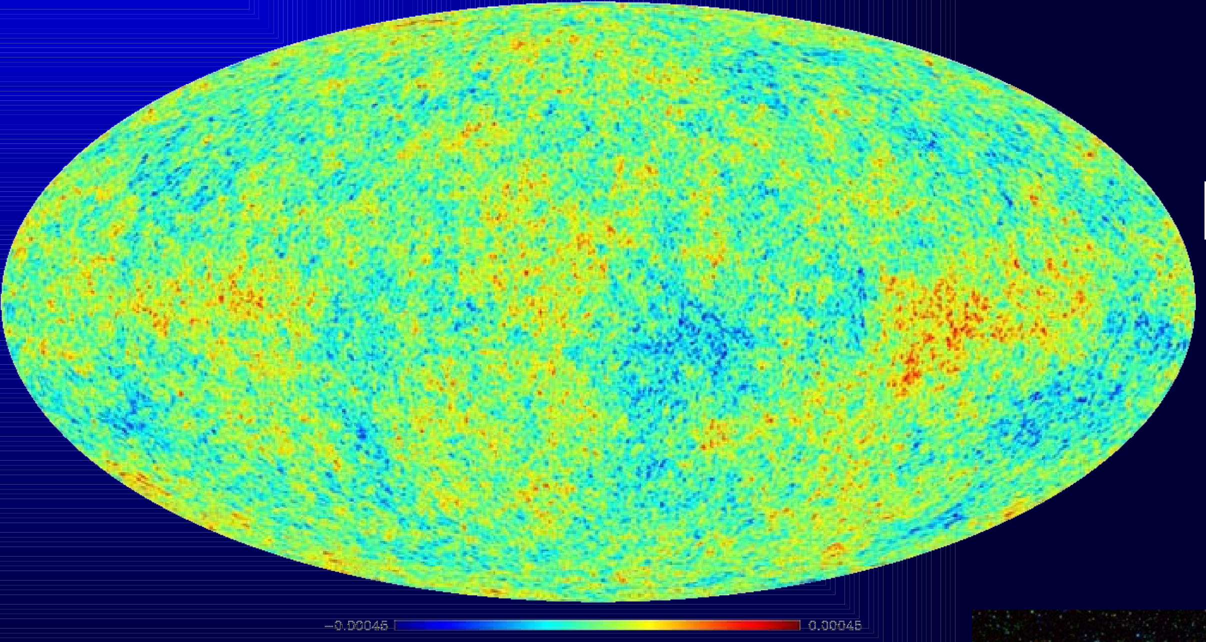


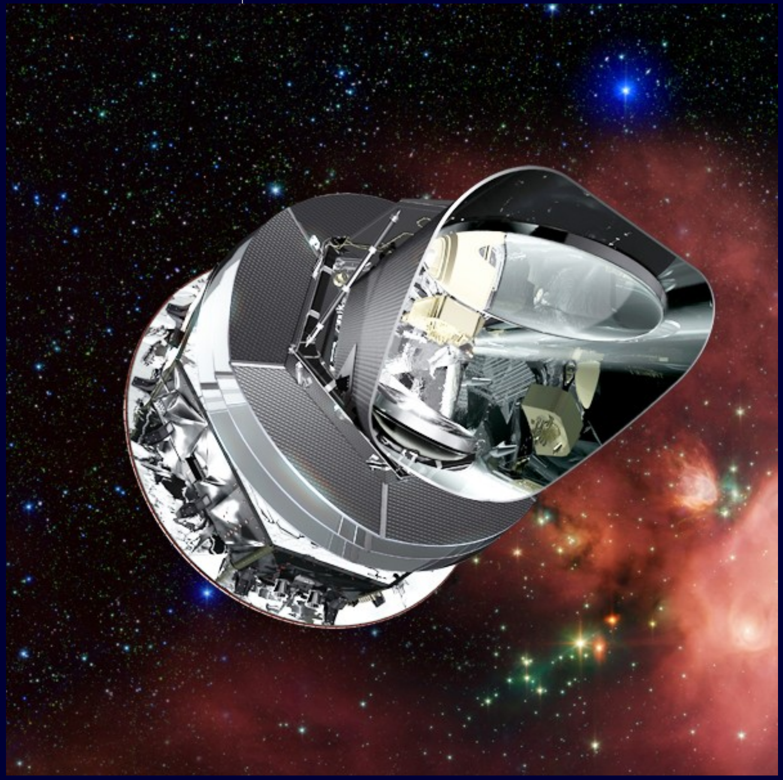

# Cosmic Beginnings and Cosmic Fate

*ou: La révolution non-Gaussienne*

***Benjamin D. Wandelt***

***Institut d'Astrophysique de Paris***

***Université Pierre et Marie Curie***



# Why cosmology?

The big questions are:

"How did the Universe begin (if it did)?"

"Whence the laws of Nature?"

# Why cosmology?

The big questions are:

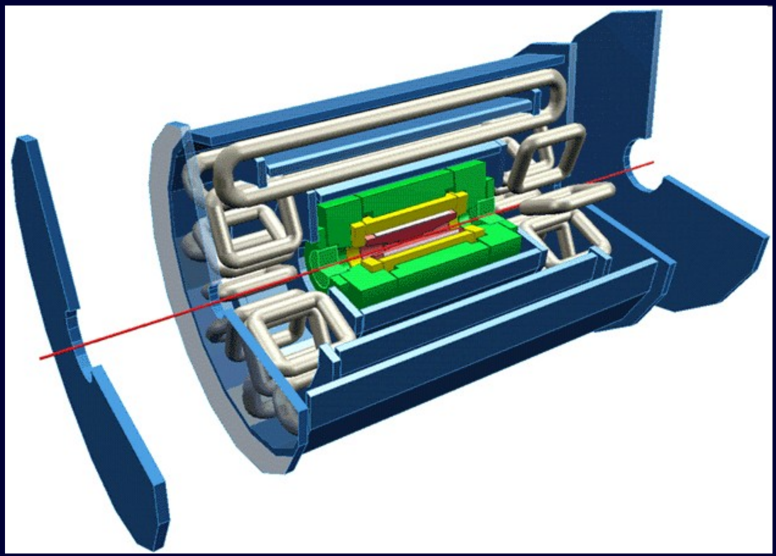
"What happened at t = 0 ?"

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

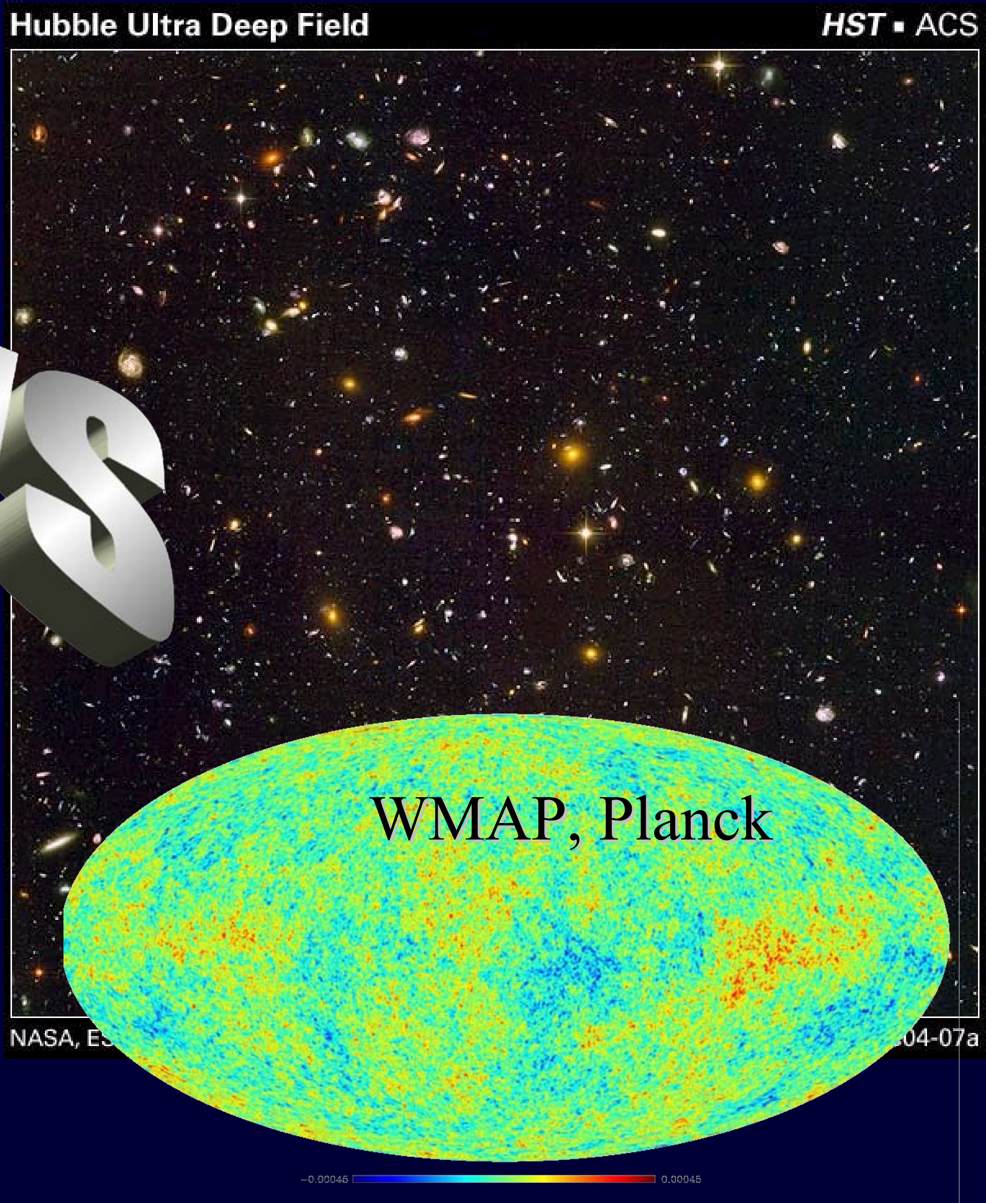
# How do we study what happens at the highest energy scales and at the shortest time scales?

# Showdown


LHC at CERN
France
Switzerland
4.3 km



VS


Hubble Ultra Deep Field
HST ▪ ACS
WMAP, Planck

# Energy and Time scales

Planck energy

(Quantum Gravity)

Unification of forces

CERN

…

Everyday energies

Low energies

Planck time $10^{-42}$ s

…

…

$10^{-22}$ s

nanoseconds

seconds

# Will accelerators work?

| | |
|---|---|
| Planck energy | Planck time $10^{-42}$s |
| (Quantum Gravity) | |
| | … |
| Unification of forces | … |

***Hard technological limit:***

| | |
|---|---|
| CERN | $10^{-22}$ s |
| … | |
| Everyday energies | nanoseconds |
| Low energies | seconds |

# Accelerators are ***very*** useful

**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 the lab.

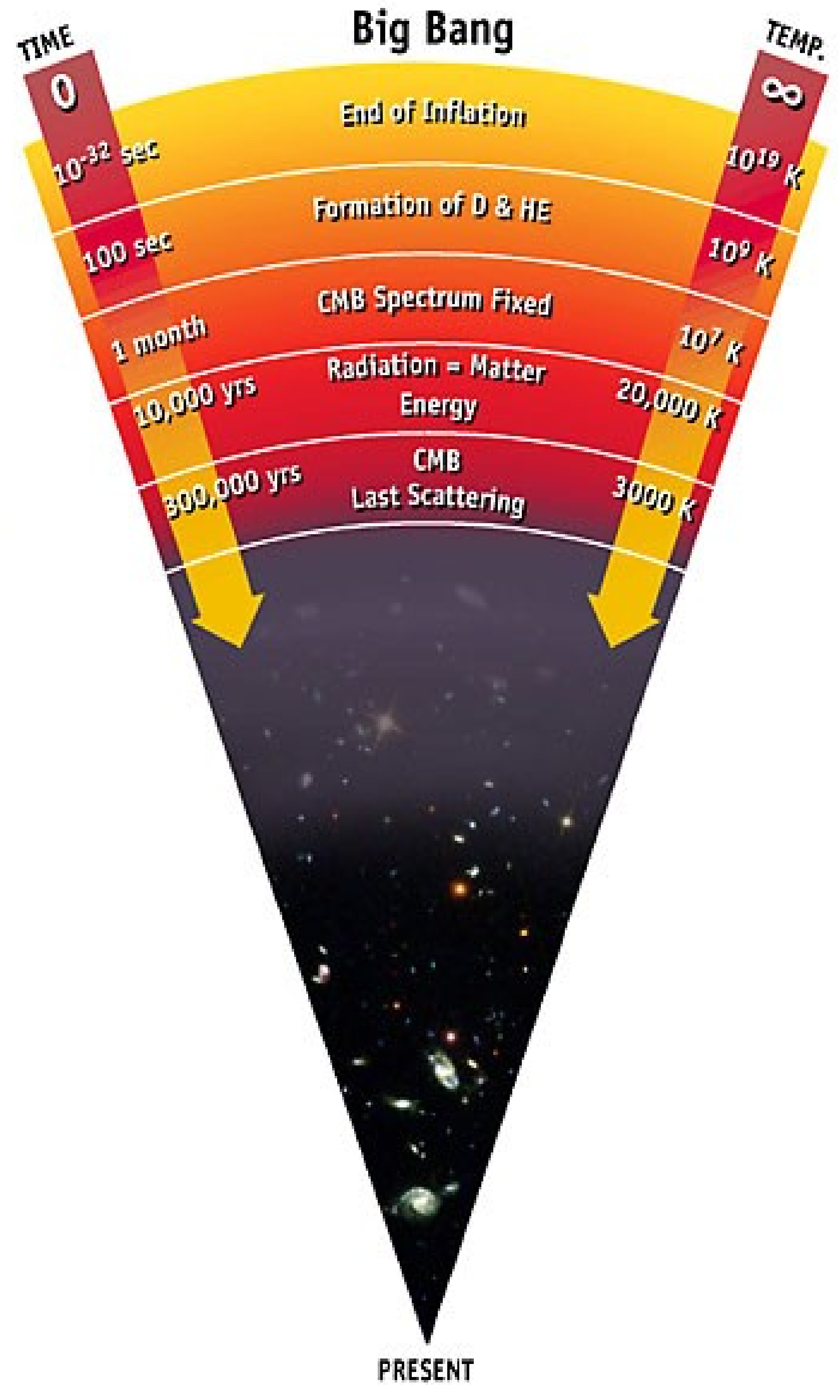
“Can Astronomy do better than accelerators?”

# Enter: the Cosmic Microwave Background (CMB)

# What is the Cosmic Microwave Background?

Before the Universe turned ~380,000 years old, it was hot and dense, a plasma opaque to photons.

When it cooled to 3000 Kelvin, electrons and protons combined into neutral H atoms and the Universe became transparent (**decoupling**).



# What is the CMB?

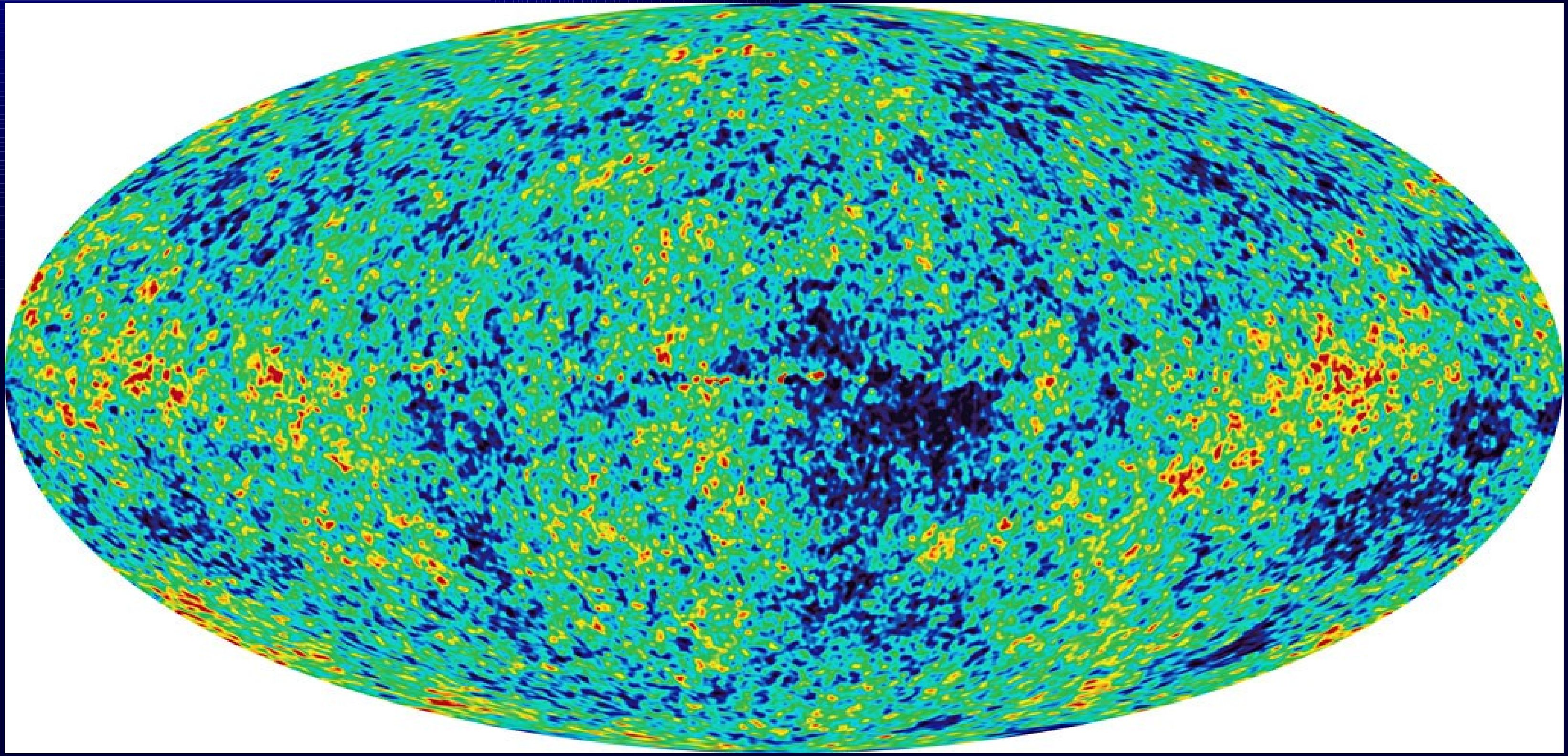
Photons we see today which interacted with matter last at **decoupling** make up the Cosmic Microwave Background (CMB).

Gravitational potential perturbations in the infant universe cause anisotropies in the CMB.

# So the CMB is the ultimate time-capsule

The Universe conveniently sent us a baby picture of itself!

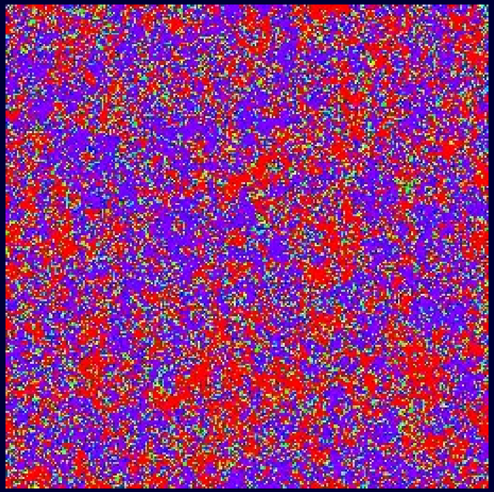
# And here it is



credit: WMAP

# We'd like to probe structure formation

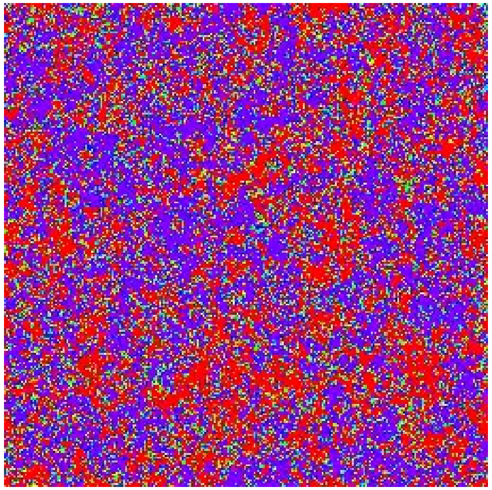
Some quantum mechanical fluctuations, e.g. during inflation, seed potential **pertur-bations** in a huge, smooth Universe

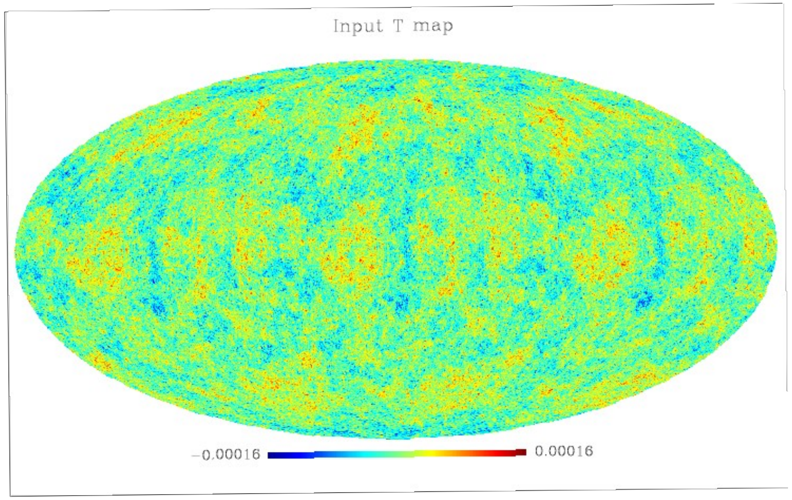


How do we get back to these very early times (fractions of a second)?

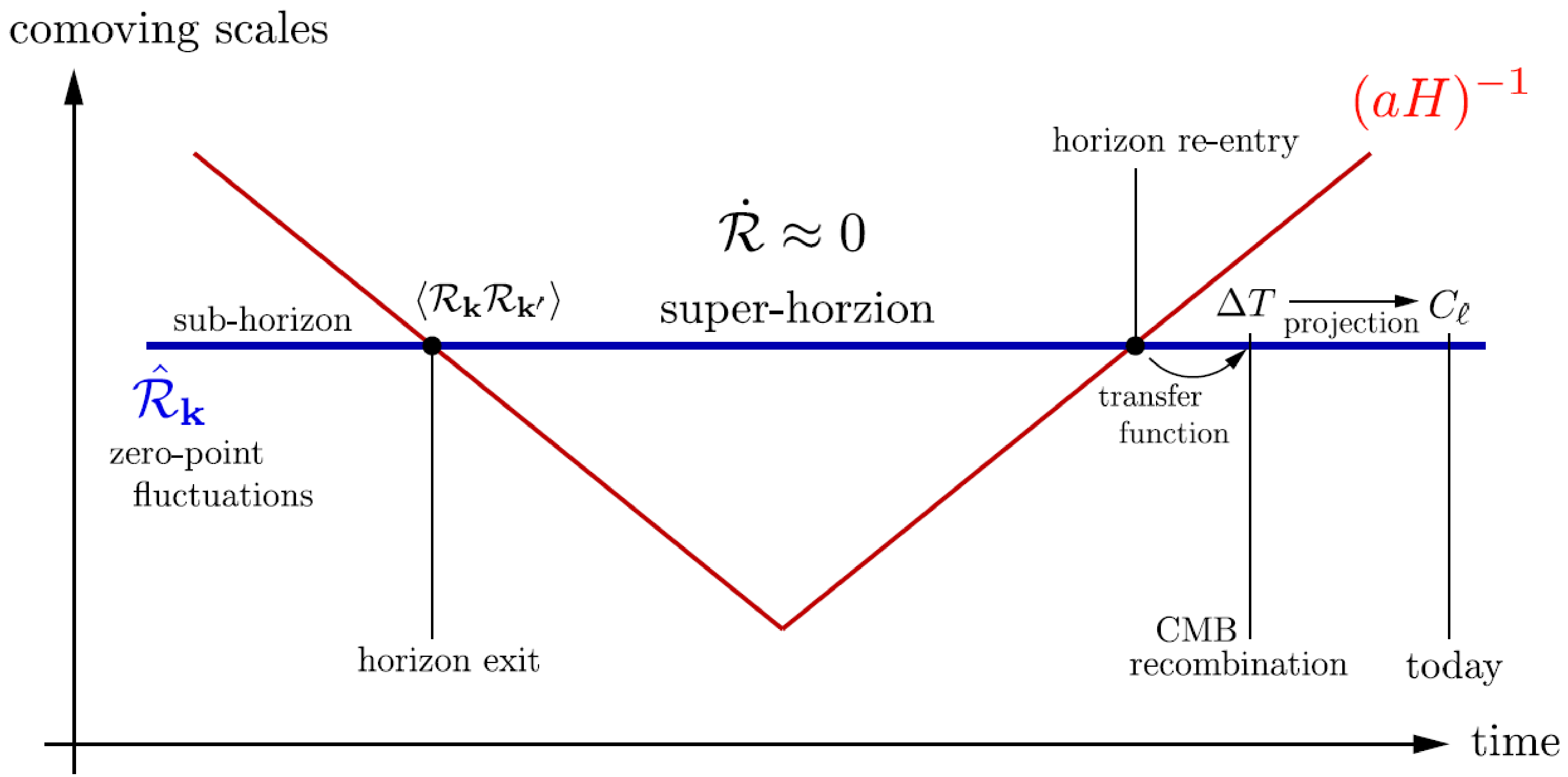
# Part II of the time machine:

# Calculating back from the Cosmic Microwave Background to the primordial perturbations



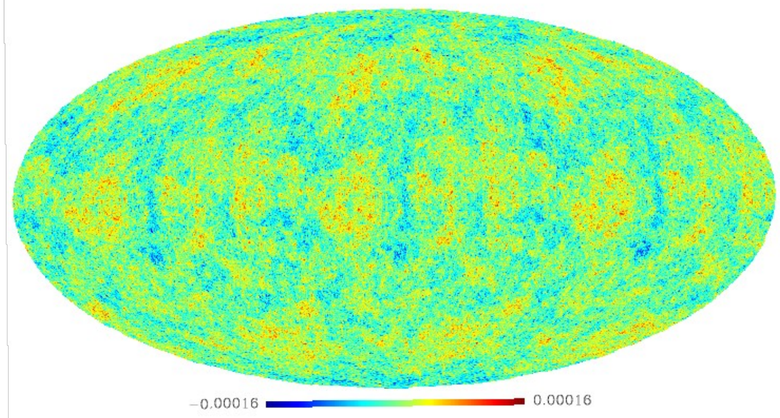


# Imprinting primordial perturbations



# Reconstructing Primordial Perturbations

**CMB DATA $a_{lm}$**

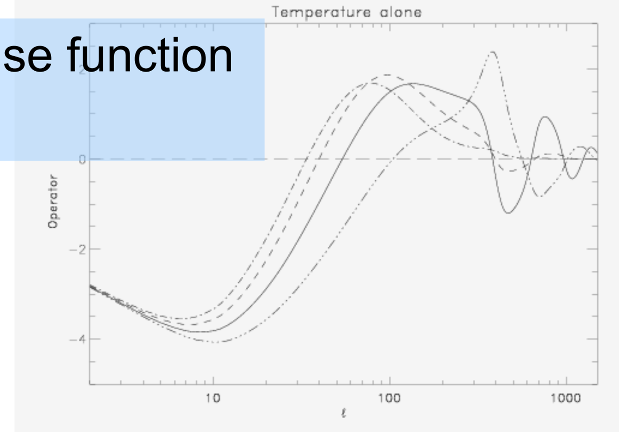



$\Phi_{lm} = O_l a_{lm}$

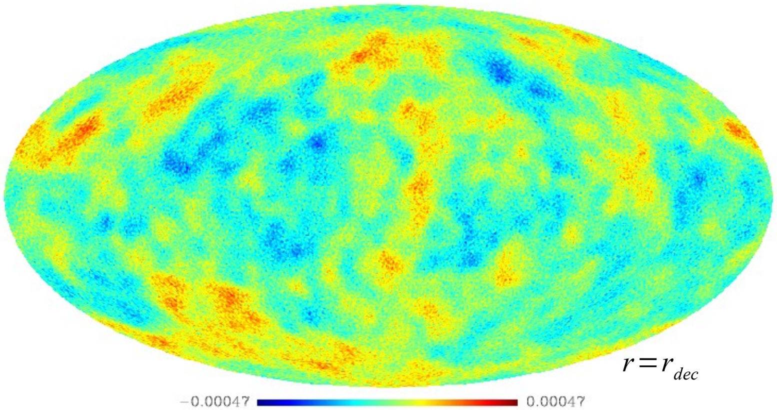
SW limit

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

Response function
$O_l = \beta_l / C_l$




Reconstructed Primordial perturbations with T alone



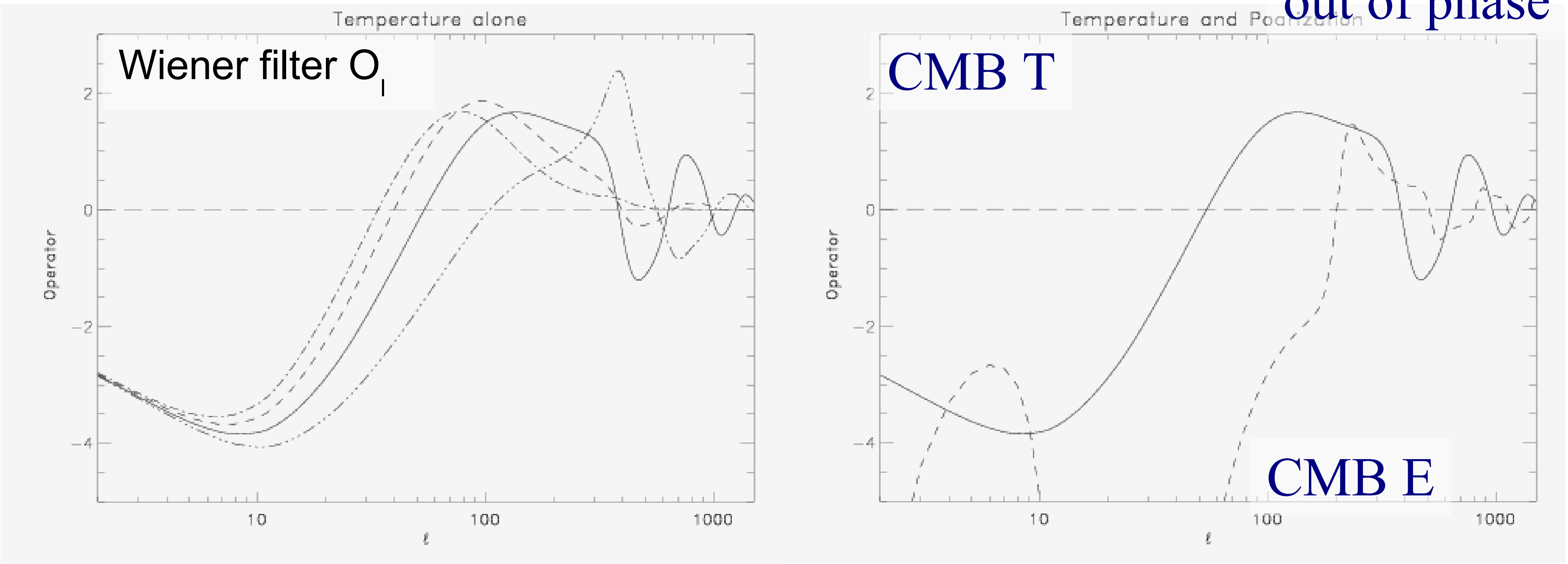

$r = r_{dec}$

$$\beta^i_\ell(r) = \frac{2b^i_\ell}{\pi}\int k^2 dk P_\phi(k) g^i_\ell(k)\, j_\ell(kr),$$

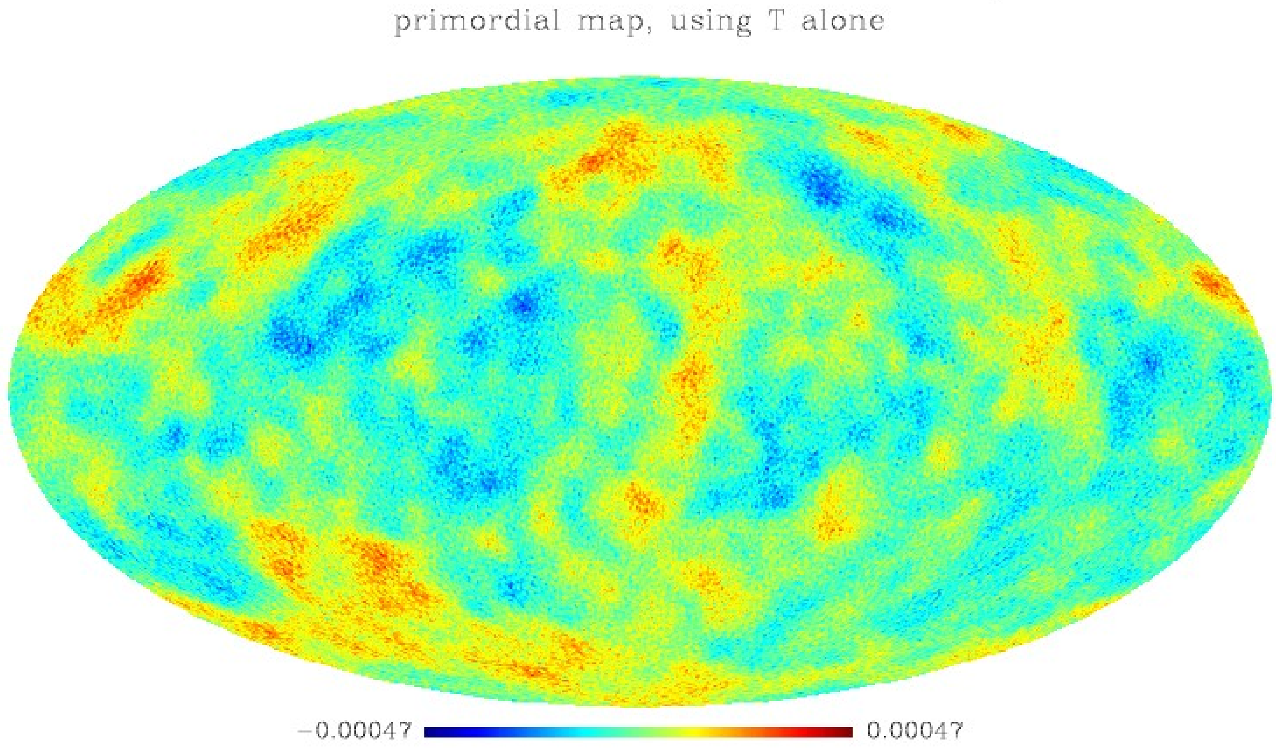
# The curvature perturbation leaves a unique signature also in the polarization anisotropies

- Note negative response on large scales

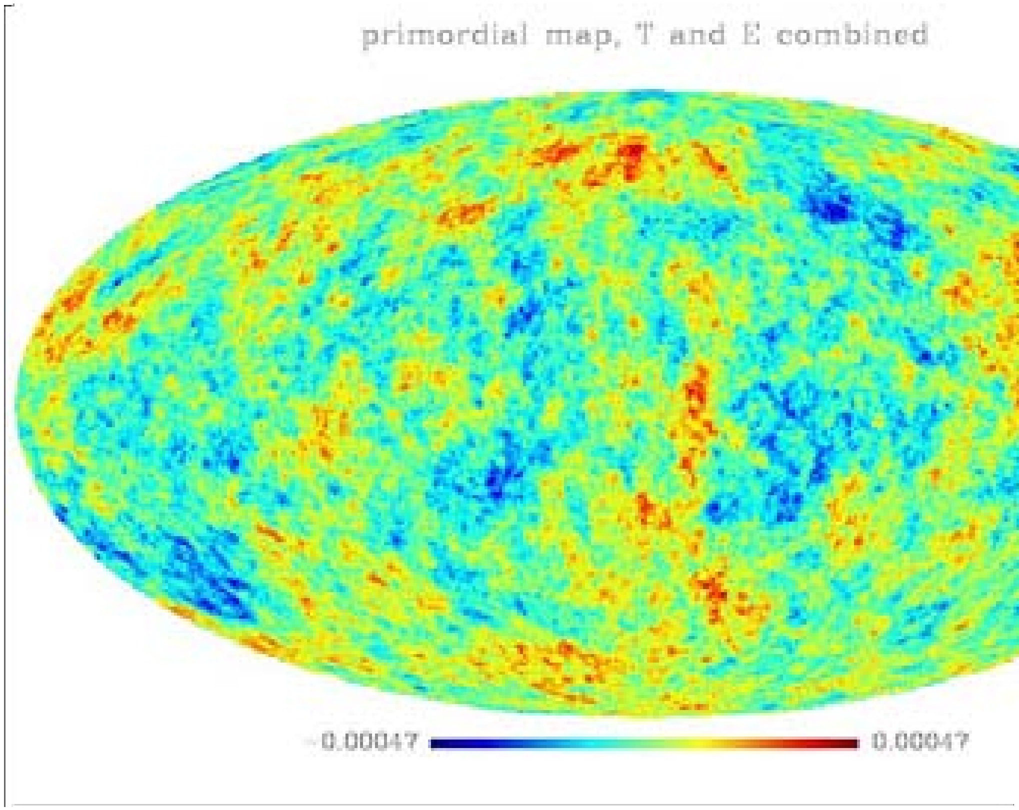
T and E are out of phase




*Yadav, and Wandelt, PRD (2005)*

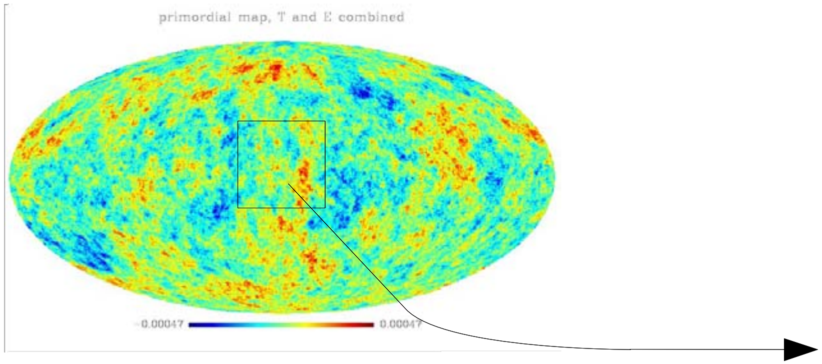



*Yadav, and Wandelt, PRD (2005)*

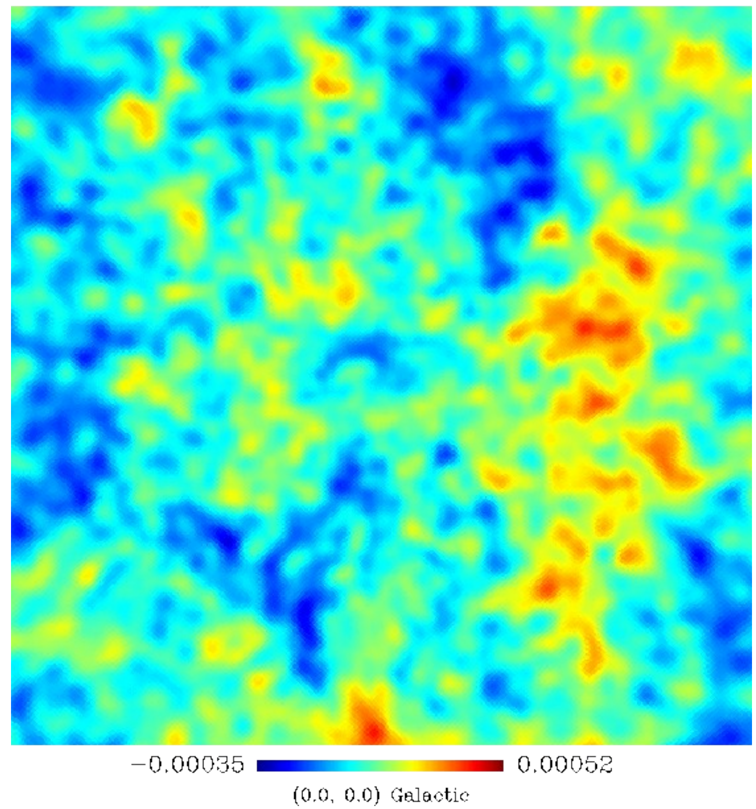


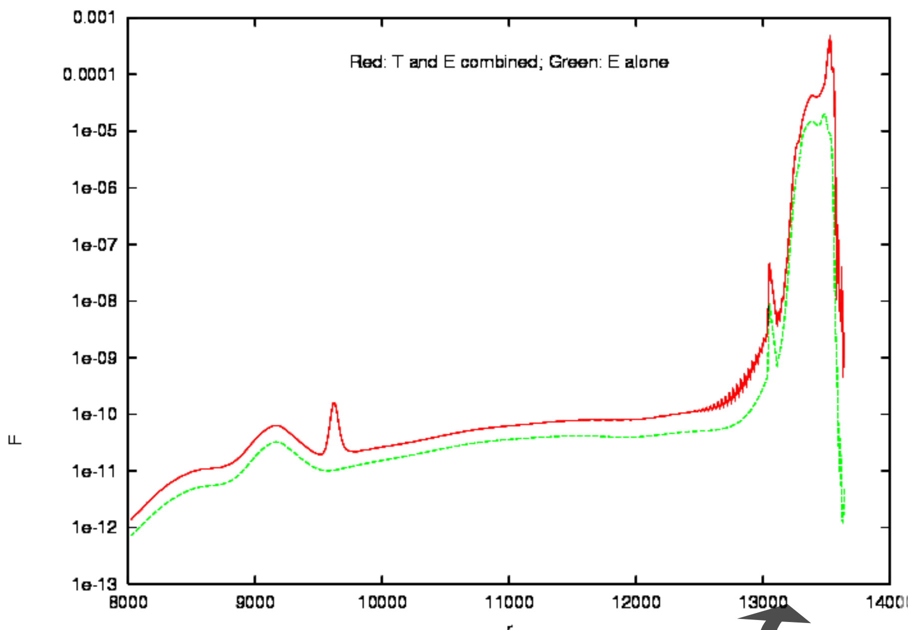

*Yadav, and Wandelt, PRD (2005)*

# Curvature perturbations at different r




Curvature perturbations



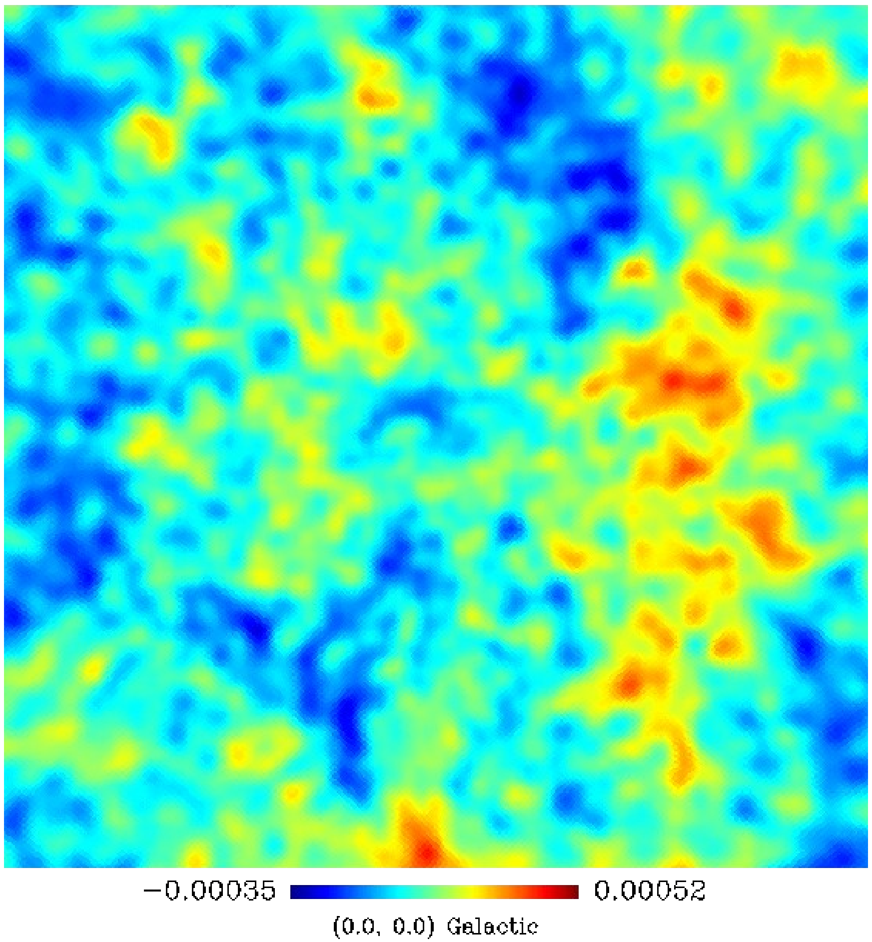




**Decoupling**

*Yadav, and Wandelt, PRD (2005)*

# Tomographic reconstruction of inflationary curvature perturbations from CMB temperature and polarization.

Curvature perturbations




One can invert the linear radiative transport generating the primordial curvature perturbations .

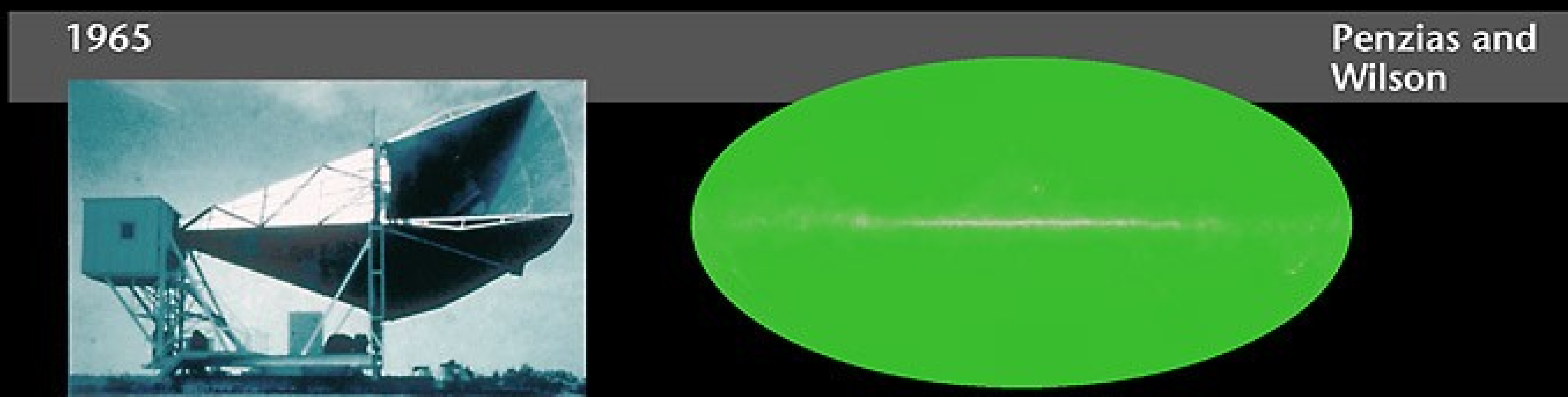
They contain all the information about the initial scalar seed perturbations in the CMB T&E.

*Yadav and Wandelt 2006*

# Observational Status and Prospects for the CMB

A major international effort is under way to make high quality observations of the microwave sky using ground-based, balloon borne and space missions.

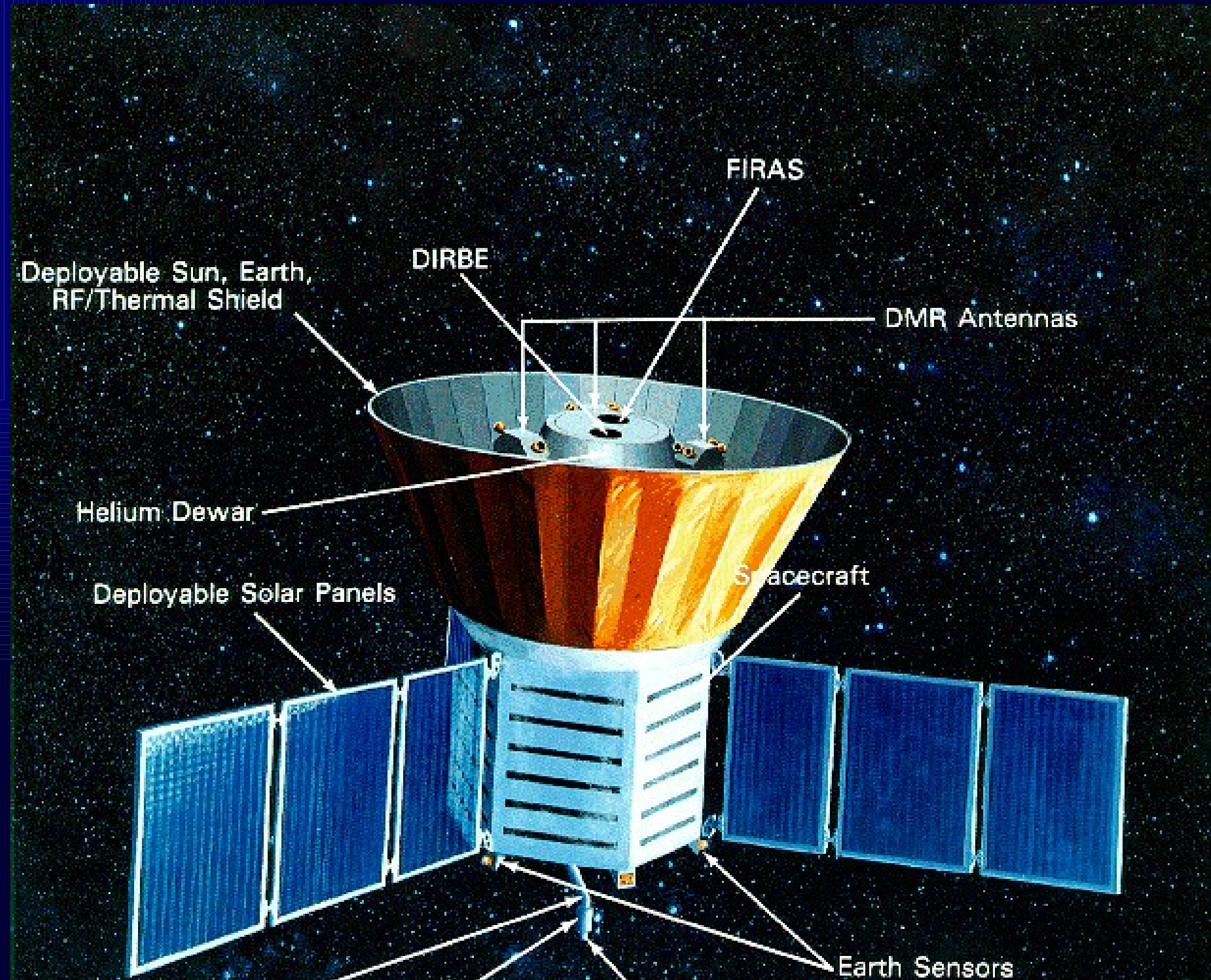
# Observing the CMB



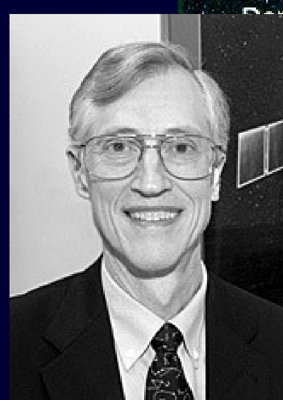

Penzias and Wilson, Nobel Prize Physics 1978

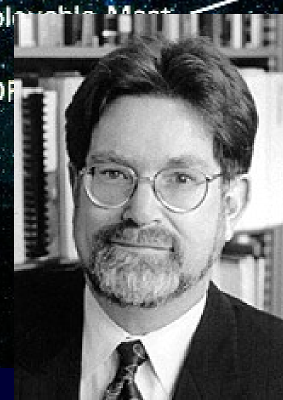
# 1990's: COBE-DMR

The discovery of primordial fluctuations and the blackbody nature of the CMB

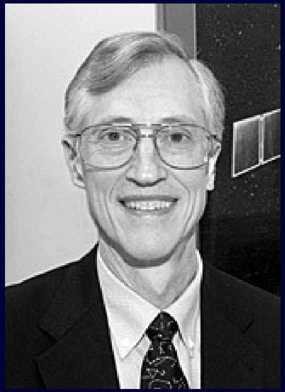


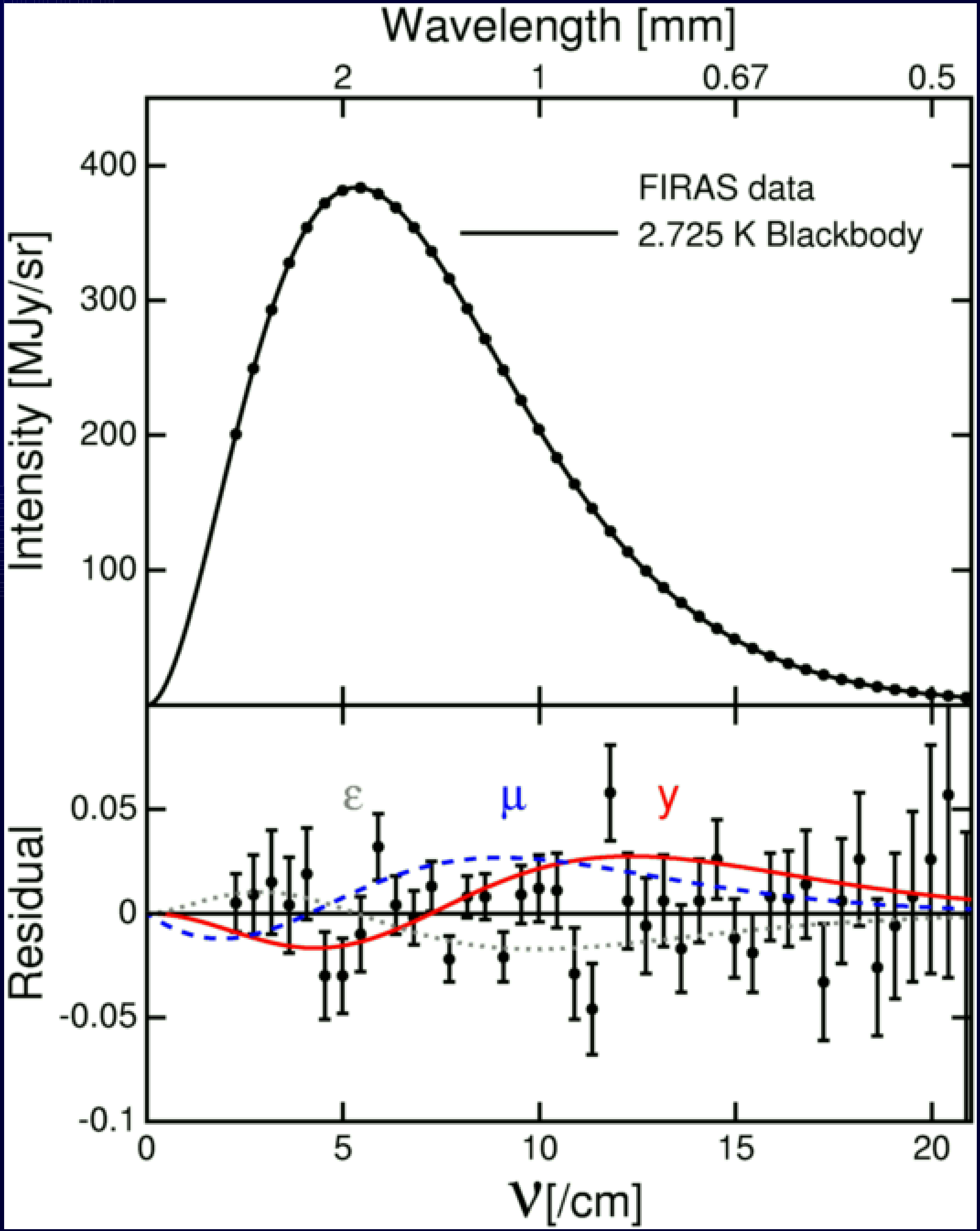

Nobel Prize Physics 2006: Mather and Smoot



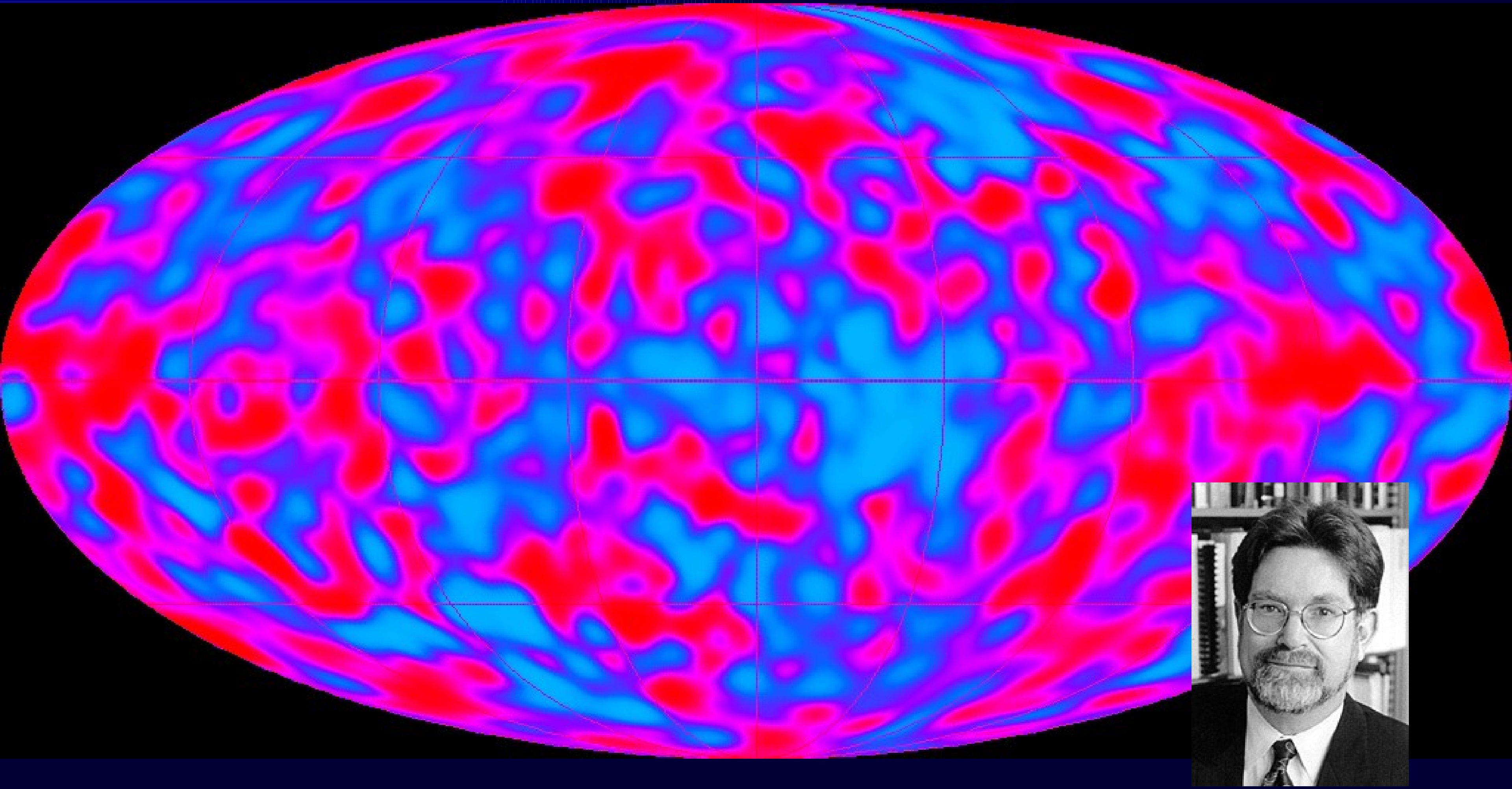


# The cosmic microwave background **is** blackbody radiation



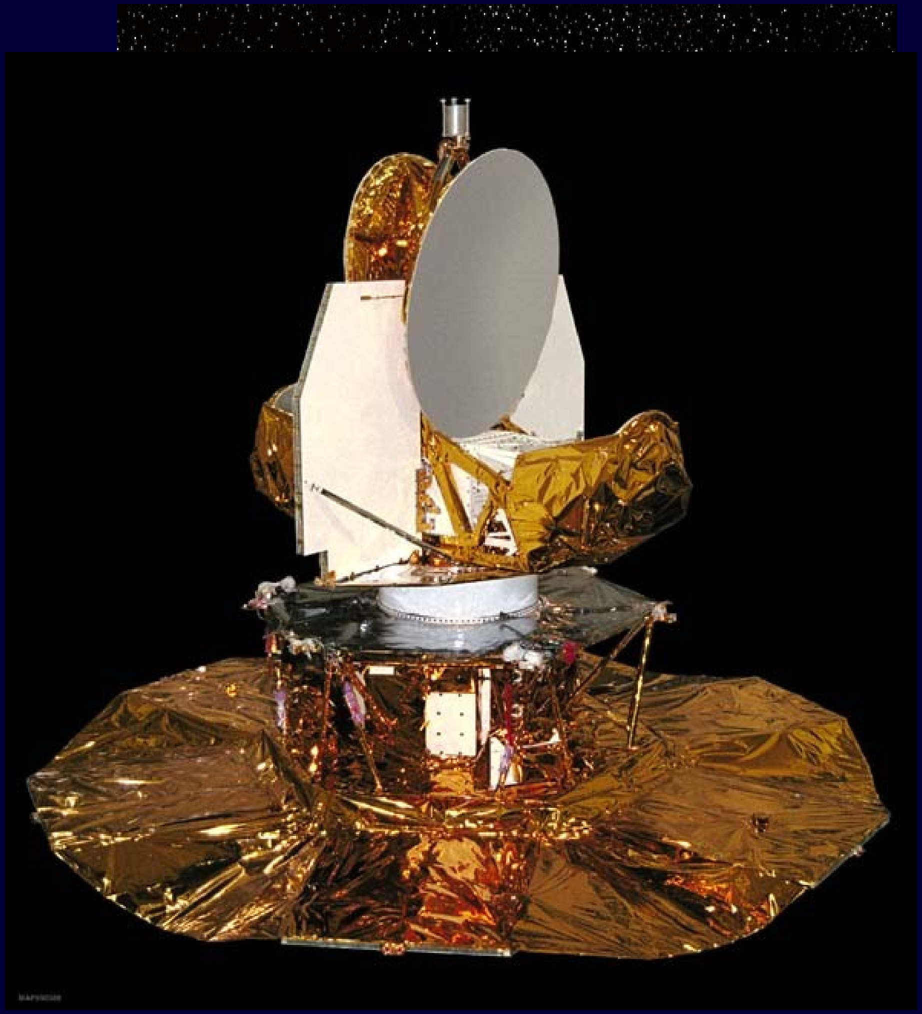


# CMB *anisotropies* as observed by COBE-DMR



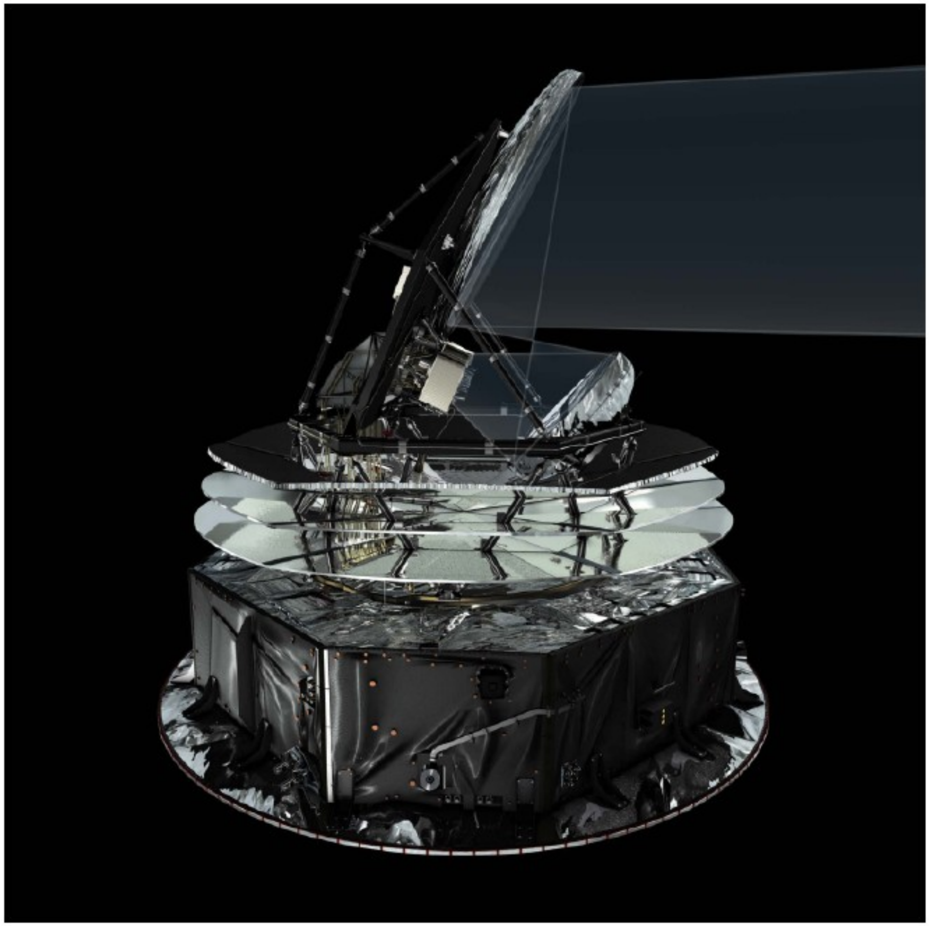
# The Wilkinson Microwave Anisotropy Probe

- NASA MIDEX mission
- Currently in Operation
  - Reached observing location (L2) in 2001
  - YR1 data released in early 2003
  - YR3 data released in 2006
  - YR5 data released in 2008
- Harbinger of precision cosmology



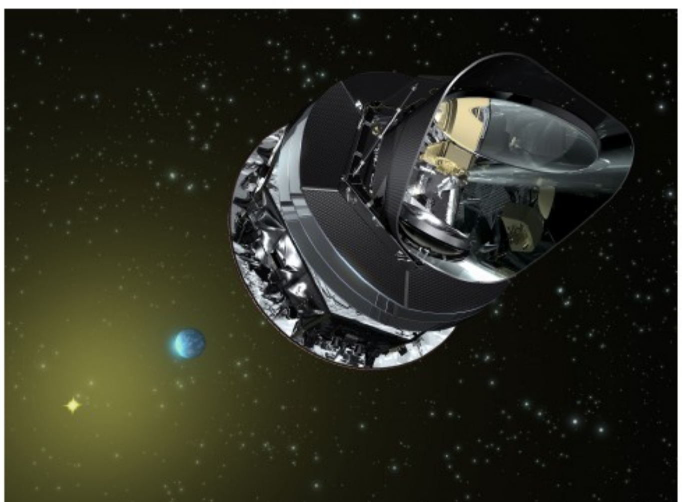
# The Planck mission

- Planck is a major joint ESA/NASA mission to L2.
- Principal scientific goal:
  - to make definitive all-sky maps of CMB temperature anisotropy down to 5' resolution.
- Two instruments:
  - Low Frequency Instrument (PI: Reno Mandolesi)
  - High Frequency Instrument (PI: Jean-Loup Puget)
- Temperature measurement at 9 frequencies
  - 30, 44, 70, 100, 143, 217, 353, 545, 857 GHz
- Polarization measurement at 7 frequencies
  - 30, 44, 70, 100, 143, 217, 353 GHz
- Detailed Planck Science Case in the "Blue Book:"

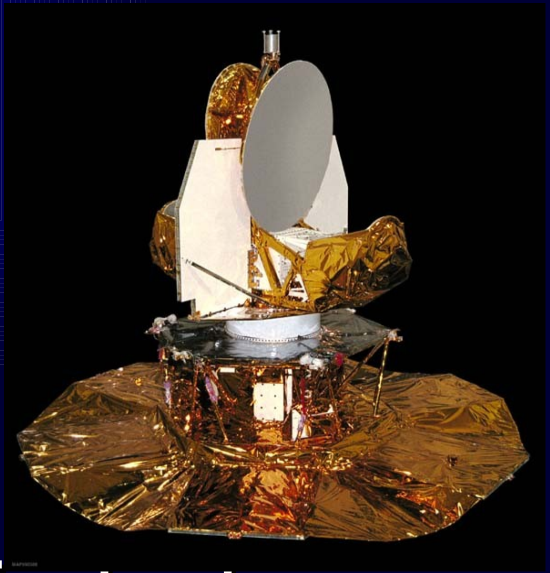


# Launch

- Planck launch date: May 14, 2009.
- Dual launch with Herschel on an Ariane 5 rocket
- Then cruise to L2



# So where do we stand?



What do we find when we analyze the WMAP, suborbital CMB, and other astronomical data? And what can we expect from Planck?

# We now have a Standard Model of Cosmology!

- Bad news for theorists:

  We now know the basic global properties of the Universe.

- Good news for theorists:

  We don't understand most of the constituents of the Universe.
  We don't know how it began

# Observer's recipe for Universe pie

# Theorist's recipe for Universe pie

One inflationary Universe:

Use recipe below to make 4-D effective field theory.

Start with smooth patch + GR.

Let the field with the largest potential energy inflate

patch while cooling. Reheat.

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...

OR: set up parallel colliding branes. OR...

Razzle Dazzle Recipes

# Theorist's recipe for Universe pie

Dark matter recipes:

One inflationary Universe:

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# Theorist's recipe for Universe pie

Dark energy recipes:

Dark matter recipes:

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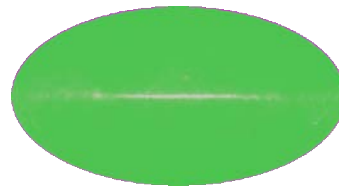
# The Physics of the Beginning

- Why Homogeneity and Isotropy?



CMB

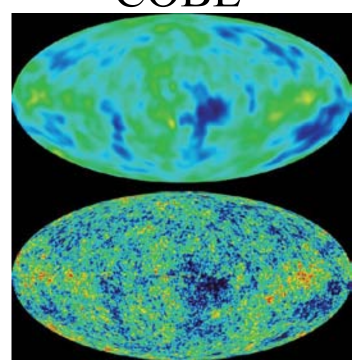
1978 Nobel Prize in Physics

Robert Wilson and Arno Penzias

- Why Flatness?

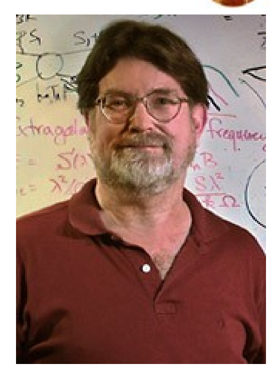
- Whence the seed perturbations?

COBE



WMAP

2006 Nobel Prize in Physics



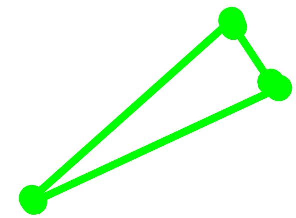
George Smoot

John C. Mather

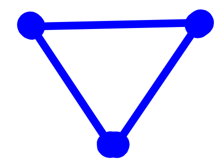
# The CMB and the Beginning

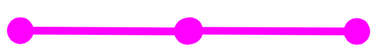
| Test | Std. Inflation | Ekpyrosis | Obs |
|---|---|---|---|
| • Is observable universe flat? | • Yes. | • Built in. | • Yes, to ~2% |
| • Do the fluctuations have the predicted correlations (nearly scale independent)? | • Yes. | • Yes. | • Yes, to few % |
| • Are fluctuation adiabatic? | • Yes. | • ? | • 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** | • **~2σ hints of deviation from Gaussianity from WMAP data** |

# Primordial perturbations and Gaussianity



- Slow-roll-> shallow potential-> nearly free field; has Gaussian quantum perturbations (field modes in S.H.O. potential). Theorem for single field.
- If multi-field (or ekpyrosis), can have isocurvature perturbations convert into non-Gaussian curvature pert. outside horizon -> local bispectrum
- Non-standard kinetic term: can inflate in spite of steep potential -> equilateral bispectrum
- Vacuum state – can get flattened triangle contributions if not Bunch-Davies.





# Non-Gaussianity – a new frontier

- In addition to the information to be gained from 2-point correlations, non-Gaussianity opens a new and much richer window on the Physics of the Beginning
- What is the research program?
  - Reliable theoretical prediction of non-Gaussianity from models of the early Universe
  - Characterization of non-Gaussian confusion effects
  - Development of efficient and practical statistical methods to draw inferences about non-Gaussianity from the data.

# $f_{NL}$ – a specific parameterization 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

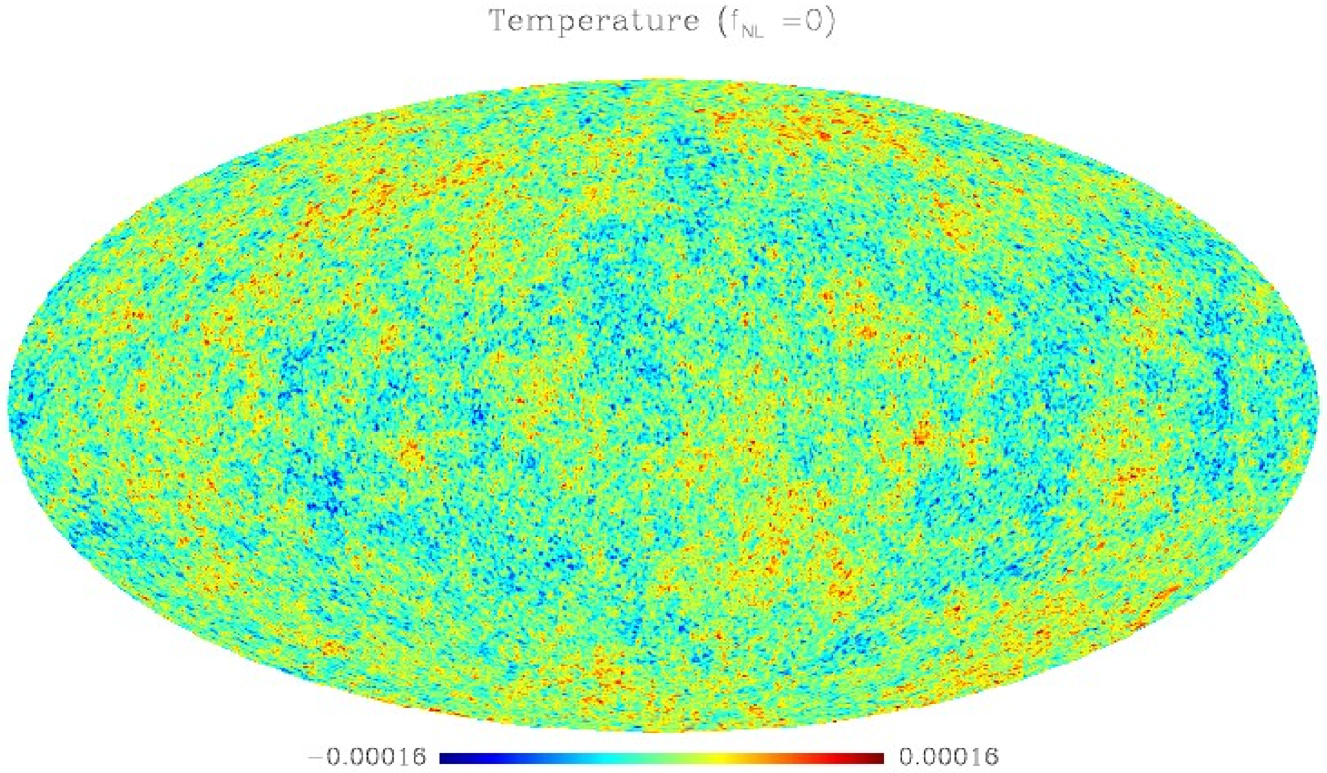
- This non-Gaussianity creates a bispectrum signature (as well as higher order moments)
  $\langle\Phi(k_1)\Phi(k_2)\Phi(k_3)\rangle = 2(2\pi)^3 f_{NL}\delta(k_1+k_2+k_3)P(k_1)P(k_2),$

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

- This translates into a bispectrum signature in the CMB through

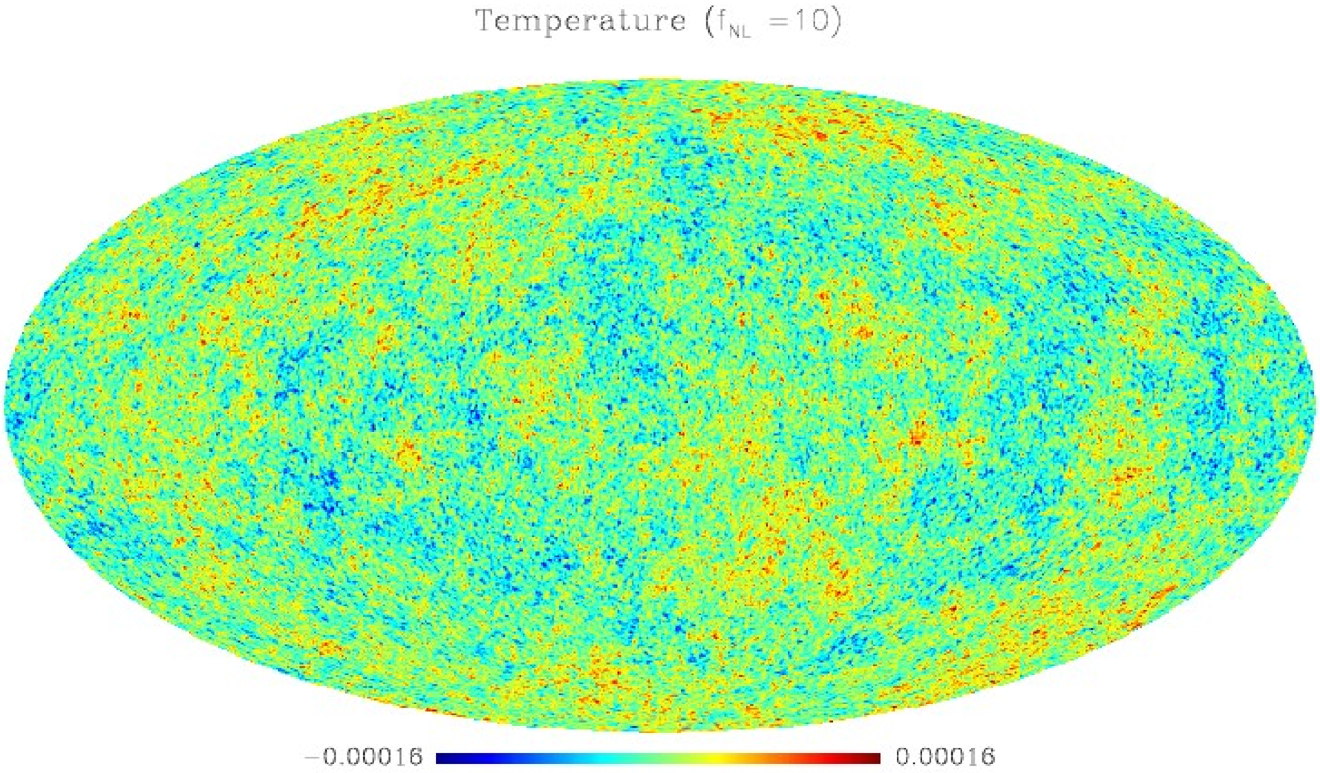
$$a_{lm} = 4\pi(-i)^l \int \frac{d^3\mathbf{k}}{(2\pi)^3}\Phi(\mathbf{k})g_{Tl}(k)Y_{lm}^*(\hat{\mathbf{k}})$$

$f_{NL} = 0$



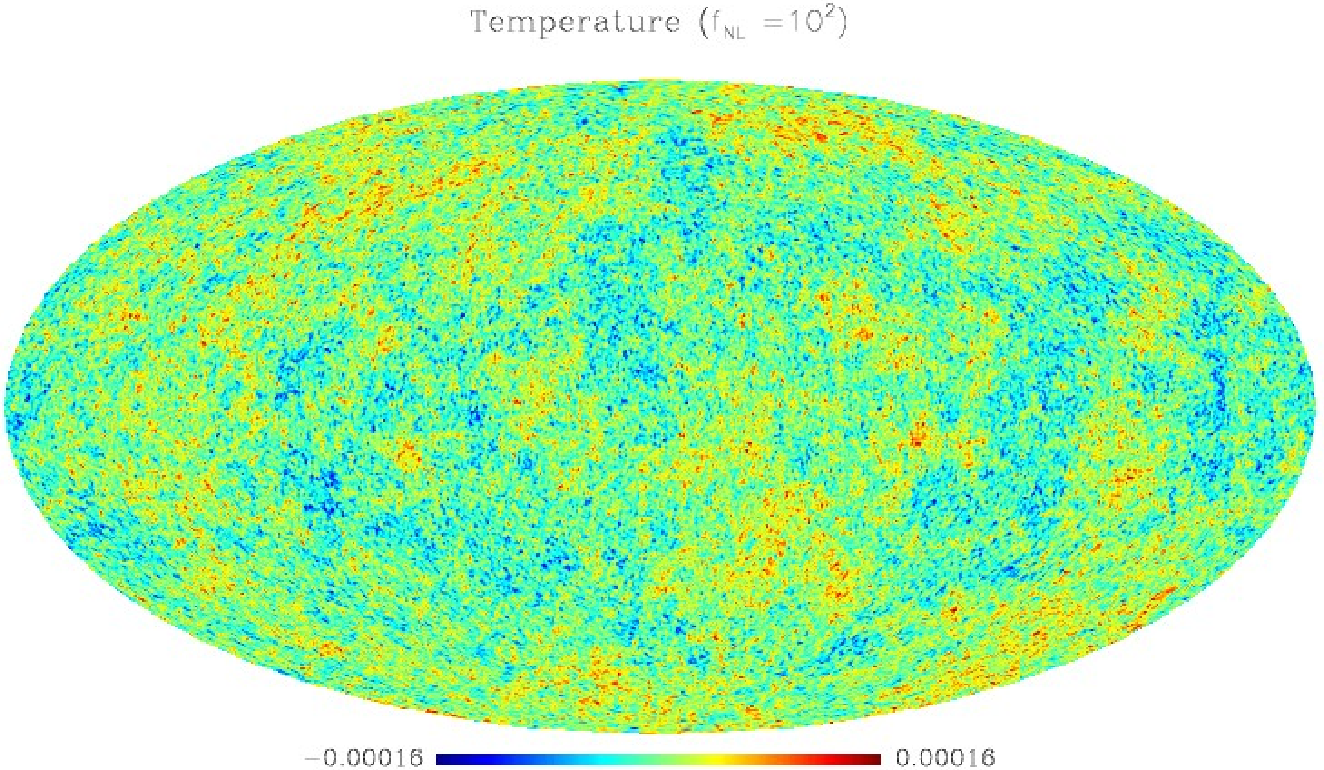

Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt 2007

# $f_{NL} = 10^1$



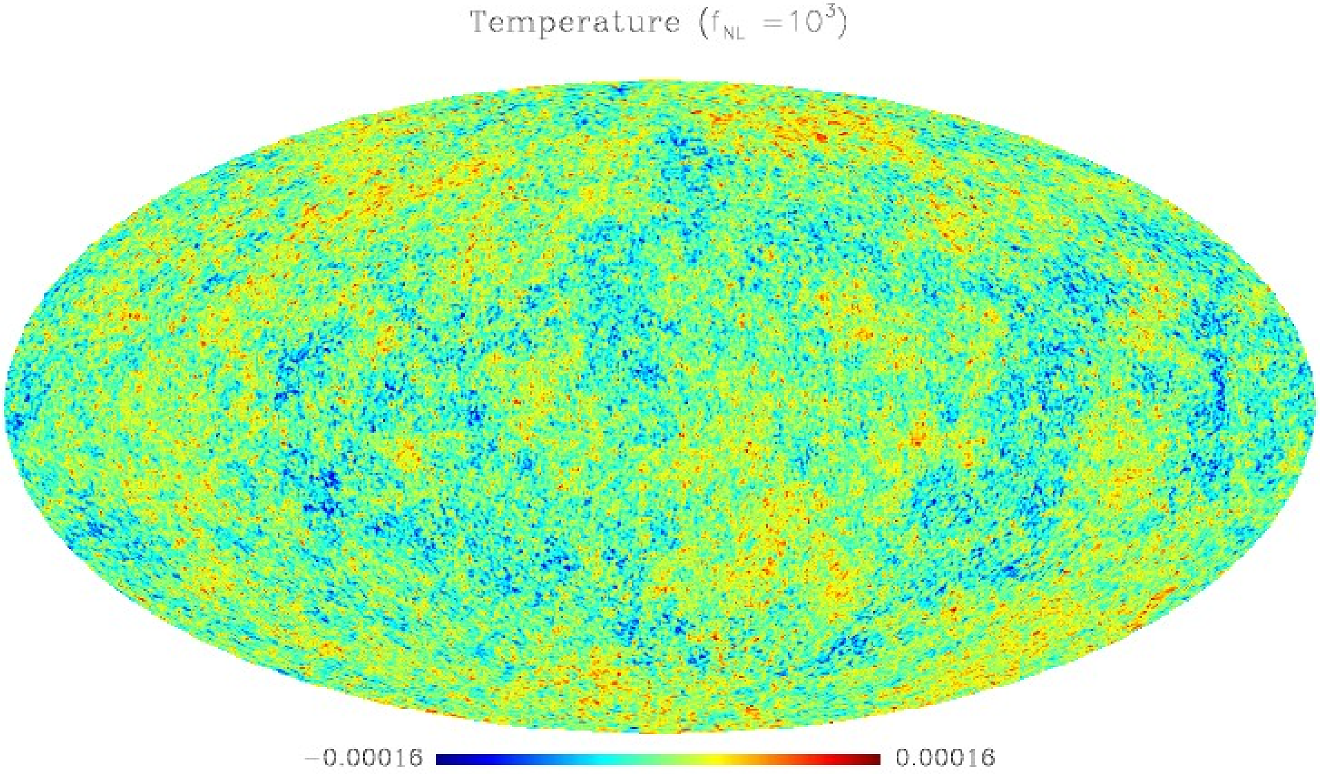

Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt 2007

$$f_{NL} = 10^2$$



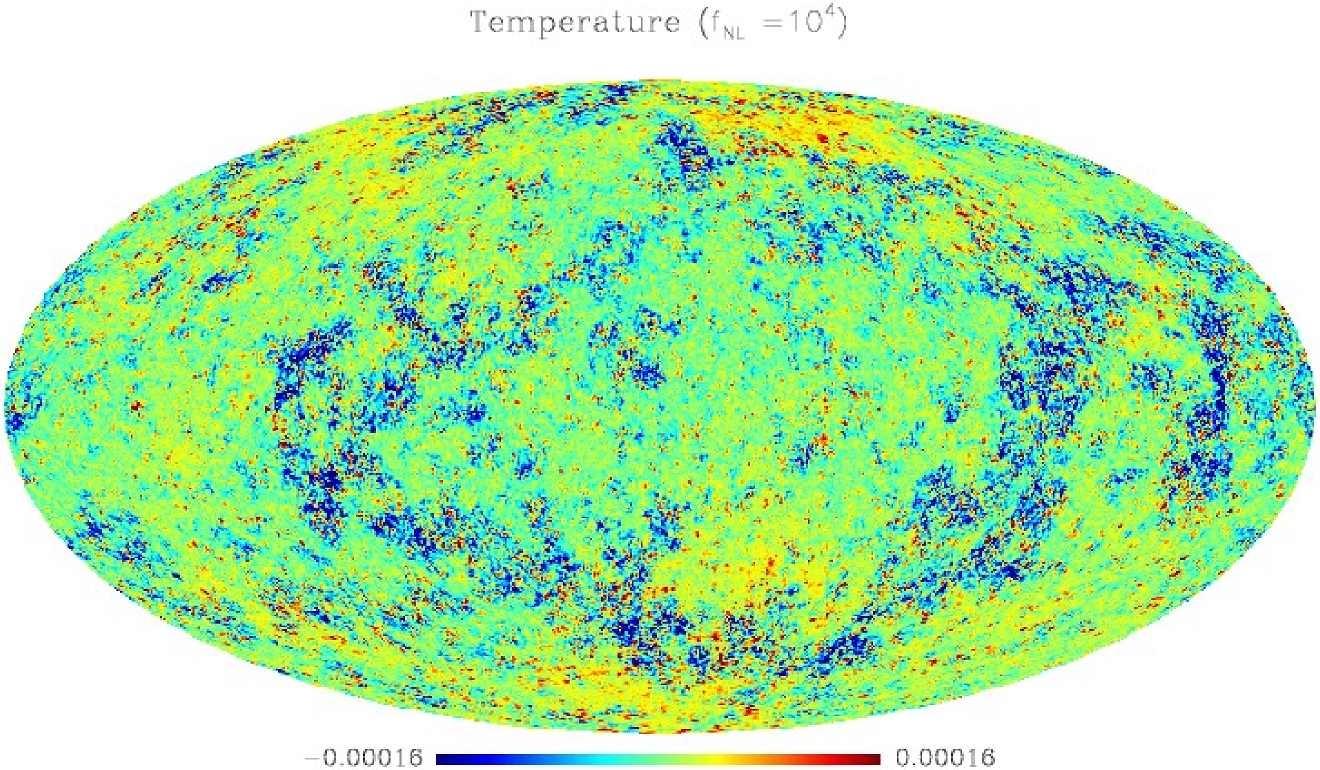

Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt 2007

$$f_{NL} = 10^3$$




Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt 2007

$$f_{NL} = 10^4$$




Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt 2007

# Estimating non-Gaussianity

## Fast Cubic Statistic:

$$\hat{S}_{prim} = \frac{1}{f_{sky}} \int r^2 dr \int d^2\hat{n} B(\hat{n},r) B(\hat{n},r) A(\hat{n},r)$$

Komatsu, Spergel and Wandelt 2005

$$B(\hat{n},r) \equiv \sum_{ip} \sum_{lm} (C^{-1})^{ip} a^i_{\ell m} \beta^p_\ell(r) Y_{\ell m}(\hat{n})$$

**B(r) is a map of reconstructed primordial perturbations**

$$A(\hat{n},r) \equiv \sum_{ip} \sum_{lm} (C^{-1})^{ip} a^i_{\ell m} \alpha^p_\ell(r) Y_{\ell m}(\hat{n})$$

**A(r) picks out relevant configurations of the bispectrum**

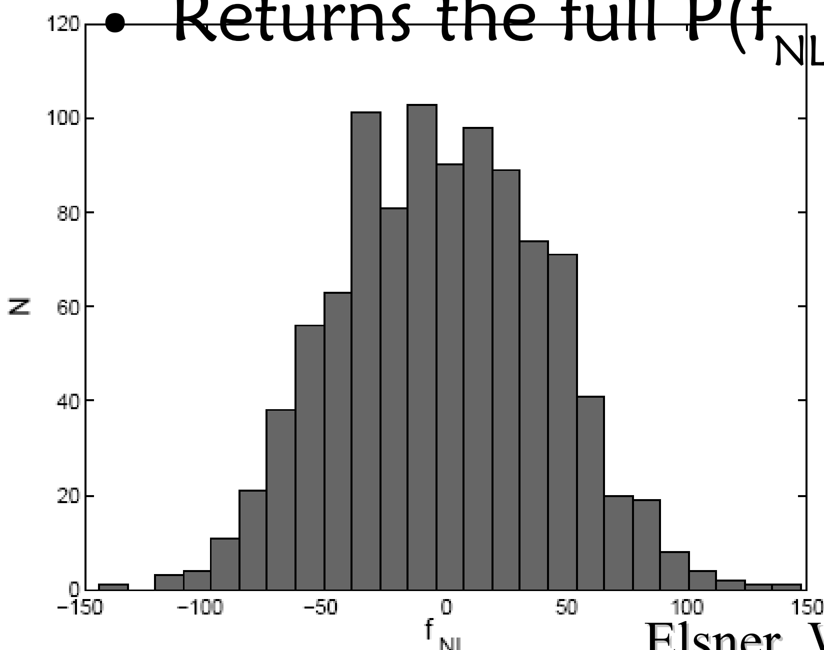
$S_{prim}$ combines all bispectrum configurations nearly optimally for "local" primordial non-Gaussianity $f_{NL}$ while avoiding brute force computation of the bispectrum.

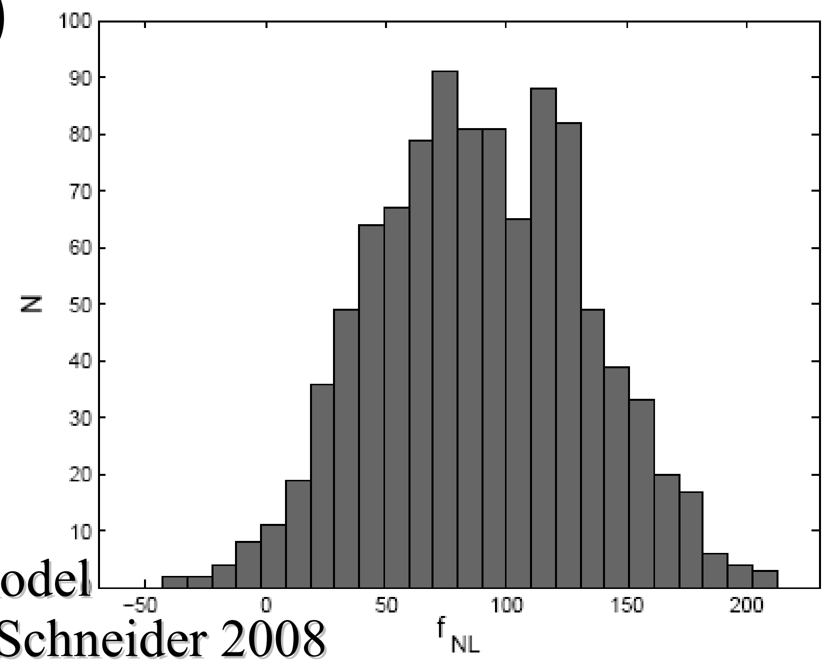
# $f_{NL}$ phenomenology from the CMB bispectrum

Komatsu & Spergel 2001 – CMB bispectrum from $f_{NL}$
Verde et al. 2002
Komatsu, Wandelt, Spergel, Banday, Gorski 2001 – $f_{NL}$ from COBE
Komatsu Spergel & Wandelt 2003 – fast $f_{NL}$ estimator
Komatsu et al (WMAP team) 2003 – WMAP1 analysis using KSW
Babich and Zaldarriaga 2004 – temperature + polarization
Creminelli, Nicolis, Senatore, Tegmark, Zaldarriaga 2006 – introduce linear term to improve KSW estimator
Spergel et al (WMAP team) 2006 – WMAP3 analysis using KSW
Creminelli, Senatore, Tegmark, Zaldarriaga 2006 – apply cubic + linear term to WMAP3 data
Yadav & Wandelt 2005 – tomography of the curvature perturbations
Yadav Komatsu & Wandelt 2007 – KSW generalized to T+P
Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt 2007 – calibrate YKW estimator against non-Gaussian simulations
Yadav, Komatsu, Wandelt, Liguori, Hansen, Matarrese 2007 – Creminelli et al. corrected and generalized to T+P
Yadav & Wandelt 2007 – application of YKWLHM07 to WMAP3
Komatsu et al 2008 – application of YKWLHM07 to WMAP5
Smith, Senatore, Zaldarriaga 2009 – least squares bispectrum estimator, WMAP5
[...]

# Fully Bayesian non-Gaussianity analysis

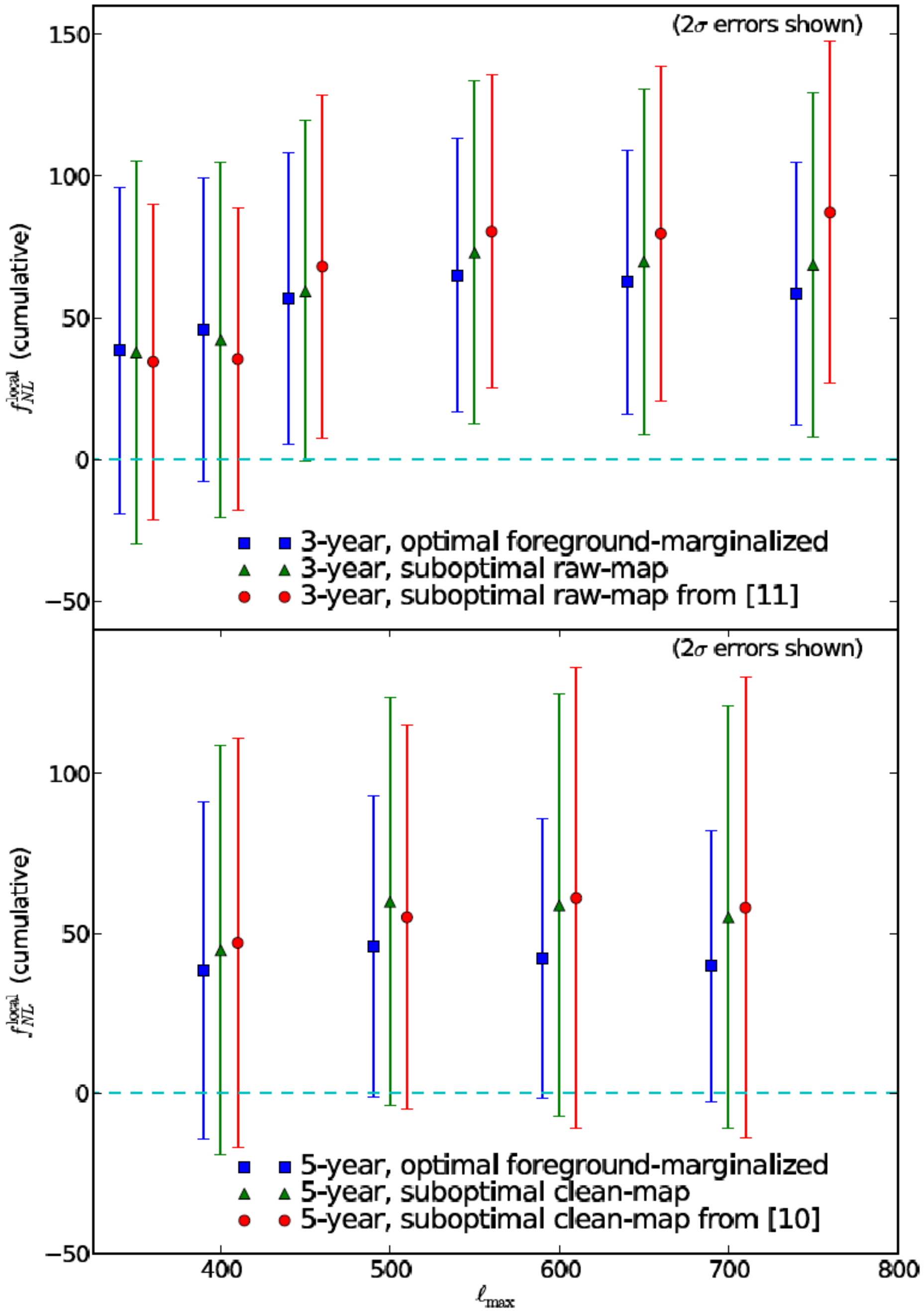
- Instead of going via the bispectrum, build full statistical model of the data, including general local non-Gaussianity, (including cubic perturbation predicted by ekpyrotic model) and a detailed model of the observations
- Returns the full $P(f_{NL}|\text{data})$




Toy model

Elsner, Wandelt, Schneider 2008




- Overview of current observational status

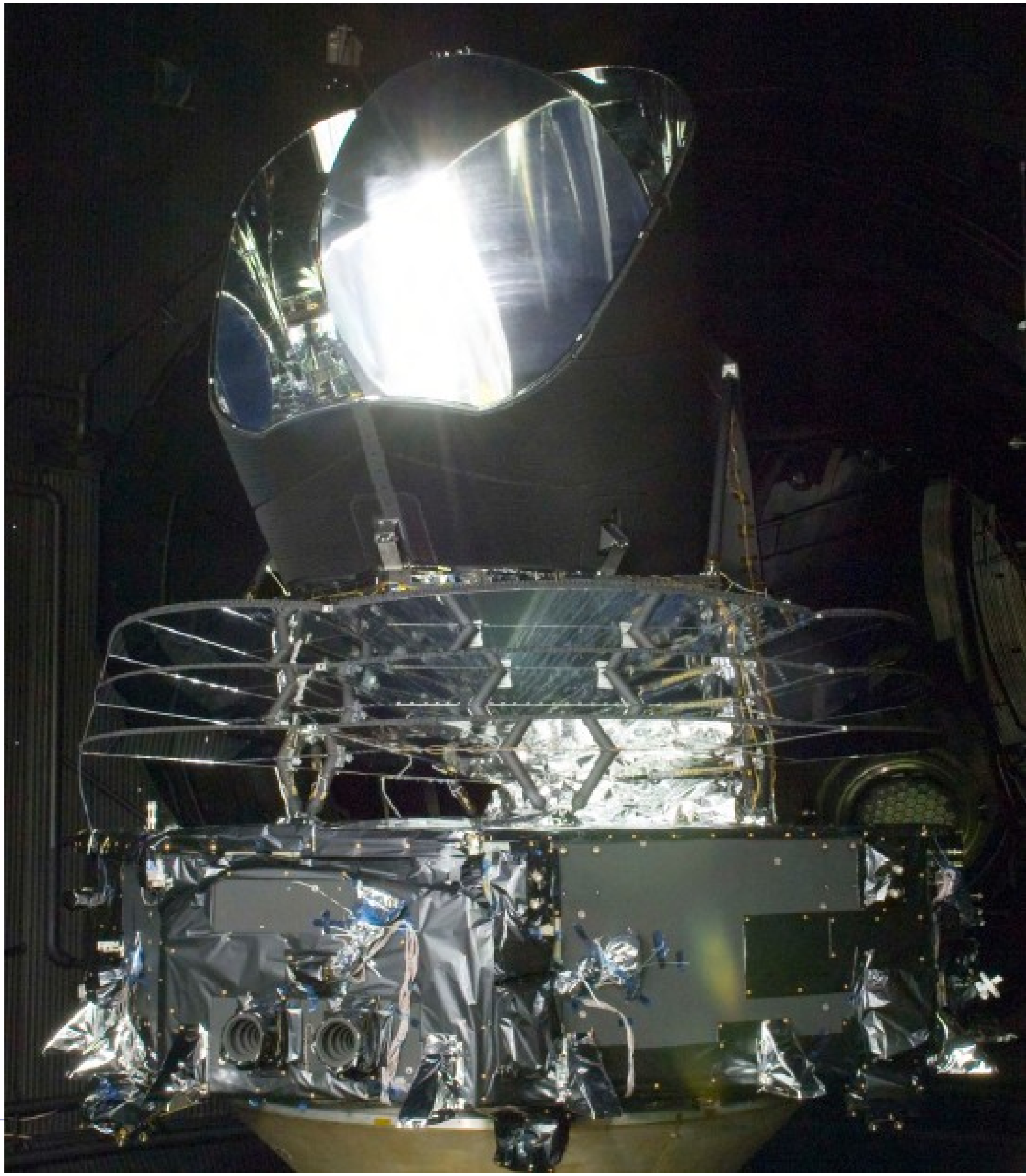
# Non-Gaussianity and Planck

- Non-Gaussianity with Planck will be a new window on the early Universe, complementary to the wealth of information in the two-point function.
- Different early Universe models have distinct predictions for the type and amount of non-Gaussianity expected.
- Ekpyrotic/Cyclic models generically predict non-Gaussianity at detectable levels for Planck $-50 < f_{NL} < 200$ (Leners&Steinhardt 2008)
- New ekpyrotic models are already being hit by current constraints.
- The search for non-Gaussianity is 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 $f_{NL}$ error bars by a factor 4.

# Non-Gaussianity and Planck

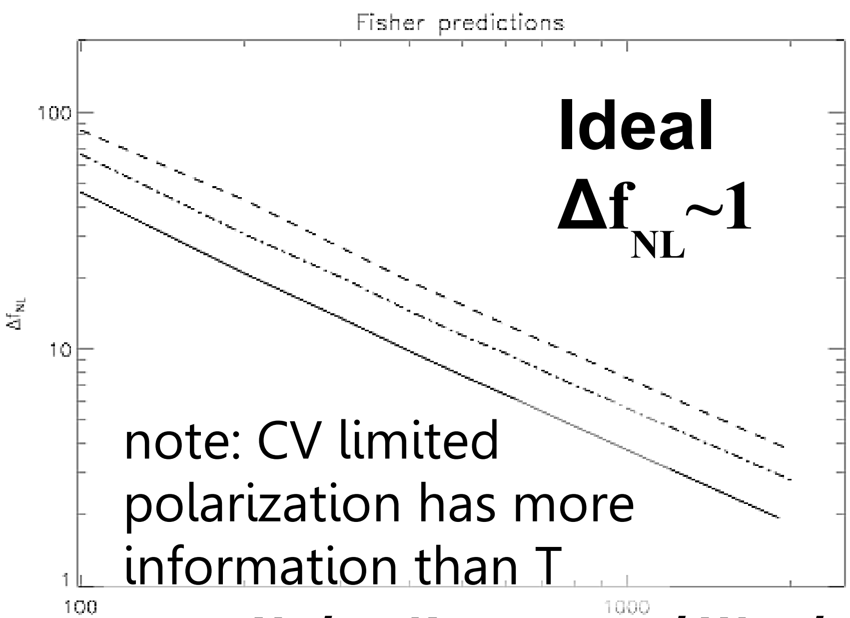
One of the lasting impacts of Yadav and Wandelt 2008: search for primordial NG using bispectrum templates is *much more robust* to systematic error than was previously realized.

- Even though non-Gaussianity is small, the radiation transfer functions give the bispectrum of primordial non-Gaussianity a very different signature from late time secondary effects, foregrounds, or non-Gaussian instrument systematics
- Temperature and Polarization are complementary and can give independent and combined constraints.
- Expect that this robustness will enable the study of primordial non-Gaussianity with Planck.



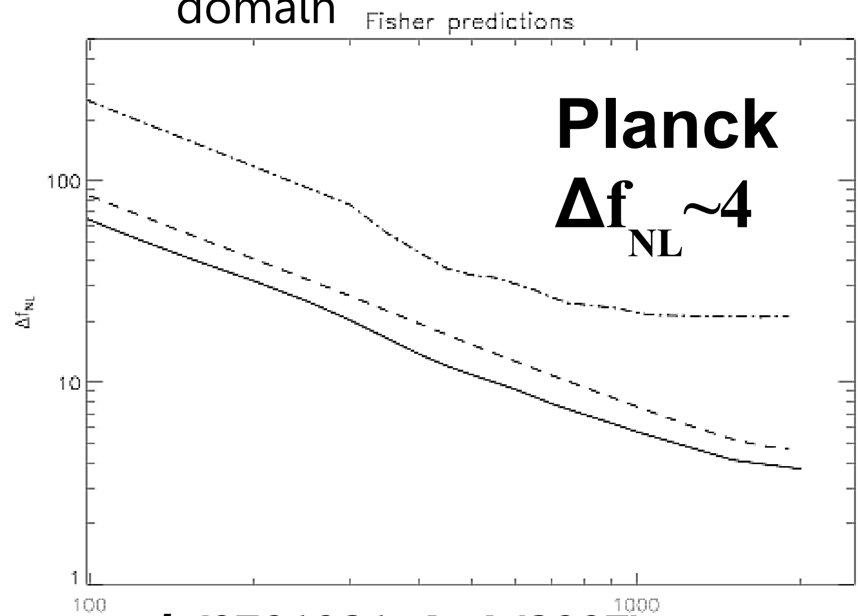
# Planck's promise for Non-Gaussianity

- 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




**Ideal**
**$\Delta f_{NL}$~1**

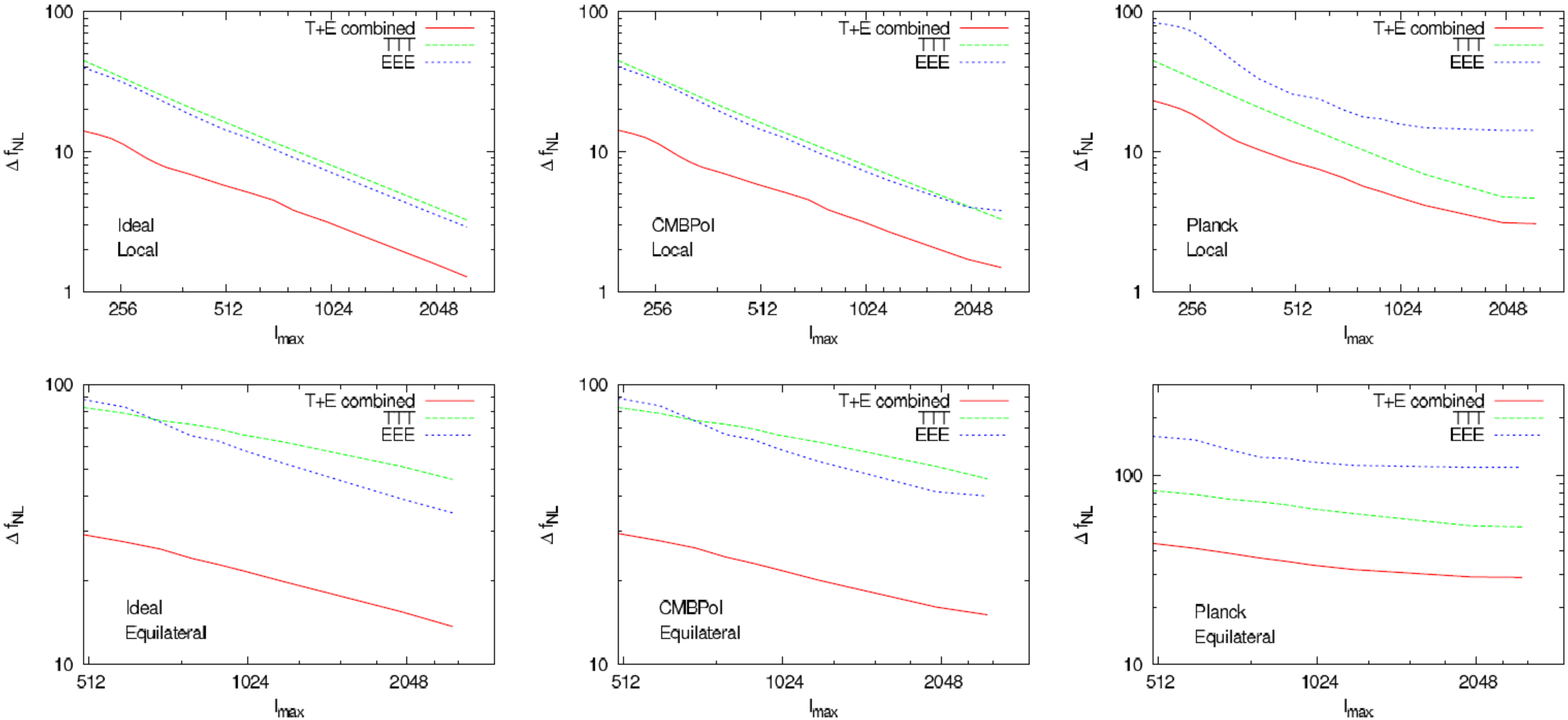
note: CV limited polarization has more information than T




**Planck**
**$\Delta f_{NL}$~4**

***Yadav, Komatsu and Wandelt, astro-ph/0701921, ApJ (2007)***

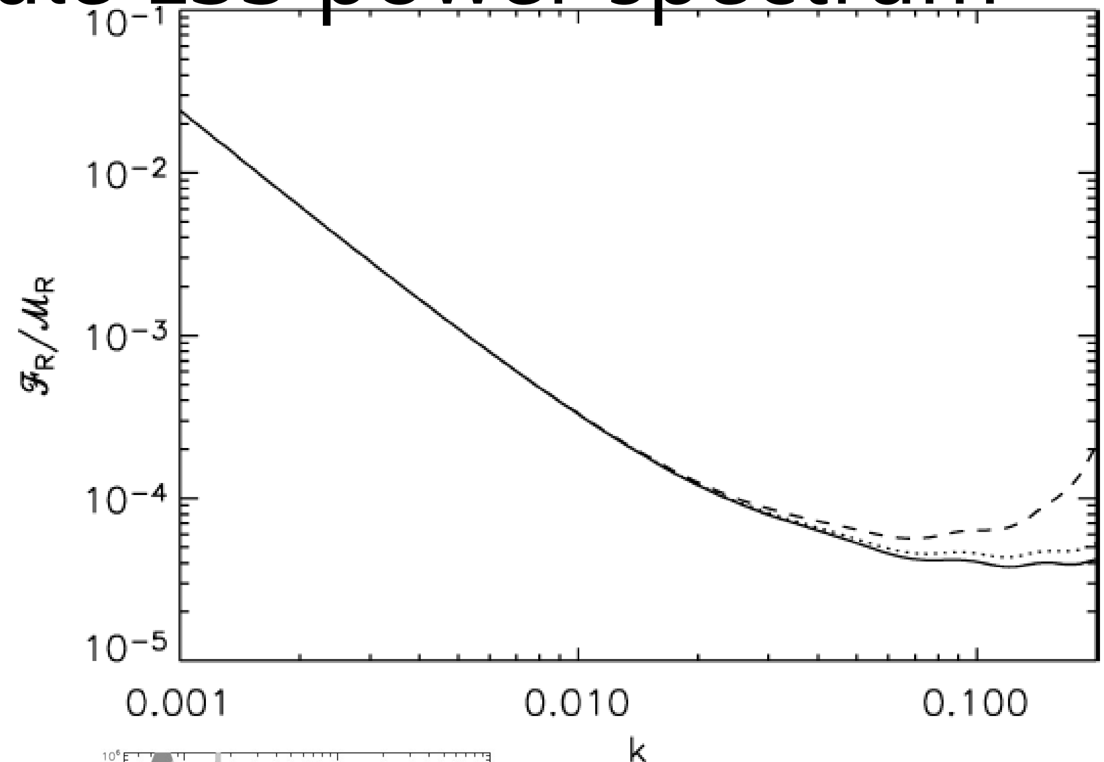
# The future

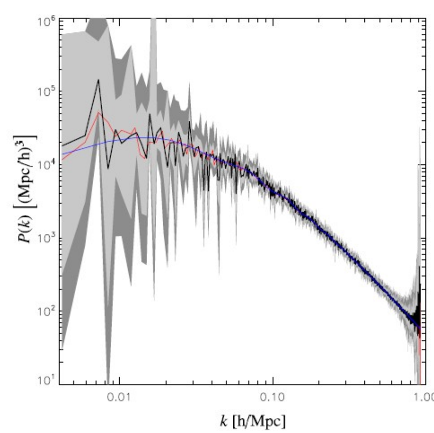



$\Delta f_{NL} \sim 1$ is within reach!

# Fully independent probe of local NG from large scale LSS power spectrum

- local non-linear transformation of the potential leaves imprint on large scale correlations of collapsed structures (Dalal et al. 2008, Verde&Matarrese 2008, Slosar et al 2008)
- promises $\Delta f_{NL}$~1 with future very large scale redshift surveys
- requires very careful power spectrum analysis (Jasche, Kitaura Wandelt Ensslin 2009)



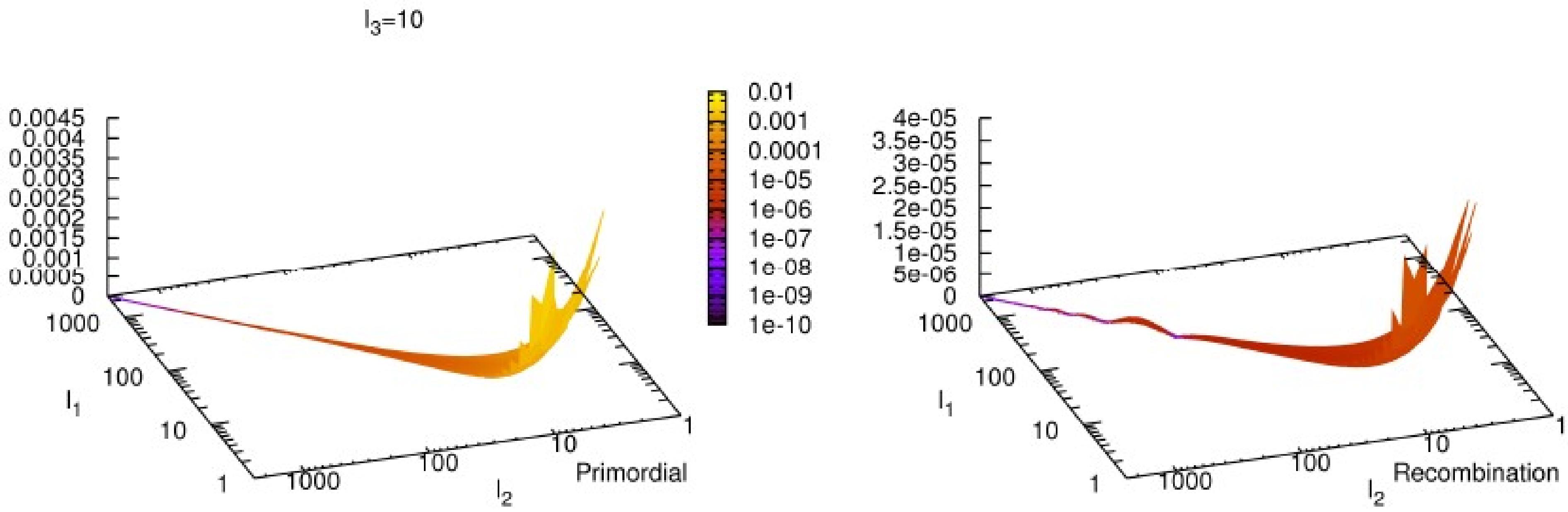
# Non-Gaussianity due to “crinkles” in the surface of last scattering

- The electron density is not homogeneous – recombination occurs at slightly different times in different places

  → **crinkles in the surface of last scattering**

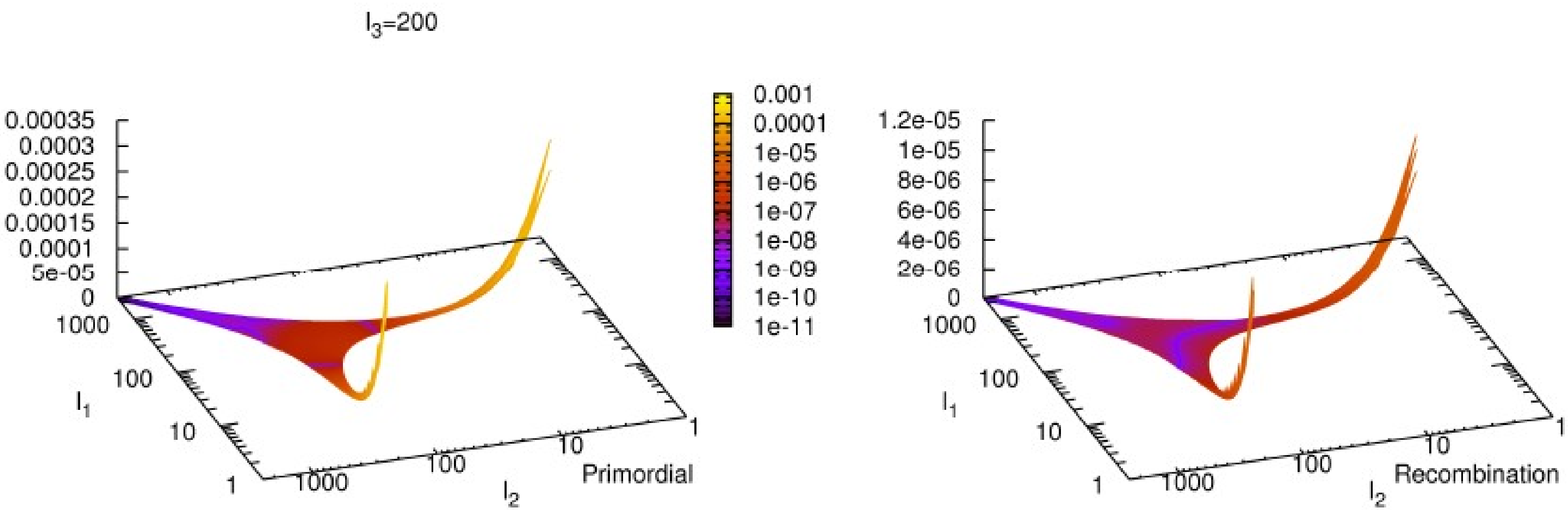
- Perturbations in the free electron density (ionization fraction) can be larger than perturbations in the baryon density by a factor of 5 (Novosyadlyj, MNRAS 2006; Senatore, Tassev, Zaldarriaga arxiv:0812.3652).
- Does this produce non-Gaussianity observable by Planck?

# Crinkles vs. primordial non-Gaussianity give similar but not identical bispectrum




Khatri & Wandelt, PRD 2008
Khatri & Wandelt, arxiv:0903.0871

# Crinkles vs. primordial non-Gaussianity give similar but not identical bispectrum




Khatri & Wandelt, PRD 2008
Khatri & Wandelt, arxiv:0903.0871

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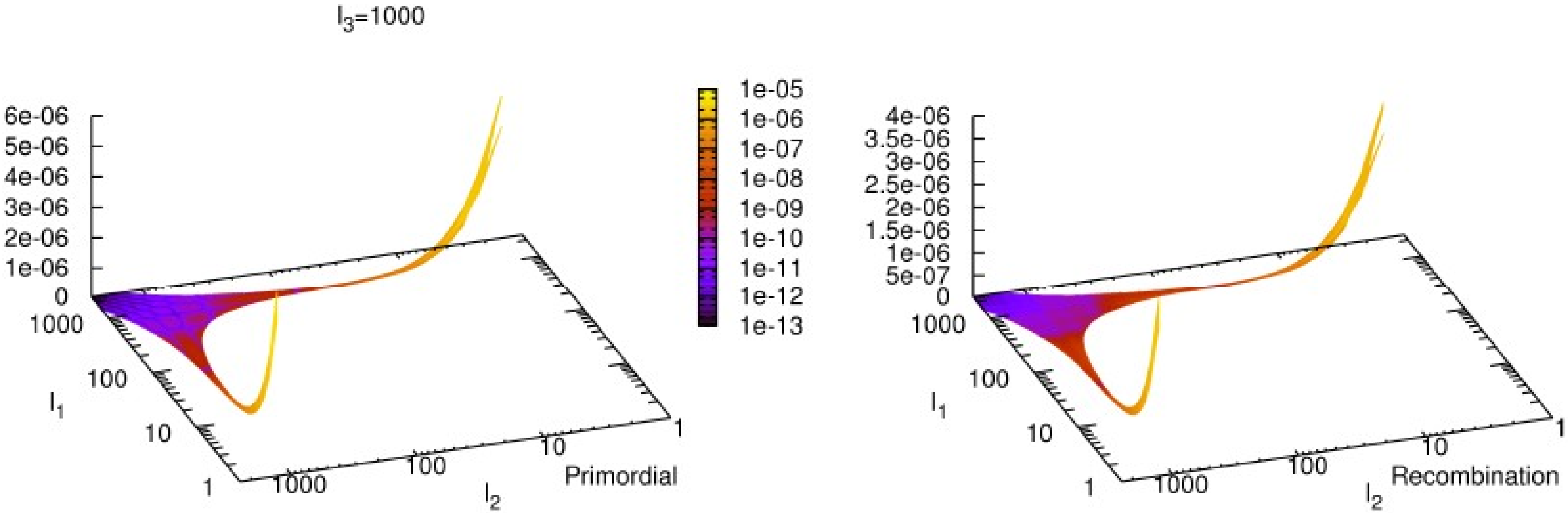


Khatri & Wandelt, PRD 2008
Khatri & Wandelt, arxiv:0903.0871

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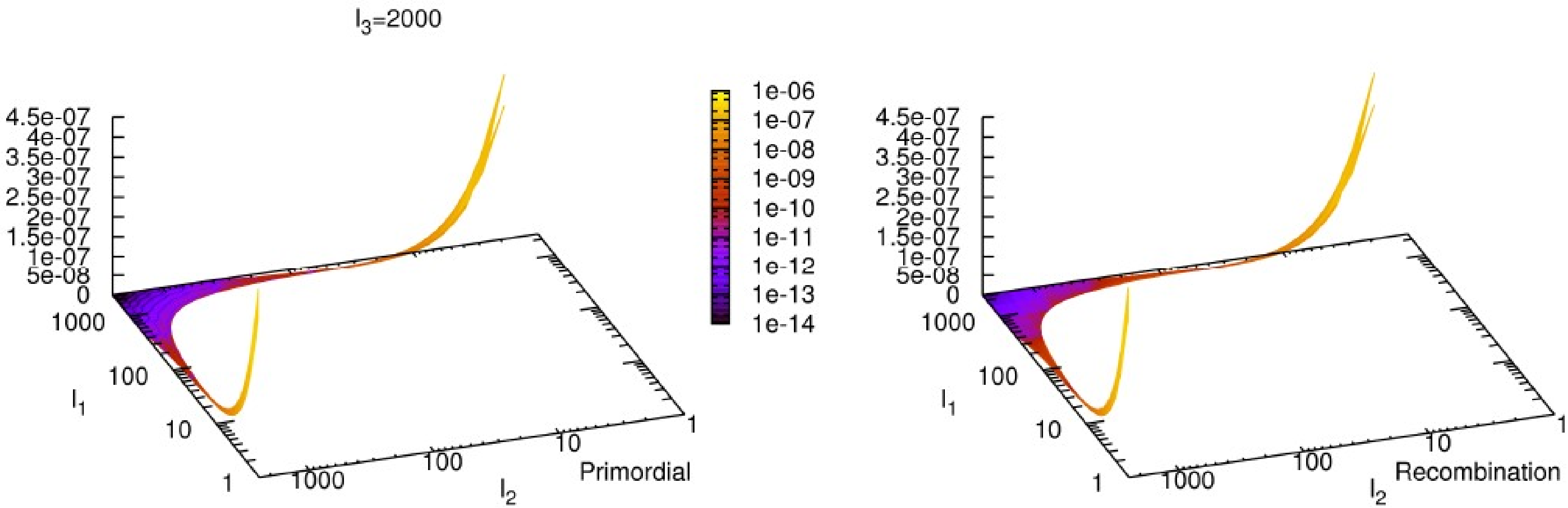
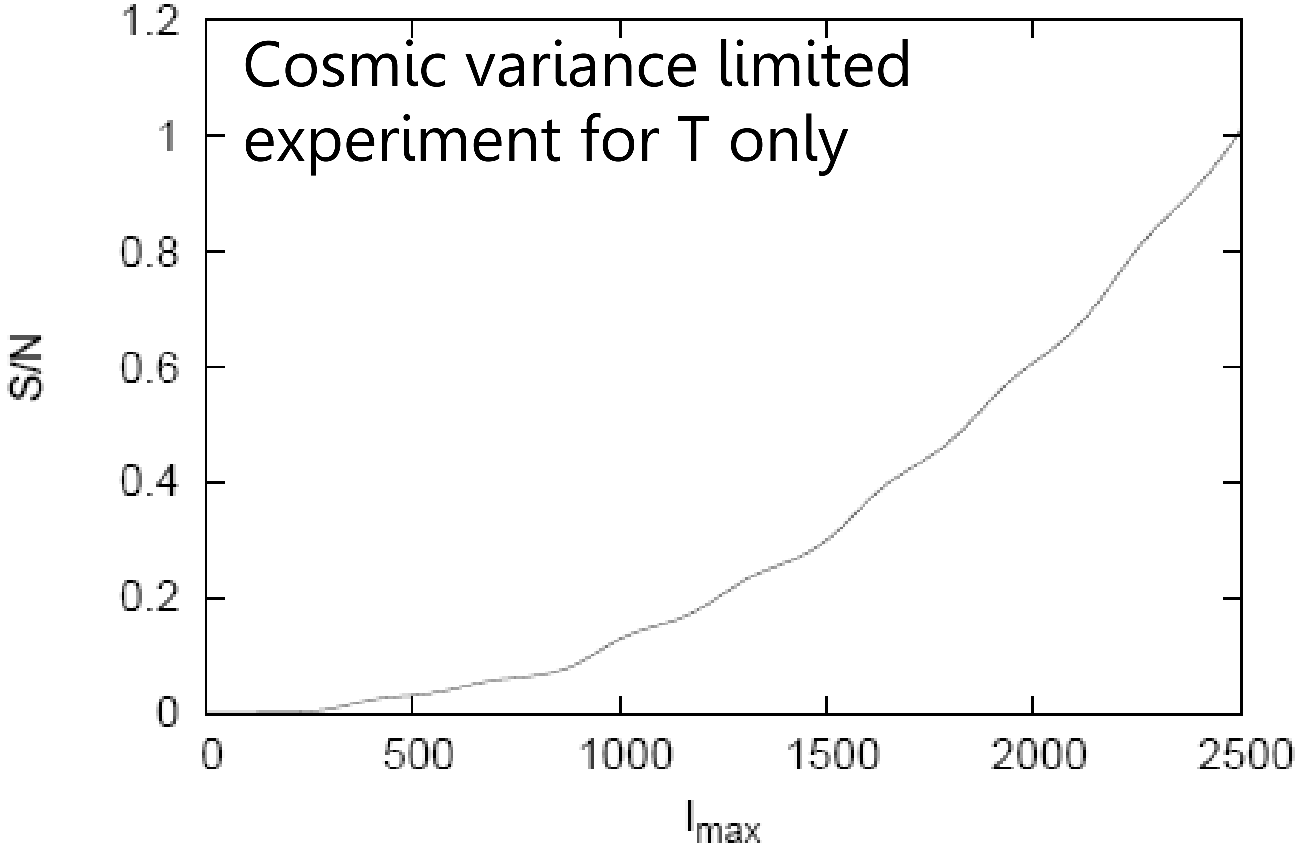


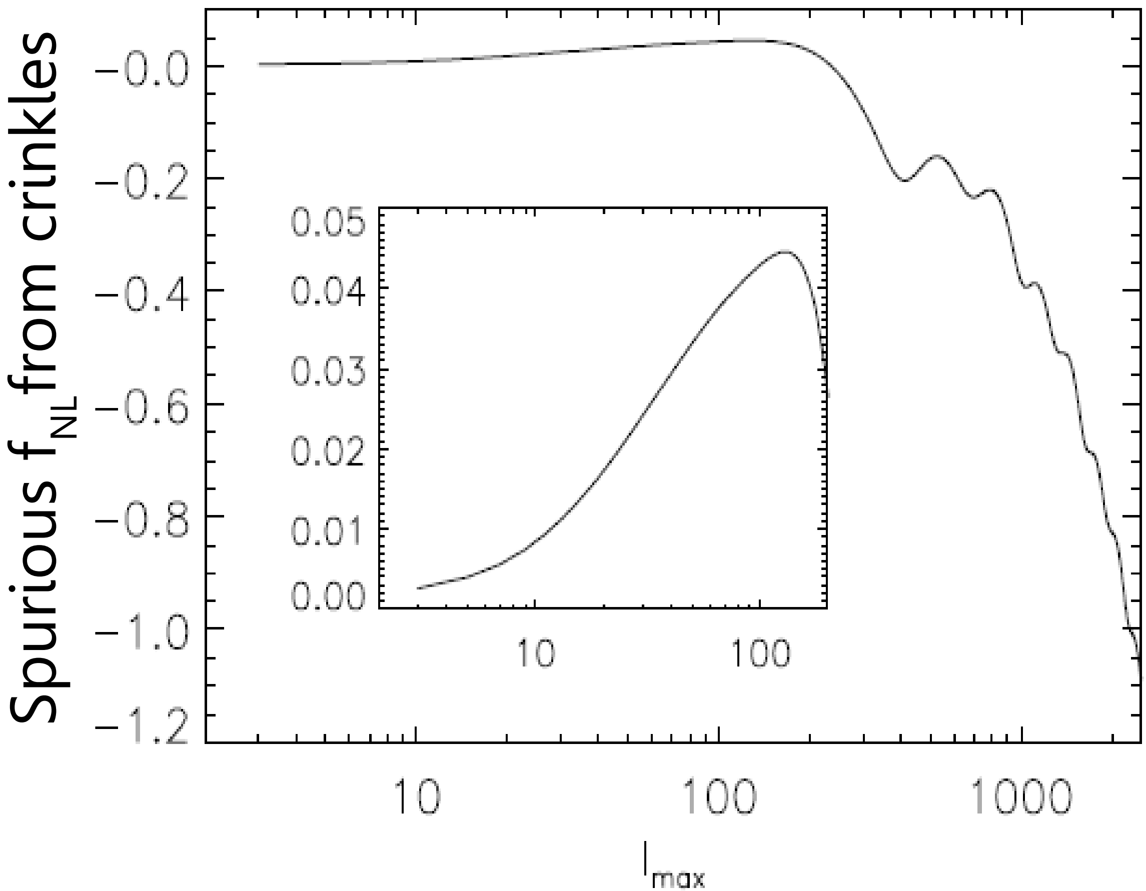

Khatri & Wandelt, PRD 2008
Khatri & Wandelt, arxiv:0903.0871

# Can we see non-Gaussianity from Crinkles?




Khatri & Wandelt, PRD 2008
Senatore, Tassev, Zaldarriaga: arXiv:0812.3652/8
Khatri & Wandelt, arxiv:0903.0871

# Are crinkles an important "background" for primordial $f_{NL}$?




At the level of $f_{NL}$~-1 for Temperature

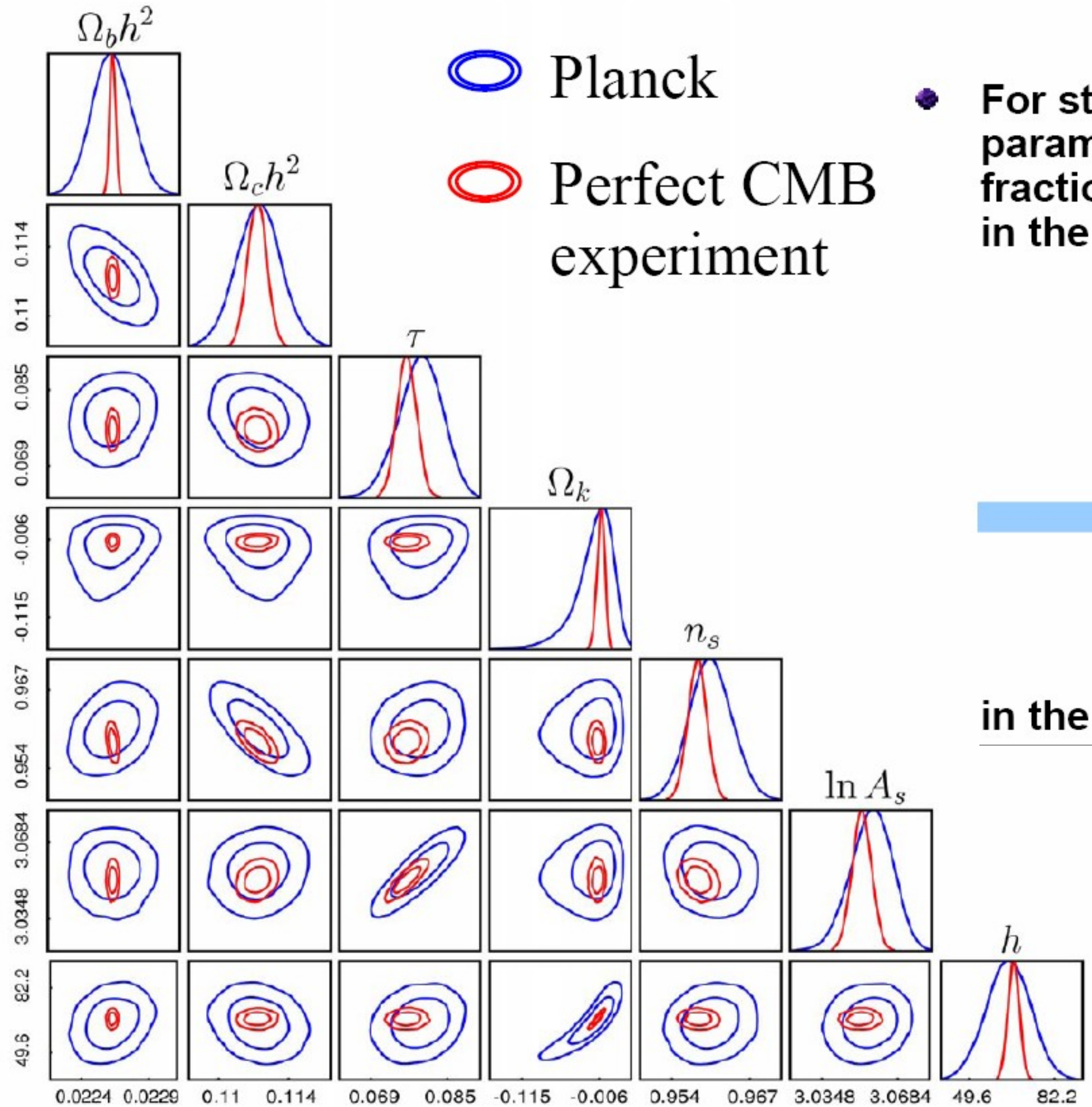
# What about other second-order effects?

- Pitrou ,Uzan Bernadeau 2010: full second order calculation gives $f_{NL}$~5 with Gaussian primordial fluctuations
- This would mean non-Gaussianity cannot be ignored in analysis of future CMB experiments ***even if the primordial perturbations are Gaussian***

# The Gaussian Universe is dead!

# Long live the *almost* Gaussian Universe!

# The end of the line for cosmological parameters




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

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

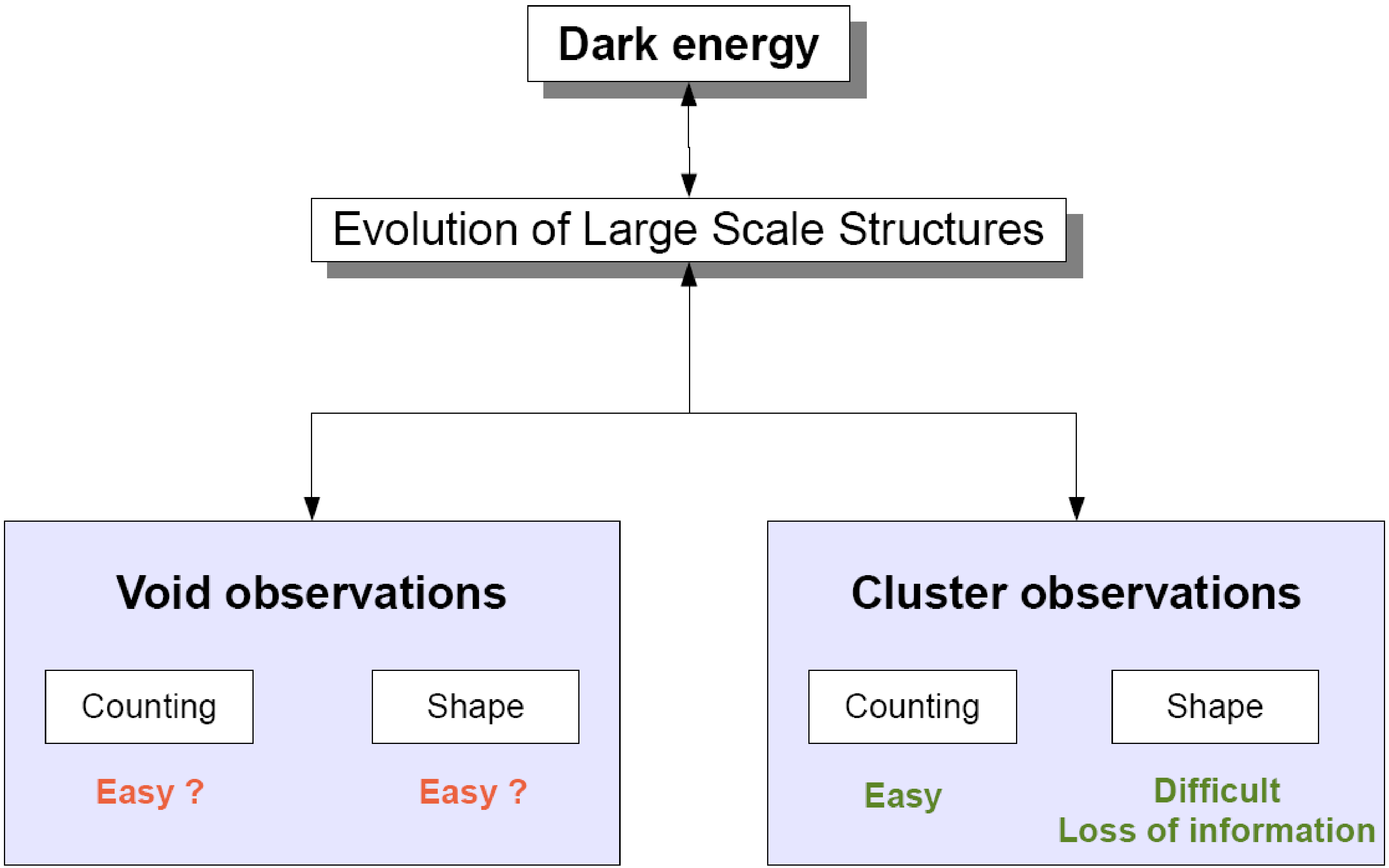
**in the standard cosmological model.**

# The non-Gaussian revolution

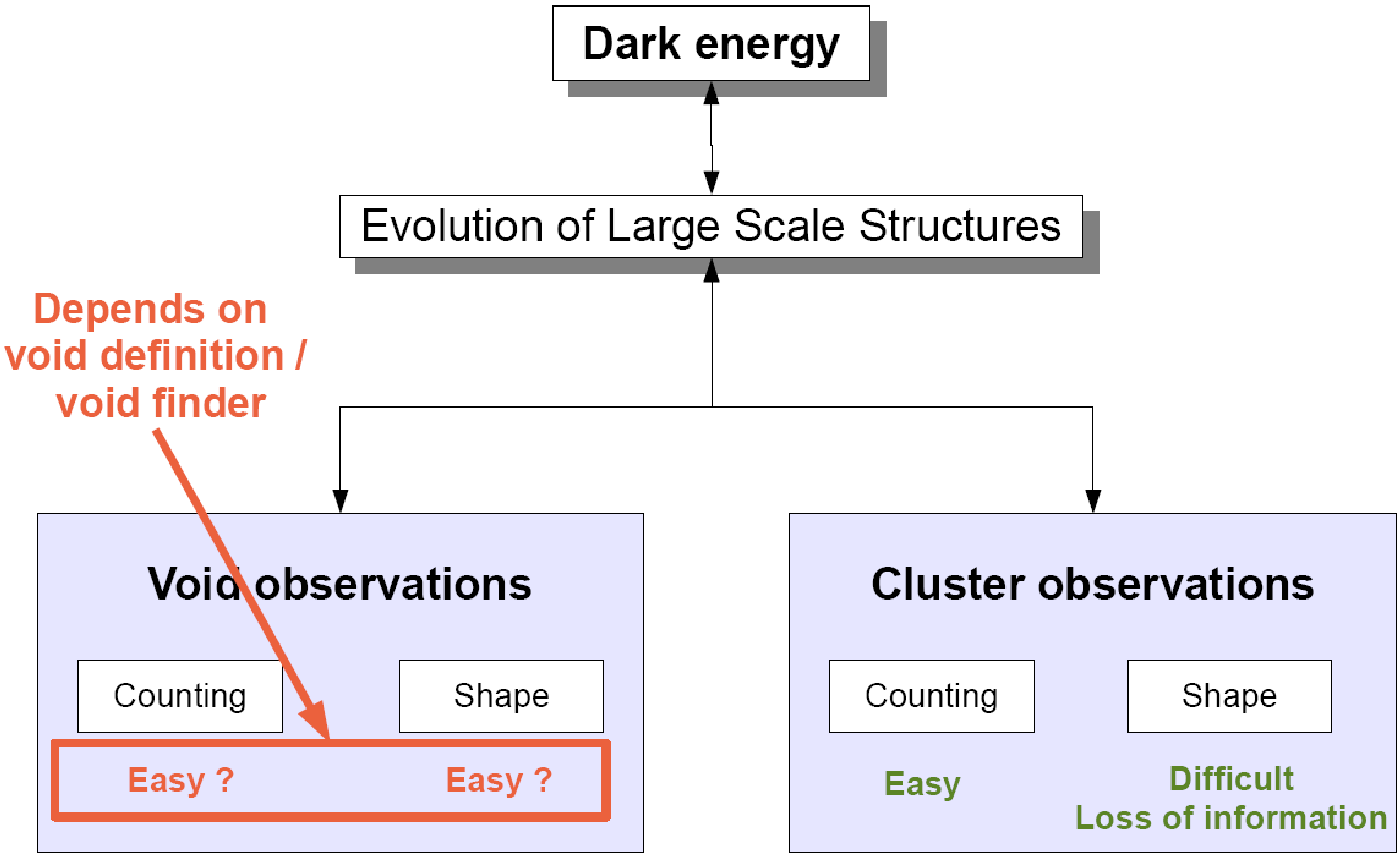
- The coming decade will be the era of extraction of information from non-Gaussian sources
  - probe of primordial non-Gaussianity
  - secondary anisotropies (lensing)
  - high precision Large Scale Structure analysis
    - dark energy
    - primordial non-Gaussianity
- This will require new ways of connecting theory with observations
- Will conclude by mentioning a few projects that have clear applications in this direction

# Identification and characterization of cosmic voids

# Why look at voids ?



# Why look at voids ?



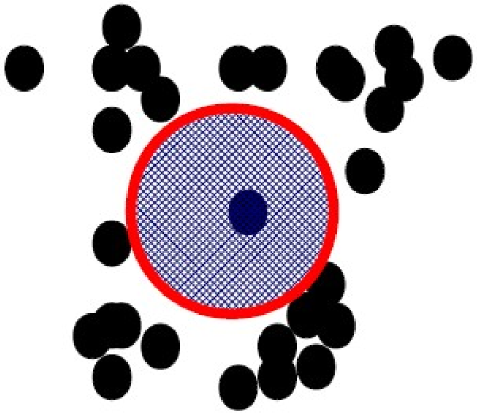
# Several definition of voids

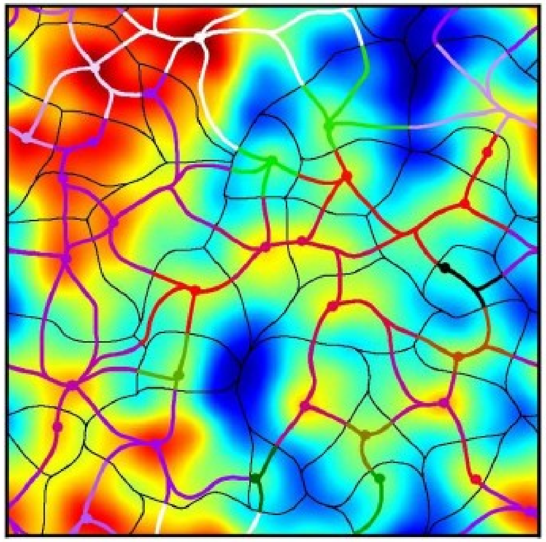
What is a void ?

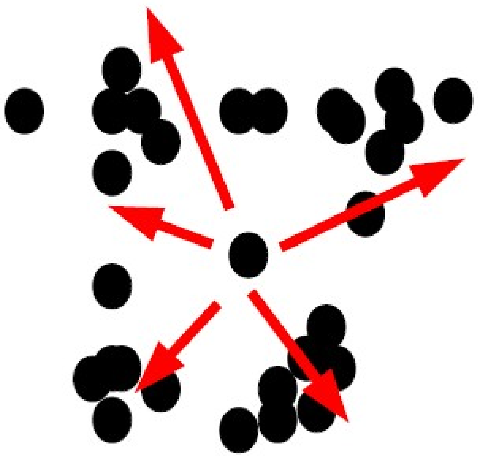
Holes in a distribution of galaxy

Dip in the matter density field

Unstable/expanding patch of matter

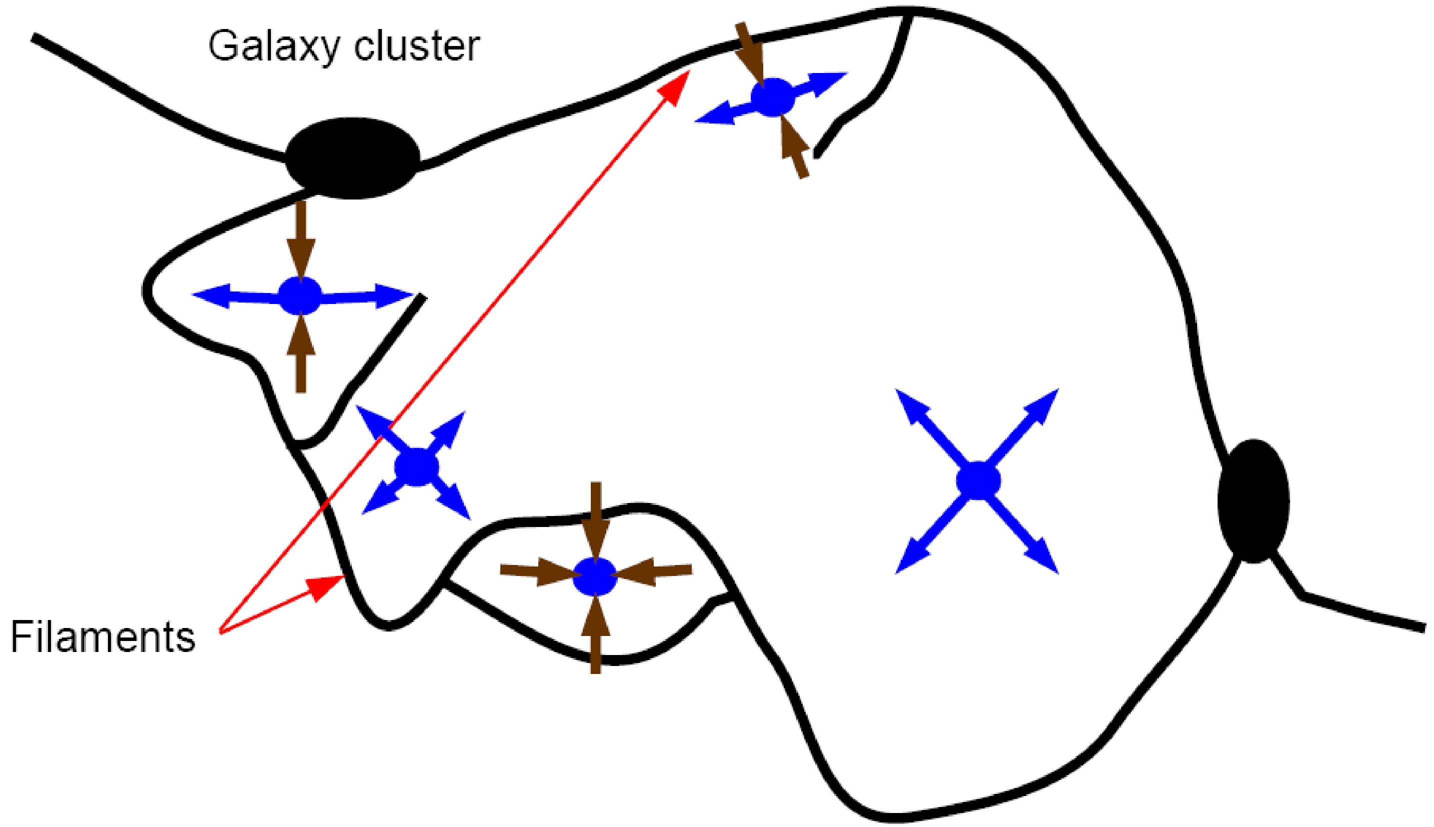






# A dynamical definition of voids

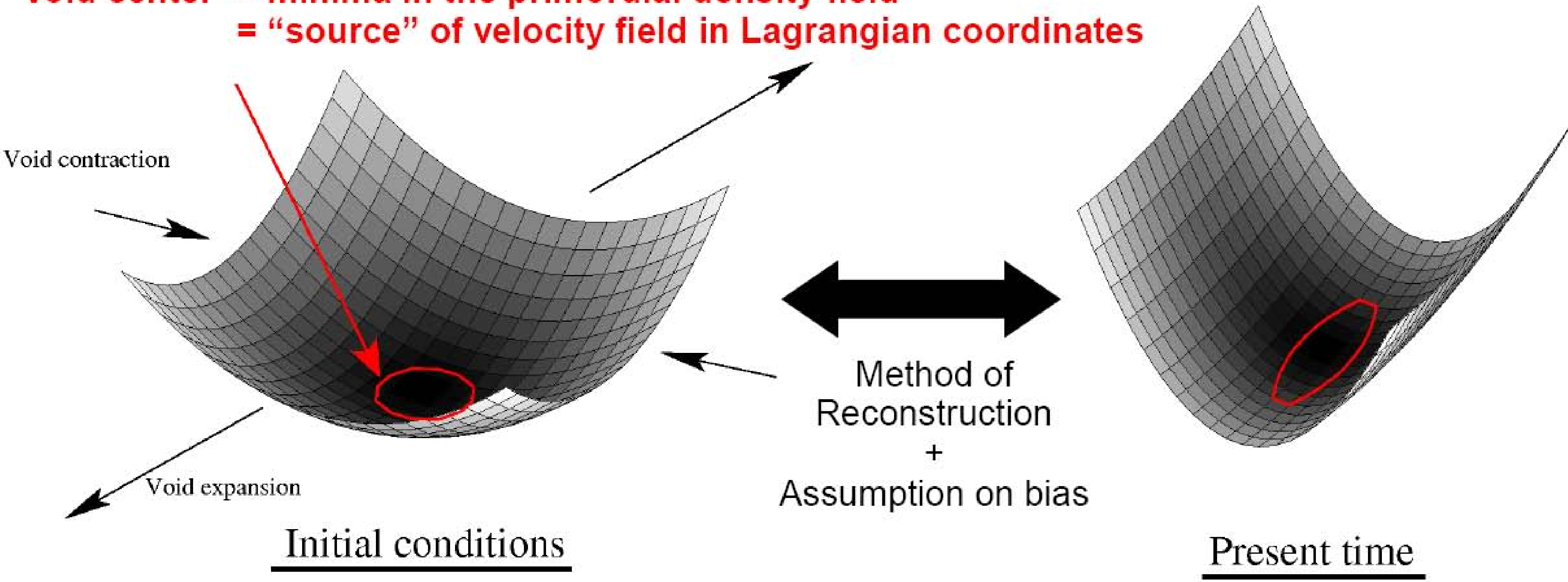
## Voids in structures




Lavaux & Wandelt (2009, MNRAS)

# A dynamical definition of voids

**Void center = minima in the primordial density field**
**= "source" of velocity field in Lagrangian coordinates**



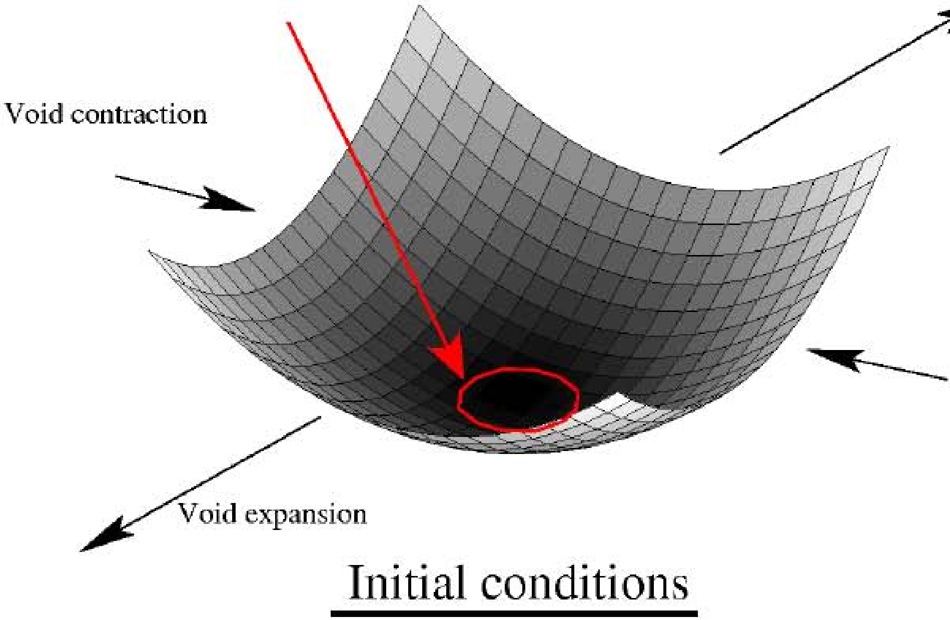

How many ?

~0.05 by $(10\ \mathrm{Mpc}/h)^3$
or ~9,000 voids } in SDSS $z \leq 0.2$

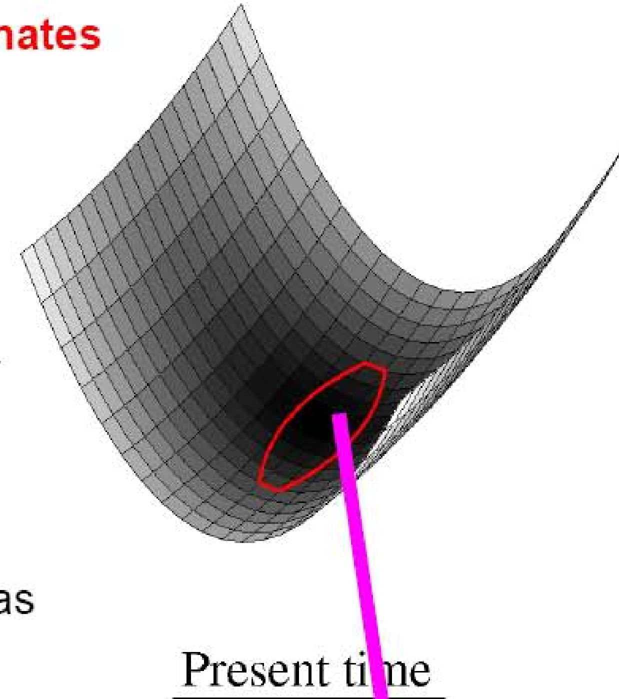
Lavaux & Wandelt (2009, MNRAS)

# A dynamical definition of voids

**Void center = minima in the primordial density field**
**= "source" of velocity field in Lagrangian coordinates**



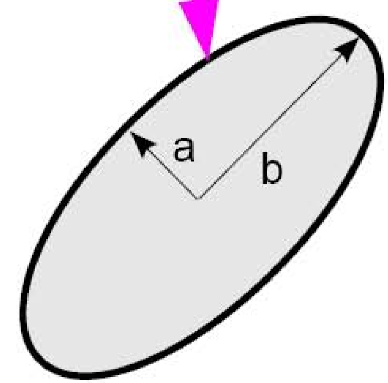

Method of Reconstruction
+
Assumption on bias



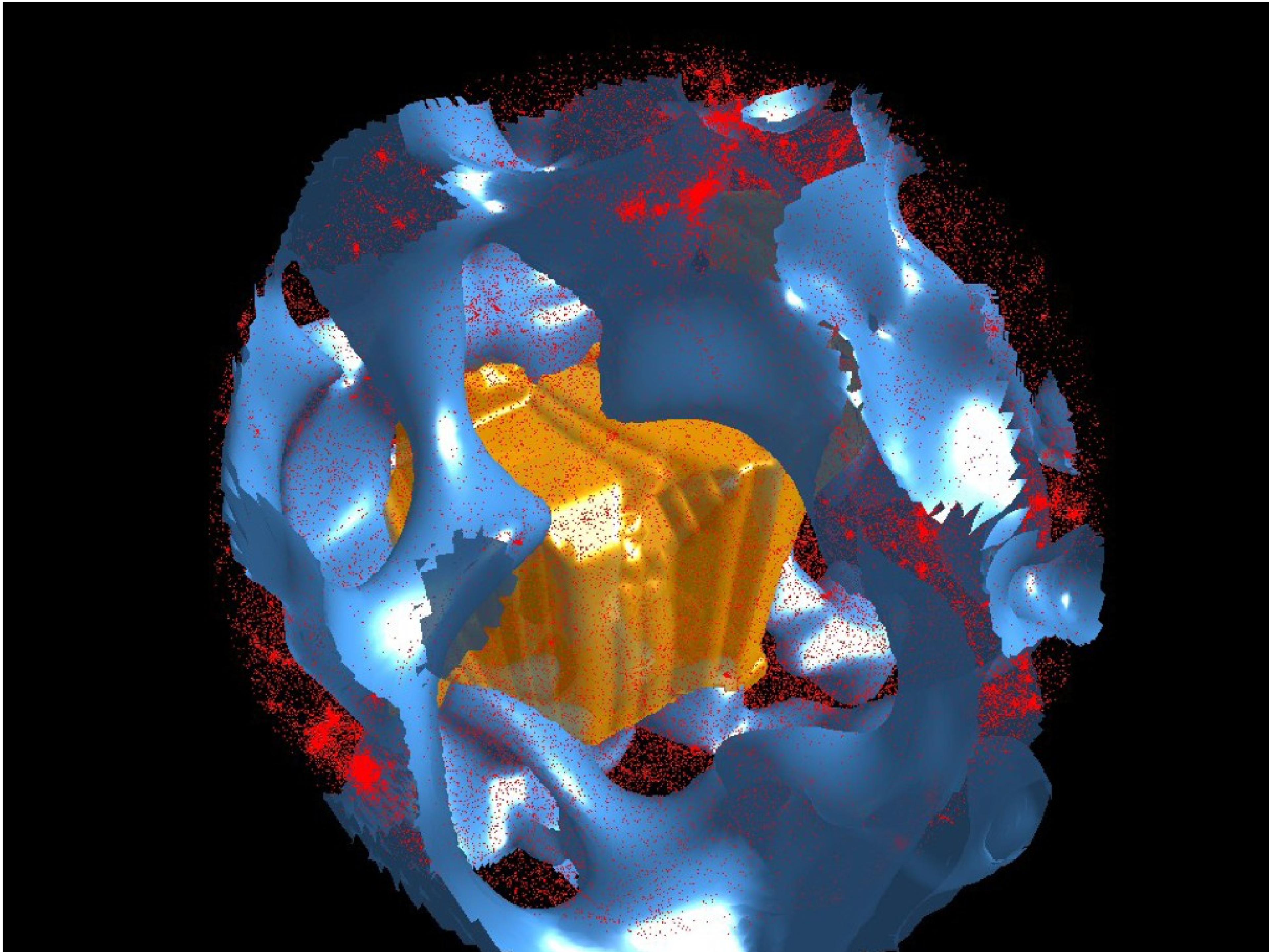

How many ?

~0.05 by $(10\ \mathrm{Mpc}/h)^3$ or ~9,000 voids } in SDSS $z \leq 0.2$

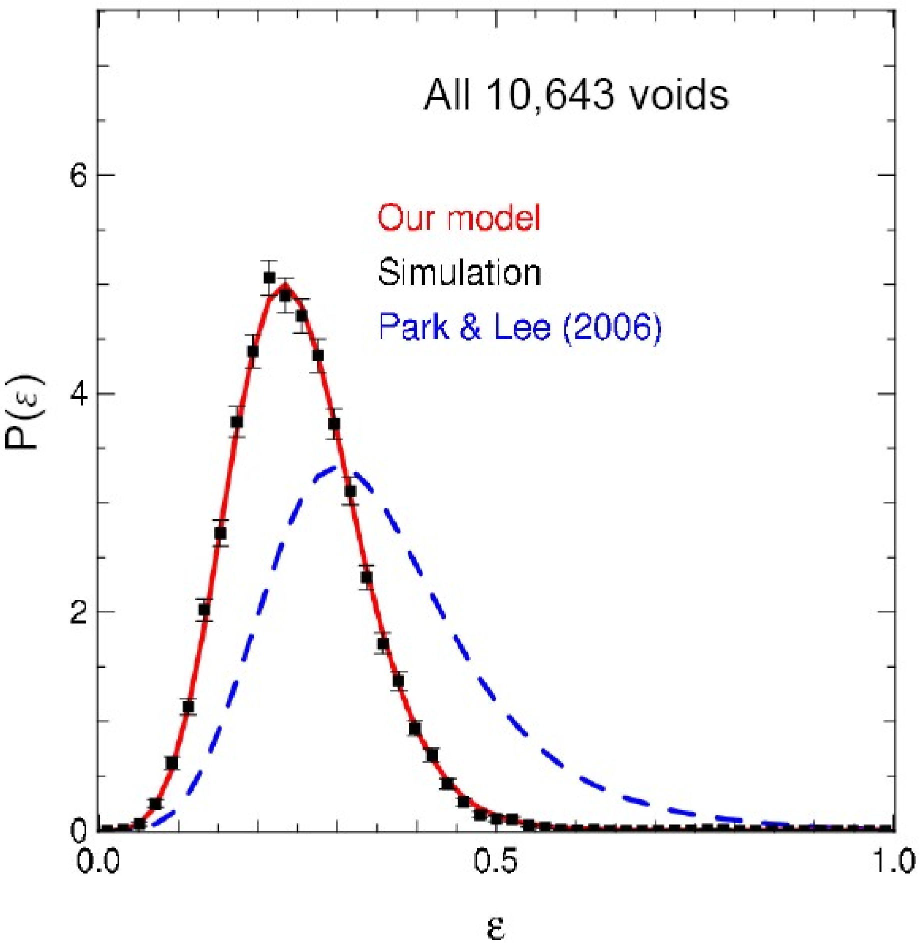
$$\varepsilon = 1 - \sqrt{\frac{a}{b}}$$



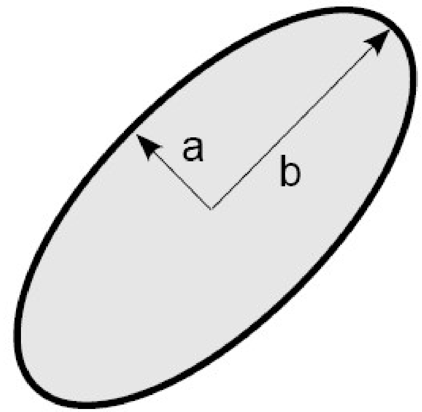

Lavaux & Wandelt (2009, MNRAS)



# Simulation vs Theory



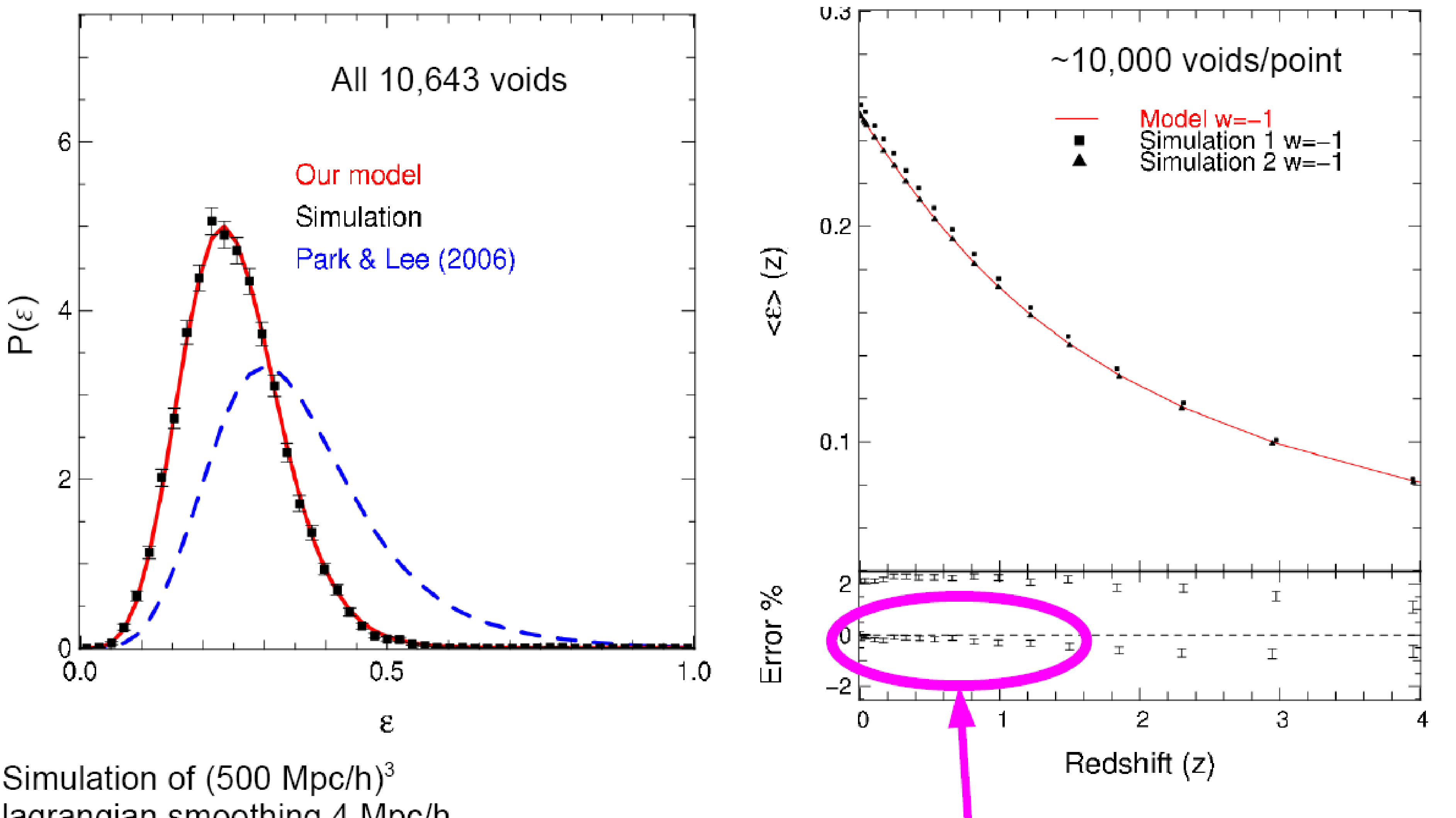

Simulation of $(500\ \mathrm{Mpc}/h)^3$
lagrangian smoothing 4 Mpc/h




$$\varepsilon = 1 - \sqrt{\frac{a}{b}}$$

Lavaux & Wandelt (2009, MNRAS)

# Simulation vs Theory

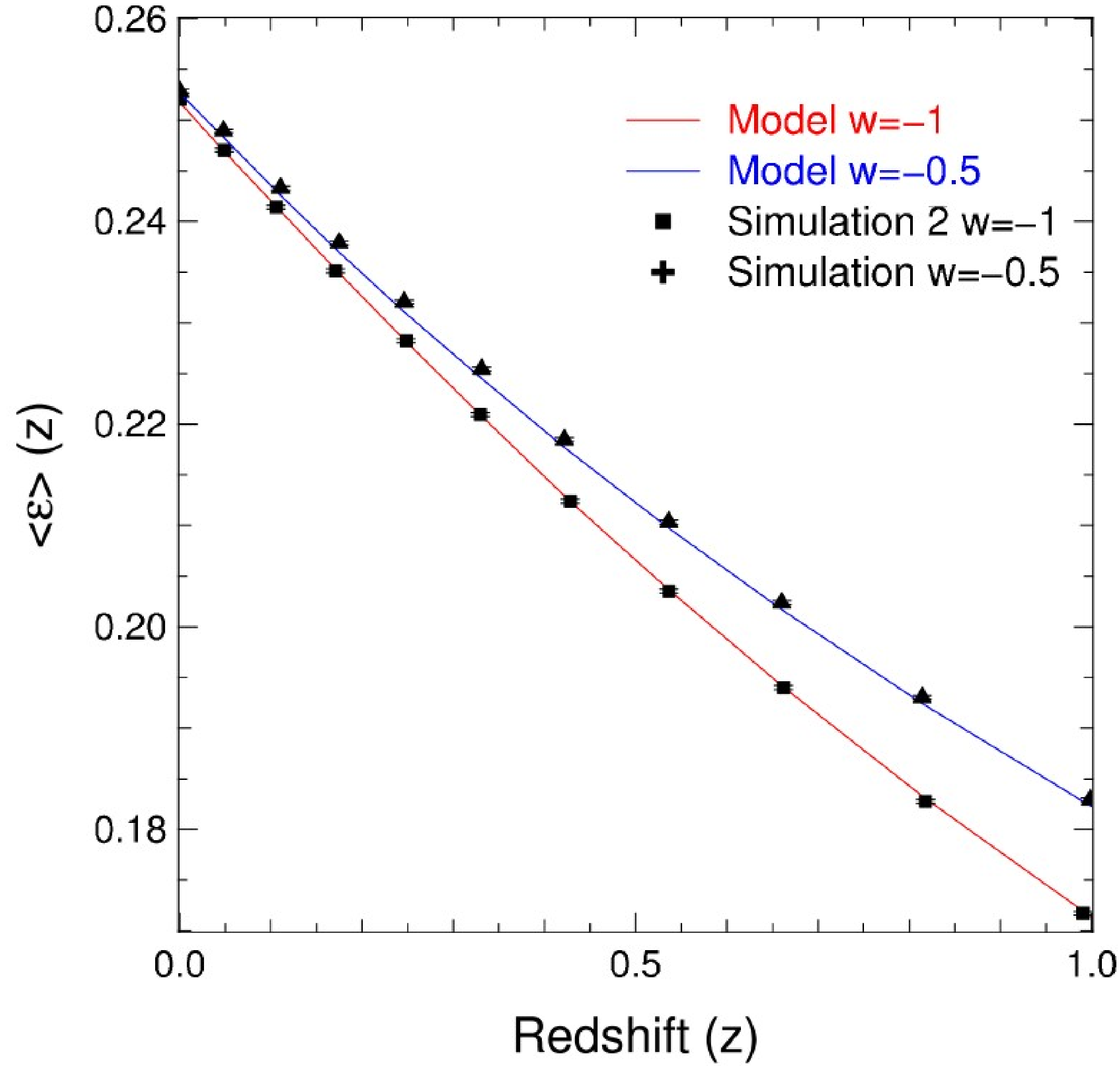



Simulation of (500 Mpc/h)$^3$
lagrangian smoothing 4 Mpc/h

~0.1% error

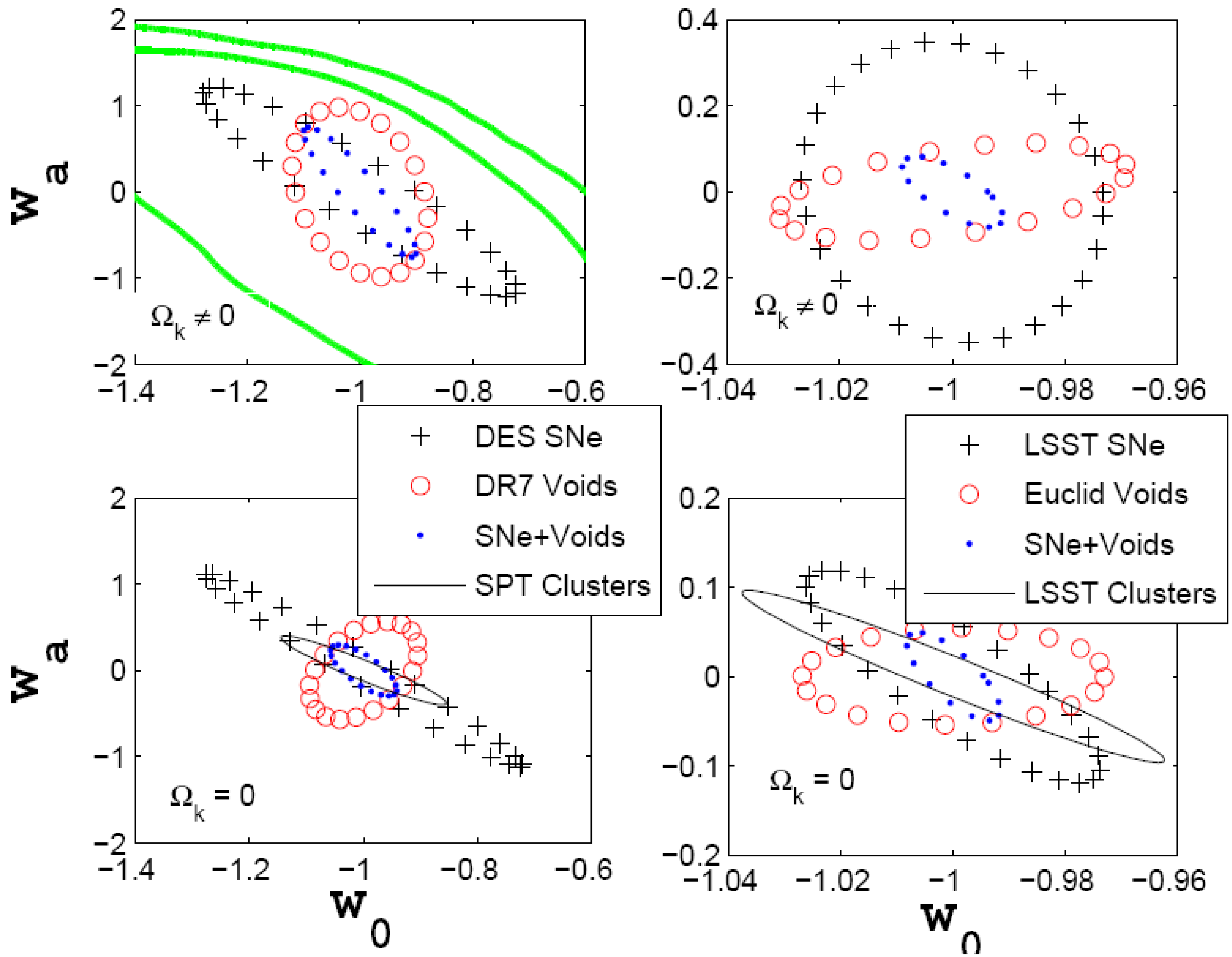
Lavaux & Wandelt (2009, MNRAS)

# Mean ellipticity for different *w*CDM




Lavaux & Wandelt (2009, MNRAS)

# Voids a promising complementary probe of dark energy



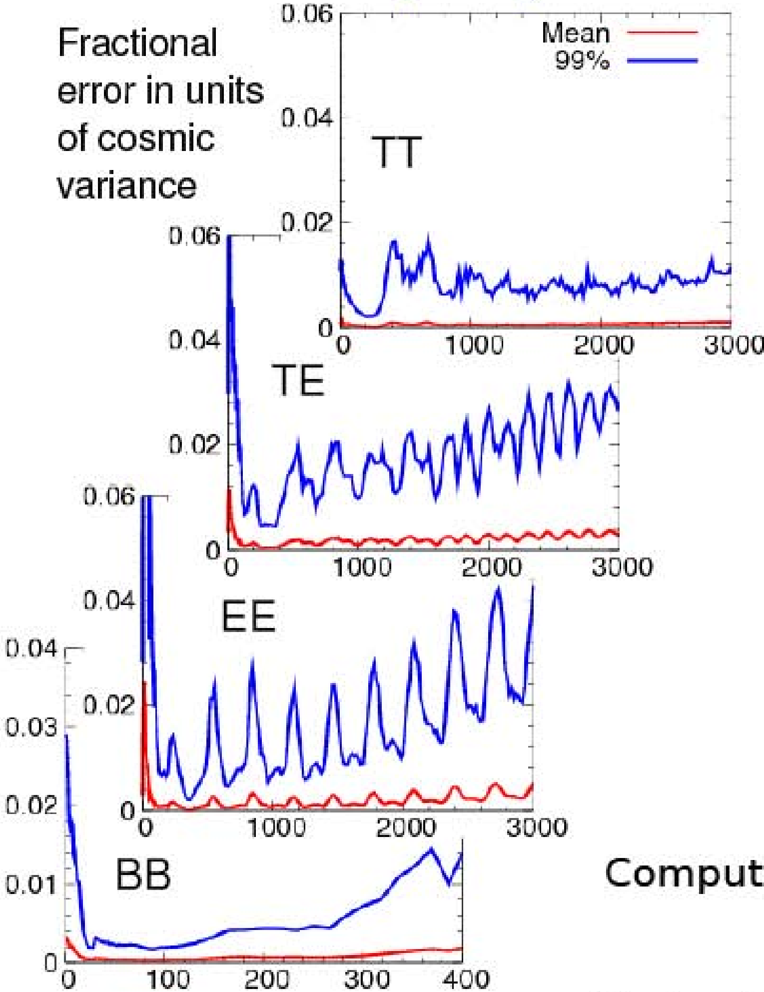
# APPLE: Acceleration through Parallel Precomputation and LEarning.

- Developed to enable high precision cosmological parameter estimation from Planck
- Implemented in Pico (Parameters for the impatient cosmologist) (Fendt and Wandelt 2006,8)
- Planck will produce spectra of such high accuracy that standard methods for extracting cosmological parameters will be either be
  - to inaccurate, or
  - too slow
- **Allows using massively distributed computing for sequential problems**

# Pico

Pico performs regression on a training set of $\{\Theta, C_\ell\}$

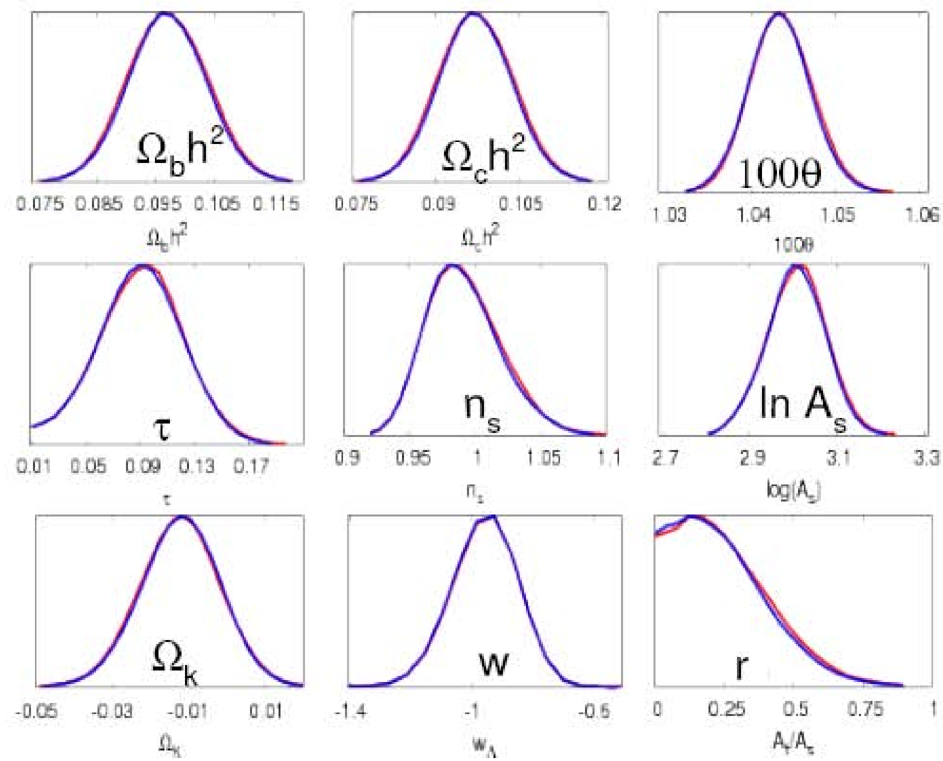
**Fast**: ~25 ms per $C_\ell$




**Accurate**

WMAP + SDSS Posteriors

PICO CAMB

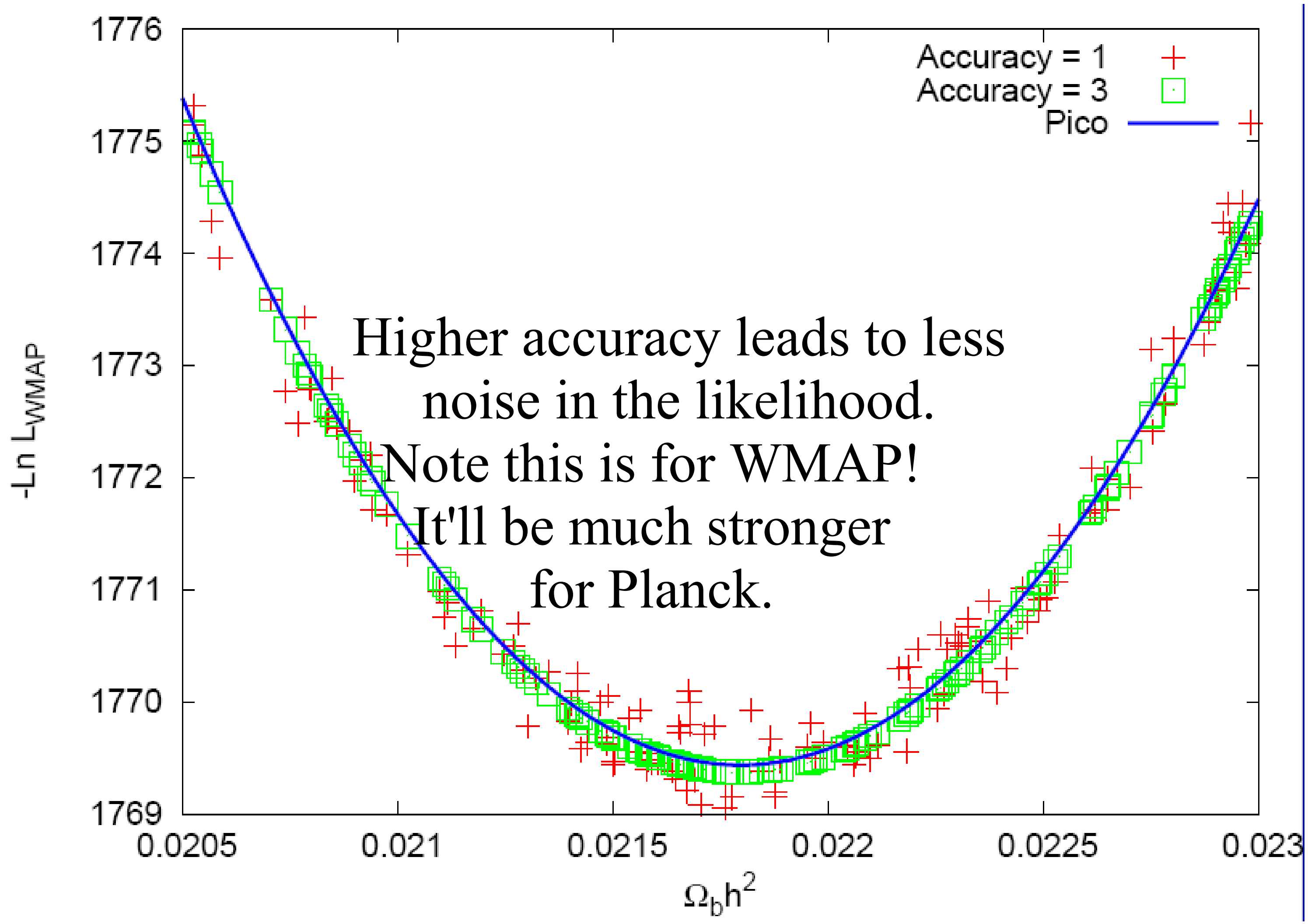



Computes scalar $C_\ell$'s, tensor $C_\ell$'s, matter transfer function and jacobian $C_\ell$'s of w.r.t to parameters

Trained on high accuracy $C_\ell$'s

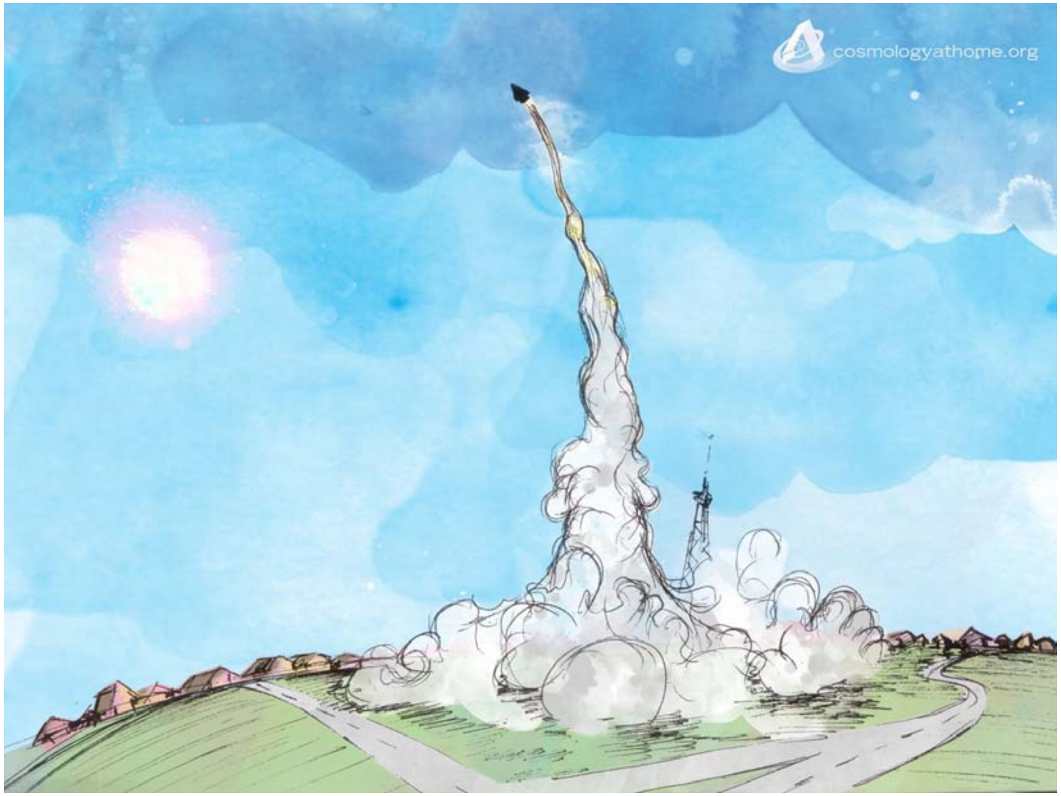
Download: cosmos.astro.uiuc.edu/pico

# PICO reduces noise in the likelihood



# cosmology@home

- Use BOINC platform to enable people everywhere to donate CPU time
- many 1000s of users
- 10,000s of CPUs
- can generate training sets very quickly
- turns homes into cosmology research centers worldwide



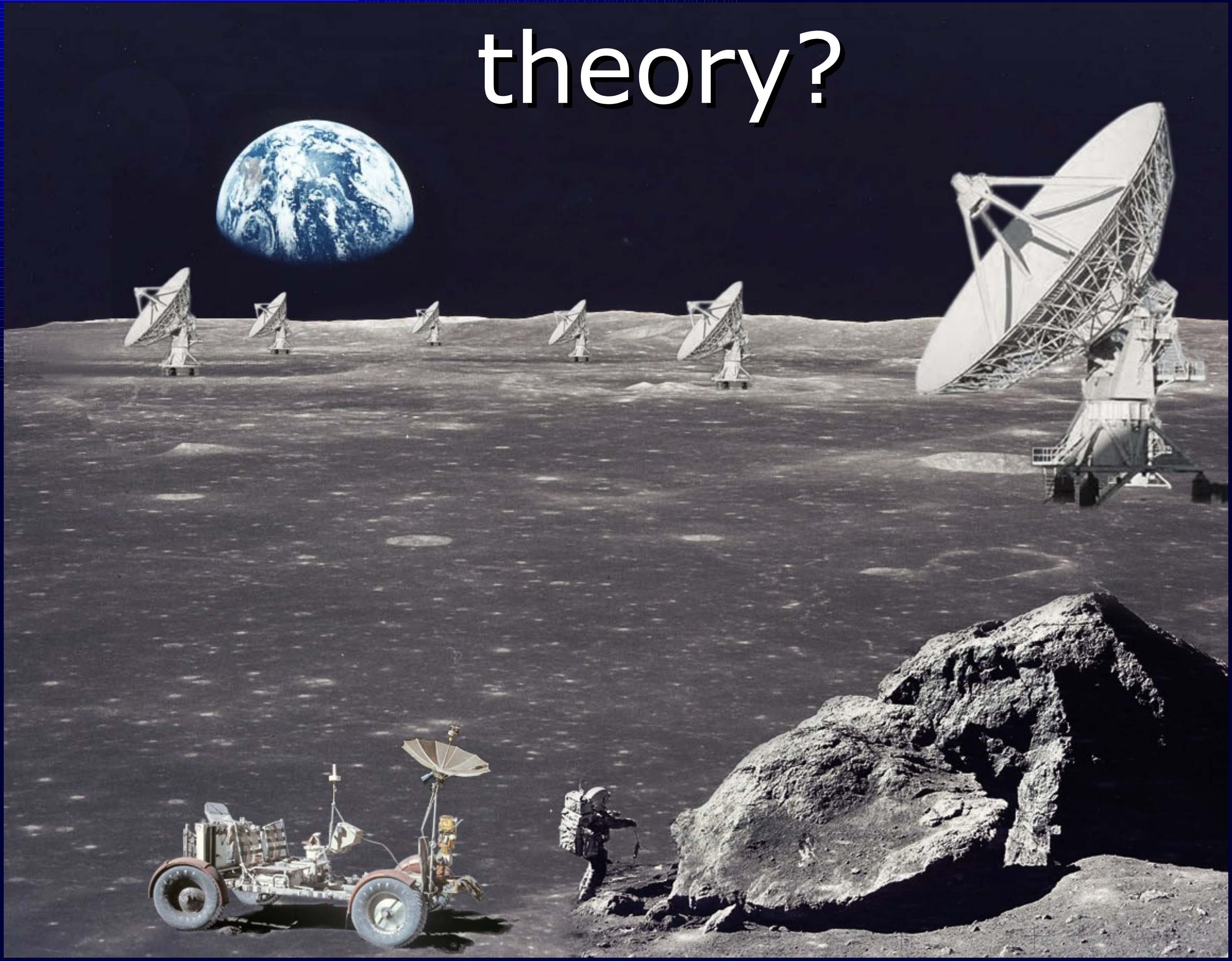
# PICO application: RICO

- RICO is PICO applied to detailed cosmological recombination physics
- Reduces the main theoretical uncertainty in CMB power spectrum calculations
- Brute force Codes take days to finish for a single run.
- We were able to fit n(z) with a few 100 training samples => running time is now 25ms.
- Can now be included in Boltzmann codes.

http://cosmos.astro.uiuc.edu/rico
[Fendt et al. 2008]

# Onto the far future

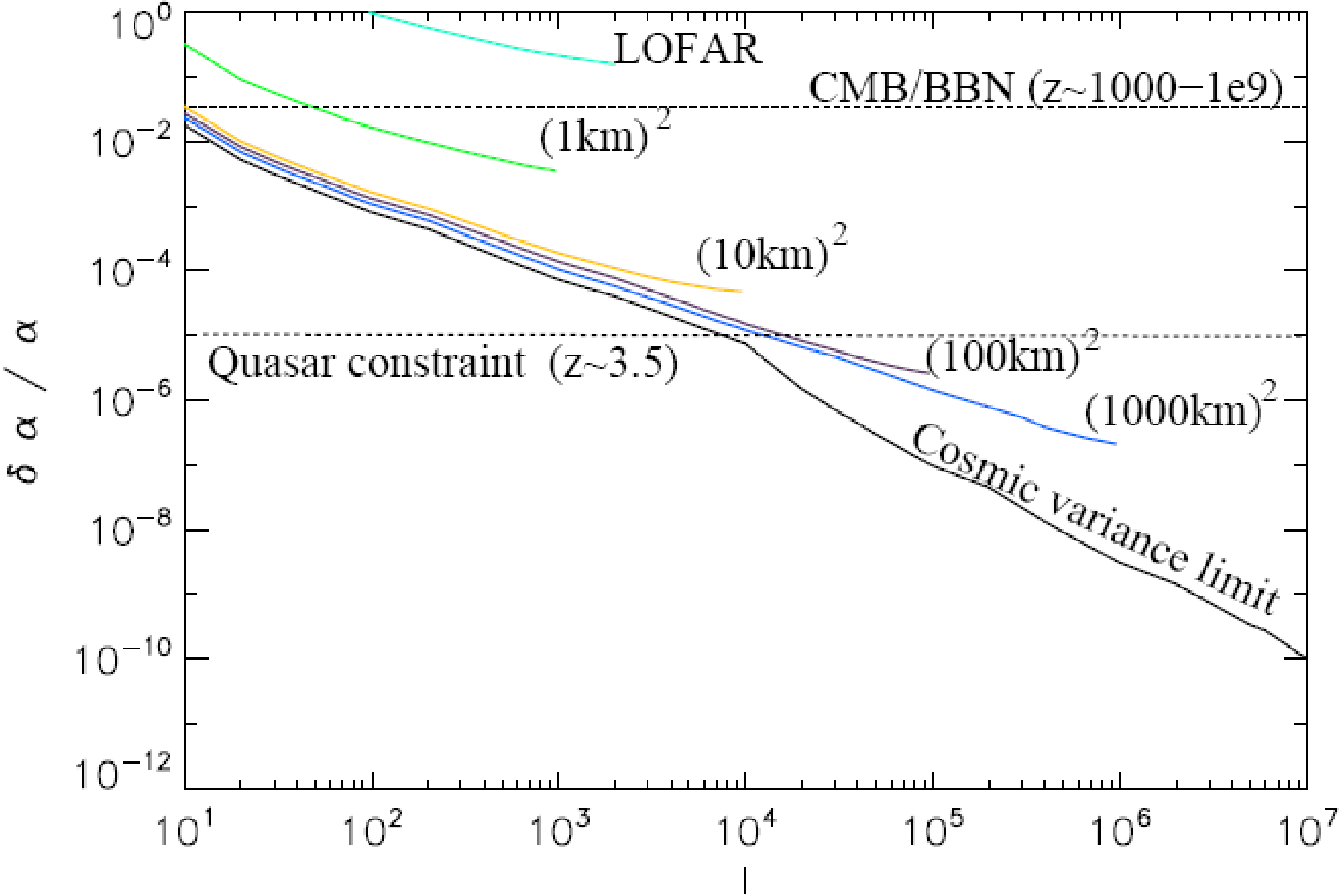
# 21cm observations from the Moon – tests of string theory?



Cooray 2007

Khatri and Wandelt 2007, 2008

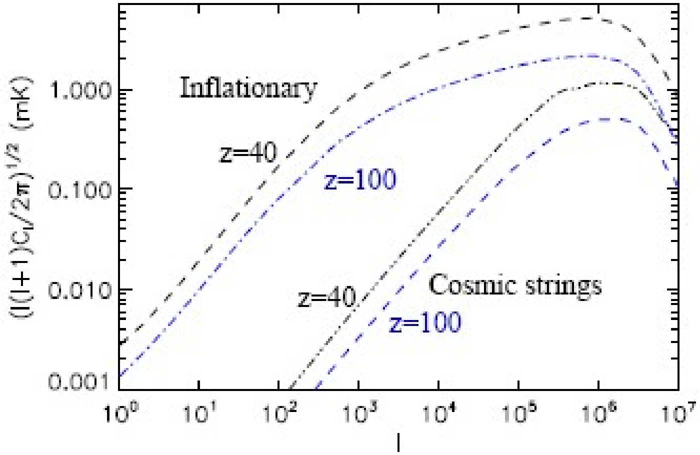
# dalpha/alpha from 21cm



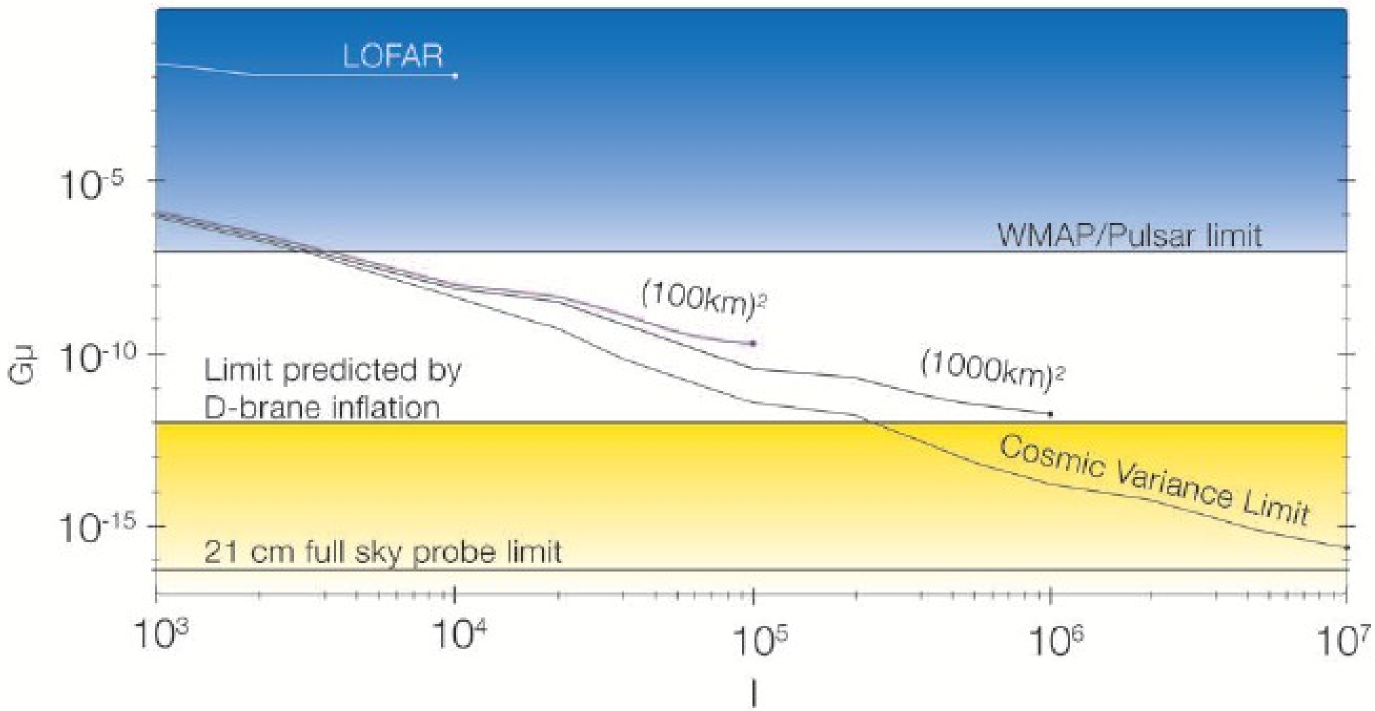
Cosmic string induced perturbations from CMBACT *Pogosian and Vachaspati 1999*

$\mu \sim M_s^2, M_{GUT}^2$

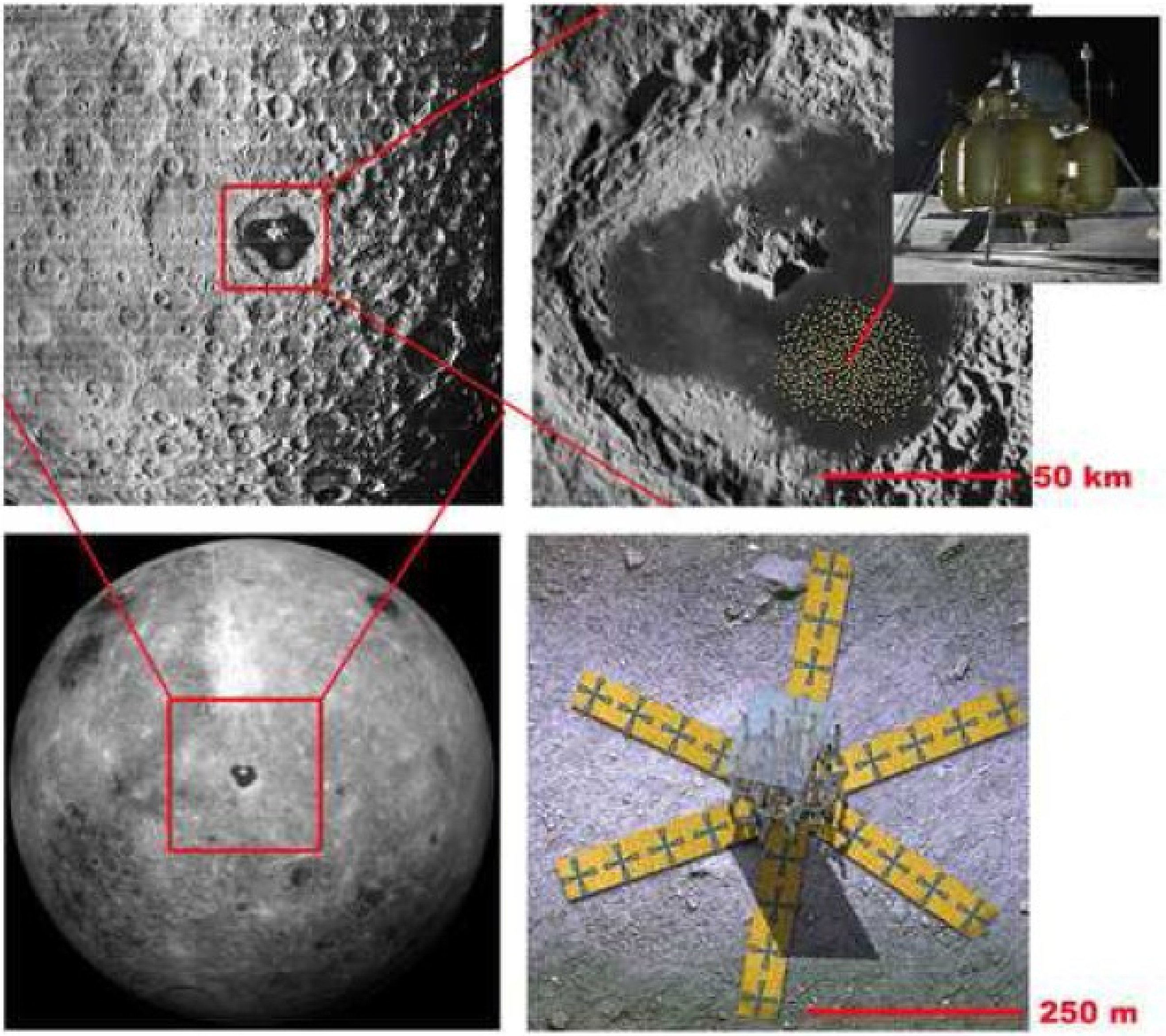
$G\mu = 10^{-12} \Rightarrow M_s, M_{GUT} \sim 10^{13}\mathrm{GeV}.$




*Khatri & Wandelt 2008*

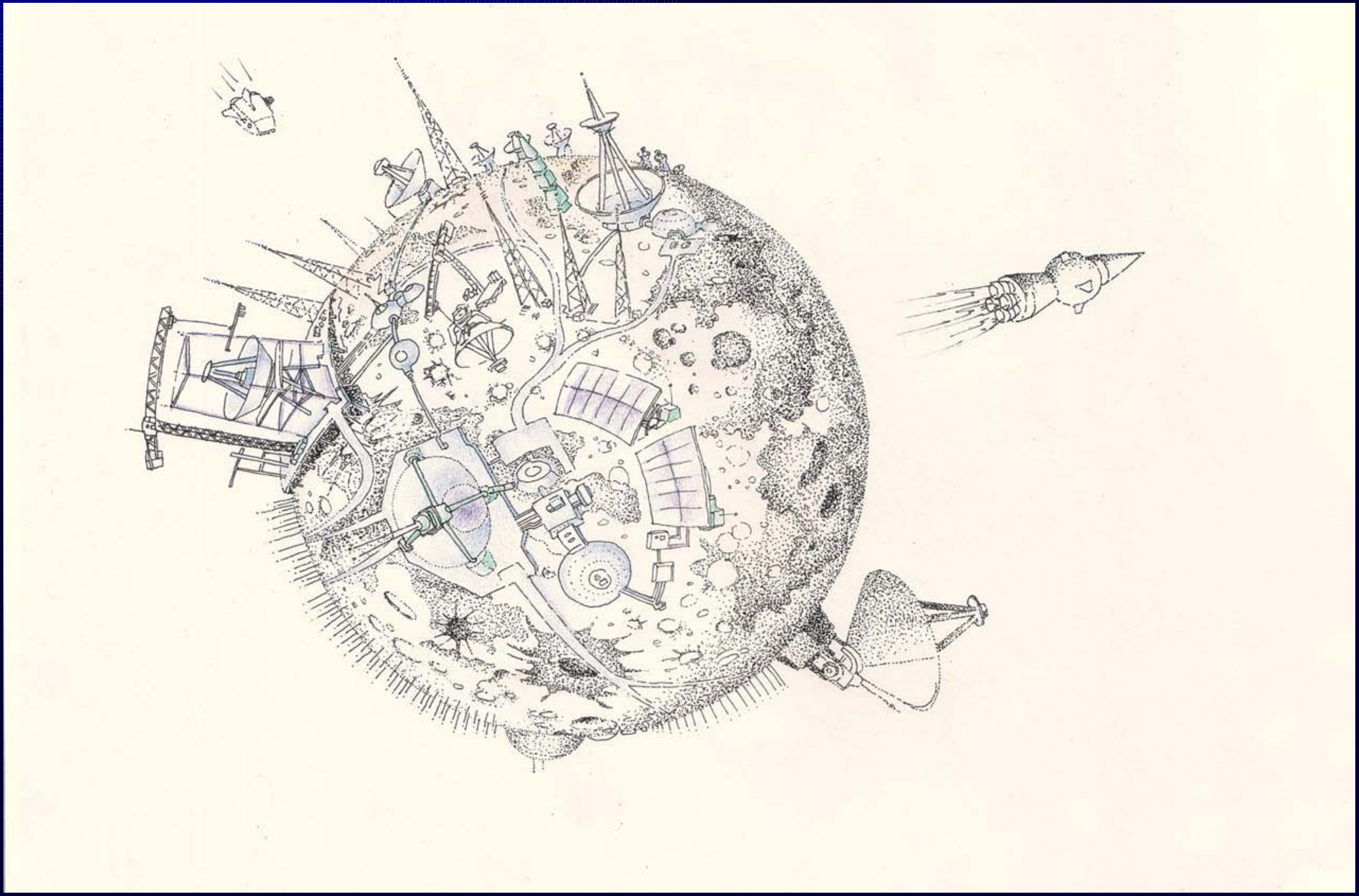


# Dark Ages Lunar Interferometer




Source: Naval Research Lab

# A scientific future for the Moon?



# Conclusions

- The non-Gaussian revolution is here
- Non-Gaussian sources of information probe the cosmic beginning and cosmic fate
- Many opportunities for cross-checks between different primordial NG channels: E and T, large scale structure power spectrum, void morphology
- Exciting time ahead for cosmological probes of fundamental physics
- Planck is the Next Big Thing in CMB non-Gaussianity

cosmologyathome.org

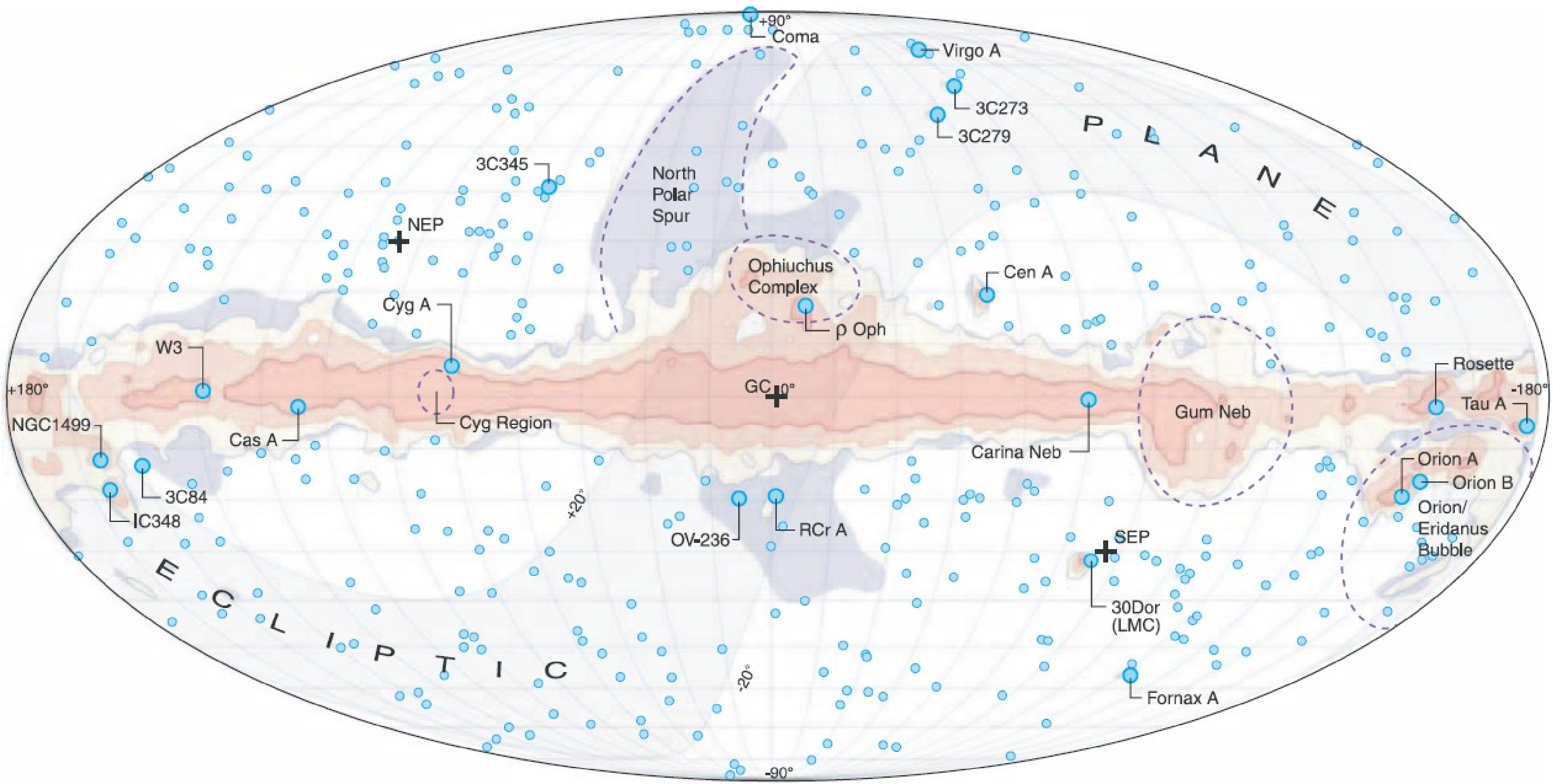

Fendt and Wandelt 2007, 2008; http://cosmos.astro.uiuc.edu/pico

# Credits

- Many thanks to my current graduate students
  - Esfandiar Alizadeh
  - Charmaine Armitage
  - Rahul Biswas
  - Chad Fendt
  - Rishi Khatri
  - Amit Yadav
  - Franz Elsner (external: MPA)
- Senior Thesis student: Scott Kruger
- Former group members (cosmos.astro.uiuc.edu)
- Artwork: Nikita Sorokin

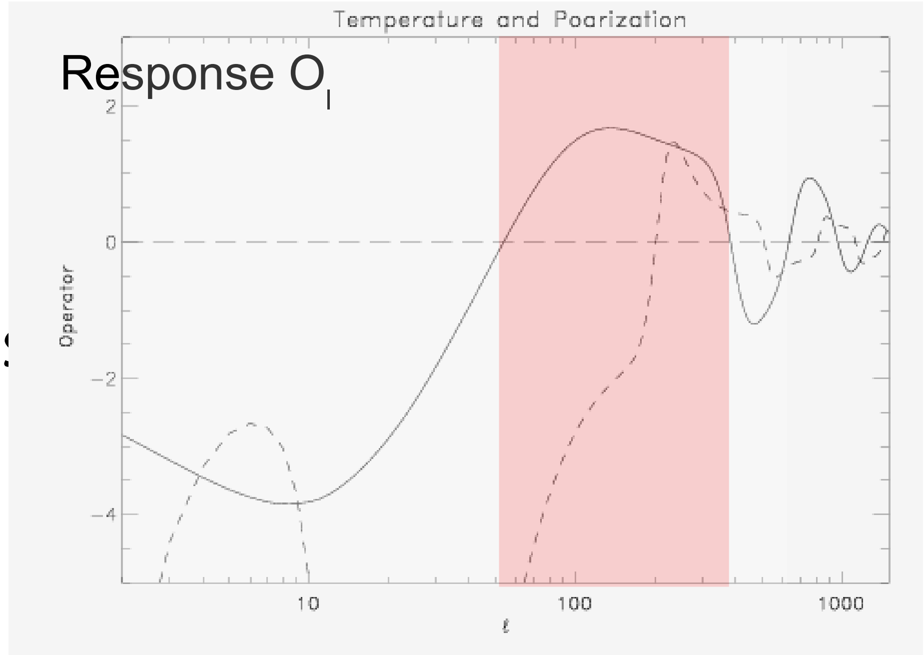
# The Appendices

Supplementary slides


+90°
Coma
Virgo A
3C273
3C279
P L A N E
3C345
North Polar Spur
NEP
Ophiuchus Complex
Cen A
Cyg A
ρ Oph
W3
Rosette
+180°
GC 0°
-180°
Tau A
Gum Neb
NGC1499
Cyg Region
Cas A
Carina Neb
Orion A
Orion B
3C84
Orion/ Eridanus Bubble
IC348
+20°
OV-236
RCr A
SEP
E C L I P T I C
30Dor (LMC)
-20°
Fornax A
-90°

# Foregrounds?

- Remember – large scale skewness in the Temperature map corresponds to *negative* $f_{NL}$ .
- The added l modes at 400<l<550 correspond to modes where positive skewness also gives *negative* contributions.




- At intermediate scales positive skewness gives *positive* $f_{NL}$.

# Filter functions

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

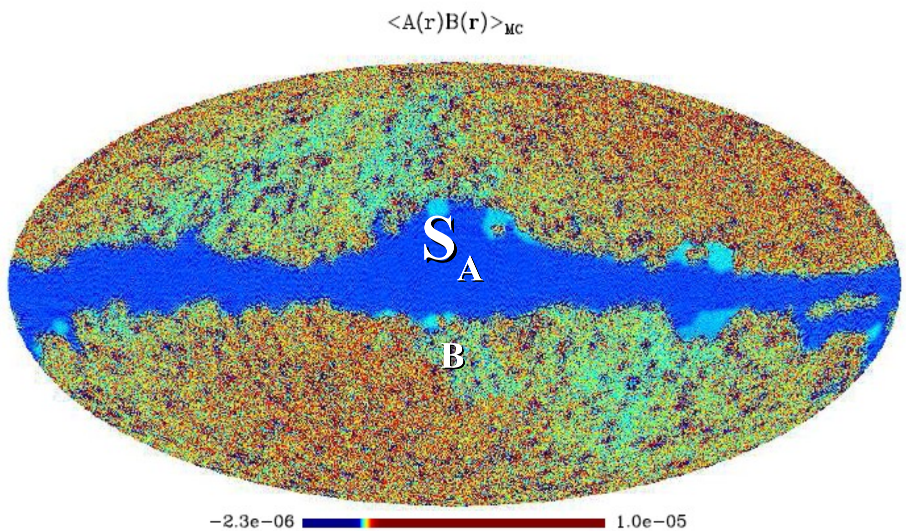
$$\alpha_\ell^i(r) = \frac{2b_\ell^i}{\pi} \int k^2 dk g_\ell^i(k)\, j_\ell(kr),$$

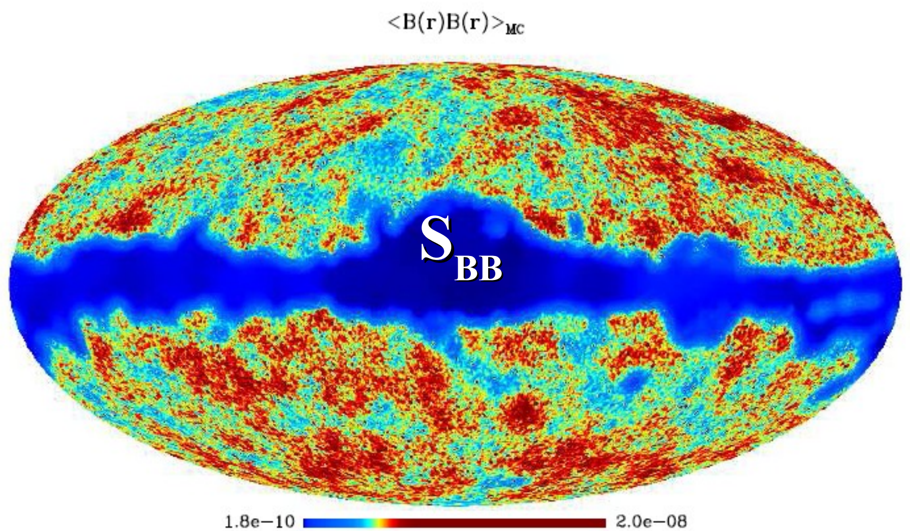
# Anisotropic noise

- Linear weight maps make linear term maximally anticorrelated with the cubic term to reduce its variance due to anisotropic noise

$$S_{AB}(\hat{n},r) \equiv \sum_{ipqr} \sum_{\ell_1 m_1 \ell_2 m_2} \beta^i_{\ell_1}(r)(C^{-1})^{ip})_{\ell_1} Y_{\ell_1 m_1}(\hat{n}) \alpha^j_{\ell_2}(r)(C^{-1})^{jq}_{\ell_2} Y_{\ell_2 m_2}(\hat{n}) \langle a^p_{\ell_1 m_1} a^q_{\ell_2 m_2} \rangle$$

$$S_{BB}(\hat{n},r) \equiv \sum_{ipqr} \sum_{\ell_1 m_1 \ell_2 m_2} \beta^i_{\ell_1}(r)(C^{-1})^{ip})_{\ell_1} Y_{\ell_1 m_1}(\hat{n}) \beta^j_{\ell_2}(r)(C^{-1})^{jq}_{\ell_2} Y_{\ell_2 m_2}(\hat{n}) \langle a^p_{\ell_1 m_1} a^q_{\ell_2 m_2} \rangle$$



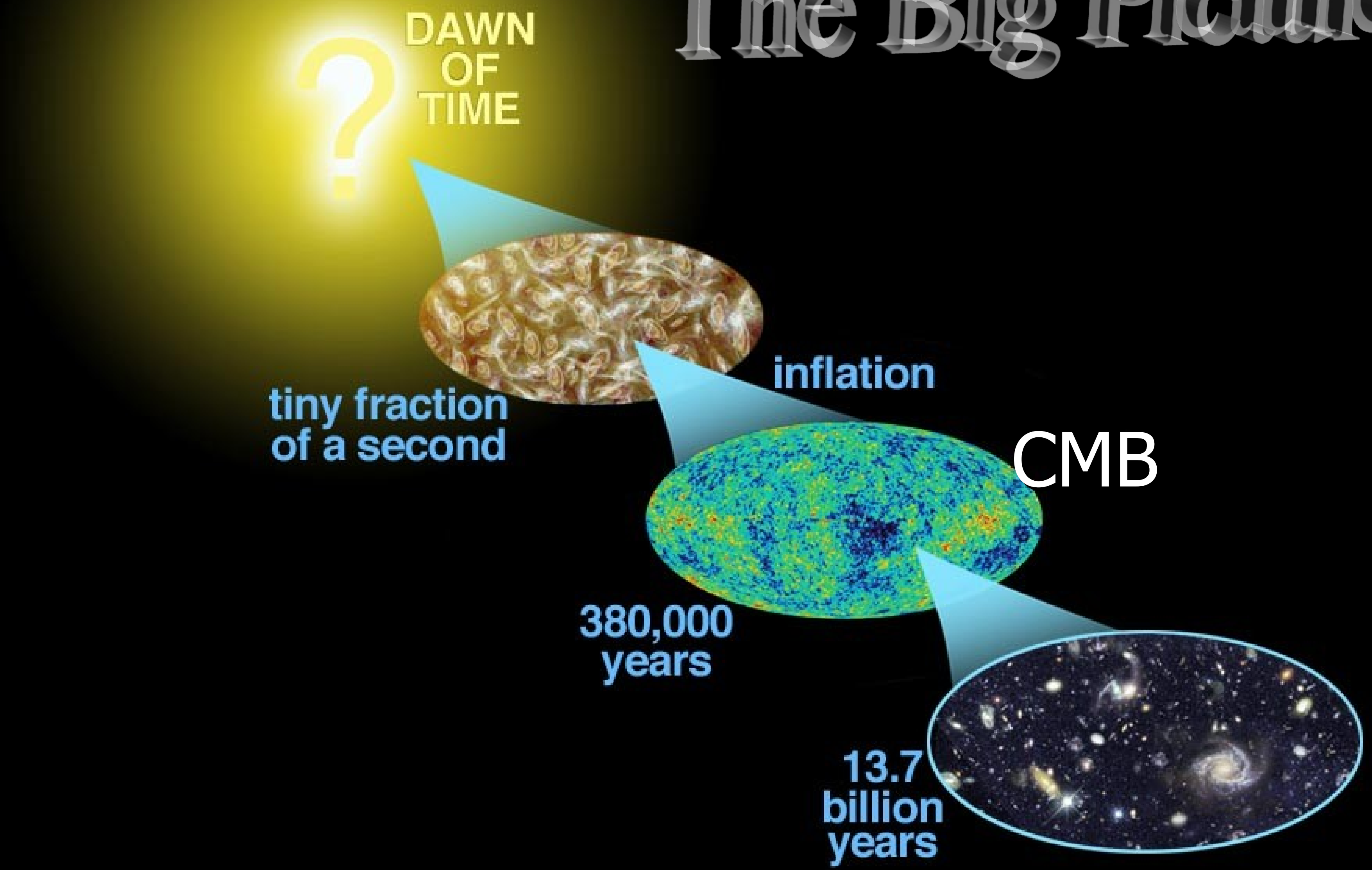
## Q+V+W Channels

| $\ell_{\max}$ | $f_{NL}$ | | | |
|---|---|---|---|---|
| | $f_{sky} = 94.2\%$ Kp12 | $f_{sky} = 84.7\%$ Kp2 | $f_{sky} = 76.8\%$ Kp0 | $f_{sky} = 64.3\%$ **giant mask** |
| 350 | -2383.67 | -75.16 | 24.91 | 8.32 |
| 450 | -2791.83 | -79.79 | 55.36 | 65.31 |
| 550 | -3135.82 | -93.49 | 65.57 | 79.93 |
| 650 | -3307.15 | -93.7 | 62.91 | 77.02 |
| 750 | -3368.26 | -108.23 | 64.75 | 78.35 |

## V+W channels

| $\ell_{\max}$ | $f_{NL}$ | | | |
|---|---|---|---|---|
| | $f_{sky} = 94.2\%$ Kp12 | $f_{sky} = 84.7\%$ Kp2 | $f_{sky} = 76.8\%$ Kp0 | $f_{sky} = 64.3\%$ **giant mask** |
| 350 | -3145.22 | -26.68 | 34.62 | 19.24 |
| 450 | -1425.06 | -15.63 | 67.94 | 64.69 |
| 550 | -1509.92 | -13.09 | 79.99 | 83.53 |
| 650 | -1559.91 | -22.43 | 79.18 | 81.29 |
| 750 | -1575.11 | -22.81 | 86.81 | 86.52 |

# The Big Picture




Credit: WMAP

# Testing the Inflationary Paradigm

- Probes of inflation:
  - Inflation generates primordial fluctuations in space-time
    - Fluctuations in radiation
      - Cosmic Microwave Background Temperature anisotropies
      - CMB E-polarization anisotropies
    - Fluctuations in matter
      - Dark matter distribution (Gravitational lensing etc.)
      - Galaxy and gas distribution (Redshift surveys, Lyman-alpha clouds, cosmological 21-cm radiation, etc)
    - Fluctuations in space time itself
      - Primordial Gravitational Waves (eg. Primordial B-modes of CMB)

# Instrument systematics?
# I) Beam asymmetries

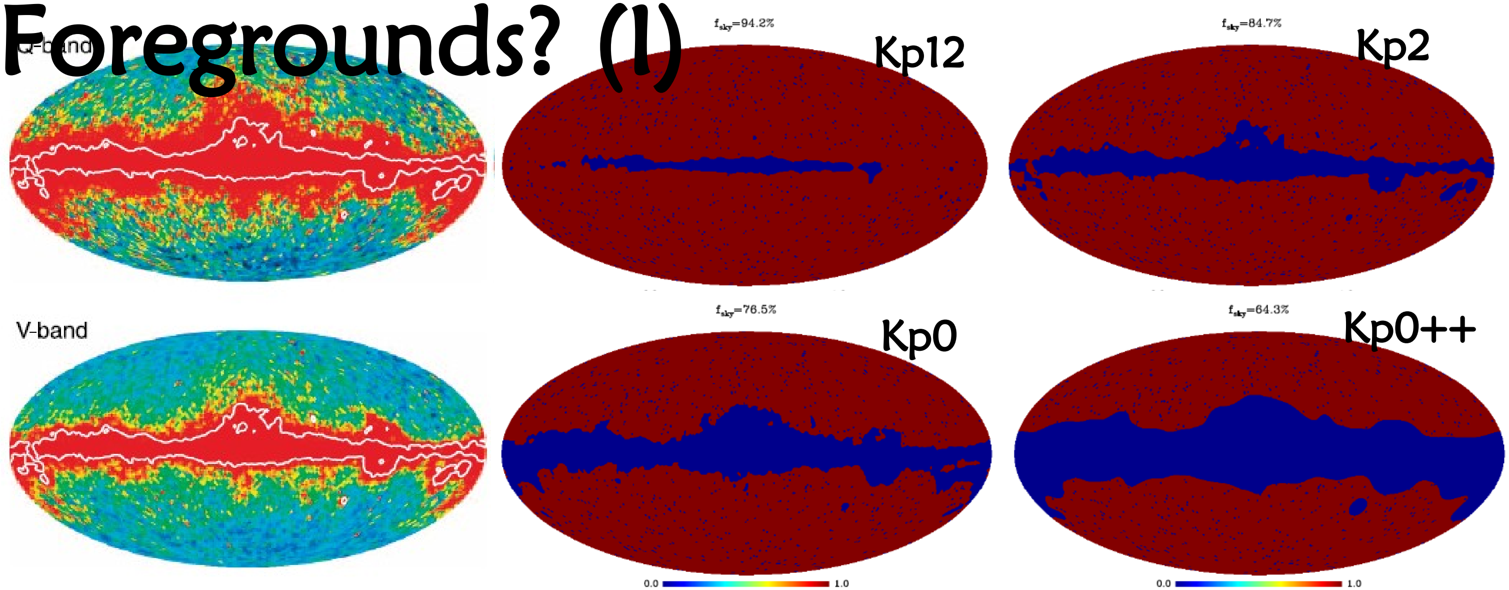
- If the CMB is Gaussian, no asymmetry of the main beam can produce non-vanishing bispectrum.

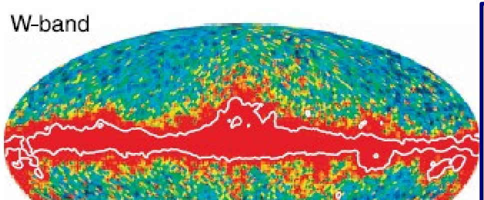
- If there are large side-lobes that spread foreground around the sky they will produce large scale features – unlikely to affect the high l regime. Further, we do not see evidence for frequency dependence.

# Instrument systematics? II: WMAP Noise

- Noise correlations (striping)
  - As long as noise is Gaussian, **no** noise correlations will produce a bispectrum.
- Non-Gaussian noise?
  Analyzed differences of WMAP yearly maps
  - year1-year2 $f_{NL}$=1.1 (+/- ~60 at 95% C.L.)
  - year2-year3 fNL=1.8
  - year1-year3 fNL=-3.4
- **So to explain our results an instrumental systematic has to be 1) non-Gaussian, 2) the same in individual years and 3) mimic the specific bispectrum signature of $f_{NL}$.**

# Foregrounds? (I)



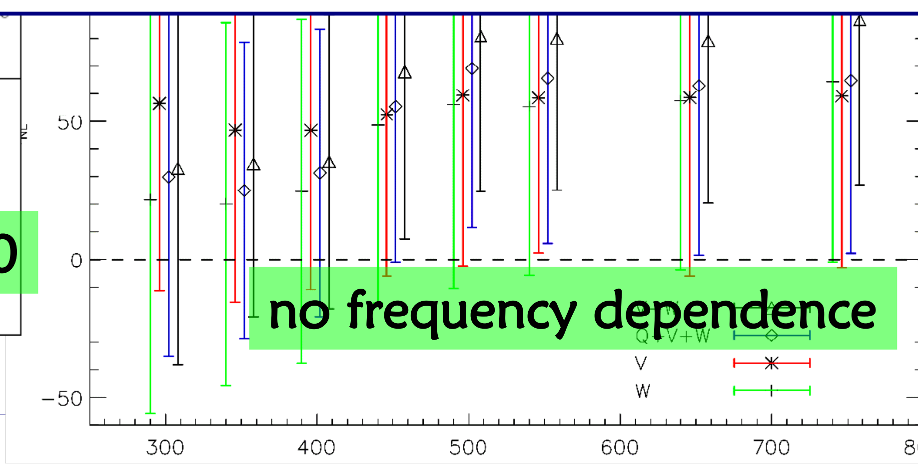




We test the impact of foregrounds as a function of frequency and as a function of mask. V and W channels are the least foreground contaminated. Choice of V+W is driven by foreground considerations. Analysis on *raw* maps to avoid FG oversubtraction.

| $\ell_{max}$ | f… | | | |
|---|---|---|---|---|
| | $f_{sky} = 94.2\%$ Kp12 | $f_{sky} = 84.7\%$ Kp2 | Kp0 | |
| 350 | -3145.22 | -26.68 | 34.62 | 19.24 |
| 450 | -1425.06 | -15.63 | 67.94 | 64.69 |
| 550 | -1509.92 | -13.09 | 79.99 | 83.53 |
| 650 | -1559.91 | -22.43 | [illegible] | [illegible] |
| 750 | -1575.11 | -22.81 | 86.81 | 86.52 |

stable beyond kp0

Benjamin




no frequency dependence

# Foregrounds? (II)

- WMAP raw maps vs WMAP cleaned maps
  - Foreground subtracted maps do not show negative $f_{NL}$ behavior
  - Same level of $f_{NL}$, uniformly higher for FG subtracted maps
  - We quote the result from raw maps to be conservative and because the cleaned maps could contain *oversubtracted* foregrounds giving a positive bias.

# Foregrounds (III)

- Simulations ofGaussian CMB + Foregrounds + WMAP Noise
  - negative for smaller masks
  - goes to zero by the time you reach Kp0 mask
  - is consistent with zero for masks greater than kp0

| $\ell_{\max}$ | VW | | | | Q | QVW | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Kp12 | Kp2 | Kp0 | Kp0+ | Kp0 | Kp12 | Kp2 | Kp0 | Kp0+ |
| 350 | -1290 | -27 | 35 | 19 | 1 | -2384 | -75 | 25 | 8 |
| 450 | -1425 | -16 | 68 | 65 | -6 | -2792 | -80 | 55 | 65 |
| 550 | -1510 | -13 | 80 | 84 | -11 | -3136 | -94 | 66 | 80 |
| 650 | -1560 | -22 | 79 | 81 | -14 | -3307 | -94 | 63 | 77 |
| 750 | -1575 | -23 | 87 | 87 | -20 | -3368 | -108 | 65 | 78 |
| 750* | $-1105\pm^{19}_{19}$ | $-42\pm^{5}_{5}$ | $-6\pm^{4}_{4}$ | $-0.3\pm^{4}_{4}$ | | | | $-13\pm^{5}_{5}$ | $1\pm^{6}_{6}$ |

# Secondary Anisotropies?

- Point sources, including SZ
  - Orthogonal overlap with primordial bispectrum. Bias of $|f_{NL}|<1|$. SZ and point sources have opposite signs.
- Serra and Cooray (arxiv:0801.3276)
  - dominant secondary confusion level to WMAP bispectrum arises from
    - ISW-lensing bispectrum (positive bias)
    - SZ-lensing bispectrum (negative bias)
  - **If $f_{NL}$=20** effective bias around 10%. **Negligible** for $f_{NL}$>20, because effects add in quadrature.

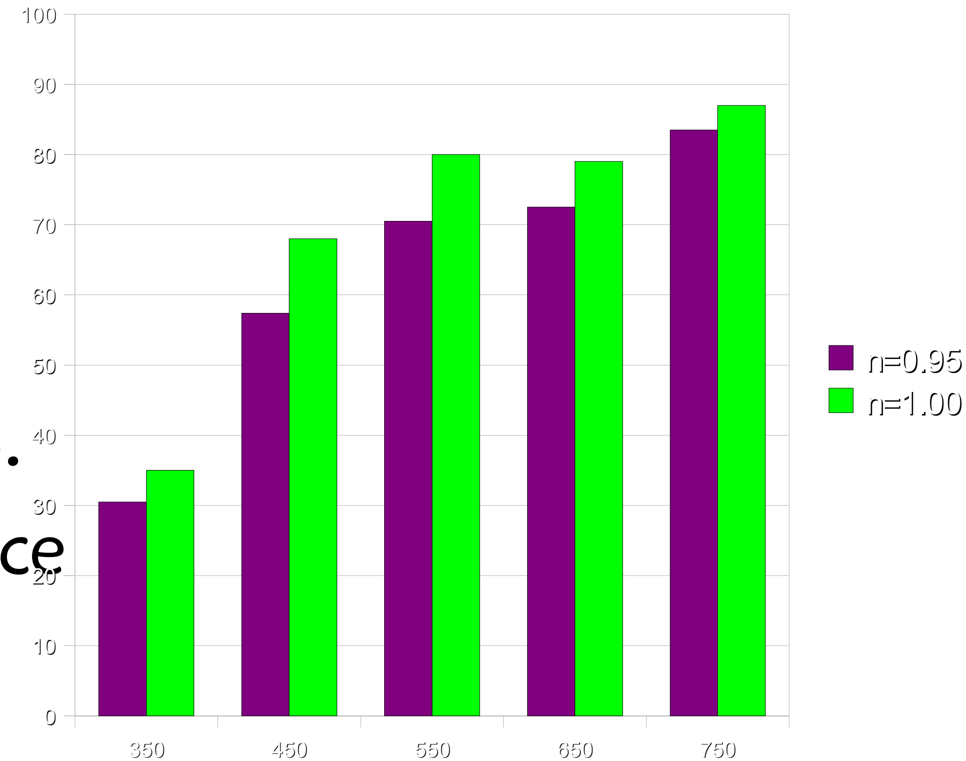
# Re-discovery of another non-Gaussian signal?

- Larson/Wandelt (hot and cold spots not hot or cold enough):
  - at smaller angular scales X
  - symmetric-> no odd correlation. Probably noise model.
- The Cold Spot (Vielva et al. 2004) is localized in the map and covers a particular range in scale. X
  Preliminary result: **$f_{NL}$=94 +/-60 (95% C.L.)**
- Large Scale anomaly? Can check by removing large scale signal. Preliminary result: X
  **Removing l<21, $f_{NL}$=135 +/-96 (95% C.L.)**


Benjamin D. Wandelt

# Sensitivity to assumed cosmology

- The filters depend weakly on assumed cosmology. We used n=1.
- Choosing n=0.95 reduces the error bars by 10%, and reduces the central values between 5% and 15%.
- At $l_{max}$=750, significance *increases* to just over 3 sigma; at lower $l_{max}$ significance *decreases slightly.*



# Noise fluctuation?

- Possible.
- It's a 2.5-3 sigma result. $P \leq 0.01$

2.5 sigma for conservative increase of error bar for possible systematics

The most aggressive interpretation of the data would be a 3.3 sigma effect (correcting for negative foreground bias and using best fit WMAP parameters)

# Summary and Conclusions

- $\Delta f_{NL} \sim 30$ for all of WMAP 3 using YKWLHM07 and WMAP best fit parameters (statistical)
- First bispectrum-based analysis of the full WMAP3 data
- First significant departure of $f_{NL}$ from 0 at >99% C.L.
- Estimators tested against Gaussian and non-Gaussian simulations with and without inhomogeneous noise
- If any bias, it is likely to be negative. Guess of systematic error bar: -0/+5
- 2.5-2.8 sigma, depending on choices and assumptions

# Conclusion

We wrote:

"If our result holds up to scrutiny and the statistical weight of future data [...] we conclude that single field slow roll inflation is disfavored by the WMAP data."

# WMAP 5-year analysis

- Komatsu et al. 2008
- Somewhat more conservative analysis:
  - mask shape that enhances the statistical error compared to the 3-yr mask;
  - stop at $l_{max}$=500
  - subtract very generous estimate of point source bias.
- Quoted result: $f_{NL}^{local}$ = 51+/- 60 (95%)
- Significance: 1.7 sigma
- 2.3 sigma for analysis closer to ours
- Differences understood => Consistent with our analysis

# WMAP 5 year constraint on $f^{equil}$

$$-151 < f_{NL}^{equil} < 253$$

- Of interest for DBI inflation, ghost condensation

# WMAP 5 year continued…

- A ***very preliminary*** result by Kendrick Smith et al., obtained at the Perimeter Workshop **4** days ago:

$$f_{NL}^{local} = 21 +/- 44\ (95\%)$$

- Note that this uses the exact same data as the WMAP 5, so the difference is entirely due to different weighting in the estimator.
  - Smaller error bar due to optimal weighting
  - This remains to be checked and the differences remain to be understood.