... a lingering issue

- Theory: $\Omega = 1$
  - via fine-tuning, inflation, structure seeds & formation
- Observations:
  - $\Omega_0 \sim 0.3$ (< 0.1 baryonic, 0.2 non-baryonic CDM)
  - $H_0 = 72 \pm 7$
  - $H_0 = 72, \Omega_0 \sim 0.3 \rightarrow t_{\text{univ}} = 11.8 \times 10^9 \text{ yr}$
  - but oldest stars $> 12.0 \times 10^9 \text{ yr}$!!
  - if $\Omega_{\text{matter}} = 1$ then $H_0 = 72$ implies $t_{\text{univ}} = 9 \times 10^9 \text{ yr}$!
  - we’re still missing something...

The “cosmological constant”

- Einstein (1915) - a free constant of integration in General Relativity that he called $\Lambda$... set to 0 to keep Universe from expanding
- Corresponds to a “vacuum energy” of empty space
- if $\Lambda \neq 0$ then it contributes to $\Omega$ that adds ‘energy’ to the universe as it expands
- $\Omega = \Omega_{\text{matter}} + \Omega_\Lambda$
Looking for lambda...

- departures from the Hubble Law at very large distances (long look-back times)
- if $\Lambda > 0$ then the Universe should have been expanding more SLOWLY in the past than if $\Lambda = 0$
- $\Omega_\Lambda > 0$ adds an acceleration to the Universe as time advances

\[
\Omega_\Lambda = \Omega_{\text{matter}} = 0 \quad \Omega_\Lambda > 0
\]

\[
Z (\text{redshift}) \quad \text{NOW}
\]

\[
R = R_0/(1+Z)
\]

\[
R_0/(1+Z) = \text{lookback distance}
\]

\[
\text{Time} = d/c
\]
Signature of acceleration in the Hubble Law

- Type Ia Supernovae are reliable distance indicators to large distances
- farther = fainter
- SN with large redshift (velocity) will appear fainter than the Hubble Law suggests if $\Omega_\Lambda > 0$
The Accelerating Universe

- The Universe is now accelerating
  - expanding faster than it should even if there was no mass at all to slow the expansion
- Prior to Z~1 matter was slowing down the expansion
  - the end of the “deceleration epoch”
- SN @ Z< 1.2 show the effect
- SN @ Z> 1.2 slowly return to ‘standard’

Putting it all together...

- $\Omega_{\text{total}} = 0.996 \pm 0.060$
- $\Omega_m = 0.238 \pm 0.040$
- $\Omega_{\lambda} = 0.758 \pm 0.040$
- $\Omega_{\text{bary}} = 0.041 \pm 0.002$
- $H_0 = 73.4 \pm 3.2$
- $t_o = 13.73 \pm 0.15$ Gyr
- $Z_{\text{ cmb}} = 1089 \pm 1$
CBR “polarization”
the BICEP-2 result from March 2014
(Background Imaging of Cosmic Extragalactic Polarization)

- during the inflationary epoch, ‘quantum’ fluctuations produced variations in the mass-energy density and gravitational radiation (GR) fields.

- ‘pure’ gravitational radiation driven by GR variations partially align vibrations of E&M field

- this partially ‘polarizes’ photons in a particular way called ‘B-mode’ polarization

- “ordinary” clumping of mass (gravitational lensing) does not produce this kind of polarization

Polarization of the CMB

relic B-mode polarization
(BICEP-2: 2014)
produced by GR perturbation