Hierarchy in the cosmic structures

Hubble Ultra Deep Field
@ $t=0.1\text{Gyr}$

Cosmic Microwave Background
@ $t=0.4\text{Myr}$

Simulated halo
@ $t=10\text{Gyr}$

Solar system
@ $t=13.7\text{Gyr}$

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From $t=13.7 \text{ Gyr}$ to $t=0$
From our local universe (SDSS) to Cosmic Microwave Background (WMAP)
Hierarchical structures in the universe

- Cosmic Microwave Background
- Galaxy cluster
- Solar system
- Large-scale structure
- Earth

Distance scales:
- $10^{26}$ m
- $10^{25}$ m
- $10^{23}$ m
- $10^{12}$ m
- $10^7$ m
Temperature map of Cosmic Microwave Background

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

\[ C_\ell = \left\langle |a_{\ell m}|^2 \right\rangle \]

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

WMAP 5yr
Komatsu et al. (2008)

dark matter, dark energy, age and curvature of the universe etc. are imprinted
Baryon Acoustic Oscillation imprinted in galaxy distribution

4,7000 Luminous Red Galaxies @ z~0.3 over 3800 deg² from Sloan Digital Sky Survey

Eisenstein et al. (2005)

BAO peak as a standard ruler: probe of dark energy
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)

![Diagram showing the comparison between theoretical and simulated power spectrum](image)

**symbol: N-body simulation**

**Difference between theory and simulation**
Formation of galaxies and clusters from dark matter halos

N-body simulations of dark matter halos in $\Lambda$CDM

- $z=4.2$
- $z=2.1$
- $z=1.0$

present epoch ($z=0$)

$4 \times 10^{14} M_{\text{sun}}$

Jing & Suto (2000)
Apparent diversities of dark matter halos with different mass and environments

Galaxy scales
\( \sim 5 \times 10^{12} M_{\text{sun}} \)

Group scales
\( \sim 5 \times 10^{13} M_{\text{sun}} \)

Cluster scales
\( \sim 3 \times 10^{14} M_{\text{sun}} \)

Jing & Suto (2000)
Universal density profile of dark matter halos: NFW profile

Symbols: simulations
Lines: NFW profile

Regularity behind diversity

Dark halos exhibit an unexpected scaling law in the nonlinear gravitational evolution process

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

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)
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.

**Idealized cloudless earth**

- **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?**

Fujii et al. (2010, 2011)
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


HD209458: the first transiting planet discovered in 1999

\[ \lambda = -4.4 \pm 1.4 \]
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

- **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

*(Nagasawa et al. 2008, 2011)*
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

- **eccentricity**
  - Highly eccentric orbit
  - Circular orbit

- **inclination**
  - Retrograde
  - Polar-orbit
  - Prograde

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

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