Astronomy

- The oldest science?
- One of the most rapidly evolving fields of modern research.
- Driven by observations and instruments
Cosmology

- Intersection of **physics** (fundamental laws) and **astronomy** (contents of the universe)
- Study of the Universe viewed as a whole
  Not a very humble field of science!
  Must coarse-grain and shove some details under the rug.
Questions in Cosmology

- Why is the universe expanding?
- What caused the ‘big bang’?
- What caused inflation?
- Is General Relativity a correct description?
- What is the universe made of?
- Why is the ‘normal matter’ mostly H + He?
- What is dark matter and dark energy?
- How did stars and galaxies form?
- What is the origin of initial fluctuations?
- What is the ultimate fate of the universe?
A Copernican-style revolution

95 % of universe is made of unidentified stuff!

- Dark Energy
- Dark Matter
- Neutrinos
- Ordinary gas and stars
A cosmologist’s toolkit

- **general relativity** (back bone)
- **astronomy** (supporting data)
- **statistics** (large scale description, initial cond’s)
- **plasma physics** (a physical system; objects)
- **thermodynamics** (of an expanding plasma)
- **chemistry** (late evolution; individual objects)
- **nuclear physics** (evolution at earlier times)
- **particle physics** (evolution at earliest epochs)
- **mathematical physics** (initial “quantum” era)
- … **cosmetology** (“kosmos” = “harmony”)
The Standard Model of Cosmology

- I. Cosmological Principle
  homogeneous and isotropic on large scales
- II. Expansion: kinematics
  expanding in a way that preserves I.
- III. Expansion: dynamics
  obeys general relativity theory
- IV. Hot Big Bang
  hot dense state, dominated by thermal radiation
- V. Inflation(*)&n
  initial exponential (“superluminal”) expansion
- VI. The Dark Sector(*)
  to account for apparent acceleration + large structures
The Standard Model

- ~ 100 years old (external galaxies, expansion)
- ~ 50 yrs ago: CMB (hot big bang, structures)
- ~ 30 yrs: Inflation (?) Dark Matter (?)
- ~ 10 yrs: Dark Energy (???)

- cf. Particle Physics:
  less rigorously defined
  open questions, puzzles are more
  numerous, and more fundamental
Census of the Extragalactic Universe

The “visible” constituents of the Universe:

- Non-relativistic particles (“baryons”):
  - Galaxies / Clusters / Super-clusters
  - Intergalactic Medium
- Relativistic particles: radiation + neutrinos

“Dark sector”:

- Dark matter: can clump and make structures
- Dark energy: smooth, only global effects
Galaxies

Individual Galaxies: Milky Way

Mass:
6x10^{11} M_{\odot} (15 kpc)
2x10^{12} M_{\odot} (100 kpc)

Age:
1.2x10^{10} yr
Milky Way: Halo

- Weighs $\sim 4 \times 10^{11} M_\odot$ (<15 kpc)
- Extends to ~100 kpc
  - roughly spherical distribution

- Old stars
  - little or no gas or dust – metal poor

- Globular clusters
  - $10^6 M_\odot$ clumps of old stars; formed first?

- Mostly dark matter by mass
  - MACHOs (but can make up only ~20% of mass)
Milky Way: Disk

- Weighs $\sim 2 \times 10^{11} M_\odot$

- Thin pancake of stars
  - 15 kpc radius, $\sim 300$ pc thickness (CD-Rom)
  - stars $\sim 2$ pc apart

- Interstellar medium
  - gas (40% by mass)
  - dust (1% of gas by mass)
Milky Way: Disk

- **Spiral Arms**
  - traced by young stars – triggered star formation
  - a wave phenomenon (material structure would wind up)

- **Solar system**
  - about 8 kpc from center
  - ecliptic plane nearly perpendicular to disk
  - moves around Galactic center at ~250 km/s

- **Differential Rotation**
  - important in generation of spiral density waves
  - “rotation curve” $v(r)$ can be used to estimate mass from $GM(<r)/r^2 = v^2/r$
Milky Way: Bulge

- Weighs ~4x10^{10} M_{\odot}

- Dense cluster of old stars
  - 1 kpc radius, core 10^5 times as dense as disk
  - almost no gas or dust
  - randomly oriented orbits

- Nucleus
  - (4 \pm 0.4) \times 10^6 M_{\odot} black hole at center (Sagittarius A*)
  - inactive

- Formed before disk?
Galaxies

Galaxy Types: The “Hubble Sequence”

- Based on morphology
- Disks vs. Ellipticals

M87 in Virgo
The Hubble Sequence

Is this physics or taxonomy?
The Hubble Sequence

Taxonomy

- Ellipticals (E0-E7)
  - by axis ratio

- Disk galaxies with no spiral arms (S0)
  - rare, old, live in dense environments

- Galaxies with spiral arms (S)
  - common, young – with (Sb) or without (S) a bar

- Irregular galaxies (Irr)
  - no spiral arms or bulges
The Hubble Sequence

Physics

- Evolutionary sequence
  - early types (E) vs late types (S)
  - not clear if correct (e.g. Toomre)

- Flattened vs. Puffed up Structures
  - determined by efficiency of cooling
  - ordered vs disordered orbits of stars

- Irregulars
  - more common at earlier epochs, merger-triggered bursts?
Galaxies

Quiet vs. Active

- **Active**: super-massive \((10^6-10^9 \text{ M}_\odot)\) black hole at the nucleus
  - accretes gas at a high rate
  - converts rest mass to light efficiently

- **Quiet**: no sign of active nucleus
  - either no SMBH
  - or inefficient accretion/radiation
Galaxies

Quiet vs. Active

- The nucleus of an active galaxy normally outshines the starlight from rest of the galaxy
  - unresolved point source called “quasar” or QSO
  - discovered by Maarten Schmidt (1963)
  - host galaxies hard to image, but few examples

- Supermassive black holes
  - now thought to reside at the centers of all galaxies
  - found in all of the ~100 nearby galaxies studied
Galaxies as a Population

Scaling Laws

- **Spiral Galaxies (Tully-Fisher relation)**
  \[ v_{\text{circ}} = 220 \left( \frac{L}{L_*} \right)^{1/4} \text{ km/s} \]

- **Elliptical Galaxies (Faber-Jackson relation)**
  \[ \sigma = 160 \left( \frac{L}{L_*} \right)^{1/4} \text{ km/s} \]
  \[ v_{\text{circ}} = 2^{1/2} \sigma = 220 \left( \frac{L}{L_*} \right)^{1/4} \text{ km/s} \]
Galaxies as a Population

Luminosity Function

\[ \frac{d\Phi}{dL} = \left( \frac{\Phi_*}{L_*} \right) \left( \frac{L}{L_*} \right)^\alpha \exp\left( - \frac{L}{L_*} \right) \]

Schechter function:
- characteristic galaxy luminosity \( L_* \) or mass \( M_* \)
- upper cutoff
- \( \alpha \approx -1 \): total light: \( \rho_L = \Gamma(\alpha+2)\Phi_*L_* \) is finite
  total number: diverges \( \rightarrow \) lower cutoff
Andromeda (M31)

- Nearest large galaxy, similar to MW
- Spectrum blue-shifted by ~100 km/s
- Distance 800 kpc ($v=H_0 r=60$ km/s)
- Weighs $\sim 10^{12} M_\odot$ ~half of MW
- Linear radius ~40 kpc twice MW
  (3 x 1 deg = 6 moons)
- Member of Local Group
Andromeda (in Galex)
The Local Group

- dominated by MW and M31
- ~30 “satellite” galaxies (LMC/SMC, M32)
- radius ~1Mpc
- gravitational interaction and member exchange with nearby groups (Sculptor, Maffei,..)
- Moving relative to CMB at ~600 km/s
- Fall into Virgo Cluster, ~16 Mpc away (~200 km/s)
Galaxy Clusters

Coma cluster: ~ 1 Mpc in size, ~2000 galaxies
Galaxy Clusters

- Galaxies are not isolated entities in space
  - rather, cluster in sizes from $N=2$ to $N\sim10,000$

- Milky Way is in “Local Group”
  - ~1 Mpc in size, ~30 galaxies

- Closest rich cluster is Virgo
  - ~16 Mpc away, ~2000 galaxies (mix of spirals and E)
  - ~100 Mpc away is Coma, ~2000 galaxies (mostly E)
Galaxy Cluster: Properties

- Most massive gravitationally bound systems in nature
  \(~10^{15} \text{ solar masses}\)

- Ingredients
  - Dark Matter (70%) - original discovery of DM
  - Hot gas (25%) - 10-100 million K, emits X-rays
  - Galaxies (5%) - icing on the cake

- Groups contain most of the mass of the universe
- Evolve much more significantly than galaxies
  - very few galaxy clusters exist beyond z~1
The Local Super-cluster

- ~10,000 galaxies, centered on Virgo cluster
- ~30 Mpc diameter, flat (pancake) structure
The Local Super-cluster

- ~100 galaxy groups and clusters
- total mass $\sim 10^{15}M_{\odot}$
- Moving as a whole towards Great Attractor
Larger Scale Structures

CFA redshift survey: ~200 Mpc slice with ~1000 galaxies:

- “finger of god”: artificial feature
- “great wall”: physical structure ~100 Mpc long
Out to the Hubble Distance

2dF, Sloan:  \( z \approx 0.2 \),  \( v \approx 60,000 \text{ km/s} \),  \( d \approx 1 \text{ Gpc} \):

1 billion galaxies
Sloan Digital Sky Survey
(Michael Blanton; NYU)
Hubble Ultra Deep Field

- Deepest view of the Universe
- Most objects are galaxies not stars
- Faintest galaxies 13 billion lyr away
- Tiny area of sky
- Record holders: galaxy $z \approx 8.6-10.2$, quasar $z \approx 7.1$, gamma-ray burst $z \approx 8.2$
Hubble Ultra Deep Field – Zoom
Quasars and Galaxies Evolve

Quasar space density

\[ \log \frac{n(z)}{n(\text{peak})} \]

redshift

Star formation rate

\[ \log \left[ \frac{d\rho_*/dt}{M_\odot \text{yr}^{-1} \text{Mpc}^{-3}} \right] \]

redshift

(Madau 1999)
Quasars and Galaxies Evolve

- Characteristic epochs of galaxy/quasar activity
  - coincide at z~2
  - which came first, the galaxies or their nuclei?

- Galaxies in the past
  - smaller
  - more irregular
  - preferentially elliptical
  - contain less heavy elements

- Quasars in the past
  - more luminous
  - more numerous
  - same metallicity
The Intergalactic Medium

What about space between galaxies and galaxy clusters?

empty ?
The Spectra of High Redshift Quasars

Redshift $z=3.62$  
QSO 1422+23

(Womble et al. 1996)
The Intergalactic Medium

More distant IGM (z~3) is well understood

- can be studied in absorption against spectra of distant quasars
- smooth H + He gas, with mild fluctuations
- statistics of these fluctuations supports inflation theory
- known to contain most of the baryons (recall BBNS value) at z~2
- very highly ionized (neutral H: 1 part in $\sim 10^6$)
- in photo-ionization equilibrium
- contains trace metals as far out as we can see (z~5)
The Intergalactic Medium

Local IGM:
- turns out much more puzzling
- absorption lines weak and difficult to observe
  1. wrong wavelength
  2. universe too dilute
- the “missing baryons”:
  most baryons locked up in discrete objects?
  or most baryons in WHIM phase at $10^5$ degrees?
- recent searches for WHIM in OVI recombination
### TABLE 3
THE BARYON BUDGET

<table>
<thead>
<tr>
<th>Component</th>
<th>Central</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Observed at z ≈ 0</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Stars in spheroids</td>
<td>0.0026 $h_7^{-1}$</td>
<td>0.0043 $h_7^{-1}$</td>
<td>0.0014 $h_7^{-1}$</td>
<td>A</td>
</tr>
<tr>
<td>2. Stars in disks</td>
<td>0.00086 $h_7^{-1}$</td>
<td>0.00129 $h_7^{-1}$</td>
<td>0.00051 $h_7^{-1}$</td>
<td>A−</td>
</tr>
<tr>
<td>3. Stars in irregulars</td>
<td>0.000069 $h_7^{-1}$</td>
<td>0.000116 $h_7^{-1}$</td>
<td>0.000033 $h_7^{-1}$</td>
<td>B</td>
</tr>
<tr>
<td>4. Neutral atomic gas</td>
<td>0.00033 $h_7^{-1}$</td>
<td>0.00041 $h_7^{-1}$</td>
<td>0.00025 $h_7^{-1}$</td>
<td>A</td>
</tr>
<tr>
<td>5. Molecular gas</td>
<td>0.00030 $h_7^{-1}$</td>
<td>0.00037 $h_7^{-1}$</td>
<td>0.00023 $h_7^{-1}$</td>
<td>A−</td>
</tr>
<tr>
<td>6. Plasma in clusters</td>
<td>0.0026 $h_7^{-1.5}$</td>
<td>0.0044 $h_7^{-1.5}$</td>
<td>0.0014 $h_7^{-1.5}$</td>
<td>A</td>
</tr>
<tr>
<td>7a. Warm plasma in groups</td>
<td>0.0056 $h_7^{-1.5}$</td>
<td>0.0115 $h_7^{-1.5}$</td>
<td>0.0029 $h_7^{-1.5}$</td>
<td>B</td>
</tr>
<tr>
<td>7b. Cool plasma</td>
<td>0.002 $h_7^{-1}$</td>
<td>0.003 $h_7^{-1}$</td>
<td>0.0007 $h_7^{-1}$</td>
<td>C</td>
</tr>
<tr>
<td>7’. Plasma in groups</td>
<td>0.014 $h_7^{-1}$</td>
<td>0.030 $h_7^{-1}$</td>
<td>0.0072 $h_7^{-1}$</td>
<td>B</td>
</tr>
<tr>
<td>8. Sum (at $h = 70$ and $z ≈ 0$)</td>
<td>0.021</td>
<td>0.041</td>
<td>0.007</td>
<td>…</td>
</tr>
</tbody>
</table>

| Gas components at z ≈ 3       |         |         |         |       |
| 9. Damped absorbers           | 0.0015 $h_7^{-1}$ | 0.0027 $h_7^{-1}$ | 0.0007 $h_7^{-1}$ | A−    |
| 10. Lyα forest clouds         | 0.04 $h_7^{-1.5}$ | 0.05 $h_7^{-1.5}$ | 0.01 $h_7^{-1.5}$ | B     |
| 11. Intercloud gas (He II)    | …       | 0.01 $h_7^{-1.5}$ | 0.0001 $h_7^{-1}$ | B     |

| Abundances of:                |         |         |         |       |
| 12. Deuterium                 | 0.04 $h_7^{-2}$ | 0.054 $h_7^{-2}$ | 0.013 $h_7^{-2}$ | A     |
| 13. Helium                    | 0.010 $h_7^{-2}$ | 0.027 $h_7^{-2}$ | …       | A     |
| 14. Nucleosynthesis           | 0.020 $h_7^{-2}$ | 0.027 $h_7^{-2}$ | 0.013 $h_7^{-2}$ | …     |

*Confidence of evaluation, from A (robust) to C (highly uncertain).*
Photons

Extragalactic Background (Hauser & Dwek 2001)
Cosmic Microwave Background

- Mean temperature: \( T = 2.725 \pm 0.001 \) K
- Spectral Deviation: Compton-y parameter

\[
y = \int \sigma_T n_e \frac{kT}{m_e c^2} \, dl \leq 1.5 \times 10^{-5} \quad \text{(COBE 1992)}
\]

- Energy Density:

\[
u = a_B T^4 = 4.8 \times 10^{-34} \text{ g/cm}^3
\]

\[
n_\gamma = 420 \text{ cm}^{-3}
\]

\[
\langle h\nu \rangle = 6.3 \times 10^{-4} \text{ eV}
\]

\[
\Omega_\gamma = 5 \times 10^{-5} \approx 10^{-3} \Omega_b
\]

\[
n_\gamma / n_b = 2 \times 10^9
\]
Other Relativistic Particles?

Neutrinos

- Not observed directly
- Electron, muon, tau neutrinos – finite mass from oscillations: seasonal fluctuation in Solar ν rate:
  \[ \Delta(m_\nu^2c^2) = 5 \times 10^{-5} eV^2 \] (also from atmospheric ν’ s)
- Theoretically predicted (weak interactions in early universe)
- Fermi-Dirac distribution at late times (after T~m_e)
- Characterized by single parameter: temperature
- \[ T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma = 1.95 \, K \] (or: \( \langle E \rangle \sim 4 \times 10^{-4} eV \))
- \[ \Omega_\nu = 3 \times \frac{7}{8} \times \left(\frac{4}{11}\right)^{4/3} \Omega_\gamma = 0.68 \times \Omega_\gamma = 3.4 \times 10^{-5} \] (relativistic)
- \[ \Omega_\nu = n_\nu m_\nu = 3 \times \left(\frac{3}{11}\right) \times n_\gamma \times m_\nu = \frac{m_\nu}{46eV} \] (present day)