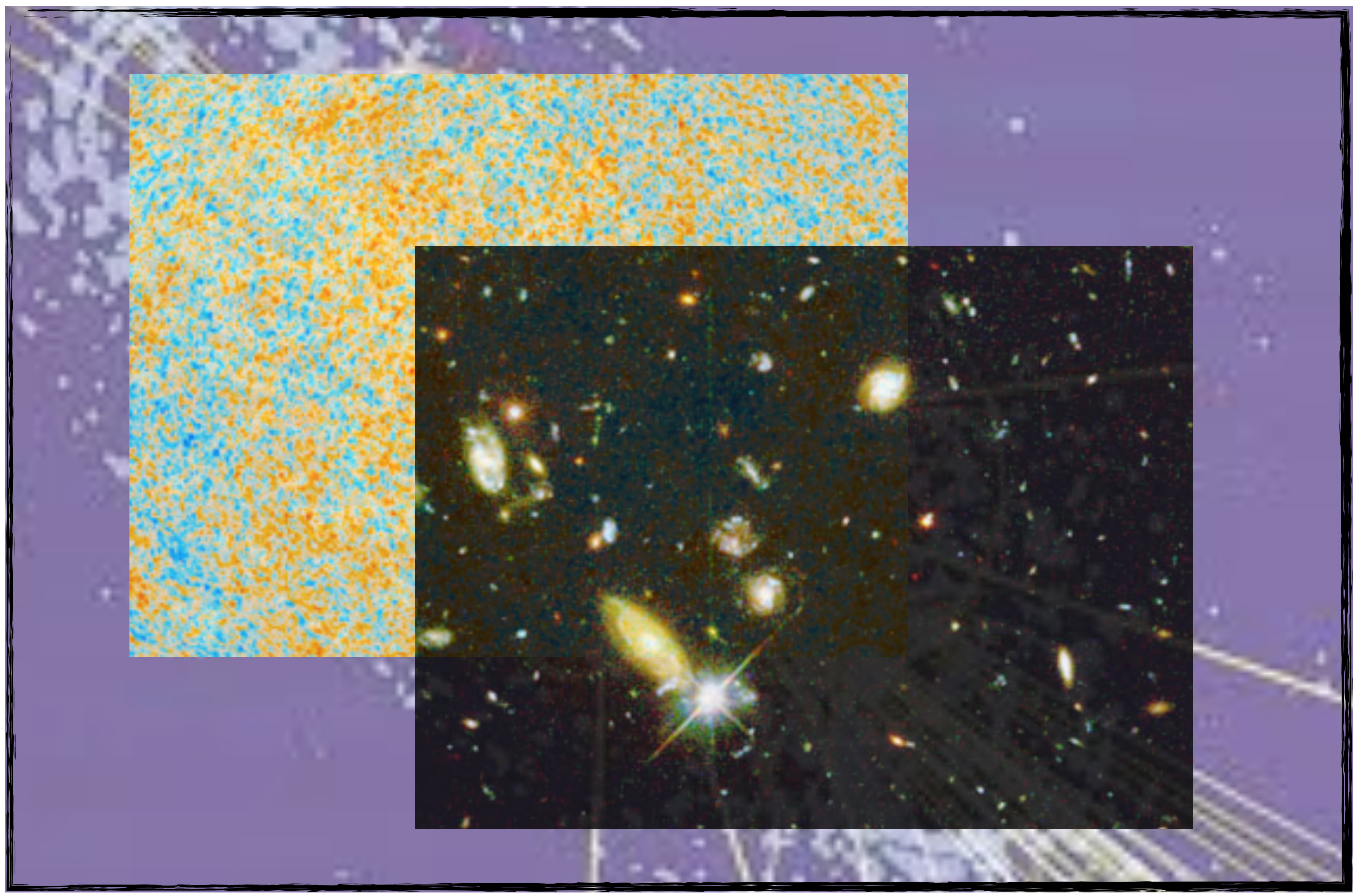
Probing fundamental physics with the Cosmic Microwave Background & Large Scale Structures



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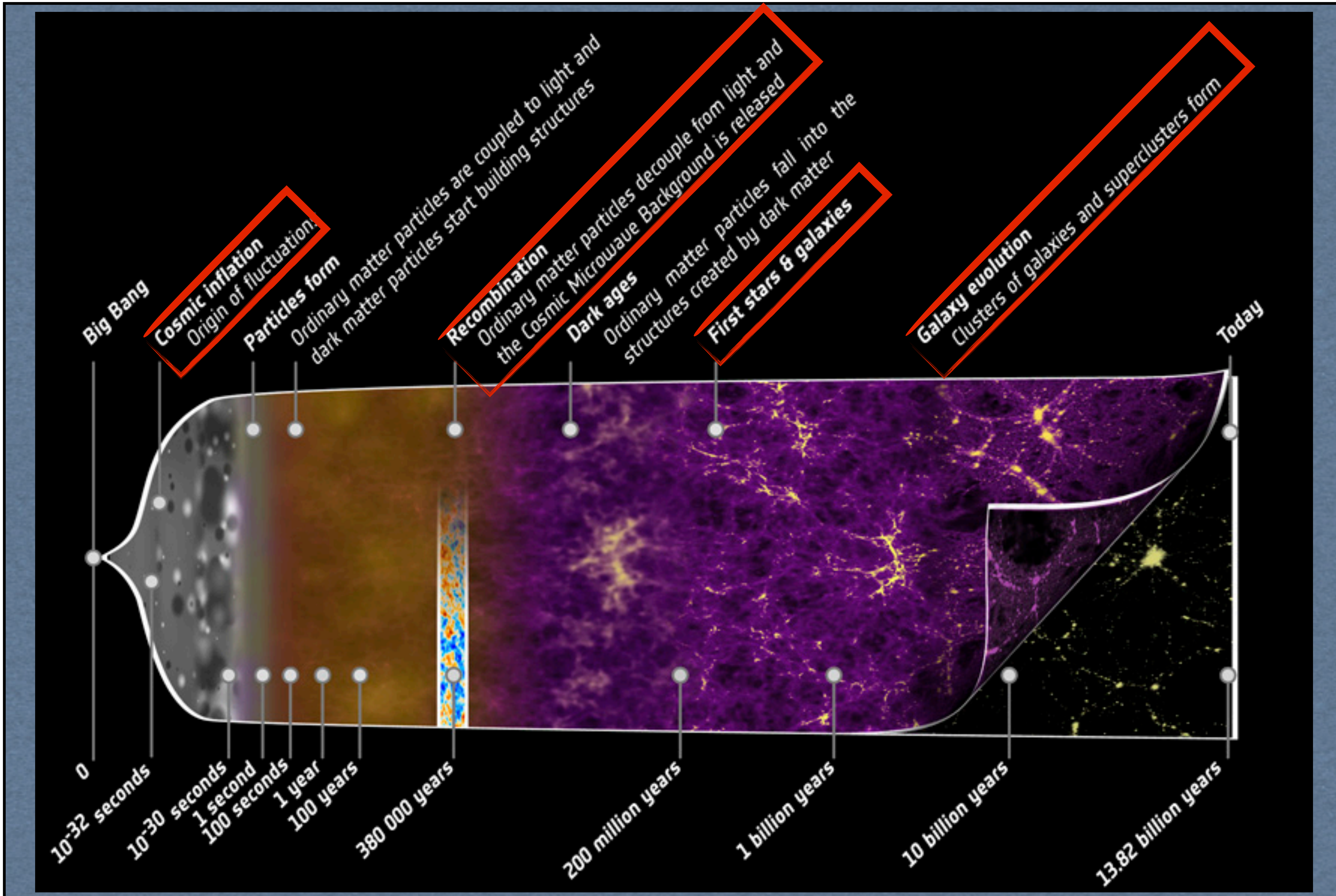
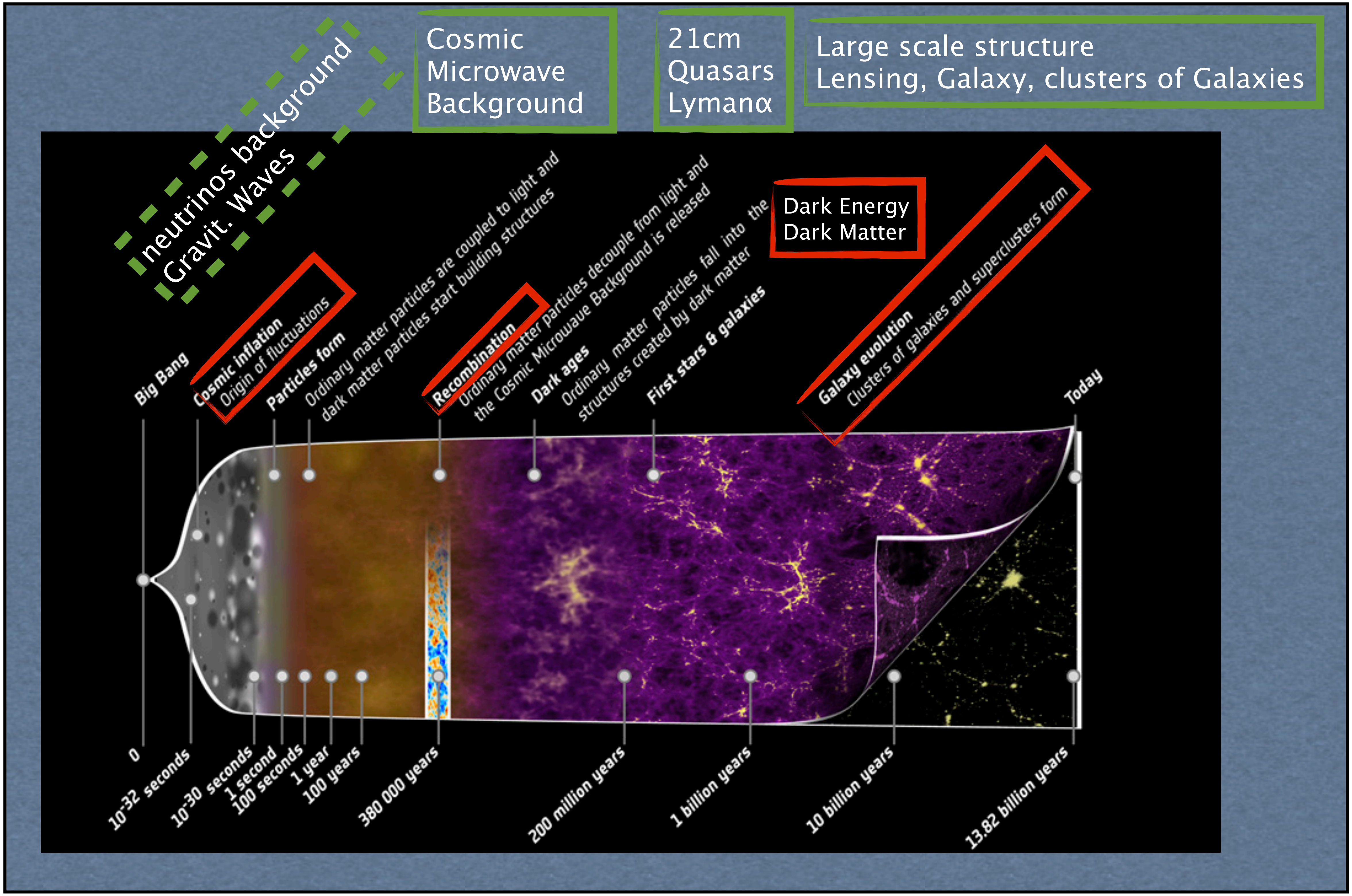
LAPTH 21 November 2013

The Universe's history



The observable Universe

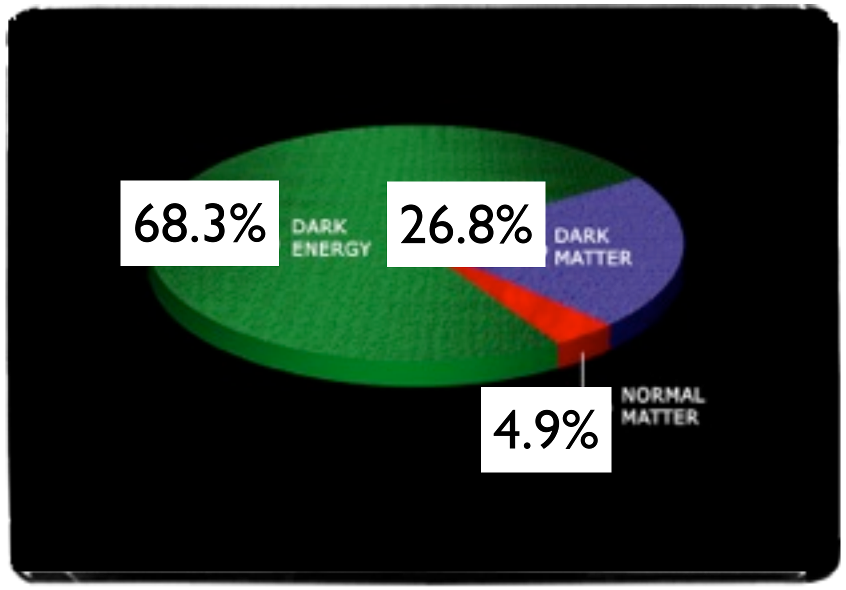


Concordance ΛCDM cosmological model

The questions list for Cosmology

ΛCDM

reference model = 



what is the universe made of?

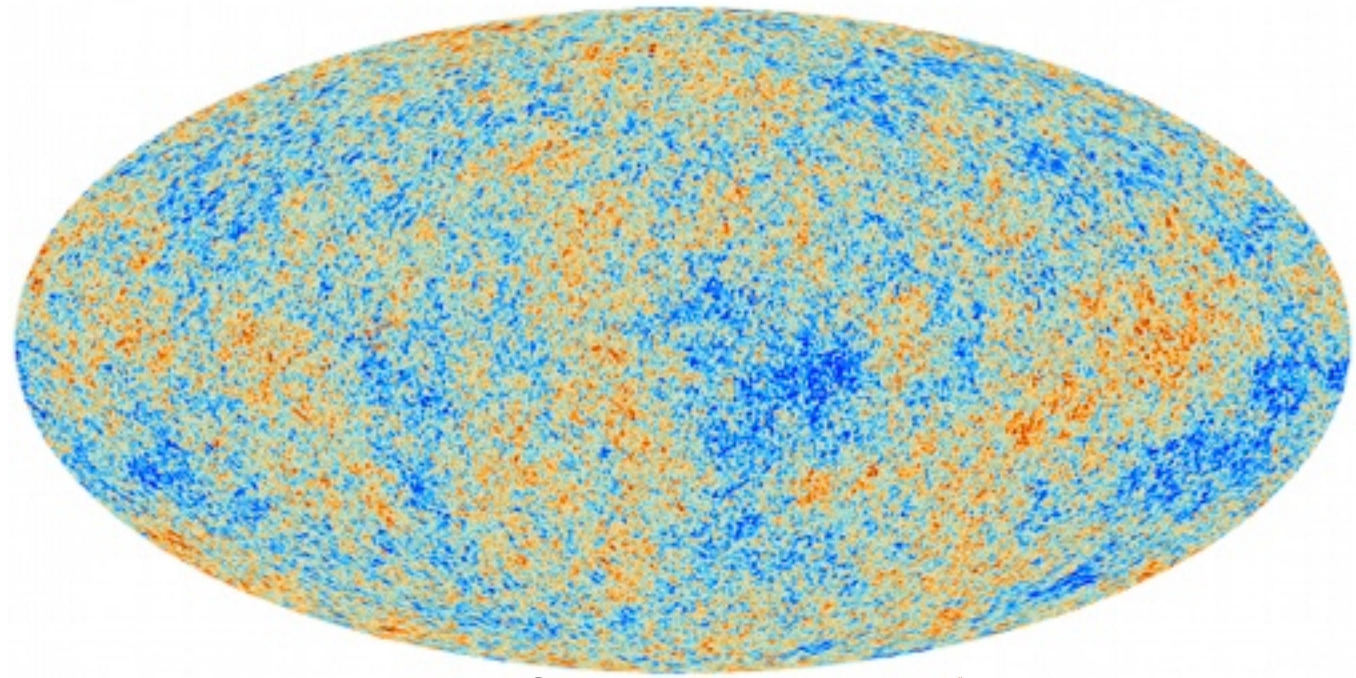
what is the nature of dark energy?

what is the nature of dark matter?

what is Inflation?

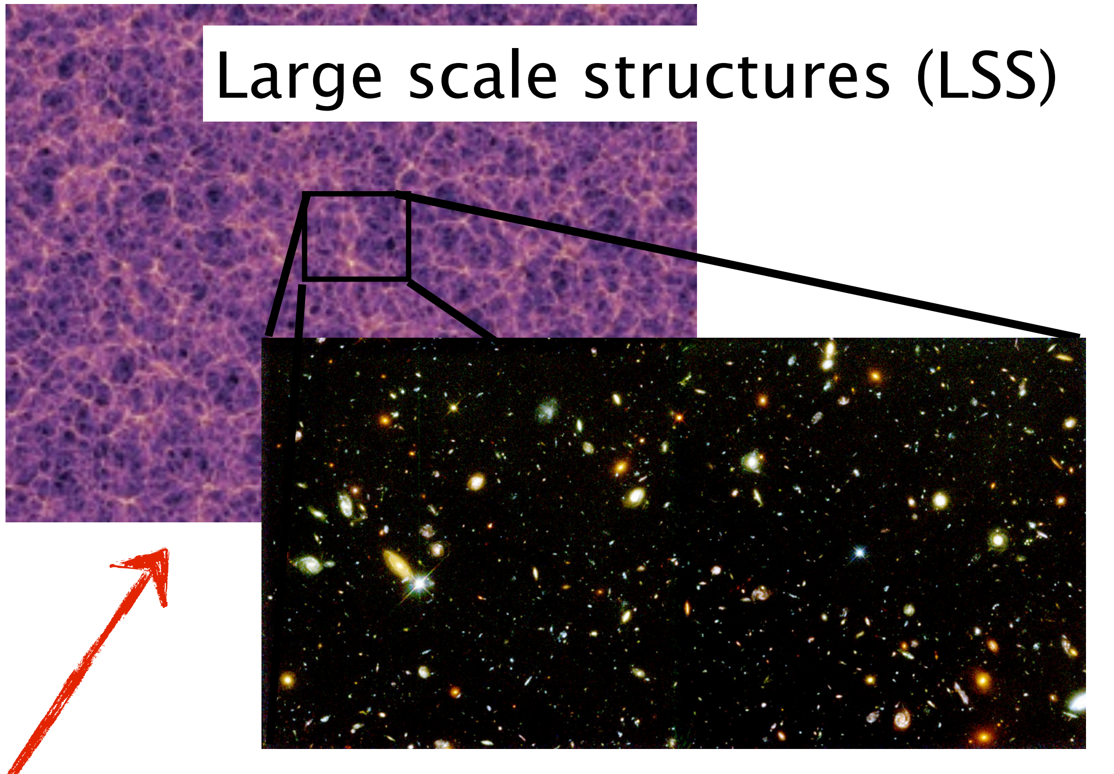
Where to search for answers

The Cosmic Microwave Background (CMB)



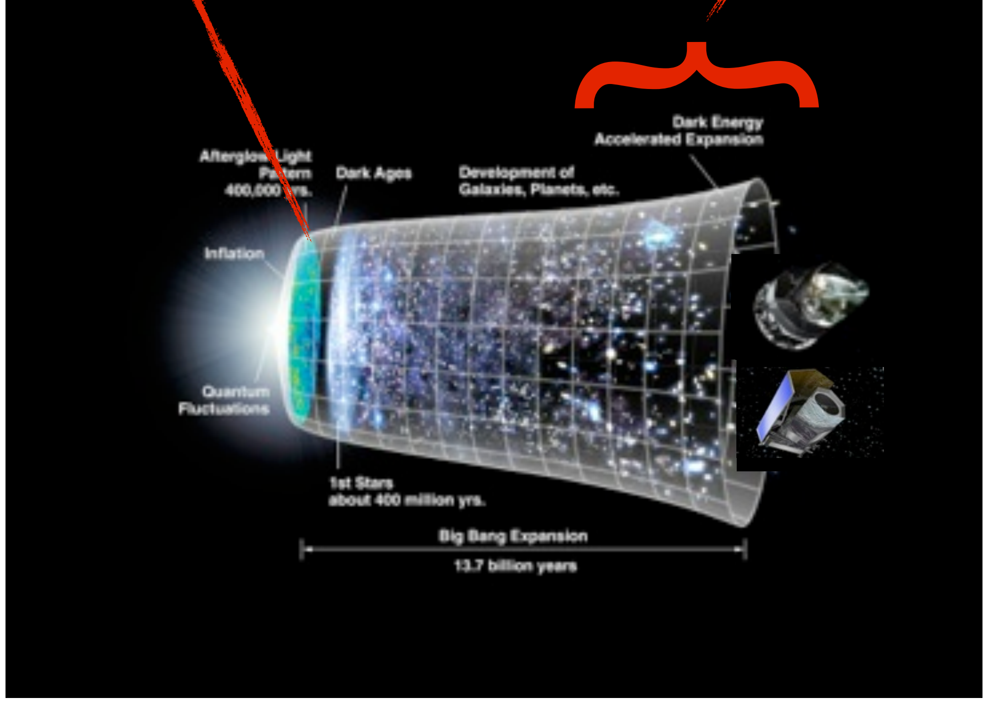
Primordial quantum fluctuations!

Large scale structures (LSS)

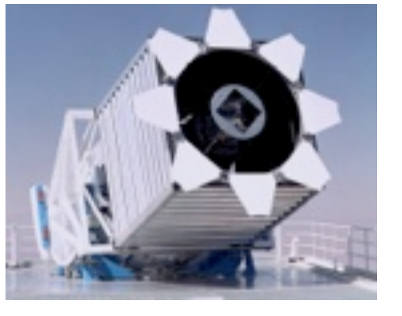


Planck

CMB Telescopes



EUCLID



LSS galaxy surveys

New observational data from CMB and galaxy surveys allow for precision tests of ΛCDM model and beyond!

Outline

- Probing late time evolution and primordial physics with the Cosmic Microwave Background (CMB) non-Gaussianity (NG)

  Why CMB non-Gaussianity

  Primordial and “late time” non-Gaussian signals

  Planck Data analysis and future prospect

- CMB, Large scale structure and initial conditions

  Constraining the nature of primordial perturbations beyond the ΛCDM model

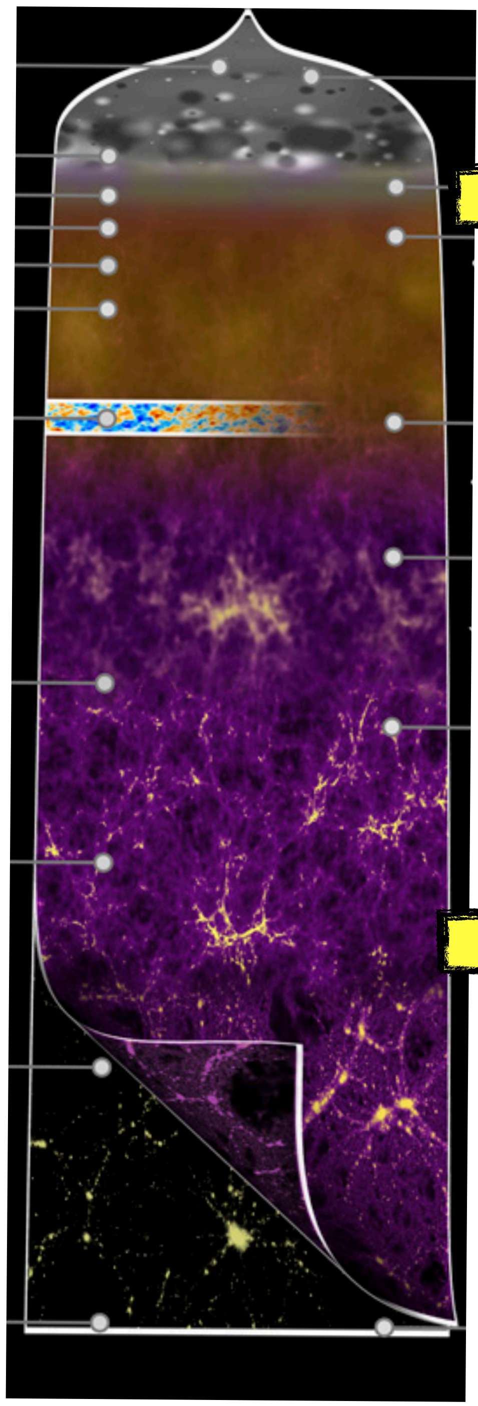
  Implications for CMB and LSS

  Euclid+Planck forecasts

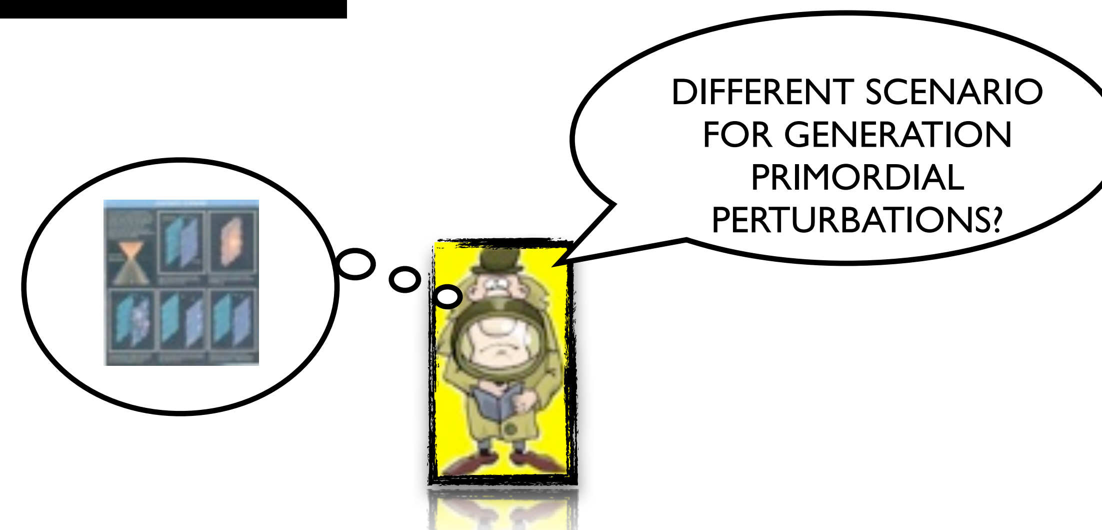
Why looking for non-Gaussianity (NG) in the CMB?

<u>STANDARD INFLATIONARY MODEL</u> predicts GAUSSIAN CMB anisotropies

If non-Gaussian signal in the CMB



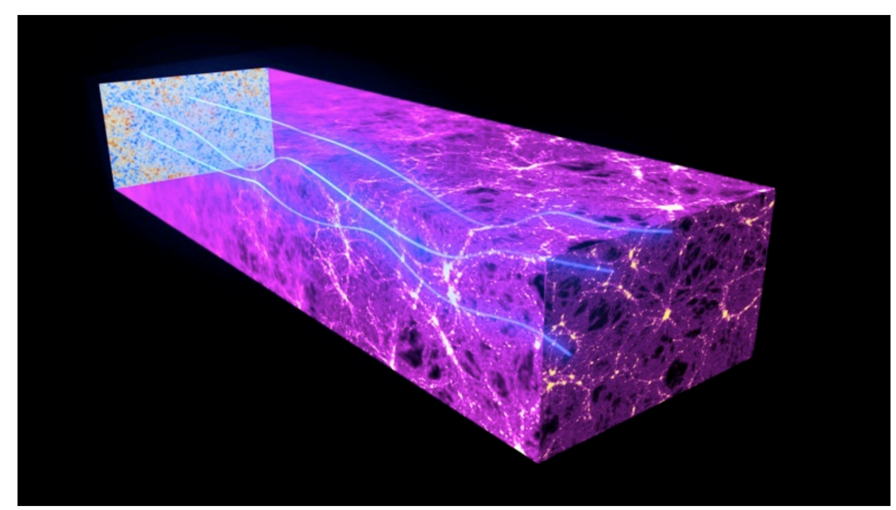
PRIMORDIAL NG



The CMB non-Gaussianity is a very high precision test of standard inflation!

Complementary to the search for CMB B-modes and power spectrum analysis

"LATE-TIME" NG



Primordial non-Gaussianity: an example

Non-linear gravitational potential perturbations

$$\Phi(\mathbf{x}) = \Phi_L(\mathbf{x}) + f_{NL}\left(\Phi_L^2(\mathbf{x}) - \langle \Phi_L^2(\mathbf{x}) \rangle\right)$$

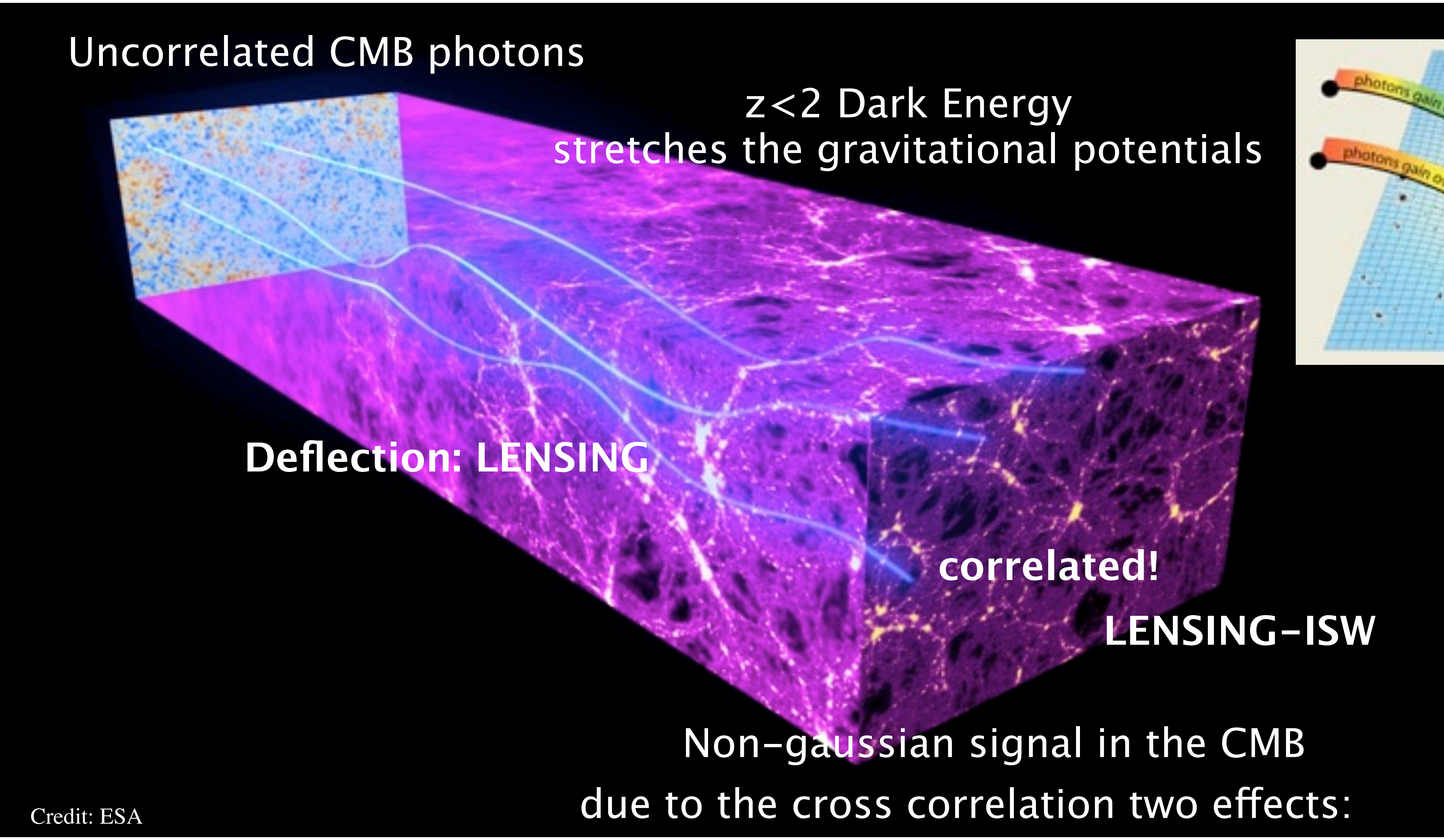
Salopek & Bond 1990, Gangui et al. 1994
Verde et al. 2000, Komatsu & Spergel 2001

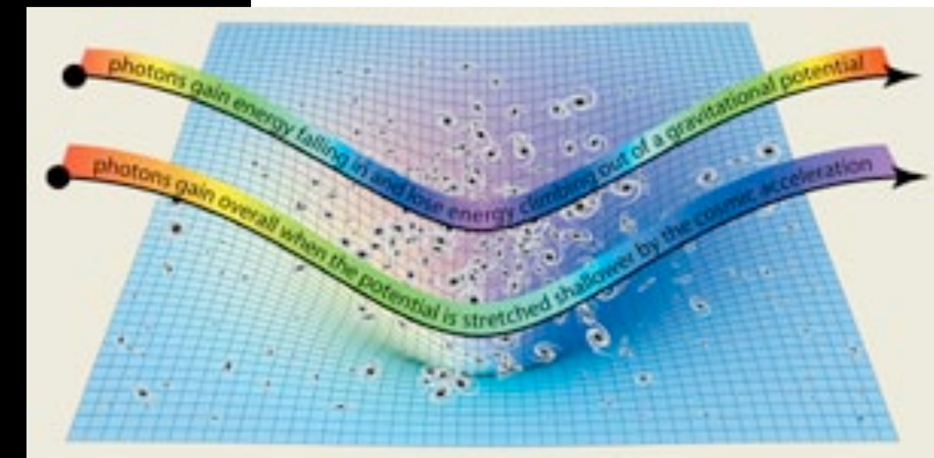
AMPLITUDE of the quadratic non-linear correction

Small for standard slow roll inflation, large for models e.g. multi field inflation

Different NG phenomena leave **different imprints** in the CMB sky which can be used to **constrain the physical mechanism** behind them.

The “late-time” CMB non-Gaussianity





ISW=Integrated Sachs Wolfe

$$\dot{\Phi} \neq 0$$

ISW - CMB photon red/blue shifted: dark energy stretches the gravitational potential wells

LENSING - CMB photon deflected by the forming structures

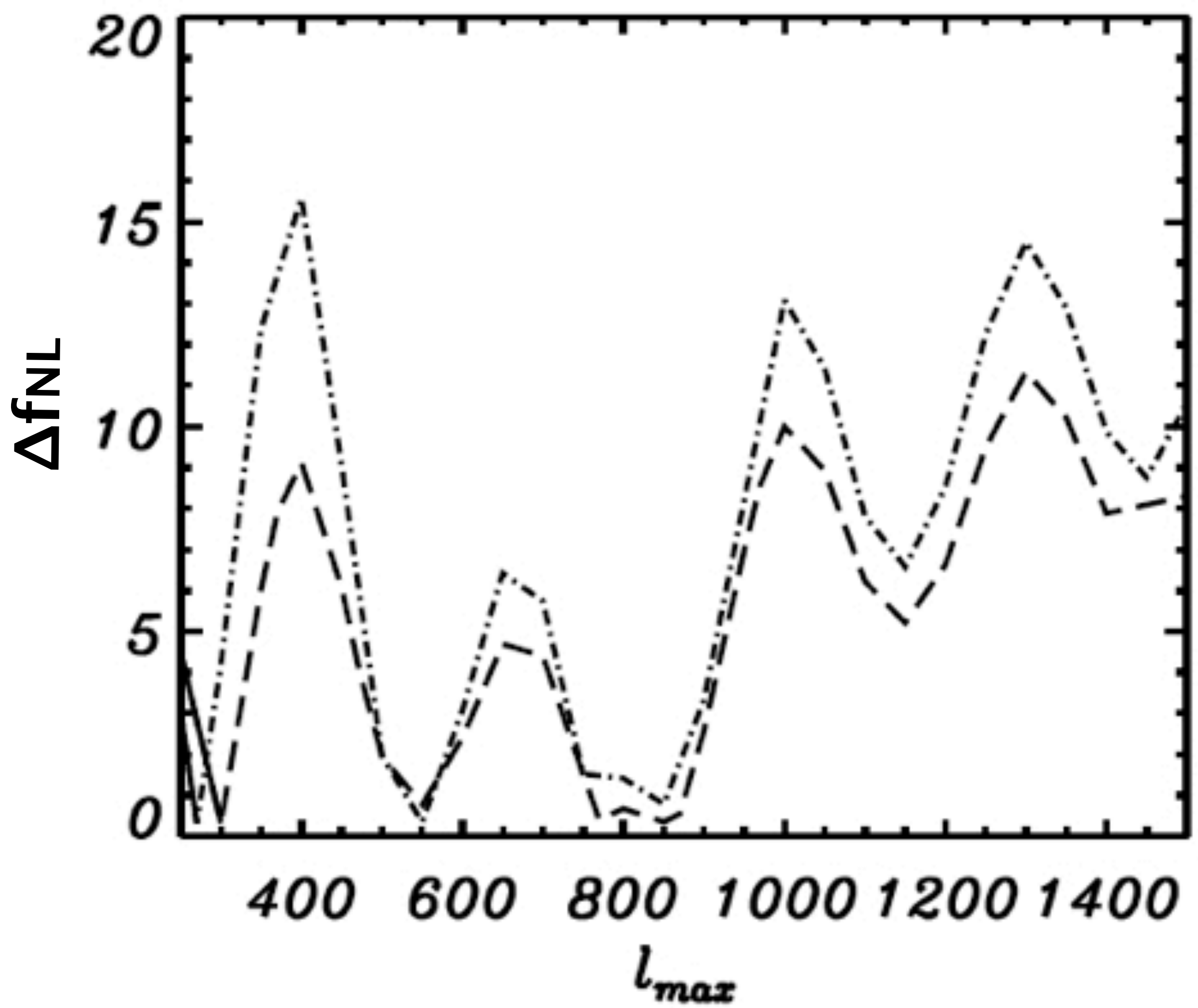
The CMB lensing-ISW non-Gaussianity

Direct probe of the action of Dark Energy on the evolution of structures

The lensing-ISW biases the primordial NG

Contamination of primordial local non-Gaussianity due to the late time signal

BIAS:



Mangilli&Verde 2009

BIAS to the primordial signal: Δf_{NL} of order 10, bigger than Planck 1-σ error on primordial f_{NL}

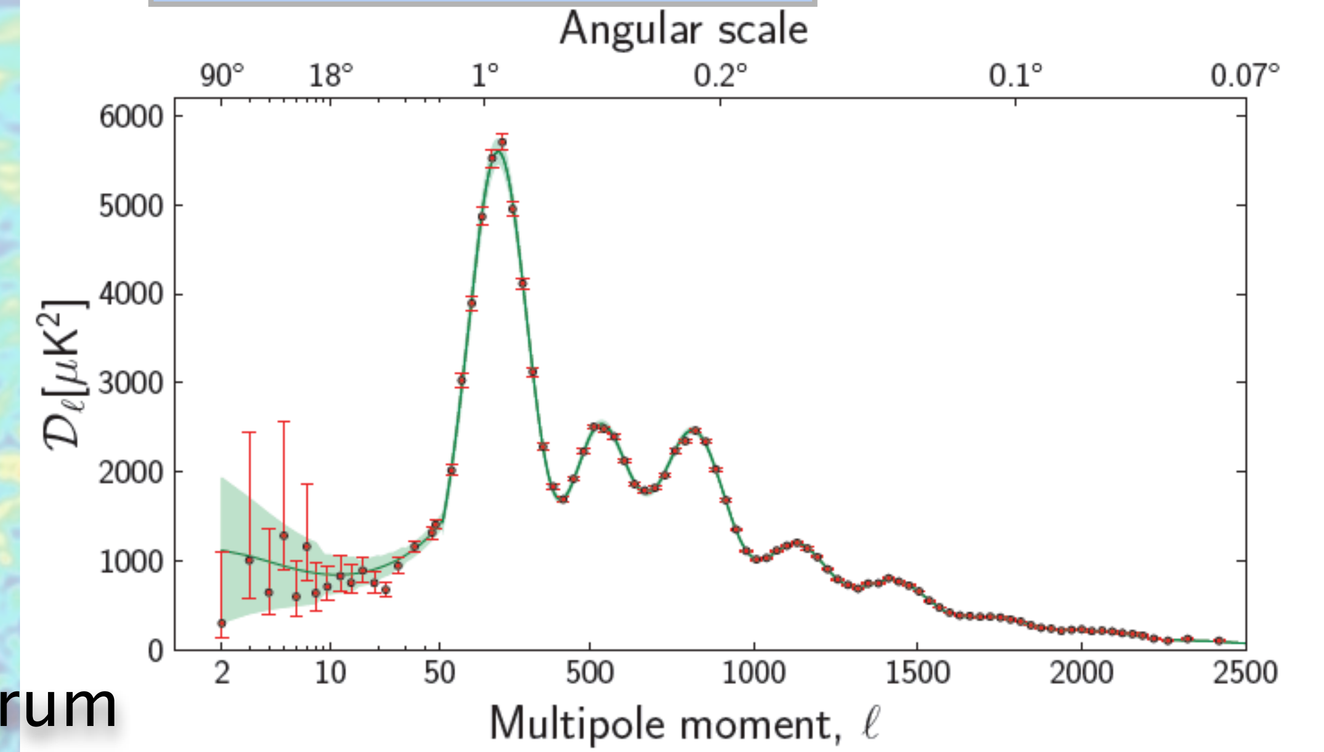
How look for non-Gaussianity in the CMB

2-points correlation function

$$\left\langle \frac{\Delta T}{T}(\mathbf{x}_1)\frac{\Delta T}{T}(\mathbf{x}_2)\right\rangle$$

$$\frac{\Delta T(\mathbf{n})}{T_0} = \sum_{\ell=0}^{\infty}\sum_{m=-\ell}^{\ell} a^T_{\ell m} Y_{\ell m}(\mathbf{n})$$

$$\langle a_{lm} a^*_{l'm'}\rangle = \delta_{ll'}\delta_{mm'}C_\ell$$



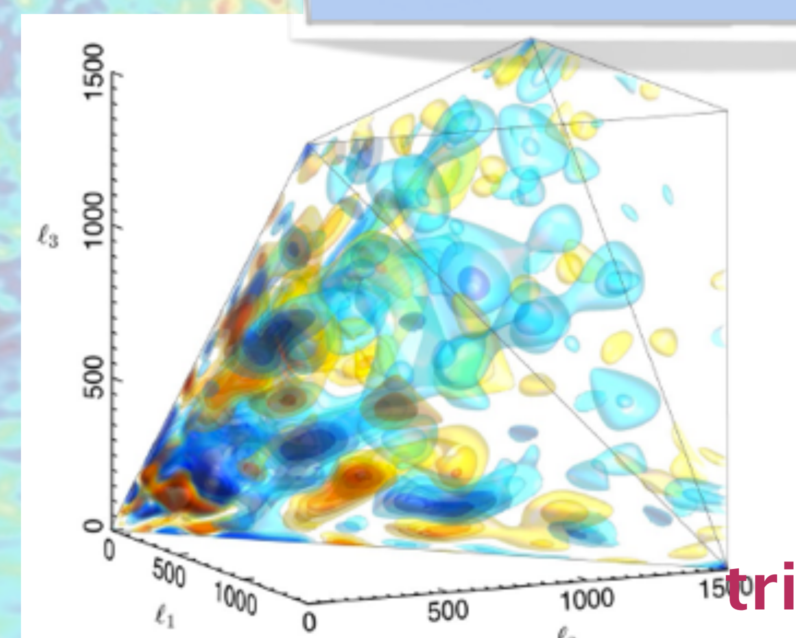
Angular power spectrum

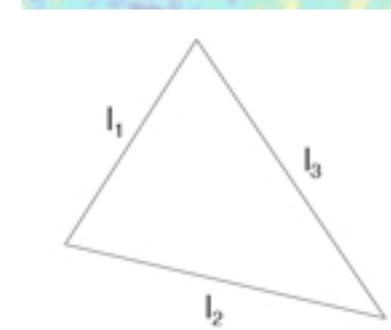
Non-Gaussianity? More information!
Look at the higher order statistics beyond the power spectrum

3-points correlation function

$$\left\langle \frac{\Delta T}{T}(\mathbf{x}_1)\frac{\Delta T}{T}(\mathbf{x}_2)\frac{\Delta T}{T}(\mathbf{x}_3)\right\rangle$$

$$B^{m_1 m_2 m_3}_{\ell_1 \ell_2 \ell_3} \equiv \langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3}\rangle$$





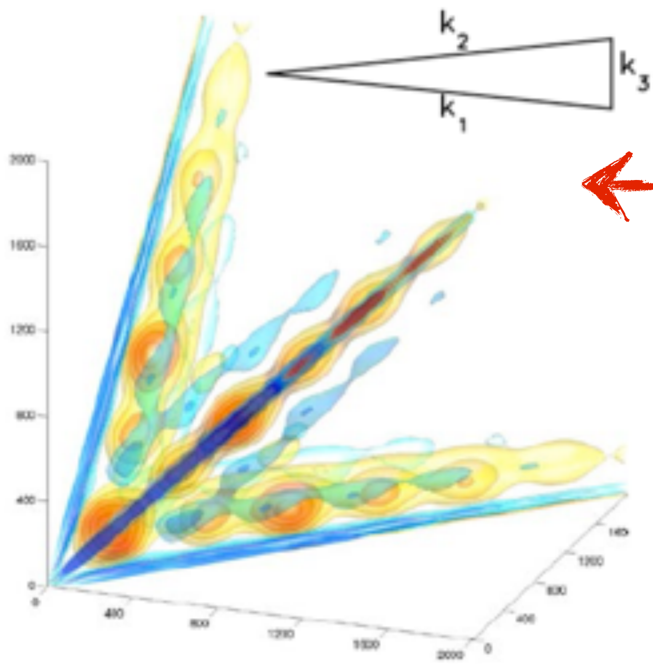
Angular bispectrum

Look at triangles in the CMB!

Different mechanisms, different amplitudes and shapes!

$$B(\ell_1, \ell_2, \ell_3) = f_{\rm NL} F(\overbrace{\ell_1, \ell_2, \ell_3}^{\text{SHAPE}})$$

Squeezed shape



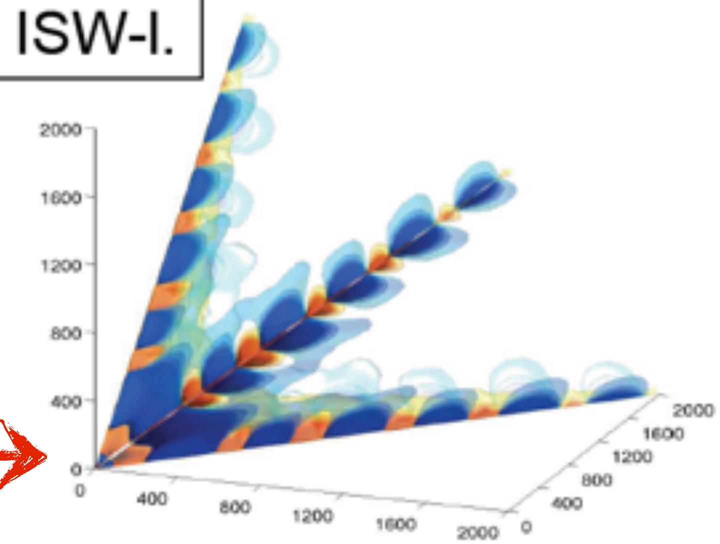
Primordial (local type):

- Multi-fields inflation
- Ekpyrotic/cyclic models
- Curvaton isocurvature model

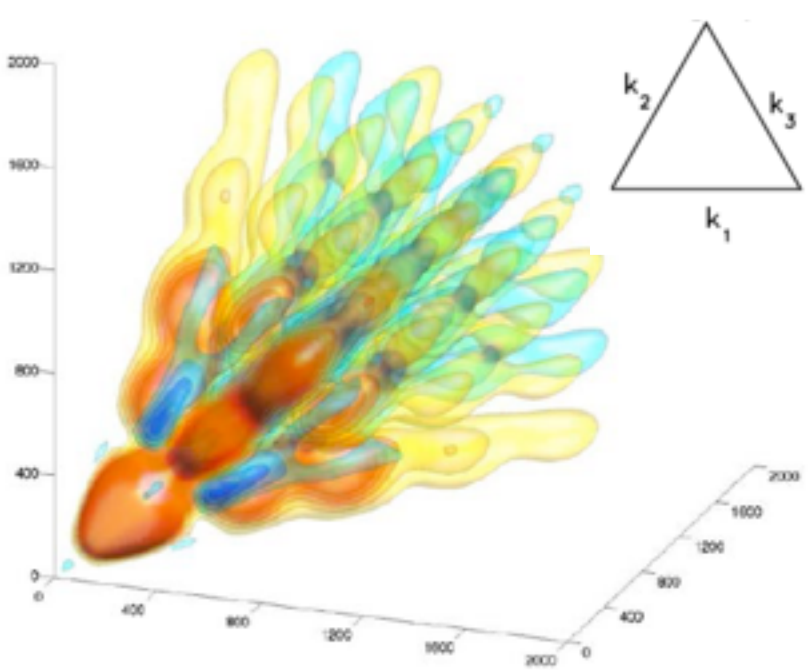
Non-primordial:

- Lensing-ISW correlation

ISW-l.

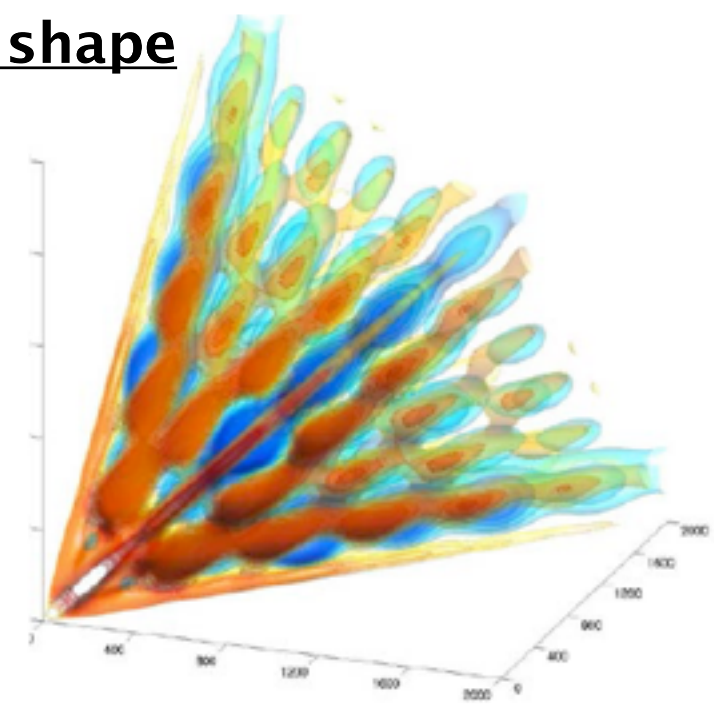


EQUILATERAL shape



- non-canonical kinetic term
- Dirac-Born-Infield (DBI) inflation
- Ghost inflation

ORTHOGONAL shape



- non-canonical kinetic term
- higher derivatives interactions

credit: Planck Collaboration

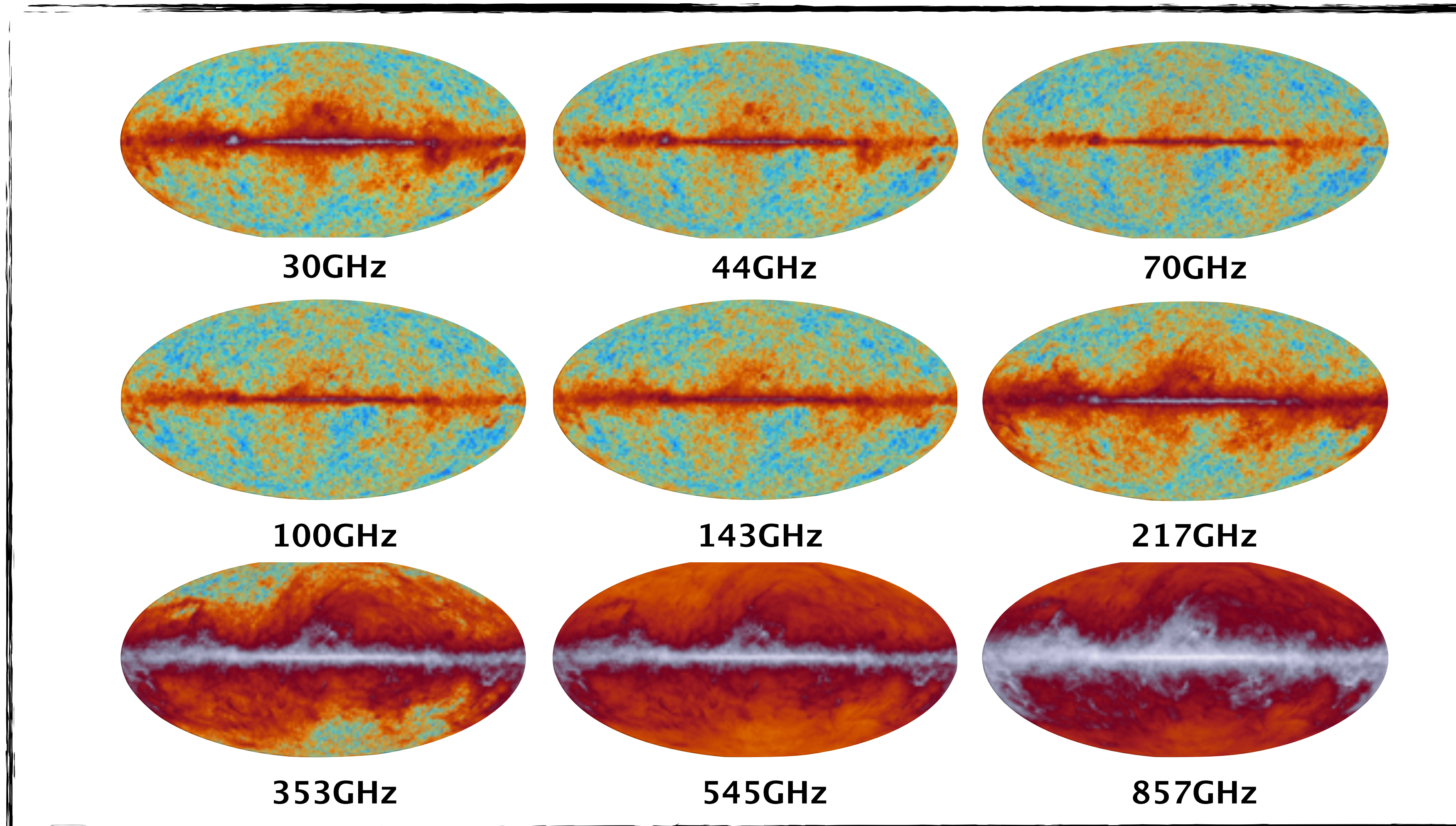
Planck data analysis and results on CMB non-Gaussianity

On behalf of the Planck collaboration

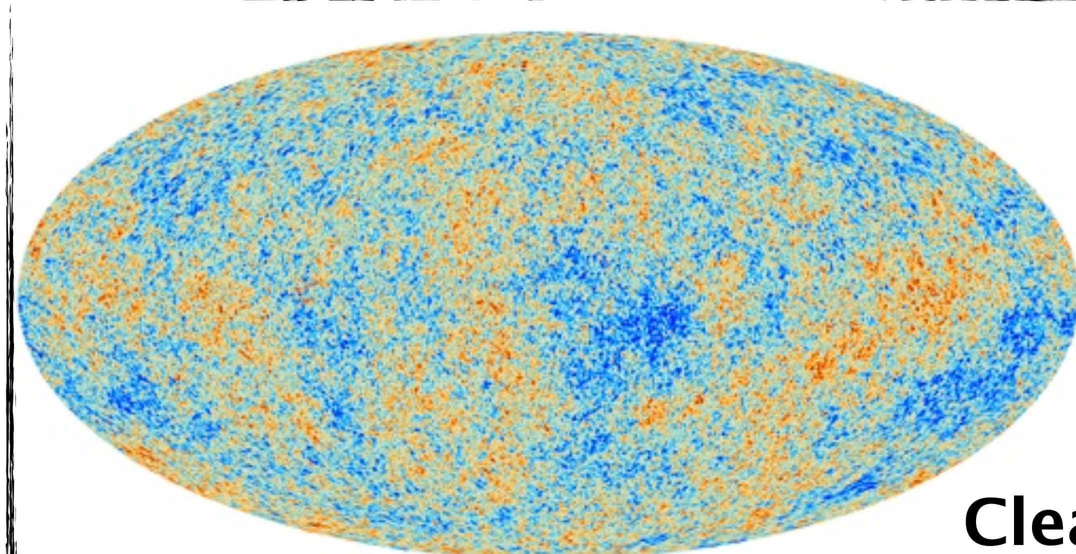
Anna Mangilli (IAP) - LAPTH 21 Nov 2013

The Planck experiment

Planck is an ESA mission which observed the sky in 9 frequency bands from 30 to 857 GHz with an unprecedented sensitivity

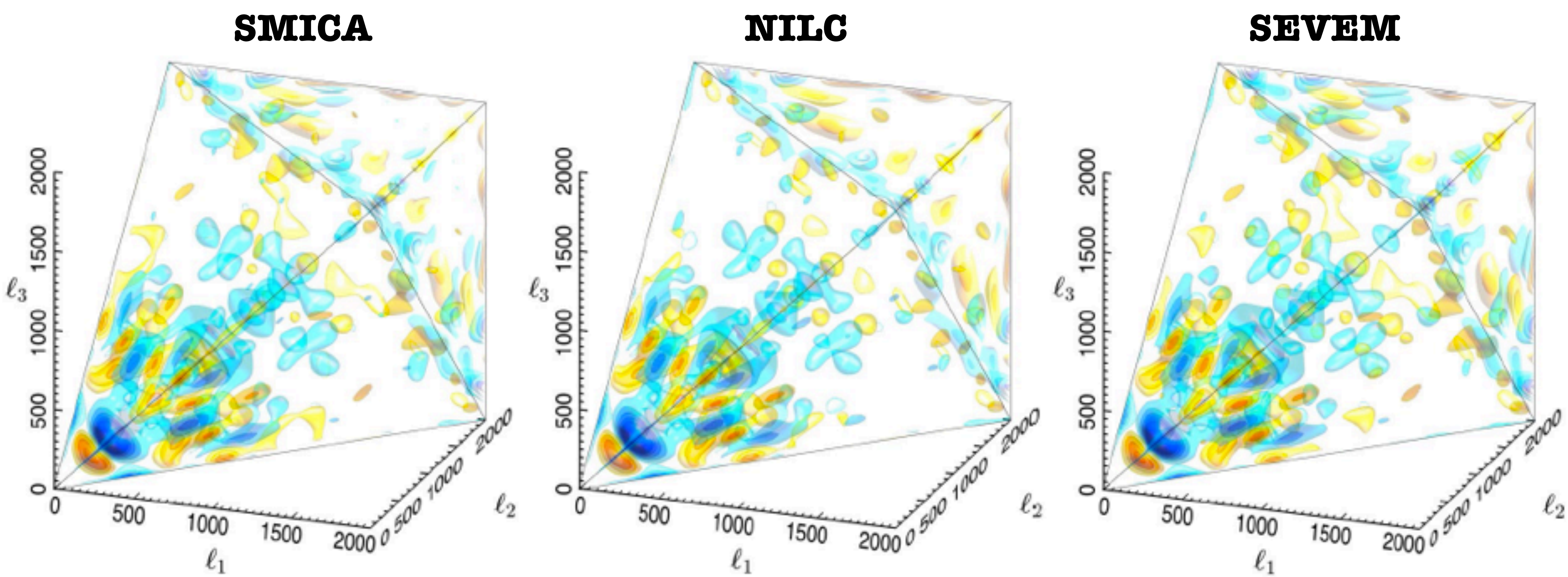


Component separation to remove foregrounds.



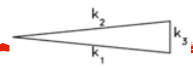
Cleaned Planck CMB map

The Planck bispectrum

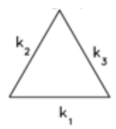


Robust to foreground cleaning

Constraints on fNL from Planck data

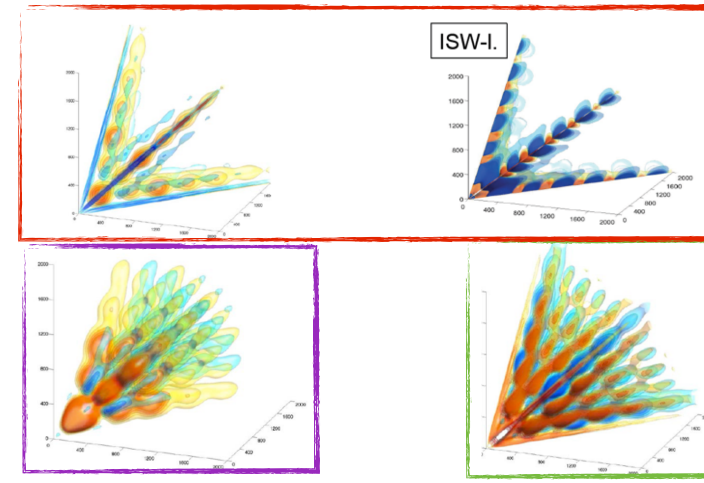


Local squeezed



Equilateral

Orthogonal



	KSW	Binned	Modal
SMICA			
Local	9.8 ± 5.8	9.2 ± 5.9	8.3 ± 5.9
Equilateral	−37 ± 75	−20 ± 73	−20 ± 77
Orthogonal	−46 ± 39	−39 ± 41	−36 ± 41

Lensing-ISW bias

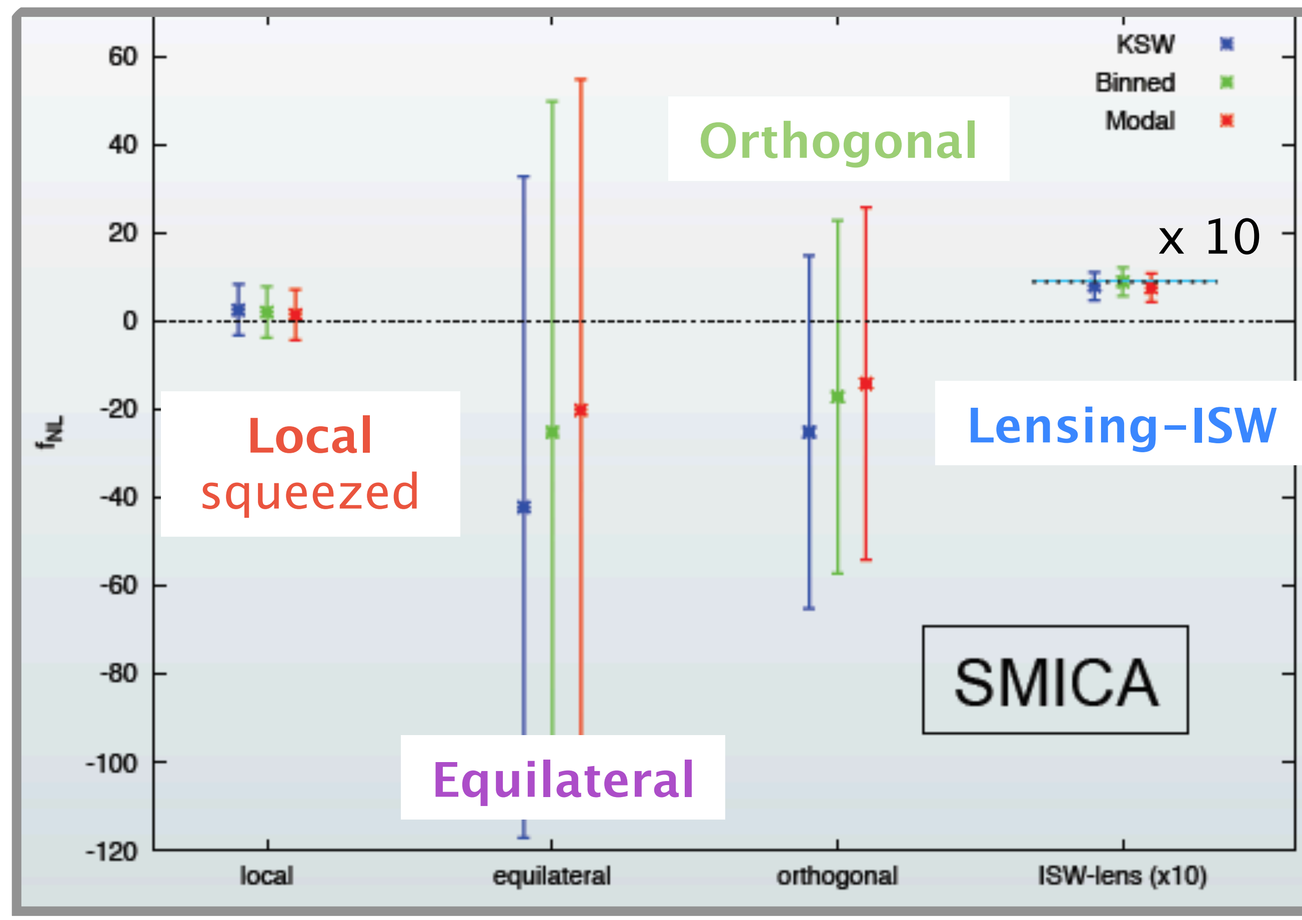
KSW	7.7 ± 1.5
Binned	7.7 ± 1.6
Modal	10 ± 3

Planck Collaboration 2013

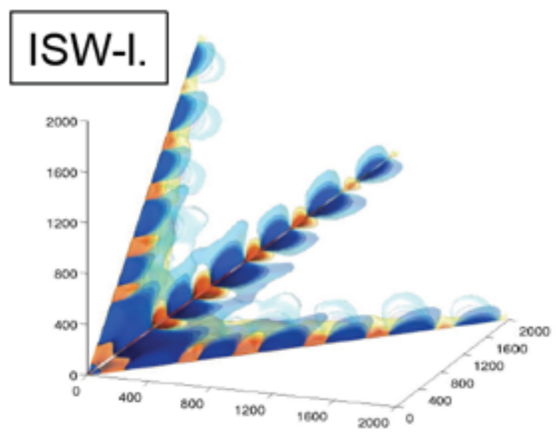
Mangilli&Verde 2009

ISW-lensing subtracted		
KSW	Binned	Modal
2.7 ± 5.8	2.2 ± 5.9	1.6 ± 6.0
−42 ± 75	−25 ± 73	−20 ± 77
−25 ± 39	−17 ± 41	−14 ± 42

No evidence of primordial NG in Planck Data

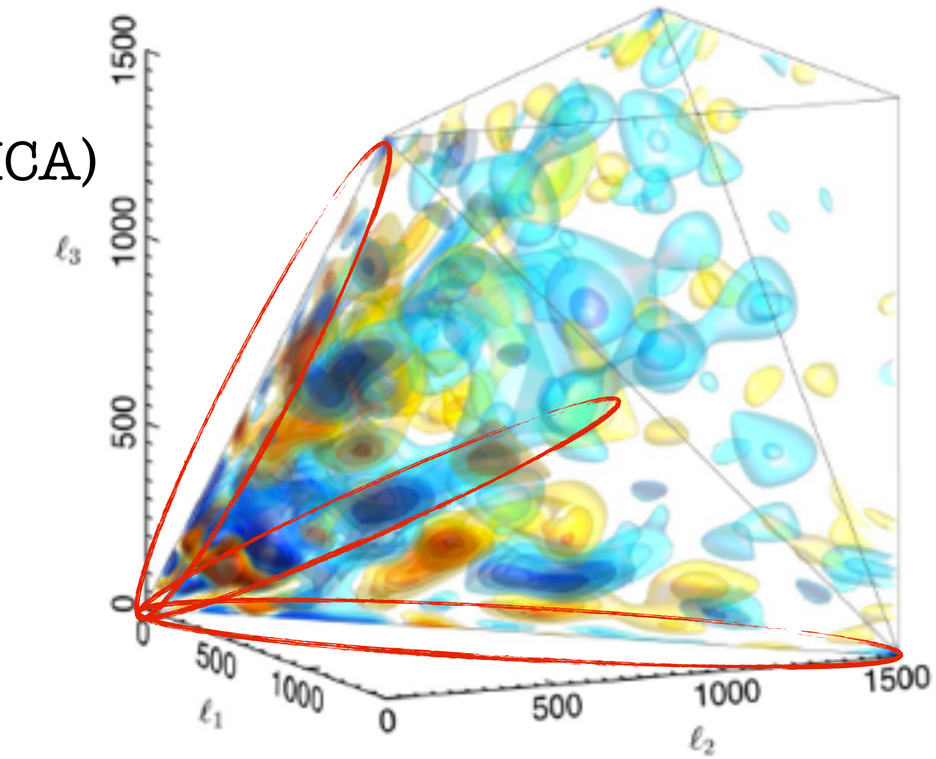


Planck results on the lensing-ISW



Bispectrum template

Planck data (SMICA)



Specific estimators calibrated for the L-ISW signal

Mangilli et. al 2013

Planck Collaboration 2013

Amplitude of the lensing-ISW bispectrum $f_{NL}^{ISW\text{-}L}$

Estimator	NILC	SEVEM	SMICA
$T\phi$	0.75 ± 0.28	0.62 ± 0.29	0.70 ± 0.28
KSW	0.85 ± 0.32	0.68 ± 0.32	0.81 ± 0.31
binned	1.03 ± 0.37	0.83 ± 0.39	0.91 ± 0.37
modal	0.93 ± 0.37	0.60 ± 0.37	0.77 ± 0.37

Expected amplitude LCDM

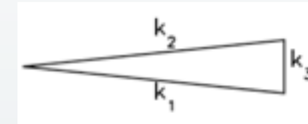
$$f_{NL}^{ISW\text{-}L} = 1$$

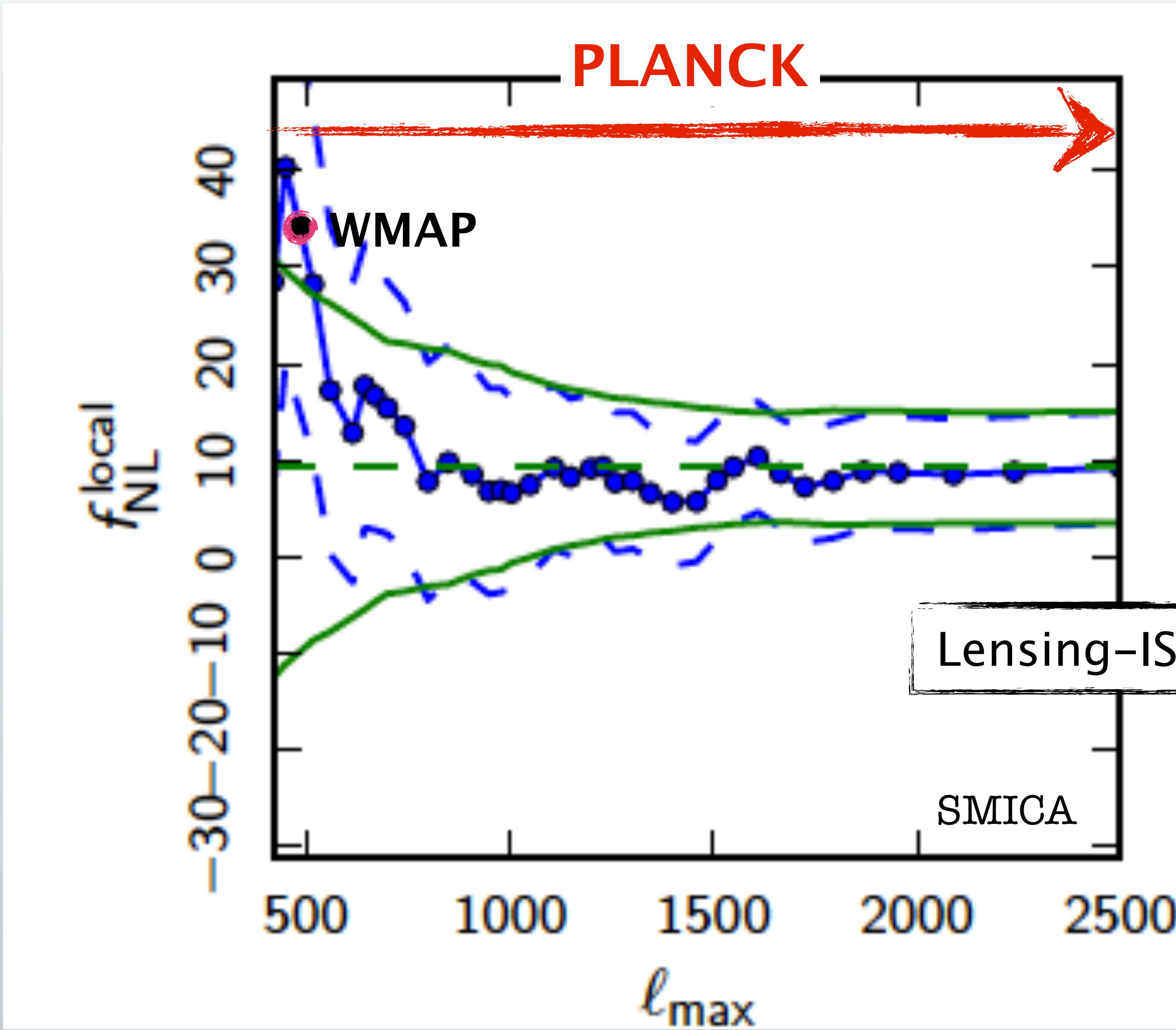
Consistent results from all estimators and data maps with different component separation methods

Planck finds evidence for the first time of the Lensing-ISW signal at 2.7σ

Planck high resolution!

Primordial non-Gaussianity: Local shape





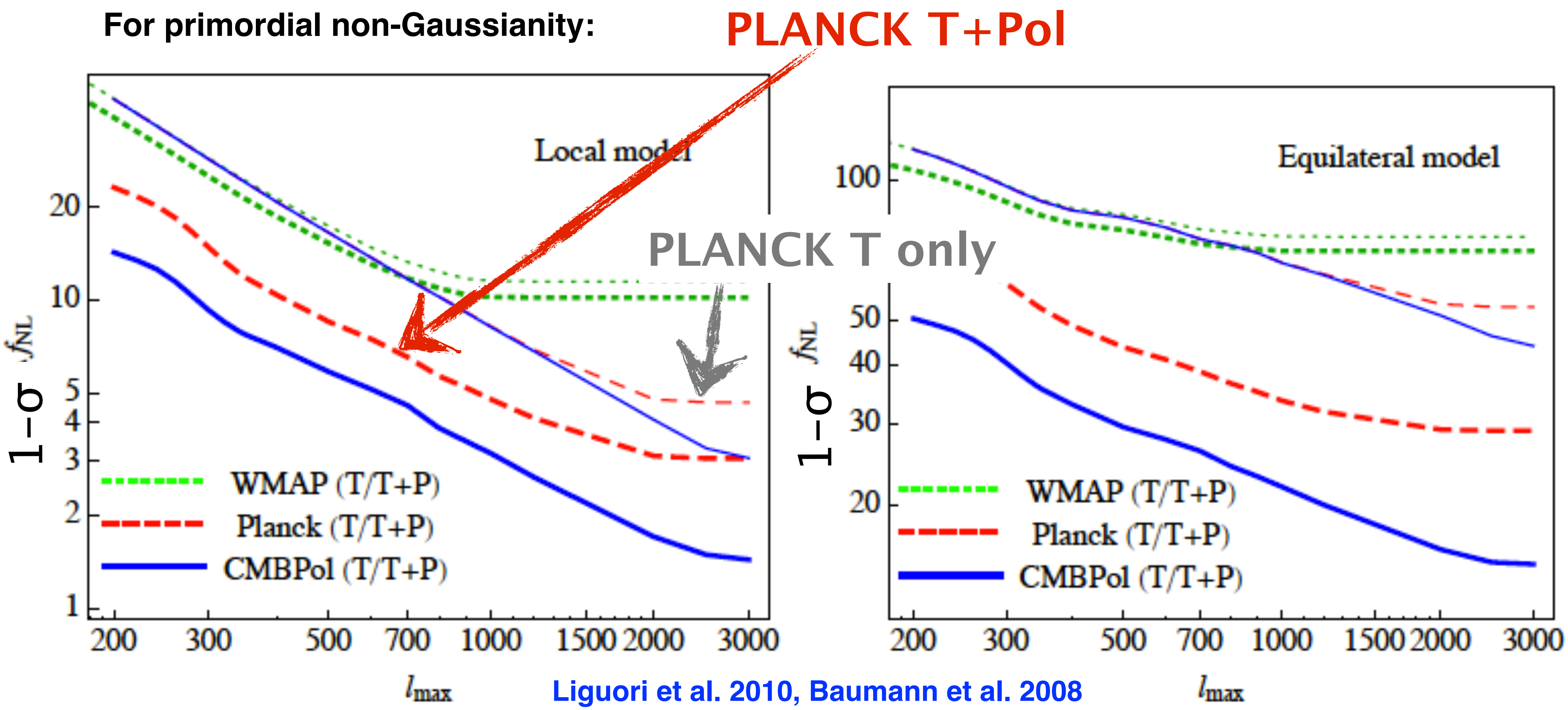
fnl_local WMAP9=37+/-20
Bennet et al. 2012

fnl_local Planck 2013 =9.8+/-5.8
The Planck collaboration 2013

Consistency with WMAP

Polarization forecasts

For primordial non-Gaussianity:



Liguori et al. 2010, Baumann et al. 2008

For lensing-ISW non-Gaussianity:

	$\sigma_{f_{NL}}$	σ_{lens}	correlation	bias on f_{NL}	$\sigma_{f_{NL}}^{marge}$
T	4.31	0.19	0.24	9.5	4.44
T+E	2.14	0.12	0.022	2.6	2.14
Planck T	5.92	0.26	0.22	6.4	6.06
Planck T+E	5.19	0.22	0.13	4.3	5.23

Lewis et al. 2011

T+Pol ∼ 15% improvement

CMB non-Gaussianity: TAKE AWAY message!

- **Non-Gaussianity in the CMB: powerful tool to constrain primordial physics and Dark Energy (late-time lensing-ISW bispectrum)**

- **Planck constrained for the first time CMB Non-Gaussianity with unprecedented precision!**

  - Planck favors the simplest models for inflation

  - Planck finds evidence <u>for the first time</u> of the Integrated-Sachs-Wolfe-lensing bispectrum. Signal compatible with the LCDM scenario

- **Future prospects:**

  - Planck polarization data 2014 release!

  - Lensing-ISW bispectrum: <u>new observable</u> to be used to constrain dark energy properties.

Outline

- Probing late time evolution and primordial physics with the Cosmic Microwave Background (CMB) non-Gaussianity (NG)

    Why CMB non-Gaussianity

    Primordial and “late time” non-Gaussian signals

    Planck Data analysis and future prospect

- CMB, Large scale structure and initial conditions

    Constraining the nature of primordial perturbations beyond the ΛCDM model

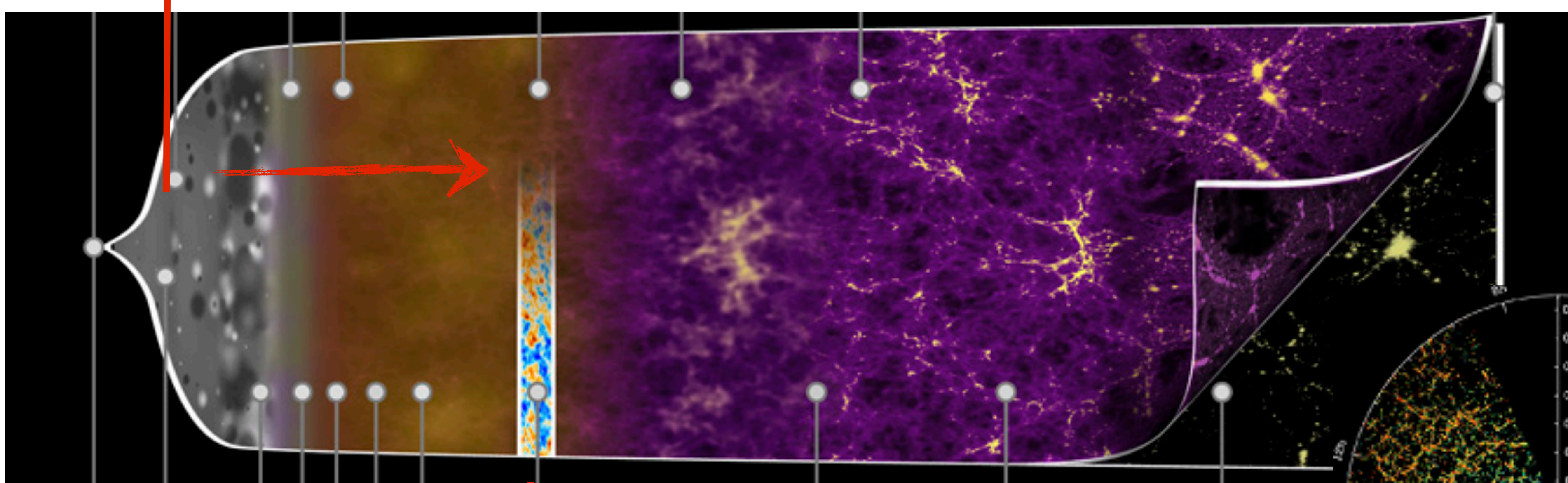
    Implications for CMB and LSS

    Euclid+Planck forecasts

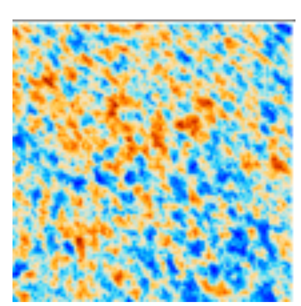
Standard model for structure formation

standard INFLATION: single scalar field, the inflaton, drives accelerated expansion **and** produce primordial perturbations

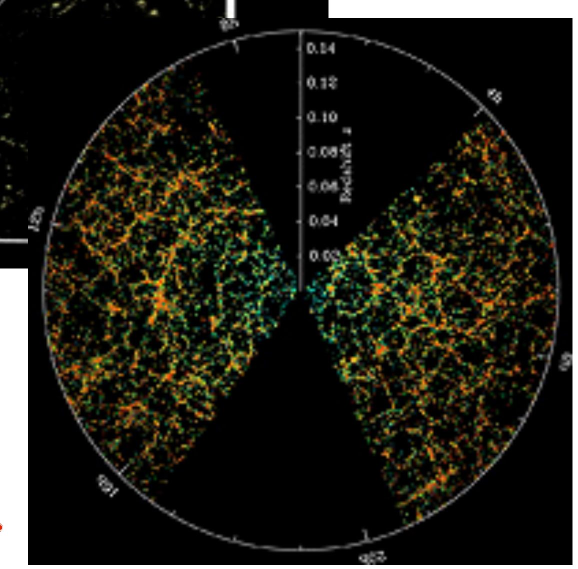
Cosmic inflation: Origin of the perturbations



Primordial perturbations imprinted in the CMB

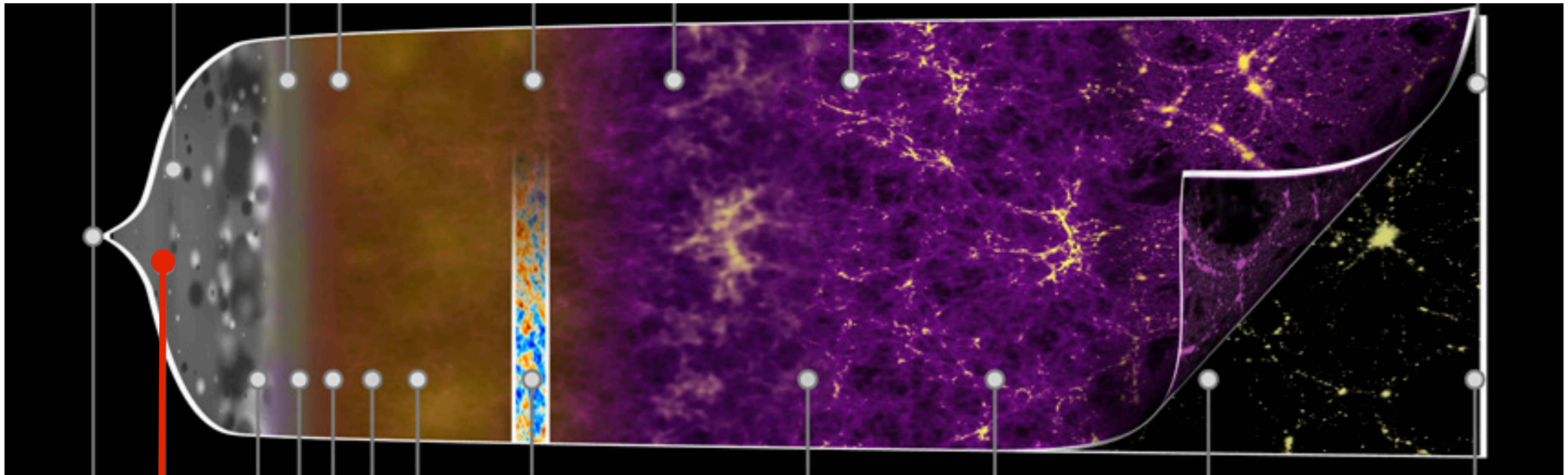


Gravitational instability



Large scale structure of the Universe

What is the nature of the primordial fluctuations?



Cosmic inflation: Origin of the perturbations

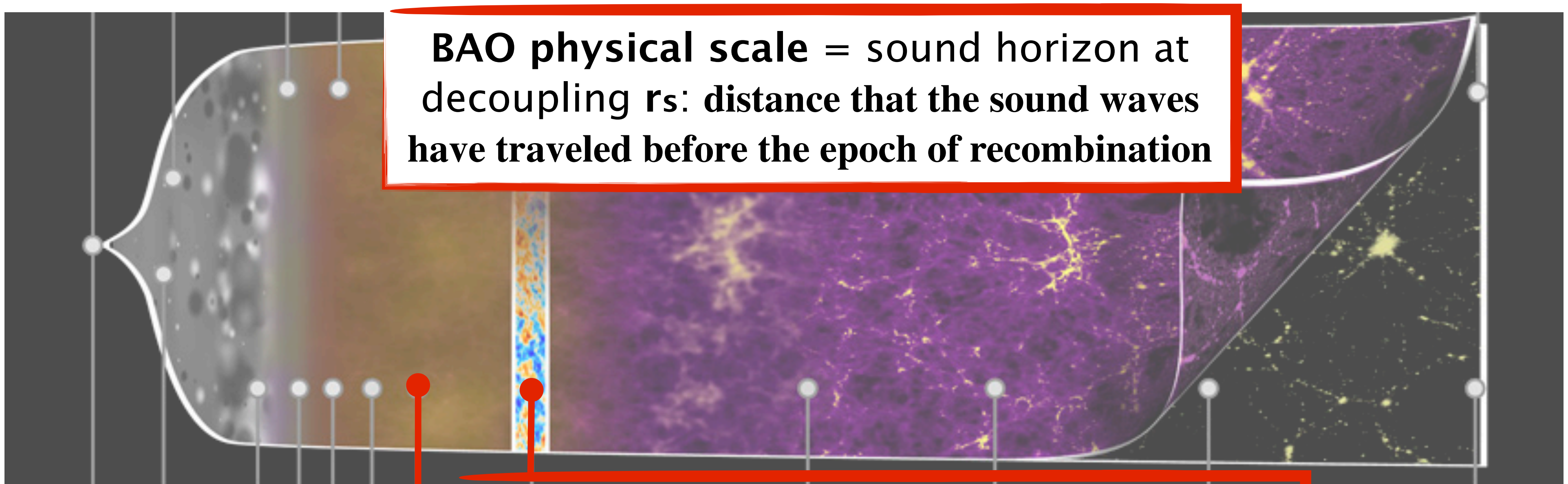
Curvature adiabatic perturbation

Standard Inflationary dynamics implies that constant density perturbations are present initially. Perturbations in all components are spatially homogeneous.

Isocurvature entropy perturbation

No initial curvature perturbations. Fluctuation in number density between different components. The initial density fluctuations are created from stresses in the radiation-matter component. E.g. Cold Dark Matter and Neutrinos Isocurvature modes.

New observational data from CMB and galaxy surveys offers precision tests of the nature of the primordial perturbations

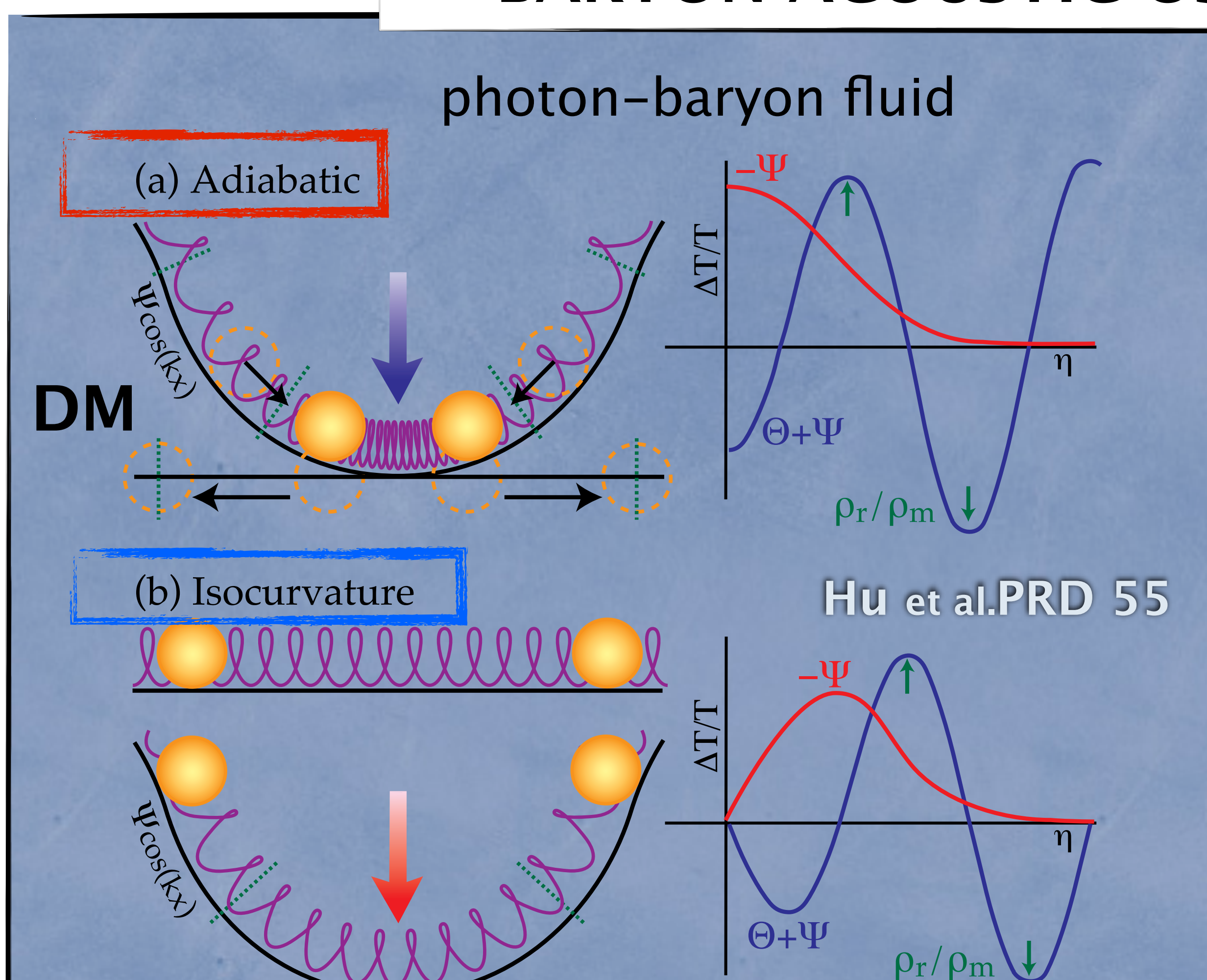


BAO physical scale = sound horizon at decoupling **rs**: **distance that the sound waves have traveled before the epoch of recombination**

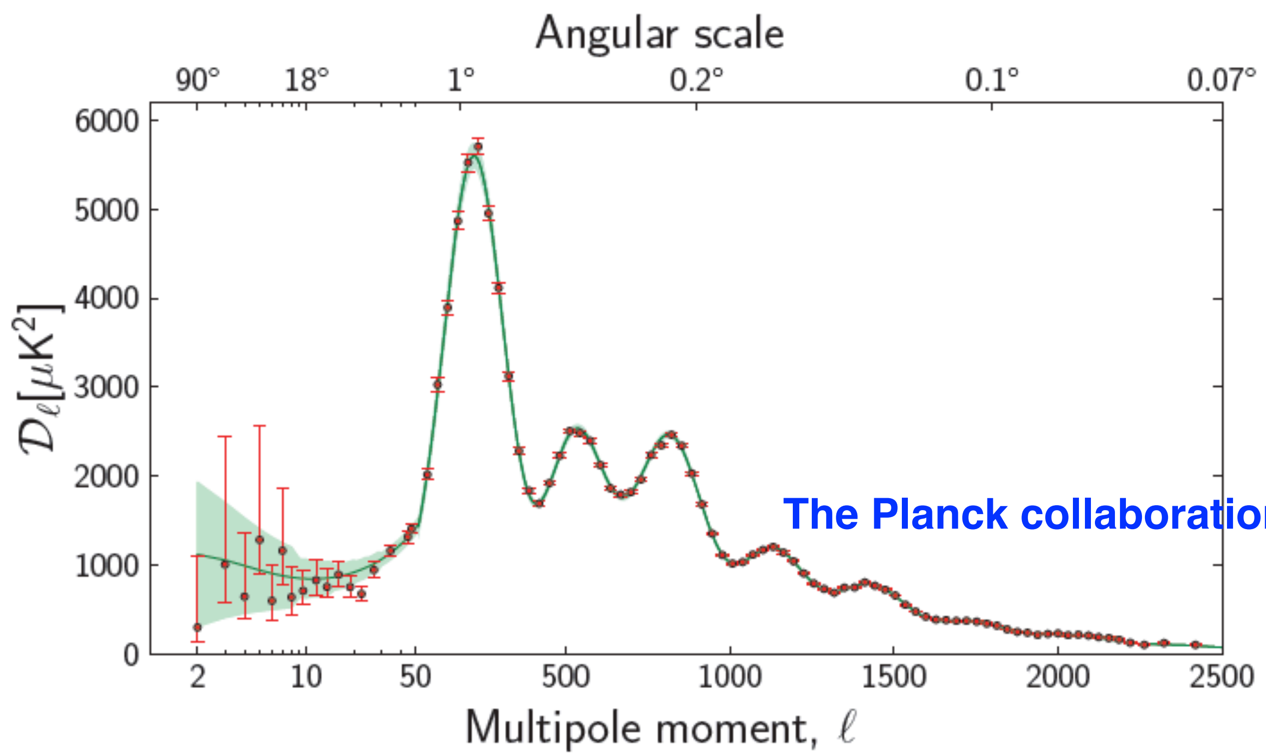
Photon and matter **decoupling**: CMB

Dark matter + baryon and photons tightly coupled

BARYON ACOUSTIC OSCILLATIONS (BAO) = sound waves



BAO froze at decoupling leaving an imprint in the CMB: the characteristic peak structure in the CMB power spectrum!



The Planck collaboration 2013

Pure isocurvature ruled out but ...

Current observations allow for mixed Adiabatic+Isocurvature initial conditions

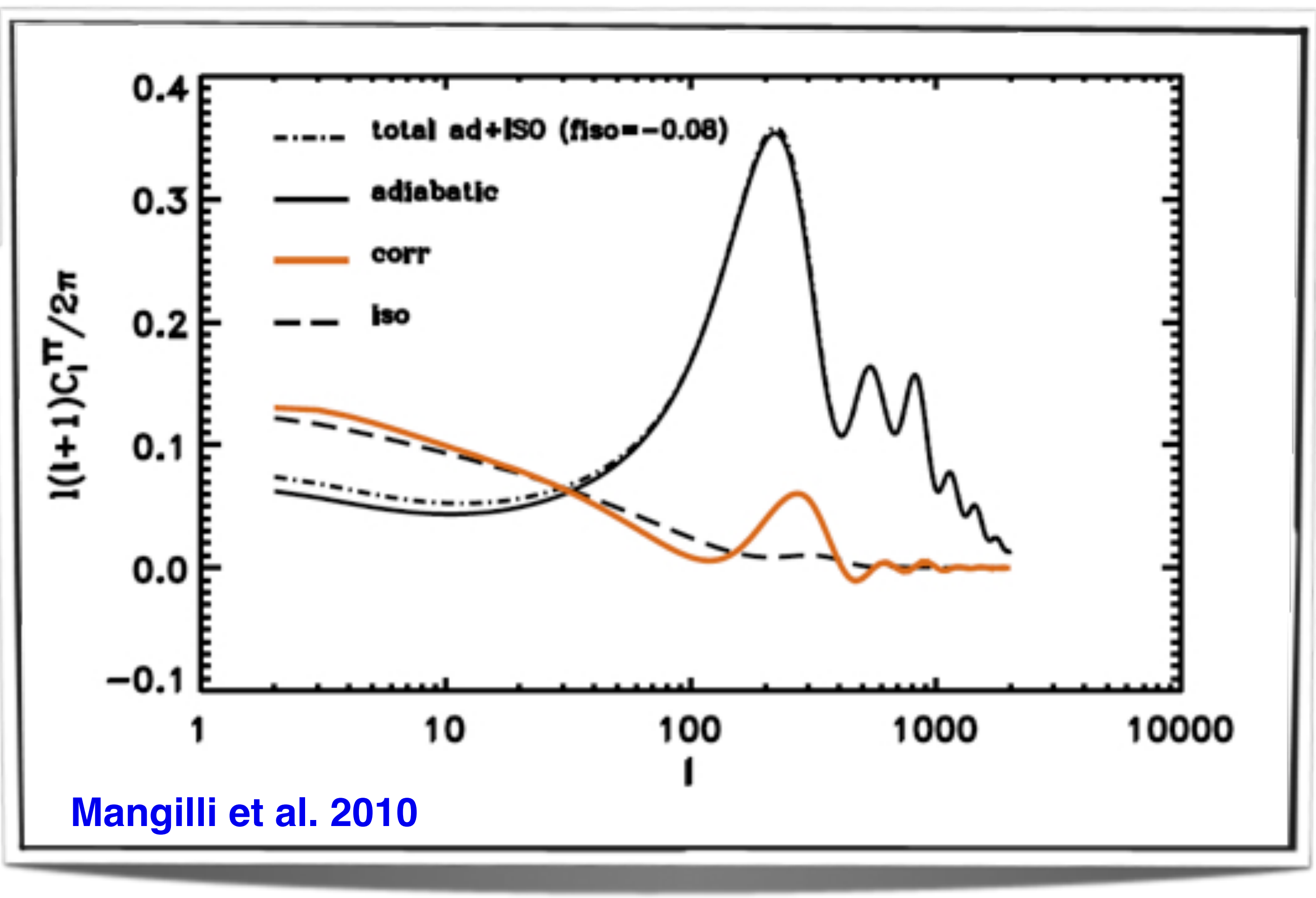
f_{iso}

Isocurvature/adiabatic ratio parameter

95% CL upper bound

		f_{iso}
General model:		
CDM isocurvature	dark matter	0.39
ND isocurvature		0.27
NV isocurvature	neutrinos	0.14
Special CDM isocurvature cases:		
Uncorrelated, $n_{\mathcal{II}} = 1$, ("axion")		0.039
Fully correlated, $n_{\mathcal{II}} = n_{\mathcal{RR}}$, ("curvaton")		0.0025
Fully anti-correlated, $n_{\mathcal{II}} = n_{\mathcal{RR}}$		0.0087

The Planck collaboration 2013



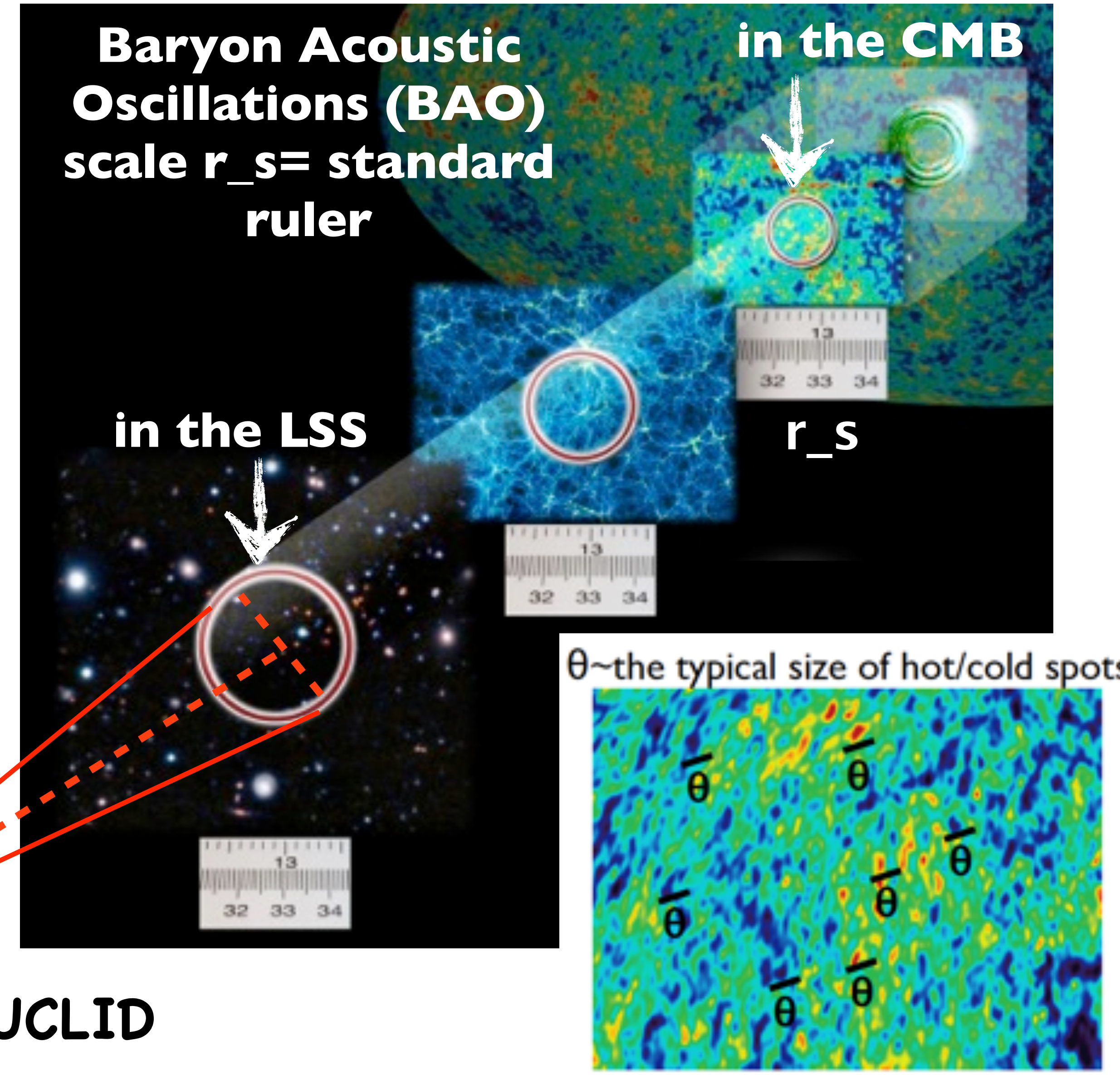
Mangilli et al. 2010

✓ Allowing for **isocurvature** modes introduces new **degeneracies in the parameters space** which can compromise accuracy of parameters constraints (**systematic shifts and bias**)

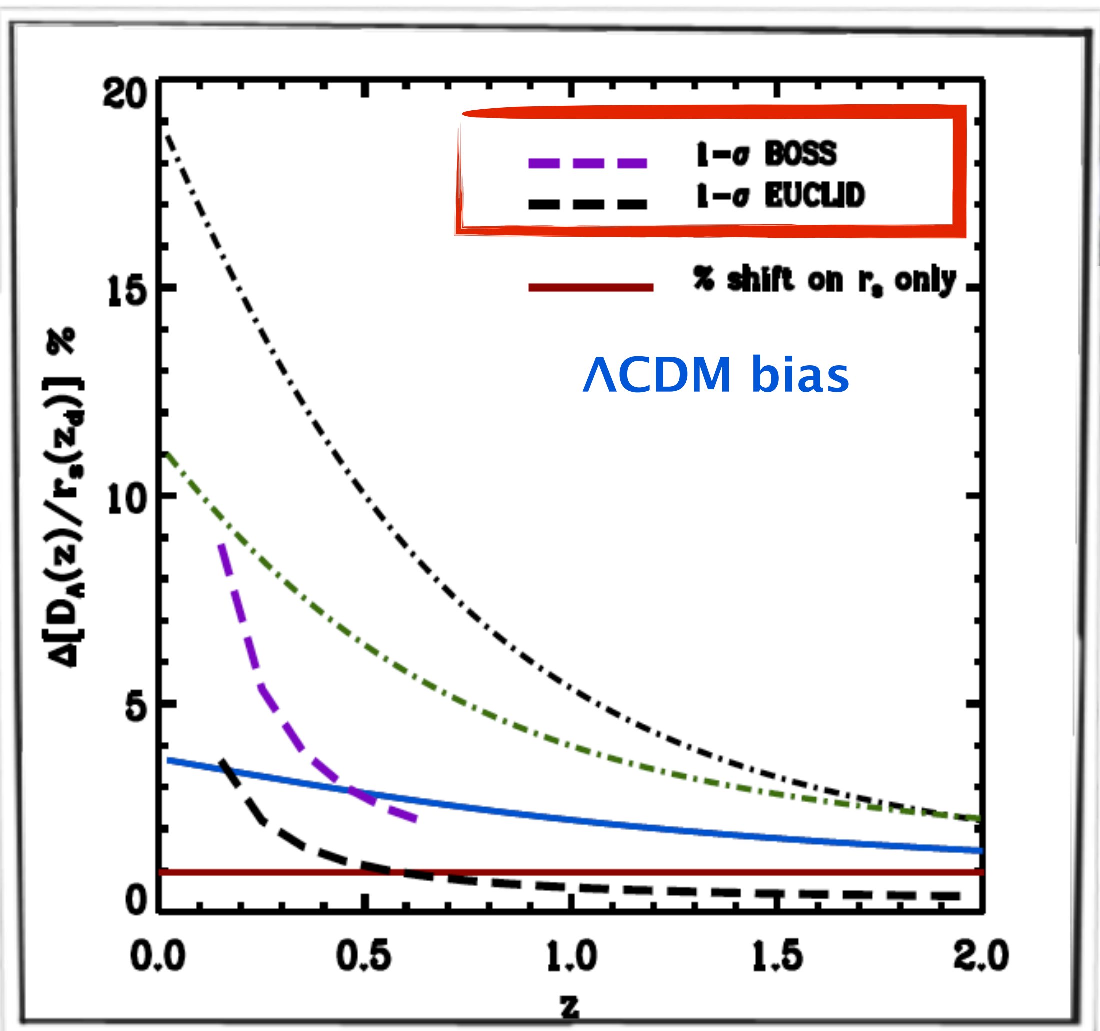
Extra isocurvature contribution can bias CMB parameter estimation and modify the constraint of the typical scale of the Baryon Acoustic Oscillation imprinted in the CMB

The BAO scale as imprinted in the CMB evolves as the Universe expands and remains also imprinted in the large scale matter distribution and can be used to probe Dark Energy by galaxy surveys

Future surveys i.e . Euclid will be able to measure BAO scale with very high accuracy



EUCLID



Mangilli et al. 2010

A wrong assumption on the nature of primordial perturbations leads to a systematic bias on the BAO scale measurements from large scale structure surveys bigger than survey experimental errors i.e EUCLID

Wrong interpretation of Dark energy properties from galaxy surveys data

Combining CMB and Large scale structures

Combining the information from Large Scale Structure (LSS) survey and CMB breaks parameter degeneracies and greatly improves constraint on the nature of the primordial perturbations and on Dark Energy parameters

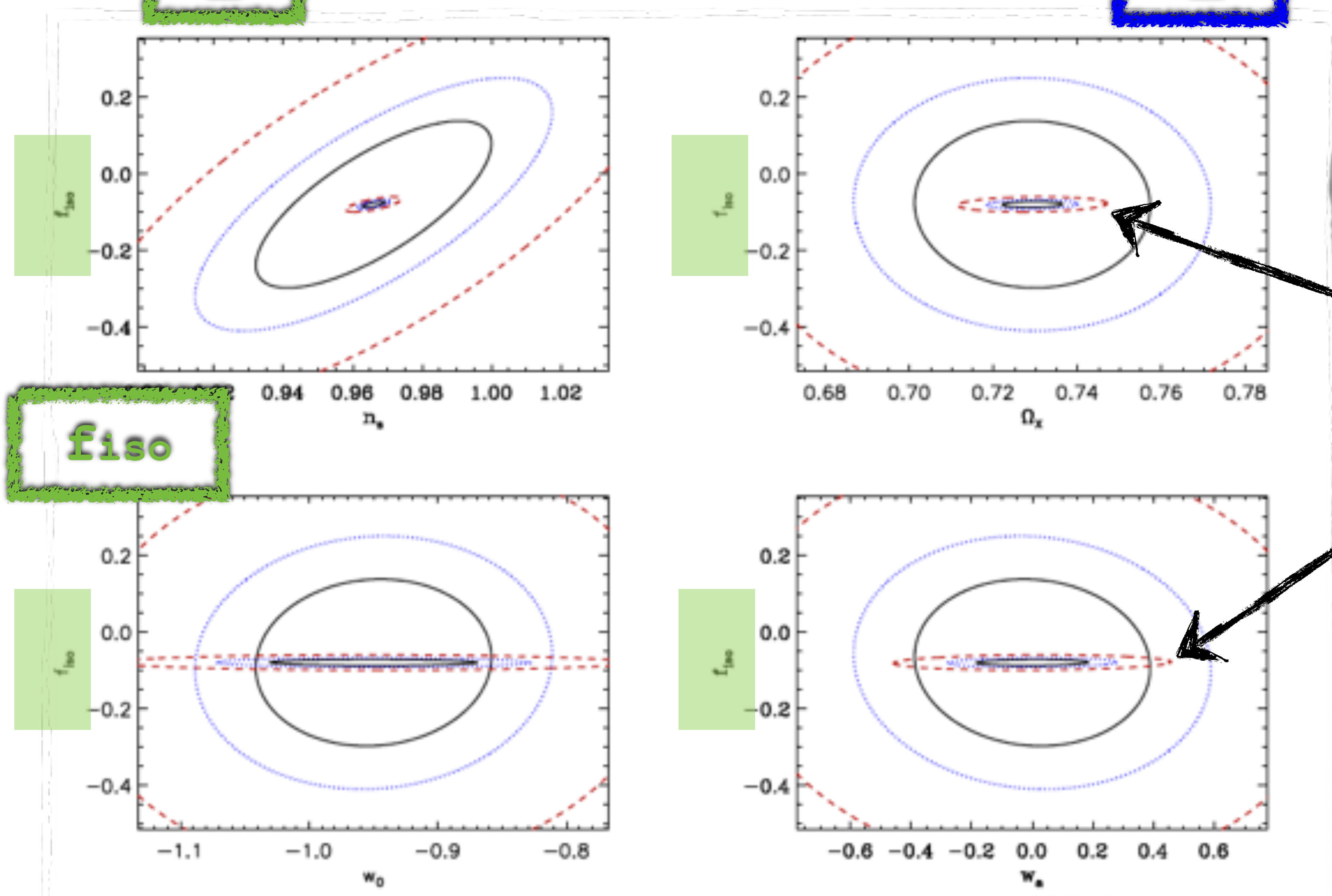
Carbone, **Mangilli** & Verde **(2011)**

n_s

Ω_Λ

fiso

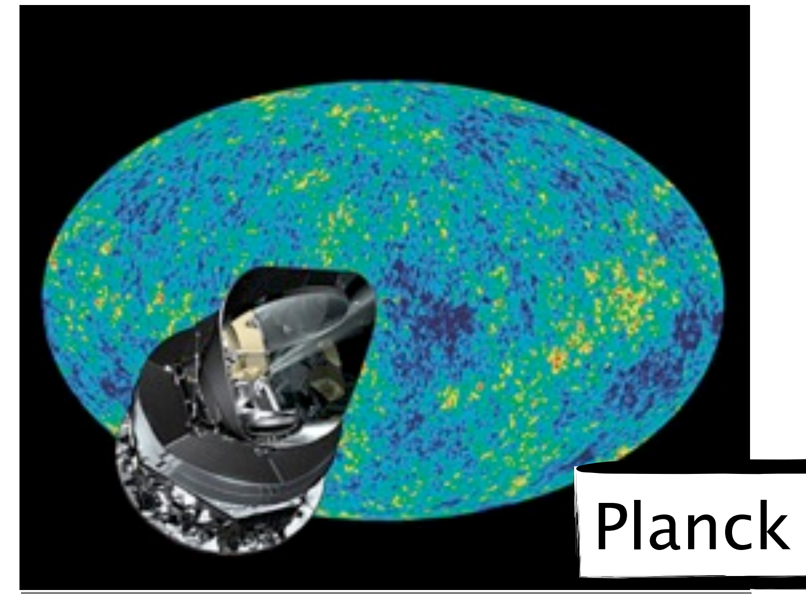
isocurvature fraction parameter



w_0

w_a

Dark energy equation of state parameters



EUCLID + Planck (TT&Pol)

CMB and galaxy surveys allow for precision tests of the standard ΛCDM and beyond!

- **Planck constrained for the first time CMB Non-Gaussianity with unprecedented precision!**

Planck favors the simplest models for inflation

Planck finds evidence <u>for the first time</u> of the Integrated-Sachs-Wolfe-lensing bispectrum: new observable!

- **Combining CMB + Large Scale Structure very powerful! Degeneracies are solved (no systematic shifts) and constraints on the nature of primordial perturbations improved even for extended model**

More data!

Planck full mission and **POLARISATION** data on 2014

THANK YOU FOR YOUR ATTENTION!

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Mangilli, Verde, Beltran JCAP 2010
Mangilli, Verde PRD 2009
The Planck Collaboration (including Mangilli), Planck results 2013:
XXIV. Constraints on primordial non-Gaussianity
XIX. The integrated Sachs-Wolfe effect
XVII. Gravitational lensing by large-scale structure, A&A 2013