TRR33: THE DARK UNIVERSE

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1. INTRODUCTION

In the standard cosmological model, normal baryonic matter contributes only roughly 5% to the overall density of our universe, the rest being in the form of dark matter (27%) and dark energy (68%).

Whereas dark matter has already been postulated by **Zwicky** in 1933, the existence and dominance of dark energy was unexpected and raised fundamental questions such as the range of validity of **Einstein's gravity**, the role of extra dimensions, the existence of new forces, the nature of vacuum, the relation to the inflationary field and to the particle physics models.

Our transregional research center 'The Dark Universe' (2006-2018) investigates these topics and in particular, the dark energy responsible for the accelerated expansion of the Universe by means of theoretical approaches, observations, and numerical simulations.
An overview of the 18 different projects within the transregio in the third funding period 7/2014-6/2018 can be found on the website

http://darkuniverse.uni-hd.de

2. SUPERNOVA Ia OBSERVATIONS

The 2011 Nobel Prize in Physics has been awarded “For the discovery of the accelerating expansion of the Universe through observations of distant supernovae“. The observations were first published in 1998. They have been made using supernovae of the type Ia in remote galaxies (see Figs.1-3), which may be used as standard candles and hence provide accurate distance and velocity measurements.

Although the statistical and, in particular, the systematic uncertainties of this observation are still significant and call for improvement through future measurements, there is a number of additional observations that corroborate the discovery.

The accelerated expansion is attributed to dark energy, which counteracts the attractive gravitational interaction. Dark energy may correspond to a cosmological term in Einstein‘s field equations: This approach yields agreement with abundant cosmological observations but does not answer the question of its physical origin since an estimate based on the vacuum energy does not give the correct order of magnitude.
Dark energy may also be related to a scalar field and vary with time, which would have great importance for astrophysics and cosmology.

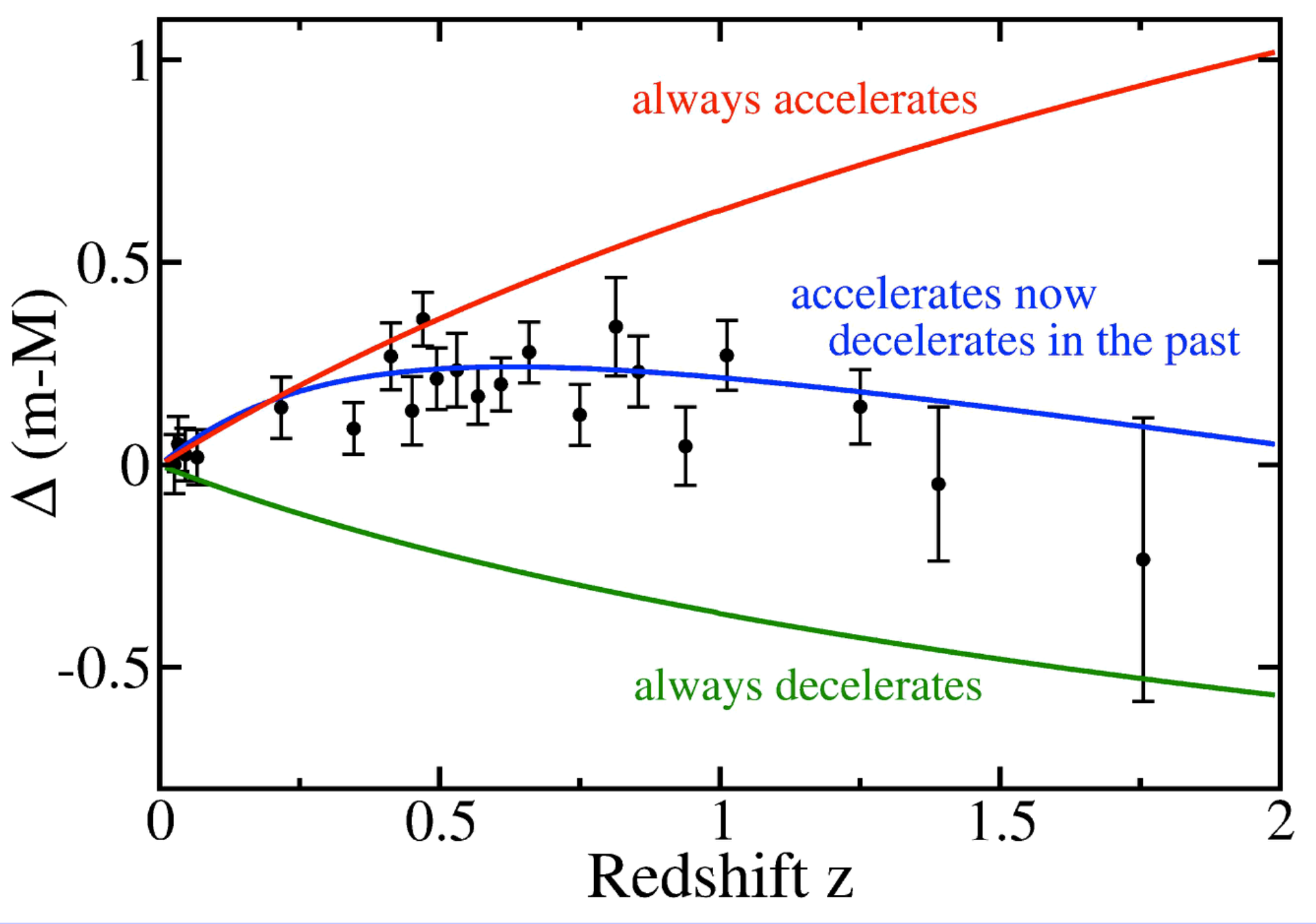

Fig. 1: Cosmic acceleration as deduced from supernova Ia data. © D. Huterer, M. Turner

3. FURTHER INDICATORS FOR COSMIC ACCELERATION

Supernova data have provided the first indicator for cosmic acceleration, but there are various others.

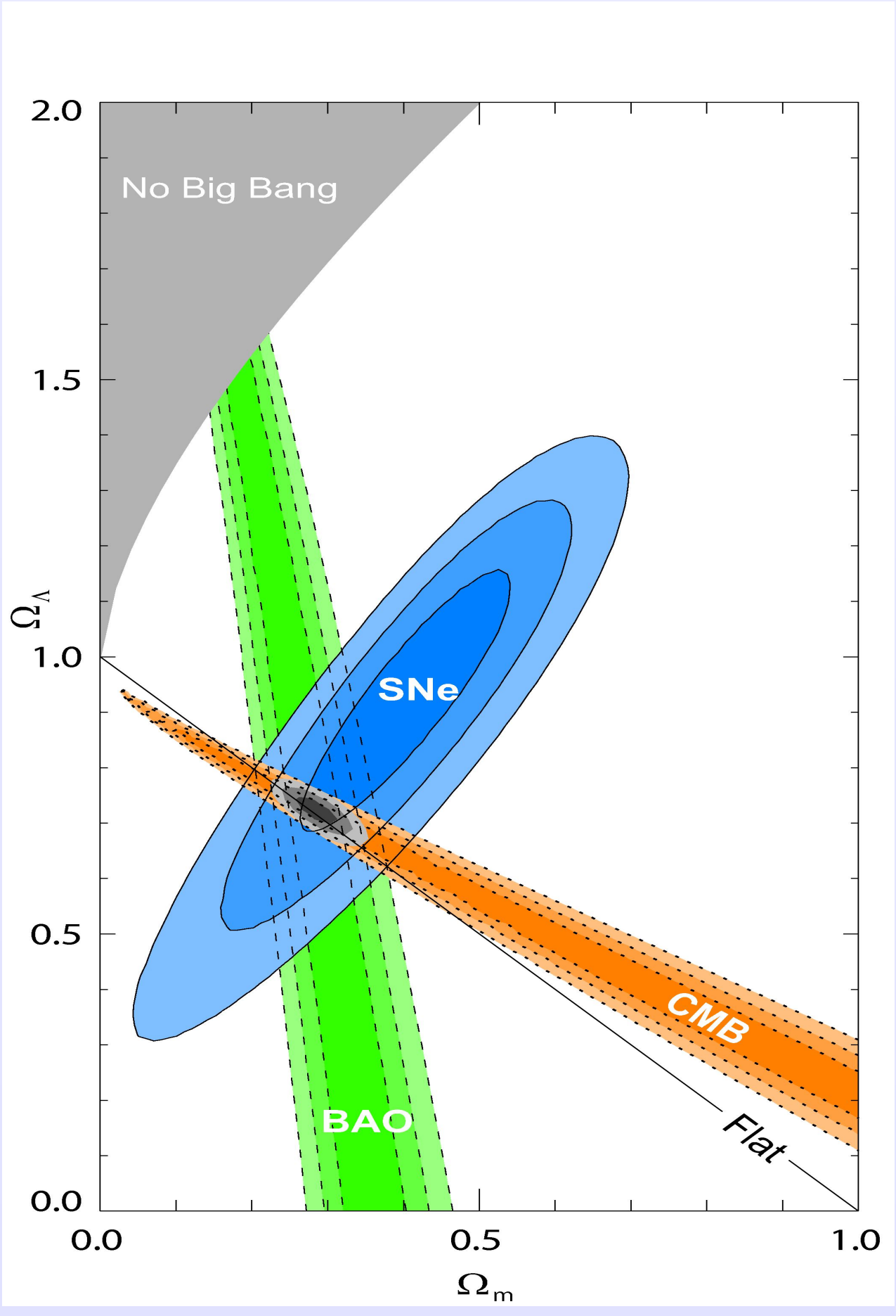

Fig. 2: Evidence for accelerated expansion from supernovae Ia, temperature fluctuations of the cosmic microwave background (CMB) and baryonic acoustic oscillations (BAO) through measurements of the matter density Ω_m and the density Ω_Λ associated with dark energy. © M. Kowalski et al.

Precise analyses of the temperature fluctuations of the **Cosmic Microwave Background (CMB)** as observed by the WMAP satellite, and more recently (2015, Fig.4) by the Planck satellite of the European Space Agency ESA, have revealed a similar fraction of the energy density of the Universe being due to dark energy as was deduced from the supernovae results, Fig.2.

Another important observable are **Baryonic Acoustic Oscillations (BAO**, Fig.2): Sound waves in the early Universe imprinted a pattern on the distribution of galaxies that is measurable today, and which yields results for the dark-energy density that are consistent with the ones from the other methods.

Counting of **galaxy clusters** (Fig.5) which have formed due to gravitational attraction provide yet another indication for dark energy since accelerated expansion tends to yield smaller cluster densities than expected from uniform expansion.

Fig. 3: Supernova 1994D in the galaxy NGC 4526 which is part of the Virgo cluster in a distance of 55 million lightyears. © Hubble Space Telescope/ NASA

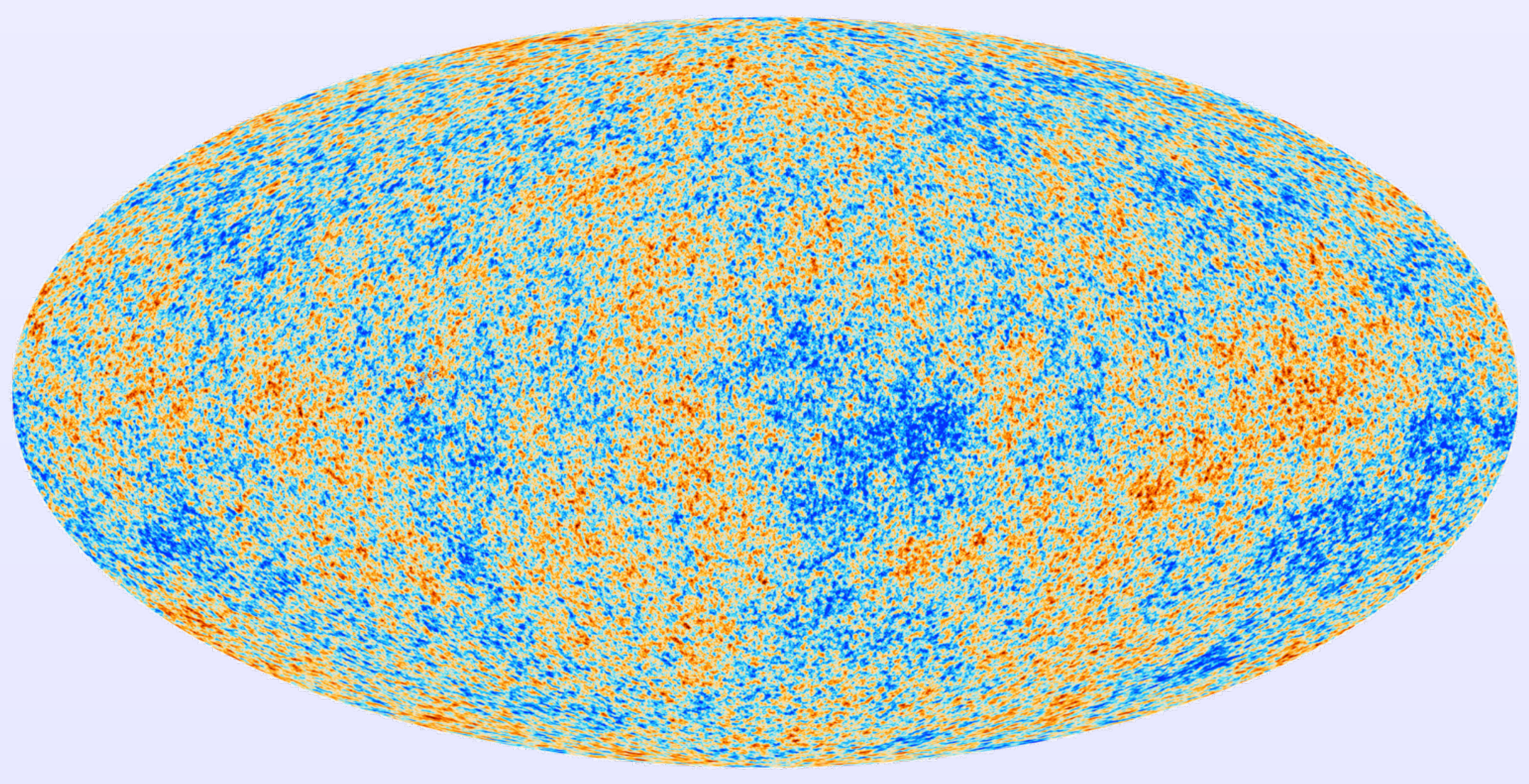

Fig. 4: Temperature fluctuations of the Cosmic Microwave Background (CMB) as recorded by the Planck Satellite. © Planck Collaboration/ ESA

4. CONCLUSION and OUTLOOK

In spite of considerable efforts and a few hundred peer-reviewed scientific publications in renowned international journals resulting from TR33 alone, it is presently still an open question whether the observed accelerated expansion of the Universe is due to a cosmological constant of unknown physical origin, a time-dependent scalar field opposing the gravitational attraction, or caused by a modification of the laws of Einstein‘s gravity required on very large scales.

Clearly more data from cosmological observations are needed to eventually resolve the problem. The so-called Dark Energy Survey (DES) was started in 2013 with the Inter-American Telescope in Chile. It will until 2018 deliver a high-resolution map with 200 million galaxies and a supernova catalogue that will enable a precise measurement of the accelerated expansion.

Fig. 5: South Pole Telescope (SPT) for the observation of distant galaxy clusters. © Jeff McMahon

Even more conclusive observational information is expected from the Large Synoptic Survey Telescope (LSST) that will start to map the entire visible sky in 2021 with a new 8.4 meter telescope in Chile, as well as planned NASA and ESA space missions.

In particular the European satellite Euclid will map the geometry of the dark Universe by measuring shapes and redshifts of galaxies and clusters of galaxies to a look-back time of 10 billion years. In this way, Euclid will cover the entire period over which dark energy played a significant role in accelerating the expansion and probably allow to distinguish the effect of a cosmological constant from that of a scalar field.

ACKNOWLEDGEMENT

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