# Probing Dark Energy & Non-Gaussianity: How Well Can We Do?


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In collaboration with:

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University of Oxford Cosmology Seminar January 29, 2009

# Agenda

## Theoretical Uncertainties in Dark Energy Measurements

- Constraining the EOS
- To Bin or Not to Bin
- SNe Ia ++
- Lensing of SNe
- Other Worries

## Primordial Non-Gaussianity and CMB Bispectrum

- Beyond Gaussianity
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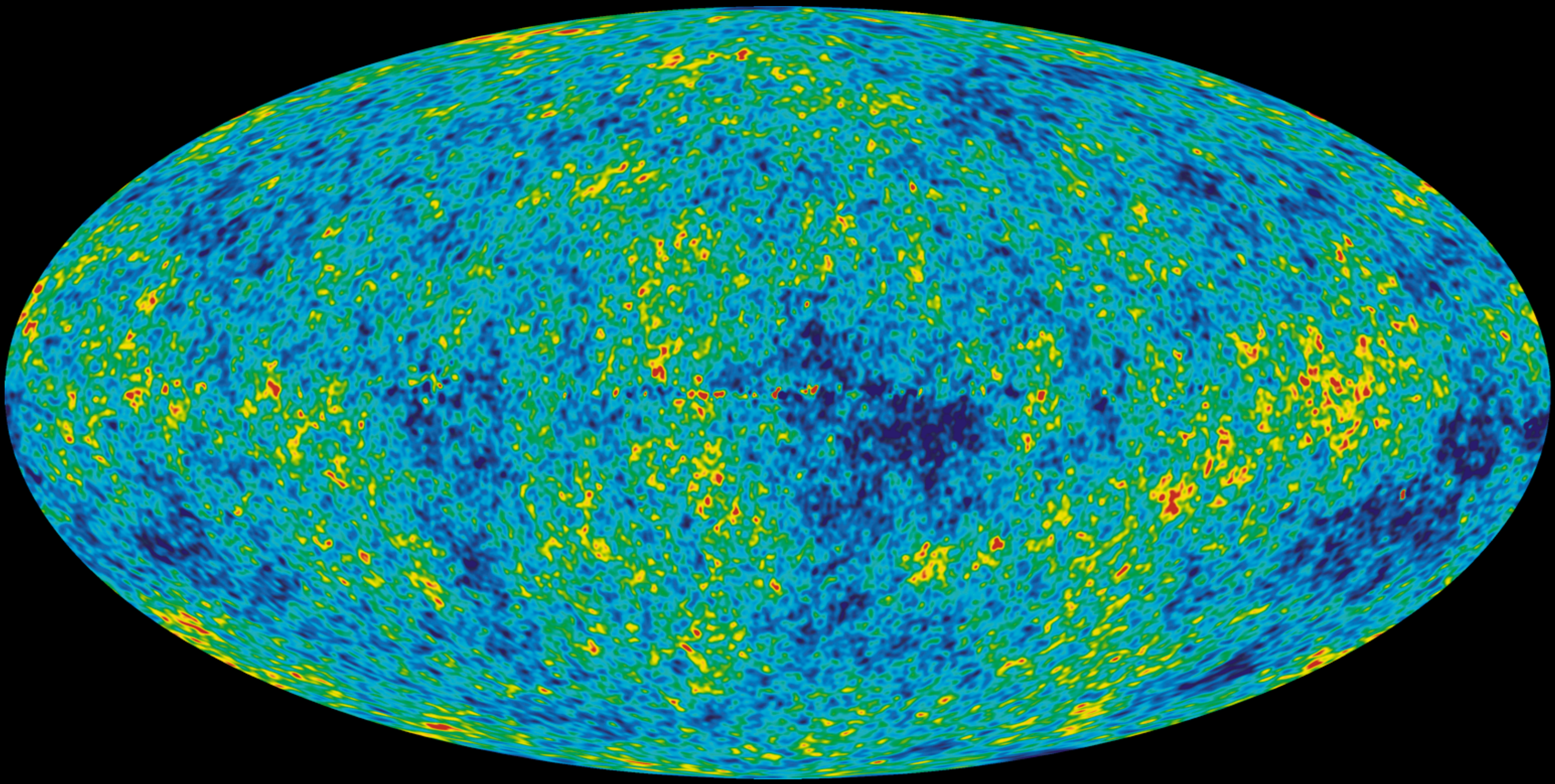
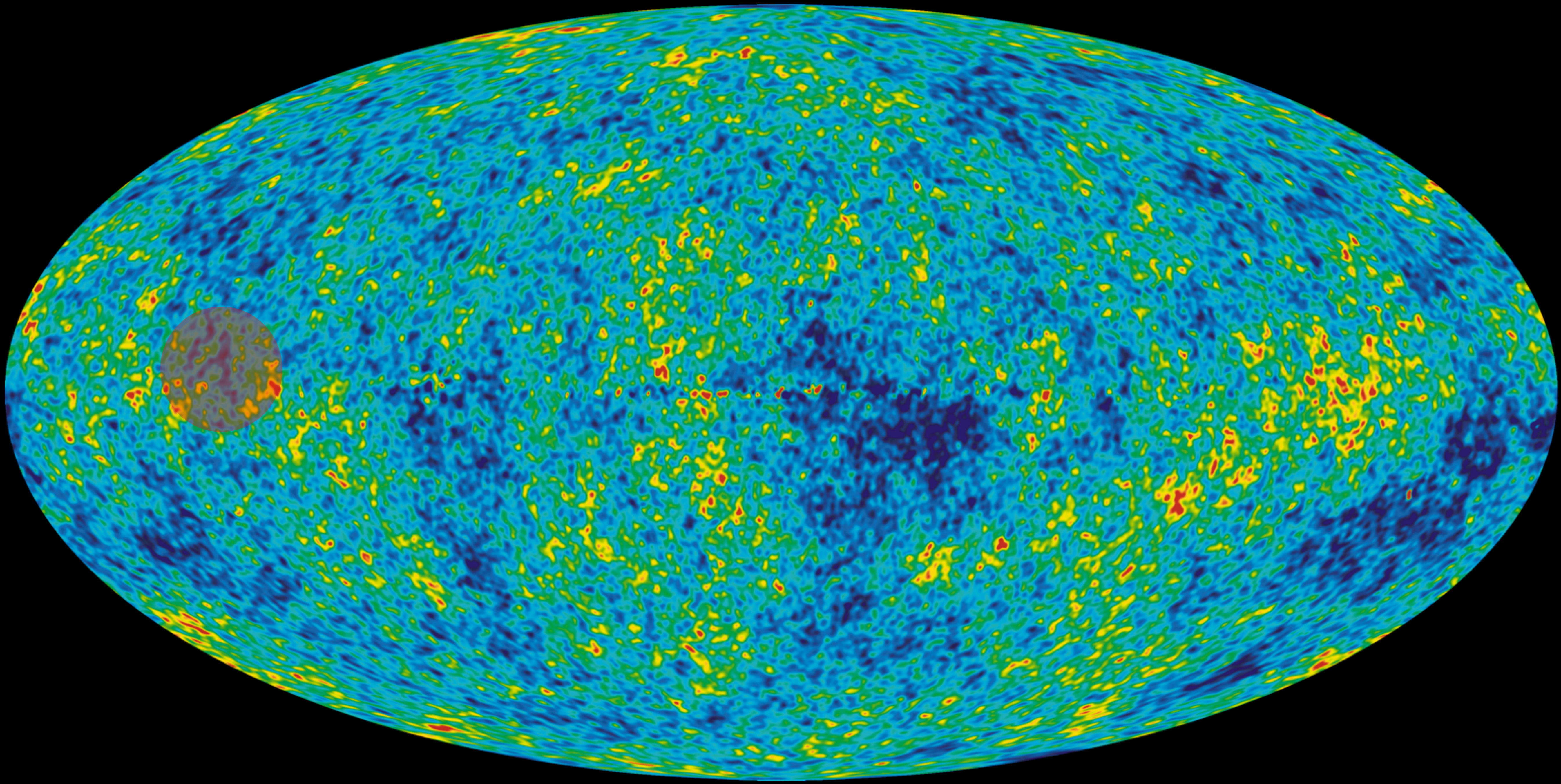


Credit: NASA/WMAP Science Team



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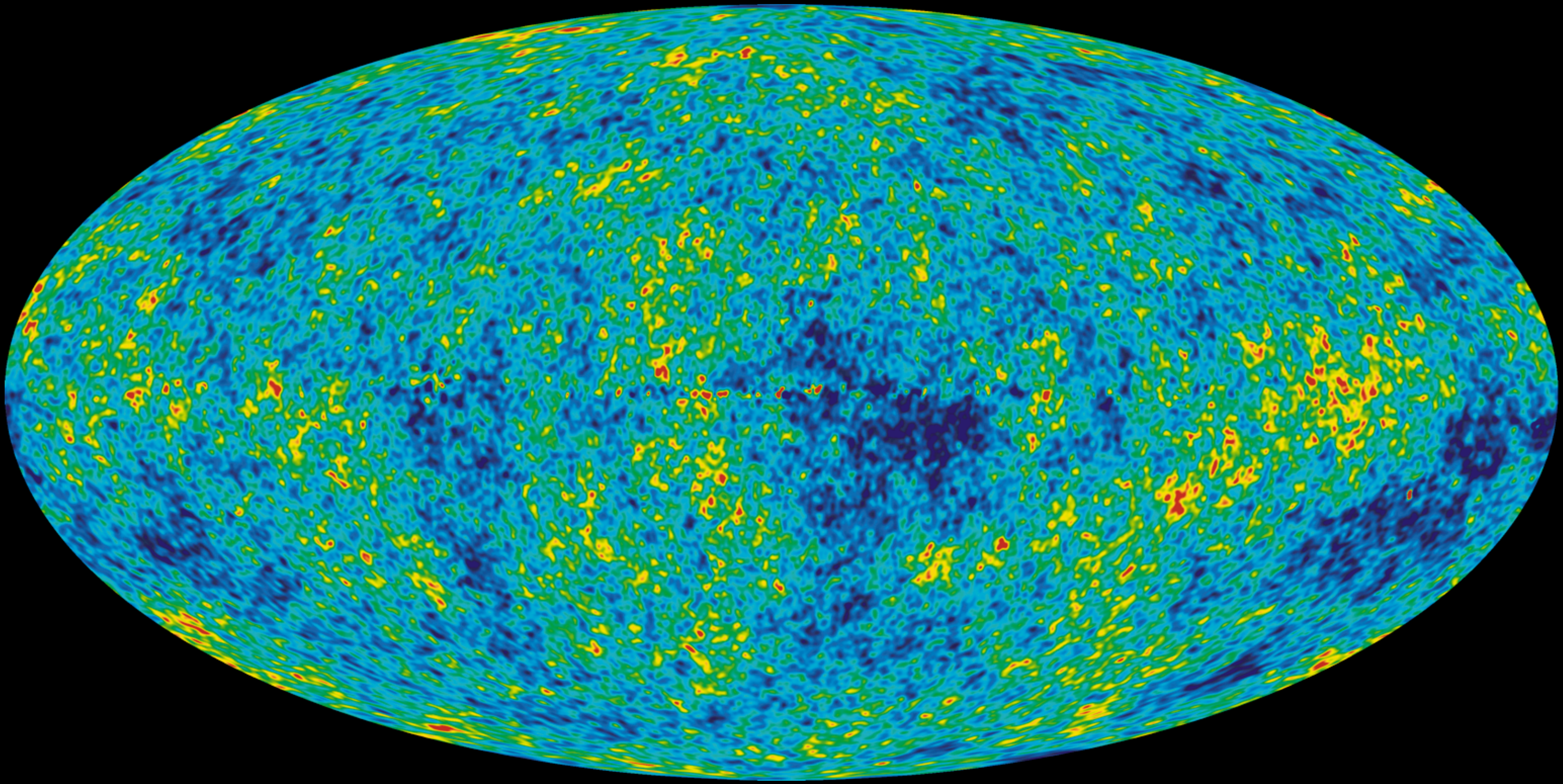

Credit: NASA/WMAP Science Team

THE ASTRONOMICAL JOURNAL, 116:1009–1038, 1998 September


# OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

ADAM G. RIESS,[1] ALEXEI V. FILIPPENKO,[1] PETER CHALLIS,[2] ALEJANDRO CLOCCHIATTI,[3] ALAN DIERCKS,[4] PETER M. GARNAVICH,[2] RON L. GILLILAND,[5] CRAIG J. HOGAN,[4] SAURABH JHA,[2] ROBERT P. KIRSHNER,[2] B. LEIBUNDGUT,[6] M. M. PHILLIPS,[7] DAVID REISS,[4] BRIAN P. SCHMIDT,[8,9] ROBERT A. SCHOMMER,[7] R. CHRIS SMITH,[7,10] J. SPYROMILIO,[6] CHRISTOPHER STUBBS,[4] NICHOLAS B. SUNTZEFF,[7] AND JOHN TONRY[11]
*Received 1998 March 13; revised 1998 May 6*

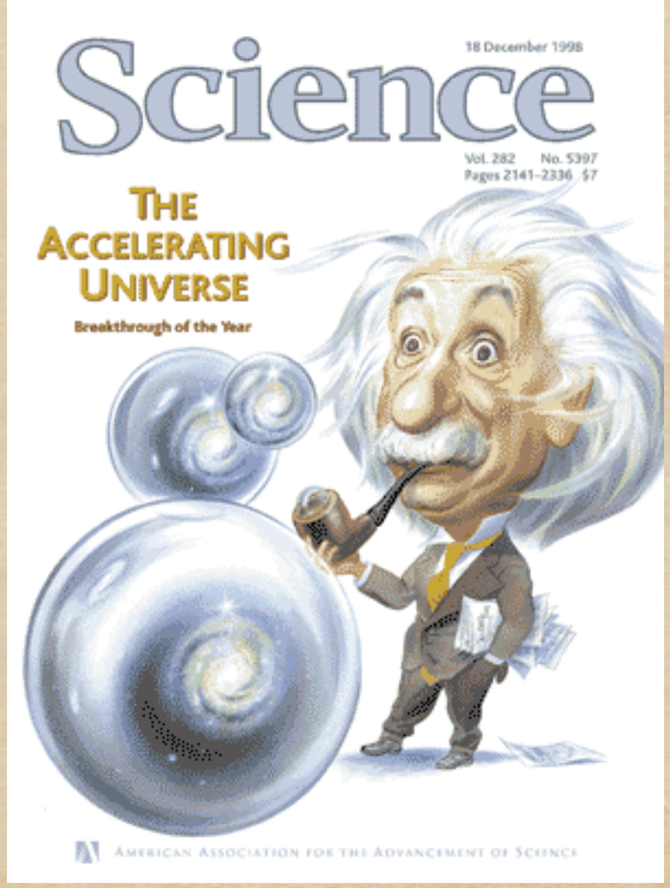


Illustration: John Kascht

THE ASTROPHYSICAL JOURNAL, 517:565–586, 1999 June 1


# MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

S. PERLMUTTER,[1] G. ALDERING, G. GOLDHABER,[1] R. A. KNOP, P. NUGENT, P. G. CASTRO,[2] S. DEUSTUA, S. FABBRO,[3]
A. GOOBAR,[4] D. E. GROOM, I. M. HOOK,[5] A. G. KIM,[1,6] M. Y. KIM, J. C. LEE,[7] N. J. NUNES,[2] R. PAIN,[3]
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A. V FILIPPENKO AND T. MATHESON
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Fermi National Laboratory, Batavia, IL

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W. J. COUCH
University of New South Wales, Sydney, Australia

(THE SUPERNOVA COSMOLOGY PROJECT)

*Received 1998 September 8; accepted 1998 December 17*

The Astrophysical Journal, 607:665–687, 2004 June 1


# TYPE Ia SUPERNOVA DISCOVERIES AT $z > 1$ FROM THE *HUBBLE SPACE TELESCOPE*: EVIDENCE FOR PAST DECELERATION AND CONSTRAINTS ON DARK ENERGY EVOLUTION[1]

Adam G. Riess,[2] Louis-Gregory Strolger,[2] John Tonry,[3] Stefano Casertano,[2] Henry C. Ferguson,[2] Bahram Mobasher,[2] Peter Challis,[4] Alexei V. Filippenko,[5] Saurabh Jha,[5] Weidong Li,[5] Ryan Chornock,[5] Robert P. Kirshner,[4] Bruno Leibundgut,[6] Mark Dickinson,[2] Mario Livio,[2] Mauro Giavalisco,[2] Charles C. Steidel,[7] Txitxo Benítez,[8] and Zlatan Tsvetanov[8]

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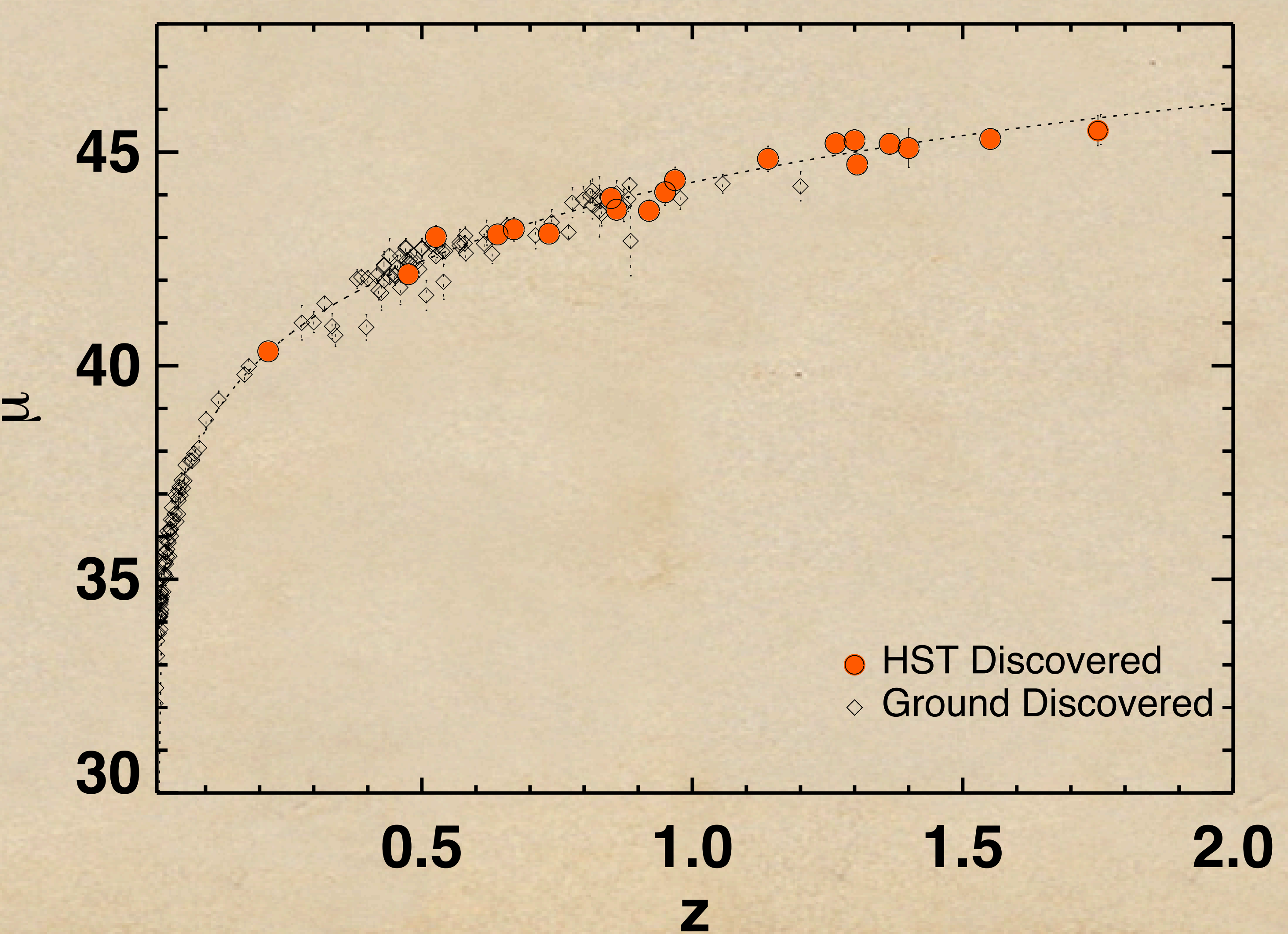

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E

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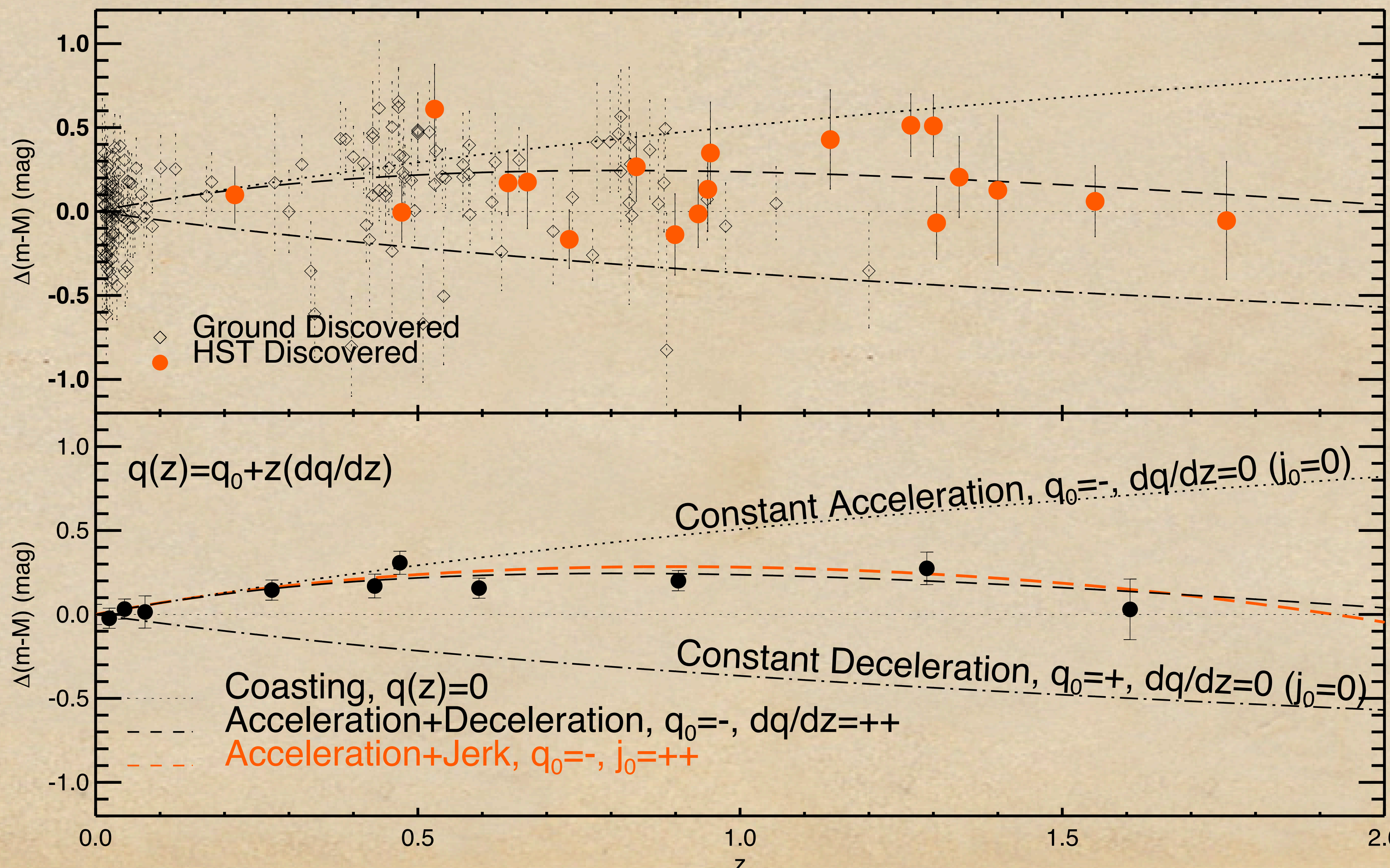
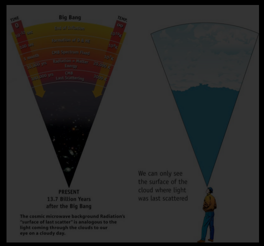
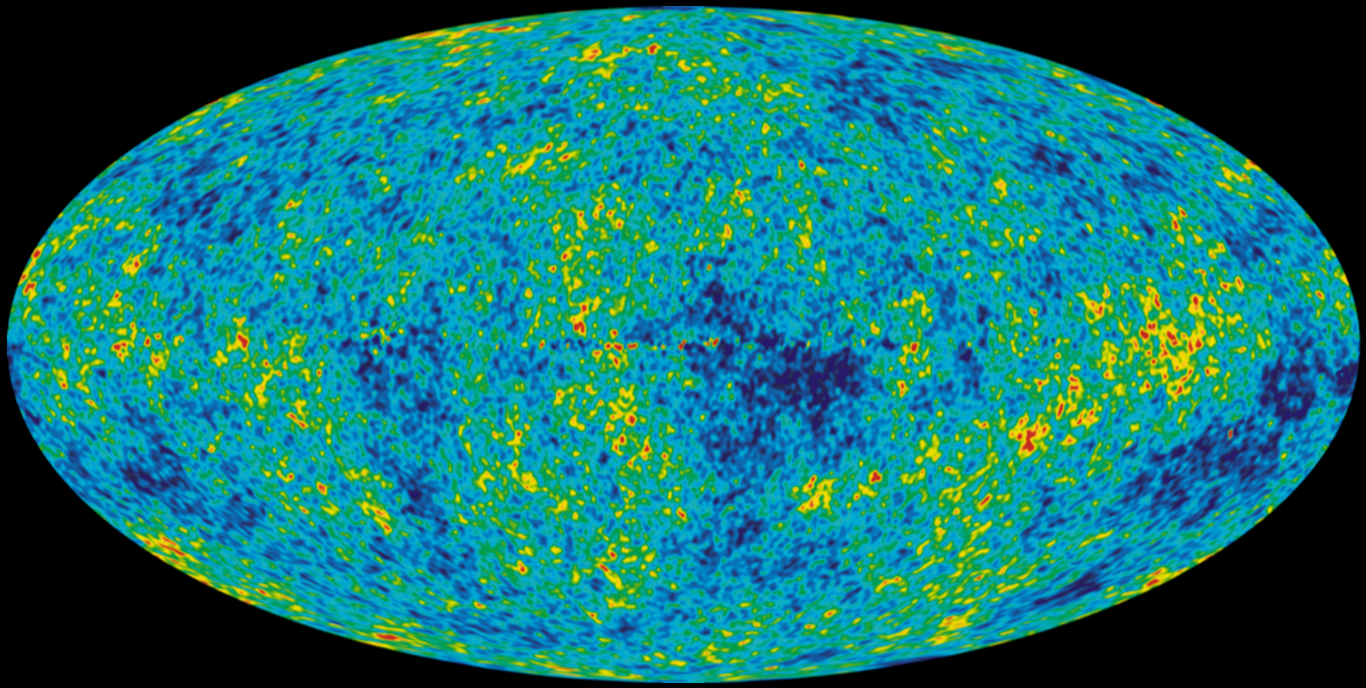
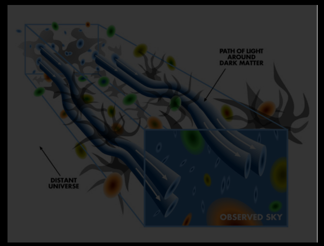


# Probing Dark Energy





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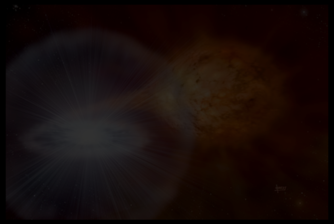
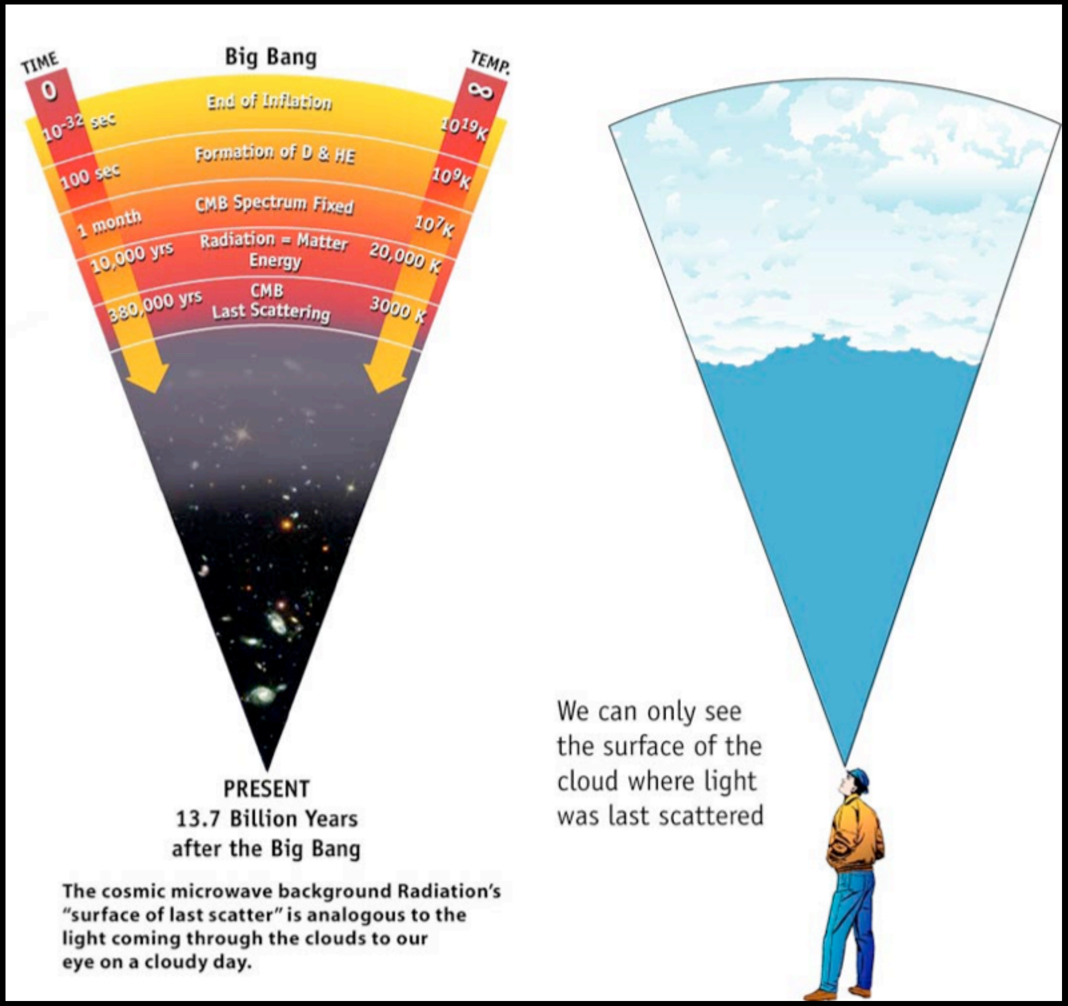
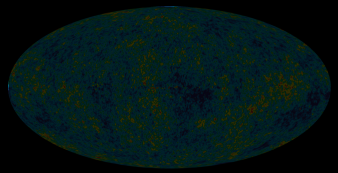





**The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.**



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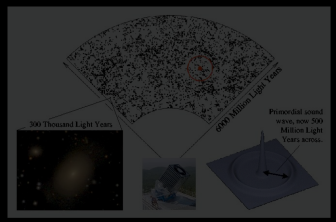

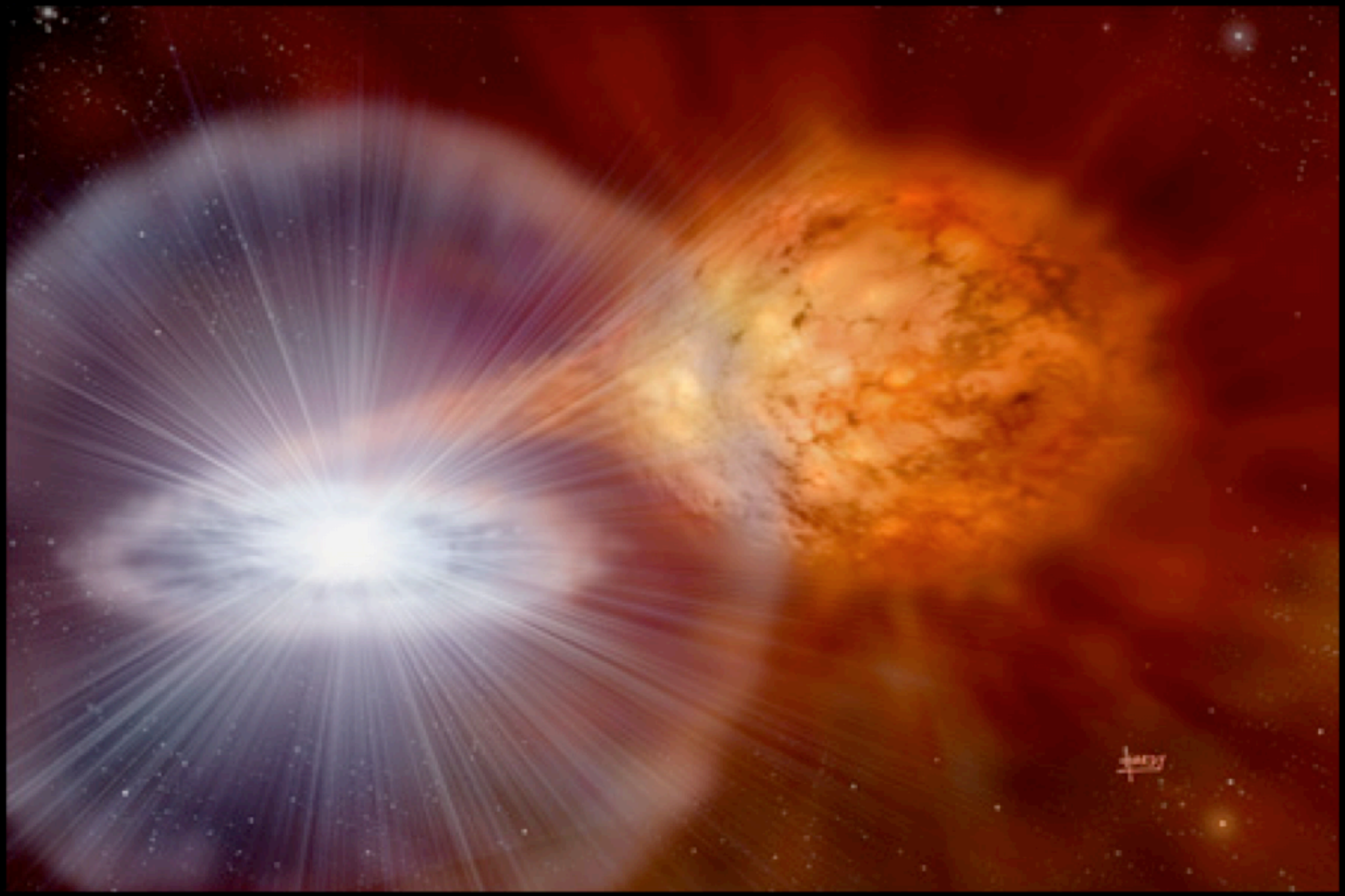

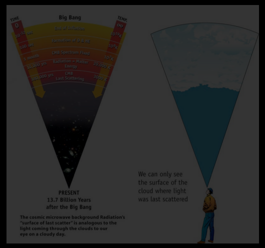

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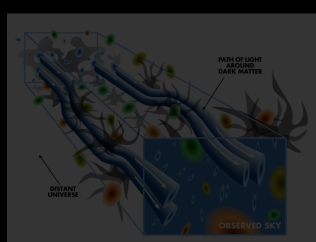

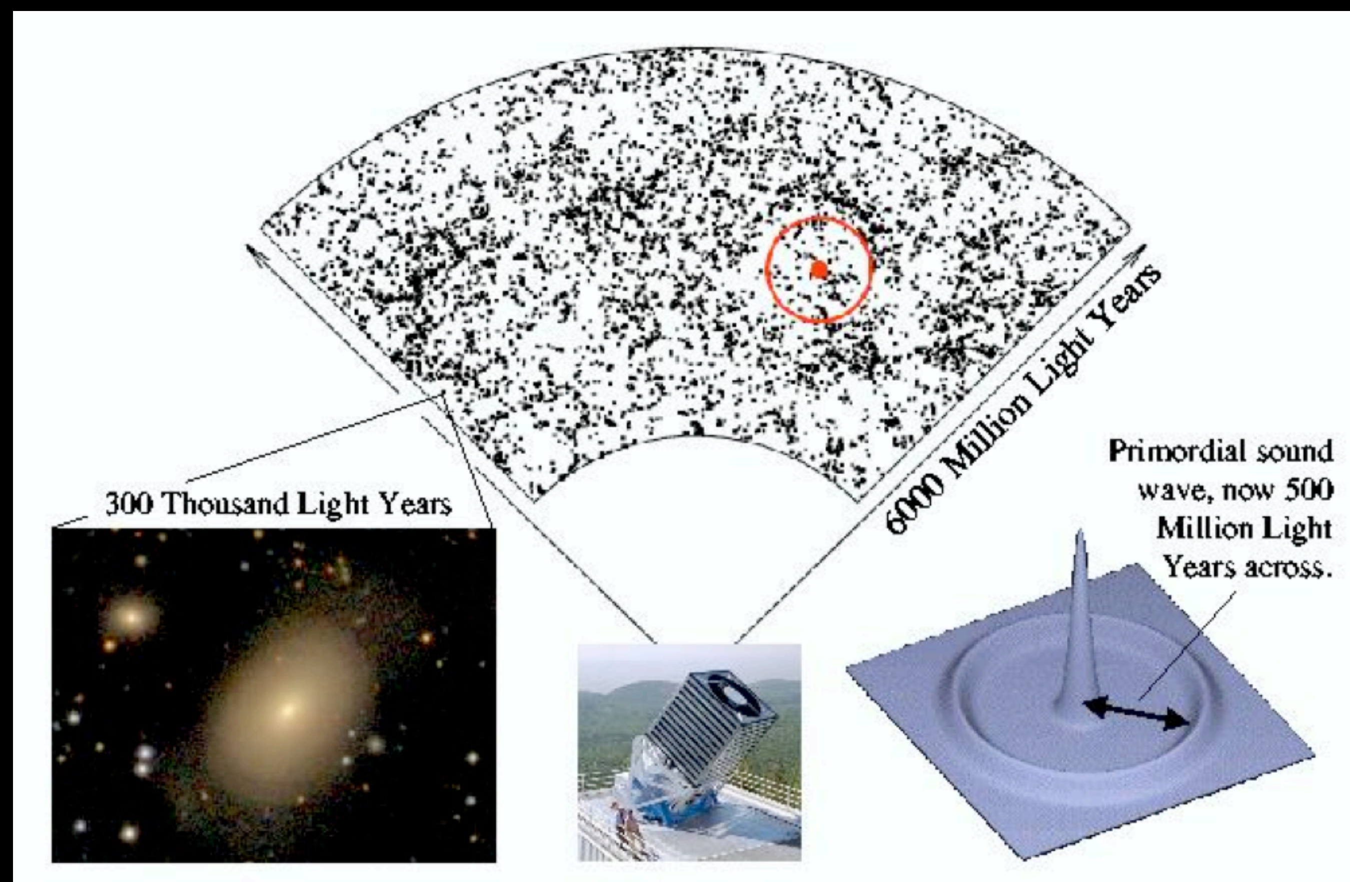


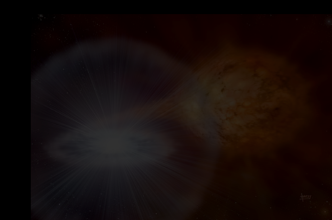

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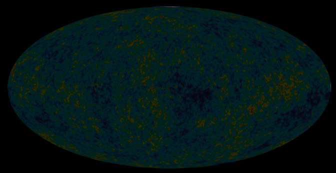
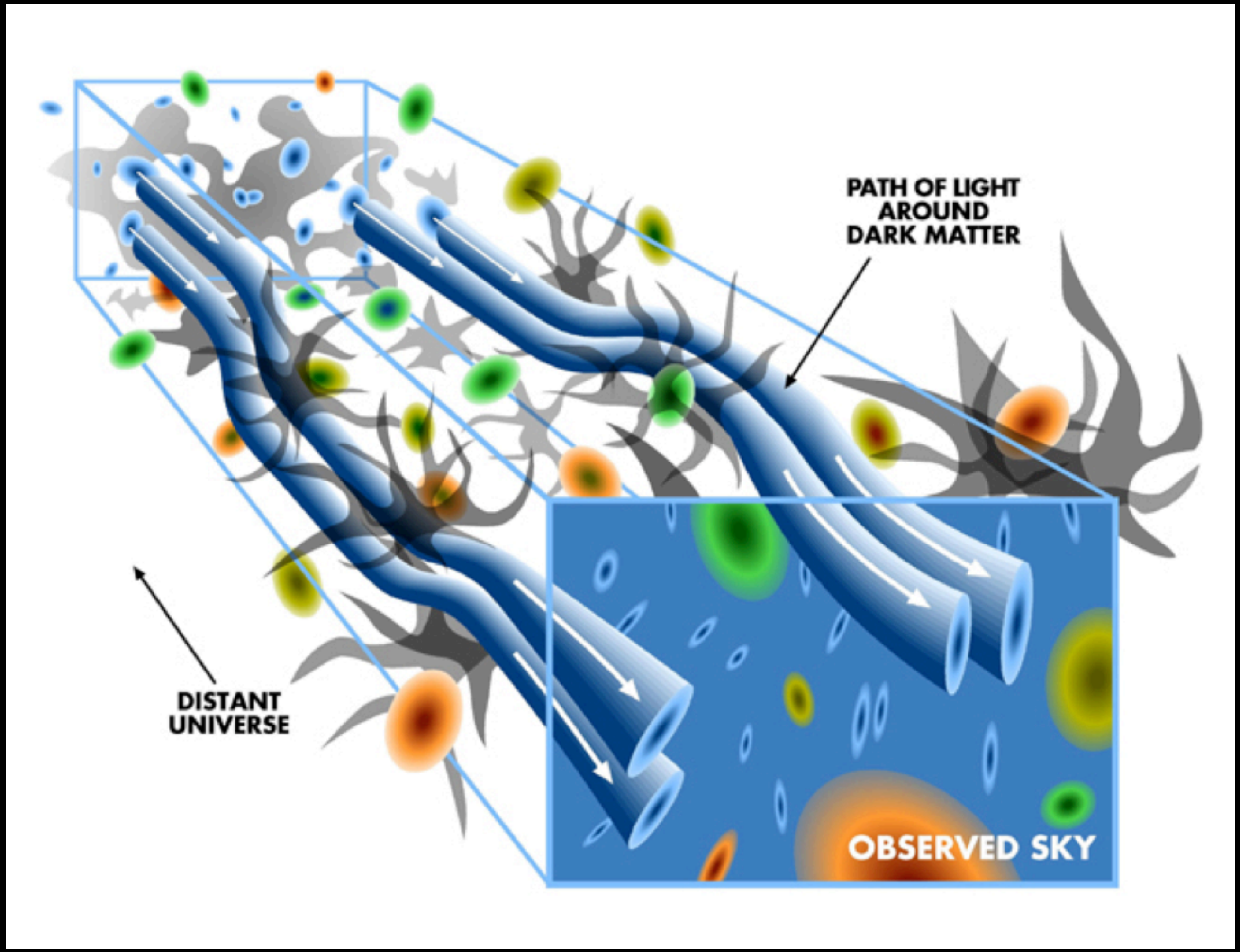
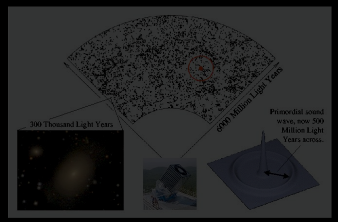
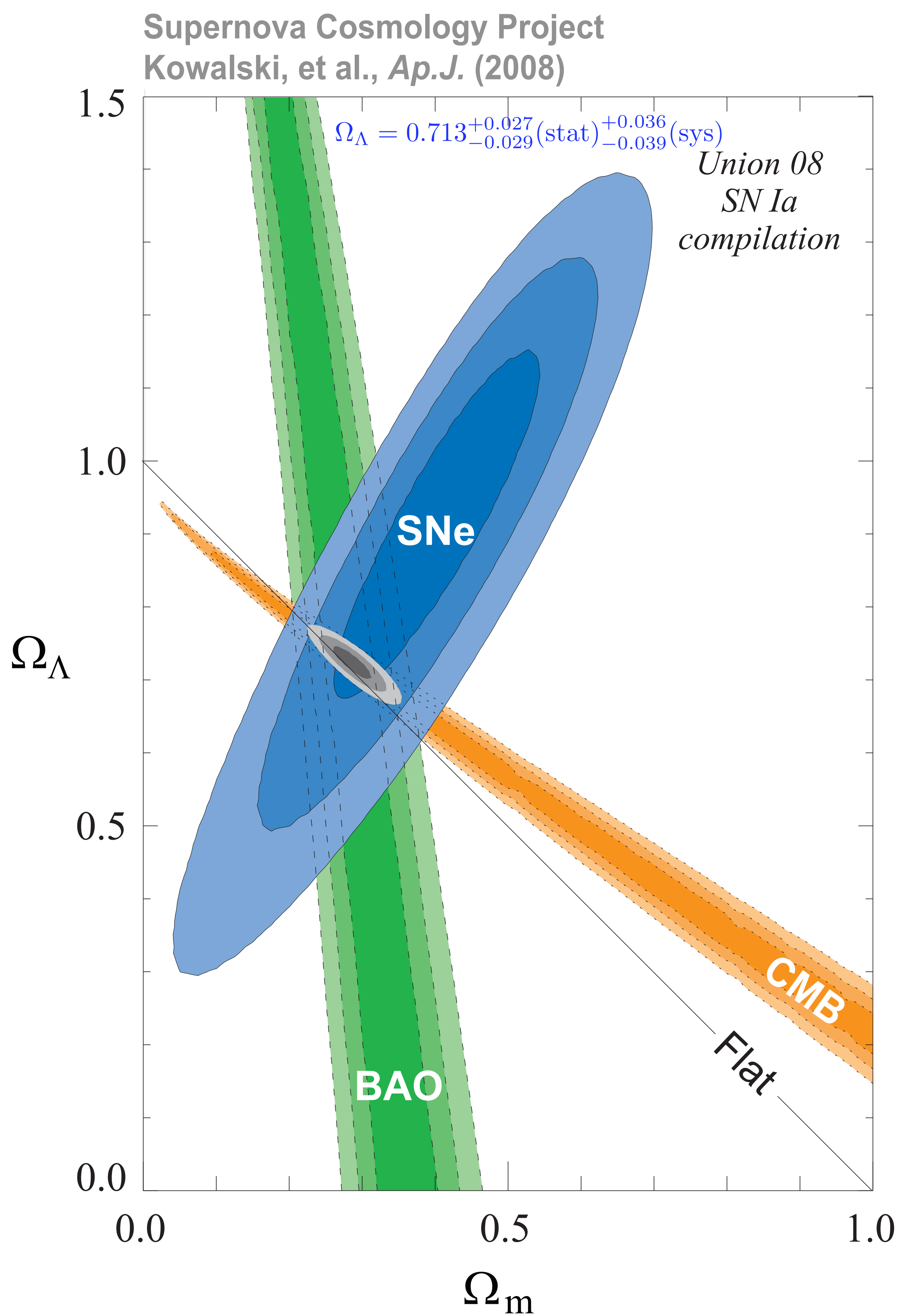
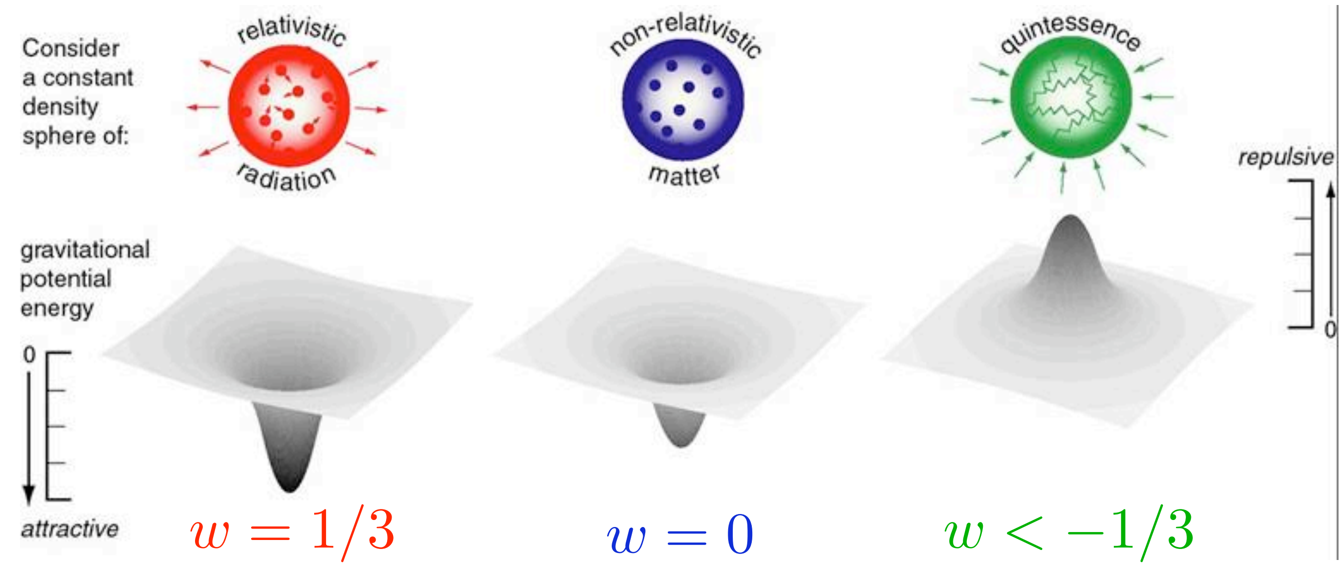


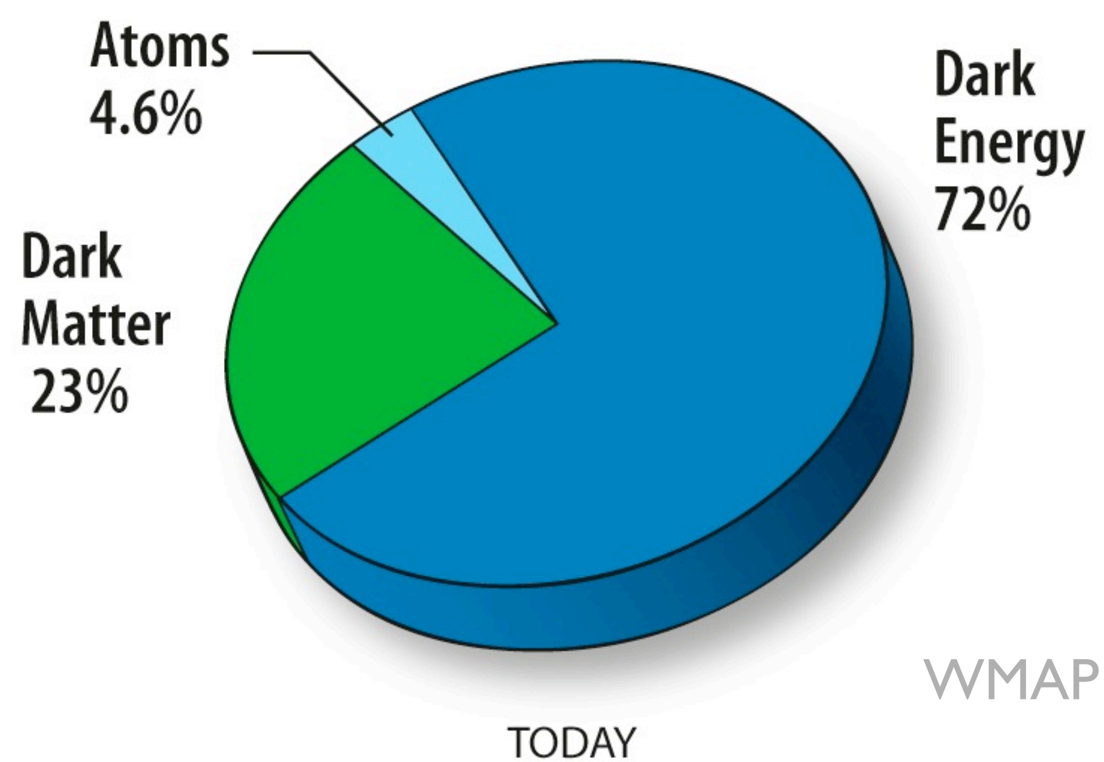



Supernova Cosmology Project
Kowalski, et al., Ap.J. (2008)
$\Omega_\Lambda = 0.713^{+0.027}_{-0.029}(\text{stat})^{+0.036}_{-0.039}(\text{sys})$
Union 08
SN Ia
compilation
SNe
CMB
BAO
Flat
$\Omega_\Lambda$
$\Omega_m$
0.0
0.5
1.0
1.5


Consider a constant density sphere of:
relativistic
radiation
non-relativistic
matter
quintessence
gravitational potential energy
0
attractive
repulsive
$w = 1/3$
$w = 0$
$w < -1/3$

$$w = p/\rho$$


Atoms
4.6%
Dark
Energy
72%
Dark
Matter
23%
TODAY
WMAP

# Seeking Temporal Evolution of "w"

1. Parametrize w(z) [Adopted by DETF]

$$w(z) = w_0 + w_a z/(1+z)$$

Chevallier and Polarski 2001, Linder 2003

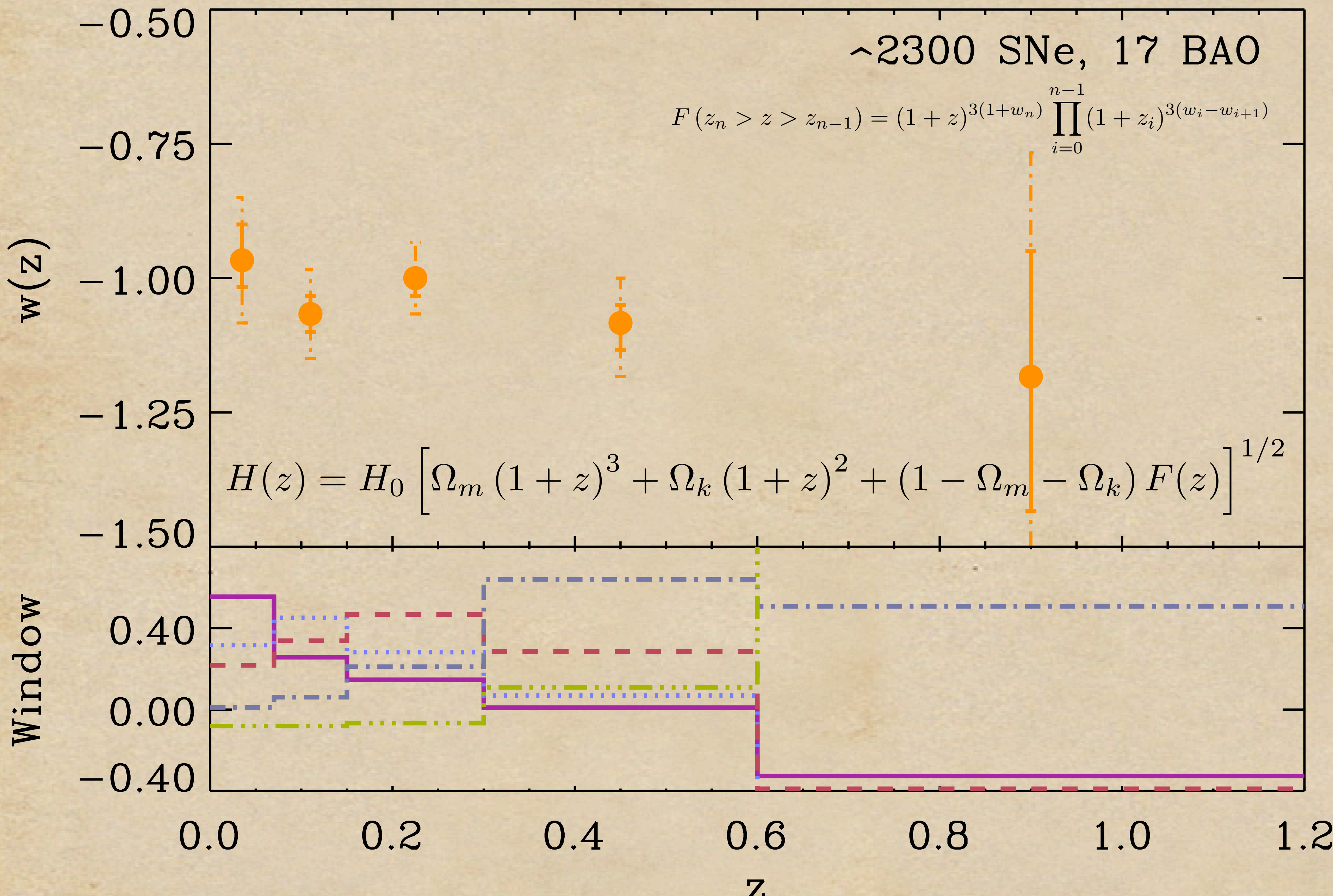
2. Principal Component Analysis

Huterer and Starkman 2003

3. Uncorrelated Estimates of w(z)

Huterer and Cooray 2005

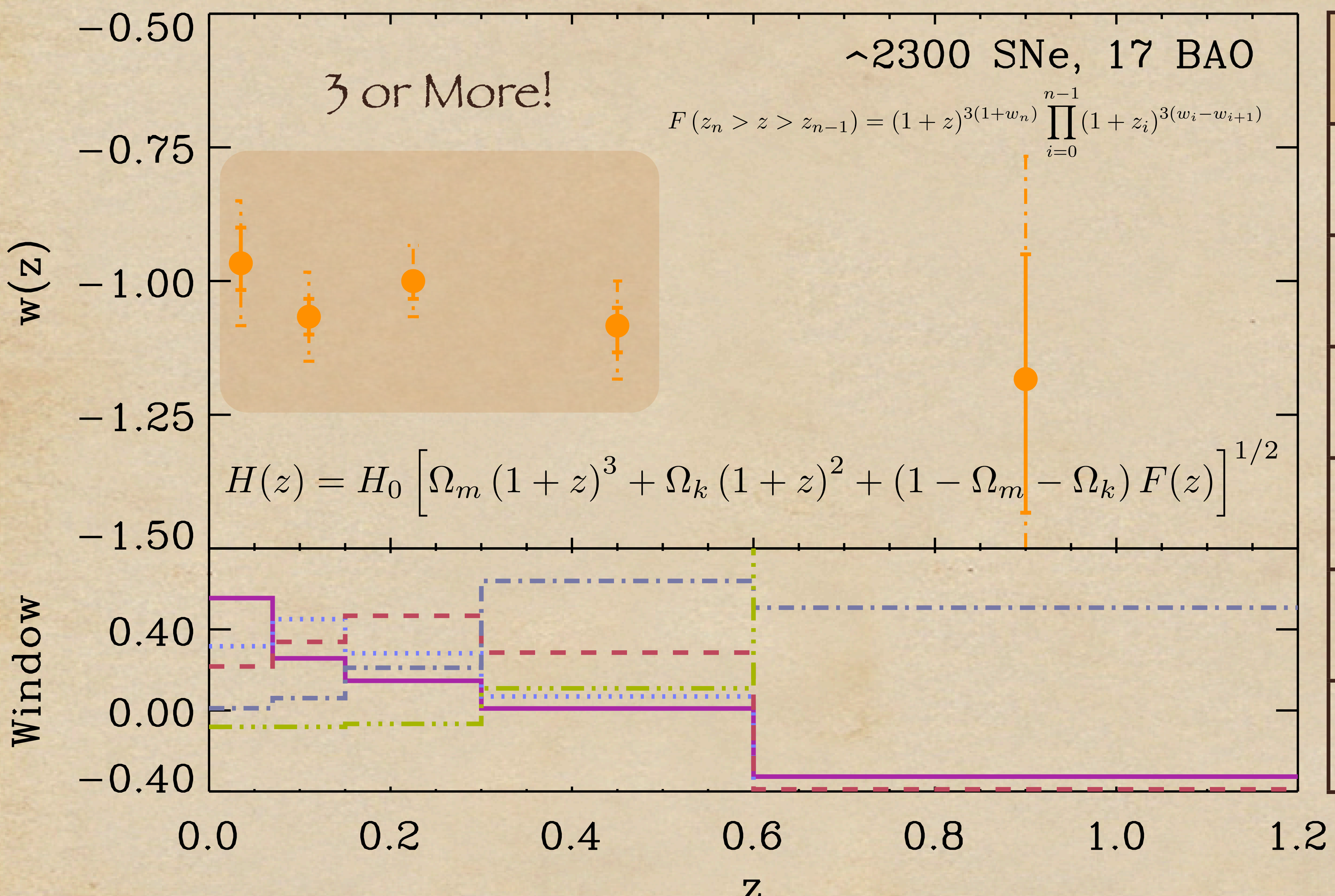
# Going Model-Independent: The Future!




| W | $z_{up}$ |
|---|---|
| $w_1$ | 0.07 |
| $w_2$ | 0.15 |
| $w_3$ | 0.3 |
| $w_4$ | 0.6 |
| $w_5$ | 1.2 |
| $w_6$ | 1.8 |

D.S., S. Sullivan, S. Joudaki, A. Amblard, D. Holz, and A. Cooray, PRL 100, 241302 (2008)

# Going Model-Independent: The Future!




| W | Zup |
|---|---|
| $w_1$ | 0.07 |
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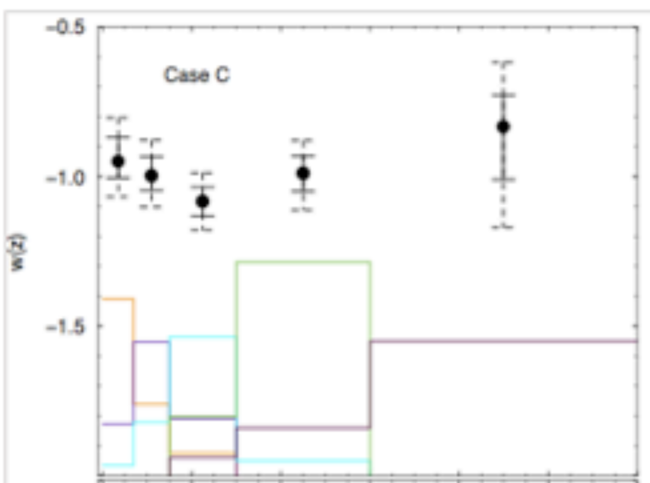
# DevdeepSarkar

center for cosmology, uc irvine



## wzBinned Code

*wzBinned* is a numerical code to extract uncorrelated binned estimates of the dark energy equation of state, w(z), using Type Ia supernovae distance-redshift data and other cosmological probes and priors. It is written in C programming language and based on Markov chain Monte Carlo method. For further details please refer to Sarkar et al., Phys. Rev. Lett. 100 241302 (2008), and Sullivan et al., JCAP 09 004 (2007).




## Other Resources

- COSMOMC
- CMBFAST
- IDL Astro

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# Influence of Gravitational Lensing?

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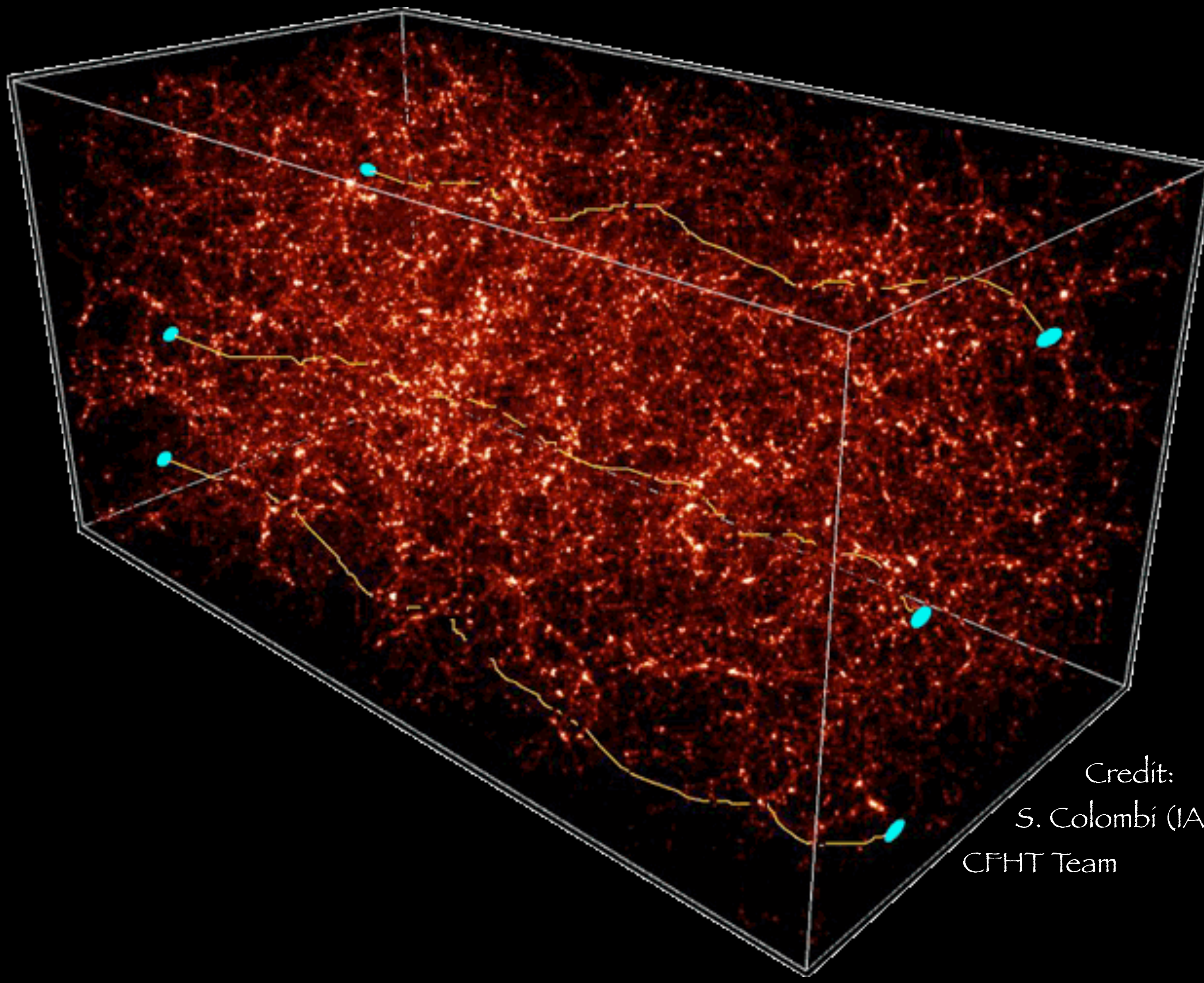
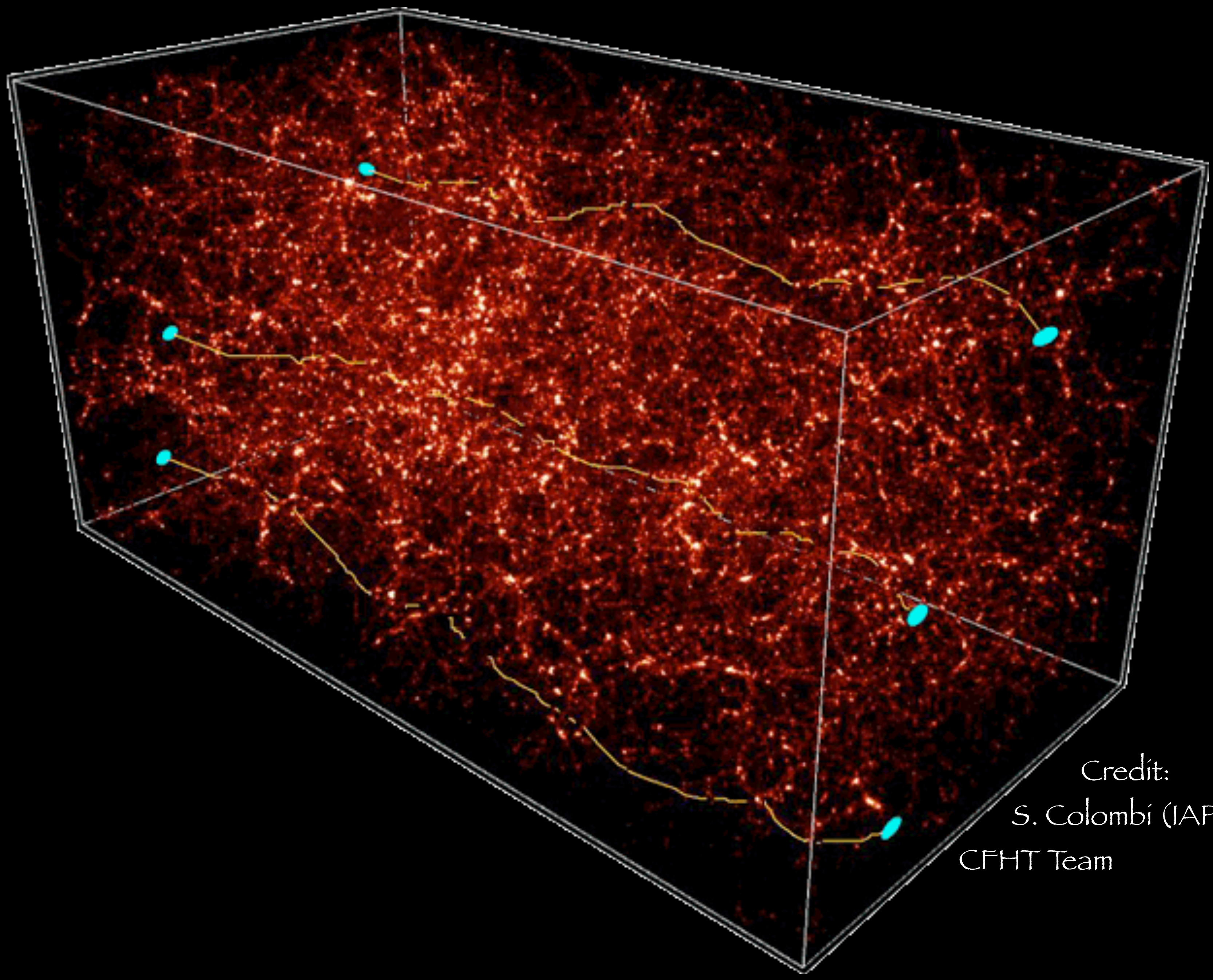


Credit:
S. Colombi (IAP),
CFHT Team

# Influence of Gravitational Lensing?



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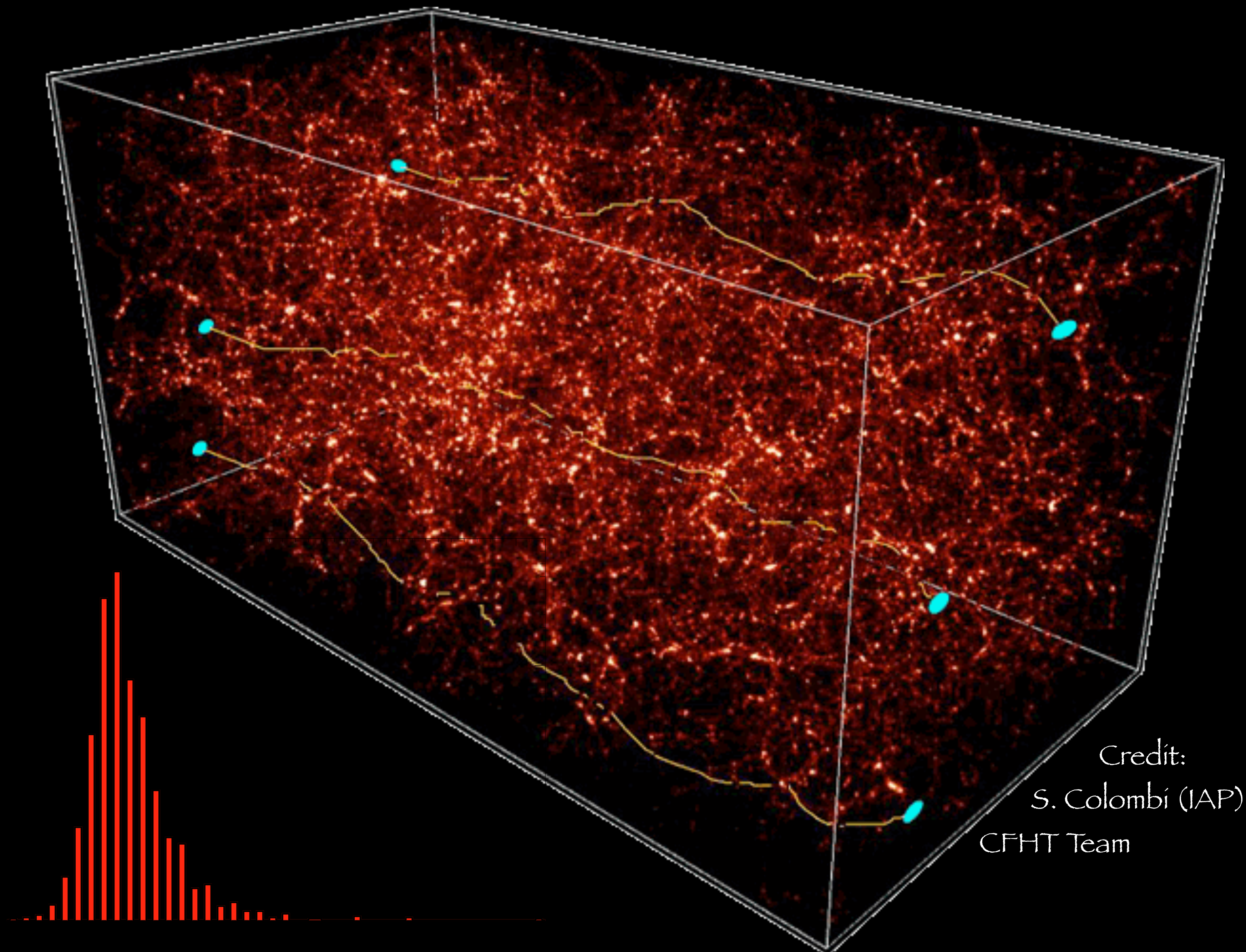
$$\mathcal{F}^{\rm obs,lensed}(z,\hat{\mathbf{n}}) = \mu(z,\hat{\mathbf{n}})\mathcal{F}^{\rm obs,true}(z)$$

# Influence of Gravitational Lensing?

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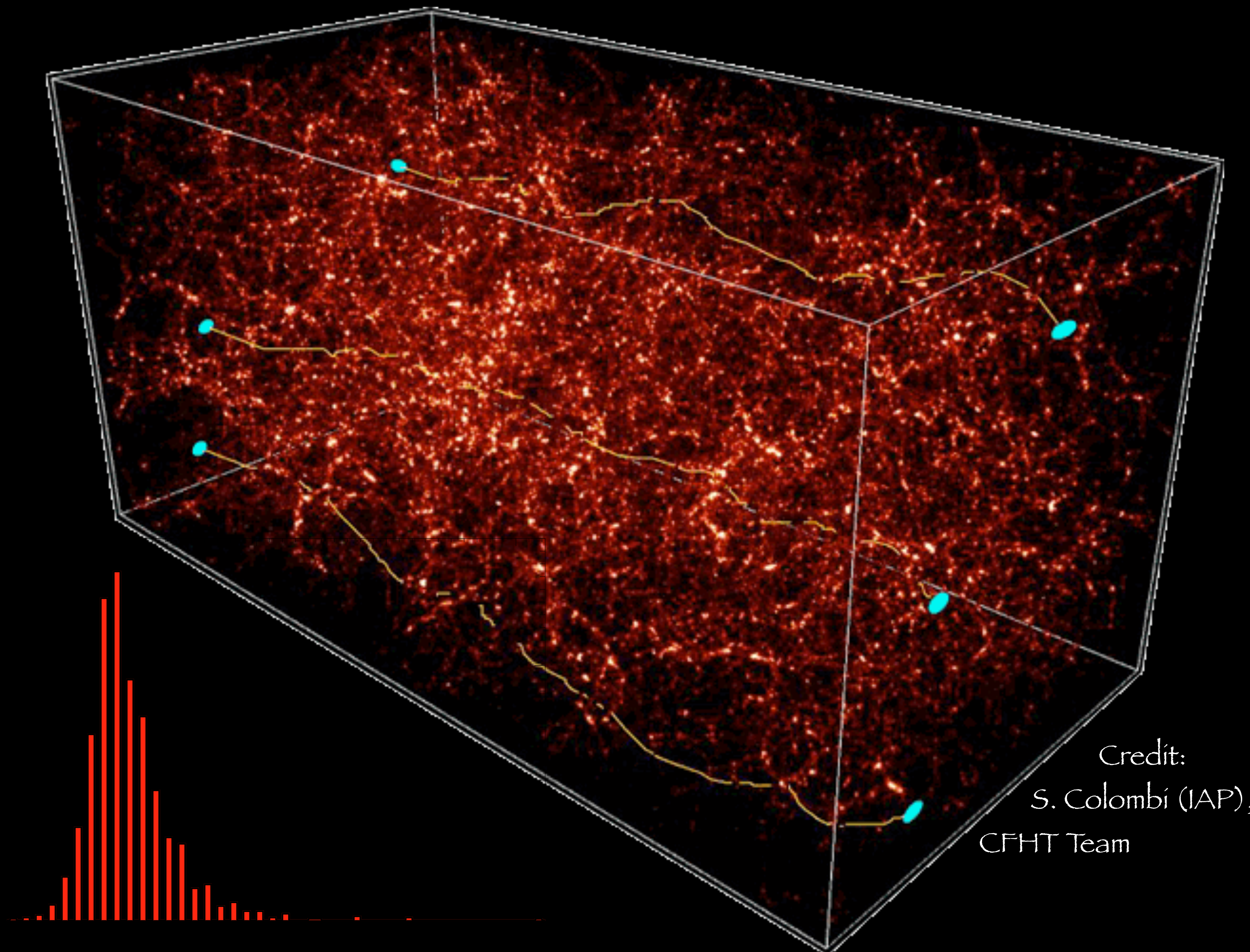
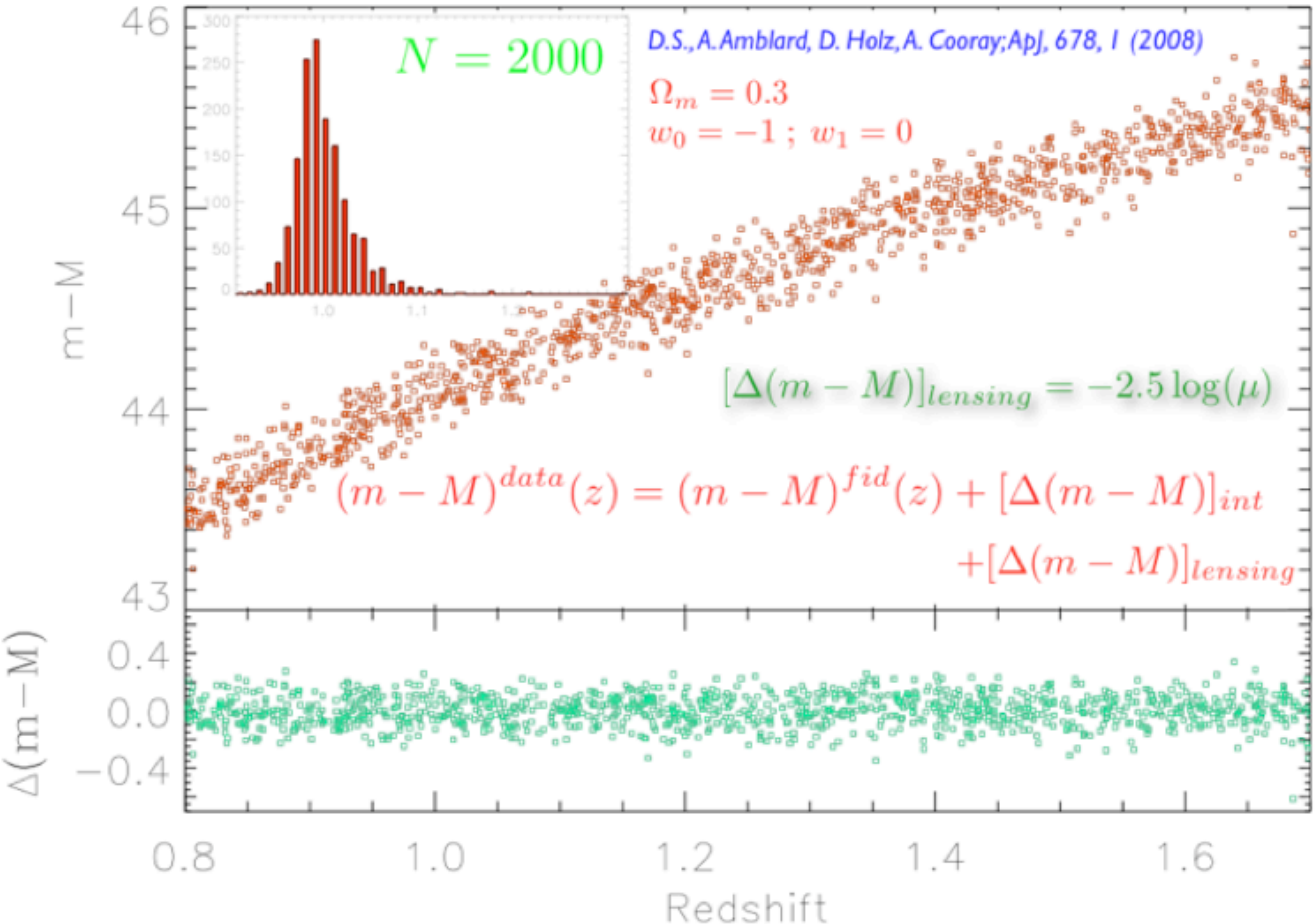


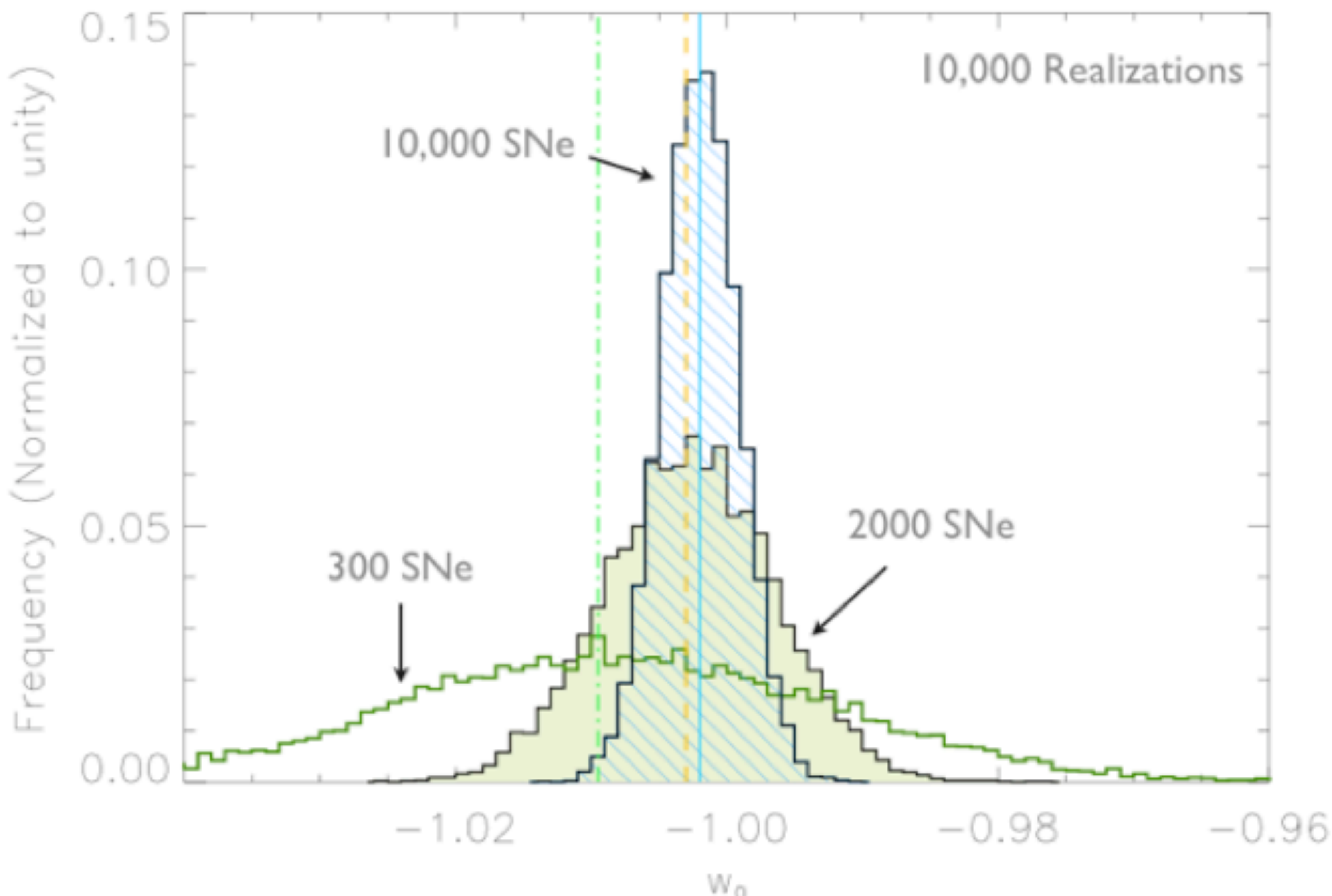

$$\mathcal{F}^{\mathrm{obs,lensed}}(z,\hat{\mathbf{n}}) = \mu(z,\hat{\mathbf{n}})\mathcal{F}^{\mathrm{obs,true}}(z)$$

Weak lensing can modify the SNa flux & bias estimates of w

# Our Analysis with Mock Catalogs

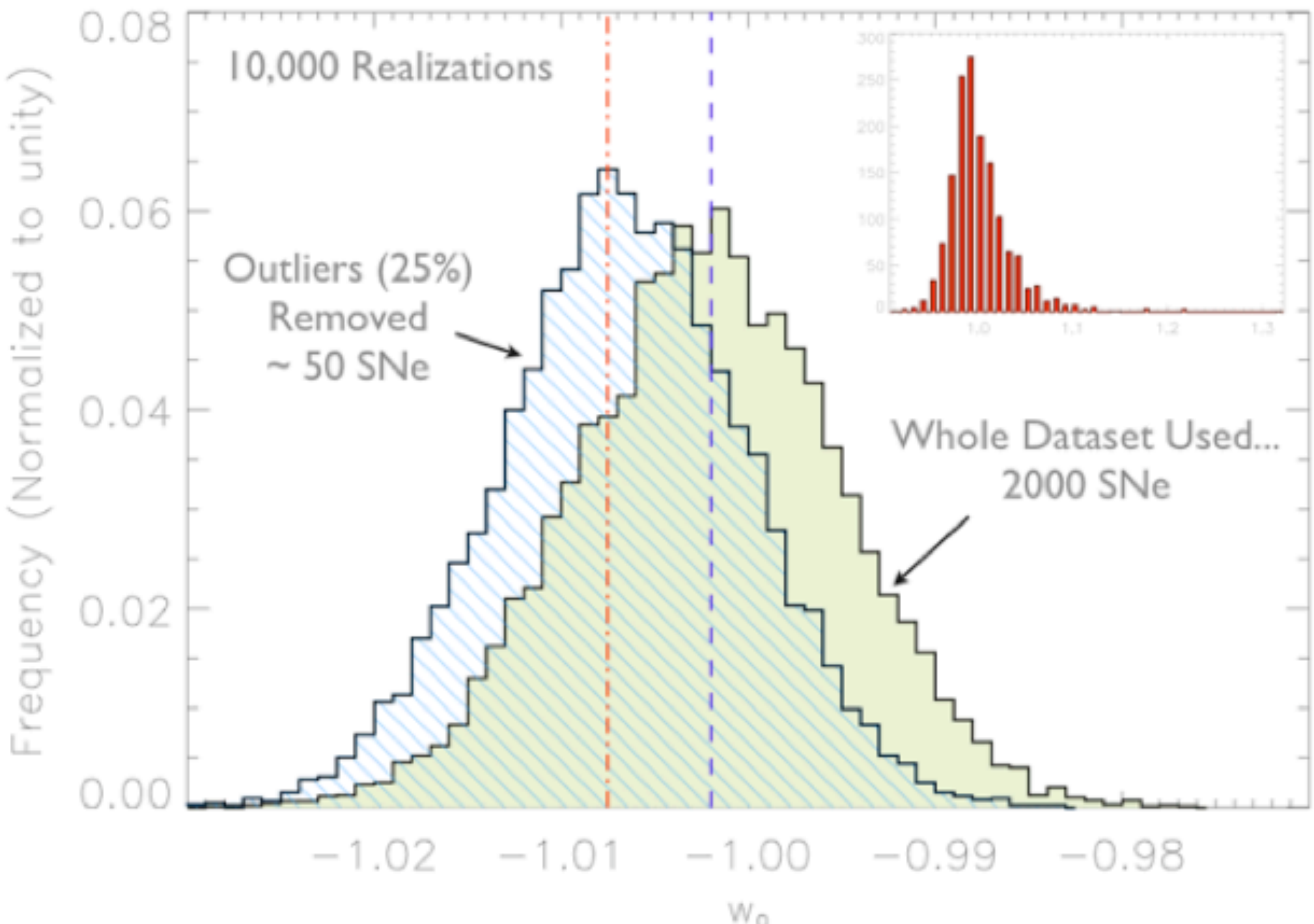


# Effect of Weak Lensing on Estimates of "w"




*D.S., A. Amblard, D. Holz, A. Cooray; ApJ, 678, 1 (2008)*

# Effect of Removing the Outliers

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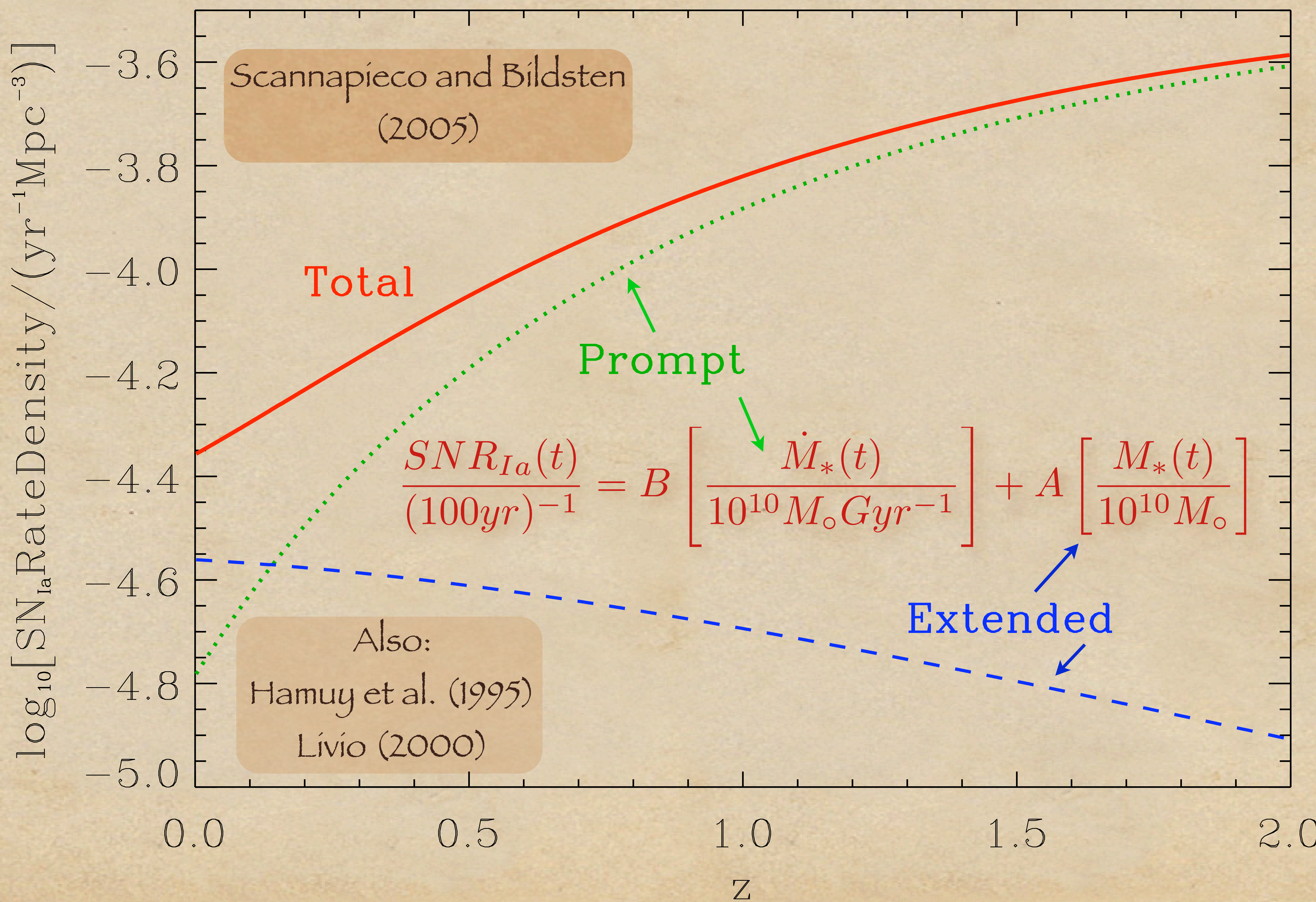
# Two Supernova Populations



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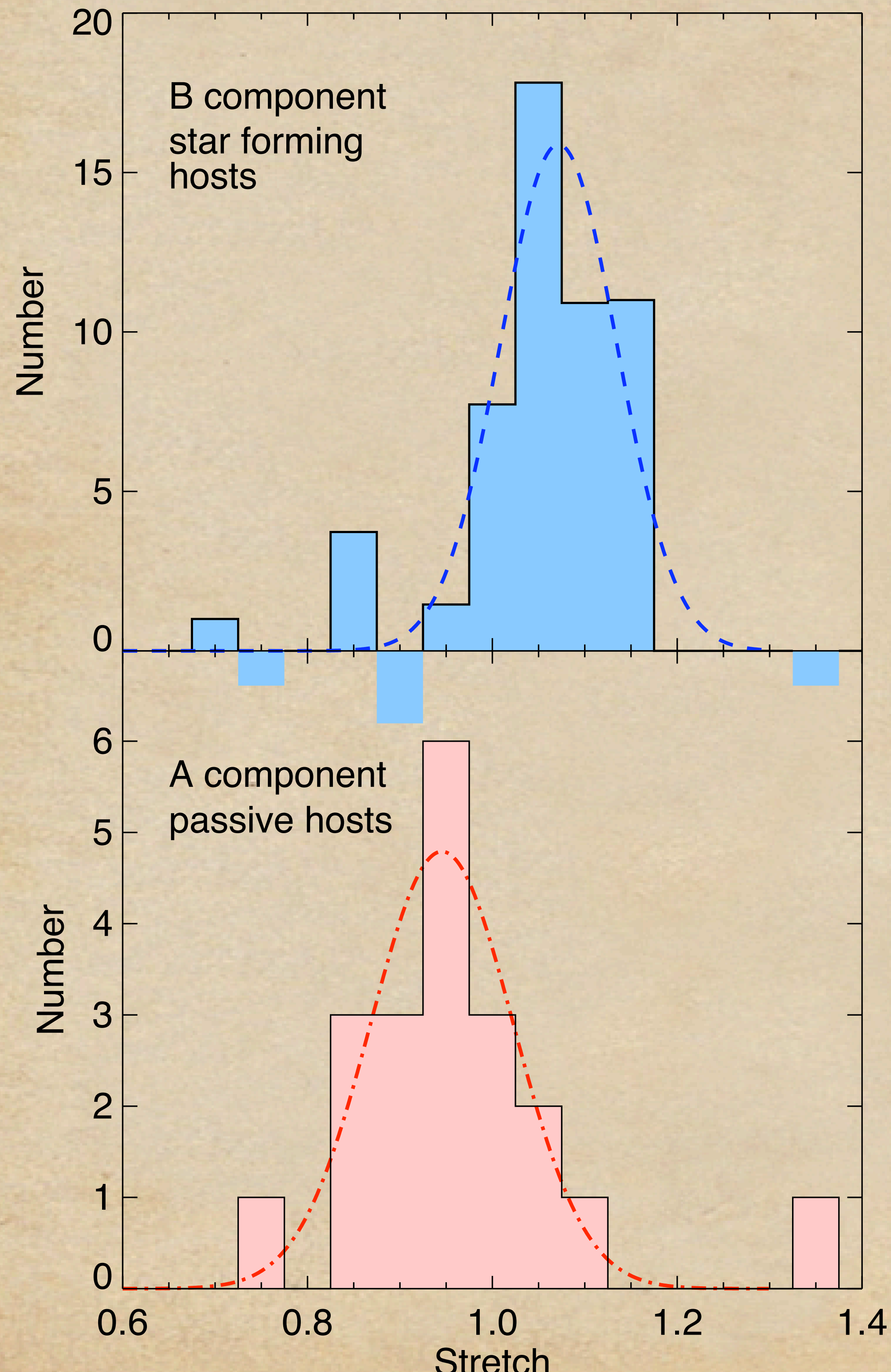


$$\mu_B = m_B^* - M + \alpha(s-1) - \beta c$$

Tripp (1998), Guy et al. (2005)

PROMPT

12% Dfference

in

Intrinsic Luminosity

$$\mathcal{L}_P = \mathcal{L}_E + \Delta\mathcal{L}$$

DELAYED

*Howell et al. 2007*

*Data Source: Sullivan et al. 2006 (SNLS)*

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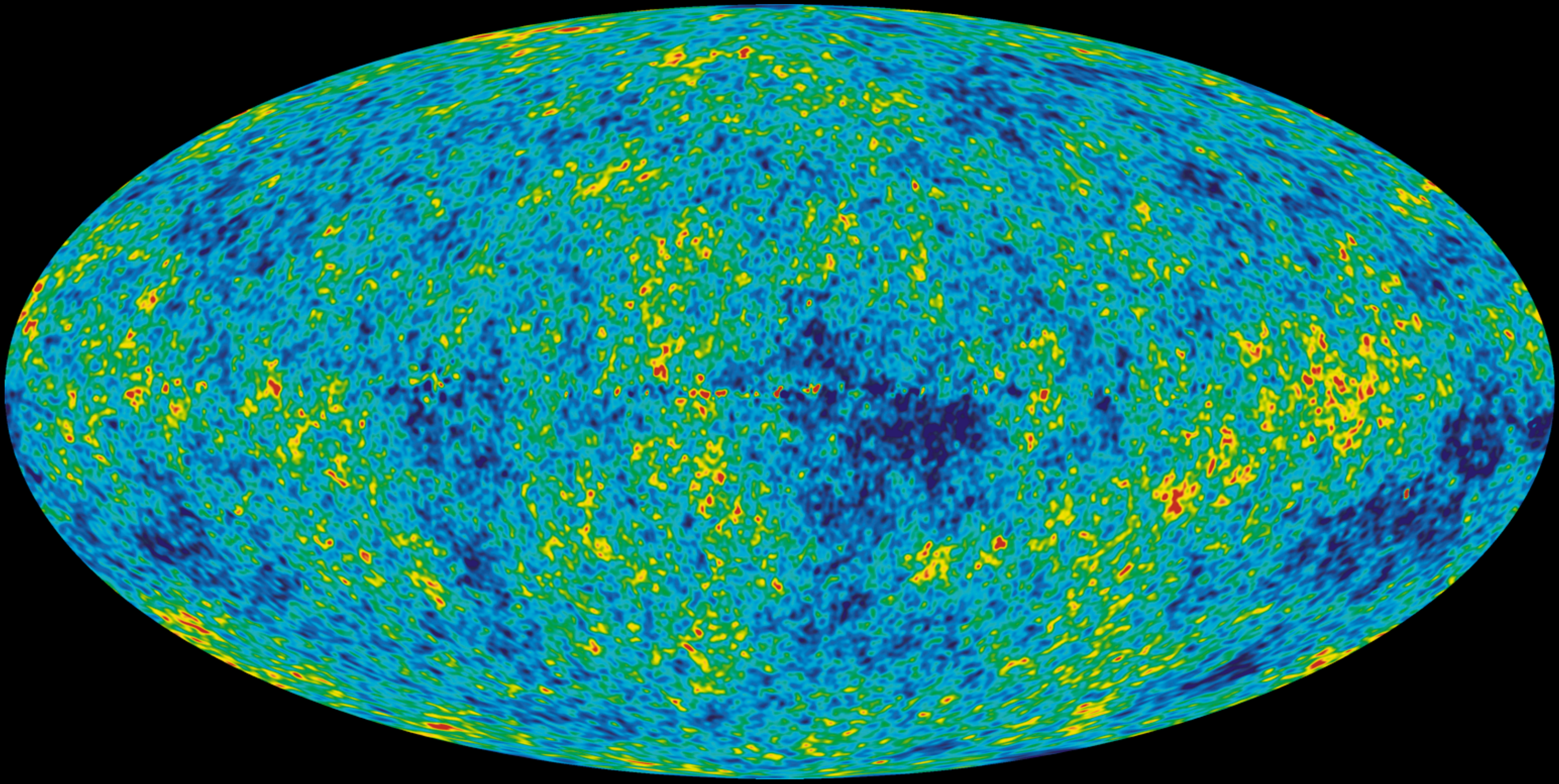
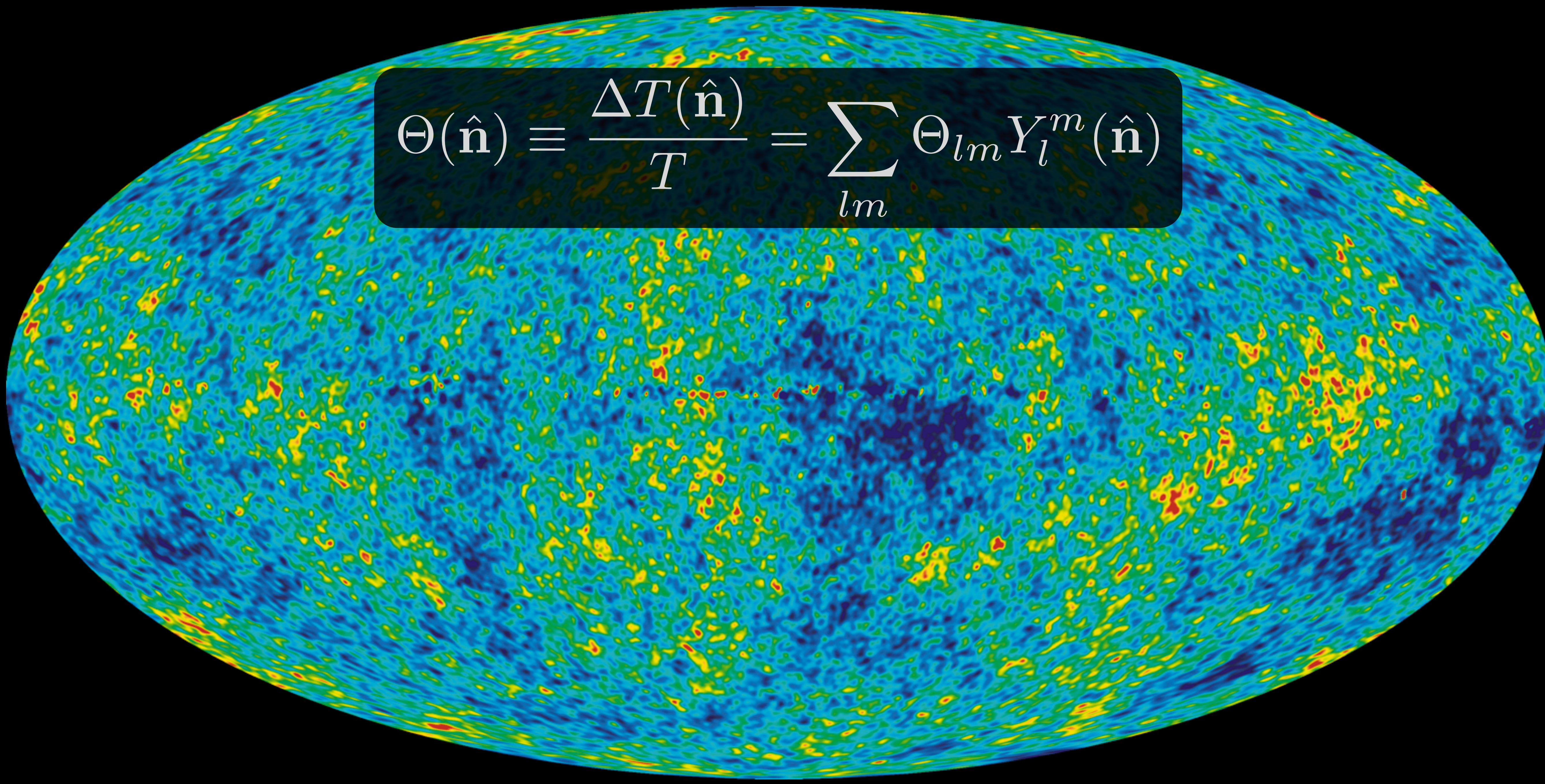


Credit: NASA/WMAP Science Team

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



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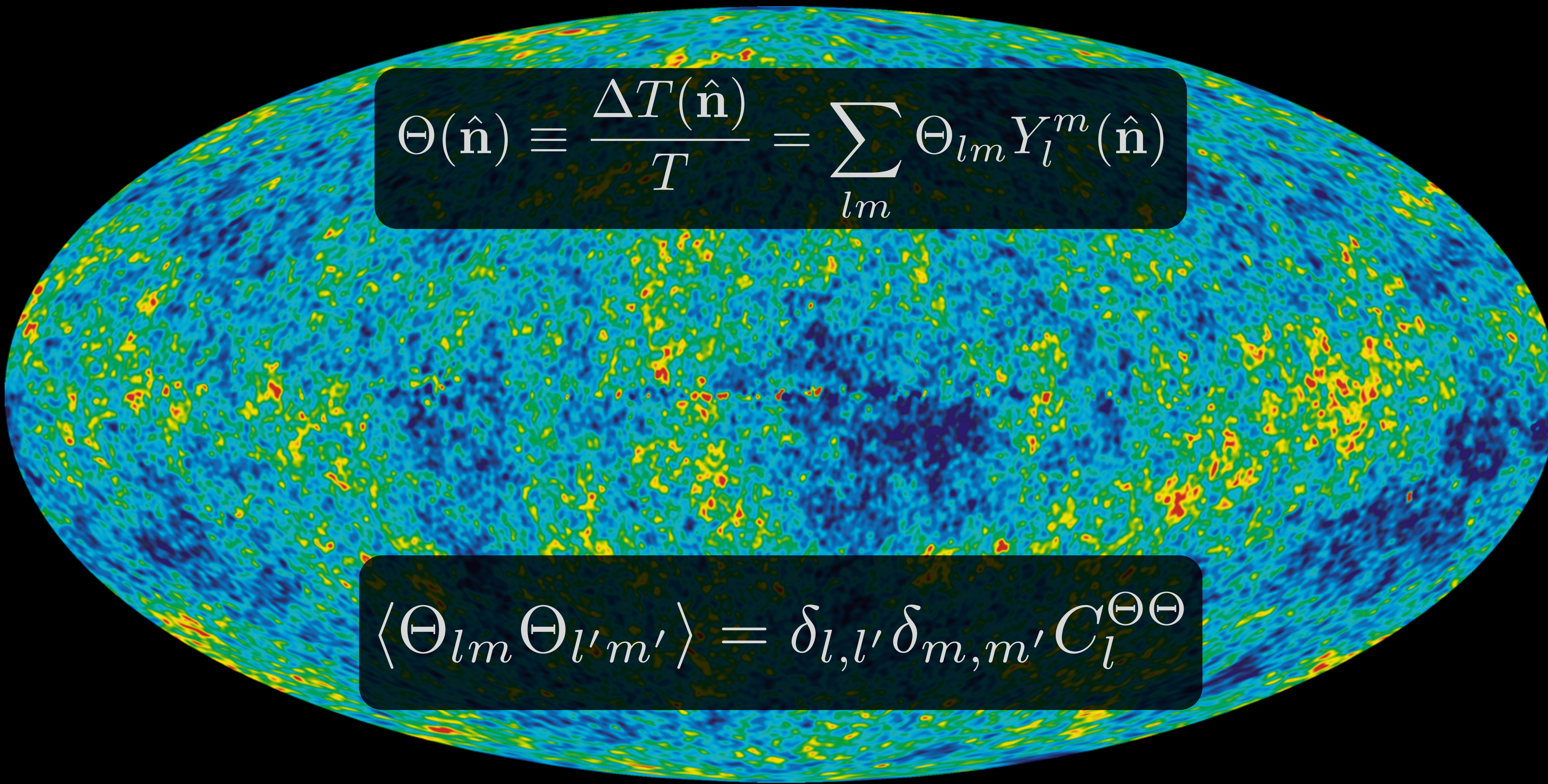
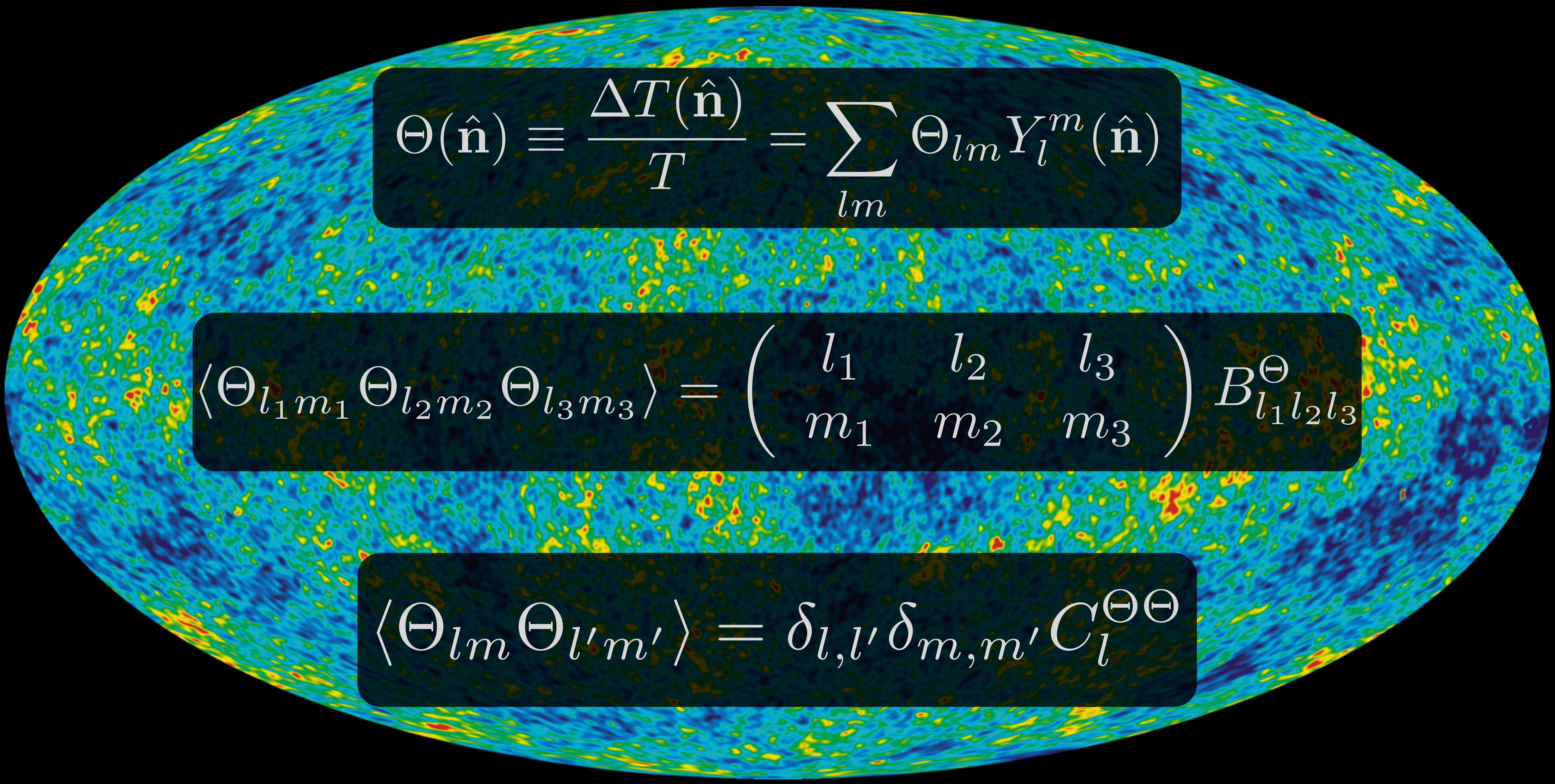


$$\Theta(\hat{\mathbf{n}}) \equiv \frac{\Delta T(\hat{\mathbf{n}})}{T} = \sum_{lm} \Theta_{lm} Y_l^m(\hat{\mathbf{n}})$$

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

Credit: NASA/WMAP Science Team



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

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

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

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 $2.8\sigma$

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(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 $2.8\sigma$, 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 $2.5\sigma$ to be conservative.

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

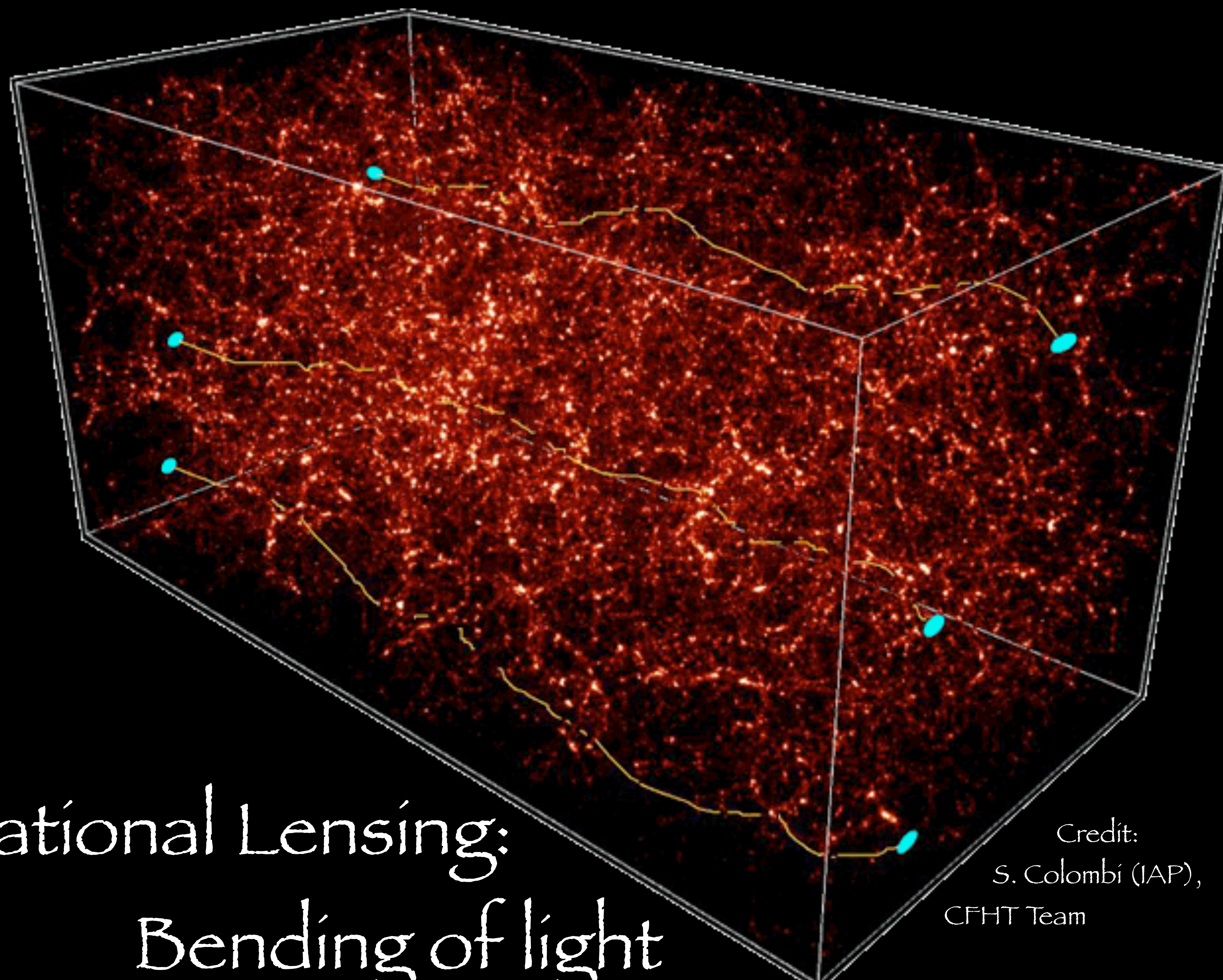
E. Komatsu [1], J. Dunkley [2,3,4], M. R. Nolta [5], C. L. Bennett [6], B. Gold [6], G. Hinshaw [7], N. Jarosik [2], D. Larson [6], M. Limon [8] L. Page [2], D. N. Spergel [3,9], M. Halpern [10], R. S. Hill [11], A. Kogut [7], S. S. Meyer [12], G. S. Tucker [13], J. L. Weiland [10], E. Wollack [7], and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



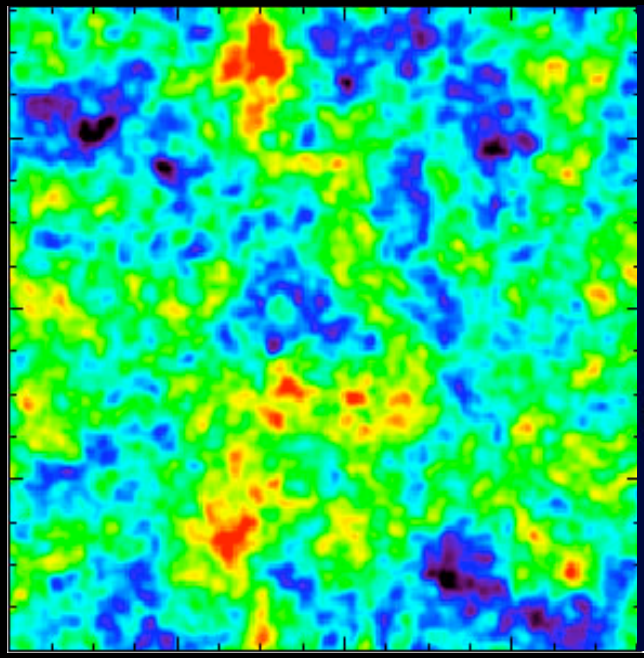
Weak

Gravitational Lensing:

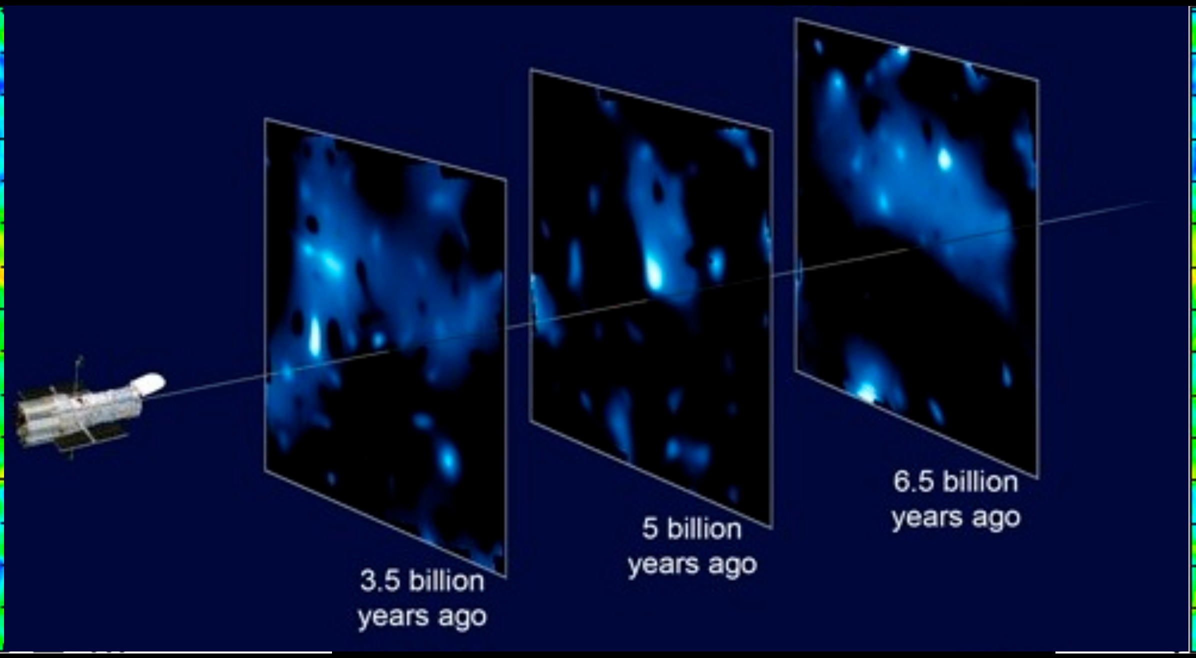
Bending of light

Credit:
S. Colombi (IAP),
CFHT Team

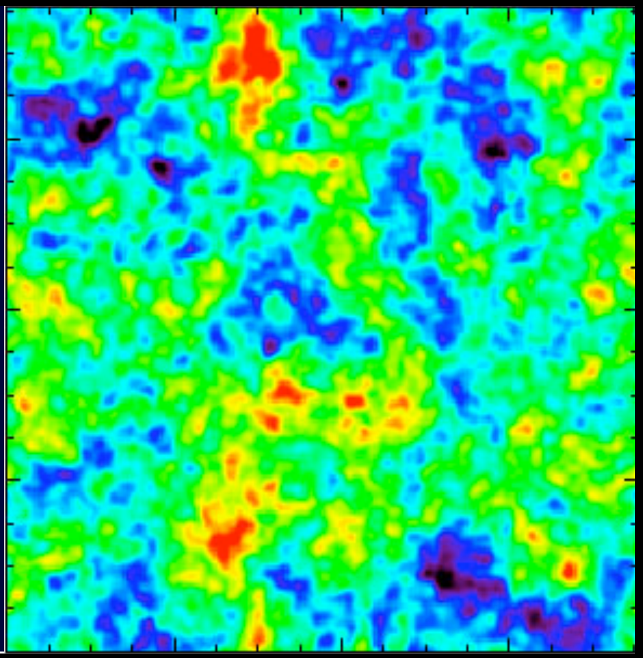
# Weak Lensing of the Primary Bispectrum



Credit: Vale, Amblard, White (2004)




NASA, ESA, and R. Massey (CalTech)



Credit: Vale, Amblard, White (2004)

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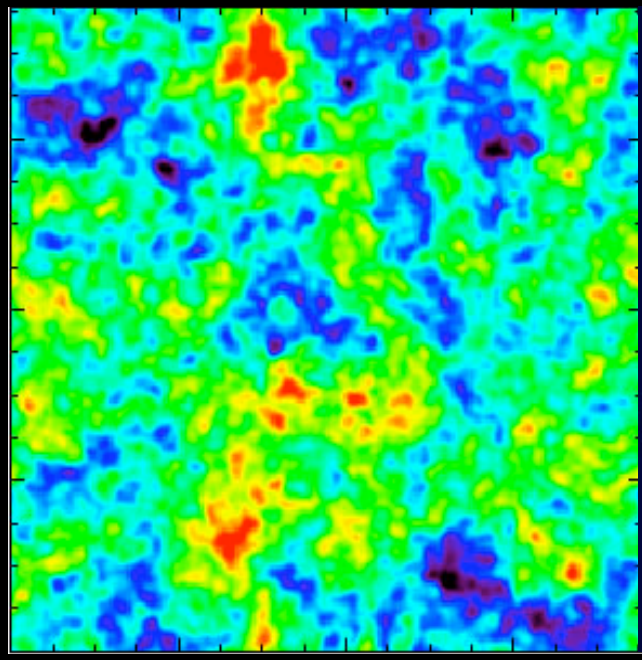
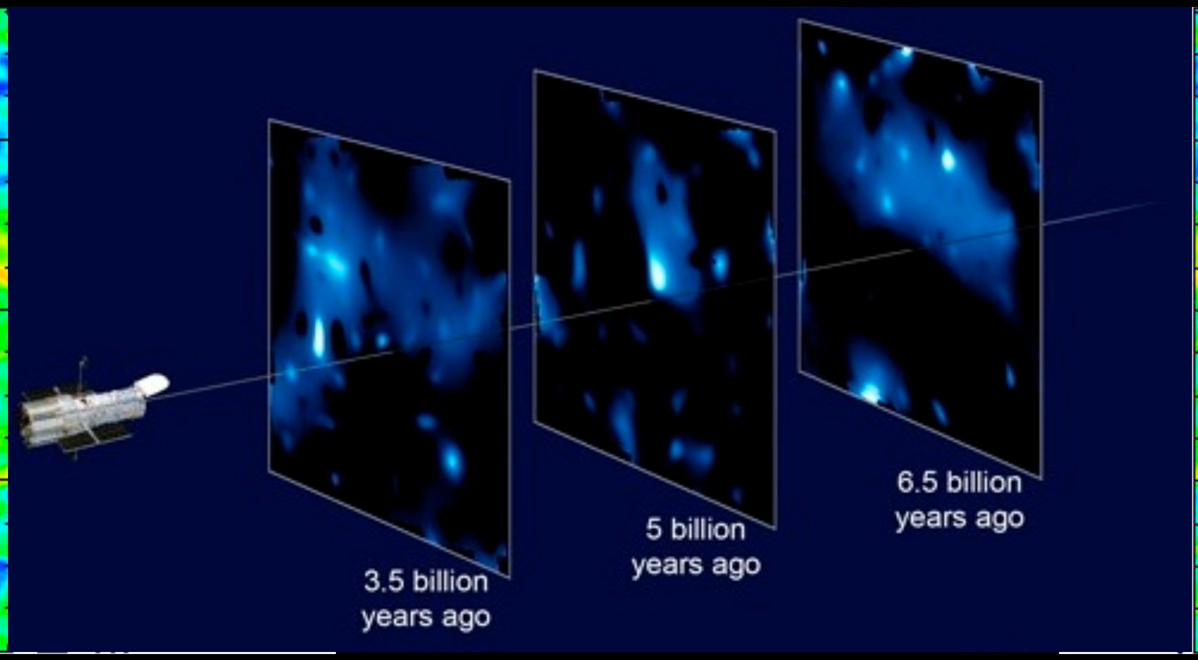
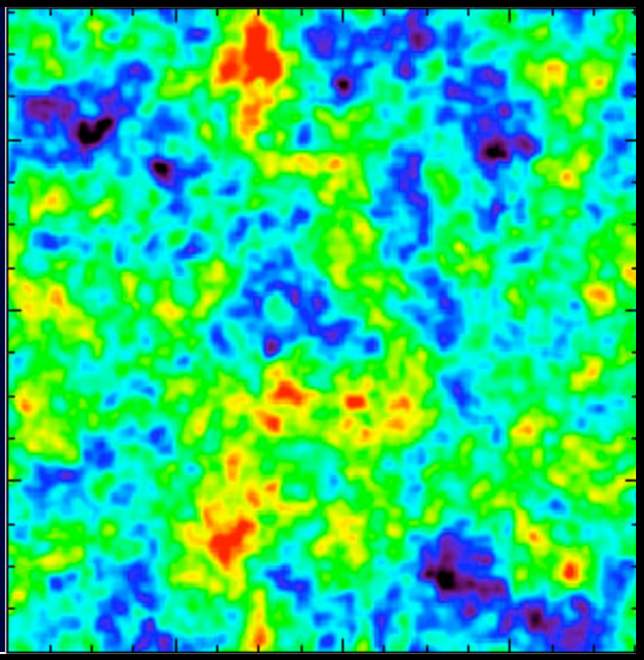


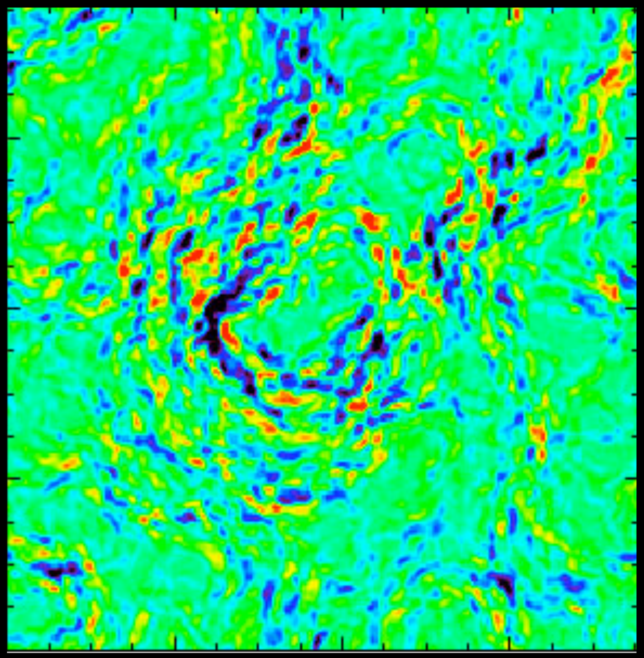
Credit: Vale, Amblard, White (2004)



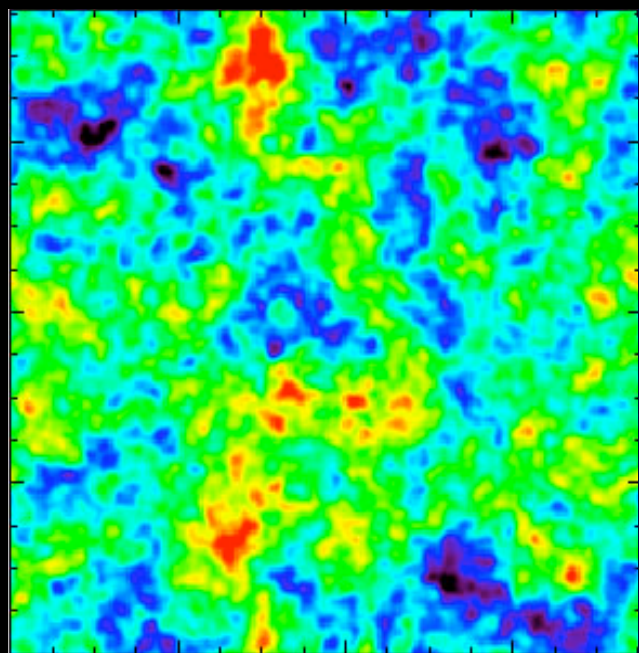

NASA, ESA, and R. Massey (CalTech)



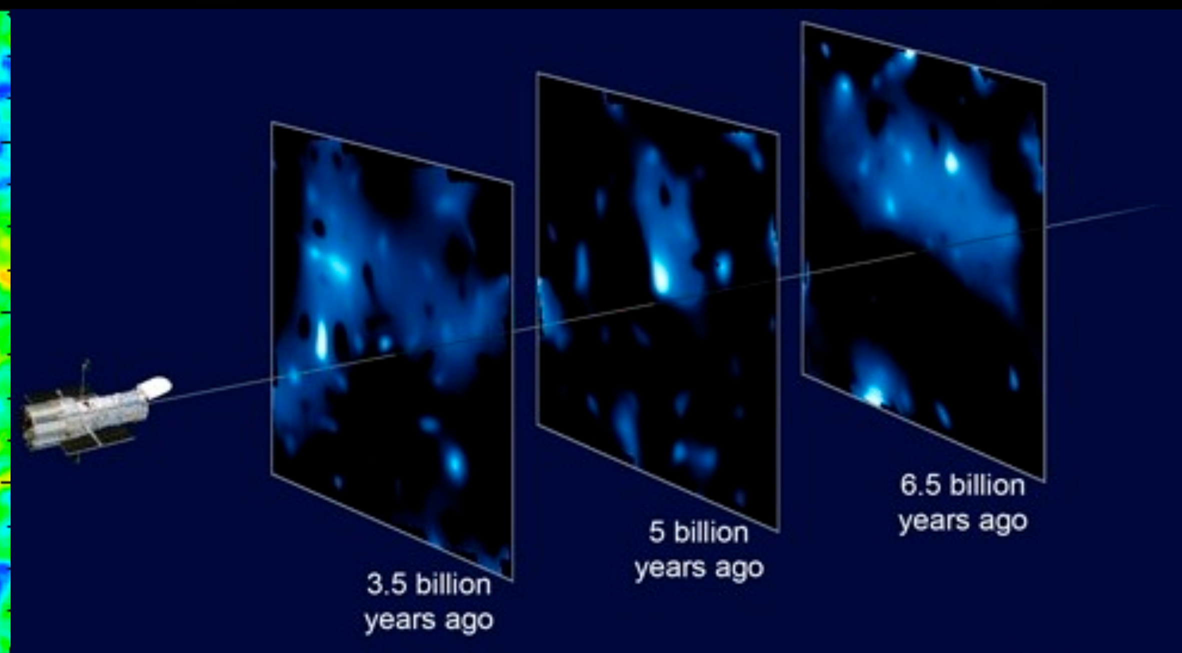
Credit: Vale, Amblard, White (2004)



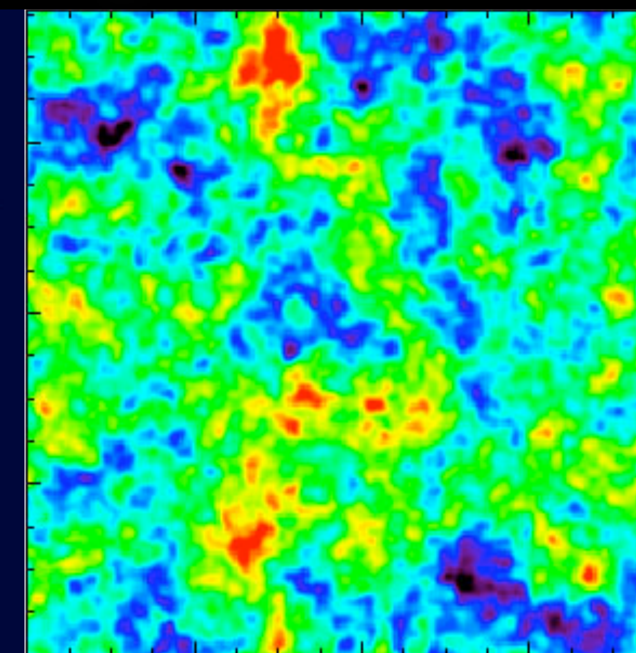
# Weak Lensing of the Primary Bispectrum



Credit: Vale, Amblard, White (2004)

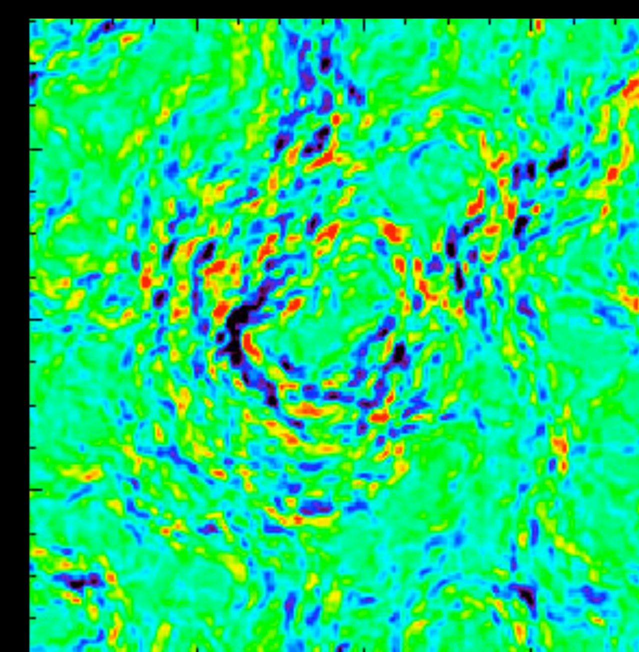



NASA, ESA, and R. Massey (CalTech)

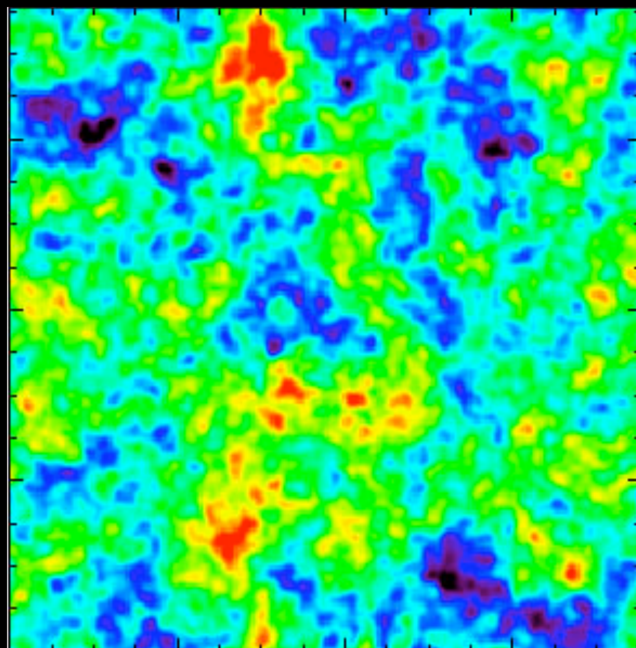


Credit: Vale, Amblard, White (2004)

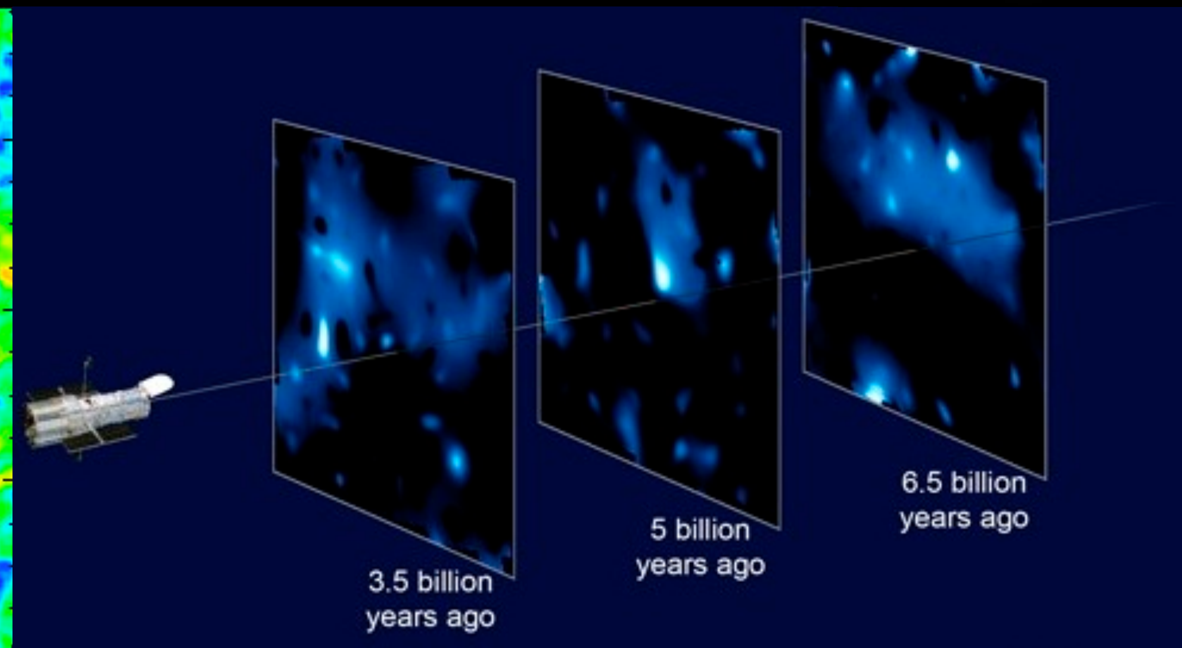
$$\tilde{\Theta}(\hat{\mathbf{n}}) = \Theta\left[\hat{\mathbf{n}} + \hat{\alpha}\right]$$



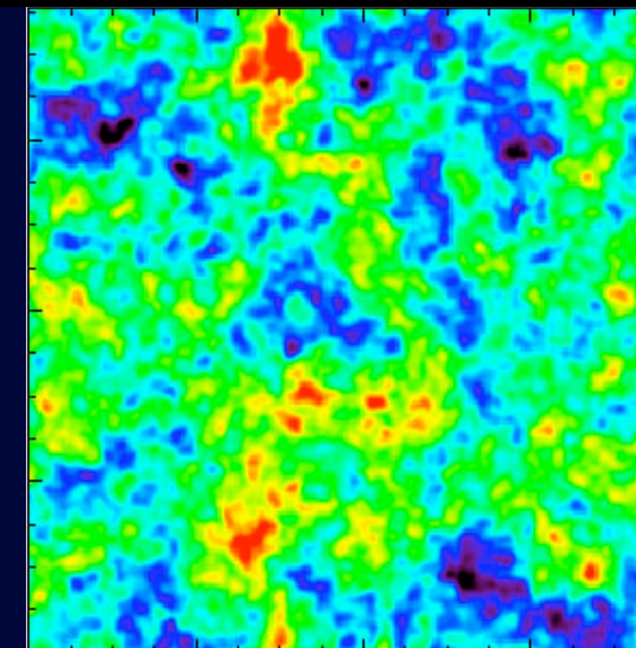
# Weak Lensing of the Primary Bispectrum



Credit: Vale, Amblard, White (2004)

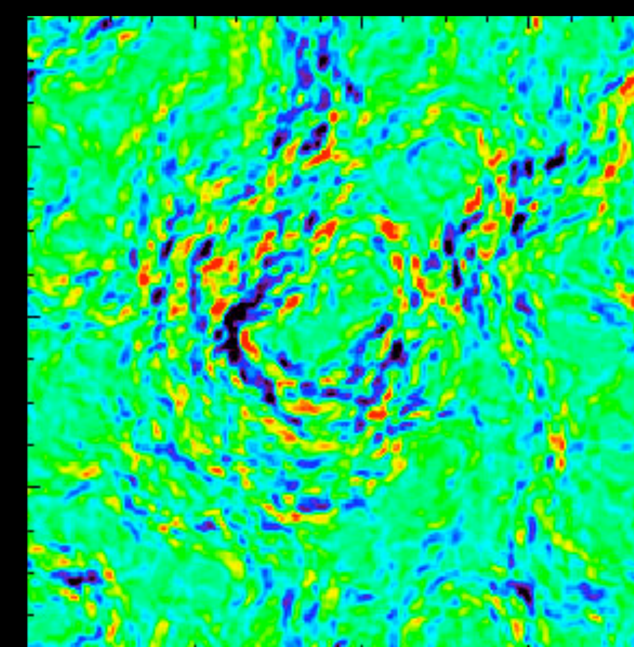



NASA, ESA, and R. Massey (CalTech)

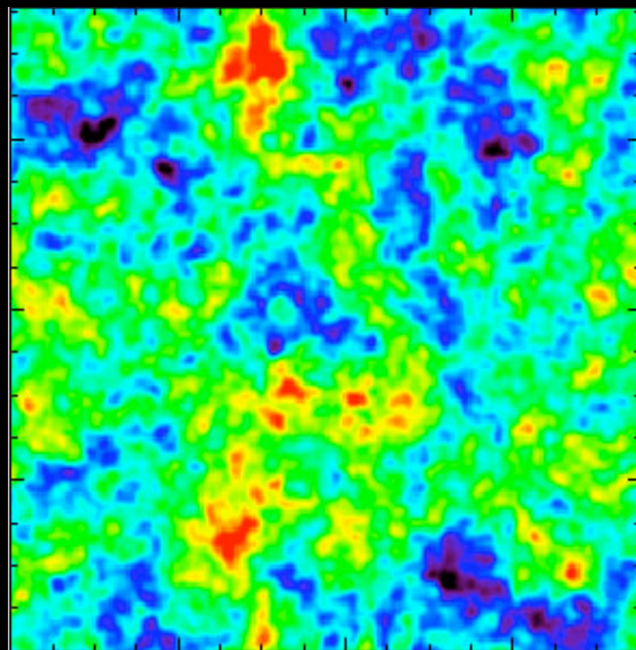


Credit: Vale, Amblard, White (2004)

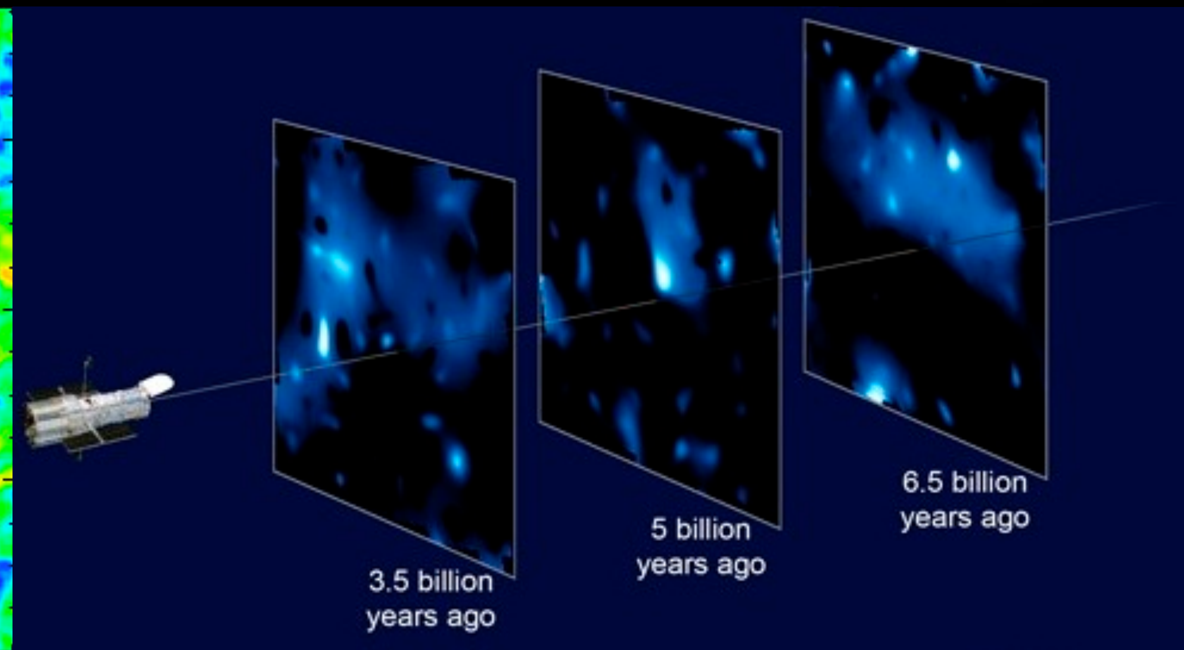
$$\tilde{\Theta}(\hat{\mathbf{n}}) = \Theta\left[\hat{\mathbf{n}} + \hat{\alpha}\right]$$
$$= \Theta\left[\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}})\right]$$



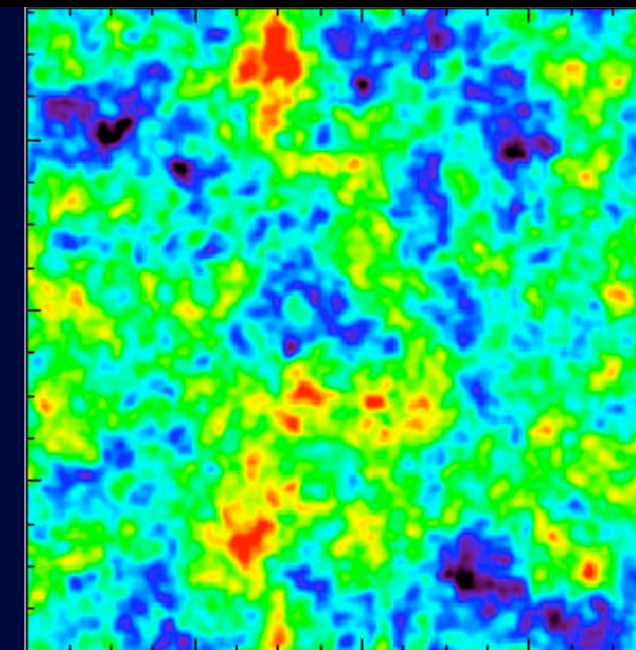
# Weak Lensing of the Primary Bispectrum



Credit: Vale, Amblard, White (2004)

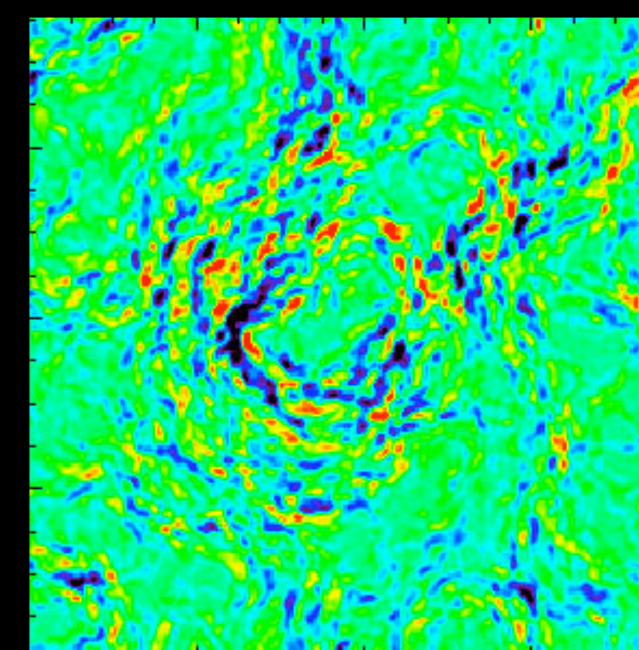



NASA, ESA, and R. Massey (CalTech)

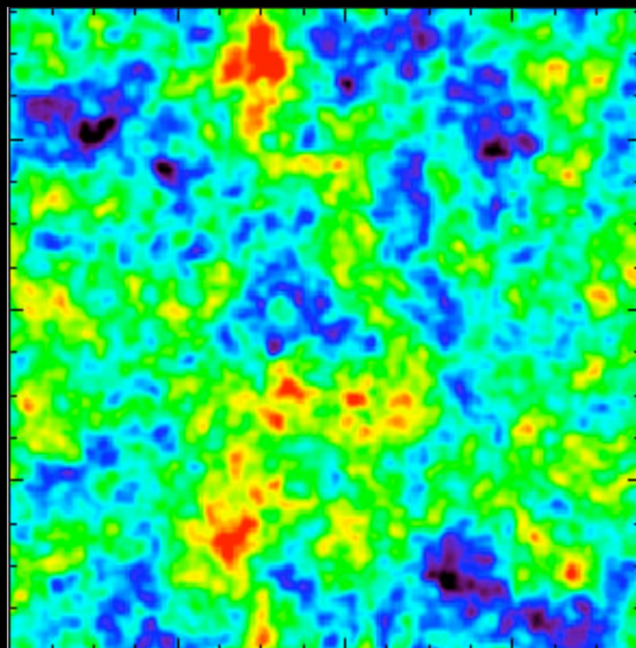


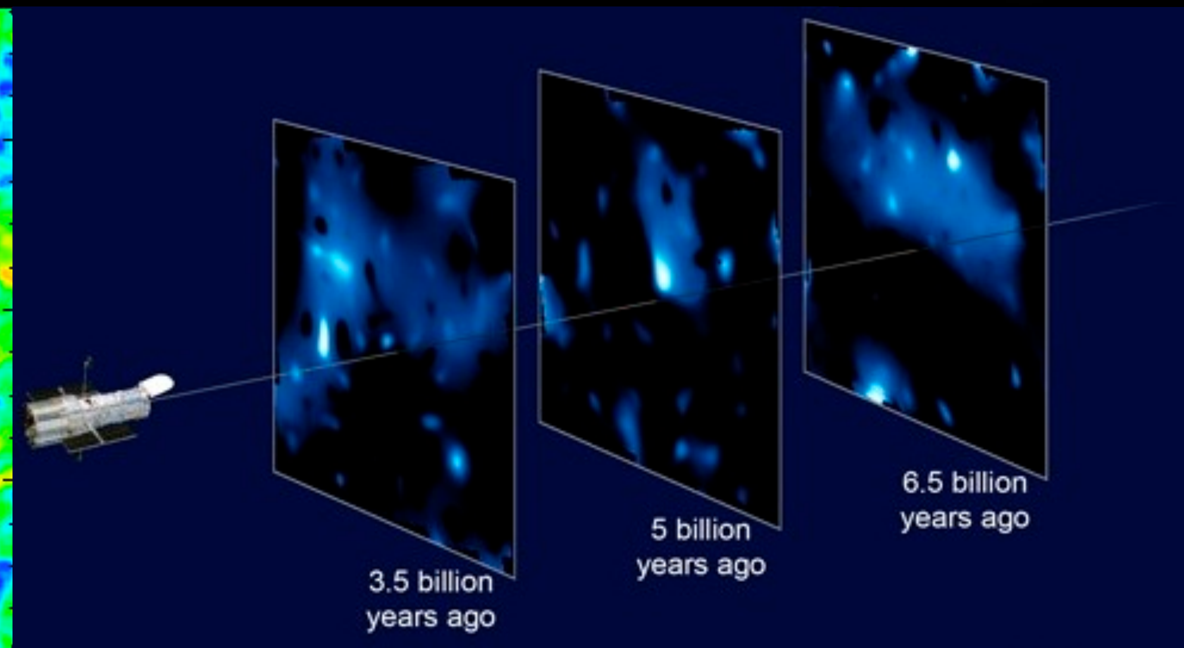
Credit: Vale, Amblard, White (2004)

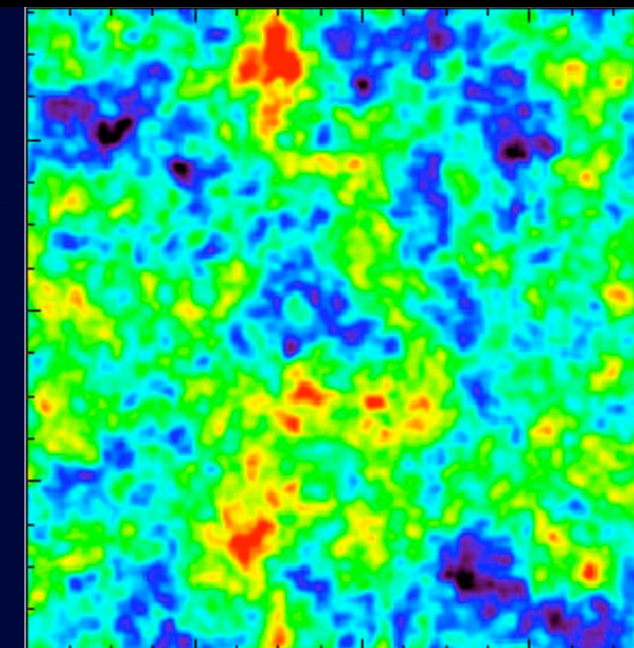
$$
\begin{aligned}
\tilde{\Theta}(\hat{\mathbf{n}}) &= \Theta\left[\hat{\mathbf{n}} + \hat{\alpha}\right] \\
&= \Theta\left[\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}})\right] \\
&\approx \Theta(\hat{\mathbf{n}}) + \nabla_i\phi(\hat{\mathbf{n}})\nabla^i\Theta(\hat{\mathbf{n}}) \\
&\qquad + \frac{1}{2}\nabla_i\phi(\hat{\mathbf{n}})\nabla_j\phi(\hat{\mathbf{n}})\nabla^i\nabla^j\Theta(\hat{\mathbf{n}})
\end{aligned}
$$



# Weak Lensing of the Primary Bispectrum

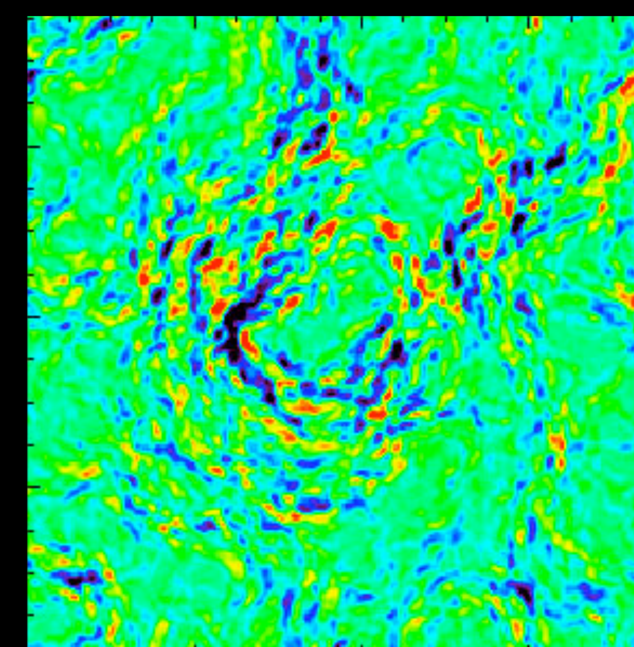




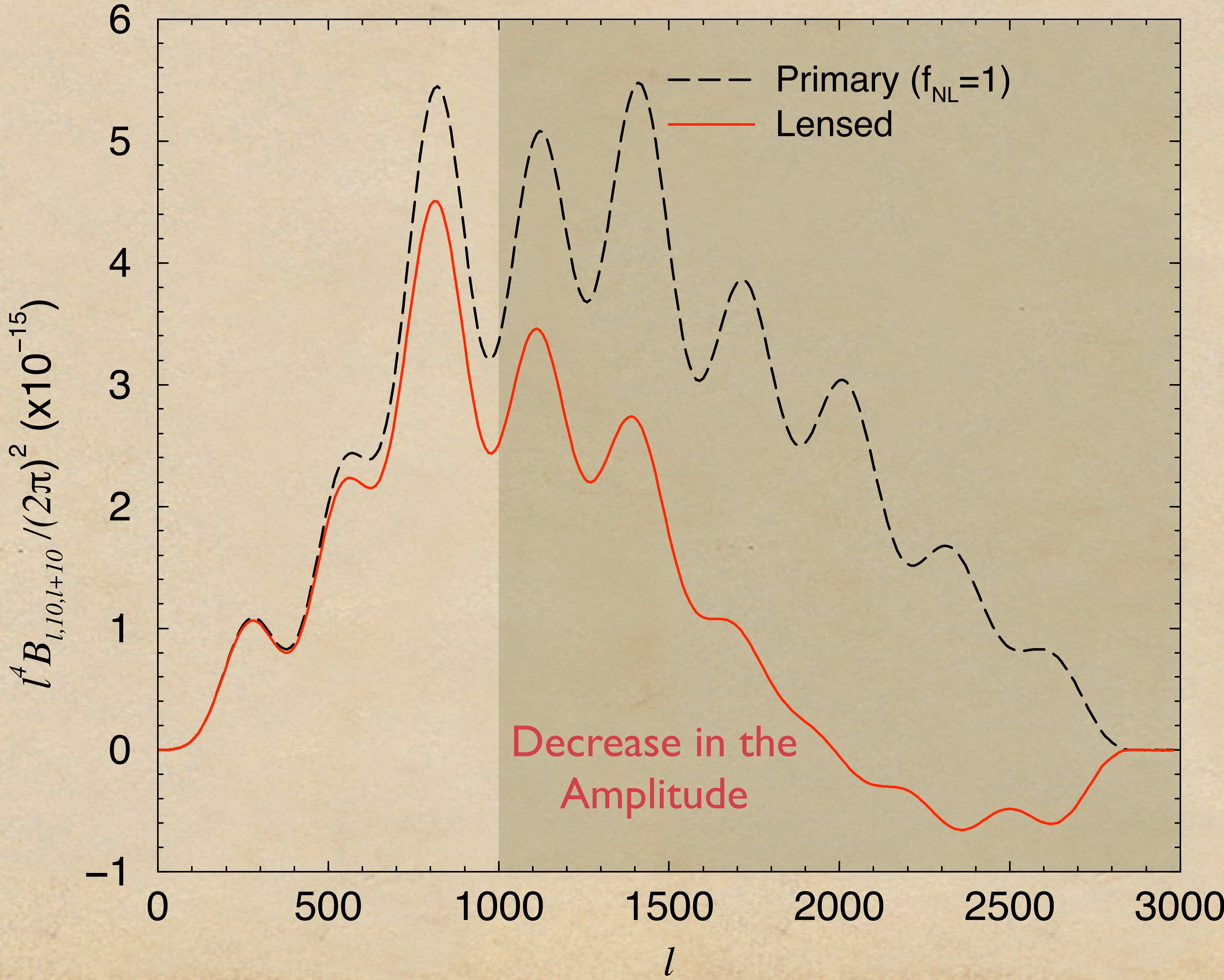
Credit: Vale, Amblard, White (2004) NASA, ESA, and R. Massey (CalTech) Credit: Vale, Amblard, White (2004)

$$\begin{aligned}\tilde{\Theta}(\hat{\mathbf{n}}) &= \Theta\left[\hat{\mathbf{n}} + \hat{\alpha}\right] \\ &= \Theta\left[\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}})\right] \\ &\approx \Theta(\hat{\mathbf{n}}) + \nabla_i\phi(\hat{\mathbf{n}})\nabla^i\Theta(\hat{\mathbf{n}}) \\ &\qquad + \frac{1}{2}\nabla_i\phi(\hat{\mathbf{n}})\nabla_j\phi(\hat{\mathbf{n}})\nabla^i\nabla^j\Theta(\hat{\mathbf{n}})\end{aligned}$$



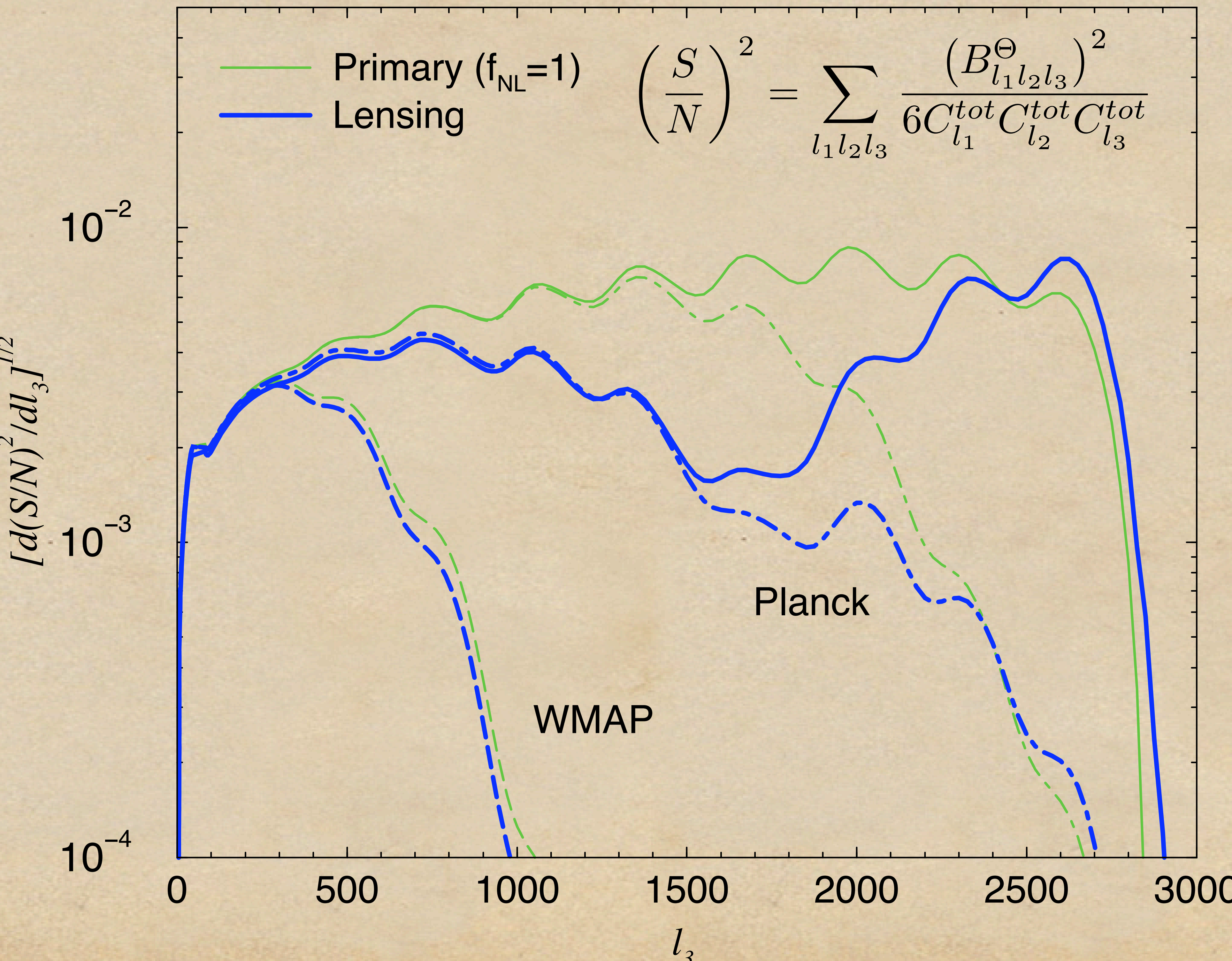
$$\tilde{B}^{\Theta}_{l_1 l_2 l_3} = \sum_{m_1 m_2 m_3} \begin{pmatrix} l_1 & l_2 & l_3 \\ m_1 & m_2 & m_3 \end{pmatrix} \langle \tilde{\Theta}_{l_1 m_1} \tilde{\Theta}_{l_2 m_2} \tilde{\Theta}_{l_3 m_3} \rangle$$

# 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




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

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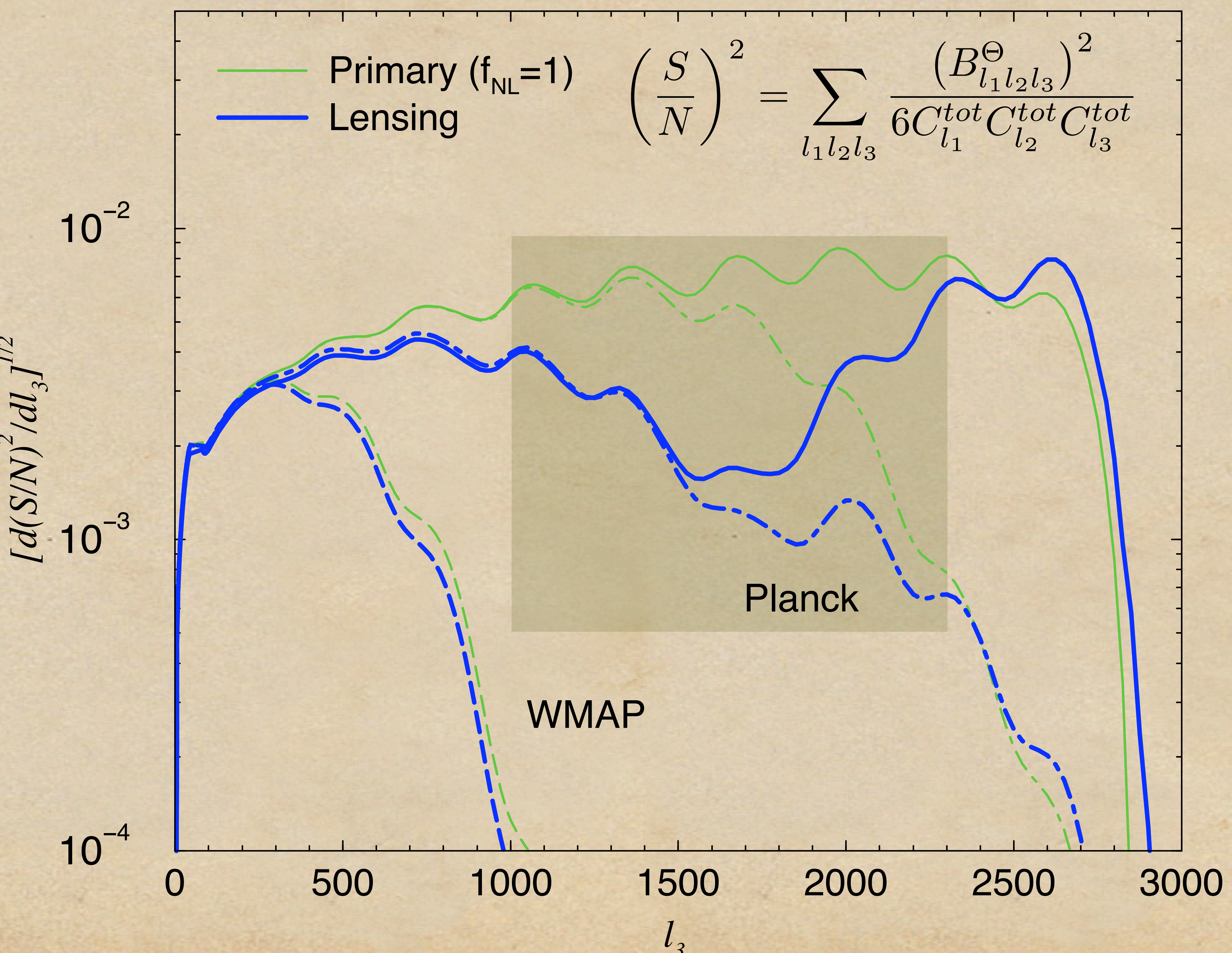
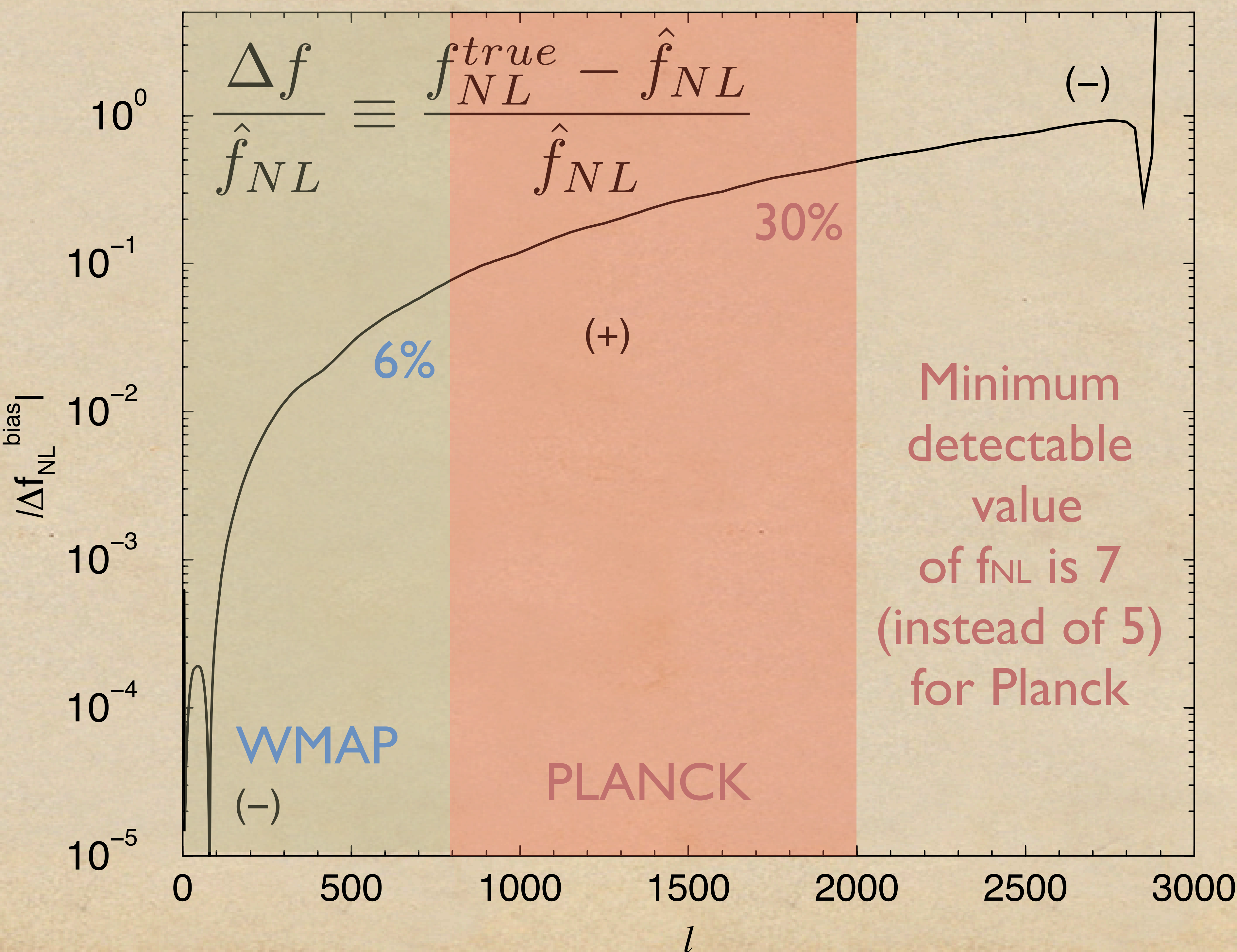



A. Cooray, D. Sarkar, and P. Serra; Phys. Rev. D, 77, 123006 (2008)

# Bias in the non-Gaussian Parameter




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

# Agenda

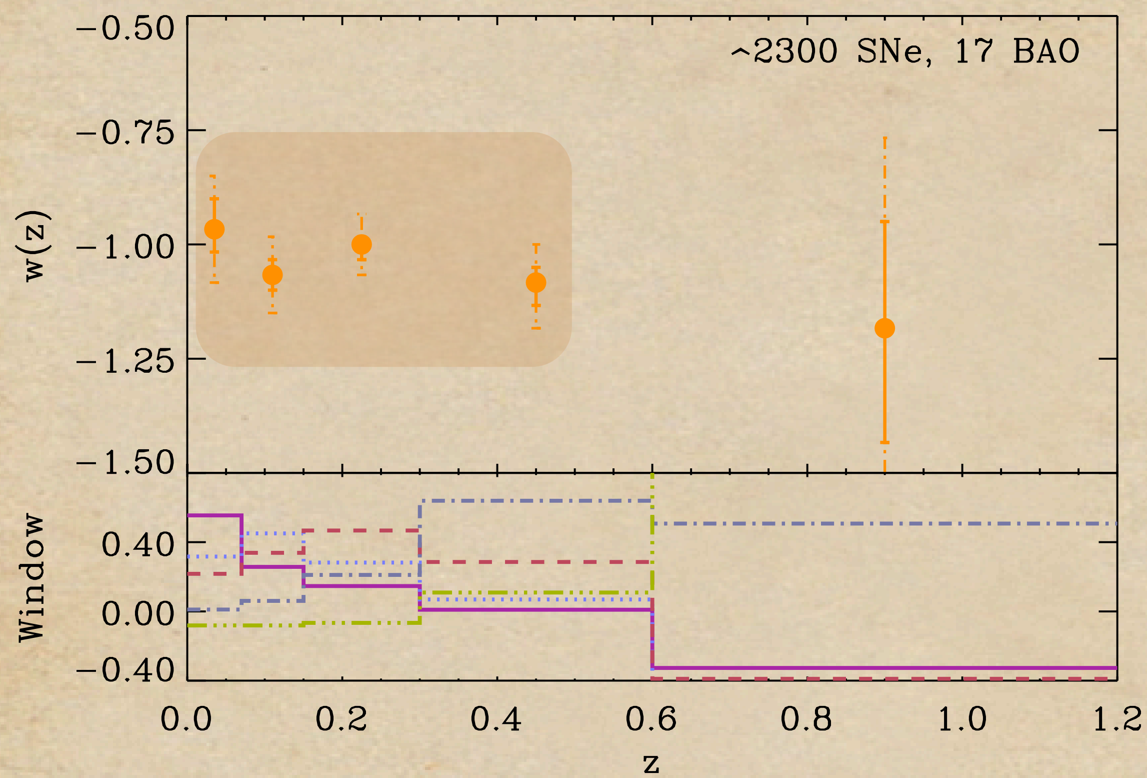
## Theoretical Uncertainties in Dark Energy Measurements

- Constraining the EOS
- To Bin or Not to Bin
- SNe Ia ++
- Lensing of SNe
- Other Worries

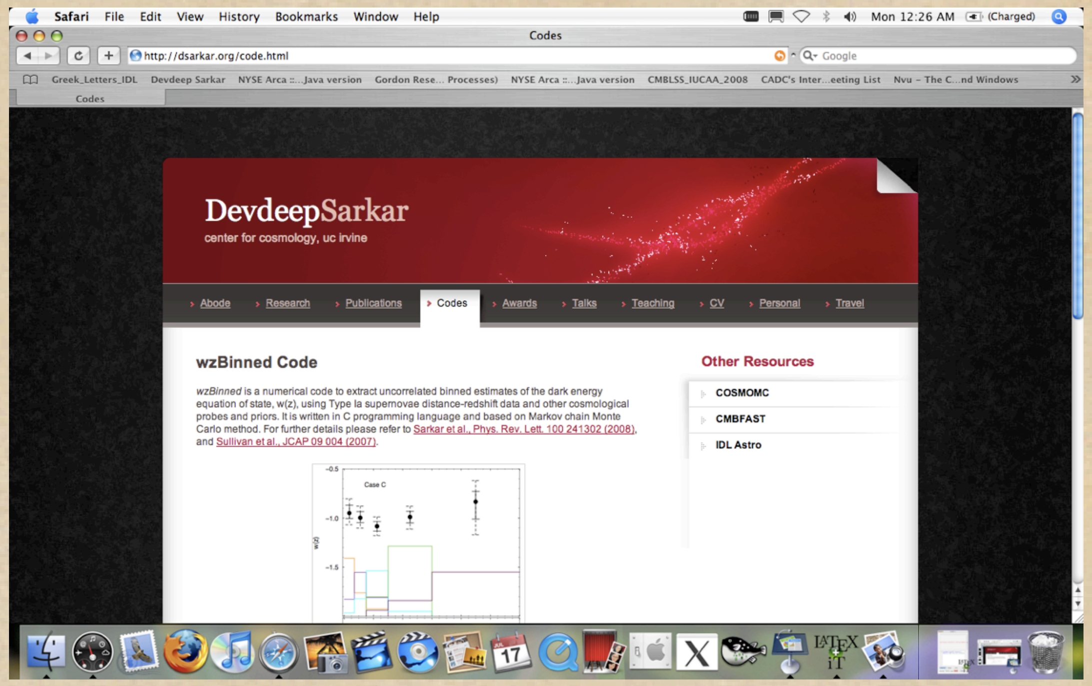
## Primordial Non-Gaussianity and CMB Bispectrum

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

# Summary



~2300 SNe, 17 BAO
w(z)
−0.50
−0.75
−1.00
−1.25
−1.50
Window
0.40
0.00
−0.40
0.0
0.2
0.4
0.6
0.8
1.0
1.2
z

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Mon 12:26 AM
Codes
http://dsarkar.org/code.html
DevdeepSarkar
center for cosmology, uc irvine
Abode
Research
Publications
Codes
Awards
Talks
Teaching
CV
Personal
Travel
wzBinned Code
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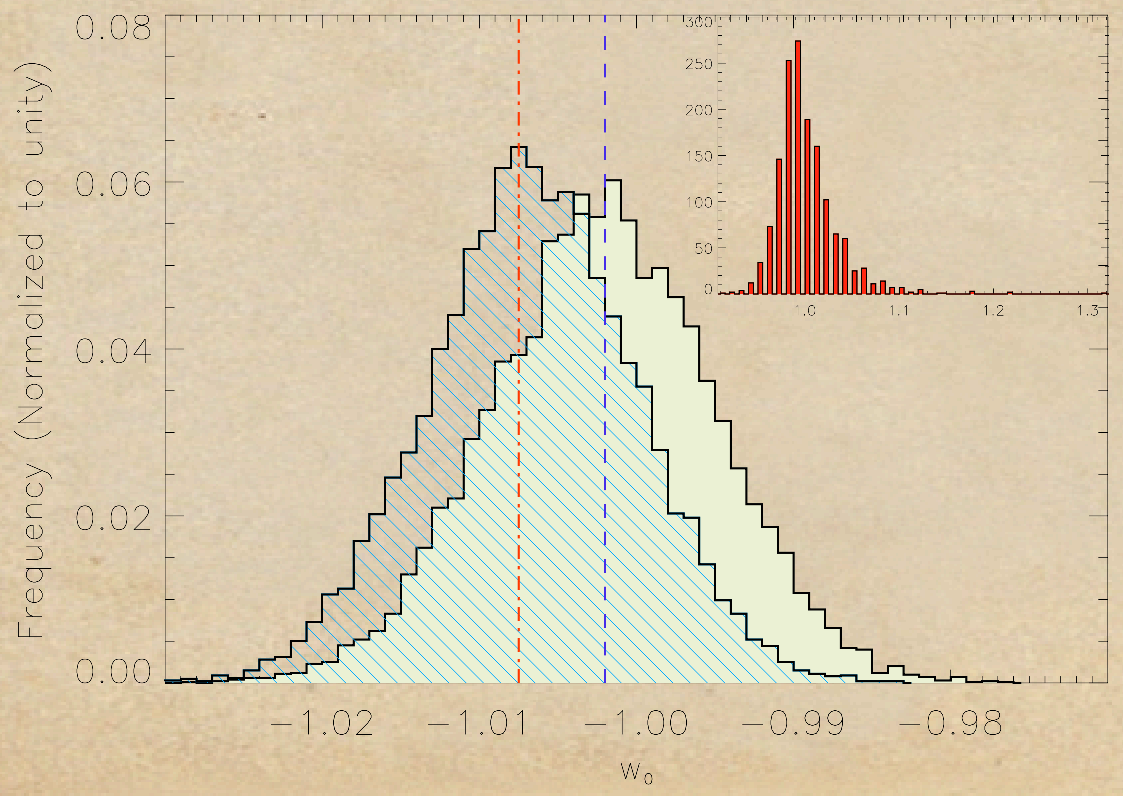
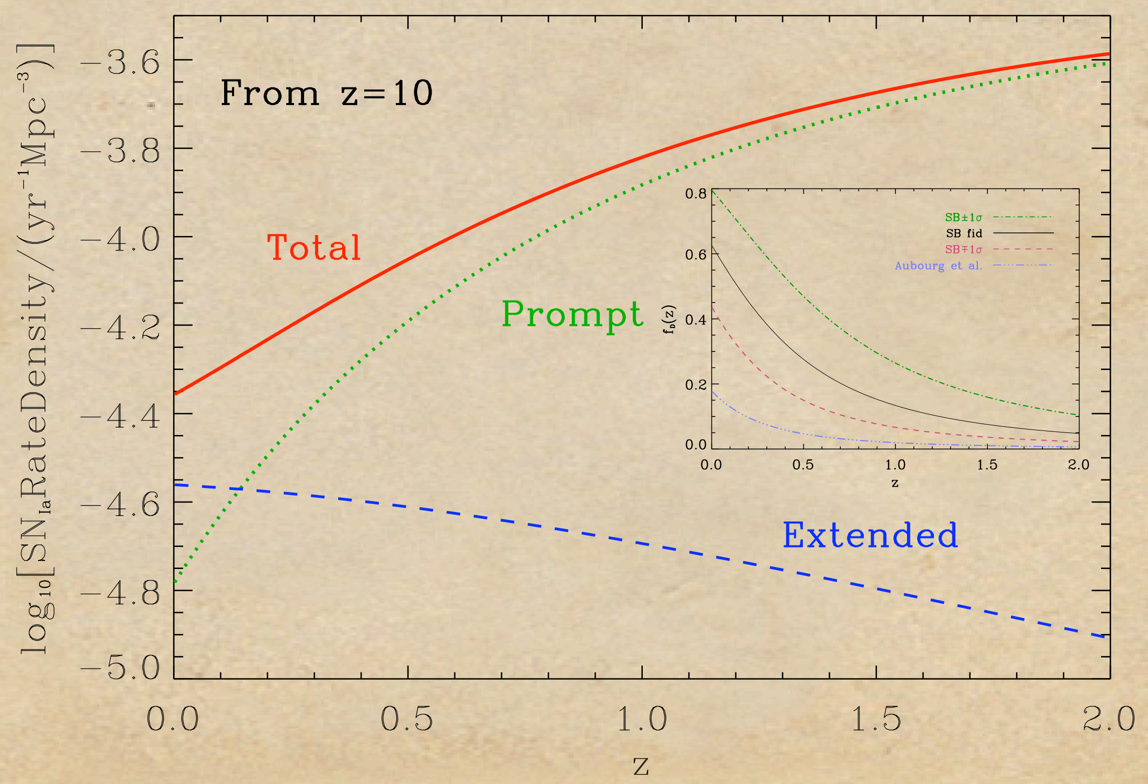
COSMOMC
CMBFAST
IDL Astro

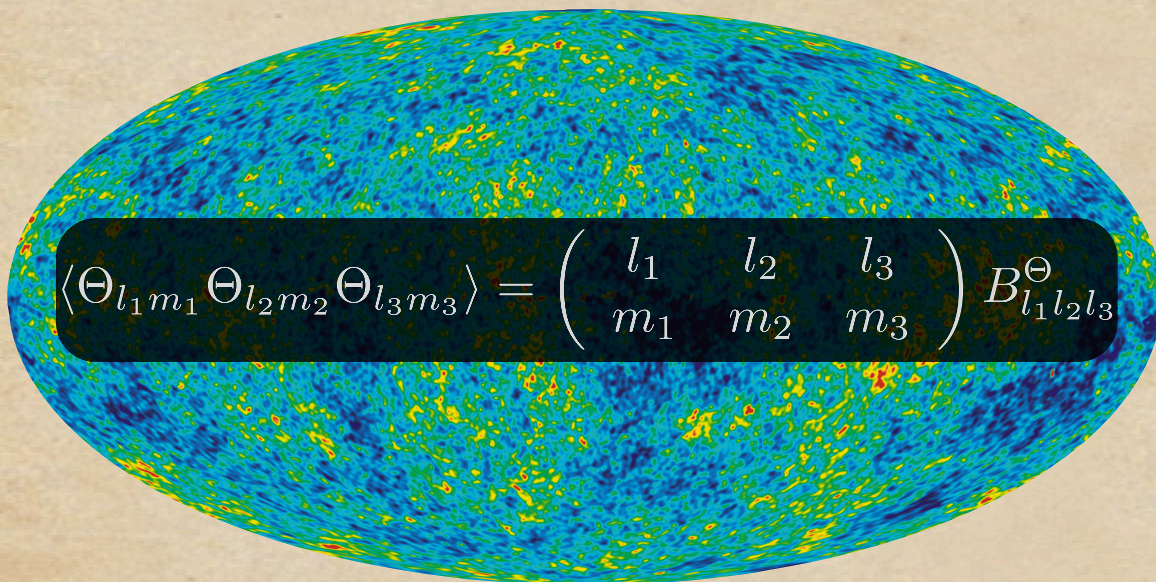



Frequency (Normalized to unity)
0.08
0.06
0.04
0.02
0.00
−1.02
−1.01
−1.00
−0.99
−0.98
$w_0$
300
250
200
150
100
50
0
1.0
1.1
1.2
1.3

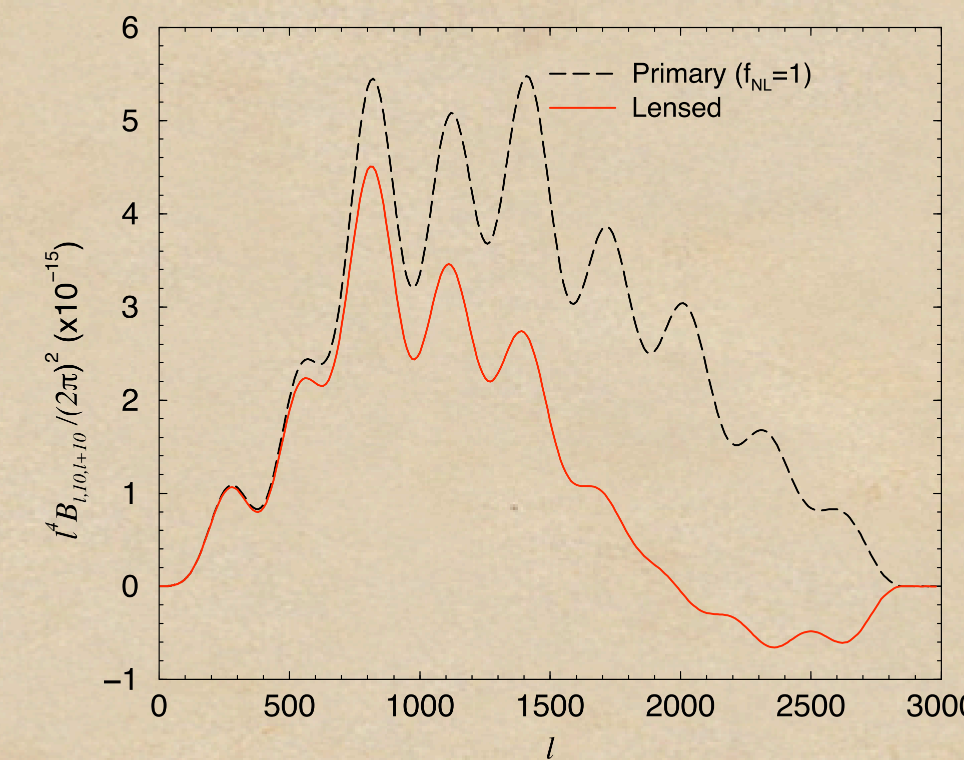



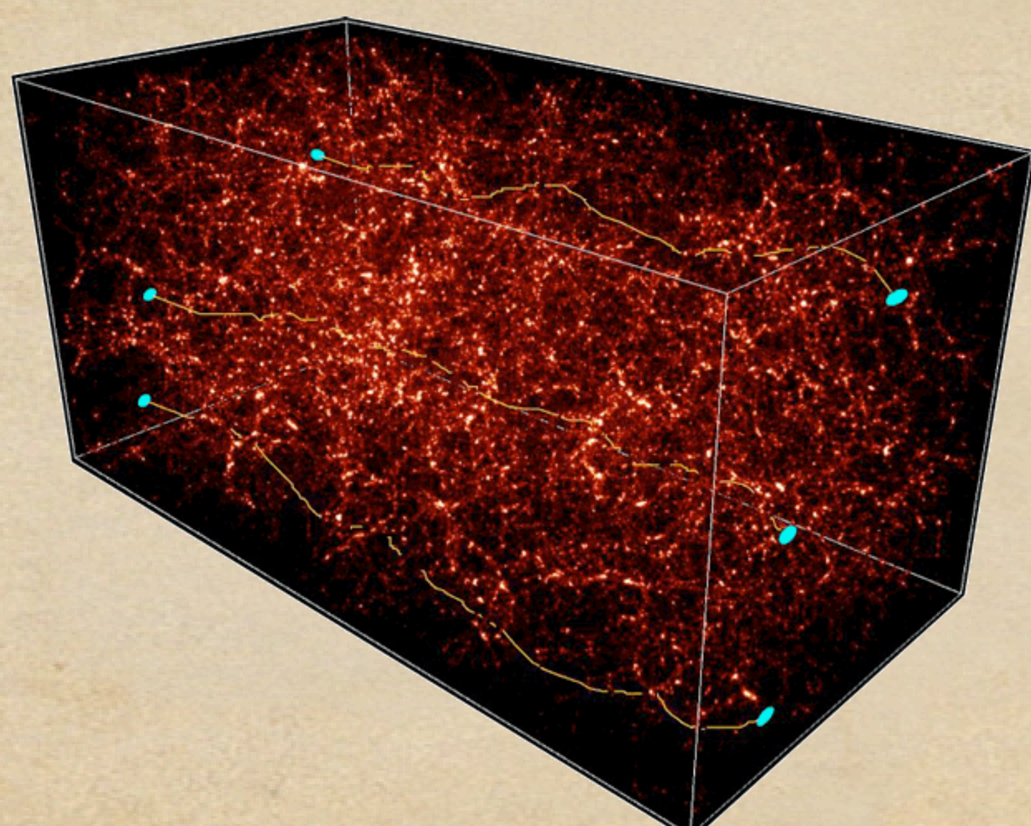
From z=10
Total
Prompt
Extended
$\log_{10}[\mathrm{SN_{Ia}RateDensity}/(\mathrm{yr^{-1}Mpc^{-3}})]$
−3.6
−3.8
−4.0
−4.2
−4.4
−4.6
−4.8
−5.0
0.0
0.5
1.0
1.5
2.0
z
SB fid
Aubourg et al.

# Summary



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



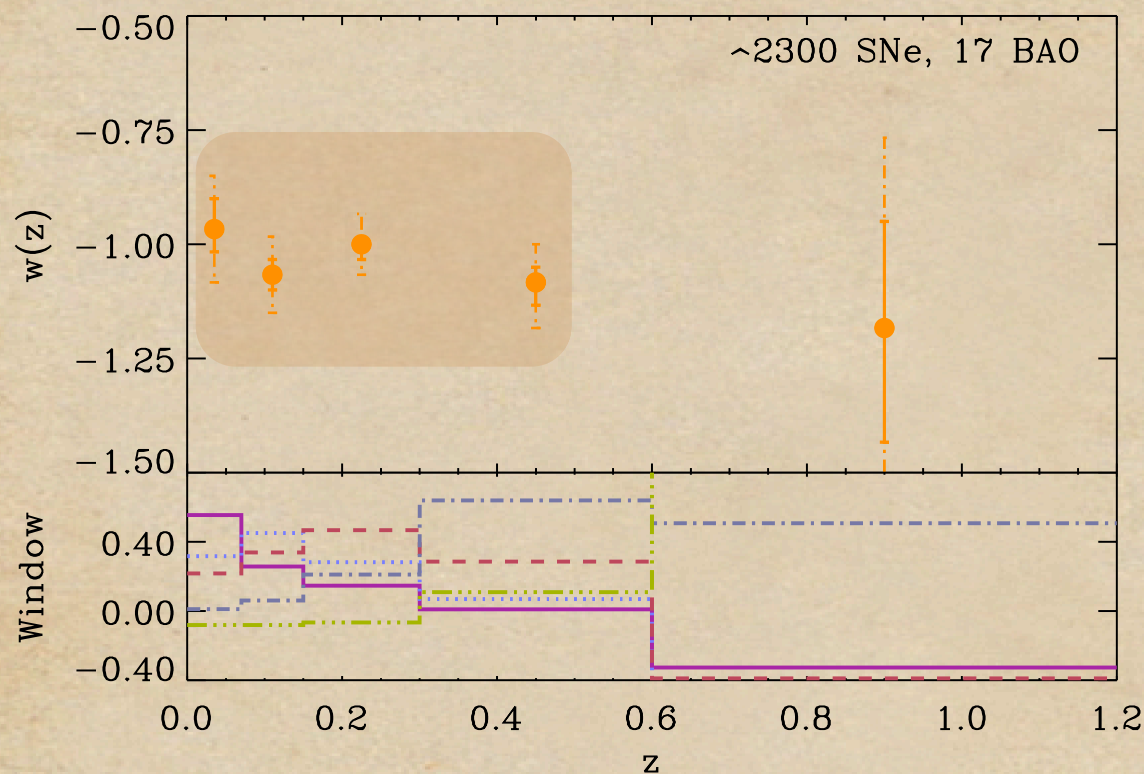
6% Bias for WMAP

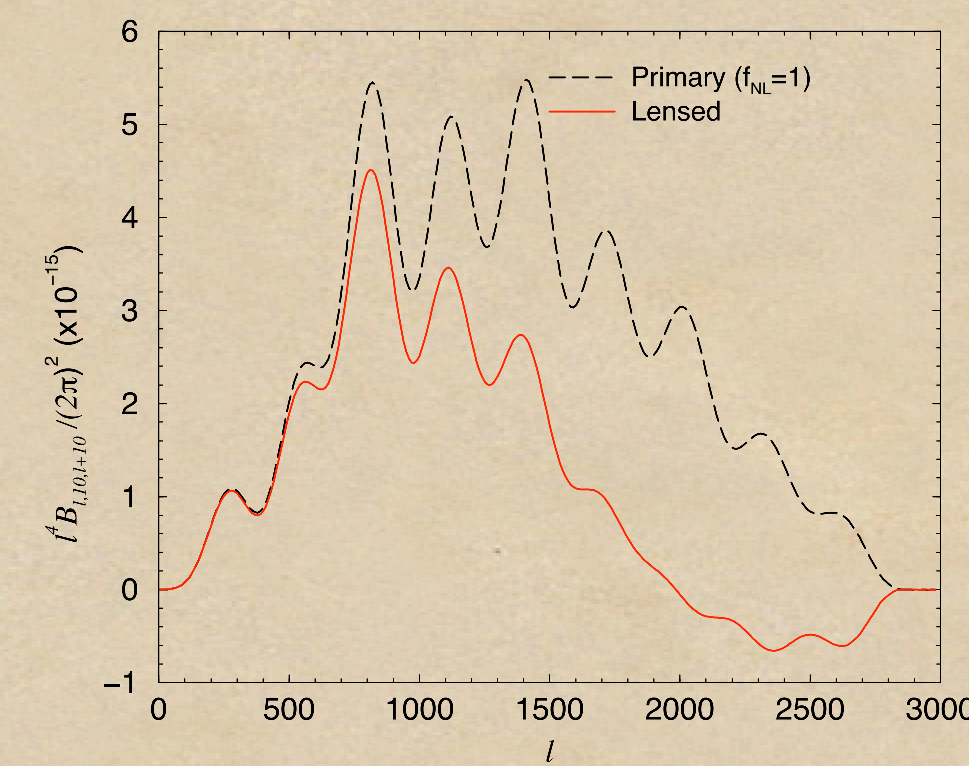
30% Bias for Planck

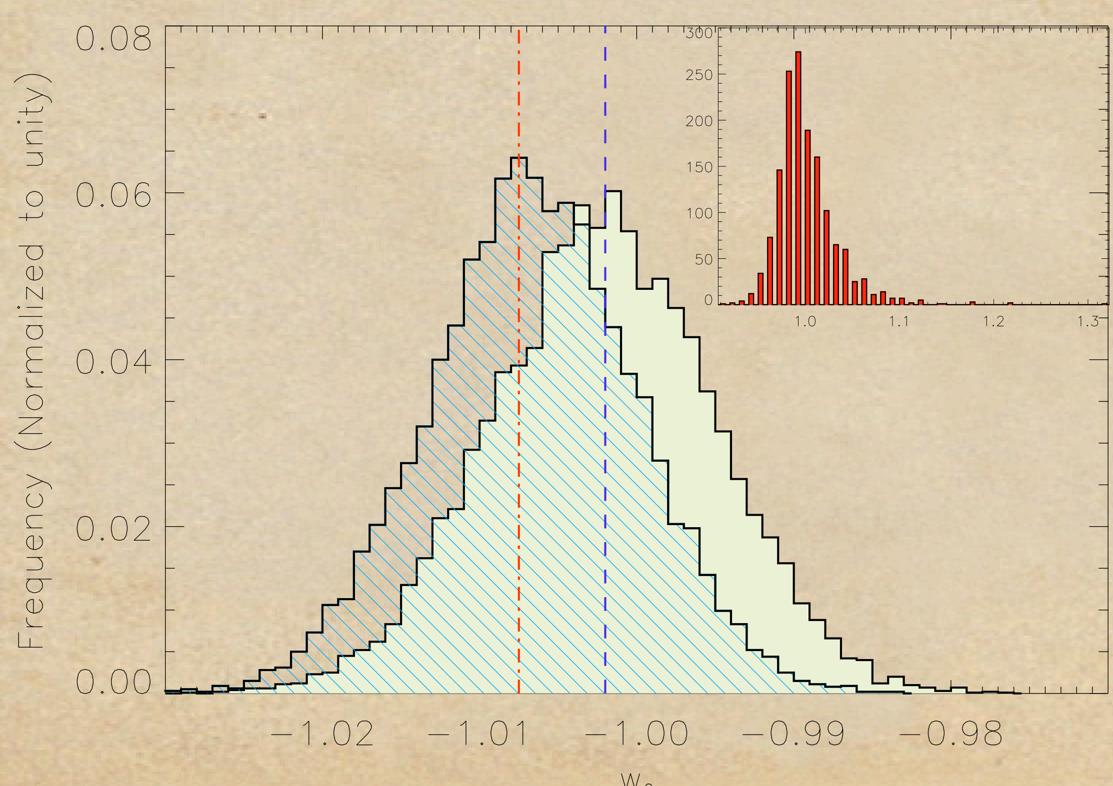
Minimum $f_{NL}$ 7


DSARKAR.ORG

# Summary

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