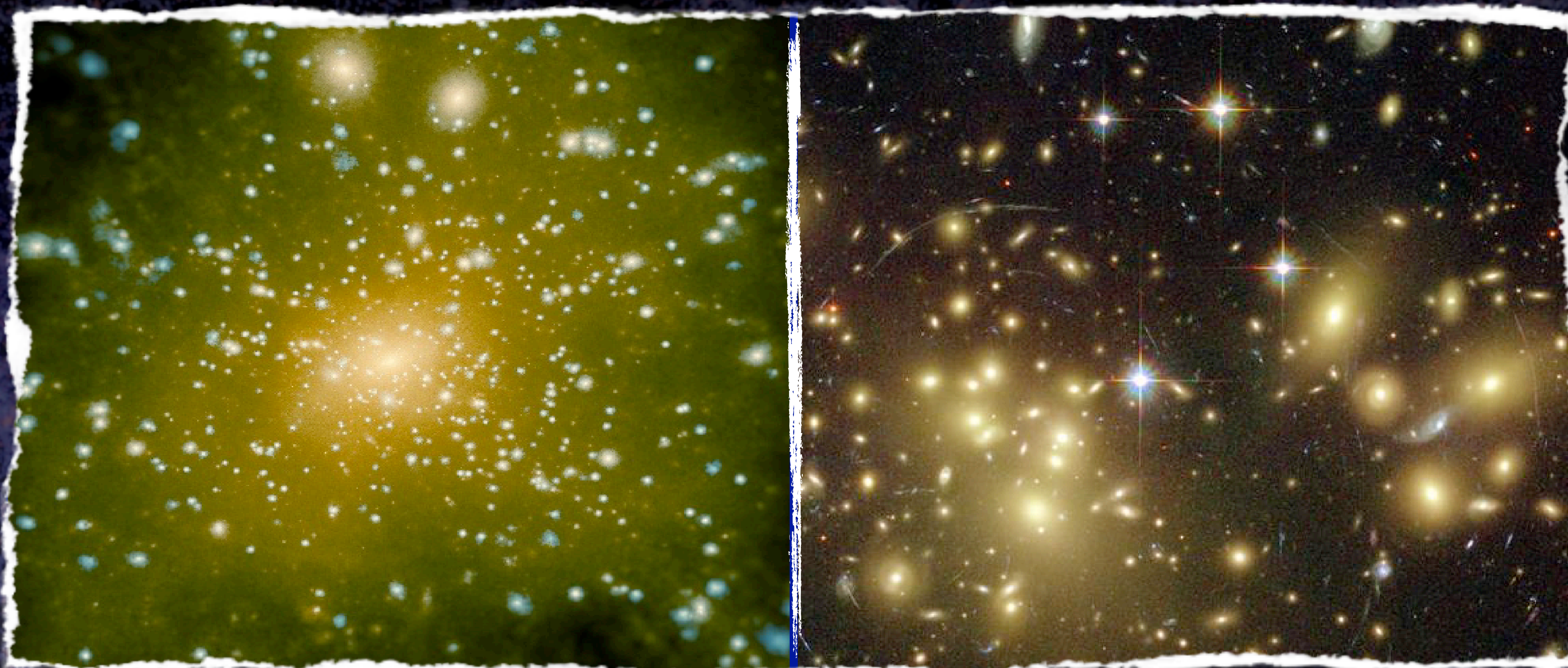
The Galaxy-Dark Matter Connection

...Shedding Light on the Dark...



Frank van den Bosch

University of Utah

In collaboration with:

Surhud More (KICP), Marcello Cacciato (HU)

Houjun Mo (UMass), Xiaohu Yang (SHAO)

The Standard Paradigm

Hot Big Bang

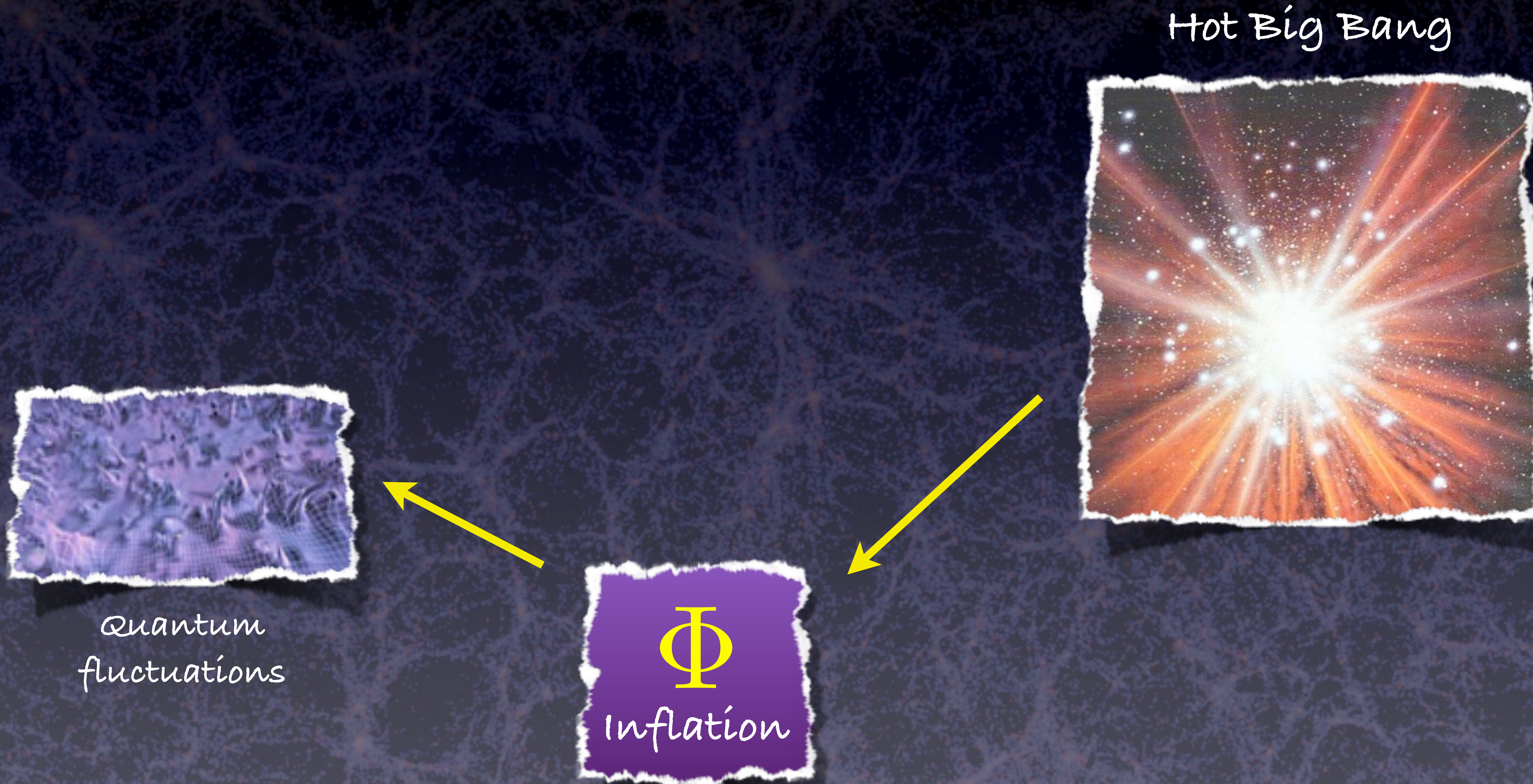
The Standard Paradigm

Hot Big Bang

Φ

Inflation

The Standard Paradigm



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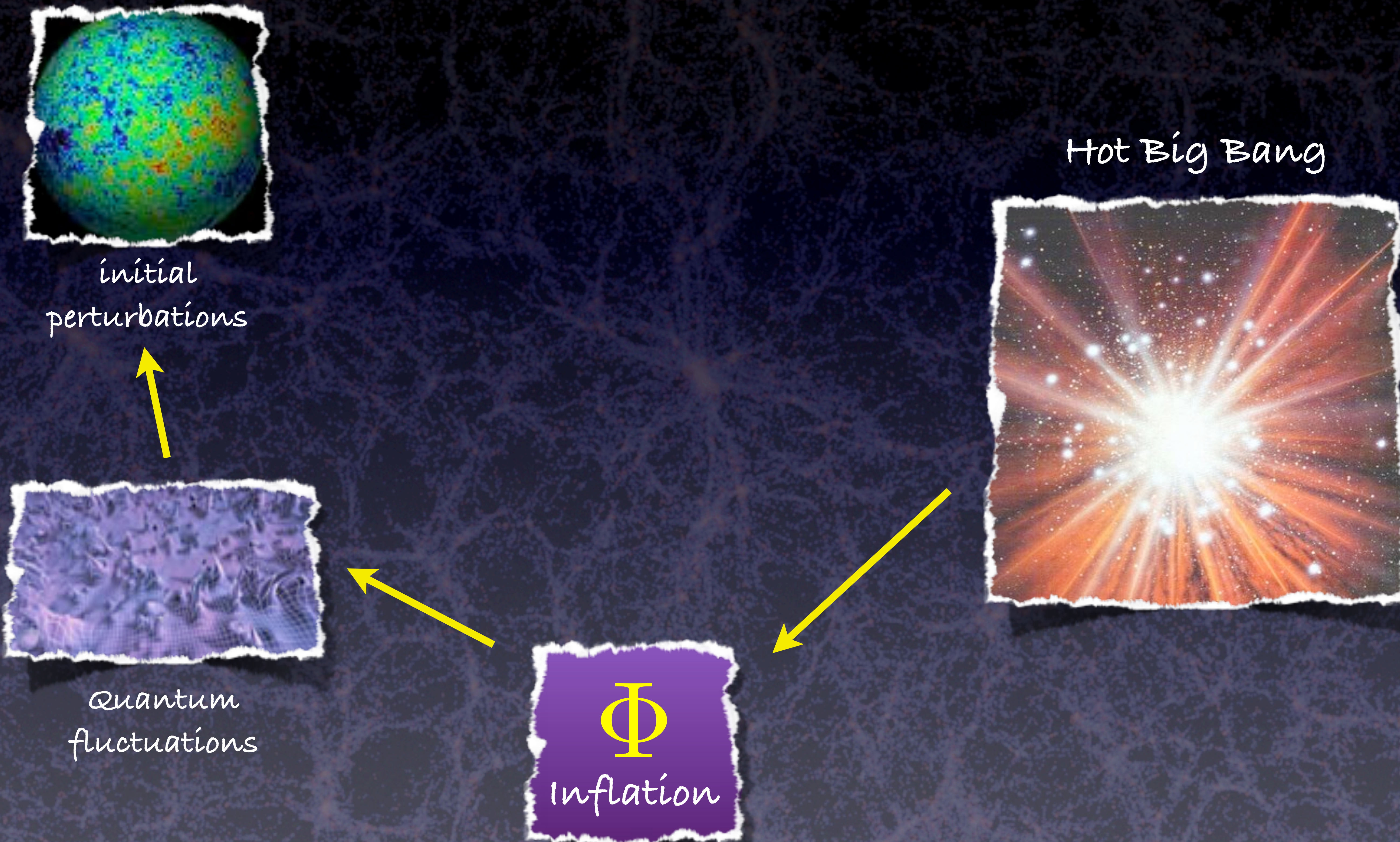

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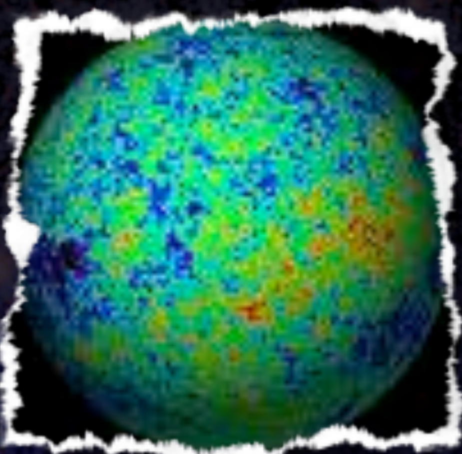
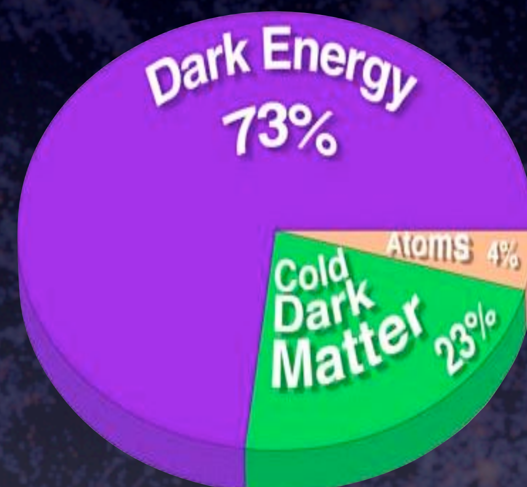


initial perturbations



Hot Big Bang

Quantum fluctuations

Φ

Inflation

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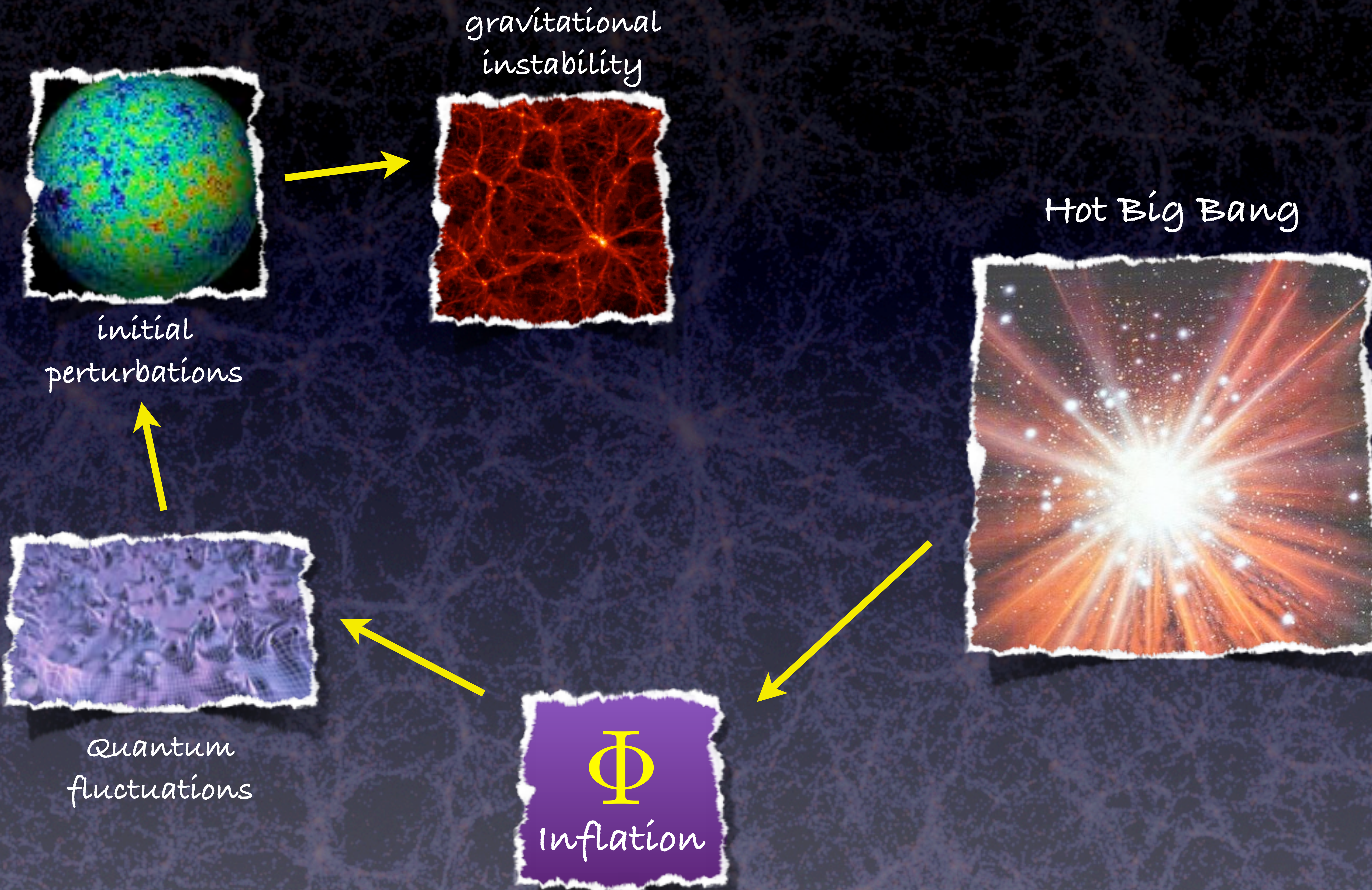
The Standard Paradigm



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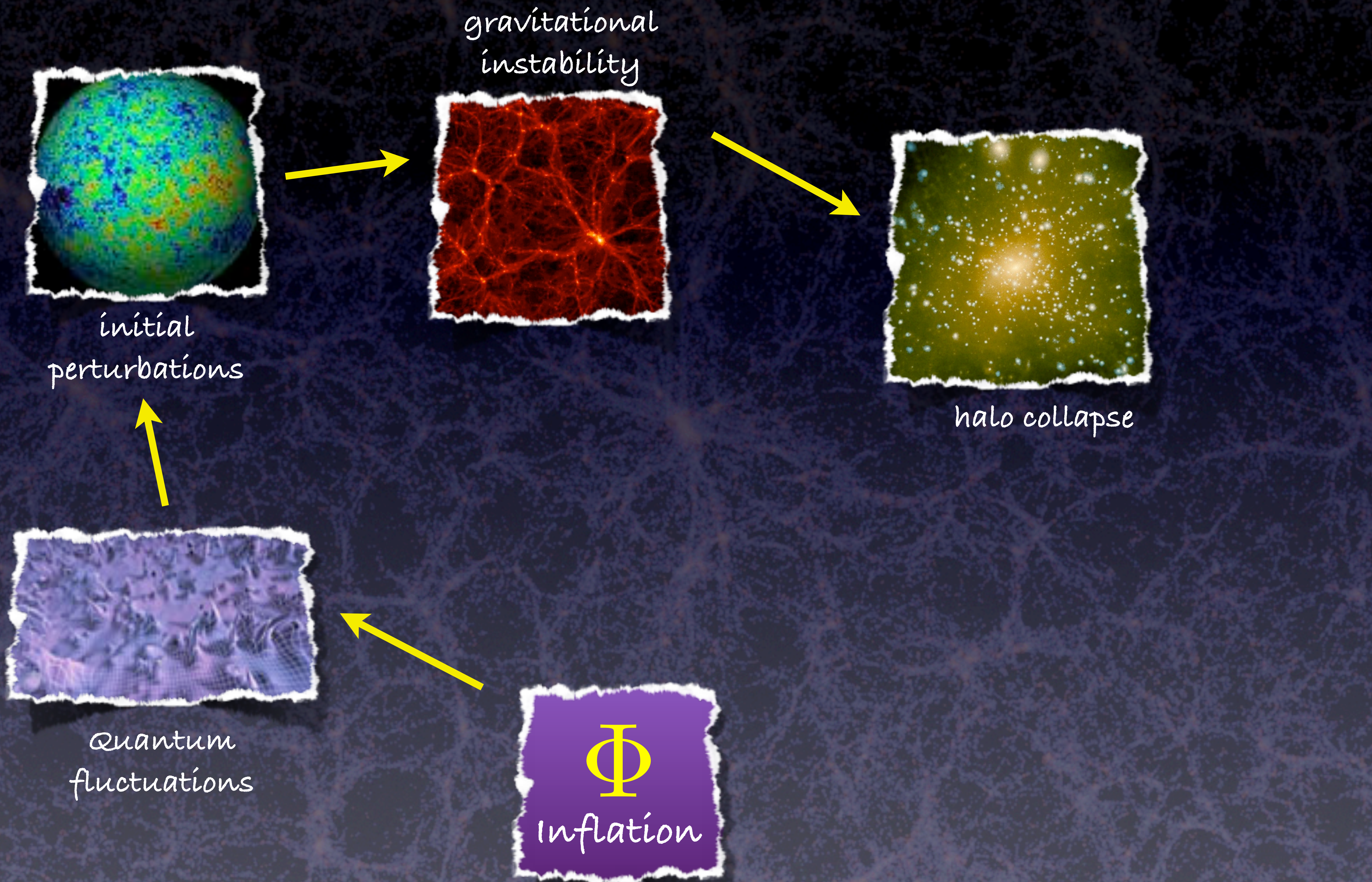

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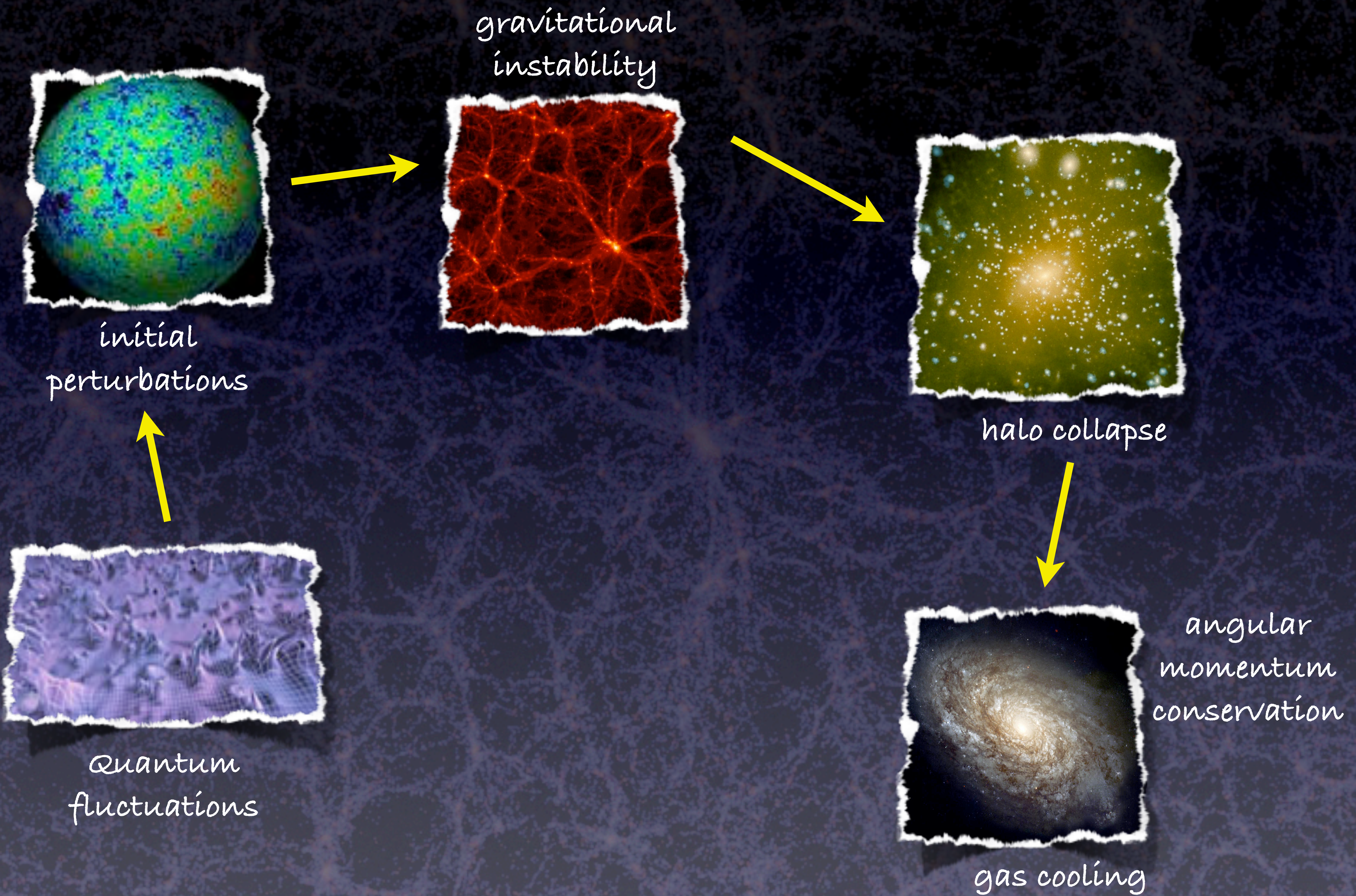

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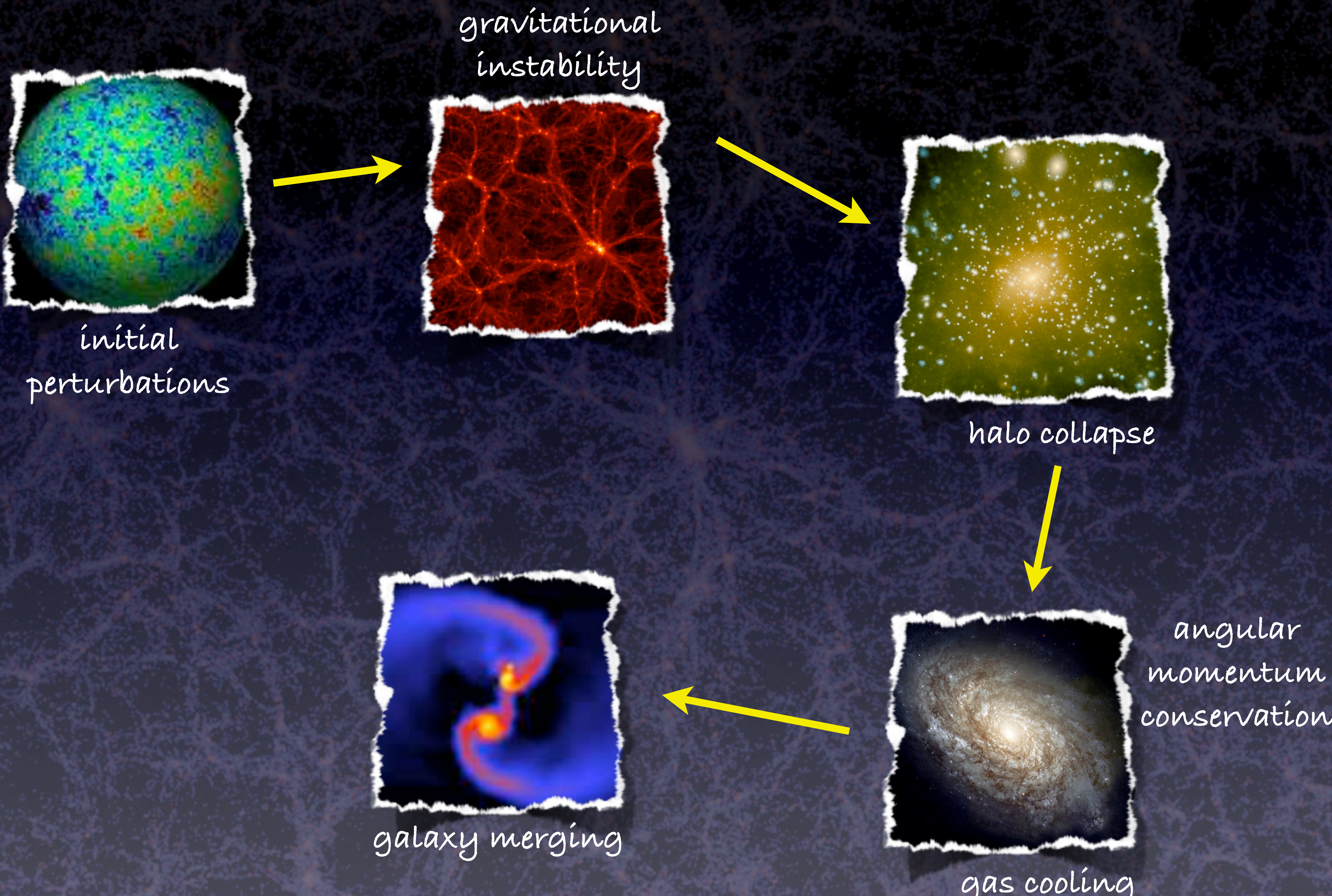
The Standard Paradigm



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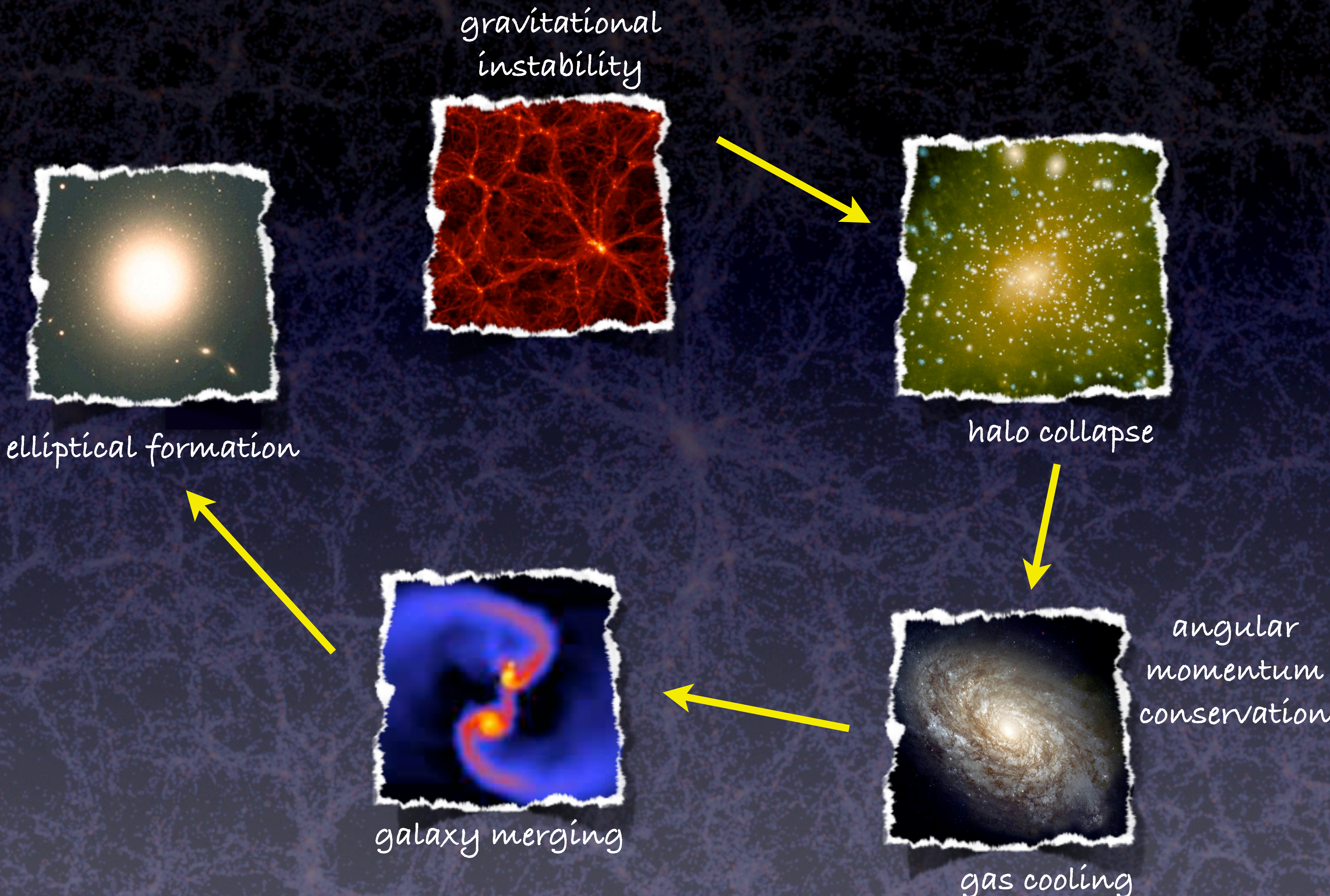
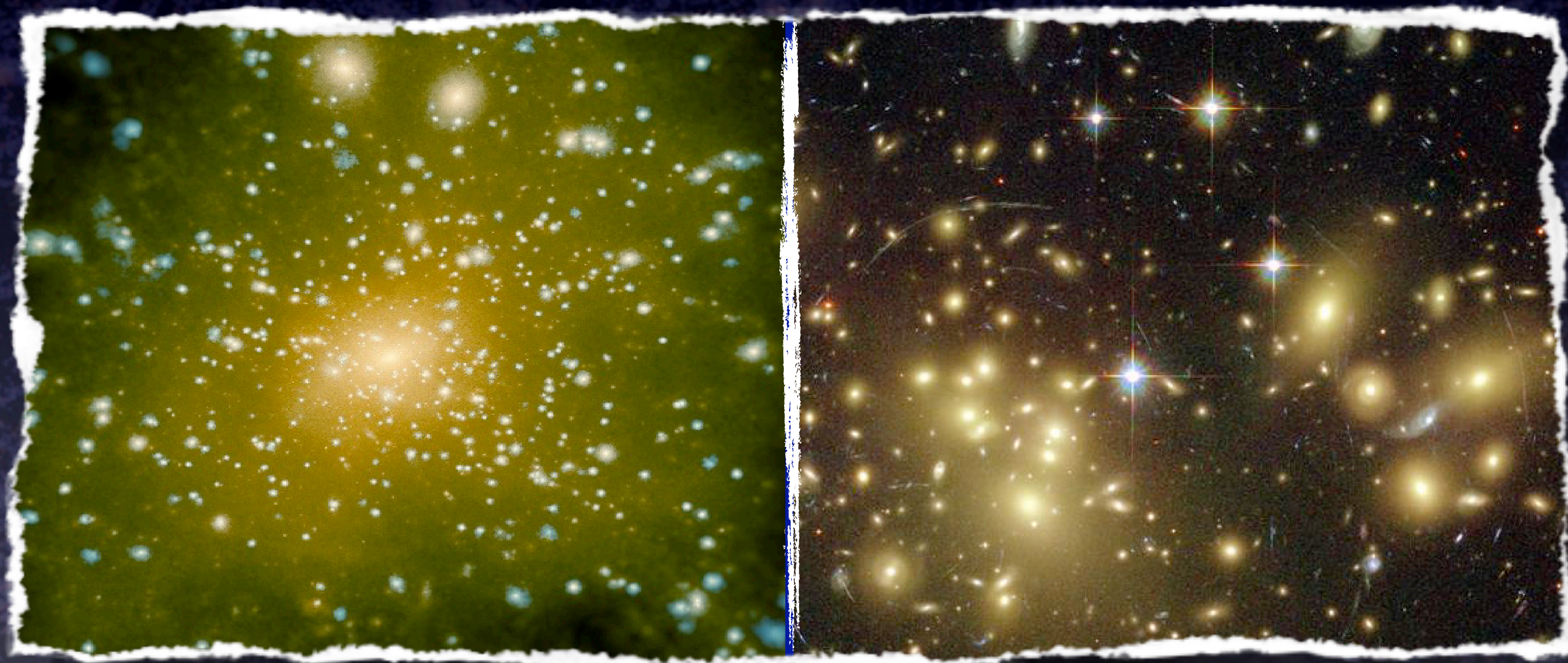


Introduction: Motivation & Goal

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

Statistical Formalism

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.

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

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

$$\langle N \rangle_M = \int_{L_{\rm min}}^{\infty} \Phi(L|M) \mathrm{d}L$$

- 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

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Galaxy luminosity function

Halo mass function

- Describes occupation statistics of dark matter haloes
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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.

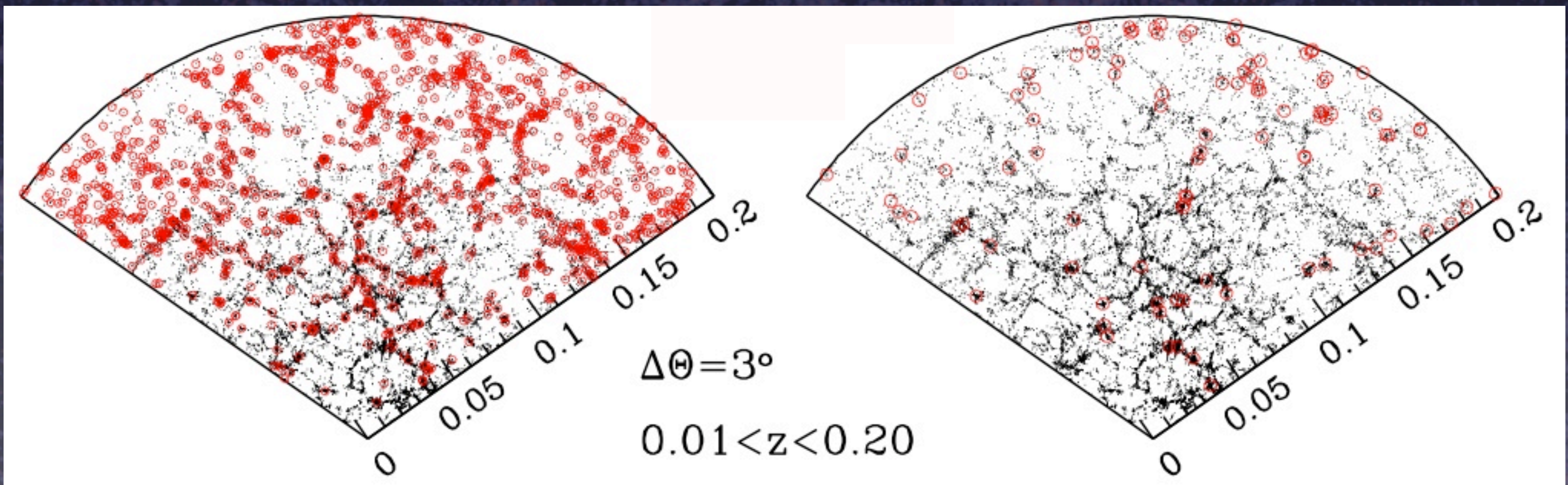
Galaxy Group Catalogues

Constructing Galaxy Group Catalogues

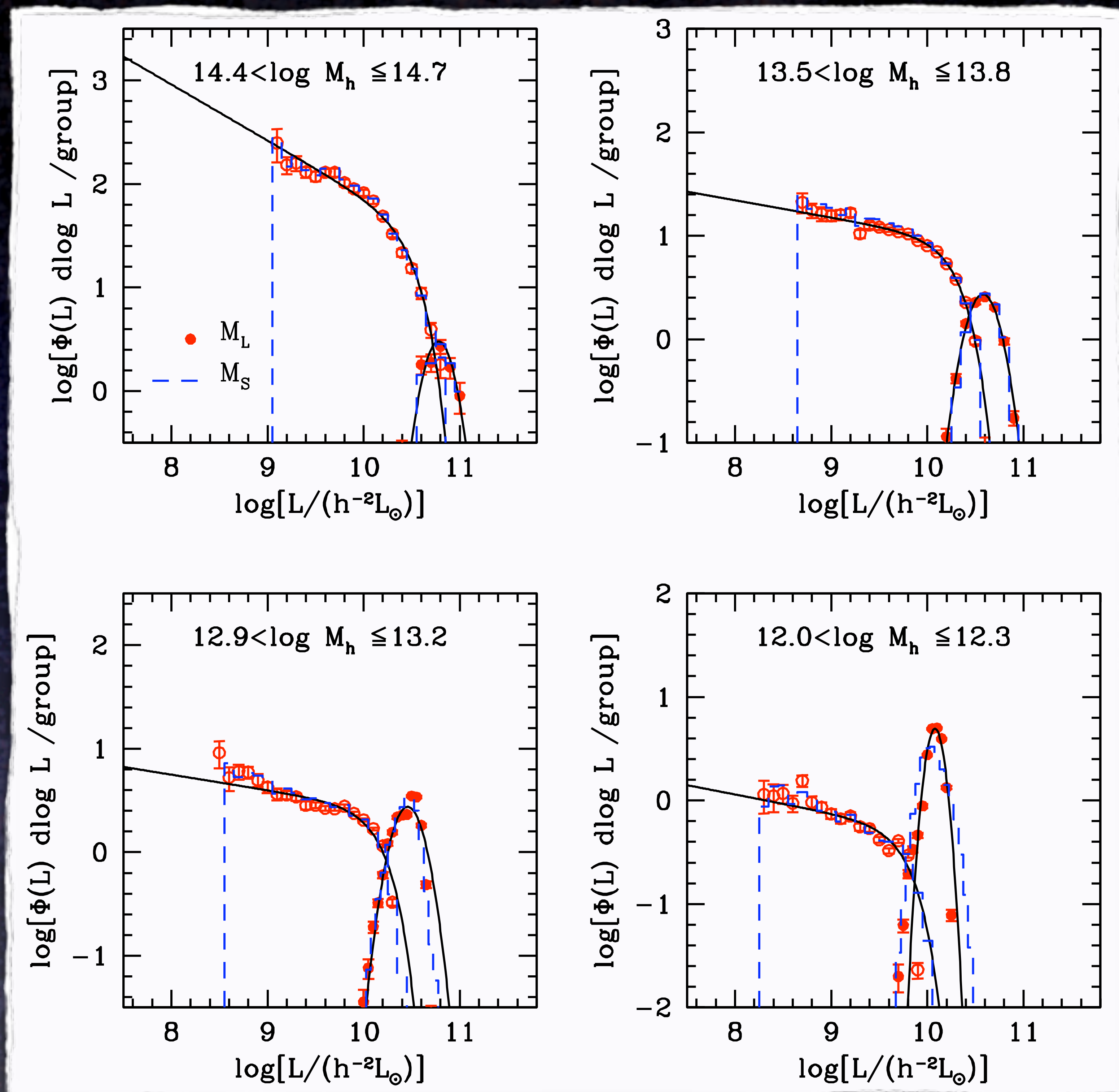
We have developed a new, iterative group finder which uses an adaptive filter modeled after halo virial properties.

- 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



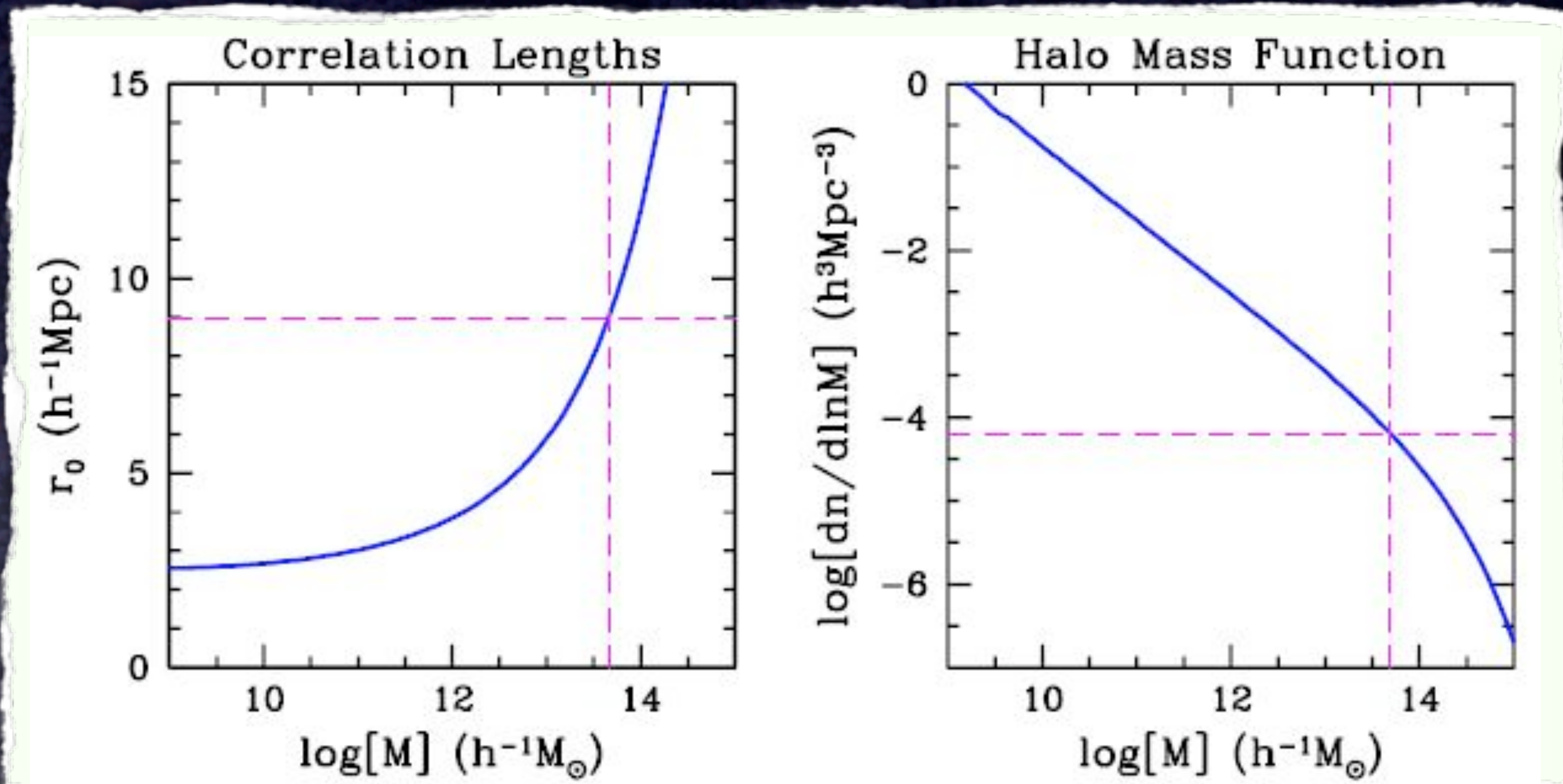
Yang, Mo & vdB (2008)

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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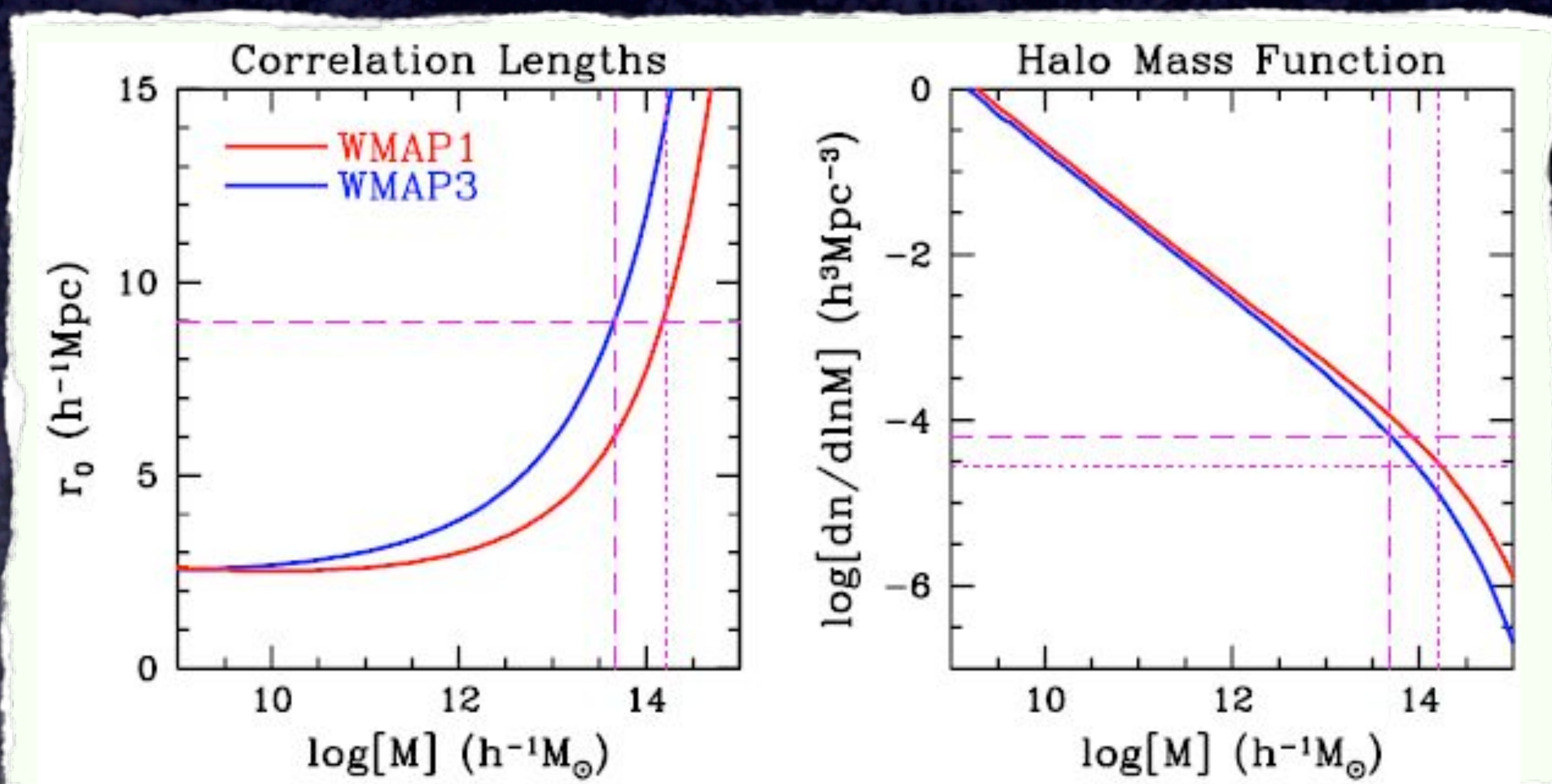


WMAP1

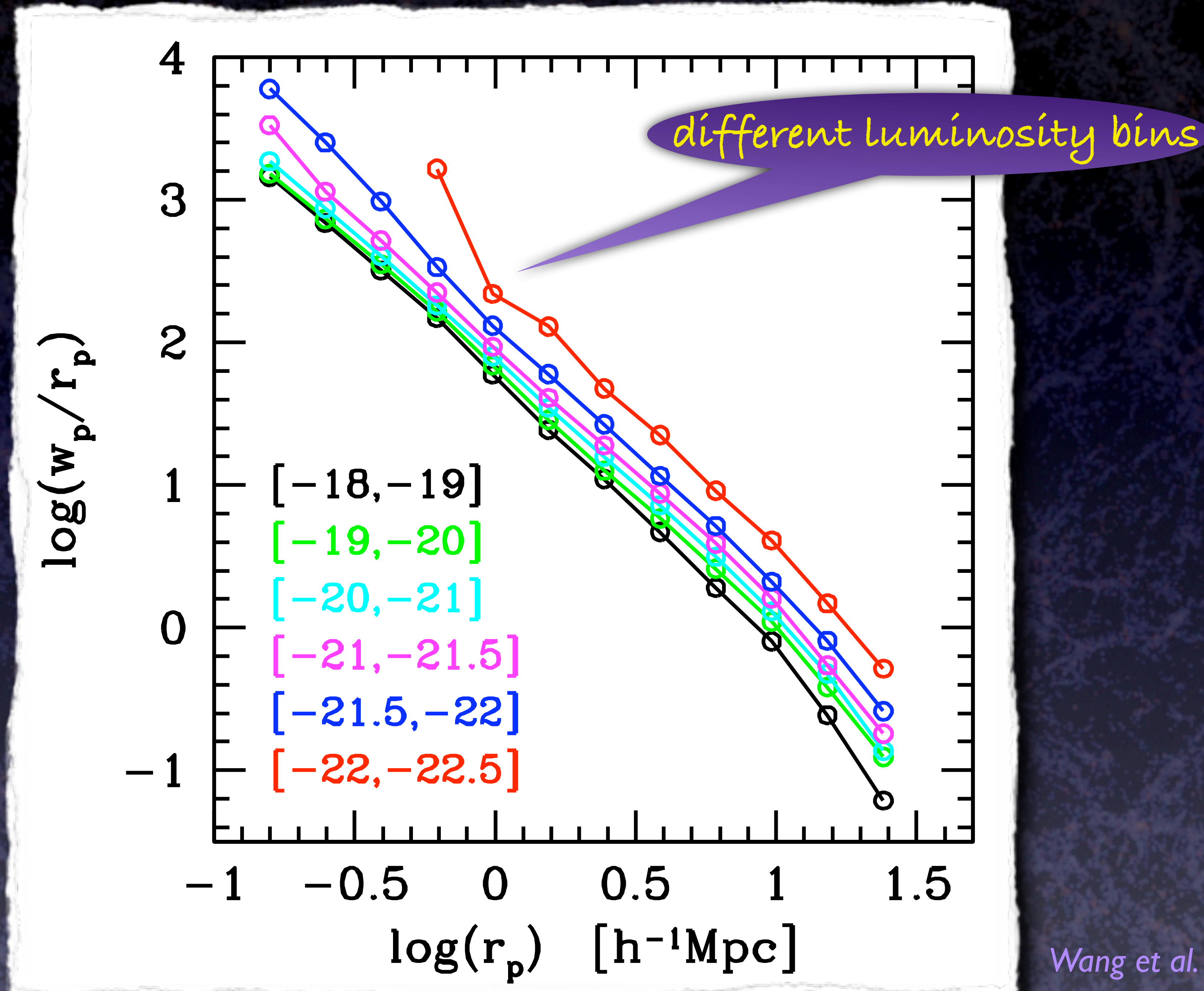
$\Omega_m = 0.30$
$\Omega_\Lambda = 0.70$
$\sigma_8 = 0.90$

WMAP3

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

CAUTION: results depend on cosmology

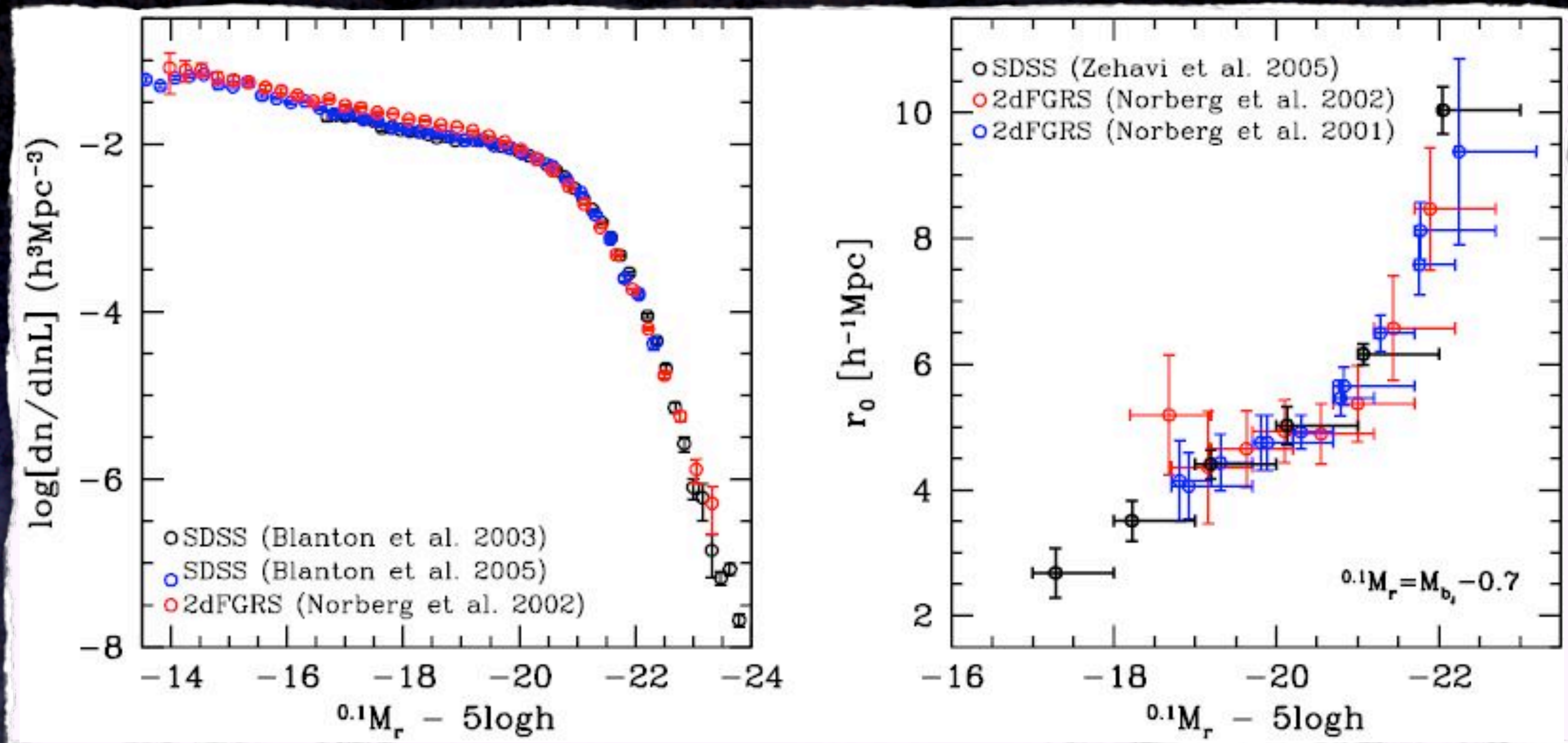
Galaxy Clustering: The Data



Wang et al. (2007)

More luminous galaxies are more strongly clustered

Luminosity & Correlation Functions

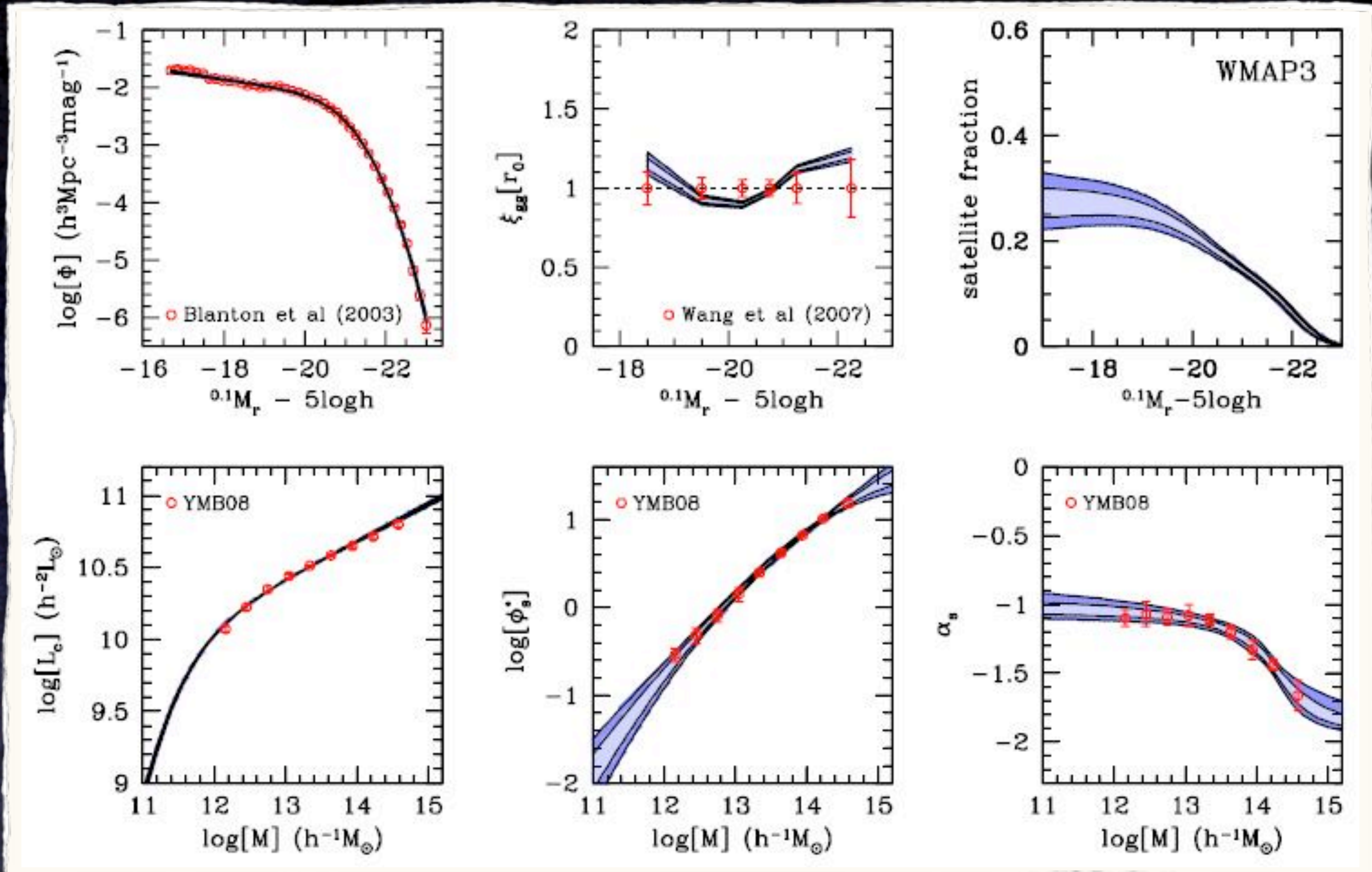


DATA: more luminous galaxies are more strongly clustered

LCDM: more massive halos are more strongly clustered

CONCLUSION: more luminous galaxies reside in more massive halos

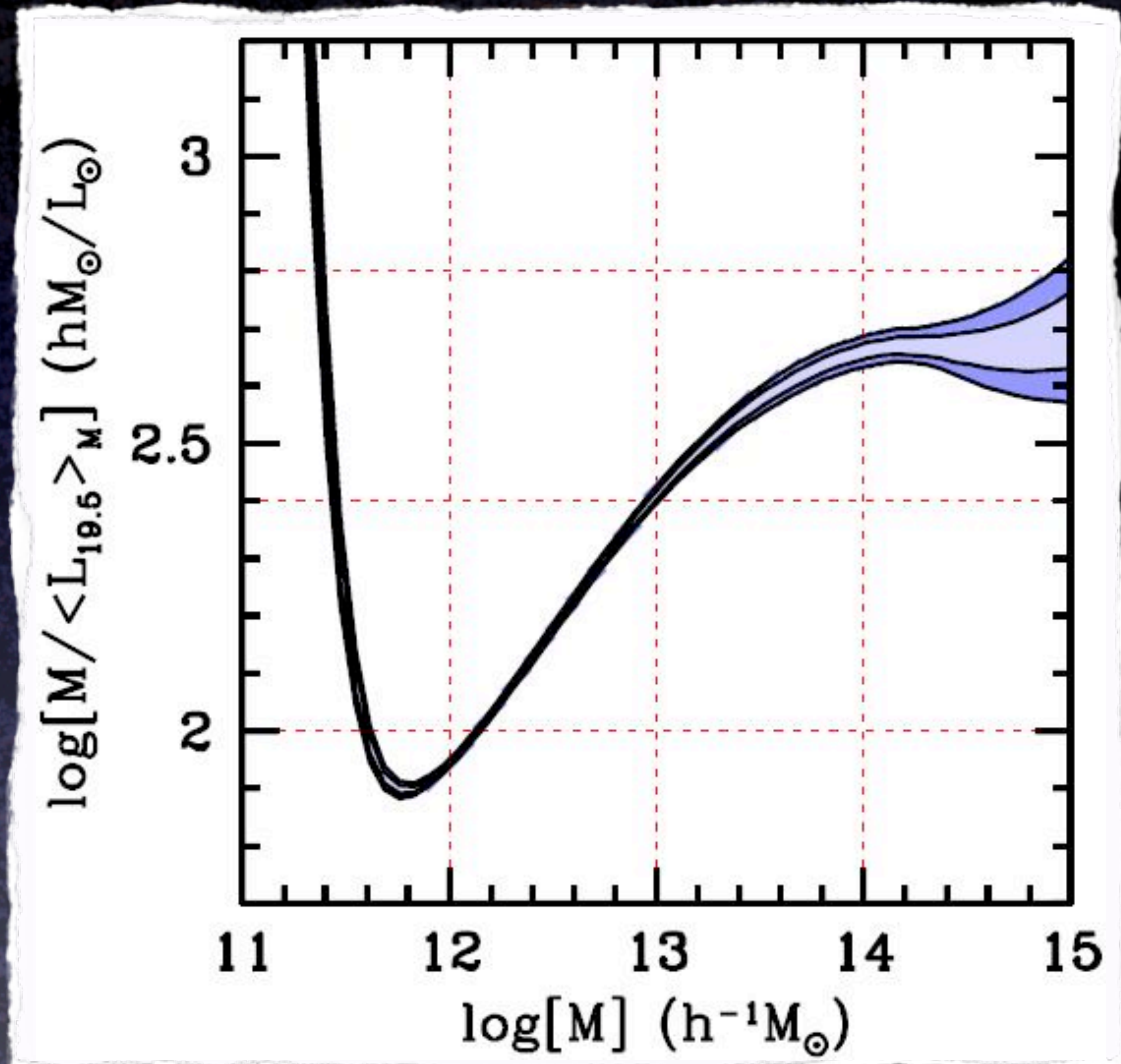
Results from MCMC Analysis



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



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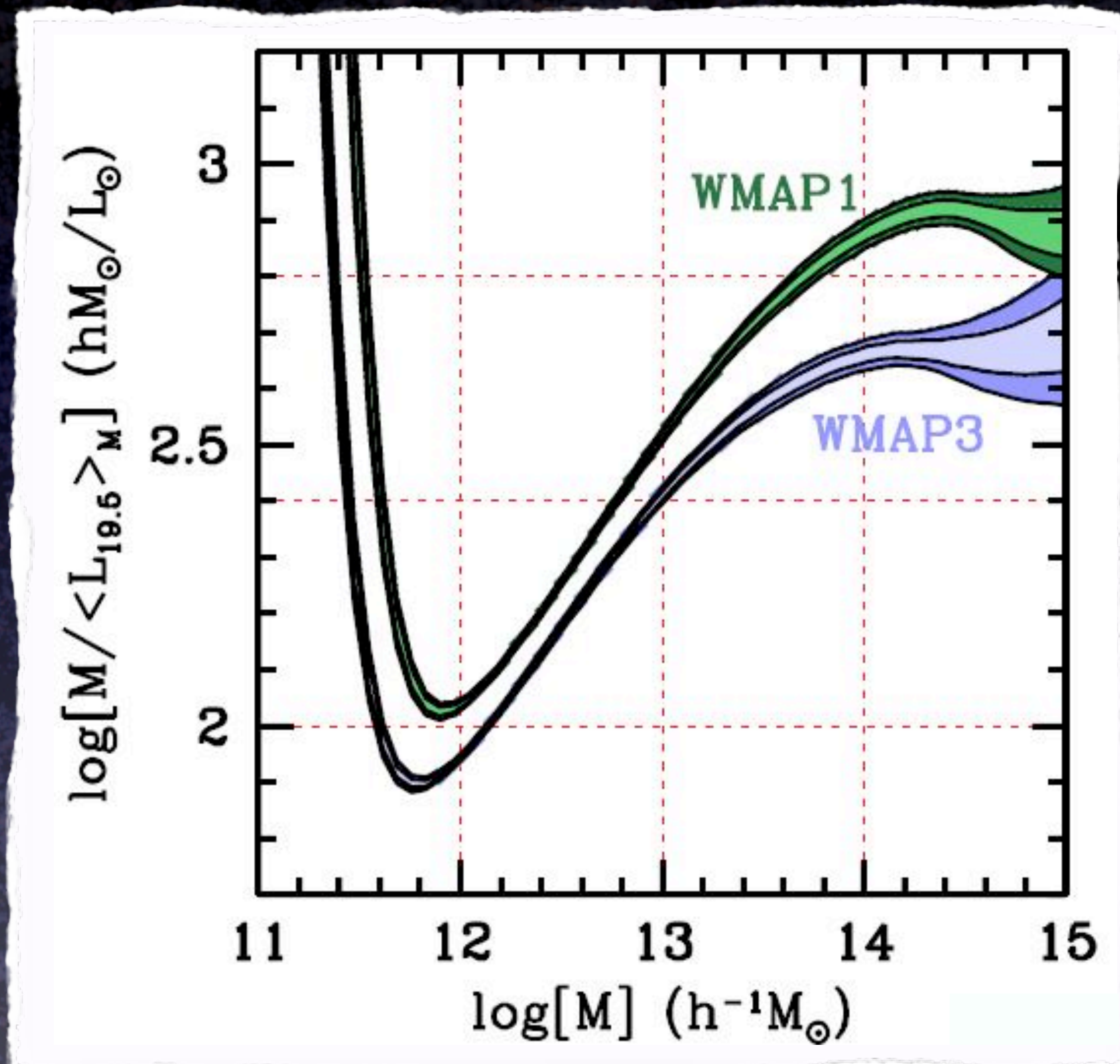
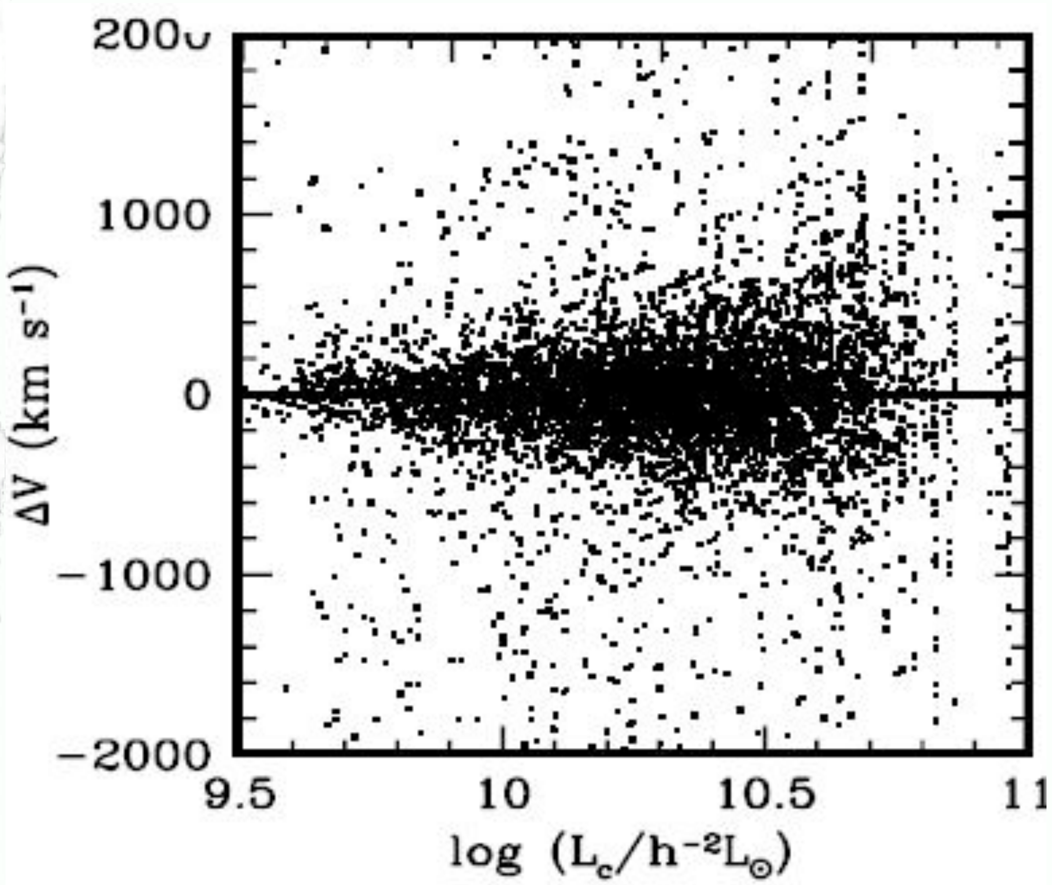


Satellite Kinematics

Satellite Kinematics: Methodology

Select centrals and their satellites from a redshift survey

Using redshifts, determine $\Delta V = V_{\rm sat} - V_{\rm cen}$ as function of $L_{\rm c}$



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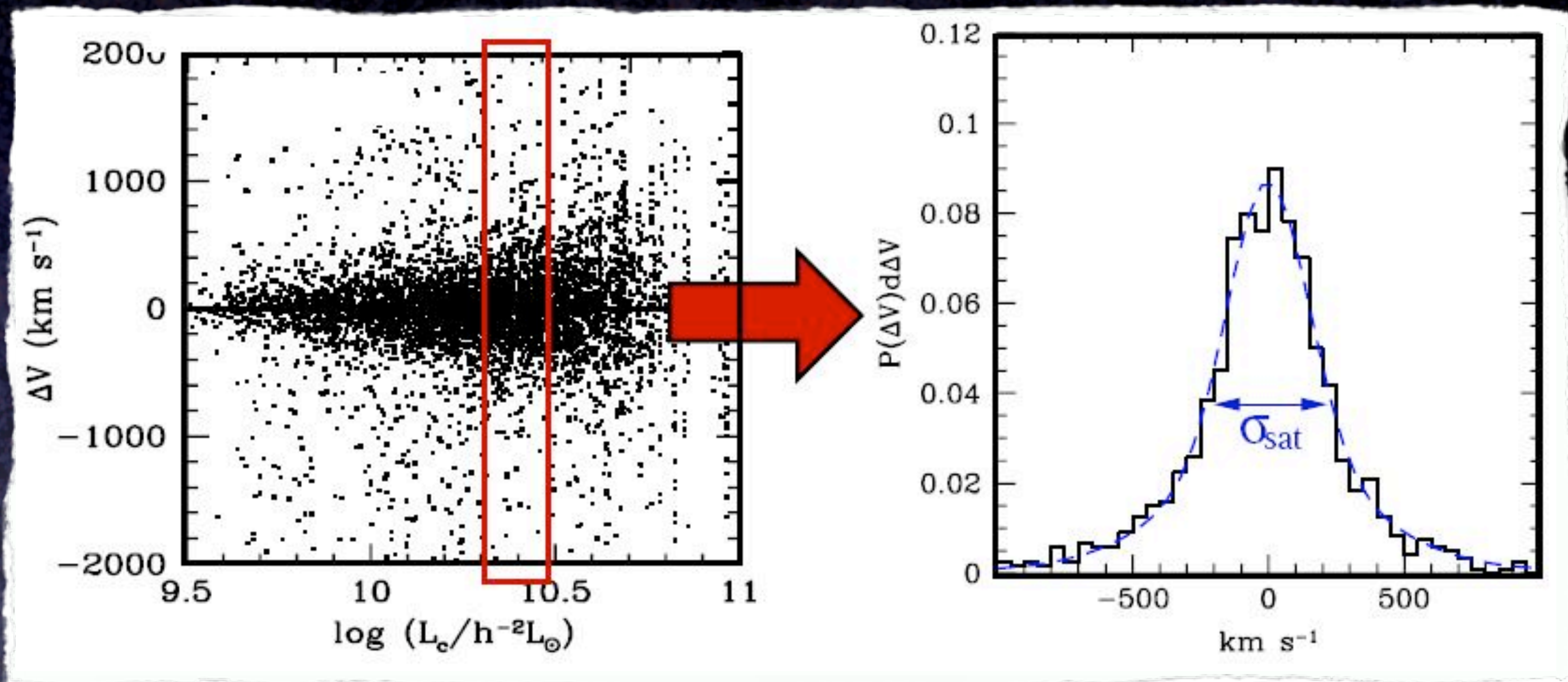

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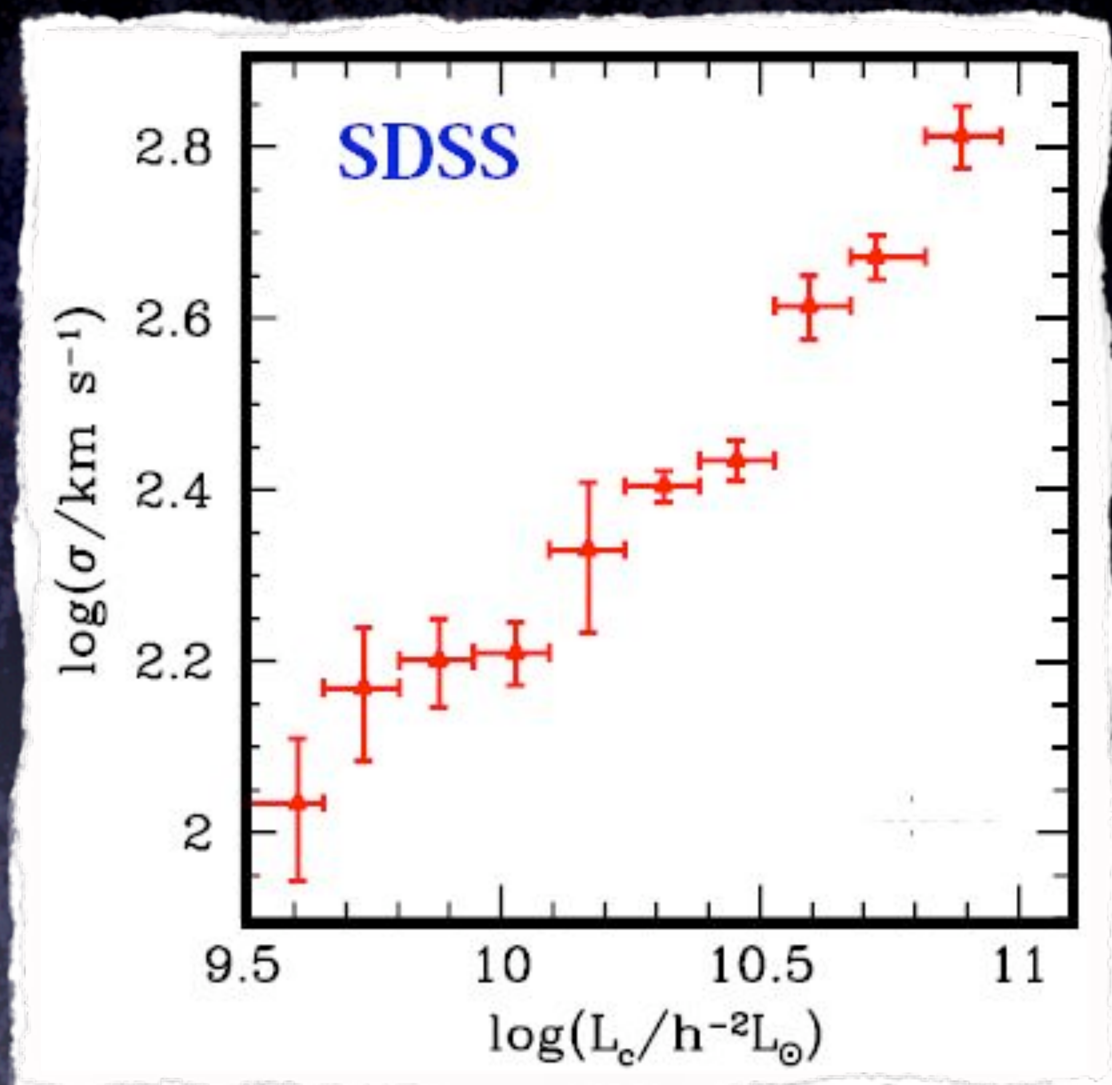


Brighter centrals reside in more massive haloes

Satellite Kinematics: Mass Estimates

Using virial equilibrium and spherical collapse model:

$$\sigma^2 \propto \frac{GM}{R} \qquad M \propto R^3 \qquad \sigma \propto M^{1/3}$$

On average only ~2 satellites per central → stacking

Unless $P(M|L_c)$ is a Dirac delta function, stacking means combining halos of different masses

Consequently, one has to distinguish two weighting schemes:

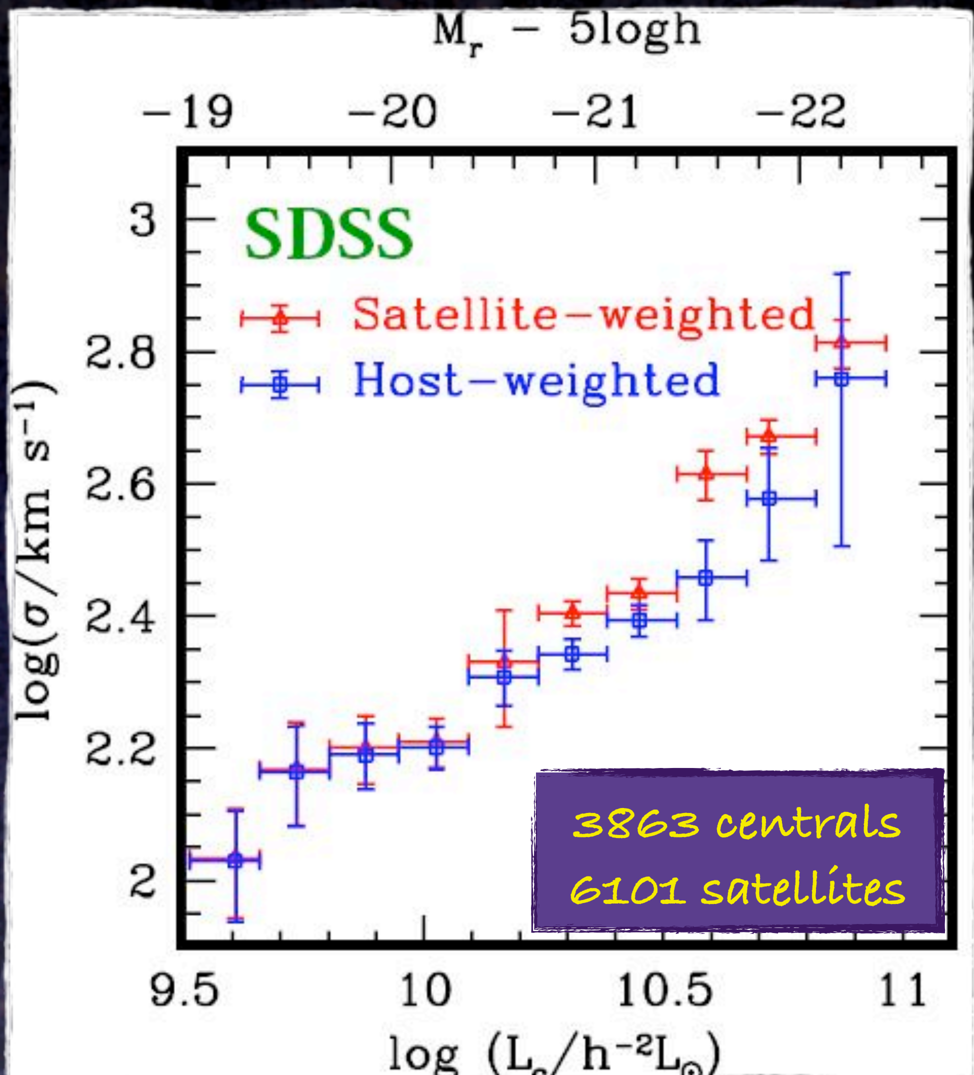
Satellite Weighting: each satellite receives equal weight of one

$$\sigma^2_{\rm sw} = \frac{\int P(M|L_c)\, \langle N_{\rm sat}\rangle_M\, \sigma^2_{\rm sat}(M)\, {\rm d}M}{\int P(M|L_c)\, \langle N_{\rm sat}\rangle_M\, {\rm d}M}$$

Host Weighting: each host receives equal weight of one

$$\sigma^2_{\rm hw} = \frac{\int P(M|L_c)\, \mathcal{P}_1(M)\, \sigma^2_{\rm sat}(M)\, {\rm d}M}{\int P(M|L_c)\, \mathcal{P}_1(M)\, {\rm d}M}$$

Satellite Kinematics: Results



More, vdB et al. (2009)

Combination of satellite- and host-weigthed velocity dispersions holds information on both the mean and scatter of P(M|L)

Methodology

$$\sigma^2_{\rm sw} = \frac{\int P(M|L_{\rm c})\,\langle N_{\rm sat}\rangle_M\,\sigma^2_{\rm sat}(M)\,{\rm d}M}{\int P(M|L_{\rm c})\,\langle N_{\rm sat}\rangle_M\,{\rm d}M}$$

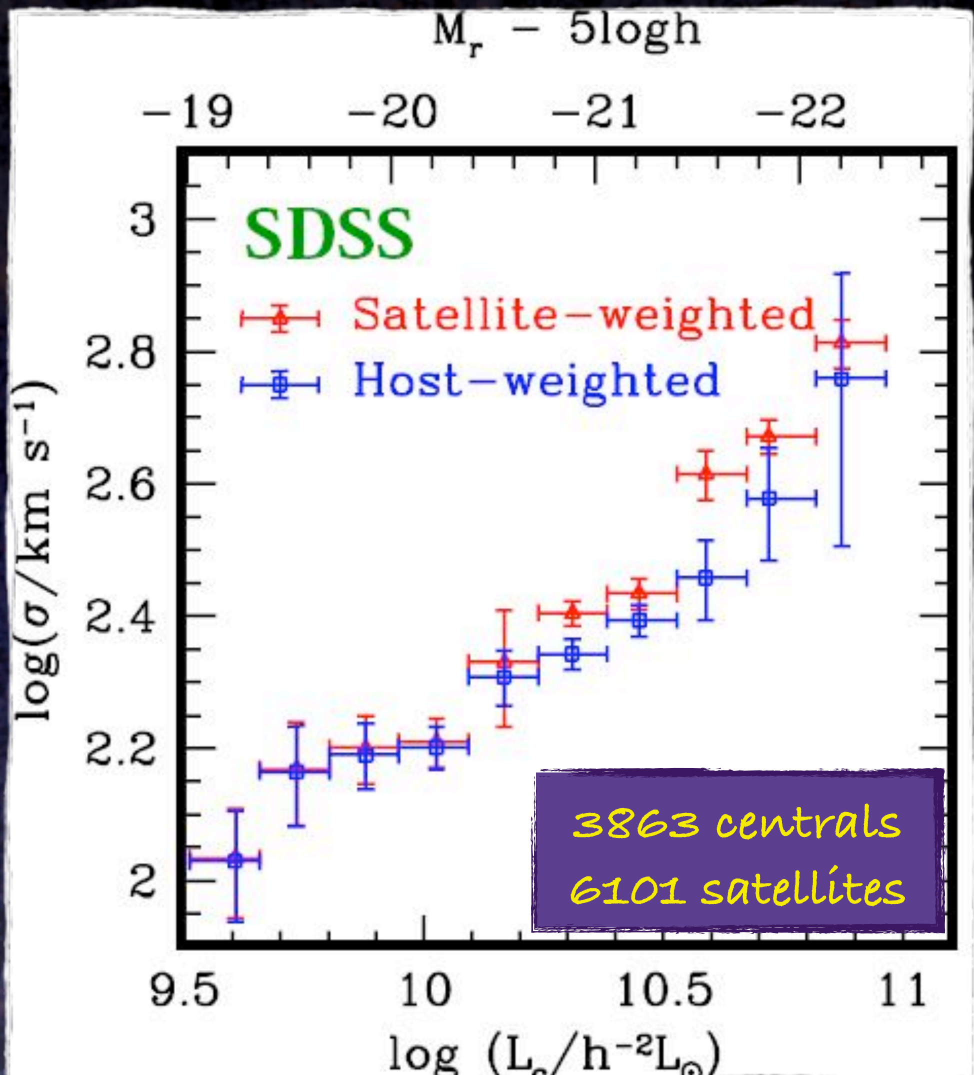
$$\sigma^2_{\rm hw} = \frac{\int P(M|L_{\rm c})\,\mathcal{P}_1(M)\,\sigma^2_{\rm sat}(M)\,{\rm d}M}{\int P(M|L_{\rm c})\,\mathcal{P}_1(M)\,{\rm d}M}$$

Jeans Equations yield $\sigma^2_{\rm sat}(M)$ for NFW halos

$P(M|L_{\rm c})$ and $\langle N_{\rm sat}\rangle_M$ follow from CLF

Constrain CLF model parameters by fitting the observed $\sigma_{\rm sw}(L_{\rm c})$ and $\sigma_{\rm hw}(L_{\rm c})$

Satellite Kinematics: Results



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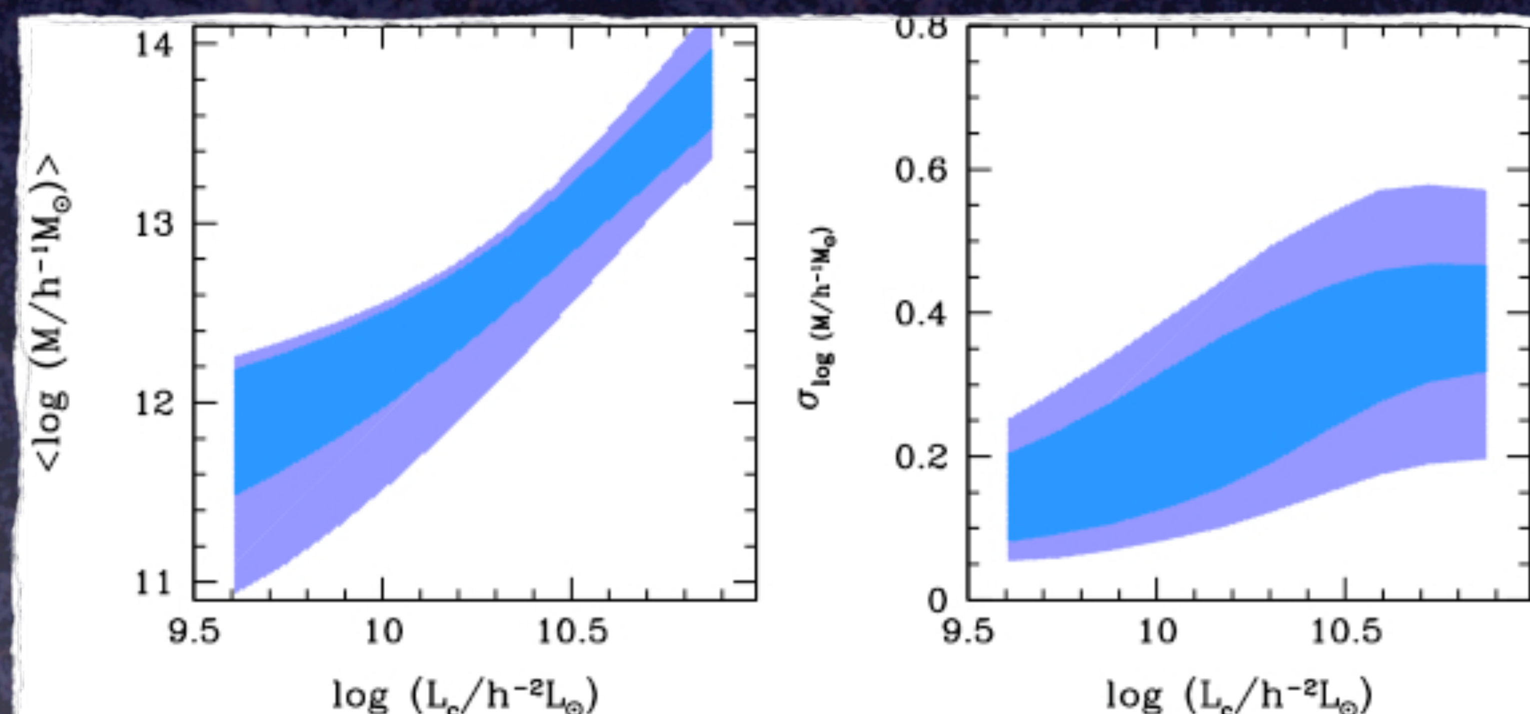

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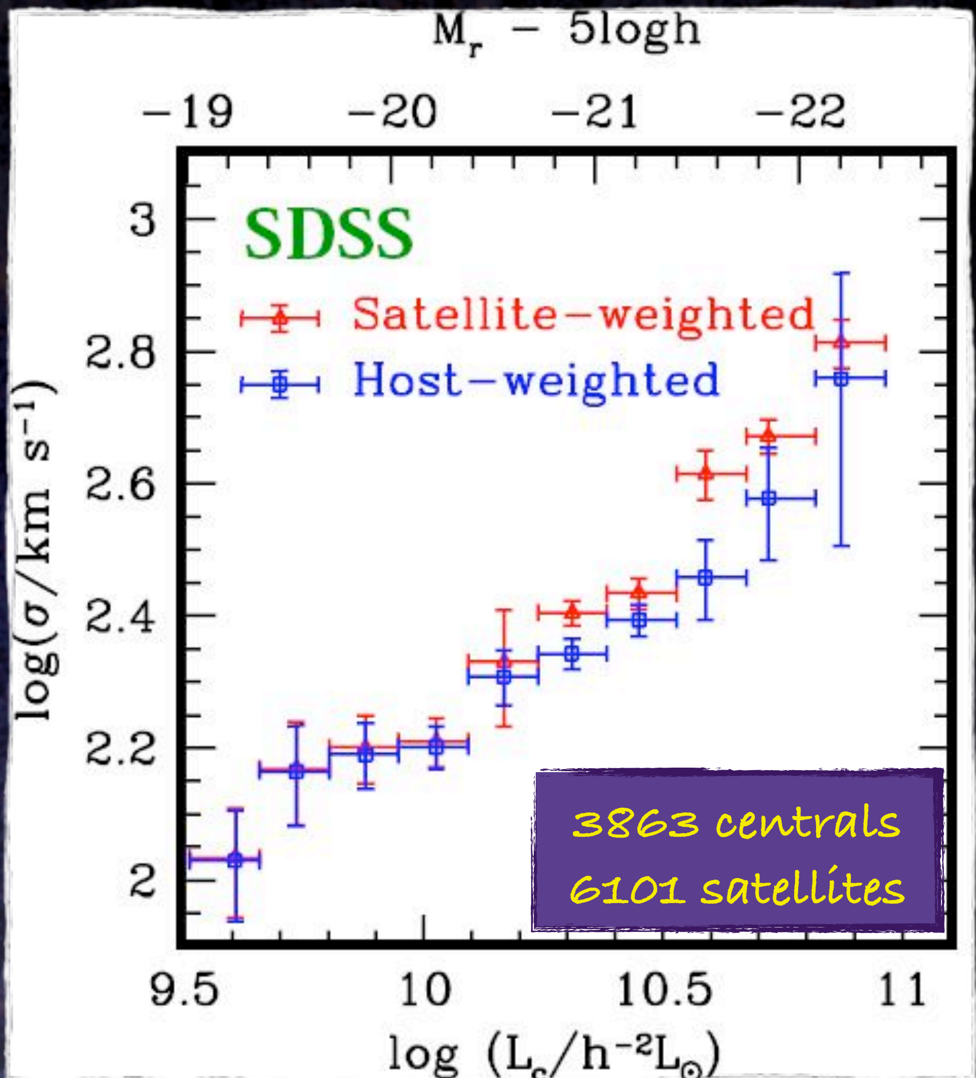

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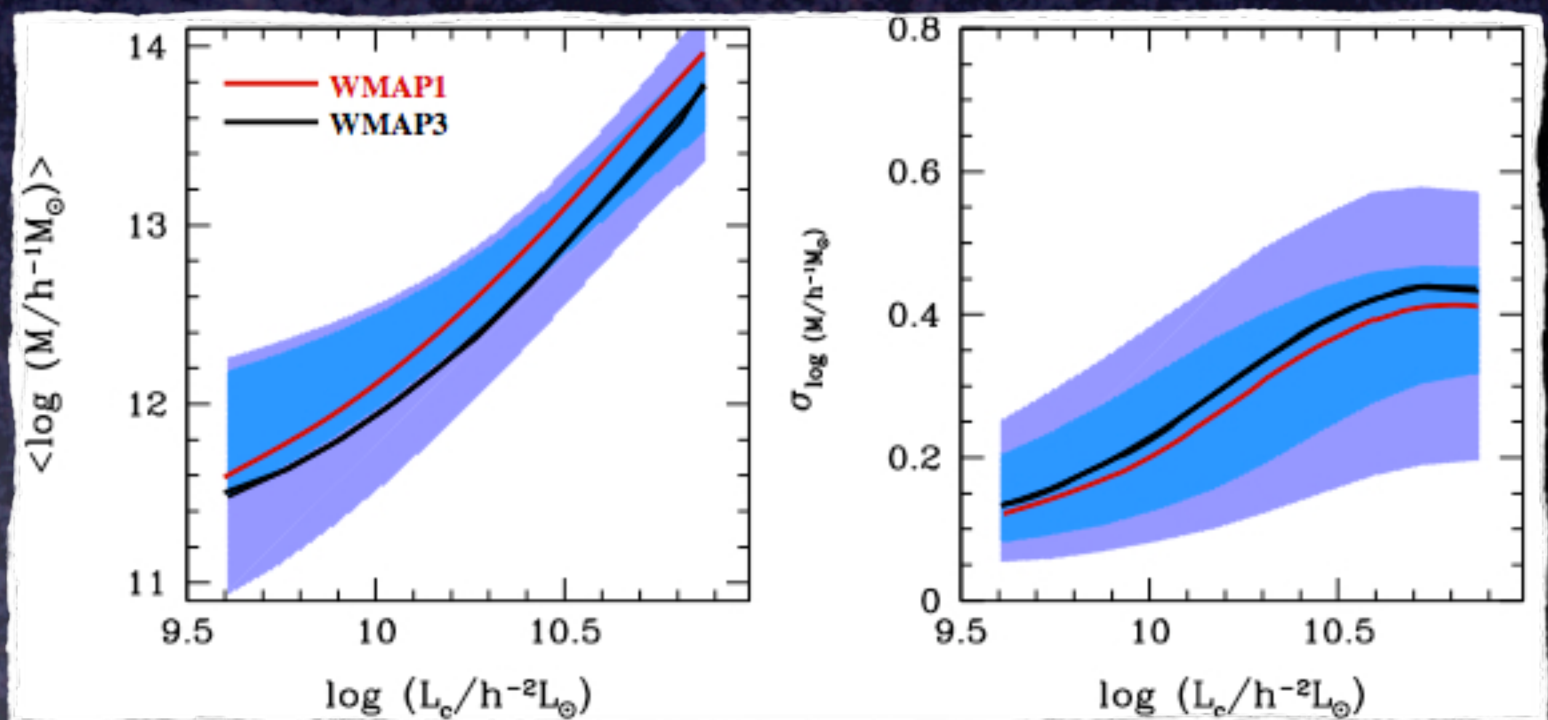

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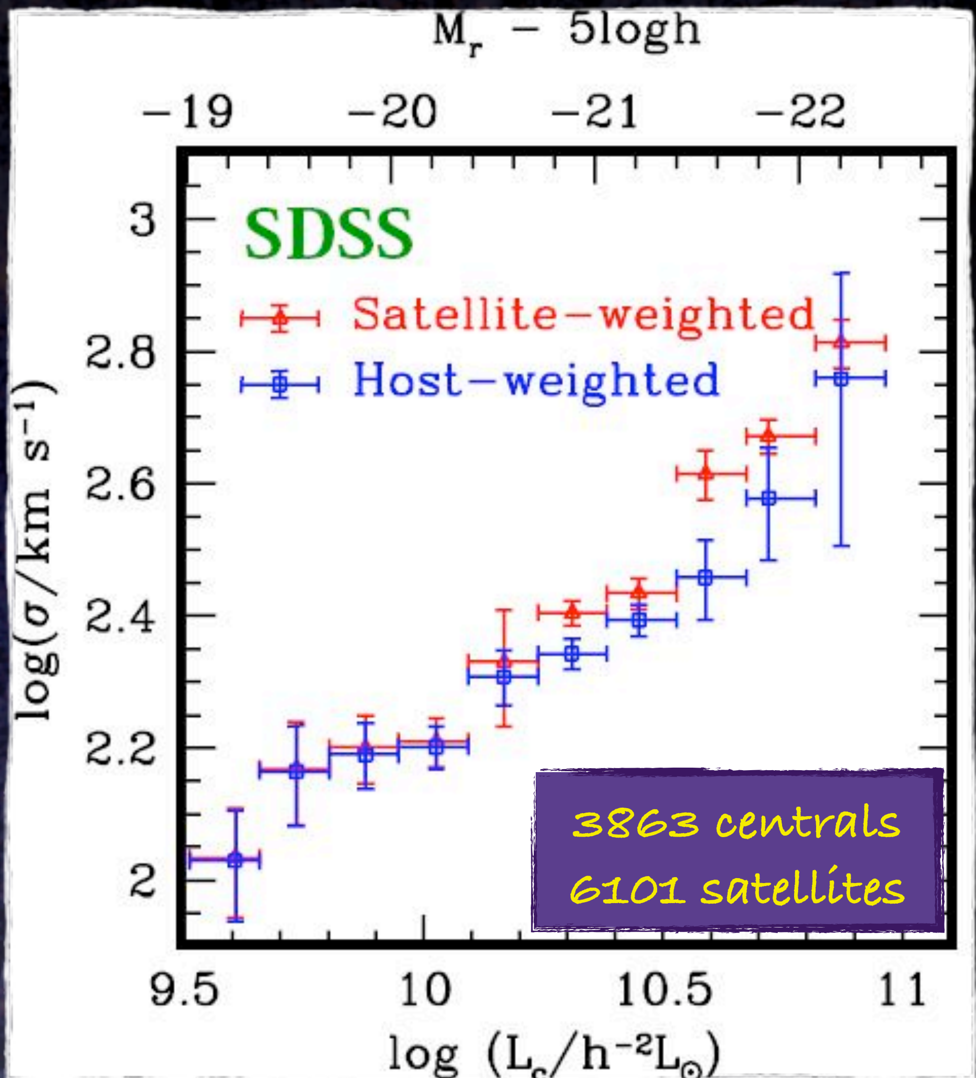

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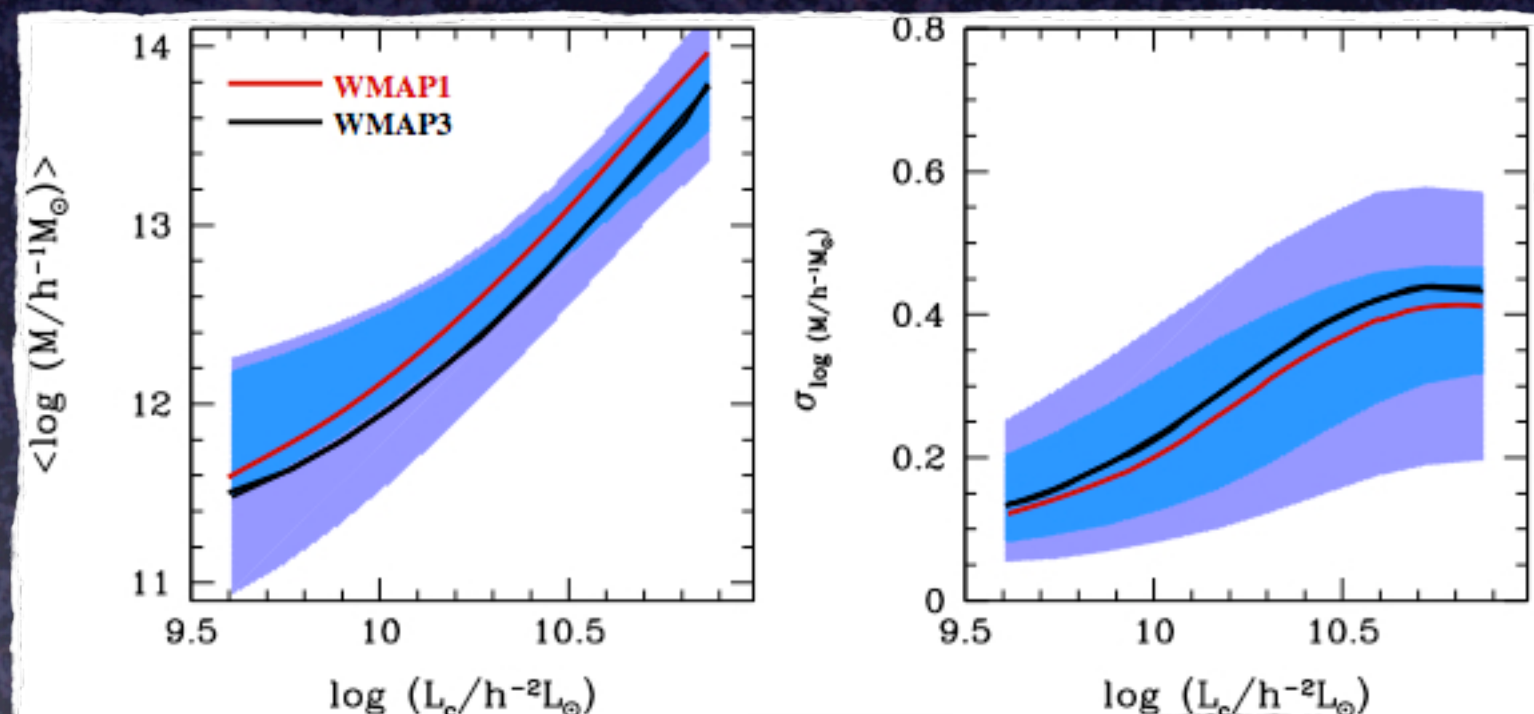
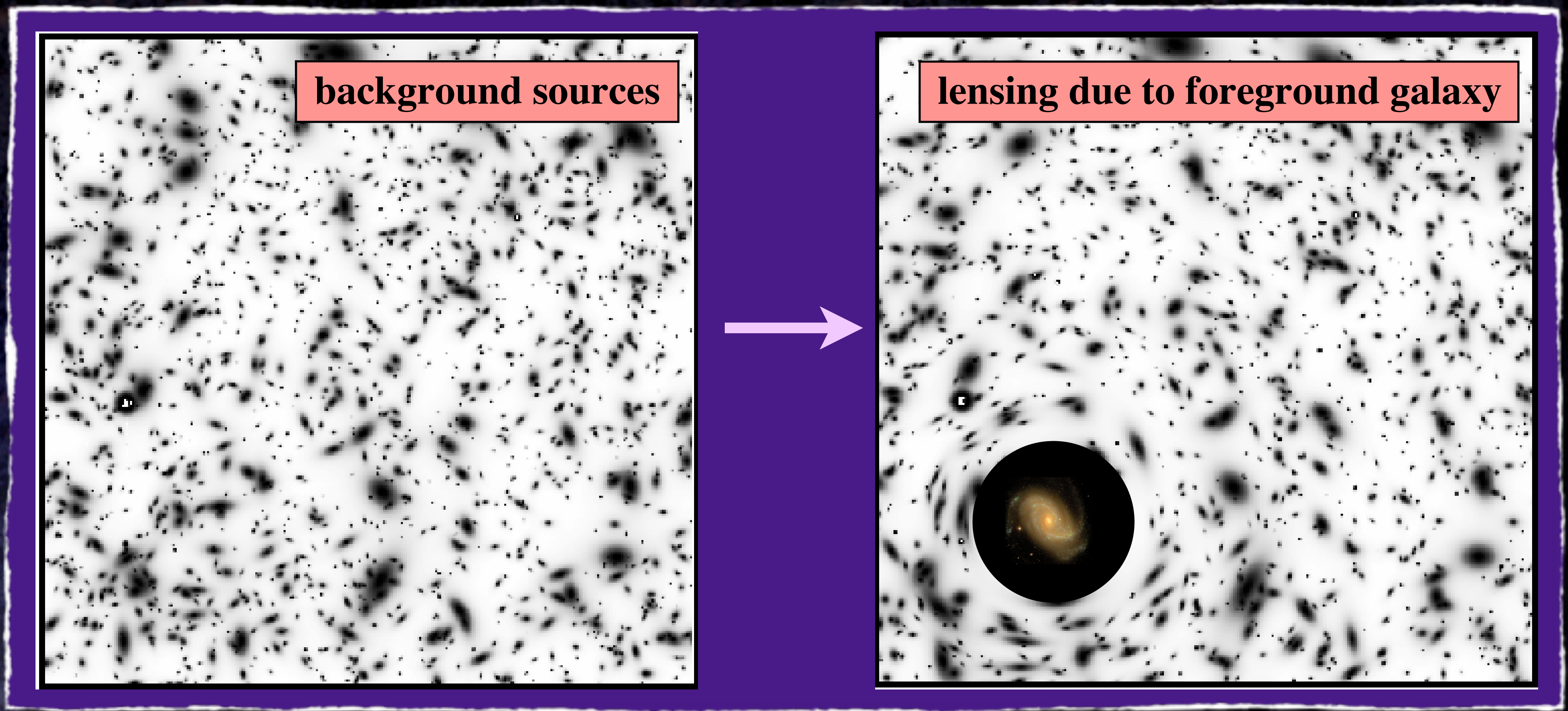


Excellent agreement with results from clustering analysis, but statistical errors too large to break degeneracy with cosmology...

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

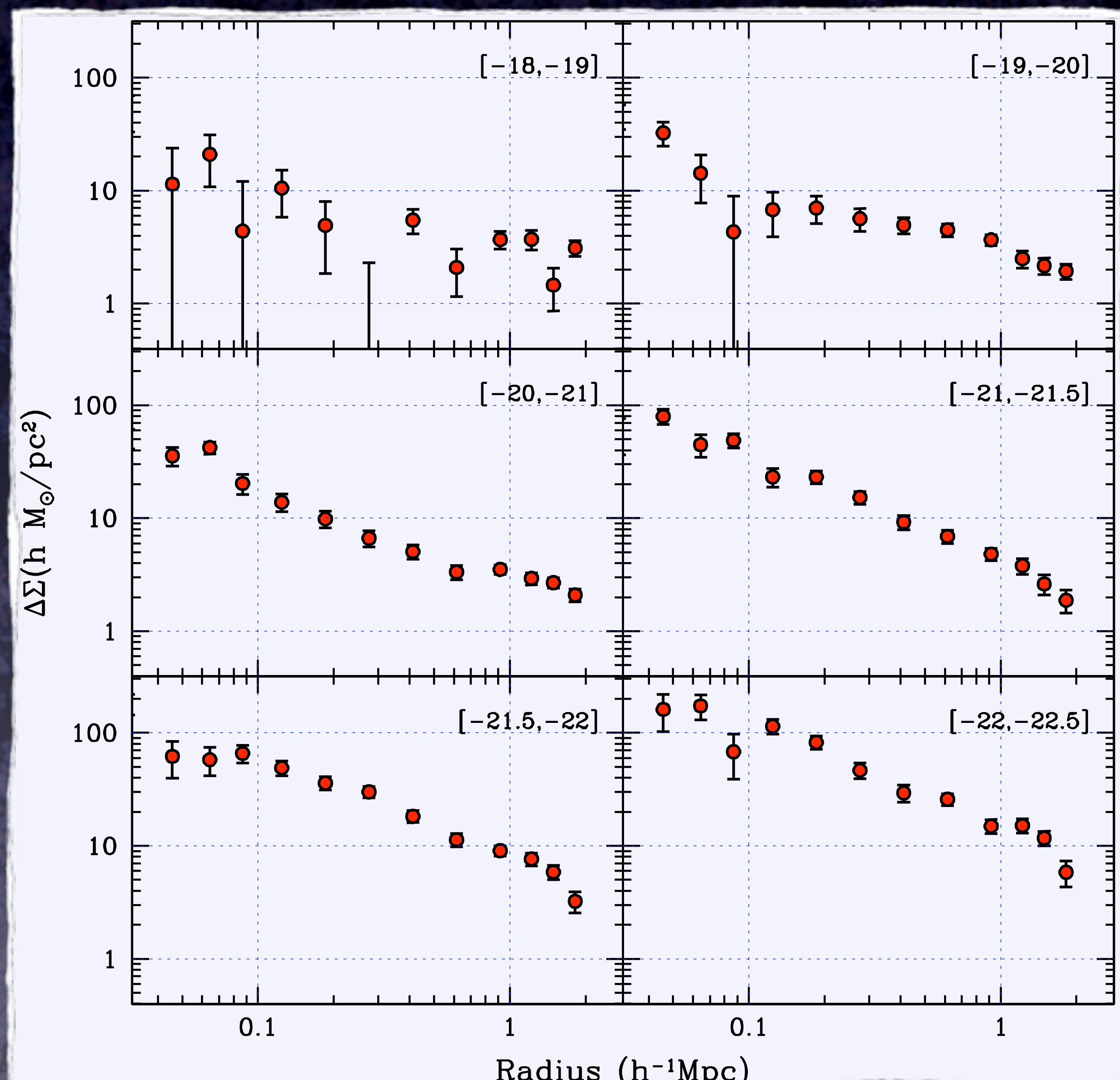
$$\gamma_{\rm t}(R)\Sigma_{\rm crit} = \Delta\Sigma(R) = \bar{\Sigma}(< R) - \Sigma(R)$$

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

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

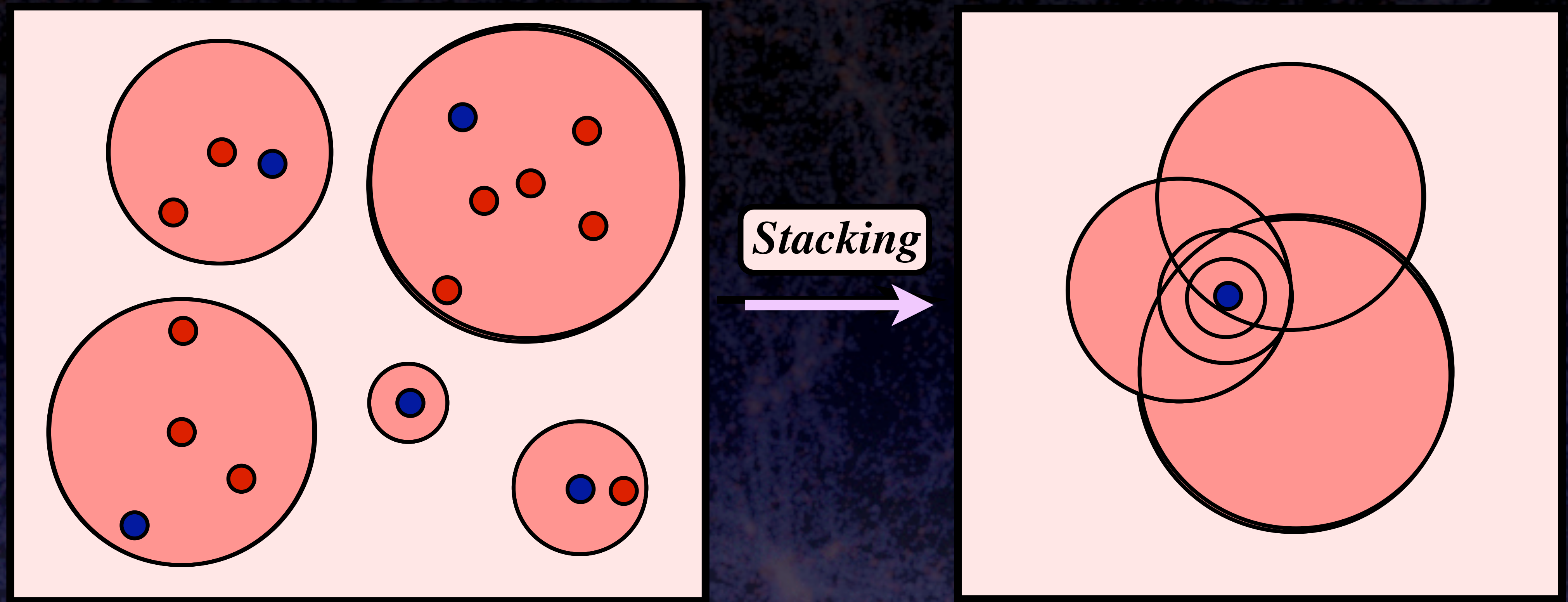
Galaxy-Galaxy Lensing: The Data

- 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

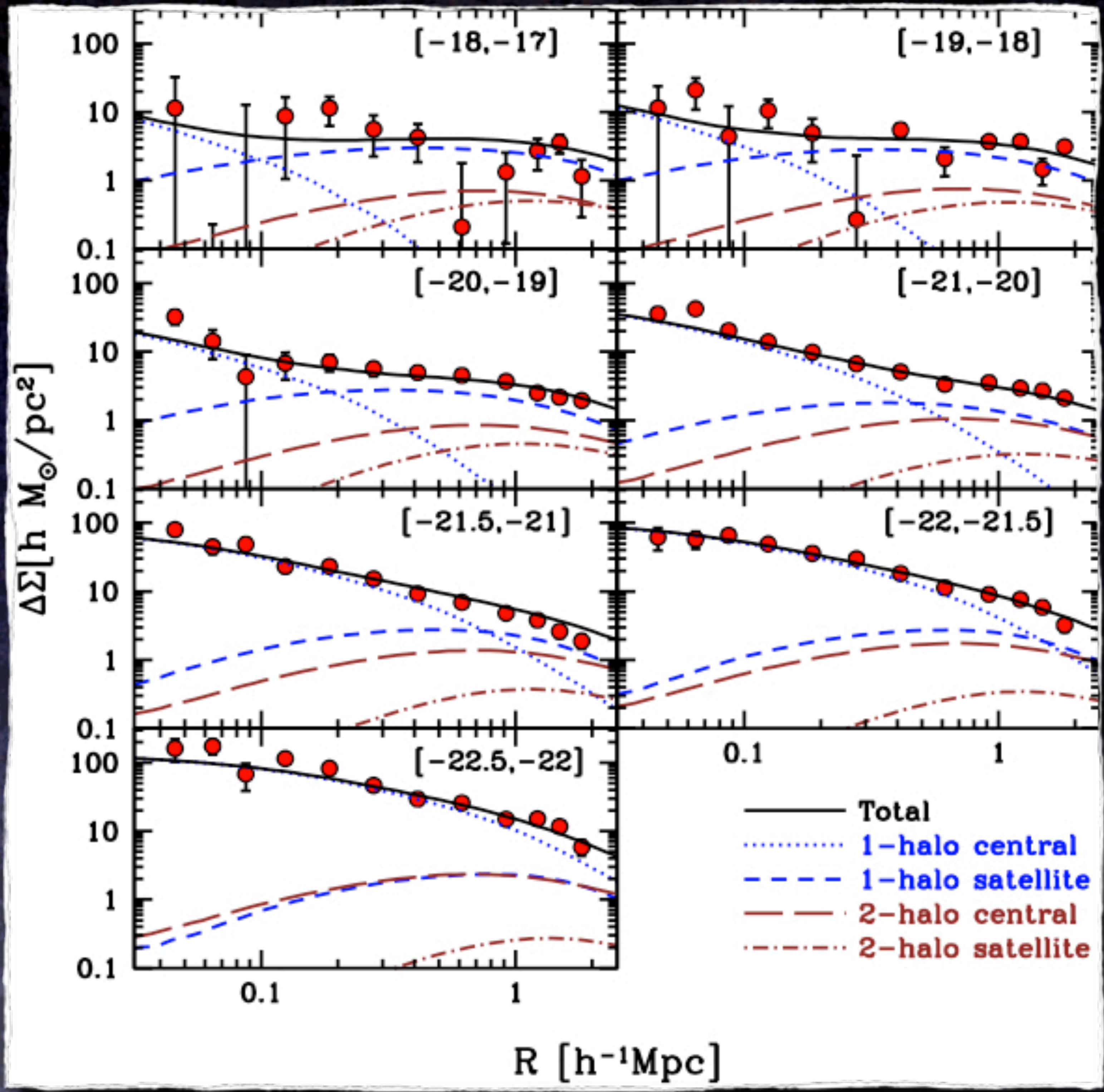
In order to model the data, what is required is:

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

These can all be computed from the CLF...

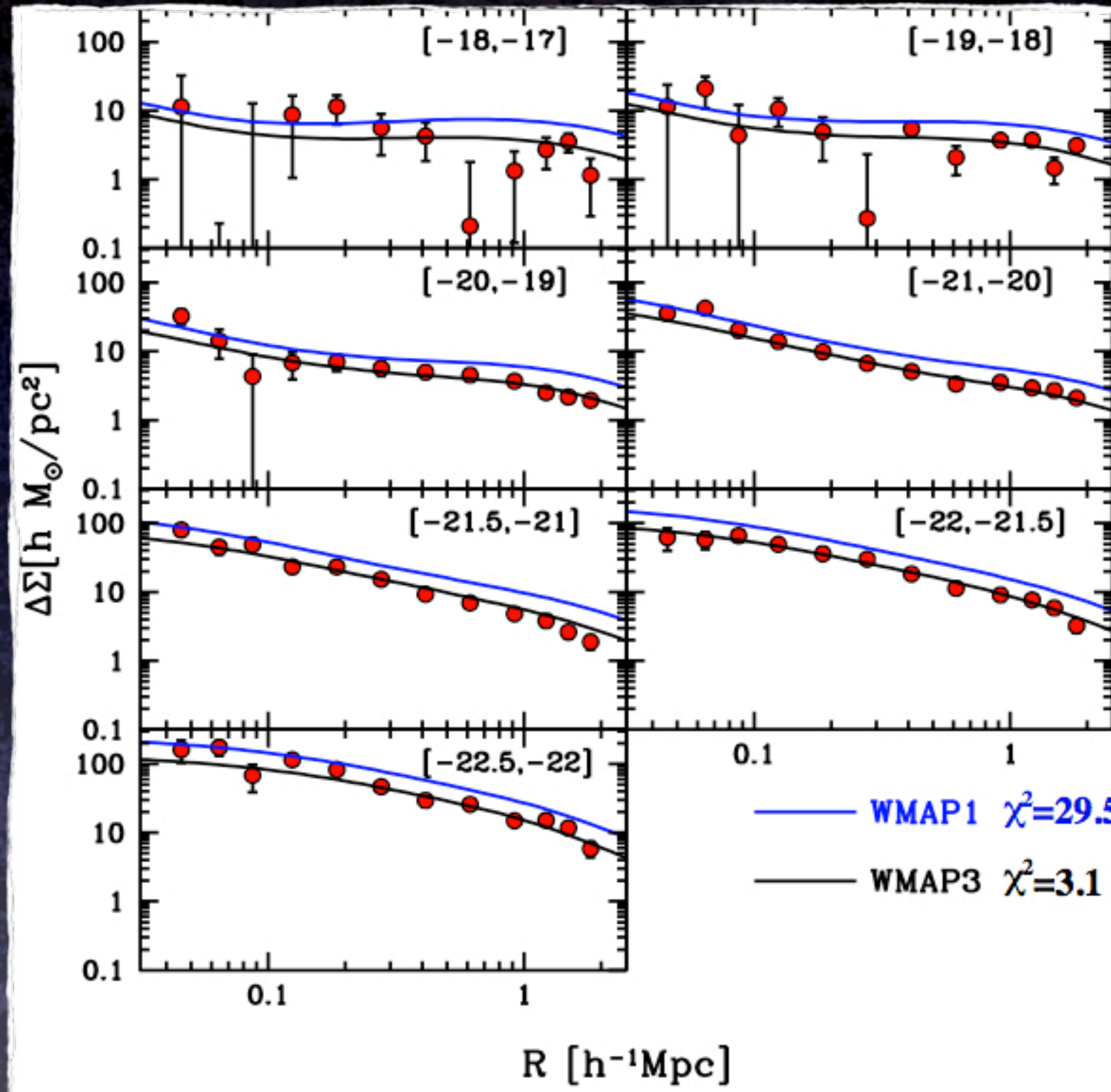
For a given $\Phi(L|M)$ we can predict the lensing signal $\Delta\Sigma(R|L_1, L_2)$

Galaxy-Galaxy Lensing: Results



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

Galaxy-Galaxy Lensing: Results



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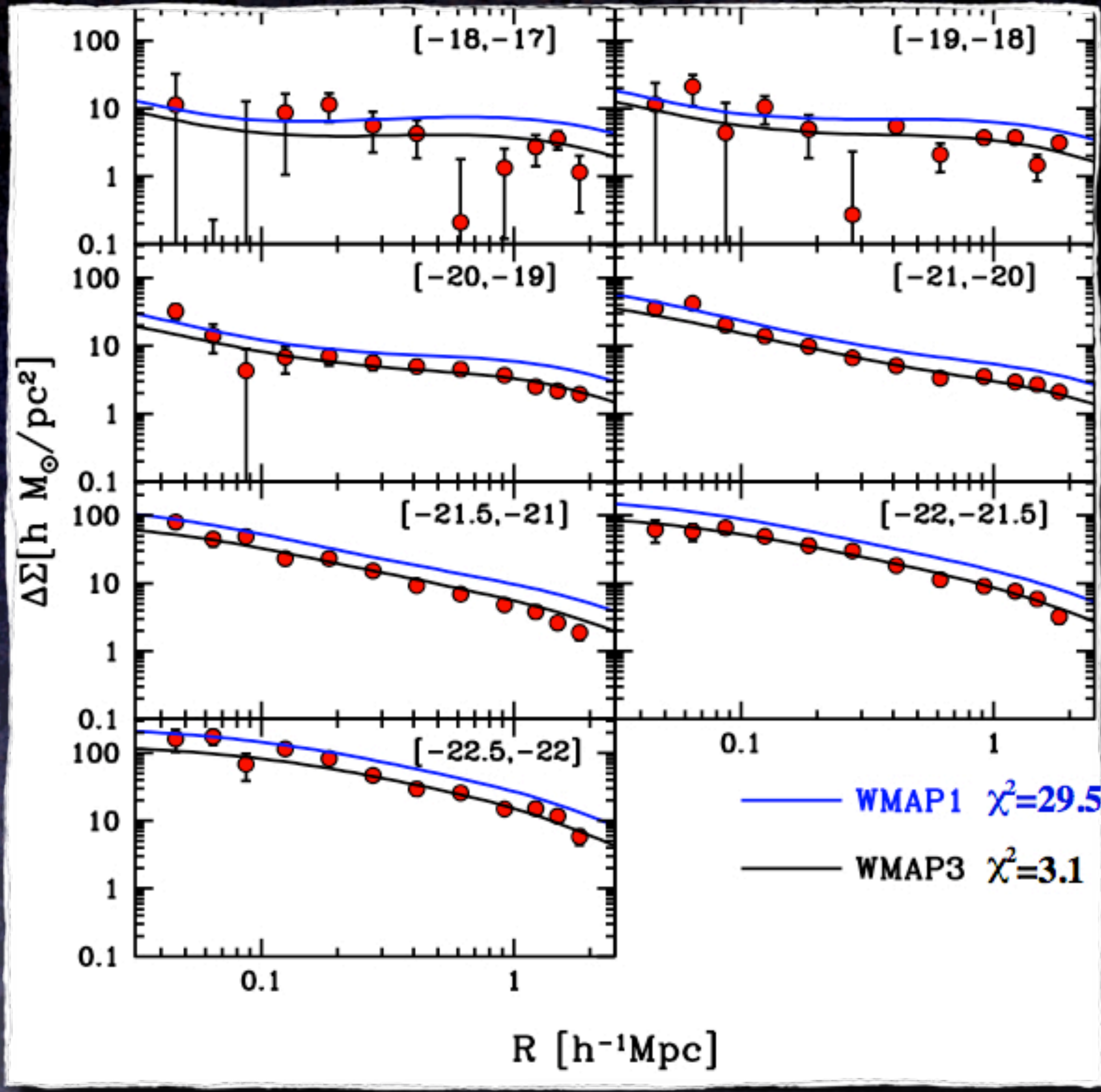


Combination of clustering & lensing can constrain cosmology!!!

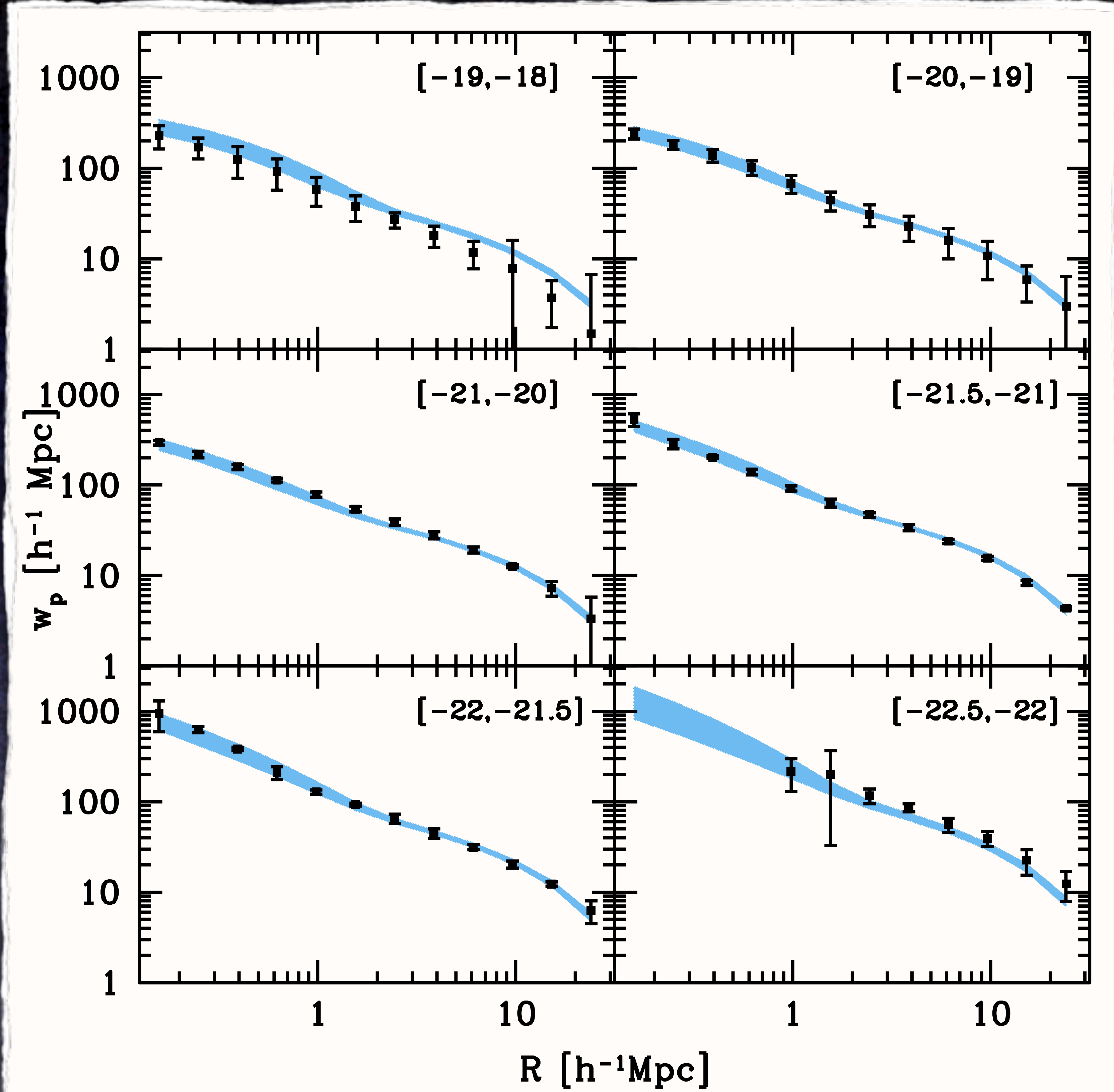
Constraining Cosmology

Fiducial Model

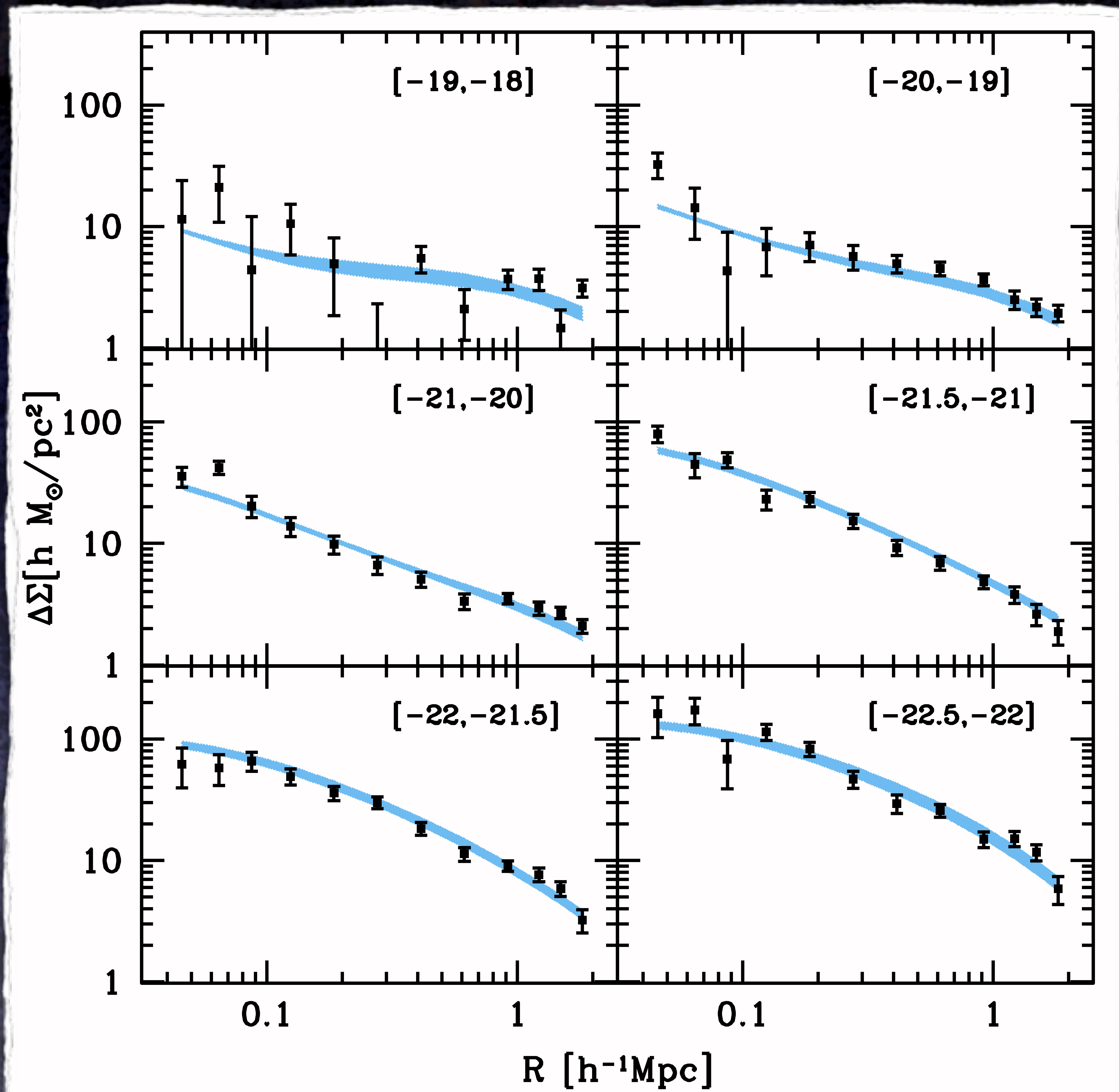
- Total of 13 free parameters:
  - 11 parameters to describe CLF
  - 2 cosmological parameters; $\Omega_{\rm m}$ and σ_8

  Total of 172 data points.
- All other cosmological parameters kept fixed at the best-fit WMAP5 values.
- 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 Sheth & Tormen (1999).

Results: Clustering Data

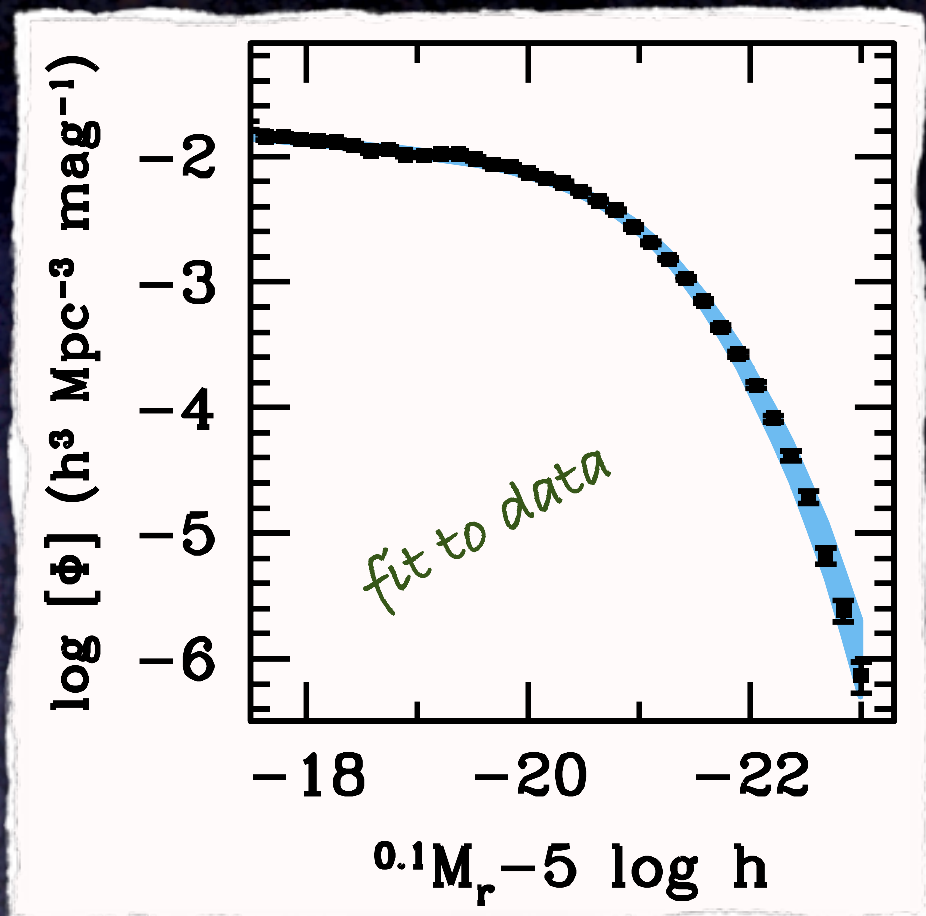


Results: Lensing Data

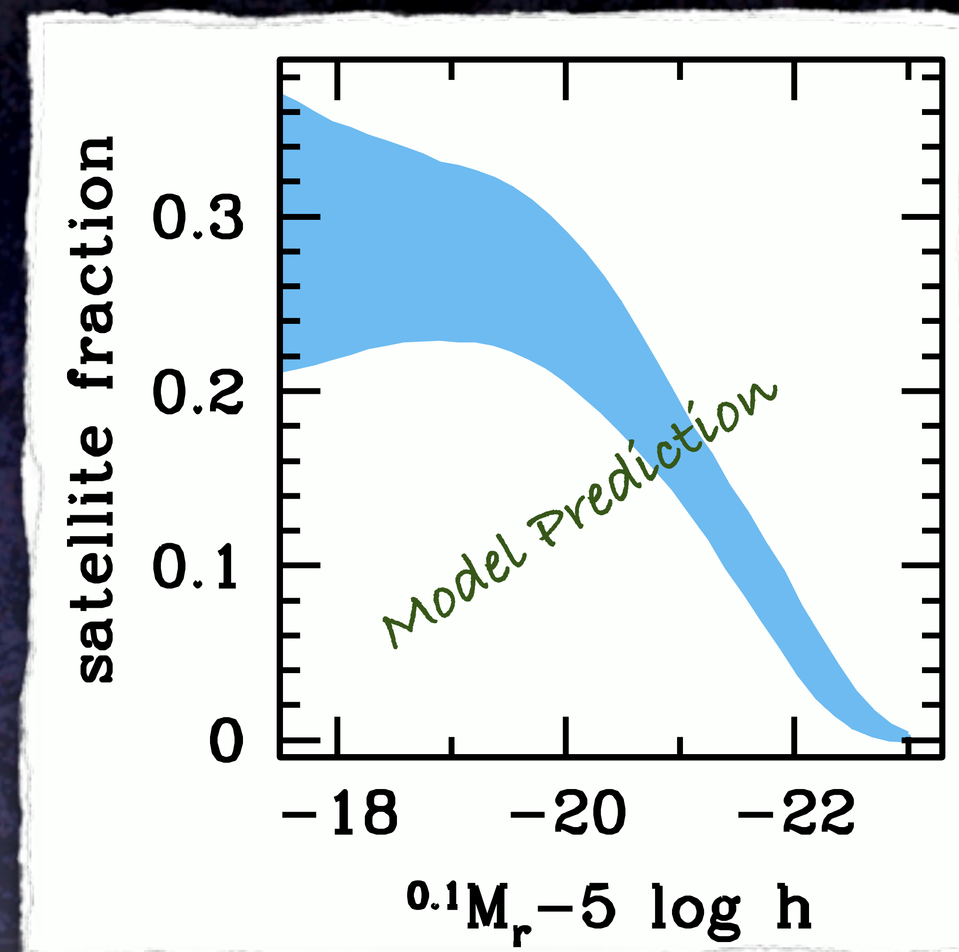


Luminosity Function & Satellite Fractions

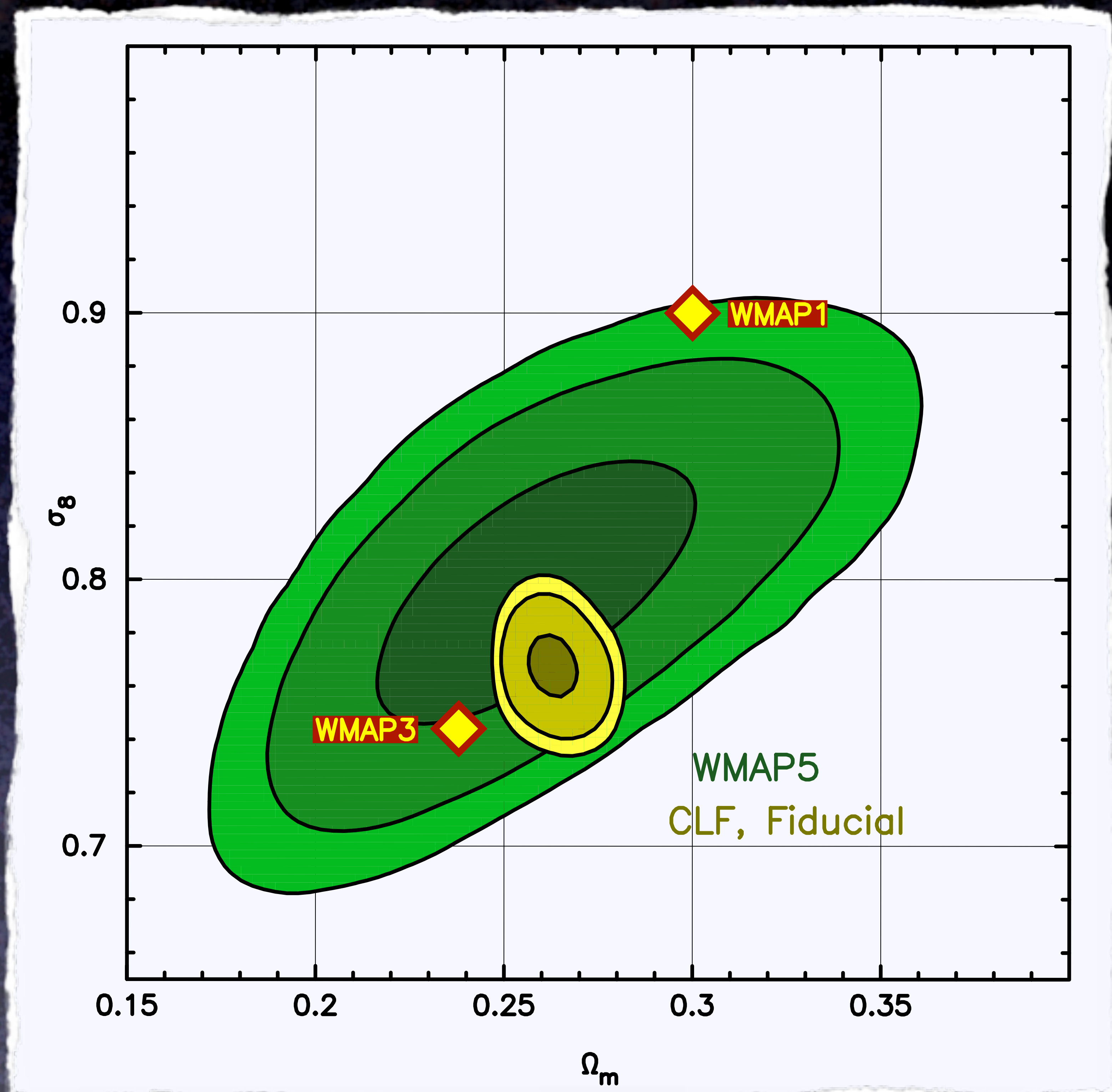
Luminosity Function



Satellite Fractions

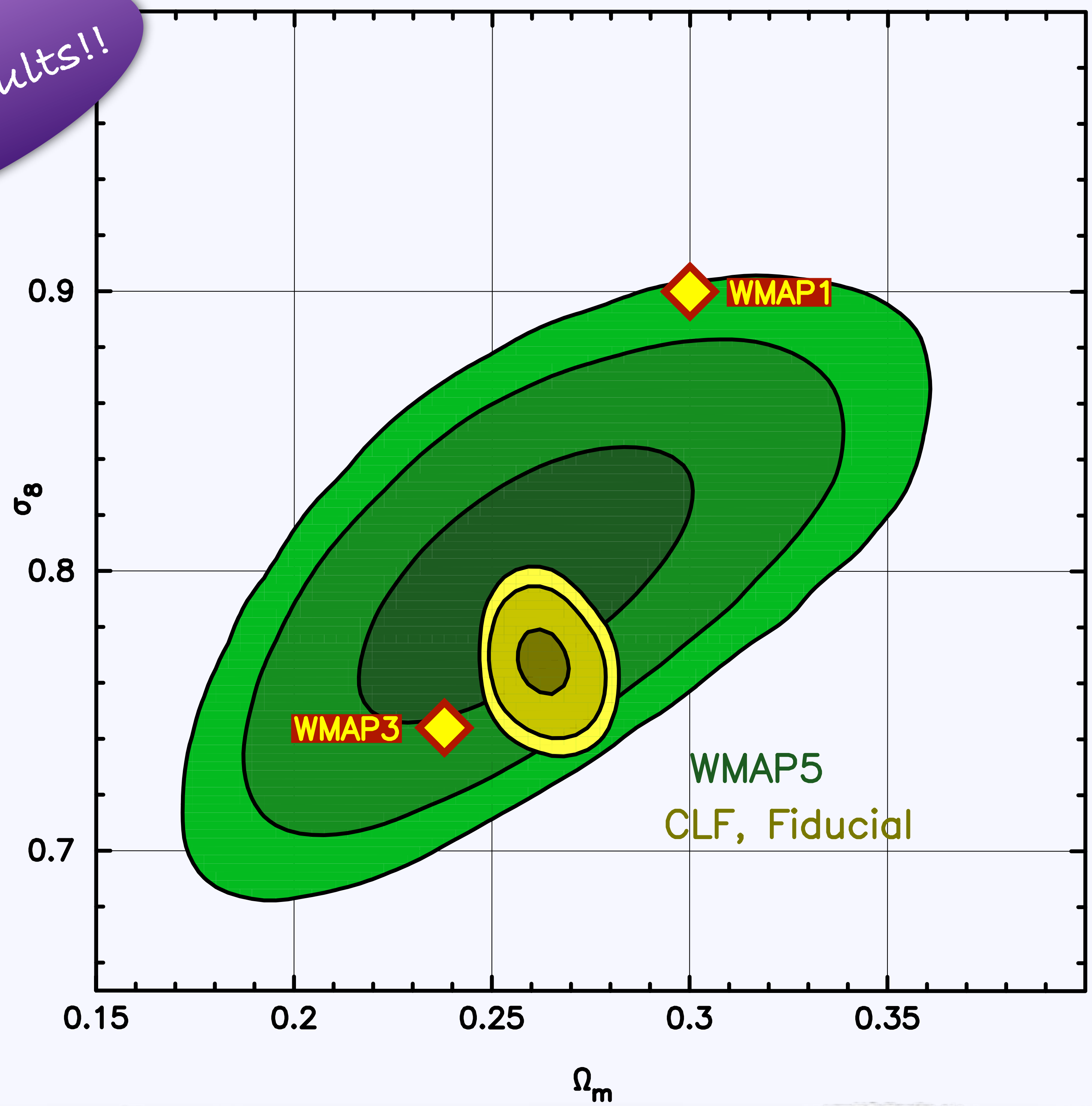


Cosmological Constraints



Cosmological Constraints

WARNING: preliminary results!!

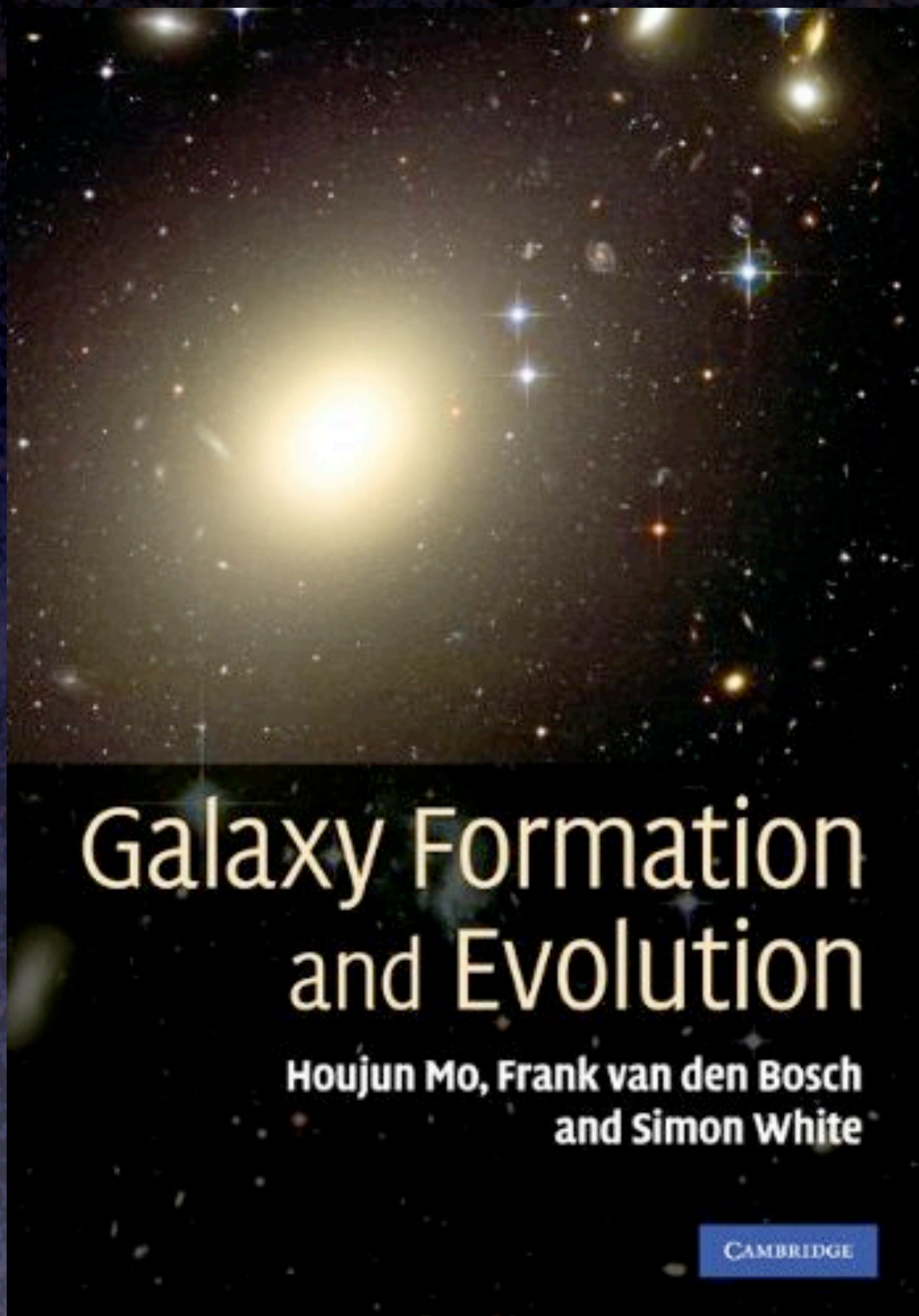


Conclusions

- Recent years have seen enormous progress in establishing galaxy-dark matter connection
- 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 WMAP5

The End

New Graduate Text Book



Release expected in May/June 2010

Contents

cosmology
structure formation
gravitational collapse
dark matter haloes
gas physics
star formation
stellar populations
galaxy formation & interactions
large scale structure
intergalactic medium
and much, much more...

840 pages

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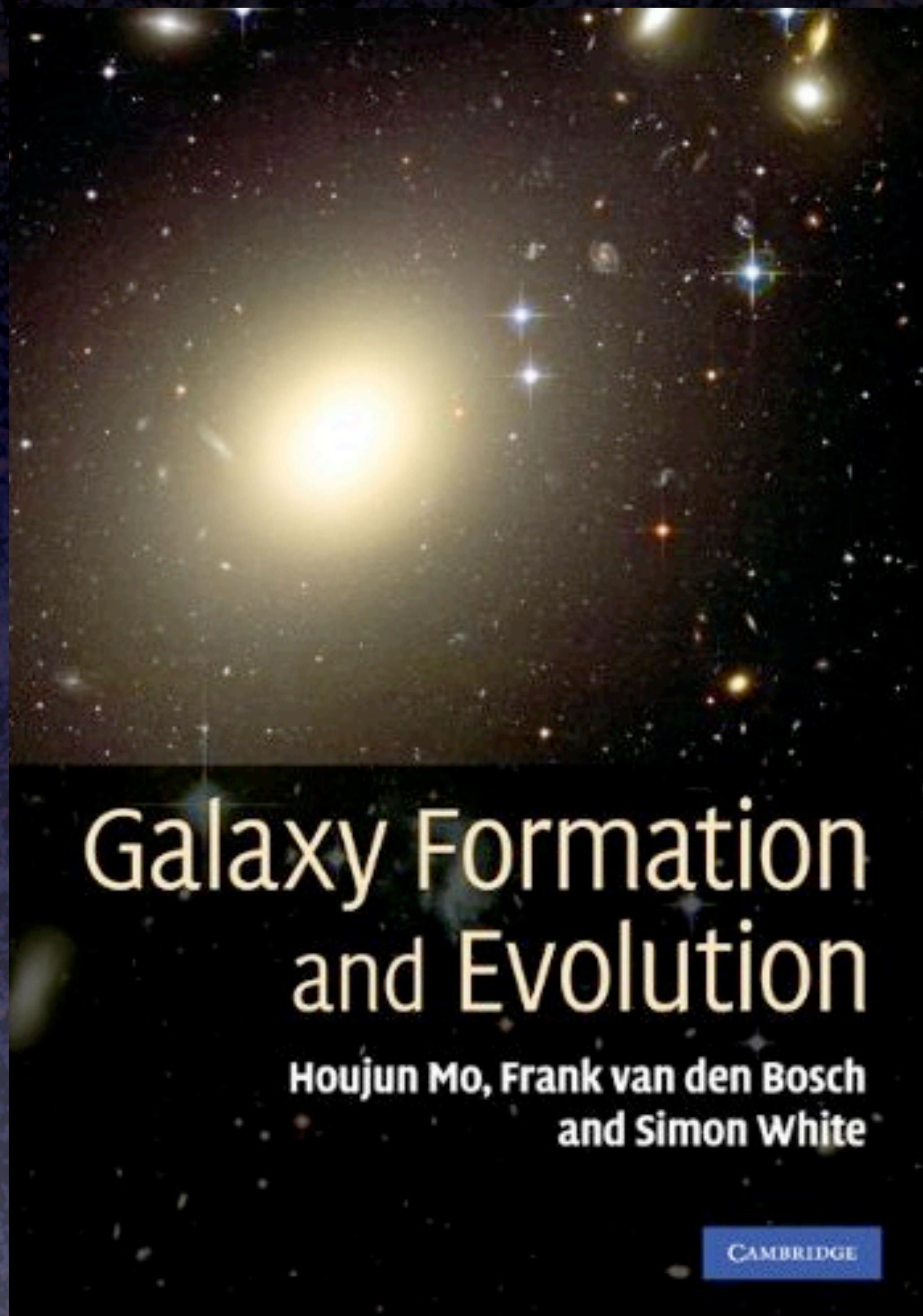

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