Title: Primordial Non-Gaussianity: A New Frontier

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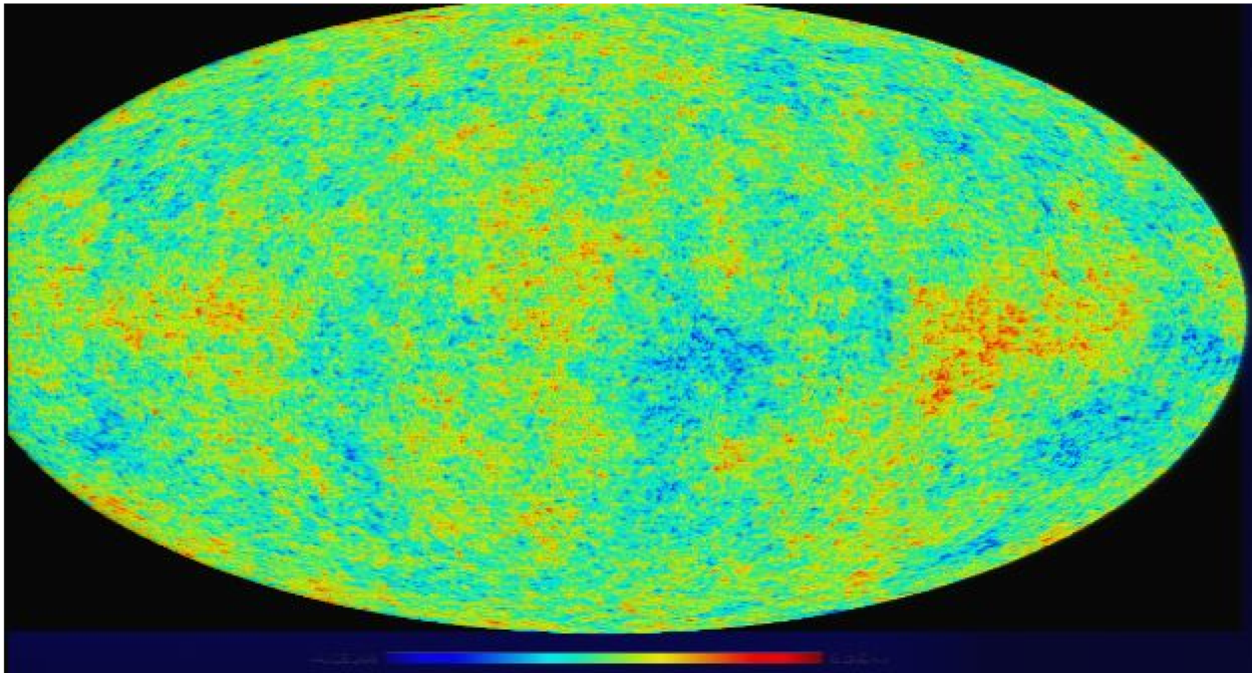
Abstract:



Primordial non-Gaussianity - a new frontier

Benjamin D. Wandelt
Amit P. Yadav

UIUC Physics/Astronomy

Physics Illinois

ASTRONOMY

Why are we interested in cosmology?

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The big questions are:

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

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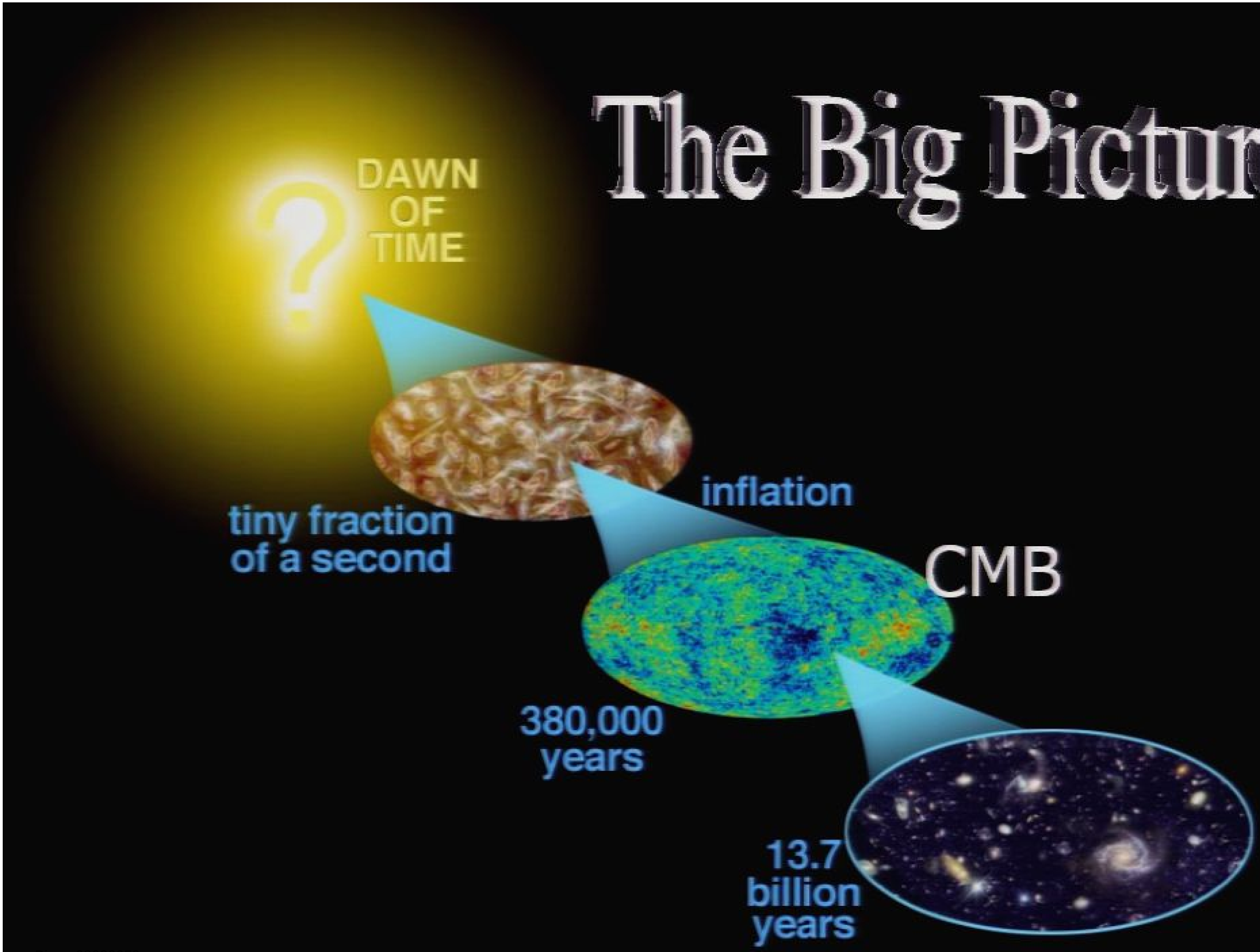
The Big Picture

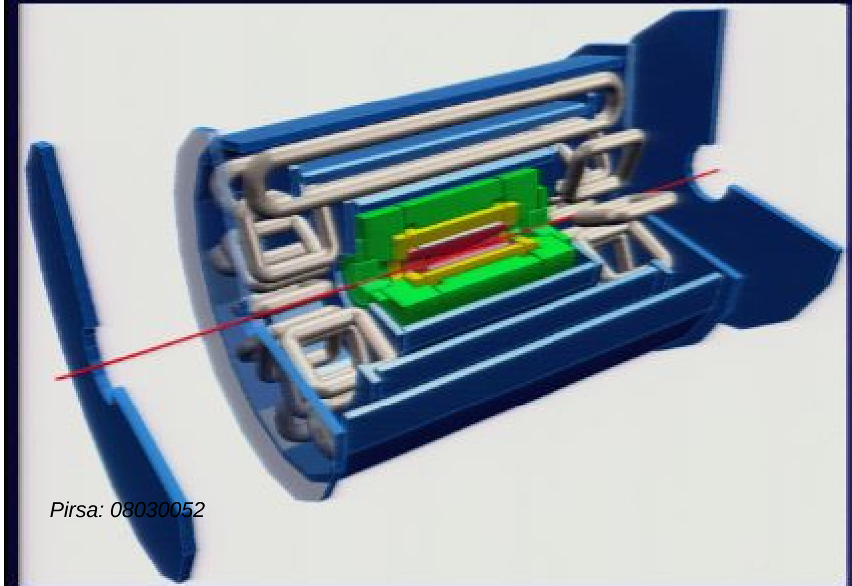


How do we study what happens at the highest energy scales and at the shortest time scales?

Showdown

WMAP, Planck

Showdown



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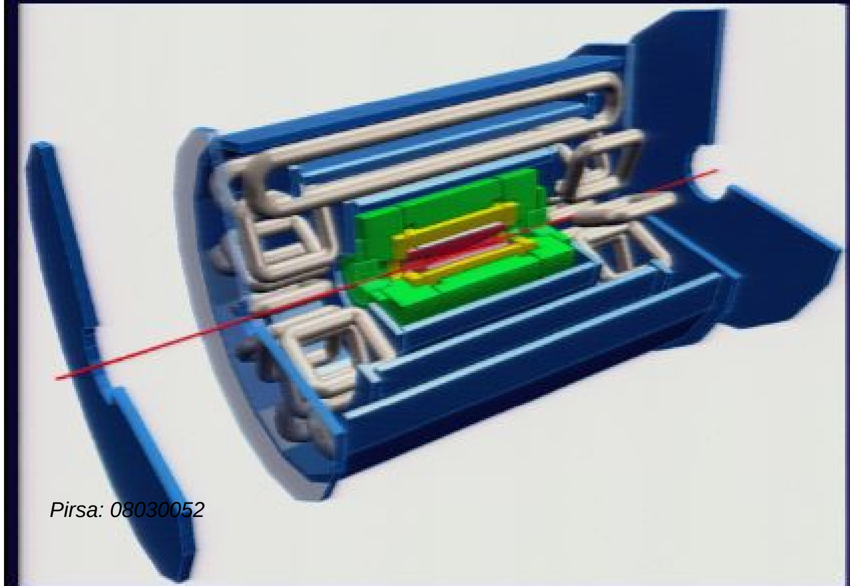
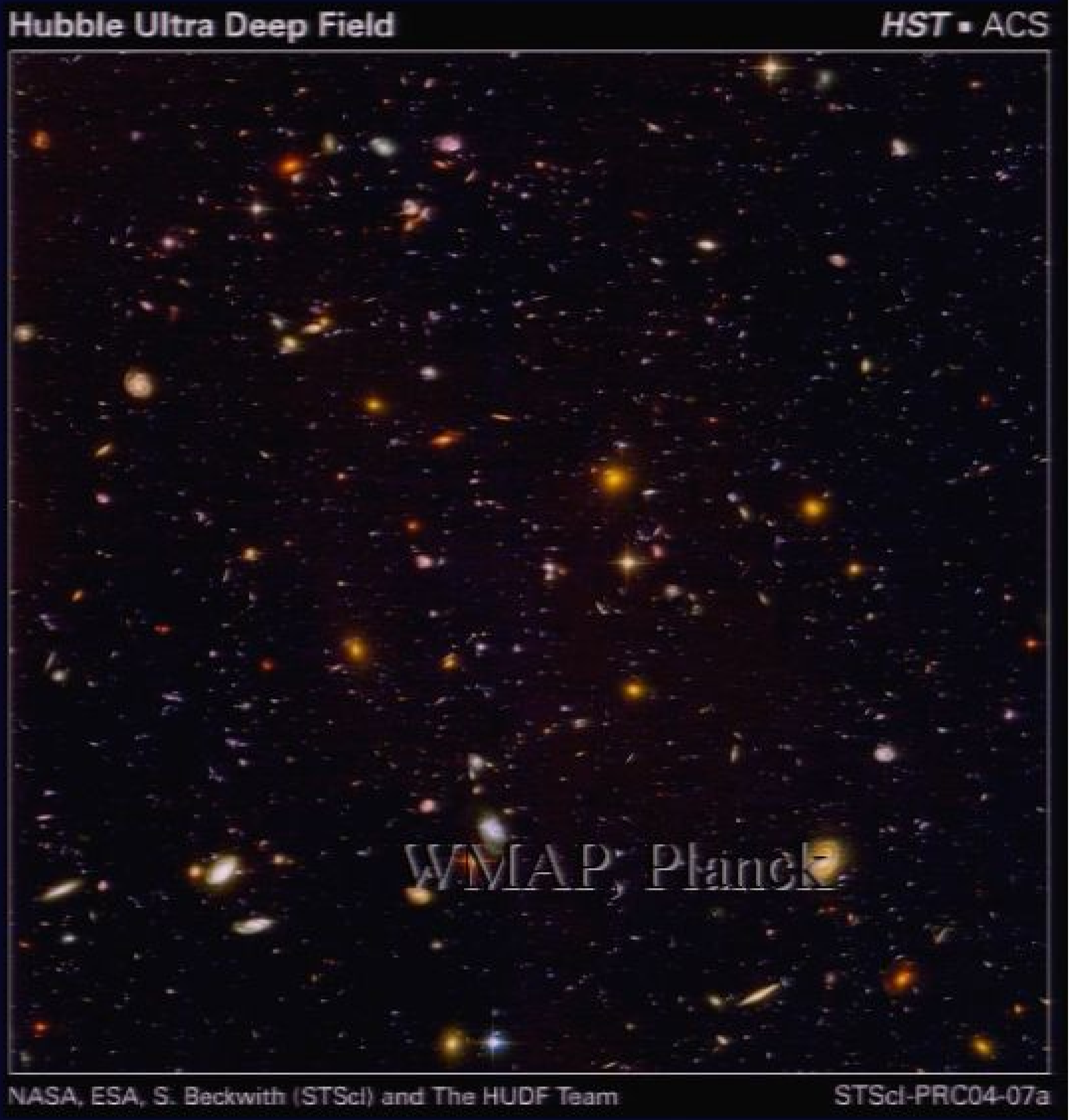
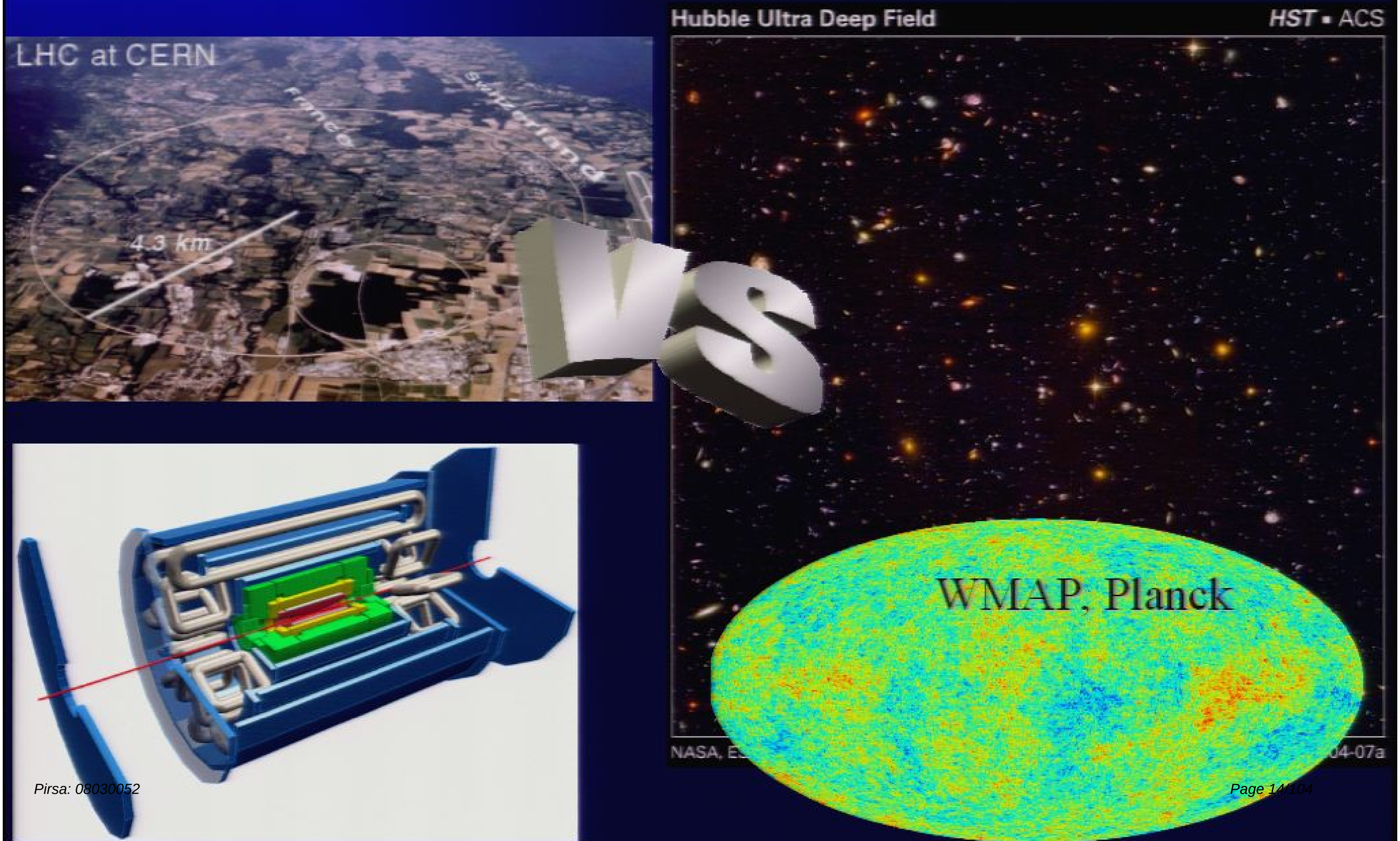


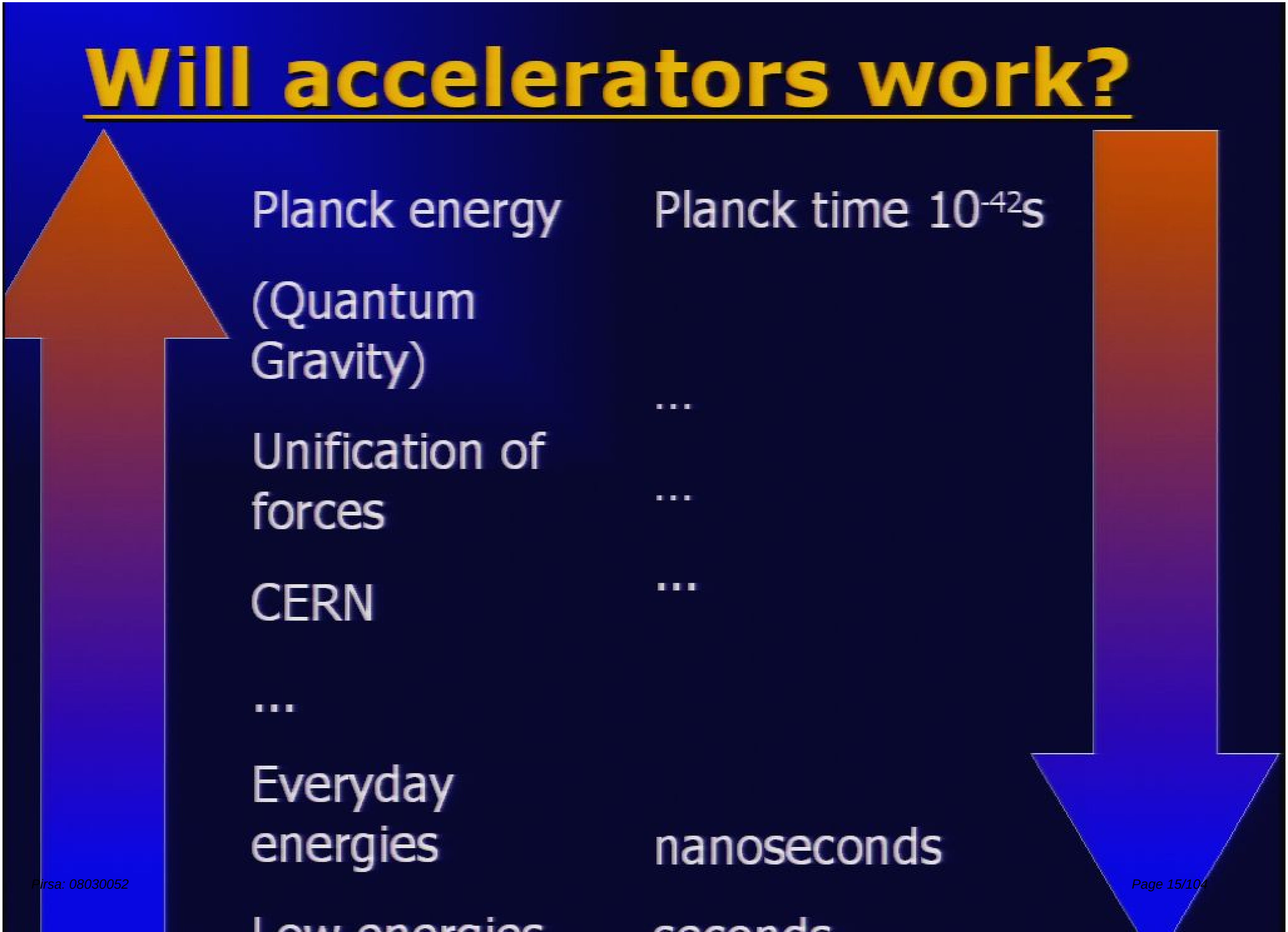


WMAP, Planck

NASA, ESA, S. Beckwith (STScI) and The HUDF Team STScI-PRC04-07a

Showdown


LHC at CERN
France
Switzerland
4.3 km
VS
Hubble Ultra Deep Field
HST • ACS
NASA, E
04-07a
WMAP, Planck



Will accelerators work?

Planck energy	Planck time 10^{-42}s
(Quantum Gravity)	…
Unification of forces	…
CERN	…
…	
Everyday energies	nanoseconds
Low energies	seconds

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Hard technological limit:

CERN	...
...	
Everyday energies	nanoseconds
Low energies	seconds

Back to the Big Picture

(Big Bang ++)

Structure formatio

- Some process, e.g. inflation, seeds **curvature perturbations** in a huge, smooth Universe at.
- Due to gravity these density fluctuations start to grow. Eventually, overdensities become so large that they collapse to form galaxies and clusters

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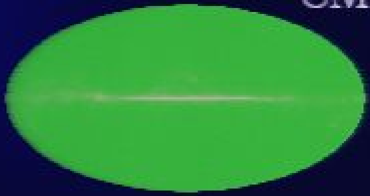
Data

1978 Nobel Prize in Physics

- Homogeneity and Isotropy

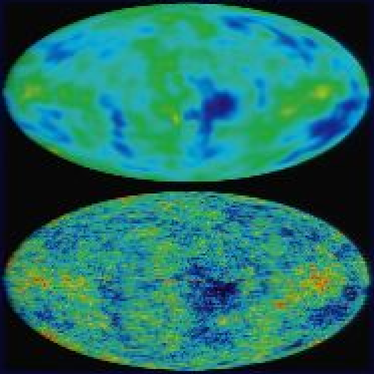
CMB



Robert Wilson and Arno Penzias

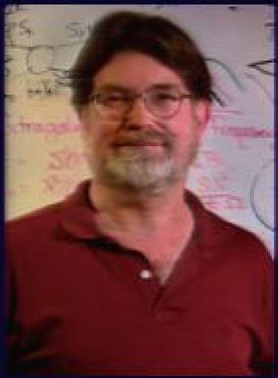
- Flatness
- Seed perturbations

COBE



WMAP

2006 Nobel Prize in Physics



George Smoot

John C. Mather

Testing Inflationary Paradigm

- Probes of inflation:
  - Inflation generates primordial fluctuations in space-time
    - Fluctuations in radiation
      - CMB T
      - CMB E-polarization
    - 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)

Testing Inflationary Paradigm

- 0^{th} Order Tests:
  - Is observable universe flat ?
  - Are fluctuations nearly Gaussian ?
  - Are fluctuation nearly scale independent ?
  - Are fluctuation adiabatic ?

Testing Inflationary Paradigm

(i) Flat, homogeneous and isotropic ✓

Eg: WMAP 08
+HST

(ii) Seed perturbations: *canonical models predict*

- Nearly adiabatic: $\frac{\delta\rho_i}{\dot{\rho}_i}=\frac{\delta\rho}{\dot{\rho}}$

- Close to Gaussian $\langle\Phi(\vec{k})\Phi(\vec{k}')\rangle=P_\Phi(k)\delta^3(\vec{k}-\vec{k}')$?

-Nearly Scale Invariant $k^3 P_\Phi(k)=A k^{n_s-1}$ ✓

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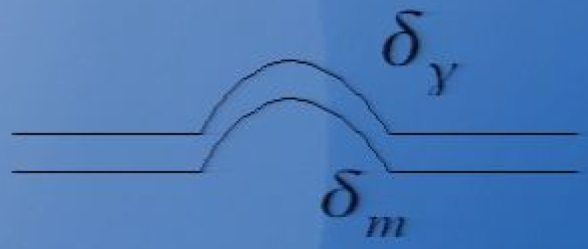

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-Nearly Scale Invariant

$$k^3P_\Phi(k)=A\,k^{n_s-1}$$ ✓

Eg: WMAP 08

Do we expect primordial perturbations to be absolutely positively Gaussian ?

- NO!
- Different inflationary models predict different amounts of NG so detection of NG helps distinguishing them.
- Even the 2nd order GR perturbations produce some NG ($f_{NL} \sim 1$)

Amplitude of non-Gaussianity. fNL=0 for Gaussian perturbations and the larger the value the larger the non-Gaussianity

Are primordial perturbations really Gaussian ?

Non-Gaussianity from the Early Universe

$f_{NL} \sim 0.05$ canonical inflation (single field, couple of derivatives) (Maldacena 2003, Acquaviva etal 2003)

$f_{NL} \sim 0.1\text{--}100$ higher order derivatives

DBI inflation (Alishahiha et. al 2004)

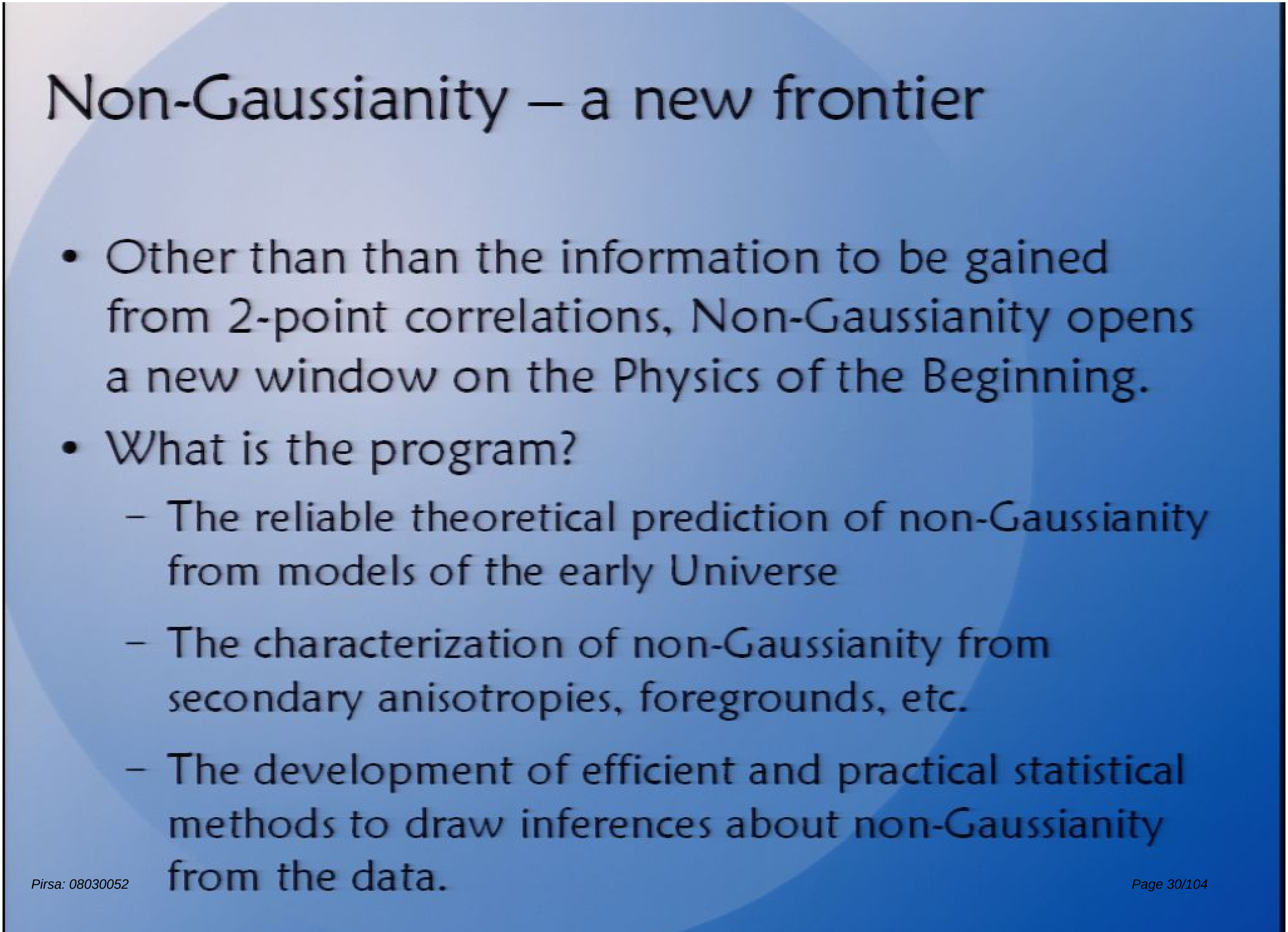
UV cutoff (Creminelli 2003)

$f_{NL} > 10$ curvaton models (Lyth et. al 2003)

$f_{NL} \sim 100$ ghost inflation (Arkani-Hamed et al., 2004)

$f_{NL} \sim 20\text{-}100$ New Ekpyrotic models (Creminelli and Senatore 2007, Buchbinder et. al 2007, Koyama et. al 2007)

$f_{NL} \sim -50\text{-}200$ Ekpyrotic models (Lehners and Steinhardt 2008)



Non-Gaussianity – a new frontier

- Other than than the information to be gained from 2-point correlations, Non-Gaussianity opens a new window on the Physics of the Beginning.
- What is the program?
  - The reliable theoretical prediction of non-Gaussianity from models of the early Universe
  - The characterization of non-Gaussianity from secondary anisotropies, foregrounds, etc.
  - The development of efficient and practical statistical methods to draw inferences about non-Gaussianity from the data.

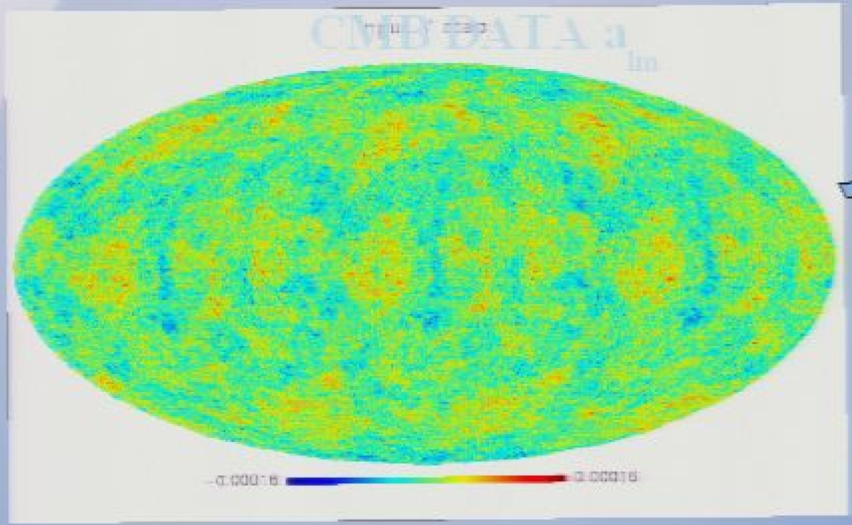
Our push at the frontier

- How to search for primordial non-Gaussianity
- How to search for f_{NL}
- What we find
- How to interpret our result
- Lessons for Planck
- Future prospects

How to search for (weak) primordial non-

- Reconstruct curvature perturbation from data
- Test for non-Gaussian features
- Compute error bars using Gaussian Monte Carlo realizations of the data

Reconstructed Primordial Perturbations

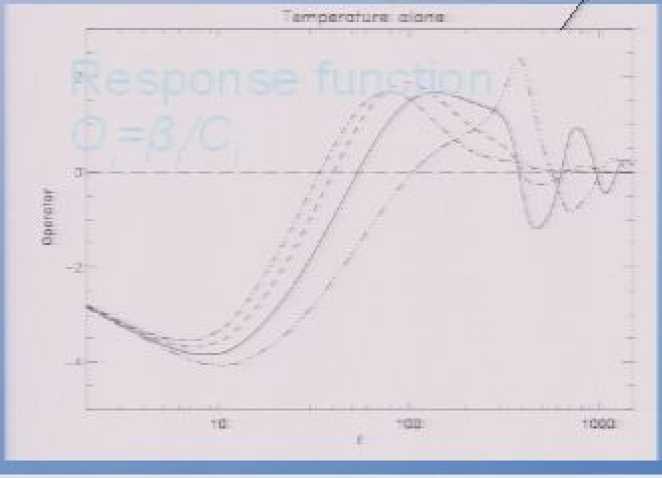


CMB DATA a_{lm}

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

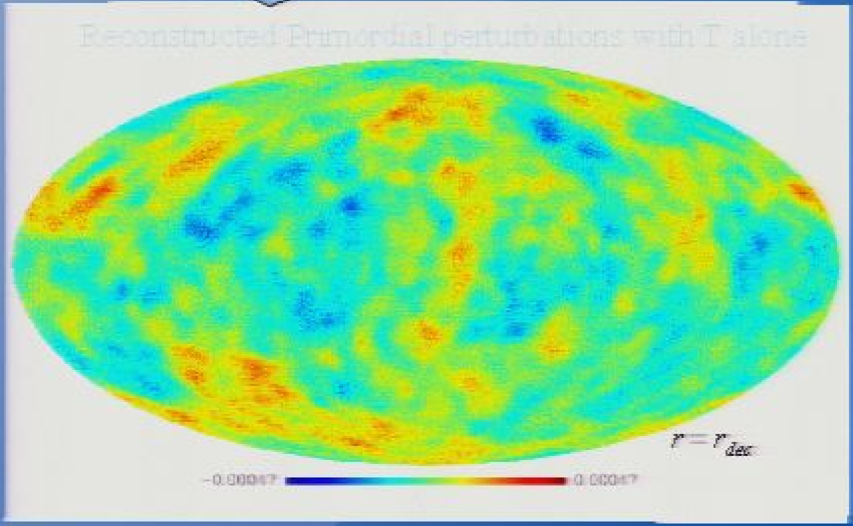
SW limit

$$\frac{\delta\phi}{\phi} = \frac{-1}{3}\frac{\delta T}{T}$$



Response function

$O_l = \beta_l / C_l$

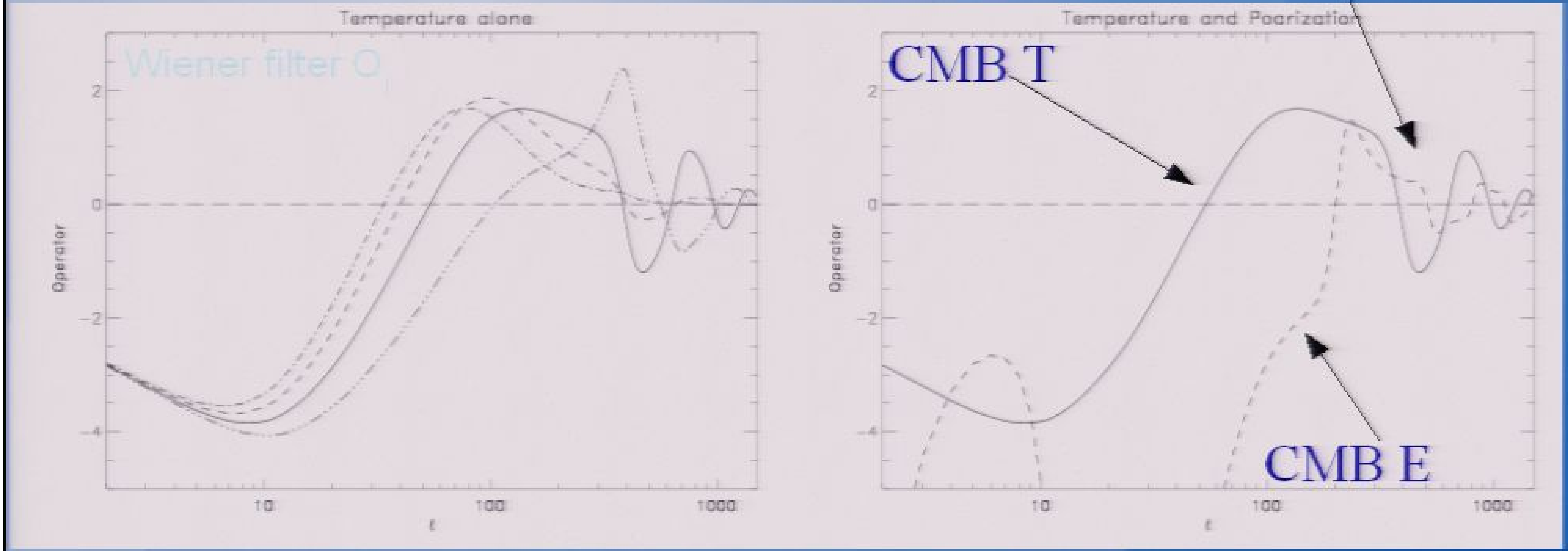


$r = r_{dec}$

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

The curvature perturbation leaves a *unique signature* in T & E

- Note negative response on large scales



T and E are out of phase

Yadav, and Wandelt, PRD (2005)

No Signal

VGA-1

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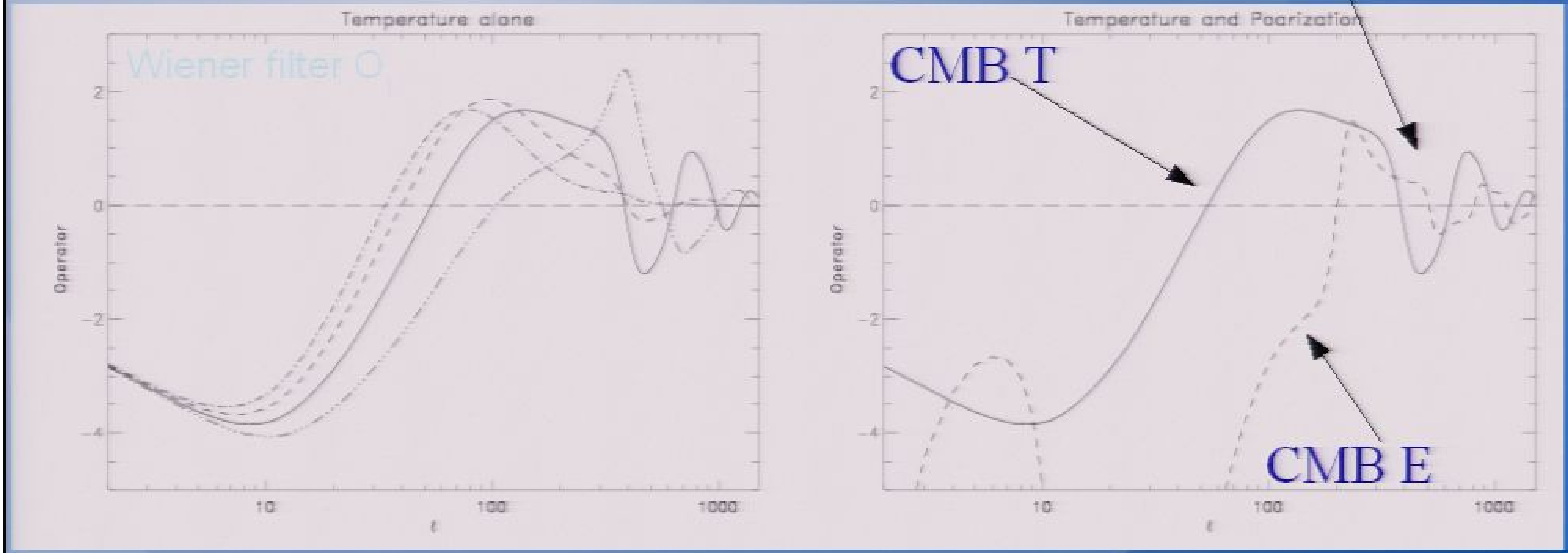

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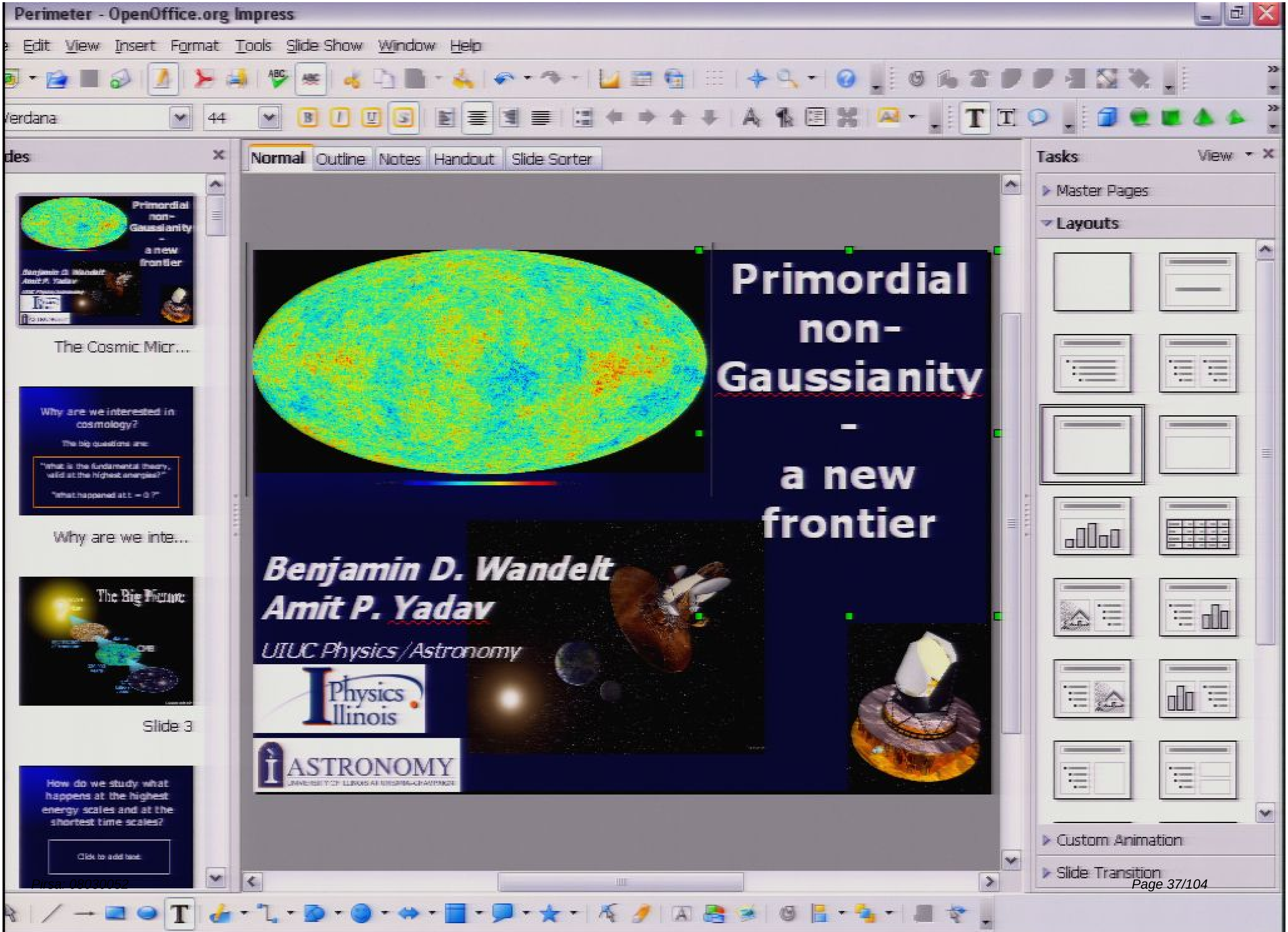

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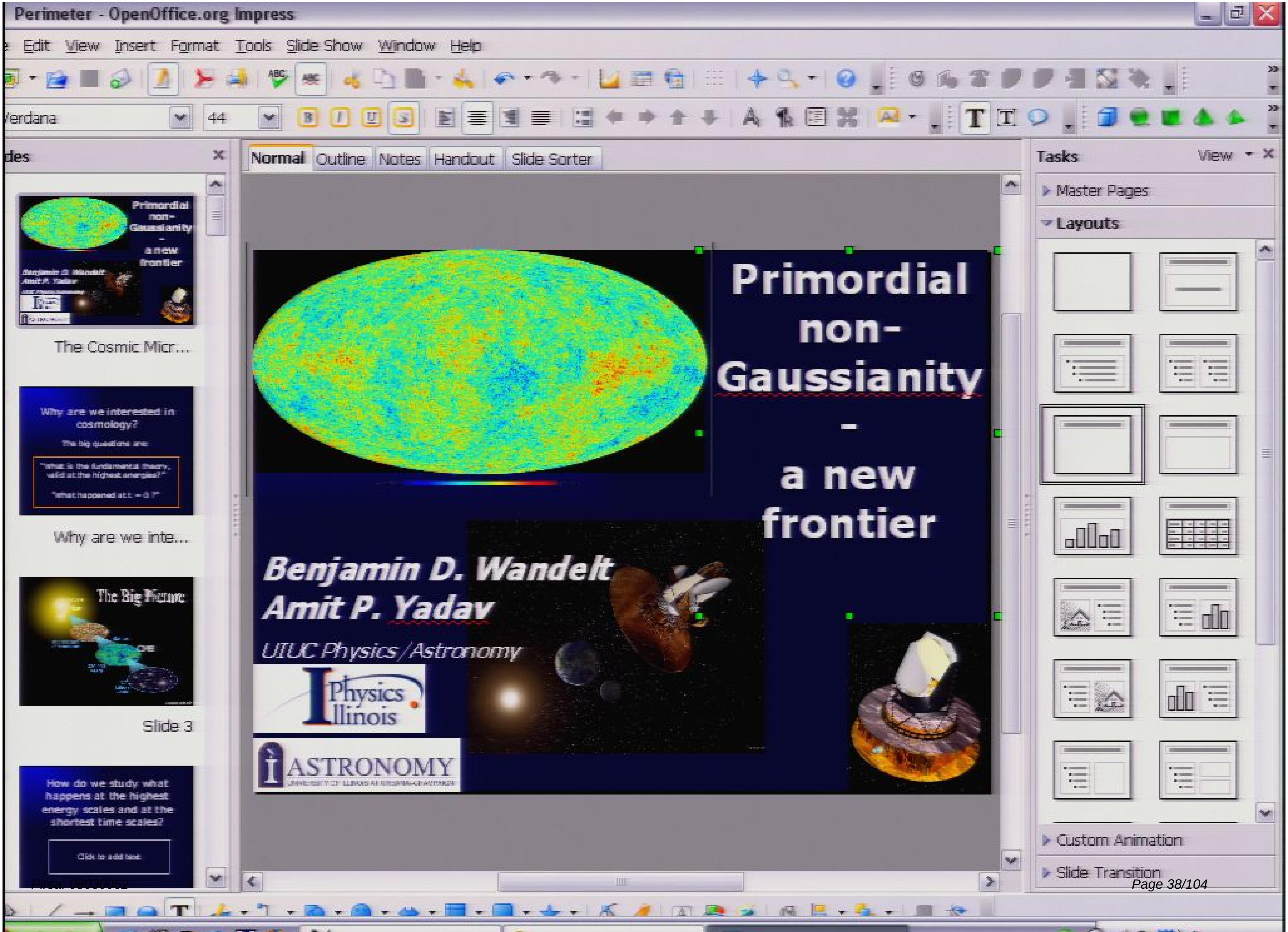

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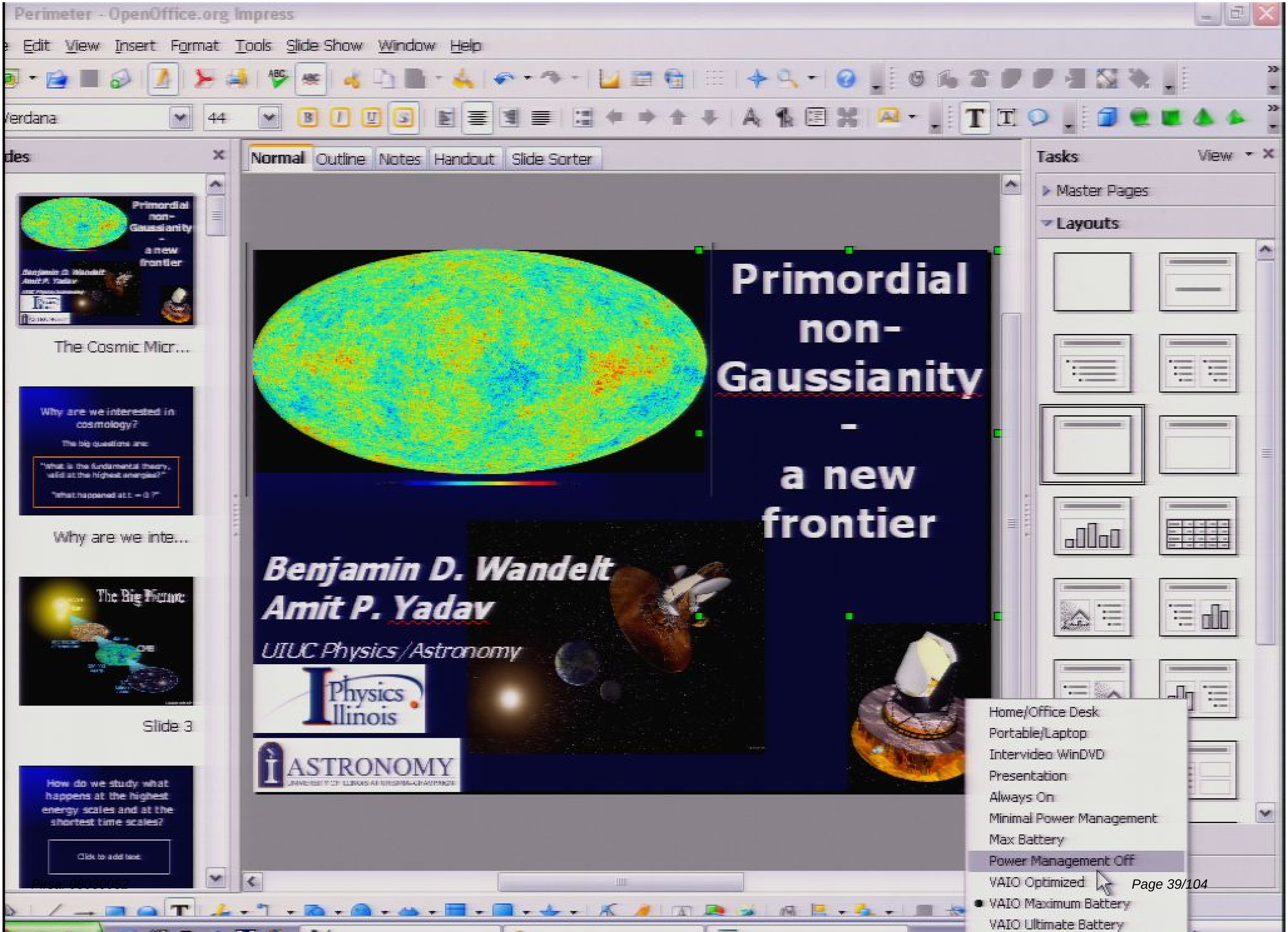

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ASTRONOMY
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

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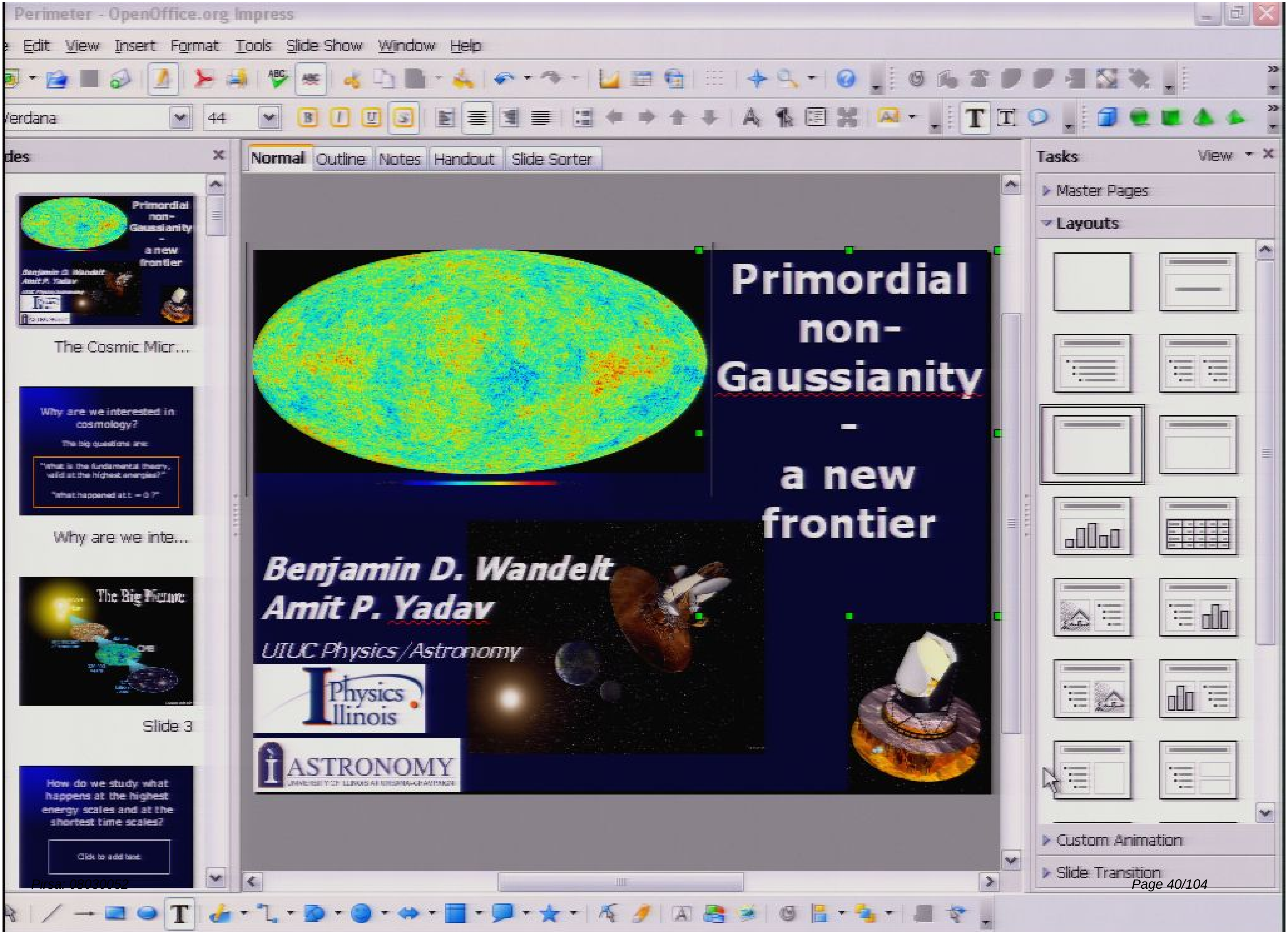

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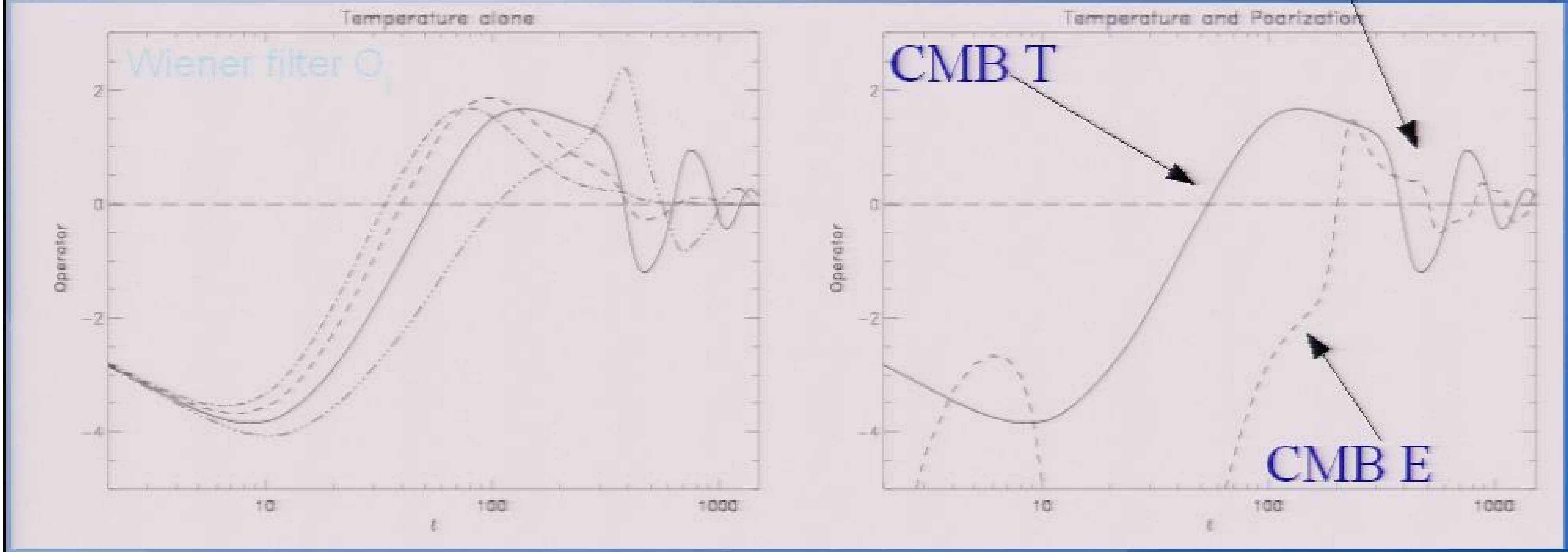
T and E are out of phase



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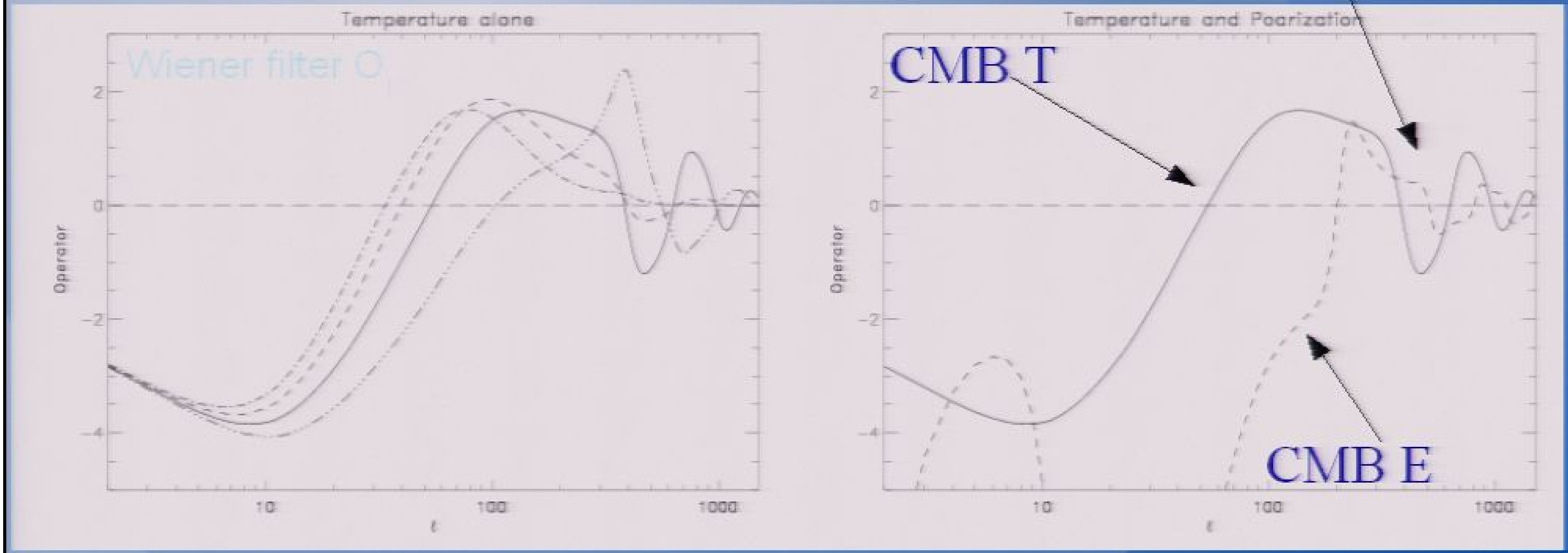

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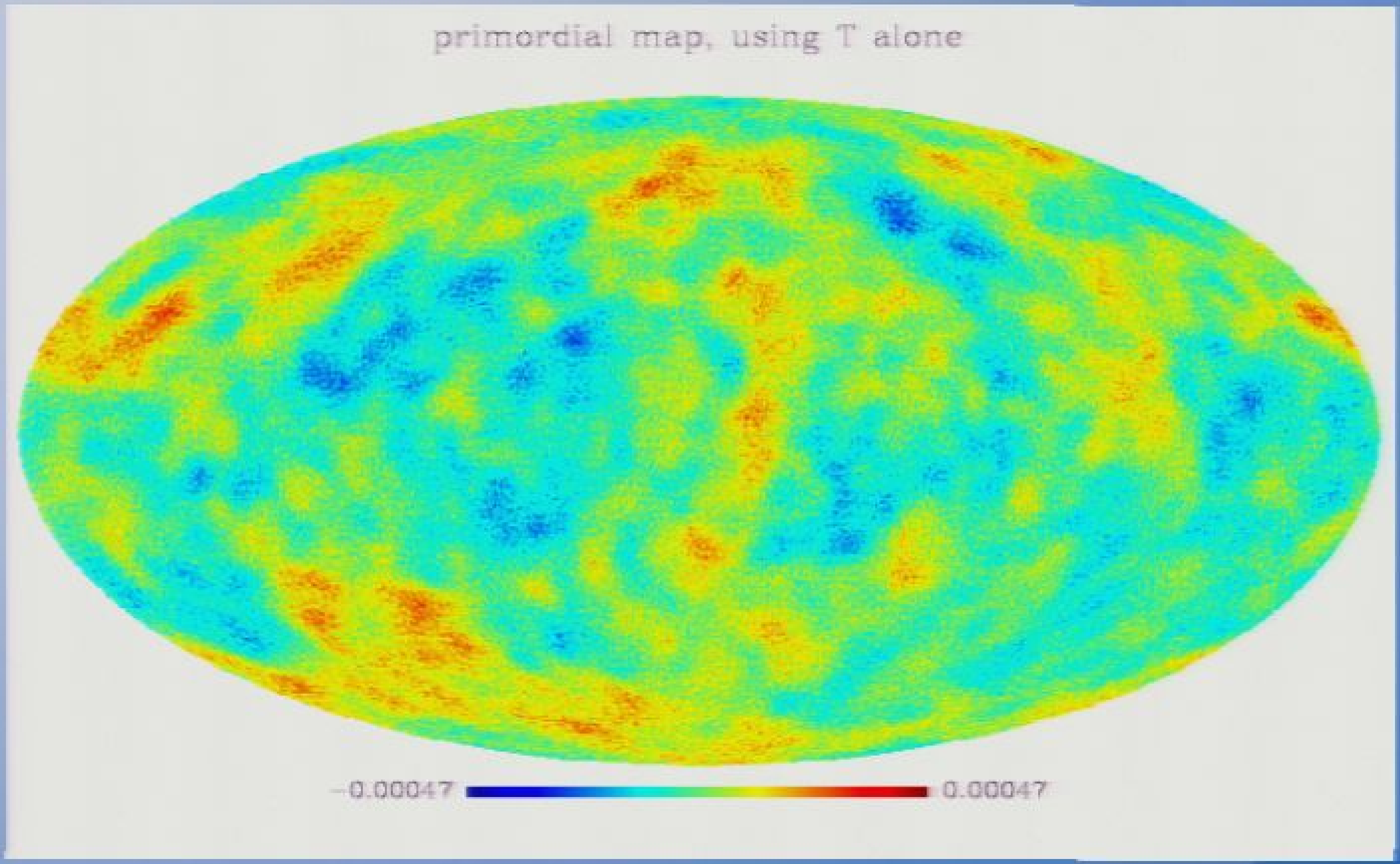

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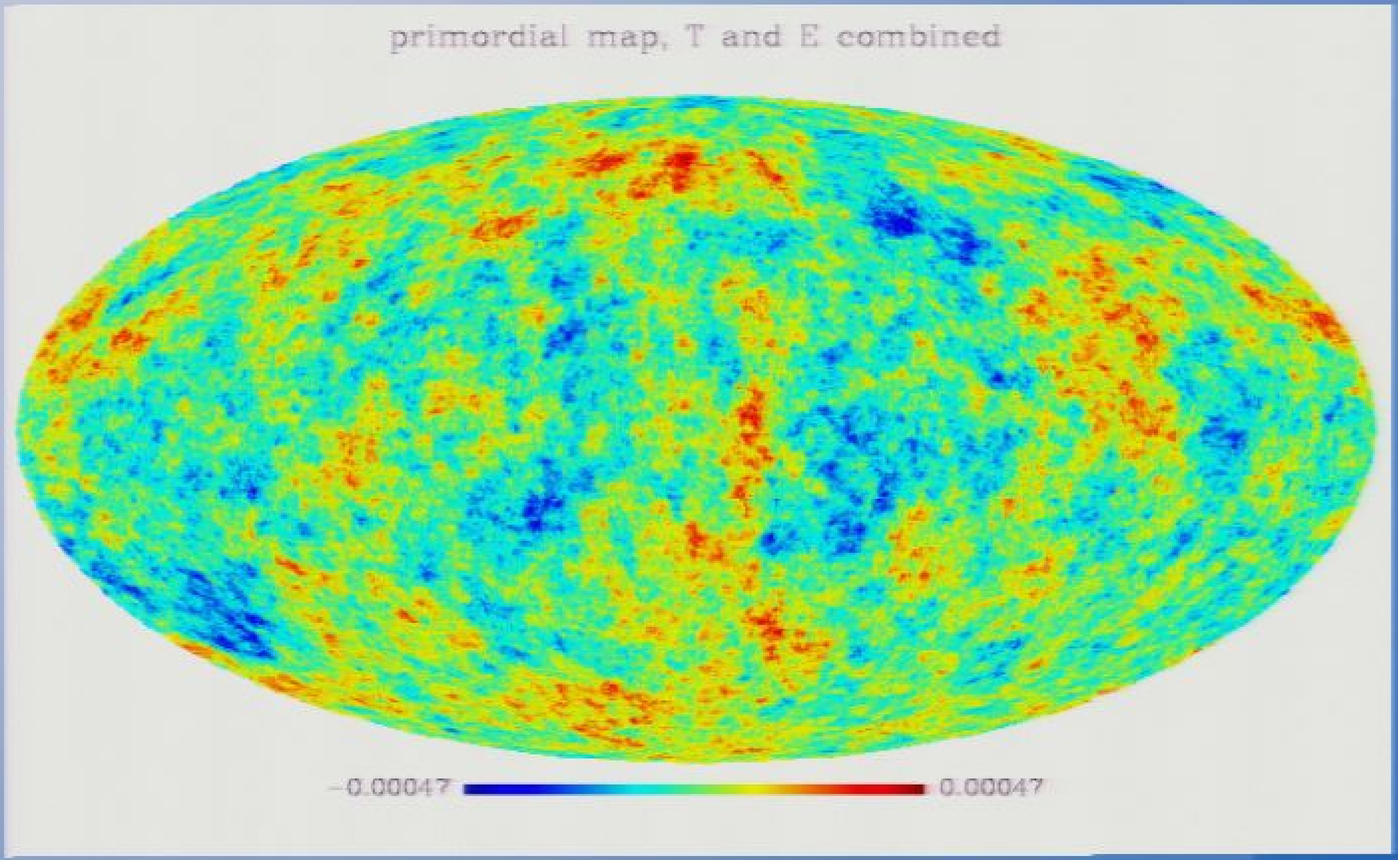
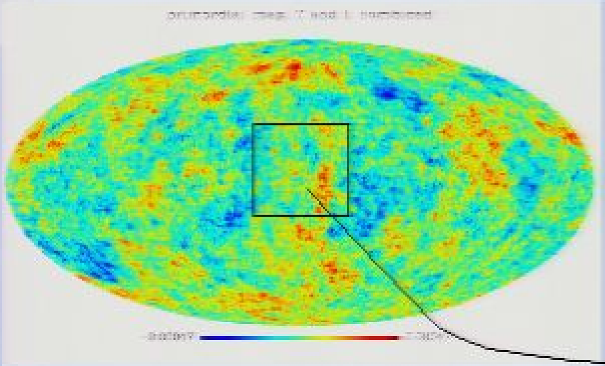
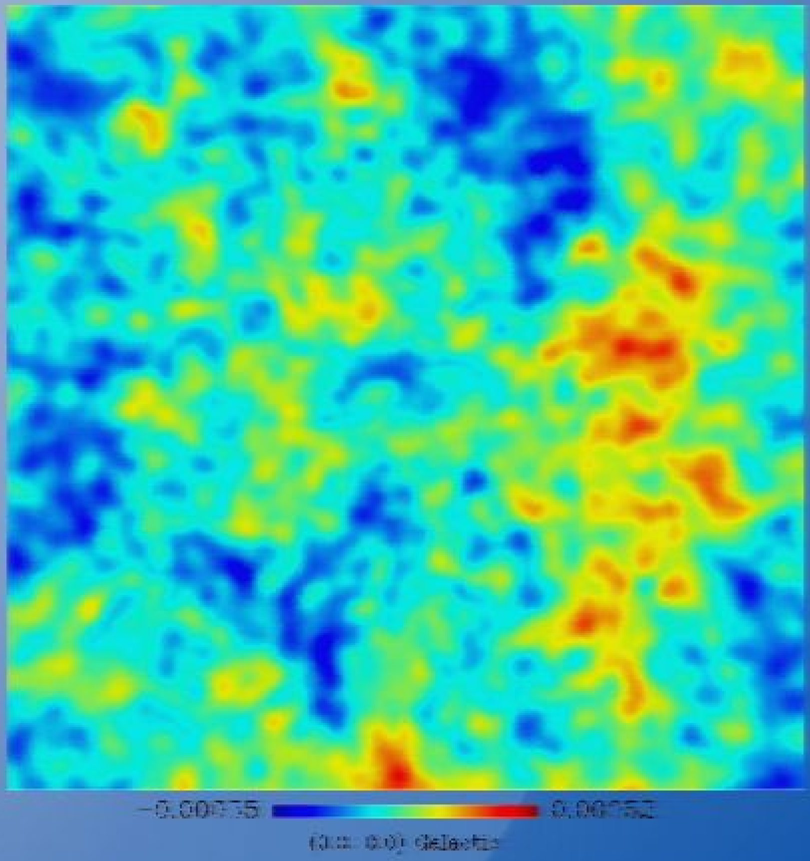


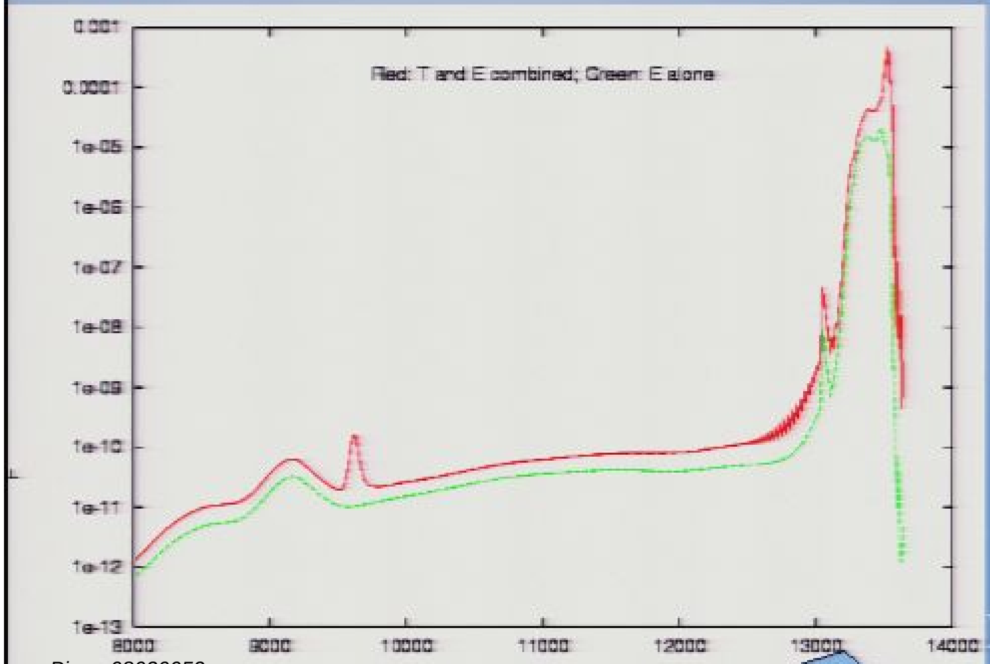
Yadav, and Wandelt, PRD (2005)

Reconstructed perturbations at different radii



Curvature fluctuations





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Decoupling

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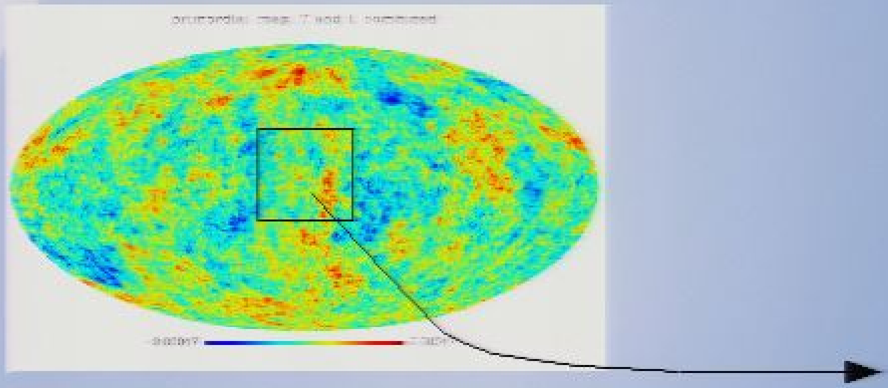

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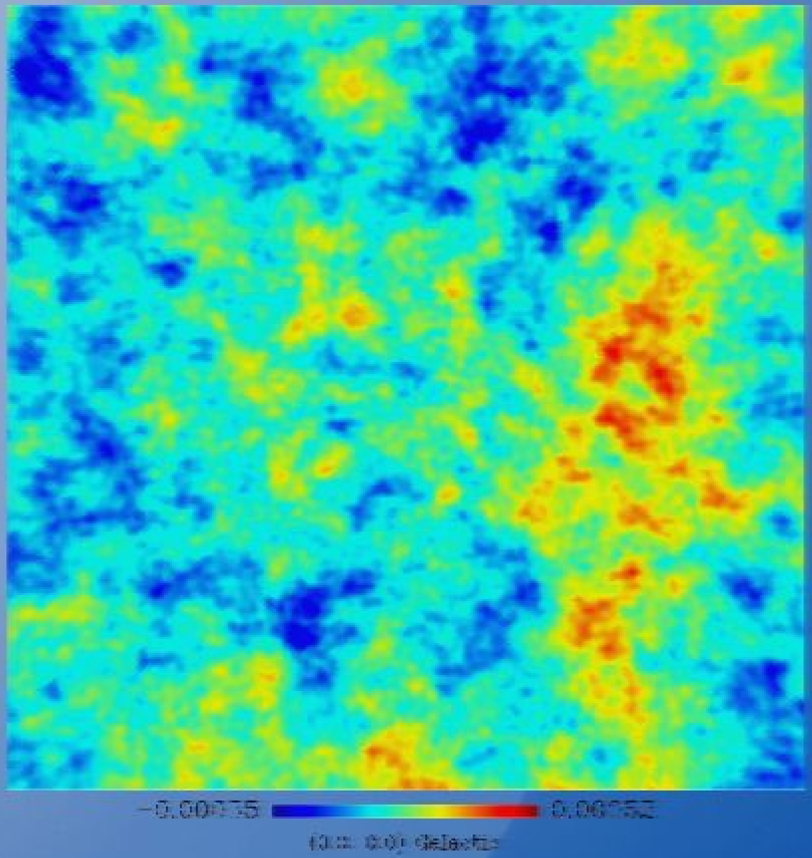

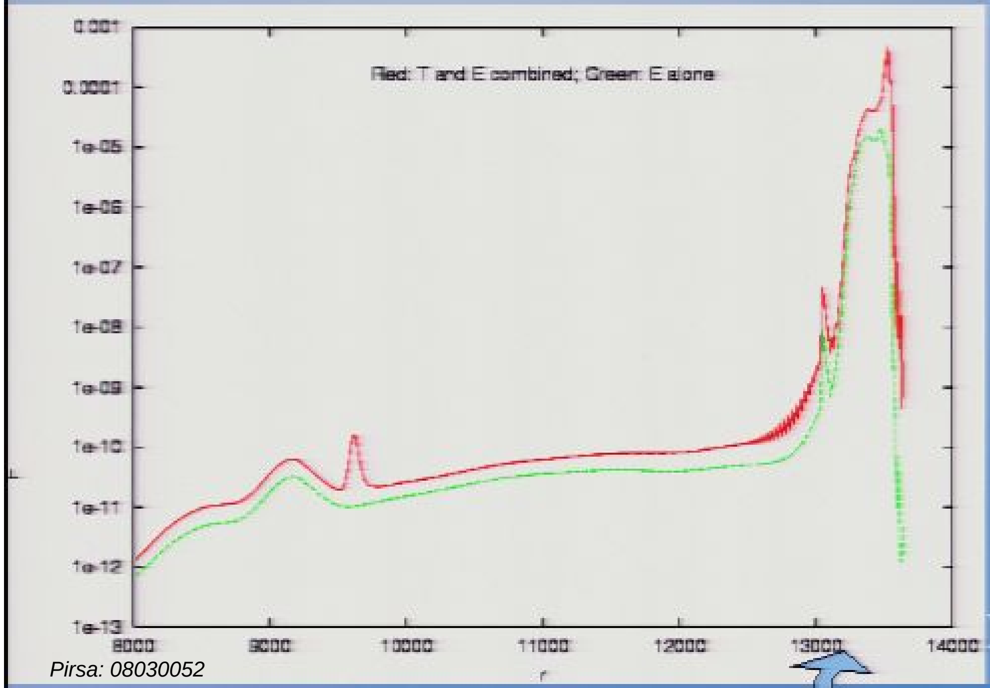

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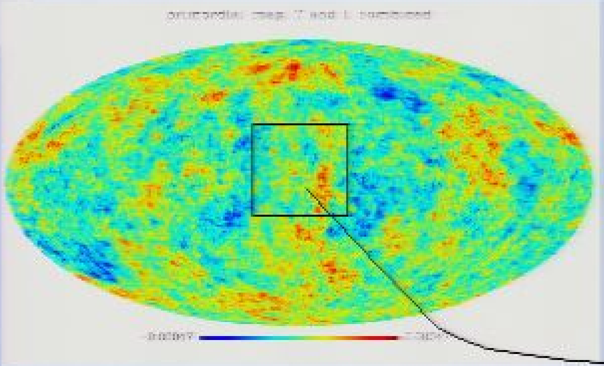

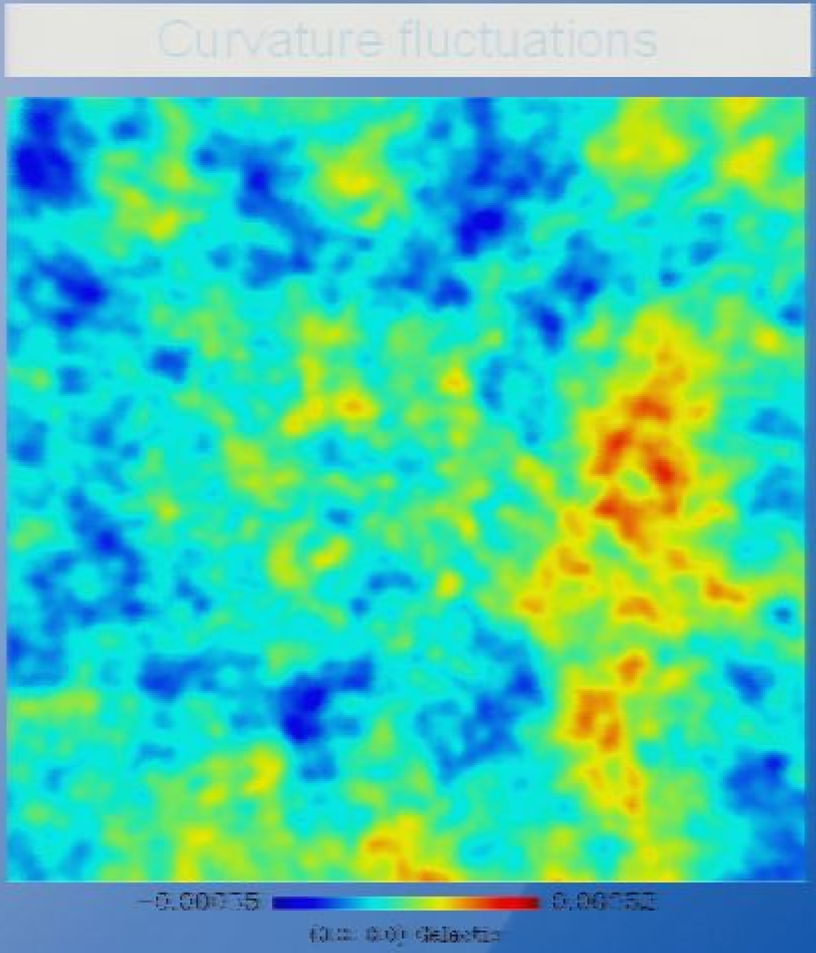
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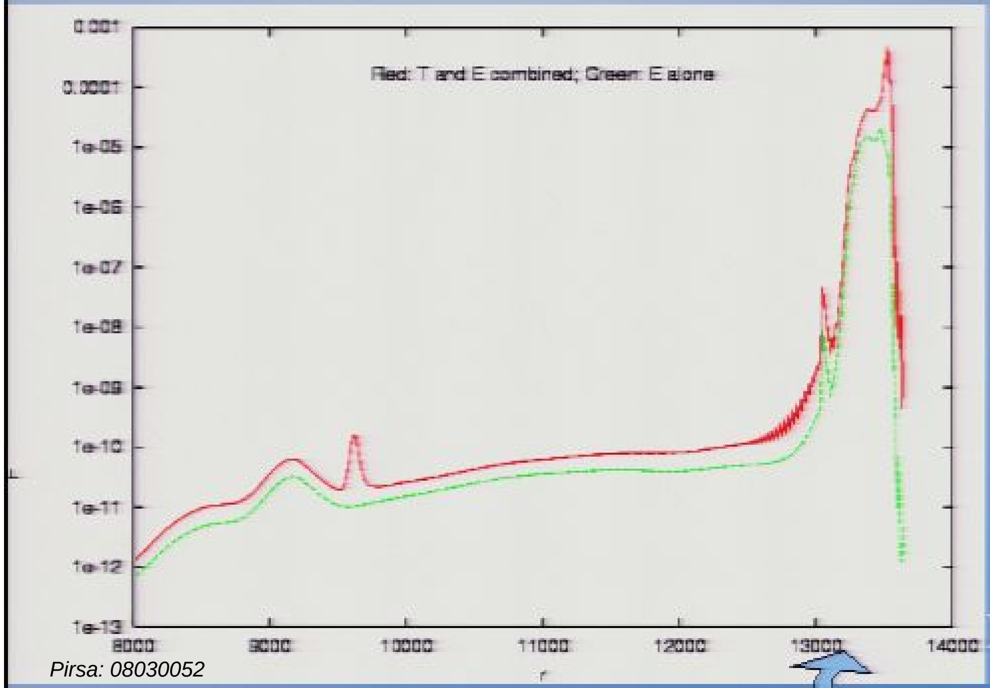

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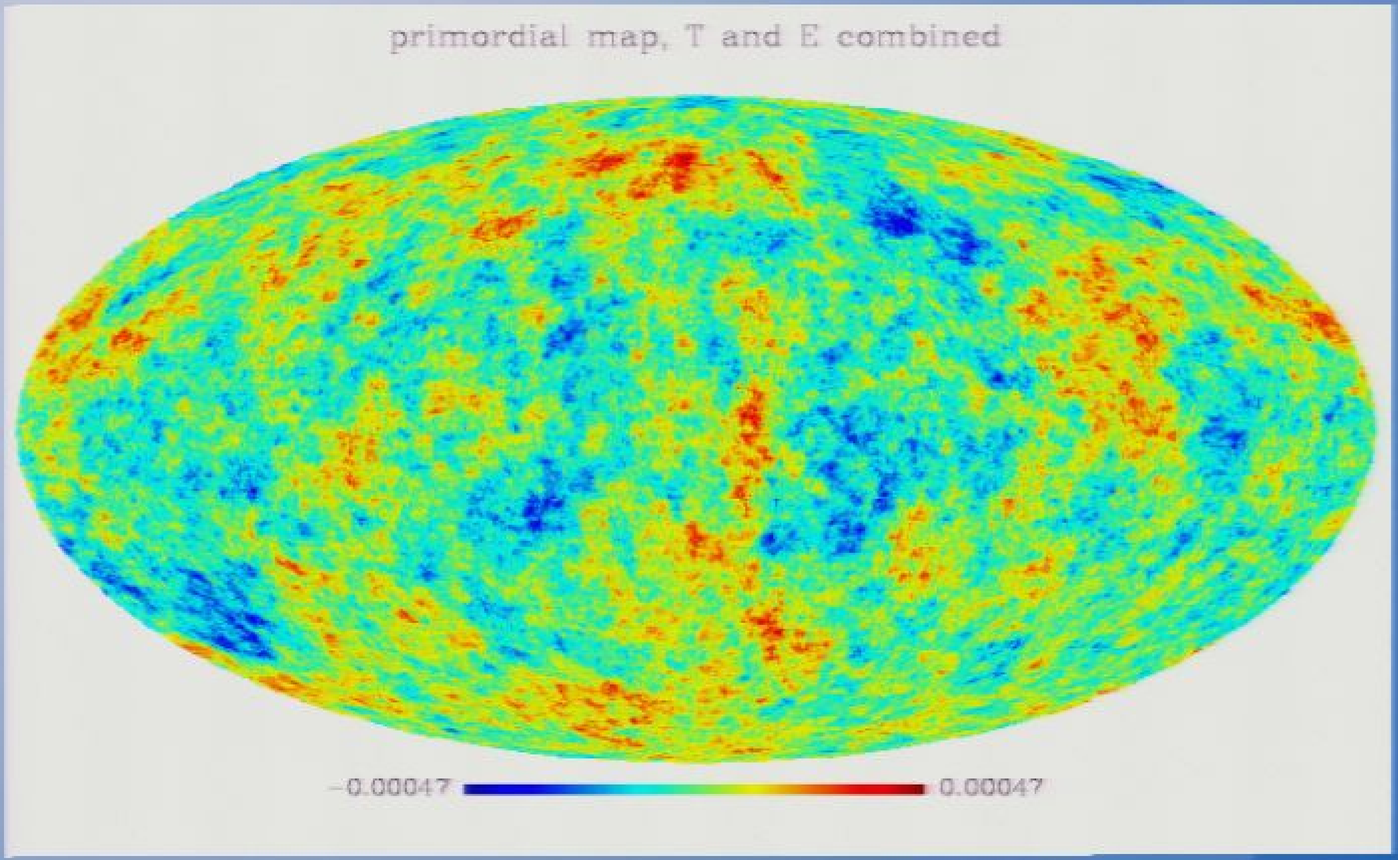

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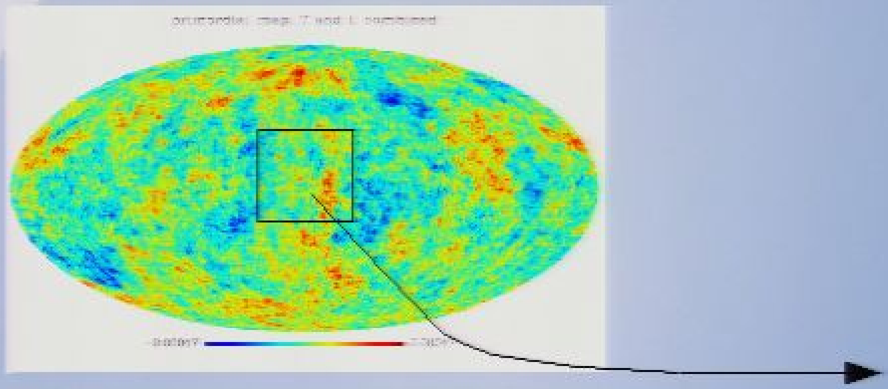

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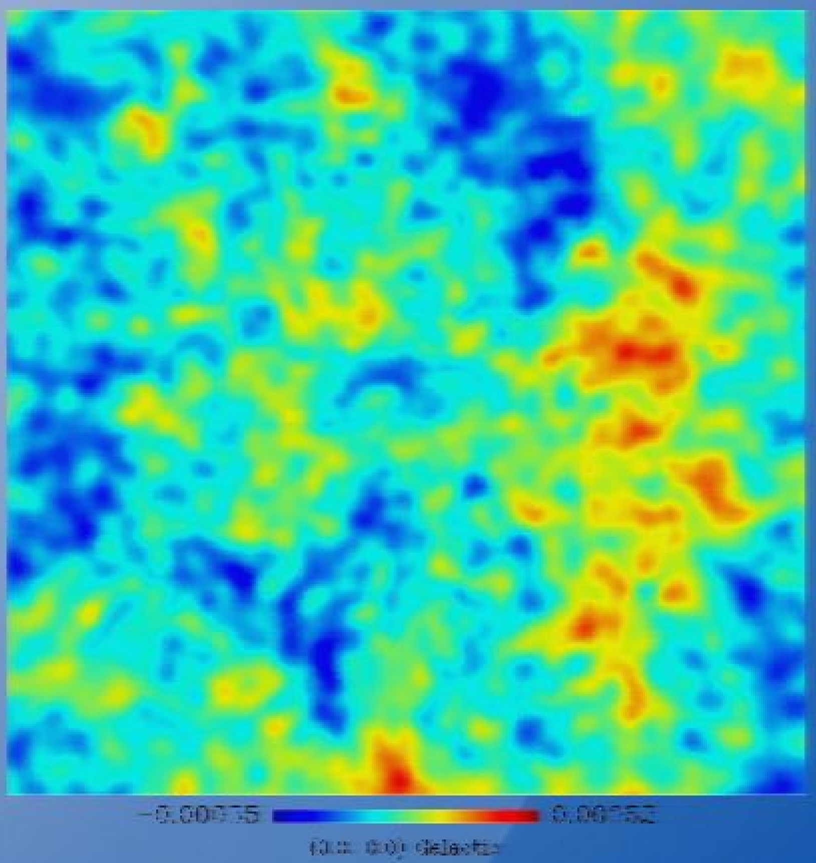

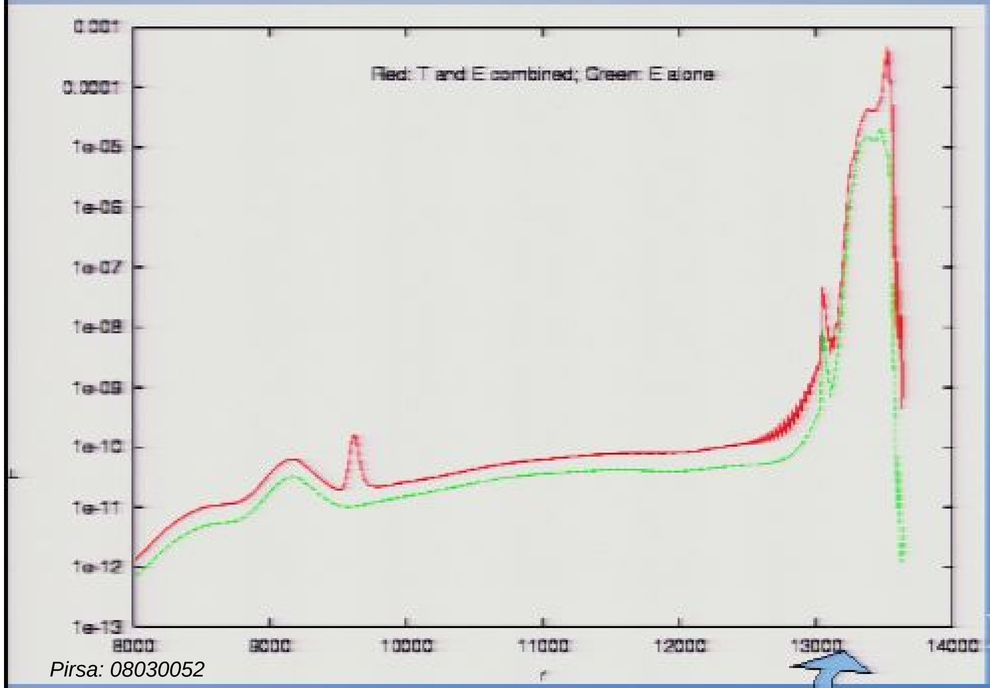

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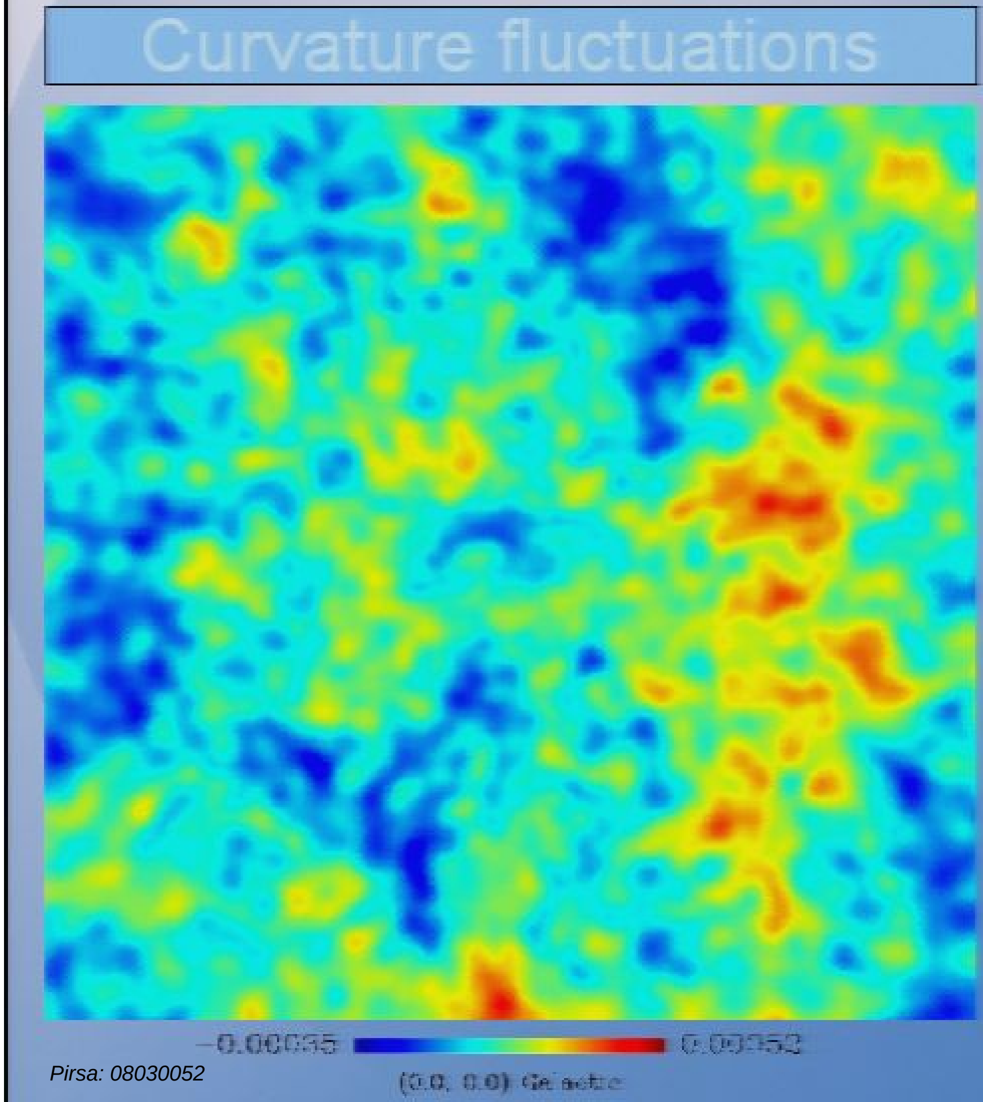
Decoupling

Tomographic reconstruction of inflationary scalar curvature

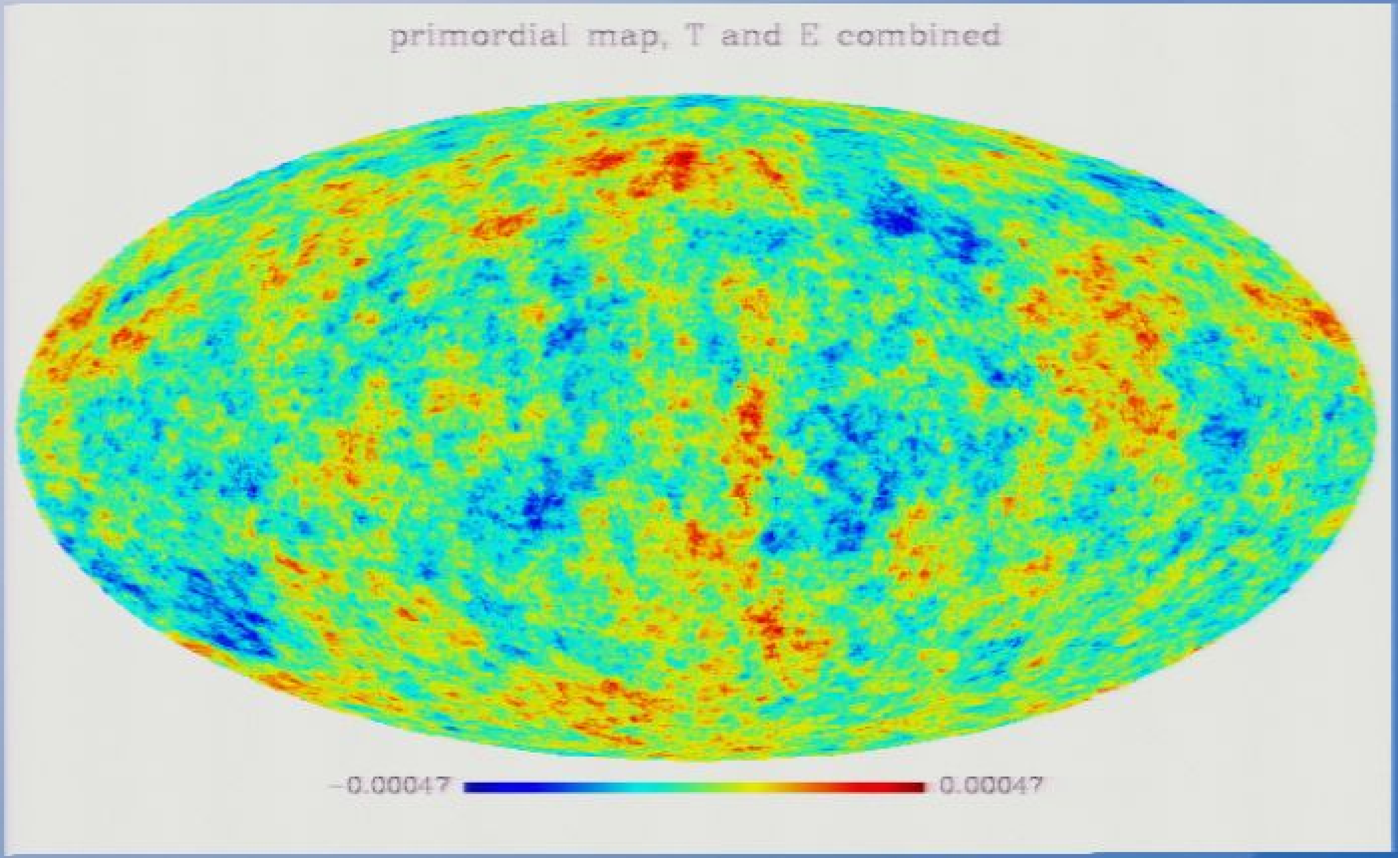

Curvature fluctuations

We construct filters that invert linear radiative transport.

Generates a single scalar that contains all the information from T&E.

Anyone intending to test primordial non-Gaussianity (and anisotropy!) in T and/or E data should do so using curvature perturbations obtained with our filters.

Yadav and Wandelt 2006



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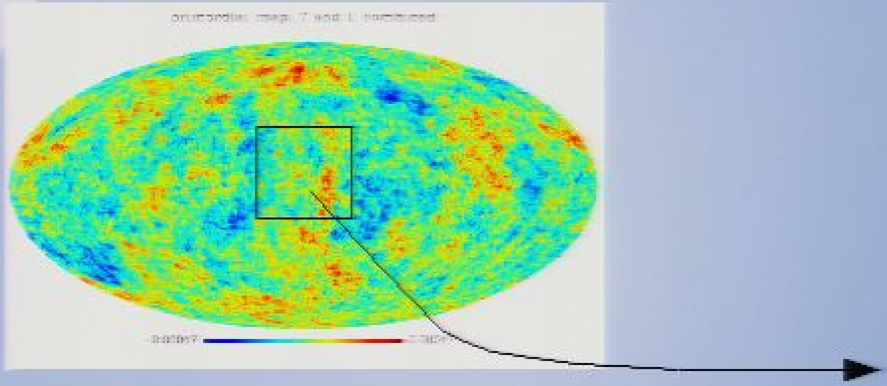

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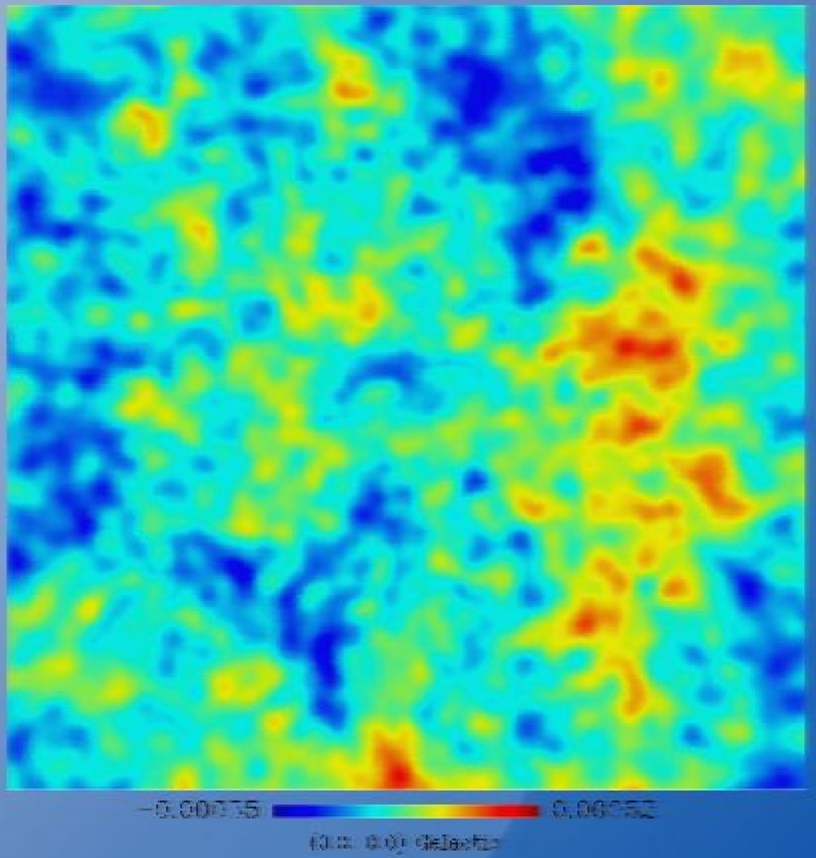

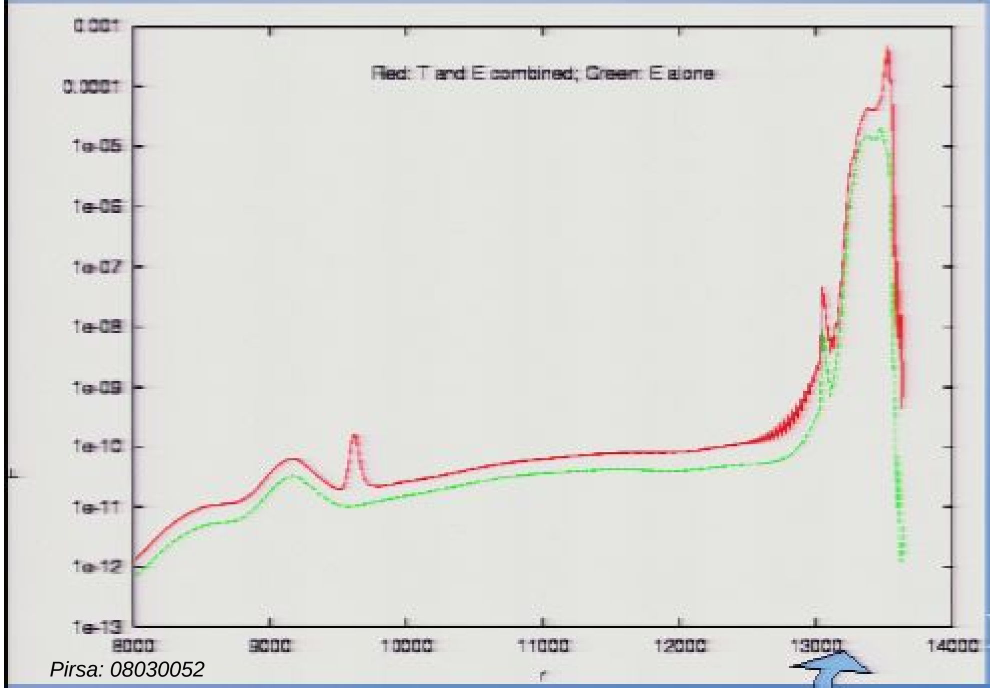

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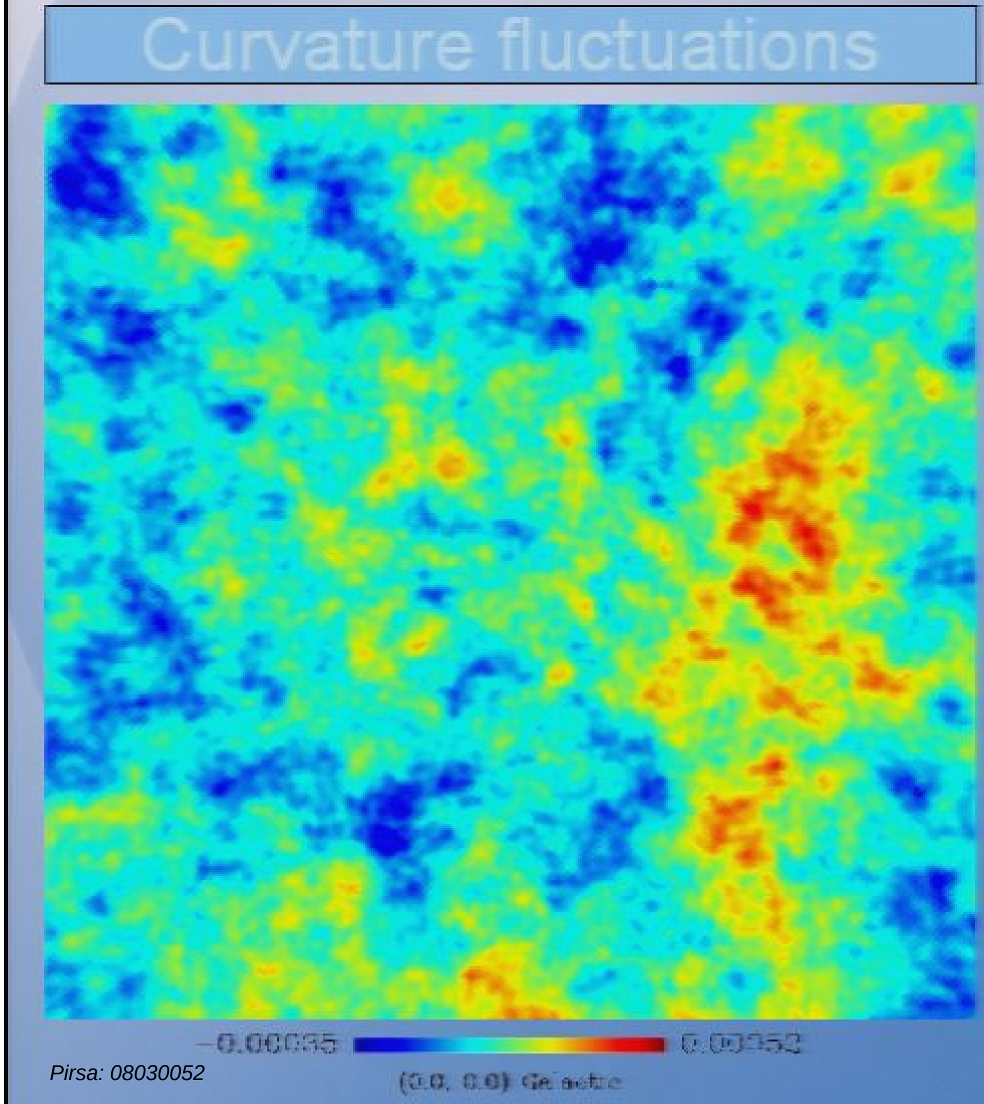

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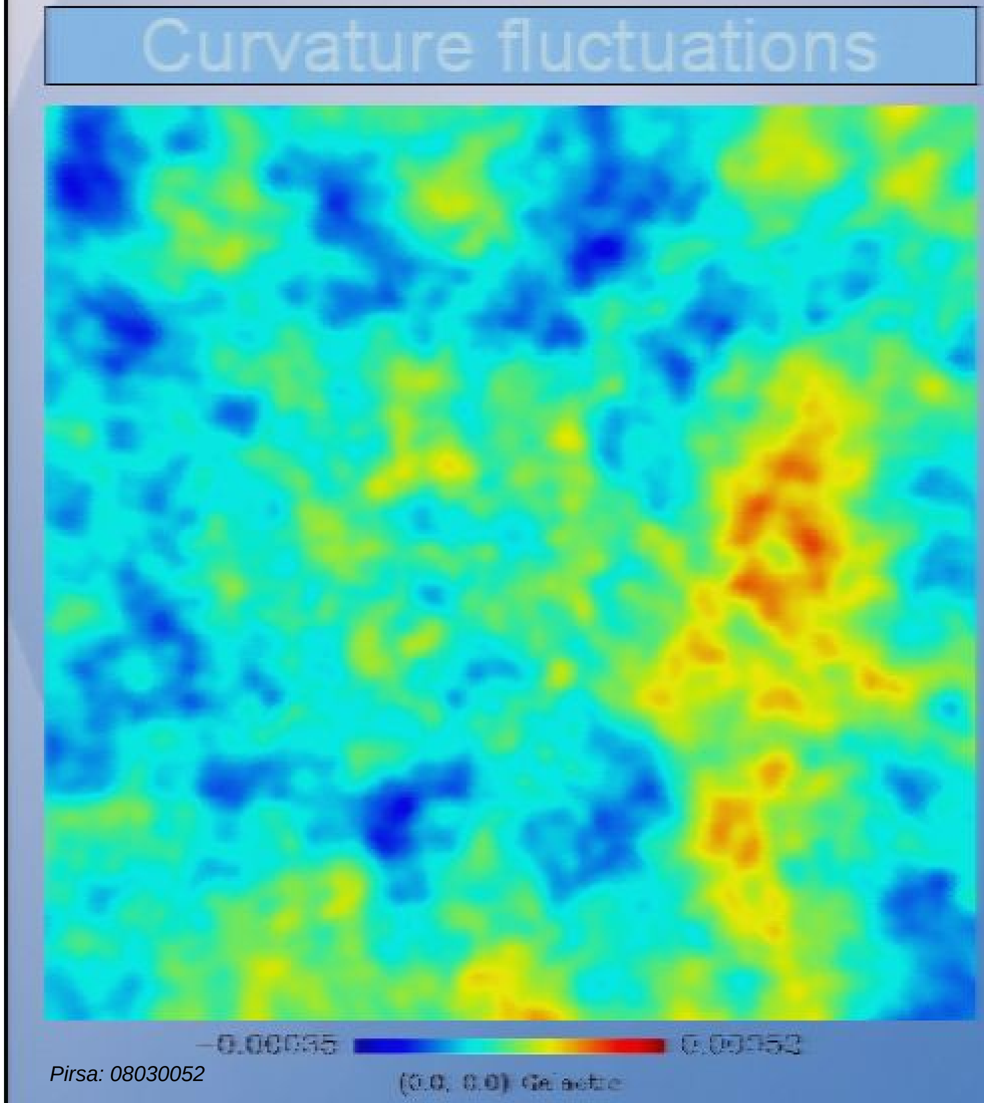

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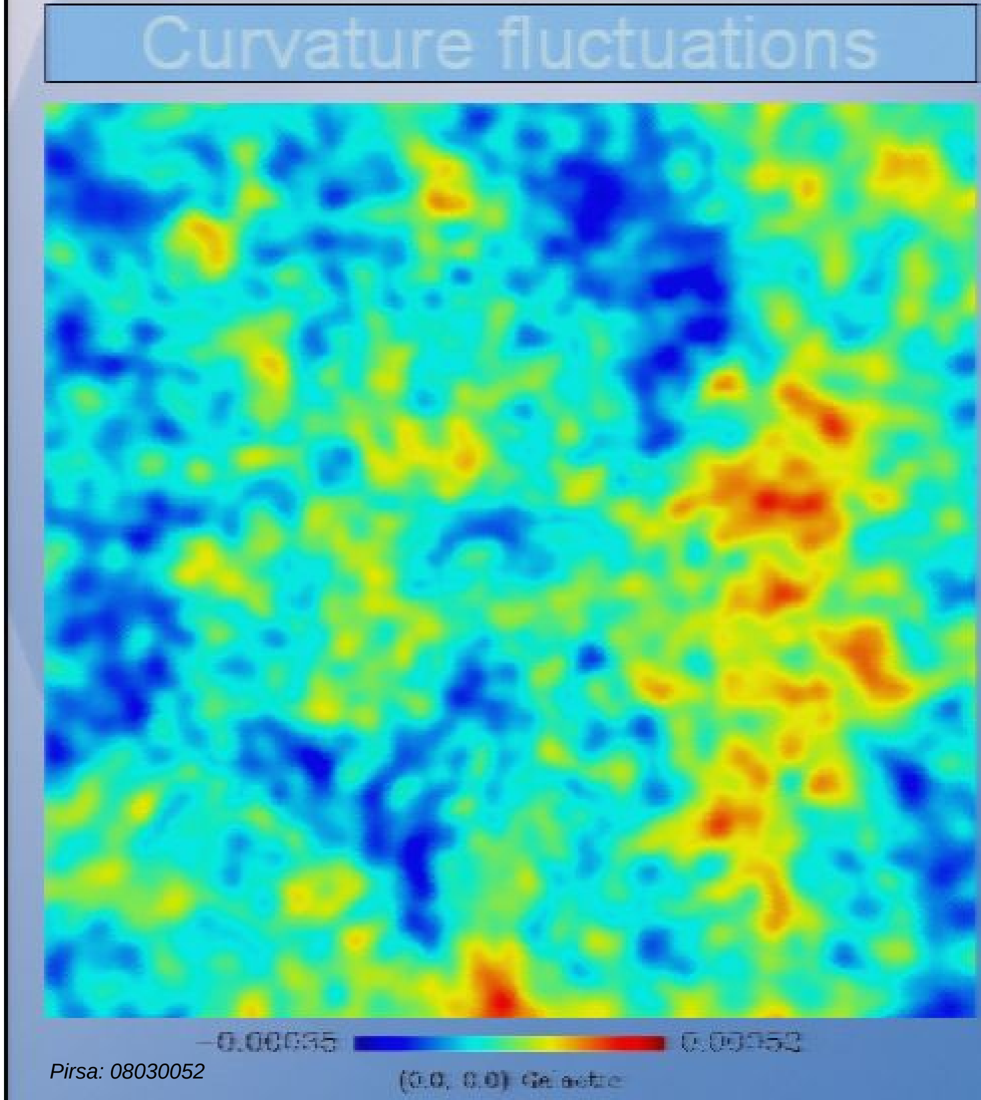

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Yadav and Wandelt 2006

How to search for 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

on-Gaussianity

Non-Gaussianity from Inflation

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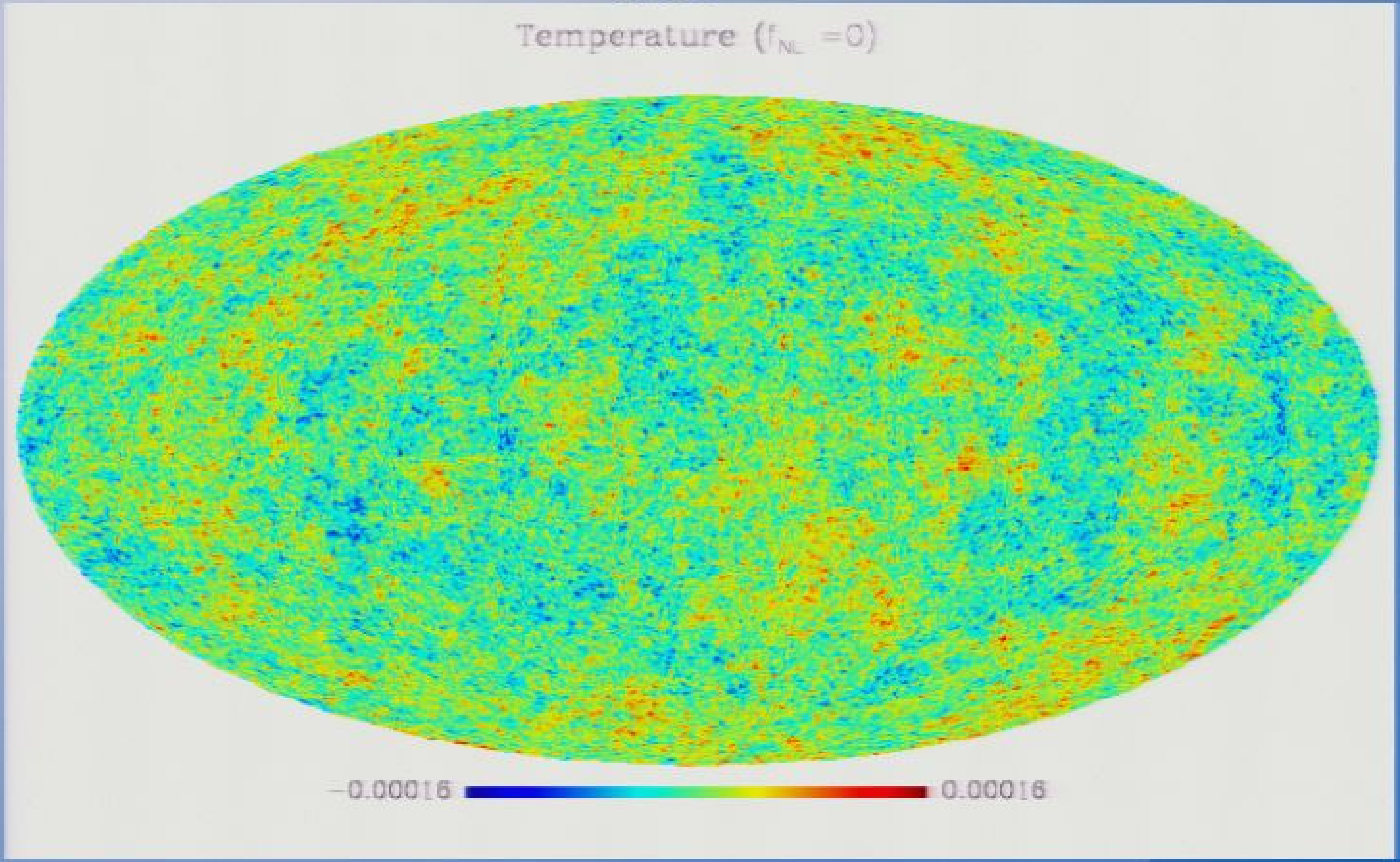
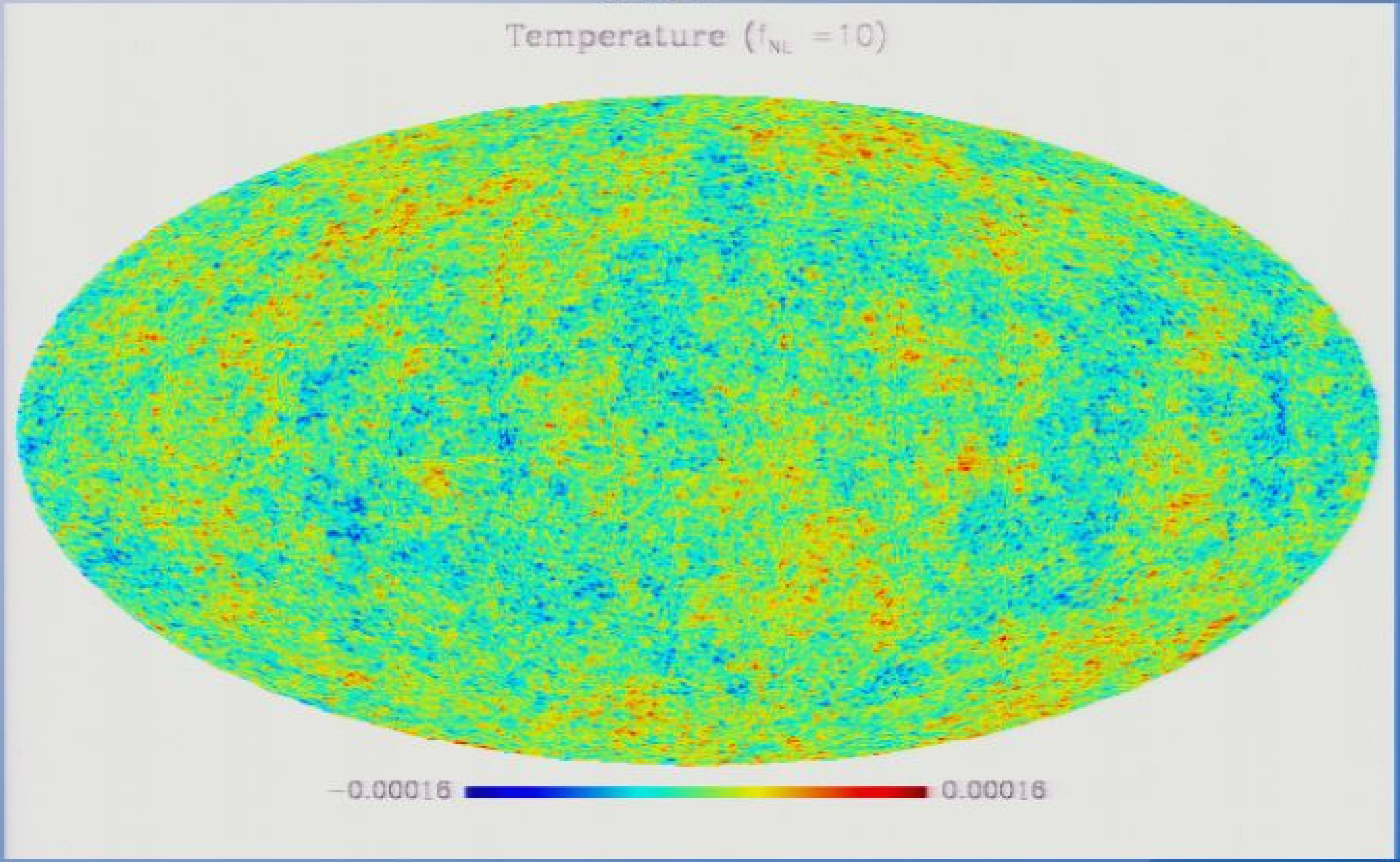
$f_{NL} = 0$



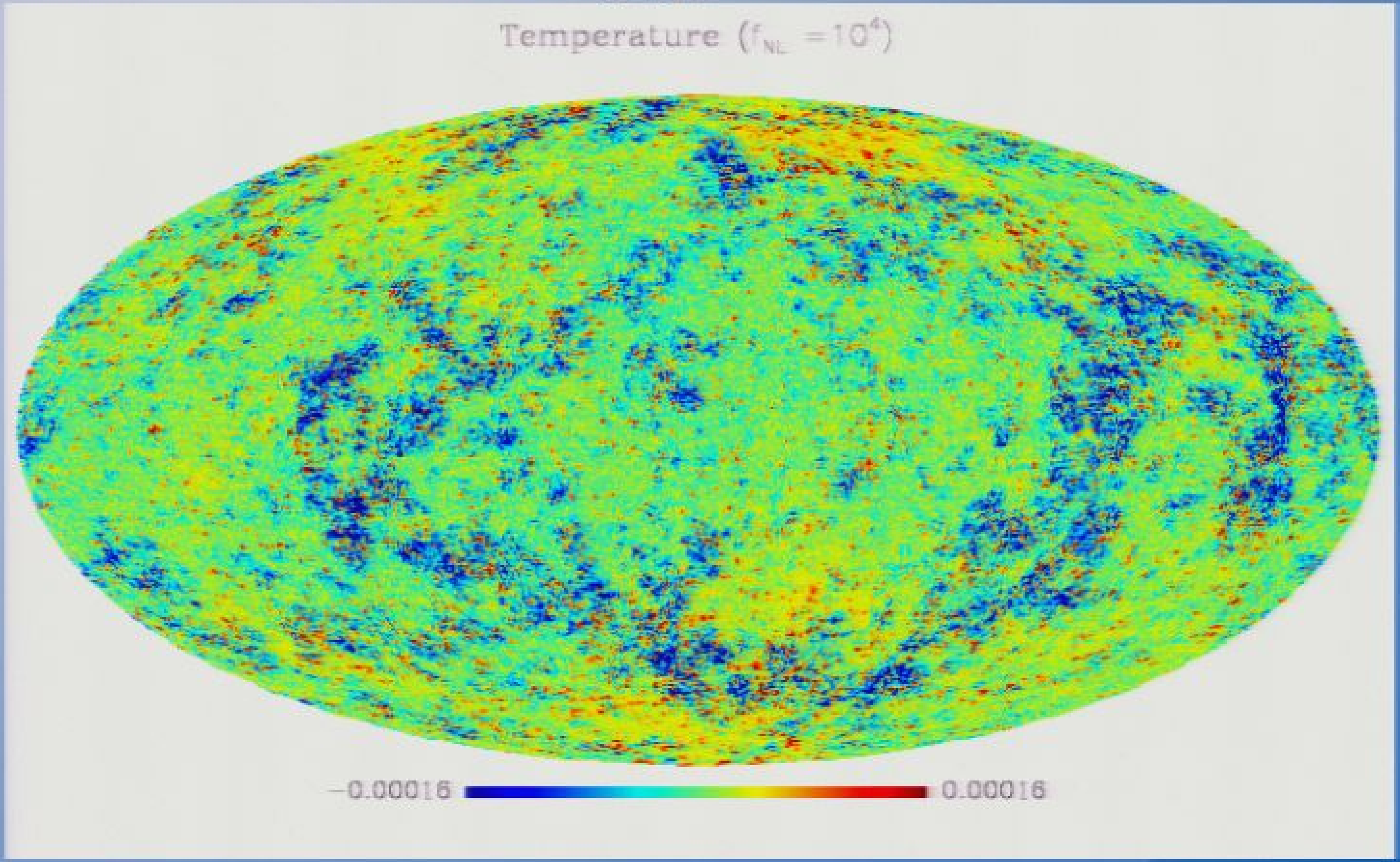
Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt 2007

$$f_{NL} = 10^1$$



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

$f_{NL} = 10^4$



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

Why use the bispectrum?

$$B_{\text{non-Gaussian}} = 0 + f_{NL} b^2$$

$$T_{\text{non-Gaussian}} = T_{\text{Gaussian}} + f_{NL}{}^2 \delta T$$

For weak non-Gaussianity any even moment has a much larger contribution from Gaussian perturbations. This makes measuring the non-Gaussian component difficult.

Babich (2005): bispectrum contains nearly all the information about f_{NL}. Kogo&Komatsu: Trispectrum contains complementary information

Unfortunately evaluating all $B_{l l' l''}$ is too expensive.

f_{NL} phenomenology from the bispectrum

- Komatsu & Spergel 2001 – CMB bispectrum from f_{NL}
- 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`

Fast, bispectrum based estimator of local f_{NL}

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

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

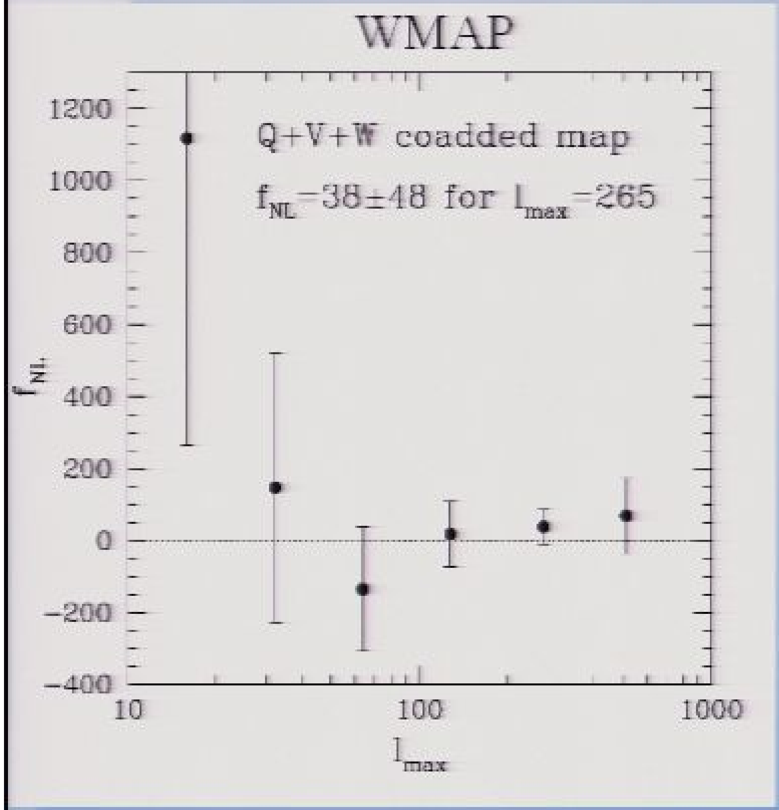
mordial perturbations

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

tions of the bispectrum

Abc ll configurations of bispectrum such that it most sensitive to "local" primordial non-Gaussianity i.e f_{NL}`

Status before December 2007



$-58 < f_{NL} < 137$ (95%) **WMAP 1yr**

$-54 < f_{NL} < 114$ (95%) **WMAP 3yr**

$-36 < f_{NL} < 100$ (95%) **Creminelli et. al. 2006 using WMAP 3yr data**

$$2\Delta f_{NL} \sim 70$$

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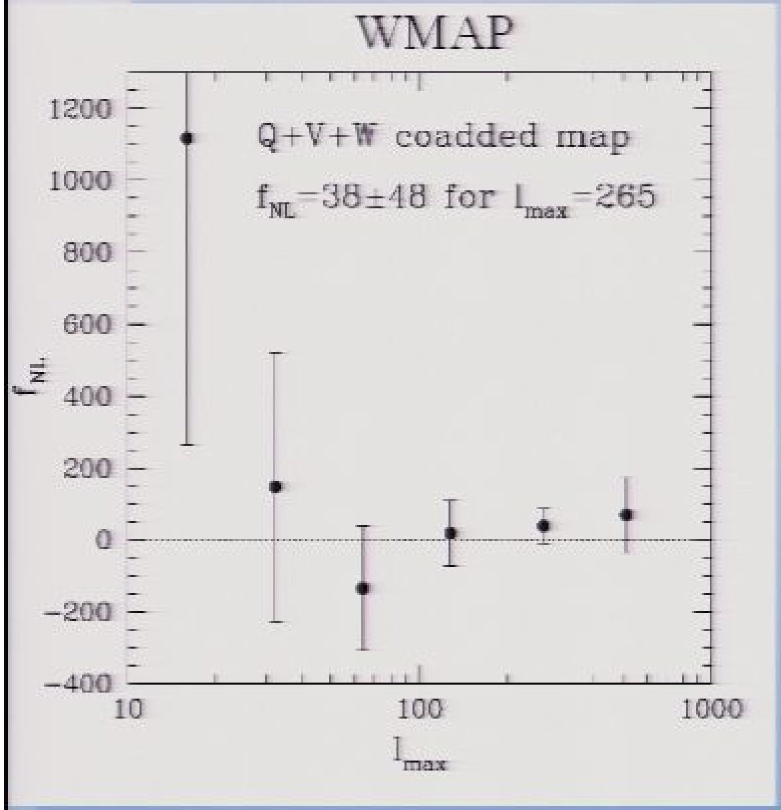

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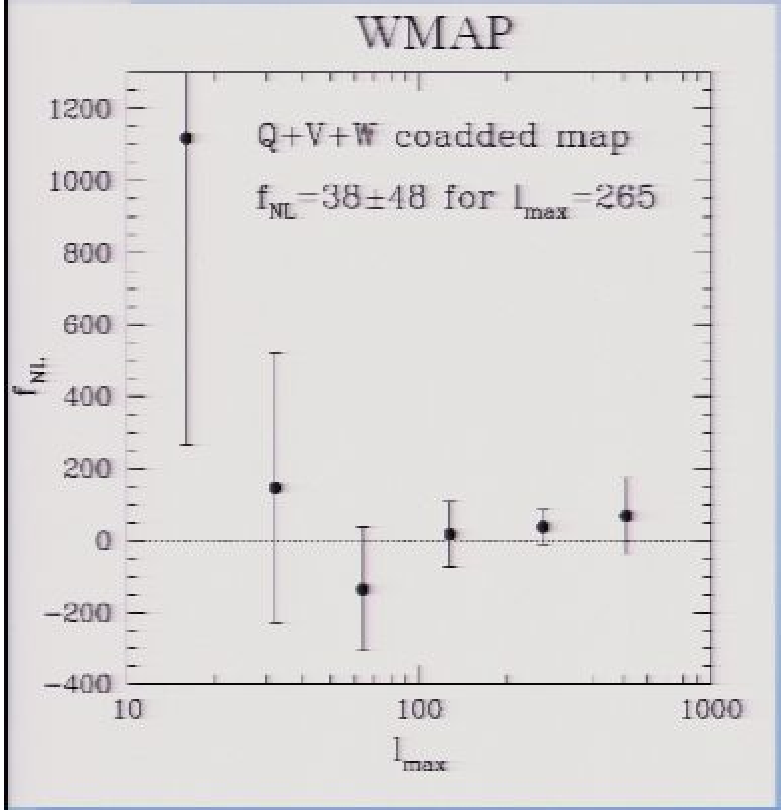

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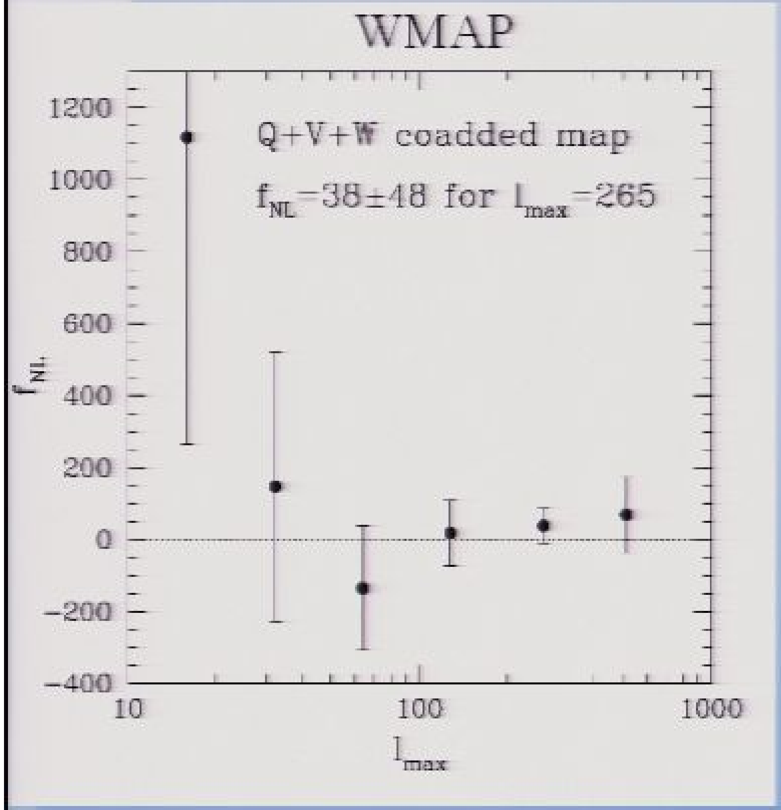

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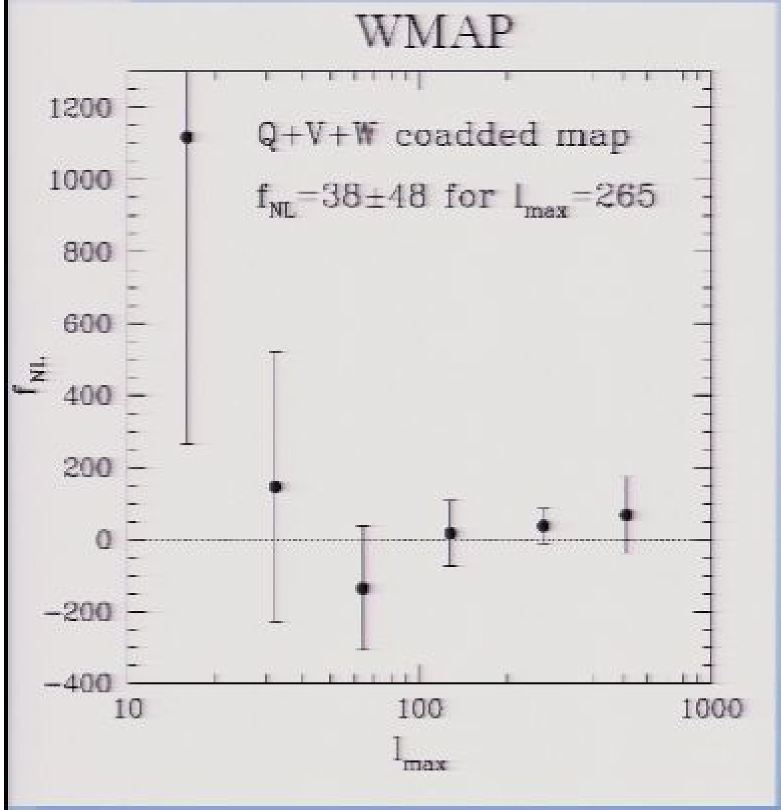

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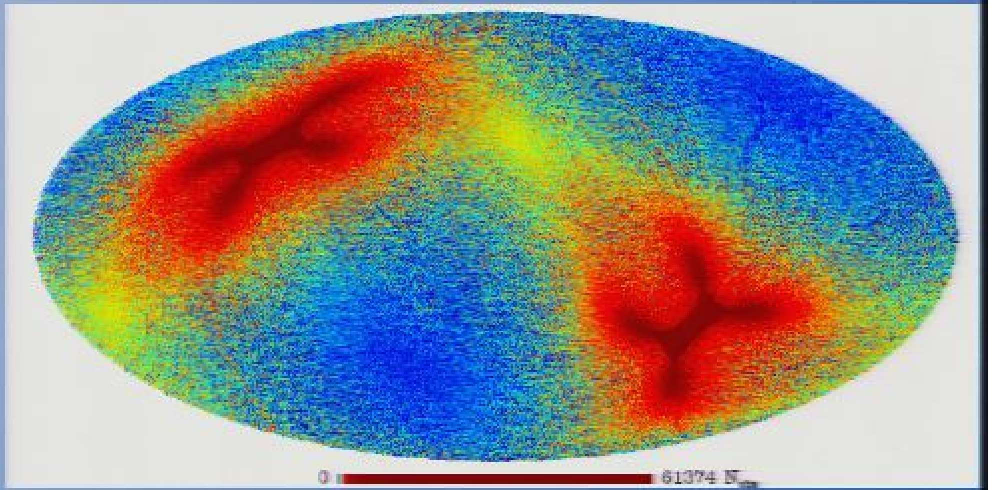
We are far from $\Delta f_{NL} \sim 1$ but can already start putting constraints on some models like DBI inflation, ghost inflation etc.

Anisotropic sky coverage

- The KSW and YKWLHM estimators are optimal only for uniform sky coverage and noise distribution. Anisotropic noise distribution couples different l and produces excess variance.



- For non-uniform noise the addition of a linear te the variance of the est (Creminelli et al. 2005)

$$\hat{S}^{linear}_{prim} = \frac{-3}{f_{sky}} \int r^2 dr \int d^2\hat{n} \left\{ B(\hat{n},r) S_{AB}(\hat{n},r) + S_{BB}(\hat{n},r) A(\hat{n},r) \right\}$$

- We (Yadav, Komatsu, Wandelt, et al. arxiv:0711.4933) generalized this estimator to include polarization; and discovered and corrected an error in the linear term.

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

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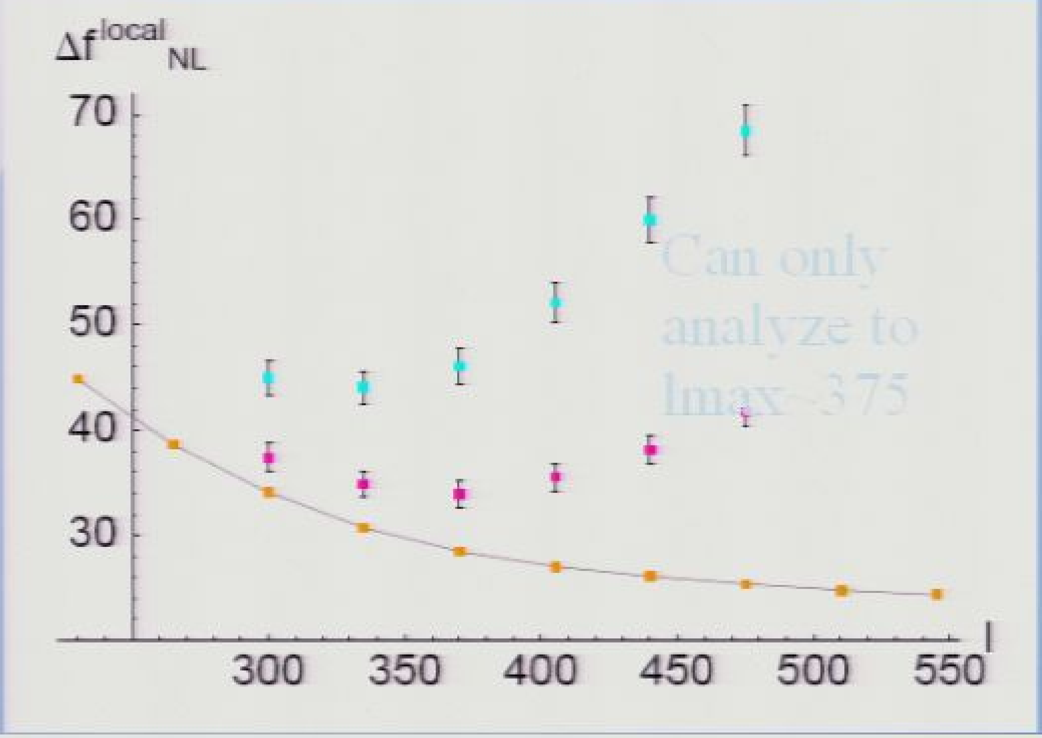
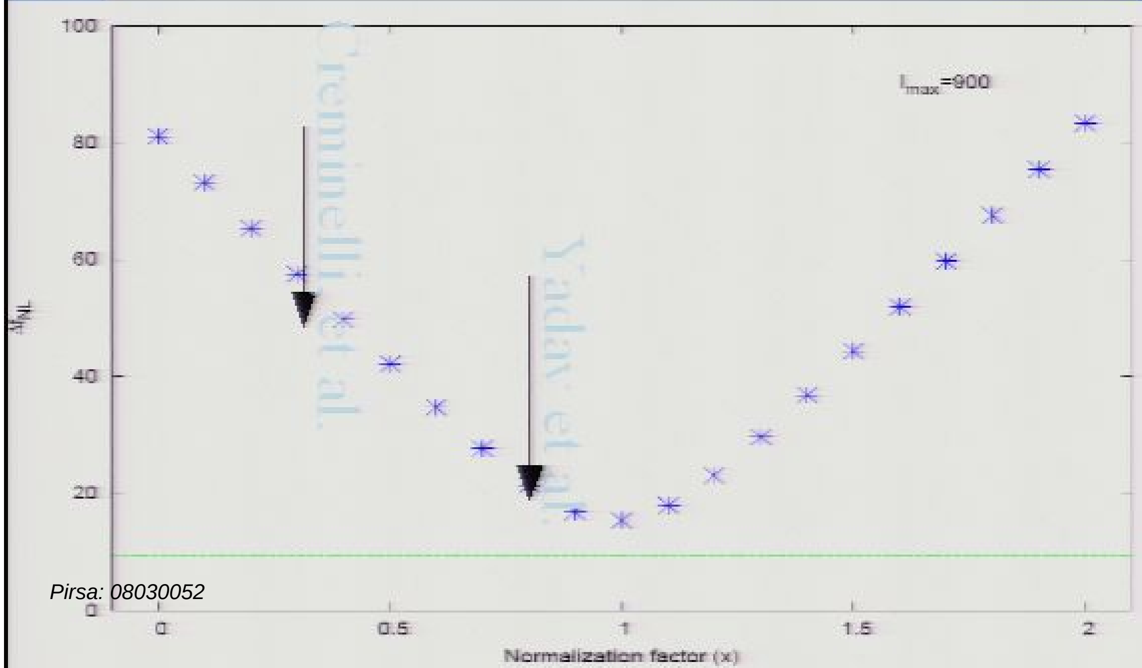
What is new in Yadav & Wandelt 2008?

Creminelli et al 2006 Q+V+W

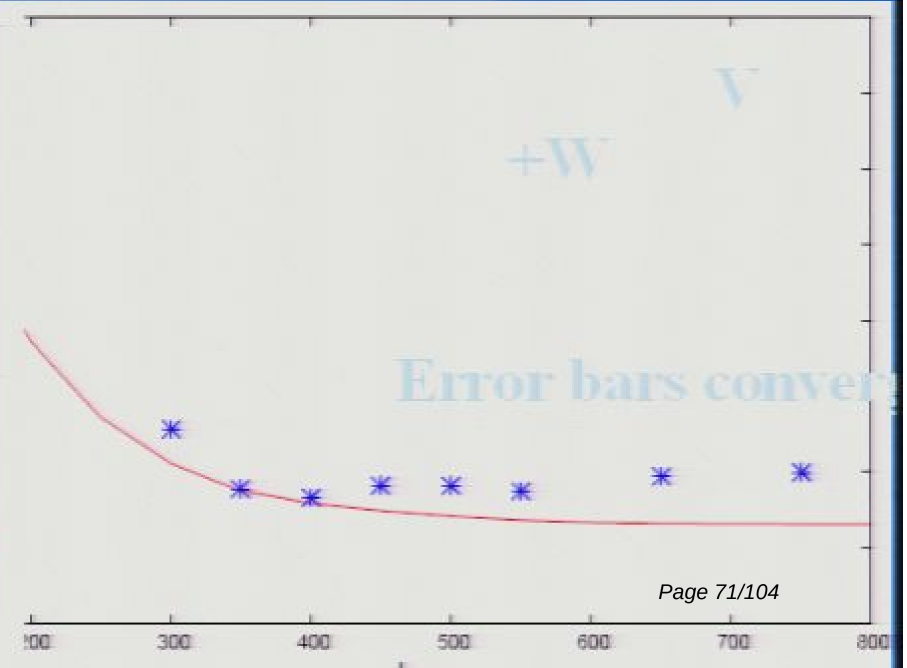


Can only analyze to lmax~375



Creminelli et al.

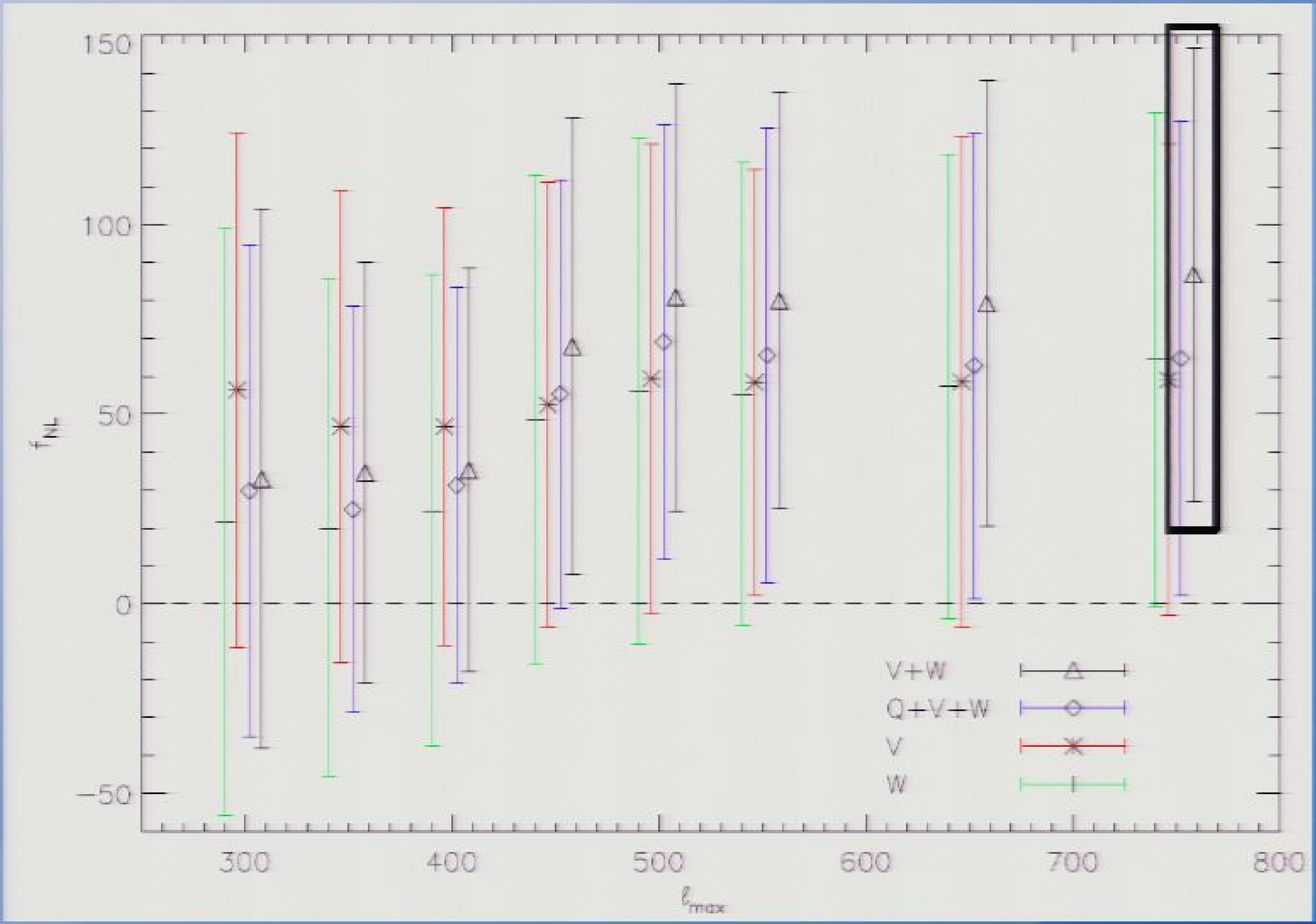
Yadav et al.



V +W

Error bars conver

Our result:



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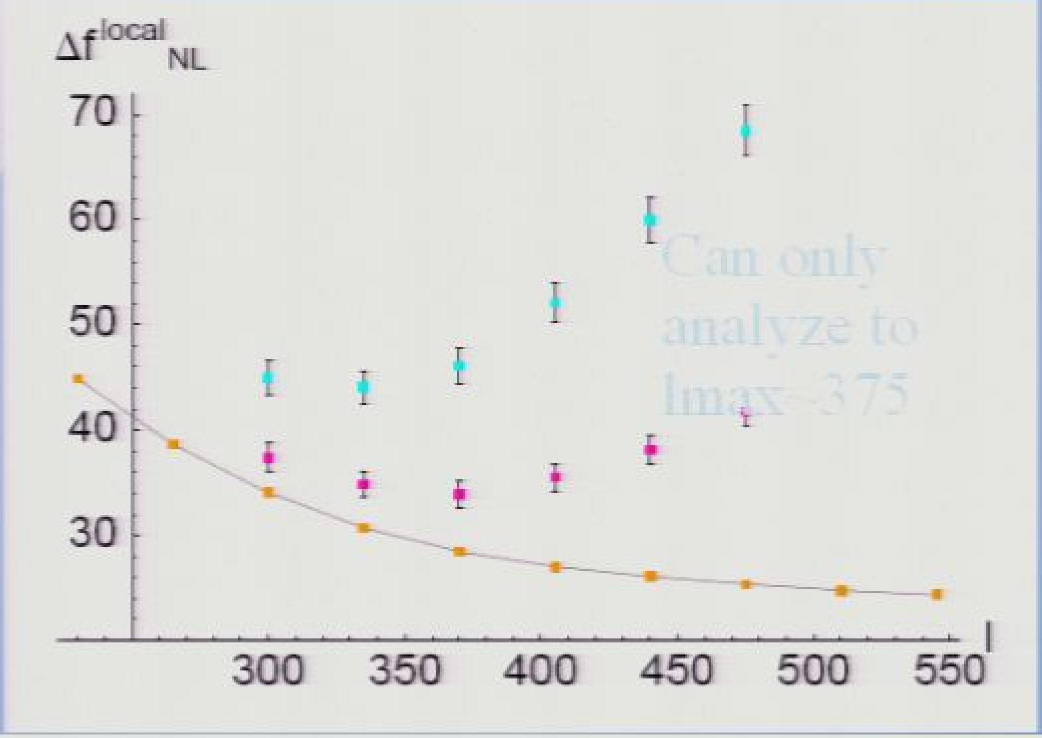

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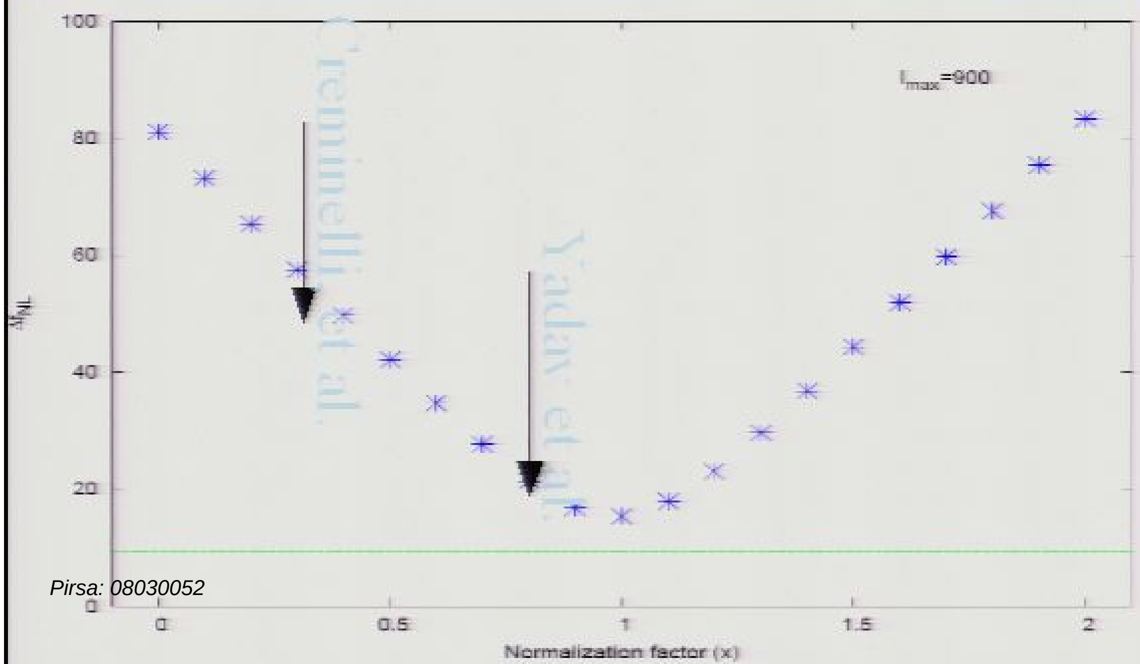
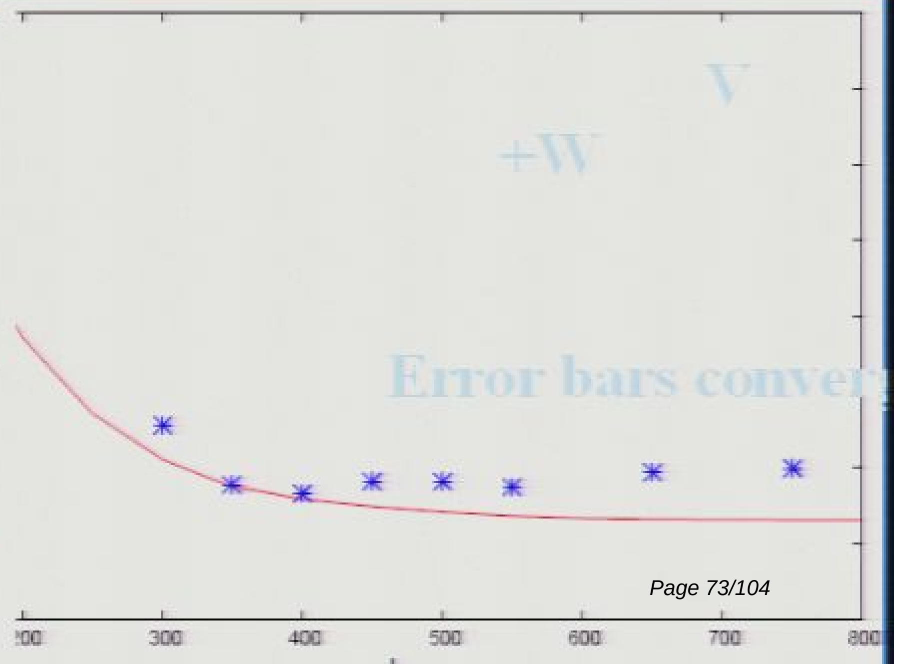
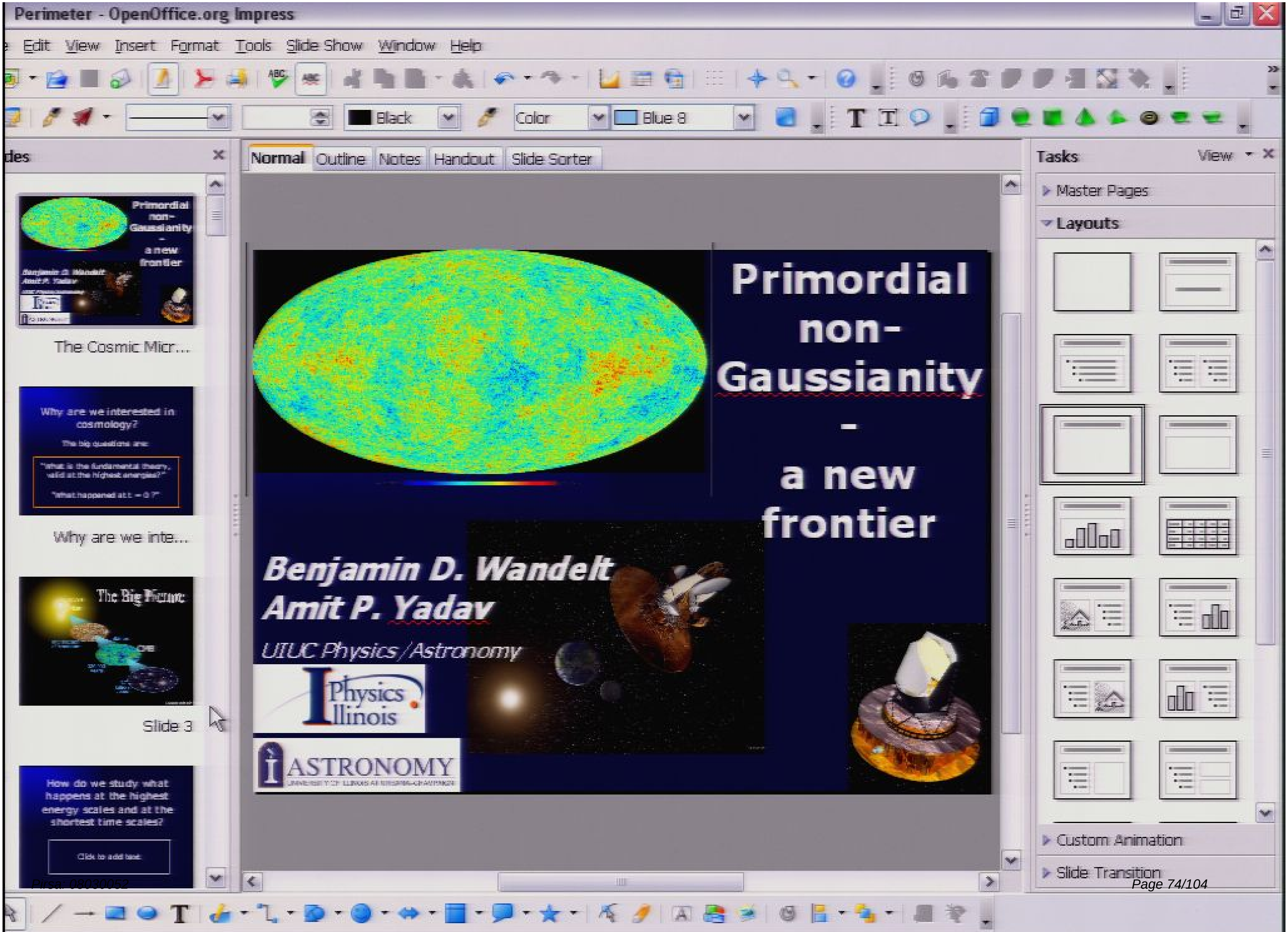






Primordial non-Gaussianity - a new frontier

Benjamin D. Wandelt
Amit P. Yadav

UIUC Physics/Astronomy

Physics Illinois

ASTRONOMY
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Why are we interested in cosmology?

The big questions are:

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

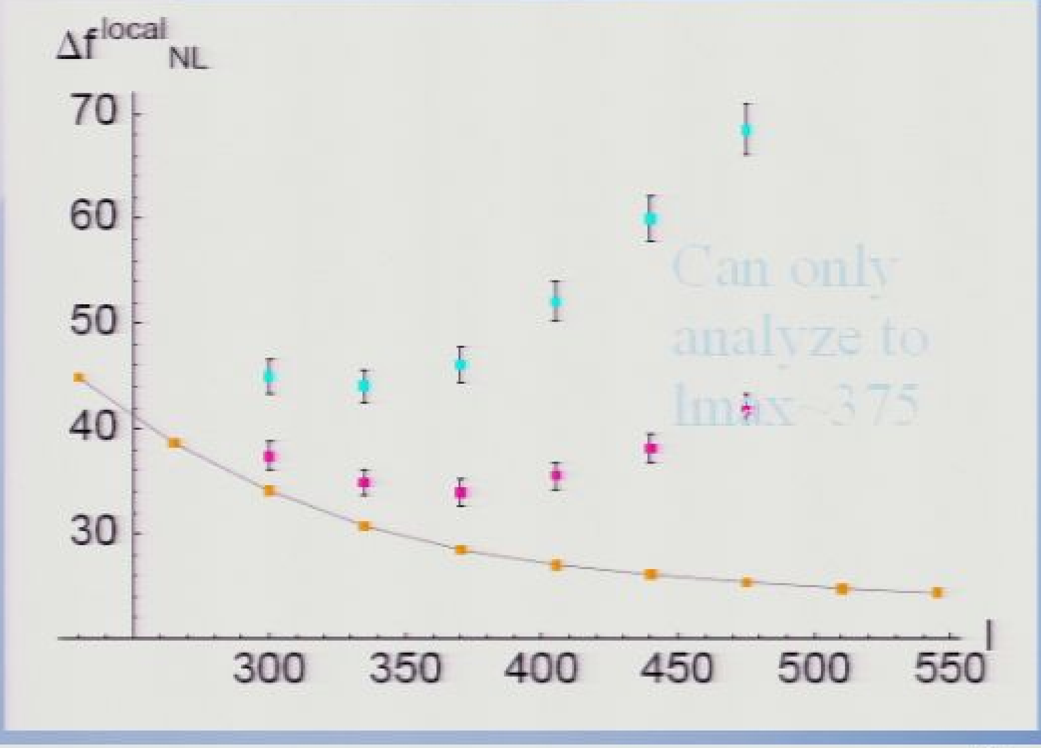
"What happened at t = 0?"

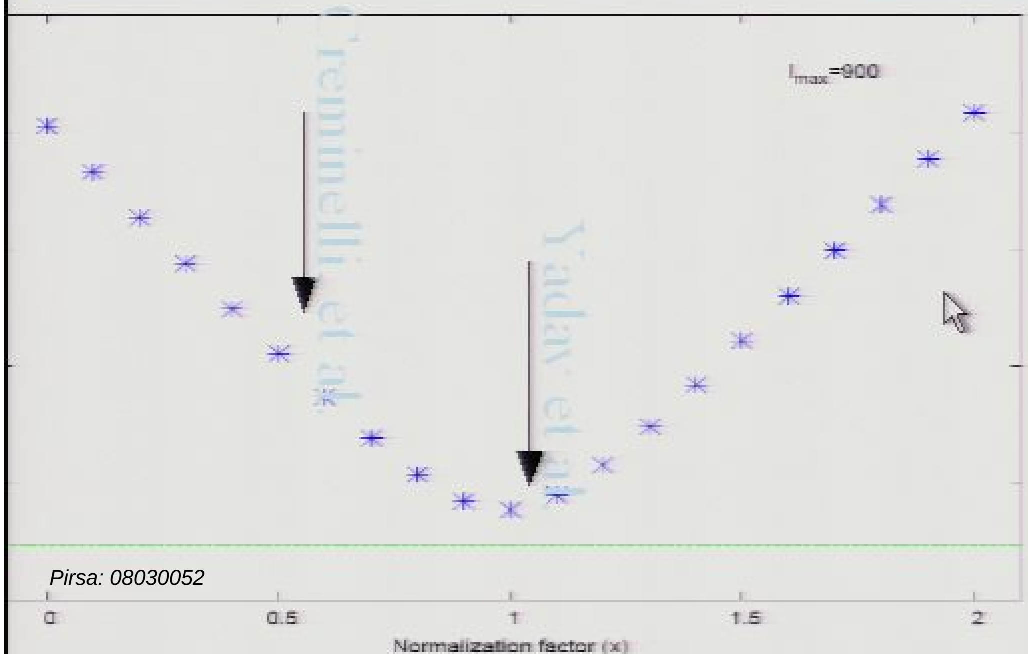
How do we study what happens at the highest energy scales and at the shortest time scales?

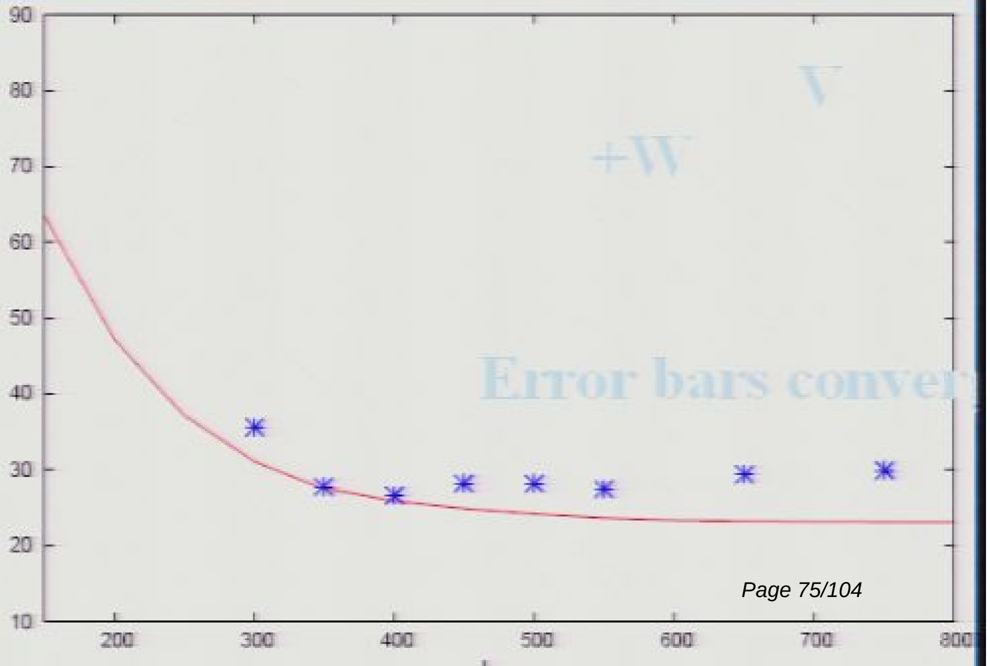
Click to add text

Creminelli et al 2006 Q+V+W

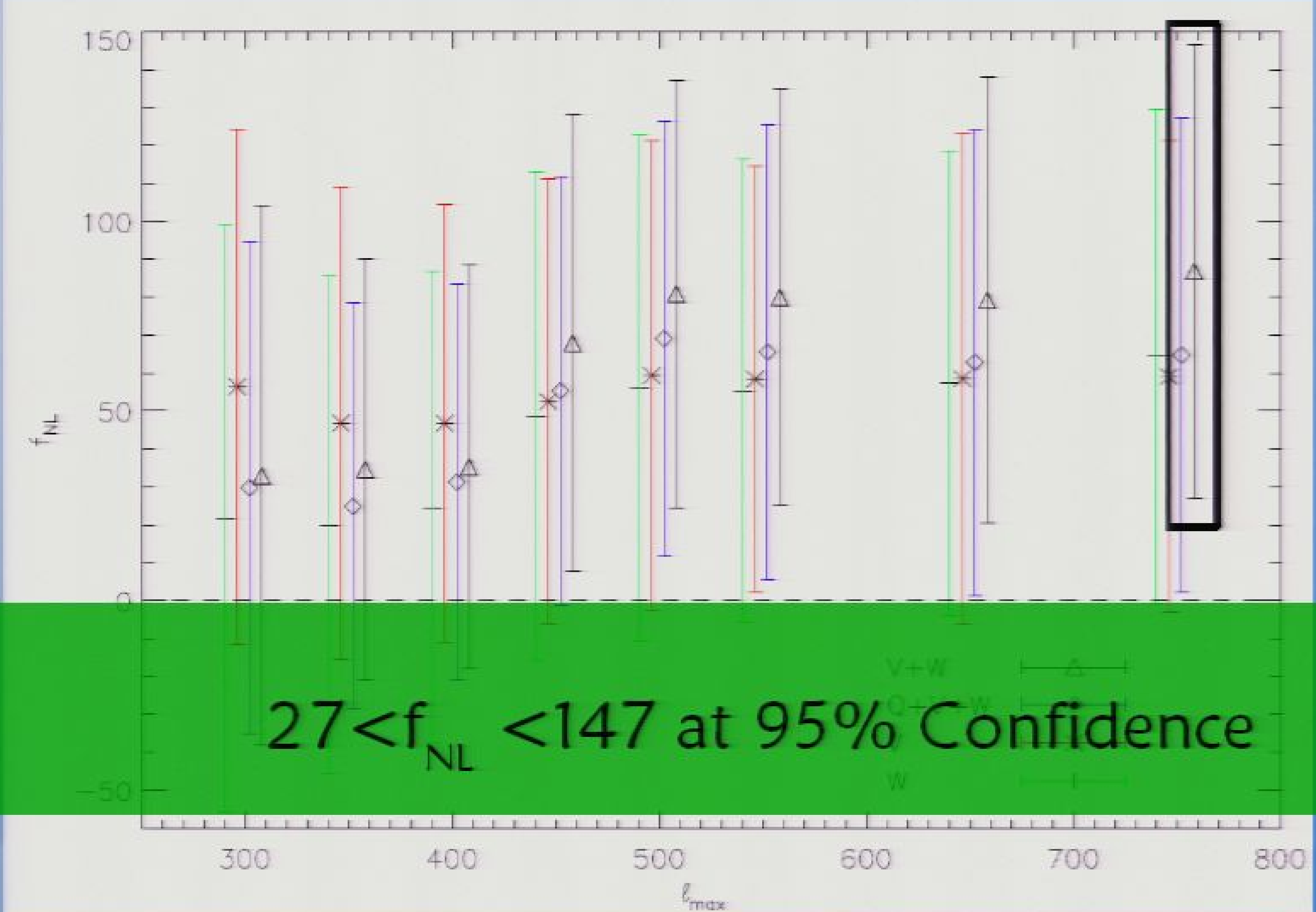
What is new in Yadav & Wandelt 2008?







Our result:



$27 < f_{NL} < 147$ at 95% Confidence

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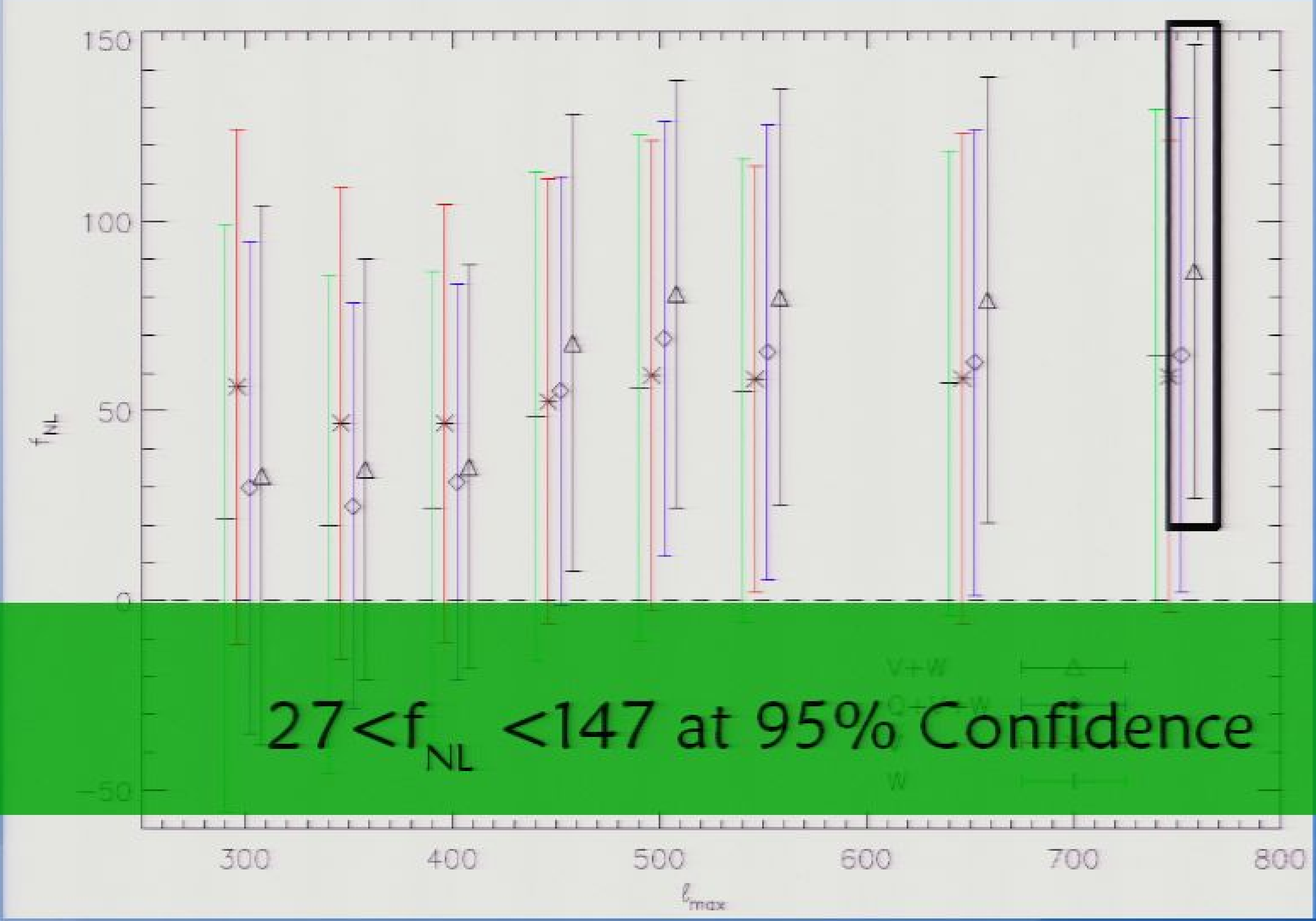

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Questions you might ask

Might his result be due to…

- Instrument systematics?
- Foregrounds?
- Secondary anisotropies?
- Just rediscovery of other non-Gaussian signals?
- Noise fluctuation?

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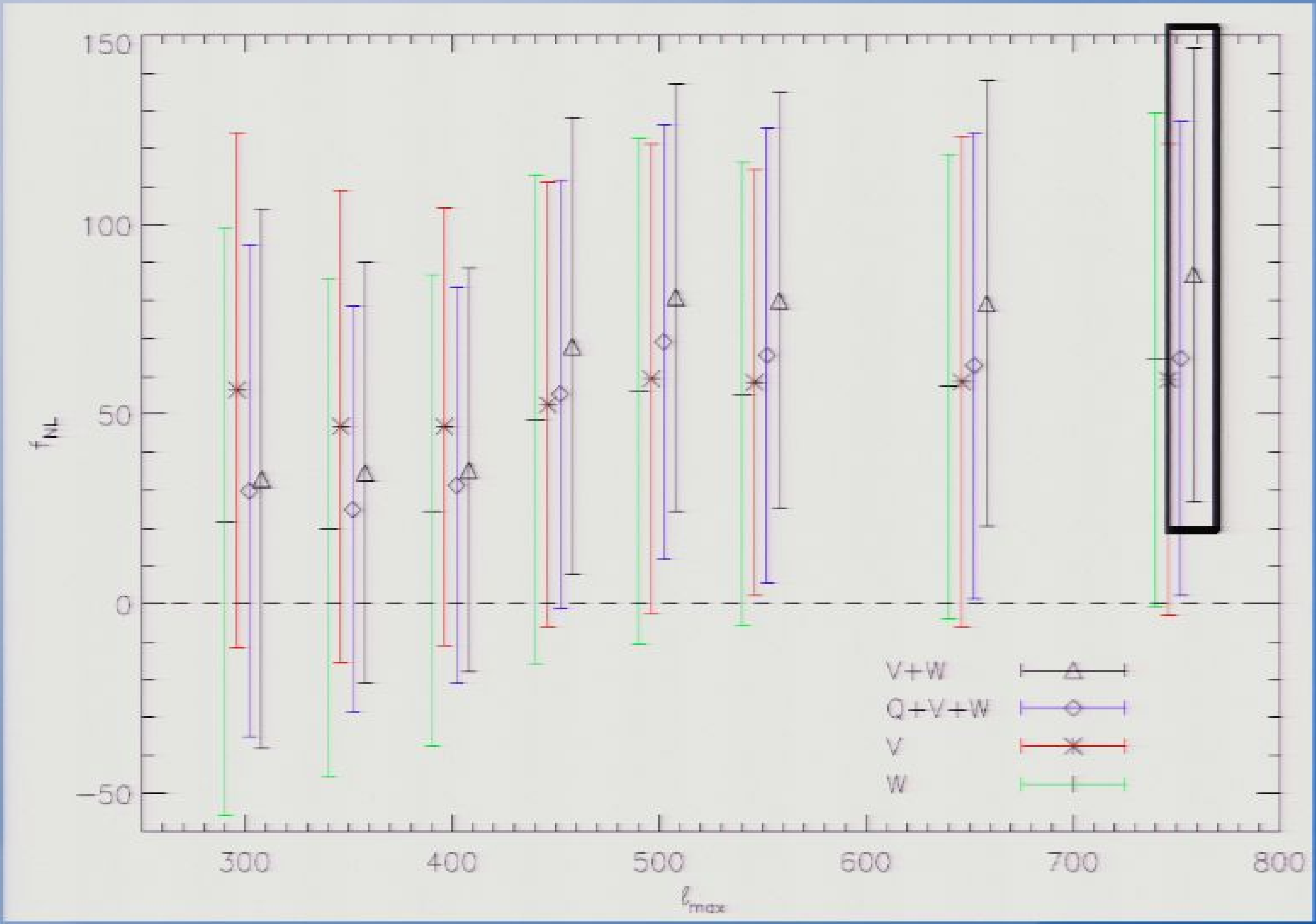

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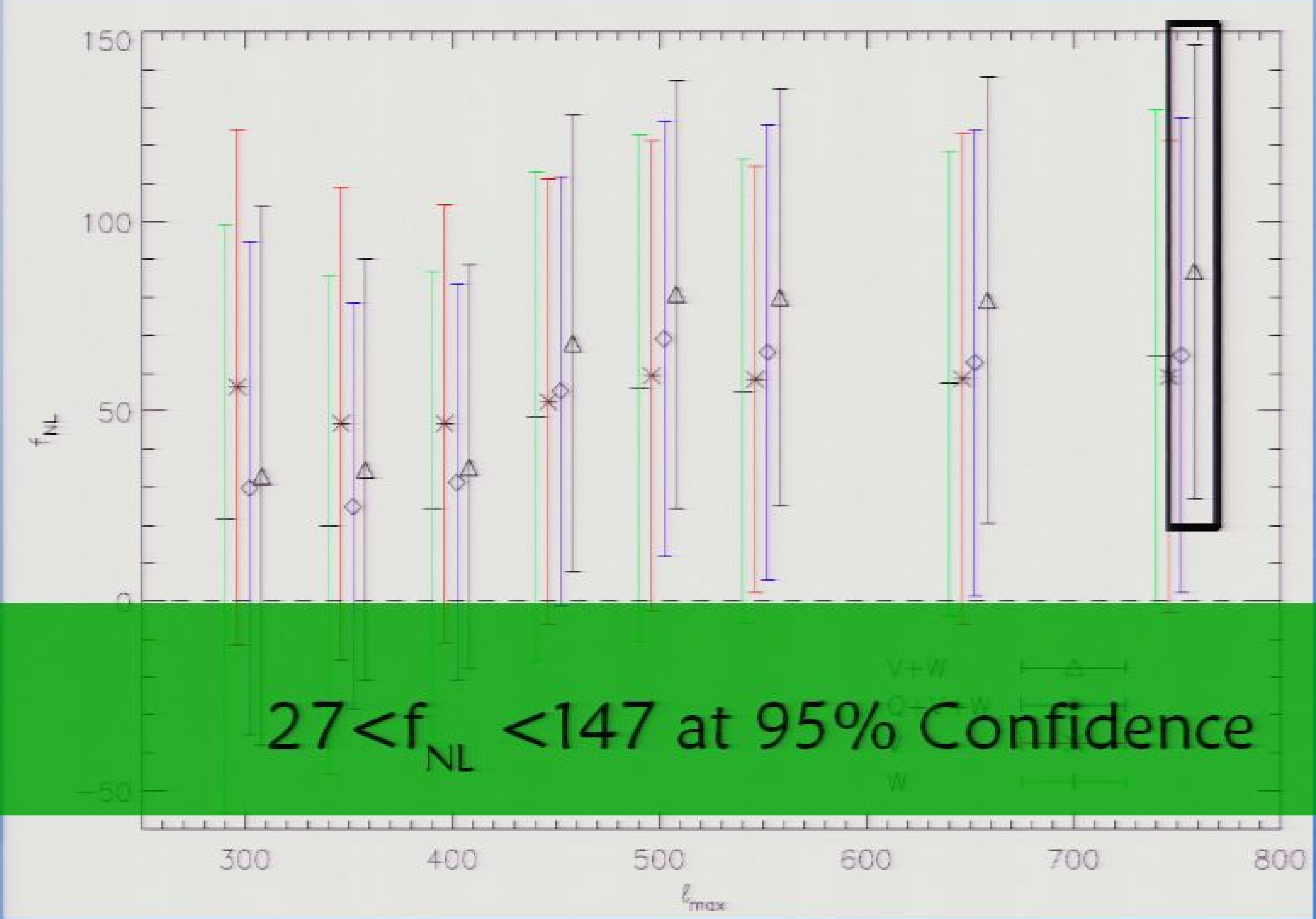

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Instrument systematics?
I) Beam asymmetries

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

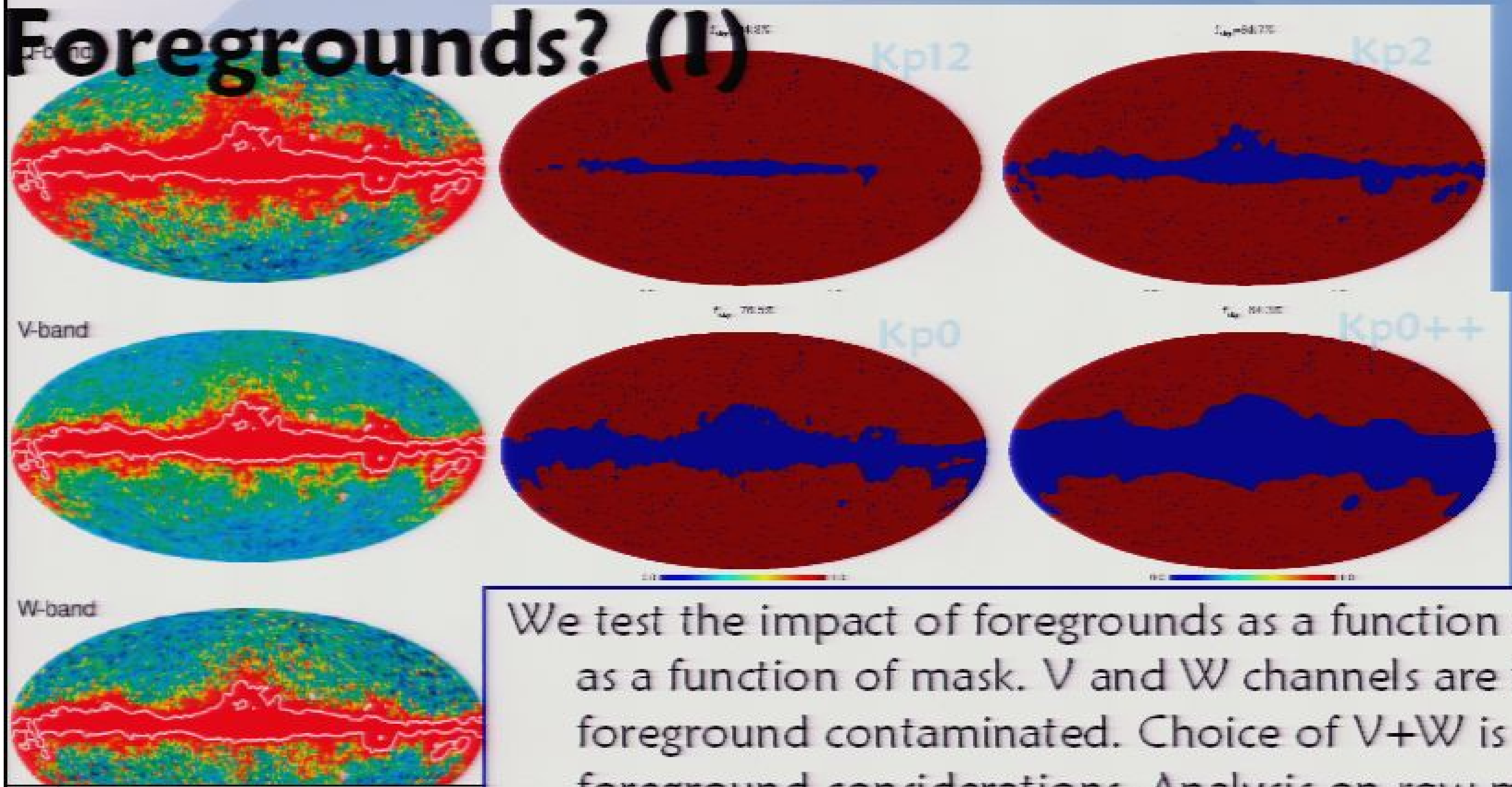
- If there are large side-lobes that spread foreground around the sky they will produce large scale features – unlikely to affect the high l regime. Further, we do not see evidence for frequency dependence.

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}.**

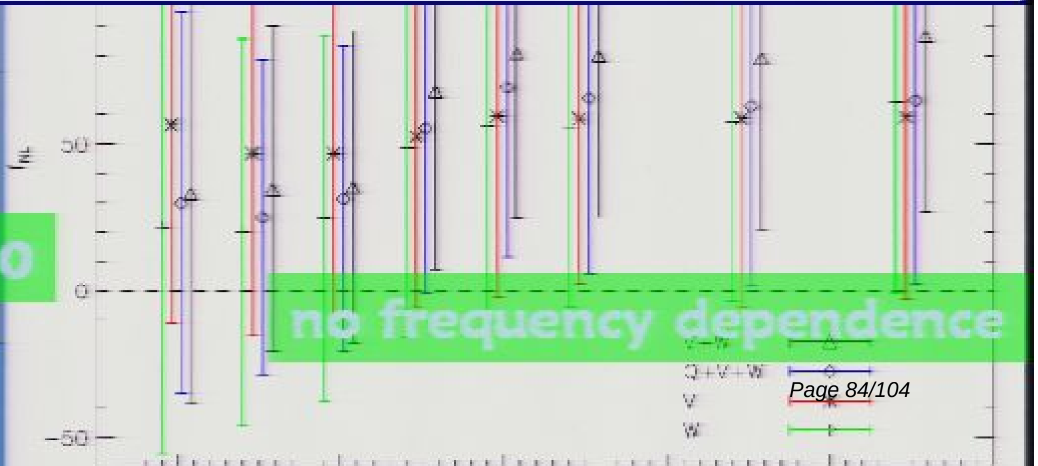
Foregrounds? (I)



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.

nax	$f_{sky} = 94.2\%$ Kp12	$f_{sky} = 84.7\%$ Kp2	Kp0	
50	-3145.22	-26.68	34.62	19.24
50	-1425.06	-15.63	67.94	64.69
50	-1509.92	-13.09	79.99	83.53
50	-1559.91	-22.43	[illegible]	[illegible]
50	-1575.11	-22.81	86.81	86.52

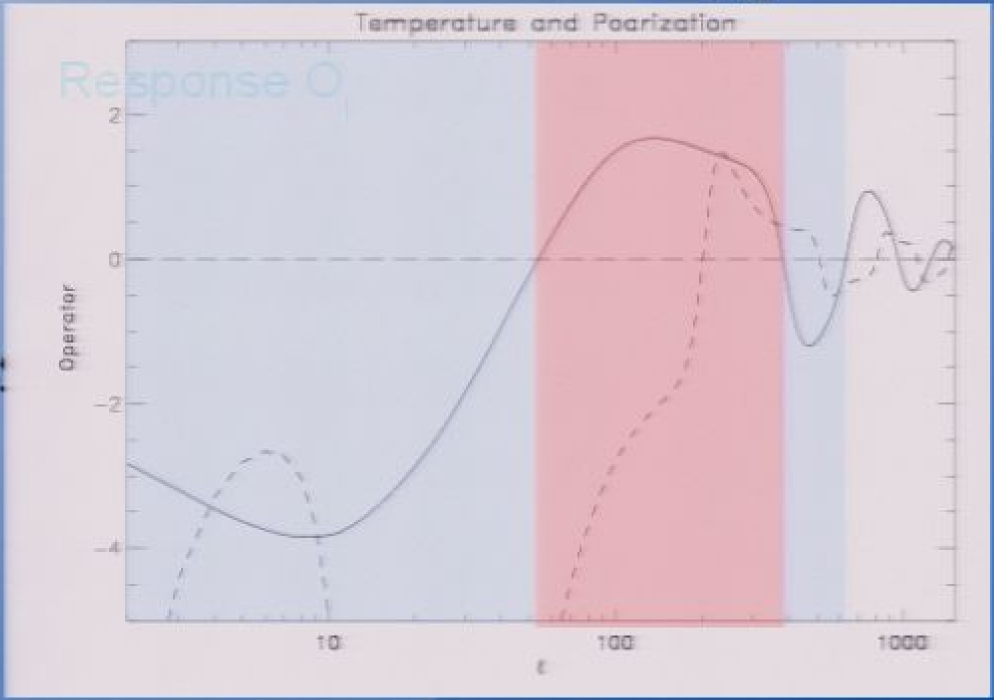
stable beyond kp0



no frequency dependence

Foregrounds? (II)

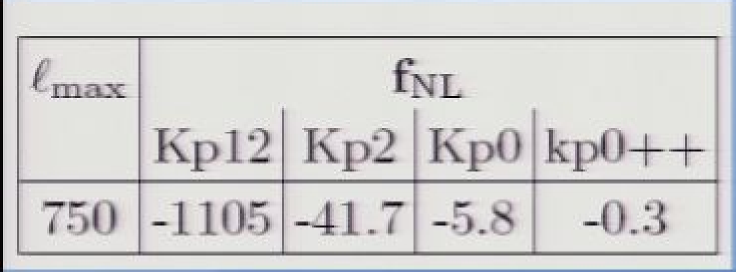
- Remember – large scale skewness in the Temperature map corresponds to *negative* f_{NL} .
- The added l modes at 400<l<550 correspond to modes where positive skewness also gives *negative* contributions.



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

Foregrounds? (III)

- WMAP Raw maps vs WMAP foreground subtracted maps
  - Foreground subtracted maps do not show negative f_{NL} behavior
  - Same level of f_{NL}, slightly higher for FG subtracted maps
- Gaussian CMB + Foregrounds + WMAP Noise



$\ell_{\max}$	f_{NL}			
	Kp12	Kp2	Kp0	kp0++
750	-1105	-41.7	-5.8	-0.3

- negative for smaller masks
- goes to zero by the time you reach Kp0 mask
- is consistent with zero for masks greater than kp0

Secondary Anisotropies?

- Point sources, including SZ X
  - 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** X 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.)**

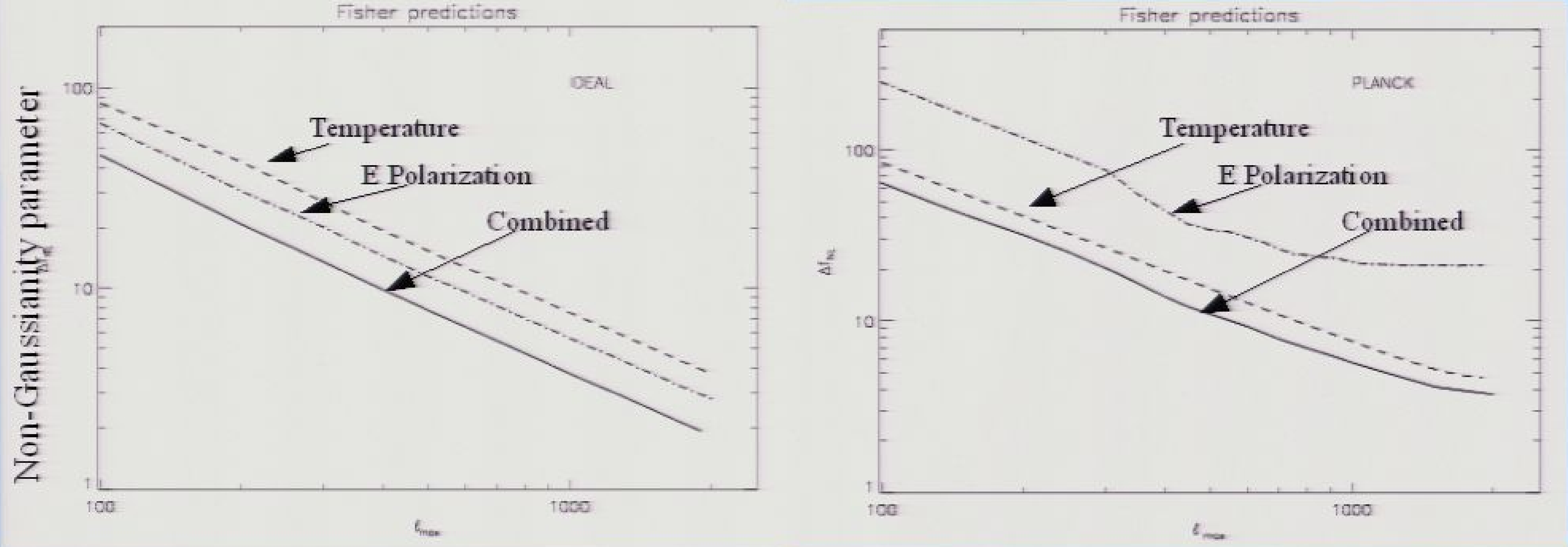
Noise fluctuation?

- 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)

Non-Gaussianity post WMAP



Smaller scales →

For and Ideal CMB experiment and using both temperature and polarization we can get down to $\Delta f_{NL} \sim 1$

For Planck the Cramer Rao limit is $\Delta f_{NL} \sim 3$.

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

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

Our detailed tests back up the analysis and arguments in Yadav & Wandelt 2007.

Conclusions and Outlook

- **“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.”**

Outlook

- New data to come soon! Forecasts:
  - WMAP 5 year: Δf_{NL} ~25 (See Eiichiro's talk!)
  - WMAP 8 year: Δf_{NL} ~21
- Δf_{NL} ~5 from Planck T and E polarization (in <5 yrs!)
- Cross-checks using temperature and polarization
- f_{NL} is complementary to tensor modes as a way to distinguish between classes of models that give similar predictions for the two-point correlations
- Great news for very early Universe cosmology!

No Signal

VGA-1

No Signal

VGA-1

No Signal

VGA-1

No Signal

VGA-1

No Signal

VGA-1

No Signal
VGA-1

No Signal

VGA-1

No Signal

VGA-1

No Signal

VGA-1

No Signal

VGA-1

WMAP 5-Year Results: Measurement of f_{NL}

Eiichiro Komatsu
University of Texas at Austin
"Origins and Observations of Primordial Non-Gaussianity"
Perimeter Institute, March 8, 2008