Summary

FSK

September 22

During September 18-22 2017, 31 lecturers (6 ERC grant holders, 9 Ramon y Cajal holders, 4 Marie-Curie holders, 1 Rutherford Fellow, 1 Lagrange Fellow, 1 Humboldt Fellow, 2 Karl-Schwarzschild Fellows), leaders in their respective fields (and in projects such as BOSS, eBOSS, DESI, EUCLID, 4MOST, JPAS, Alhambra, DES, SKA, WFIRST), from 16 different countries, have taught on cosmology presenting their latest results to about 50 students from all over the world.

The attendants had the opportunity to revise the techniques which are developed to detect the primordial gravitational waves which were produced during the cosmic inflation epoch, just a fraction of a second after the Big Bang, up to the most sophisticated tools with which the large galaxy surveys are carried out to model and reconstruct the distribution of galaxies and the nature of dark matter and dark energy.

The content of the school has covered all main epochs of the cosmic evolution of the Universe, in which big questions are still alive.

The techniques to study the first instant of the Universe and the echo left in the cosmic microwave background were presented. It was also discussed how to access the dark ages of the Universe and the epoch of the generation of the first stars with modern technology.

Moreover the latest techniques to model galaxy formation were analysed, together with the structure formation of the cosmic web. One of the focus was to understand the nature of dark energy responsible for the accelerated expansion of the Universe. A whole range of alternative theories of general relativity and how to test them with the peculiar motions of the galaxies were considered. Large part of the lectures were focused on studying the techniques to measure the Universe starting in the local environment, to larger distances with Supernovae, to even larger distances with baryon acoustic oscillations using the latest statistical techniques.

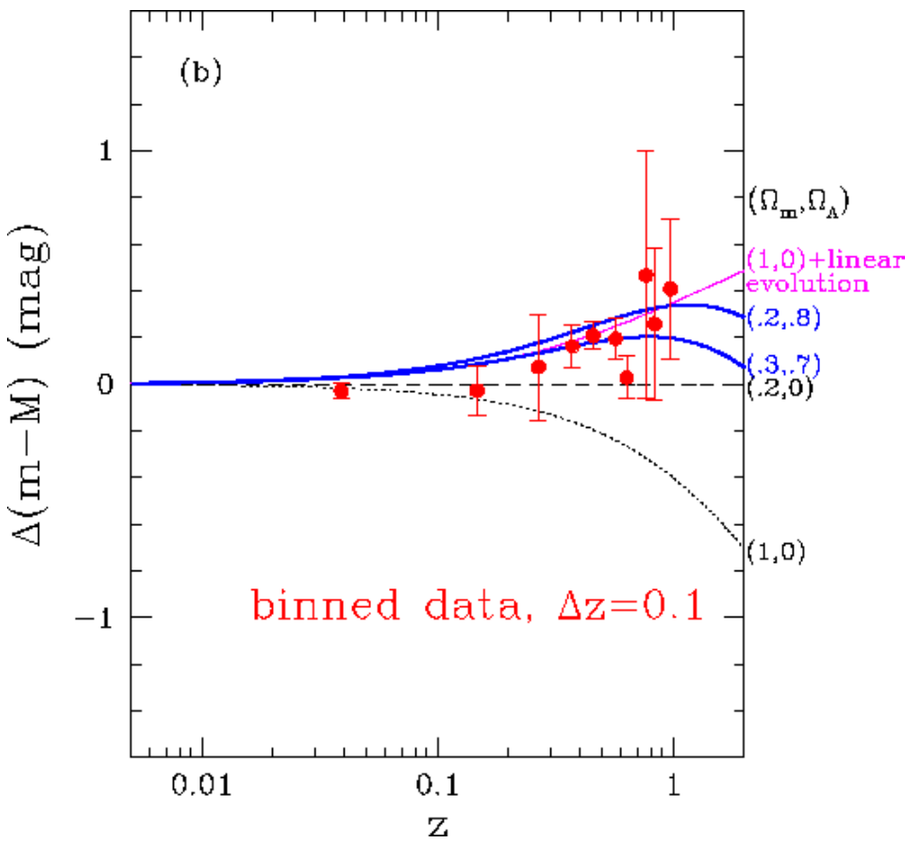
Dark Energy: accelerated expansion of the Universe

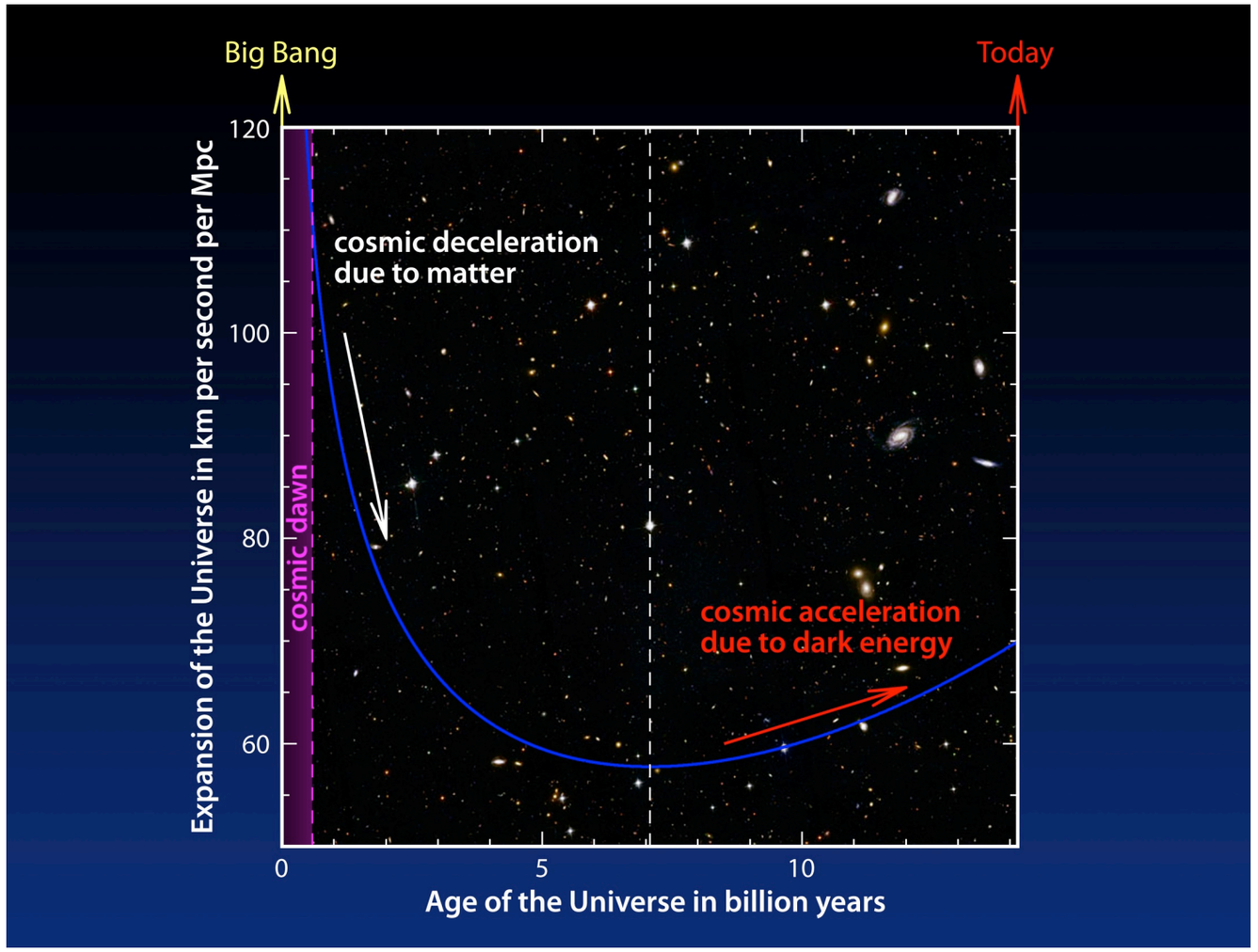
Yun introduced the dark energy probes: SN Type1a / Weak Lensing / BAO/ RSD /Clusters
(see **Yun Wang** notes for details on SN as standard candle and clusters (and a bit on lensing, BAO, and clusters),
see **Ben Metcalf** notes for details on Lensing
see **Will Percival** notes for details on BAO)

Wang & Pyle

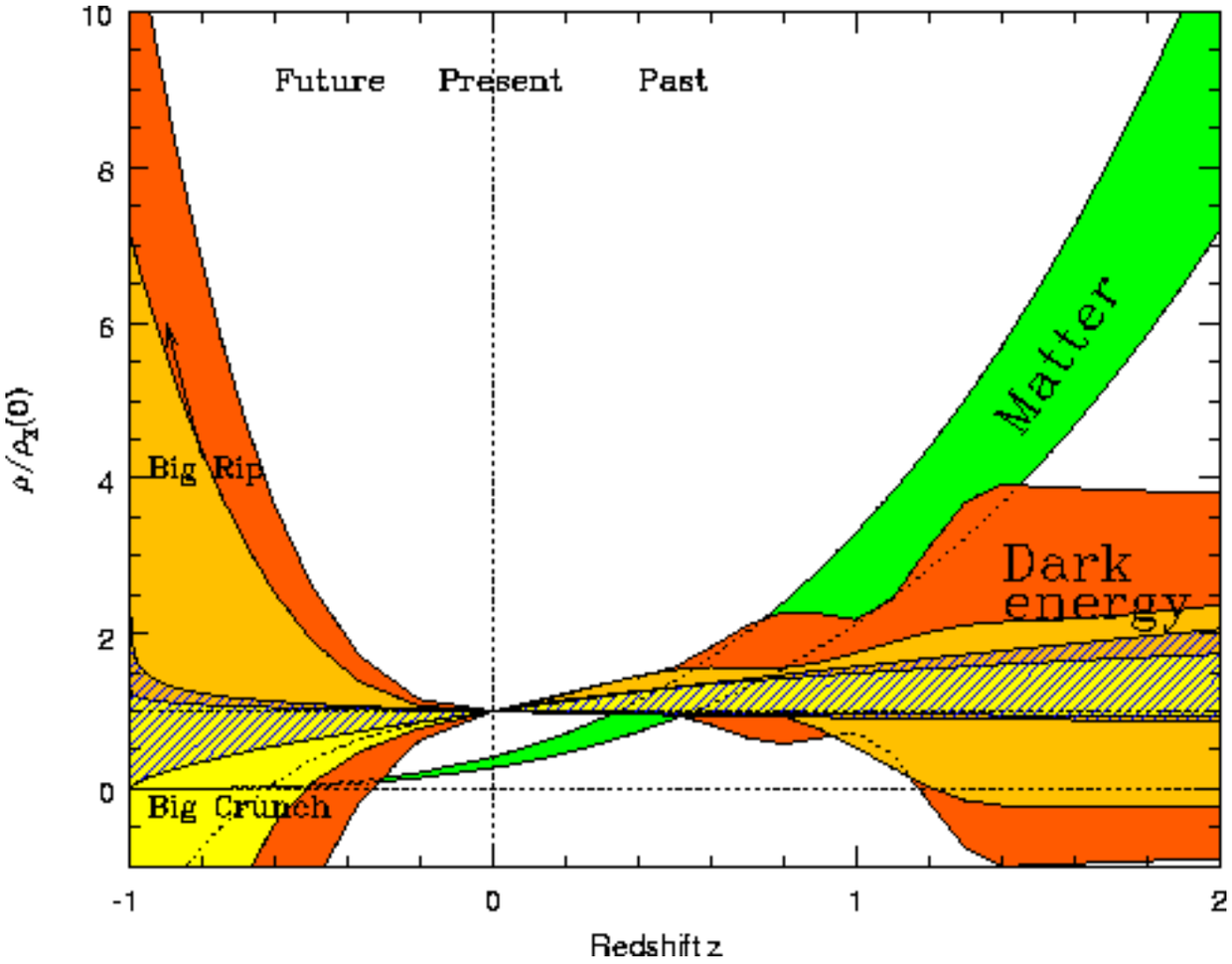
Wang et al 2000

Chi-square by eye





Fate of the Universe



Sausage of the Universe

Wang & Tegmark 2004

Doomsday model: we have at least 24 gigayears

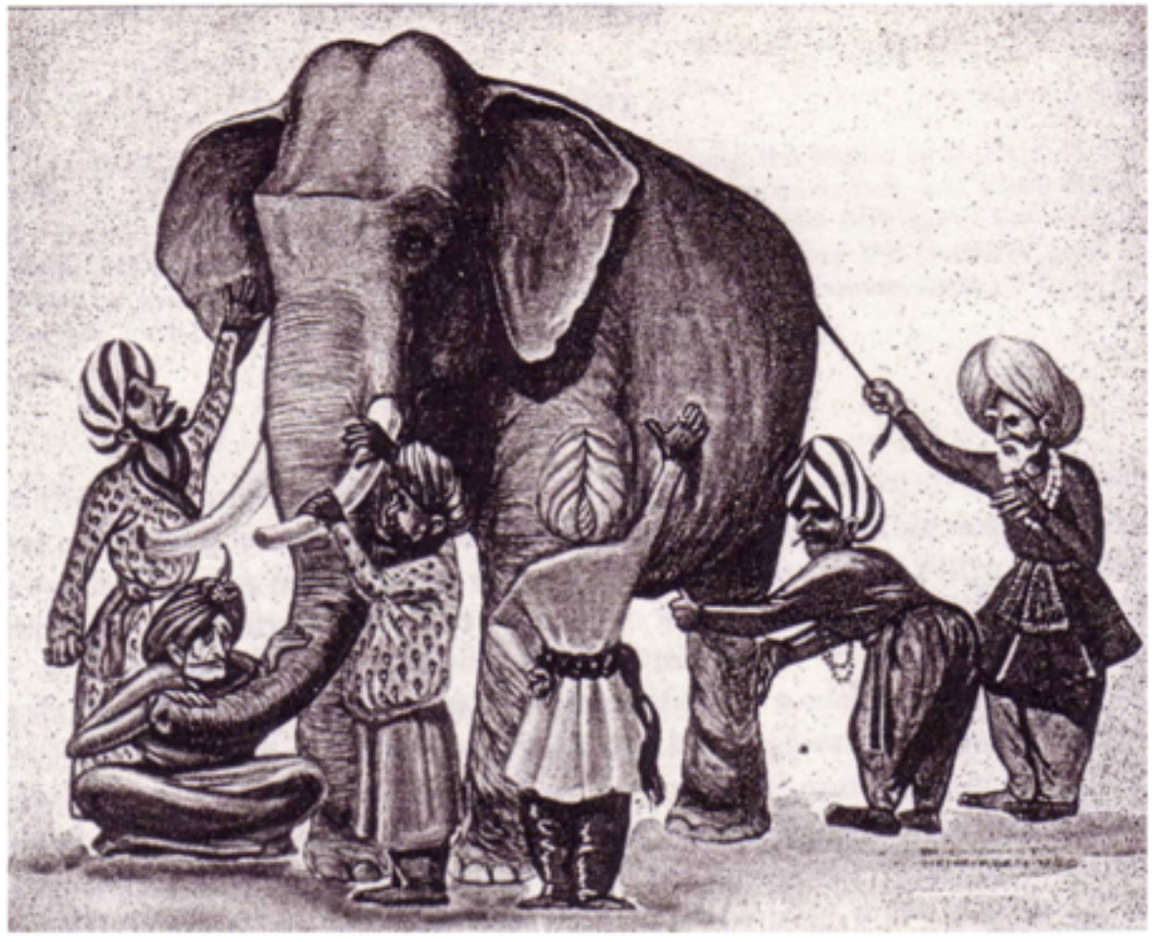
Figure Of Merit for dark energy from galaxy surveys (EUCLID/WFIRST):

At $a=a_p$, $w_p = w_0 + (1-a_p)w_a$ $\quad FoM = 1/[\det Cov(w_0 w_a)]^{1/2} = 1/[(w_a)(w_p)]$

Wang (2008)

Analytical description of structure formation (based on GR)

Diego Blas elefant:
particle physicists vs astrophysicists and the community in general should agree on what they talk about.



At initial cosmic times perturbations are linear Boltzman equation can be solved (including baryons) and produce power spectra at high z with a given cosmological parameters. (CLASS)

At later times (lower z) structure formation becomes nonlinear and perturbation theory becomes more complex. Vlasov equation dark matter only: SPT
Martín Crocce showed that 1 loop and 2 loop corrections are overestimating and underestimating the Pk respectively and you need. So he showed Renormalised PT (resummation of IR modes). (MPTbreeze, RegPT). New approach response function for UV modes.
We also saw another approach: effective field theory.

Alternative theories of gravity

Miguel Zumalacárregui

he showed how to extend the Lagrangian: quintessence, Brans-Dicke, Galileon.
And how to describe all families with Hordenski theory
and how to compute D(a), Cl, Pk with hi_class

Bayesian model estimation

Antonio Cuesta

Use CosmoMC or Montepython to get cosmological parameters comparing model to observations (Pk), how these methods work with MCMC and CAMB, CLASS, or hi_class.

Neutrinos

Sergio Pastor

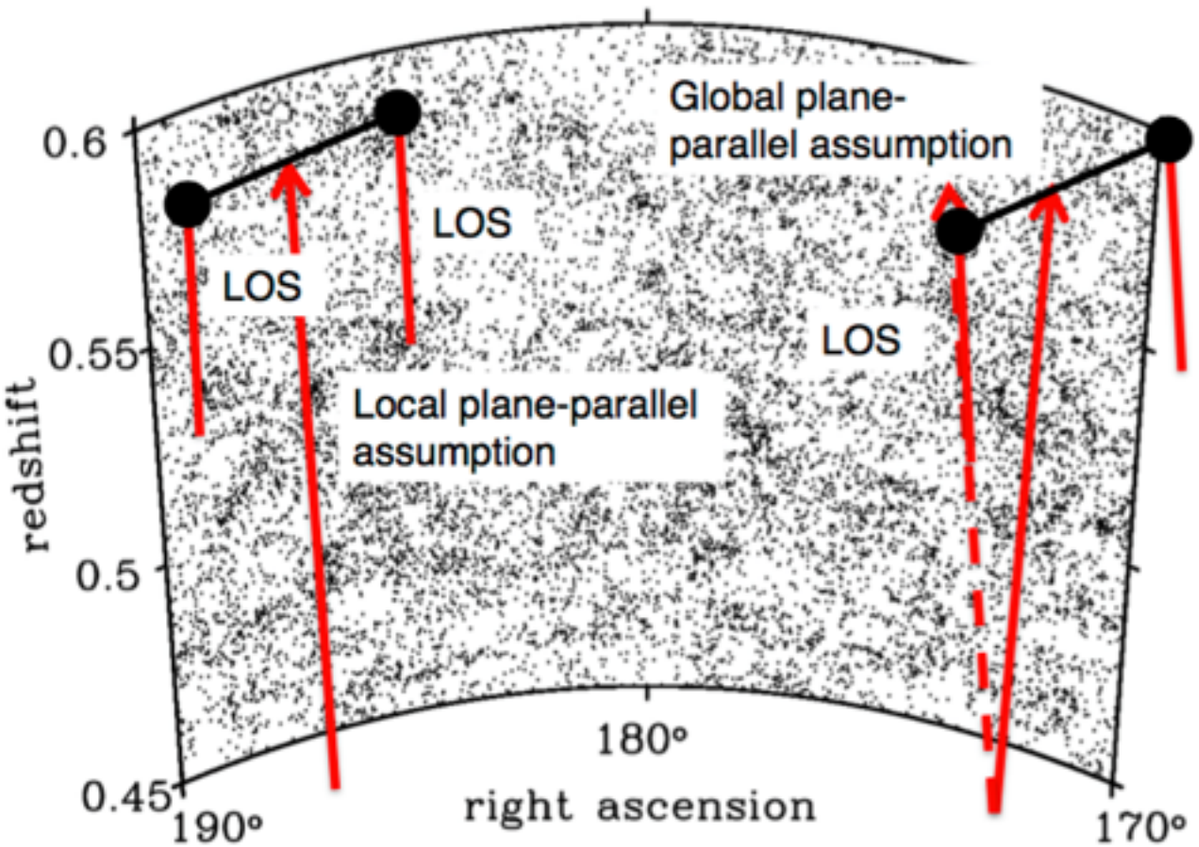
introduced neutrinos and the normal and inverted mass scenarios, the cosmic neutrino background, and the concept of N_eff, which is not exactly 3 for 3 neutrino species, but 3.045! He further discussed how neutrinos affect structure formation, the Pk in the CMB, and the present bounds of neutrino mass from neutrino detectors and LSS probes.

Galaxy surveys

Will Percival

gave a historical overview of galaxy surveys from CfA with 3500 galaxies to BOSS with 1.5 M!

Introduction to
2-point correlation function throwing sticks of different length.
Formation of BAO peak in the correlation function.
Improved calculations with galaxy weighting.
Take into account in future surveys:
relative velocity effect.
He explained how to use BAO as a standard ruler and measure the AP effect, and reduce nonlinearities with BAO reconstruction.
Ongoing and future surveys: eBOSS, MOS, DESI, EUCLID



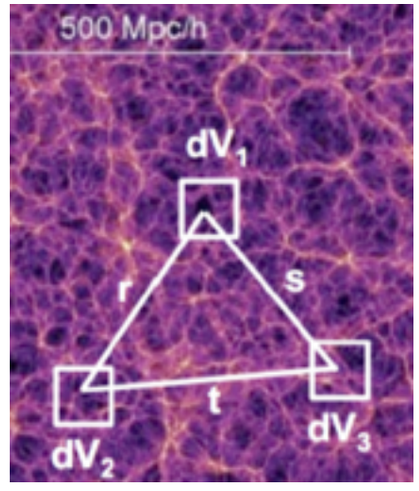
RSD and 3pt stats

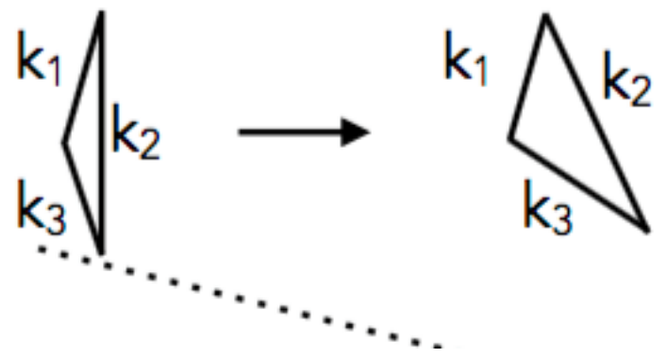
Yi Zheng

gave an introduction to RSD: doppler effect because of peculiar motion of galaxies, distorts Hubble distance to the galaxy. Kaiser effect (coherent flows)+finger of god (dispersed motions). He showed how RSD can be used to test modified gravity (righ hand side of GR eqs) and modified gravity (left hand side of the GR eqs). With the growth rate we can test LCDM against f(R), DGP models, etc.
Modelling RSD with perturbation theory and calibrating to N-body sims.

Hector Gil Marín

He showed how to compute Pk from galaxy surveys including window function, selection function, and shot noise and the multipoles: monopole and quadrupole.
Hankel transformation makes the link from Correlation function to Pk.
He showed how to get equations for b_1sigma_8 and fsigma_8.
Bispectrum as a probe of GR: 3-point statistics throwing triangles in Fourier space and how to model it with perturbation theory (Martín Crocce) and relate to primordial non-gaussianities.
Then he moved on to nonlinear and nonlocal bias modelling.

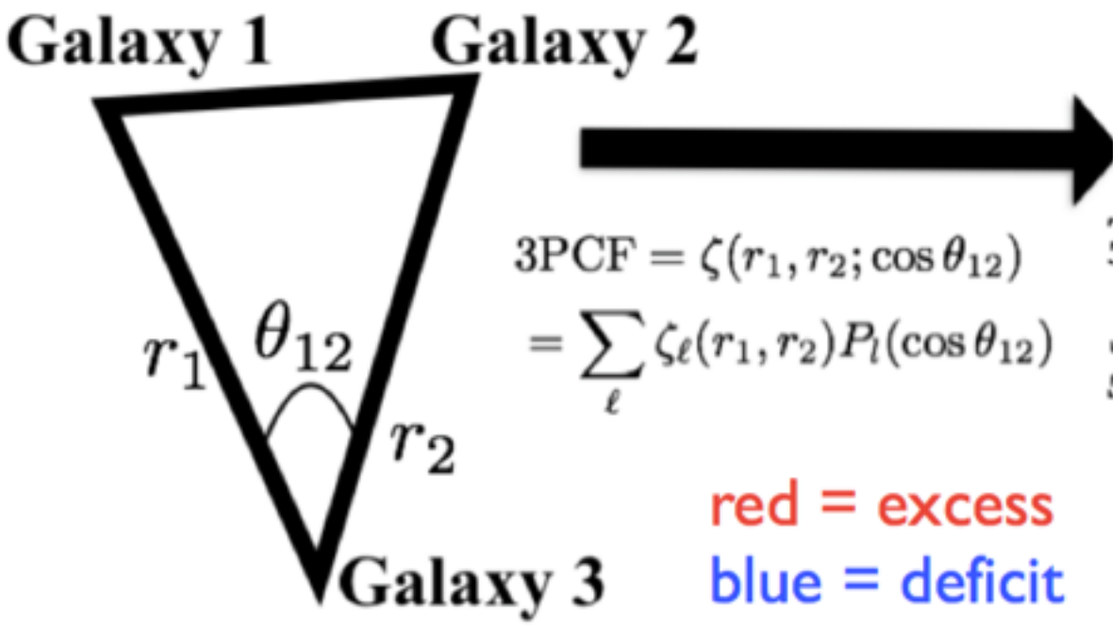


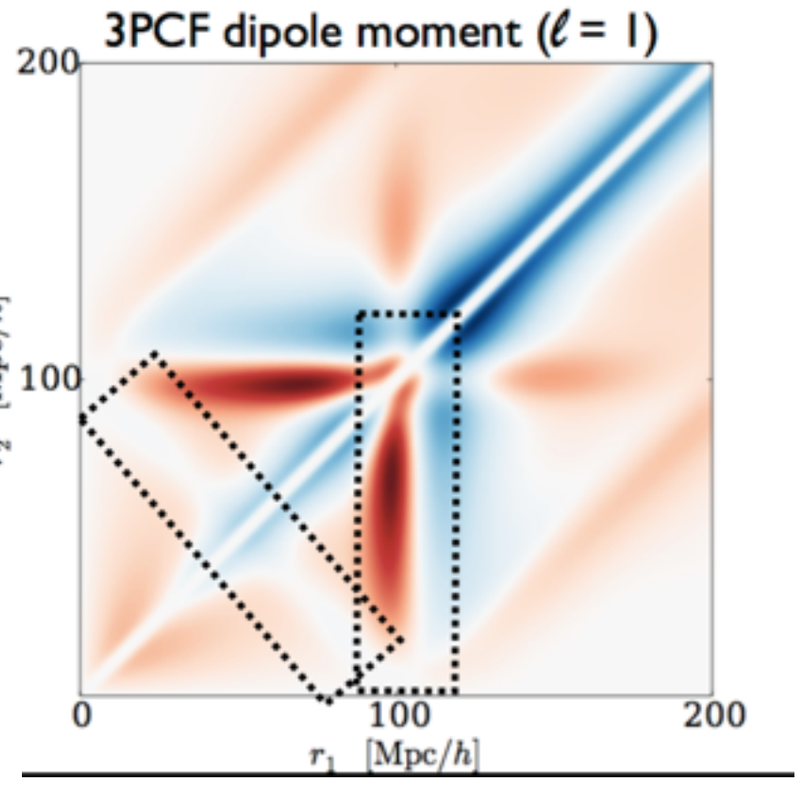


3pt stats

Zachary Slepian

showed us the multipole expansion to measure 3pt and measure BAO! and study bias!





efficient computations with spherical harmonics

Angular clustering from photos data

Andrés Balaguera Antolinez

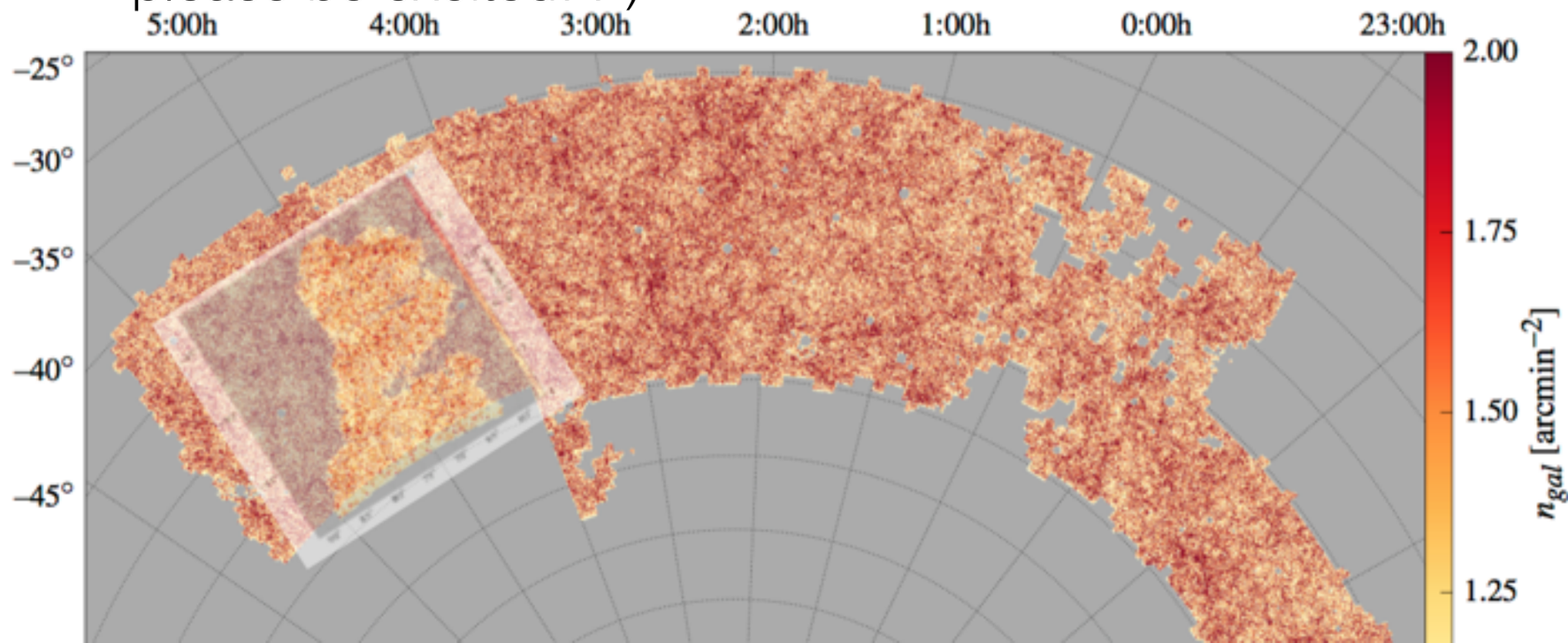
introduced the angular clustering in Fourier space and the application to extract cosmological parameters with the 2MPZ galaxy sample

Vincent Martínez showed how to explore small scale clustering with Alhambra with 25 bands! as an exercise for J-PAS which will use 56!

Martín Crocce

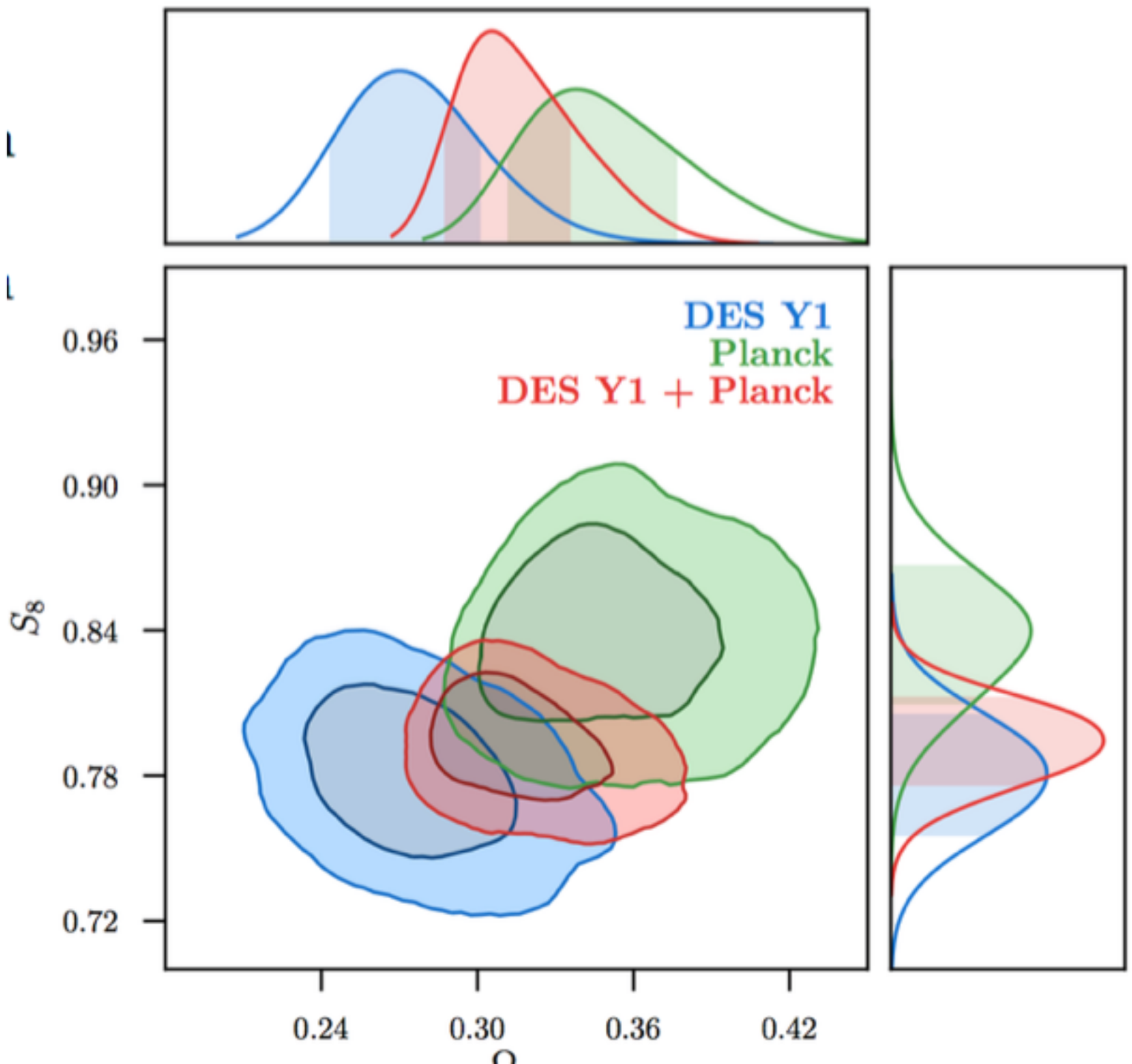
showed DES results and in particular cross correlation of galaxies with lensing using the Angular Clustering in configuration space. They used 26 M galaxies with shapes. Martín please be excited! :-)

redMaGic luminous red galaxies



Martín Crocce: LSS (with lensing) starts to be as accurate as CMB

Bayes Factor 4.2 – no evidence for inconsistency between DES and Planck



Nonlinear Cosmic Web

Rien van de Weaygert

gave a historical overview introducing modern concepts which were then extended by the focused lecturers: Zeldovich, Topology, Cosmic Web classification (**Marius Cautun**), phase space foldings (**Raul Angulo** including overview on N-body codes), caustics, multi streaming regions (**Bridget Falk**), catastrophies…

Statistical inference

FSK

Introduction to information (entropy, Kullback-Leibler), Bayesian model comparison, Bayesian inference (Gibbs-, Hamiltonian Metropolis Hastings sampling), and applications

Local Universe

Jenny Sorce

Distance estimators and biases, Wiener reconstructions from velocity data, constrained simulations

CMB and cross correlation with LSS

nice coordination Planck style!

Introduction by **Nabila Aghanim** (throwing balls to visualise the formation of harmonics in the baryon acoustic oscillations seen in the power spectrum of the CMB). From Nabila's talk (the perfect structure of the day):

Introduction
CMB spectrum and spectral distorsions **Jens Chluba**
Planck satellite and CMB maps
Foregrounds **Ricardo Génova-Santos**
Component separation **Belén Barreiro**
CMB angular power spectrum
Cosmology with CMB
Secondary anisotropies: CMB lensing & thermal Sunyaev-Zel'dovich (SZ)
Secondary anisotropies: kinetic SZ & ISW
Carlos Hernández Monteagudo
CMB polarisation status & future
Jose Alberto Rubiño Martín

We learned a new window to study the early Universe

We learned the importance to properly clean maps from foregrounds (see BICEP2).

We learned how to study dark energy cross correlating the large scale structure with the CMB to see the gravitational potentials get swallower (ISW). And how to study the missing baryons with the kSZ.

We learned how to study the primordial GW. In particular how the Stokes parameters are related to the E and B modes in the polarisation of the CMB and that E modes look the same in a mirror, but B-modes don't.

Galaxy formation

Claudio dalla Vecchia

Introduced methods to compute cosmological hydrodynamical simulations including: cooling/heating, star formation, feedback: black holes, SN winds, radiative transport, …

Chris Brook

Frenk's principle: CDM +physics

He introduced abundance matching, missing satellites, too big to fail, measuring velocities, modelling galaxies…

Ariana Di Cintio

gave a lecture on the internal structure of dark matter halos in the presence of baryons. She reported on the cusp-core problem and its relation to the SN feedback, and the way to test LCDM with density profiles and rotation curves and the recently discovered ultra-diffused galaxies (UDGs)

Reionisation, 21cm line

Andrea Ferrara

Introduced reionisation in the Universe first of single sources, then multiple sources. Bubbles, and then radiative transfer (different approaches) in cosmological context. The principal uncertainty coming from the uncertainty in the escape fraction of ionising photons.
He introduced the Gunn Peterson effect, the Wouthyusen-Field effect (Lyman alpha pumping), and presented the SKA project. There was discussion on the origin of the ionising photons coming fro Pop II and Pop III stars.

Andreu Font-Ribera

introduced the Ly-alpha forest as a cosmological probe and as a more complex biased tracer than galaxies. And finally how to analyse it and measure BAOs and cosmological parameters.

THANKS TO EVERYBODY attending this school!