NEW DIRECTIONS:
Inflation and Dark energy..what next??

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Inflation: CMB and new pathways

- A number of inflationary parameters have been constrained with great accuracy (*Planck)*:
  - amplitude of density (scalar) perturbations A_s
  - spectral index n_s (and its running)
  - amplitude of gravity waves (tensor-to-scalar ratio r) ←→ energy scale of inflation
  - primordial non-Gaussianity: a laboratory for cosmological scattering experiments
  f_{NL} (g_{NL}): amplitude of bi(tri)spectrum – 3(4)point function -- of primordial perturbations
- Despite the simplicity of the inflationary mechanism, the precise model has still to be identified

- ***There is a huge potential improvement***

- CMB E and B mode polarization
- Primordial NG from: Large-Scale Structure surveys (scale-dependent halo bias+ bispectrum) CMB spectral distortion; high-redshift 21 cm fluctuations
- Recently developed pipelines to constrain CMB trispectrum
- Synergies between CMB and interferometers

Primordial non-Gaussianity

	$f_{NL}^{loc} \lesssim 1$	$f_{NL}^{loc} \gtrsim 1$
$f_{NL}^{eq, orth} \lesssim 1$	Single-field slow-roll	Multi-field
$f_{NL}^{eq, orth} \gtrsim 1$	Single-field non-slow-roll	Multi-field

- **Primordial non-Gaussianity (NG) is a crucial observable to test the fundamental physics of inflation. It probes interaction terms of quantum fields at extreme energies. Of paramount importance to distinguish inflation models.**
- Best constraints to date come from *Planck* observations of CMB anisotropies
- Core+ can improve by a factor of 2 by fully exploiting polarization information

$$f_{NL}(local) = 2.5 \pm 5.7 \;\; (68\% \text{ CL})$$

$$f_{NL}(equilateral) = -16 \pm 70$$

$$g_{NL} = -(9.0 \pm 7.7) \times 10^4$$

A *crucial* prediction of Standard Single Field Inflation: $f_{NL} \sim 0.01 \sim O(\varepsilon,\eta)$

Acquaviva,Bartolo, Riotto, Matarrese et al 2002; Maldacena 2002

Primordial non-Gaussianity: galaxy and radio surveys

- e.g. Scale-dependent halo bias and large radio surveys

Shape	$\mathrm{EMU}_C^{100\mu Jy}$	$\mathrm{EMU}_O^{100\mu Jy}$	$\mathrm{EMU}_C^{50\mu Jy}$	$\mathrm{EMU}_O^{50\mu Jy}$	$\mathrm{SKA}_C^{5\mu Jy}$	$\mathrm{SKA}_O^{5\mu Jy}$	SKA_C^{100nJy}	SKA_O^{100nJy}	Futuristic	CMB
$\sigma(f_{\rm NL})$ local	11.94	5.54	9.26	4.37	1.62	1.06	0.67	0.51	0.21	5.7
$\sigma(f_{\rm NL})$ equilateral	221.14	79.84	179.03	62.58	22.24	9.09	6.18	2.83	0.42	70
$\sigma(f_{\rm NL})$ orthogonal	102.97	39.04	82.25	30.69	15.30	7.40	6.71	3.35	0.54	33
$\sigma(f_{\rm NL})$ folded	151.48	56.45	121.50	44.35	20.29	9.25	8.15	4.14	0.96	65
$\sigma(c_{L=1})$	1916.29	721.15	1519.8	558.35	200.62	78.32	41.81	17.54	2.14	103
$\sigma(c_{L=2})$	10874.9	4113.82	8436.7	2952.5	1098.93	393.60	193.48	76.55	9.22	26

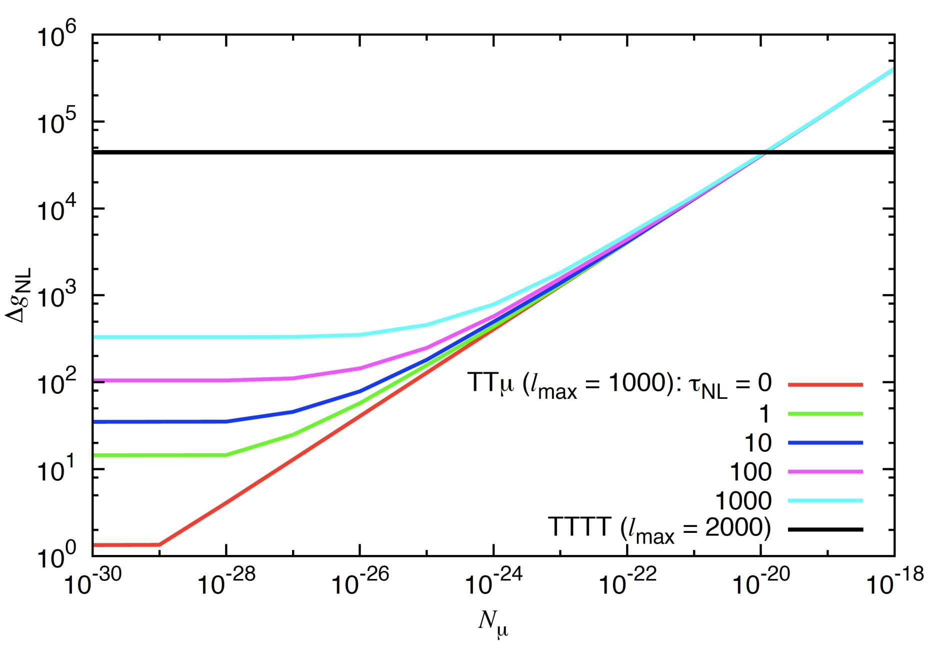
Raccanelli et al. 15

1σ CMB *Planck 2015*
Standard models of inflation predict f_{NL}~0.01
FUDAMENTAL TEST OF STANDARD MODELS OF INFLATION.

- Euclid will be able to achieve a sensitivity down to f_{NL}=2.

N.B.: Methods, statistical estimators developed within CMB *Planck* analysis for primordial NG can be applied to test primordial NG from Large-Scale Structure surveys

New future probes: CMB spectral distortions & 21 cm

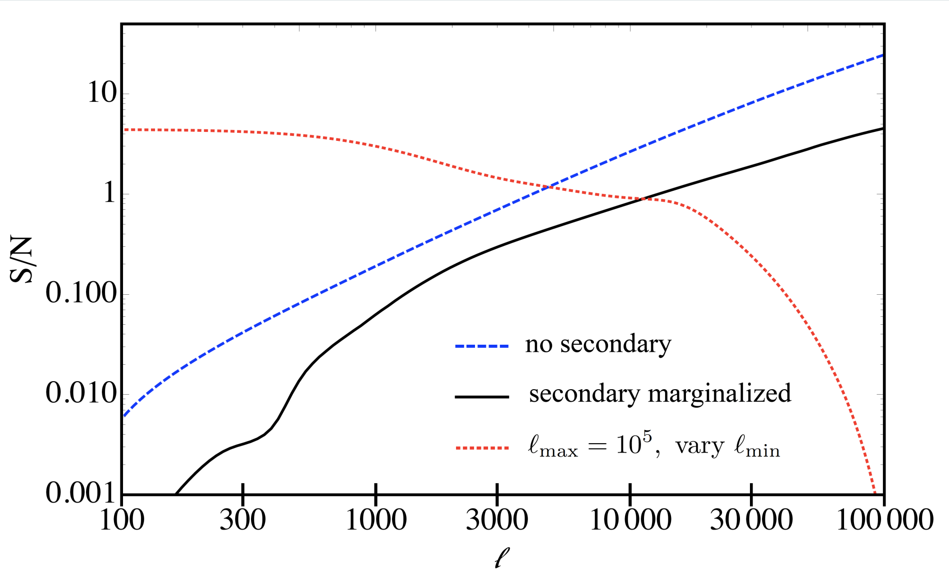


Cross-correlation CMB T anisotropies and CMB μ-spectral distortions: a cosmic-variance limited experiment can reach

f_{NL}(local)~0.001 !!!! (for PRISM ~23)

g_{NL}~4 !!!!! (for CMBPol ~5×10^5)

Pajer and Zaldarriaga '12
Ganc & Komatsu 2012
Bartolo, Liguori, Shiraishi 2015



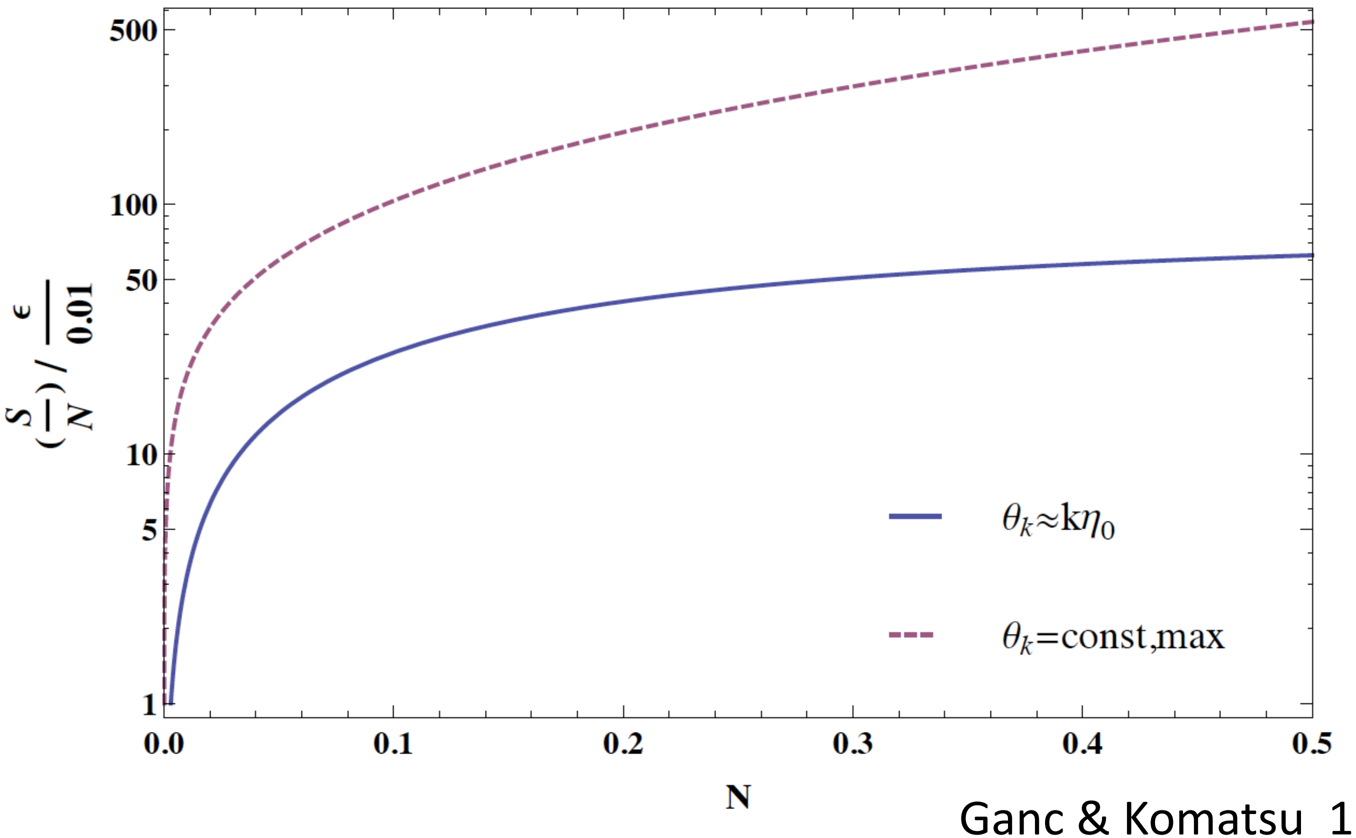
High-z 21cm fluctuations: a cosmic-variance limited experiment can reach

f_{NL}(local)~0.03

f_{NL}(equil.)~0.04 !!!!!

Munoz, Ali-Haimond, Kamionkowski '15
A. Cooray, 06
Pillepich, Porciani, Matarrese 07

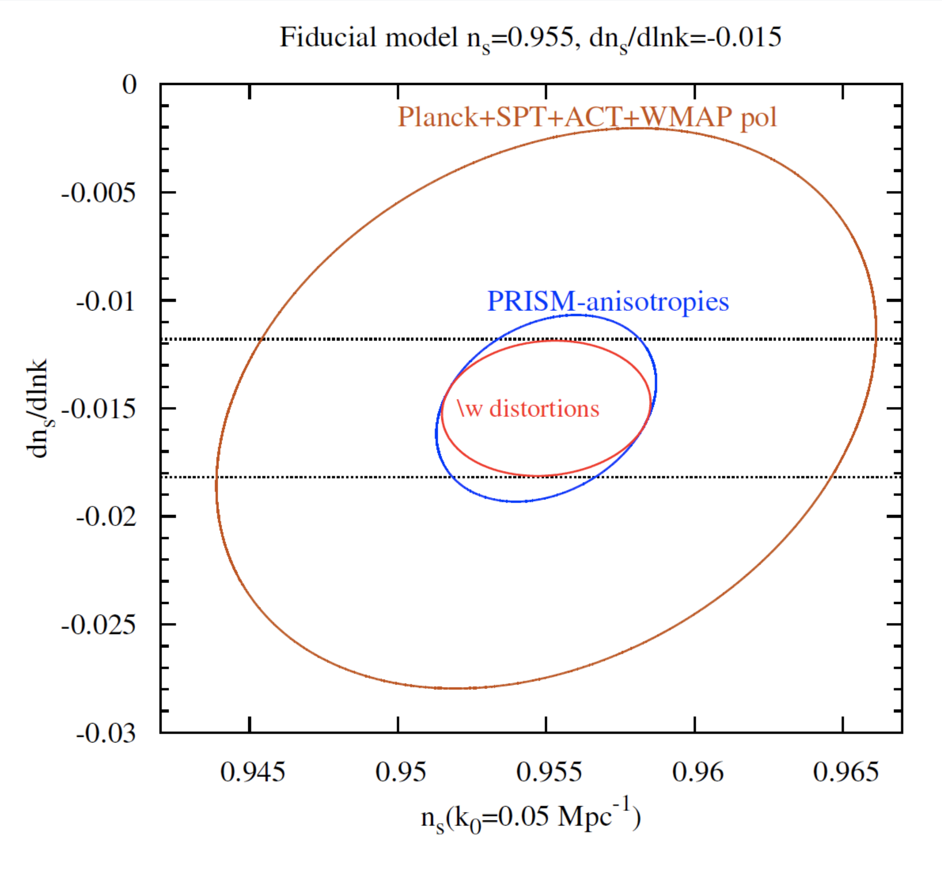
New future probes: CMB spectral distortions & 21 cm

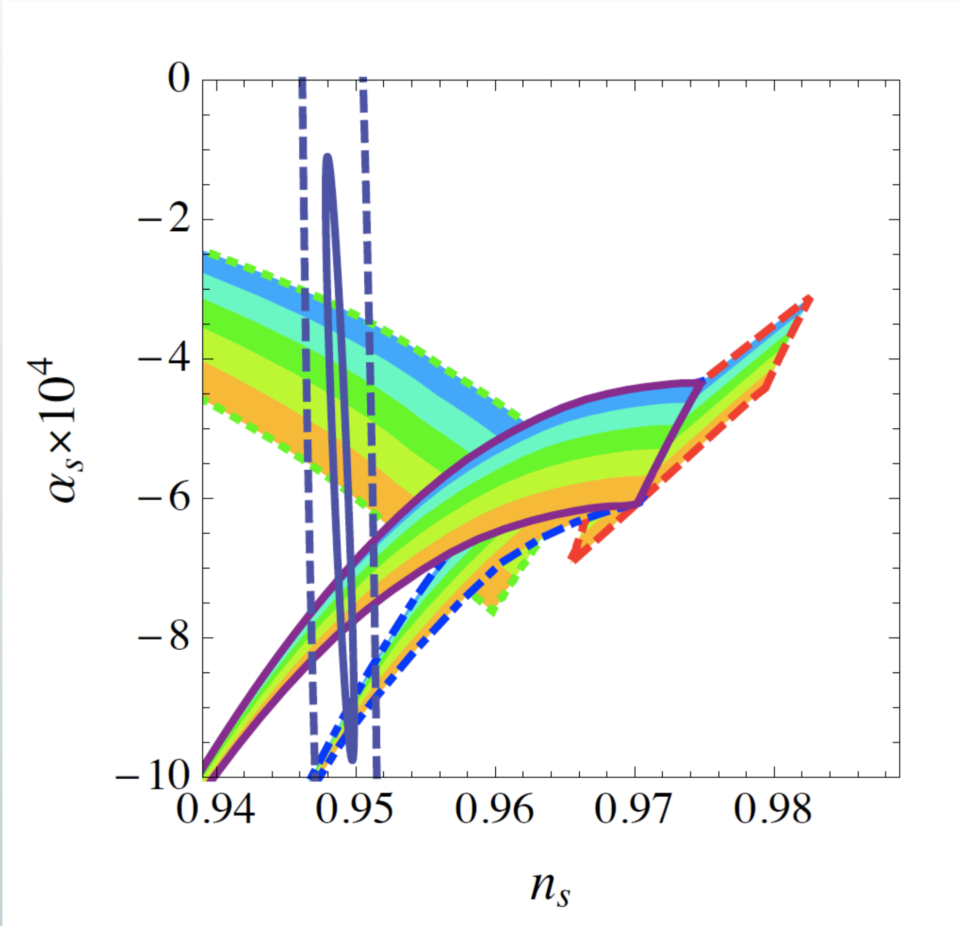


Ganc & Komatsu 13

Deviations from a non-Bunch Davies vacuum state during inflation *could* be already detected by *Planck via CMB μ-spectral distortions;*
for sure they are at the reach of a PIXIE like experiment

Running of the spectral index

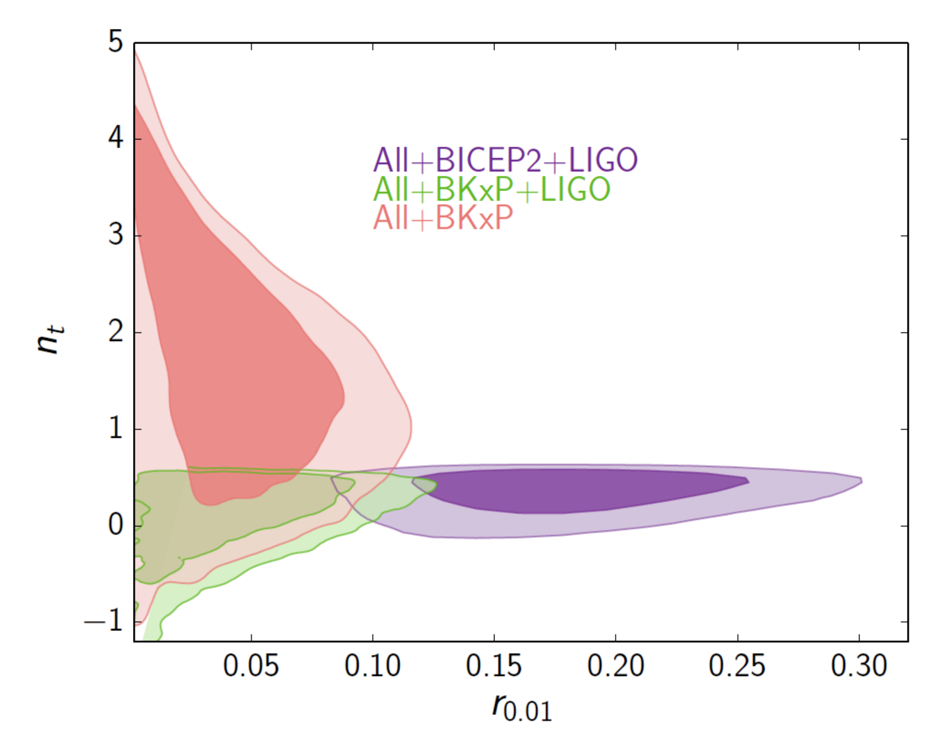


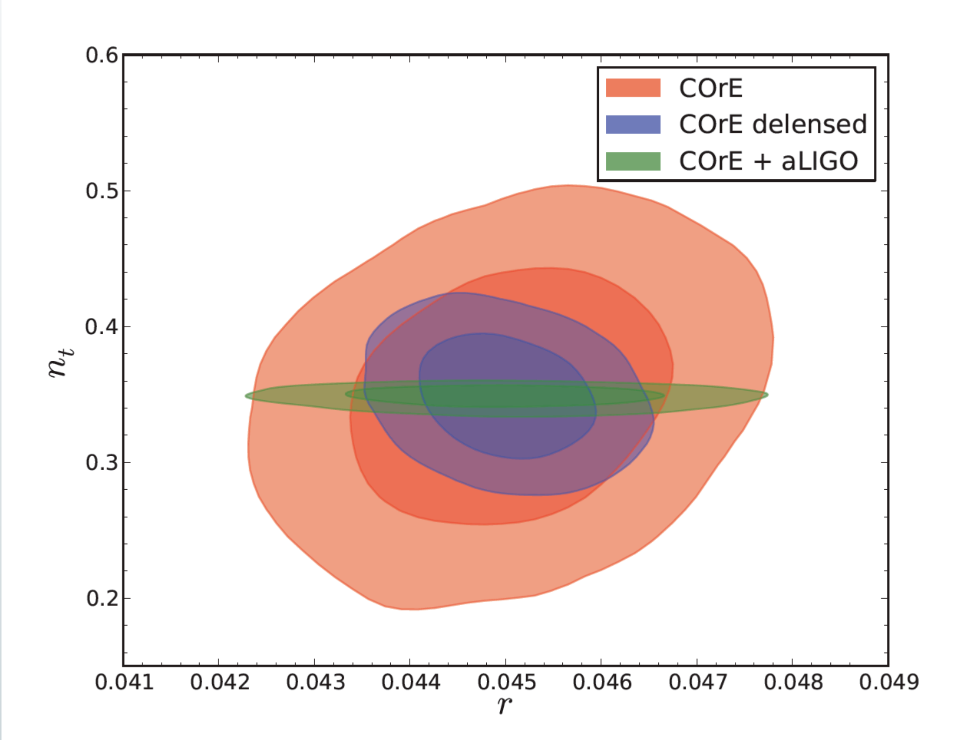


With the CMB spectral distortions an exp. like PRISM can measure the running more precisely Wthan *Planck* by a factor of 3

With 21 cm the running can be measured more precisely than *Planck* by a factor of 10

Synergies between CMB and interferometers





Meerburg et al. 1502.00302
(see also, e.g., Cabass et al 1511.05146;
Lasky et al. 1511.05995
Blair et al. 1602.02872)

Cabass et al 1511.05146

LARGE-SCALE-STRUCTURE SURVEYS AND DARK ENERGY

Euclid - INFN

- Da inizio 2015 partecipazione dell'INFN alla costruzione del satellite EUCLID
- Responsabilità dei gruppi BO-Pd sull'integrazione hardware/software dell'elettronica a caldo dello strumento che opera nell'infrarosso (NISP)

  (per la parte teorica molti altri nodi INFN gia` coinvolti)
- Partecipazione allo sviluppo del software di bordo.
- Attività future / Opportunità:
  - *Partecipazione alla presa dati (NISP Operational Team)*
  - *Contributo gestione dati del Science Ground Segment*
  - *Attività di ricostruzione e simulazione osservabili , in particolare Weak Lensing e Galaxy Clustering (natura Dark Energy e Dark Matter)*
  - *Sviluppo di algoritmi di analisi*

NB: L'entità dell'impegno futuro è condizionato alla disponibilità di (auspicabili) nuove forze

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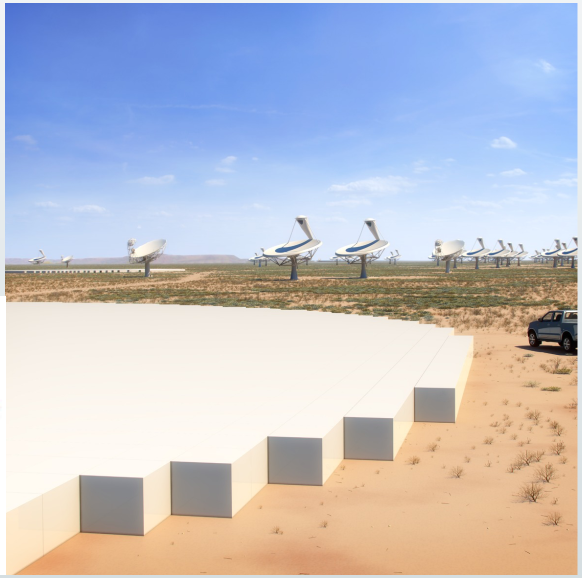
- Interessante esempio di collaborazione tra enti di ricerca (comunita` scientifiche) con know-how diversificati. Gia` molte le competenze in questo ambito di ricerca all'interno di IS INFN astroparticellari, pronte a far supporto alla parte sperimentale per analisi dati
- Altro esempio: supporto INFN a analisi dati di non-Gaussianity per terza release di *Planck*
- Altro campo di interesse puo` essere HPC per simulazioni cosmo. di ΛCDM (e oltre) o per sviluppare pipelines di applicazione di estimatori statistici in diff. tipi di analisi dati

The Square Kilometer Array

https://www.skatelescope.org/

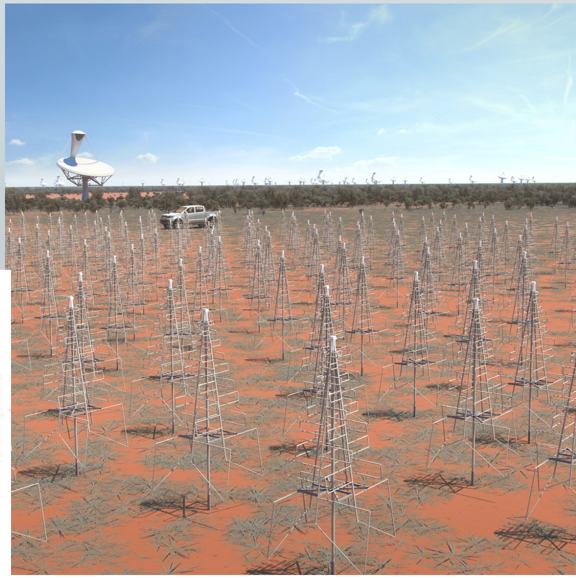
New re-baselining (as of March 2015)



SKA1-Mid

➔Freq. range: 300 MHz - 15 GHz

➔130 15m dishes in South Africa



SKA1-Low

➔Freq. range: 50-350 MHz

➔~ 130.000 low-frequency dipoles in Australia

2018-2023: Construction of SKA1;
2020+ SKA1 Early Science

SKA – Surveys for Cosmology:

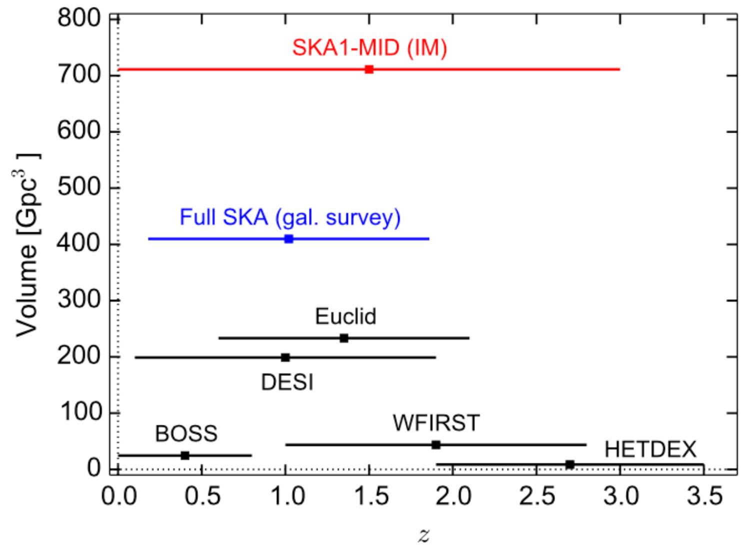
1. **HI Intensity Mapping** [BAO, super-horizon, etc.]
   All-sky**; low-resolution >30'**; 0<z<3

2. **HI Threshold:** galaxy redshift survey [BAO, RSD]
   SKA1: 5 10^6 gals @ z<0.5
   SKA2: ~10^9 gals @ z<2

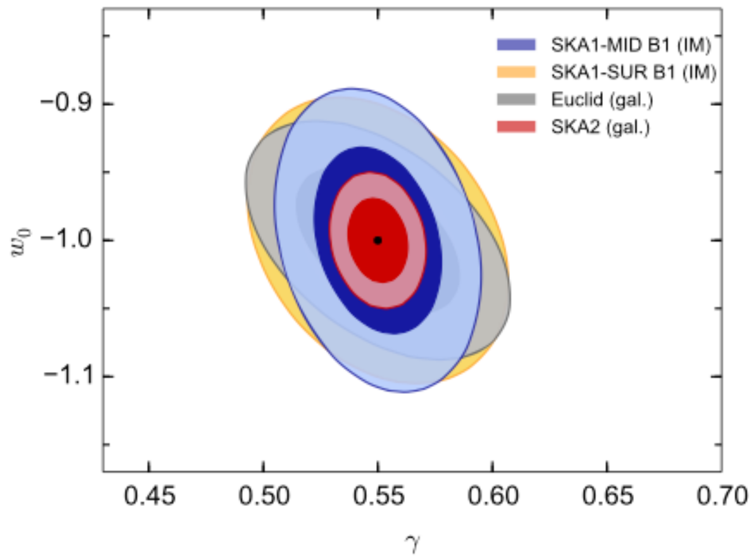
3. **Continuum** [weak lensing, angular clustering, ISW]:
   → All-Sky Survey (~ 1-2" res.)
   → Weak Lensing Survey (0.5" res.)

DM, DE, testing GR and initial conditions
Euclid + SKA: huge synergies
→ Scientific: smaller volume higher res. vs large volume low-res, complementary constraints, multi-tracers, etc.
→ Programmatics: e.g. simulations, likelihood definitions and coding, etc.

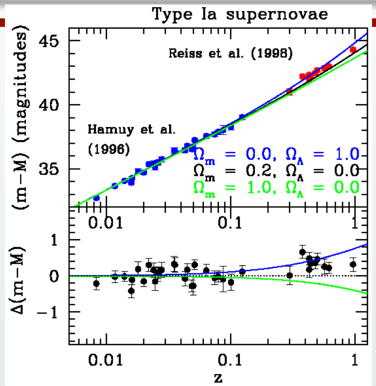
Maartens+15



Raccanelli+14



SN-Ia + CMB + surveys: a ``single experiment''



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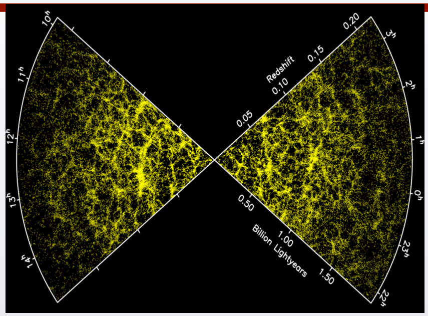

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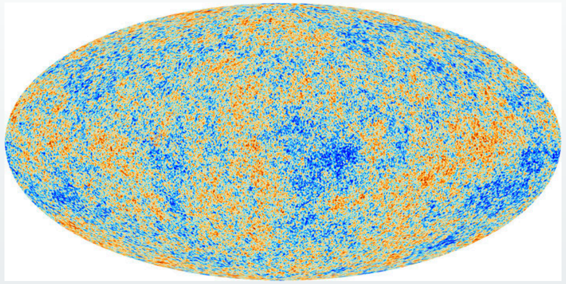
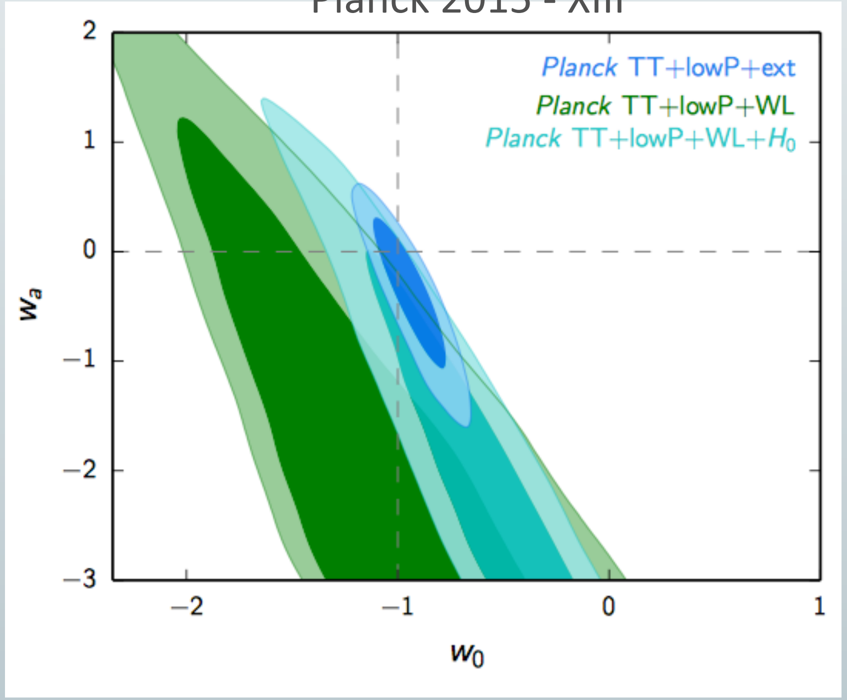
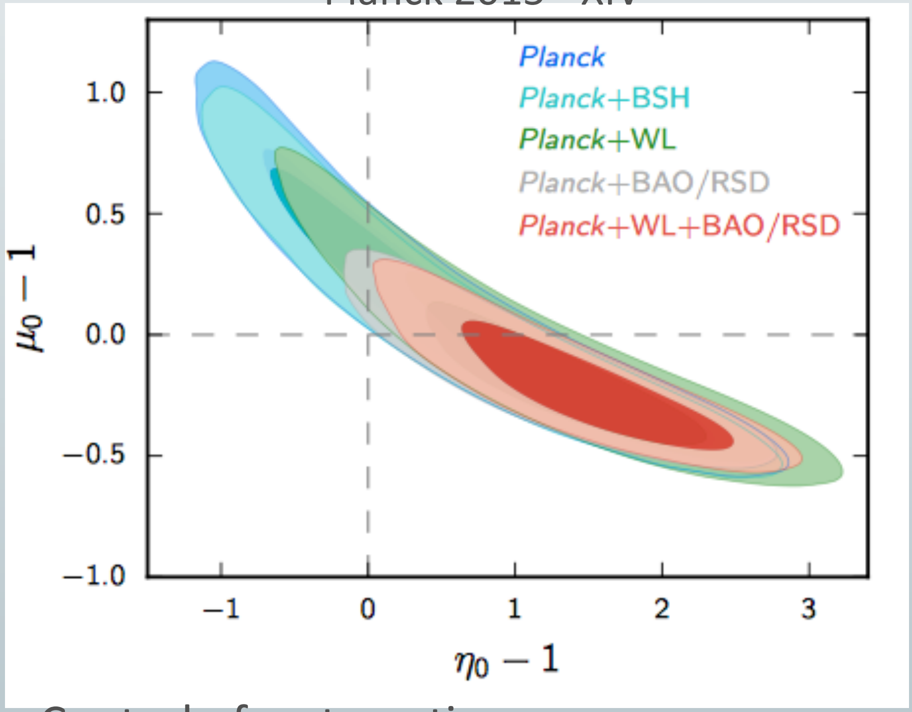


The combination is much more than the sum of the parts

Planck 2015 - XIII



Planck 2015 - XIV



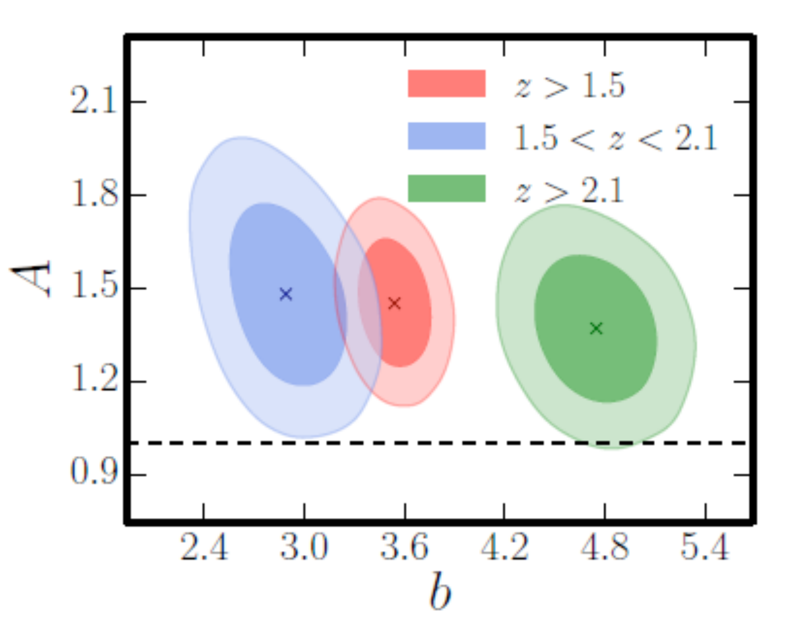
Signatures of new physics ➔ Control of systematics

CMB ⊗ LSS: Metodologies for Cross-Correlation & Separation

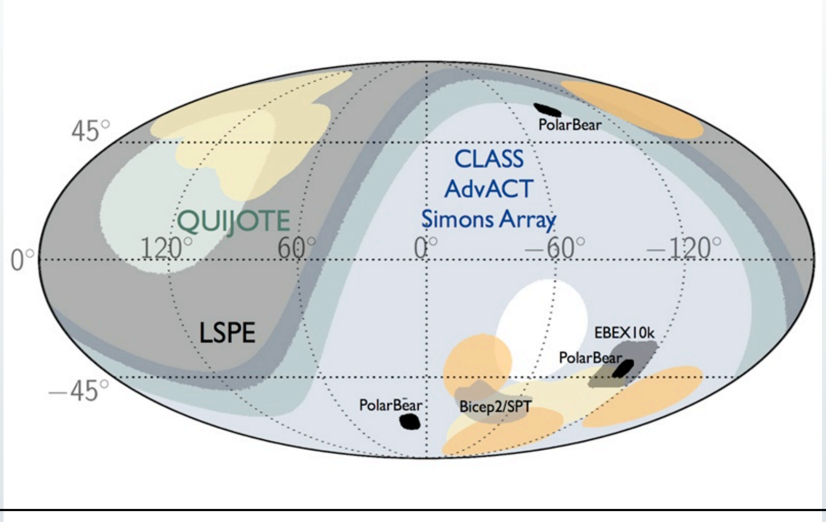
- Context and Relevance
  - *CMB lensing relevant for Dark Energy, Neutrino Mass, De-Lensing for B-mode experiments*
  - *CMB lensing takes power at high redshifts compared to Euclid (z<=2), peaking between 1 and 3 with a long tail extending to the reionization epoch. It is and will be used in combination/cross-correlation with LSS data in order to constrain the DE/MG at the corresponding epochs.*

    (Acquaviva e Baccigalupi 06).
  - *Context: CMBXC WG in Euclid, exploitation of Planck, operating CMB polarization experiments from the ground (PolarBear2, Spider, ...), future ones from the ground, balloon, space (S4, LSPE, CORE, ...)*
- Tasks
  - *Observe and Simulate Cross-Correlation between CMB lensing and LSS fields*
  - *CMB rendering through study and rmoval of diffuse polarized foregrounds in polarization*
- Status
  - *Planck lensing ⊗ Herschel detected with high confidence, dealing with systematics, constraining bias and signal amplitude (Bianchini et al. 2016)*
  - *CMB-N-body lensing implemented (Calabrese et al. 2015) for simulating CMB-LSS XC*
  - *Diffuse polarized foreground studies using existing satellite data (Krachmalnicoff et al. 2016), RADIOFOREGROUND COMPET-5 H2020 Grant starting in 2016*
- Issues: demanding simulations and computing resources, need for grants, coordinating within large collaborations, implementing multi-platform data analysis software, ...

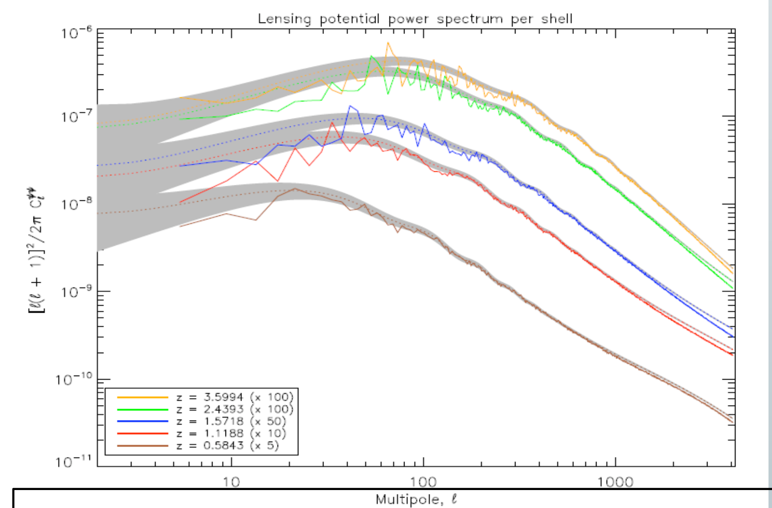
CMB ⊗ LSS: Highlights on Results



Evidence for bias evolution in tomographic analysis CMB lensing (Planck) and Herschel LSS Cross-Correlation, along with correlation excess (Bianchini et al. 2016, ApJ submitted)



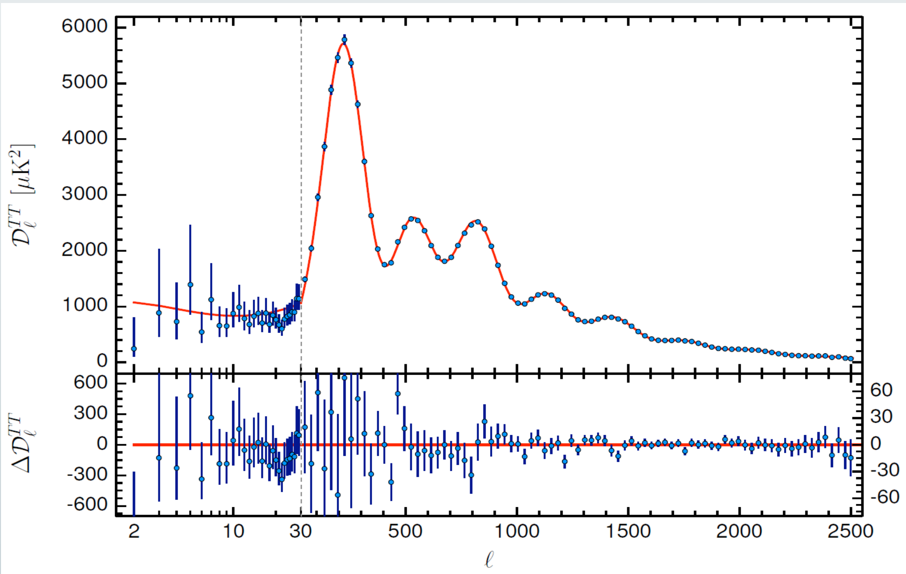
Regions of High Diffuse Polarized Foreground Contamination vs opearting and forthcoming CMB experiments (Krachmalnicoff et al., A&A 2016)



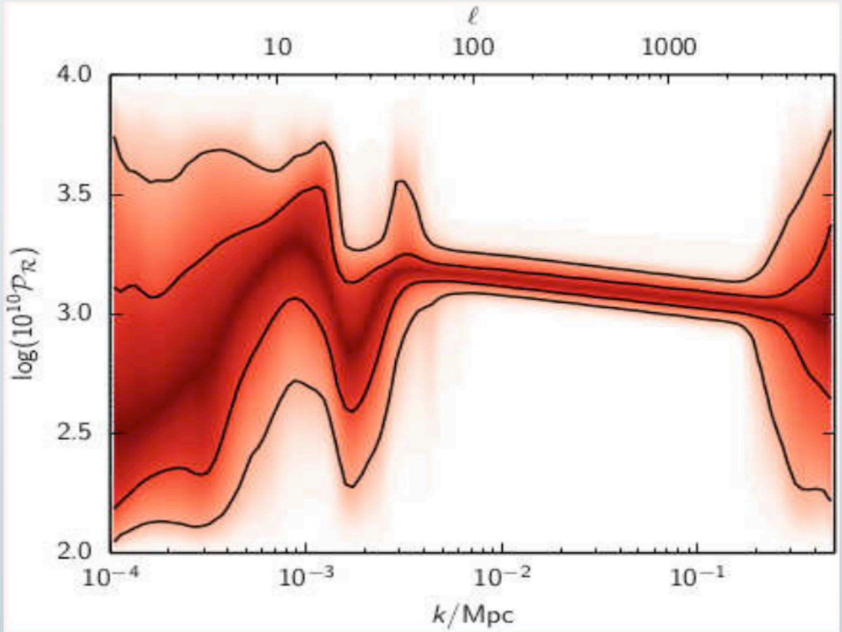
CMB-N-Body Lensing Potential in redshift shells (Calabrese et al., JCAP 2015)

Inflation with violation of slow-roll and future galaxy surveys

- Future galaxy surveys, in combination with Planck plus future CMB measurments, has also the capability to probe selected violations of slow-roll which could be the origin of the puzzles at low and intermediate multipoles in the temperature power spectrum (a low amplitude at l < 40 and a feature at l = 20) seen by Planck.



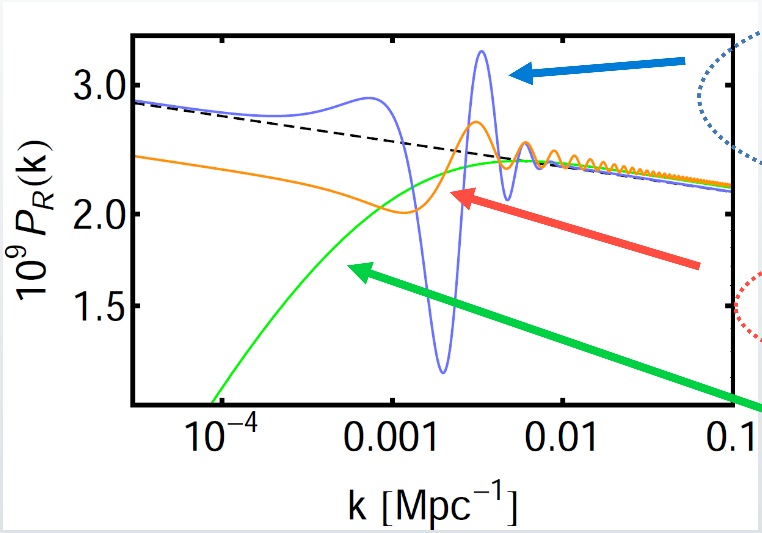
Planck 2015 results. XVI. Cosmological parameters



Planck 2015 results. XX. Constraints on inflation

- Because of cosmic variance, these anomalies in the CMB temperature power spectrum are not statistically significant but …
- ...you can look elsewhere: CMB polarization (Planck, ACTpol, CLASS, LSPE, ...)
  Galaxy surveys(DESI, EUCLID, SPHEREx, ...)

Several inflationary models can produce features in the primordial power spectrum which fit these anomalies, few examples:

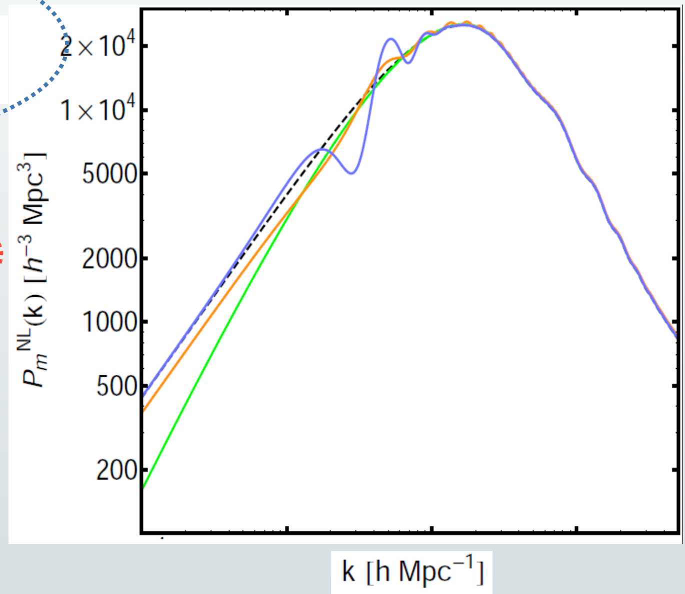


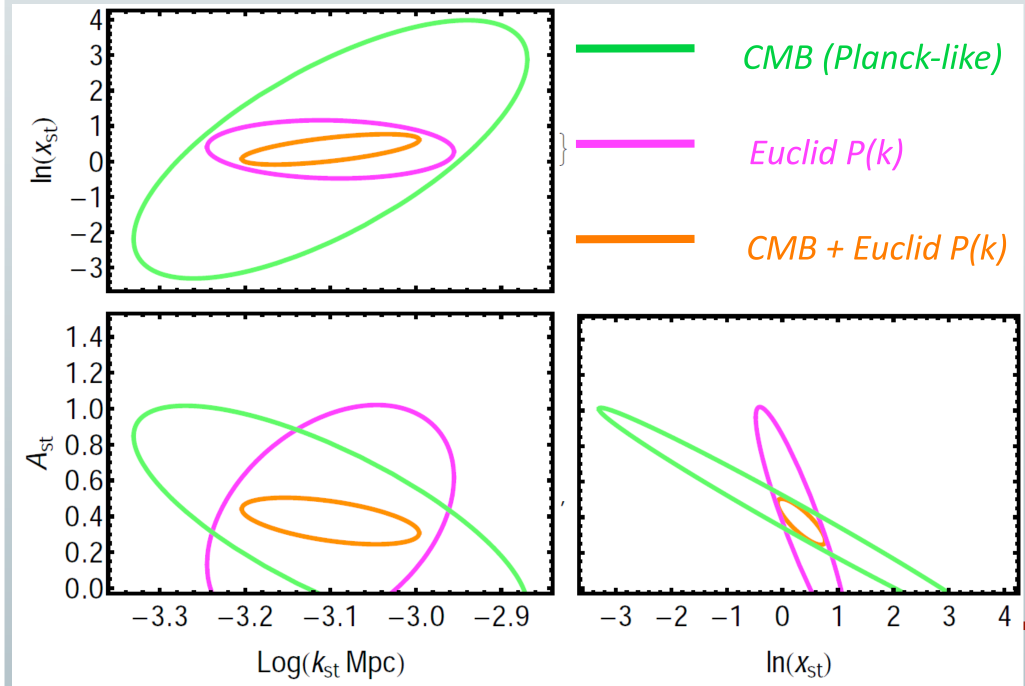
Step in the potential

$$V(\phi) = V_0(\phi)\left[1 + c\tanh\left(\frac{\phi - \phi_0}{d}\right)\right]$$

Discontinuity in the first derivative of the potential

Cutoff

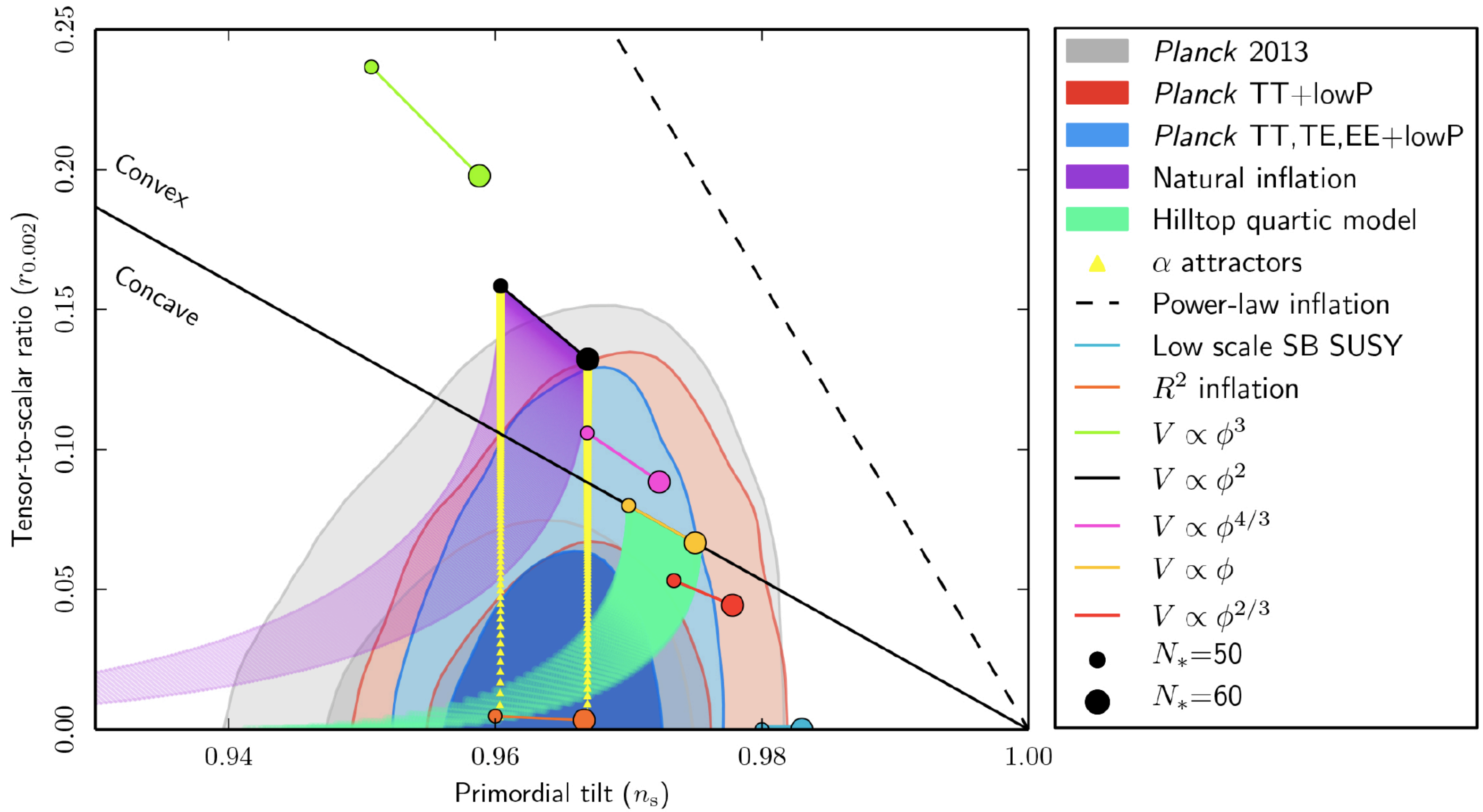




For the example of a step in the potential (A_{st}, k_{st}, x_{st} being the parameters of the model) the complementarity between the CMB and the galaxy power spectra (as from EUCLID, for istance) can efficiently proble primordial origin of these anomalies!

Ballardini+ 2016, to appear

Planck 2015 constraints on inflation



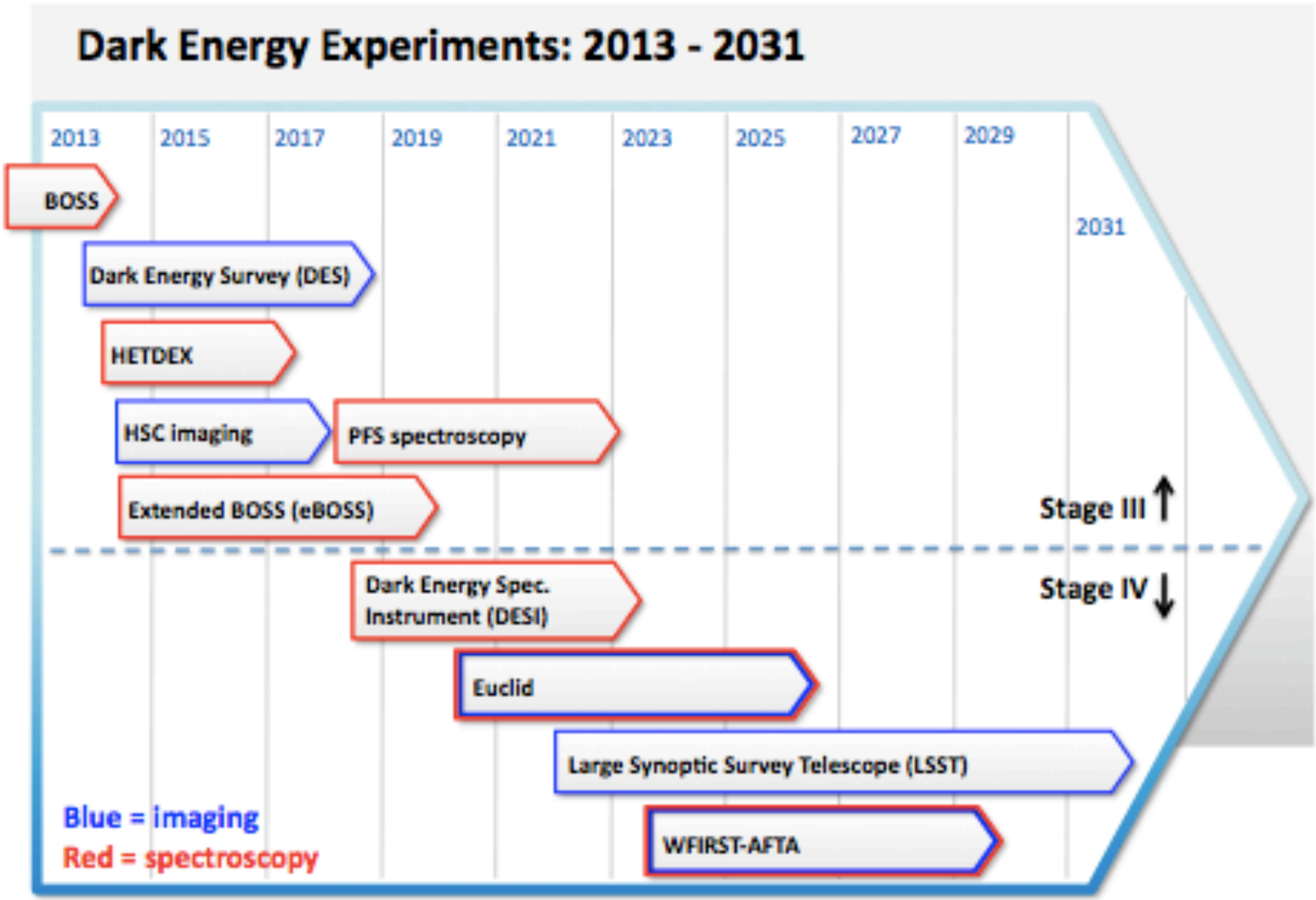
$$V^{1/4} = 1.94 \times 10^{16} \left(\frac{r}{0.12}\right)^{1/4} \text{GeV}$$

Results consistent with *Planck* 2013;

$r_{0.002}$<0.11 @95% CL consistent with Bicep2/Keck & *Planck* joint

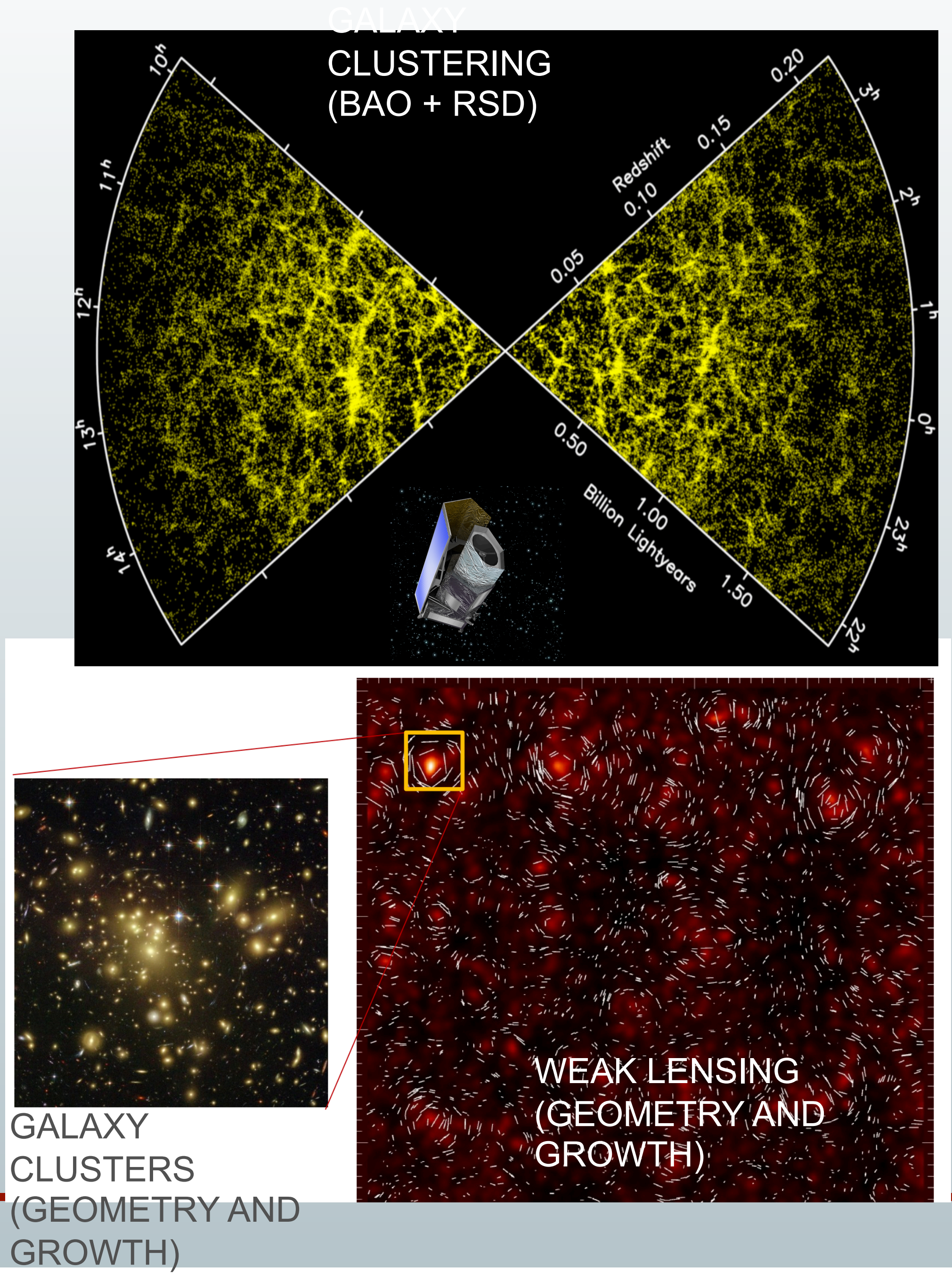
Increased precision

V(ϕ) ~ ϕ^2 disfavored wr.t. Starobinski model R+R^2



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



- Visible imaging (1 band)
- Infrared imaging (Y,J,H)
- Infrared slitless spectroscopy
- Approved 2011; Launch 2020

- 15,000 deg^2 survey
- Images for $2x10^9$ galaxies
- Spectra for ~5 x 10^7 galaxies (0.9<z<1.8)

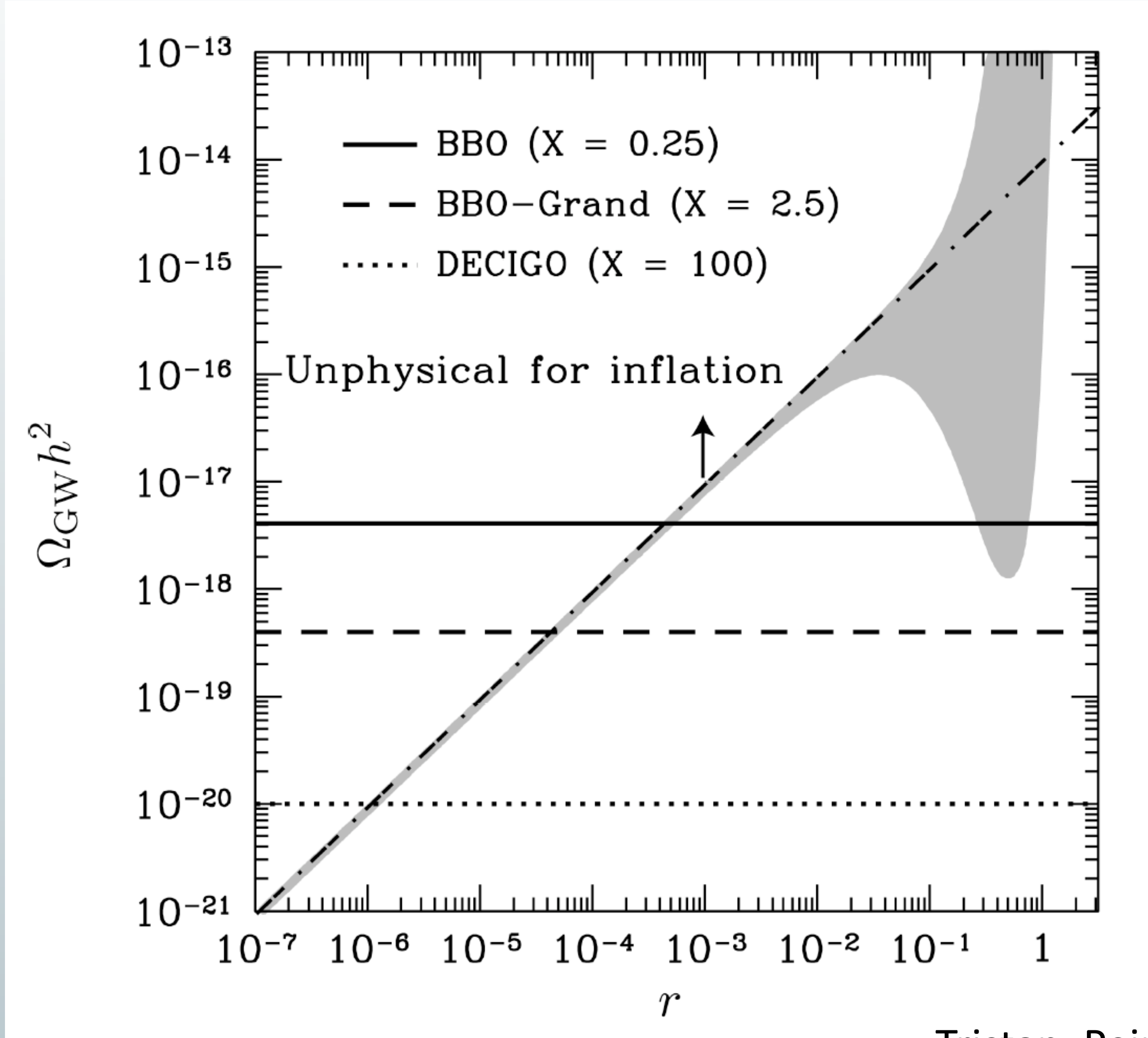
Objectives:
- Build a map of dark and luminous matter over 1/3 of the sky and to z~2
- Unveil the nature of dark matter
- Trace the origin of cosmic acceleration
- Use multiple probes → max control over systematic errors

Euclid – expected results

	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



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