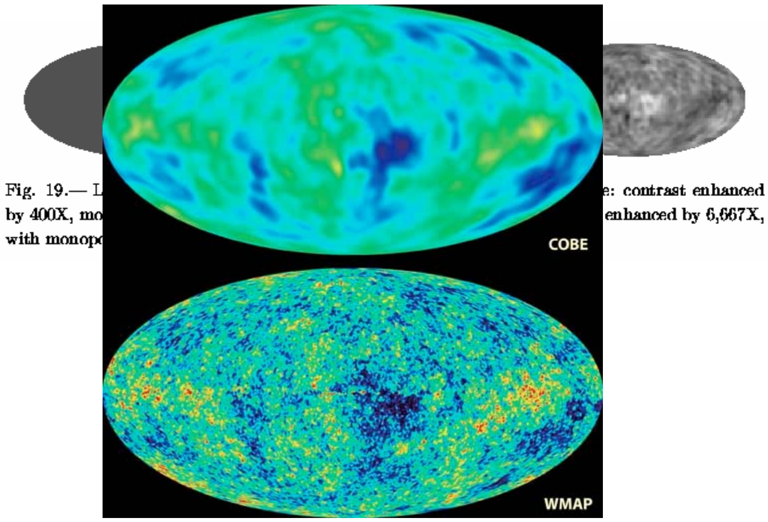
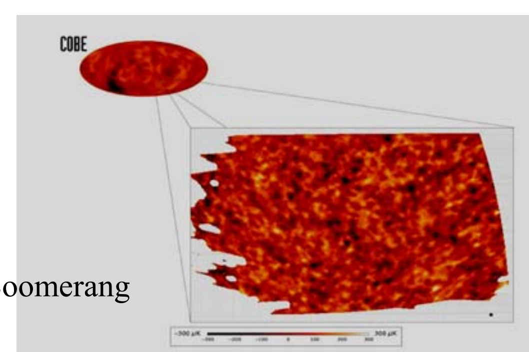
Cosmic Microwave Background Anisotropies = structure in the CMB



Structure in the CMB

Boomerang balloon flight.

Mapped Cosmic Background Radiation with far higher angular resolution than previously available.



Boomerang

Launch near Mt. Erebus in Antarctica

Astrophysical Journal Supplement 148, pg. 1 (September 2003)

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Received 2003 February 11; accepted 2003 May 29

Results:

- Total density: $\Omega_o = \Omega_{tot} = 1.02 \pm 0.02$
- Age of Universe: $t_o = 13.7 \pm 0.2$ Gyr
- Matter density: $\Omega_m h^2 = 0.135\ {}^{+0.008}_{-0.009}$ ➔ $\Omega_m = 0.27$
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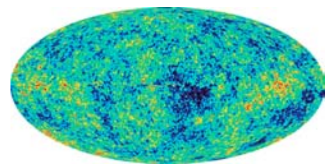

73% Dark Energy, 22% Dark Matter,
4.4% Baryonic Matter

Flat Universe with density fluctuations $P(k) \sim k^n$, $n \sim 1$

➔ **INFLATION**

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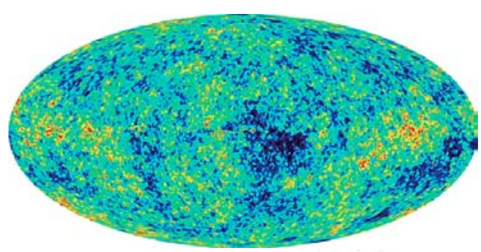
What is measured?



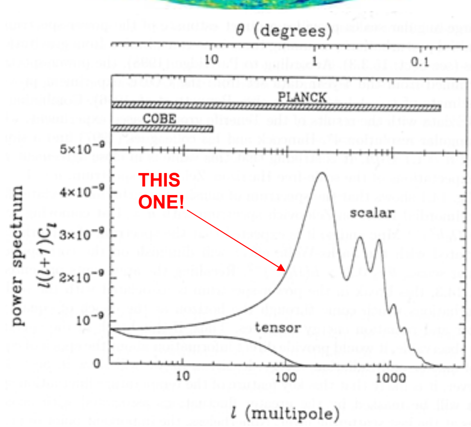
Basically,

Power spectum of

$\Delta T/T$

vs. $l = \pi/\theta$

(think of Fourier transforming the sky in angular coordinates)



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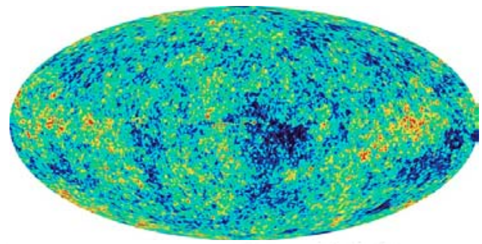

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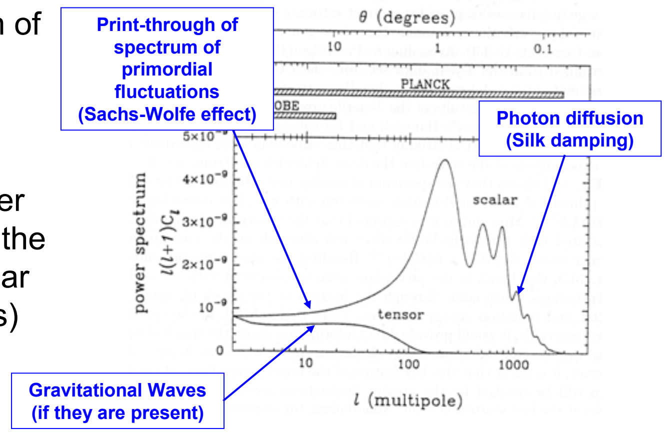
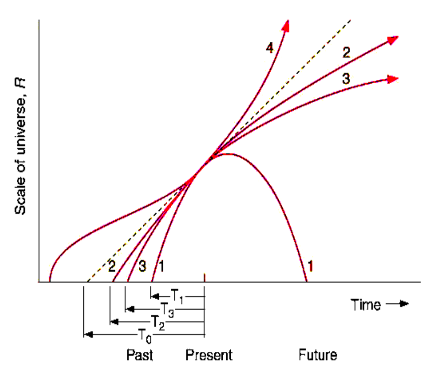


Position of 1st peak:

- Density fluctuations print through as CBR fluctuations.

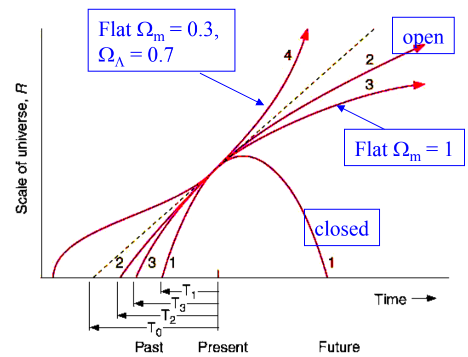
  $\delta\rho/\rho = 3\delta T/T$ [CO 28.11]
- Measures angular size of sound waves which permeated universe just before decoupling of CBR.
- Linear size of largest structure

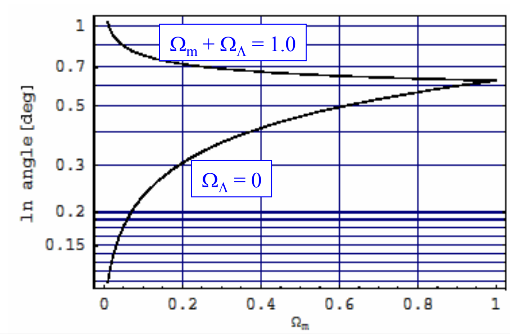
  = (speed of sound) x (age of universe at that time)
- Linear size/Angular size = distance
- Distance depends on Ω_{tot}
  - $D = (2c / H_o \Omega_o)$ for large z.



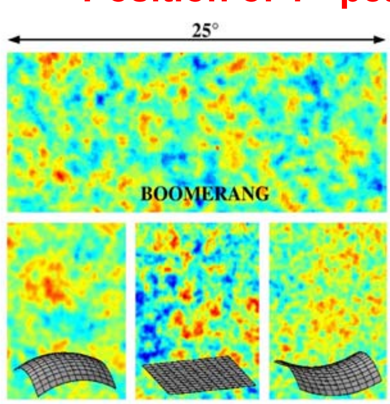
How can curves 3 and 4 give same angular size?

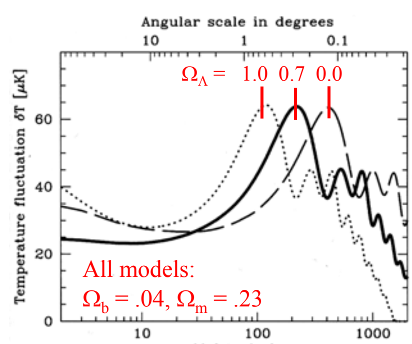
- Decoupling occurred at $z \sim 1100$ in any cosmological model ➔ *R(t)* same for all models.
- Angular Size Distance to $z = 1100$ depends on curvature and on presence/absence of cosmological constant.
- But age of universe at $z = 1100$ also depends on cosmological model.
- Age effect cancels out distance effect for differing values of Ω_Λ, but not for different curvatures.



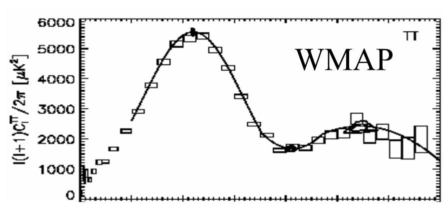


Position of 1st peak measures curvature

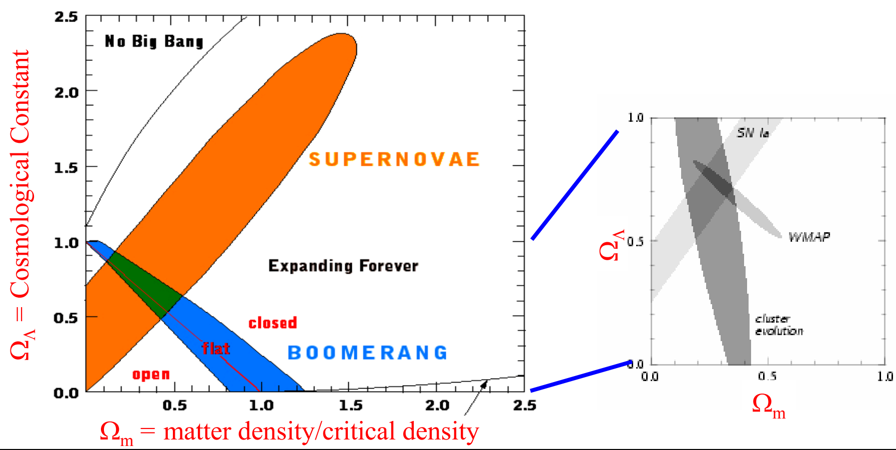




First peak:
Size of "acoustic horizon"
$r = v_s t_{Decoupling}$
$\theta = r/\chi(d)$
$\chi = \sin(d), d, \sinh(d)$
$l_{peak} = 220/\Omega_{tot}^{1/2}$
Measured l_{peak} ➔ $\Omega_{tot} = 1.02 \pm .02$



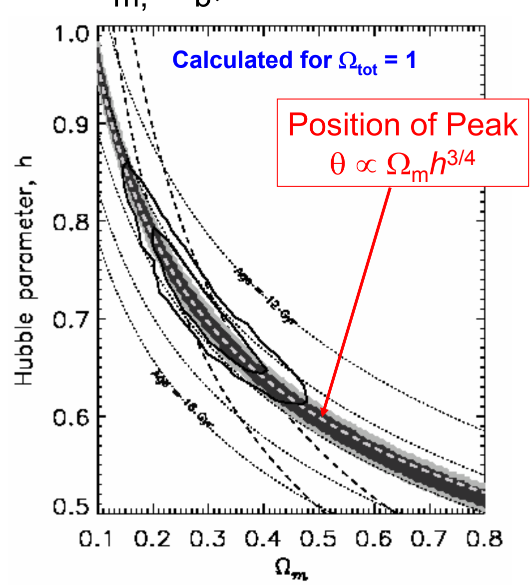
- Type Ia Supernovae as “standard candles”
  - ➔ accelerating expansion
  - ➔ $q_o = \Omega_m/2 - \Omega_\Lambda$
- CBR anisotropy ➔ $\Omega_{total} = \Omega_m + \Omega_\Lambda$



Position & height of first peak also depend on $\Omega_{m,}$ Ω_b, h

Height of peak

- Larger Ω_m ➔ all peaks have smaller amplitudes.
  - Through change in matter/radiation density ratio during radiation-dominated phase.
  - Through effect on when universe becomes matter dominated.



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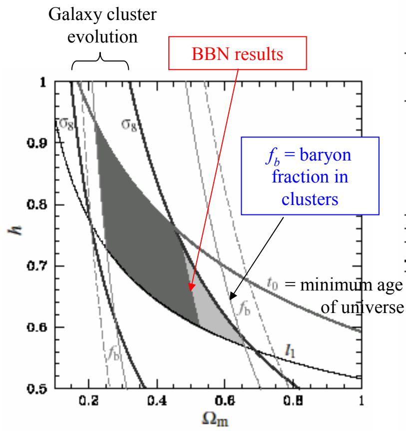
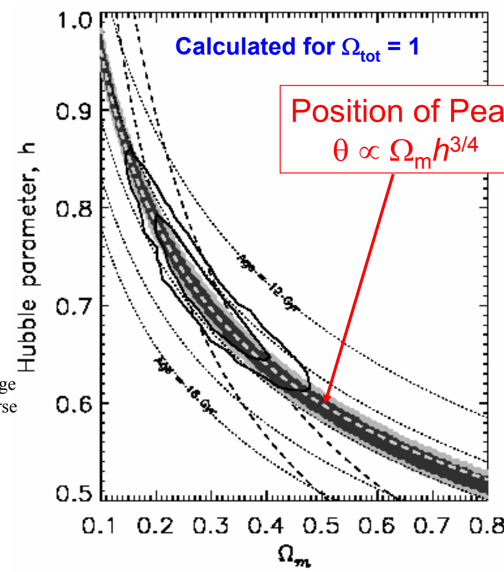
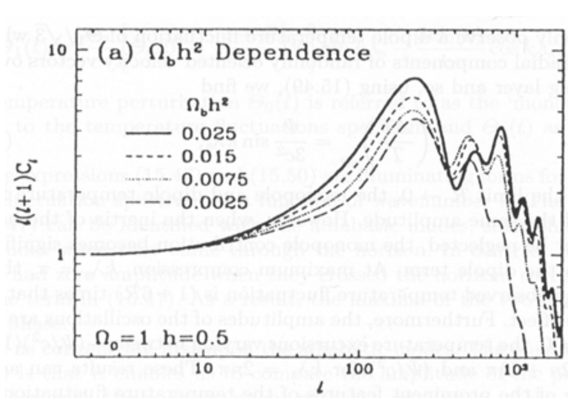
So use constraints from other measurements:





WMAP also measured second peak



- Due to rarefaction of an acoustic wave.
- Larger Ω_b ➔ smaller amplitude of second peak.
  - greater inertial mass in oscillating plasma

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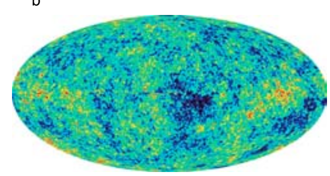

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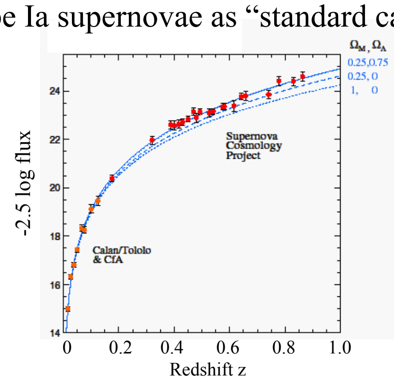
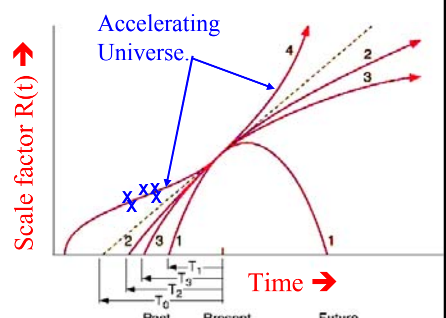
Dark Energy Measured using Type Ia supernovae as "standard candles"





Ed Loh + collaborators (Baldwin, Donahue, Zepf)

- Use Spartan Infrared Camera on SOAR to measure SNe at greater distances.
- Are SNe *really* reliable "standard candles"?
  - Dimming by dust?
  - Luminosity evolves with lookback time?
    - use $dL/L \propto 1/\text{time}$ as strawman.

Dark Energy

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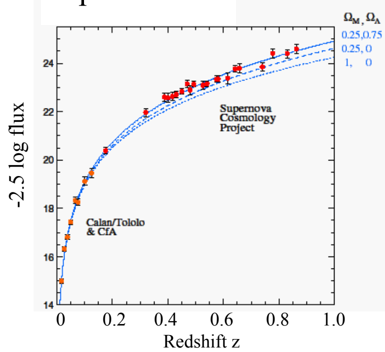

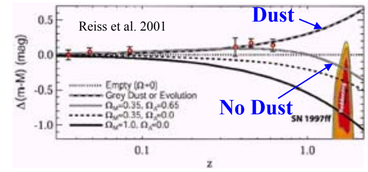

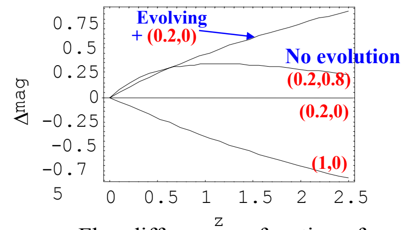

Flux difference as function of *z*

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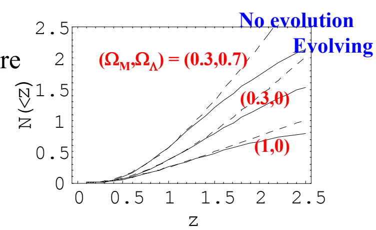
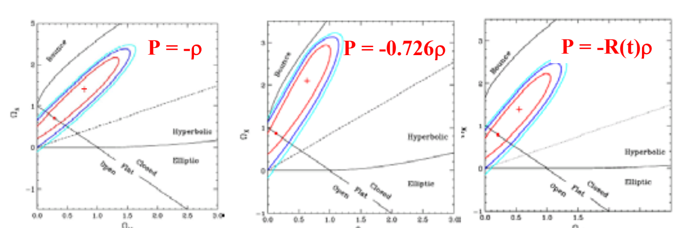


Number per 4 hr SOAR exposure

Dark Energy "Equation of State"

- P-ρ relation is unknown
- Results usually shown assuming P = -ρ (pressure; energy density)
  - "Cosmological constant"



Dicus & Repko 2003: Goodness of fit contours for various equations of state.

- But poorly constrained.
- Can be measured using high-precision SN observations.
  - HST results are coming in.
  - Proposed SNAP satellite project?
  - But meanwhile, can make progress with SOAR + larger telescopes