From Microwave to Gravity Waves: The Role of Gravitational Lensing

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Center for Cosmology, UC Irvine

In collaboration with:
Daniel Baumann (Princeton), Kiyotomo Ichiki (Tokyo), Paolo Serra (UCI), Asantha Cooray (UCI).

Univ. of Michigan — "Informal" Talk — January 16, 2009

Agenda

Primordial Non-Gaussianity and CMB Bispectrum

- Beyond Gaussianity
- CMB Bispectrum
- Lensing of CMB
- Lensed Bispectrum
- S/N Reduction & Bias

Prospects of Detecting Gravity Waves via Weak Lensing

- ABC of Gravity Waves
- Lensing 201 Revisited
- Gravity Wave Spectra
- Detection Prospects
- Conclusions

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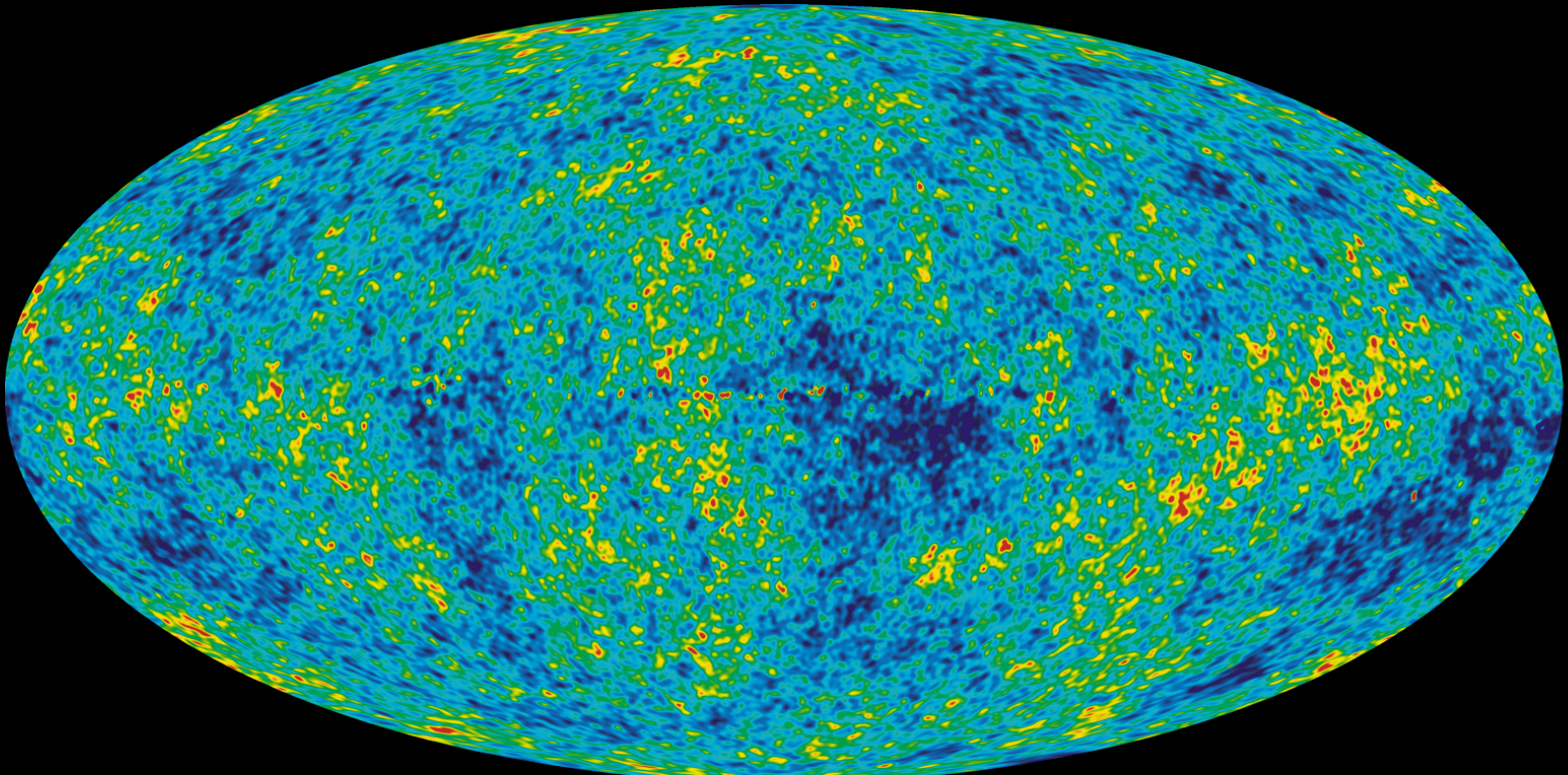
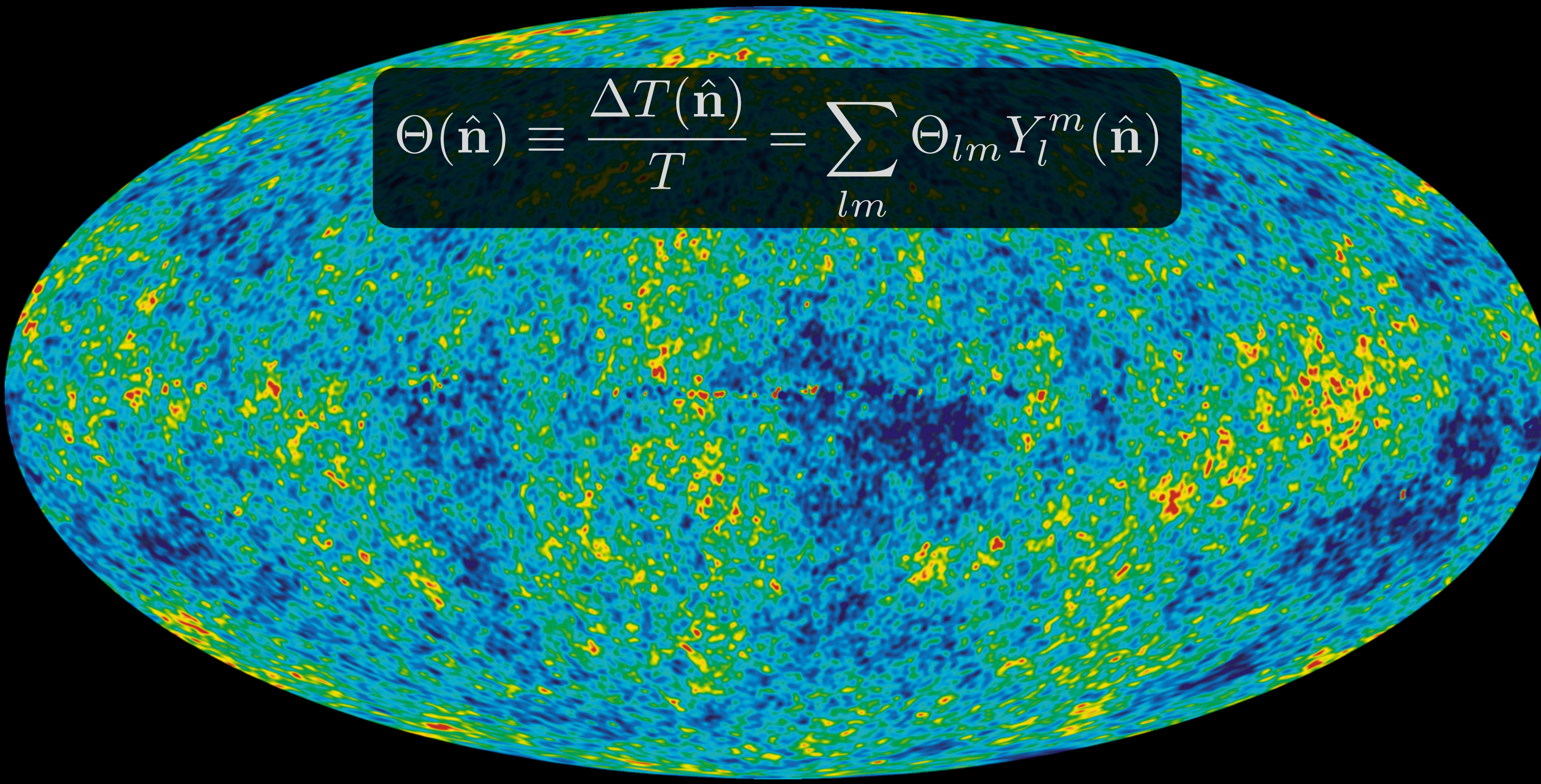
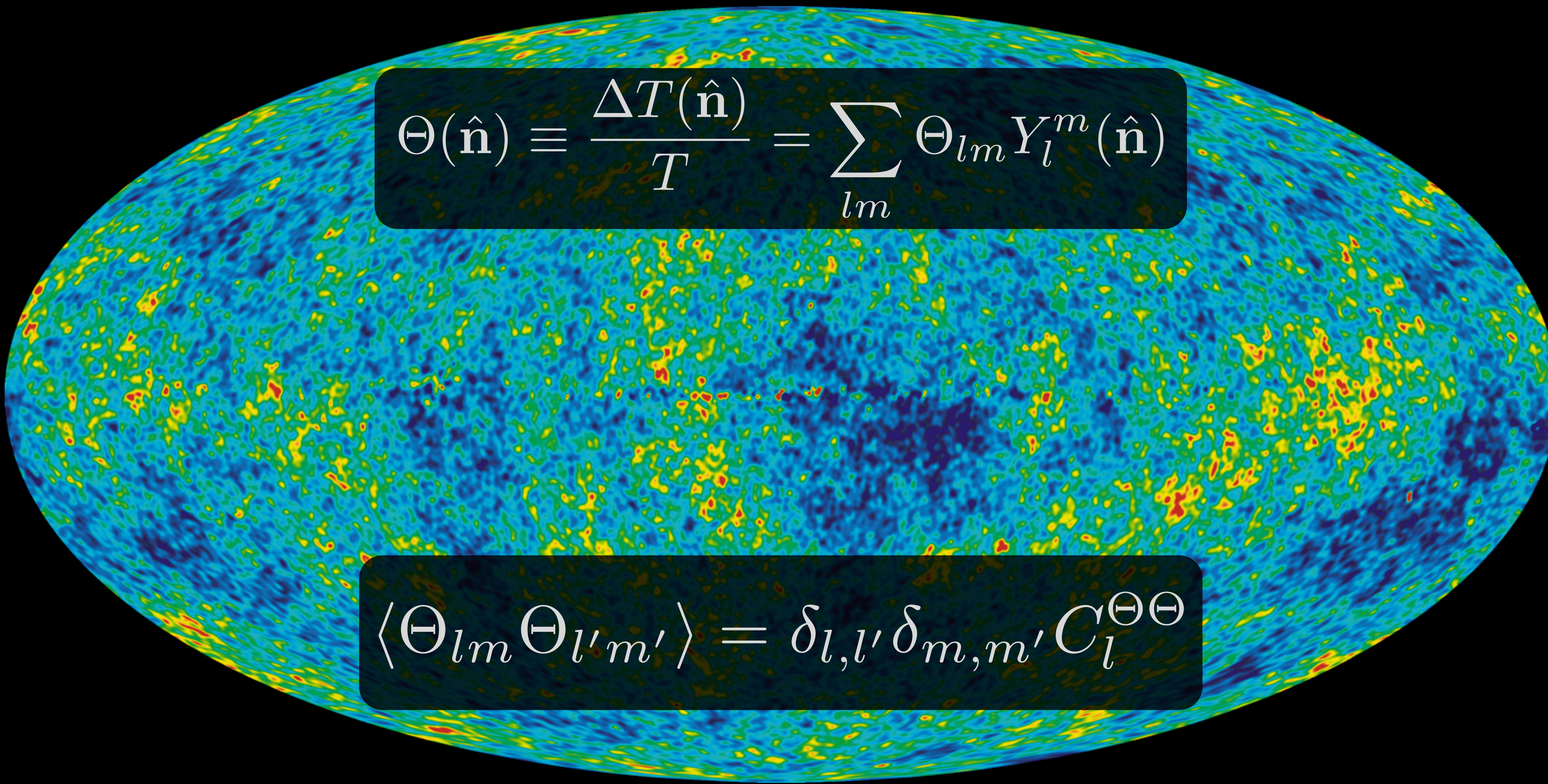


Credit: NASA/WMAP Science Team



$$\Theta(\hat{\mathbf{n}}) \equiv \frac{\Delta T(\hat{\mathbf{n}})}{T} = \sum_{lm} \Theta_{lm} Y_l^m(\hat{\mathbf{n}})$$

Credit: NASA/WMAP Science Team



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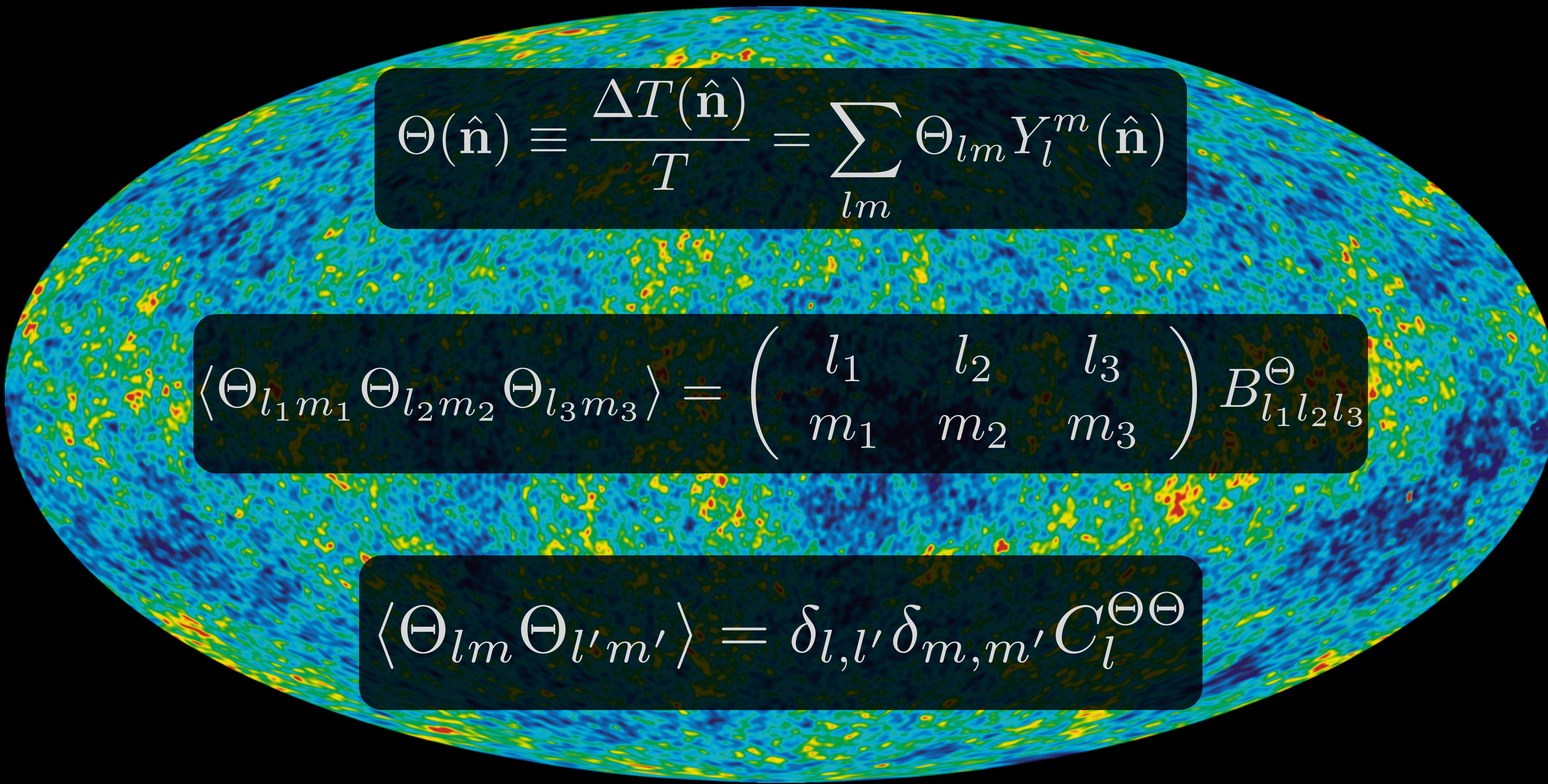
$$\langle \Theta_{lm} \Theta_{l'm'} \rangle = \delta_{l,l'} \delta_{m,m'} C_l^{\Theta\Theta}$$

Credit: NASA/WMAP Science Team



$$\Theta(\hat{\mathbf{n}}) \equiv \frac{\Delta T(\hat{\mathbf{n}})}{T} = \sum_{lm} \Theta_{lm} Y_l^m(\hat{\mathbf{n}})$$

$$\langle \Theta_{l_1 m_1} \Theta_{l_2 m_2} \Theta_{l_3 m_3} \rangle = \begin{pmatrix} l_1 & l_2 & l_3 \\ m_1 & m_2 & m_3 \end{pmatrix} B^{\Theta}_{l_1 l_2 l_3}$$

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Credit: NASA/WMAP Science Team

Primordial non-Gaussianity

→ Primary CMB Bispectrum

Primordial non-Gaussianity

→ Primary CMB Bispectrum

Gaussian Quantum Fluctuation

↓

Non-Gaussian Inflation Fluctuation

↓

Non-Gaussian Curvature Perturbation

↓

Non-Gaussian CMB Anisotropy

Primordial non-Gaussianity

→ Primary CMB Bispectrum

$$\frac{\Delta T(\mathbf{x})}{T} \sim \Phi(\mathbf{x})$$

↕

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

↑ Non-Linear Coupling Parameter

Measurement of non-Gaussian CMB anisotropies can potentially constrain non-linearity, "slow-rollness", and "adiabaticity" in inflation.

Primordial non-Gaussianity

Primary CMB Bispectrum

Non-Gaussianity from the simplest inflation model is very small:

$$f_{NL} \sim 0.01 - 1$$

Much higher level of primordial non-Gaussianity is predicted by:

- Models with Multiple Scalar Fields
- Non-Adiabatic Fluctuations
- Features in the Inflation Potential
- Non-Canonical Kinetic Terms
- ...

Review: N. Bartolo, E. Komatsu, S. Matarrese, and A. Riotto, Phys. Rep. 402, 103 (2004)

PRL 100, 181301 (2008) PHYSICAL REVIEW LETTERS week ending 9 MAY 2008

Evidence of Primordial Non-Gaussianity ($f_{\rm NL}$) in the Wilkinson Microwave Anisotropy Probe 3-Year Data at 2.8σ

Amit P. S. Yadav[1] and Benjamin D. Wandelt[1,2]

[1]*Department of Astronomy, University of Illinois at Urbana-Champaign, 1002 W. Green Street, Urbana, Illinois 61801, USA*
[2]*Department of Physics, University of Illinois at Urbana-Champaign, 1110 W. Green Street, Urbana, Illinois 61801, USA*

(Received 7 December 2007; revised manuscript received 6 March 2008; published 7 May 2008)

We present evidence for primordial non-Gaussianity of the local type ($f_{\rm NL}$) in the temperature anisotropy of the cosmic microwave background. Analyzing the bispectrum of the Wilkinson Microwave Anisotropy Probe 3-year data up to $\ell_{\rm max} = 750$ we find $27 < f_{\rm NL} < 147$ (95% C.L.). This amounts to a rejection of $f_{\rm NL} = 0$ at 2.8σ, disfavoring canonical single-field slow-roll inflation. The signal is robust to variations in $l_{\rm max}$, frequency and masks. No known foreground, instrument systematic, or secondary anisotropy explains it. We explore the impact of several analysis choices on the quoted significance and find 2.5σ to be conservative.

FIVE-YEAR WILKINSON MICROWAVE ANISOTROPY PROBE (WMAP[1]) OBSERVATIONS: COSMOLOGICAL INTERPRETATION

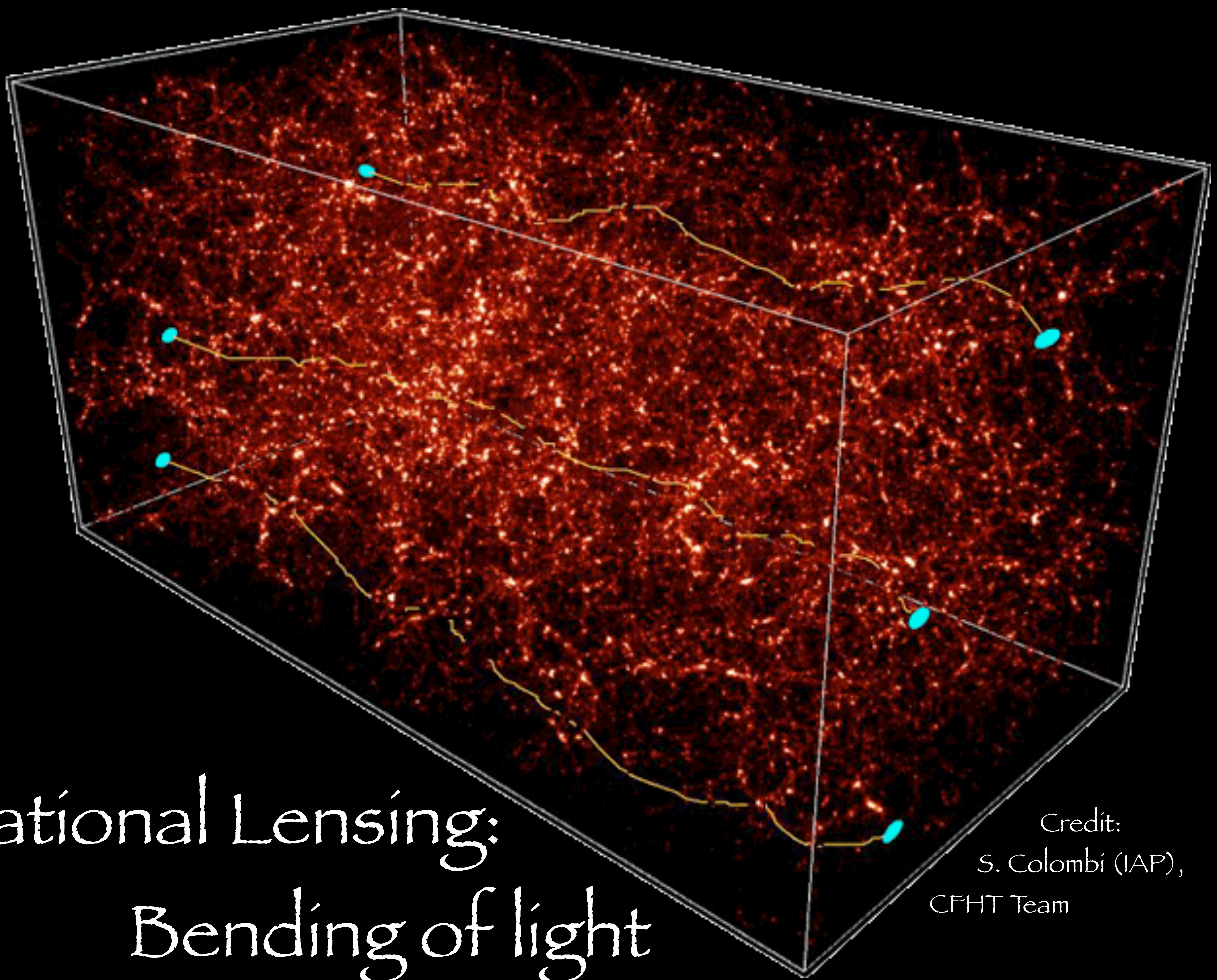
E. Komatsu [1], J. Dunkley [2,3,4], M. R. Nolta [5], C. L. Bennett [6], B. Gold [6], G. Hinshaw [7], N. Jarosik [2], D. Larson [6], M. Limon [8] L. Page [2], D. N. Spergel [3,9], M. Halpern [10], R. S. Hill [11], A. Kogut [7], S. S. Meyer [12], G. S. Tucker [13], J. L. Weiland [10], E. Wollack [7], and E. L. Wright [14]

Submitted to the Astrophysical Journal Supplement Series

ABSTRACT

$$-9 < f_{NL}^{local} < 111 \text{ and } -151 < f_{NL}^{equil} < 253 (95\% \, CL)$$

Journey Through the "Clumpy" Universe



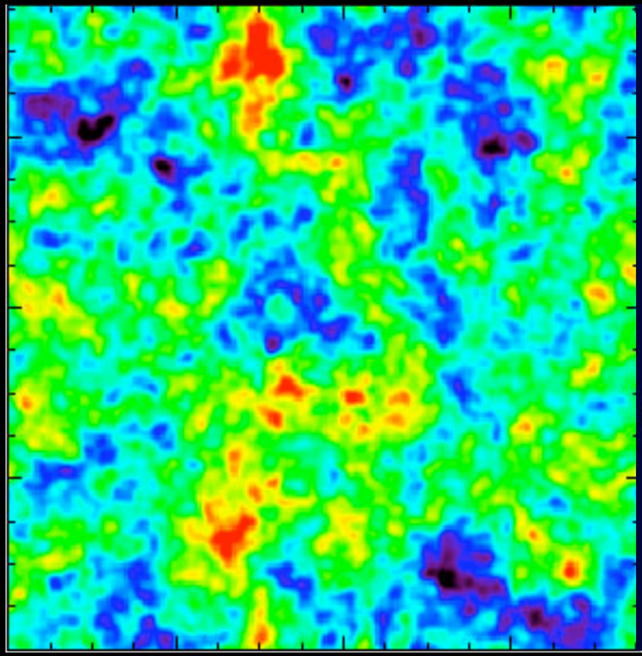
Weak

Gravitational Lensing:

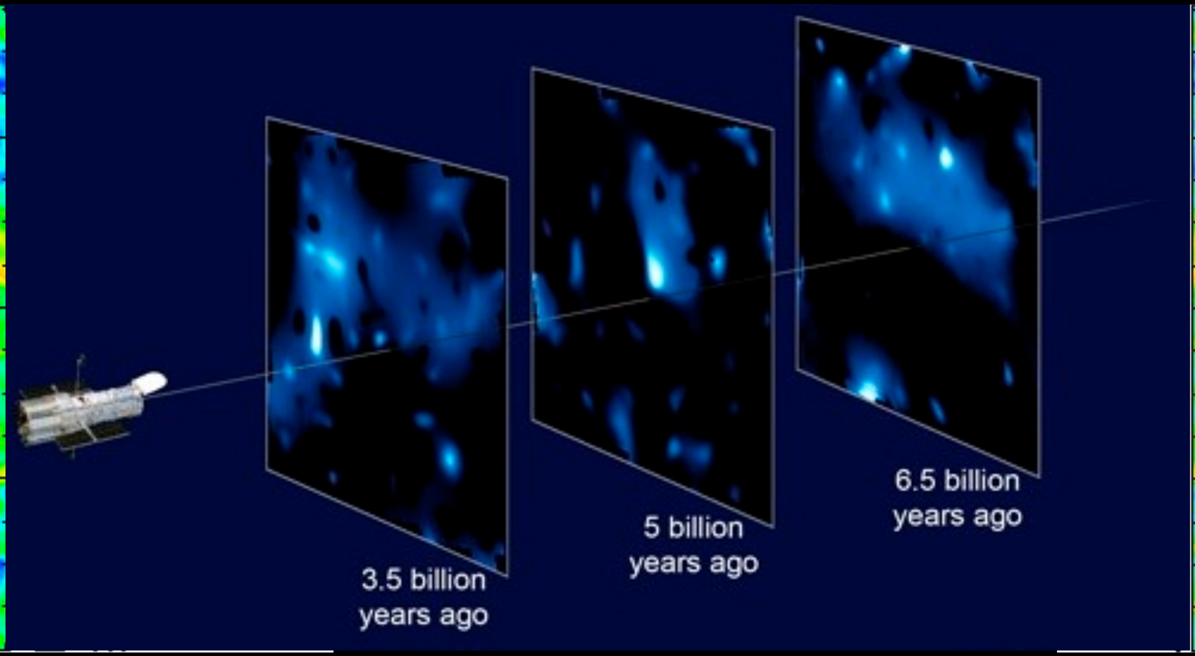
Bending of light

Credit:
S. Colombi (IAP),
CFHT Team

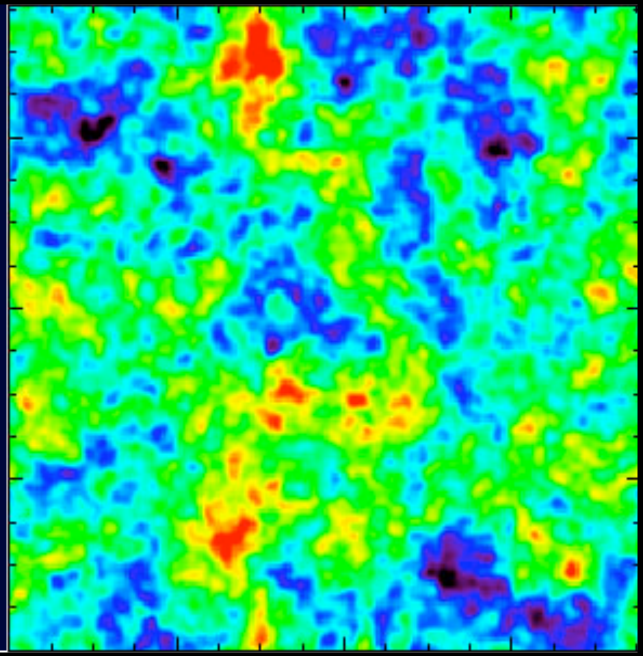
Weak Lensing of the Primary Bispectrum



Credit: Vale, Amblard, White (2004)



NASA, ESA, and R. Massey (CalTech)



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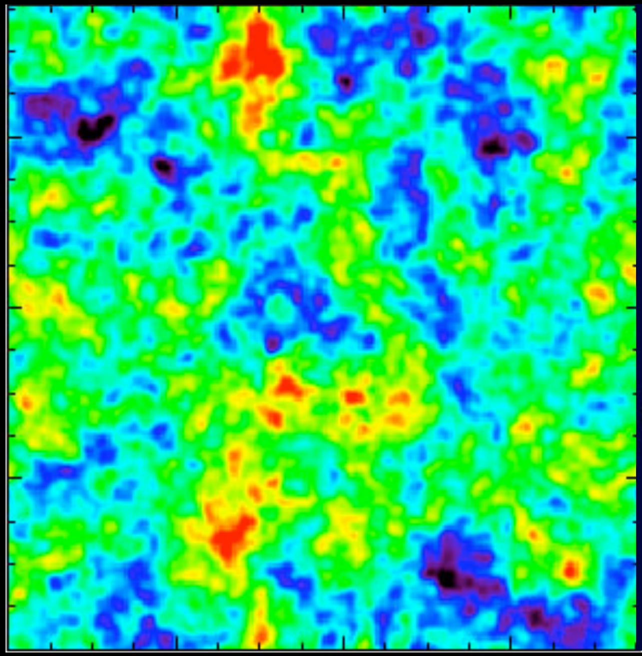

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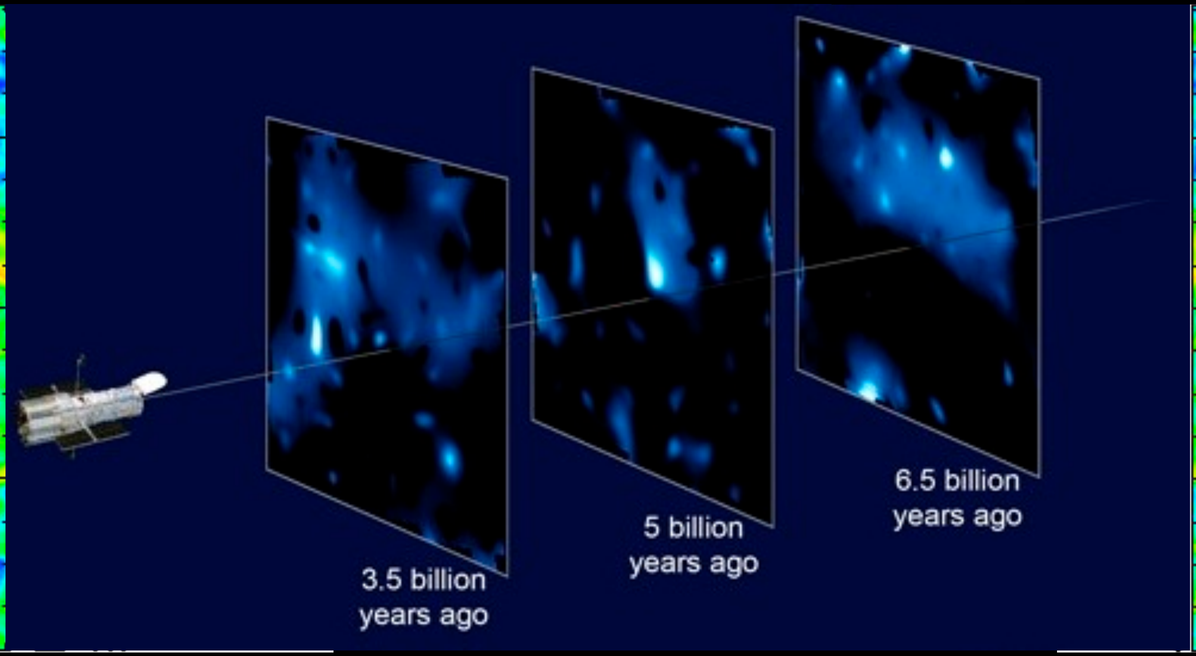

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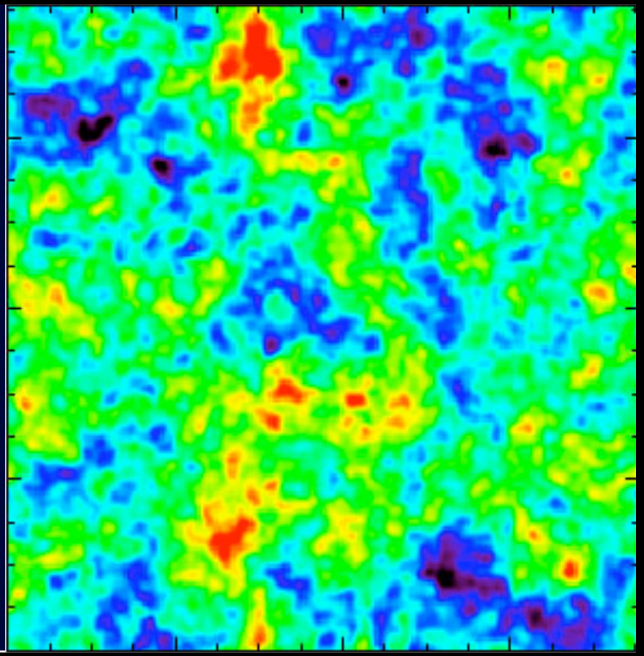

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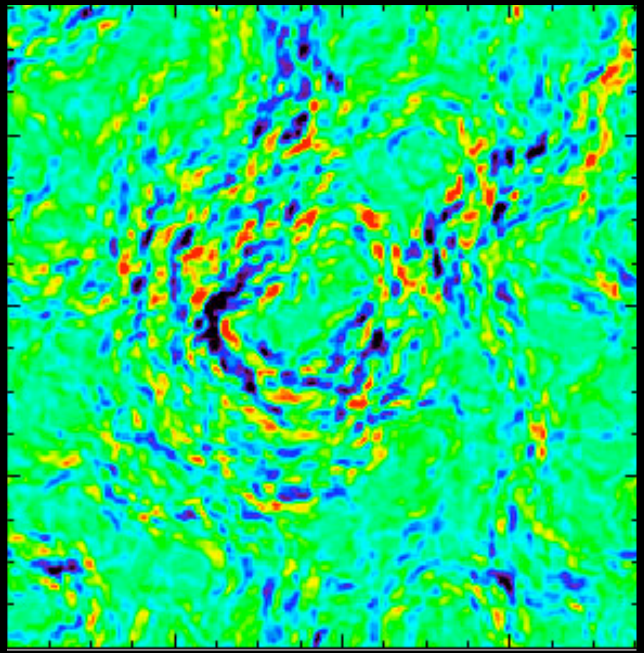

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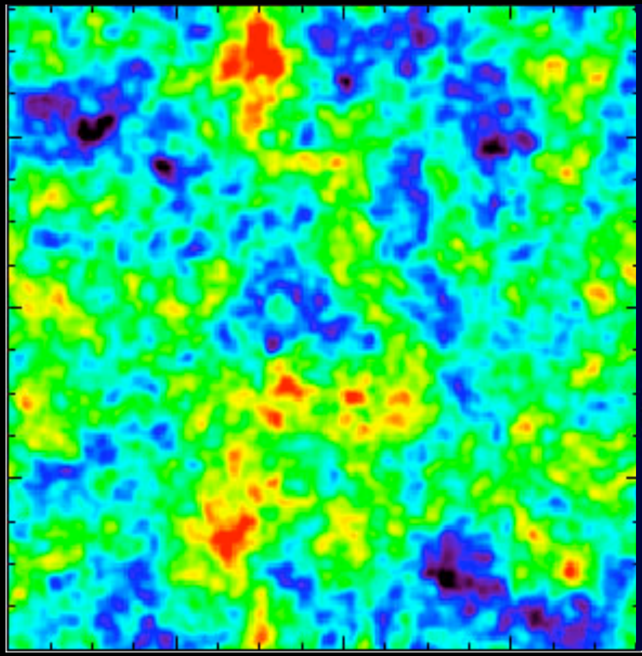

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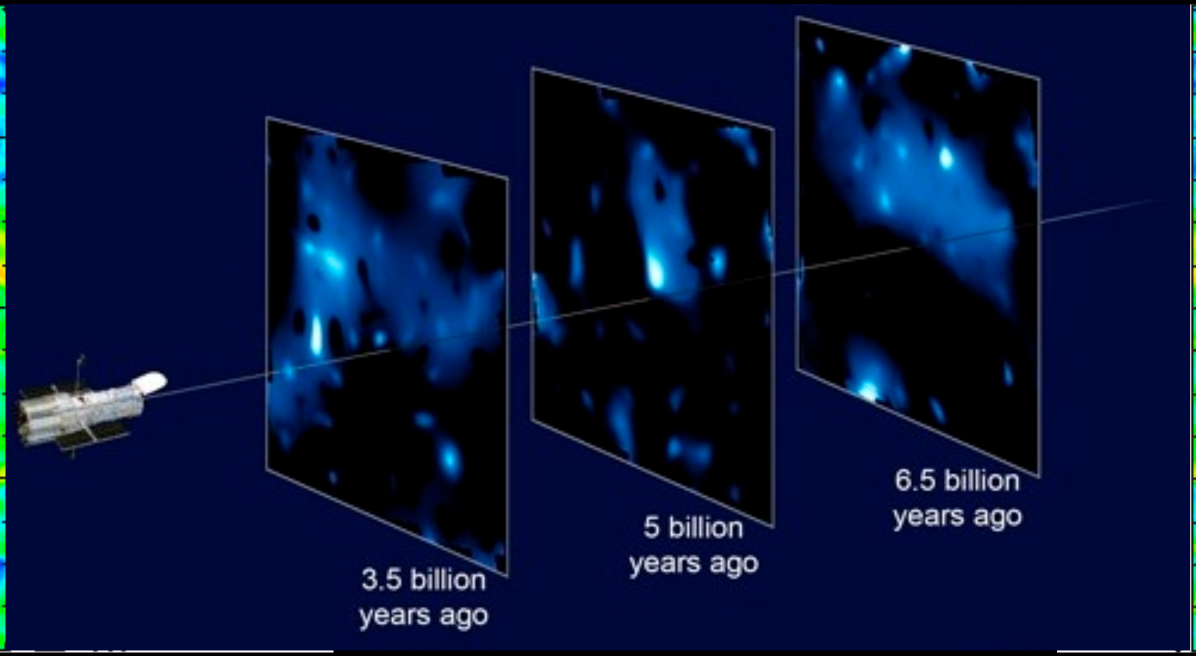

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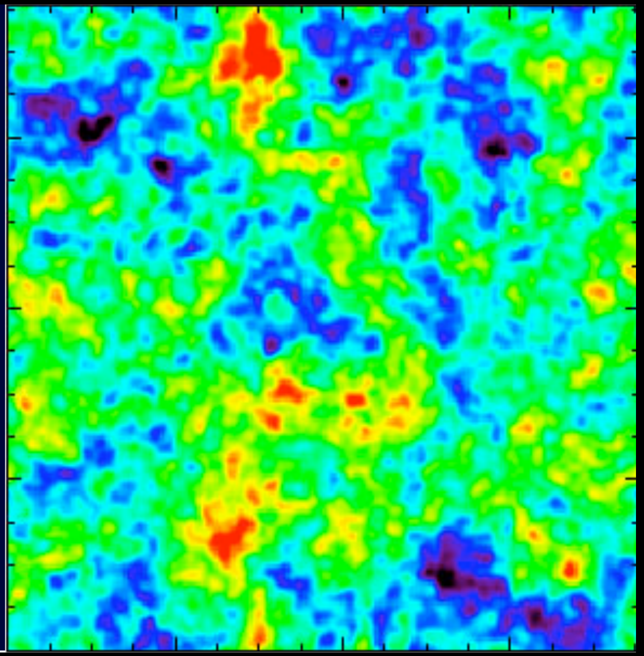

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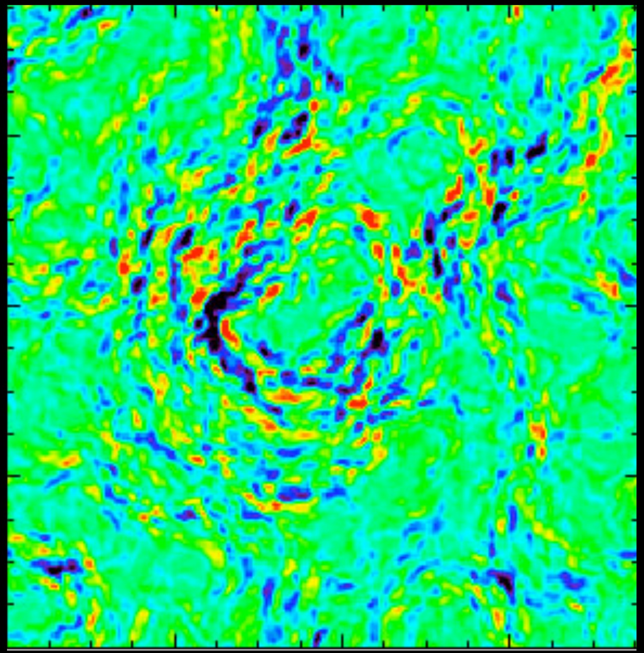
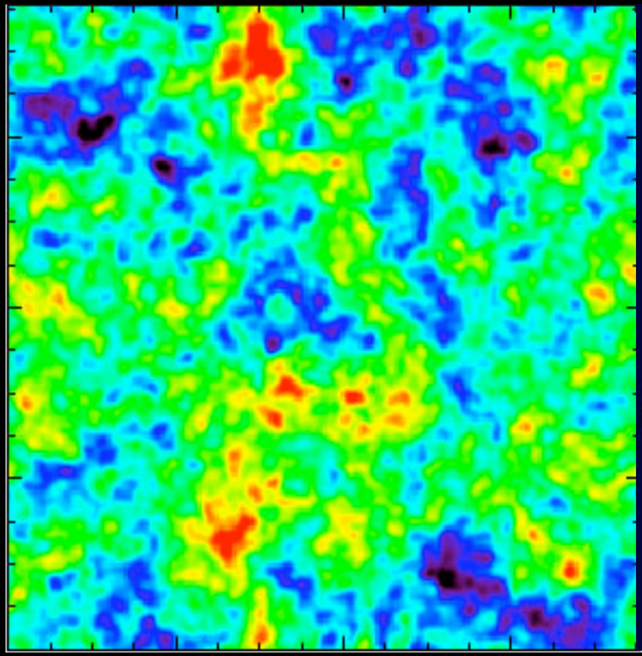


Weak Lensing of the Primary Bispectrum



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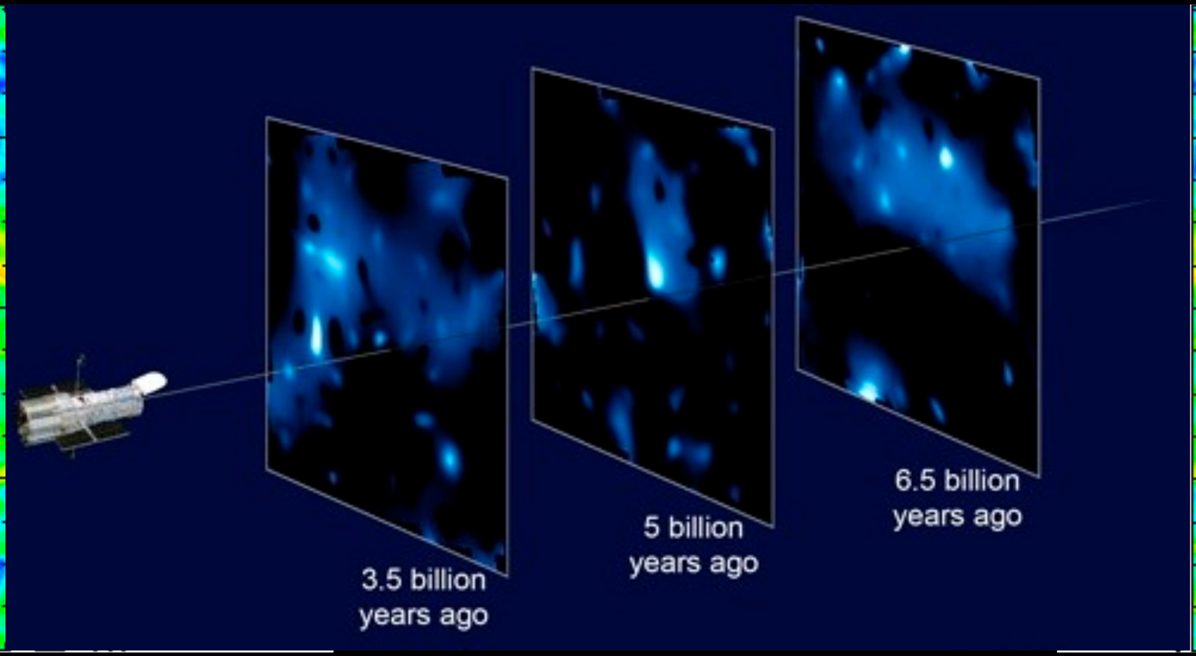

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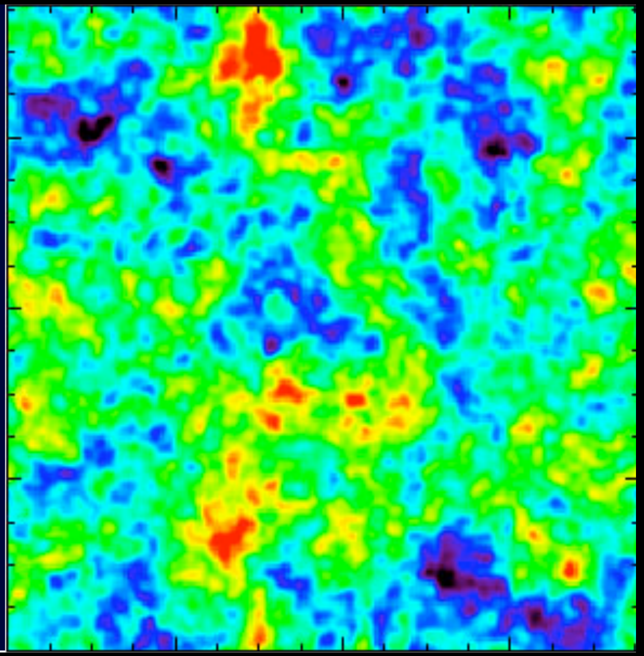

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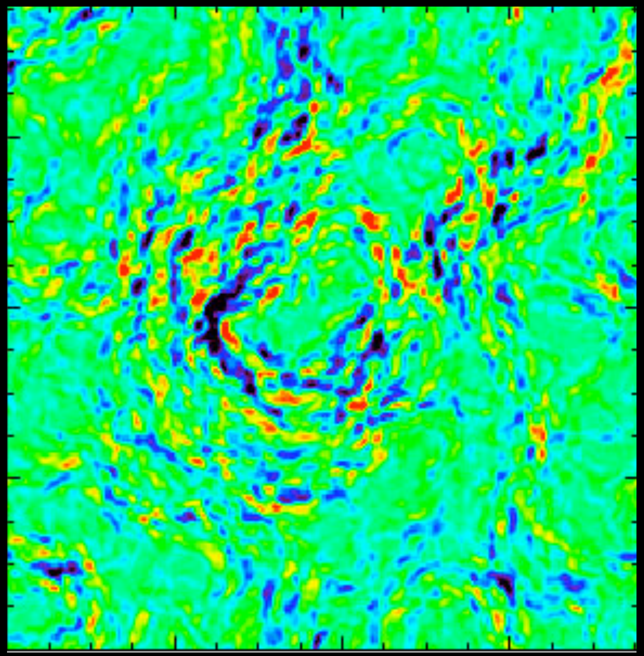

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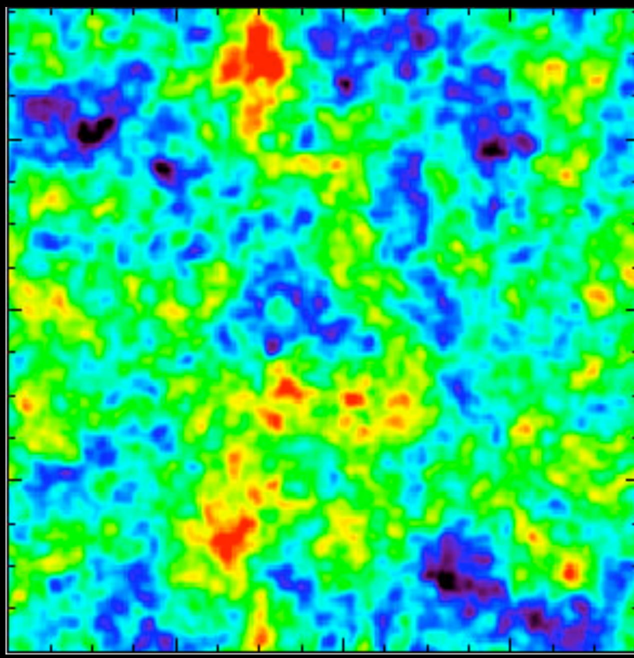

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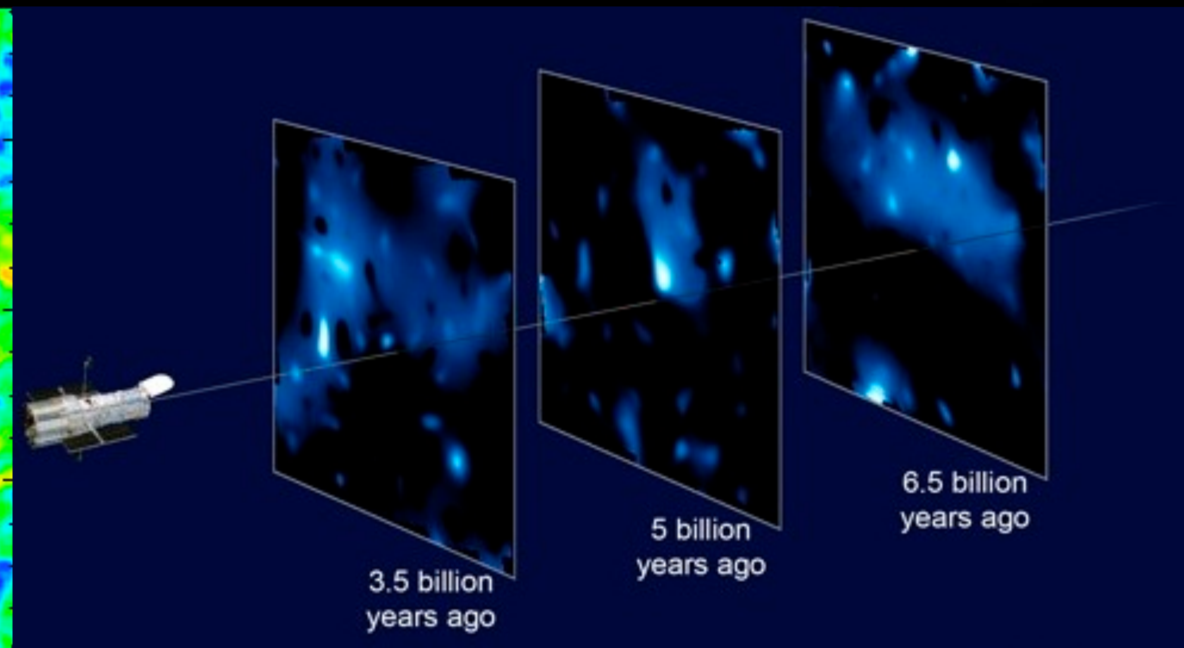

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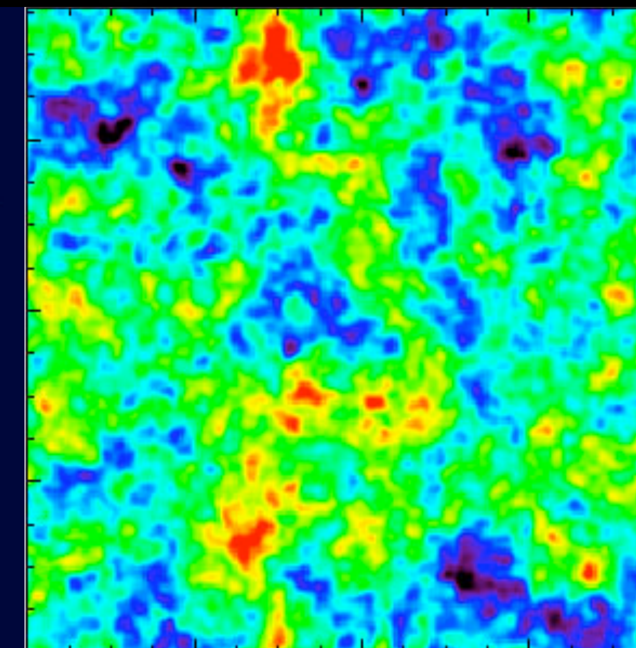

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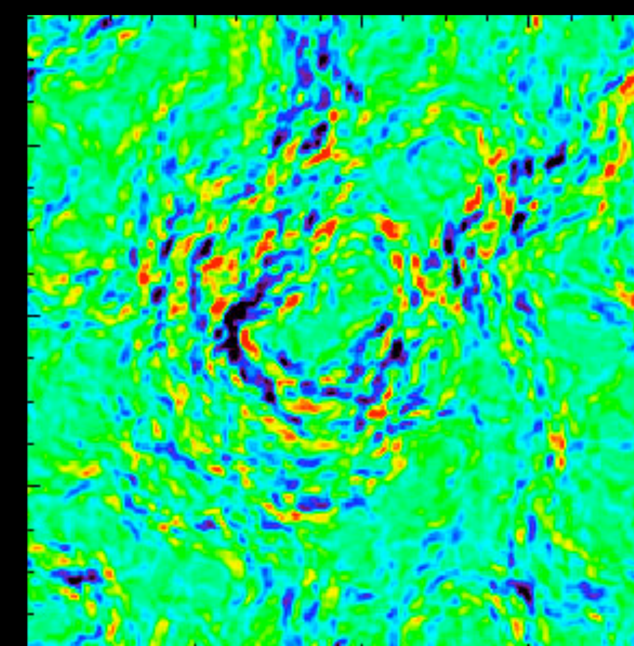

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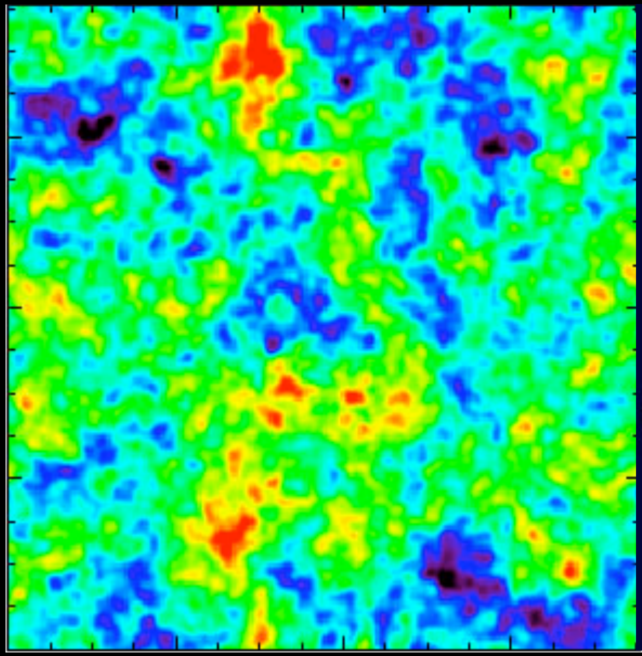

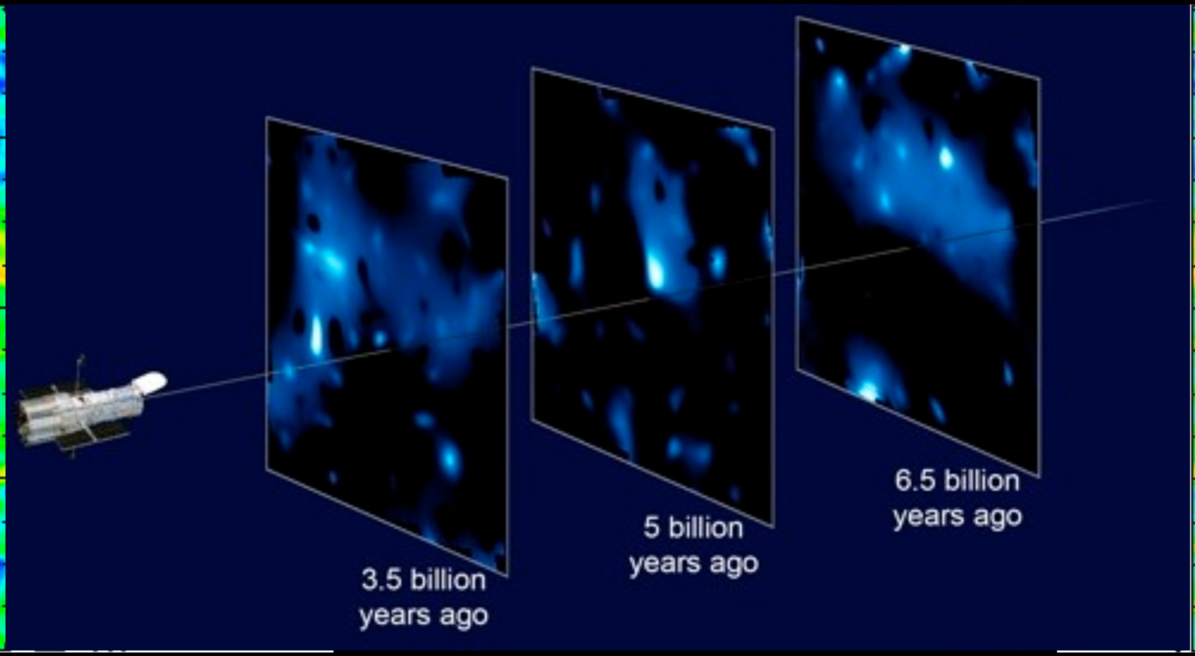

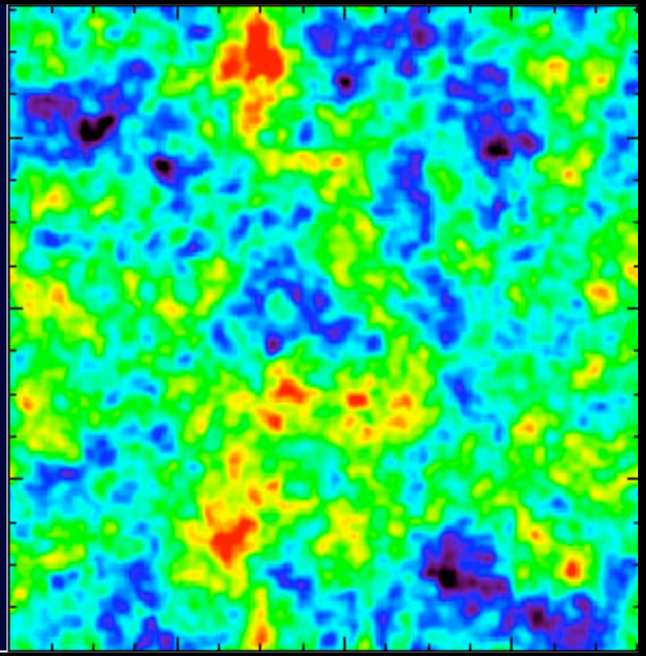

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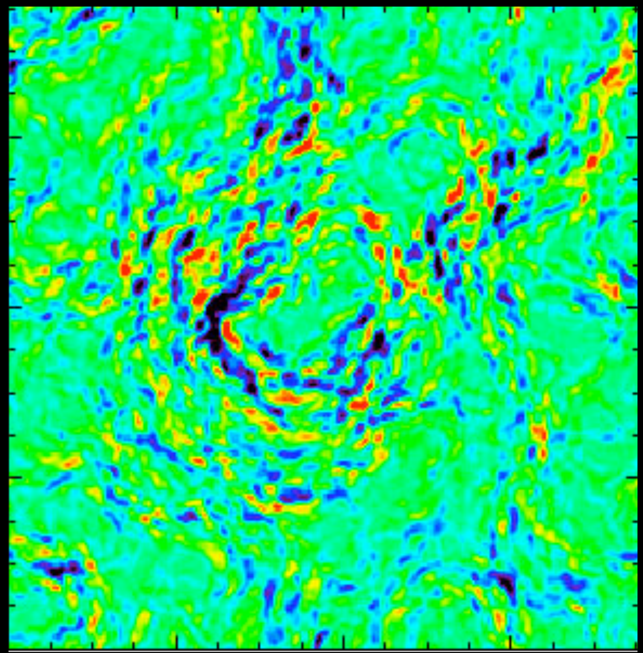
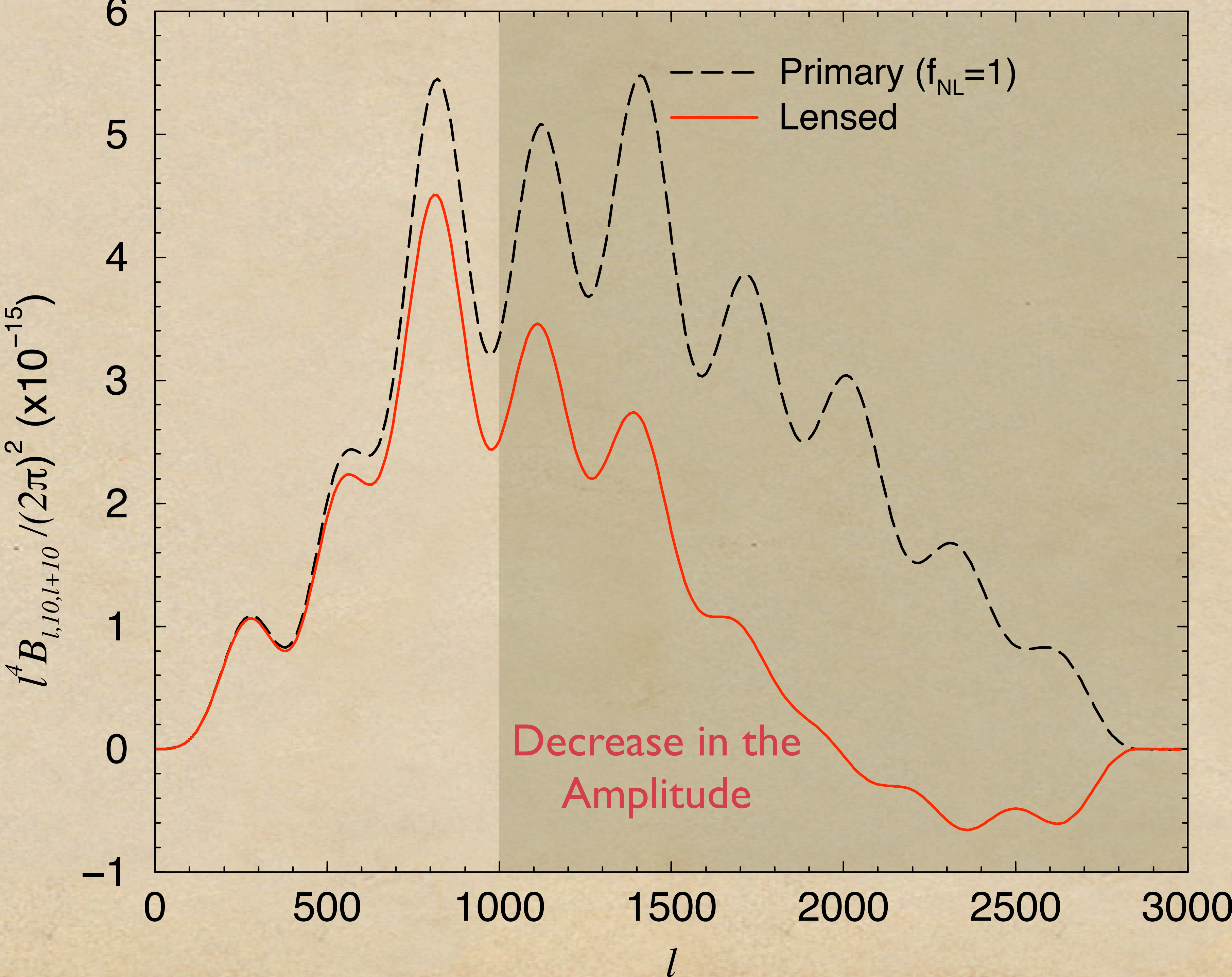


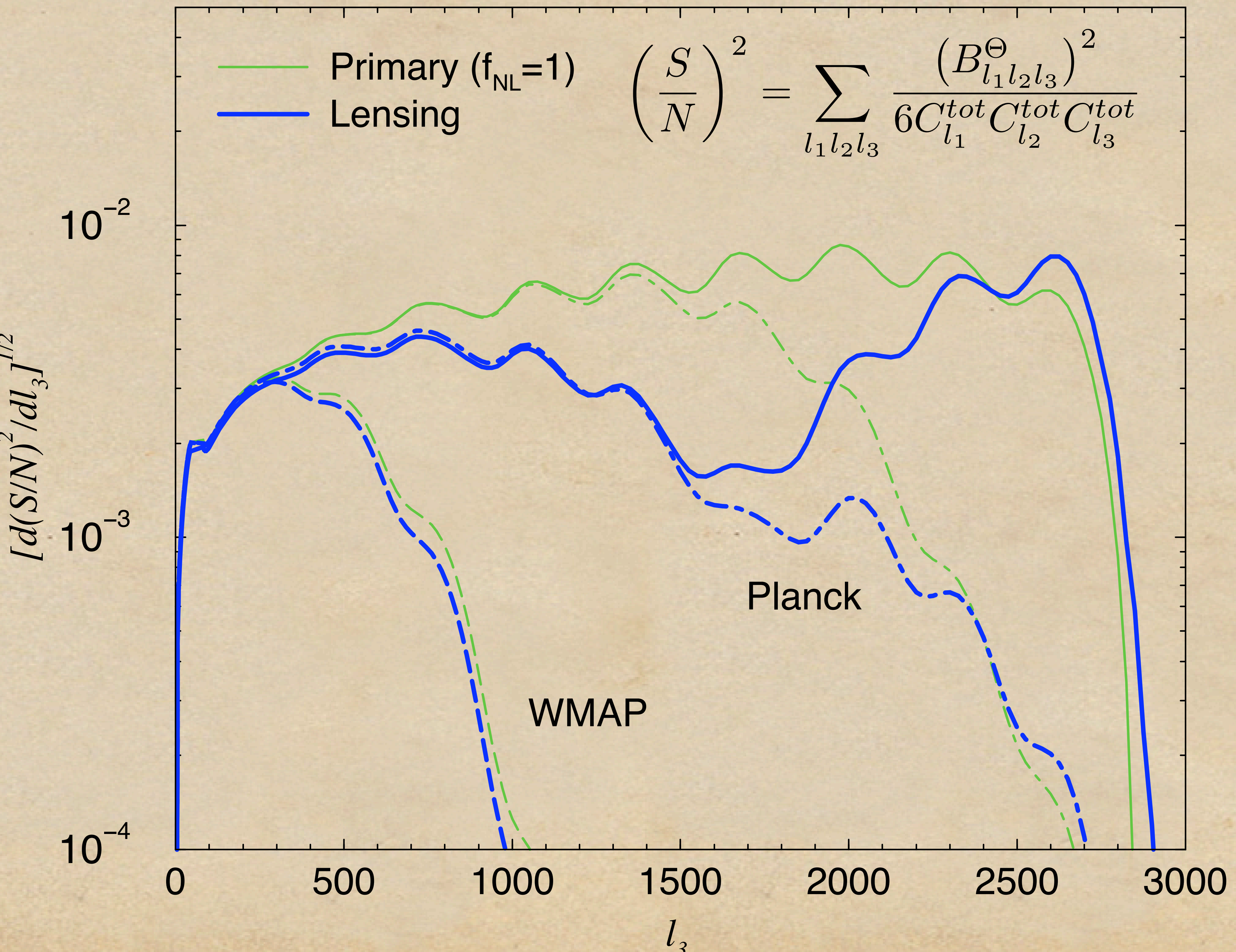
$$\tilde{B}^{\Theta}_{l_1 l_2 l_3} = \sum_{m_1 m_2 m_3} \begin{pmatrix} l_1 & l_2 & l_3 \\ m_1 & m_2 & m_3 \end{pmatrix} \langle \tilde{\Theta}_{l_1 m_1} \tilde{\Theta}_{l_2 m_2} \tilde{\Theta}_{l_3 m_3} \rangle$$

The Effect of Lensing on the Bispectrum



A. Cooray, D. Sarkar, and P. Serra; Phys. Rev. D, 77, 123006 (2008)

Reduction in the S/N due to Lensing



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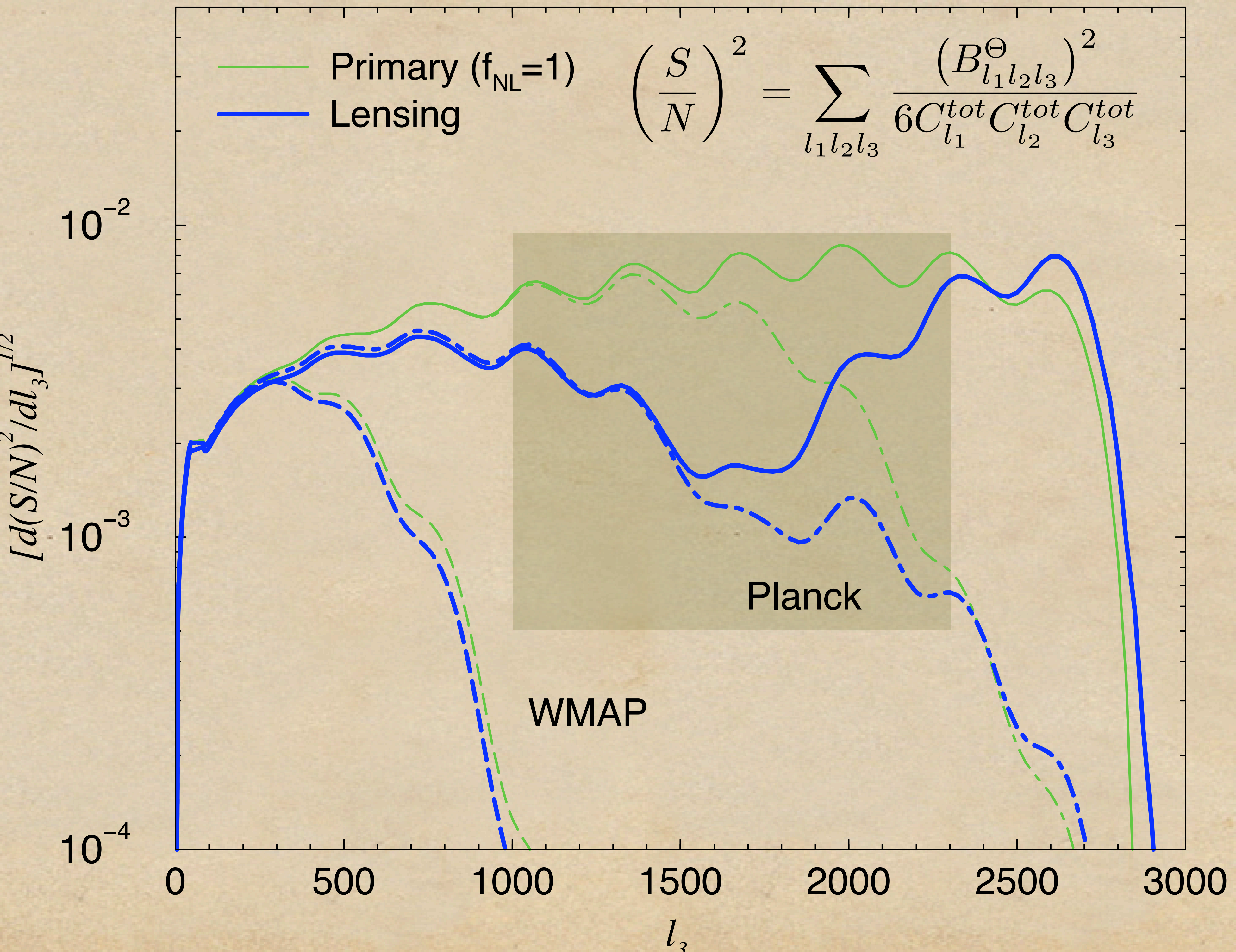

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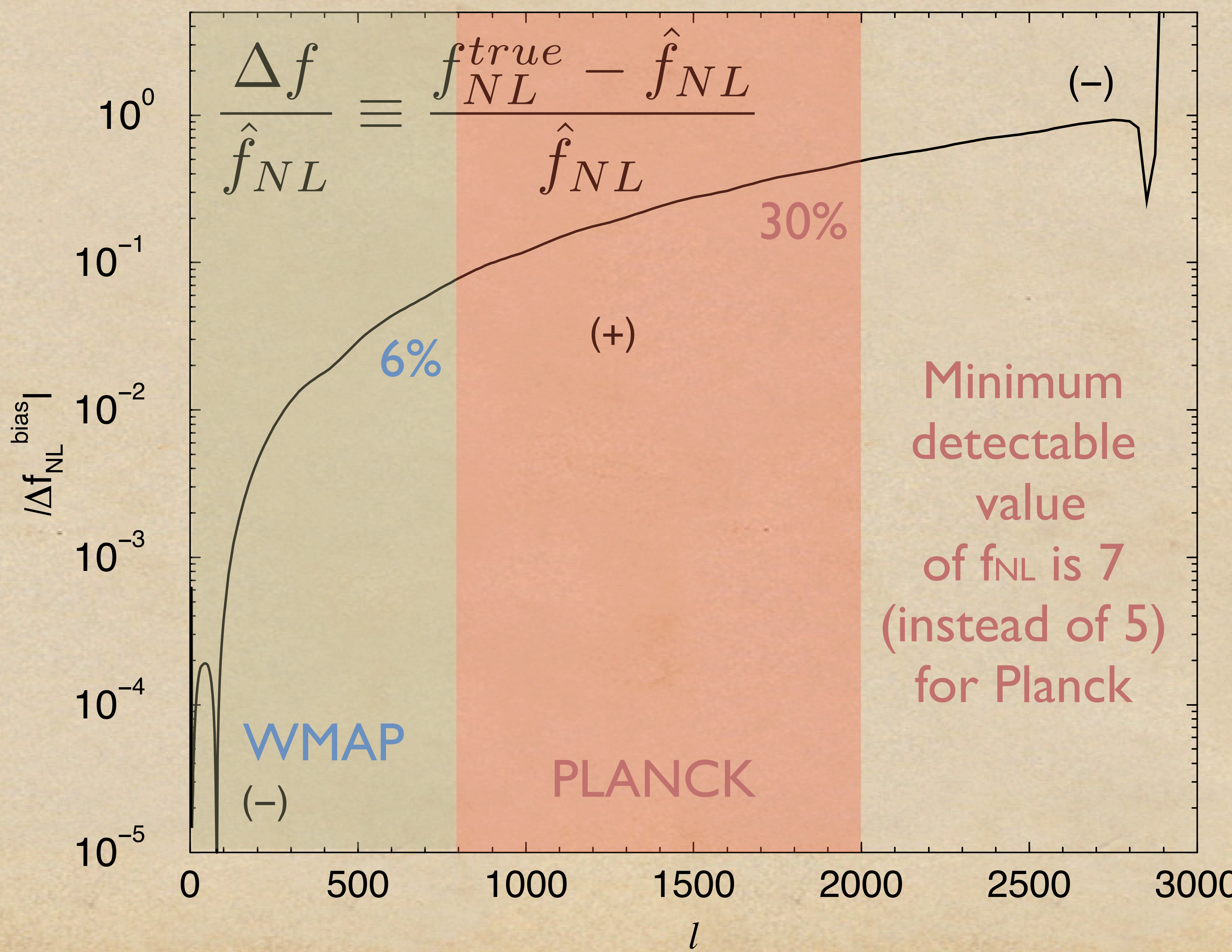
Bias in the non-Gaussian Parameter



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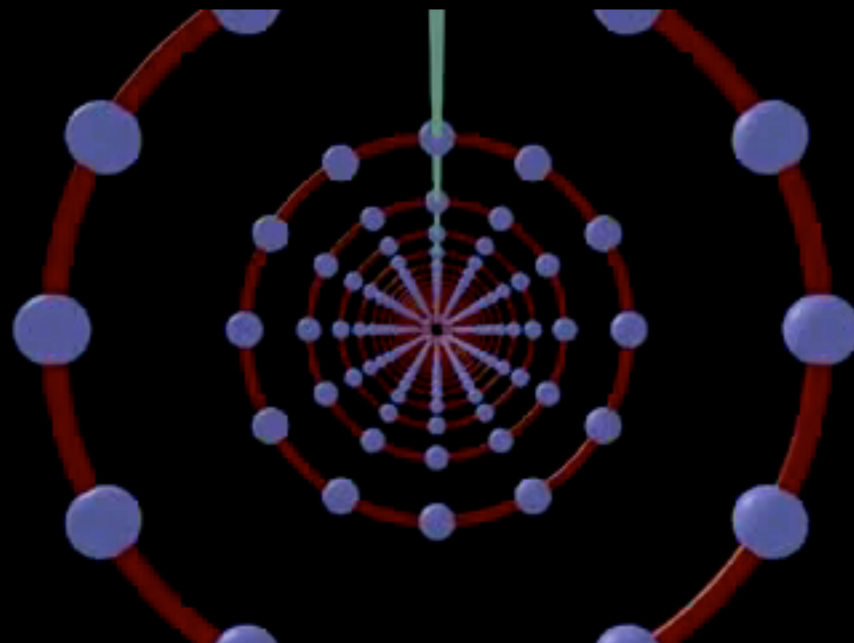
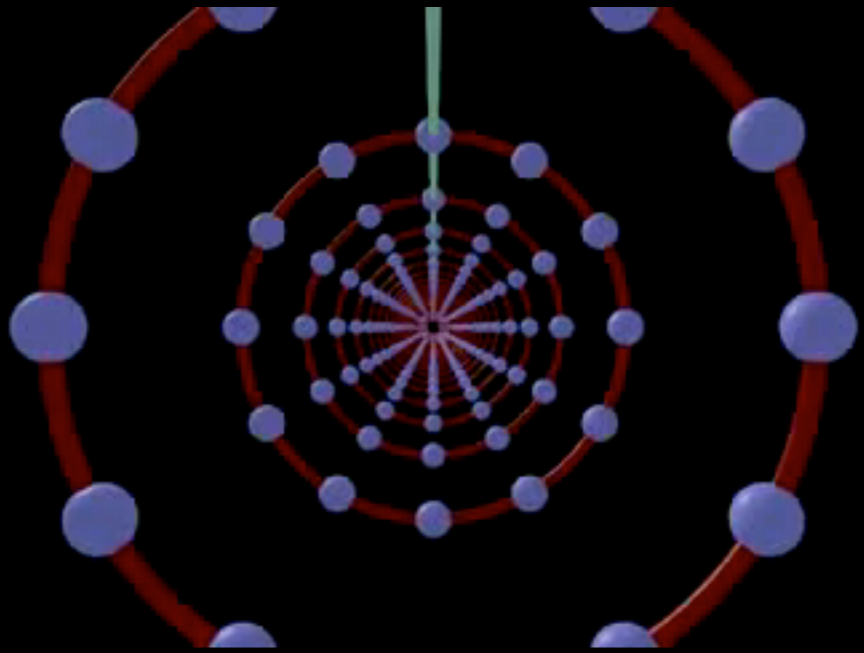
Gravitational Waves



Credit: Michael
Penn State Schuylkill

Gravitational Waves



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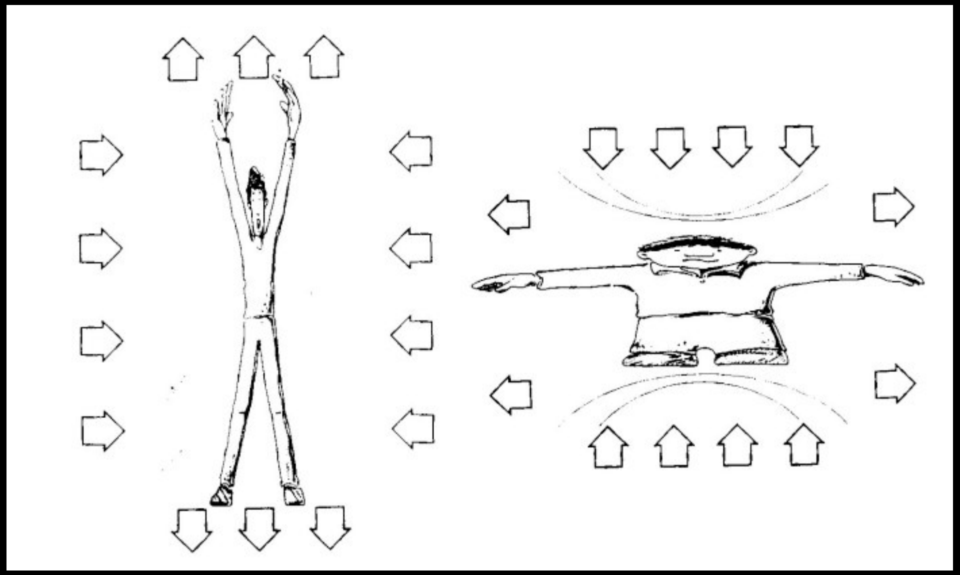
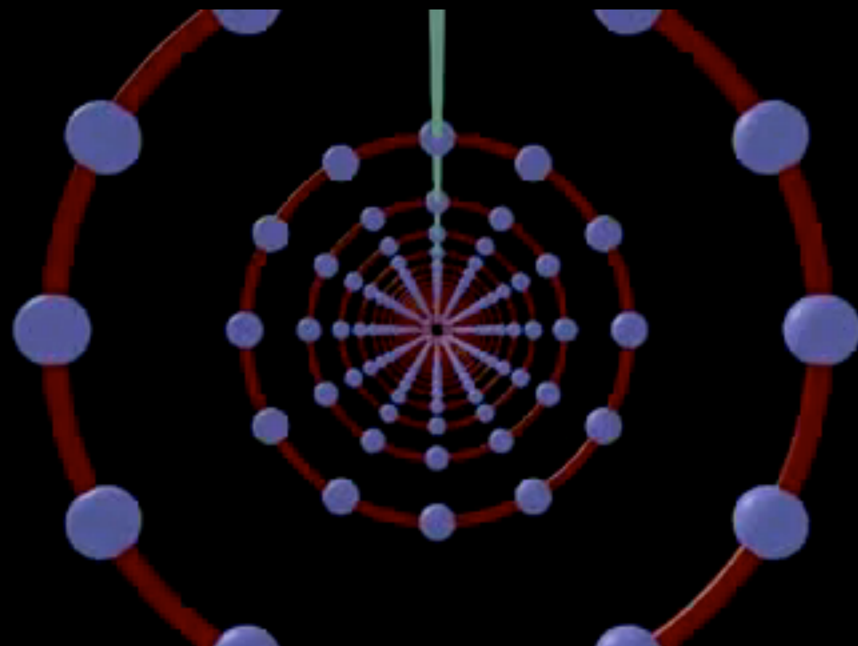


credit: http://www.lnl.infn.it/~auriga/

Gravitational Waves



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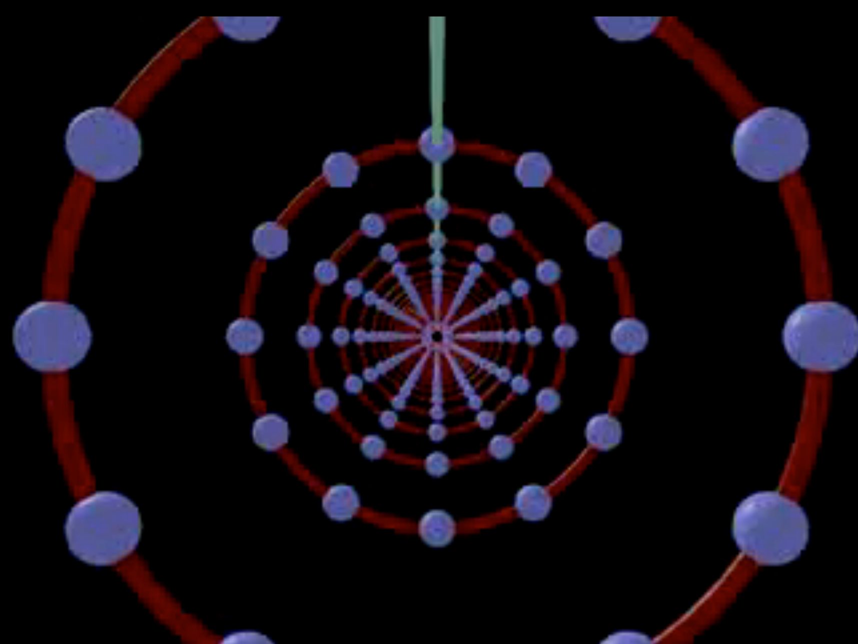

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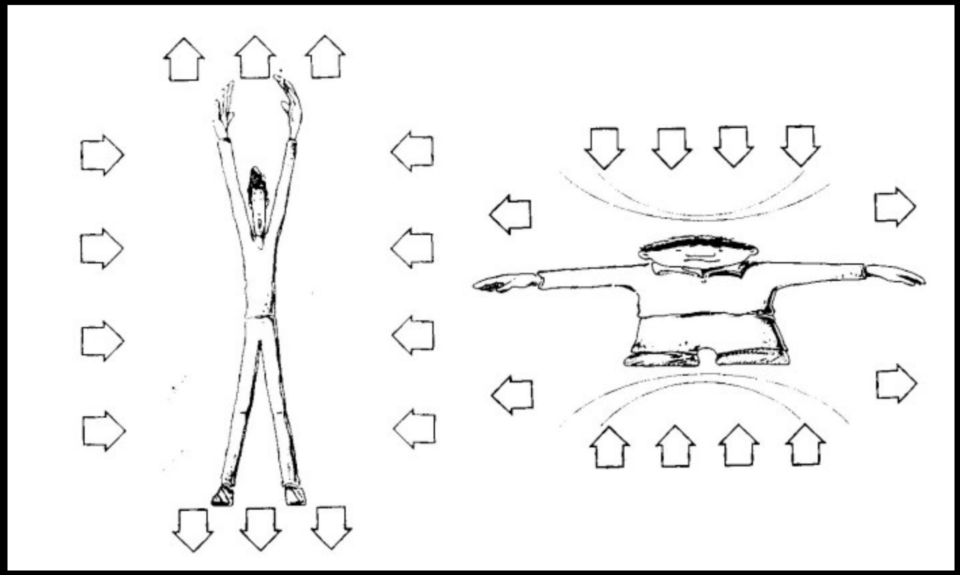

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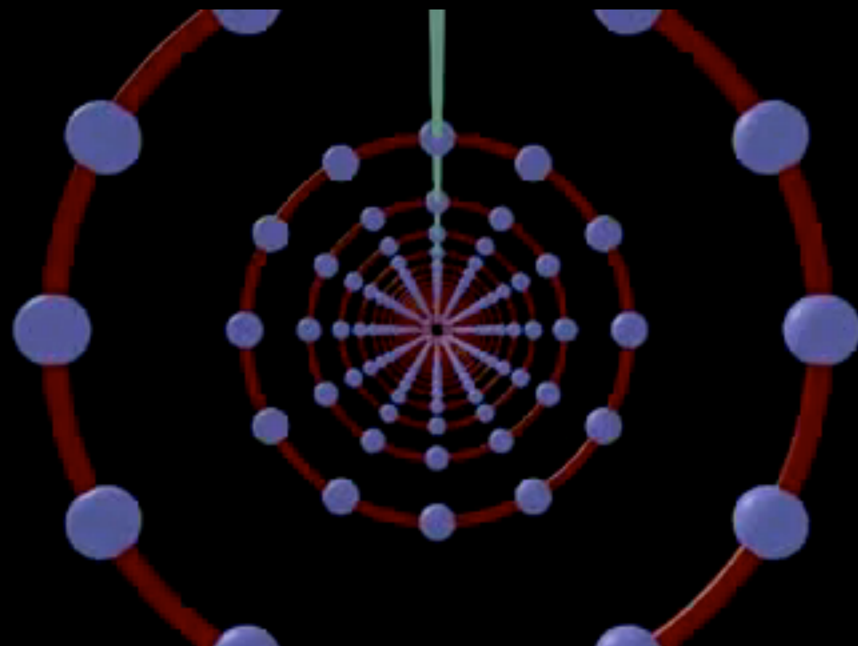
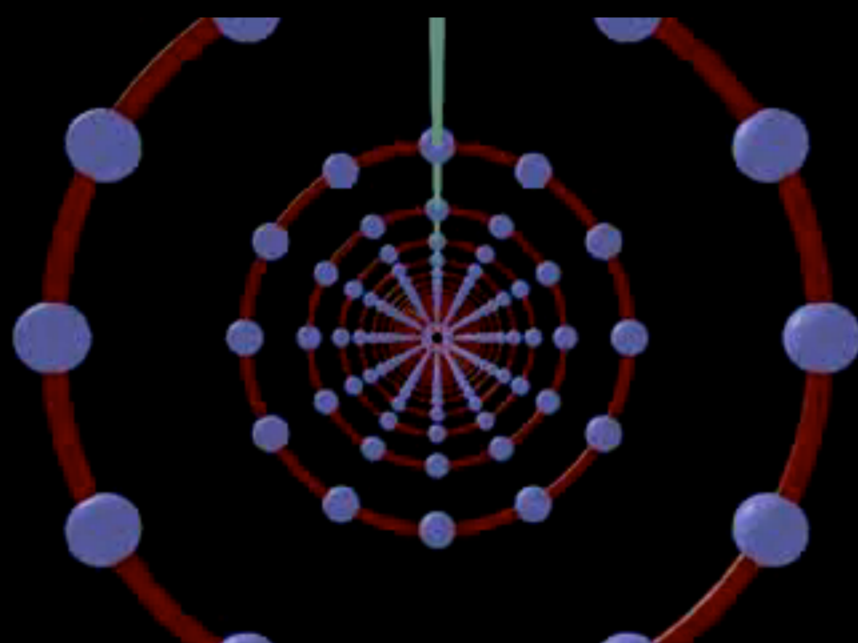


Credit: Michael
Penn State Schuylkill

Credit: GSFC/D. Berry



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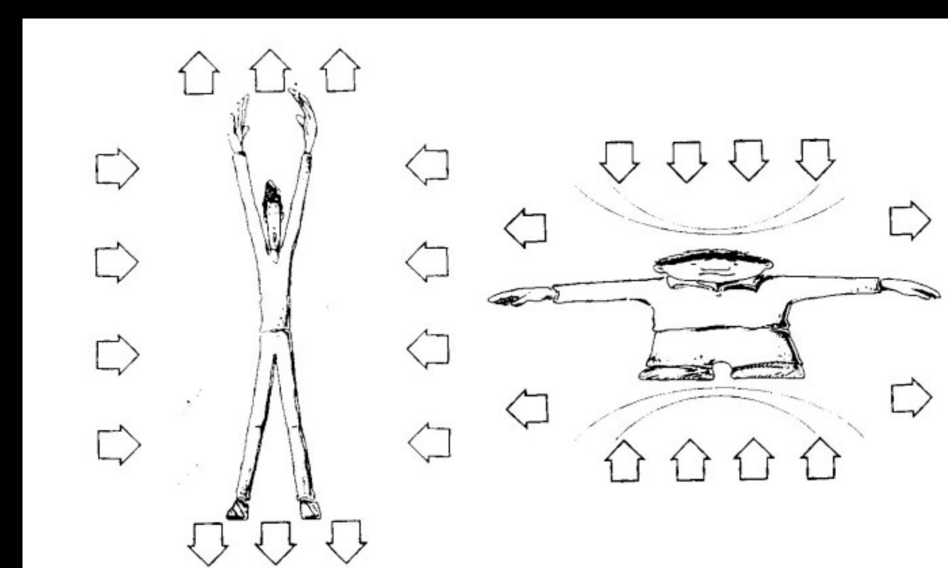

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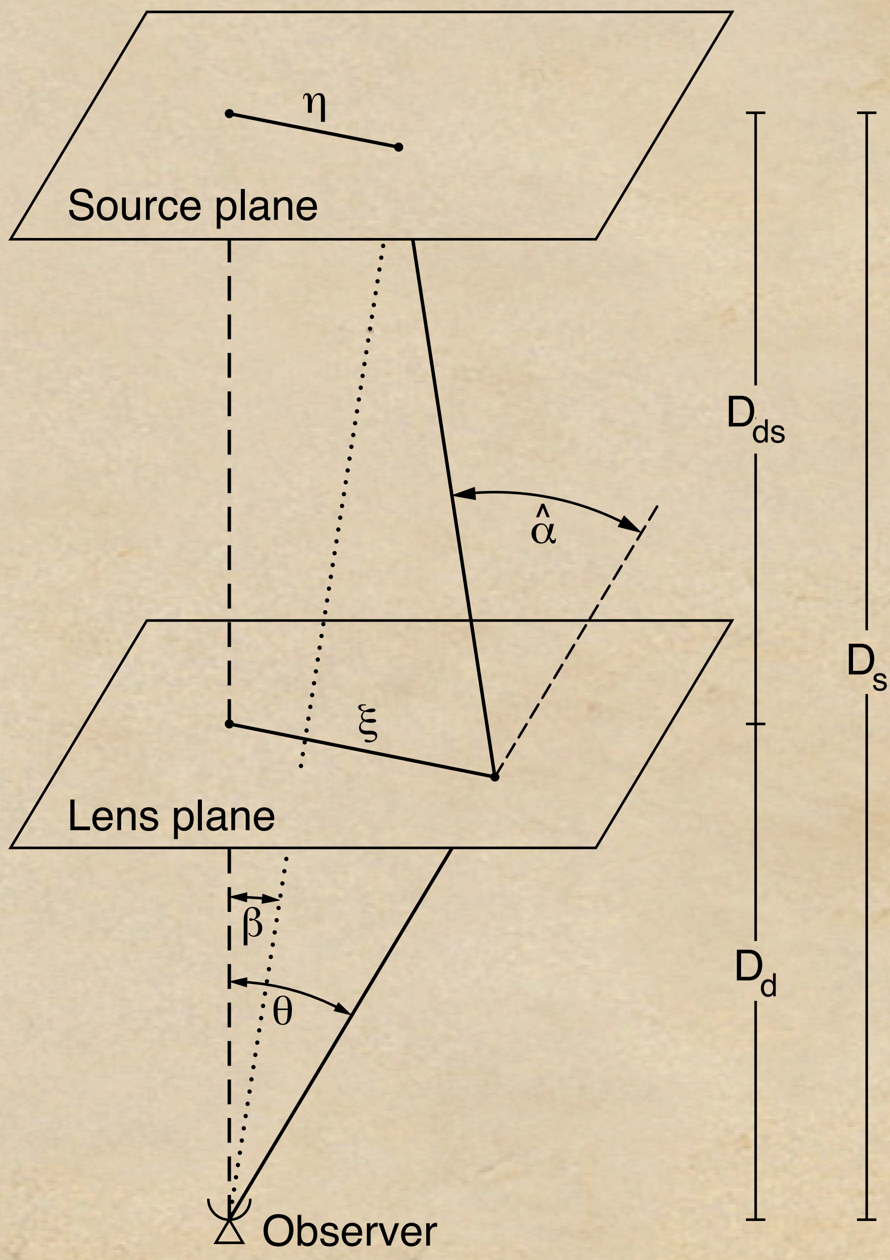
Gravitational Lensing and GW

The Deflection:

$$\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})$$



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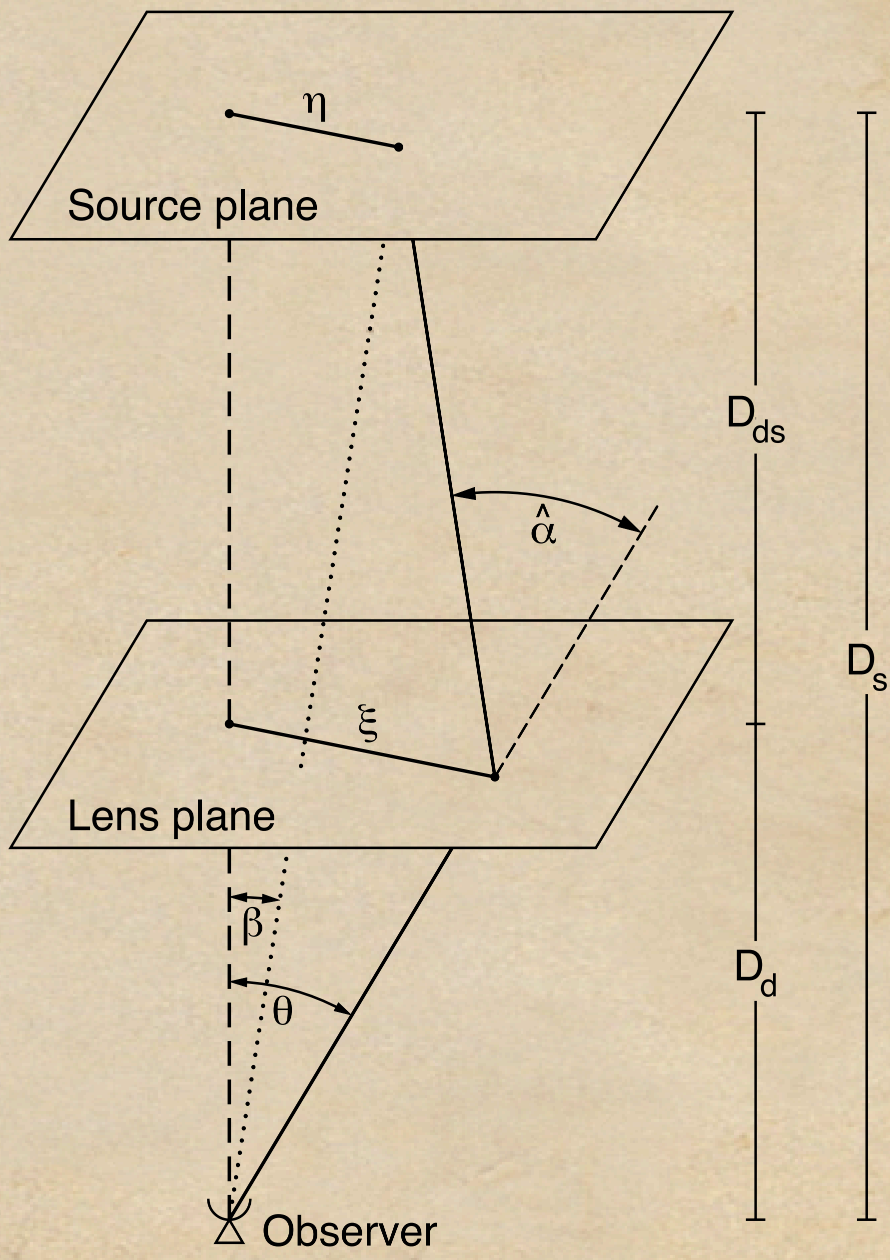

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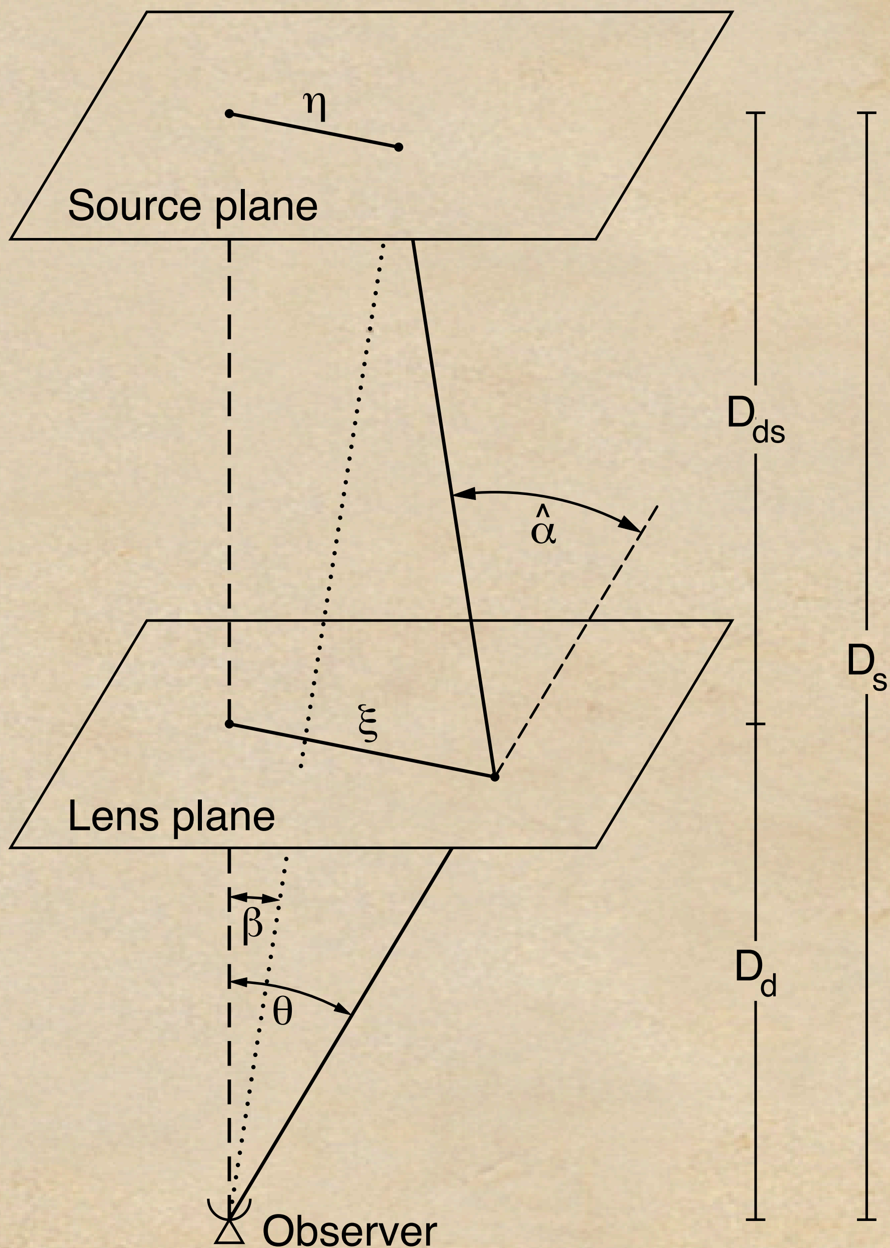

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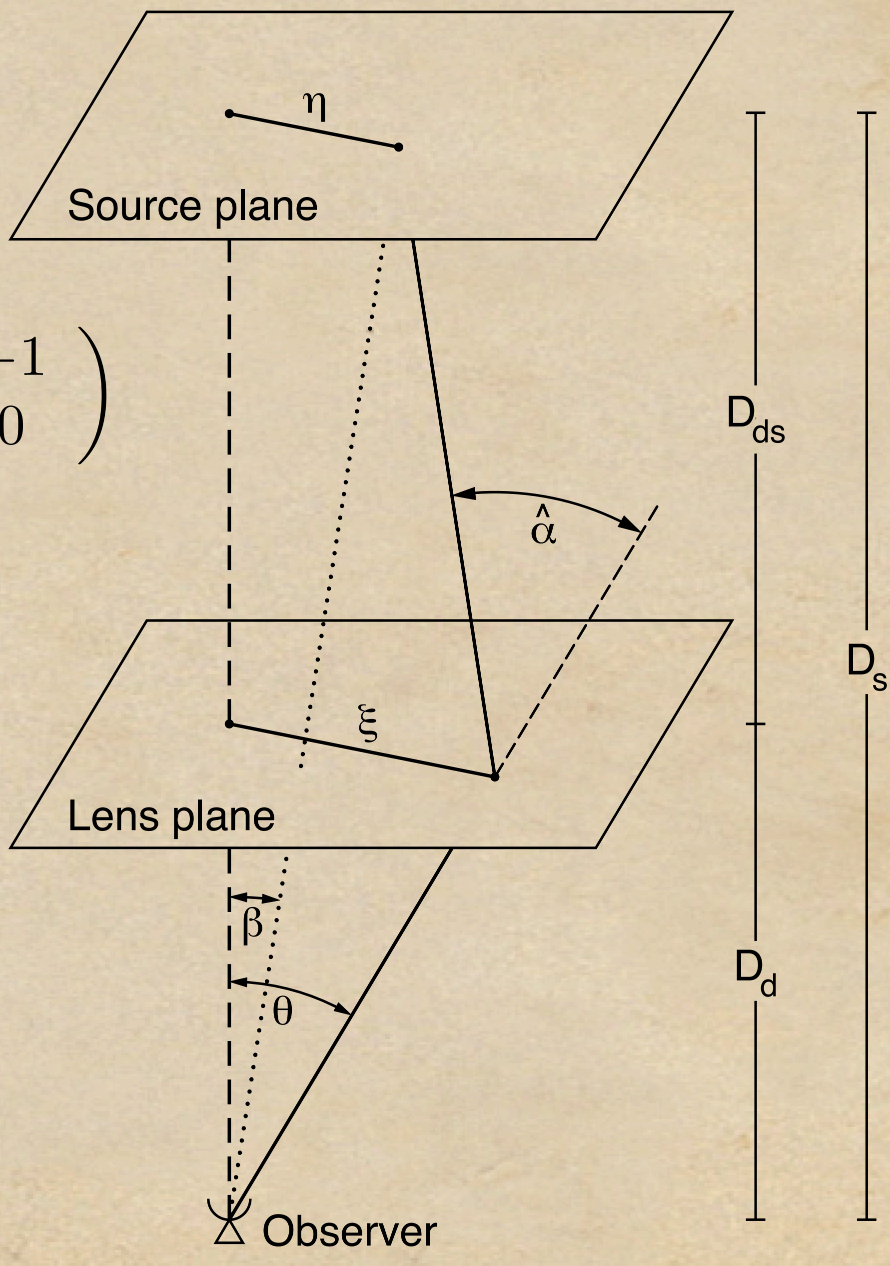
$$\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

$$= (1-\kappa)\delta_{ij} - \gamma_{ij} + \omega\epsilon_{ij}$$

trace

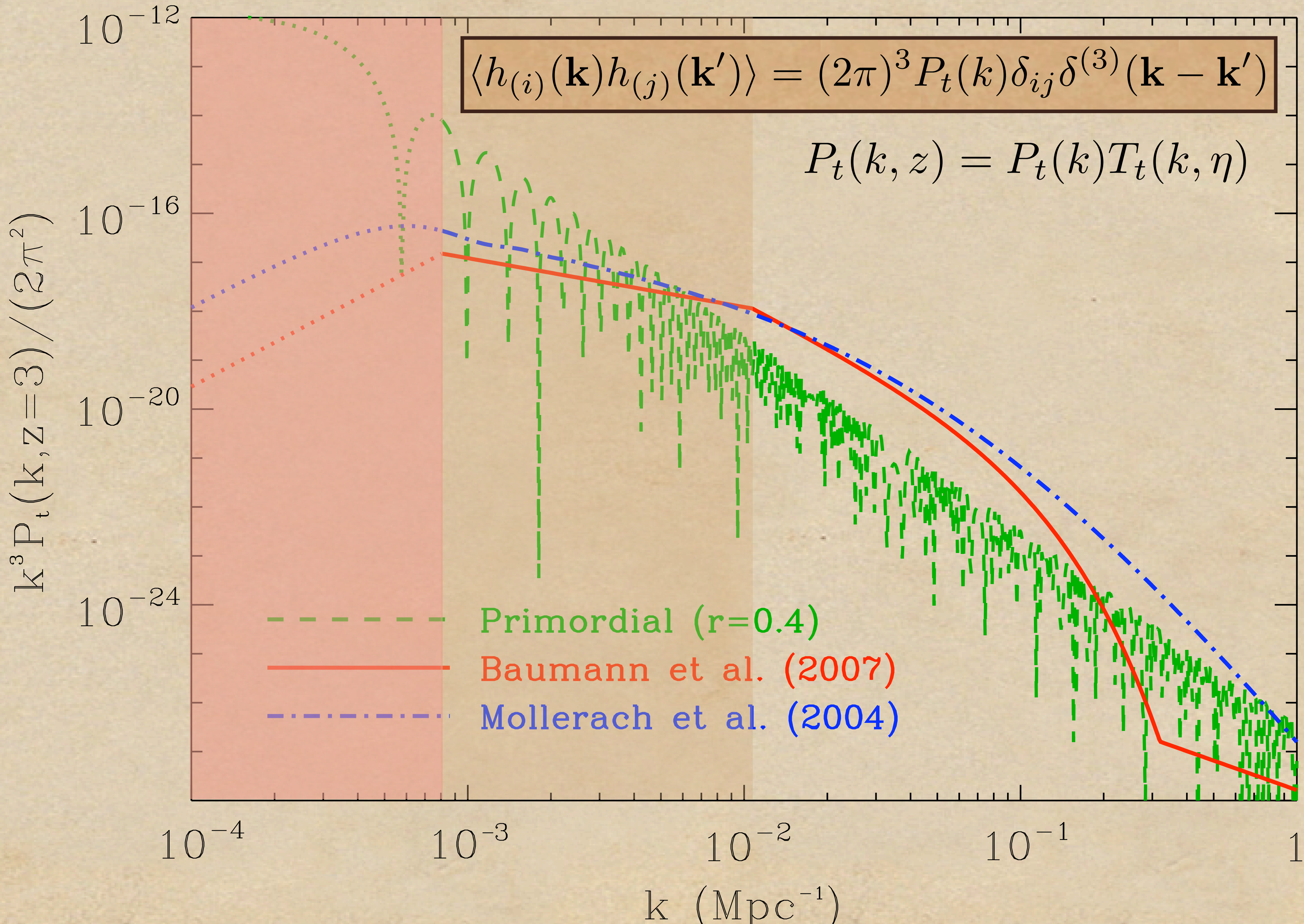
symmetric traceless

antisymmetric rotation



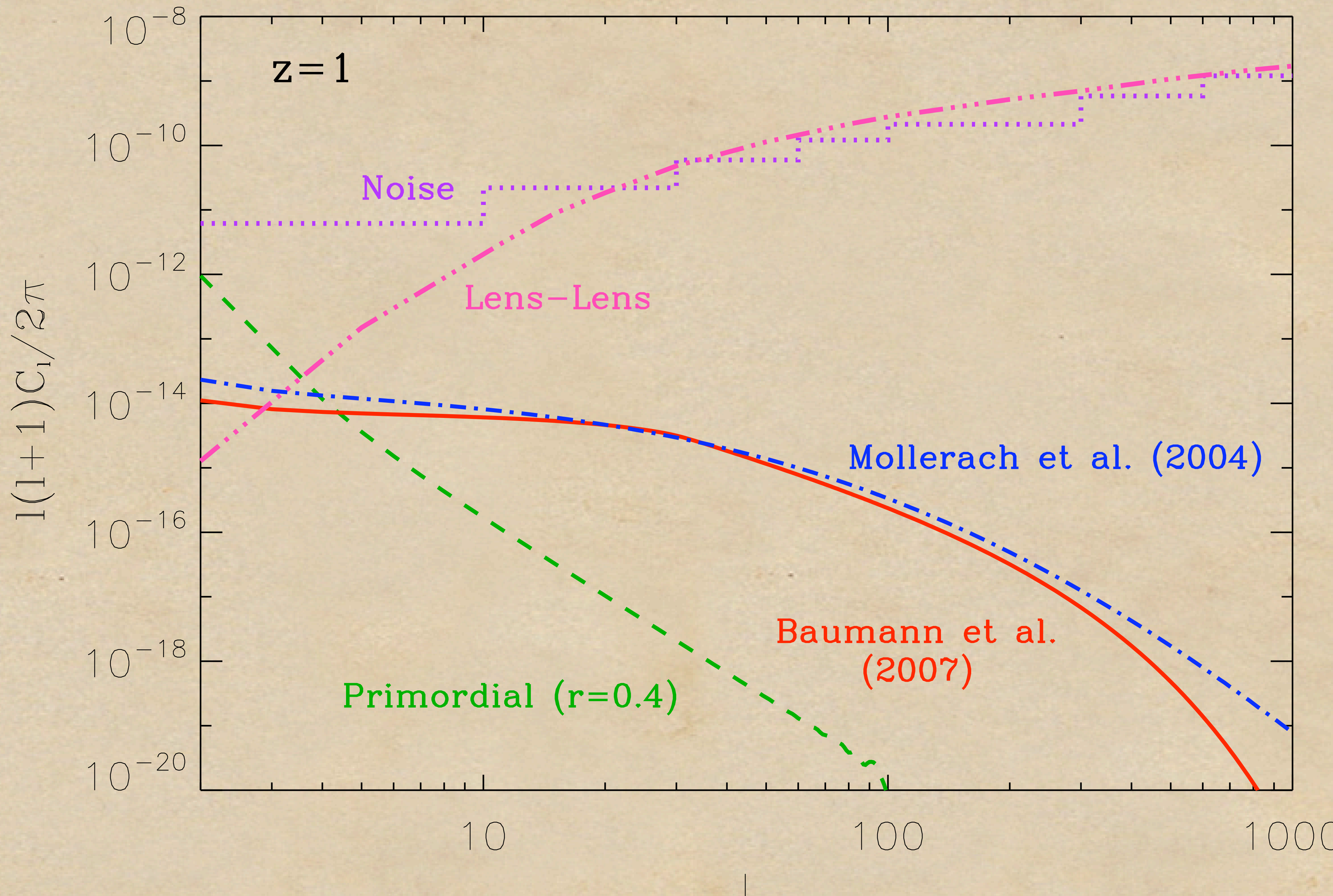
Credit: Bartelmann and Schneider 2001

GW Power Spectra



D.S., P. Serra, A. Cooray, K. Ichiki, D. Baumann, PRD, 77, 103515 (2008)

Cosmic Shear Curl Mode Power Spectra



D.S., P. Serra, A. Cooray, K. Ichiki, D. Baumann, PRD, *77*, 103515 (2008)

Agenda

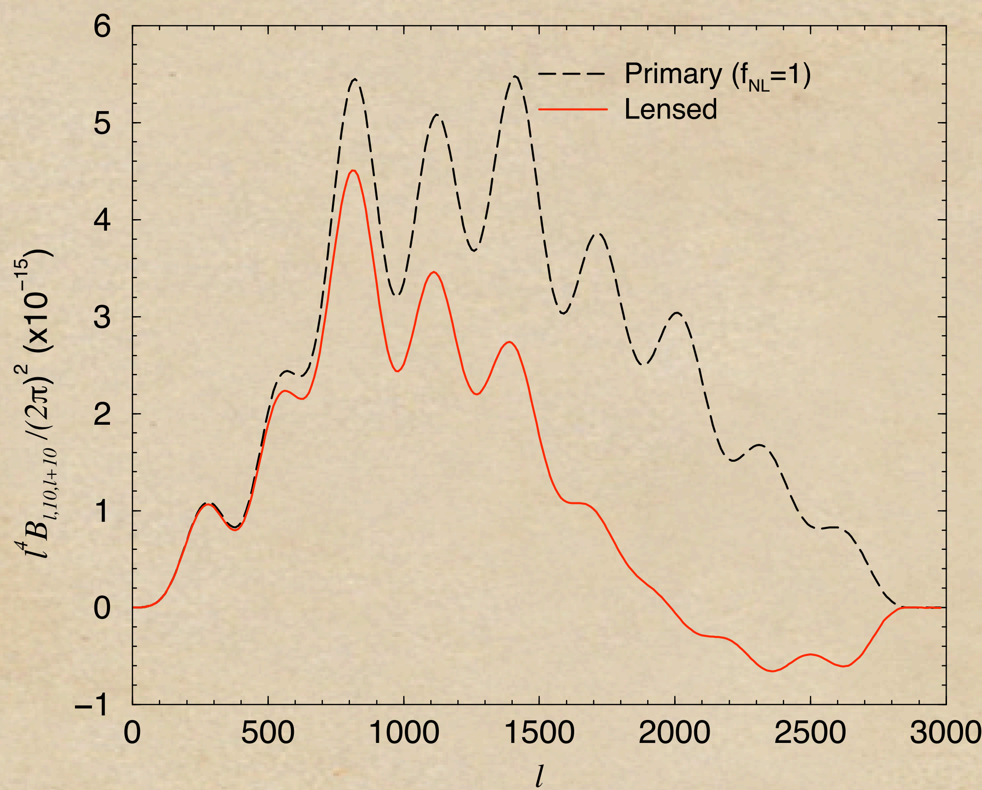
Primordial Non-Gaussianity and CMB Bispectrum

- Beyond Gaussianity
- CMB Bispectrum
- Lensing of CMB
- Lensed Bispectrum
- S/N Reduction & Bias

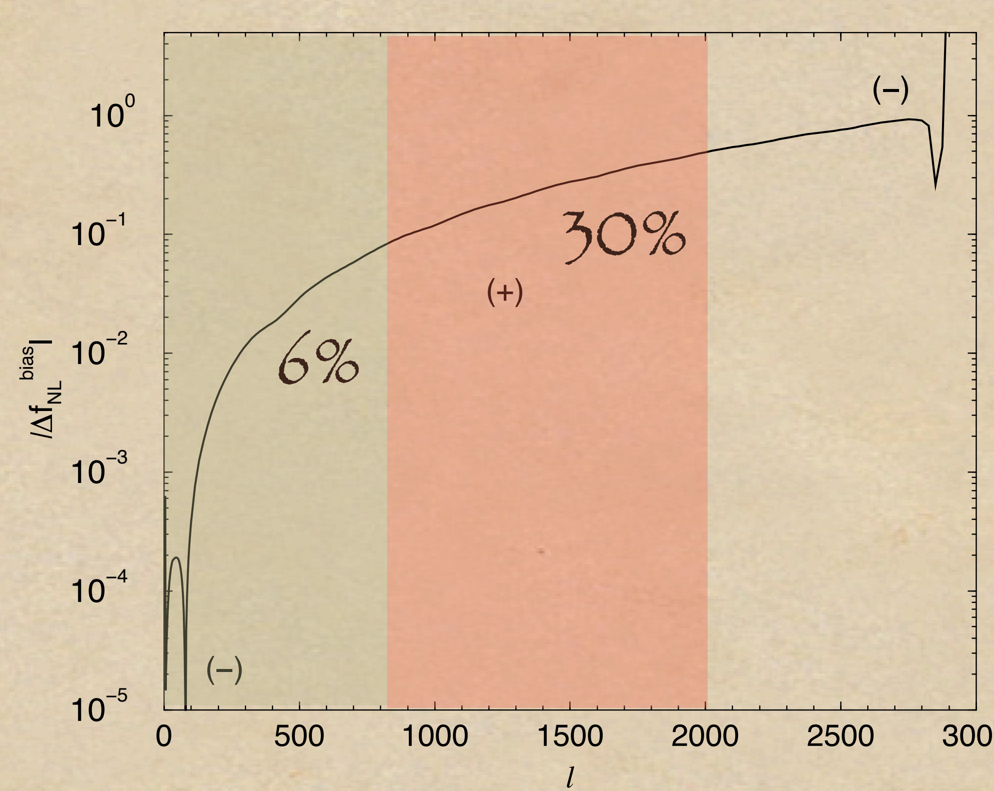
Prospects of Detecting Gravity Waves via Weak Lensing

- ABC of Gravity Waves
- Lensing 201 Revisited
- Gravity Wave Spectra
- Detection Prospects
- Conclusions

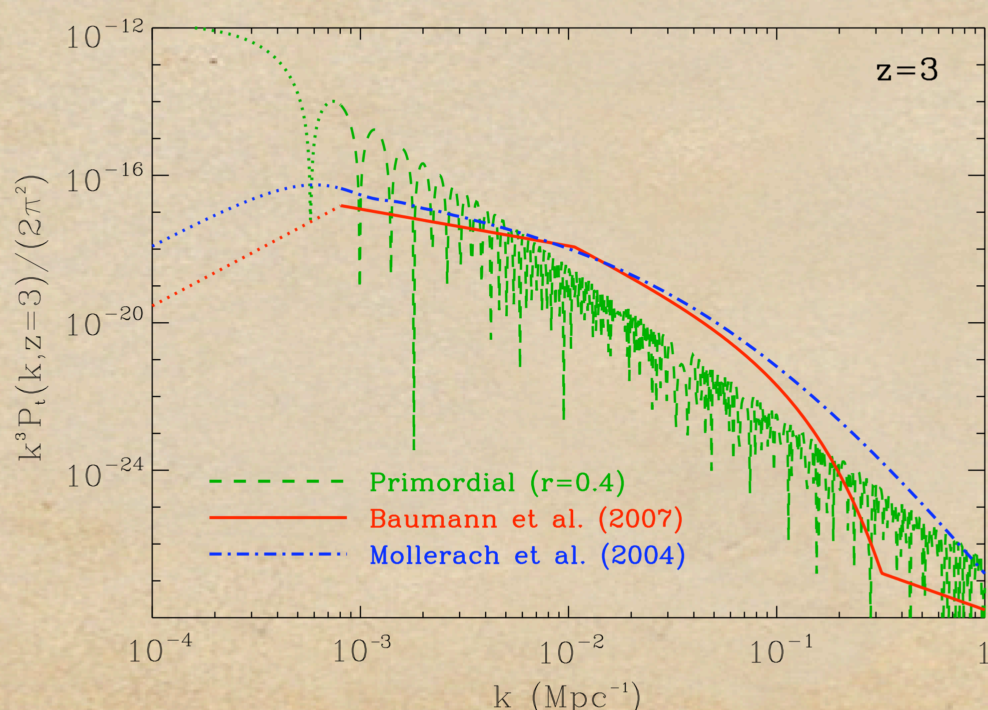
Summary



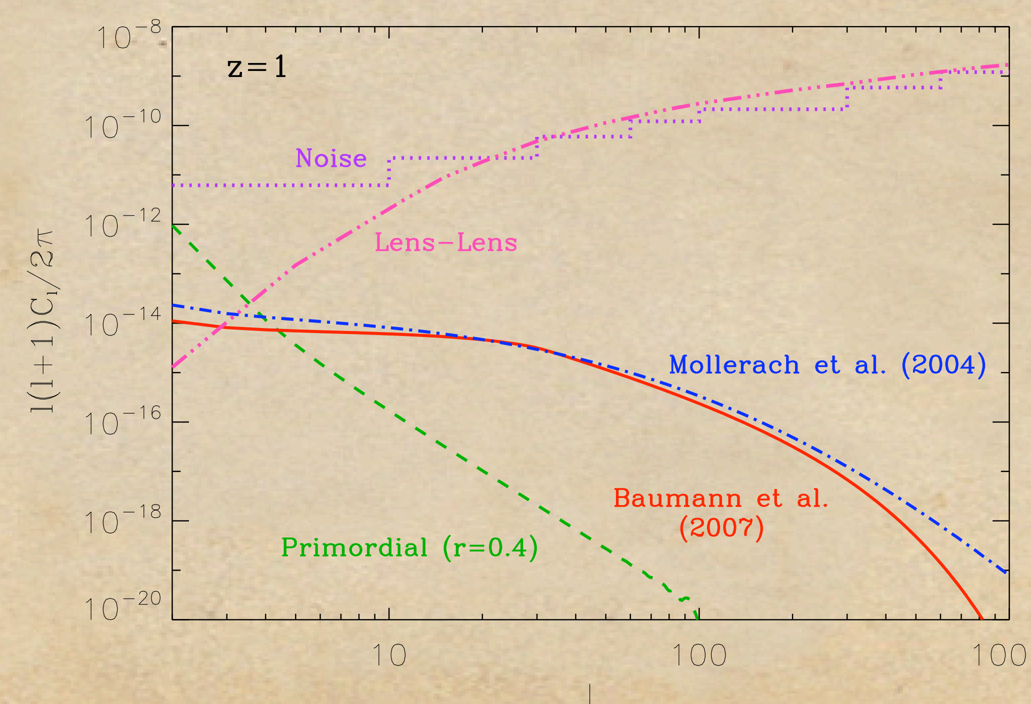
Primary (f_{NL}=1)
Lensed
$l^4 B_{l,10,l+10}/(2\pi)^2$ (x10^{-15})
l



$|\Delta f_{NL}^{bias}|$
l
6%
30%
(+)
(−)
(−)



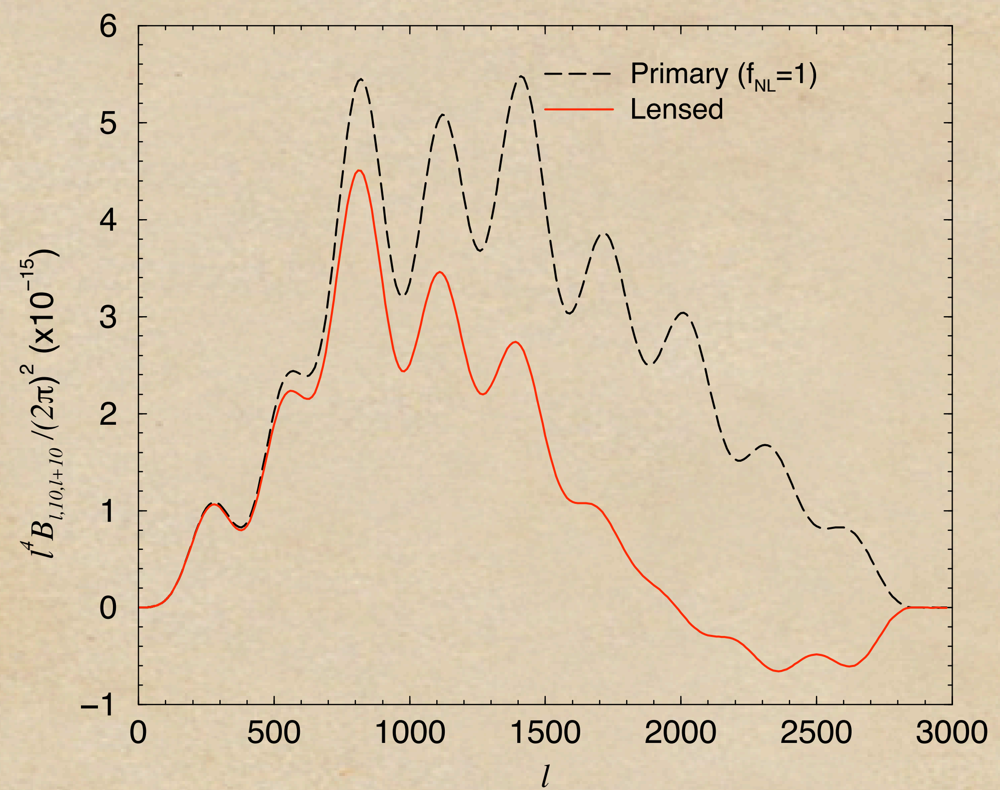
z=3
Primordial (r=0.4)
Baumann et al. (2007)
Mollerach et al. (2004)
$k^3 P_t(k,z=3)/(2\pi^2)$
k (Mpc^{-1})



z=1
Noise
Lens−Lens
Mollerach et al. (2004)
Baumann et al. (2007)
Primordial (r=0.4)
$l(l+1)C_l/2\pi$
l

DSARKAR.ORG

Summary



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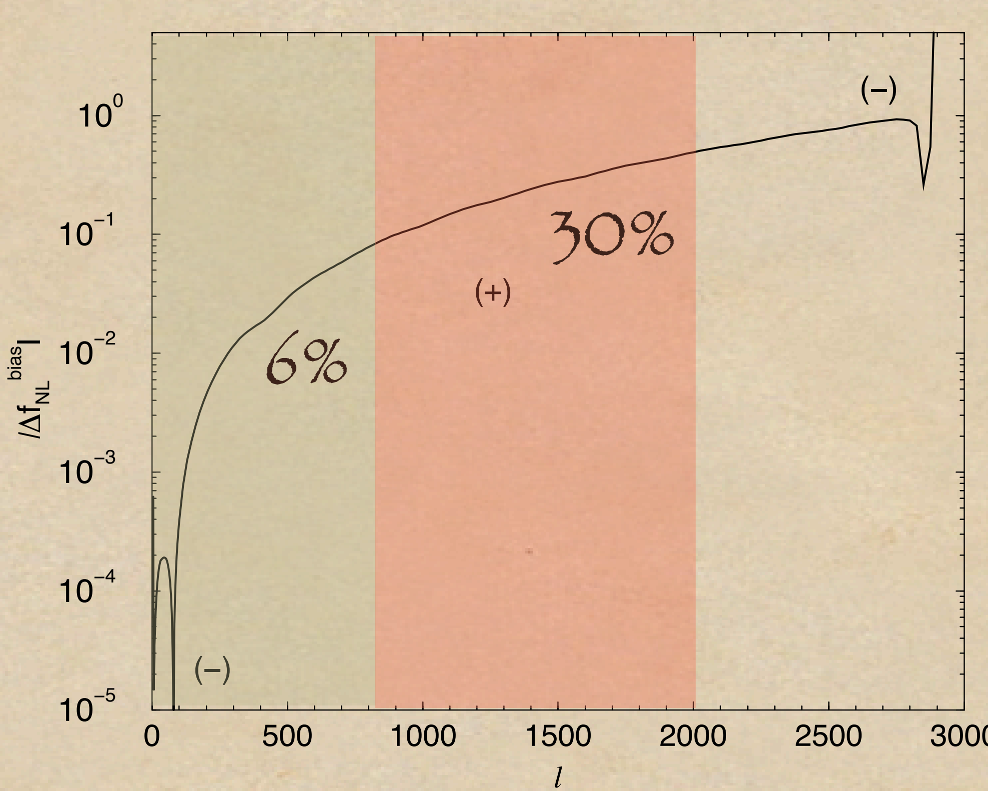

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(−)
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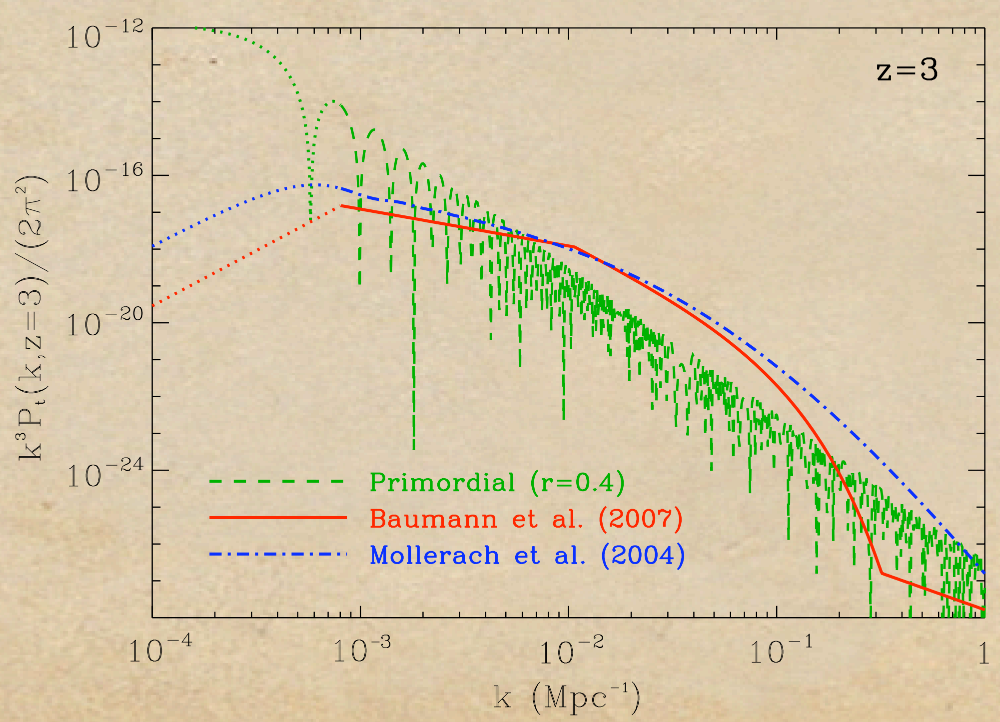

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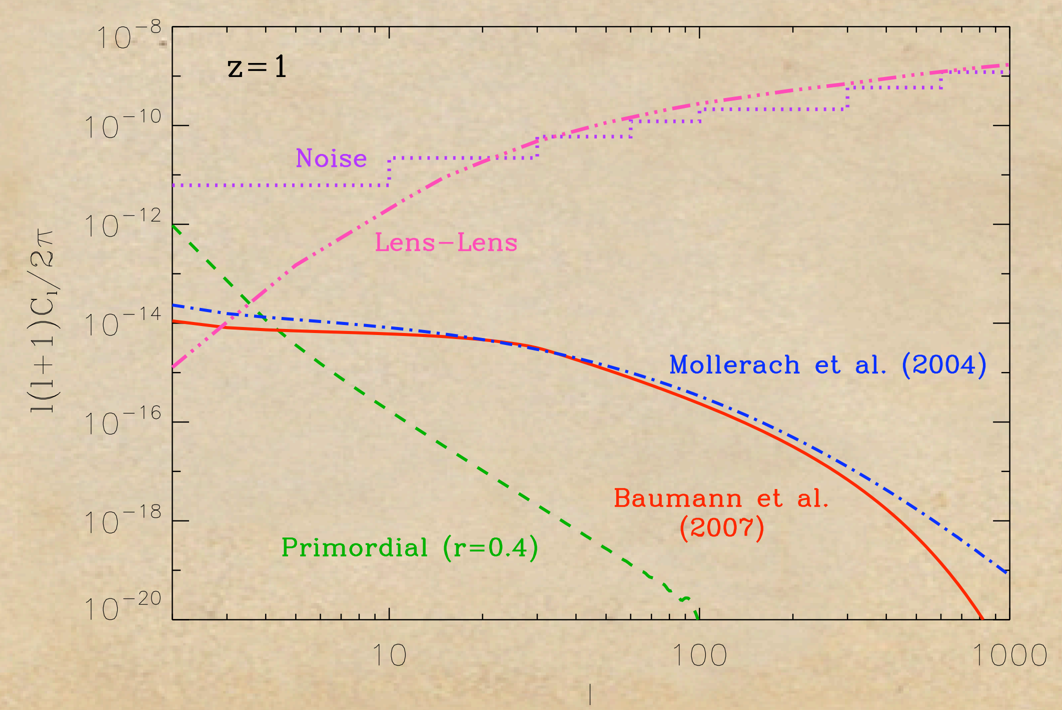
k (Mpc^{-1})



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Lens−Lens
Mollerach et al. (2004)
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Primordial (r=0.4)
l