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

Devdeep Sarkar
Center for Cosmology, UC Irvine

In collaboration with:
Scott Sullivan (UCI/UCLA), Shahab Joudaki (UCI), Alexandre Amblard (UCI), Paolo Serra (UCI), Daniel Holz (Los Alamos), Asantha Cooray (UCI).

UC San Diego | CASS Astrophysics Seminar | Jan 21, 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
- CMB Bispectrum
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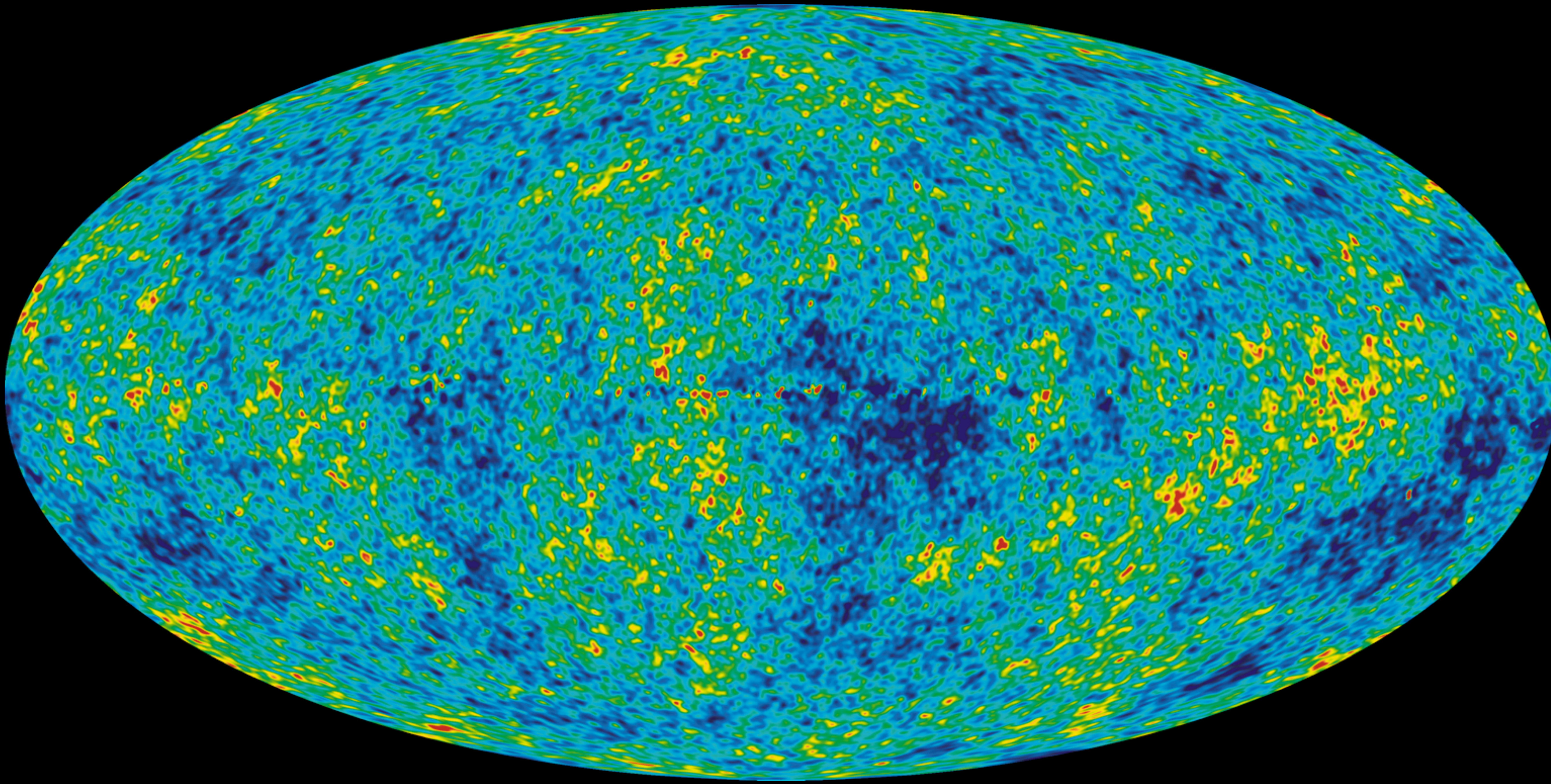
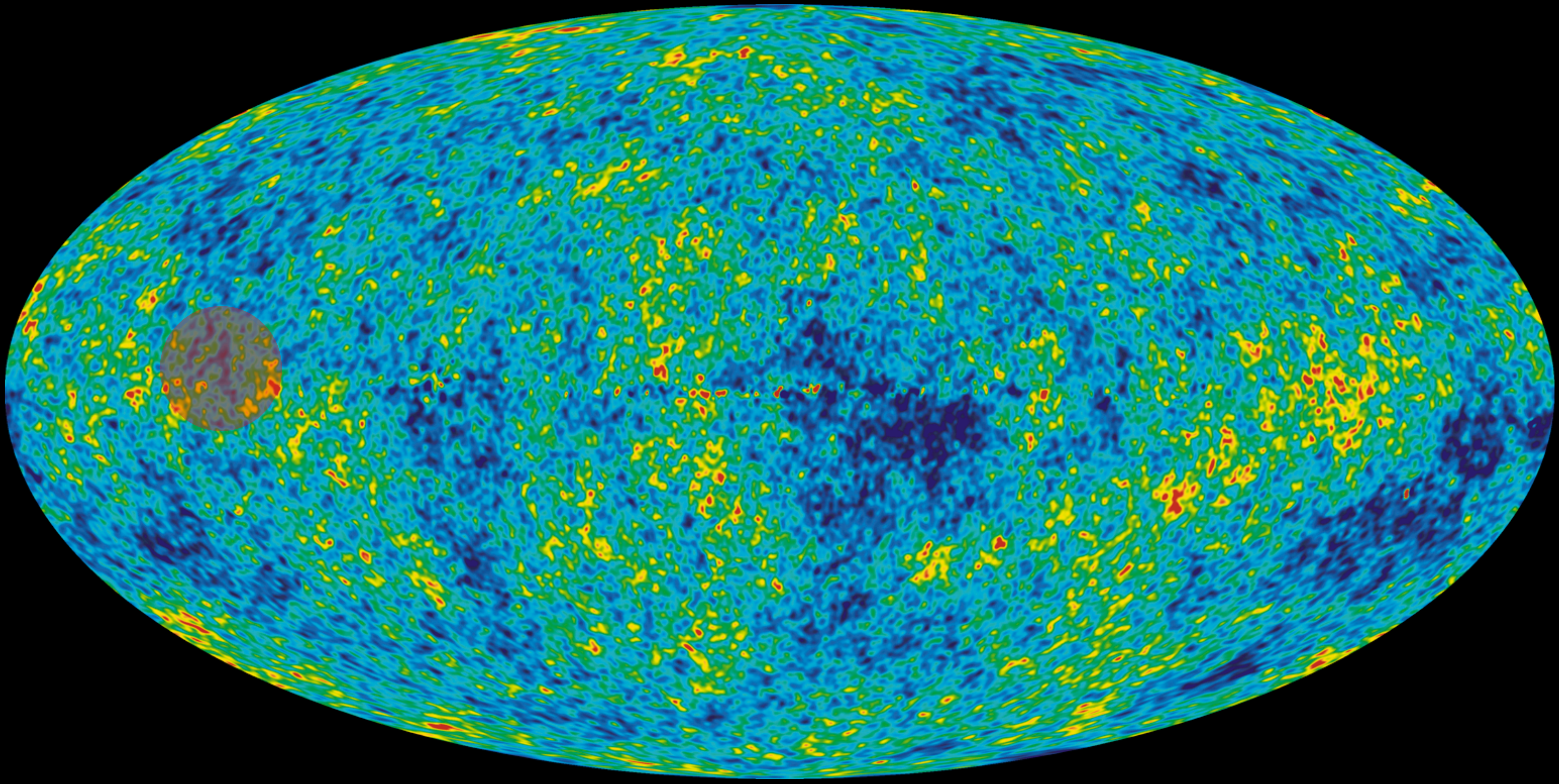
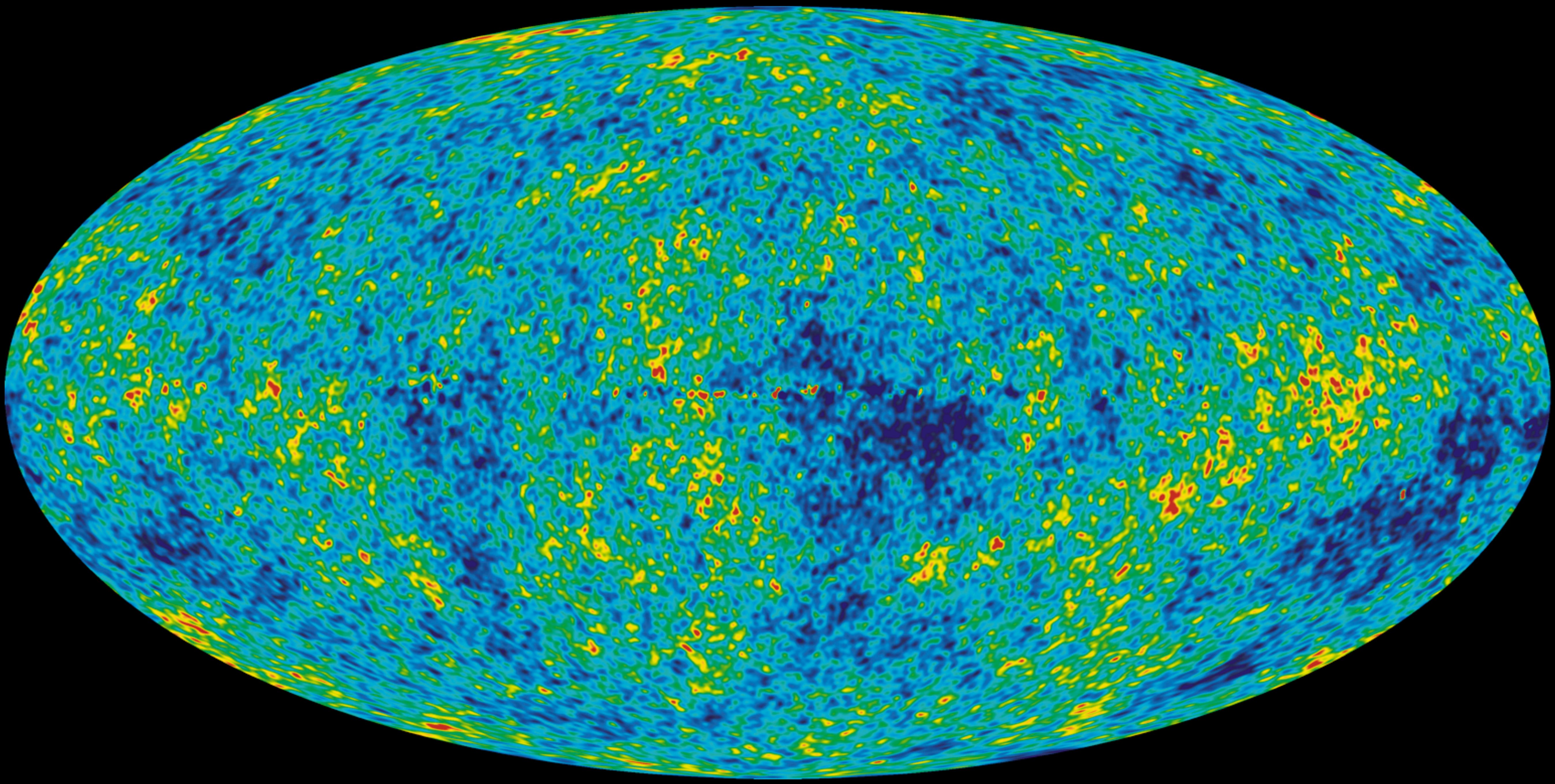


Credit: NASA/WMAP Science Team



Credit: NASA/WMAP Science Team



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]
C. R. PENNYPACKER,[8] AND R. QUIMBY
Institute for Nuclear and Particle Astrophysics, E. O. Lawrence Berkeley National Laboratory, Berkeley, CA 94720

C. LIDMAN
European Southern Observatory, La Silla, Chile

R. S. ELLIS, M. IRWIN, AND R. G. MCMAHON
Institute of Astronomy, Cambridge, England, UK

P. RUIZ-LAPUENTE
Department of Astronomy, University of Barcelona, Barcelona, Spain

N. WALTON
Isaac Newton Group, La Palma, Spain

B. SCHAEFER
Department of Astronomy, Yale University, New Haven, CT

B. J. BOYLE
Anglo-Australian Observatory, Sydney, Australia

A. V FILIPPENKO AND T. MATHESON
Department of Astronomy, University of California, Berkeley, CA

A. S. FRUCHTER AND N. PANAGIA[9]
Space Telescope Science Institute, Baltimore, MD

H. J. M. NEWBERG
Fermi National Laboratory, Batavia, IL

AND

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]

Received 2004 January 20; accepted 2004 February 16

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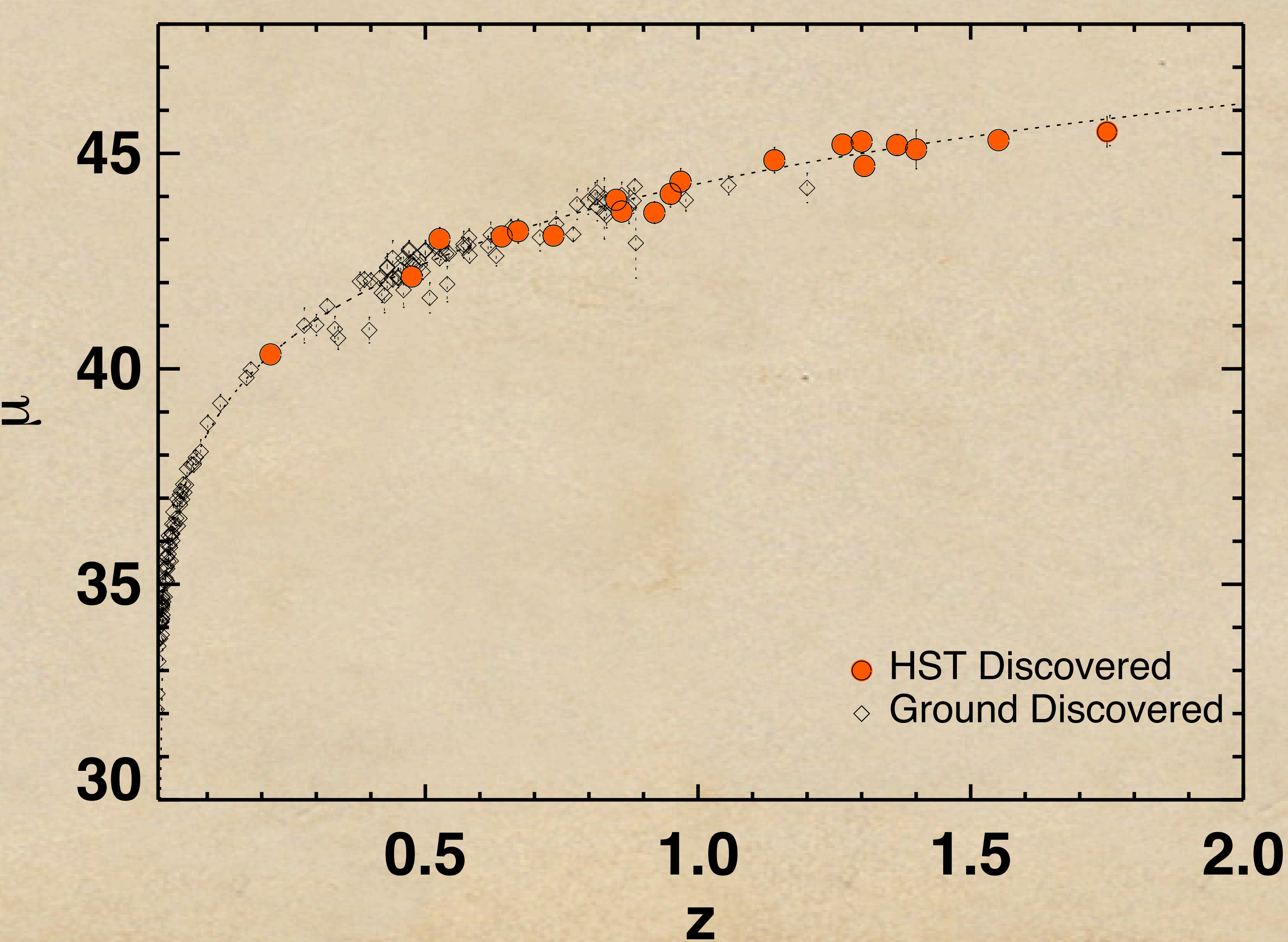

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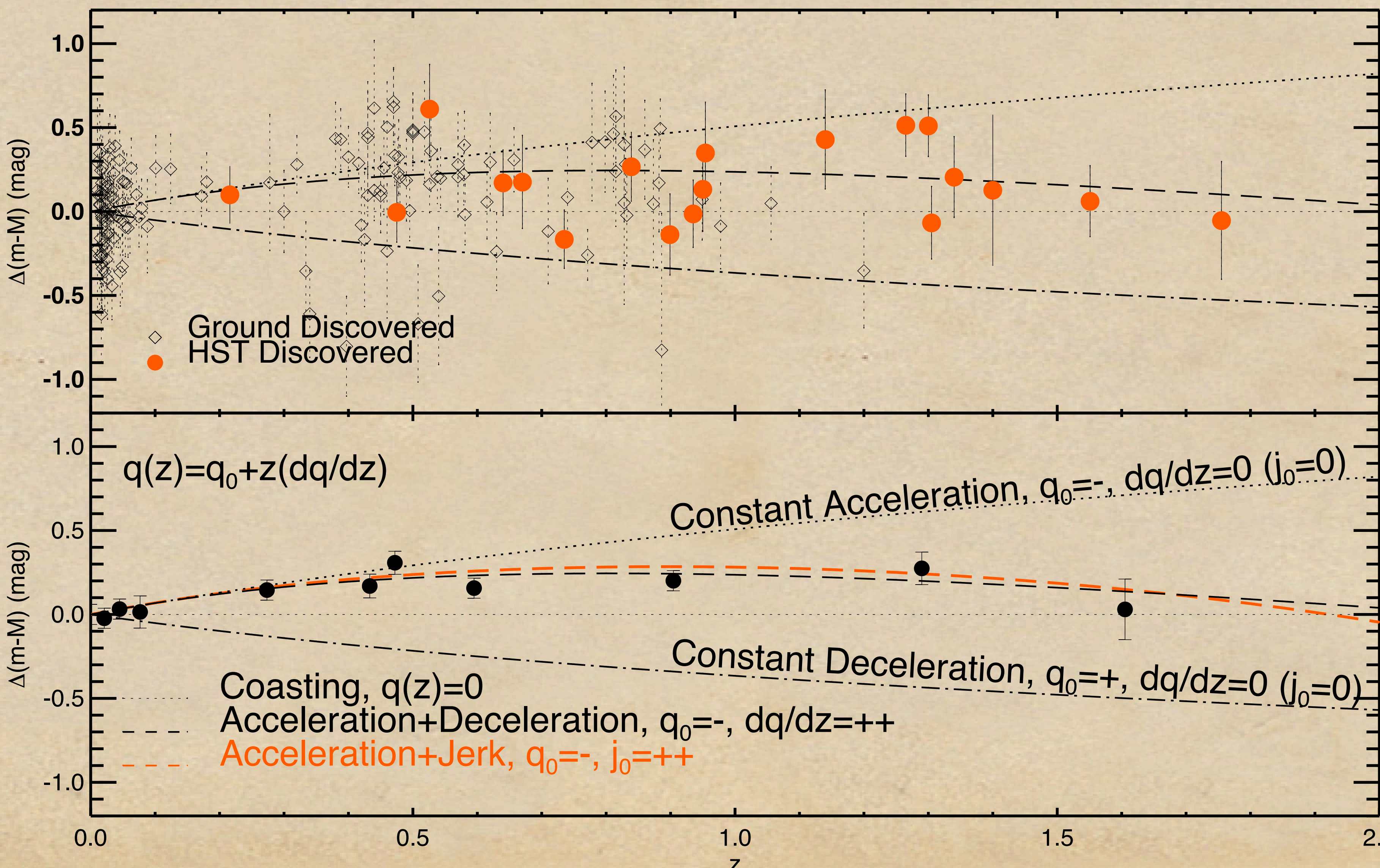
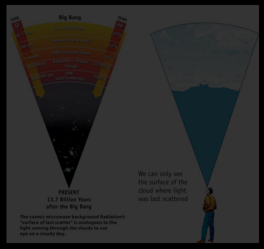
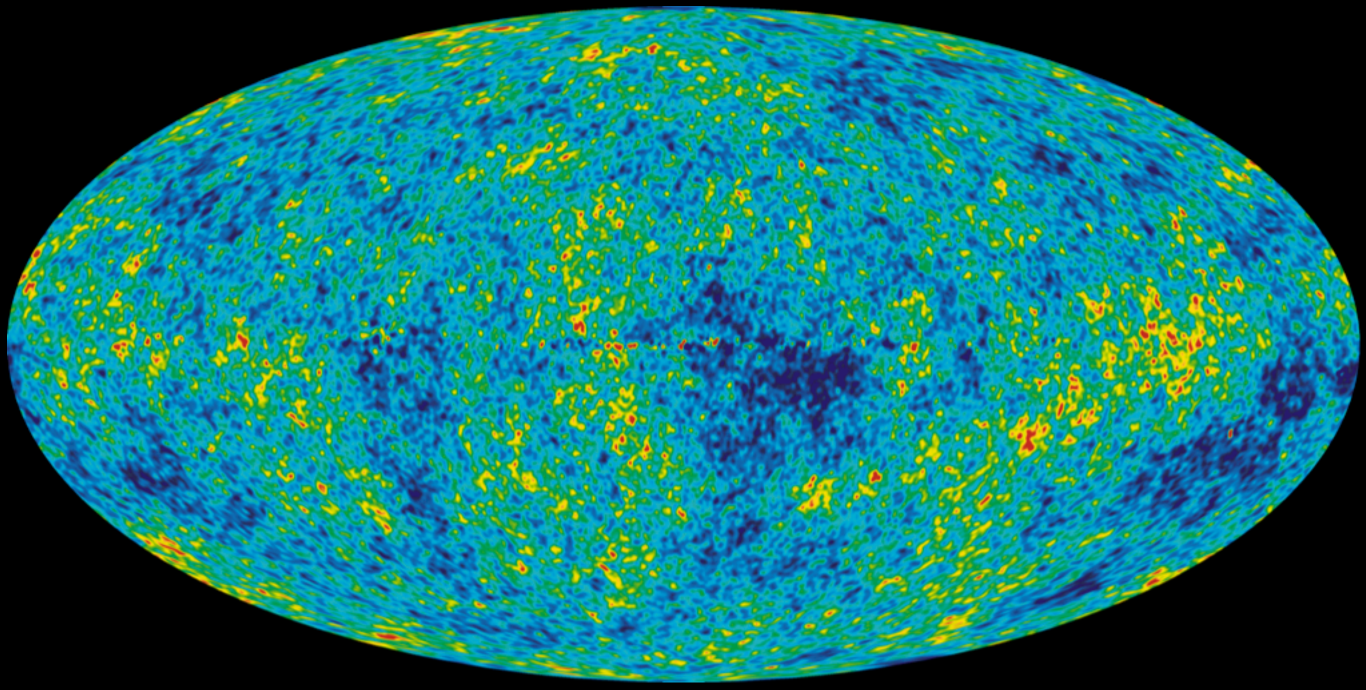
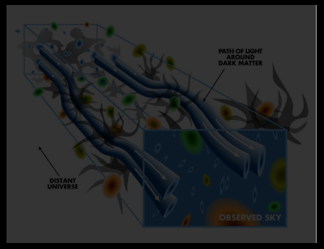


Probing Dark Energy







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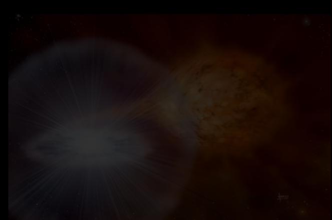
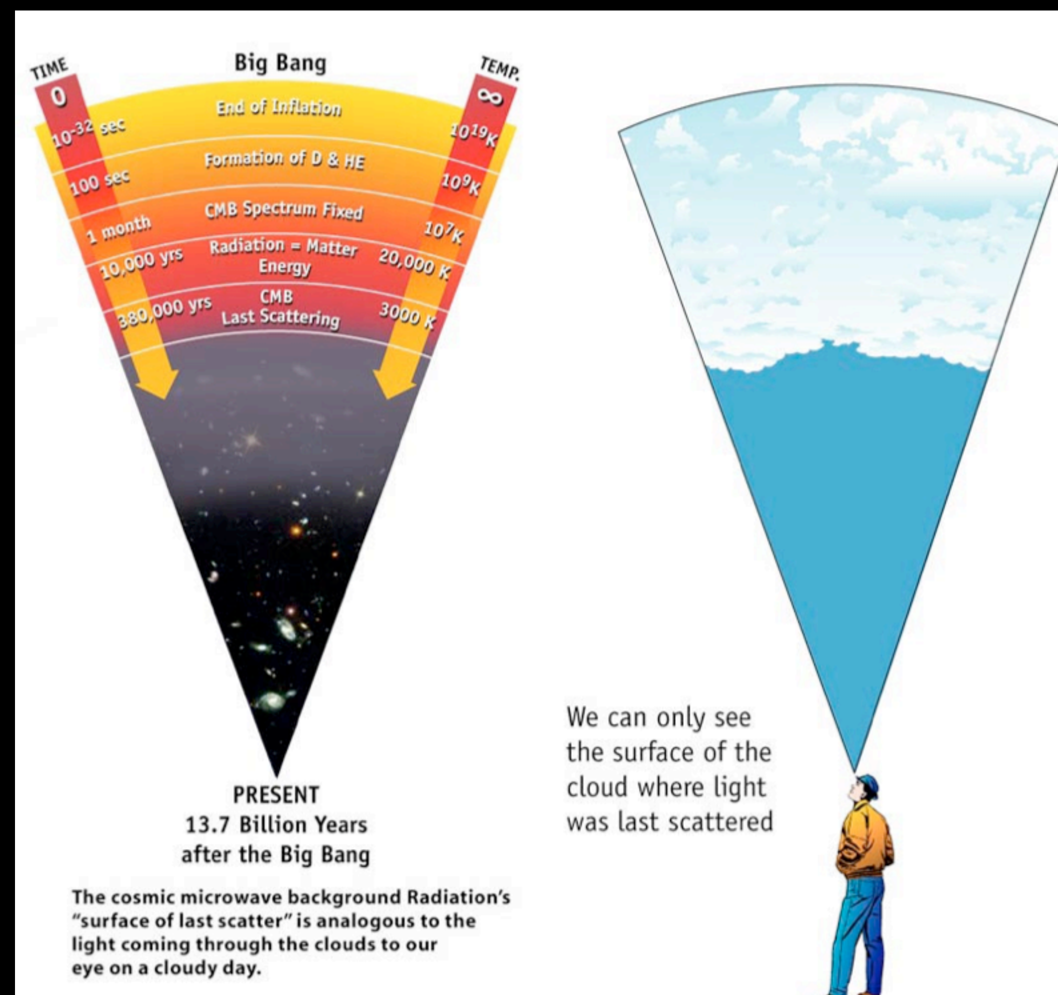
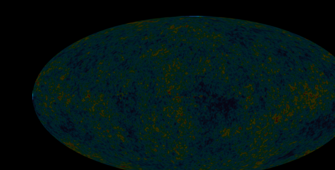
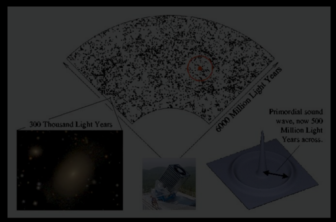


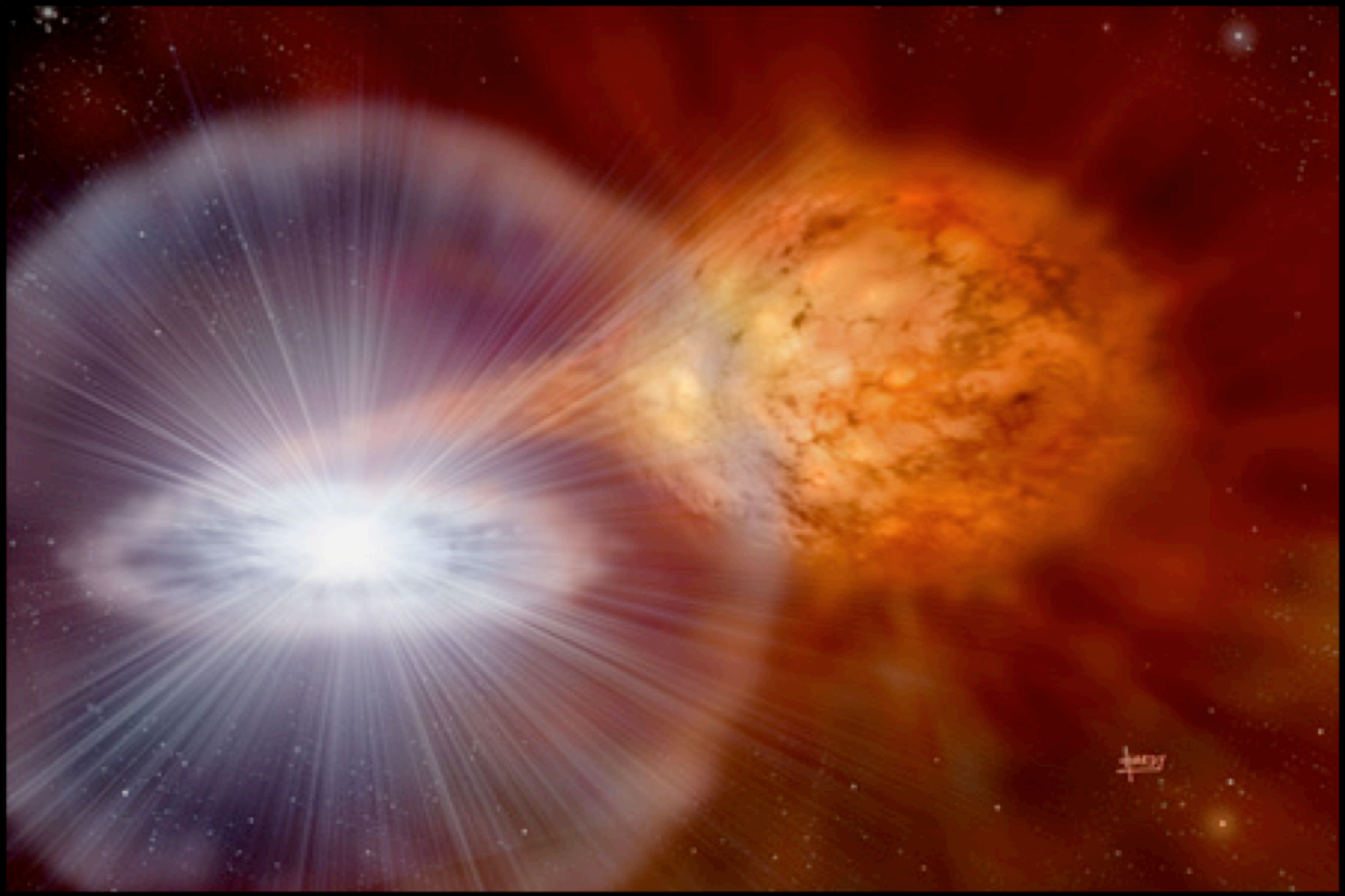


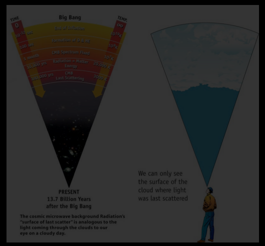
The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



Probing Dark Energy







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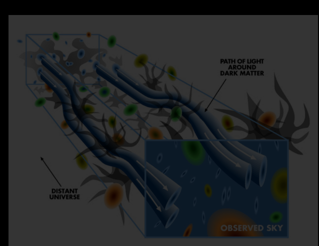

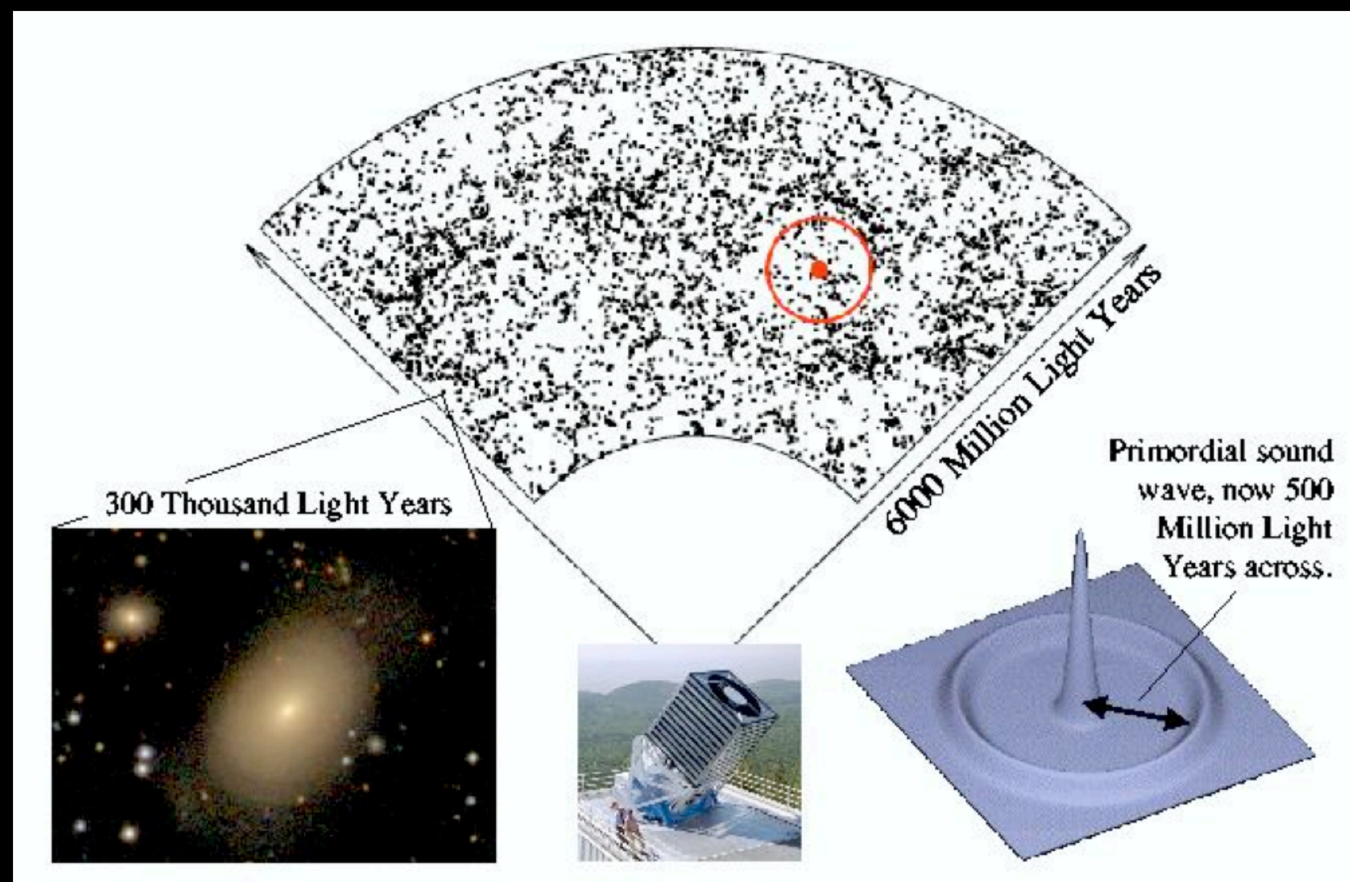

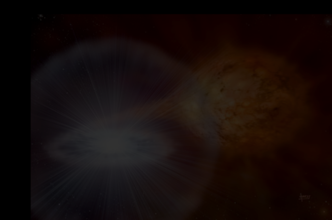

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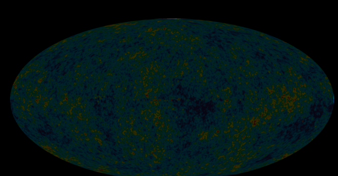
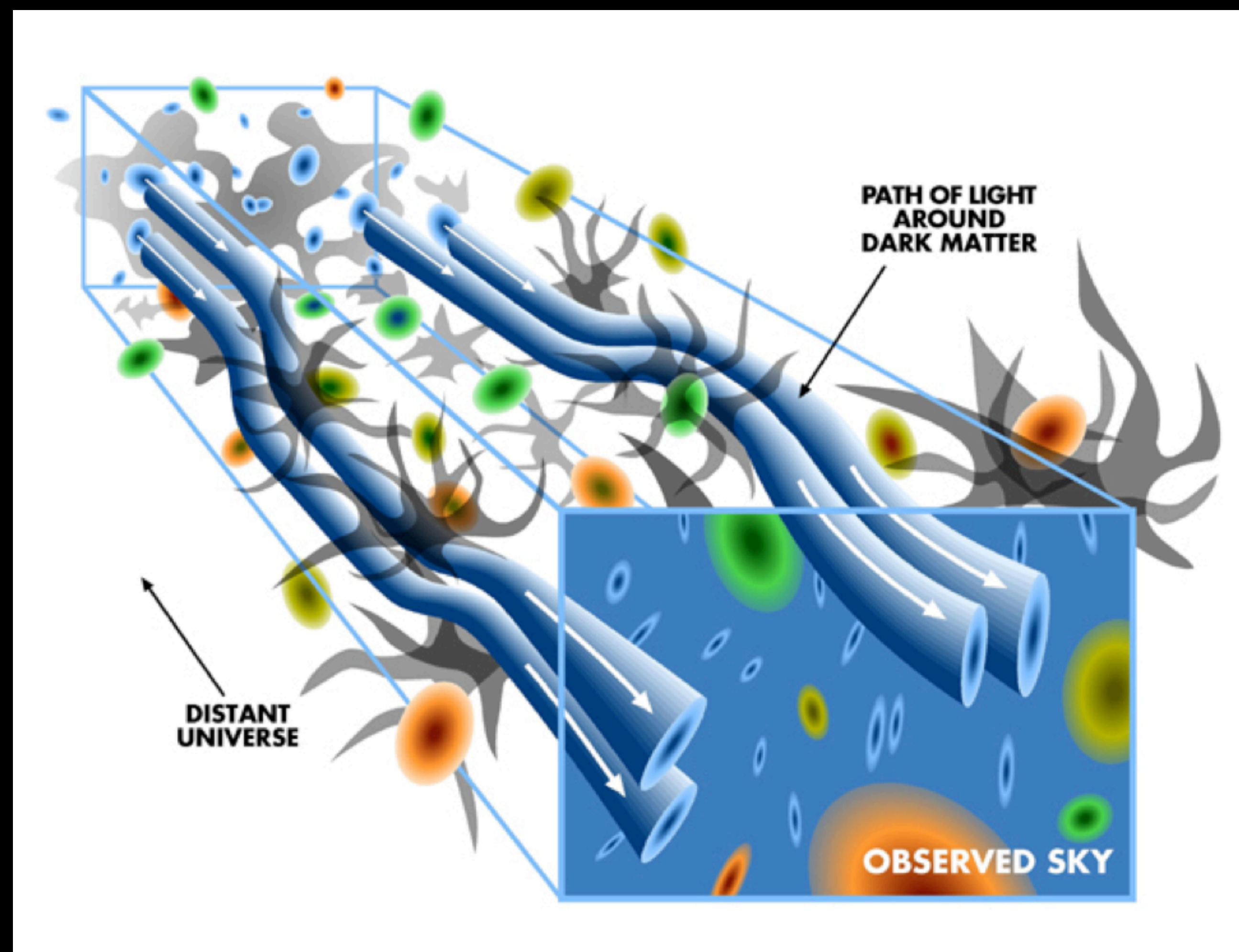
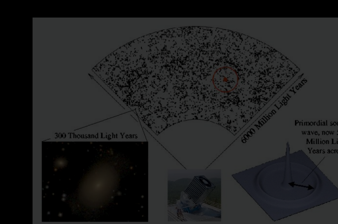
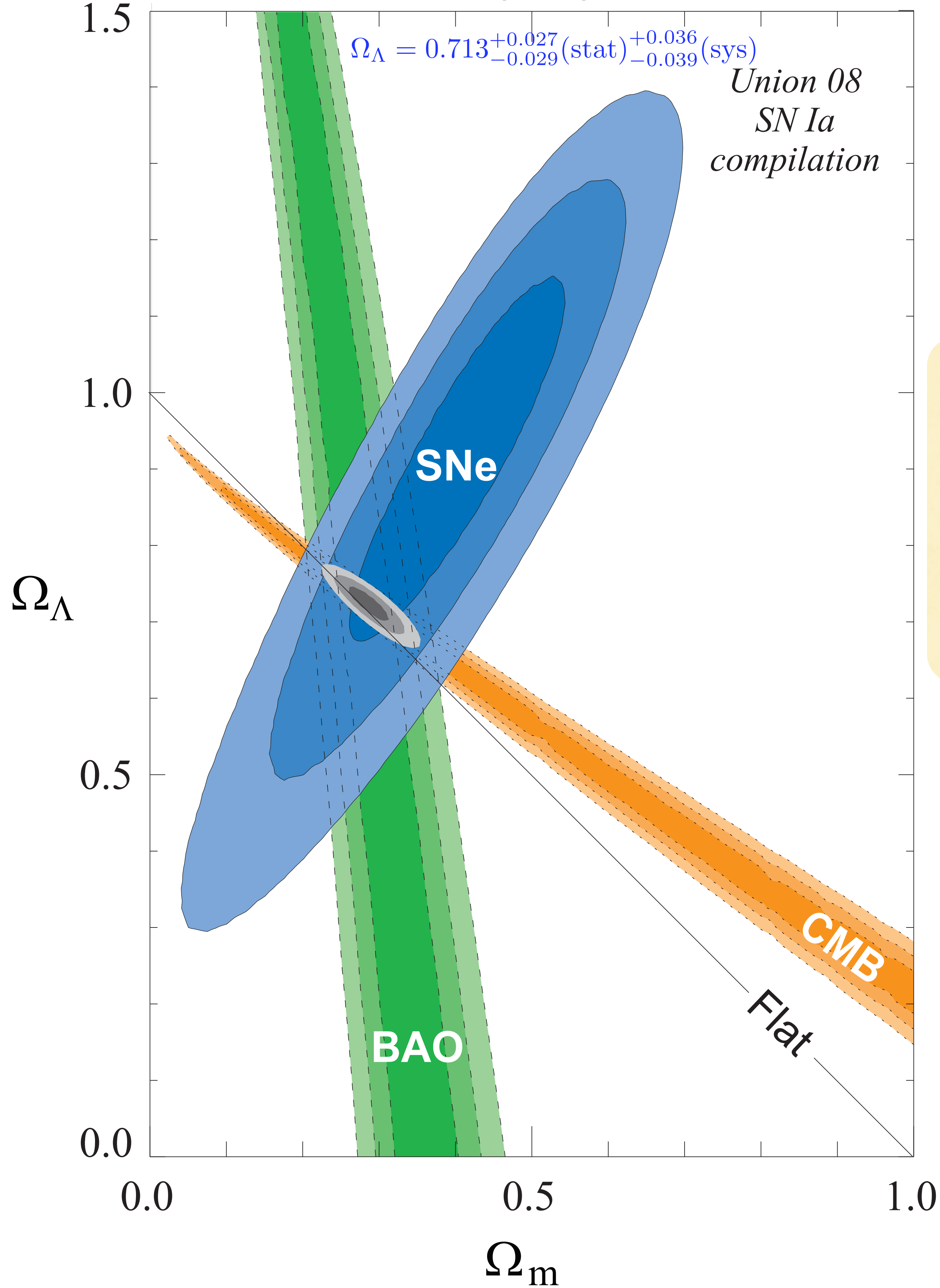
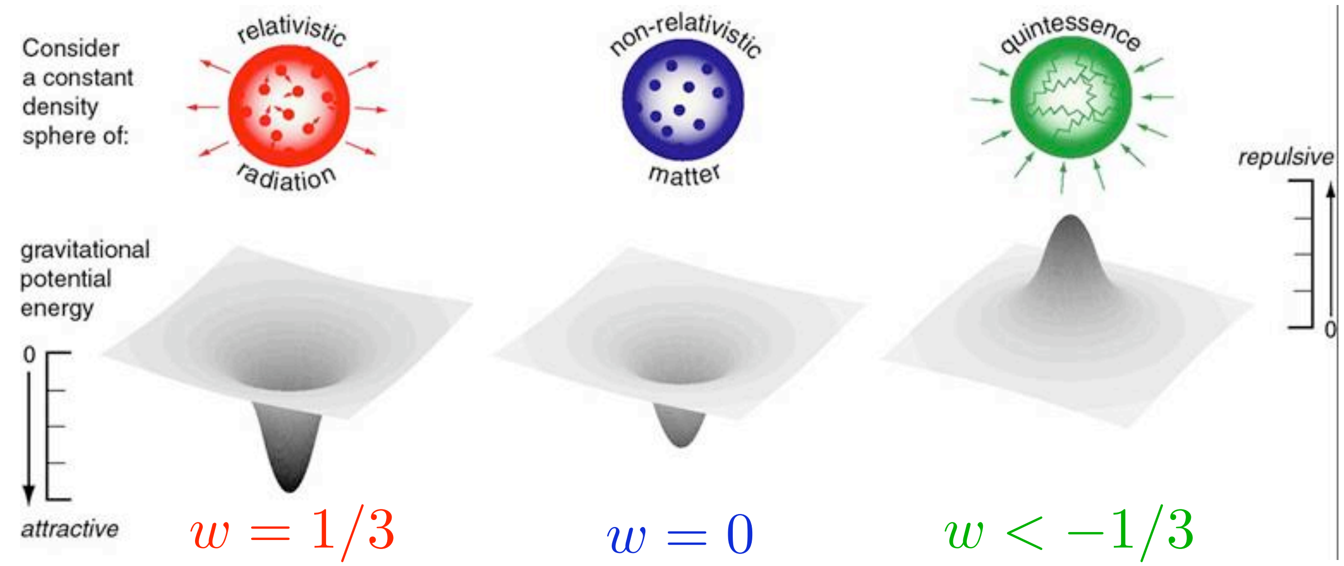






Supernova Cosmology Project
Kowalski, et al., *Ap.J.* (2008)

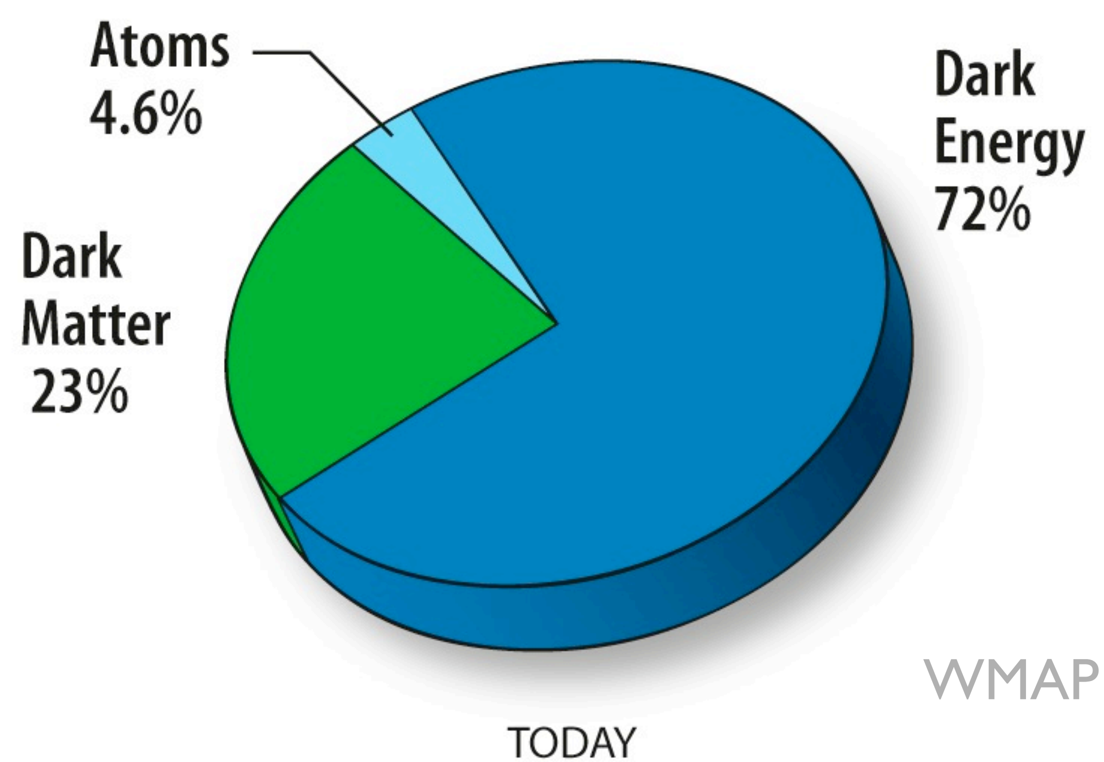




$$w = -0.969^{+0.059}_{-0.063}(\mathrm{stat})^{+0.063}_{-0.066}(\mathrm{sys})\ [\mathrm{Union}]$$

$$w = -\mathrm{x.xxx}^{+0.077}_{-0.077}(\mathrm{stat})^{+0.071}_{-0.071}(\mathrm{sys})\ [\mathrm{SNLS}]$$

(Guy, Conley: Talk at TEXAS 2008 on Dec 09, 2008)



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

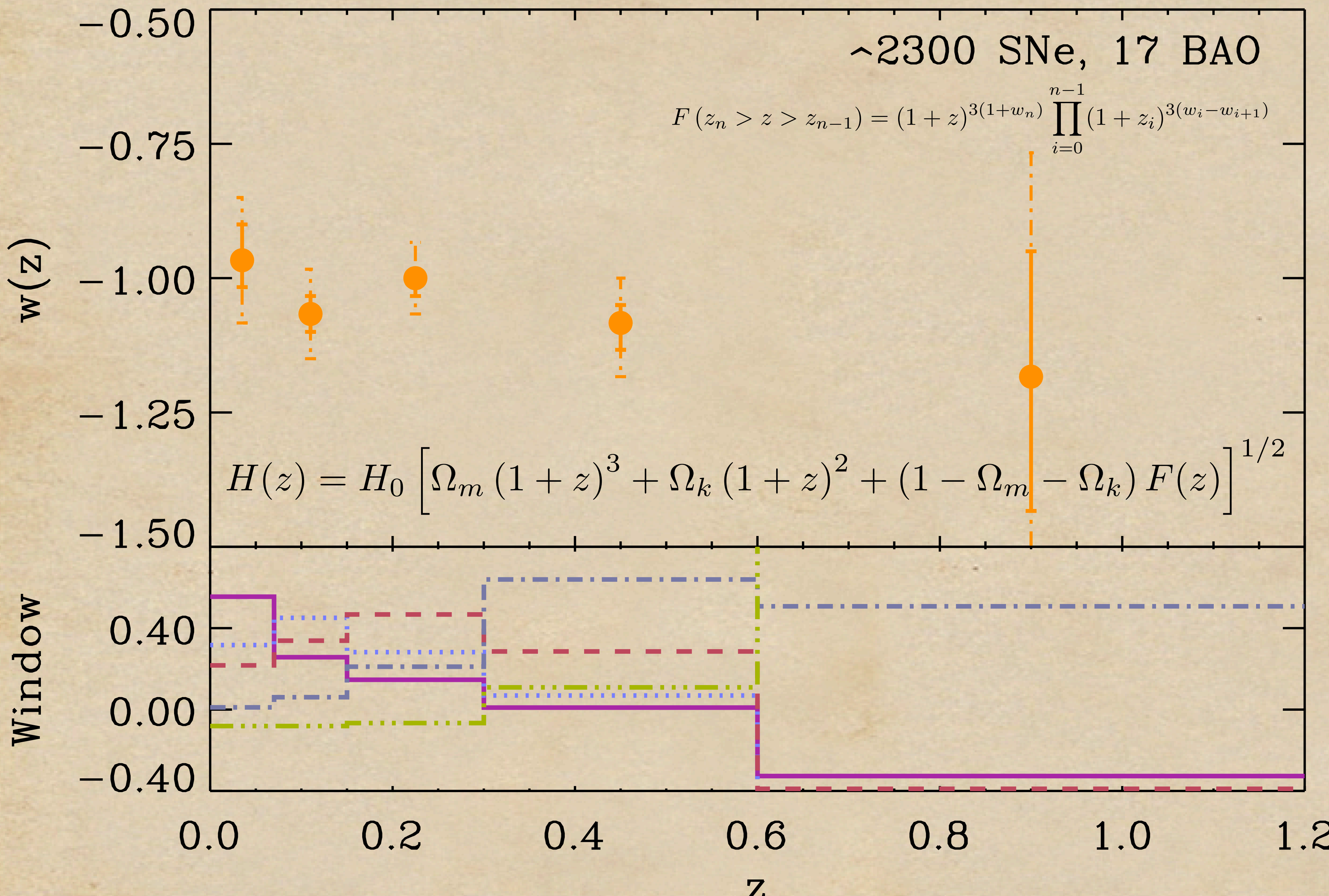
2. Principal Component Analysis

Huterer and Starkman 2003

3. Uncorrelated Estimates of w(z)

Huterer and Cooray 2005

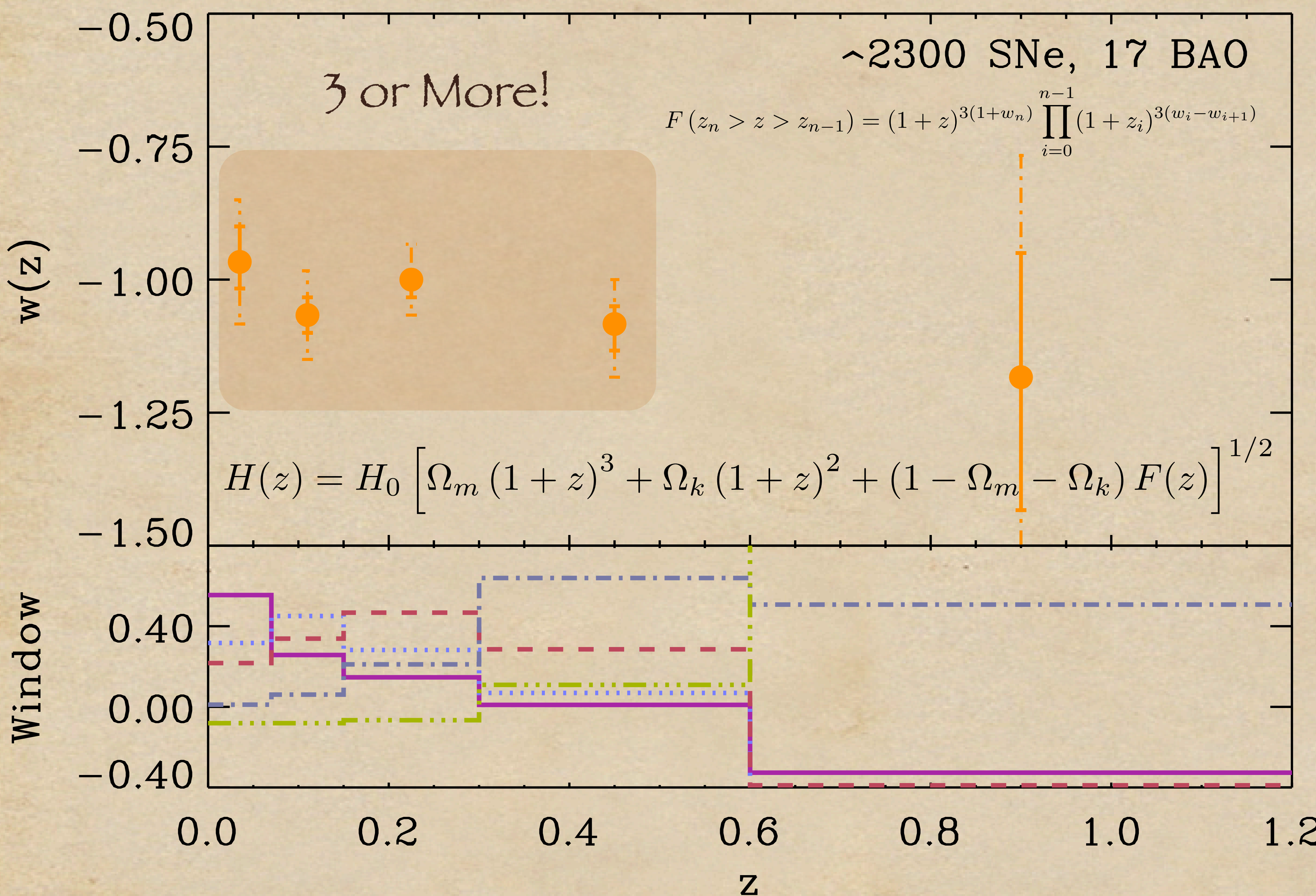
Going Model-Independent: The Future!



W	Zup
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!



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

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Codes

http://dsarkar.org/code.html

ters_IDL Devdeep Sarkar NYSE Arca ::...Java version Gordon Rese... Processes) NYSE Arca ::...Java version CMBLSS_IUCAA_2008 CADC's Inter...eeting List Nvu – The C...nd Win

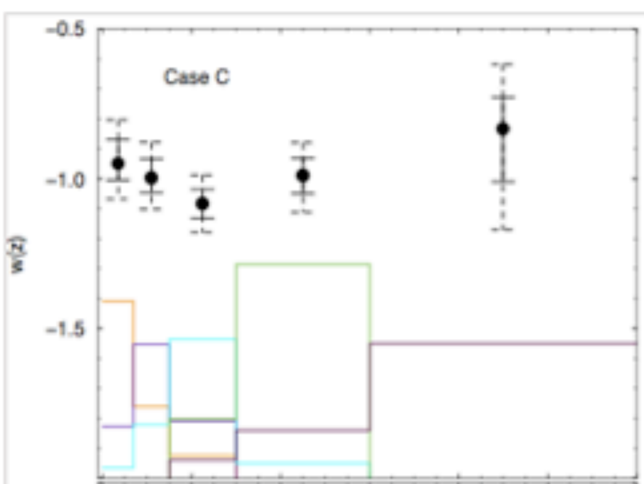
DevdeepSarkar

center for cosmology, uc irvine

Abode | Research | Publications | Codes | Awards | Talks | Teaching | CV | Personal | Travel

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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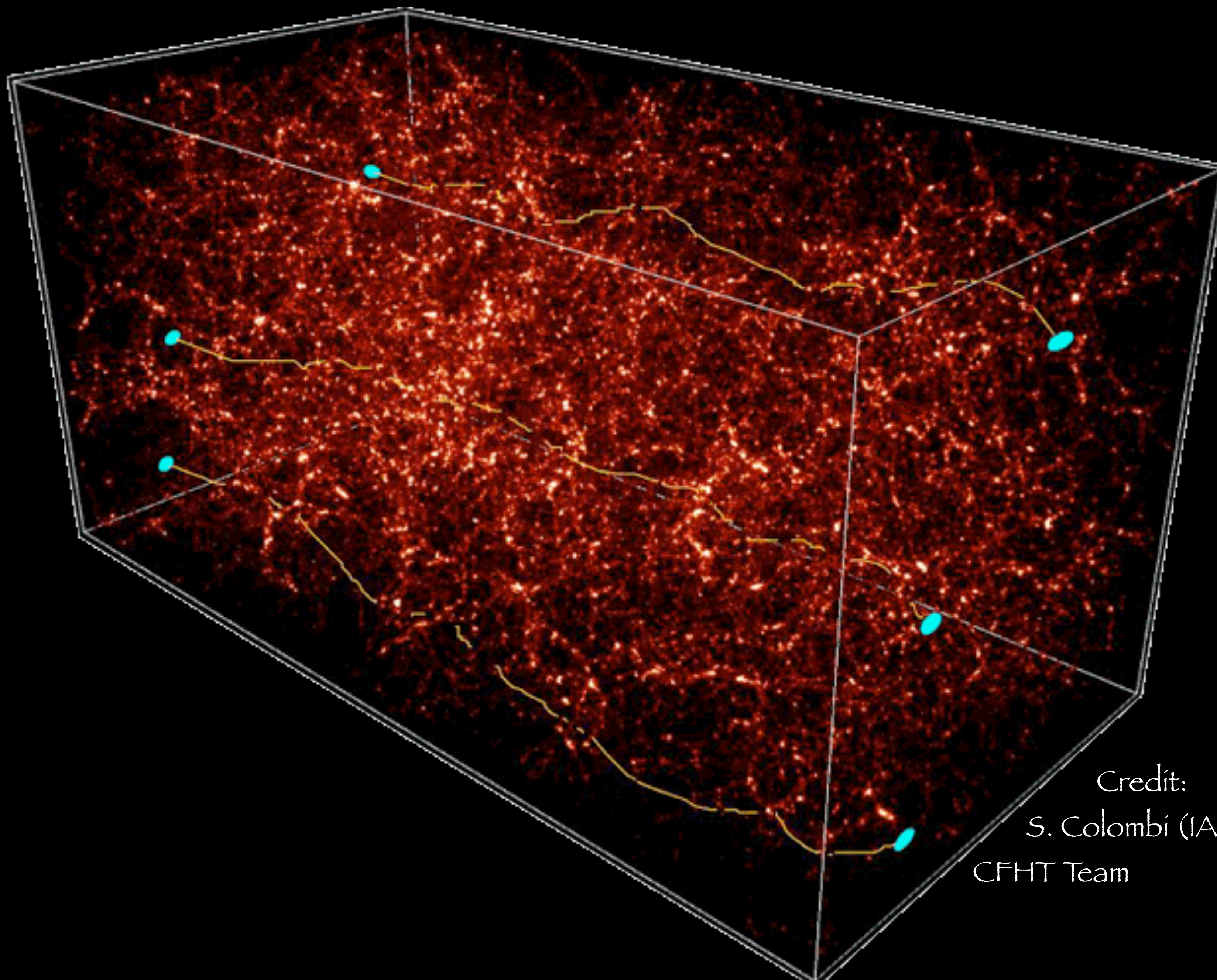
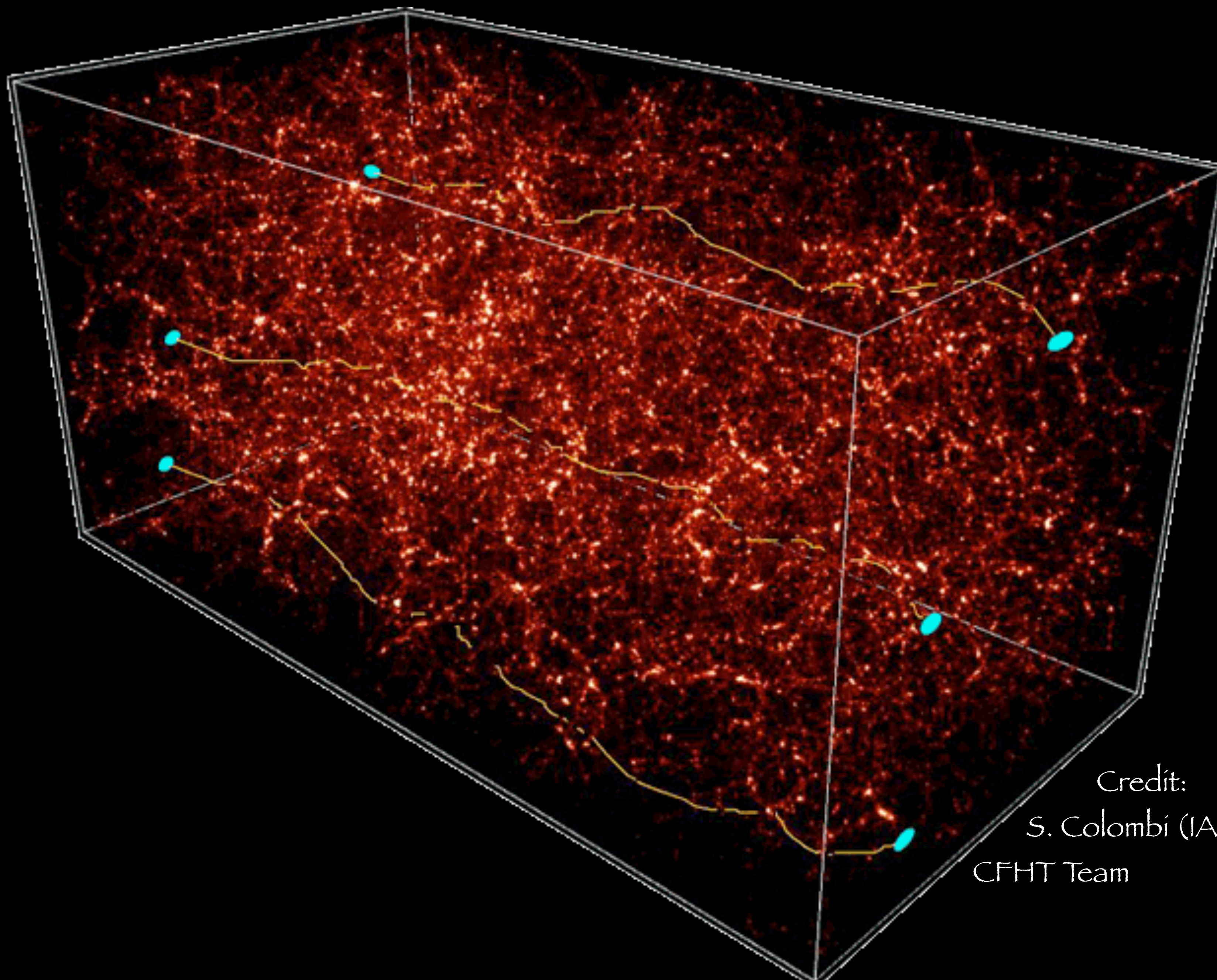


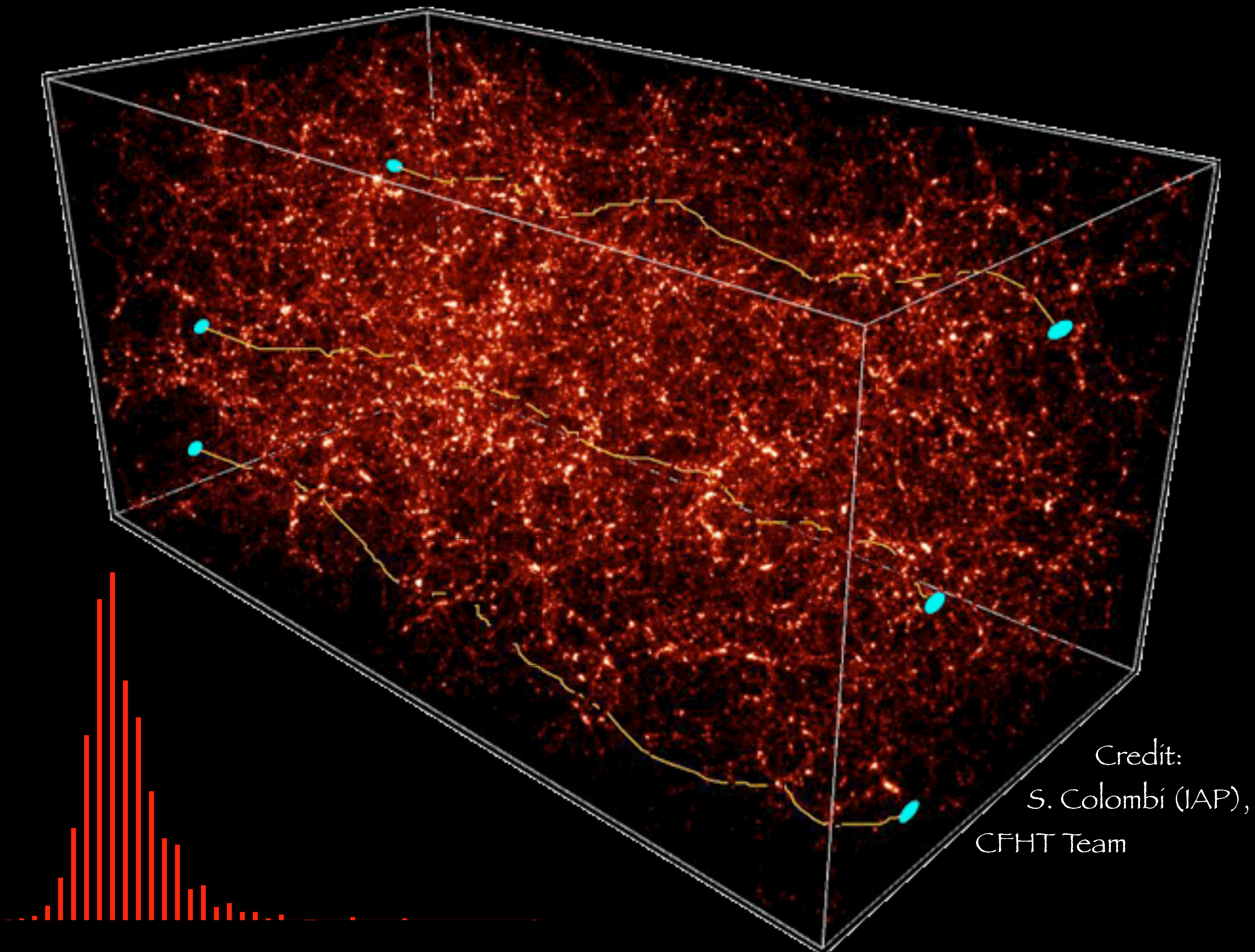
Credit:
S. Colombi (IAP),
CFHT Team

Influence of Gravitational Lensing?



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

Influence of Gravitational Lensing?



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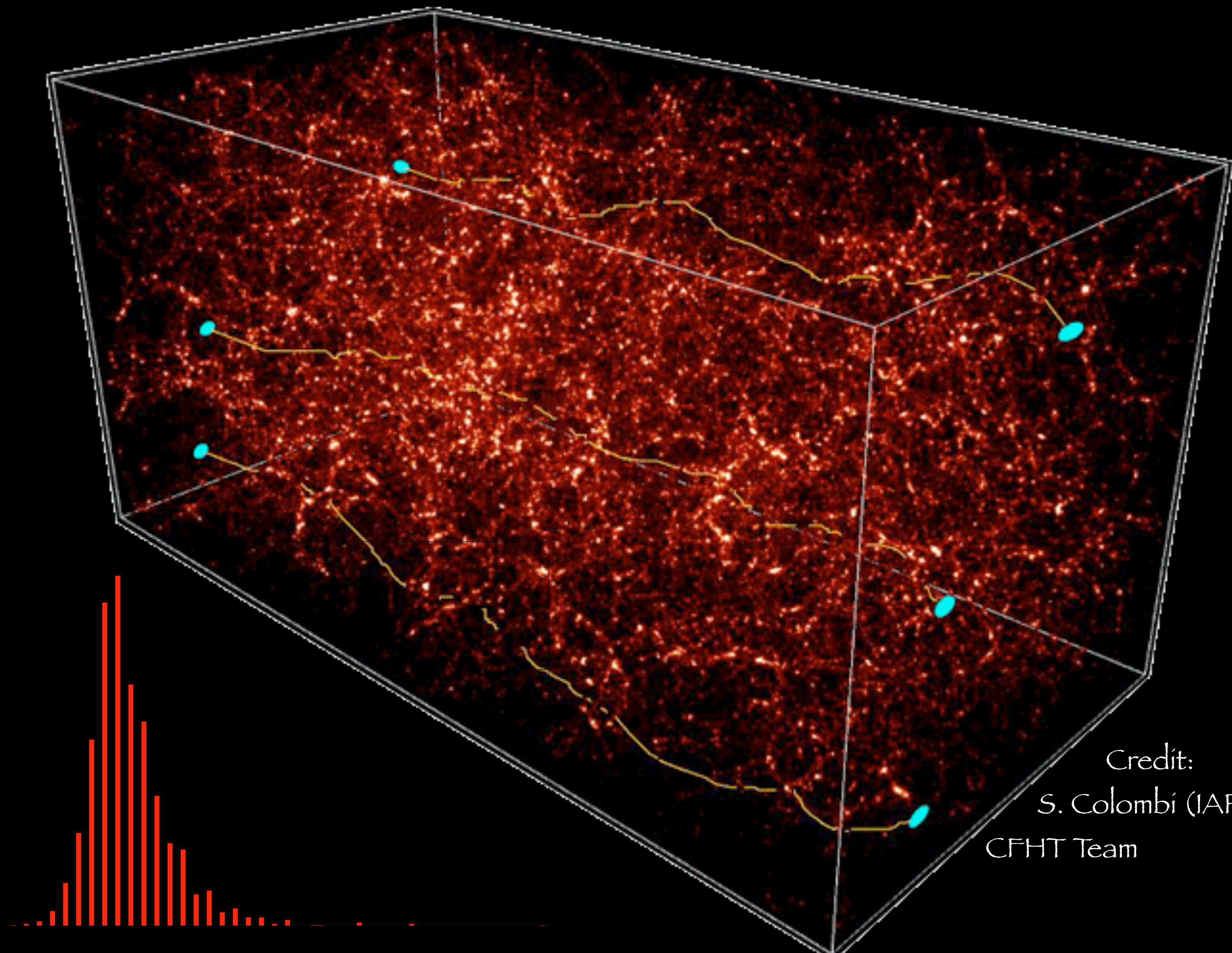
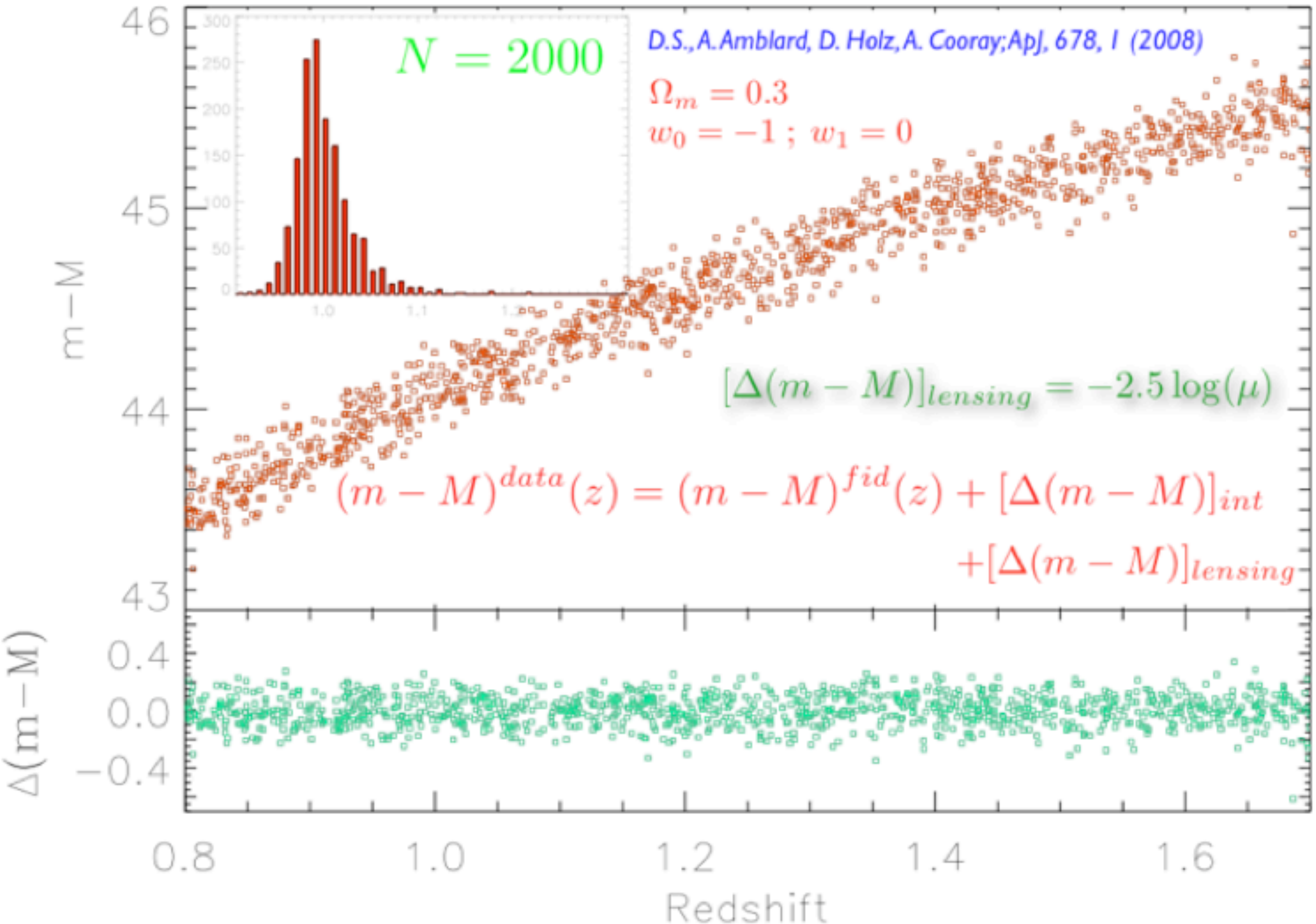


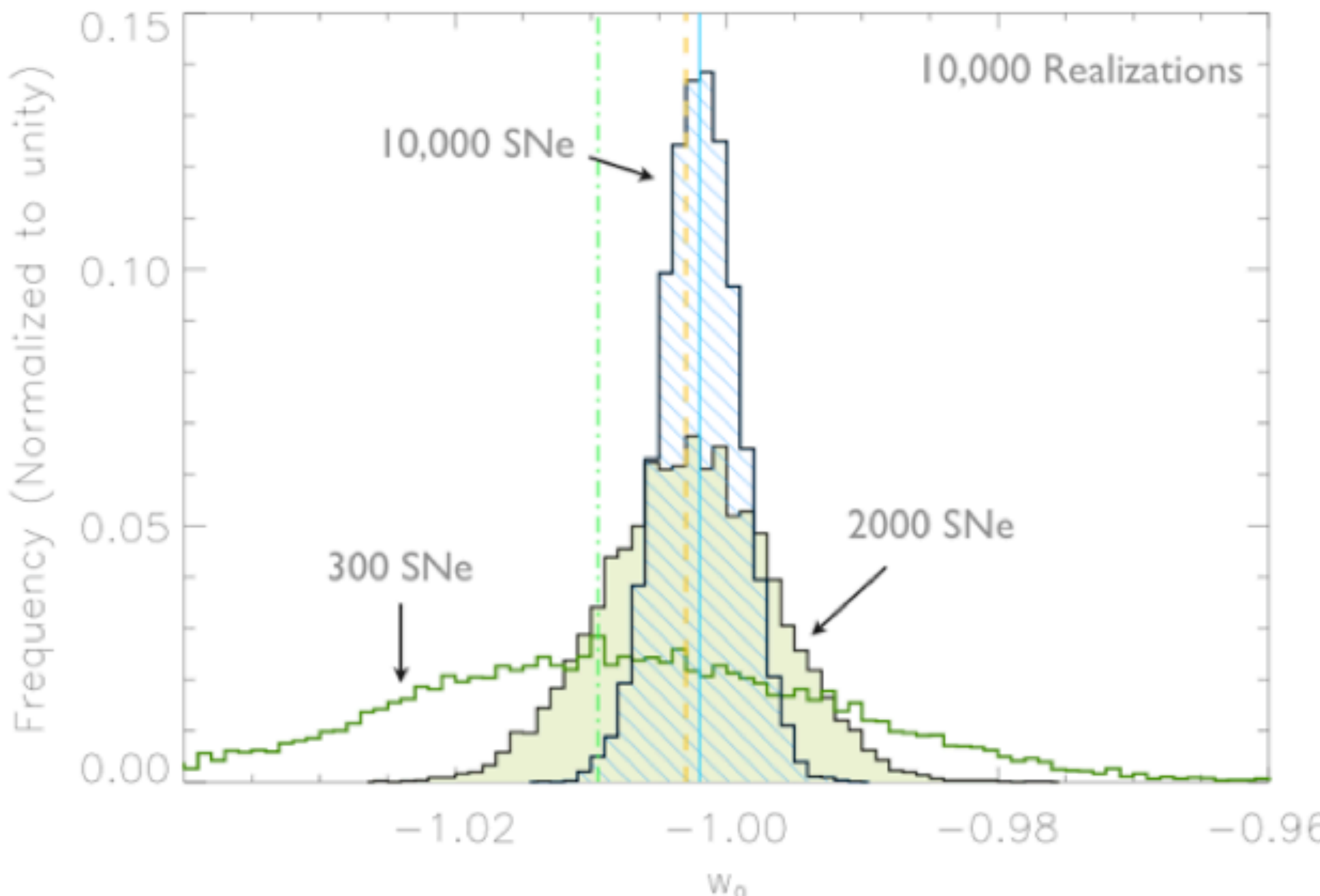
$$\mathcal{F}^{\rm obs,lensed}(z,\hat{\mathbf{n}}) = \mu(z,\hat{\mathbf{n}})\mathcal{F}^{\rm obs,true}(z)$$

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

Our Analysis with Mock Catalogs

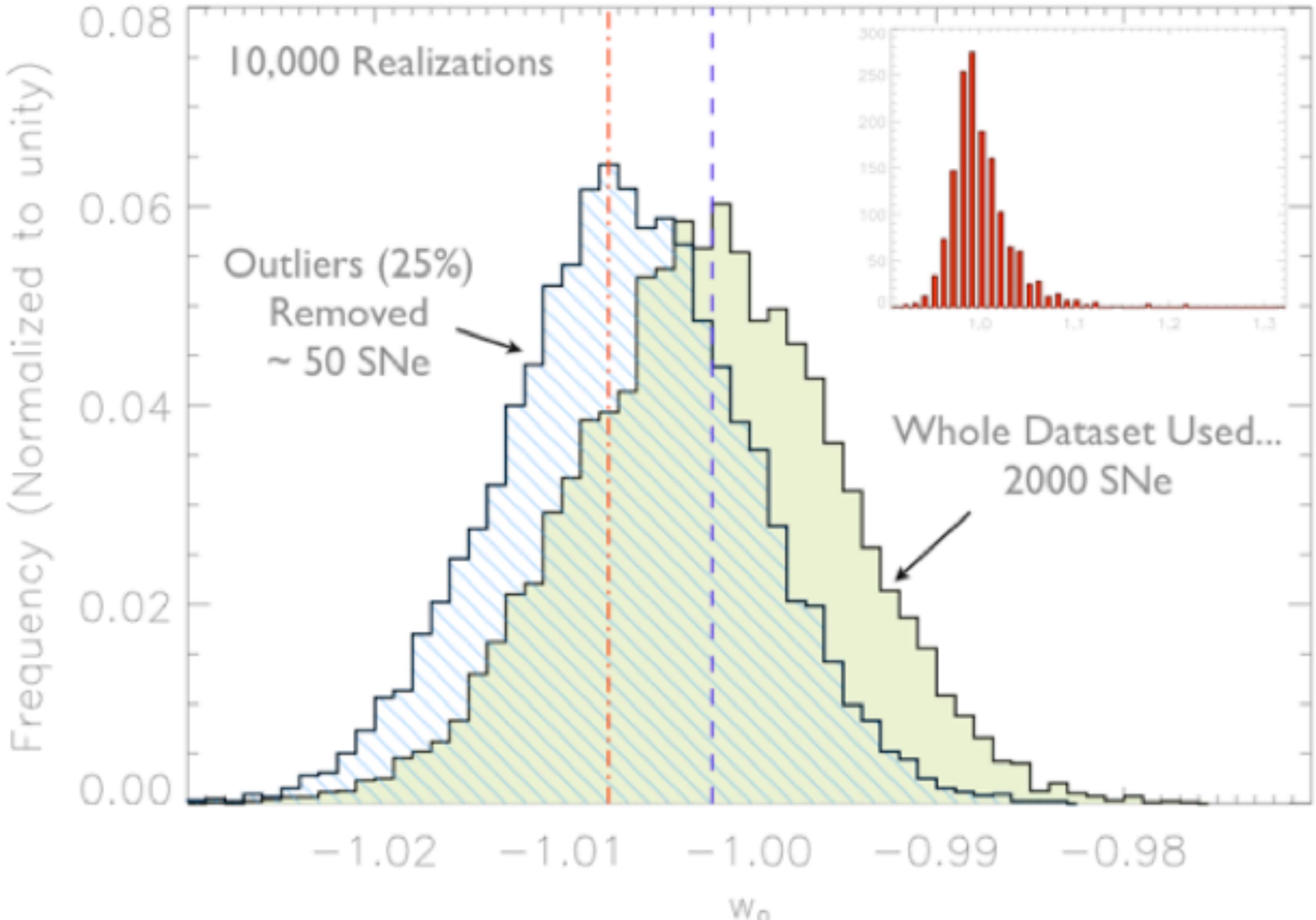


Effect of Weak Lensing on Estimates of "w"



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

Effect of Removing the Outliers



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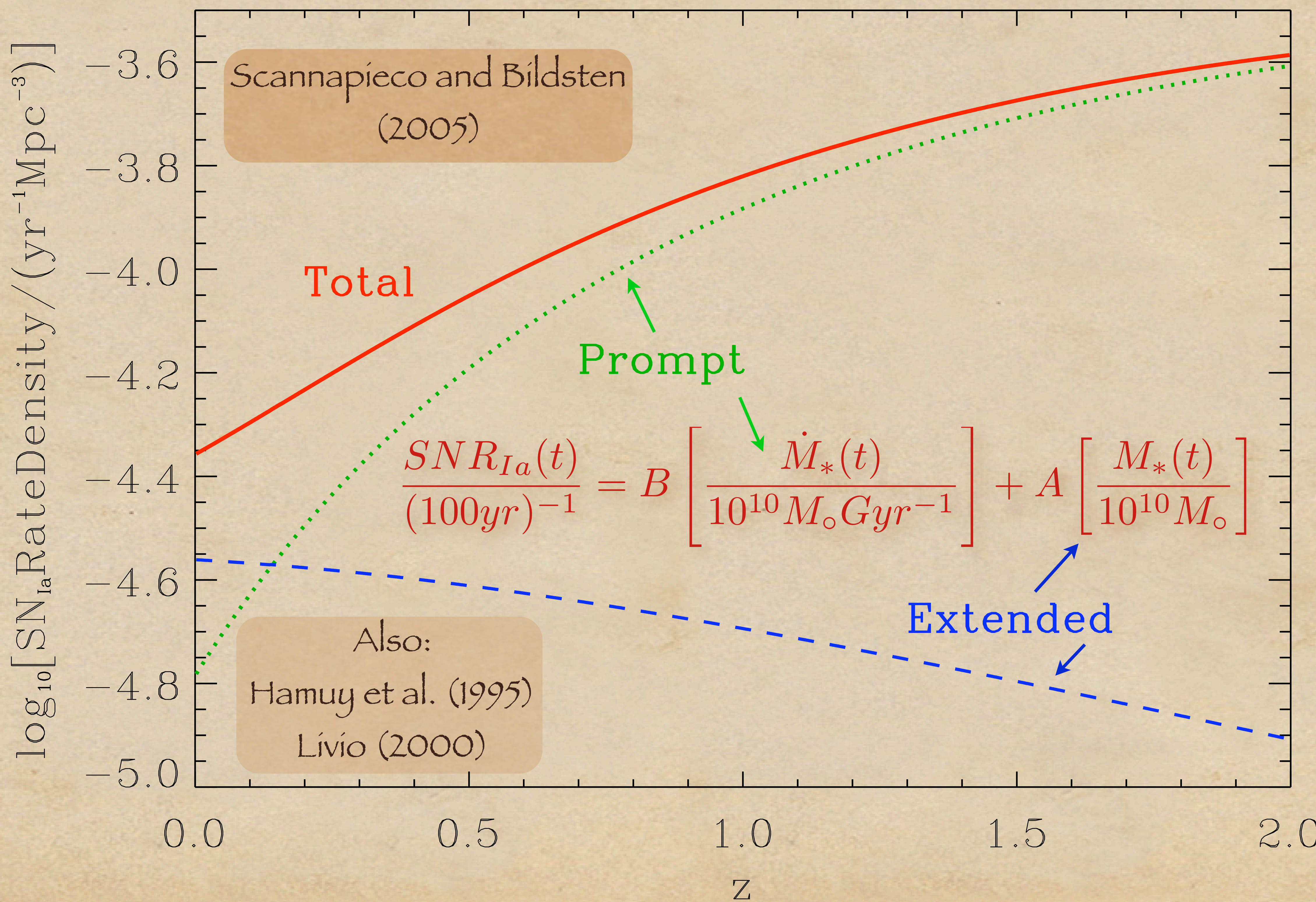
Two Supernova Populations



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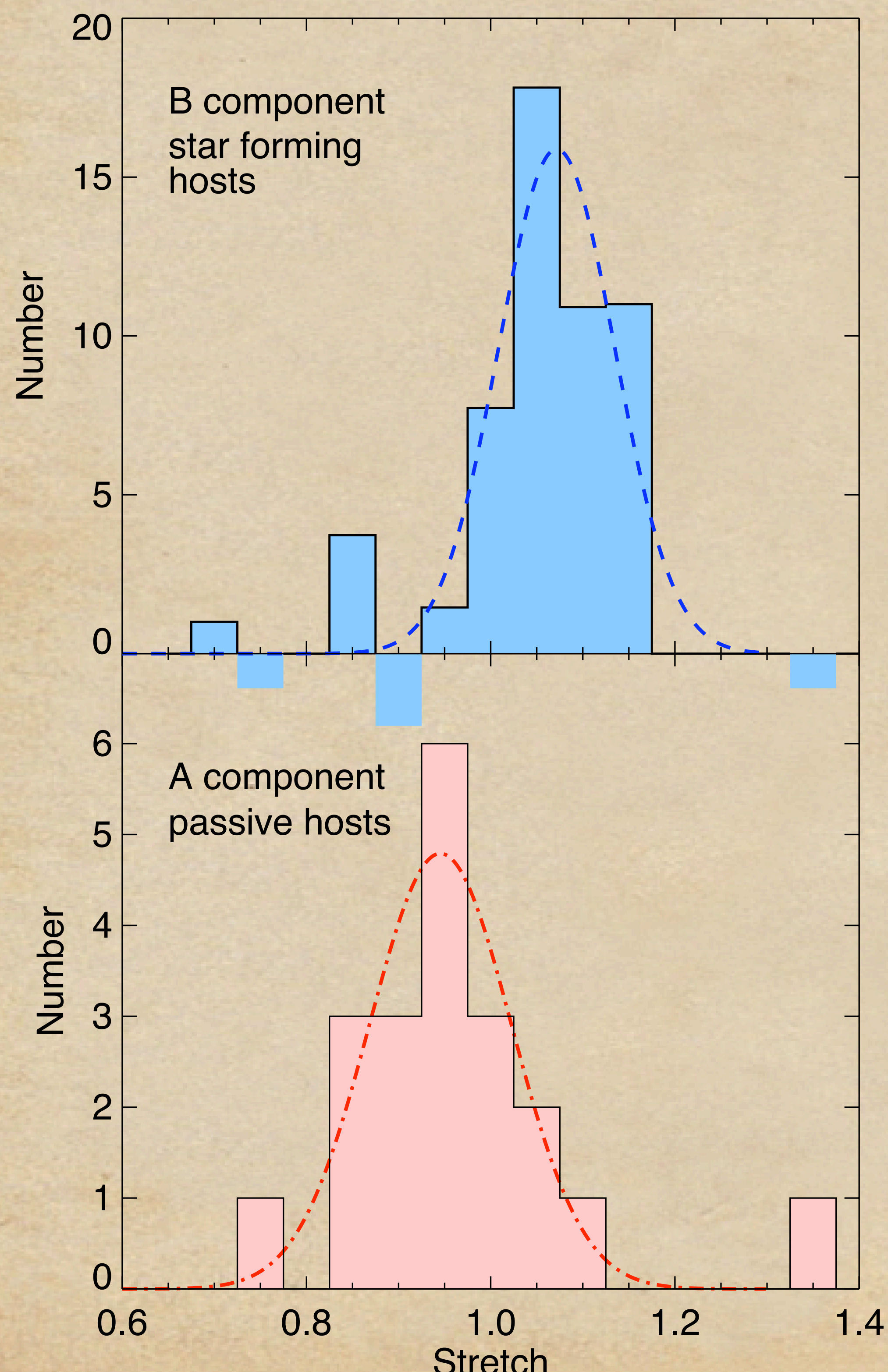

$$\mu_B = m_B^* - M + \alpha(s-1) - \beta c$$

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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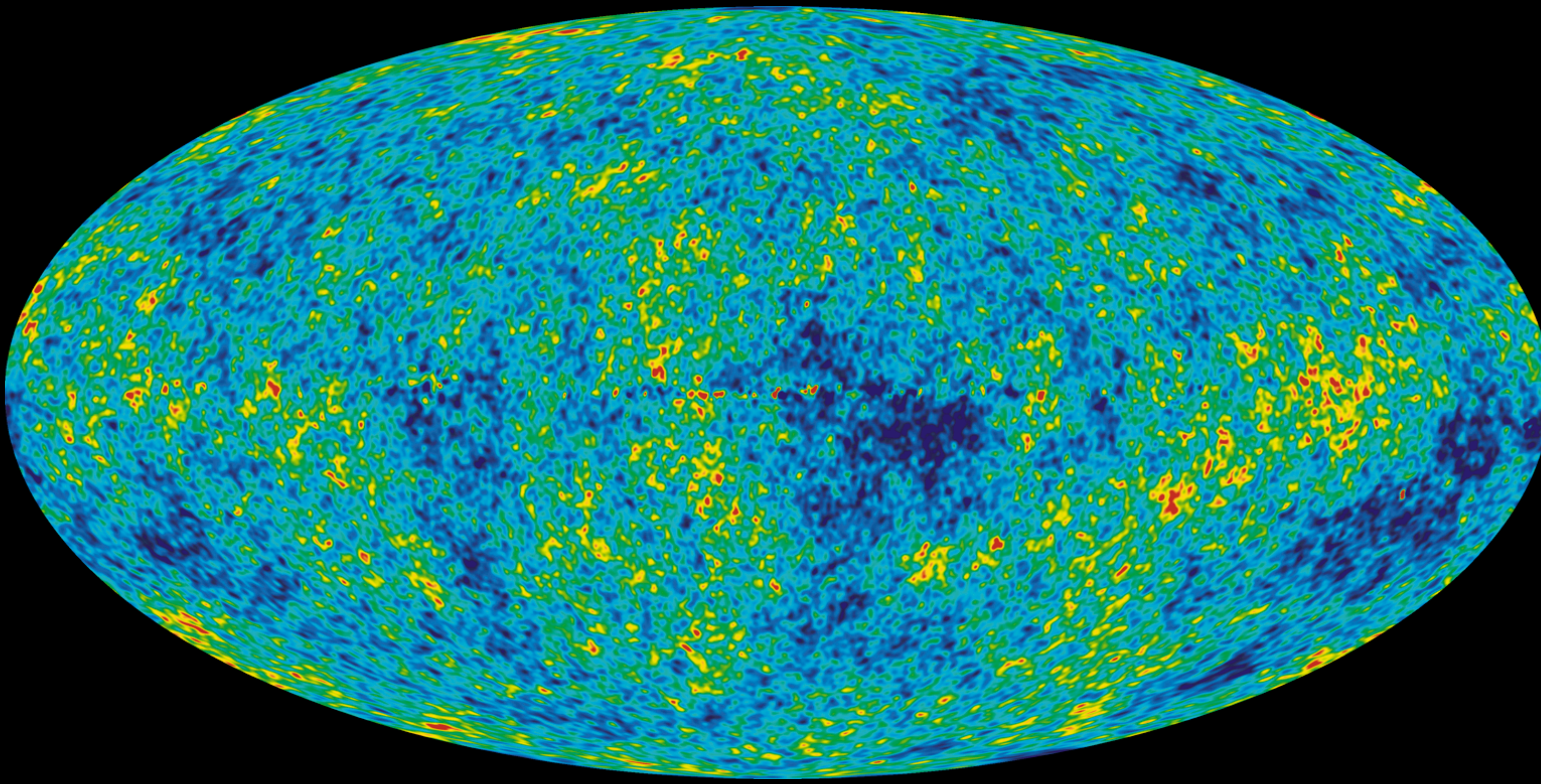
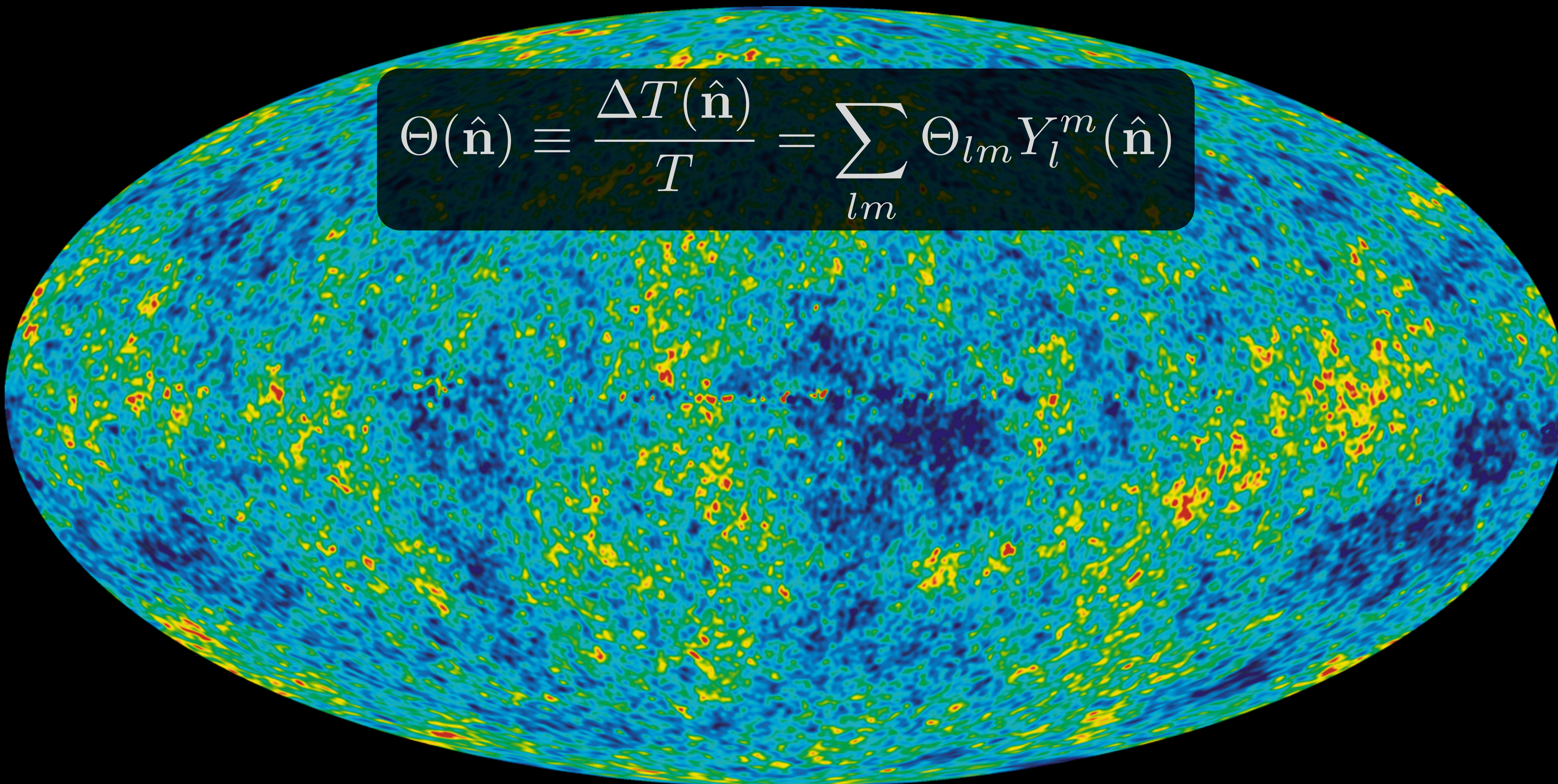
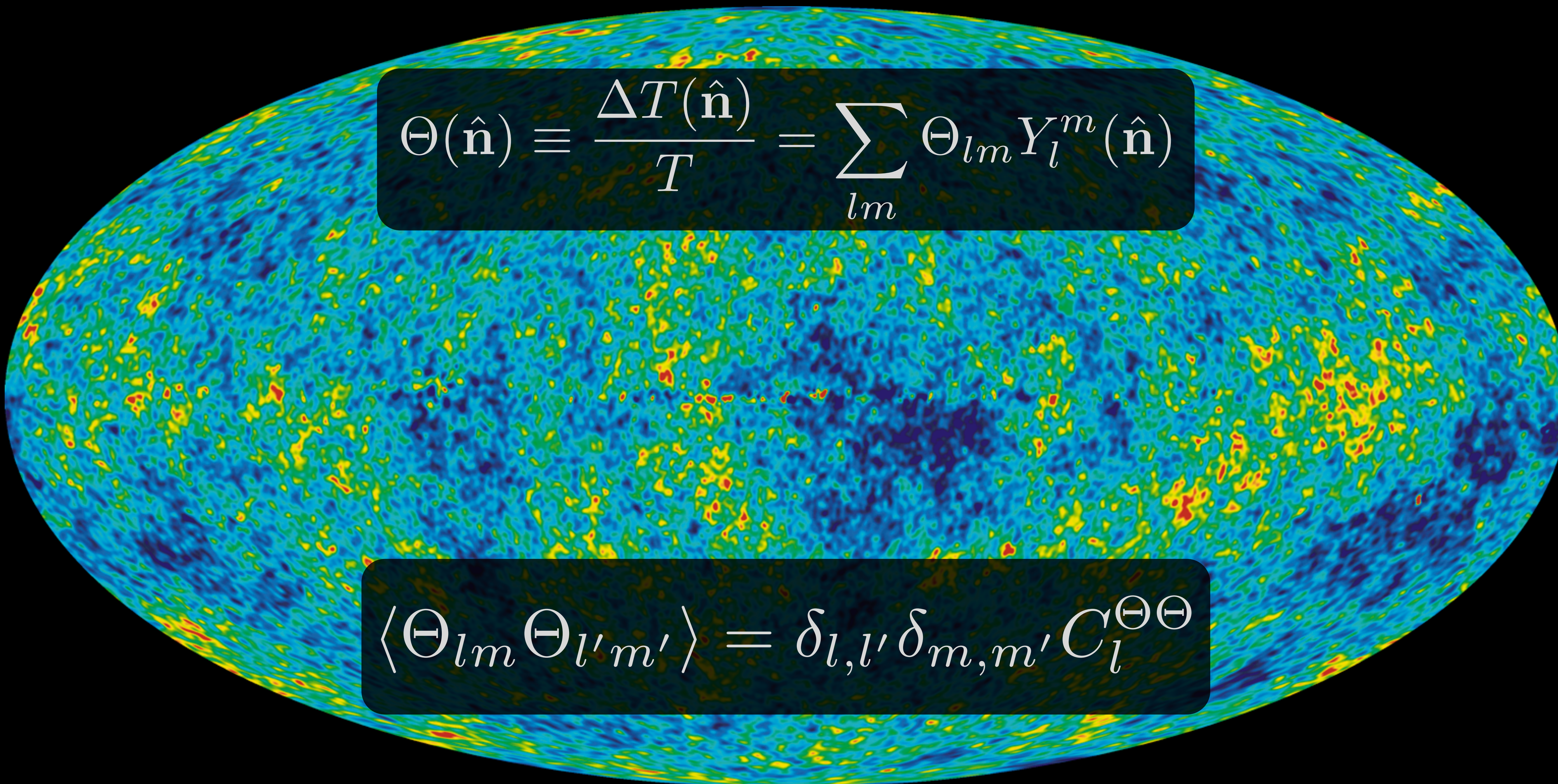


Credit: NASA/WMAP Science Team



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

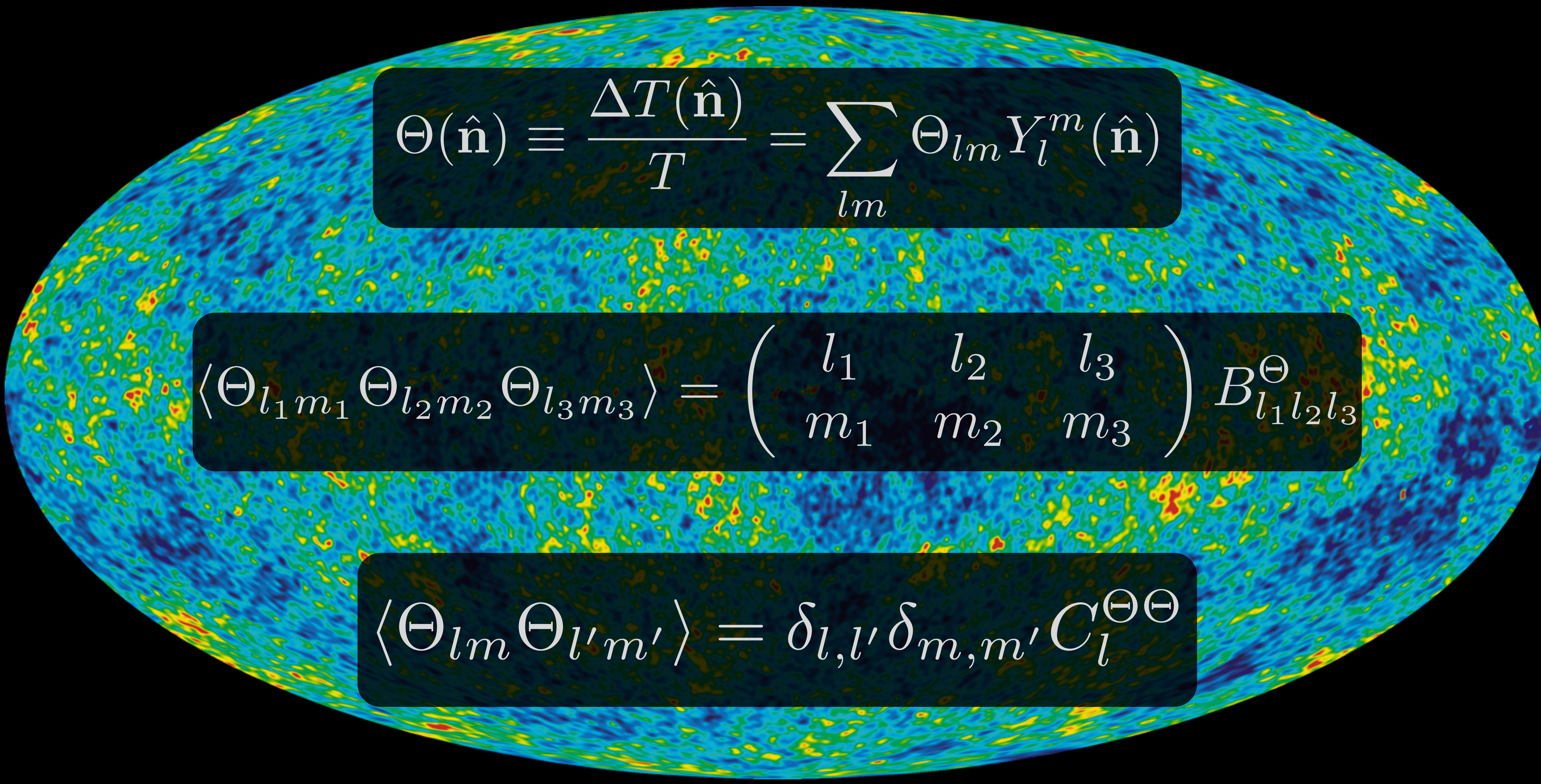
Credit: NASA/WMAP Science Team



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

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

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

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

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

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_{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_{NL}) in the temperature anisotropy of the cosmic microwave background. Analyzing the bispectrum of the Wilkinson Microwave Anisotropy Probe 3-year data up to $\ell_{max} = 750$ we find $27 < f_{NL} < 147$ (95% C.L.). This amounts to a rejection of $f_{NL} = 0$ at 2.8σ, disfavoring canonical single-field slow-roll inflation. The signal is robust to variations in l_{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

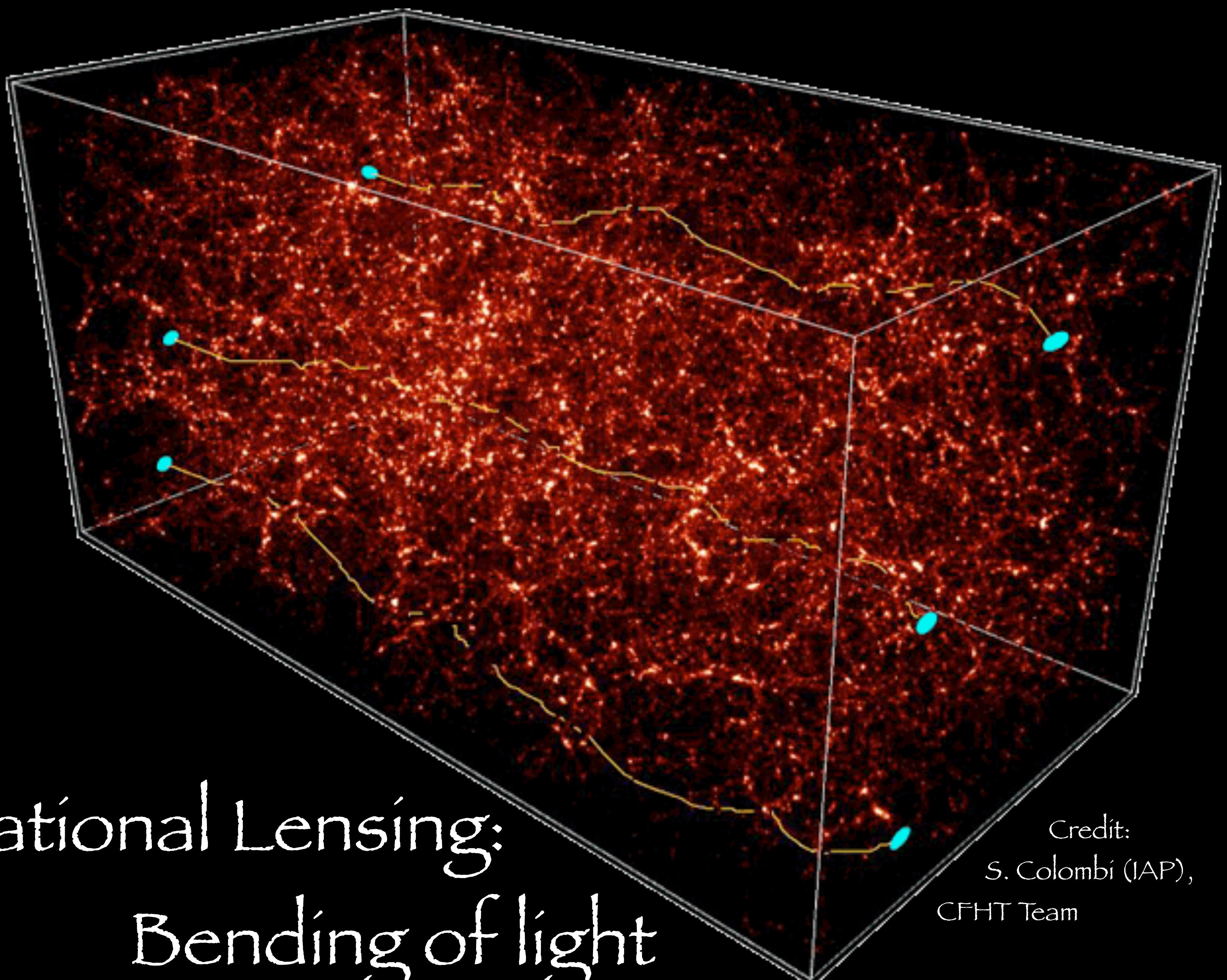
E. Komatsu [1], J. Dunkley [2,3,4], M. R. Nolta [5], C. L. Bennett [6], B. Gold [6], G. Hinshaw [7], N. Jarosik [2], D. Larson [6], M. Limon [8] L. Page [2], D. N. Spergel [3,9], M. Halpern [10], R. S. Hill [11], A. Kogut [7], S. S. Meyer [12], G. S. Tucker [13], J. L. Weiland [10], E. Wollack [7], and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

Submitted to the Astrophysical Journal Supplement Series

ABSTRACT

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

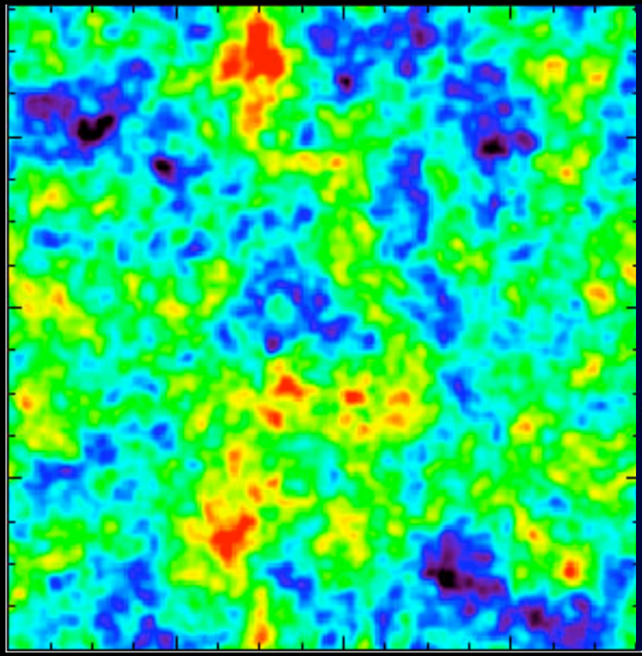
Journey Through the "Clumpy" Universe



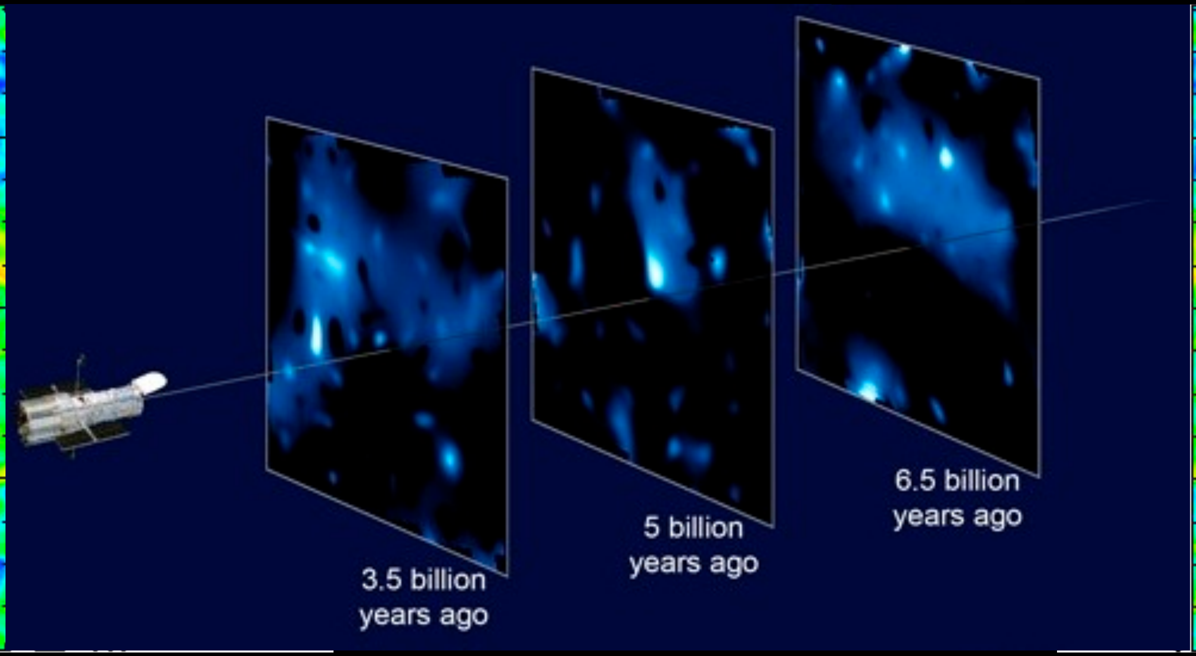
Weak
Gravitational Lensing:
Bending of light

Credit:
S. Colombi (IAP),
CFHT Team

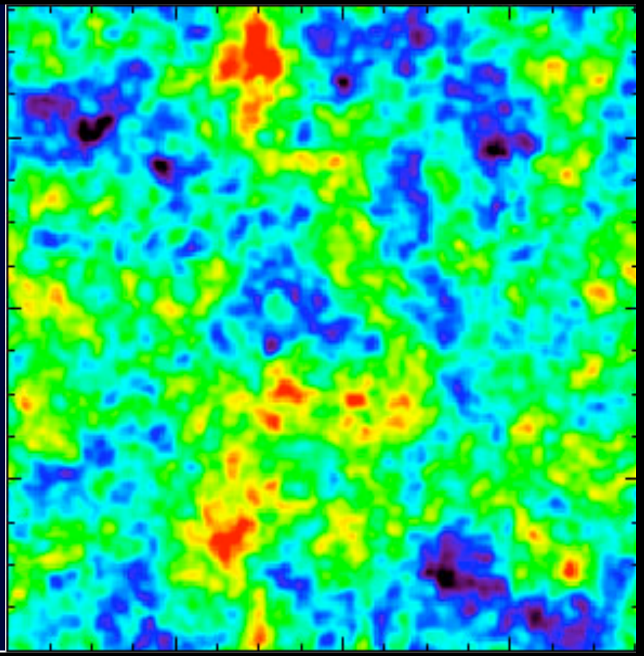
Weak Lensing of the Primary Bispectrum



Credit: Vale, Amblard, White (2004)



NASA, ESA, and R. Massey (CalTech)



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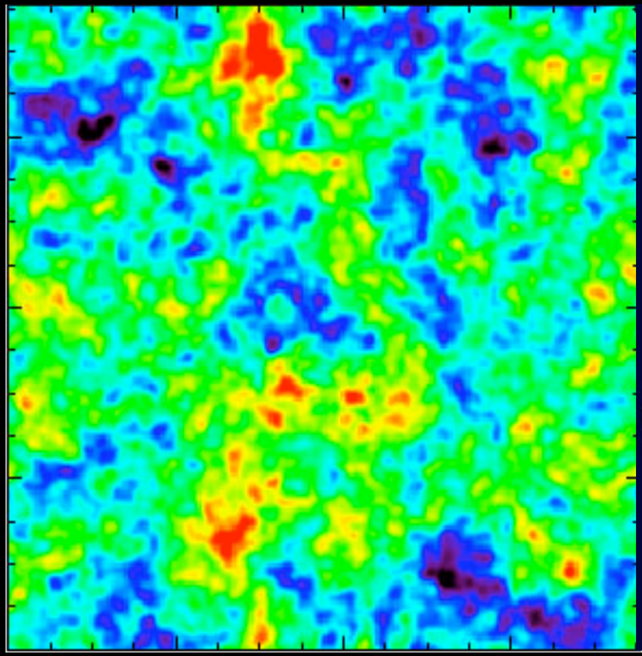

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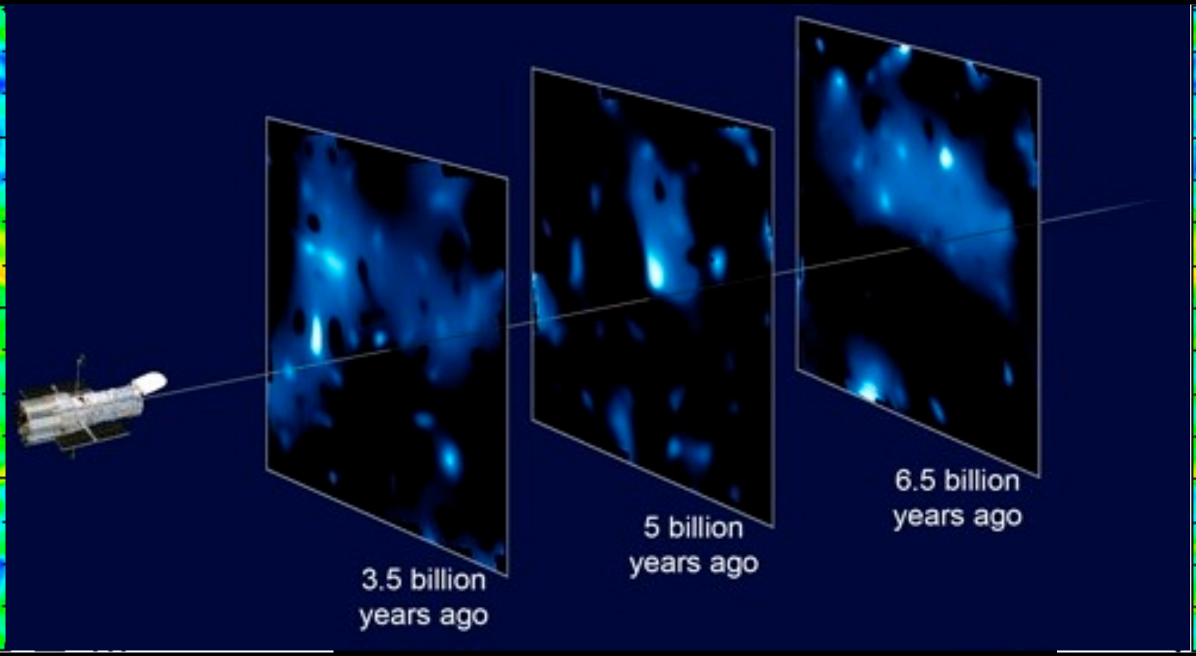

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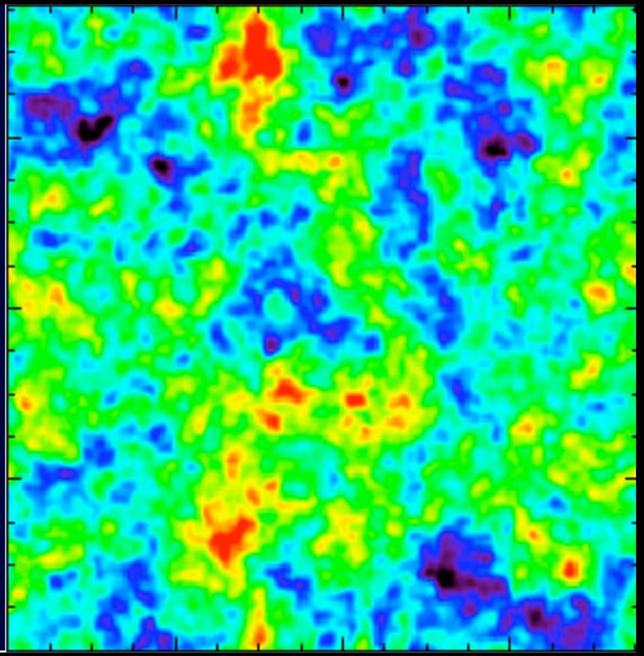
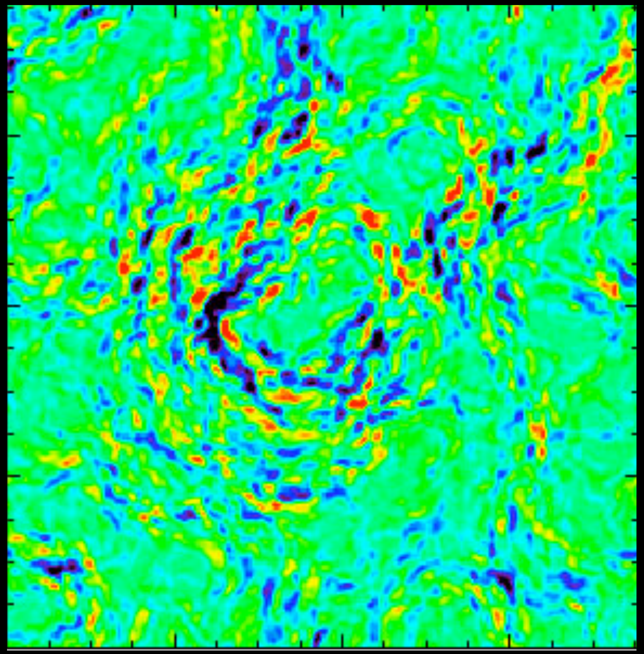


Credit: Vale, Amblard, White (2004)



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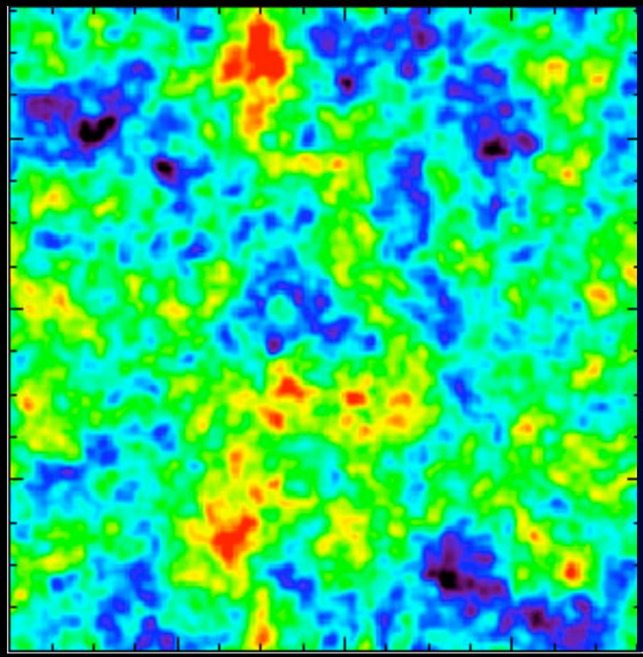
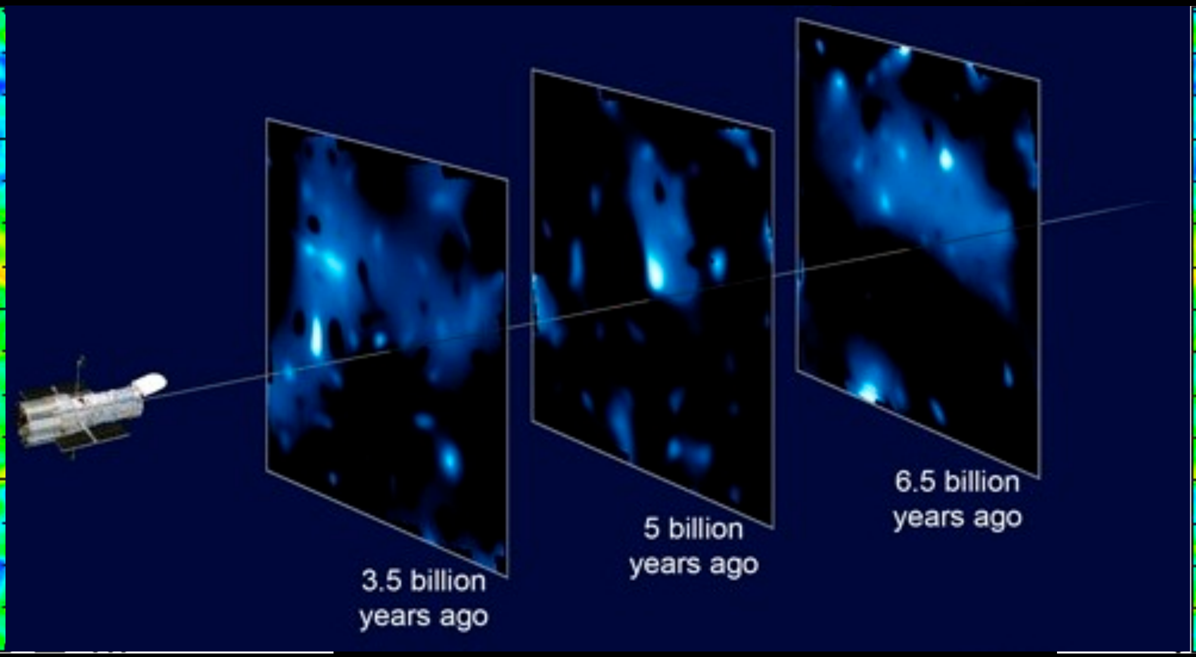


Credit: Vale, Amblard, White (2004)



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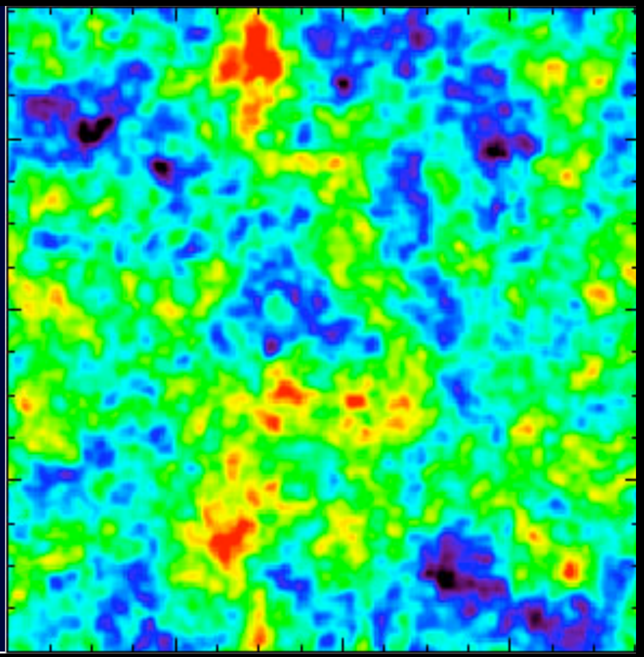
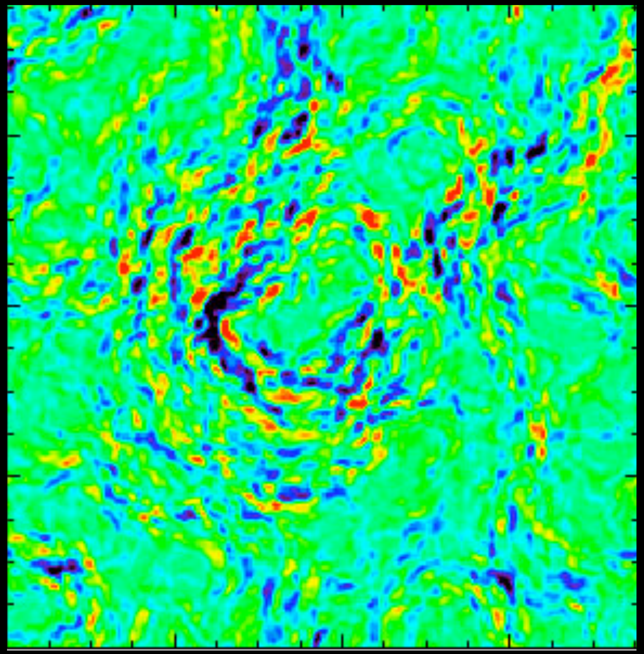


Credit: Vale, Amblard, White (2004)

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



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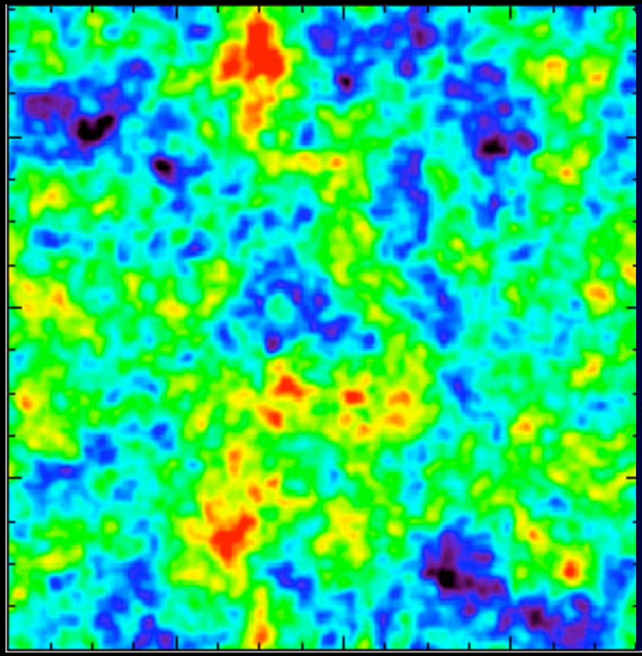
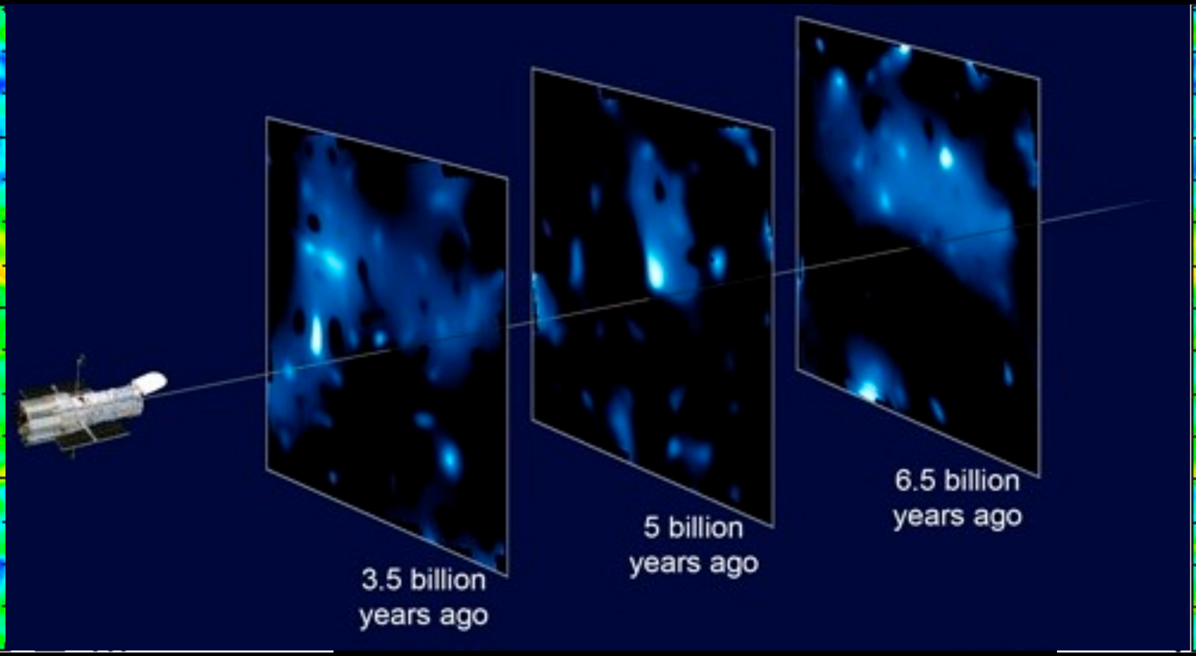
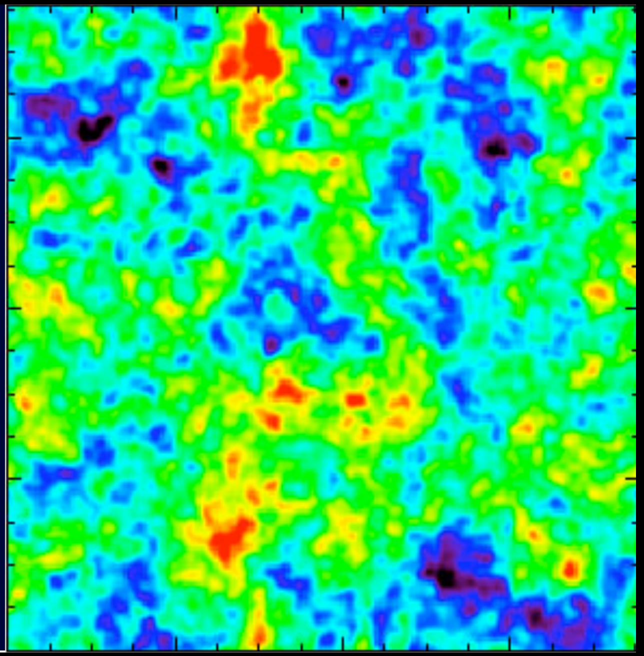


Credit: Vale, Amblard, White (2004)

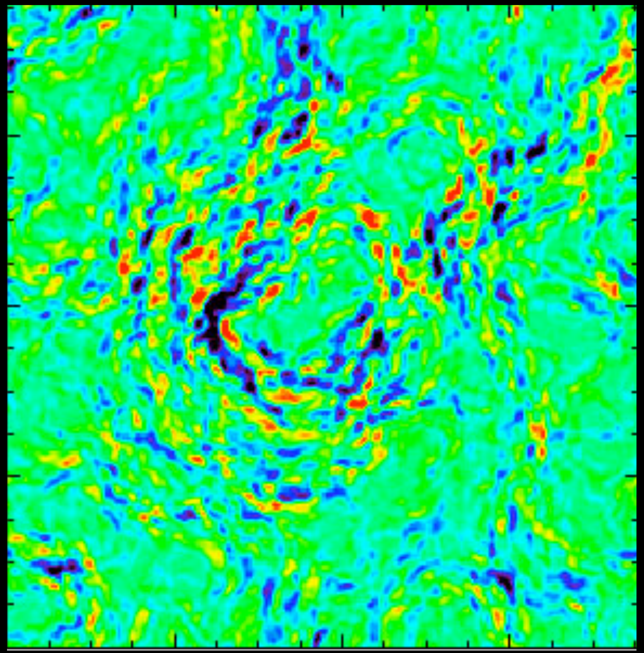


NASA, ESA, and R. Massey (CalTech)

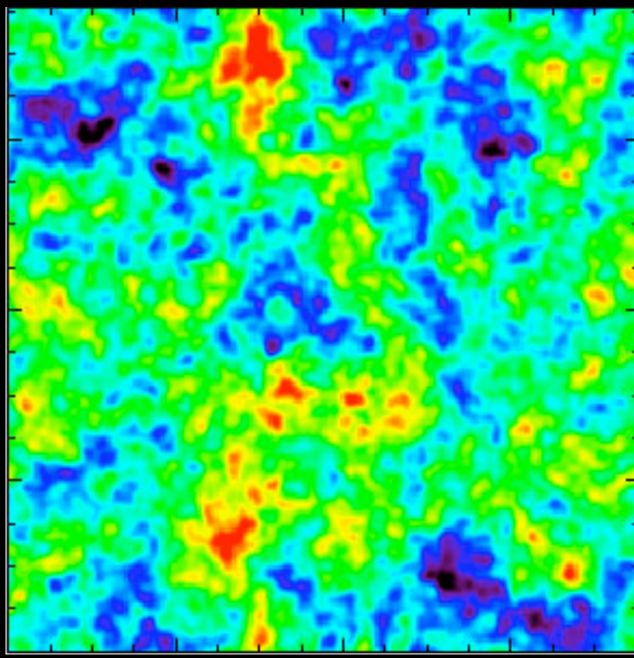


Credit: Vale, Amblard, White (2004)

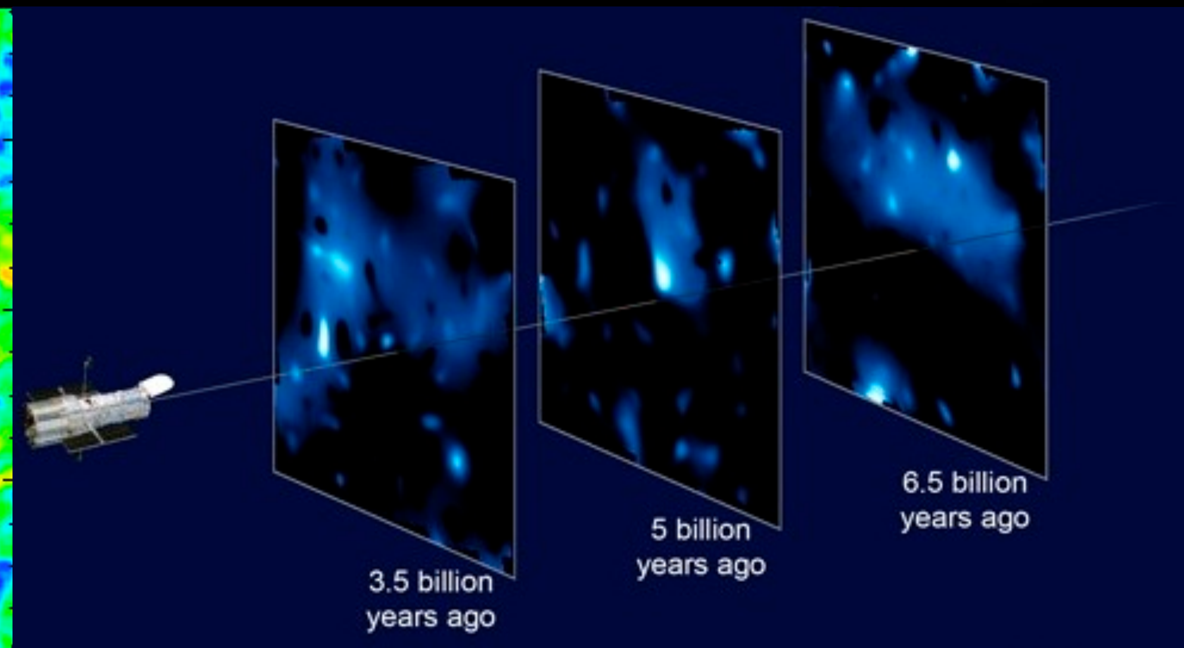
$$\tilde{\Theta}(\hat{\mathbf{n}}) = \Theta\left[\hat{\mathbf{n}} + \hat{\alpha}\right]$$
$$= \Theta\left[\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}})\right]$$



Weak Lensing of the Primary Bispectrum



Credit: Vale, Amblard, White (2004)



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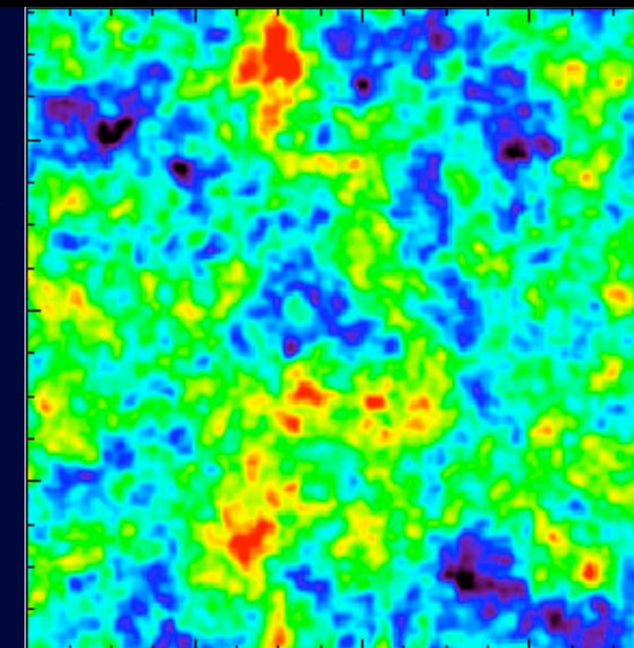
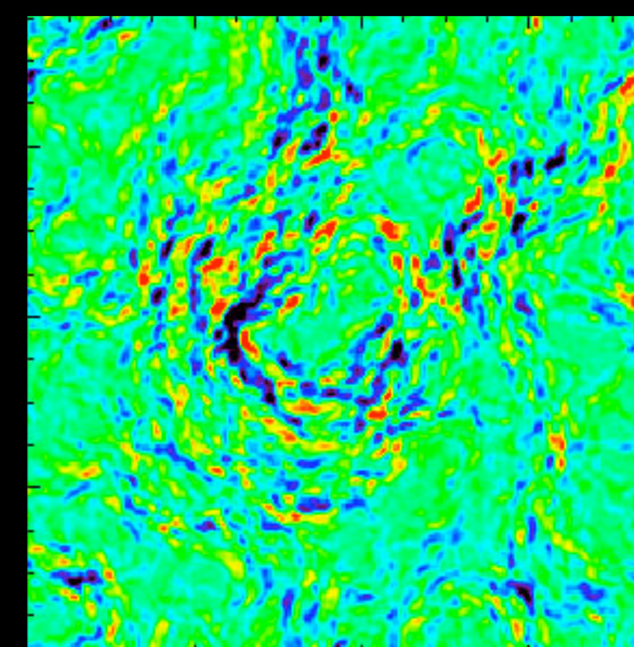
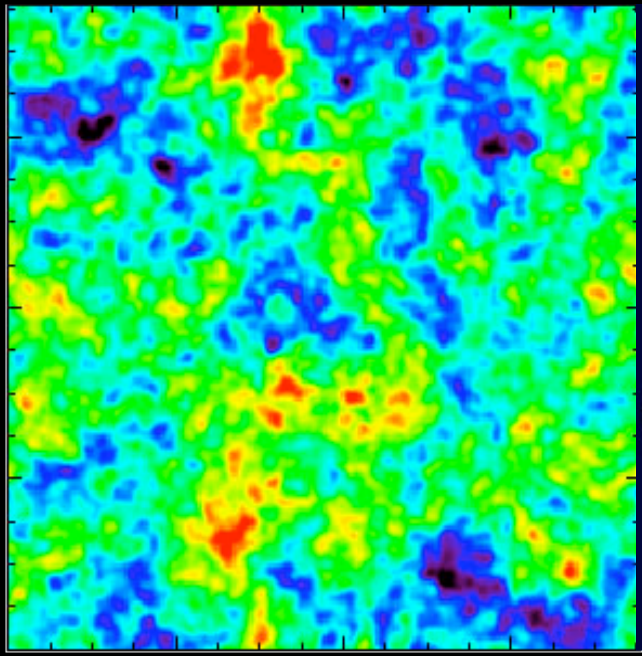


Credit: Vale, Amblard, White (2004)

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



Weak Lensing of the Primary Bispectrum



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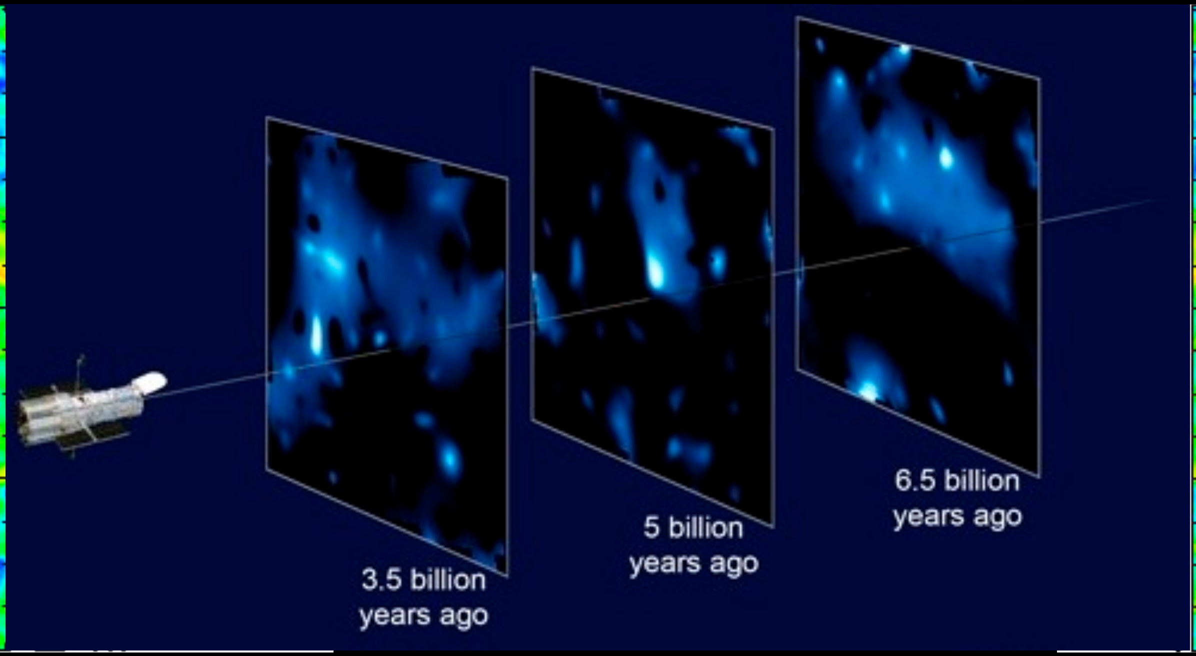

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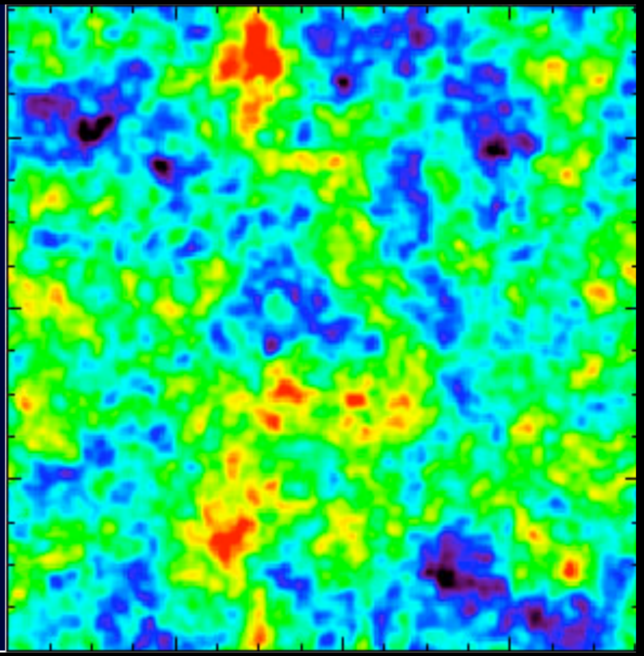

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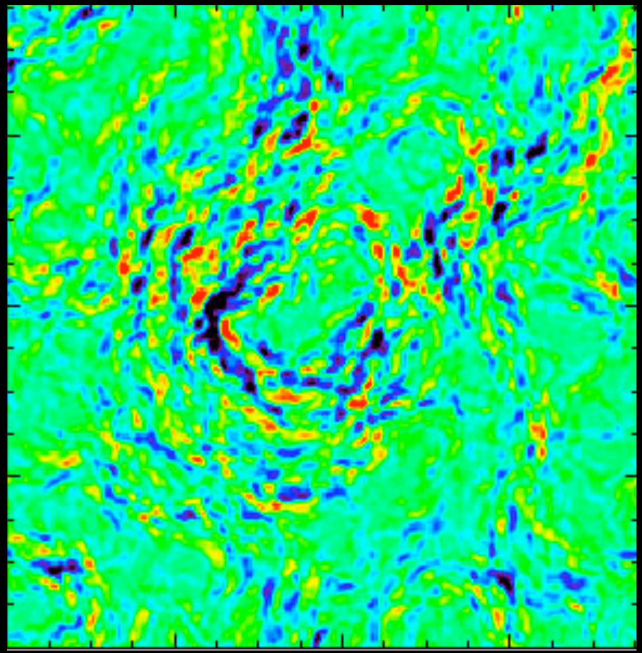
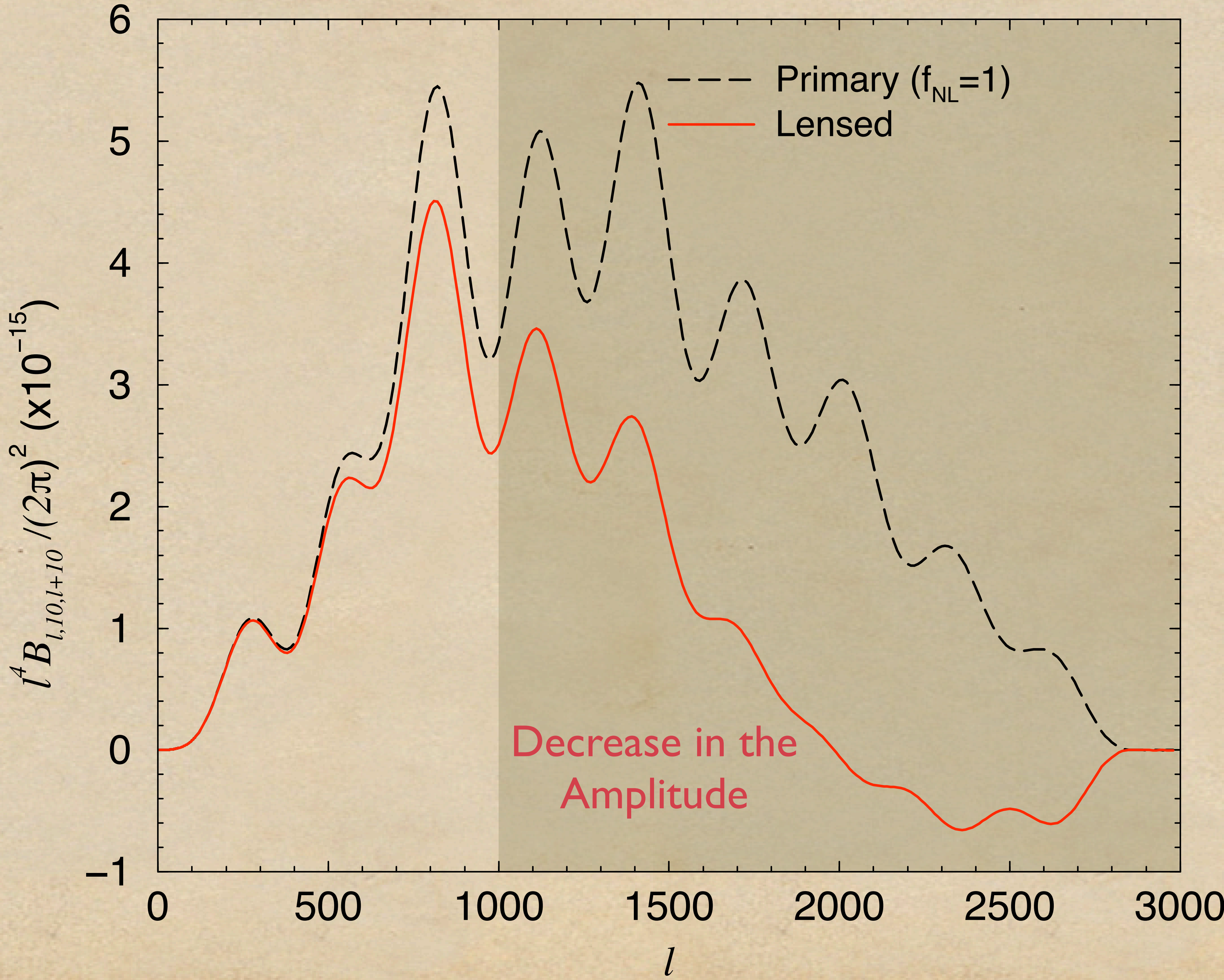


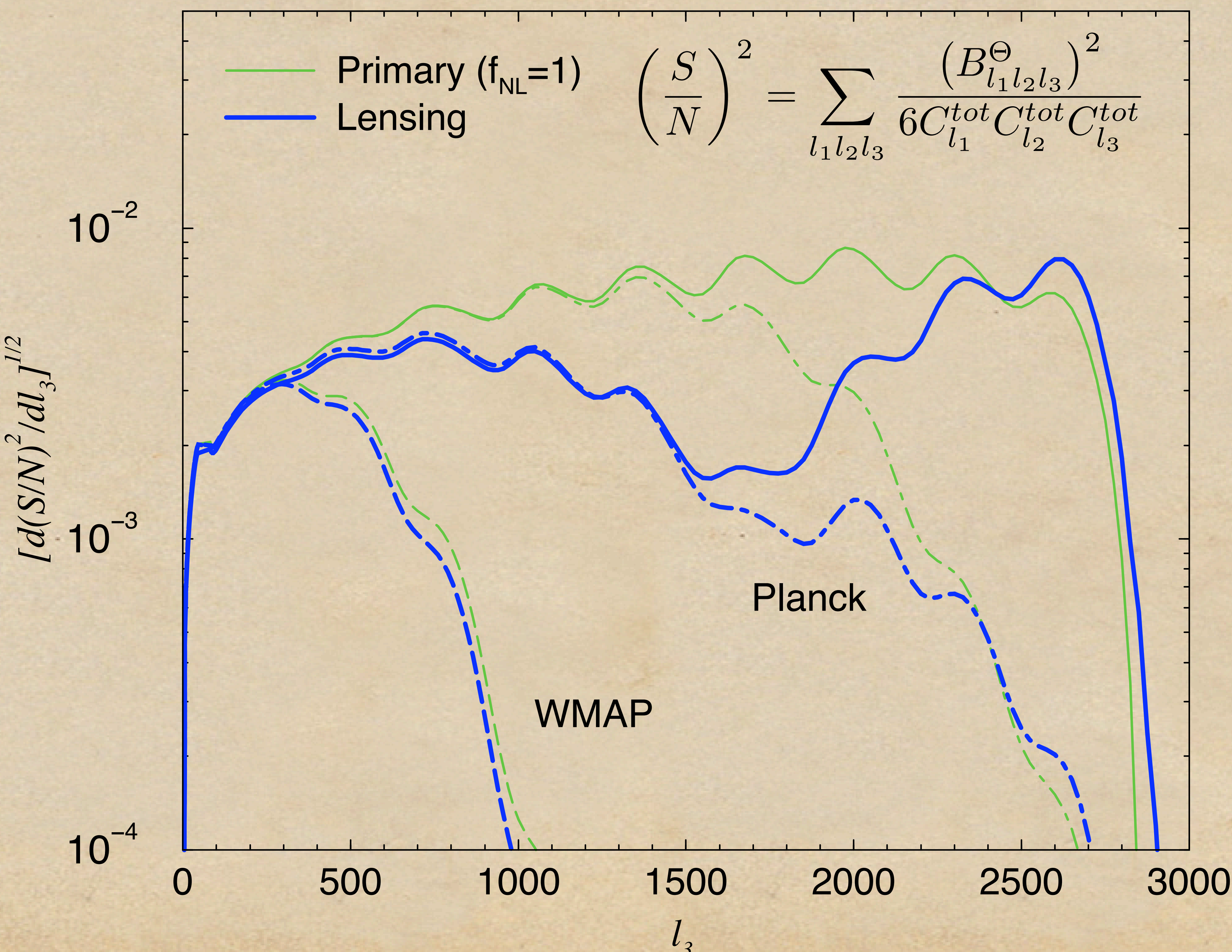
$$\tilde{B}^{\Theta}_{l_1 l_2 l_3} = \sum_{m_1 m_2 m_3} \begin{pmatrix} l_1 & l_2 & l_3 \\ m_1 & m_2 & m_3 \end{pmatrix} \langle \tilde{\Theta}_{l_1 m_1} \tilde{\Theta}_{l_2 m_2} \tilde{\Theta}_{l_3 m_3} \rangle$$

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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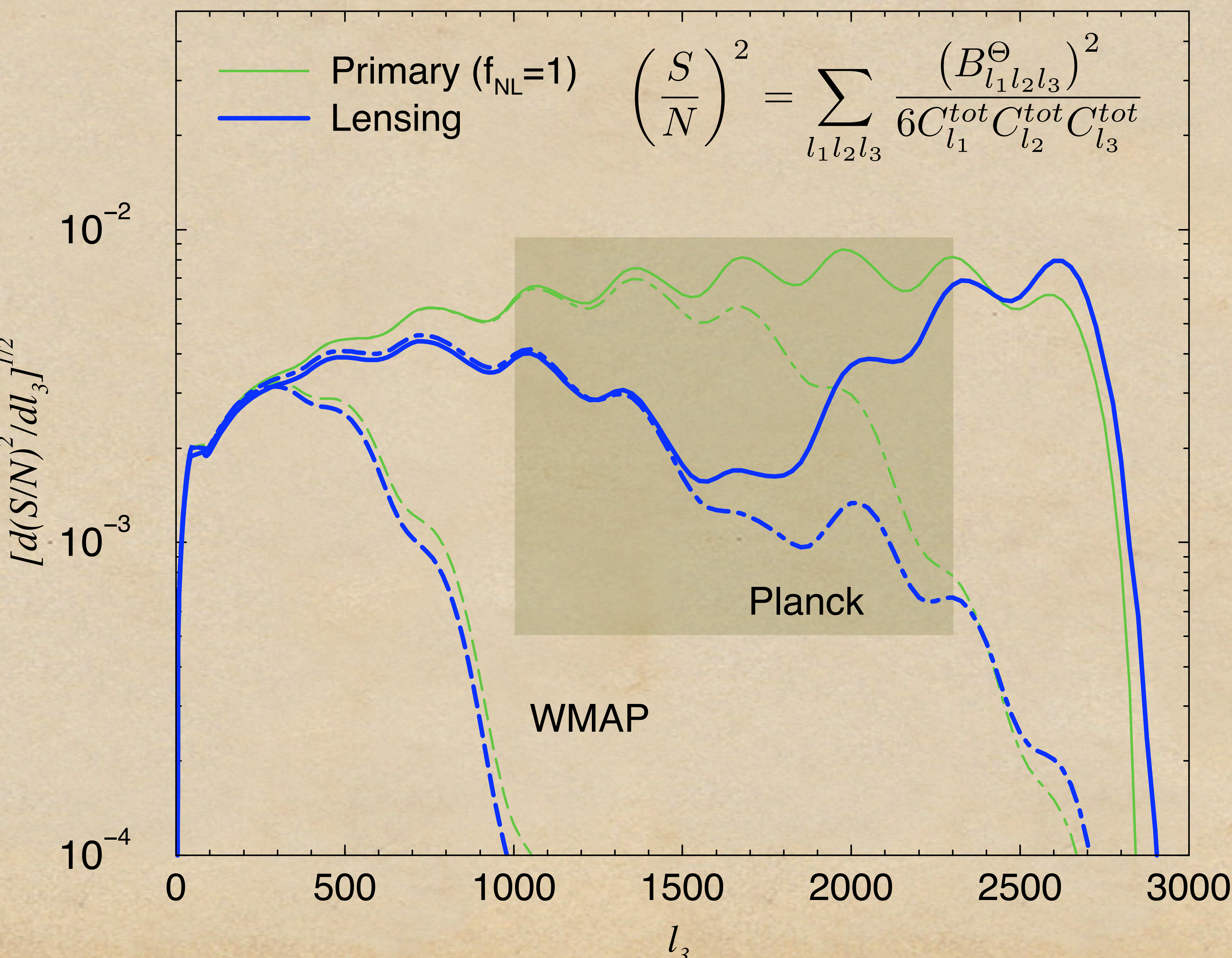
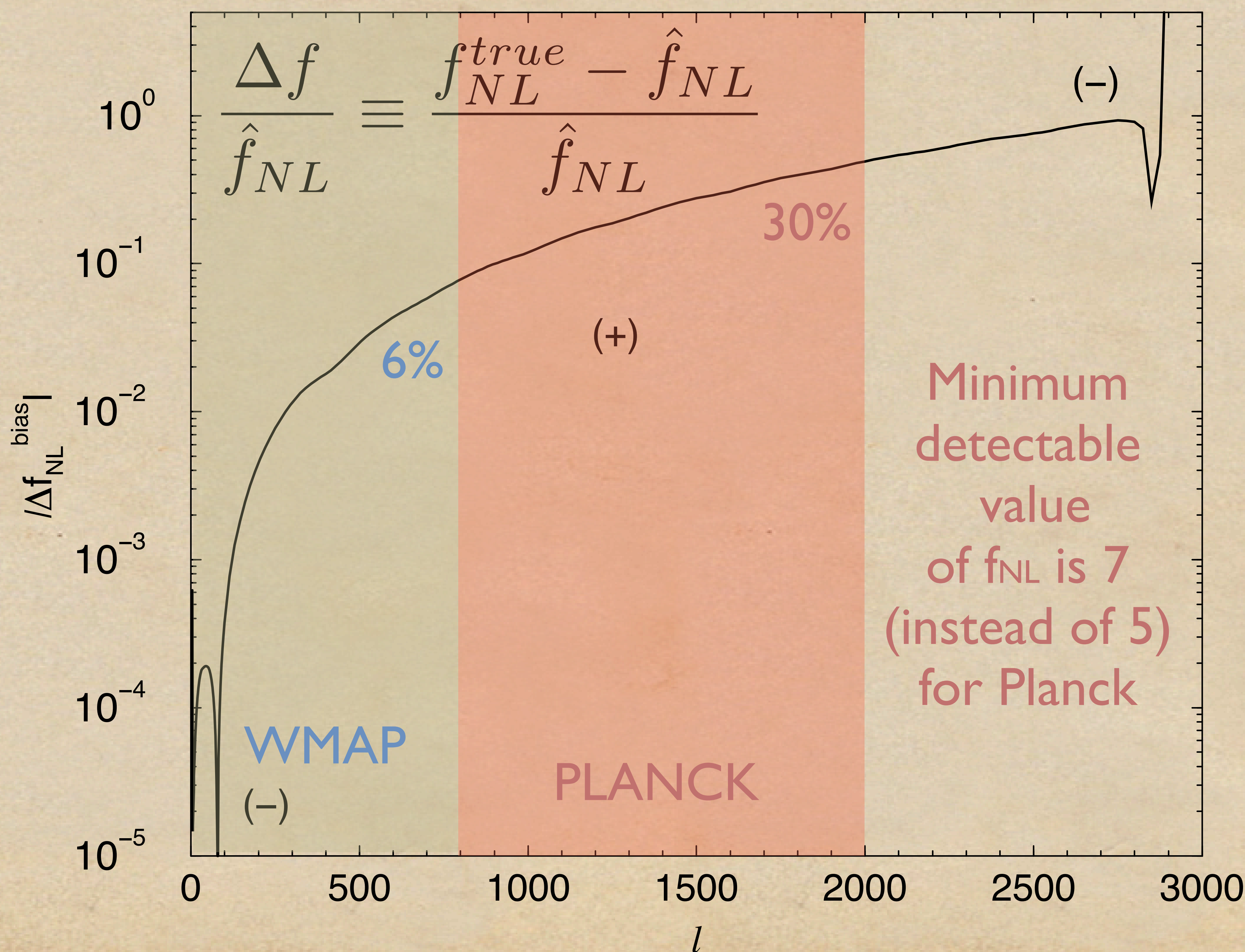


A. Cooray, D. Sarkar, and P. Serra; Phys. Rev. D, 77, 123006 (2008)

Bias in the non-Gaussian Parameter



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

Agenda

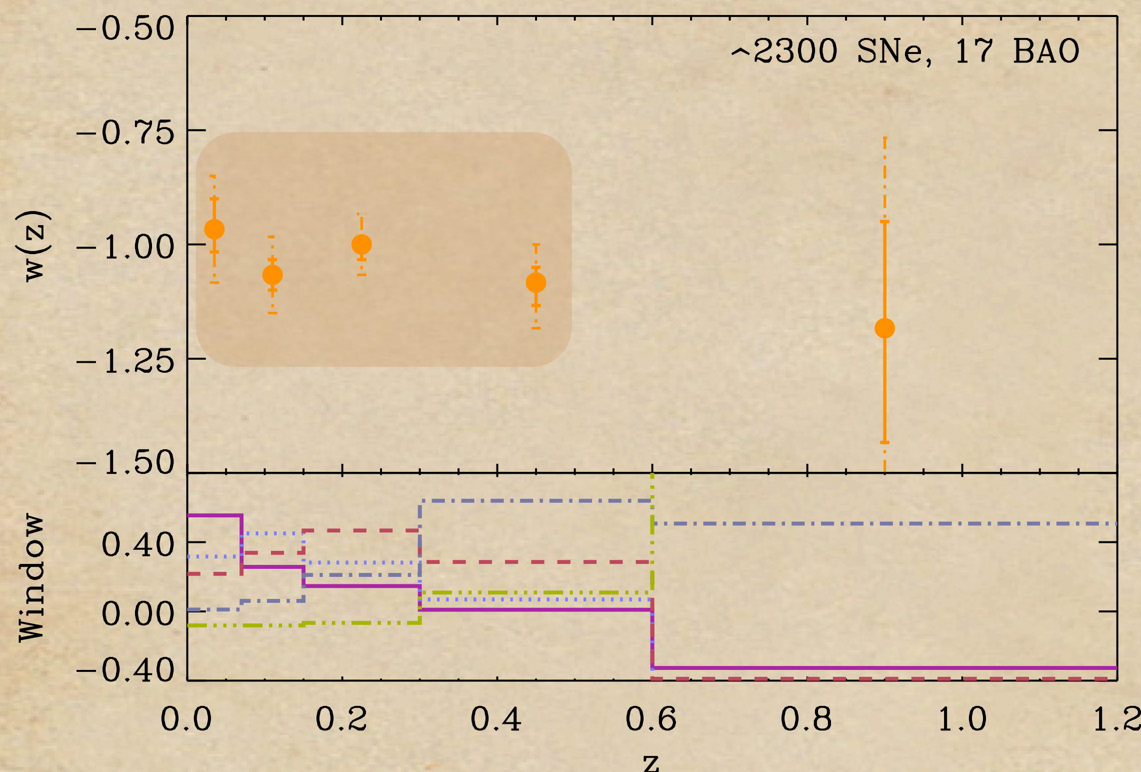
Theoretical Uncertainties in Dark Energy Measurements

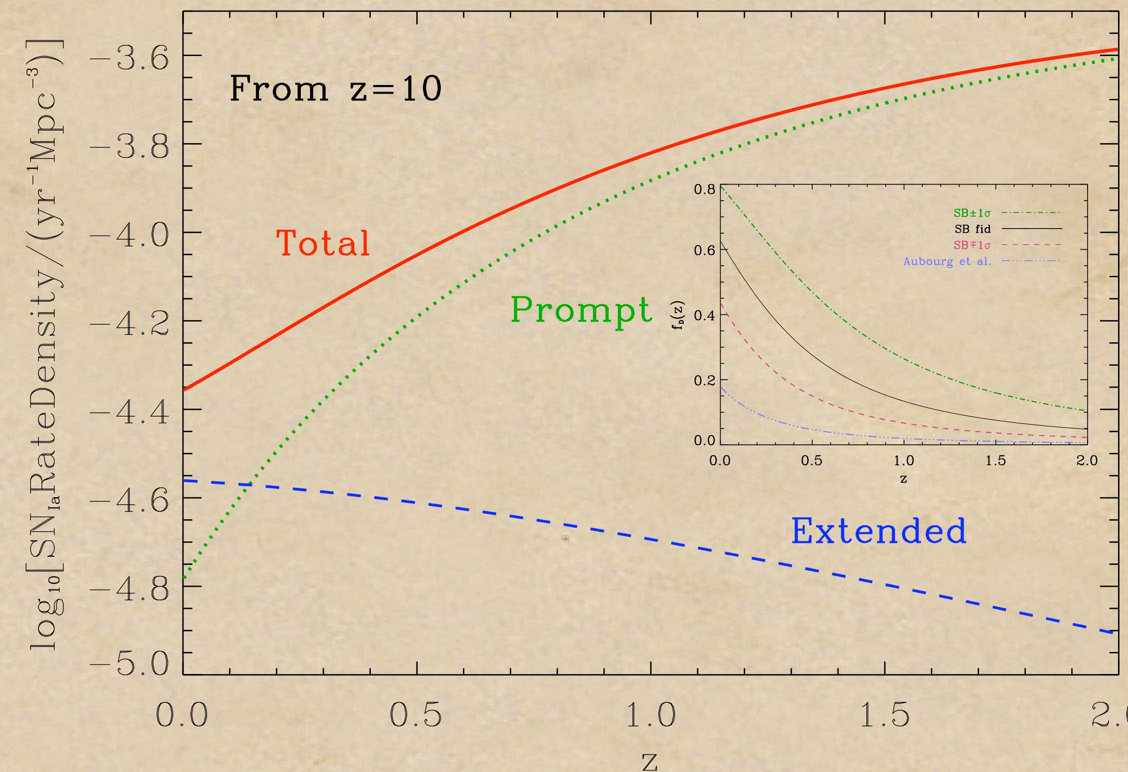
- Constraining the EOS
- To Bin or Not to Bin
- SNe Ia ++
- Lensing of SNe
- Other Worries

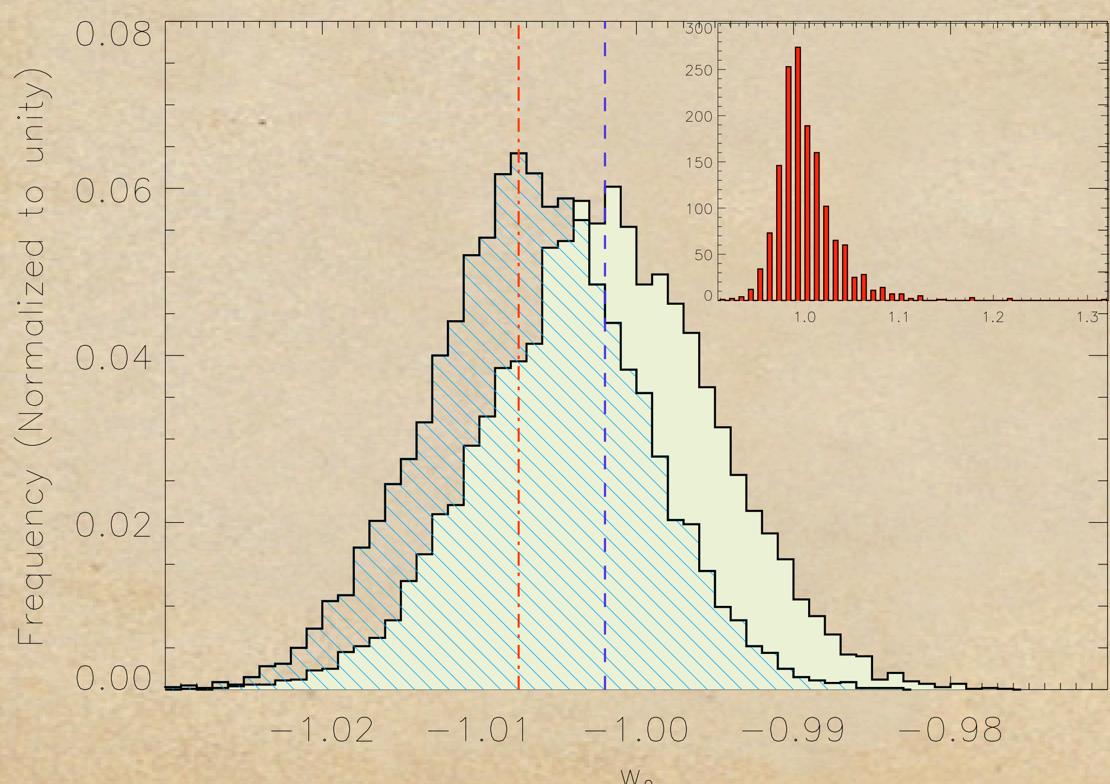
Primordial Non-Gaussianity and CMB Bispectrum

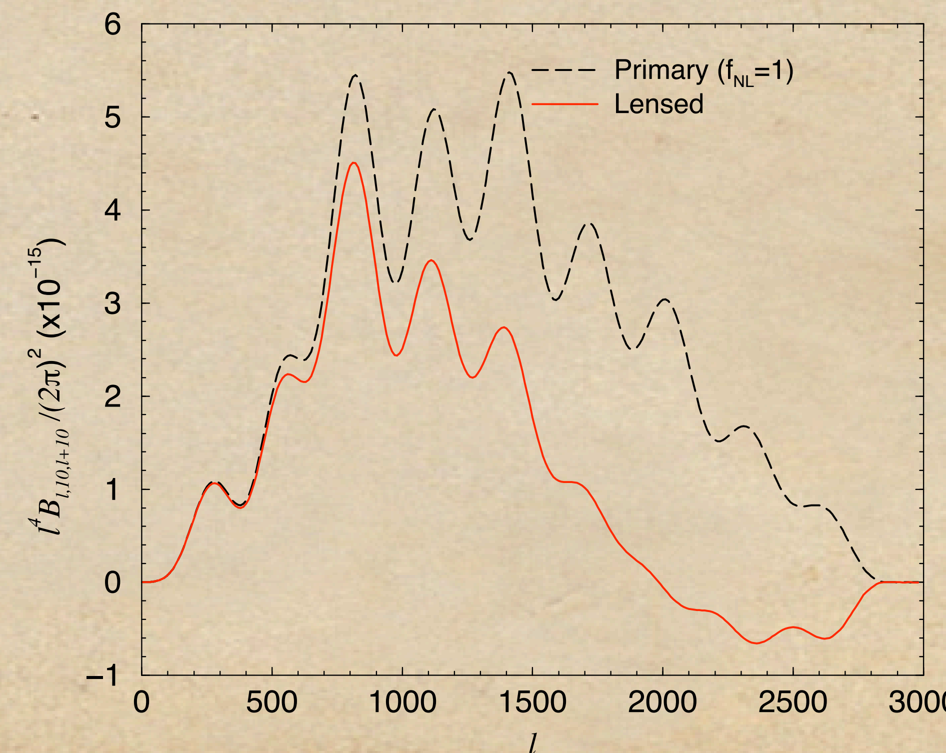
- Beyond Gaussianity
- CMB Bispectrum
- Lensing of CMB
- Lensed Bispectrum
- S/N Reduction & Bias

Summary


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

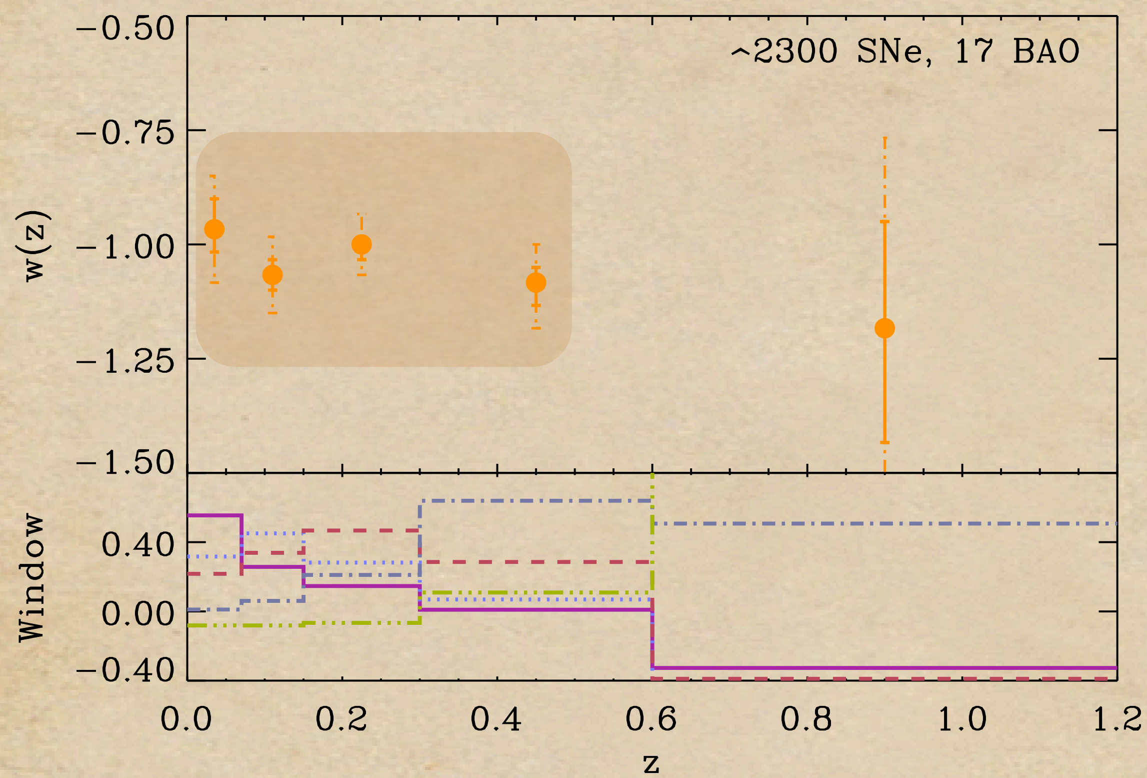

From z=10
Total
Prompt
Extended
log$_{10}$[SN$_{Ia}$RateDensity/(yr^{-1}Mpc^{-3})]
z
−3.6
−3.8
−4.0
−4.2
−4.4
−4.6
−4.8
−5.0
0.0
0.5
1.0
1.5
2.0
SB±1σ
SB fid
SB∓1σ
Aubourg et al.

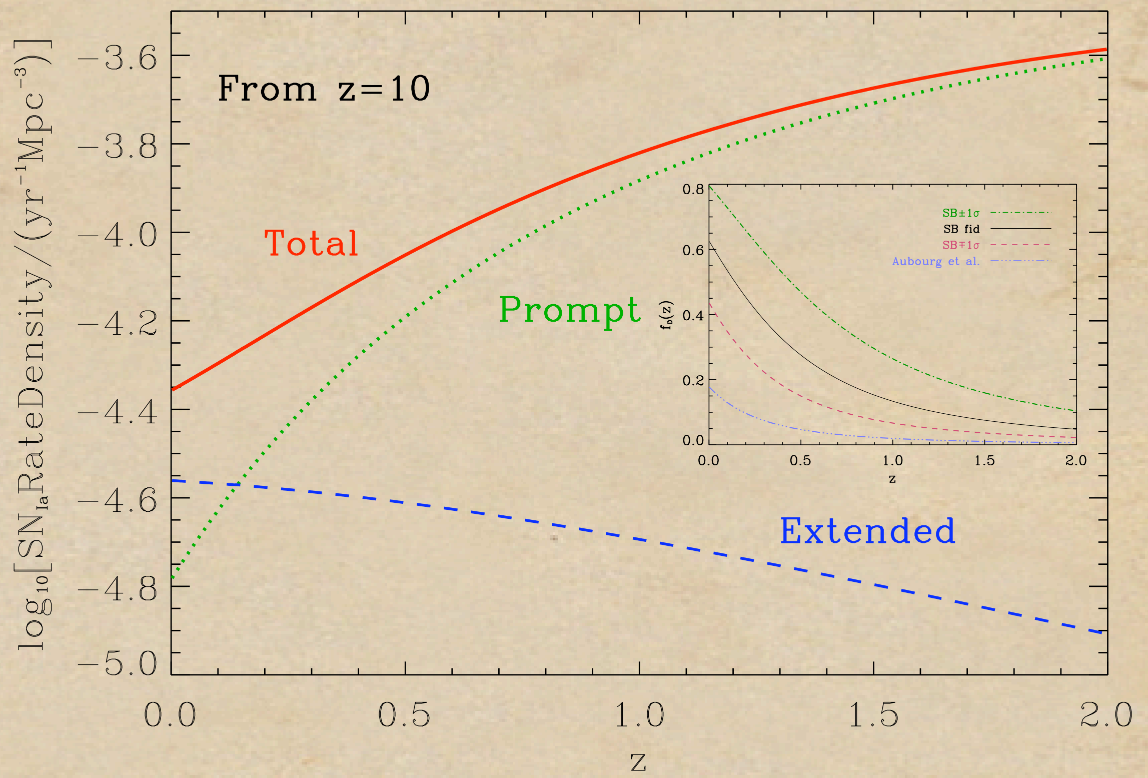

Frequency (Normalized to unity)
w$_0$
0.08
0.06
0.04
0.02
0.00
−1.02
−1.01
−1.00
−0.99
−0.98

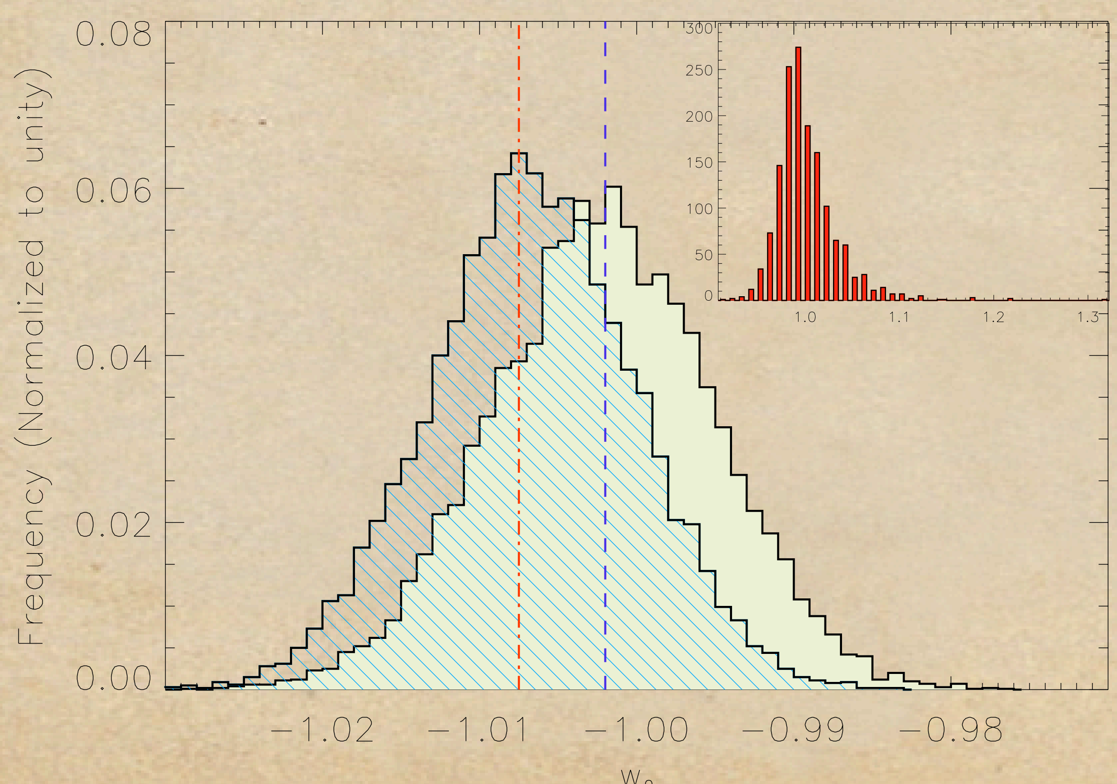

Primary (f$_{NL}$=1)
Lensed
$l^4 B_{l,10,l+10}/(2\pi)^2$ (x10^{-15})
l
6
5
4
3
2
1
0
−1
0
500
1000
1500
2000
2500
3000

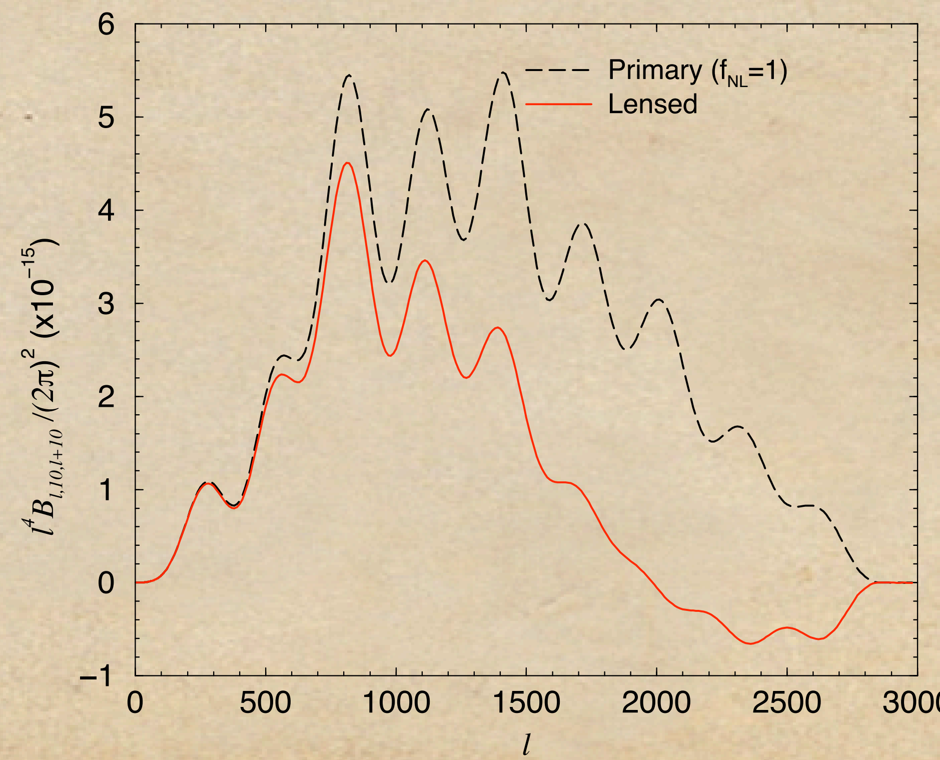
DSARKAR.ORG

Summary









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