Measuring Dark Energy and Primordial Non-Gaussianity: Things To (or Not To?) Worry About!

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in collaboration with:

Scott Sullivan (UCI/UCLA), Shahab Joudaki (UCI), Alexandre Amblard (UCI), Paolo Serra (UCI), Daniel Holz (Chicago/LANL), and Asantha Cooray (UCI)

UC Berkeley-LBNL   Cosmology Group Seminar   September 16, 2008

Outline

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

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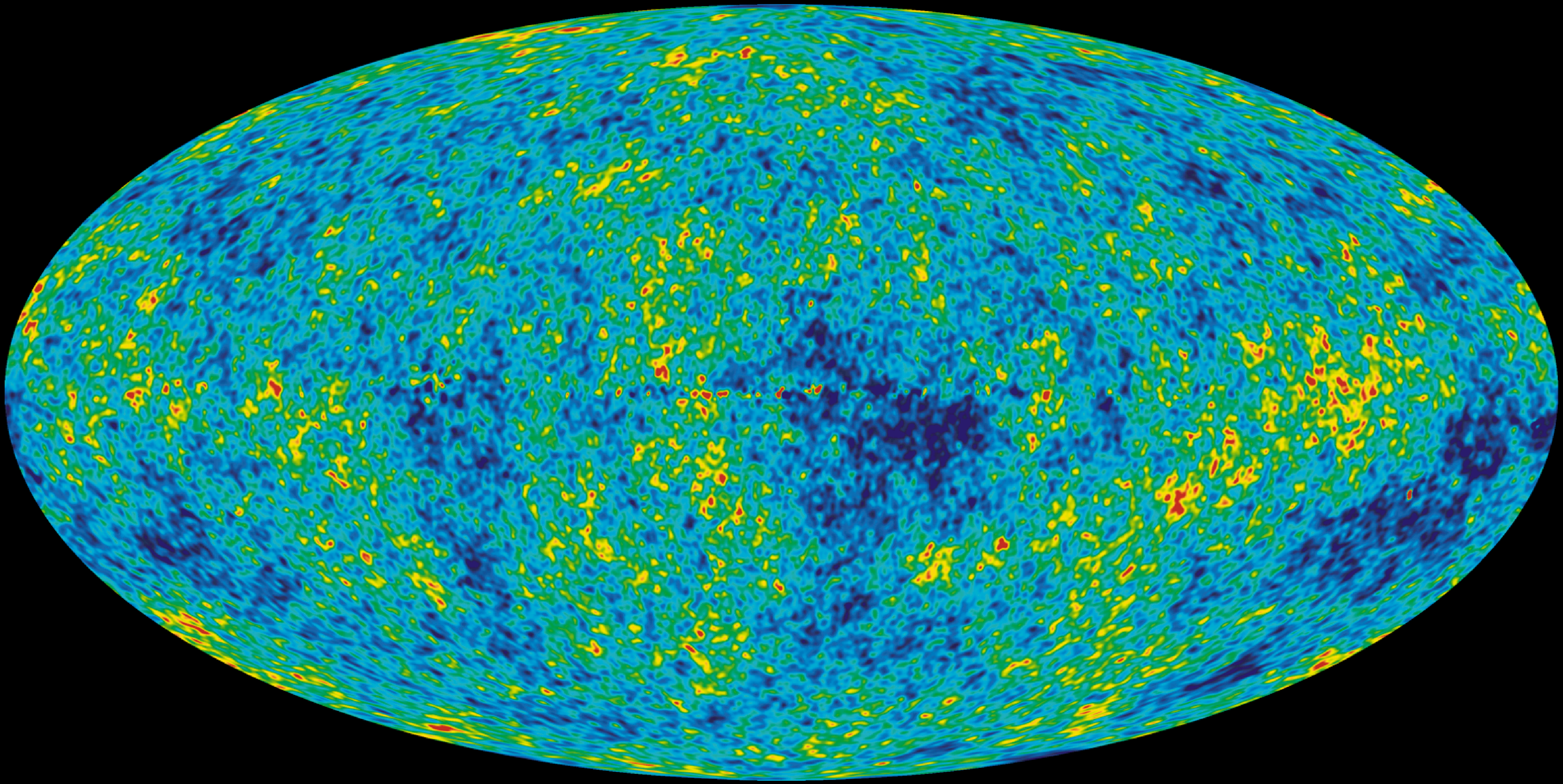
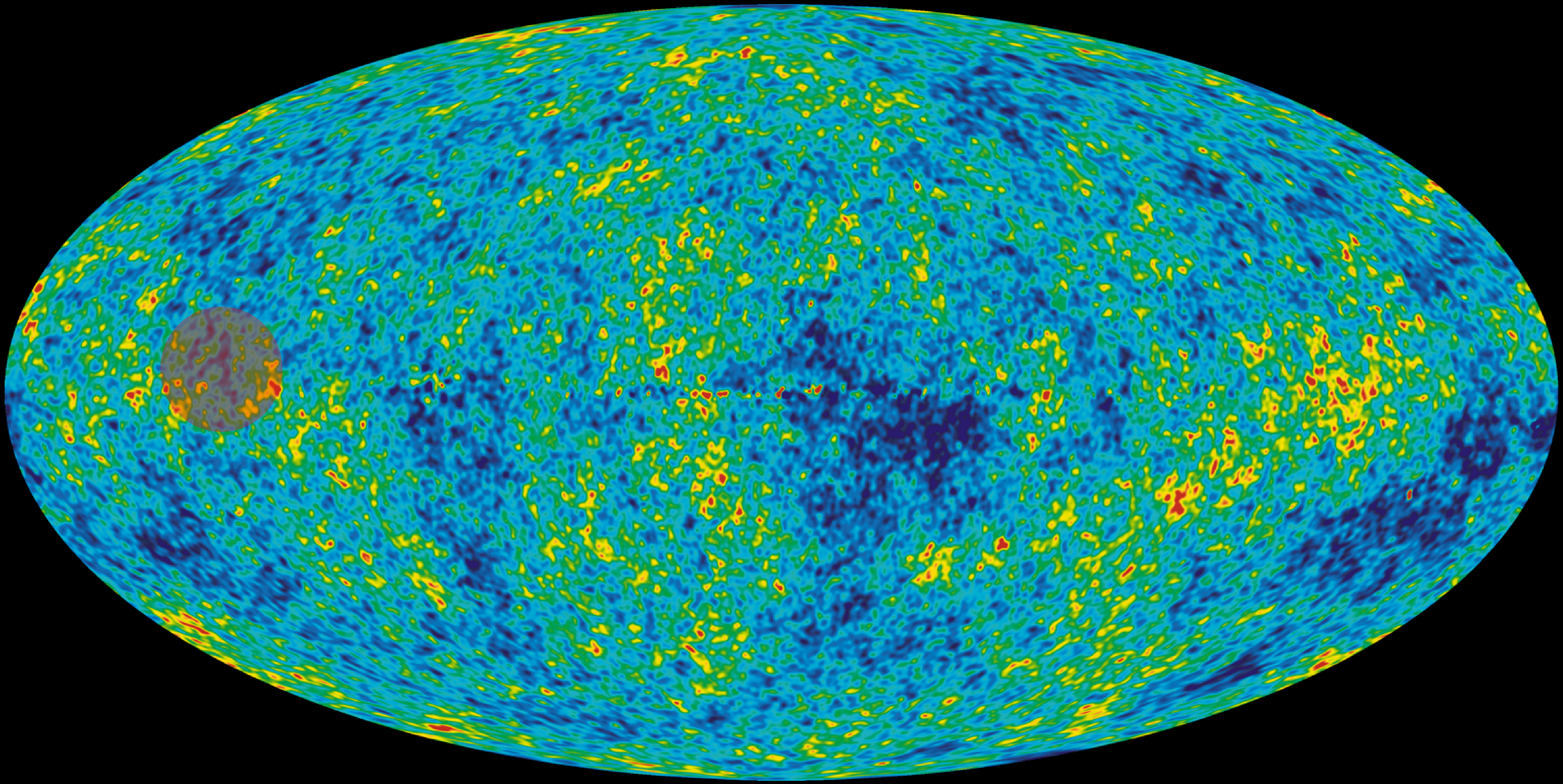


Credit: NASA/WMAP Science Team



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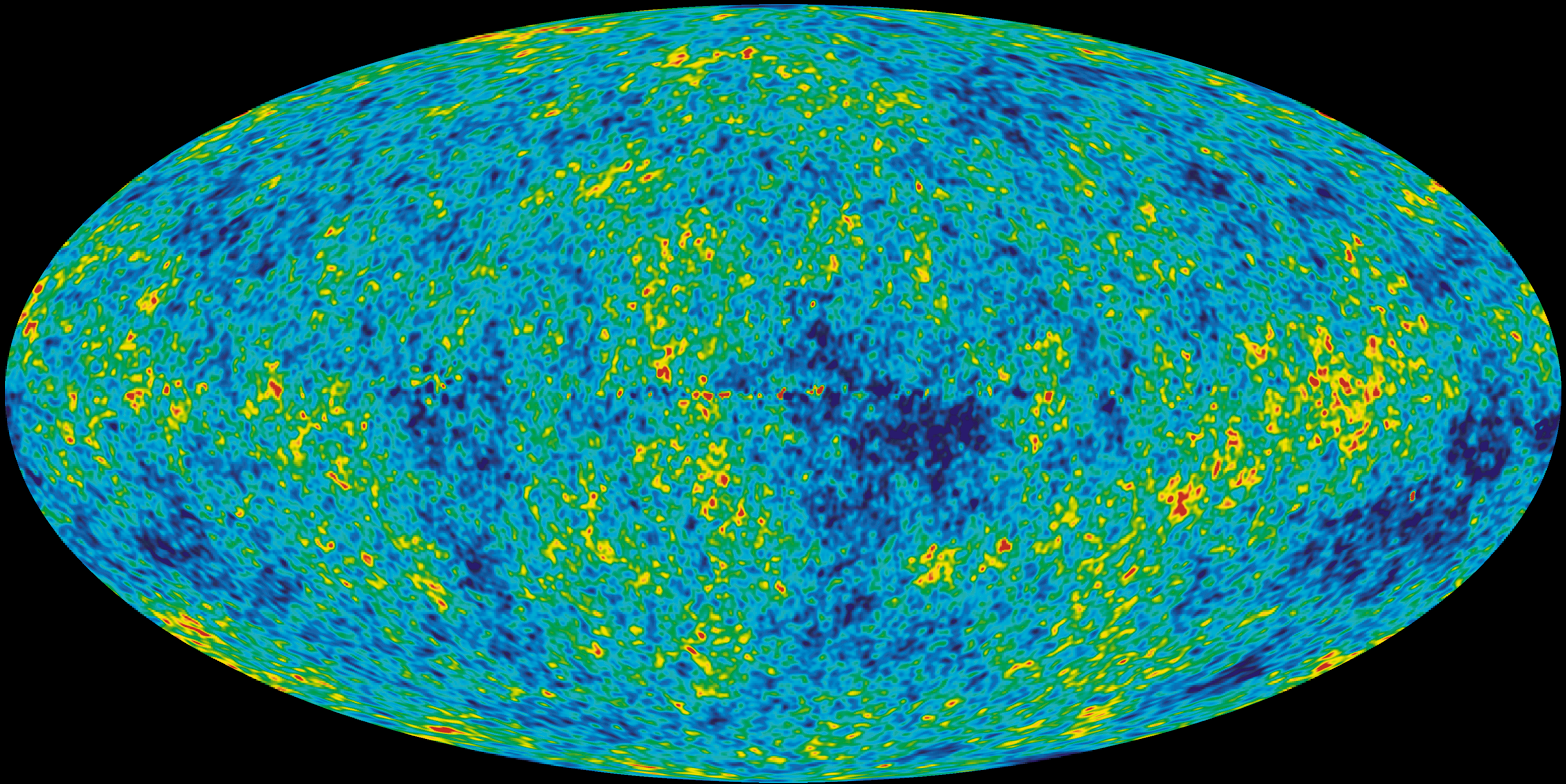

Credit: NASA/WMAP Science Team

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

ABSTRACT

We present spectral and photometric observations of 10 Type Ia supernovae (SNe Ia) in the redshift range $0.16 \leq z \leq 0.62$. The luminosity distances of these objects are determined by methods that employ relations between SN Ia luminosity and light curve shape. Combined with previous data from our High-z Supernova Search Team and recent results by Riess et al., this expanded set of 16 high-redshift supernovae and a set of 34 nearby supernovae are used to place constraints on the following cosmological parameters: the Hubble constant (H_0), the mass density (Ω_M), the cosmological constant (i.e., the vacuum energy density, Ω_Λ), the deceleration parameter (q_0), and the dynamical age of the universe (t_0). The distances of the high-redshift SNe Ia are, on average, 10%–15% farther than expected in a low mass density ($\Omega_M = 0.2$) universe without a cosmological constant. Different light curve fitting methods, SN Ia subsamples, and prior constraints unanimously favor eternally expanding models with positive cosmological constant (i.e., $\Omega_\Lambda > 0$) and a current acceleration of the expansion (i.e., $q_0 < 0$). With no prior constraint on mass density other than $\Omega_M \geq 0$, the spectroscopically confirmed SNe Ia are statistically consistent with $q_0 < 0$ at the 2.8 σ and 3.9 σ confidence levels, and with $\Omega_\Lambda > 0$ at the 3.0 σ and 4.0 σ confidence levels, for two different fitting methods, respectively. Fixing a "minimal" mass density, $\Omega_M = 0.2$, results in the weakest detection, $\Omega_\Lambda > 0$ at the 3.0 σ confidence level from one of the two methods. For a flat universe prior ($\Omega_M + \Omega_\Lambda = 1$), the spectroscopically confirmed SNe Ia require $\Omega_\Lambda > 0$ at 7 σ and 9 σ formal statistical significance for the two different fitting methods. A universe closed by ordinary matter (i.e., $\Omega_M = 1$) is formally ruled out at the 7 σ to 8 σ confidence level for the two different fitting methods. We estimate the dynamical age of the universe to be 14.2 ± 1.7 Gyr including systematic uncertainties in the current Cepheid distance scale. We estimate the likely effect of several sources of systematic error, including progenitor and metallicity evolution, extinction, sample selection bias, local perturbations in the expansion rate, gravitational lensing, and sample contamination. Presently, none of these effects appear to reconcile the data with $\Omega_\Lambda = 0$ and $q_0 \geq 0$.

Key words: cosmology: observations — supernovae: general

The Astrophysical Journal, 517:565–586, 1999 June 1

MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

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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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(The Supernova Cosmology Project)
Received 1998 September 8; accepted 1998 December 17

ABSTRACT

We report measurements of the mass density, Ω_M, and cosmological-constant energy density, Ω_Λ, of the universe based on the analysis of 42 type Ia supernovae discovered by the Supernova Cosmology Project. The magnitude-redshift data for these supernovae, at redshifts between 0.18 and 0.83, are fitted jointly with a set of supernovae from the Calán/Tololo Supernova Survey, at redshifts below 0.1, to yield values for the cosmological parameters. All supernova peak magnitudes are standardized using a SN Ia light-curve width-luminosity relation. The measurement yields a joint probability distribution of the cosmological parameters that is approximated by the relation $0.8\Omega_M - 0.6\Omega_\Lambda \approx -0.2 \pm 0.1$ in the region of interest ($\Omega_M \lesssim 1.5$). For a flat ($\Omega_M + \Omega_\Lambda = 1$) cosmology we find $\Omega_M^{\rm flat} = 0.28^{+0.09}_{-0.08}$ (1 σ statistical) $^{+0.05}_{-0.04}$ (identified systematics). The data are strongly inconsistent with a $\Lambda = 0$ flat cosmology, the simplest inflationary universe model. An open, $\Lambda = 0$ cosmology also does not fit the data well: the data indicate that the cosmological constant is nonzero and positive, with a confidence of $P(\Lambda > 0) = 99\%$, including the identified systematic uncertainties. The best-fit age of the universe relative to the Hubble time is

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

ABSTRACT

We have discovered 16 Type Ia supernovae (SNe Ia) with the *Hubble Space Telescope* (*HST*) and have used them to provide the first conclusive evidence for cosmic deceleration that preceded the current epoch of cosmic acceleration. These objects, discovered during the course of the GOODS ACS Treasury program, include 6 of the 7 highest redshift SNe Ia known, all at $z > 1.25$, and populate the Hubble diagram in unexplored territory. The luminosity distances to these objects and to 170 previously reported SNe Ia have been determined using empirical relations between light-curve shape and luminosity. A purely kinematic interpretation of the SN Ia sample provides evidence at the greater than 99% confidence level for a transition from deceleration to acceleration or, similarly, strong evidence for a cosmic jerk. Using a simple model of the expansion history, the transition between the two epochs is constrained to be at $z = 0.46 \pm 0.13$. The data are consistent with the cosmic concordance model of $\Omega_M \approx 0.3$, $\Omega_\Lambda \approx 0.7$ ($\chi^2_{\rm dof} = 1.06$) and are inconsistent with a simple model of evolution or dust as an alternative to dark energy. For a flat universe with a cosmological constant, we measure $\Omega_M = 0.29^{+0.05}_{-0.03}$ (equivalently, $\Omega_\Lambda = 0.71$). When combined with external flat-universe constraints, including the cosmic microwave background and large-scale structure, we find $w = -1.02^{+0.13}_{-0.19}$ (and $w < -0.76$ at the 95% confidence level) for an assumed static equation of state of dark energy, $P = w\rho c^2$. Joint constraints on both the recent equation of state of dark energy, w_0, and its time evolution, dw/dz, are a factor of ~8 more precise than the first estimates and twice as precise as those without the SNe Ia discovered with *HST*. Our constraints are consistent with the static nature of and value of w expected for a cosmological constant (i.e., $w_0 = -1.0$, $dw/dz = 0$) and are inconsistent with very rapid evolution of dark energy. We address consequences of evolving dark energy for the fate of the universe.

Subject headings: cosmology: observations — distance scale — galaxies: distances and redshifts — supernovae: general

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

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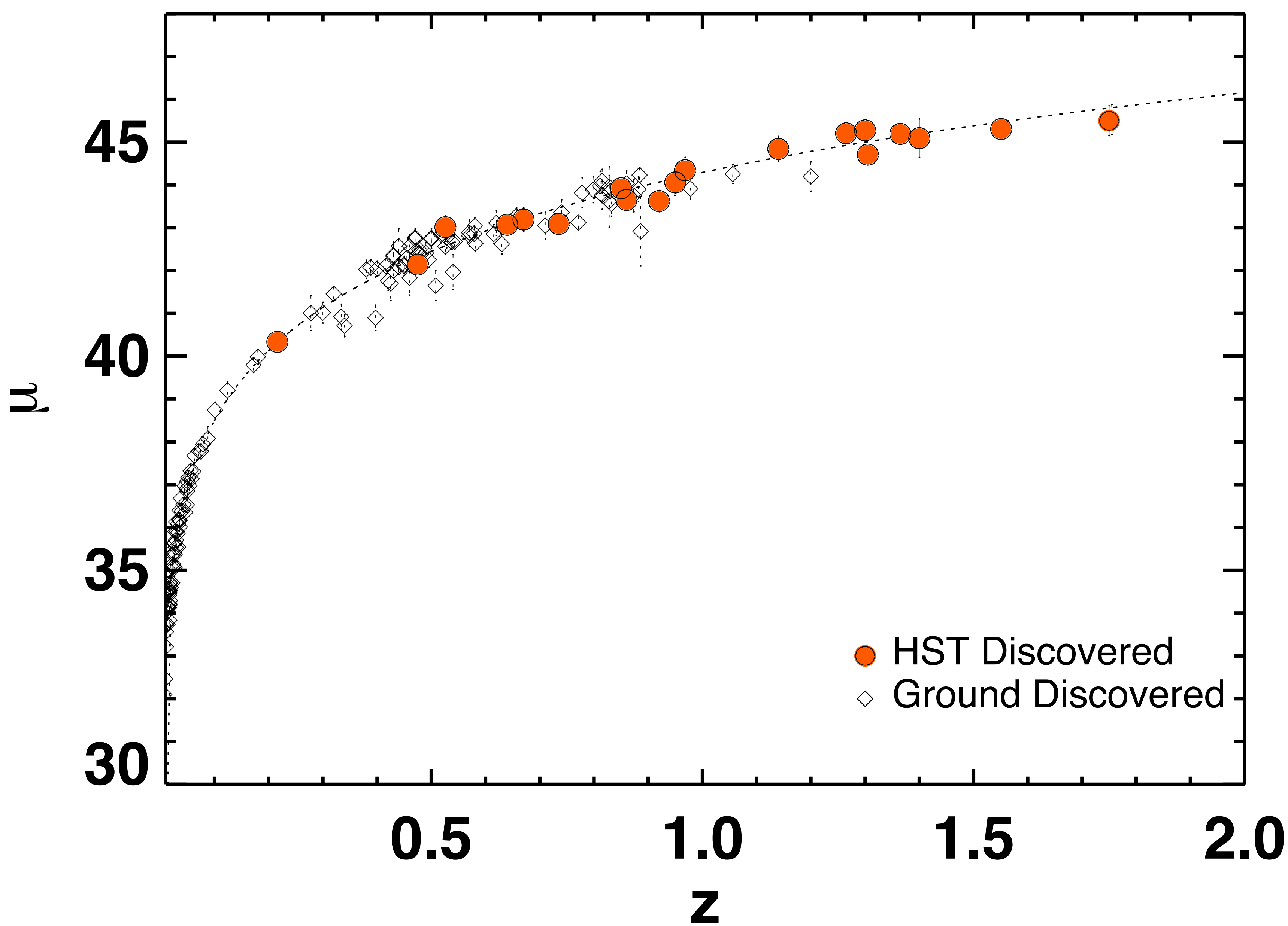

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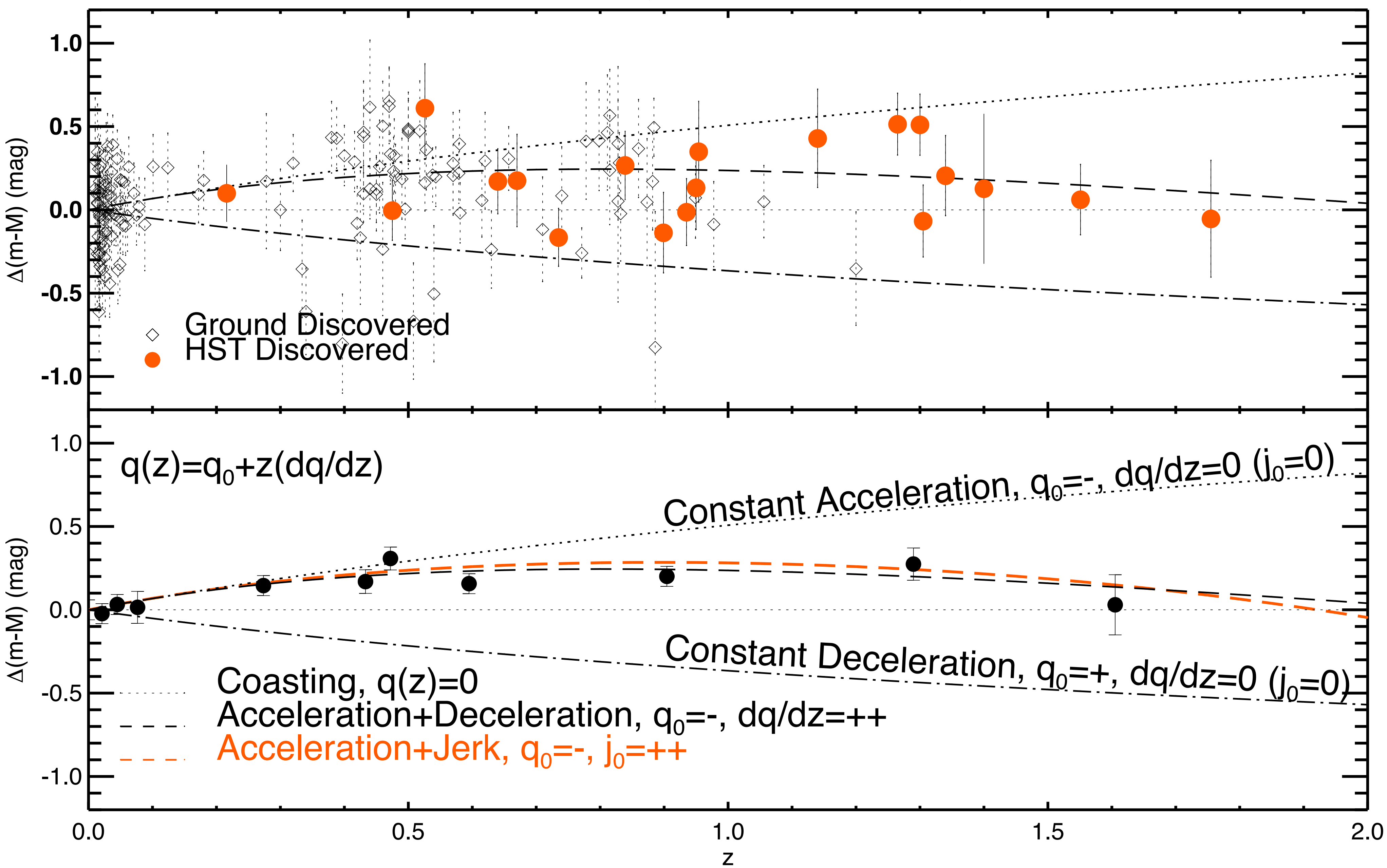
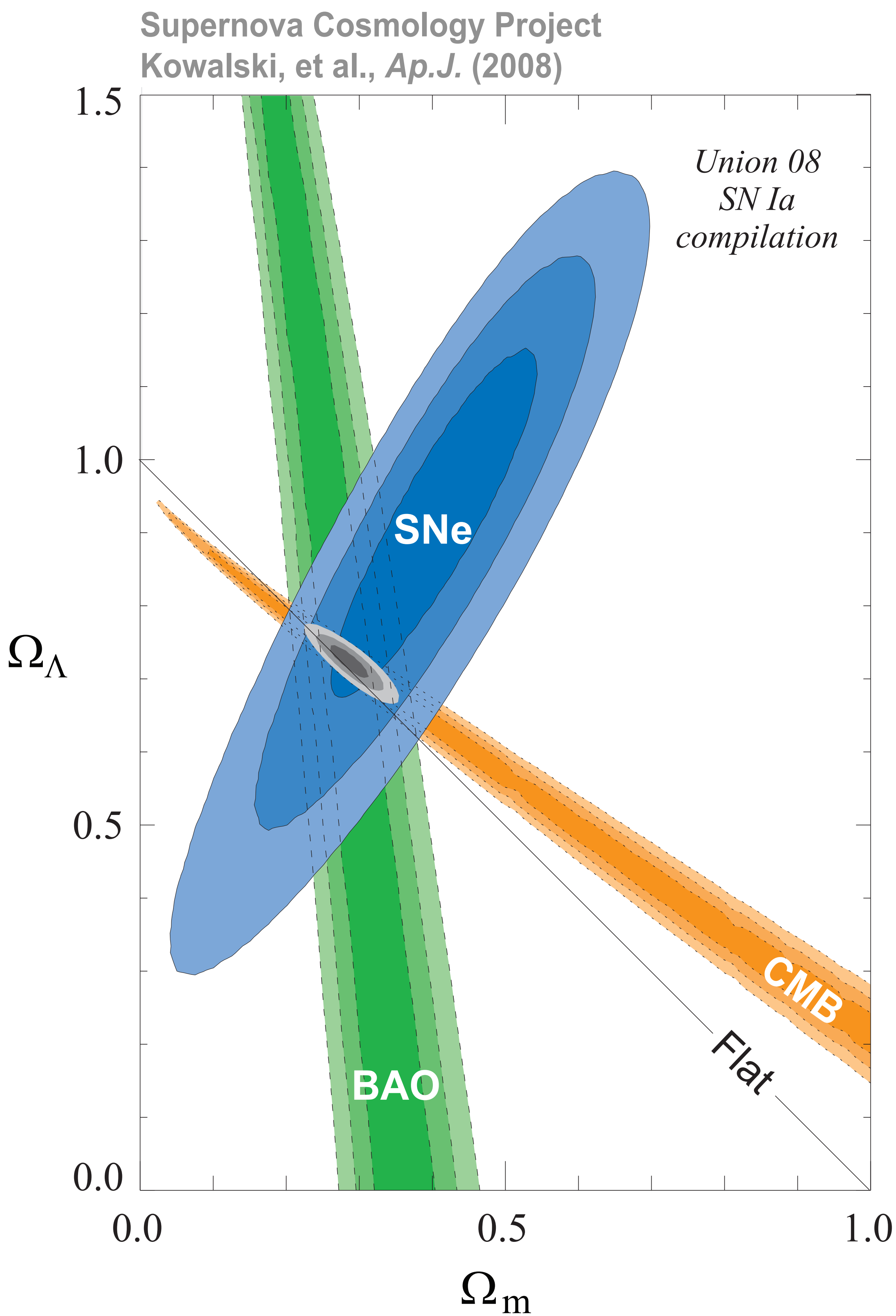
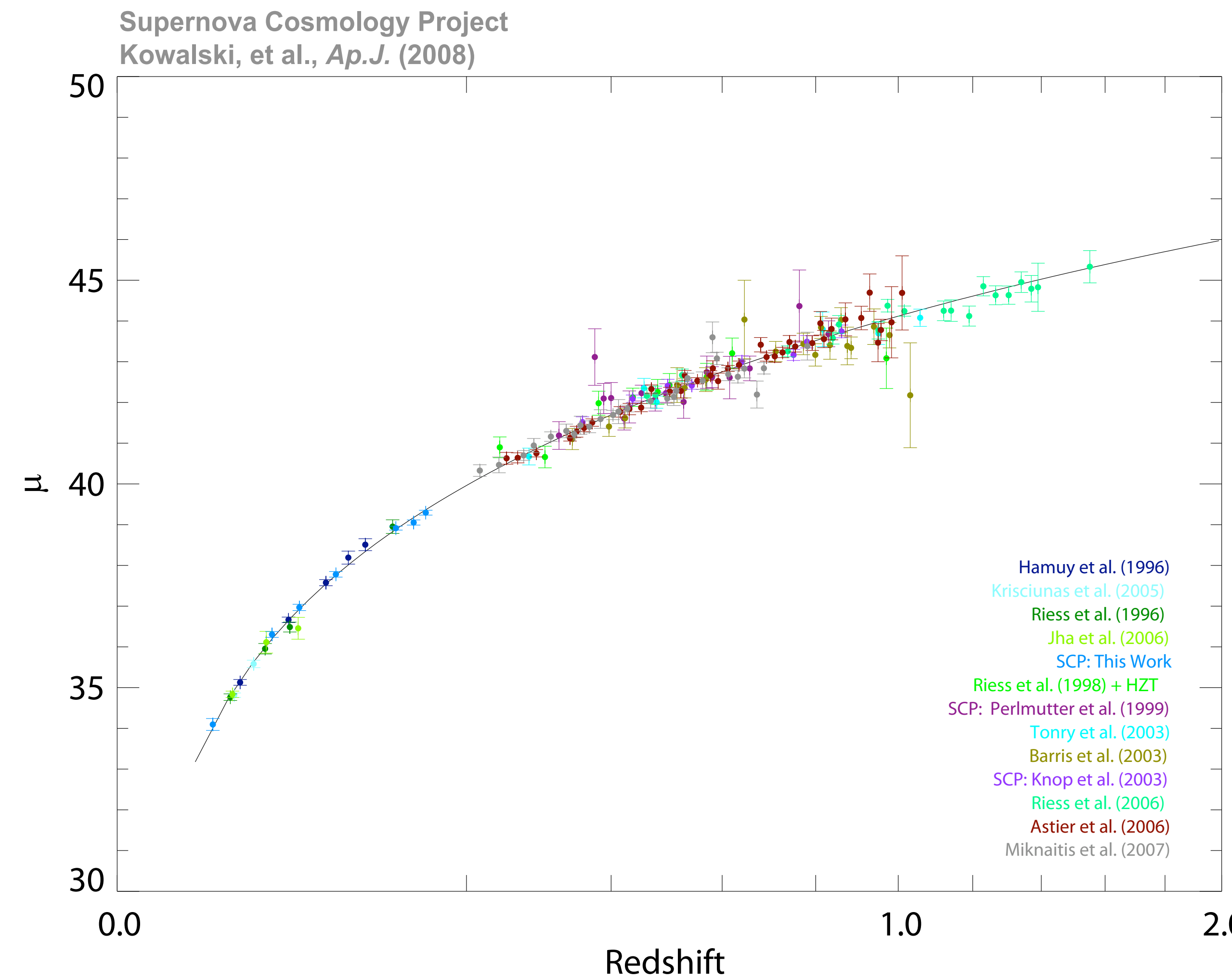
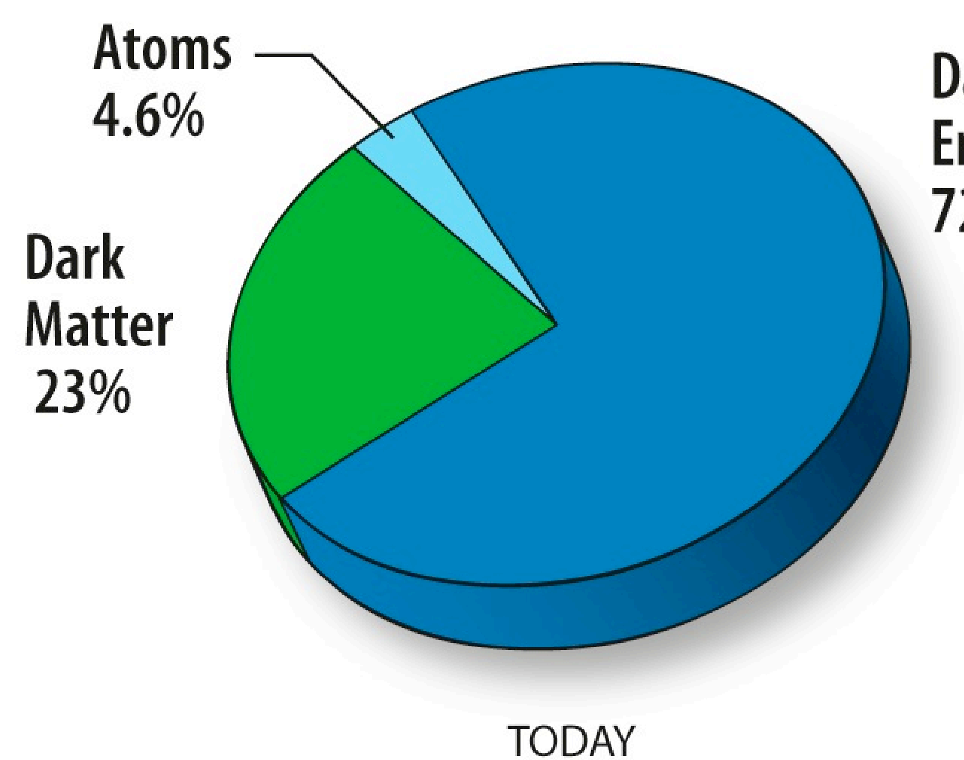


$$\Omega_\Lambda = 0.713^{+0.027}_{-0.029}(\mathrm{stat})^{+0.036}_{-0.039}(\mathrm{sys})$$







WMAP

Cosmic Acceleration

Modified Gravity ↔ Dark Energy

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

Modification of Friedmann equation (5D Gravity)

Phenomenological modification to the GR Lagrangian

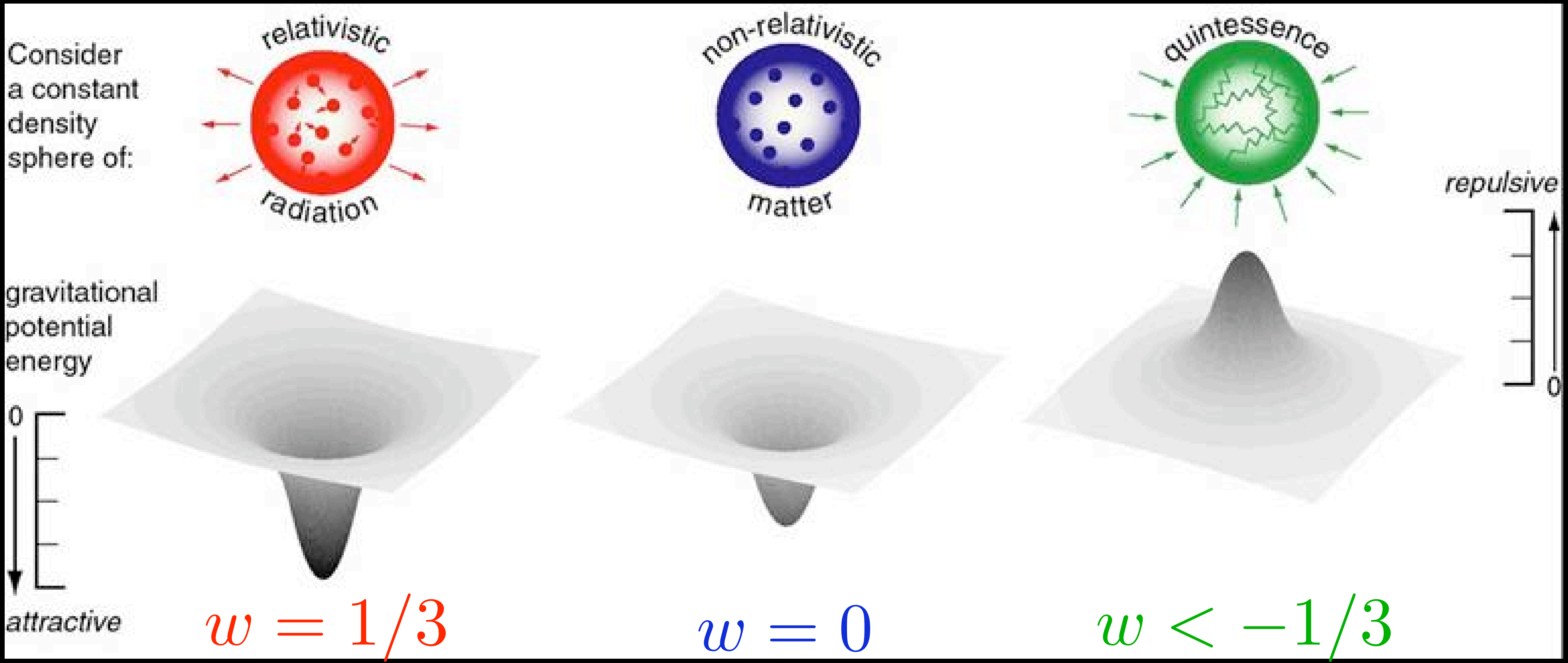
Vacuum Energy (Cosmological Constant)

Scalar Fields
Evolving Equation of State

New Physics/Surprises?

Dark Energy Equation Of State

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



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

DE EOS Revisited: Different Approaches...

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

$$w(a) = w_0 + (1 - a)w_a$$

Chevallier & Polarski (2001)
(Linder 2003)

DE EOS Revisited: Different Approaches...

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(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]

"Seeing" The Dark Energy

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

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

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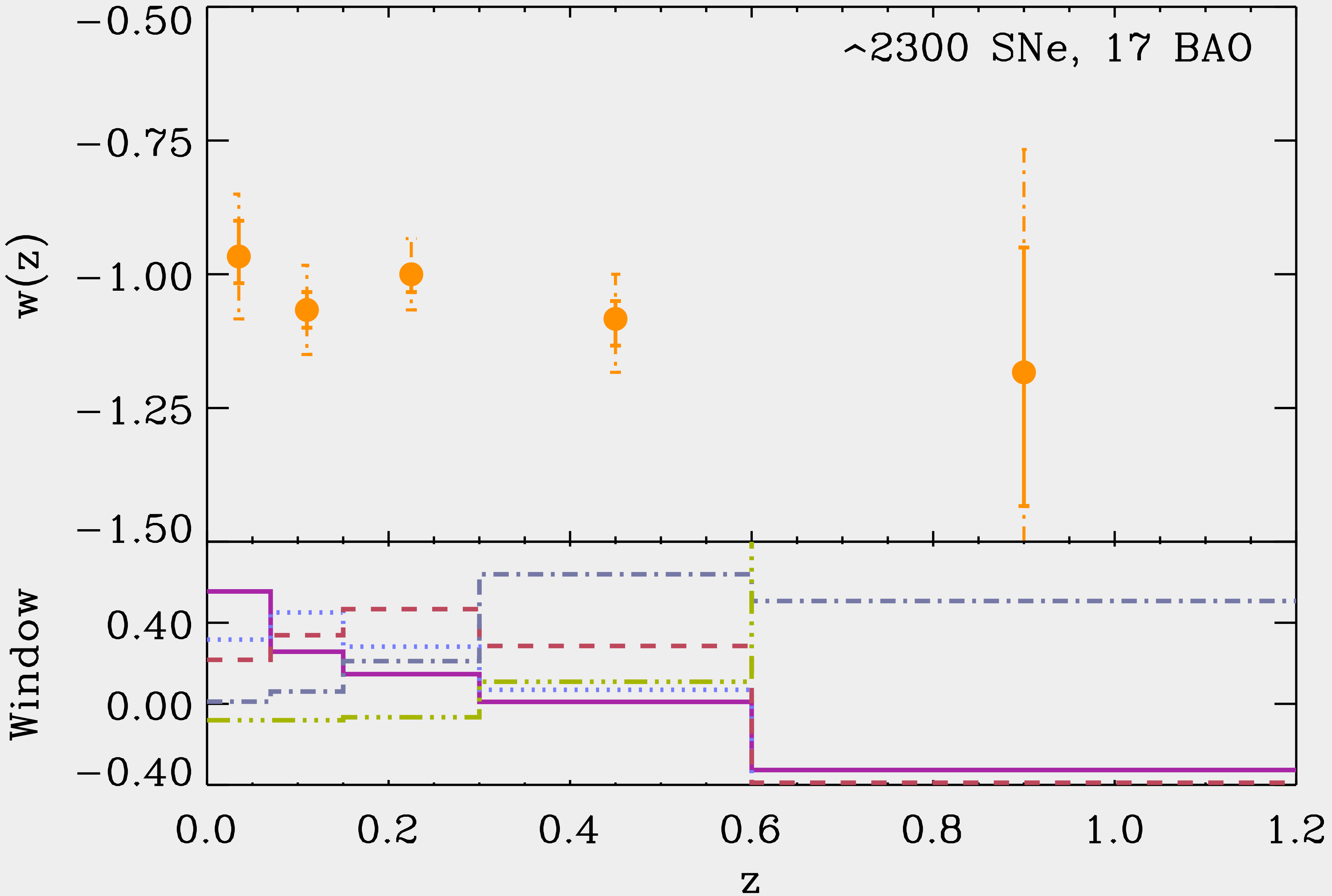
Approaches...

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

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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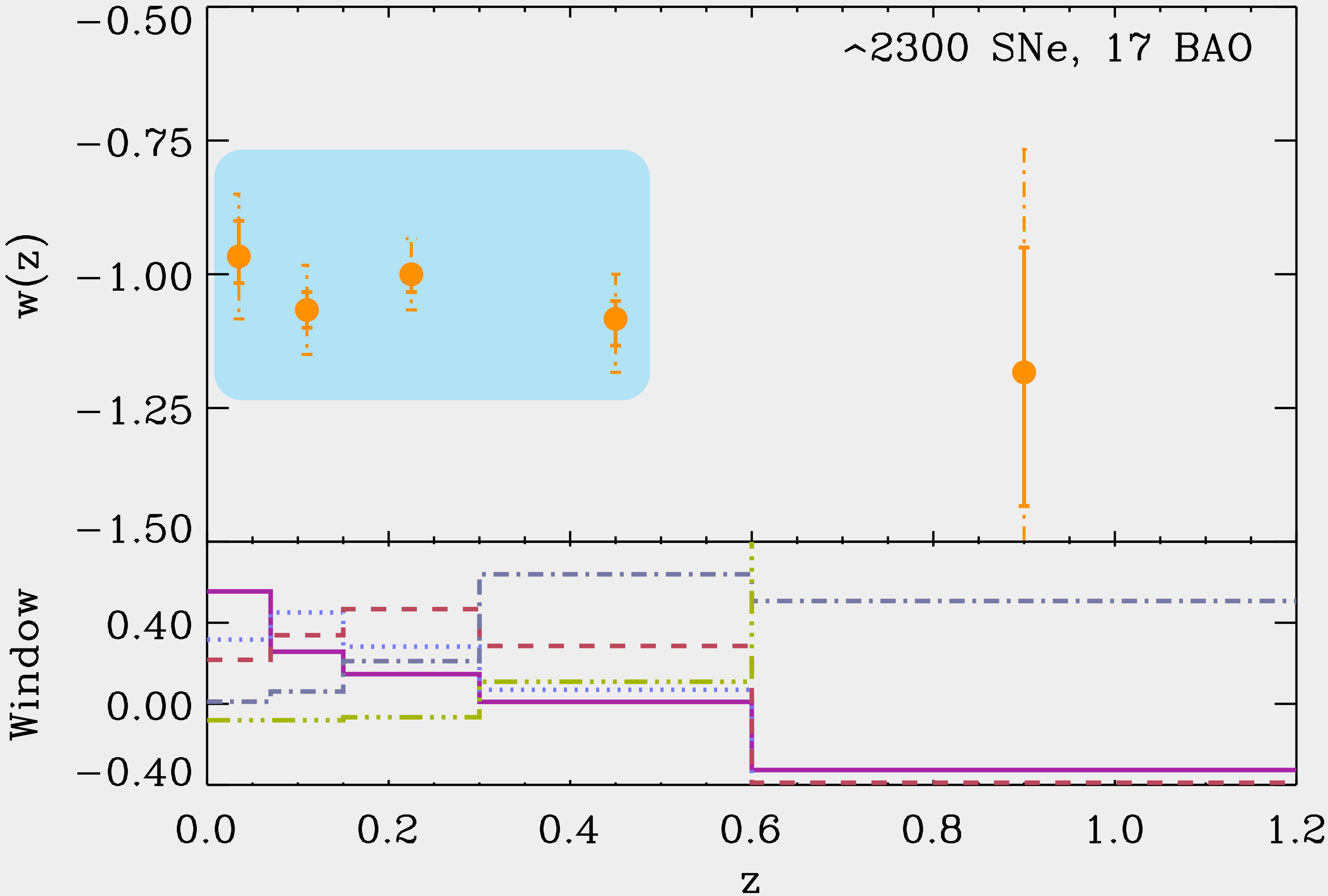

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Codes

http://dsarkar.org/code.html

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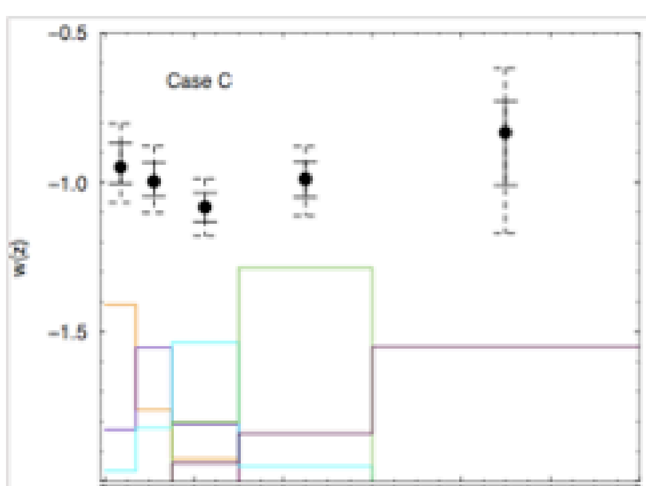
DevdeepSarkar

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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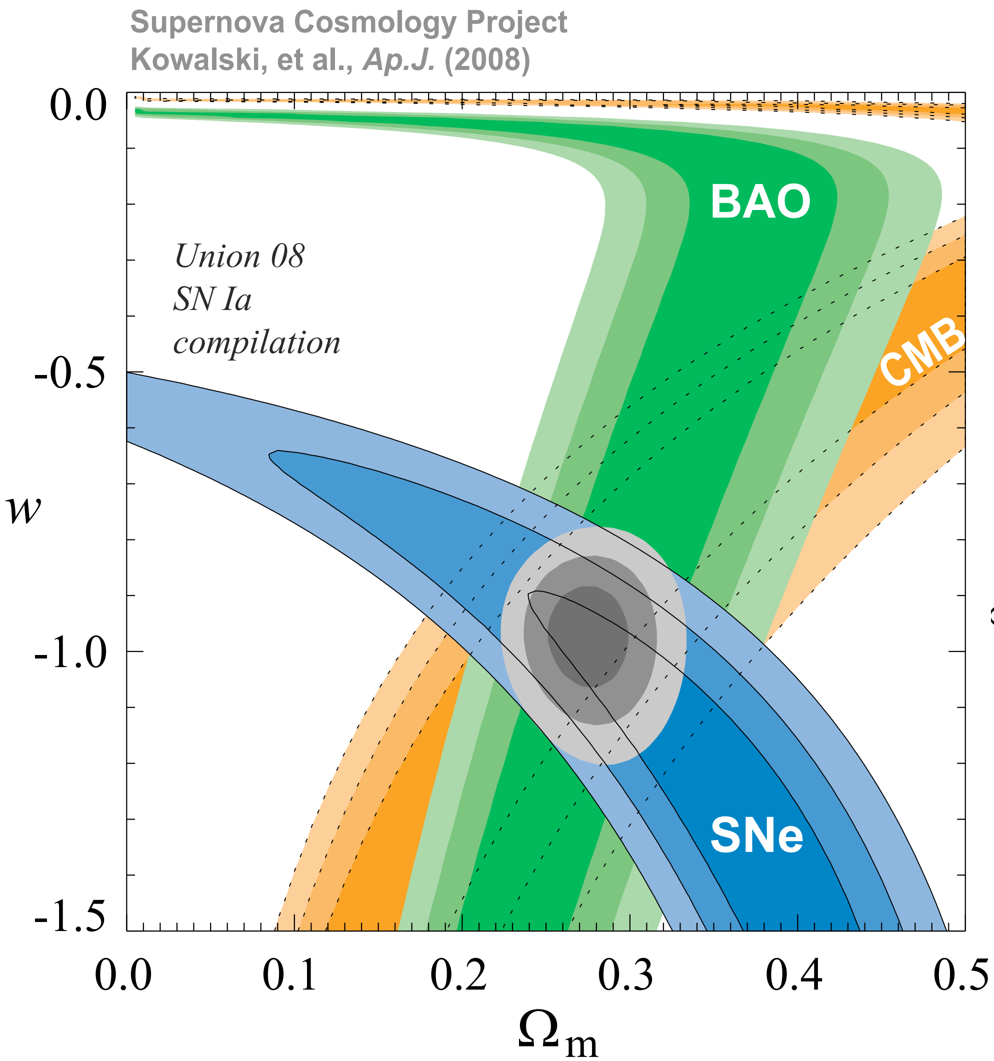
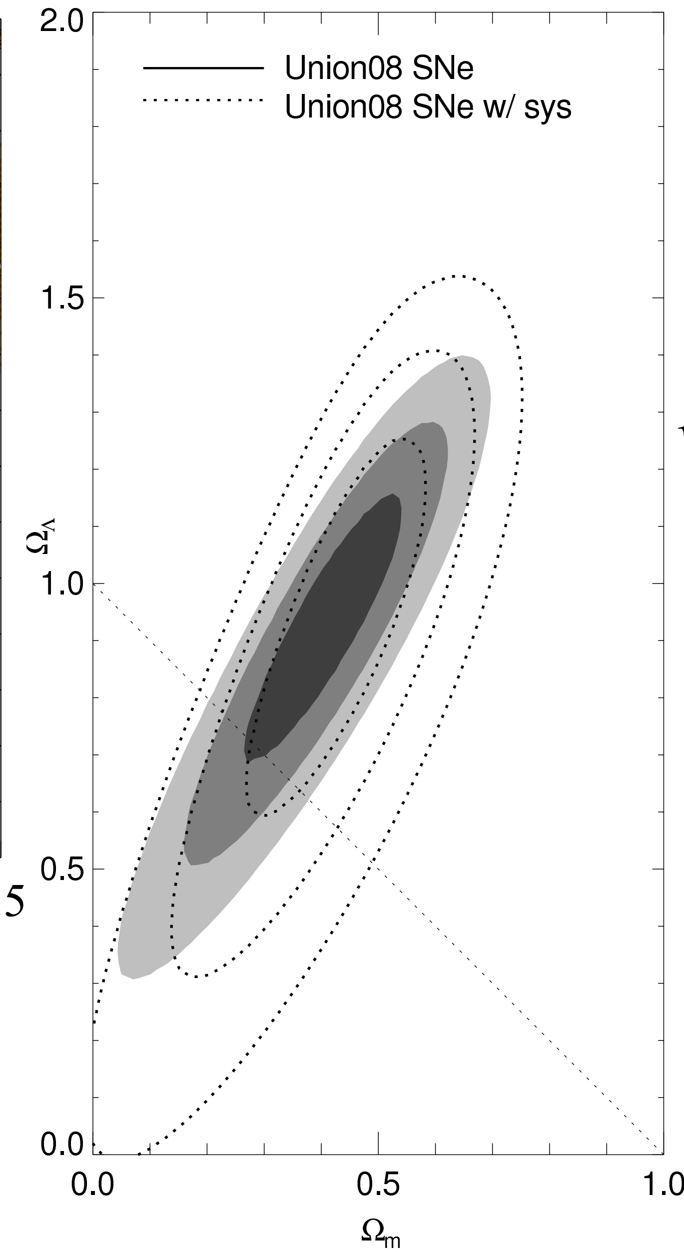
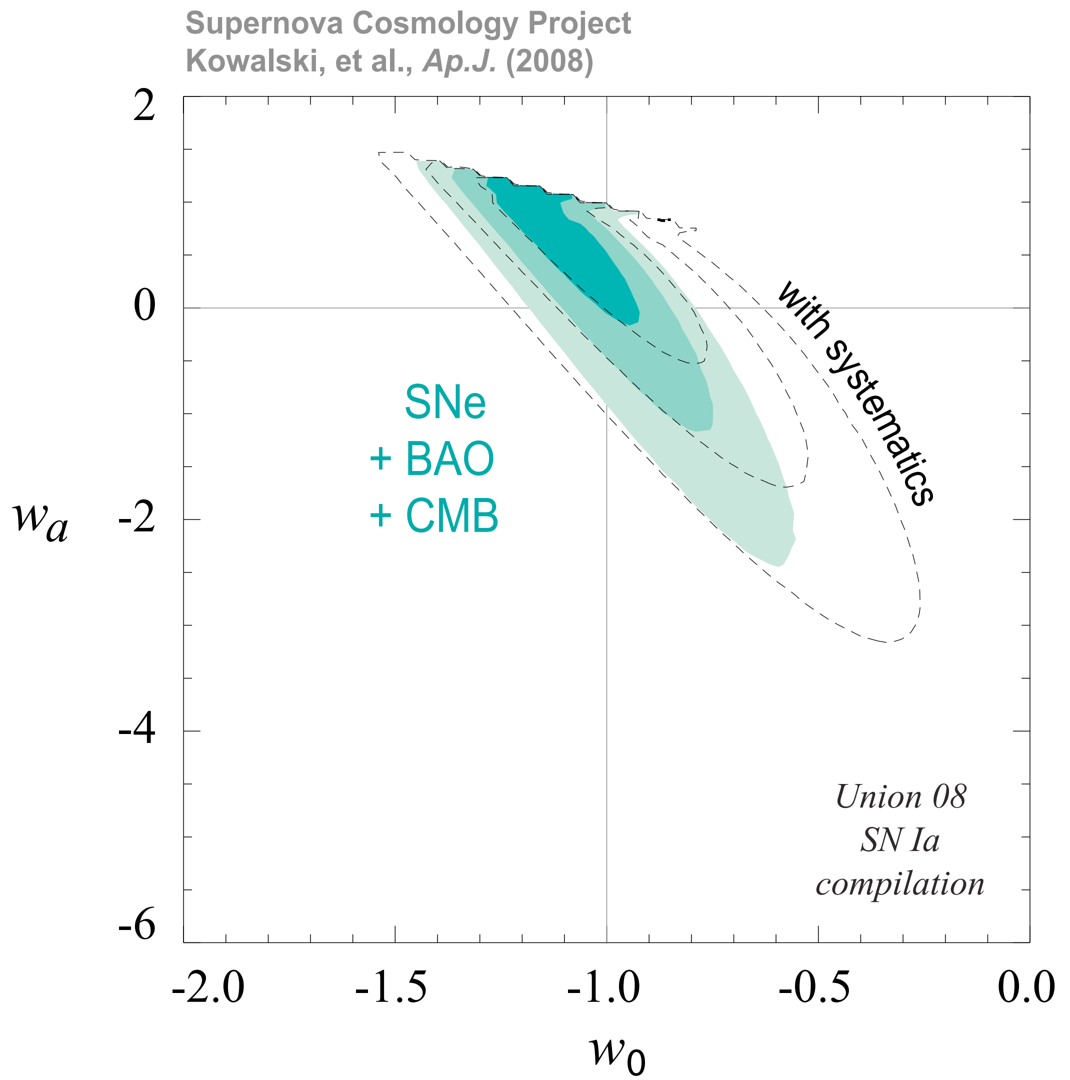
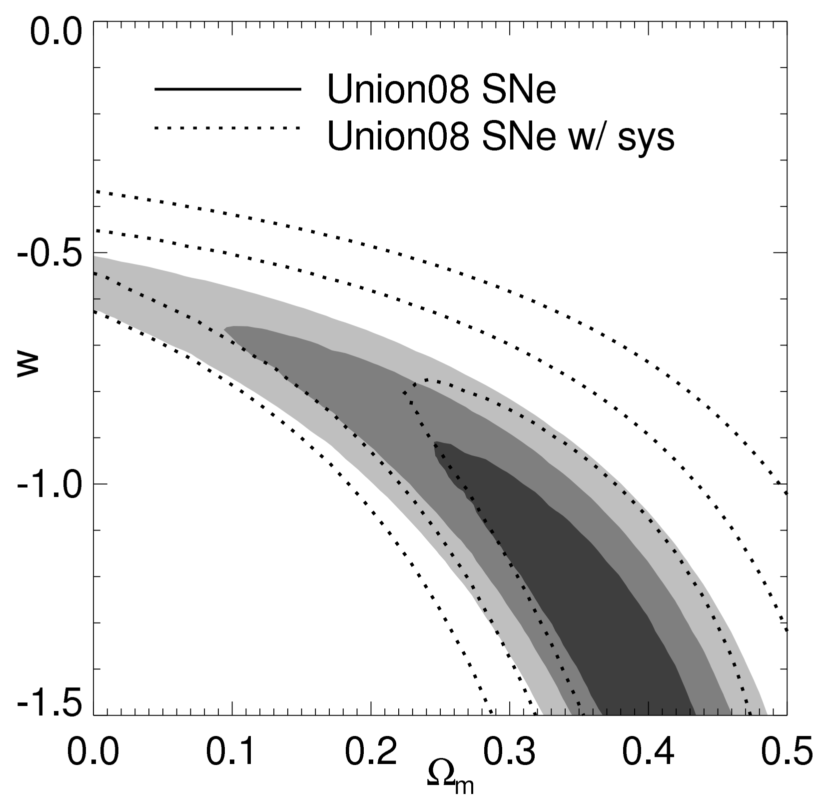
Systematic Matters!









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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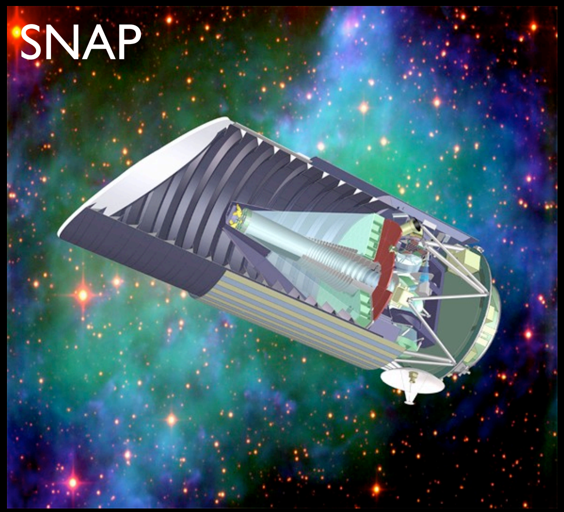
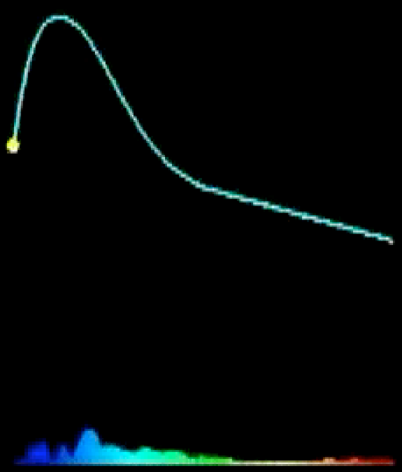
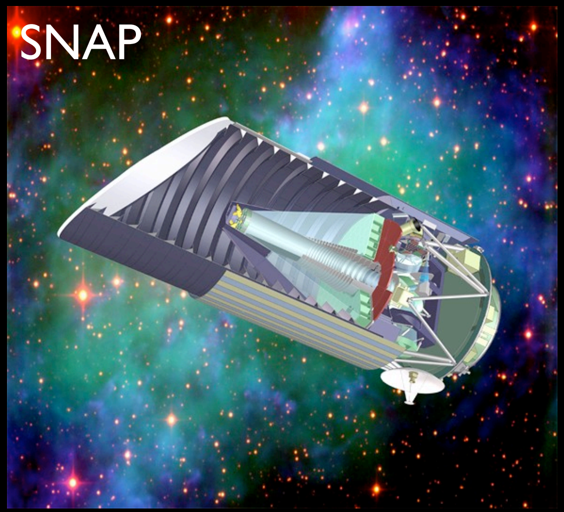
Cosmology with SNe Ia: Revisited

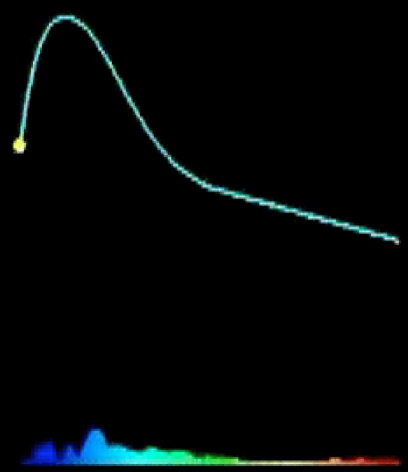




Credit: This clip was prepared by the Supernova Cosmology Project (P. Nugent: spectral sequence; A. Conley: image sequence) with the help of Lawrence Berkeley National Laboratory's Computer Visualization Laboratory (N. Johnston: animation) at the National Energy Research Scientific Computing Center.

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.

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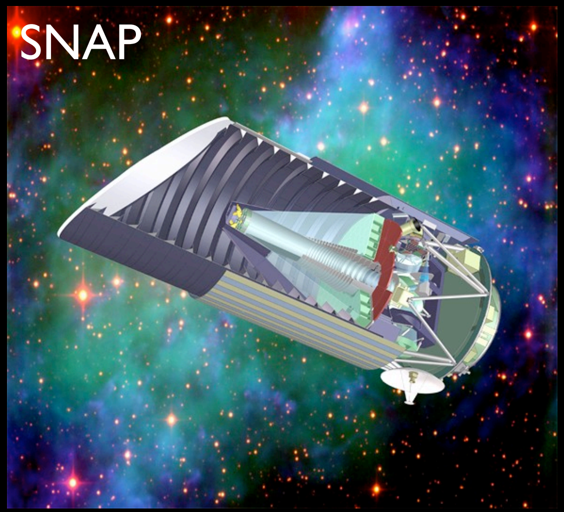

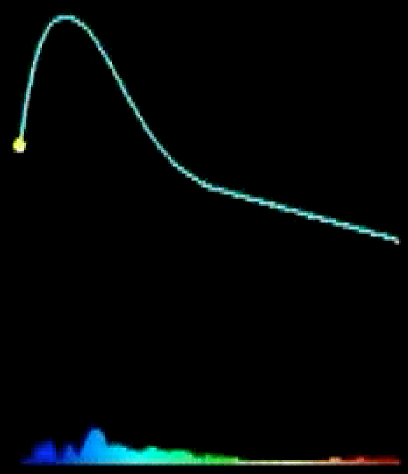

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Challenges

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

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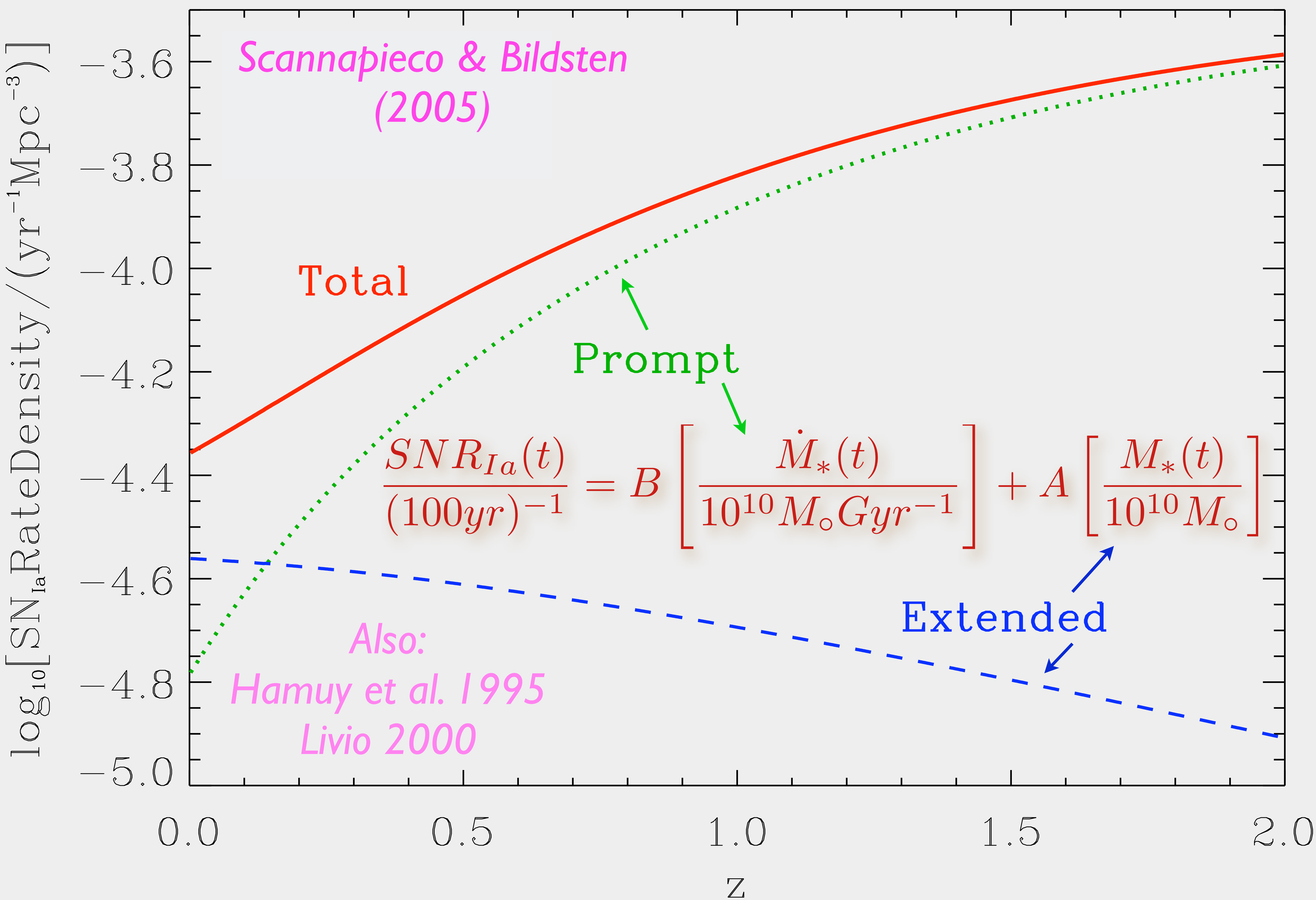
Kowalski et al. (2008), Carnegie Supernova Project: W. Freedman

2-Population	
Lensing	

Evolution based on Two SN Populations



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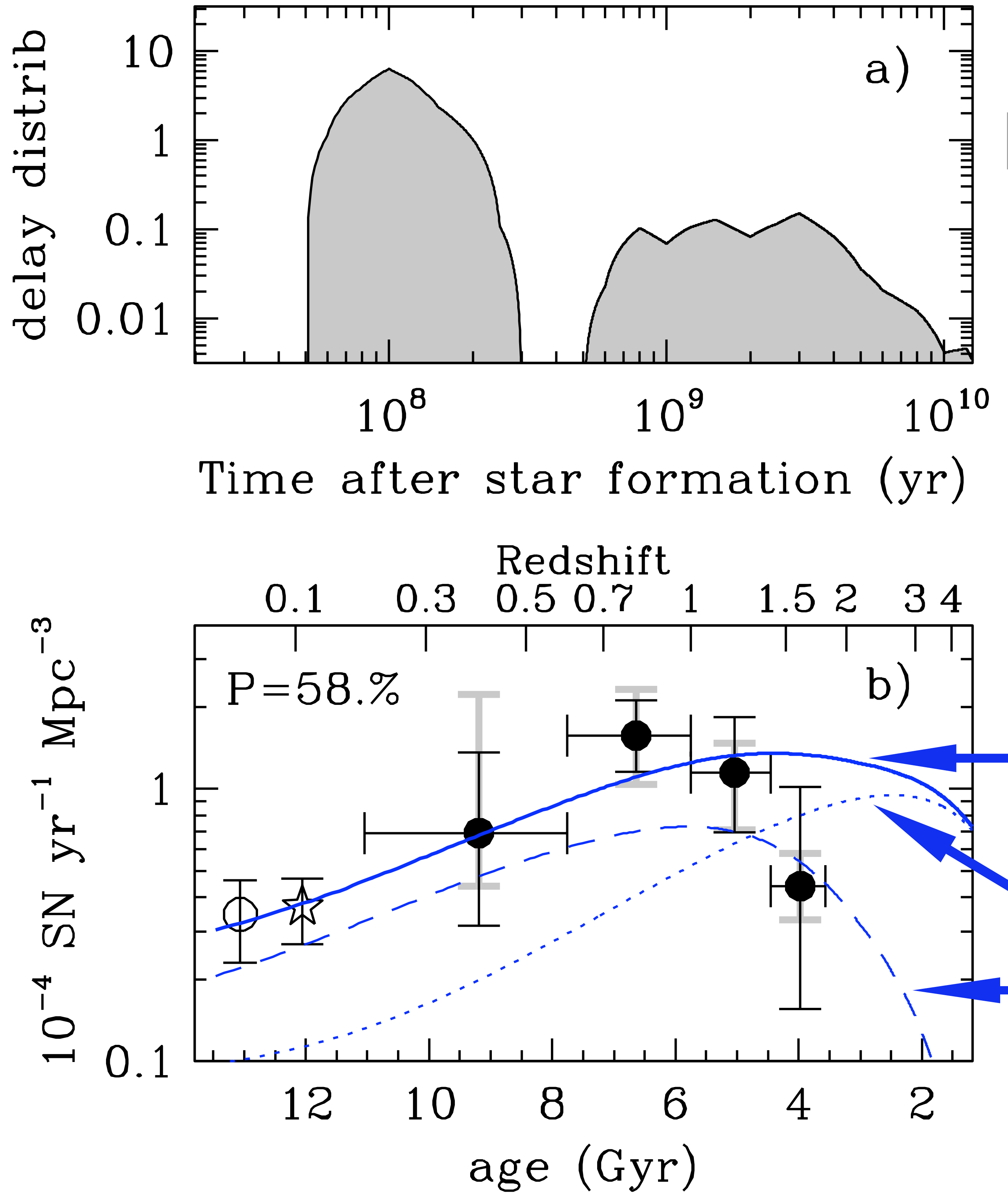


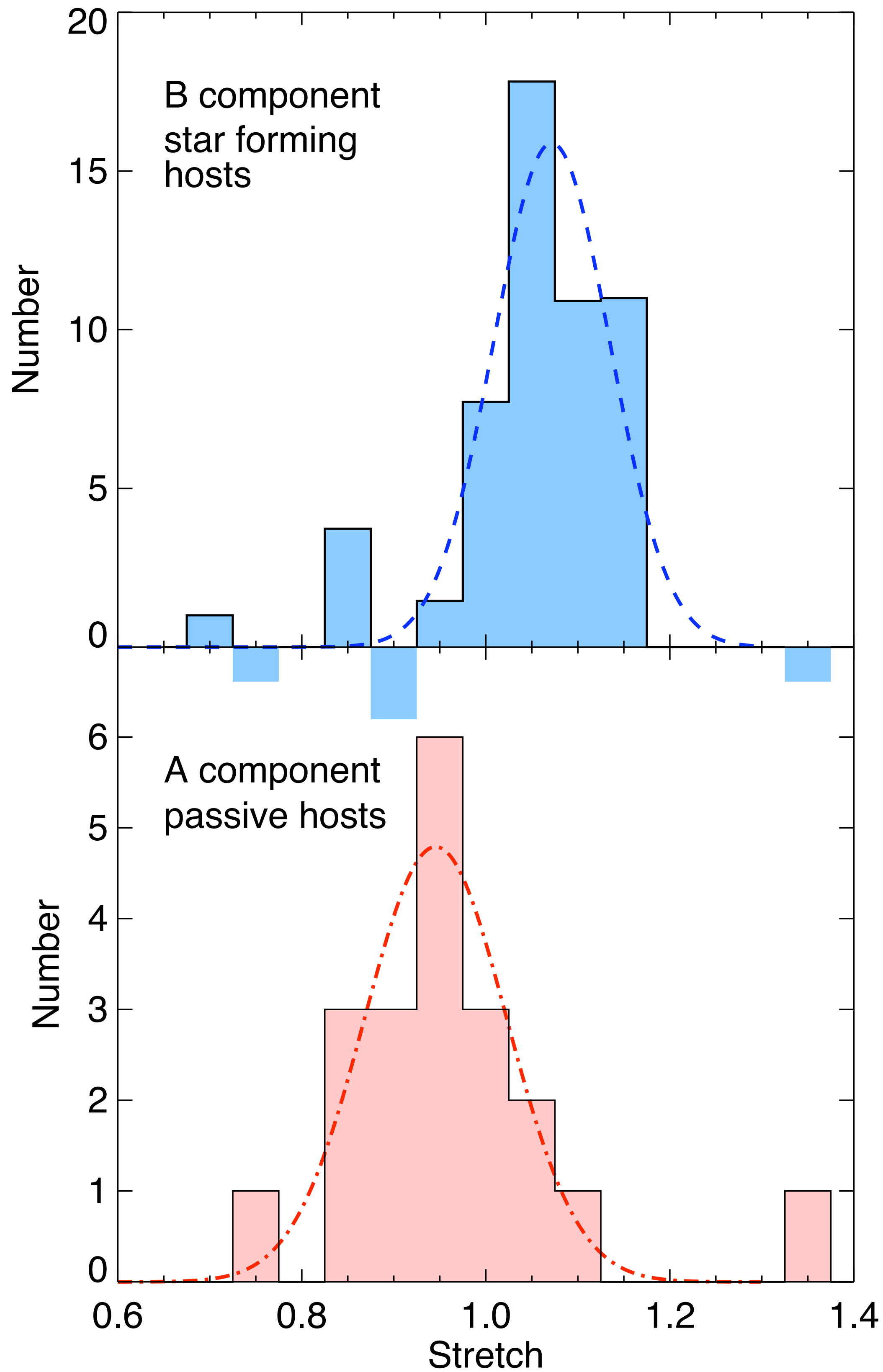
Bimodal
Delay Time Distribution

Belczynski et al. 2005

Mannucci et al. 2006

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

Evolution based on Two SN Populations



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

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

PROMPT

12% Dfference
in
Intrinsic Luminosity

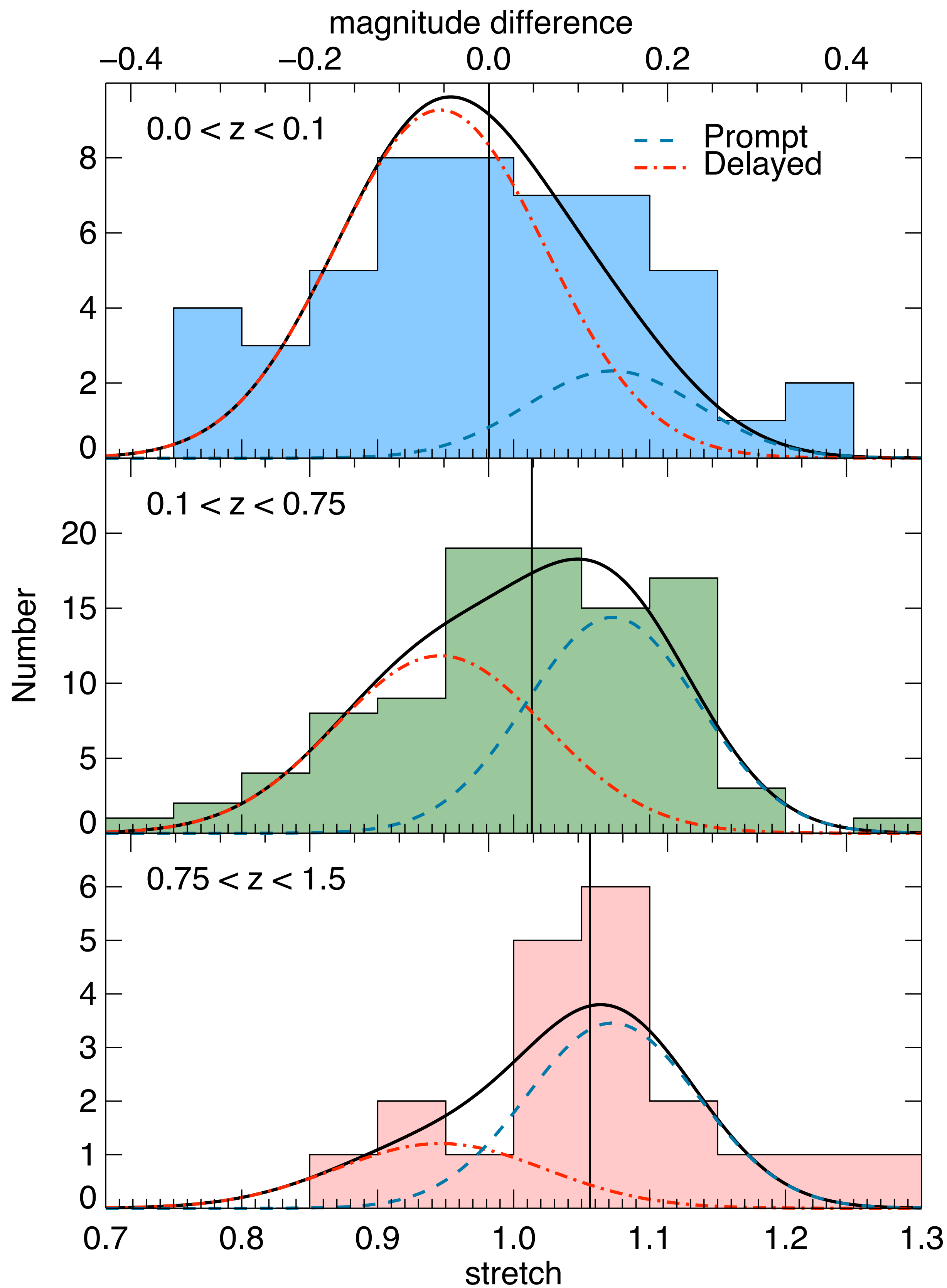
$$\mathcal{L}_P = \mathcal{L}_E + \Delta\mathcal{L}$$

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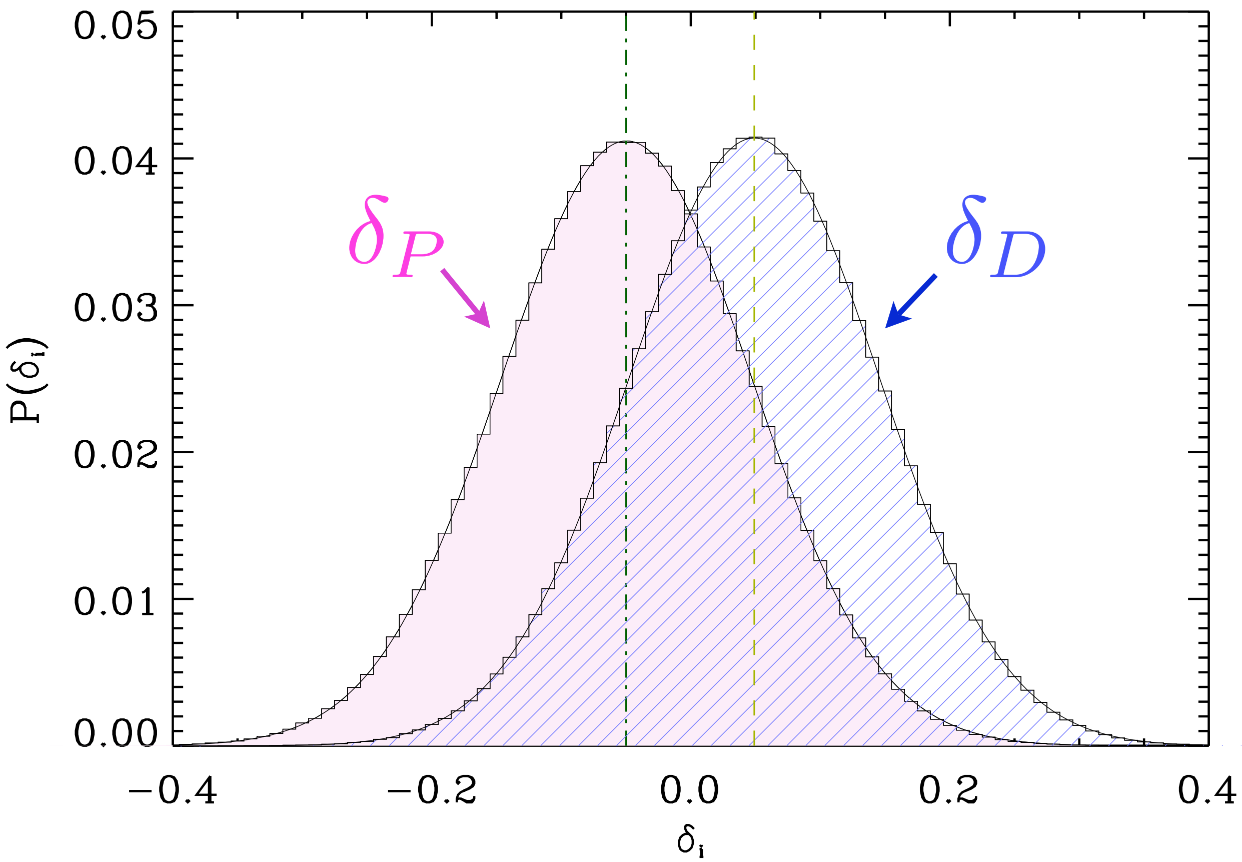
$$m - M = 5\log\left(\frac{d_L}{\mathrm{Mpc}}\right) + 25 + \mathcal{M}$$

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?

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



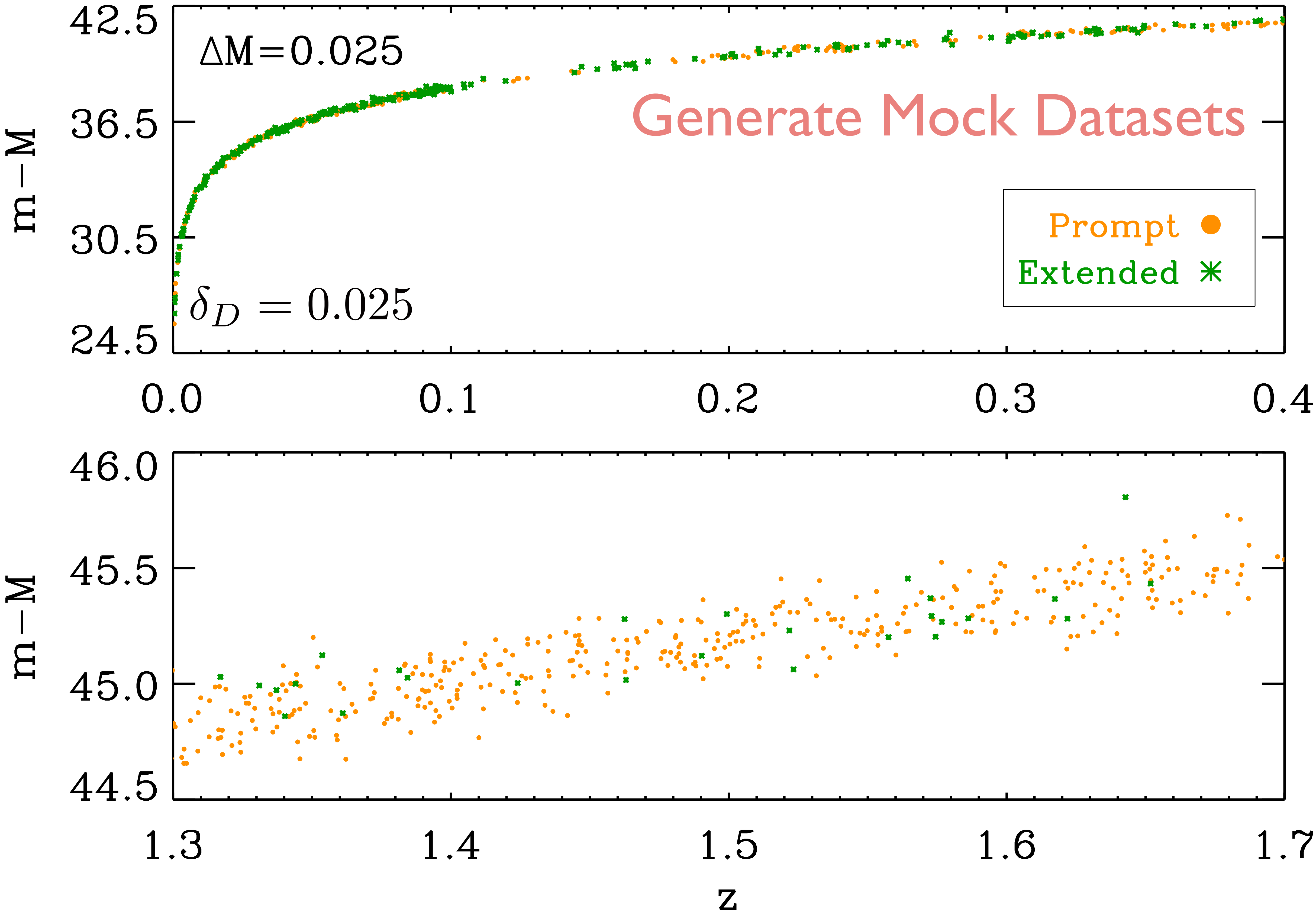
With current data (192 SNe from Davis et al. 2007), the residual is consistent with zero:

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

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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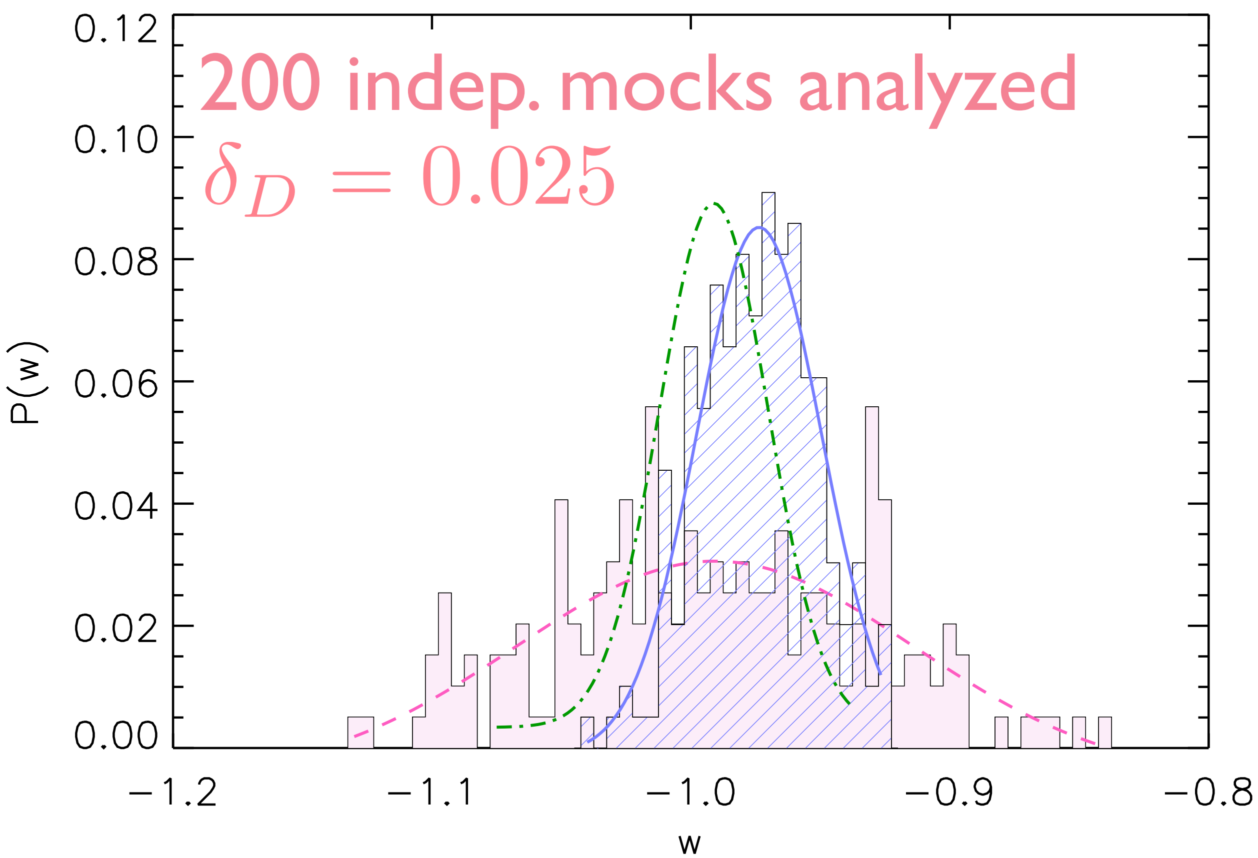

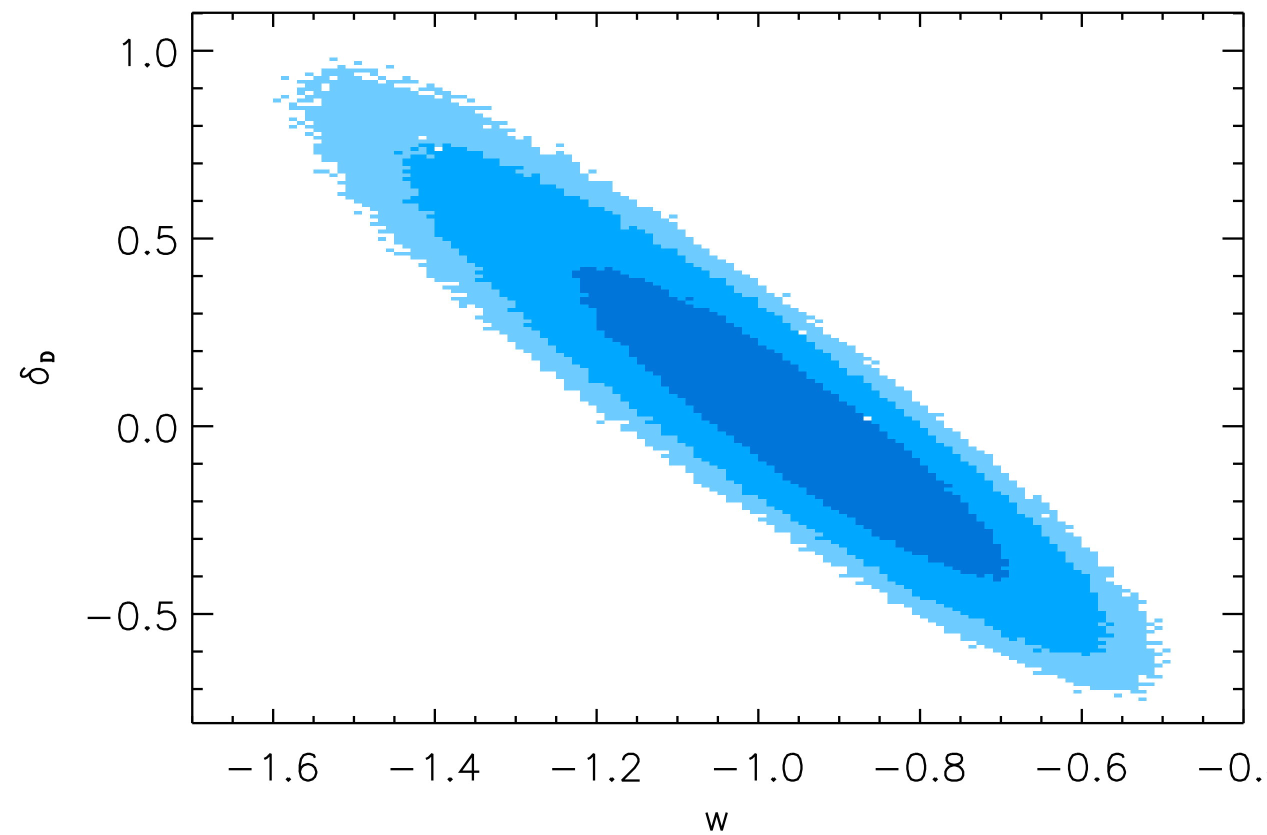

~1-sigma bias in "w"

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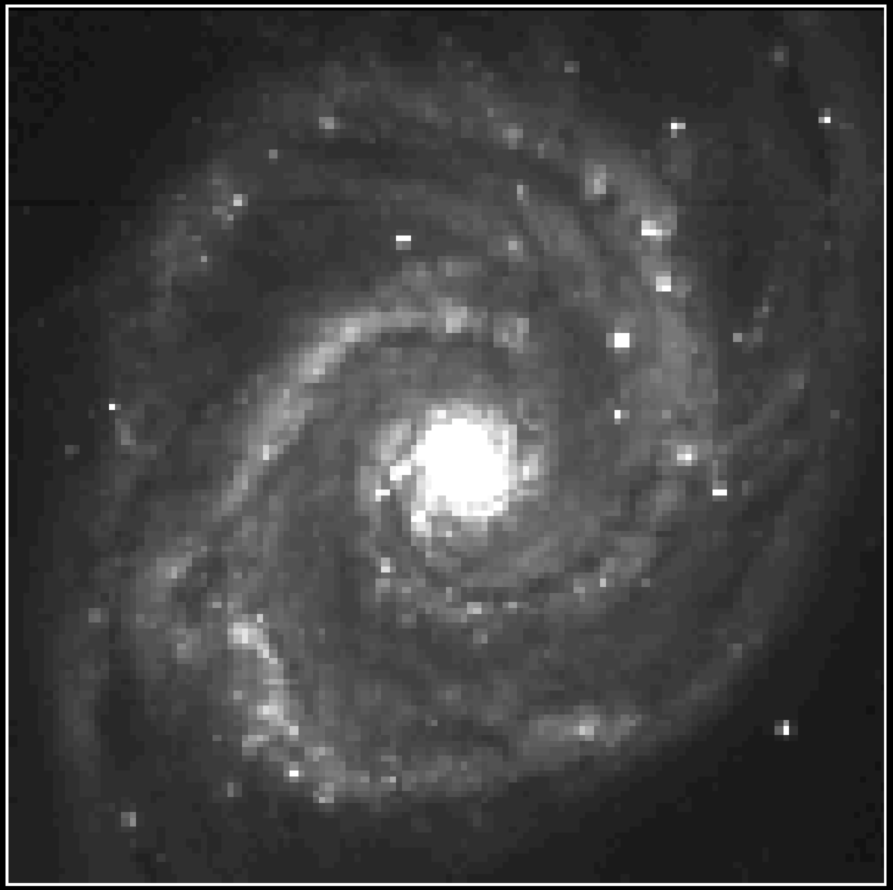
Kowalski et al. (2008), Carnegie Supernova Project: W. Freedman

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

Influence of Gravitational Lensing?



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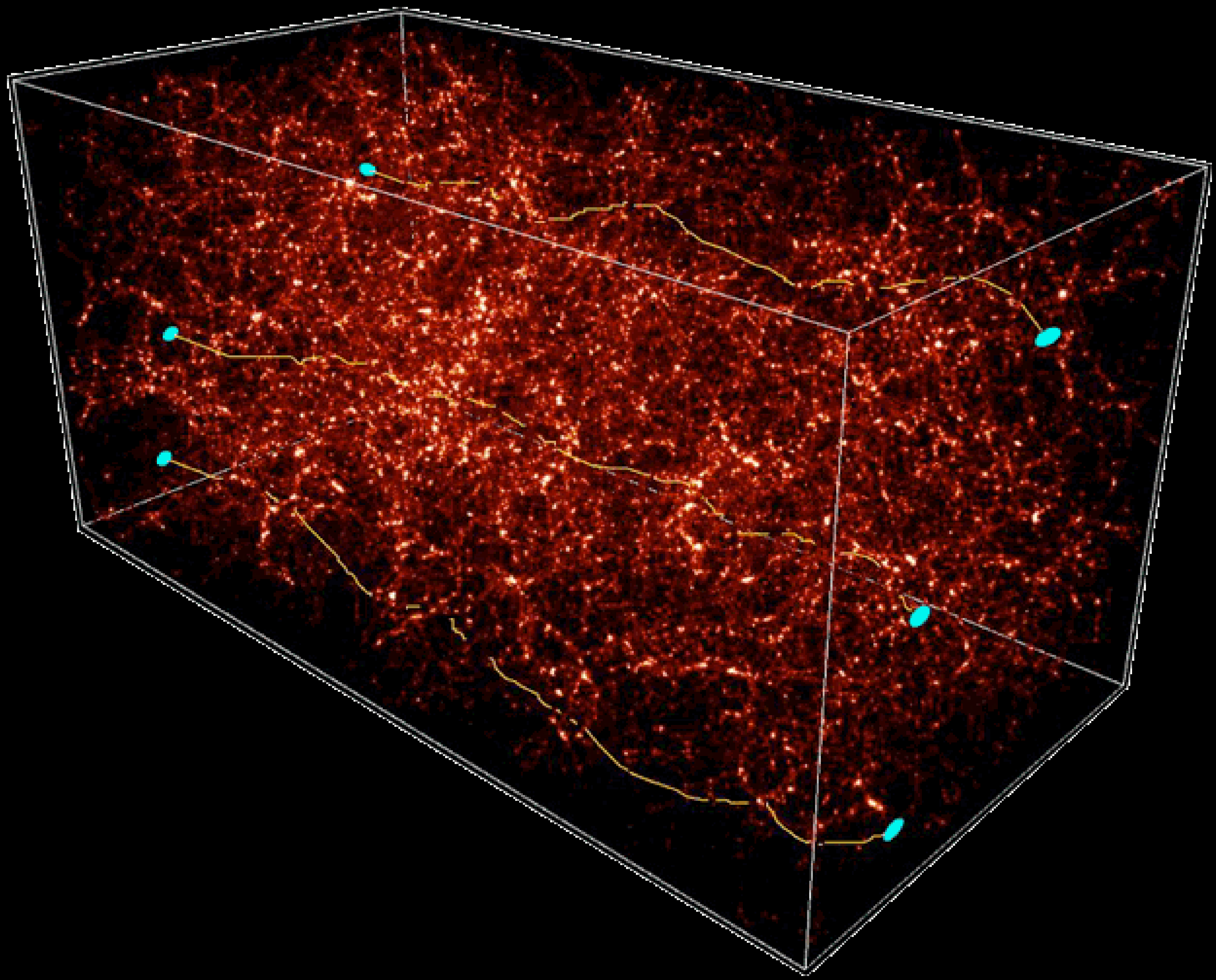

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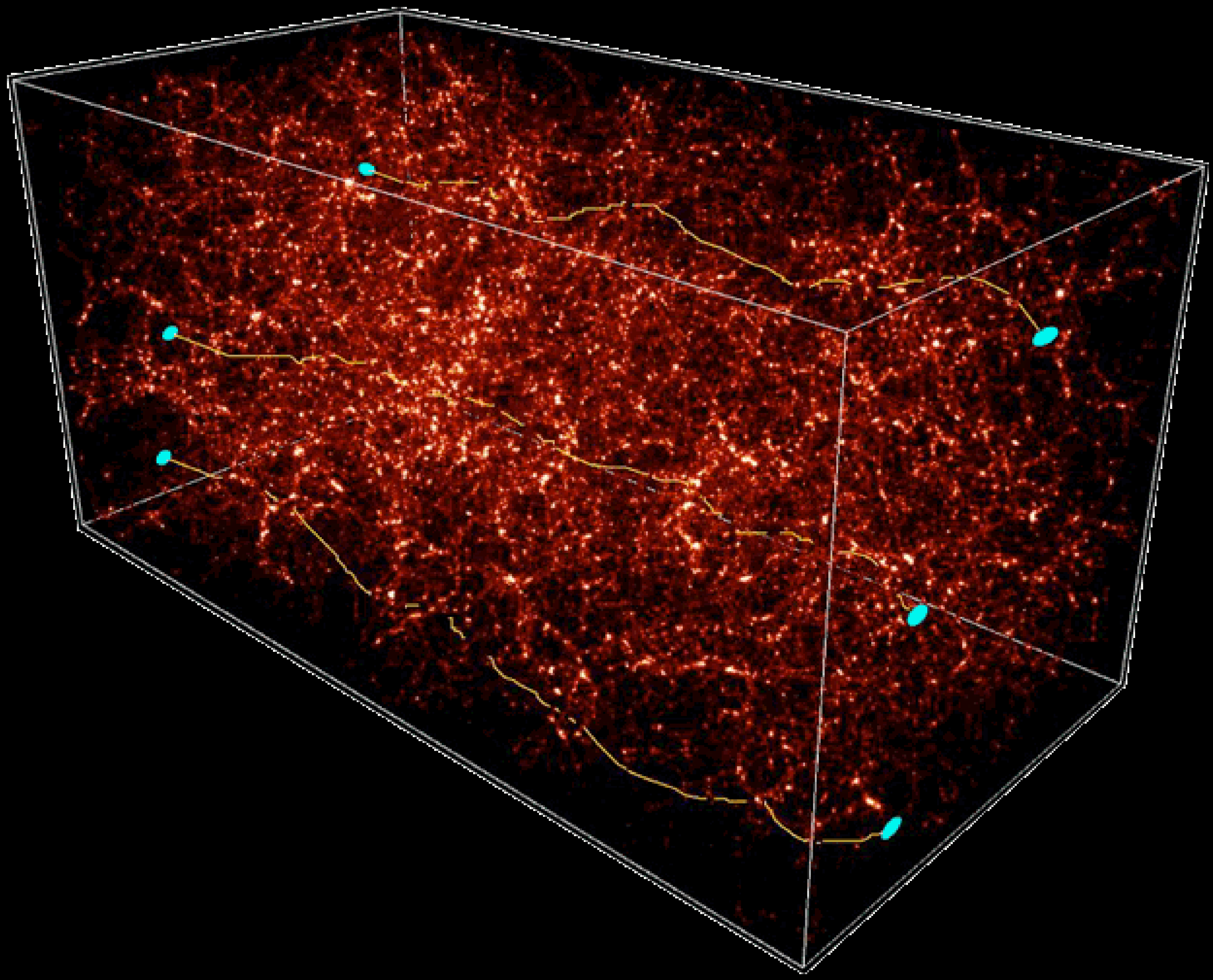
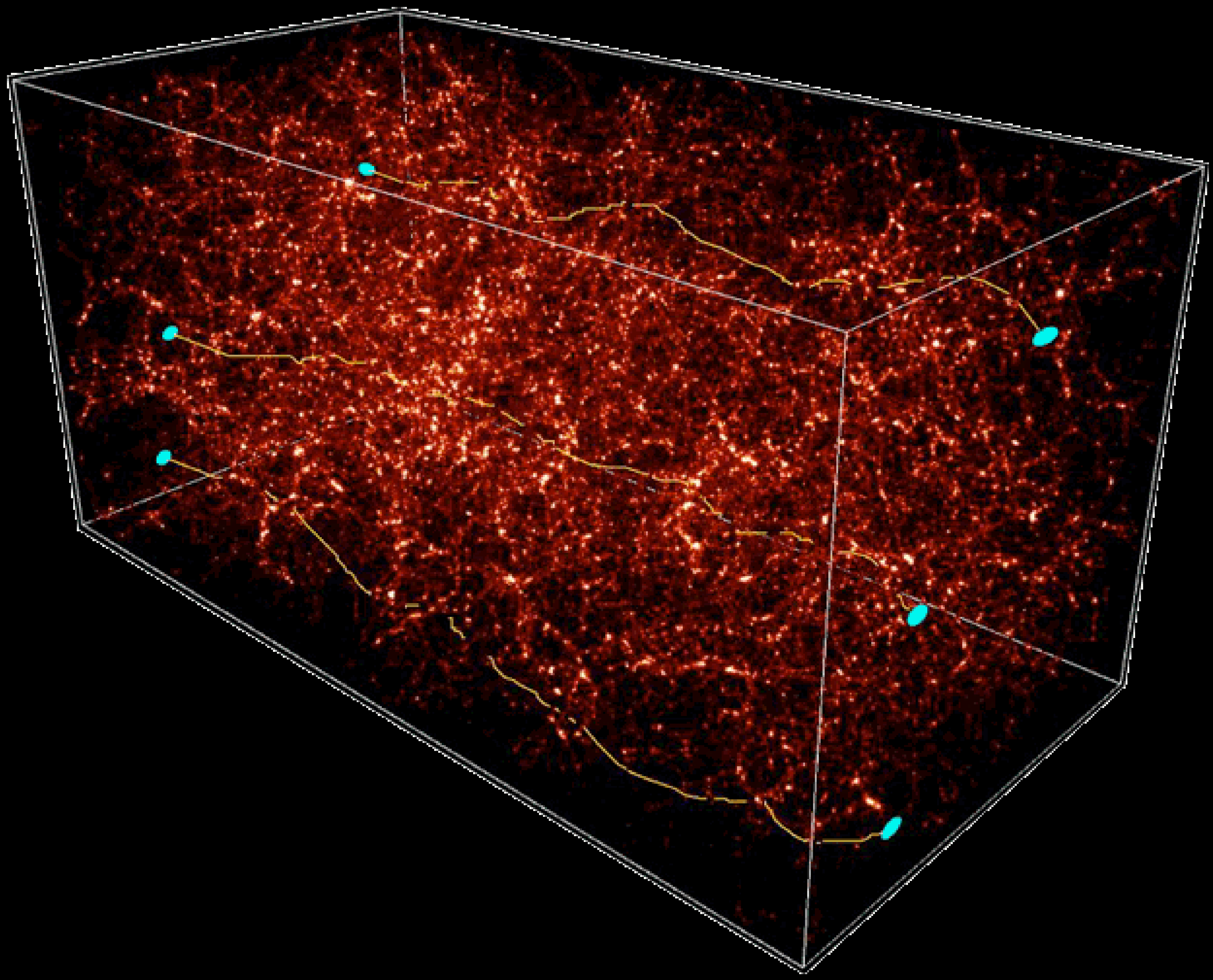


$$\mathcal{F}^{\mathrm{obs,lensed}}(z, \hat{\mathbf{n}}) = \mu(z, \hat{\mathbf{n}})\mathcal{F}^{\mathrm{obs,true}}(z)$$

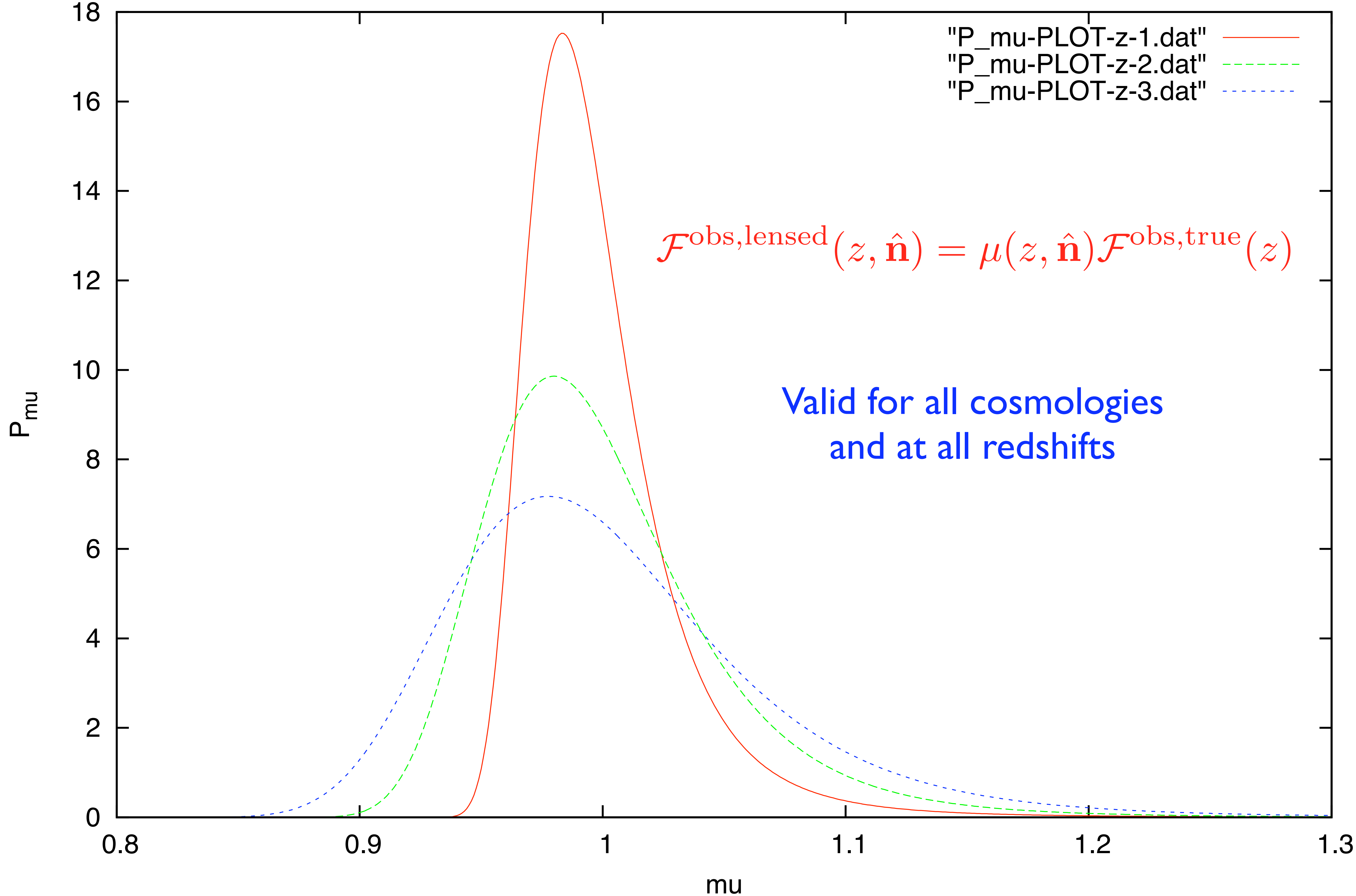
Influence of Gravitational Lensing?



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

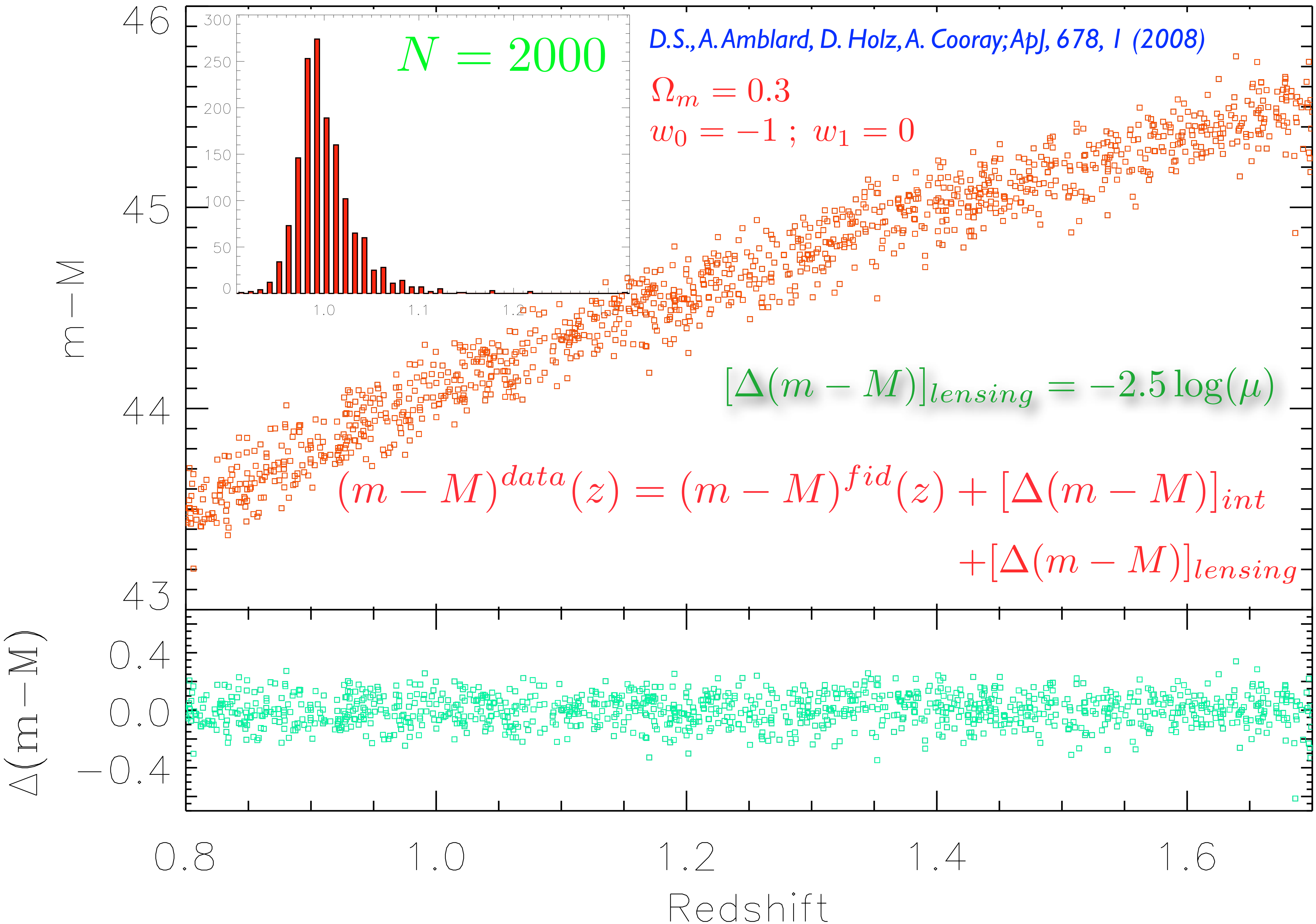
Weak lensing can modify the SNa flux & bias estimates of w

Amplification Probability Distribution

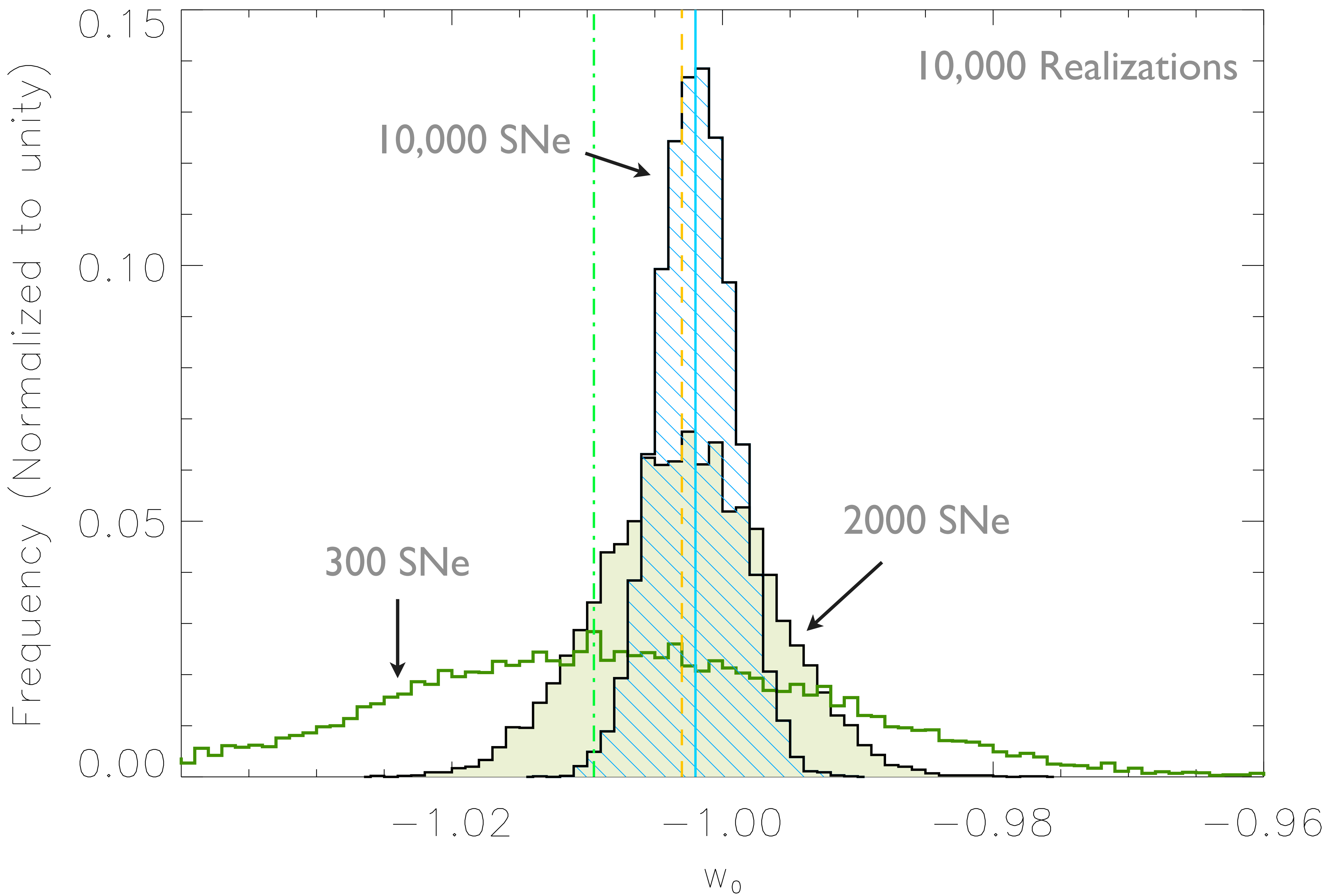


*Wang, Y., Holz, D. E., & Munshi, D., 2002, ApJ, **572**, L15*

Our Analysis with Mock Catalogs

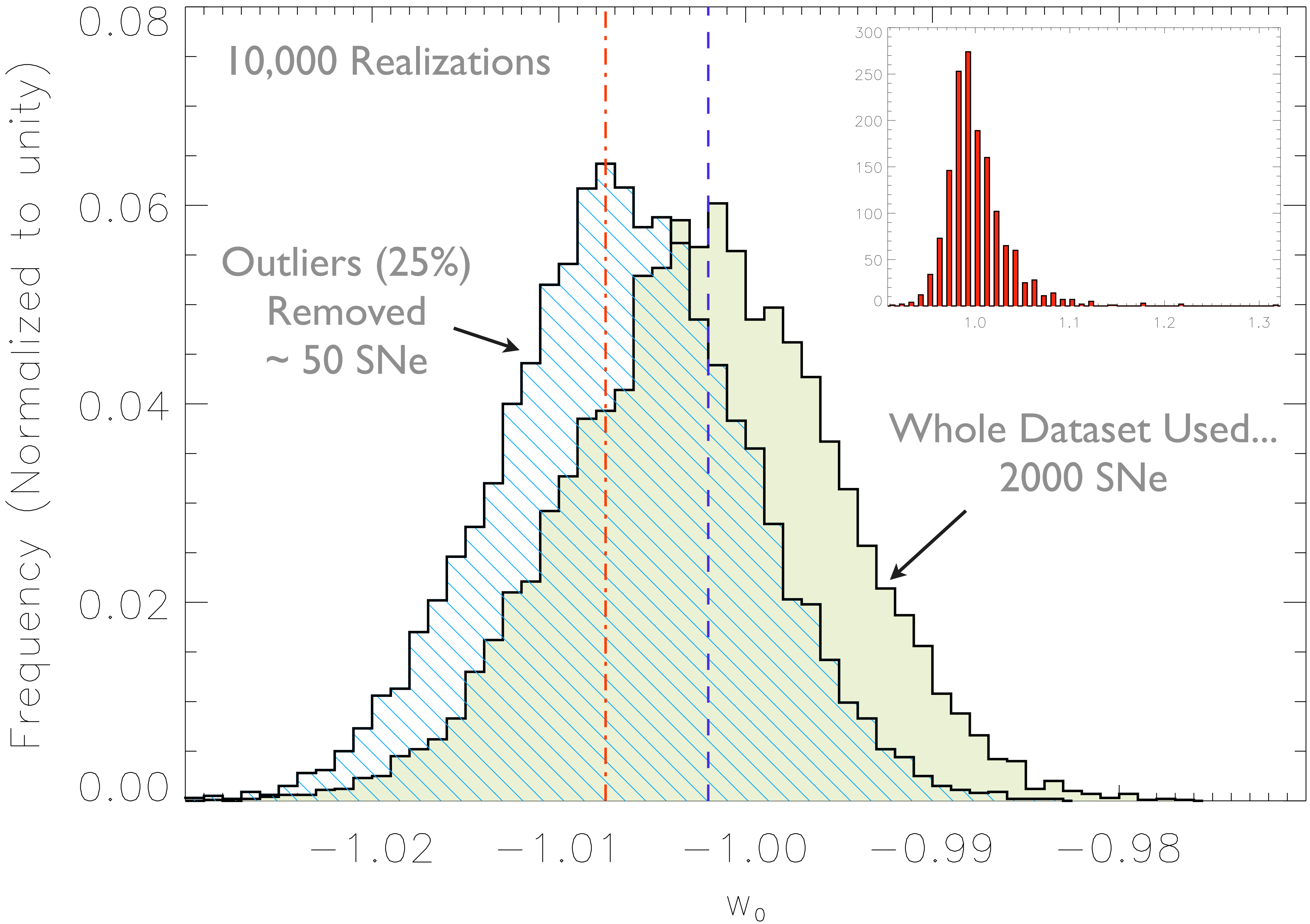


Effect of Weak Lensing on Estimates of “w”



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)

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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?
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- DE from SNe Ia ++
- Beware of Systematics
  - Two Population Model
  - Gravitational Lensing

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Primordial Non-Gaussianity: Primary CMB Bispectrum

Gaussian Quantum Fluctuation

Falk et al. (1993) ↓ $$\delta\phi \sim g_{\delta\phi}\left(\eta + m_{pl}^{-1} f_\eta \eta^2\right)$$ ↓ Starobinsky (1986) Gangui et al. (1994)

Non-Gaussian Inflation Fluctuation

↓ $$\Phi \sim m_{pl}^{-1} g_\Phi \left(\delta\phi + m_{pl}^{-1} f_{\delta\phi} \delta\phi^2\right)$$ ↓ Salopek & Bond (1990)

Non-Gaussian Curvature Perturbation

↓ $$\frac{\Delta T}{T} \sim g_T \left(\Phi + f_\Phi \Phi^2\right)$$ ↓ Pyne & Carroll (1996)

Non-Gaussian CMB Anisotropy

Primordial Non-Gaussianity: Primary CMB Bispectrum

Combining all the contributions:

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

where:

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

Non-Linear
Coupling Parameter

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

- Komatsu 2002

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

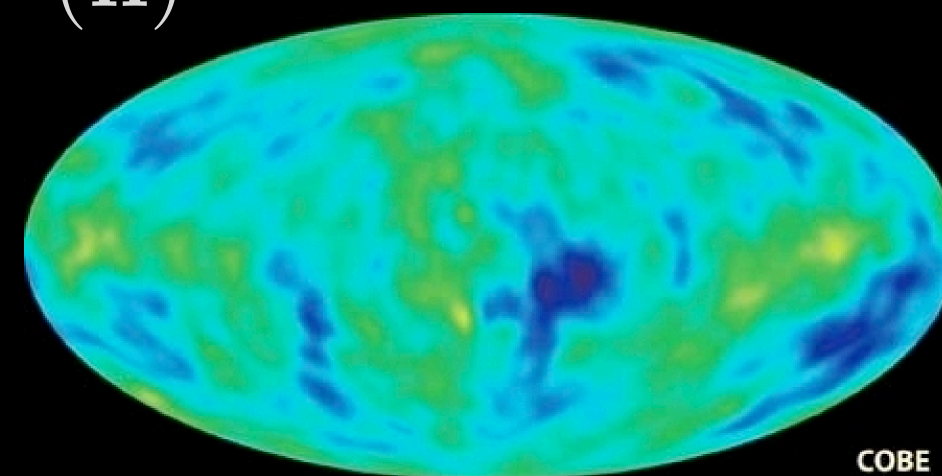
- Models with multiple scalar fields
- Non-Adiabatic Fluctuations
- Features in the inflation potential
- Non-canonical kinetic terms
- ...

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

Primary CMB Bispectrum

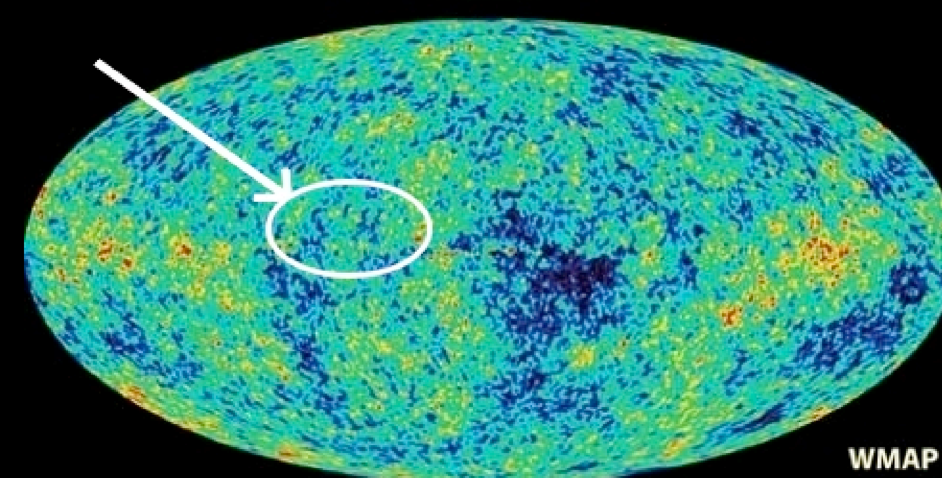
The CMB Temperature Perturbation in the Sky:

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



Power Spectrum:

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



Angular Bispectrum:

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

Measurement of primordial non-Gaussianity

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

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

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

[1]*Department of Astronomy, University of Illinois at Urbana-Champaign, 1002 W. Green Street, Urbana, Illinois 61801, USA*
[2]*Department of Physics, University of Illinois at Urbana-Champaign, 1110 W. Green Street, Urbana, Illinois 61801, USA*
(Received 7 December 2007; revised manuscript received 6 March 2008; published 7 May 2008)

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

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

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

Submitted to the Astrophysical Journal Supplement Series

ABSTRACT

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

Measurement of primordial non-Gaussianity

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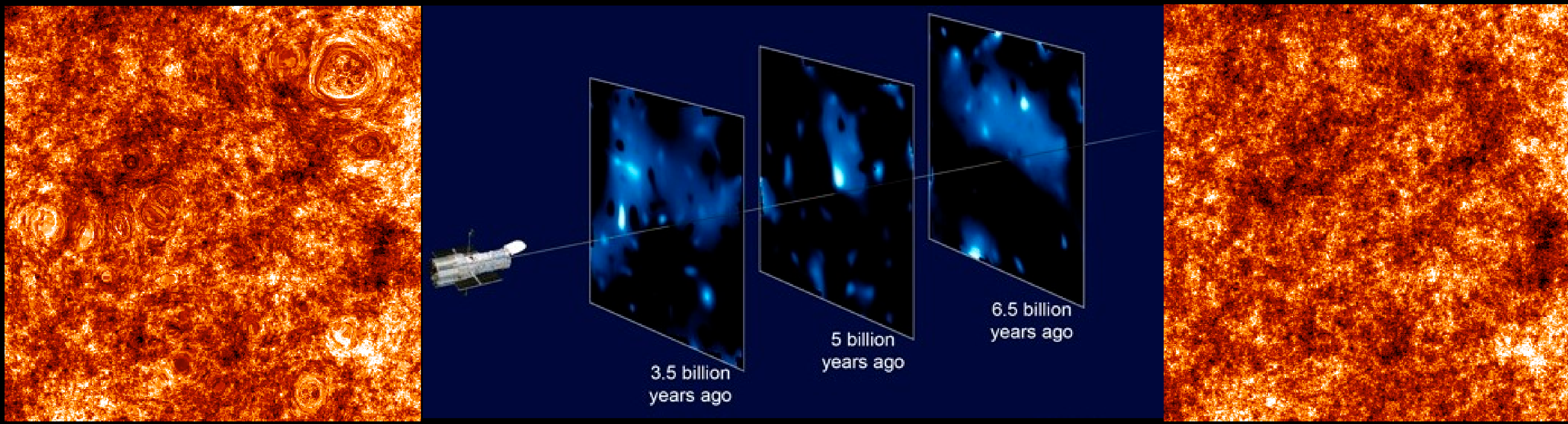
Constraints on local primordial non-Gaussianity from large scale structure

Anže Slosar,[1] Christopher Hirata,[2] Uroš Seljak,[3,4] Shirley Ho,[5] and Nikhil Padmanabhan[6]

$$-29(-65) < f_{NL} < +70(+93)$$

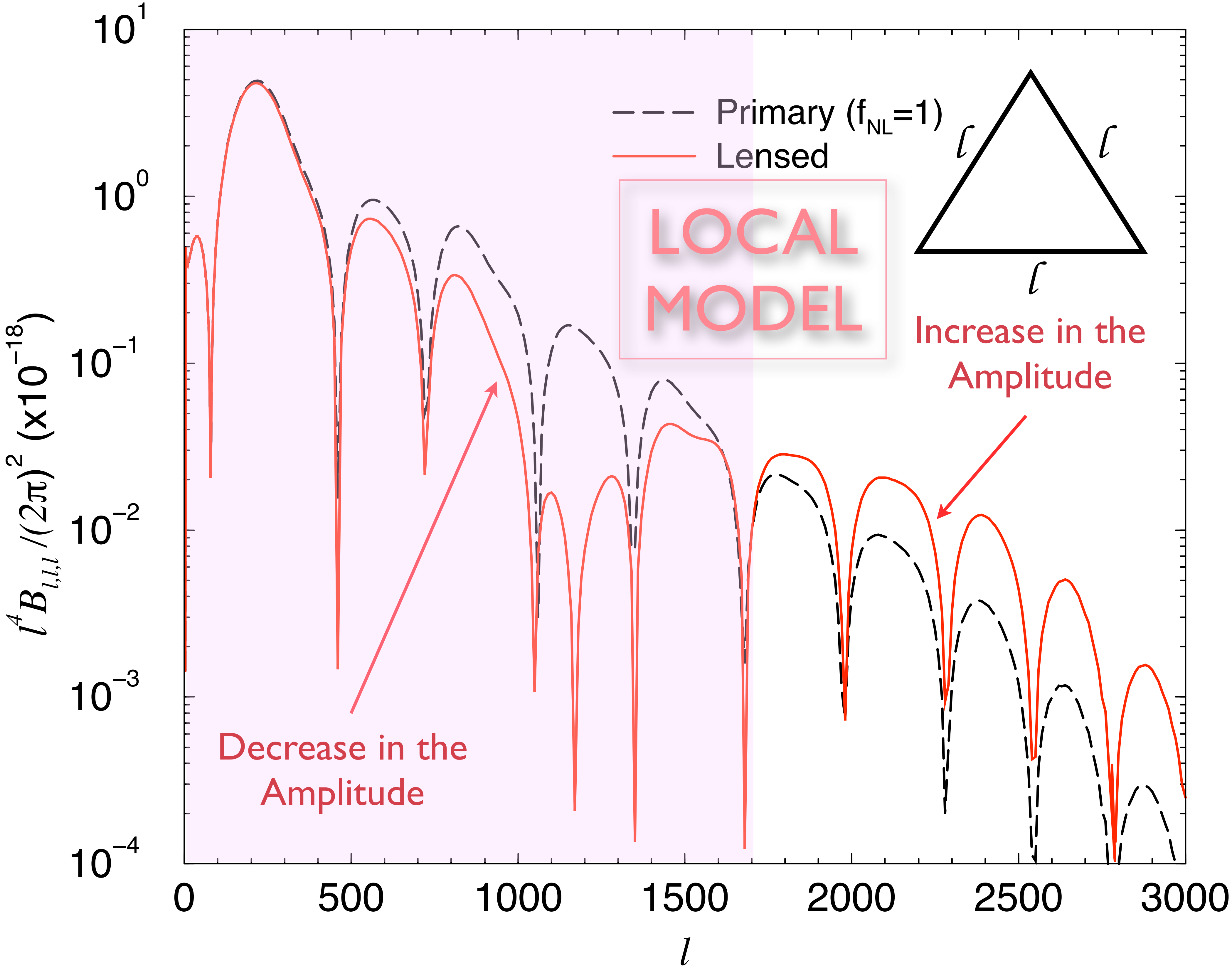
Weak Lensing of the Primary Bispectrum



$$\tilde{\Theta}(\hat{\mathbf{n}}) = \Theta[\hat{\mathbf{n}} + \hat{\alpha}]$$
$$= \Theta[\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}})]$$
$$\approx \Theta(\hat{\mathbf{n}}) + \nabla_i\phi(\hat{\mathbf{n}})\nabla^i\Theta(\hat{\mathbf{n}}) + \frac{1}{2}\nabla_i\phi(\hat{\mathbf{n}})\nabla_j\phi(\hat{\mathbf{n}})\nabla^i\nabla^j\Theta(\hat{\mathbf{n}})$$

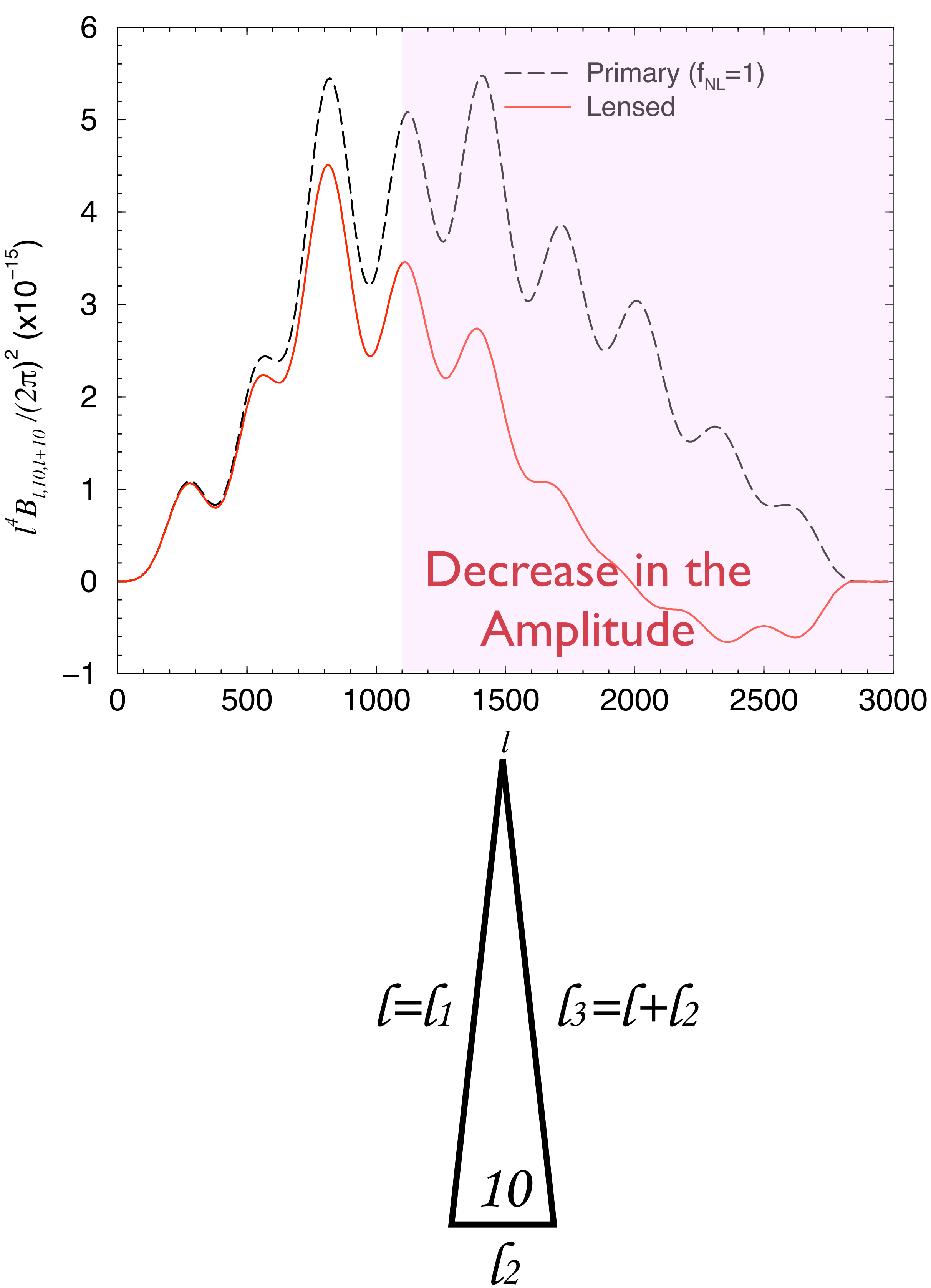
$$\tilde{B}^{\Theta}_{l_1 l_2 l_3} = \sum_{m_1 m_2 m_3} \begin{pmatrix} l_1 & l_2 & l_3 \\ m_1 & m_2 & m_3 \end{pmatrix} \langle \tilde{\Theta}_{l_1 m_1} \tilde{\Theta}_{l_2 m_2} \tilde{\Theta}_{l_3 m_3} \rangle$$

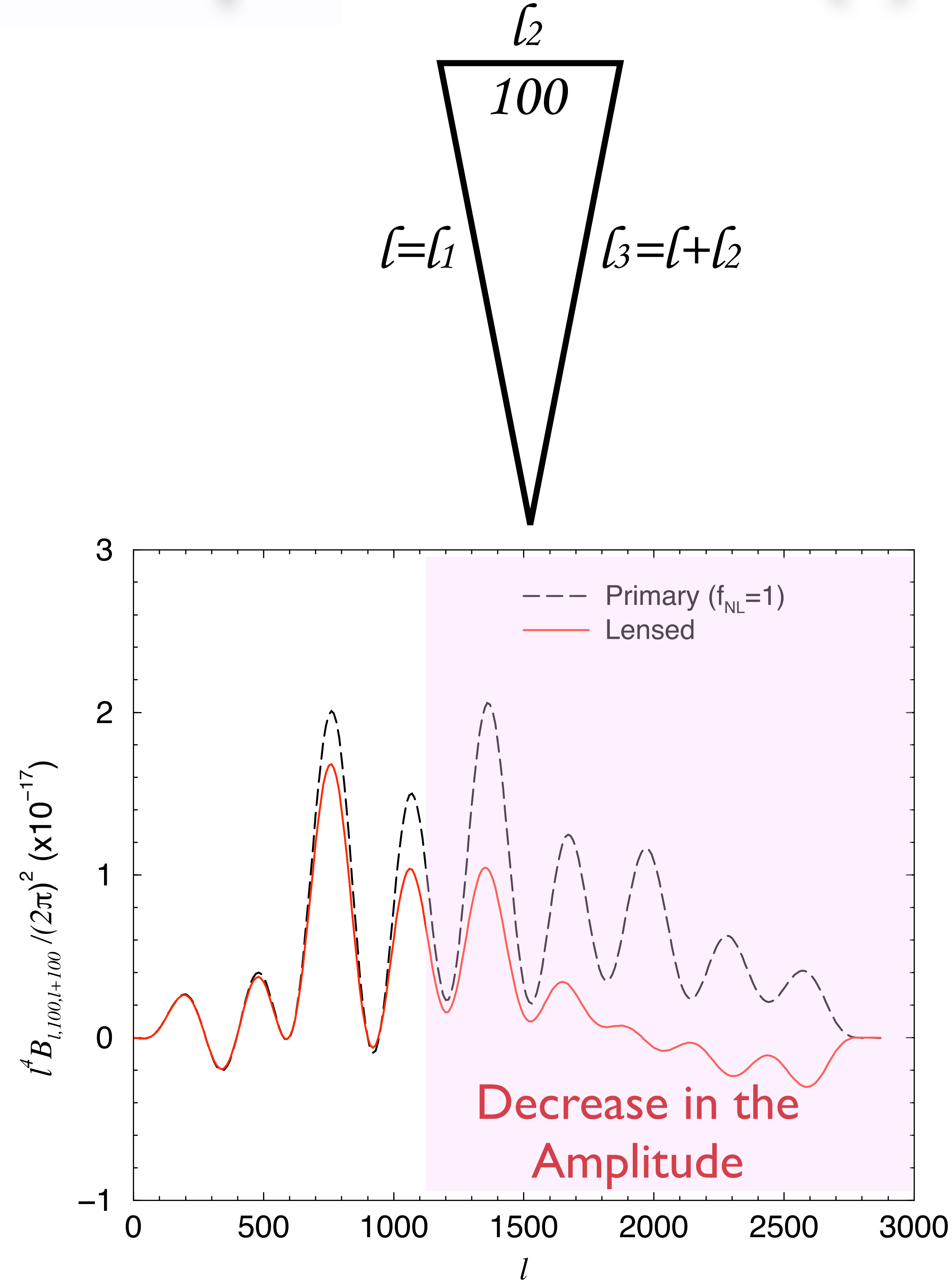
CMB Bispectrum of the Equilateral Case



A. Cooray, D.S., P. Serra; PRD, 77, 123006 (2008)

CMB Bispectrum of the Squeezed Case(s)



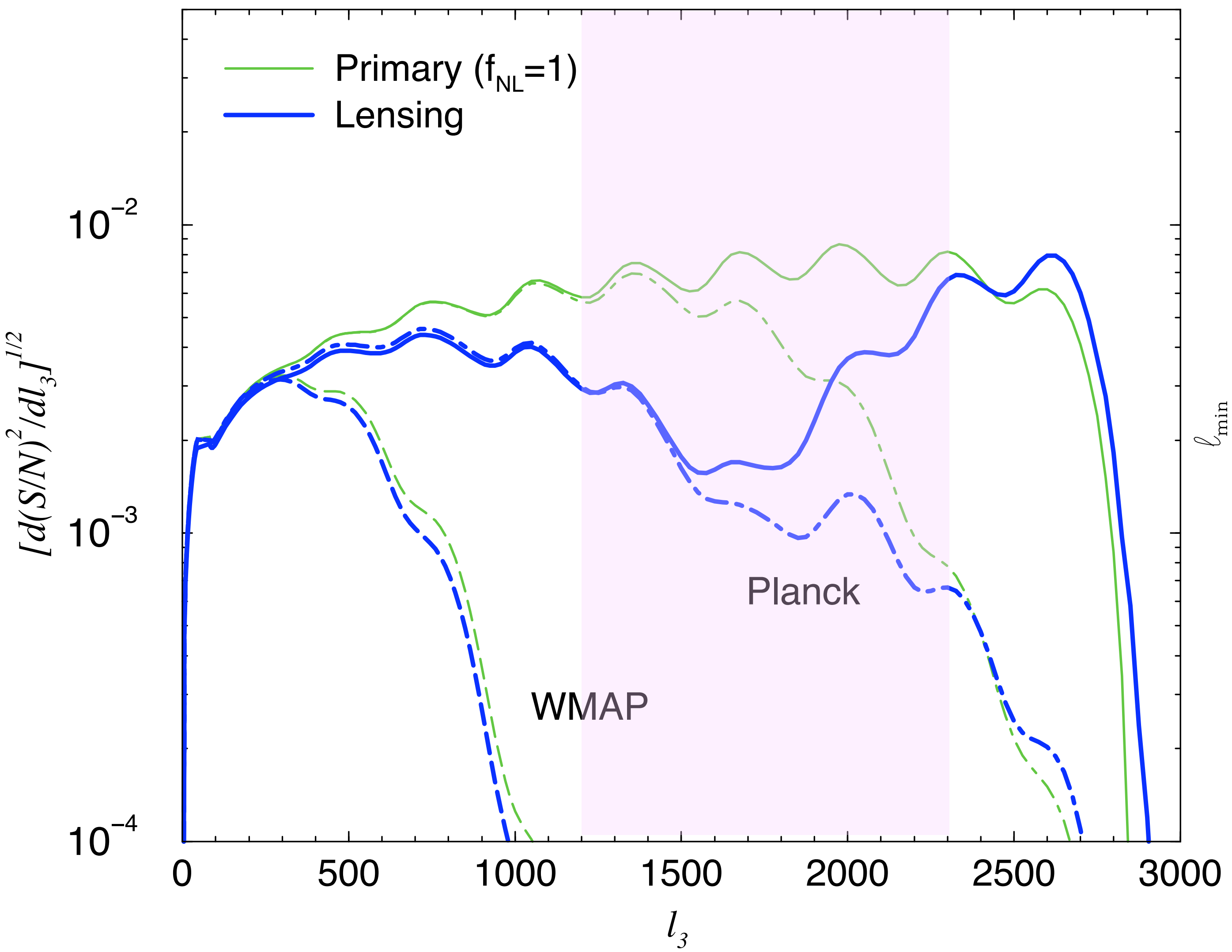


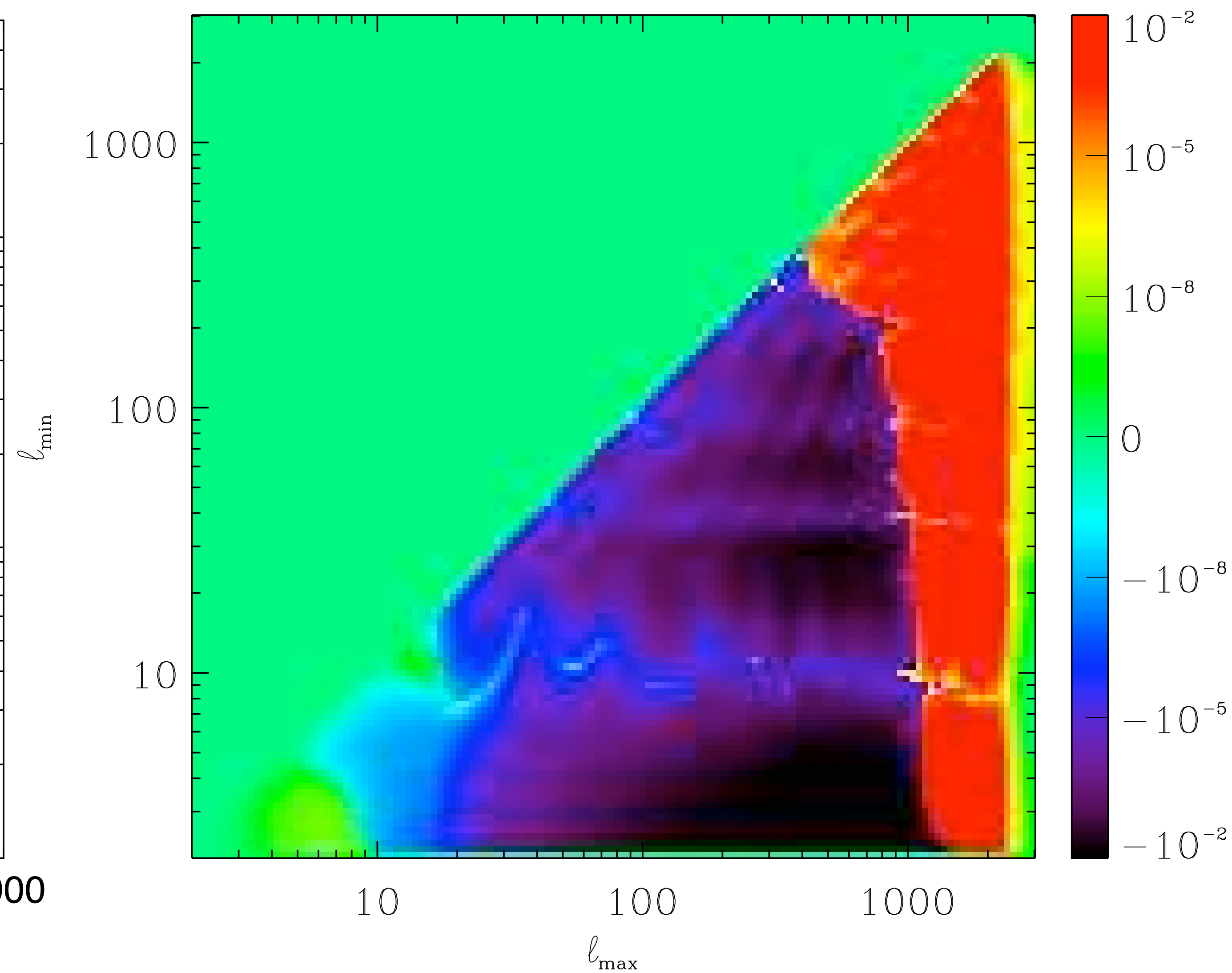
A. Cooray, D.S., P. Serra; PRD, 77, 123006 (2008)

Reduction in the S/N due to Lensing

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

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

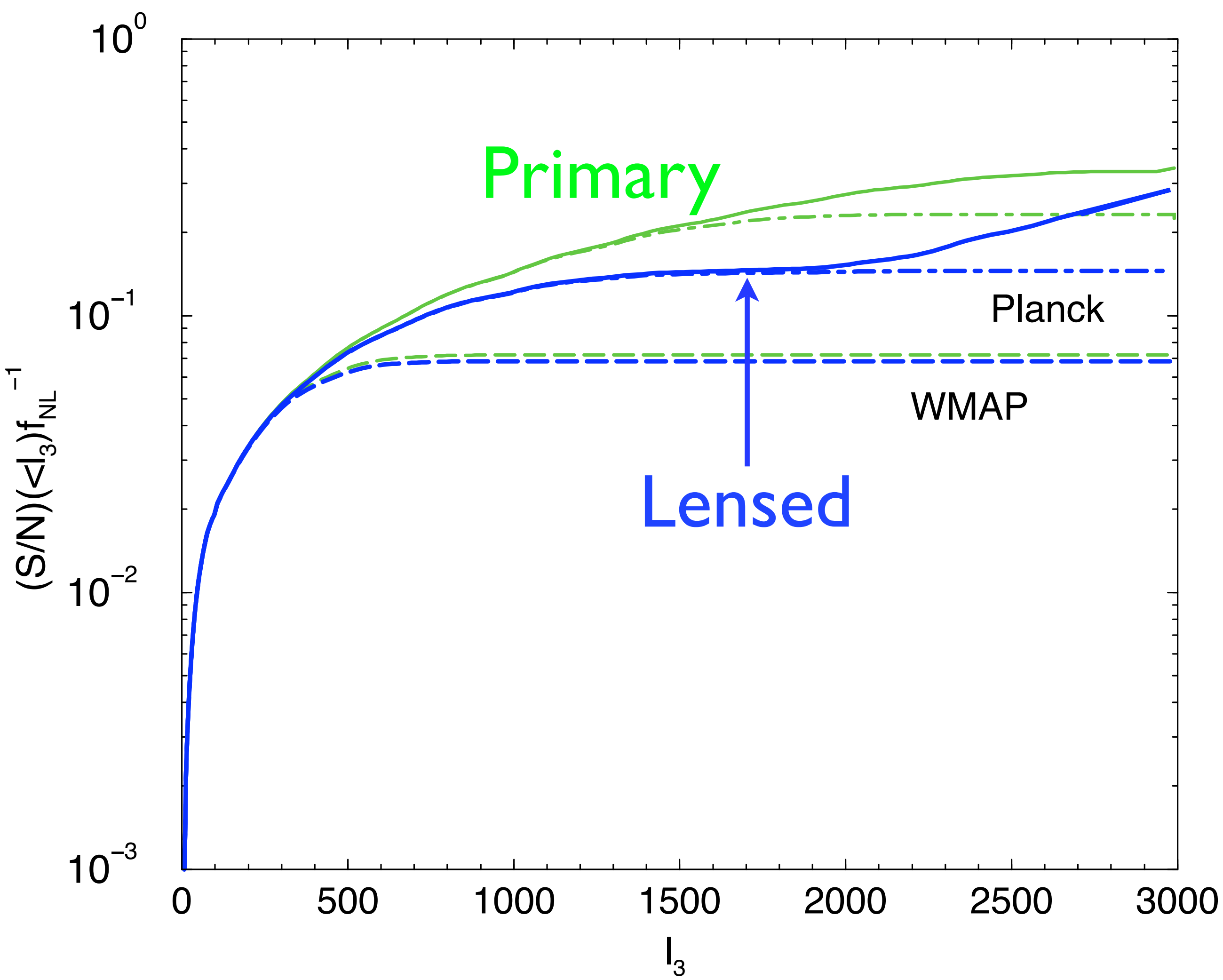


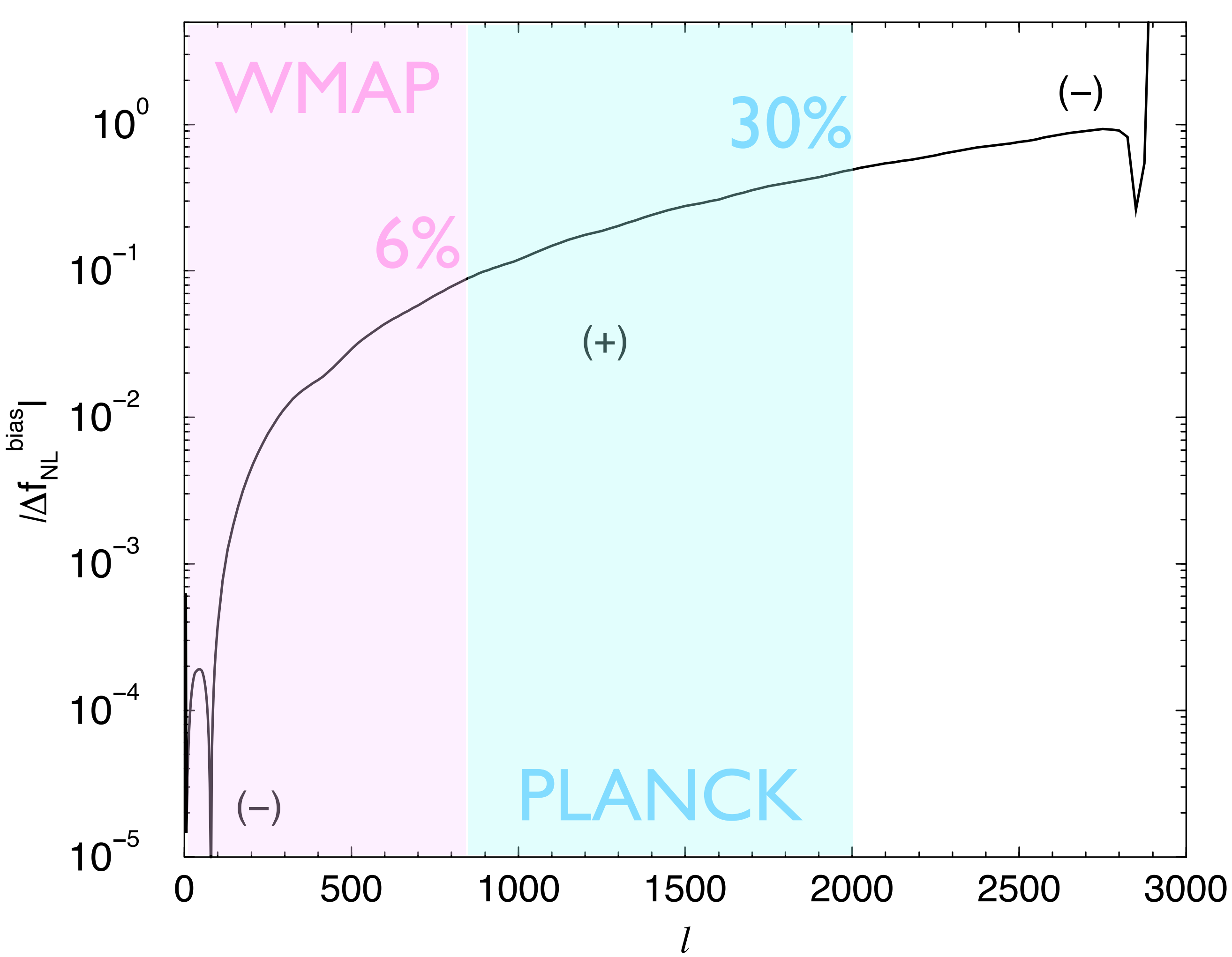


A. Cooray, D.S., P. Serra; PRD, 77, 123006 (2008)

Bias in the Non-Gaussianity Parameter

$$\frac{\Delta f}{\hat{f}_{NL}} \equiv \frac{f_{NL}^{true} - \hat{f}_{NL}}{\hat{f}_{NL}} = 1 - \frac{\sum B^{\Theta}_{l_1 l_2 l_3} \sigma^{-2} \tilde{B}^{\Theta}_{l_1 l_2 l_3}}{\sum B^{\Theta}_{l_1 l_2 l_3} \sigma^{-2} B^{\Theta}_{l_1 l_2 l_3}}$$





Minimum detectable value of f_{NL}
7 (instead of 5) for Planck

A. Cooray, D.S., P. Serra; PRD, 77, 123006 (2008)

At the End of 50 Minutes...

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* 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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EXTRA SLIDES

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

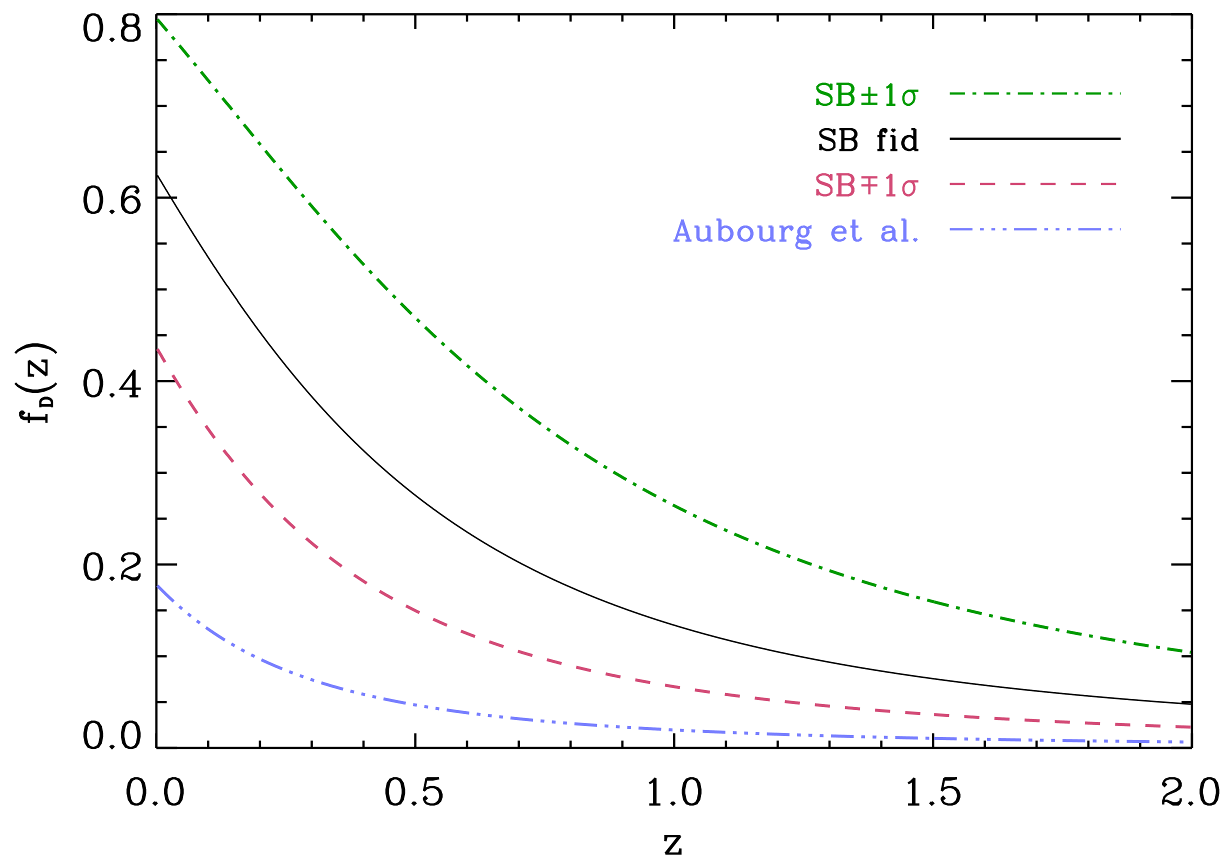
$$\phi(\hat{\mathbf{n}}) = \sum_{lm}\phi_{lm}Y_l^m(\hat{\mathbf{n}}) \qquad \langle\phi_{lm}\phi_{l'm'}\rangle = \delta_{l,l'}\delta_{m,m'}C_l^\phi$$

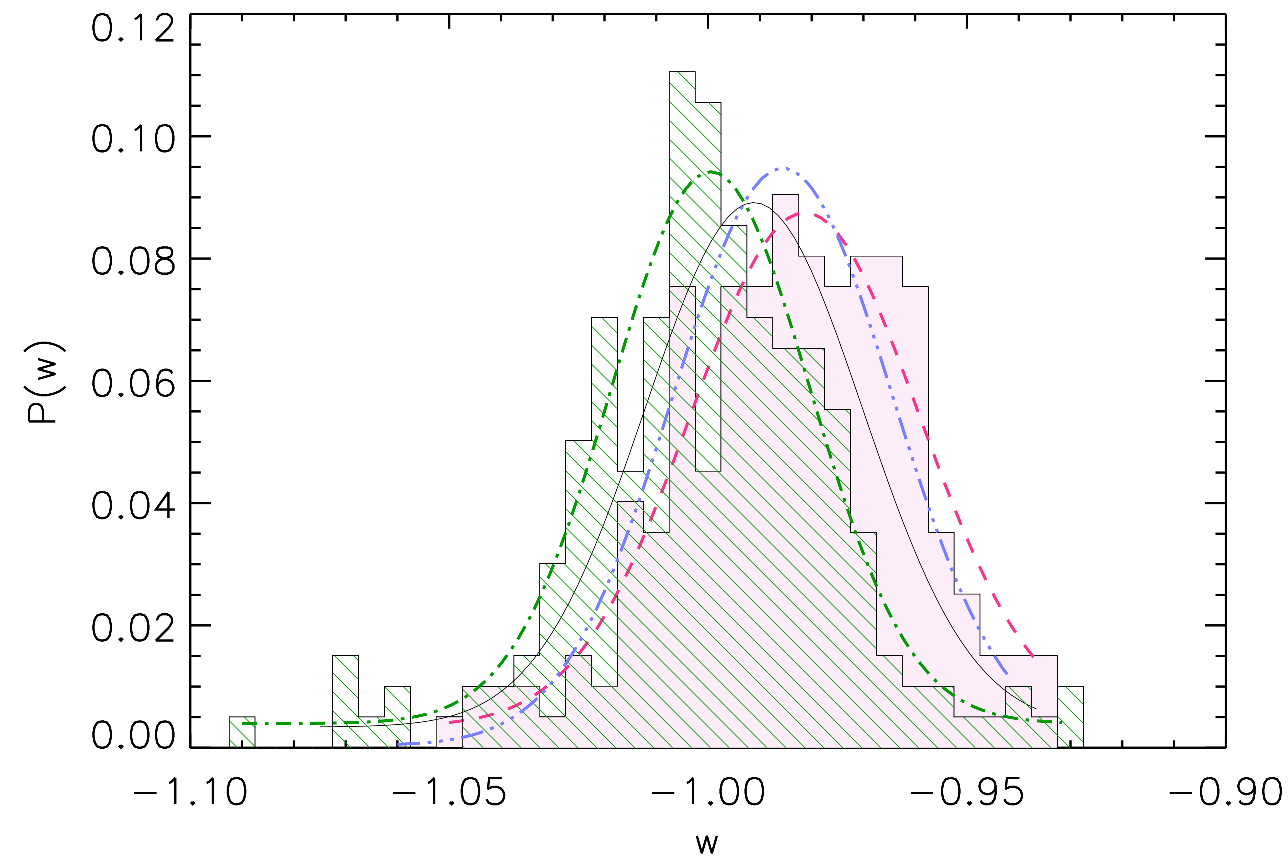
$$C_l^\phi = \frac{2}{\pi}\int k^2 dk P_\Phi(k)[I_l^{len}(k)]^2$$

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

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

Uncertainty in Star Formation: Bias in "w"



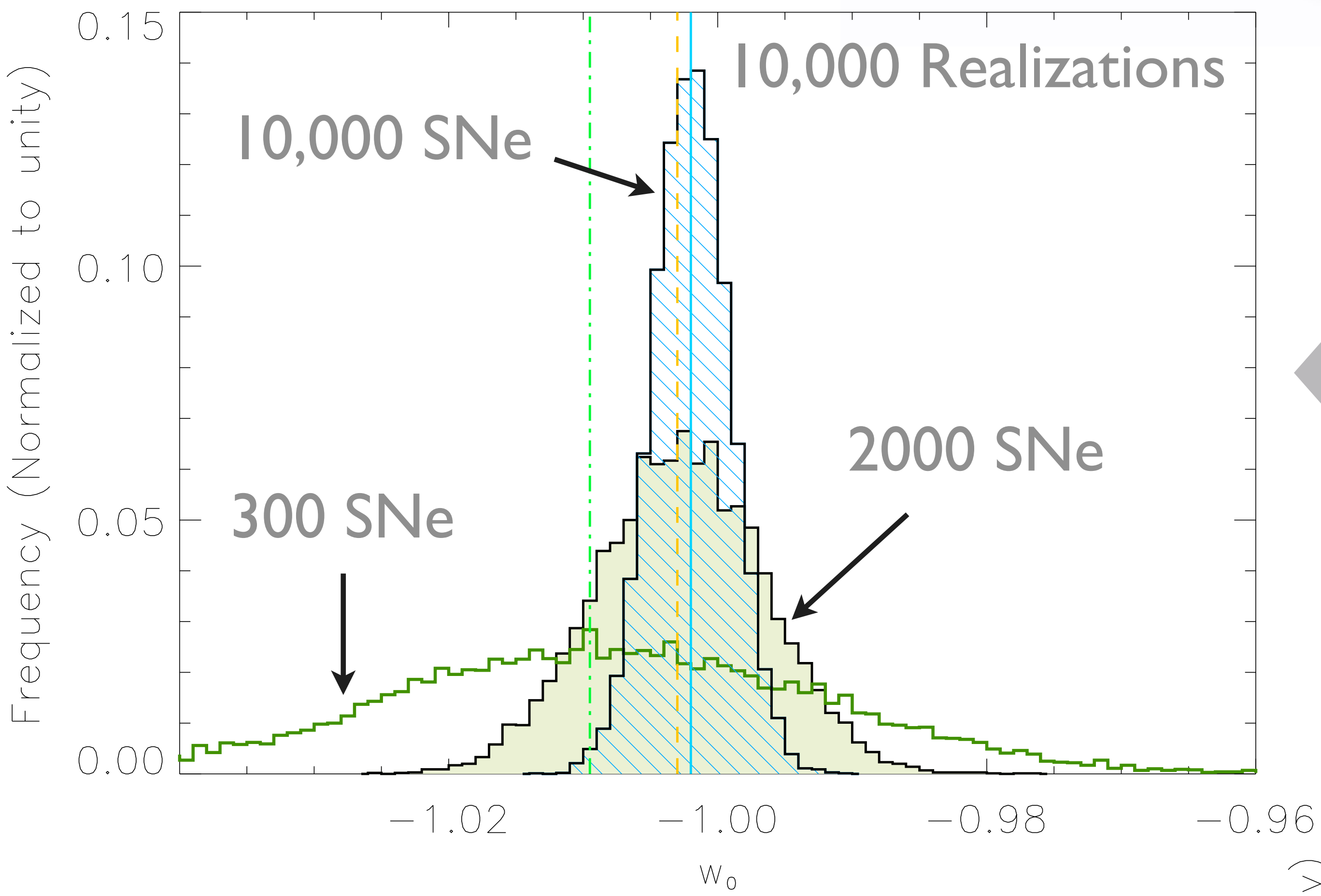


Delayed Fraction

Bias in "w"

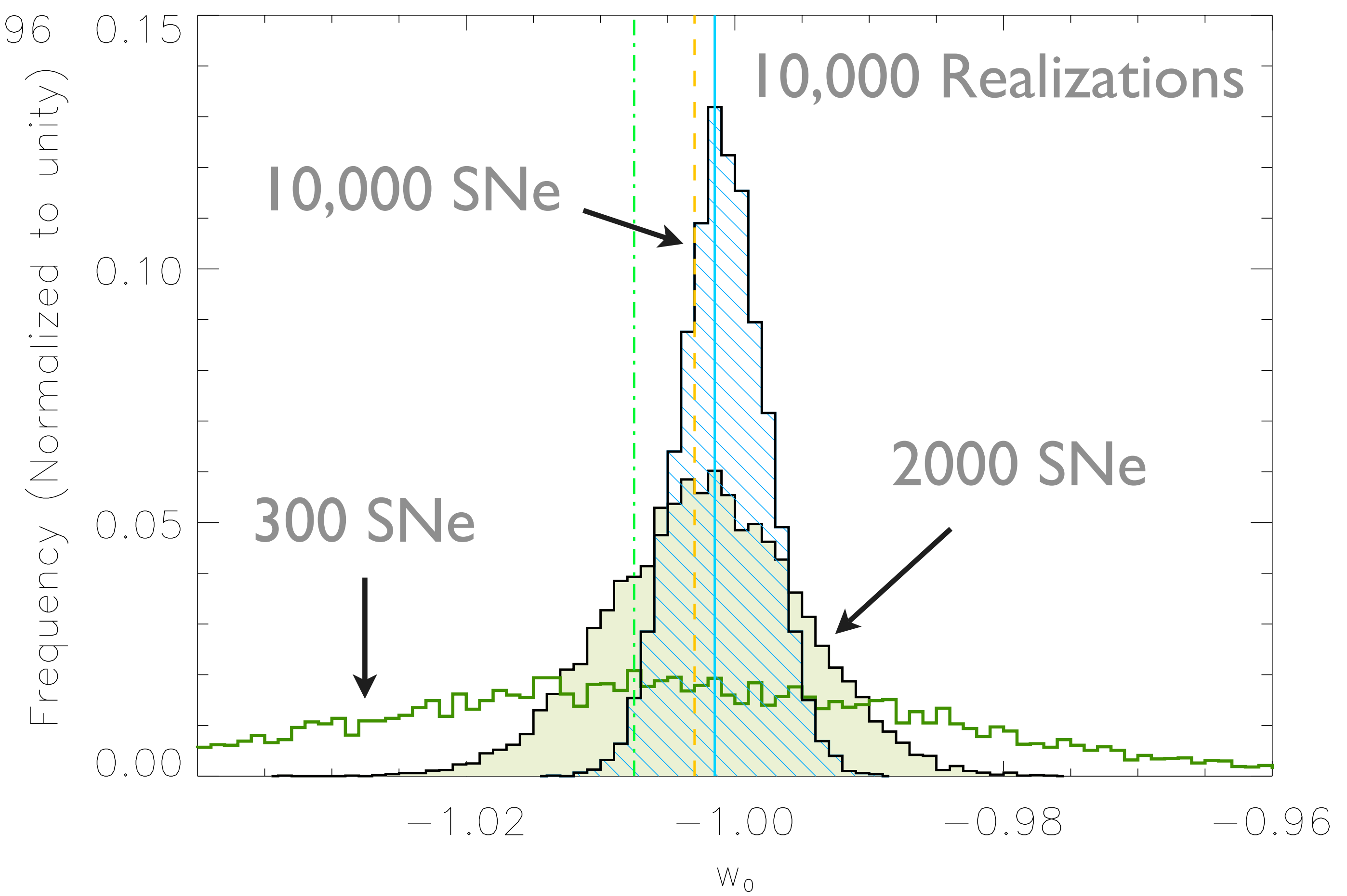
D.S., A. Amblard, A. Cooray, and D. Holz; ApJL, 684, L13 (2008)

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."