Cosmology with the large-scale structure of the universe

Takahiko Matsubara

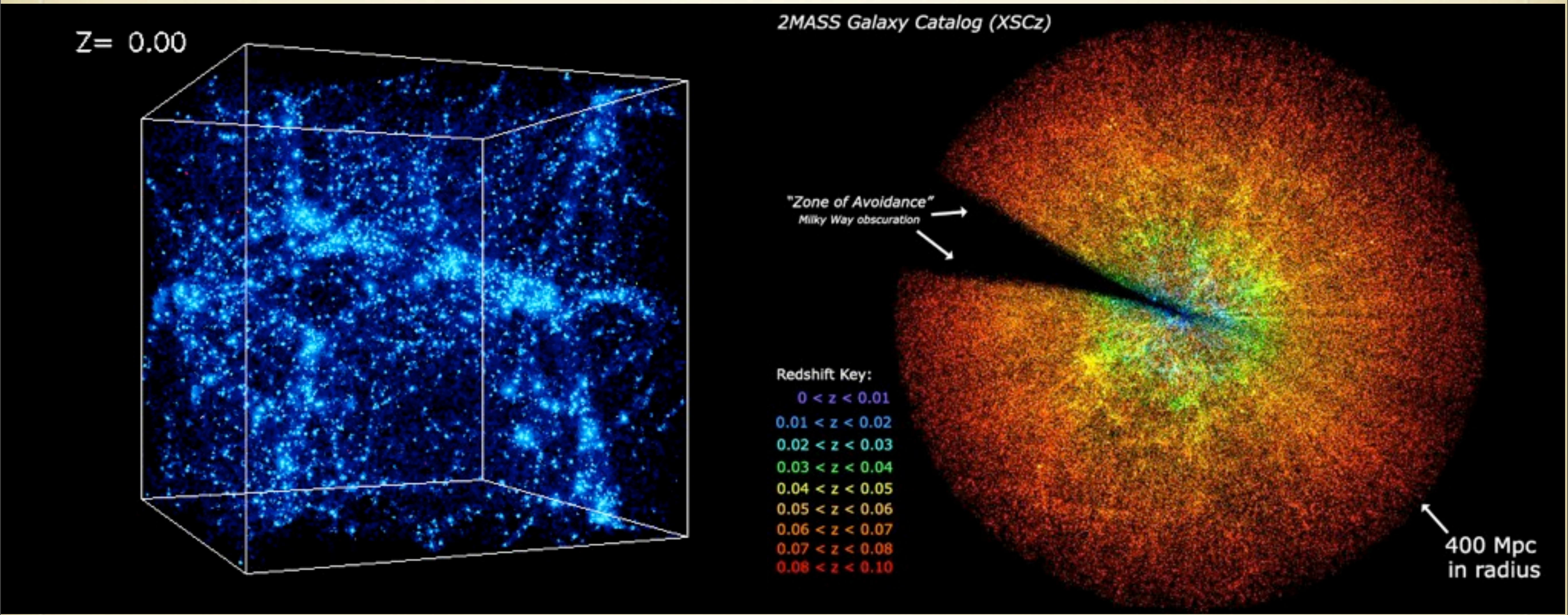
(Nagoya U.)

@KMIIN

2011/10/24

The Large-Scale Structure (LSS)

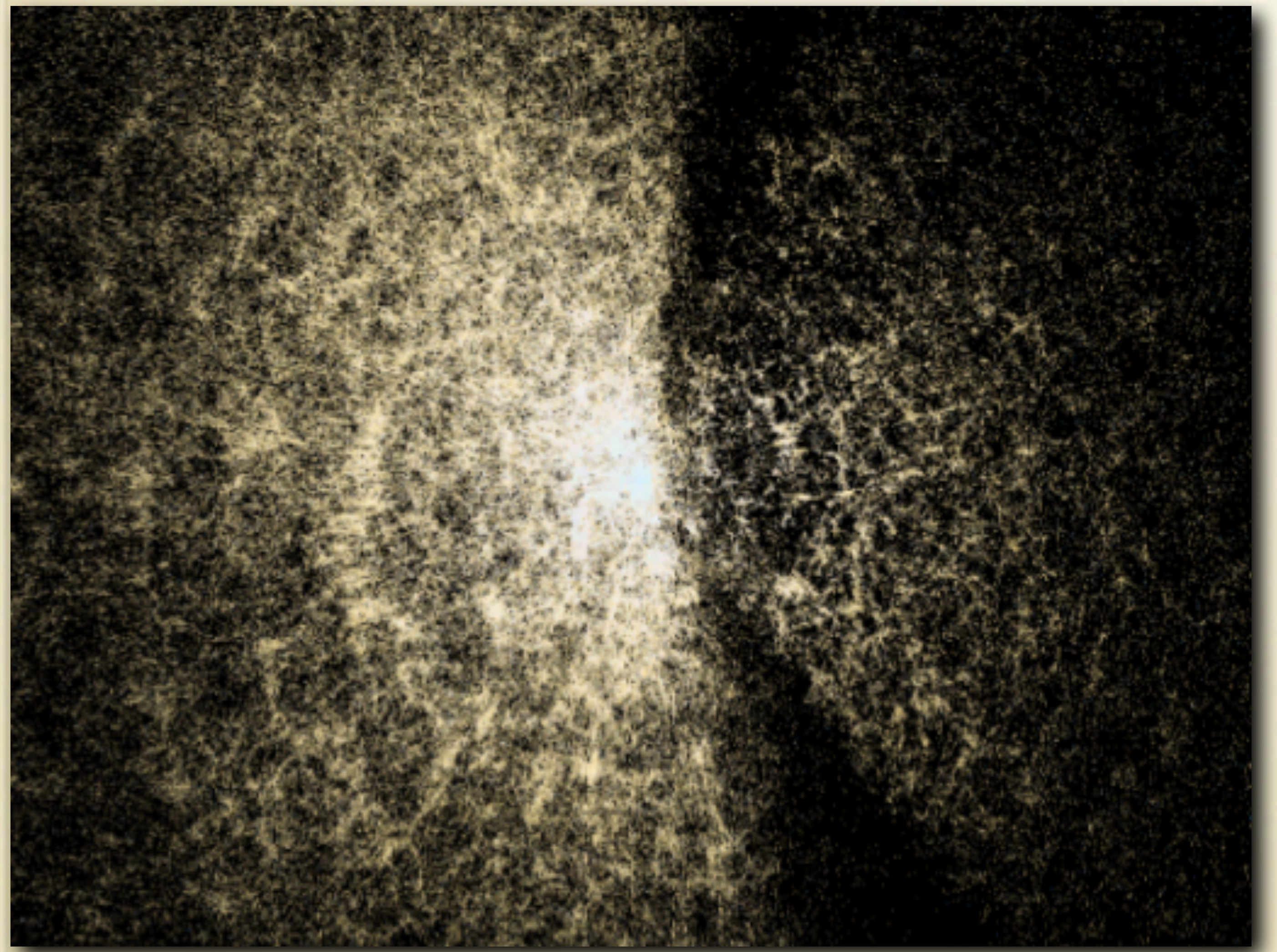
- 3D structure of the observable universe
- Galaxy redshift surveys probe LSS

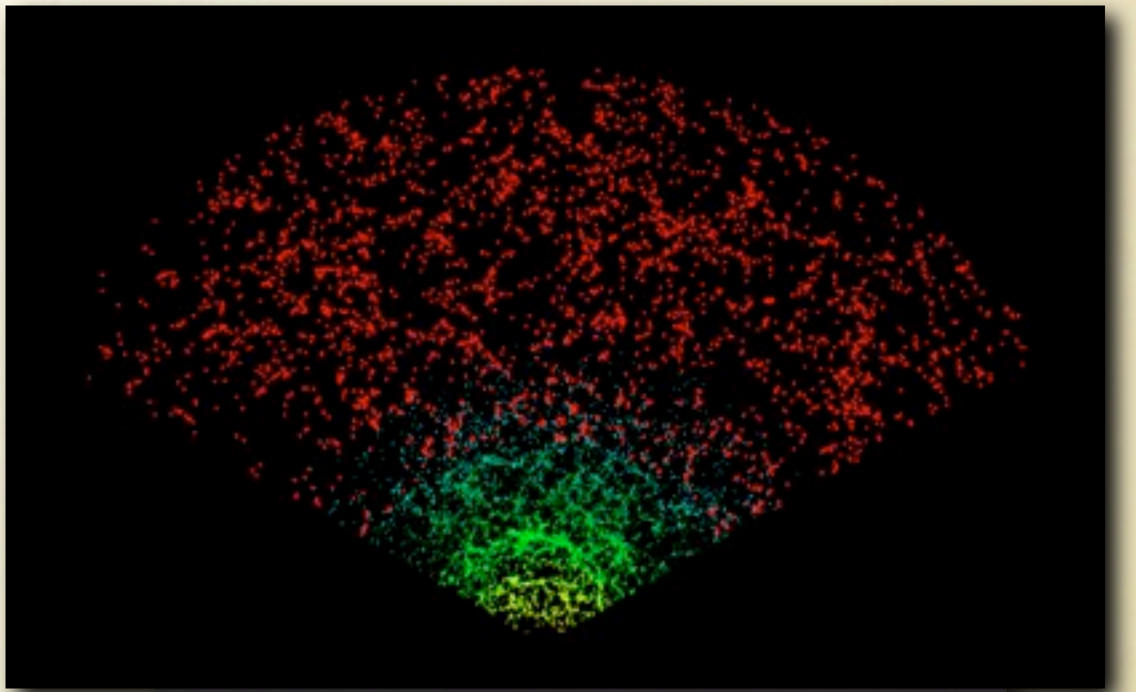


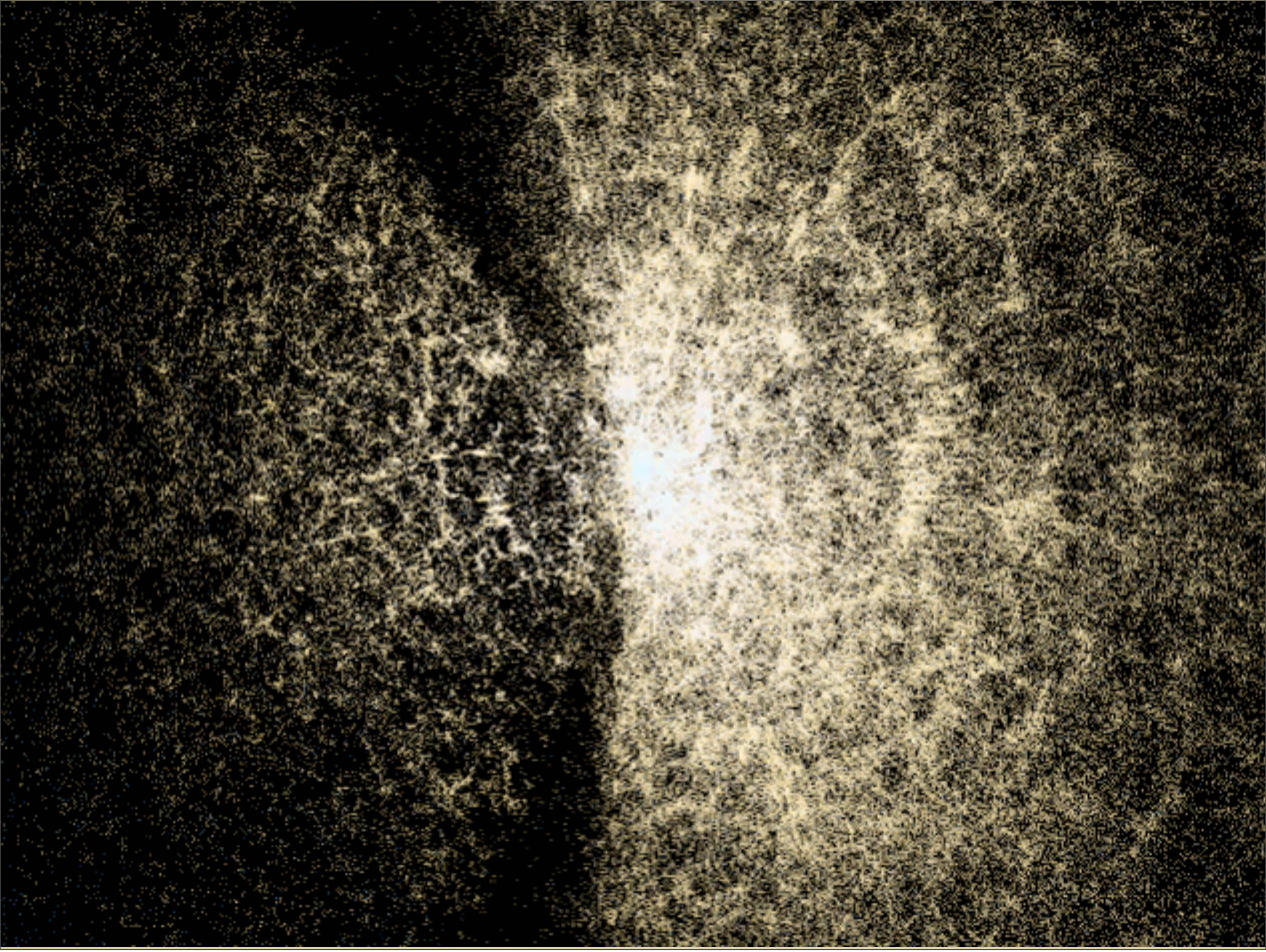
From: KICP homepage, 2MASS homepage

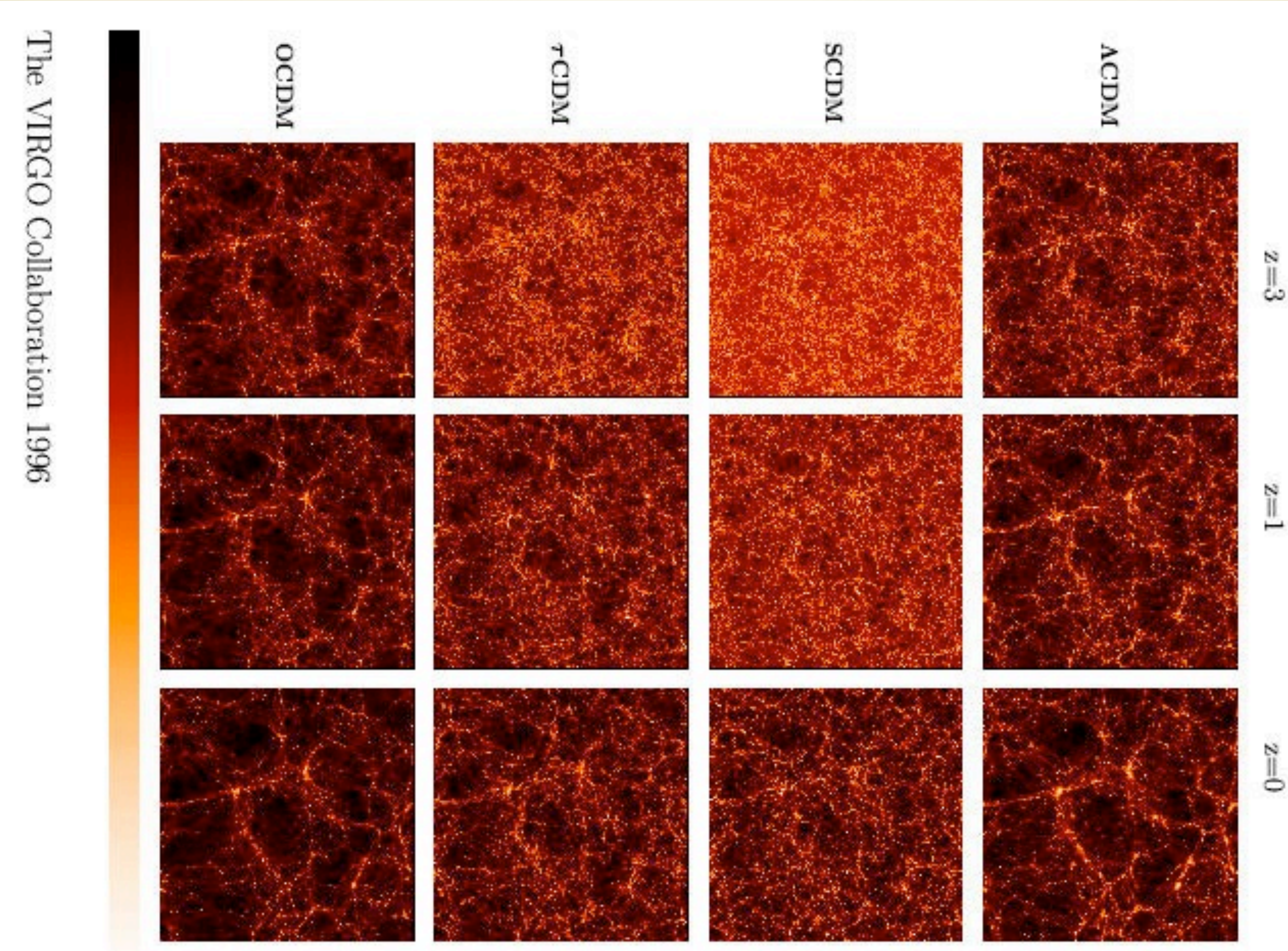
Galaxy redshift survey

- Sloan Digital Sky Survey (SDSS): The largest redshift survey ever made









From: Virgo simulations: Jenkins+ (1998)

Table 2. The Cosmological Tests

Test	Einstein-de Sitter	$\Omega_m = 0.25 \pm 0.1$ Flat	Open
1a. Dynamical mass measures	X	✓	✓
1b. World time $t(z)$: ages of stars & elements	X??	✓?	✓?
1c. Redshift-magnitude relation	X	✓	X??
1d. Lensing of quasars by galaxies	✓?	X??	✓?
1e. Counts: $dN = f(m, z)dm\,dz$	?	?	?
2a. Large-Scale structure	X?	✓?	✓?
2b. CBR anisotropy	X?	✓?	✓??
2c. Cluster evolution	X?	✓?	✓?
2d. Baryon mass fraction in clusters	X	✓	✓
2e. Galaxy formation	?	?	?
3a. Aesthetics	✓	X?	X?
3b. Inflation	✓	✓	??

$z < 0.1$

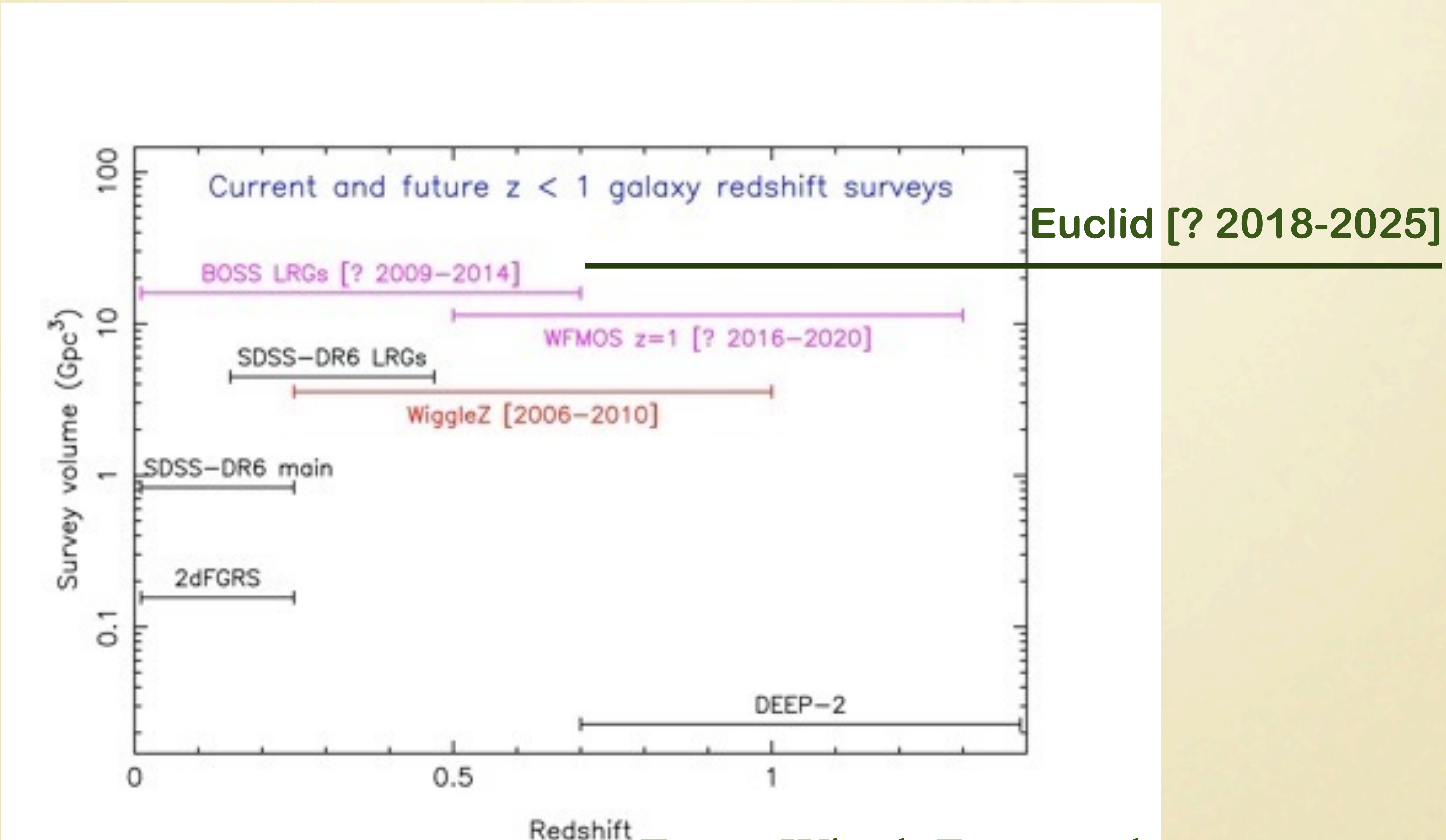
From: P.J.E.Peebles, "Is Cosmology Solved? An Astrophysical Cosmologist's Viewpoint" (1998)

Survey should be DEEPER & WIDER

- Merits of deep survey (z ~ 1 or larger)
  - expansion history
  - geometry
  - evolution of structures
- Merits of wide survey (~10,000 square degrees)
  - statistics
  - large-scale clustering (> 100 Mpc)

Current & Future galaxy surveys

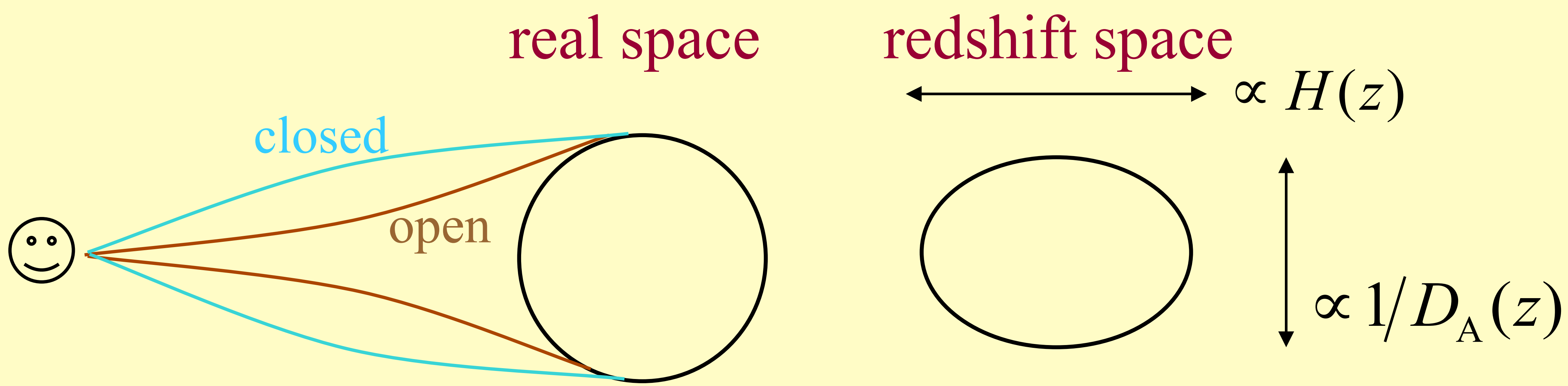
- deeper and wider surveys are going on



From: WiggleZ survey homepage + Euclid

Cosmology with galaxy clustering

- Cosmological redshift-space distortion

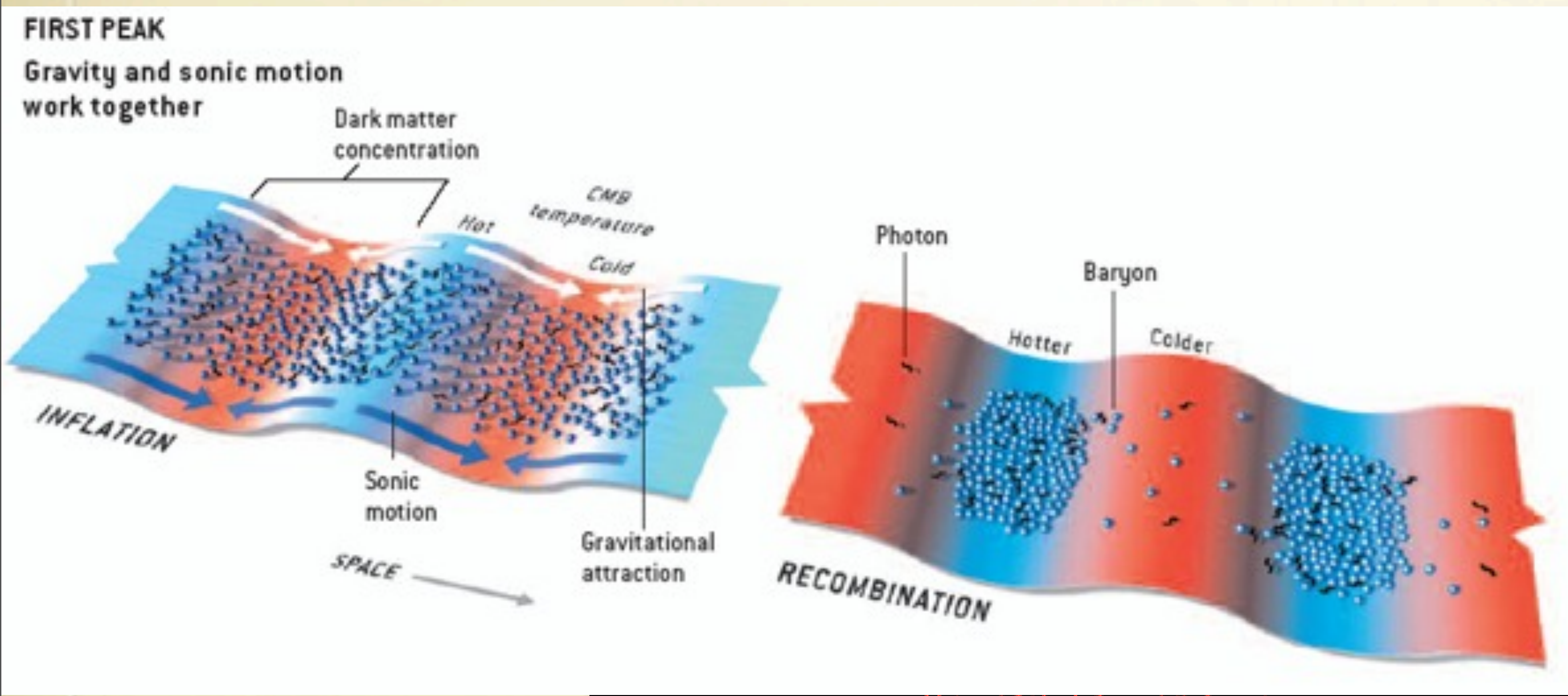


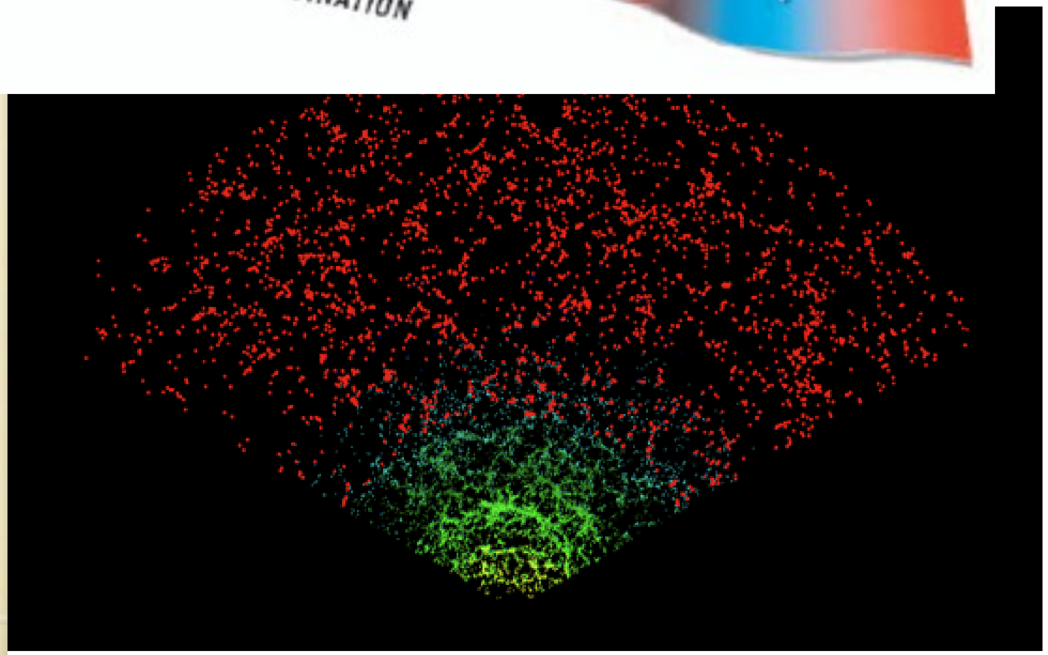
$$D_A(z) = \frac{1}{H_0\sqrt{\Omega_K}} \sinh\left(H_0 \sqrt{\Omega_K} \int_0^z \frac{dz'}{H(z')} \right) \equiv (1+z) d_A(z)$$

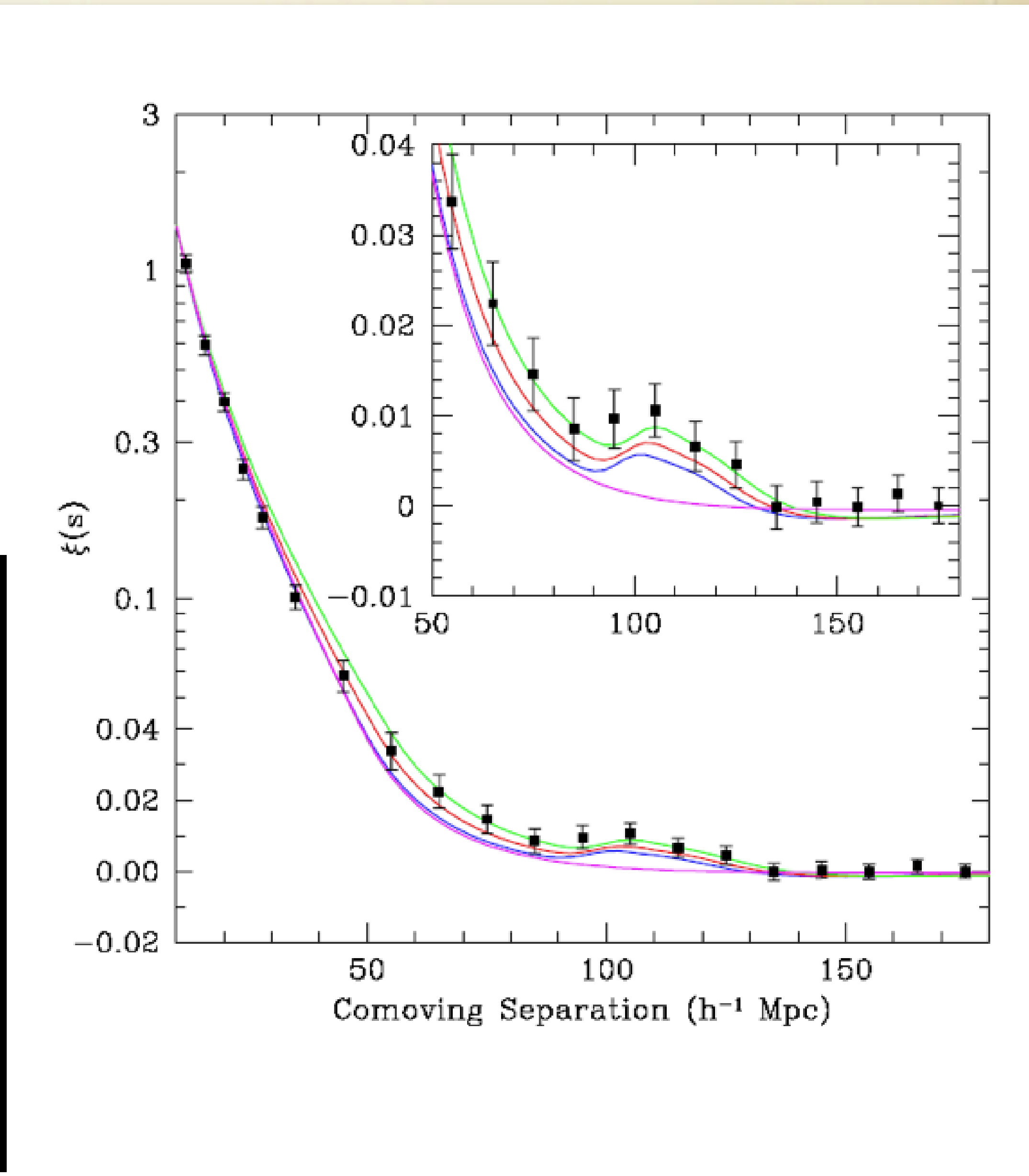
$$H(z) = H_0 \sqrt{(1+z)^3 \Omega_M + (1+z)^2 \Omega_K + (1+z)^3 \exp\left(3\int_0^z \frac{w_{DE} dz}{1+z} \right) \Omega_{DE}}$$

BAO as a standard ruler

- Baryon Acoustic Oscillations (BAO)
  - Oscillation scale can be calculated

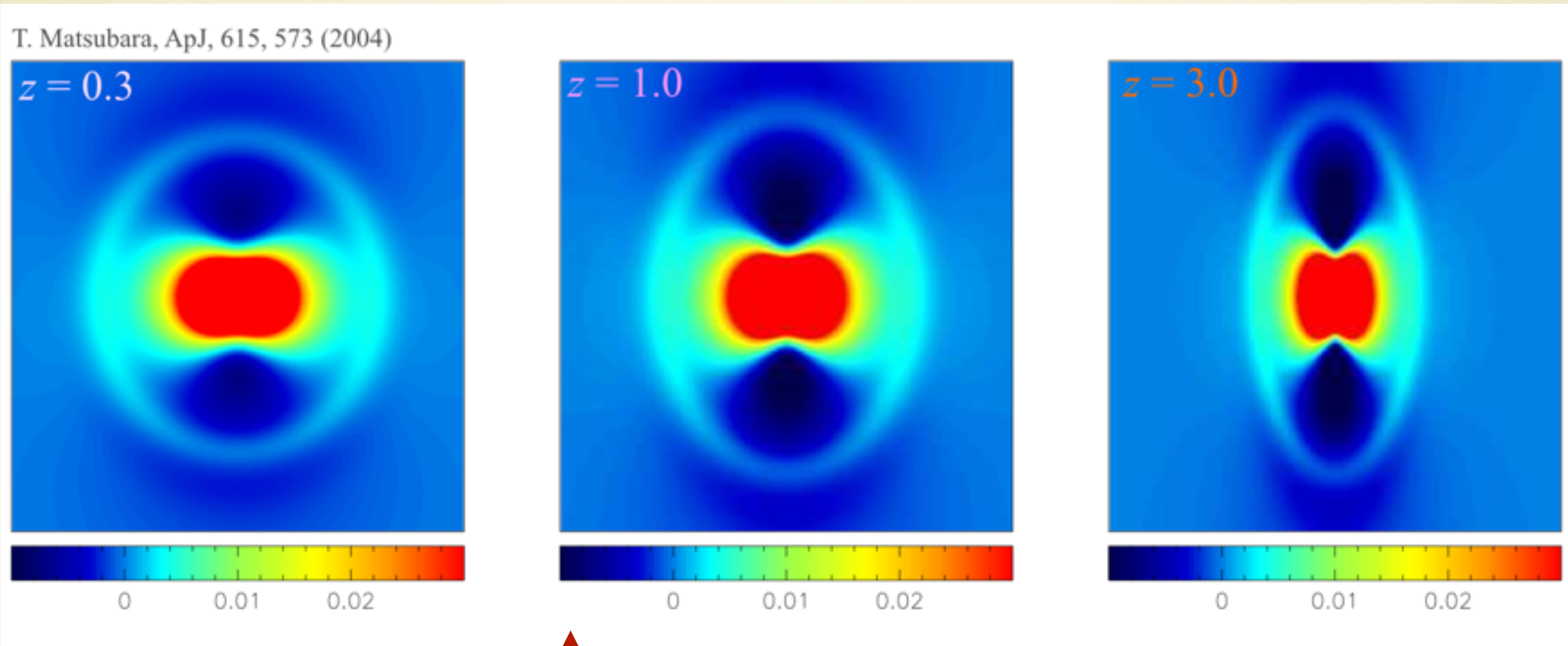






Correlation function in 2D

- In 2D, “BAO ring” is a double ruler
  - (velocity distortions included)



Lines of sight

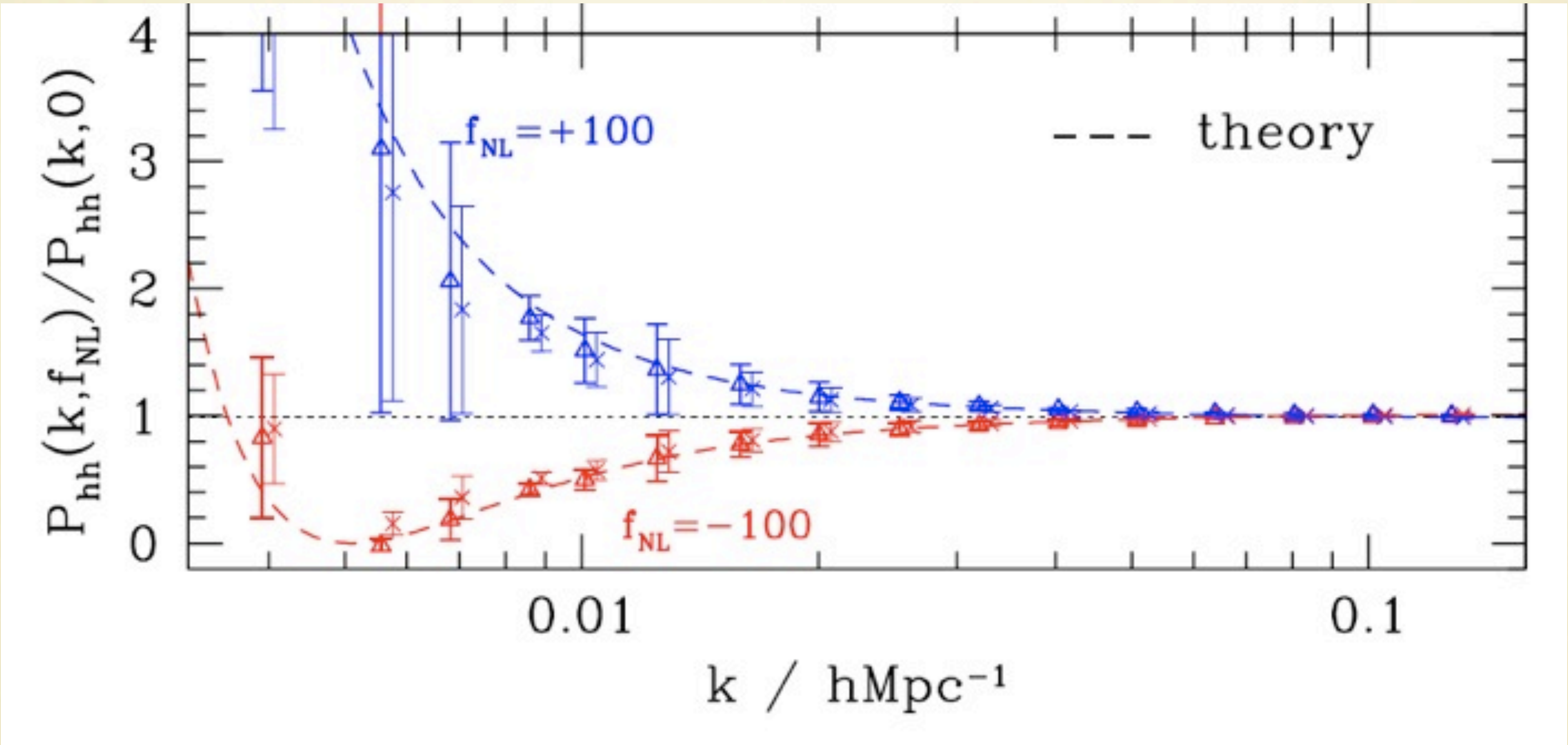
From: TM (2004)

Primordial non-Gaussianity in LSS

- **Primordial non-Gaussianity increases the power spectrum of galaxies on VERY LARGE SCALES**

$$\Phi(\mathbf{r}) = \Phi_L(\mathbf{r}) + f_{\rm NL}\left(\Phi_L^2(\mathbf{r}) - \langle\Phi_L^2(\mathbf{r})\rangle\right)$$

$$\Delta b(M,k) = 3 f_{\rm NL}(b-1)\delta_c \frac{\Omega_m}{k^2 T(k) D(z)}\left(\frac{H_0}{c}\right)^2$$

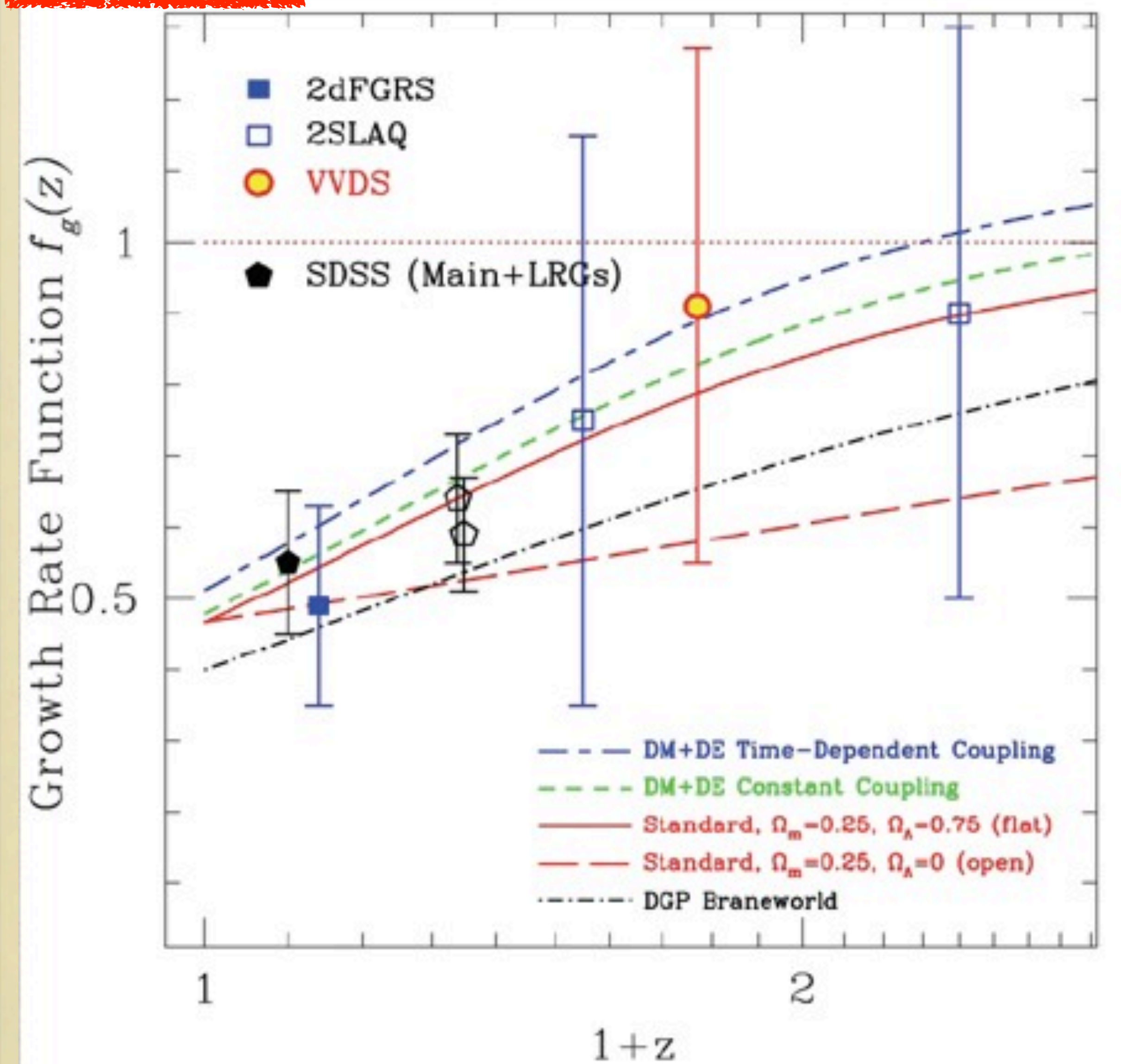


From: Desjacque+ (2009)

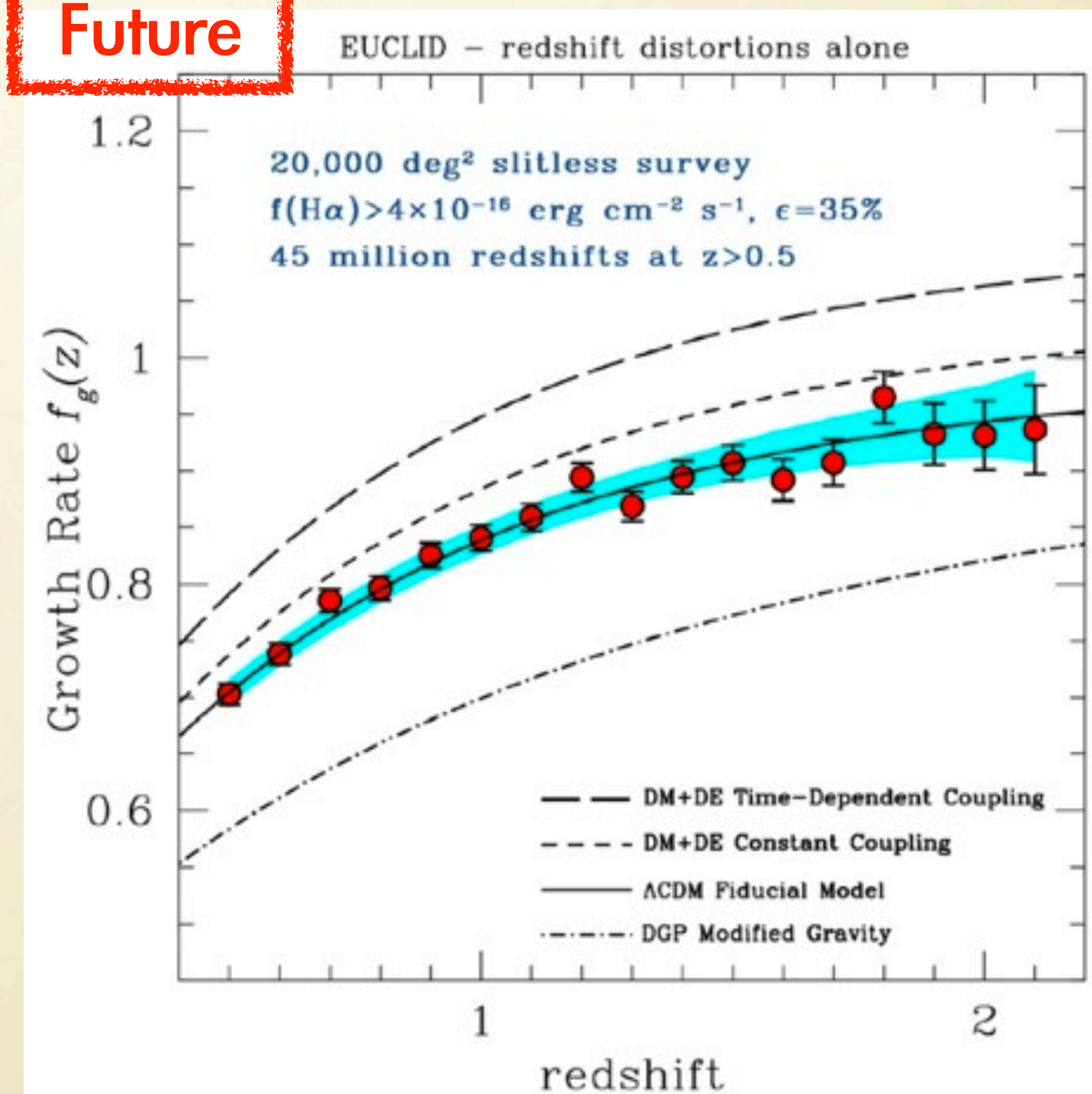
Constraining modified gravity

$$f_g(z) = \frac{d\ln D}{d\ln a} \simeq \Omega_M^{\gamma}$$

Current



Future



From: Guzzo+ (2008); Euclid Yellow Book (2011)

Warning: Some complexities

- Nonlinear evolutions
  - analytically hard problem
  - even important on large-scales (for precision cosmology)
- Redshift-space distortions (RSD)
  - peculiar velocities of galaxy displace the position in redshift space
- Biasing
  - galaxies are not unbiased tracers of matter

Perturbation theory approach

- **Nonlinear evolutions can be solved by the perturbation theory (on large scales)**

Tomita (1967), Juszkiewicz (1981), Vishniac (1983), Goroff et al. (1986), Makino et al. (1992), ...

Continuity: $$\frac{\partial \delta}{\partial t} + \frac{1}{a}\boldsymbol{\nabla} \cdot [(1+\delta)\boldsymbol{v}] = 0$$

Euler: $$\frac{\partial \boldsymbol{v}}{\partial t} + \frac{\dot{a}}{a}\boldsymbol{v} + \frac{1}{a}(\boldsymbol{v} \cdot \boldsymbol{\nabla})\boldsymbol{v} = -\frac{1}{a}\boldsymbol{\nabla}\Phi$$

Poisson: $$\triangle \Phi = 4\pi G a^2 \bar{\varrho} \delta$$

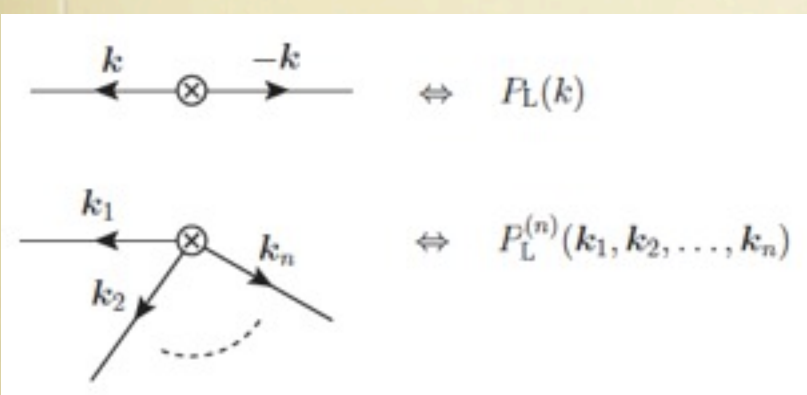
$$\delta = \delta^{(1)} + \delta^{(2)} + \delta^{(3)} + \cdots$$

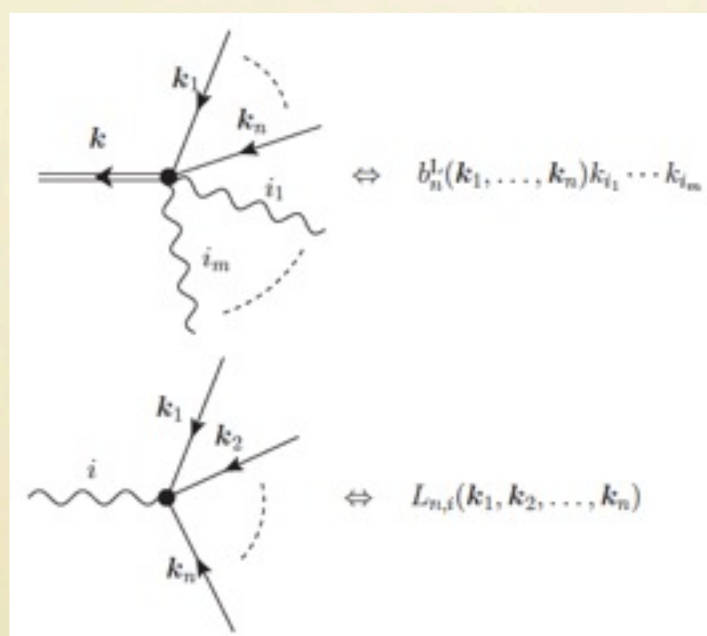
Integrated perturbation theory (iPT)

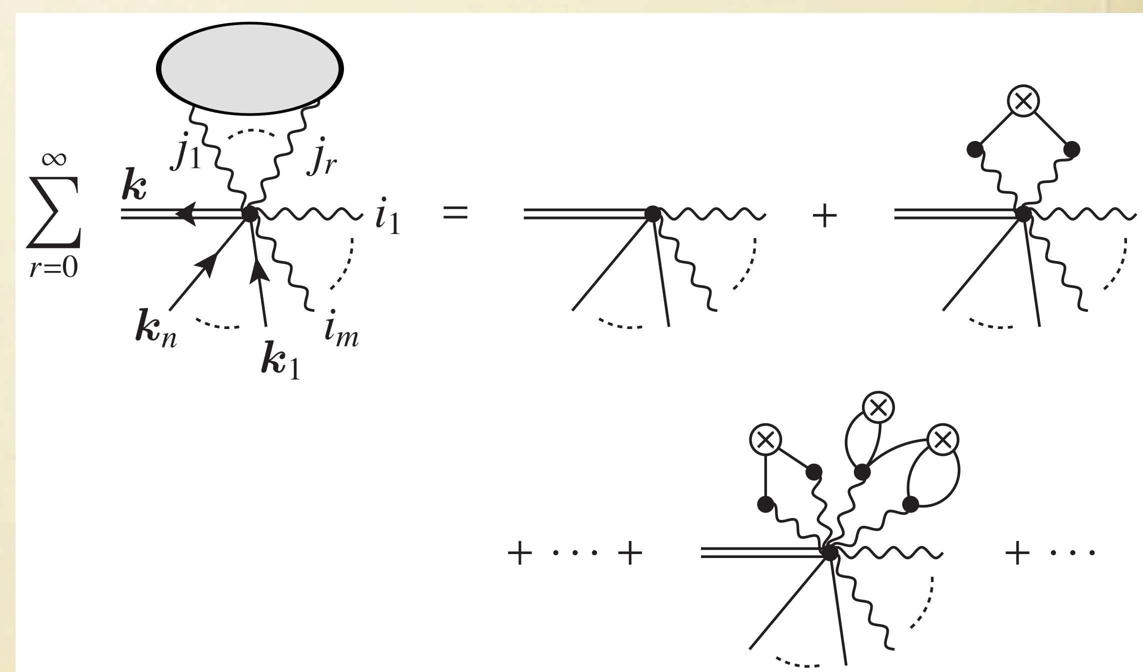
- Integration of Four "Non-'s"
  - nonlinear perturbation theory
  - nonlocal bias
  - nonlinear redshift-space distortions
  - non-Gaussianity of primordial density fields

Integrated perturbation theory (iPT)

- Lagrangian resummation theory
- nonlinear RSD
- nonlocal biasing scheme
- primordial nG

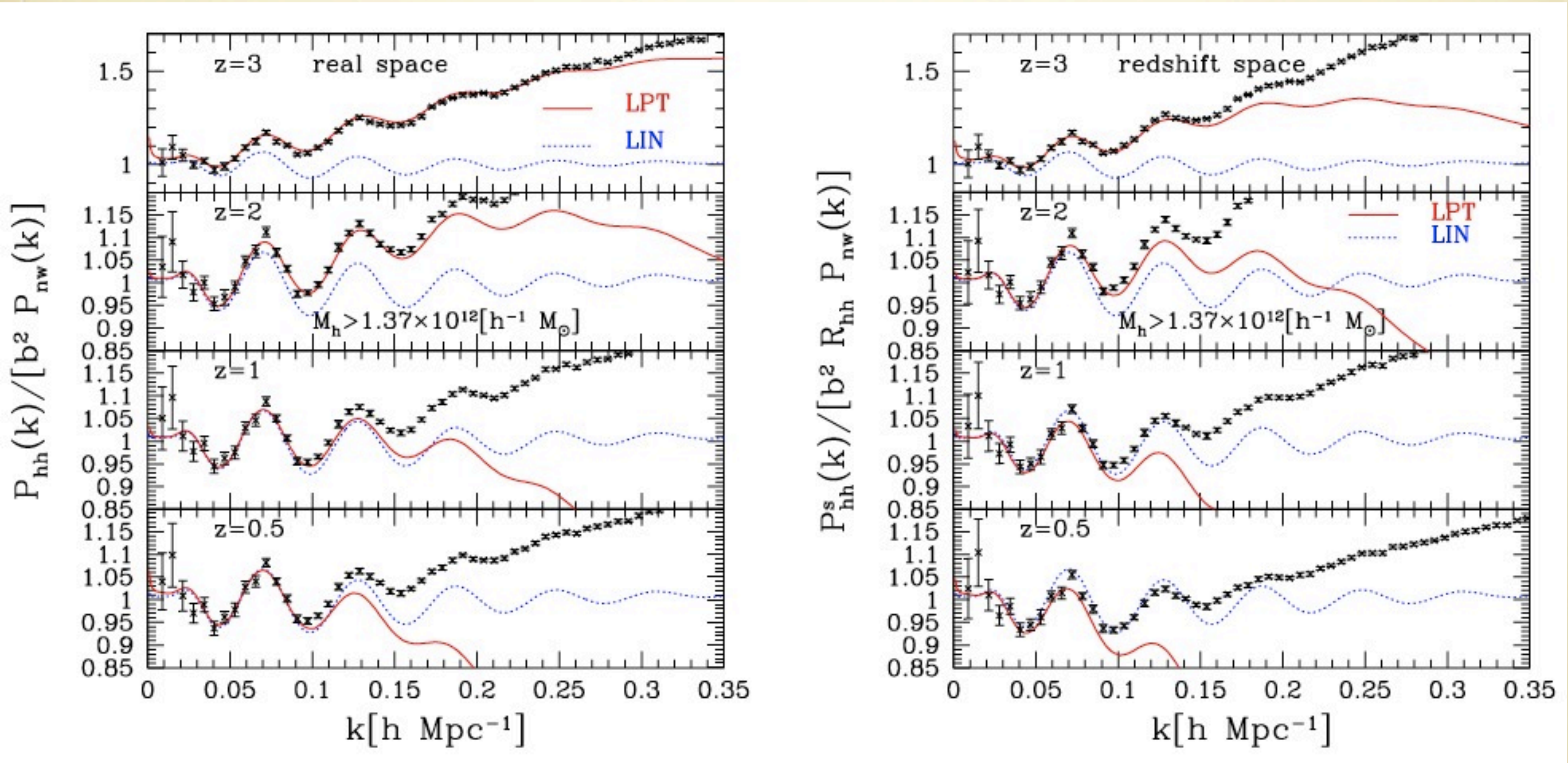






BAO with iPT

One-loop

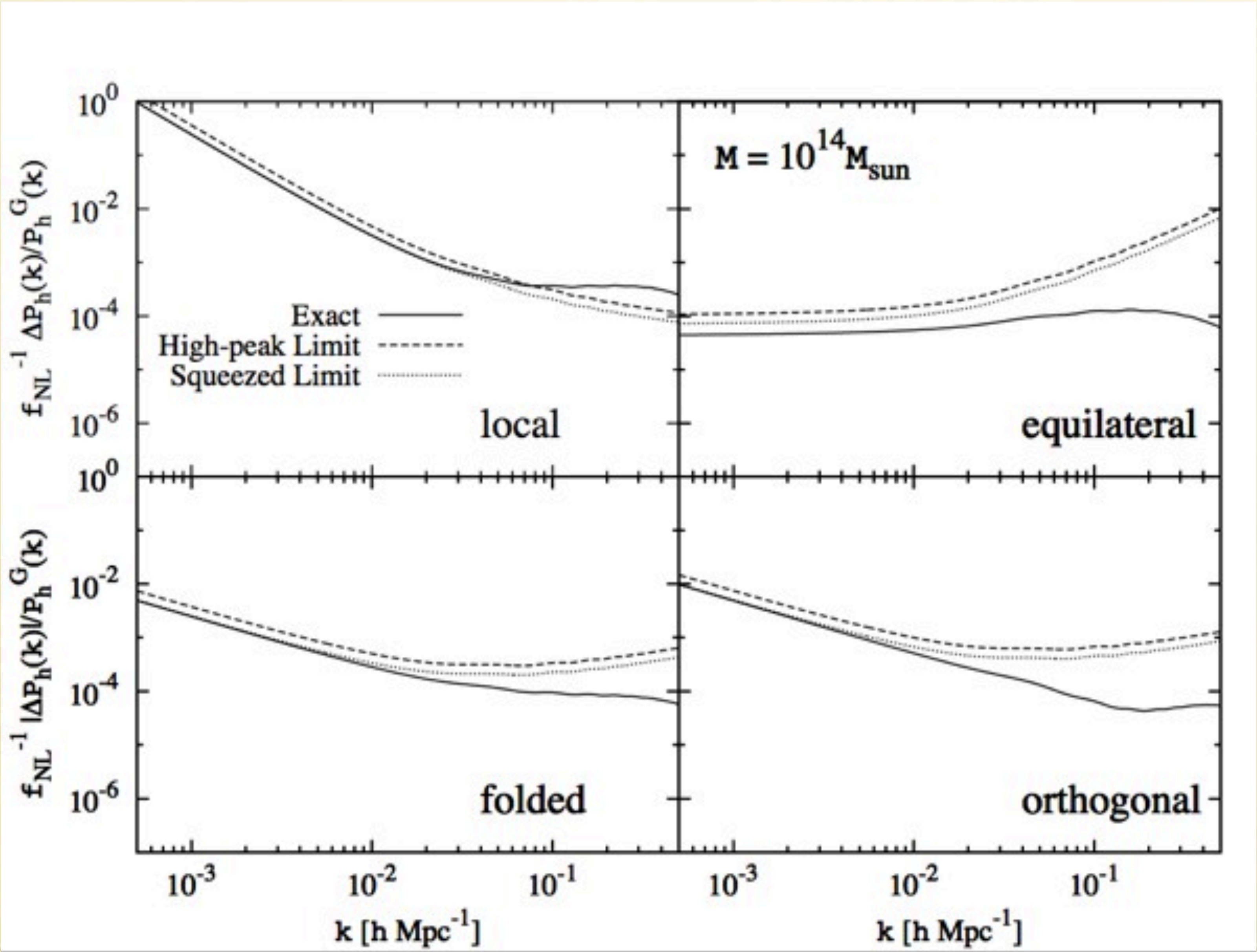


(scale-dependent bias due to nonlinearity)

From: Sato, TM (2011)

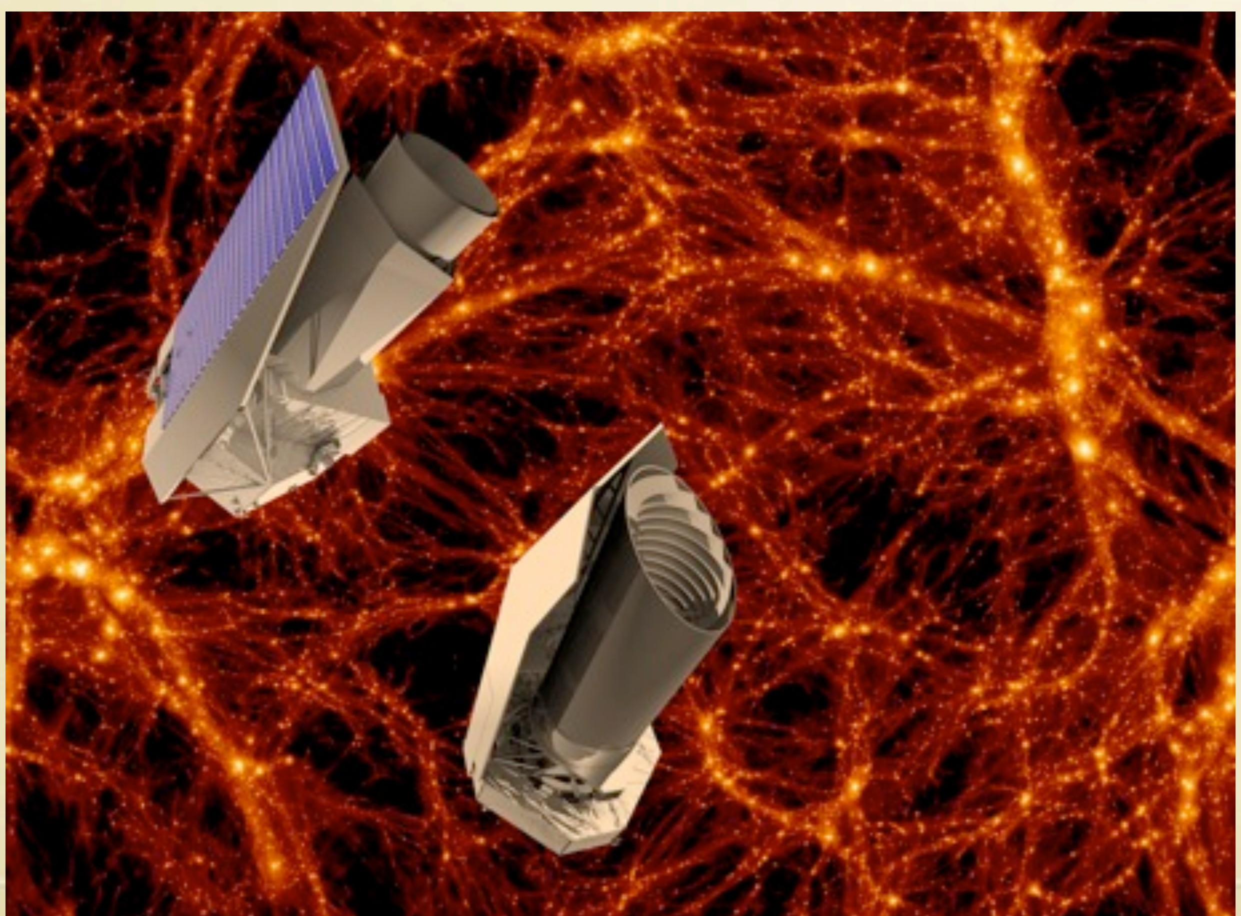
Scale-dependent bias from nG with iPT

- Most accurate among known methods
  - powerful probe of primordial nG



From: TM, in prep

	Modified Gravity	Dark Matter	Initial Conditions	Dark Energy		
Parameter	γ	m_ν/eV	f_{NL}	w_p	w_a	FoM
Euclid Primary	0.010	0.027	5.5	0.015	0.150	430
Euclid All	0.009	0.020	2.0	0.013	0.048	1540
Euclid+Planck	0.007	0.019	2.0	0.007	0.035	4020
Current	0.200	0.580	100	0.100	1.500	~10
Improvement Factor	**30**	**30**	**50**	**>10**	**>50**	**>300**



From: Euclid Red Book

In Summary

- LSS is a powerful tool in cosmology
  - dark energy (expansion history)
  - primordial density field (Inflation? or other?)
  - tests of gravity (Einstein? or modified?)
- Needs for precise modeling
  - nonlinear evolutions
  - nonlinear RSD
  - biasing
  - => developing a perturbation theory approach