Halo bias, super-survey effects and cosmology

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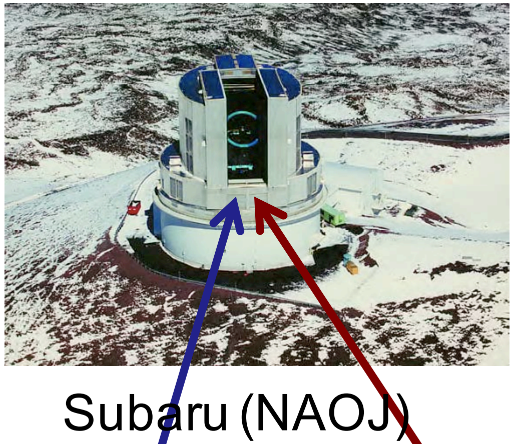
wpi

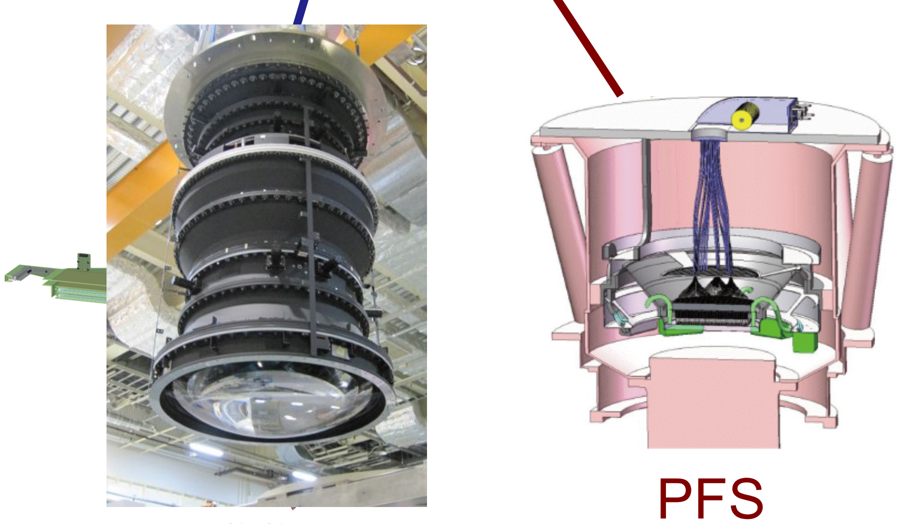
"Cosmology WS" @Kyoto, Nov, 2015

SuMIRe = Subaru Measurement of Images and Redshifts

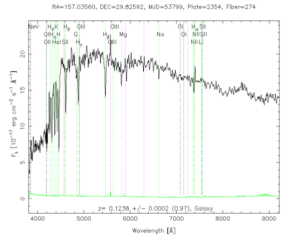
H. Murayama (Kavli IPMU Director)

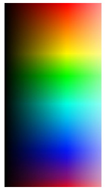
- IPMU director Hitoshi Murayama funded (~$32M) by the Cabinet in Mar 2009, as one of the stimulus package programs
- Build *wide-field* camera (Hyper Suprime-Cam) and *wide-field* multi-object spectrograph (Prime Focus Spectrograph) for the Subaru Telescope (8.2m)
- Explore the fate of our Universe: dark matter, dark energy
- Keep the Subaru Telescope a world-leading telescope in the TMT era
- Precise images of 1B galaxies
- Measure distances of ~4M galaxies
- **Do SDSS-like survey at z>1**





HSC





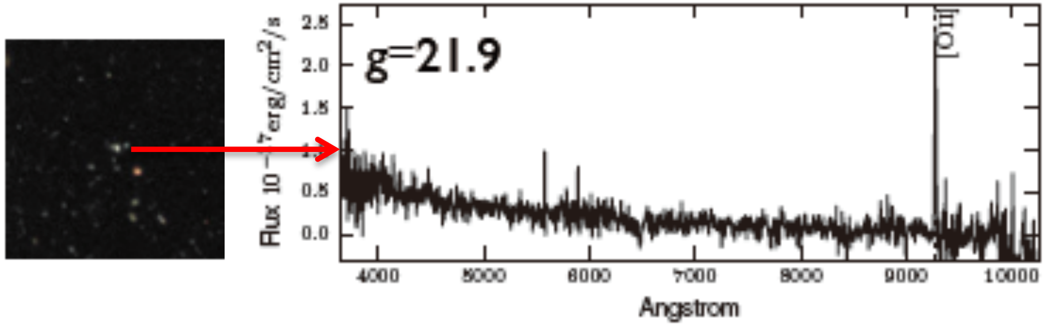
Galaxy survey; imaging vs. spectroscopy

Imaging

- Find objects
  - Stars, galaxies, galaxy clusters
- Measure the image shape of each object → *weak gravitational lensing*
- For cosmology purpose
  - *Pros*: many galaxies, a reconstruction of dark matter distribution
  - *Cons*: 2D information, limited redshift info. (photo-z at best)

Spectroscopy

- Measure the photon-energy spectrum of *target* object
- Distance to the object can be known → *3D clustering analysis*
- For cosmology
  - *Pros*: more fluctuation modes in 3D than in 2D
  - *Cons*: need the pre-imaging data for targeting; observationally more expensive (or less galaxies)

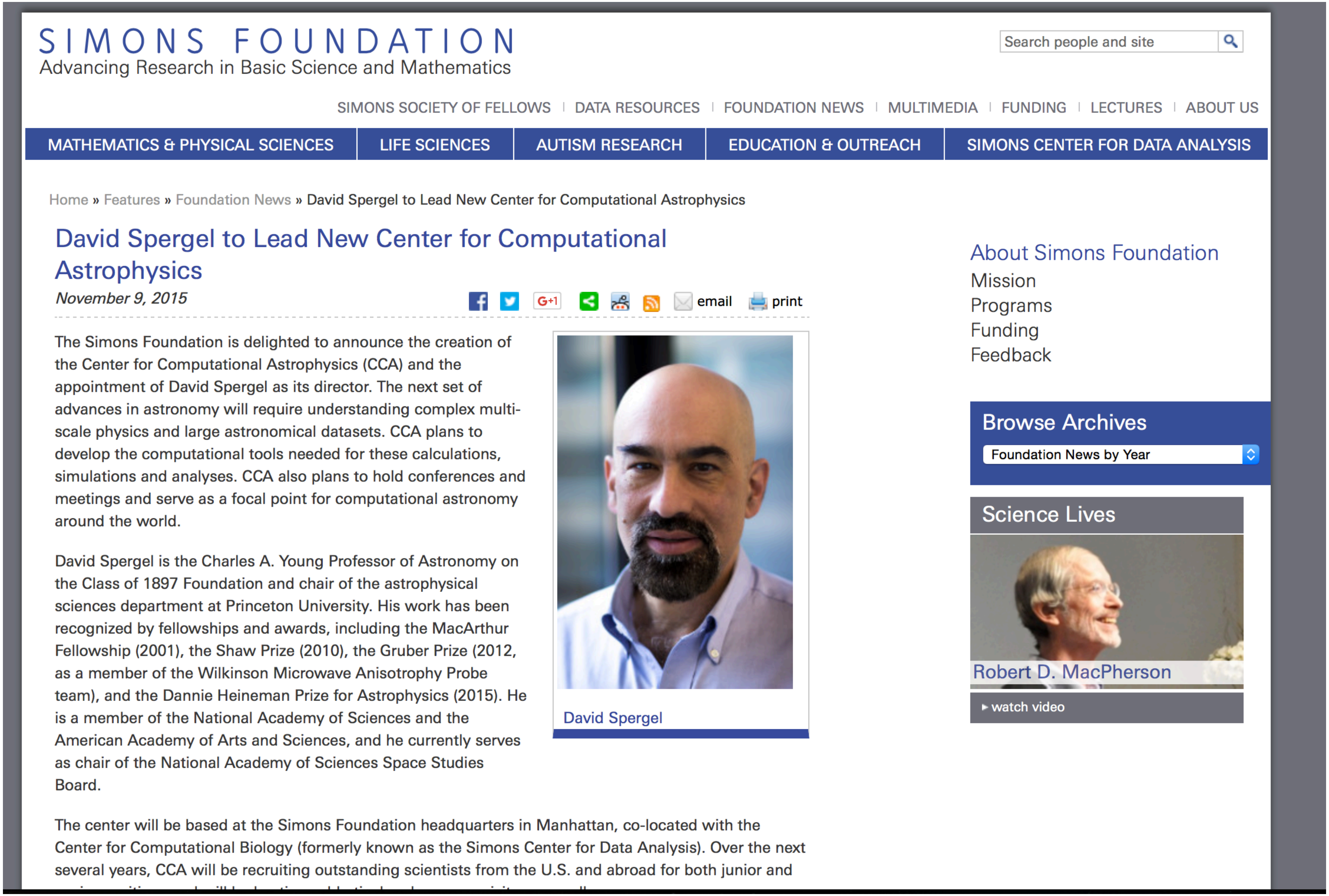


HSC/PFS collaboration

- Mailing lists (general discussion, each science working groups)
  ⇒ Ask either Takada, Oguri-san, Hamana san, …
- Wiki pages (sharing documents/material/information)
  - HSC: http://hscsurvey.pbworks.com
  - PFS: http://sumire.pbworks.com
- Collaboration meeting, Telecons…

@ PFS collaboration meeting

New center in Manhattan (HSC, PFS, LSST, WFIRST, …), ~60 scientists



David Spergel to Lead New Center for Computational Astrophysics

November 9, 2015

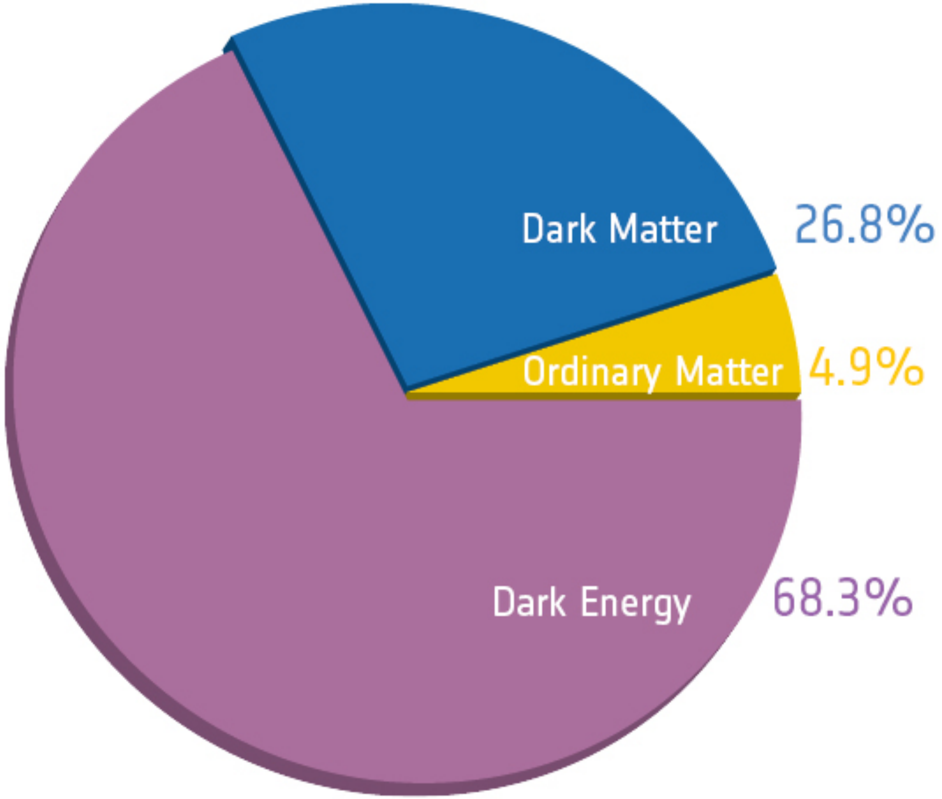
The Simons Foundation is delighted to announce the creation of the Center for Computational Astrophysics (CCA) and the appointment of David Spergel as its director. The next set of advances in astronomy will require understanding complex multi-scale physics and large astronomical datasets. CCA plans to develop the computational tools needed for these calculations, simulations and analyses. CCA also plans to hold conferences and meetings and serve as a focal point for computational astronomy around the world.

David Spergel

David Spergel is the Charles A. Young Professor of Astronomy on the Class of 1897 Foundation and chair of the astrophysical sciences department at Princeton University. His work has been recognized by fellowships and awards, including the MacArthur Fellowship (2001), the Shaw Prize (2010), the Gruber Prize (2012, as a member of the Wilkinson Microwave Anisotrophy Probe team), and the Dannie Heineman Prize for Astrophysics (2015). He is a member of the National Academy of Sciences and the American Academy of Arts and Sciences, and he currently serves as chair of the National Academy of Sciences Space Studies Board.

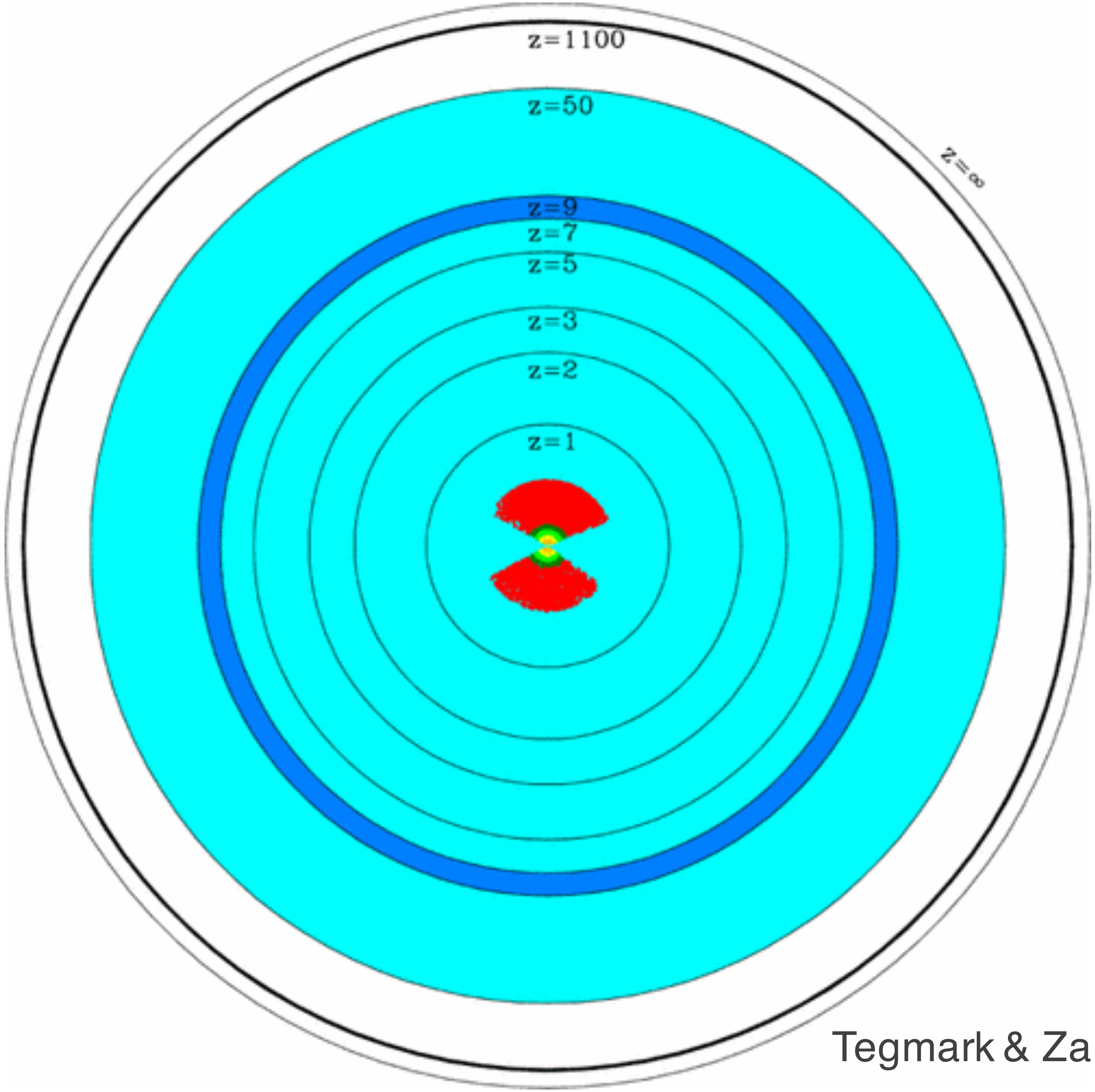
The center will be based at the Simons Foundation headquarters in Manhattan, co-located with the Center for Computational Biology (formerly known as the Simons Center for Data Analysis). Over the next several years, CCA will be recruiting outstanding scientists from the U.S. and abroad for both junior and

Science Objectives in 2020 era



- Dark energy/Gravity test
- Dark matter
- Neutrino mass
- Physics of inflation (curvature, PNG, primordial spectrum, isocurvature,….)

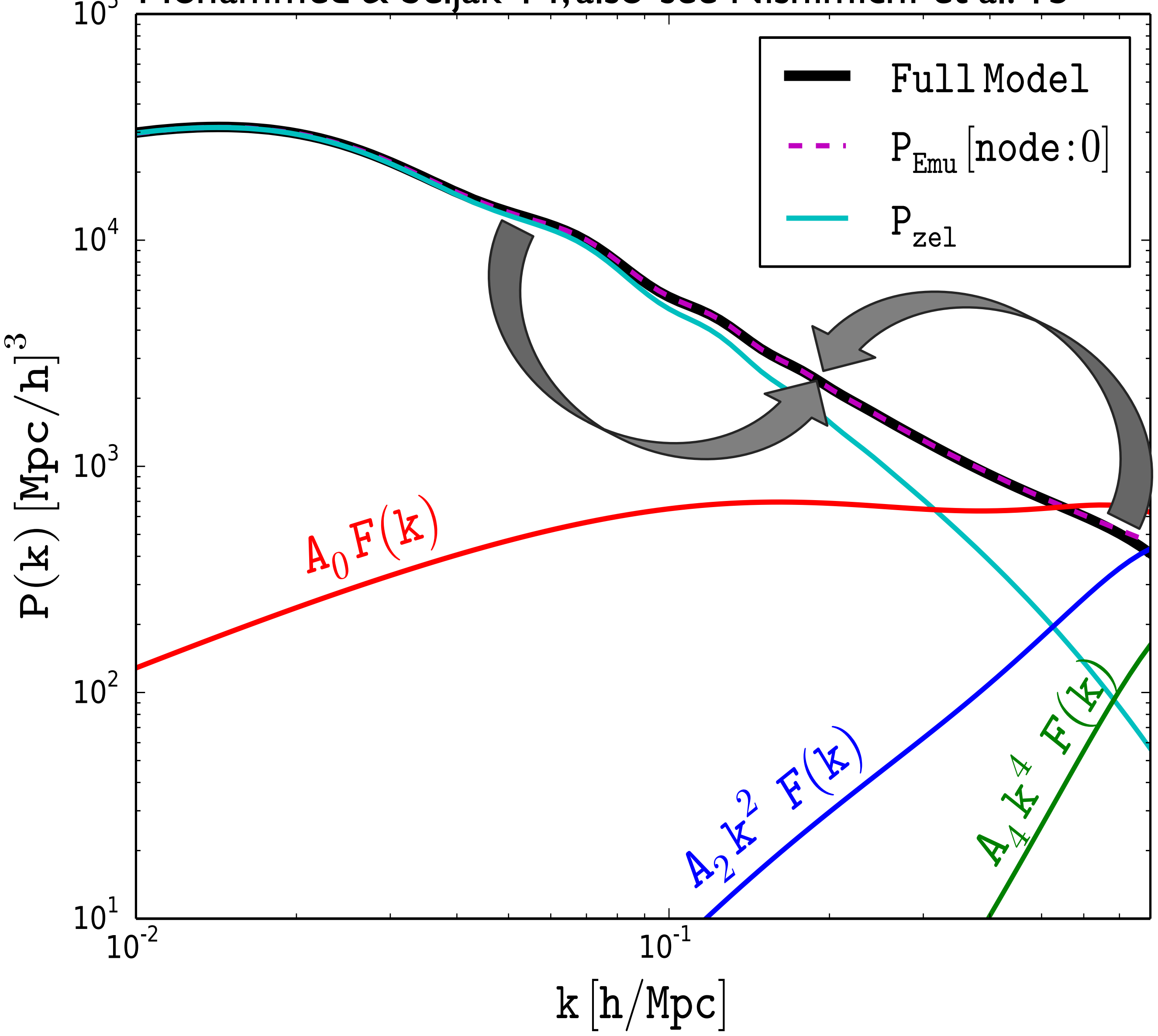
Cosmology with “3D” Galaxy Survey



- Wide-are galaxy surveys
- CMB=a 2D snapshot of the universe at z~1000
- Galaxy survey carries 3D information
- 3D≫2D
- Can be very powerful

Tegmark & Zaldarriaga 09

Challenge!: Nonlinear mode coupling



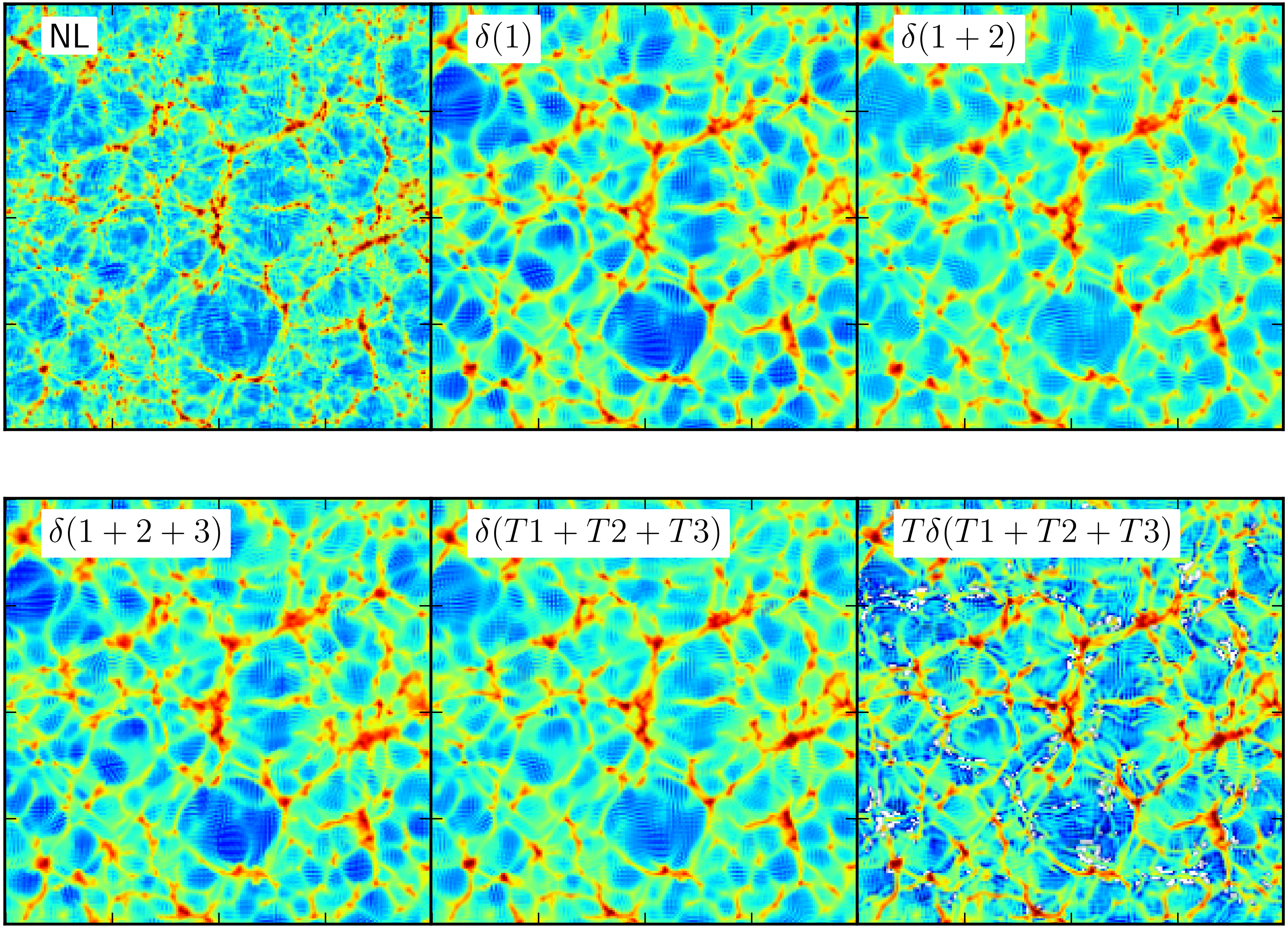
Mohammed & Seljak 14, also see Nishimichi et al. 15

- Peebles (1980)
- Non-linear gravity causes a mode-coupling btw different Fourier modes
  - Large-scale modes: can predict from ICs
  - Small scales: stochasticity due to halos ⇒ don't have robust predictions (baryon physics)
- *Goal*: up to k~a few 0.1 h/Mpc
- Nishimichi et al. 15

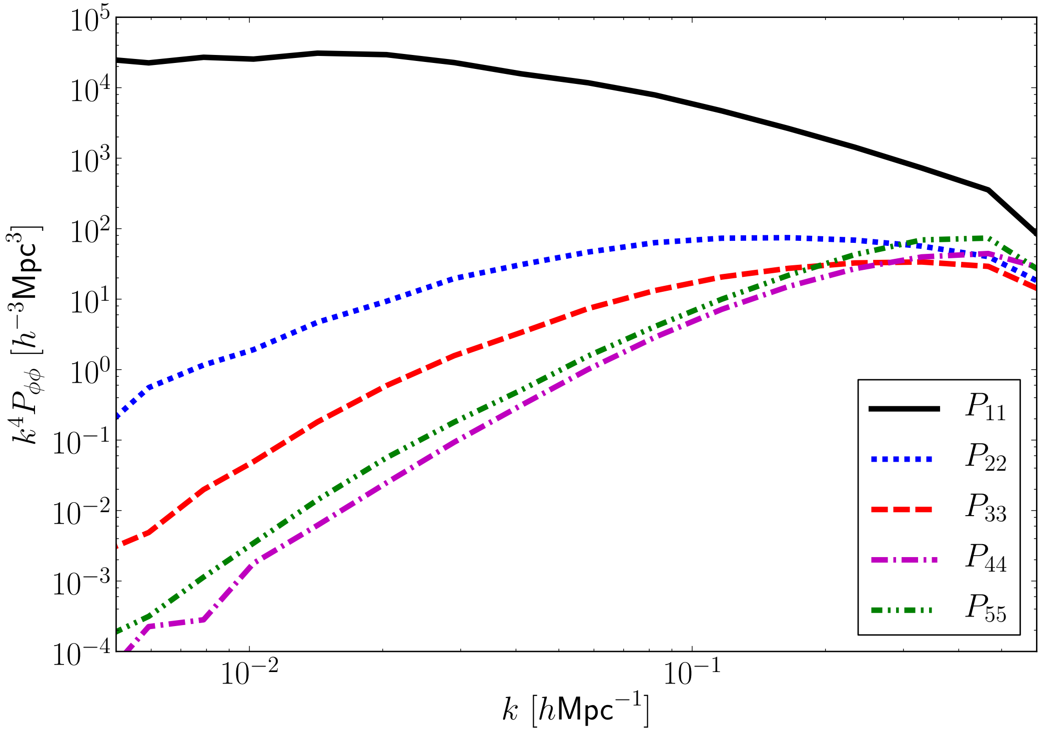
$$K(k,q;z)=q\frac{\partial P^{\rm NL}(k;z)}{\partial P^{\rm lin}(q;z)}$$

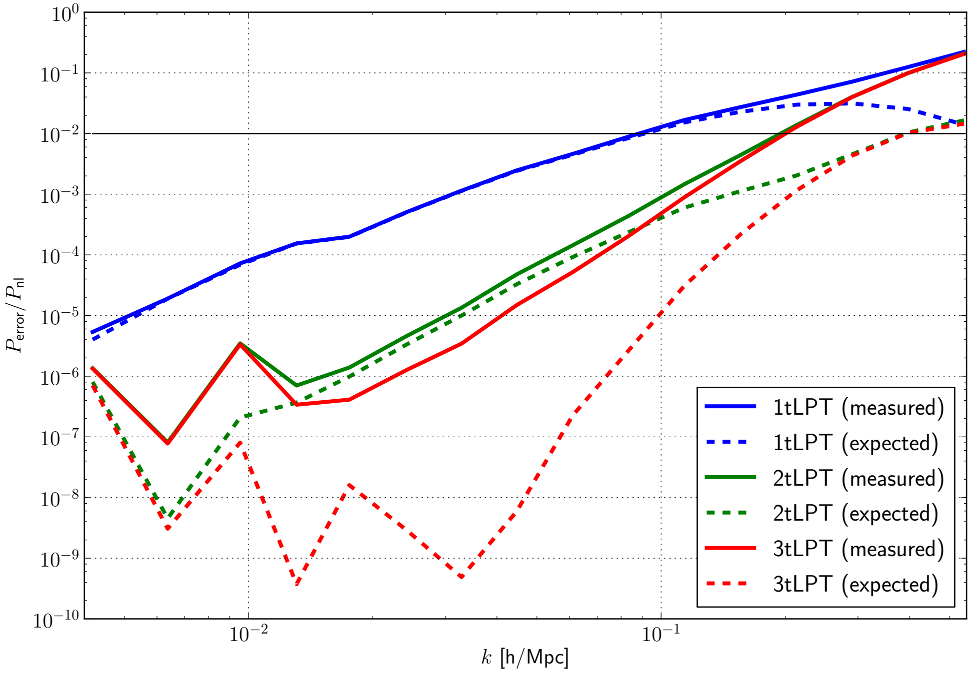
The limitation of PT

Baldauf, Schaan, Zaldarriaga 15a,b

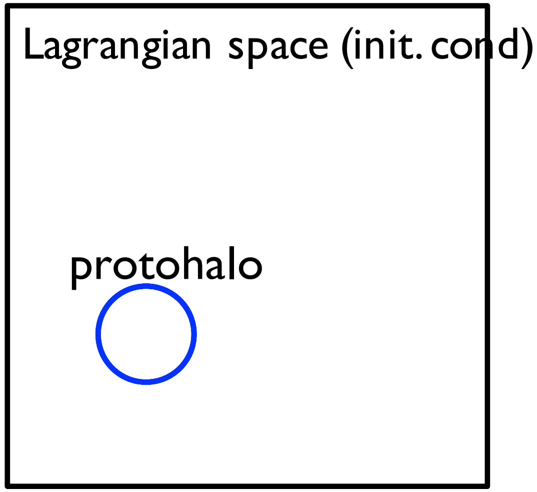


Stochasticity due to halos



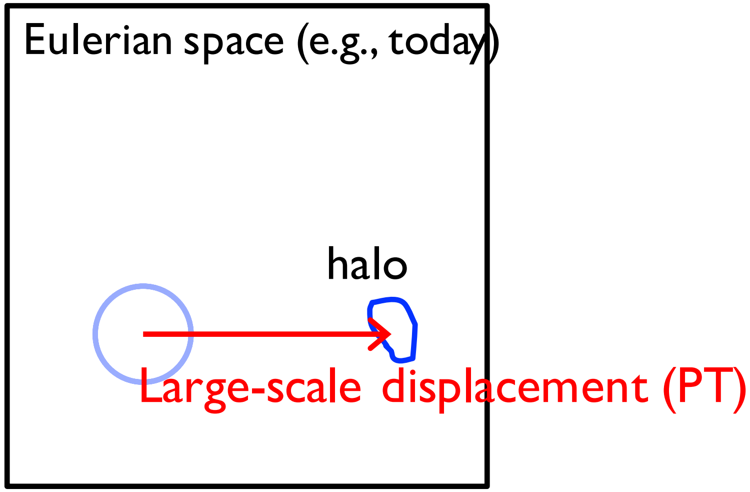


$$P^{\rm error}(k) = P^{\rm N-body}(k) - P^{\rm PT}(k)$$



Lagrangian space (init. cond)

protohalo

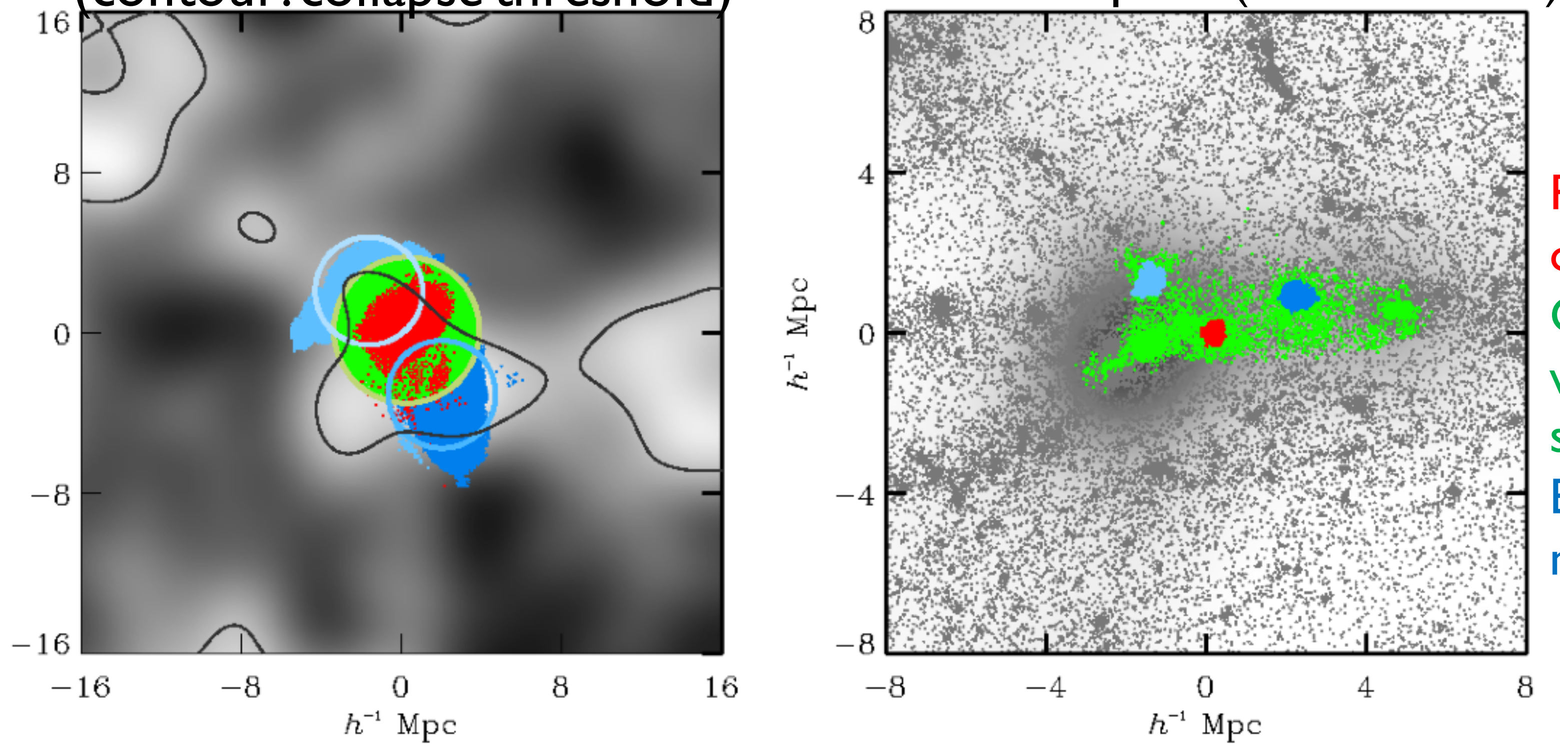


Eulerian space (e.g., today)

halo

Large-scale displacement (PT)

Refinement of halo model



smoothed initial field
(contour: collapse threshold)

Eulerian space (around halos)

Red: member particles of central halo

Green: particles within Lagrangian sphere

Blue(s): particles in neighboring halos

- Halo boundary
- Stochastic/discrete nature of halos
- Halo density profile
- Number of halos

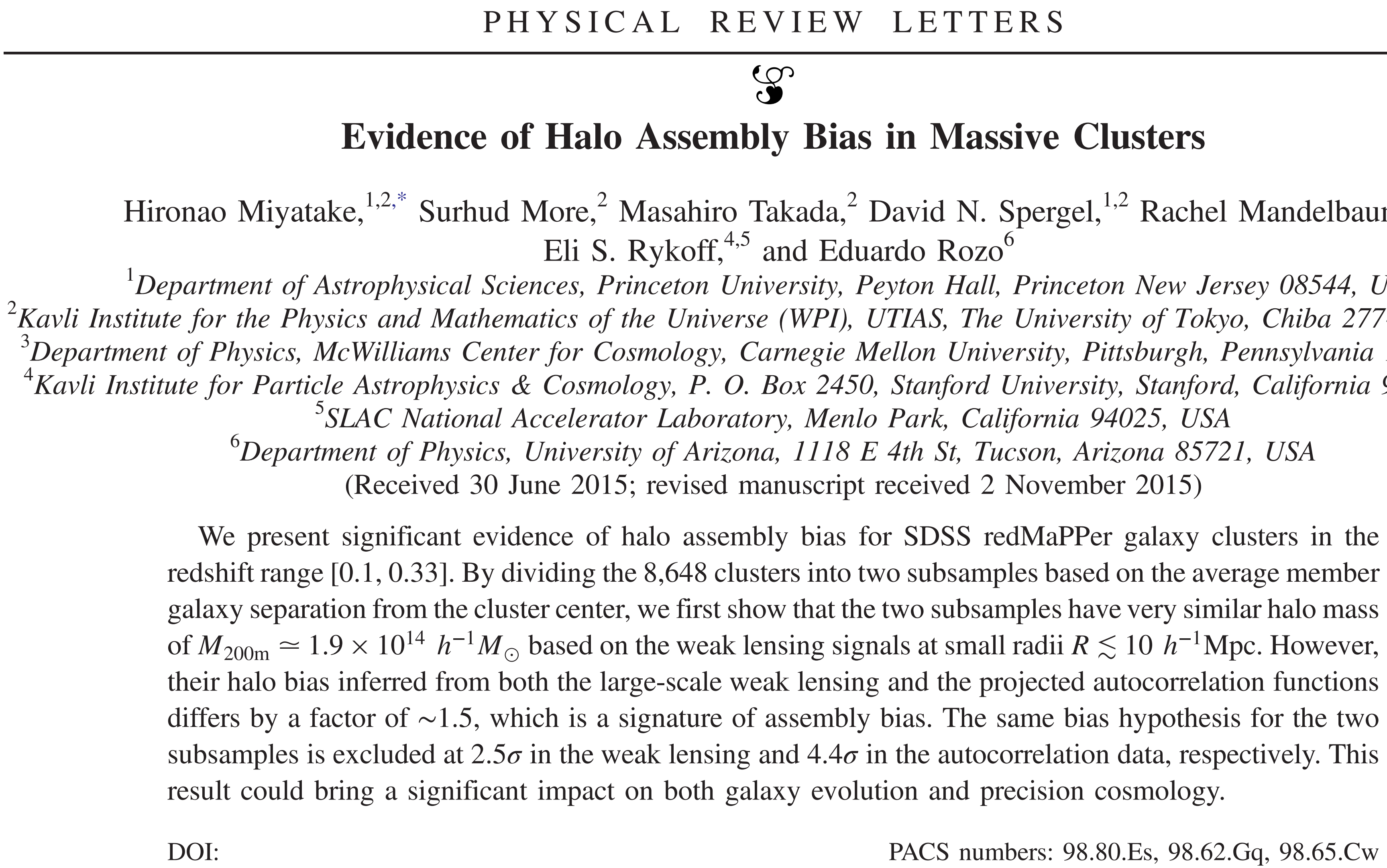
Cooray & Sheth 01
Valageas & Nishimichi 11a,b
Mohammed & Seljak 14
Baldauf, Schaan et al. 15a,b
Baldauf et al. 15
Schmidt 15

Combining cosmological probes (imaging+spec-z)

H. Miyatake
(JPL/Caltech)

S. More
(IPMU)

Coming soon (Dec 21): Editor's suggestion



PHYSICAL REVIEW LETTERS

Evidence of Halo Assembly Bias in Massive Clusters

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(Received 30 June 2015; revised manuscript received 2 November 2015)

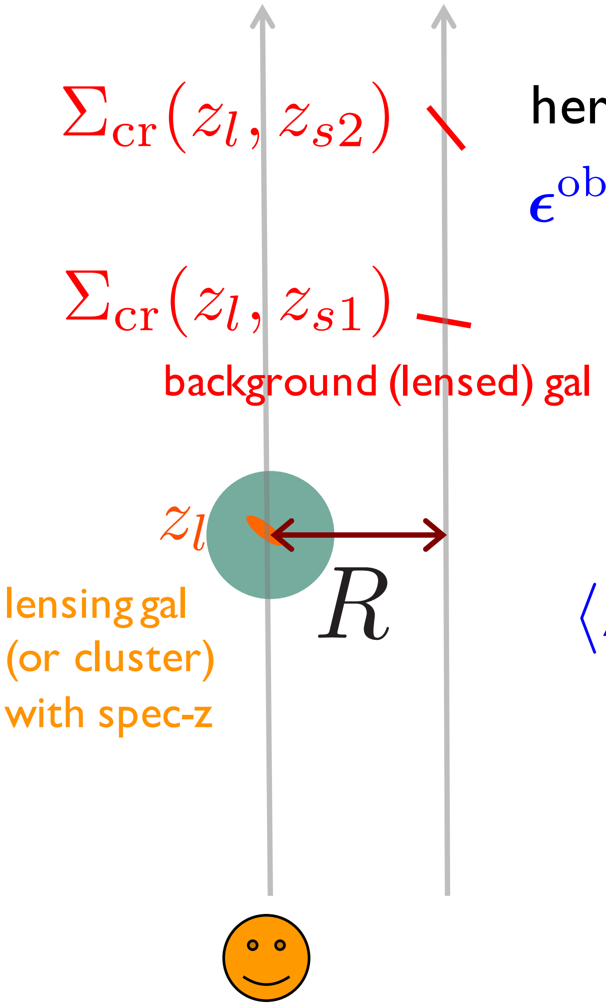
We present significant evidence of halo assembly bias for SDSS redMaPPer galaxy clusters in the redshift range [0.1, 0.33]. By dividing the 8,648 clusters into two subsamples based on the average member galaxy separation from the cluster center, we first show that the two subsamples have very similar halo mass of $M_{200\mathrm{m}} \simeq 1.9 \times 10^{14}\ h^{-1} M_\odot$ based on the weak lensing signals at small radii $R \lesssim 10\ h^{-1}$Mpc. However, their halo bias inferred from both the large-scale weak lensing and the projected autocorrelation functions differs by a factor of ~1.5, which is a signature of assembly bias. The same bias hypothesis for the two subsamples is excluded at 2.5σ in the weak lensing and 4.4σ in the autocorrelation data, respectively. This result could bring a significant impact on both galaxy evolution and precision cosmology.

DOI: PACS numbers: 98.80.Es, 98.62.Gq, 98.65.Cw

Galaxy (Cluster)-galaxy lensing

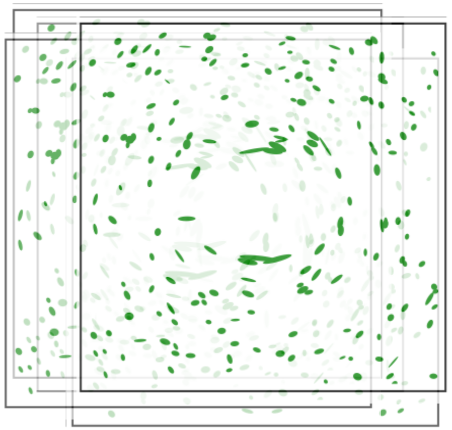
Oguri & MT 11

$$\widehat{\langle\Delta\Sigma\rangle}(R) = \frac{1}{N_{\rm pair}} \sum_{\text{all pairs};\, z_l, z_s} \Sigma_{\rm cr}(z_l, z_s)\,\epsilon_+^{(z_s)}\Big|_{R=\chi_l\Delta\theta_{ls}}$$



here

$$\boldsymbol{\epsilon}^{\rm obs} = \Sigma_{\rm cr}^{-1}(z_l, z_s)\boldsymbol{\Delta\Sigma}^{\rm lens} + \boldsymbol{\gamma}^{\rm cs} + \boldsymbol{\epsilon}^{\rm int}$$

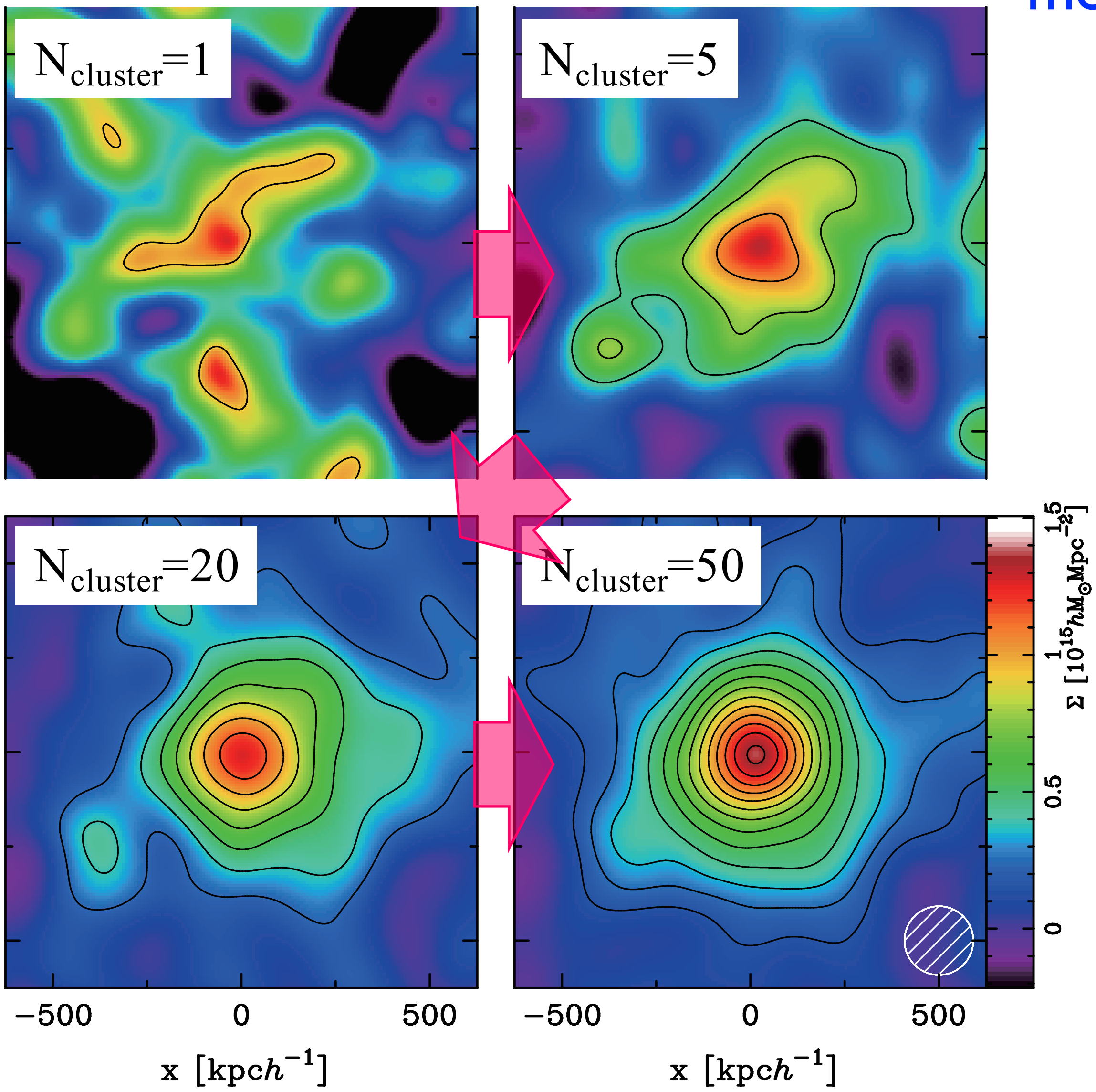


$$\langle\Delta\Sigma\rangle(R) = \int \frac{k\mathrm{d}k}{2\pi} P_{\rm hm}(k) J_2(kR)$$

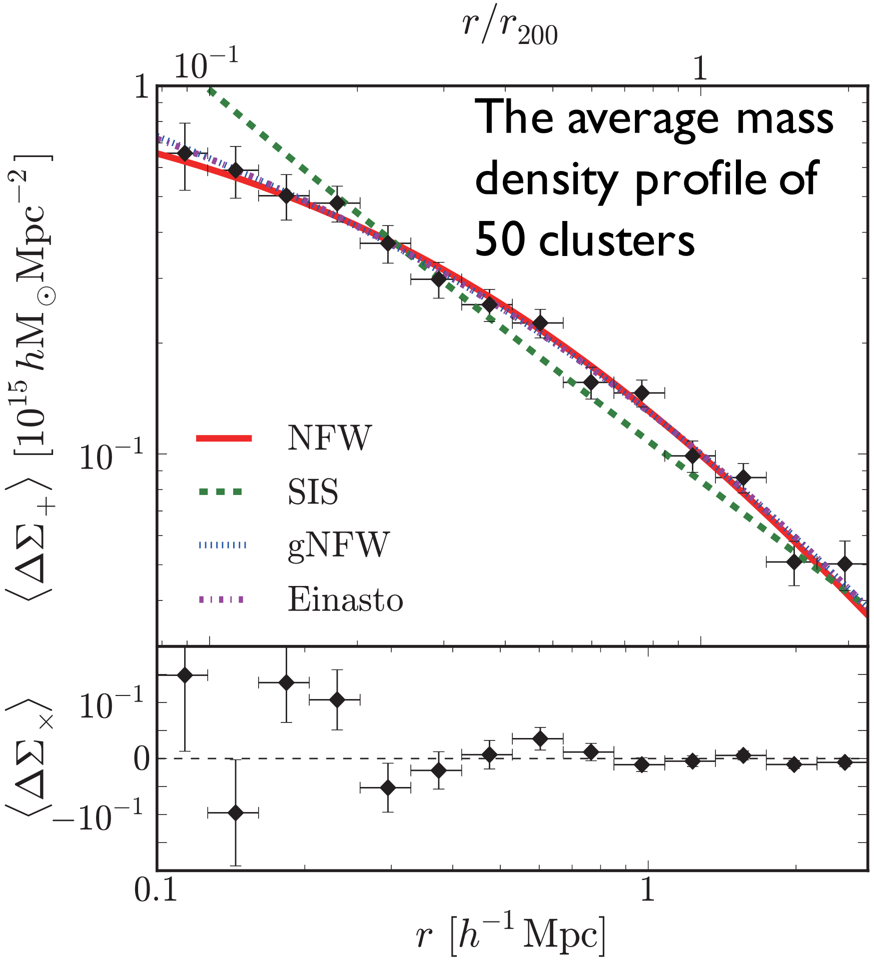
- Directly probe the “3D” halo-matter power spectrum

Cluster-galaxy lensing

Okabe et al. 13; Niikura et al. 15

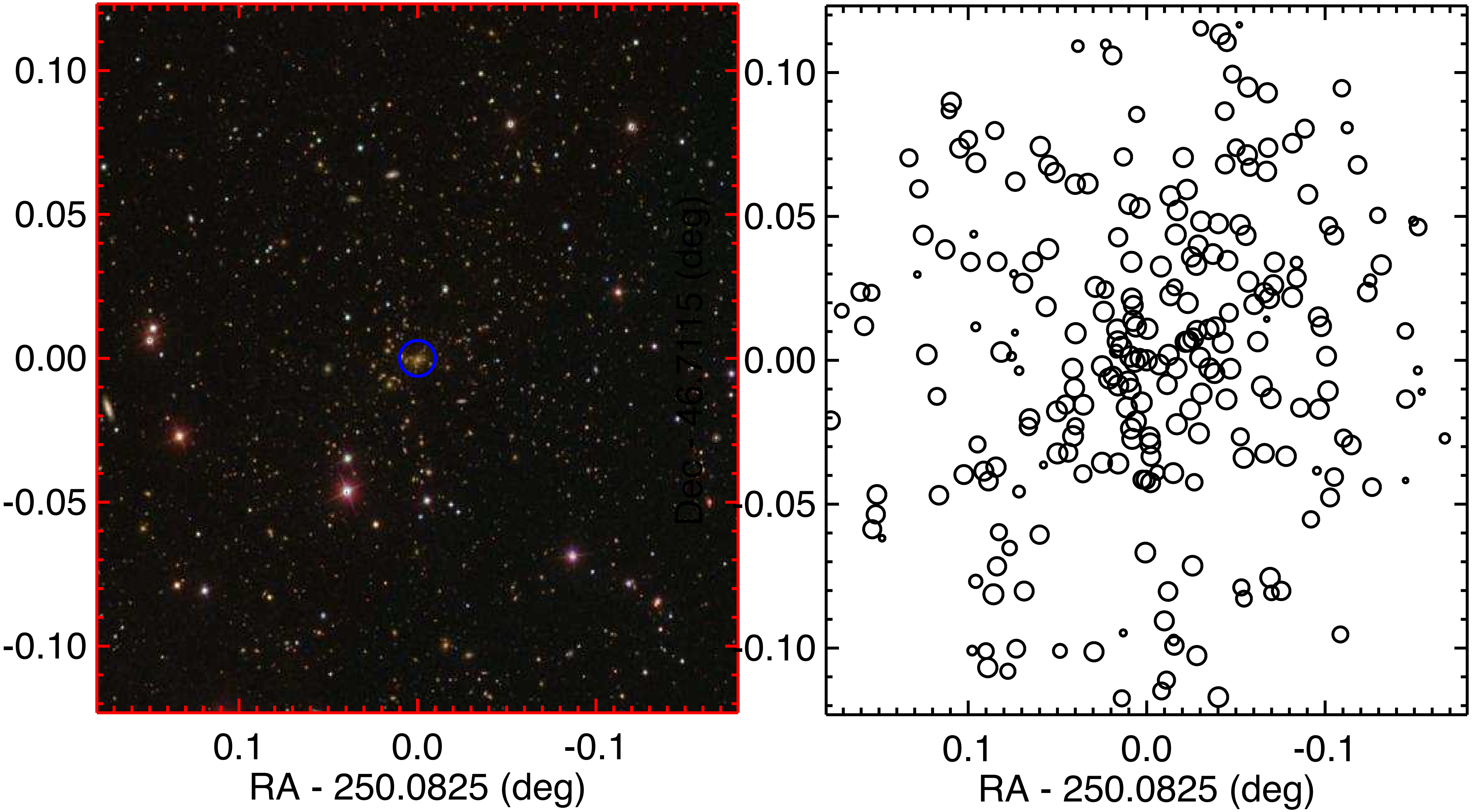


Subaru WL measurements of 50 most massive clusters



The average mass density profile of 50 clusters

Clusters = Most massive self-grav. system



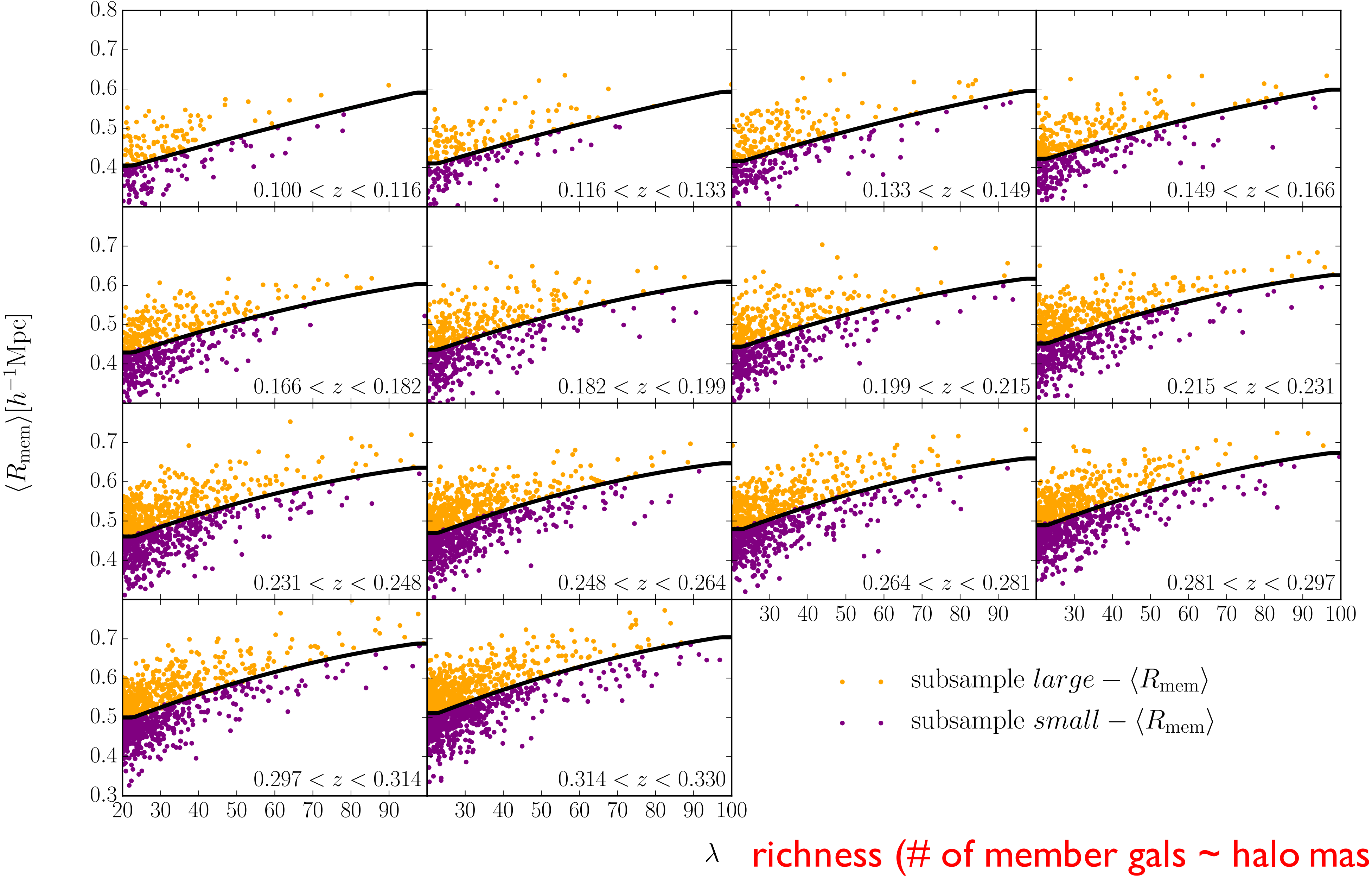
Clusters easy to find…

Rykoff, Rozo+ 2014

~9000 clusters from SDSS DR8

concentration of member galaxies

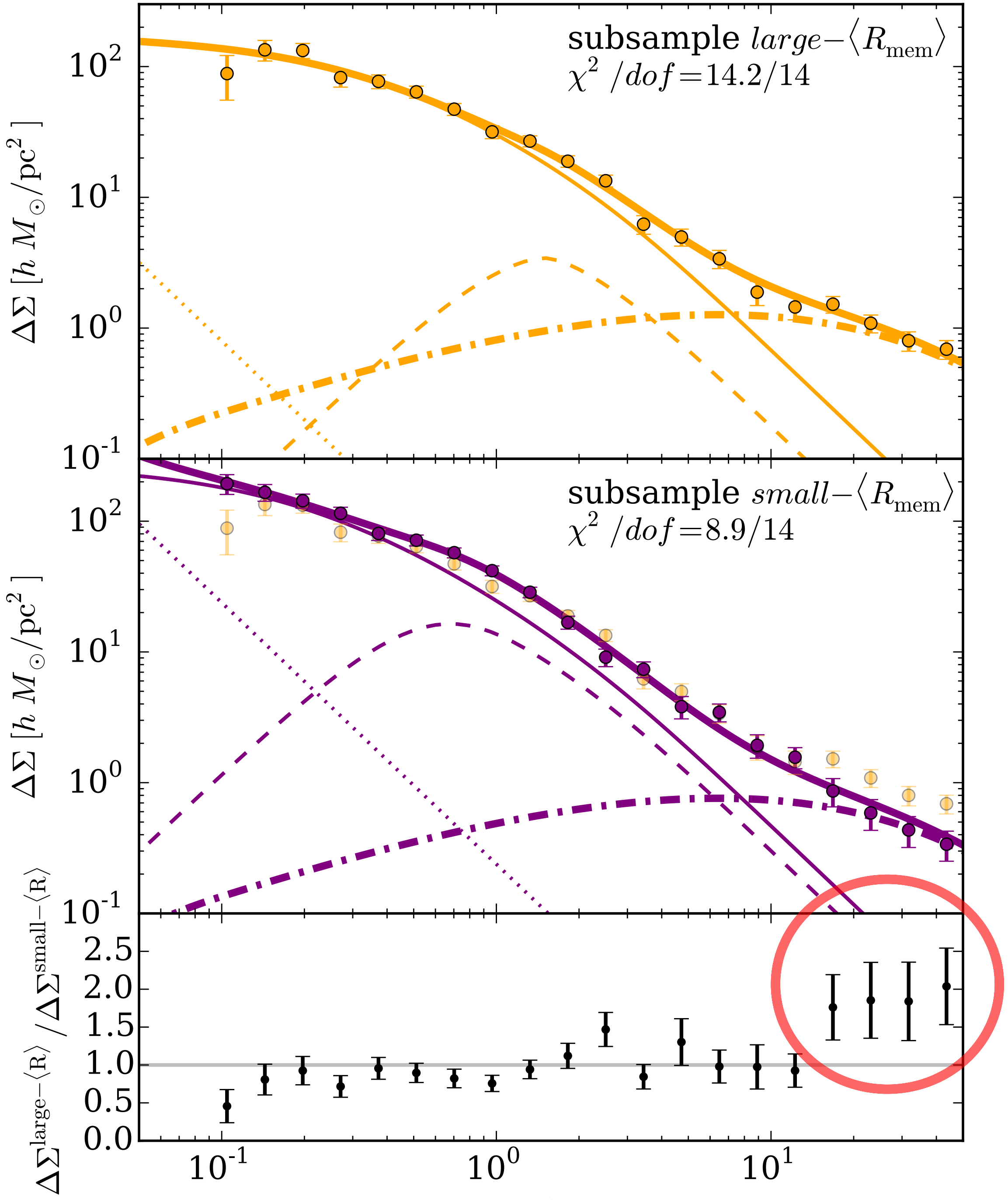
$$\langle R_{\rm mem}\rangle = \sum_i p_{{\rm mem},i} R_{{\rm mem},i} \Big/ \sum_i p_{{\rm mem},i}$$



concentration of member gals

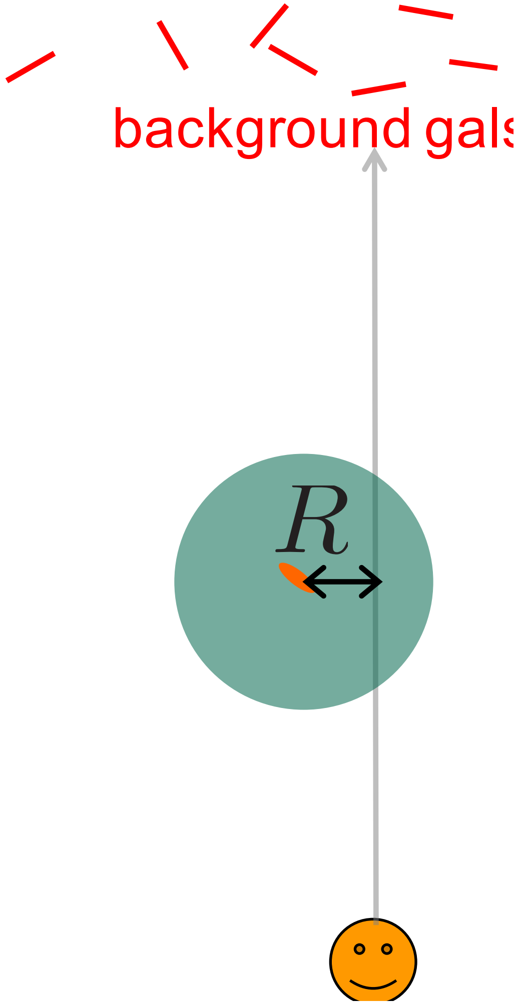
richness (# of member gals ~ halo mas

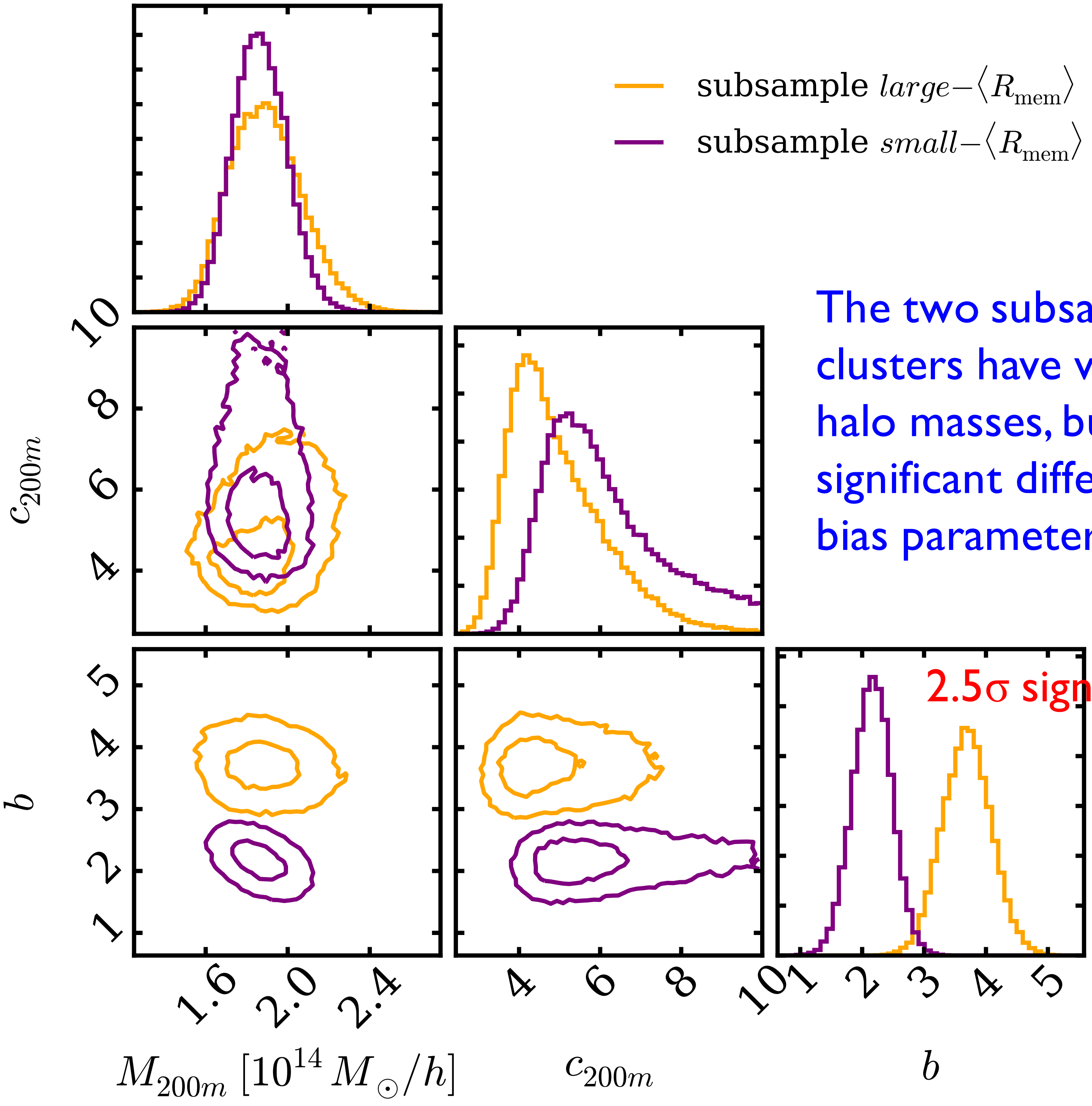
Weak lensing signal



Proxy of halo assembly history for each cluster

$$\langle R_{\rm mem}\rangle \equiv \frac{\sum_i p_{{\rm mem},i} R_{{\rm mem},i}}{\sum_i p_{{\rm mem},i}}$$

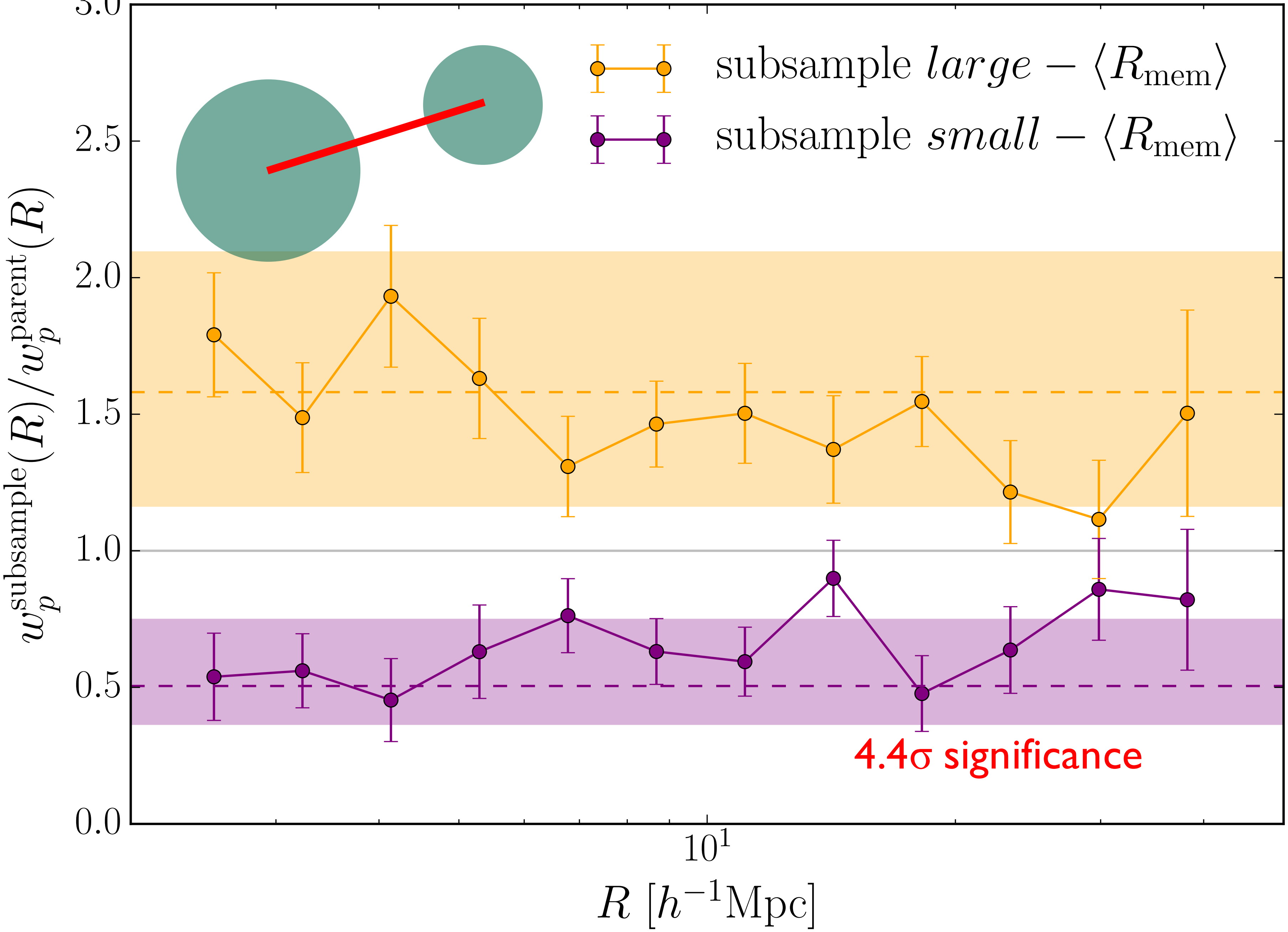




2.5σ significance

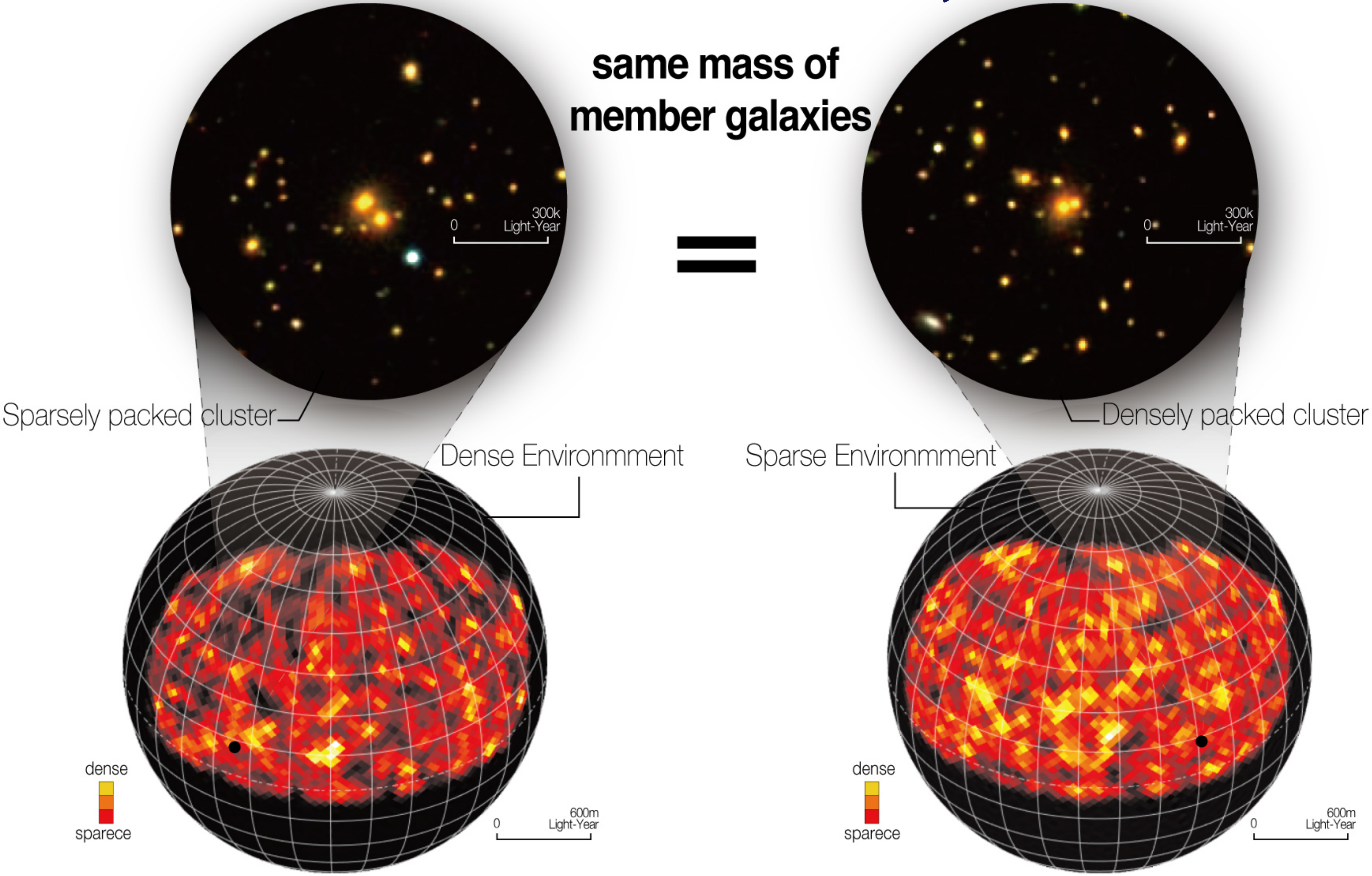
The two subsamples of clusters have very similar halo masses, but display a significant difference of their bias parameters

Auto-correlation functions of the two subsamples



4.4σ significance

Detection of Halo Assembly Bias



same mass of member galaxies

=

Sparsely packed cluster

Densely packed cluster

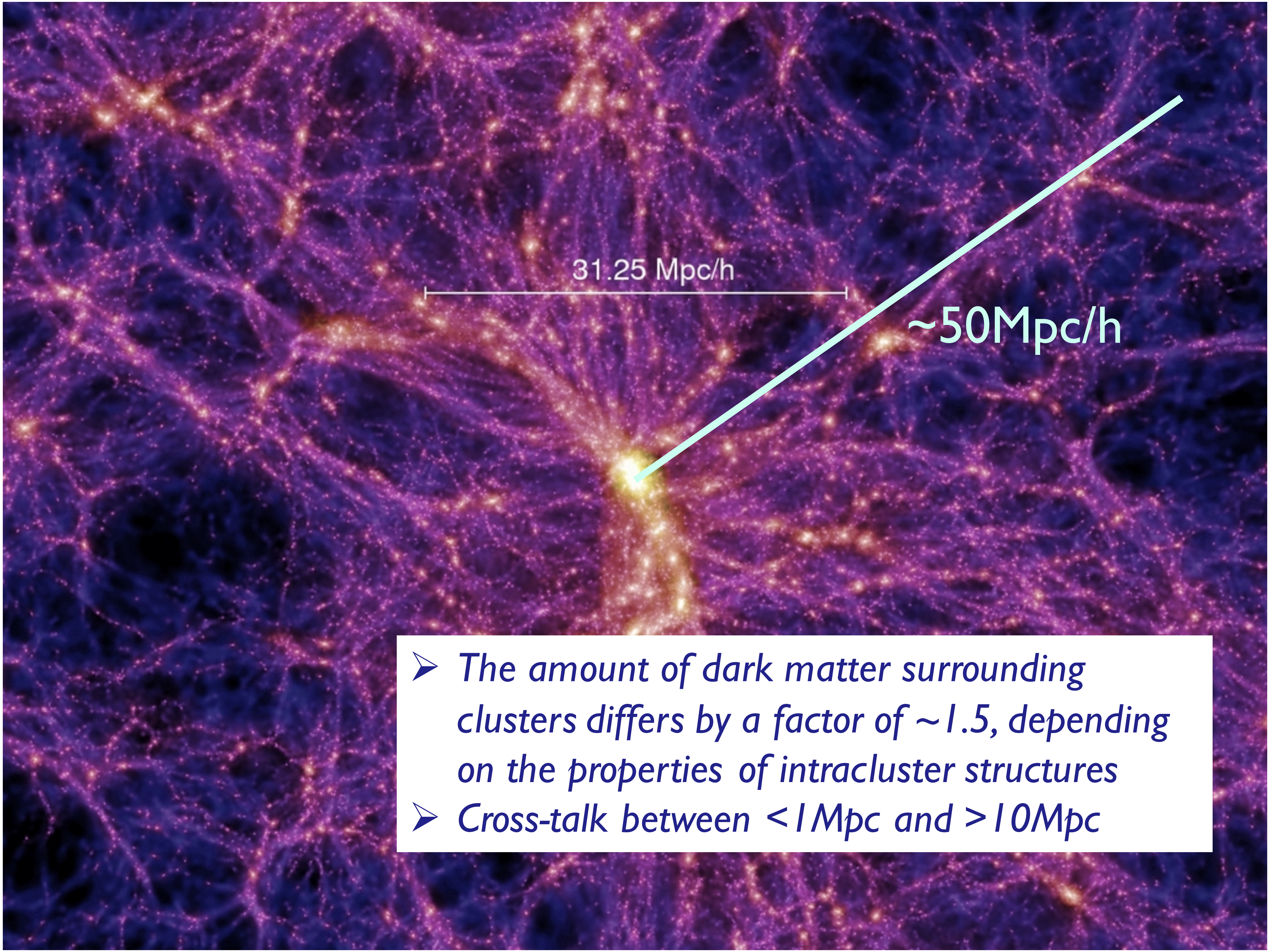
Dense Environmment

Sparse Environmment

density map of galaxy cluster distribution on the sky

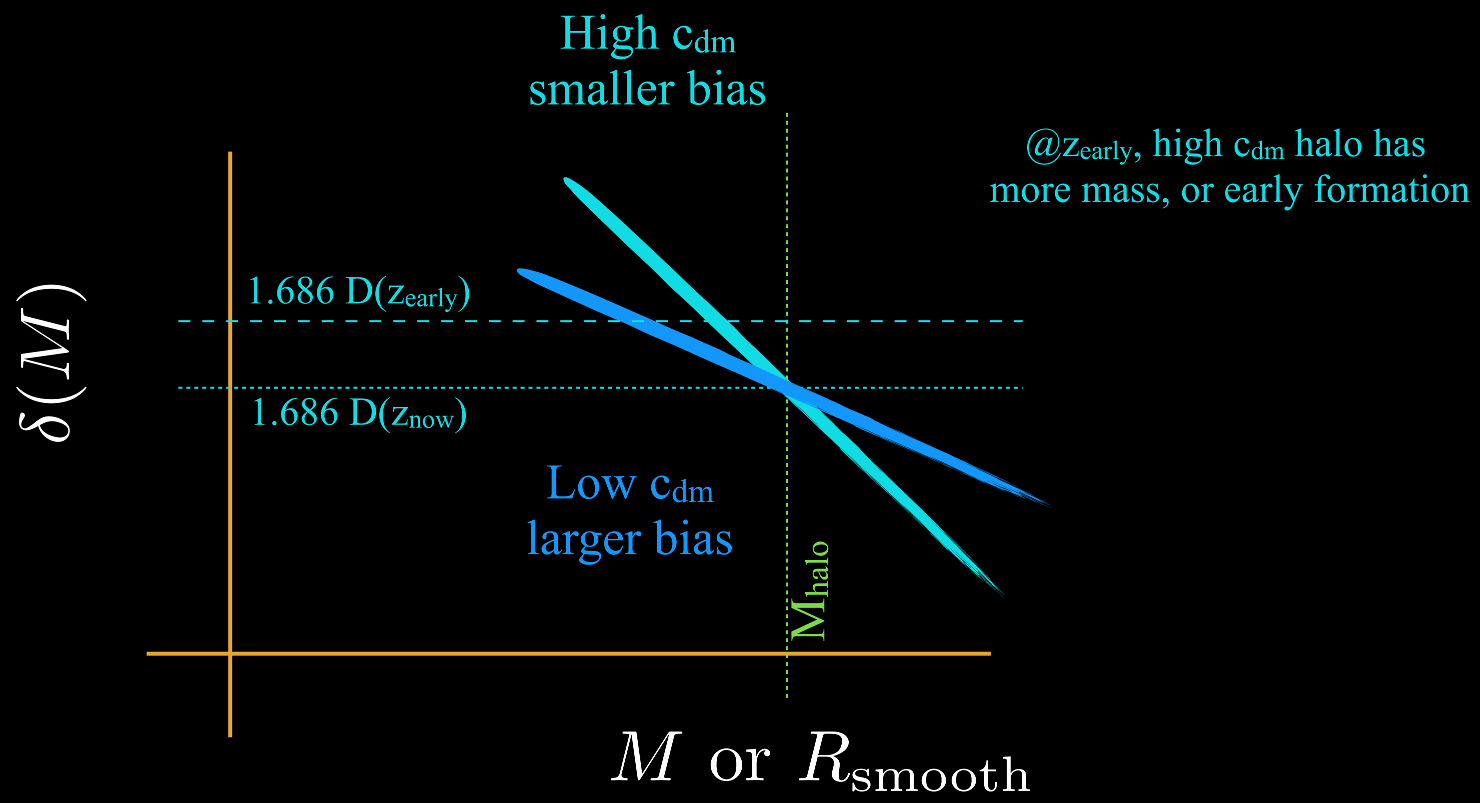
density map of galaxy cluster distribution on the sky

For press release….



- The amount of dark matter surrounding clusters differs by a factor of ~1.5, depending on the properties of intracluster structures
- Cross-talk between <1Mpc and >10Mpc

Halo assembly bias



- The cartoon picture! See Dalal et al. 2008 for equations.

THE ASTROPHYSICAL JOURNAL, **304**:15–61, 1986 May 1

BBKS

THE STATISTICS OF PEAKS OF GAUSSIAN RANDOM FIELDS

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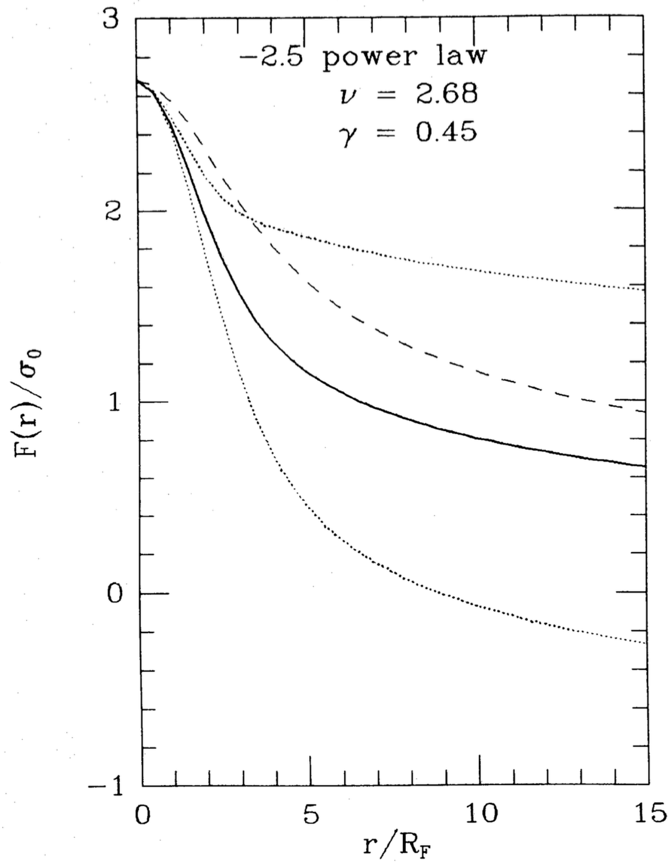
Received 1985 July 25; accepted 1985 October 9

Can be modified by
Primordial NG
Massive neutrinos
Modified gravity
....



ABSTRACT

ıs are often assumed to be Gaussian random fields. The local maxima of
e formation of nonlinea
nces and clustering prop
eaks of various heights
cale overdense regions; (
ted, with special emphas
eaks. To illustrate the p
rmation in the adiabati
form only at those peak
ıold height $\nu_t \approx 3$ fixed by normalizing to the galaxy number density. We
ıf the peak-peak two- and three-point correlation functions for the adiabatic

$$b_1 \simeq 1 + \frac{1}{\sigma(M)}\frac{\nu - \gamma x}{1-\gamma^2}$$

$$\gamma \equiv \langle \nu x \rangle$$

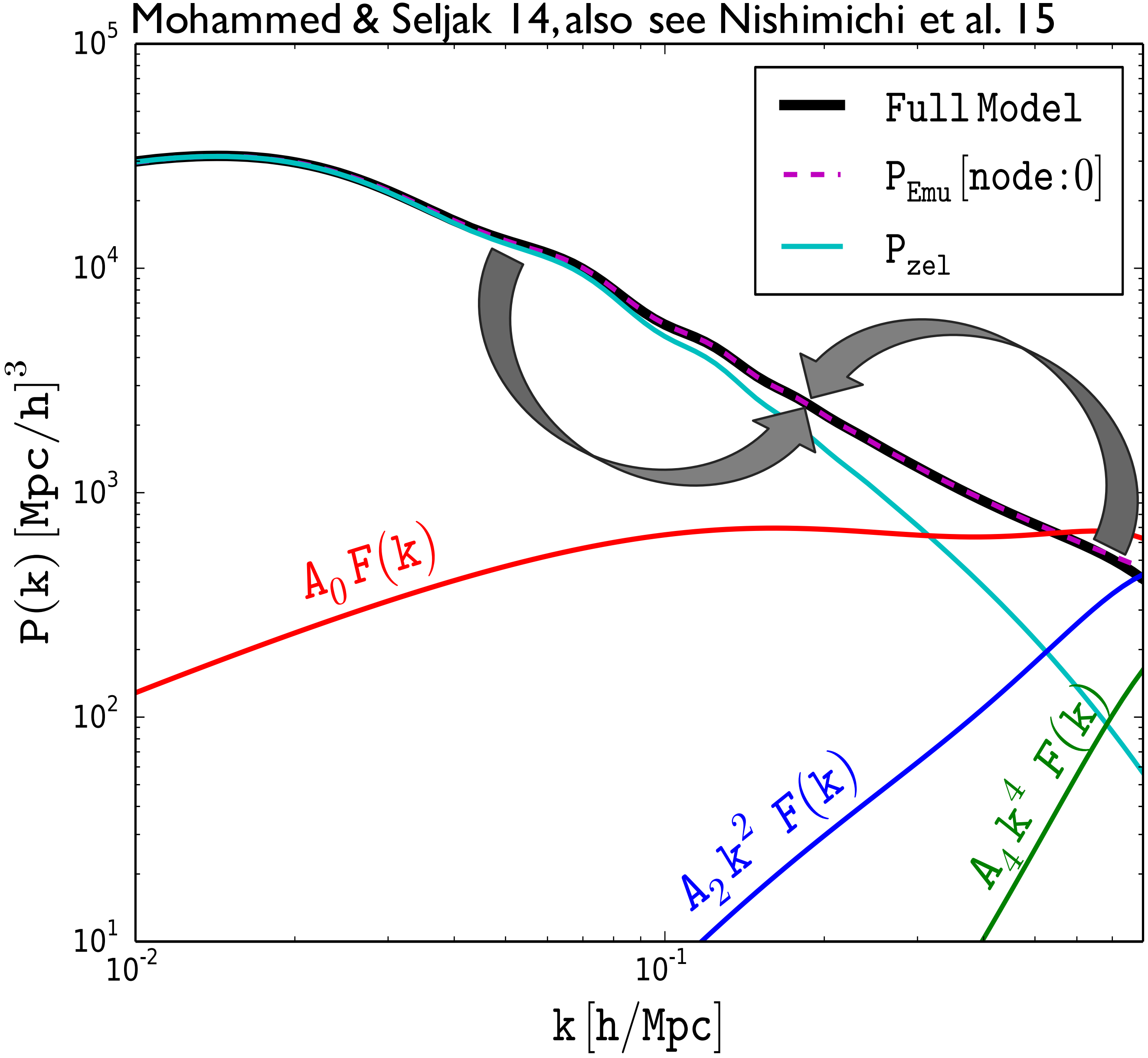
x : curvature of density peak

$$\frac{\bar{F}(\boldsymbol{r})}{\sigma_0} = \frac{\langle F(\boldsymbol{r})\,|\,C\rangle}{\sigma_0} = \frac{\nu}{(1-\gamma^2)}\left(\psi + \frac{\nabla^2\psi}{3}\right) - \frac{x/\gamma}{(1-\gamma^2)}\left(\gamma^2\psi + \frac{\nabla^2\psi}{3}\right) + \frac{5}{2}\left(\frac{x}{\gamma}\right)\left(\frac{\psi'}{r} - \frac{\nabla^2\psi}{3}\right)A(e, p)\,,$$

3–4 is predicted. We show that the mass-per-peak ratio in clusters, and thus presumably the cluster mass-to-

Nonlinear mode coupling

Mohammed & Seljak 14, also see Nishimichi et al. 15



- Peebles (1980)
- Non-linear gravity causes a mode-coupling btw different Fourier modes
  - Large-scale modes: we can predict from initial conditions
  - Small scales: stochasticity due to halos $\Rightarrow$ don't have robust prediction (baryon physics)
- Nishimichi et al. 15

$$K(k,q;z) = q\frac{\partial P^{\mathrm{NL}}(k;z)}{\partial P^{\mathrm{lin}}(q;z)}$$

Super-survey (sample) modes

MT & Hu 13

- The observed field is given as

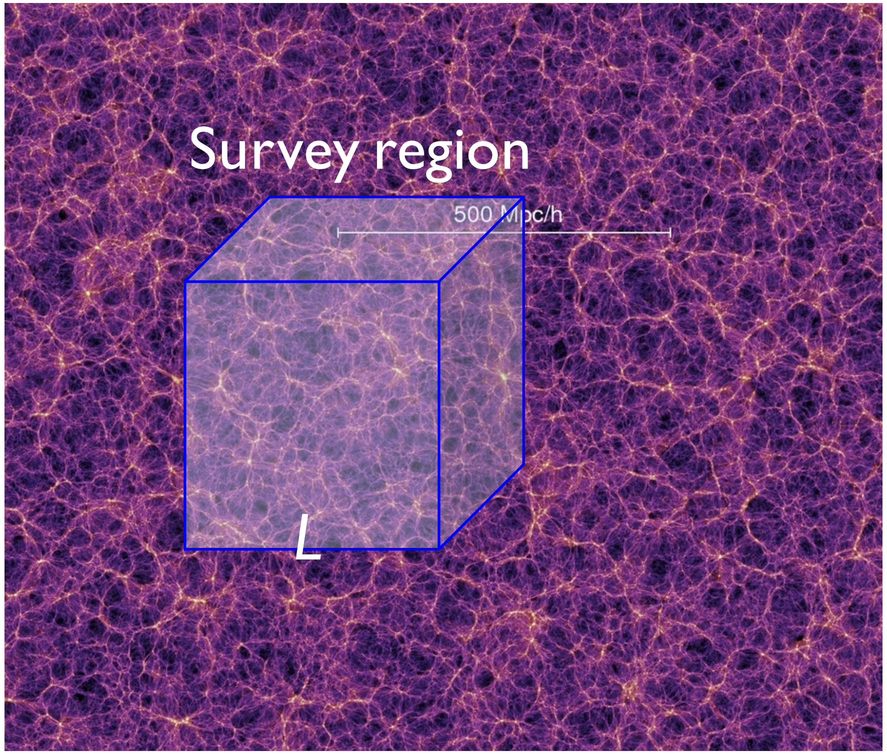
$$\delta_W(\mathbf{x}) = W(\mathbf{x})\delta(\mathbf{x})$$

$W(\mathbf{x}) = 1 \text{ if } \mathbf{x} \in \mathbf{S}$

$\text{otherwise } W(\mathbf{x}) = 0$

- The Fourier-transformed field is

$$\tilde{\delta}_{W,\mathbf{k}} = \int \frac{d^3\mathbf{q}}{(2\pi)^3} \tilde{W}_{\mathbf{k}-\mathbf{q}} \tilde{\delta}_{\mathbf{q}}$$



  - The width of W(k) is ~1/L
  - In this way, we can explicitly include contributions of modes outside a survey region

- The background density mode within a survey region

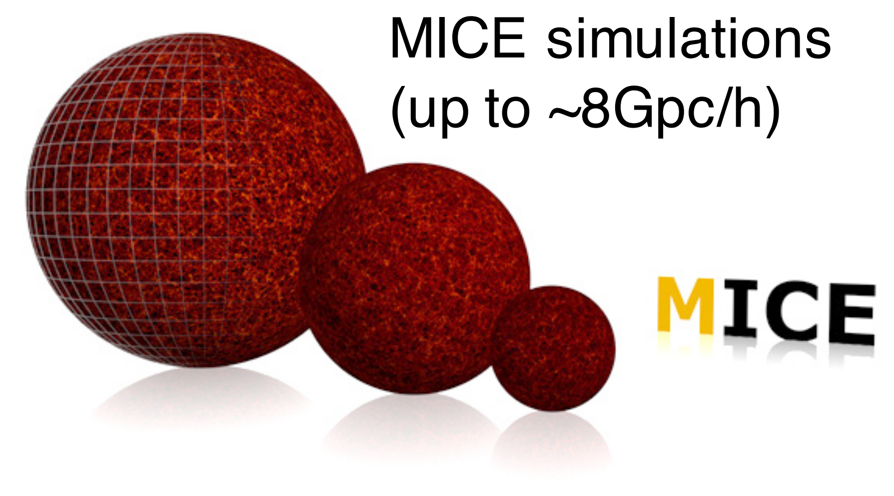
$$\bar{\delta}_b = \frac{1}{V_S} \int d^3\mathbf{x} W(\mathbf{x})\delta(\mathbf{x})$$

generally non-zero on realization basis

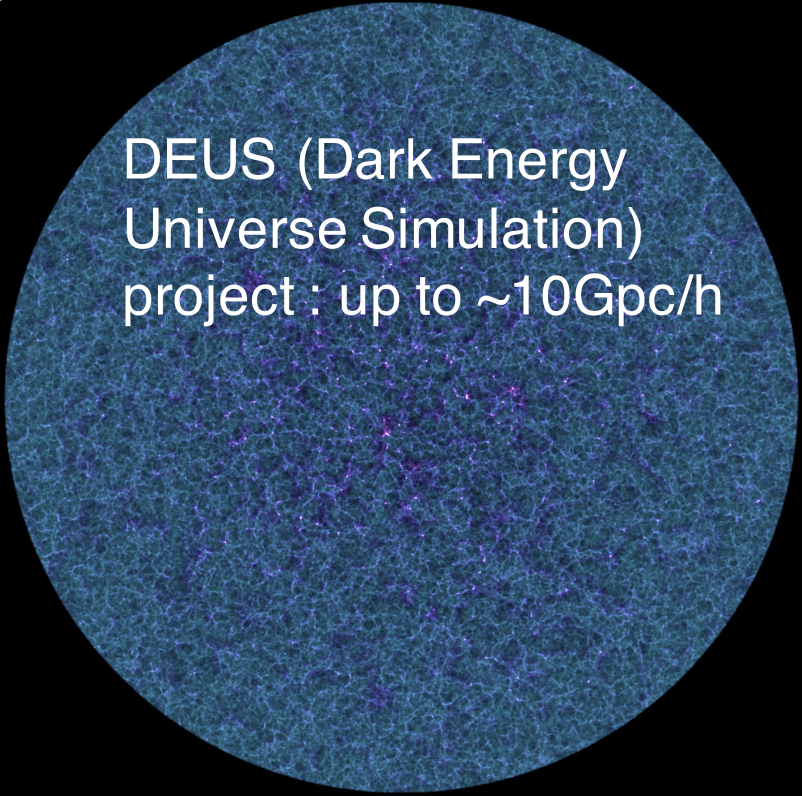
$$\langle \bar{\delta}_b \rangle_{\rm ens} = 0$$

$$\sigma_b^2 = \langle \bar{\delta}_b^2 \rangle \neq 0$$

Limitations of N-body simulations?

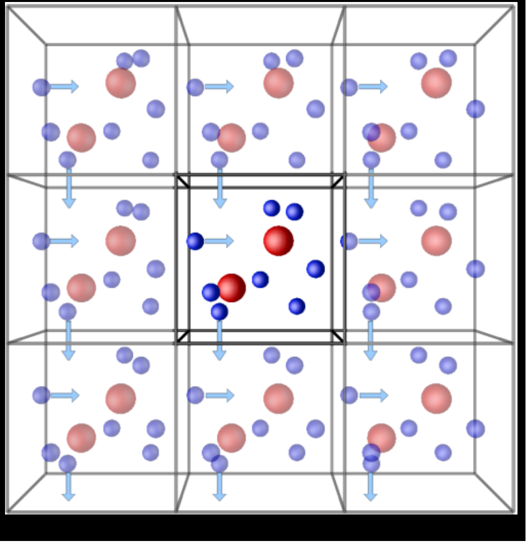


MICE simulations
(up to ~8Gpc/h)

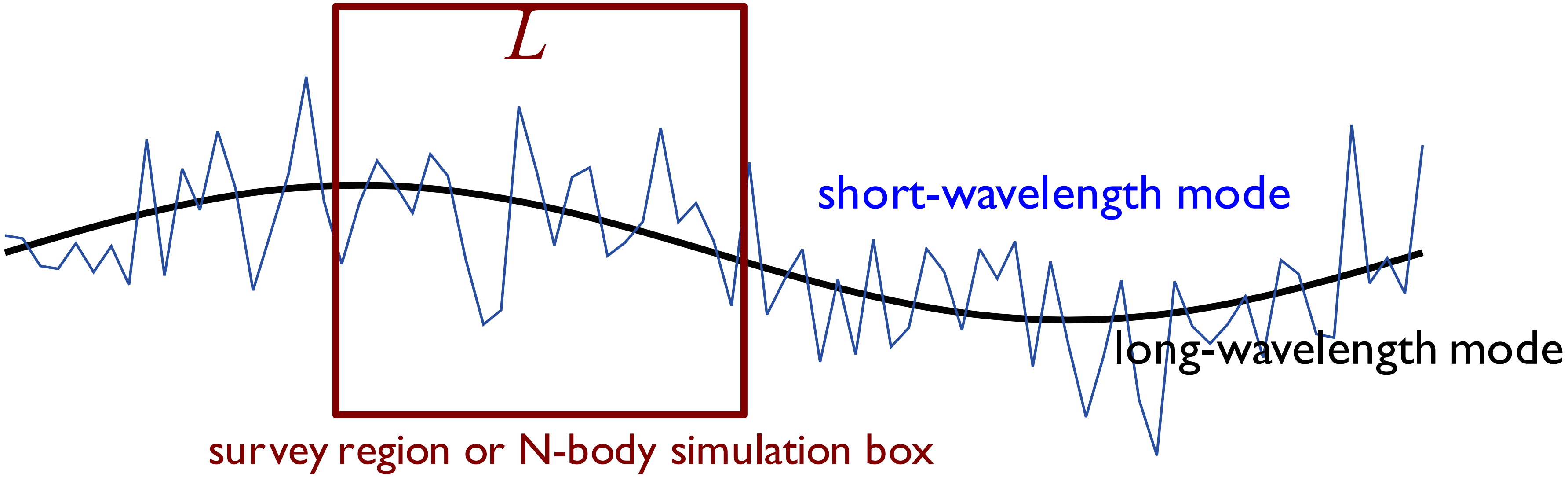


DEUS (Dark Energy
Universe Simulation)
project : up to ~10Gpc/h

- N-body sim. now 40 yrs history
- *Employ periodic boundary conditions*
- How large volume do we need?
- If we run a very large-box simulation, most of the computation time is for the linear or quasi-nonlinear dynamics? Is this against the aim of N-body simulations?
- How to include a super-box mode (DC mode)?
- Occasionally some papers have discussed the effect of DC mode (e.g., Pen 99; Sirko 05), but has not really implemented



Super-survey or -box modes



L

short-wavelength mode

long-wavelength mode

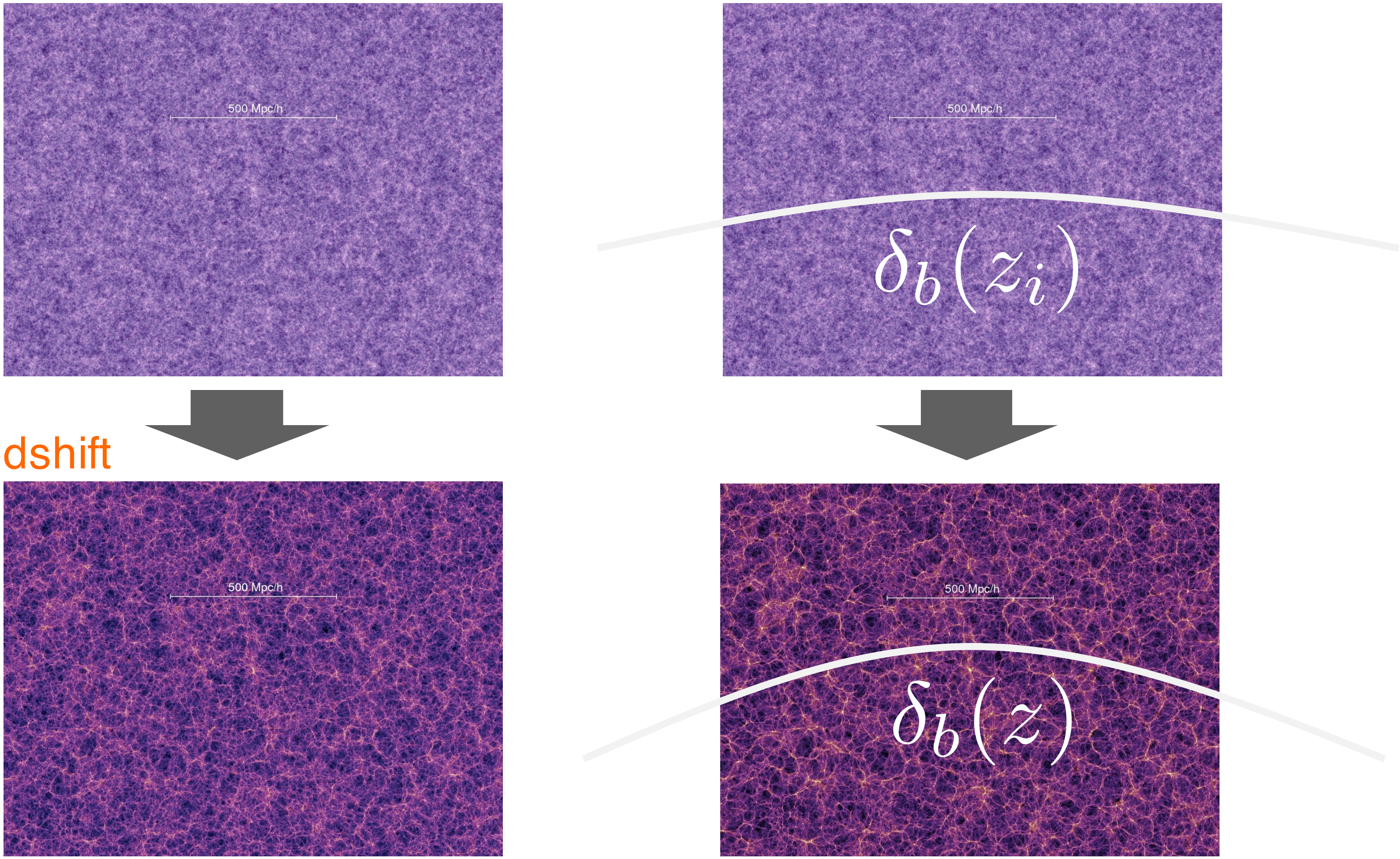
survey region or N-body simulation box

Long-wavelength modes can be expanded around the survey region

$$\begin{aligned}
\Phi_L(\mathbf{x}) &\simeq \bar{\Phi}_L + \nabla_i \Phi_L(\mathbf{x}) L_i + \frac{1}{2}\nabla_i\nabla_j \Phi_L L_i L_j + \cdots \\
&= \bar{\Phi}_L + \frac{1}{2}(\Delta\Phi_L)\frac{1}{3}L^2 + \nabla_i \Phi_L(\mathbf{x}) L_i + \frac{1}{2}\tau_{ij} L_i L_j + \cdots \\
&= \bar{\Phi}_L + \underbrace{2\pi G \bar{\rho}\bar{\delta}_b \frac{1}{3} L^2}_{\text{mean density modulation}} + \underbrace{\nabla_i \Phi_L(\mathbf{x}) L_i}_{\text{gradient field}} + \underbrace{\frac{1}{2}\tau_{ij} L_i L_j}_{\text{tidal field}} + \cdots
\end{aligned}$$

Separate universe simulation

Li, Hu & MT 14a,b; 15


initial redshift

later redshift

$\delta_b(z_i)$

$\delta_b(z)$

- How can we include the super-box (DC) mode in a simulation?
- We know that the DC mode grows according to the linear growth rate
  - For a sufficiently high redshift such as the initial redshift employed in a simulation (say z~50 or 100), the amplitude is very small and the effect is negligible

Separate universe simulation (contd.)

- Full GR can solve the dynamics of all-wavelength modes

$$G_{\mu\nu}[g_{\alpha\beta}] = 8\pi G T_{\mu\nu}(\rho)$$

- Usually employ a decomposition of background and perturbations

$$g_{\alpha\beta}(\mathbf{x}, t) = \bar{g}_{\alpha\beta}[a(t)] + \delta g_{\alpha\beta}(\mathbf{x}, t)$$
$$\rho(\mathbf{x}, t) = \bar{\rho}(t) + \delta\rho(\mathbf{x}, t)$$

- *Separate universe technique*: the mean density modulation is absorbed into background quantities

$$\bar{\rho}_W(t) = \bar{\rho}(t)\left[1 + \bar{\delta}_b(t)\right]$$
$$\bar{\rho}a^3 = \bar{\rho}_W a_W^3 \longrightarrow a_W \simeq a\left[1 - \frac{1}{3}\bar{\delta}_b(t)\right]$$

Separate universe simulation (contd.)

- The Hubble expansion rate is modified as

$$H_W(t) \simeq H(t) - \frac{1}{3}\dot{\bar{\delta}}_b(t) \qquad \text{cf. } \bar{\delta}_b \propto D(t)$$

- The comoving wavelength in SU is also modified as

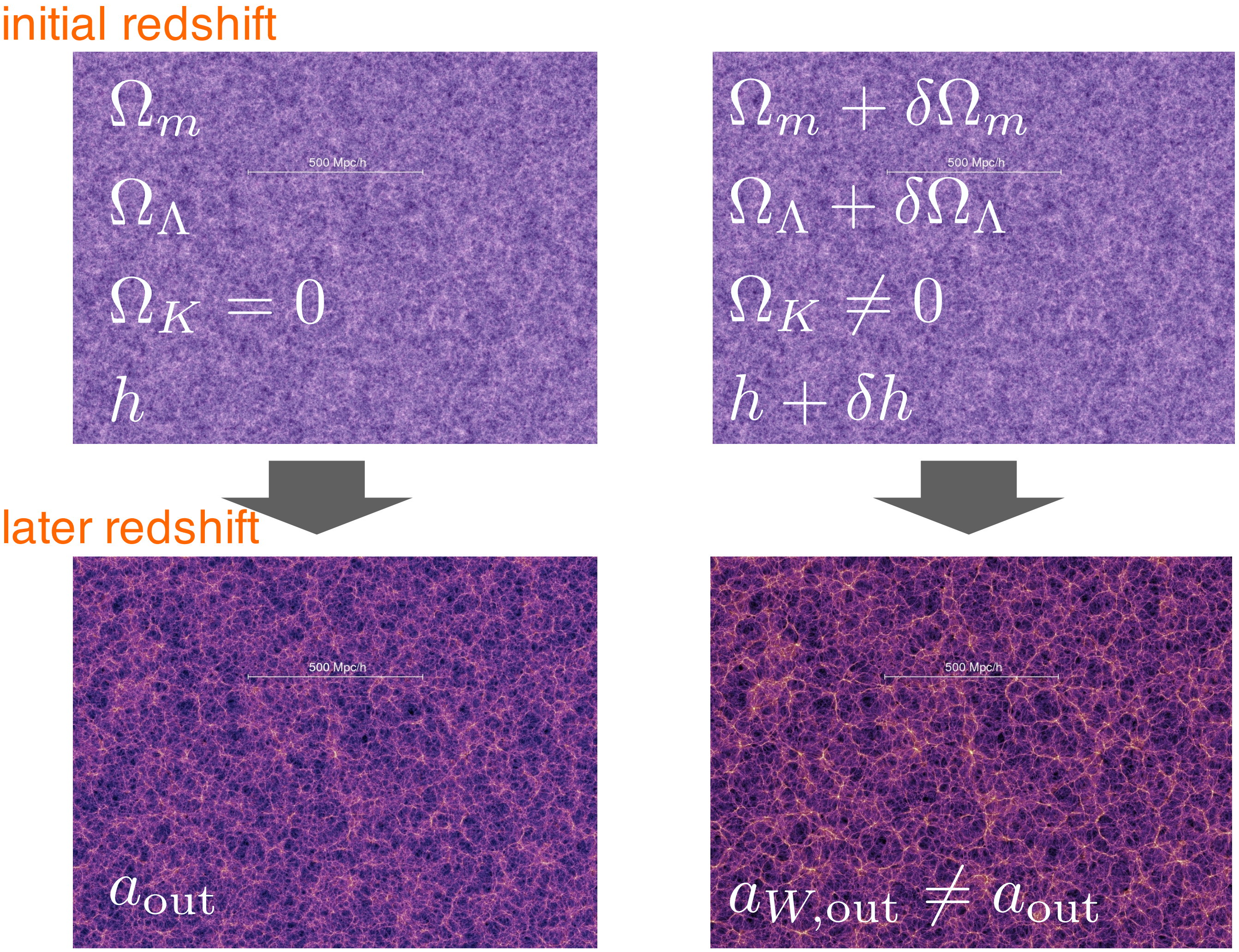
$$\lambda^{\rm phy} = \lambda_W^{\rm phy} \quad \rightarrow \quad a\lambda^{\rm co} = a_W \lambda_W^{\rm co}$$

$$\rightarrow \quad k_W \simeq k\left[1 - \frac{1}{3}\bar{\delta}_b(t)\right]$$

The super-survey mode causes a shift in the location of BAO peaks

Separate universe simulation (contd.)

The effect of such a super-survey (here DC) mode can be treated by changing the background cosmological model (an effective curvature parameter)   (also, Frenk+ 88; Sirko 05; Gnedin+09; Baldauf et al. 12)



Li, Hu & MT 14

$$\bar{\rho}_{m,W} = \bar{\rho}_m \left(1 + \delta_b(z)\right)$$

$$a_W \approx a\left(1 - \frac{\delta_b}{3}\right)$$

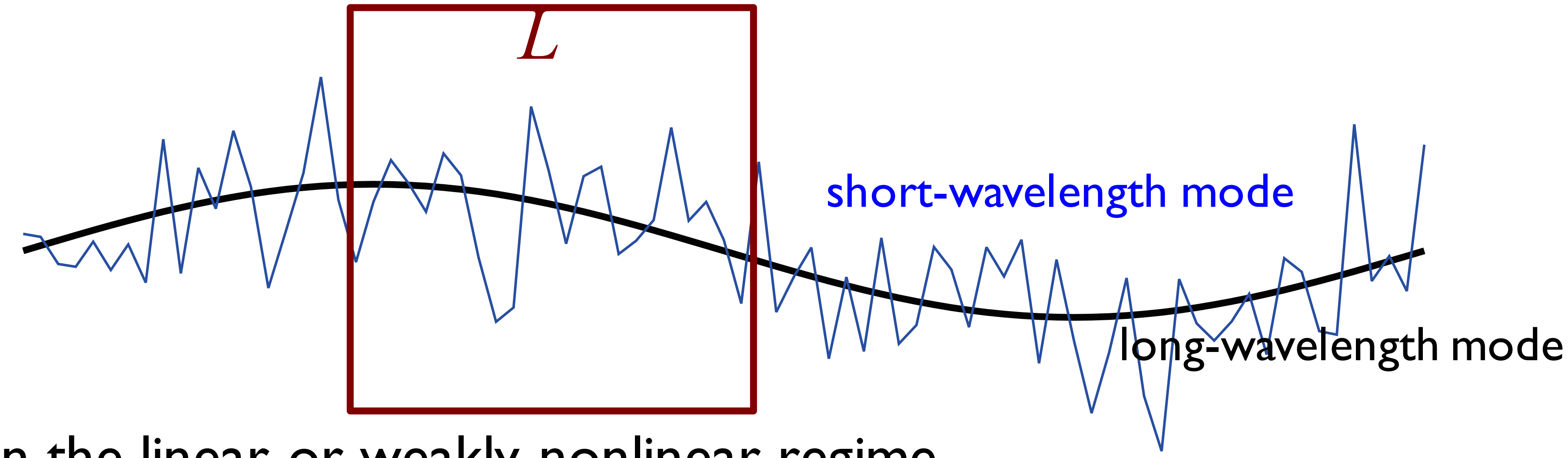
$$\frac{\delta h}{h} \approx -\frac{5\Omega_m}{6}\frac{\delta_b}{D}$$

$$\frac{\delta\Omega_m}{\Omega_m} = \frac{\delta\Omega_\Lambda}{\Omega_\Lambda} \approx -2\frac{\delta h}{h}$$

The two simulations look identical at sufficiently high redshift

We can use the same seeds of the initial density fluctuations (which help to reduce the stochasticity)

Effects of super-survey modes on the NL dynamics of short-wavelength modes



- In the linear or weakly nonlinear regime

$$\ddot{\delta}_s + 2H_W\dot{\delta}_s - 4\pi G\bar{\rho}_W\delta_s = 0$$

$$\ddot{\delta}_s + 2H\dot{\delta}_s - 4\pi G\bar{\rho}\delta_s = \frac{2}{3}\dot{\bar{\delta}}_b\dot{\delta}_s + 4\pi G\bar{\rho}\bar{\delta}_b\delta_s$$

➡ $\delta_s \propto D(t)\left[1 + \frac{13}{21}\bar{\delta}_b\right]$

All short-wavelength modes are affected (also see P. Valageas 14)

Power spectrum response

- *Power spectrum response*: the response of power spectrum at each *k* bin to the super-survey mode

$$P(k;\delta_b) \simeq P(k;\delta_b=0) + \underline{\left.\frac{\partial P}{\partial \delta_b}\right|_{\delta_b=0}}\,\delta_b$$

Power spectrum response (assuming the linear delta_b)

- Different LSS probes have different response
  - Weak lensing shear: $\gamma \sim \partial_i\partial_j\Phi \sim \bar{\rho}\delta$
  - Galaxy clustering: $\delta_g \equiv \dfrac{\delta n_g}{\bar{n}_{W,g}} \sim \dfrac{\delta}{1+\delta_b}$

- *Reponses of the power spectra wrt "global" or "local" mean*

$$P(k) = (1+\delta_b)^2 P_W(k) \rightarrow \frac{\partial \ln P(k)}{\partial \delta_b} = 2 + \frac{\partial \ln P_W(k)}{\partial \delta_b}$$

“Growth” and “Dilation” effects in Power spectrum response

- The power spectrum response has two contributions

$$\begin{aligned}
\left.\frac{d\ln\Delta^2(k_W,\delta_b)}{d\delta_b}\right|_k &= \left.\frac{\partial\ln\Delta_W^2(k_W,\delta_b)}{\partial\delta_b}\right|_{k_W} + \frac{\partial\ln\Delta_W^2(k_W,\delta_b)}{\partial\ln k_W}\frac{\partial\ln k_W}{\partial\delta_b} \\
&\simeq \left.\frac{\partial\ln\Delta_W^2(k_W,\delta_b)}{\partial\delta_b}\right|_{k_W} - \frac{1}{3}\frac{\partial\ln\Delta_W^2(k_W,\delta_b)}{\partial\ln k_W} \\
&\simeq \underbrace{\left.\frac{\partial\ln\Delta_W^2(k_W,\delta_b)}{\partial\delta_b}\right|_{k_W}} - \underbrace{\frac{1}{3}\frac{\partial\ln\Delta^2}{\partial\ln k}}
\end{aligned}$$

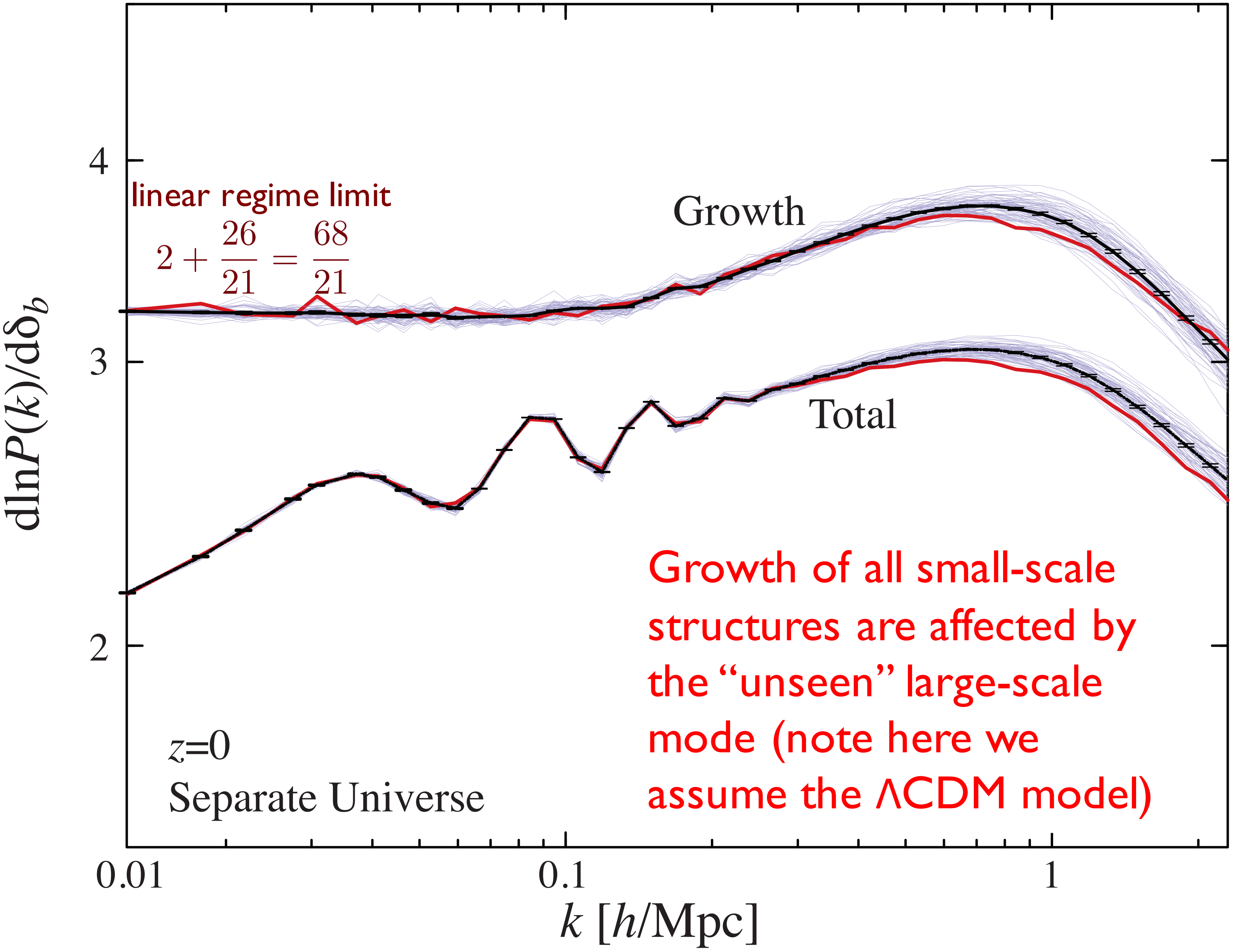
Growth effect

enhancement/suppression in the growth of short-wavelength modes due to delta_b

Dilation effect

More contraction/expansion of comoving volume due to delta_b

Power spectrum response



linear regime limit

$$2+\frac{26}{21}=\frac{68}{21}$$

Growth of all small-scale structures are affected by the "unseen" large-scale mode (note here we assume the ΛCDM model)

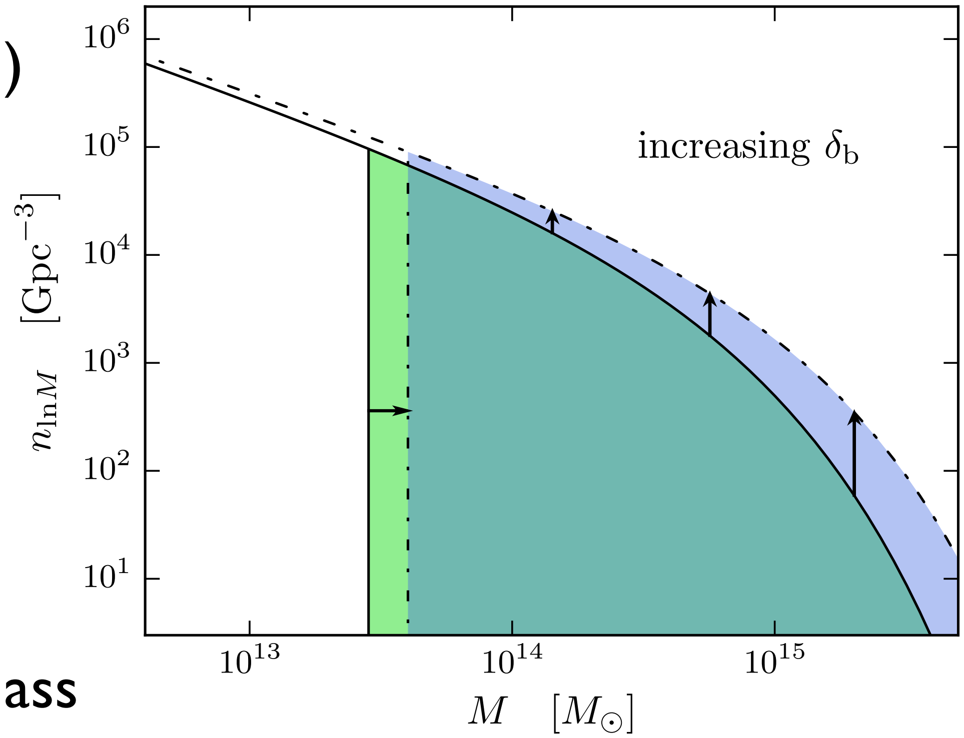
Halo bias consistency relation

Li, Hu & Takada 15

- "response" halo bias, defined by the response of halo mass function to the background mode (one point function)

$$b_1(M) \equiv \frac{\mathrm{d}\ln n_{\ln M}(M)}{\mathrm{d}\delta_\mathrm{b}}$$

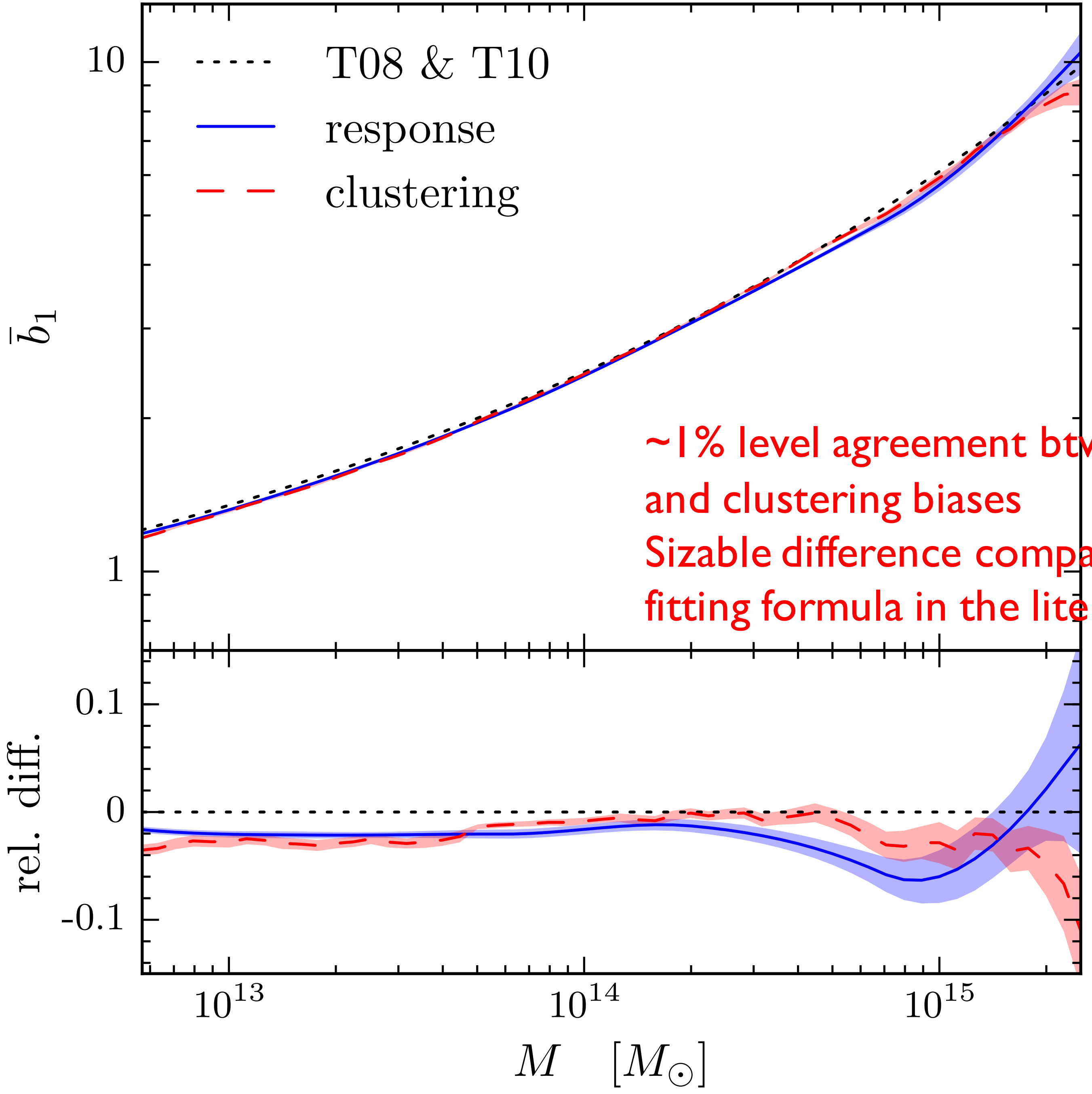
Include all effects (merger, mass accretion, …); doesn't assume universality of mass func.



- Clustering bias, defined via the halo-mass cross-correlation (two-point function)

$$b_1(M) \equiv \lim_{k\to 0}\frac{P_\mathrm{hm}(k)}{P_\mathrm{mm}(k)}$$

Halo bias consistency relation

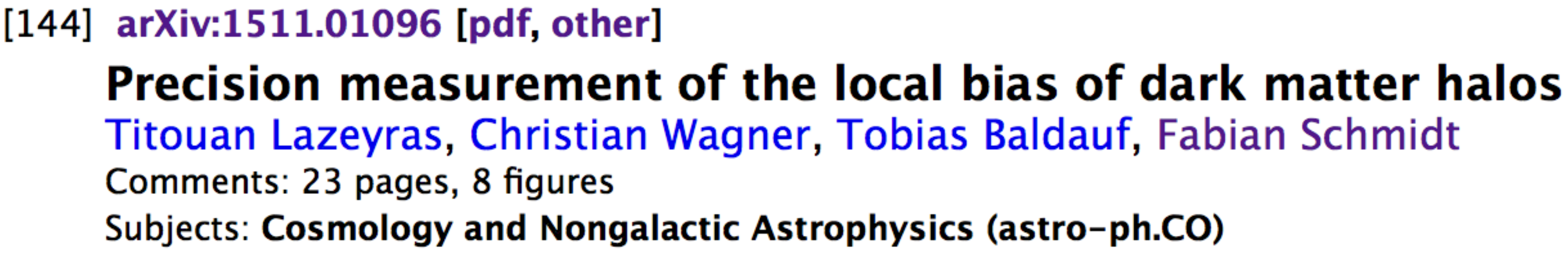


~1% level agreement btw response and clustering biases

Sizable difference compared to the fitting formula in the literature

3 papers on the same day, Nov 3 2015

response bias, curvature bias, separate universe bias



[144] **arXiv:1511.01096 [pdf, other]**

Precision measurement of the local bias of dark matter halos

Titouan Lazeyras, Christian Wagner, Tobias Baldauf, Fabian Schmidt

Comments: 23 pages, 8 figures

Subjects: **Cosmology and Nongalactic Astrophysics (astro-ph.CO)**

[202] **arXiv:1511.01454 [pdf, other]**

Separate Universe Consistency Relation and Calibration of Halo Bias

Yin Li, Wayne Hu, Masahiro Takada

Comments: 11 pages, 8 figures

Subjects: **Cosmology and Nongalactic Astrophysics (astro-ph.CO)**

[203] **arXiv:1511.01465 [pdf, other]**

Linear response to long wavelength fluctuations using curvature simulations

Tobias Baldauf, Uroš Seljak, Leonardo Senatore, Matias Zaldarriaga

Comments: 29 pages, 14 figures

Subjects: **Cosmology and Nongalactic Astrophysics (astro-ph.CO)**; General Relativity and Quantum Cosmology (gr-qc)

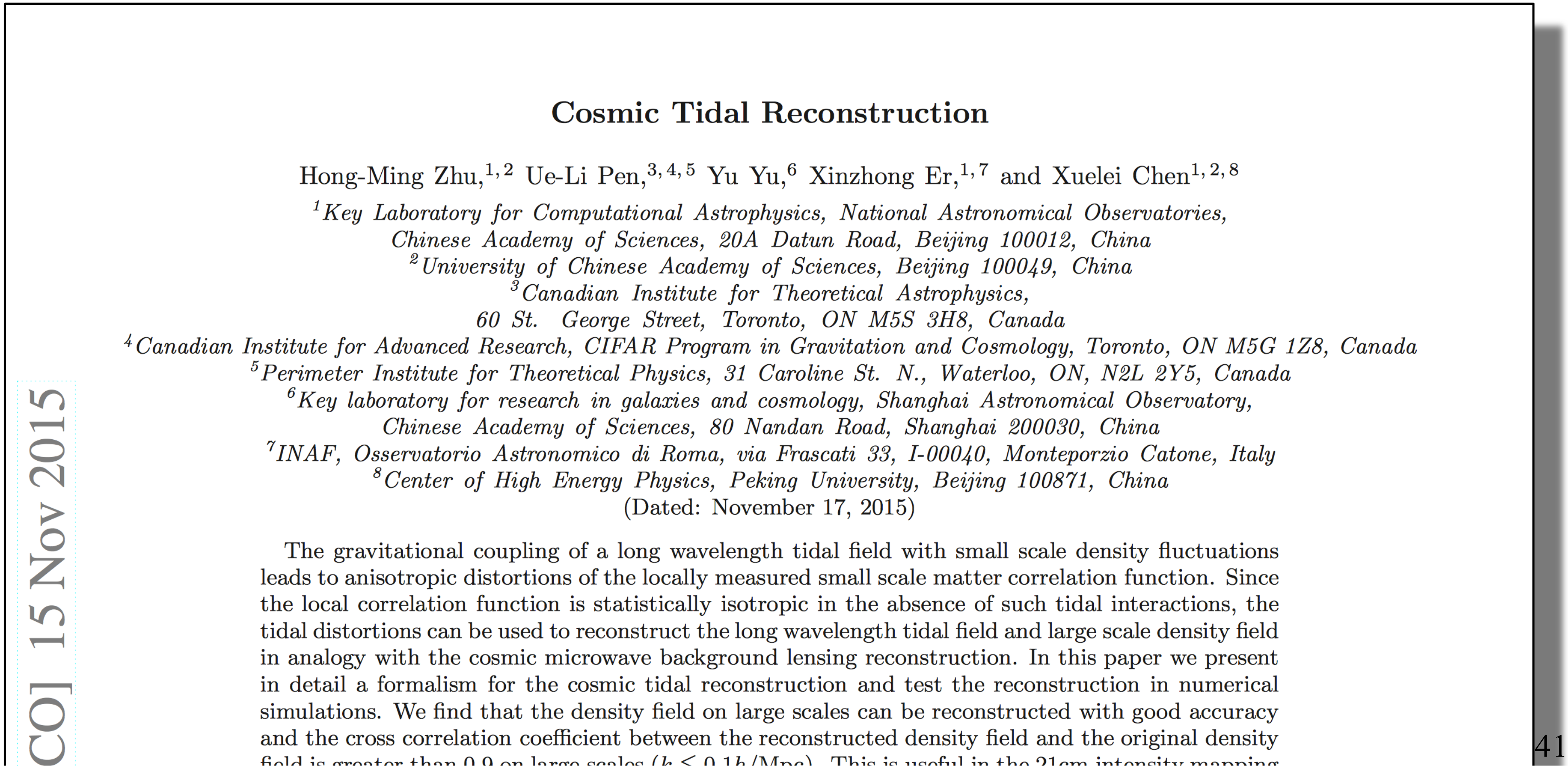
Super-survey effects

For any LSS observable we can define $\frac{\mathrm{d}O}{\mathrm{d}\delta_{\mathrm{b}}}$

- A consequence of nonlinear mode coupling
- Studying the small-scale structures to *constrain* the large-scale mode that contains cleaner information on inflation physics (Li et al. 14b)
- So far assumed ΛCDM model; therefore the following physics should modify the super-survey effects or consistency relations ⇒ a signature beyond standard ΛCDM model
  - Dark energy
  - Massive neutrinos
  - Primordial non-Gaussianity

Effects of large-scale tide

- Now some people start to consider ….



Cosmic Tidal Reconstruction

Hong-Ming Zhu,[1,2] Ue-Li Pen,[3,4,5] Yu Yu,[6] Xinzhong Er,[1,7] and Xuelei Chen[1,2,8]
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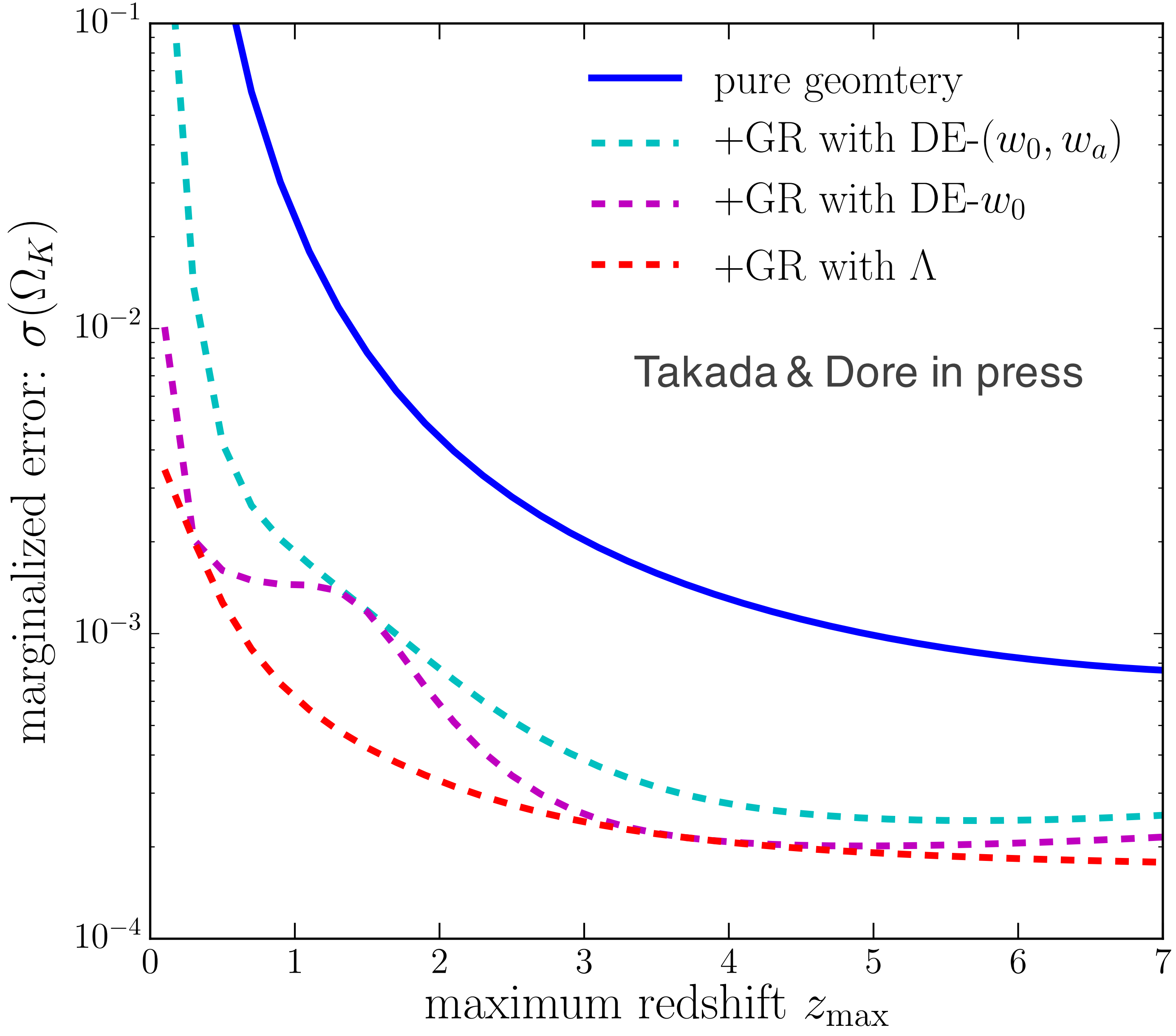
[8] *Center of High Energy Physics, Peking University, Beijing 100871, China*
(Dated: November 17, 2015)

The gravitational coupling of a long wavelength tidal field with small scale density fluctuations leads to anisotropic distortions of the locally measured small scale matter correlation function. Since the local correlation function is statistically isotropic in the absence of such tidal interactions, the tidal distortions can be used to reconstruct the long wavelength tidal field and large scale density field in analogy with the cosmic microwave background lensing reconstruction. In this paper we present in detail a formalism for the cosmic tidal reconstruction and test the reconstruction in numerical simulations. We find that the density field on large scales can be reconstructed with good accuracy and the cross correlation coefficient between the reconstructed density field and the original density field is greater than 0.9 on large scales ($k \lesssim 0.1h$/Mpc). This is useful in the 21cm intensity mapping

Falsifying multiverse scenario

$$D_A(z) \simeq D_c(z)\left[1-\frac{1}{6}KD_c(z)^2\right], D_c(z)=\int_0^z \frac{dz'}{H(z')}$$



- Eternal inflation
- Multiverse
- Large-field finlation
- Arrow of time

Coleman & de Luccia 82
Yamamoto et al. 95
Guth & Nomura 11
Kleban & Schillo 11
Bousso et al. 14
Kanno et al. 14
Boddy et al. 15
East et al. 15
….

Summary

- Subaru Hyper Suprime-Cam (imaging) and Prime Focus Spectrograph (spec-z) are VERY exciting projects
- Weak lensing (dark matter) and 3D galaxy (cluster) clustering
- Galaxy ⇒ halo ⇒ cosmology (inside 1-halo term = stochastic noise or nuisance parameters)
- Currently the biggest uncertainty is “bias”
- Super-survey effects are novel effects of large-scale mode on small-scale modes
  - Can use these effects to infer largest-scale mode in a given realization
  - Any deviation from the consistency relation is a signature beyond standard ΛCDM model