Fundamental Physics with Planck

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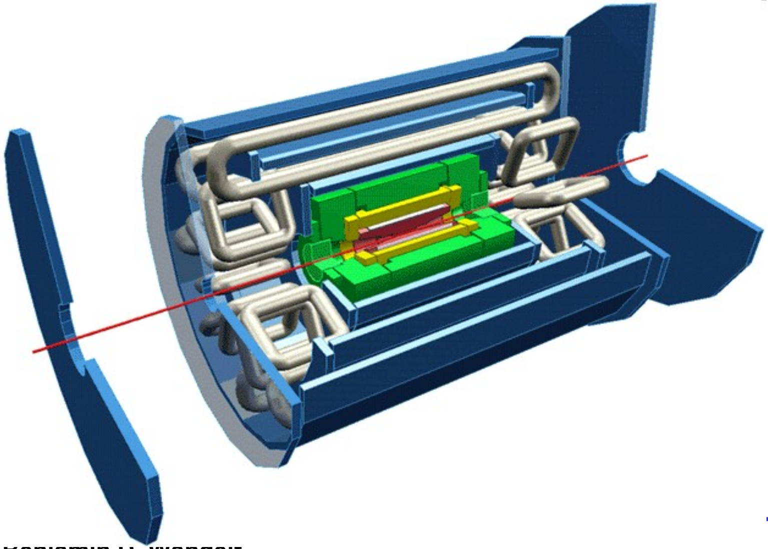
The big questions are:

"What happened at t = 0 ?"

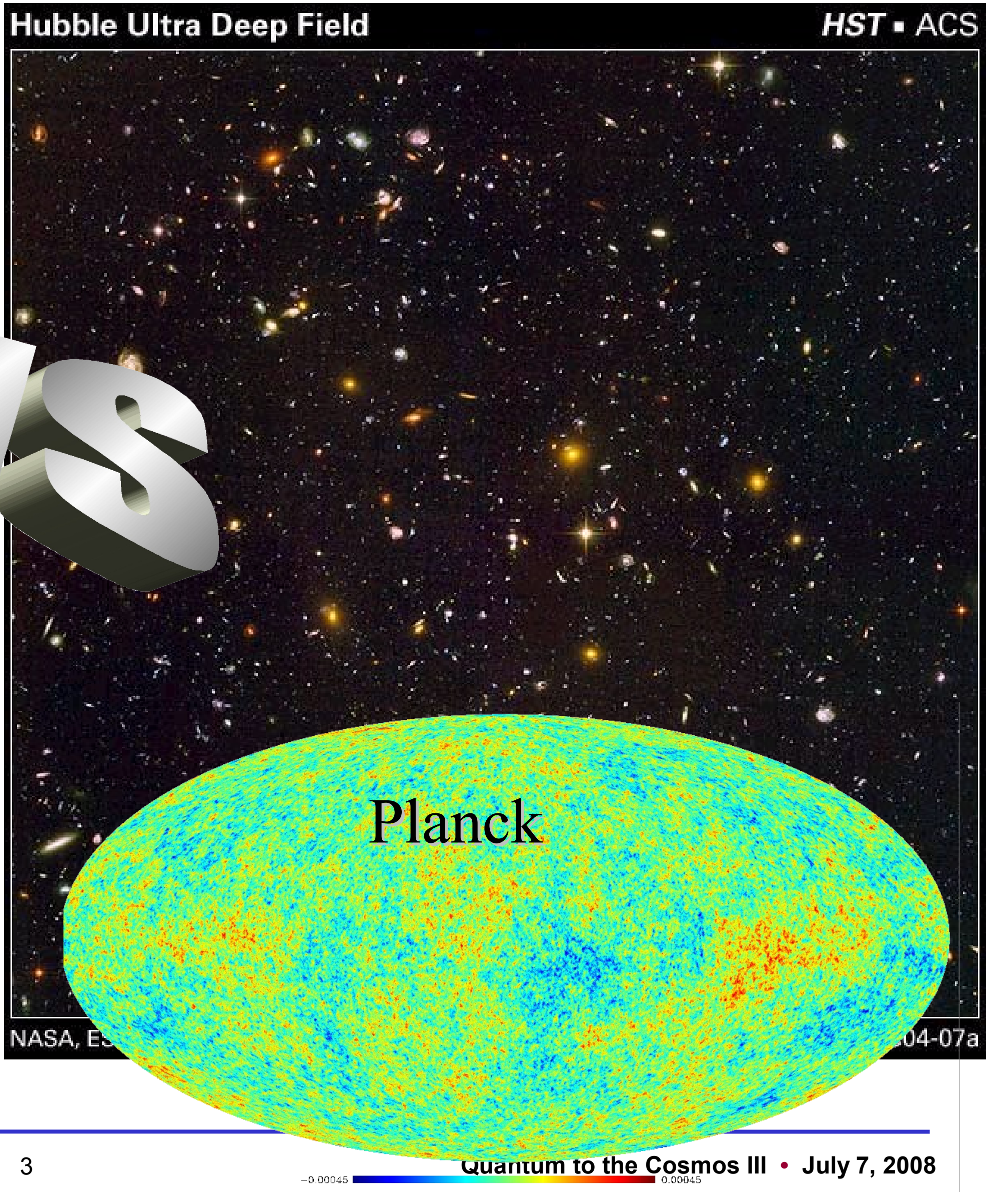
"What is the fundamental theory, valid at the highest energies?"

Showdown


LHC at CERN
France
Switzerland
4.3 km



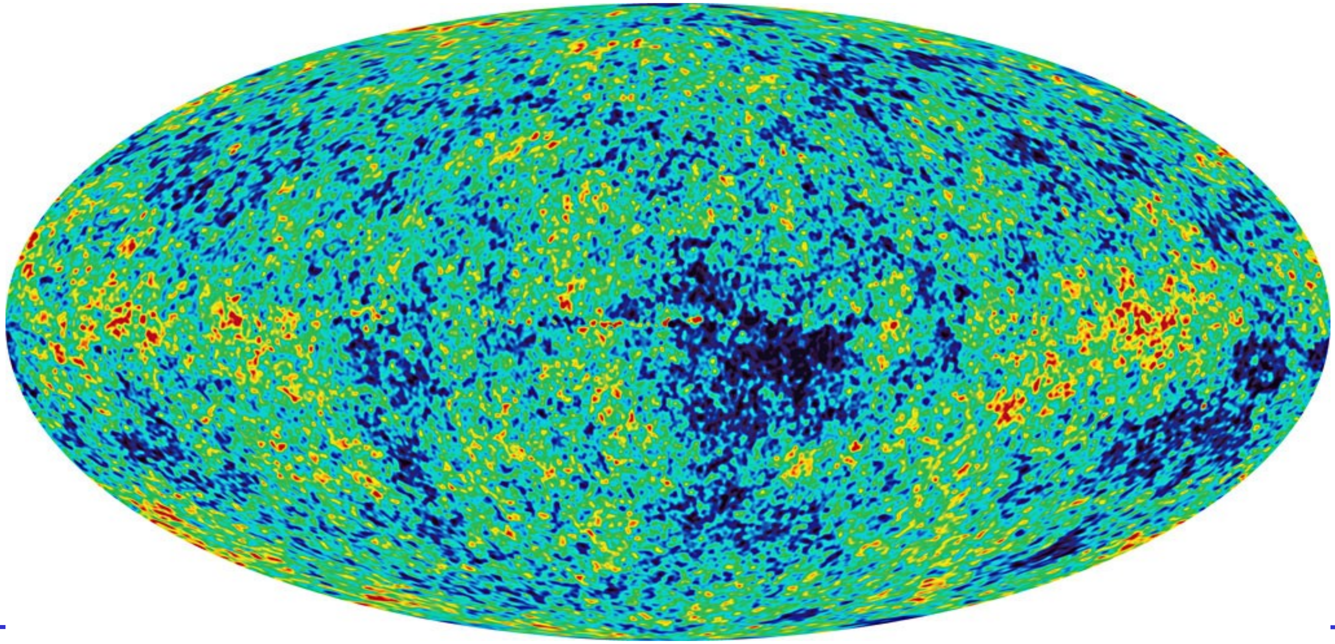
VS


Hubble Ultra Deep Field
HST ▪ ACS
Planck
−0.00045
0.00045

Cosmos to the Quantum!

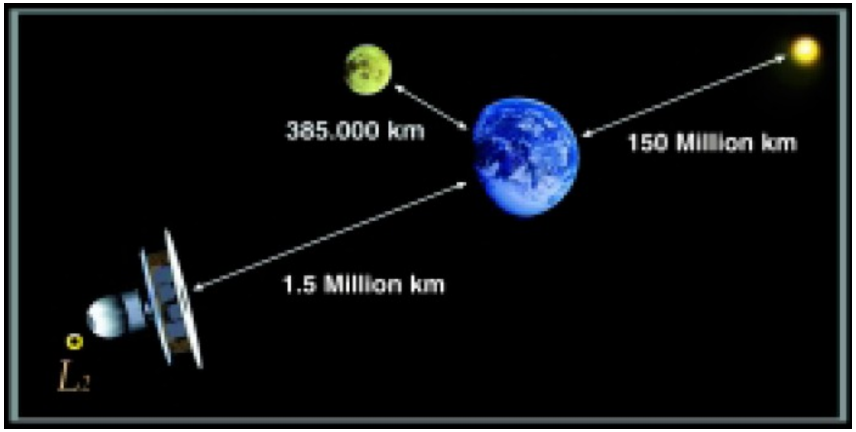
- But: basically, trying to study physics at the very highest energies in a particle accelerator is too ambitious.
- It's brute force.
- It involves creating early Universe conditions in a lab!

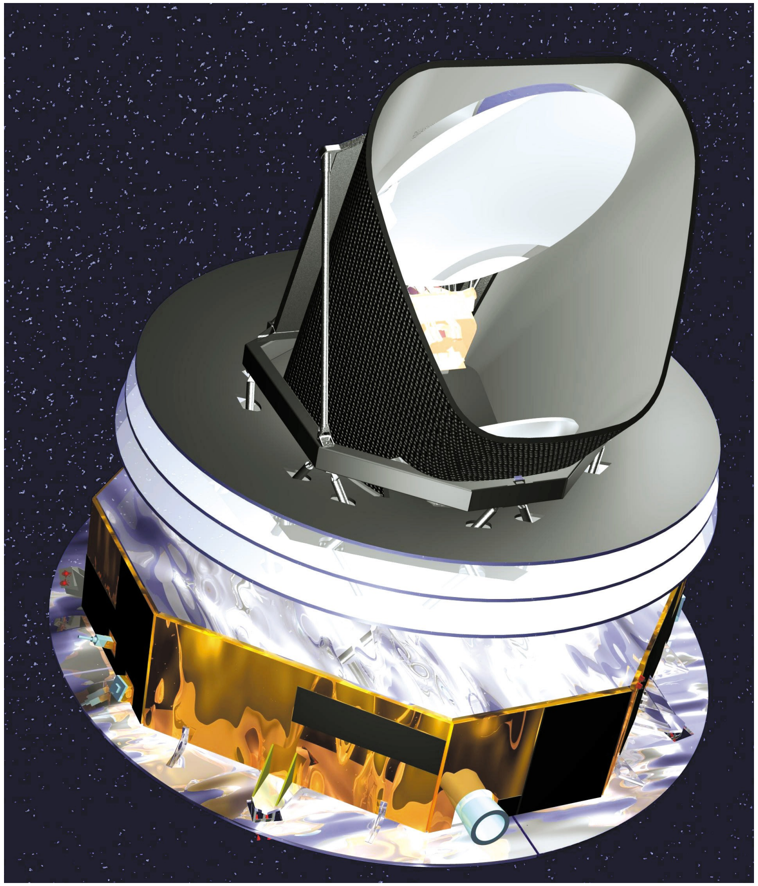
Conveniently, the Universe sent us a baby picture of itself. We can use to infer the initial conditions of the Universe: Cosmos to the Quantum!



The Planck Mission

- Planck is a major joint ESA/NASA mission to L2 to make definitive all-sky maps of CMB temperature anisotropy.
- The Planck science case is in the "Planck Blue Book"
  http://www.rssd.esa.int/index.php?project=Planck
- Planck will launch in months, not years!
- Current launch date in December 2008.





Planck is real!

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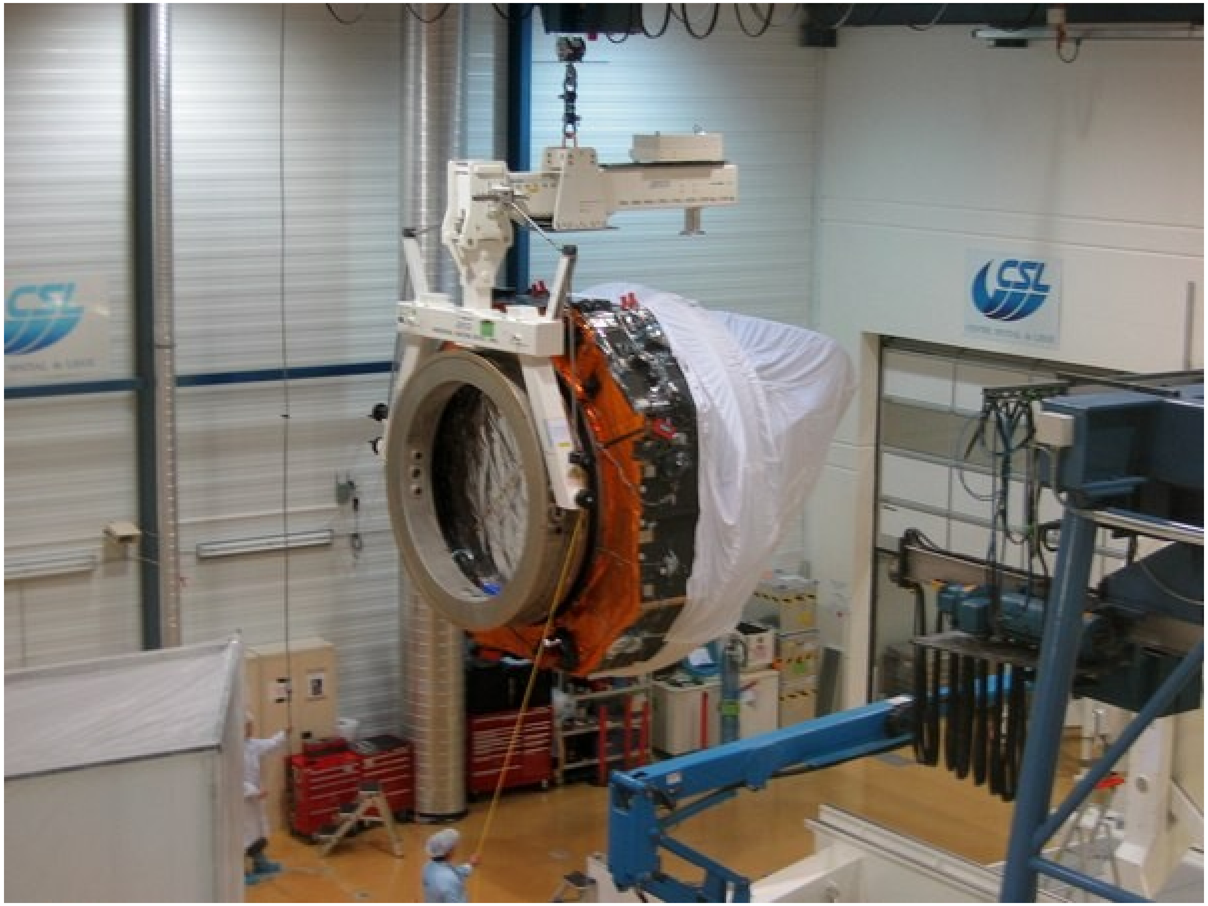
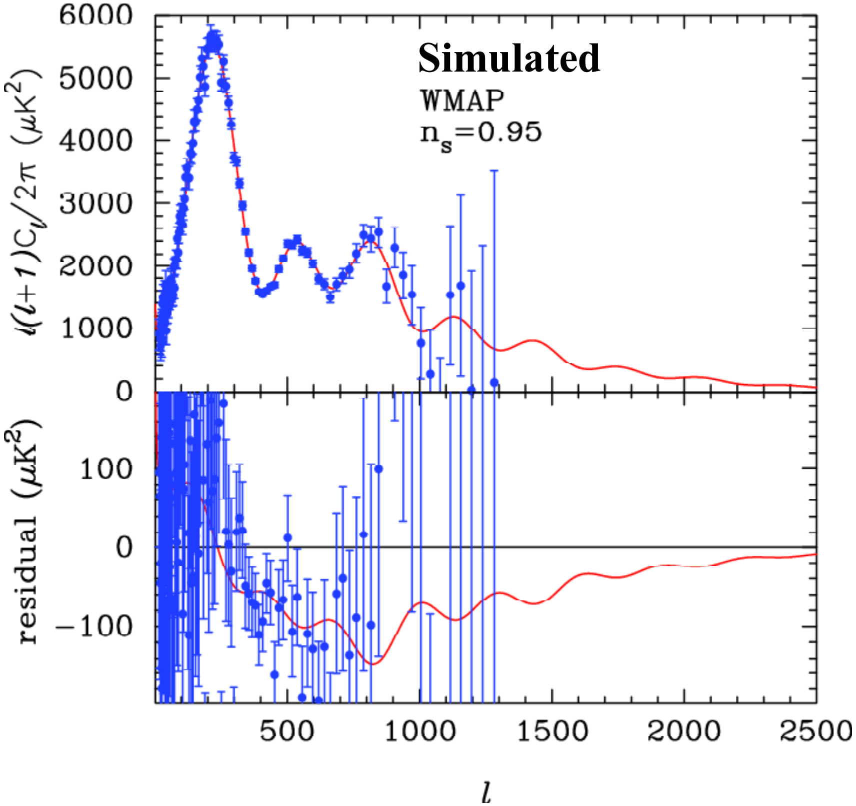


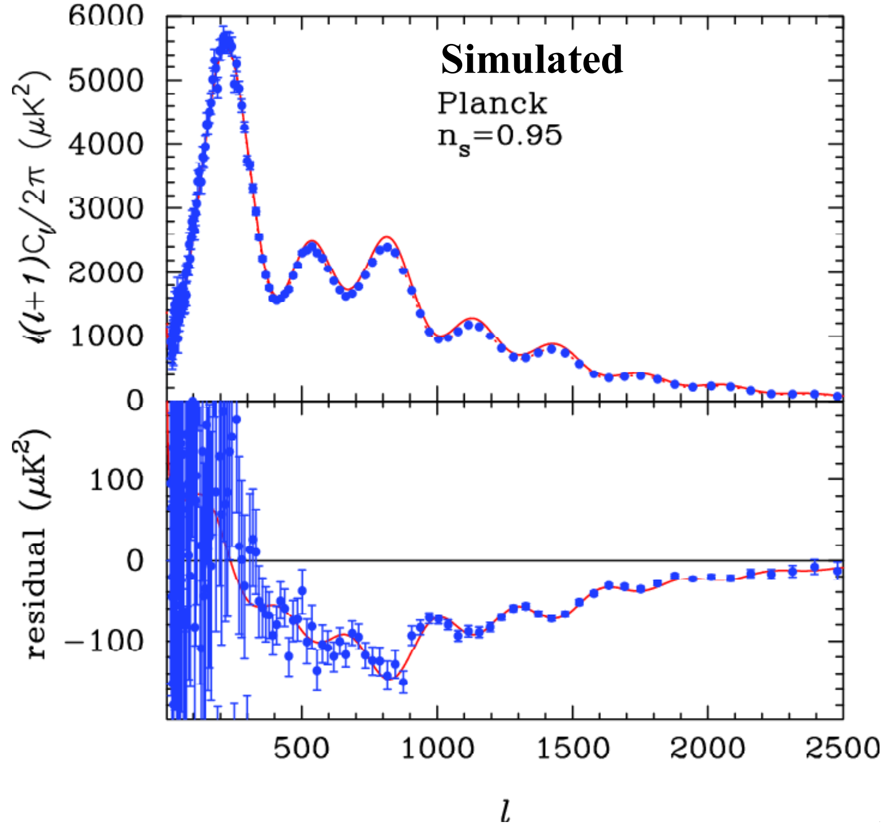
Planck is real!

Preparation for cold test (now ongoing)

Forecasted Planck TT Power Spectrum Errors

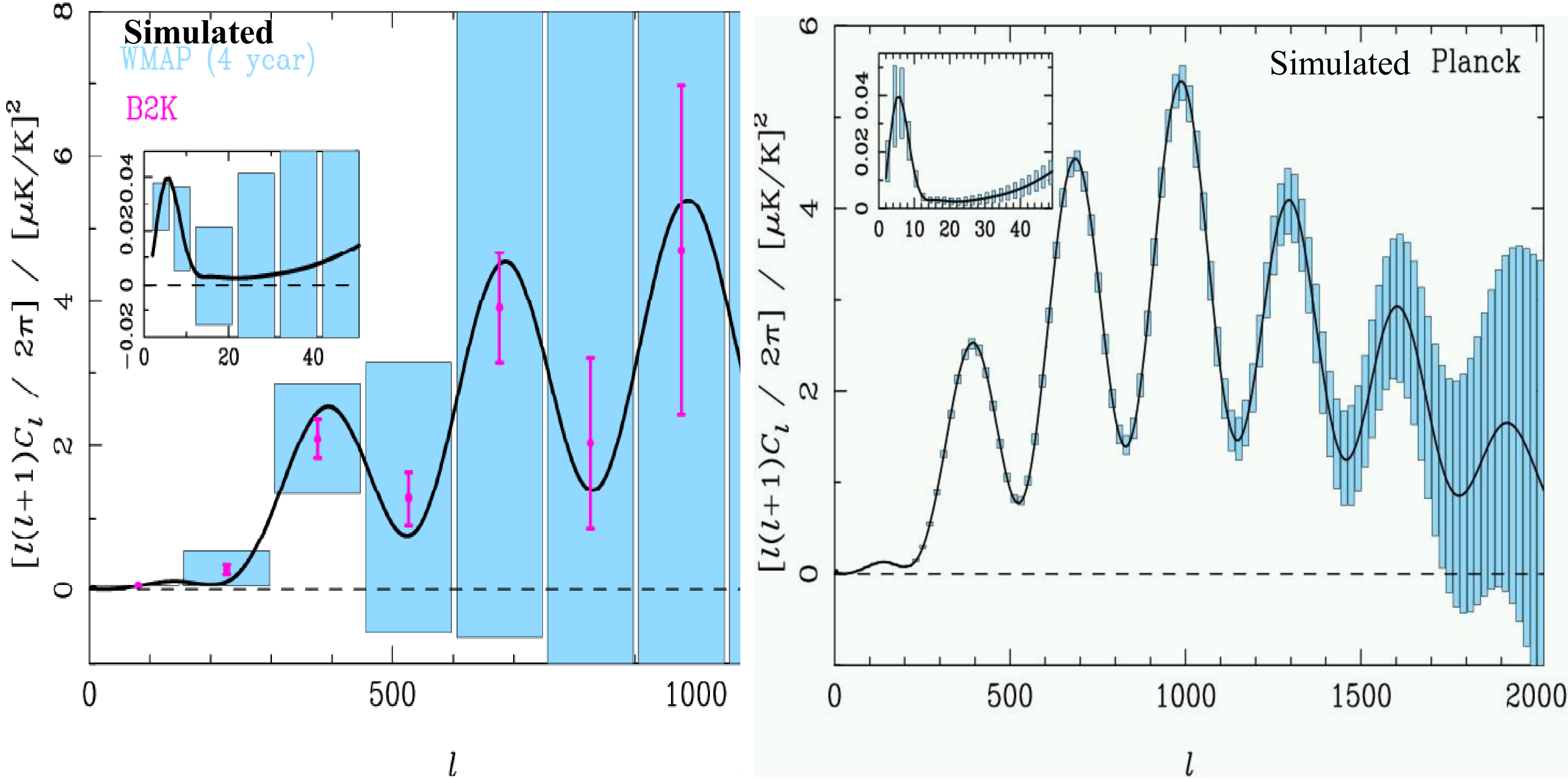
Model (red curves) has n_s = 1



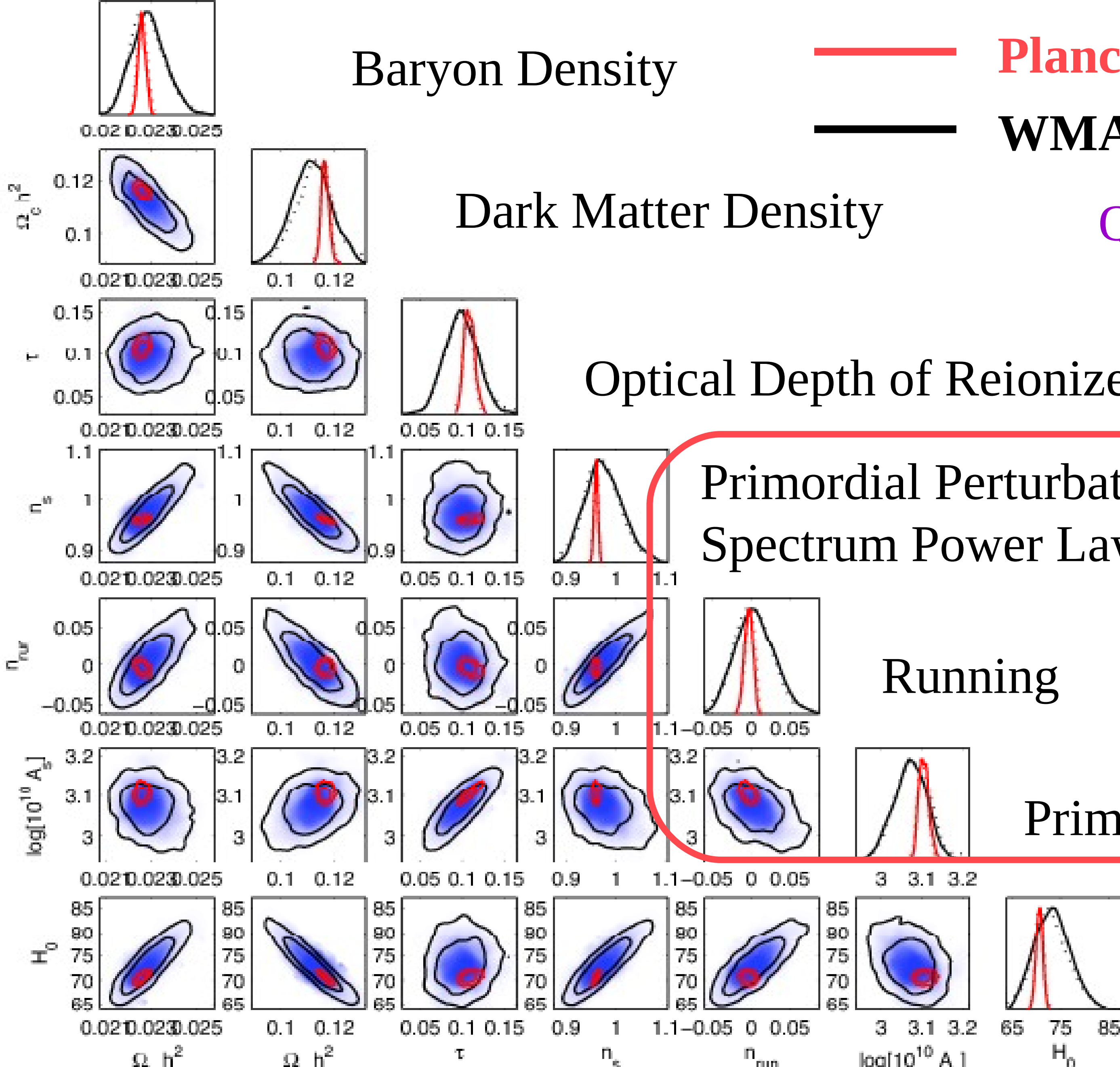


Planck will obtain a full characterization of the primordial CMB temperature perturbation

Forecasted Planck EE Power Spectrum Errors



Enabled by Planck's greater sensitivity, angular resolution and frequency coverage



Baryon Density

Planck

WMAP

Dark Matter Density

Qualitative Advance in Precision

Optical Depth of Reionized IGM

Primordial Perturbation Power Spectrum Power Law Spectral Index

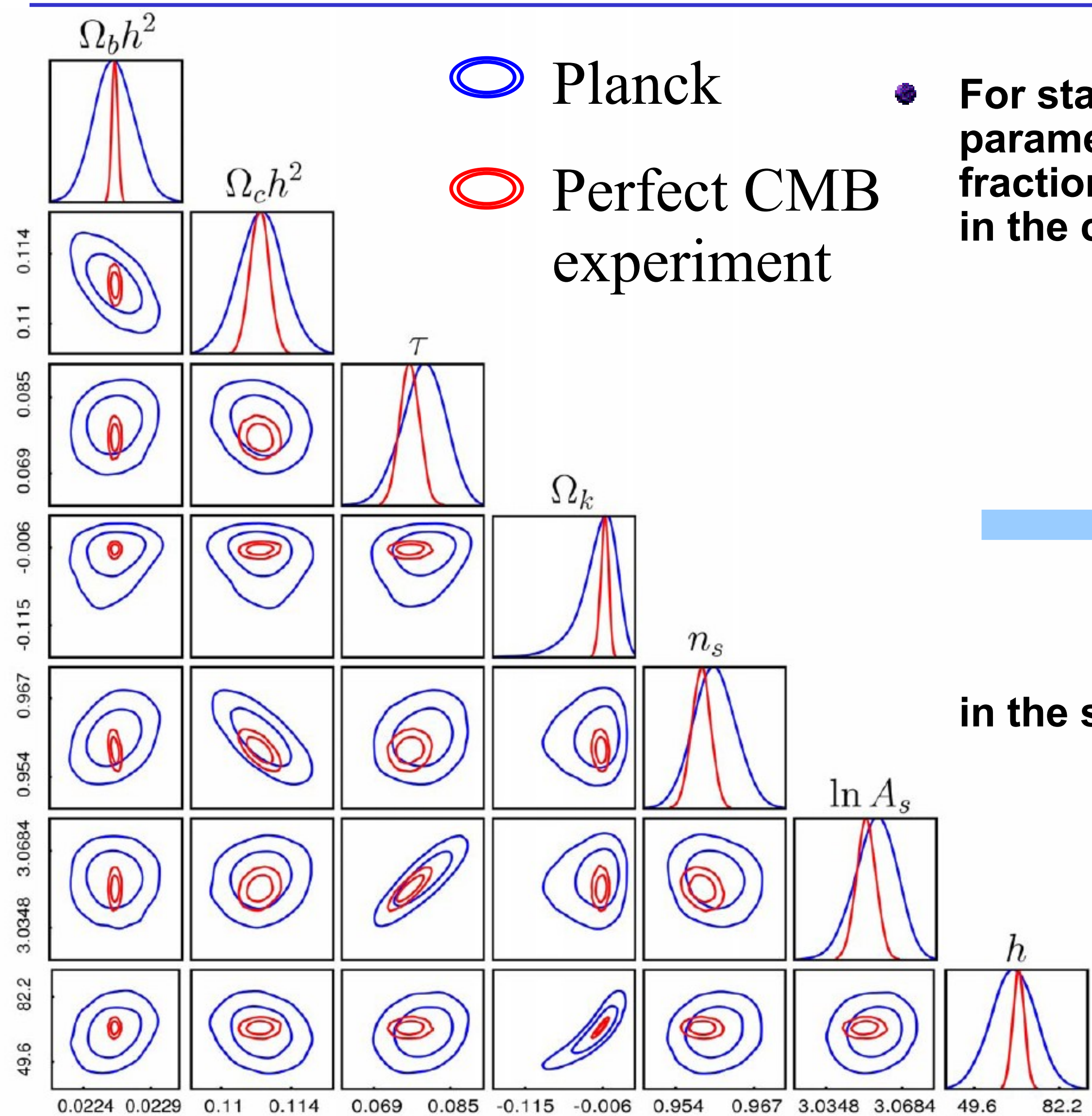
Running

Inflation

Primordial Amplitude

Expansion Rate

Predicted Planck constraints for the standard cosmological model



Planck

Perfect CMB experiment

- **For standard cosmological parameters Planck will extract a large fraction of the information contained in the cosmic microwave background!**

$$\frac{\sigma_{Planck}}{\sigma_{Perfect}} = O(1)$$

in the standard cosmological model.

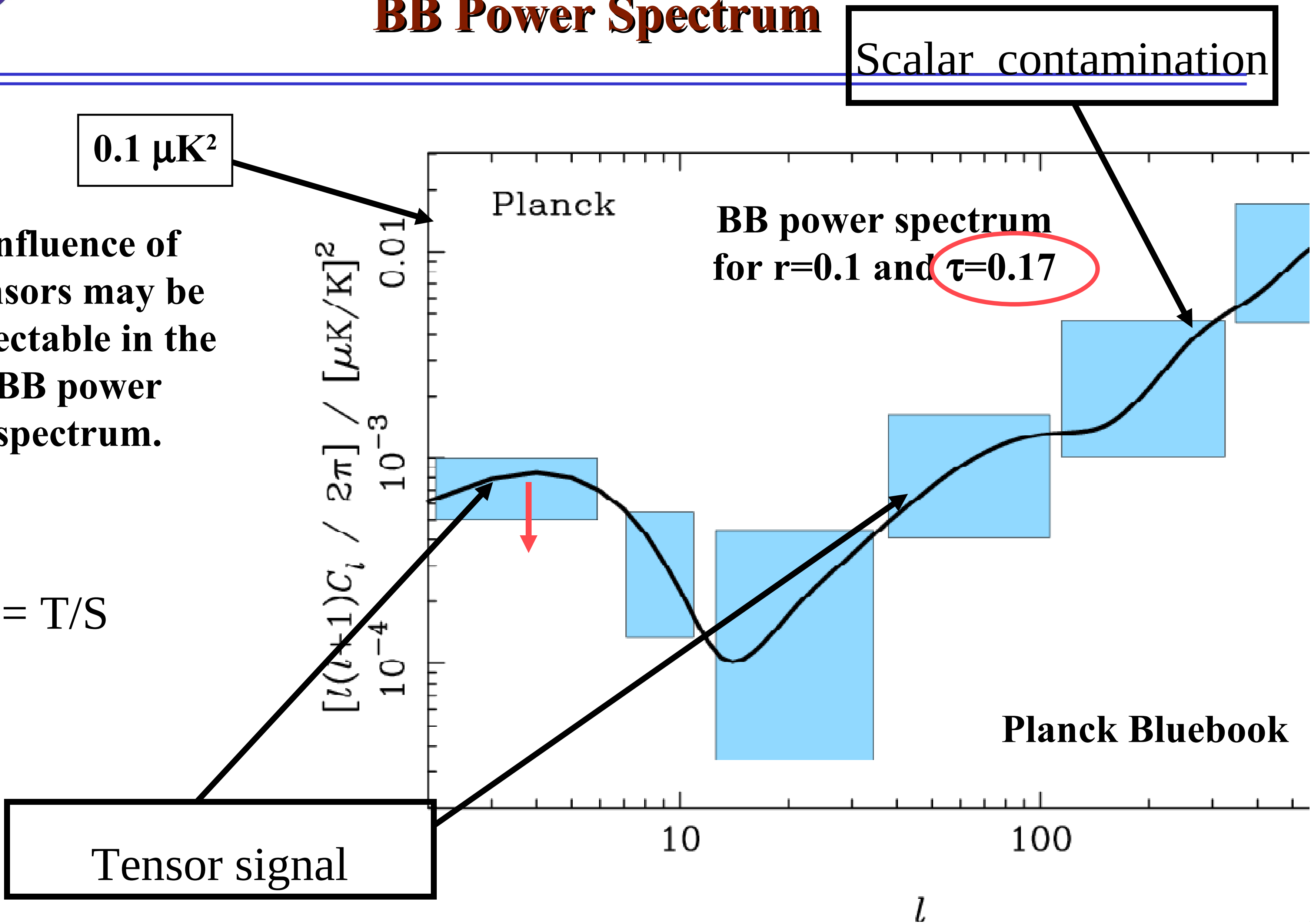
Detecting Tensor (Gravitational Wave) Perturbations

- The scalar perturbation spectrum is a great probe of inflation, but the tensor perturbation spectrum is more direct.
- The scalar spectrum is determined by a combination of the expansion rate during inflation and how it's changing with time. The tensor spectrum depends only on the expansion rate during inflation, and thus the energy scale of inflation.
- Tensor perturbations produce polarization B modes, while scalar perturbations, to first-order, do not.
- Detectability of tensor B modes depends sensitively on this energy scale.
  - + GUT-scale inflation produces detectable tensor perturbations.
  - + Simplest models of inflation, when tuned to have the observed scalar perturbation amplitude, have an energy scale ~ GUT-scale.
  - + Gauge-coupling unification hints at new physics at the GUT scale.

BB Power Spectrum

Influence of tensors may be detectable in the BB power spectrum.

r = T/S



Planck and the Standard Model of Cosmology

- Current *observational* status:
  - We now know the basic global properties of the Universe.
  - The standard model correctly predicts (almost) all observed phenomena.

- Current *theoretical* status:
  - We don't understand most of the constituents of the Universe.
  - We don't know how it began

How to make a Universe: the observer's recipe

One delicious Universe:

3 cups dark energy
1 cup dark matter
a pinch of baryonic matter for flavor

microwave at 2.7 K

Razzle Dazzle Recipes

How to make a Universe: the theorist's view

Dark energy recipes:

Dark matter recipes:

One inflationary Universe:
Use recipe below to make 4-D effective field theory.
Make smooth patch. Add GR.
Let the field with the largest potential energy inflate patch while cooling. Reheat.

OR: set up parallel colliding branes. OR:

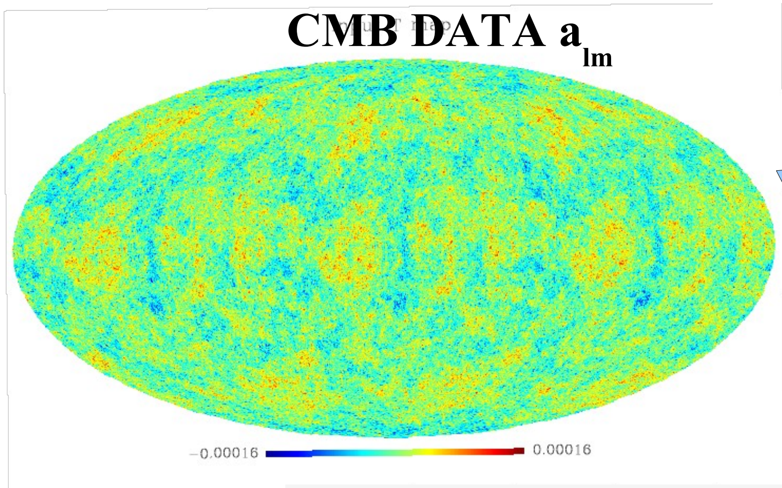
One 4-D effective theory:
Strings? 10 to 11 space-time dimensions.
Compactify to 4 or 5 "large" dimensions, to taste.
How many branes in the Calabi-Yau? Where?
What causes inflation? Find effective 4-D description...

Razzle Dazzle Recipes

Fundamental physics with Planck

- Planck probes physics as fundamental as it gets:
  - Probe Nature of the primordial quantum fluctuations
  - What banged at the Big Bang?
  - Variations of fundamental constants
  - Tests of isotropy, topology, fundamental symmetries
  - Dark energy
- Planck constraints will be less dependent on assumptions than current constraints

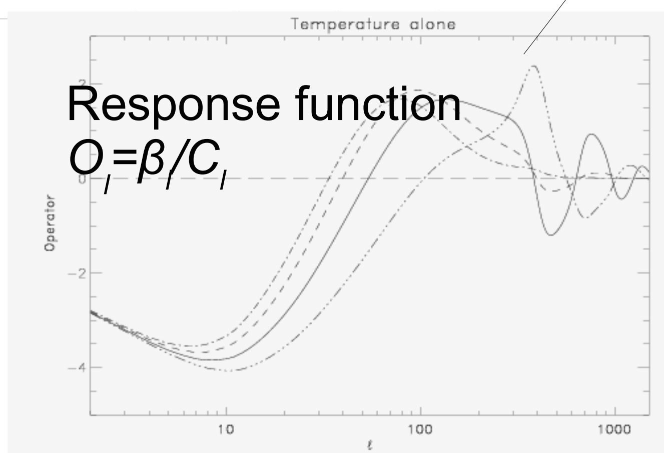
The fingerprint of primordial perturbations

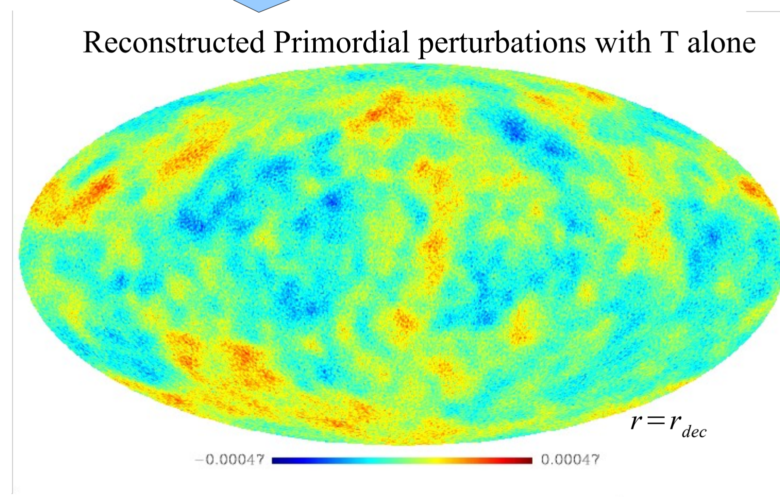


$\Phi_{lm} = O_l \, a_{lm}$

SW limit

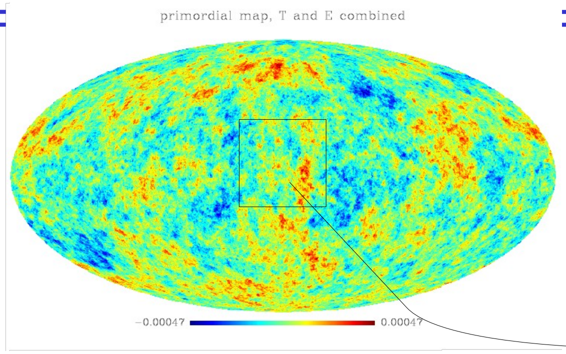
$$\frac{\delta\phi}{\phi} = -3\,\frac{\delta T}{T}$$



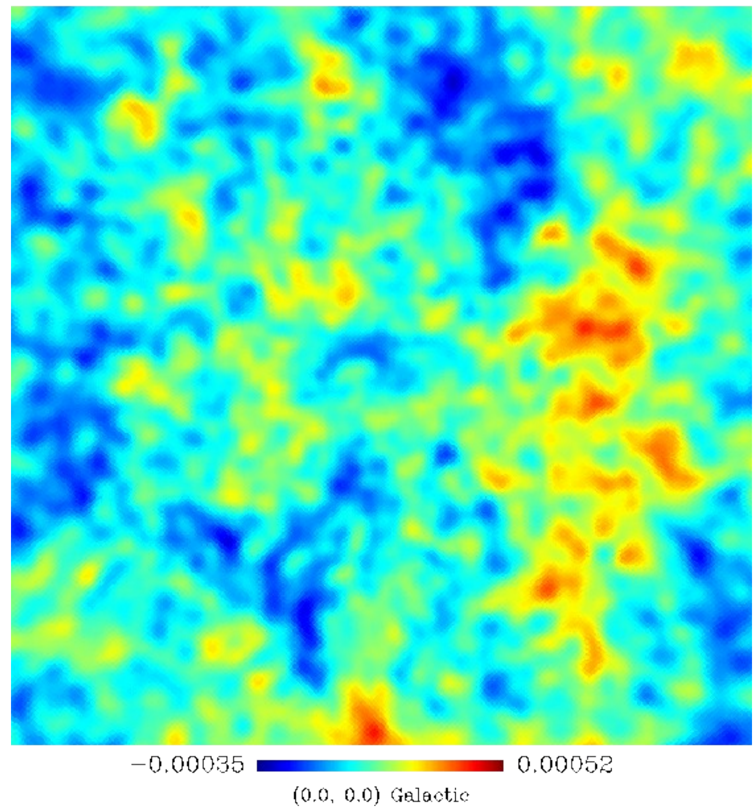


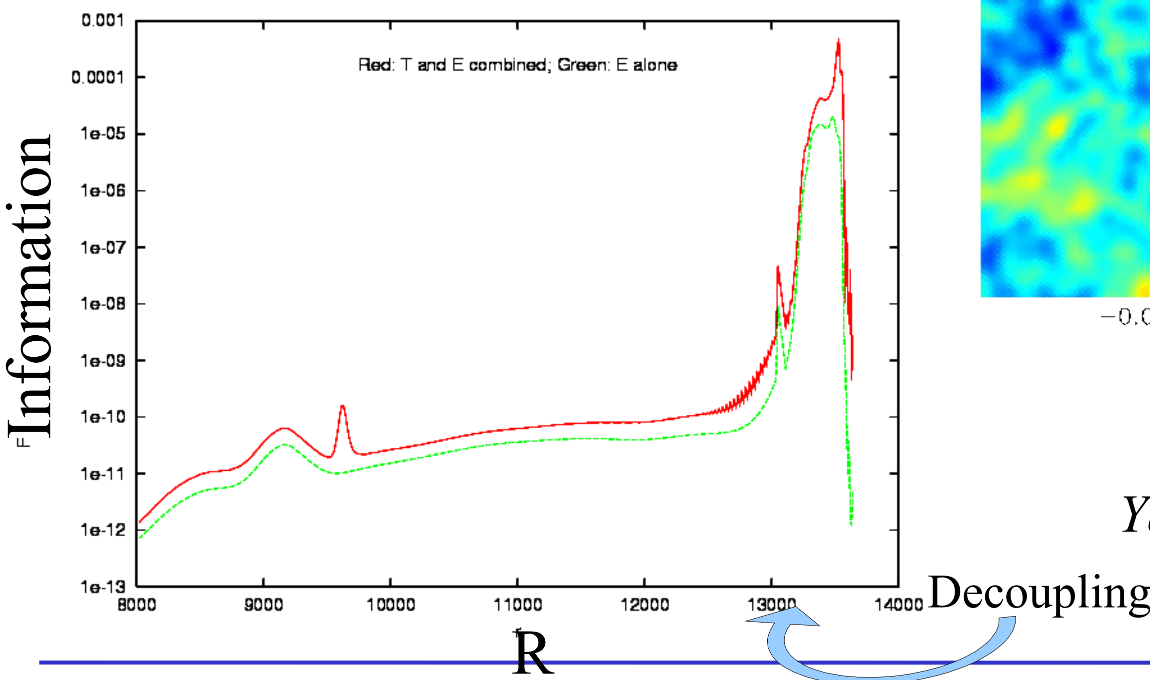
$$\beta_\ell^i(r) = \frac{2b_\ell^i}{\pi} \int k^2 dk \, P_\phi(k) g_\ell^i(k) \, j_\ell(kr),$$

CMB Tomography



Primordial curvature fluctuations





Yadav, and Wandelt, PRD (2005)

CMB tests of inflation: Current Status

Tests	Std. Inflation	Ekpyrosis	Observations
Is observable universe flat?	Yes.	Built in.	Yes, to ~2%
Do the fluctuations have the predicted correlations (nearly scale independent)?	Yes.	Yes.	Yes, to few %
Are fluctuation adiabatic?	Yes.	?	Yes, to ~10%
primordial gravitational waves	Maybe	No	?
Are fluctuations nearly Gaussian?	Yes: predicted to be true at 0.001%!	Much higher deviations from Gaussianity	Hints of deviation from Gaussianity in WMAP data!

Yadav & Wandelt 2007
Komatsu et al. (WMAP5) 2008

Planck and non-Gaussianity

- **Primordial non-Gaussianity is a separate window on the very early Universe, complementary to the wealth of information in the two-**
- **Different models of the early Universe have distinct predictions regarding the type and the amount of non-Gaussianity expected.**
- **Ekpyrotic/Cyclic models generically predict non-Gaussianity at detectable levels for Planck.**
- **The search for non-Gaussianity is also complementary to the search for primordial gravitational waves**
  - **Primordial B-modes are the "smoking gun" of inflation**
  - **Finding primordial non-Gaussianity would rule out all single-field models of slow-roll inflation**
- **Planck will improve WMAP non-Gaussianity error bars by nearly one order of magnitude**

Local f_{NL} – a specific type of non-Gaussianity

$$\Phi(x) = \Phi_G(x) + f_{NL}\Phi_G^2(x)$$

Salopek & Bond 1990
Komatsu & Spergel 2001

Characterizes the amplitude of non-Gaussianity

- **This non-Gaussianity creates a bispectrum signature (as well as higher order moments)**

$$<\Phi(k_1)\Phi(k_2)\Phi(k_3)>=2(2\pi)^3 f_{NL}\delta(k_1+k_2+k_3)P(k_1)P(k_2),$$

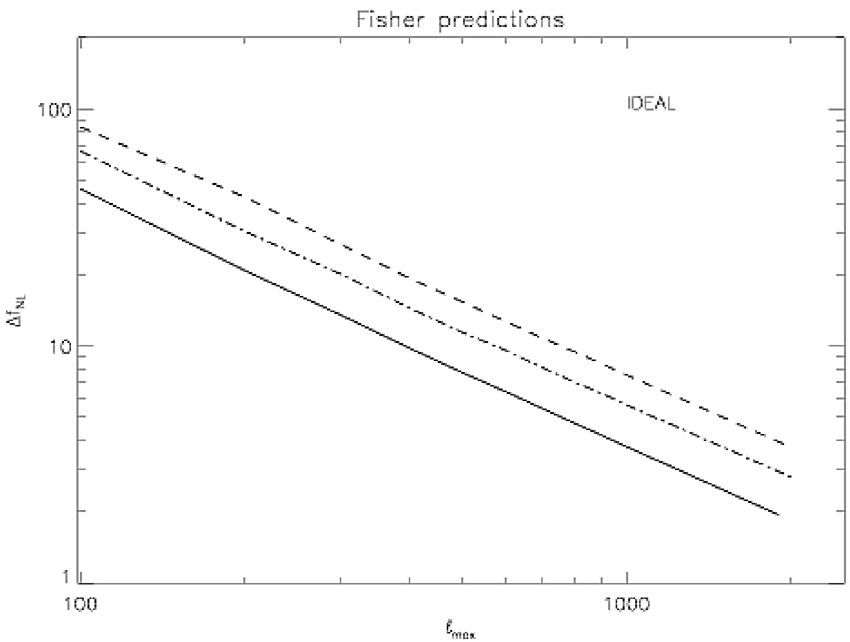
where $(2\pi)^3\delta(k_1+k_2)P(k_1)=<\Phi(k_1)\Phi(k_2)>$

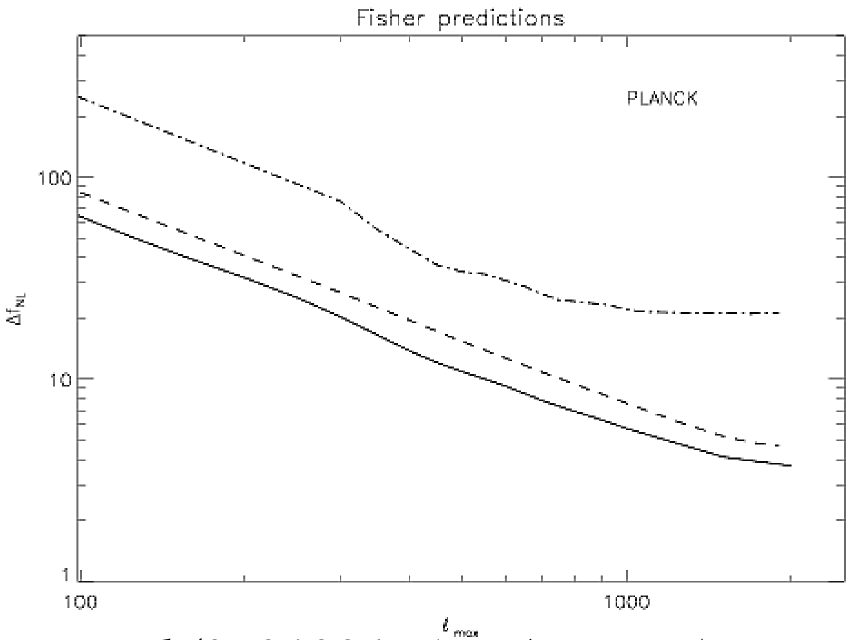
- This translates into a bispectrum signature in the CMB through

$$a_{lm} = 4\pi(-i)^l \int \frac{d^3\mathbf{k}}{(2\pi)^3}\Phi(\mathbf{k})g_{Tl}(k)Y^*_{lm}(\hat{\mathbf{k}})$$

Planck's promise for Non-Gaussianity work

- **Many modes**
  - large sky coverage
  - high resolution
- **Frequency coverage**
  - foreground removal
- **Polarization**
  - complementary to T
  - adds a great deal of information
- **Multiple sky coverages**
  - control of systematics in time-domain





Yadav, Komatsu and Wandelt et al., astro-ph/0701921, ApJ (in press)

Status of NG work

- Yadav&Wandelt (2008) and Komatsu et al (2008) see 2.5-2.8 sigma and 1.7-2.3 sigma hints of local NG in the WMAP 3-year and 5-year data, respectively.
- LSS constraints consistent with CMB constraints (Sloszar et al 2008)
- We have demonstrated feasibility and near-optimality of the YKW f_{NL} estimator for Planck data (Yadav et al. 2008, ApJ 678, 578)
  - can take into account inhomogeneous noise distribution
  - can deal with smooth sky mask
  - performance of estimator insensitive to residual noise correlations (Donzelli, Liguori, in prep.)
- Equilateral f_{NL} of interest for DBI inflation models with non-standard kinetic term.
  - Current constraint: $-151 < f_{NL,\, equil} < 253$; $\Delta f_{NL,equil} \sim 200$
  - Expect Planck constraints of $\Delta f_{NL,equil} \sim 30$.

Tests of primordial non-Gaussianity

- Non-Gaussianity is a powerful probe of the physics of the beginning
- In combination with power spectrum a very powerful test of inflation vs its alternatives.
- Currently the highest precision test of inflation
  - non-Gaussianity is a ~0.1% test
  - flatness in second place ~1.5%
- A way to distinguish between classes of models that give similar predictions for the two-point correlations
- Already starting to rule out significant portions of parameter space, for inflation as well as cyclic/ekpyrotic/new ekpyrotic models.
- Complementary to tensor modes
- A new, exciting and fast-moving frontier

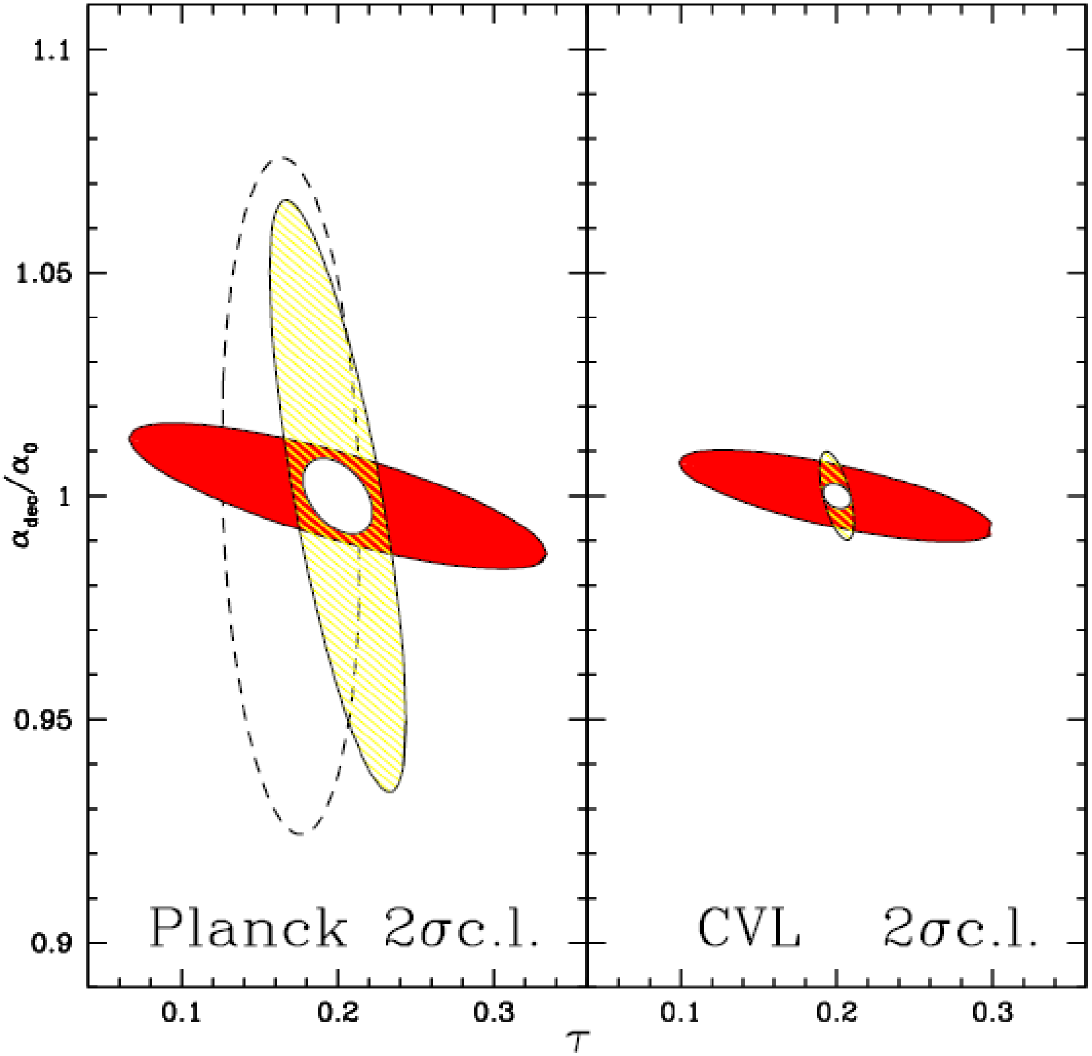
Reducing Model Dependence with Planck

- **Planck will enable us to obtain much more model-independent constraints than current data.**
- **Model independent primordial power spectrum constraints**
- **BBN example:**
  - **Assuming no isocurvature modes the WMAP3 constraints on baryon density have errors of a few per cent.**
  - **Dropping this assumption the uncertainty becomes 20%, assuming 4 years of WMAP and 2% assuming Planck.**
  - **There are interesting discrepancies in light element abundance determinations. Only deuterium agrees with nominal WMAP constraint.**

Isocurvature modes

- Some (string inspired) inflation models produce isocurvature perturbations.
- Allowing for the presence of these modes introduces degeneracies in cosmological parameters with current data. (Bucher, Moodley and Turok 2001; Dunkley et al 2005)
- Planck’s polarization measurements enable it to set much tighter upper limits on isocurvature mode amplitudes, or possibly detect them.

Variations of the fine structure constant

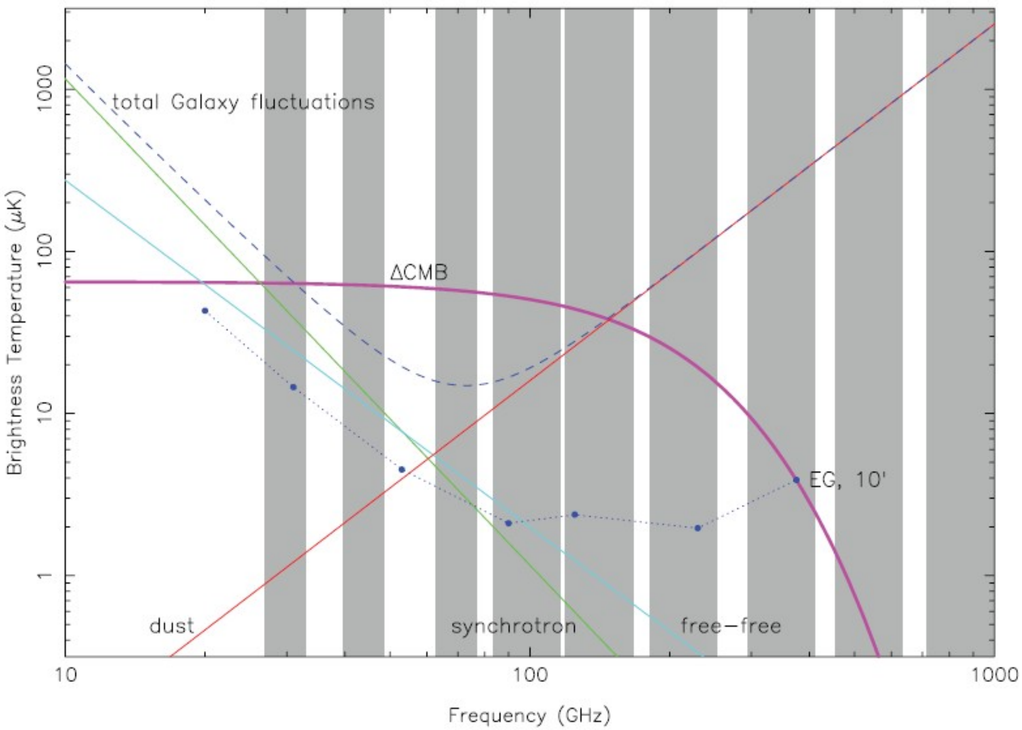


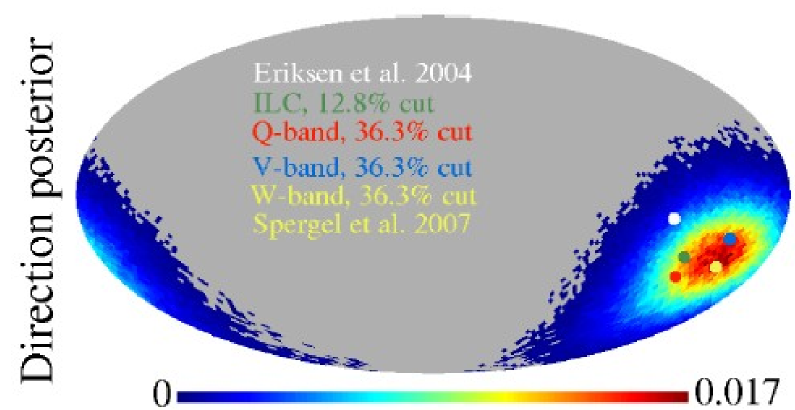
- Planck will uniquely constrain the value of the fine structure constant at z~1000.

Rocha et al. 2004

Tests of global geometry/topology/symmetries

- The WMAP maps have subjected to extensive tests of the large scale isotropy of the Universe.
- Planck will have unprecedented rejection of foreground contamination for a CMB experiment – more sky will be available for CMB science.
- Any test of the properties of the Universe on the largest scales will benefit from Planck's larger sky coverage





Dark Energy

- CMB experiments are important for Dark Energy probes because they pin down the parameters of the high-redshift Universe, the distance to last scattering and the details of the structure formation model.
- All forecasts for proposed dark energy probes assume that
  - Planck flies
  - The data are analyzed
  - The data are released

Fundamental Physics with Planck

- The CMB has been *the* technique for studying fundamental physics with Astronomical data.
- Most of the information content in the CMB has not yet been revealed, but will be by Planck
- Planck is an inflation probe that is going to happen soon.
- Planck will have a major impact on BBN.
- Planck data is necessary for learning about dark energy.
- Planck will allow us to test many assumptions of the cosmological standard model.

- Final instrument tests are ongoing – watch this space for updates on expected Planck performance!