

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.

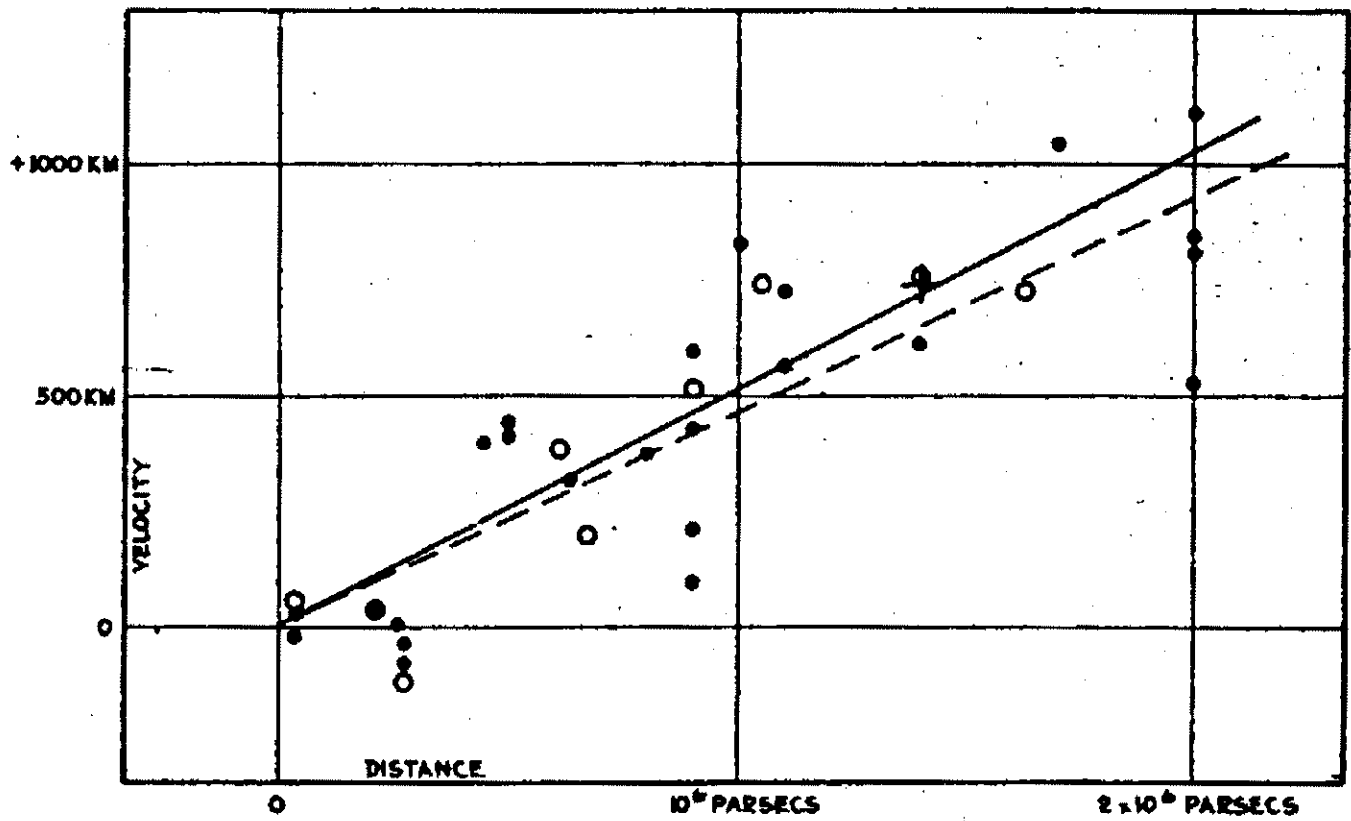


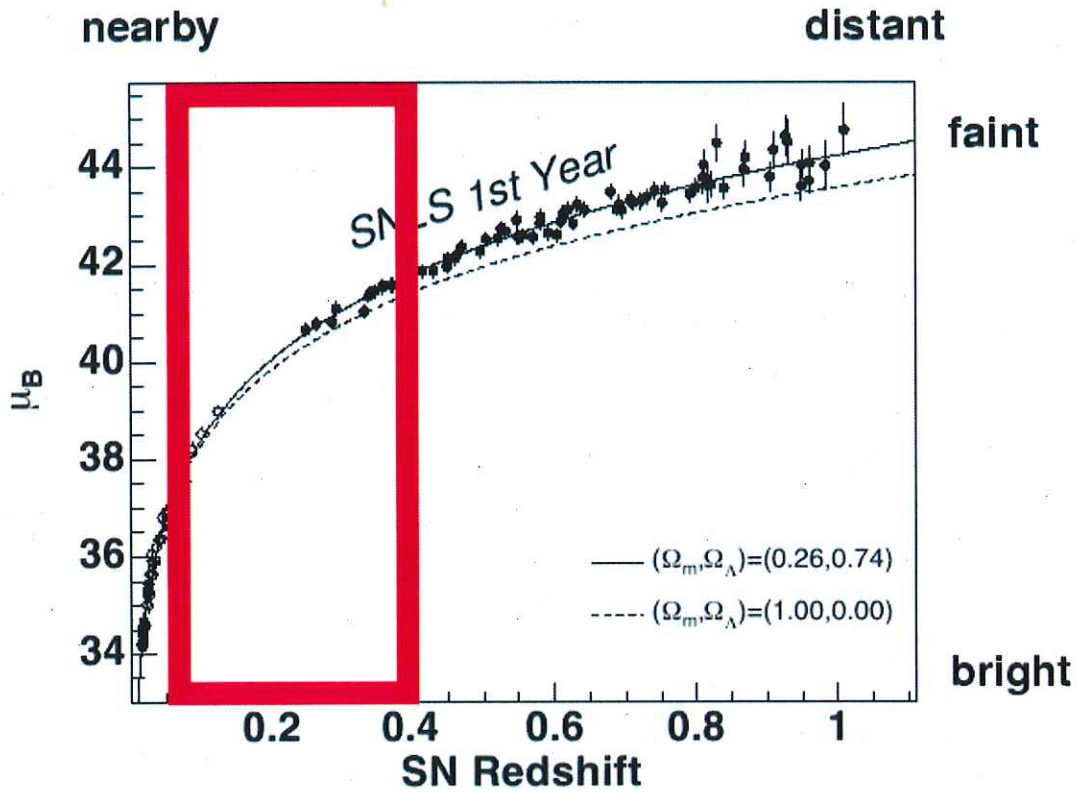
FIGURE 1

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

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

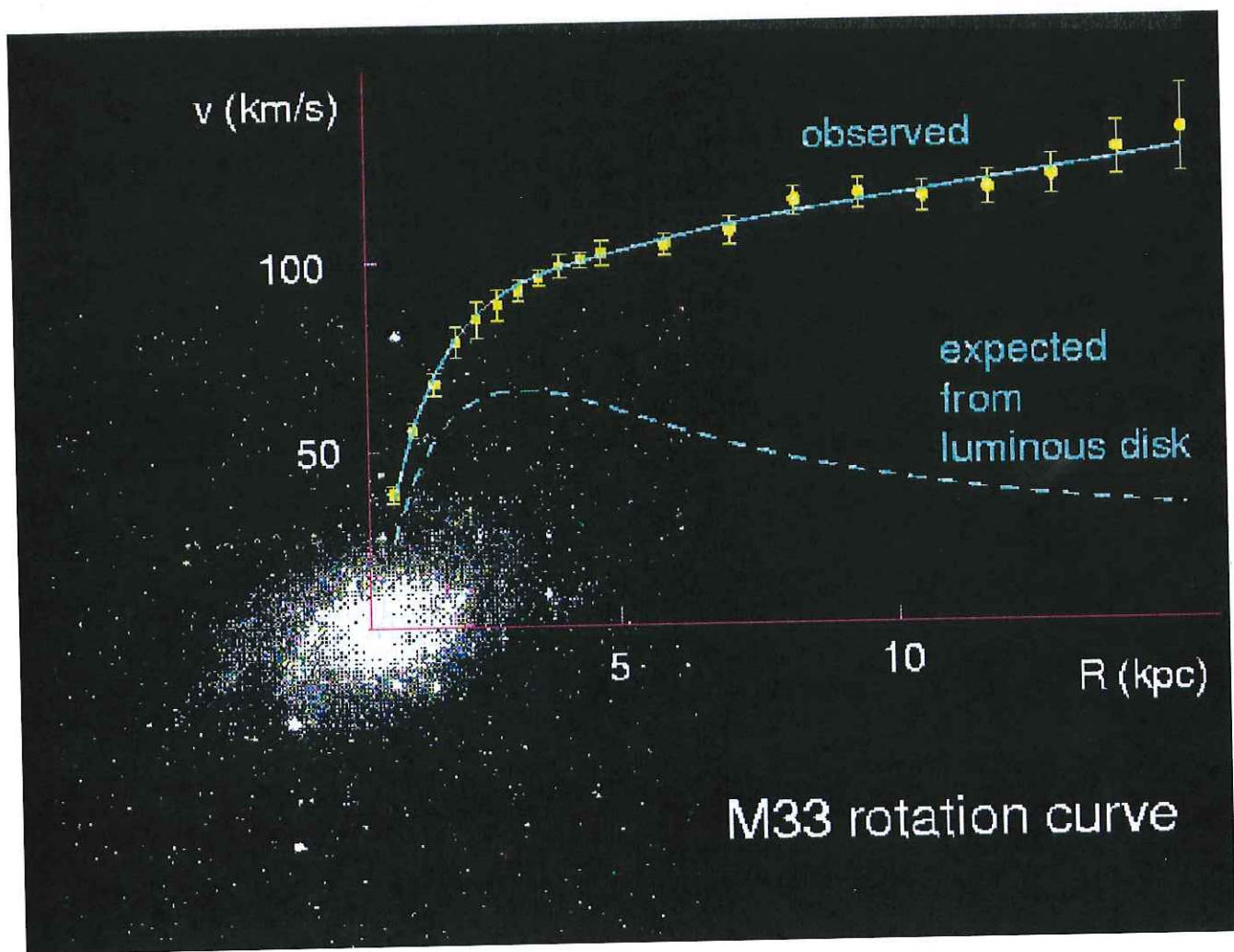
Today's measured value (WMAP 9 yr):  $70 \text{ km/s/Mpc}$

# Type Ia Supernovae



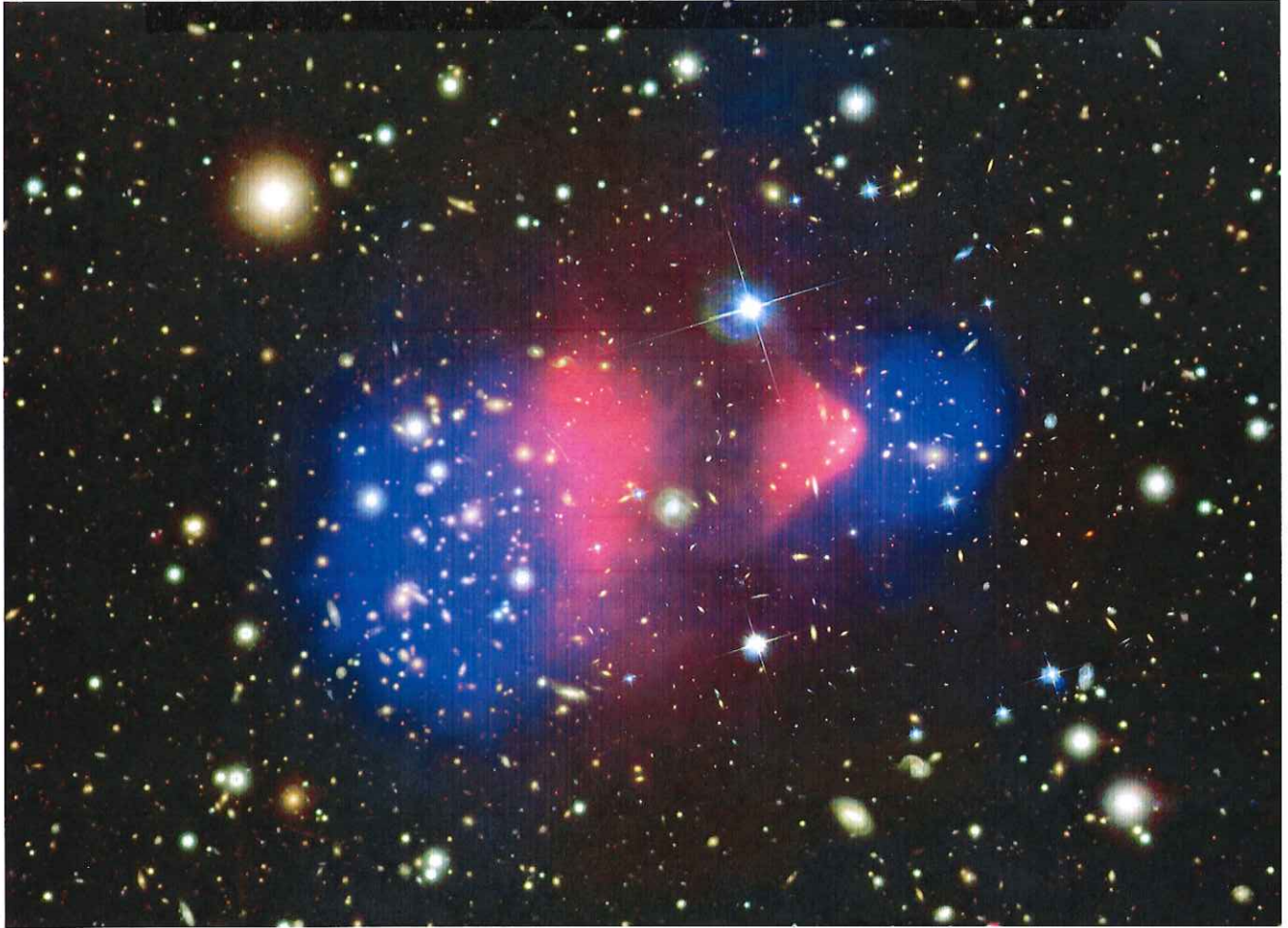
[spiff.rit.edu/richmond/sdss/sn-survey/](http://spiff.rit.edu/~richmond/sdss/sn-survey/)  
sn-survey.1.htm

# Galactic Rotation Curves



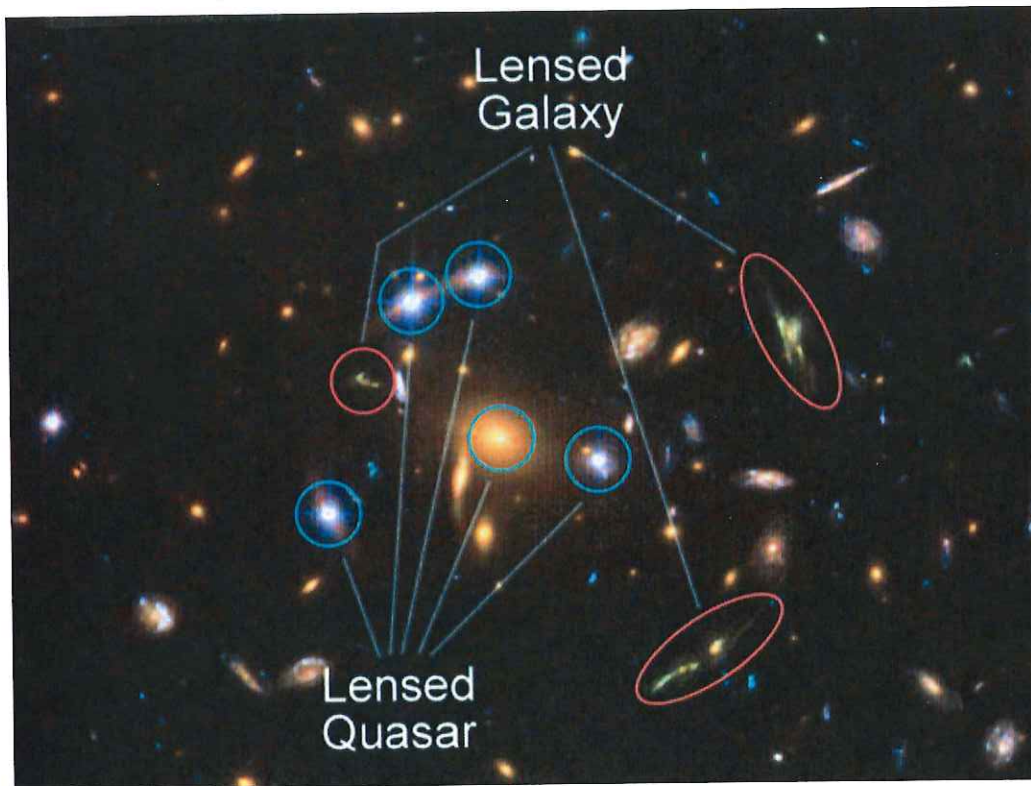
[www.hep.stef.ac.uk/research/dm/intro.php](http://www.hep.stef.ac.uk/research/dm/intro.php)

Bullet Cluster



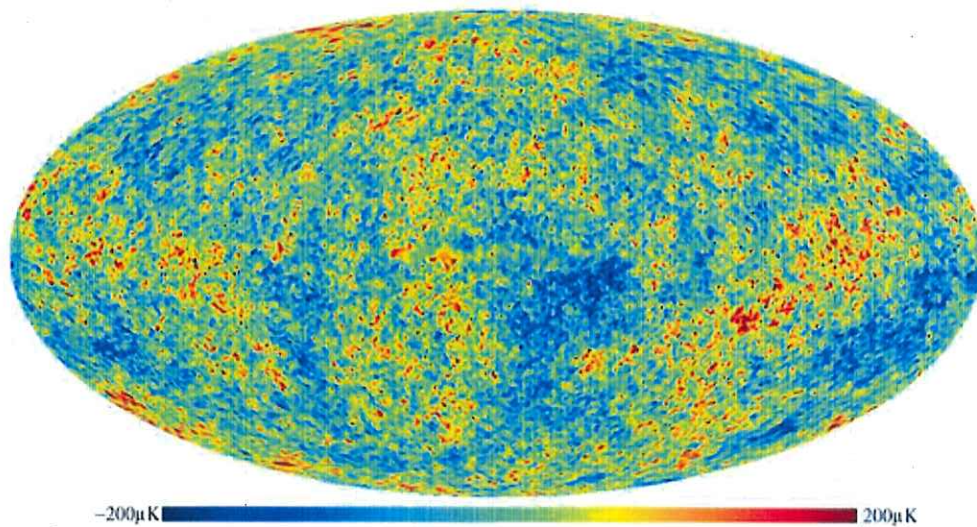
NASA

# Gravitational Lensing

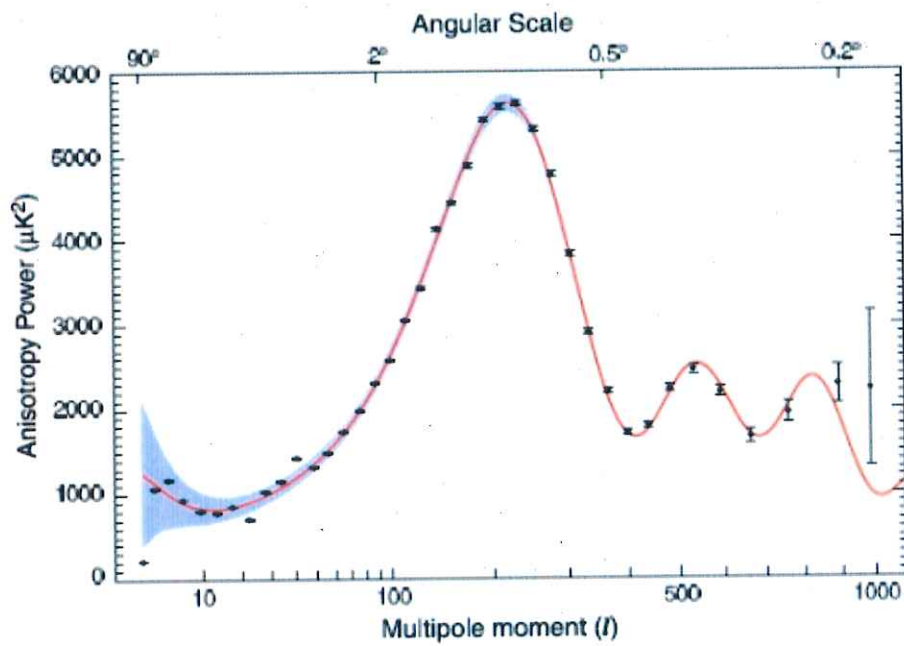


NASA

# Cosmic Microwave Background



NASA/WMAP



NASA/WMAP

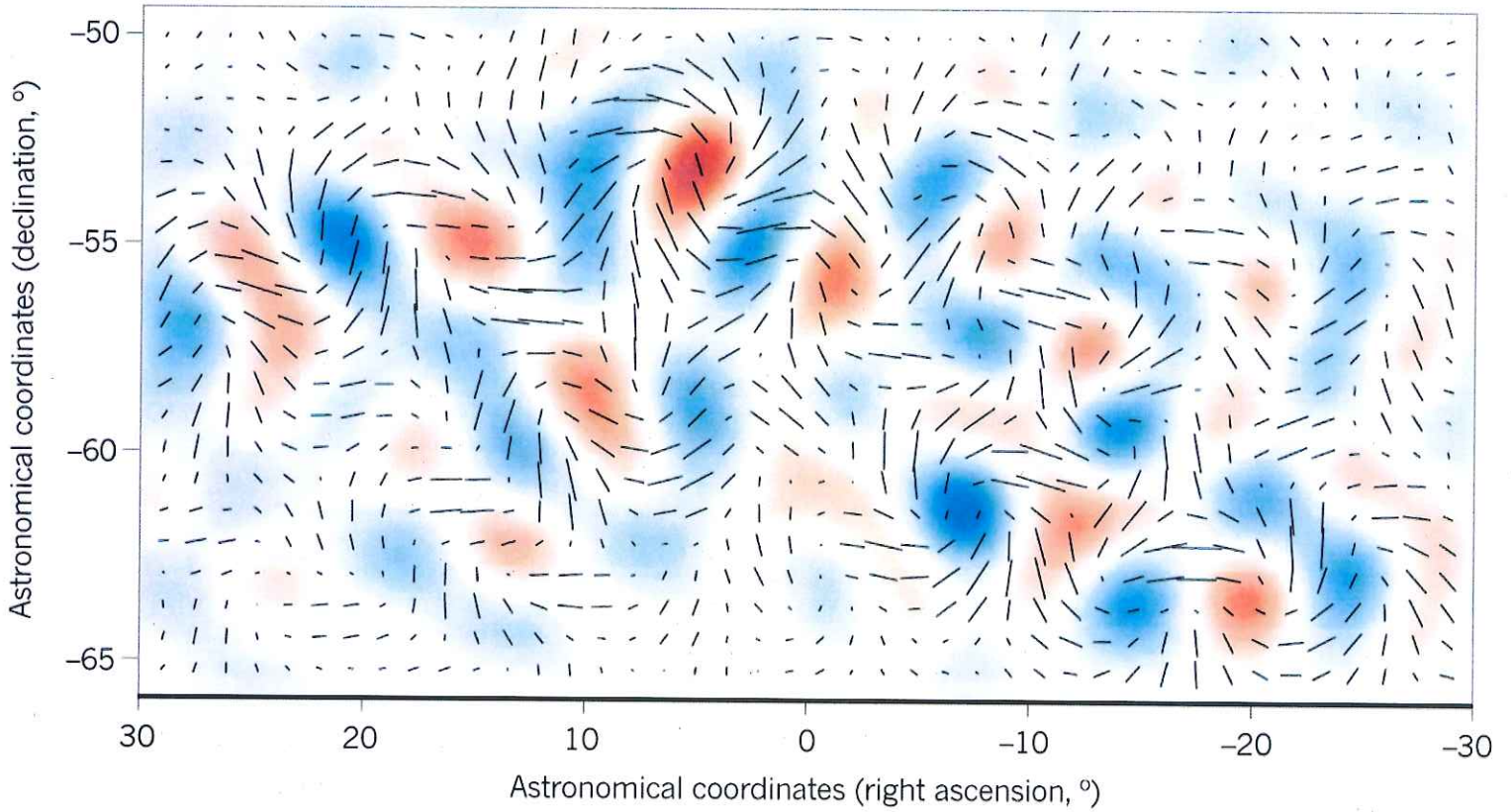
# COSMIC CURL

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

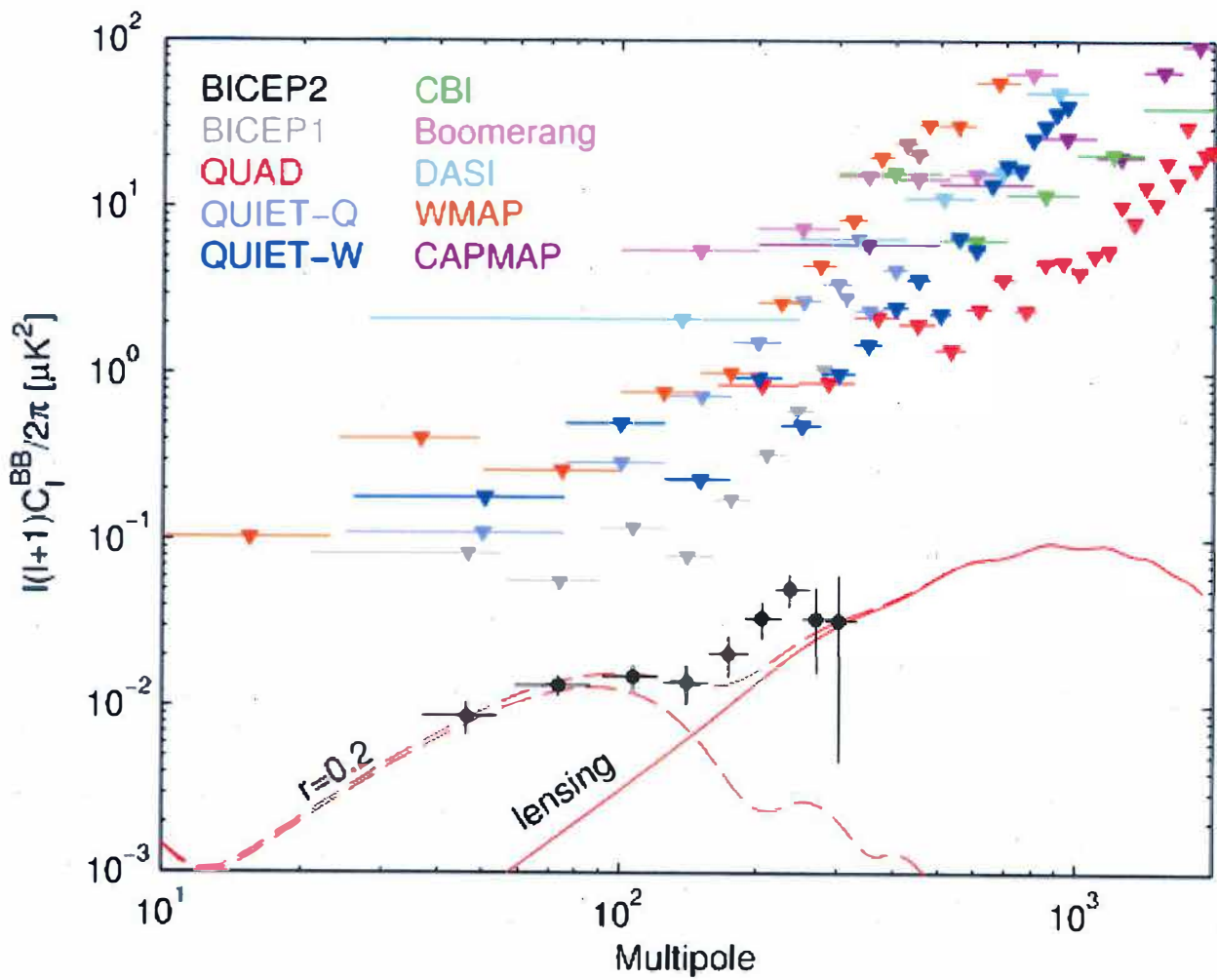
■ Clockwise ■ Anti-clockwise

— 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

Update: B modes observation consistent with polarization due to scattering of CMB off of dust in the Milky Way. (Planck+Keck+BICEP2, March 2014 - January 2015)