

Sources of Cosmological Data include Type Ia supernova surveys of redshift vs. brightness (a proxy for distance); the power spectrum of the Cosmic Microwave Background (which so far agrees with predictions of inflation); the distribution of galaxies and galaxy clusters; gravitational lensing surveys; galactic rotation curves; ...

The resulting picture is that the universe is composed of:

- 4.6% ordinary "baryonic" matter
- 23.5% Dark Matter
- 71.9% Dark Energy

(WMAP 9-year, June 2013)

Dark Matter $\hat{=}$ pressureless fluid $w=0$, $\Omega_M = 0.235$

Dark Energy $\hat{=}$ cosmological const. $w=-1$, $\Omega_\Lambda = 0.719$

Baryonic Matter = intergalactic gas, stars, etc., $\Omega_B = 0.04$

assumes $\Omega_M + \Omega_\Lambda + \Omega_B = 1$

Age of universe: 13.8 billion yrs.

$H_0 = 69.7 \text{ km/s/Mpc}$

$\hat{=} 3.3 \times 10^6 \text{ light yrs.}$

} WMAP 9-yr.

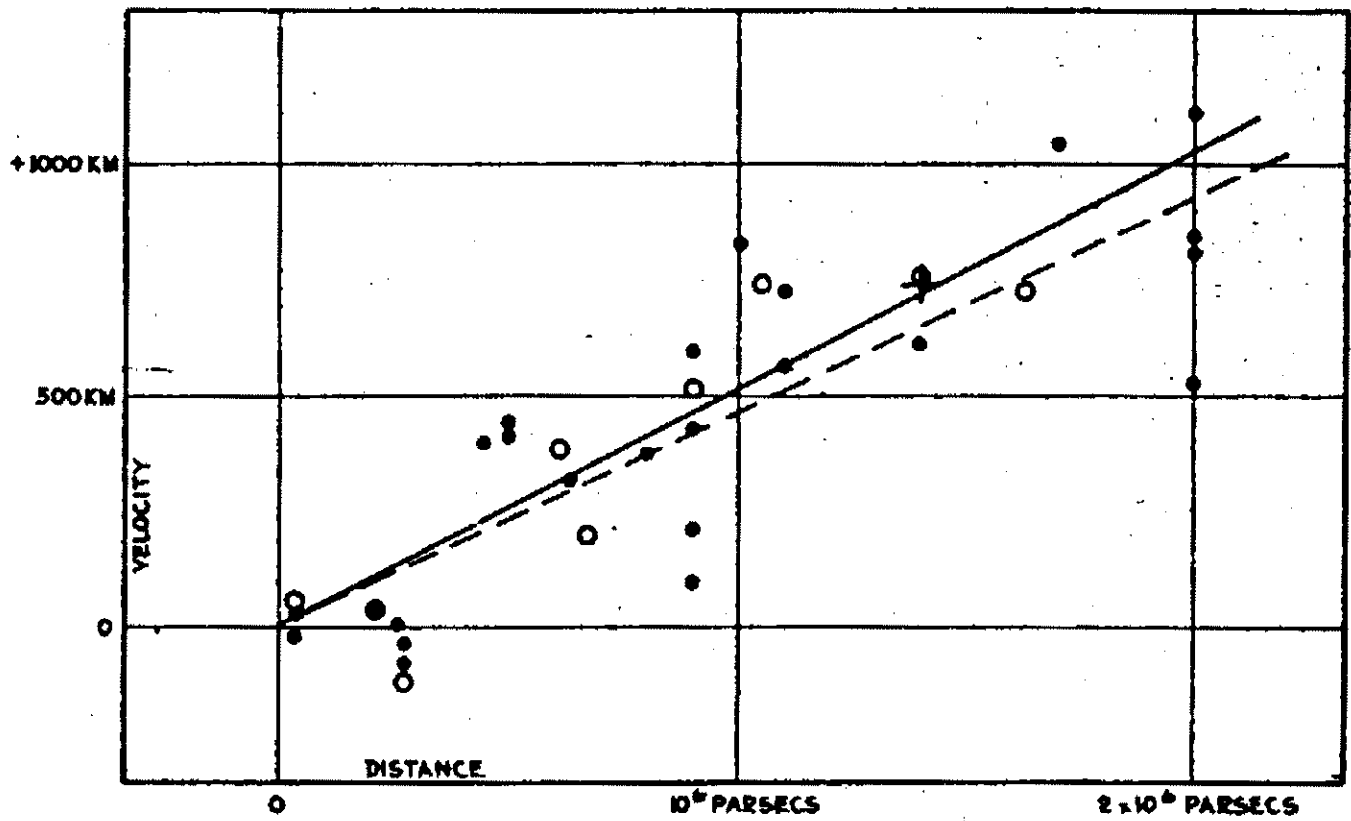


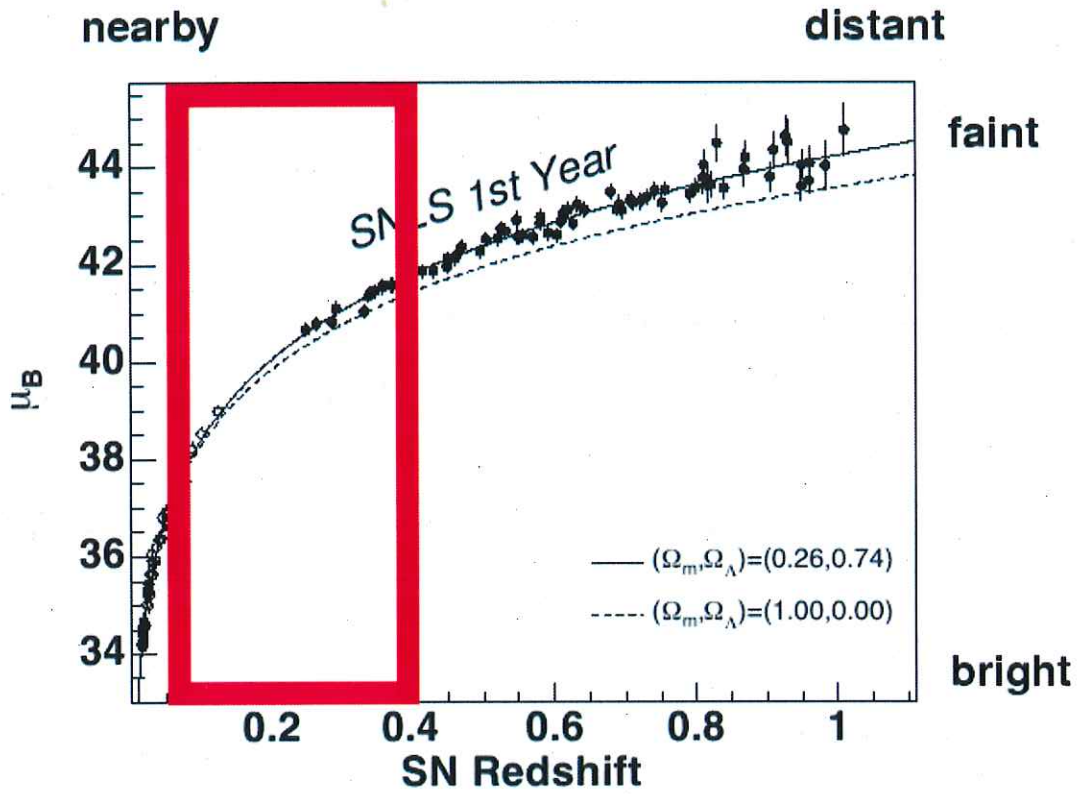
FIGURE 1

Edwin Hubble's original (1929) velocity-distance data

Estimated Hubble constant $H_0 \approx 500 \text{ km/s/Mpc}$

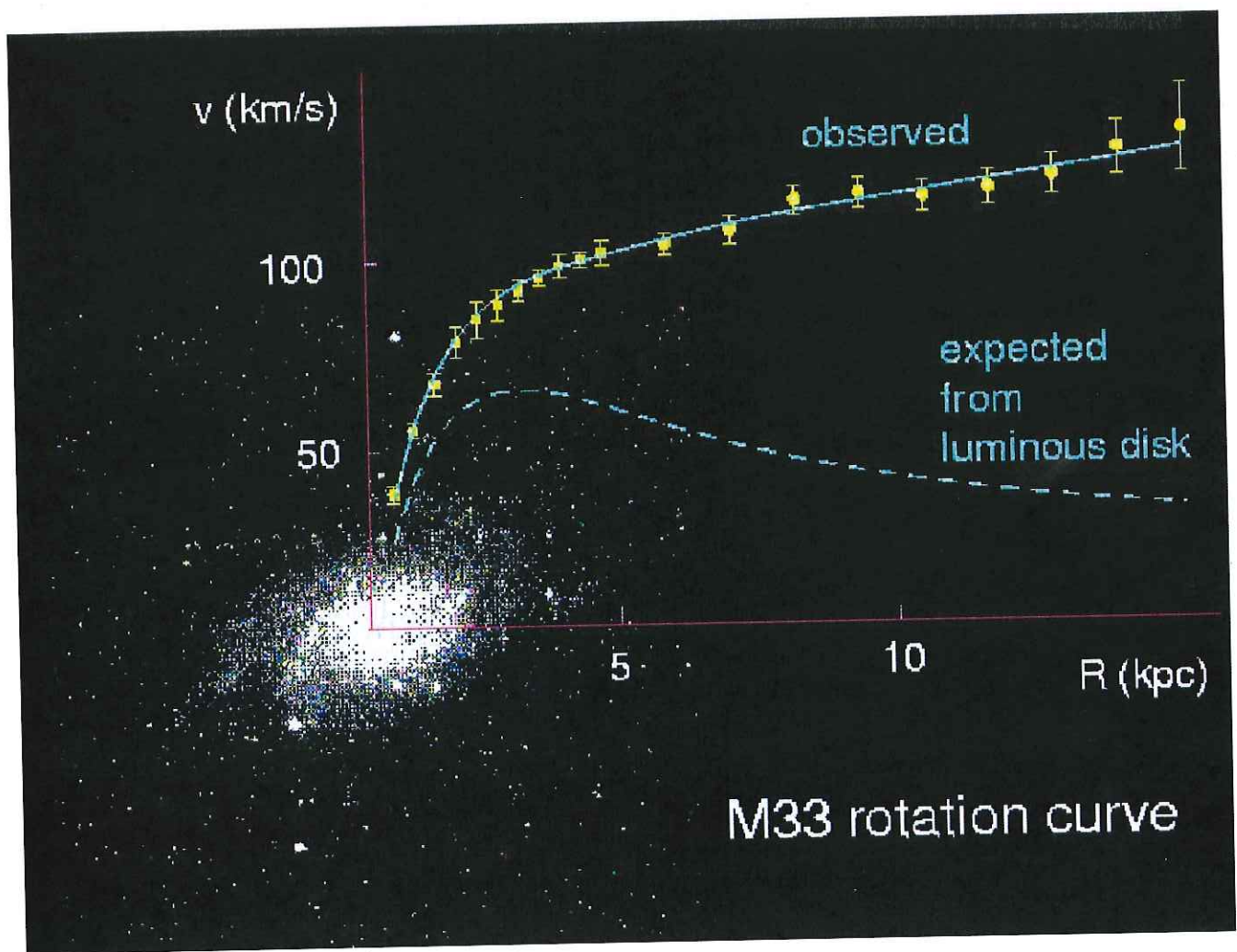
Today's measured value (WMAP 9 yr): 70 km/s/Mpc

Type Ia Supernovae



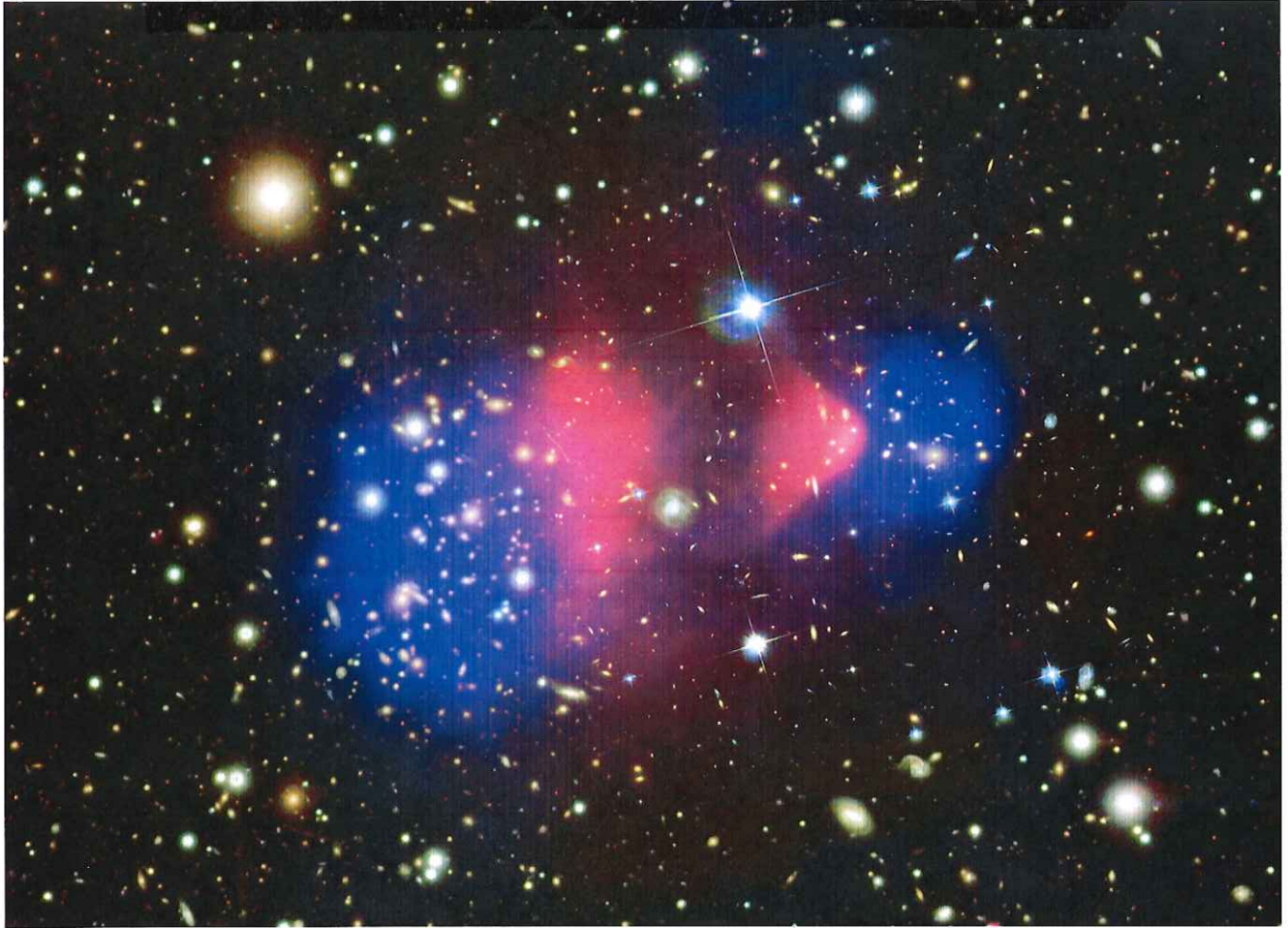
[spiff.rit.edu/richmond/sdss/sn-survey/](http://spiff.rit.edu/~richmond/sdss/sn-survey/)
sn-survey.1.htm

Galactic Rotation Curves



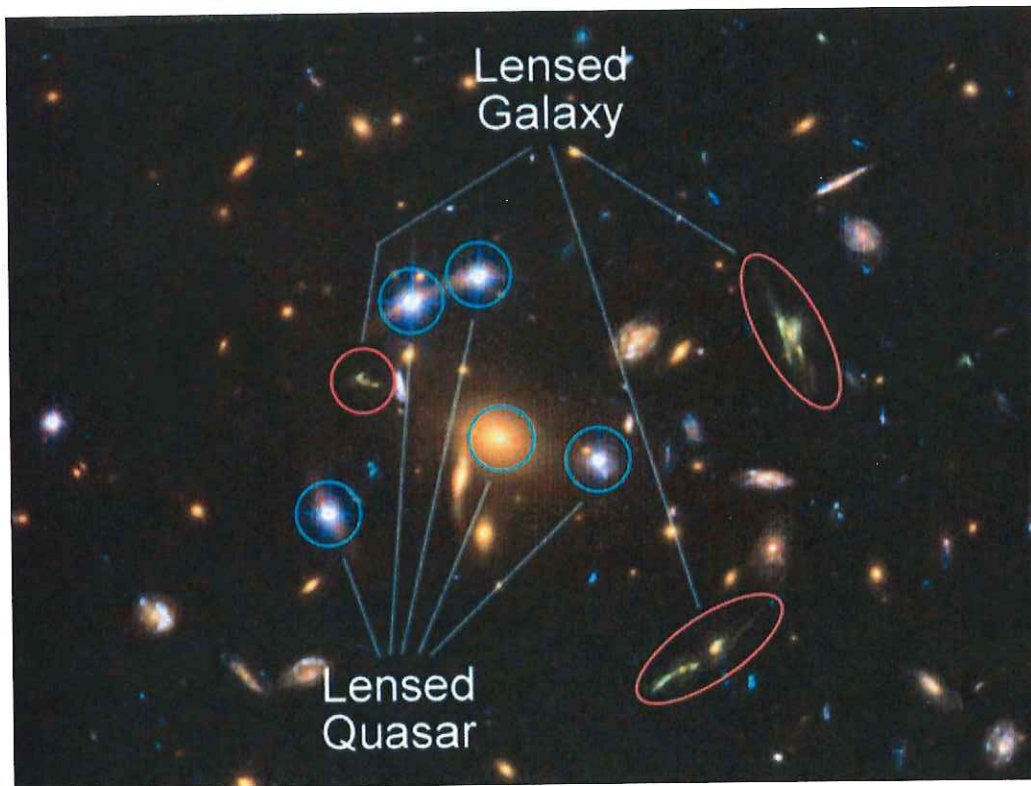
www.hep.stef.ac.uk/research/dm/intro.php

Bullet Cluster



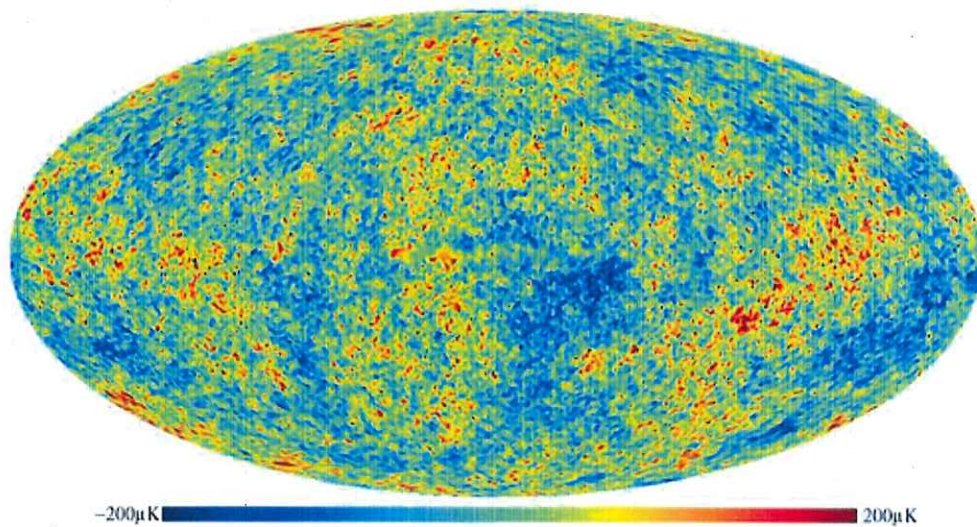
NASA

Gravitational Lensing

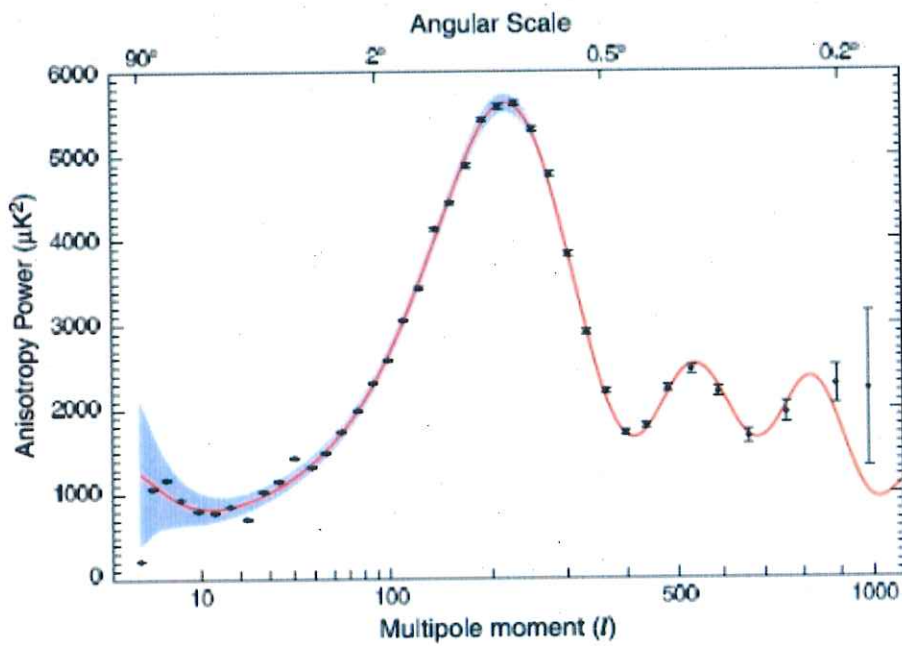


NASA

Cosmic Microwave Background



NASA/WMAP



NASA/WMAP

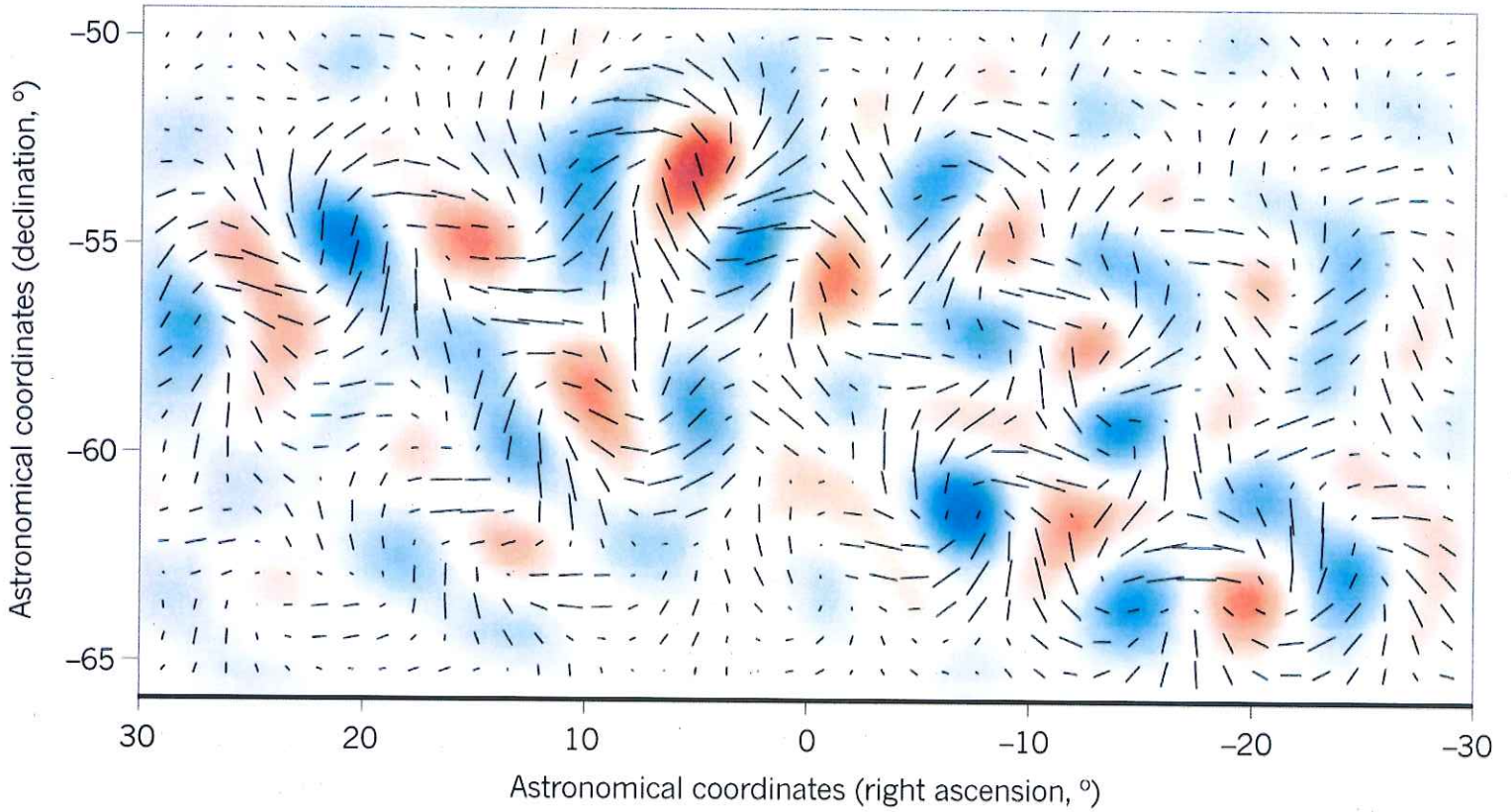
COSMIC CURL

The BICEP2 instrument observed a faint but distinctive twisting pattern, or spin, known as a curl or B-mode, in the polarization of the cosmic microwave background. This is the first evidence for gravitational waves generated by rapid inflation of the Universe some 13.8 billion years ago.

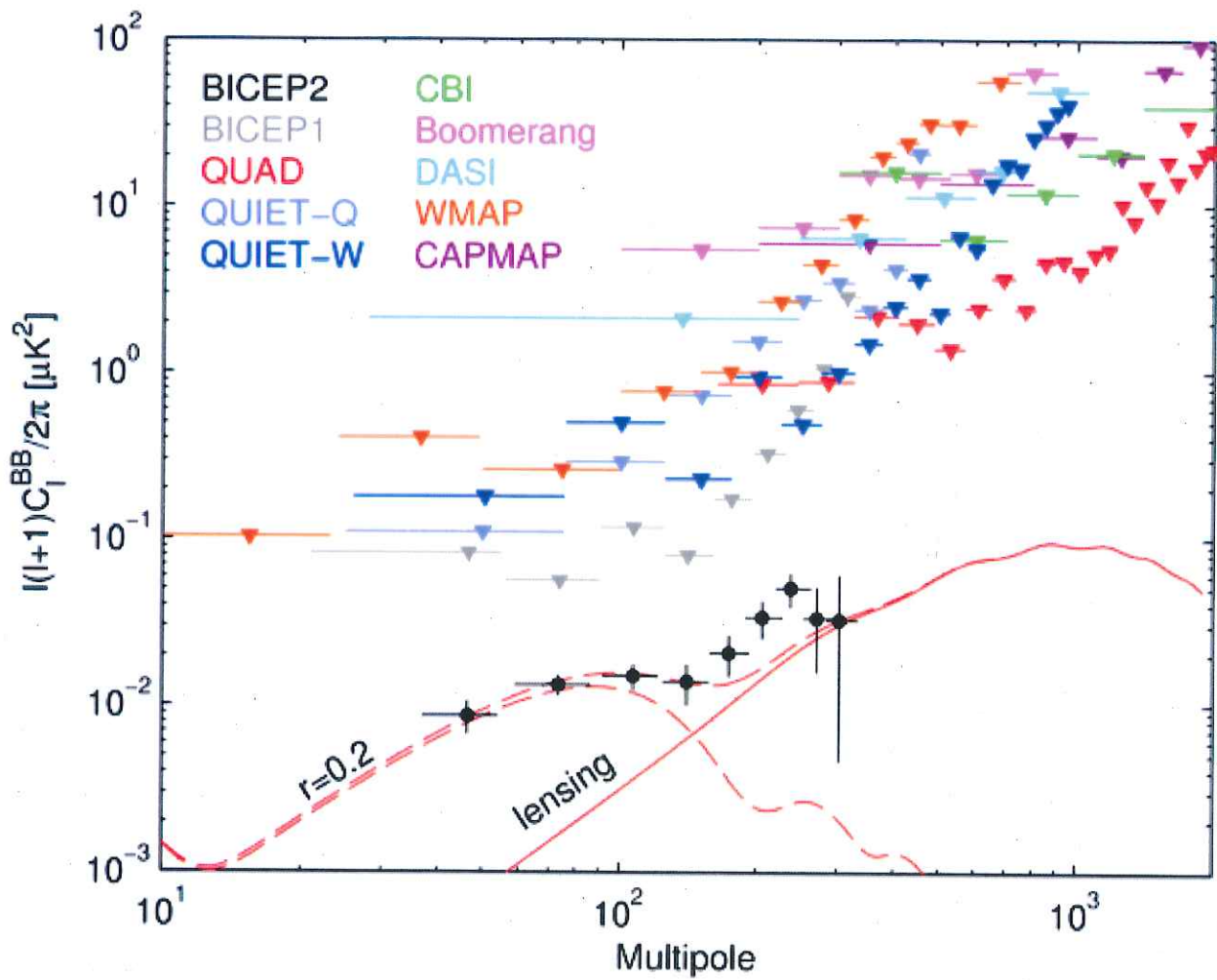
Spin intensity

■ Clockwise ■ Anti-clockwise

— Polarization strength and orientation at different spots on the sky.



From Nature



From BICEP collaboration, March 2014

B-modes in polarization of CMB
 -consistent w/ gravity waves produced during inflation