Virtual Galaxies

Chair: Jun Makino
National Astronomical Observatory of Japan

Speakers:

Masao Mori, Senshu University
Julien Devriendt, Centre de Recherche Astronomique de Lyon
Introduction overview

- Why “Virtual Galaxy”?
- Brief history of our understanding of galaxies
- Computer modeling of galaxy formation
Why “Virtual Galaxy”?  

- To make galaxies in a lab is just impossible.  
  - (true for almost every astronomical object...)
  
- Timescale depends on average density.

- Real experiment would require degenerated matter

So how we study astronomical objects?
Modern Astronomy

Kepler’s laws explained by Newton’s equation of motion and law of gravity.

Behavior of heavenly bodies can be described by physics laws we learn from experiment.

Certainly true for motion of planets. How about stars and galaxies?
History of our understanding of galaxies

18 C: W. Herschel assumed all stars are of the same luminosity.
Early 20C: H. Shapley

Our solar system is not at the center of the Galaxy.
Many nebulae are galaxies similar to our own.

Galaxies can be classified to ”Hubble Sequence”.
Early 20C: E. Hubble (2)

Distant galaxies are receding from us faster than nearby ones.

"Cosmic Expansion"

Our universe started with "Big Bang".

Hubble’s data was wrong by almost a factor of 10, resulting in a very short age estimate...
Can we “understand” galaxies from basic laws of physics?

- Essentially the same question as that Newton asked for the motion of planets.
- Somewhat more difficult to answer...
  - Initial/boundary condition
  - Equations to be solved
Initial/boundary condition

Big bang
Small density fluctuations → gravitational instability → galaxies
Determining initial/boundary conditions

- How the universe as a whole behaves?
- What’s the origin of the fluctuations from which structures evolve?
- Until very recently, there was no consistent model which has no serious flaw.
- Partly because over-interpretation of observational data...
Variation of Hubble’s “constant”

Causes of large errors:

- wrong interpretation of the luminosity of variable stars
- Effect of large-scale inhomogeneity of the distribution of galaxies
- ...

![Graph showing H₀ over time](https://example.com/graph.png)
Variation of Hubble’s “constant”

- Rather surprisingly, data from different measurements “converged”.
- Hubble Space Telescope played a very important role.
The way the universe behaves

- Open: Universe = Baryons
- F w/o DE: = B + Dark Matter
- F w DE: = B + DM + DE

Measurements of distant Supernovae and other data rejected everything other than F w DE.
Origin of density fluctuation

- Thermal fluctuation
  - Hot dark matter (Neutrino)
  - Cold dark matter (Unknown elementary particles)
- Domain defects (Cosmic strings)
- others...

High-accuracy measurements provided us sufficient data to resolve the issue...
SDSS, WMAP, etc etc ...
WMAP observation

COBE (1993): For the first time, fluctuation of cosmic microwave background actually measured!

WMAP (2003-): Much higher resolution and accuracy
Theoretical prediction (Flat, CDM+DE, Thermal fluctuation) agrees with observational data very well (almost too well...)

WMAP power spectrum

![Graph showing WMAP power spectrum with theoretical and observational data comparison.](image)
“Concordance” Cosmology

For the first time in the history of modern science, we have one consistent view of the universe.
“Concordance” Cosmology

For the first time in the history of modern science, we have one consistent view of the universe.

(hard to believe....)
“Concordance” Cosmology

For the first time in the history of modern science, we have one consistent view of the universe.

(hard to believe....)

- Flat universe with dark matter and dark energy
- Cold dark matter
- Thermal fluctuation
“Concordance” Cosmology

For the first time in the history of modern science, we have one consistent view of the universe.

(hard to believe....)

- Flat universe with dark matter and dark energy
- Cold dark matter
- Thermal fluctuation

So we now know the initial and boundary conditions.
“Concordance” Cosmology

For the first time in the history of modern science, we have one consistent view of the universe.

(hard to believe....)

- Flat universe with dark matter and dark energy
- Cold dark matter
- Thermal fluctuation

So we now know the initial and boundary conditions.

(even harder to believe....)
Solving equations

- Structure formation through gravitational instability
  - “Dark Matter”, gravity and equation of motion

- Baryon (normal matter)
  - Hydrodynamics
  - Radiative transfer
  - Chemical reaction
  - Star formation and stellar evolution
    * Nuclear reaction
    * ...

...
Dark Matter

Many-body problem
Gravitational interaction
“N-body simulation”
Up to $10^{10}$ particles

“Easy” part of the problem
By the way, what I study?

I have been studying these easy problems. (called “stellar dynamics”)

And even have built a series of computers to solve easy (but computationally expensive) problems.

GRAPE-6, 64 Tflops (2002)
Baryon Physics and more

Two approaches

- Detailed simulation of single galaxy
  - Solve hydrodynamics
  - Solve radiative transfer (well...)
  - Model star formation
  - ....

- “Semi-analytic” modeling of statistical sample of galaxies
  - Model the Baryon physics within each “Dark halo” as “sub-grid physics”
  - make statistical comparison with observations
What we learned?
What we learned?

Will be presented by two speakers.
What we learned?

Will be presented by two speakers.

Stay tuned!
Speakers

- Masao Mori
  - One of the most detailed simulations of single galaxy

- Julien Devriendt
  - Semi-analytic models
  - Full simulations