BICEP2 – the path to gravitational waves

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***Cosmology* – deals with the Universe as a whole (its roots, physical processes which underwent during its evolution, its construction and content, its future).**

Cosmological theories are scientific which means that they can be verified by experiment (astronomical observations and particle experiments in accelerators)

Big-Bang theory – based on Einstein general relativity

Energy density and *pressure* *formally infinite!*

The whole content of the universe was squeezed and started to expand about 13.8 Gy ago.

We measure the **expansion** of the universe by Doppler effect in galaxies spectra
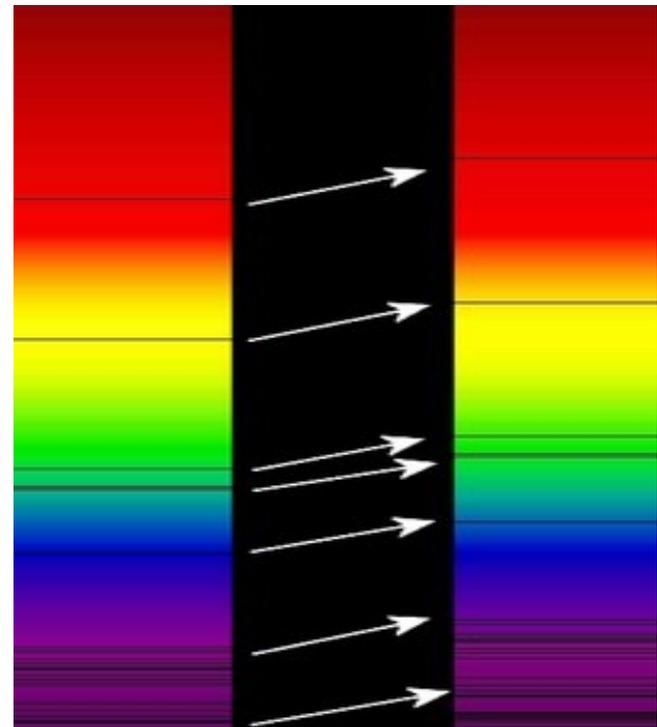
Hubble law (1928) -
galaxies *escape* from each other;
Perlmutter at al. (1999), Riess et al. (1999)
– Nobel 2011 -
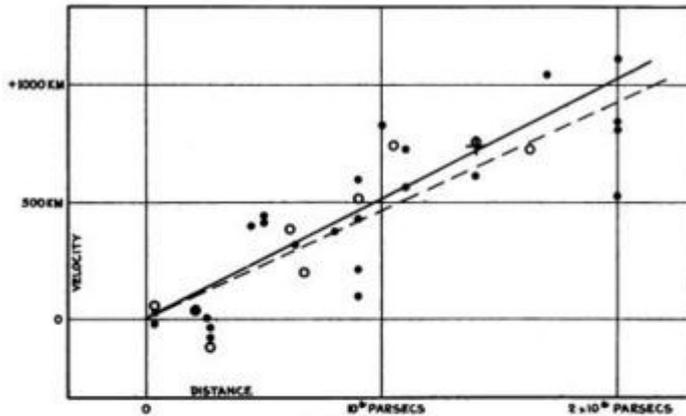# they escape faster and faster (*accelerate*)

FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and mean luminosities of nebulae in a cluster. The black discs and full line represent the solution for solar motion using the nebulae individually; the circles and broken line represent the solution combining the nebulae into groups; the cross represents the mean velocity corresponding to the mean distance of 22 nebulae whose distances could not be estimated individually.

$$H_0 = cz / D$$

Hot Big-Bang theory – based on successes of particle physics

Three relics of the early universe:

- gravitational wave background ($t=10^{-35}$ s)
- cosmic neutrino background CvB ($t=1s$; $T=1.95$ K)
- cosmic microwave background CMB ($t=380.000$ years, $T=2.7$ K)

Cosmic Microwave Background - the only relict which was detected so far – it proved the existence of a ``dense soup'' of protons, electrons and photons until

380.000 years after Big-Bang

when

protons and electrons formed atoms while CMB radiation decoupled and now fills in the universe almost uniformly.

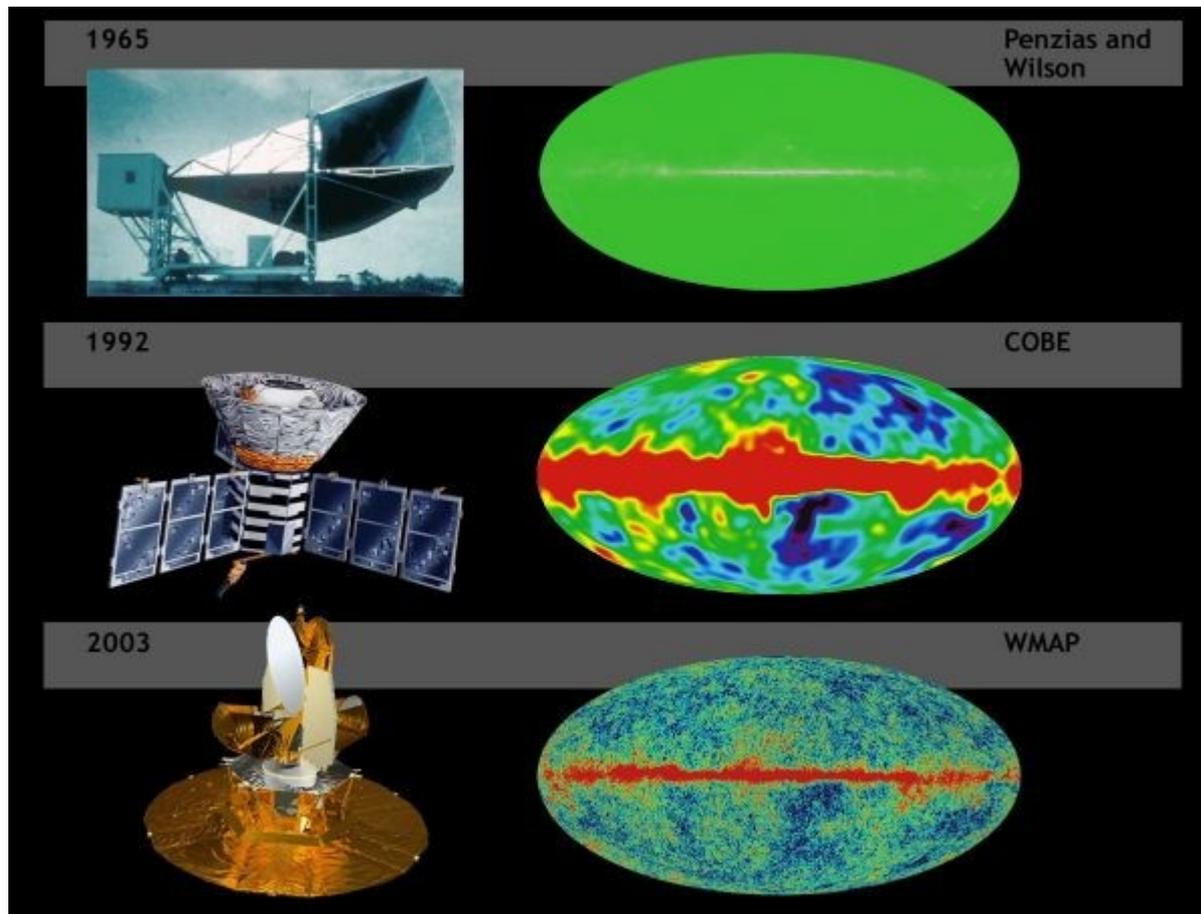**A.Penzias and R.Wilson** 1965 (Nobel 1978)
proved **existence** of CMB
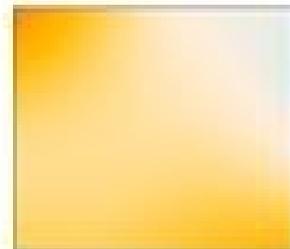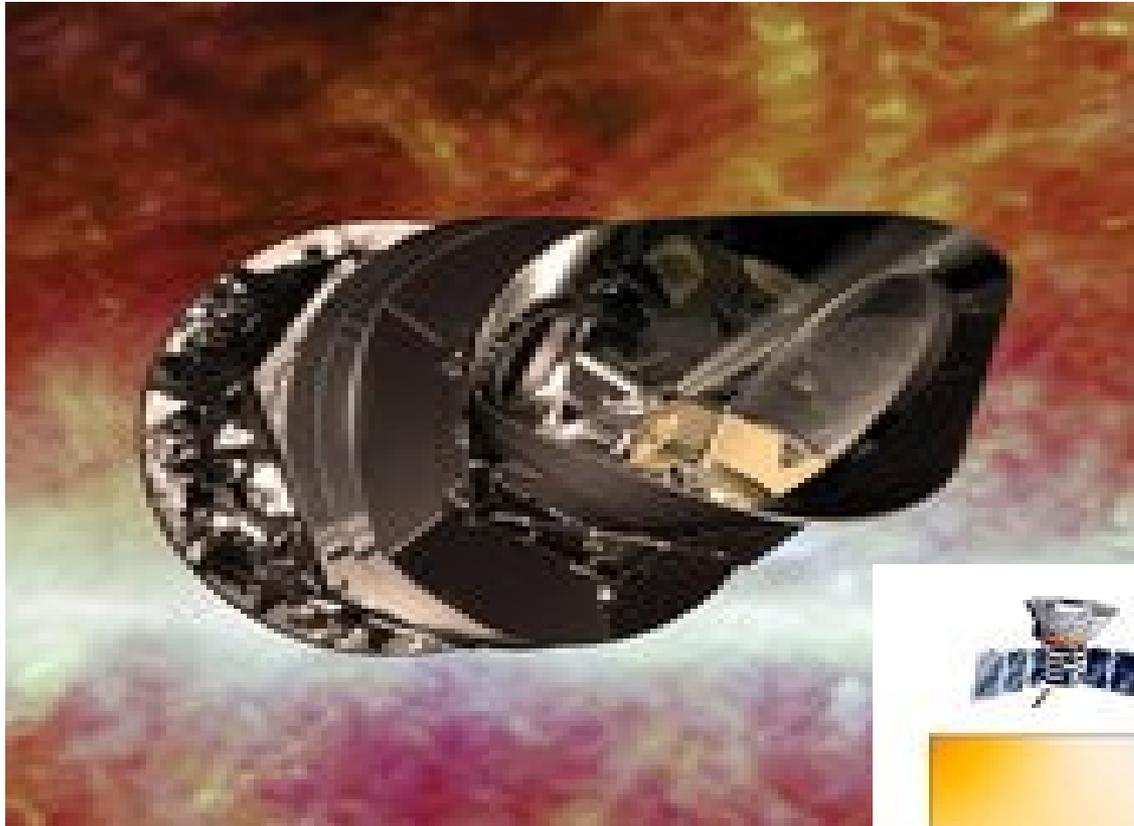**J.Mather and G.Smoot** '92-'03 (Nobel 2006)
proved that CMB had imprinted **fluctuations**
from inflationary era just after Big-Bang which
further developed to matter condensates -
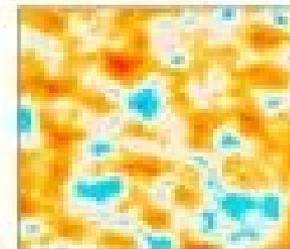galaxies
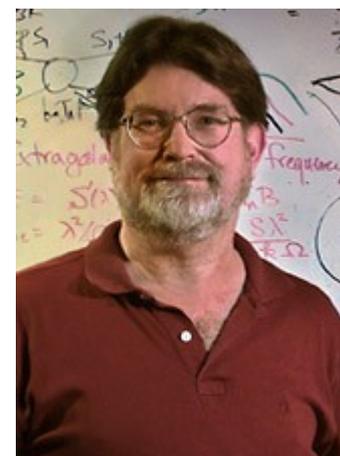
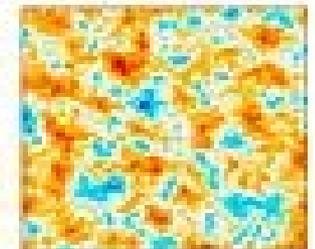# Penzias/Wilson antenna and COBE/WMAP satellites

Planck satellite (current) – better resolution

COBE   WMAP   Planck

Determination of cosmic parameters by Planck (03/13)

Age of the universe: $t = 13.82$ **Gy**

Hubble parameter: **67.11 km/s Mpc**

Spectral index: $n\_s = 0.9624$

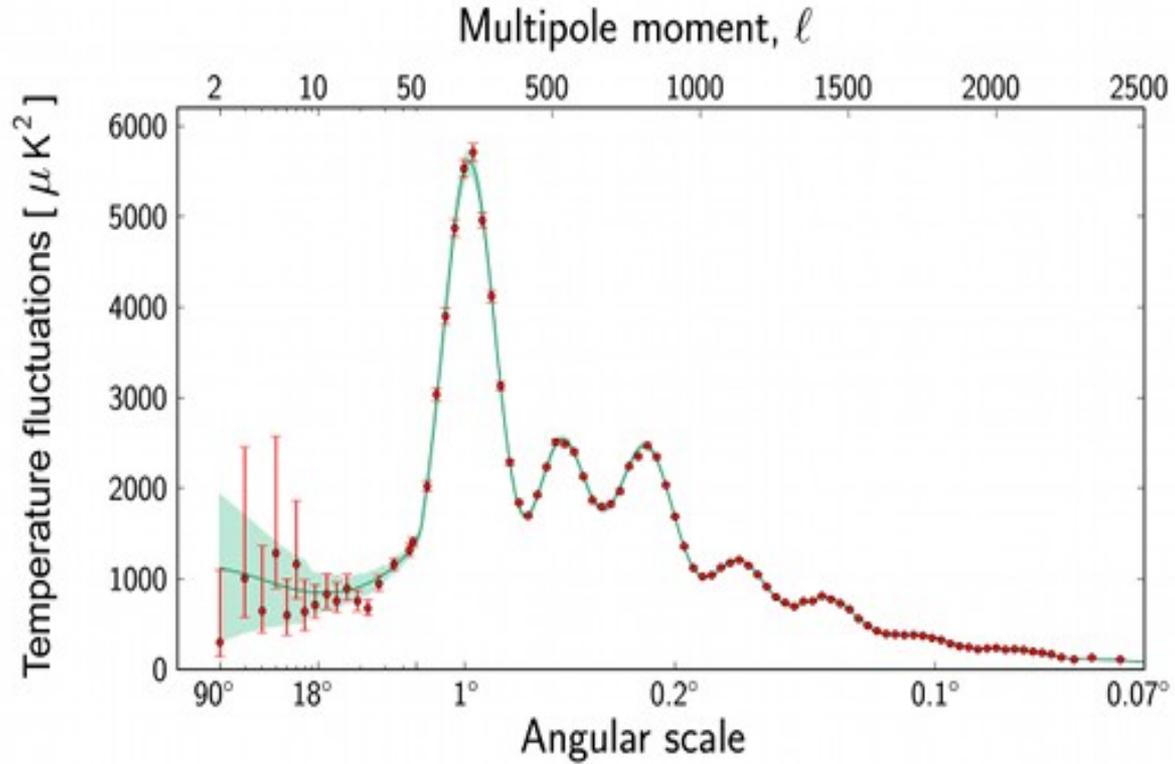**Dark energy density:** $\Omega\_\Lambda = 0.6825$

Baryon density: $\Omega\_B\ h^2 = 0.022$

Cold dark matter density: $\Omega\_c\ h^2 = 0.12$

CMB temperature anisotropies: $\Delta T/T = 10^{-5}$

Ratio of tensor-to-scalar mode: $r < 0.11$ (95% CL)

Power spectrum of perturbations

How about gravitational waves? What are they?

Space is an elastic medium which can sustain waves.

Einstein equations:
(matter) T = (c⁴/8 πG) E (geometry)

Hooke's law:
F = k x

(c⁴/G) ≈ 10⁴³ (extremely rigid)

Dimensionless amplitude of a wave:

h = (time-dependent part of the potential)/c²

Fully relativistic picture (Einstein) - h is a tensor

$$g^{\mu\nu} = \eta^{\mu\nu} + h^{\mu\nu}, |h^{\mu\nu}| << 1$$

- traceless, symmetric, transverse,
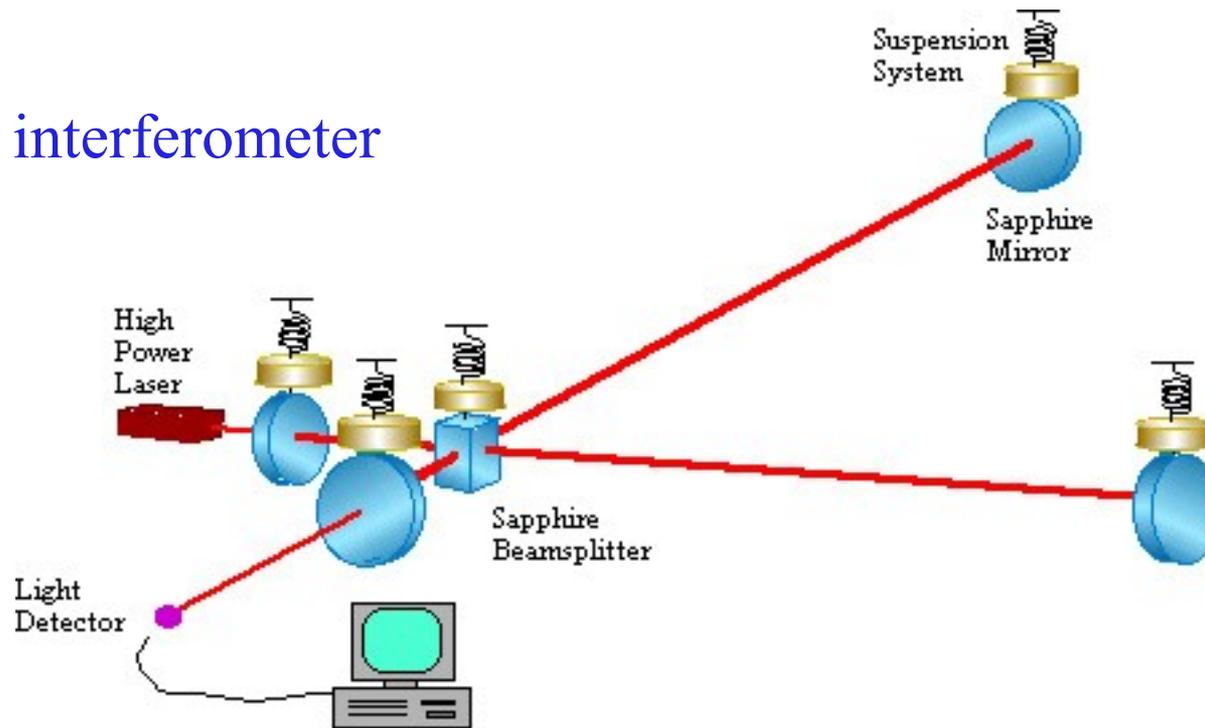
2 independent polarization states h_+ and h_x

- h is always tiny: one measures the extension of the arm of a detector

(e.g. $\approx 10^{-21}$ for 10 Mpc supernovae)

h_+ and h_x polarizations

Laser interferometer

Operating detector (LIGO - Laser Interferometer Gravitational-wave Observatory)

Other Earth-based detectors:
GEO600 (Hannover)
VIRGO (Pisa, Italy)
TAMA (Tokyo)

Space borne detectors (planned):
LISA (Laser Interferometer Satellite Antenna)
DECIGO (DECI-hertz Gravitational wave Observatory)
BBO – Big-Bang Observer
LISA-pathfinder

Key point – gravitational radiation is of quadrupole nature

$$\text{Monopole} = \int \rho \, d^3y = \text{source mass} = \text{const.}$$

$$\text{Dipole} = \int \rho \, V_i \, d^3y = p_i = \text{const.}$$

(momentum of a source is conserved)

$$\text{Quadrupole} = \int \frac{d^2}{dt^2}(\rho) y_i y_j \, d^3y = \frac{d^2}{dt^2}(I_{ij})$$

(Second derivative of a quadrupole moment)

Does CMB has anything to do with gravitational waves?

According to Einstein relativity inflation generated three types of density perturbations: *scalar, vector, and tensor (gravity waves)*

CMB polarization vector can be split onto an electric E-mode and a magnetic B-mode.
According to Poincare lemma:
E is *irrotational* (rot E = 0);
B is *sourceless* (div B = 0)

Scalar perturbations: mainly E-modes
Vector perturbations: mainly B-modes
(hint: we doubt in early universe rotation)
Tensor perturbations: E-modes and B-modes
(analogous tensor split according to Poincare)
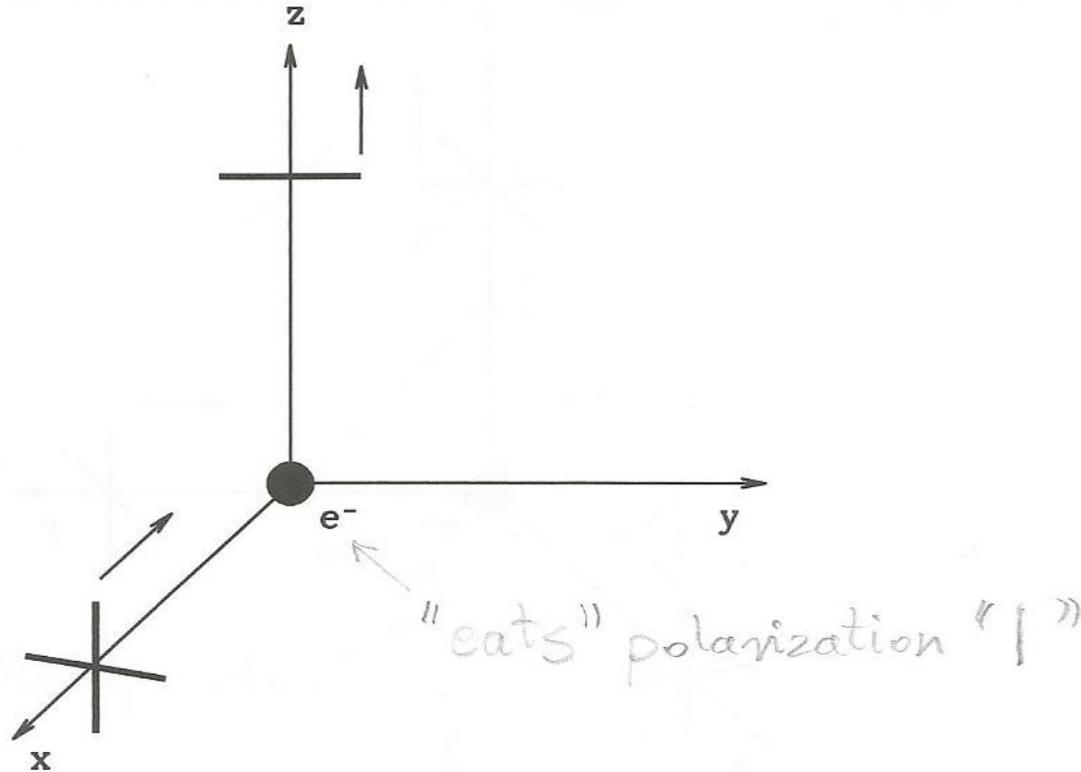*(hint: E-modes also due to scalar perturbations while*

B-modes unique for tensor perturbations which were imprinted into CMB by primordial gravitational background!!!)
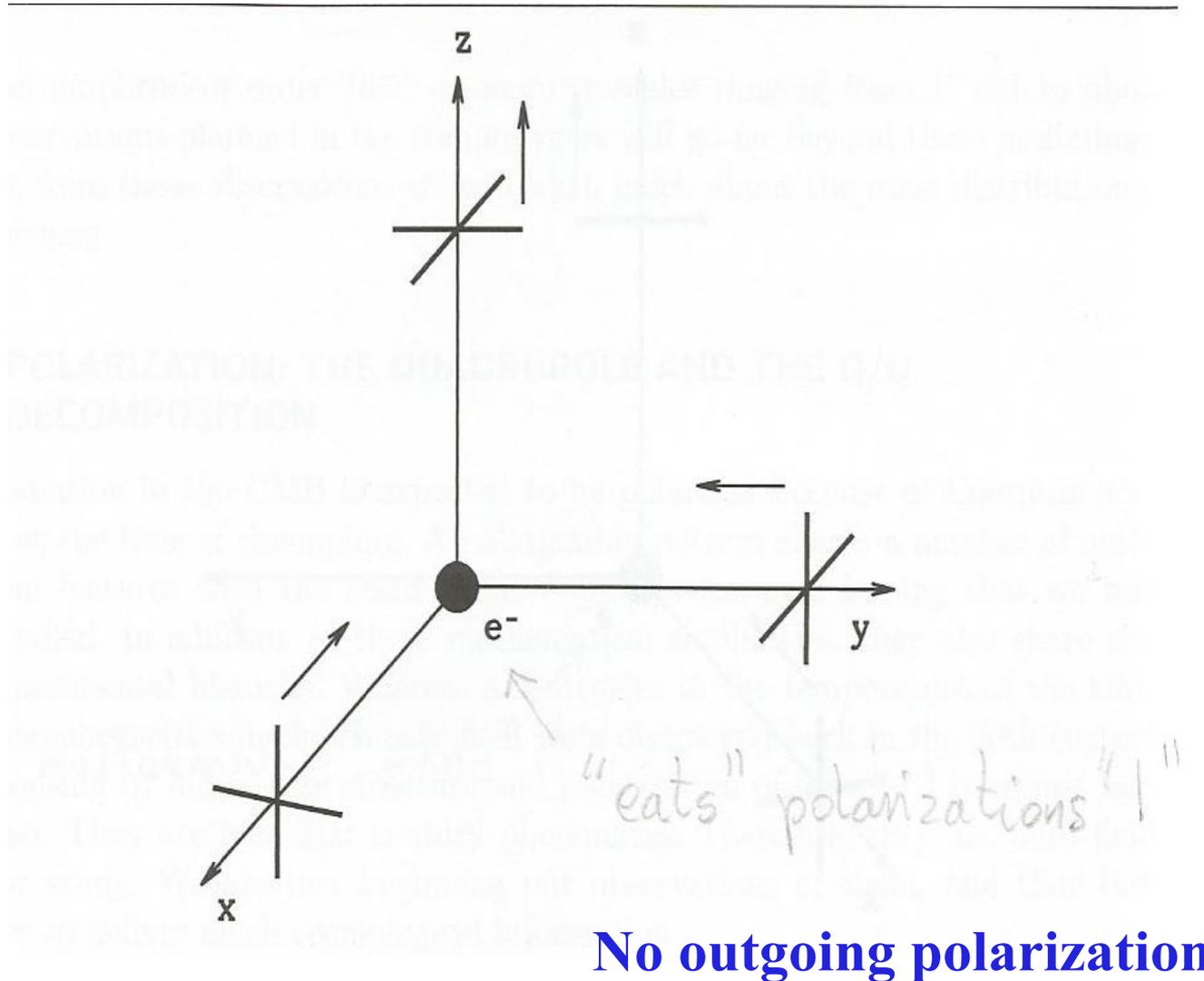
The mechanism – Thompson scaterring
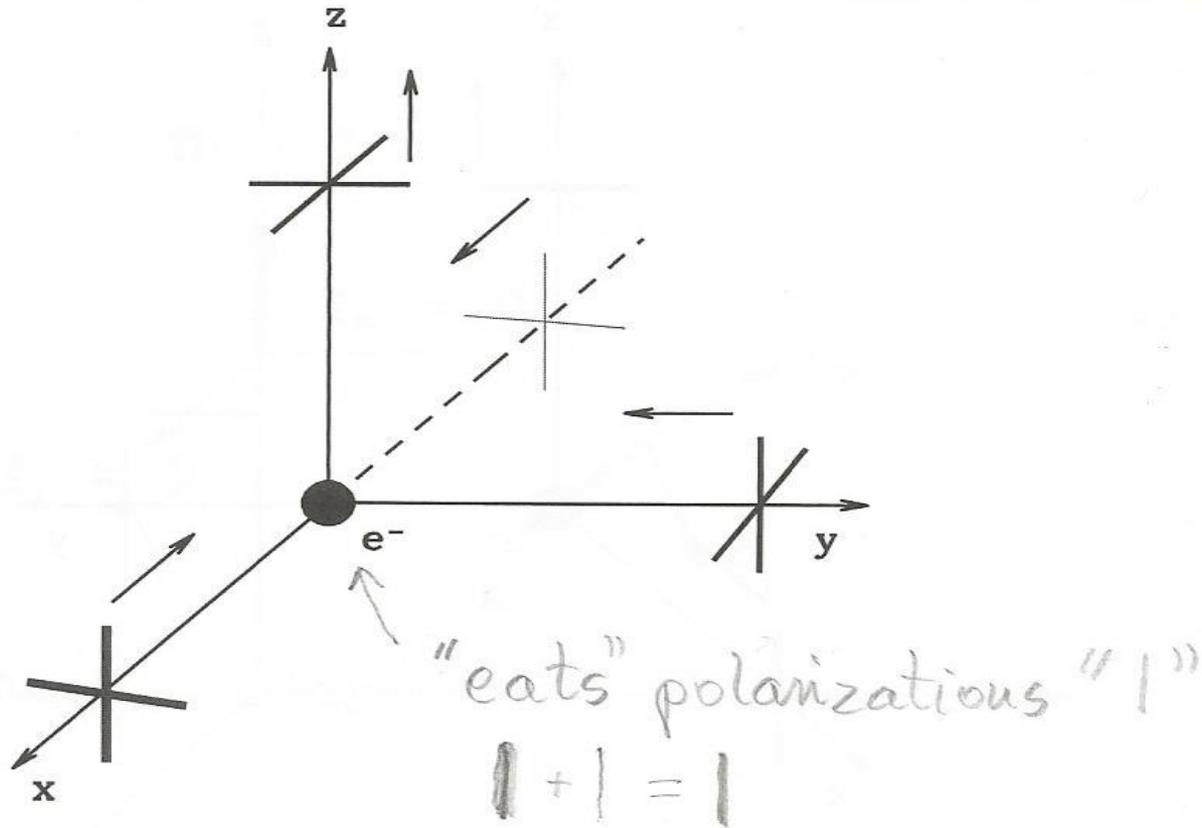
Unpolarized photon scattered into z-direction

Outgoing polarized photon

Incoming isotropic photons scattered into z-direction
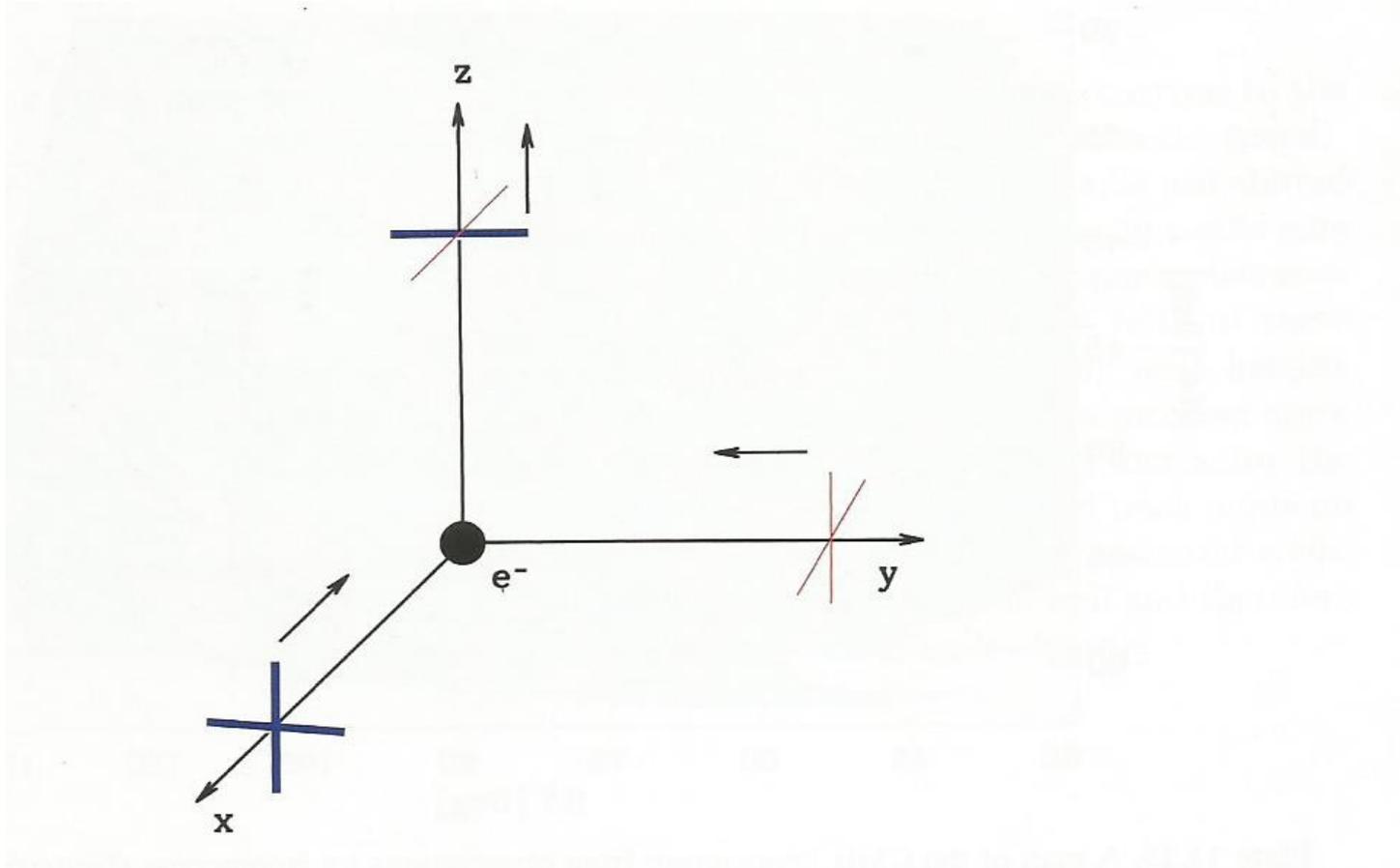

No outgoing polarization

Incoming dipole photons scattered into z-direction

No outgoing polarization

Incoming **quadrupole** photons scattered into z-direction

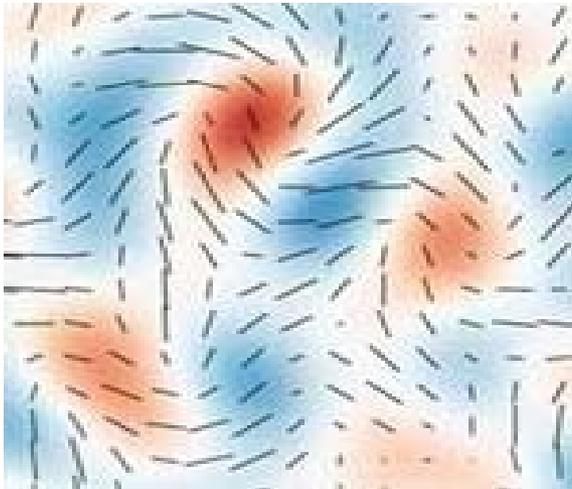**Outgoing polarized photons**

# Background Imaging of Cosmic Extragalactic Polarization (BICEP2)

The claim of 17.03.2014 by John Kovac from Harvard-Smithsonian Center for Astrophysics

``*We found a B-mode pattern r = 0.20 (+0.07; - 0.05) and the data excludes r = 0 at 7σ* ''

Radiation 150 GHz; degree scale 380 square degrees;
Multipole range from l=20 to l=340
(B-mode peak at l=80; E-mode peak at l=1000)

Below: 50 < l < 120; red and blue – twists of polarization in
opposite directions; signal 1 part per 10 million of CMB
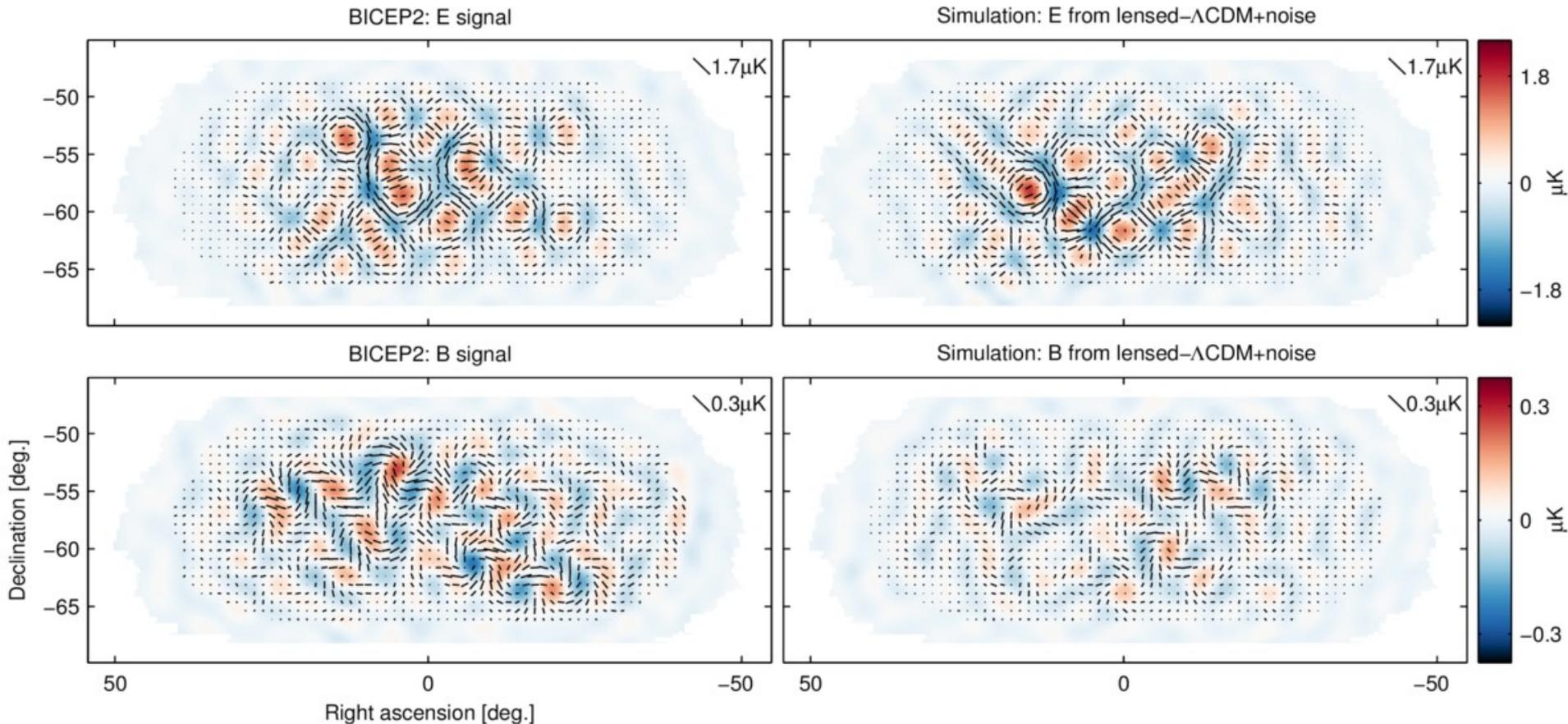
Criticisms/Flaws:

Raphael Flauger from Princeton University on 15th of May: *"light scaterring from dust and the synchrotron radiation generated by electrons moving around galactic magnetic fields within our own galaxy can also produce the B-mode"* - *an artifact of dust in our galaxy which was not taken into account by BICEP2 people.*

Problem: claims were made in support to inflationary universe (e.g. Guth, Linde)

Paul Steinhardt (Nature, 510, 9 (5 June 2014)):

"announcement influenced decisions about academic appointments and the rejections of papers and grants"

Flauger: "I am still hoping that after all I have done, there is a signal there"

Curious reply from supporters of inflation: "inflation is equally valid whether or not gravity waves are detected"

Steinhard then concludes: "inflationary theory is so flexible that it is immune to experimental and observational tests – so it is unfalsifiable" (however, Steinhardt supports concurrent cyclic universes based on superstring theory)

Good motto (for young people):

"Science is freedom"

References:

Mateusz Lisaj, Polarization of the microwave background as a signal from gravity waves, M.Sc. thesis (Szczecin, 2010)

Scott Dodelson, Modern Cosmology, Academic Press (2003)

Bernard Schutz, Gravitational waves on the back of an envelope, Am. J. Phys. 52 (5), 412 (1994)

P.A.R. Ade et al. (BICEP2 Collaboration) - ArXiv: 1403.3985

R. Flauger, J.C. Hill, and D.N. Spergel – ArXiv: 1405.7351

A. Cho, Blockbuster claim could collapse in a cloud of dust; Science 344, 790, 23 May 2014

Conclusions:

As you like!

Thanks for your attention!