DEUSS

Dark Energy Universe Simulation Series

PROJET HORIZON

Clustering of Matter in Dark Energy Cosmology

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Outline

Part I

- Dark Energy Quest
- Observational Status
- Future Probes

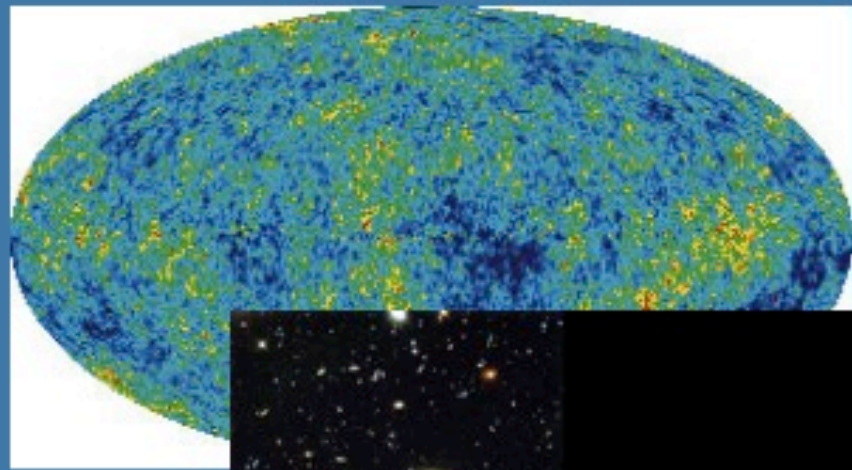
Part II

- Linear Regime Reminder
- Non-Linear Clustering – N-body
- Babel Runs - DEUSS data

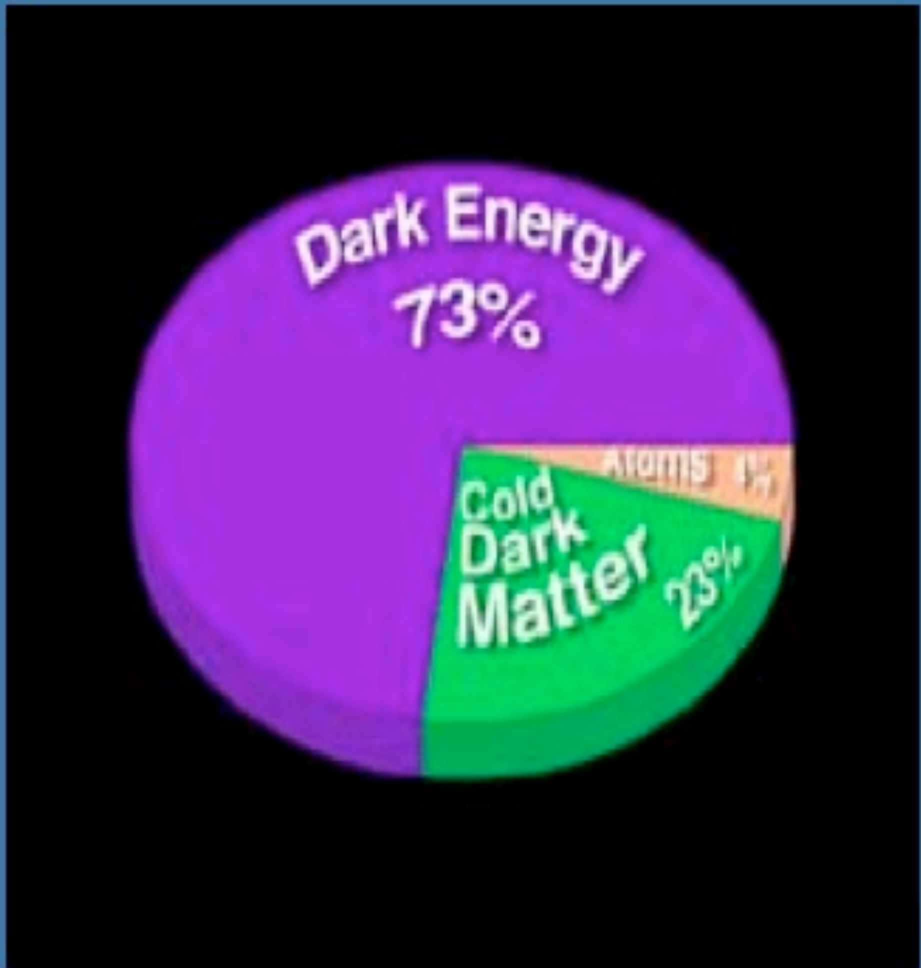
Cosmological Paradigm

General Relativity
+
Homogeneity-Isotropy

- **Light Elements Abundances**
- **Geometry of Space-Time**
- **Cosmic Expansion**
- **Formation and Evolution of LSS**
- **Primordial Spectrum of Fluctuations**
- **Reionization**



The Dark Universe



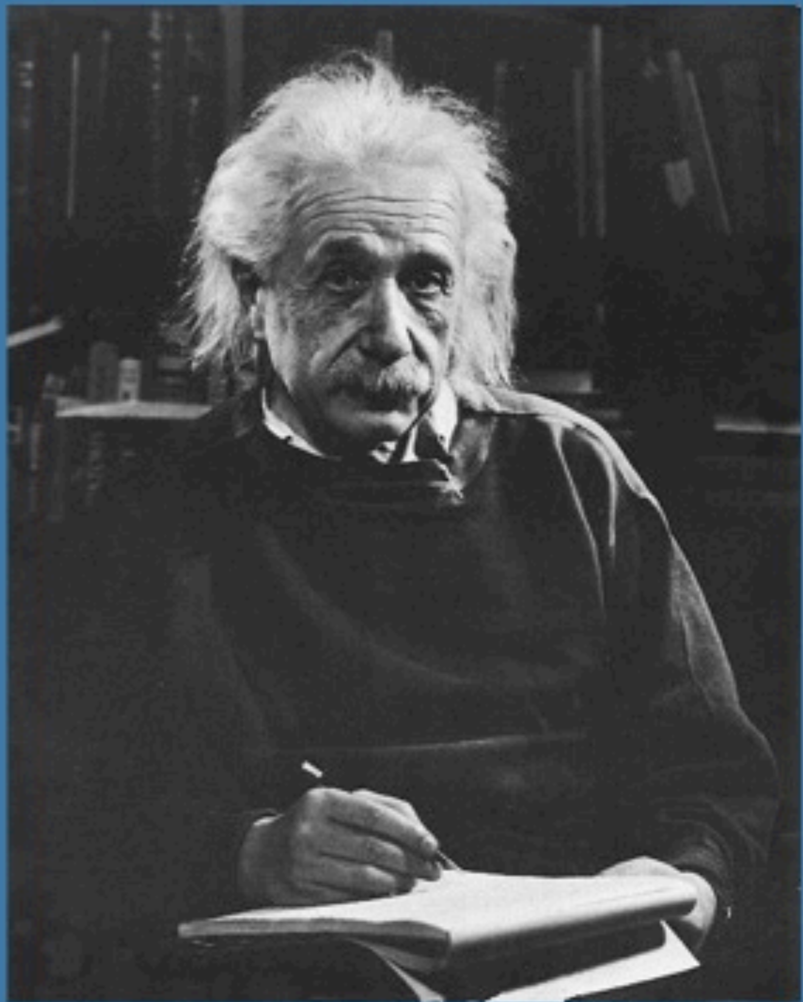
DM: $\Omega_m = 0.23 \pm 0.03$

- Postulated since long time
- Beyond SM particle candidates

DE: $\Omega_{DE} = 0.73 \pm 0.03$

- No clue and if any it is not self-consistent

Why not just Λ?



Cosmological Constant

$$G_{\mu\nu} - \Lambda g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

$$p_\Lambda = -\rho_\Lambda$$

Eureka?

Not so much, let's look at what De Sitter had to say in a letter to Einstein…

Brief Historical Diversion (I)

(credit to Rob Caldwell for pointing out to this correspondence)

*"It cannot be denied that the introduction of the constant… **detracts from the simplicity and elegance of the original theory**…**one of whose great charms was that it embraced so much without introducing a new empirical constant**."* (Letter to Einstein 1917)

*"In any case, one thing stands. The general theory of relativity allows the addition of the [cosmological constant] in the field equations. **One day, our actual knowledge of the composition of the fixed-star sky, the apparent motions of the fixed stars, the position of the spectral lines as a function of distance**, will probably have come far enough for us to be able to decide empirically the question of whether or not vanishes."*

(Letter to De Sitter 14 April 1917)

Brief Historical Diversion (II)

"The main point in our 'difference in creed' is that you have a specific belief and I am a skeptic. Observations will never be able to prove that vanishes, only that is smaller than a given value. Today I would say that is certainly smaller than 10^{-45} cm^{-2} and is probably smaller than 10^{-50} cm^{-2}. Maybe one day observations will also provide a specific value, but up to know I have no knowledge of anything pointing to this."

(Letter to Einstein 18 April 1917)

After 90 years the issue is back and more troublesome than ever

The Cosmological Constant Problem

Vacuum Energy: $T_{\mu\nu}^{\text{vac}} = \rho_{\text{vac}} g_{\mu\nu}$ (Lemaitre 1934; Zeldovich 1968)

$$G_{\mu\nu} = 8\pi G\left[T_{\mu\nu}^{SM} + T_{\mu\nu}^{DM} + T_{\mu\nu}^{\text{vac}}\right]$$

QFT: $\rho_{\text{vac}} = \hbar k_{\max}^4$ $\rho_{EW}^{\text{vac}} = (200\ \text{GeV})^4$ $\rho_{SUSY}^{\text{vac}} \cong (1\ \text{TeV})^4$

$$\rho_{\Lambda}^{\text{obs}} = (10^{-12}\ \text{GeV})^4$$

Geometrical Constant: $G_{\mu\nu} - \Lambda g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$ **Two constants!**

Cosmic Coincidence: **Λ could be anything but strangely allows for sufficient structure formation**

Alternative Proposals

Beyond Standard Model:

$$G_{\mu\nu} = 8\pi G\left[T_{\mu\nu}^{SM} + T_{\mu\nu}^{DM} + T_{\mu\nu}^{DE}\right]$$

- Quintessence Models
- PNG-Boson
- Interacting DE-DM
- ....

Generic feature w = w(z)

Beyond Einstein Gravity:

$$\widetilde{G}_{\mu\nu}(k) = 8\pi G\, T_{\mu\nu}^{Matter}$$

- Higher Order Corrections to GR
- Gravity in Extra-Dimension: RS, DGP

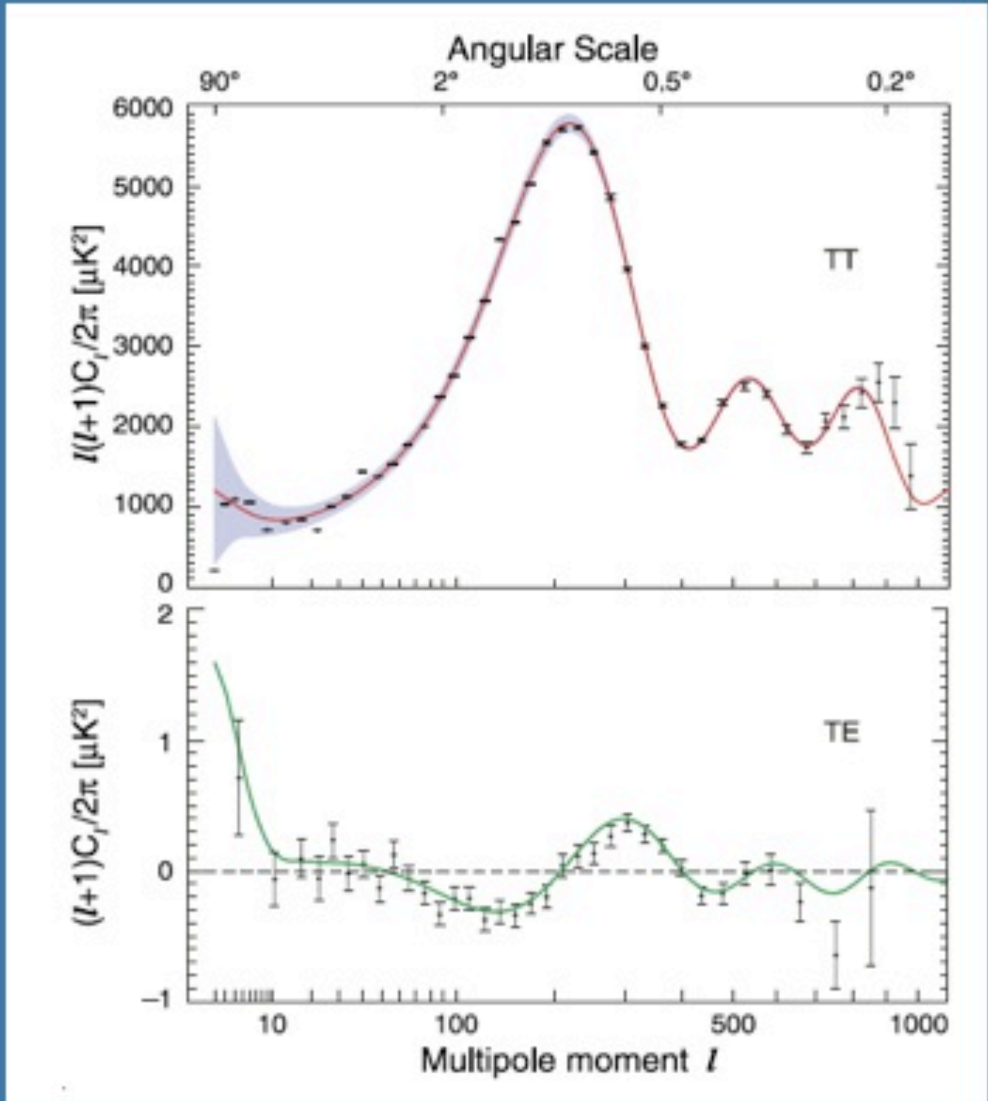
What Should We Look For?

Λ or not Λ is that the question?

- $w = -1$ (constant) ?
- $w = w(z)$ (evolving)?
- c_s (clustering)?

Are these the right questions?

CMB Power Spectra

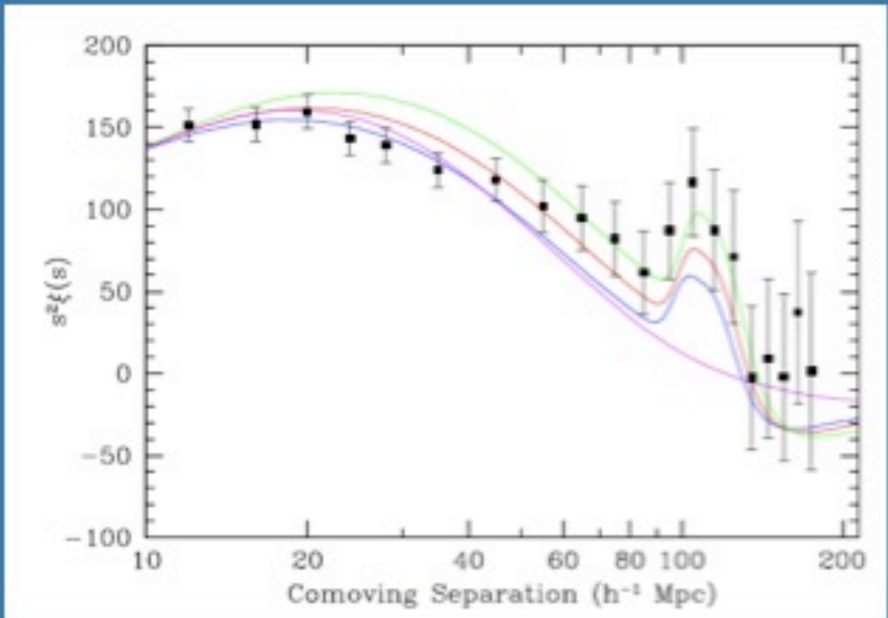


(Hinshaw et al 2008)

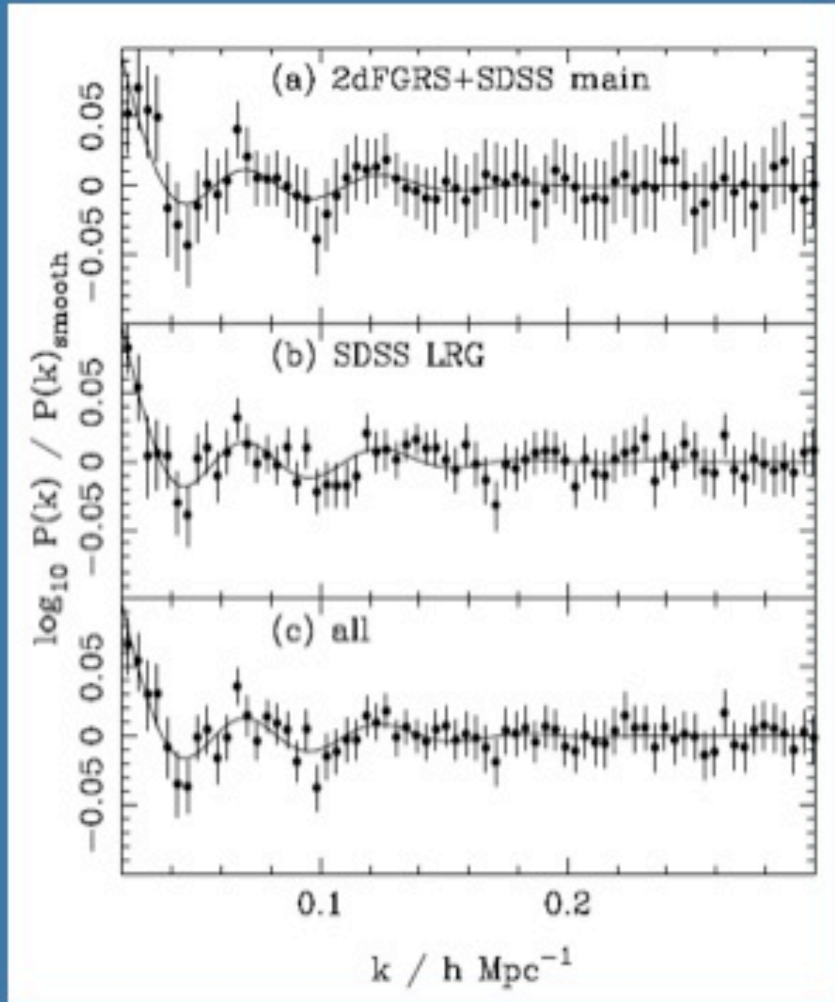
- Distance to last scattering, i.e. position of the CMB peaks and dips
- ISW effect and dark energy perturbations
- Additional information on Ω_m in the full CMB power spectrum
- Full CMB analysis is preferable

Baryon Acoustic Oscillations

- Acoustic oscillations imprinted in the galaxy distribution
- Standard ruler $r_s/D_V(z)$
- Model dependent assumptions



(Eisenstein et al 2005)

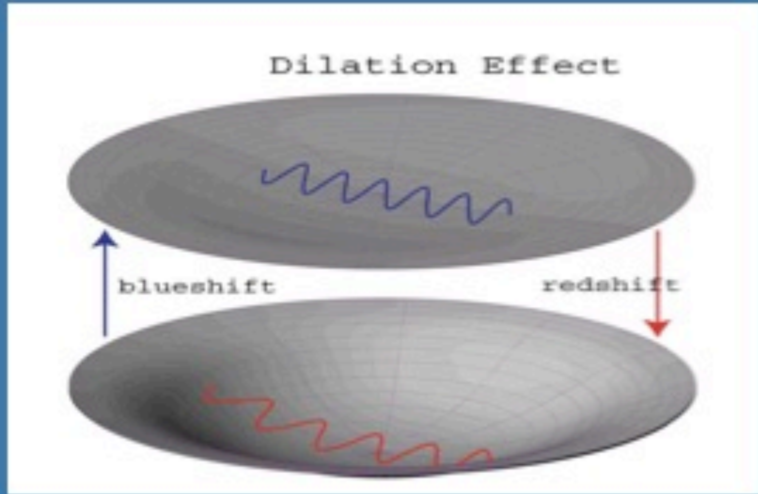


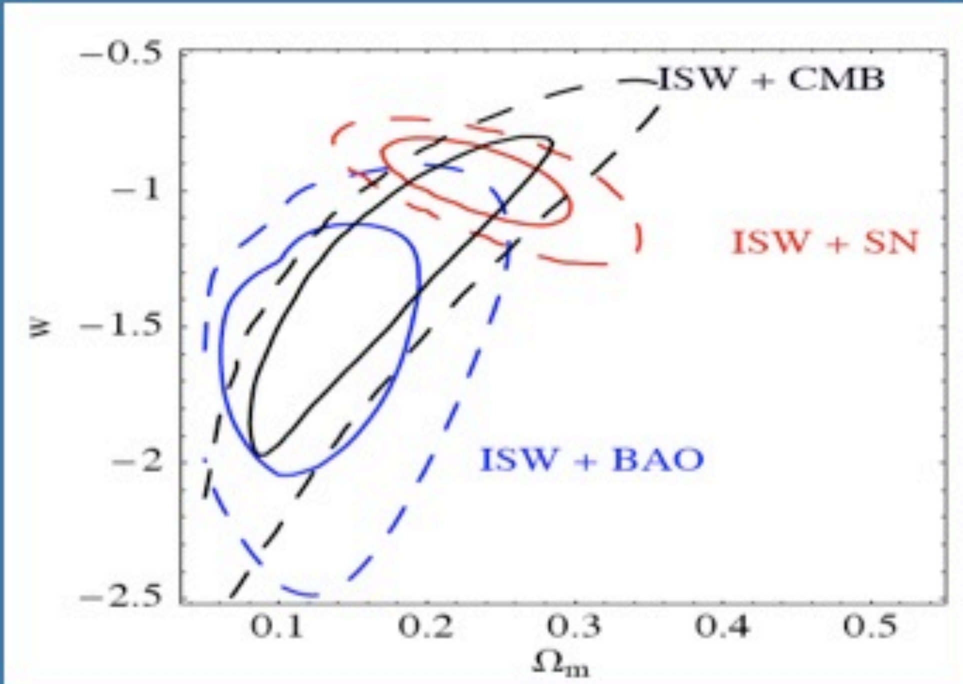
(Percival et al 2007)

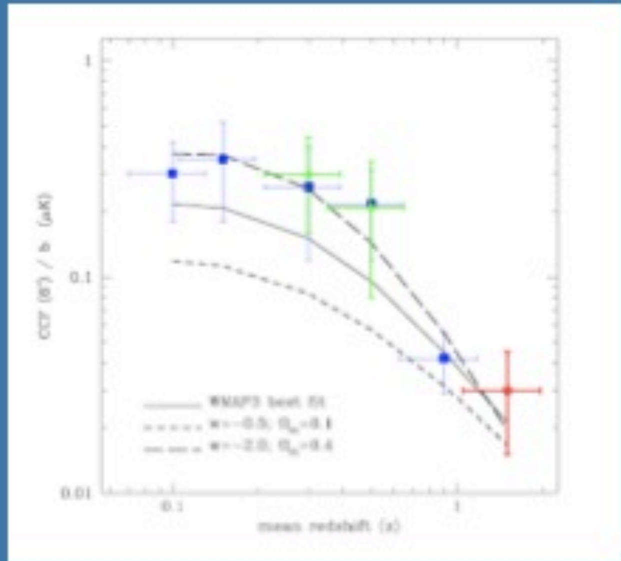
ISW-Correlation

- Late time ISW anisotropies
- Correlated with angular distribution of structures (Crittenden & Turok 1996)

- Several detections

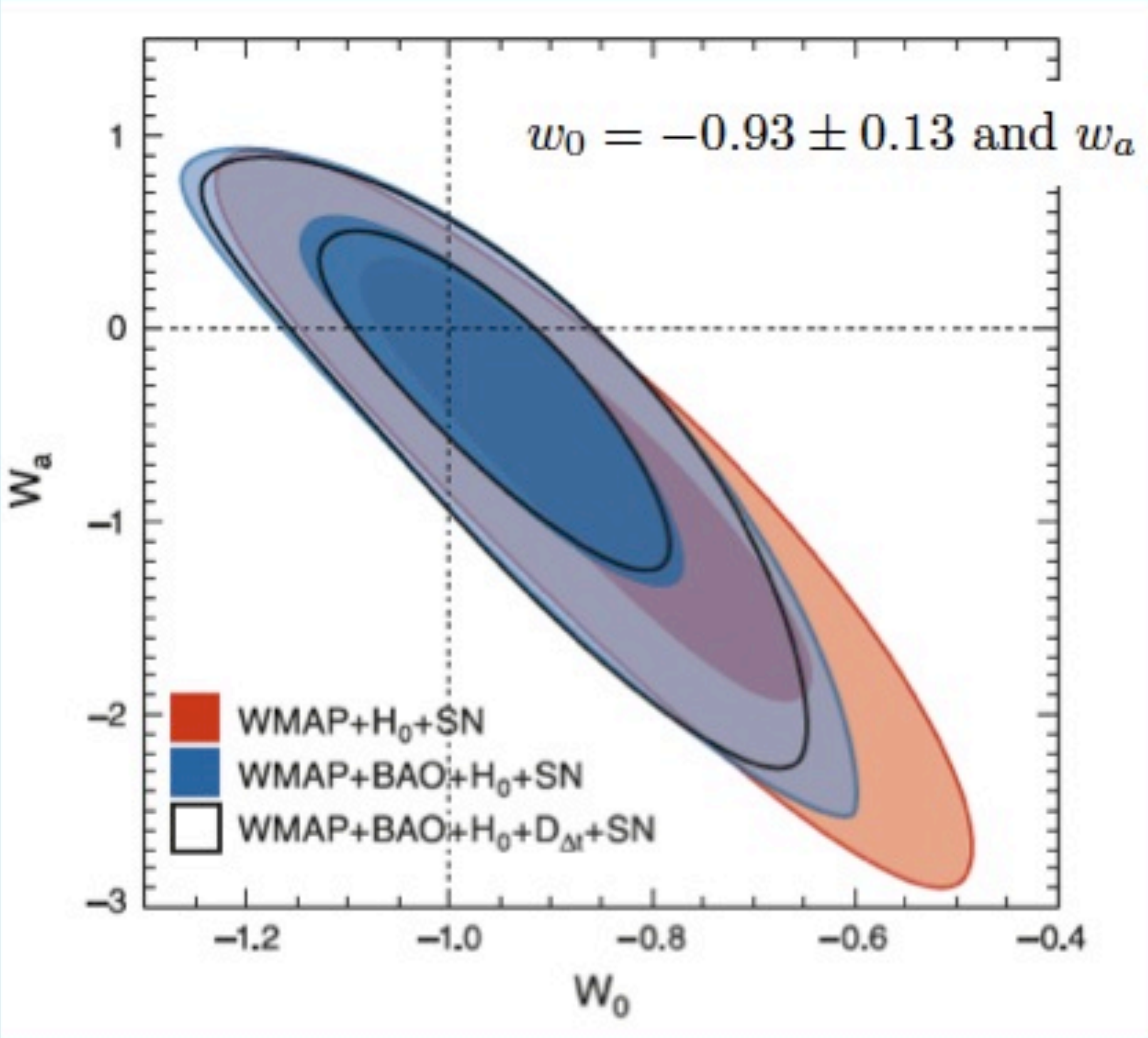






(Giannantonio et al. 2007)

Current Constraints on w(z)



$$w_0 = -0.93 \pm 0.13 \text{ and } w_a = -0.41^{+0.72}_{-0.71} \text{ (68\% CL)}$$

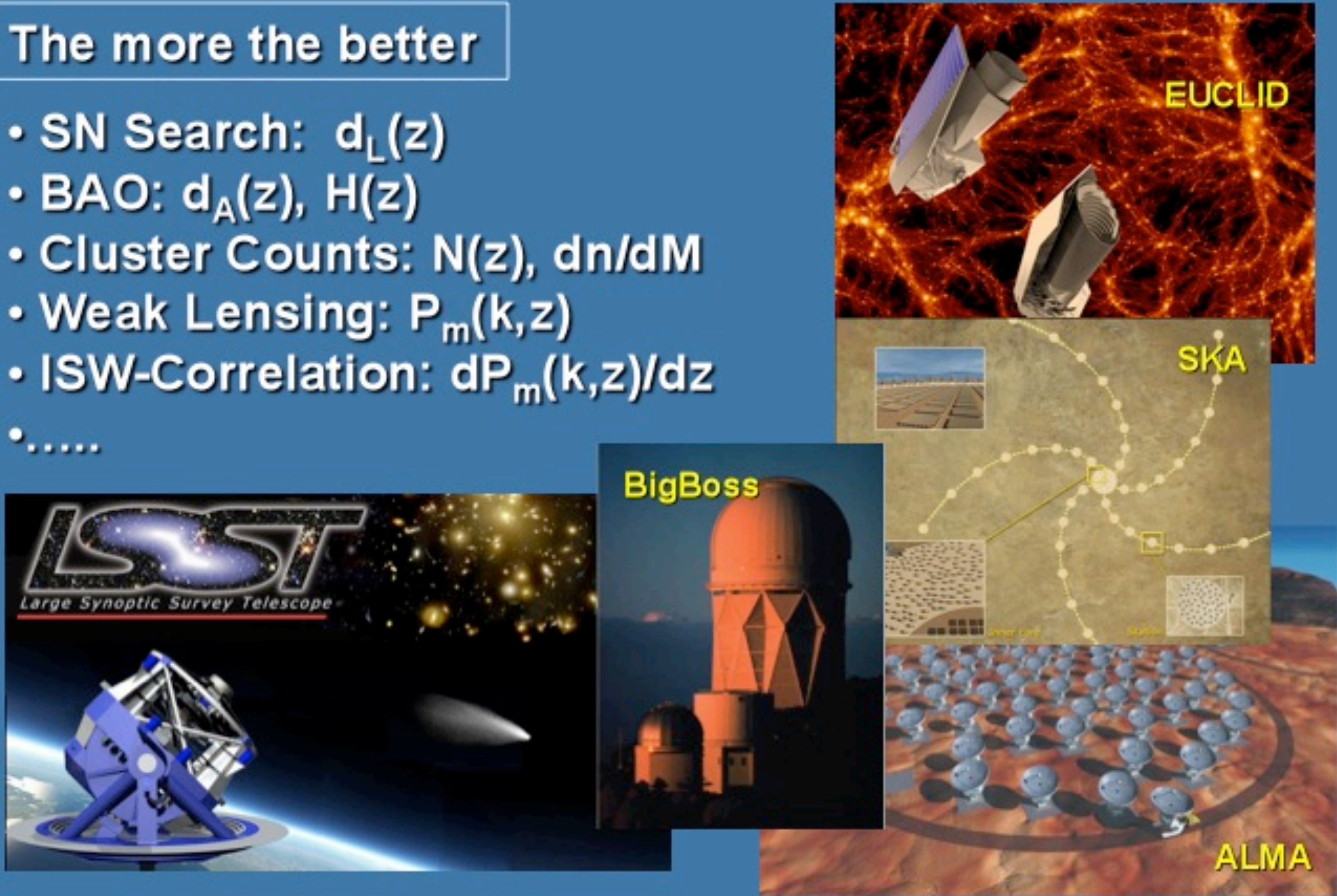
A new generation of experiments in cosmology is needed!

(Komatsu et al 2010)

Future Tests

The more the better

- SN Search: $d_L(z)$
- BAO: $d_A(z)$, $H(z)$
- Cluster Counts: $N(z)$, dn/dM
- Weak Lensing: $P_m(k,z)$
- ISW-Correlation: $dP_m(k,z)/dz$
- .....



Part II

Quintessence Cosmologies

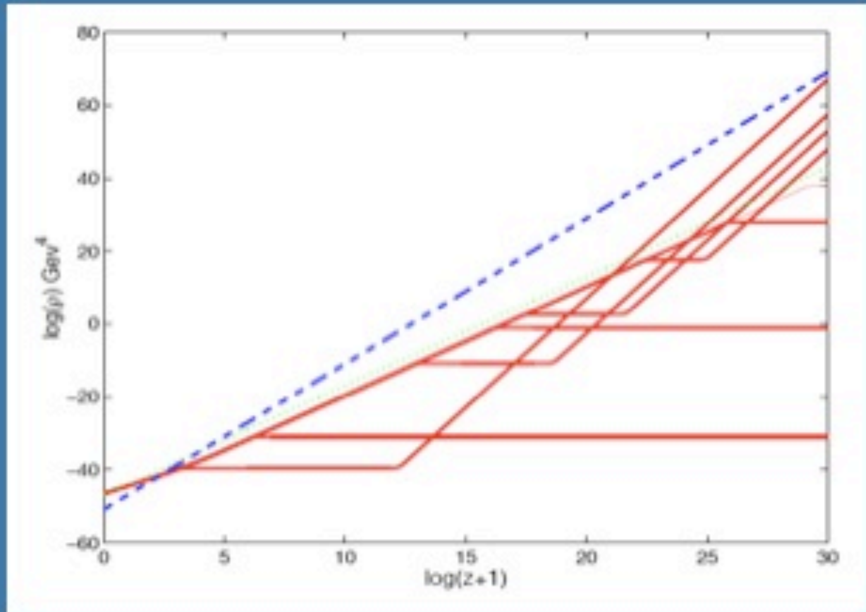
DE as Scalar Field:

- Light scalar field evolving with self-interaction potential
- Several realization with "tracker" potential:

$$\ddot{\varphi} + 3H\dot{\varphi} + \frac{dV}{d\varphi} = 0$$

Ratra-Peebles: $V_{RP}(\varphi) = \frac{\lambda^{4+\alpha}}{m_{Pl}^{\alpha}\varphi^{\alpha}}$

SUGRA: $V_{SU}(\varphi) = \frac{\lambda^{4+\alpha}}{m_{Pl}^{\alpha}\varphi^{\alpha}} e^{4\pi\varphi^2}$



- Model dependent features of late time cosmic expansion

- Scalar field inhomogeneities

$$\delta\varphi'' + 2\mathcal{H}\delta\varphi' + \left(k^2 + \frac{a^2}{m_{Pl}^2}\frac{d^2V}{d\varphi^2}\right)\delta\varphi + 2\Phi\frac{a^2}{m_{Pl}^2}\frac{dV}{d\varphi} - (3\Psi' + \Phi')\varphi' = 0\cdot$$

Effects on Linear Structure Formation

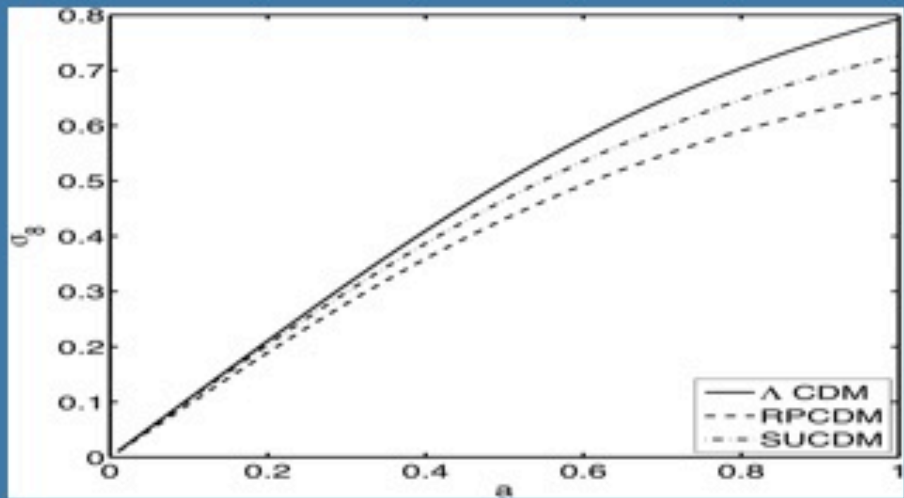
Large Scales (linear regime):

• Background Evolution and DE clustering: Scale and time dependent modification of DM clustering
(growth rate is scale dependent and differ from LCDM)

$$\frac{d^2 D_+}{da^2} + \left(\frac{d\ln\mathcal{H}}{da} + \frac{2}{a}\right)\frac{dD_+}{da} - \frac{3\Omega_m H_0^2}{2a^3\mathcal{H}^2}D_+ = \frac{1}{a^2\mathcal{H}^2 T_m(k)}\left(\frac{a^2\delta\varphi}{m_{Pl}^2}\frac{dV}{d\varphi} - 2a^2\mathcal{H}^2\frac{d\varphi}{da}\frac{d\delta\varphi}{da}\right)$$

• Background Effect:

- Overall suppression of DM linear growth
- Correlated with q(a) evolution of each model



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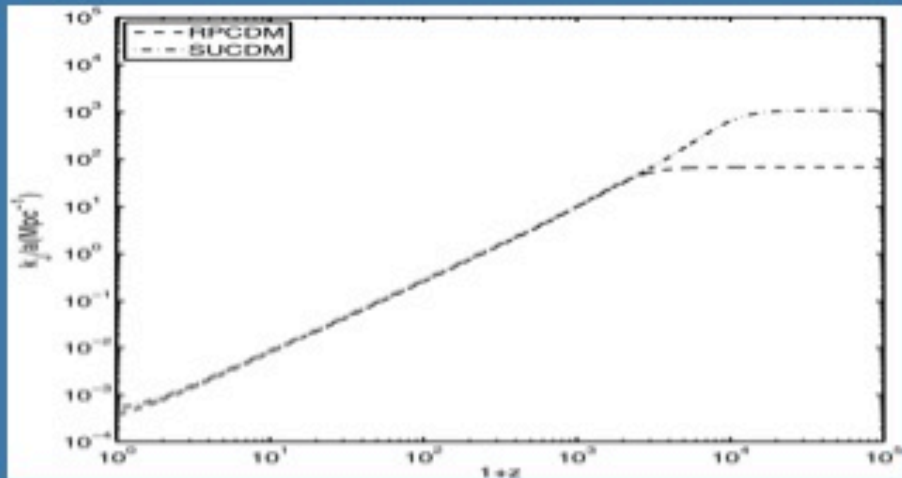
- DE perturbations:

  - Time dependent Jeans-length, $k_J/a\sim\sqrt{V''}$
  - Homogenization $k>k_J$
  - DE clustering on large scales



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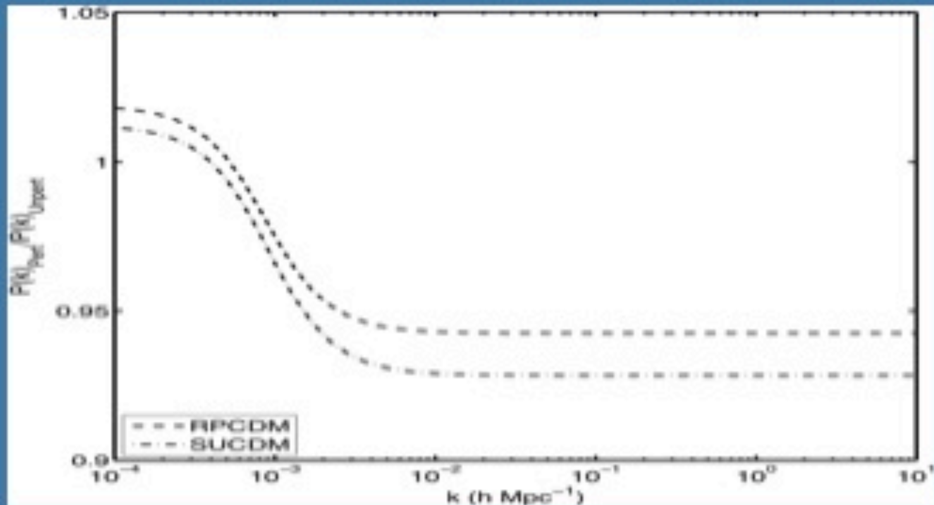
- Combined Effect:

  - Enhancement on large scales
  - Suppression on small scales



How about non-linear regime?

Large Scales:

- DE Linear effects not dramatic, but present and testable:

e.g. ISW-correlation, BAO, Weak Lensing, Peculiar Velocities

Small Scales (non-linear regime): (the common understanding)

- DE does not directly affect DM collapse
- Indirect influence only from different background evolution
- DE model details are not relevant:

- Universal halo mass function (e.g. Jenkins et al. '01)
- Non-linear corrections to power spectrum (e.g. Smith et al. '03)

To what extent these statements are valid?

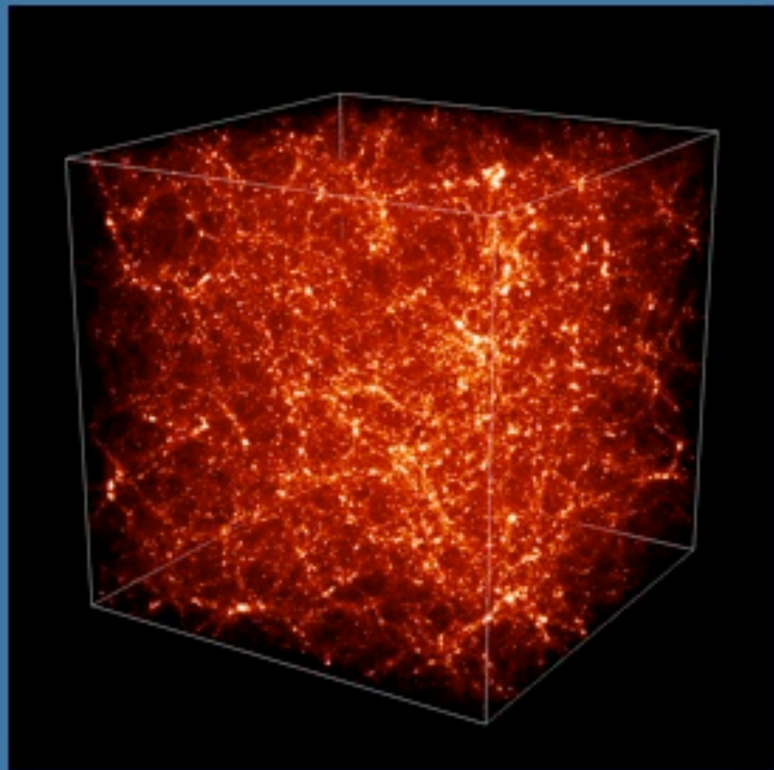
N-Body Simulations

Concept:

- Generate initial 3D-particle distribution
- Follows dynamics evolution of Newtonian collapse in FLRW

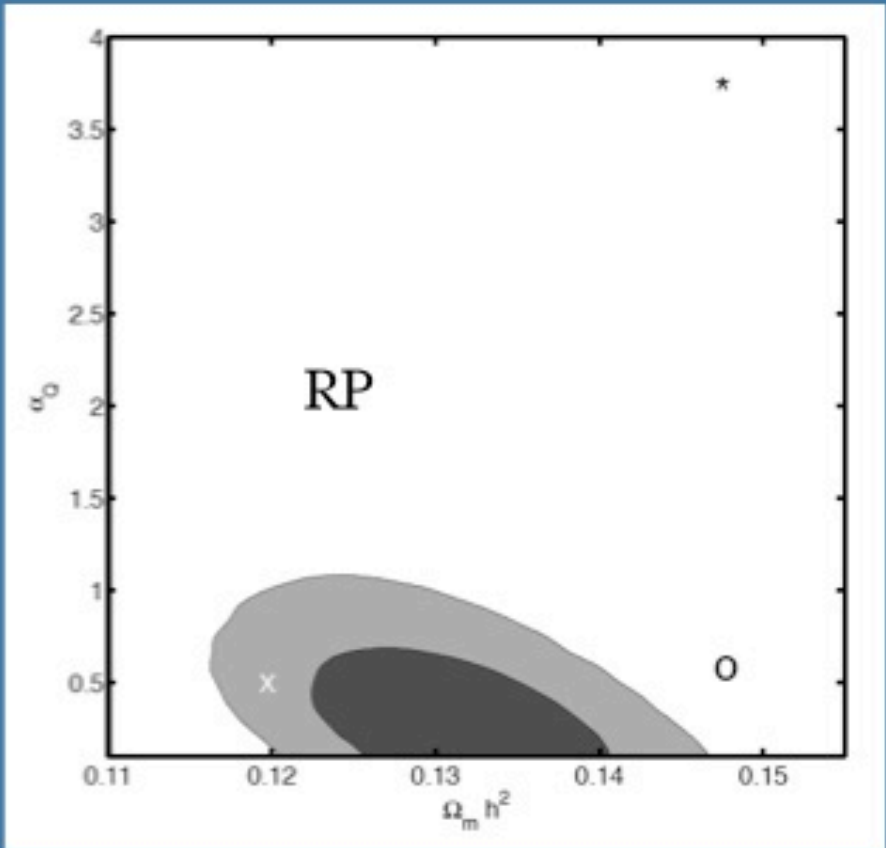
$$\ddot{\mathbf{x}} + 2\frac{\dot{a}}{a}\dot{\mathbf{x}} = -\frac{1}{a^2}\nabla\phi$$
$$\nabla^2\phi = 4\pi G\bar{\rho}(t)a^2\delta = \frac{3}{2}H_0^2\Omega_0\frac{\delta}{a}$$

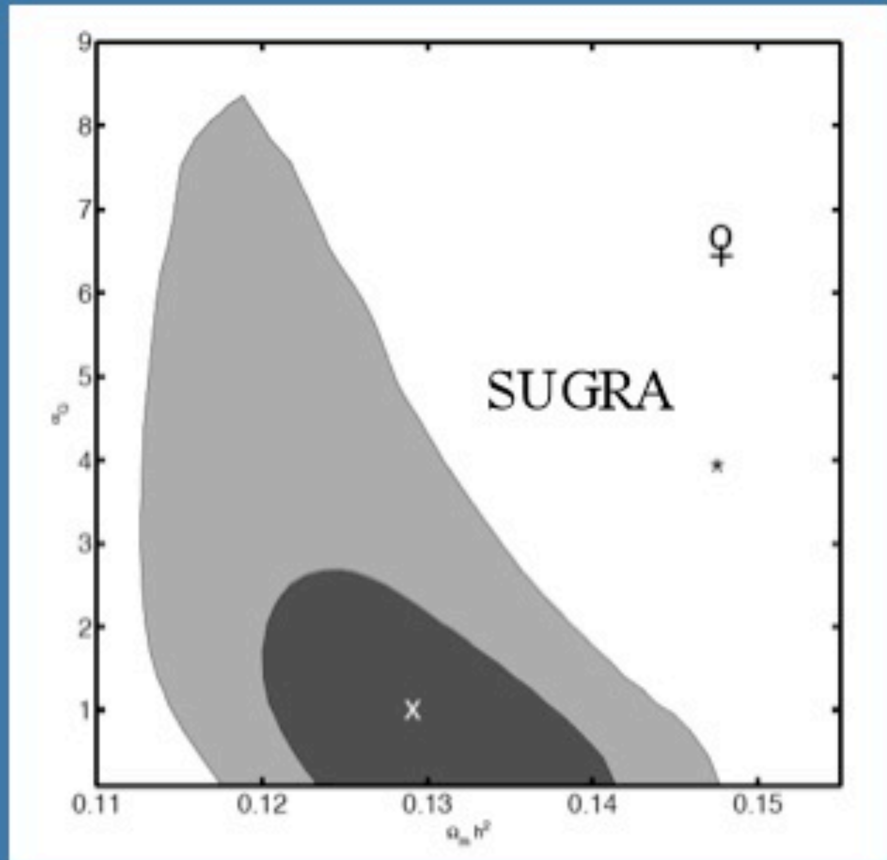
$$\frac{d\mathbf{p}}{da} = -\frac{\nabla\phi}{\dot{a}}, \qquad \frac{d\mathbf{v}}{dt} + 2\frac{\dot{a}}{a}\mathbf{v} = -\frac{\nabla\phi'}{a^3}$$
$$\frac{d\mathbf{x}}{da} = \frac{\mathbf{p}}{\dot{a}a^2}, \qquad \frac{d\mathbf{x}}{dt} = \mathbf{v}$$
$$\nabla^2\phi = 4\pi G\Omega_0\delta_{\rm dm}\rho_{\rm cr,0}/a, \quad \phi' = a\phi$$
$$\dot{a} = H_0\sqrt{1+\Omega_0\left(\frac{1}{a}-1\right)+\Omega_\Lambda\left(a^2-1\right)}$$



Quintessence and N-Body Simulations

Model Calibration: WMAP5 + UNION SN Ia + SDSS

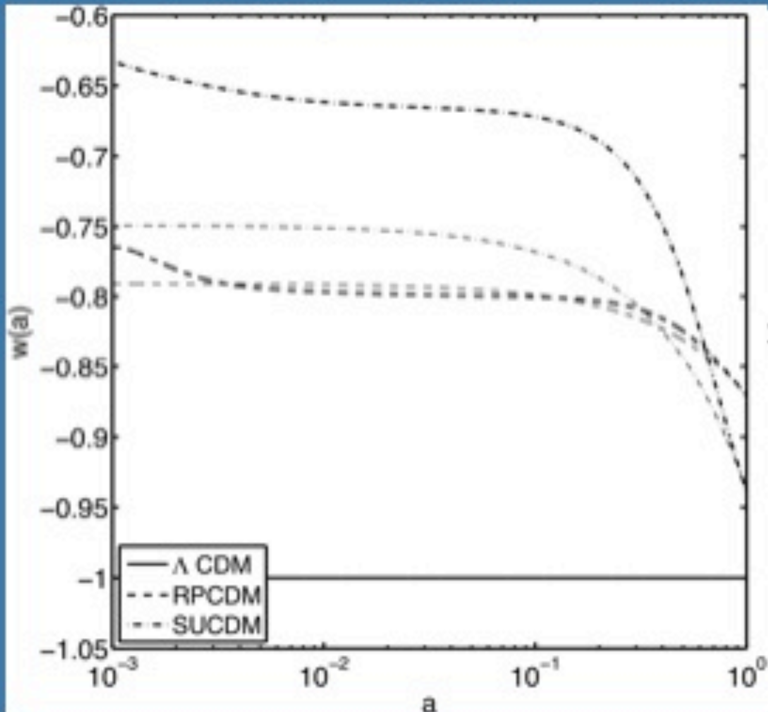


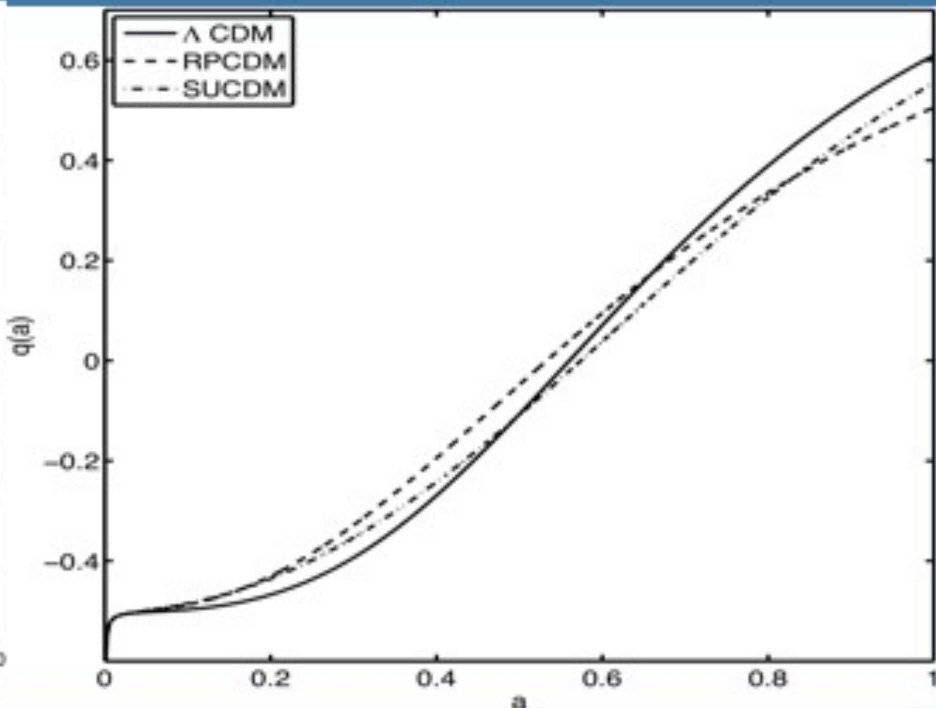


(Alimi et al. '10)

Benchmark Models

Parameters	ΛCDM	RPCDM	SUCDM
Ω_m	0.26	0.23	0.25
α	0	0.5	1
A_S	2.1×10^{-9}	2.0×10^{-9}	2.1×10^{-9}
Derived parameters			
σ_8^{lin}	0.80	0.66	0.73
λ(eV)	2.4×10^{-3}	4.9	2.1×10^{3}





Software Implementation & N-body runs

Linear Pow including DE perturbations:

CAMB (Lewis, Challinor & Lasenby '00)

N-Body Initial conditions:

- **MPGRAFIC** (modified for DE cosmo)
- **Horizon White Noise**
- **z_{ini} determined solving***

$$\frac{\sigma(L/n, z_i)}{\sigma(L/n, z=0)} = D_+(z_i)$$

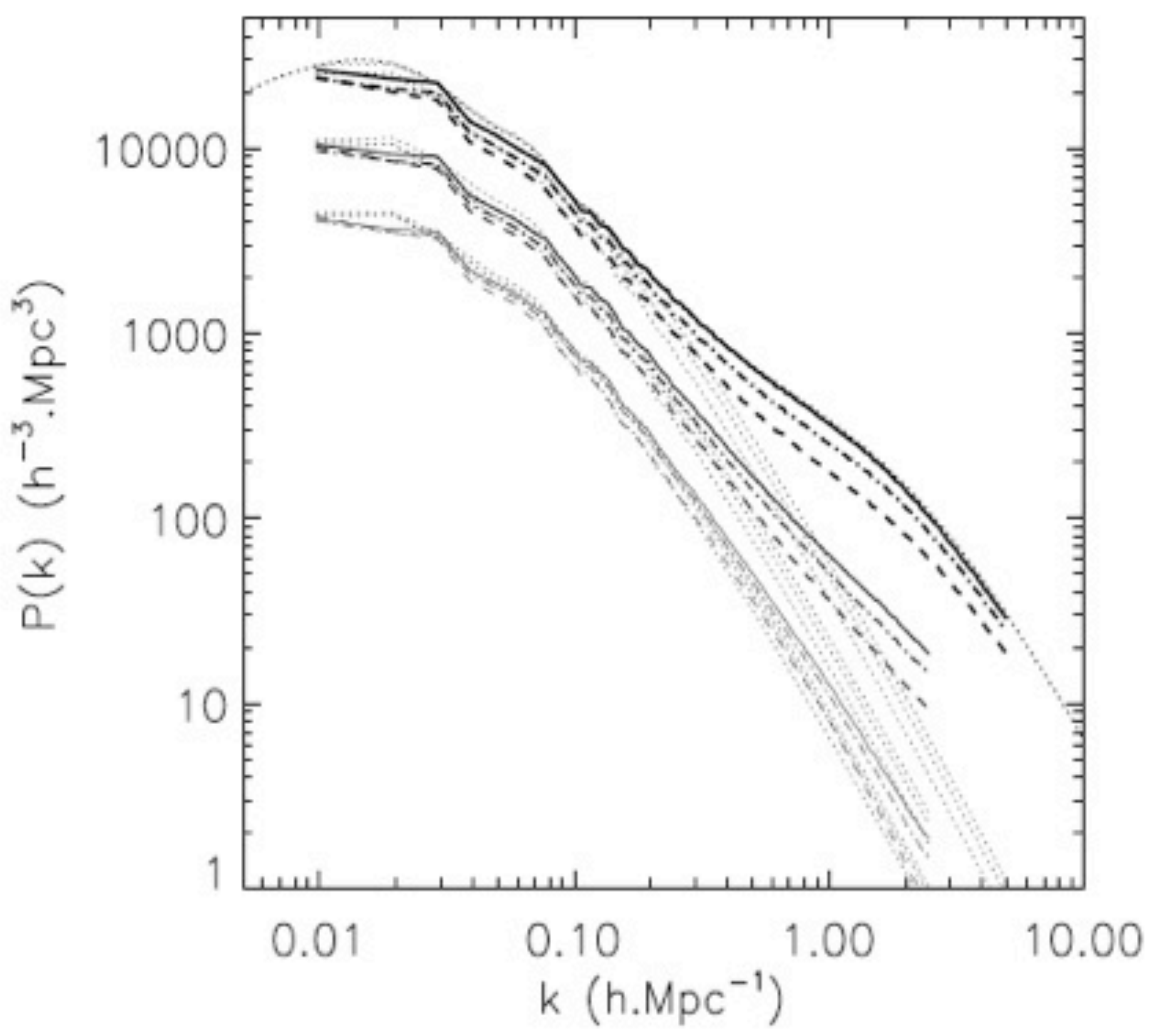
*starting at very high z to avoid spurious effects (see **Crocce, Pueblas and Scoccimarro '06**)

Parameters	162 h^{-1}Mpc	648 h^{-1}Mpc	1296 h^{-1}Mpc
z_{in}	93	56	41
$m_p(h^{-1}M_\odot)$	2.28×10^9	1.46×10^{11}	1.17×10^{12}
$\Delta_x(h^{-1}kpc)$	2.47	19.78	39.55
l_{max}	7	6	6
z_{in}	81	50	37
$m_p(h^{-1}M_\odot)$	2.02×10^9	1.30×10^{11}	1.04×10^{12}
$\Delta_x(h^{-1}kpc)$	2.47	19.78	39.55
l_{max}	7	6	6
z_{in}	92	55	40
$m_p(h^{-1}M_\odot)$	2.20×10^9	1.41×10^{11}	1.13×10^{12}
$\Delta_x(h^{-1}kpc)$	2.47	19.78	39.55
l_{max}	7	6	6

N-Body Code: **RAMSES (Teyssier '02)**

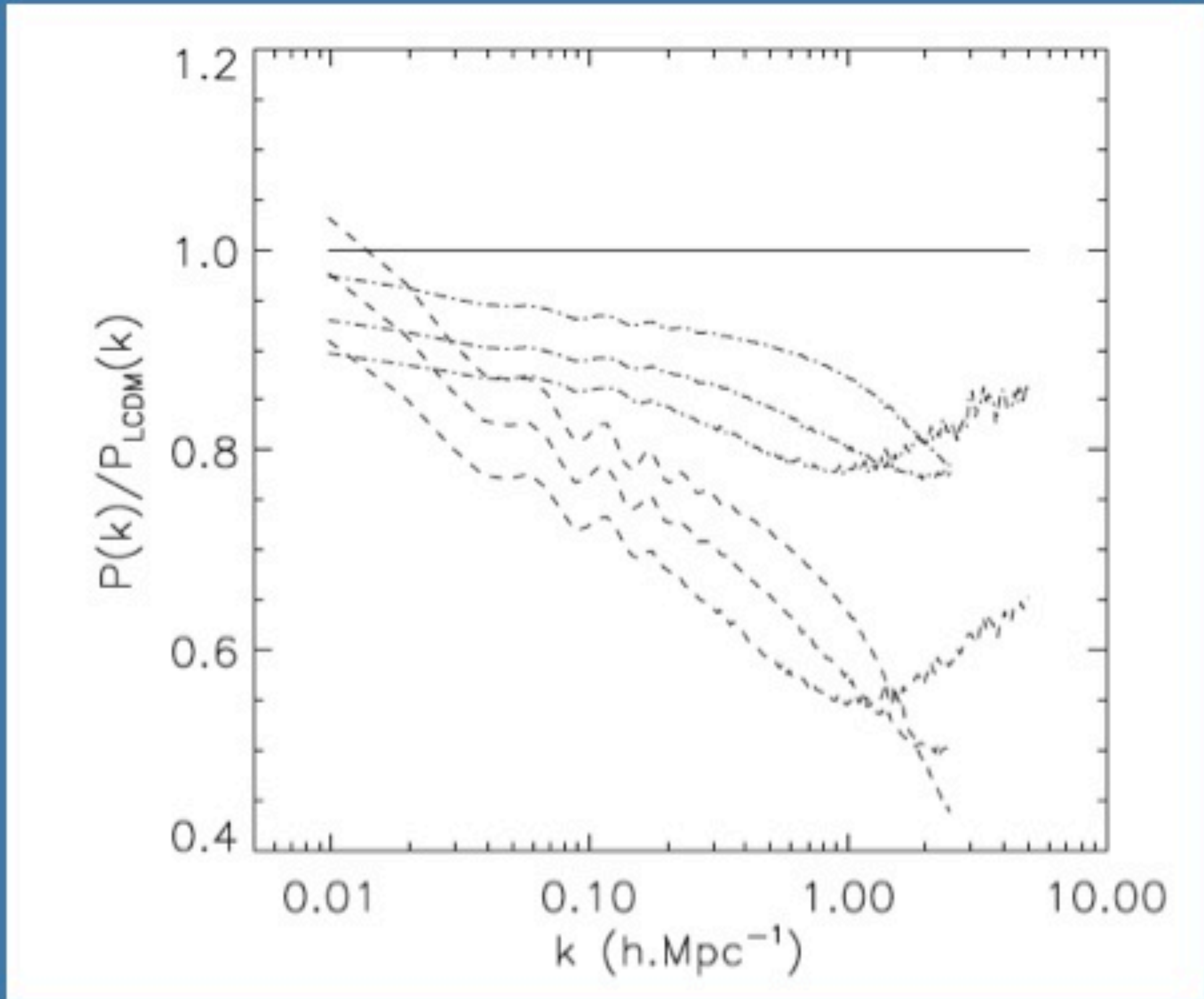
Pow Estimator: **POWMES (Colombi et al. '09)**

Non-Linear Matter Power Spectrum



$P(k)$ vs $P_{LCDM}(k)$

- Advantage of ratio analysis (McDonald, Trac & Contaldi '06)
- DE model power spectrum suppressed compared to LCDM
- Model dependent features



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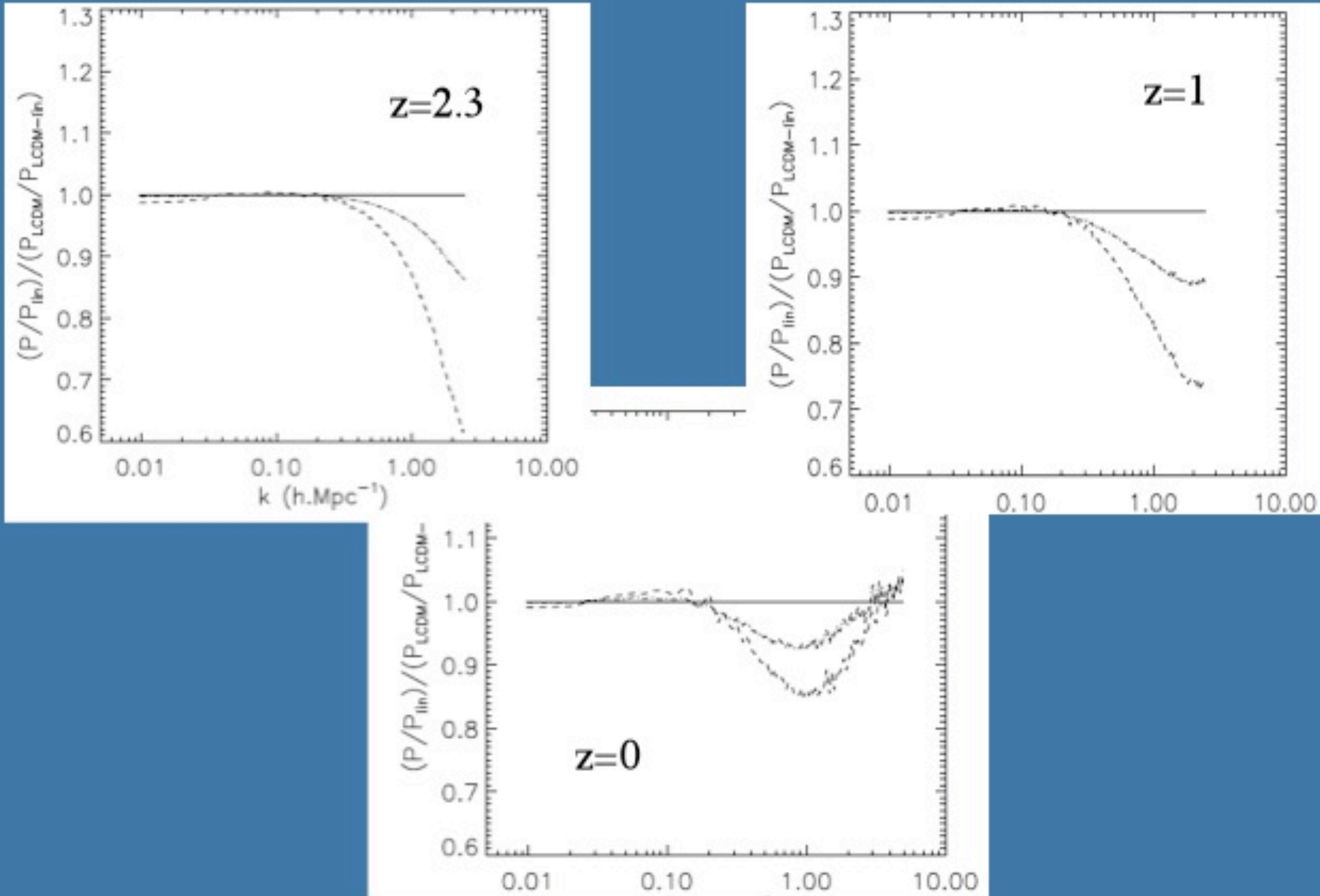
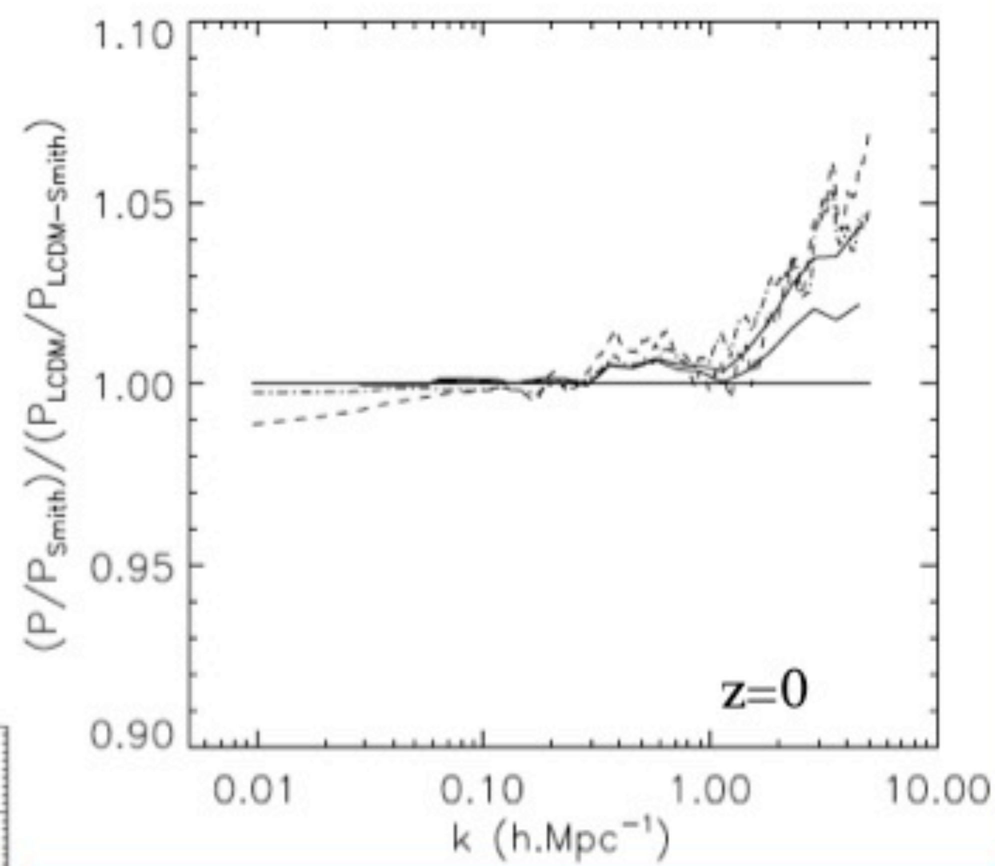
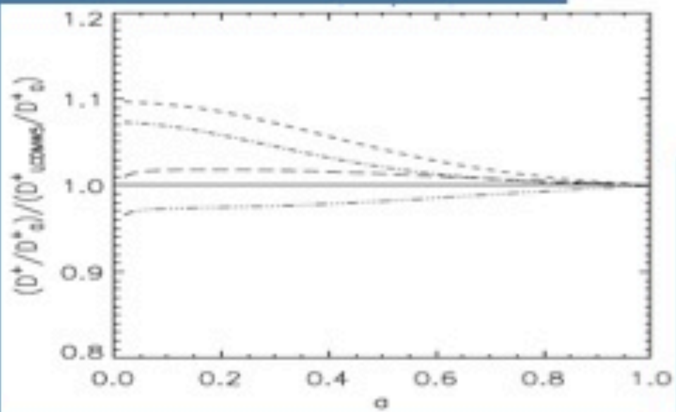


Non-Linear Effects

- Deviations from one model to another scale as their relative growth histories (in agreement with Ma '07)
- NL does not completely erase traces of the linear regime
- Small clustering maintains a fossil record of past evolution





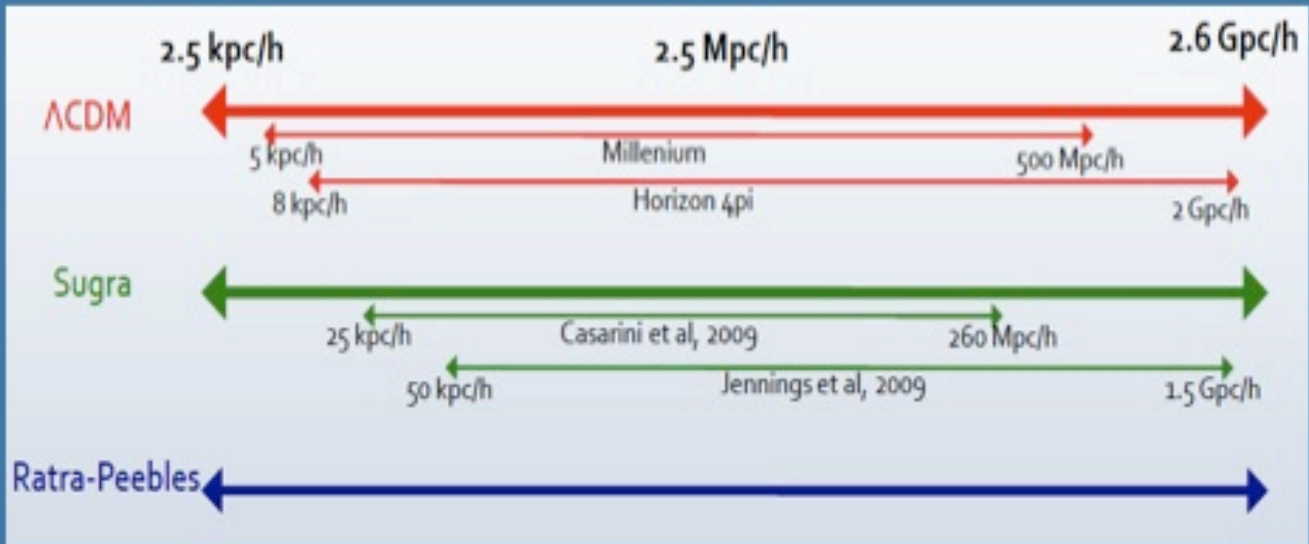
DEUSS - Babel Runs

High-performance parallel computing:

IBM Bluegene/P at IDRIS

Simulation Series Characteristics:

- 1024^3 particles
- 3 box length: 2592, 648, 162 h^{-1} Mpc
- mass resolution: 2×10^{10} - 6×10^{16} h^{-1} $M_{\oplus}$



- 5 000 000 mono-cpu hours (600 yrs) of elapsed time on 12288 cores

DEUSS - DATA

Raw data (user un-friendly):

- RAMSES parallelization: MPI with Peano-Hilbert domain
- Data produced along Peano-Hilbert curve!!

Post-processed data (user friendly):

- Parallel slicer (F. Roy): data redistributed in cubic sub-volumes

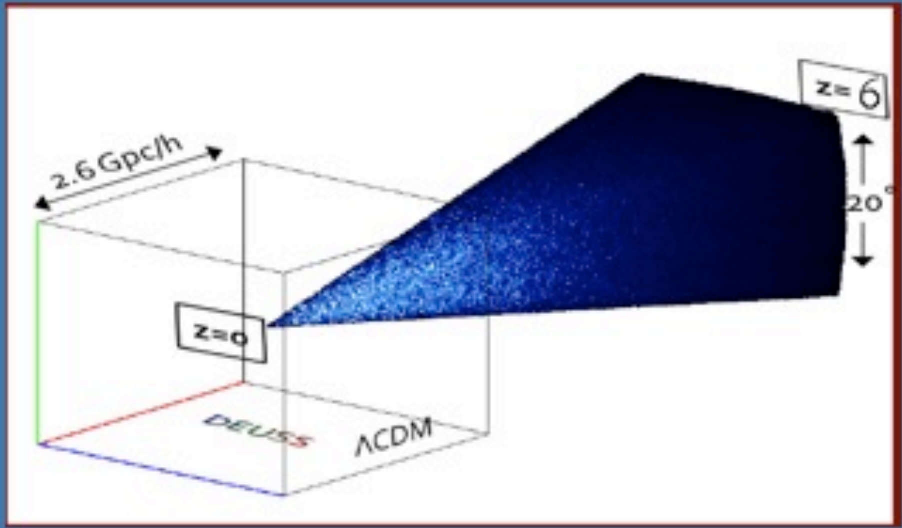
- 40 TB of data in 216 snapshots: 24 snapshots per simulation within z=0,100

- FOF detection: up to 500 000 halos per snapshot containing from 100 to 3 000 000 particles, with $M=3\times10^{10} - 8\times10^{15}\,h^{-1}\,M_{\oplus}$

Data structure:

2 type of data files

- particles per halo: i_H, M_H, r_{CM}, $N_{particle}$
- particles per region: M_H, r_{vir}, r_{av}, r_{CM}, v_{CM}, T_{kin}, L^T_{kin}, $\rho(r)$, $\rho_{vel}(r)$, $T_{kin}(r)$, $L^t_{kin}(r)$



Light cones for each cosmological simulation:

- Full sky light-cones (4pi) up to z=1 per simulation
- 2 narrow light-cones (20°×20°) up to z=6

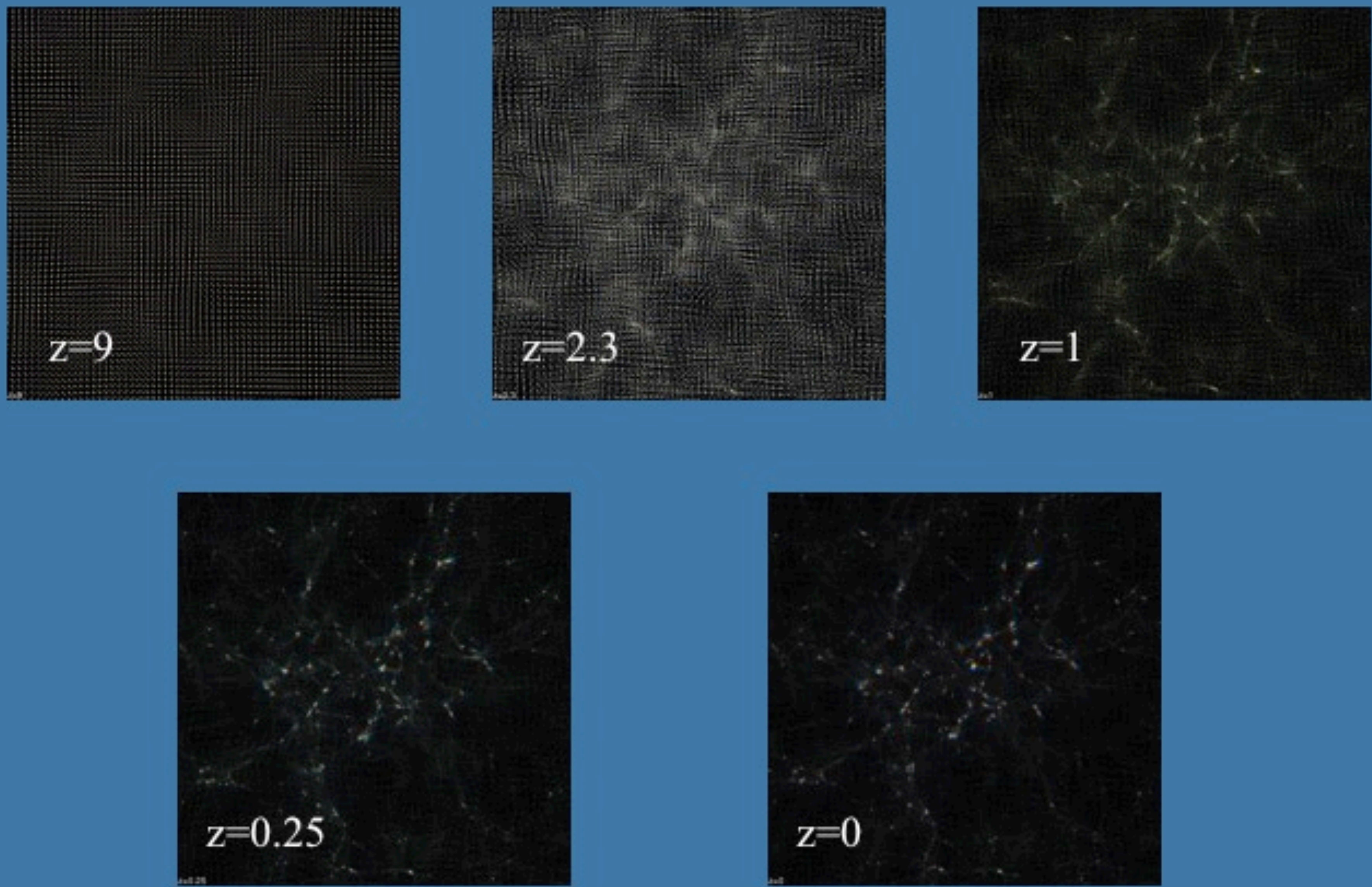
What can you do with these mass of data?

Cubic Volumes : Any field oriented analysis e.g. correlations, distribution and filaments for BAO, WL, etc..

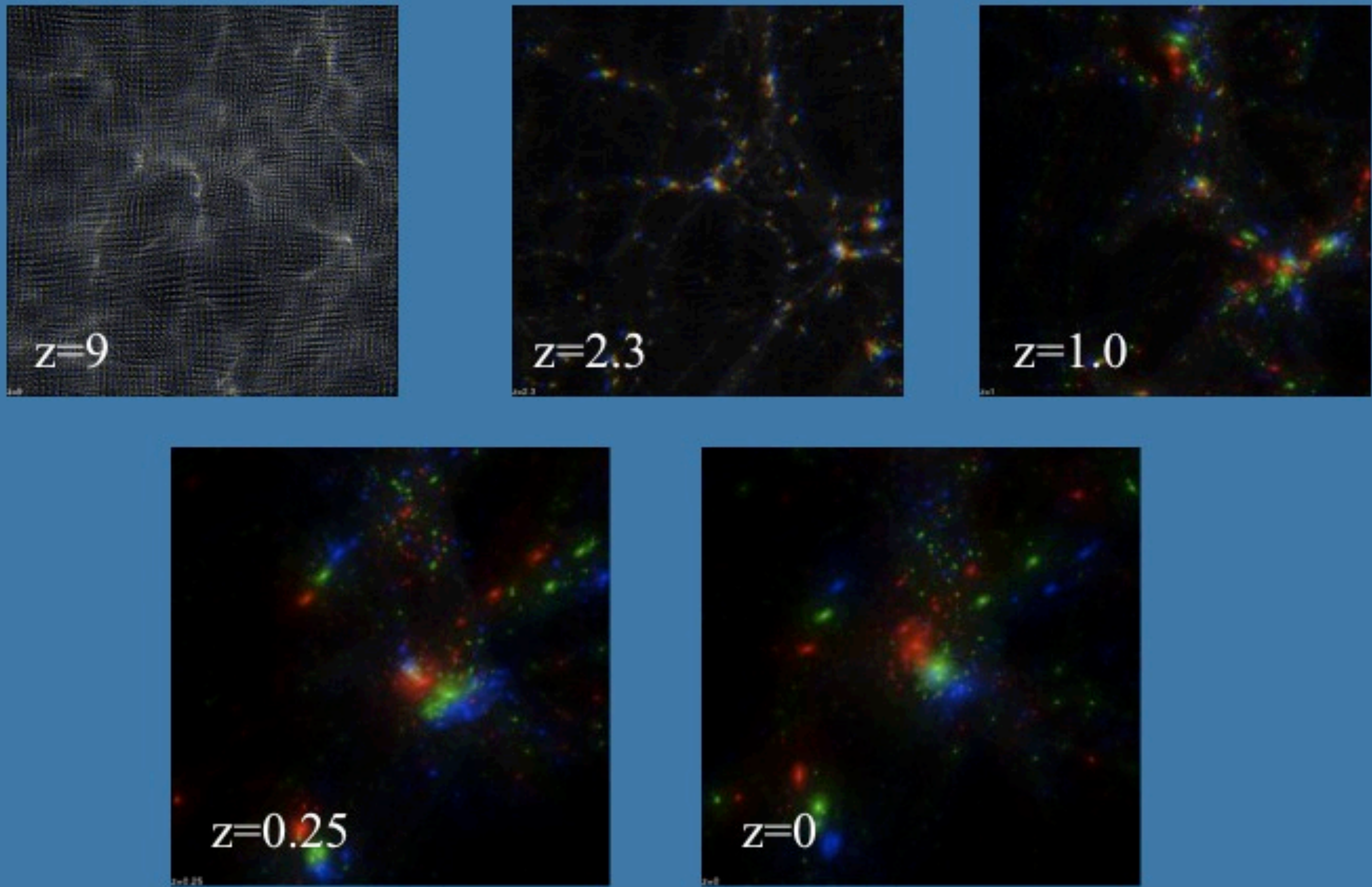
Halos : Cluster counts, Strong Lensing, statistical properties, internal profiles and dynamics

Light- Cones : Observations/Surveys oriented studies

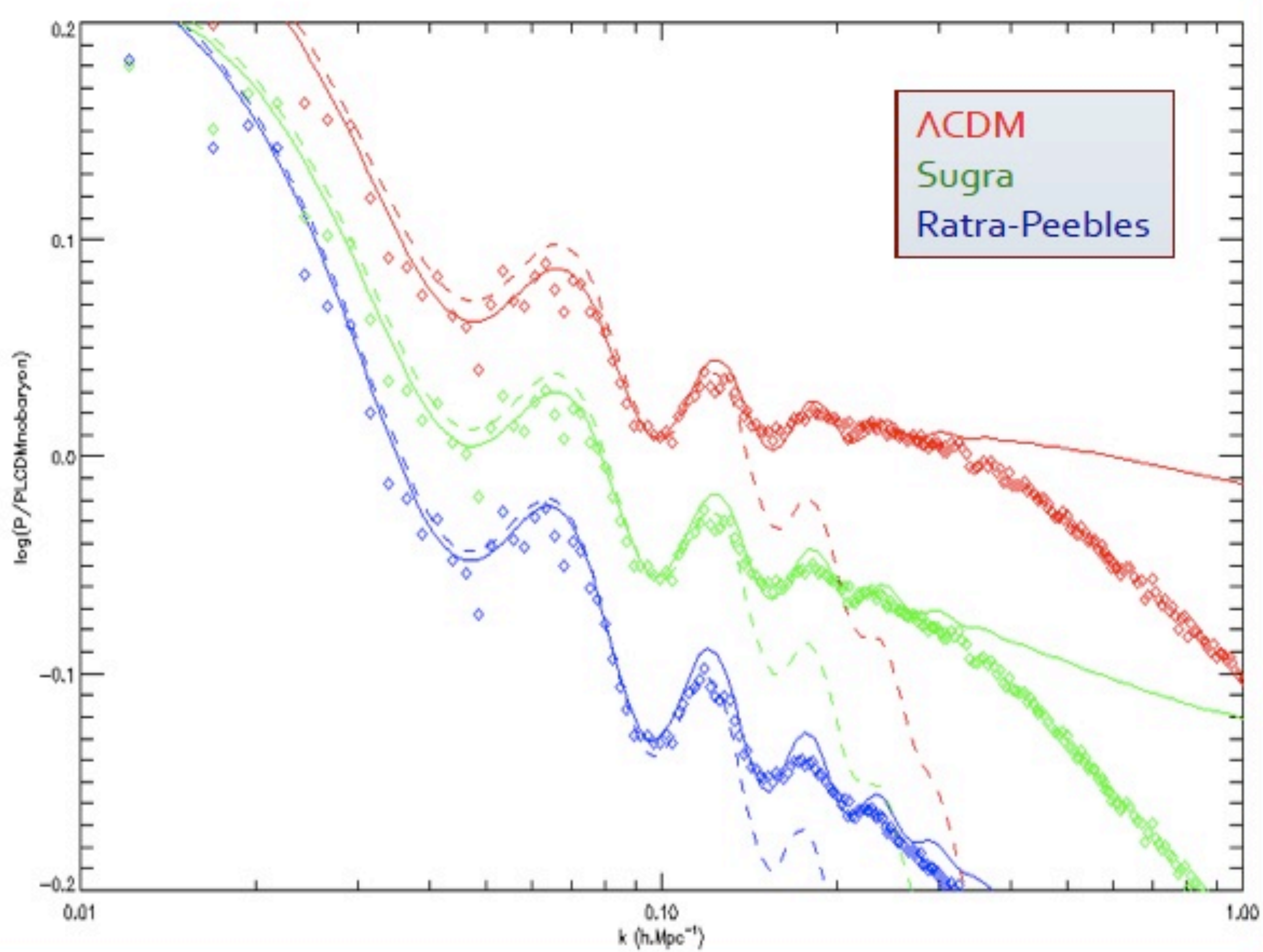
Subvolume of 162 h^{-1}Mpc from 2592 h^{-1} Mpc



Subvolume of 10 h^{-1}Mpc from 162 h^{-1} Mpc

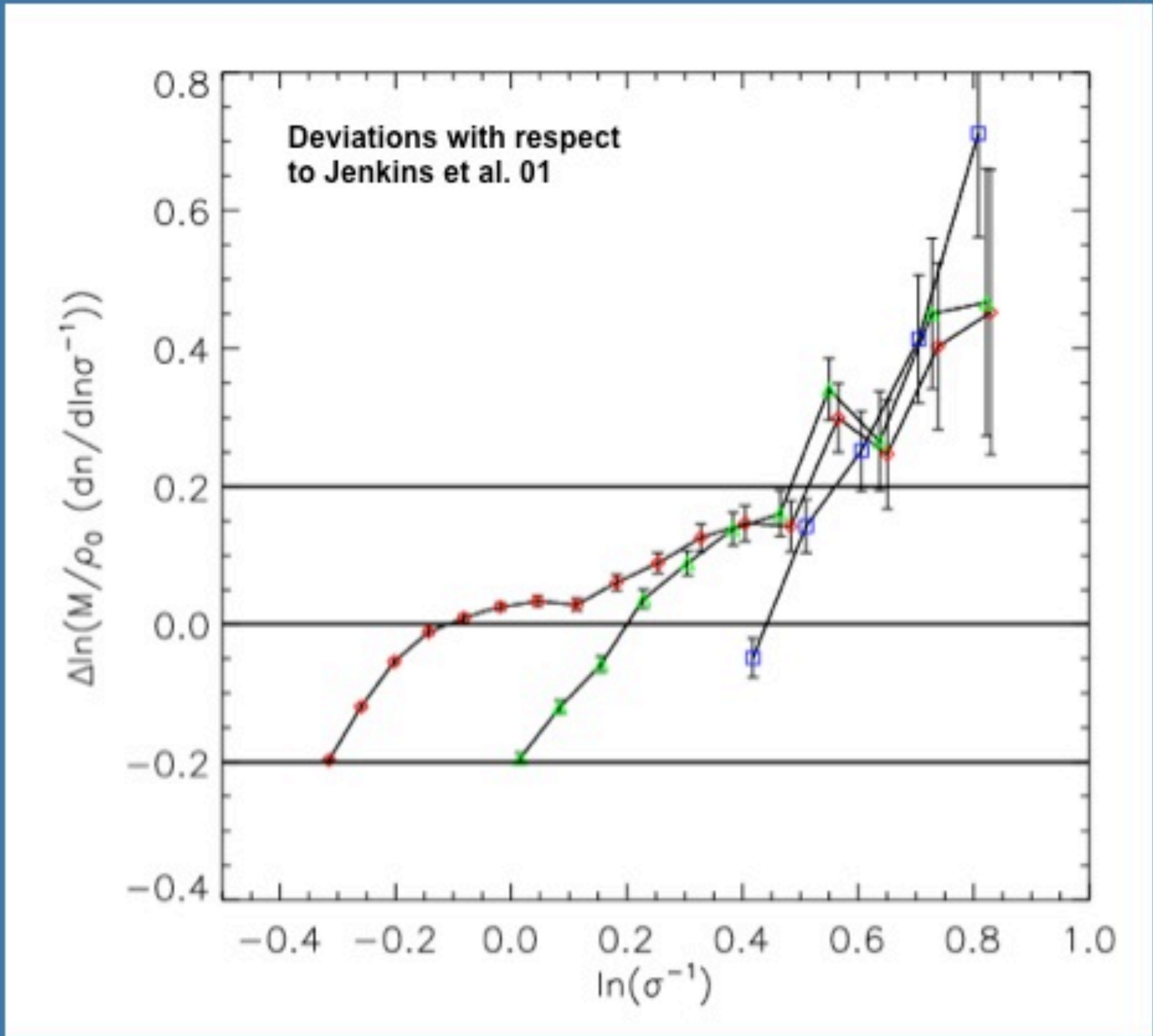


BAO



ΛCDM
Sugra
Ratra-Peebles
log(P/PLCDMnobaryon)
k (h.Mpc⁻¹)
0.2
0.1
0.0
−0.1
−0.2
0.01
0.10
1.00

Halo Mass Function



- for a detailed study of the non-universality of the mass function with pre-DEUSS data see (Courtin et al. '10)

Conclusions

- Dark Energy leaves subtle effects on Cosmic Structure Formation

- Detailed analysis of N-body simulations indicates DE model dependent features in DM non-linear collapse

- Grand-Challenge simulations necessary to fully evaluate the impact of these DE signatures

- Relevant area of research in view of future Cosmic Structure Survey – Exciting Times Head of US

- Work in progress: www.deus-consortium.org