Modern cosmology 2: More about Λ

- Distances at z ~1
- Type Ia supernovae
- SNe Ia and cosmology
- Results from the Supernova Cosmology Project, the High z Supernova Search, and the HST
- Conclusions

More astrophysical evidence for accelerating expansion

- Is Λ constant?
- Cosmological consequences
- Outstanding problems

Gravitational lensing and Λ

- Lensing occurs when there is a massive galaxy or cluster between the source and the observer
- How often will this happen?
  - relevant distance is angular diameter distance
  - if Λ > 0, the angular diameter distance is larger, so there are more potential lensing galaxies, so there will be more lensed systems

PKS 1830–211, J. Lovell et al., CSIRO
Gravitational lensing and $\Lambda$

- Lens statistics are rather low, so difficult to get good constraints
  - resulting contour similar in orientation to SNe Ia
    - both measure at $z \sim 1$
    - result is less precise but consistent

X-ray clusters and $\Lambda$

- Rich clusters of galaxies contain an intracluster medium of hot X-ray emitting gas
- This gas accounts for most of the cluster’s baryonic mass
- It is low density and optically thin
**X-ray clusters and Λ**

- If the electron density of the gas is \( n_e \) and the core radius of the cluster is \( r_c \)
  - \( M_g \propto n_e r_c^3 \) where \( M_g \) is the gas mass
  - \( L_X \propto n_e^2 r_c^3 \) where \( L_X \) is the X-ray luminosity
  - so \( M_g \propto r_c^{3/2} L_X^{1/2} \)
- Also, we can use hydrostatic equilibrium to calculate the total mass of the cluster
  - \( \Delta \propto r_c \)
- Now \( r_c = \theta_c d_L \) and \( L_X = 4\pi f_X d_L^2 = 4\pi (1+z)^4 f_X d_L^2 \)
  - \( M_g/M_{\text{tot}} \propto (1+z)^2 d_L^{3/2} \)

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**X-ray clusters and Λ**

- Calculated value of \( M_g/M_{\text{tot}} \) depends on assumed cosmology
  - if we assume \( M_g/M_{\text{tot}} \) should not depend on \( z \) we can fit cosmological parameters
  - this is most sensitive to \( \Omega_m \) because absolute value of \( M_g/M_{\text{tot}} \) gives \( \Omega_m \) directly if \( \Omega_b \) known

Is $\Lambda$ constant?

- Remember we parametrise the equation of state as $P = w\rho$
  - $w = -1$ for $\Lambda$; this gives constant $\rho$
  - for acceleration require only $w < -\frac{1}{3}$
  - however all data are consistent with $w = -1$
    - non-standard models which agree with data “mimic” simple cosmological constant

\[
\frac{\dot{a}}{a} = -\frac{4\pi G}{3c^2}(\rho + 3P)
\]

It is possible that $w$ could vary with time
- even if $w = -1$ now, this may not always be true
- might also address “fine tuning” problem of why observed $\Lambda$ is so small
- data do not currently provide very good constraints on this
Effects of $\Lambda > 0$

- Age of universe is increased
  - this is a good thing: if $H_0 \sim 70$ km/s/Mpc, $\frac{1}{3} H_0^{-1} \sim 9.3$ Gyr, significantly less than astrophysically estimated ages of globular clusters (~12 Gyr)
- Evolution of structure is modified
  - see later
- Universe will definitely expand forever
  - even if closed

Problems with $\Lambda > 0$

- Why is it so small?
  - can attempt to estimate likely size of vacuum energy density
  - get values $\sim 10^{120} \times$ what we have!
    - “worst failure of an order of magnitude estimate in the history of physics” (Weinberg)
- Why is $\Omega_\Lambda$ so similar to $\Omega_m$?
  - $\Omega_m/\Omega_\Lambda = 8\pi G p/\Lambda \propto 1/a^3$ (if $\Lambda$ is really constant)
  - so for most of the history of the universe one is much bigger than the other
  - why would we happen to live in the brief epoch when they are nearly equal?
- Conclusion: we don’t understand the physics of $\Lambda$
Conclusions

• Results from Type Ia supernovae clearly indicate that $\Lambda > 0$
  ▶ gravitational lens statistics and X-ray data from clusters of galaxies support this (so does CMB)
• This improves our description of the universe
  ▶ age in better agreement with stellar astrophysics
  ▶ better description of large-scale structure
• But we do not understand how it works
  ▶ no theory predicts or even explains what we see