1. Role of Observations in Cosmology & Galaxy Formation
   Key Results and the Standard Model ($\Lambda$CDM)
   Observational Probes of the Dark Matter Distribution

2. High Redshift Galaxies:
   Cosmic Star Formation History and Mass Assembly
   Cosmic Dawn: Searching for the Earliest Sources

3. Observational Probes of Dark Energy
   Supernovae, weak gravitational lensing and studies of large scale structure
Role of Observations

Many of the key features which define our current view of the Universe came through surprising observations:

1. Cosmic expansion (Slipher/Hubble): Einstein preferred a static Universe and disregarded the early observations
2. Big Bang (Penzias & Wilson): Hoyle and others considered the Steady State theory to be the `natural’ solution
3. Dark Matter (Zwicky, Rubin & others): Dominant role in structure formation followed the observational evidence
4. Dark Energy (Perlmutter et al, Riess et al): Although $\Lambda$ was invoked many times in the past, cosmic acceleration was an unpredicted result
5. More surprises in store??

The observational opportunities have advanced dramatically & many puzzles remain, so lots to do!
Cosmic expansion (Hubble 1929):
Rate in km s\(^{-1}\) Mpc\(^{-1}\) is Hubble’s constant \(H_0\)
\(H_0\) governs physical scale and age of the cosmos

**Key Result #1: Cosmic Expansion**

\[ V = H_0 \, d \]

Distance to galaxy \(d\) (using luminous variable stars)

Recession velocity \(V\) from the spectrum

Cosmic expansion (Hubble 1929):
Hubble Space Telescope Key Project eventually determined $H_0$ via Tully-Fisher relation for spirals calibrated via Cepheid distances.
Two-stage determination of Hubble’s Constant $H_0$

1. Period-luminosity relation

Primary Cepheid calibration of distances to nearby spirals (affected by galaxy pec. velocities)

2. Spiral rotation-luminosity relation

Secondary Tully-Fisher distances for distant spirals in the smooth Hubble flow

Final result (Freedman et al Ap J 553, 47, 2001):

$$H_0 = 72 \pm 8 \text{ kms s}^{-1} \text{ Mpc}^{-1}$$
Blackbody spectrum of CMB corresponds to decoupling of matter & radiation at redshift $z = 1088 \pm 1$ when $t = 372 \pm 14$ kyr.
Progress in measuring CMB Fluctuations

Flat Ω_m = 0.3 (vacuum dominated)

Open Ω_m = 0.3 (no vacuum)
STOP PRESS!

WMAP 3 year data
Key Result #3: Clustering of Galaxies

Statistical description emerged in the 1970’s (Peebles)

Angular and spatial correlation functions $w(\theta), \xi(r)$

$$\delta P = N[1 + w(\theta)]d\Omega$$
$$\delta P = \rho[1 + \xi(r)]dV$$

Excess probability of finding a pair with separation $\theta$ or $r$

Also will need power spectrum of density fluctuations

$$P(k) = \langle \delta_k^2 \rangle = \int \xi(r)\exp(ik.r)d^3r$$

Formalism of gravitational instability developed via angular (2-D, $w(\theta)$) and spectroscopic (3-D, $\xi(r)$) surveys
Angular Clustering: e.g. APM Galaxy Catalog


\[ \delta P = N[1 + w(\theta)] \delta \Omega \]

\( w(\theta) \) measures excess probability of pairs on a given scale \( \theta \) for mean surface density \( N \) in area \( \delta \Omega \)

Find \( w(\theta) = A \theta^{-0.8} \)

Power law indicates growth by gravitational instability

Amplitude \( A \) decreases with increasing depth due to increase in no. of uncorrelated pairs, angular diameter distance and (ultimately) less developed structure
Inverting $v = cz = H_0 d$ gives an approximate distance.

Applied to galaxies on a strip on the sky, gives a ‘slice of the universe’

YOU ARE HERE

240 Mpc for $H=100$
The 2 degree field instrument

© Anglo-Australian Observatory

Prime Focus
2dF on the AAT
2dF Galaxy Redshift Survey

225,000 galaxy redshifts

Stromlo–APM (1992)

CfA I (1982)

2dFGRS (2002)
2dFGRS Galaxy Redshift Survey
Power spectrum of local galaxy distribution can be reconciled with models of LSS that fit CMB angular fluctuations.


\[ P(k) = \left\langle |\delta_k|^2 \right\rangle = \int \xi(r) \exp(ik \cdot r) d^3r \]

\[ k/h \text{ Mpc}^{-1} \]
Gravitational instability:

Hierarchical collapse generates ever larger structures

Hierarchical growth:
understand galaxies and clustering as one process
Key Result #4: Dark Matter

Cluster dynamics (Zwicky 1930’s):
stability requires high mass/light ratio
via virial theorem

\[ 2T - U = 0 \]
\[ M = 3 < v_{los}^2 > \frac{n_{cd}}{G} \]

Gravitational lensing provides a clearer
geometric measure of mass:

\[ \theta_E = \left( \frac{4GM}{c^2} \right)^{1/2} D^{-1/2} \]

\[ D = D_s D_d / D_{ds} \]

in several cases both methods can be applied and agree.
Circular orbits implies:

Flat rotation curve, $V \sim \text{const}$, implies $M(<R) \propto R$

Spiral galaxy is embedded in dark, extensive halo

$$\frac{GM(<R)}{R^2} = \frac{V^2}{R}$$

$$M \sim \frac{RV^2}{G}$$
Dark Matter on Galactic Scales: Ellipticals

Stellar velocity dispersion $\sigma$ determined from broadening of absorption lines and `converted' into an equivalent `rotation' curve (Gerhard et al 2001)
Galaxy distribution is distorted in redshift space

Kaiser (1987 MNRAS 227, 1) showed that peculiar velocities distort the distribution of galaxies in redshift space; this can provide a measure of the mass density of dark matter associated with galaxies on larger scales.
Dark matter via redshift-space clustering

- Distortions due to peculiar velocities arising from mass probed by $\xi(\sigma, \pi)$.
- Two effects:
  - Small separations on sky: ‘Finger-of God’
  - Large separations on sky: flattening along line of sight

$$\sigma_p = 385 \pm 50 \text{ km/s}$$
$$\Omega^{0.6}/b = 0.43 \pm 0.07$$

where $b$ accounts for a possible bias between galaxy & DM distribution
Non-baryonic Dark Matter

**Primordial isotope abundances**

- Helium 4 ($^4$He)
- Deuterium ($^2$H)
- Helium ($^3$He)
- Lithium ($^7$Li)

Element Abundance (Relative to Hydrogen)

**CMB Fluctuations (WMAP)**

- $\ell(l+1)C_\ell / 10^{-10}$

- multipole number $l$

- curvature
- baryons
- total density

\[ \Omega_b h^2 = 0.0237^{+0.0013}_{-0.0012} \]

\[ \eta = (6.5^{+0.4}_{-0.3}) \times 10^{-10} \]


Cosmic Expansion History

Prior to 1980 cosmologists attempted to measure two quantities:

• Hubble’s constant: \( H_0 = \frac{dR/dt}{R(t)}; \tau \sim 1/ H_0 \) → scale & age

• Deceleration parameter \( q_0 = -\frac{d^2R/dt^2}{(dR/dt)^2} \) → fate of expansion

In the simplest Friedmann cosmologies containing gravitating matter:

\[
\Omega_M = \frac{\rho_M}{\rho_{crit}} = 2q_0
\]

Two ways to determine the fate of expansion:

• Census of gravitating matter \( \rho_M \) (redshift surveys): \( \Omega_M < 0.3 \)

• Distance-redshift relation over significant look-back times

\[
d_L(z,q_0) = \frac{cz}{H_0 q_0^2} \left[ zq_0 + (q_0 - 1)\{(2q_0 z + 1)^{1/2} - 1\} \right]
\]

Inflation (horizon and flatness) suggested \( \Omega_M = 2q_0 = 1 \)
Key Result #5: Cosmic acceleration

In generalized Friedmann models $q_0 = \frac{\Omega_M}{2} - \frac{3\Lambda}{2}$

Negative $q_0$ is acceleration and implies $\Lambda \neq 0$

Perlmutter et al
“Concordance Cosmology”

“Precision Cosmology?”

- $\Omega_{DM} \approx 0.24 \pm 0.03$ (dark matter)
- $\Omega_B \approx 0.042 \pm 0.004$ (baryons)
- $\Omega_{\Lambda} \approx 0.73 \pm 0.04$ (dark energy)

(Bennett et al 2003, Spergel et al 2006)

All 3 ingredients comparable in magnitude but only one component physically understood!

Dark Energy equation of state:

$$\frac{p}{\rho} = w = -0.97 \pm 0.08$$

$w = -1$ corresponds to Einstein $\Lambda$

$w < -1/3$ required for acceleration
Gravitational Lensing:

• Rapidly developing area with ground and space-based telescopes

• Enables mapping of the distribution of matter in the foreground ‘lens’ regardless of whether that mass is radiating.

• Aim here to illustrate a few examples
Verifying Einstein’s prediction: deflection of starlight by Sun

The predicted deflection at the limb is only $4GM/Rc^2 = 1.7$ seconds of arc
The observed positions of stars in the Hyades cluster are carefully compared with those taken earlier in the year when the sun is not in the light path to test theory.
Gravitational lensing: three regimes

The image, viewed through the lens, depends on the focusing power of the lens (its mass), the relative distances of lens & source and the degree of alignment.
In case of elliptical lens, no ring is produced, but as background source moves closer in alignment, multiple images, some highly magnified appear – these are known as “giant arcs”
The First Giant Arc

In 1987 Genevieve Soucail at Observatoire de Midi Pyrenees (Toulouse) demonstrated the arc in the galaxy cluster Abell 370 represents light of a single background galaxy distorted by the foreground cluster lens.
QuickTime™ and a Sorenson Video decompressor are needed to see this picture.
For a compact strong lens aligned with a background source, a ring of light is seen at a radius depending on the geometry and the lens mass, i.e. this allows us to measure the mass of the lens.
Combining Lensing & Stellar Dynamics

In elliptical galaxies, lensing and stellar dynamics provide constraints on the mass distribution on complementary scales. In combination, therefore, they constrain the outer slope, $\gamma$, of the total mass distribution (i.e. in the halo).
**Lensing vs Dynamical Masses**

Singular Isothermal Ellipsoid

\[ \rho(r) = \frac{\sigma_{SIE}^2}{2\pi G r^2} \]

\[ \frac{\langle \sigma / \sigma_{SIE} \rangle}{1.010 (0.065)} \text{ (aper = } r_e/8) \]

\[ \frac{\langle \sigma_{ap} / \sigma_{SIE} \rangle}{0.950 (0.055)} \text{ (SDSS aper = 3''')} \]

\( \sigma_{SIE} \) derived from singular isothermal ellipsoid fit to lensing geometry

Total Mass Density Profile

\[ \rho_{\text{tot}}(r) = \rho_0 \left( \frac{r}{r_0} \right)^{-\gamma'} \]

\[ \rho_{\text{lum}}(r) = \frac{M_* r_*}{2\pi r (r + r_*)^3} \]

\[ \rho_{\text{DM}}(r) = \frac{\rho_{\text{DM,0}} r_b^3}{r \gamma \left( r_b^2 + r^2 \right)^{(3-\gamma)/2}} \]

Find total mass profile is isothermal with mass tracing light in shape and remarkably little evolution in density profile with redshift - indicates collisional coupling of gas and DM in ellipticals

\[ \langle \gamma' \rangle = 2.01^{+0.02}_{-0.03} \]
Numerical simulations suggest cold (non-interacting) dark matter concentrates with a \textit{inner} density profile \( \rho_D \propto r^{-\beta} \) whose form is "universal": \( 1.0 < \beta < 1.5 \). Can gravitational lensing be used to separate dark matter from baryons and see how it is distributed on small scales?
Mass profiles in cluster cores

Presence of radial and tangential arcs of known z strongly constrains mass on 20-50 kpc scales

MS2137-23 (z=0.313)
Arcs & Multiple Images - Reminder

Origin of tangential and radial arcs
Best-fitting density profile for MS2137-23

\[ \rho(r) \]

\[ r \text{ (kpc)} \]
Multiple Images

The exquisite resolution of Hubble locates same source seen in 3 different locations!

This is particularly informative if the distances to the lens and the source can be determined as it tells us how lensing matter is distributed in the cluster.
Analysis of Multiple Images

We find the dark matter is:

• dominant (50-100 times more than the mass associated with the visible cluster galaxies)

• smoothly distributed, broadly following that of the smoothed light
Weak Statistical Distortions ("Shear")

As we move away from the lens center, the arcs decrease in prominence. Because faint galaxies have their own intrinsic shapes, we must average over many faint galaxies to see the stretching effect clearly.
Dark Matter Profile on Large Scales
Cl0024 (Kneib et al. 2003)

\[ M_{200} = 6.1 \pm 1.1 \times 10^{14} \, h^{-1} M_\odot \]

Sparse-sampled Hubble pointings detect shear to 5 Mpc

Combining weak+strong lensing yields density profile \( \rho \propto r^{-n} \) with \( n > 2.4 \)

Consistent with universal NFW profile (c=22)
Mass Distribution in Abell 1689


- 4-band ACS imaging +
ground based data

- 106 multiple images from
30 background sources

- Most distant arc: $\theta_E \sim 50''$
probing $M(<150 \text{ kpc})$

- $\sum \propto r^{-0.55\pm0.1}$

for the total surface mass
matching universal NFW
profile (c=8)
Instead of measuring lensing in "special" regions like clusters can we use it to make statements about dark matter everywhere?

Expect to see statistical distortions arising from large scale structure in any direction.
Techniques are available for converting the measured shear (vectors) into the foreground mass distribution (blue scale)
The technology to make dark matter maps outside of clusters is hard but we can statistically compare the signals with theory.
Panoramic Cameras on Canada-France & Subaru

CFHT: 100deg² (Mellier et al)
Subaru: 30 deg² (Miyazaki et al)
Hubble “Cosmic Evolution Survey”

- 2 deg² Hubble data in 625 contiguous fields (largest ever Hubble program)
- > 2 million faint galaxies with measurable shapes
- Multicolor follow-up from Subaru to get distances
- Many other datasets in this special deep field, e.g. X-rays sensitive to hot hydrogen gas in clusters of galaxies
Hubble “Cosmic Evolution Survey”

- 2 deg² Hubble data in 625 ACS contiguous fields (largest ever Hubble program)
- > 2 million faint galaxies with measurable shapes
- Multicolor follow-up from Subaru to get photo-z
- Demonstration of lensing tomography

\( z_B = 0.7, 1, 2 \)

_Massey, Rhodes et al_
Lensing mass vs X-ray data in COSMOS

Subaru vs Hubble

X-ray map from XMM satellite
Summary of Lecture #1

• Great progress is being made in observational cosmology thanks to powerful ground and space-based facilities.

• But we should not confuse the *precision measurement* of the key components ($\Omega_M, \Omega_\Lambda, H_0$...) with *physical understanding*: dark matter and dark energy constitute 95% of the energy density but neither is understood.

• Gravitational lensing offers a unique probe of the distribution of dark matter for comparison with numerical models: observational techniques are well-advanced for studying both its large and small scale distribution.