Physics 463:
Special Topics in
Astrophysics:
Theoretical Cosmology

Structure Formation & Galaxy Formation

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the basic goal:
what’s so great about galaxies?

- the basic building block of the Universe
- your link to the dark sector
- huge range of scales important; huge range of astrophysical processes to understand
- can learn about everything from star formation & evolution to the nature & contents of the Universe
• The Universe started in a hot dense state & has since been cooling & expanding.

• The Universe is homogeneous & isotropic on large scales.

• The Universe has structure on smaller scales.

• The Universe is not made of the same stuff we are.
the expanding Universe

(1929) Hubble used the 100 in on Mt Wilson to measure the distances to 40 galaxies using cepheids (‘standard candles’)

\[ v = H_0 d \]
the expanding Universe

the modern Hubble diagram:
Type Ia SN as “standard candles”
the expanding Universe

small, hot universe at 380,000 years

large, cold universe today
structure: CMB

- CMB anisotropies: the seeds of structure formation
- (first discovered by COBE 93. high precision from WMAP)
structure in the galaxy distribution
LSS
substructure in the MW
the power spectrum
hierarchical clustering

- density fluctuations on a wide range of scales
- fluctuations are bigger on small scales
- this power spectrum implies that small things collapse first, merge to become bigger ones
- lots of merging, especially at early times
- galaxies are the first units to collapse: key to understanding this process (& what caused the fluctuations)
matter in the Universe

- (at least) two kinds of matter
  - the stuff we are made of: hydrogen, helium, heavier elements ~15%
  - something else: “dark matter” ~85%
    - primarily non-baryonic (doesn’t radiate)
    - small fraction is massive neutrinos “hot”
    - ps implies that most is “cold” (WIMP, axion, etc)
galaxies

- Baryons & dark matter are radially separated in galaxies
  - Baryons in central regions; dm in outer parts
- Key difference: baryons dissipate radiation
  - Dark matter must be dissipationless
galaxy formation: the short story

- dark matter virializes (gravity in dense regions overcomes the hubble flow)
- gas heats & cools
- (or doesn’t heat. or gets reheated or ejected.)
- dense gas forms stars
• two components
  • disks: flattened, ~ circular rotation
  • spheroids: ellipsoidal, eccentric orbits
• combination of components gives rise to the Hubble sequence
Hubble Sequence

- E0
- E6
- Irr

(S0, Sa, Sb, Sc)

(Barred examples)
galaxy properties

- galaxy type is correlated with several other properties
  - mass
  - star formation rate
  - stellar age
  - environment
galaxy merging

• why are there two components? what drives the correlations?

• the simple picture:
  • angular momentum from tidal torques allows cooling gas to form a disk
  • galaxies merge, scramble everything up, and form ellipticals & bulges
  • disks: lots of stars since the merger
  • spheriods: stars before or during the merger
correlations along the Hubble sequence

elliptical galaxies
big (v~350 km/s)
old/red stars
highly clustered
short star formation timescales
rare

dwarf galaxies
small (v~50 km/s)
young stars
weakly clustered
long star formation timescales
common
global star formation rate related to the merging rate of dark matter halos?
clues to the nature of dark matter

- expansion rate -- amount of dark matter
- CMB: total mass density & mass density in baryons
- how cold is it?
- clues from the small scale power spectrum (primary measurements from galaxies & small-scale features that are affected by baryons)
a short history

• 13.7 billion years ago, the universe was very hot, dense & smooth
• quantum fluctuations in the first fraction of a second created small density perturbations
• hydrogen & helium were synthesized in the first few minutes
• baryons (mostly H, He~15%) and dark matter (~85%) were smoothly distributed and well mixed, with density fluctuations at the level of 1 part in 100000 @ 400000 years after the BB
• gravity amplified small initial density fluctuations, halting the expansion in some regions
• gas cooled and decoupled from dark matter, sinking to the center of gravitationally bound regions
• cold gas in dense regions (initially, in the high peaks, later in disks & mergers) formed stars
• heavy elements were created in massive stars, and were ejected into their surroundings in massive supernovae explosions
• structure formed hierarchically: small things first
• young galaxies have a lot of gas and a high interaction rate,
  • both of which result in a high star formation rate
• galaxy collisions produce spheroids and tidal features
• present day galaxies have turned most of their gas into stars
• about half way through the age of the Universe, it began accelerating due to “dark energy”
goals of the course

• understand the nature of structure formation in LCDM

• understand the basic processes in galaxy formation

• current puzzles & problems

• how can LCDM (including nature of dm & de) be tested with observations of lss & galaxies?