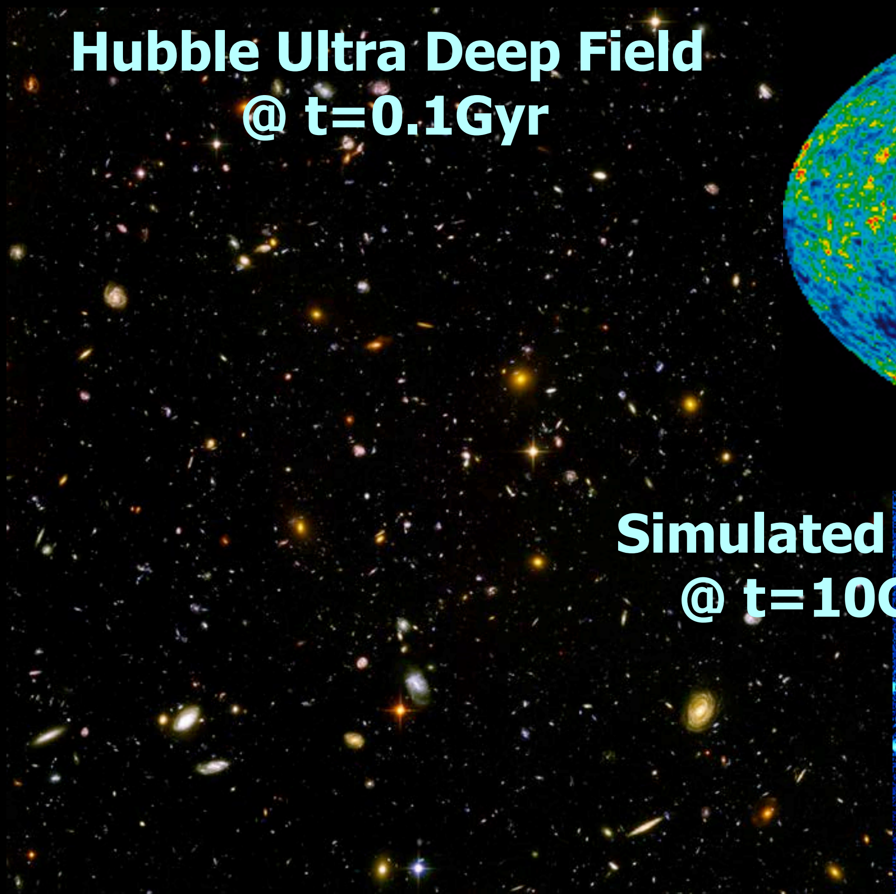
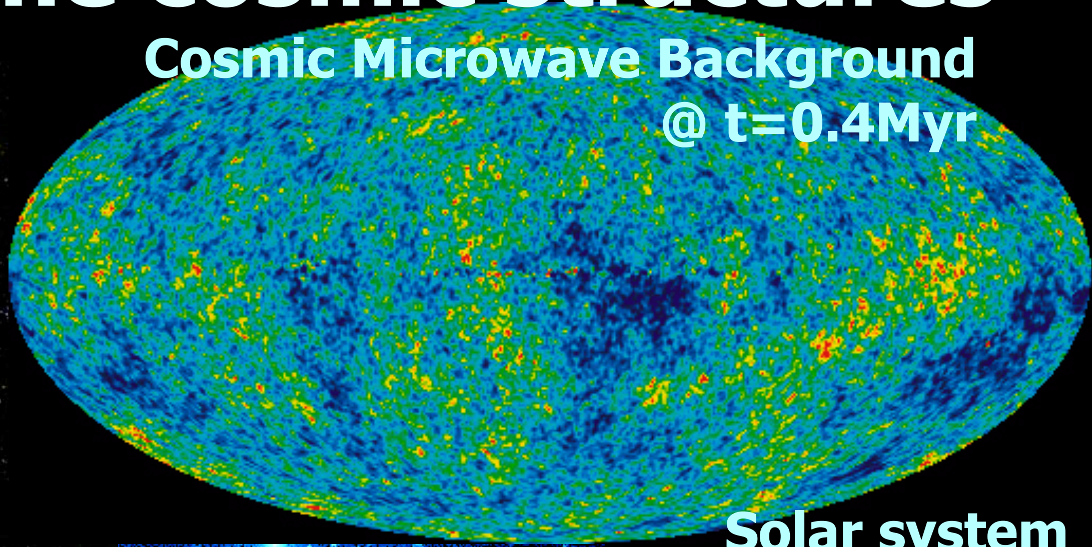
Hierarchy in the cosmic structures

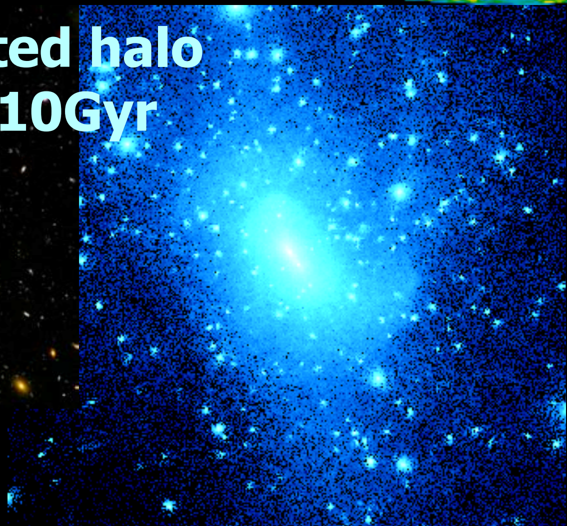
Hubble Ultra Deep Field
@ t=0.1Gyr



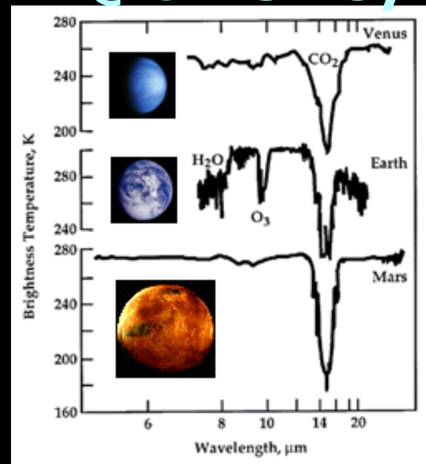
Cosmic Microwave Background
@ t=0.4Myr



Simulated halo
@ t=10Gyr



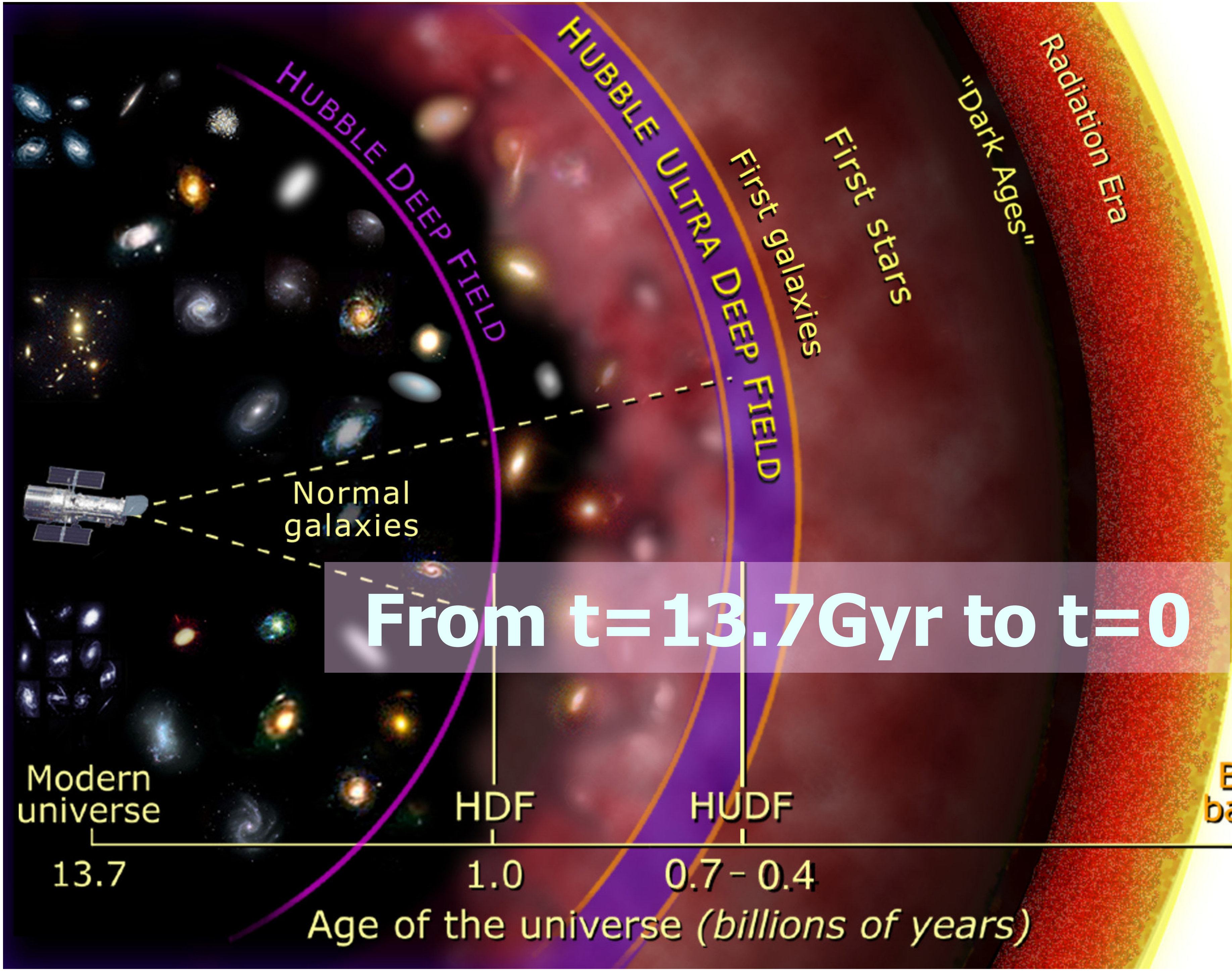
Solar system
@ t=13.7Gyr



Yasushi Suto

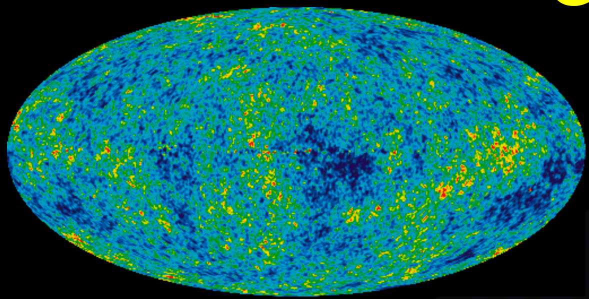
Department of Physics, The University of Tokyo

Kyoto University GCOE symposium "Links among Hierarchies"
16:20-16:50 February 13, 2012


From t=13.7Gyr to t=0
HUBBLE DEEP FIELD
HUBBLE ULTRA DEEP FIELD
First galaxies
First stars
"Dark Ages"
Radiation Era
Normal galaxies
Modern universe
HDF
HUDF
Big bang
13.7
1.0
0.7 – 0.4
Age of the universe (billions of years)

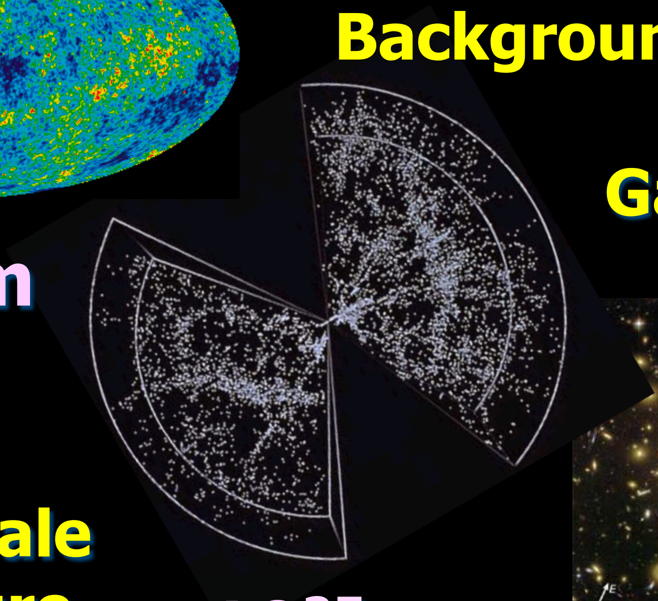
From our local universe (SDSS) to Cosmic Microwave Background (WMAP)

Hierarchical structures in the universe



Cosmic Microwave Background

10^{26}m



Large-scale structure

10^{25}m

Galaxy cluster

10^{23}m

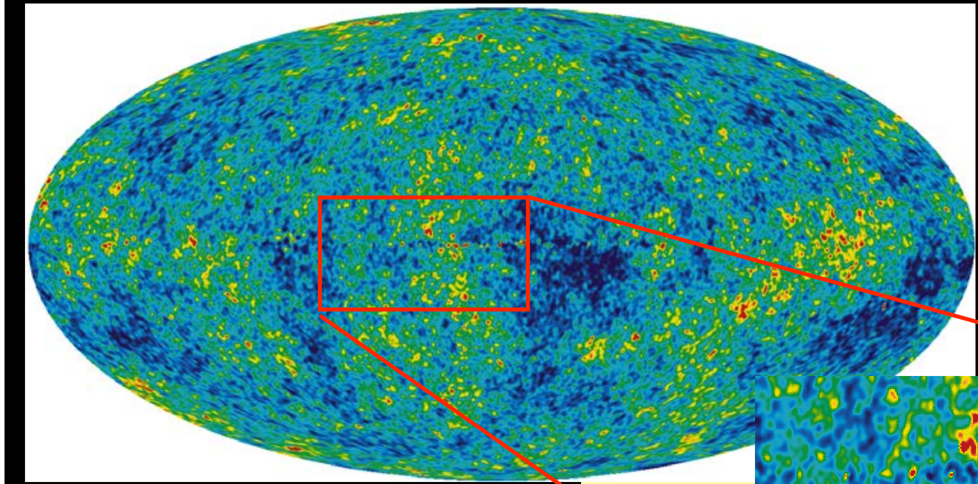
10^{12}m

Solar system

Earth

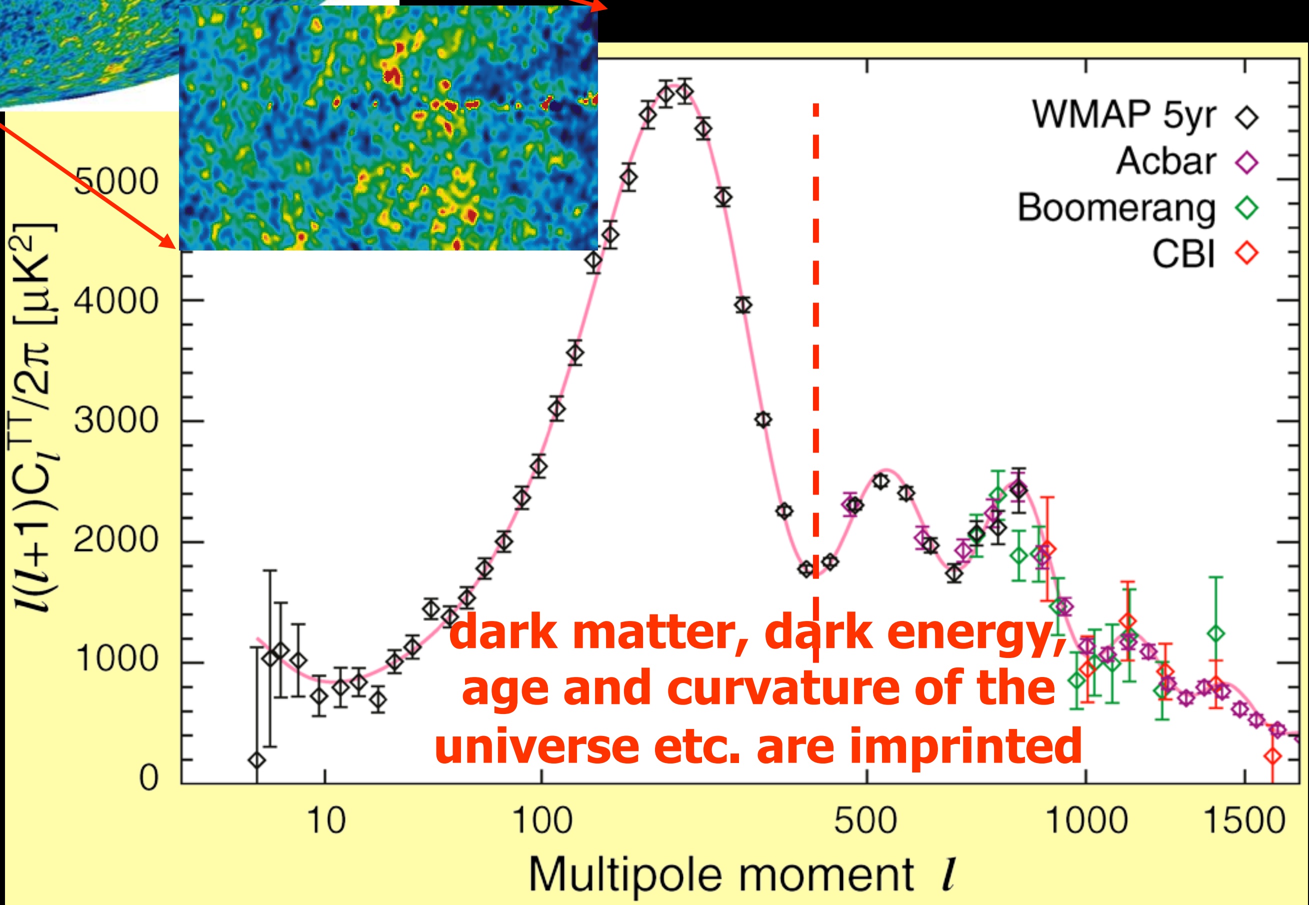
10^{7}m

Temperature map of Cosmic Microwave Background



$$\Delta T(\theta,\varphi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\theta,\varphi)$$

$$C_\ell = \langle |a_{\ell m}|^2 \rangle$$

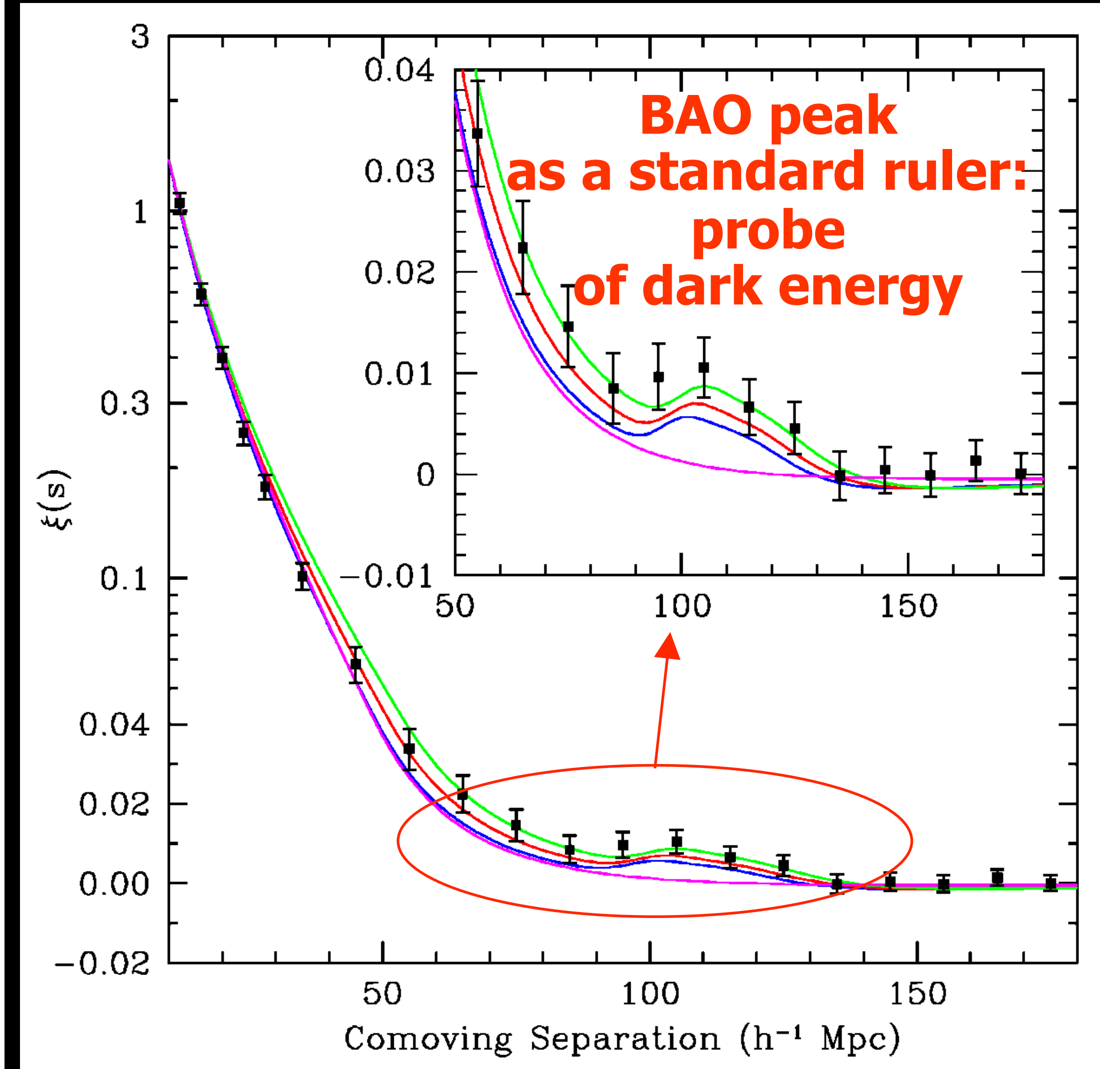


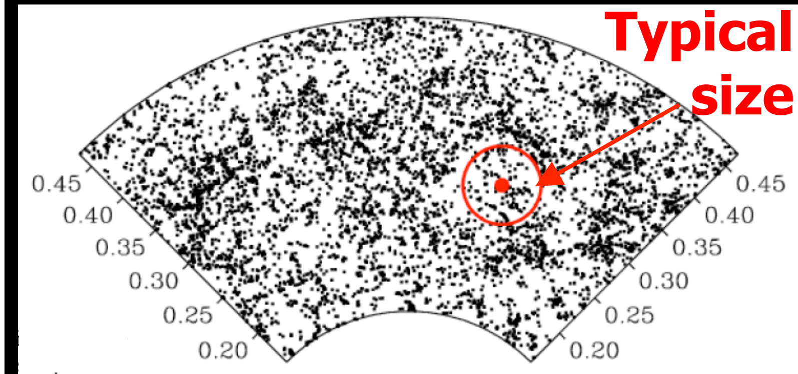
Amazing agreement between (linear) theory and observations
⇒ Precision measurement of cosmological parameters

WMAP 5yr

Komatsu et al. (2008)

Baryon Acoustic Oscillation imprinted in galaxy distribution



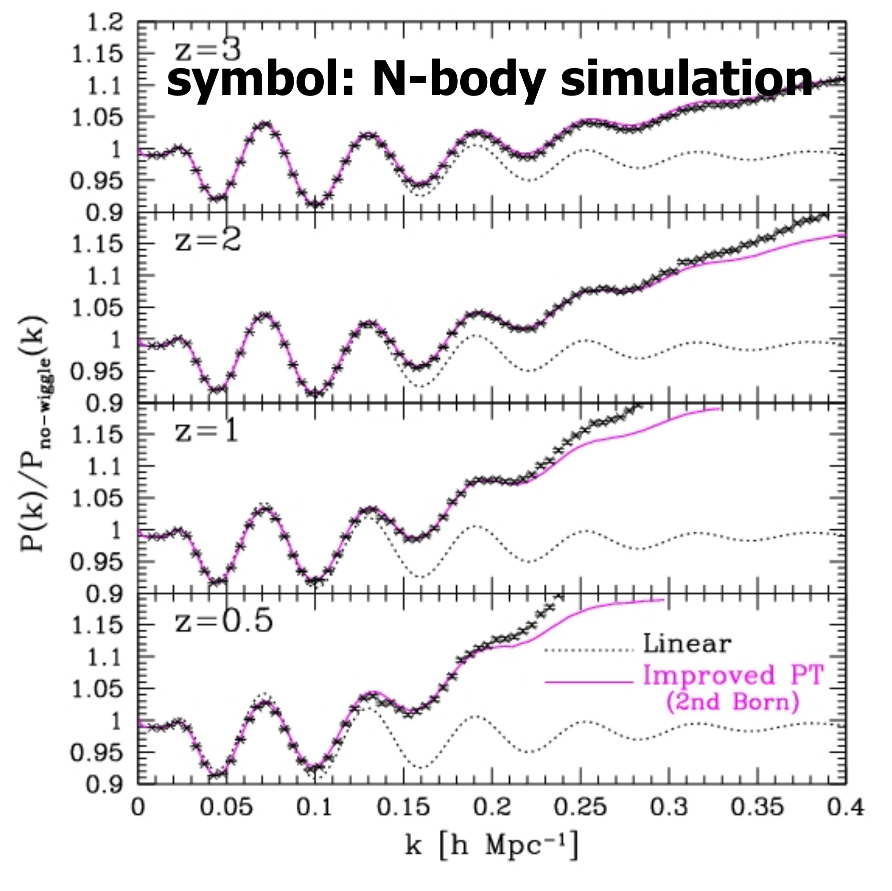


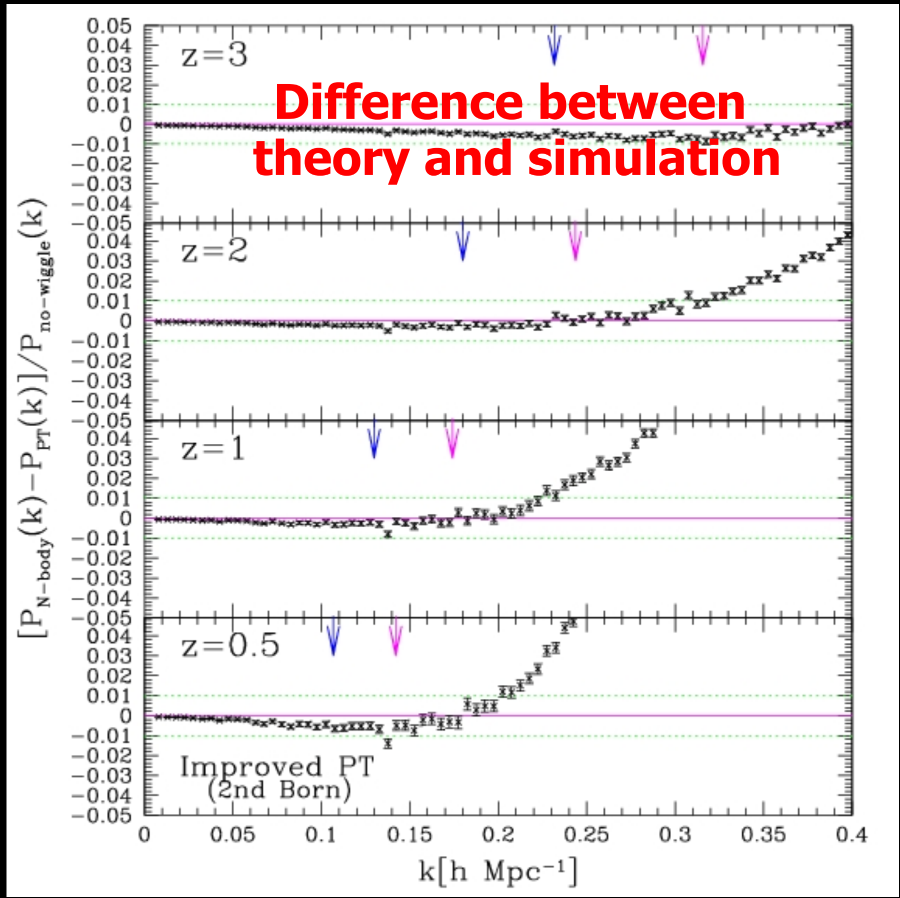
4,7000 Luminous Red Galaxies @ z~0.3 over 3800 deg^2 from Sloan Digital Sky Survey

Eisenstein et al. (2005)

Baryon Acoustic Oscillation in galaxy power spectrum: probe of dark energy

- Sub-percent level accuracy is achieved with improved perturbation theory of gravitational evolution of dark matter (Taruya et al. 2009,2010)

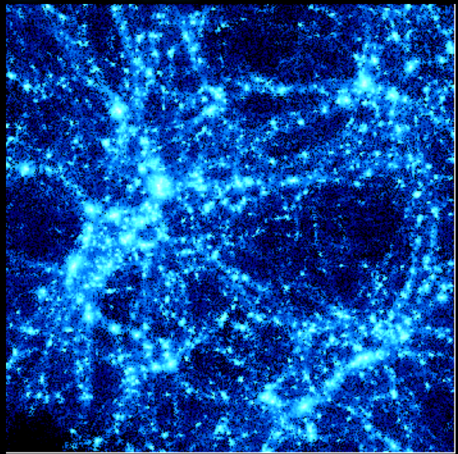




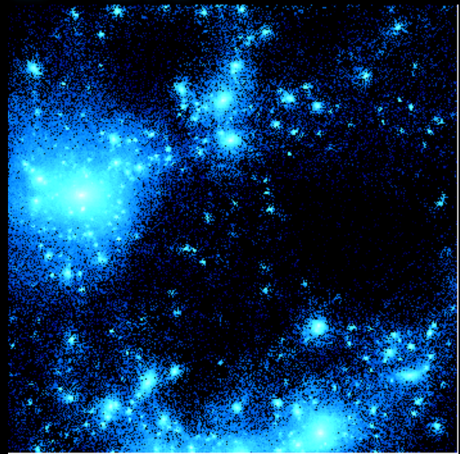
Formation of galaxies and clusters from dark matter halos

N-body simulations of dark matter halos in ΛCDM

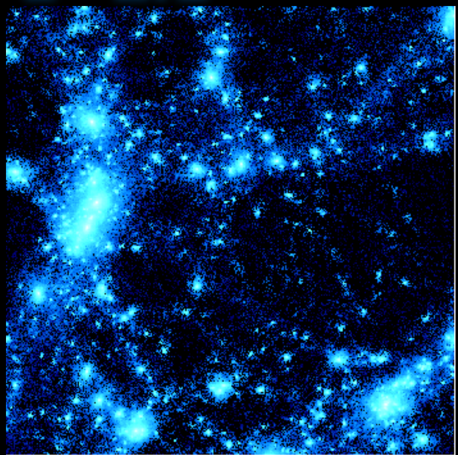
z=4.2



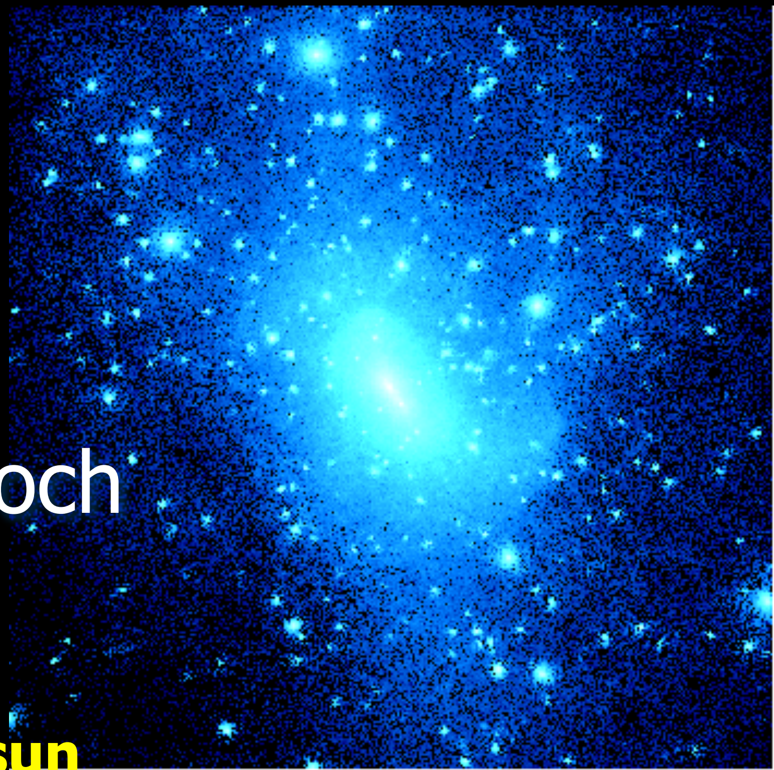
z=1.0



z=2.1



Jing & Suto (2000)



present epoch
(z=0)

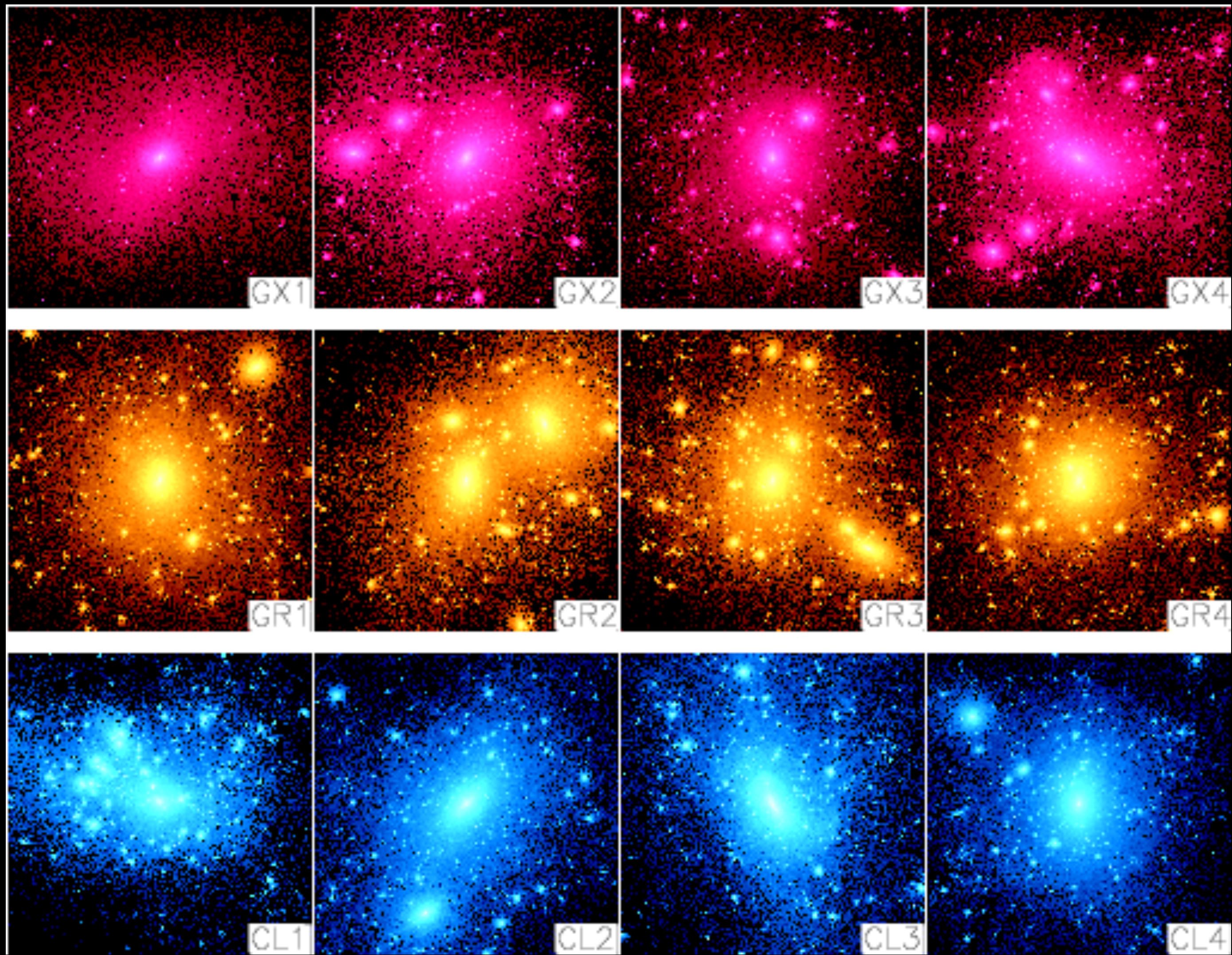
$4x10^{14}M_{sun}$

Apparent diversities of dark matter halos with different mass and environments

Galaxy scales
~ $5 \times 10^{12} M_{sun}$

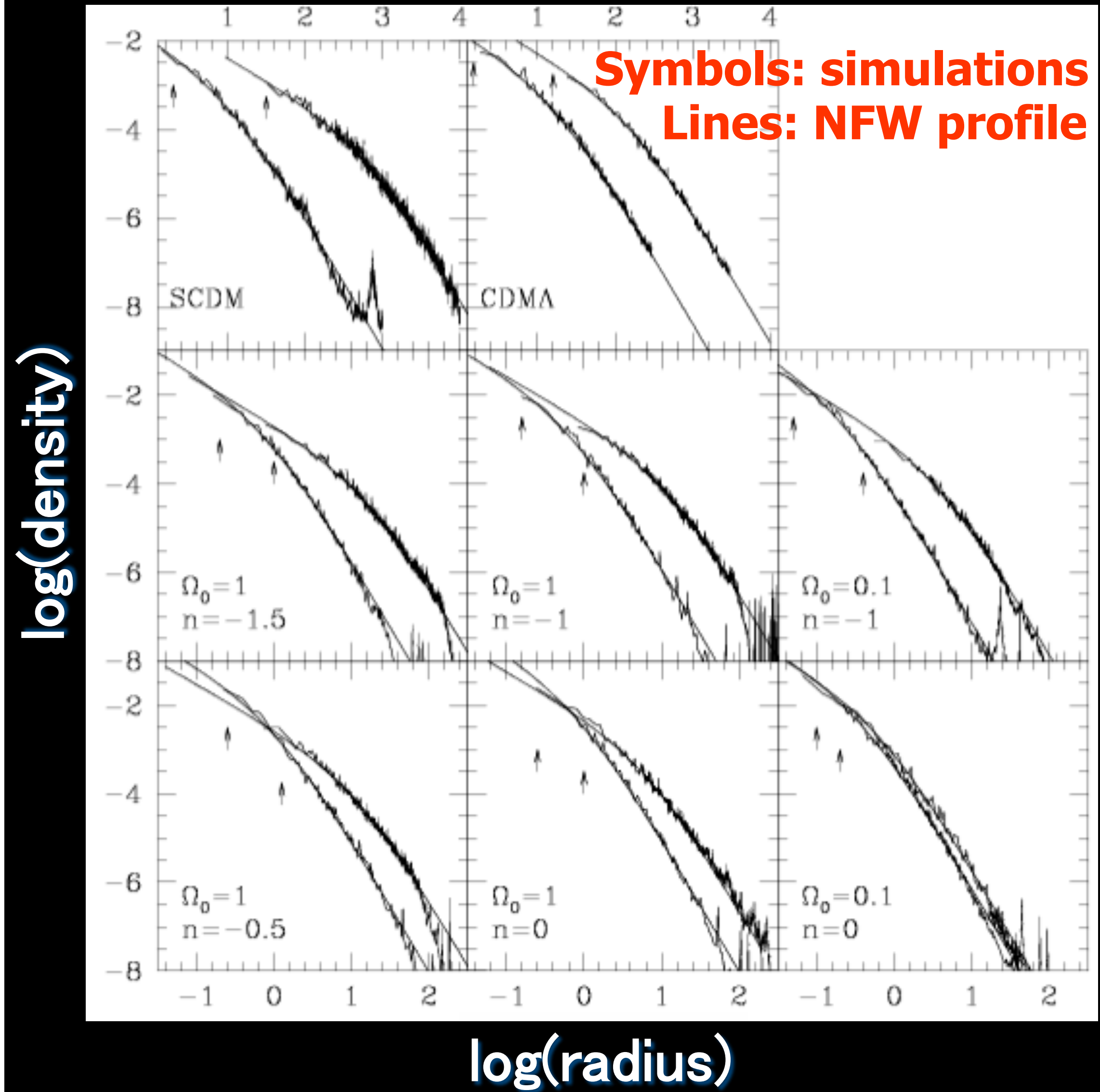
Group scales
~ $5 \times 10^{13} M_{sun}$

Cluster scales
~ $3 \times 10^{14} M_{sun}$



Jing & Suto (2000)

Universal density profile of dark matter halos: NFW profile

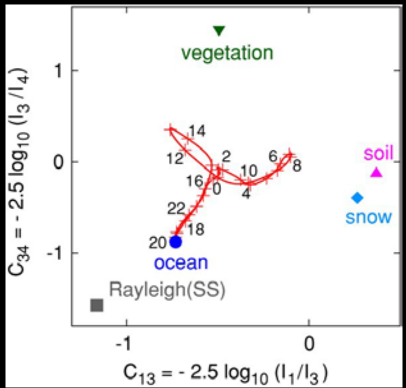


- Regularity behind diversity
- *Dark halos exhibit an unexpected scaling law in the nonlinear gravitational evolution process*

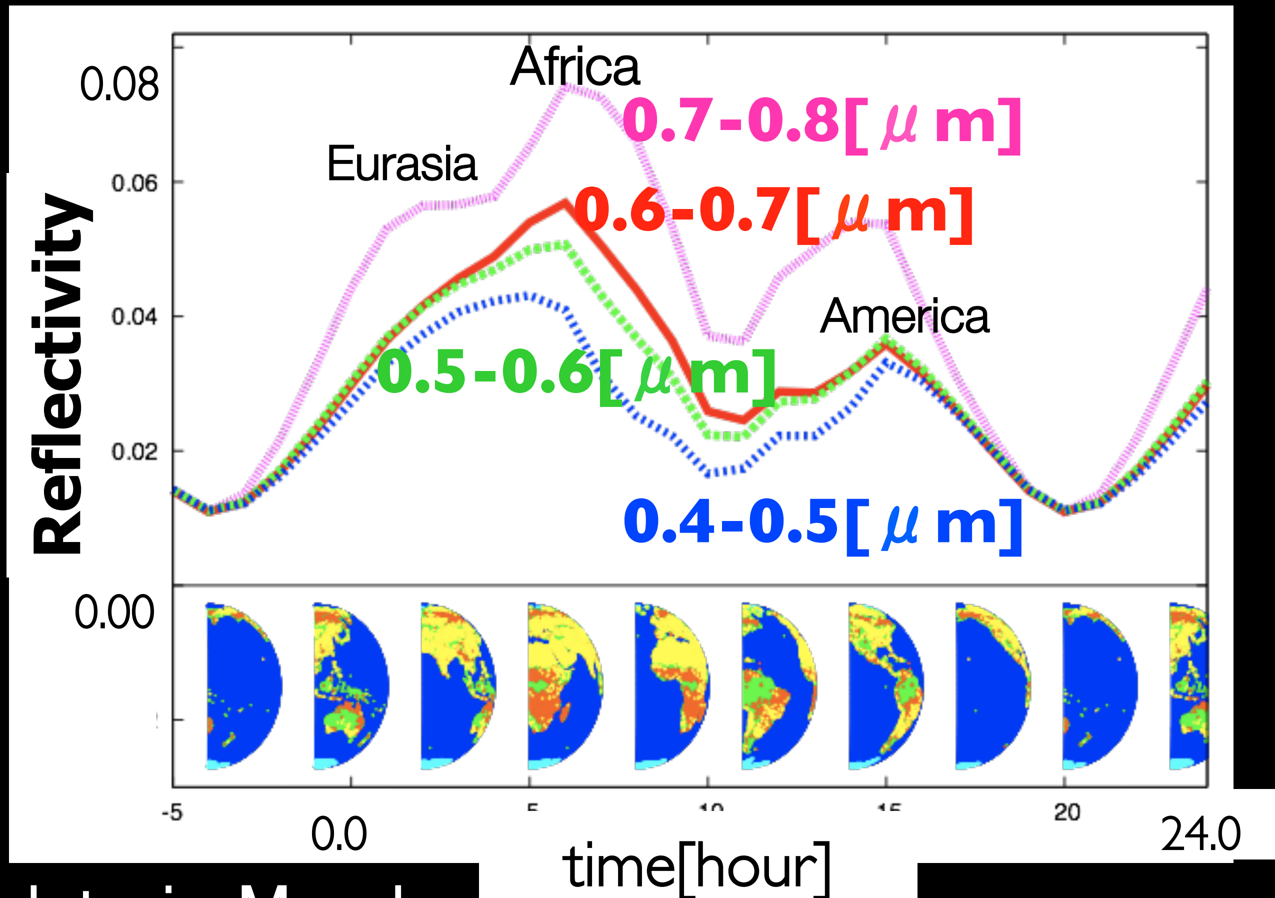
$$\rho(r) = \frac{\delta_c \rho_{crit}}{(r/r_s)(1+r/r_s)^2}$$

Navarro, Frenk & White (1997)

A pale blue dot ? Not really



Simulated photometric light-curves of Earth



- Adopted Earth data in March
- Spin inclination = 0 (vernal equinox)
- cloudless

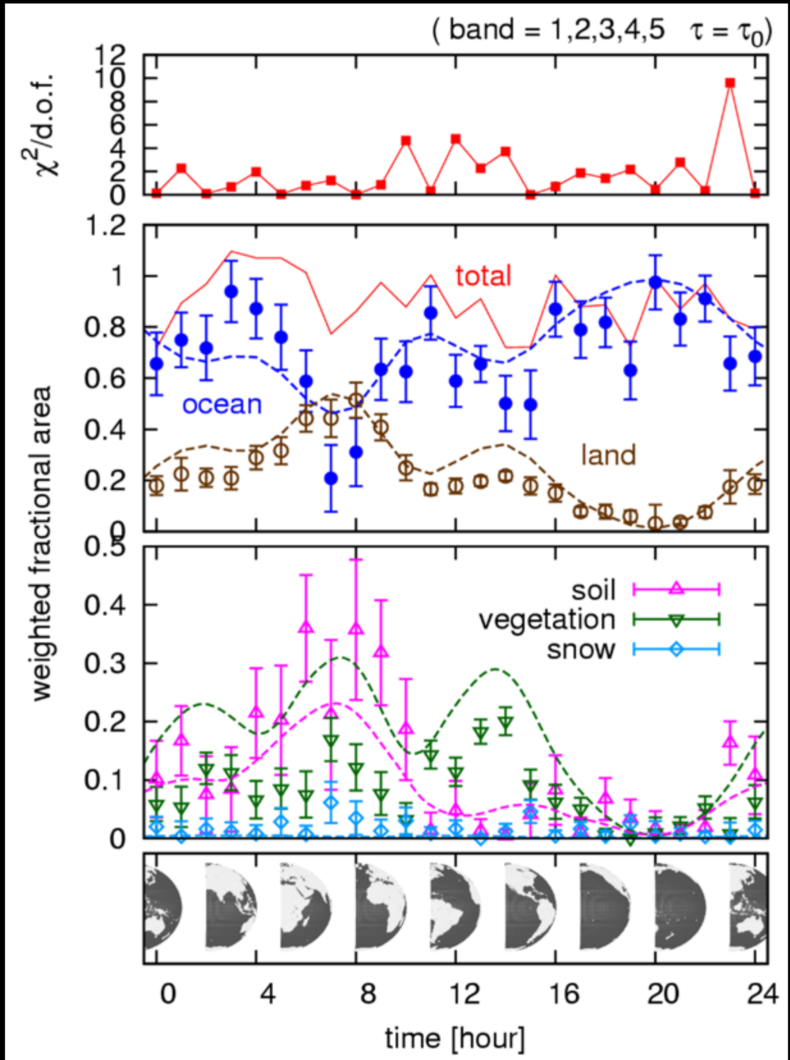
Fujii et al. (2010)

Color-Changing Planets Could Hold Clues to Alien Life (May 13, 2010 in SPACE.com)

- A new way of comparing the color and intensity changes of light reflected off of Earth's surface to the flickers from exoplanets may help reveal the presence of oceans, continents and – possibly – life on alien worlds.
- By comparing the changes in observed hues of an alien planet as it rotates to this distinct Earthly color palette, "we can infer the surface composition of the [exo]planet," said Yuka Fujii, a doctoral student at the University of Tokyo and lead author of a paper published in the May 4 issue of the Astrophysical Journal.

http://www.space.com/scienceastronomy/color-changing-planets-alien-life-100513.html

Idealized cloudless earth



Fujii et al. (2010,2011)

- Input data
  - 5 light-curves using anisotropic scattering (BRDF) model
  - 2 week observation of a cloudless Earth at 10 pc away
- Inversion assumptions
  - Ocean, soil, vegetation and snow only (with atmosphere)
  - Isotropic scattering assumed
- Results
  - Estimated areas (symbols) vs Surface classification data (dashed line)
  - Reasonably well reproduced.
  - Can identify vegetation !
- Useful to identify a second earth ?

From deterministic to stochastic

- **Regularities and diversities in astrophysics**
- **Deterministic on larges scales and stochastic on small scales**
  - **CMB**: perfect match with linear theory predictions
  - **LSS**: perturbation theory works well
  - **Galaxy clusters**: nonlinear gravitational evolution leads to a class of regularity in density profiles
  - **Galaxies**: huge varieties, roughly classified in the Hubble sequence
  - **Planetary systems**: until 1995, we did not even know if planets outside the Solar system exist at all
  - **Another Earth**: still unknown, our biological world on the earth is just accidental, or a generic outcome of the inflationary cosmology paradigm

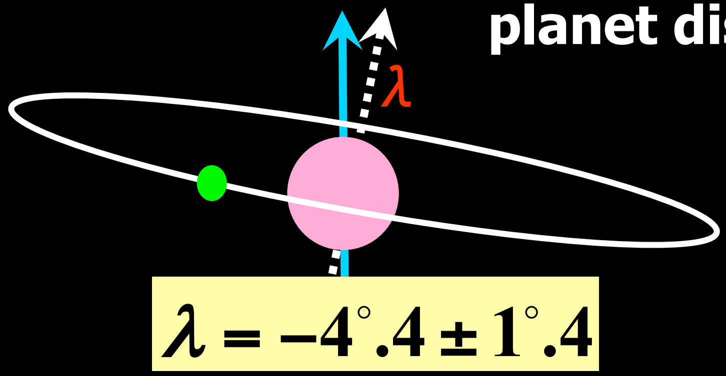
"Central dogma" in cosmology or a reductionist's point of view

- **Inflation will fix the initial condition of the universe**
  - **Quantum fluctuations generated during the inflation epoch are responsible for the origin of all the structures in the universe**
- **Maybe right in principle, but in reality, can we extract any initial memory of the early universe out the motion of planets in our solar system ?**
  - **Competition between the initial condition and chance/stochasticity**
  - **Analogous to different perspectives between particle physicists and solid-state physicists**

Measurement of Spin-Orbit alignment in an Extrasolar Planetary System

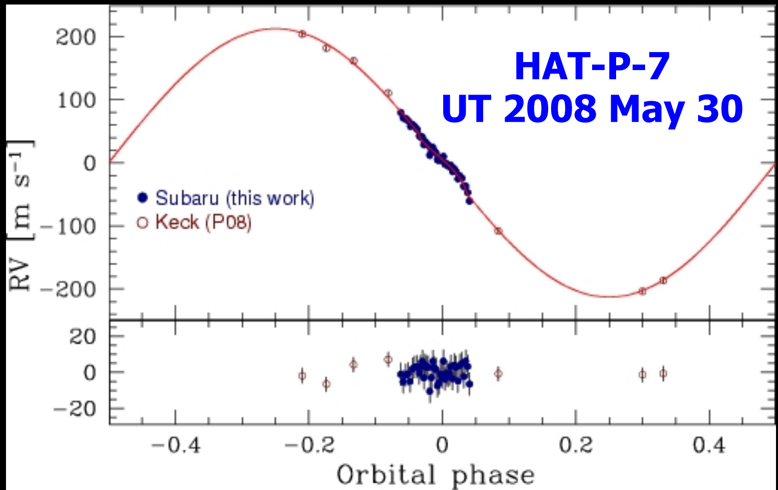
- **Joshua N. Winn (MIT)**, **R.W. Noyes, M.J. Holman, D.B. Charbonneau, Y. Ohta, A. Taruya, Y. Suto, N. Narita, E.L. Turner, J.A. Johnson, G.W. Marcy, R.P. Butler, & S.S. Vogt**
  - **ApJ 631(2005)1215 (astro-ph/0504555)**

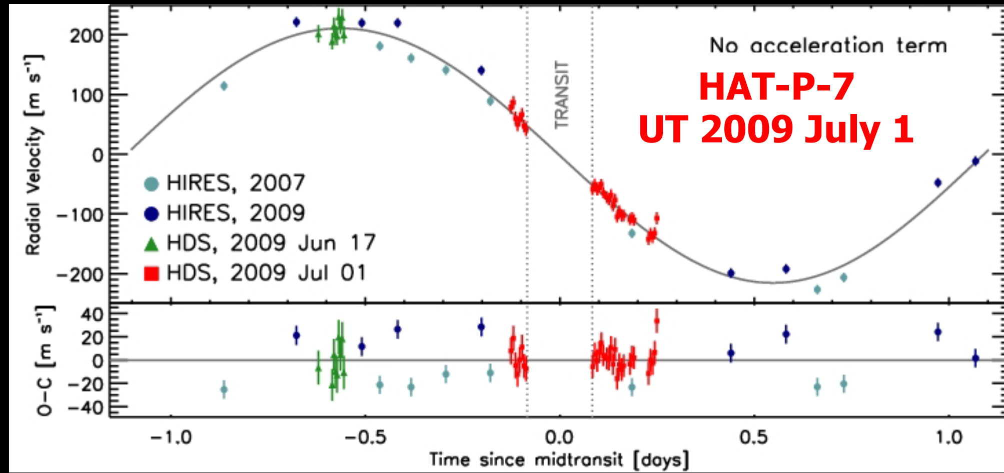
HD209458: the first transiting planet discovered in 1999

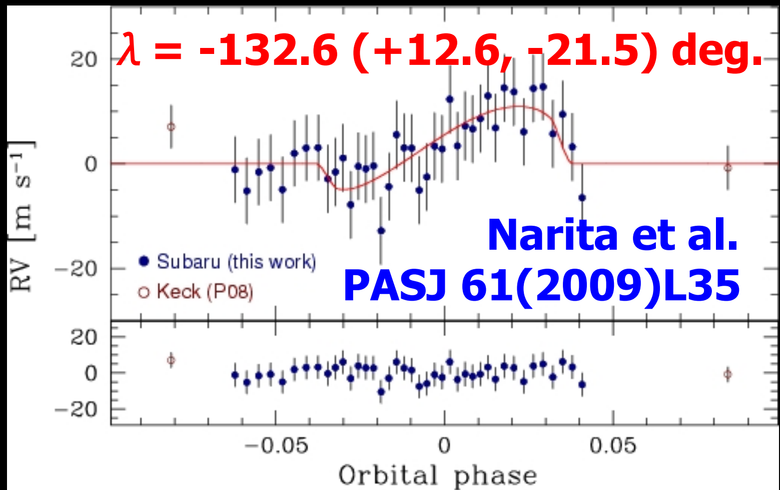


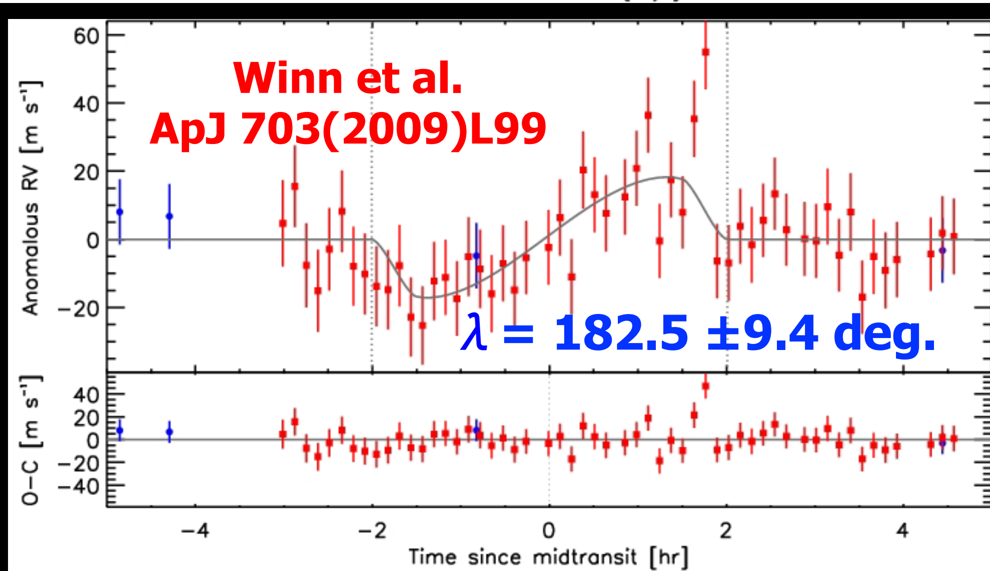
- Motivated by an analytical perturbation formula for the Rossier-McLaughlin effect by Ohta, Taruya & Suto: ApJ 622(2005)1118

Discovery of a retrograde/polar orbit of HAT-P-7 with Subaru via the RM effect









- Origin of the retrograde/polar orbit is unknown

Formation of retrograde planets

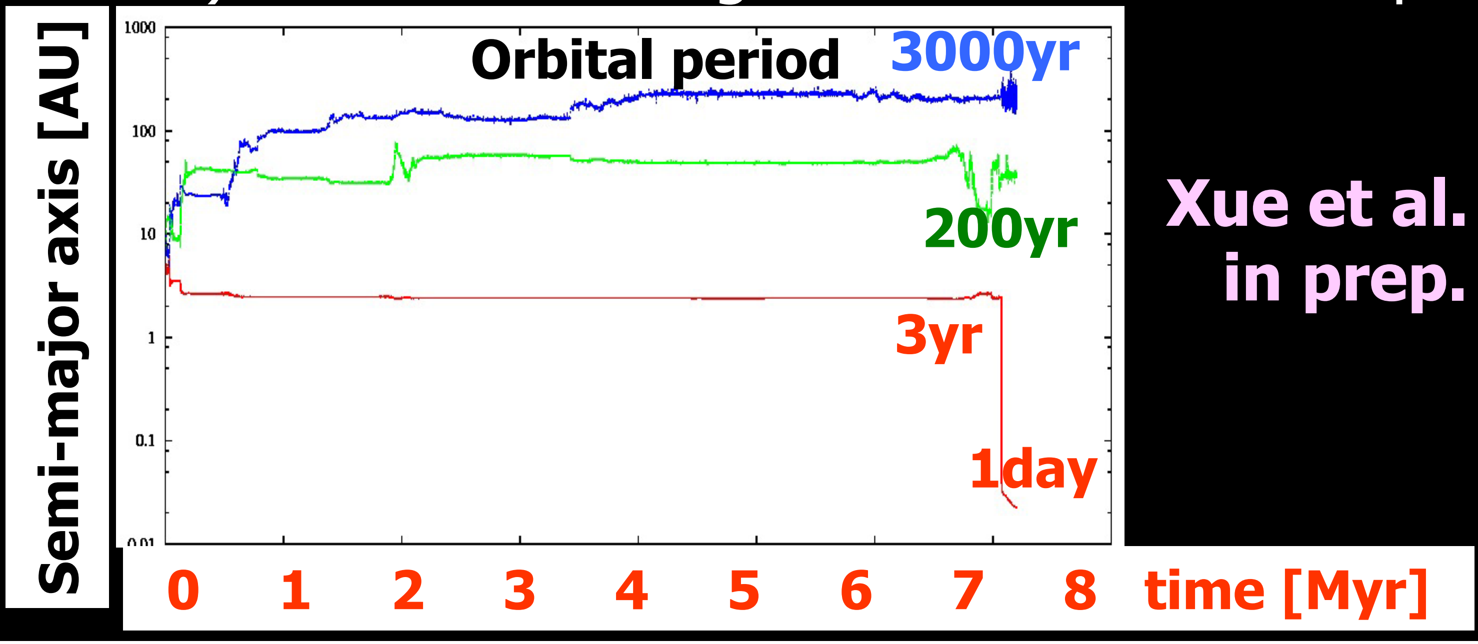
- Initial condition
  - Central star with 1 solar mass
  - Three planets all with 1 Jupiter mass
  - Circular orbits (e=0)
  - semi-major axis: 5AU, 7.25AU, 9.5AU
  - Inclination: 0.5deg, 1.0deg, 1.5deg
  - Random phases

(Nagasawa et al. 2008,2011)

- Evolution
  - Simple gravitational few body system
  - Orbit-crossing and scale segregation (ejection of a planet)
  - formation of a close-in planet (due to tidal dissipation)
  - Perturbation from the outer planet significantly changes the dynamics of the inner planet via the Kozai mechanism

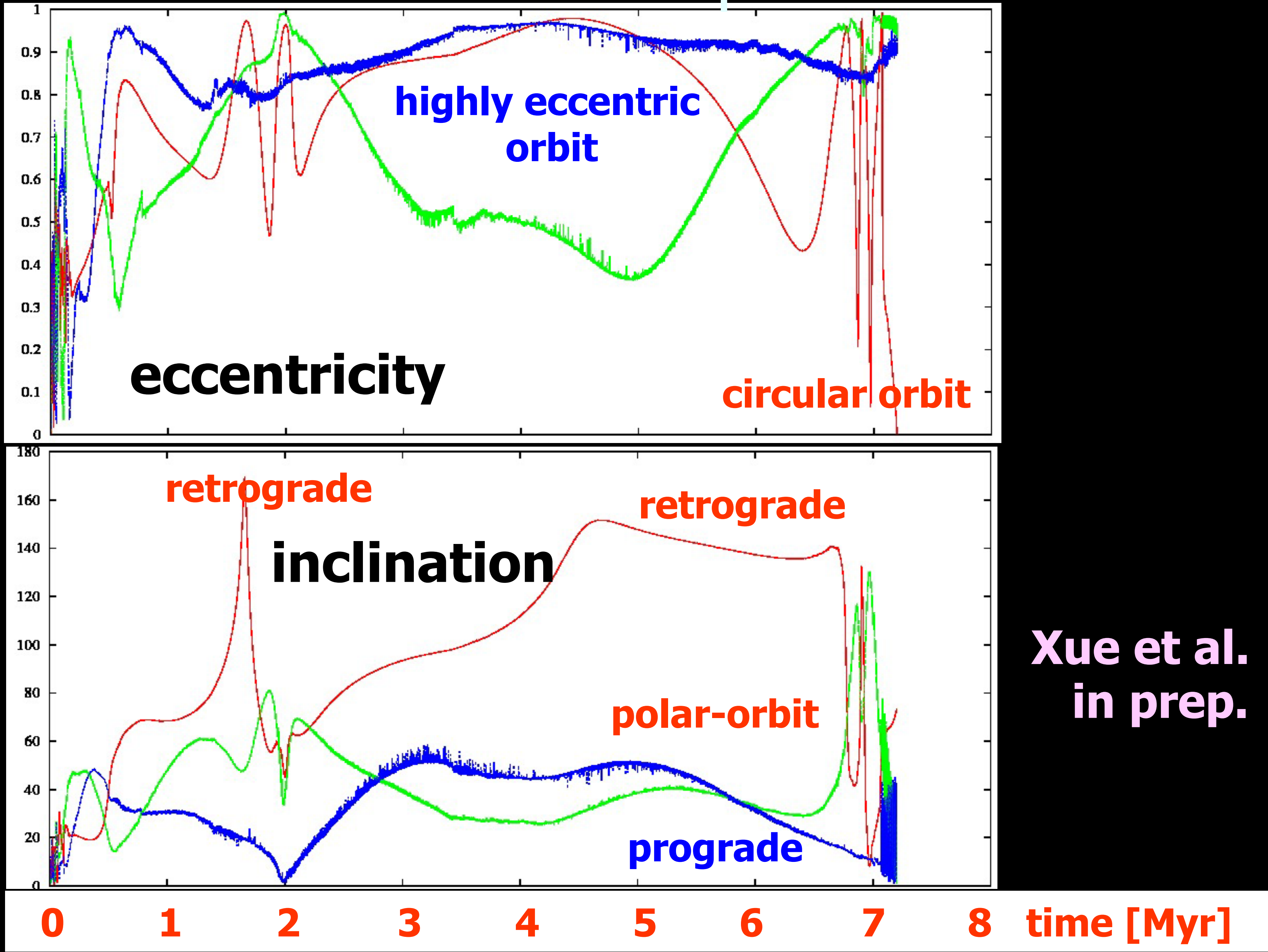
Segregation of small and large scales

- Initially similar scale orbits
  - semi-major axis: 5AU, 7.25AU, 9.5AU
- Chaotic evolution and energy exchange
  - Orbit-crossing and segregation of outer and inner planets
- Energy and angular-momentum dissipation
  - formation of a close-in planet (due to tidal dissipation)
- Interaction between different scales
  - Perturbation from the outer planet (via the Kozai mechanism) results in a retrograde orbit of the inner planet



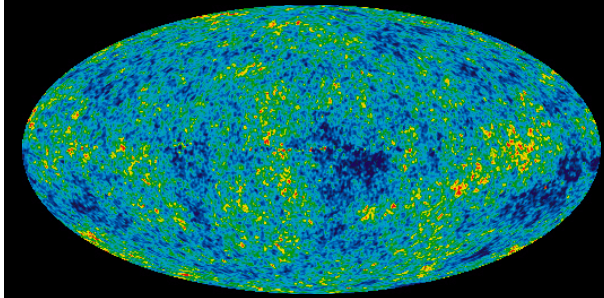
Xue et al. in prep.

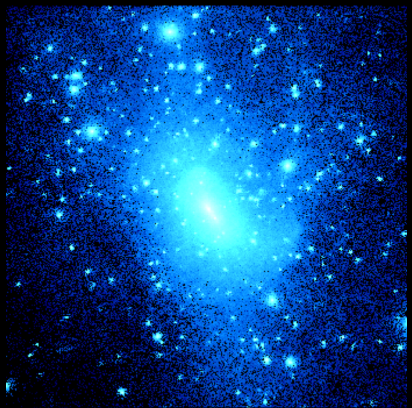
Evolution of three planets



Xue et al. in prep.

Co-evolution and co-existence of hierarchical structures in the universe





- **Primordial density fluctuations**
  - **seeded in the inflationary epoch**
- **Gravitational evolution**
  - **linear**
  - **dissipationless nonlinear**
- **Non-gravitational evolution**
  - **Radiative processes**
  - **Energy dissipation**
  - **Angular-momentum transfer**
  - **Segregation of scales**
- **Co-existence**
  - **Huge difference among their time-scales**

$$t_{grav} \approx \frac{1}{\sqrt{G\rho}} \approx 10\mathrm{Gyr}\sqrt{\frac{10^{-29}\,\mathrm{g/cc}}{\rho_{universe}}} \approx 0.1\mathrm{m\,sec}\sqrt{\frac{10^{14}\,\mathrm{g/cc}}{\rho_{neutron\ star}}}$$