The legacy of Planck and the future of observational cosmology in the era of large-scale surveys

Peter Johansson
Department of Physics, University of Helsinki

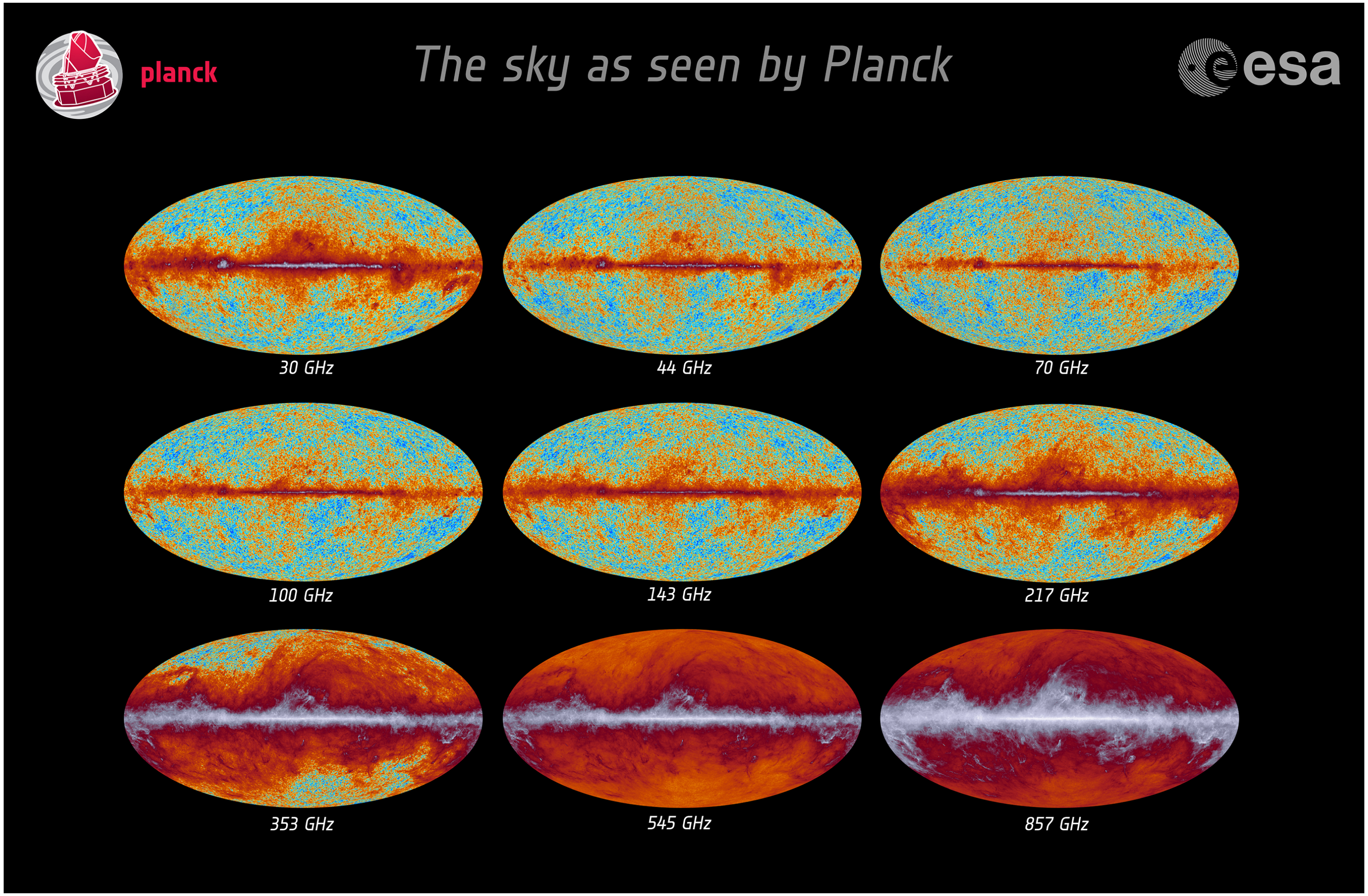
Finland in Cospar - 50 years anniversary seminar
Helsinki, June 2nd, 2014

1. The present: The Planck mission

- The PLANCK mission was launched in 2009 with the objective of mapping the cosmic microwave background at unprecedented resolution at 9 frequencies (30-857 GHz).
- First data release in March 2013, the next data release will be in October 2014 followed by a final data release towards the end of 2015.

Thus, it is still too early to talk about the legacy of Planck. Instead I will here present a mid-term review of Planck and some thoughts on the future directions of observational cosmology.

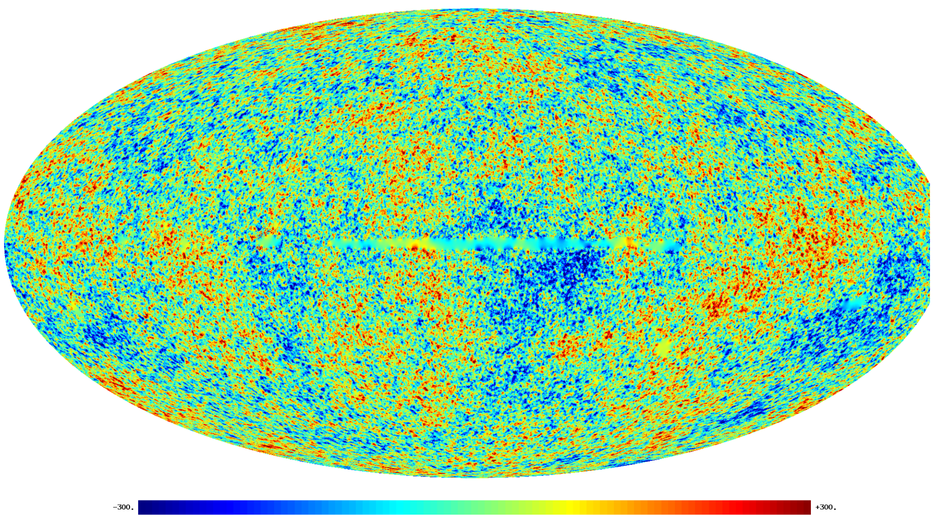
The sky seen by Planck

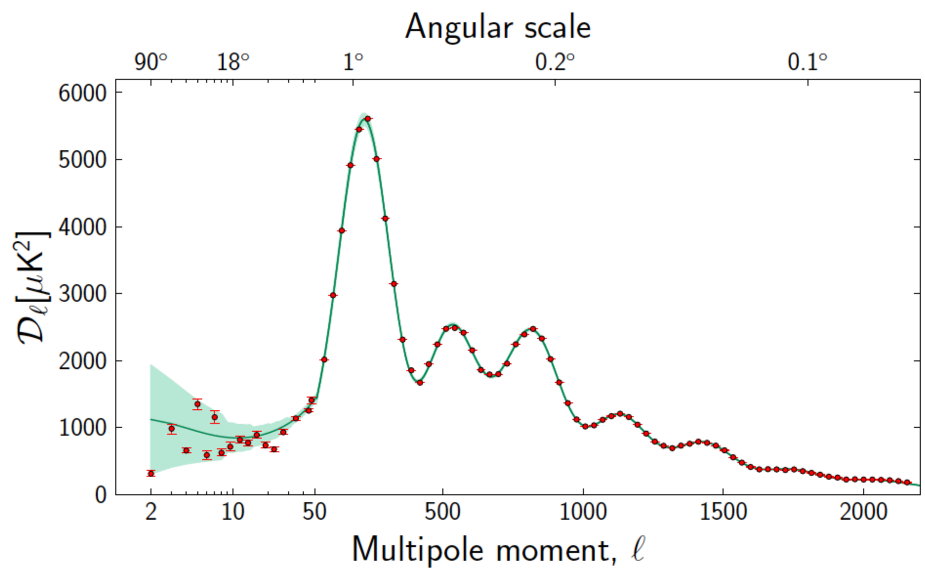


- At higher frequencies increasing contribution from foreground dust in the Milky Way. The cosmological results are limited by the foreground subtraction.

UNIVERSITY OF HELSINKI

Planck cosmological results





The measured temperature of the CMB is T=2.72548±0.00057 K with the fluctuations being of the of order $\Delta T/T \sim 10^{-5}$.

The measured temperature fluctuations can be described by a power spectrum, which shows that the largest fluctuations are on scales of 1°.

- The figures show essentially the imprint of sound waves in the primordial plasma at the time of last scattering at redshift of z~1100 (t380,000 yrs after the Big Bang).
- From theory we can calculate the physical sizes of the sound waves and then by comparing to their angular sizes on the sky we can derive cosmological parameters.

UNIVERSITY OF HELSINKI

Cosmological parameters

- The standard ΛCDM model can be characterized by the following six parameters when the total density equals the critical density (i.e. a flat Universe) and the dark energy is described by a vacuum energy component.

1. Ω_b: the density parameter of baryonic matter with respect to the critical density.
2. Ω_c: the density parameter of cold dark matter.
3. Ω_Λ: the density parameter of dark energy.
4. τ: the optical depth to "last scattering surface", depends on the fraction of CMB photons that scattered from interstellar electrons. In deriving this Planck used WMAP polarization data.
5. n_S: power index of primordial scalar density perturbations.
6. A_S: amplitude of primordial density perturbations.

$$P(k) = A_S^2 \left(\frac{k}{k_0}\right)^{n-1}, \quad n = 1 \ \text{ scale invariant}$$

UNIVERSITY OF HELSINKI

Results: Planck cosmological parameters

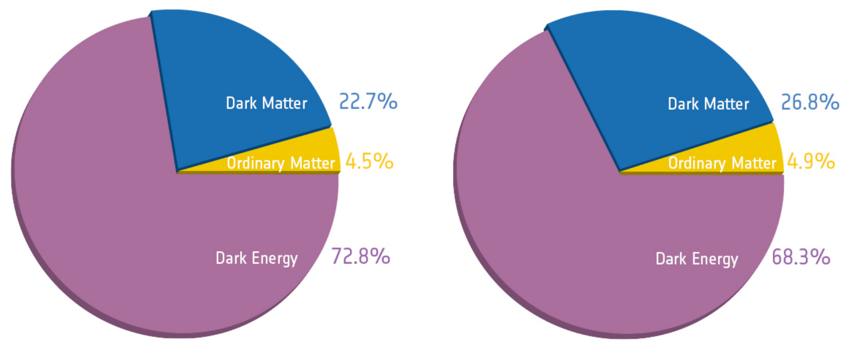
Parameter	Planck	Planck+WP	+highL	+BAO
$\Omega_b h^2$	0.02207±33	0.02205±28	0.02207±27	0.02214±24
$\Omega_c h^2$	0.1196±31	0.1199±27	0.1198±26	0.1187±17
Ω_Λ	0.686±20	0.685±17	0.685±17	0.692±10
τ	0.097±38	0.089±13	0.091±13	0.092±13
n_s	0.9616±94	0.9603±73	0.9585±70	0.9608±54
$\ln(10^{10} A_s^2)$	3.203±72	3.089±26	3.087±24	3.091±25

(errors are for the least significant digits)

Ω_m	0.314±20	0.315±17	0.315±17	0.308±10
H_0	67.4±1.4	67.3±1.2	67.3±1.2	67.8±0.8
Age/Gyr	13.813±58	13.817±48	13.813±47	13.798±37

Summary of Planck results

- The Planck March 2013 data release found no evidence for anything beyond the standard ΛCDM model:
- No primordial non-Gaussianity, no isocurvature modes, no primordial gravitational waves, no running of the the spectral index, no dark radiation (e.g. extra types of neutrinos), no curvature, no defects (cosmic strings).
- Instead Planck found "everything" predicted by the standard ΛCDM model:
- Lensing of the CMB, first detections of non-Gaussianity due to lensing of foreground structures, lensing – cosmic infrared background correlation and the effect of our motion on the higher CMB multipoles.



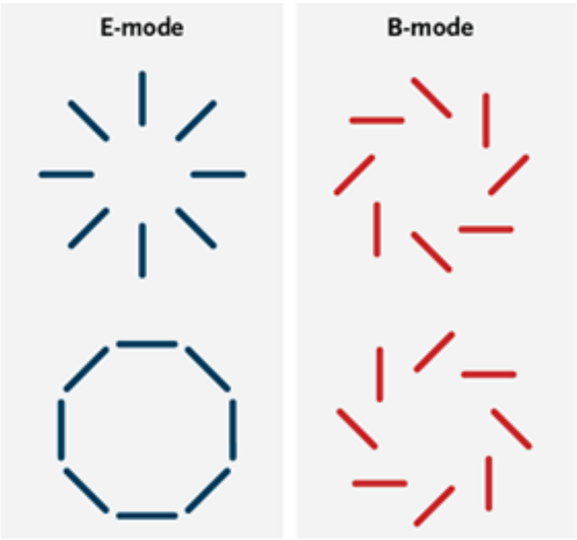
Before Planck After Planck

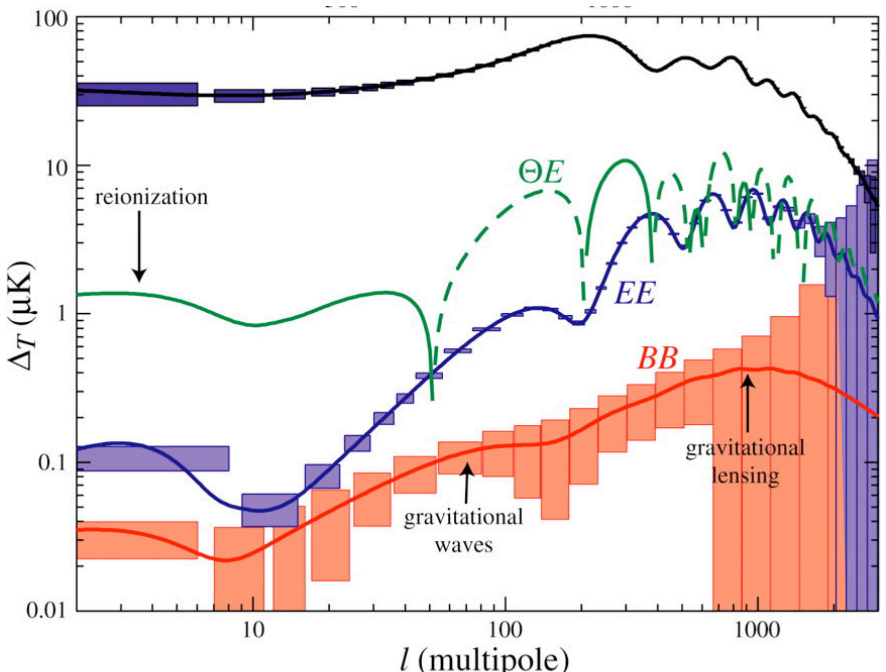
- Planck did also discover as of yet unexplained anomalies in the CMB at large scales (small l) at the ~2σ level. The small scale structure (large l) is very well fit by ΛCDM.

UNIVERSITY OF HELSINKI

Polarization of the CMB

- The CMB can also be polarized depending on the relative different directions of the density (scalar) and gravitational wave (tensor) perturbations.
- A density perturbation can give rise to only primordial E-mode polarization.
- A gravitational wave perturbation can give rise to both primordial E-mode and B-mode polarization.
- B-mode polarization at small scales (l~1000) can also be created by foreground lensing.





Inflation and primordial gravitational waves

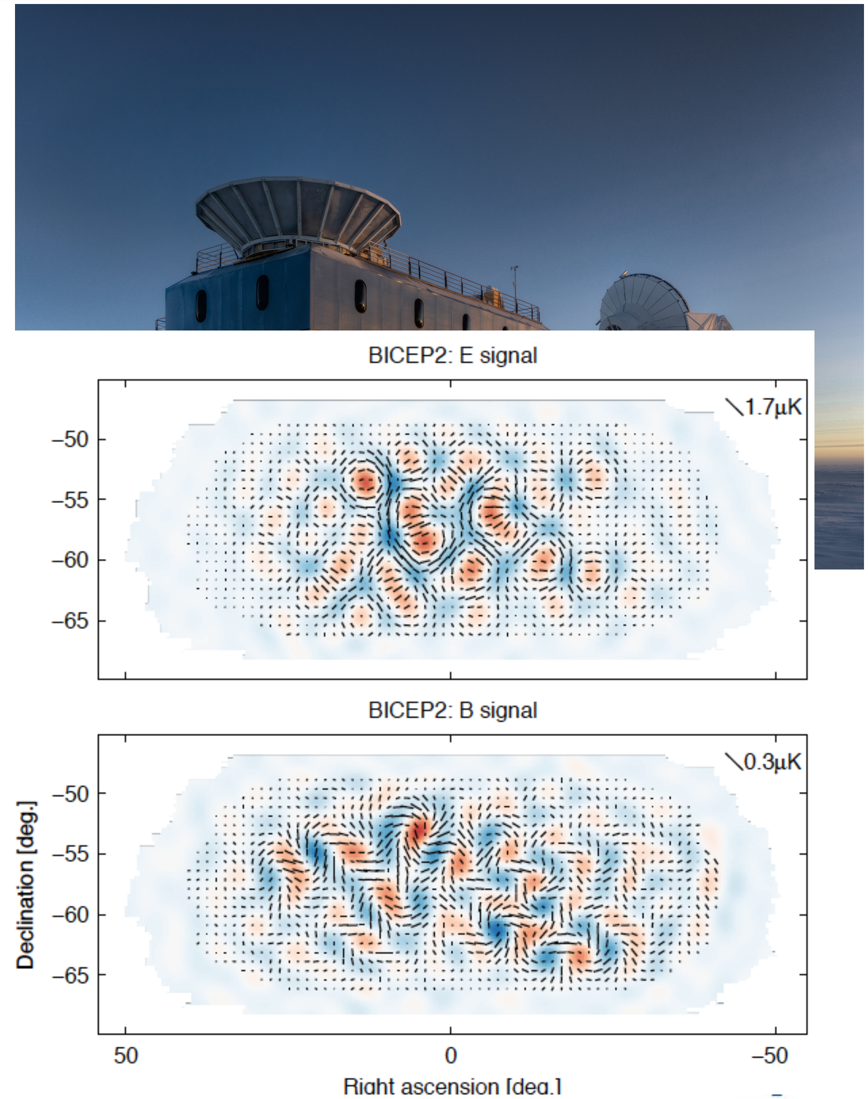
- Inflation was a period of accelerated expansion in the very early Universe ($t \sim 10^{-36}$-10^{-32} s after the Big Bang) driven by a scalar field during which the Universe expanded by a factor of at least $e^{50\text{-}60}$.
- Confirmed predictions of the Inflation model is that the Universe is flat ($\Omega=1$) and that the primordial density perturbations are almost scale invariant ($n_S=1$): $n_S=0.9585$, also the running of the spectral index $d \ln n_s / d \ln k$ should be undetectably small.
- The inflationary model also predicts that there should be primordial gravitational waves (tensor perturbations) from quantum fluctuations of the space-time during the inflationary epoch.
- The strength of the perturbations are quantified by r=tensor/scalar ratio and using r the energy scale of inflation can be derived:

$$E_{\rm scale} \sim r^{1/4} A_S^{1/4} \times 5 \cdot 10^{18}\ \text{GeV}\ (\text{"Planck scale"})$$

UNIVERSITY OF HELSINKI

BICEP2 claimed a detection of the primordial B mode

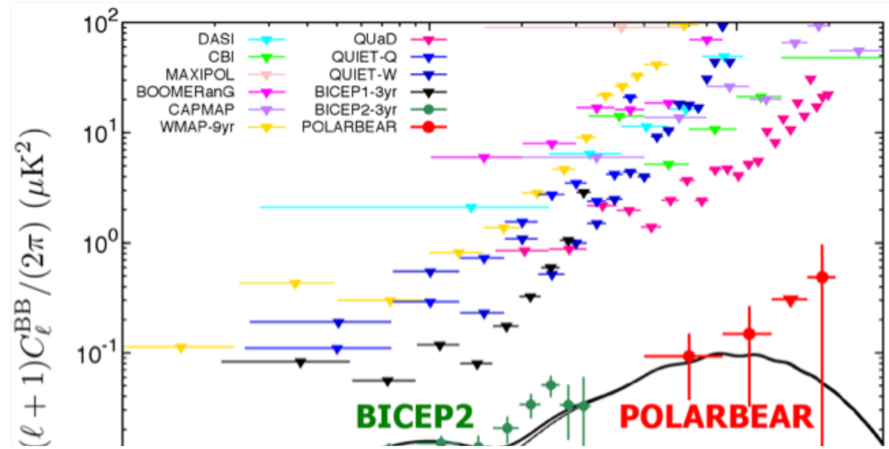
- In March, 2014 the BICEP2 collaboration operating a dedicated CMB polarization mission on the South pole claimed a detection of primordial gravitational waves with r=0.2 (Planck upper limit r=0.11).
- BICEP 2 concentrated on a small patch of the sky in one single frequency band (150 GHz) with no foreground separation. The instrument was designed to minimize polarization systematics.

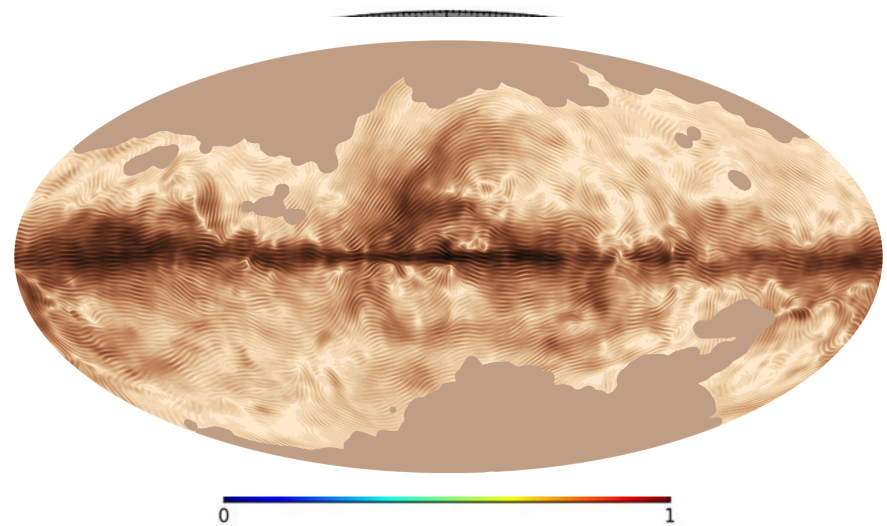


BICEP2 Collaboration, arXiv:1403.3985 (March 17, 2014)

BICEP2 signal -- is it cosmological?

- The BICEP2 discovery was presented at a big Harvard press conference and at first greeted with huge enthusiasm.
- Recently rumors have been flying (many originating in Princeton) stating that the detected signal might be mostly (or all) due to foreground polarization in the Milky Way.
- This issue should be resolved in October, when Planck publishes its results on both the dust foreground and the polarization signal it sees.



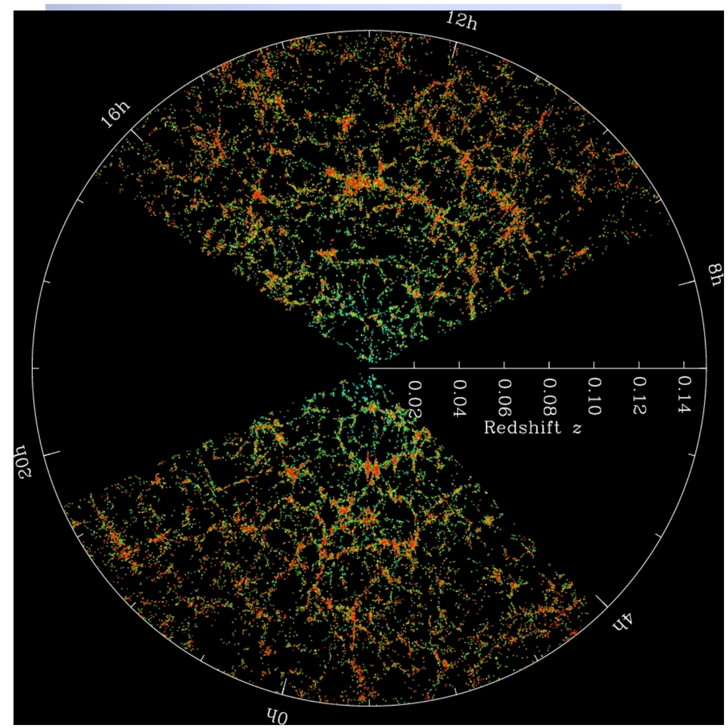


Planck is optimized for CMB temperature measurements. The correction for polarization systematics is very demanding.

UNIVERSITY OF HELSINKI

2. The future: Large-scale surveys

- The US decadal survey for Astronomy and Astrophysics recommended as top priorities for the coming decades the space based Wide-Field Infrared Survey Telescope and the ground based Large Synoptic Survey Telescope.
- Both are large-scale survey telescopes, with one of the main survey goals being the mapping of galaxies out to high redshifts and studying the dark constituents of the Universe (dark matter and dark energy).



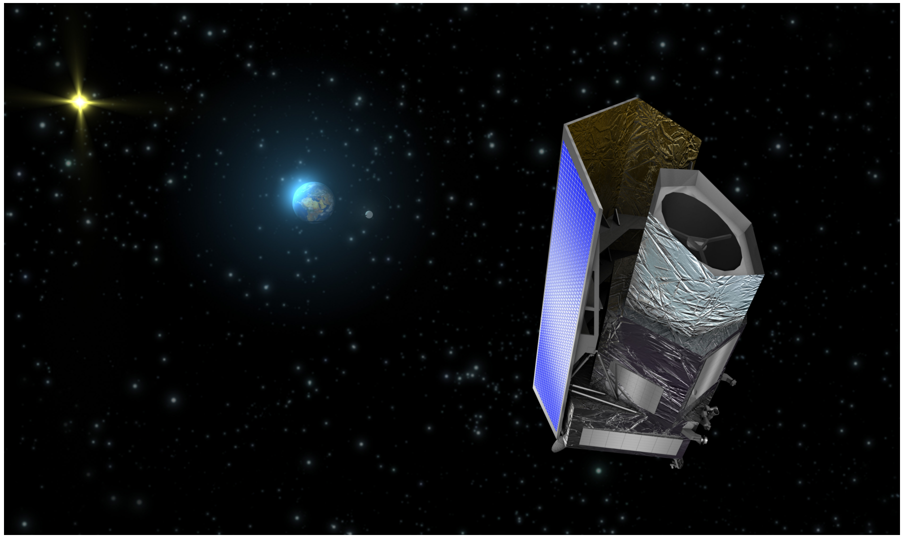
As measured by citations the modestly sized (2.5m) Sloan Digitial sky survey telescope has been the most successful telescope in the world. The data set includes 500 million photometric observations and over 1 million spectra with several scientific firsts.

UNIVERSITY OF HELSINKI

Euclid

- Euclid is an ESA M-class mission that will be launched in 2020.
- Euclid has a 1.2 m mirror with a very wide 0.5 square degree field of view.
- Euclid is equipped with a visual imager (VIS) and a near-infrared spectrometer and photometer (NISP).
- The goal is to image 1.5 billion galaxies and take the spectra of 50 million galaxies up to redshift 2 (the last 10 billion years).
- More than 1000 scientists, about 15 from Finland, Finnish PI Hannu Kurki-Suonio and the University of Helsinki.

Euclid consortium



The scientific objects include studying the evolution of dark energy and mapping the dark matter distribution in the Universe.

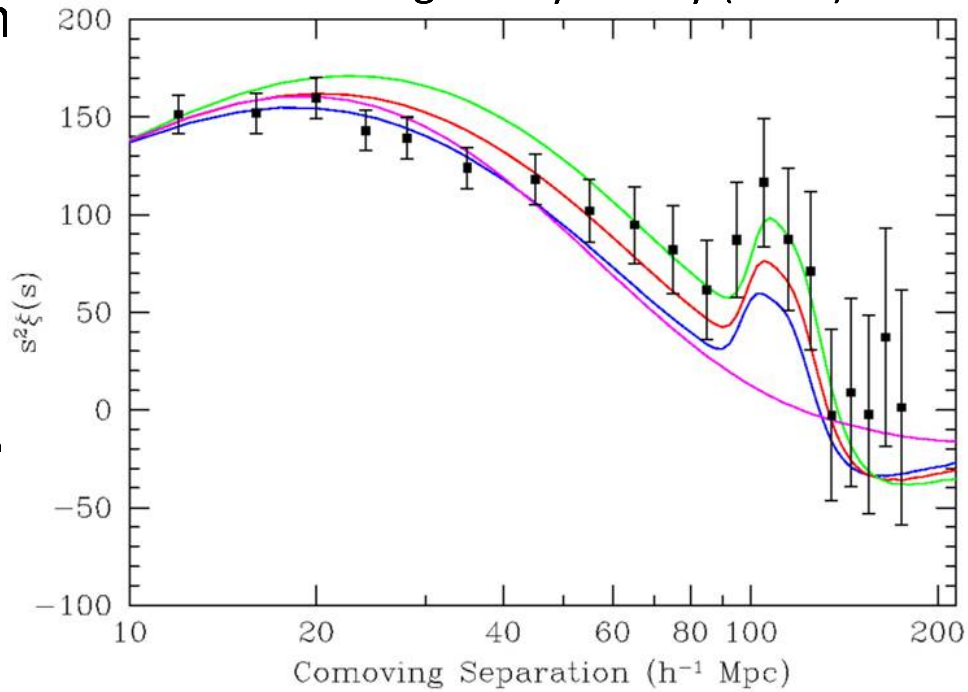
Why large-scale surveys?

- The CMB pros and cons: The CMB provides an incredibly detailed picture of the Universe, when it was still in an early state of its evolution and relatively simple. However the CMB is just one snapshot of a complicated story, for example the amount of dark energy was completely negligible at z~1100.
- Large-scale surveys pros and cons: Unlike CMB measurements galaxy surveys can provide a view of the evolution of the entire galaxy population for 10 Gyrs. Dark energy started dominating the energy budget of the Universe relatively recently (z~0.7) and in order to study the evolution of dark energy galaxy surveys are indispensable. However the astrophysics of galaxy formation and evolution is complicated as structures evolve into the non-linear regime.

Baryonic acoustic oscillations (BAO)

- The scale of the oscillations seen in the CMB is set by the sound horizon.
- This scale can later be seen in the galaxy power spectrum as a series of oscillations, with a relatively subtle amplitude since galaxies are dark-matter dominated and the baryons are only a minority component.
- We can measure the angular size of the BAO scale as a function of redshift. Similar to the CMB, but now we have multiple redshifts.

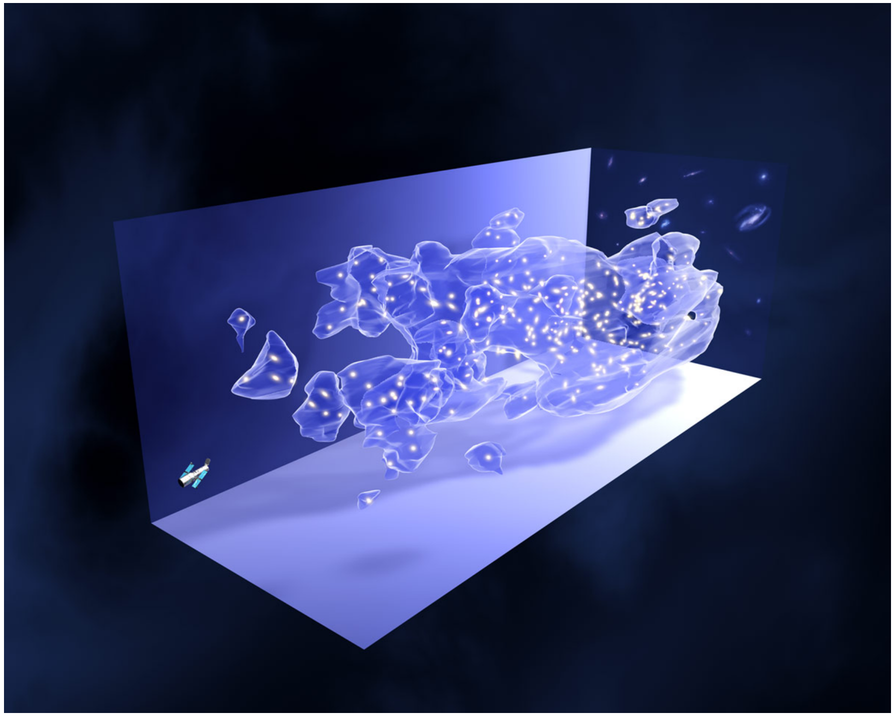
Sloan digital sky survey (2005)



- From this we can solve the relationship between redshift and distance -> study the evolution of dark energy as a function of redshift.

Weak gravitational lensing observations

- By measuring the correlations and shapes of 1.5 billion galaxies using Euclid, the expansion and growth history of the Universe can be determined.
- In weak lensing the gravitational potential of intervening structures perturbs the paths of photons ever so slightly and the amplitude of this distortion provides us with a direct measure of the gravitational field that can be used to map the total matter distribution directly.



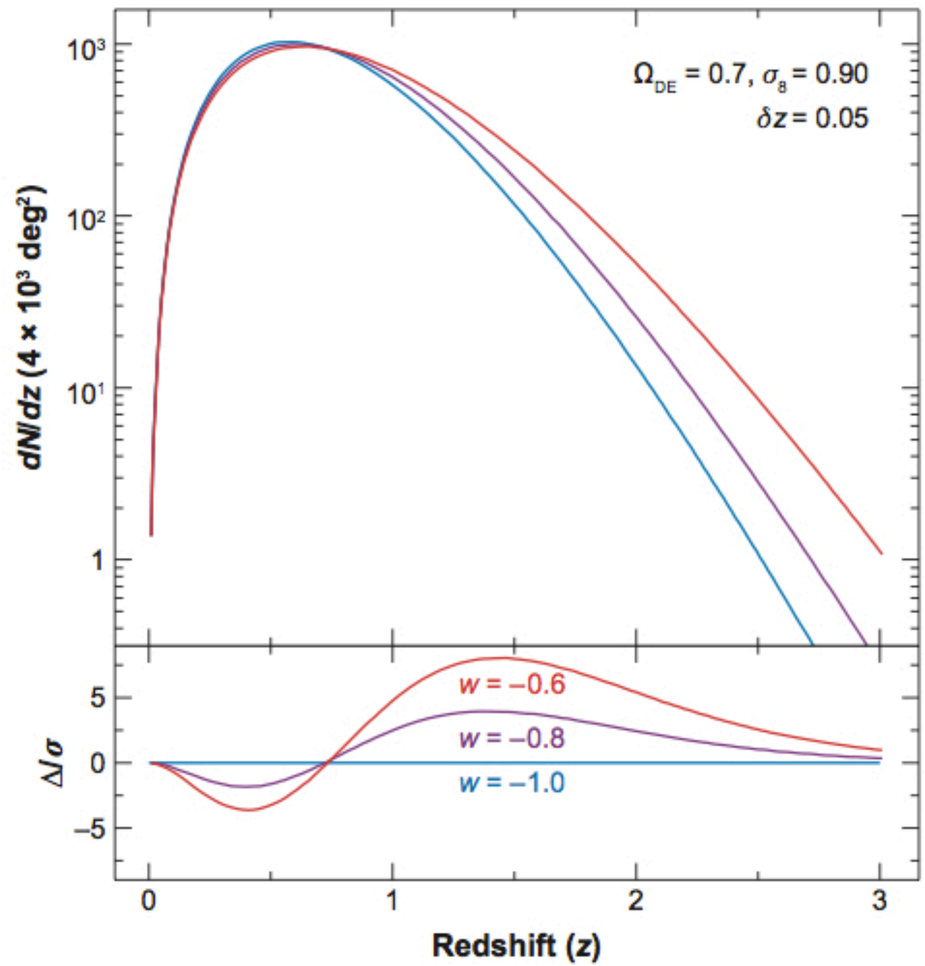
- In order to have statistically viable results one needs high spatial resolution (space mission) and large numbers (good sensitivity).

UNIVERSITY OF HELSINKI

Clusters of galaxies as probes

- Clusters of galaxies are the most massive virialized structures in the Universe and can be used as cosmological probes:
- Galaxy clusters probe sensitively the exponential tail of the primordial spectrum of density perturbations.
- The number of clusters within a given redshift range depends also on the comoving volume and is thus dependent on the cosmological parameters.

Mohr (2005)

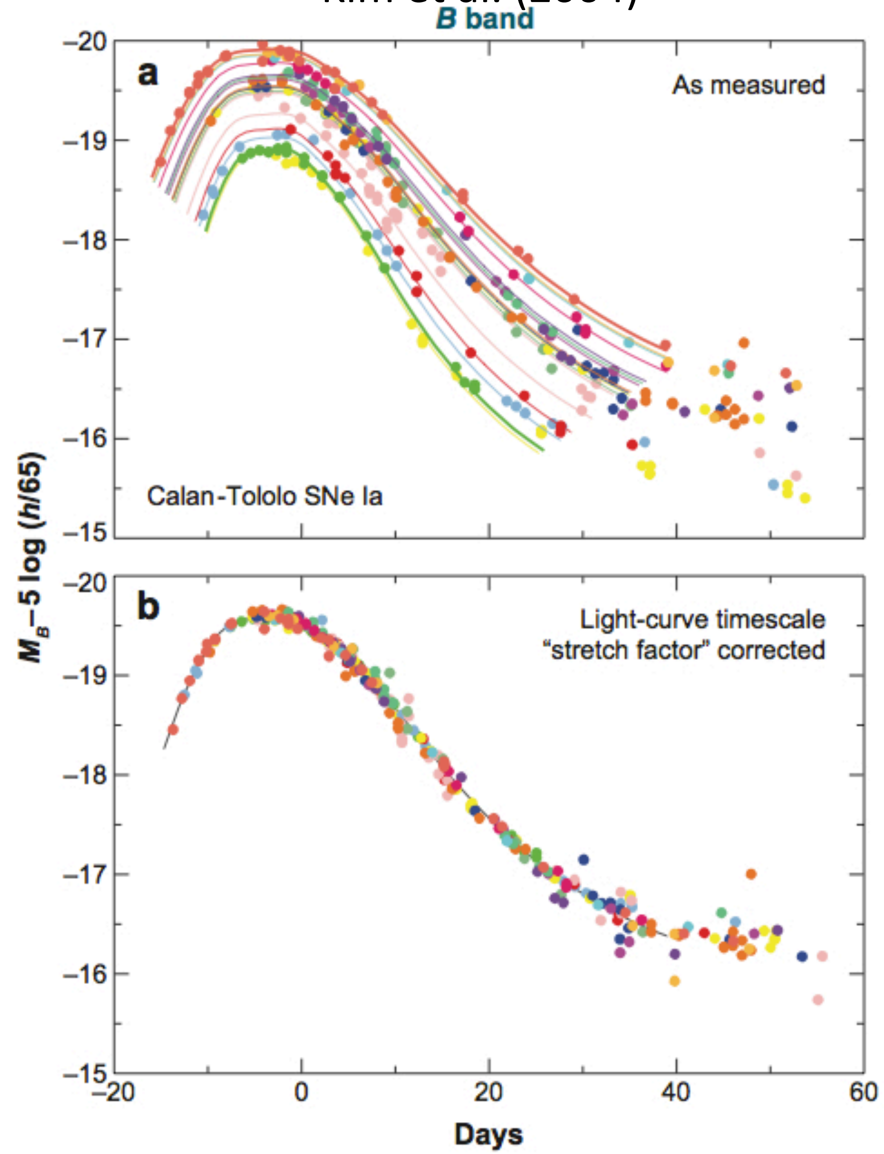


UNIVERSITY OF HELSINKI

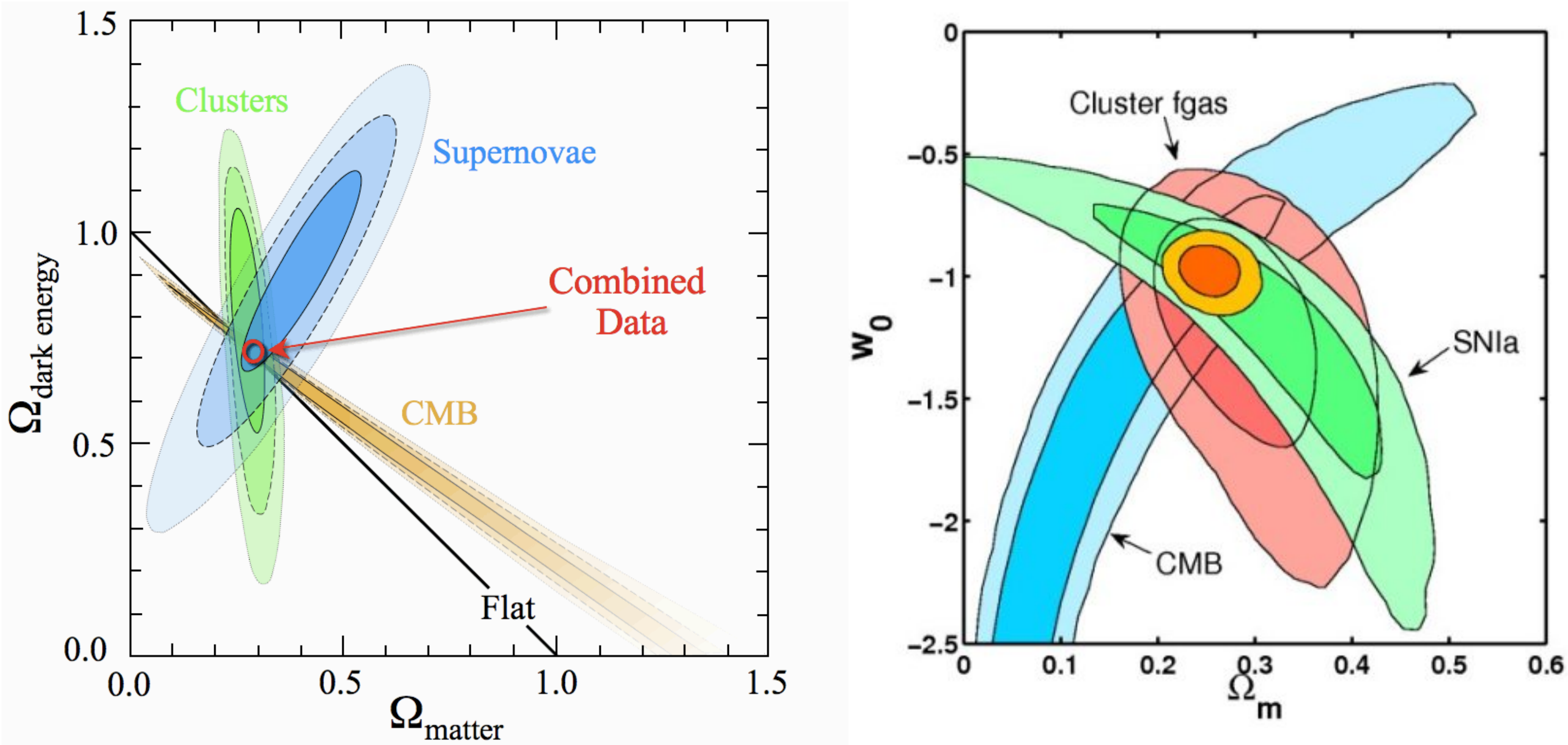
Measurements of type Ia supernovae

- Supernovae Ia are the end points of degenerate white dwarfs and should all detonate at similar luminosities as the white dwarf crosses the Chandrasekhar limit.
- Supernovae Ia can be made good standard candles by applying an empirical “stretch factor” correlation. Intrinsically more luminous Sne Ia decay more slowly.
- The accelerated expansion was first discovered using Sne Ia (Nobel prize 2011).

Kim et al. (2004)



Combination of data sets



- It is important to combine different cosmological data sets as they often probe complimentary and orthogonal regions in the parameter space. The Sn Ia data alone would not have been convincing, but the combination of multiple data sets convinced even the notoriously sceptical Nobel Prize committee.

UNIVERSITY OF HELSINKI

Legacy science with large-scale surveys

Euclid legacy in numbers

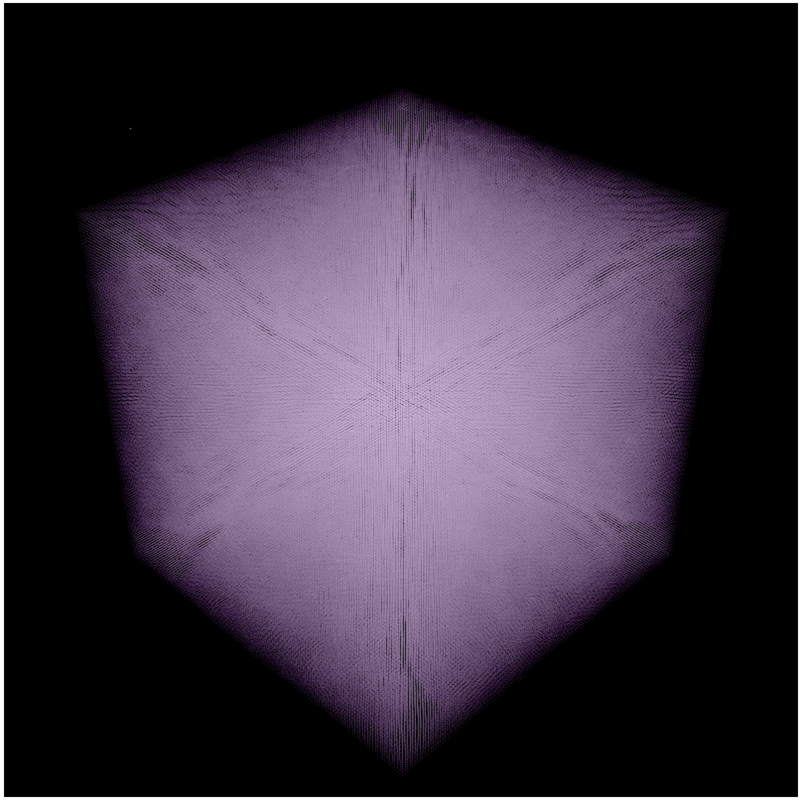
Slide from Jarle Brinch-mann's Euclid Legacy talk.

What	Euclid	Before Euclid
Galaxies at $1<z<3$ with good mass estimates	$\sim 2\times10^8$	$\sim 5\times10^6$
Massive galaxies ($1<z<3$) w/ spectra	~few x 10^3	~few tens
$H\alpha$ emitters/metal abundance in z~2-3	$\sim 4\times10^7/10^4$	$\sim 10^4/\sim 10^2$?
Galaxies in massive clusters at $z>1$	$\sim 2\times10^4$	$\sim 10^3$?
Type 2 AGN ($0.7<z<2$)	$\sim 10^4$	$<10^3$
Dwarf galaxies	$\sim 10^5$	
T_{eff} ~400K Y dwarfs	~few 10^2	<10
Strongly lensed galaxy-scale lenses	~300,000	~10-100
$z > 8$ QSOs	~30	None

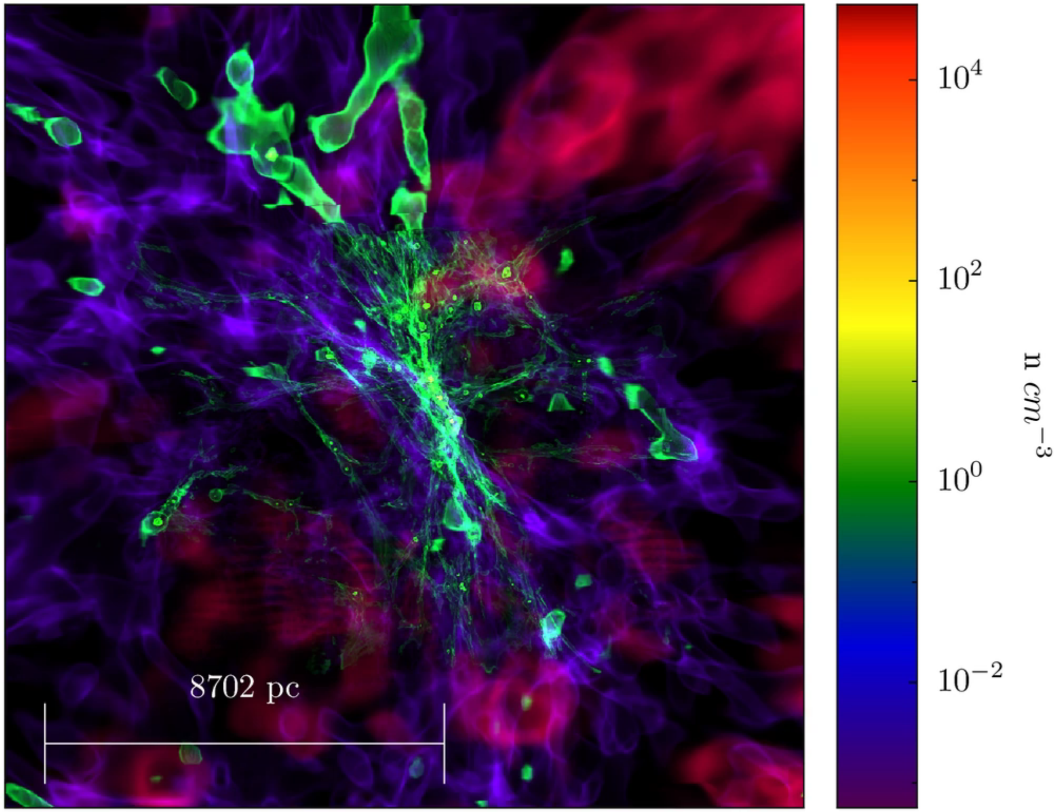
- Apart from the important cosmological data products the legacy science of large-scale surveys such as Euclid will be immense for all fields of astrophysics from exoplanets to galaxies.

Theoretical astrophysics -interpretation of the results

Evolution of 100 Mpc box (Antti Rantala).



Formation of the first supermassive black hole (John Regan).



- In order to properly understand the observations and their correct interpretation input from theoretical astrophysics and numerical simulations are required.

Conclusions

- The first data release from Planck provided strong evidence in support of the standard ΛCDM model, but did not find any evidence for physics beyond this standard model.
- The BICEP2 mission claimed a detection of primordial gravitational waves from inflation through the measurement of primordial B-mode polarization in the CMB. If true this would be a revolution in modern cosmology, however, the results still must be confirmed as foreground polarization remains an issue.
- The future in observational cosmology lies in large-scale galaxy surveys such as Euclid, which is able to probe the evolution of the galaxy population for the past 10 Gyr. Important measurements are astrophysical in nature and include: the Baryonic Acoustic Oscillation measurements, weak gravitational lensing, galaxy clusters and measurements of type Ia supernovae.

UNIVERSITY OF HELSINKI