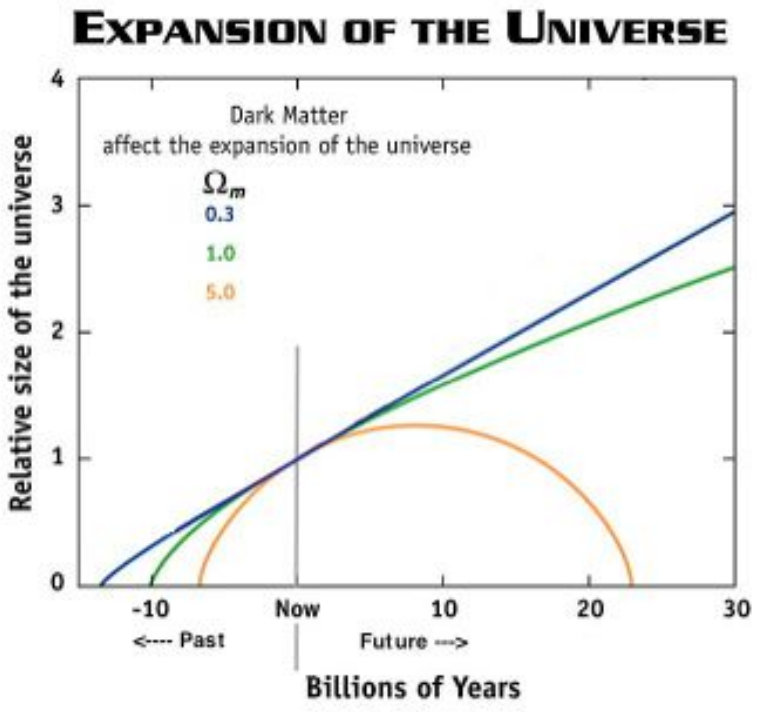
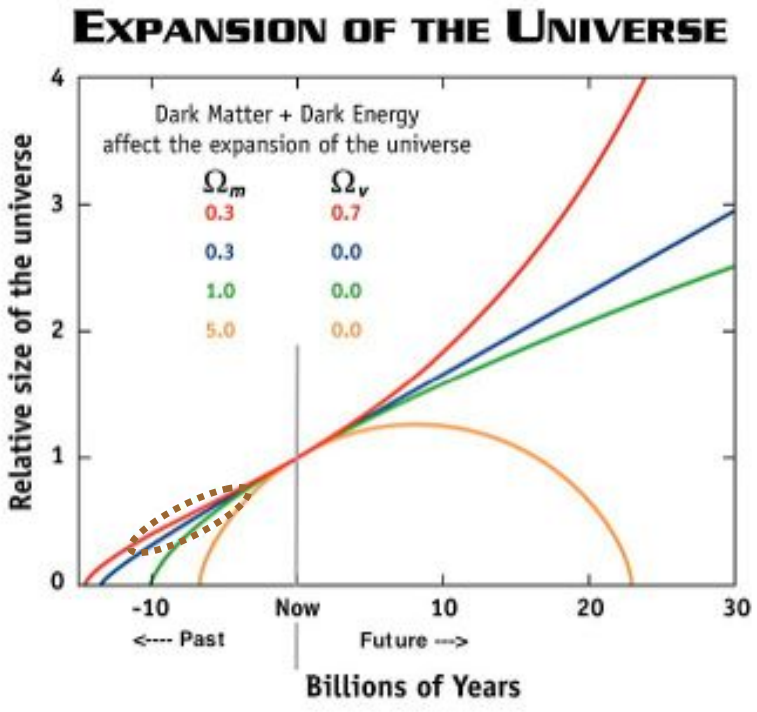
... a lingering issue

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



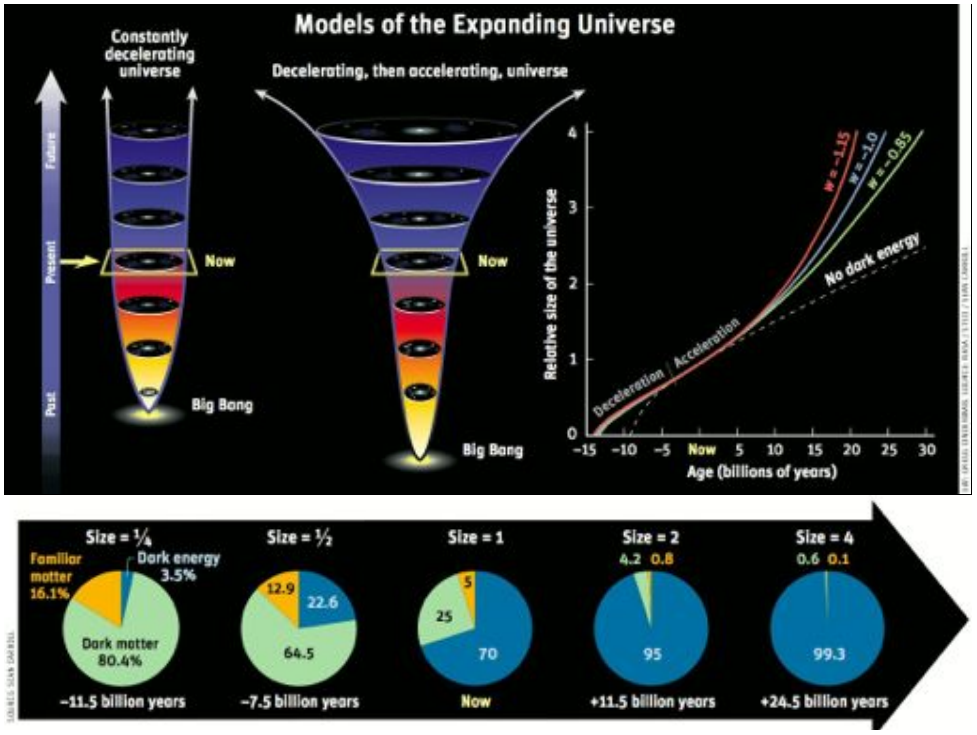
The "cosmological constant"

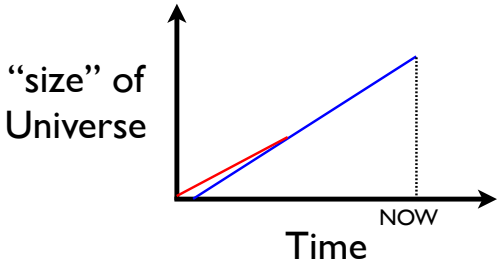
- Einstein (1915) - a free constant of integration in General Relativity that he called Λ... set to 0 to keep Universe from expanding
- Corresponds to a "vacuum energy" of empty space
- if $\Lambda \neq 0$ then it contributes to Ω that adds 'energy' to the universe as it expands
- **$\Omega = \Omega_{matter}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



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

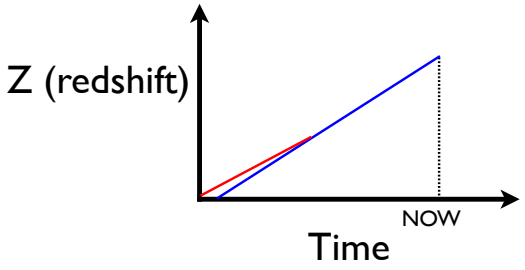


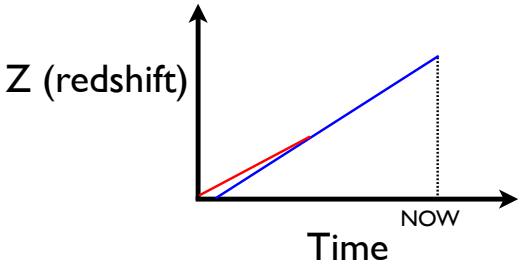


$\Omega_\lambda = \Omega_{matter} = 0$

$\Omega_\lambda > 0$

$R = R_o/(1+Z)$

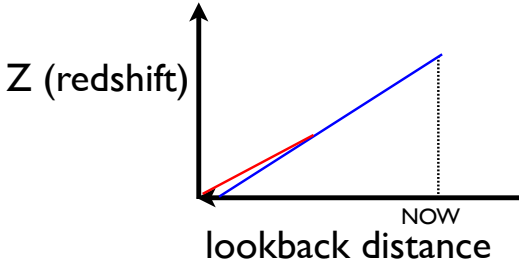


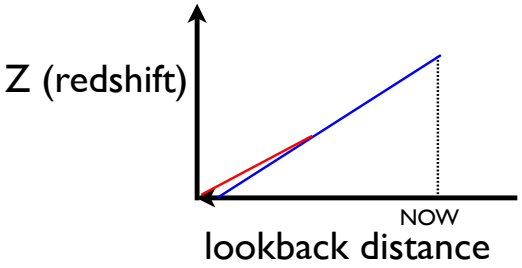


$\Omega_\lambda = \Omega_{matter} = 0$

$\Omega_\lambda > 0$

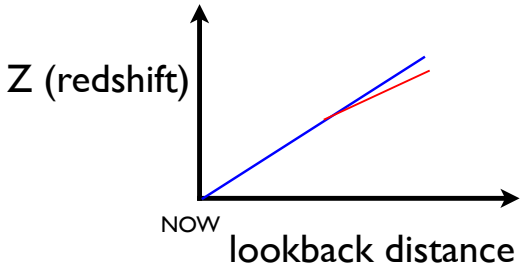
Time = d/c





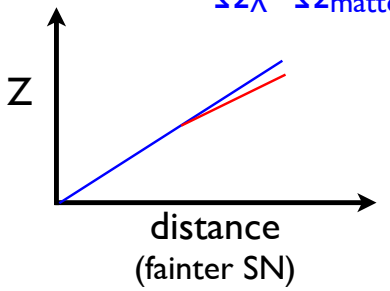
$\Omega_\lambda=\Omega_{matter}=0$

$\Omega_\lambda>0$

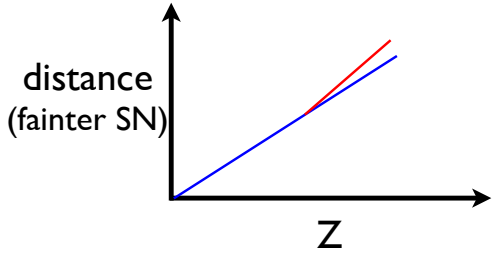


Signature of acceleration in the Hubble Law

$\Omega_\lambda=\Omega_{matter}=0$

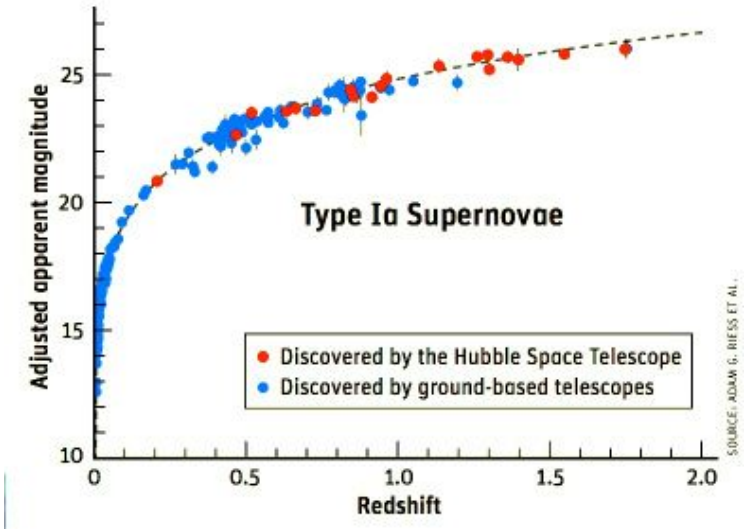


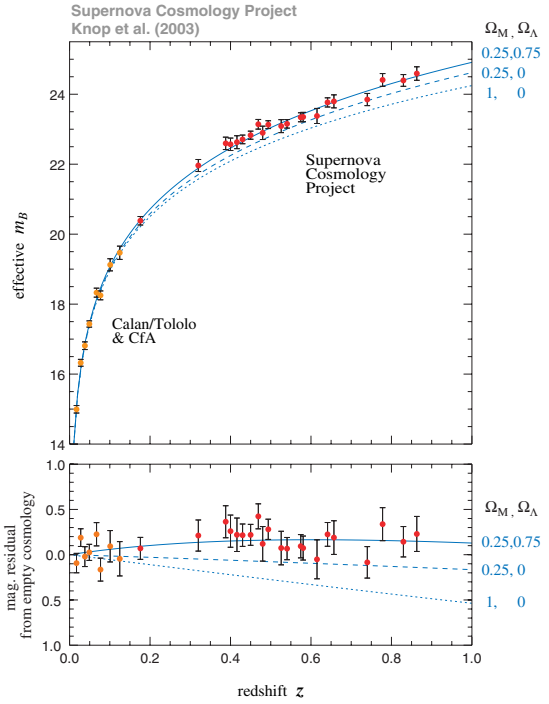
$\Omega_\lambda>0$



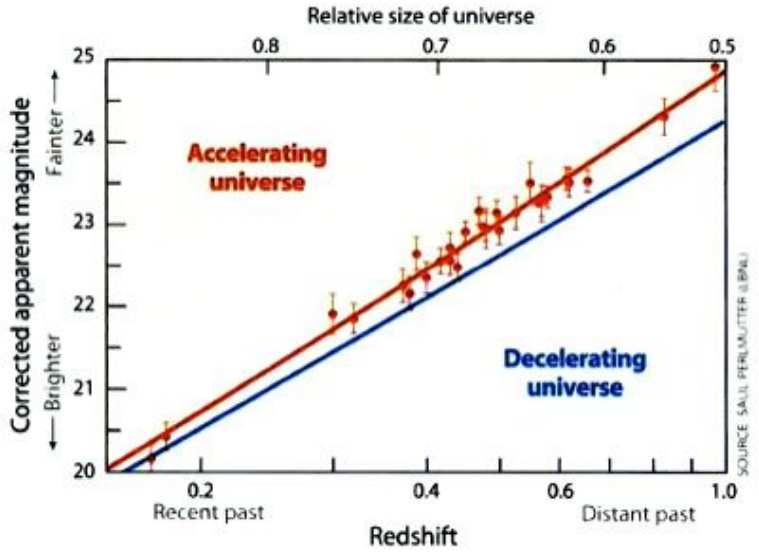
- Type Ia Supernovae are reliable distance indicators to large distances
- farther = fainter
- SN with **large redshift** (velocity) will appear **fainter** than the Hubble Law suggests **if $\Omega_\lambda>0$**

Supernova Cosmology



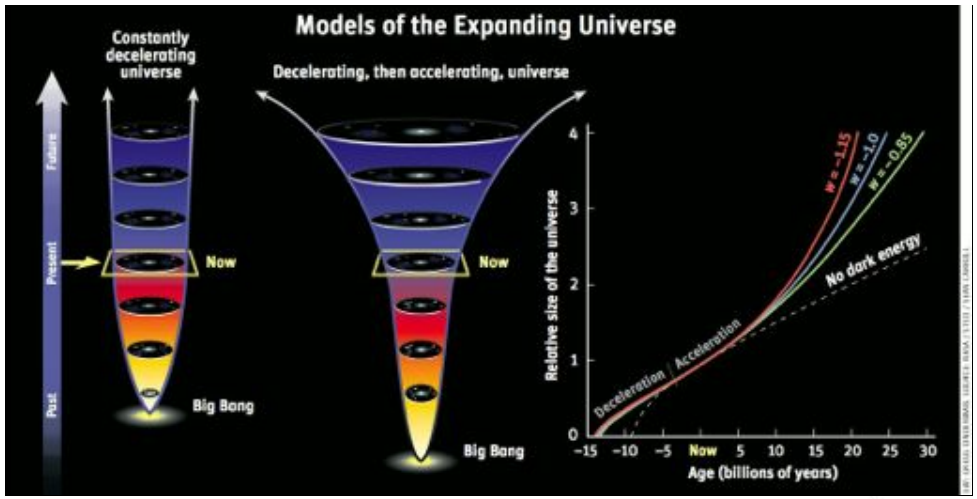


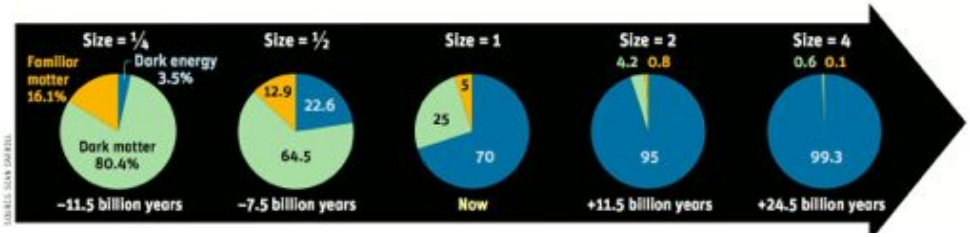
Supernova Cosmology



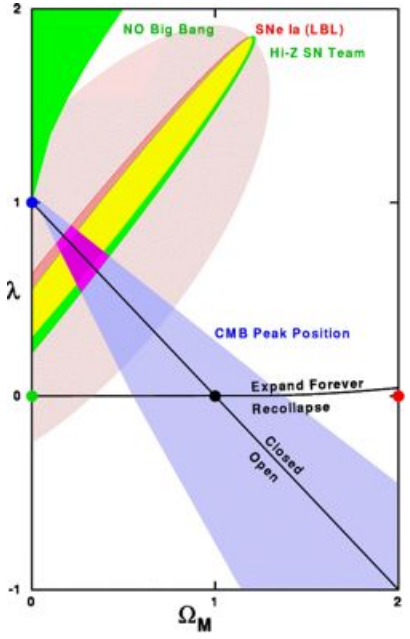
The Accelerating Universe

- 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...



- Ω_{total} **=0.996 ± 0.060**
  - Ω_m= 0.238 ± 0.040
  - Ω_λ = 0.758 ± 0.040
  - Ω_{bary}= 0.041 ± 0.002
- H_o = 73.4 ± 3.2
- t_o = 13.73 ± 0.15 Gyr
- Z_{cmb} = 1089 ± 1

CBR “polarization”

the BICEP-2 result from March 2014

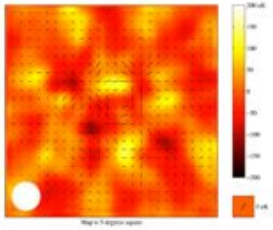
(**B**ackground **I**maging of **C**osmic **E**xtragalactic **P**olarization)

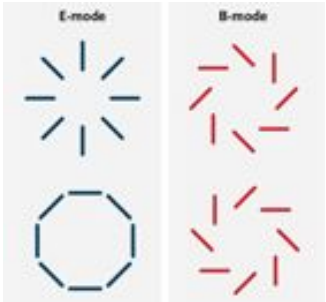
- during the inflationary epoch, ‘quantum’ fluctuations produced variations in the mass-energy density and gravitational radiation (GR) fields.
- ‘pure’ gravitational radiation driven by GR variations partially align vibrations of E&M field
- this partially ‘polarizes’ photons in a particular way called ‘B-mode’ polarization
- “ordinary” clumping of mass (gravitational lensing) does not produce this kind of polarization

Polarization of the CMB

CBR polarization (DASI: 2002)

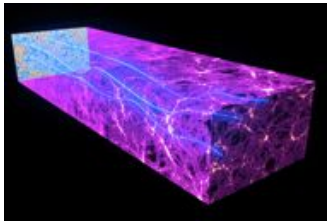
E-mode lensing by density perturbation





B-mode polarization

produced by multiple lensing of CBR signal



Polarization of the CMB

relic B-mode polarization

(BICEP-2: 2014)

produced by GR perturbation