At the Party with the Physicists (and some non-)...

- Coulomb got a real charge out of the whole thing.
- Einstein thought it was a relatively good time
- Cauchy, being the mathematician, still managed to integrate well with everyone.
- Thompson enjoyed the plum pudding.
- Pascal was under too much pressure to enjoy himself.
- Ohm spent most of the time resisting Ampere's opinions on current events.
- Volta thought the social had a lot of potential.
- Hilbert was pretty spaced out for most of it.
- Heisenberg may or may not have been there.
- Feynman got from the door to the buffet table by taking every possible path.
- van der Waals forced himself to mingle.
- Millikan dropped his Italian oil dressing.
- de Broglie mostly just stood in the corner and waved.
- Hollerith liked the hole idea.
- Stefan and Boltzman got into some hot debates.

http://www.physlink.com/fun/PhysicsParty.cfm

At the Party with the Physicists (and some non-)...

- Compton was a little scatter-brained at times.
- Watt turned out to be a powerful speaker.
- Hertz went back to the buffet table several times a minute.
- Faraday had quite a capacity for food.
- The microwave started radiating in the background when Penzias and Wilson showed up.
- Instead of coming through the front door Josephson tunnelled through.
- Shakespeare could not decide whether to be or not to be at the party.
- Witten bought a present all tied up with superstrings.
- The food was beautifully laid out by Mendeleyev on the periodic table.
- Maxwell's demon argued with Dawkin's friend, the selfish Gene.
- Rontgen saw through everybody.
- After one bite Chandrasekhar reached his limit.
- Gamow left the party early with a big bang while Hoyle stayed late in a steady state.

http://www.physlink.com/fun/PhysicsParty.cfm

Prospects for 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 Santa Barbara Astrophysics Seminar November 12, 2008

Outline

Outline

Start With...

Dark Energy

- Why Pursue Dark Energy?
- DE Equation of State (EOS)
- DE from SNe Ia ++
- Beware of Systematics
  - Two Population Model
  - Gravitational Lensing

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And Then...

CMB Bispectrum

- Why Non-Gaussianity?
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- The f_{NL}
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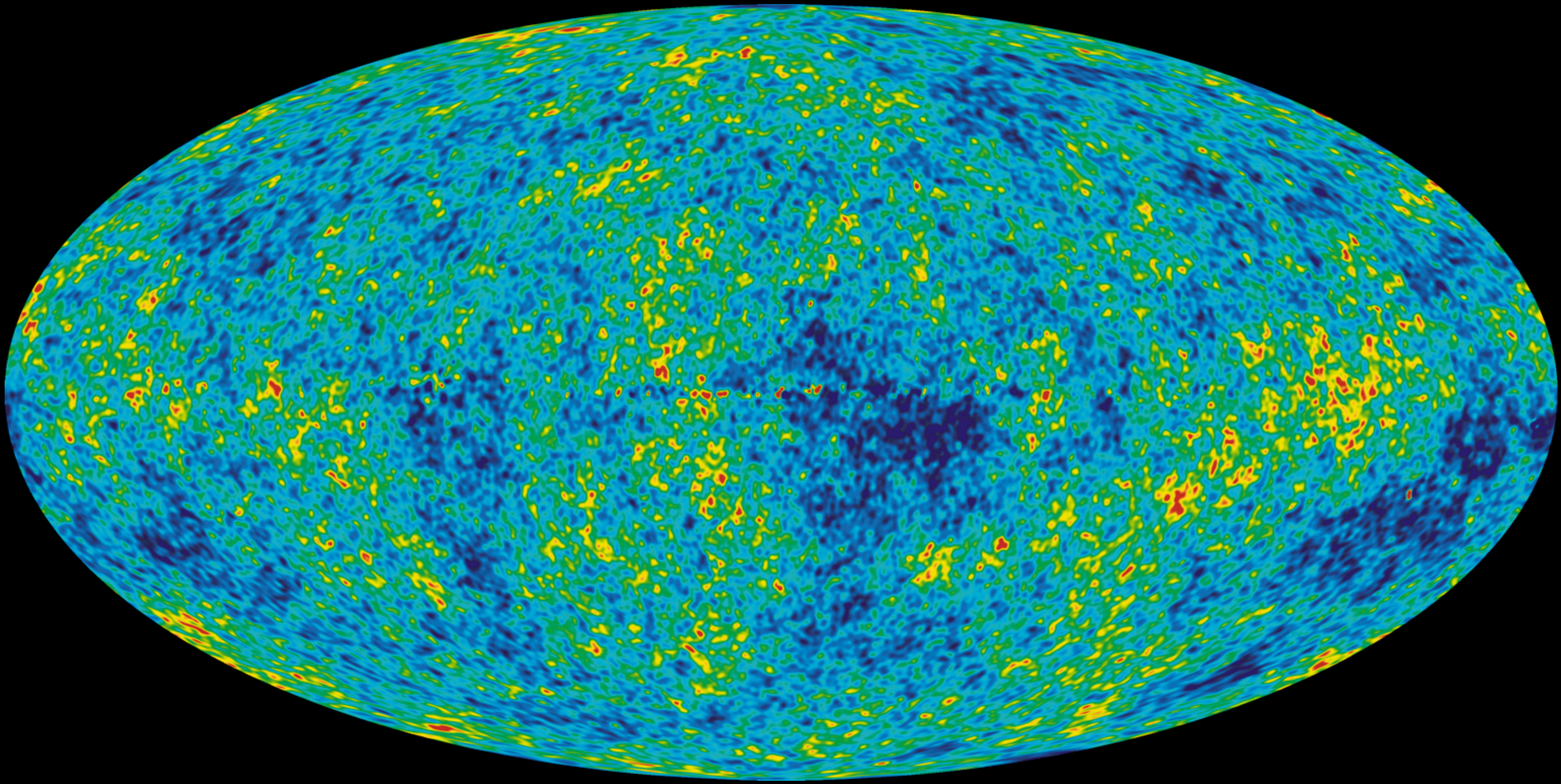
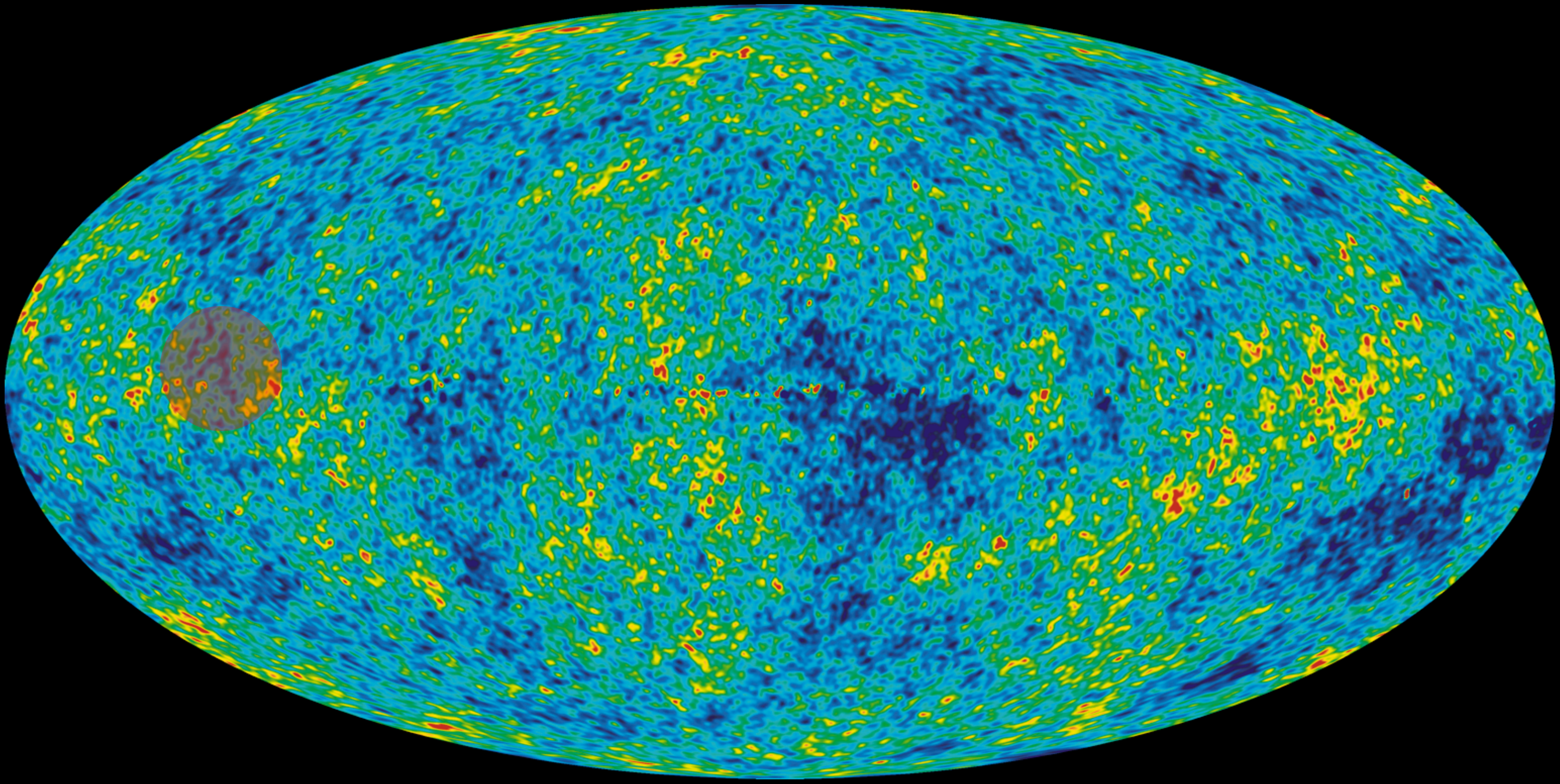
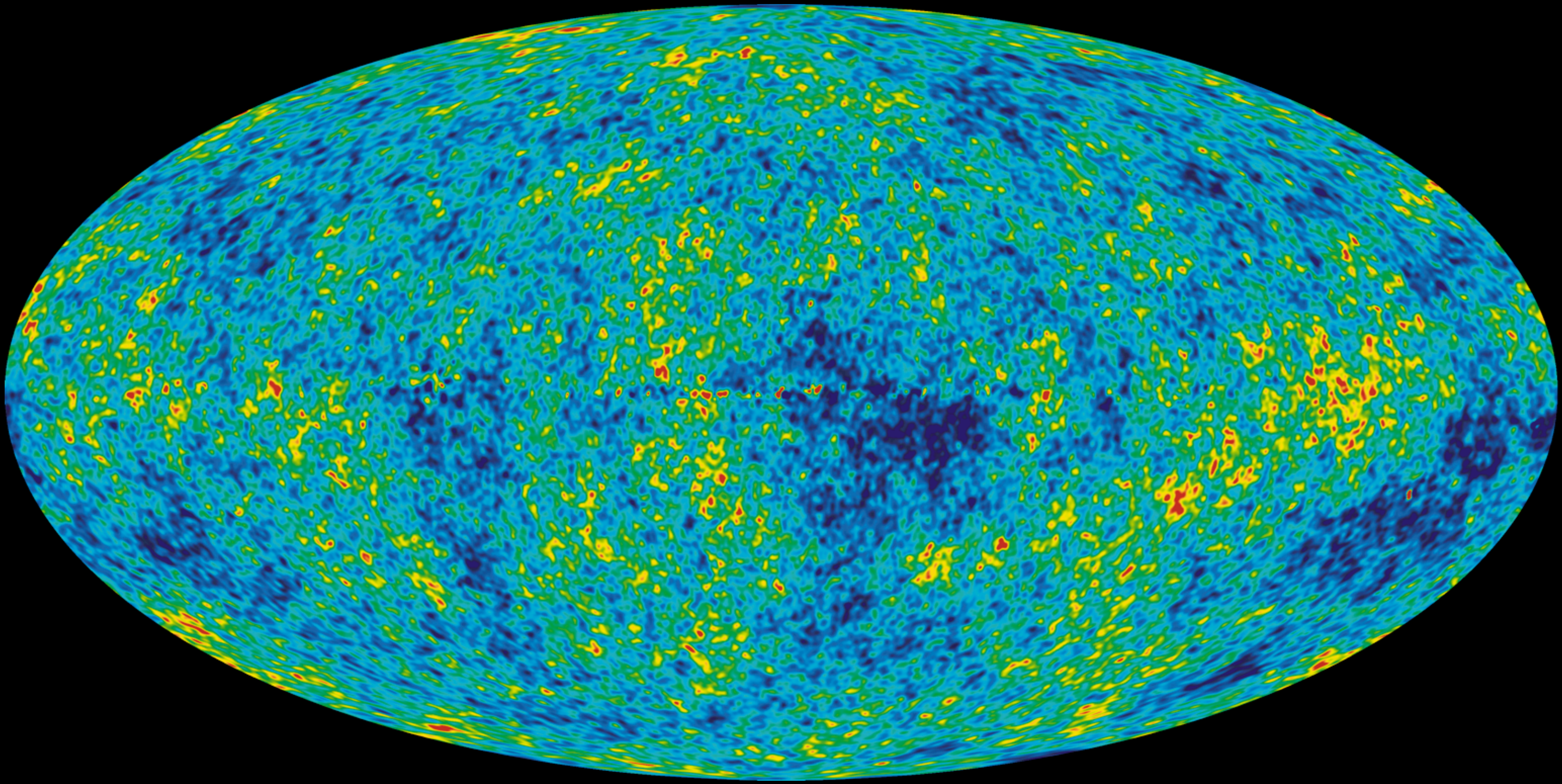

Credit: NASA/WMAP Science Team



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
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C. Lidman
European Southern Observatory, La Silla, Chile

R. S. Ellis, M. Irwin, and R. G. McMahon
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P. Ruiz-Lapuente
Department of Astronomy, University of Barcelona, Barcelona, Spain

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Isaac Newton Group, La Palma, Spain

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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

THE ASTROPHYSICAL JOURNAL, 607:665–687, 2004 June 1

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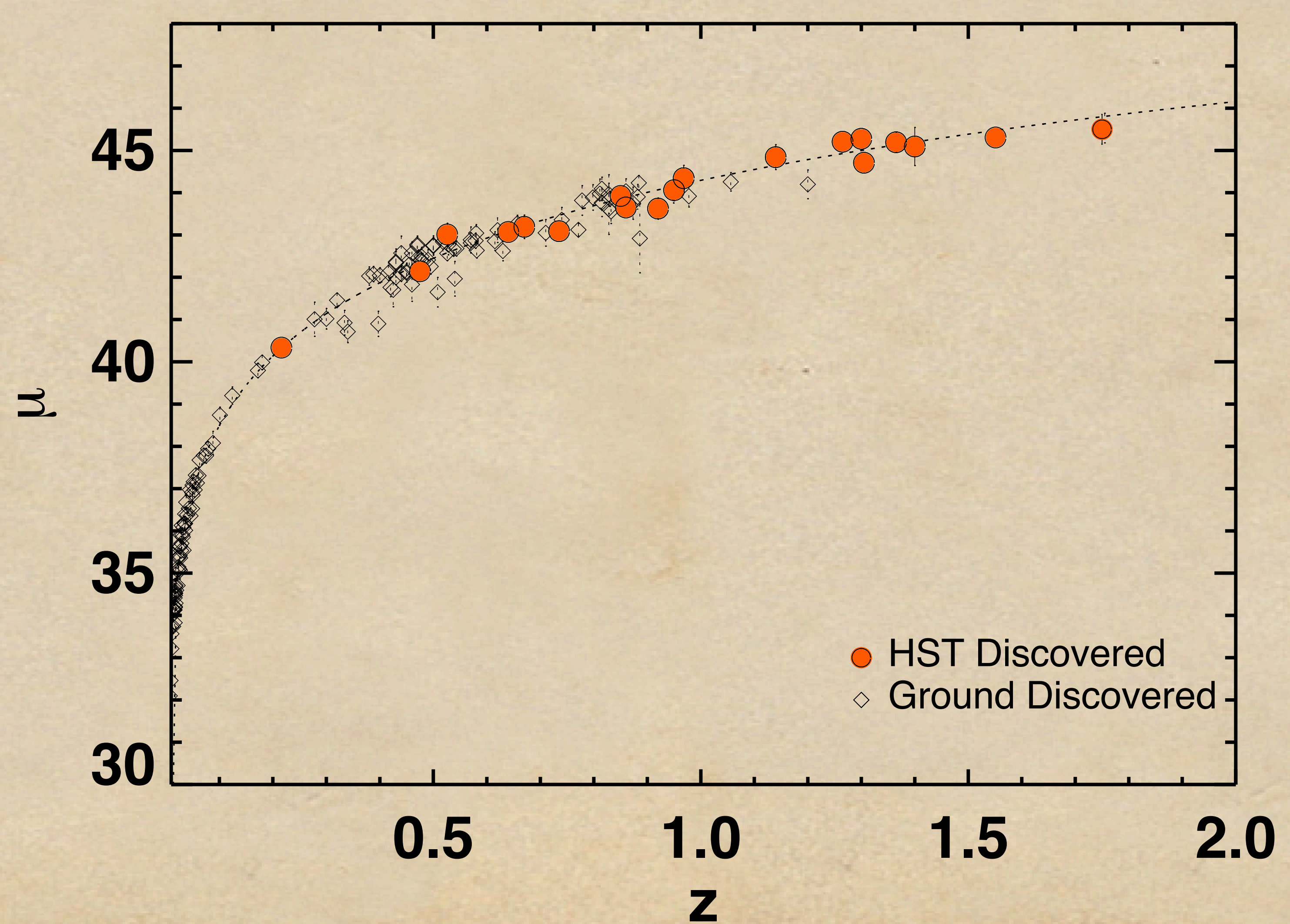

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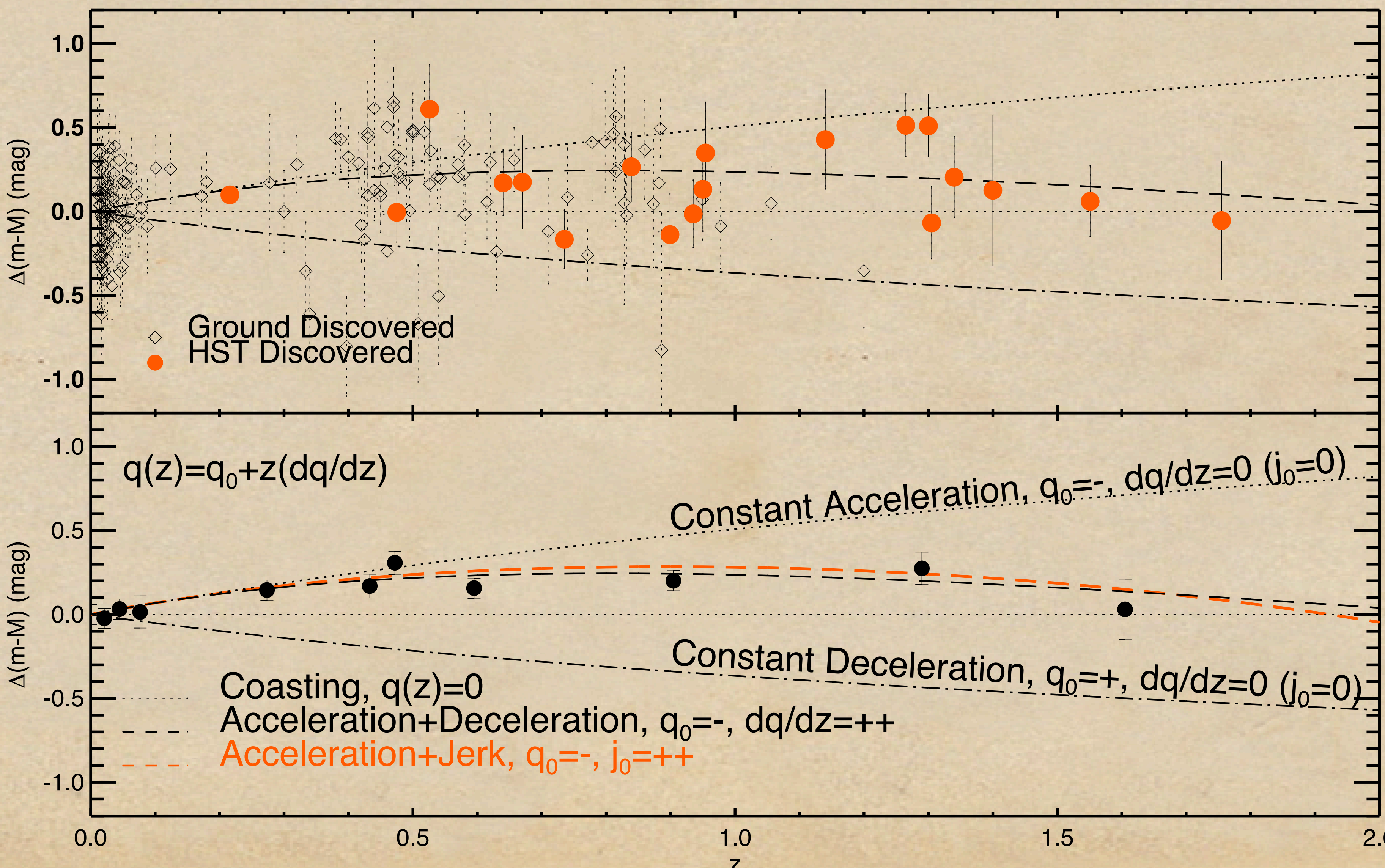


Cosmic Acceleration

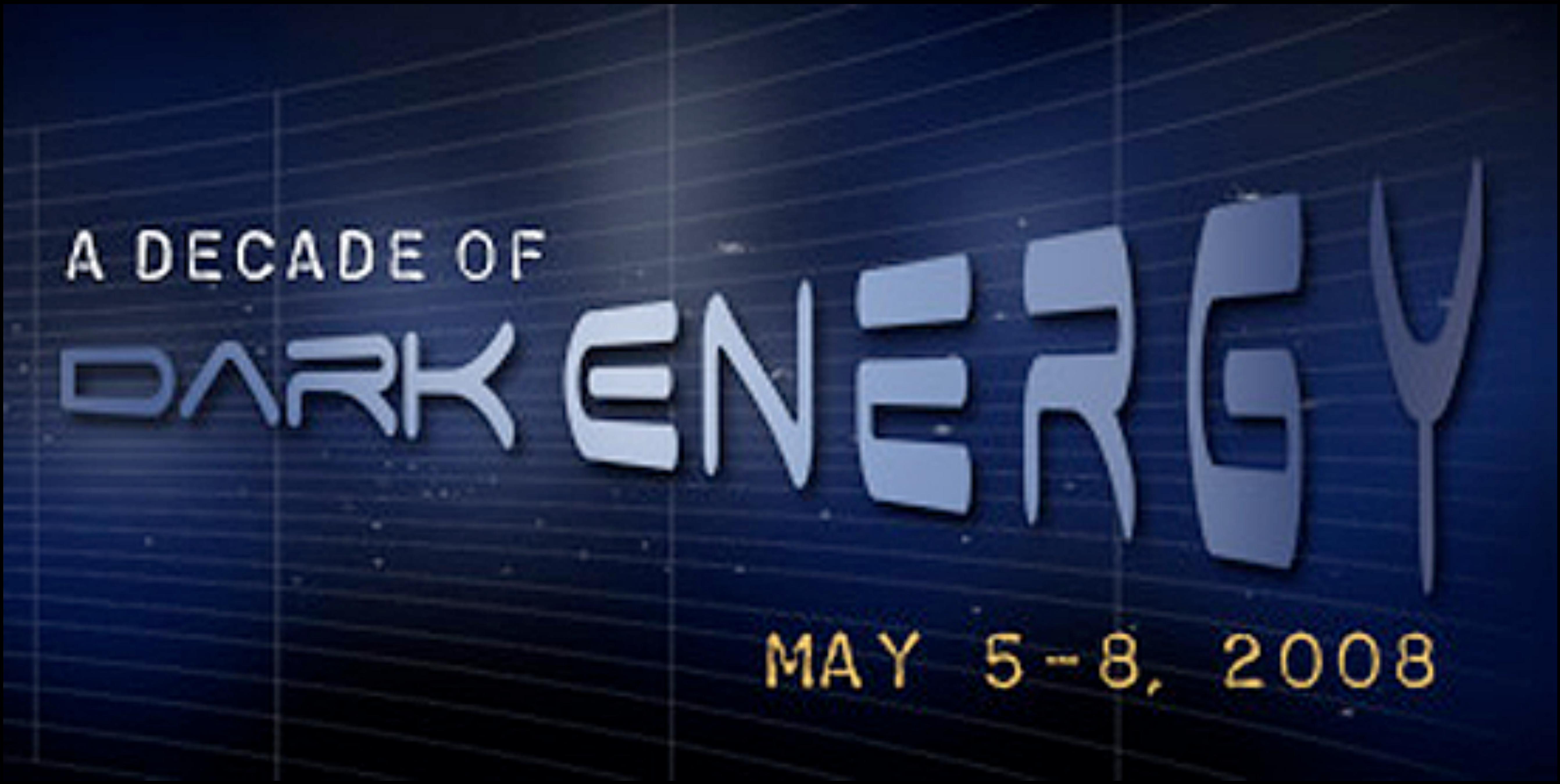
Modified Gravity ⟷ Dark Energy

$$H^2 - \boxed{\frac{H}{r_c}} = \frac{8\pi G}{3}(\rho + \rho_V)$$

Modified Gravity	Dark Energy
Modification of Friedmann equation (5D Gravity)	Vacuum Energy (Cosmological Constant)
Phenomenological modification to the GR Lagrangian	Scalar Fields Evolving Equation of State

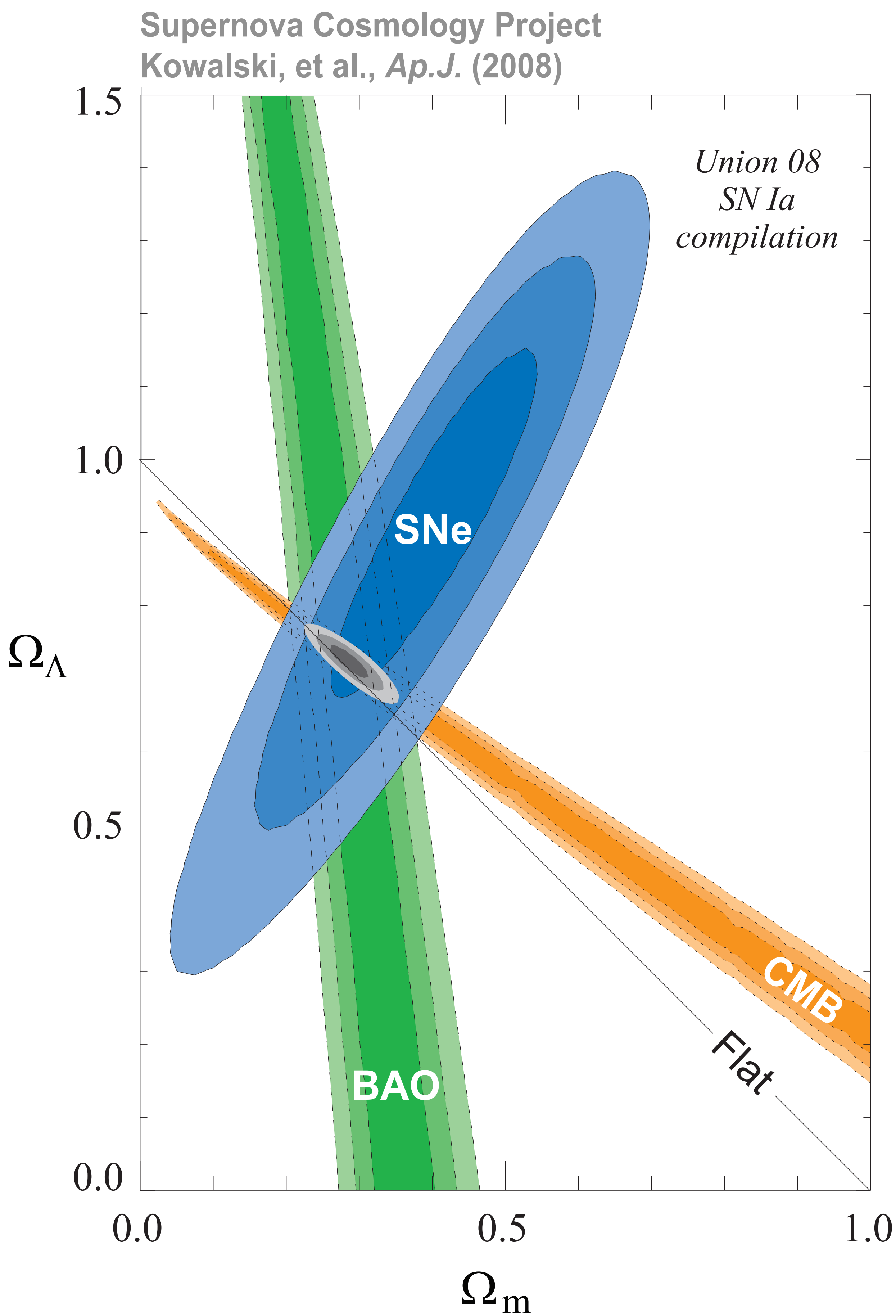
New Physics/Surprises?

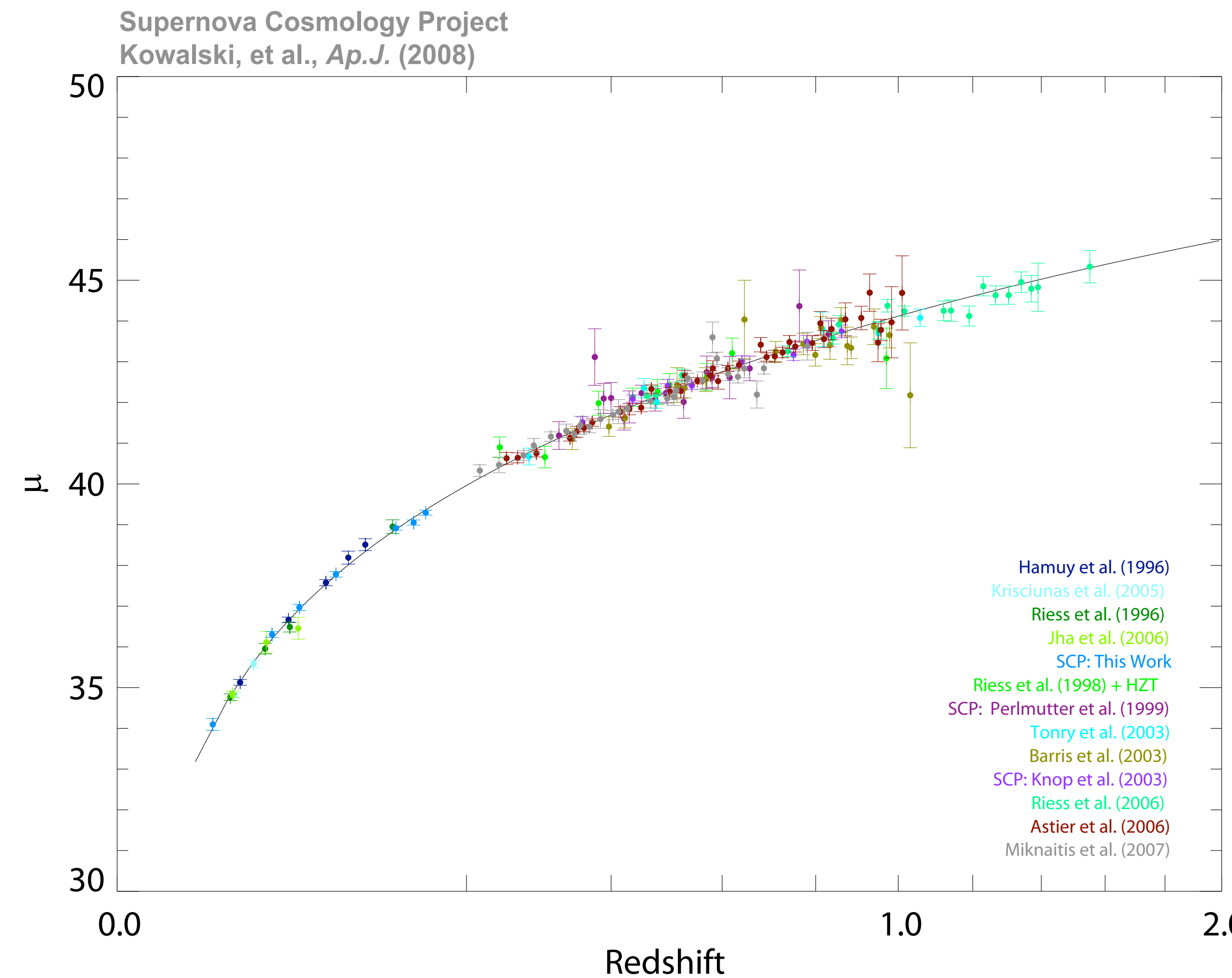
Where Do We Stand?
After...

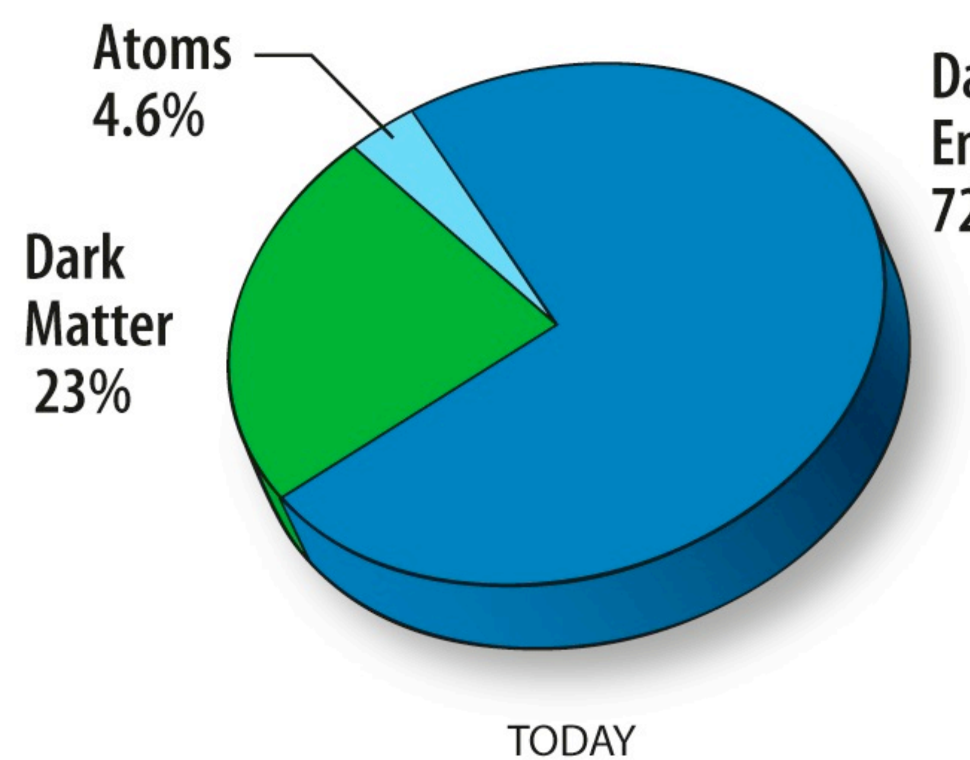


Space Telescope Science Institute, Baltimore, MD

$$\Omega_\Lambda = 0.713^{+0.027}_{-0.029}(\mathrm{stat})^{+0.036}_{-0.039}(\mathrm{sys})$$







WMAP

What is Dark Energy?

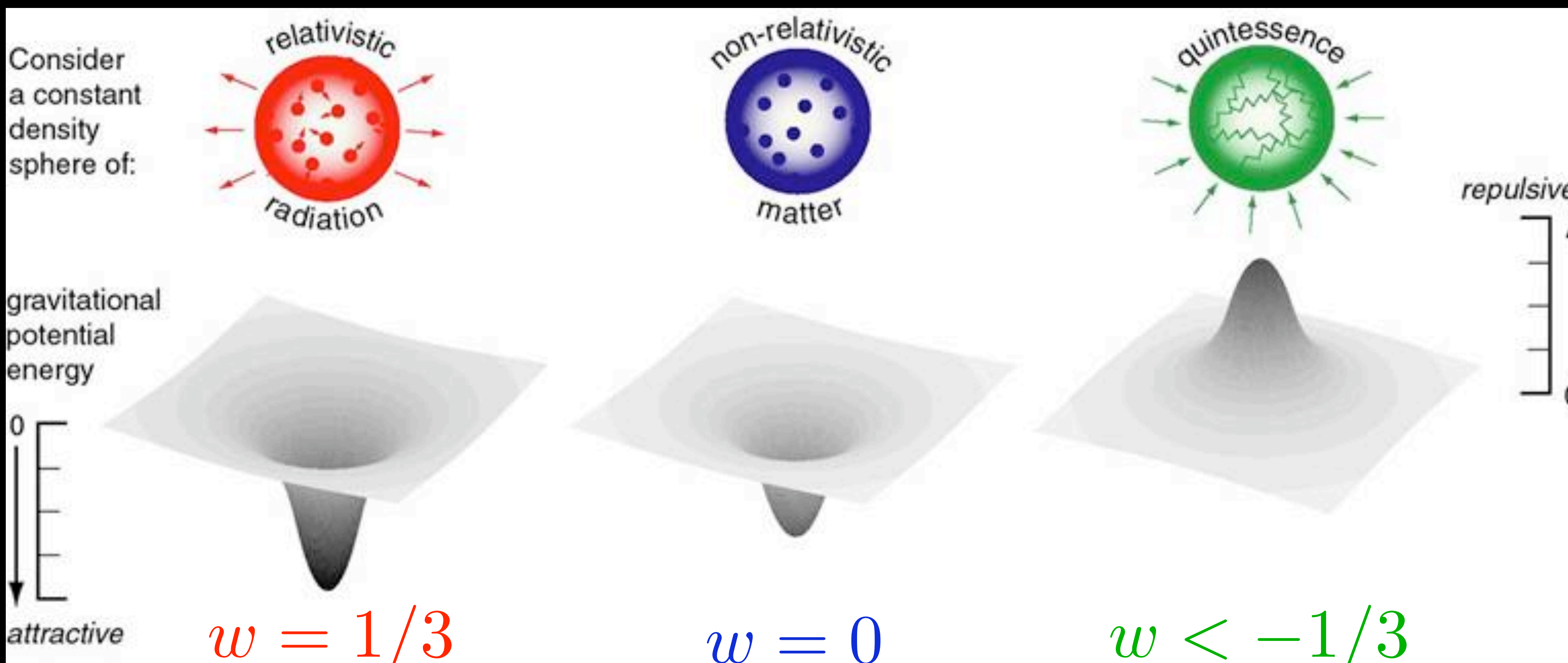
What is Dark Energy?

"Dark Energy is made from an exclusive blend of vital L-amino acids, beneficial vitamins and bionutrients that allows faster and greater ion penetration of the cell walls, visibly enhancing the rate of growth"

GrowLightSource.com

Dark Energy Equation Of State

$$T^{\nu}_{\mu} = diag(\rho, -p, -p, -p) \qquad p = w\rho$$



For Cosmological Constant... $w = -1$

"Seeing" The Dark Energy

...via its effect on the expansion of the Universe

$$H(z) = H_0 \left[\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + (1-\Omega_k-\Omega_m)F(z)\right]^{1/2}$$

"Seeing" The Dark Energy

...via its effect on the expansion of the Universe

$$H(z) = H_0 \left[\Omega_m (1+z)^3 + \Omega_k (1+z)^2 + (1 - \Omega_k - \Omega_m) F(z)\right]^{1/2}$$

$$F(z) = \exp\left(3 \int_0^z dz' \frac{1 + w(z')}{1 + z'}\right)$$

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$$H(z) = H_0 \left[\Omega_m (1+z)^3 + \Omega_k (1+z)^2 + (1 - \Omega_k - \Omega_m) F(z) \right]^{1/2}$$

$$F(z) = \exp\left(3 \int_0^z dz' \frac{1 + w(z')}{1 + z'} \right)$$

Approaches...

- Standard Candles: Luminosity Distance of SNe
- Standard Rulers:
  - Angular Diameter Distance via BAO
  - Distance to the Last Scattering Surface
- Weak Lensing Tomography

DE EOS Revisited: Different Approaches...

(A) Parameterize w(z) [Adopted by the DETF]

$$\boxed{w(a) = w_0 + (1 - a)w_a}$$

Chevallier & Polarski (2001)
(Linder 2003)

DE EOS Revisited: Different Approaches...

(A) Parameterize w(z) [Adopted by the DETF]

$$\boxed{w(z) = w_0 + w_a z/(1+z)}$$

Chevallier & Polarski (2001)
(Linder 2003)

DE EOS Revisited: Different Approaches...

(A) Parameterize w(z) [Adopted by the DETF]

$$\boxed{w(z) = w_0 + w_a z/(1+z)}$$

Chevallier & Polarski (2001)
(Linder 2003)

(B) Non-Parametric w(z)

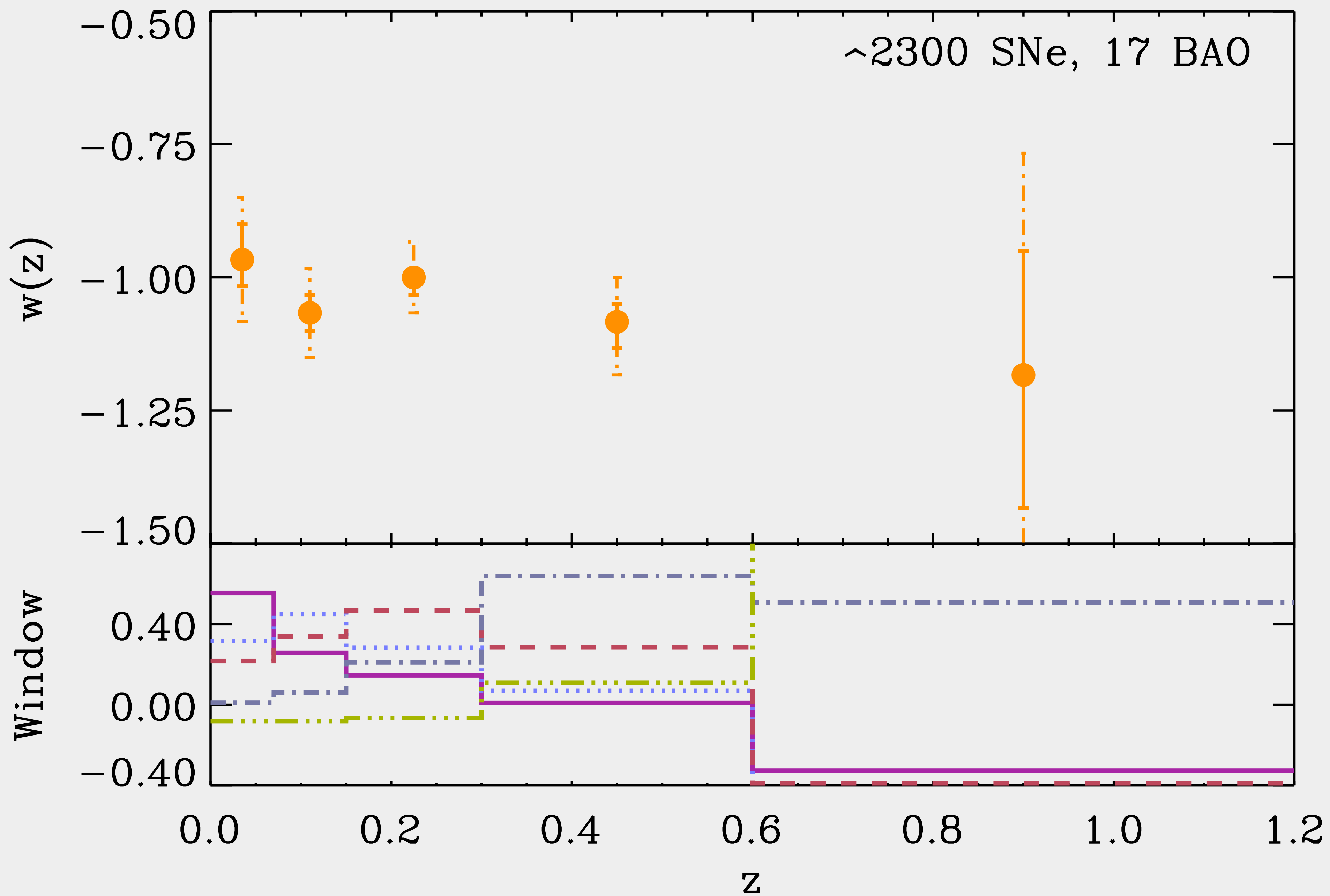
✓Unbiased Estimate of DE Density (Wang & Lovelace 2001)
✓Principal Component Approach (Huterer & Starkman 2003)
✓Uncorrelated Estimates (Huterer & Cooray 2005)

✓...

For a review: Please see Sahni and Starobinsky (2006) [arXiv:astro-ph/0610026]

Binned Estimates: Future

$$F(z_n > z > z_{n-1}) = (1+z)^{3(1+w_n)} \prod_{i=0}^{n-1} (1+z_i)^{3(w_i - w_{i+1})}$$



w_1	0-.07
w_2	.07-.15
w_3	0.15-.3
w_4	0.3-0.6
w_5	0.6-1.2
w_6	1.2-2.0

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

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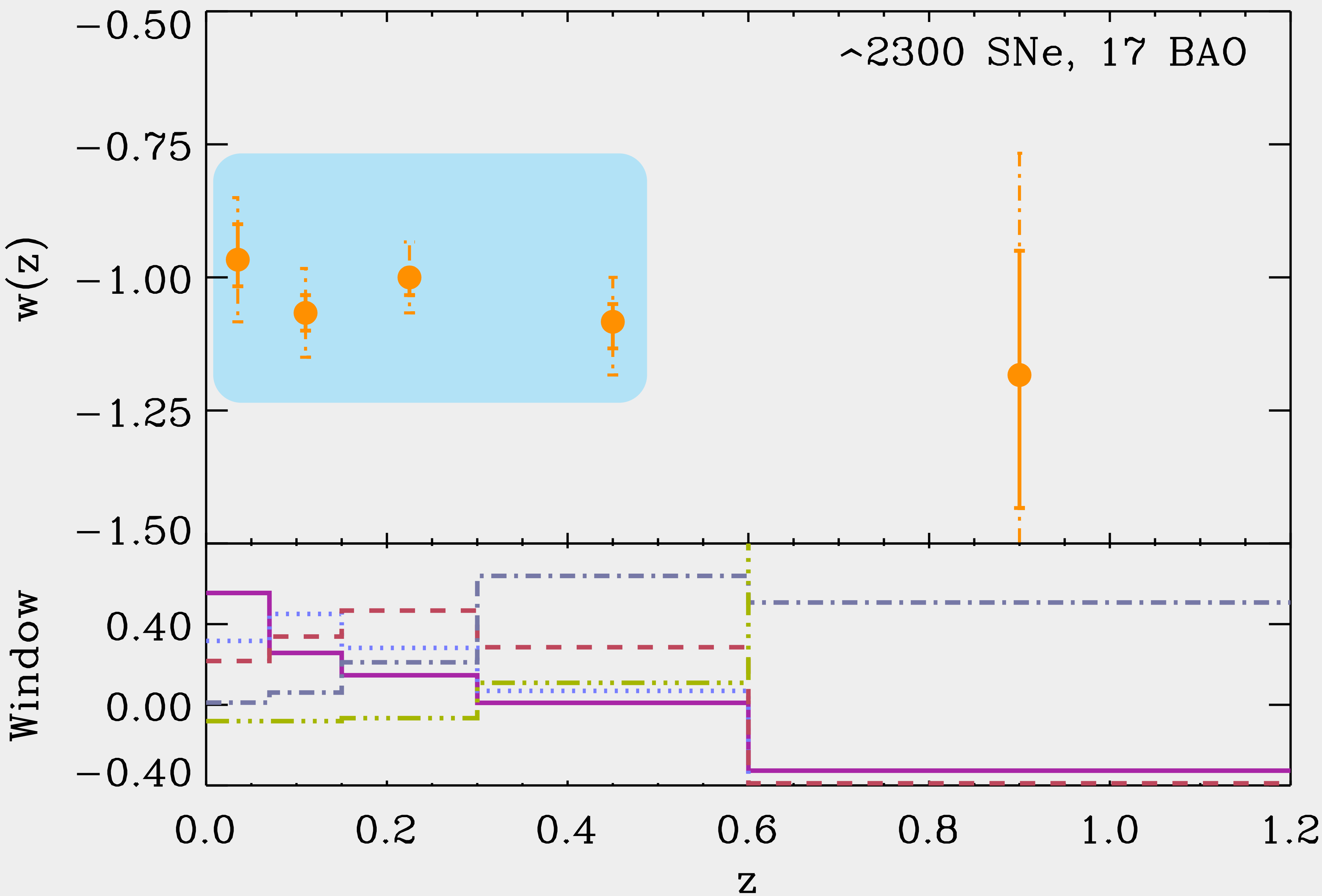

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File Edit View History Bookmarks Window Help Mon 12:26 AM

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

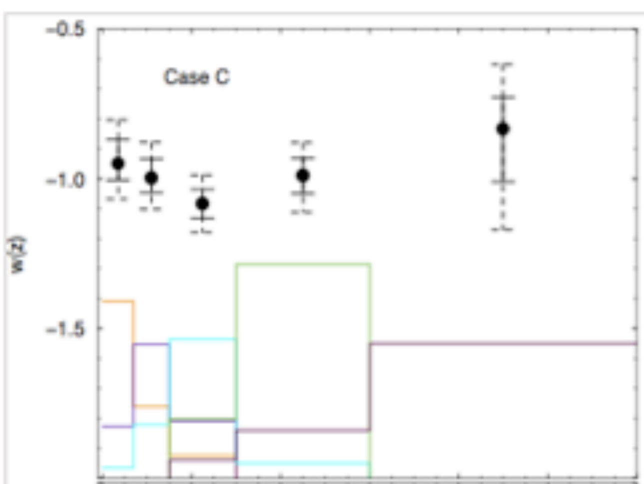
DevdeepSarkar

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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  - Gravitational Lensing

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- Why Non-Gaussianity?
- Why in CMB Bispectrum?
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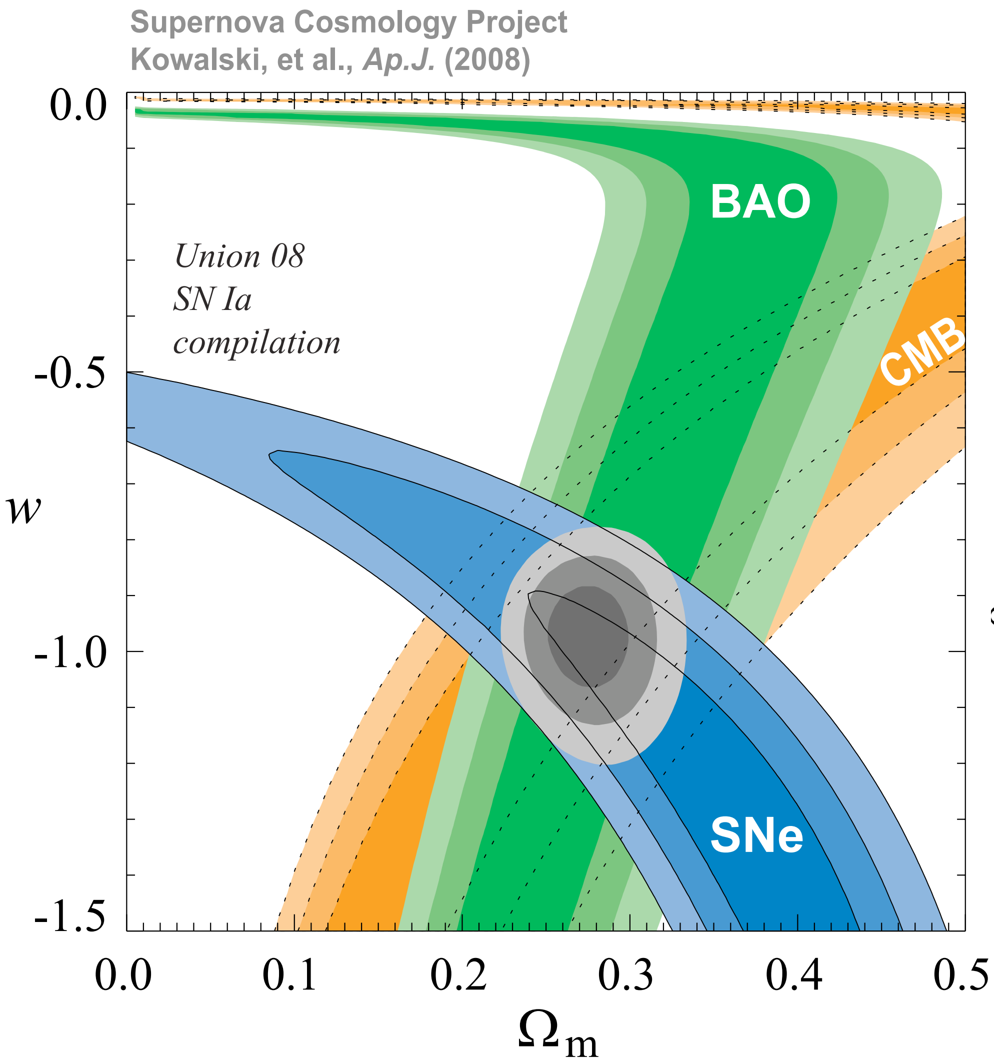
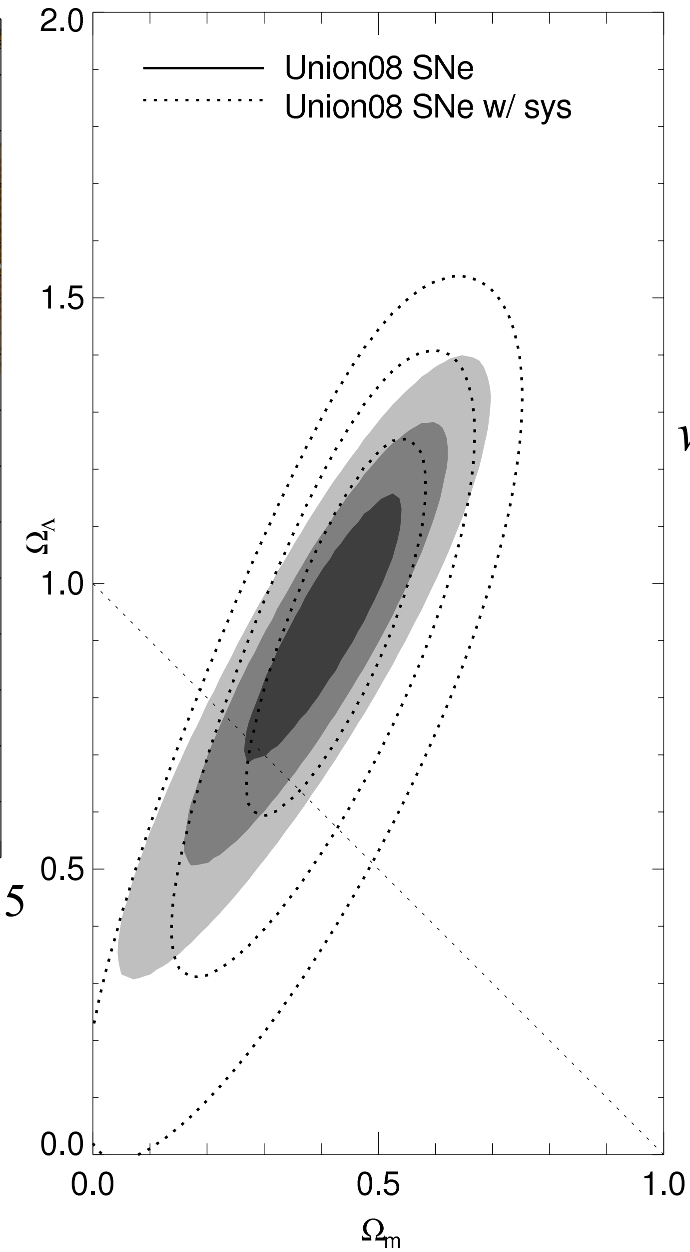
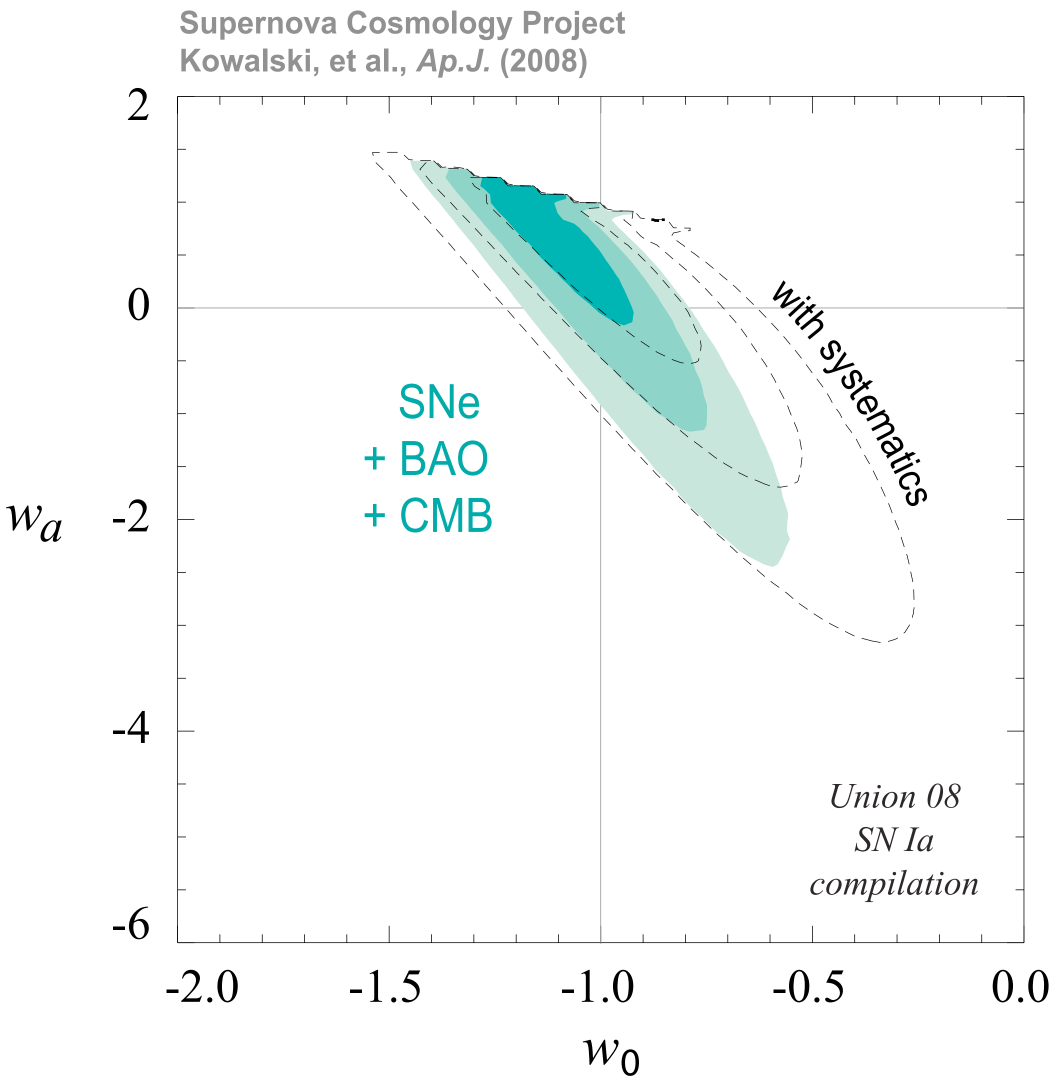
  - Analytical Sketch
  - Numerical Results

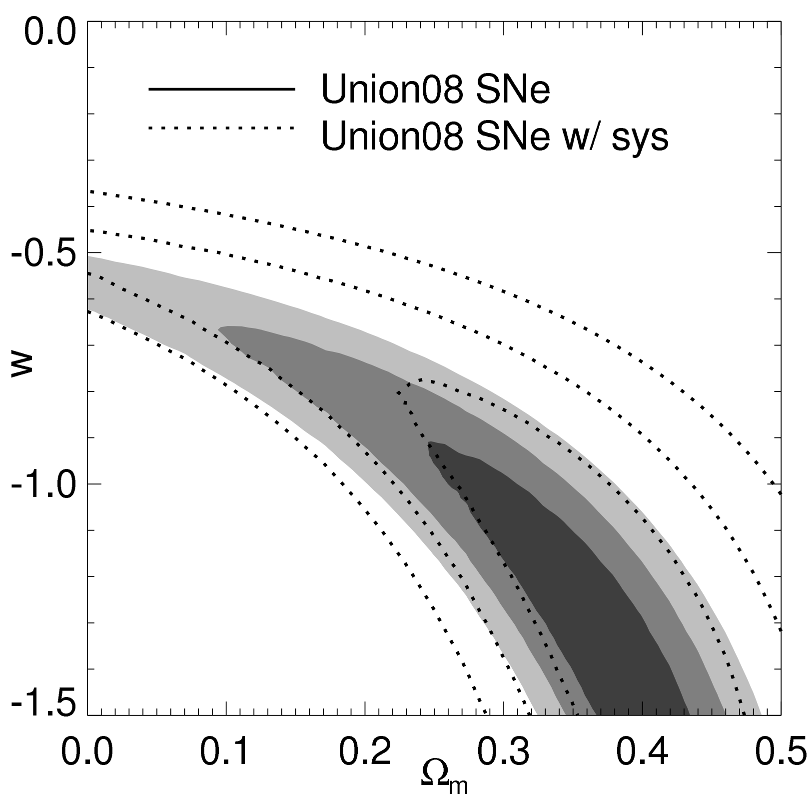
Systematic Matters!







Kowalski et al. (2008)



$$\Omega_\Lambda = 0.713^{+0.027}_{-0.029}(\mathrm{stat})^{+0.036}_{-0.039}(\mathrm{sys})$$

$$w = -0.969^{+0.059}_{-0.063}(stat)^{+0.063}_{-0.066}(sys)$$

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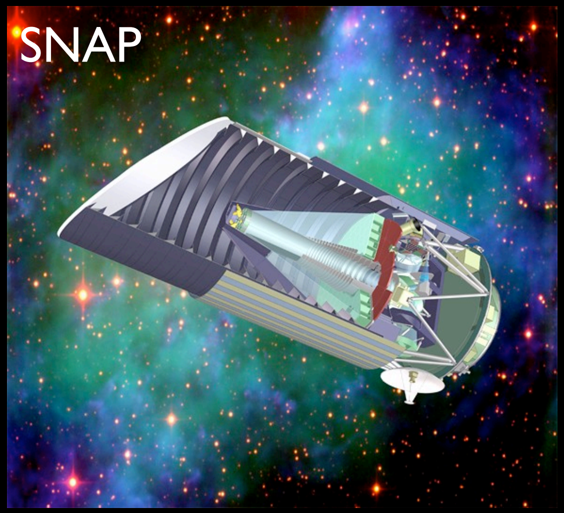
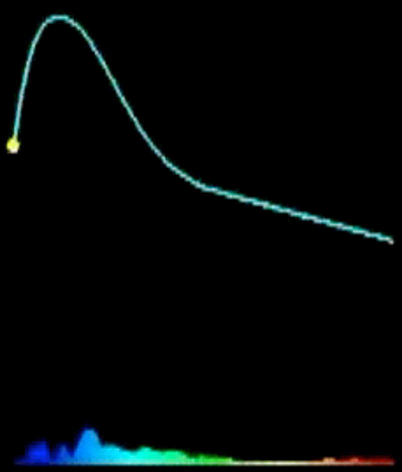
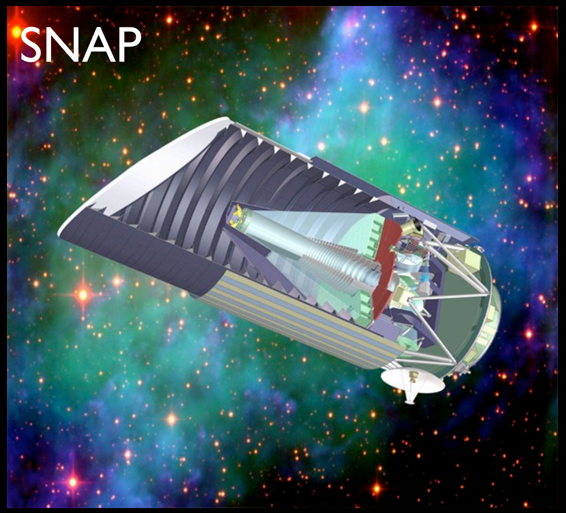
Cosmology with SNe Ia: Revisited

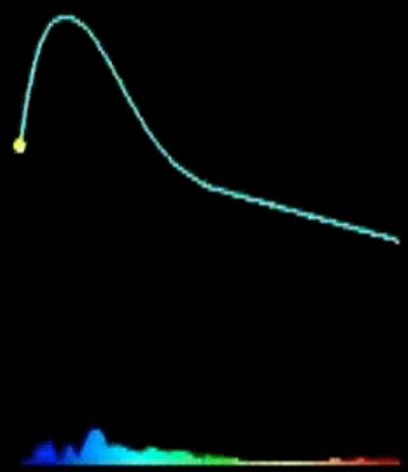




Credit: This clip was prepared by the Supernova Cosmology Project (P. Nugent: spectral sequence; A. Conley: image sequence) with the help of Lawrence Berkeley National Laboratory's Computer Visualization Laboratory (N. Johnston: animation) at the National Energy Research Scientific Computing Center.

Cosmology with SNe Ia: Revisited





Advantages

- ✓ Direct measure of accl.
- ✓ Small dispersion
- ✓ Single objects (easier!)
- ✓ Can be observed over wide z
- ✓ Not cosmic variance limited
- ✓ Straightforward tests of sys.

Credit: This clip was prepared by the Supernova Cosmology Project (P. Nugent: spectral sequence; A. Conley: image sequence) with the help of Lawrence Berkeley National Laboratory's Computer Visualization Laboratory (N. Johnston: animation) at the National Energy Research Scientific Computing Center.

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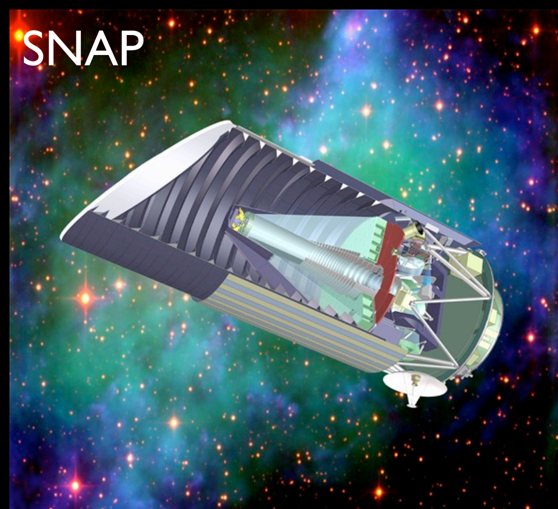

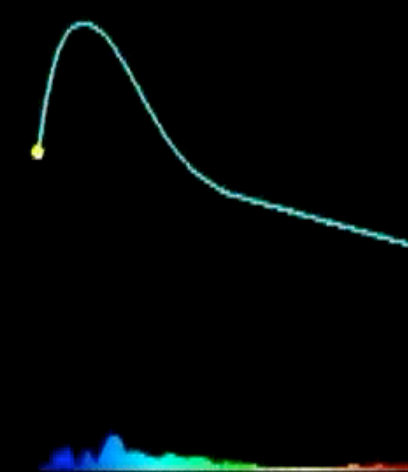

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Challenges

- Dust extinction
- Photometric calibration (Vega)
- Malmquist bias
- K-corrections
- Evolution, chemical comp.
- Population bias + Grav. Lensing

Credit: This clip was prepared by the Supernova Cosmology Project (P. Nugent: spectral sequence; A. Conley: image sequence) with the help of Lawrence Berkeley National Laboratory's Computer Visualization Laboratory (N. Johnston: animation) at the National Energy Research Scientific Computing Center.

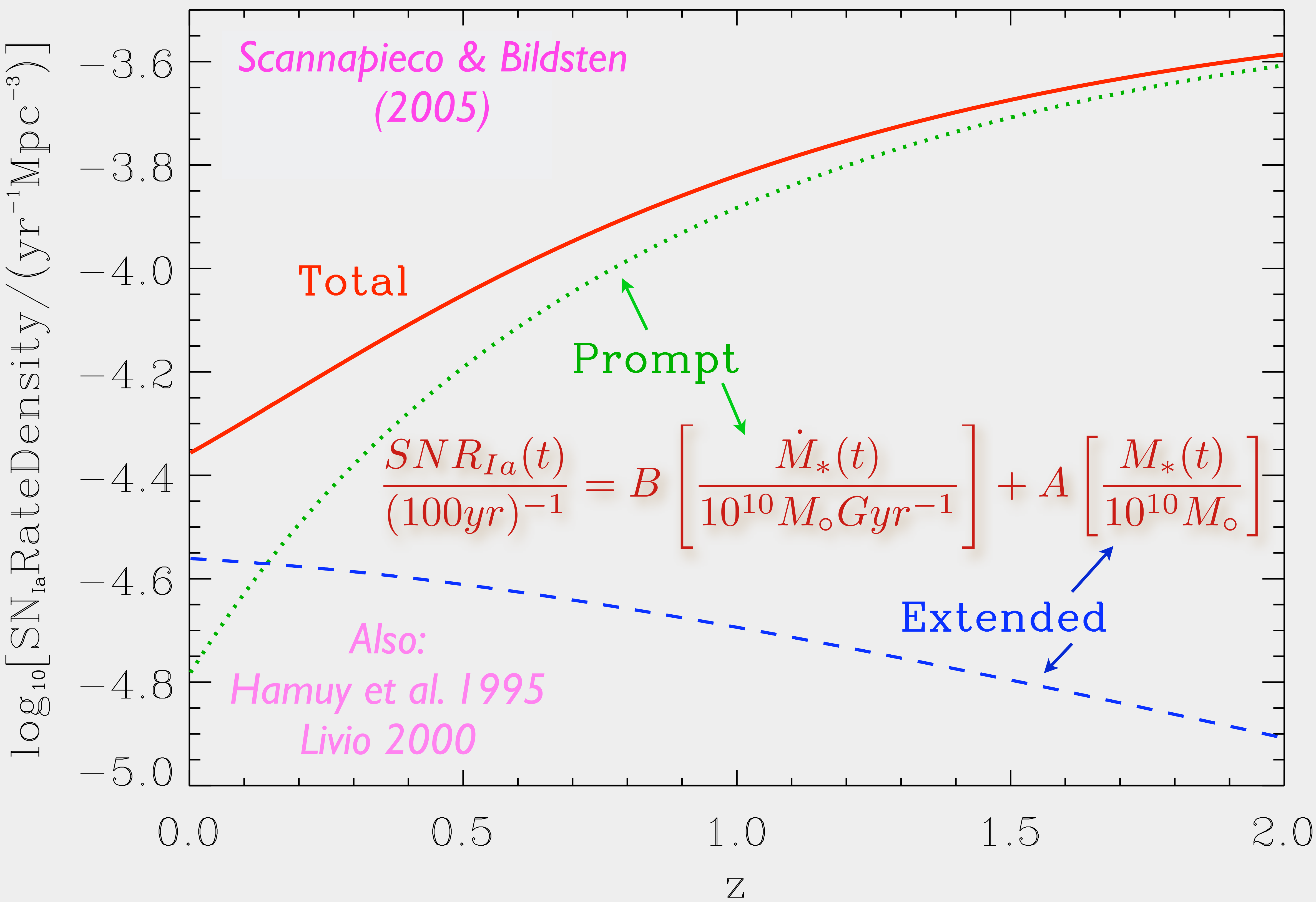
Challenges: Systematic Uncertainties

source of uncertainty	common (mag)	sample-dep.(mag)	treatment
Extinction	0.013	-	Multi-band photometry including near-IR
Calibration	0.021	0.021	Calibration of standard stars (optical thru near-IR) to <1%
Malmquist	-	0.020	High S/N lightcurves & spectra; requirement of pre-rise data
Lightcurve	0.028	-	SN spectra with broad λ, temporal coverage
Evolution	0.015	-	High-resolution spectroscopy

Kowalski et al. (2008), Carnegie Supernova Project: W. Freedman

2-Population	
Lensing	

Evolution based on Two SN Populations



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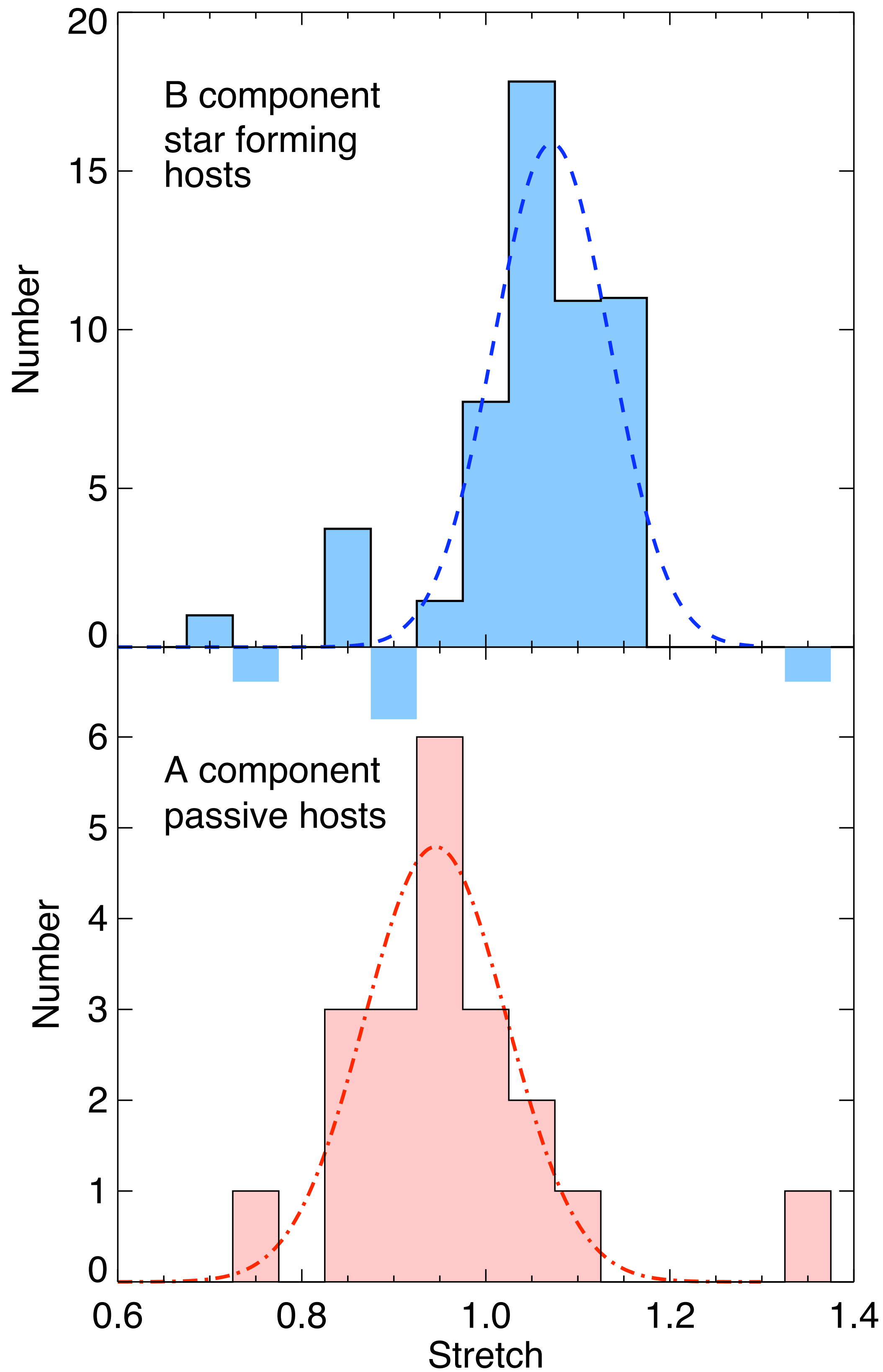


$$\mu_B = m_B^* - M + \alpha(s-1) - \beta c$$

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

PROMPT

12% Dfference
in
Intrinsic Luminosity

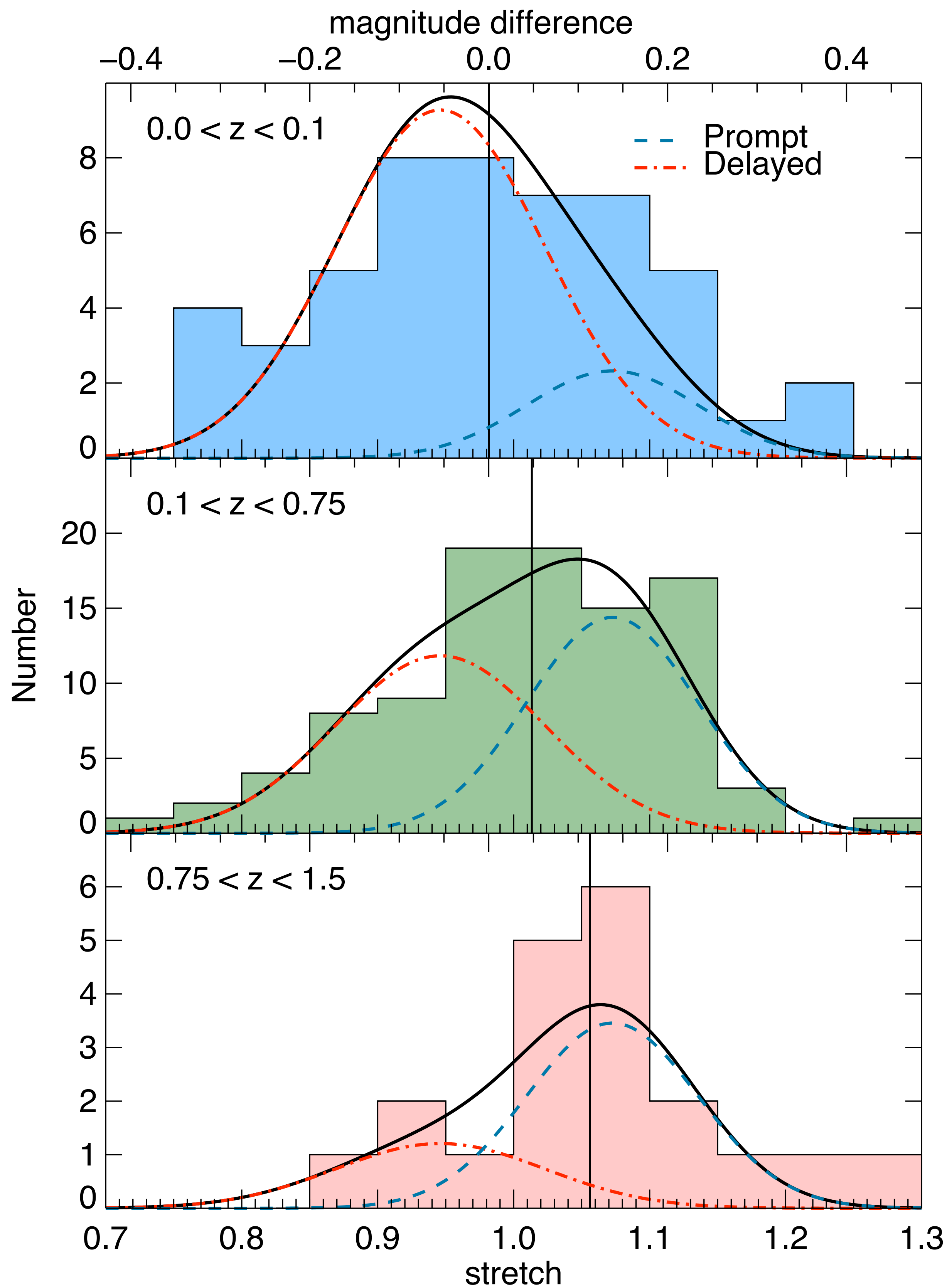
$$\mathcal{L}_P = \mathcal{L}_E + \Delta\mathcal{L}$$

DELAYED

Howell et al. 2007

Data Source: Sullivan et al. 2006 (SNLS)

Evolution based on Two SN Populations



Median Redshift: 0.026
N=50

Median Redshift: 0.55
N=99

Median Redshift: 1.12
N=20

Howell et al. 2007

Is there a Signature in the Hubble Diagram?

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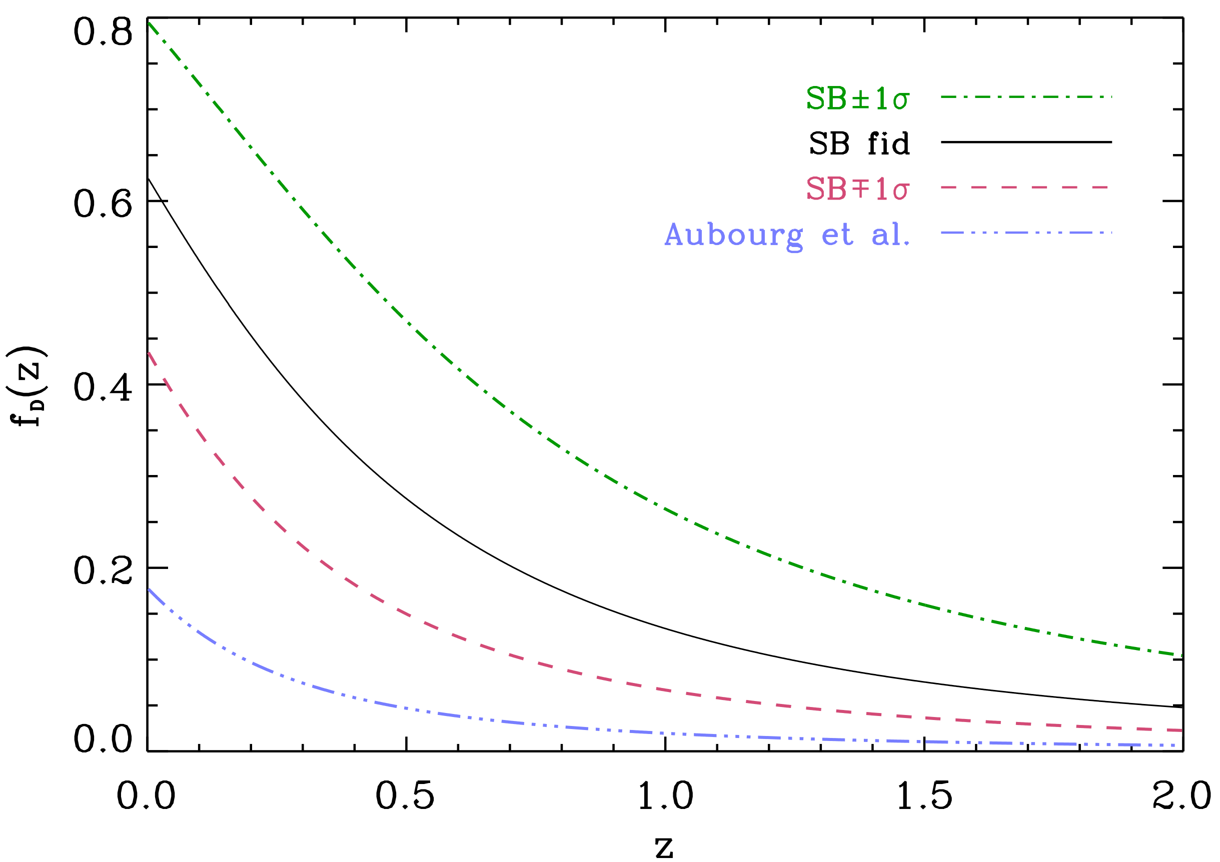
$$m - M = 5 \log \left(\frac{d_L}{\mathrm{Mpc}} \right) + 25 + \mathcal{M}$$

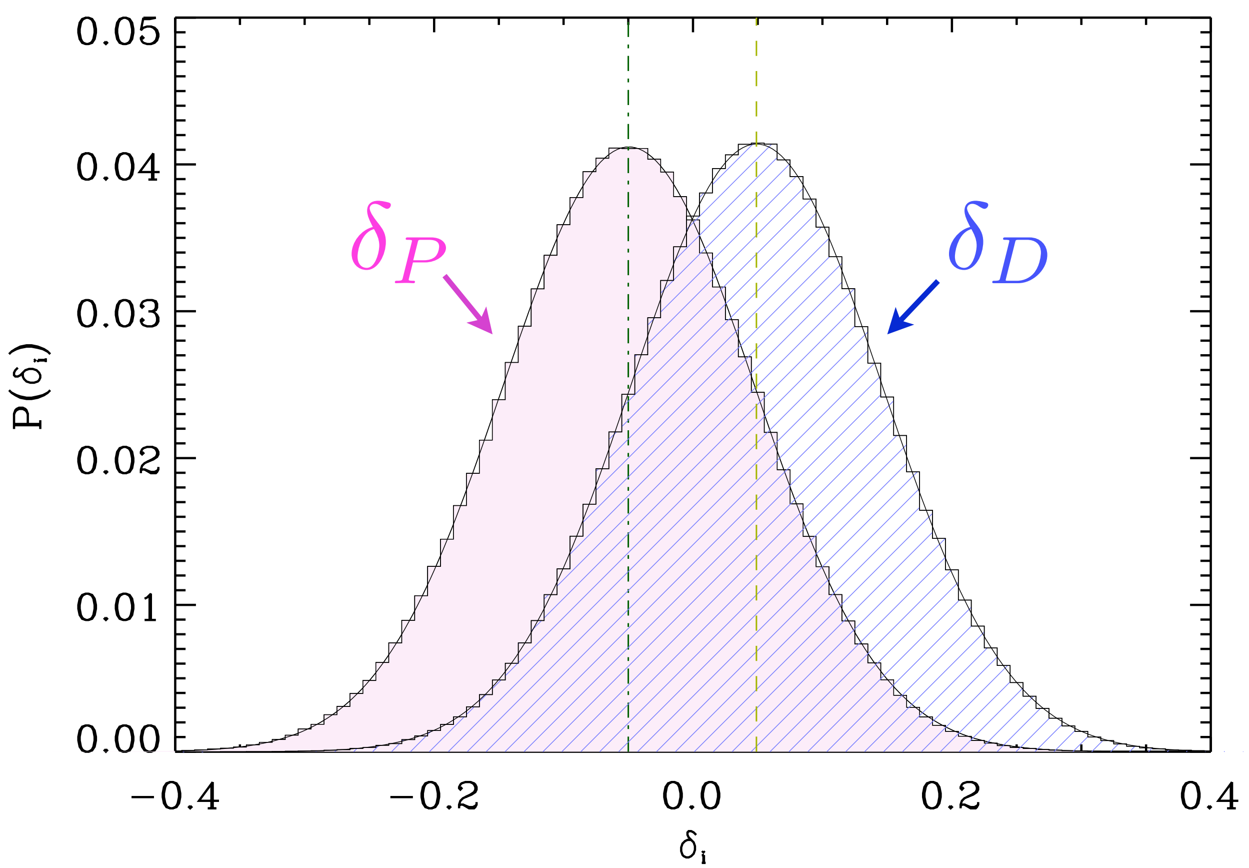
Is there a Signature in the Hubble Diagram?

$$m - M = 5\log\left(\frac{d_L}{\mathrm{Mpc}}\right) + 25 + \mathcal{M} + \delta_D * f_D(z)$$



Is there a Signature in the Hubble Diagram?

$$m - M = 5\log\left(\frac{d_L}{\mathrm{Mpc}}\right) + 25 + \mathcal{M} + \delta_D * f_D(z)$$



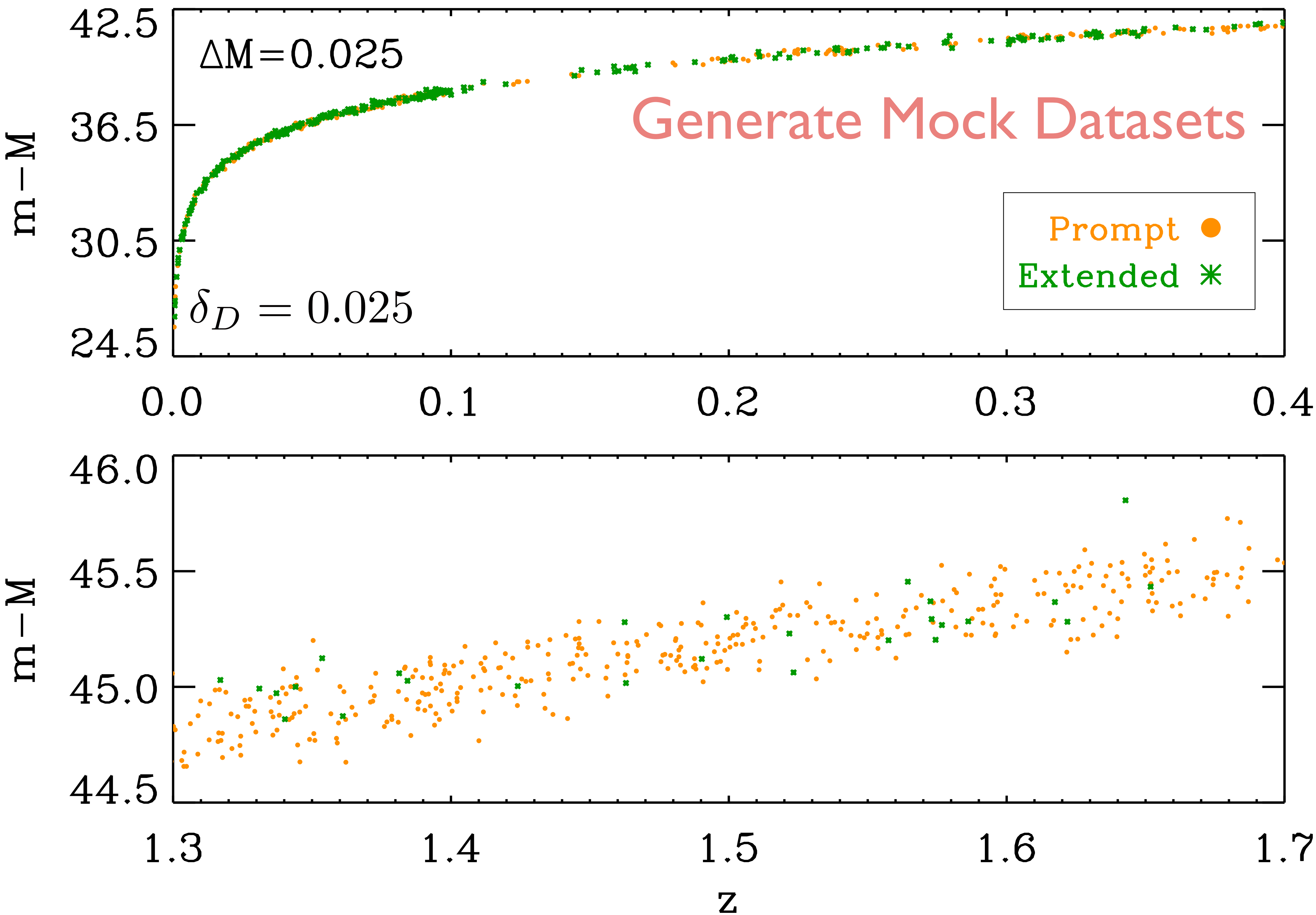
With current data (192 SNe from Davis et al. 2007), the residual is consistent with zero:

$$\delta_D \sim (5 \pm 9)\%$$

With future data, one will be able to constrain the residual much better.

D.S., A. Amblard, A. Cooray, and D. Holz; ApJL, 684, L13 (2008)

Effect on the EOS Estimates: Bias in "w"



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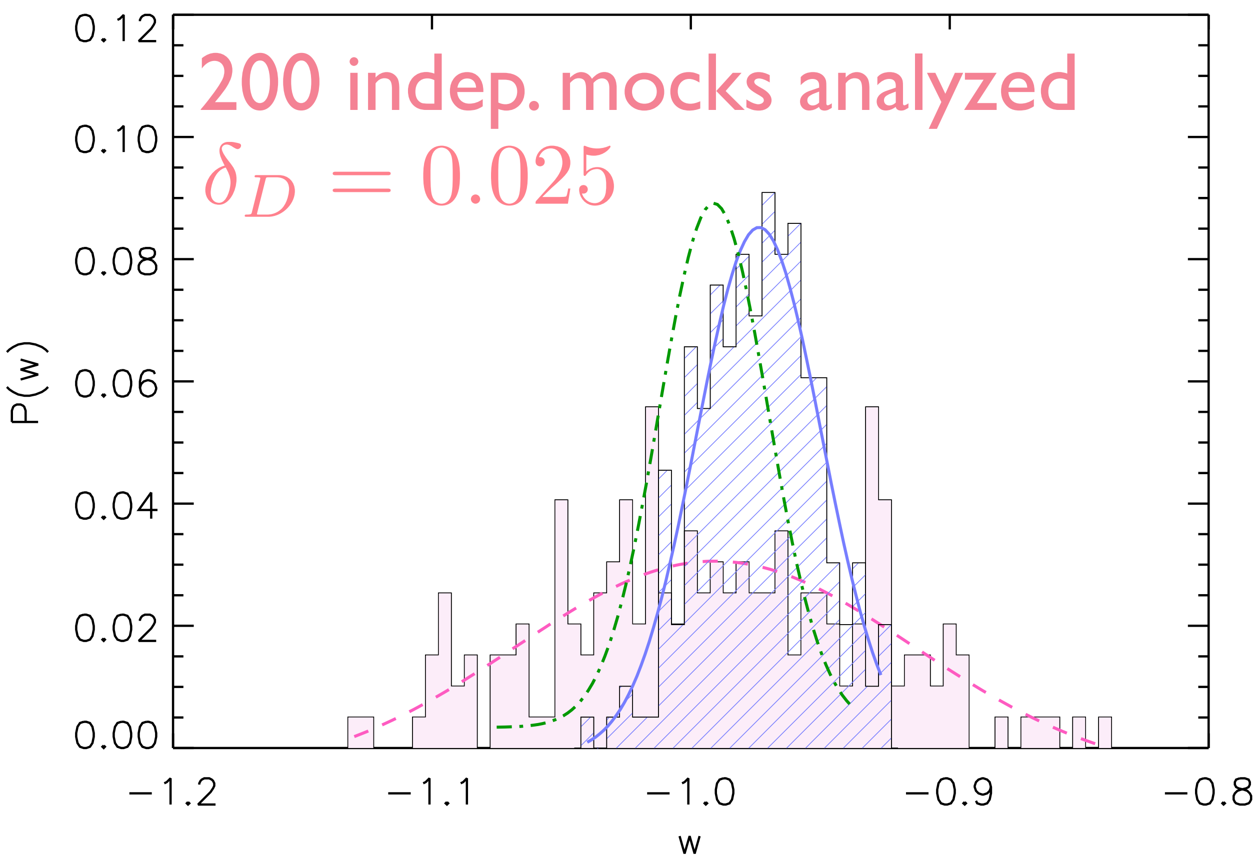
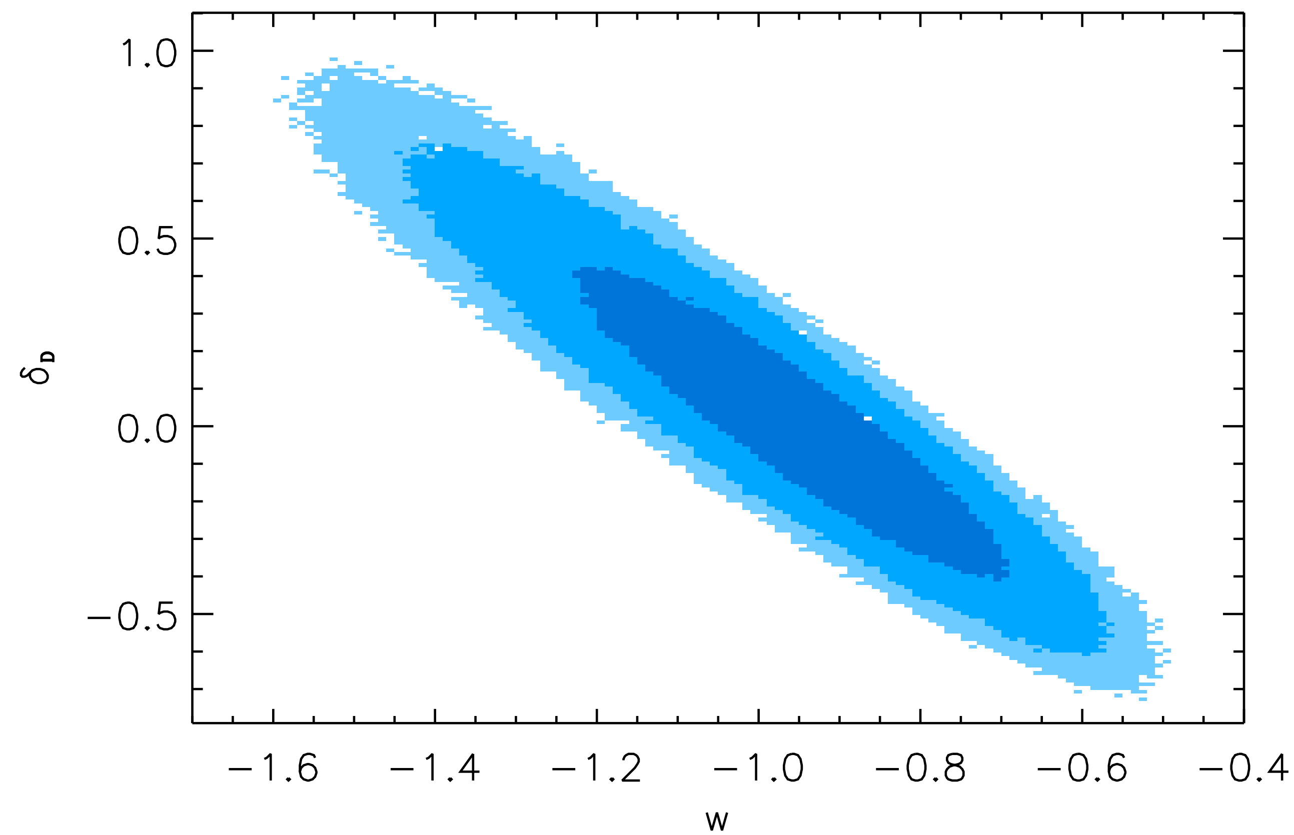




~1-sigma bias in "w"

Correlation

While model-fitting the data:

$$\delta_D = 0 \Rightarrow \sim 1\sigma \text{ bias in } w$$

$$\delta_D = \text{FREE} \Rightarrow \text{ NO bias in } w, \text{ BUT Error bar increased by 2.5 times}$$

$$\text{Best situation: Constrain } \delta_D <= 2\% \text{ with confidence}$$

D.S., A. Amblard, A. Cooray, and D. Holz; ApJL, 684, L13 (2008)

Challenges: Systematic Uncertainties

source of uncertainty	common (mag)	sample-dep.(mag)	treatment
Extinction	0.013	-	Multi-band photometry including near-IR
Calibration	0.021	0.021	Calibration of standard stars (optical thru near-IR) to <1%
Malmquist	-	0.020	High S/N lightcurves & spectra; requirement of pre-rise data
Lightcurve	0.028	-	SN spectra with broad λ, temporal coverage
Evolution	0.015	-	High-resolution spectroscopy

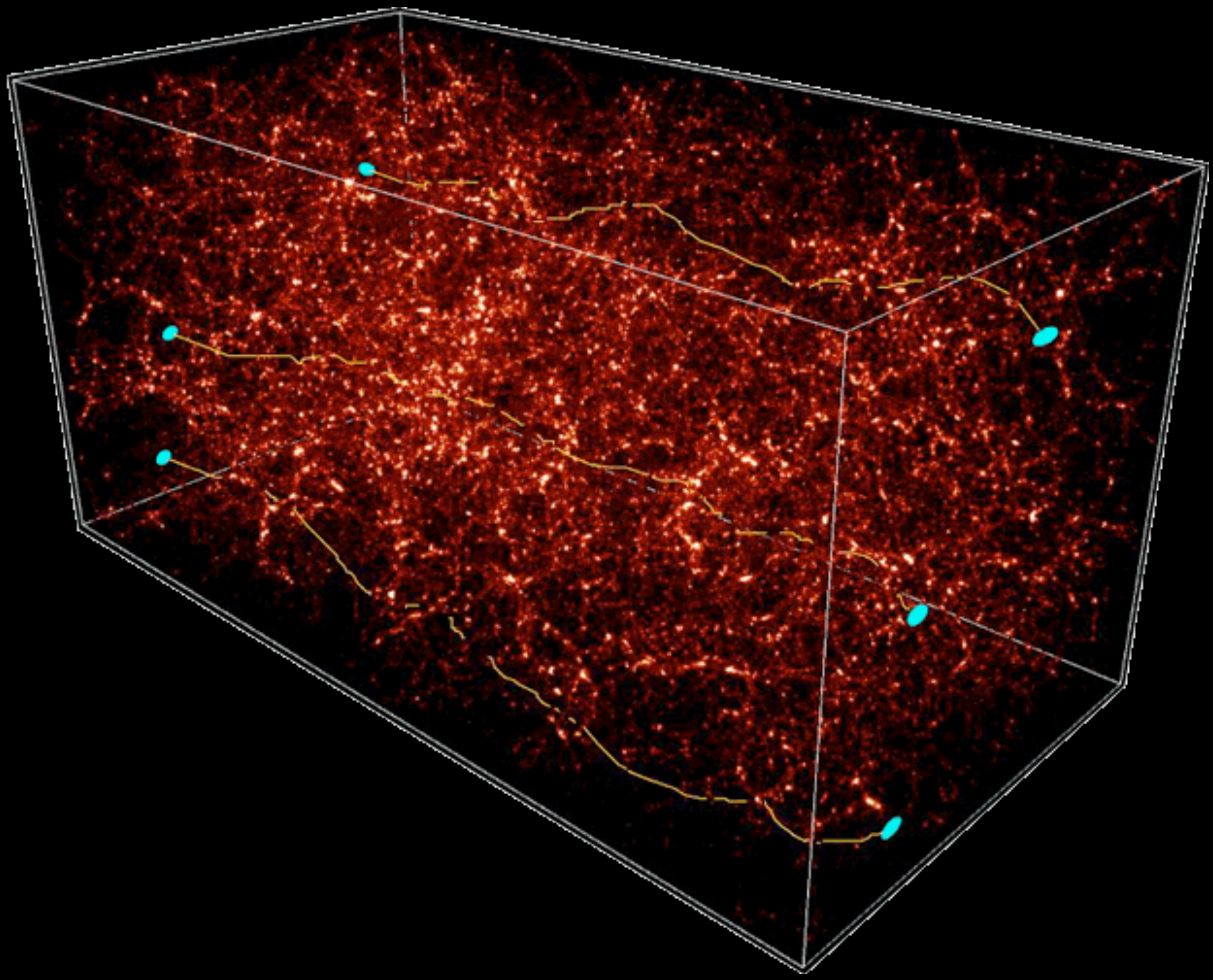
Kowalski et al. (2008), Carnegie Supernova Project: W. Freedman

2-Population	Constrain the systematics to < 2% level to have the bias on "w" less than 1-sigma level without increasing error bar!
Lensing	

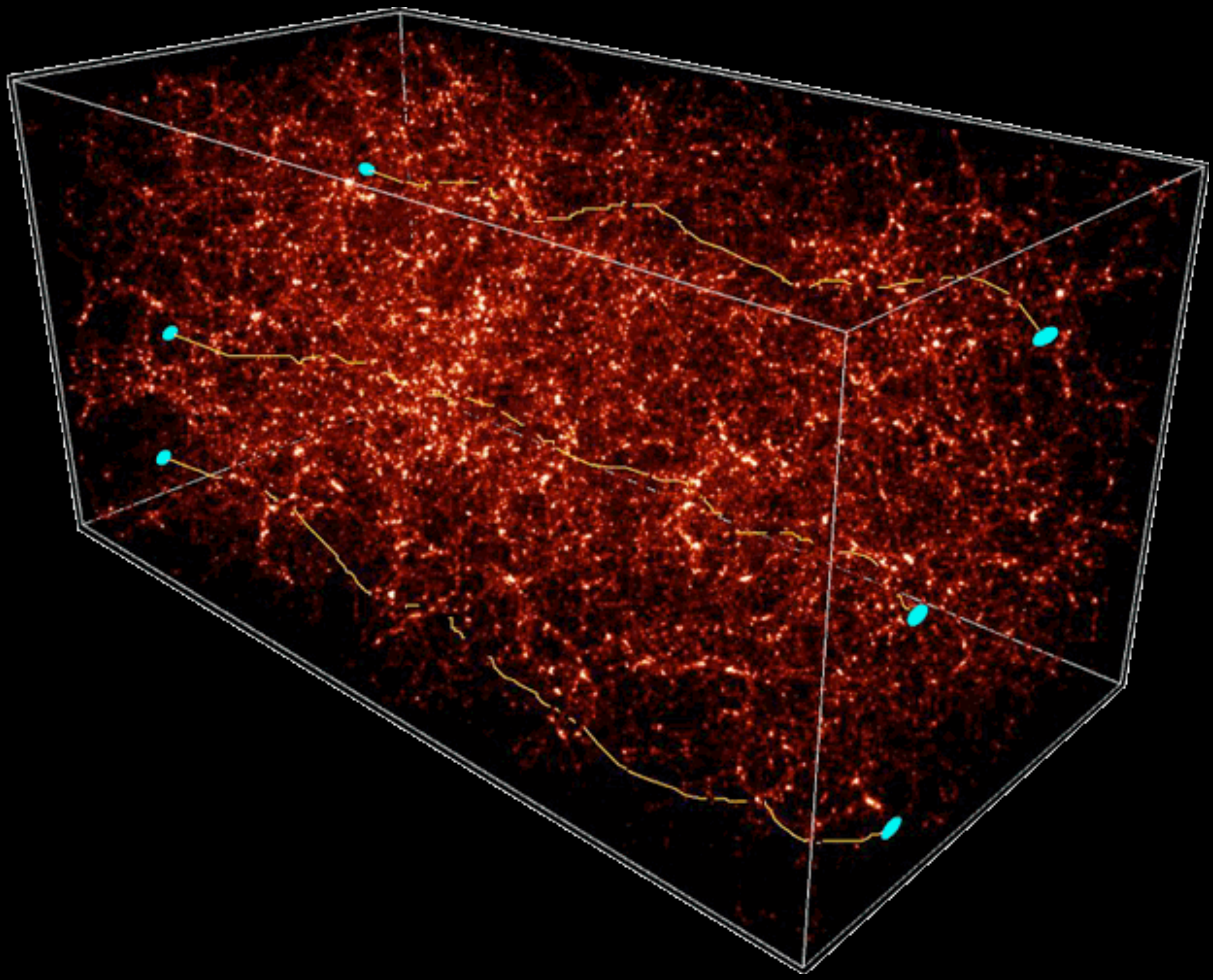
Influence of Gravitational Lensing?

Lensing Galaxy

Influence of Gravitational Lensing?

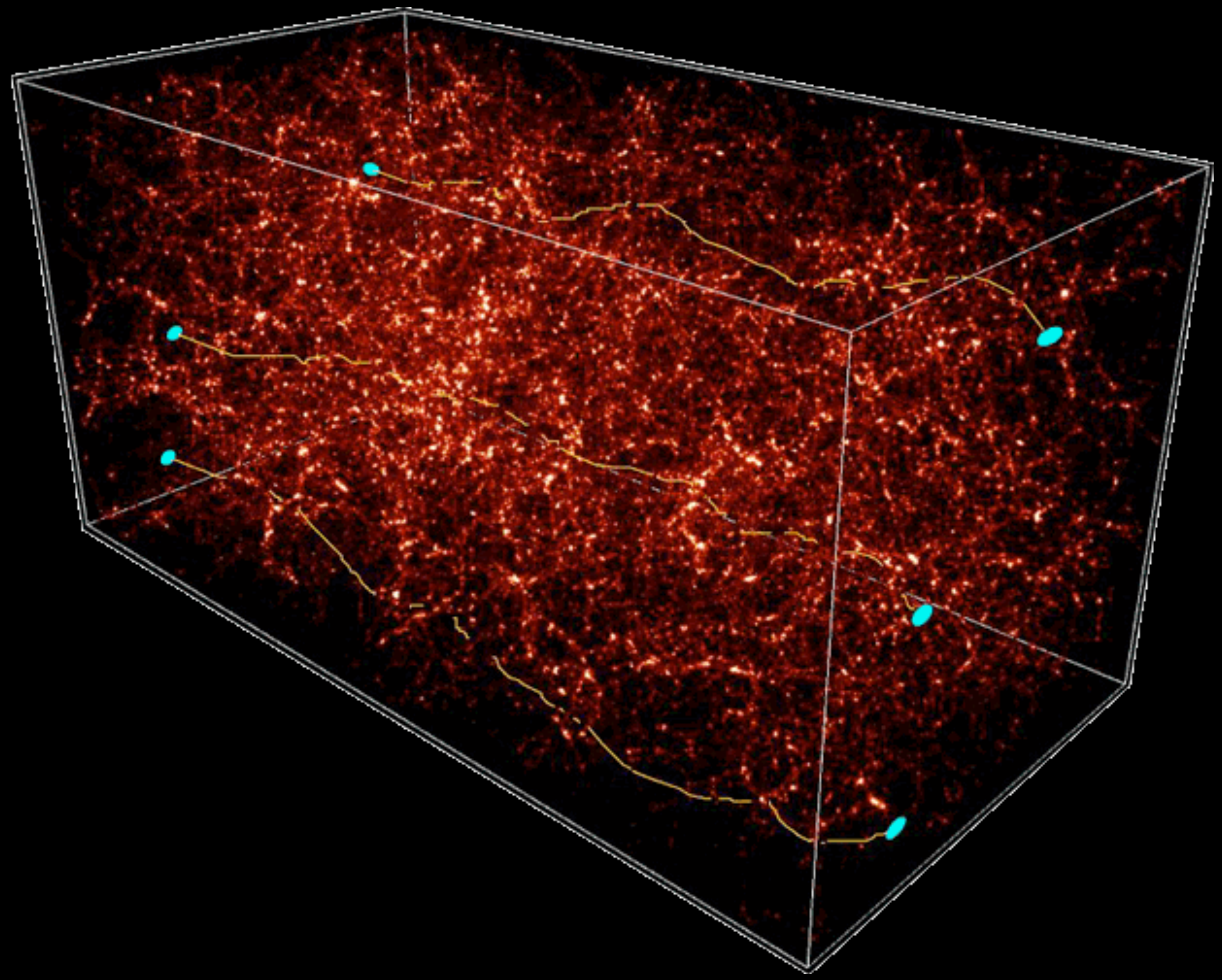


Influence of Gravitational Lensing?



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

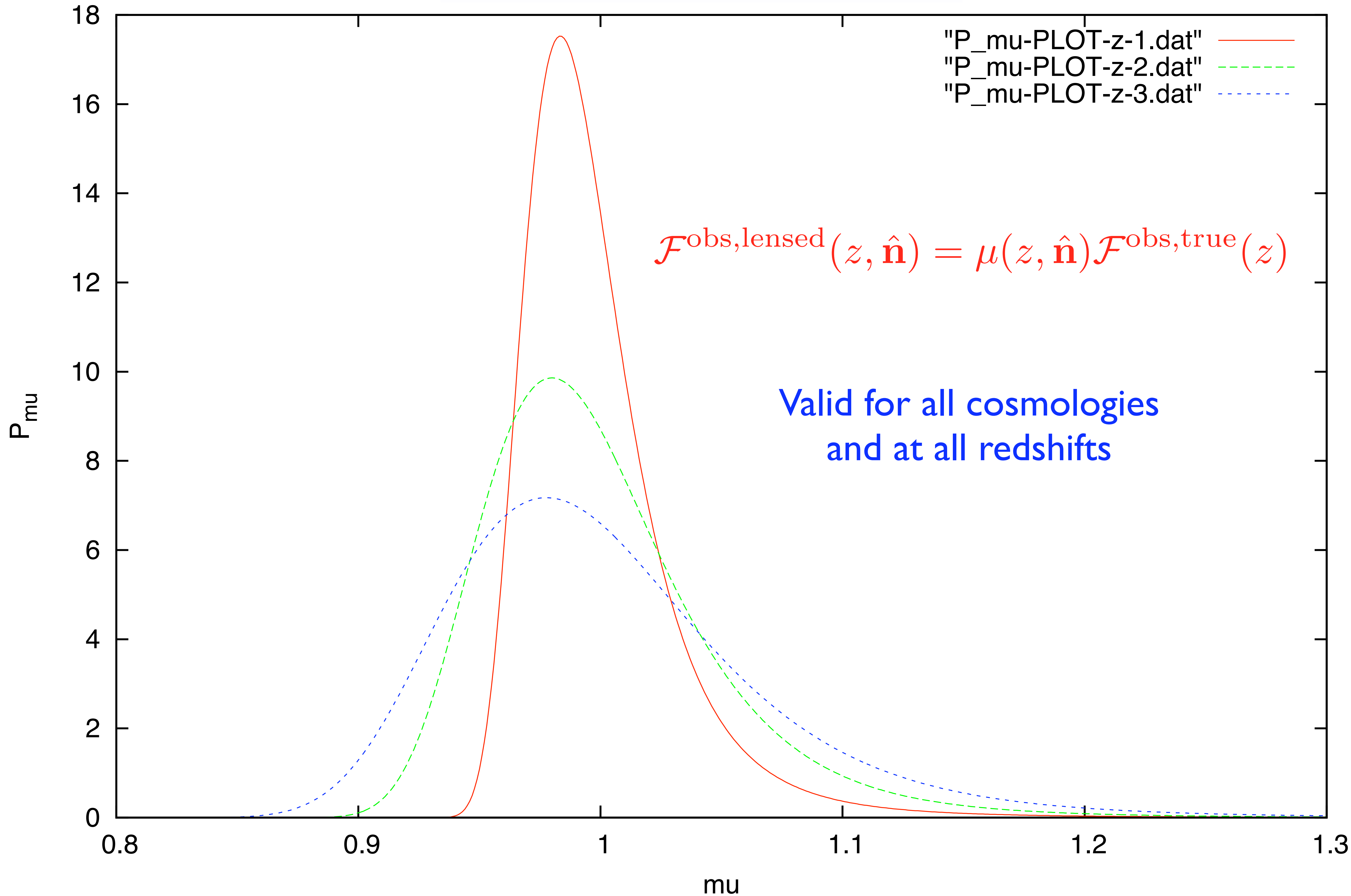
Influence of Gravitational Lensing?



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

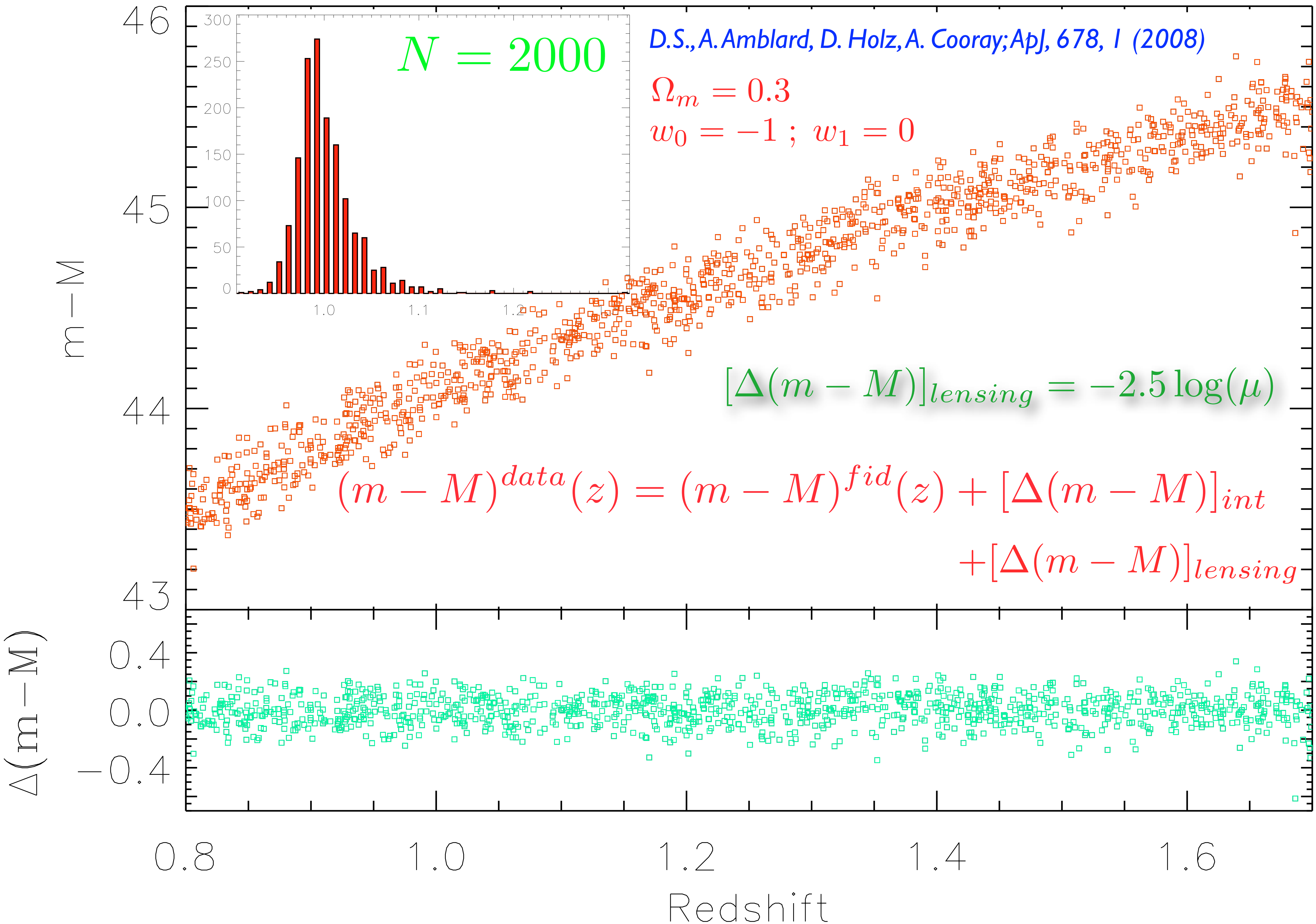
Weak lensing can modify the SNa flux & bias estimates of w

Amplification Probability Distribution

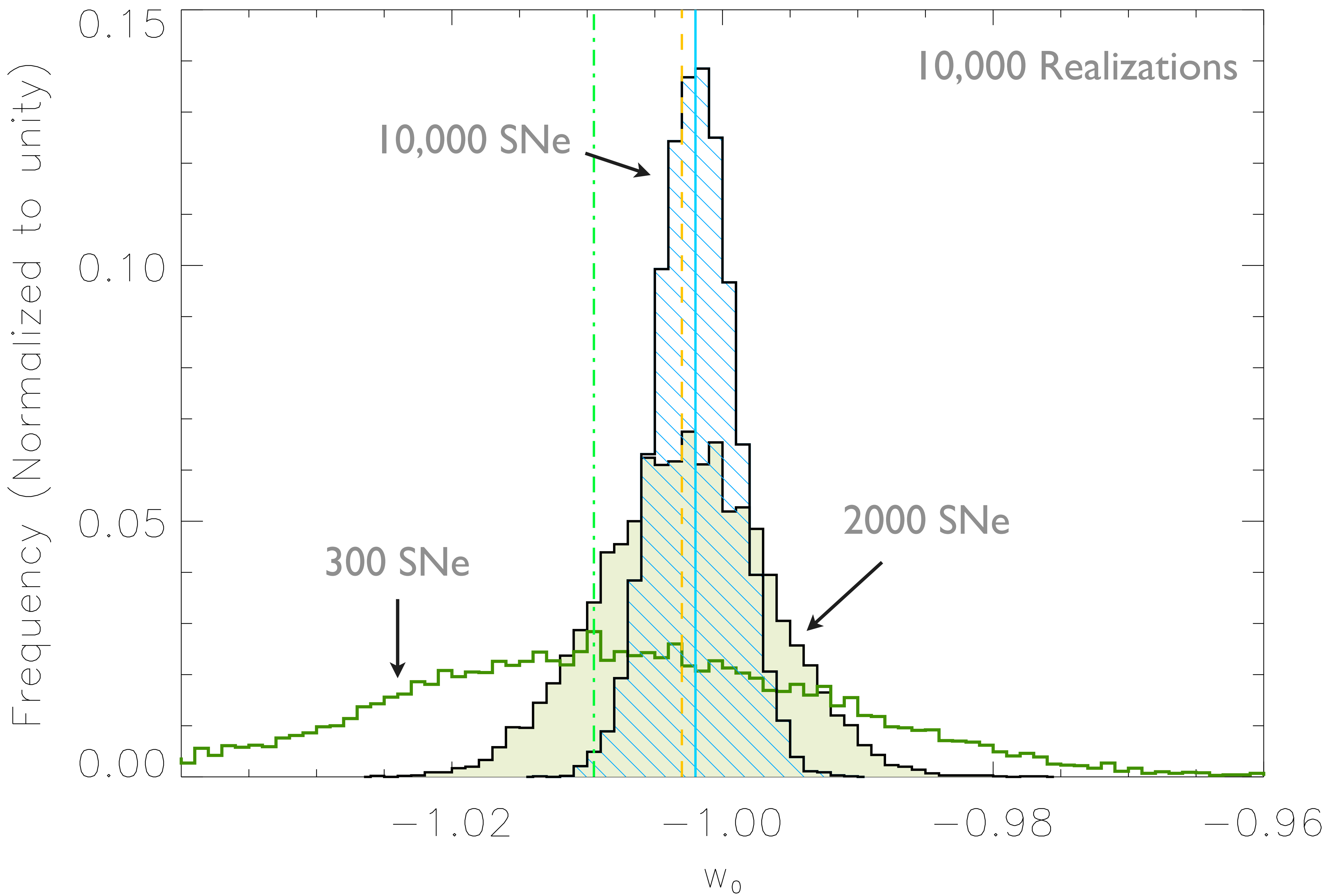


*Wang, Y., Holz, D. E., & Munshi, D., 2002, ApJ, **572**, L15*

Our Analysis with Mock Catalogs

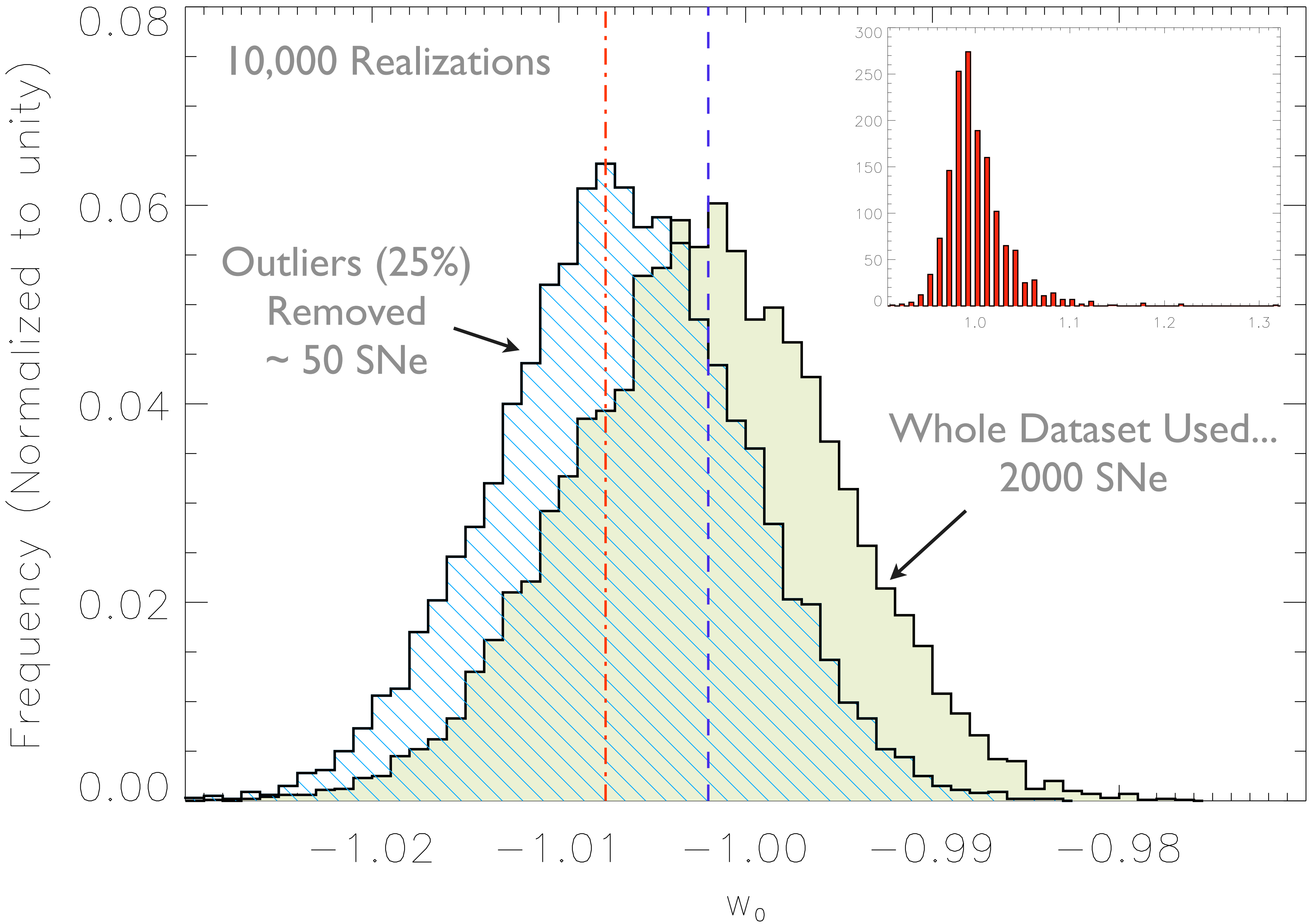


Effect of Weak Lensing on Estimates of "w"



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

Effect of Removing the Outliers



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

Challenges: Systematic Uncertainties

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Kowalski et al. (2008), Carnegie Supernova Project: W. Freedman

2-Population	Constrain the systematics to < 2% level to have the bias on "w" less than 1-sigma level without increasing error bar!
Lensing	Need a large # of SNe per redshift bin to keep bias < 1%

Outline

Dark Energy

- Why Pursue Dark Energy?
- DE Equation of State (EOS)
- DE from SNe Ia ++
- Beware of Systematics
  - Two Population Model
  - Gravitational Lensing

CMB Bispectrum

- Why Non-Gaussianity?
- Why in CMB Bispectrum?
- The f_{NL}
- WL of CMB Bispectrum
  - Analytical Sketch
  - Numerical Results

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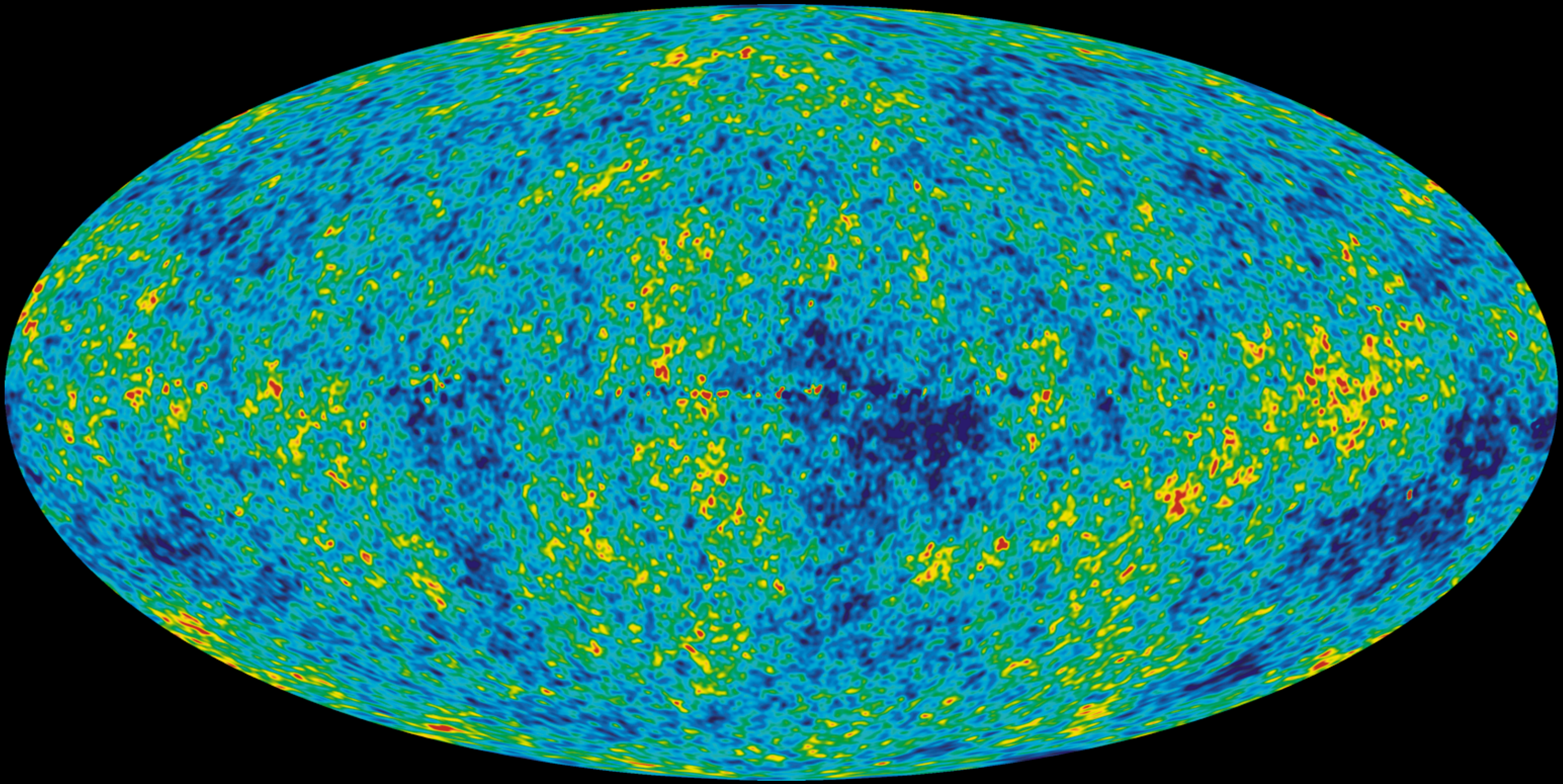
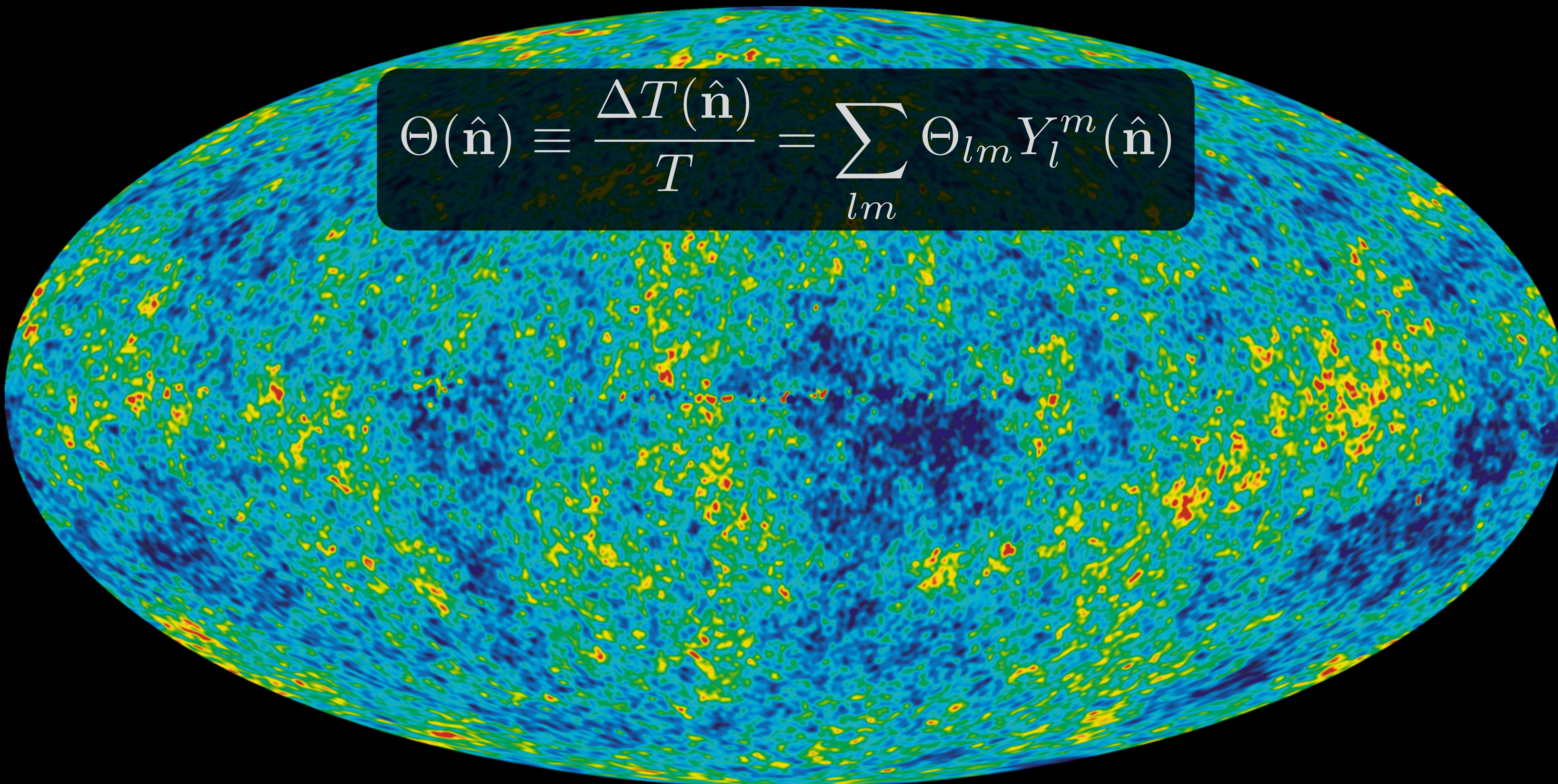
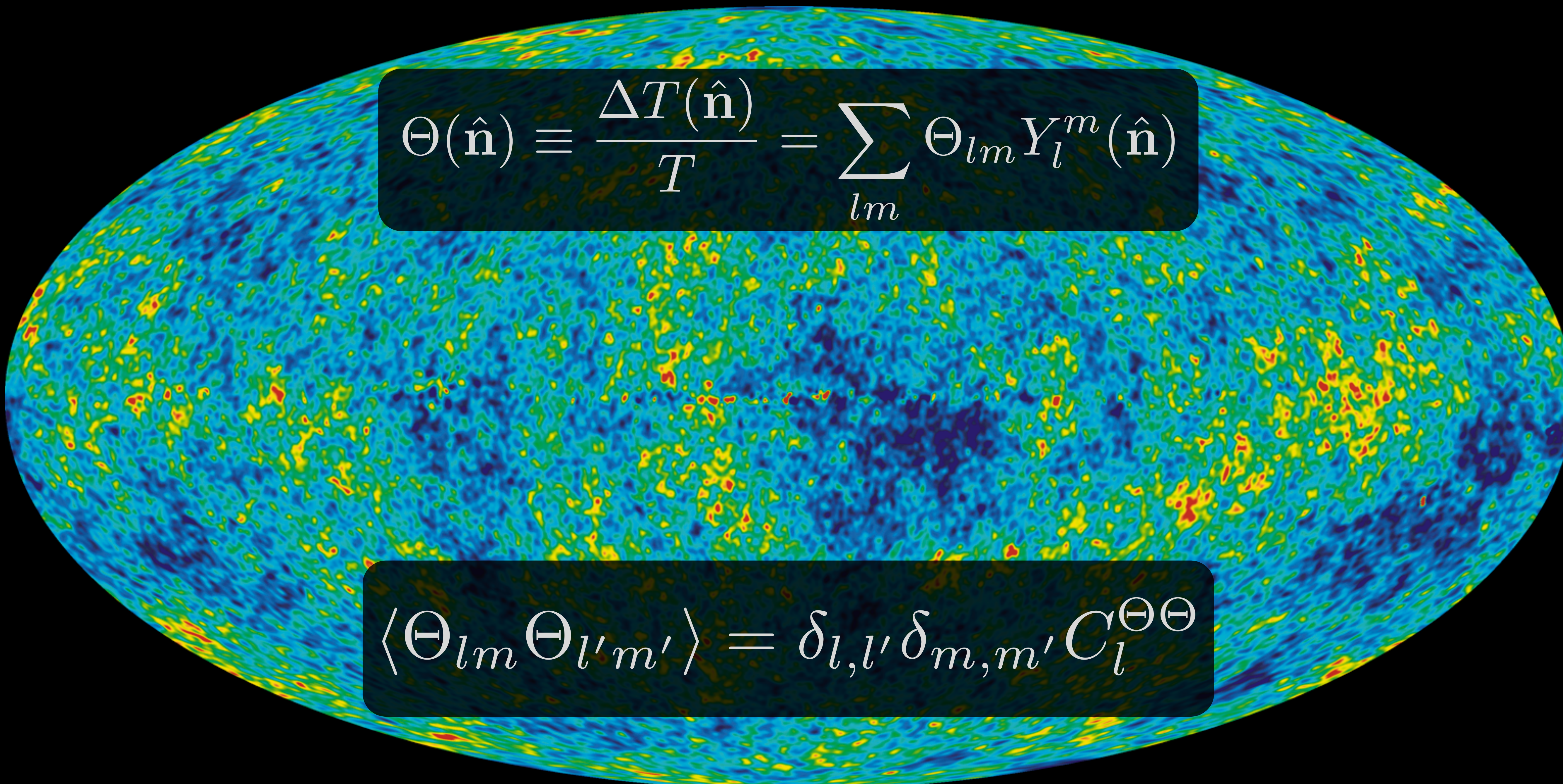


Credit: NASA/WMAP Science Team



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

Credit: NASA/WMAP Science Team



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

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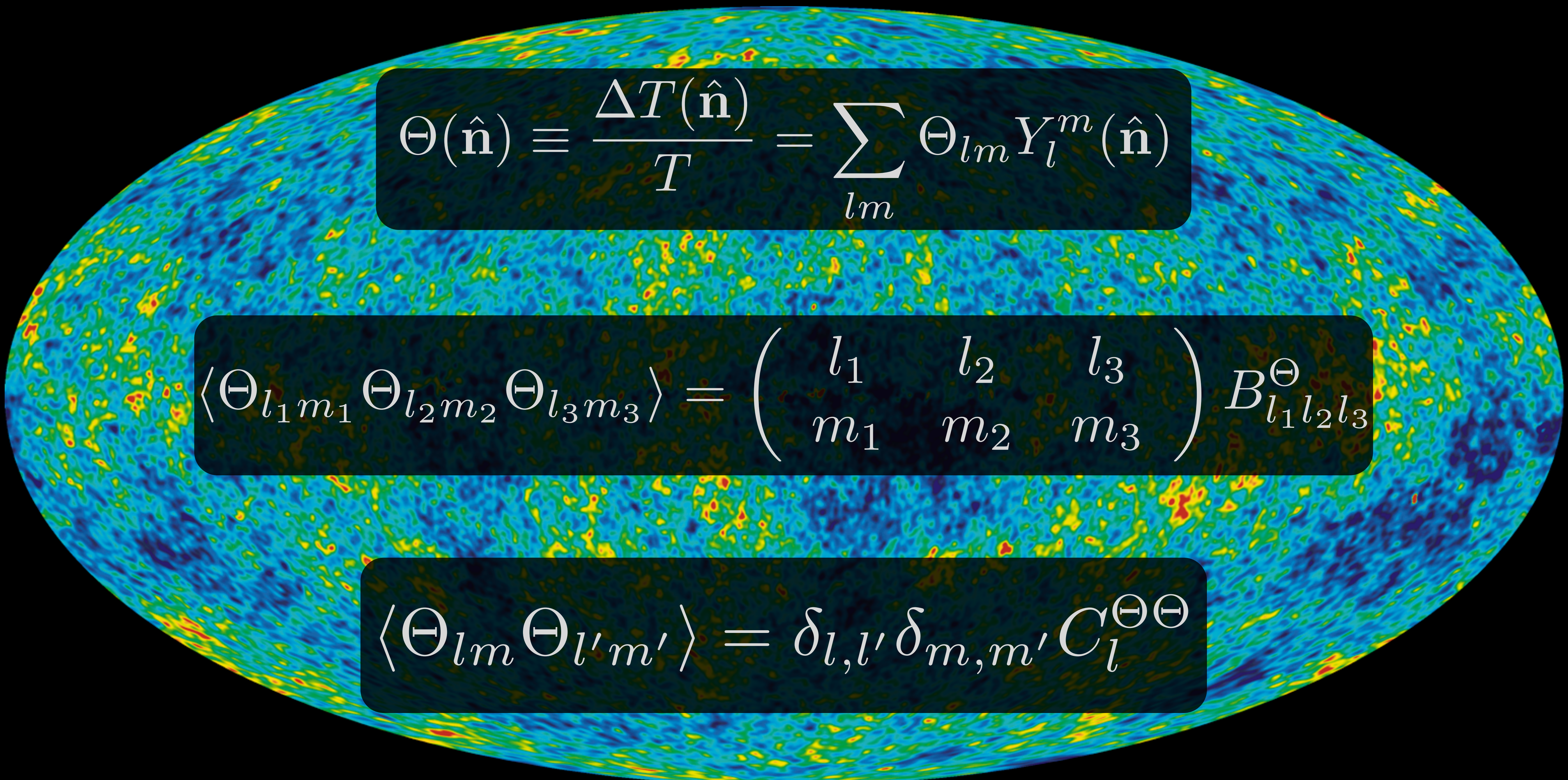


$$\Theta(\hat{\mathbf{n}}) \equiv \frac{\Delta T(\hat{\mathbf{n}})}{T} = \sum_{lm} \Theta_{lm} Y_l^m(\hat{\mathbf{n}})$$

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

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

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 $27 < f_{\mathrm{NL}} < 147$ (95% C.L.). This amounts to a rejection of $f_{\mathrm{NL}} = 0$ 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

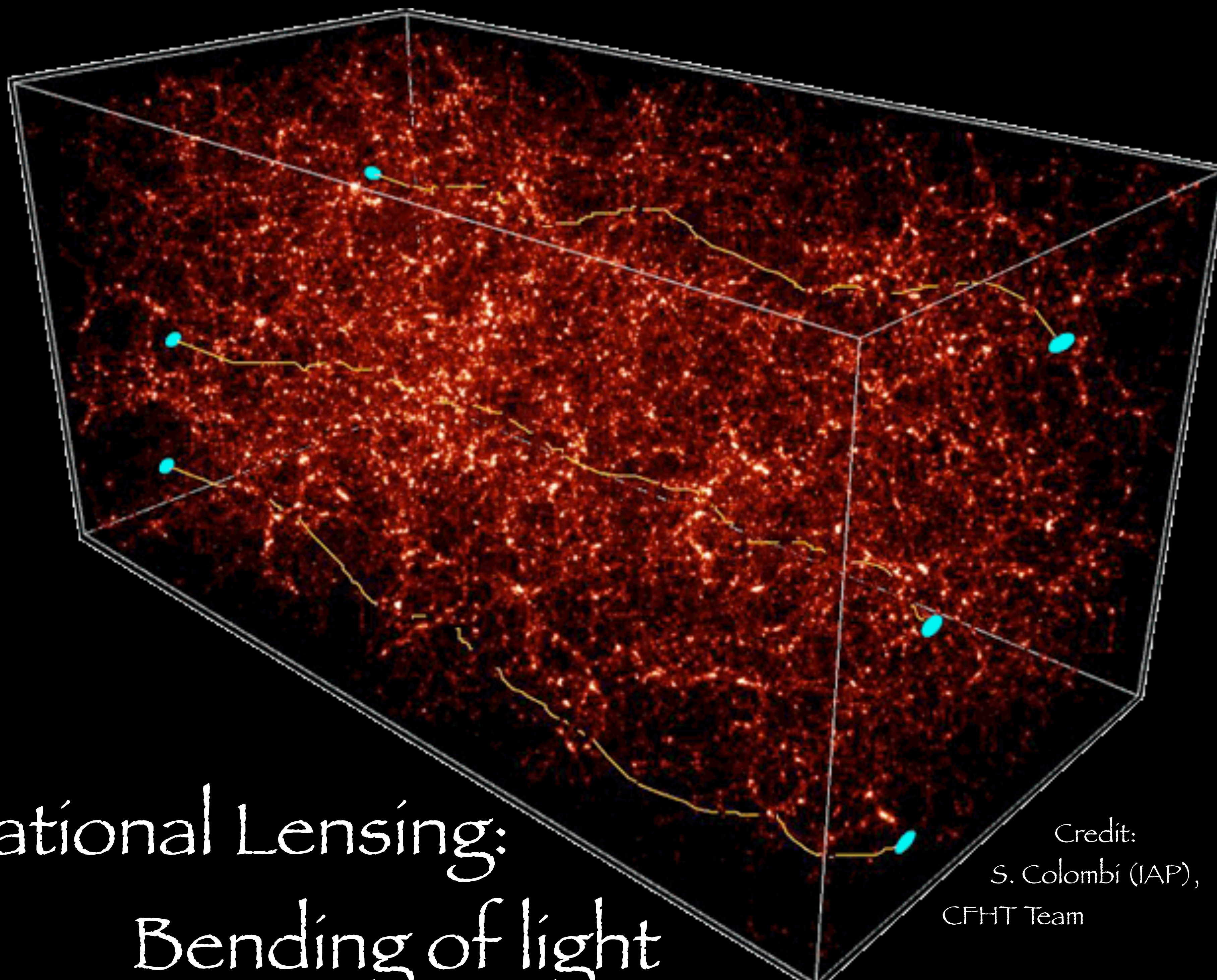
E. Komatsu [1], J. Dunkley [2,3,4], M. R. Nolta [5], C. L. Bennett [6], B. Gold [6], G. Hinshaw [7], N. Jarosik [2], D. Larson [6], M. Limon [8] L. Page [2], D. N. Spergel [3,9], M. Halpern [10], R. S. Hill [11], A. Kogut [7], S. S. Meyer [12], G. S. Tucker [13], J. L. Weiland [10], E. Wollack [7], and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



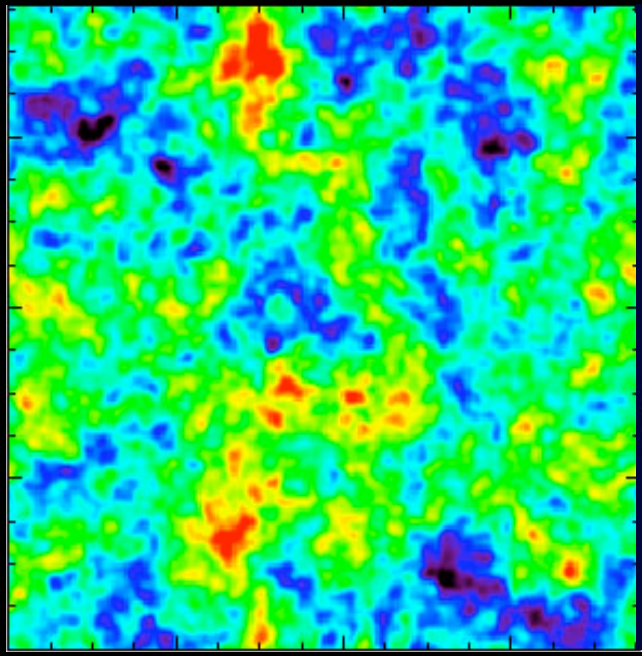
Weak

Gravitational Lensing:

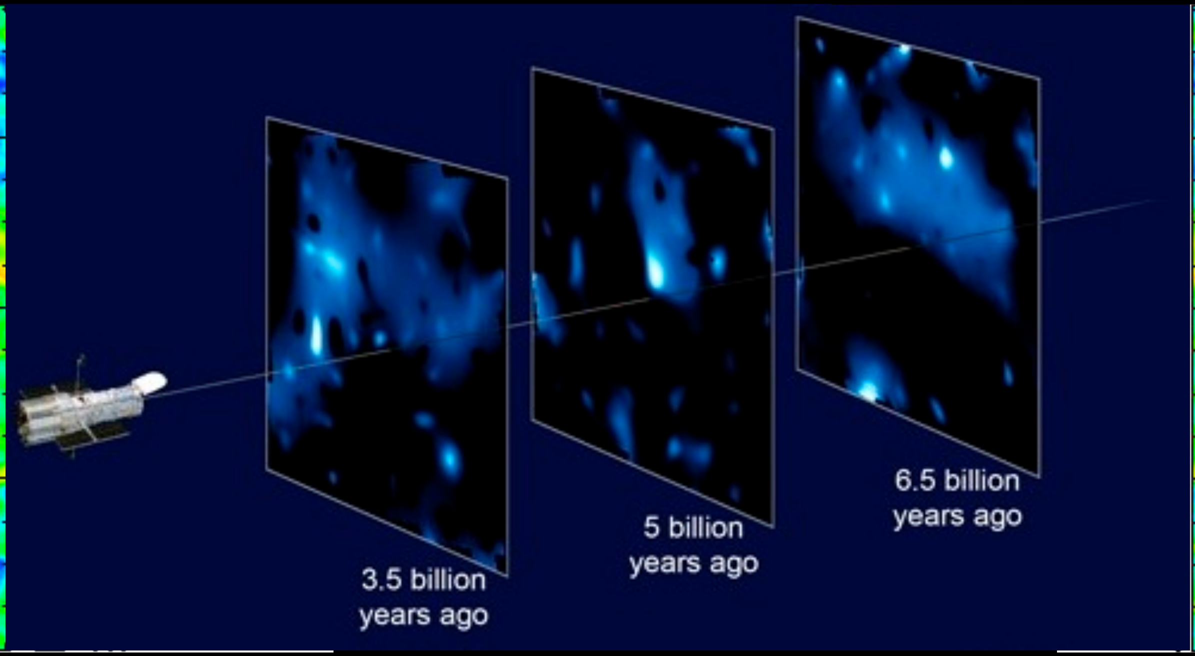
Bending of light

Credit:
S. Colombi (IAP),
CFHT Team

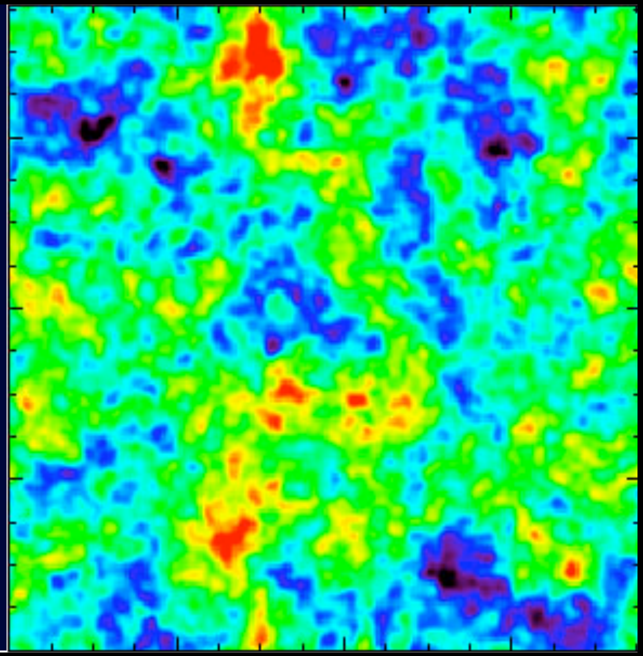
Weak Lensing of the Primary Bispectrum



Credit: Vale, Amblard, White (2004)



NASA, ESA, and R. Massey (CalTech)



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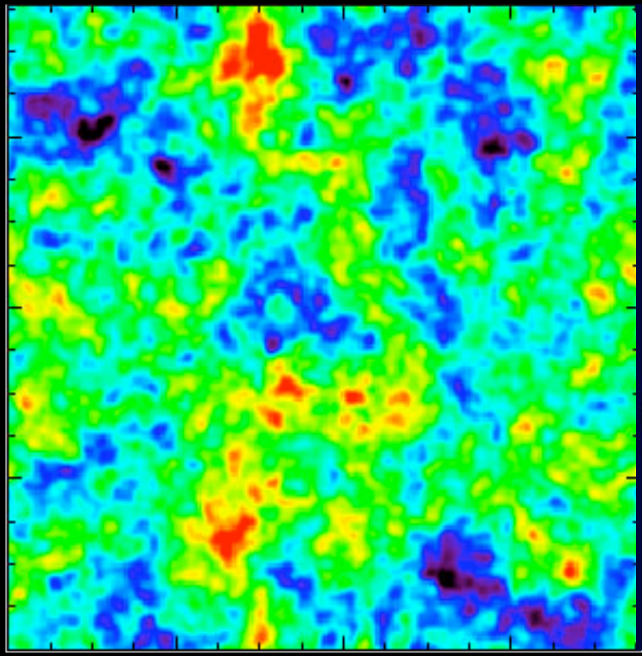

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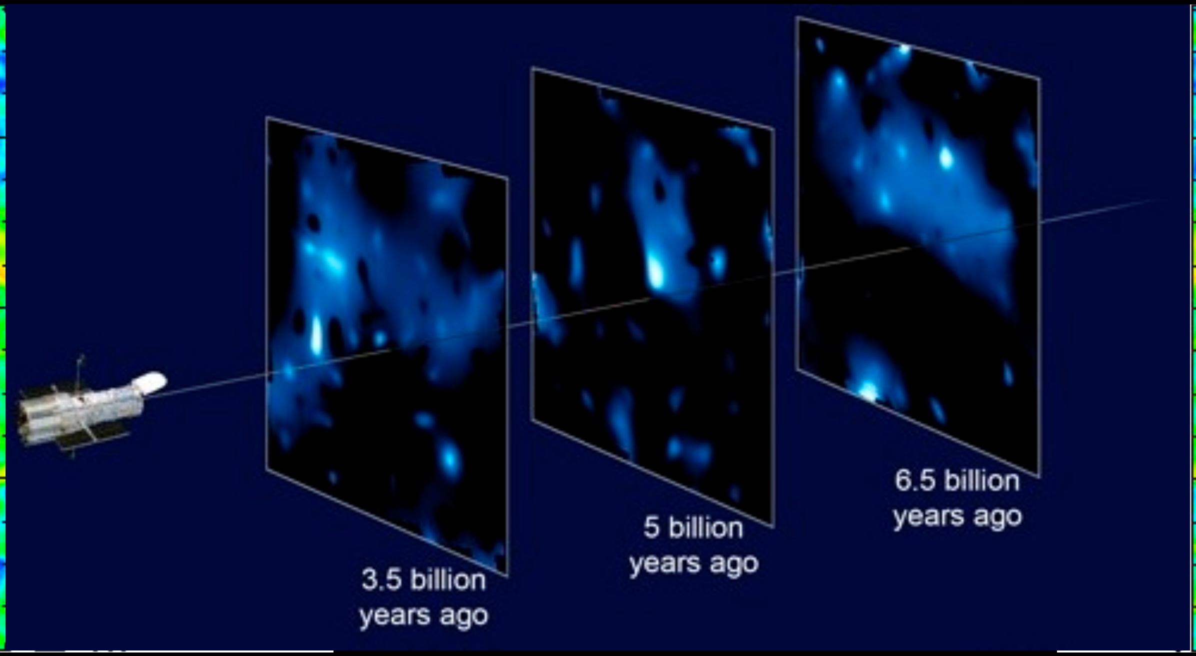

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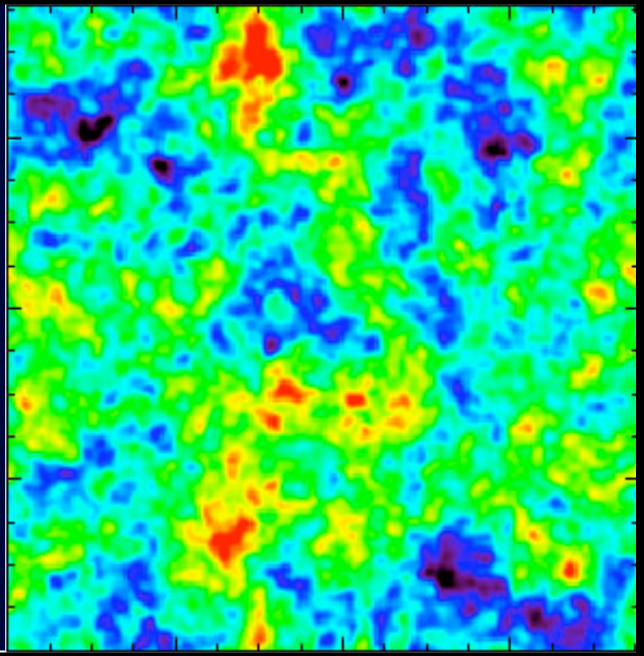

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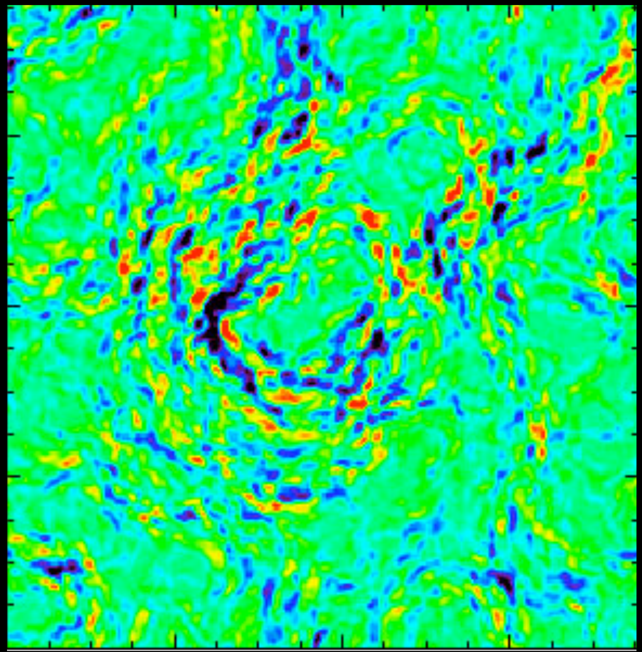
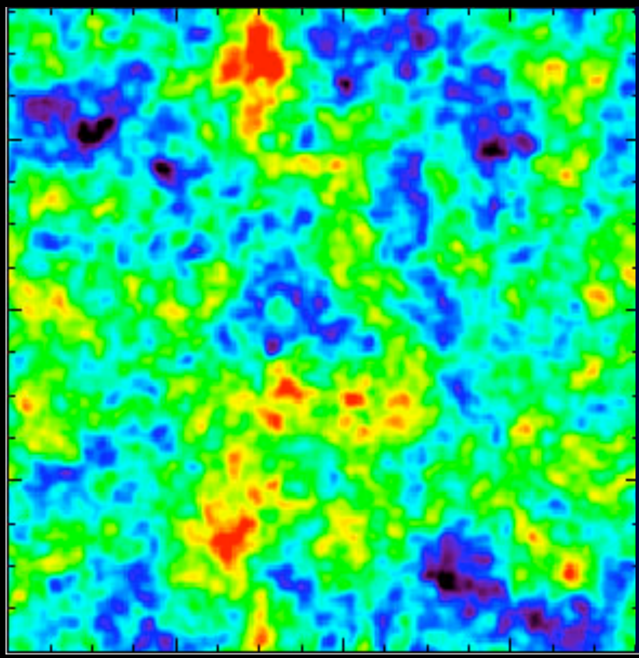


Weak Lensing of the Primary Bispectrum



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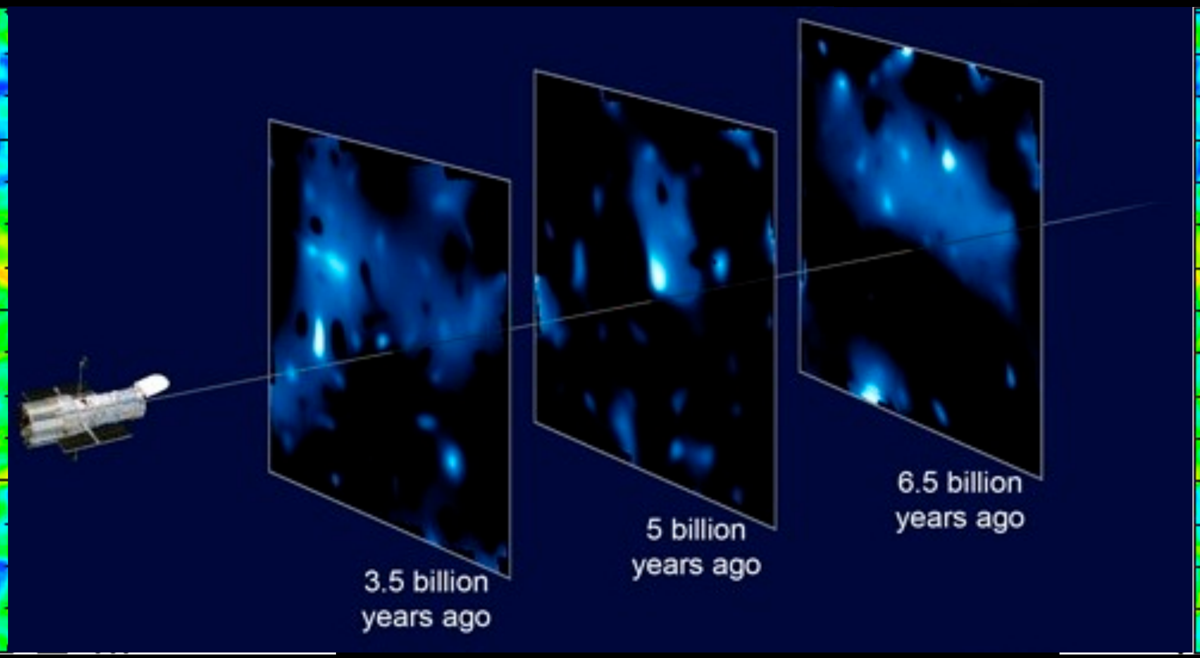

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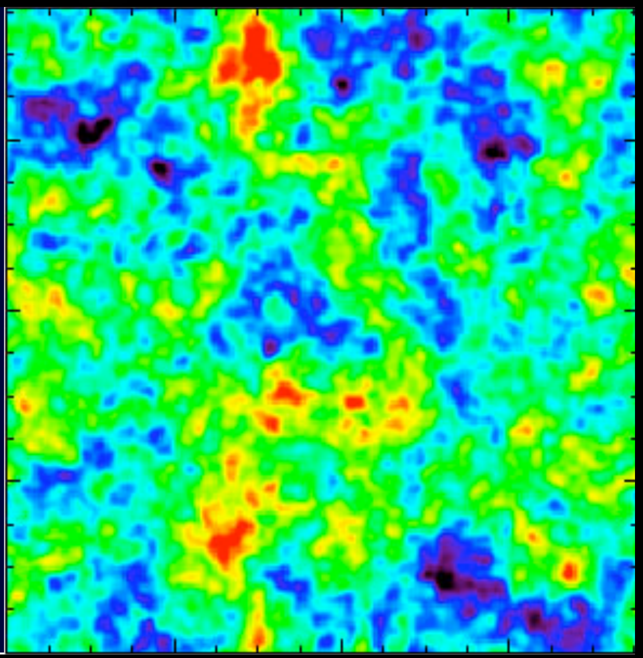

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\begin{aligned}
\tilde{\Theta}(\hat{\mathbf{n}}) &= \Theta[\hat{\mathbf{n}} + \hat{\alpha}] \\
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&\approx \Theta(\hat{\mathbf{n}}) + \nabla_i\phi(\hat{\mathbf{n}})\nabla^i\Theta(\hat{\mathbf{n}}) \\
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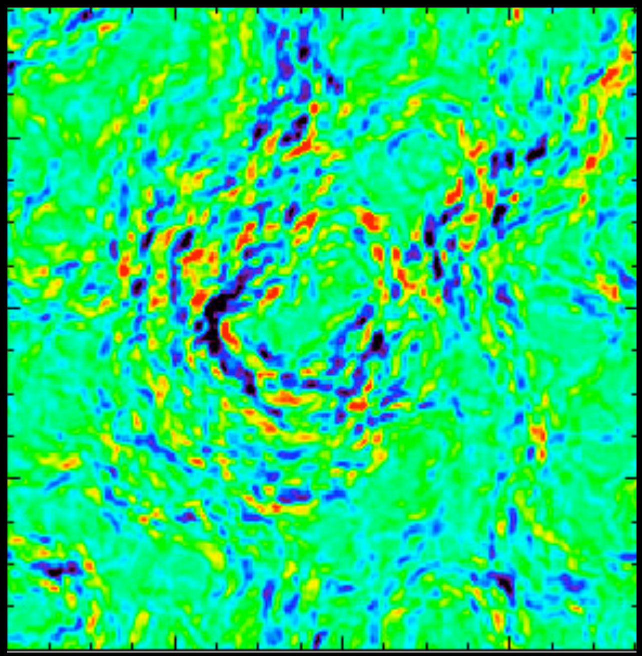

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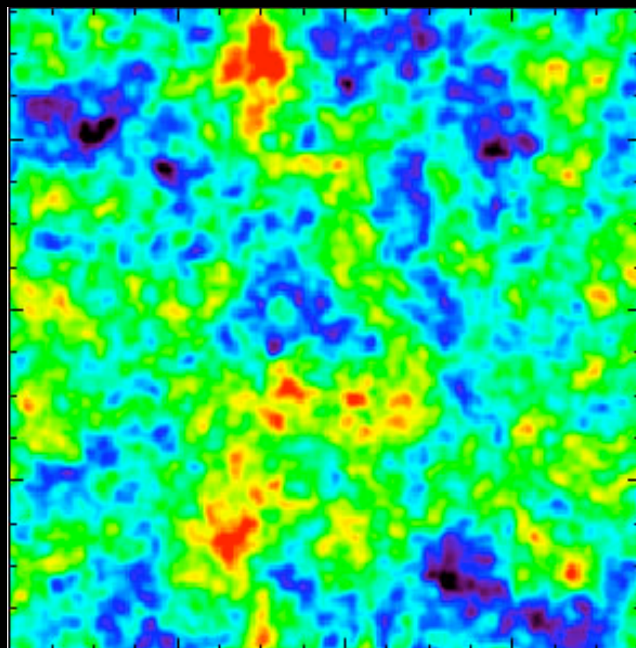

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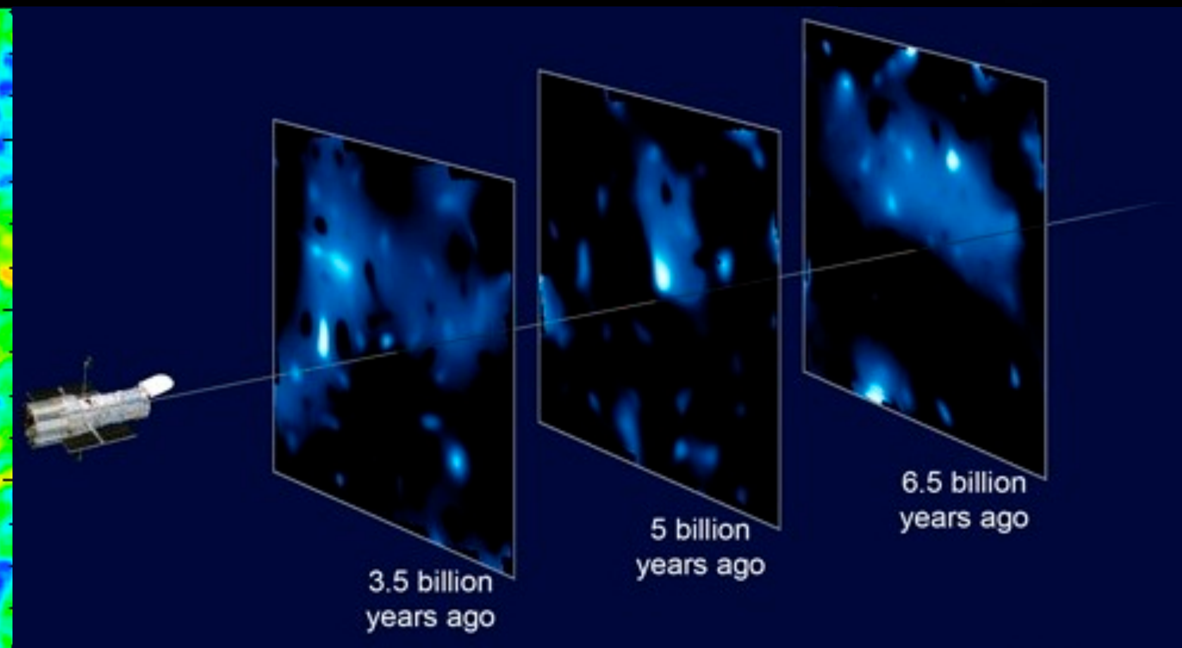

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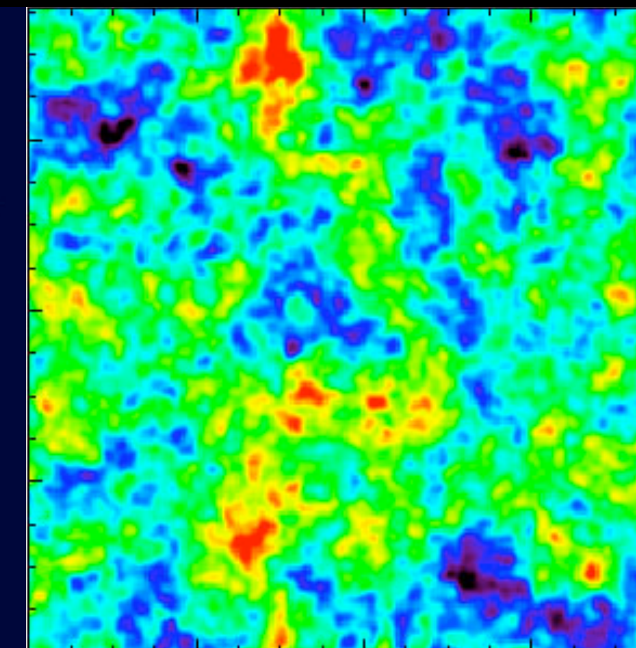

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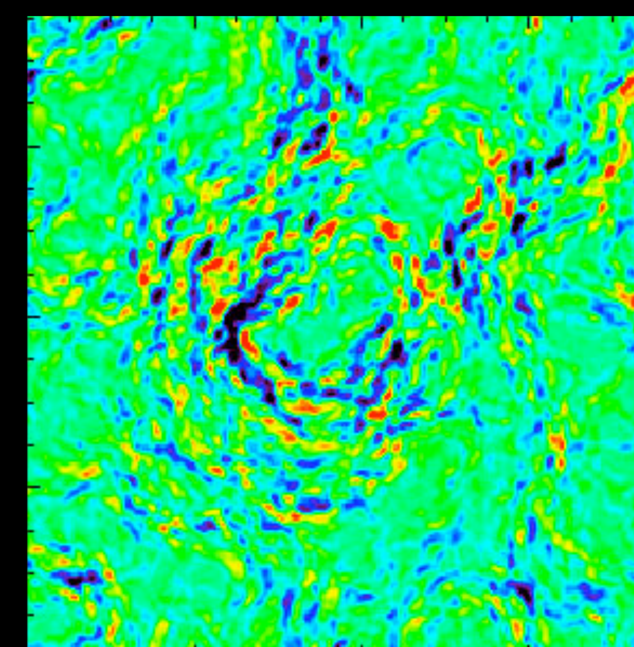

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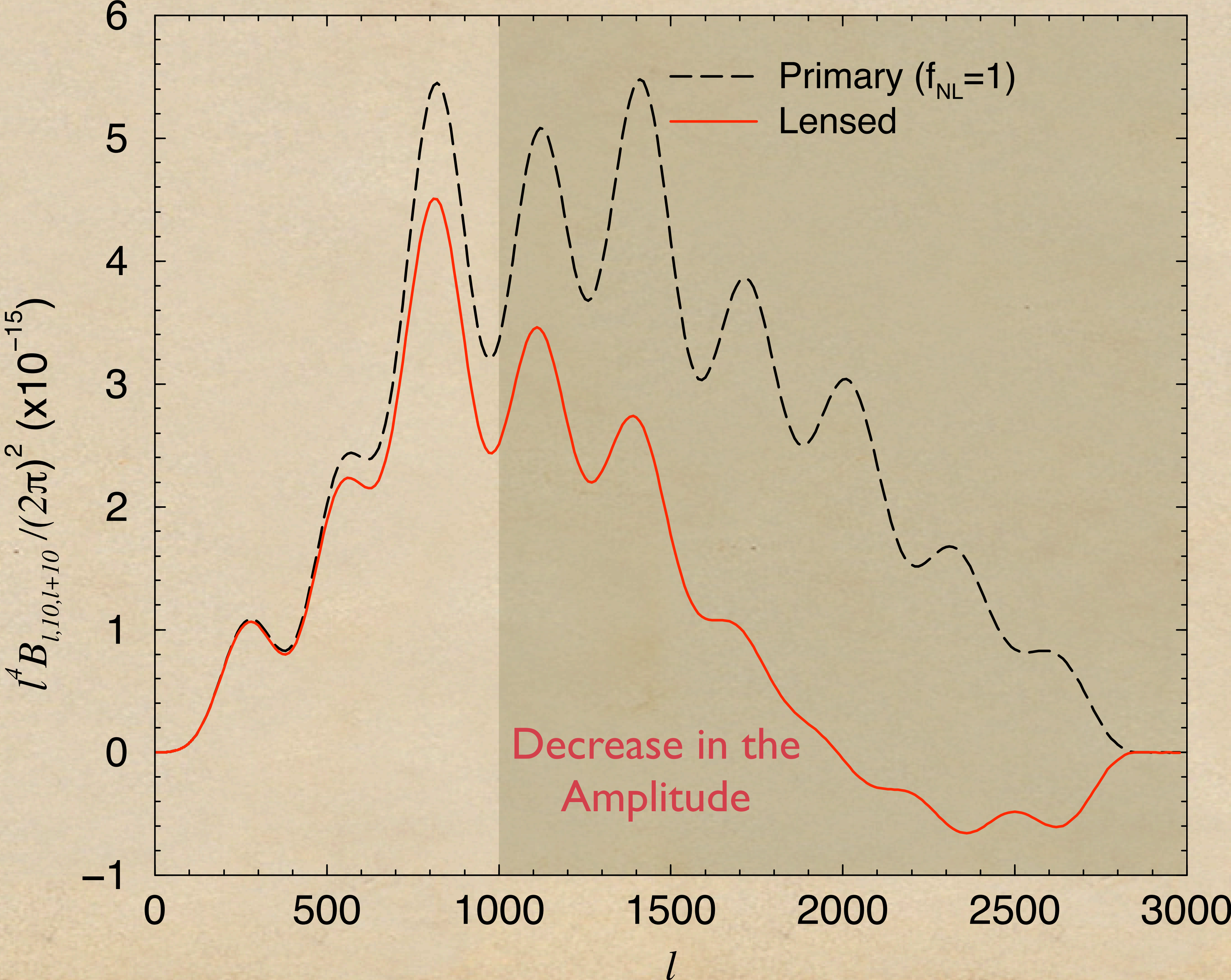
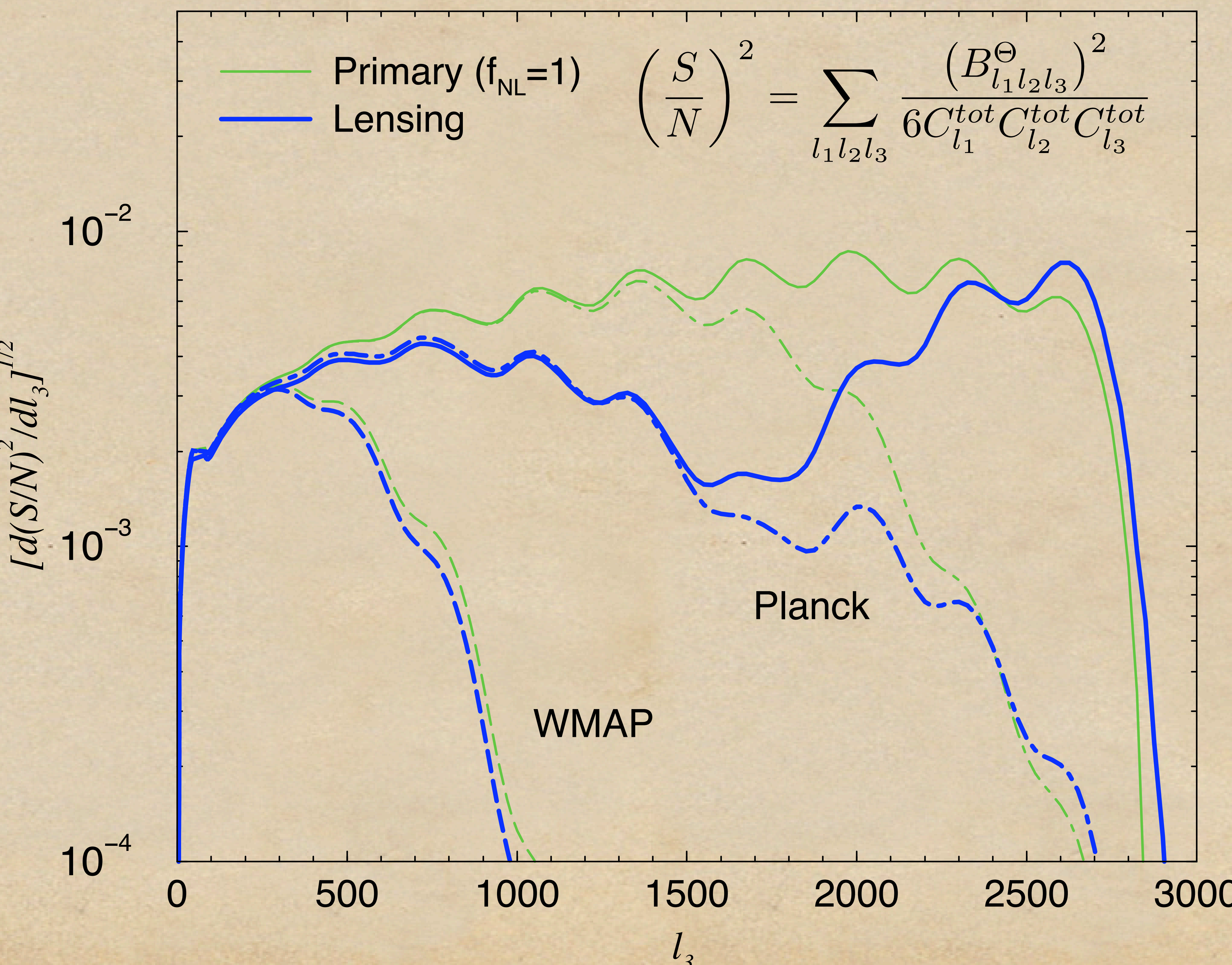
$$

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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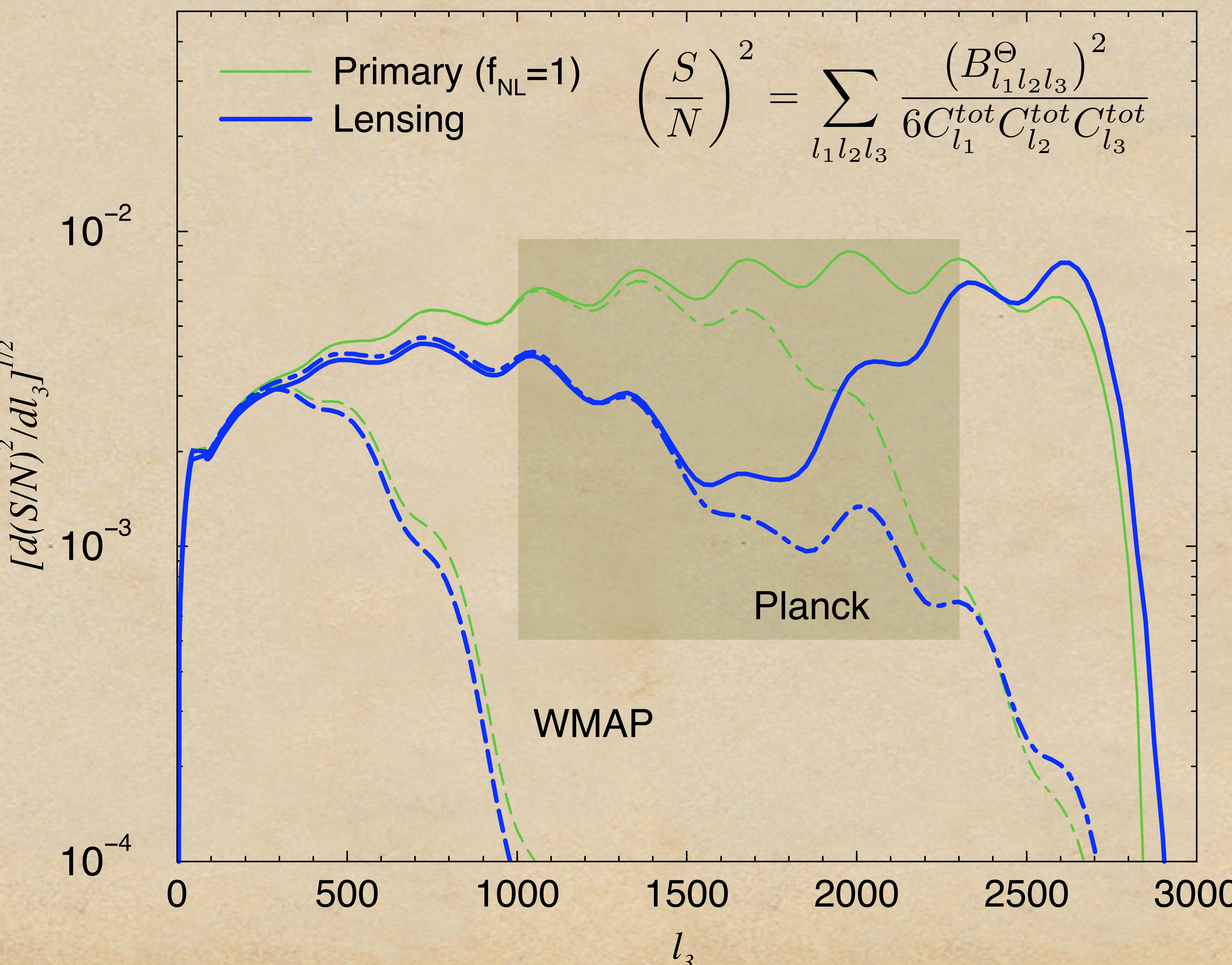

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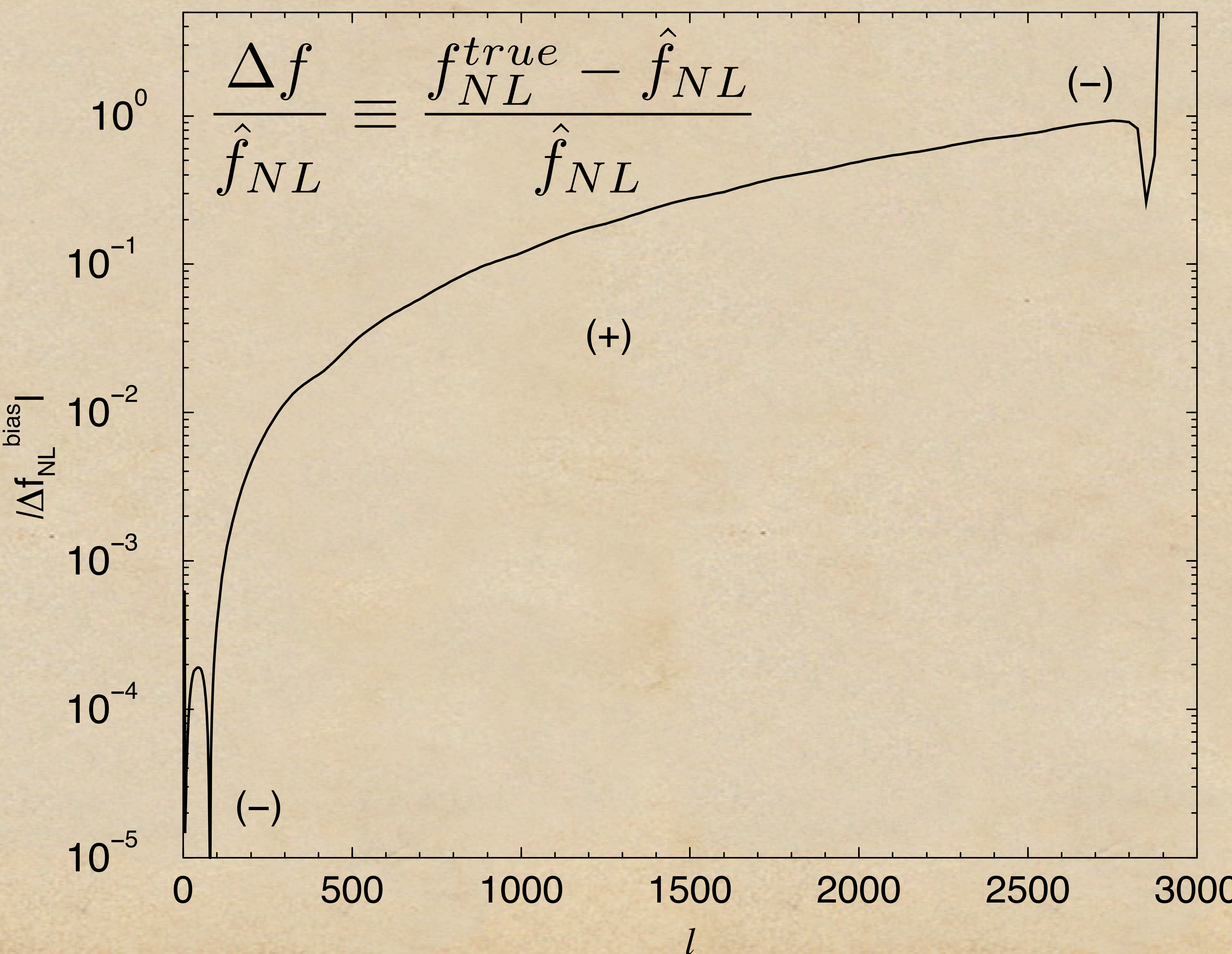
Bias in the non-Gaussian Parameter



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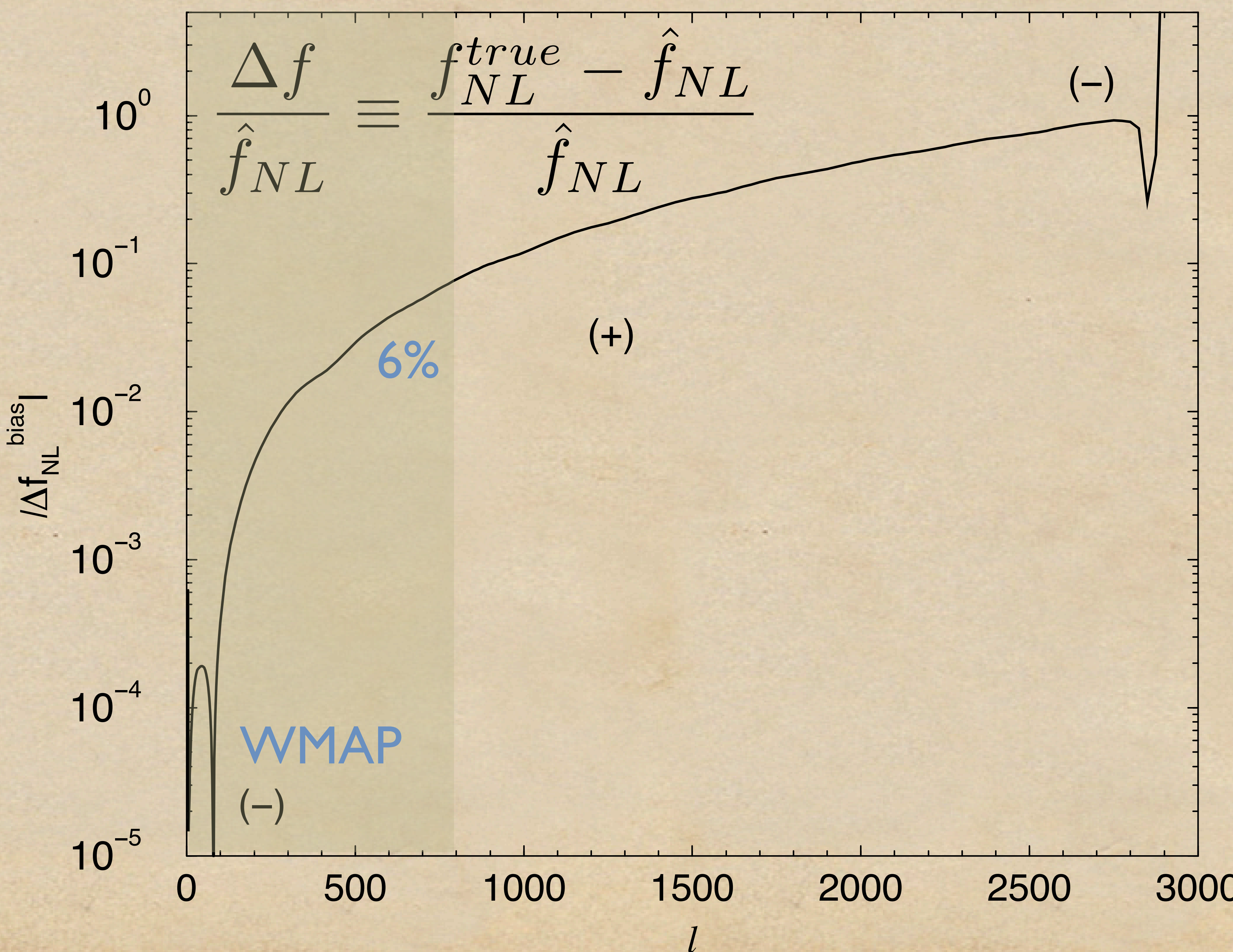

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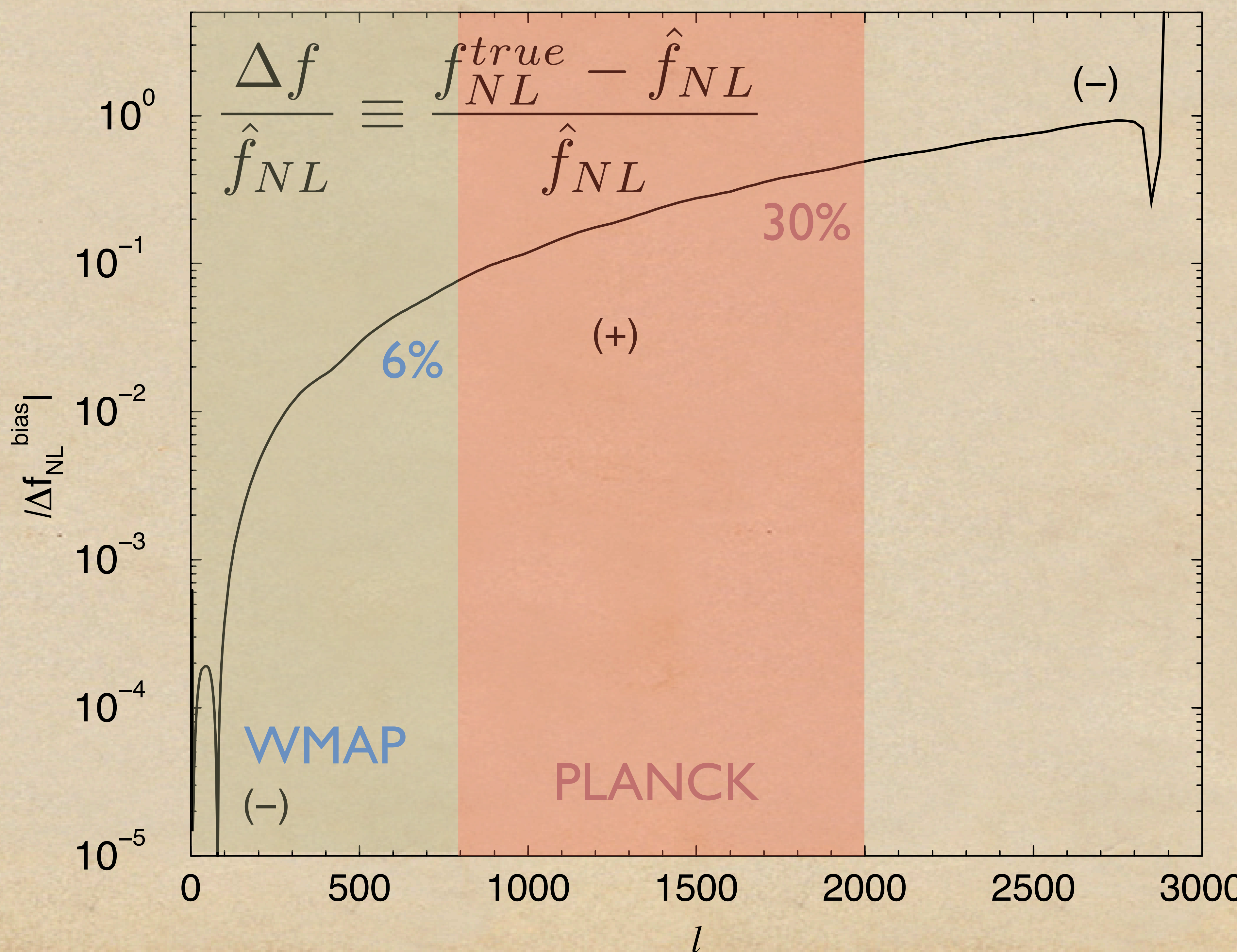

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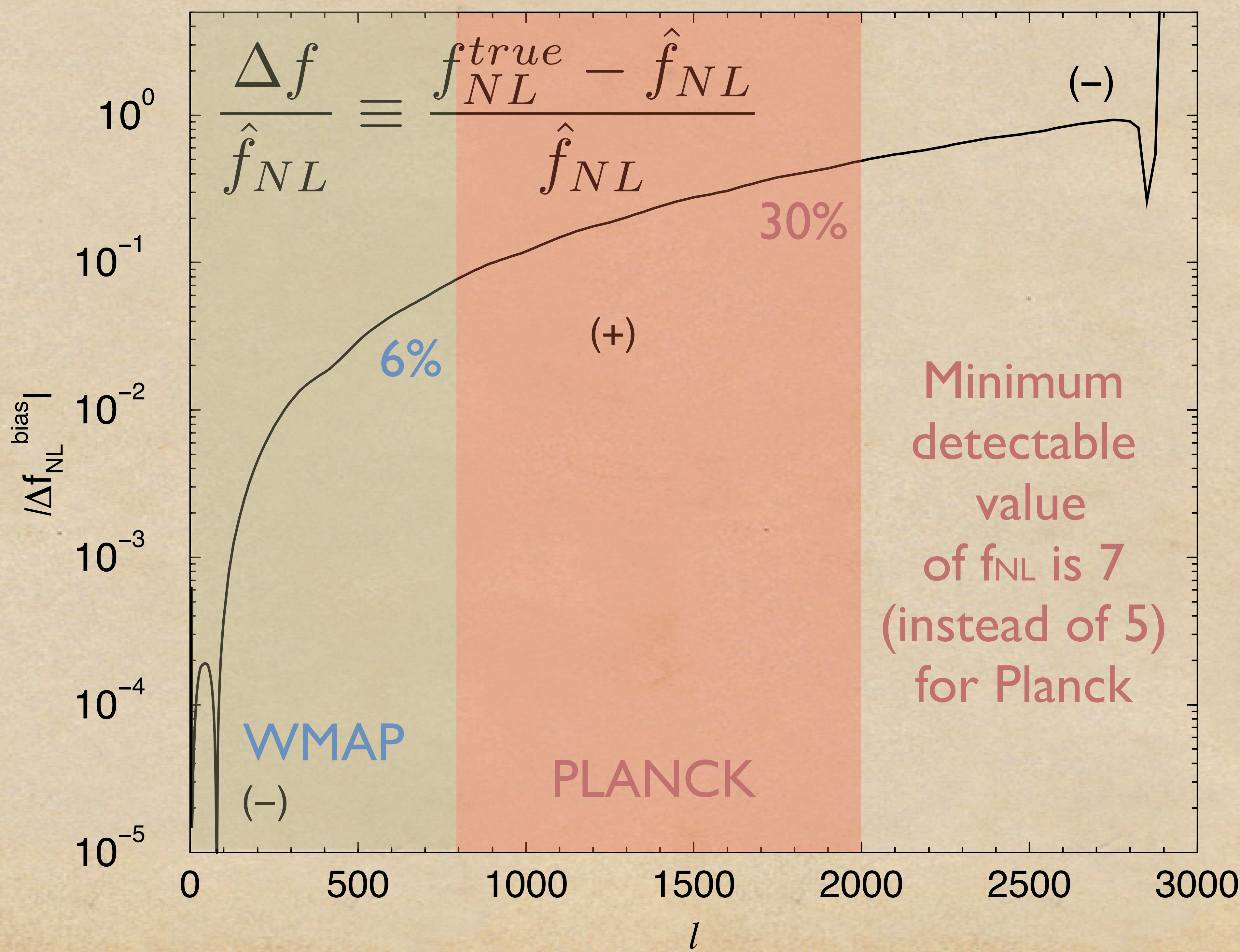
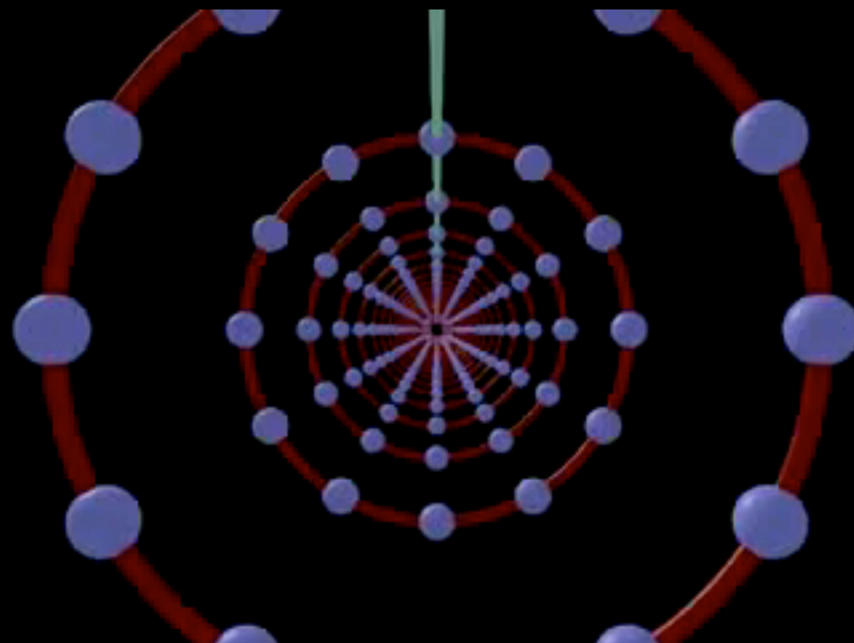


A. Cooray, D. Sarkar, and P. Serra; Phys. Rev. D, 77, 123006 (2008)

Gravitational Waves

Credit: Michael
Penn State Schuylkill



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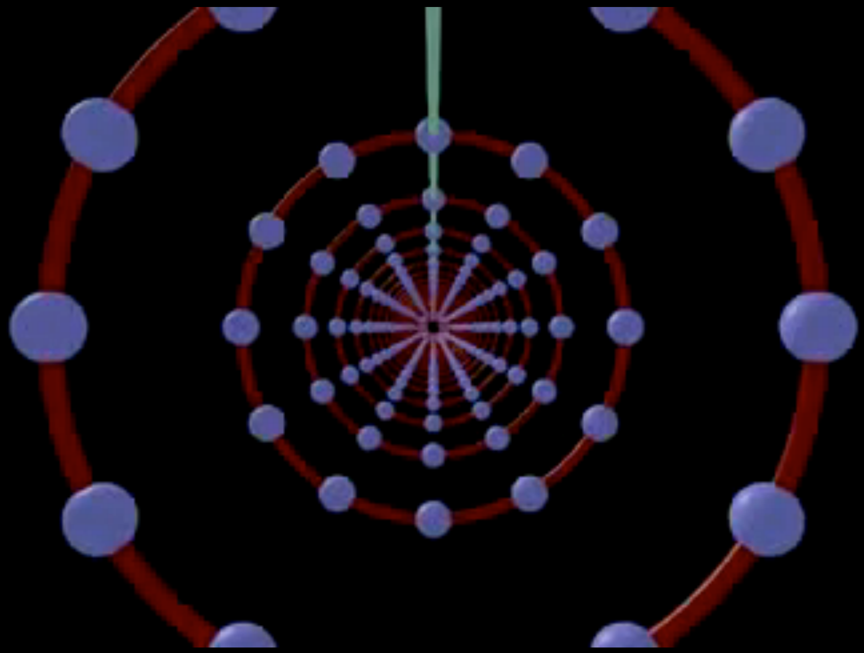

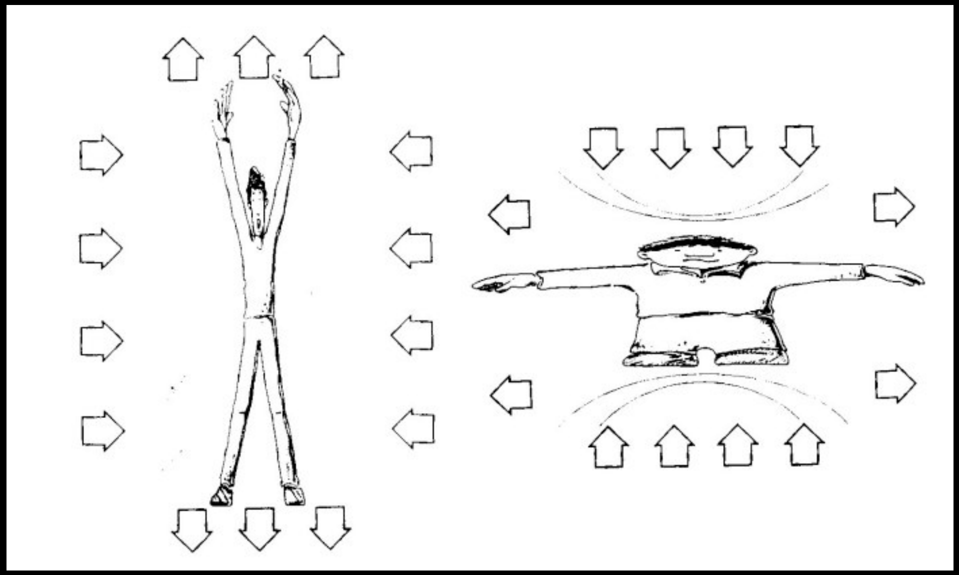

credit: http://www.lnl.infn.it/~auriga/

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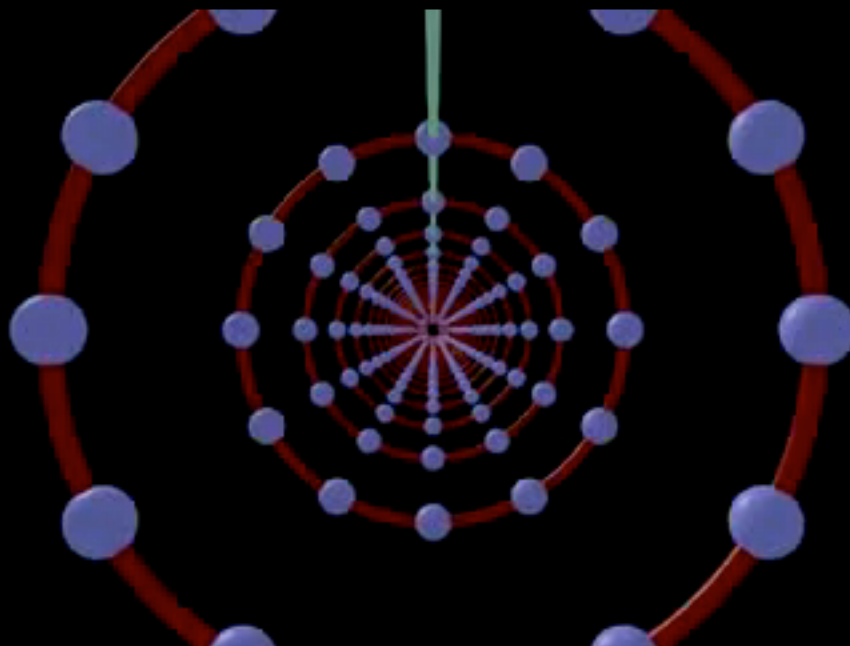
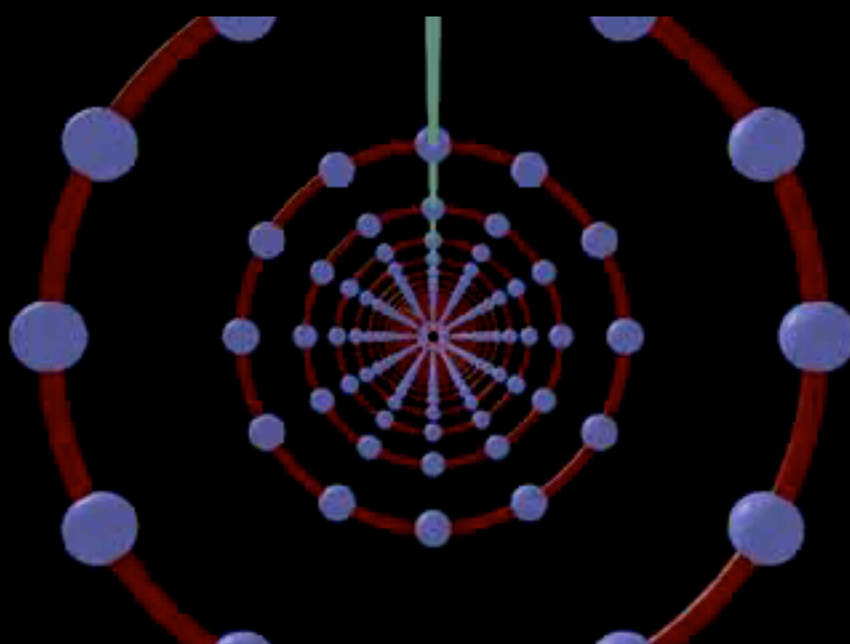
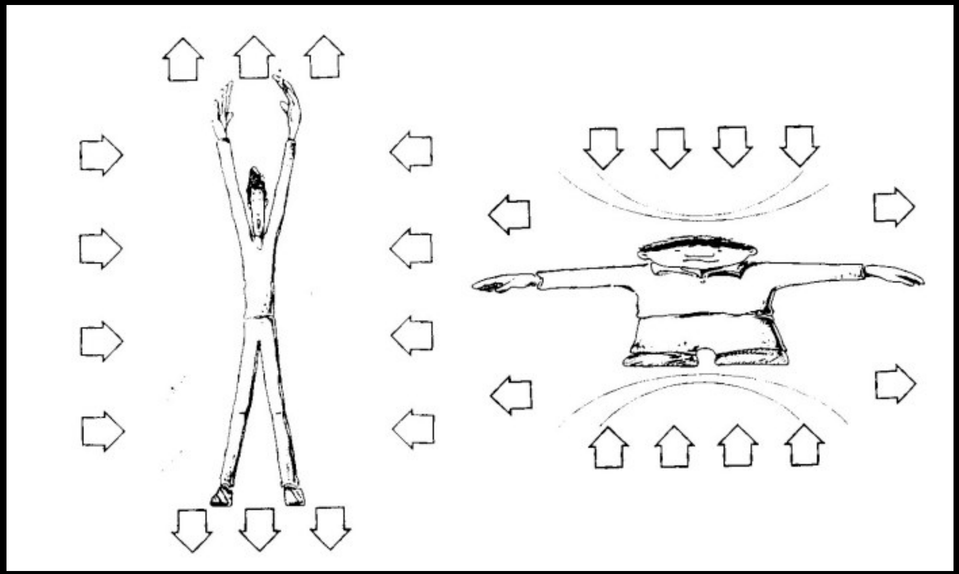


Credit: Michael
Penn State Schuylkill

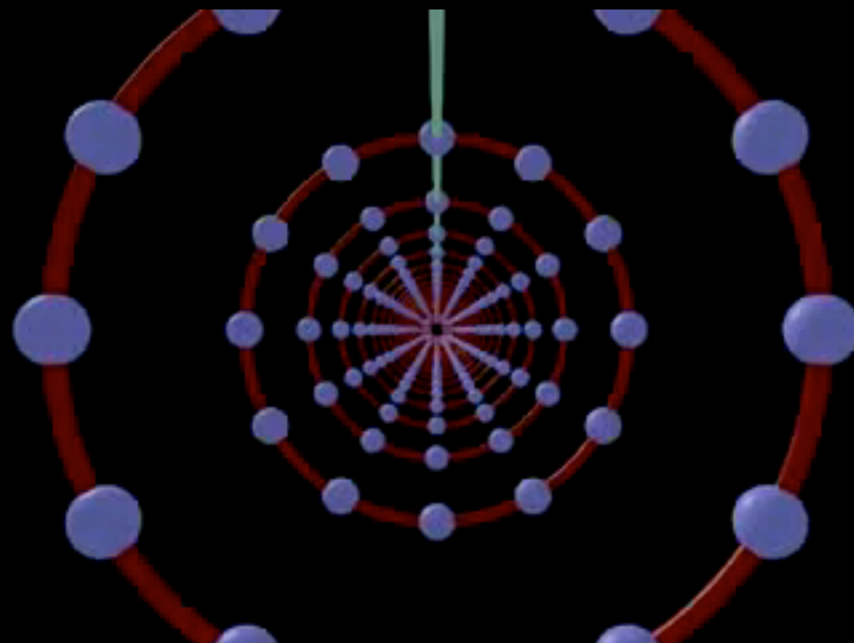




credit: http://www.lnl.infn.it/~auriga/

Gravitational Waves

Credit: Michael
Penn State Schuylkill



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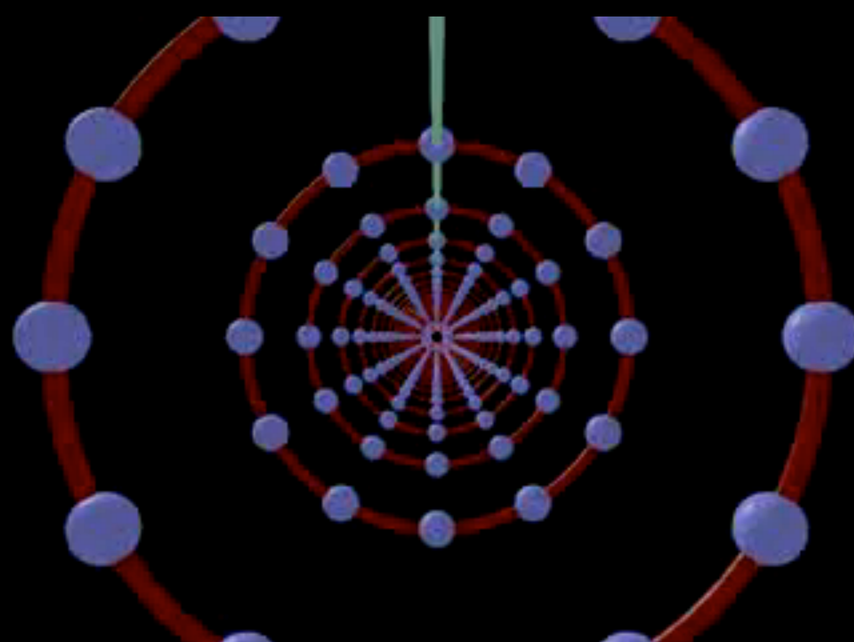
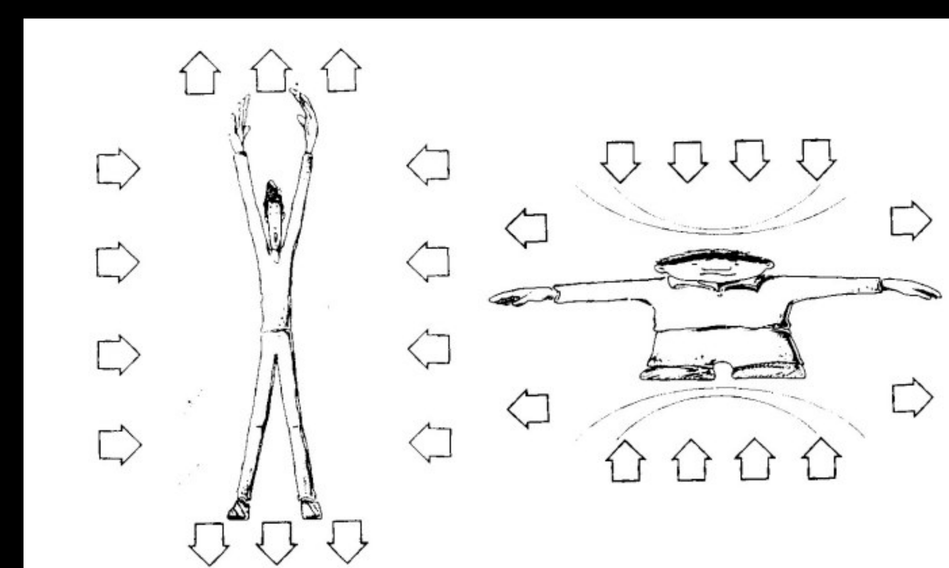


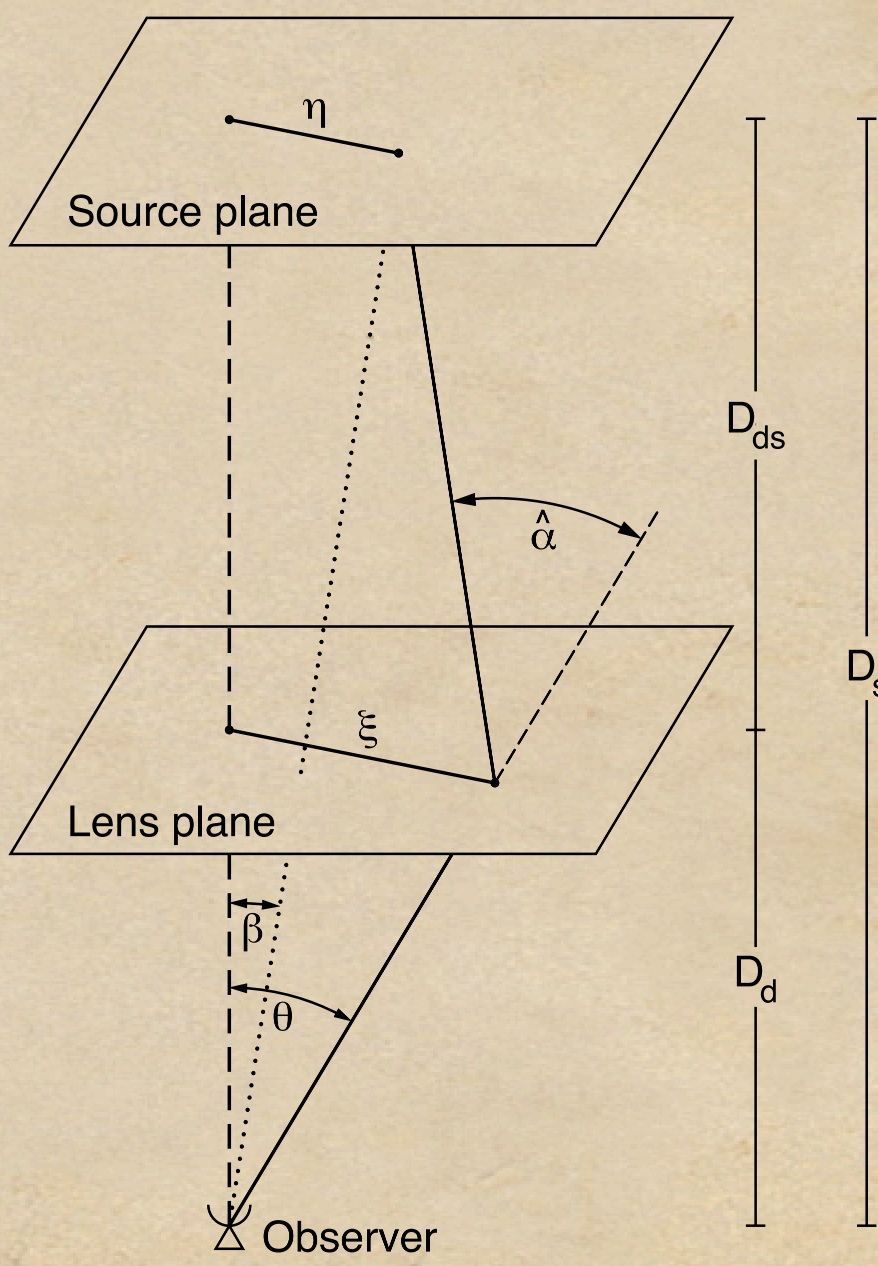


credit: http://www.lnl.infn.it/~auriga/

Gravitational Lensing and GW

The Deflection:

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



Credit: Bartelmann and Schneider 2001

Gravitational Lensing and GW

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

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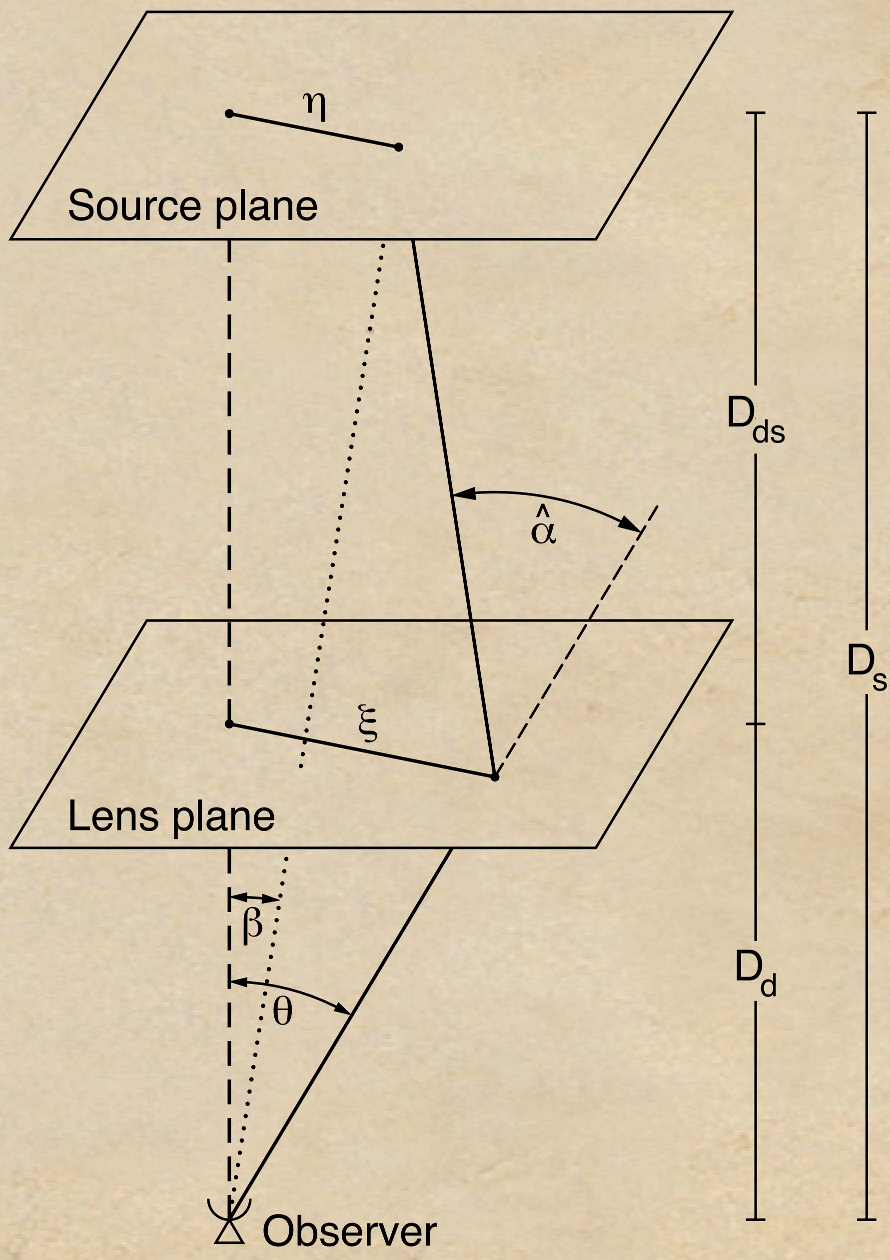

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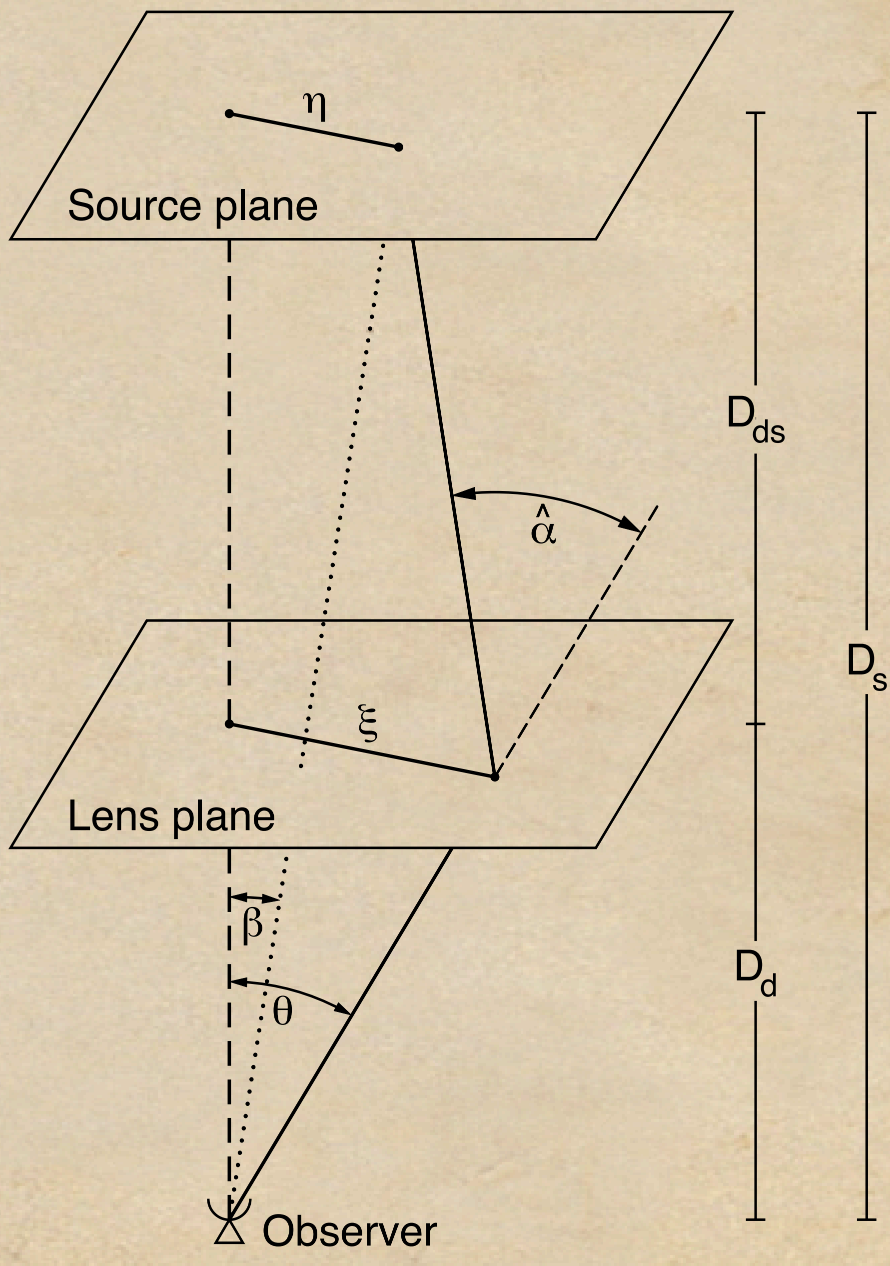

Credit: Bartelmann and Schneider 2001

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

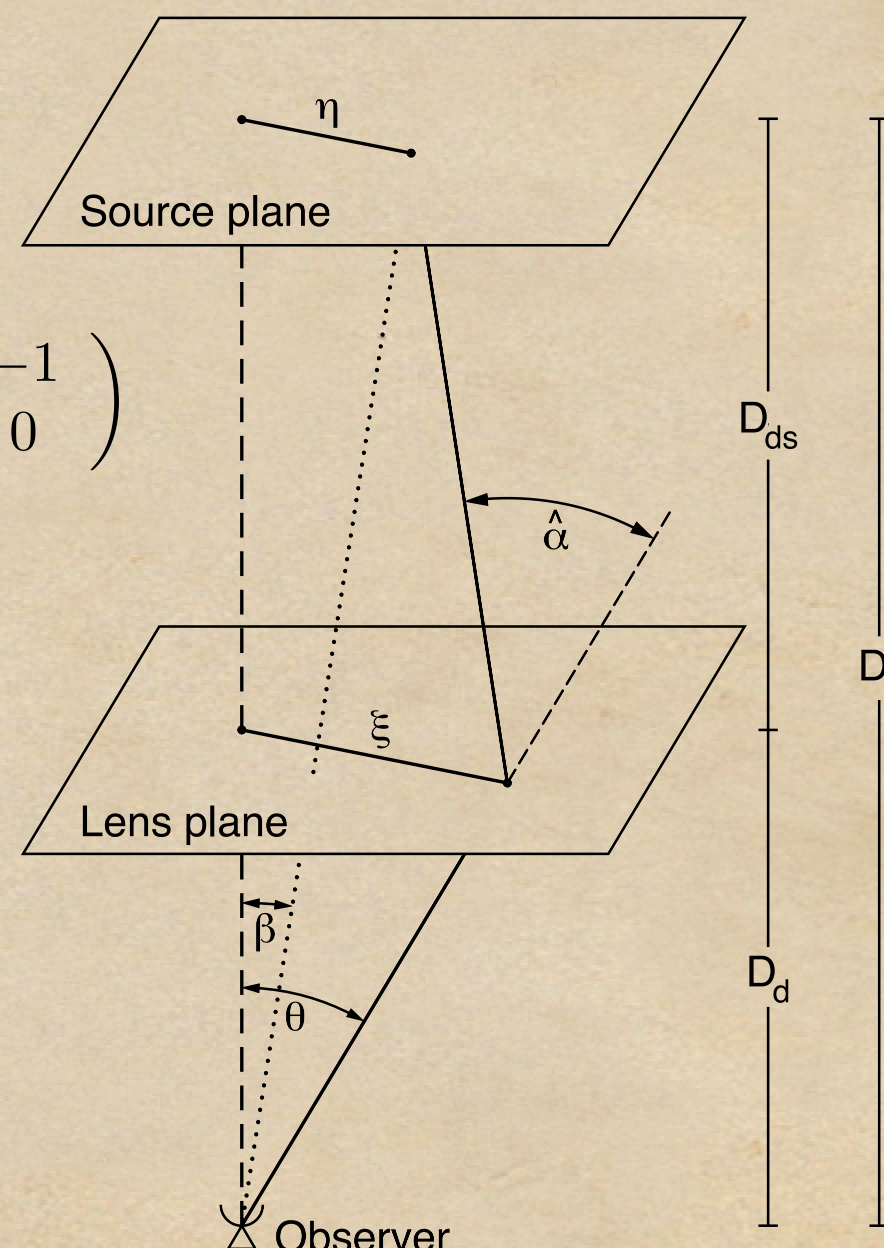
$$\mathcal{A}_{ij} = \frac{\partial x_i^S}{\partial x_j^I}$$

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

trace

symmetric traceless

antisymmetric rotation



Credit: Bartelmann and Schneider 2001

Gravitational Lensing and GW

The Deflection:

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

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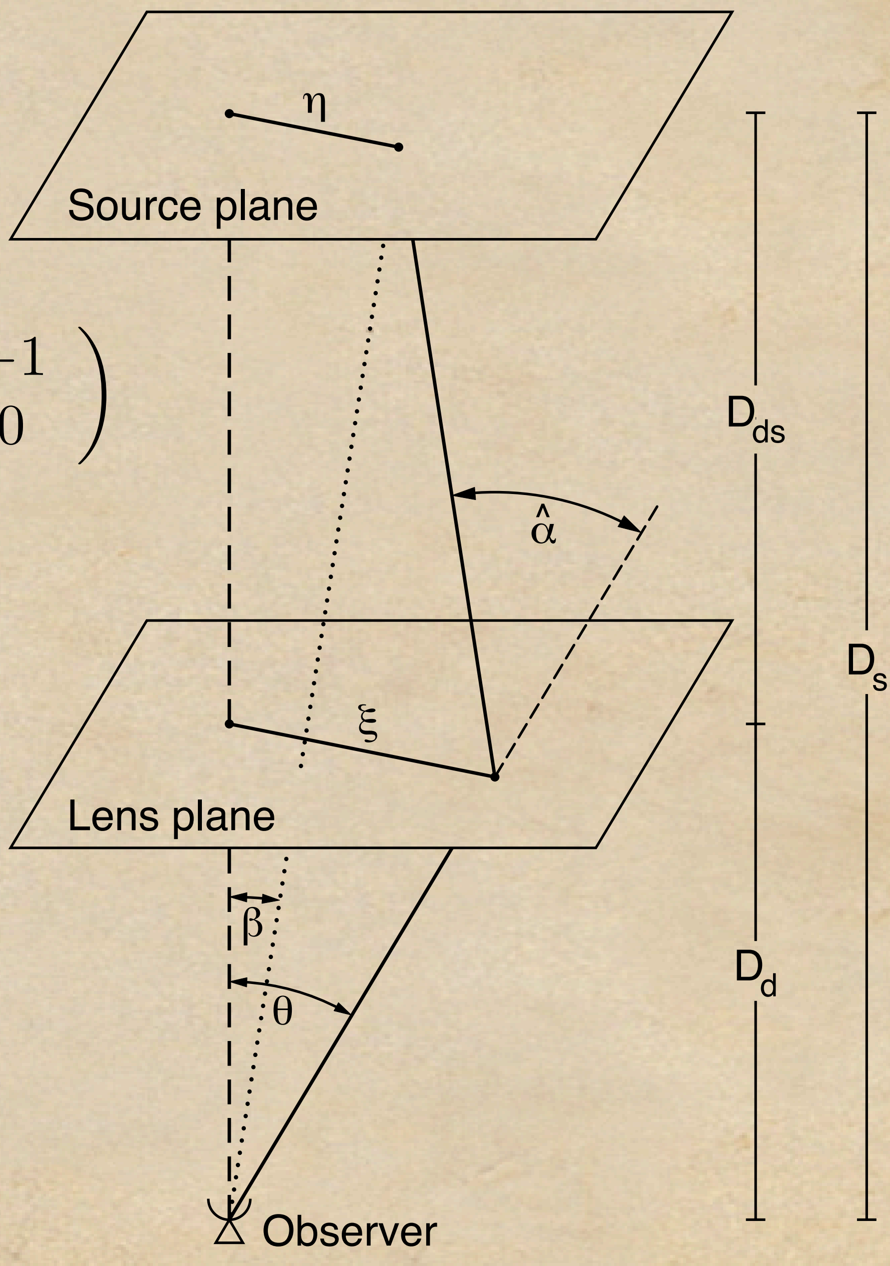

Credit: Bartelmann and Schneider 2001

At the End of the Hour...

Dark Energy

- Why Pursue Dark Energy?
- DE Equation of State (EOS)
- DE from SNe Ia ++
- Beware of Systematics
  - Two Population Model
  - Gravitational Lensing

CMB Bispectrum

- Why Non-Gaussianity?
- Why in CMB Bispectrum?
- The f_{NL}
- WL of CMB Bispectrum
  - Analytical Sketch
  - Numerical Results

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Summary

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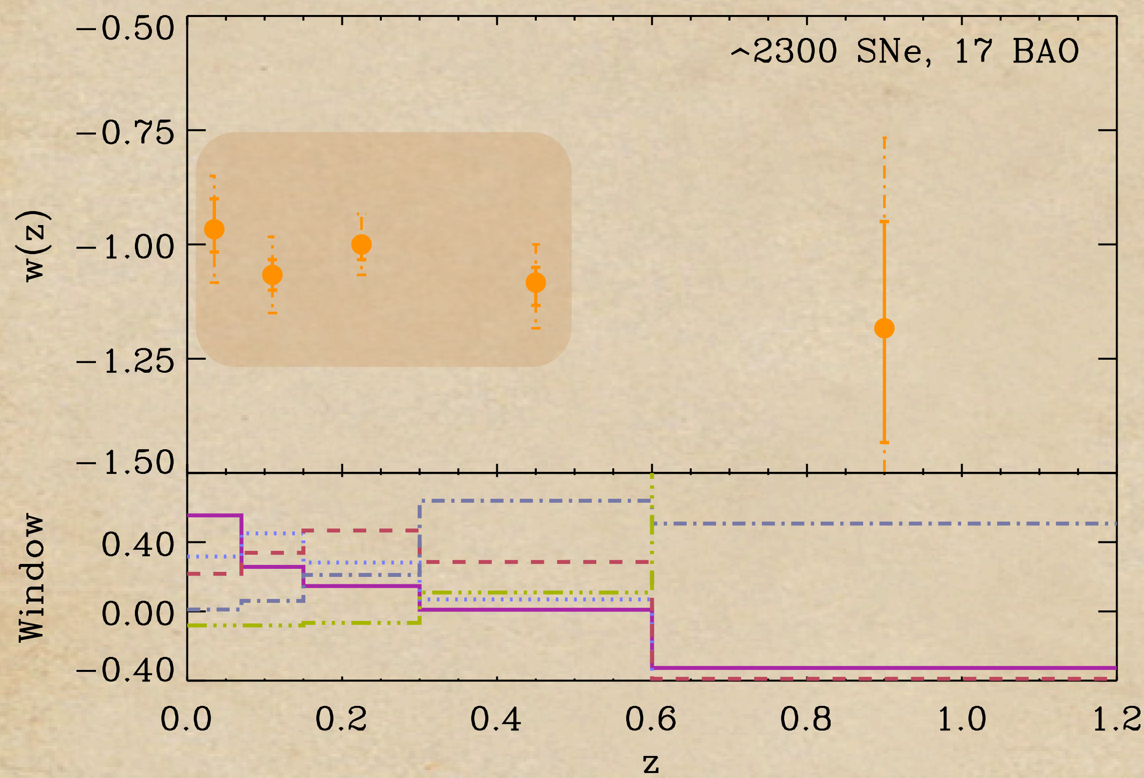
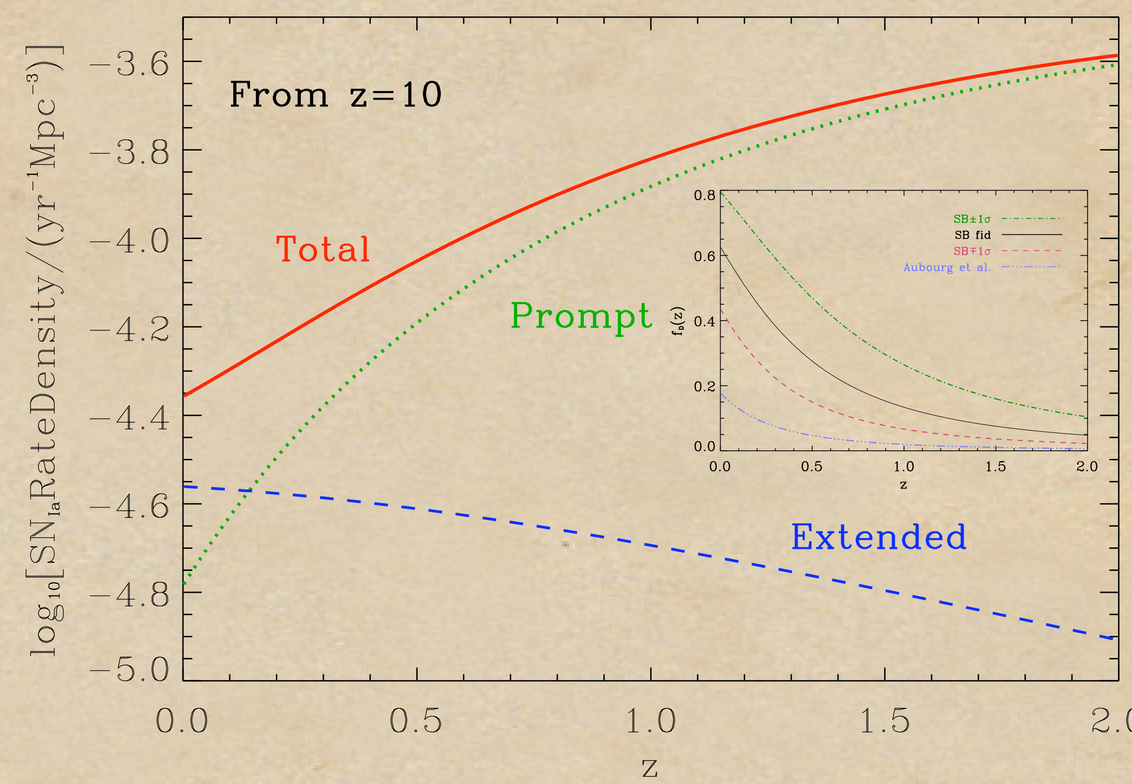
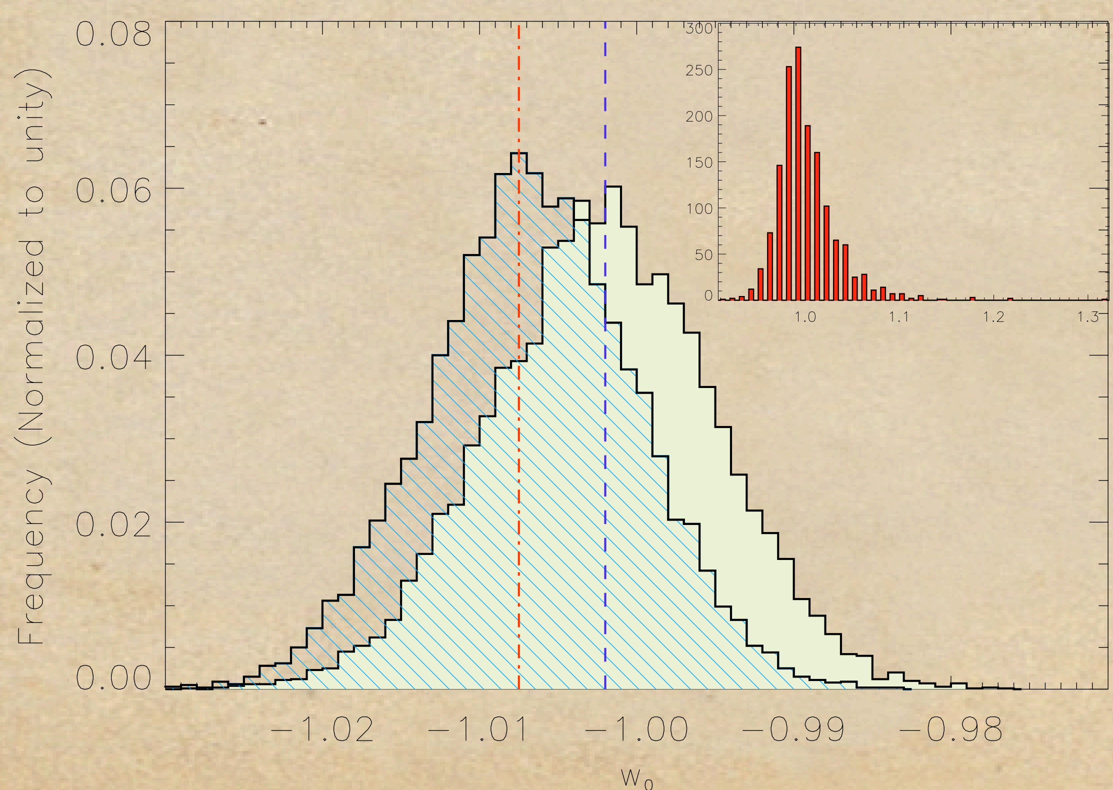
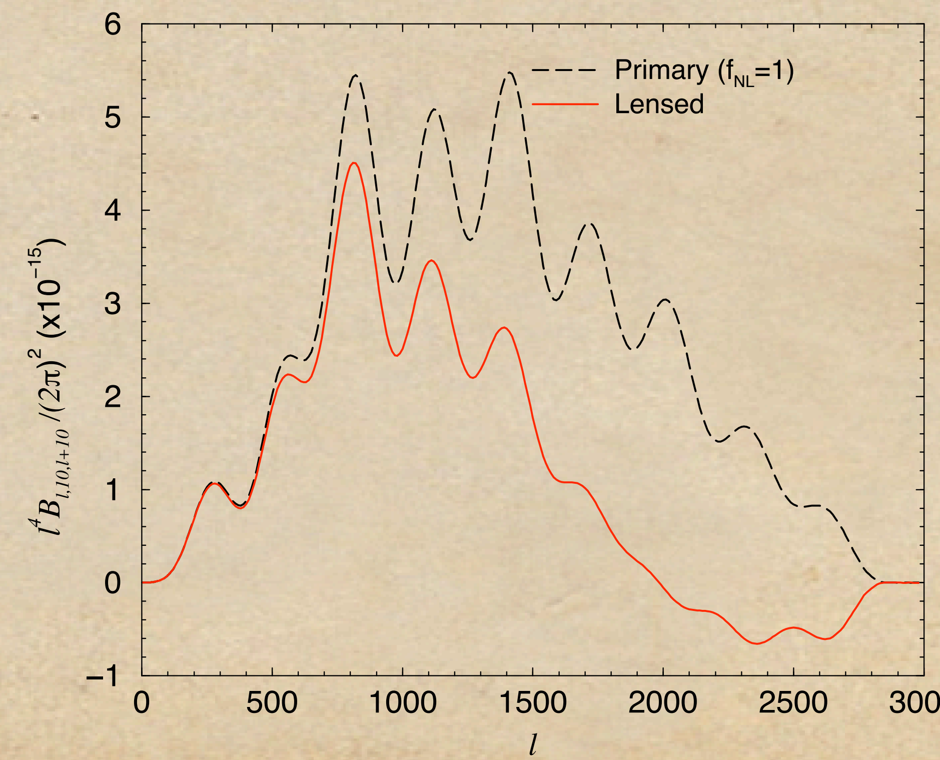

~2300 SNe, 17 BAO
w(z)
−0.50
−0.75
−1.00
−1.25
−1.50
Window
0.40
0.00
−0.40
0.0
0.2
0.4
0.6
0.8
1.0
1.2
z

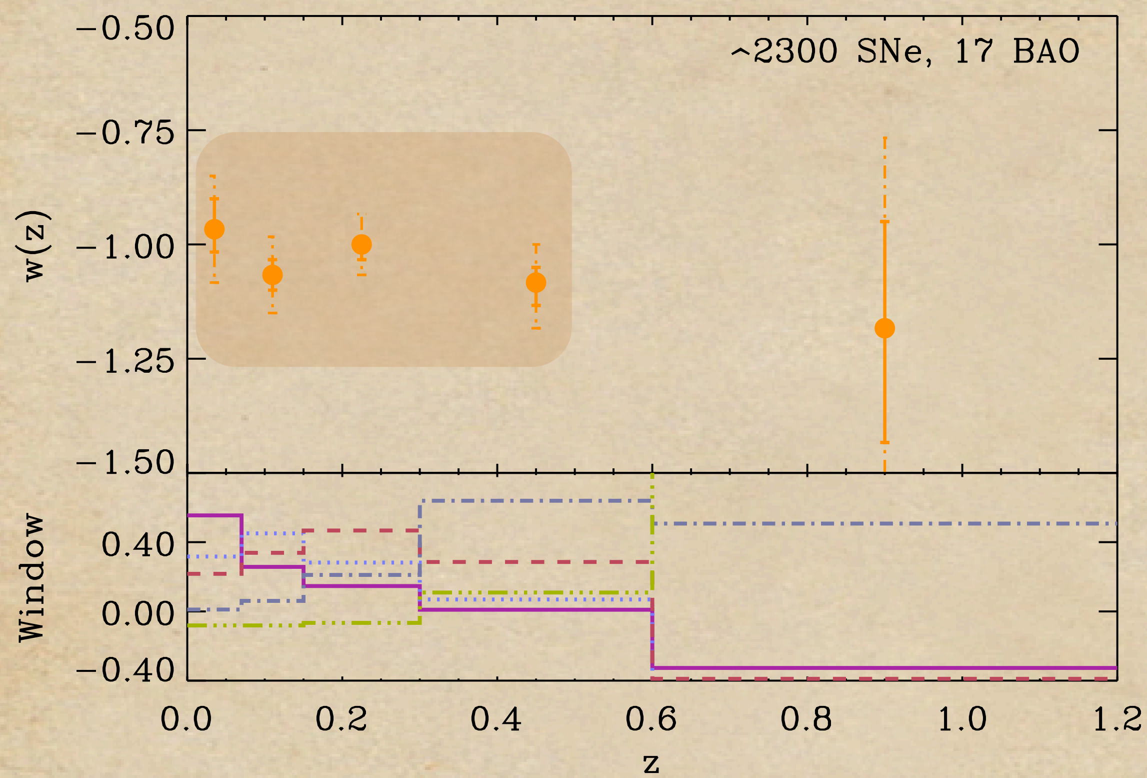

From z=10
Total
Prompt
Extended
$\log_{10}[\mathrm{SN_{Ia}RateDensity}/(\mathrm{yr}^{-1}\mathrm{Mpc}^{-3})]$
−3.6
−3.8
−4.0
−4.2
−4.4
−4.6
−4.8
−5.0
0.0
0.5
1.0
1.5
2.0
z

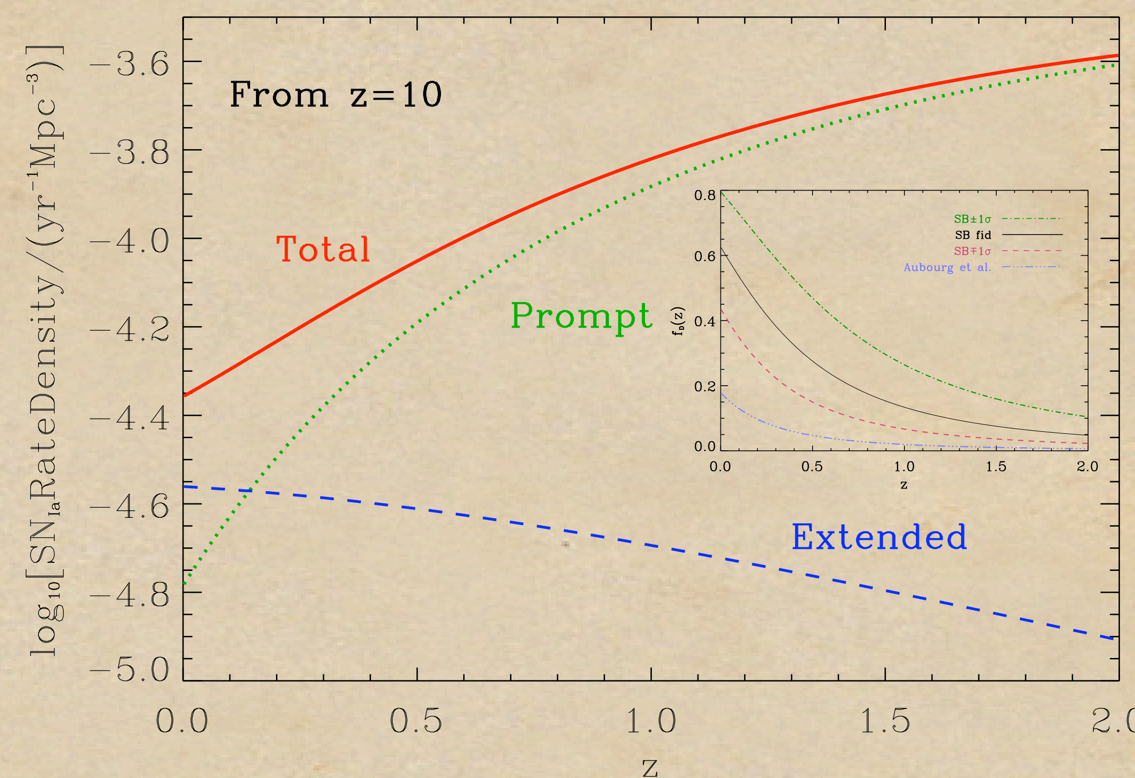

Frequency (Normalized to unity)
0.08
0.06
0.04
0.02
0.00
−1.02
−1.01
−1.00
−0.99
−0.98
w_0

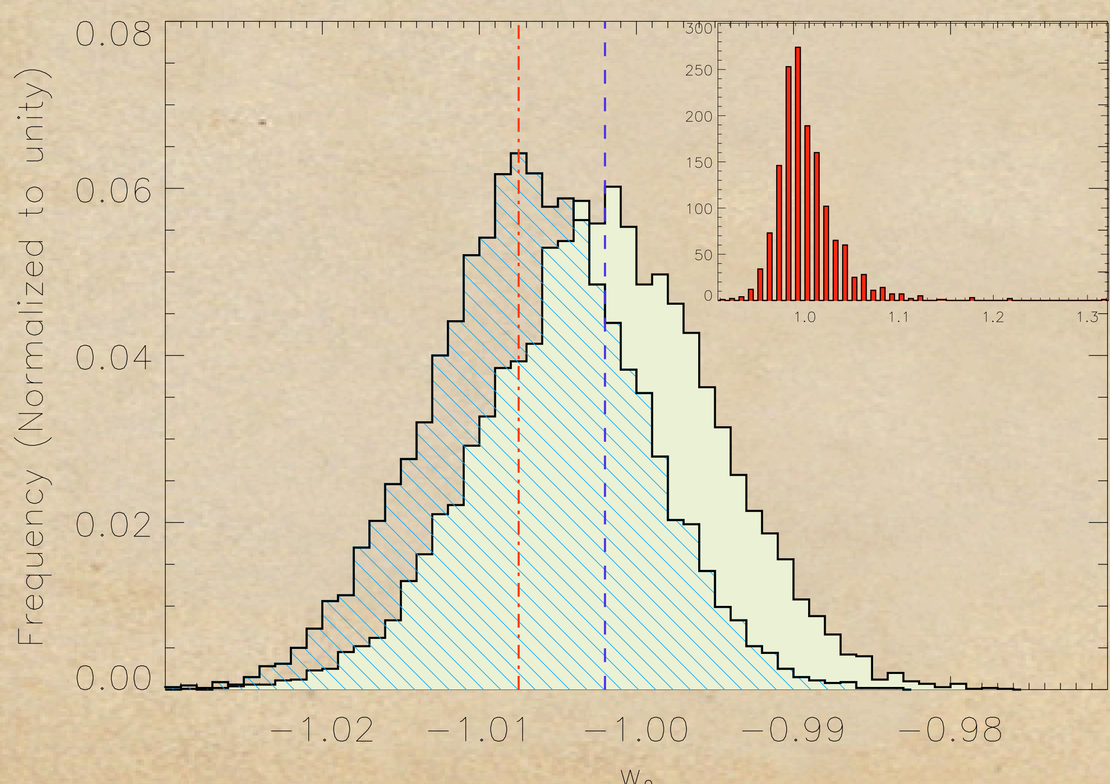

Primary (f_{NL}=1)
Lensed
$l^4 B_{l,10,l+10}/(2\pi)^2$ ($\times 10^{-15}$)
6
5
4
3
2
1
0
−1
0
500
1000
1500
2000
2500
3000
l

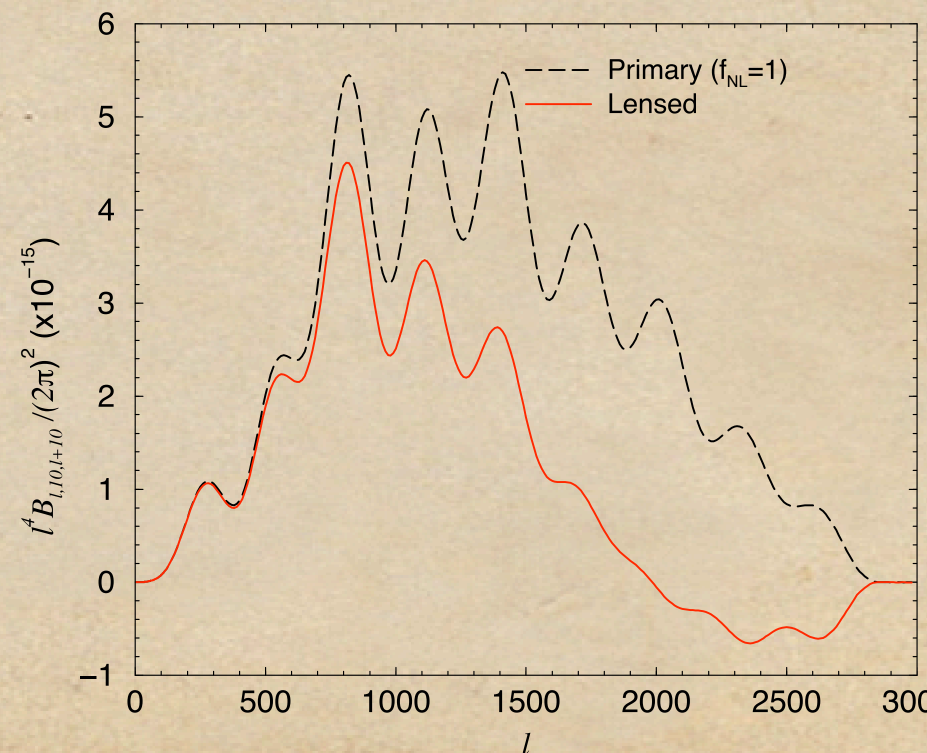
DSARKAR.ORG

Summary


~2300 SNe, 17 BAO
w(z)
Window
z


From z=10
Total
Prompt
Extended
$\log_{10}[\mathrm{SN_{Ia}RateDensity}/(\mathrm{yr^{-1}Mpc^{-3}})]$
z


Frequency (Normalized to unity)
w_0


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

Summary

- We have shown that the next-generation surveys will be able to constrain the dark energy equation of state in three or more independent redshift bins to better than 10%.

- We have found that a post-calibration shift in the standard candle brightness between delayed and prompt SNe can introduce bias in the best-fit dark energy parameters. By controlling the magnitude of any resulting two-population difference to better than 0.025 mag, the bias can be kept under 1-σ for a JDEM-like survey without significantly degrading the accuracy of the dark energy measurements.

- For a JDEM-like survey, we have shown that the bias in the equation of state measurement is less than a percent level (so long as all the SNe are used in the Hubble diagram).

- We have discussed the lensing modification to the CMB bispectrum and demonstrated that lensing leads to an overall decrease in the amplitude of the primary bispectrum at multipoles of interest between 100 and 2000 through additional smoothing introduced by lensing. For a high resolution experiment such as Planck, the lensing modification to the bispectrum must be properly included when attempting to estimate the primordial non-Gaussianity. An ignorance will bias the estimate at the level of 30%.

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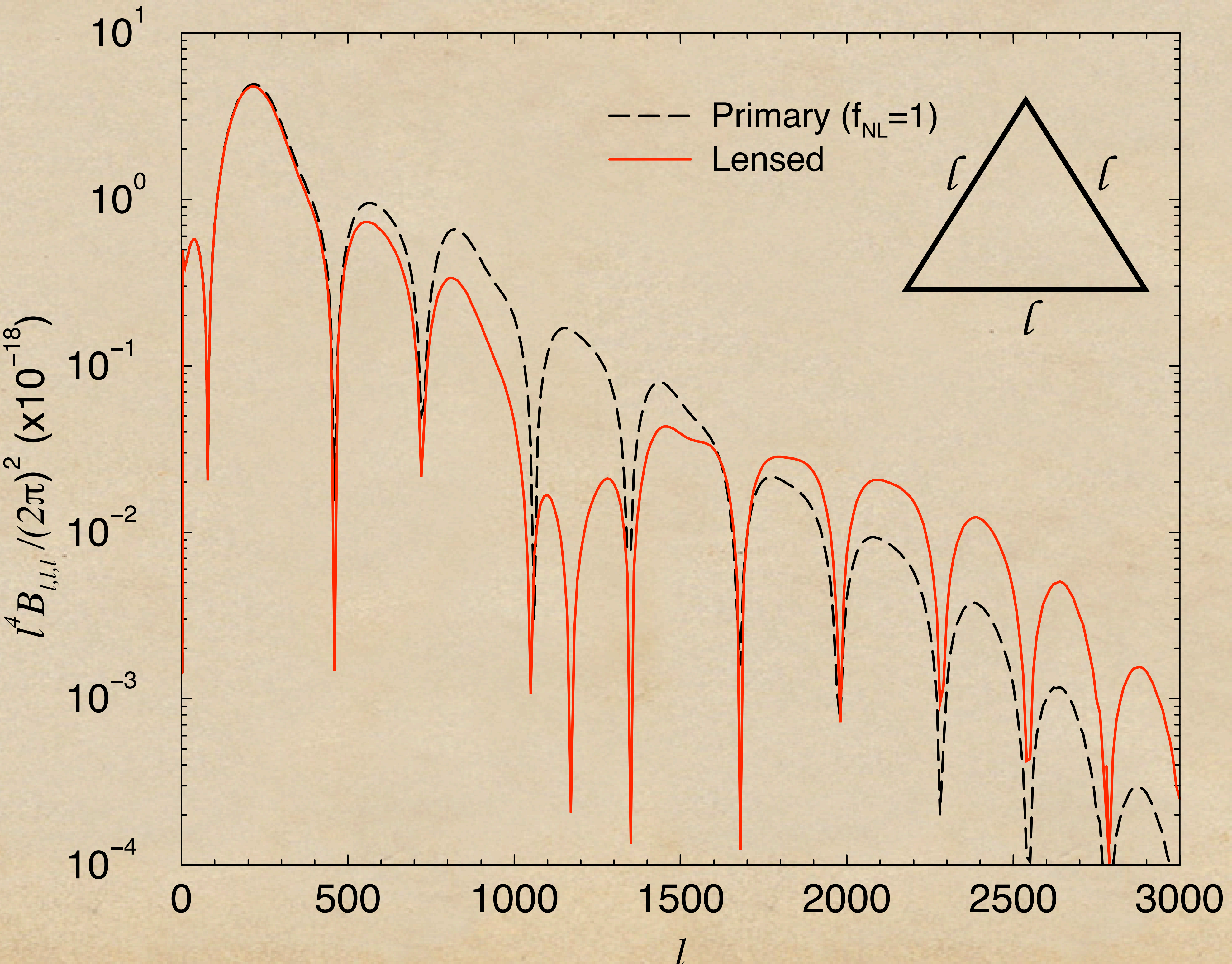
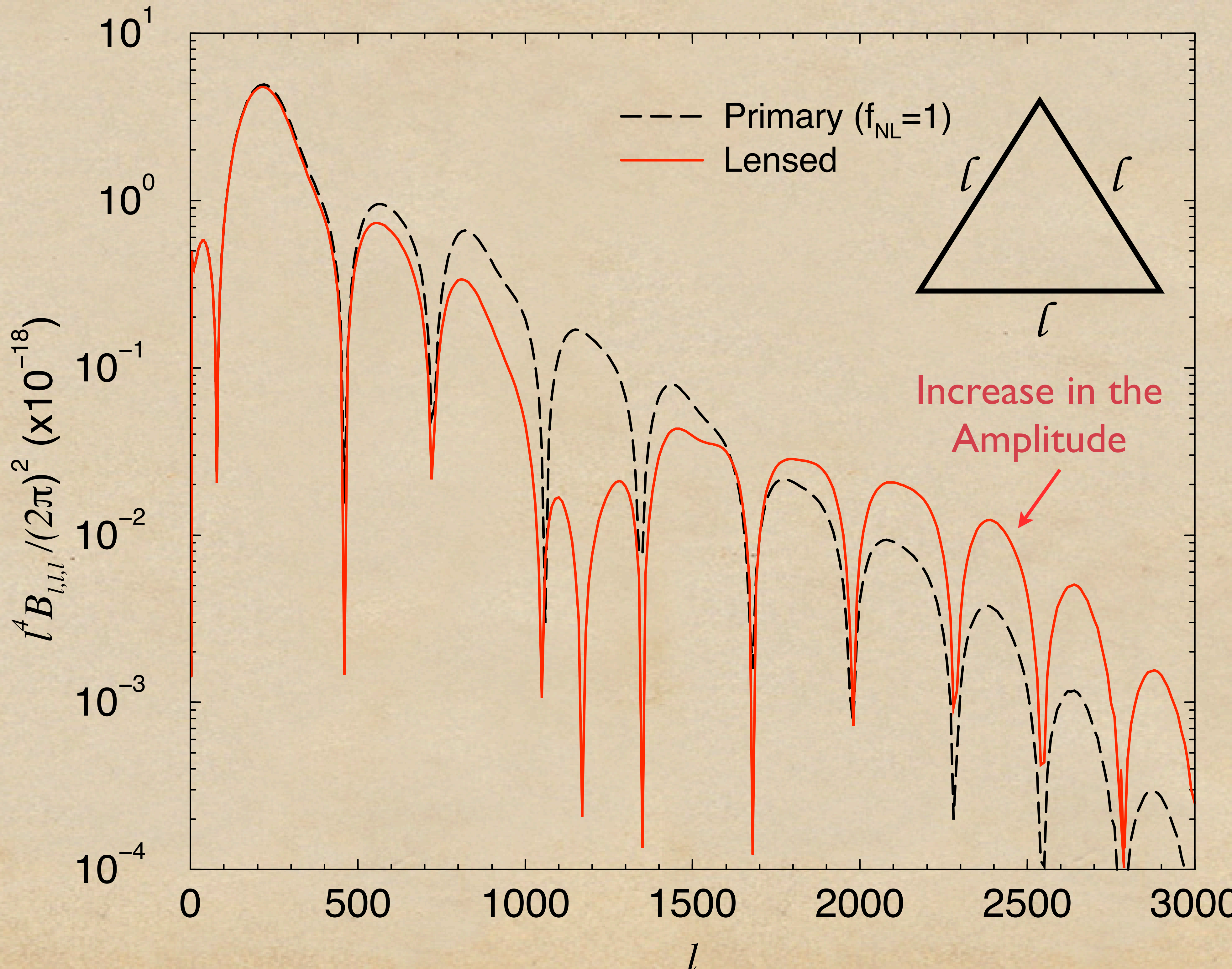
XTRA SLIDES

CMB Bispectrum of the equilateral case



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

CMB Bispectrum of the equilateral case



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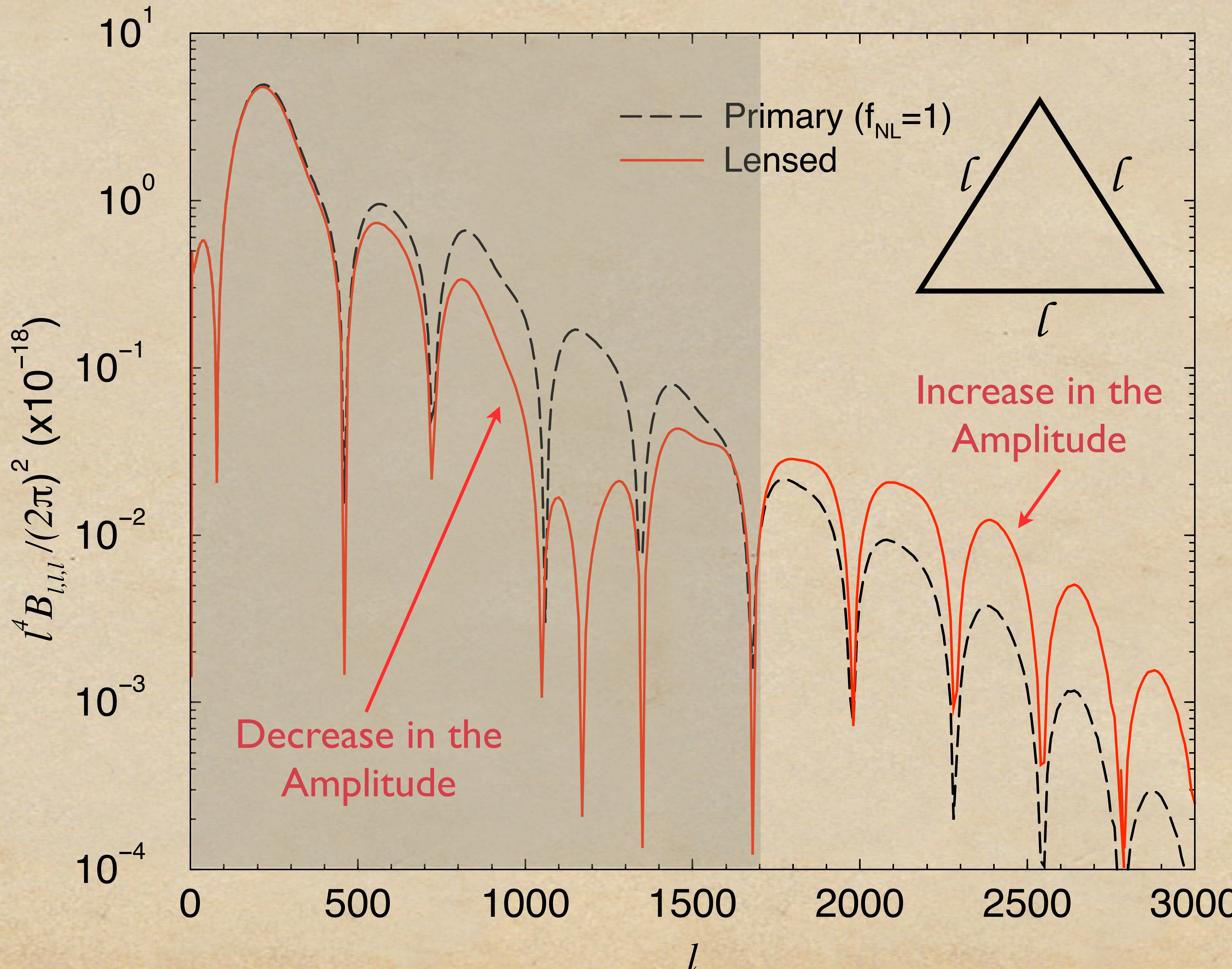
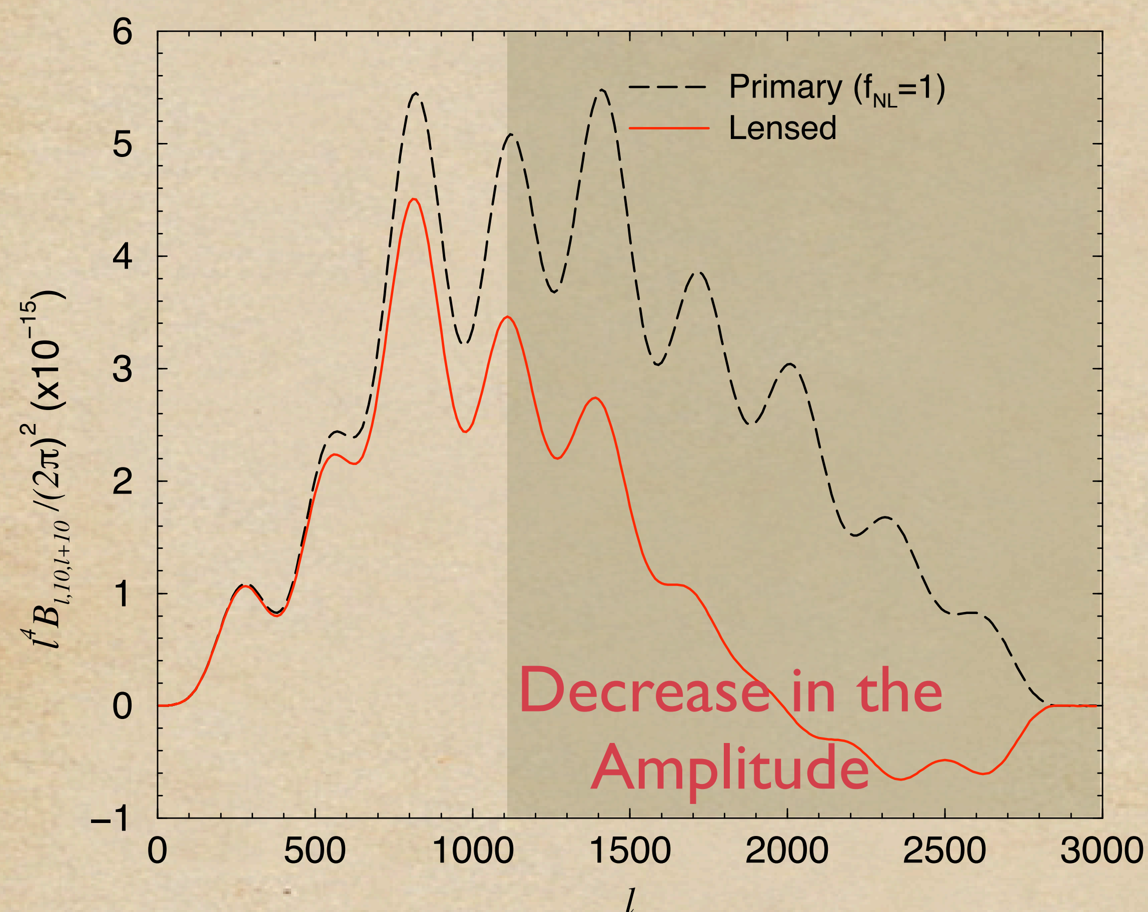
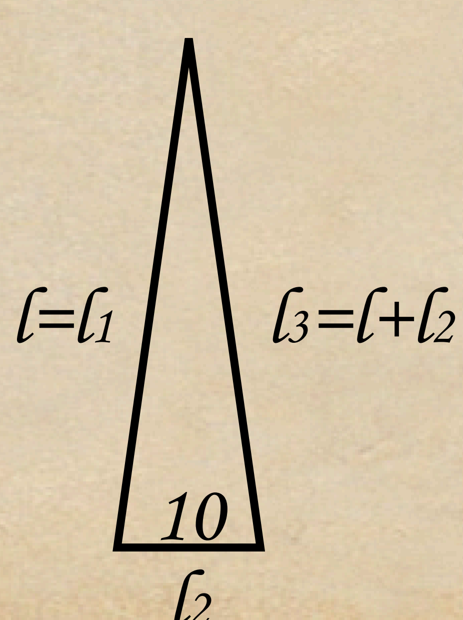


A. Cooray, D. Sarkar, and P. Serra; Phys. Rev. D, 77, 123006 (2008)

CMB Bispectrum of the squeezed case(s)





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

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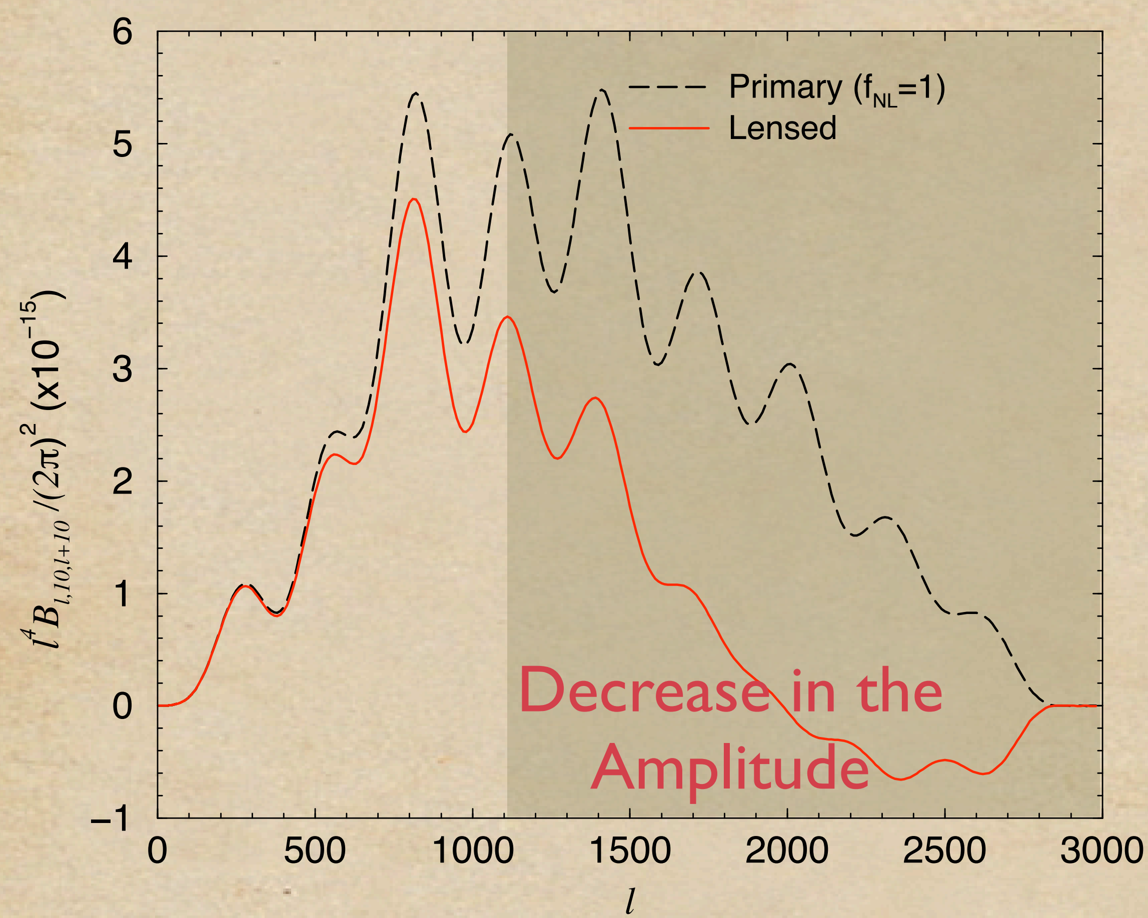
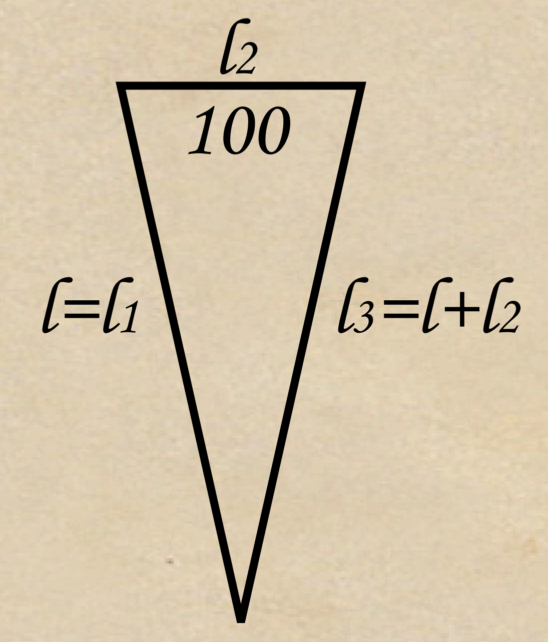
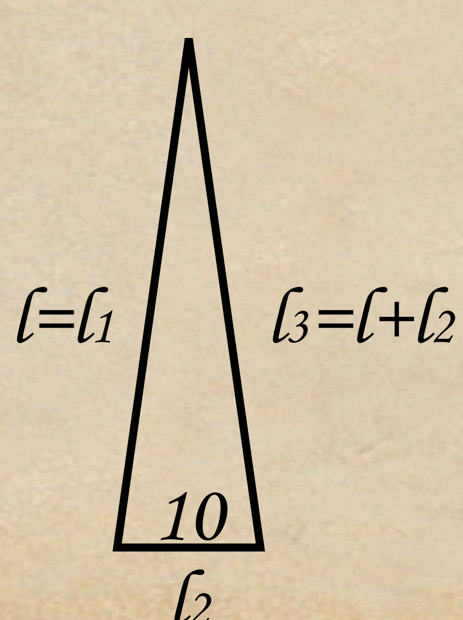
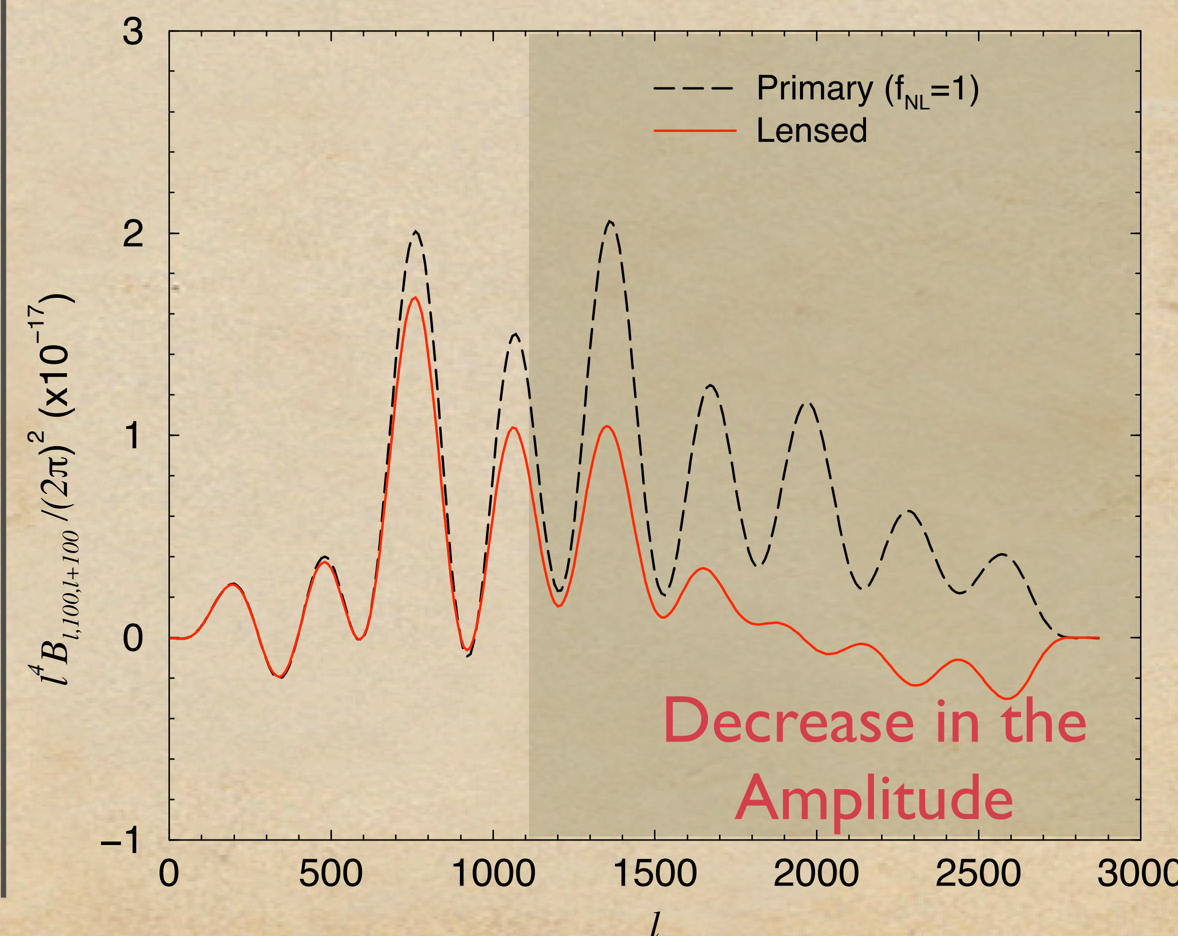


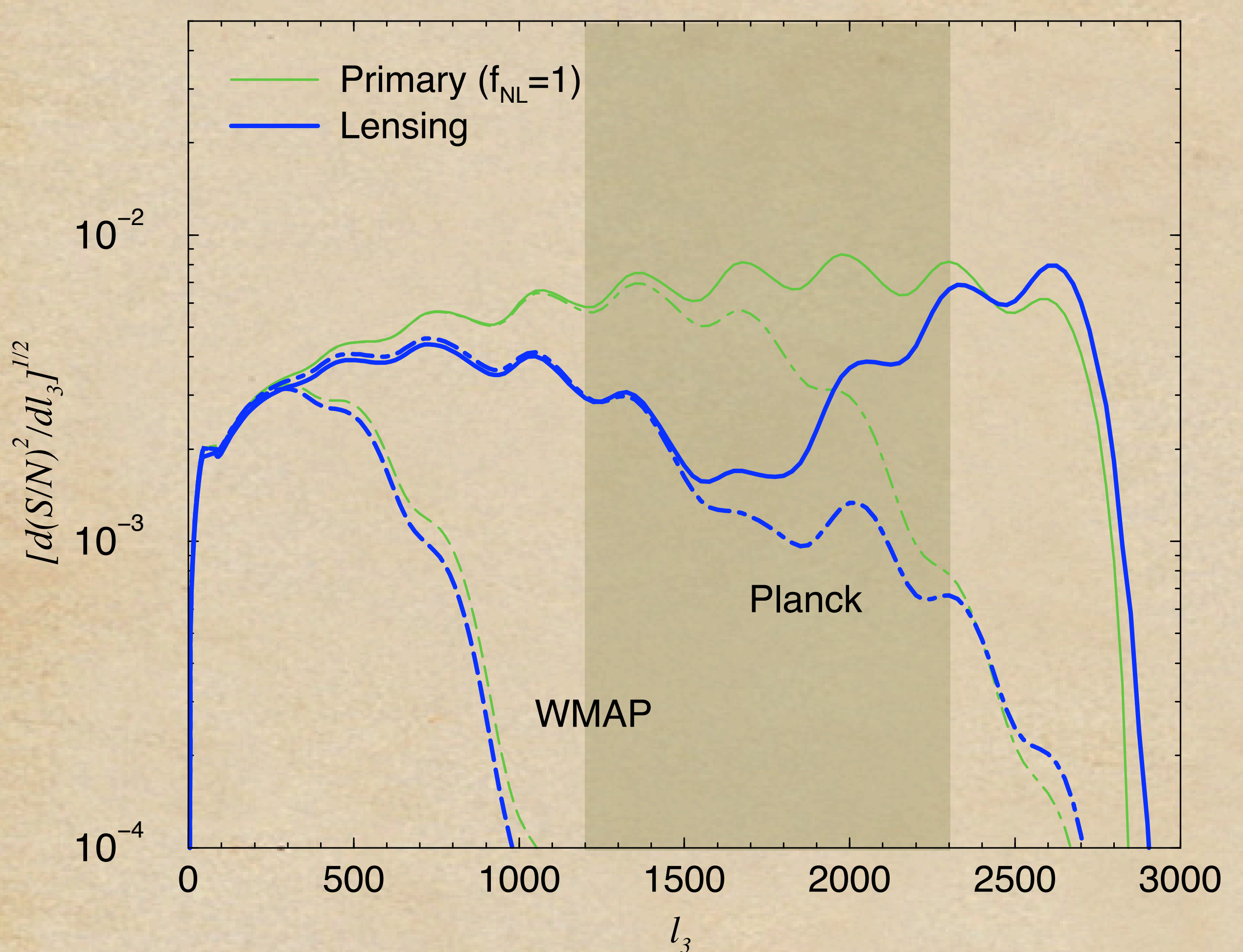






A. Cooray, D. Sarkar, and P. Serra; Phys. Rev. D, 77, 123006 (2008)

Reduction in the S/N due to Lensing



$$\left(\frac{S}{N}\right)^2 = \sum_{l_1 l_2 l_3} \frac{\left(B^{\Theta}_{l_1 l_2 l_3}\right)^2}{6 C^{tot}_{l_1} C^{tot}_{l_2} C^{tot}_{l_3}}$$

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

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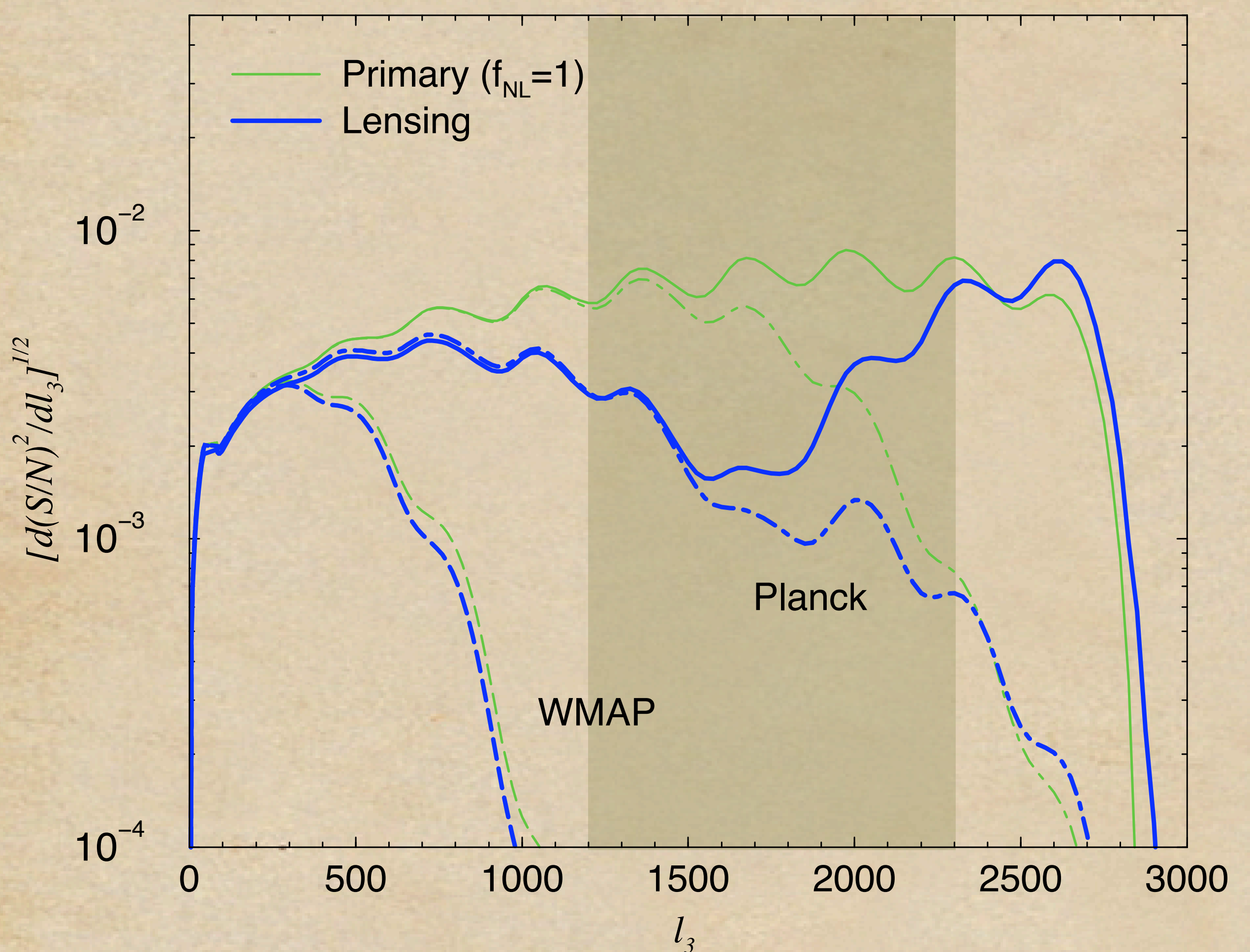
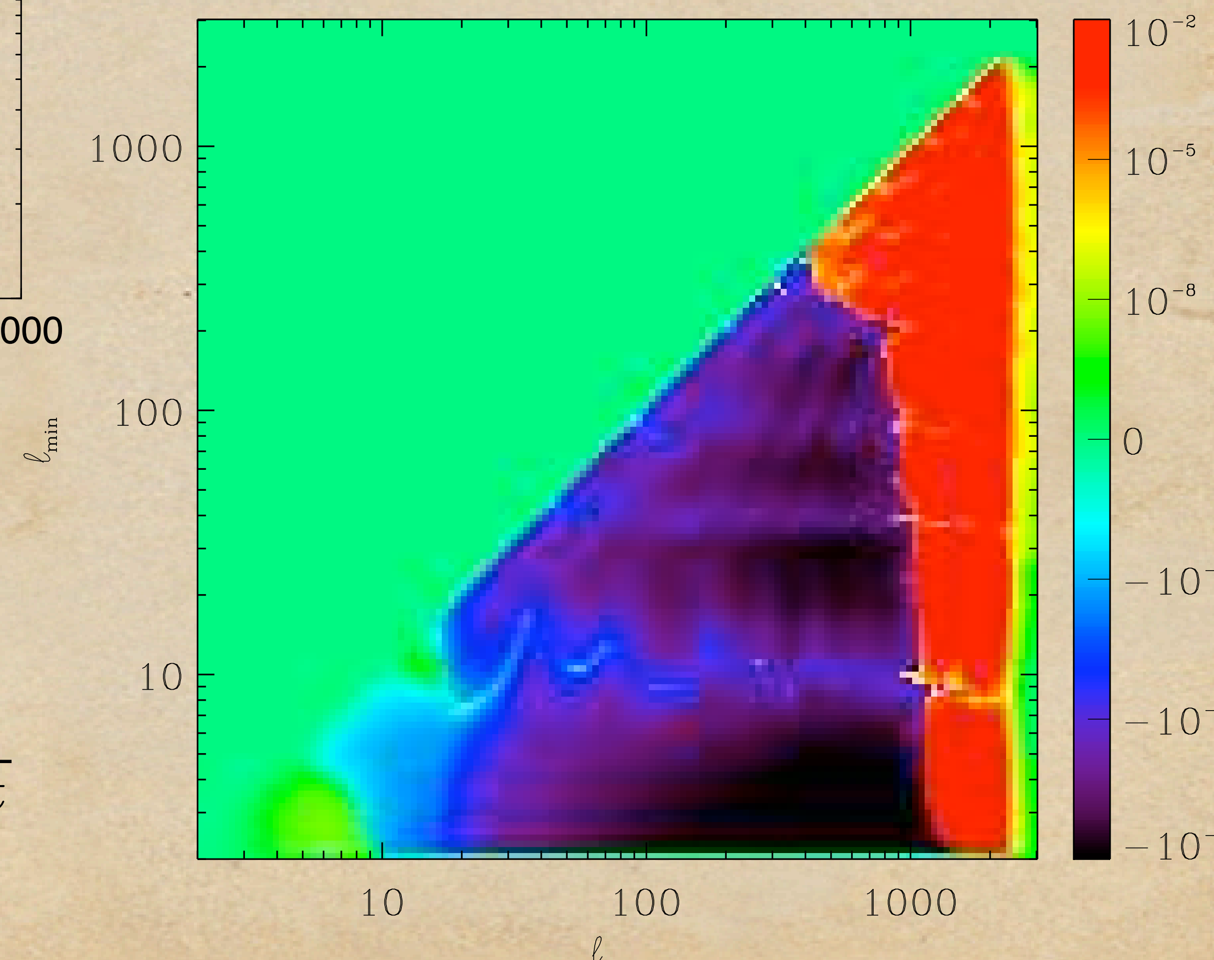


$$\frac{d\left[\left(\frac{S}{N}\right)^2_{lensed} - \left(\frac{S}{N}\right)^2_{unlensed}\right]}{d\log l_{max} d\log l_{min}}$$



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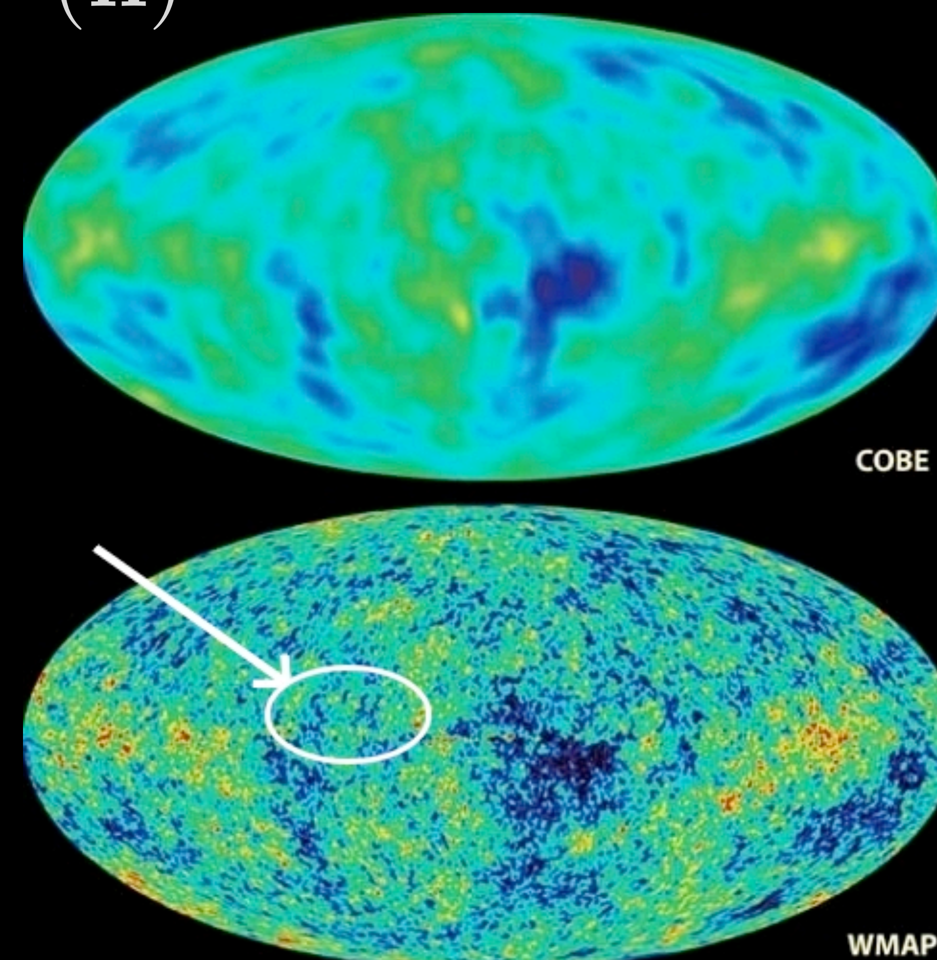
A. Cooray, D. Sarkar, and P. Serra; Phys. Rev. D, 77, 123006 (2008)

Primary CMB Bispectrum

The CMB Temperature Perturbation in the Sky:

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



Power Spectrum:

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

Angular Bispectrum:

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

Primordial Non-Gaussianity: Primary CMB Bispectrum

Gaussian Quantum Fluctuation

Falk et al. (1993)

$$\downarrow \; \delta\phi \sim g_{\delta\phi}\left(\eta + m_{pl}^{-1} f_\eta \eta^2\right) \; \downarrow$$

Starobinsky (1986)
Gangui et al. (1994)

Non-Gaussian Inflation Fluctuation

$$\downarrow \; \Phi \sim m_{pl}^{-1} g_\Phi \left(\delta\phi + m_{pl}^{-1} f_{\delta\phi} \delta\phi^2\right) \; \downarrow$$

Salopek & Bond (1990)

Non-Gaussian Curvature Perturbation

$$\downarrow \; \frac{\Delta T}{T} \sim g_T \left(\Phi + f_\Phi \Phi^2\right) \; \downarrow$$

Pyne & Carroll (1996)

Non-Gaussian CMB Anisotropy

A Word or Two on Weak Lensing

Lensing Potential (under the Born approximation)

$$\phi(\hat{\mathbf{n}}) = -2\int_0^{r_s} dr'\,\frac{d_A(r_s - r')}{d_A(r_s)d_A(r')}\Phi(\mathbf{x}(\hat{\mathbf{n}}), r')$$

Lensing Power Spectrum

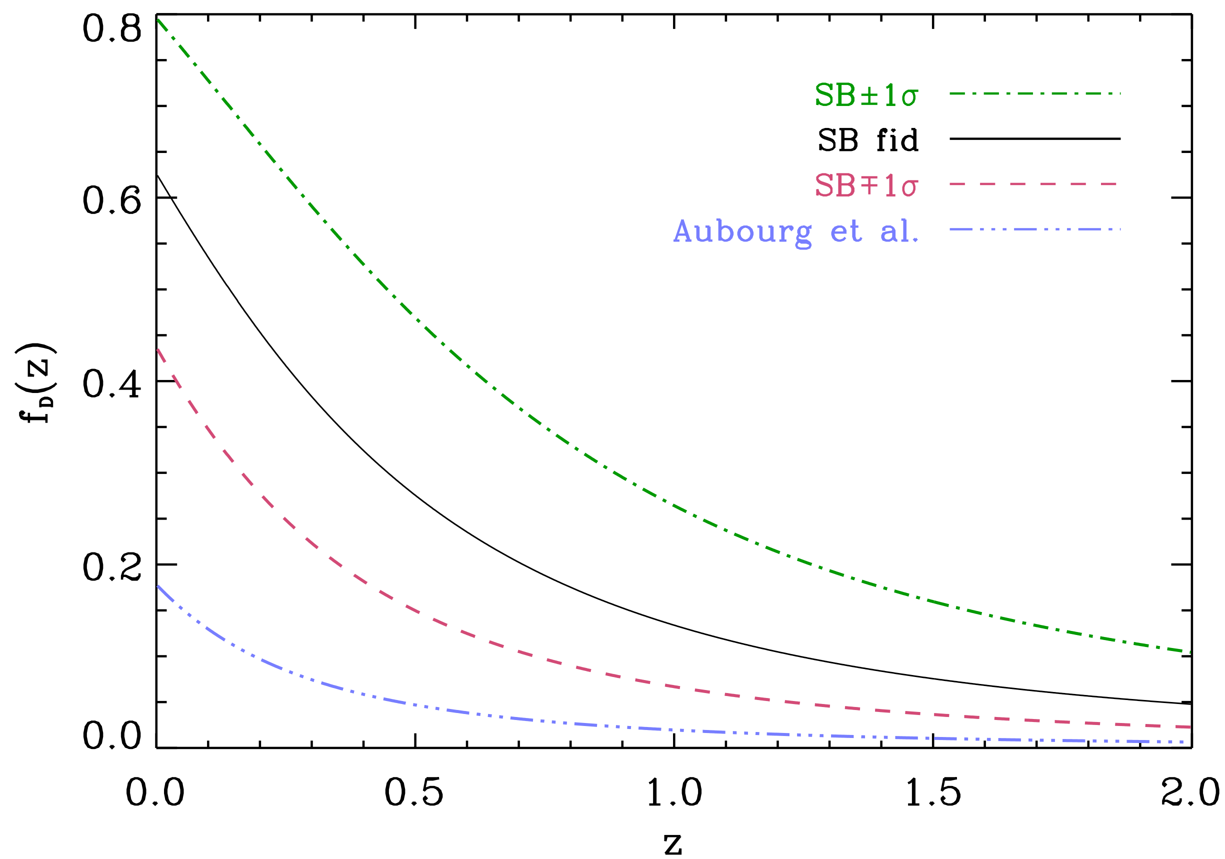
$$\phi(\hat{\mathbf{n}}) = \sum_{lm}\phi_{lm}Y_l^m(\hat{\mathbf{n}}) \qquad \langle\phi_{lm}\phi_{l'm'}\rangle = \delta_{l,l'}\delta_{m,m'}C_l^\phi$$

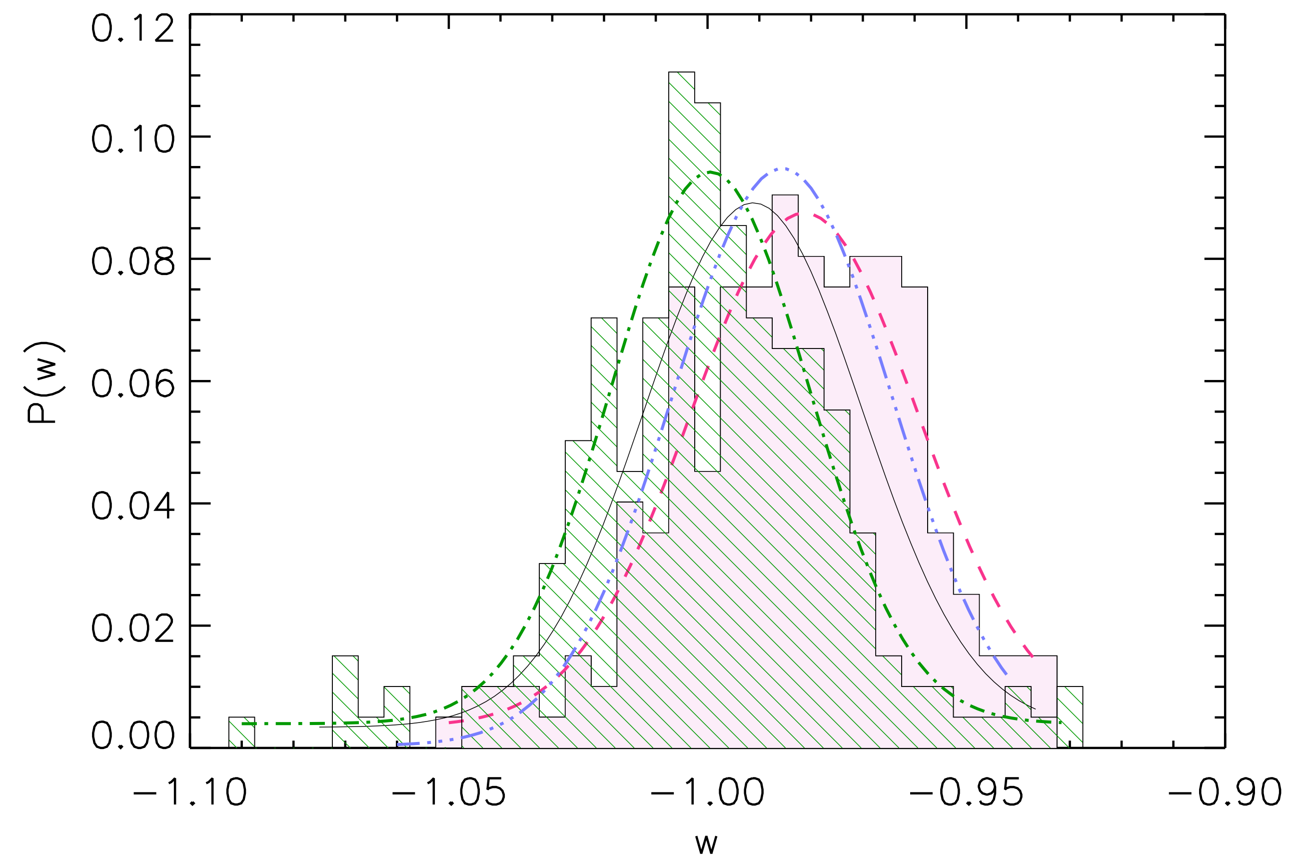
$$C_l^\phi = \frac{2}{\pi}\int k^2 dk P_\Phi(k)[I_l^{len}(k)]^2$$

$$I_l^{len}(k) = \int dr W^{len}(r) j_l(kr)$$

$$W^{len}(r) = -2F(r)\frac{d_A(r_s - r)}{d_A(r)d_A(r_s)}$$

Uncertainty in Star Formation: Bias in “w”



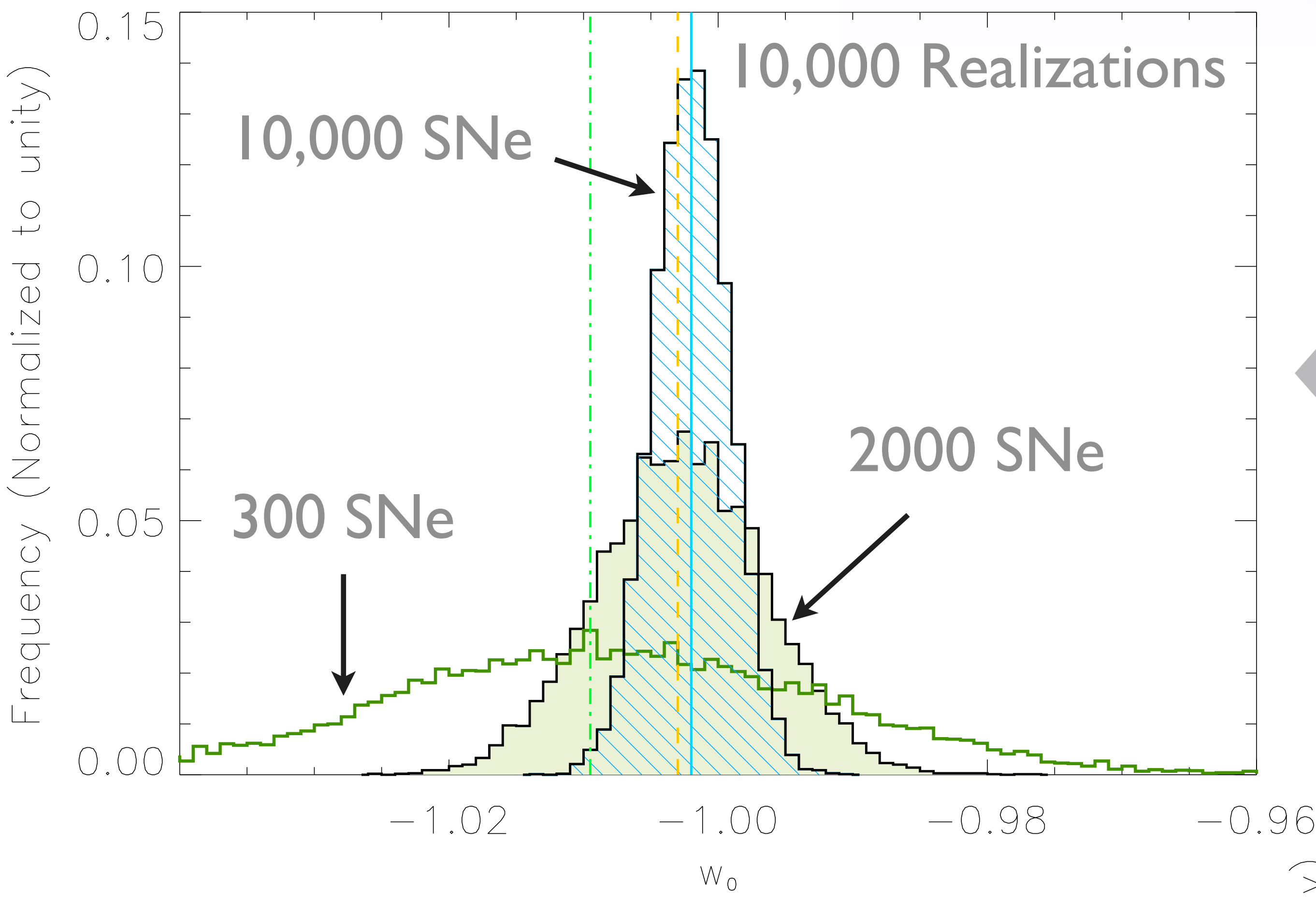


Delayed Fraction

Bias in “w”

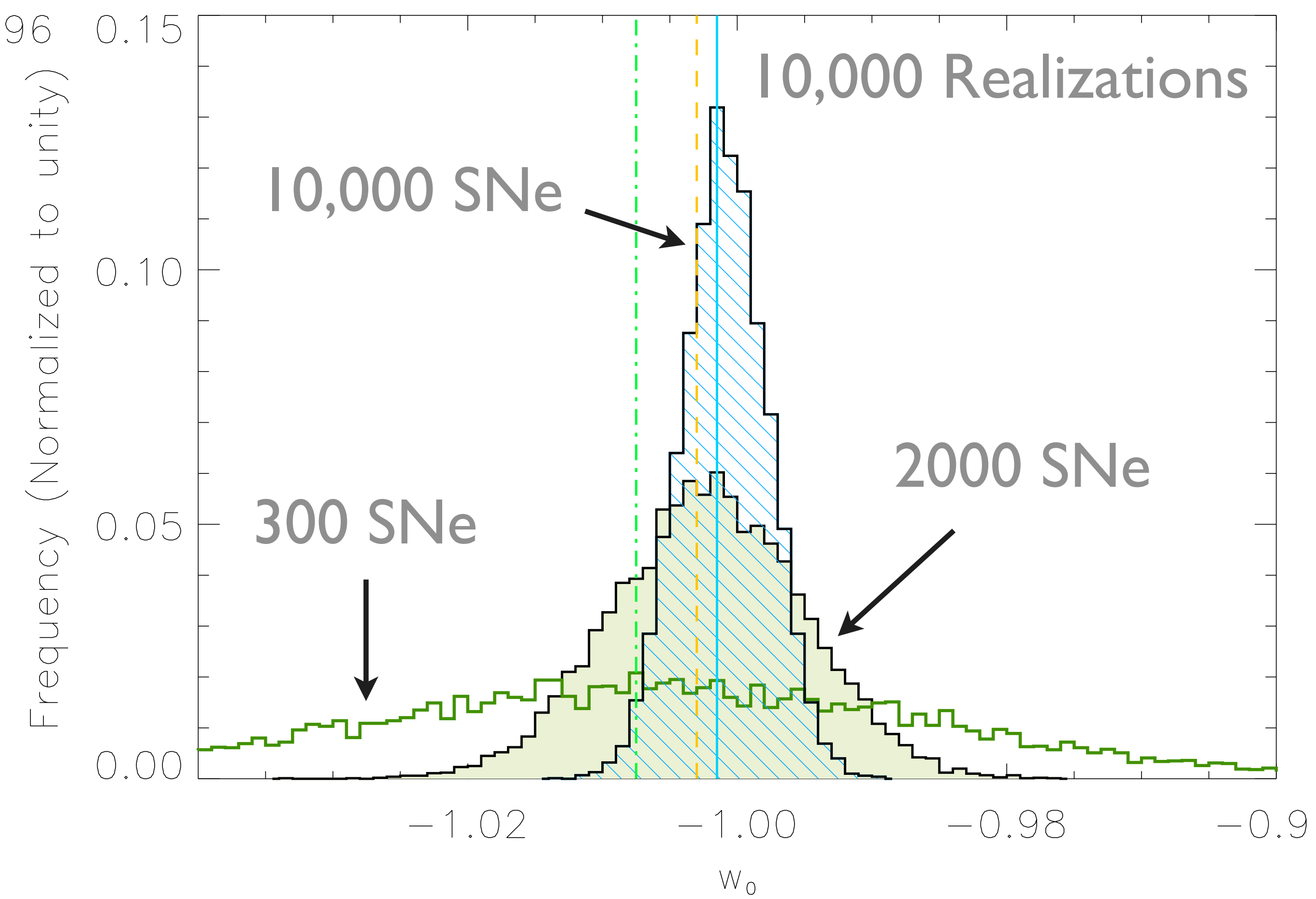
D.S., A. Amblard, A. Cooray, and D. Holz; ApJL, 684, L13 (2008)

Effect of Weak Lensing on Estimates of "w"



Magnitude Analysis

Flux Averaging Technique



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

A Little Bit of History

J. E. Gunn and B. M. Tinsley, Nature, 257, 454 (1975)

"New data on the Hubble diagram, combined with constraints on the density of the Universe and the ages of galaxies, suggest that the most plausible cosmological models have a positive cosmological constant, are closed, too dense to make deuterium in the big bang, and will expand for ever. Possible errors in the supporting arguments are discussed."

G. Efstathiou, W. J. Sutherland, and S. J. Maddox, Nature, 348, 705 (1990)

"...We argue here that the successes of the CDM theory can be retained and the new observations accommodated in a spatially flat cosmology in which as much as 80% of the critical density is provided by a positive cosmological constant, which is dynamically equivalent to endowing the vacuum with a non-zero energy density. In such a universe, expansion was dominated by CDM until a recent epoch, but is now governed by the cosmological constant ..."

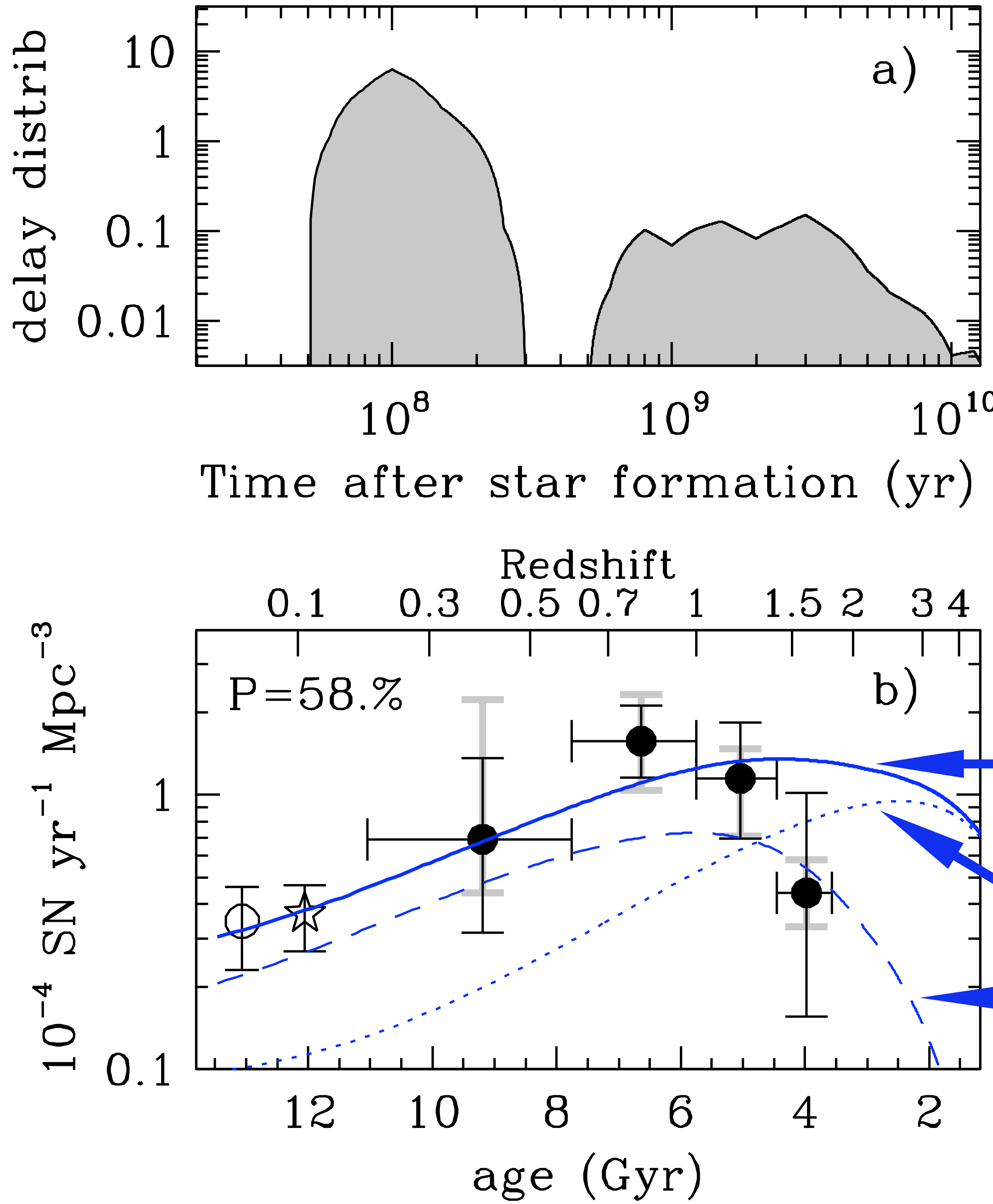
J. P. Ostriker and P. J. Steinhardt, Nature, 377, 600 (1995)

"OBSERVATIONS are providing progressively tighter constraints on cosmological models advanced to explain the formation of large-scale structure in the Universe ... The observations do not yet rule out the possibility that we live in an ever-expanding open Universe, but a Universe having the critical energy density and a large cosmological constant appears to be favoured."

J. S. Bagla, T. Padmanabhan, and J.V. Narlikar, Comments Astrophys., 18, 275 (1996)

"... the conclusion today is inescapable that the standard big bang models without the cosmological constant are effectively ruled out."

Evolution based on Two SN Populations



Total

Prompt

Delayed/Extended/Tardy

Bimodal
Delay Time Distribution

Belczynski et al. 2005

Mannucci et al. 2006

Data From:
Mannucci et al. 2005
Strolger et al. 2003
Dahlen et al. 2004