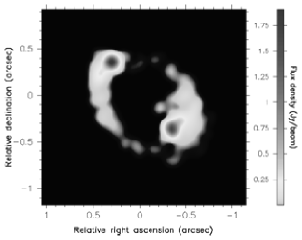
Modern cosmology 2: More about Λ

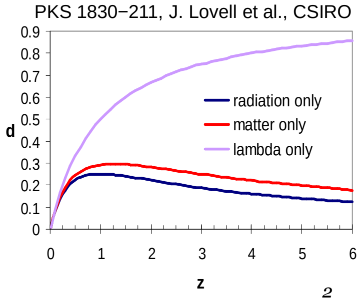
- Distances at *z* ~1
- Type Ia supernovae
- SNe Ia and cosmology
- Results from the Supernova Cosmology Project, the High z Supernova Search, and the HST
- Conclusions
- More astrophysical evidence for accelerating expansion
- Is Λ constant?
- Cosmological consequences
- Outstanding problems

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 $\Lambda > 0$, the angular diameter distance is larger, so there are more potential lensing galaxies, so there will be more lensed systems

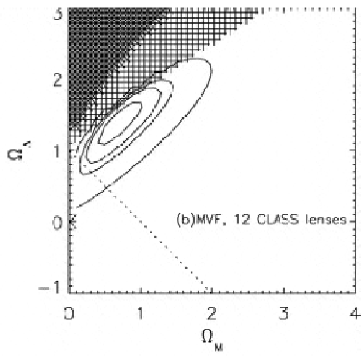


PKS 1830−211, J. Lovell et al., CSIRO



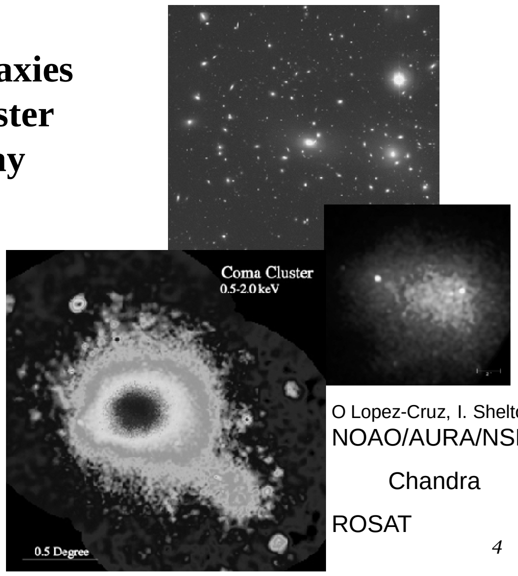
Gravitational lensing and Λ

- **Lens statistics are rather low, so difficult to get good constraints**
  - **paper by Mitchell et al.** (*ApJ* **622** (2005) 81) **uses CLASS radio lens survey plus SDSS galaxy survey**
  - **resulting contour similar in orientation to SNe Ia**
    - both measure at *z* ~ 1
    - result is less precise but consistent



X-ray clusters and Λ

- **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**



O Lopez-Cruz, I. Shelton
NOAO/AURA/NSF

Chandra

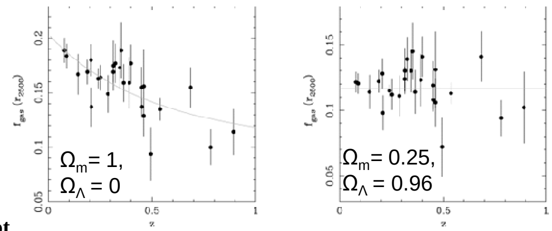
ROSAT

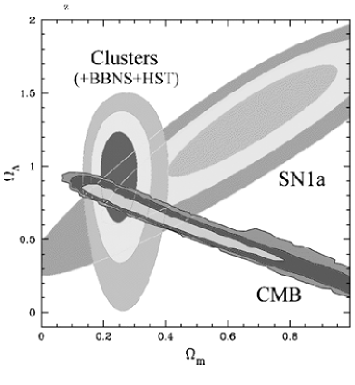
X-ray clusters and Λ

- **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**
  - **$M_{tot} \propto r_c$**
- **Now $r_c = \theta_c d_A$ and $L_X = 4\pi f_X d_L^2 = 4\pi(1+z)^4 f_X d_A^2$**
  - **$M_g/M_{tot} \propto (1+z)^2 d_A^{3/2}$**

X-ray clusters and Λ

- **Calculated value of M_g/M_{tot} depends on assumed cosmology**
  - **if we assume M_g/M_{tot} should not depend on z we can fit cosmological parameters**
  - **this is most sensitive to Ω_m, because absolute value of M_g/M_{tot} gives Ω_m directly if Ω_b known**





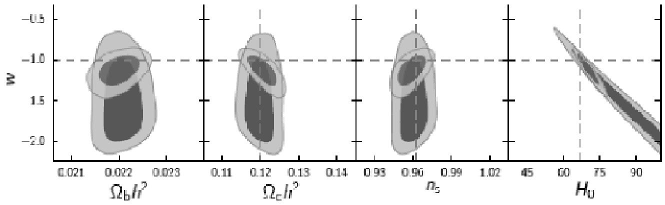
Allen et al, *MNRAS* **353** (2004) 457

Is Λ constant?

- **Remember we parametrise the equation of state as $P = w\varepsilon$**
  - **$w = -1$ for Λ; this gives constant ε**
  - **for acceleration require only $w < -⅓$**
  - **however all data are consistent with $w = -1$**
    - non-standard models which agree with data "mimic" simple cosmological constant

$$\boxed{\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\varepsilon + 3P)}$$

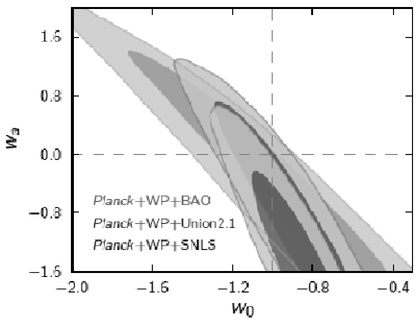
Planck 2013



Is Λ constant?

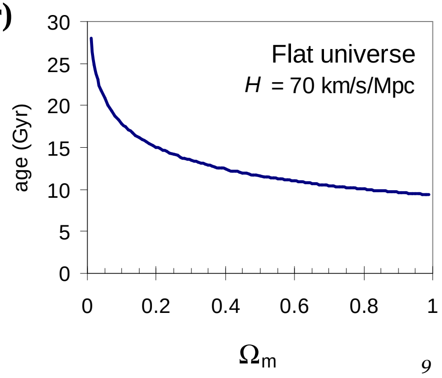
- **It is possible that w could vary with time**
  - **even if $w = -1$ now, this may not always be true**
  - **might also address "fine tuning" problem of why observed Λ is so small**
  - **data do not currently provide very good constraints on this**

Planck 2013



Effects of Λ>0

- **Age of universe is increased**
  - **this is a good thing: if H_0 ~ 70 km/s/Mpc, ⅔H_0^{-1} ~ 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 Λ>0

- **Why is it so small?**
  - **can attempt to estimate likely size of vacuum energy density**
  - **get values ~10^{120} × what we have!**
    - "worst failure of an order of magnitude estimate in the history of physics" (Weinberg)
- **Why is Ω_Λ so similar to Ω_m?**
  - **$\Omega_m/\Omega_\Lambda = 8\pi G\rho/\Lambda \propto 1/a^3$ (if Λ 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 Λ**

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**