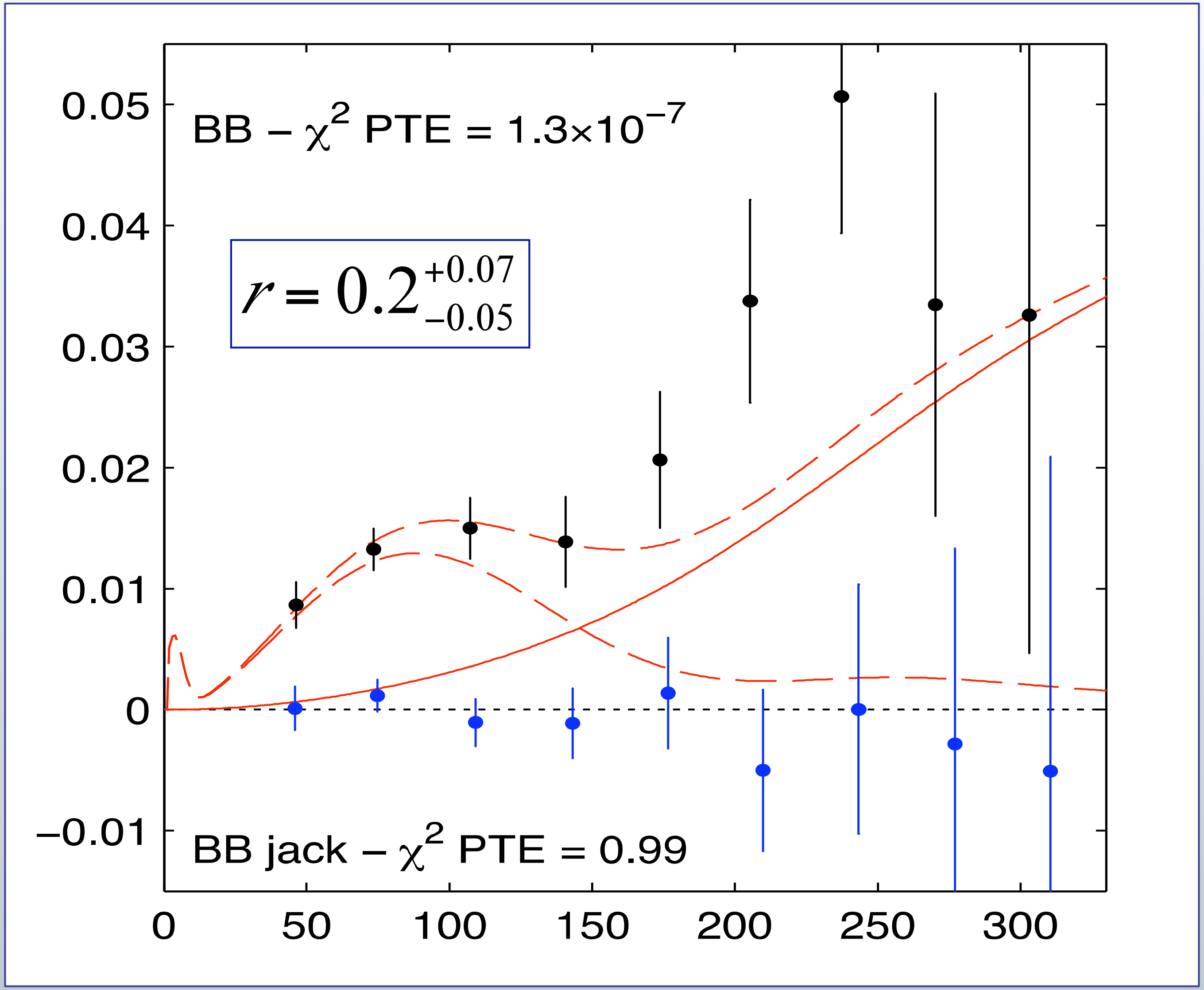
INFLATION AND DARK ENERGY: WHAT NEXT??

Thanks to the contributions of: C. Baccigaluppi, M. Baldi, E. Branchini, C. De Boni, A. Diaferio, F. Finelli, N. Fornengo, M. Liguori, S. Matarrese, L. Moscardini, M. Pietroni, M. Viel

BICEP2 results: BB power spectrum



r=0 excluded at the 5.9 σ level

NEW PHYSICS ON THE HORIZON??

- Tremendously high-energy scales never achievable in laboratories

$$V^{1/4} = 1.94 \times 10^{16} \left(\frac{r}{0.12}\right)^{1/4} \mathrm{GeV}$$

that points to the GUT scale.

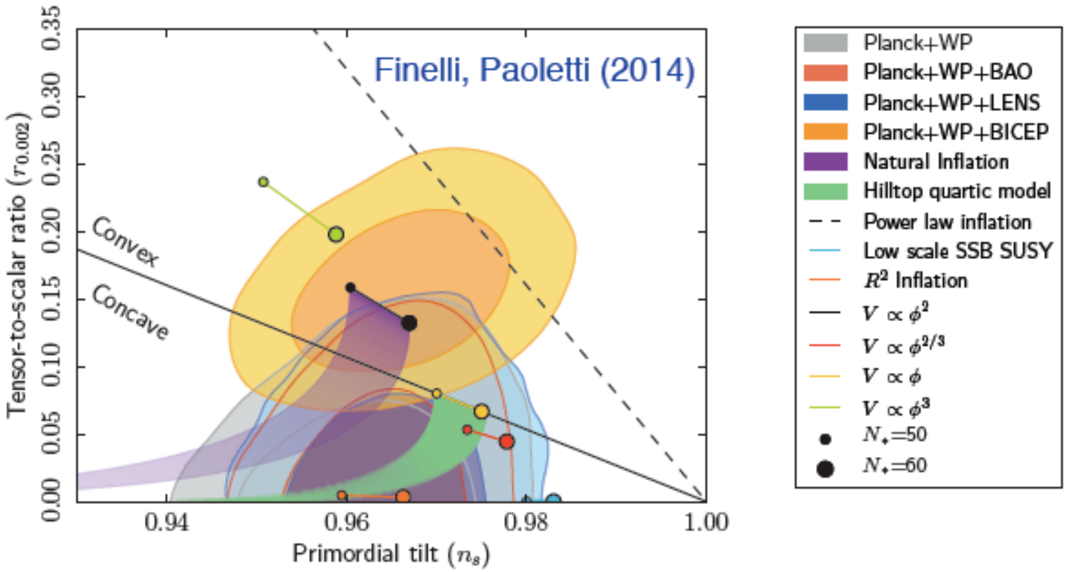
- Inflation is providing a clear evidence of physics beyond the Standard Model of particle physics

- Who is the inflaton??
  Now this question is becoming more and more pressing
  (most probably it is not the Higgs field).

After BICEP2....Consequences for inflationary models

Planck 2013 + BICEP 2

How Fig. 1 of the Planck 2013 results. XXII. Constraints on inflation would be modified with the addition of the BICEP 2 data publicly available



Low-energy scale inflation models are strongly RULED OUT

- Higgs-inflation (Bezrukov & Shaponiskov 2008)
  Prediction: r≈0.0034: RULED OUT
  (other variants on ``Higgs-inflation'' scenario still allowed)
- R^2 inflation (Starobinsky '80): RULED OUT
- Axion monodromy (Silverstain & Westphal, 2008): $V(\phi) \propto \phi$ OUT at 2σ

➢ ***A simple quadratic potential*** $V(\phi) = \frac{m^2}{2}\phi^2$ ***(Linde '82) perfectly sits within 1σ-regions.***

The future: a new era of gravity-wave based cosmology!

- Measure the tensor spectral index

$$\mathcal{P}_{\rm T}(k) = \frac{128}{3}\frac{V}{M_{\rm Pl}^4}\left(\frac{k}{k_0}\right)^{n_{\rm T}}$$

Tensor spectral index: $n_{\rm T} = -2\epsilon$

- Test the consistency relation (``the holy grail of inflation''):

$$r = -8n_T$$

- Try to measure higher-order correlators of the tensor perturbations, like the 3-point function of tensors <hhh> → graviton interactions

- Try to constrain deviation from GR at very high-energies.

WHAT NEXT INFLATION 1:

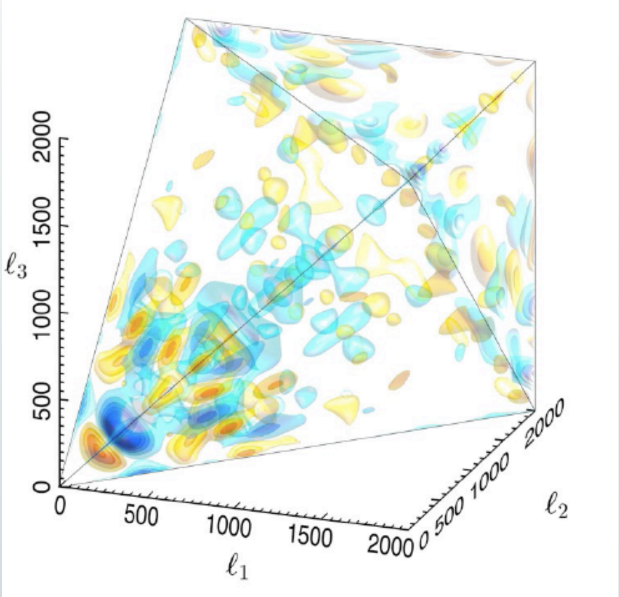
- Implications of BICEP2, inflation, new physics
  (F. Finelli)

- Using CMB polarization to test inflationary models
  (Martina Gerbino)

WHAT NEXT INFLATION 2:
NEW PATHWAYS TO PRIMORDIAL NON-GAUSIANITY

Michele Liguori , Sabino Matarrese, Padova

The CMB bispectrum as seen by Planck



Planck 2013 results. XXIV. Constraints on primordial non-Gaussianity

$$f_{NL}(local) = 2.7 \pm 5.8$$

$$f_{NL}(equilateral) = -42 \pm 75$$

$$f_{NL}(orthogonal) = -25 \pm 39$$

- **Primordial non-Gaussianity (NG) is a crucial observable to test the Physics of inflation. It tests interaction terms in the inflaton Lagrangian.**
- Best constraints to date come from observations of CMB anisotropies (*Planck*).
- But a lot of information can be extracted from LSS data. Euclid will be able to achieve a sensitivity to f_{NL}=2.

A *crucial* prediction of Standard Single Field Inflation: f_{NL}~ 0.01 ~O(ε,η)

Acquaviva et al 2002; Maldacena 2002.

WHAT NEXT INFLATION 2: PRIMORDIAL NON-GAUSSIANITY MANY OPEN QUESTIONS

1. **Can we in the future achieve the sensitivity to test f_{NL}(local) ~ 0.01?**
   IT WOULD BE ANOTHER FUDAMENTAL TEST OF STANDARD MODELS OF INFLATION.

   - LSS: scale dependent halo bias+bispectrum
   - CMB: spectral distorsions
   - 21 cm: Physics under control ? (and much further away in the future than the two above)

2. **Are there missing shapes/parameters to test in current and forthcoming polarization CMB datasets? Yes!**

   e.g. Very little work so far on Trispectrum (g_{NL},τ_{NL})

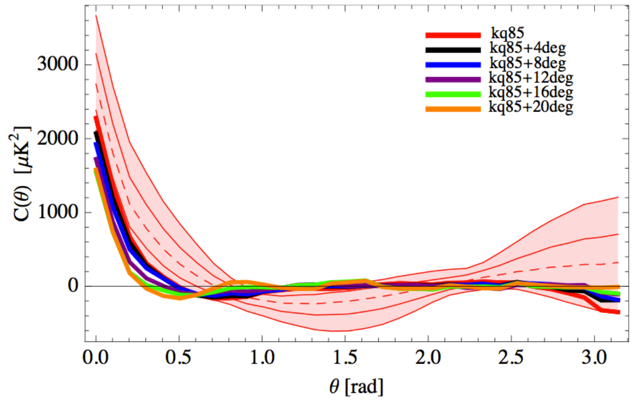
3. **Can we use NG to test gravity? What about 3-point function of tensor perturbations?**

Michele Liguori , Sabino Matarrese, Padova

The CMB as a window to the very early universe

- Unexpected features from large angle anisotropies. These scales are the most primordial.
- Long list of "anomalies": lack of correlation, low variance, alignments, power asymmetry etc. Origin unknown. Are they real?Are they hinting at new physics?
- Polarization analysis will provide a clue. Need new models to provide explanations/observables.

e.g.:
Gruppuso MNRAS 2014
Gruppuso, Natoli, Paci et al. JCAP 2013
Paci, Gruppuso, Finelli et al. MNRAS 2013
Hansen, Banday, Gorski et al. ApJ 2009

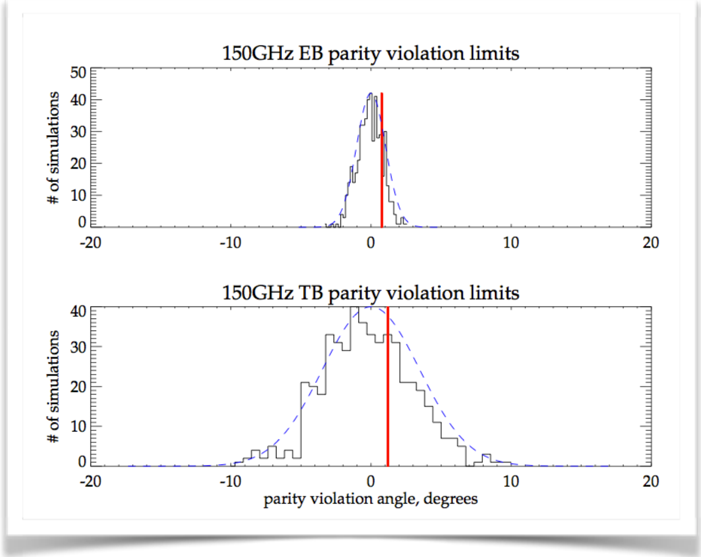


A. Gruppuso, M. Lattanzi, P. Natoli

The CMB as a laboratory to probe new physics

- Cosmic birefringence: standard tracer of parity violation in the EM/GW (chiral) sector.
- We look at the photons that achieve the longest possible journey.
- Need high quality CMB polarization datasets.

e.g.:
Gruppuso, Natoli, Mandolesi et al JCAP 2012
Gubitosi et al. JCAP 2012
Gluscevic & Kamionkowski PRD 2010
Cabella, Natoli & Silk PRD 2007



Example: QUAD Wu et al 2008

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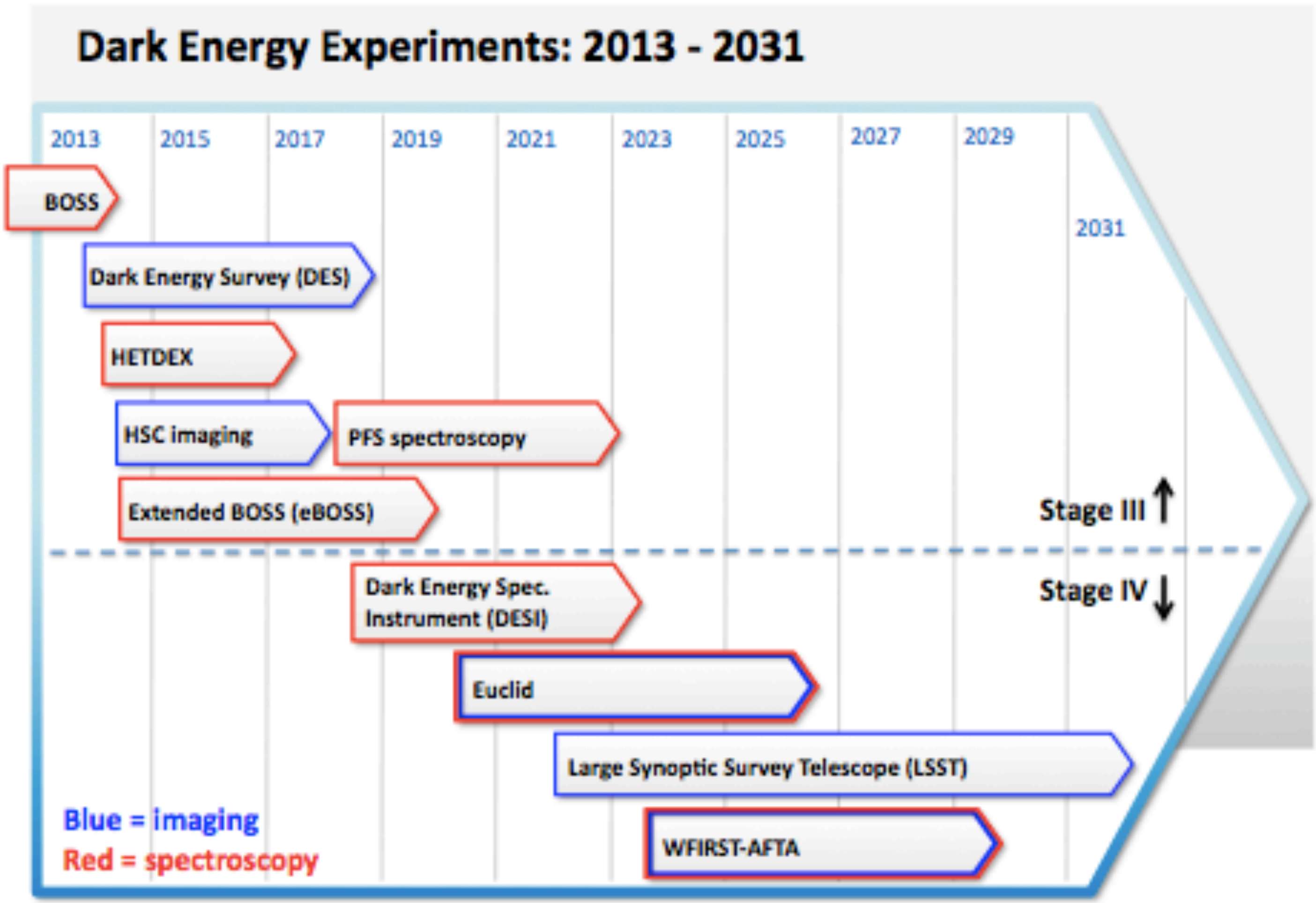
What Next?

- Exciting physics to dig out. However:
- Need data, in particular high quality CMB polarization data: Planck (ongoing), balloons + ground based, post Planck satellite (ESA/M4 call around the corner)
- Need expertise, in particular phenomenological, data analysis and interpretation. Benefit from Planck experience/legacy.

DARK ENERGY: WHAT NEXT?



Over the next 10 years or so study of galaxy clustering will be a major focus for Cosmology that will involve a significant fraction of the community worldwide and **will trigger major theoretical and technical advances** towards a better understanding of the Dark Energy, Dark Matter and Non-standard gravity issues, **inevitably involving theoretical and particle Physics**.

Euclid in a nutshell

Simultaneous (i) visible imaging (ii) NIR photometry (iii) NIR spectroscopy

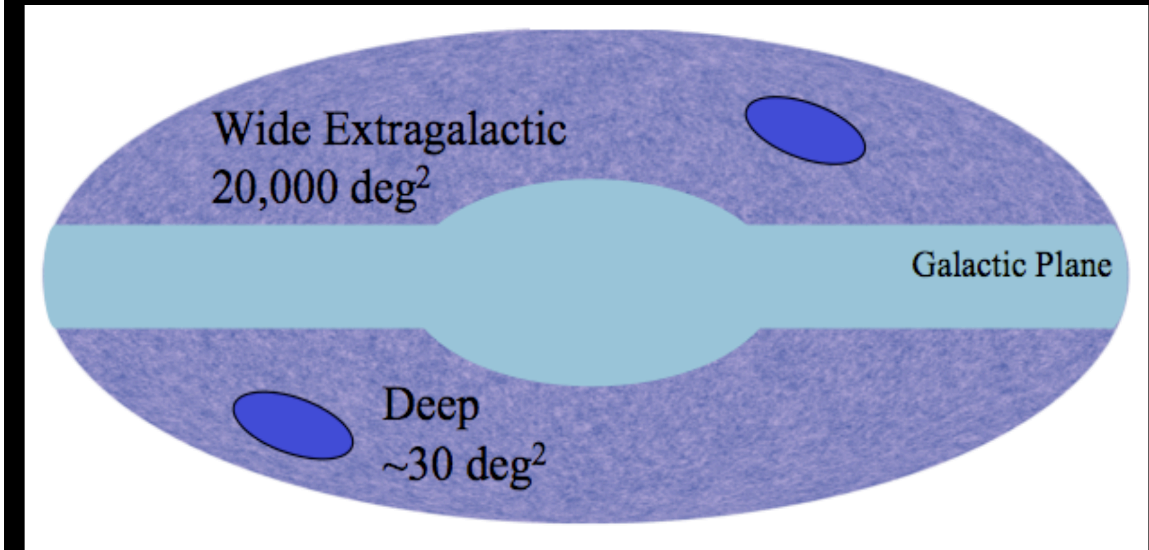
15,000 square degrees

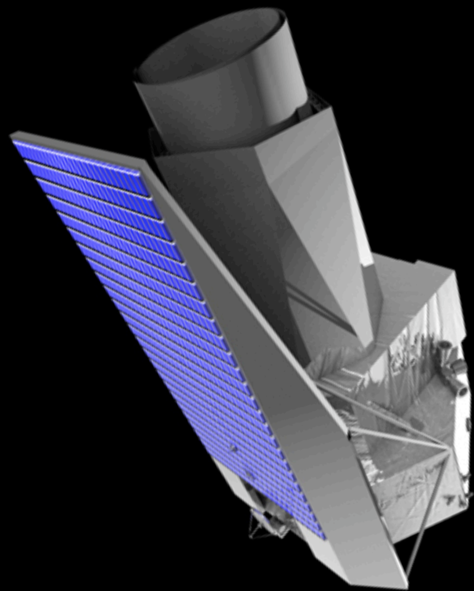
100 million redshifts, 2 billion images

Median redshift z = 1

PSF FWHM ~0.18''

>900 peoples, >10 countries





Euclid satellite

arXiv Red Book 1110.3193

	Modified Gravity	Dark Matter	Initial Conditions	Dark Energy		
Parameter	γ	m_ν /eV	f_{NL}	w_p	w_a	*FoM*
Euclid primary (WL+GC)	0.010	0.027	5.5	0.015	0.150	430
Euclid All	0.009	0.020	2.0	0.013	0.048	1540
Euclid+Planck	0.007	0.019	2.0	0.007	0.035	4020
Current (2009)	0.200	0.580	100	0.100	1.500	~10
Improvement Factor	**30**	**30**	**50**	**>10**	**>40**	**>400**

Ref: Euclid RB arXiv:1110.3193

Assume systematic errors are under control

WHAT NEXT DE 1: From here to Euclid (2020) and beyond.

Spatial distribution of galaxies and their clustering properties will be able to distinguish between DARK ENERGY VS DEVIATIONS FROM GENERAL RELATIVITY as the source of the acceleration

All this requires measurements AND model preditions at the % level.

Roadmap with several landmarks:

- Improvement of theoretical models for galaxy clustering and their anisotropies
- Development, implementation and validation of statistical estimator for galaxy clustering
- Set up numerical tools for testing purposes (i.e. N-body simulations and mock galaxy catalogs)
- Preliminary applications on available datasets as well as to new datasets from ongoing and upcoming "pathfinders" observational campaigns over redshift ranges similar to those probed by Euclid and SKA but on smaller areas and lower sensitivity (e.g. the Italy-lead VIPERS survey).

All **ongoing activities** carried out in the framework of international collaborations In which the **Italian contribution is very substantial**. They will gather more momentum **over the next decade**, with the start of the Euclid mission / new ground-based facilities such as SKA.

E. Branchini, A. Balaguera-Antolinez, M. Corsi, A. Postiglione,
ROMA TRE

WHAT NEXT DE 2: CMB-LSS Cross Correlation for Dark Energy and Modified Gravity

Providing algorithms for data analysis for the

experiments on

- **LSS: Euclid (CMBXC),**
- **CMB: Planck and forthcoming (sub-orbitals) and future satellite (ESA M4 proposal coming soon)**

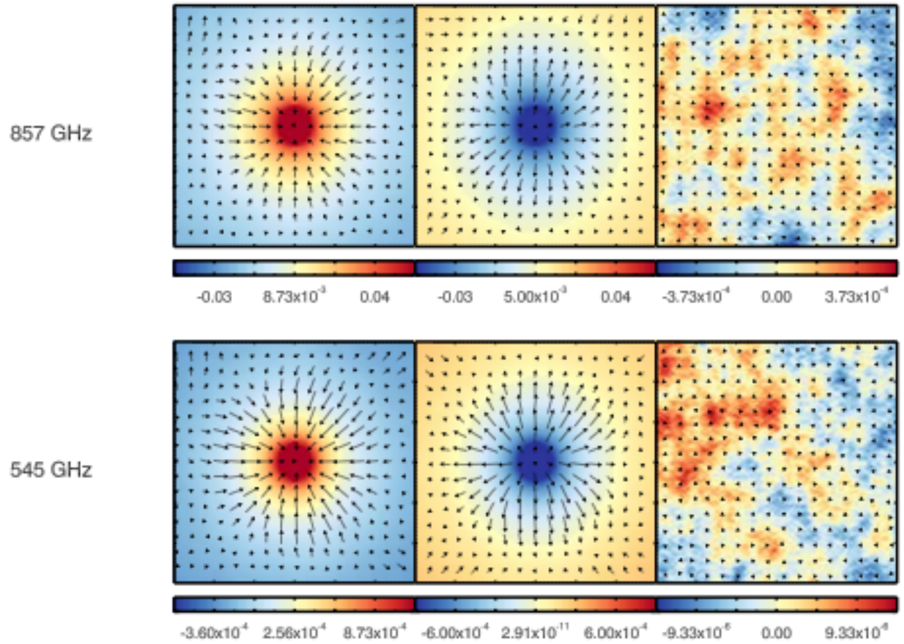
Also, Boltzmann codes for theoretical models of

Dark energy, modified gravity

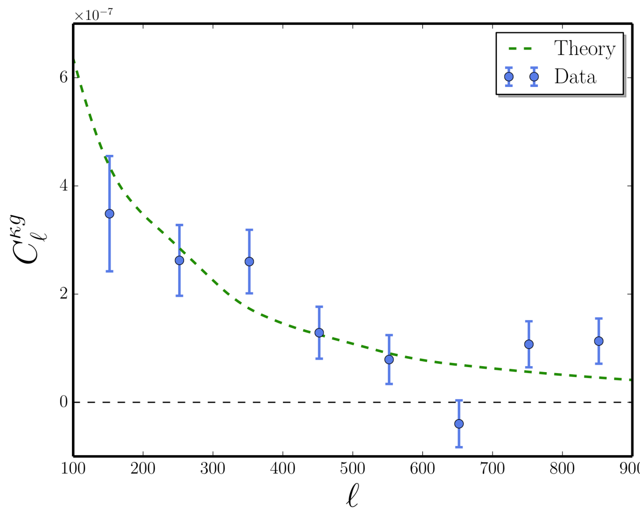
Baccigalupi, Fabbian, Martinelli, Silvestri, Antolini, Bianchini, Calabrese, Raveri, TRIESTE

WHAT NEXT DE 2: CMB-LSS cross-correlation for DARK ENERGY

- Cross-correlation between CMB and LSS due to interactions of CMB photons with tracers of LSS:
  - The ISW effect (due to changes of gravitational potential with time, direct probing of dark energy for flat Universe)
  - Gravitational lensing of CMB photons by LSS
  - The Sunyaev-Zeldovich effect (interaction of ionized intergalactic medium with CMB photons)
- Weak detection of the ISW effect (around 3σ, stronger detection possible with future galaxy surveys)
- Confirmed cross-correlations between CMB lensing potential and other tracers of LSS (quasars, galaxies, radio galaxies, clusters), examples:
  - > 40σ detection of the cross-corrrelation between CIB and the gravitational lensing potential derived from the Planck CMB maps
  - Detection of cross-correlation of the gravitational lensing potential from the Planck data and the Herschel galaxy catalogue (z > 1.5, excellent tracers of LSS lensing CMB)
- With future galaxy surveys (DES, LSST, Euclid) cross-correlation with CMB, as the most distant source of photons in the Universe, will enable to trace evolution of LSS formation, properties of dark energy and test GR for large part of the history of the Universe



Planck 2013 results XVIII



Bianchini et al. (2014), in preparation

Baccigalupi Fabbian, Martinelli, Silvestri, Antolini, Bianchini, Calabrese, Raveri, TRIESTE

WHAT NEXT DE 3: simulations of non-standard cosmologies

$$G_{\mu\nu} = 8\pi G\left(T^{\mathrm{DM}}_{\mu\nu} + T^{\mathrm{DE}}_{\mu\nu}\right)$$

OPEN QUESTIONS

Gravity	Dark Matter	Dark Energy
beyond GR?	beyond neutralinos?	beyond Λ?

MODELS

Modified Gravity theories: f(R), Dilaton, Vainshtein, Galileon, etc...	Warm Dark Matter, massive neutrinos, sterile neutrinos, etc...	Dark Energy models: Quintessence, k-essence, Phantom,Clustering DE, extended Quintessence, coupled DE, etc...

N-BODY CODES

MG-GADGET (Puchwein, Baldi & Springel 2013)	**NU-GADGET** (Viel, Haehnelt & Springel 2010)	**C-GADGET** (Baldi et al. 2010)

MAIN GOAL : identify observational features of non-standard models

WHAT NEXT DE 4:

- Cosmological parameters determination via the ISW-Lensing correlation (Eleonora di Valentino)
- CMB constraints on Alternative theories of Gravity (Andrea Marchini)
- Dark energy properties (Najla Said)
- Dark Matter-Dark enrgy interactions (Valentina Salvatelli)