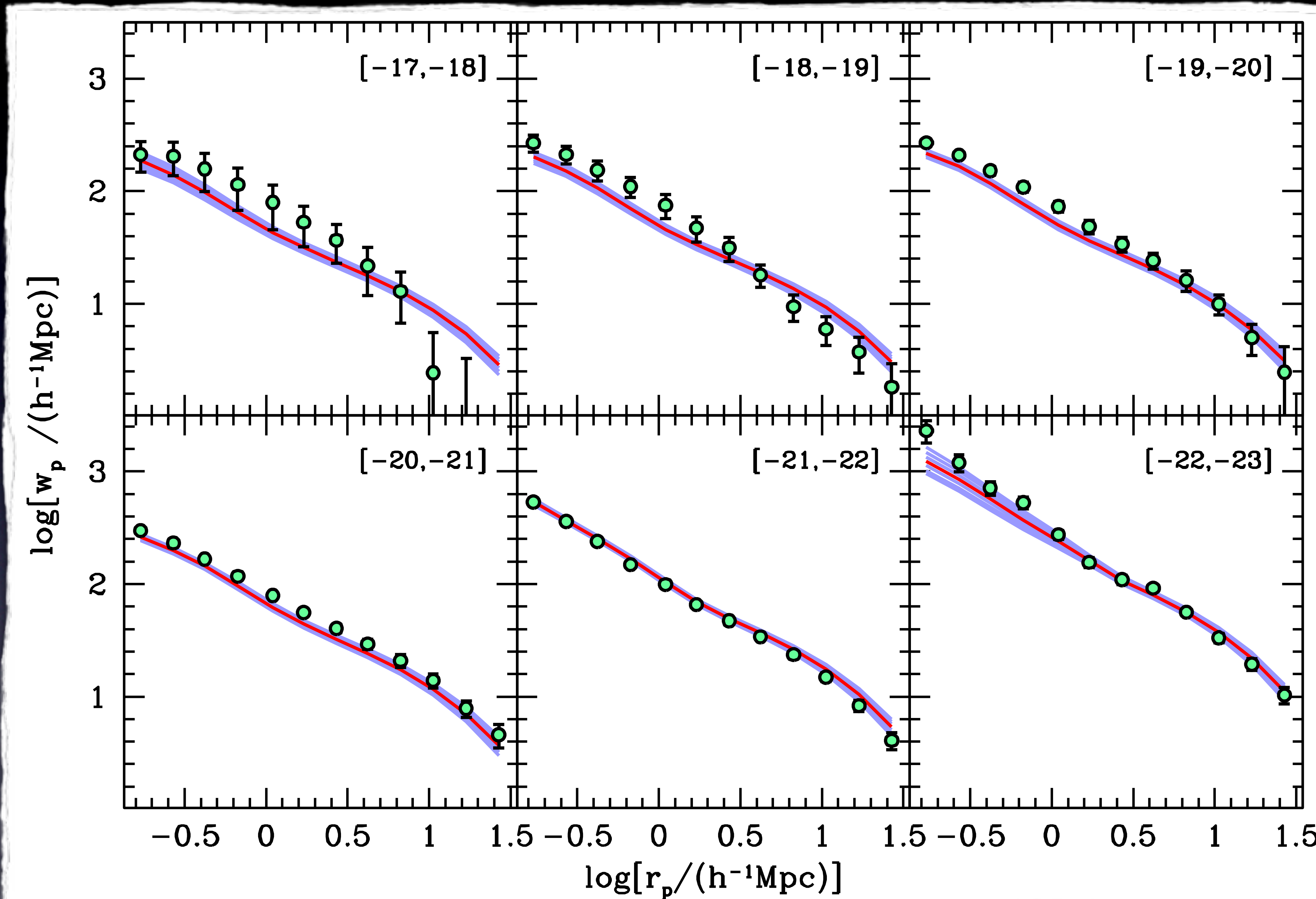
Our model is accurate to better than ~3%

Fiducial Model

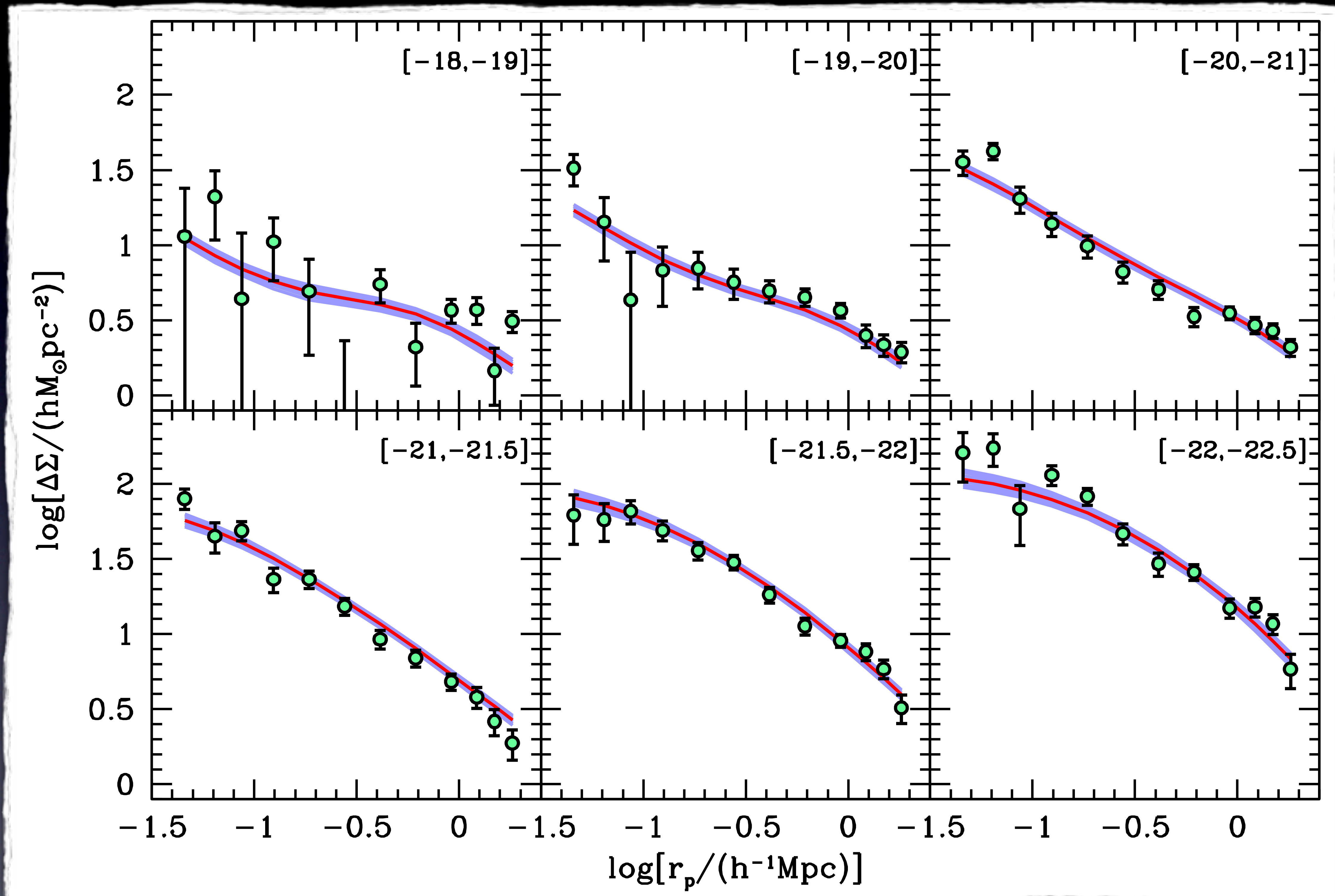
- Total of 14 free parameters:
  - 9 parameters to describe CLF
  - 5 cosmological parameters; $\Omega_{\rm m}, \Omega_{\rm b}, \sigma_8, n_{\rm s}, h$

  Total of 176 data points.
- WMAP7 priors on spectral index, baryon density & hubble parameter.
- Dark matter haloes follow NFW profile.
- Radial number density distribution of satellites follows that of dark matter particles.
- Halo mass function and halo bias function of Tinker et al. (2009,2010).

Results: Clustering Data

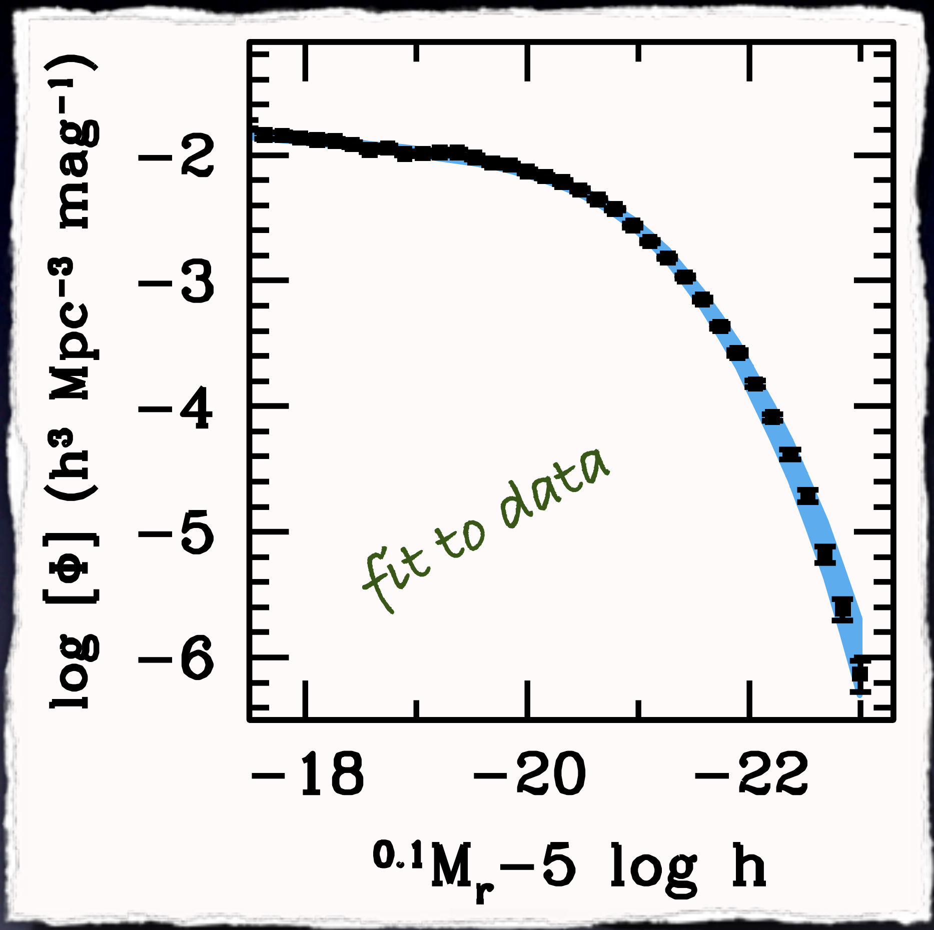


Results: Lensing Data

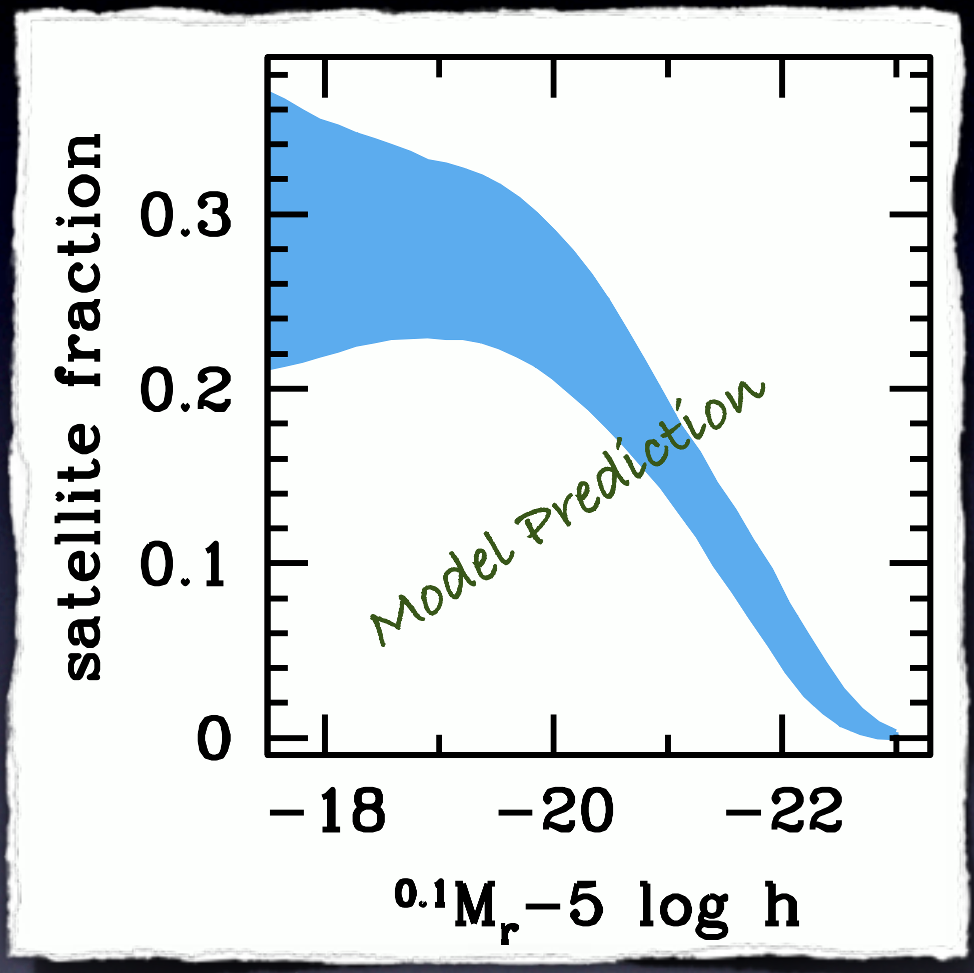


Luminosity Function & Satellite Fractions

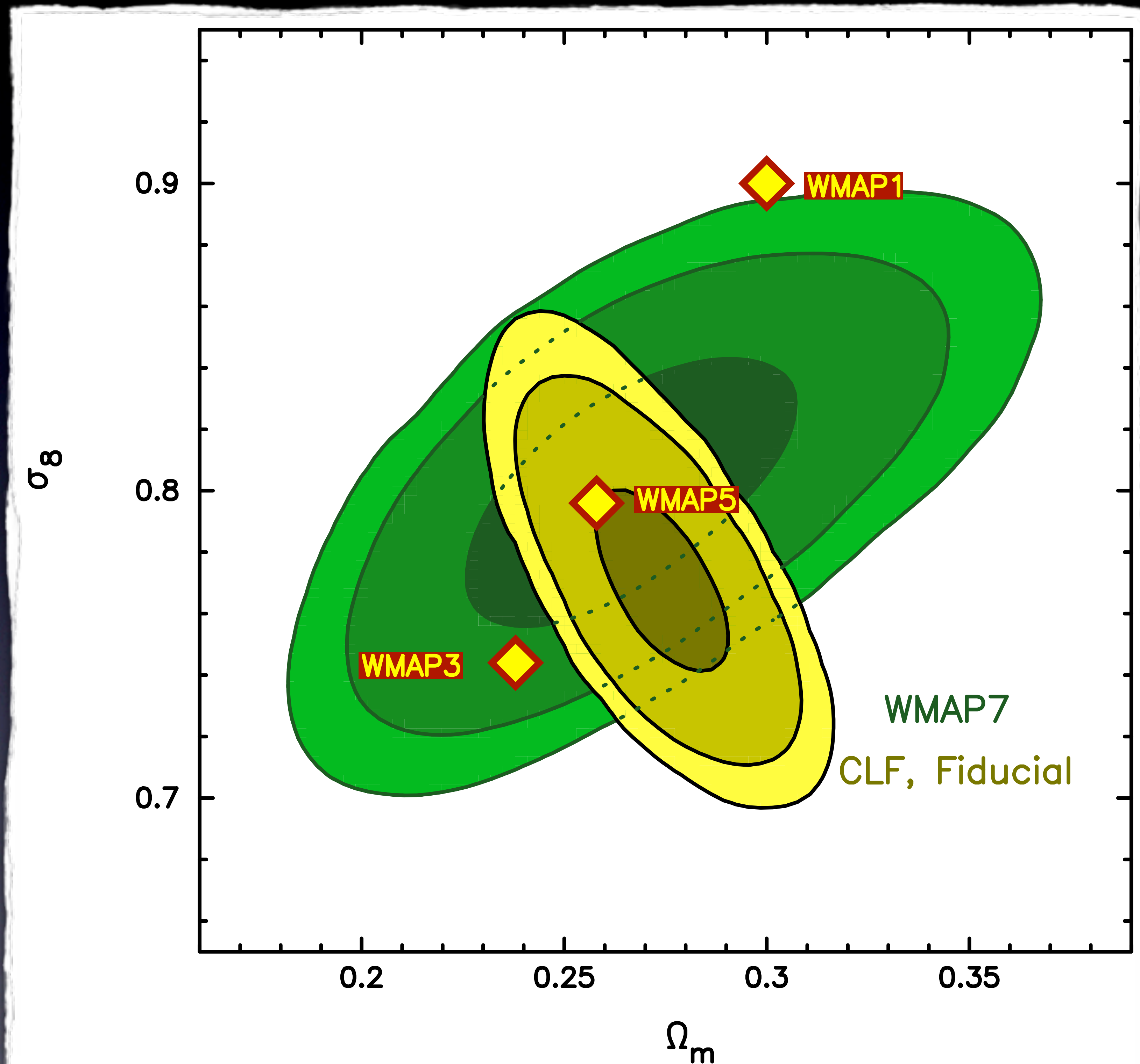
Luminosity Function



Satellite Fractions



Cosmological Constraints



Conclusions

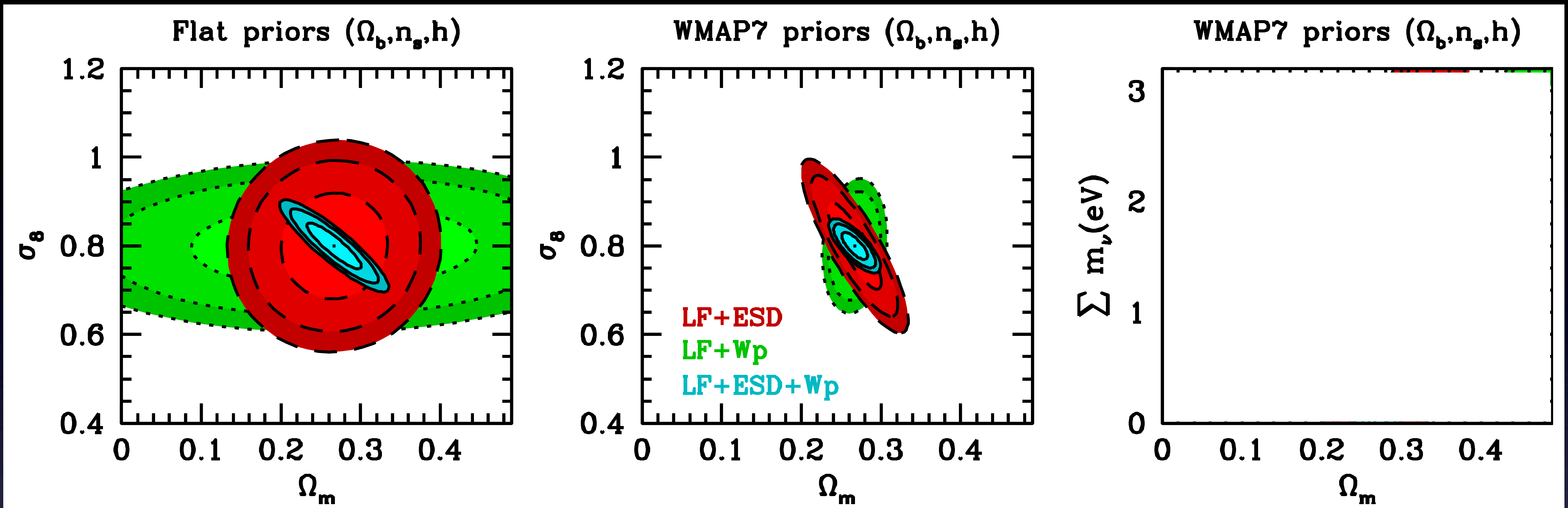
- Recent years have seen enormous progress in establishing the galaxy-dark matter connection, including its scatter!
- Different methods (group catalogues, satellite kinematics, galaxy-galaxy lensing, clustering & abundance matching) now all yield results in good mutual agreement.
- Combination of galaxy clustering and galaxy-galaxy lensing can constrain cosmological parameters.
    - This method is complementary to and competitive with BAO, cosmic shear, SNIa & cluster abundances.
    - Preliminary results are in excellent agreement with CMB constraints from WMAP7
    - Forecasting for constraints on neutrino mass, WDM and modified gravity very promising.

The End

Name: Miloš van den Bosch

Hobby: everything galaxy formation

Fishing for Information



$$\ln\mathcal{L} = -\frac{1}{2}(x-\mu)^T\, C^{-1}\,(x-\mu) \qquad \mathcal{F}_{ij} = -\frac{\partial^2\mathcal{L}}{\partial\theta_i\partial\theta_j} \qquad \mathcal{C}_{ij} = \mathcal{F}_{ij}^{-1}$$

x = data	θ = model parameters
μ = model prediction	$\mathcal{F}$ = Fisher Matrix
$\mathcal{L}$ = likelihood of model	$\mathcal{C}$ = covariance of Posterior prob distribution

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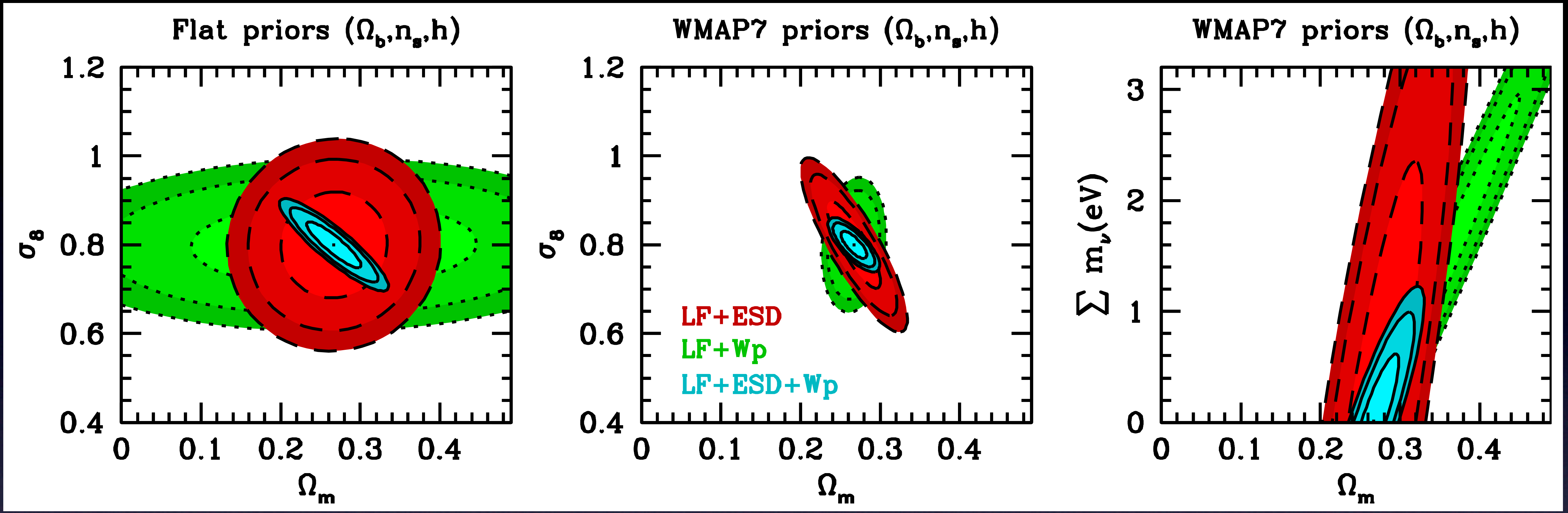

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